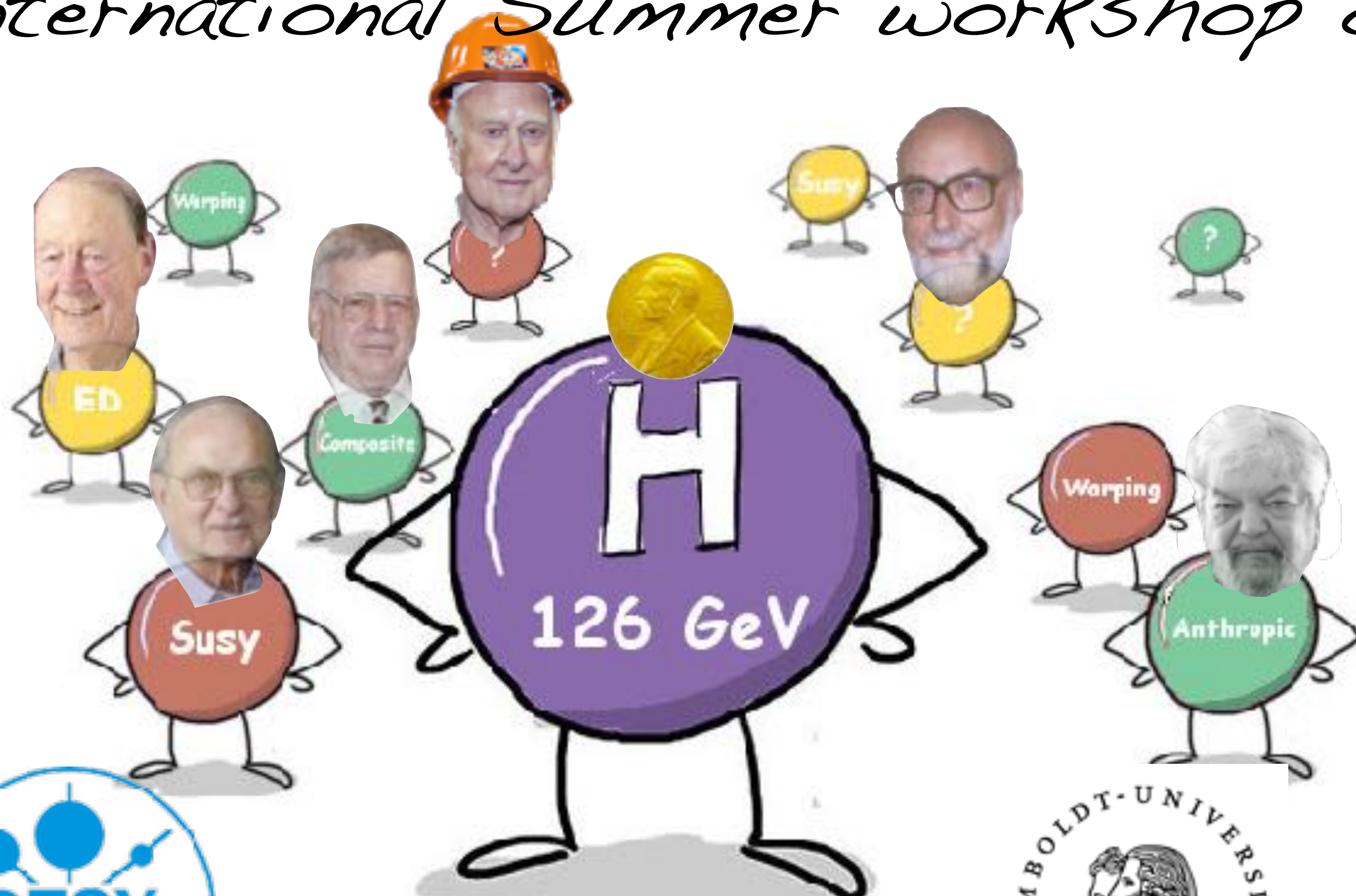
Beyond the Standard Model

TAE 2018 @ Benasque

International Summer workshop on High Energy Physics

Lecture 1/3



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Outline

Lecture #1

- General introduction: From Fermi theory to the Standard Model
- Higgs physics as a door to BSM
- Naturalness and the weak scale hierarchy problem
- Supersymmetry

Lecture #2

- Composite Higgs
- Extra dimensions
- Cosmological relaxation: a concrete example of different energy frontier
- NNaturalness

Lecture #3

- Weak gravity conjecture and the swampland
- Beyond colliders searches for new physics
  - Gravitational waves
  - AMO: isotope spectroscopy
  - Electric dipole moment
  - Neutron-antineutron oscillations
  - Primordial black holes

Some numerical values used in these lectures…

Fundamental constants

$$c \sim 3 \times 10^8 \,\mathrm{m.s}^{-1}$$
$$\hbar \sim 10^{-34}\,\mathrm{J.s}$$
$$e \sim 1.6 \times 10^{-19}\,\mathrm{C}$$
$$G_N \sim 6.67 \times 10^{-11}\,\mathrm{N.kg}^{-2}.\mathrm{m}^2$$
$$k_B \sim 1.38 \times 10^{-23}\,\mathrm{J.K}^{-1}$$

Natural units

$$1\,\mathrm{eV} = (6.6 \times 10^{-16}\,\mathrm{s})^{-1} \quad 1\,\mathrm{eV} = (2.0 \times 10^{-7}\,\mathrm{m})^{-1} \quad 1\,\mathrm{eV} = 1.8 \times 10^{-36}\,\mathrm{kg} \quad 1\,\mathrm{eV} = 1.2 \times 10^{4}\,\mathrm{K}$$

Mass spectrum

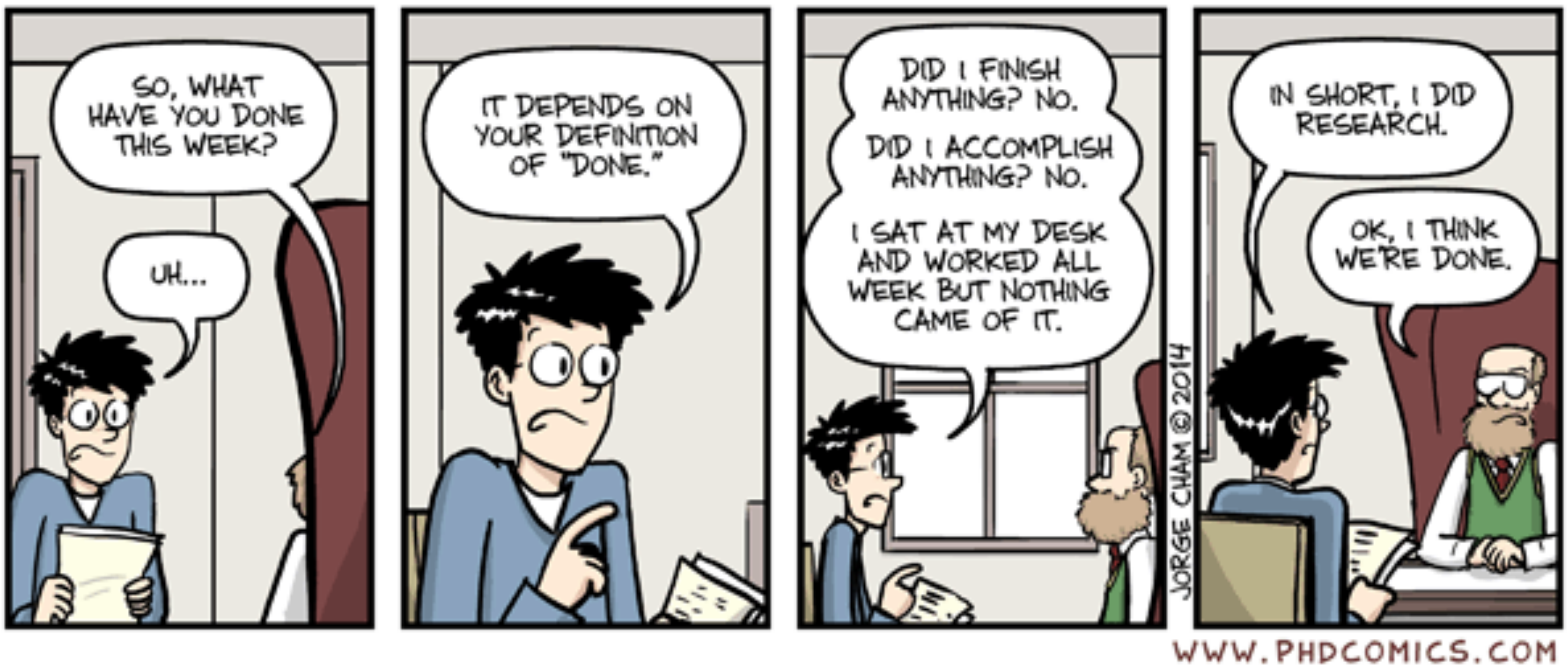
$$m_p = 938\,\mathrm{MeV} \quad m_n = 939\,\mathrm{MeV} \quad m_{\pi^\pm} = 139\,\mathrm{MeV} \quad m_{\pi^0} = 134\,\mathrm{MeV} \quad m_{K^\pm} = 494\,\mathrm{MeV} \quad m_{K^0} = 498\,\mathrm{MeV}$$
$$m_e = 511\,\mathrm{keV} \quad m_\mu = 106\,\mathrm{MeV} \quad m_\tau = 1.8\,\mathrm{GeV}$$
$$m_u = 2.3\,\mathrm{MeV} \quad m_d = 4.8\,\mathrm{MeV} \quad m_c = 1.3\,\mathrm{GeV} \quad m_s = 100\,\mathrm{MeV} \quad m_t = 173\,\mathrm{GeV} \quad m_b = 4.2\,\mathrm{GeV}$$

Astrophysics

$$M_\odot = 2 \times 10^{30}\,\mathrm{kg} \quad M_\oplus = 6.0 \times 10^{24}\,\mathrm{kg} \quad M_\circ = 7.3 \times 10^{22}\,\mathrm{kg}$$
$$\langle d_{\odot-\oplus}\rangle = 1.5 \times 10^{6}\,\mathrm{km} \quad \langle d_{\oplus-\circ}\rangle = 3.8 \times 10^{5}\,\mathrm{km}$$
$$\langle T_\odot^{\mathrm{surface}}\rangle = 5778\,\mathrm{K}$$

Ask questions!

Your work, as students, is to question all what you are listening during the lectures...



What is BSM?

?

I don't know. Nobody knows

If it were known, it would be part of the SM!

You won't learn during these lectures what BSM is.

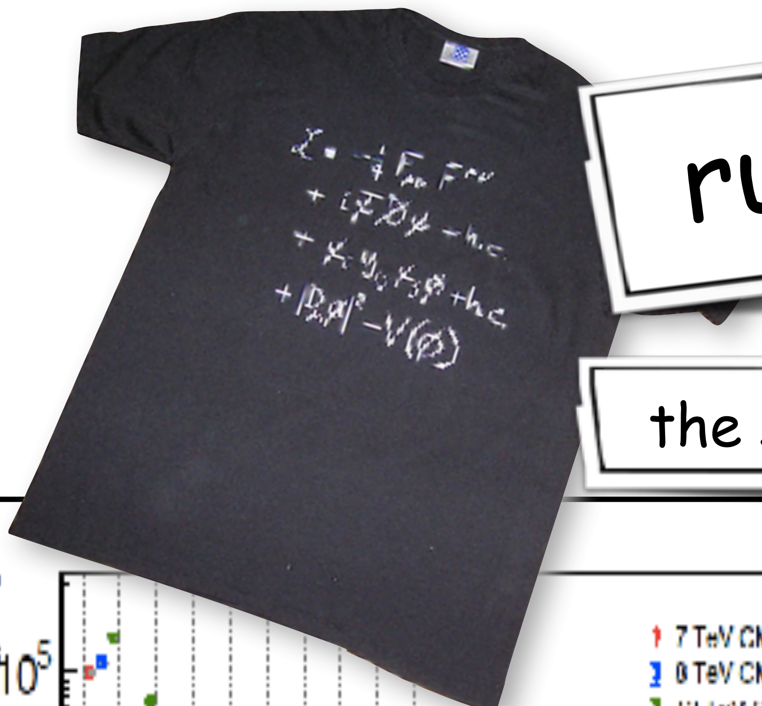
You'll learn (maybe) what BSM could be.

" Looking and not finding is different than not looking"

We'll study the limitations/defaults of the SM as a guide towards BSM.

We want to learn from our failures

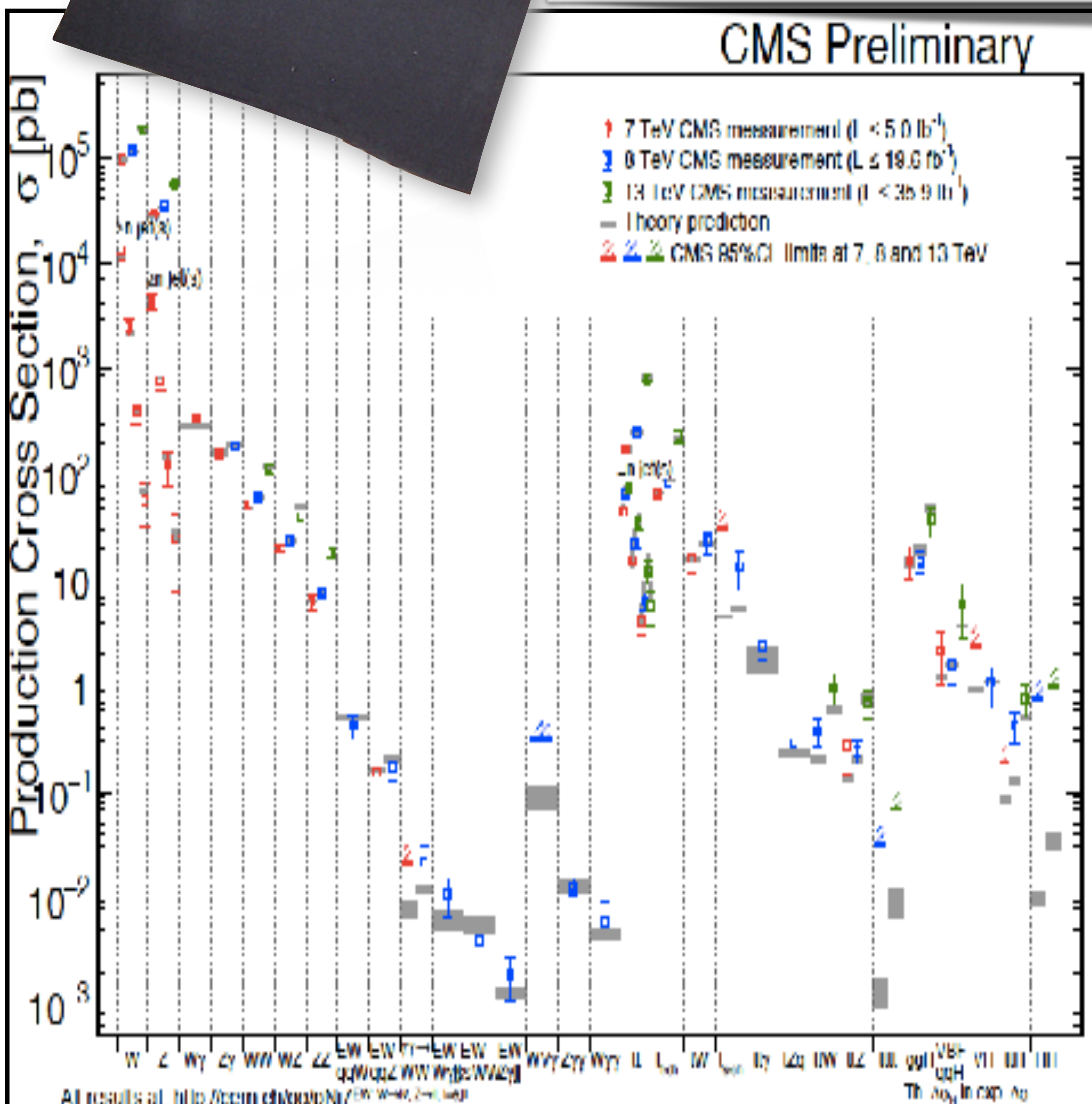
The SM and... the LHC data so far

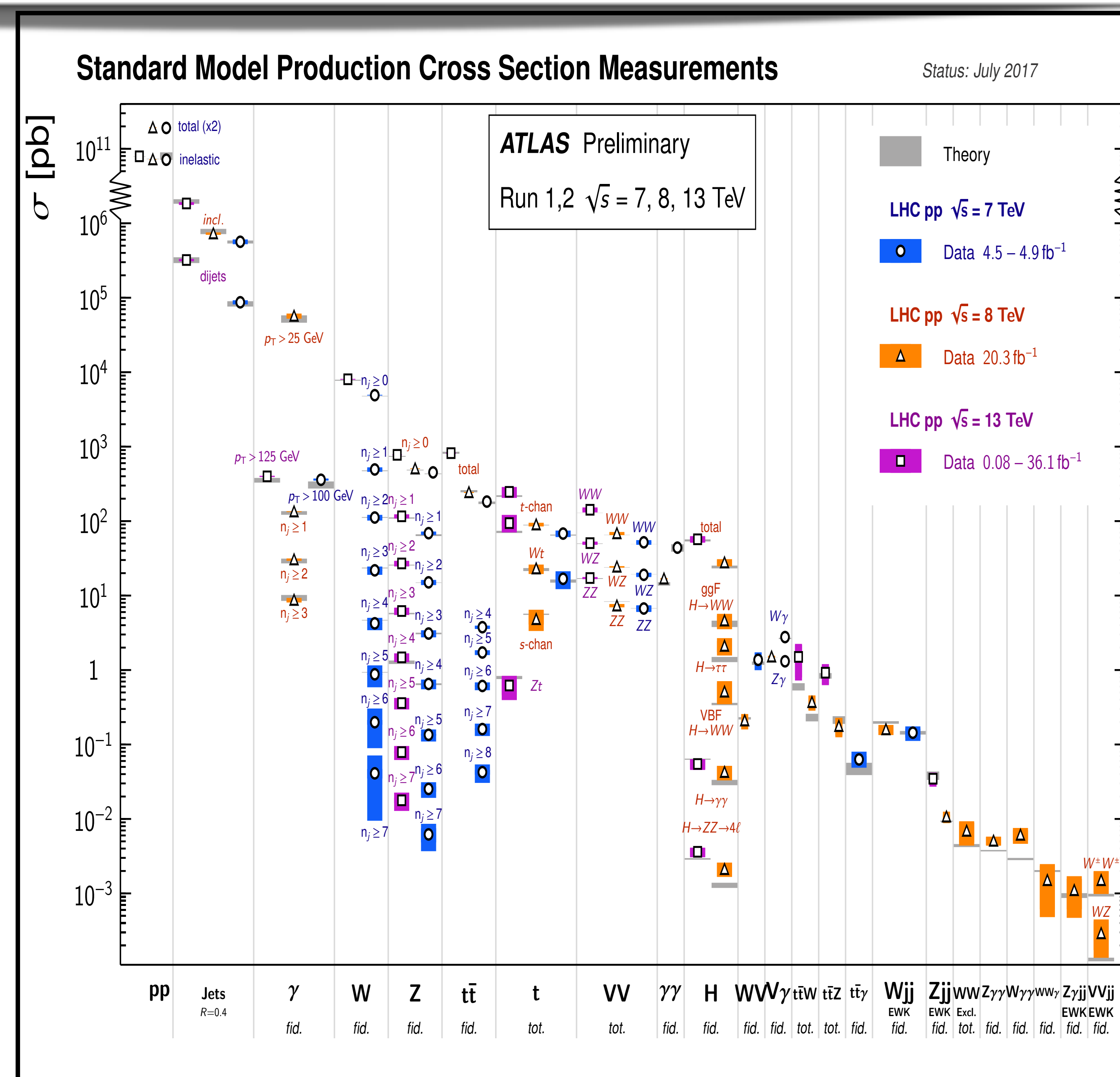


rules the world!

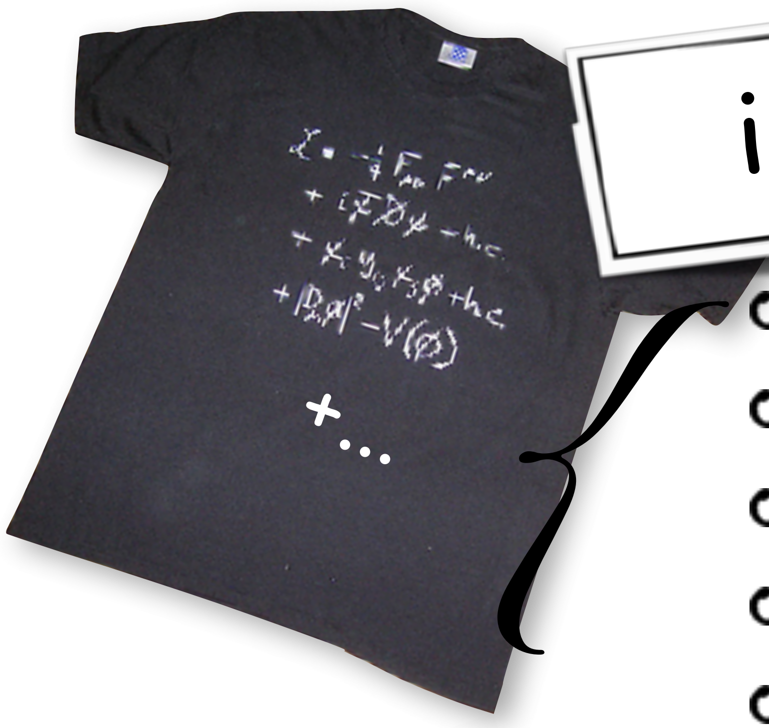
[and we, HEP practitioners, are all entitled for some royalties!]

the same set of eqs. describe phenomena over 15 orders of magnitude





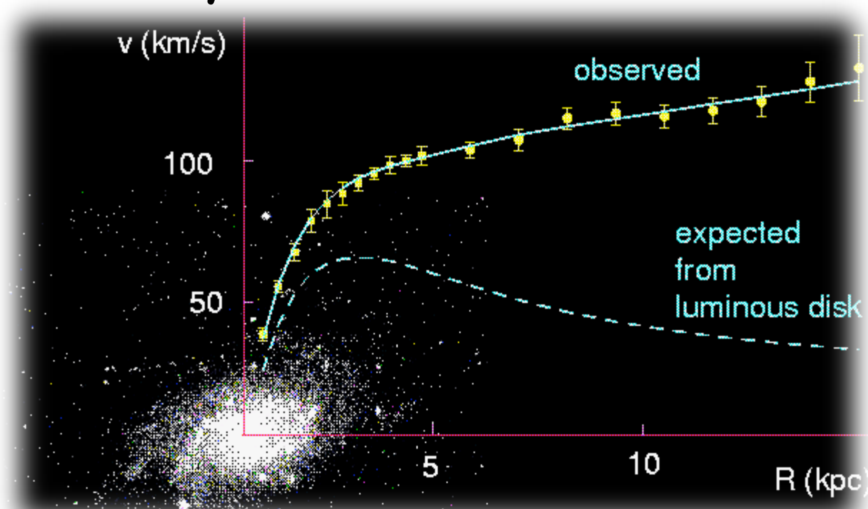
The SM and... the rest of the Universe

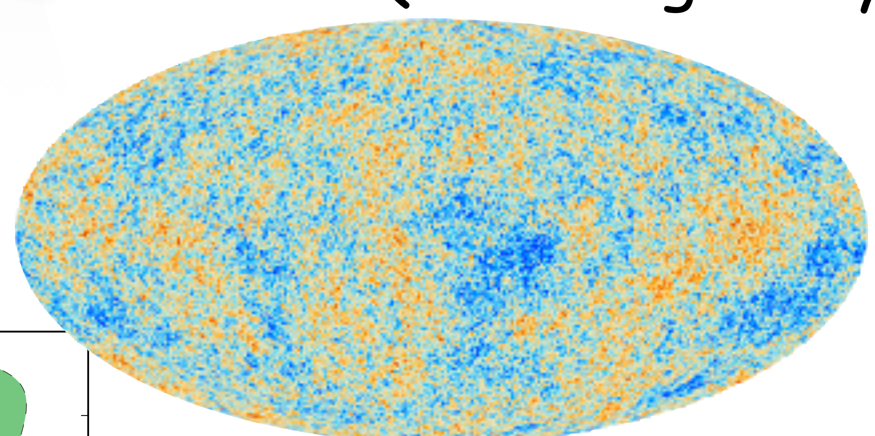


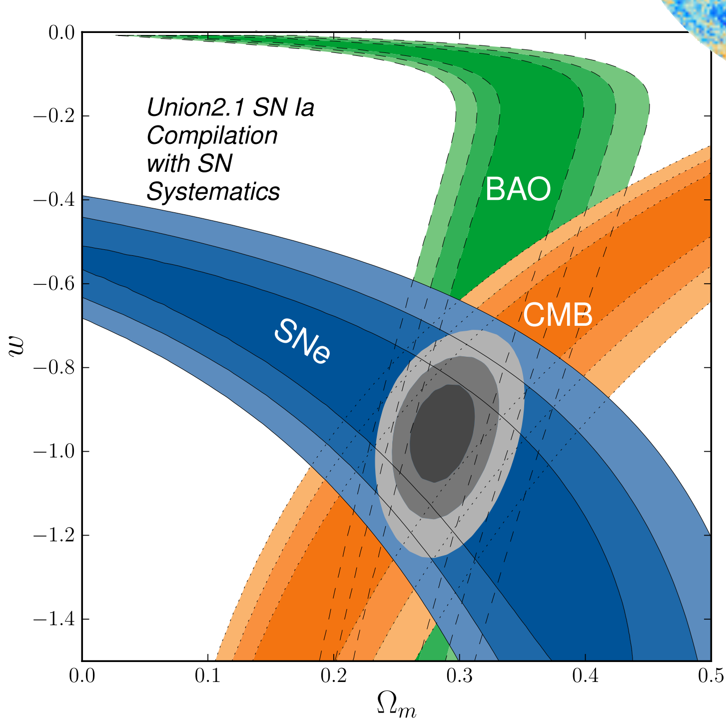
is not enough

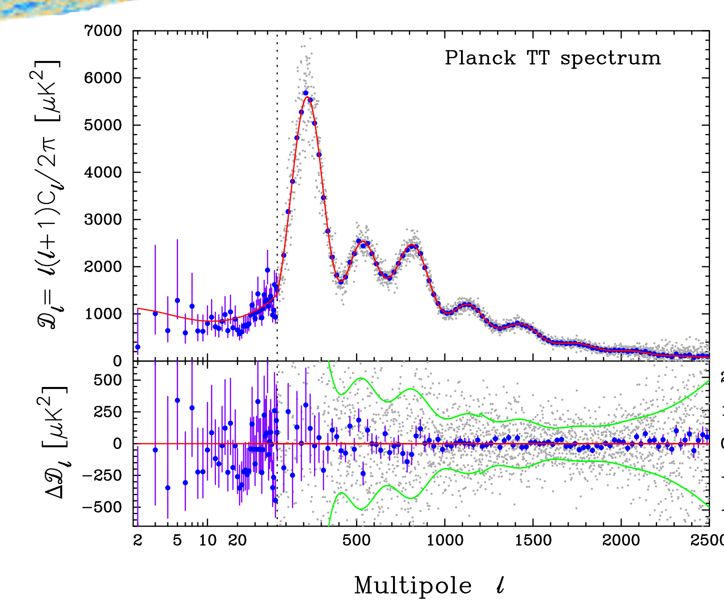
[and we all have to return our royalties!]

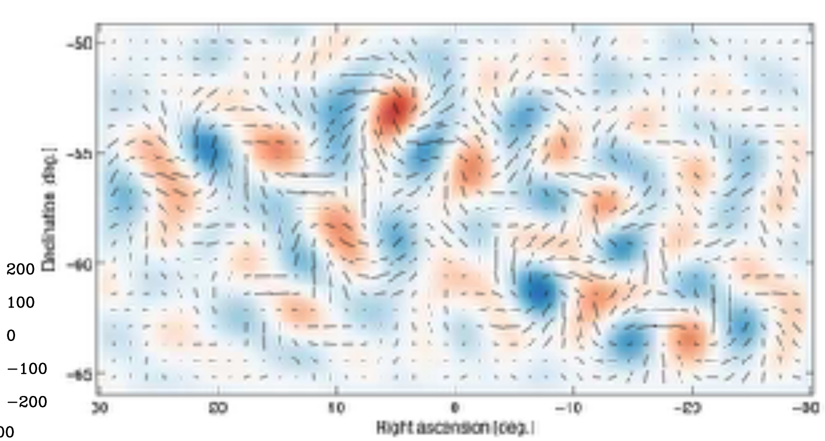
- neutrino masses
- matter-antimatter asymmetry
- Dark Matter
- Dark Energy
- Quantum gravity











What is the scale of New Physics?

High Scale Wishes

small EDMs, FCNC: $\dfrac{gF_{\mu\nu}\bar{\psi}H\sigma^{\mu\nu}\psi}{M_{\rm NP}^2}$

tiny neutrino masses: $\dfrac{(LH)^2}{M_{\rm NP}}$

slow proton decay: $\dfrac{UUDE}{M_{\rm NP}^2}$

Low Scale Wishes

small EDMs: $\mathrm{arg det Y} \leq 10^{-10}$

↪ axion?

tiny vacuum energy: $\Lambda \approx M_{\rm NP}^4 \gg \left(10^{-3}\mathrm{eV}\right)^4$

↪ ?

light Higgs boson: $m_H^2 \approx M_{\rm NP}^2 \gg (125\mathrm{GeV})^2$

↪ light susy?

Where is everyone?

even new physics at few hundreds of GeV might be difficult to see and could escape our detection

- **compressed spectra**
- **displaced vertices**
- **no MET, soft decay products, long decay chains**
- **uncoloured new physics**

$\not{R}$-susy

Neutral naturalness
(twin Higgs, folded susy)

Relaxion

Building the SM

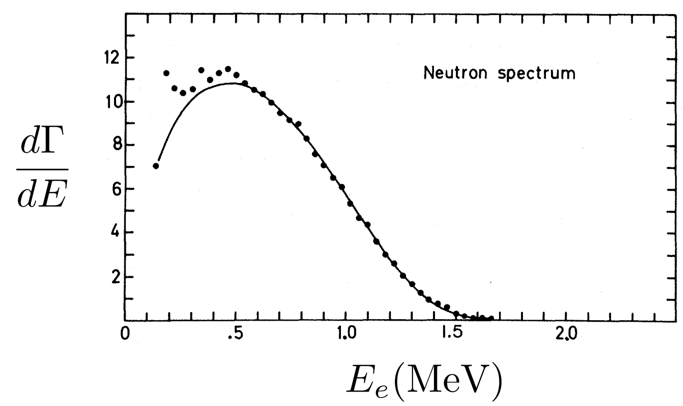
Beta decay & Fermi Theory

$${}^{40}_{19}\text{K} \to {}^{40}_{20}\text{Ca}^+ + e^- \qquad {}^{64}_{29}\text{Cu} \to {}^{64}_{30}\text{Zn}^+ + e^- \qquad {}^{3}_{1}\text{H} \to {}^{3}_{2}\text{He}^+ + e^-$$

- Two body decays: A→B+C

$$E_B = \frac{m_A^2 + m_B^2 - m_C^2}{2m_A} c^2 \qquad p = \frac{\sqrt{\lambda(m_A, m_B, m_C)}}{2m_A} c$$

$$\lambda(m_A, m_B, m_C) = (m_A + m_B + m_C)(m_A + m_B - m_C)(m_A - m_B + m_C)(m_A - m_B - m_C)$$



fixed energy of daughter particles (pure SR kinematics, independent of the dynamics)

⇛ non-conservation of energy?

Pauli '30: ∃ neutrino, very light since end-point of spectrum is close to 2-body decay limit

ν first observed in '53 by Cowan and Reines

- N-body decays: A→B$_1$+B$_2$+...+B$_N$

$$E_{B_1}^{\min} = m_{B_1} c^2 \qquad E_{B_1}^{\max} = \frac{m_A^2 + m_{B_1}^2 - (m_{B_2} + \ldots + m_{B_N})^2}{2m_A} c^2$$

$$n \longrightarrow p + e^- + \bar{\nu}_e$$

Fermi theory '33

$$\mathcal{L} = G_{\mathcal{F}} (\bar{n}p)(\bar{\nu}_e e)$$

exp: $G_F = 1.166 \times 10^{-5}$ GeV^{-2}

Need to go beyond Fermi

How are we sure that muon and neutron decays proceed via the same interactions?

$\tau_\mu \approx 10^{-6}$s vs. $\tau_{neutron} \approx 900$s

$$\underset{[\text{mass}]^4}{\mathcal{L}} = \underset{[\text{mass}]^{-2}}{G_F}\, \underset{[\text{mass}]^{3/2\times 4}}{\psi^4} \quad \Rightarrow \quad \Gamma \propto G_F^2 \underset{[\text{mass}]}{m^5}$$

for the muon, the relevant mass scale is the muon mass m_μ=105MeV: $\Gamma_\mu = \dfrac{G_F^2 m_\mu^5}{192\pi^3} \sim 10^{-19}\,\text{GeV}$

for the neutron, the relevant mass scale is (m_n-m_p)≈1.29MeV: $\Gamma_n = \mathcal{O}(1)\dfrac{G_F^2 \Delta m^5}{\pi^3} \sim 10^{-28}\,\text{GeV}$

ex: what about $\pi^\pm$ decay $\tau_\pi \approx 10^{-8}$s? Why $\dfrac{\Gamma(\pi^- \to e^- \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)} \sim 10^{-4}$?

What about weak scattering process, e.g. $e\nu_e \to e\nu_e$?

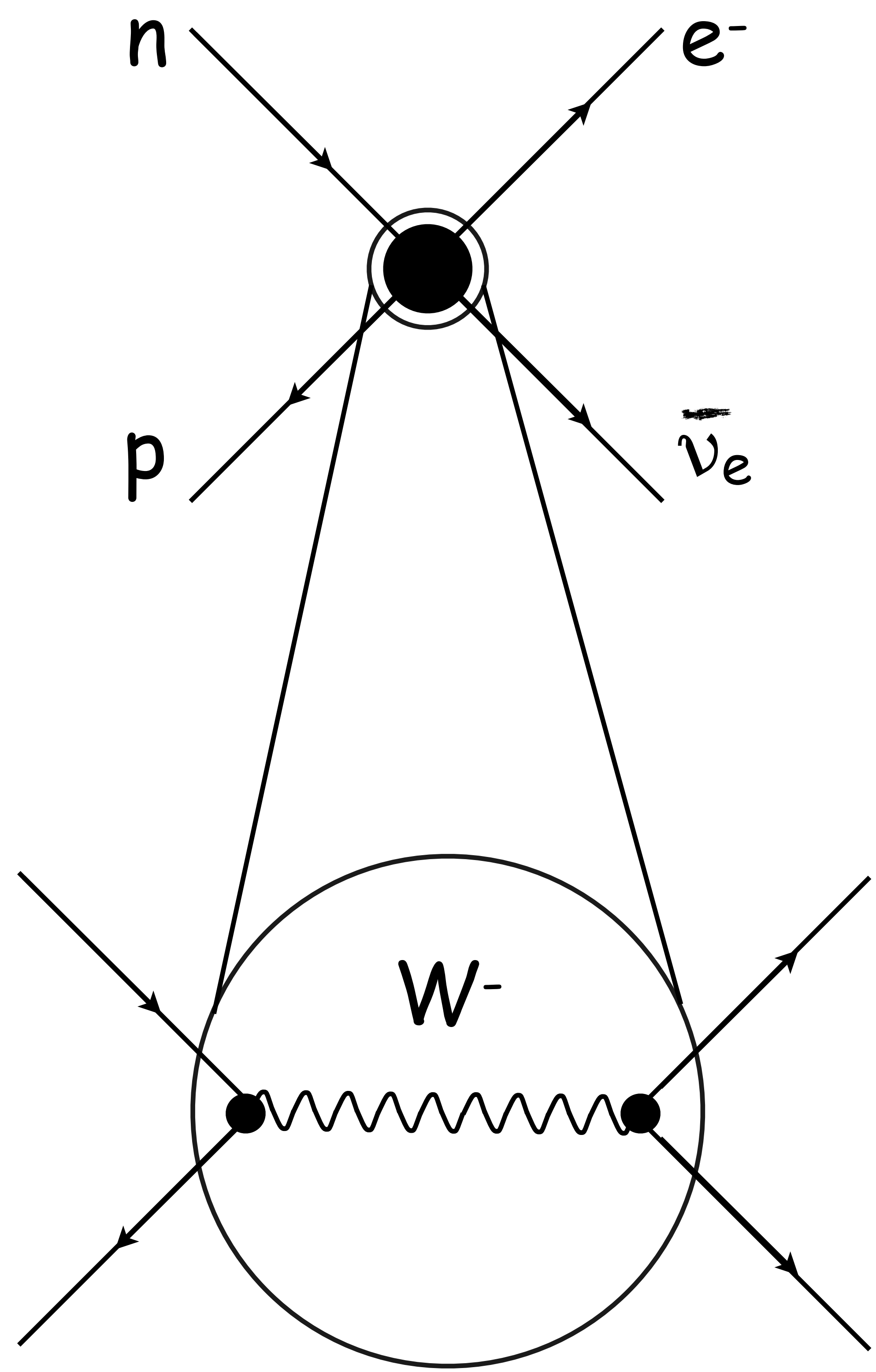
$$\underset{[\text{mass}]^{-2}}{\sigma} \propto \underset{[\text{mass}]^{-2\times 2}}{G_F^2}\, \underset{[\text{mass}]^{2}}{E^2} \quad \Rightarrow$$

non conservation of probability
(non-unitary theory)
inconsistent at energy above 300GeV

Why Gauge Theories?

What about weak scattering process, e.g. $e\nu_e \to e\nu_e$?

$$\underset{[\mathrm{mass}]^{-2}}{\sigma} \propto \underset{[\mathrm{mass}]^{-2\times 2}}{G_F^2} \underset{[\mathrm{mass}]^{2}}{E^2}$$



Gauge theory

$$\sigma \propto g^4 \frac{E^2}{m_W^2\,(E^2 + m_W^2)}$$

- match with Fermi theory at low energy $G_{\mathcal{F}} = \dfrac{\sqrt{2}g^2}{8m_W^2}$

  (we say that the Fermi theory is an **effective theory** of the weak gauge theory at low energy)

- good high energy behaviour

exp. m_W=80.4 GeV
➡ g ≈0.6, ie, same order as e=0.3
unification EM & weak interactions

From Gauge Theory back to Fermi

We can derive the Fermi current-current contact interactions by "integrating out" the gauge bosons, i.e., by replacing in the Lagrangian the W by their equation of motion. Here is a simple derivation (a better one taking into account the gauge kinetic term and the proper form of the fermionic current will be presented in the lecture, for the moment, take it as a heuristic derivation)

$$\mathcal{L} = -m_W^2 W_\mu^+ W_\nu^- \eta^{\mu\nu} + g W_\mu^+ J_\nu^- \eta^{\mu\nu} + g W_\nu^- J_\nu^+ \eta^{\mu\nu}$$

$$J^{+\mu} = \bar{n}\gamma^\mu p + \bar{e}\gamma^\mu \nu_e + \bar{\mu}\gamma^\mu \nu_\mu + \dots \qquad \text{and} \qquad J^{-\mu} = \left(J^{+\mu}\right)^*$$

The equation of motion for the gauge fields: $\dfrac{\partial \mathcal{L}}{\partial W_\mu^+} = 0 \qquad \Rightarrow \qquad W_\mu^- = \dfrac{g}{m_W^2} J_\mu^-$

Plugging back in the original Lagrangian, we obtain an effective Lagrangian (valid below the mass of the gauge bosons):

$$\mathcal{L} = \frac{g^2}{m_W^2} J_\mu^+ J_\nu^- \eta^{\mu\nu}$$

Which is the Fermi current-current interaction. The Fermi constant is given by $G_F = \dfrac{g^2}{m_W^2}$
(the correct expression involves a different normalisation factor)

In the current-current product, the term $(\bar{n}\gamma^\mu p)(\bar{\nu}_e \gamma^\nu e)\eta_{\mu\nu}$ is responsible for beta decay, while the term $(\bar{\mu}\gamma^\mu \nu_\mu)(\bar{\nu}_e \gamma^\nu e)\eta_{\mu\nu}$ is responsible for muon decay. Both decays are controlled by the same coupling, as indicated by the measurements of the lifetimes of the muon and neutron.

Why non-abelian Gauge Theories?

