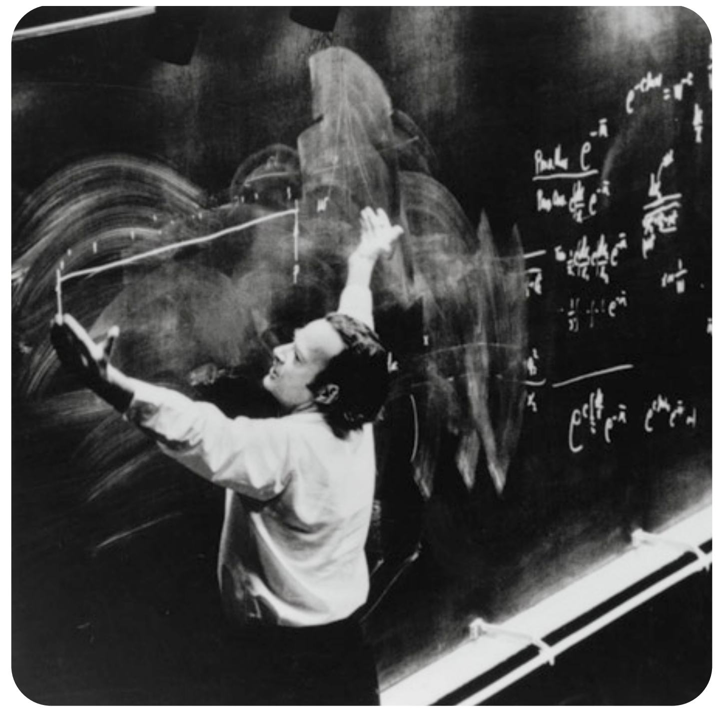
Beyond the SM 1/3



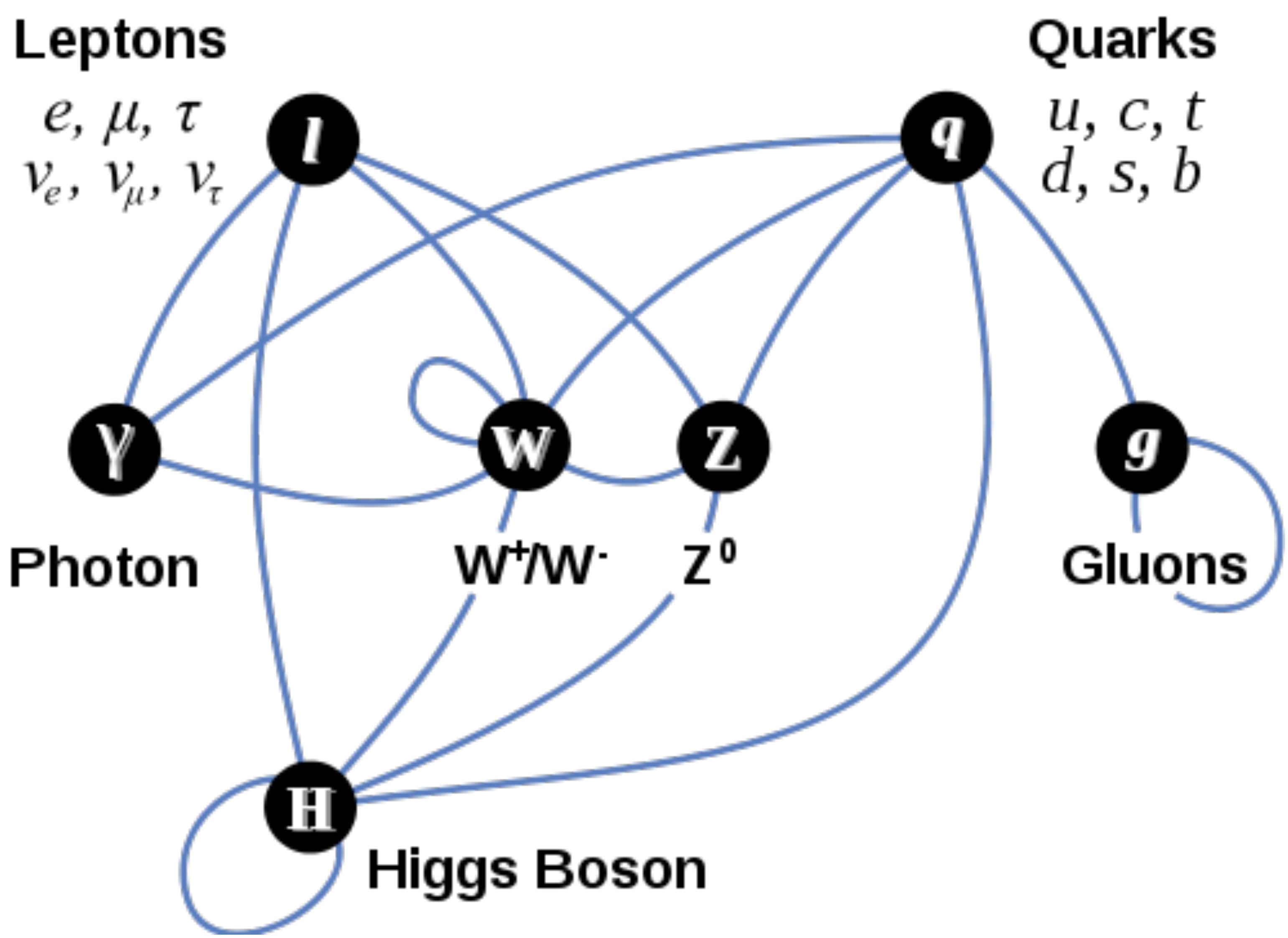
Andreas Weiler
(TU Munich)

BSM is as old as the standard model, giving rise to dominant paradigms (technicolor -> the MSSM & WIMPS -> …) that fill lectures such as these.

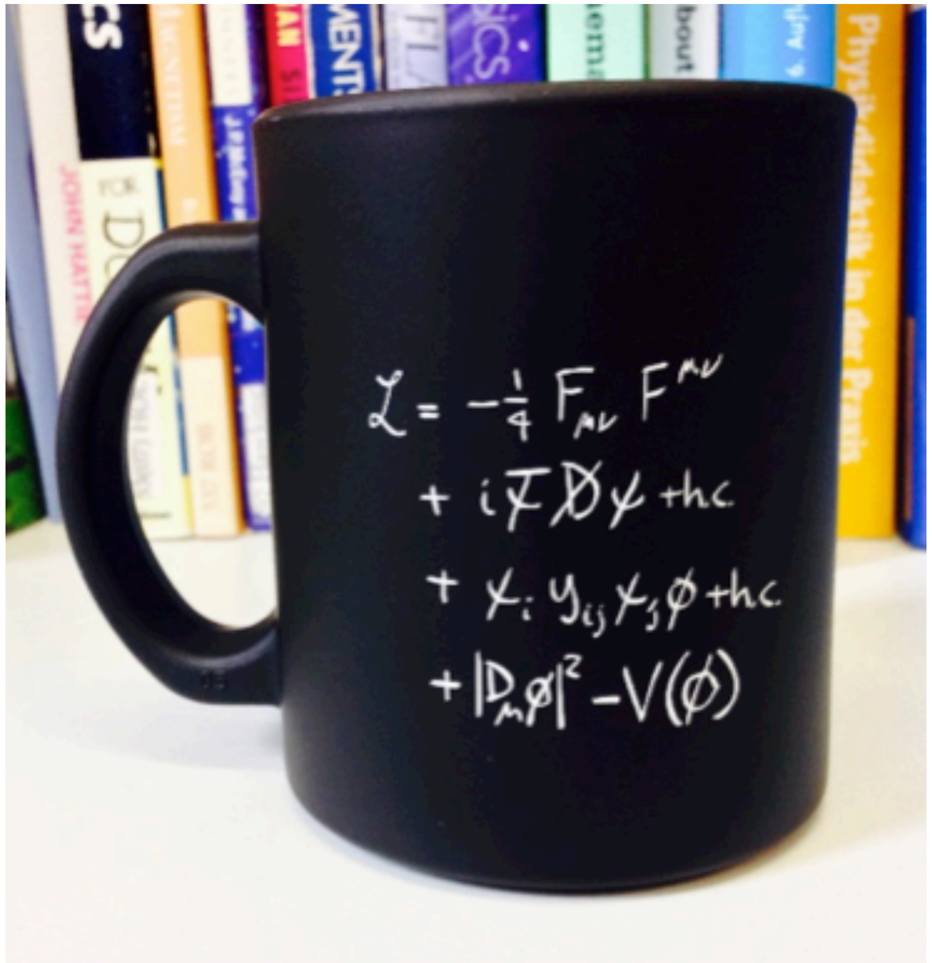
We are in an era rich with data that is challenging these paradigms: keep an eye on promising alternatives.

Prologue: the SM as an EFT

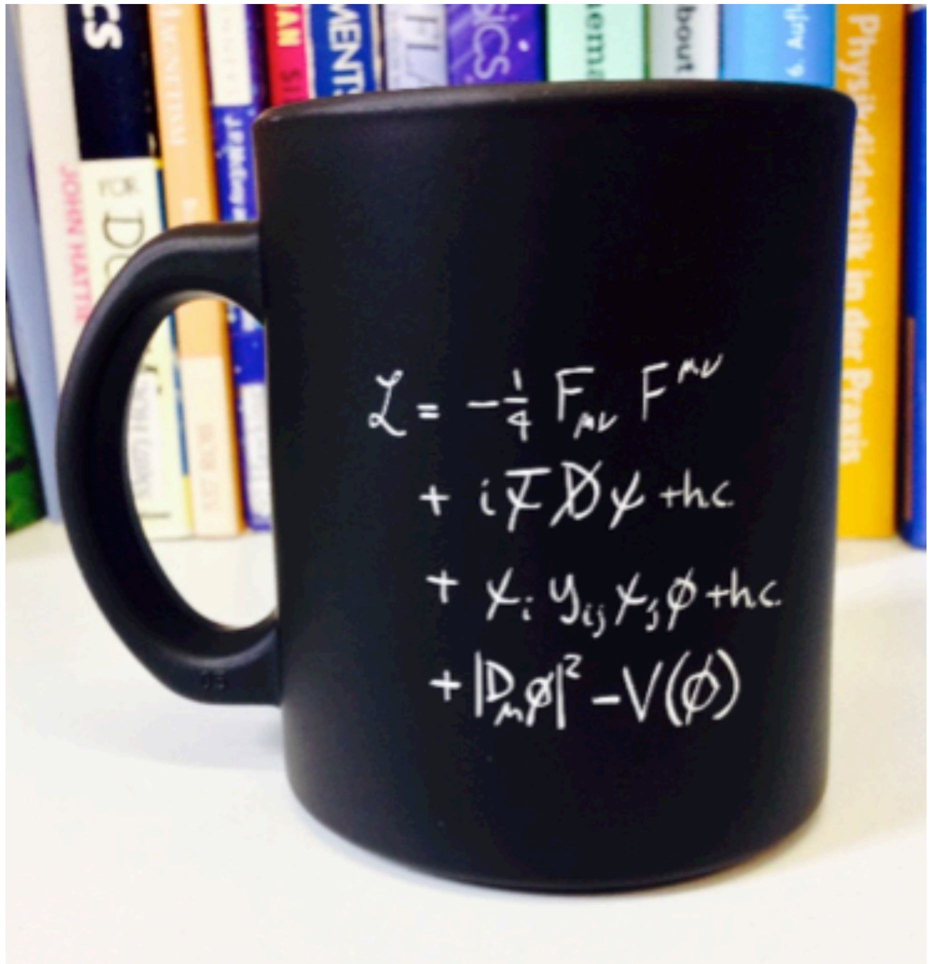
The SM



Leptons
e, μ, τ
ν_e, ν_μ, ν_τ
l
Quarks
u, c, t
d, s, b
q
γ
W
Z
g
Photon
W+/W-
Z 0
Gluons
H
Higgs Boson



SM = all possible **renormalizable** interactions,
allowed by gauge redundancy and field content
("totalitarian principle")



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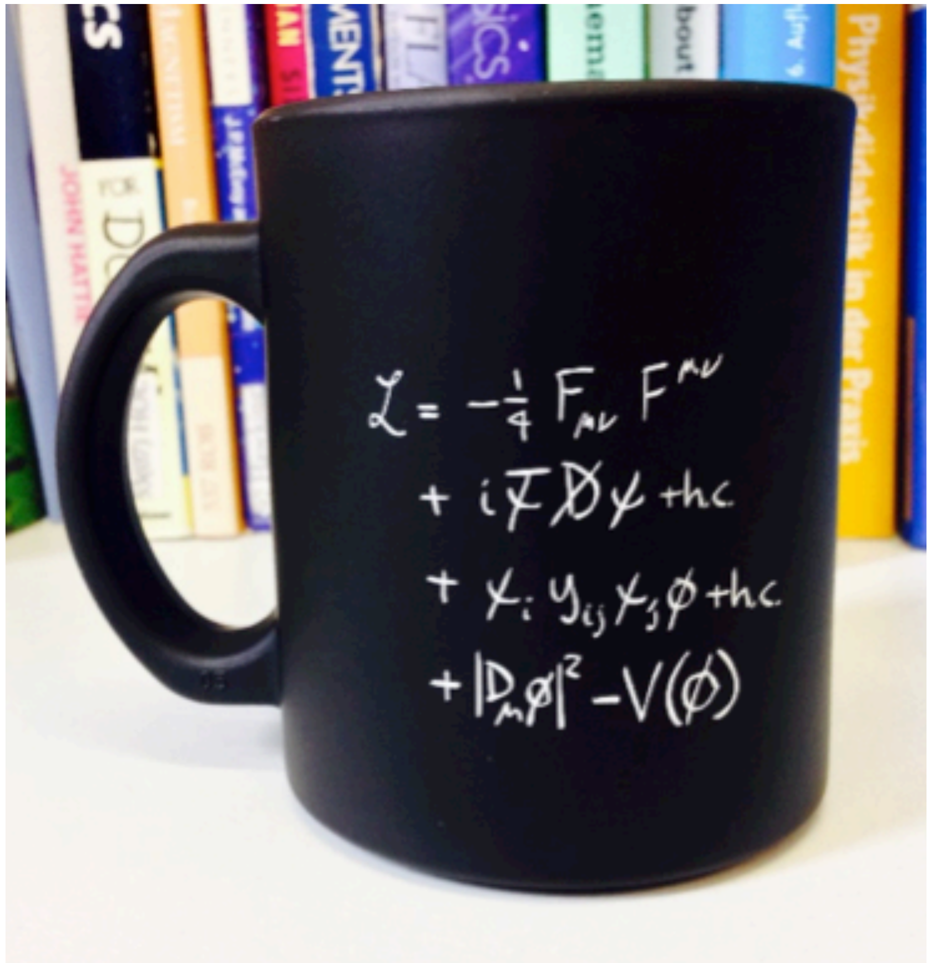
BSM = new fields ***OR*** **irrelevant** operators



$$[\phi] = 1$$

$$\mu^2 \phi^2 \qquad \lambda \phi^4$$

relevant (dim<4) and marginal (dim=4)

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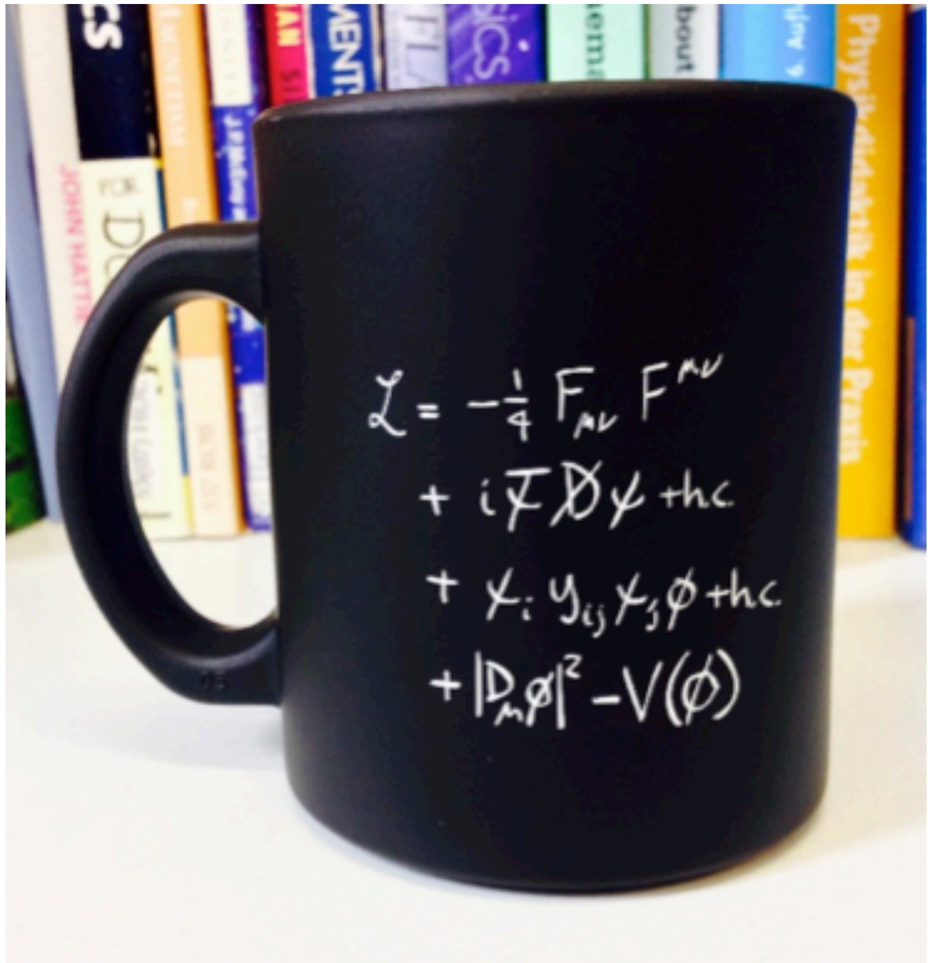

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dim > 4

Irrelevant?

Example: scalar field theory in 4D

$$\int d^4x \left(\frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m^2 \phi^2 - \lambda_3 \, \phi^3 - \lambda_4 \, \phi^4 - \lambda_5 \, \phi^5 + \ldots \right)$$

$$[\phi] = 1 \qquad [\lambda_n] = 4 - n,$$

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Study theory at long distances in scaling limit

$$x^\mu \to l x^\mu, \quad l \to \infty, \quad d^4x \to d^4x\, l^4$$

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Keep canonical kinetic term:

$$\int d^4x \frac{1}{2}\partial_\mu\phi\partial^\mu\phi \to \int d^4x \frac{1}{2} l^2 \partial_\mu\phi\partial^\mu\phi \qquad \Rightarrow \phi'(x) = l^{-1}\phi(x)$$

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$$\to \int d^4x \left(\frac{1}{2}\partial_\mu\phi'\partial^\mu\phi' - \frac{1}{2}m^2 l^2 \phi'^2 - \lambda_3\, l\phi'^3 - \lambda_4\, l^0\phi'^4 - \lambda_5\, l^{-1}\phi'^5 + \ldots \right)$$

Irrelevant!

In long distance / low energy limit, $l \to \infty$

$$\to \int d^4x \left(\frac{1}{2}\partial_\mu \phi' \partial^\mu \phi' - \frac{1}{2} m^2 l^2 \phi'^2 - \lambda_3\, l \phi'^3 - \lambda_4\, l^0 \phi'^4 - \lambda_5\, l^{-1} \phi'^5 + \ldots \right)$$

Relevant operators: importance grows — marginal constant — irrelevant shrinks

Since $[\lambda_5] = -1$ with dimensionless coupling $\tilde{\lambda}_5$ and scale *M*

$$-\frac{\tilde{\lambda}_5}{M}\, l^{-1} \phi'^5 + \ldots$$ for $l \gg 1/M$ term is irrelevant

can also see as small effective coupling $\lambda_5^{\text{eff}} = \frac{\tilde{\lambda}_5}{lM} \ll 1$

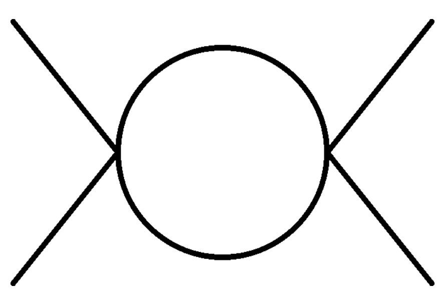
Renormalizable

Historically, imposed renormalizability to preserve **predictivity**.

If only marginal and relevant operators: counterterms to absorb infinities are also only from marginal & relevant set.

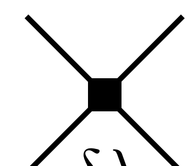
Recall: 1) loops introduce divergencies, 2) remove with counter-terms, 3) fix counterterms with data.

IN OUR EXAMPLE, DIVERGENCE FROM MARGINAL/RELEVANT OPERATORS IS



$$\sim \lambda^2 \int \frac{d^4k}{k^4} \sim \lambda^2 \log \Lambda$$

$\Rightarrow$NEED COUNTERTERM

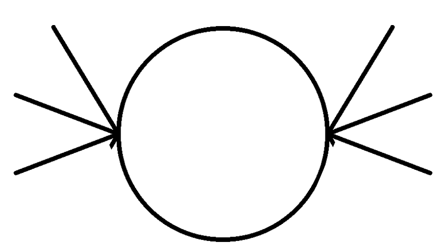


$\delta\lambda$

RENORMALIZES THE MARGINAL OPERATOR

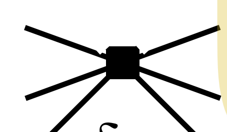
$$\lambda\phi^4$$

BUT IRRELEVANT OPERATOR ϕ^5 GENERATES



$$\sim \lambda_5^2 \int \frac{d^4k}{k^4} \sim \lambda_5^2 \log \Lambda$$

$\Rightarrow$NEED COUNTERTERM



$\delta\rho$

RENORMALIZES *NEW* IRRELEVANT OPERATOR

$$\lambda_6\phi^6$$

Adding ϕ^5 operator, generates ϕ^6, and so on ad infinitum. Infinite measurements needed to fix all counterterms… ?!

Can we live with a non-renormalizable theory?

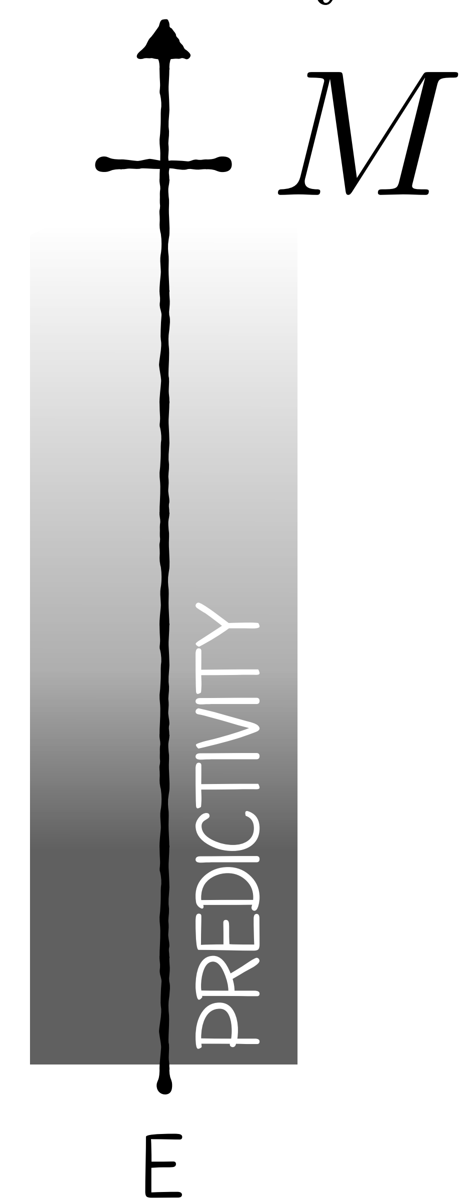
$$-\frac{\tilde{\lambda}_5}{M}\, l^{-1} \phi'^5 + \ldots$$ with energy of experiment $$E = \frac{1}{l}$$

$$-\tilde{\lambda}_5 \frac{E}{M} \phi'^5 - \tilde{\lambda}_6 \frac{E^2}{M^2} \phi'^6 + \ldots$$

As long as we work with $E \ll M$

can ignore ϕ^6 term, relative to leading ϕ^5

expansion in $(E/M)^n$ <- powercounting



Standard model as an EFT

Why worry about non-renormalizable operators in SM? Reason:

The SM is not UV complete!

1) Gravity requires UV completion

irrelevant op.

$$S_{\mathrm{EH}} = -\frac{M_{pl}^2}{2}\int d^4x\sqrt{-g}R \sim \int d^4x \left(\frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{M_{pl}} h^2 \Box h + \dots\right)$$

2) We know we need to add more fields to SM, given evidence on dark matter, inflation, …

Bottom-up EFT

UNDERLYING THEORY IS UNKNOWN OR MATCHING IS TOO DIFFICULT TO CARRY OUT

$$\sum_n \mathcal{L}_{low}^{(n)}$$

$$\boxed{\begin{array}{c} ??? \\ \downarrow \\ \text{Theory 2} \end{array}}$$

WRITE DOWN ALL INTERACTIONS CONSISTENT W/ SYMMETRIES. COUPLINGS NOT PREDICTED, BUT FIT TO DATA.

E.G. CHIRAL LAGRANGIAN, QUANTUM EINSTEIN GRAVITY, OR **STANDARD MODEL**

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6} + \ldots$$

EFT contains most general departure from SM at low-E,

2499 distinct operators (at D <= 6):

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu \tau^I q_r)(\bar q_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu \tau^I l_r)(\bar q_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$				

Buchmüller, Wyler ‘86
B. Grzadkowski et al’10, etc

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$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\,\varphi)(\bar l_p \tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\,\varphi)(\bar q_p \tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

Include gravity: GRSMEFT

Ruhdorfer, Serra, AW '19

Parametrization of all the physically distinct low-energy deviations from fundamental interactions known to date:

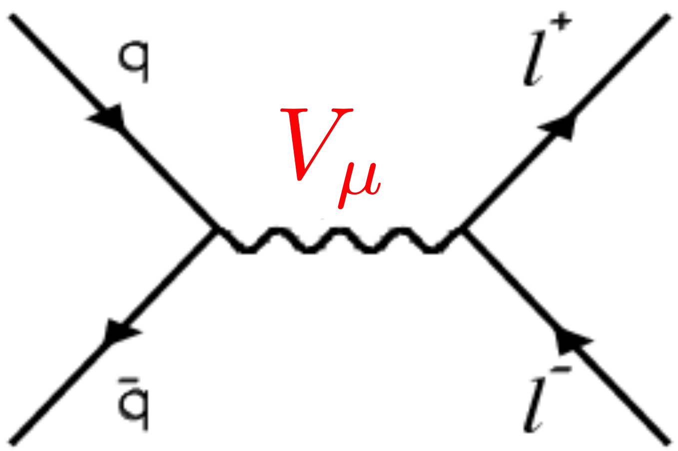
$$
\begin{aligned}
\mathcal{L}_6 = \;& \frac{c_1}{\Lambda^2} C_{\mu\nu}{}^{\rho\sigma} C^{\mu\nu\alpha\beta} C_{\alpha\beta\rho\sigma} + \frac{\tilde{c}_1}{\Lambda^2} C_{\mu\nu}{}^{\rho\sigma} C^{\mu\nu\alpha\beta} \tilde{C}_{\alpha\beta\rho\sigma} \\
& + \frac{c_2}{\Lambda^2} H^\dagger H C_{\mu\nu\rho\sigma} C^{\mu\nu\rho\sigma} + \frac{\tilde{c}_2}{\Lambda^2} H^\dagger H C_{\mu\nu\rho\sigma} \tilde{C}^{\mu\nu\rho\sigma} \\
& + \frac{c_3}{\Lambda^2} B^{\mu\nu} B^{\rho\sigma} C_{\mu\nu\rho\sigma} + \frac{\tilde{c}_3}{\Lambda^2} B^{\mu\nu} B^{\rho\sigma} \tilde{C}_{\mu\nu\rho\sigma} + \frac{c_4}{\Lambda^2} G^{\mu\nu} G^{\rho\sigma} C_{\mu\nu\rho\sigma} + \frac{\tilde{c}_4}{\Lambda^2} G^{\mu\nu} G^{\rho\sigma} \tilde{C}_{\mu\nu\rho\sigma} \\
& + \frac{c_5}{\Lambda^2} W^{\mu\nu} W^{\rho\sigma} C_{\mu\nu\rho\sigma} + \frac{\tilde{c}_5}{\Lambda^2} W^{\mu\nu} W^{\rho\sigma} \tilde{C}_{\mu\nu\rho\sigma} \,.
\end{aligned}
$$

*Use Weyl-tensor instead of Riemann, since in vac: $R_{\mu\nu} = R = 0$

$$C_{\mu\nu\rho\sigma} \equiv R_{\mu\nu\rho\sigma} - \left(g_{\mu[\rho} R_{\sigma]\nu} - g_{\nu[\rho} R_{\sigma]\mu}\right) + \frac{1}{3} g_{\mu[\rho} g_{\sigma]\nu} R \,,$$

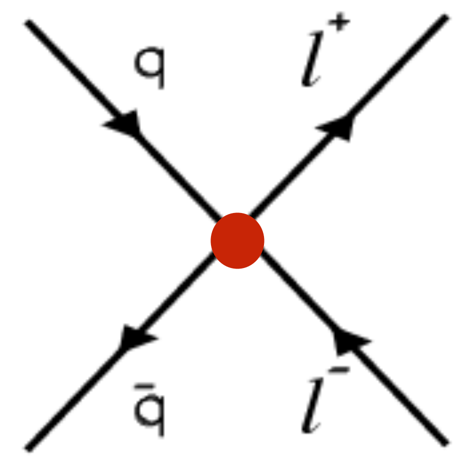
Top-down EFT

Full theory



$$\xrightarrow{q^2 \ll m_V^2}$$

EFT



$$g_q g_f \frac{-i g_{\mu\nu}}{q^2 - m_V^2 + i m \Gamma}$$

$$\tilde{c}\,(\bar{q}\gamma^\mu q)(\bar{l}\gamma_\mu l)$$

with $\tilde{c} = -\frac{g_q g_f}{m_V^2} = \frac{c}{\Lambda^2}$

Enormous reduction of complexity (& loss of information)

EFT Exercise

- *Lorentz structure?* Integrate out a scalar field and vector field (interaction D<=4) coupled to fermions and derive the EFT.

- Bonus: do it in two different ways! (Feynman matching and EOM method).

Power of indirect searches

- Using EFT, can catch new physics by its tail

Power of indirect searches

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Power of indirect searches

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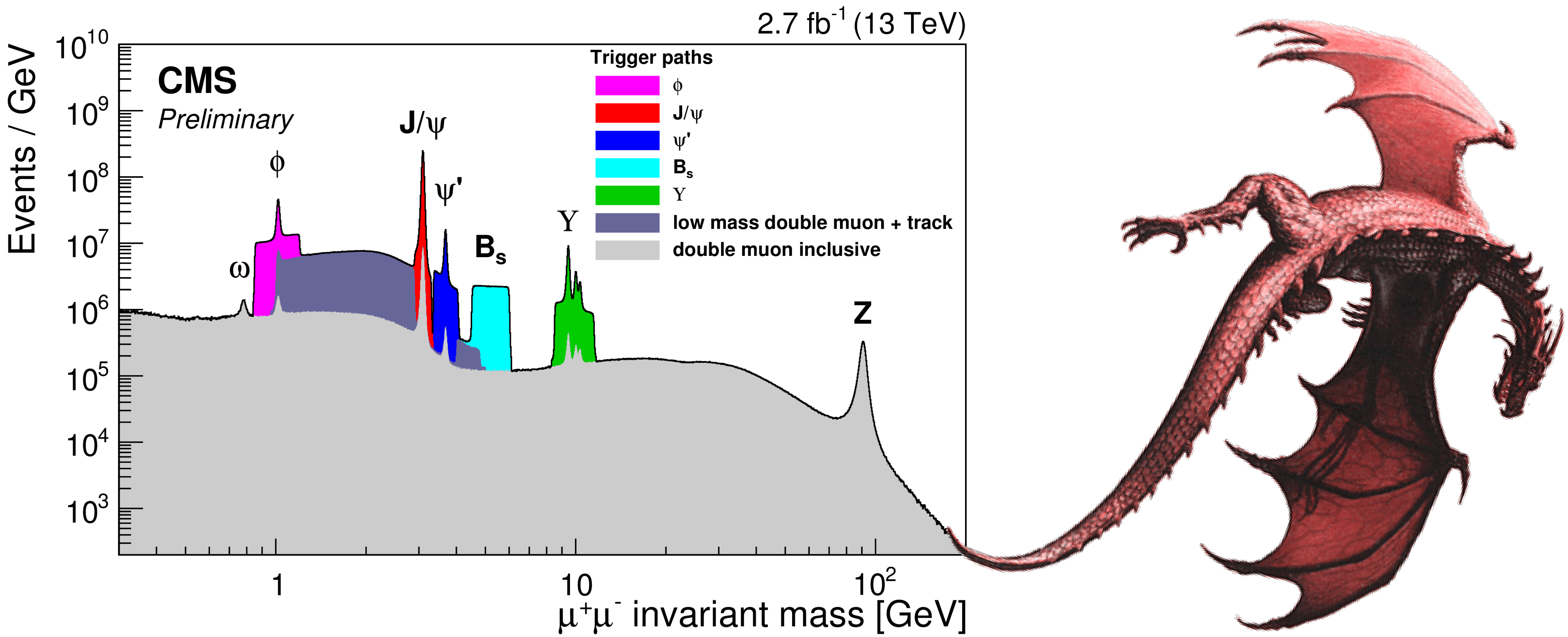
Power of indirect searches

- Using EFT, can catch new physics by its tail



If scale of new physics beyond kinematic reach, EFT systematically captures information about BSM in a *model-independent* way. Easy to recast.

Only requirement: $\Lambda \gg E_{\text{experiment}}$

Which operators are important?

- For a given process, only a small number of EFT operators contribute
- Ignore those already very constrained:
  LEP Z-Pole, low-energy precision experiments
- Find convenient parametrization which makes poorly constrained directions obvious

How can we test EFTs?

- Precision
- Energy

Precision

Focus on EW sector:

Measure at fixed energy scale:

- Higgs, Z, t decays
- Inclusive SM x-sec's

$$E \sim \mu_{\rm SM}$$

$$\frac{\sigma}{\sigma_{\rm SM}} = \left| 1 + c\, \frac{\mu_{\rm SM}^2}{\Lambda^2} \right|^2$$

Precision

Measure at fixed energy scale:

Focus on EW sector:

- Higgs, Z, t decays
- Inclusive SM x-sec's

$$E \sim \mu_{\rm SM} \qquad\qquad \frac{\sigma}{\sigma_{\rm SM}} = \left| 1 + c\, \frac{\mu_{\rm SM}^2}{\Lambda^2} \right|^2$$

If we can reach 1% precision in $\frac{\sigma}{\sigma_{\rm SM}}$, translates to*

$$\delta \sim \left(\frac{m_h}{\Lambda}\right)^2 \longrightarrow \Lambda \sim 1.2\,\mathrm{TeV}$$

Ultimately limited by systematics, but useful for poorly constrained directions (e.g. pp->HH).

Energy

Look into high-E tails of distributions, e.g. m_{ll}, $p_T(H)$, …

$$E \sim m_{ll} \gg \mu_{\mathrm{SM}} \qquad\qquad \frac{\sigma}{\sigma_{\mathrm{SM}}} = \left| 1 + c\,\frac{E^2}{\Lambda^2} \right|^2$$

Energy

Look into high-E tails of distributions, e.g. m_{ll}, $p_T(H)$, …

$$E \sim m_{ll} \gg \mu_{\mathrm{SM}} \qquad \frac{\sigma}{\sigma_{\mathrm{SM}}} = \left| 1 + c\,\frac{E^2}{\Lambda^2} \right|^2$$

Can reach large scales, even if precision is low,

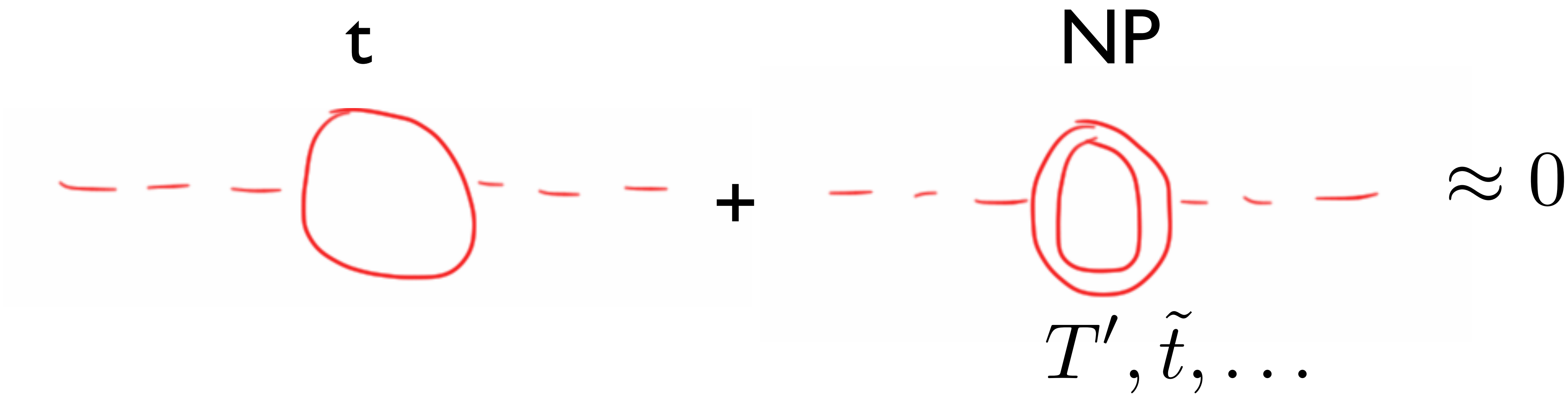
$$\delta \sim \left(\frac{E}{\Lambda}\right)^2 \quad \xrightarrow[E\,=\,1\,\mathrm{TeV}]{\delta\,\sim\,10\%} \quad \Lambda \sim 3\,\mathrm{TeV}$$

Additional benefit: often probes new directions

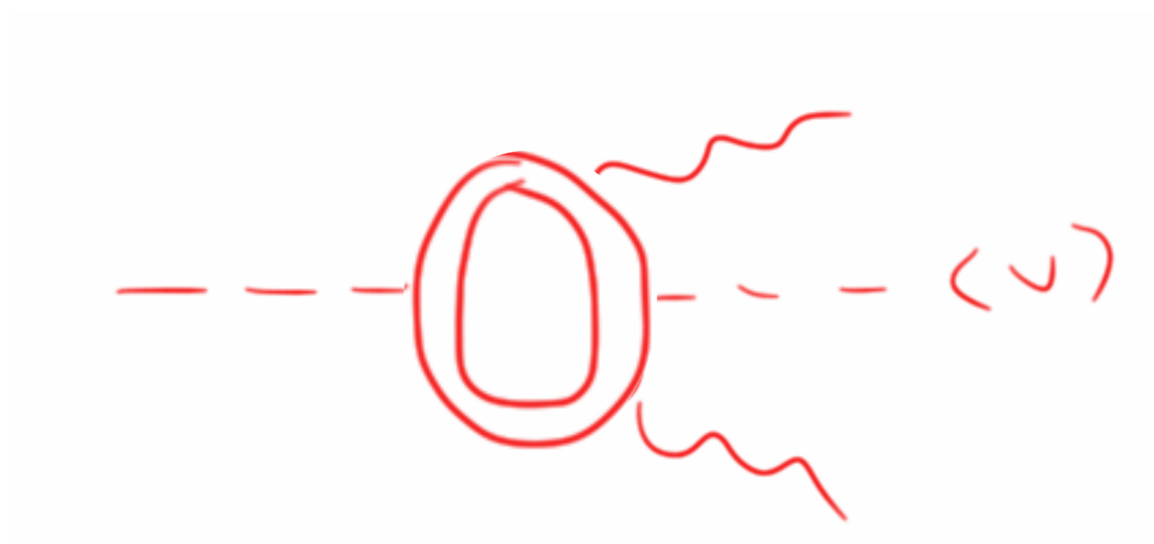
Example: single Higgs

$$\sigma(pp \to h + X)$$

The hierarchy problem…

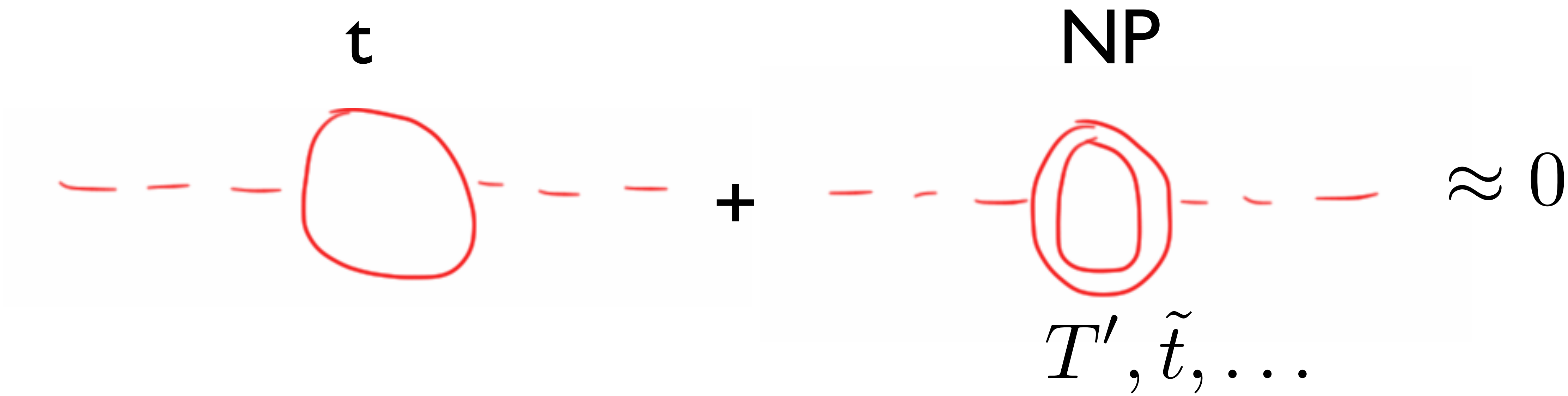


… motivates deviations in

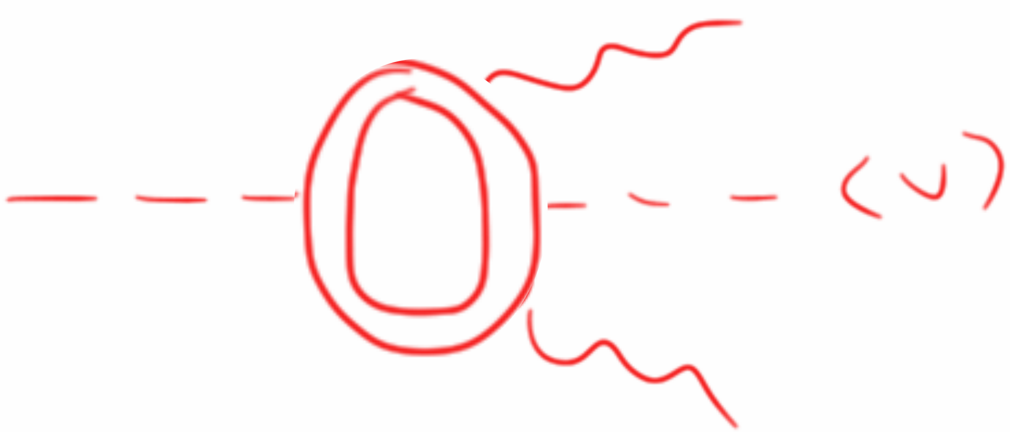


see e.g. Low, Vichi, Rattazzi

The hierarchy problem…



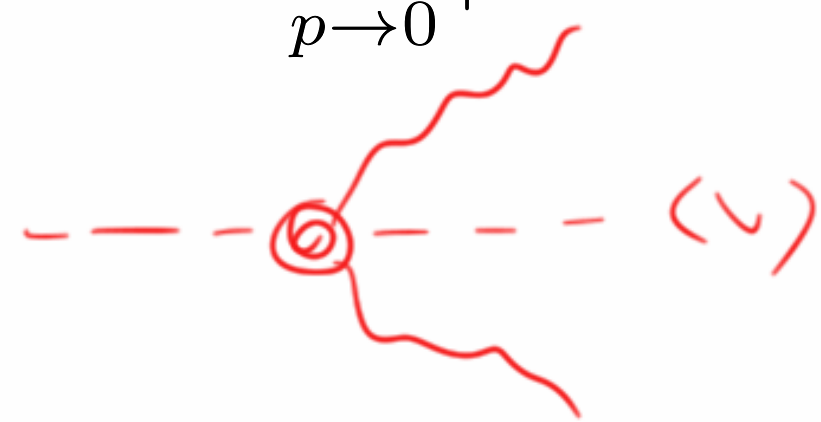
… motivates deviations in



see e.g. Low, Vichi, Rattazzi

… but we actually measure:

$$\propto \lim_{p \to 0} |\mathrm{SM} + \mathrm{NP}|^2$$



Inclusive Higgs

$$\mathcal{O}_t = \frac{y_t}{v^2}|H|^2\bar{Q}_L\tilde{H}t_R\,, \qquad \mathcal{O}_g = \frac{\alpha_s}{12\pi v^2}|H|^2 G^a_{\mu\nu}G^{a\,\mu\nu}\,,$$

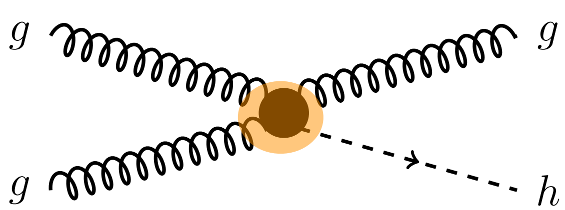
$$\mu_{\rm incl}(c_t, k_g) = \frac{\sigma^{\rm BSM}_{\rm incl}(c_t, k_g)}{\sigma^{\rm SM}_{\rm incl}} = (c_t + k_g)^2$$

Precision only : a degenerate direction!

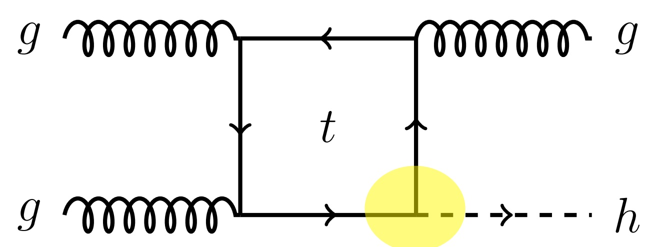
Composite Higgs predicts: $c_t \approx -k_g$

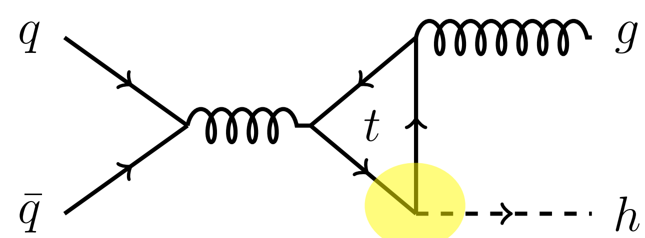
Use Energy: p_T(H)

UV

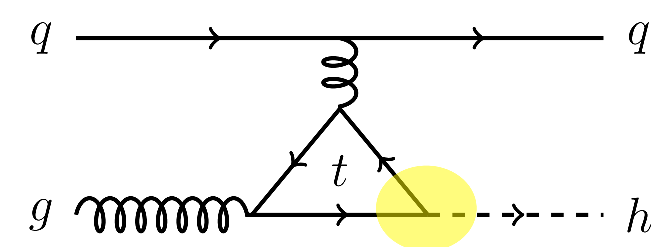


vs.





IR



$$\hat{\sigma}_{p_T^{min}}(c_t, k_g, \hat{s}) \propto \frac{1}{16\,\pi\,\hat{s}^2} \int_{t_{min}}^{t_{max}} \mathrm{d}t \, \left| c_t \mathcal{M}_{IR} + k_g \mathcal{M}_{UV} \right|^2$$

$$t_{\substack{min \\ max}} = \frac{1}{2}\left(m_h^2 - \hat{s} \mp \sqrt{m_h^4 - 2\,\hat{s}\,(m_h^2 + 2\,(p_T^{min})^2) + \hat{s}^2} \right)$$

Grojean, Schlaffer, Salvioni, AW

Grojean, Schlaffer, Salvioni, AW

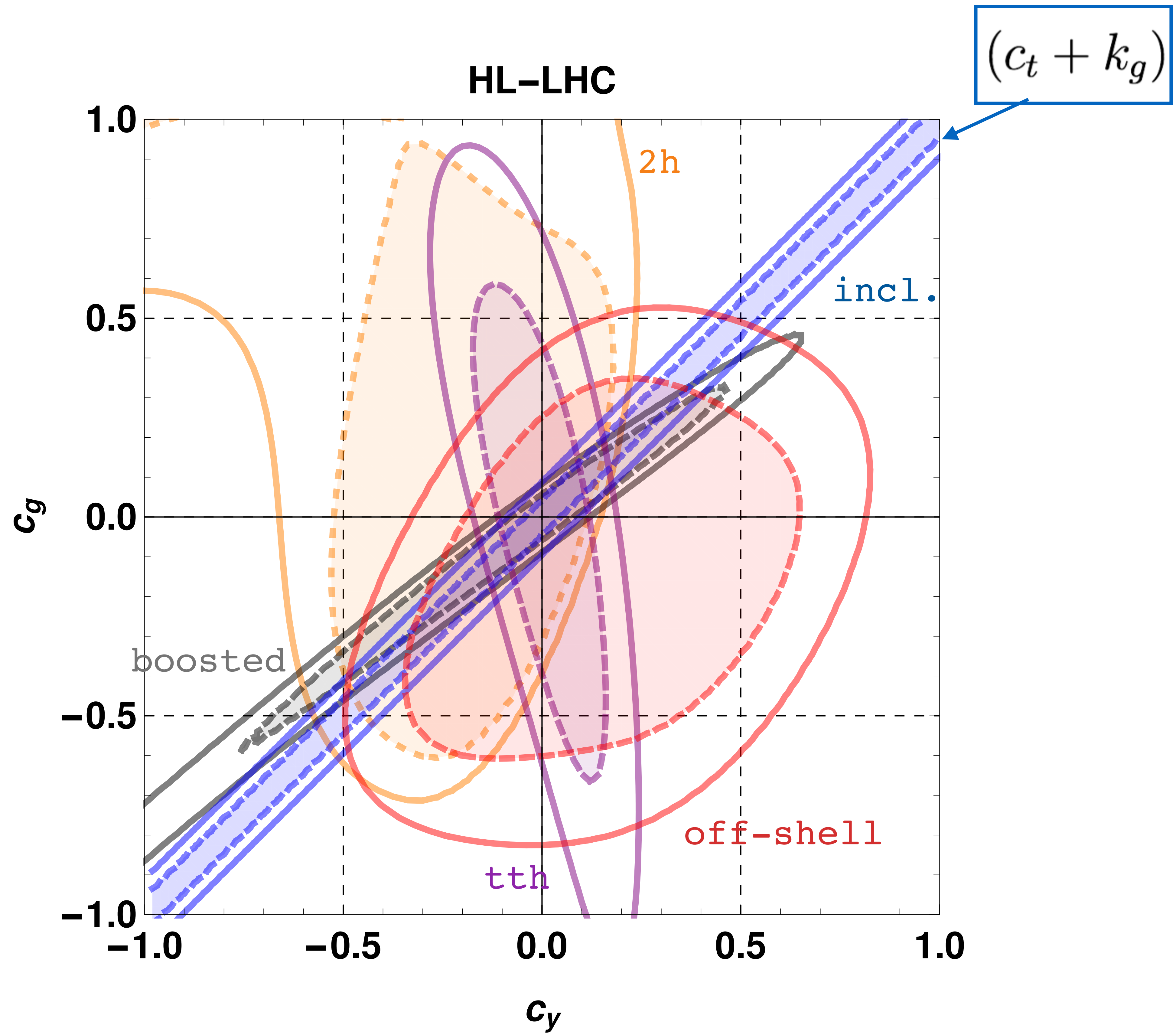
$$\frac{\sigma_{p_T^{min}}(c_t, k_g)}{\sigma^{SM}_{p_T^{min}}} = (c_t + k_g)^2 + \delta\, c_t\, k_g + \kappa\, k_g^2$$

degeneracy

$$\sigma_{p_T^{min}}(c_t, k_g) = \int_{s_{min}/s}^{1} \mathrm{d}\tau\, \mathcal{L}_{part}(\tau)\, \hat{\sigma}_{p_T^{min}}(c_t, k_g, \tau\, s)$$

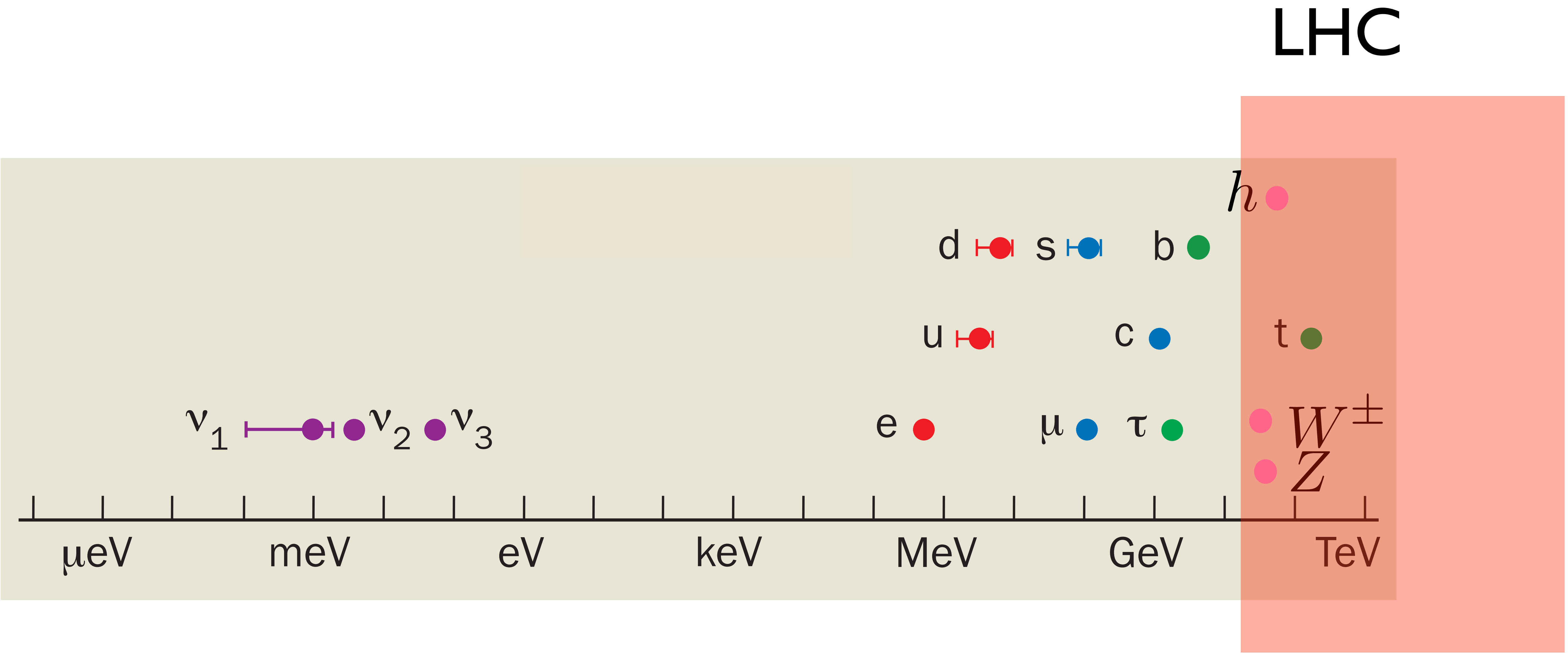
resolve UV vs IR

p_T^{min} [GeV]	$\sigma^{SM}_{p_T^{min}}$ $[fb]$	δ	κ
100	2200	0.016	0.023
150	840	0.069	0.13
200	350	0.20	0.31
250	160	0.39	0.56
300	75	0.61	0.89
350	38	0.86	1.3
400	20	1.1	1.8
450	11	1.4	2.3
500	6.3	1.7	2.9
550	3.7	2.0	3.6
600	2.2	2.3	4.4
650	1.4	2.6	5.2
700	0.87	3.0	6.2
750	0.56	3.3	7.2
800	0.37	3.7	8.4



Updated version of: Azatov, Grojean,Paul, Salvioni '16

The energy frontier



What can we expect to discover?

Before LHC

theorists' statements

Supersymmetry is right
around the corner

Dark matter is a WIMP
and we'll produce it at LHC

We'll see non-SM CP and
flavor violation

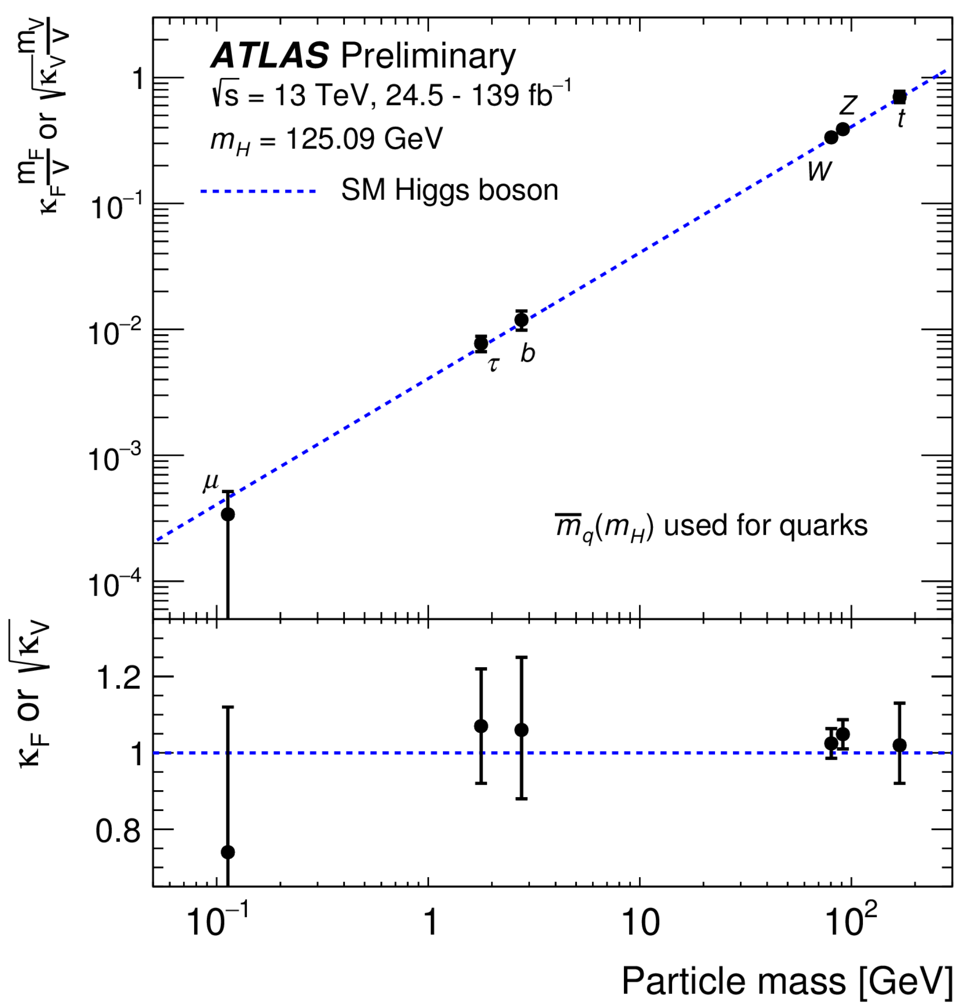
Extra-dimensions will
manifest itself through KK-states

We'll have a portal
to hidden sectors

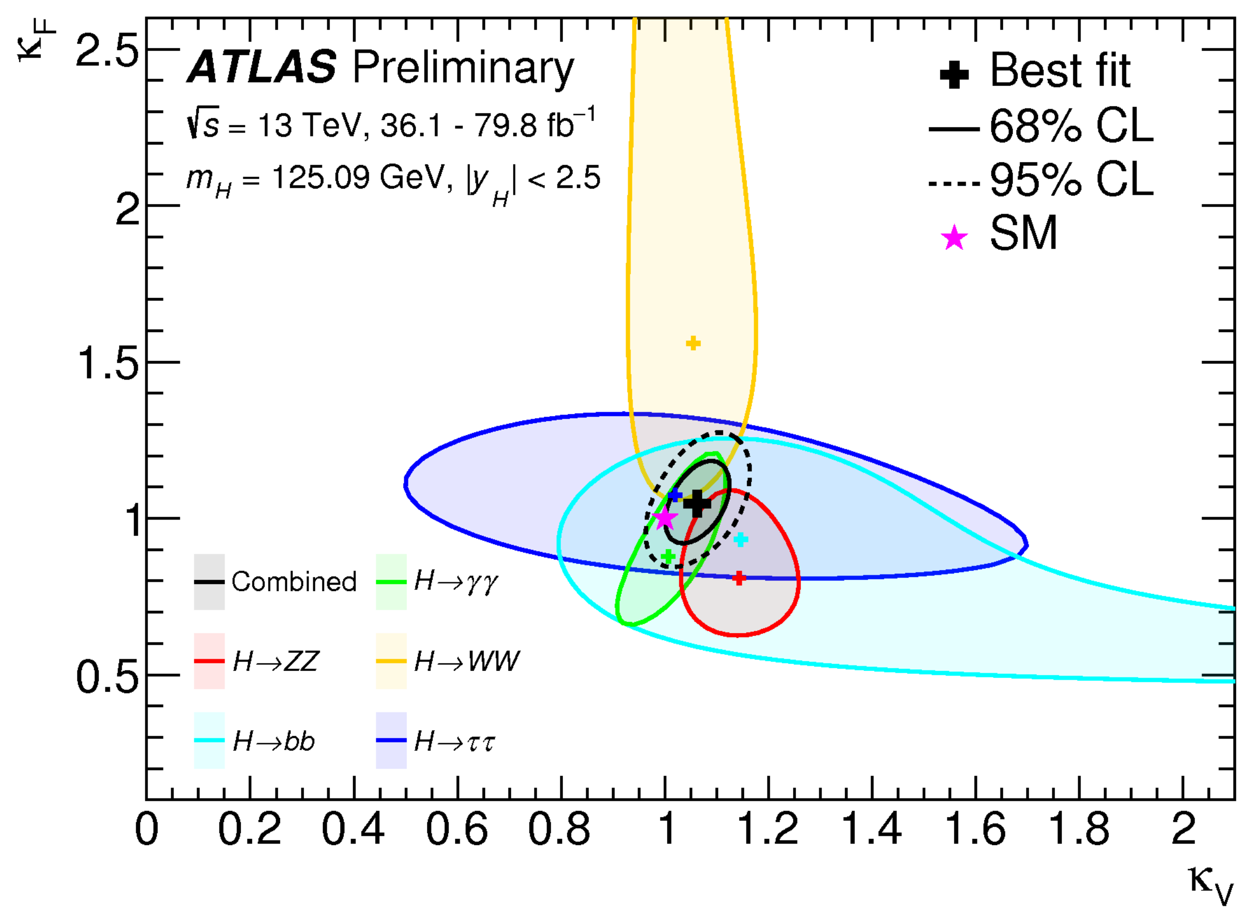
Higgs

Related to EWSB

coupling λ



mass (GeV)

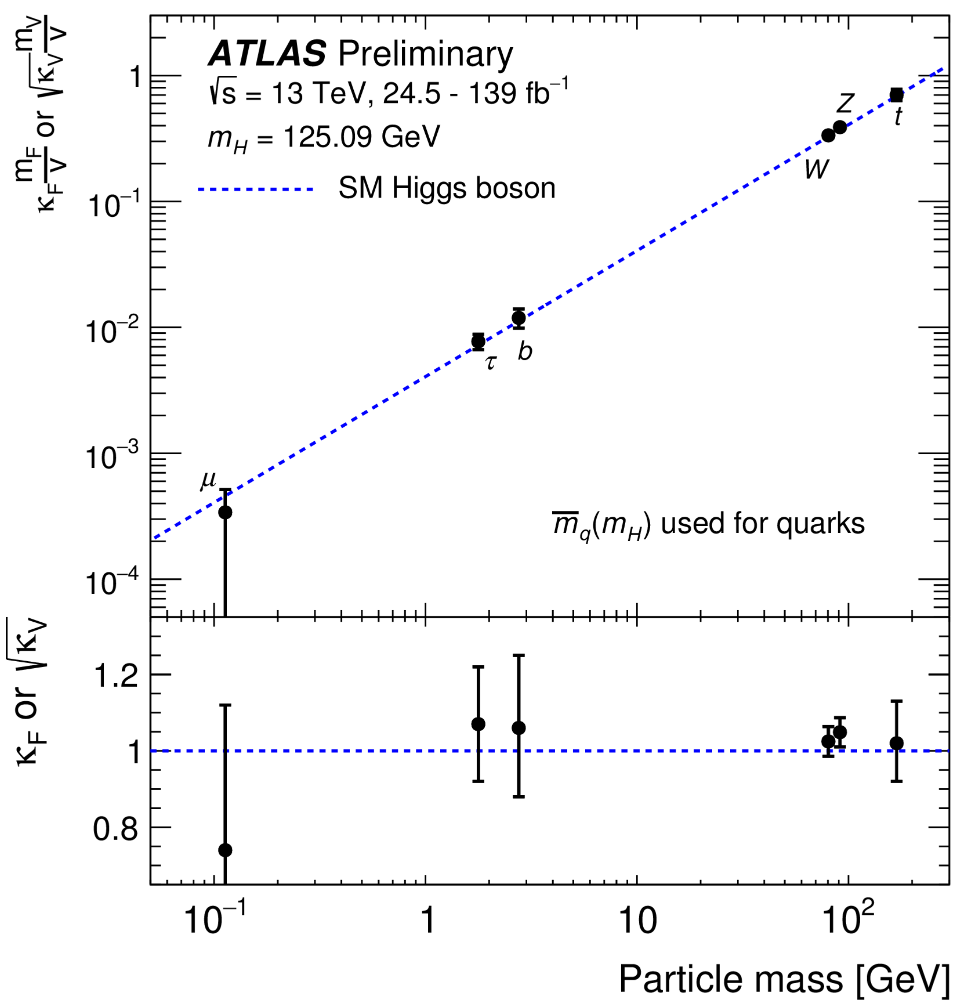


$$\lambda_\psi \propto \frac{m_\psi}{v}\,, \qquad \lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2}$$

Higgs

Related to EWSB

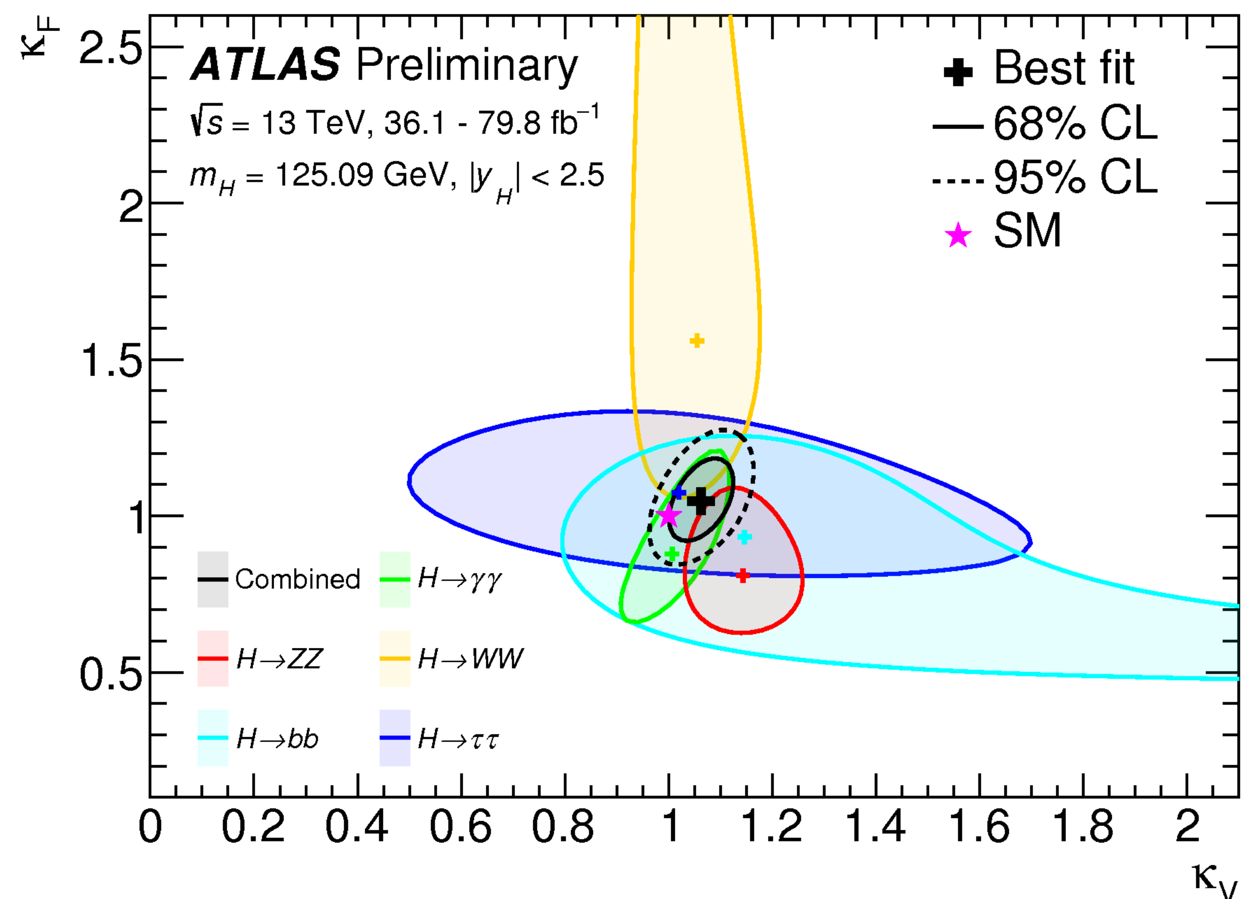
coupling λ



mass (GeV)

$$\lambda_\psi \propto \frac{m_\psi}{v}\,, \qquad \lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2}$$

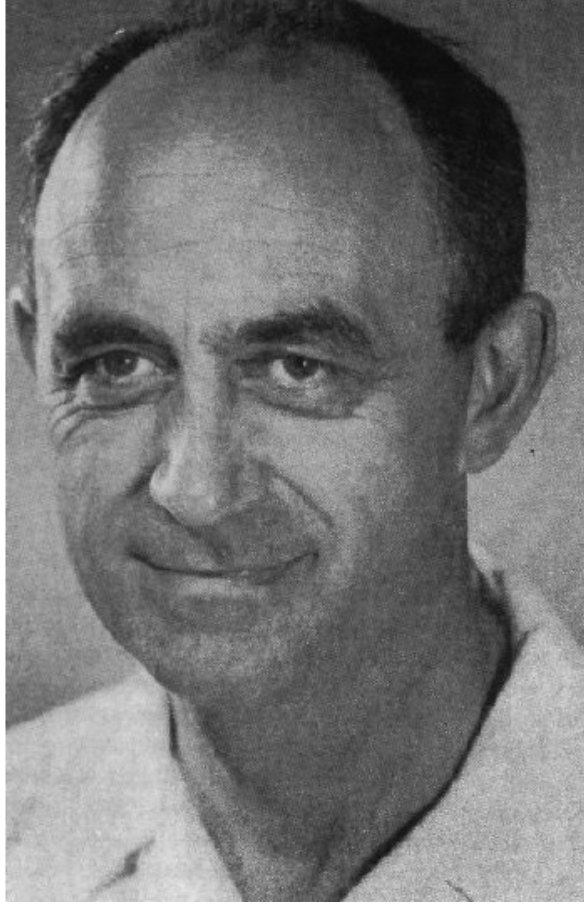
overall compatible w/ SM



Good time for BSM?

- Fundamental scalars abound (Higgs, inflation)
- Are we done?

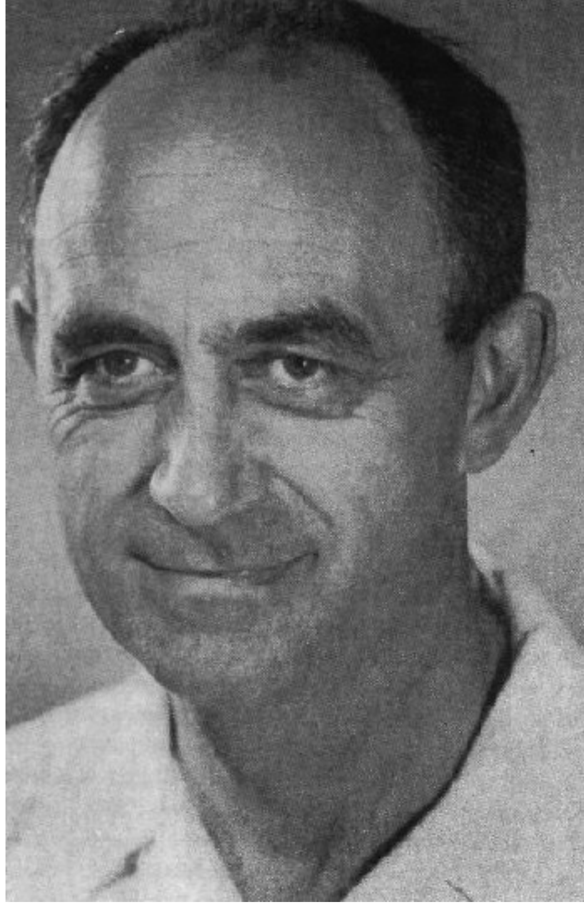
Fermi theory



G_F

$$\frac{g^2}{M_W^2}(\bar{\nu}_\mu \gamma_L^\alpha \mu)(\bar{e}\gamma_L^\alpha \nu_e)$$

Fermi theory

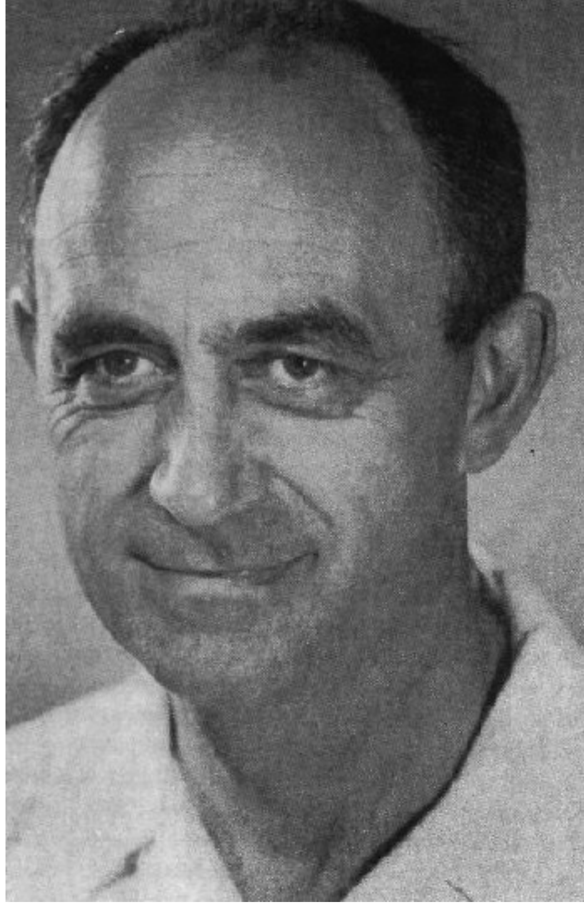


G_F

$$\frac{g^2}{M_W^2}(\bar{\nu}_\mu \gamma_L^\alpha \mu)(\bar{e}\gamma_L^\alpha \nu_e)$$

scale!