EM = exchange of photon = U(1) gauge symmetry

EM U(1) $\quad \phi \to e^{i\alpha}\phi \quad$ but $\quad \partial_\mu \phi \to e^{i\alpha}\,(\partial_\mu\phi) + \underbrace{i(\partial_\mu\alpha)}_{\neq 0 \text{ if local transformations}}\,\phi$

EM field and covariant derivative $\quad \partial_\mu\phi + ieA_\mu\phi \to e^{i\alpha}(\partial_\mu\phi + ieA_\mu\phi)$

if $\quad A_\mu \to A_\mu - \frac{1}{e}\partial_\mu\alpha$

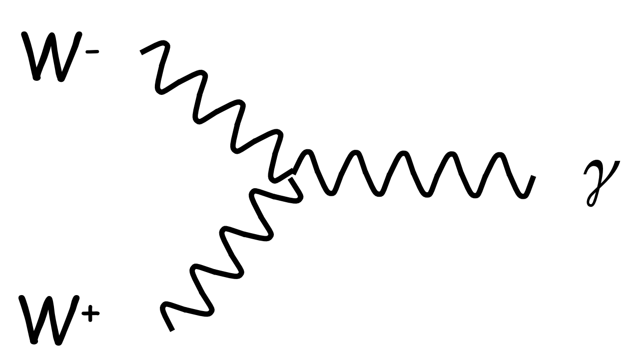
the EM field keeps track of the phase in different points of the space-time

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \quad \to F_{\mu\nu}$$

photon do not interact with itself because it doesn't carry an electric charge

W carries an electric charge since it mediates charged current interactions

W interacts with the photon ☛ non-abelian interactions

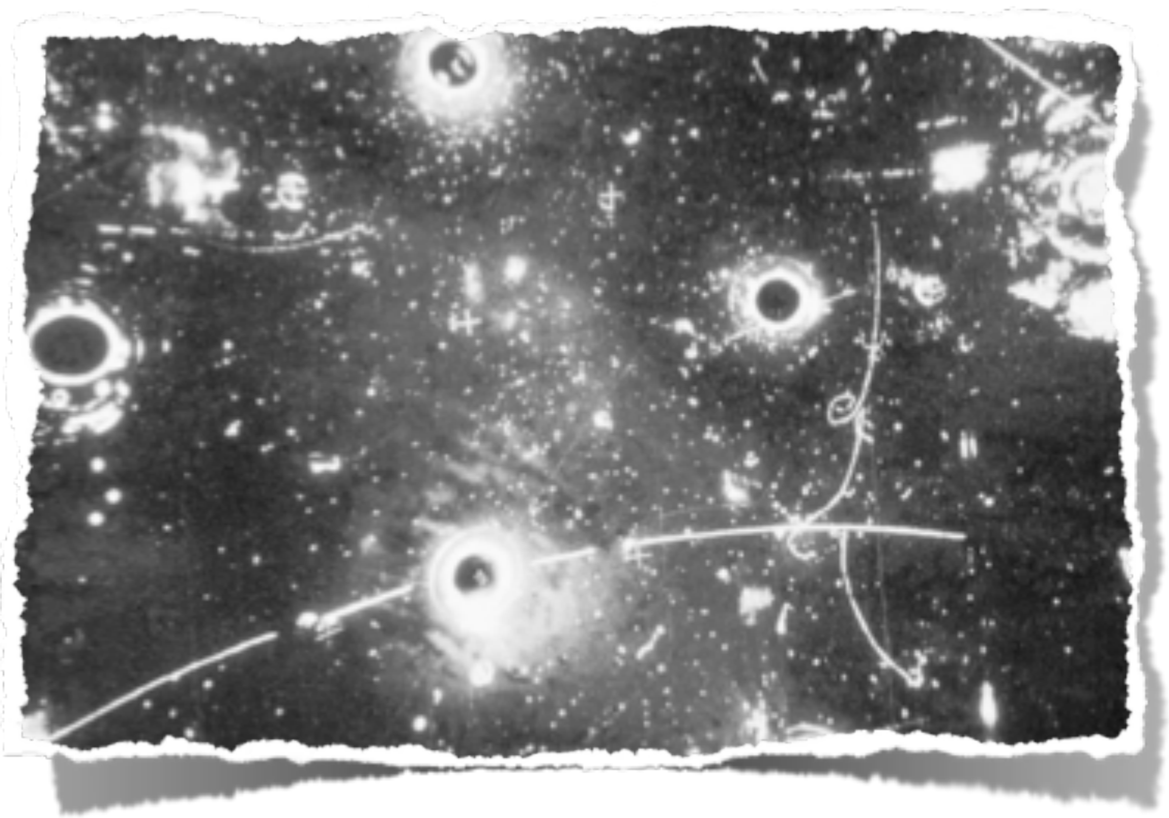


The Standard Model

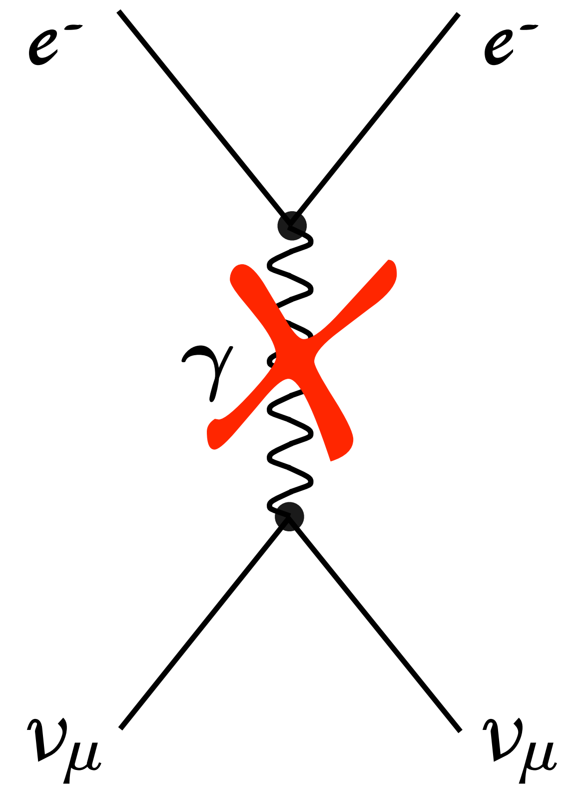
the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

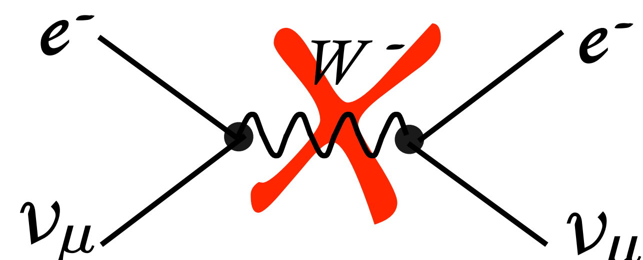
$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

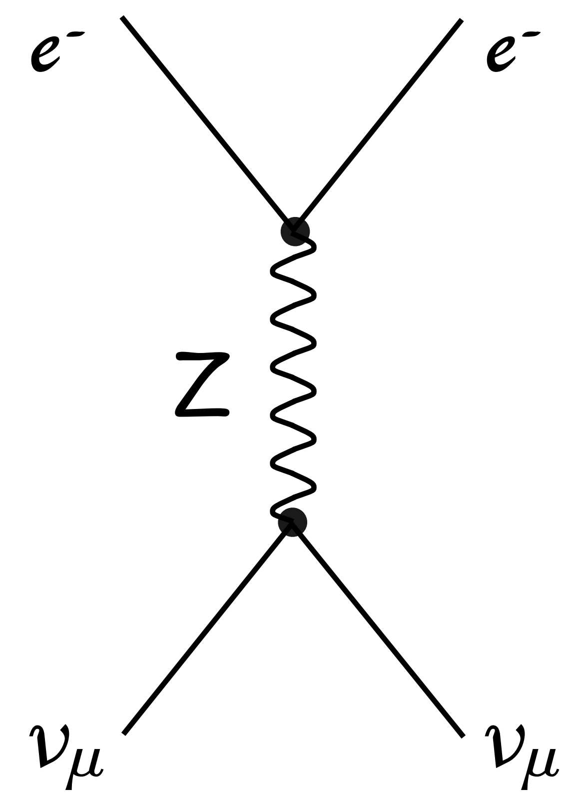
$$\nu_\mu e^- \to \nu_\mu e^-$$



[Gargamelle collaboration, '73]





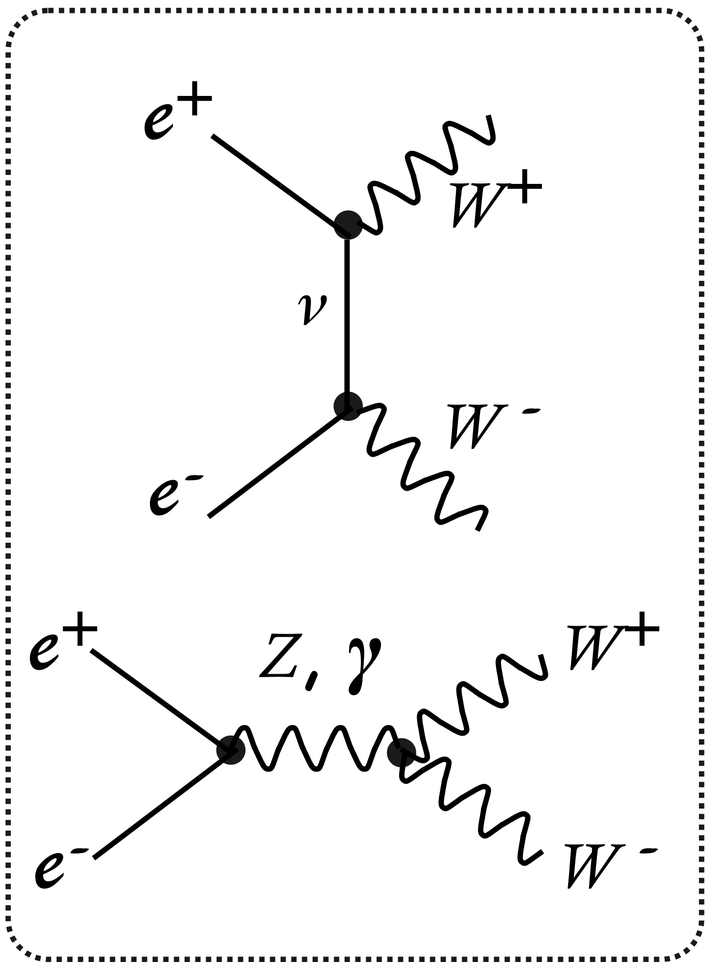


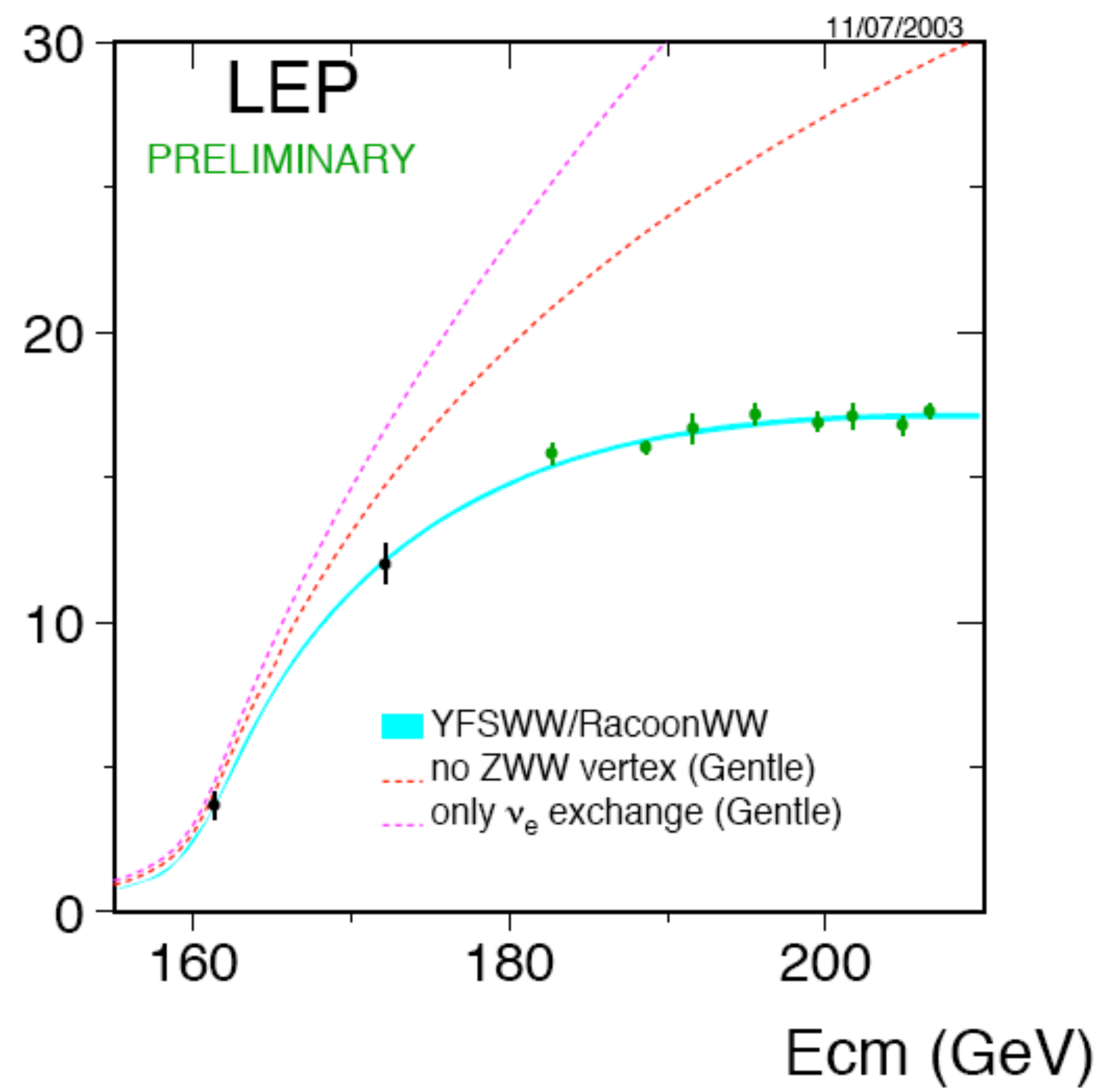
Gauge Theory as a Dynamical Principle

the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y$

$e^+e^- \to W^+W^-$





The SM and the Mass Problem

the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y$

the masses of the quarks, leptons and gauge bosons don't obey the full gauge invariance

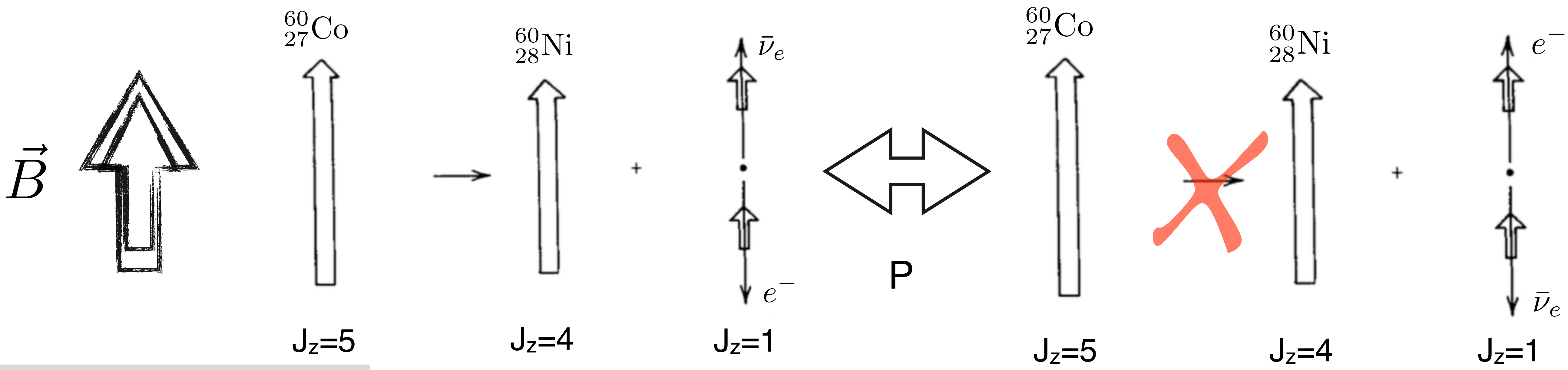
$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$ is a doublet of $SU(2)_L$ but $\quad m_{\nu_e} \ll m_e$

a mass term for the gauge field isn't invariant under gauge transformation $\quad \delta A_\mu^a = \partial_\mu \epsilon^a + g f^{abc} A_\mu^b \epsilon^c$

$\Rightarrow$ spontaneous breaking of gauge symmetry $\Leftarrow$

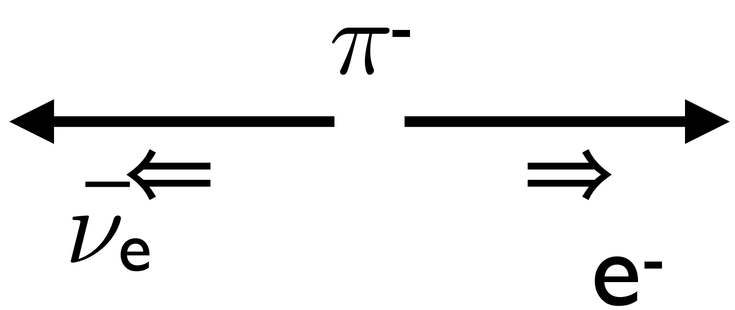
SM is a Chiral Theory

Weak interactions maximally violates P



$^{60}_{27}\mathrm{Co} \to {}^{60}_{28}\mathrm{Ni} + e^- + \bar{\nu}_e$ only LH e- produced

TH: Yang&Lee '56. EXP: Wu '57



Conservation of momentum and spin imposes to have a RH e-

Weak decays proceed only w/ LH e-
So the amplitude is prop. to m_e

$$\frac{\Gamma(\pi^- \to e^- \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)} \propto \frac{m_e^2}{m_\mu^2} \sim 2 \times 10^{-5} \sim 10^{-4}_{\text{obs}}$$

Extra phase-space factor

Fermion Masses

SM is a chiral theory (≠ QED that is vector-like)

$$m_e \bar{e}_L e_R + h.c. \quad \text{is not gauge invariant}$$

The SM Lagrangian doesn't not contain fermion mass terms
fermion masses are emergent quantities
that originate from interactions with Higgs vev

$$y_{ij} \bar{f}_{L_i} H f_{R_j} = \frac{y_{ij} v}{\sqrt{2}} \bar{f}_{L_i} f_{R_j} + \frac{y_{ij}}{\sqrt{2}} h \bar{f}_{L_i} f_{R_j}$$

Fermion Masses

In SM, the Yukawa interactions are the only source of the fermion masses

$$y_{ij}\bar{f}_{L_i}Hf_{R_j} = \underbrace{\frac{y_{ij}v}{\sqrt{2}}\bar{f}_{L_i}f_{R_j}}_{\text{mass}} + \underbrace{\frac{y_{ij}}{\sqrt{2}}h\bar{f}_{L_i}f_{R_j}}_{\text{higgs-fermion interactions}}$$

both matrices are simultaneously diagonalizable

⇩ ⇩ ⇩

no tree-level Flavor Changing Current induced by the Higgs

Not true anymore if the SM fermions mix with vector-like partners(*) or for non-SM Yukawa

$$y_{ij}\left(1+c_{ij}\frac{|H|^2}{f^2}\right)\bar{f}_{L_i}Hf_{R_j} = \frac{y_{ij}v}{\sqrt{2}}\left(1+c_{ij}\frac{v^2}{2f^2}\right)\bar{f}_{L_i}f_{R_j} + \left(1+3c_{ij}\frac{v^2}{2f^2}\right)\frac{y_{ij}}{\sqrt{2}}h\bar{f}_{L_i}f_{R_j}$$

Look for SM forbidden Flavor Violating decays $h \to \mu\tau$ and $h \to e\tau$

(look also at $t \to hc$ ATLAS '14)

- weak indirect constrained by flavor data ($\mu \to e\gamma$): BR<10%
- ATLAS and CMS have the sensitivity to set bounds O(1%)
- ILC/CLIC/FCC-ee can certainly do much better

Blankenburg, Ellis, Isidori '12

Harnik et al '12
Davidson, Verdier '12
CMS-PAS-HIG-2014-005

(*) e.g. Buras, Grojean, Pokorski, Ziegler '11

Fermion Masses

In SM, the Yukawa interactions are the only source of the fermion masses

$$y_{ij}\bar{f}_{L_i} H f_{R_j} = \frac{y_{ij} v}{\sqrt{2}} \bar{f}_{L_i} f_{R_j} + \frac{y_{ij}}{\sqrt{2}} h \bar{f}_{L_i} f_{R_j}$$

mass

higgs-fermion interactions

both matrices are simultaneously diagonalizable

no tree-level Flavor Changing Current induced by the Higgs

Quark mixings

$$\mathcal{L}_{Yuk} \quad = \quad \lambda^L_{ij}(\bar{L}^i_L \phi^c) l^j_R + \lambda^U_{ij}(\bar{Q}^i_{L,\alpha}\phi) u^j_{R,\alpha} + \lambda^D_{ij}(\bar{Q}^i_{L,\alpha}\phi^c) d^j_{R,\alpha} + cc$$

$$\mathcal{L}^\dagger_L \left(\frac{v}{\sqrt{2}}\lambda^L\right)\mathcal{L}_R = \begin{pmatrix} m_e & & \\ & m_\mu & \\ & & m_\tau \end{pmatrix}$$

$$\mathcal{U}^\dagger_L \left(\frac{-v}{\sqrt{2}}\lambda^U\right)\mathcal{U}_R = \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix}$$

$$\mathcal{D}^\dagger_L \left(\frac{v}{\sqrt{2}}\lambda^D\right)\mathcal{D}_R = \begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix}$$

$$\begin{aligned} \mathcal{L}_{Yuk\,quad} = & - \left(\bar{e}_L, \bar{\mu}_L, \bar{\tau}_L\right) \begin{pmatrix} m_e & & \\ & m_\mu & \\ & & m_\tau \end{pmatrix} \begin{pmatrix} e_R \\ \mu_R \\ \tau_R \end{pmatrix} \\ & - \left(\bar{u}_{L,\alpha}, \bar{c}_{L,\alpha}, \bar{t}_{L,\alpha}\right) \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix} \begin{pmatrix} u_{R,\alpha} \\ c_{R,\alpha} \\ t_{R,\alpha} \end{pmatrix} \\ & - \left(\bar{d}_{L,\alpha}, \bar{s}_{L,\alpha}, \bar{b}_{L,\alpha}\right) \mathcal{V}^\dagger_{KM} \begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix} \begin{pmatrix} d_{R,\alpha} \\ s_{R,\alpha} \\ b_{R,\alpha} \end{pmatrix} \\ & + \; cc \end{aligned}$$

$$\mathcal{V}_{KM} = \mathcal{D}^\dagger_L \mathcal{U}_L$$

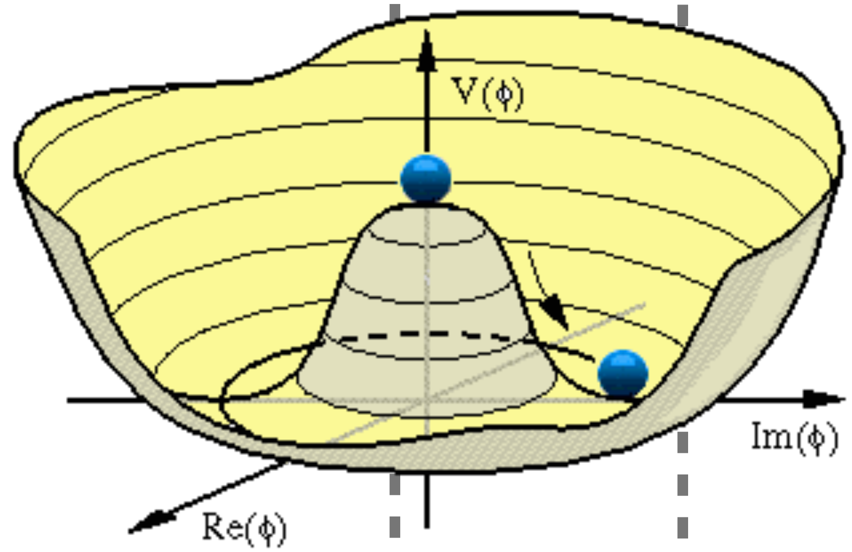
Spontaneous Symmetry Breaking

Symmetry of the Lagrangian

$$SU(2)_L \times U(1)_Y$$

Higgs Doublet

$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$



Symmetry of the Vacuum

$$U(1)_{e.m.}$$

Vacuum Expectation Value

$$\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \quad \text{with} \quad v \approx 246 \text{ GeV}$$

$$D_\mu H = \partial_\mu H - \frac{i}{2} \begin{pmatrix} g W^3_\mu + g' B_\mu & \sqrt{2} g W^+_\mu \\ \sqrt{2} g W^-_\mu & -g W^3_\mu + g' B_\mu \end{pmatrix} H \quad \text{with} \quad \mathrm{W}^\pm_\mu = \tfrac{1}{\sqrt{2}} \left(\mathrm{W}^1_\mu \mp \mathrm{W}^2_\mu \right)$$

$$|D_\mu H|^2 = \tfrac{1}{4}\, g^2 v^2\, W^+_\mu W^{-\,\mu} + \tfrac{1}{8} \left(W^3_\mu \; B_\mu \right) \begin{pmatrix} g^2 v^2 & -g g' v^2 \\ -g g' v^2 & g'^2 v^2 \end{pmatrix} \begin{pmatrix} W^{3\,\mu} \\ B^\mu \end{pmatrix}$$

- Gauge boson spectrum
  - electrically charged bosons $\quad M_W^2 = \frac{1}{4} g^2 v^2$
  - electrically neutral bosons

$$Z_\mu = c W^3_\mu - s B_\mu$$
$$\gamma_\mu = s W^3_\mu + c B_\mu$$

Weak mixing angle

$$c = \frac{g}{\sqrt{g^2 + g'^2}} \qquad s = \frac{g'}{\sqrt{g^2 + g'^2}}$$

$$M_Z^2 = \tfrac{1}{4} (g^2 + g'^2) v^2$$

$$M_\gamma = 0$$

Interactions Fermions-Gauge Bosons

Gauge invariance says:

$$\mathcal{L} = gW^3_\mu \left(\sum_i T_{3L\,i}\ \bar{\psi}_i \bar{\sigma}^\mu \psi_i \right) + g' B_\mu \left(\sum_i y_i\ \bar{\psi}_i \bar{\sigma}^\mu \psi_i \right)$$

Going to the mass eigenstate basis:

$$Z_\mu = cW^3_\mu - sB_\mu \qquad \text{with} \qquad c = \frac{g}{\sqrt{g^2+g'^2}}$$

$$\gamma_\mu = sW^3_\mu + cB_\mu \qquad \qquad s = \frac{g'}{\sqrt{g^2+g'^2}}$$

$$Q = T_{3L} + Y$$

$$\boxed{\mathcal{L} = \sqrt{g^2+g'^2} Z_\mu \left(\sum_i (T_{3L\,i} - s^2 Q_i)\ \bar{\psi}_i \bar{\sigma}^\mu \psi_i \right) + \frac{gg'}{\sqrt{g^2+g'^2}} \gamma_\mu \left(\sum_i Q_i\ \bar{\psi}_i \bar{\sigma}^\mu \psi_i \right)}$$

not protected by gauge invariance
corrected by radiative corrections + new physics

protected by $U(1)_{em}$ gauge invariance
$\Rrightarrow$ no correction

electric charge

$$e = \frac{gg'}{\sqrt{g^2+g'^2}} = sg = cg'$$

Custodial Symmetry

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_w} = \frac{\frac{1}{4}g^2 v^2}{\frac{1}{4}(g^2+g'^2)v^2\frac{g^2}{g^2+g'^2}} = 1$$

- Consequence of an approximate global symmetry of the Higgs sector

$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$ Higgs doublet = 4 real scalar fields

$$V(H) = \lambda\left(H^\dagger H - \frac{v^2}{2}\right)^2$$ is invariant under the rotation of the four real components

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

$$SU(2)_R$$

$$SU(2)_L \Rightarrow \begin{pmatrix} i\sigma^2 H^\star & H \end{pmatrix} = \Phi$$

2x2 matrix

$$\Phi^\dagger\Phi = H^\dagger H \begin{pmatrix} 1 & \\ & 1 \end{pmatrix}$$

$$V(H) = \frac{\lambda}{4}\left(\mathrm{tr}\Phi^\dagger\Phi - \mathrm{v}^2\right)^2$$

explicitly invariant under $SU(2)_L \times SU(2)_R$

Custodial Symmetry

Higgs vev

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

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

unbroken symmetry in the broken phase

$$(W^1_\mu, W^2_\mu, W^3_\mu) \quad \text{transforms as a triplet}$$

$$(Z_\mu \, \gamma_\mu) \begin{pmatrix} M_Z^2 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} Z^\mu \\ \gamma^\mu \end{pmatrix} = (W^3_\mu \, B_\mu) \begin{pmatrix} c^2 M_Z^2 & -csM_Z^2 \\ -csM_Z^2 & s^2 M_Z^2 \end{pmatrix} \begin{pmatrix} W^{3\,\mu} \\ B^\mu \end{pmatrix}$$

The $SU(2)_V$ symmetry imposes the same mass term for all W^i thus $c^2 M_Z^2 = M_W^2$

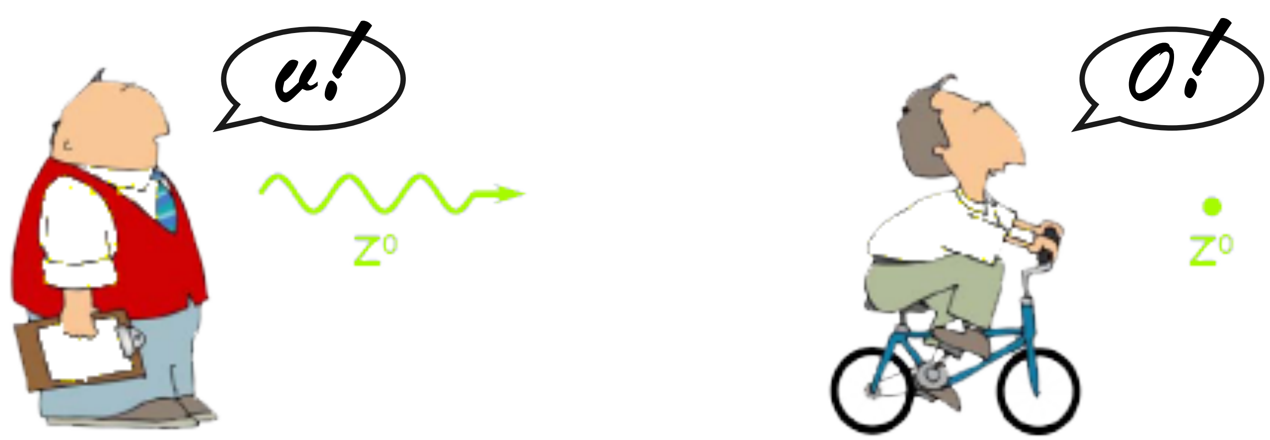
$\rho = 1$

The hypercharge gauge coupling and the Yukawa couplings break the custodial $SU(2)_V$, which will generate a (small) deviation to $\rho = 1$ at the quantum level.

The longitudinal polarization of massive W, Z

a massless particle is never at rest: always possible to distinguish (and eliminate!) the longitudinal polarization

3=2+1
Guralnik et al '64



the longitudinal polarization is physical for a massive spin-1 particle

(pictures: courtesy of G. Giudice)

symmetry breaking: new phase with more degrees of freedom

$$\epsilon_{\parallel} = \left(\frac{|\vec{p}|}{M}, \frac{E}{M} \frac{\vec{p}}{|\vec{p}|} \right)$$ polarization vector grows with the energy

The longitudinal polarization of W, Z

Indeed a massive spin 1 particle has 3 physical polarizations:

$$A_\mu = \epsilon_\mu \; e^{ik_\mu x^\mu}$$

$$\epsilon^\mu \epsilon_\mu = -1 \qquad k^\mu \epsilon_\mu = 0$$

$$k^\mu = (E, 0, 0, k)$$

with $\quad k_\mu k^\mu = E^2 - k^2 = M^2$

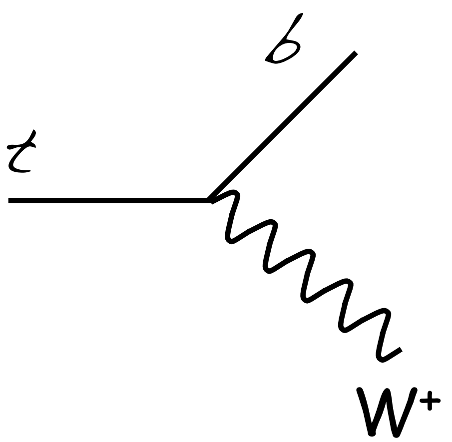
- 2 transverse: $\begin{cases} \epsilon_1^\mu = (0,1,0,0) \\ \epsilon_2^\mu = (0,0,1,0) \end{cases}$
- 1 longitudinal: $\epsilon_\parallel^\mu = (\frac{k}{M}, 0, 0, \frac{E}{M}) \approx \frac{k^\mu}{M} + \mathcal{O}(\frac{E}{M})$

(in the R-ξ gauge, the time-like polarization ($\epsilon^\mu \epsilon_\mu = 1 \quad k^\mu \epsilon_\mu = M$) is arbitrarily massive and decouple)

in the particle rest-frame, no distinction between L and T polarizations
in a frame where the particle carries a lot of kinetic energy, the L polarization "dominates"

The BEH mechanism: “V_L=Goldstone bosons”

At high energy, the physics of the gauge bosons becomes simple



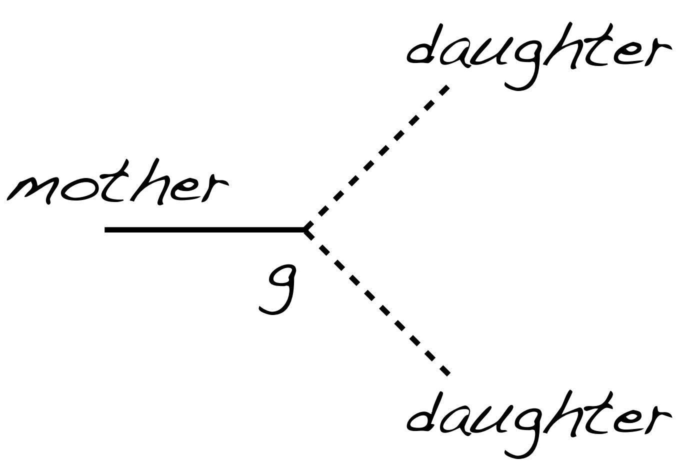
$$\Gamma(t \to bW_L) = \frac{g^2}{64\pi} \frac{m_t^2}{m_W^2} \frac{(m_t^2 - m_W^2)^2}{m_t^3}$$

$$\Gamma(t \to bW_T) = \frac{g^2}{64\pi} \frac{2(m_t^2 - m_W^2)^2}{m_t^3}$$

- at threshold ($m_t \sim m_W$) democratic decay
- at high energy ($m_t \gg m_W$) W_L dominates the decay

At high energy, the dominant degrees of freedom are W_L

~~ why you should be stunned by this result: ~~



we expect: (dimensional analysis) $\Gamma \sim g^2\, m_{\text{mother}}$

instead $\Gamma \propto m^3_{\text{mother}}$ means $g \propto m$ like the Higgs couplings!

very efficient way to get energy from the mother particle $\tau \ll \tau_{\text{naive}}$

Goldstone equivalence theorem
$W^\pm_L$, Z_L ≈ SO(4)/SO(3)

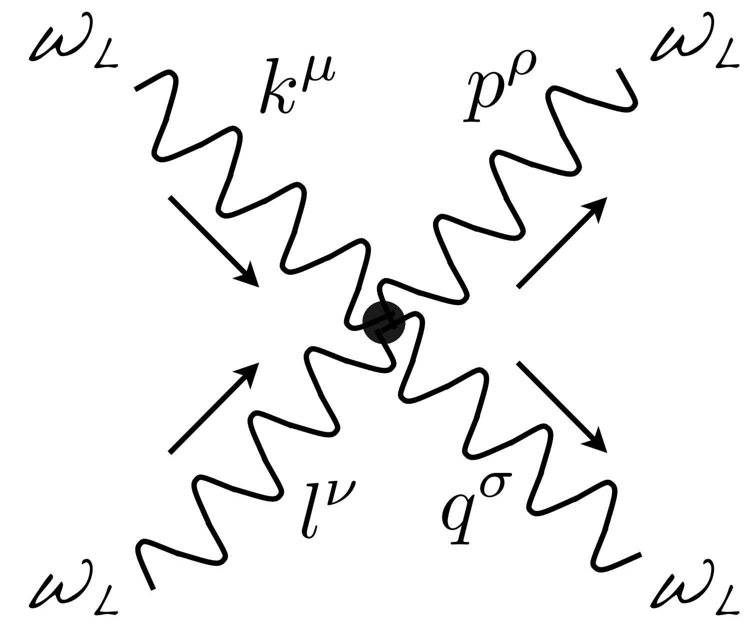
This is the physics that was understood at LEP
The pending question was then: is there something else?
That was the job of the LHC

Call for extra degrees of freedom

NO LOSE THEOREM

Bad high-energy behaviour for the scattering of the longitudinal polarizations

$$\mathcal{A} = \epsilon_{\parallel}^{\mu}(k)\epsilon_{\parallel}^{\nu}(l)g^2\left(2\eta_{\mu\rho}\eta_{\nu\sigma} - \eta_{\mu\nu}\eta_{\rho\sigma} - \eta_{\mu\sigma}\eta_{\nu\rho}\right)\epsilon_{\parallel}^{\rho}(p)\epsilon_{\parallel}^{\sigma}(q)$$



$$\boxed{\mathcal{A} = g^2\frac{E^4}{4M_W^4}}$$

violations of perturbative unitarity around E ~ M/√g (actually M/g)

Extra degrees of freedom are needed to have a good description of the W and Z masses at higher energies

numerically: E ~ 3 TeV ⇦ the LHC was sure to discover something!

What is the SM Higgs?

A single scalar degree of freedom that couples to the mass of the particles

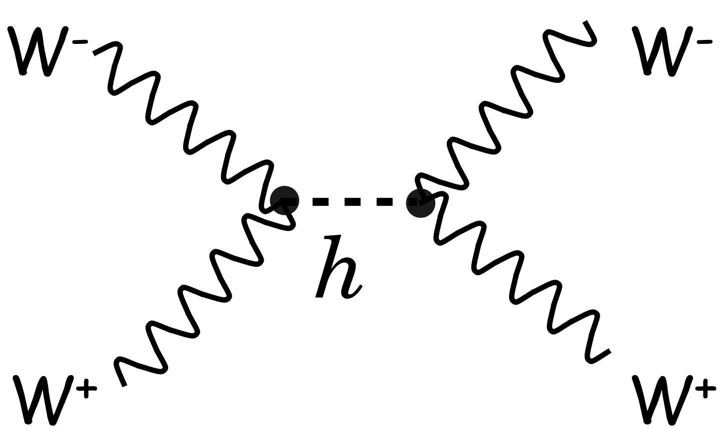
$\Sigma = e^{i\pi^a \sigma^2 / v}$ parametrises the coset SO(4)/SO(3)

$$\mathcal{L} = \frac{v^2}{4} \mathrm{Tr}\, D_\mu \Sigma^\dagger D^\mu \Sigma \xrightarrow{\Sigma = \mathbb{1}} m_W^2 W_\mu^+ W_\mu^+ + \frac{1}{2} m_Z Z_\mu Z^\mu$$

$$\mathcal{L} = \frac{v^2}{4} \mathrm{Tr}\, D_\mu \Sigma^\dagger D^\mu \Sigma \xrightarrow[g = g' = 0]{} \frac{1}{2}(\partial\pi)^2 + \frac{1}{v^2}\partial^2\pi^4 + \ldots$$

$$\mathcal{L}_{\mathrm{EWSB}} = m_W^2 W_\mu^+ W_\mu^+ \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - m_\psi \bar{\psi}_L \psi_R \left(1 + c\frac{h}{v}\right)$$

'a', 'b' and 'c' are arbitrary free couplings



$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{a^2 s^2}{s - m_h^2}\right)$$

growth cancelled for
a = 1
restoration of
perturbative unitarity

What is the Higgs the name of?