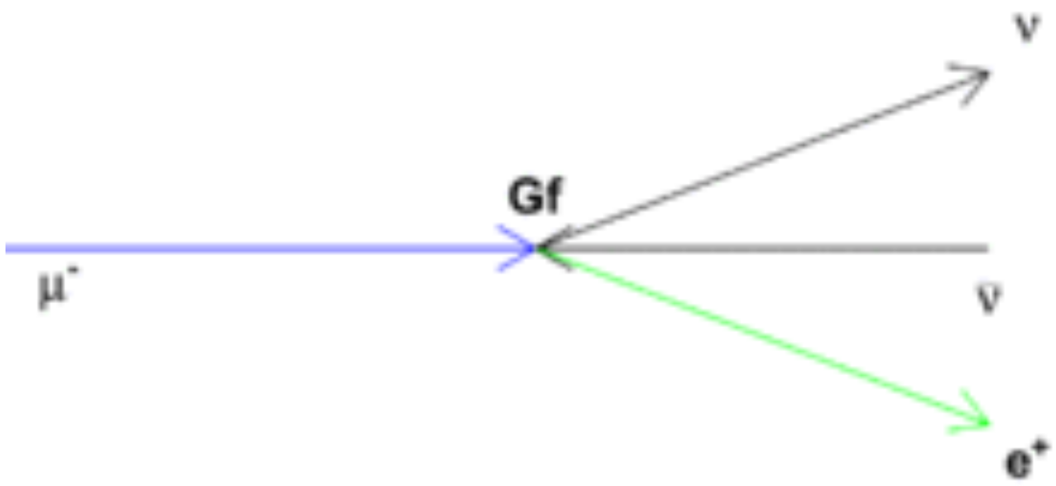
Fermi theory



G_F

$$\frac{g^2}{M_W^2}(\bar{\nu}_\mu \gamma_L^\alpha \mu)(\bar{e}\gamma_L^\alpha \nu_e)$$

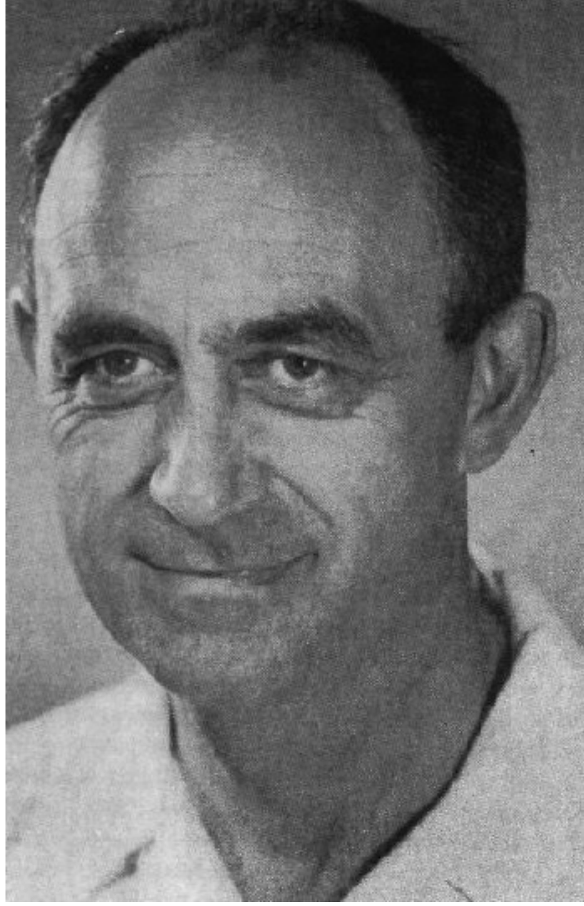
scale!



dimensional analysis

$$\sigma \propto \frac{g^4}{M_W^4} E^2$$

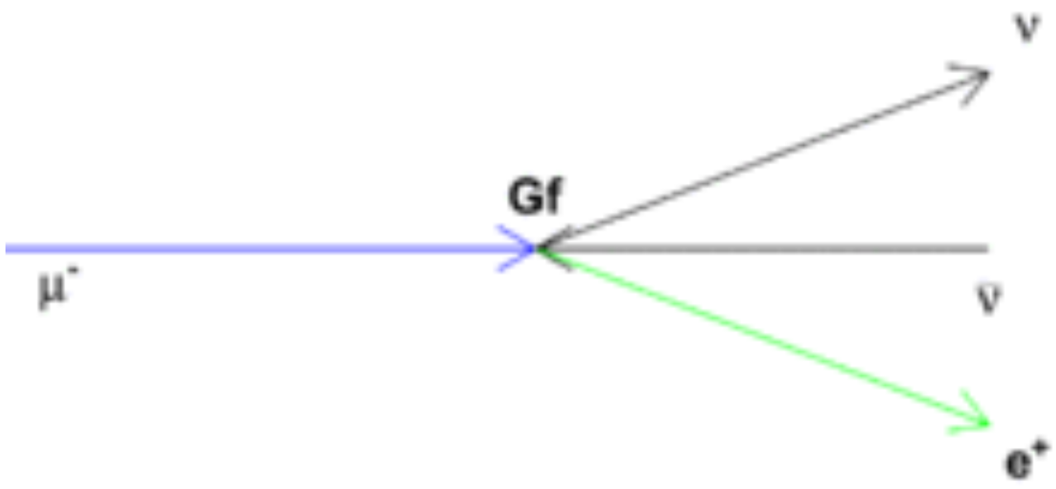
Fermi theory



$$G_F$$

$$\frac{g^2}{M_W^2}(\bar{\nu}_\mu \gamma_L^\alpha \mu)(\bar{e}\gamma_L^\alpha \nu_e)$$

scale!

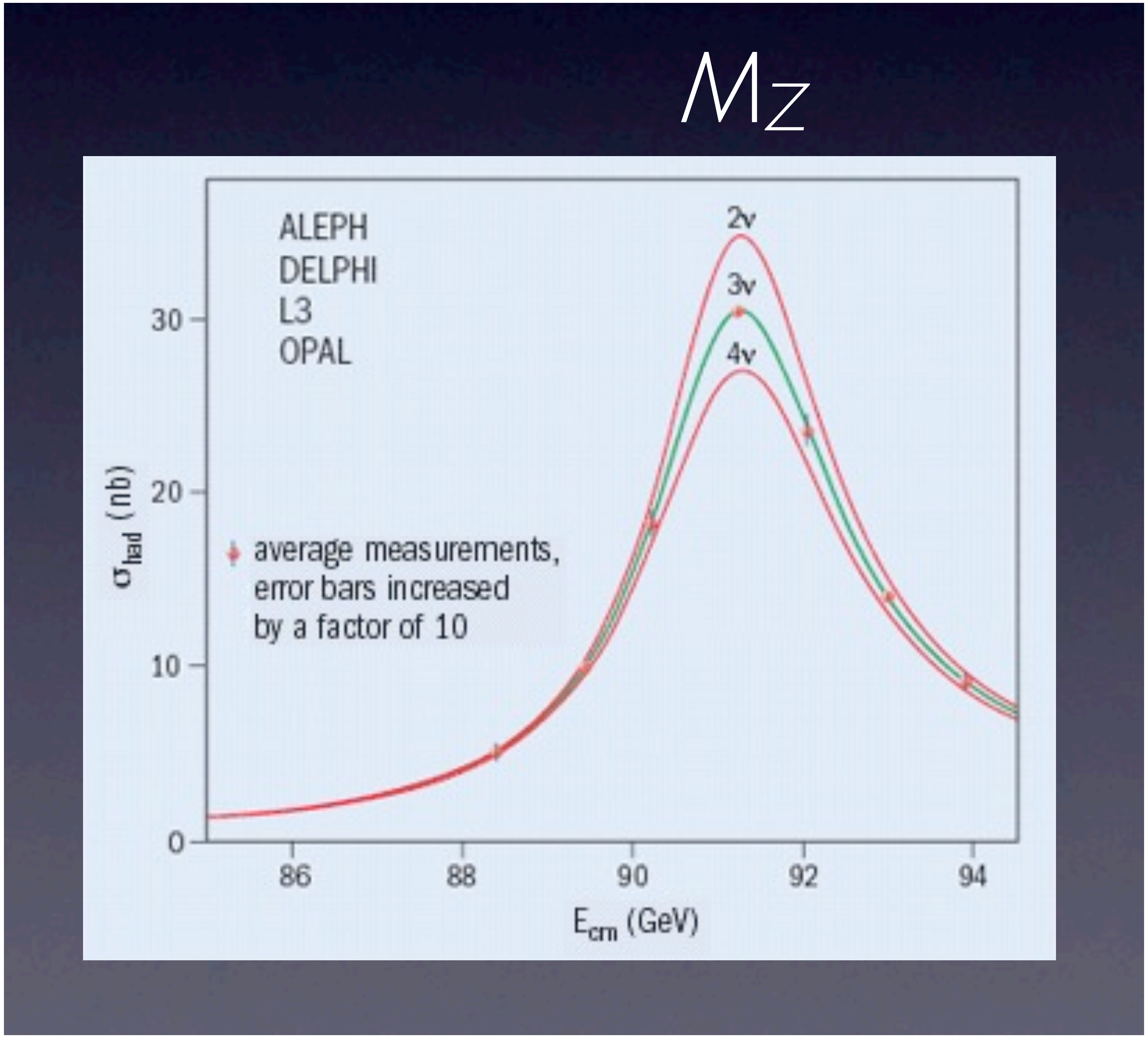


dimensional analysis

$$\sigma \propto \frac{g^4}{M_W^4} E^2$$

something interesting will happen around ***E ~ M$_W$!***

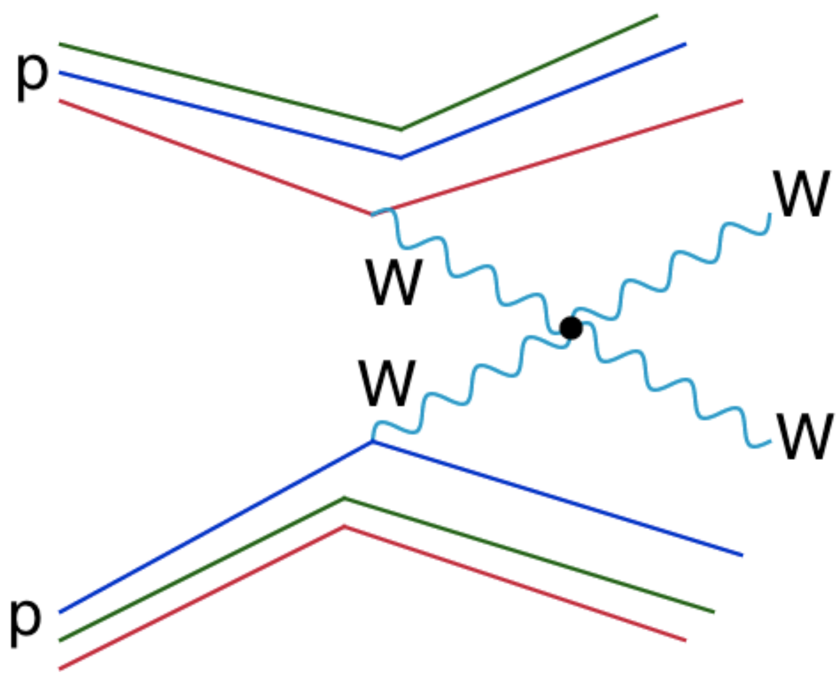
LEP

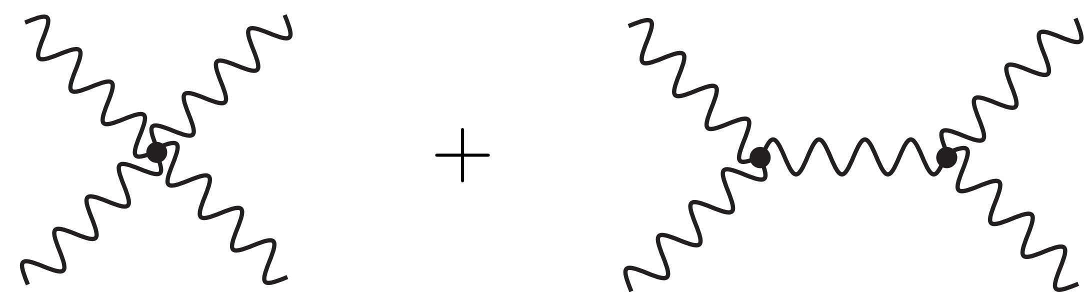


M_Z
ALEPH
DELPHI
L3
OPAL
2ν
3ν
4ν
average measurements, error bars increased by a factor of 10
σ_{had} (nb)
E_{cm} (GeV)
0
10
20
30
86
88
90
92
94

SM without the Higgs

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}}(\cancel{h^0}, A_\mu, W^\pm_\mu, Z_\mu, G_\mu, q, \ell)$$ (unitary gauge)





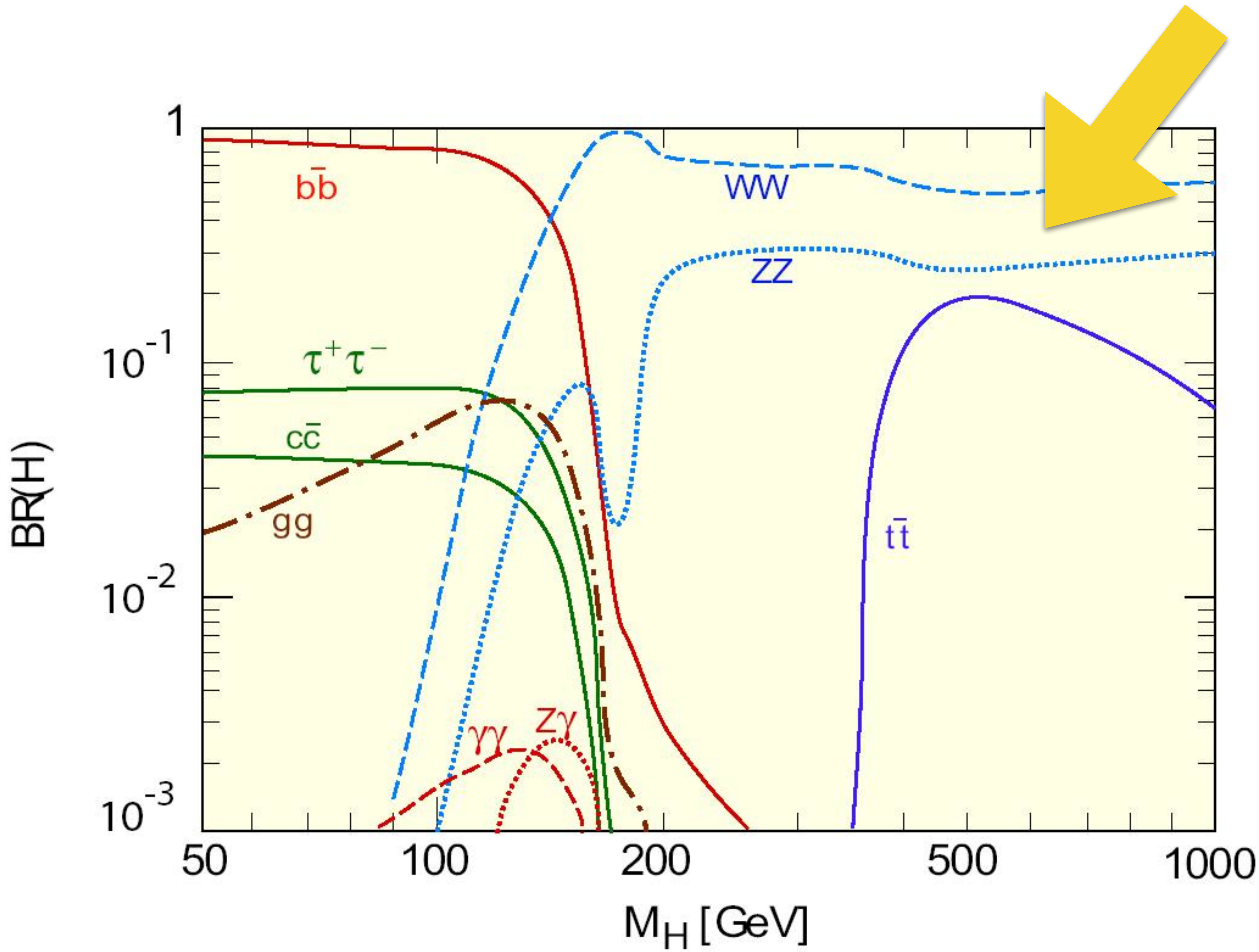
$\sim E^2$

$\sim \cancel{E^4} + E^2 + \cdots \qquad \sim \cancel{E^4} + E^2 + \cdots$

Coupling strength grows with Energy, longitudinally polarised EW bosons

$$\epsilon_L = \frac{1}{M}\left(|\mathbf{p}|; E\frac{\mathbf{p}}{|\mathbf{p}|}\right) \quad \Rightarrow \quad \epsilon_L = \frac{p}{M} + O(\frac{M}{E}) \quad \sim \frac{E}{v}$$

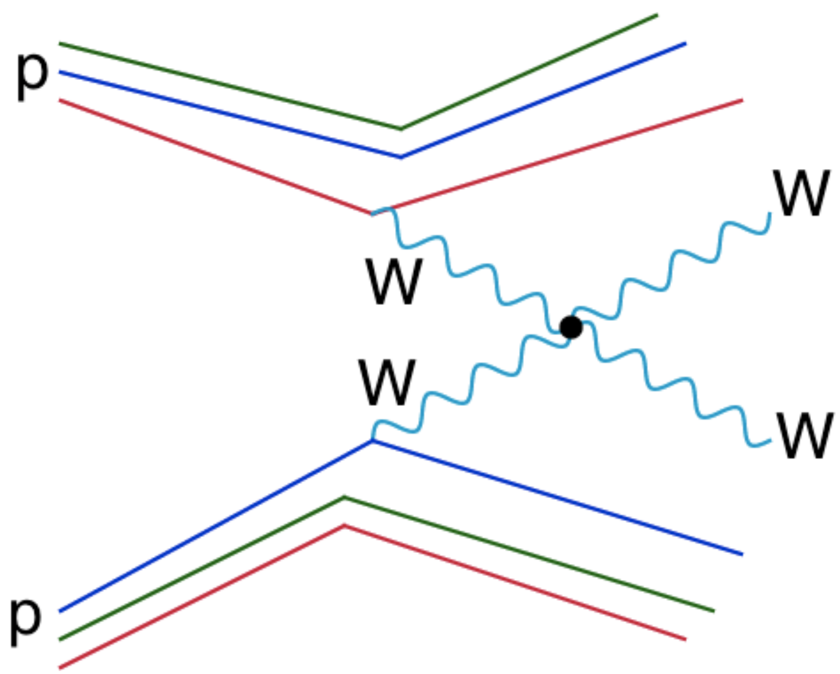
Br(WW/ZZ) >> Br(tt̲)

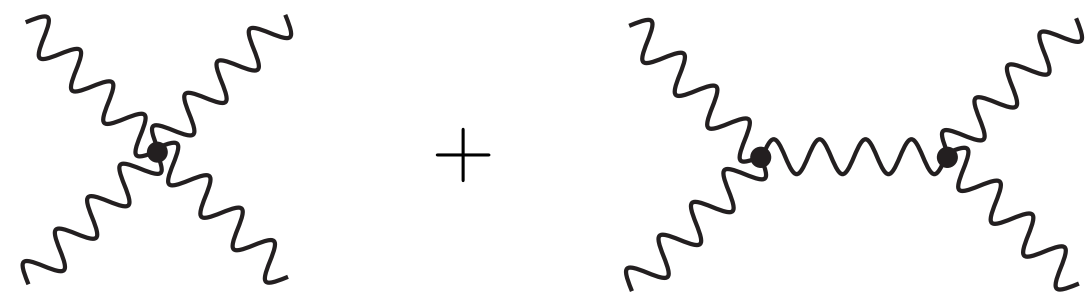


1
10^{-1}
10^{-2}
10^{-3}
BR(H)
$b\bar{b}$
WW
ZZ
$\tau^+\tau^-$
$c\bar{c}$
gg
$t\bar{t}$
$\gamma\gamma$
$Z\gamma$
50
100
200
500
1000
M_H [GeV]

SM without the Higgs

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM}(\cancel{h^0}, A_\mu, W_\mu^\pm, Z_\mu, G_\mu, q, \ell)$$ (unitary gauge)





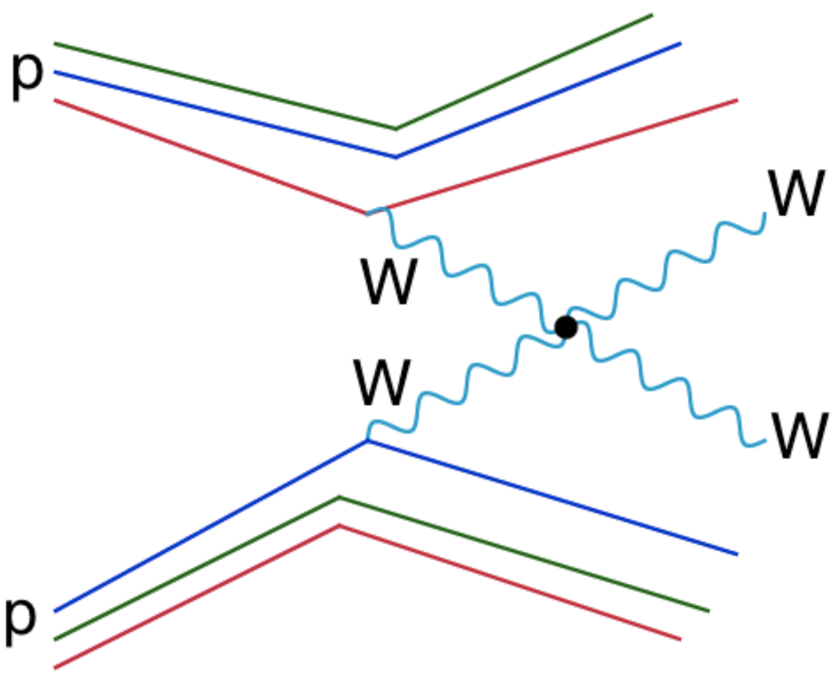
$\sim E^2$

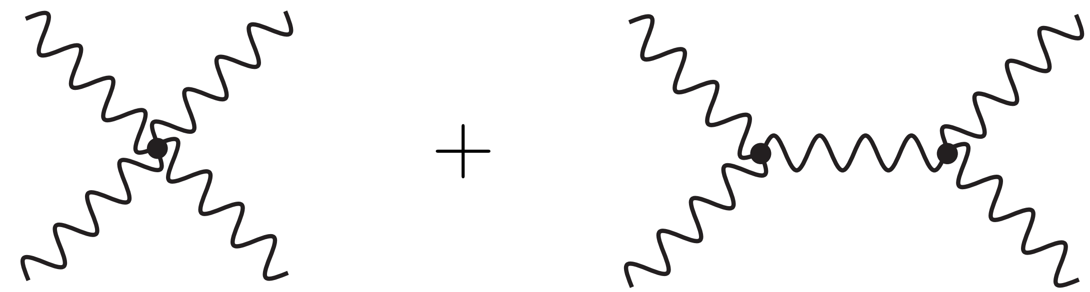
Amplitude grows with energy,

$$A(W_L^+ W_L^- \to Z_L Z_L) = \frac{s}{v^2}$$

SM without the Higgs

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}}(\cancel{h^0}, A_\mu, W^\pm_\mu, Z_\mu, G_\mu, q, \ell) \qquad \text{(unitary gauge)}$$





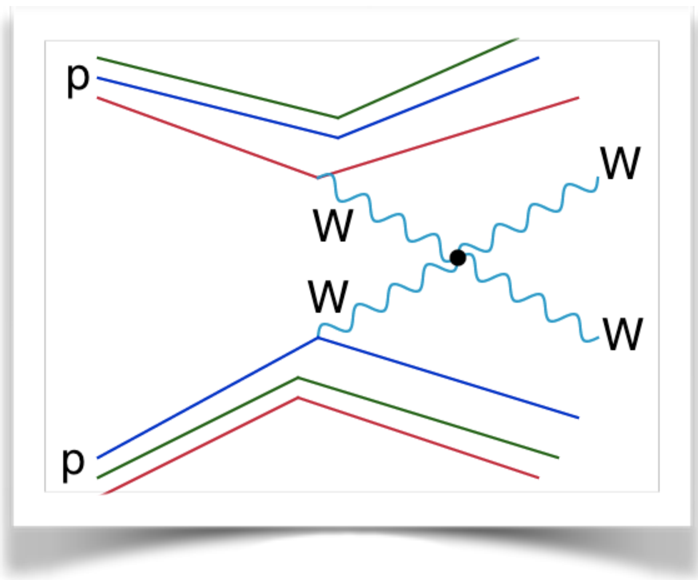
$\sim E^2$

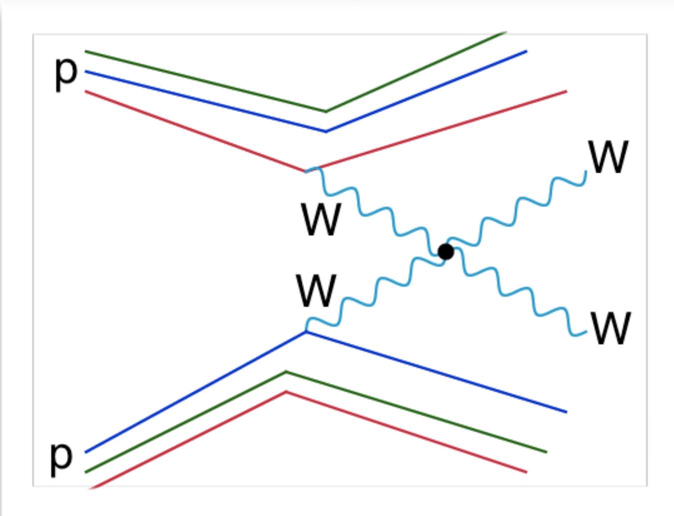
Amplitude grows with energy,

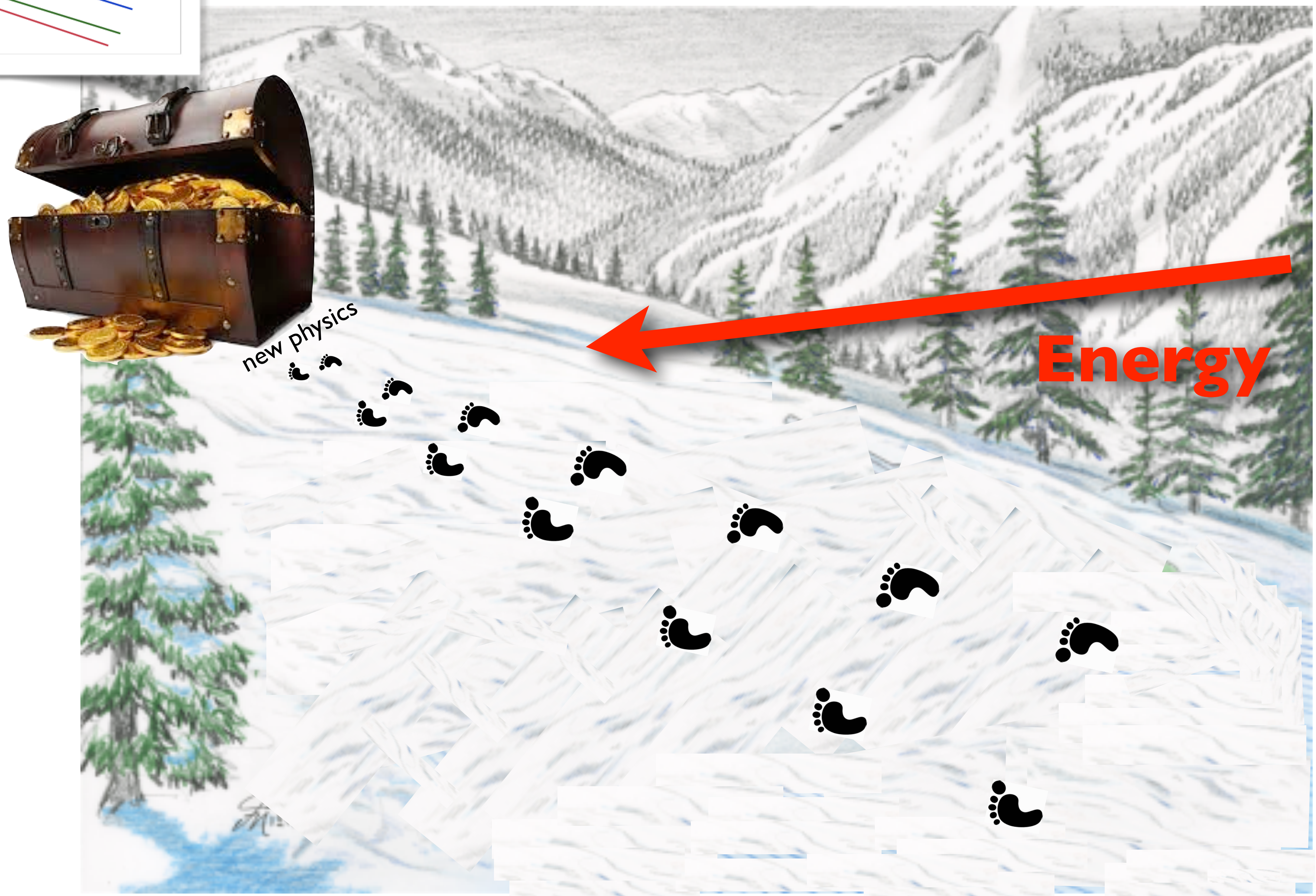
$$A(W_L^+ W_L^- \to Z_L Z_L) = \frac{s}{v^2}$$

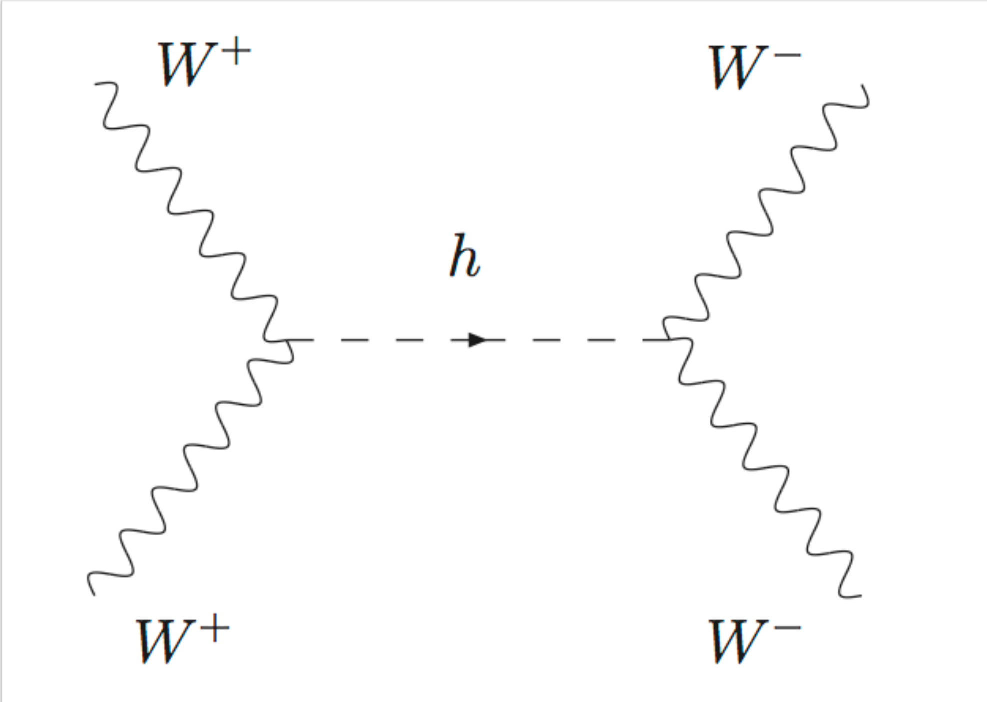
$$\boxed{\Lambda \approx 4\pi v \approx 3\,\text{TeV}}$$

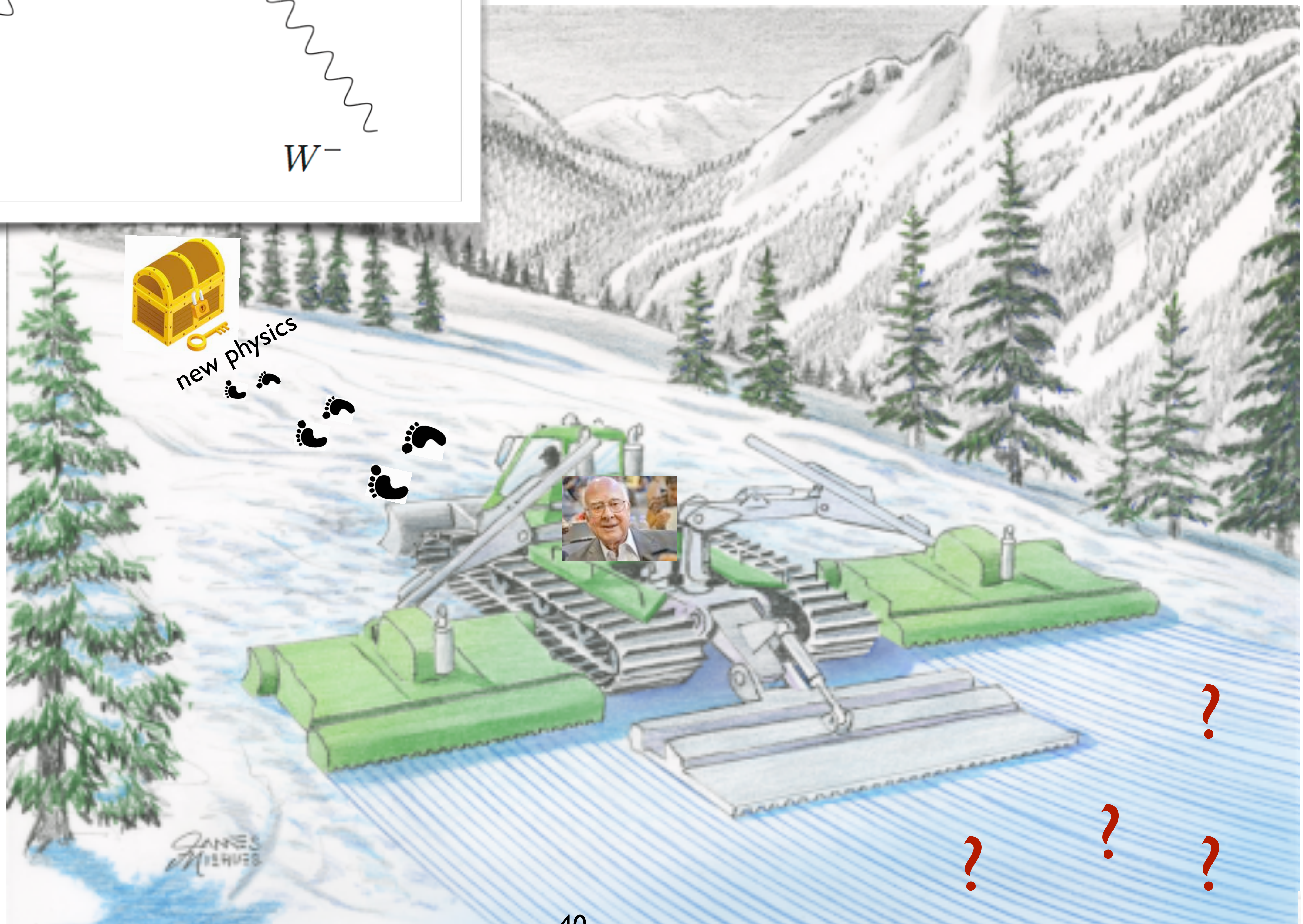
New physics to show
up below this scale


p
W
W
W
W
p


p
W
W
W
W
p

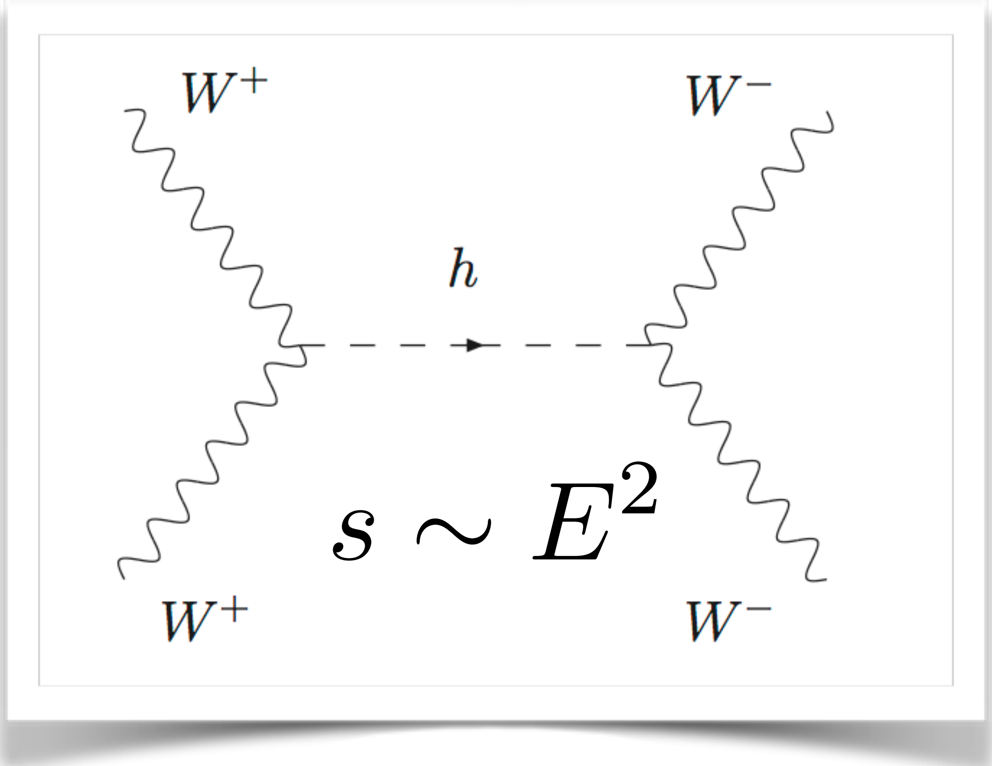

new physics
Energy


W^+
W^-
h
W^+
W^-


new physics
?
?
?
?

Adding SM-like Higgs

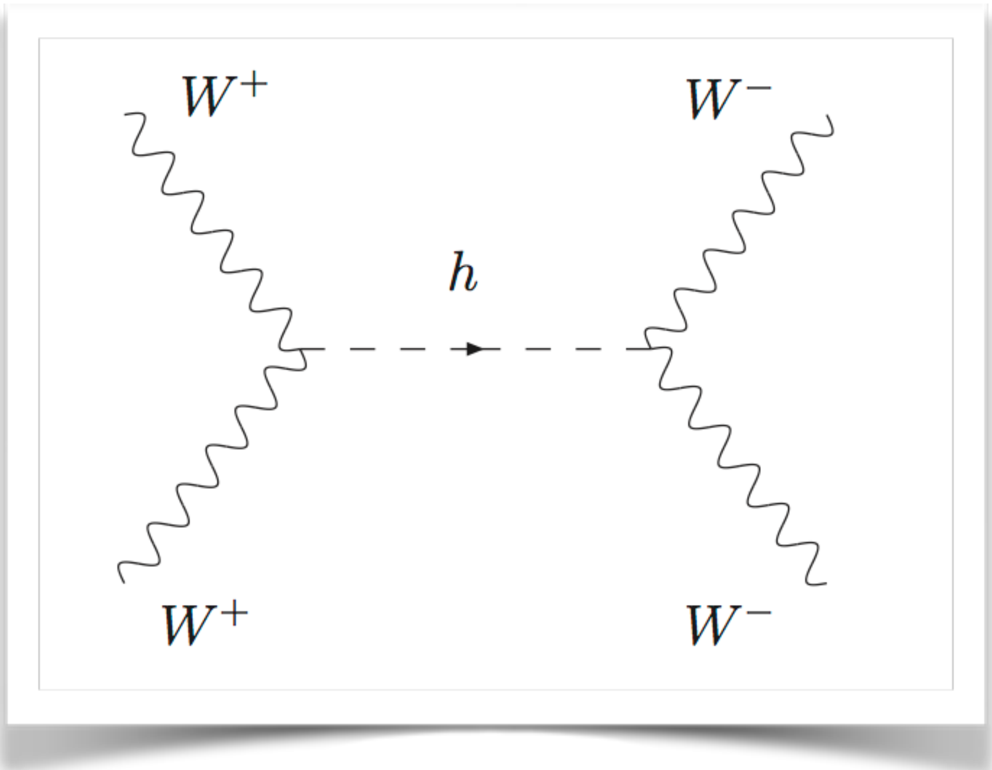
SM works up to $\Lambda \gg \mathrm{LHC}$



$$\mathcal{A} \simeq \frac{1}{v^2}\left[s - \frac{s^2}{s - m_h^2} + \ldots\right] \rightarrow \sqrt{s} \gg v$$

Adding SM-like Higgs

SM works up to $\Lambda \gg \mathrm{LHC}$

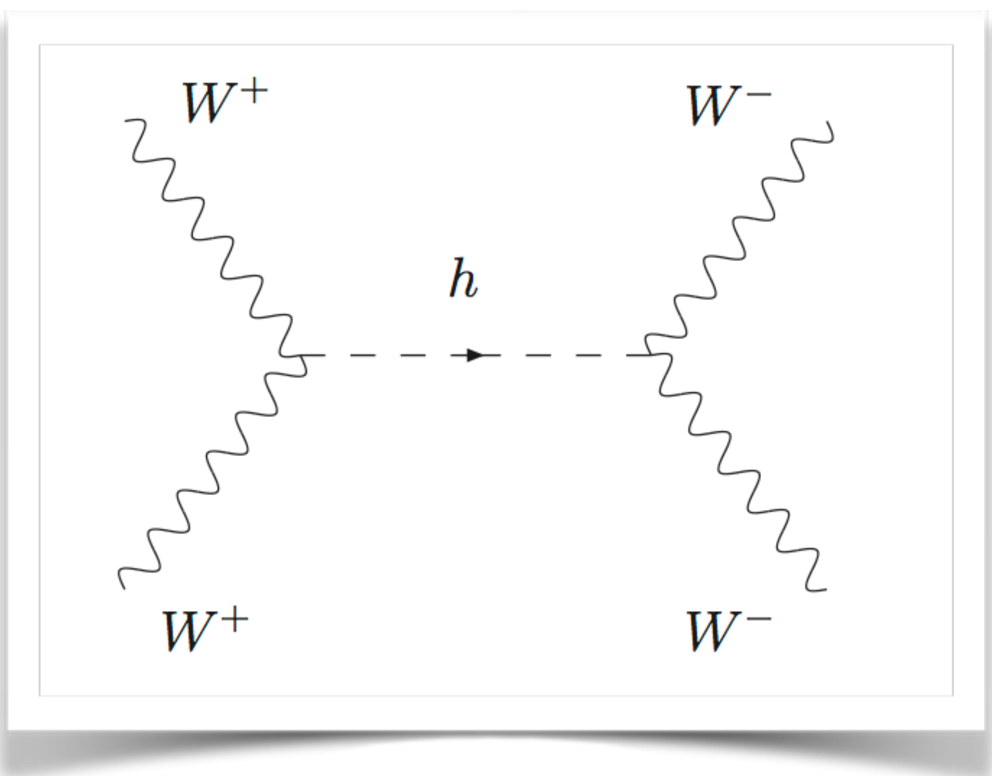


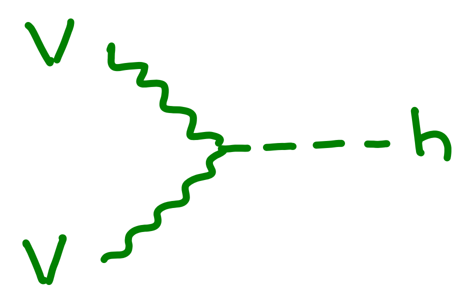
Finite !

$$\mathcal{A} \overset{s \sim E^2}{\simeq} \frac{1}{v^2}\left[m_h^2 + \frac{m_h^4}{s} + \dots\right] \qquad \sqrt{s} \gg v$$

Adding a SM-like Higgs

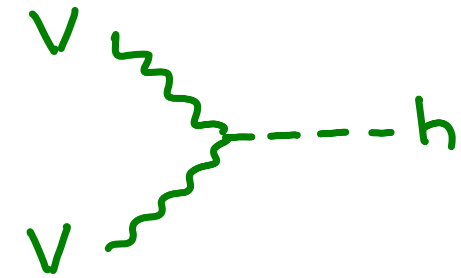
What if the coupling is not exactly like in the SM?





$a\, g_{hVV}^{SM}$

$$\Lambda \approx 4\pi v \longrightarrow \frac{4\pi v}{\sqrt{1-a^2}}$$



$a\, g_{hVV}^{SM}$

$$\Lambda \approx 4\pi v \longrightarrow \frac{4\pi v}{\sqrt{1-a^2}}$$

Even if we measure $a < 1$, weaker guarantee for new physics in reach of LHC.

Example: composite pseudo-Goldstone Higgs:

$$a = \sqrt{1-(v/f)^2} \approx 0.8 \dots 0.9$$

$$\Lambda > 6 \dots 8\,\mathrm{TeV}$$

Where is the next scale?

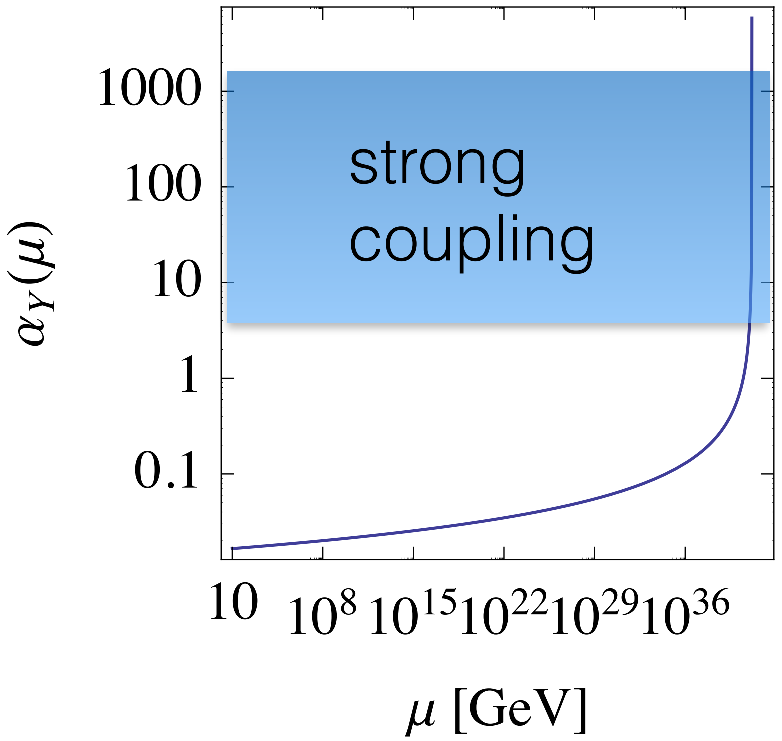
- 14 TeV enough to reveal fundamental physics?
- First time in history without guarantee for a nearby new scale: all couplings dimensionless (marginal) or of positive mass dimension (relevant)
- Remaining hopes?
  - Landau pole of hyper charge $U(1)_Y$
  - Gravity scale (M_{Planck})

SM Hyper-charge

Hyper-charge is not asymptotically free, will blow up at (very) high energies — Landau Pole

$$1/\alpha_Y(M_Z) = 1/\alpha_Y(\Lambda) + \frac{b_Y}{2\pi} \ln \frac{\Lambda}{M_Z} \qquad b_Y = \frac{41}{10}$$

$$\Lambda \sim M_Z\, e^{2\pi/\alpha_Y b_Y} \sim 10^{41}\,\mathrm{GeV}$$



Gravity

- Strong coupling problem, e.g. graviton-graviton scattering

$$\sigma \sim \frac{E^n}{M_{pl}^{n+2}} \qquad\qquad M_{pl} \simeq 10^{19}\ \mathrm{GeV}$$

End of lecture 1


BSM lecture 2/3
Andreas Weiler
(TU Munich)

BSM lecture 2/3

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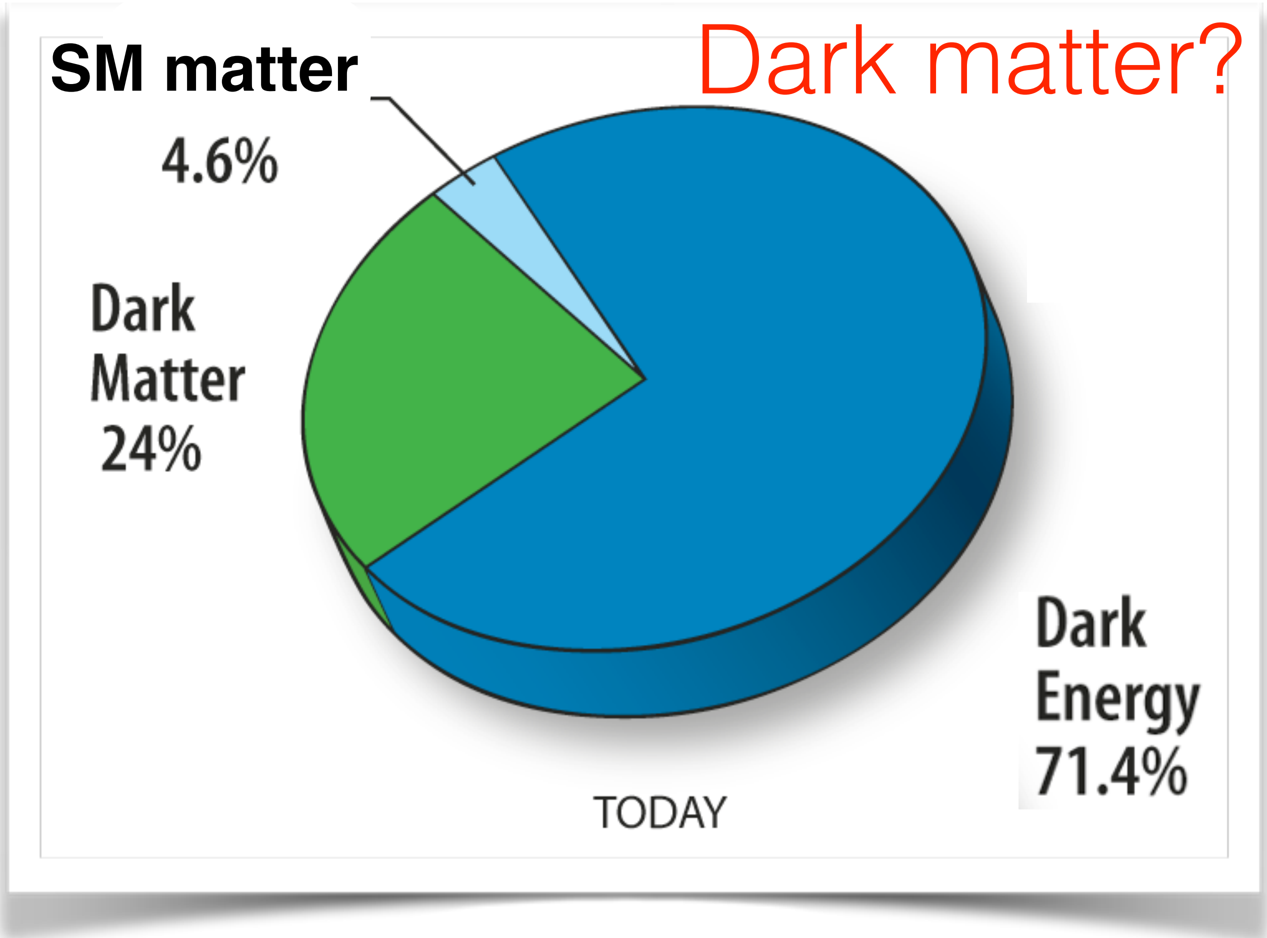
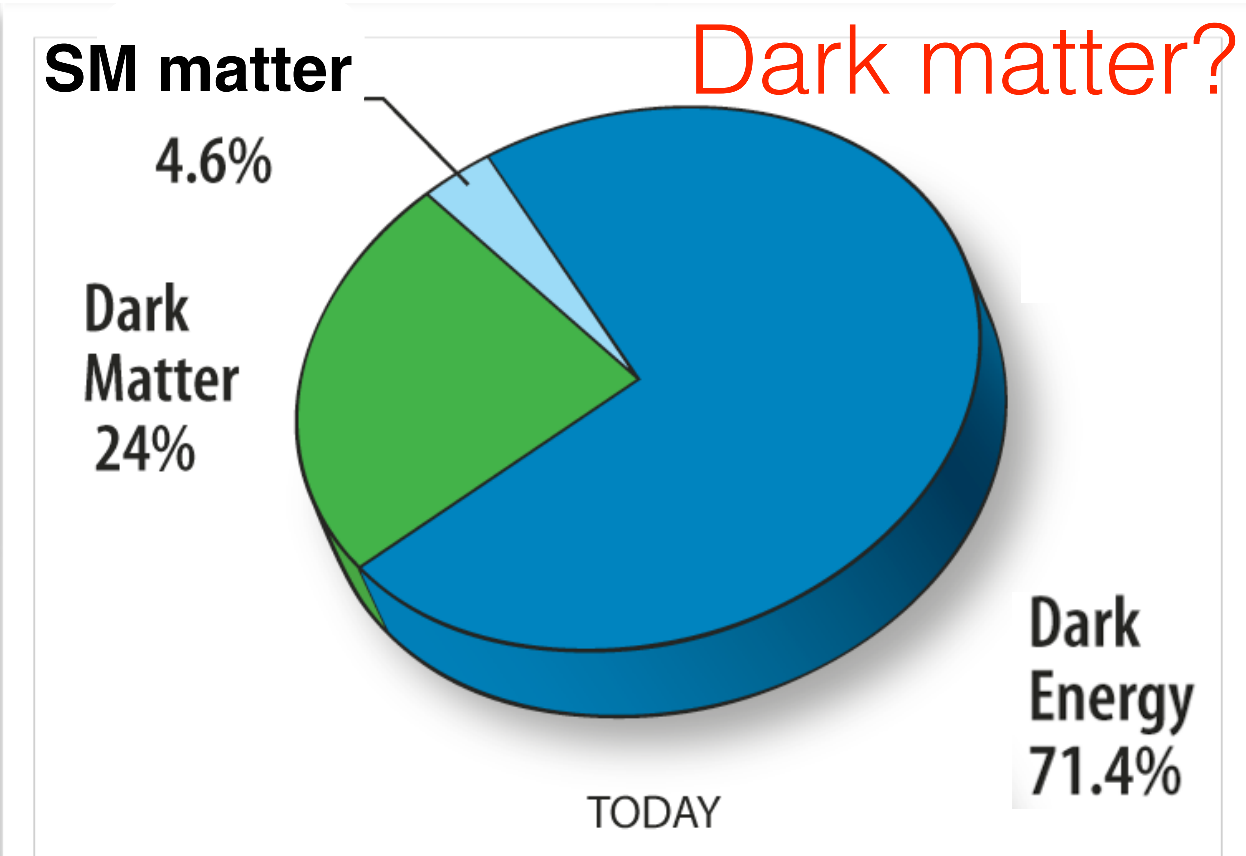
Open questions of the SM

The SM is incomplete

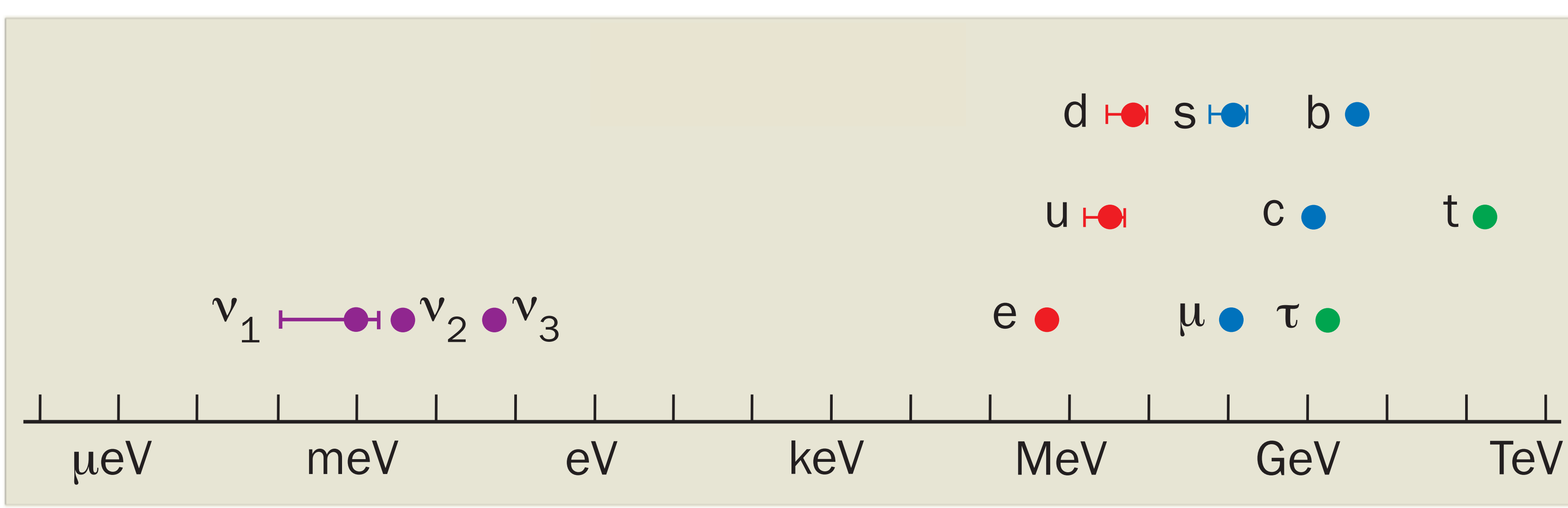


The SM is incomplete

Dark matter?



Origin of SM flavor and mass hierarchies?



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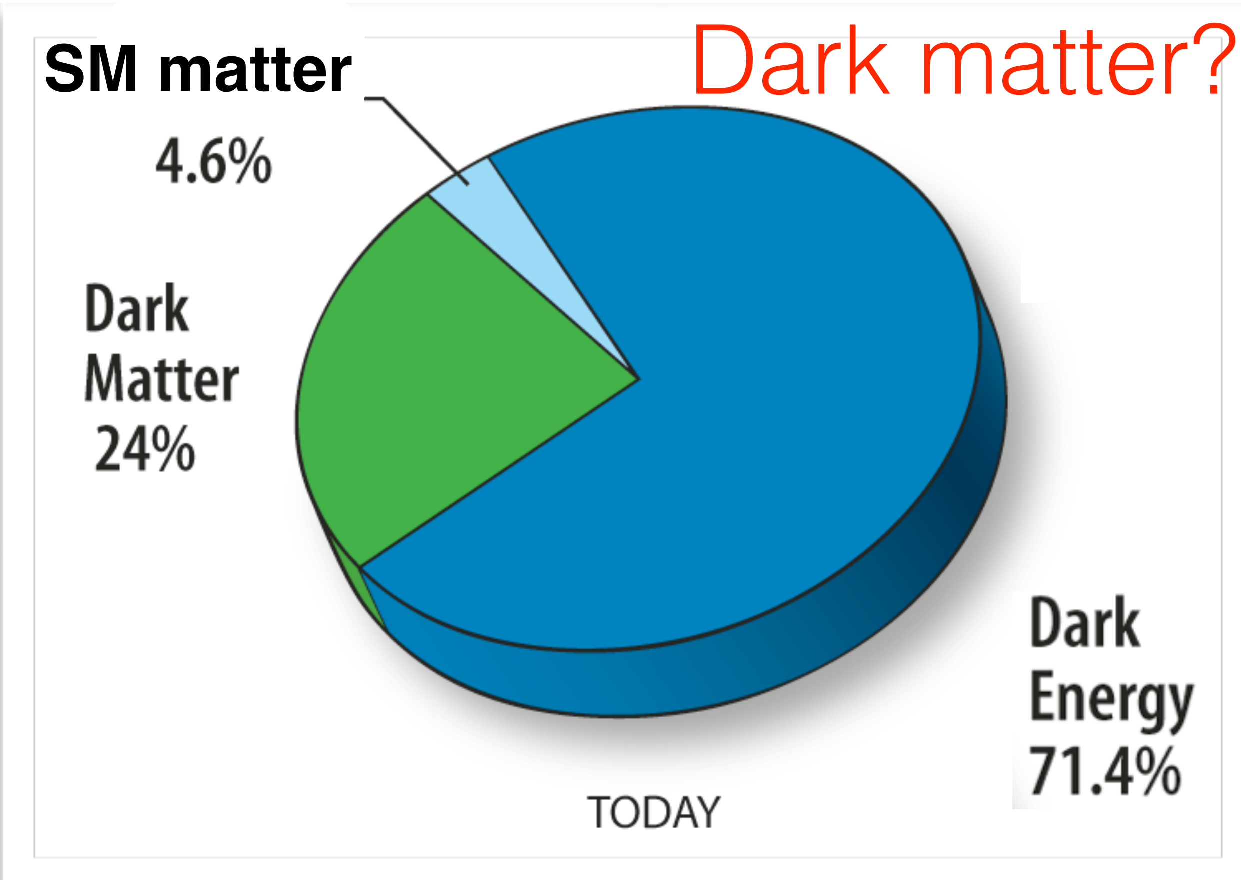
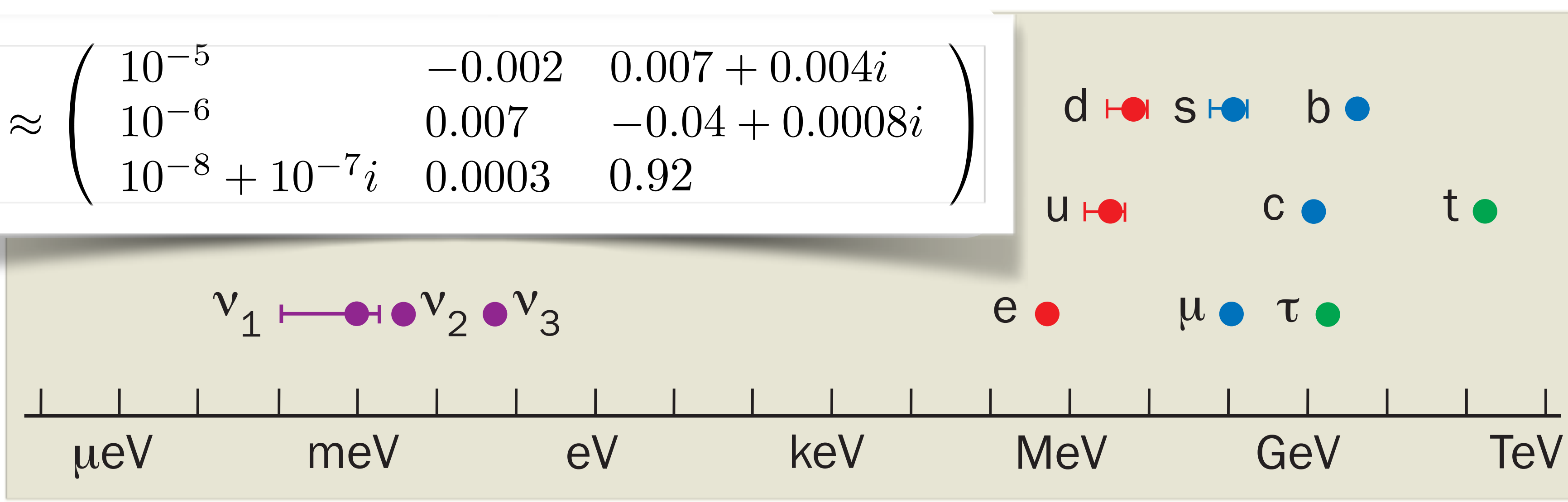


Origin of SM flavor and mass hierarchies?

$$Y_U \approx \begin{pmatrix} 10^{-5} & -0.002 & 0.007 + 0.004i \\ 10^{-6} & 0.007 & -0.04 + 0.0008i \\ 10^{-8} + 10^{-7}i & 0.0003 & 0.92 \end{pmatrix}$$



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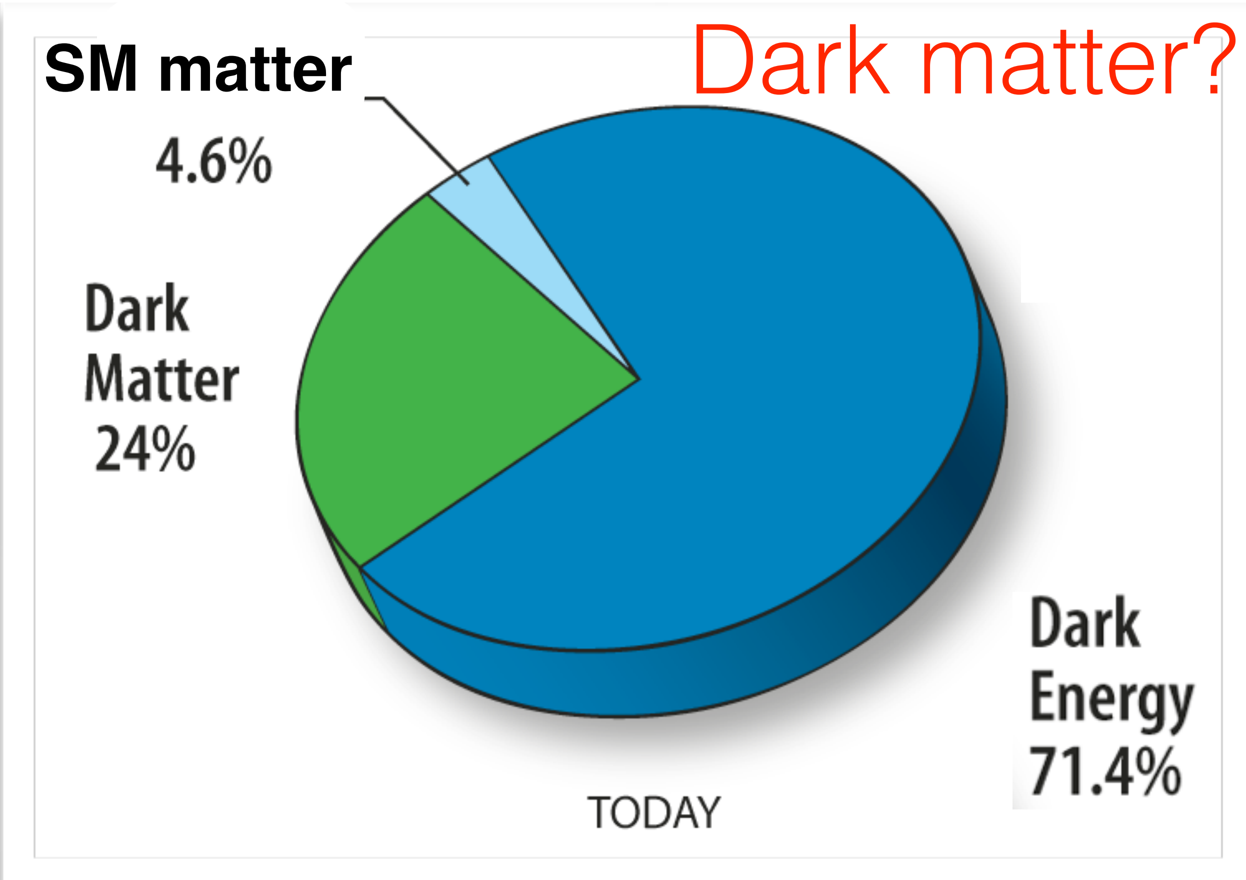

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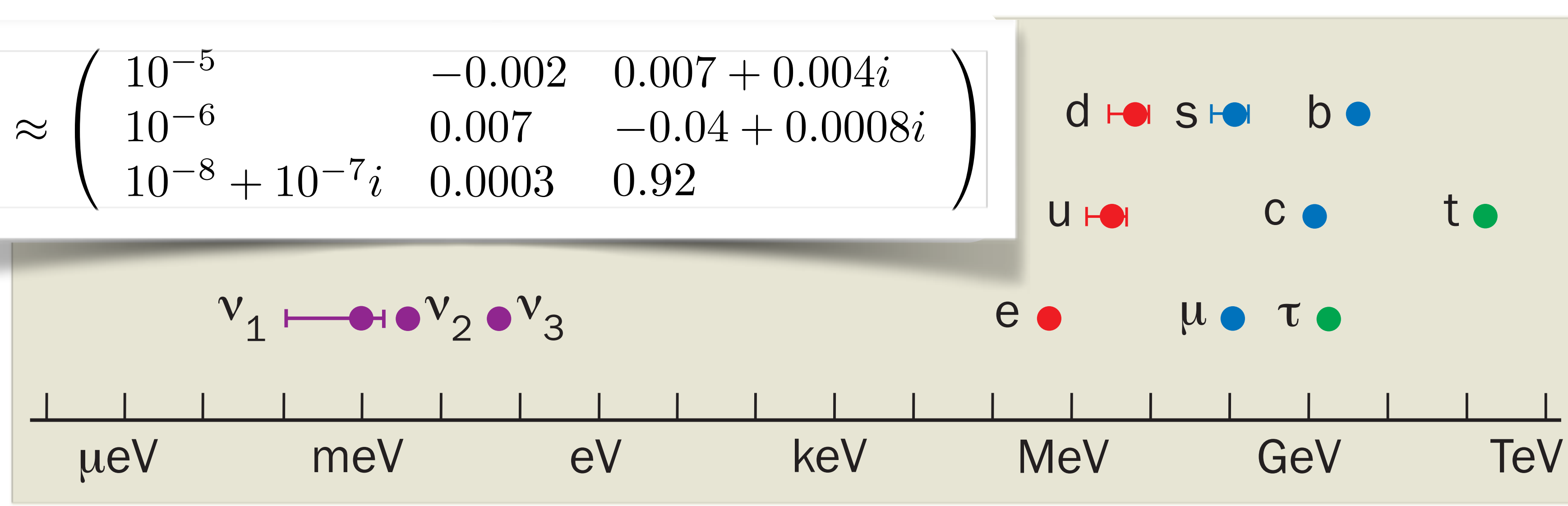
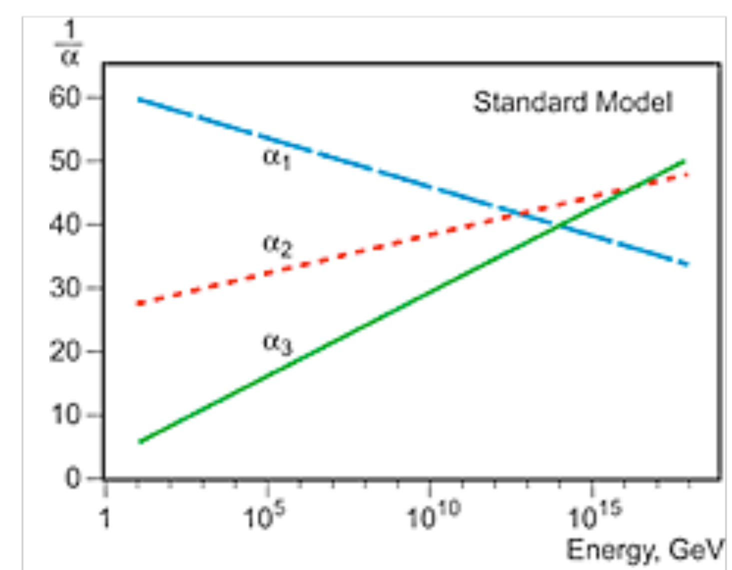


Unity of forces?