A single scalar degree of freedom that couples to the mass of the particles

$$\mathcal{L}_{\rm EWSB} = m_W^2 W_\mu^+ W_\mu^+ \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - m_\psi \bar{\psi}_L \psi_R \left(1 + c\frac{h}{v}\right)$$

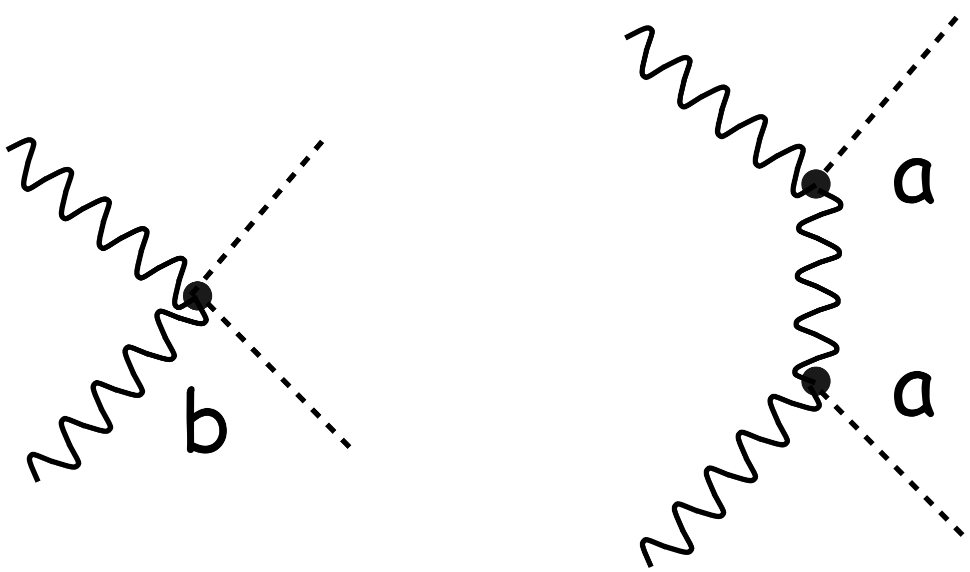
'a', 'b' and 'c' are arbitrary free couplings

For a=1: perturbative unitarity in elastic channels WW $\to$ WW

For b = a^2: perturbative unitarity in inelastic channels WW $\to$ hh

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10



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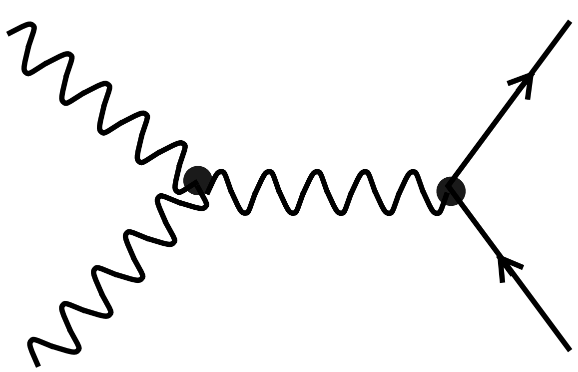
For a=1: perturbative unitarity in elastic channels WW → WW

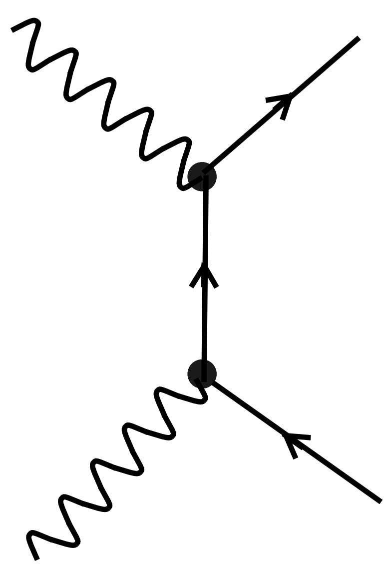
For b = a^2: perturbative unitarity in inelastic channels WW → hh

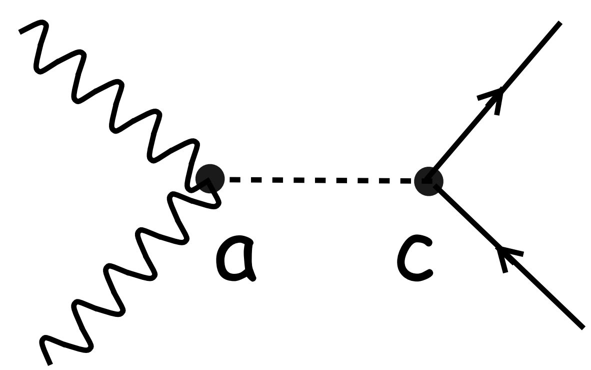
For ac=1: perturbative unitarity in inelastic WW → $\psi\ \psi$

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10







What is the Higgs the name of?

A single scalar degree of freedom that couples to the mass of the particles

$$\mathcal{L}_{\rm EWSB} = m_W^2 W_\mu^+ W_\mu^+ \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - m_\psi \bar{\psi}_L \psi_R \left(1 + c\frac{h}{v}\right)$$

'a', 'b' and 'c' are arbitrary free couplings

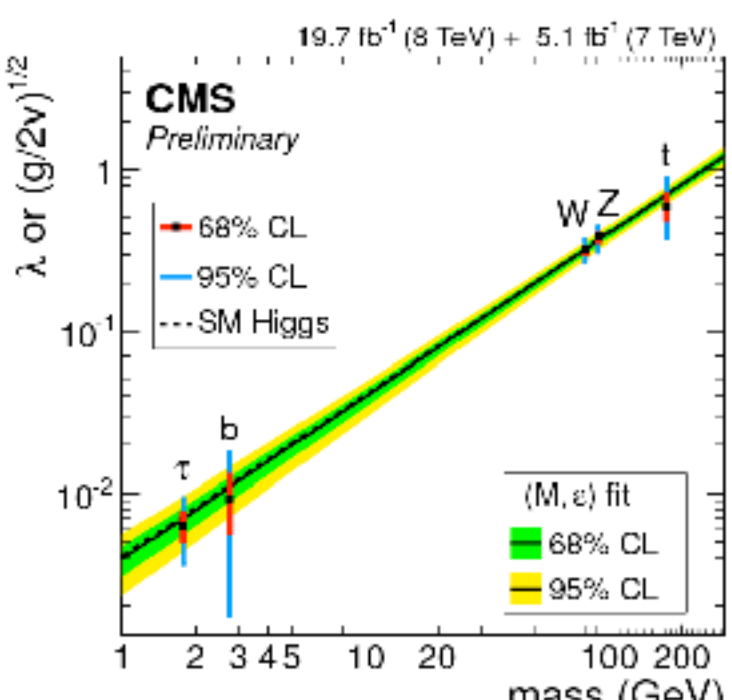
For a=1: perturbative unitarity in elastic channels WW $\to$ WW

For b = a^2: perturbative unitarity in inelastic channels WW $\to$ hh

For ac=1: perturbative unitarity in inelastic WW $\to \psi\,\psi$

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10



CMS PAS-HIG-14-009

Higgs couplings
are proportional
to the masses of the particles

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

HEP with a Higgs boson

The Higgs discovery has been an important milestone for HEP
but it hasn't taught us much about **BSM** yet

typical Higgs coupling deformation: $\frac{\delta g_h}{g_h} \sim \frac{v^2}{f^2} = \frac{g_*^2 \, v^2}{\Lambda_{\rm BSM}^2}$

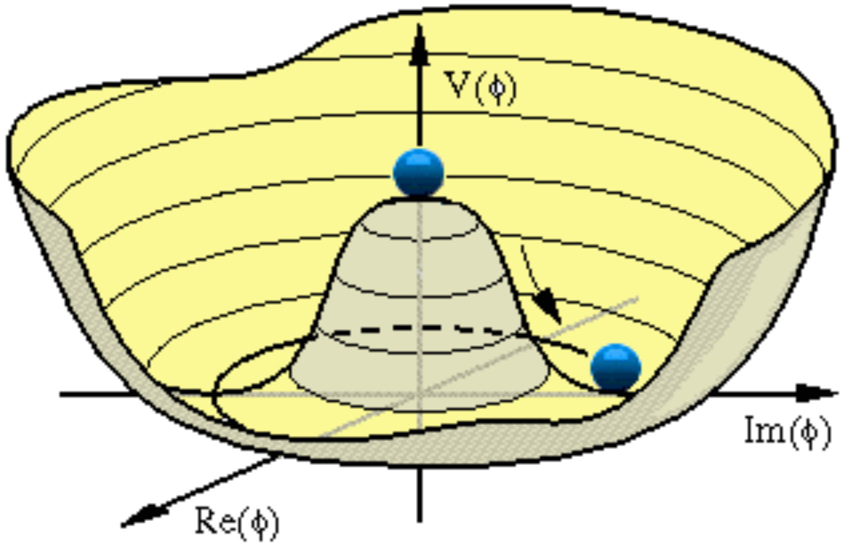
current (and future) LHC sensitivity
O(10-20)% ⇔ Λ_{BSM} > 500(g_*/g_{SM}) GeV

not doing better than direct searches unless in the case of strongly coupled new physics
(notable exceptions: New Physics breaks some structural features of the SM
e.g. flavor number violation as in h→$\mu\tau$)

Higgs precision program is very much wanted
to probe BSM physics

Higgs as a door to BSM

Higgs and EW vacuum Stability

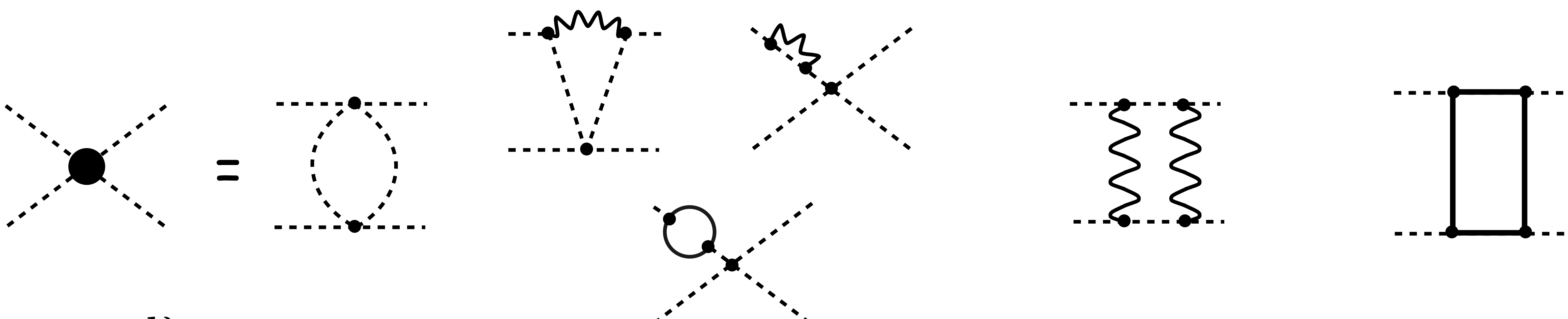


$$\boxed{V(h) = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4}$$

vev: $v^2 = \mu^2/\lambda$ mass: $m_H^2 = 2\lambda v^2$

the vacuum is not empty even classically $(\hbar \to 0)$

How is Quantum Mechanics changing the picture?



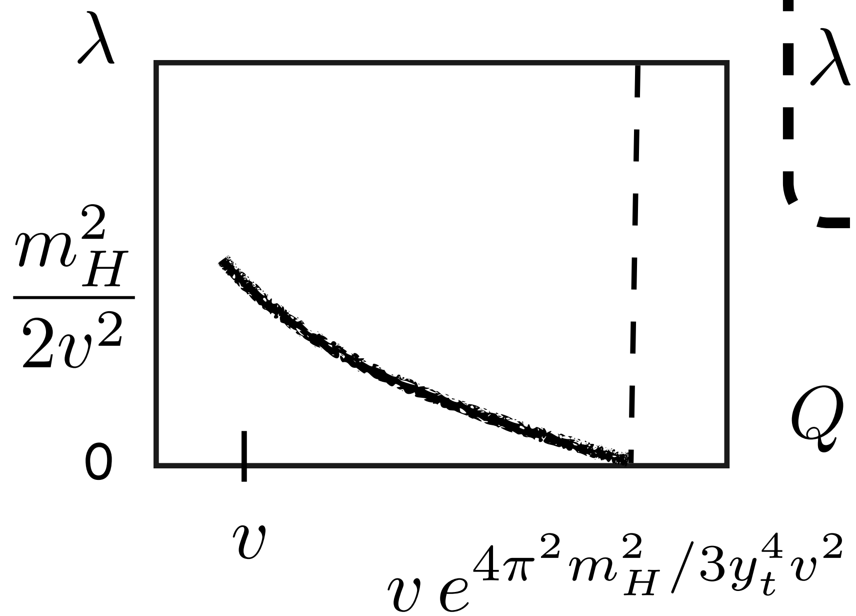
$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \tfrac{3}{8}g'^4 + \tfrac{3}{4}g'^2 g^2 + \tfrac{9}{8}g^4 - 6y_t^4 +$$ Higher loops Small Yukawa

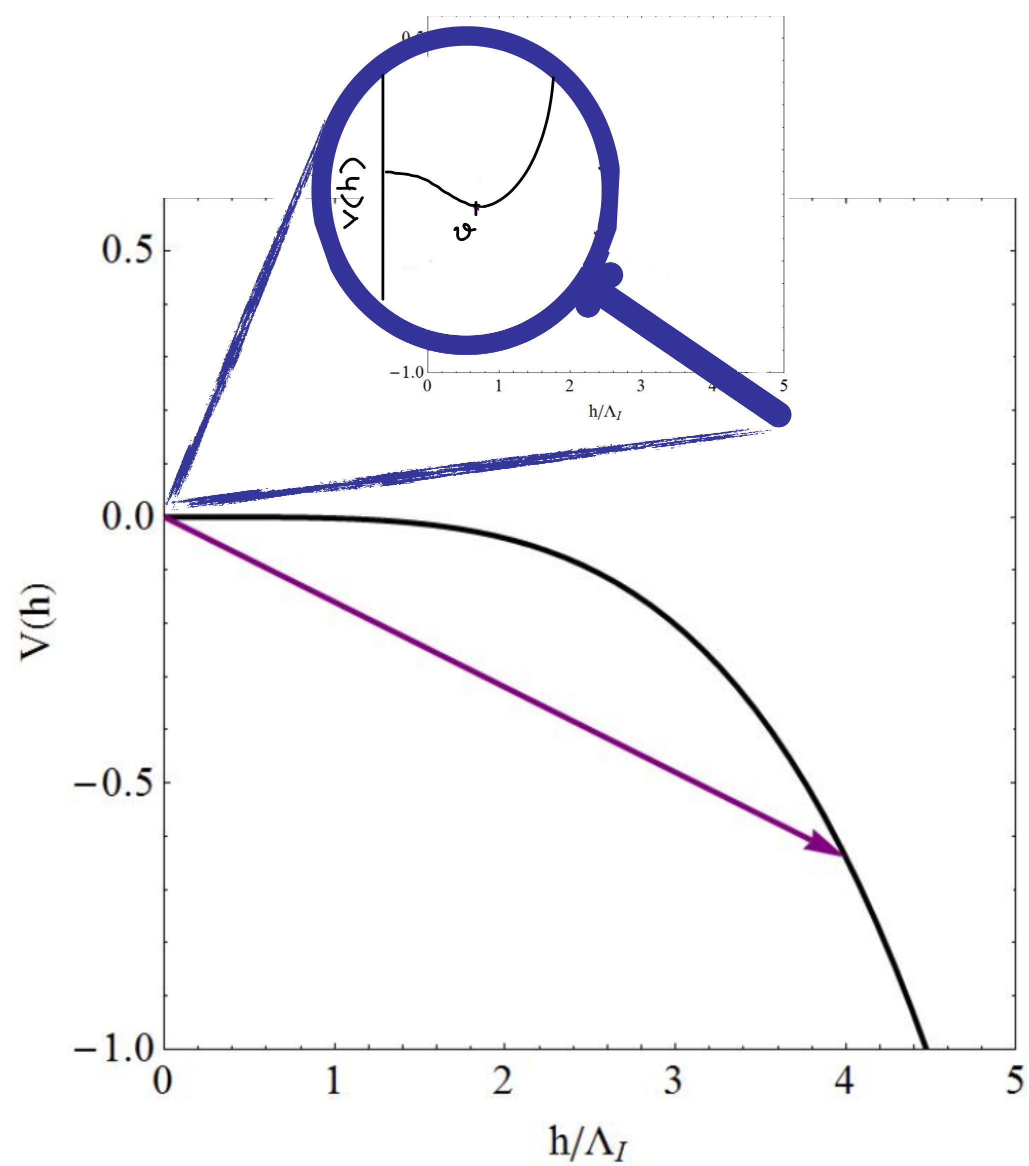
Higgs and EW vacuum Stability

Small mass (y_t dominated RGE)

$$\lambda(Q) = \lambda_0 - \frac{\frac{3}{8\pi^2} y_0^4 \ln \frac{Q}{Q_0}}{1 - \frac{9}{16\pi^2} y_0^2 \ln \frac{Q}{Q_0}}$$

Linde '76, '80
Weinberg '76
Maini et al '78, '79
Politzer, Wolfram '79
Lindner '86
+...





$\lambda < 0$ ⇛ potential unbounded from below

$$\Lambda \leq v\, e^{4\pi^2 m_H^2/3y_t^4 v^2}$$

New physics should appear before that point to restore stability

Higgs and EW vacuum Stability

Small mass (y_t dominated RGE)

$$\lambda(Q) = \lambda_0 - \frac{\frac{3}{8\pi^2} y_0^4 \ln \frac{Q}{Q_0}}{1 - \frac{9}{16\pi^2} y_0^2 \ln \frac{Q}{Q_0}}$$

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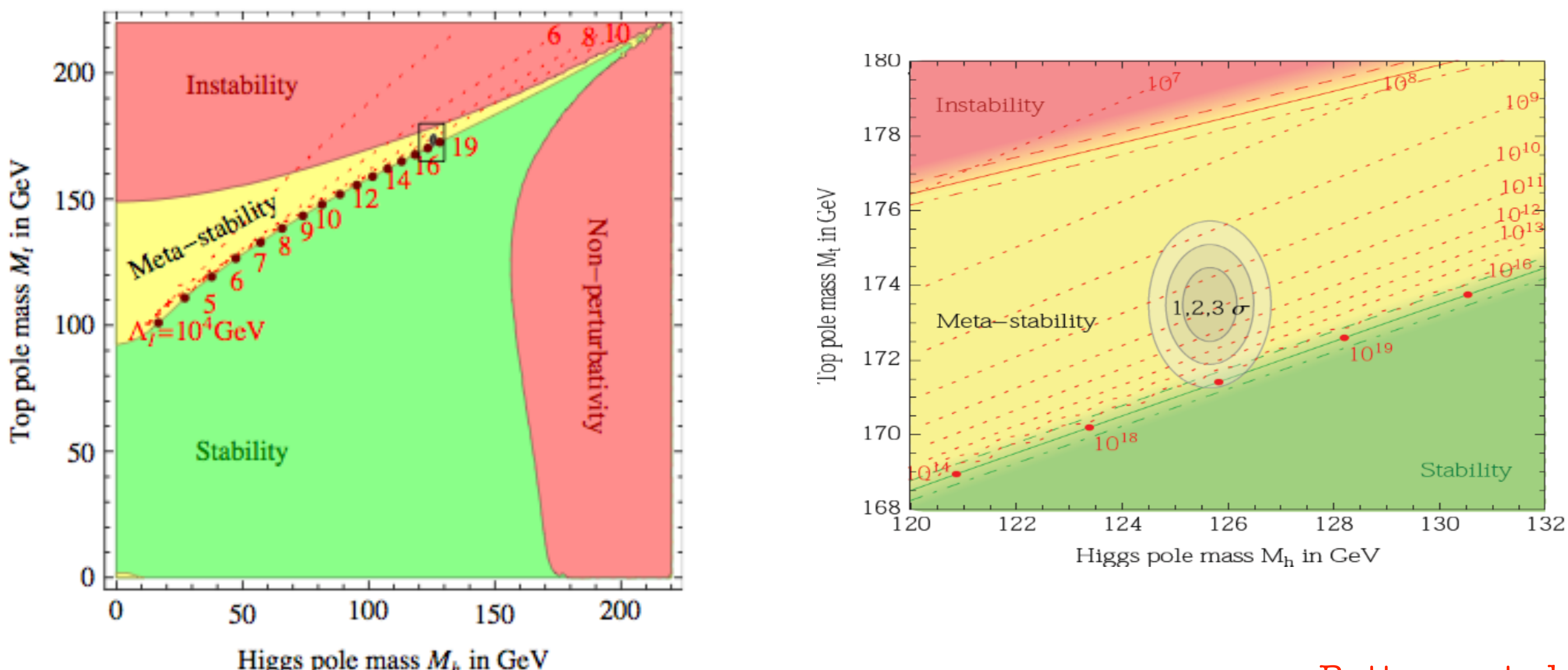
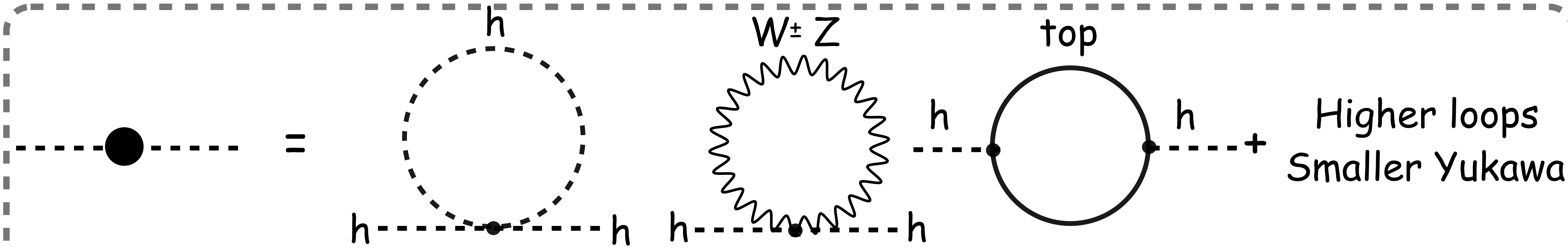


Buttazzo et al '13

Quantum Instability of the Higgs Mass

so far we looked only at the RG evolution of the Higgs quartic coupling (dimensionless parameter). The Higgs mass has a totally different behavior: it is highly dependent on the UV physics, which leads to the so called hierarchy problem



$$\int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m^2} \propto \Lambda^2 \qquad \int \frac{d^4k}{(2\pi)^4}\frac{k^2}{(k^2-m^2)^2} \propto \Lambda^2$$

Weisskopf '39
't hooft '79

$$\delta m_H^2 = \left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)\frac{3G_F\Lambda^2}{8\sqrt{2}\pi^2}$$

$$m_H^2 \sim m_0^2 - (115\ \mathrm{GeV})^2\left(\frac{\Lambda}{700\ \mathrm{GeV}}\right)^2$$

The hierarchy problem made easy

only a few electrons are enough to lift your hair (~ 10^{25} mass of e^-)

the electric force between 2 e^- is 10^{43} times larger than their gravitational interaction

we don't know why gravity is so weak?

we don't know why the masses of particles are so small?

Several theoretical hypotheses

new dynamics? new symmetries? new space-time structure?

modification of special relativity? of quantum mechanics?

Naturalness principle @ work

Following the arguments of Wilson, 't Hooft (and others):
only small numbers associated to the breaking of a symmetry survive quantum corrections

Introduce new degrees of freedom to regulate the high-energy behavior

Beautiful examples of naturalness to understand the need of "new" physics

see for instance Giudice '13 (and refs. therein) for an account

- the need of the **positron** to screen the electron self-energy: $\Lambda < m_e/\alpha_{\rm em}$
- the **rho meson** to cutoff the EM contribution to the charged pion mass: $\Lambda < \delta m_\pi^2/\alpha_{\rm em}$
- the kaon mass difference regulated by the **charm** quark: $\Lambda^2 < \dfrac{\delta m_K}{m_K}\dfrac{6\pi^2}{G_F^2 f_K^2 \sin^2\theta_C}$
- the light **Higgs** boson to screen the EW corrections to gauge bosons self-energies
- ...
- **new physics** at the weak scale to cancel the UV sensitivity of the Higgs mass?

The different paths to Higgs naturalness

- Single vacuum

the low Higgs mass is screened from large quantum corrections by

1. a symmetry (Susy, PQ)
2. a form factor (composite Higgs)
3. a low UV scale (xdim, RS, large N…)
4. a combination of the above

- Multiple vacua

many metastable vacua
with a vast range of values for m_H
Dynamical (or anthropic selection) of $m_H \ll \Lambda$

1. anthropic multiverse
2. NNaturalness with 10^{16} copies of SM
3. relaxion and cosmological scanning with non-trivial back reaction

How to Stabilize the Higgs Potential

The spin trick

a particle of spin s: 2s+1 polarization states

...with the only exception of a particle moving at the speed of light

... fewer polarization states

Spin 1 Gauge invariance $\longrightarrow$ no longitudinal polarization $\searrow$

Spin 1/2 Chiral symmetry $\longrightarrow$ only one helicity $\nearrow$

m=0

If the symmetries are broken, the radiative mass will be set by the scale of symmetry breaking, not the UV/Planck scale

... but the Higgs is a spin 0 particle

Symmetries to Stabilize a Scalar Potential

Supersymmetry

fermion ~ boson

Higher Dimensional Lorentz invariance

$\Lleftarrow$ gauge-Higgs unification models

[Manton '79, Fairlie 79, Hosotani '83 +...]

$$A_\mu \sim A_5$$

4D spin 1   4D spin 0

These symmetries cannot be exact symmetry of the Nature. They have to be broken. We want to look for a soft breaking in order to preserve the stabilization of the weak scale.

Other approaches to the hierarchy problem

the hierarchy problem can be reformulated as:
why the weak scale so much smaller than the Planck scale of quantum gravity?

$$M_{\rm Pl} = \sqrt{\frac{\hbar c}{G_{\rm N}}} \sim 10^{19}\,{\rm GeV}/c^2$$

✳ **large extra dimensions (~1mm)**: dilute gravitational interactions into large volume not accessible to other forces. Scale of quantum gravity around 1TeV. Black holes could be produced at the LHC.

✳ **many different species**: $M_* = M_{Pl}/\sqrt{N}$. $M_* \sim 1$TeV if $N \sim 10^{32}$

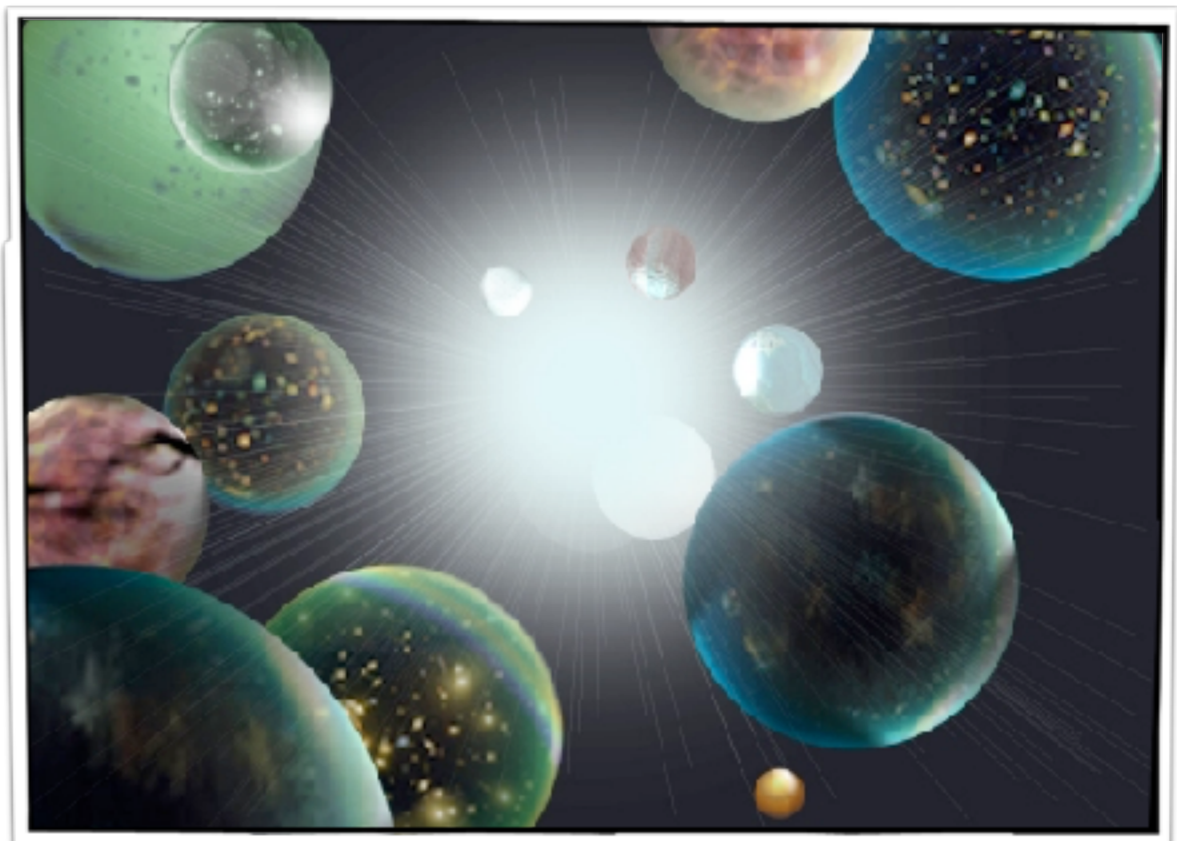
✳ **composite Higgs**: above the scale of compositeness, the Higgs boson dissolves into its fundamental constituents. Momentum-dependent form factors cut off the divergent integrals

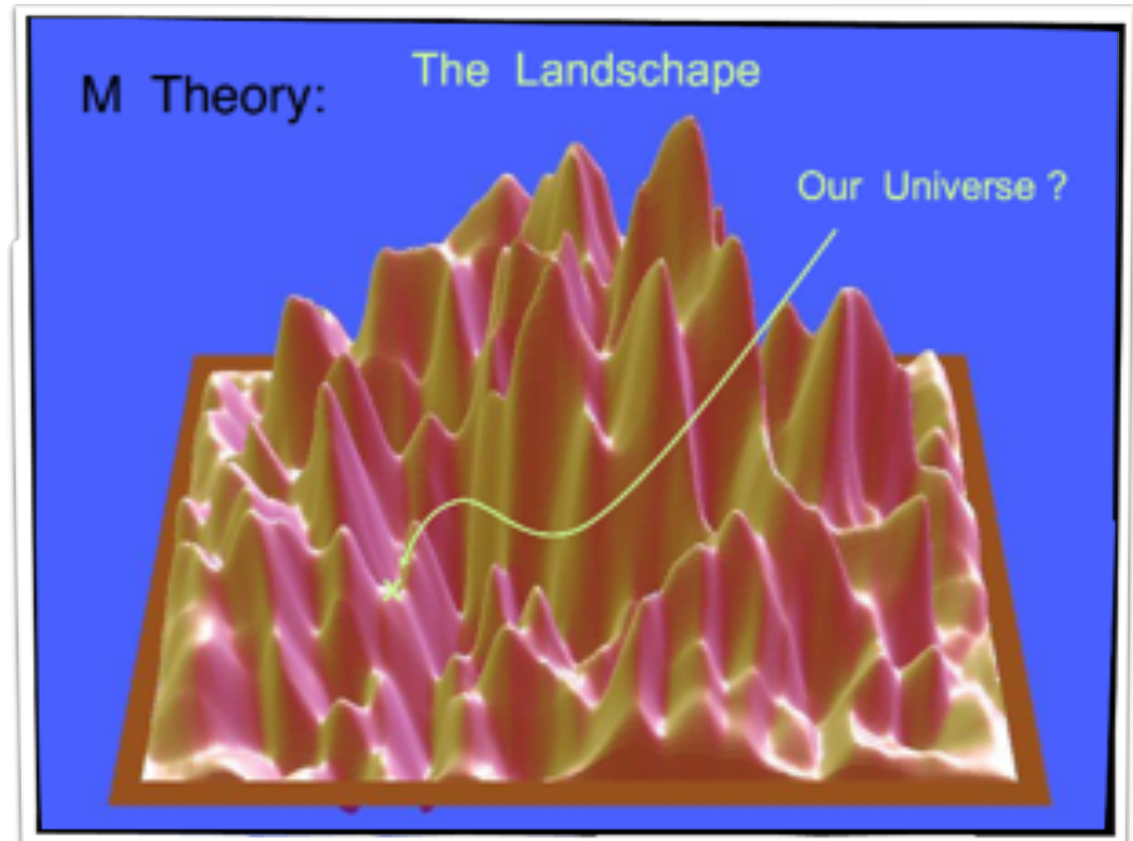
✳ ~~break EW symmetry **without a Higgs boson**, aka technicolor models~~. Ruled out by the Higgs boson discovery

Could the EW scale accidentally small?

The Sun and the Moon have the same angular size seen from Earth. Why?

- Dynamical explanation?
- Accident?
- Multiverse... there exist many (exo)planets with moons!
- Anthropic selection (probably not for the Moon, but maybe for the Higgs)





Number of string vacua: $10^{500 \pm 272\,000}$

Taylor, Wang '15

Supersymmetry

SUSY 1.0.1

Wess, Zumino '74

fermion ⇔ boson

$$\mathcal{L} = \partial^\mu \phi^\dagger \partial_\mu \phi + i\bar{\psi}\gamma^\mu \partial_\mu \psi$$

- susy transformations:

$$\delta\phi = \bar{\epsilon}\psi$$
$$\delta\psi = -i\left(\gamma^\mu \partial_\mu \phi\right)\epsilon$$

$$\delta\mathcal{L} = \text{total derivative}$$

- susy algebra:

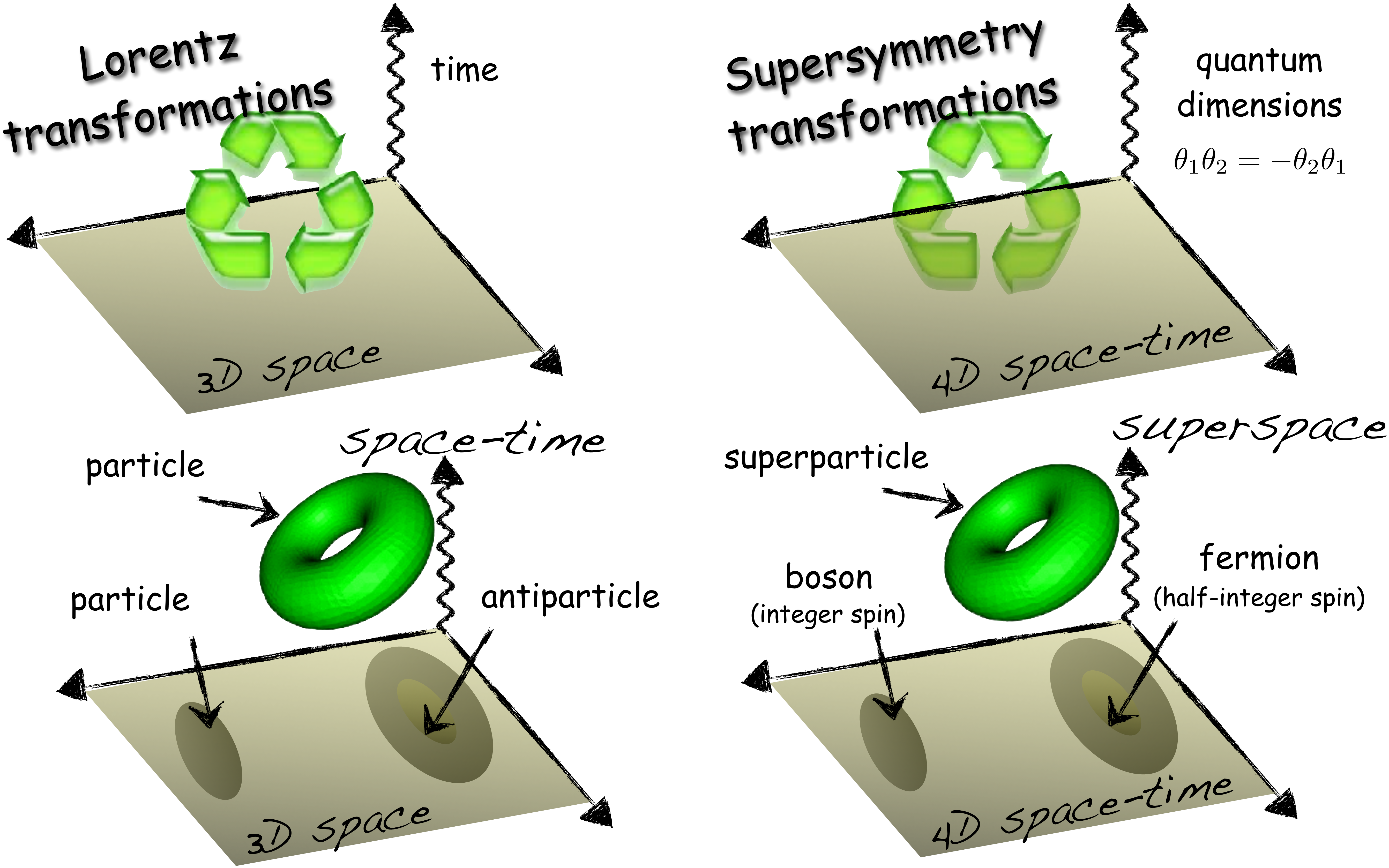
$$[\delta_{\epsilon_1}, \delta_{\epsilon_2}] \begin{pmatrix} \phi \\ \psi \end{pmatrix} = -i\left(\bar{\epsilon_2}\gamma^\mu \epsilon_1\right)\partial_\mu \begin{pmatrix} \phi \\ \psi \end{pmatrix}$$

susy^2 = 4D translation

How to introduce interactions?

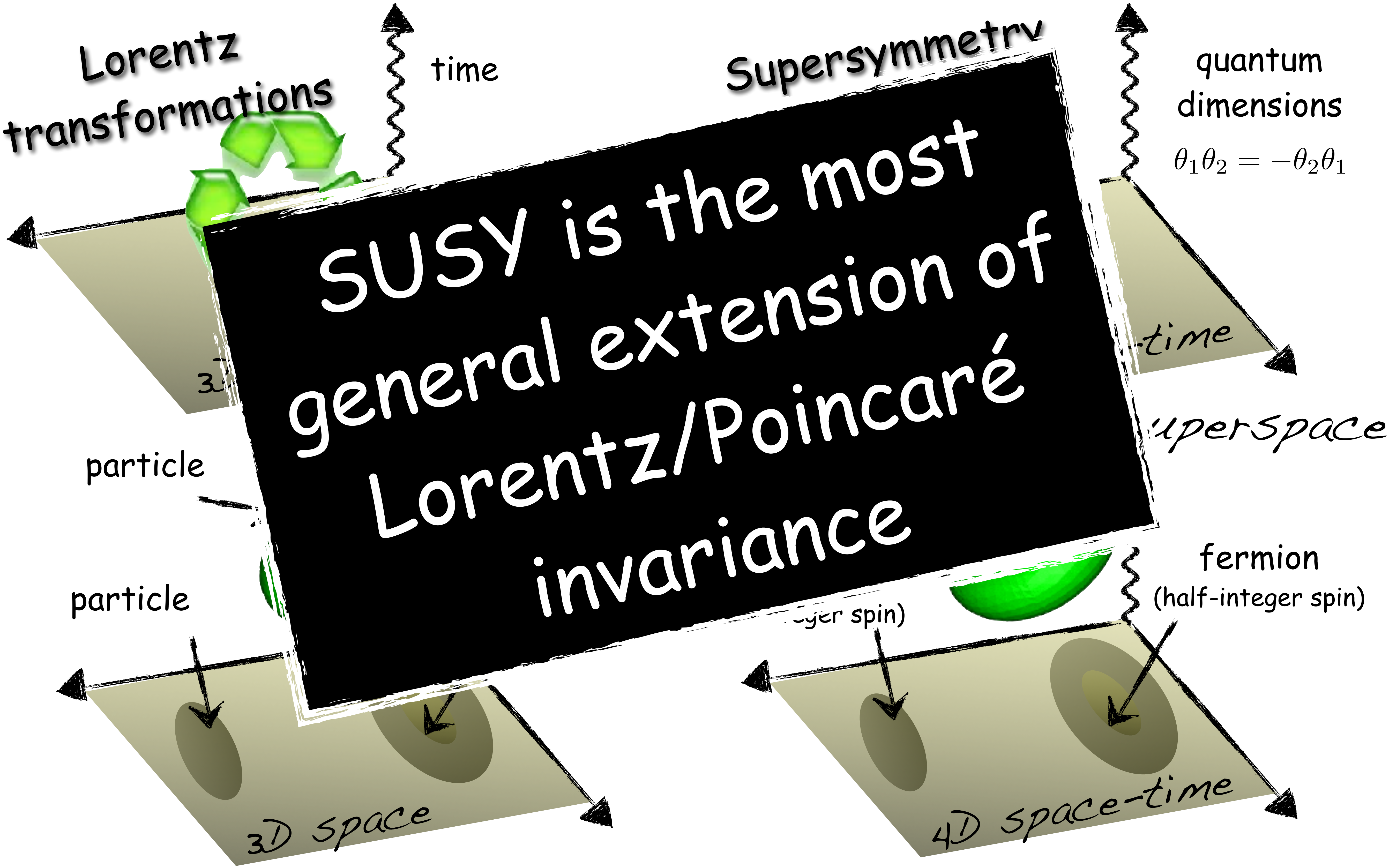
SUSY: a quantum space-time

(G. Giudice HCPSS'09)



SUSY: a quantum space-time

(G. Giudice HCPSS'09)



SUSY is the most general extension of Lorentz/Poincaré invariance

Superspace

$$\left(x^\mu, \theta, \bar\theta\right)$$

usual 4D space-time coordinates

new fermionic/Grassmanian coordinates

A general superfield can be Taylor-expanded in the superspace

$$F(x,\theta,\bar\theta) = f(x) + \theta\chi(x) + \bar\theta\bar\chi(x) + \theta\theta m(x) + \bar\theta\bar\theta\bar m(x) + \theta\sigma^\mu\bar\theta v_\mu(x) + i\theta\theta\bar\theta\bar\lambda(x) - i\bar\theta\bar\theta\theta\lambda(x) + \frac{1}{2}\theta\theta\bar\theta\bar\theta d(x)$$

complex spin-0 fields: $f(x), m(x), \bar m(x), d(x)$ 4x2=8 real off-shell degrees of freedom

complex spin-1 fields: $v_\mu(x)$ 1x8=8 real off-shell degrees of freedom

Weyl spin-1/2 fields: $\chi(x), \bar\chi, \lambda(x), \bar\lambda(x)$ 4x4=16 real off-shell degrees of freedom

- Chiral superfield $\bar D_{\dot\alpha} F = 0$

covariant derivative

ie commute with supersymmetry

$\Rightarrow$

	$F = \phi(x)$	$+\,\theta\psi(x)$	$+\,\theta\theta f(x)$
off-shell dof	2	4	2
on-shell dof	2	2	0

chiral fermion!