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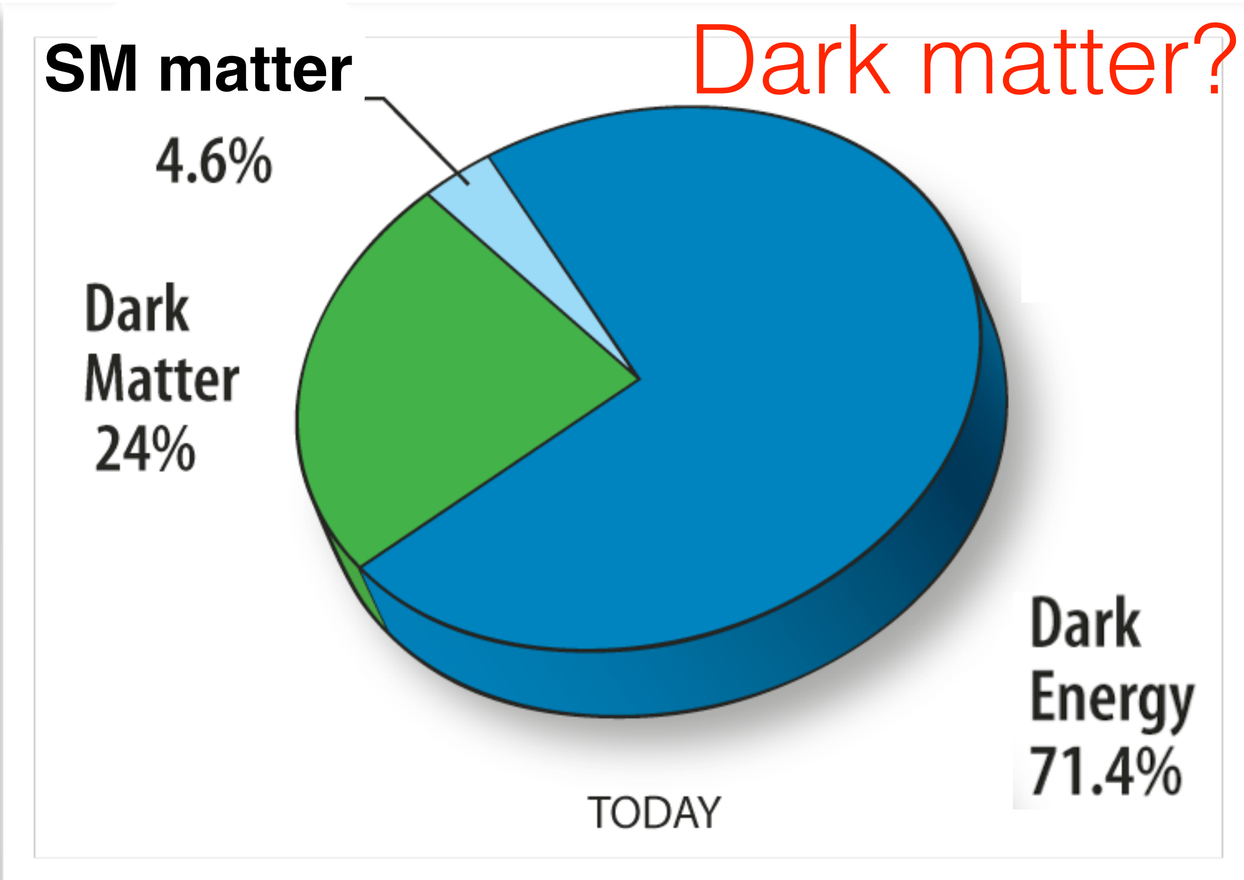
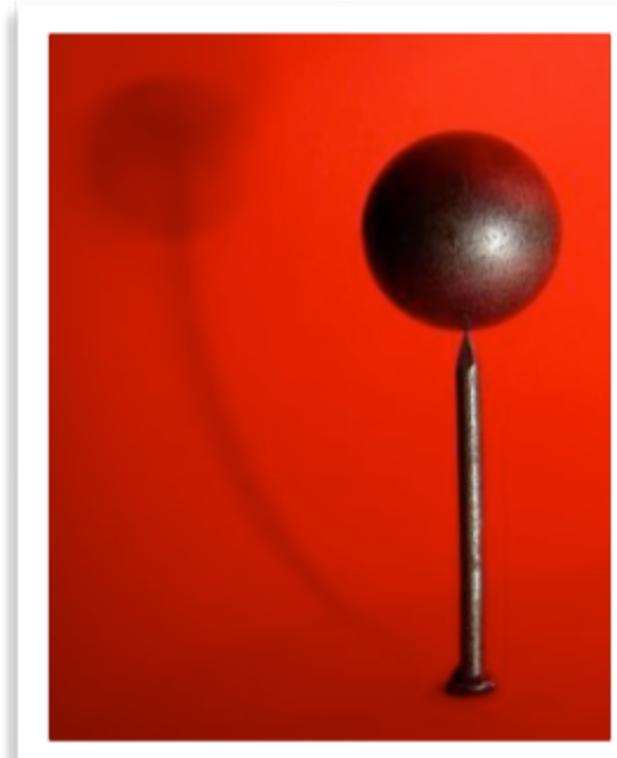


Fine-tuning?



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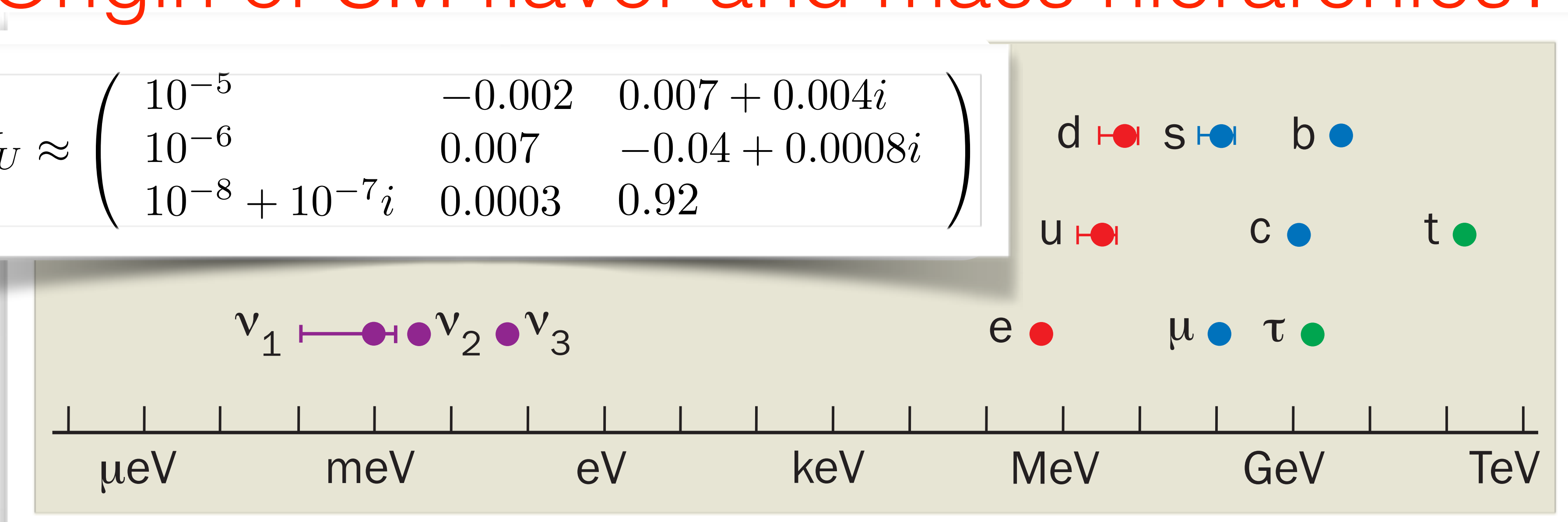

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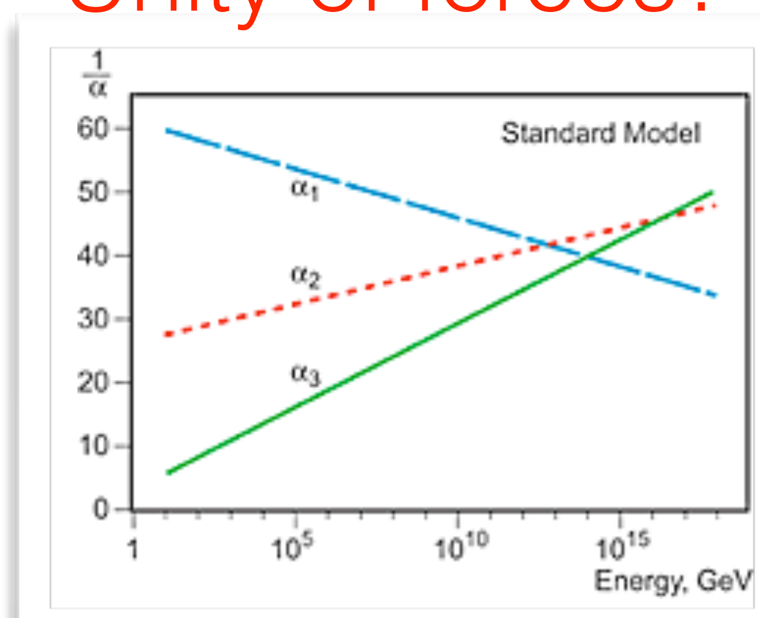
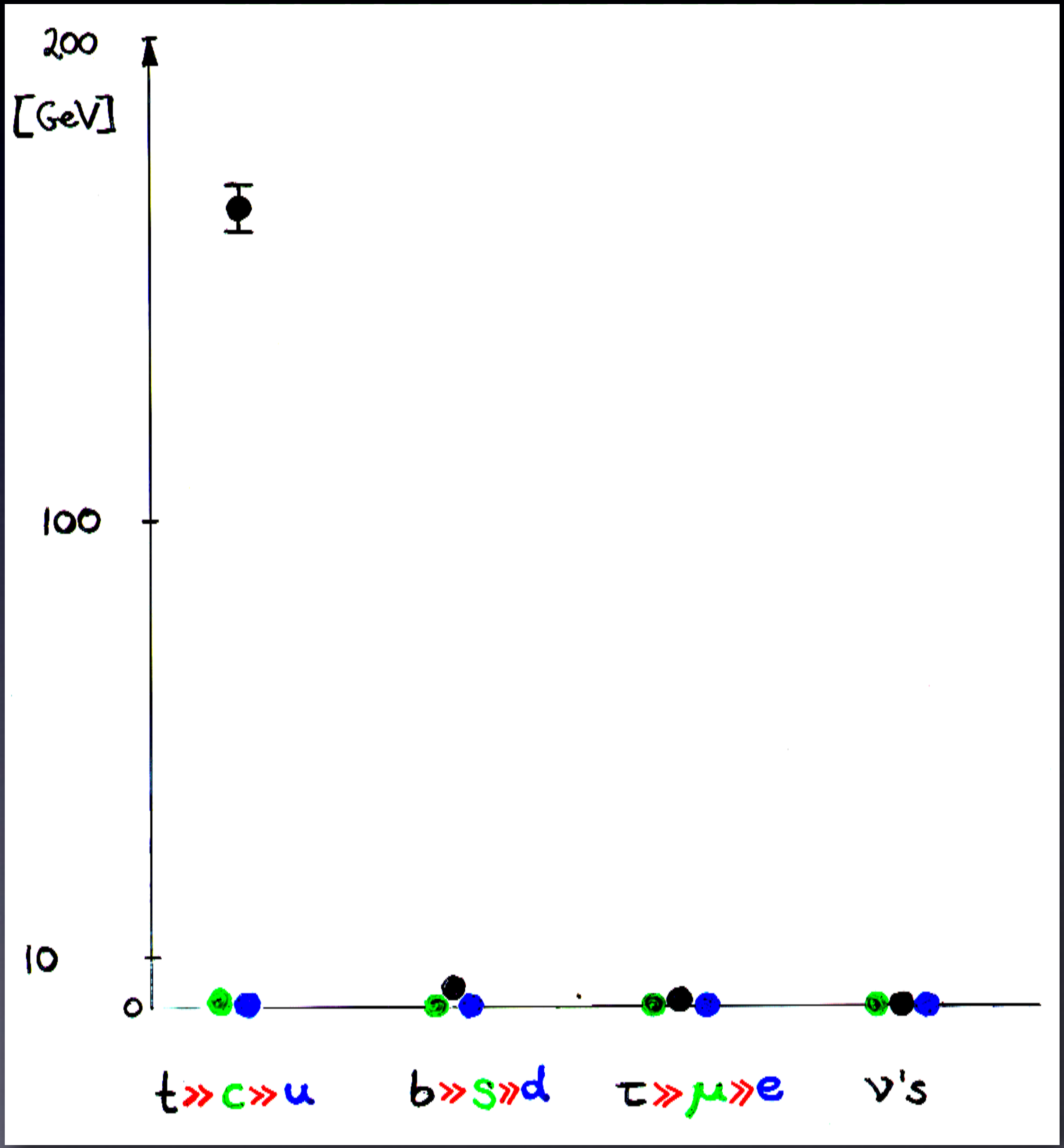


The SM

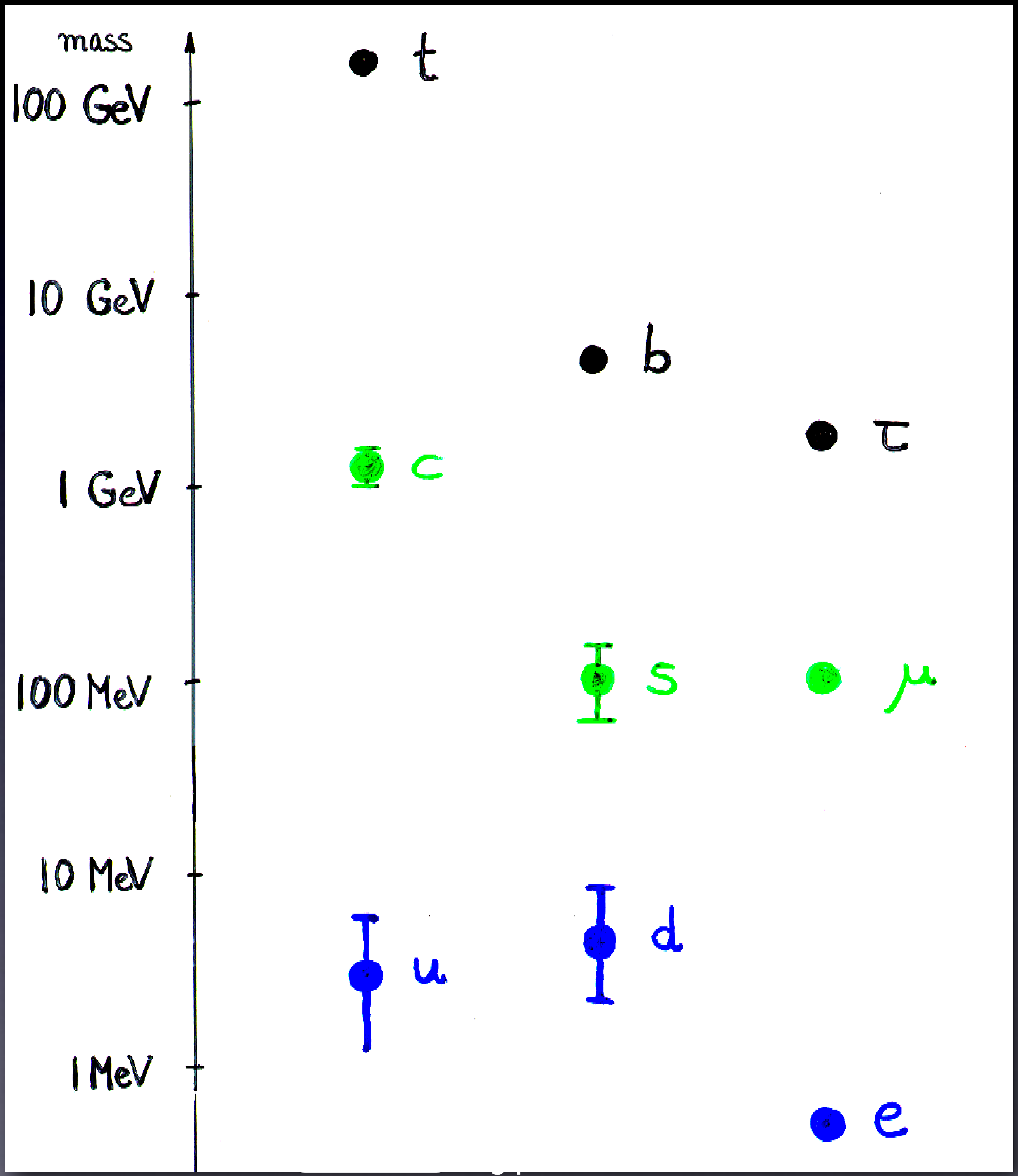
$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\
& + i\bar{\psi}\not{D}\psi + h.c. \\
& \boxed{+ \psi_i y_{ij} \psi_j \phi + h.c.} \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

fermion
masses
& mixings

Quark and Lepton mass hierarchy



Masses on a Log-scale



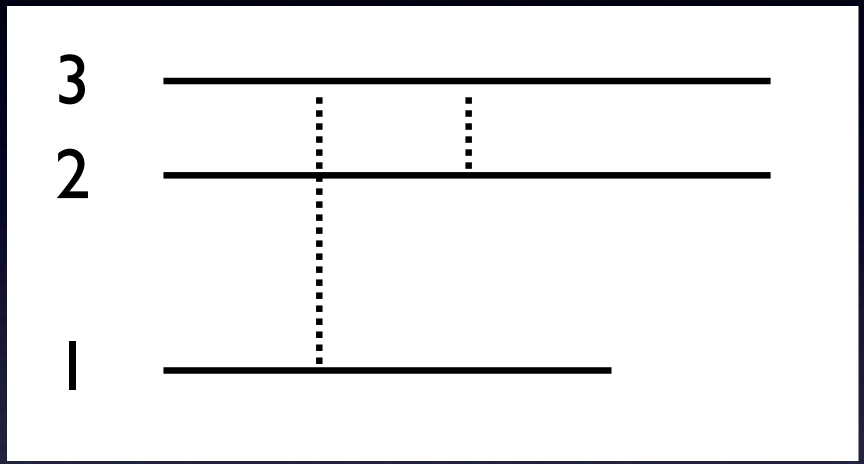
$$Y_D = (m_d, m_s, m_b)/v$$
$$Y_U = V^\dagger_{\text{CKM}}(m_u, m_c, m_t)/v$$

$$Y_D \approx (10^{-5}, 0.0005, 0.026)$$
$$Y_U \approx \begin{pmatrix} 10^{-5} & -0.002 & 0.007 + 0.004i \\ 10^{-6} & 0.007 & -0.04 + 0.0008i \\ 10^{-8} + 10^{-7}i & 0.0003 & 0.96 \end{pmatrix}$$

SM quark masses: mostly small & hierarchical.
Origin of this structure?

Compare to: $g_s \sim 1$, $g \sim 0.6$, $g' \sim 0.3$, $\lambda_{\text{Higgs}} \sim 1$

Analog to mysterious spectral lines before QM



$$\nu = \left(\frac{1}{n^2} - \frac{1}{m^2}\right) R$$

Explained by Bohr

$$E_n = -\frac{2\pi^2 e^4 m_e}{h^2 n^2}$$

Is there an analogue to the Bohr atom, we might discover at the LHC?

Flavor dynamics @ LHC ?

Possible, but ...

TeV? 10^3 TeV? 10^{16} GeV?

1) Lack of scale

$$\mathcal{L}_{\text{flavor}} = [Y^U]_{ij}\,\bar{Q}_i H_c u_j + \ldots$$

dim 0 + 3/2+1+3/2 = 4

2) Very strong constraints from flavor physics:
Generic flavor dynamics >> 100 TeV

The SM

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\psi} \not{D} \psi + h.c.$$

$$+ \psi_i y_{ij} \psi_j \phi + h.c.$$

$$\boxed{+ |D_\mu \phi|^2 - V(\phi)}$$

Higgs potential

Top as a destabilizing agent

Stability and meta-stability

Cabibbo, Maiani, Parisi, Petronzio, '79; Hung '79; Lindner 86; Sher '89; …

Tree-level

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

$$|\phi|^2 \gg \mu^2$$

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What happens at $|\phi| \gg v$? Focus on λ, $|\phi|^2 \gg \mu^2$

Quantum fluctuations change potential:

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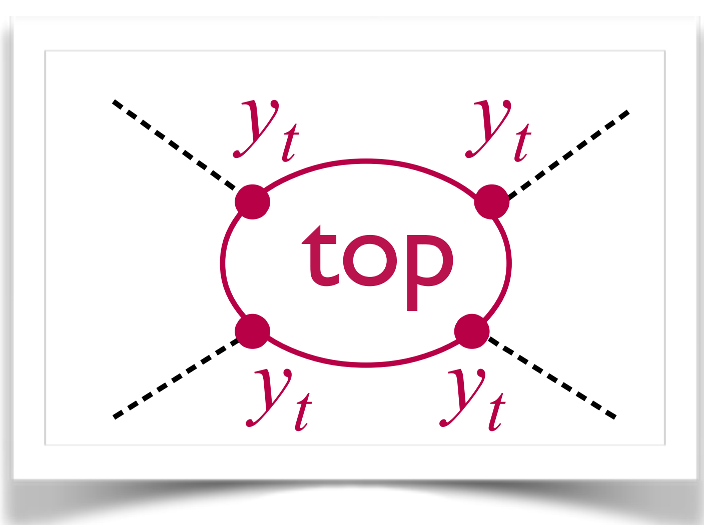
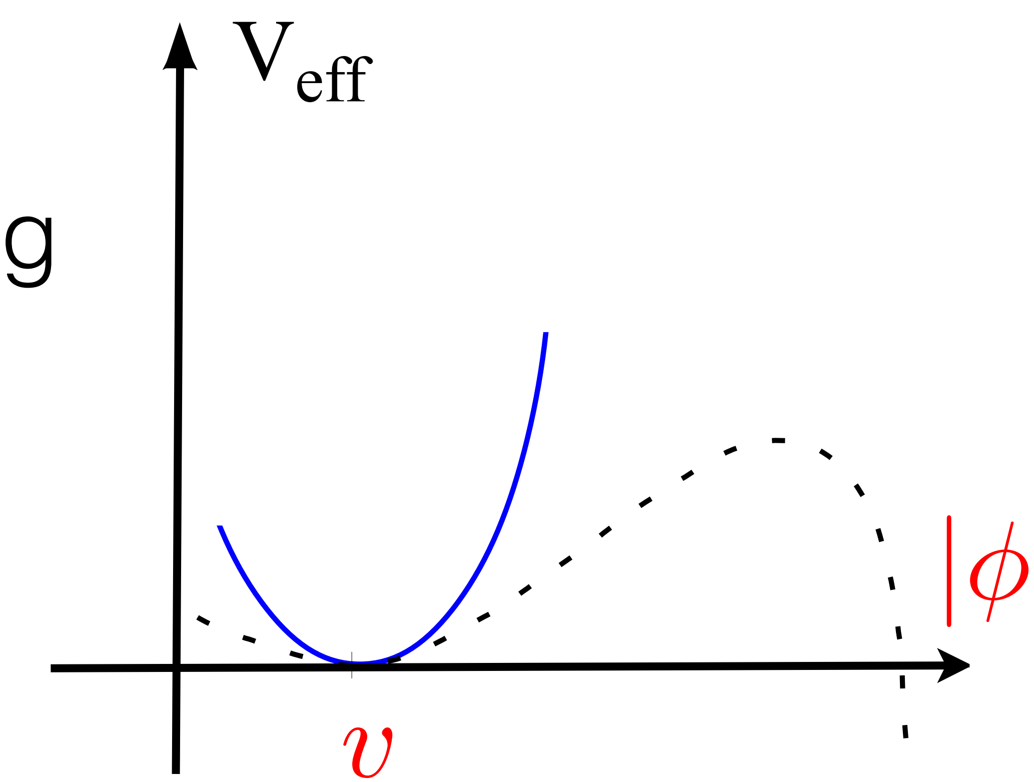
Quantum fluctuations change potential:

$$V \simeq \lambda(|\phi|)\,|\phi|^4$$



λ decreasing
at large
energies



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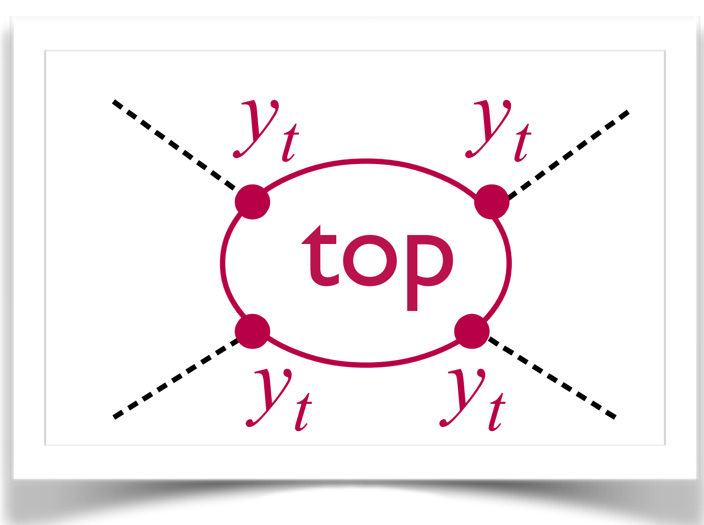

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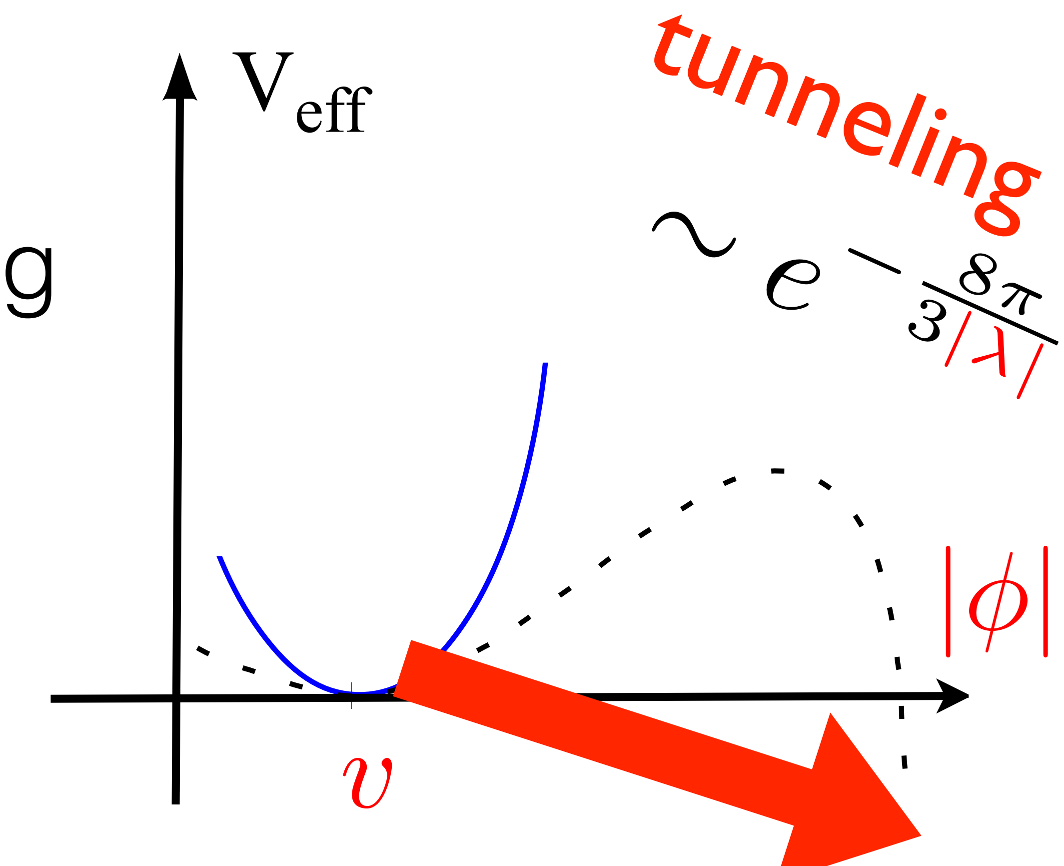
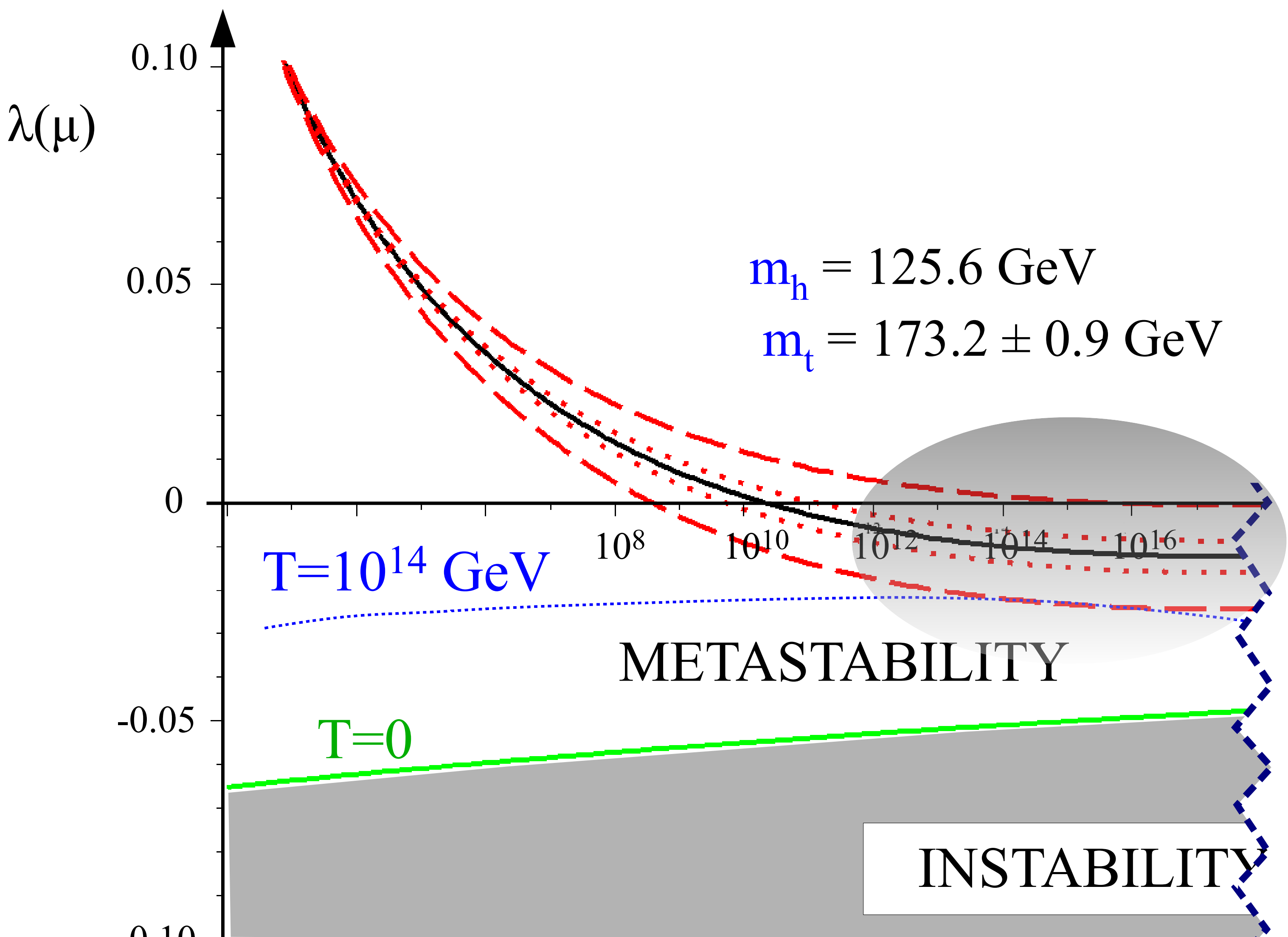


Stability and meta-stability

SM vacuum is unstable but sufficiently long-lived,
(depends on m_{top}, m_{Higgs})

cf Elias-Miro et al. '12
Degrassi et al. '12
Buttazzo et al. '12



Unlikely the full story, assumes nothing but SM up to the Planck scale …

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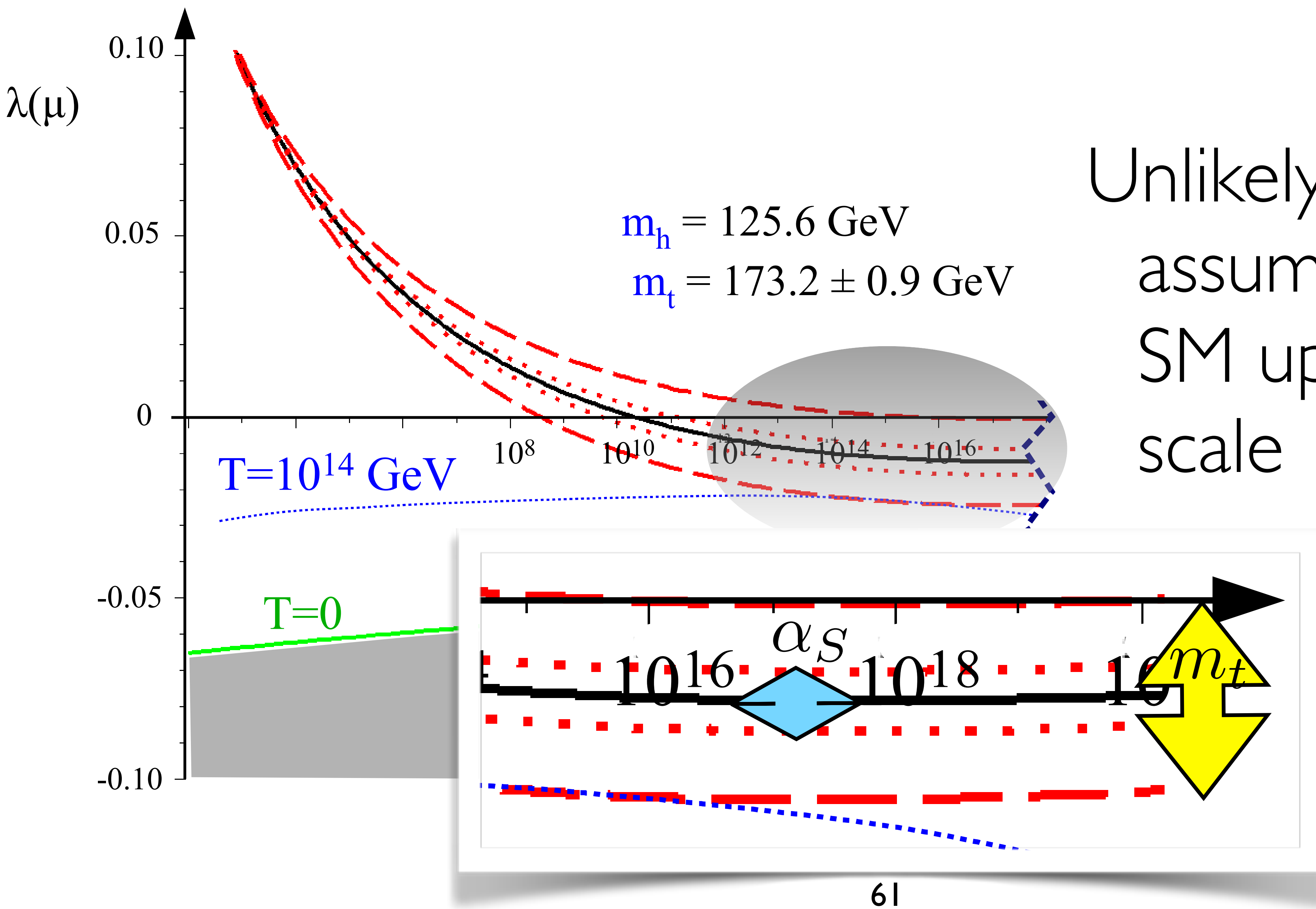
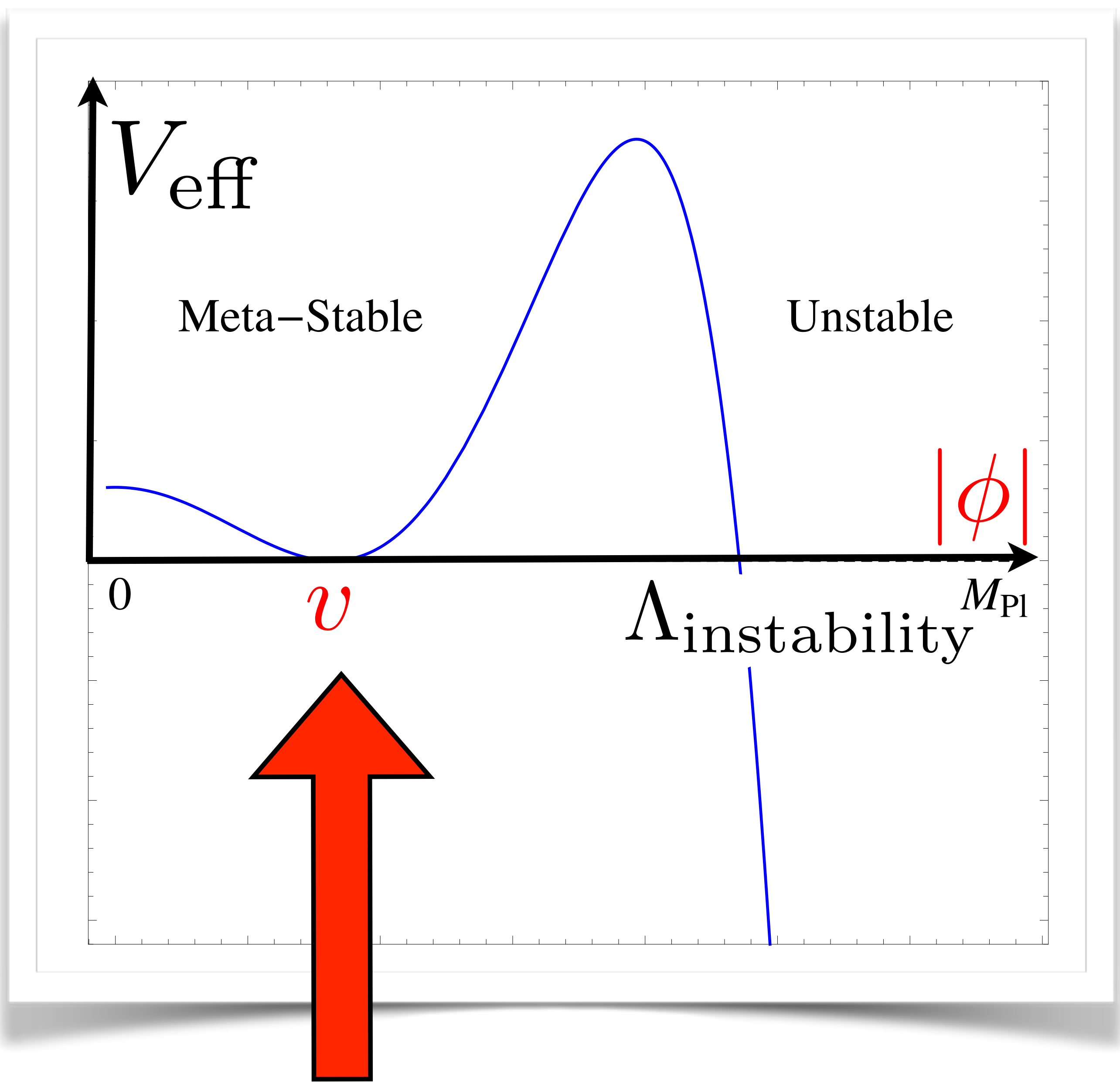


Unlikely the full story, assumes nothing but SM up to the Planck scale …

decisive uncertainty m_{top}

If metastable: How did we end up in the energetically disfavoured vacuum?



You are here?!

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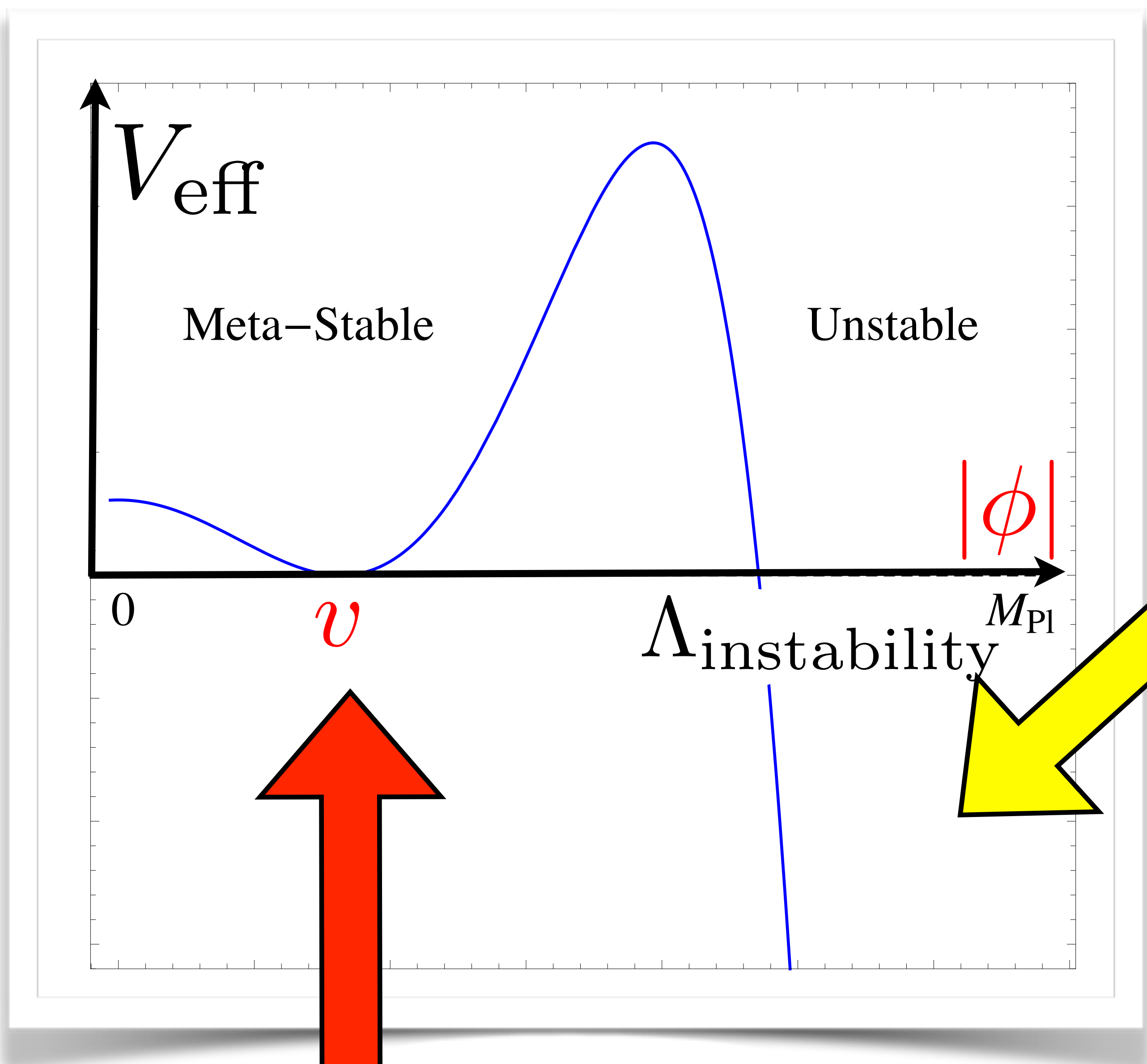


You are here?!

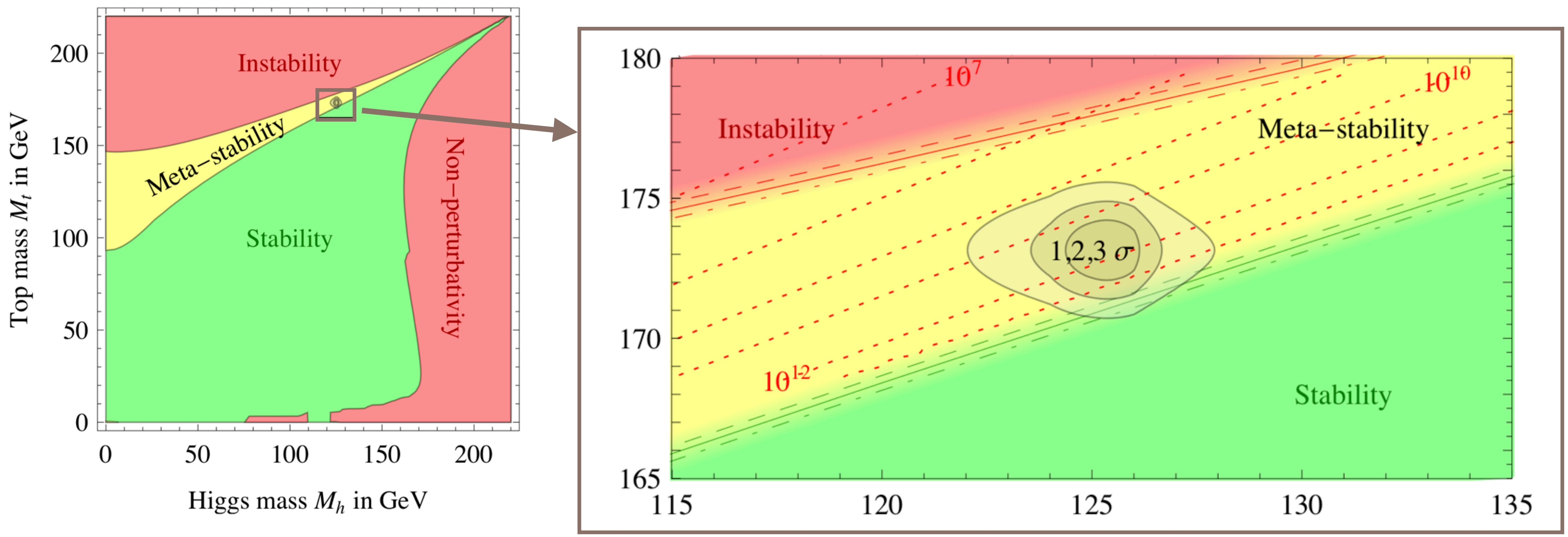
Universe is overwhelmingly likely to evolve to wrong minimum

Fine-tuning of initial conditions?

$$\sim \Lambda_{\text{instability}}/M_{\text{Planck}}$$

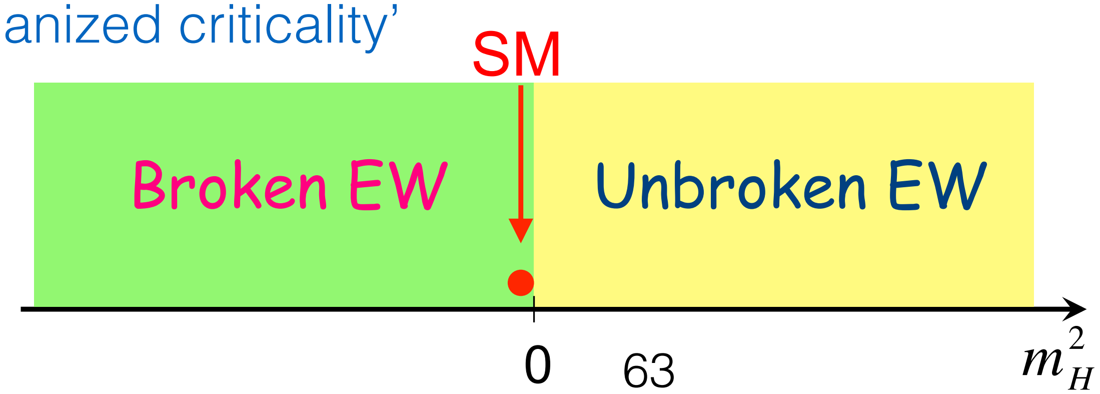
For $\Lambda_{\text{instability}} \sim 10^{10}\,\text{GeV} \rightarrow 10^{-8}$ tuning

Just the SM?



We seem to be living close to a critical condition, similar to Planck-Weak hierarchy …

Giudice, Rattazzi, ‘Self-organized criticality’



The hierarchy problem

Higgs potential

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

quantum fluctuations
destabilise Higgs mass^2

The hierarchy problem

Higgs potential

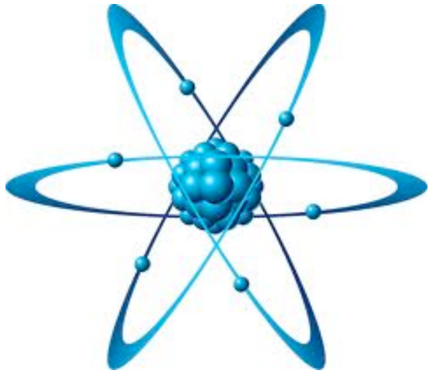
$$V(\phi) = \boxed{-\mu^2|\phi|^2} + \lambda|\phi|^4$$

quantum fluctuations
destabilise Higgs mass^2

Principle: UV insensitivity

Naturalness : absence of special conspiracies between phenomena occurring at very different length scales.

Planets do not care about QED.



QED at $E \sim m_e$ does not care about the Higgs.

blackboard

Naturally small parameters and spurions

Consider toy model:

$$\mathcal{L} = \bar{\psi} i \not{\partial} \psi + \frac{1}{2}(\partial_\mu h)^2 - \frac{m_h^2}{2} h^2 - \frac{\lambda}{4!} h^4 + y h \bar{\psi}\psi$$

This theory has a discrete symmetry:

$$S \begin{cases} \psi \to \gamma_5 \psi \\ h \to -h \end{cases} \qquad (*)$$

which forbids a fermion mass term (since $\bar{\psi}\psi \xrightarrow{S} -\bar{\psi}\psi$)

What if we add a relevant operator to the effective Lagrangian

$$\Delta\mathcal{L}_{\text{relev.}} = m_\psi \bar{\psi}\psi$$

Q: Do we encounter a similar issue as with $m^2 H^2$-term? (scalar mass)

This term was forbidden by chiral symmetry $\mathcal{S}$ (*), so it is natural to omit this term.

This symmetry also means that it is natural for the mass m_ψ to be non-zero but very small, e.g.

natural that $\quad m \ll M$

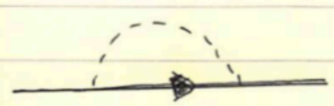
Effects of the breaking of $\mathcal{S}$ are only due to m_ψ

Compute 1-loop correction to m_ψ

$$m_\psi^{1\text{-loop}} = m_\psi + \frac{y^2}{16\pi^2} \cdot \xi \cdot m_\psi \ln\left(\frac{\Lambda}{M_\phi}\right) + \dots$$

with

$\xi \sim 1 \quad$ coefficient after calculating diagram:



$$\sim \int^{\Lambda} d^4k \, \frac{1}{k^2 - M_\phi^2} \, \frac{1}{\not{k} - m_\psi}$$

$$\sim \cancel{a\Lambda} + b\, m_\psi \ln \frac{\Lambda}{M} + \dots$$

(a,b,c are coefficients)

$$+ \, c \, \cancel{M \ln \frac{\Lambda}{m_\psi}} + \dots$$

$a = c = 0 \quad$ because the size of loop correction is controlled by m_ψ required to break $\mathcal{S}$ symmetry.

<u>Explanation:</u> We can formalize this: assume that parameter m_ψ transforms under $\mathcal{S}$ as

$$m_\psi \xrightarrow{\mathcal{S}} -m_\psi \qquad \text{(like a non-dynamical field)}$$

If we think of m_ψ as a 'field', with numerical mass m_ψ = vacuum exp. value of this field, then even

$$\Delta \mathcal{L}_{rel} = m_\psi \bar{\psi}\psi \rightarrow (-m_\psi)(-1)\bar{\psi}\psi$$
$$= m_\psi \bar{\psi}\psi$$

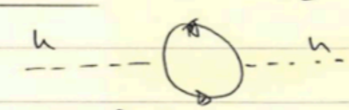
is symmetric under $\mathcal{S}$! Chiral symmetry is formally a good symmetry.

We call m_ψ a "<u>SPURION FIELD</u>"

$\Rightarrow$ all expressions must depend on m_ψ in such a way that $\mathcal{S}$ is a good symmetry (if you formally include $m_\psi \rightarrow -m_\psi$ in transf.)

Very useful trick! Only $b \neq 0$ has correct symmetry properties, $a = c = 0$.

<u>Quantum correction to scalar mass</u> $\quad \mathcal{L} \supset \frac{1}{2} M^2 h^2$



① $$M^{(1\text{-loop})} \underset{\Lambda}{=} M^2 + \frac{y^2}{16\pi^2}\left[c_1 \Lambda^2 + c_2 m_\psi^2 \ln\left(\frac{\Lambda}{\mu}\right) + c_3 M^2 + \dots \right]$$

with an explicit cut-off Λ, c_i : coefficients of $\mathcal{O}(1)$

② In dimensional regularization:

$$M^{(1\text{-loop})} \underset{DR}{=} M^2 + \frac{y^2}{16\pi^2}\left[\frac{\tilde{c}_2}{\epsilon} M^2 + \tilde{c}_3 m_\psi^2 + \mathcal{O}(\epsilon) \right]$$

In either case, we can write for the renormalized mass

$$M^2_{ren}(\mu=M) = M^2(\mu=M) + c_3' \frac{y^2}{4\pi^2} m_\psi^2$$

IF we want to make the scalar light compared to scale m_ψ (say for $M \ll m_\psi$), we must tune the fundamental couplings in the renormalized theory, so that there is a cancellation in ① or ②

We find: <u>naturalness problem</u>

"relevant operators not forbidden by symmetries are sensitive to heavy physical thresholds in the theory"

The hierarchy problem

- The SM is a great success also because of its accidental symmetries, all null-tests successful so far

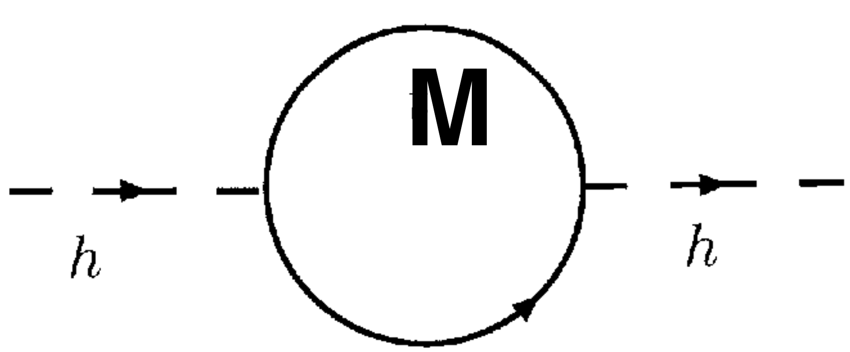
- *B*,*L*, *CP* and flavor are conserved or only broken by tiny amounts

- Broken by **irrelevant** operators of SM fields, suppressed by mass scale. Success of SM means hierarchy of scales!

e.g. $\Lambda_{\rm SM} \ll \Lambda_{\not B}$

Running of m_H^2

$$\beta_{m_h^2} = \frac{dm_h^2}{d\log\bar{\mu}} = \frac{3m_h^2}{8\pi^2}\left(2\lambda + y_t^2 - \frac{3g^2}{4} - \frac{g'^2}{4}\right)$$ (SM)



(heavy fermion)

Running of m_H^2

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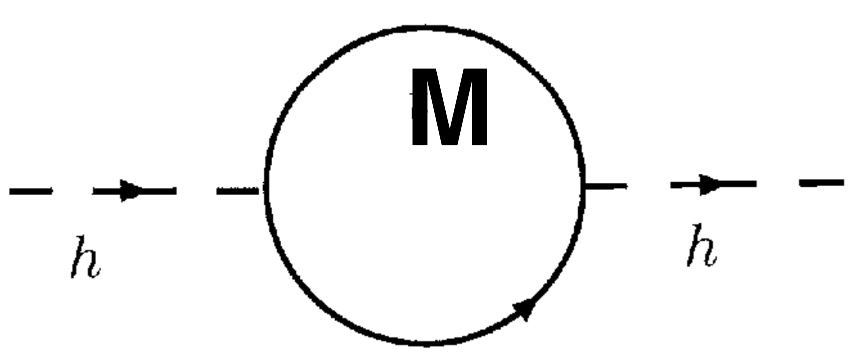
Add new Dirac fermion of mass *$M >> m_h$* *and*

$$\delta m_h^2 = \mathrm{Re}\,\Pi_{hh}|_{p^2=m_h^2} = \frac{y^2}{2(4\pi)^2}\mathrm{Re}\left[\Delta_\epsilon + (m_h^2 - 4M^2)B_0(m_h; M, M) - 2A_0(M)\right.$$

$$= \frac{y^2}{2(4\pi)^2}\left(\Delta_\epsilon + (6M^2 - m_h^2)\log\frac{m_h^2}{\bar{\mu}^2} + f(m_h, M)\right),$$



(heavy fermion)

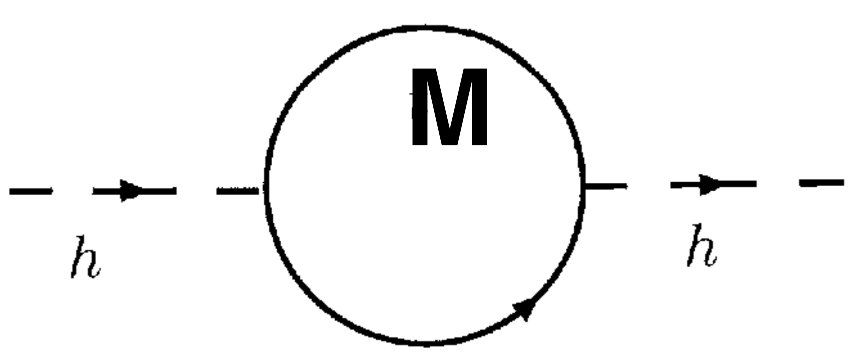
Running of m_H^2

$$\beta_{m_h^2} = \frac{dm_h^2}{d\log\bar\mu} = \frac{3m_h^2}{8\pi^2}\left(2\lambda + y_t^2 - \frac{3g^2}{4} - \frac{g'^2}{4}\right)$$ (SM)

Add new Dirac fermion of mass *M >> m_h and*

$$\delta m_h^2 = \mathrm{Re}\,\Pi_{hh}\big|_{p^2=m_h^2} = \frac{y^2}{2(4\pi)^2}\mathrm{Re}\left[\Delta_\epsilon + (m_h^2 - 4M^2)B_0(m_h;M,M) - 2A_0(M)\right.$$
$$= \frac{y^2}{2(4\pi)^2}\left(\Delta_\epsilon + (6M^2 - m_h^2)\log\frac{m_h^2}{\bar\mu^2} + f(m_h,M)\right),$$

$$\beta_{m_h^2} = \frac{d\,m_h^2(\bar\mu)}{d\log\bar\mu} = \frac{y^2}{(4\pi)^2}(m_h^2 - 6M^2) + \cdots$$



(heavy fermion)

The hierarchy problem

$$\beta_{m_h^2} = \frac{dm_h^2}{d\log\bar{\mu}} = \frac{3m_h^2}{8\pi^2}\left(2\lambda + y_t^2 - \frac{3g^2}{4} - \frac{g'^2}{4}\right) \qquad \text{(SM)}$$

SM + Dirac fermion of mass *M >> m_h and yukawa y*

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Two contributions in have to balance out with very high accuracy to generate a Higgs boson mass much smaller than $\Lambda_{\rm NP}$

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For Λ = M_{Planck} , M_{GUT} , 10 TeV : $\epsilon \sim 10^{-32}, 10^{-28}, 10^{-4}$

Comments

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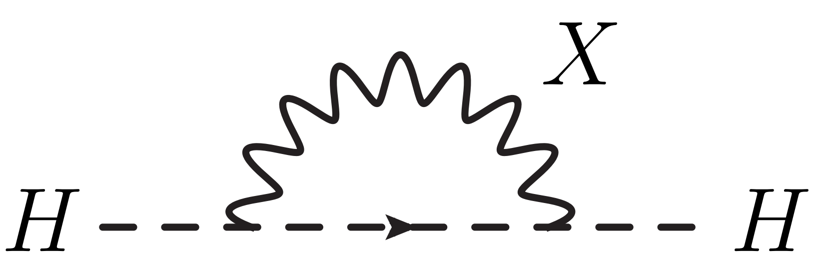
e.g. GUT



$$\Rightarrow \Delta m_H^2 \sim \frac{g_{\mathrm{GUT}}^2}{16\pi^2} M_X^2 \sim (10^{15}\ \mathrm{GeV})^2$$

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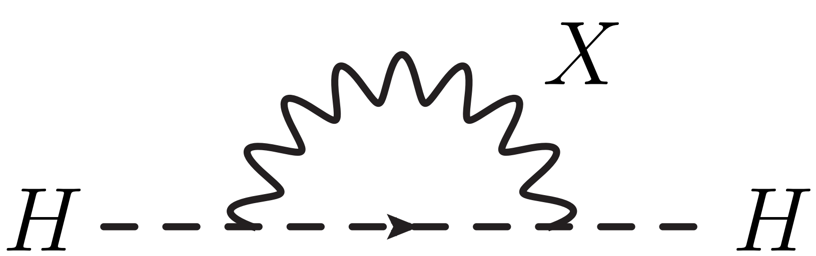


$$\Rightarrow \Delta m_H^2 \sim \frac{g_{\mathrm{GUT}}^2}{16\pi^2} M_X^2 \sim (10^{15}\ \mathrm{GeV})^2$$

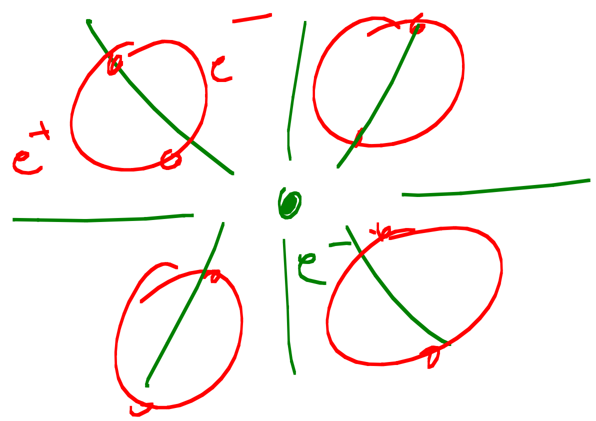
- The hierarchy problem needs a ‘hierarchy of scales’. The SM alone (no gravity, nothing else) if fine → no hierarchy, no problem!

Famous naturalness disaster

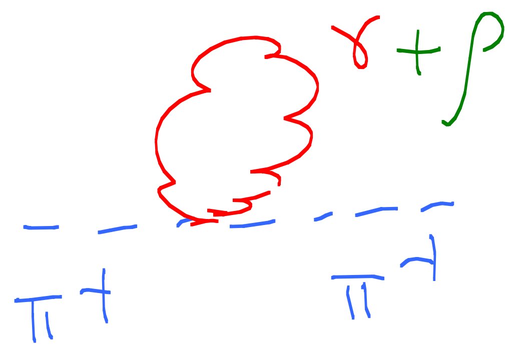
- We don't understand the cosmological constant $CC = \Lambda_0 \approx (10^{-3}\,\mathrm{eV})^4$

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,(R-\Lambda_0)$$

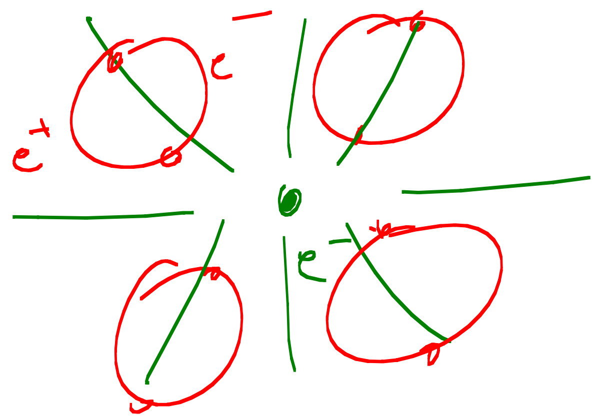
$\delta\Lambda_0 \approx \Lambda^4$ → new physics at $10^{-3}\,\mathrm{eV}$
~ few mm !?!



Supersymmetry
(new space-time symmetry)



Composite Higgs



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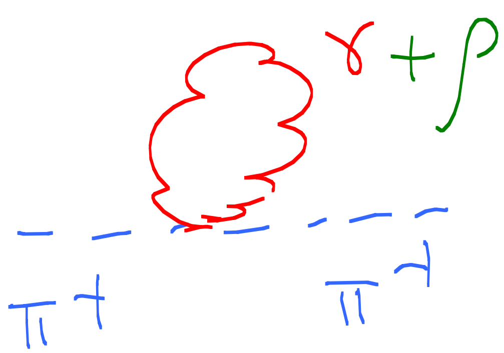

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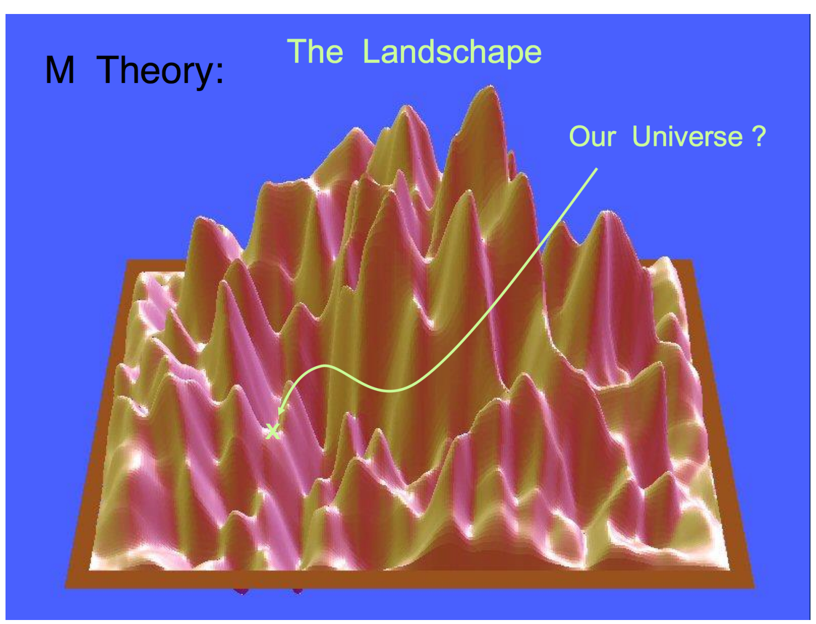
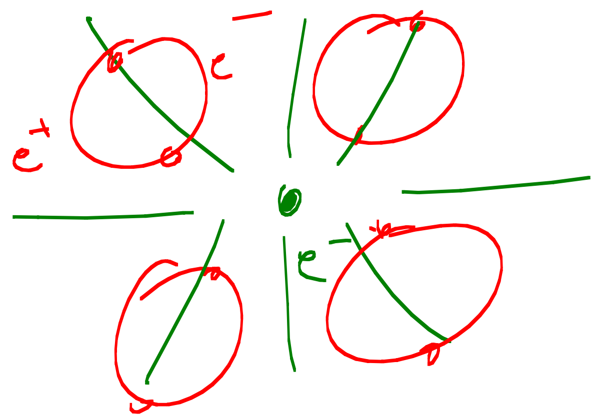


anthropic principle?