- Vector superfield

$$F = F^\dagger$$

$\Rightarrow$

	$F = \theta\sigma^\mu\bar\theta v_\mu(x)$	$+\,i\theta\theta\bar\theta\bar\lambda(x) - i\bar\theta\bar\theta\theta\lambda(x)$	$+\,\frac{1}{2}\theta\theta\bar\theta\bar\theta d(x)$
off-shell dof	3	4	1
on-shell dof	2	2	0

massless gauge field

Superspace Integrals and SUSY

Any polynomial of superfields is a superfield itself

$$\int d\theta\, \theta = 1$$

$$\int d^2\theta d^2\bar{\theta}\, F(\theta, \bar{\theta}) \quad \text{and} \quad \int d^2\theta\, Q(\theta)$$

are two quantities invariant by supersymmetry

All particles are seen as superfields and using the results above, one can easily construct Lagrangians as polynomials of these superfields, these Lagrangians are automatically invariant under supersymmetry

SUSY Interactions - Superpotential

superpotential W = holomorphic fct of chiral superfields

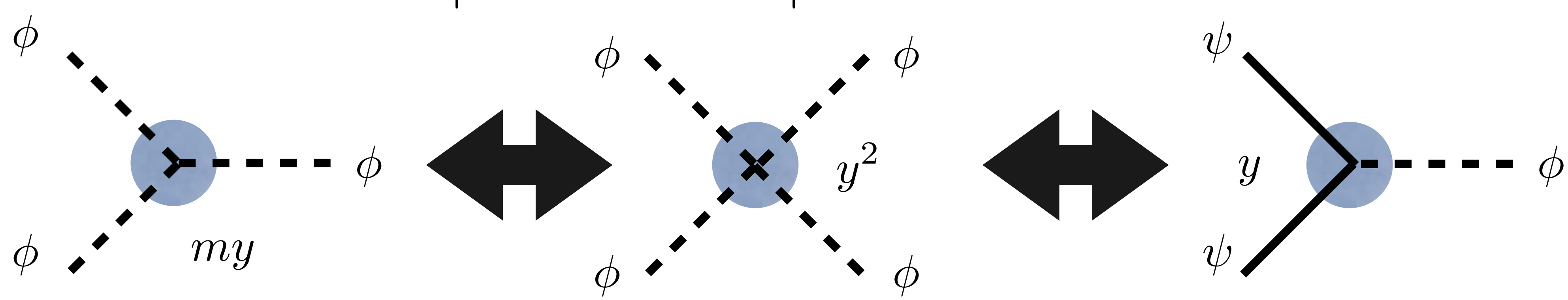
$$\mathcal{L} = \mathcal{L}_{\text{kin}} - \left|\frac{\partial W}{\partial \phi}\right|^2_{|\theta=0} - \frac{1}{2}\frac{\partial^2 W}{\partial \phi^2}_{|\theta=0} \psi\psi + h.c.$$

is invariant under susy

example: susy Yukawa interaction

$$W = \frac{1}{2}m\phi^2 + \frac{1}{3!}y\phi^3 \qquad \partial_\phi W = m\phi + \frac{1}{2}y\phi^2 \qquad \partial^2_\phi W = m + y\phi$$

$$\mathcal{L} = \mathcal{L}_{\text{kin}} - \left|m\phi + \frac{1}{2}y\phi^2\right|^2 - \frac{1}{2}\left(m + y\phi\right)\psi\psi + h.c.$$

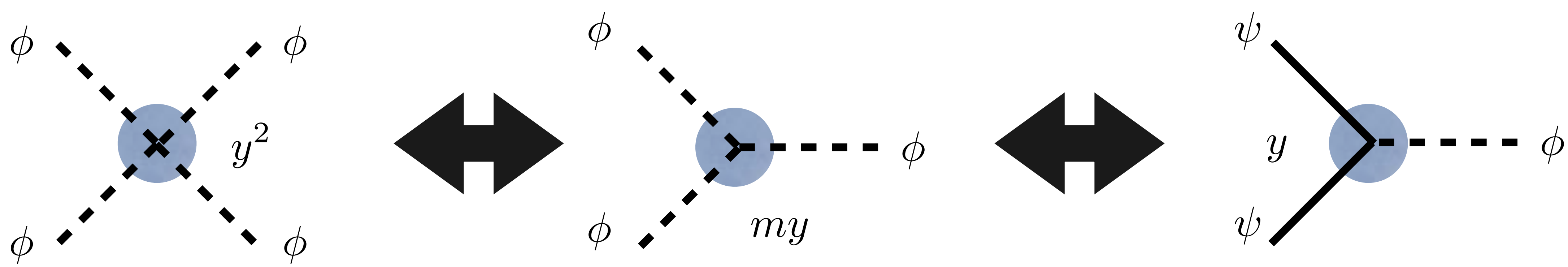


will be modified by soft susy breaking

will survive soft susy breaking

SUSY Interactions

heuristic rule:
replace bosons with fermions in the interaction



Scalar potential is not arbitrary any longer:
dictated by gauge and Yukawa interactions.
One important consequence: upper bound on Higgs mass in simplest models

SUSY predictions

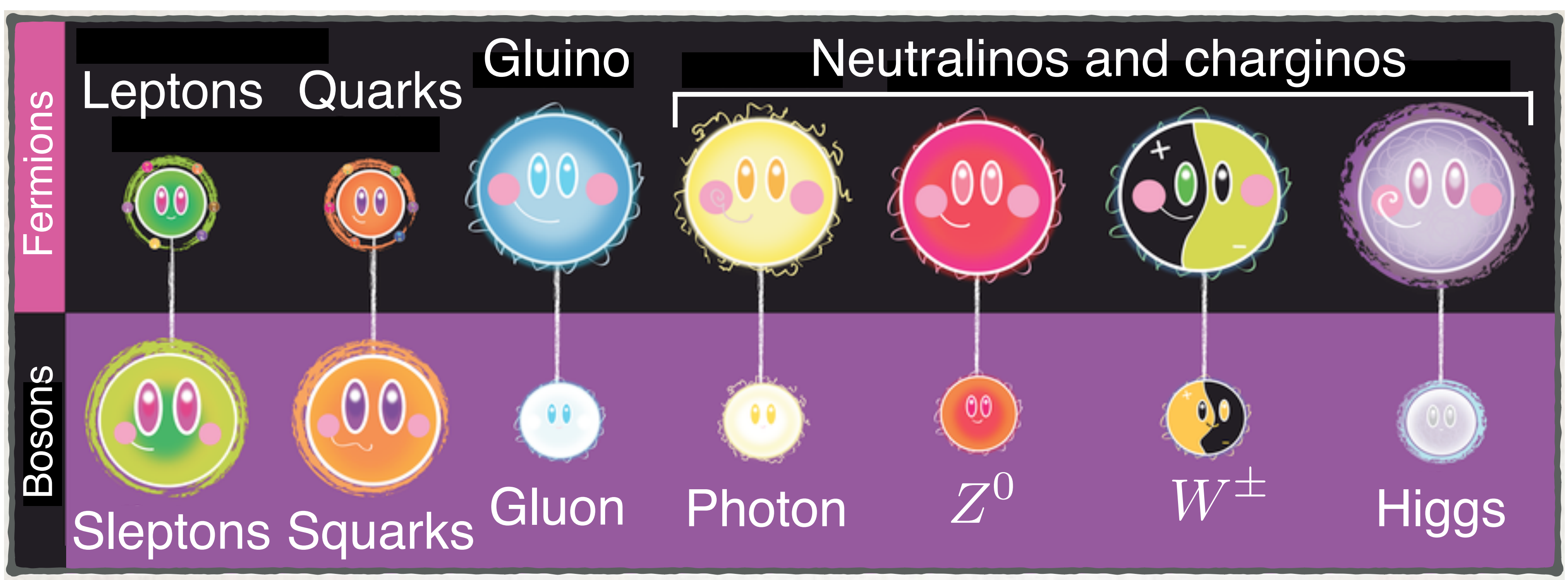
many new particles

many new interactions

MSSM - Matter Content

	particles				Sparticles		
quarks	$\begin{pmatrix}u_L\\ d_L\end{pmatrix}$	u_R	d_R	squarks	$\begin{pmatrix}\tilde{u}_L\\ \tilde{d}_L\end{pmatrix}$	$\tilde{u}_R$	$\tilde{d}_R$
leptons	$\begin{pmatrix}e_L\\ \nu_L\end{pmatrix}$	e_R		sleptons	$\begin{pmatrix}\tilde{e}_L\\ \tilde{\nu}_L\end{pmatrix}$	$\tilde{e}_R$	
Higgs doublets	H_1 (hypercharge $=-1$) H_2 (hypercharge $=+1$)			Higgsinos	$\tilde{H}_1$ $\tilde{H}_2$		
	$W^\pm_\mu, W^3_\mu$			winos	$\tilde{\omega}^\pm, \tilde{\omega}^3$		
	B_μ			bino	$\tilde{b}$		
	G^A_μ	$A=1,\ldots,8$		gluinos	$\tilde{g}^A$		

(G. Giudice HCPSS'09)



MSSM Superpotential

the most general ("renormalizable") superpotential of the MSSM

$$W = H_u QD + H_u QU + H_d LE + \mu H_u H_d + LQD + UDD + LLE + \mu_L LH_u$$

$\cancel{B}, \cancel{L}$

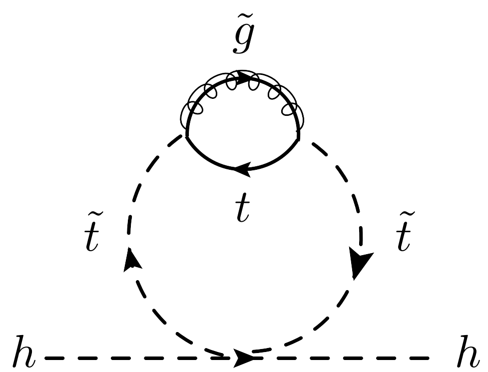
lead to fast p decay

R parity forbids all the dangerous terms

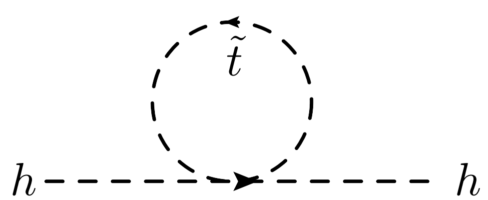
superfields		R-parity doesn't commute with susy		fields
$Q, D, U, L : -1$ $H_u, H_d : +1$	$\Rightarrow$	$\theta : -1$	$\Rightarrow$	$\phi_{\rm SM} : +1$ $\phi_{\rm superpartner} : -1$

nice consequences:
- superpartners are pair-produced
- Lightest Supersymmetric Particle is stable → DM?

Probing natural SUSY

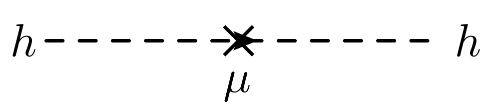


$$\delta m_H^2 \sim -\frac{y_t^2}{\pi^2}\frac{\alpha_s}{\pi} m_{gluino}^2 \left(\log \frac{\Lambda}{m_{gluino}}\right)^2$$



$$\delta m_H^2 \sim -\frac{3}{8\pi^2} y_t^2 m_{stop}^2 \log \frac{\Lambda}{m_{stop}}$$

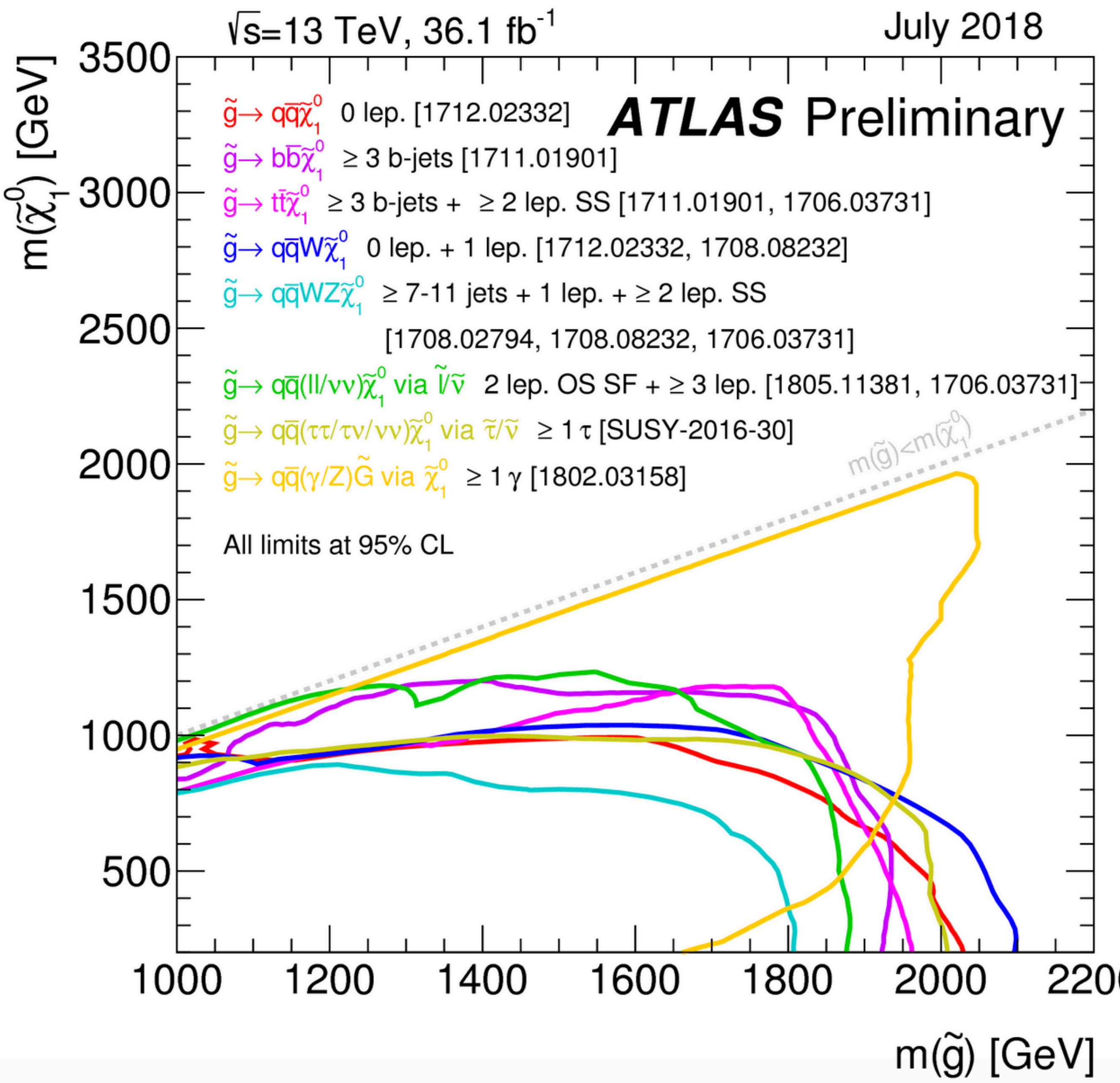
light stops, light gluinos!
well tested @ LHC
but most questionable predictions
(RG effects)

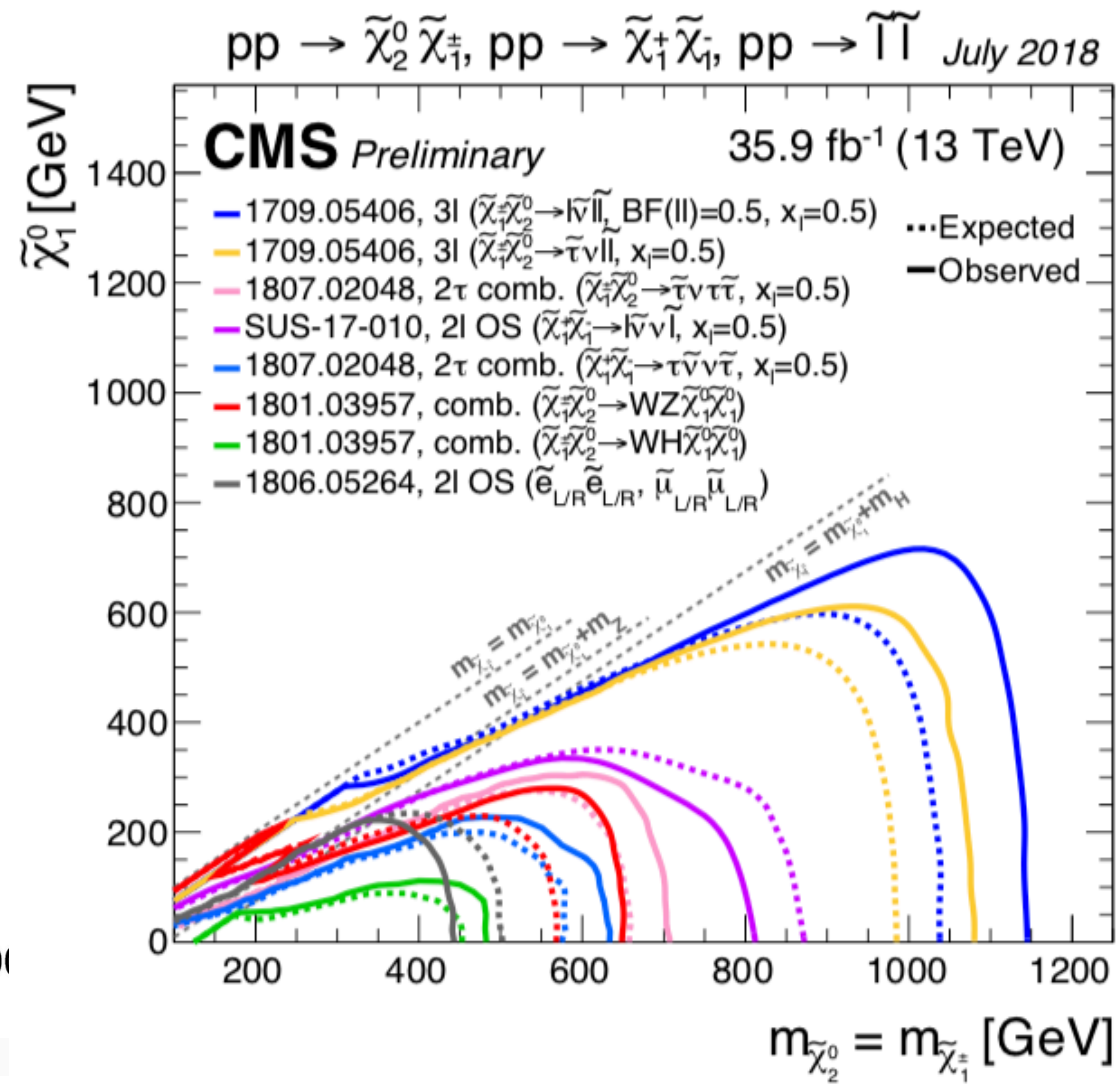


$$\delta m_H^2 \sim |\mu|^2$$

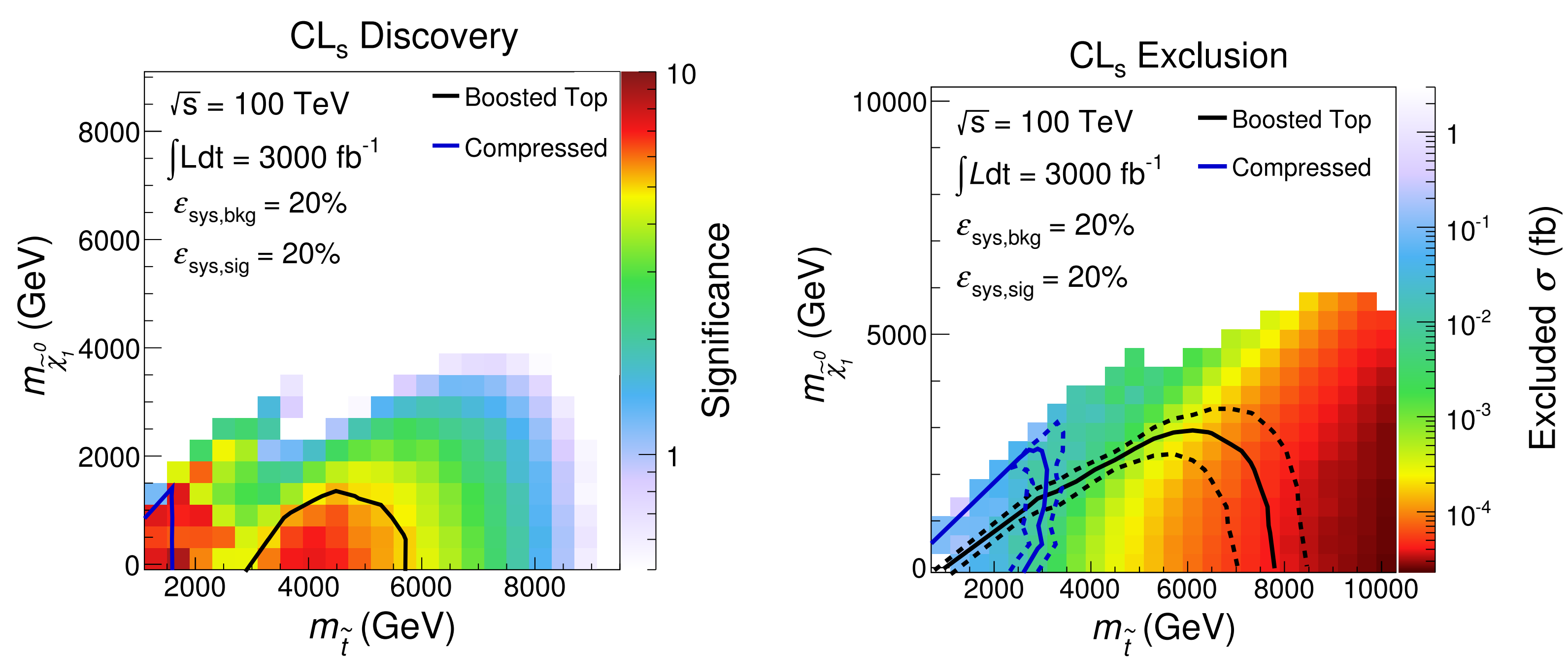
light Higgsinos!
very low sensitivity @ LHC
ILC needed to probe the other side

Probing natural SUSY





Probing natural SUSY



Collider	Energy	Luminosity	Cross Section	Mass
LHC8	8 TeV	20.5 fb^{-1}	10 fb	650 GeV
LHC	14 TeV	300 fb^{-1}	3.5 fb	1.0 TeV
HL LHC	14 TeV	3 ab^{-1}	1.1 fb	1.2 TeV
HE LHC	33 TeV	3 ab^{-1}	91 ab	3.0 TeV
FCC-hh	100 TeV	1 ab^{-1}	200 ab	5.7 TeV

Fig. 12: Left: Discovery potential and Right: Projected exclusion limits for 3000 fb^{-1} of total integrated luminosity at $\sqrt{s} = 100$ TeV. The solid lines show the expected discovery or exclusion obtained from the boosted top (black) and compressed spectra (blue) searches. In the boosted regime we use the $\not{E}_T$ cut that gives the strongest exclusion for each point in the plane. The dotted lines in the left panel show the $\pm 1\sigma$ uncertainty band around the expected exclusion.

Probing natural SUSY

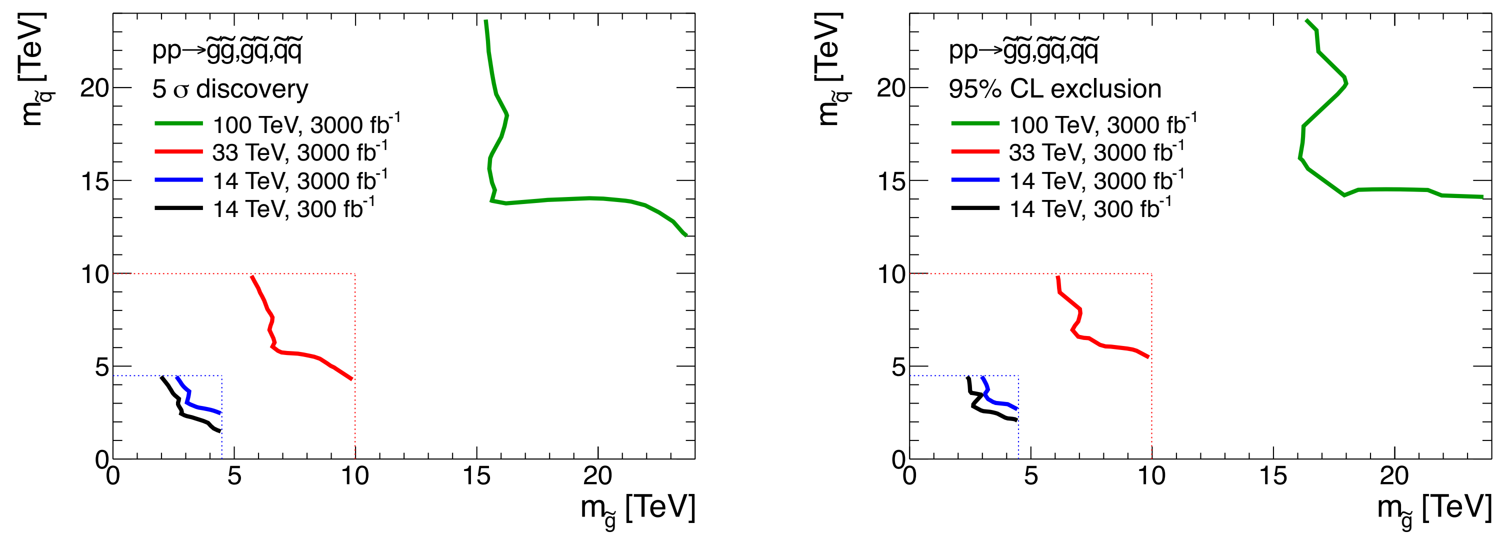
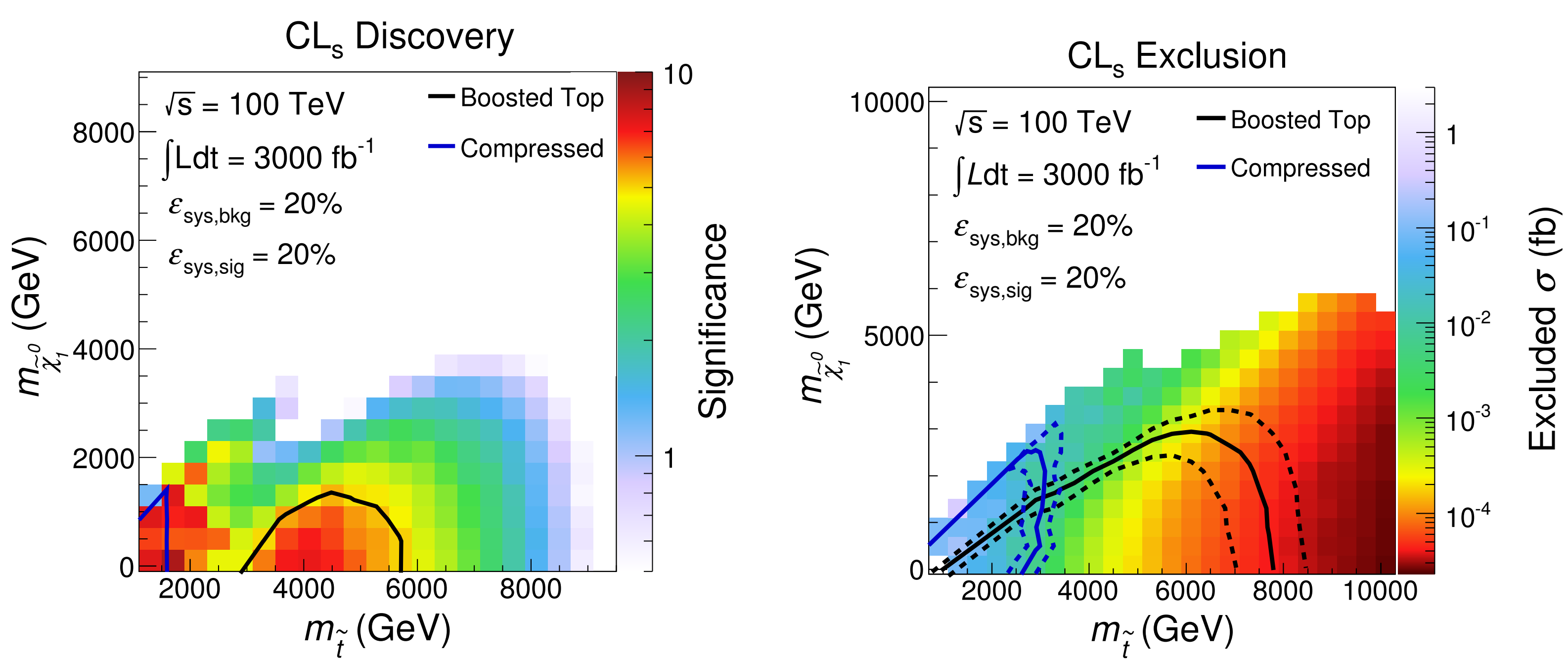


Fig. 16: Results for the gluino-squark-neutralino model. The neutralino mass is taken to be 1 GeV. The left [right] panel shows the $5\,\sigma$ discovery reach [95% CL exclusion] for the four collider scenarios studied here. A 20% systematic uncertainty is assumed and pile-up is not included.



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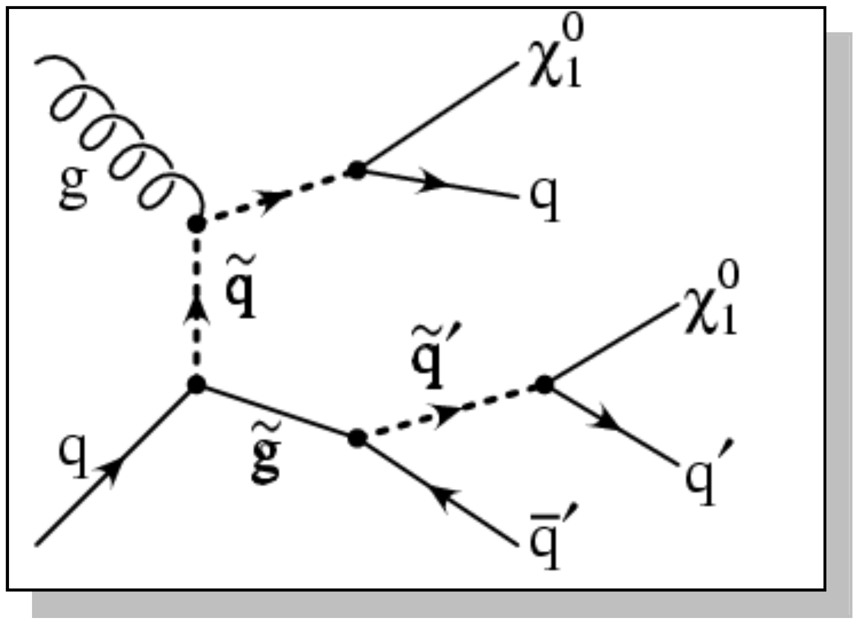
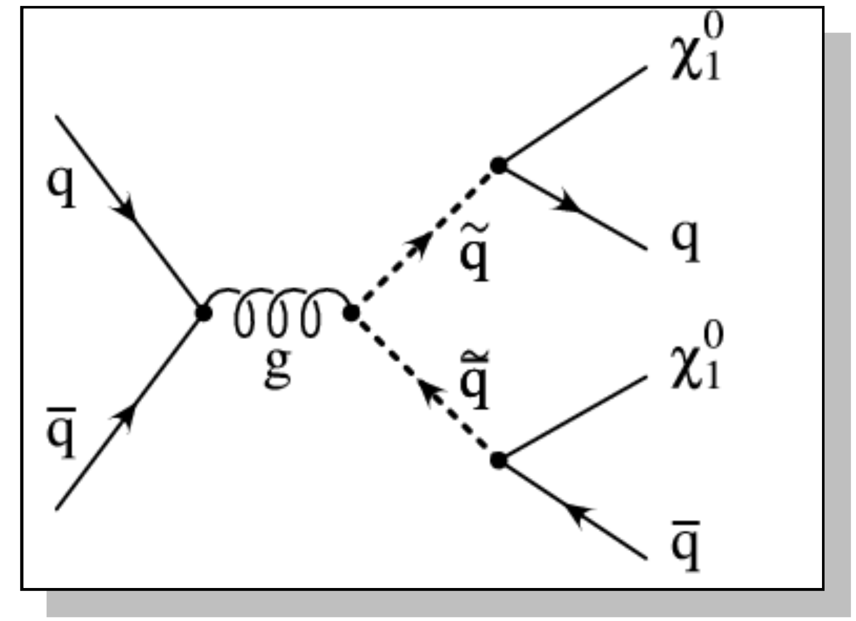
SUSY searches

gluinos and squarks are produced by QCD interactions





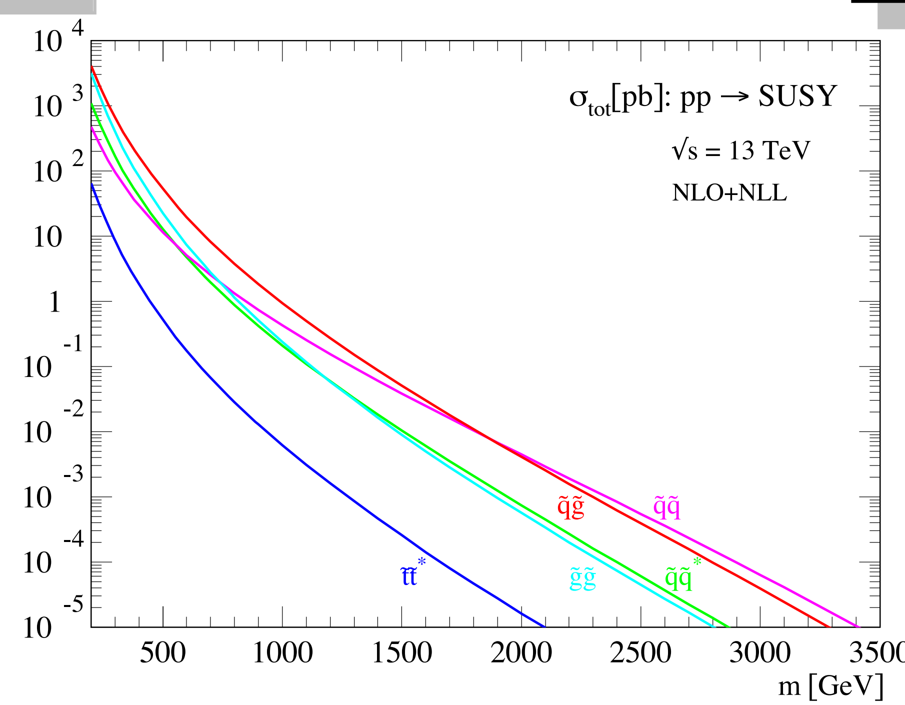
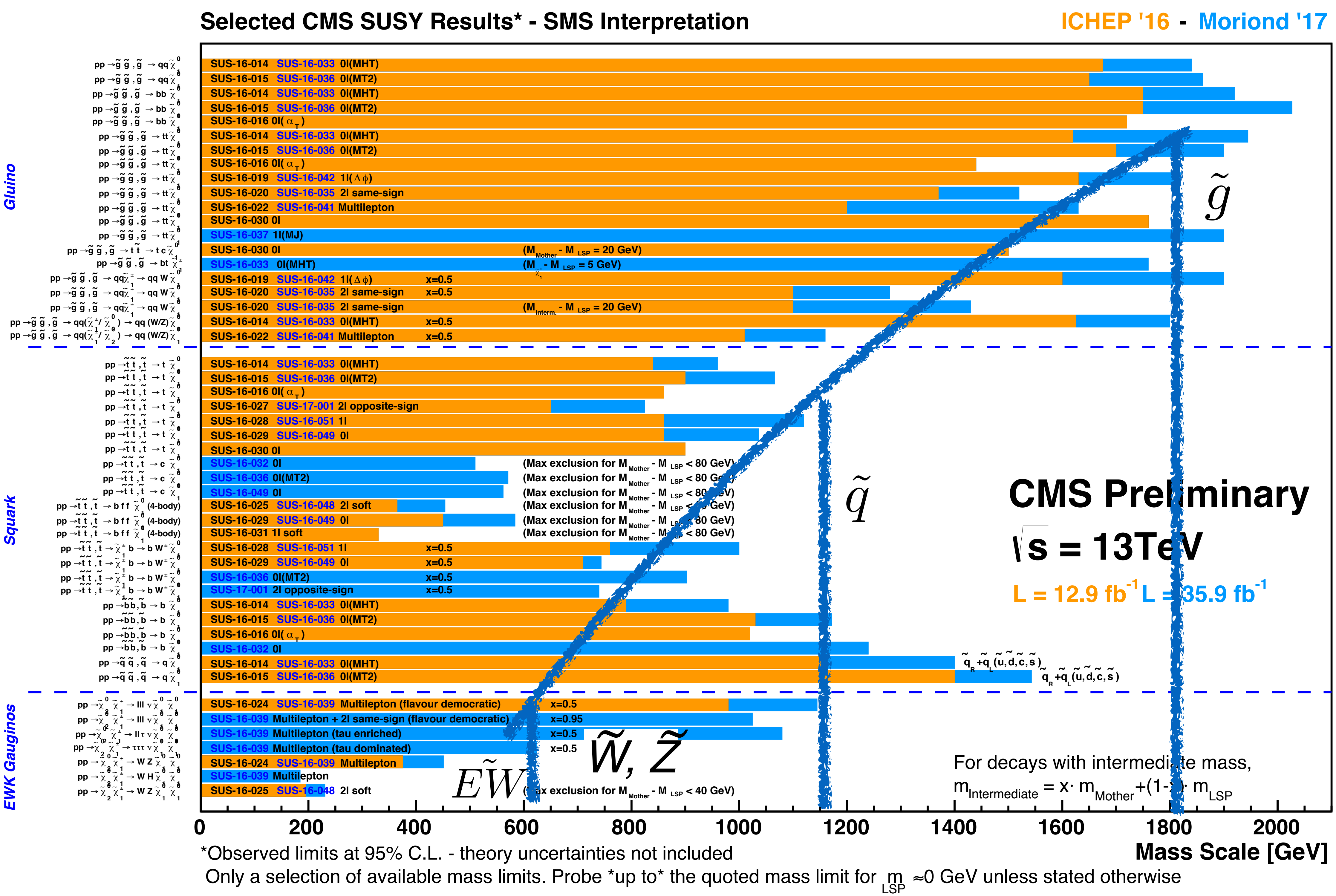


Figure 1: NLO+NLL production cross sections for the case of equal degenerate squark and gluino masses as a function of mass at $\sqrt{s} = 13$ TeV.

LSP (lightest supersymmetric particle) is stable ≈ Missing Energy

SUSY searches

gluinos and squarks are produced by QCD interactions



LSP (lightest supersymmetric particle) is stable ≈ Missing Energy

MSSM Higgs mass and stop searches

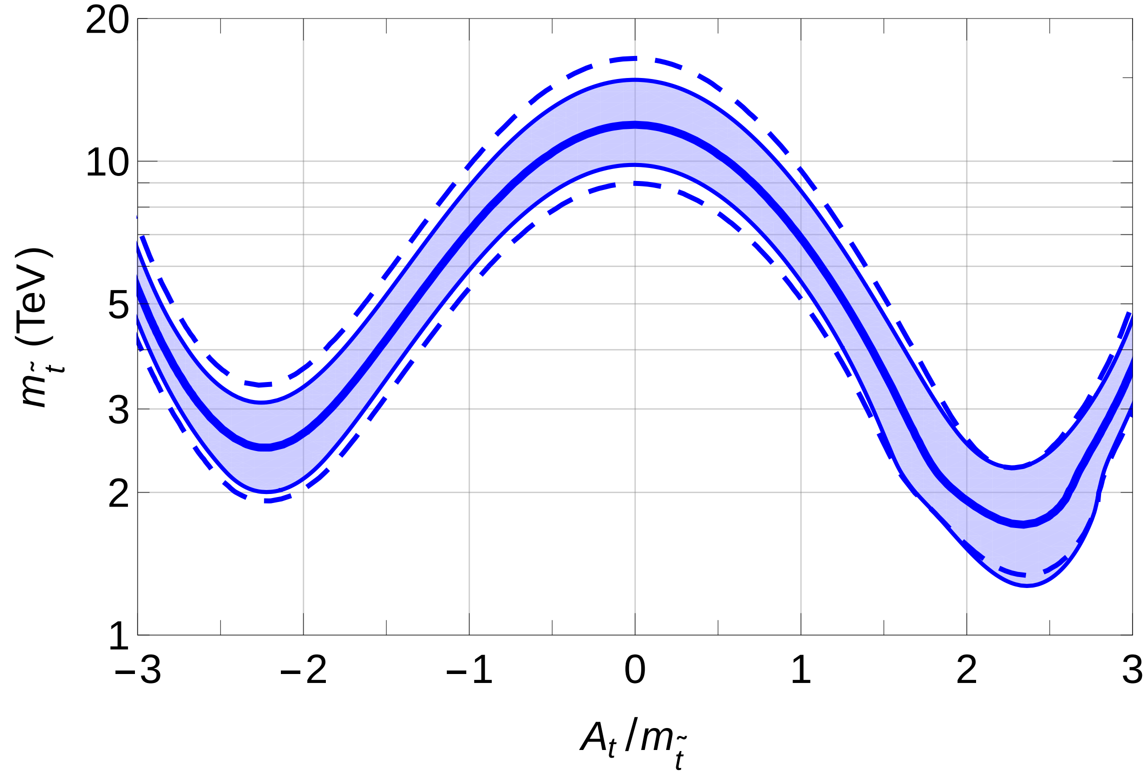


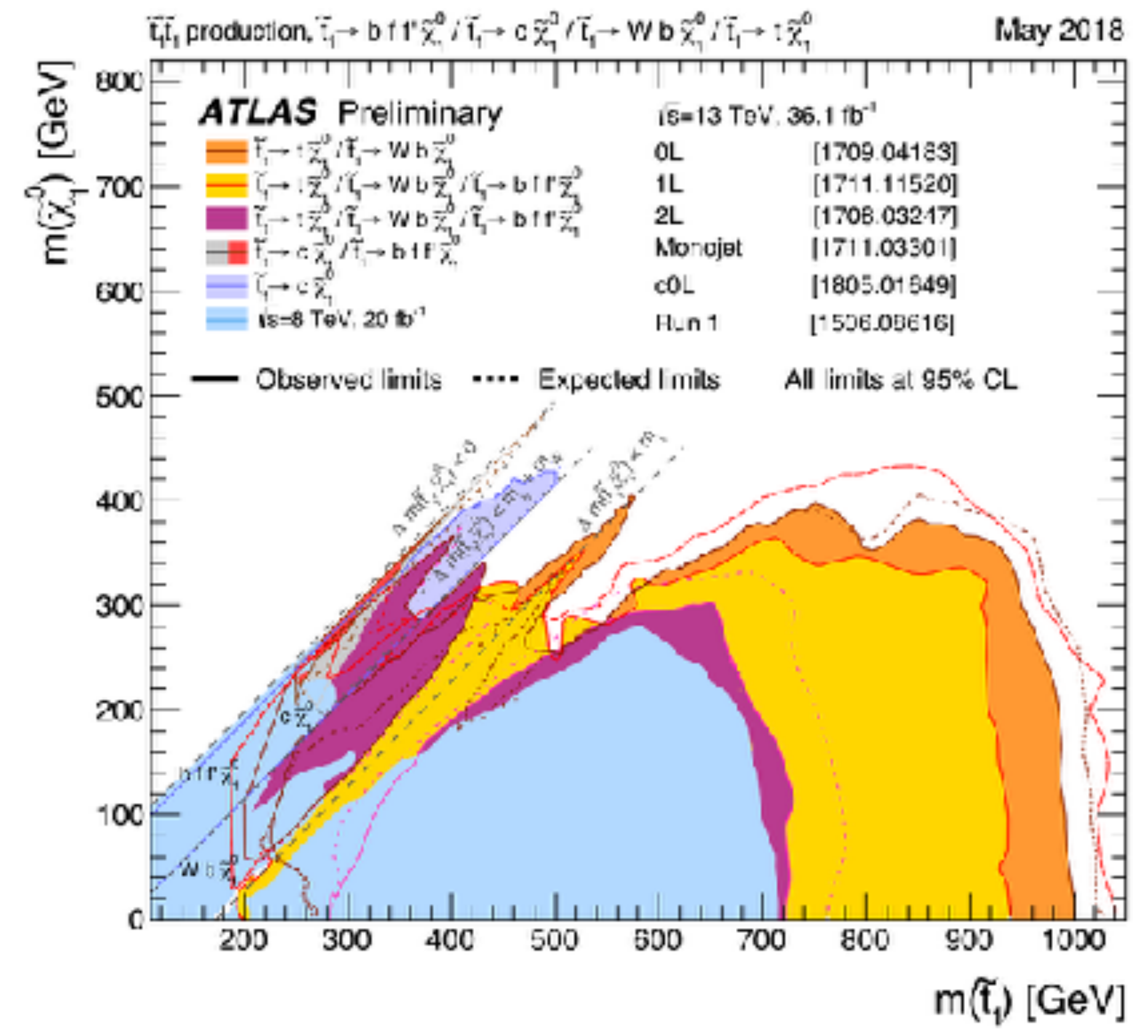
Figure 5: *Allowed values of the OS stop mass reproducing $m_h = 125$ GeV as a function of the stop mixing, with $\tan\beta = 20$, $\mu = 300$ GeV and all the other sparticles at 2 TeV. The band reproduce the theoretical uncertainties while the dashed line the 2σ experimental uncertainty from the top mass. The wiggle around the positive maximal mixing point is due to the physical threshold when $m_{\tilde{t}}$ crosses $M_3 + m_t$.*

Pardo Vega, Villadoro '15 + many others

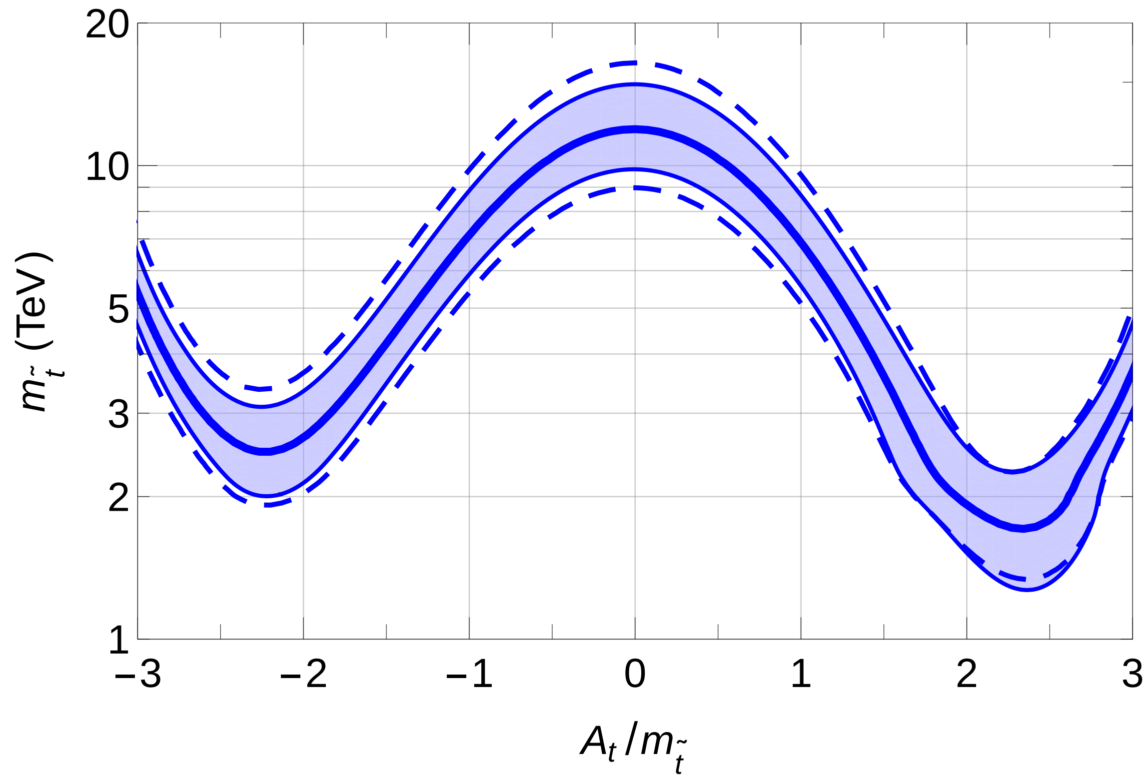
One needs heavy stop(s)
to obtain a 125GeV Higgs
(within the MSSM)

Current and future
bounds on stop mass

LHC (2018)



MSSM Higgs mass and stop searches



Pardo Vega, Villadoro '15 + many others

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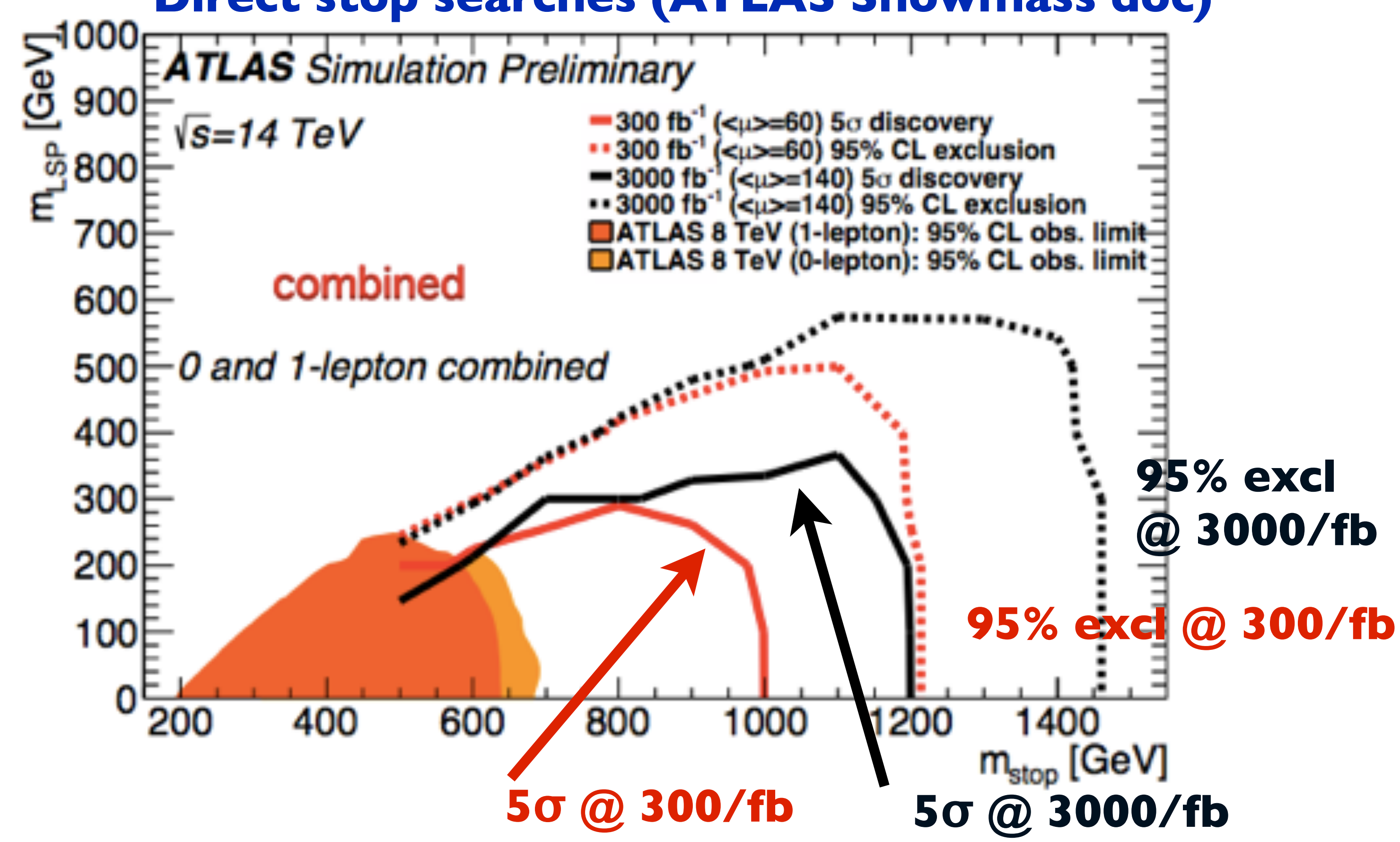
Figure 5: *Allowed values of the OS stop mass reproducing $m_h = 125$ GeV*
$\tan\beta = 20$, $\mu = 300$ GeV and all the other sparticles at 2 TeV. The band r
while the dashed line the 2σ experimental uncertainty from the top mass. Th
mixing point is due to the physical threshold when $m_{\tilde{t}}$ crosses $M_3 + m_t$.

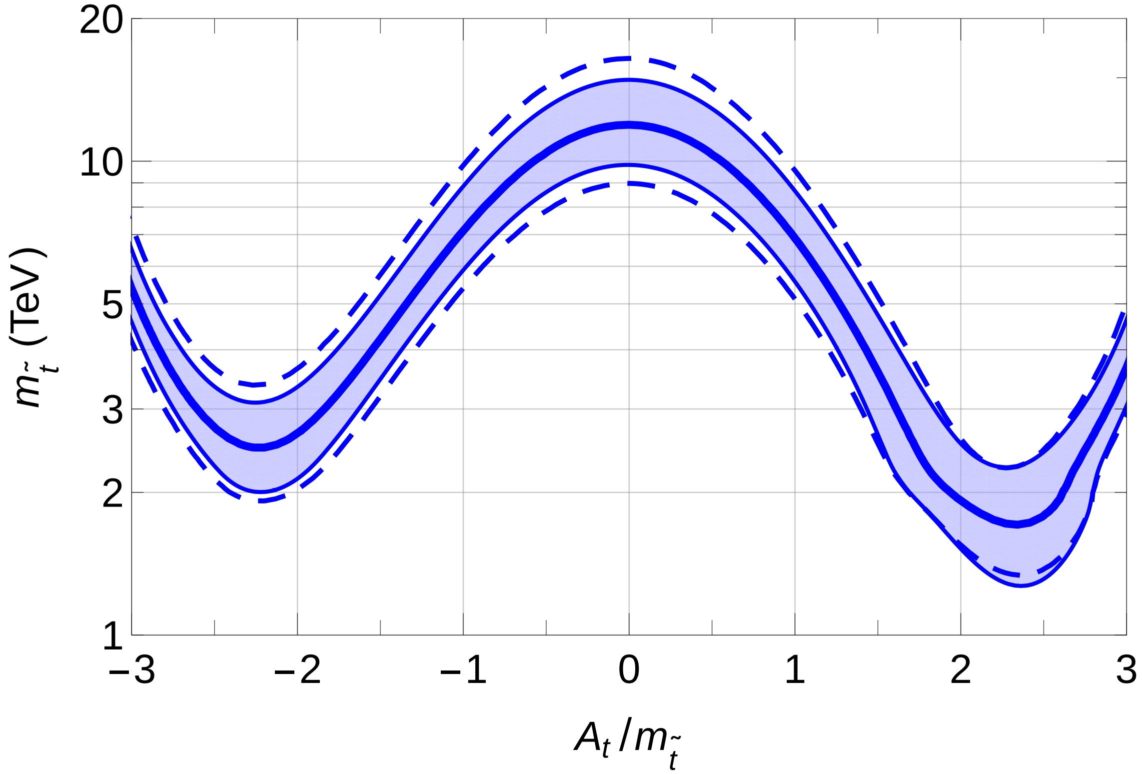
Current and future
bounds on stop mass

HL-LHC (2030)

Direct stop searches (ATLAS Snowmass doc)



MSSM Higgs mass and stop searches



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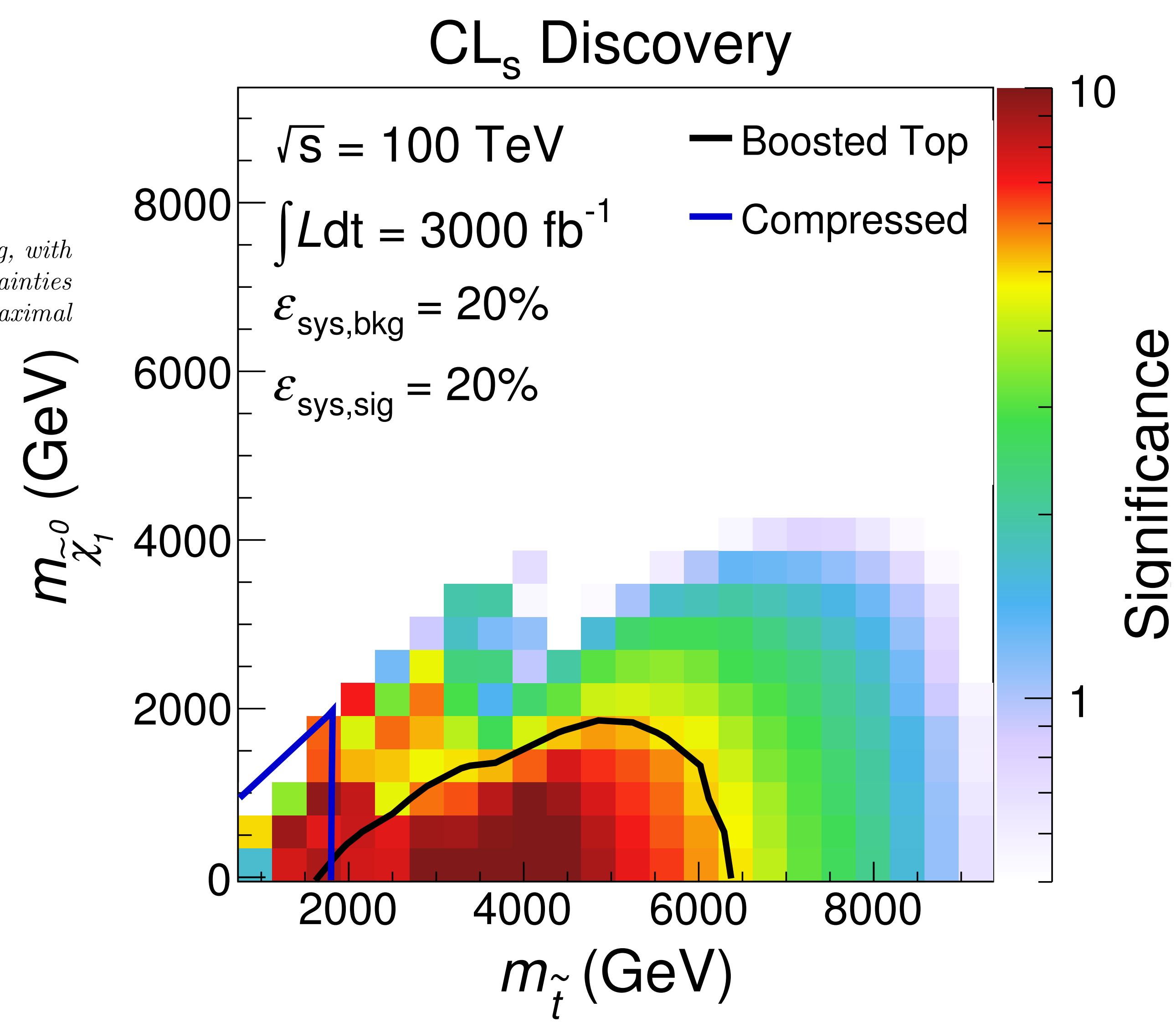
Pardo Vega, Villadoro '15 + many others

One needs heavy stop(s) to obtain a 125GeV Higgs (within the MSSM)

Current and future bounds on stop mass

FCC-hh @ 100TeV (2060)



Saving SUSY

SUSY is Natural
but not plain vanilla

- ~~CMSSM~~
- pMSSM
- NMSSM
- colorless stops ("folded susy")
- Hide SUSY, e.g. smaller phase space
  - reduce production (eg. split families) Mahbubani et al
  - reduce MET (e.g. R-parity, Csaki et al compressed spectrum)
  - dilute MET (decay to invisible particles with more invisible particles)
  - soften MET (stealth susy, stop -top degeneracy) Fan et al

$LHC_{300(0)fb^{-1}}$ will tell!

Good coverage of

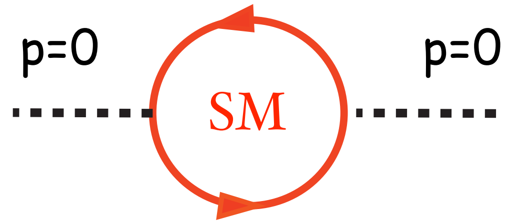
hidden natural susy

- mono-top searches (DM, flavored naturalness - mixing among different squark flavors-, stop-higgsino mixings)
- mono-jet searches with ISR recoil (compressed spectra)
- precise tt inclusive measurement+ spin correlations (stop → top + soft neutralino)
- multi-hard-jets (RPV, hidden valleys, long decay chains)

Neutral naturalness, aka Twin Higgs

Neutral Naturalness

$$-(125\ \text{GeV})^2\left(\frac{\Lambda}{600\ \text{GeV}}\right)^2 \qquad\qquad \frac{g_*^2}{16\pi^2}\Lambda^2$$

$\delta m_H^2 \quad =$ 

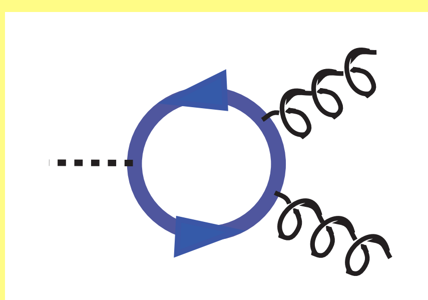
$+$ 

$\sim m_H^2$

generically

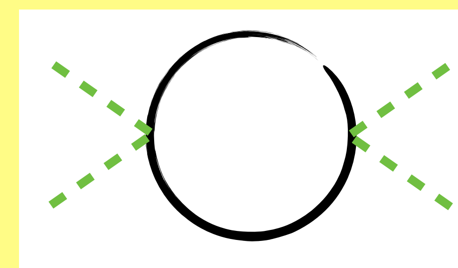
charged particles

neutral particles



$$\frac{g_s^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 G_{\mu\nu}^2 \qquad \frac{e^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 F_{\mu\nu}^2$$

$$\frac{\Delta BR(h\to\gamma\gamma, Z\gamma, gg)}{\text{SM}} \sim \frac{g_*^2 v^2}{m_*^2}$$



$$\frac{g_*^2}{16\pi^2}\frac{1}{m_*^2}\left(\partial_\mu |H|^2\right)^2$$

$$BR(h\to ii) = BR_{\text{SM}} \qquad \Gamma = \left(1-\frac{g_*^2 v^2}{16\pi^2 m_*^2}\right)\Gamma_{\text{SM}}$$

$$\delta\sigma_{Zh} = -\frac{g_\star^2}{8\pi^2}\frac{v^2}{m_\star^2}$$

nice to be able to measure Zh & Γ

Colorful naturalness probed @ LHC

Neutral naturalness (invisible?) @ LHC

Twin Higgs

[Chacko, Goh, Harnik '05]

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

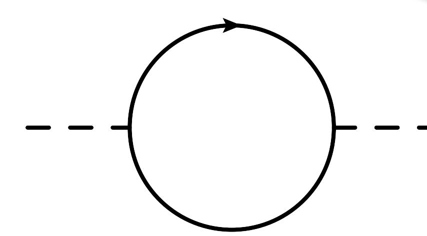
Radiative corrections to the Higgs mass are SU(4) symmetric thanks to Z_2:

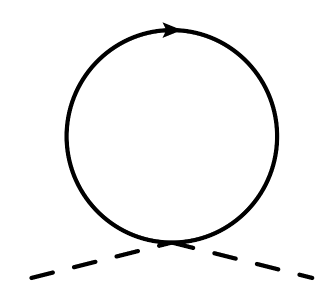
$$V(H) \supset \frac{\Lambda^2}{16\pi^2}\left(-6y_t^2 + \frac{9}{4}g^2 + \ldots\right)\left(|H_A|^2 + |H_B|^2\right)$$

(N. Craig @ Paris'18)

Higgs is a PNGB of ~SU(4), but partner states neutral under SM.

$$\mathcal{L} \supset -y_t \underbrace{H_A}_{h+\ldots} Q_3^A \bar{u}_3^A - y_t \underbrace{H_B}_{f - \frac{h^2}{2f} + \ldots} Q_3^B \bar{u}_3^B$$





Neutral Naturalness: new signatures

" Looking and not finding is different than not looking "

giving the null search results, the top partners should either be

- **heavy** (harder to produce because of phase space)
- **stealthy** (easy to produce but hard to distinguish from background, e.g. $m_{stop} \sim m_{top}$)
- **colorless** (hard to produce, unusual decay)

(C. Verhaaren@NKPI'16)

need to go beyond traditional searches

	Scalar Top Partner	Fermion Top Partner
All SM Charges	SUSY '70	pNGB/RS '00
EW Charges	Folded SUSY '05	Quirky Little Higgs '02
No SM Charges	Hyperbolic Higgs '18	Twin Higgs '05

only little corner of theory/model space has been explored so far

require **hidden QCD** with a higher confining scale:

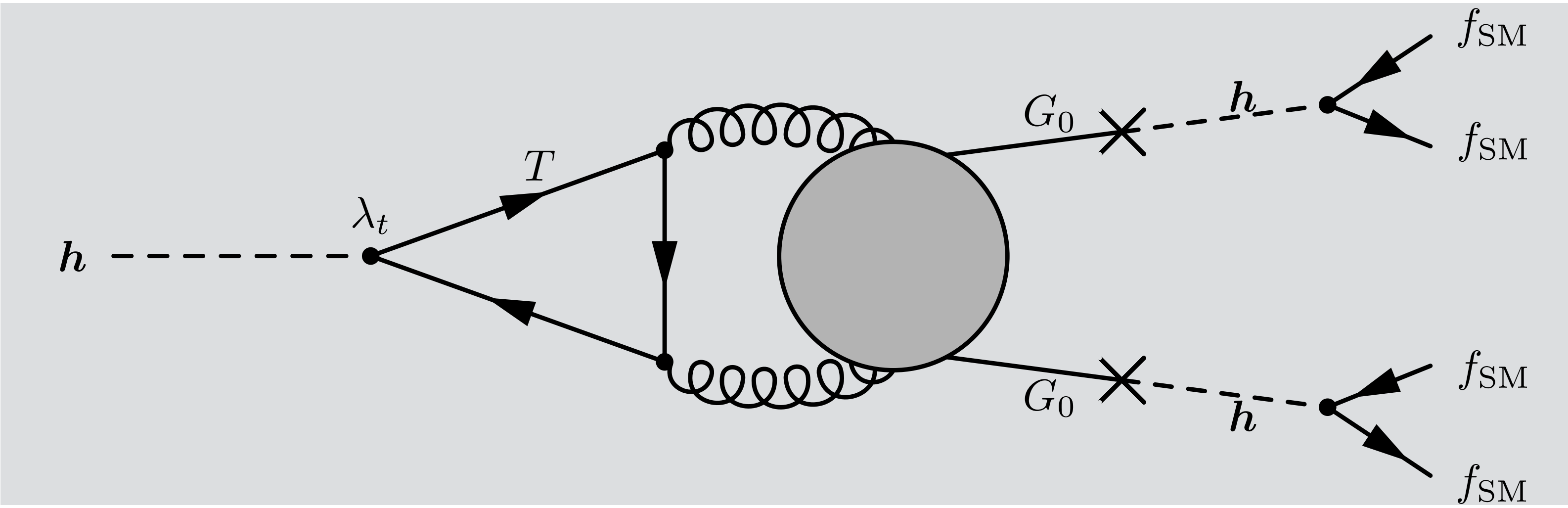
⇒ 1) hidden glueball (0^{++}) that can mix with Higgs
$h \to G_0 G_0 \to 4l$ with displaced vertices

Curtin, Verhaaren '1

⇒ 2) emerging jets

Schwaller, Stolarski, Weiler '15

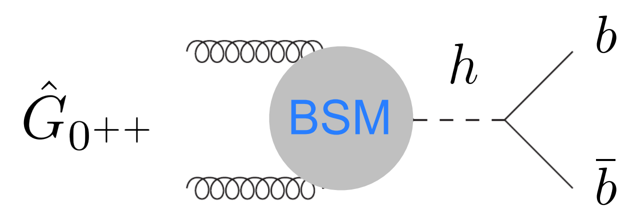
Neutral Naturalness

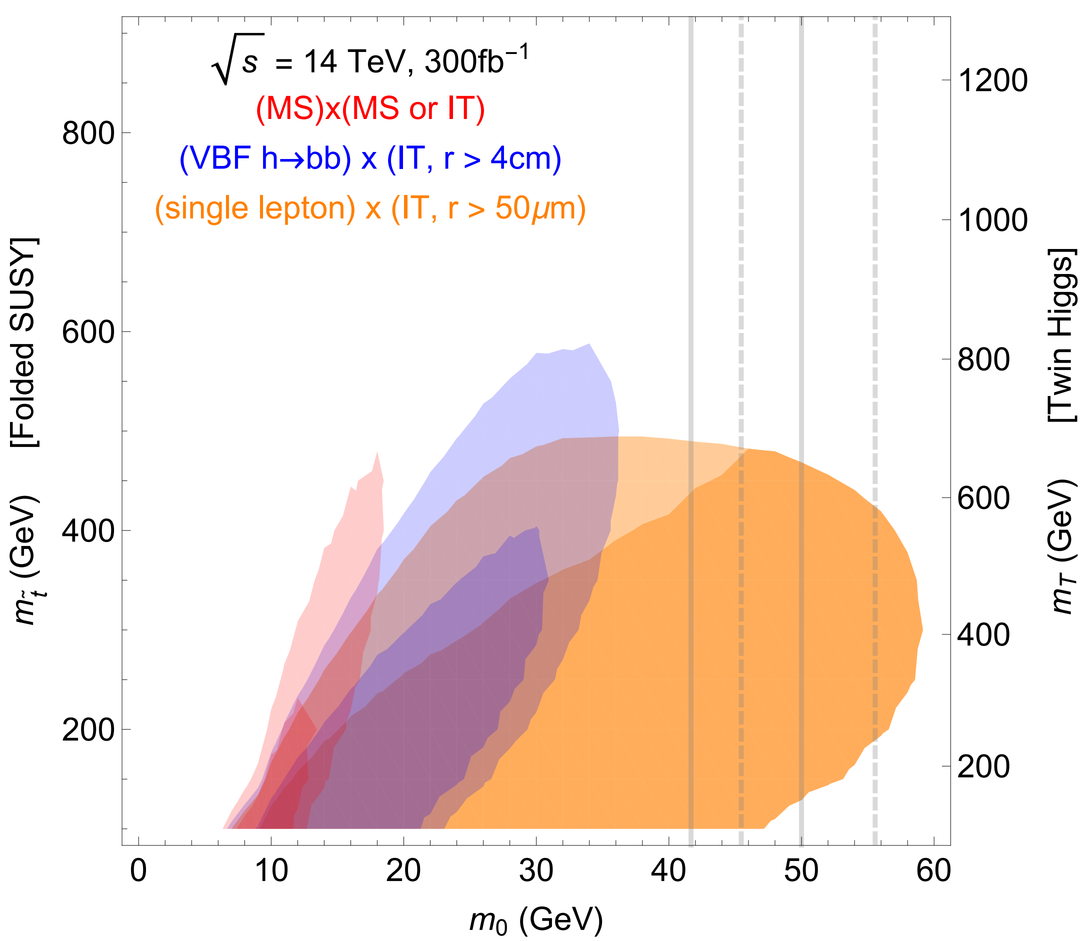


top parters are EW charged: m>100GeV (LEP)
Lightest hidden states are glueballs of QCD' that can mix with the Higgs boson

Exotic Higgs decays with displaced vertices

Curtin, Verhaaren '15





Higgs couples to QCD' bound states

Produce in rare Higgs decays (BR~10^{-3}-10^{-4})

$$gg \to h \to 0^{++} + 0^{++} + \ldots$$

Decay back to SM via Higgs

$$0^{++} \to h^* \to f\bar{f}$$

Long-lived, length scale ~ LHC detectors

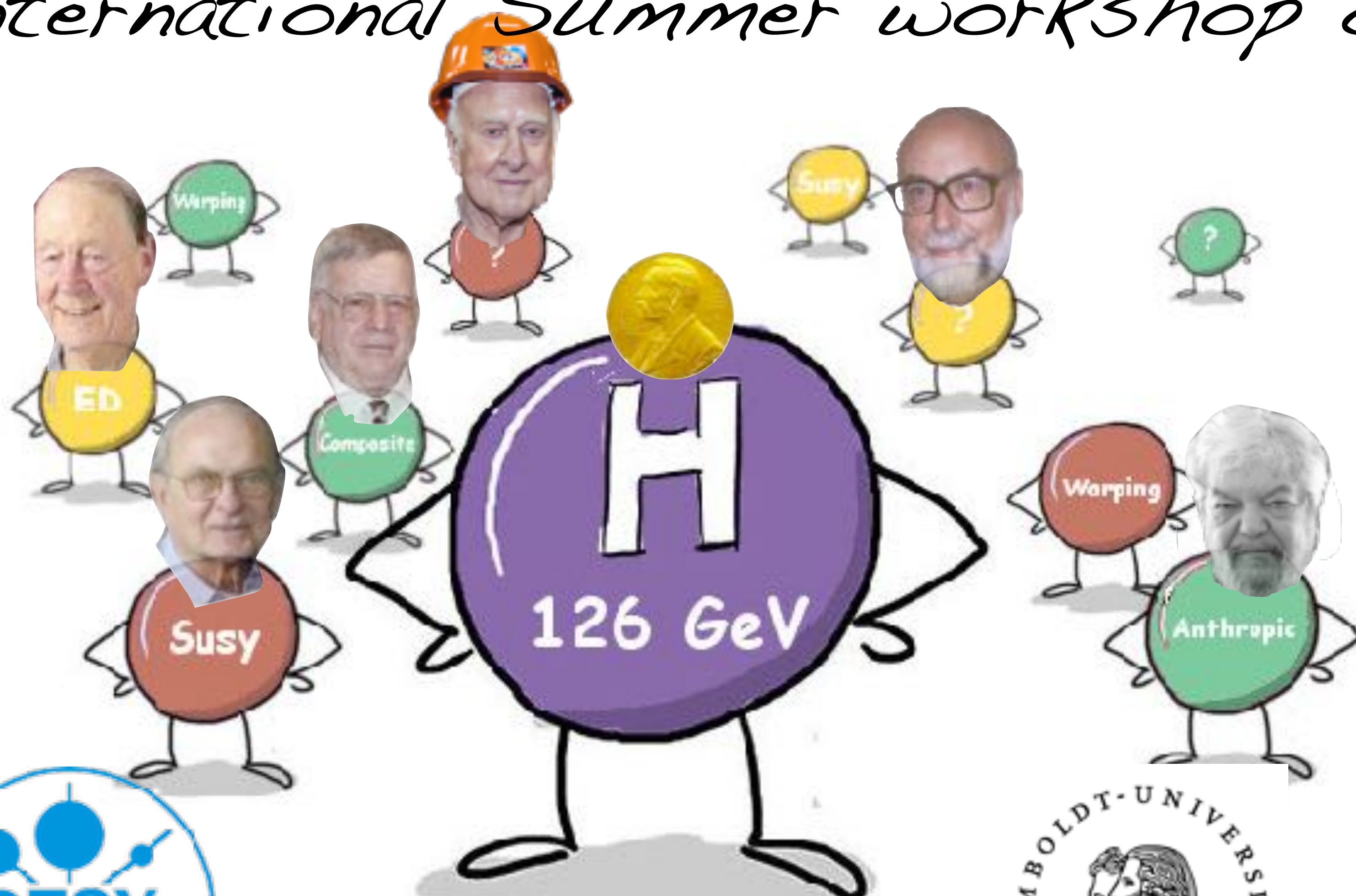
Mathusla to detect Long Lived Particles? Precise timing within ATLAS/CMS detectors?