Multiverse



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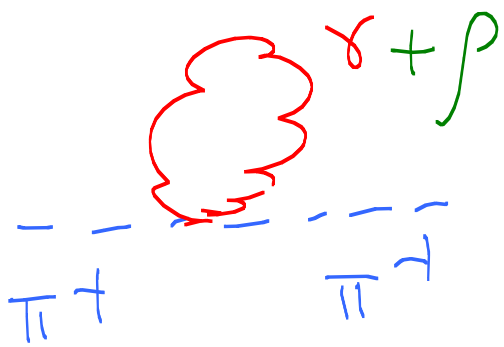

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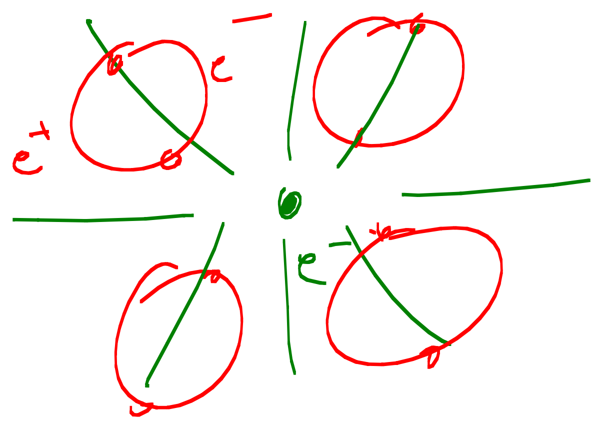

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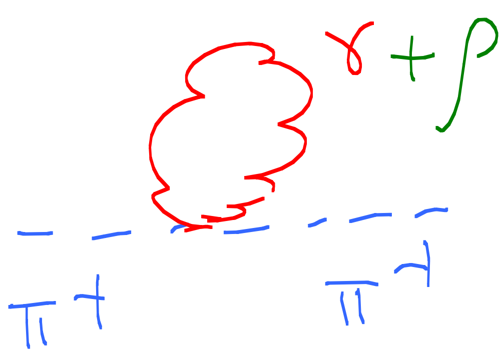

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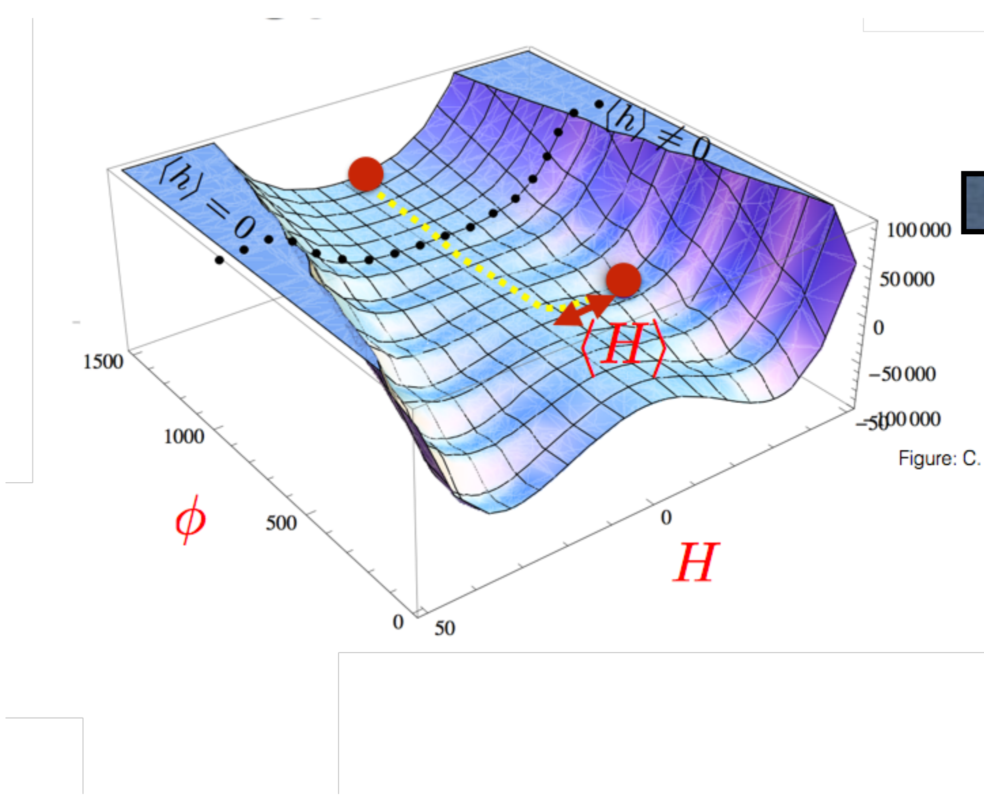
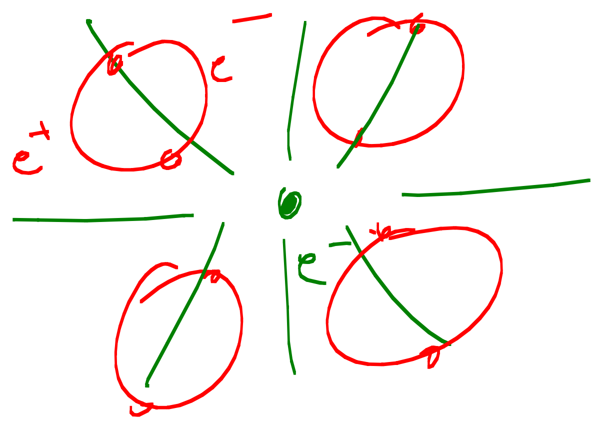


Figure: C. Grojean

Relaxion



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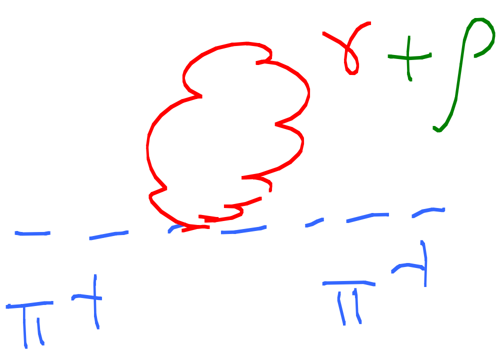

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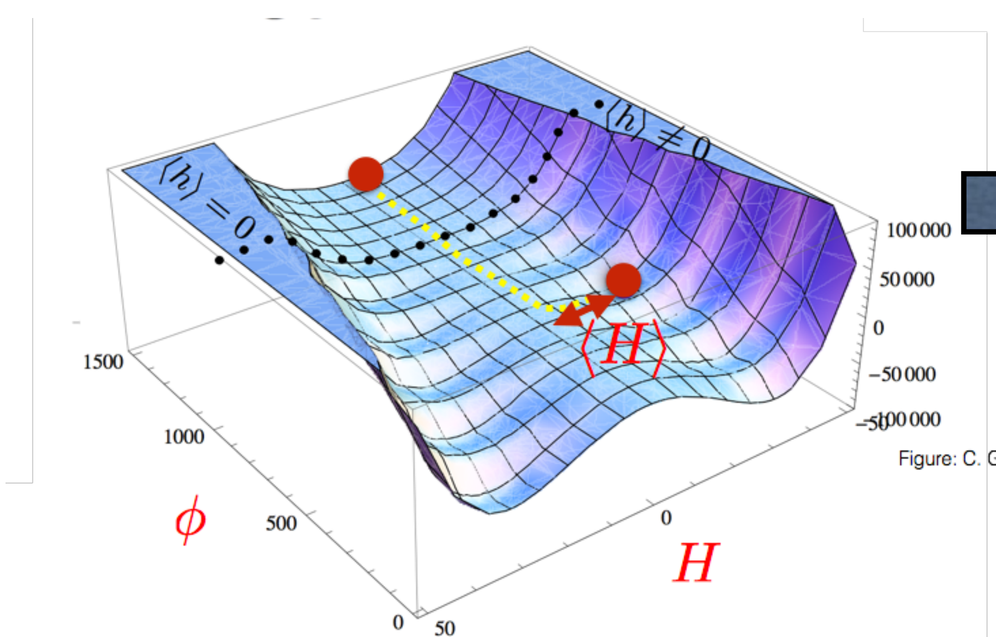

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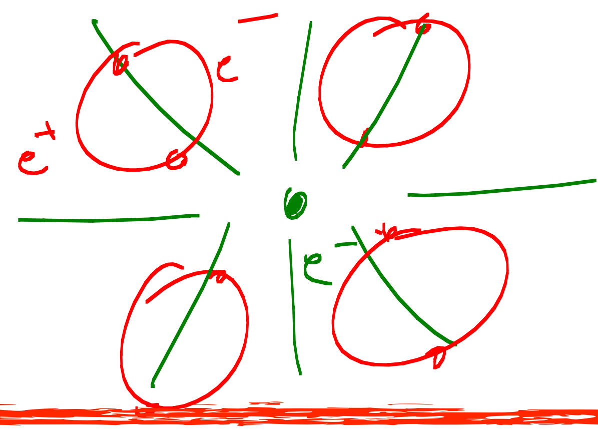

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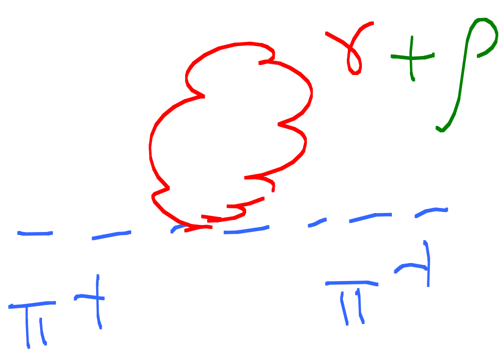

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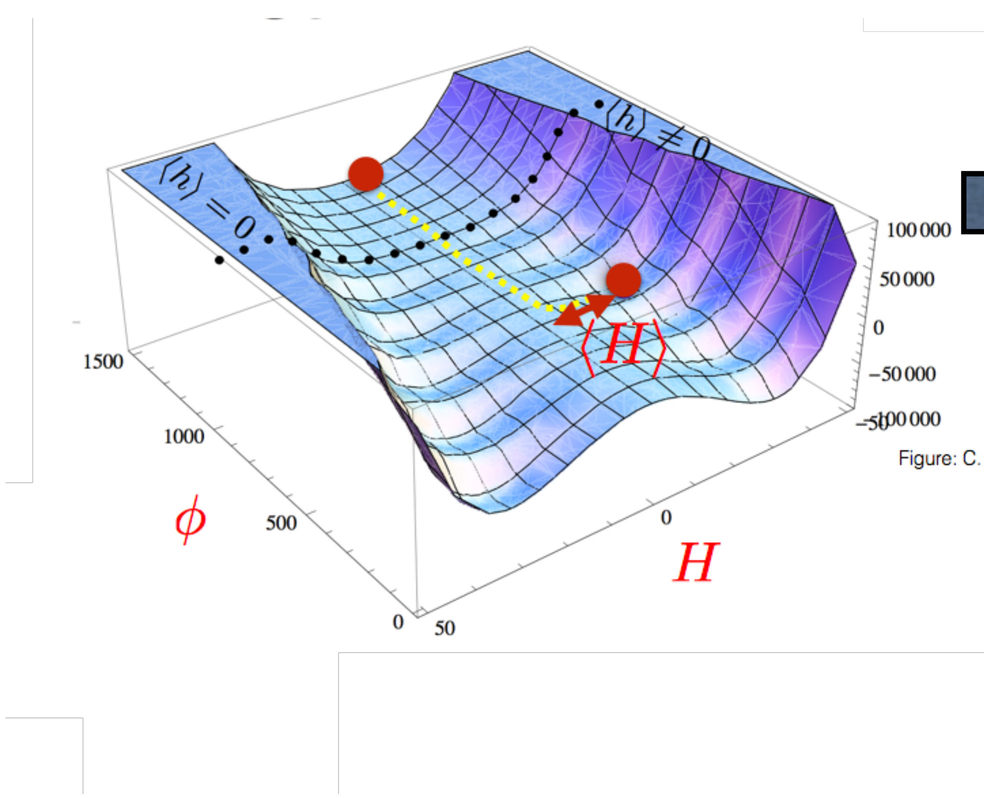

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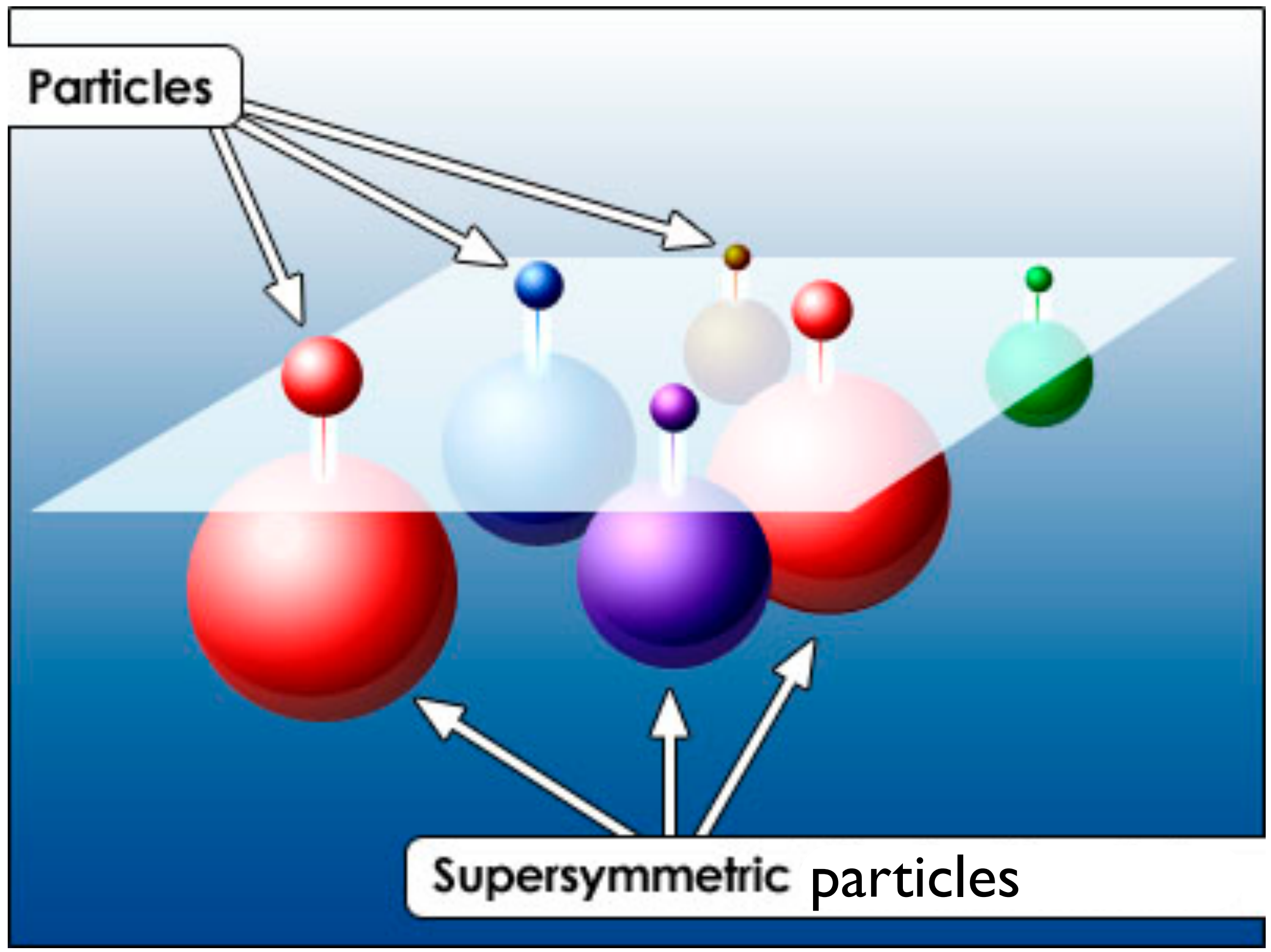


$$S = \int \mathrm{d}^4x \left(\mathrm{d}^2\theta \mathrm{d}^2\bar{\theta}\, \Phi_i^* \exp\left(2g_A T_A^a V_A^a\right) \Phi_i + \left\{ \mathrm{d}^2\theta \left[\mathcal{W}(\{\Phi_i\}) + \frac{1}{4} W_A^a W_A^a \right] + \mathrm{h.c.} \right\} \right)$$

Super-multiplets

Invariance of interactions manifest if we can group together states which transform into each other

eg. SU(2)

$$\Phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \qquad \Phi \to U\Phi$$

Invariance obvious if $\mathcal{L}(\Phi^\dagger \Phi)$

- Supersymmetry is generalisation
- Rotates bosons into fermions and vice versa
- Generators are fermionic, anti-commuting

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle$$
$$Q|\text{Fermion}\rangle = |\text{Boson}\rangle$$

- Algebra

$$\{Q, Q^\dagger\} = P^\mu,$$
$$\{Q, Q\} = \{Q^\dagger, Q^\dagger\} = 0,$$
$$[P^\mu, Q] = [P^\mu, Q^\dagger] = 0,$$

$$\left(\{Q_\alpha, Q^\dagger_{\dot\alpha}\} = -2\sigma^\mu_{\alpha\dot\alpha} P_\mu\right)$$

(in components)

Susy algebra

fermionic generators

$$\{Q_\alpha, Q^\dagger_{\dot\alpha}\} = 2\sigma^\mu_{\alpha\dot\alpha} P_\mu$$

$$Q_\alpha = (Q_1, Q_2)$$

mass spin

$$Q_1^\dagger |m, s, s_z, q\rangle \quad \rightarrow \quad \sqrt{2m}|m, s+\frac{1}{2}, s_z+\frac{1}{2}, q\rangle$$

$$Q_2^\dagger |m, s, s_z, q\rangle \quad \rightarrow \quad \sqrt{2m}|m, s+\frac{1}{2}, s_z-\frac{1}{2}, q\rangle$$

$$Q|F>=|B>,\ Q|B>=|F>$$

Space-time symmetry: cannot select which particles have super-partners, all or nothing…

Super-fields

- Put bosons and fermions in multiplets together
  - chiral superfield (2 real bosons, 1 Weyl fermion)

$$\Phi(y,\theta) = \varphi(y) + \sqrt{2}\theta\psi(y) + \theta^2 F(y)$$

anti-commuting
Grassmann variable
(superspace coordinate)

complex
scalar

left-handed
Weyl fermion

auxiliary
field

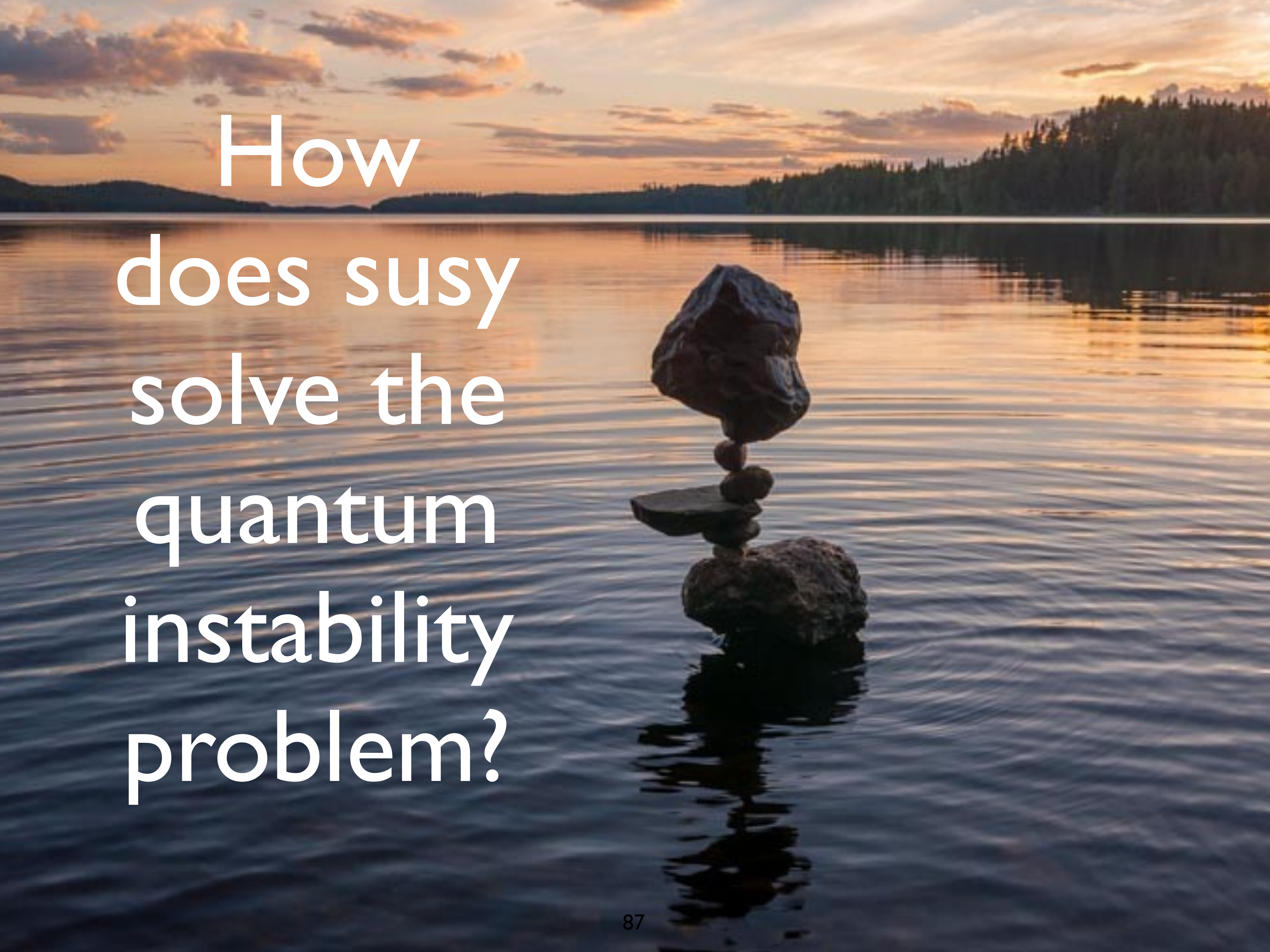
- In addition: vector superfield (1 vector boson, 1 Weyl fermion)

$$V = -\,\theta\sigma^{\mu}\bar{\theta}V_{\mu}(x) + i\theta^{2}\bar{\theta}\bar{\lambda}(x) - i\bar{\theta}^{2}\theta\lambda(x) + \frac{1}{2}\theta^{2}\bar{\theta}^{2}D(x)$$

- Equal number of bosonic and fermionic degrees of freedom

- No SM fields are superpartners of eachother

→ double field content!

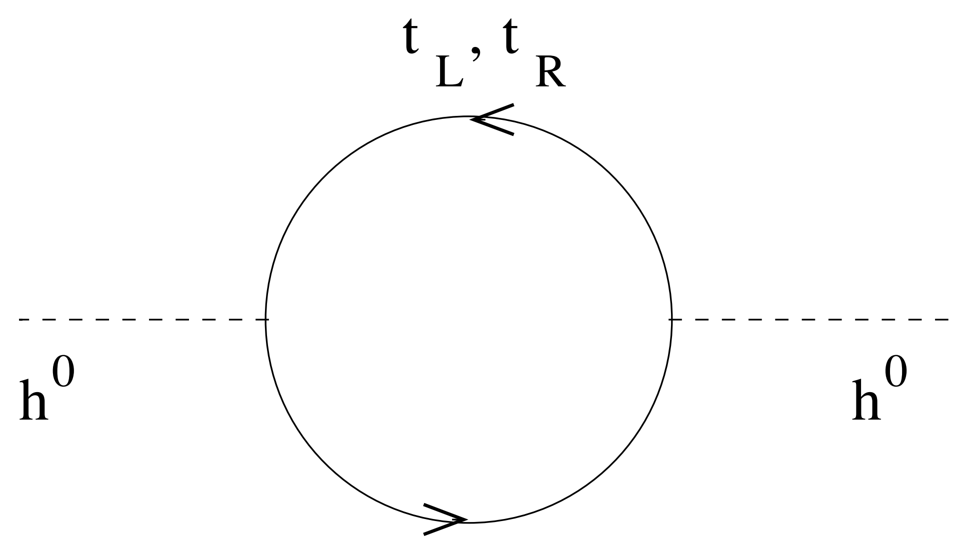

How
does susy
solve the
quantum
instability
problem?

In words

- Supersymmetry associates a fermion with each scalar and predicts ‘symmetric dynamics’.
- Fermion masses are protected by chiral symmetry → scalar masses are protected.

SM quantum instability

$$\mathcal{L}_{\text{Yukawa}} = -\frac{y_t}{\sqrt{2}} H^0 \overline{t_L} t_R + h.c.$$



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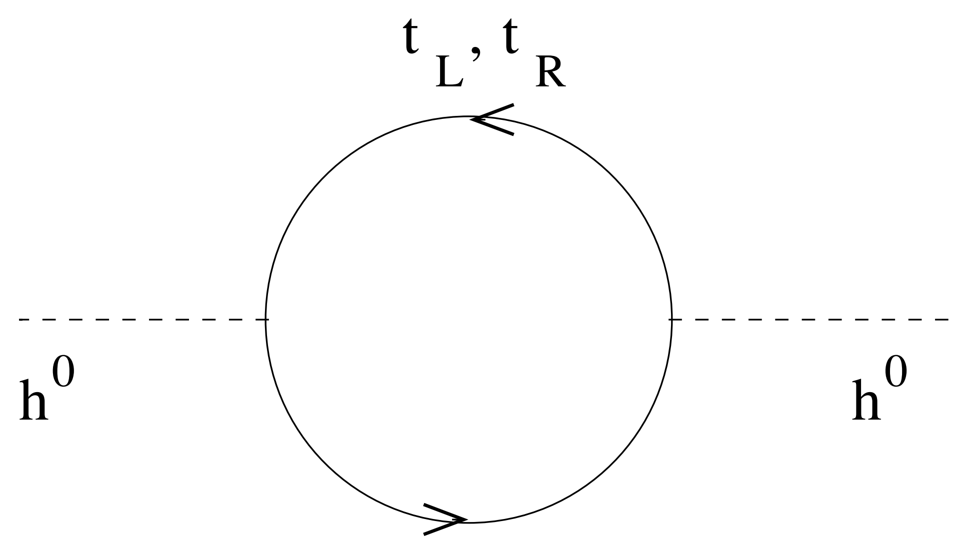

$$\begin{aligned}
-i\delta m_h^2|_{\text{top}} &= (-1) N_c \int \frac{d^4k}{(2\pi)^4} \text{Tr}\left[\frac{-iy_t}{\sqrt{2}} \frac{i}{\not{k} - m_t} \left(\frac{-iy_t^*}{\sqrt{2}}\right) \frac{i}{\not{k} - m_t}\right] \\
&= -2N_c |y_t|^2 \int \frac{d^4k}{(2\pi)^4} \frac{k^2 + m_t^2}{(k^2 - m_t^2)^2}
\end{aligned}$$

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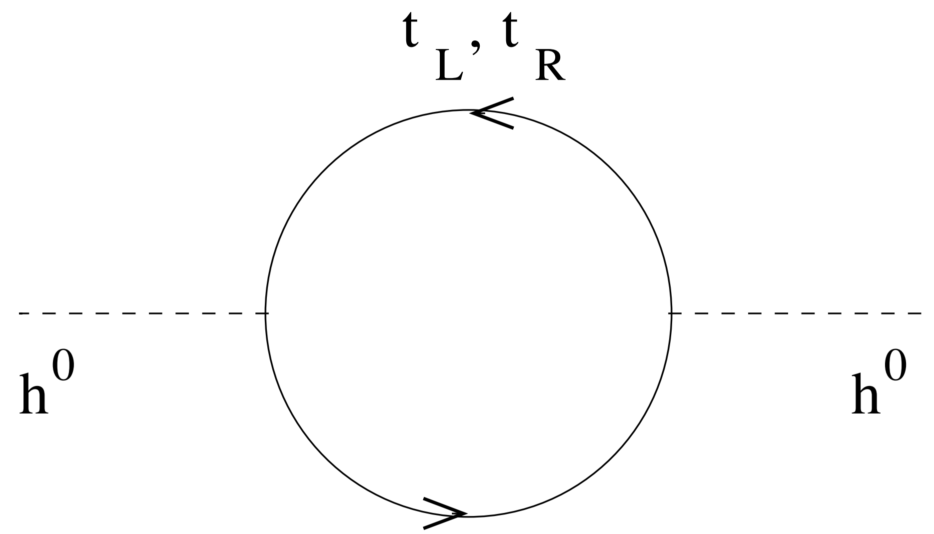

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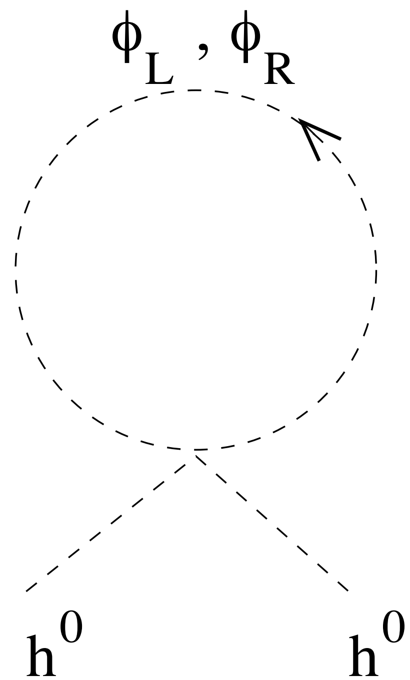
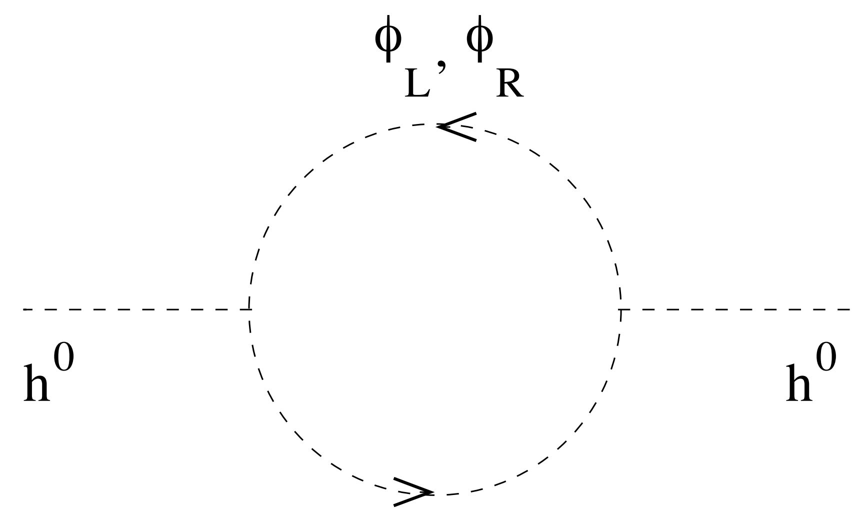
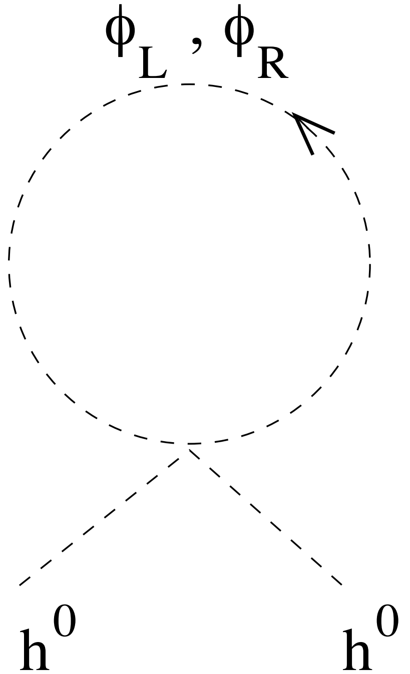
$$\begin{aligned} \delta m_h^2|_{\text{top}} &= -\frac{N_c|y_t|^2}{8\pi^2} \int_{m_t^2}^{\Lambda^2} dx \left(1 - \frac{3m_t^2}{x} + \frac{2m_t^4}{x^2}\right) \\ &= -\frac{N_c|y_t|^2}{8\pi^2} \left[\Lambda^2 - 3\, m_t^2\, \ln\left(\frac{\Lambda^2+m_t^2}{m_t^2}\right) + \ldots\right] \end{aligned}$$

Add scalar partners

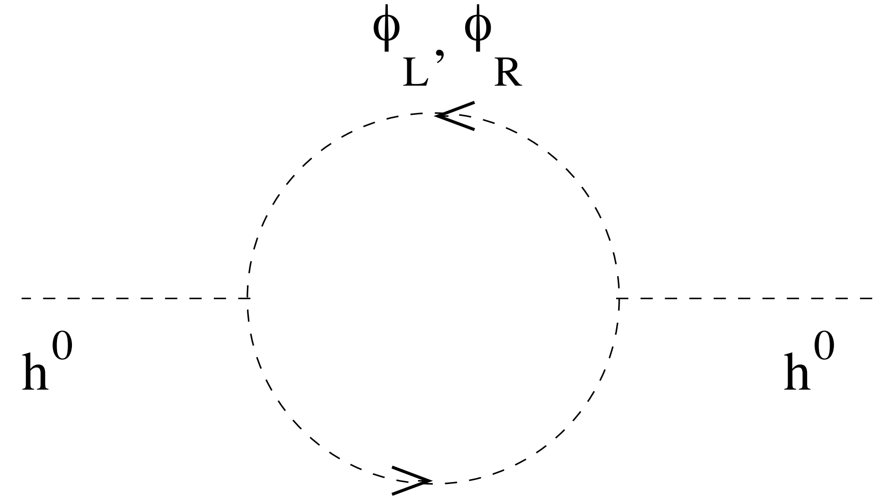
$$\mathcal{L}_{\rm scalar} = -\frac{\lambda}{2}(h^0)^2(|\phi_L|^2+|\phi_R|^2) - h^0(\mu_L|\phi_L|^2+\mu_R|\phi_R|^2) -m_L^2|\phi_L|^2 - m_R^2|\phi_R|^2$$







(2)



(3)

$$\delta m_h^2|_2 = \frac{\lambda N}{16\pi^2}\left[2\Lambda^2 - m_L^2 \ln\left(\frac{\Lambda^2+m_L^2}{m_L^2}\right) - m_R^2 \ln\left(\frac{\Lambda^2+m_R^2}{m_R^2}\right) + \ldots\right].$$

$$\delta m_h^2|_3 = -\frac{N}{16\pi^2}\left[\mu_L^2\ \ln\left(\frac{\Lambda^2+m_L^2}{m_L^2}\right) + \mu_R^2\ \ln\left(\frac{\Lambda^2+m_R^2}{m_R^2}\right) + \ldots\right]$$

New Interactions

$$\mathcal{L}_{\text{scalar}} = -\frac{\lambda}{2}(h^0)^2(|\phi_L|^2 + |\phi_R|^2) - h^0(\mu_L|\phi_L|^2 + \mu_R|\phi_R|^2) - m_L^2|\phi_L|^2 - m_R^2|\phi_R|^2$$

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SM top loop

$$\delta m_h^2|_{\text{top}} = -\frac{N_c|y_t|^2}{8\pi^2}\left[\Lambda^2 - 3\,m_t^2 \ln\left(\frac{\Lambda^2+m_t^2}{m_t^2}\right) + \ldots\right]$$

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= softly broken susy

$$\boxed{\text{If } N = N_c \text{ and } \lambda = |y_t|^2 \text{ then } \Lambda^2 \text{ cancels!}}$$

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= unbroken susy

If $m_t = m_L = m_R$ and $\mu_L^2 = \mu_R^2 = 2\lambda m_t^2$

SM top loop

$$\delta m_h^2|_{\text{top}} = -\frac{N_c|y_t|^2}{8\pi^2}\left[\cancel{\Lambda^2} - 3\,m_t^2 \ln\left(\frac{\Lambda^2+m_t^2}{m_t^2}\right) + \dots\right]$$

New Interactions

$$\mathcal{L}_{\text{scalar}} = -\frac{\lambda}{2}(h^0)^2(|\phi_L|^2 + |\phi_R|^2) - h^0(\mu_L|\phi_L|^2 + \mu_R|\phi_R|^2)$$
$$-m_L^2|\phi_L|^2 - m_R^2|\phi_R|^2$$

= softly broken susy

If $N = N_c$ and $\lambda = |y_t|^2$ then Λ^2 cancels!

New partners

$$\delta m_h^2|_2 = \frac{\lambda N}{16\pi^2}\left[2\cancel{\Lambda^2} - m_L^2 \ln\left(\frac{\Lambda^2+m_L^2}{m_L^2}\right) - m_R^2 \ln\left(\frac{\Lambda^2+m_R^2}{m_R^2}\right) + \ldots\right].$$

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Supersymmetry guarantees these relations!

No UV sensitivity :

Need specific structure in dimensionless couplings $\lambda = |y_t|^2$

Matching # of degrees of freedom $N = N_c$

But no need for equal masses (stop/stop) nor other dimensionful couplings (e.g. trilinear scalar) to be the same

No UV sensitivity :

super-potential

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But no need for equal masses (stop/stop) nor other dimensionful couplings (e.g. trilinear scalar) to be the same

soft susy breaking

Super-multiplets

- Chiral multiplet
  - On-shell: free particles.
  - complex scalar: ϕ, two on-shell degrees of freedom
  - Weyl fermion (2-component): ψ, two on-shell degrees of freedom.
- Examples of chiral multiplet
  - Starting from SM model quark (left or right handed), $q_{L,R}$
  - Adding scalar partner: squark. $\tilde{q}_{L,R}$
  - Form a chiral multiplet.

Super-multiplets

- Vector multiplet (on-shell).
  - Spin-1: vector A_μ (massless, 2 degrees of freedom)
  - Weyl fermion: λ (2 d.o.f.)
- Example:
  - Starting with SM gauge bosons, such as the 8 gluons $G^a{}_\mu$ (a=1, ..., 8)
  - Adding their partners, $\tilde{g}^a$ 8 gluinos.

MSSM

Every elementary particle is part of a super-multiplet: super-partners

SM int.	gauge boson, spin-1	Super-partner, spin-1/2
$SU(3)_C$	$g^a,\ a = 1, 2, ..., 8$	gluino: $\tilde{g}^a$
$SU(2)_L$	$W_{1,2,3}$	wino: $\tilde{W}_{1,2,3}$
$U(1)_Y$	B_μ	bino: $\tilde{B}$

squarks, quarks	Q	$(\widetilde{u}_L \ \ \widetilde{d}_L)$	$(u_L \ \ d_L)$	$(\mathbf{3},\ \mathbf{2},\ \frac{1}{6})$
($\times$3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \ \ \widetilde{e}_L)$	$(\nu \ \ e_L)$	$(\mathbf{1},\ \mathbf{2},\ -\frac{1}{2})$
($\times$3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H^+_u \ \ H^0_u)$	$(\widetilde{H}^+_u \ \ \widetilde{H}^0_u)$	$(\mathbf{1},\ \mathbf{2},\ +\frac{1}{2})$
	H_d	$(H^0_d \ \ H^-_d)$	$(\widetilde{H}^0_d \ \ \widetilde{H}^-_d)$	$(\mathbf{1},\ \mathbf{2},\ -\frac{1}{2})$

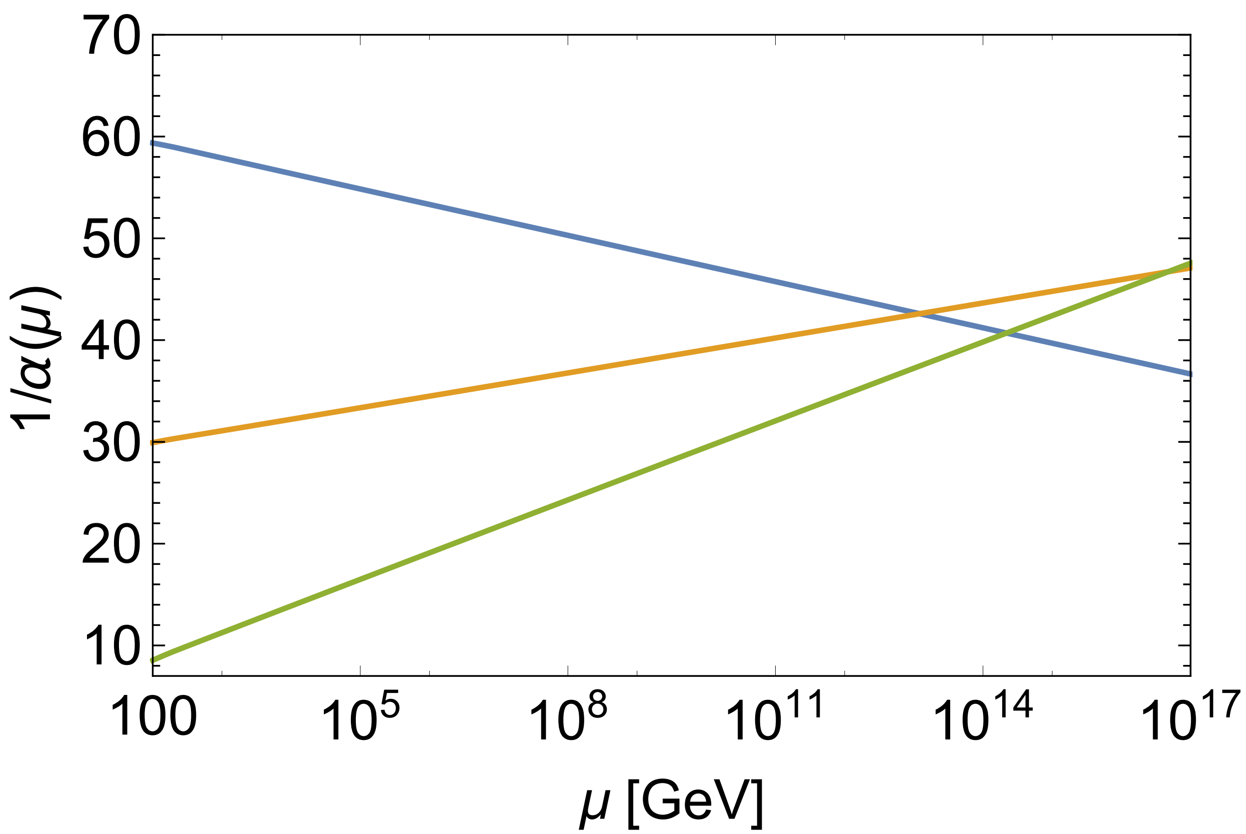
Minimal Supersymmetric Standard Model (MSSM)

UNIFICATION

GIVEN MEASURED SM GAUGE COUPLINGS AT WEAK SCALE, CAN STUDY EVOLUTION TO HIGHER SCALES WITH RGES.

$$\frac{\partial \alpha_i}{\partial \ln \mu} = \beta_i = b_i \frac{\alpha_i^2}{2\pi} + \ldots \quad \Rightarrow \frac{1}{\alpha_i(\mu)} - \frac{1}{\alpha_i(m_Z)} = -\frac{b_i}{2\pi} \ln\left(\frac{\mu}{m_Z}\right) + \ldots \qquad \boxed{\alpha_i \equiv \frac{g_i^2}{4\pi}}$$

$$b_1 = 41/10 \qquad b_2 = -19/6 \qquad b_3 = -7$$



SUGGESTIVELY, THE THREE APPEAR TO CROSS (MISSING TRIPLE INTERSECTION BY O(10%)) AROUND 10^{15} GEV.

CONSISTENT WITH UNIFICATION OF SU(3)XSU(2)XU(1) INTO COMMON GAUGE GROUP.

CONVENIENTLY $\quad SO(10) \supset SU(5) \supset SU(3) \times SU(2) \times U(1)$

Gauge coupling running

for $SU(5)_{GUT}$

$$g_1 \equiv \boxed{\sqrt{\tfrac{5}{3}}g'}, \quad g_2 \equiv g, \quad g_3 \equiv g_C, \quad \alpha_i \equiv \frac{g_i^2}{4\pi}$$

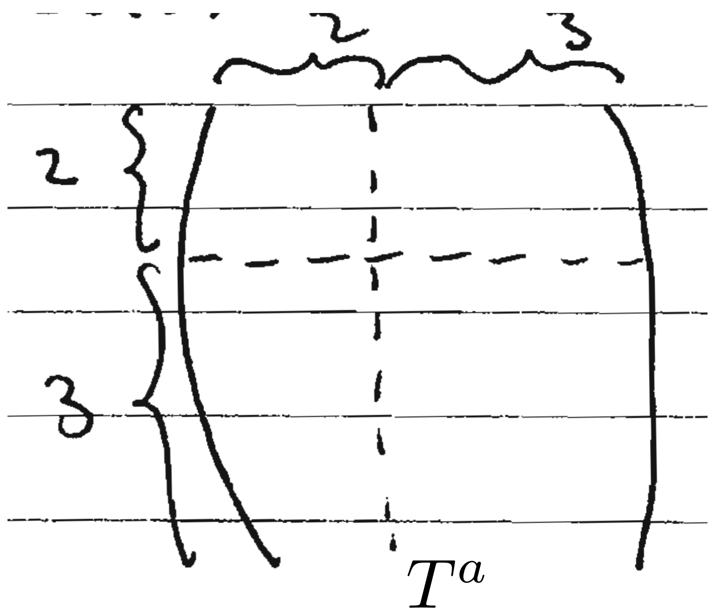
1-loop running

$$\mu \frac{dg_a}{d\mu} = -\frac{1}{16\pi^2} b_a g_a^3$$

$$\begin{aligned} b_a^{\mathrm{SM}} &= (-41/10, 19/6, 7) \\ b_a^{\mathrm{MSSM}} &= (-33/5, -1, 3) \end{aligned}$$

How is SU(3)xSU(2)xU(1) exactly contained in SU(5)?

SU(5) N^2 - 1 = 24 generators



SU(2)

SU(3)

$$D_\mu = \partial_\mu - i g_{\mathrm{SU}(5)} A^a_\mu T^a$$

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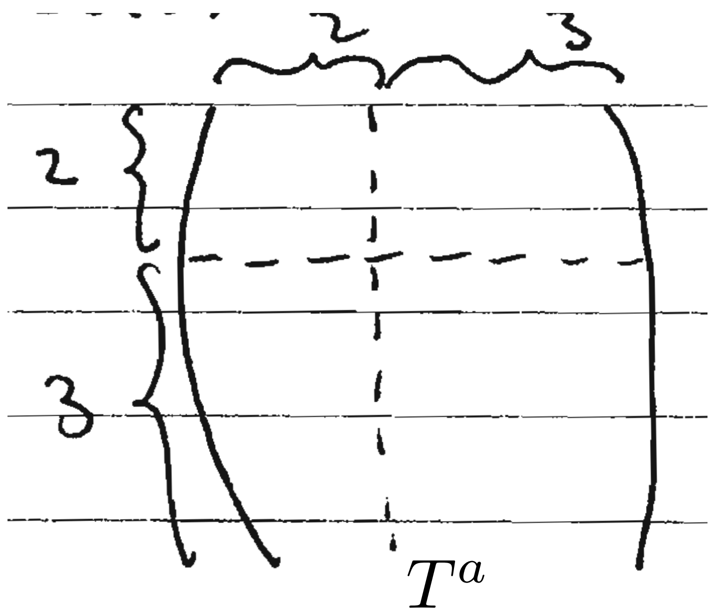

SU(2)

SU(3)

$$D_\mu = \partial_\mu - i g_{\mathrm{SU}(5)} A_\mu^a T^a$$

$Y = c\, T_{12} =$

some constant

U(1)$_Y$

$$T^{12} = \begin{pmatrix} 3 & & & & \\ & 3 & & & \\ & & -2 & & \\ & & & -2 & \\ & & & & -2 \end{pmatrix} \frac{1}{\sqrt{60}} \quad \leftarrow U(1)_Y$$

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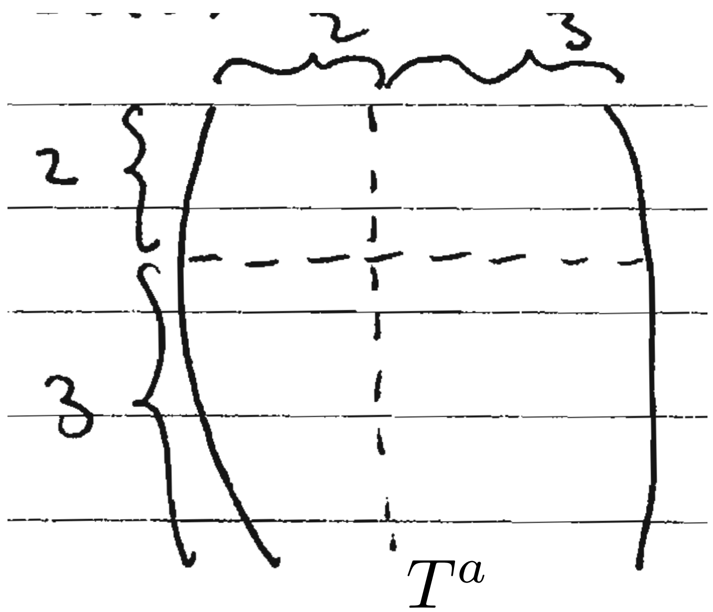

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$$D_\mu = \partial_\mu - i g_{\mathrm{SU}(5)} A_\mu^a T^a$$

SU(2)

$$T^{1,2,3} = \begin{pmatrix} \tau^{1,2,3} & \\ & \end{pmatrix} \qquad \text{eg. } \frac{1}{2}\begin{pmatrix} 1 & & & & \\ & -1 & & & \\ & & 0 & & \\ & & & 0 & \\ & & & & 0 \end{pmatrix}$$

$\leftarrow$ SU(2)

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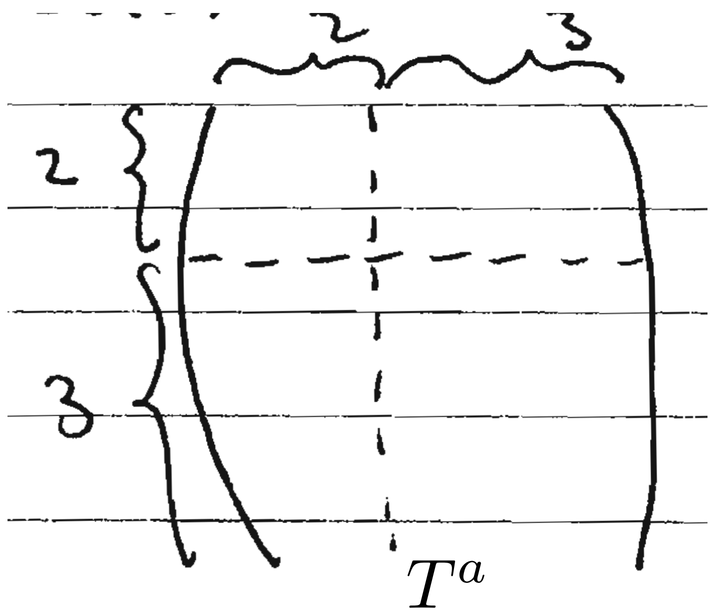

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$$Y = \underset{\substack{\uparrow \\ \text{some constant}}}{c}\, T_{12} =$$

SU(3)

$$T^{4,5,6,\dots,11} = \left(\begin{array}{c|c} & \\ \hline & \lambda^{1,\dots,8} \end{array}\right)$$

U(1)$_Y$

$$T^{12} = \begin{pmatrix} 3 & & & & \\ & 3 & & & \\ & & -2 & & \\ & & & -2 & \\ & & & & -2 \end{pmatrix} \frac{1}{\sqrt{60}} \quad \leftarrow \mathrm{U}(1)_Y$$

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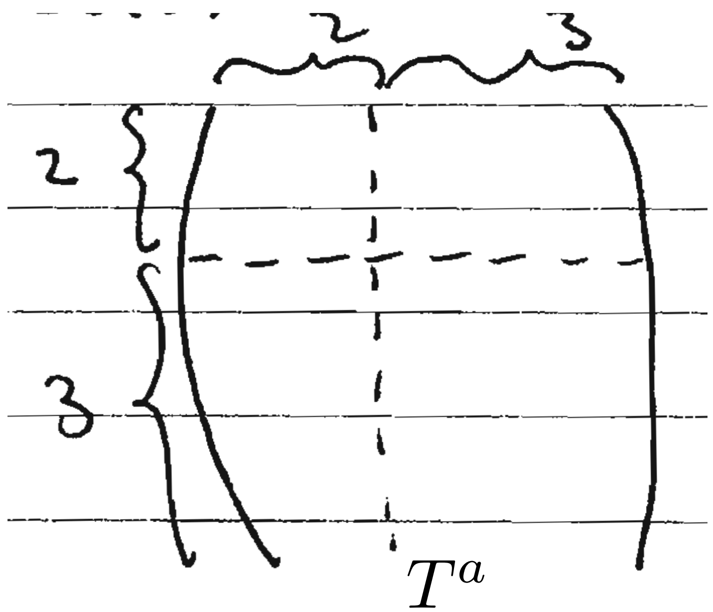

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← SU(2)

$Y = c\, T_{12}$

↑ some constant

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Need embedding of fermions into SU(5).
VERY non-trivial!

$$\bar{5} = \begin{pmatrix} L \\ \bar{d}_R \end{pmatrix}$$

LH lepton doublet, RH down quark unify

$$Y = \frac{c}{\sqrt{60}} \begin{pmatrix} 3 & & & & \\ & 3 & & & \\ & & -2 & & \\ & & & -2 & \\ & & & & -2 \end{pmatrix} \longrightarrow \begin{pmatrix} 1/2 & & & & \\ & 1/2 & & & \\ & & -1/3 & & \\ & & & -1/3 & \\ & & & & -1/3 \end{pmatrix}$$

$$\frac{c}{\sqrt{60}} 3 \overset{!}{=} \frac{1}{2} \quad \Rightarrow \quad c = \sqrt{\frac{5}{3}}$$

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LH quark and, RH elec. in 10

$$10^{ij} \quad \left[\begin{array}{cc|ccc} 0 & \bar{e}_R & u_1 & u_2 & u_3 \\ & 0 & d_1 & d_2 & d_3 \\ \hline & & 0 & \bar{u}_3 & -\bar{u}_2 \\ & & & 0 & \bar{u}_1 \\ & & & & 0 \end{array}\right]$$

SM $\subset$ GUT

SM is completely contained in, quantum numbers match!

$\mathbf{5^c}$ + $\mathbf{10}$ (+ $\mathbf{1}$)

L, d_R Q, e_R, u_R

SM ⊂ GUT

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Extremely non-trivial!

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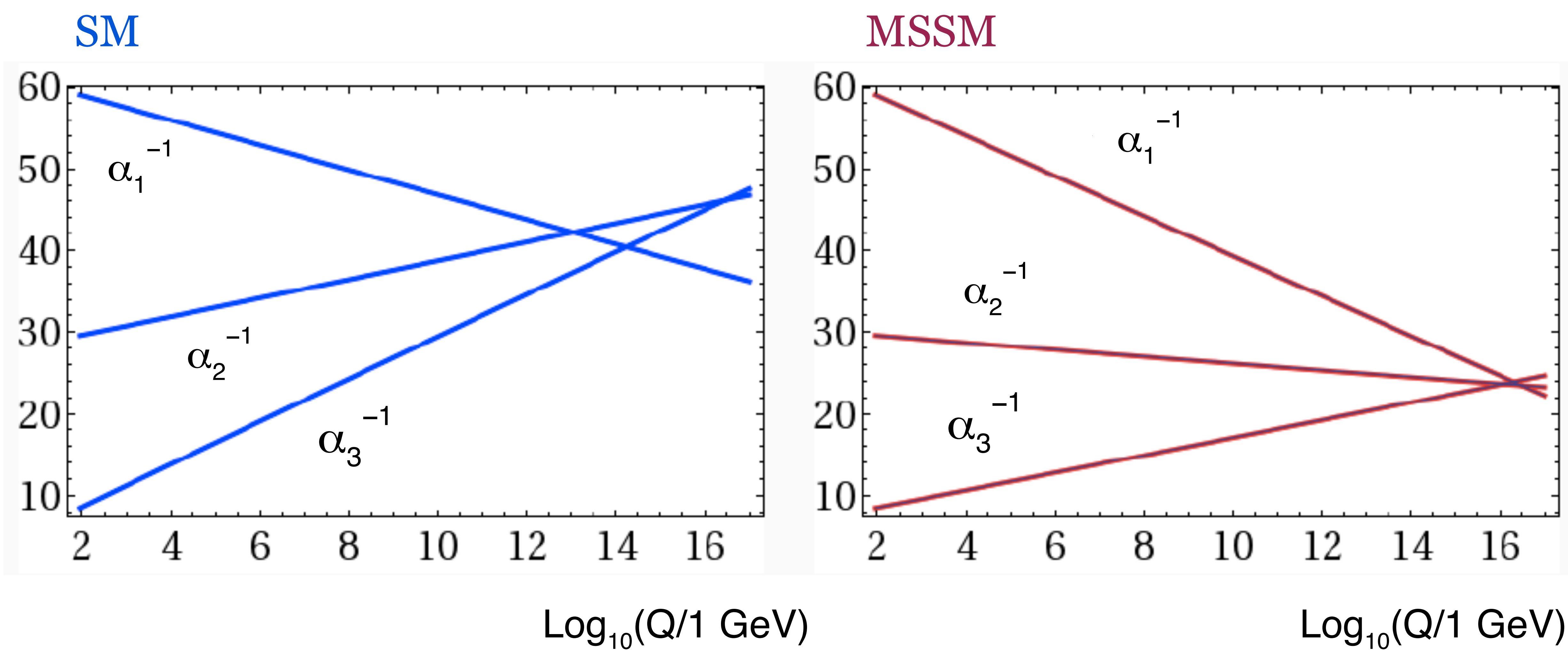
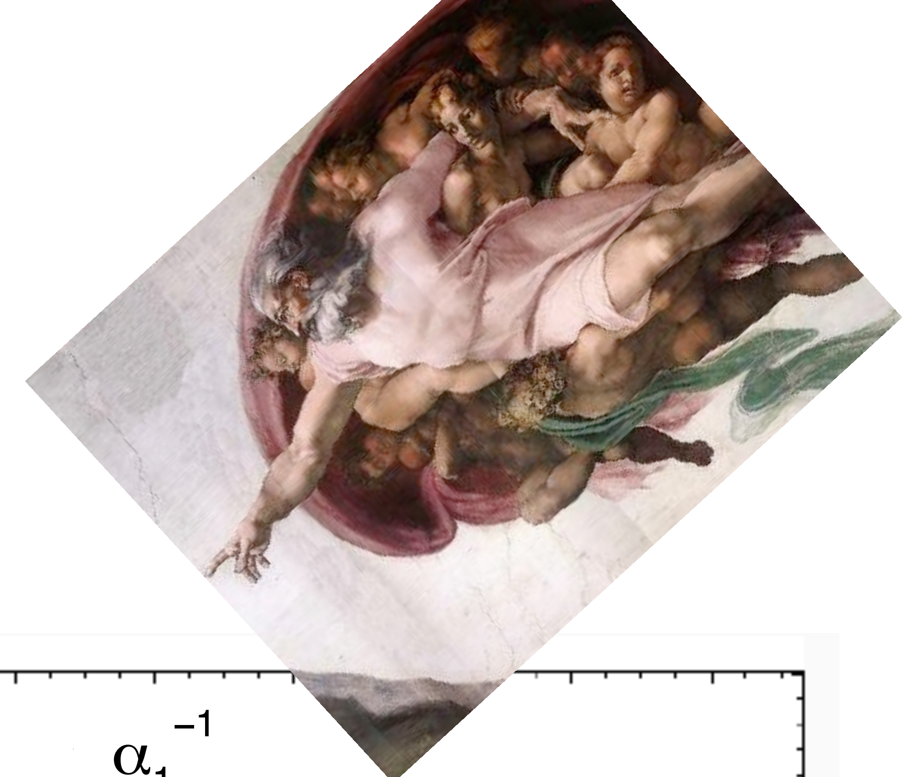
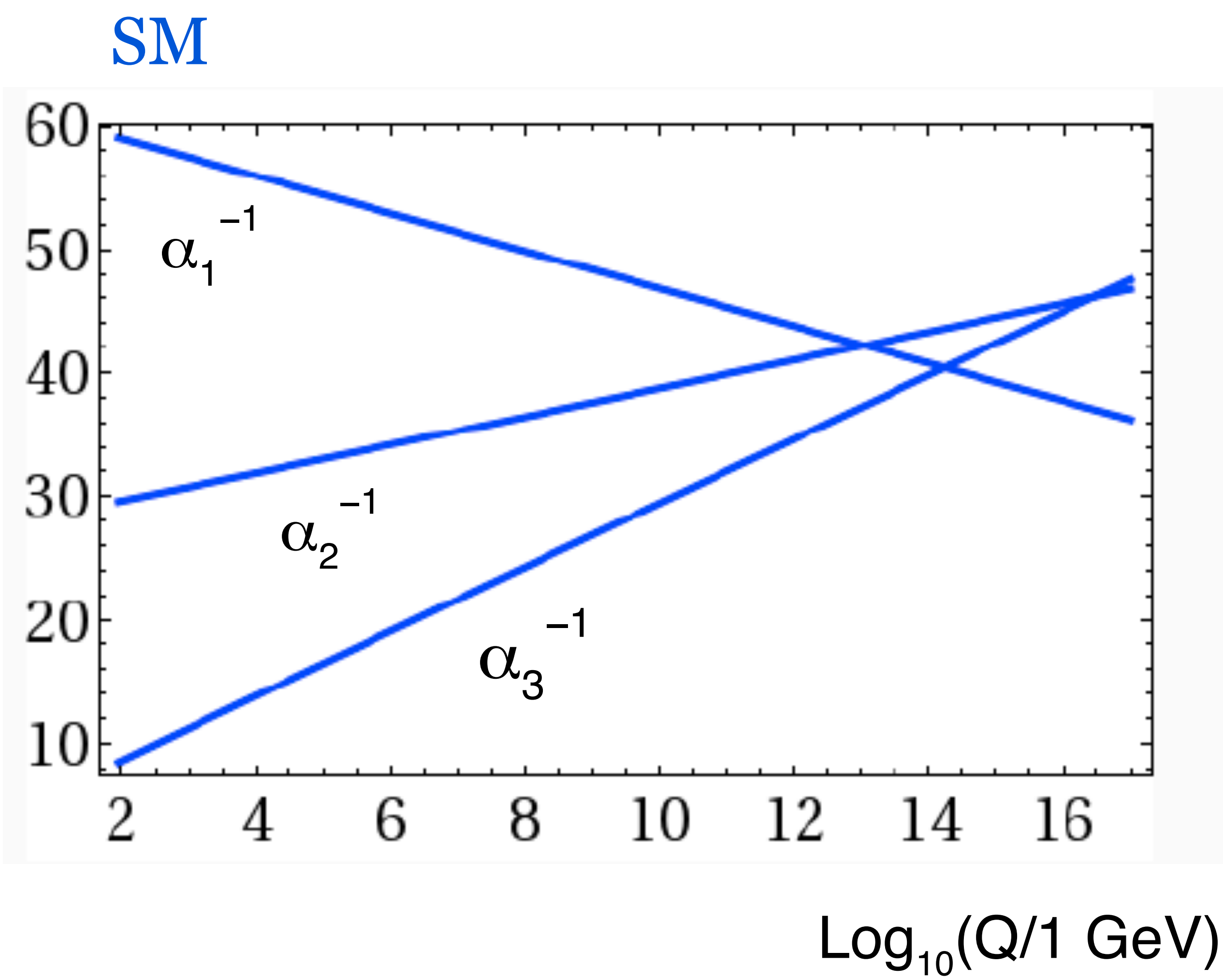


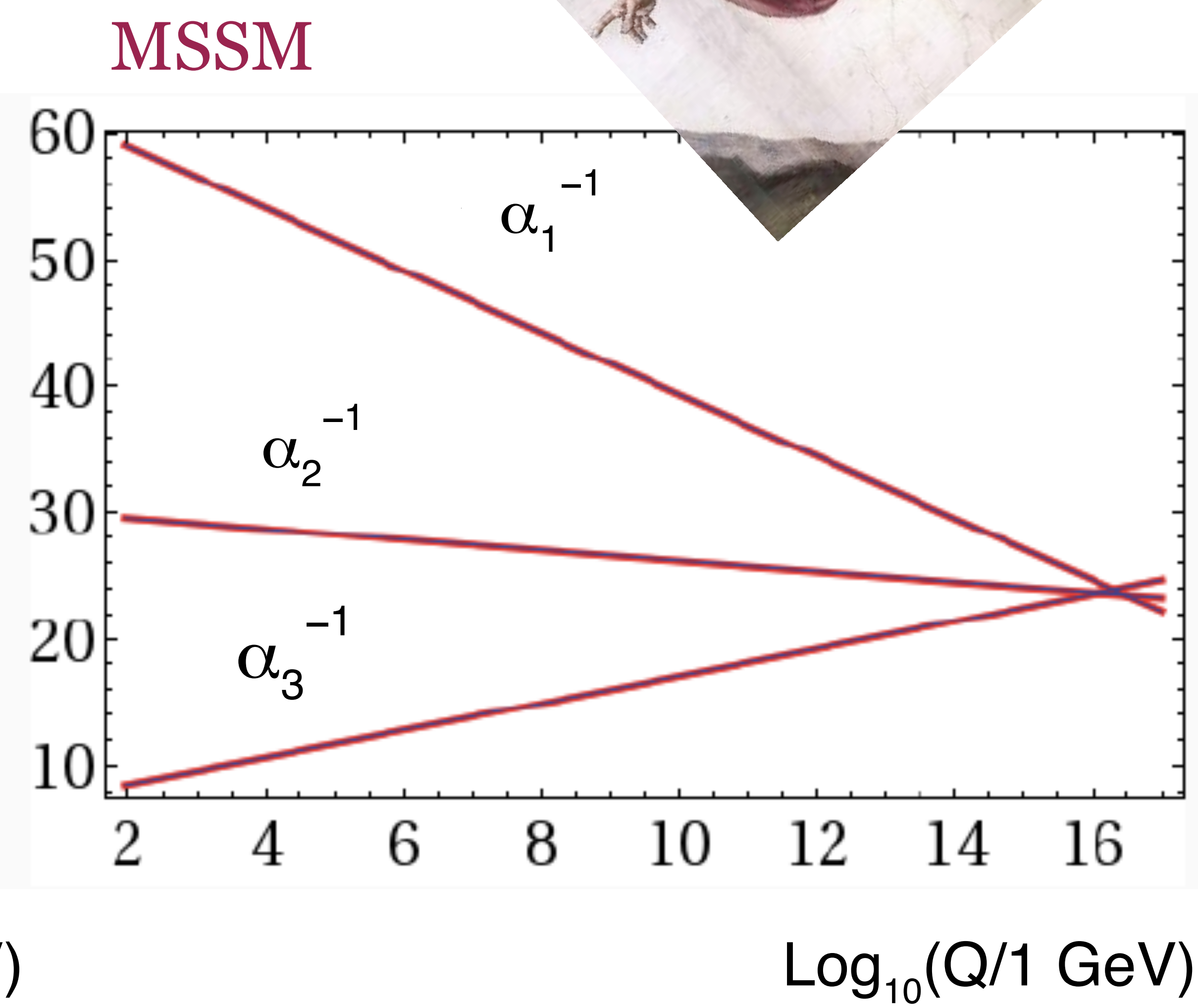
Gauge Coupling running at two loops

Note, still works with M_{SUSY} = 100 TeV.

A hint?







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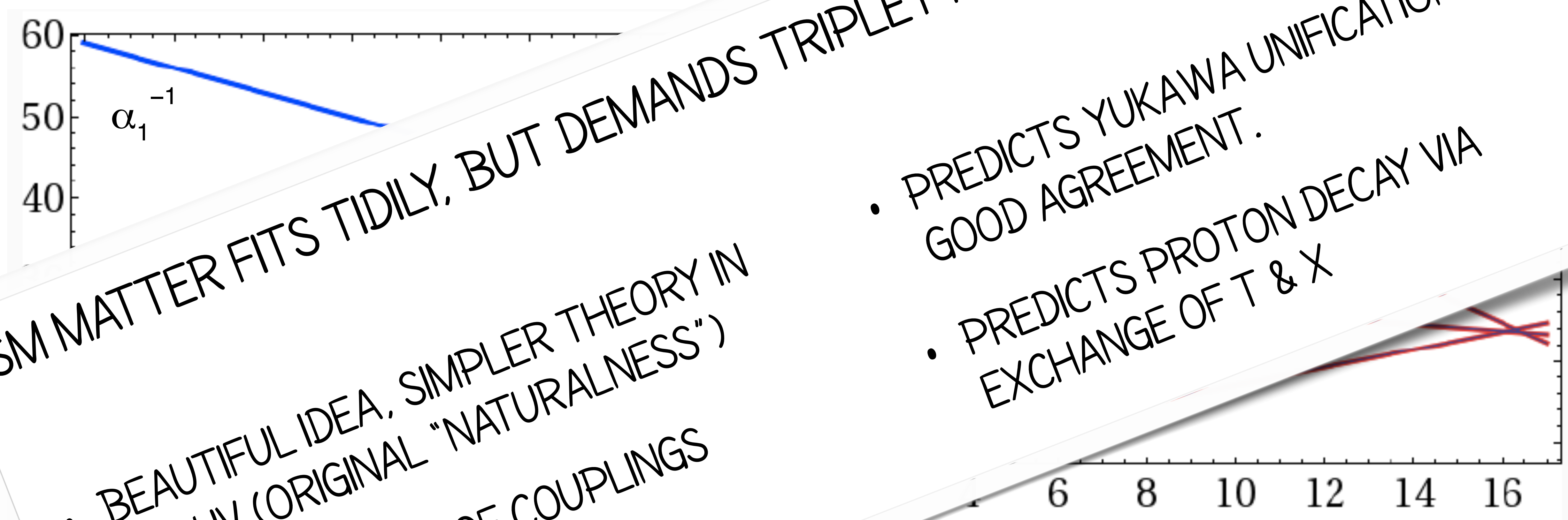

auge Coupling running at two loops

SM MATTER FITS TIDILY, BUT DEMANDS TRIPLET HIGGS & NEW GAUGE BOSONS.

- BEAUTIFUL IDEA, SIMPLER THEORY IN FAR UV (ORIGINAL "NATURALNESS")
- BUT UNIFICATION OF COUPLINGS IMPERFECT @ 10% LEVEL.
- PREDICTS YUKAWA UNIFICATION, NOT IN GOOD AGREEMENT.
- PREDICTS PROTON DECAY VIA EXCHANGE OF T & X

Note, still works with M_{SUSY} = 100 TeV.

MSSM

	bosons	fermions	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Q_i	$(\widetilde{u}_L, \widetilde{d}_L)_i$	$(u_L, d_L)_i$	$\square$	$\square$	$\frac{1}{6}$
$\overline{u}_i$	$\widetilde{u}^*_{Ri}$	$\overline{u}_i = u^\dagger_{Ri}$	$\overline{\square}$	$\mathbf{1}$	$-\frac{2}{3}$
$\overline{d}_i$	$\widetilde{d}^*_{Ri}$	$\overline{d}_i = d^\dagger_{Ri}$	$\overline{\square}$	$\mathbf{1}$	$\frac{1}{3}$
L_i	$(\widetilde{\nu}, \widetilde{e}_L)_i$	$(\nu, e_L)_i$	$\mathbf{1}$	$\square$	$-\frac{1}{2}$
$\overline{e}_i$	$\widetilde{e}^*_{Ri}$	$\overline{e}_i = e^\dagger_{Ri}$	$\mathbf{1}$	$\mathbf{1}$	1
H_u	(H_u^+, H_u^0)	$(\widetilde{H}_u^+, \widetilde{H}_u^0)$	$\mathbf{1}$	$\square$	$\frac{1}{2}$
H_d	(H_d^0, H_d^-)	$(\widetilde{H}_d^0, \widetilde{H}_d^-)$	$\mathbf{1}$	$\square$	$-\frac{1}{2}$
G	G^a_μ	$\widetilde{G}^a$	$\mathbf{Ad}$	$\mathbf{1}$	0
W	$W^3_\mu,\, W^\pm_\mu$	$\widetilde{W}^3,\, \widetilde{W}^\pm$	$\mathbf{1}$	$\mathbf{Ad}$	0
B	B_μ	$\widetilde{B}$	$\mathbf{1}$	$\mathbf{1}$	0

MSSM

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Q_i	$(\widetilde{u}_L,\, \widetilde{d}_L)_i$	$(u_L, d_L)_i$	$\square$	$\square$	$\frac{1}{6}$
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$\overline{d}_i$	$\widetilde{d}^*_{Ri}$	$\overline{d}_i = d^\dagger_{Ri}$	$\overline{\square}$	$\mathbf{1}$	$\frac{1}{3}$
L_i	$(\widetilde{\nu}, \widetilde{e}_L)_i$	$(\nu, e_L)_i$	$\mathbf{1}$	$\square$	$-\frac{1}{2}$
$\overline{e}_i$	$\widetilde{e}^*_{Ri}$	$\overline{e}_i = e^\dagger_{Ri}$	$\mathbf{1}$	$\mathbf{1}$	1
H_u	(H_u^+, H_u^0)	$(\widetilde{H}_u^+, \widetilde{H}_u^0)$	$\mathbf{1}$	$\square$	$\frac{1}{2}$
H_d	(H_d^0, H_d^-)	$(\widetilde{H}_d^0, \widetilde{H}_d^-)$	$\mathbf{1}$	$\square$	$-\frac{1}{2}$
G	G^a_μ	$\widetilde{G}^a$	$\mathbf{Ad}$	$\mathbf{1}$	0
W	$W^3_\mu,\, W^\pm_\mu$	$\widetilde{W}^3,\, \widetilde{W}^\pm$	$\mathbf{1}$	$\mathbf{Ad}$	0
B	B_μ	$\widetilde{B}$	$\mathbf{1}$	$\mathbf{1}$	0

same quantum # !

Yukawa couplings, Higgsino mass, cubic scalar terms …

$$W_{\rm Higgs} = \overline{u}\mathbf{Y_u}QH_u - \overline{d}\mathbf{Y_d}QH_d - \overline{e}\,\mathbf{Y_e}LH_d + \mu H_u H_d$$

same quantum # $\quad L_i \leftrightarrow H_d$

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same quantum # $\quad L_i \leftrightarrow H_d$

$$W_{\rm disaster} = \alpha^{ijk}Q_iL_j\overline{d}_k + \beta^{ijk}L_iL_j\overline{e}_k + \gamma^i L^i H_u + \delta^{ijk}\overline{d}_i\overline{d}_j\overline{u}_k$$

Yukawa couplings, Higgsino mass, cubic scalar terms …

$$W_{\rm Higgs} = \overline{u}\mathbf{Y_u}QH_u - \overline{d}\mathbf{Y_d}QH_d - \overline{e}\,\mathbf{Y_e}LH_d + \mu H_u H_d$$

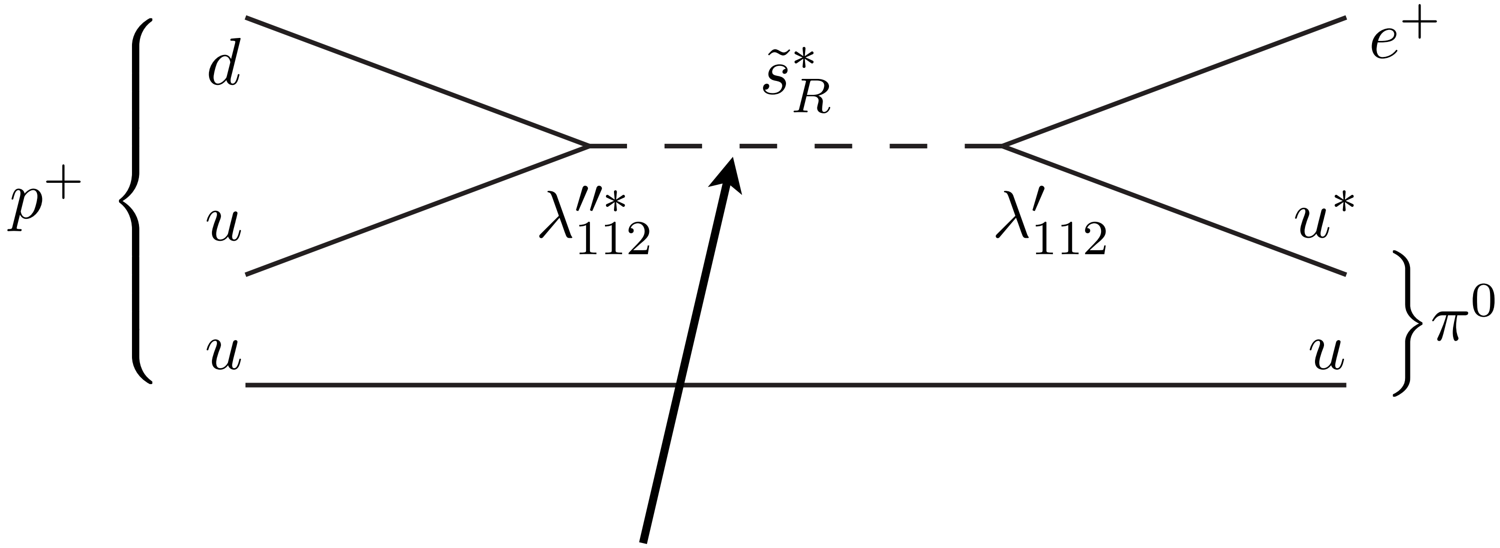
same quantum # $\quad L_i \leftrightarrow H_d$

$$W_{\rm disaster} = \alpha^{ijk}Q_iL_j\overline{d}_k + \beta^{ijk}L_iL_j\overline{e}_k + \gamma^i L^i H_u + \delta^{ijk}\overline{d}_i\overline{d}_j\overline{u}_k$$

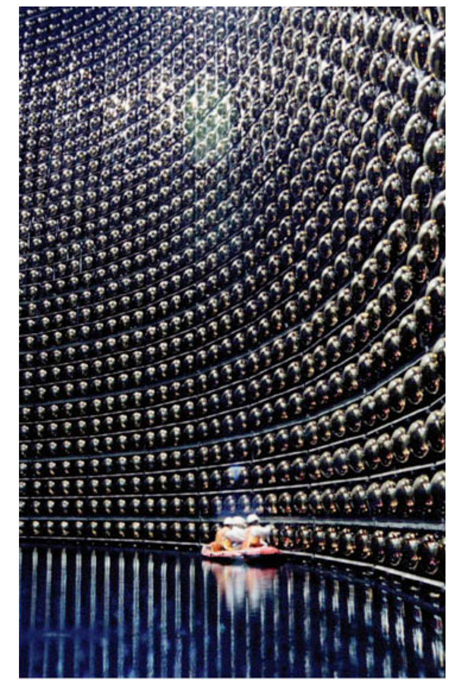
$W_{\rm disaster}$ violates lepton and baryon number!