Beyond the Standard Model

TAE 2018 @ Benasque

International Summer workshop on High Energy Physics

Lecture 2/3



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Humboldt University (Berlin)
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Outline

Lecture #1

- General introduction: From Fermi theory to the Standard Model
- Higgs physics as a door to BSM
- Naturalness and the weak scale hierarchy problem
- Supersymmetry

Lecture #2

- Composite Higgs
- Extra dimensions
- Cosmological relaxation: a concrete example of different energy frontier
- NNaturalness

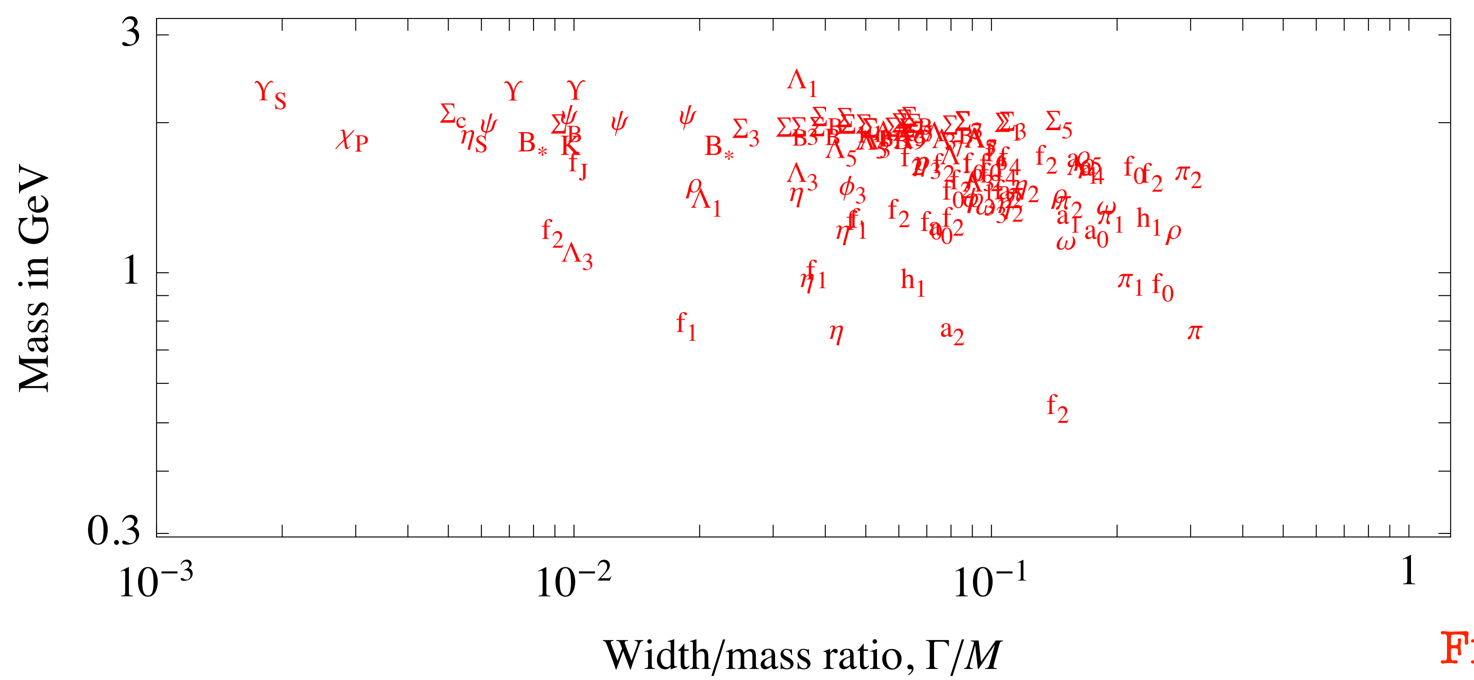
Lecture #3

- Weak gravity conjecture and the swampland
- Beyond colliders searches for new physics
  - Gravitational waves
  - AMO: isotope spectroscopy
  - Electric dipole moment
  - Neutron-antineutron oscillations
  - Primordial black holes

Composite Higgs Models

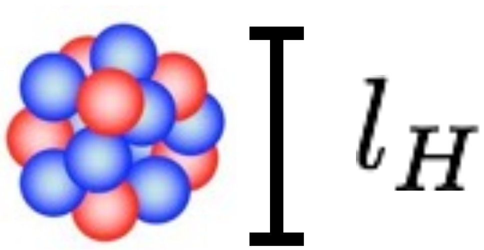
Composite Higgs

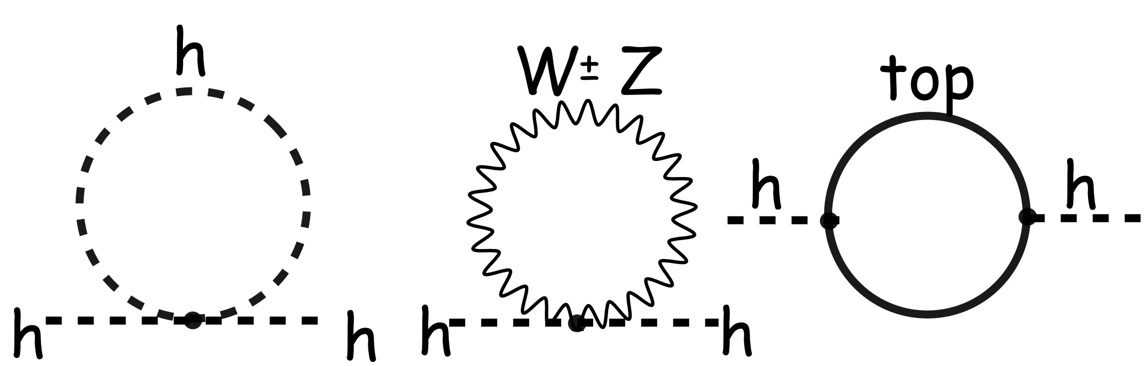
Light scalars exist in Nature but
all the ones observed before Higgs discovery were composite bounds states



Franceschini et al. '15

Could the Higgs be a "hadron" of a new strong force?

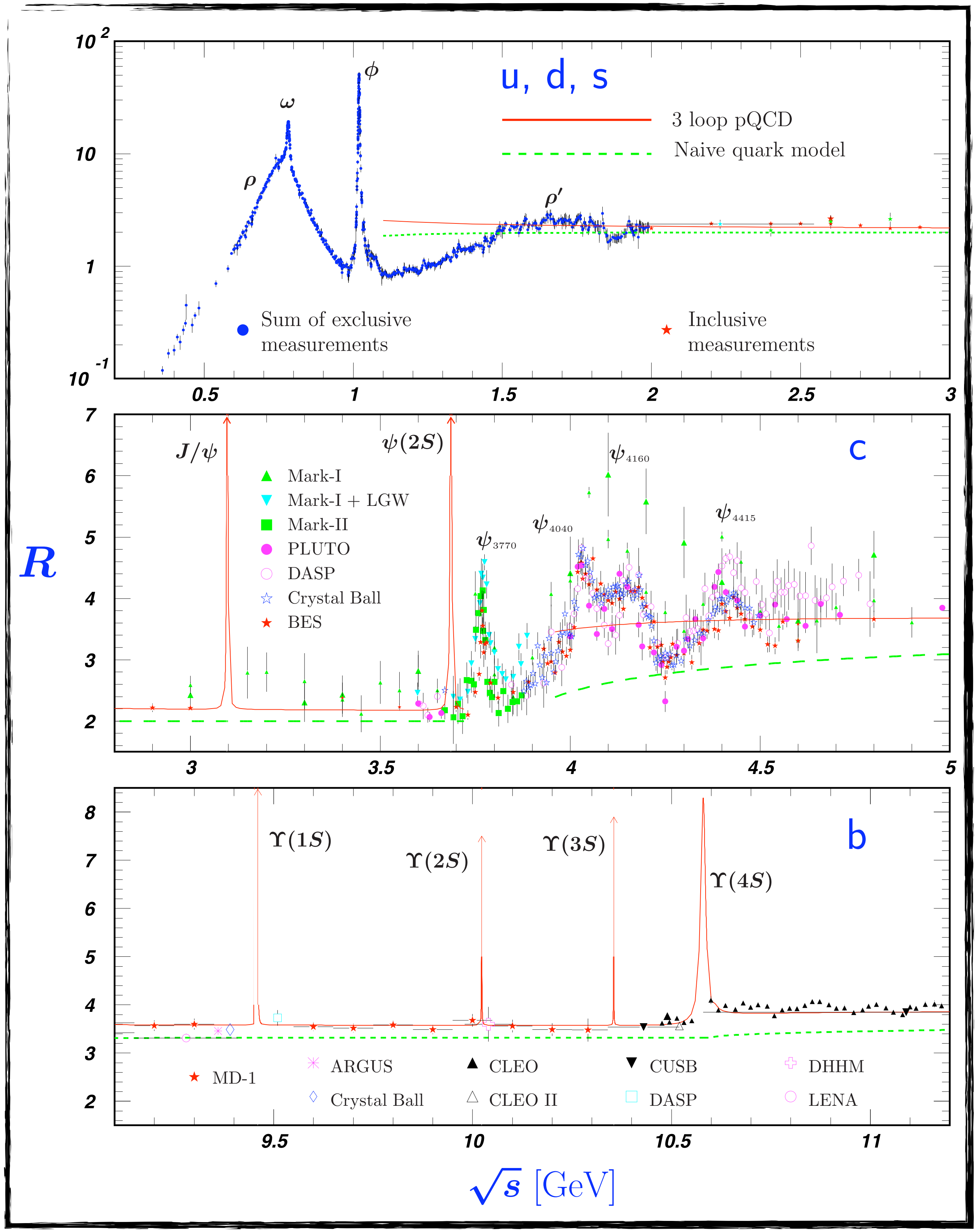




At energy above $1/\ell_H$, the Higgs dissolves, the integrals are smoothed out

$$\int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m^2} \propto \Lambda^2 \qquad \int \frac{d^4k}{(2\pi)^4}\mathcal{F}_H(k)\frac{1}{k^2-m^2} \propto 1/l_H^2$$

Higgs as a bound state



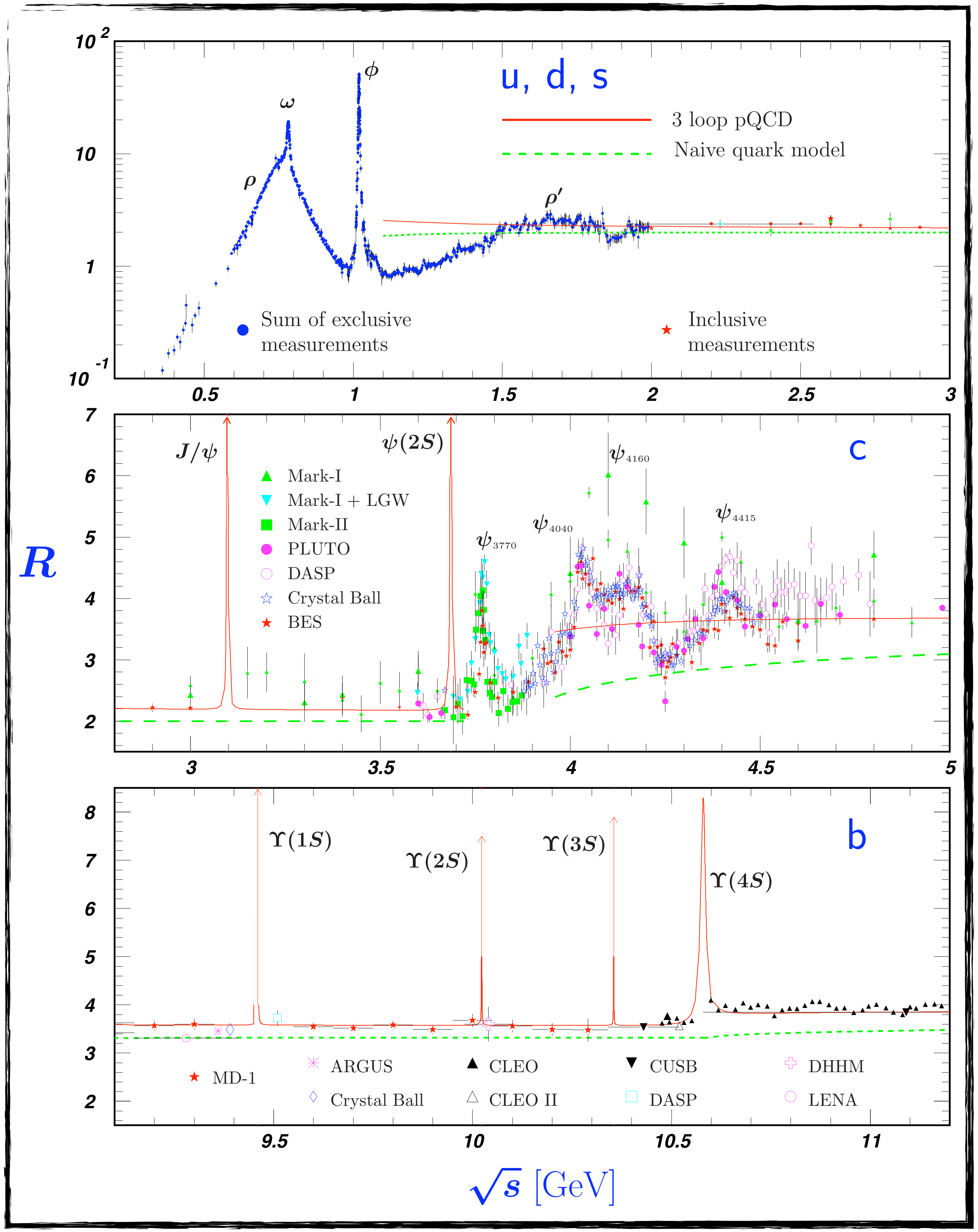
Structure of QCD was understood from inelastic scattering experiments

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

Shows some peaks/resonances at each QCD bound states

Eventually the asymptotic value of R also tells the number of color of QCD

Higgs as a bound state



The Higgs discovery would be the first step of rich physics ahead of us:

- discover a new SU(N_c) force
- access to the fundamental constituents
- rich spectrum of bound states

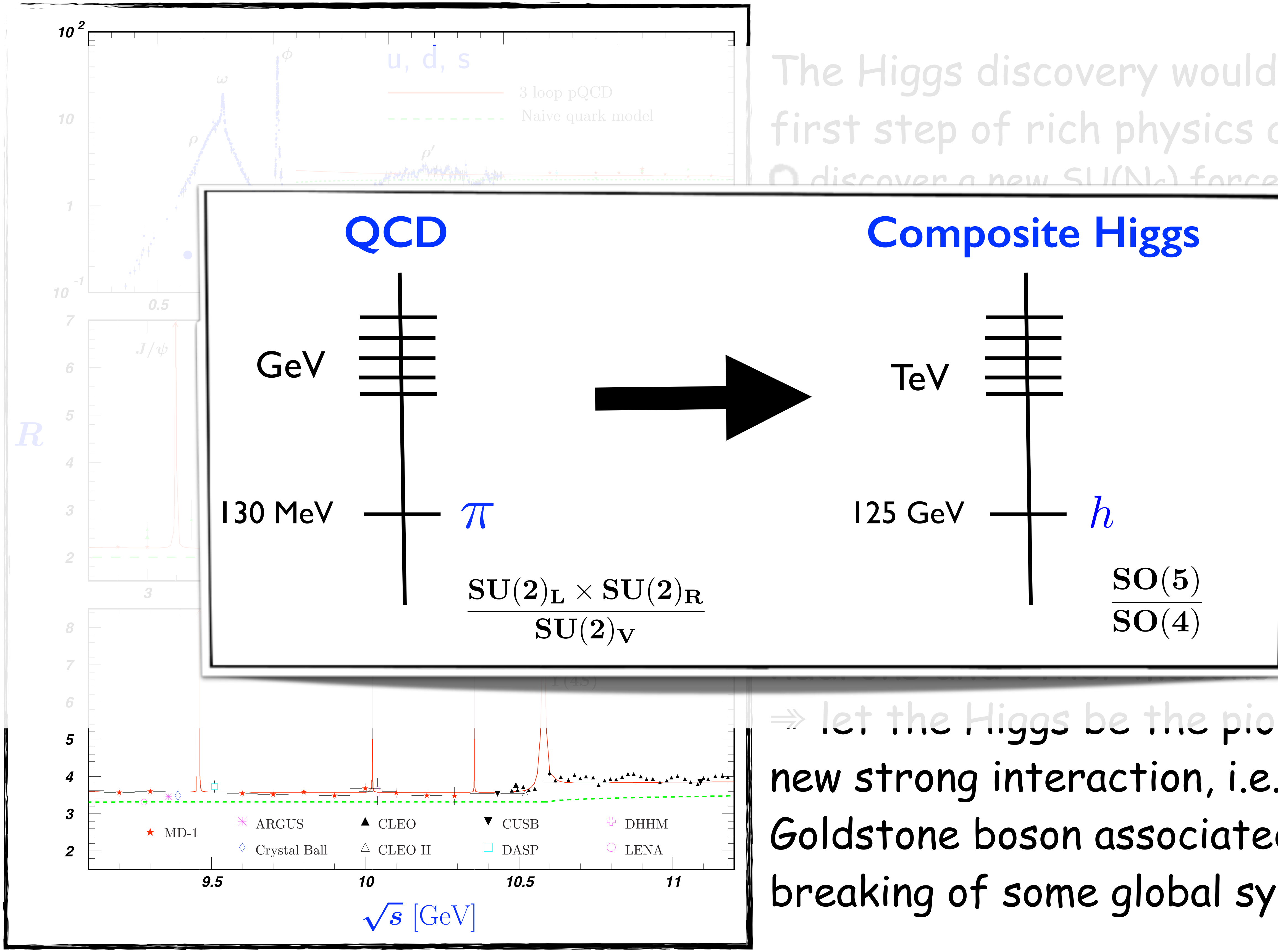
But how come we haven't seen anything of these yet?

⇛ The Higgs has to be lighter than the other bound states

⇛ pions are lighter than nucleons, hadrons and other mesons

⇛ let the Higgs be the pions of the new strong interaction, i.e., the Goldstone boson associated to the breaking of some global symmetry

Higgs as a bound state



The Higgs discovery would be the first step of rich physics ahead of us:

$\Rightarrow$ let the Higgs be the pions of the new strong interaction, i.e., the Goldstone boson associated to the breaking of some global symmetry

Higgs as a Goldstone boson

SM $SO(4)/SO(3)$ $W^{\pm}_L$ & Z_L $\Rightarrow$ G/H $W^{\pm}_L$ & Z_L & h BSM

Examples: $SO(5)/SO(4)$: 4 PGBs=$W^{\pm}_L$, Z_L, h ⟷ Minimal Composite Higgs Model

dim=10 dim=6

Agashe, Contino, Pomarol '04

$SO(6)/SO(5)$: 5 PGBs=H, a ⟷ Next MCHM

dim=15 dim=10

$SU(4)/Sp(4,\mathbb{C})$: 5 PGBs=H, s

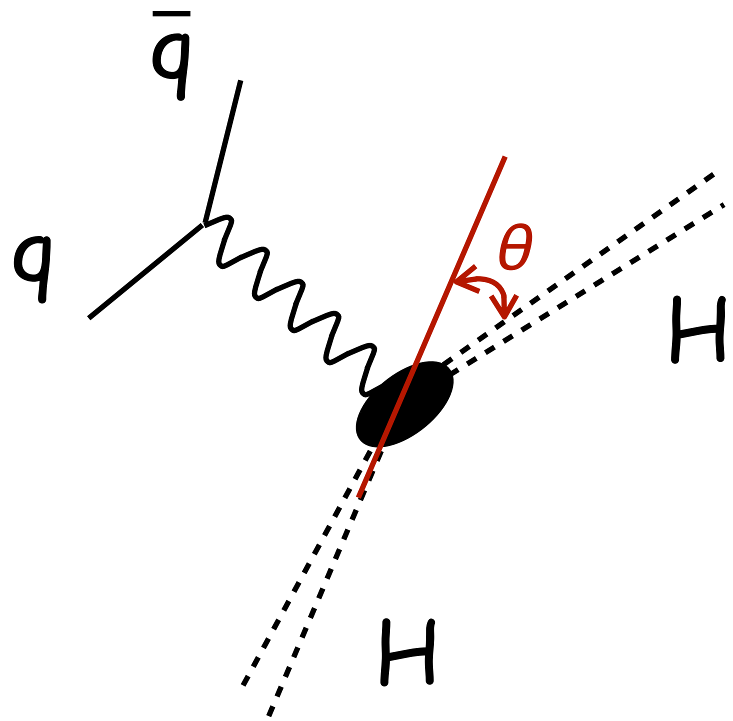
dim=15 dim=10

$SO(6)/SO(4)\times SO(2)$: 8 PGBs=H_1+H_2 ⟷ Minimal Composite Two Higgs Doublets

dim=15 dim=7

Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

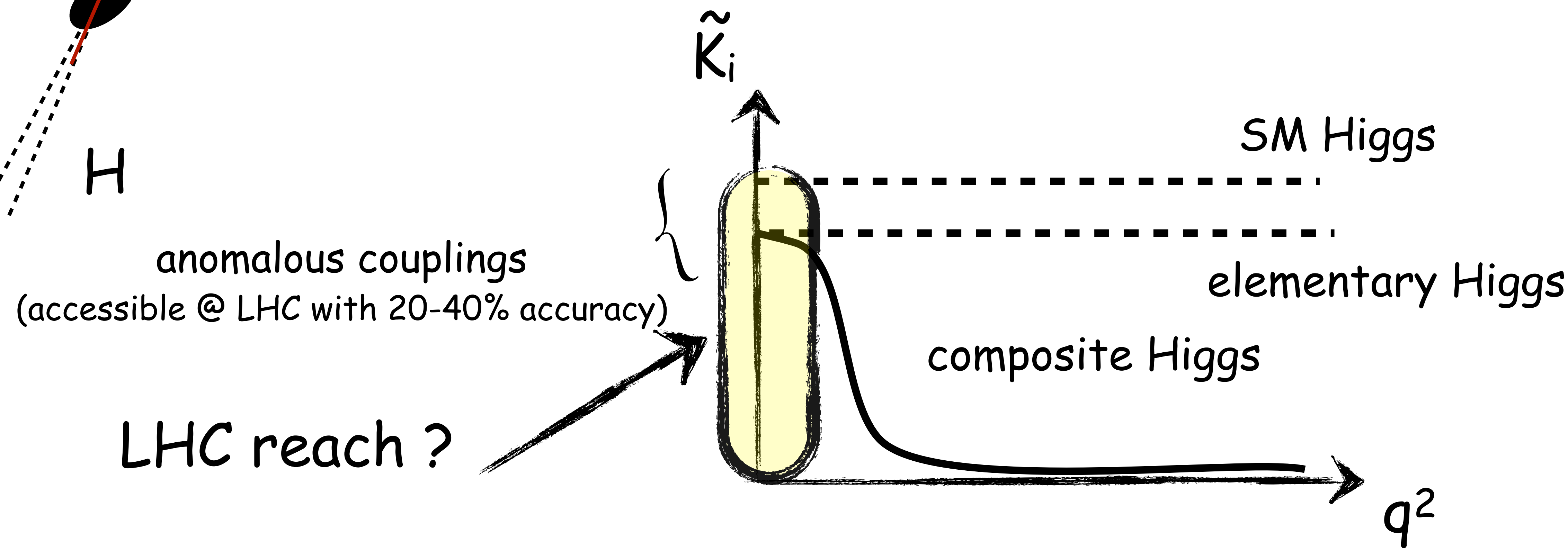
Probe the compositeness of the Higgs?



Rosenbluth-type cross-section

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{16 m_H^2 \sin^4\theta/2}\frac{E'}{E^3}\left(2\tilde{K}_1 q^2 \sin^2\theta/2 + \tilde{K}_2 \cos^2\theta/2\right)$$

Constants factor for point-like target
Momentum-dependent when target has an internal structure



Need to develop tools to understand the physics of a composite Higgs

- use effective theory approach
- rely on symmetries of the problem

} identify interesting processes

Composite Higgs Anomalous Couplings

Giudice, Grojean, Pomarol, Rattazzi '07

$$\mathcal{L} \supset \frac{c_H}{2f^2}\partial^\mu\left(|H|^2\right)\partial_\mu\left(|H|^2\right) \qquad c_H \sim \mathcal{O}(1)$$

f=compositeness scale of the Higgs boson

$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \Longrightarrow \mathcal{L} = \frac{1}{2}\left(1 + c_H\frac{v^2}{f^2}\right)(\partial^\mu h)^2 + \ldots$$

Modified Higgs propagator ~ Higgs couplings rescaled by $\frac{1}{\sqrt{1+c_H\frac{v^2}{f^2}}} \sim 1 - c_H\frac{v^2}{2f^2} \equiv 1-\xi/2$

Higgs anomalous coupling: a = √1-ξ ≈ 1-ξ/2

$$\xi = v^2/f^2$$

EFT = dimensional analysis

It is important to remember that couplings are not dimensionless

		M^n	$\hbar^n$
scalar field	ϕ	1	$1/2$
fermion field	ψ	$3/2$	$1/2$
vector field	A_μ	1	$1/2$
mass	m	1	0
gauge coupling	g	0	$-1/2$
quartic coupling	λ	0	-1
Yukawa coupling	y_f	0	$-1/2$

$$\mathcal{S} = \int d^4x \left(\mathcal{L}_0 + \hbar \mathcal{L}_1 + \hbar^2 \mathcal{L}_2 + \ldots\right)$$

$$[\mathcal{L}_0]_\hbar = 1 \qquad [\mathcal{L}_1]_\hbar = 0 \qquad [\mathcal{L}_2]_\hbar = -1$$

$$[\mathcal{L}_0]_M = 4 \qquad [\mathcal{L}_1]_M = 4 \qquad [\mathcal{L}_2]_M = 4$$

v is not simply a mass scale but also a "coupling"

$$[v]_\hbar = 1/2$$

$$\mathcal{A}_{W_L W_L \to W_L W_L} = \frac{s}{v^2}$$ even when gauge coupling are zero

$$\frac{1}{M^2} \underbrace{g_*^2}_{[\cdot]_\hbar = -1} \underbrace{\left(\partial^\mu |H|^2\right)^2}_{[\cdot]_\hbar = 2}$$

$$\frac{i c_W}{2M^2} \underbrace{\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)}_{[\cdot]_\hbar = 1} \underbrace{\left(g\, D^\nu W_{\mu\nu}\right)^i}_{[\cdot]_\hbar = 0}$$

SILH Effective Lagrangian

(strongly-interacting light Higgs)

Giudice, Grojean, Pomarol, Rattazzi '07

- extra Higgs leg: H/f
- extra derivative: ∂/m_ρ

Genuine strong operators (sensitive to the scale f)

$$\frac{c_H}{2f^2}\left(\partial^\mu |H|^2\right)^2$$

$$\frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)^2$$

custodial breaking

$$\frac{c_y y_f}{f^2}|H|^2 \bar{f}_L H f_R + \text{h.c.}$$

$$\frac{c_6 \lambda}{f^2}|H|^6$$

Form factor operators (sensitive to the scale m_ρ)

$$\frac{ic_W}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i$$

$$\frac{ic_B}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$

$$\frac{ic_{HW}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu}$$

$$\frac{ic_{HB}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

$$\frac{c_\gamma}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}$$

$$\frac{c_g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$

Goldstone sym.

Higgs anomalous couplings

$$\mathcal{L}_{\rm EWSB} = m_W^2 W_\mu^+ W_\mu^+ \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - m_\psi \bar\psi_L \psi_R \left(1 + c\frac{h}{v}\right)$$

The Higgs couplings deviates from SM ones (a=b=c=1)
and the deviations are controlled by c_H and c_y

Anomalous couplings are related to the coset symmetry and not the spectrum of resonances

Minimal composite Higgs model (MCHM): SO(5)/SO(4)

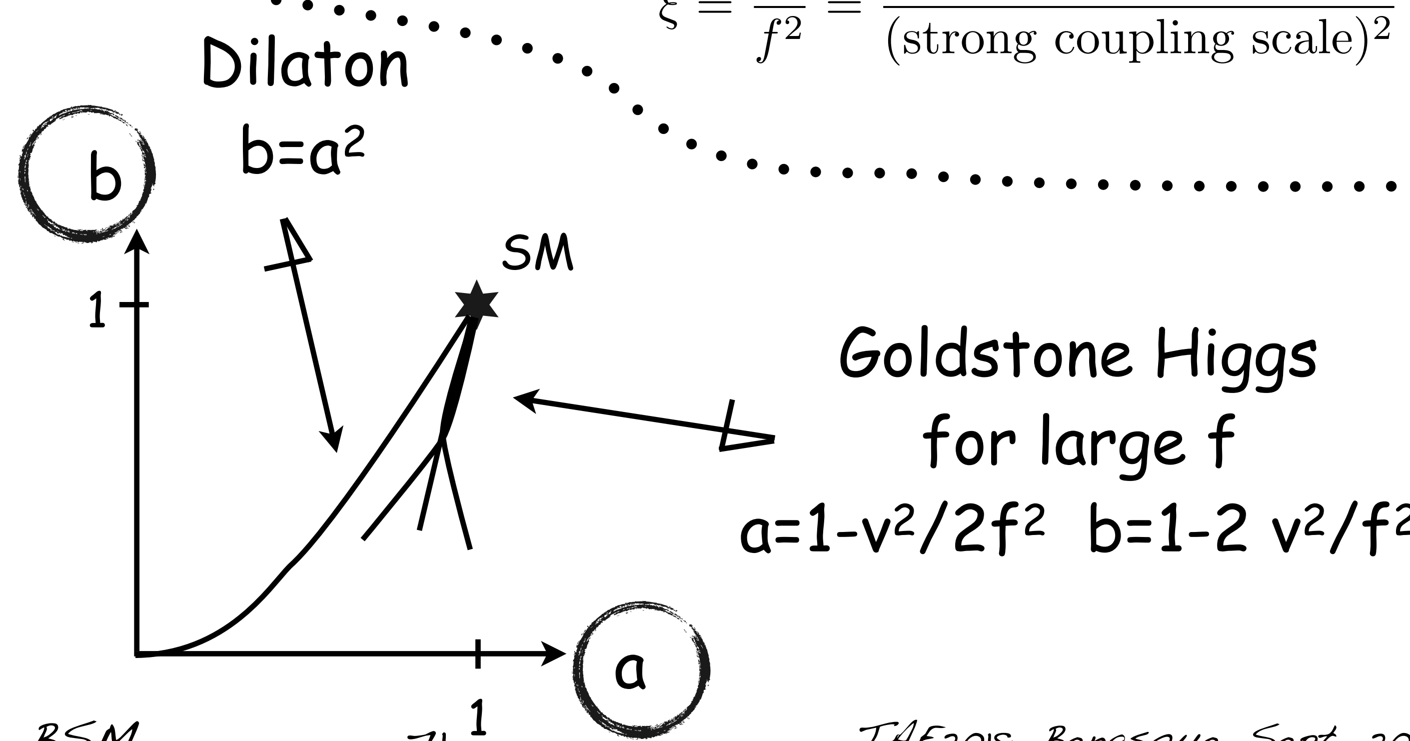
$$a = \sqrt{1-\xi} \qquad b = 1-2\xi \qquad b_3 = -\frac{4}{3}\xi\sqrt{1-\xi} \qquad c = \left(\sqrt{1-\xi}, \frac{1-2\xi}{\sqrt{1-\xi}}\right) \qquad c_2 = -(\xi, 4\xi)$$

Uniqueness of Goldstone models
in the SM vicinity

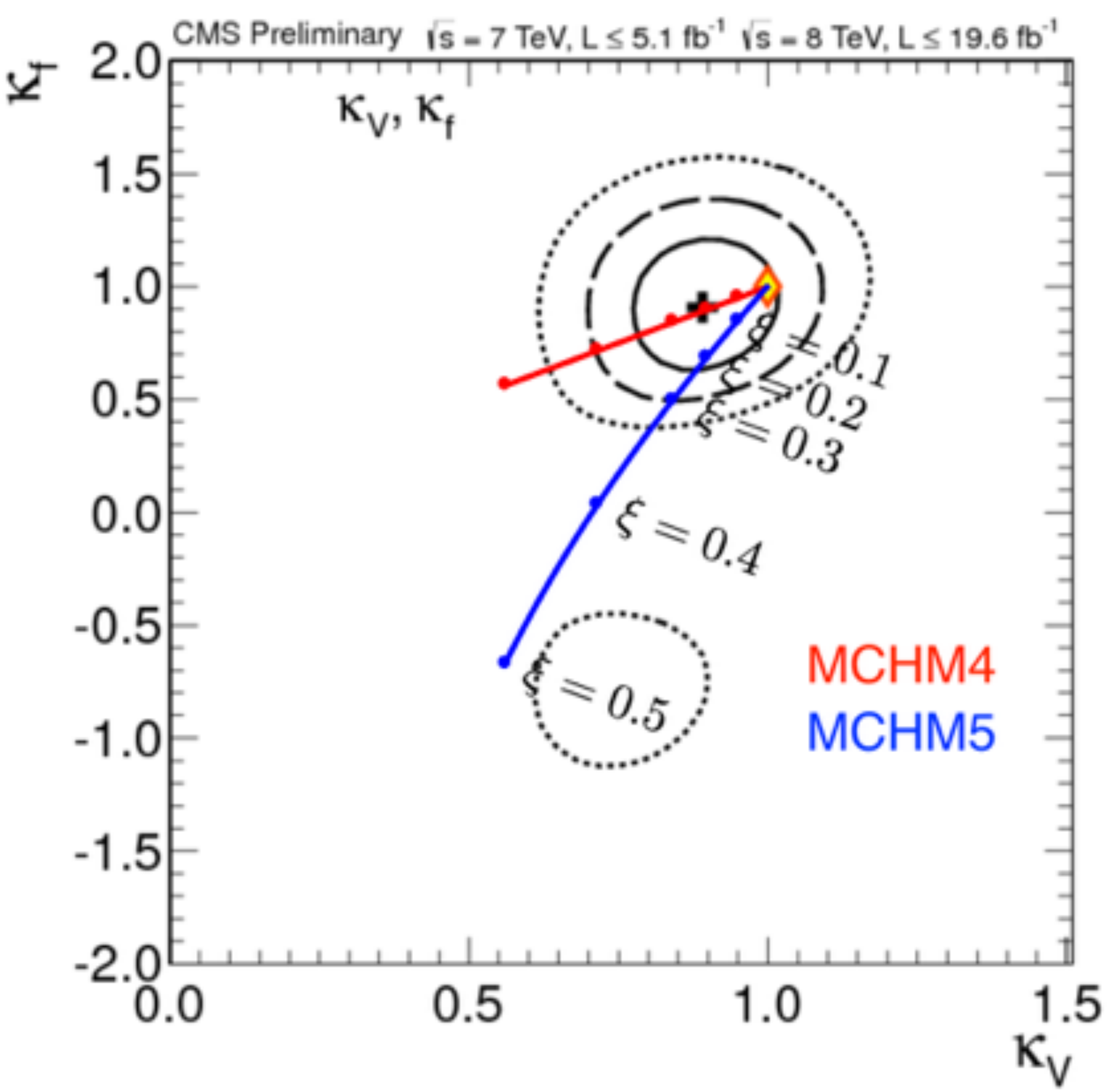
(a single operator at dimension-6 level
controls the amplitudes)

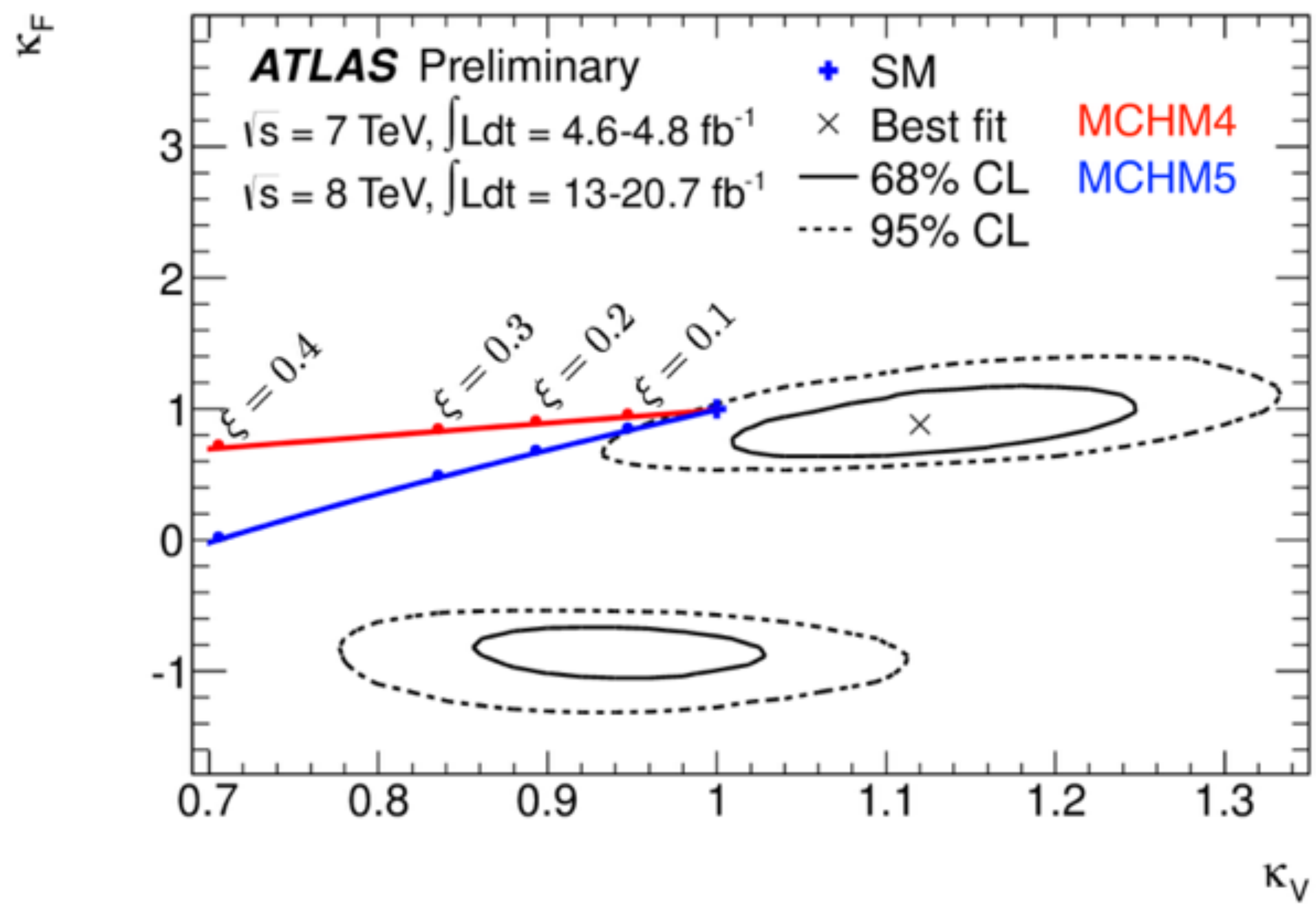
$$\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong coupling scale})^2}$$

Composite Higgs
vs.
SM Higgs



Higgs couplings fit





- MCHM4

$$\xi < 0.12 \quad \text{at } 95\%\text{CL}$$

- MCHM5

$$\xi < 0.10 \quad \text{at } 95\%\text{CL}$$

Indirect composite signatures

Assuming **composite** Higgs, **elementary** gauge bos.:

$$\mathcal{L}^{d=6}_{\rm BSM} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* H, g_w V_\mu, \partial_\mu]$$

S-parameter @ee: [De Blas et. al.] (LEP: 10^{-3})

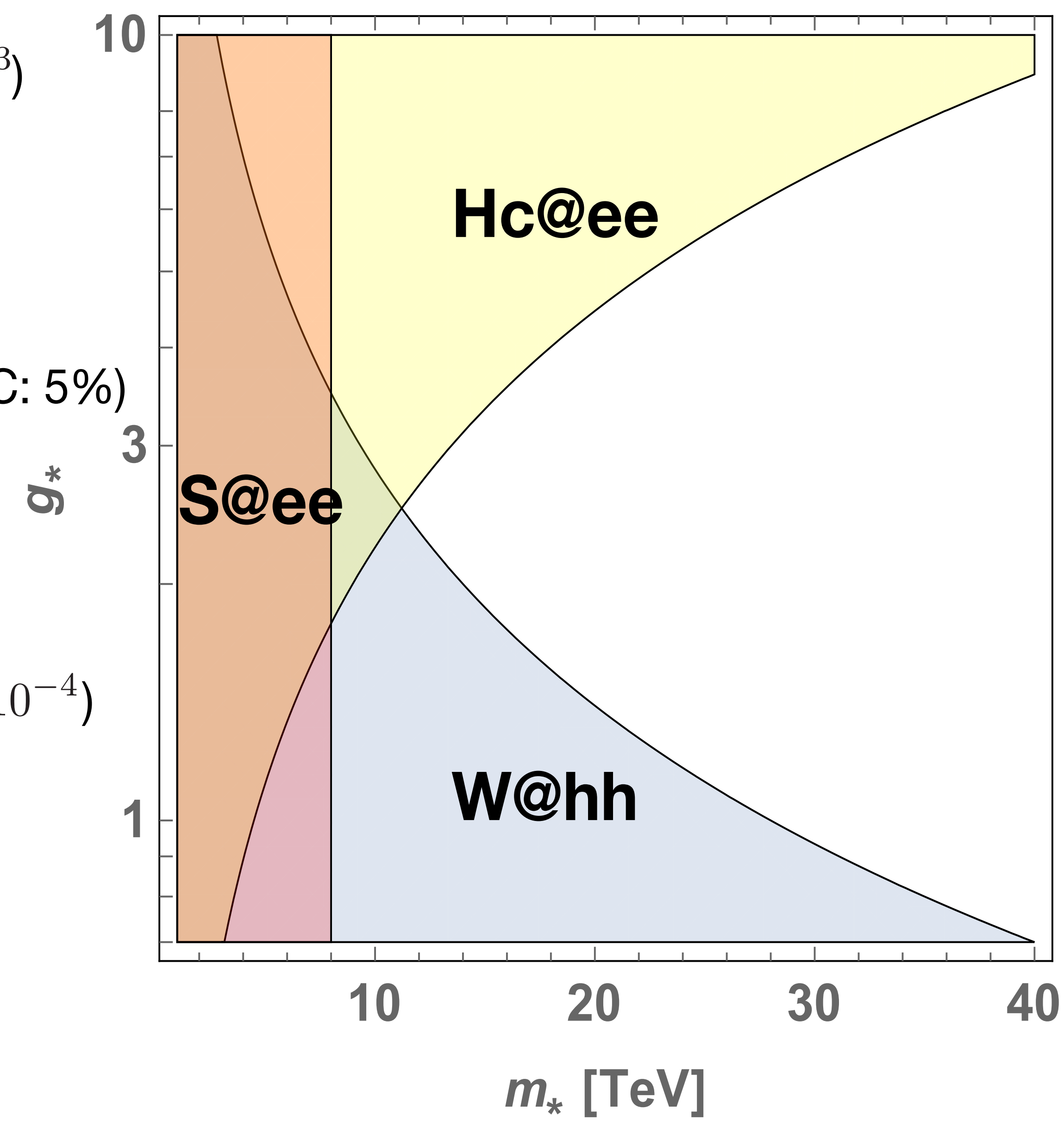
$$\frac{g_w g'}{m_*^2} H^\dagger \sigma_a H W^a_{\mu\nu} B^{\mu\nu} \Rightarrow \hat{S} = \frac{m_w^2}{m_*^2} < 10^{-4}$$

Higgs Couplings @ee: [ee Report] (HL-LHC: 5%)

$$\frac{g_*^2}{m_*^2}\partial_\mu |H|^2 \partial^\mu |H|^2 \Rightarrow \delta\kappa_{V,F} = \frac{g_*^2 v^2}{m_*^2} < 3\,10^{-3}$$

W @hh: (energy + accuracy) (HL-LHC< 10^{-4})

$$\frac{g_w^2}{g_*^2 m_*^2}(D_\mu W_{\nu\rho})^2 \Rightarrow W = \frac{g_w^2 m_w^2}{g_*^2 m_*^2} < \ 10^{-5}$$



Grojean-Wulzer @ FCC physics week '17

Indirect composite signatures

Composite tR, comp. Higgs, **elementary tL** and gauge

$$\mathcal{L}^{d=6}_{\rm BSM} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* t_R, y_t q_L, g_* H, g_w V_\mu, \partial_\mu]$$

ttH coupling @hh/ee: [Reports] (HL-LHC:10%)

$$\frac{y_t g_*^2}{m_*^2}|H|^2 \bar{q}_L H t_R \Rightarrow \frac{\delta y_t}{y_t} = \frac{g_*^2 v^2}{m_*^2} < 2\,10^{-2}$$

Diff. oper.s comb. in ee and hh!!