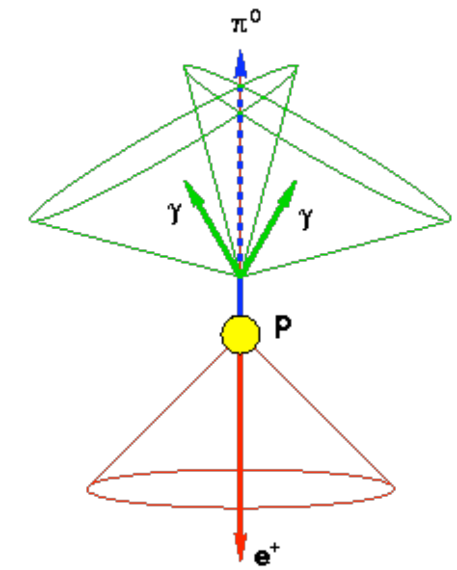
Proton decay

$$\tau_{\text{proton}} > 1.29 \times 10^{34} \text{ years}$$



$$\mathcal{A} \sim 1/m_{\tilde{d}}^2$$





Super-K

RPV couplings must be very small

$$\Gamma_{p\to e^+\pi^0} \sim m_{\text{proton}}^5 \sum_{i=2.3} |\lambda'^{11i}\lambda''^{11i}|^2/m_{\tilde{d}_i}^4$$

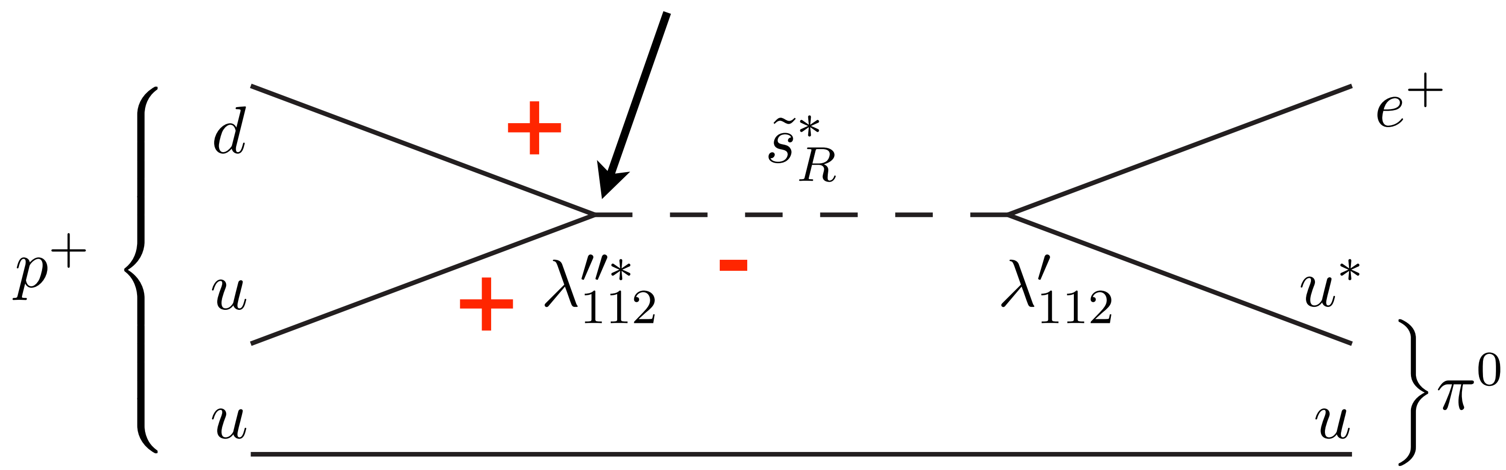
R-parity

We could require B or L, but they are not symmetries of the SM (non-perturbatively broken)

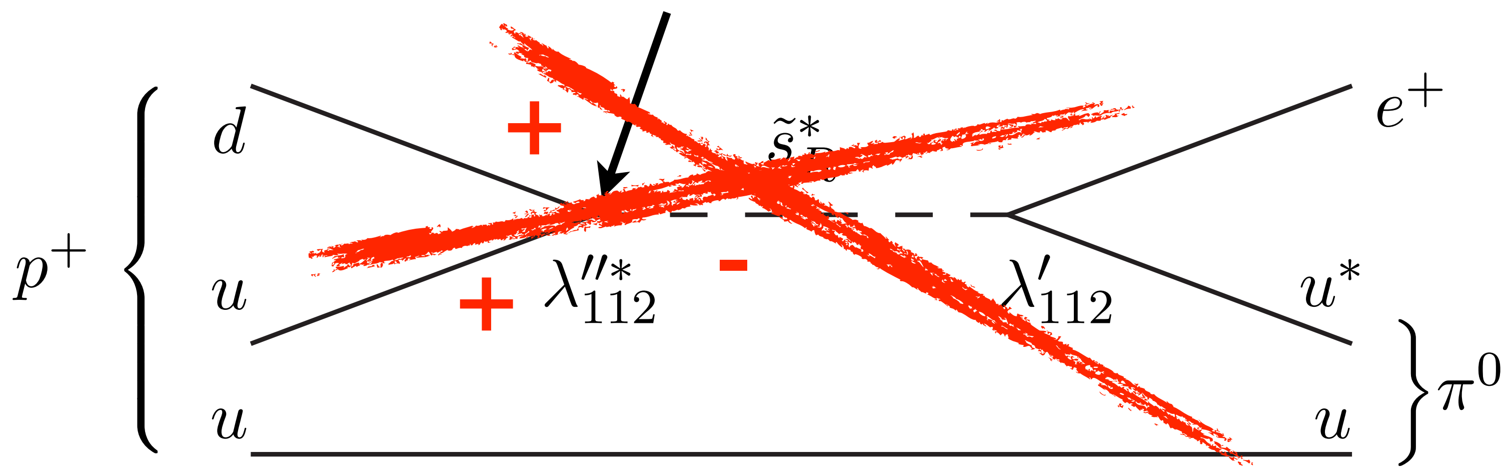
$$P_R = (-1)^{3(\mathrm{B}-\mathrm{L})+2s}$$

+	spin	**-**	spin
gluon, g	1	gluino: $\tilde{g}$	$1/2$
$W^{\pm}, Z$	1	gaugino: $\tilde{W}^{\pm}, \tilde{Z}$	$1/2$
quark: q	$1/2$	squark: $\tilde{q}$	0
$\ldots$		$\ldots$	
SM		(super)partner	

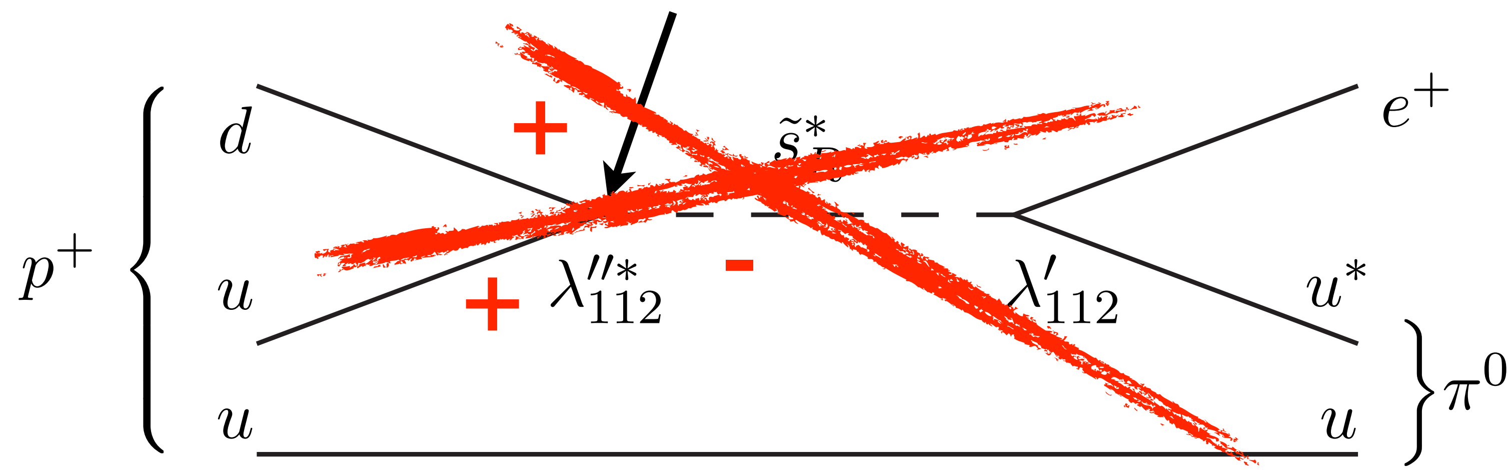
vertex forbidden: odd under P_R



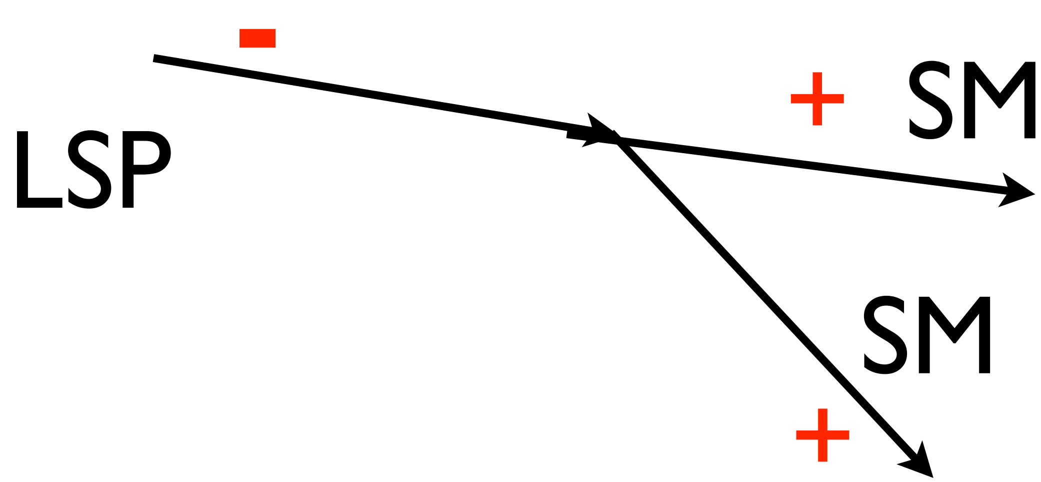
vertex forbidden: odd under P_R



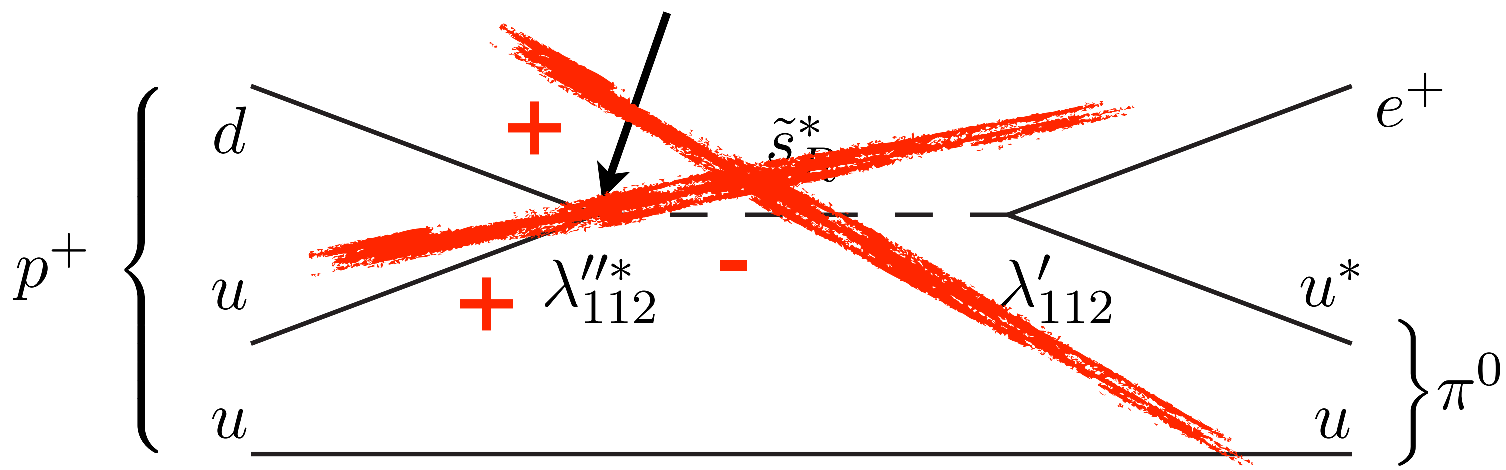
vertex forbidden: odd under P_R



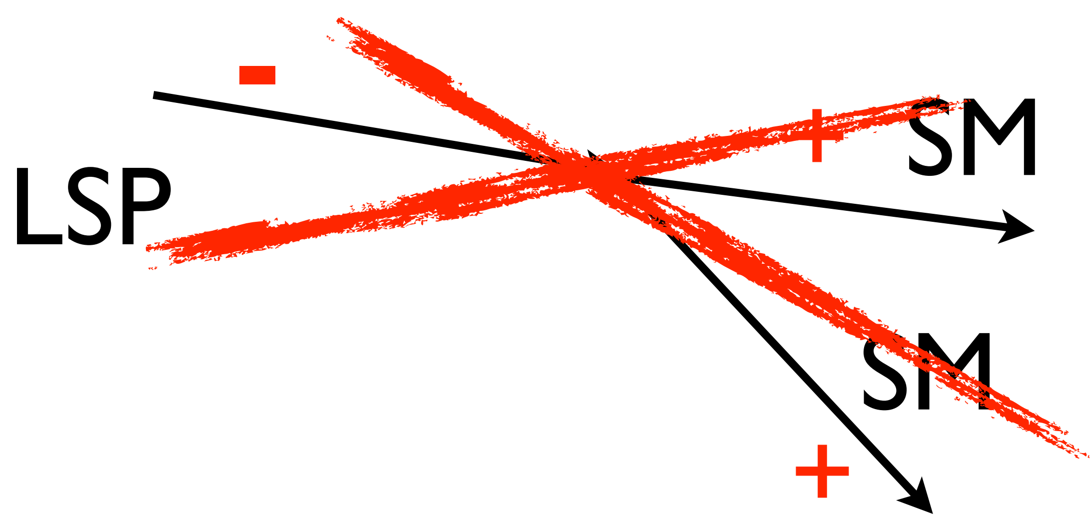
Lightest supersymmetric particle cannot decay

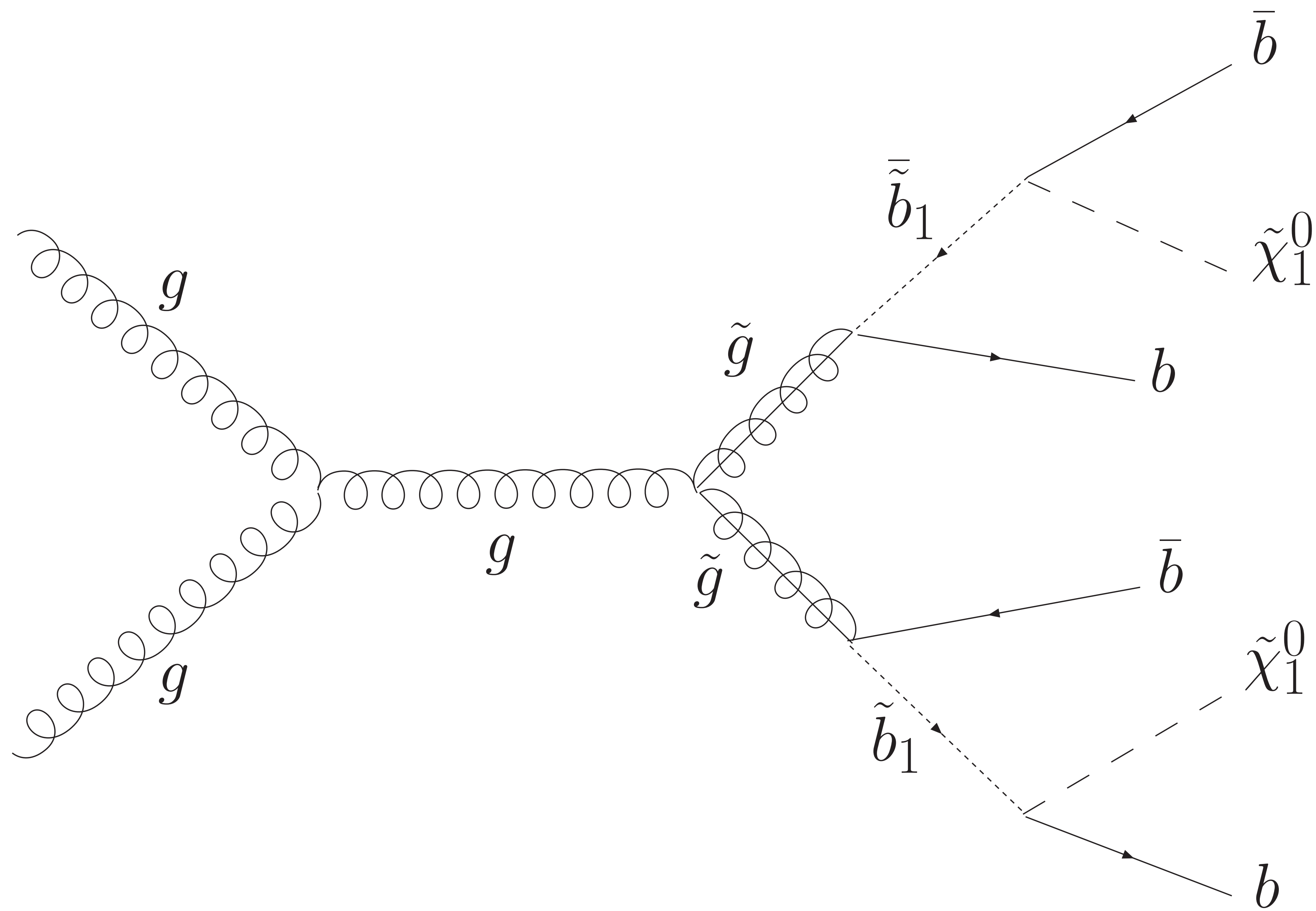


vertex forbidden: odd under P_R



Lightest supersymmetric particle cannot decay



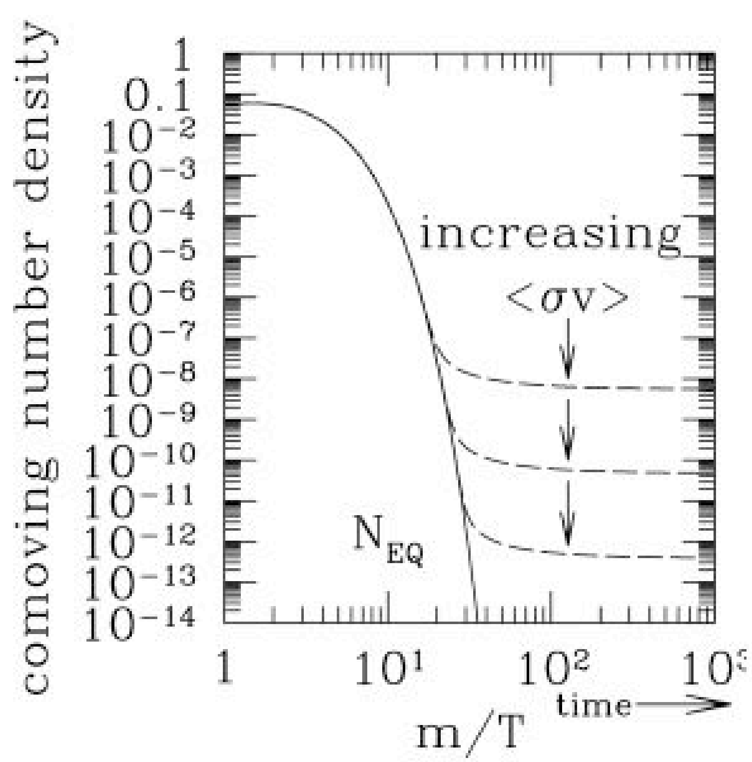


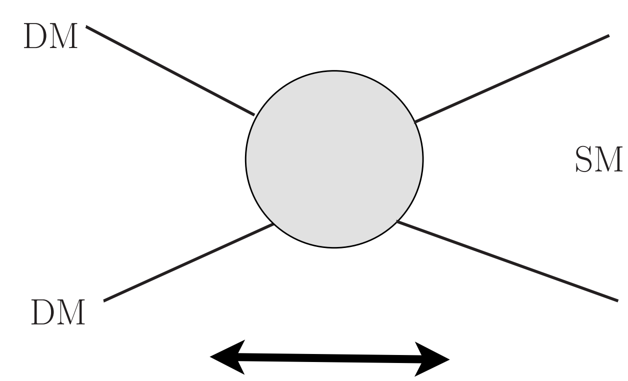
g
g
g
$\tilde{g}$
$\tilde{g}$
$\bar{\tilde{b}}_1$
$\tilde{b}_1$
$\bar{b}$
$\tilde{\chi}_1^0$
b
$\bar{b}$
$\tilde{\chi}_1^0$
b

Neutral LSP a natural candidate for WIMP dark matter.

→ M ~ O(100 GeV)
→ Weakly coupled.

Similar states in other new physics scenario. In SUSY, a consequence of forbidding proton decay.





Rate in thermal eq. $\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$

Freeze out: dropping out of thermal eq.

Stronger coupling, lower abundance.

Dark matter relic abundance

Dark matter particle X held in equilibrium

$$XX \leftrightarrow p_i \overline{p}_i$$

eventually the expansion of the Universe dilutes
the particles so they are too sparse to maintain equilibrium

$$\frac{dn}{dt} = -3Hn - \langle \sigma_A v \rangle (n^2 - n_{\rm eq}^2)$$

When $\dot{n}_{\rm annihilations} \approx \dot{n}_{\rm expansion}$

dark matter ‘freezes out’

We want to break SUSY such that Higgs – top squark quartic coupling $\lambda = |y_t|^2$. If not we reintroduce a Λ^2 divergence in the Higgs mass:

$$\delta m_h^2 \propto (\lambda - |y_t|^2)\Lambda^2$$

We know: conserved Susy does not lead to power-divergencies.

How to avoid re-introducing power-divergencies when breaking susy?

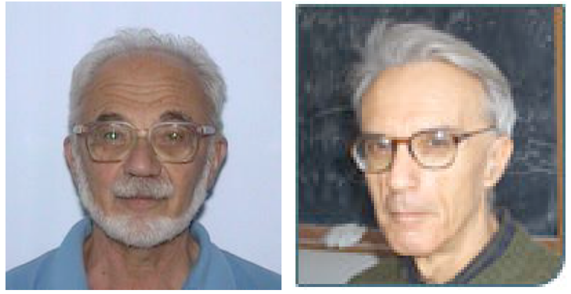
Count powers in diagrams!

If we only introduce **dimensionful couplings** will **lower** the power of divergence.

We want an *effective theory* of broken SUSY with only soft breaking terms (operators with dimension < 4). Girardello and Grisaru found:

$$
\begin{aligned}
\mathcal{L}_{\text{soft}} &= -\tfrac{1}{2}(M_\lambda \lambda^a \lambda^a + h.c.) - (m^2)^i_j \phi^{*j}\phi_i \\
&\quad -(\tfrac{1}{2} b^{ij}\phi_i\phi_j + \tfrac{1}{6} a^{ijk}\phi_i\phi_j\phi_k + h.c.) \\
&\quad -\tfrac{1}{2} c_i^{jk}\phi^{i*}\phi_j\phi_k + e^i\phi_i + h.c.
\end{aligned}
$$

Grisaru, Girardello



means couplings are dimensionful!

New Interactions

$$\mathcal{L}_{\rm scalar} = -\frac{\lambda}{2}(h^0)^2(|\phi_L|^2 + |\phi_R|^2) - h^0(\mu_L|\phi_L|^2 + \mu_R|\phi_R|^2)$$
$$-m_L^2|\phi_L|^2 - m_R^2|\phi_R|^2$$

New partners

$$\delta m_h^2|_2 = \frac{\lambda N}{16\pi^2}\left[2\Lambda^2 - m_L^2 \ln\left(\frac{\Lambda^2+m_L^2}{m_L^2}\right) - m_R^2 \ln\left(\frac{\Lambda^2+m_R^2}{m_R^2}\right) + \ldots\right].$$

$$\delta m_h^2|_3 = -\frac{N}{16\pi^2}\left[\mu_L^2\ \ln\left(\frac{\Lambda^2+m_L^2}{m_L^2}\right) + \mu_R^2\ \ln\left(\frac{\Lambda^2+m_R^2}{m_R^2}\right) + \ldots\right]$$

SM top loop

$$\delta m_h^2|_{\rm top} = -\frac{N_c|y_t|^2}{8\pi^2}\left[\Lambda^2 - 3\,m_t^2\ \ln\left(\frac{\Lambda^2+m_t^2}{m_t^2}\right) + \ldots\right]$$

$m_L \neq m_R \neq m_{\rm top}$ → susy broken softly

New Interactions

$$\mathcal{L}_{\text{scalar}} = -\frac{\lambda}{2}(h^0)^2(|\phi_L|^2 + |\phi_R|^2) - h^0(\mu_L|\phi_L|^2 + \mu_R|\phi_R|^2)$$
$$-m_L^2|\phi_L|^2 - m_R^2|\phi_R|^2$$

= softly broken susy

If $N = N_c$ and $\lambda = |y_t|^2$ then Λ^2 cancels!

New partners

$$\delta m_h^2|_2 = \frac{\lambda N}{16\pi^2}\left[2\Lambda^2 - m_L^2 \ln\left(\frac{\Lambda^2+m_L^2}{m_L^2}\right) - m_R^2 \ln\left(\frac{\Lambda^2+m_R^2}{m_R^2}\right) + \ldots\right].$$

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$$-m_L^2|\phi_L|^2 - m_R^2|\phi_R|^2$$

= softly broken susy

$\boxed{\text{If } N = N_c \text{ and } \lambda = |y_t|^2 \text{ then } \Lambda^2 \text{ cancels!}}$

New partners

$$\delta m_h^2|_2 = \frac{\lambda N}{16\pi^2}\left[2\cancel{\Lambda^2} - m_L^2 \ln\left(\frac{\Lambda^2+m_L^2}{m_L^2}\right) - m_R^2 \ln\left(\frac{\Lambda^2+m_R^2}{m_R^2}\right) + \ldots\right].$$

$$\delta m_h^2|_3 = -\frac{N}{16\pi^2}\left[\mu_L^2 \ln\left(\frac{\Lambda^2+m_L^2}{m_L^2}\right) + \mu_R^2 \ln\left(\frac{\Lambda^2+m_R^2}{m_R^2}\right) + \ldots\right]$$

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$$\mathcal{L}_{\rm scalar} = -\frac{\lambda}{2}(h^0)^2(|\phi_L|^2+|\phi_R|^2) - h^0(\mu_L|\phi_L|^2+\mu_R|\phi_R|^2)$$
$$-m_L^2|\phi_L|^2 - m_R^2|\phi_R|^2$$

= softly broken susy

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= unbroken susy

$m_L \neq m_R \neq m_{\rm top}$ → susy broken softly

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$$\mathcal{L}_{\rm scalar} = -\frac{\lambda}{2}(h^0)^2(|\phi_L|^2 + |\phi_R|^2) - h^0(\mu_L|\phi_L|^2 + \mu_R|\phi_R|^2)$$
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$$\delta m_h^2|_{\rm top} = -\frac{N_c|y_t|^2}{8\pi^2}\left[\cancel{\Lambda^2} - 3\,m_t^2 \ln\left(\frac{\Lambda^2+m_t^2}{m_t^2}\right) + \ldots\right]$$

= unbroken susy

$m_L \neq m_R \neq m_{\rm top}$ → susy broken softly

Soft terms

$$
\begin{aligned}
\mathcal{L}_{\rm soft}^{\rm MSSM} \quad = \quad & -\tfrac{1}{2}\left(M_3 \widetilde{G}\widetilde{G} + M_2 \widetilde{W}\widetilde{W} + M_1 \widetilde{B}\widetilde{B}\right) + h.c. \\
& -\left(\widetilde{\overline{u}}\,\mathbf{A_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{A_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{A_e}\,\widetilde{L}H_d\right) + h.c. \\
& -\widetilde{Q}^*\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^*\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}^*\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}} - \widetilde{\overline{d}}^*\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}} - \widetilde{\overline{e}}^*\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}} \\
& - m^2_{H_u} H_u^* H_u - m^2_{H_d} H_d^* H_d - (bH_u H_d + h.c.)\,.
\end{aligned}
$$

Soft terms

gaugino masses

$$\begin{aligned}\mathcal{L}_{\text{soft}}^{\text{MSSM}} &= -\tfrac{1}{2}\left(\boxed{M_3\widetilde{G}\widetilde{G} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B}}\right) + h.c. \\ &\quad - \left(\widetilde{\overline{u}}\,\mathbf{A_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{A_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{A_e}\,\widetilde{L}H_d\right) + h.c. \\ &\quad -\widetilde{Q}^*\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^*\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}^*\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}} - \widetilde{\overline{d}}^*\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}} - \widetilde{\overline{e}}^*\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}} \\ &\quad - m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - (bH_uH_d + h.c.)\,.\end{aligned}$$

Soft terms

gaugino masses

sfermion masses

$$\begin{aligned}
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& -\left(\widetilde{\overline{u}}\,\mathbf{A_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{A_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{A_e}\,\widetilde{L}H_d\right) + h.c. \\
& -\widetilde{Q}^*\mathbf{m_Q^2}\,\widetilde{Q} - \widetilde{L}^*\mathbf{m_L^2}\,\widetilde{L} - \widetilde{\overline{u}}^*\,\mathbf{m_{\overline{u}}^2}\,\widetilde{\overline{u}} - \widetilde{\overline{d}}^*\,\mathbf{m_{\overline{d}}^2}\,\widetilde{\overline{d}} - \widetilde{\overline{e}}^*\,\mathbf{m_{\overline{e}}^2}\,\widetilde{\overline{e}} \\
& - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_uH_d + h.c.)\,.
\end{aligned}$$

Soft terms

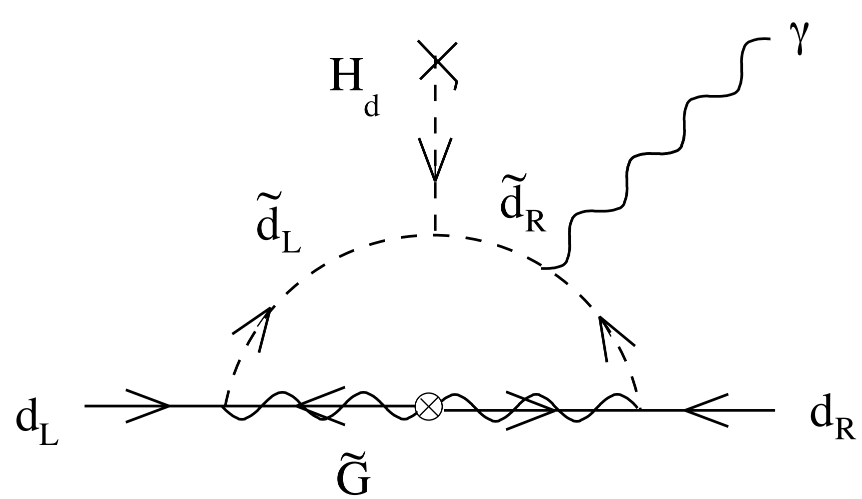
gaugino masses

$$
\begin{aligned}
\mathcal{L}_{\text{soft}}^{\text{MSSM}} &= -\tfrac{1}{2}\left(\boxed{M_3\widetilde{G}\widetilde{G} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B}}\right) + h.c. \\
&\quad - \left(\widetilde{\overline{u}}\,\mathbf{A_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{A_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{A_e}\,\widetilde{L}H_d\right) + h.c. \\
&\quad \boxed{-\widetilde{Q}^*\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^*\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}^*\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}} - \widetilde{\overline{d}}^*\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}} - \widetilde{\overline{e}}^*\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}}} \\
&\quad - m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - (bH_uH_d + h.c.)\,.
\end{aligned}
$$

sfermion masses

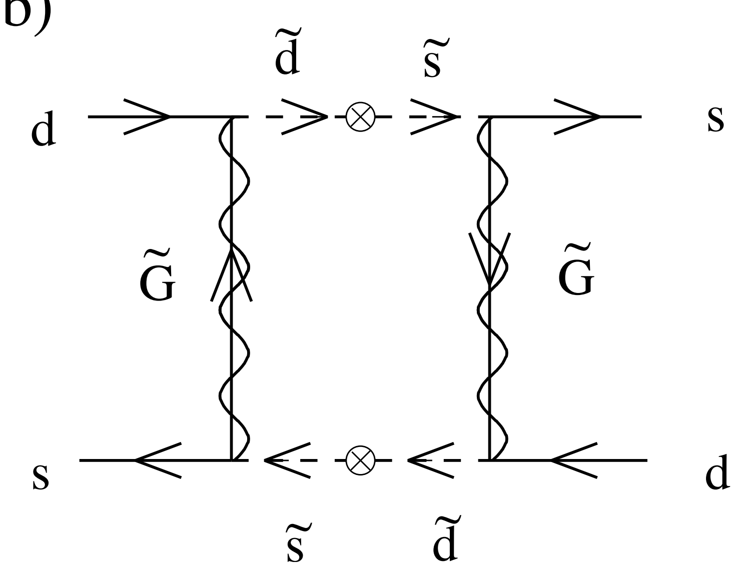
$$\mathcal{M}_{\text{EDM}} \approx \frac{\alpha_3}{4\pi}\,\frac{e\,vc_\beta\,A_{d11}\,\delta}{M^2_{\text{SUSY}}}$$

$$\mathcal{M}^{\text{MSSM}}_{K\overline{K}} \approx 4\alpha_3^2\left(\frac{\Delta m^2_Q}{M^2_{\text{SUSY}}}\right)^2\frac{1}{M^2_{\text{SUSY}}}$$



electric dipole moments

(b)



flavor violation

Too many parameters?

- Unbroken susy is very predictive
- “Adjustable” soft parameters are only adjustable in the absence of a specified computable mechanism to break SUSY
- Most of the parameter range already excluded (indirect tests)

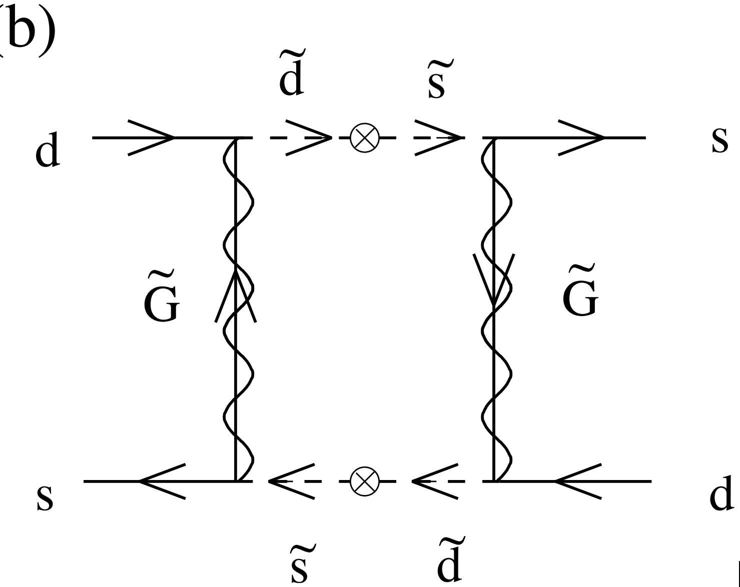
Susy flavor problem

Soft breaking terms cannot be arbitrary.
Flavor constraints: generic choice of soft masses already excluded (or very heavy squarks)

$m_{\tilde{q}} > \mathcal{O}(100)$ TeV

$$\frac{|\mathrm{Re}[m^2_{\tilde{s}^*_R \tilde{d}_R} m^2_{\tilde{s}^*_L \tilde{d}_L}]|^{1/2}}{m^2_{\tilde{q}}} < \left(\frac{m_{\tilde{q}}}{1000\ \mathrm{GeV}}\right) \times \begin{cases} 0.0016 & \text{for } m_{\tilde{g}} = 0.5 m_{\tilde{q}}, \\ 0.0020 & \text{for } m_{\tilde{g}} = m_{\tilde{q}}, \\ 0.0026 & \text{for } m_{\tilde{g}} = 2 m_{\tilde{q}}. \end{cases}$$

(b)



Kaon Mixing

SUSY breaking

Want to break SUSY softly: Expand Higgs sector, super-symmetrize, and get simultaneous EWSB and susy breaking?

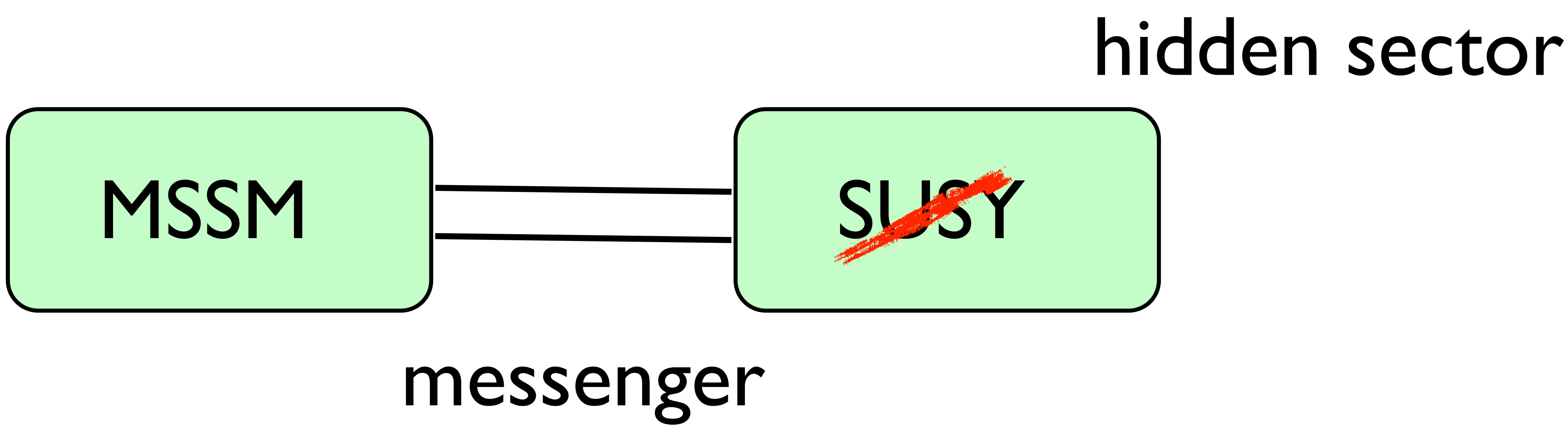
No. **Deadly sum rule:**

$$\sum m_{J=0}^2 - 2\sum m_{J=\frac{1}{2}}^2 + 3\sum m_{J=1}^2 = 0$$

Implies at least one super-partner is lighter than its SM partner. E.g. $m_{\tilde{e}_1}^2 + m_{\tilde{e}_2}^2 = 2m_e^2$

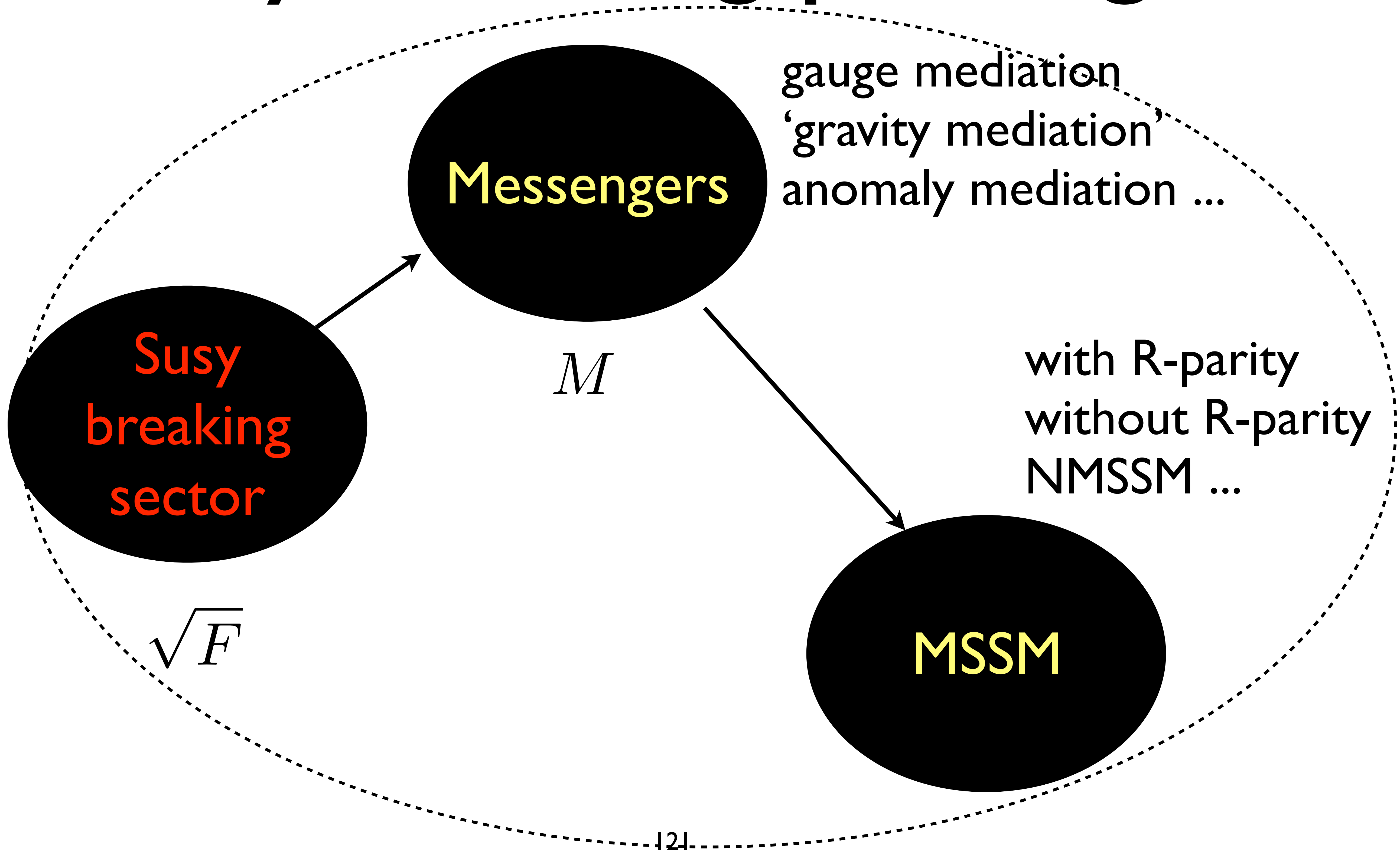
Susy breaking

Need 'hidden sector breaking' and a messenger mediating susy-breaking to the MSSM

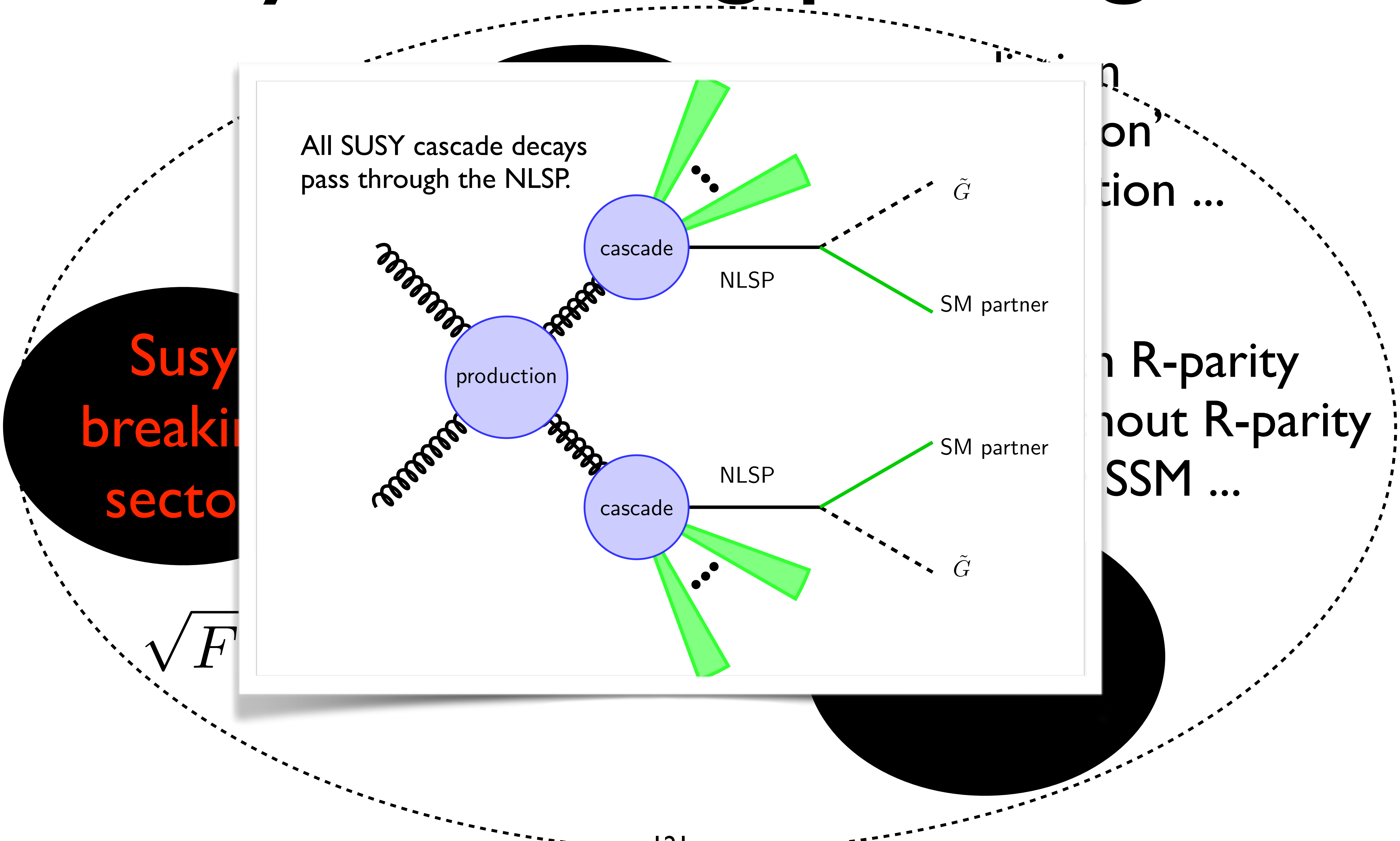


Messenger couplings either loop suppressed or higher dimensional operators, to escape the sum rule problem

Susy breaking paradigm

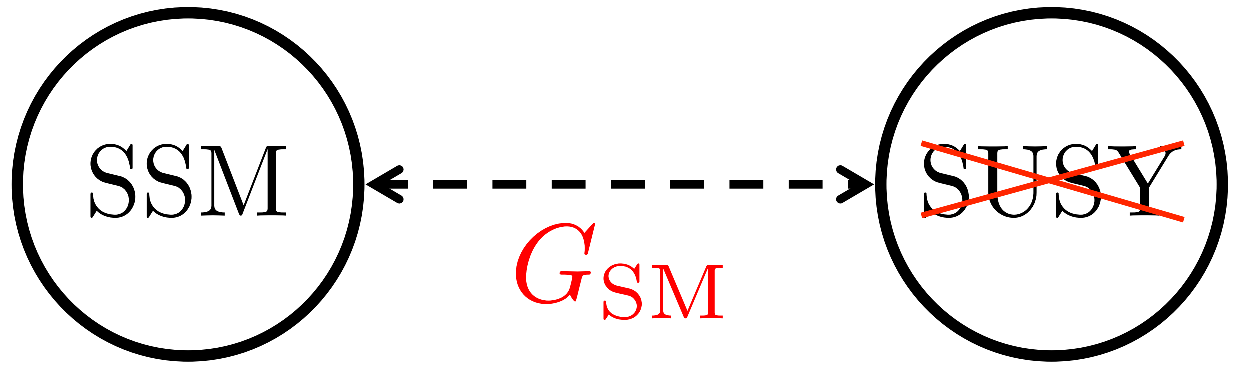


Susy breaking paradigm



Gauge Mediation

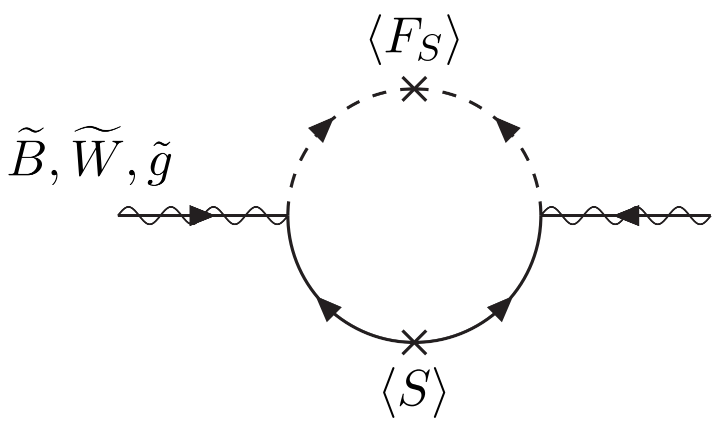
see e.g. Giudice/Rattazzi review



$$G_{\rm SM} = SU(3) \times SU(2) \times U(1)$$

Degenerate quarks at the messenger scale, no flavor problem.

Gauge mediation



1loop gaugino masses

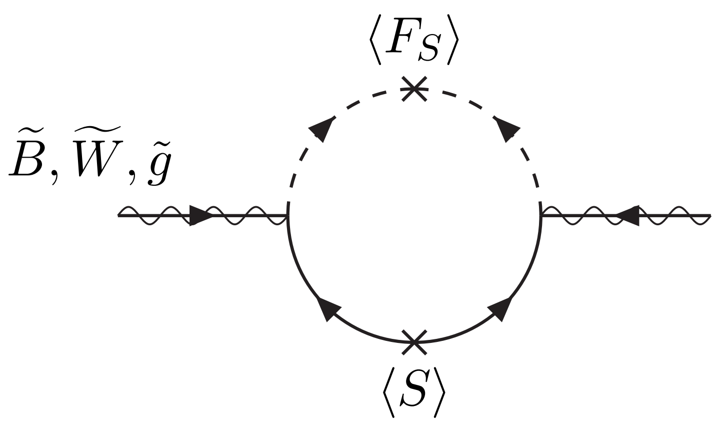
$$M_a = \frac{\alpha_a}{4\pi} M_S, \quad M_S = \frac{\langle F_S \rangle}{\langle S \rangle}$$

Messengers (S) feel SUSY breaking, charged under SM gauge symmetries.

$\sqrt{F}$ Susy breaking order parameter

Gauge mediation

1loop gaugino masses

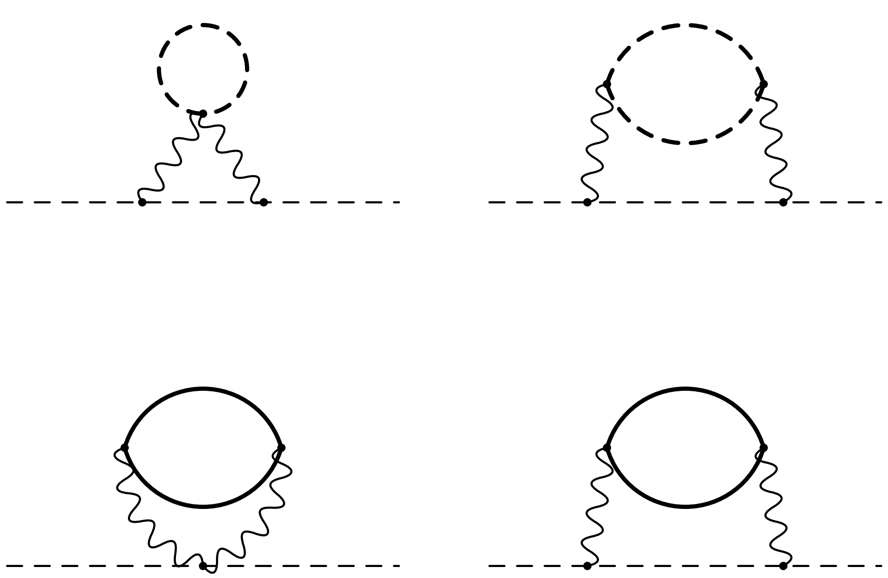


$$M_a = \frac{\alpha_a}{4\pi} M_S, \quad M_S = \frac{\langle F_S \rangle}{\langle S \rangle}$$

Messengers (S) feel SUSY breaking, charged under SM gauge symmetries.

$\sqrt{F}$ Susy breaking order parameter

2loop squark masses



+ ....

$$m^2_{\text{scalar}} = \left(\frac{\alpha}{4\pi} \right)^2 M_S^2$$

Gravitino

- SUSY spontaneously broken: goldstino
- Fermionic component of super-field w/ vev
- Becomes longitudinal component of gravitino (spin 3/2)
- If <F> << M_{pl} (e.g gauge med., gravitino LSP): gravitino LSP & NLSP can be long lived

sparticle particle gravitino

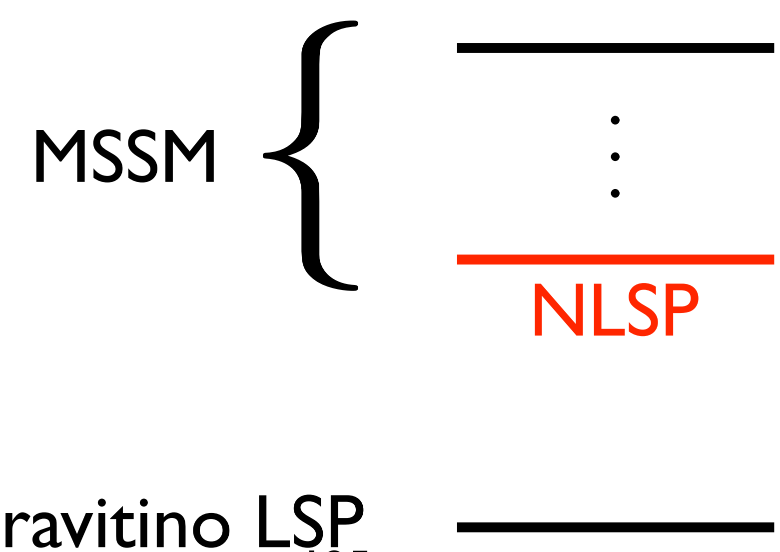
$$\Gamma(\tilde{X} \to X\tilde{G}) = \frac{m_{\tilde{X}}^5}{16\pi\langle F\rangle^2}\left(1 - \frac{m_X^2}{m_{\tilde{X}}^2}\right)^4$$

Gauge mediation

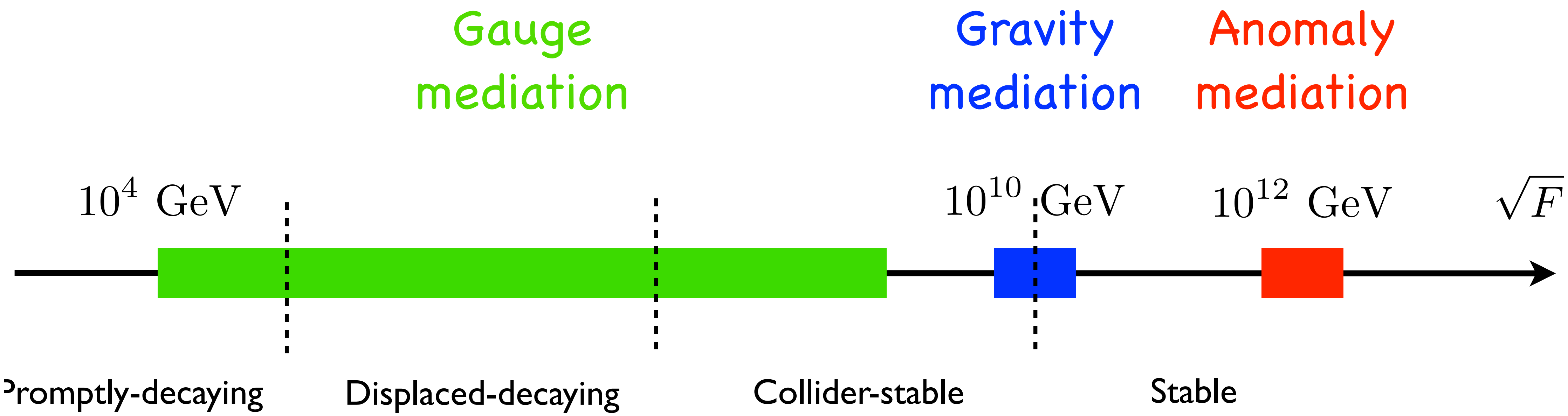
- Gravitino LSP is a universal prediction of gauge mediation models:

$$m_{3/2} = \frac{F}{\sqrt{3}M_{pl}} \quad (\sim \mathrm{eV} - \mathrm{GeV})$$

- Lightest MSSM sparticle becomes the next-to-lightest superpartner (NLSP).

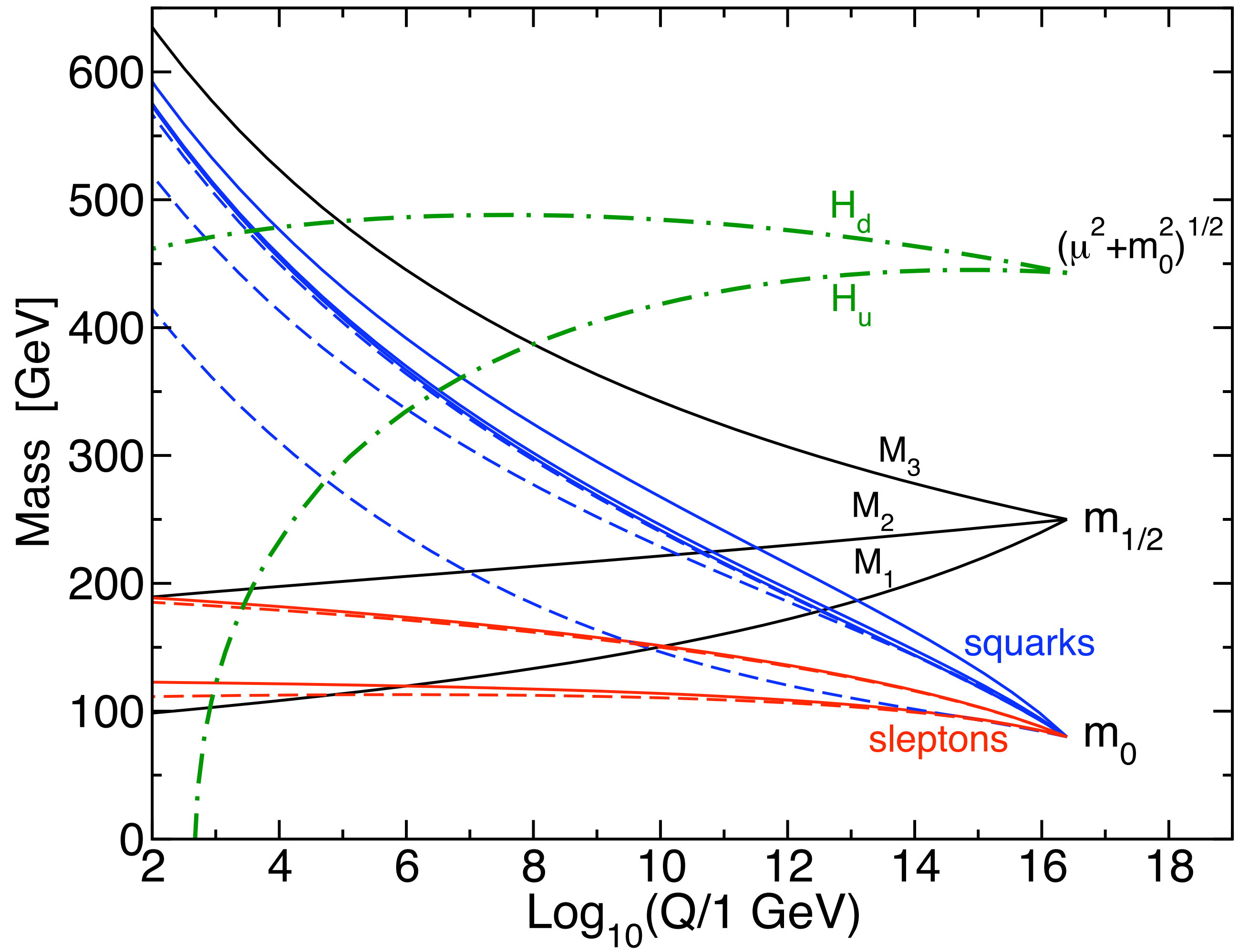


The scale of SUSY breaking determines the mediation mechanism.



It also determines the behavior of the lightest MSSM superpartner.

RGE evolution



radiative EWSB

RGE evolution: masses evolve with scale

colored particles 'run' faster, large $\mathcal{O}(\text{several})$ corrections

Higgs potential

$$
\begin{aligned}
V_H = {} & (\mu^2 + m_{H_u}^2)\,|H_u|^2 + (\mu^2 + m_{H_d}^2)\,|H_d|^2 \\
& - B_\mu \, H_u \cdot H_d + h.c. \; \boxed{+ \frac{1}{2} g^2 \left|H_u^\dagger H_d\right|^2} \\
& \boxed{+ \frac{1}{8} (g^2 + g'^2) \left(|H_u|^2 - |H_d|^2\right)^2}
\end{aligned}
$$

Neutral Higgs potential

$$V = \left(|\mu|^2 + m_{H_u}^2\right)|H_u^0|^2 + \left(|\mu|^2 + m_{H_d}^2\right)|H_d^0|^2$$
$$- B_\mu \left(H_u^0 H_d^0 + \text{h.c.}\right) \quad \boxed{+ \frac{1}{8}\left(g^2 + g'^2\right)\left(|H_u^0|^2 - |H_d^0|^2\right)^2}$$

quartic fixed by gauge interactions!

short digression →

Super YM

So full Lagrangian:

gauge trace

$$\mathcal{L} = -\frac{1}{4g^2} \mathrm{Tr}\left(W^\alpha W_\alpha \big|_{\theta^2} + \bar{W}_{\dot\alpha} \bar{W}^{\dot\alpha} \big|_{\bar\theta^2} \right)$$

$$+ \Phi^\dagger e^V \Phi \big|_{\theta^2\bar\theta^2} + W(\Phi)\big|_{\theta^2} + h.c.$$

Super YM

So full Lagrangian:

gauge trace

$$\mathcal{L} = -\frac{1}{4g^2} \mathrm{Tr}\left(W^\alpha W_\alpha \big|_{\theta^2} + \bar{W}_{\dot\alpha} \bar{W}^{\dot\alpha} \big|_{\bar\theta^2} \right)$$

$$+ \Phi^\dagger e^V \Phi \big|_{\theta^2\bar\theta^2} + W(\Phi)\big|_{\theta^2} + h.c.$$

$$\mathcal{L} = \frac{1}{4g^2} \left(W^{a\alpha} W^a_\alpha \big|_{\theta^2} + \bar{W}^a_{\dot\alpha} \bar{W}^{a\dot\alpha} \big|_{\bar\theta^2} \right)$$

$$= -1/4\, F^a_{\mu\nu} F^{a\mu\nu} + i \bar\lambda^a D_\mu \bar\sigma^\mu \lambda^a + \frac{1}{2} D^a D^a$$

Super YM

So full Lagrangian:

gauge trace

$$\mathcal{L} = -\frac{1}{4g^2} \mathrm{Tr}\left(W^\alpha W_\alpha \big|_{\theta^2} + \bar{W}_{\dot\alpha} \bar{W}^{\dot\alpha} \big|_{\bar\theta^2} \right)$$

$$+ \Phi^\dagger e^V \Phi \big|_{\theta^2\bar\theta^2} + W(\Phi)\big|_{\theta^2} + h.c.$$

$$\mathcal{L} = \frac{1}{4g^2} \left(W^{a\alpha} W^a_\alpha \big|_{\theta^2} + \bar{W}^a_{\dot\alpha} \bar{W}^{a\dot\alpha} \big|_{\bar\theta^2} \right)$$

$$= -\tfrac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i \bar\lambda^a D_\mu \bar\sigma^\mu \lambda^a + \frac{1}{2} D^a D^a$$

$$\Phi^\dagger e^V \Phi \big|_{\theta^2\bar\theta^2} = |D_\mu \varphi|^2$$

$$+ i \bar\psi D_\mu \bar\sigma^\mu \psi + F^* F$$

$$+ i\sqrt{2} \left(\varphi^* T^a \lambda^a \psi + h.c. \right)$$

$$+ \varphi^* T^a D^a \varphi$$

Need to integrate out D^a $\downarrow$ new source for scalar potential.

Full scalar potential

$$V_D = \frac{1}{2} g^2 \sum_a \left| \sum_\varphi \varphi_i^* T^a \varphi_i \right|^2$$

$$V_F = \sum_i \left| \frac{\partial W}{\partial \varphi_i} \right|^2$$

$V(\varphi) \geq 0$ as expected...

Neutral Higgs potential

$$V = \left(|\mu|^2 + m_{H_u}^2\right)|H_u^0|^2 + \left(|\mu|^2 + m_{H_d}^2\right)|H_d^0|^2$$
$$- B_\mu \left(H_u^0 H_d^0 + h.c.\right) \quad \boxed{+\frac{1}{8}\left(g^2 + g'^2\right)\left(|H_u^0|^2 - |H_d^0|^2\right)^2}$$

quartic fixed by gauge interactions!

Higgs spectrum

$$V(H_u^0, H_d^0) \;=\; (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (b\, H_u^0 H_d^0 + h.c.) + \tfrac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2.$$

- Supersymmetry: gauge interactions always come with quartic scalar interactions (*D*-term potential)

$$\frac{1}{8}\left(g^2 + g'^2\right)\left(\left|H_u^0\right|^2 - \left|H_d^0\right|^2\right)^2$$

- Implication: Higgs quartic related to gauge couplings, which also determine *W*, *Z* masses: tree-level bound

$$m_h \leq m_Z \cos(2\beta)$$

Higgs spectrum

$$\begin{aligned} V(H_u^0, H_d^0) \quad = \quad & (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (b\, H_u^0 H_d^0 + h.c.) \\ & + \tfrac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2. \end{aligned}$$

- Supersymmetry: gauge interactions always come with quartic scalar interactions (*D*-term potential)

$$\frac{1}{8}\left(g^2 + g'^2\right)\left(\left|H_u^0\right|^2 - \left|H_d^0\right|^2\right)^2$$

- Implication: Higgs
  also determine *W*,

Higgs mass maximized at *large* tan beta.

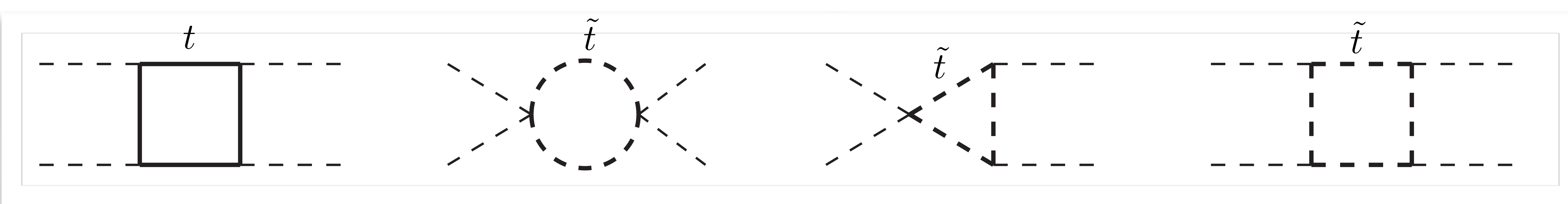
$$m_h \leq m_Z \cos(2\beta)$$

Susy and the 125 GeV Higgs

MSSM:

$$m_h^2 = \boxed{m_Z^2 c_{2\beta}^2} + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

Haber, Hempfling '91



Susy and the 125 GeV Higgs

MSSM:

tree-level bound < M_Z

Haber, Hempfling '91

$$m_h^2 = \boxed{m_Z^2 c_{2\beta}^2} + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

Susy and the 125 GeV Higgs

MSSM:

Logarithmic growth with M_{SUSY}

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\boxed{\log\left(\frac{M_S^2}{m_t^2}\right)} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right)$$

Susy and the 125 GeV Higgs

MSSM:

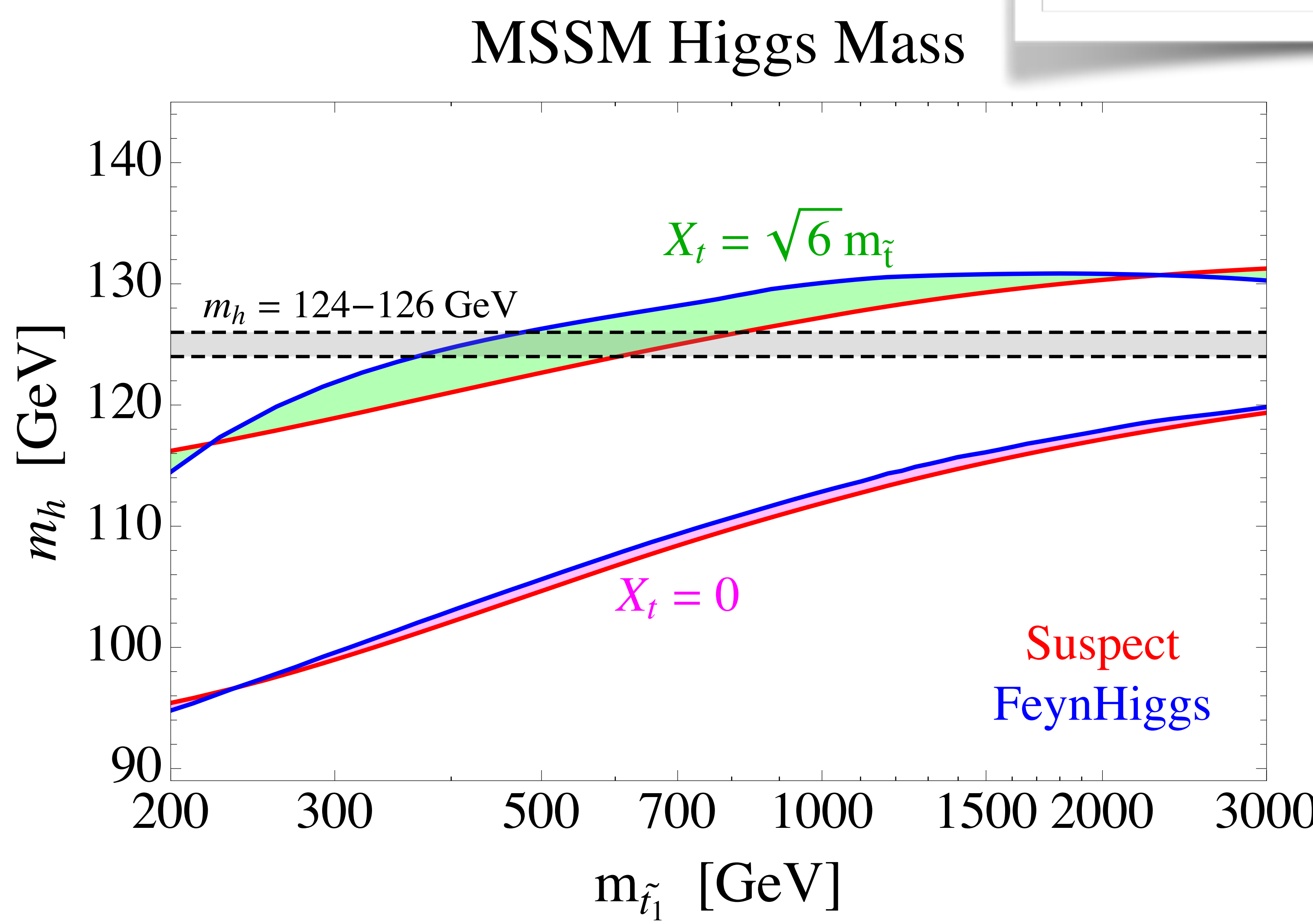
Quadratic term from stop mixing

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \boxed{\frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)}\right)$$

more: Haber, Hempfling, Hoang, Ellis, Ridolfi, Zwirner, Casas, Espinosa, Quiros, Riotto, Carena, Wagner, Degrassi, Heinemeyer, Hollik, Slavich, Weiglein

MSSM vs. the 125 GeV Higgs

$$X_t = A_t - \mu \cot \beta$$



$$\mathcal{L} \supset A_t Q \bar{u} H_u + c.c.$$

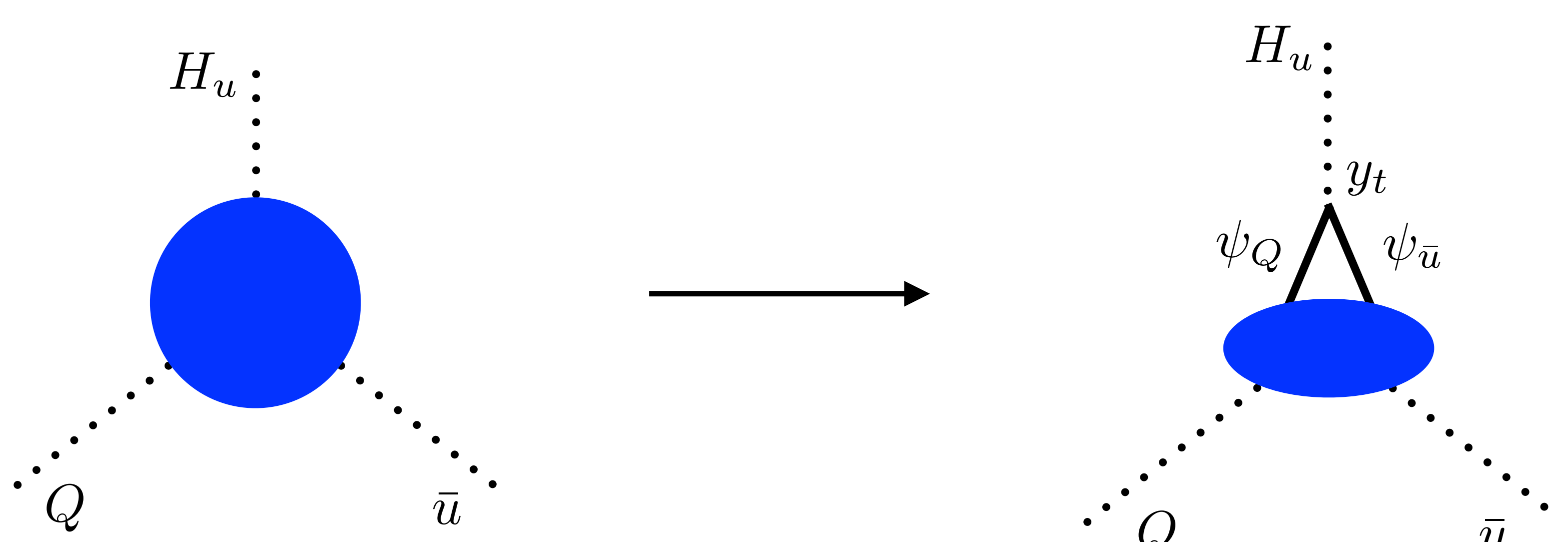
Hall, Pinner, Rudermann

A terms in gauge mediation?

$$\mathcal{L} \supset A_t Q \bar{u} H_u + c.c.$$

Like Yukawa couplings, break chiral (flavor) symmetries

Can not be induced by gauge interactions alone (those leave chiral symmetries intact) →

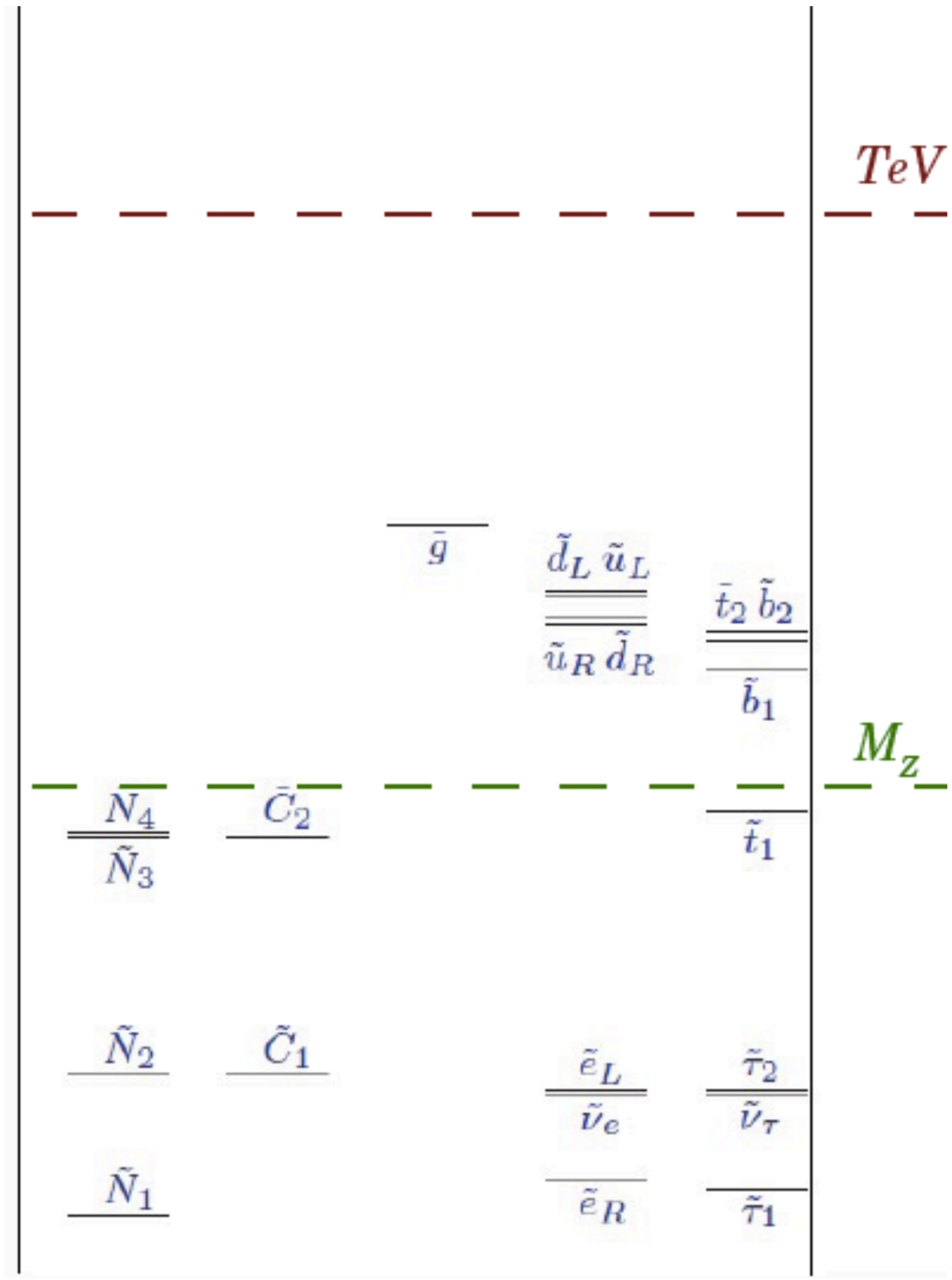


BSM lecture 3/3

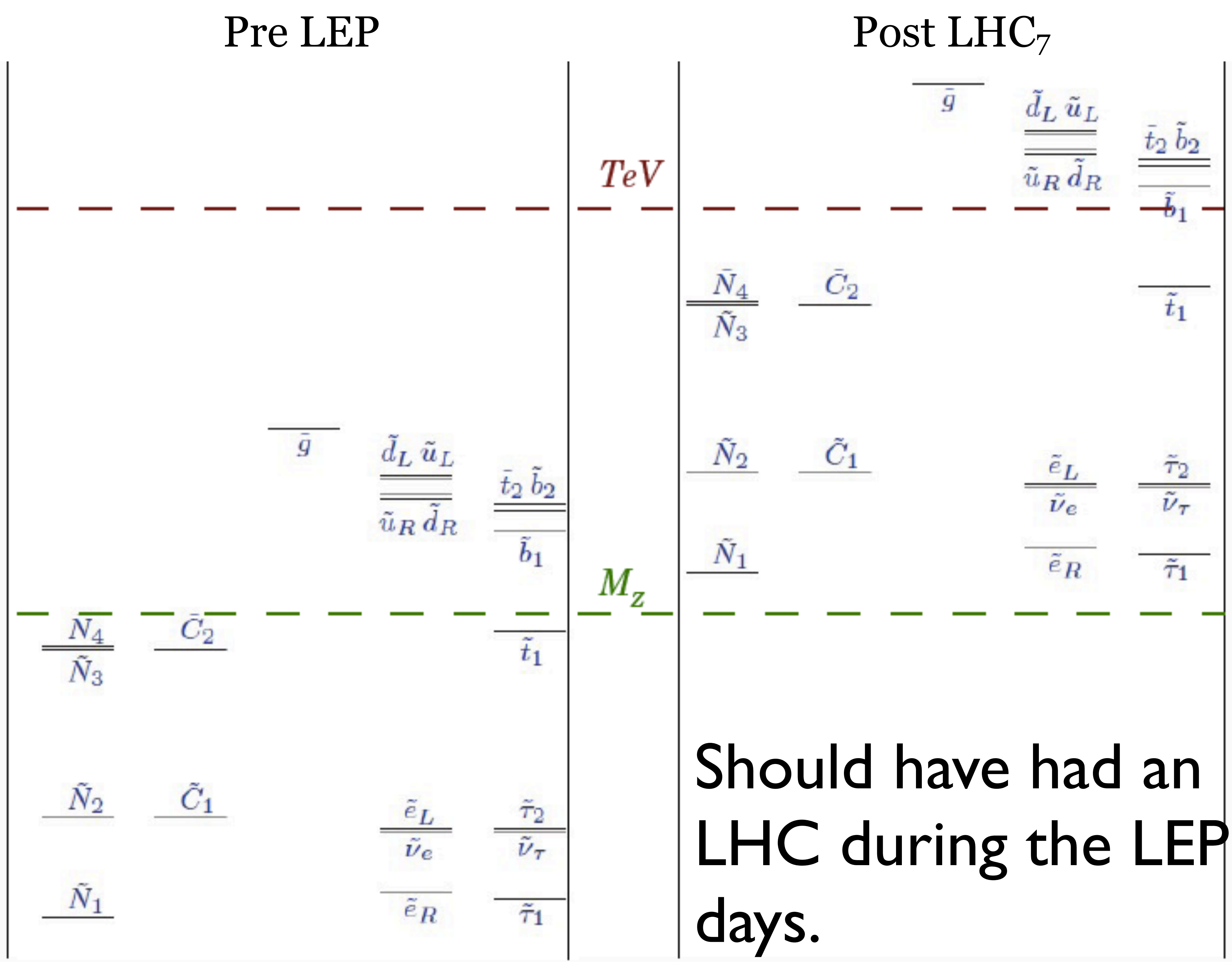
Andreas Weiler
(TU Munich)

Direct Searches for Supersymmetry

Pre LEP

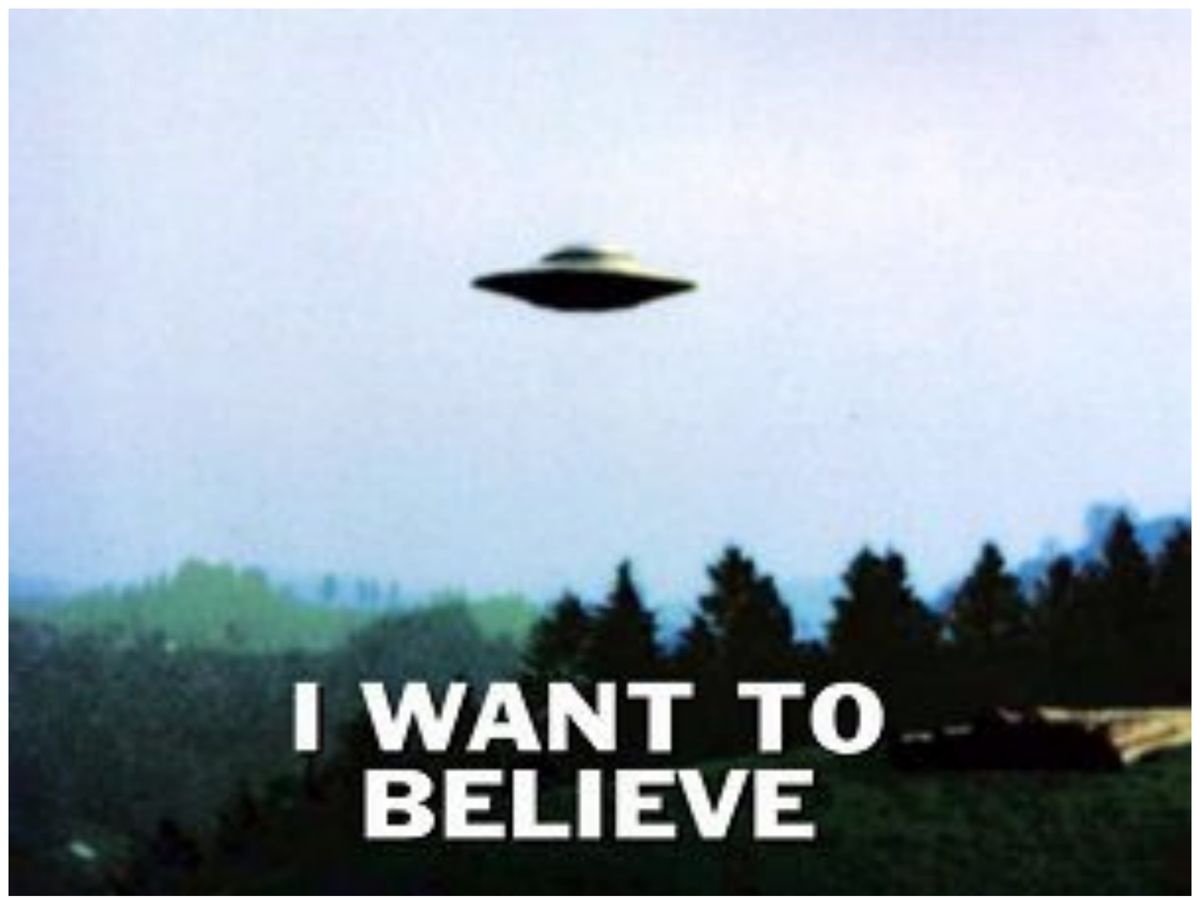


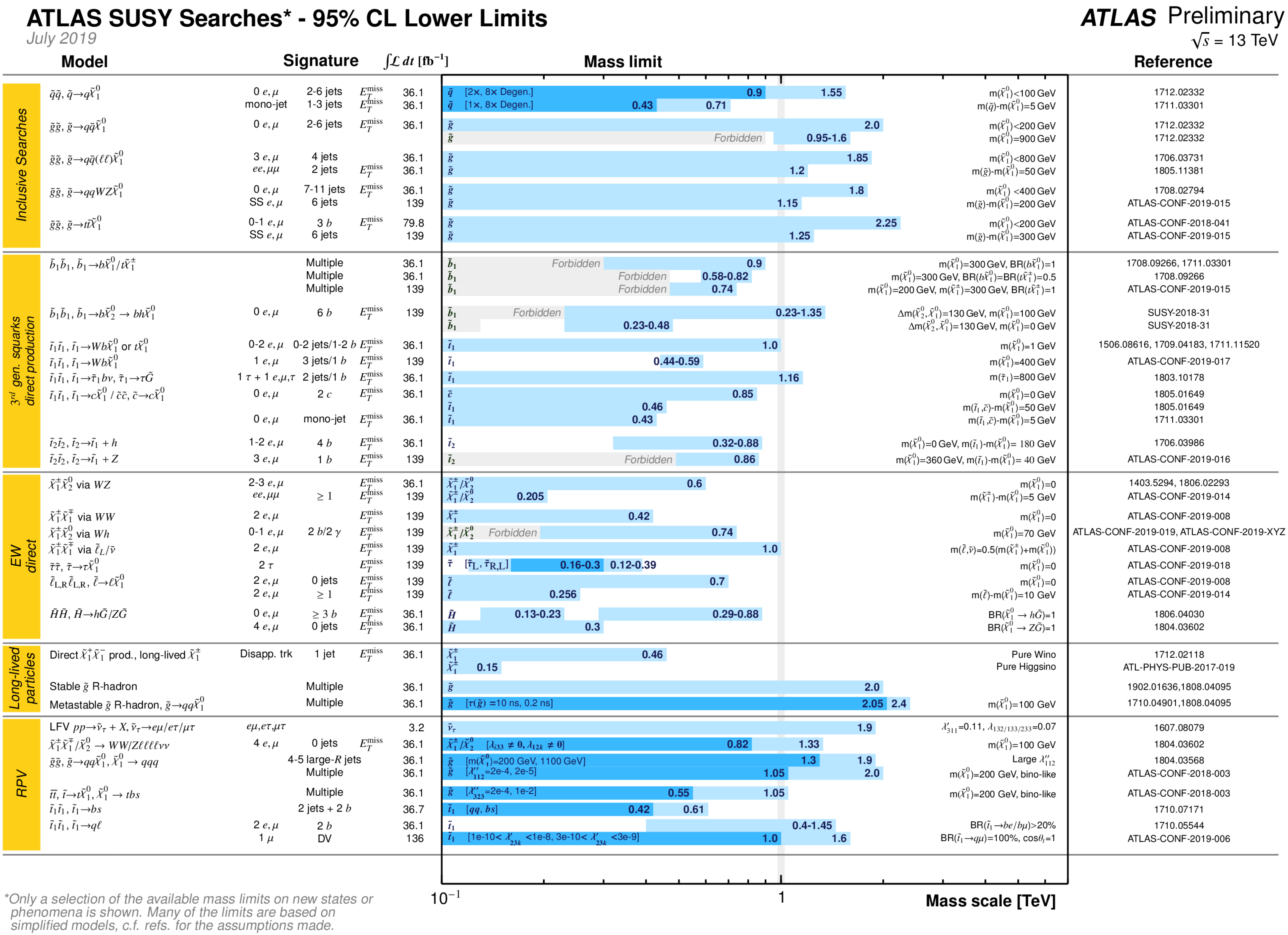
TeV
M_Z
$\tilde{g}$
$\tilde{d}_L\ \tilde{u}_L$
$\tilde{u}_R\ \tilde{d}_R$
$\tilde{t}_2\ \tilde{b}_2$
$\tilde{b}_1$
$\tilde{N}_4$
$\tilde{N}_3$
$\tilde{C}_2$
$\tilde{t}_1$
$\tilde{N}_2$
$\tilde{C}_1$
$\tilde{e}_L$
$\tilde{\nu}_e$
$\tilde{\tau}_2$
$\tilde{\nu}_\tau$
$\tilde{N}_1$
$\tilde{e}_R$
$\tilde{\tau}_1$



Should have had an LHC during the LEP days.