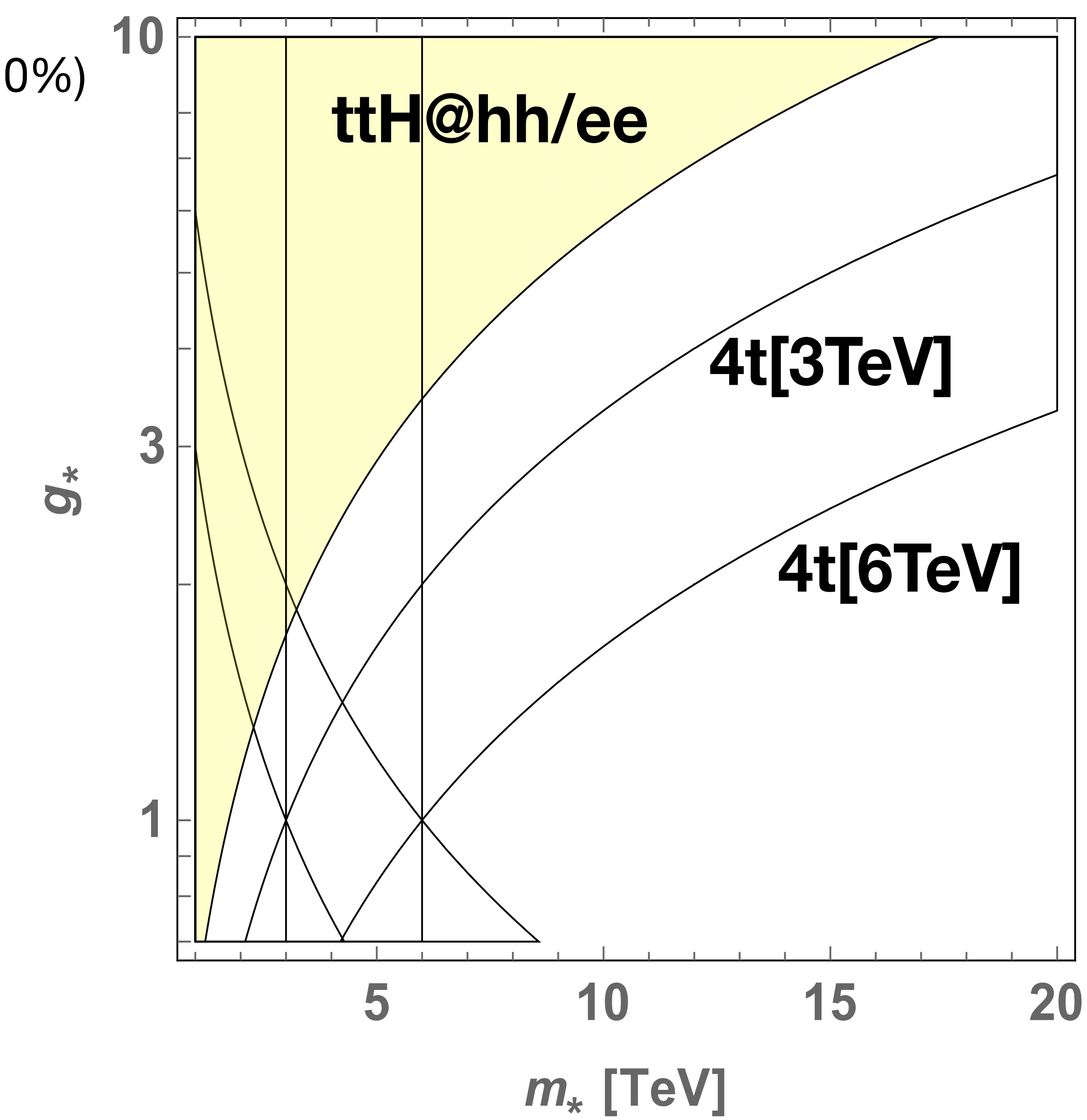
4-top contact interactions @hh:

$$\frac{g_*^2}{m_*^2}(\bar{t}_R\gamma_\mu t_R)^2 \Rightarrow \frac{g_*^2}{m_*^2} < \frac{1}{\Lambda_{4t}^2}$$

$$\frac{y_t^2}{m_*^2}(\bar{q}_L\gamma_\mu q_L)(\bar{t}_R\gamma_\mu t_R) \Rightarrow \frac{y_t^2}{m_*^2} < \frac{1}{\Lambda_{4t}^2}$$

$$\frac{y_t^4}{g_*^2 m_*^2}(\bar{q}_L\gamma_\mu q_L)^2 \Rightarrow \frac{y_t^4}{g_*^2 m_*^2} < \frac{1}{\Lambda_{4t}^2}$$

No study available (?)



Grojean-Wulzer @ FCC physics week ’17

The other resonances

3 TeV

spin-2 resonances

spin-1 resonances

1 TeV

500 GeV

color fermionic resonances

125 GeV

Higgs

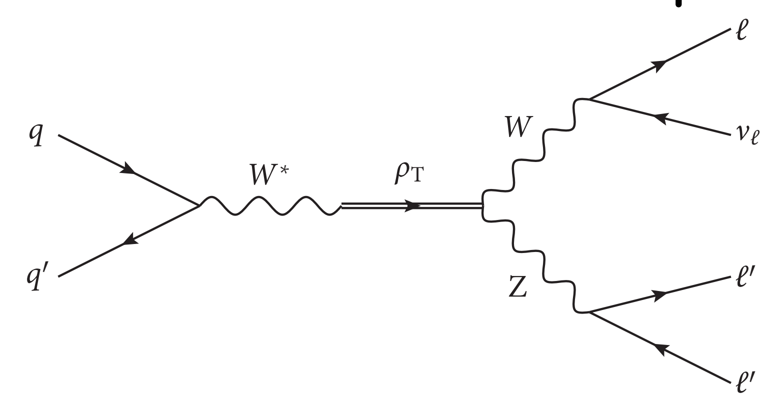
Dominant decays into longitudinal SM gauge bosons

$$\Gamma(\rho^0 \to W^+W^-) \approx \Gamma(\rho^\pm \to ZW^\pm) \approx \frac{m_\rho g^2_{\rho\pi\pi}}{48\pi} = \frac{m_\rho^5}{192\pi g_\rho^2 v^4}$$

Suppressed decays to SM quarks and leptons

$$\mathrm{Br}(\rho^\pm \to e^\pm \nu) \approx 2\mathrm{Br}(\rho^0 \to e^+e^-) \approx \frac{16 m_W^4}{m_\rho^4}$$

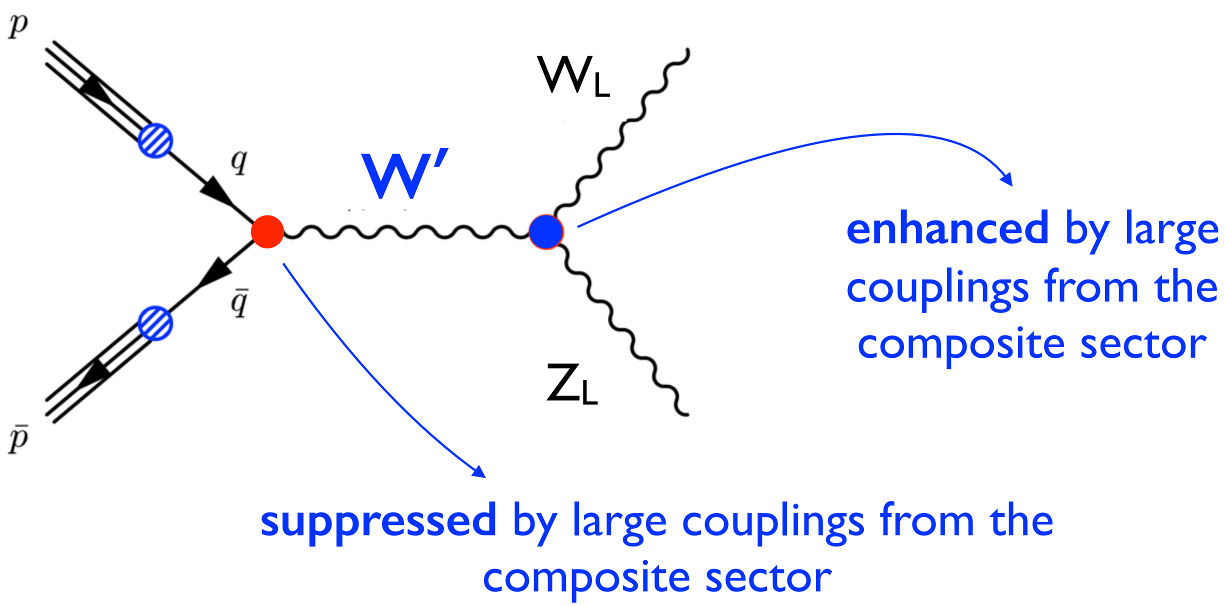
searches in WW, WZ channels in DY processes



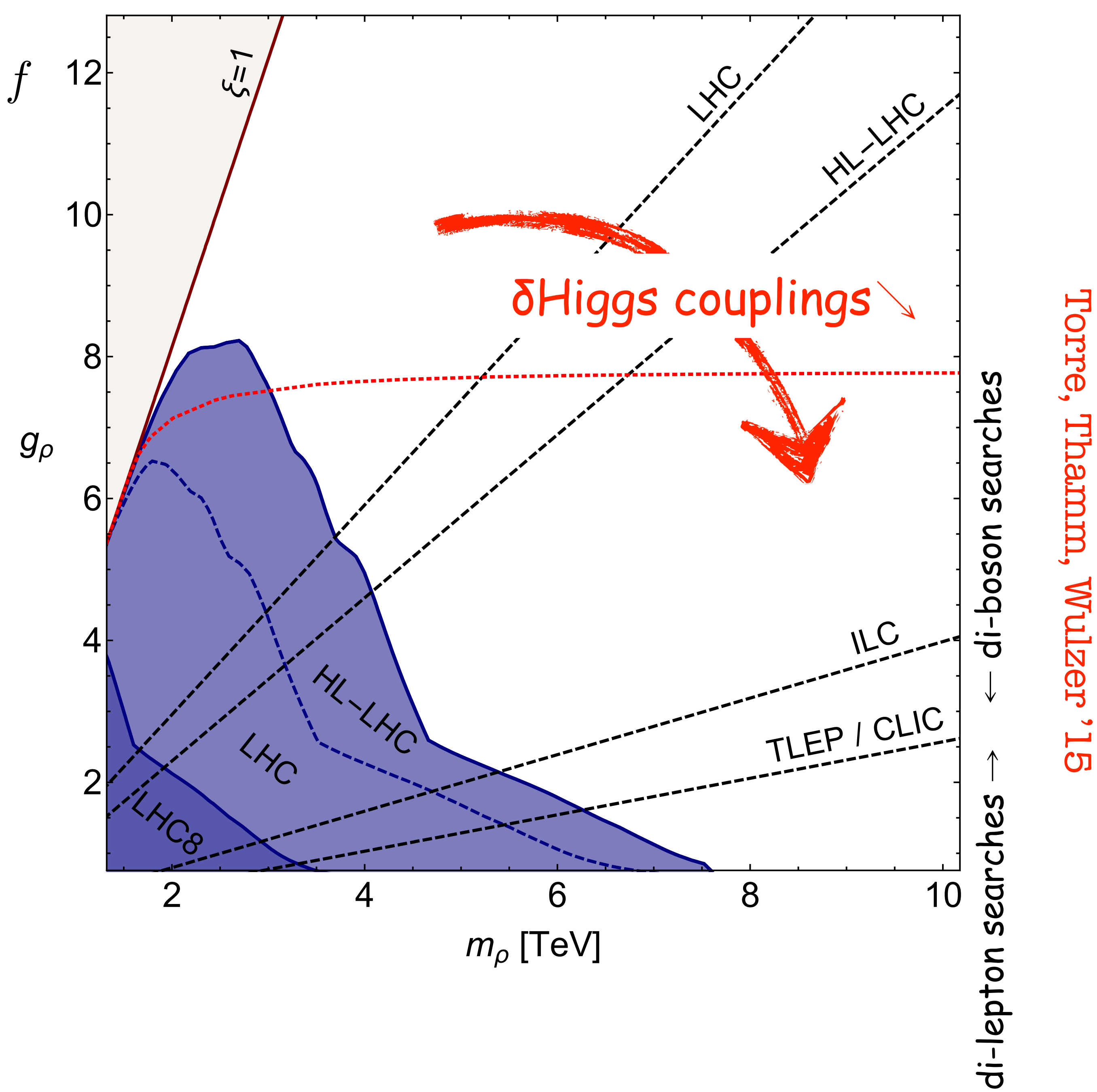
H couplings vs searches for vector resonances

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

- Precision Higgs study: $\xi \equiv \frac{\delta g}{g} = \frac{v^2}{f^2}$
- Direct searches for resonances: $m_\rho \approx g_* f$



DY production xs of resonances decreases as $1/g_\rho^2$



H couplings vs searches for vector resonances

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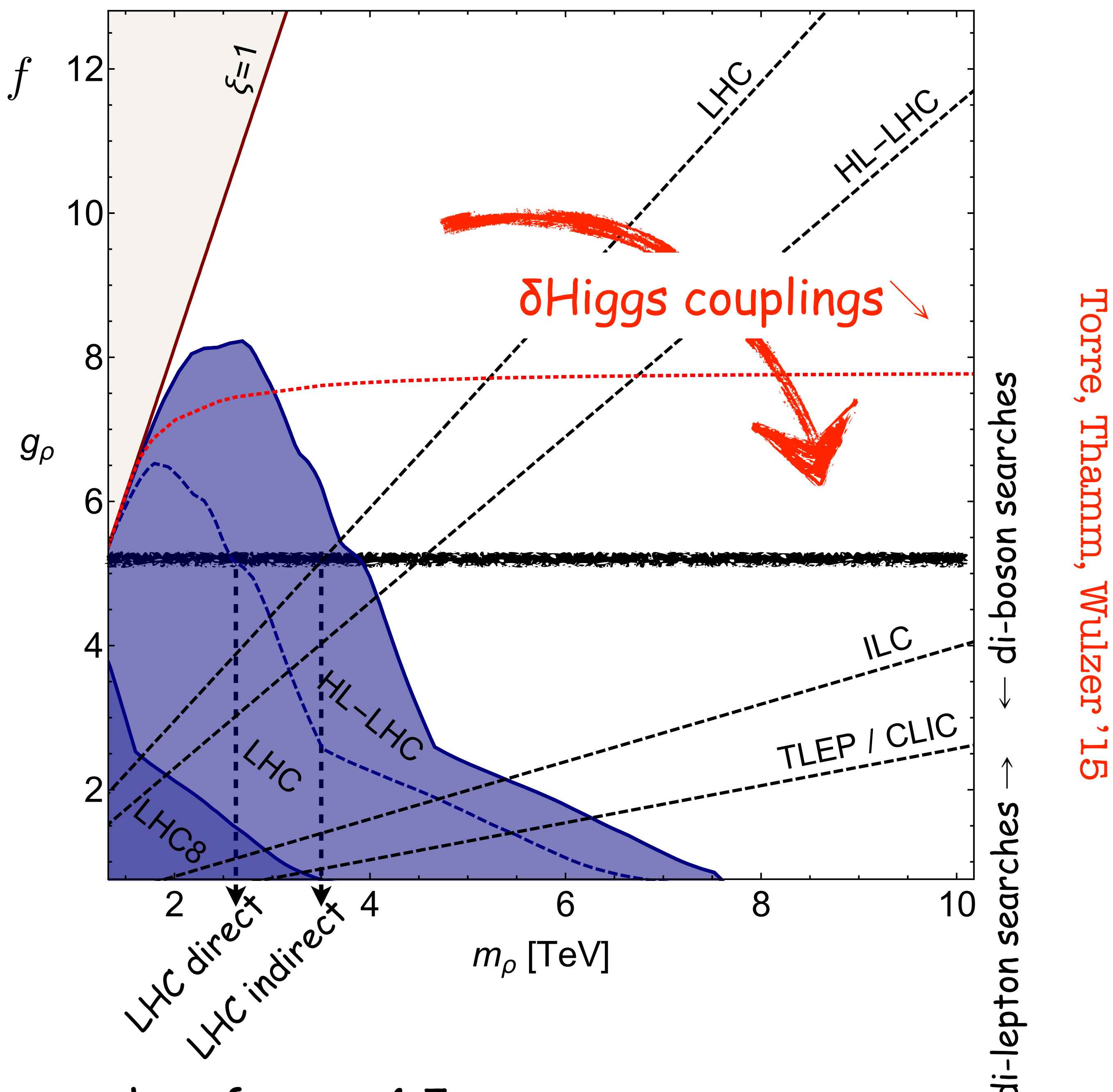
- Precision Higgs study: $\xi \equiv \dfrac{\delta g}{g} = \dfrac{v^2}{f^2}$
- Direct searches for resonances: $m_\rho \approx g_* f$

Collider	Energy	Luminosity	ξ [1σ]
LHC	14 TeV	300 fb^{-1}	$6.6 - 11.4 \times 10^{-2}$
LHC	14 TeV	3 ab^{-1}	$4 - 10 \times 10^{-2}$
ILC	250 GeV + 500 GeV	250 fb^{-1} 500 fb^{-1}	4.8-7.8 $\times 10^{-3}$
CLIC	350 GeV + 1.4 TeV + 3.0 TeV	500 fb^{-1} 1.5 ab^{-1} 2 ab^{-1}	2.2 $\times 10^{-3}$
TLEP	240 GeV + 350 GeV	10 ab^{-1} 2.6 ab^{-1}	2 $\times 10^{-3}$

DY production xs of resonances decreases as $1/g_\rho^2$



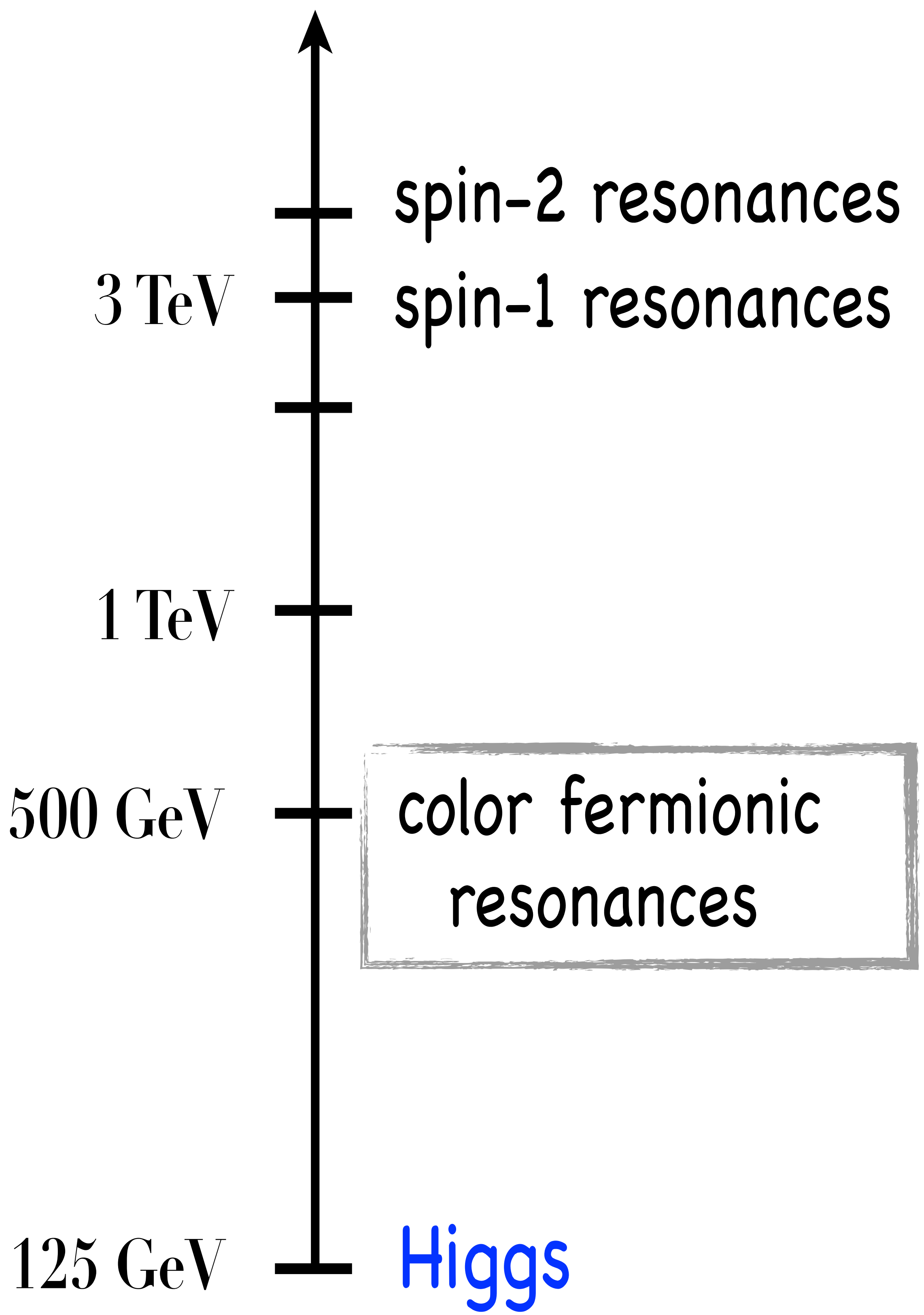
- **complementarity:**
  - direct searches win at small couplings
  - indirect searches probe new territory at large coupling

e.g.

indirect searches at LHC over-perform direct searches for g > 4.5

indirect searches at ILC over-perform direct searches at HL-LHC for g > 2

The other resonances



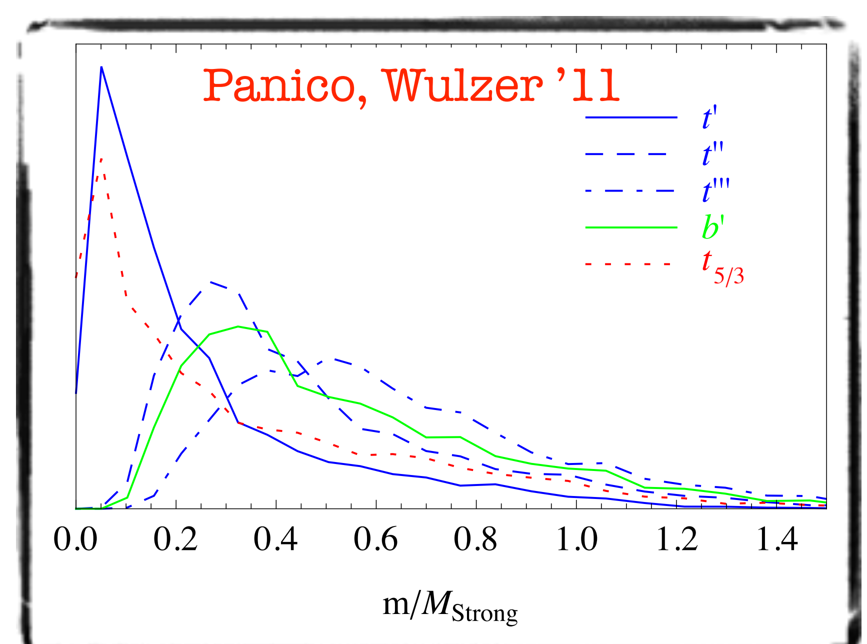
Top partners

SO(4)~SU(2)$_L$xSU(2)$_R$ embedding

$$Q_L = \begin{pmatrix} t_L^{2/3} & t_L^{5/3} \\ b_L^{-1/3} & b_L^{2/3} \end{pmatrix} \equiv (2,\bar{2})_{2/3}$$

$$t_R \equiv (1,1)_{2/3}$$

$$b_R \equiv (1,1)_{-1/3}$$



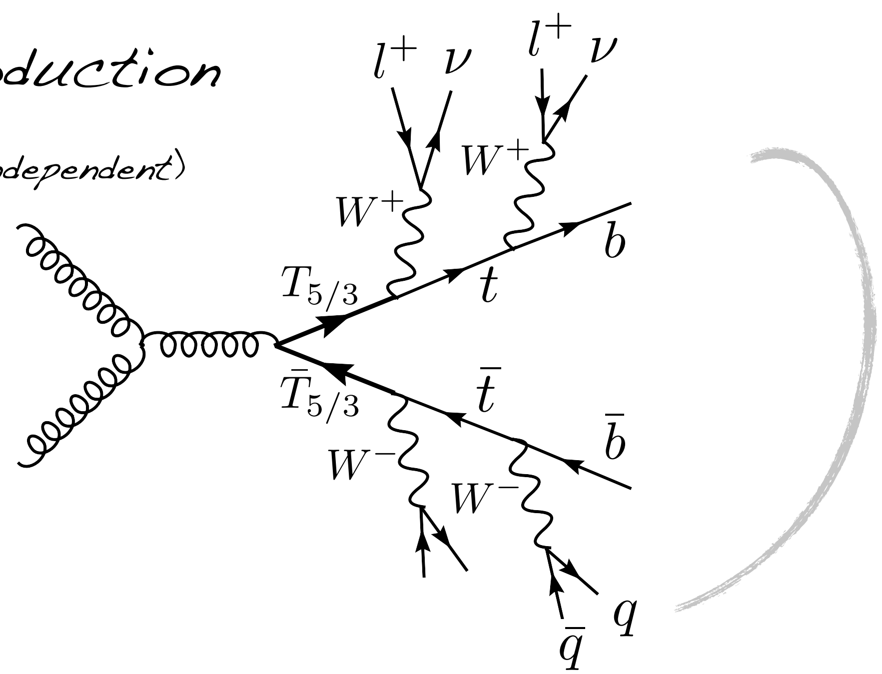
Searching for the top partners

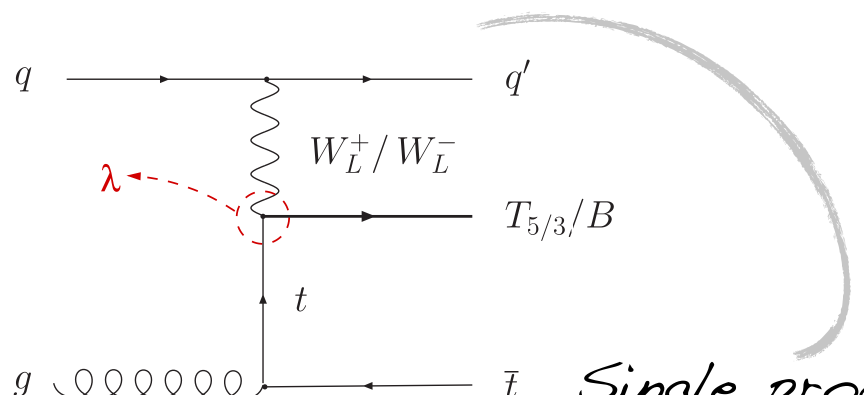
Search in same-sign dilepton events

- *tt+jets* is not a background [except for charge mis-ID and fake e-]
- the resonant (*tW*) invariant mass can be reconstructed

Pair production

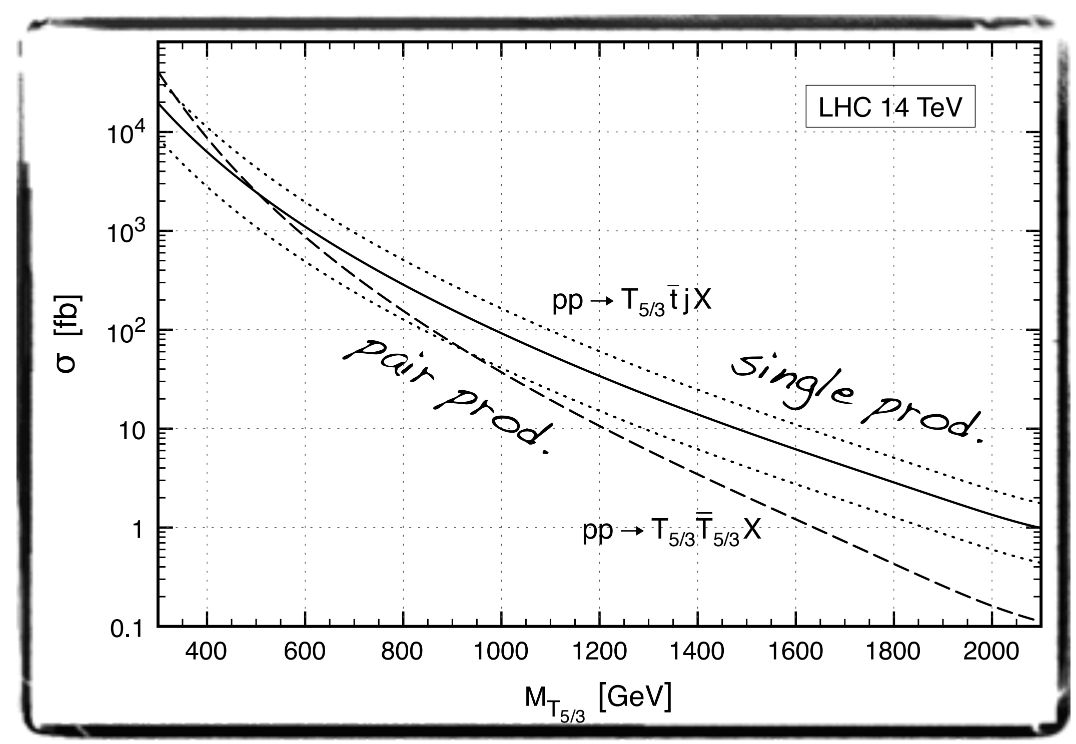
(model independent)





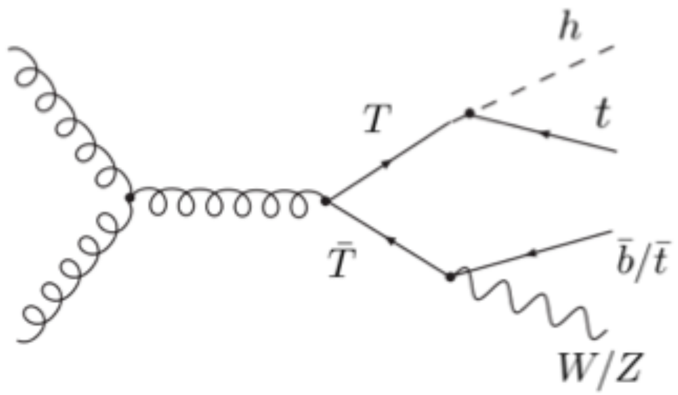
Single production

(model dependent)



[Contino, Servant '08]

Searching for the top partners



- $\ell^{\pm}$ + 4b final state Aguilar-Saavedra '09

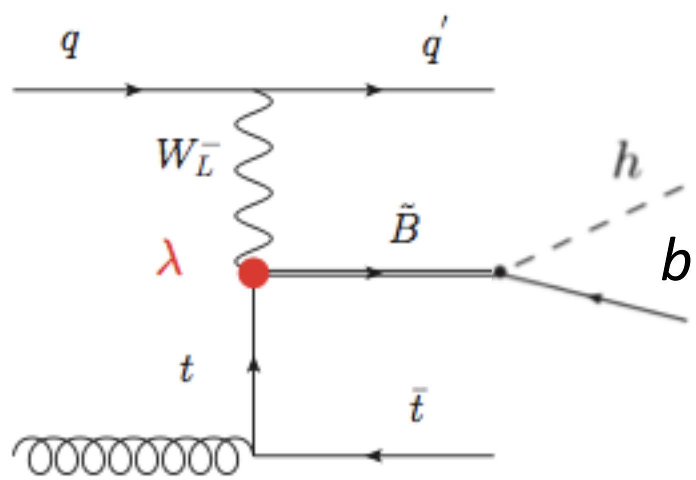
$$T\bar{T} \to HtW^-\bar{b} \to HW^+bW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}',$$
$$T\bar{T} \to HtV\bar{t} \to HW^+bVW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}', V \to q\bar{q}/\nu\bar{\nu}$$

- $\ell^{\pm}$ + 6b final state Aguilar-Saavedra '09

$$T\bar{T} \to HtH\bar{t} \to HW^+bHW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}'$$

- $\gamma\gamma$ final state Azatov et al '12

$$thbW/thtZ/thth,\ h \to \gamma\gamma$$

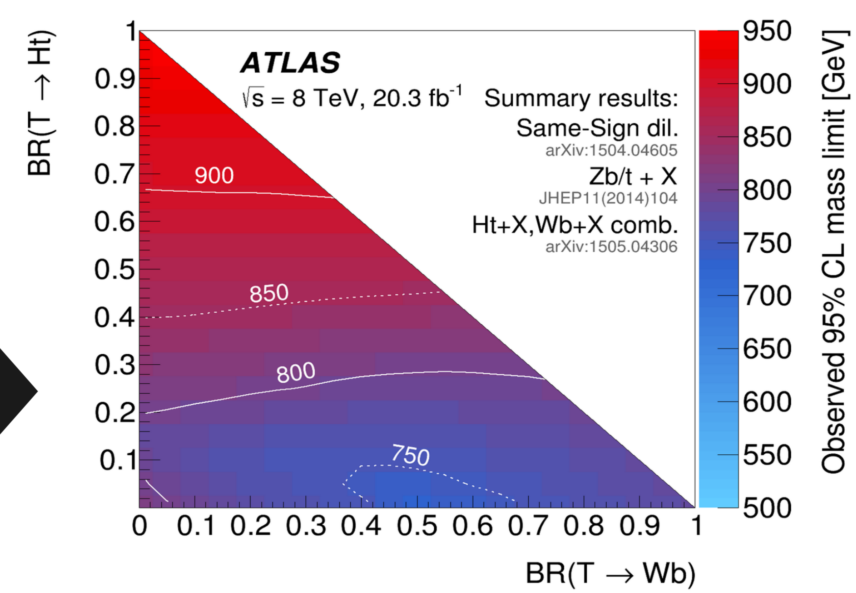


- $\ell^{\pm}$ + 4b final state Vignaroli '12

$$pp \to (\tilde{B} \to (h \to bb)b)t + X$$

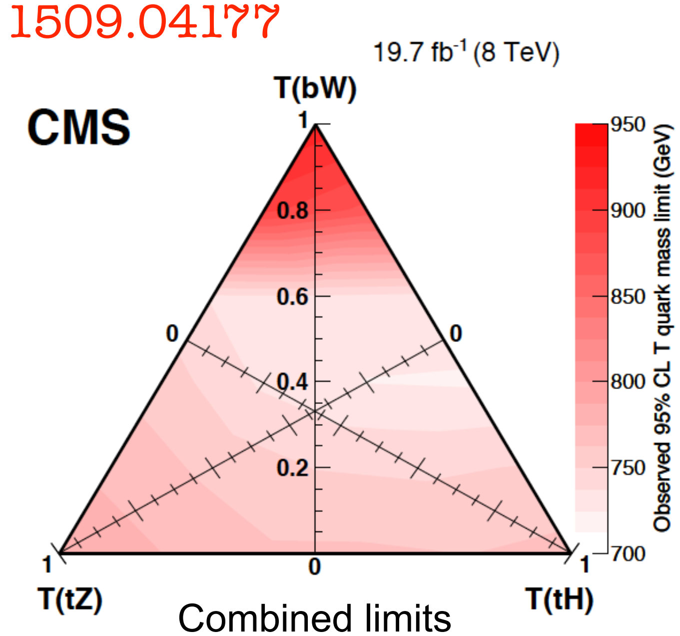
bounds on
charge 2/3 states
from pair production

1505.04306



(*) Not a combination. Only most restrictive individual bounds shown.