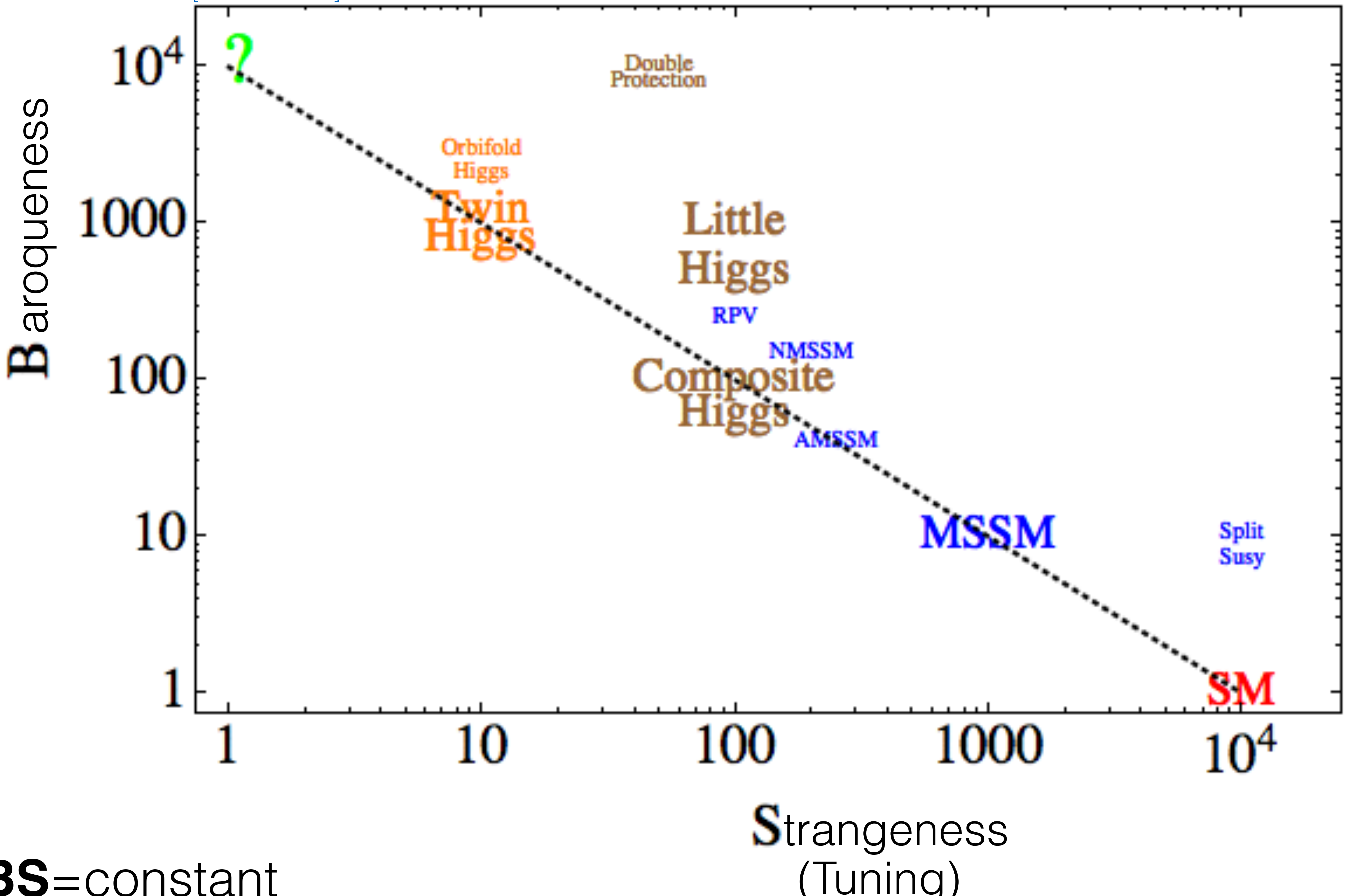
Where is everybody?



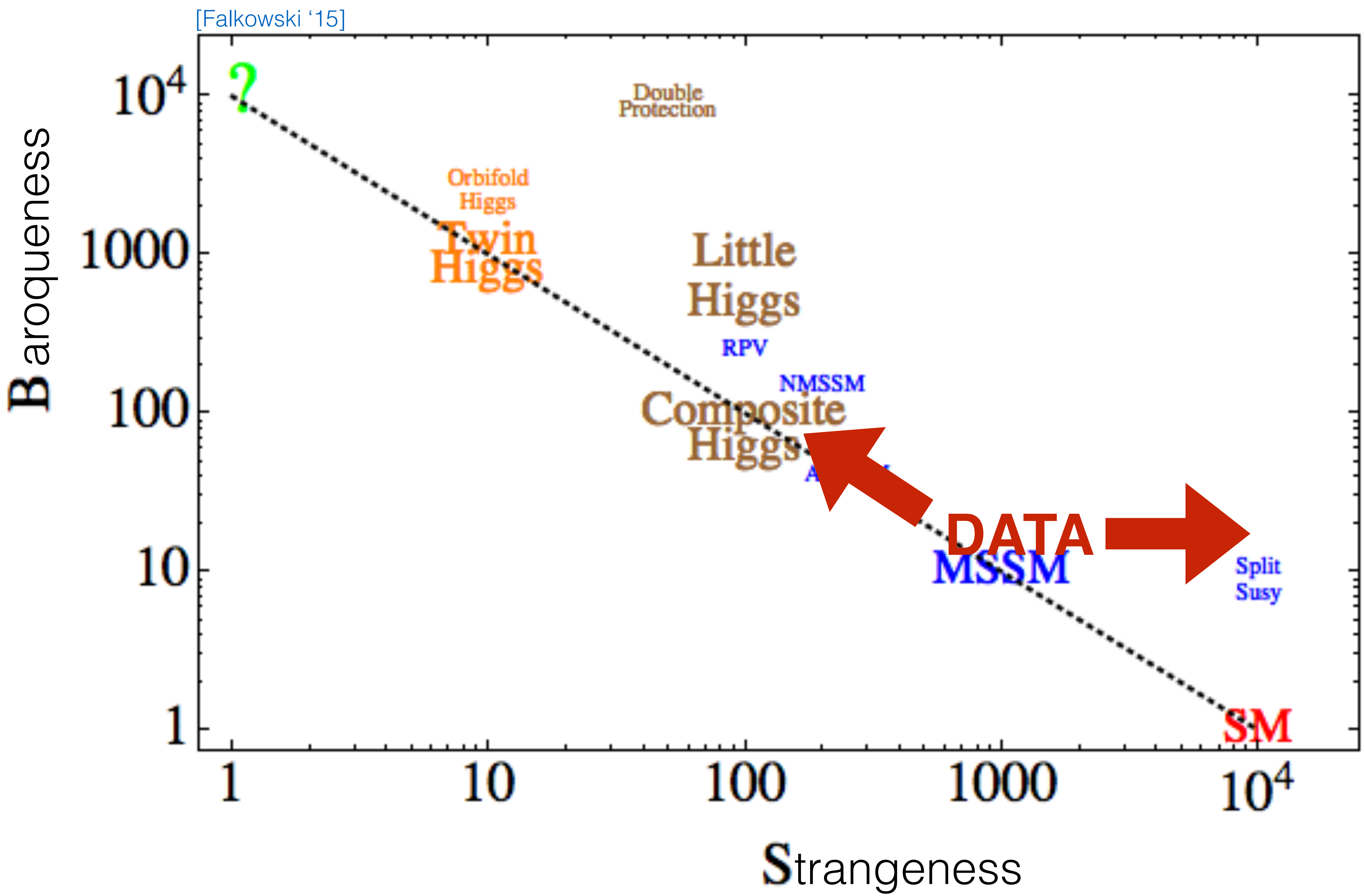


ATLAS SUSY Searches* - 95% CL Lower Limits
July 2019
ATLAS Preliminary
√s = 13 TeV
Model
Signature
∫L dt [fb⁻¹]
Mass limit
Reference
Inclusive Searches
q̃q̃, q̃→qχ̃⁰₁ | 0 e,μ 2-6 jets E_T^miss 36.1 | q̃ [2×, 8× Degen.] 0.9 1.55 | m(χ̃⁰₁)<100 GeV | 1712.02332
mono-jet 1-3 jets E_T^miss 36.1 | q̃ [1×, 8× Degen.] 0.43 0.71 | m(q̃)-m(χ̃⁰₁)=5 GeV | 1711.03301
g̃g̃, g̃→qq̄χ̃⁰₁ | 0 e,μ 2-6 jets E_T^miss 36.1 | g̃ 2.0 | m(χ̃⁰₁)<200 GeV | 1712.02332
g̃ Forbidden 0.95-1.6 | m(χ̃⁰₁)=900 GeV | 1712.02332
g̃g̃, g̃→qq̄(ℓℓ)χ̃⁰₁ | 3 e,μ 4 jets 36.1 | g̃ 1.85 | m(χ̃⁰₁)<800 GeV | 1706.03731
ee,μμ 2 jets E_T^miss 36.1 | g̃ 1.2 | m(g̃)-m(χ̃⁰₁)=50 GeV | 1805.11381
g̃g̃, g̃→qqWZχ̃⁰₁ | 0 e,μ 7-11 jets E_T^miss 36.1 | g̃ 1.8 | m(χ̃⁰₁) <400 GeV | 1708.02794
SS e,μ 6 jets 139 | g̃ 1.15 | m(g̃)-m(χ̃⁰₁)=200 GeV | ATLAS-CONF-2019-015
g̃g̃, g̃→tt̄χ̃⁰₁ | 0-1 e,μ 3 b E_T^miss 79.8 | g̃ 2.25 | m(χ̃⁰₁)<200 GeV | ATLAS-CONF-2018-041
SS e,μ 6 jets 139 | g̃ 1.25 | m(g̃)-m(χ̃⁰₁)=300 GeV | ATLAS-CONF-2019-015
3rd gen. squarks direct production
b̃₁b̃₁, b̃₁→bχ̃⁰₁/tχ̃±₁ | Multiple 36.1 | b̃₁ Forbidden 0.9 | m(χ̃⁰₁)=300 GeV, BR(bχ̃⁰₁)=1 | 1708.09266, 1711.03301
Multiple 36.1 | b̃₁ Forbidden 0.58-0.82 | m(χ̃⁰₁)=300 GeV, BR(bχ̃⁰₁)=BR(tχ̃±₁)=0.5 | 1708.09266
Multiple 139 | b̃₁ Forbidden 0.74 | m(χ̃⁰₁)=200 GeV, m(χ̃±₁)=300 GeV, BR(tχ̃±₁)=1 | ATLAS-CONF-2019-015
b̃₁b̃₁, b̃₁→bχ̃⁰₂ → bhχ̃⁰₁ | 0 e,μ 6 b E_T^miss 139 | b̃₁ Forbidden 0.23-1.35 | Δm(χ̃⁰₂,χ̃⁰₁)=130 GeV, m(χ̃⁰₁)=100 GeV | SUSY-2018-31
b̃₁ 0.23-0.48 | Δm(χ̃⁰₂,χ̃⁰₁)=130 GeV, m(χ̃⁰₁)=0 GeV | SUSY-2018-31
t̃₁t̃₁, t̃₁→Wbχ̃⁰₁ or tχ̃⁰₁ | 0-2 e,μ 0-2 jets/1-2 b E_T^miss 36.1 | t̃₁ 1.0 | m(χ̃⁰₁)=1 GeV | 1506.08616, 1709.04183, 1711.11520
t̃₁t̃₁, t̃₁→Wbχ̃⁰₁ | 1 e,μ 3 jets/1 b E_T^miss 139 | t̃₁ 0.44-0.59 | m(χ̃⁰₁)=400 GeV | ATLAS-CONF-2019-017
t̃₁t̃₁, t̃₁→τ̃₁bν, τ̃₁→τG̃ | 1 τ + 1 e,μ,τ 2 jets/1 b E_T^miss 36.1 | t̃₁ 1.16 | m(τ̃₁)=800 GeV | 1803.10178
t̃₁t̃₁, t̃₁→cχ̃⁰₁ / c̃c̃, c̃→cχ̃⁰₁ | 0 e,μ 2 c E_T^miss 36.1 | c̃ 0.85 | m(χ̃⁰₁)=0 GeV | 1805.01649
t̃₁ 0.46 | m(t̃₁,c̃)-m(χ̃⁰₁)=50 GeV | 1805.01649
0 e,μ mono-jet E_T^miss 36.1 | t̃₁ 0.43 | m(t̃₁,c̃)-m(χ̃⁰₁)=5 GeV | 1711.03301
t̃₂t̃₂, t̃₂→t̃₁ + h | 1-2 e,μ 4 b E_T^miss 36.1 | t̃₂ 0.32-0.88 | m(χ̃⁰₁)=0 GeV, m(t̃₁)-m(χ̃⁰₁)= 180 GeV | 1706.03986
t̃₂t̃₂, t̃₂→t̃₁ + Z | 3 e,μ 1 b E_T^miss 139 | t̃₂ Forbidden 0.86 | m(χ̃⁰₁)=360 GeV, m(t̃₁)-m(χ̃⁰₁)= 40 GeV | ATLAS-CONF-2019-016
EW direct
χ̃±₁χ̃⁰₂ via WZ | 2-3 e,μ E_T^miss 36.1 | χ̃±₁/χ̃⁰₂ 0.6 | m(χ̃⁰₁)=0 | 1403.5294, 1806.02293
ee,μμ ≥ 1 E_T^miss 139 | χ̃±₁/χ̃⁰₂ 0.205 | m(χ̃±₁)-m(χ̃⁰₁)=5 GeV | ATLAS-CONF-2019-014
χ̃±₁χ̃∓₁ via WW | 2 e,μ E_T^miss 139 | χ̃±₁ 0.42 | m(χ̃⁰₁)=0 | ATLAS-CONF-2019-008
χ̃±₁χ̃⁰₂ via Wh | 0-1 e,μ 2 b/2 γ E_T^miss 139 | χ̃±₁/χ̃⁰₂ Forbidden 0.74 | m(χ̃⁰₁)=70 GeV | ATLAS-CONF-2019-019, ATLAS-CONF-2019-XYZ
χ̃±₁χ̃∓₁ via ℓ̃_L/ν̃ | 2 e,μ E_T^miss 139 | χ̃±₁ 1.0 | m(ℓ̃,ν̃)=0.5(m(χ̃±₁)+m(χ̃⁰₁)) | ATLAS-CONF-2019-008
τ̃τ̃, τ̃→τχ̃⁰₁ | 2 τ E_T^miss 139 | τ̃ [τ̃_L, τ̃_R,L] 0.16-0.3 0.12-0.39 | m(χ̃⁰₁)=0 | ATLAS-CONF-2019-018
ℓ̃_L,R ℓ̃_L,R, ℓ̃→ℓχ̃⁰₁ | 2 e,μ 0 jets E_T^miss 139 | ℓ̃ 0.7 | m(χ̃⁰₁)=0 | ATLAS-CONF-2019-008
2 e,μ ≥ 1 E_T^miss 139 | ℓ̃ 0.256 | m(ℓ̃)-m(χ̃⁰₁)=10 GeV | ATLAS-CONF-2019-014
H̃H̃, H̃→hG̃/ZG̃ | 0 e,μ ≥ 3 b E_T^miss 36.1 | H̃ 0.13-0.23 0.29-0.88 | BR(χ̃⁰₁ → hG̃)=1 | 1806.04030
4 e,μ 0 jets E_T^miss 36.1 | H̃ 0.3 | BR(χ̃⁰₁ → ZG̃)=1 | 1804.03602
Long-lived particles
Direct χ̃⁺₁χ̃⁻₁ prod., long-lived χ̃±₁ | Disapp. trk 1 jet E_T^miss 36.1 | χ̃±₁ 0.46 | Pure Wino | 1712.02118
χ̃±₁ 0.15 | Pure Higgsino | ATL-PHYS-PUB-2017-019
Stable g̃ R-hadron | Multiple 36.1 | g̃ 2.0 | 1902.01636,1808.04095
Metastable g̃ R-hadron, g̃→qqχ̃⁰₁ | Multiple 36.1 | g̃ [τ(g̃) =10 ns, 0.2 ns] 2.05 2.4 | m(χ̃⁰₁)=100 GeV | 1710.04901,1808.04095
RPV
LFV pp→ν̃_τ + X, ν̃_τ→eμ/eτ/μτ | eμ,eτ,μτ 3.2 | ν̃_τ 1.9 | λ′₃₁₁=0.11, λ₁₃₂/₁₃₃/₂₃₃=0.07 | 1607.08079
χ̃±₁χ̃∓₁/χ̃⁰₂ → WW/Zℓℓℓℓνν | 4 e,μ 0 jets E_T^miss 36.1 | χ̃±₁/χ̃⁰₂ [λ_i33 ≠ 0, λ_12k ≠ 0] 0.82 1.33 | m(χ̃⁰₁)=100 GeV | 1804.03602
g̃g̃, g̃→qqχ̃⁰₁, χ̃⁰₁ → qqq | 4-5 large-R jets 36.1 | g̃ [m(χ̃⁰₁)=200 GeV, 1100 GeV] 1.3 1.9 | Large λ″₁₁₂ | 1804.03568
Multiple 36.1 | g̃ [λ″₁₁₂=2e-4, 2e-5] 1.05 2.0 | m(χ̃⁰₁)=200 GeV, bino-like | ATLAS-CONF-2018-003
t̃t̃, t̃→tχ̃⁰₁, χ̃⁰₁ → tbs | Multiple 36.1 | g̃ [λ″₃₂₃=2e-4, 1e-2] 0.55 1.05 | m(χ̃⁰₁)=200 GeV, bino-like | ATLAS-CONF-2018-003
t̃₁t̃₁, t̃₁→bs | 2 jets + 2 b 36.7 | t̃₁ [qq, bs] 0.42 0.61 | 1710.07171
t̃₁t̃₁, t̃₁→qℓ | 2 e,μ 2 b 36.1 | t̃₁ 0.4-1.45 | BR(t̃₁→be/bμ)>20% | 1710.05544
1 μ DV 136 | t̃₁ [1e-10< λ′₂₃k <1e-8, 3e-10< λ′₂₃k <3e-9] 1.0 1.6 | BR(t̃₁→qμ)=100%, cosθ_t=1 | ATLAS-CONF-2019-006
10⁻¹
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

[Falkowski '15]



BS=constant


[Falkowski '15]
Baroqueness
Strangeness
(Tuning)
?
Double Protection
Orbifold Higgs
Twin Higgs
Little Higgs
RPV
NMSSM
Composite Higgs
DATA
MSSM
Split Susy
SM
10^4
1000
100
10
1
1
10
100
1000
10^4

BS=constant

Comment on 'beauty'

- We adapt our notation to make established physics as simple as possible, the SM is economical but not minimal

original form (1865)

$e+\frac{df}{dx}+\frac{dg}{dy}+\frac{dh}{dz}=0$	(1)	Gauss' Law
$\mu\alpha=\frac{dH}{dy}-\frac{dG}{dz}$ $\mu\beta=\frac{dF}{dz}-\frac{dH}{dx}$ $\mu\gamma=\frac{dG}{dx}-\frac{dF}{dy}$	(2)	Equivalent to Gauss' Law for magnetism
$P=\mu\left(\gamma\frac{dy}{dt}-\beta\frac{dz}{dt}\right)-\frac{dF}{dt}-\frac{d\Psi}{dz}$ $Q=\mu\left(\alpha\frac{dz}{dt}-\gamma\frac{dx}{dt}\right)-\frac{dG}{dt}-\frac{d\Psi}{dy}$ $R=\mu\left(\beta\frac{dx}{dt}-\alpha\frac{dy}{dt}\right)-\frac{dH}{dt}-\frac{d\Psi}{dz}$	(3)	Faraday's Law (with the Lorentz Force and Poisson's Law)
$\frac{d\gamma}{dy}-\frac{d\beta}{dz}=4\pi p'$ $\quad p'=p+\frac{df}{dt}$ $\frac{d\alpha}{dz}-\frac{d\gamma}{dx}=4\pi q'$ $\quad q'=q+\frac{dg}{dt}$ $\frac{d\beta}{dx}-\frac{d\alpha}{dy}=4\pi r'$ $\quad r'=r+\frac{dh}{dt}$	(4)	Ampère-Maxwell Law
$P=-\xi p \quad Q=-\xi q \quad R=-\xi r$		Ohm's Law
$P=kf \quad Q=kg \quad R=kh$		The electric elasticity equation (**E** = **D**/ε)
$\frac{de}{dt}+\frac{dp}{dx}+\frac{dq}{dy}+\frac{dr}{dz}=0$		Continuity of charge

covariant form

$$\partial_\mu F^{\mu\nu}=\frac{1}{c}J^\nu \quad \text{and} \quad \partial_\mu {}^*F^{\mu\nu}=0,$$

http://ethw.org/Maxwell's_Equations

An analogy

An analogy

- Problem: Weak interactions

An analogy

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- Framework: Gauge theory

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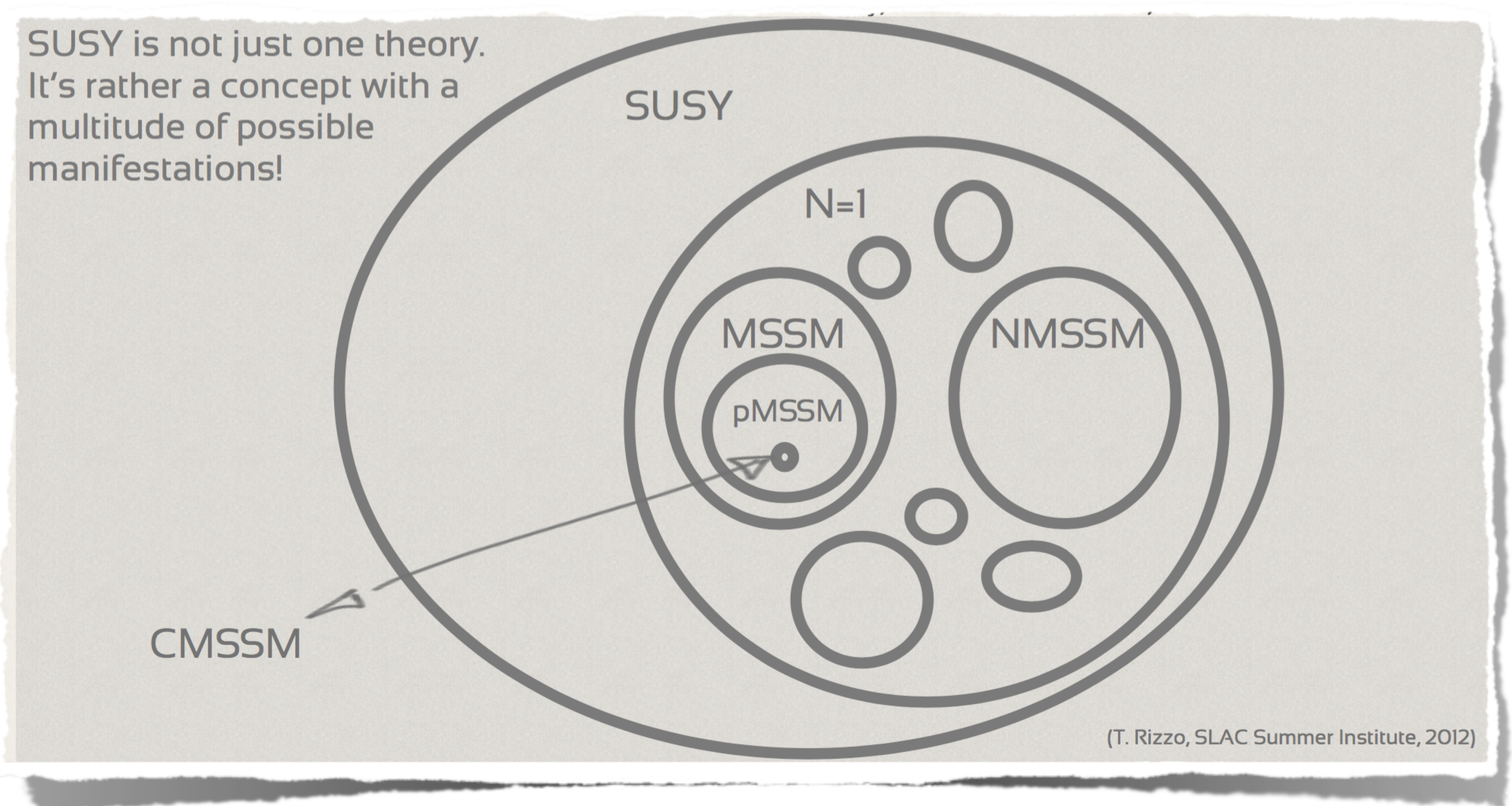
SUSY contains multitudes!



Natural EWSB & MSSM

Fine-tuning of (Higgs mass)^2

$$\frac{m_Z^2}{2} = -|\mu|^2 - \frac{m_{H_u}^2 \tan^2\beta - m_{H_d}^2}{\tan^2\beta - 1}$$

$$\approx -|\mu|^2 - m_{H_u}^2 - \delta m_{H_u}^2$$

Natural EWSB & SUSY

Fine-tuning of (Higgs mass)^2

$$\frac{m^2_{Higgs}}{2} = -|\mu|^2 + \ldots + \delta m^2_H$$

Natural EWSB & SUSY

Fine-tuning of (Higgs mass)^2

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Higgsinos

Natural EWSB & SUSY

Fine-tuning of (Higgs mass)^2

$$\frac{m^2_{Higgs}}{2} = -\boxed{|\mu|^2} + \ldots + \boxed{\delta m^2_H}$$

Higgsinos

1loop $\quad \boxed{\delta m^2_H|_{stop}} = -\frac{3}{8\pi^2} y_t^2 \left(m^2_{U_3} + m^2_{Q_3} + |A_t|^2\right) \log\left(\frac{\Lambda}{\mathrm{TeV}}\right)$

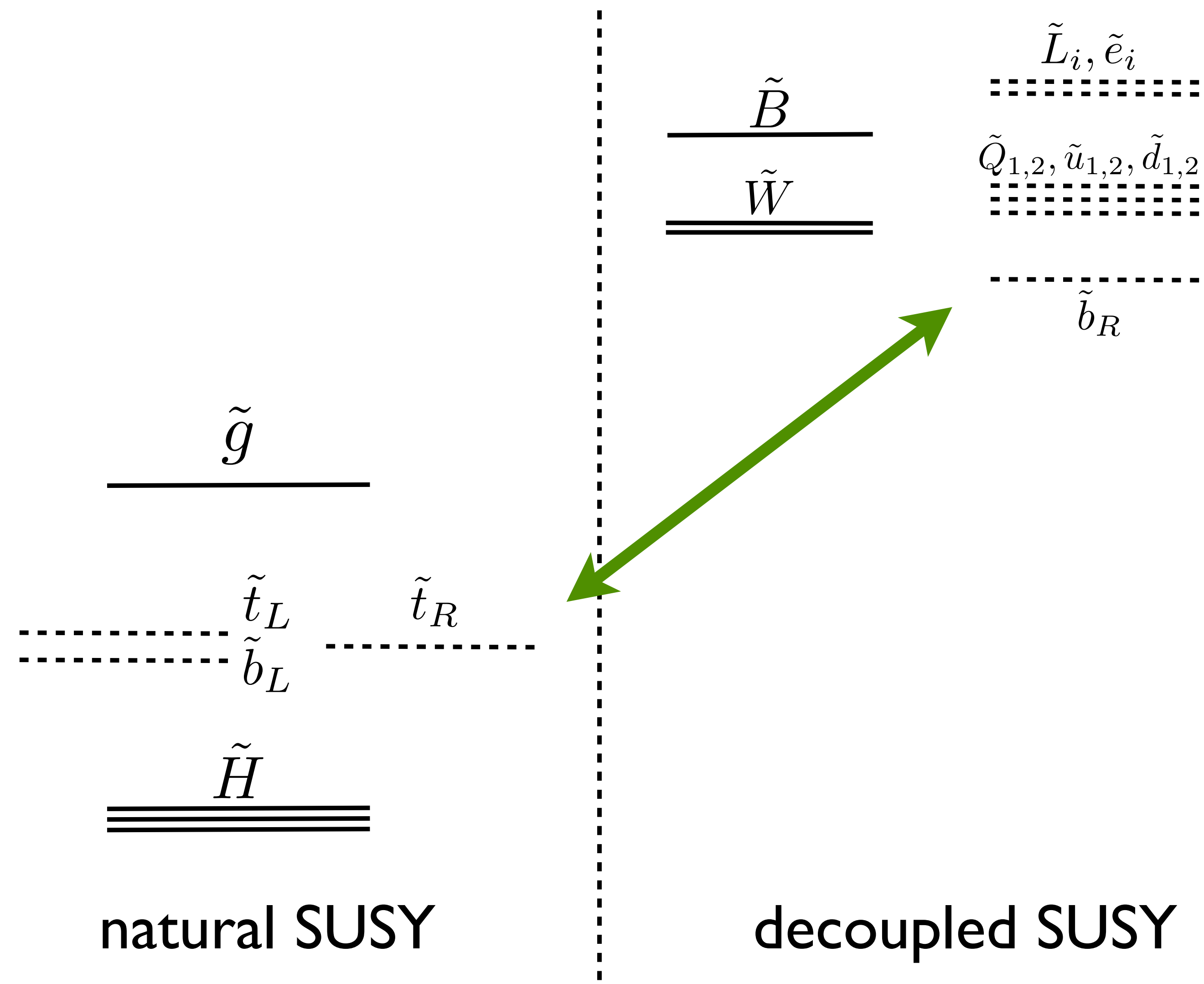
stops, sbottom$_L$

2loop $\quad \boxed{\delta m^2_H|_{gluino}} = -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right) |M_3|^2 \log^2\left(\frac{\Lambda}{\mathrm{TeV}}\right)$

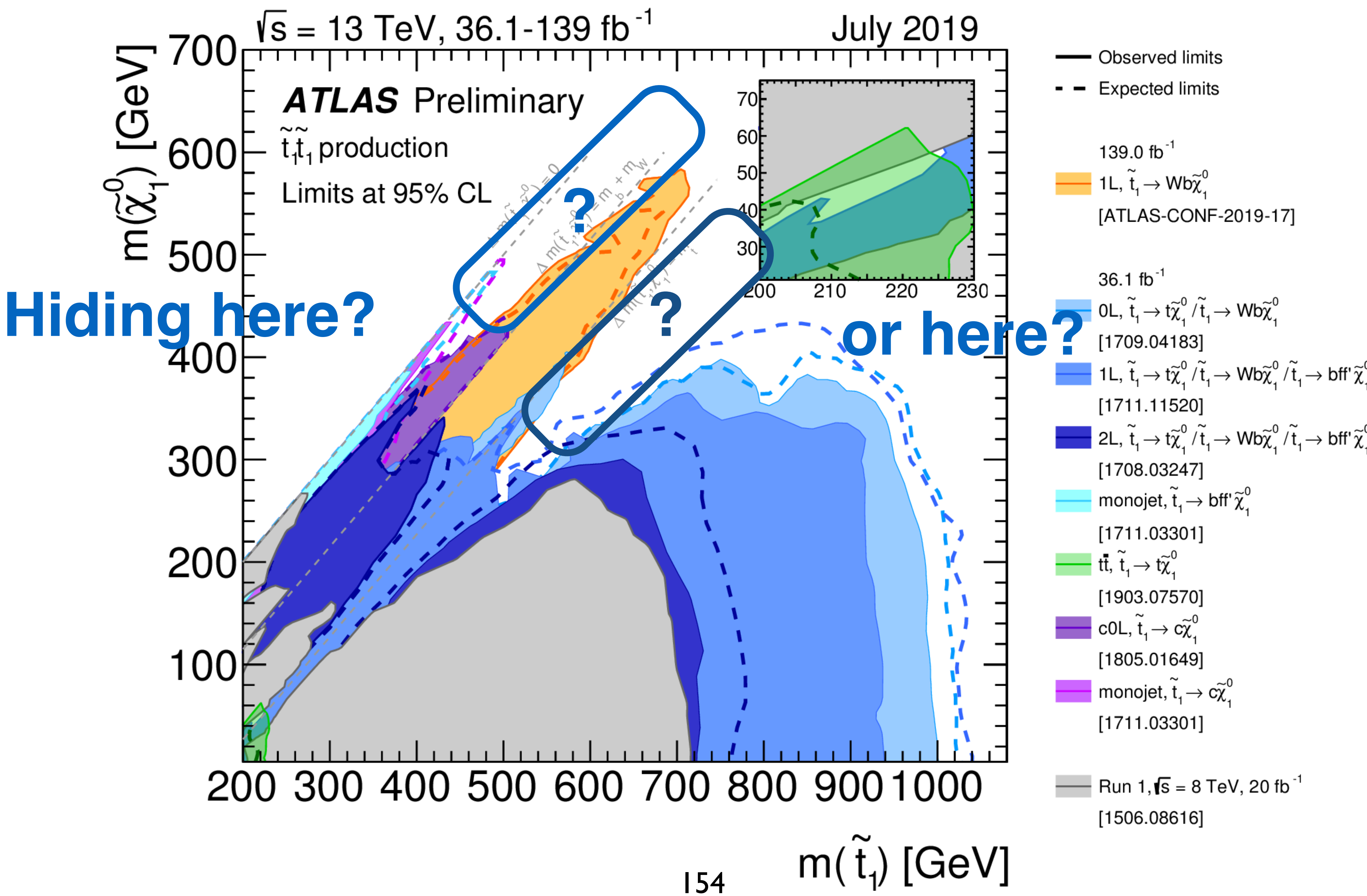
gluino

Reason for some optimism: natural susy

Scale	δm_H^2
multi TeV	<<
$\approx 1000\,\mathrm{GeV}$	2loop
$\approx 500\,\mathrm{GeV}$	1loop
$\approx 250\,\mathrm{GeV}$	tree



Stop searches



The other symmetric approach

Composite/Goldstone Higgs

Supersymmetry is a weakly coupled solution to the hierarchy problem. We can extrapolate physics to the Planck scale, complete the MSSM into a GUT.

There is another way. Nature already employs a strongly coupled mechanism to explain:

$$\Lambda_{\mathrm{QCD}} \ll M_{\mathrm{Planck}}$$

$$\sim 1\,\mathrm{GeV} \qquad 10^{19}\,\mathrm{GeV}$$

QCD

David J. Gross

H. David Politzer

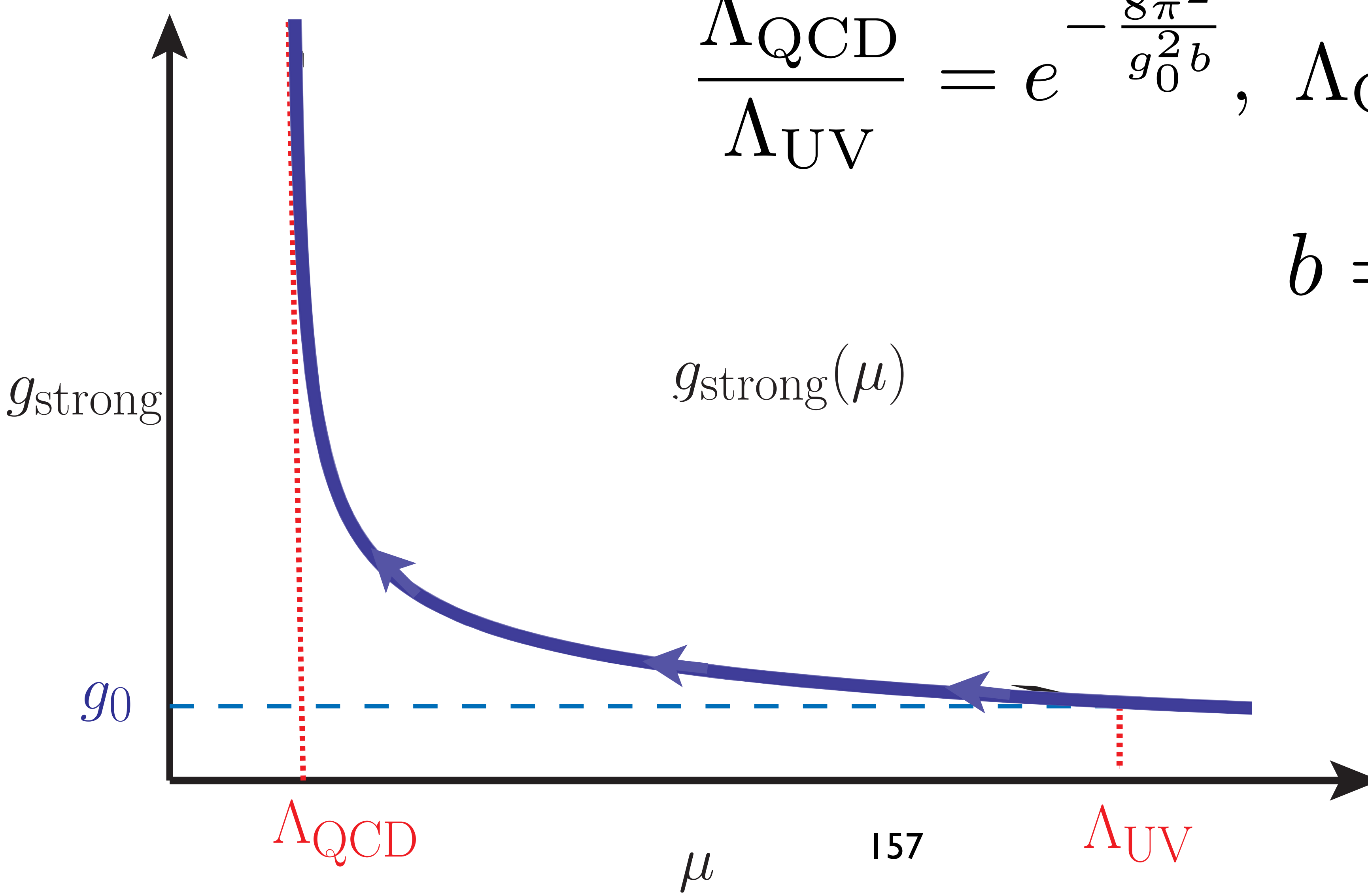
Frank Wilczek

Fix QCD coupling at some high scale

→ exponential hierarchy generated dynamically

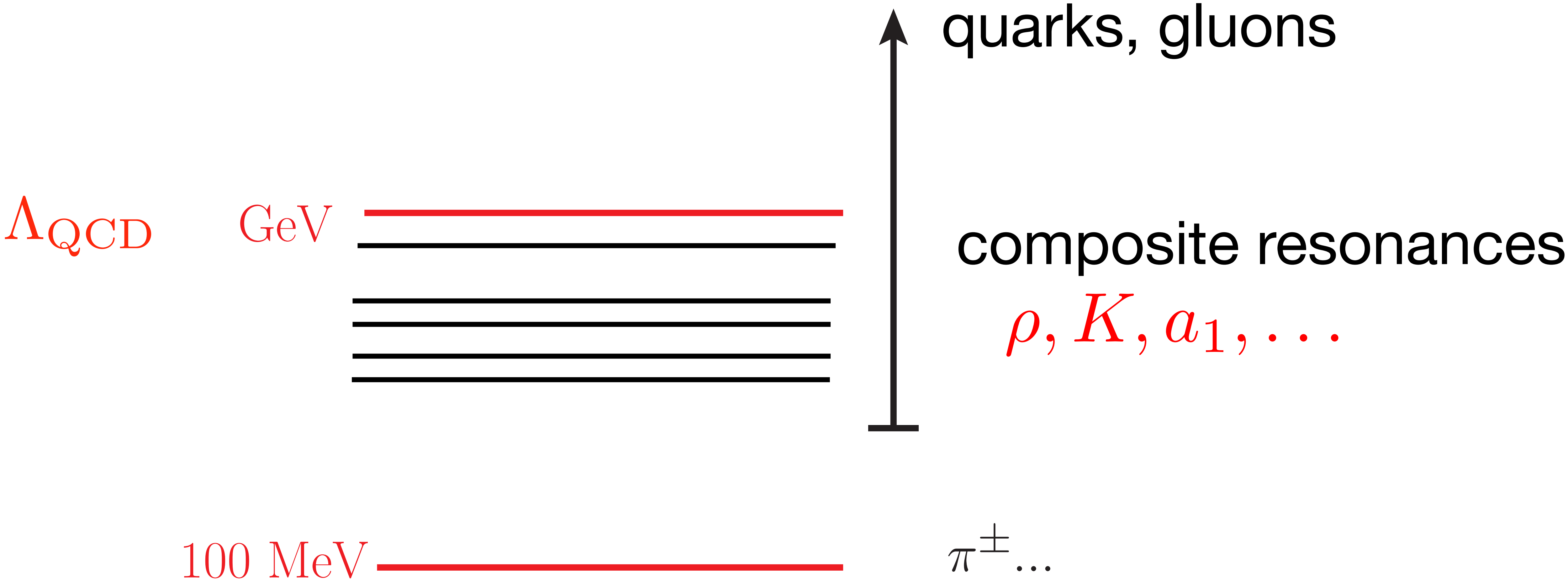
$$\frac{\Lambda_{\text{QCD}}}{\Lambda_{\text{UV}}} = e^{-\frac{8\pi^2}{g_0^2 b}}, \;\; \Lambda_{\text{QCD}} \leq \;\; \text{GeV}$$

$$b = 7$$



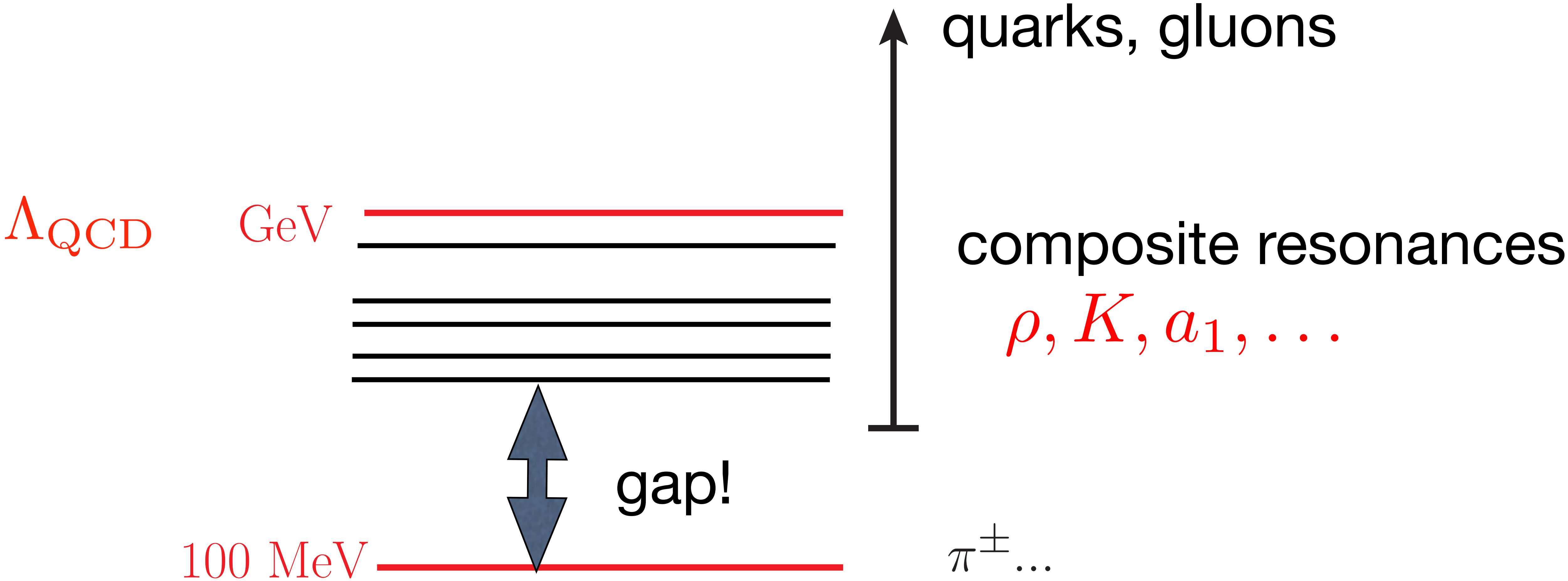
Asymptotic freedom

QCD: composite bound states



At strong coupling, new resonances are generated

QCD: composite bound states



At strong coupling, new resonances are generated

QCD vs. EWSB

QCD dynamically breaks SM gauge symmetry

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

$$\boxed{\langle \bar{q}_L q_R \rangle} \simeq \Lambda^3_{\mathrm{QCD}} \sim \ (\mathrm{GeV})^3$$

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QCD dynamically breaks SM gauge symmetry

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

$$\boxed{\langle \bar{q}_L q_R \rangle} \simeq \Lambda_{\mathrm{QCD}}^3 \sim \ (\mathrm{GeV})^3$$

The QCD masses of W/Z are small

$$m_{\mathrm{W,Z}} \sim \frac{g}{4\pi} \Lambda_{\mathrm{QCD}} \sim 100 \ \mathrm{MeV}$$

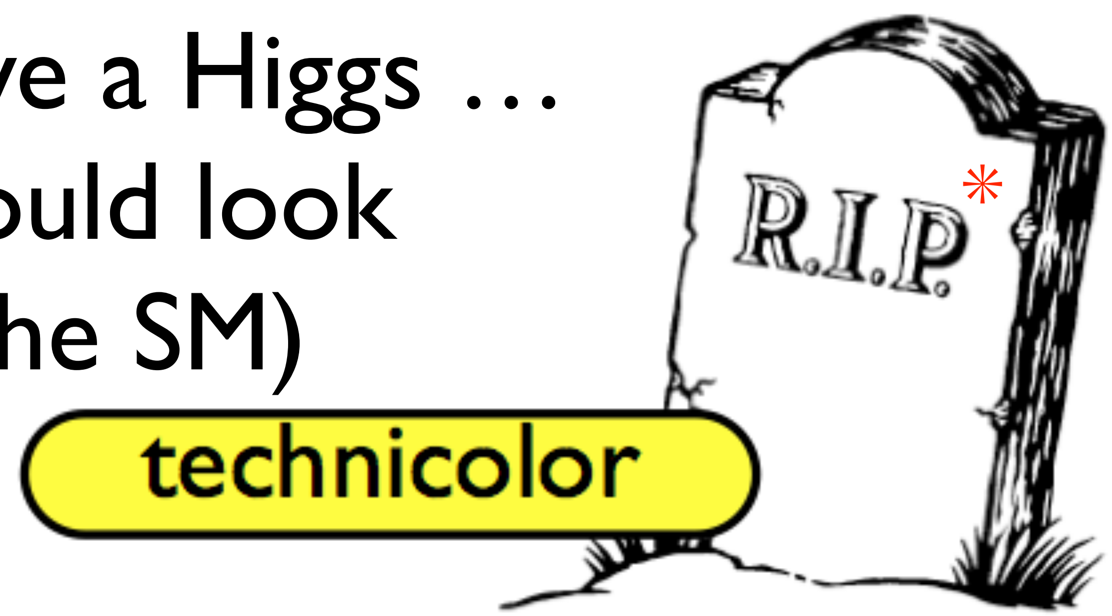
Longitudinal components of W & Z have tiny admixture of pions…

Technicolor

Scaled up version of QCD mechanism

$$\langle \bar{q}'_L q'_R \rangle \sim \Lambda^3_{\rm TC}, \quad \Lambda_{\rm TC} \sim \ {\rm TeV}$$

Technicolor, doesn't have a Higgs …
(or if there is one, it would look
very different from the SM)



* the Higgs as the dilaton
as the last bastion …

Composite Higgs

- Want to copy QCD, but extend pion sector (QCD: $\pi^0, \pi^\pm$)
- Higgs as a (pseudo) Goldstone boson

Goal

SUPERSYMMETRY

$$\phi \to \phi + \epsilon\psi$$
$$\psi \to \psi - i(\sigma^\nu \epsilon^\dagger)_\alpha \partial_\nu \phi$$

OPPOSITE-STATISTICS PARTNER
FOR EVERY SM PARTICLE

GLOBAL SYMMETRY

$$\Phi \to (1 + i\alpha T)\Phi$$

SAME-STATISTICS PARTNER
FOR EVERY SM PARTICLE

CONTRIBUTE TO THE HIGGS MASS:

$$m_h^2 \sim \frac{3y_t^2}{4\pi^2}\tilde{m}^2 \log(\Lambda^2/\tilde{m}^2)$$

adapted from N. Craig

Need to learn about goldstone bosons…

Quantum Protection

Symmetries can soften quantum behaviour

$$\mathcal{L} = |\partial_\mu \phi|^2 + \boxed{\mu^2 |\phi|^2} - \lambda |\phi|^4 + \ldots$$

breaks susy → corrections must be proportional to susy breaking

Shift symmetry

Higgs mass term can be forbidden

$$\mathcal{L} = |\partial_\mu \phi|^2 + \boxed{\mu^2|\phi|^2} - \lambda|\phi|^4 + \ldots$$

$$\phi \to e^{i\alpha}\phi$$

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does not forbid the mass^2

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$\phi \to e^{i\alpha}\phi$ does not forbid the mass^2

$\phi \to \phi + \alpha$ works!

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Can we make the Higgs transform this way?

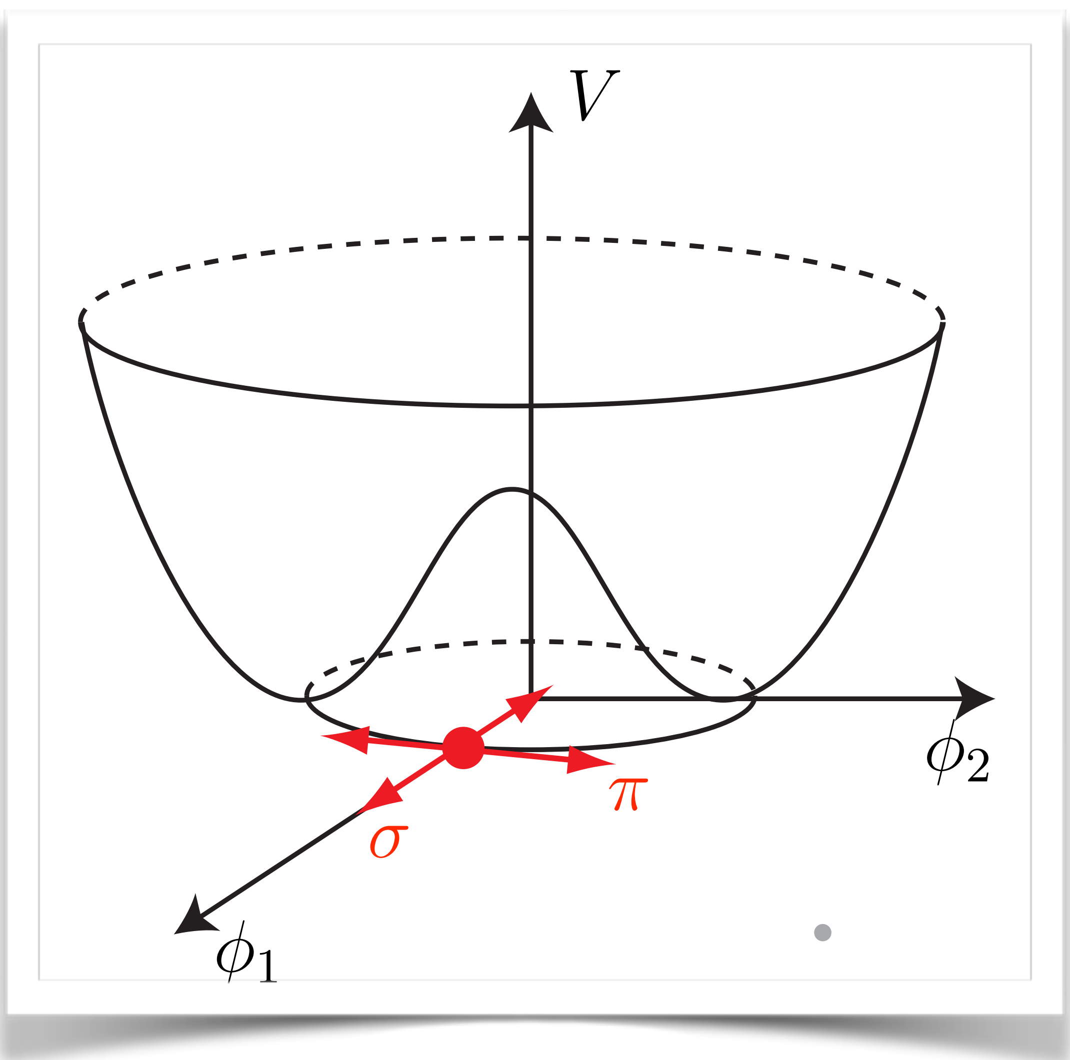
Spontaneous breaking of U(1)

$$\langle \Phi \rangle = \frac{f}{\sqrt{2}}$$

Instead using complex field

$$\mathcal{L} = |\partial_\mu \phi|^2 + \mu^2 |\phi|^2 - \lambda |\phi|^4 + \ldots$$

$$\phi = \phi_1 + i\phi_2$$



'phase' 'modulos'

Spontaneous breaking of U(1)

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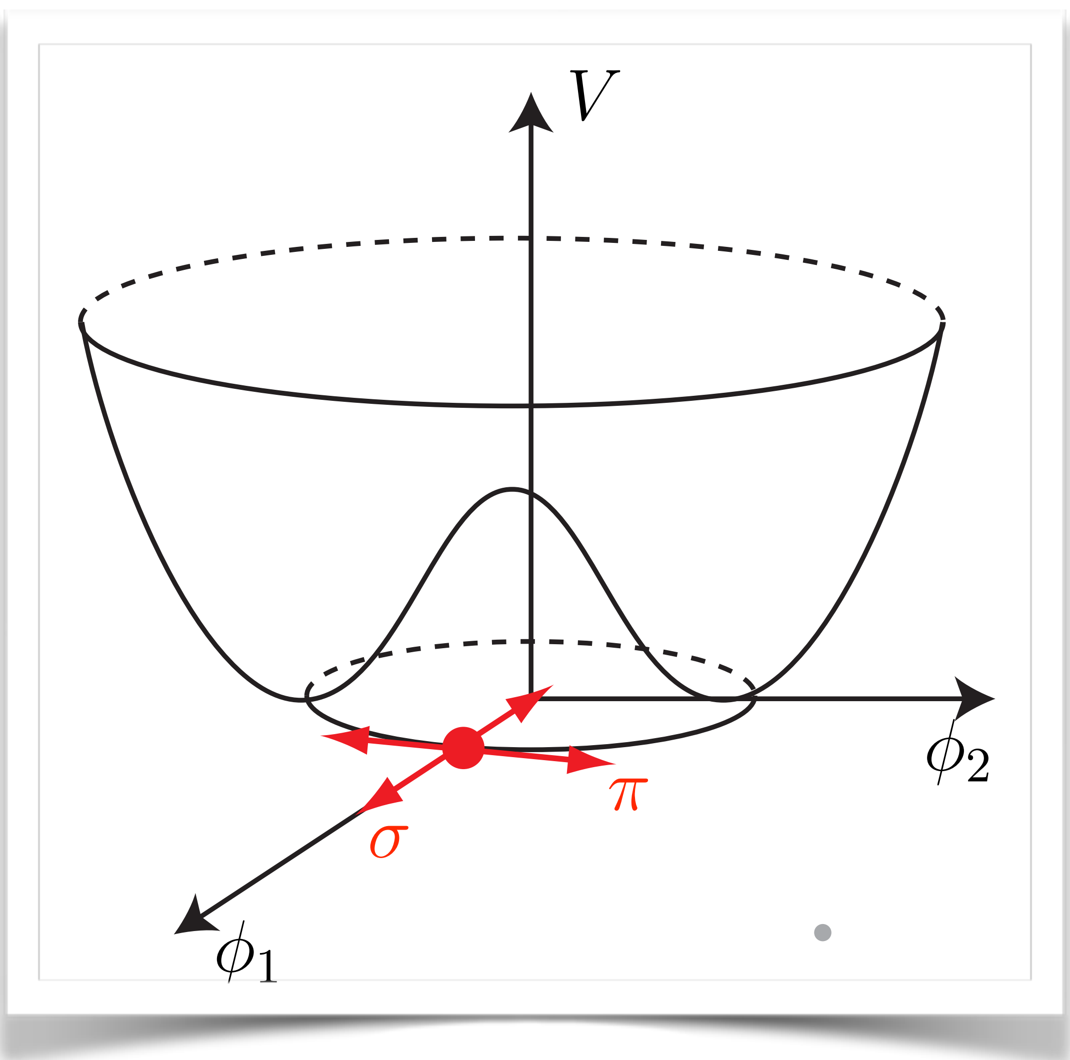

Instead using complex field

$$\phi = \phi_1 + i\phi_2$$

use real parametrisation

$$\phi(x) = \frac{1}{2} e^{i\pi(x)/f}(f + \sigma(x))$$

'phase' 'modulos'

$$\mathcal{L} = |\partial_\mu \phi|^2 + \mu^2 |\phi|^2 - \lambda |\phi|^4 + \ldots$$

use $$\phi(x) = \frac{1}{2} e^{i\pi(x)/f} (f + \sigma(x))$$

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$$\partial^\mu \phi^\dagger \partial_\mu \phi = \frac{1}{2} \partial^\mu \sigma \partial_\mu \sigma + \frac{1}{2} (1 + \sigma/f)^2 \frac{1}{2} \partial^\mu \pi \partial_\mu \pi$$

$$\mathcal{L} = |\partial_\mu \phi|^2 + \boxed{\mu^2|\phi|^2 - \lambda|\phi|^4 + \ldots} \quad V(|\phi(x)|^2)$$

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$$V(|\phi(x)|^2) = V(\sigma(x))$$

no dependence on $\pi(x)$

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$$V(|\phi(x)|^2) = V(\sigma(x))$$

no mass term

no dependence on $\pi(x)$

$$\frac{1}{2}\left(1+\sigma(x)/f\right)^2\frac{1}{2}\partial^\mu\pi\partial_\mu\pi+\frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma-V(\sigma(x))$$

Using this parameterization a new symmetry is visible:

$$\pi(x)\rightarrow\pi(x)+\alpha$$

because $\pi(x)$ has only 'derivative interactions'

$$\partial_\mu(\pi(x)+\alpha)=\partial_\mu\pi(x)$$

$$\pi(x),\sigma(x)$$

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But what happened to the U(1) symmetry ?

$\pi(x),\sigma(x)$ are real...

But what happened to the U(1) symmetry ?

$$\phi \to e^{i\alpha}\phi$$

$$e^{i\pi(x)/f}(f+\sigma(x)) \to e^{i\alpha}e^{i\pi(x)/f}(f+\sigma(x))$$

$$\Rightarrow \quad \boxed{\begin{aligned} &\sigma(x) \to \sigma(x) \\ &\pi(x) \to \pi(x) + \alpha \end{aligned}}$$

Phase rotation becomes shift symmetry

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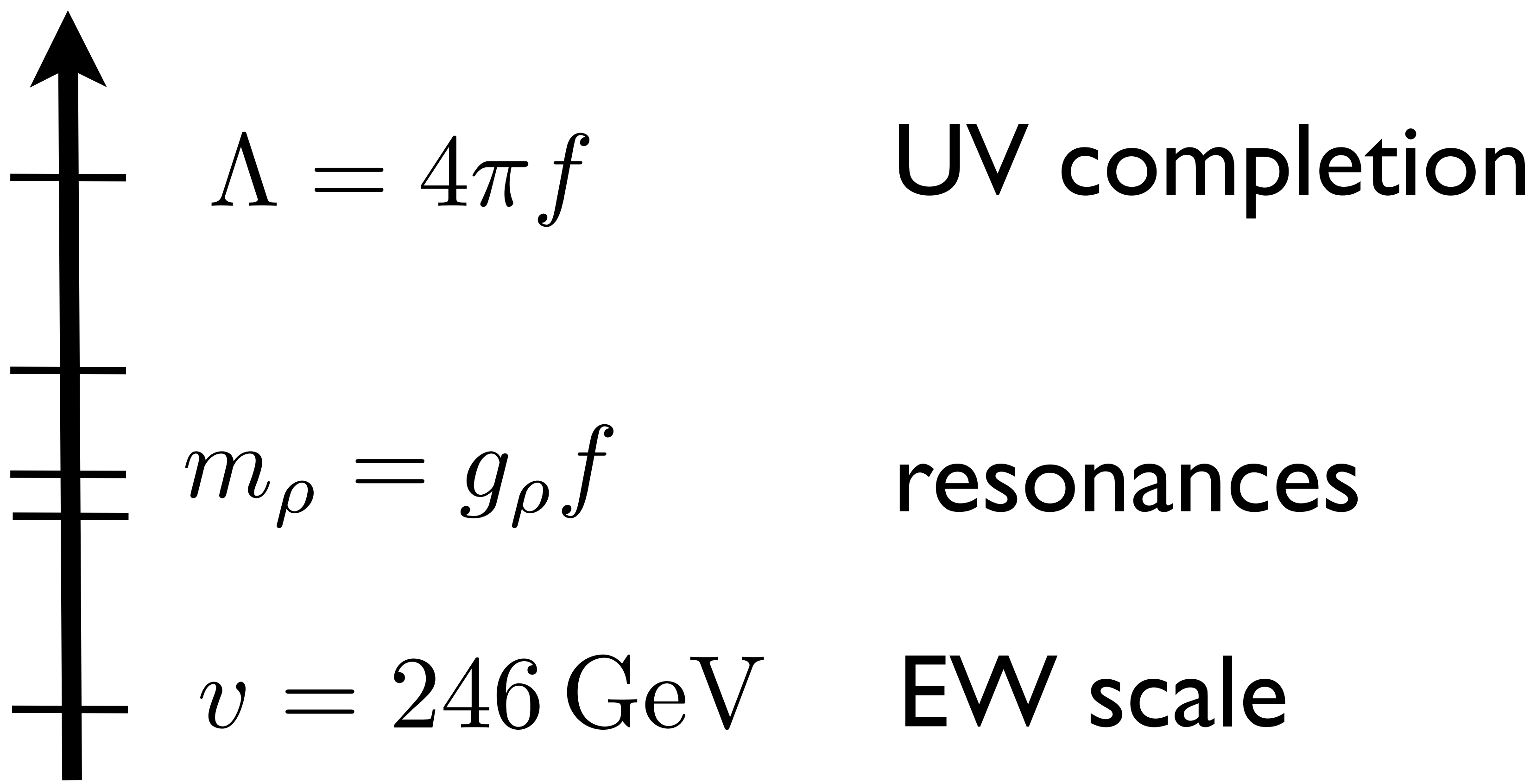
$$\Rightarrow \quad \boxed{\begin{array}{l}\sigma(x) \to \sigma(x) \\ \pi(x) \to \pi(x)+\alpha\end{array}}$$

Phase rotation becomes shift symmetry

$\pi(x)$ is massless **but** also no

- gauge couplings
- potential
- yukawas

Semi-realistic model


$\Lambda = 4\pi f$
UV completion
$m_\rho = g_\rho f$
resonances
$v = 246\,\mathrm{GeV}$
EW scale

pGB Higgs

$SU(3) \to SU(2)$

Break symmetry using $\quad \langle \Phi \rangle = \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix}$

Goldstone bosons = # broken generators

$$\Phi = \frac{1}{\sqrt{2}} e^{i\Pi/f} \begin{pmatrix} 0 \\ 0 \\ f + \sigma \end{pmatrix} \qquad \Pi = \frac{1}{\sqrt{2}} \begin{pmatrix} \eta/\sqrt{3} & 0 & H_1 \\ 0 & \eta/\sqrt{3} & H_2 \\ H_1^* & H_2^* & -2\eta/\sqrt{3} \end{pmatrix}$$

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Expand

$$\Phi(x) = \begin{pmatrix} H_1(x) \\ H_2(x) \\ -\frac{2}{\sqrt{2}}\eta(x) \end{pmatrix} + \ldots$$

Contains a Higgs: $H = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = SU(2)$ doublet

kinetic term:

$$\partial_\mu \Phi \partial^\mu \Phi^\dagger = \partial_\mu H \partial^\mu H^\dagger + \frac{(\partial_\mu H \partial^\mu H^\dagger) H^\dagger H}{f^2} + \ldots$$

Nonlinear corrections

$SU(3) \to SU(2)$

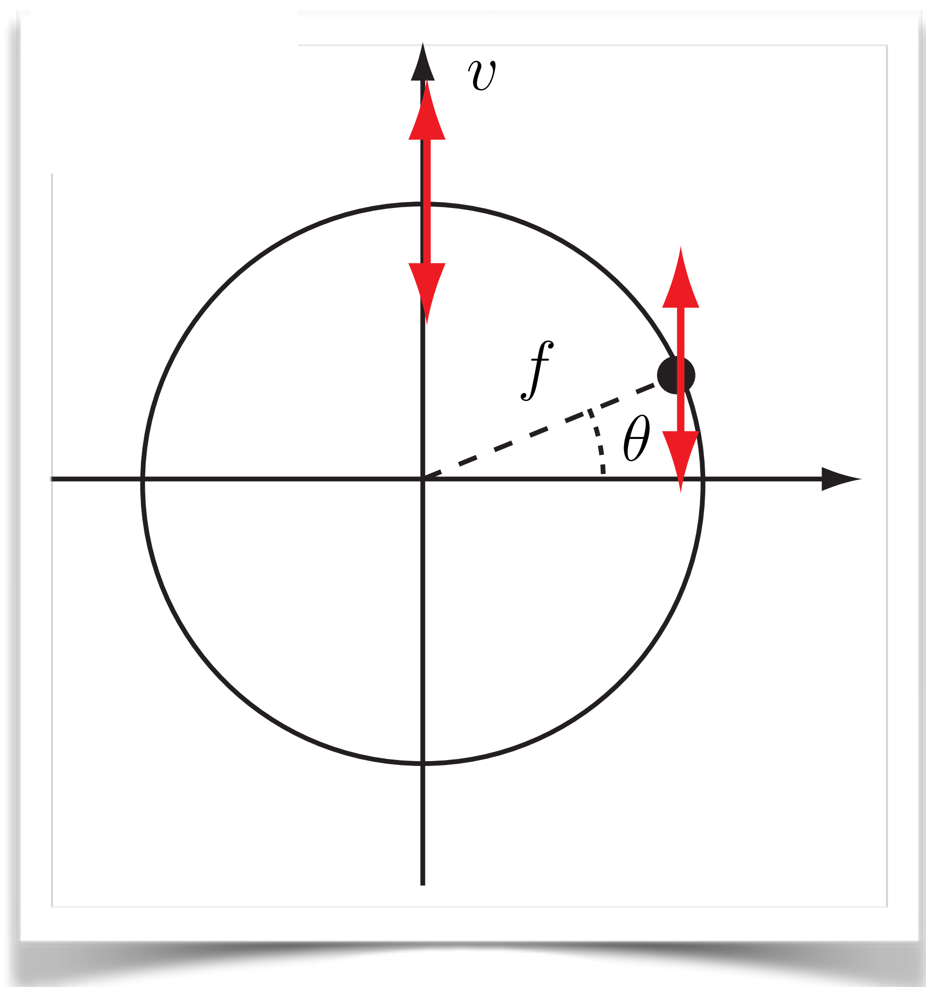
pGB Higgs

Unbroken gauge symmetry in global SU(2), dynamics generates ‘vacuum misalignment’

$SU(2)_L$ vs. SU(2)

$$\langle \Phi \rangle = \frac{f}{\sqrt{2}} \begin{pmatrix} \boxed{\begin{matrix} 0 \\ \sin\theta \end{matrix}} \\ \cos\theta \end{pmatrix} \quad SU(2)_L$$

EW symmetry broken



pGB Higgs

$$\langle \Phi \rangle = \frac{f}{\sqrt{2}} \begin{pmatrix} \boxed{\begin{matrix} 0 \\ \sin\theta \end{matrix}} \\ \cos\theta \end{pmatrix} \quad \text{SU(2)}_L$$

Electro-weak scale $v = f \sin\theta$

$f \sim$ scale of new physics

$\sin\theta \ll 1 \Leftrightarrow f \gg v$ (SM limit)

$$\Rightarrow \langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Collective Breaking

We now want to add a yukawa coupling to give mass to the top quark

$$\lambda_t \bar{Q}_i H_i^c t_R \qquad \text{i: sum over SU(2)}$$

Fundamental field is a triplet

$$\phi = \exp\left\{ i \begin{pmatrix} & & h_1 \\ & & h_2 \\ h_1^* & h_2^* & \end{pmatrix} \right\} \begin{pmatrix} \\ \\ f \end{pmatrix}$$

Top yukawa: 1st try

$$\sum_i^{2} \lambda_t \phi_i^c \bar{Q}_i t_R$$ works, gives mass to the top

… but breaks SU(3) structure explicitly, does not respect Goldstone symmetry protecting the Higgs mass:

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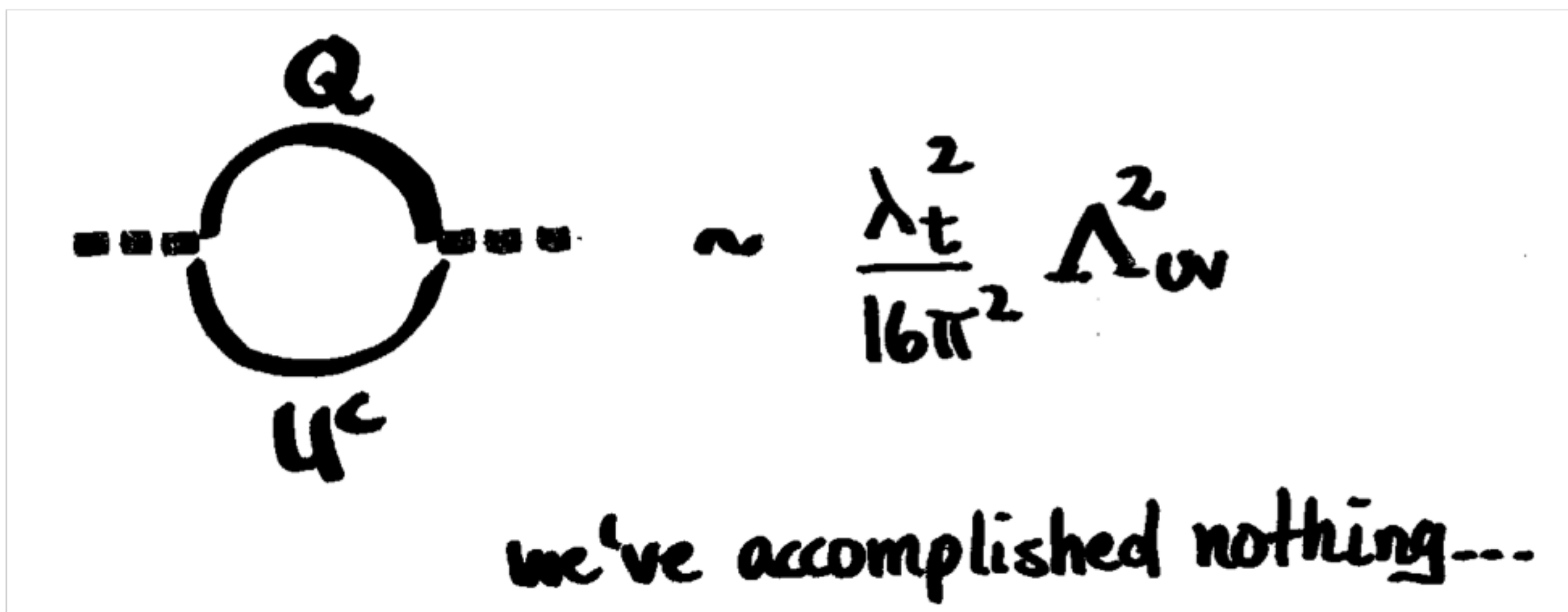

2nd try: "collective breaking"

Example: $SU(3) \to SU(2)$ (ignore $U(1)_Y$ again)

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ f_1 \end{pmatrix} \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ f_2 \end{pmatrix}$$

two scalar fields!

Gauge full $SU(3)$ ⇒ exact symmetry

$$\Psi_L = \begin{pmatrix} t_L \\ b_L \\ T_L \end{pmatrix} \qquad t_{1R},\ t_{2R},\ b_R$$

Global rotations ($SU(3)_1$ x $SU(3)_2$):

$$\Phi_1 \to U_1 \Phi_1$$

$$\Phi_2 \to U_2 \Phi_2$$

Gauge symmetry ($SU(3)_{1+2}$):

$$\Psi_L \to U_{1+2}(x) \Psi_L$$

$y_1 = 0,\ y_2 \neq 0$	$SU(3)_{1+2}$	$SU(3)_2$
$y_1 \neq 0,\ y_2 = 0$	$SU(3)_1$	$SU(3)_{1+2}$
$y_1 \neq 0,\ y_2 \neq 0$	$SU(3)_{1+2}$	

If only one y_1 or y_2 is present, then two SU(3)'s survive, one for the gauge bosons (eating the goldstones of one Φ_i) and one global SU(3) guaranteeing that the Yukawa does not contribute to Goldstone mass.

If both y_1 and y_2 present, then only one SU(3) present, and the goldstones of one combination of Φ_1 and Φ_2 are eaten, the other combination gets a mass from the Yukawa.

$$\mathcal{L}_{\text{Yukawa}} = y_1 \bar{\Psi}_L \Phi_1 t_{1R} + y_2 \bar{\Psi}_L \Phi_2 t_{2R}$$

$y_1 = 0,\ y_2 \neq 0$	$SU(3)_{1+2}$	$SU(3)_2$
$y_1 \neq 0,\ y_2 = 0$	$SU(3)_1$	$SU(3)_{1+2}$
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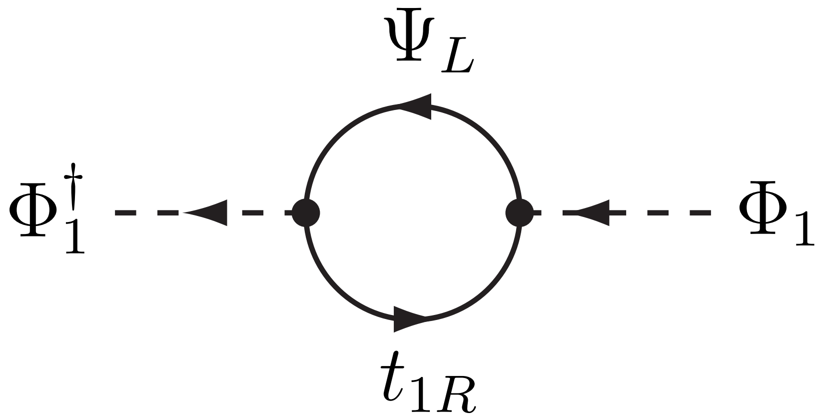
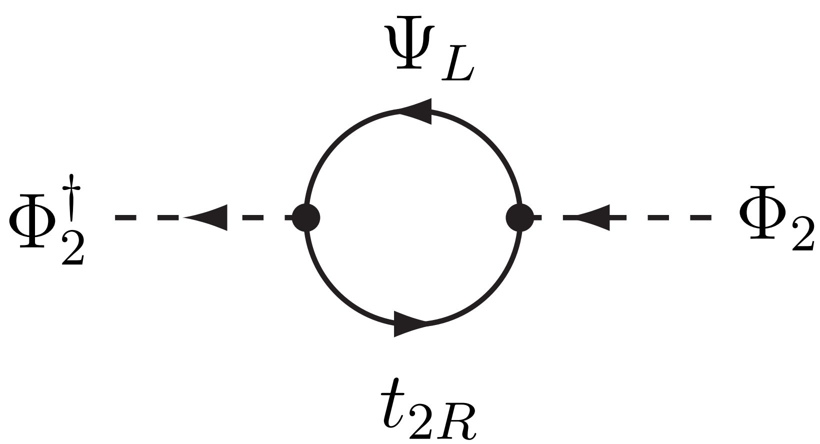


$$\sim \underbrace{\frac{y_1^2}{16\pi^2}\Lambda^2}$$

preserves $SU(3)_2 \to SU(2)_2$

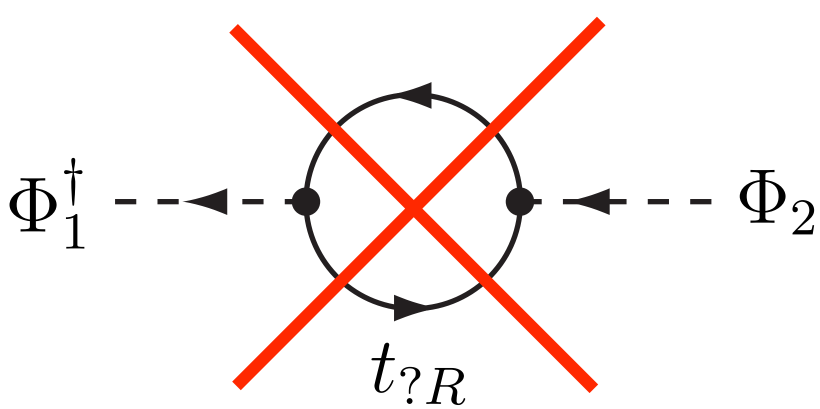
$\Rightarrow$ no PNGB Higgs mass



$$\sim \underbrace{\frac{y_2^2}{16\pi^2}\Lambda^2}$$

preserves $SU(3)_1 \to SU(2)_1$

$\Rightarrow$ no PNGB Higgs mass



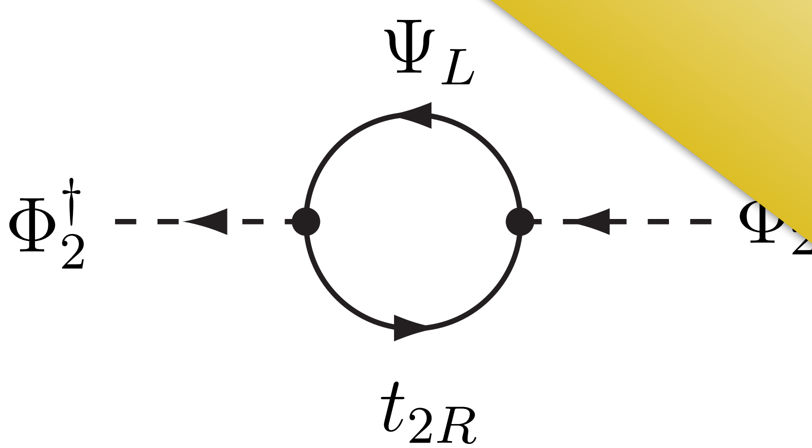
Not allowed

$\sim \underbrace{\frac{y_1^2}{16\pi^2}\Lambda^2}$

Predicts top-partners

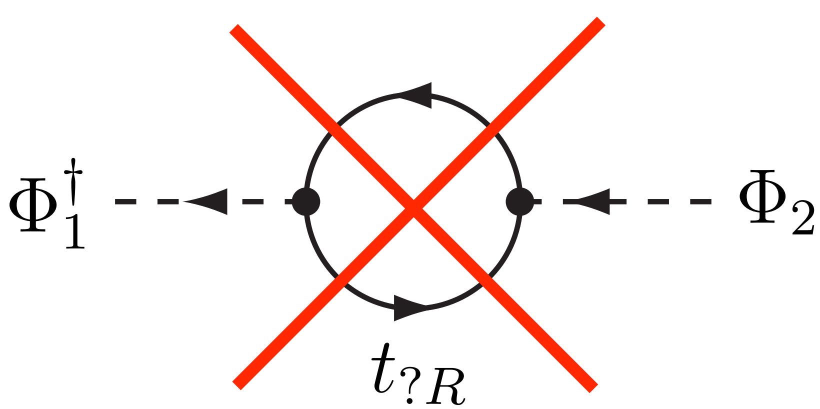
...erves $SU(3)_2 \to SU(2)_2$

...GB Higgs mass



pr... $\to SU(2)_1$

$\Rightarrow$ no ... gs mass



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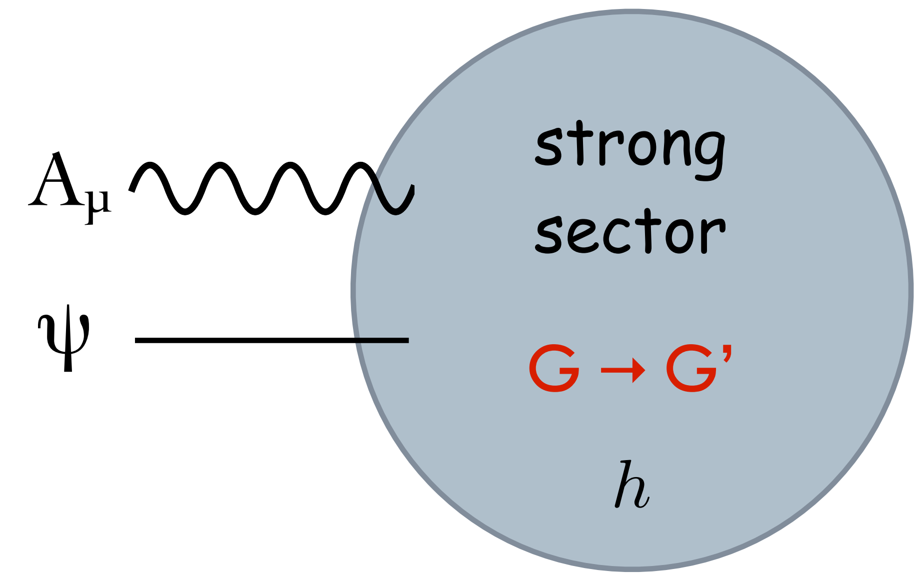
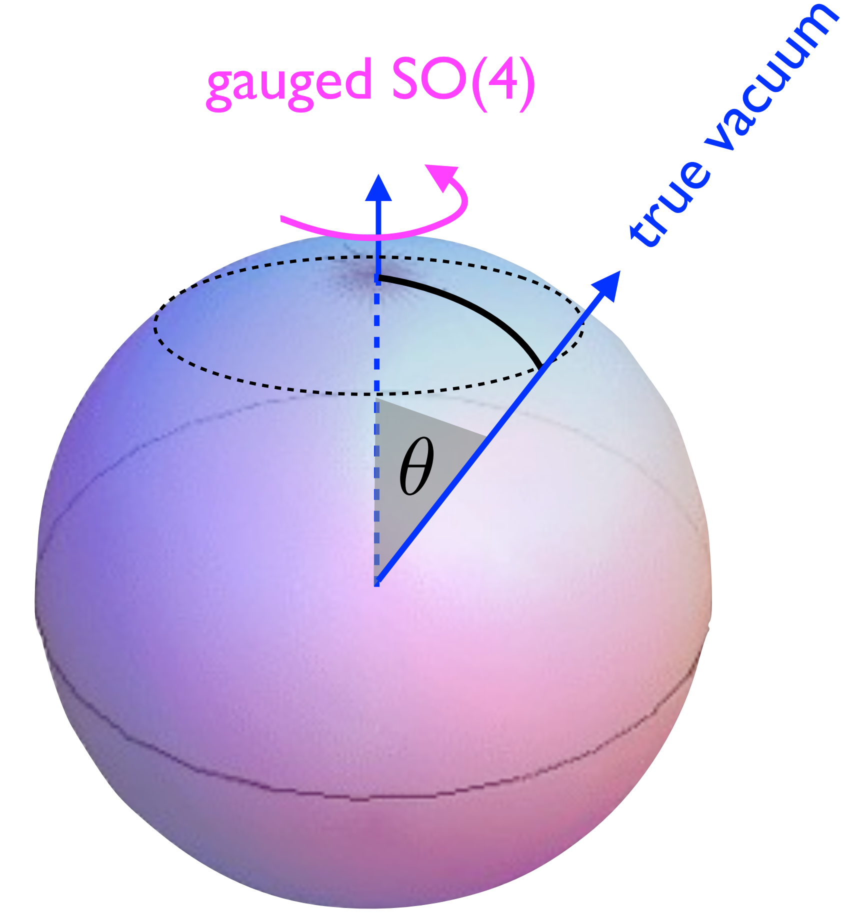
Minimal composite Higgs

Agashe et. al



Minimal bottom up construction

$$SO(5) \rightarrow SO(4) \sim SU(2)_L \times SU(2)_R$$



$SO(5)/SO(4)$

Tree level: gauge SO(4) aligned

Higgs

$$\phi = e^{i\pi^{\hat a}T^{\hat a}/f}\begin{pmatrix}0\\0\\0\\0\\1\end{pmatrix} = \begin{pmatrix}\sin(\pi/f)\times\begin{pmatrix}\hat\pi^1\\ \hat\pi^2\\ \hat\pi^3\\ \hat\pi^4\end{pmatrix}\\ \cos(\pi/f)\end{pmatrix} = \begin{pmatrix}\sin(\theta+h(x)/f)\; e^{i\chi^i(x)A^i/v}\begin{pmatrix}0\\0\\0\\1\end{pmatrix}\\ \cos(\theta+h(x)/f)\end{pmatrix}$$

1-loop $\langle\phi(x)\rangle = \theta\cdot f$

eaten by W_L, Z_L

Implications of m_H = 125 GeV

Agashe et. al

Potential is fully radiatively generated

$$V_{gauge}(h) = \frac{9}{2}\int\frac{d^4p}{(2\pi)^4}\log\left(\Pi_0(p) + \frac{s_h^2}{4}\Pi_1(p)\right) \qquad s_h \equiv \sin h/f$$

$$\Pi_0(p) = \frac{p^2}{g^2} + \Pi_a(p)\ , \qquad \Pi_1(p) = 2\big[\Pi_{\hat{a}}(p) - \Pi_a(p)\big]$$

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$$\int d^4p\, \Pi_1(p)/\Pi_0(p) \quad < \infty$$

Higgs dependent term UV finite

Implications of m$_H$ = 125 GeV

Agashe et. al

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Higgs dependent term
UV finite

→ 'Weinberg sum rules'

$$\lim_{p^2\to\infty}\Pi_1(p) = 0\ , \qquad \lim_{p^2\to\infty}p^2\Pi_1(p) = 0$$

UV finiteness requires at least two resonances

$$\Pi_1(p) = \frac{f^2 m_\rho^2 m_{a_1}^2}{(p^2 + m_\rho^2)(p^2 + m_{a_1}^2)} \qquad \text{spin 1}$$

UV finiteness requires at least two resonances

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Similarly for SO(5) fermionic contribution

Pomarol et al; Marzocca

$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

similar result in deconstruction:
Matsedonskyi et al; Redi et al

5 = 4 + 1 with EM charges 5/3, 2/3,-1/3

Q_4 Q_1

→ solve for m_h = 125 GeV

Light Higgs implies light fermionic top partners

$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

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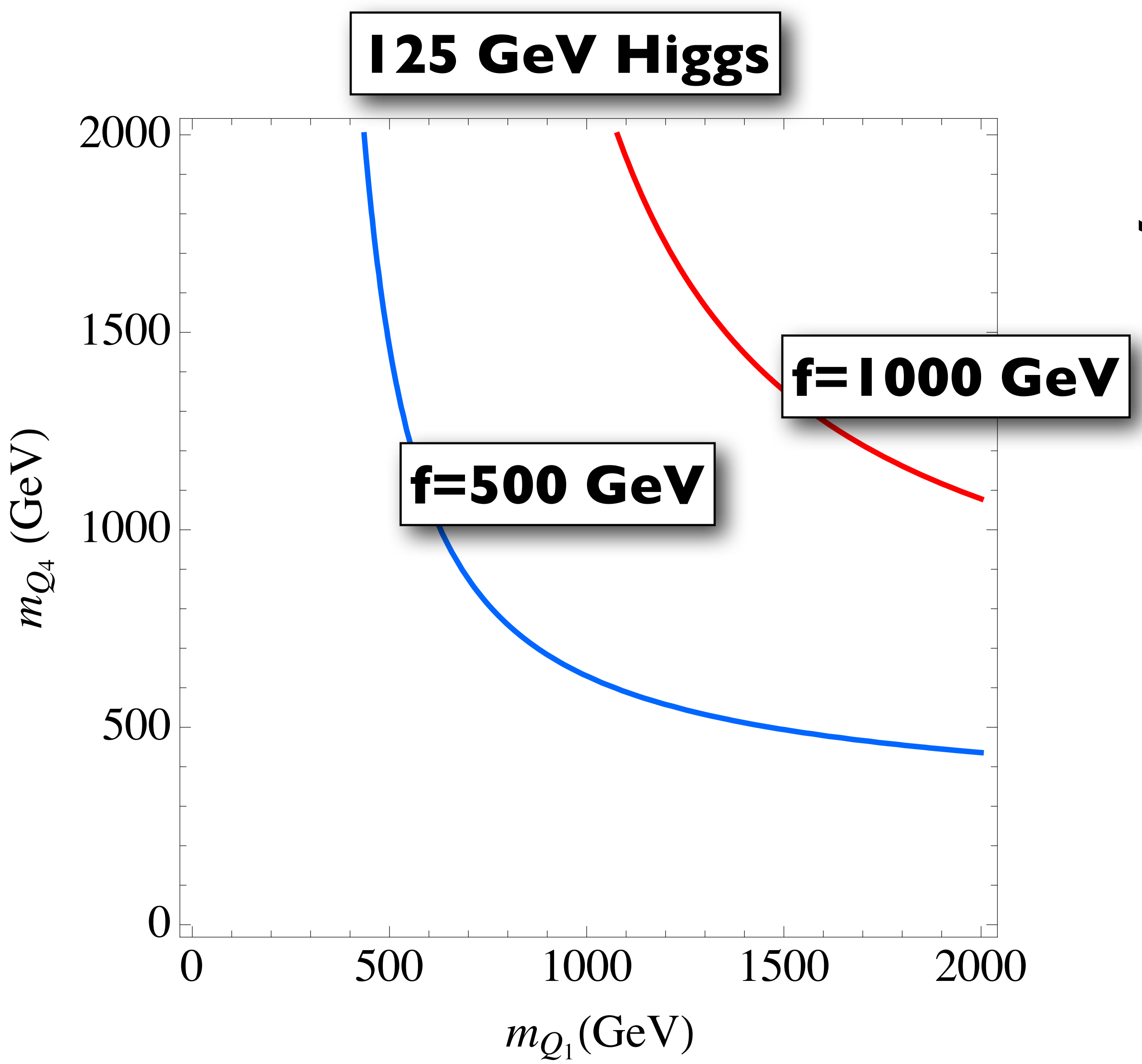

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Contino et al; Pomarol, Riva;
Matsedonskyi,Panico,Wulzer; Redi,Tesi;
Marzocca,Serone,Shu;

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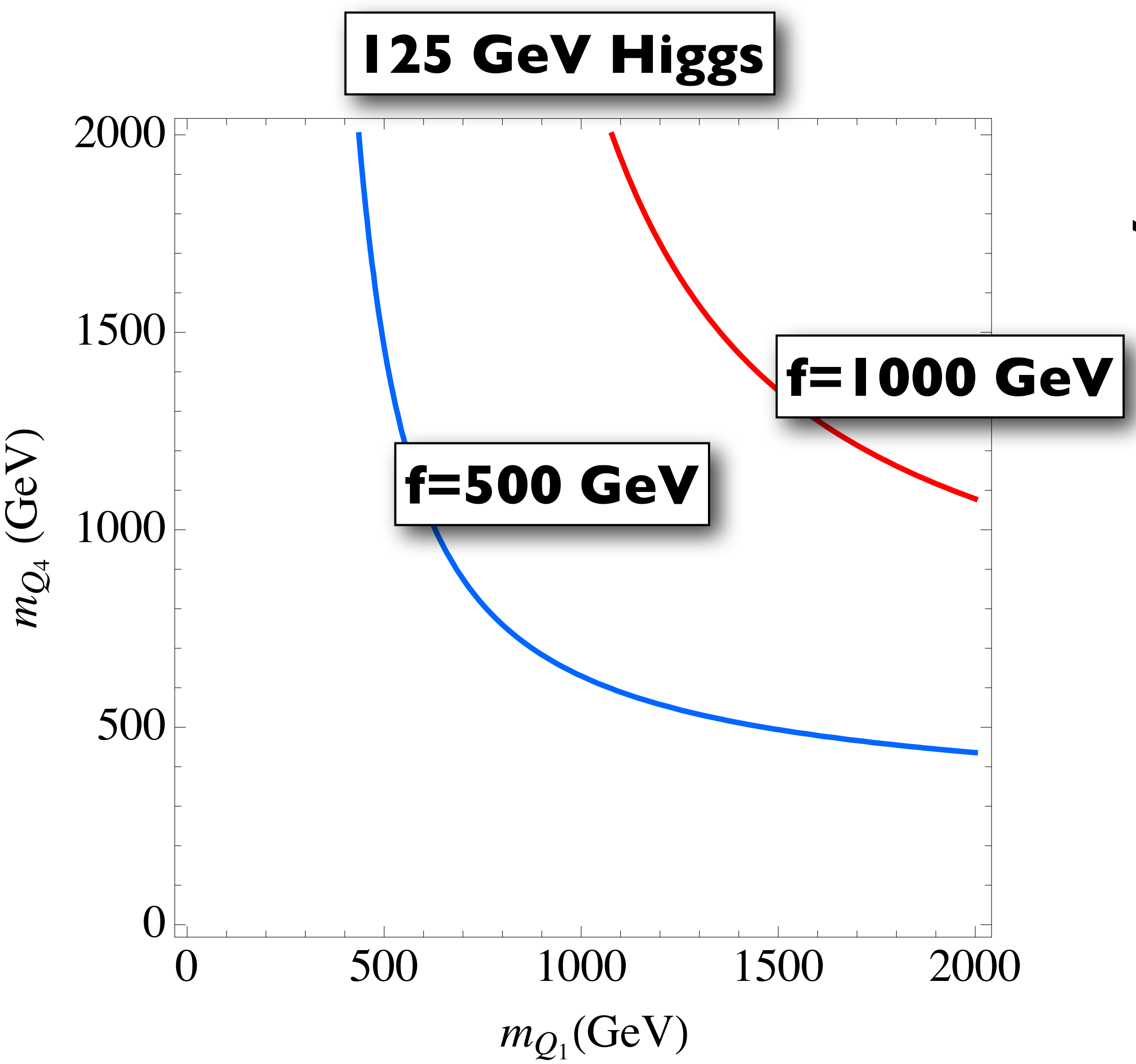

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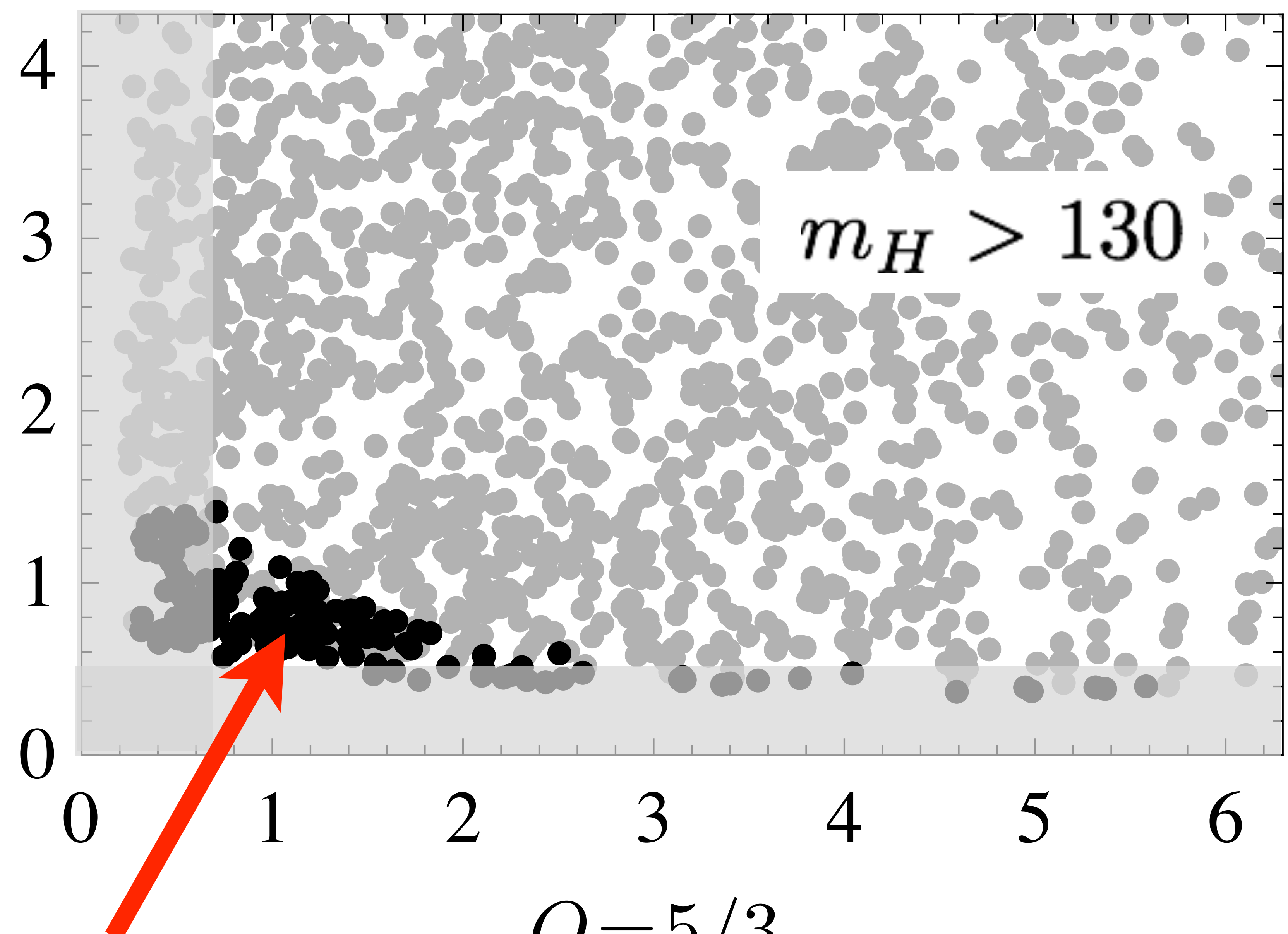
Contino et al; Pomarol, Riva; Matsedonskyi,Panico,Wulzer; Redi,Tesi; Marzocca,Serone,Shu;

Scan over composite Higgs parameter space

$\xi = 0.2$

from 1204.6333

$Q = 2/3$



$Q = 5/3$

m_H = 115 … 130 GeV

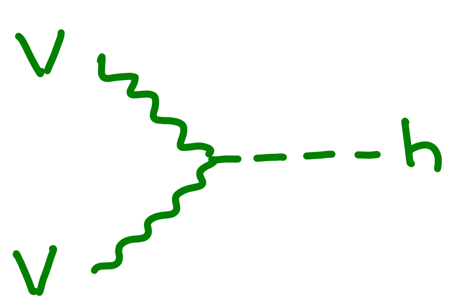
see e.g. ATLAS-CONF-2013-051

Deviations from SM Higgs

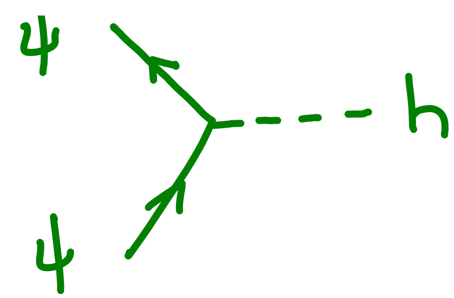
Goldstone boson nature

$$f^2\left|\partial_\mu\, e^{i\pi/f}\right|^2 = |D_\mu H|^2 + \frac{c_H}{2f^2}\left[\partial_\mu(H^\dagger H)\right]^2 + \frac{c'_H}{2f^4}(H^\dagger H)\left[\partial_\mu(H^\dagger H)\right]^2 + \dots$$

Giudice et al. JHEP 0706 (2007) 045

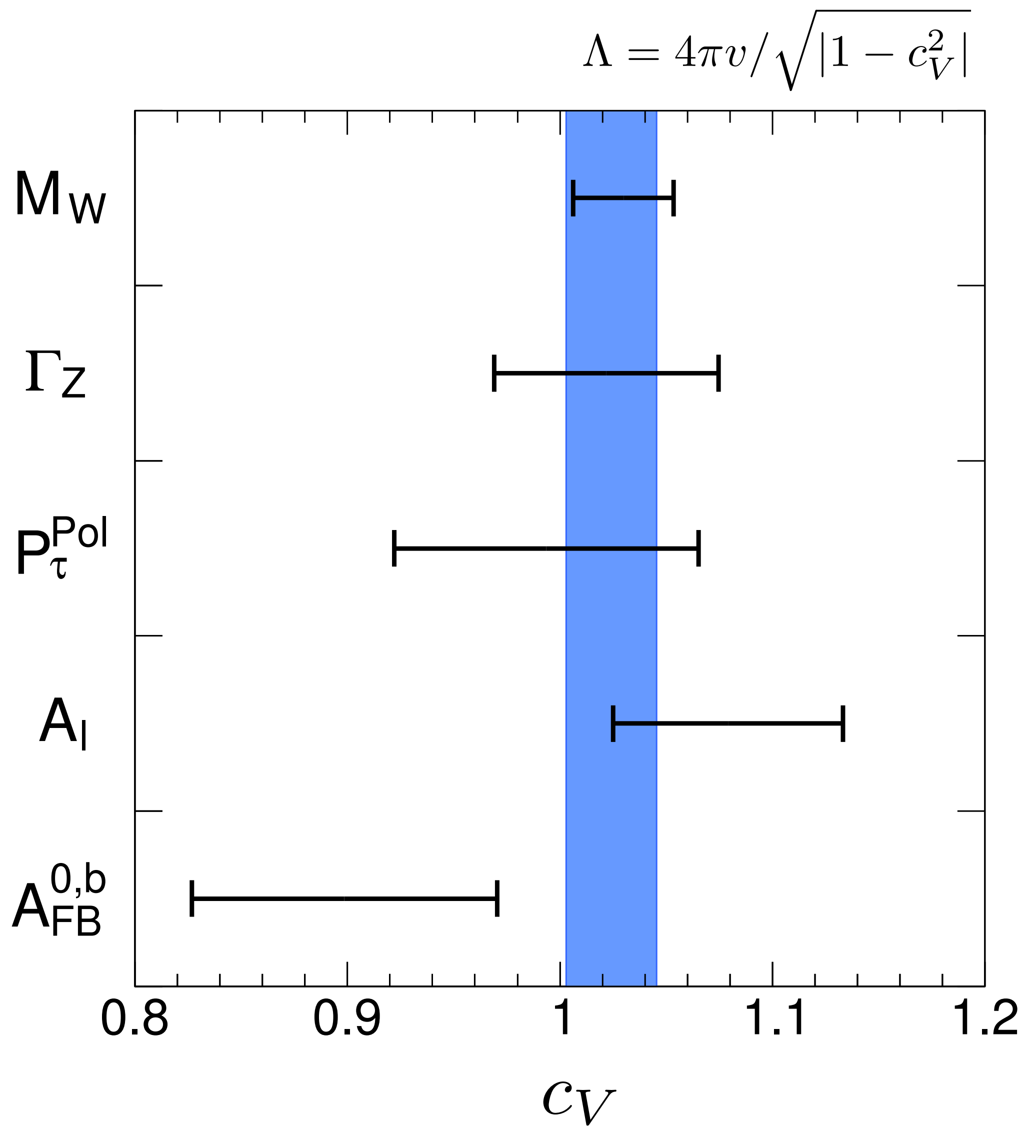


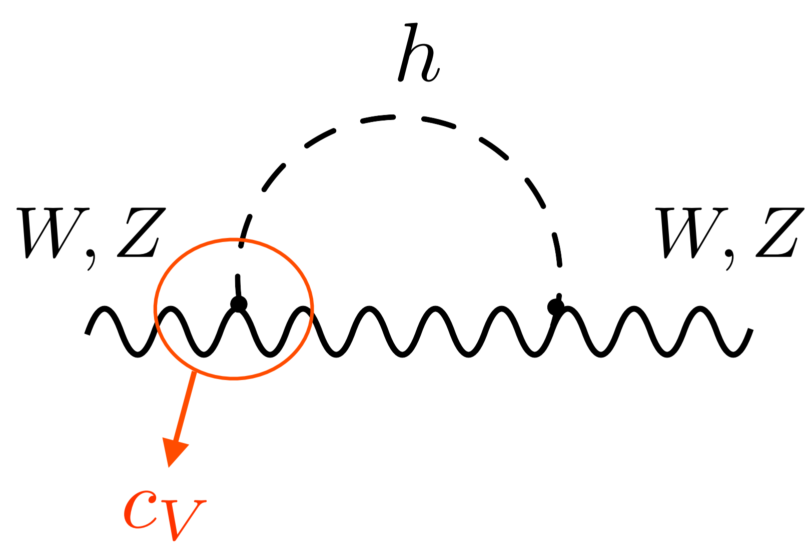
$a\, g^{SM}_{hVV}$



$c\, h^{SM}_{\psi\psi h}$

EW precision tests

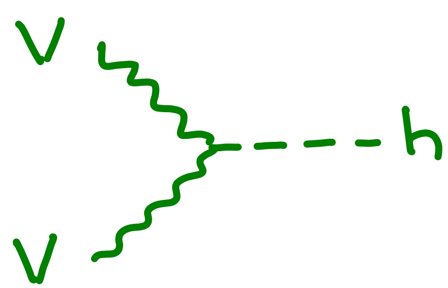




Ciuchini, Franco, Silvestrini, Mishima, arXiv:1306.4644

Higgs couplings

Have been measured to 20-30% precision



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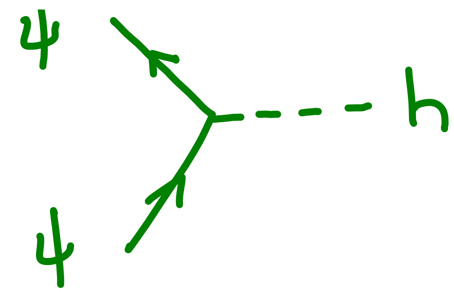


$c \, h^{SM}_{\psi\psi h}$

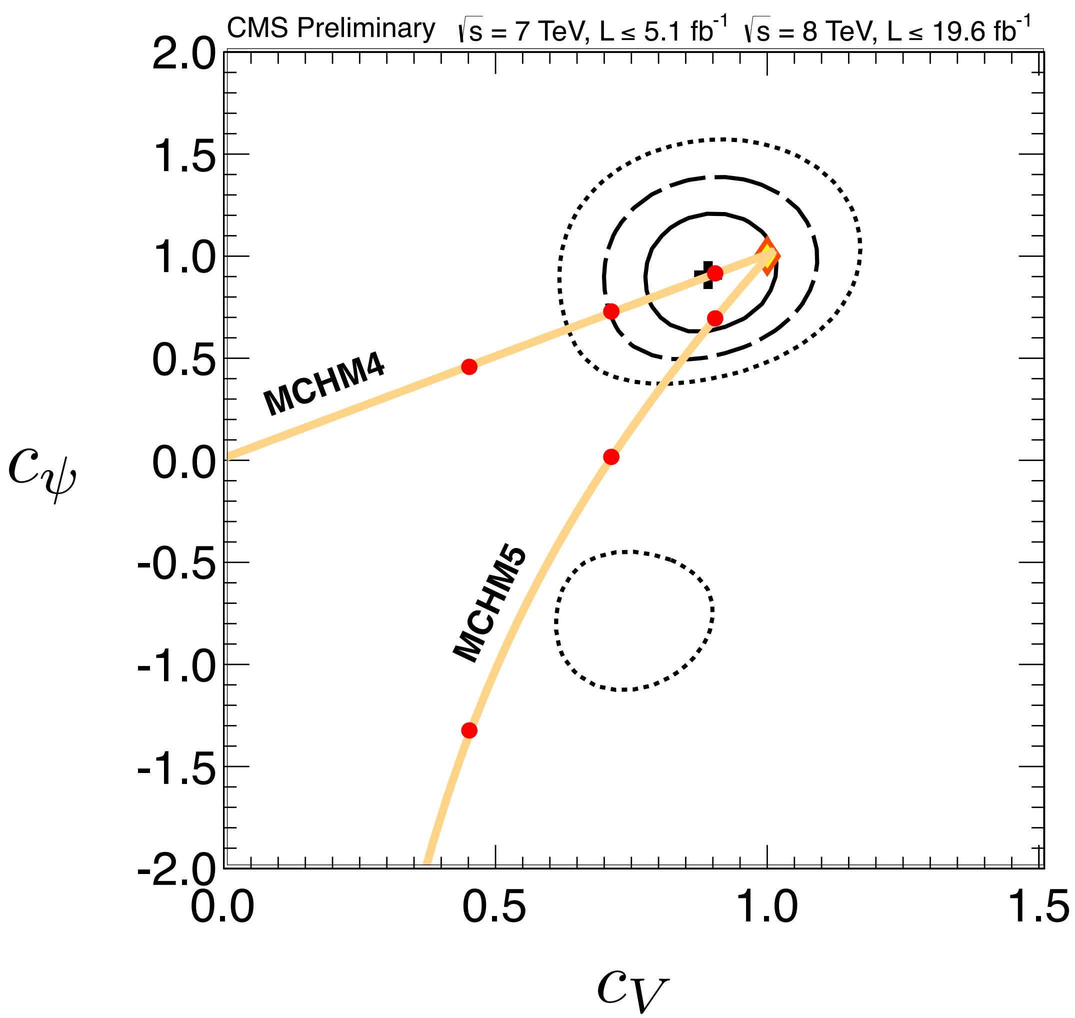
Expect deviations ~ (v/f)^2

$$\xi \equiv \frac{v^2}{f^2}$$

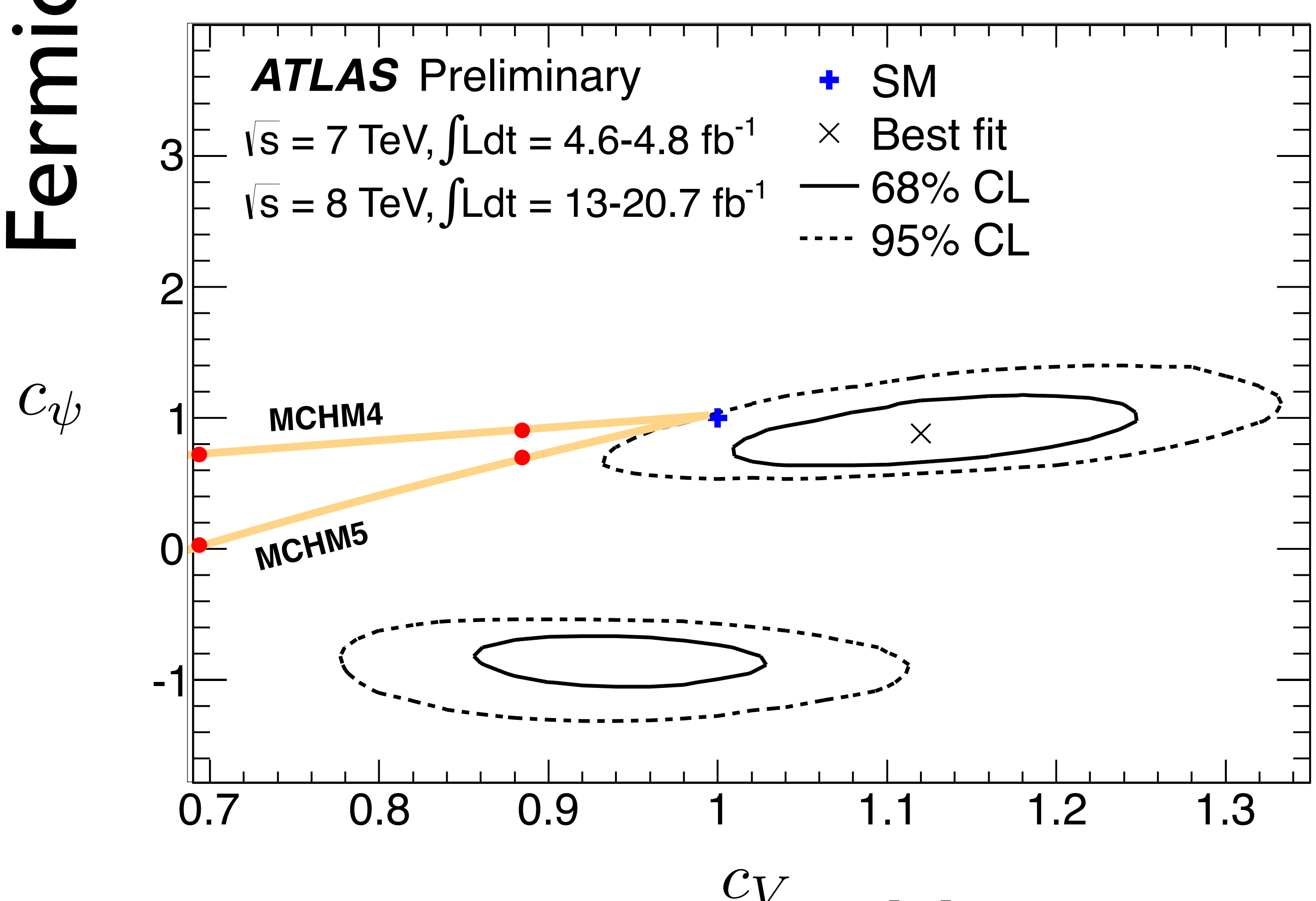
$$a = \sqrt{1-\xi}$$

$$c_f = \frac{1-(1+n)\xi}{1-\xi}$$

Higgs couplings



Fermion



Vector

Red points at $\xi \equiv (v/f)^2 = 0.2,\ 0.5,\ 0.8$

New physics & naturalness

Light Higgs

?

light stops$_{1,2}$, sbottom$_L$, higgsinos, gluinos, . . .

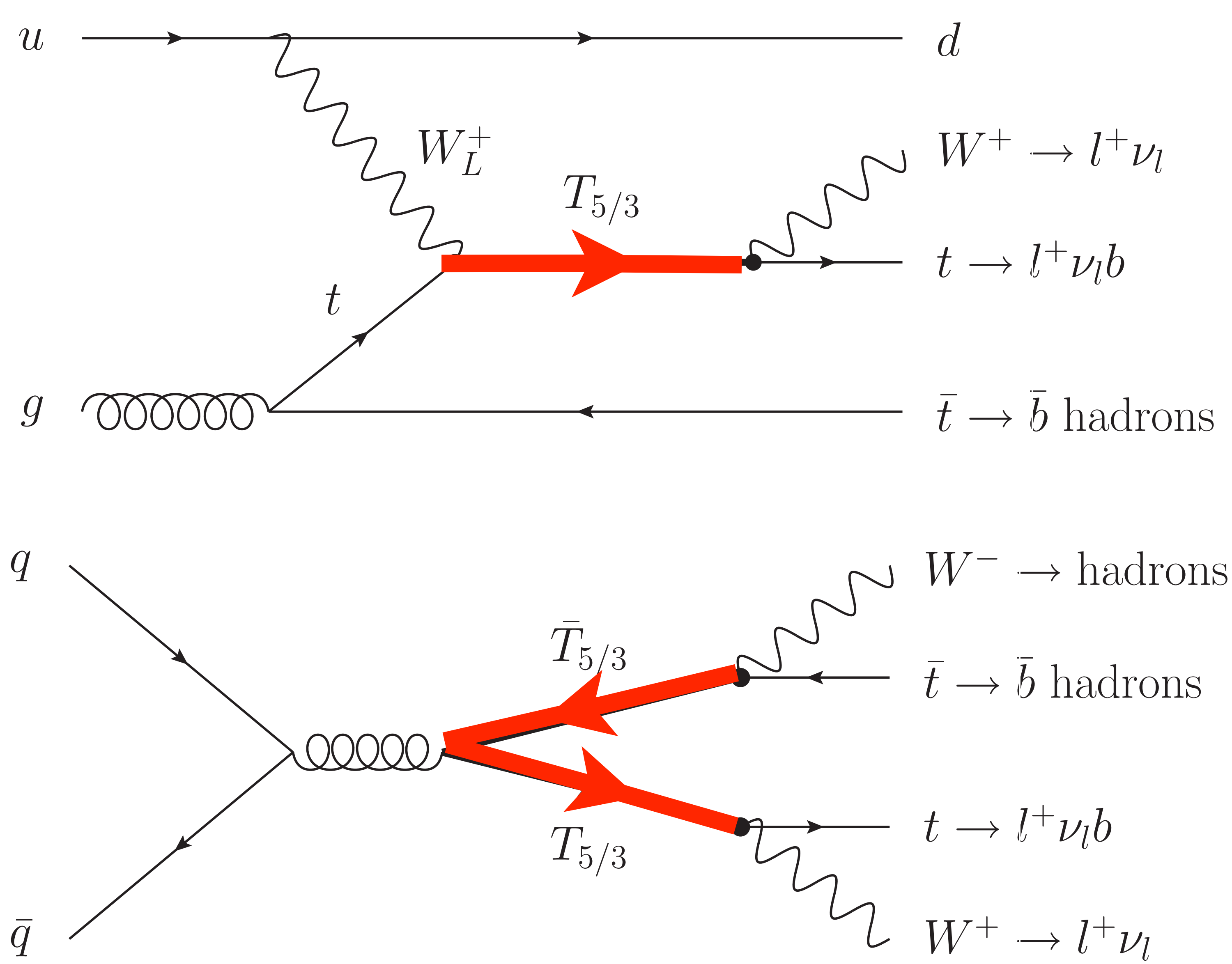
supersymmetry

light top partners (Q=5/3,2/3,1/3), anything else ?

composite Higgs

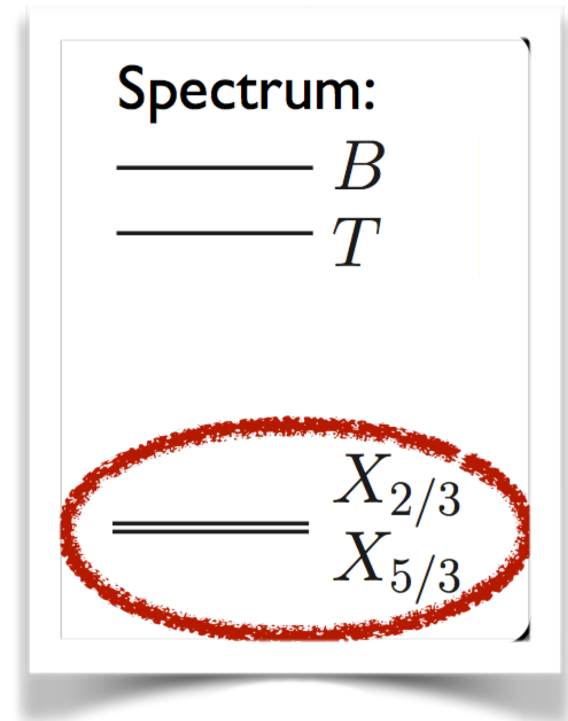
$T_{5/3}$

e.g. Perelstein, Pierce, Peskin
Contino, Servant; Mrazek, Wulzer;
De Simone, Matsedonkyi, Rattazzi, Wulzer



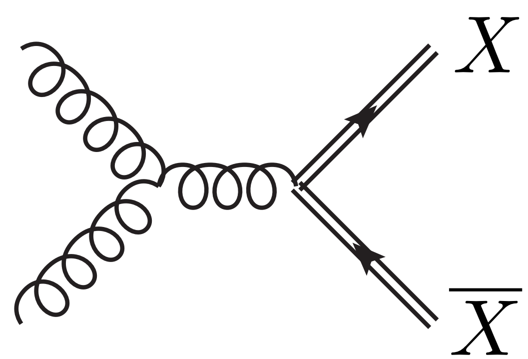
Single

Double

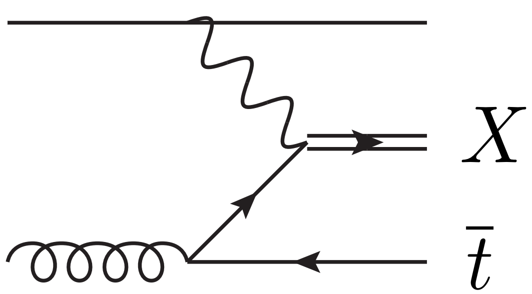


Phenomenology

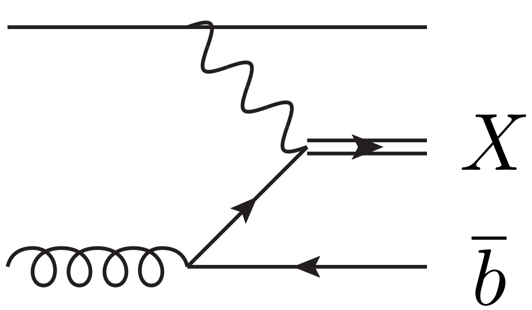
Three possible production mechanisms



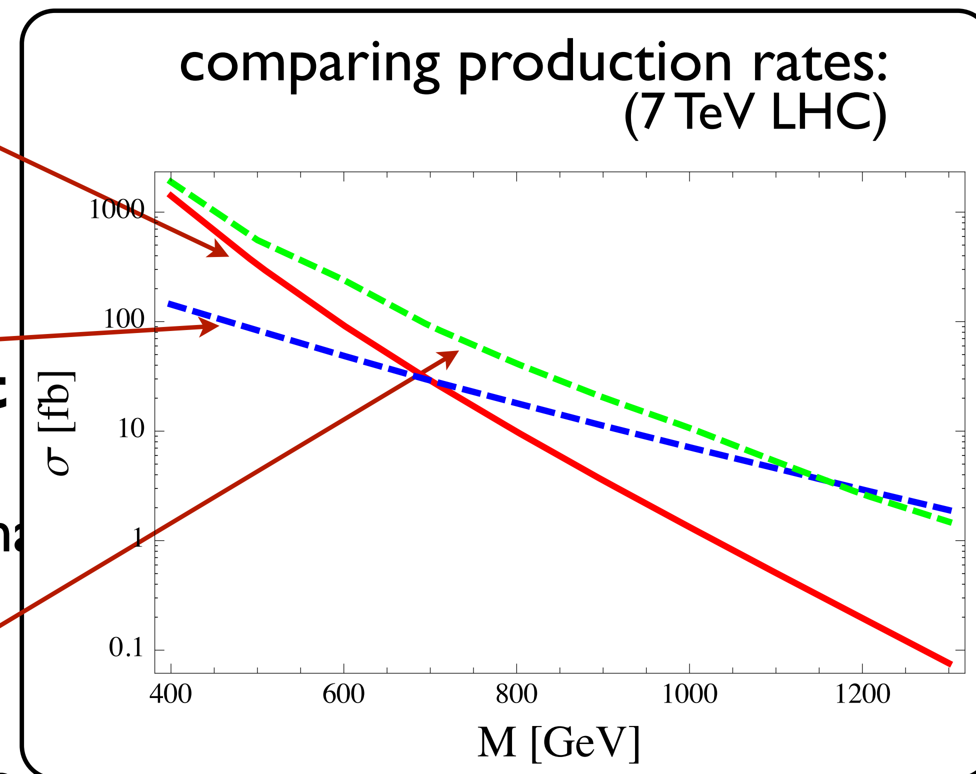
QCD **pair prod**.
model indep.,
relevant at low mass



single prod. with **t**
model dep. coupling
pdf-favored at high ma



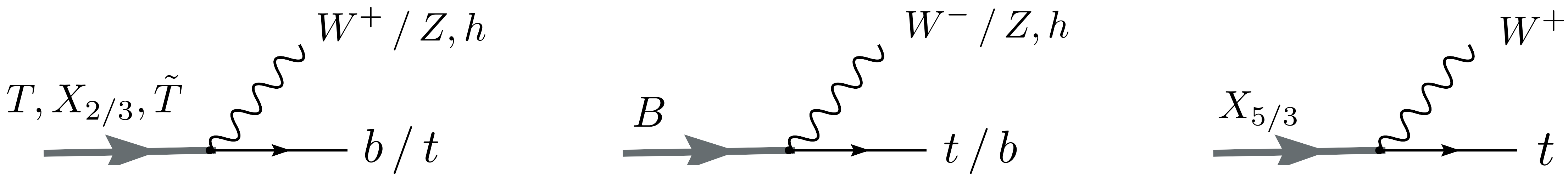
single prod. with **b**
favored by small b mass
dominant when allowed

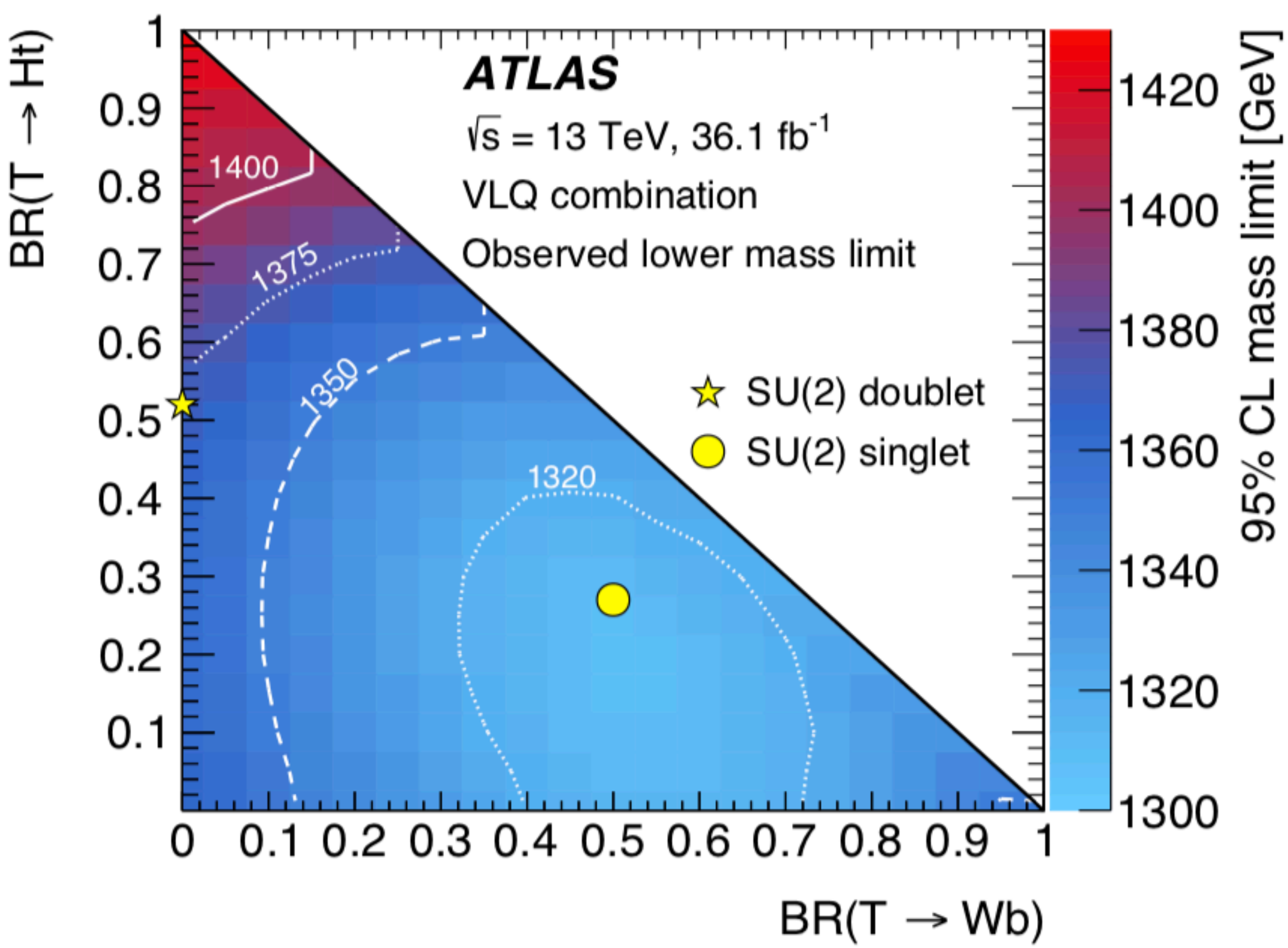


27

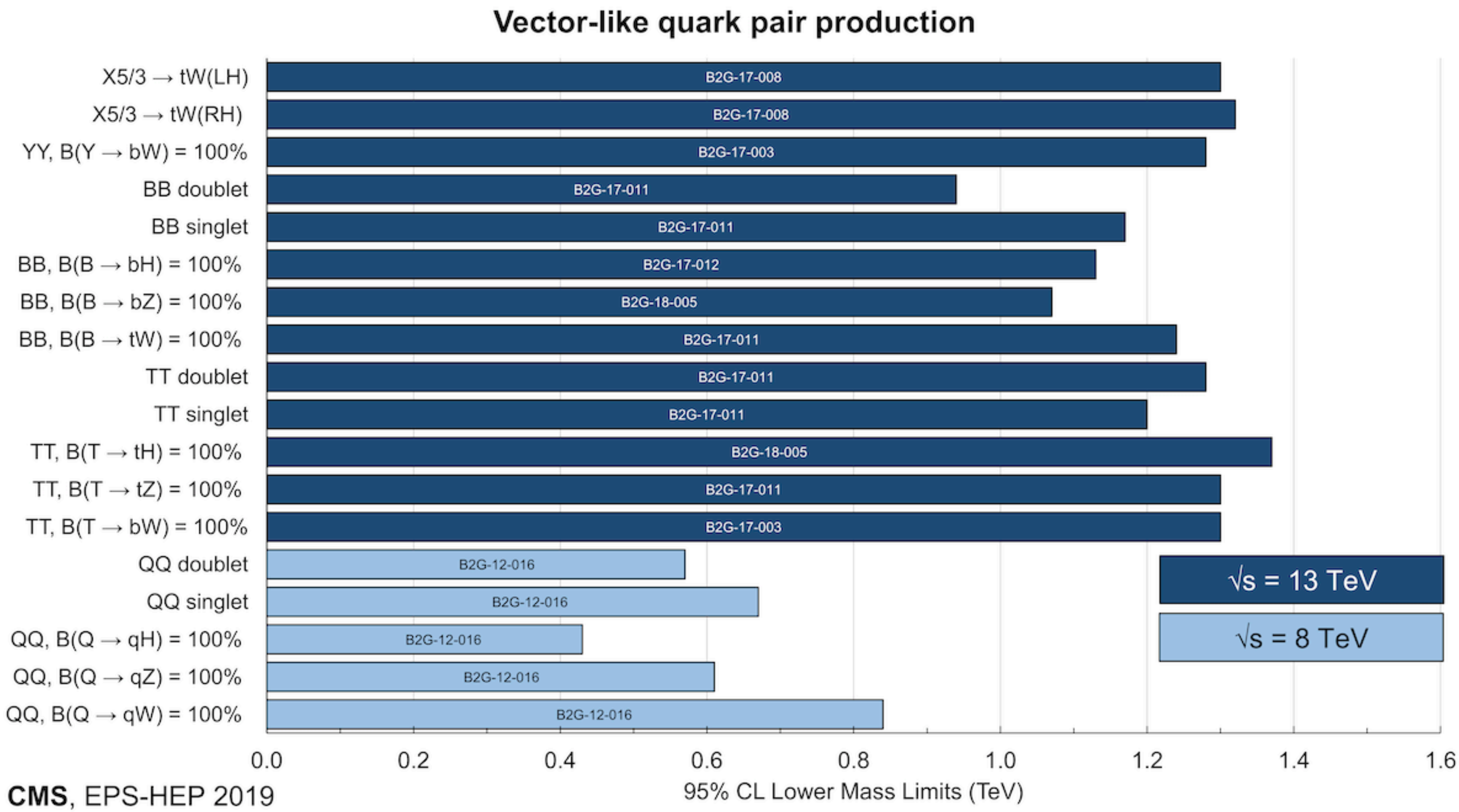
slide by A. Wulzer

Decay modes





Current limits > 1300 GeV


Vector-like quark pair production
X5/3 → tW(LH)
X5/3 → tW(RH)
YY, B(Y → bW) = 100%
BB doublet
BB singlet
BB, B(B → bH) = 100%
BB, B(B → bZ) = 100%
BB, B(B → tW) = 100%
TT doublet
TT singlet
TT, B(T → tH) = 100%
TT, B(T → tZ) = 100%
TT, B(T → bW) = 100%
QQ doublet
QQ singlet
QQ, B(Q → qH) = 100%
QQ, B(Q → qZ) = 100%
QQ, B(Q → qW) = 100%
B2G-17-008
B2G-17-008
B2G-17-003
B2G-17-011
B2G-17-011
B2G-17-012
B2G-18-005
B2G-17-011
B2G-17-011
B2G-17-011
B2G-18-005
B2G-17-011
B2G-17-003
B2G-12-016
B2G-12-016
B2G-12-016
B2G-12-016
B2G-12-016
√s = 13 TeV
√s = 8 TeV
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
95% CL Lower Mass Limits (TeV)
CMS, EPS-HEP 2019

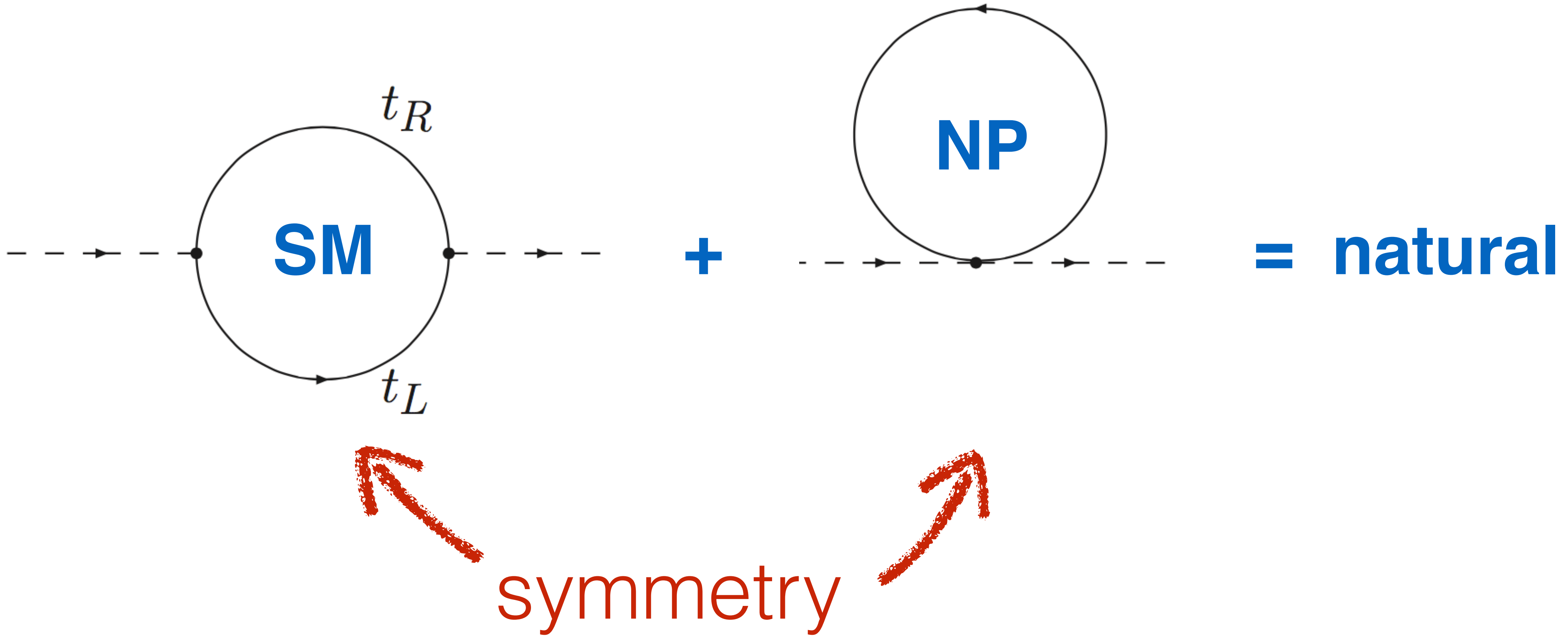
New ideas

twin Higgs

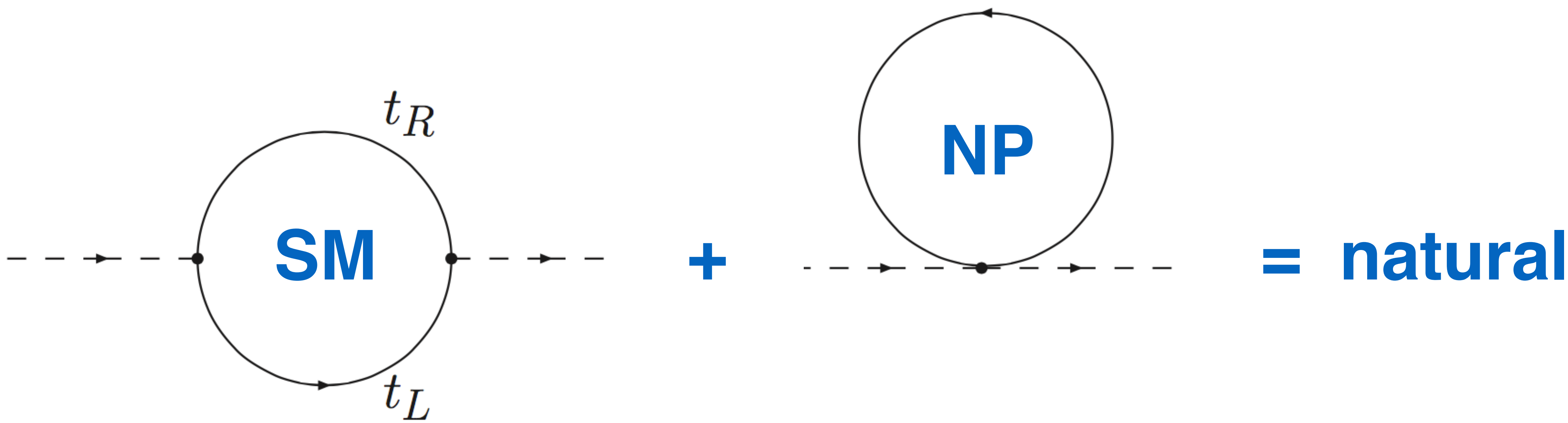
Relaxion

ION

No lose for naturalness?



No lose for naturalness?

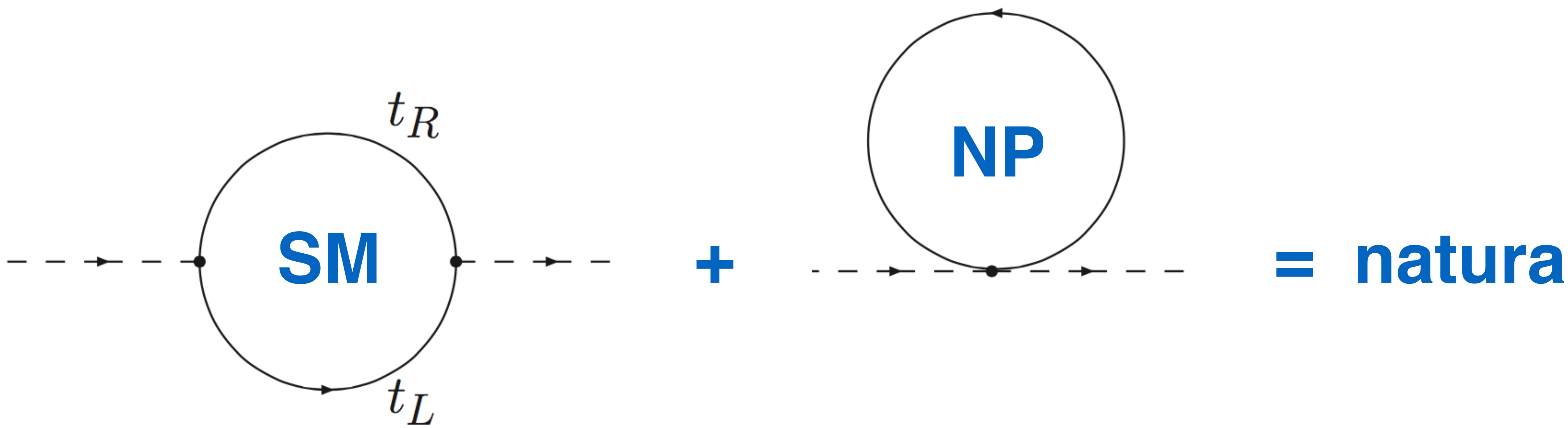


symmetry

NP is related to the top by a symmetry, natural new particle mass around TeV

Symmetry commutes with color: will be produced copiously at the LHC!

No lose for naturalness?



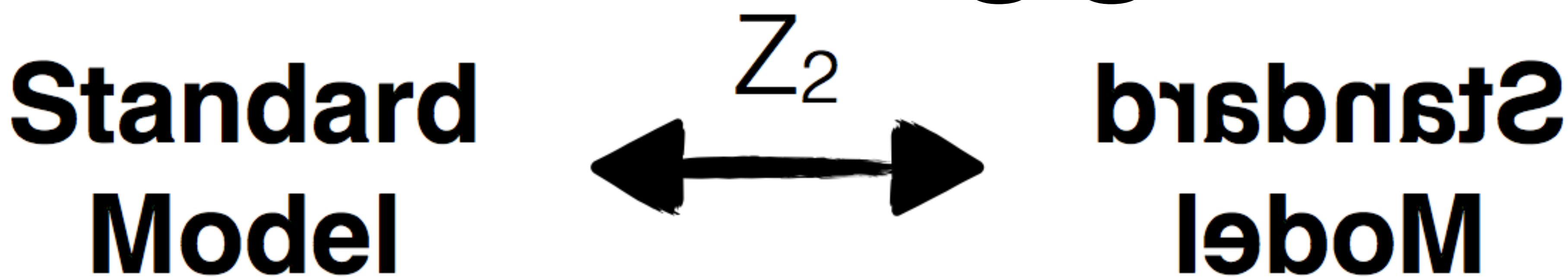
symmetry

NP is related to the top by a symmetry, natural new particle mass around TeV

Symmetry … s with color: … uced copious … he LHC!

Not true!

Twin Higgs



$SU(2)_L$ $\qquad\qquad$ $SU(2)_{\rm twin}$

Quadratic divergences from SM top quark loops cancelled by loops of “Twin” top quarks.

Twin Higgs

Standard Model $\xleftrightarrow{Z_2}$ **Standard Model**

$SU(2)_L$ $\qquad$ $SU(2)_{\text{twin}}$

Quadratic divergences from SM top quark loops cancelled by loops of "Twin" top quarks.

Global Symmetry → Twin Higgs

Chacko
Goh
Harnik
2005

Super-Symmetry → Folded SUSY

Burdmann
Chacko
Goh
Harnik
2006

Under the gauge symmetry,

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$

where H_A will eventually be identified with the Standard Model Higgs, while H_B is its `twin partner'.

Now the Higgs potential receives radiative corrections from gauge fields

$$\Delta V(H) = \frac{9 g_A^2 \Lambda^2}{64\pi^2} H_A^\dagger H_A + \frac{9 g_B^2 \Lambda^2}{64\pi^2} H_B^\dagger H_B$$

Impose a Z_2 `twin' symmetry under which A $\leftrightarrow$ B. Then $g_A = g_B = g$. Then the radiative corrections take the form

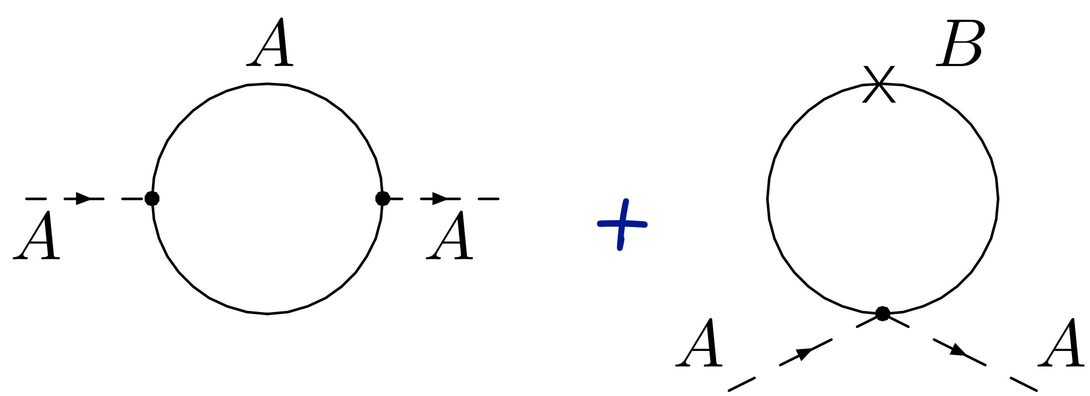
$$\Delta V = \frac{9 g^2 \Lambda^2}{64\pi^2} (H_A^\dagger H_A + H_B^\dagger H_B)$$

This is U(4) invariant and cannot give a mass to the Goldstones!

Parity symmetry enforces y_t same

$$\mathcal{L} \supset y_t H_A \bar{t}_A t_A + y_t H_B \bar{t}_B t_B$$

$$= y_t h\, \bar{t}_A t_A + y_t \left(f - \frac{|h|^2}{2f} \right) \bar{t}_B t_B + \ldots$$



Same coupling, but not same colour group for top and top partner! Still: little Higgs like cancellation.

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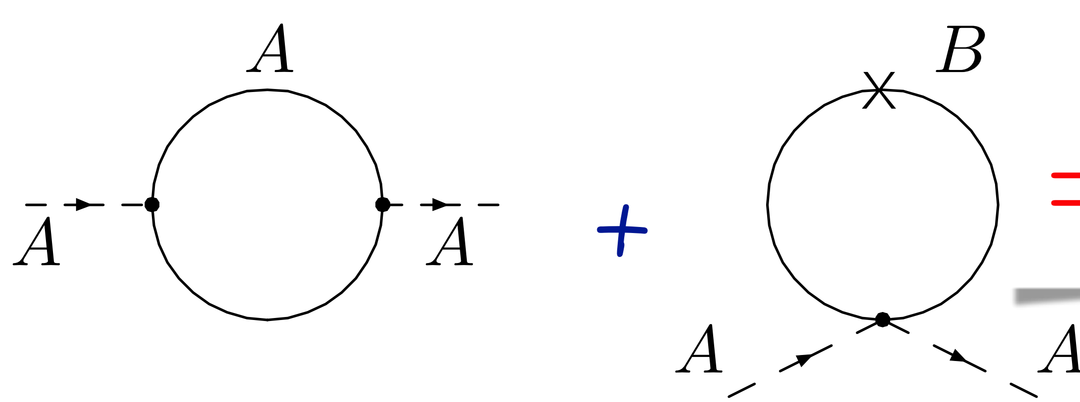


$$= 0 \times \Lambda^2$$

Same coupling, but not same colour group for top and top partner! Still: little Higgs like cancellation.

- Mirror sector is copy of SM, completely neutral under SM interactions

- Allowed interaction terms:

$$\lambda_{AB}|H_A|^2|H_B|^2$$ Higgs portal

$$\epsilon_{AB}F_{\mu\nu,A}F_B^{\mu\nu}$$ kinetic mixing portal

- Mirror sector is copy of SM, ~~completely neutral~~ under SM interactions

- Allowed interaction terms:

Hypercharged Naturalness

Javi Serra[a], Stefan Stelzl[a], Riccardo Torre[b,c], and Andreas Weiler[a]

[a] *Physik-Department, Technische Universität München, 85748 Garching, Germany*

[b] *Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland*

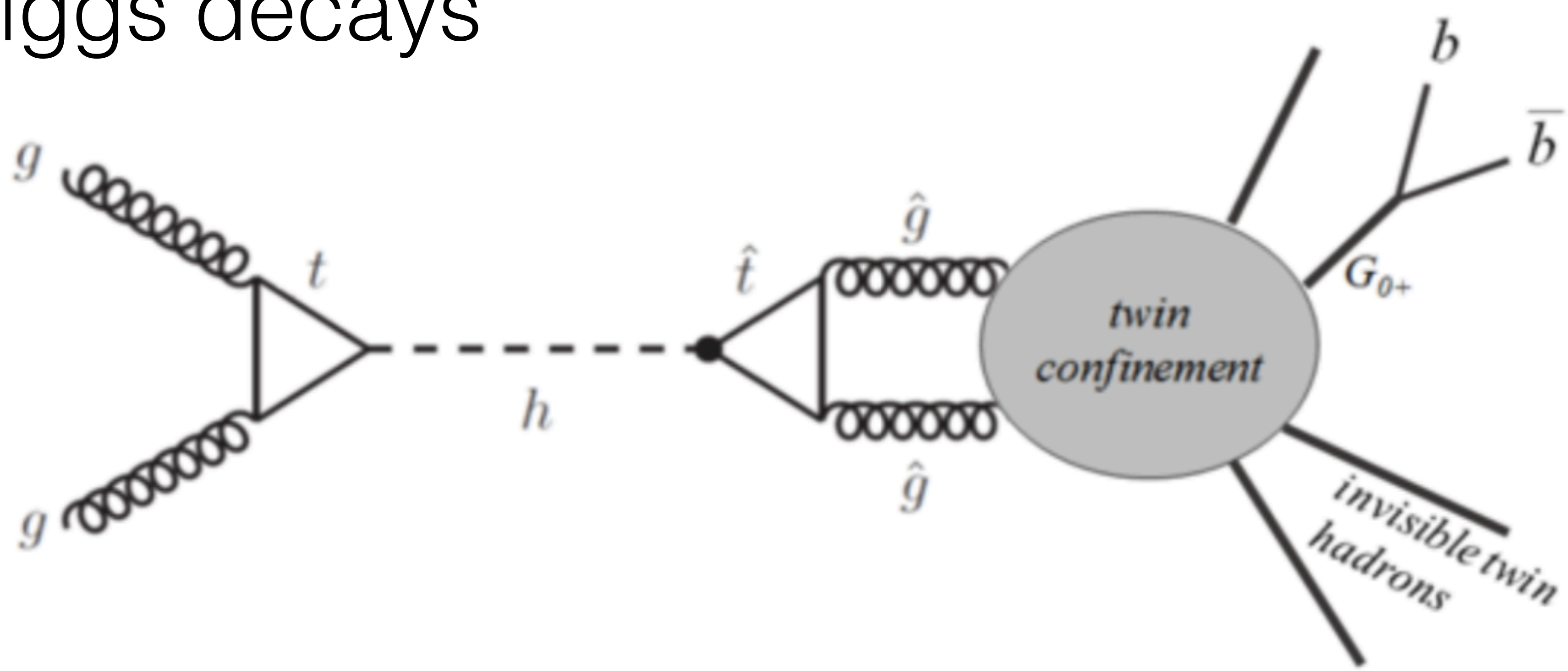
[c] *INFN, Sezione di Genova, Via Dodecaneso 33, 16146 Genova, Italy*

Abstract

We present an exceptional twin-Higgs model with the minimal symmetry structure for an exact implementation of twin parity along with custodial symmetry. Twin particles are mirrors of the Standard Model yet they carry hypercharge, while the photon is identified with its twin. We thoroughly explore the phenomenological signatures of hypercharged naturalness: long-lived charged particles, a colorless twin top with elec-

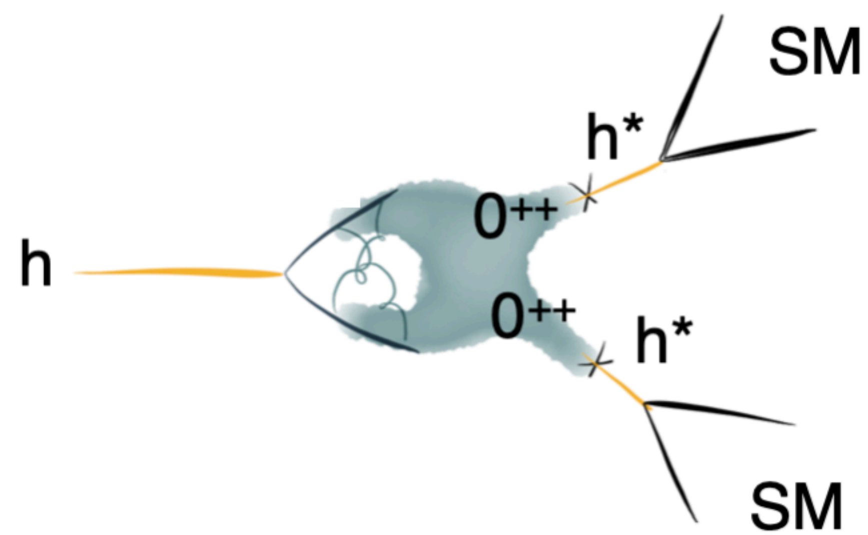
Twin Higgs consequences

- SU(3)$_B$ confines at $\Lambda_B > \Lambda_{\rm QCD}$
- Dark sector QCD-like with dark-pions, dark kaons, …
- Exotic Higgs decays



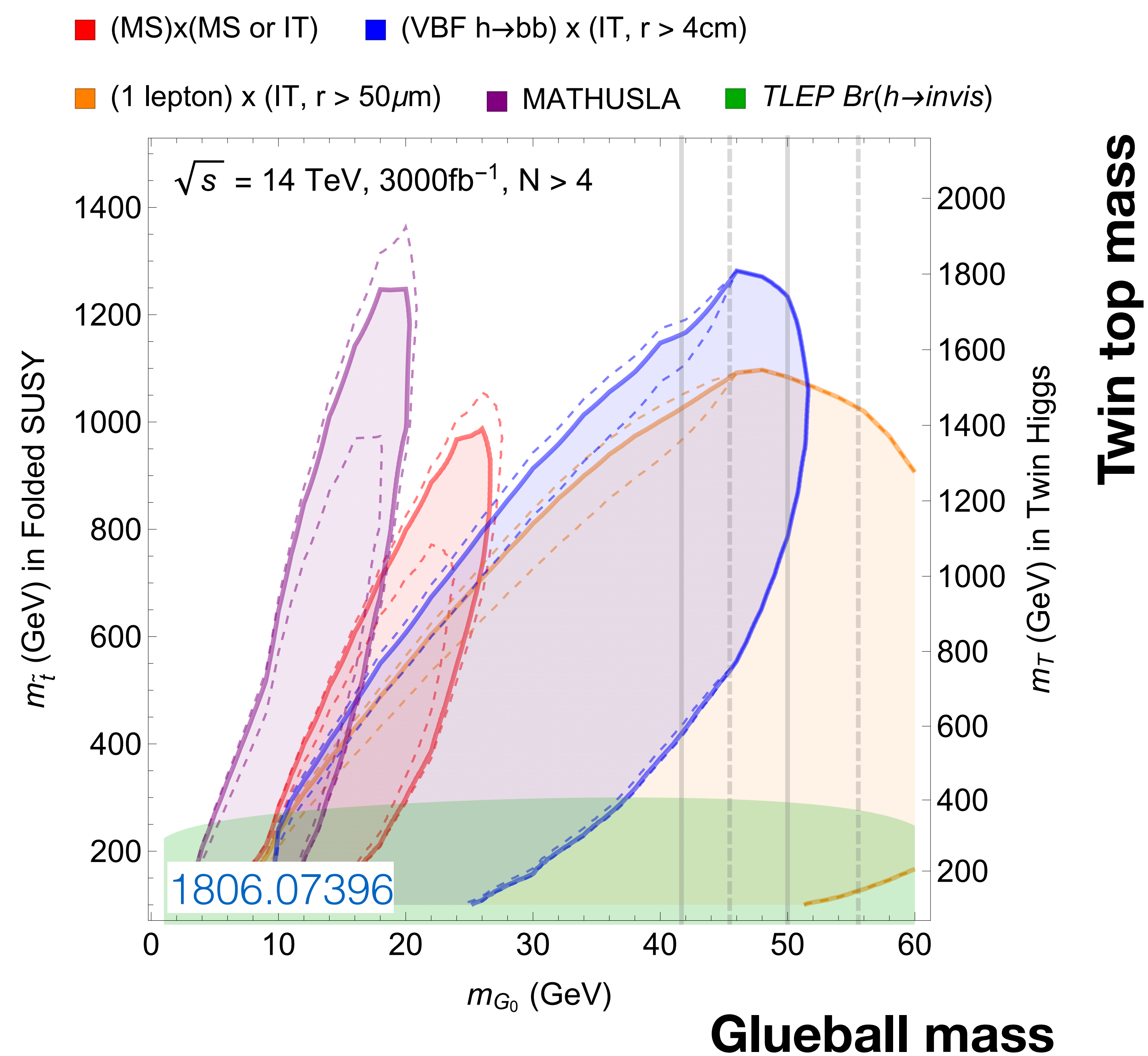
Craig, Katz, Sundrum, Strassler, 2015

New signature: exotic Higgs decays



Long-lived Glueballs; lightest have same quantum # as Higgs

$$\mathcal{L} \supset -\frac{\alpha_3'}{6\pi}\frac{v}{f}\frac{h}{f}G'^{\,a}_{\mu\nu}G'^{\,\mu\nu}_{a}$$



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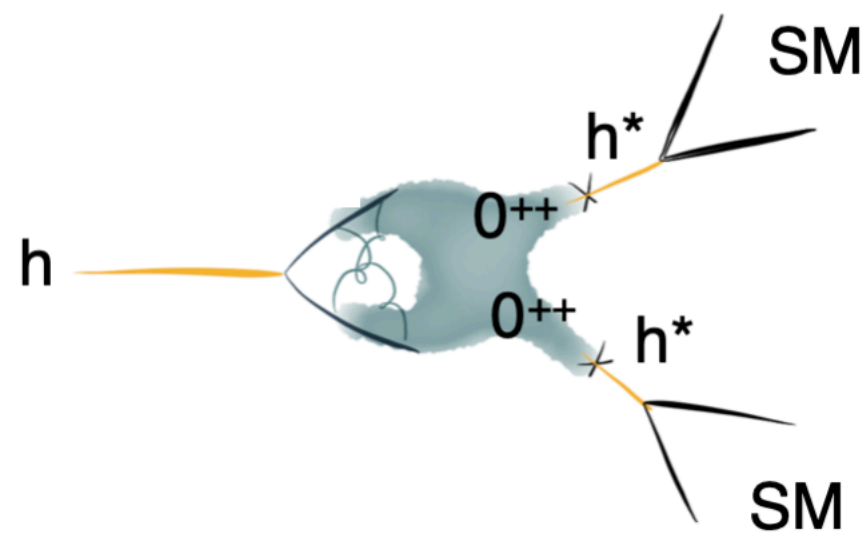

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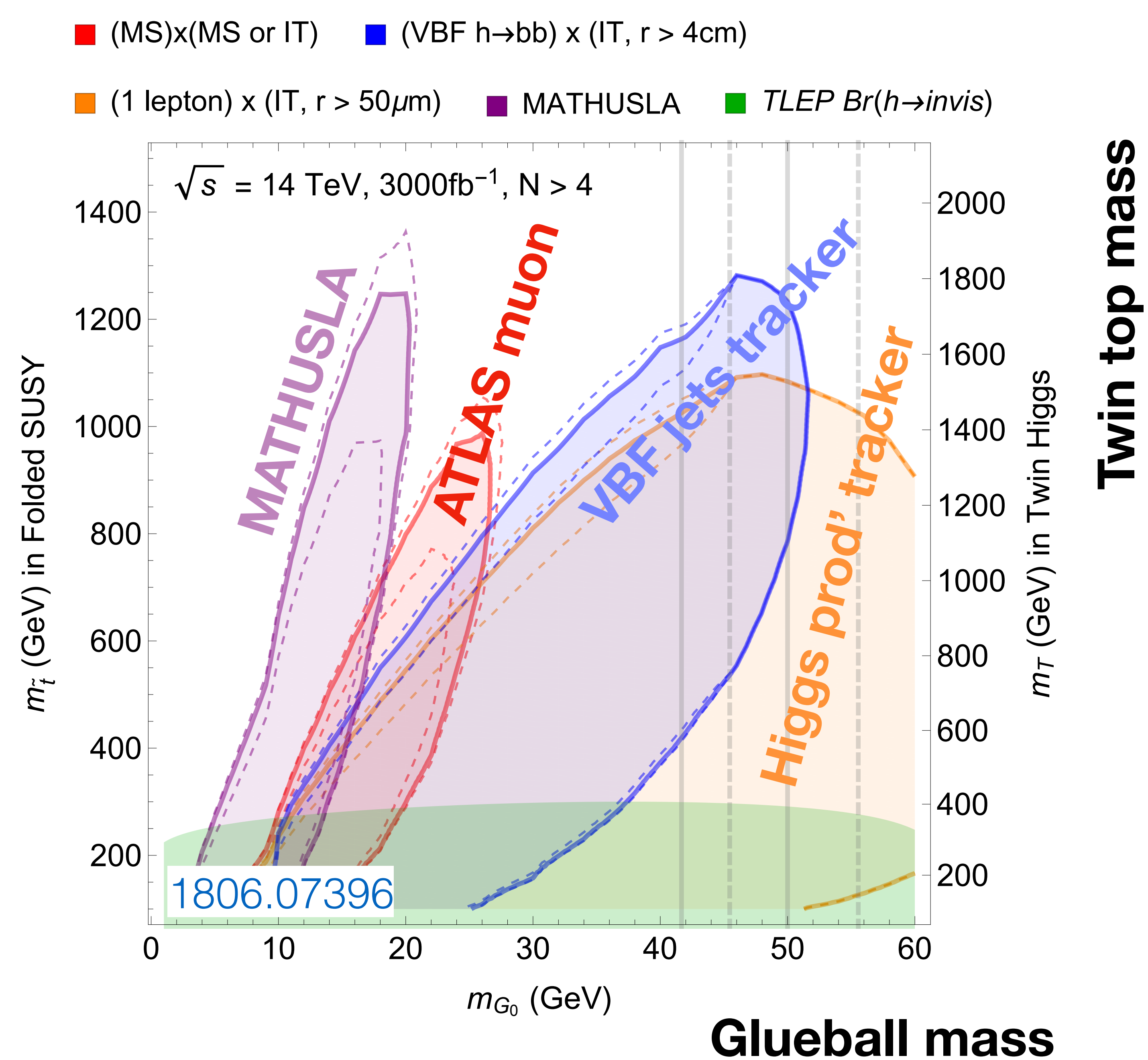
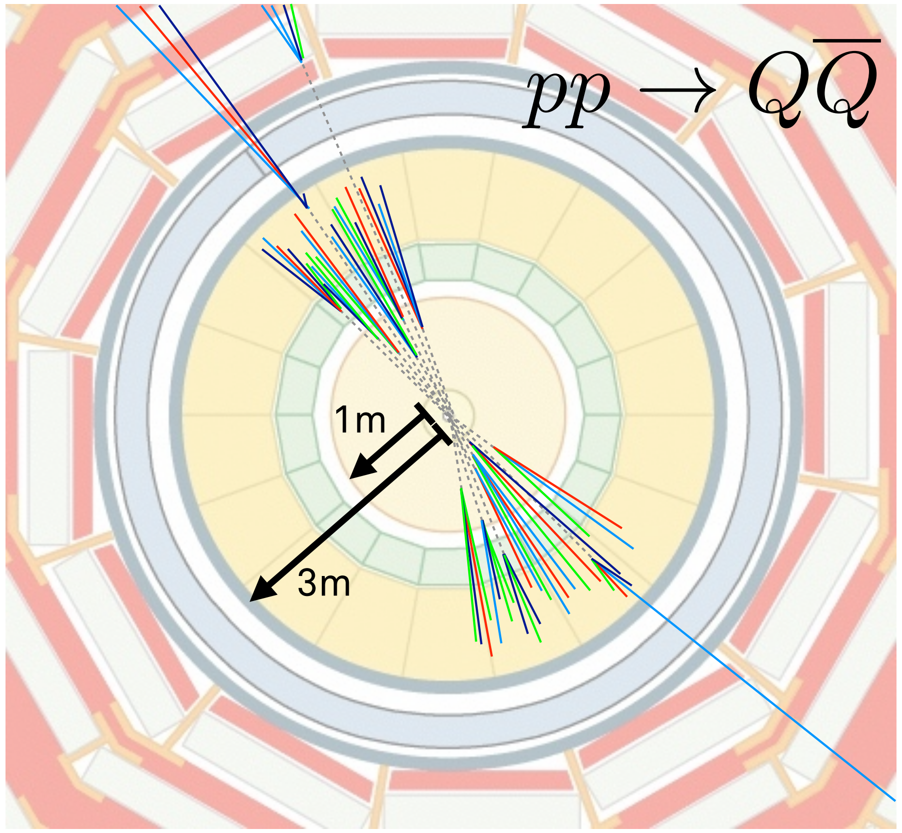
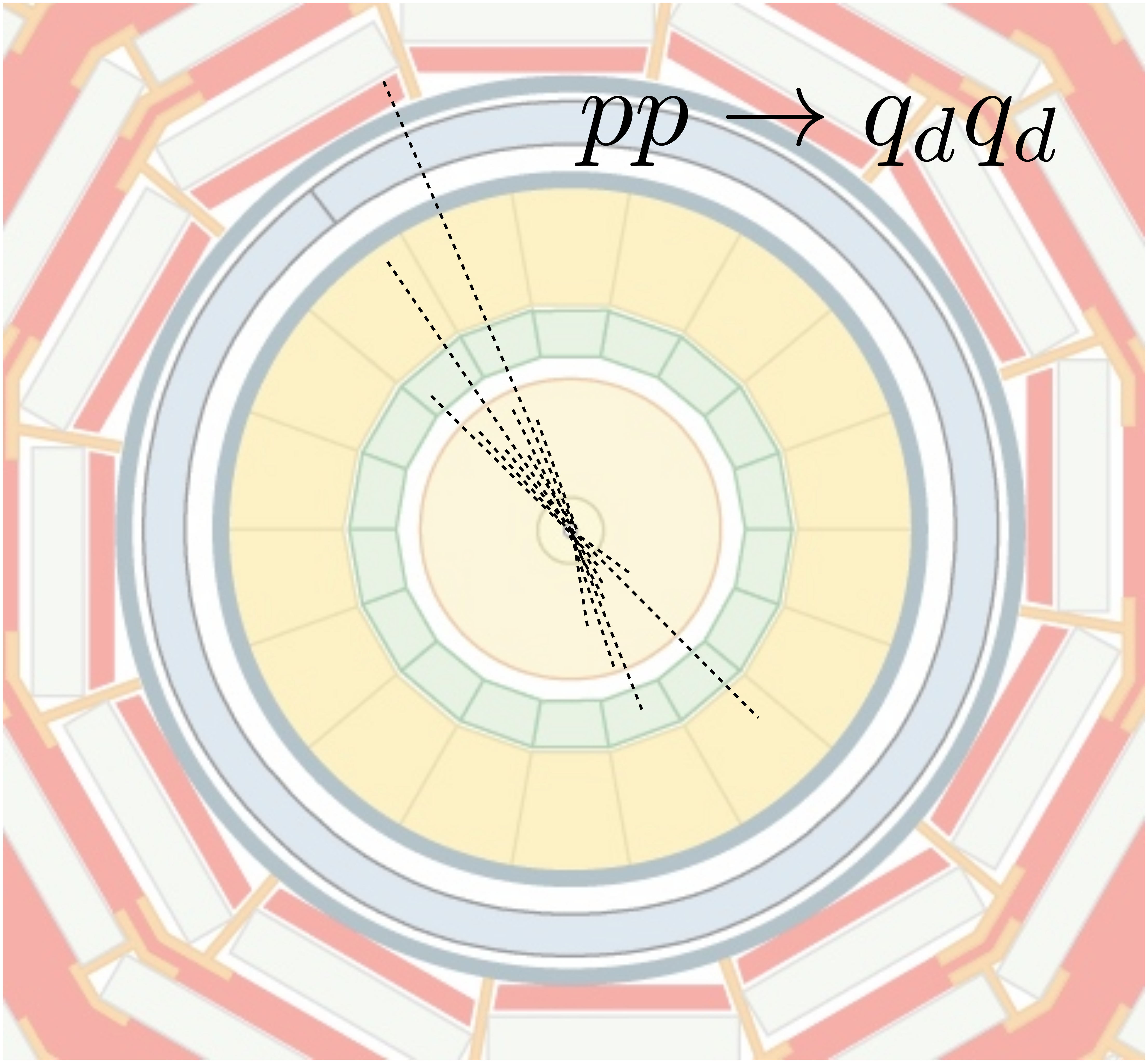


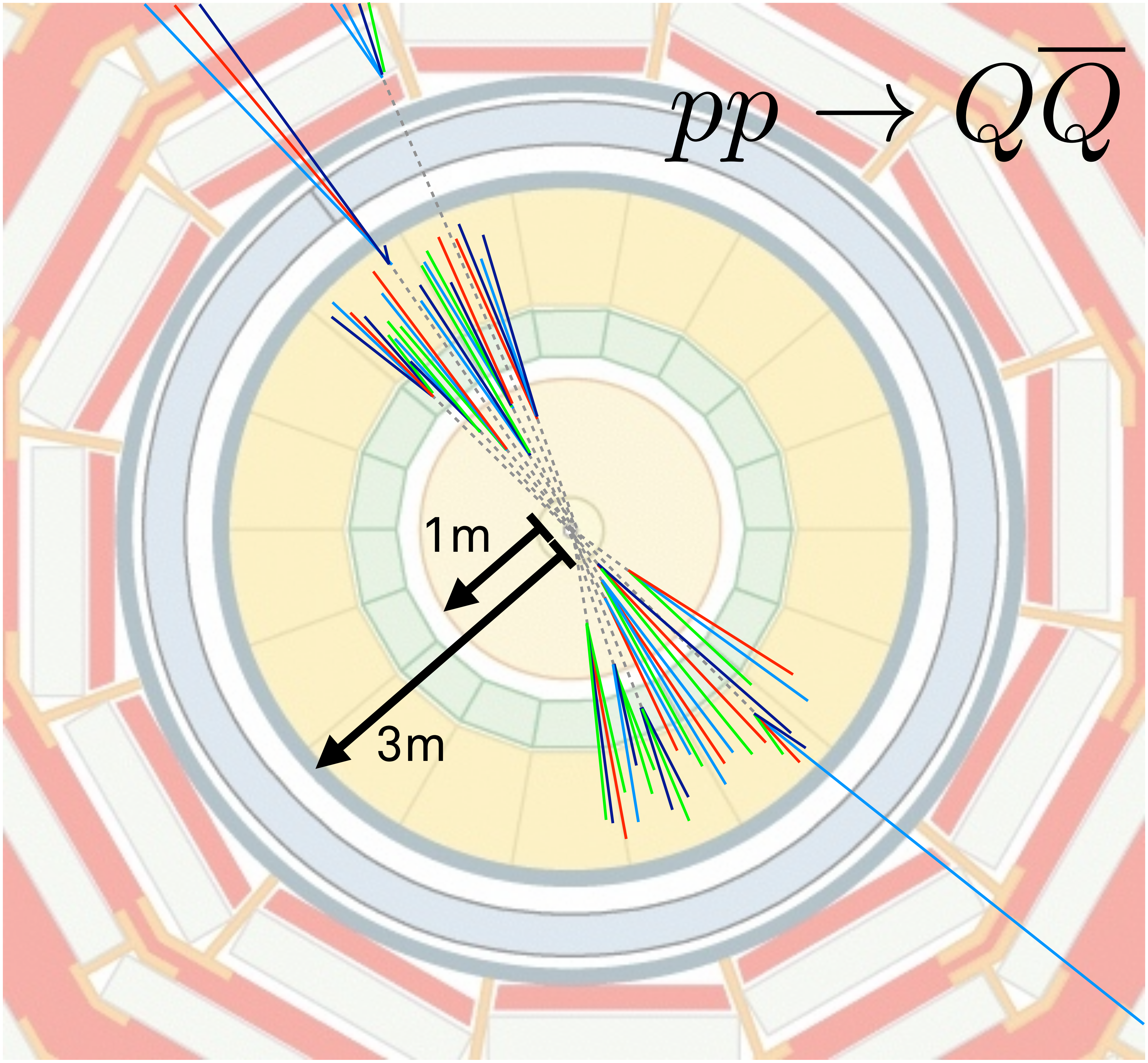
Twin Higgs pheno

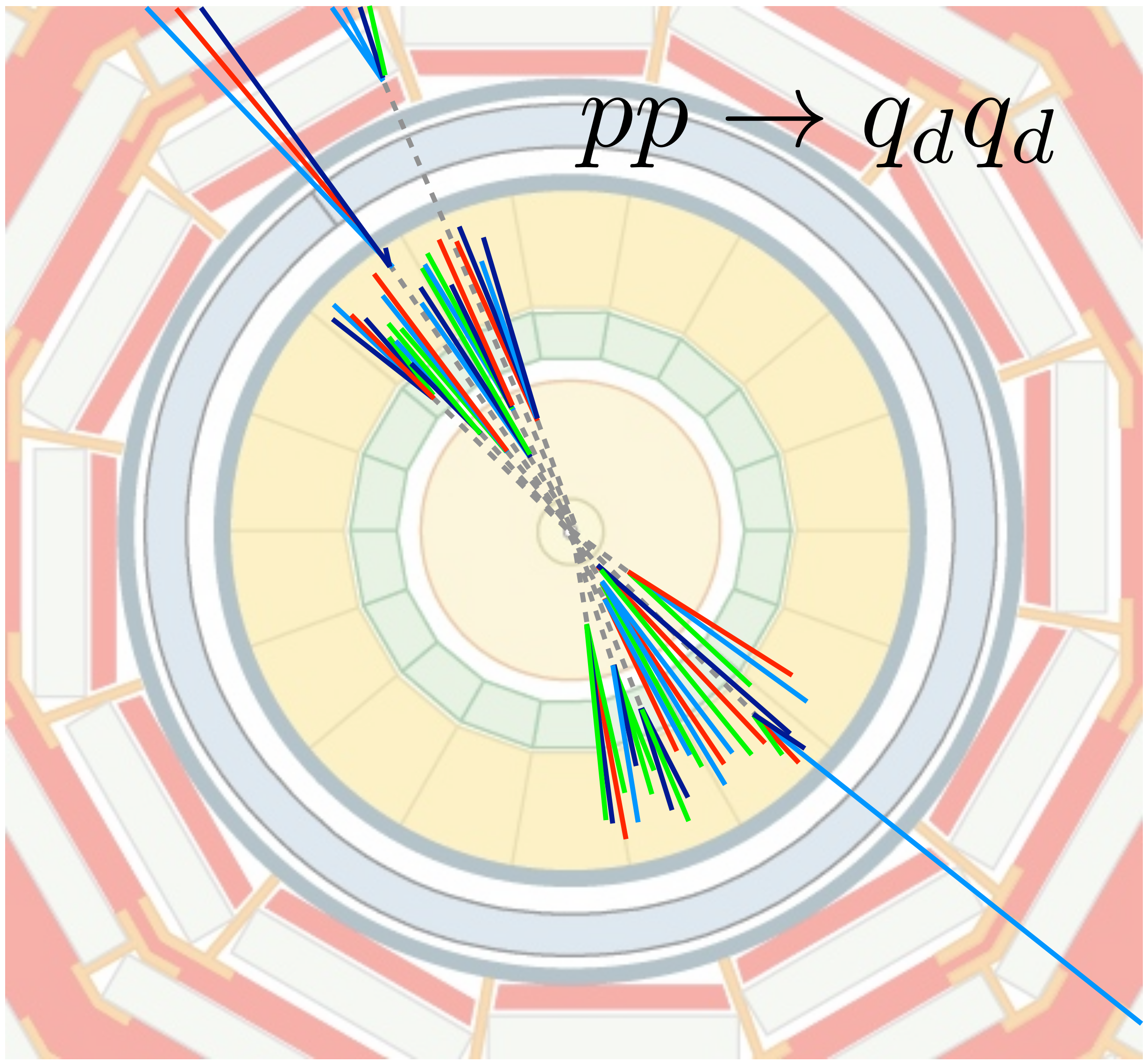
Schwaller, Stolarski, AW ‘15

- Twin parton shower -> Emerging Jets
- Signature of dark sector with long lived states




$pp \to q_d q_d$

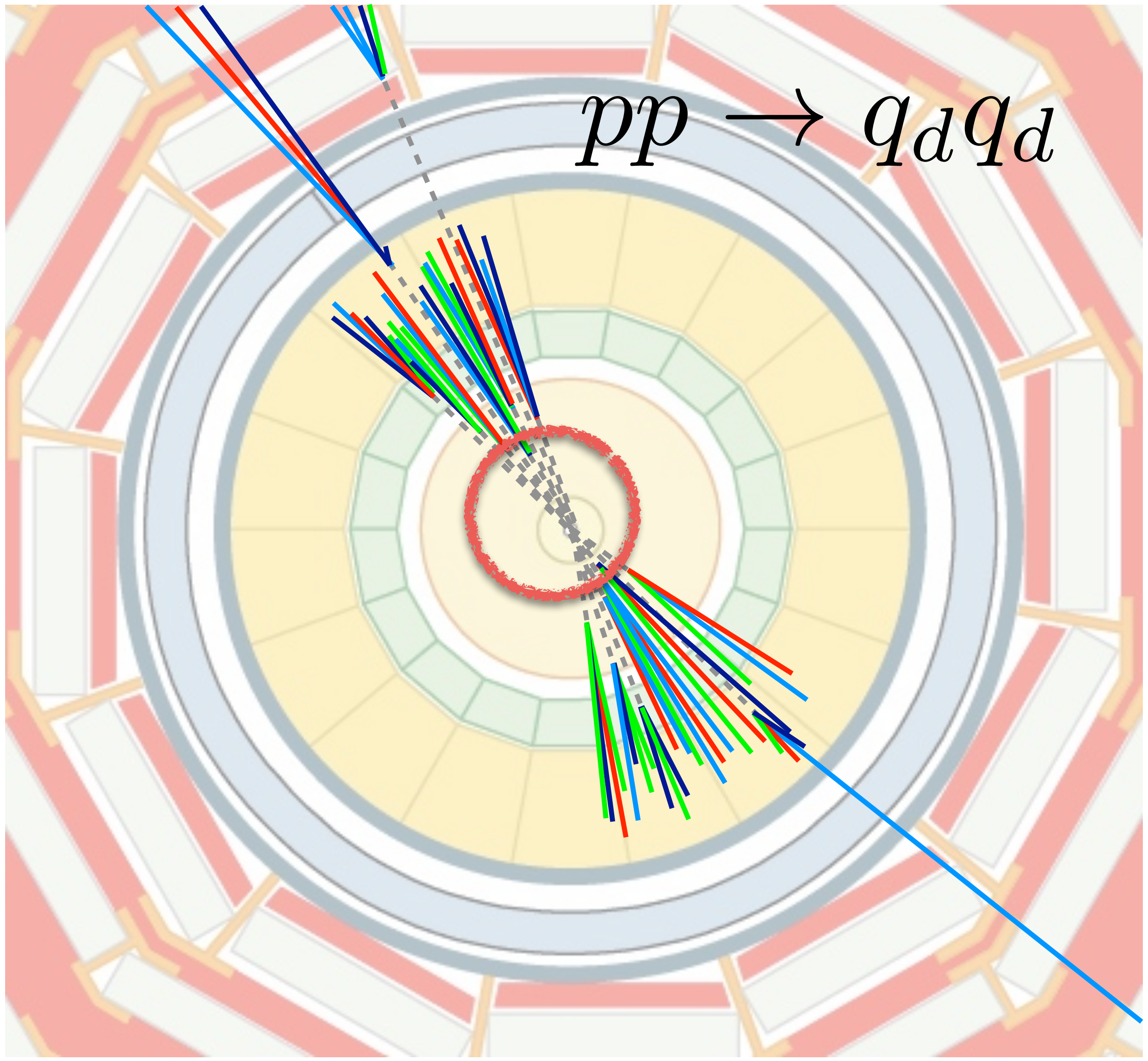

$pp \to Q\overline{Q}$
1m
3m



Decay lifetime of ~ cm

Exponential decay profile: Several displaced vertices inside a jet "cone" (or calo-jet)

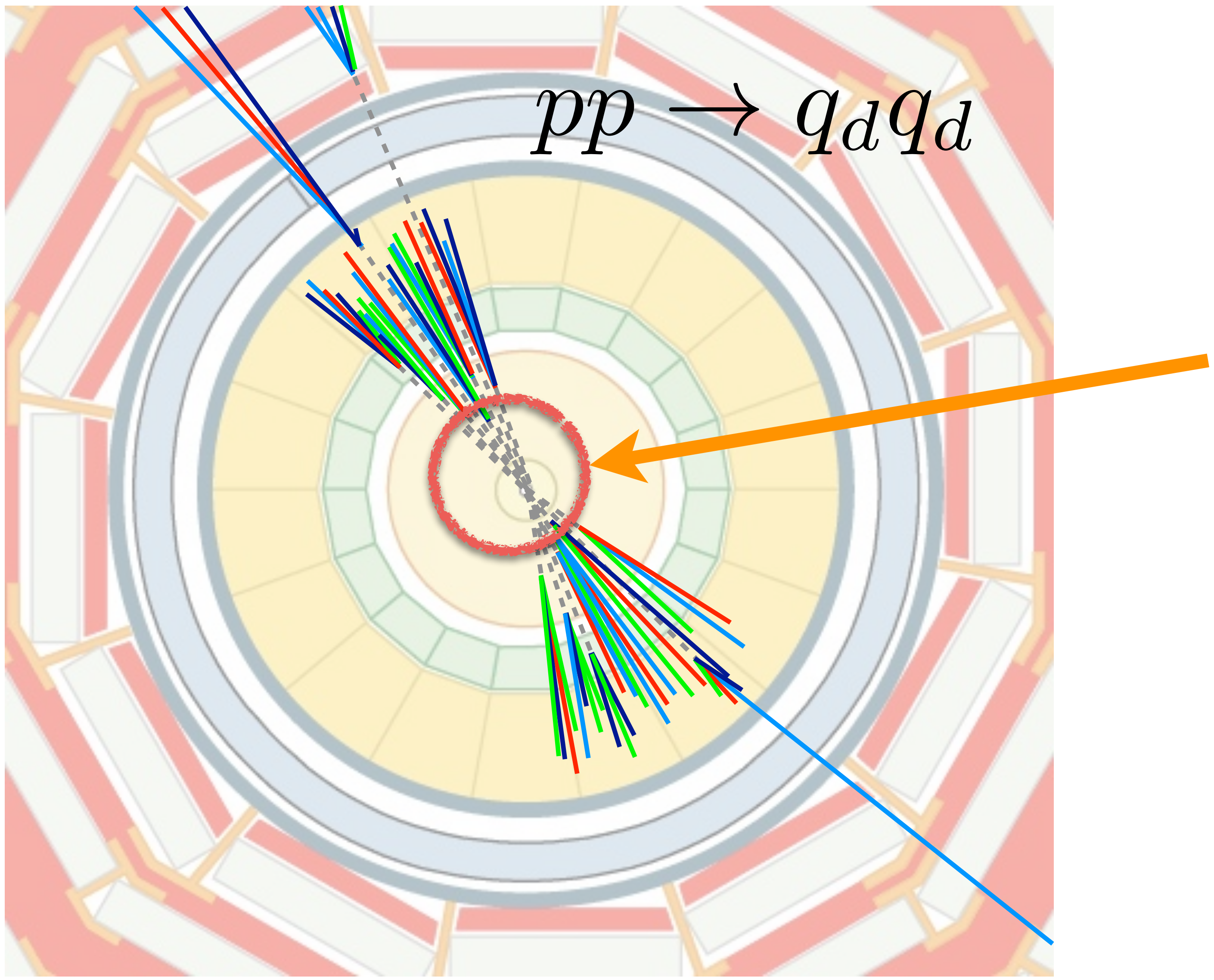
No/few tracks originating from interaction point



Look for Hcal-jets with no/few tracks below distance to inter-action point (inside circle)

New ‘track-less’ signature

Universal for a large class of displaced physics



Look for Hcal-jets with no/few tracks below distance to inter-action point (inside circle)

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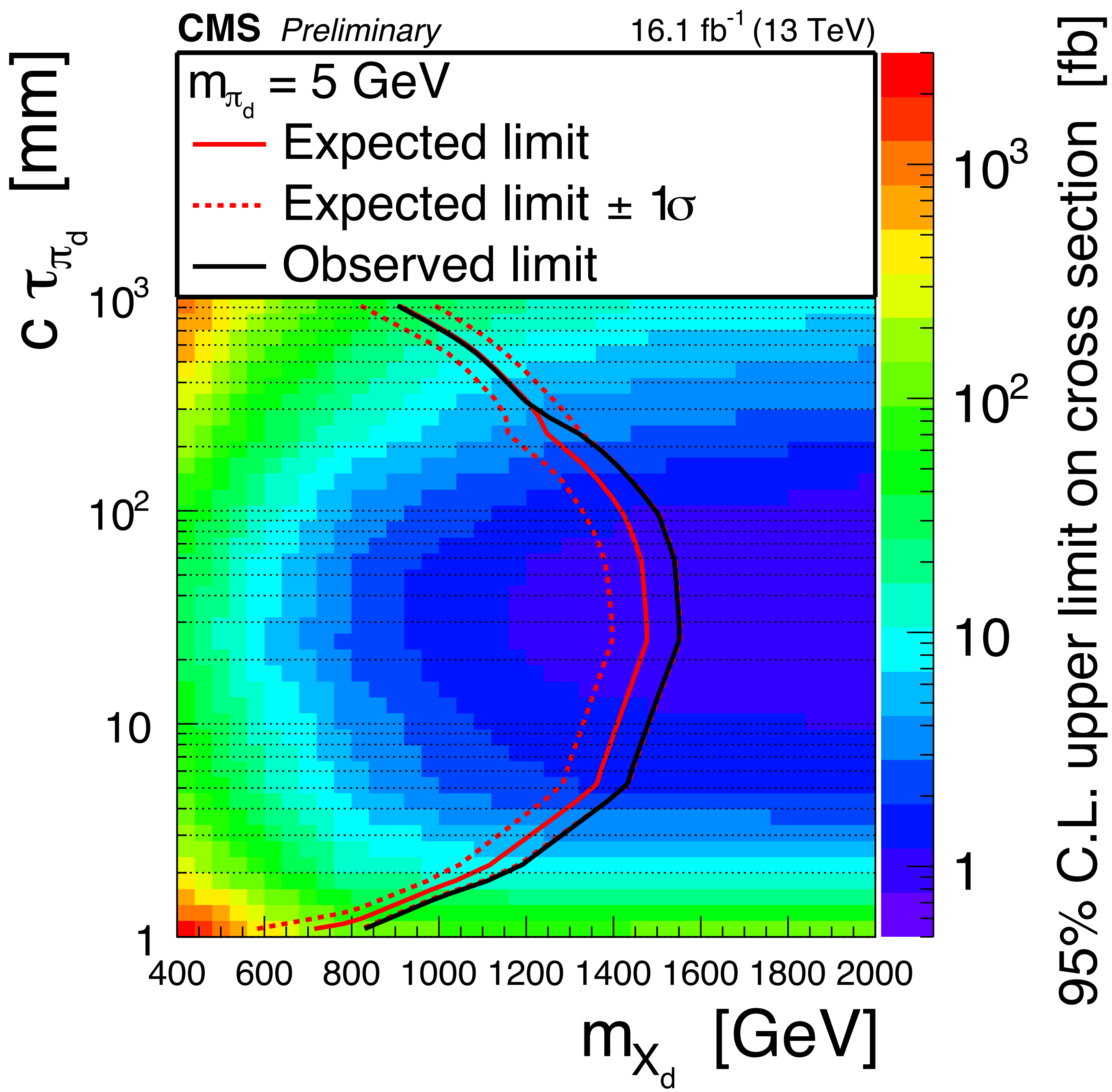
Emerging jets search

“Mediator particles with masses between 400 and 1250 GeV are excluded for dark hadron decay lengths between 5 and 225 mm.”



[CMS PAS EXO-18-001]

Amazing work by UMD CMS team (Belloni, Eno, Jeng, …)

G. Giudice

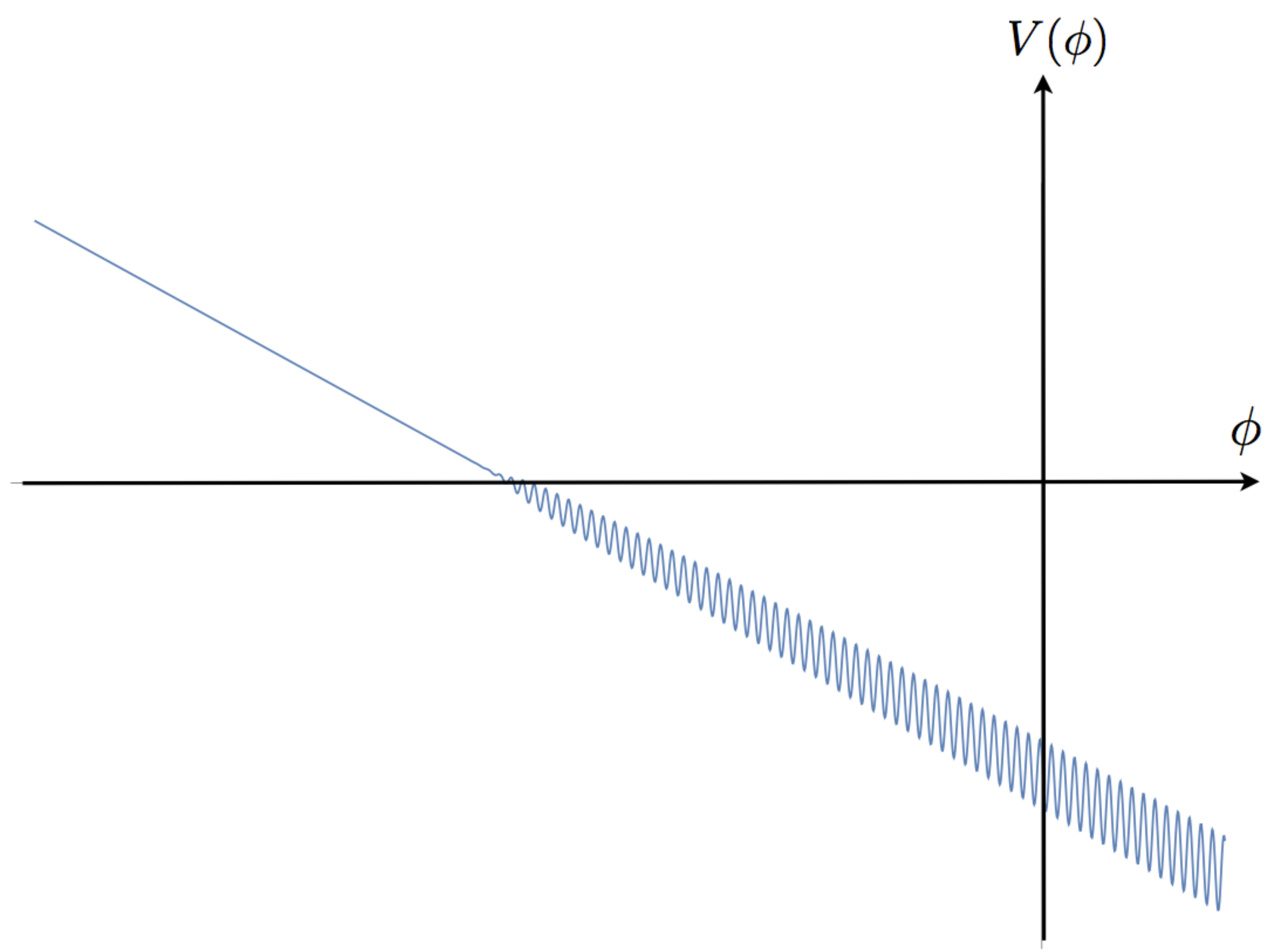
"Is neutral naturalness the beautiful reason we haven't seen anything, or the last desperate hope of theorists?"

Relaxion

ION

Relaxing towards the Fermi scale

SM + axion + m_{Higgs}^2(axion-field) + driver



Relaxion paradigm

P.W. Graham, D.E. Kaplan, S.Rajendran ‘15
(earlier work by Abbott 85, G.Dvali,A.Vilenkin 04, G.Dvali 06)

A technically natural solution to the hierarchy problem

Uses dynamics, not symmetries

Still at the drafting stage, but a very interesting framework

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$$m^2|H|^2$$

Higgs mass

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$$= \Lambda^2 - g\phi$$

$$m^2|H|^2 \longrightarrow m^2(\phi)|H|^2$$

Higgs mass   axion-field dependent mass

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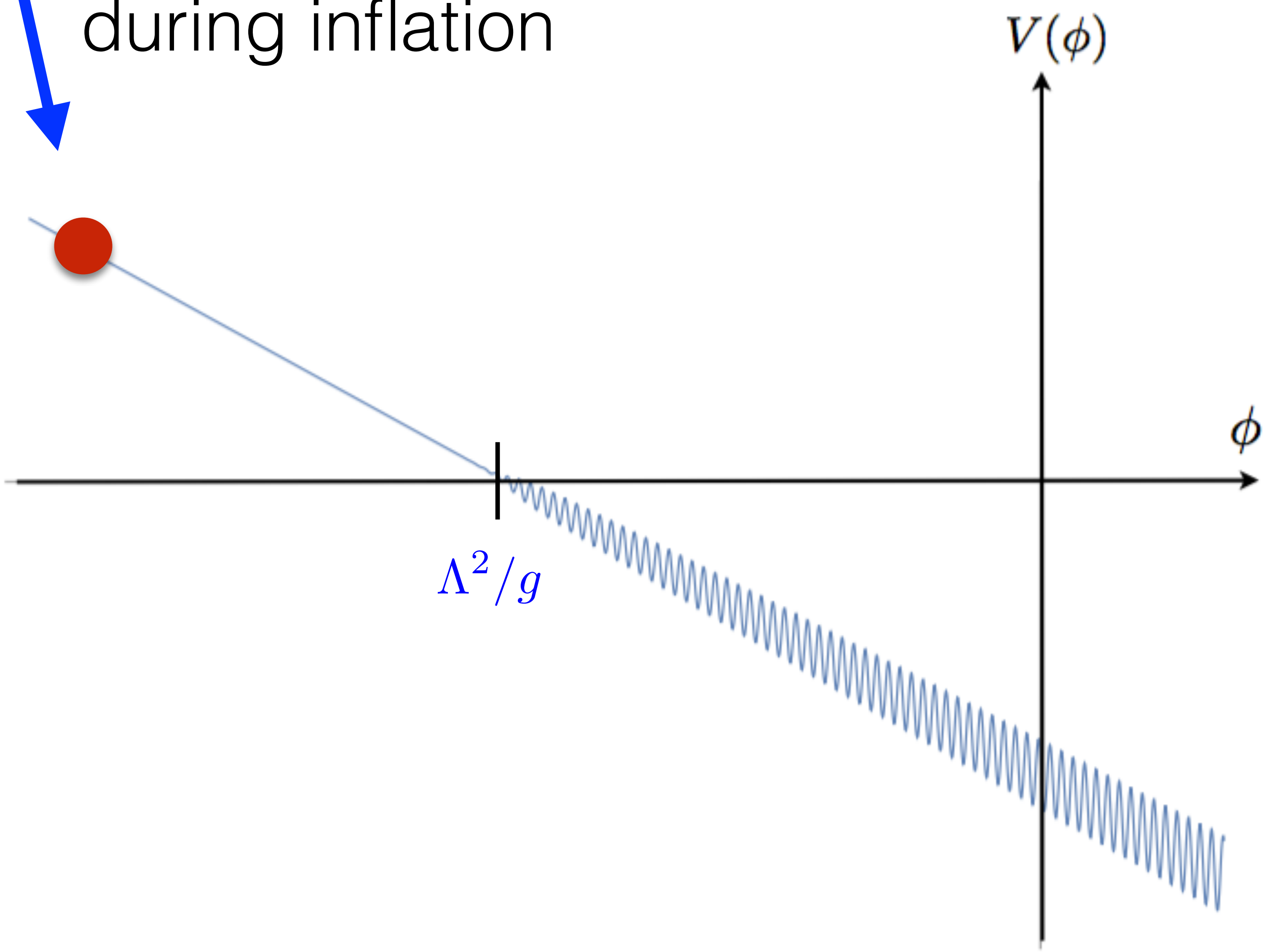
Higgs mass axion-field dependent mass

Clever dynamics stabilizes ϕ at values: $m^2(\phi) \ll \Lambda^2$

$$V(g\phi) + (\Lambda^2 - g\phi)|H|^2 + \epsilon\Lambda_{QCD}^3 h \cos\frac{\phi}{f}$$

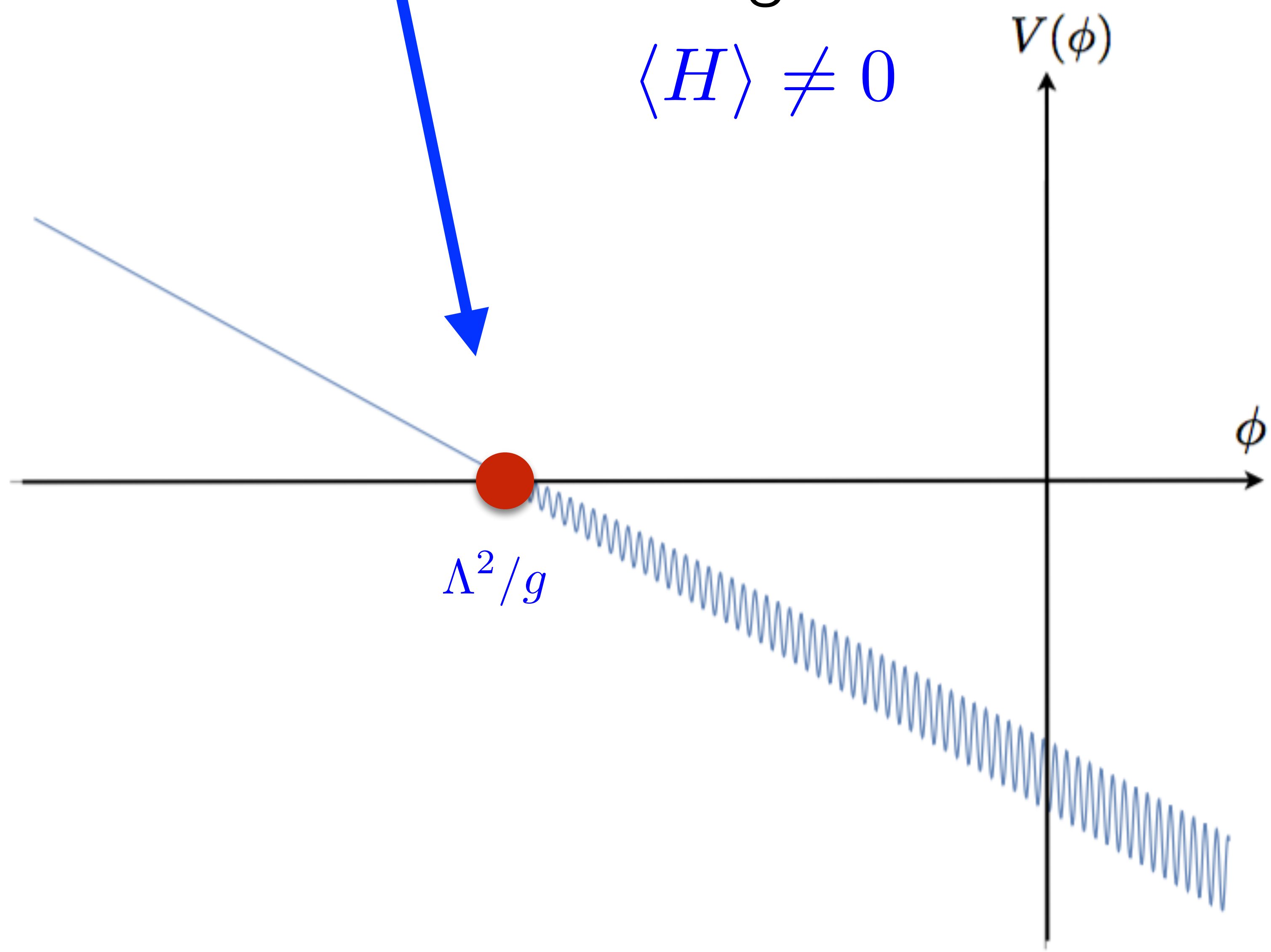
potential to slow-roll ϕ
during inflation



$$V(g\phi) + (\Lambda^2 - g\phi)|H|^2 + \epsilon\Lambda_{QCD}^3 h \cos\frac{\phi}{f}$$

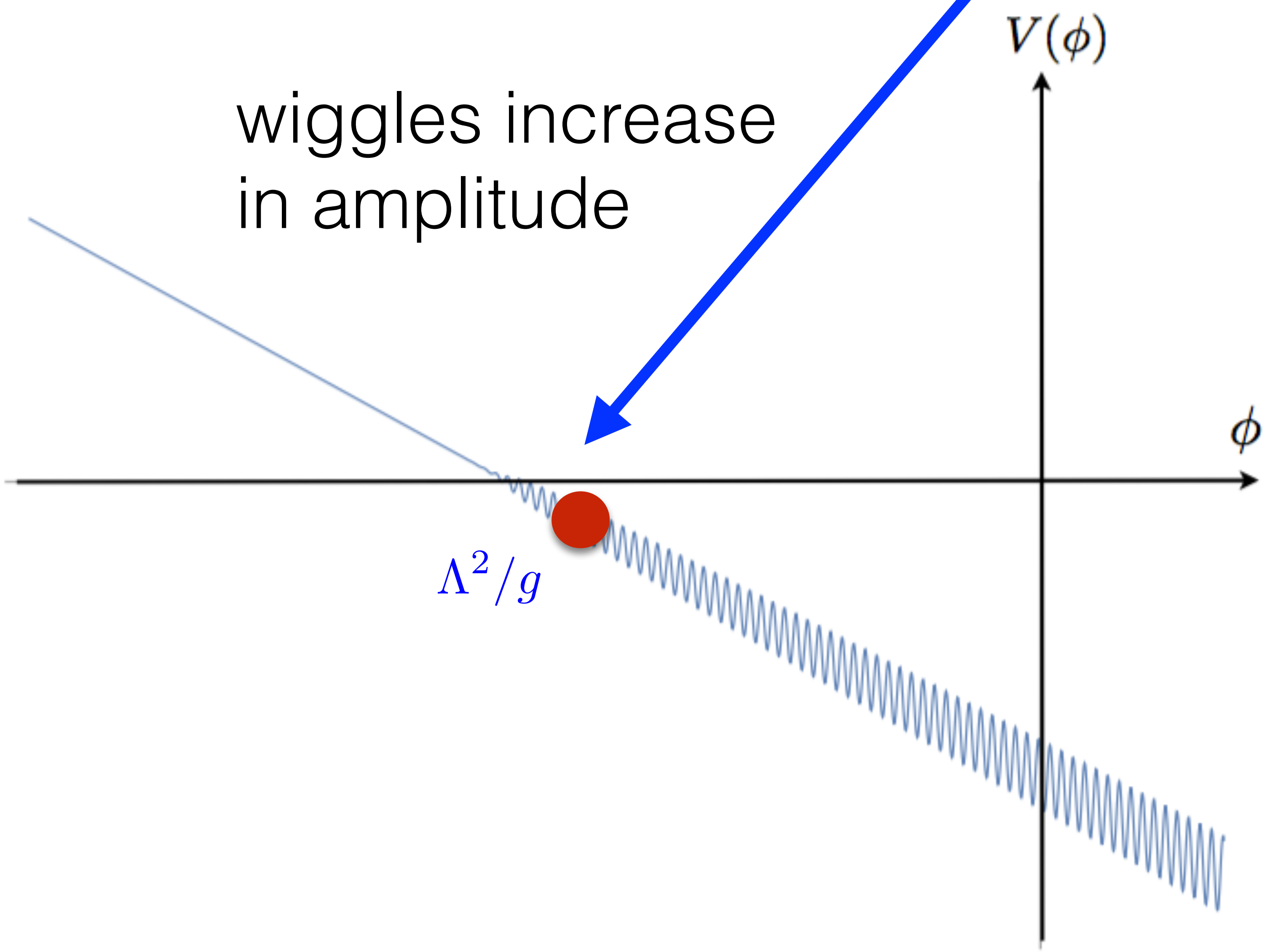
Higgs mass squared turns negative

$$\langle H \rangle \neq 0$$



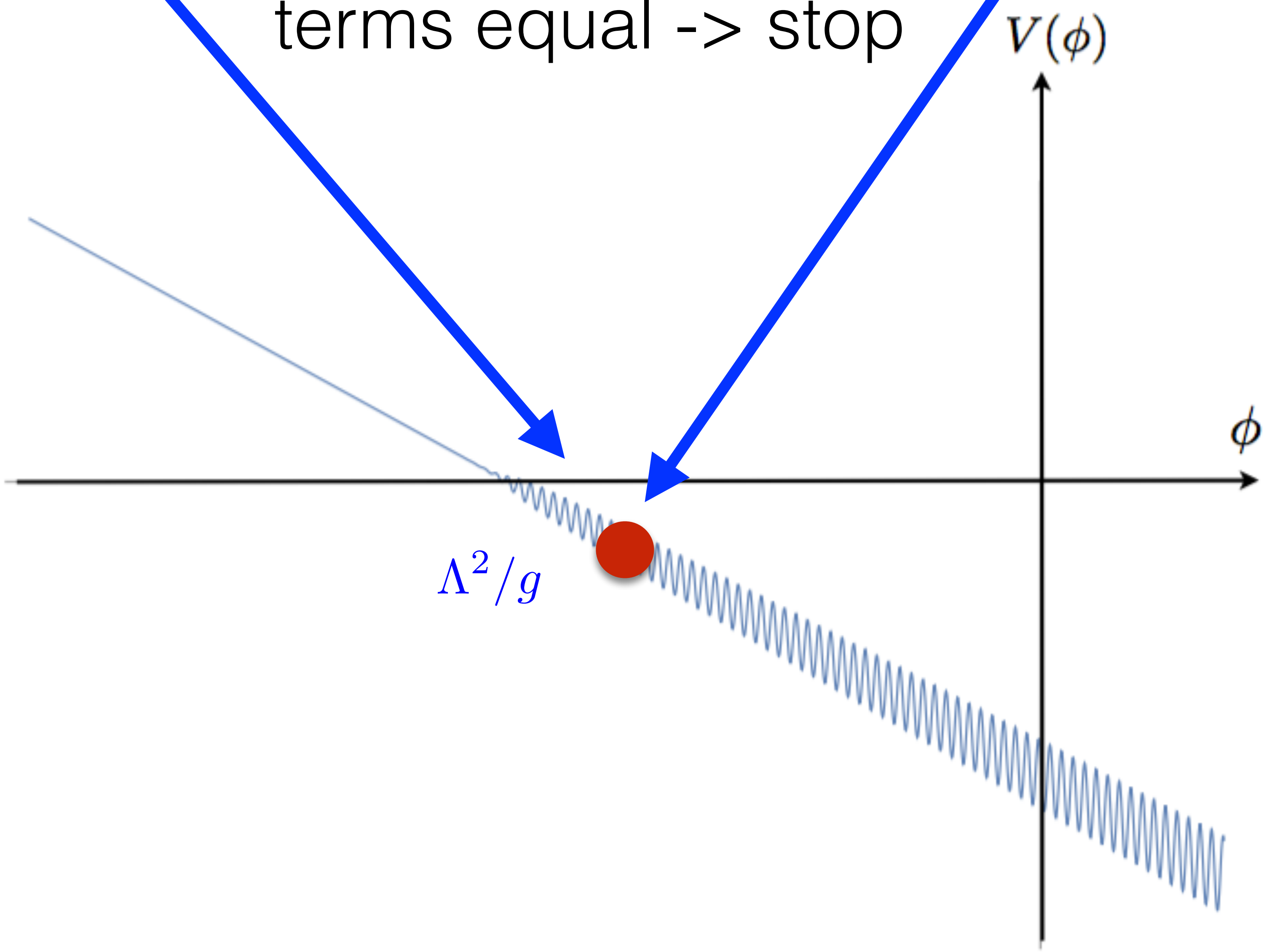
$$V(g\phi) + (\Lambda^2 - g\phi)|H|^2 + \epsilon\Lambda_{QCD}^3 h \cos\frac{\phi}{f}$$

wiggles increase
in amplitude



$$V(g\phi) + (\Lambda^2 - g\phi)|H|^2 + \epsilon\Lambda_{QCD}^3 h \cos\frac{\phi}{f}$$

steepness of
terms equal -> stop



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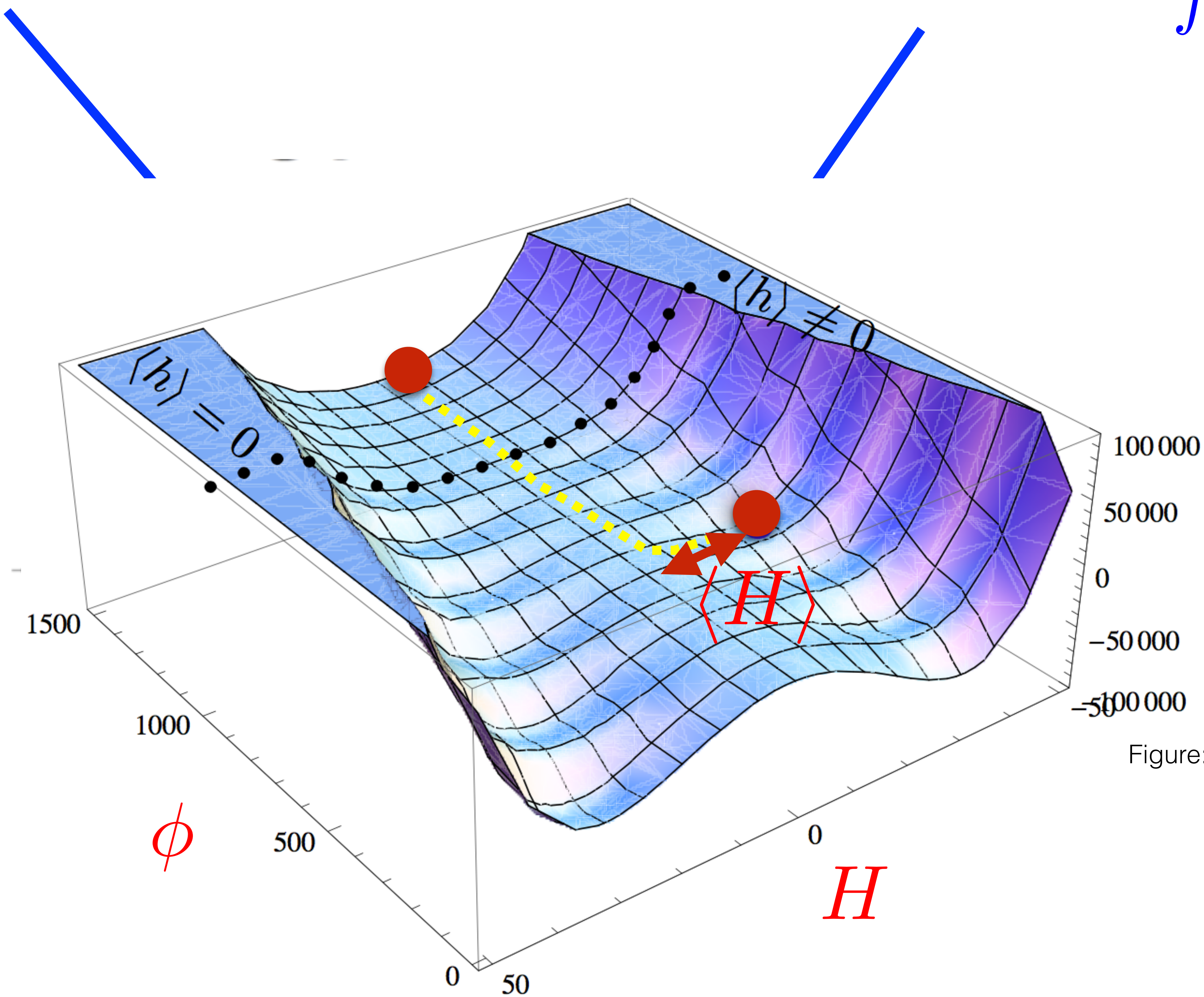


Figure: C. Grojean

- QCD axion doesn't work: $\theta_{QCD} \sim 1$ due to tilt
  - Add new QCD' group => new weak-scale signals!
  - Add additional scanning field => **no** collider signals! Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

Some points of concern:

$g \sim 10^{-27}\mathrm{GeV}$ UV completion ?

$N > H^2/g^2 \sim 10^{45}$ inflation ?

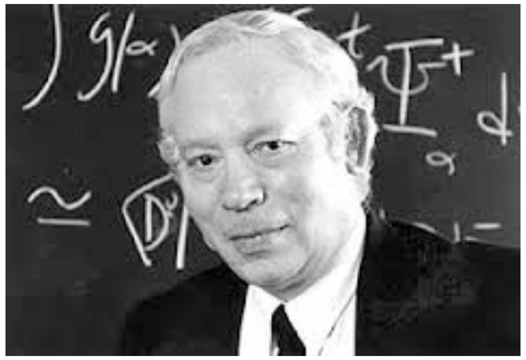
$\Delta\Phi \simeq 10^{41}\mathrm{GeV}$ large field excursions

The future

Or …


USS ENTERPRISE
BUD LIGHT

the last word…



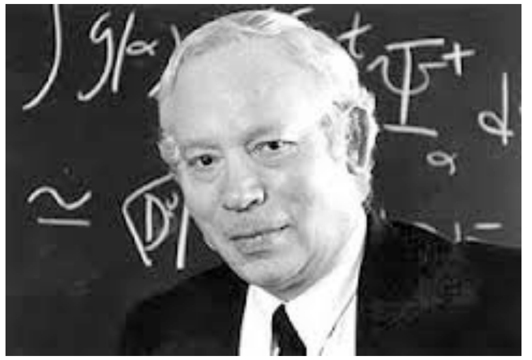
Four Lessons

1) How could I do anything without knowing everything that had already been done? […] pick up what I needed to know as I went along. It was sink or swim. […] But I did learn one big thing: that no one knows everything, and you don't have to.

2) While you are swimming and not sinking you should aim for rough water. […] My advice is to go for the messes — that's where the action is.

Scientist: Four golden lessons
Steven Weinberg, Nature 426, 389 (27 November 2003)

Four Lessons



3) Forgive yourself for wasting time. […] in the real world, it's very hard to know which problems are important, and you never know whether at a given moment in history a problem is solvable [...] get used […] to being becalmed on the ocean of scientific knowledge.

4) Learn something about the history of science […] As a scientist, you're probably not going to get rich. […] But you can get great satisfaction by recognizing that your work in science is a part of history.

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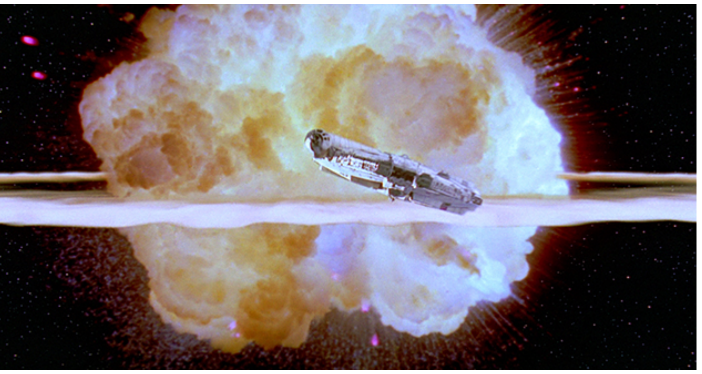

- No signs of new physics have appeared so far.

- The Higgs fine-tuning puzzle is as puzzling as ever. Do we simply live in a (mildly?) fine-tuned universe? Or is there a subtle solution?

- Themes of recent years: search for electroweak or neutral new particles at colliders to exhaust possibilities; intriguing possibilities for connections of the weak scale with cosmology.

- Amazing landscape of experiments: LHC, dark matter, EDMs, flavor physics. New physics discovery could come at any time!