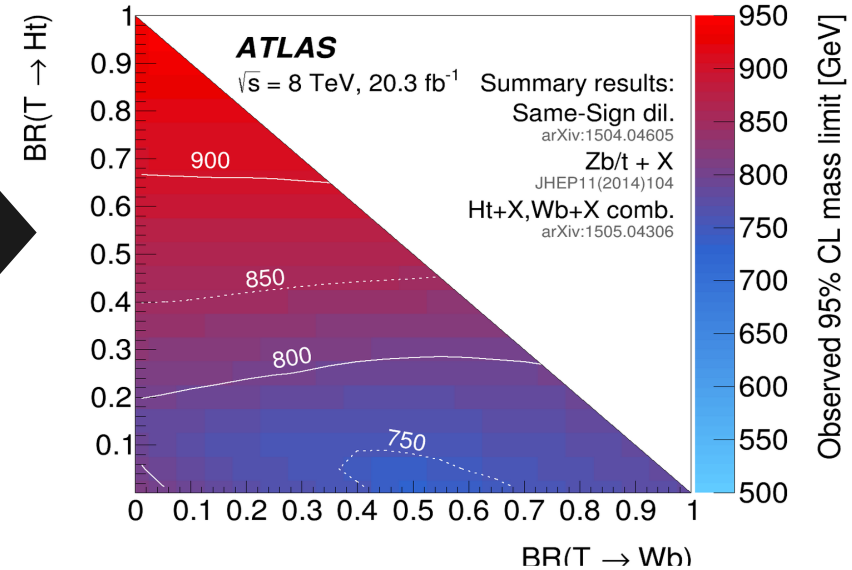
1509.04177



Searching for the top partners

bounds on
charge 2/3 states
from pair production

1505.04306



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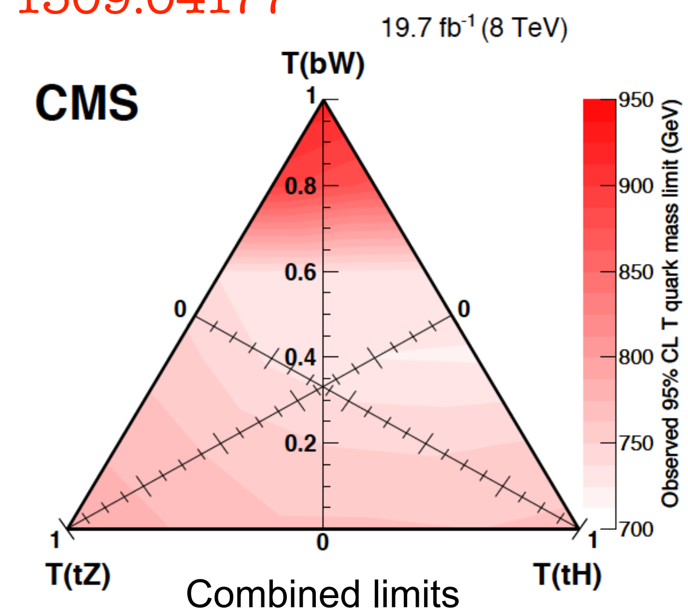
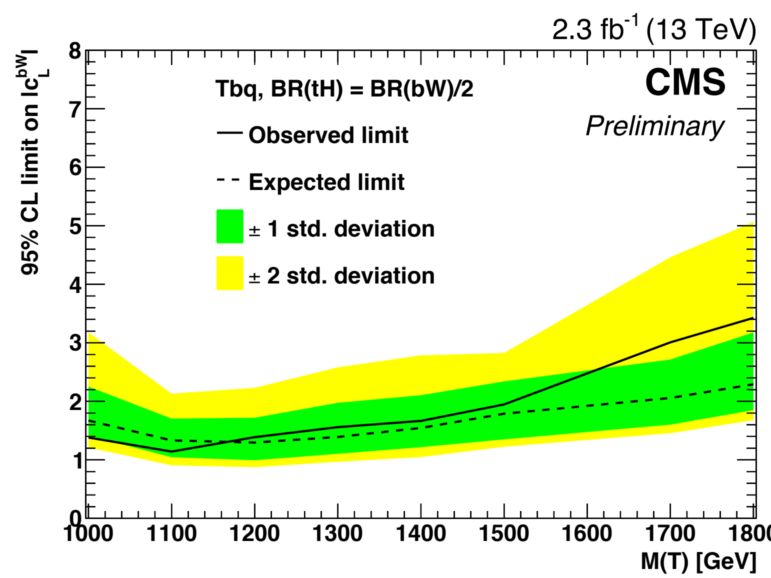
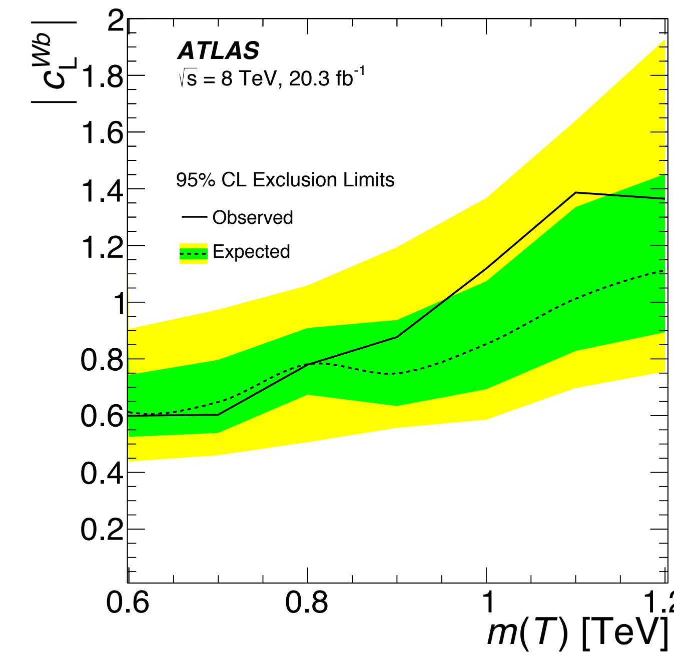
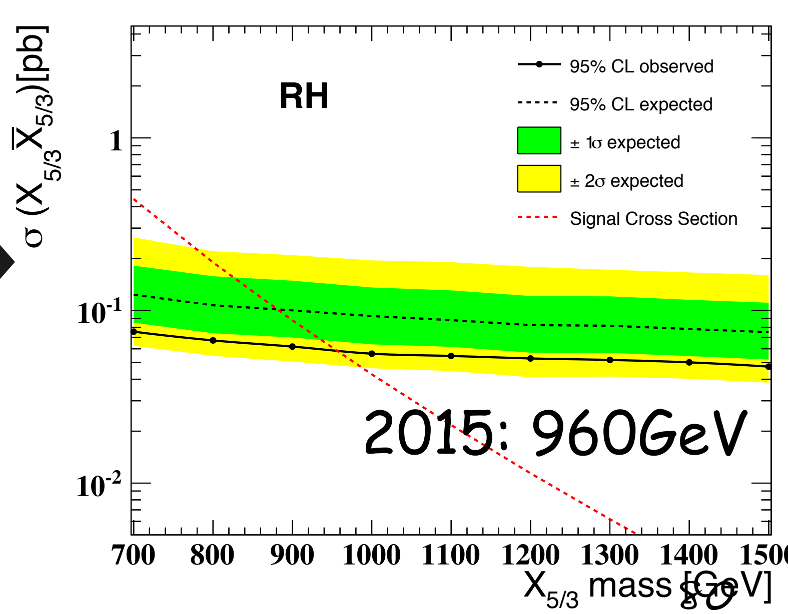


bounds on
charge 2/3 states
from single production

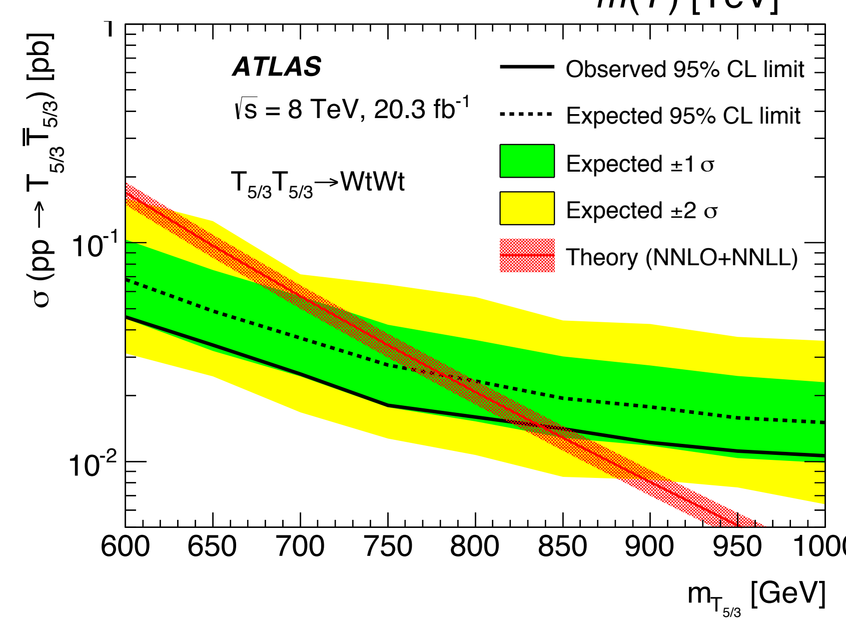




bounds on
charge 5/3 states
from single production



2015: 960GeV

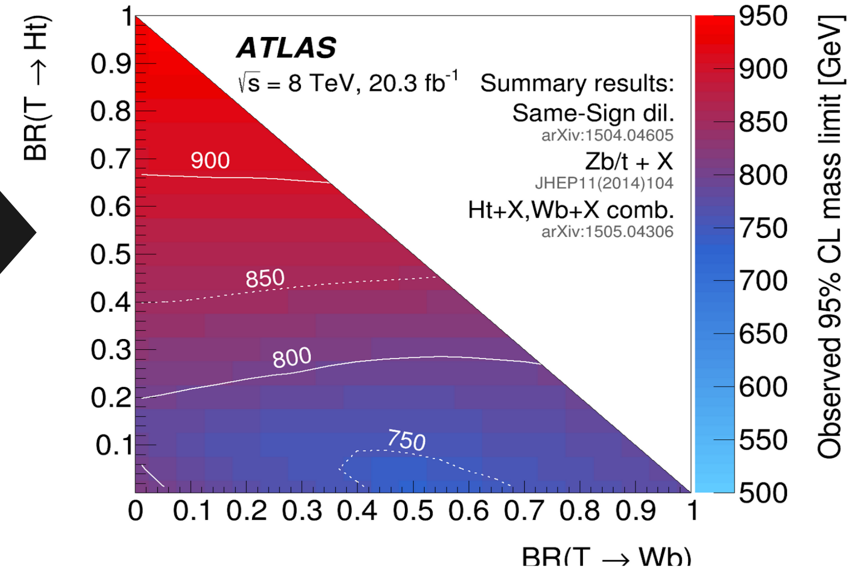


Christophe Grojean

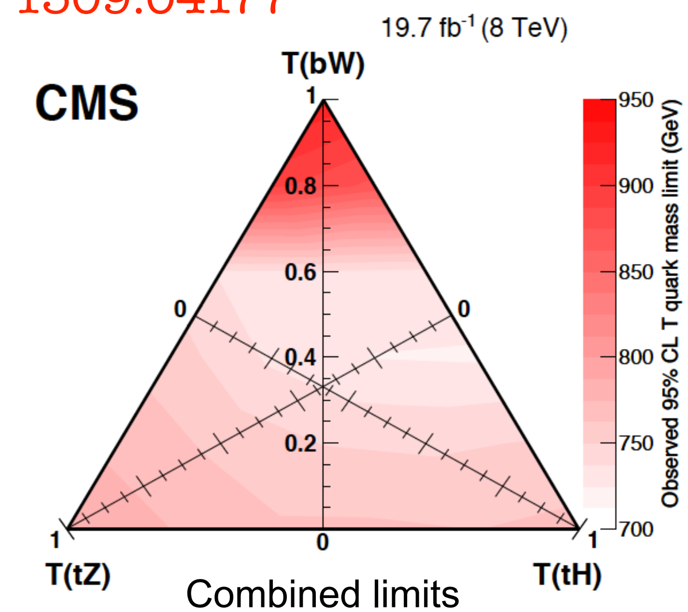
Searching for the top partners

bounds on charge 2/3 states from pair production

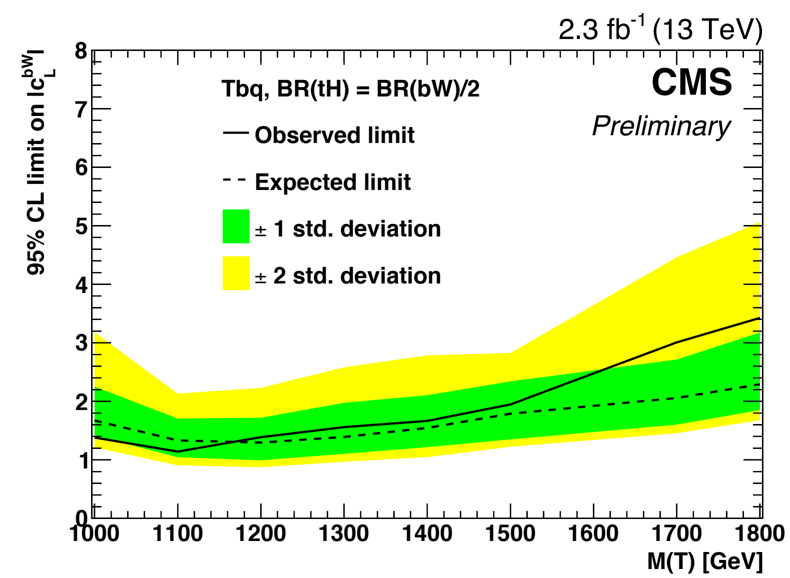
1505.04306

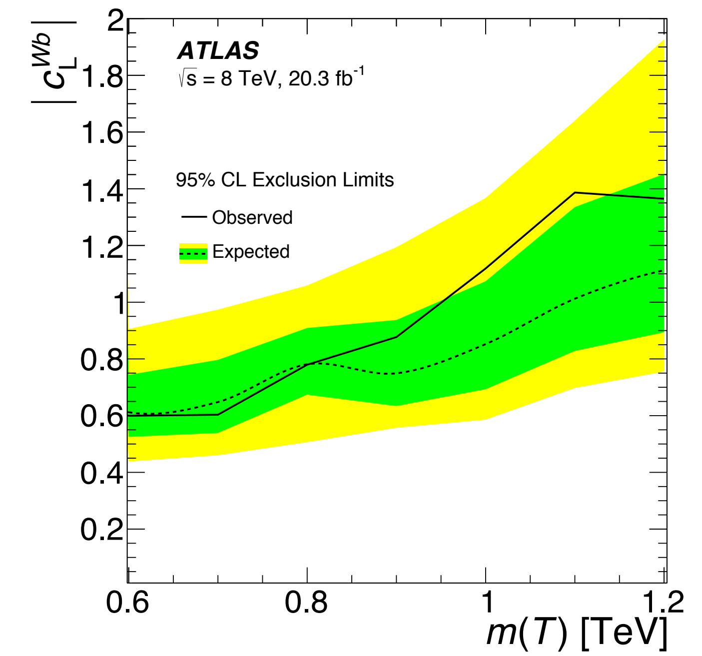


1509.04177

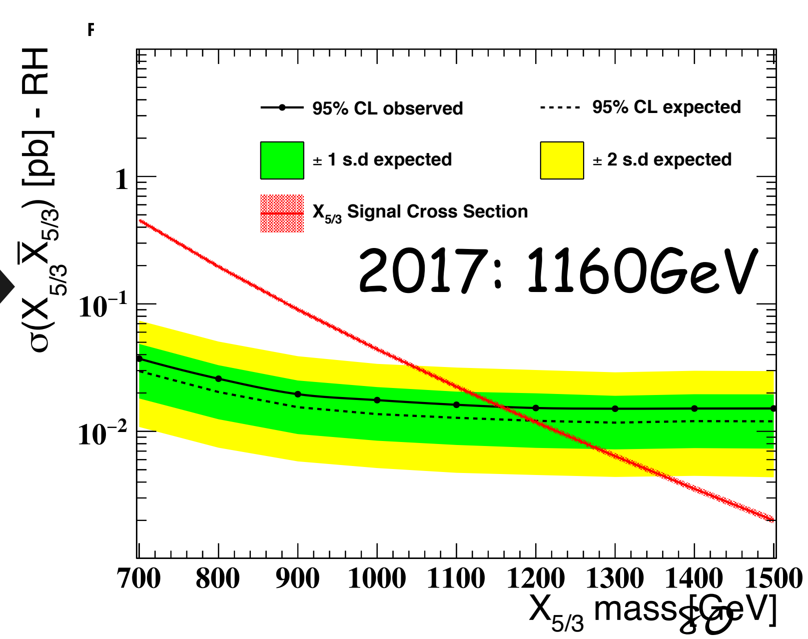


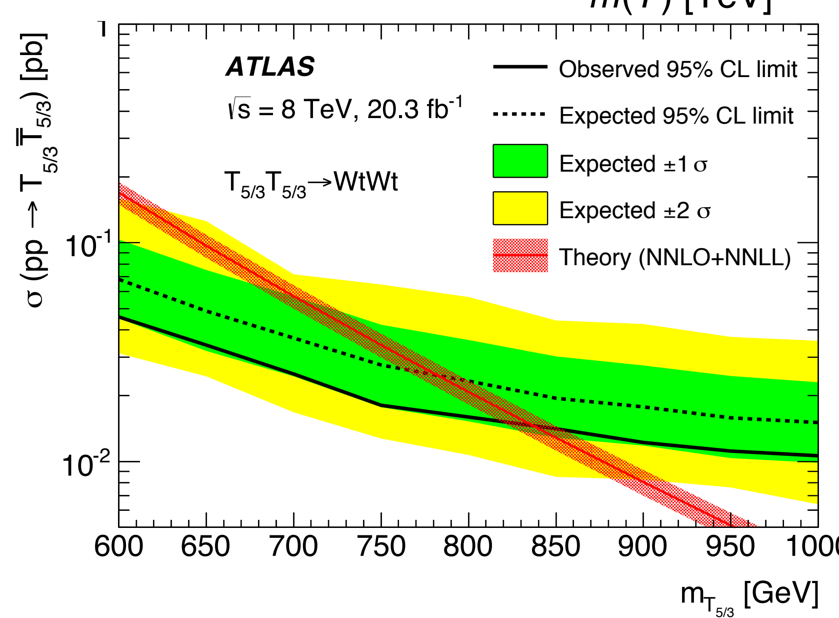
bounds on charge 2/3 states from single production





bounds on charge 5/3 states from single production





Christophe Grojean

Extra dimensions

Extra dimensions

$\vdots$ $\vdots$

$m_{5D}^2 + 9/R^2$

$m_{5D}^2 + 4/R^2$

$m_{5D}^2 + 1/R^2$

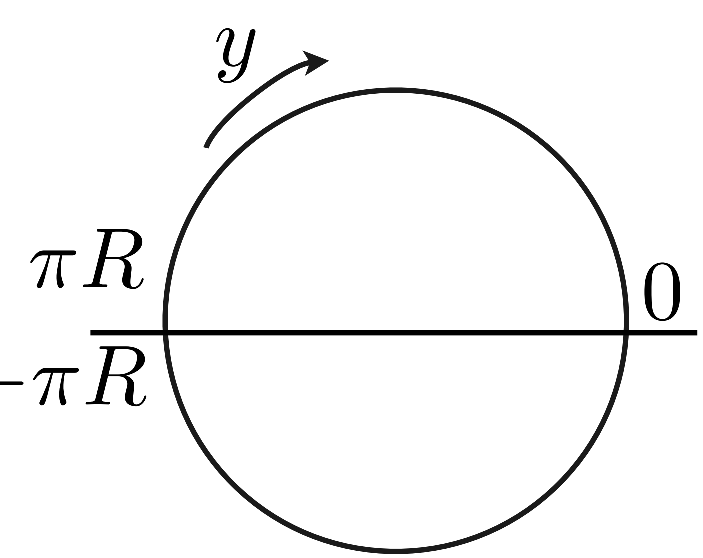
m_{5D}^2

+ states - states

5D field=infinite tower of massive 4D fields

depending of the energy available, you can probe more and more of these KK modes

~~ Compactification on a Circle ~~



circle: $y \sim y + 2\pi R$

$$\phi(y + 2\pi R) = \phi(y)$$

$$\phi(x,y) = \sum_n \frac{1}{\sqrt{2^{\delta_{n0}}\pi R}} \left(\cos\left(\frac{ny}{R}\right) \phi_n^+(x) + \sin\left(\frac{ny}{R}\right) \phi_n^-(x) \right)$$

5D field

wavefunction = localization of KK mode along the xdim

4D Kaluza-Klein modes

$$m_n = p_y^n = \frac{n}{R}$$

Extra dimensions

$\vdots \qquad \vdots$

$m_{5D}^2 + 9/R^2$

$m_{5D}^2 + 4/R^2$

$m_{5D}^2 + 1/R^2$

m_{5D}^2

+ states - states

5D field=infinite tower of massive 4D fields

depending of the energy available, you can probe more and more of these KK modes

~~ Compactification on a Circle ~~

5D General relativity = 4D GR + U(1) gauge symmetry

gauge symmetries are emerging from
gravitational interactions in extra dimensions?
beautiful idea of Kaluza & Klein
but
quantization? non-abelian structure? different gauge couplings?
no successful realization till now

localization of KK mode
along the xdim

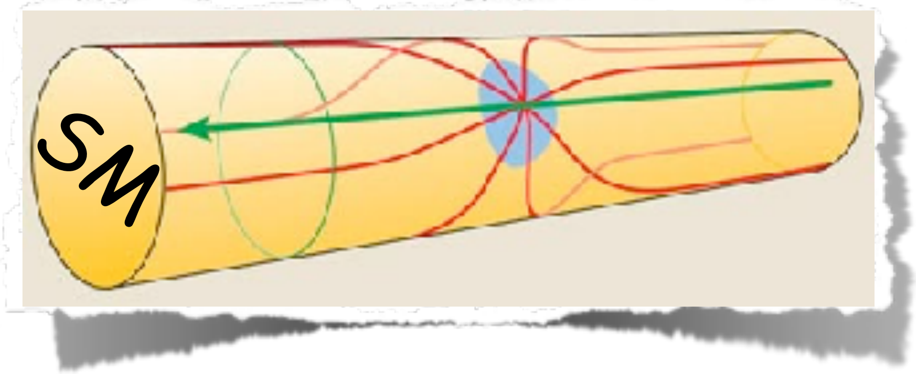
$m_n = p_y^n = \frac{n}{R}$

Extra Dimensions for TeV/LHC Physics

1) Hierarchy problem

- large (mm size) flat extra dimensions (ADD)

gravity is diluted into space while we are localized on a brane



$$\int d^{4+n}x\,\sqrt{|g_{4+n}|}M_\star^{2+n}\mathcal{R} = \int d^4x\,\sqrt{|g_4|}M_{Pl}^2\mathcal{R}$$

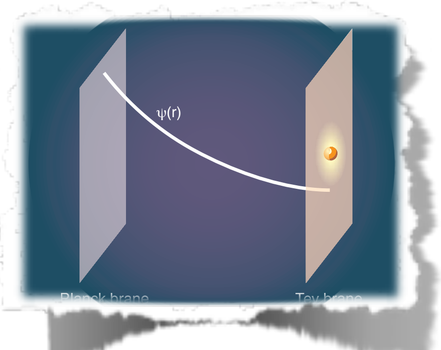
$$M_{Pl}^2 = V_n M_\star^{2+n}$$

$M_{Pl} = 10^{19}$ GeV $\qquad M_* = 1$ TeV

$V_2 = (2\,\mathrm{mm})^2 = (10^{-4}\,\mathrm{eV})^{-2}$

- warped/curved extra dimensions (RS)

gravity is localized away from SM matter and we feel only the tail of the graviton



graviton wavefunction is exponentially localized away from SM brane

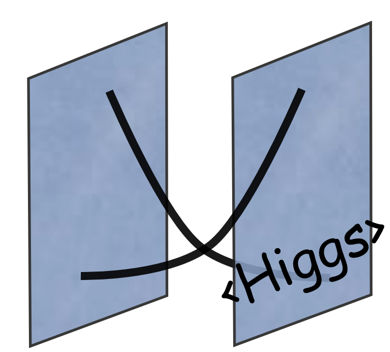
$$v = M_\star e^{-\pi R M_\star}$$

$M_* = 10^{19}$ GeV $\qquad v = 250$ GeV

$R \sim 11/M_*$

2) Fermion mass hierarchy & flavour structure

- fermion profiles:
  the bigger overlap with Higgs vev, the bigger the mass



3) EW symmetry breaking by boundary conditions

- orbifold breaking, Higgsless

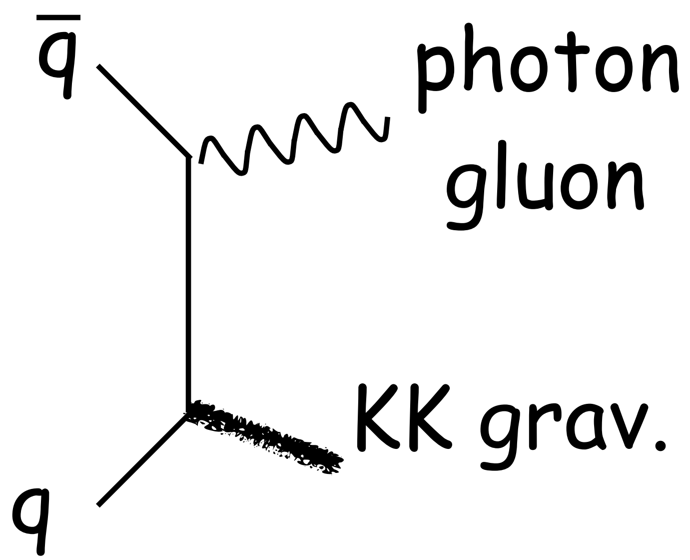
Large volume xdim phenomenology

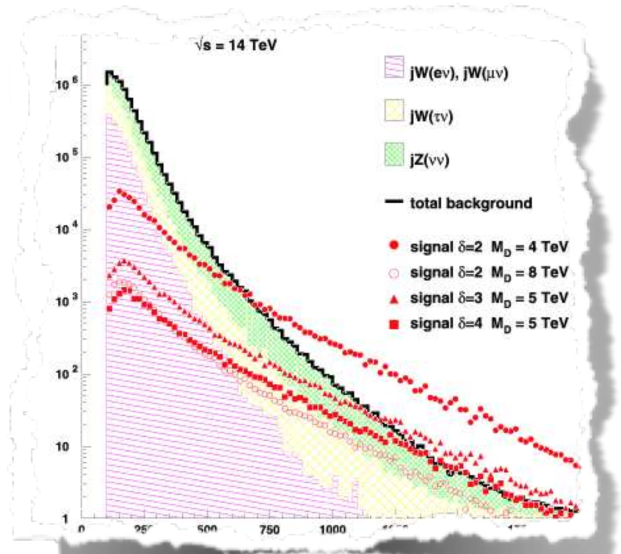
eV splitting between graviton KK modes

$1/M_{Pl}$ couplings of graviton KK modes to SM

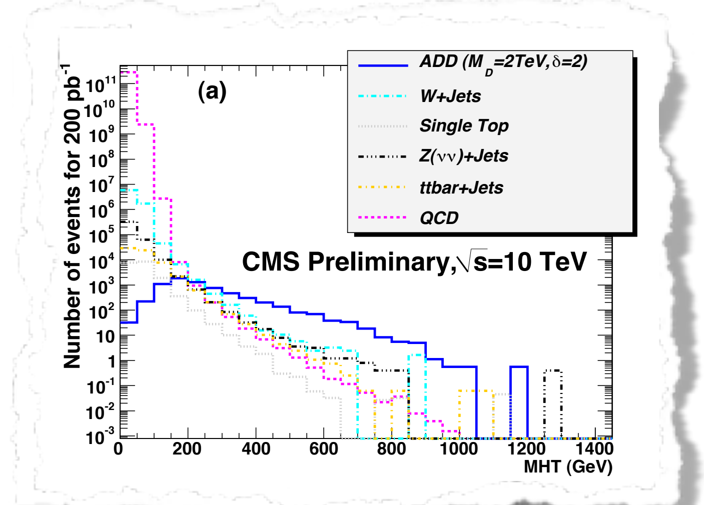
- Graviton production in colliders

monojet+$\not{E}_T$



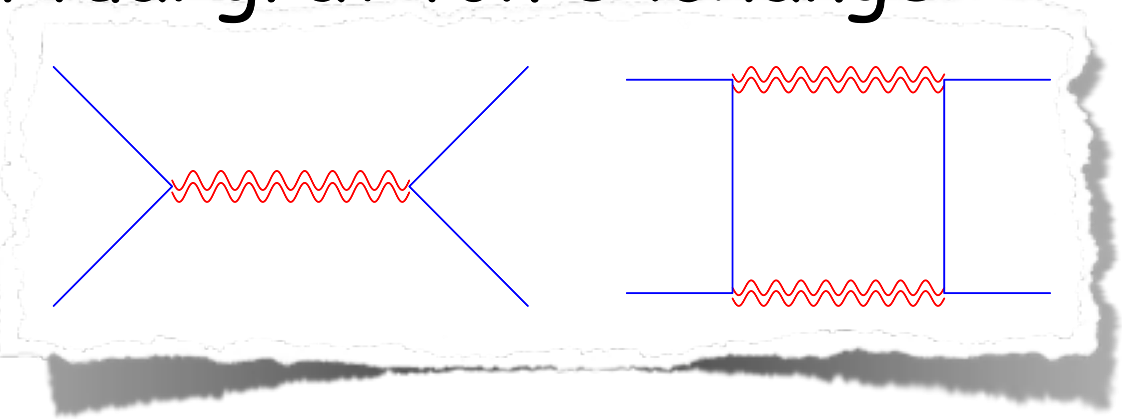


Vacavant, Hinchliffe ’01



CMS PAS EXO 09-013

- Virtual graviton exchange

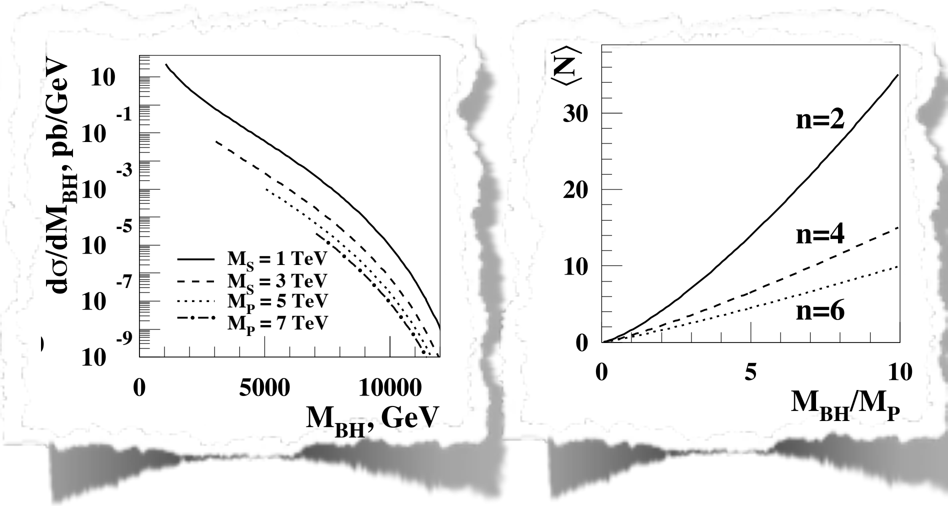


Large volume xdim phenomenology

- Supernova cooling: $M_* > 100$ TeV (for 2 xdim)

- Black Hole production

  classical production (can be very large $10^{3\text{-}4}$ pb),
  Hawking thermal decay, i.e., large decay multiplicity



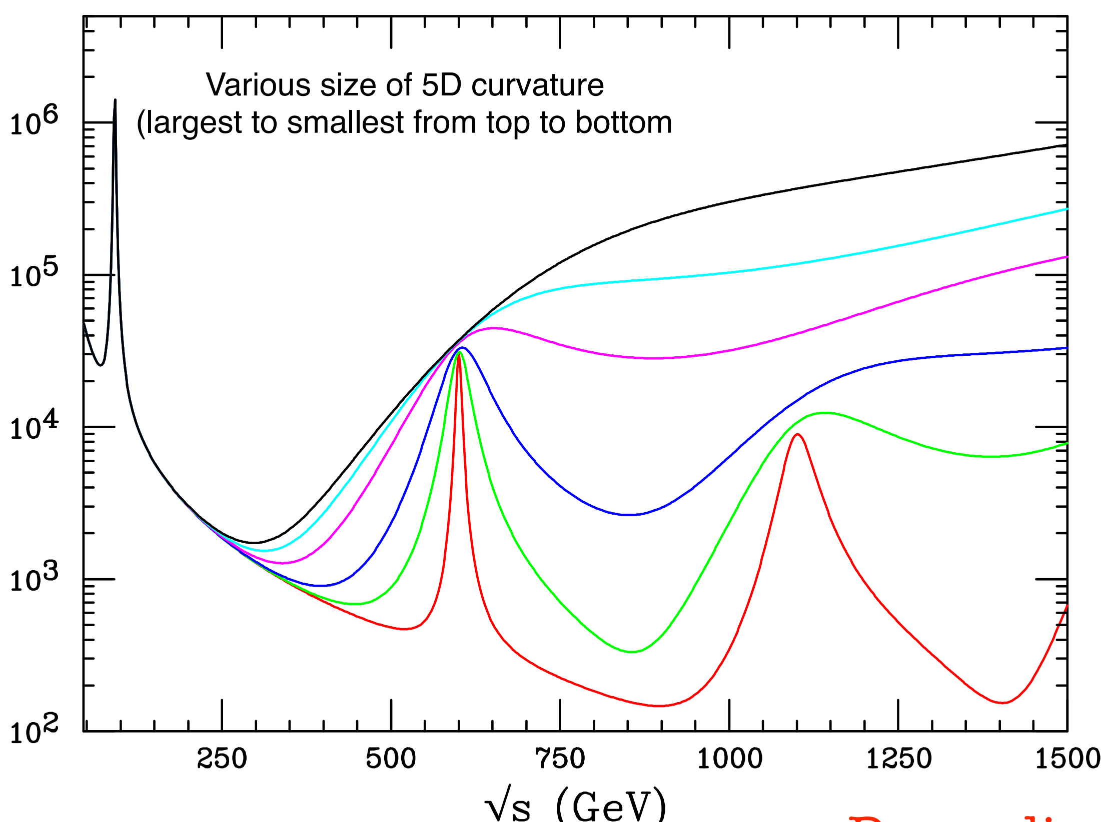
Dimopoulos, Landsberg, '01

- String resonances production

Curved xdim phenomenology

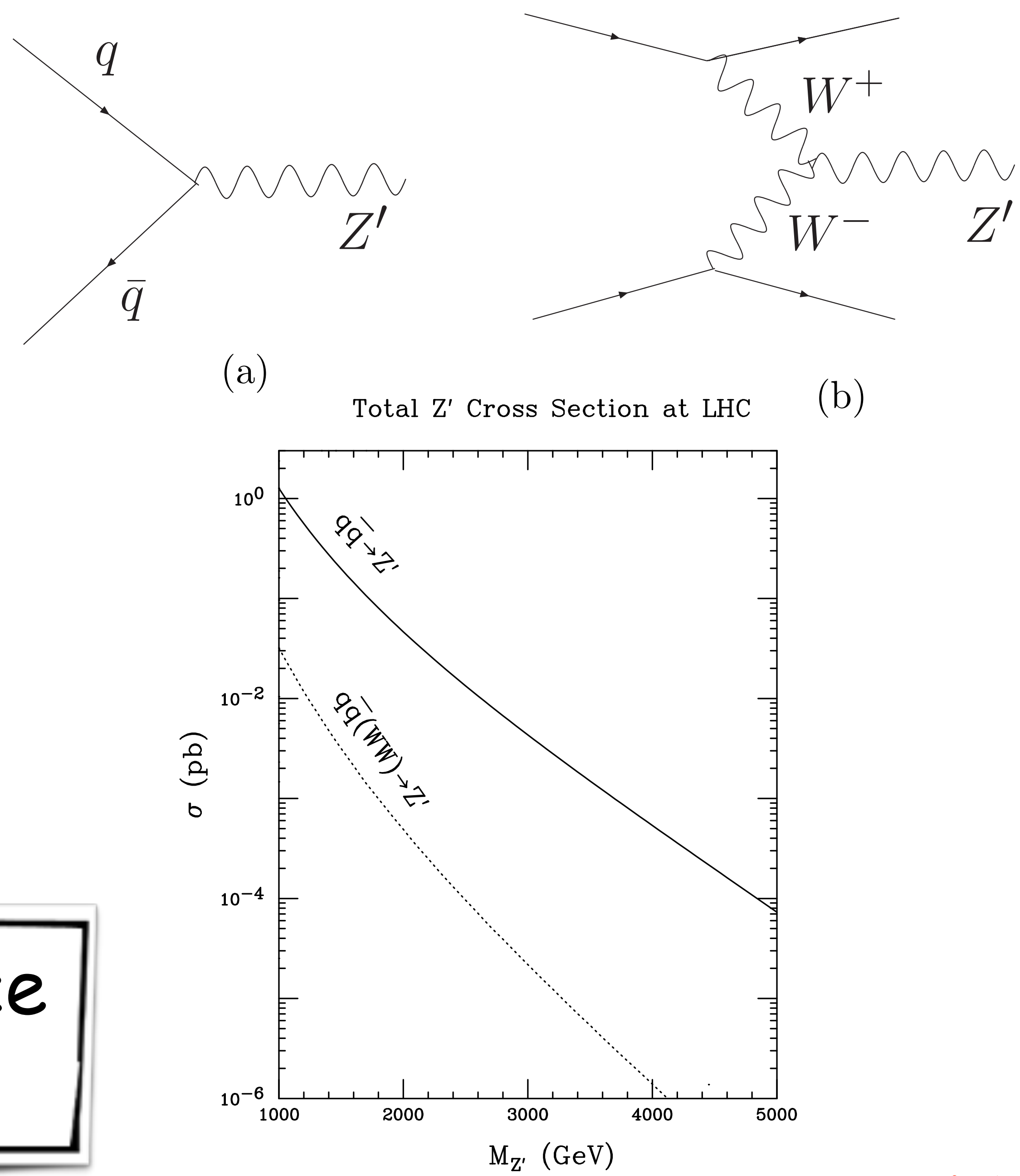
TeV splitting between gauge KK modes

$$e^+e^- \to \mu^+\mu^-$$



Davoudiasl et al '99

O(g_{SM}) couplings of gauge KK modes to SM



Agashe et al '07

current LHC bounds on KK resonance O(few) TeV

Cosmological relaxation

The Darwinian solution to the Hierarchy

Other origin of small/large numbers according to Weyl and Dirac:
hierarchies are induced/created by time evolution/the age of the Universe

Can this idea be formulated in a QFT language?
In which sense is it addressing the stability of small numbers at the quantum level?

Graham, Kaplan, Rajendran '15

Espinosa et al '15

- $m_H(t)$: $m_H^2(t=-\infty) = \Lambda_{\rm cutoff}^2 \to m_H^2(\text{now}) = -(125\,\text{GeV})^2$
- Higgs mass-squared promoted to a field.
- The field evolves in time in the early universe and scans a vast range of Higgs mass. But "Why/How/When does it stop evolving?"
- The Higgs mass-squared relaxes to a small negative value
- The electroweak symmetry breaking back-reacts on the relaxion field and stops the time-evolution of the dynamical system

Self-organized criticality

dynamical evolution of a system is stopped at a critical point due to back-reaction

hierarchies result from **dynamics** not from **symmetries** anymore!

important consequences on the spectrum of new physics

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

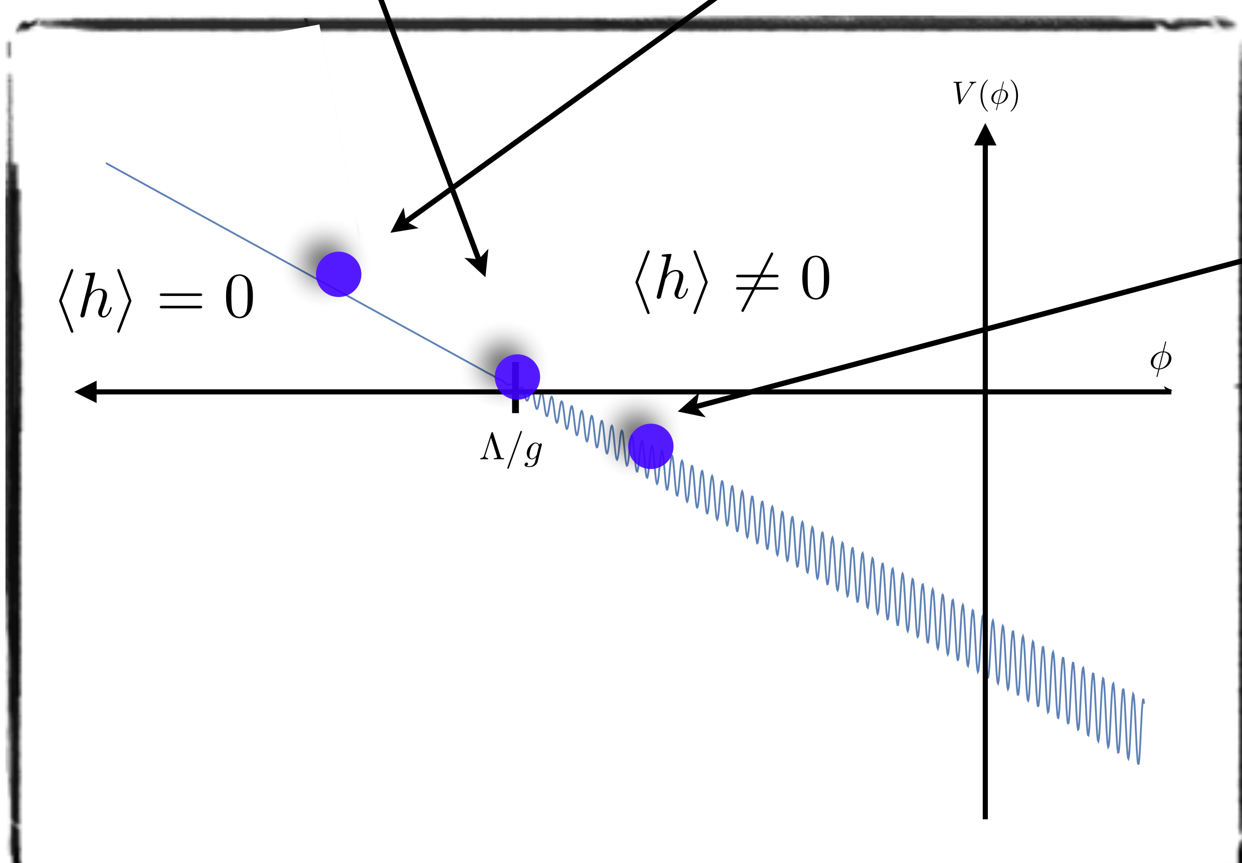
ϕ slowly rolling field (inflation provides friction) that scans the Higgs mass

$$\Lambda^2\left(-1+f\left(\frac{g\phi}{\Lambda}\right)\right)|H|^2+\Lambda^4 V\left(\frac{g\phi}{\Lambda}\right)+\frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

Higgs mass depends on ϕ

potential needed to force ϕ to roll-down in time (during inflation)

axion-like coupling that will seed the potential barrier stopping the rolling when the Higgs develops its vev



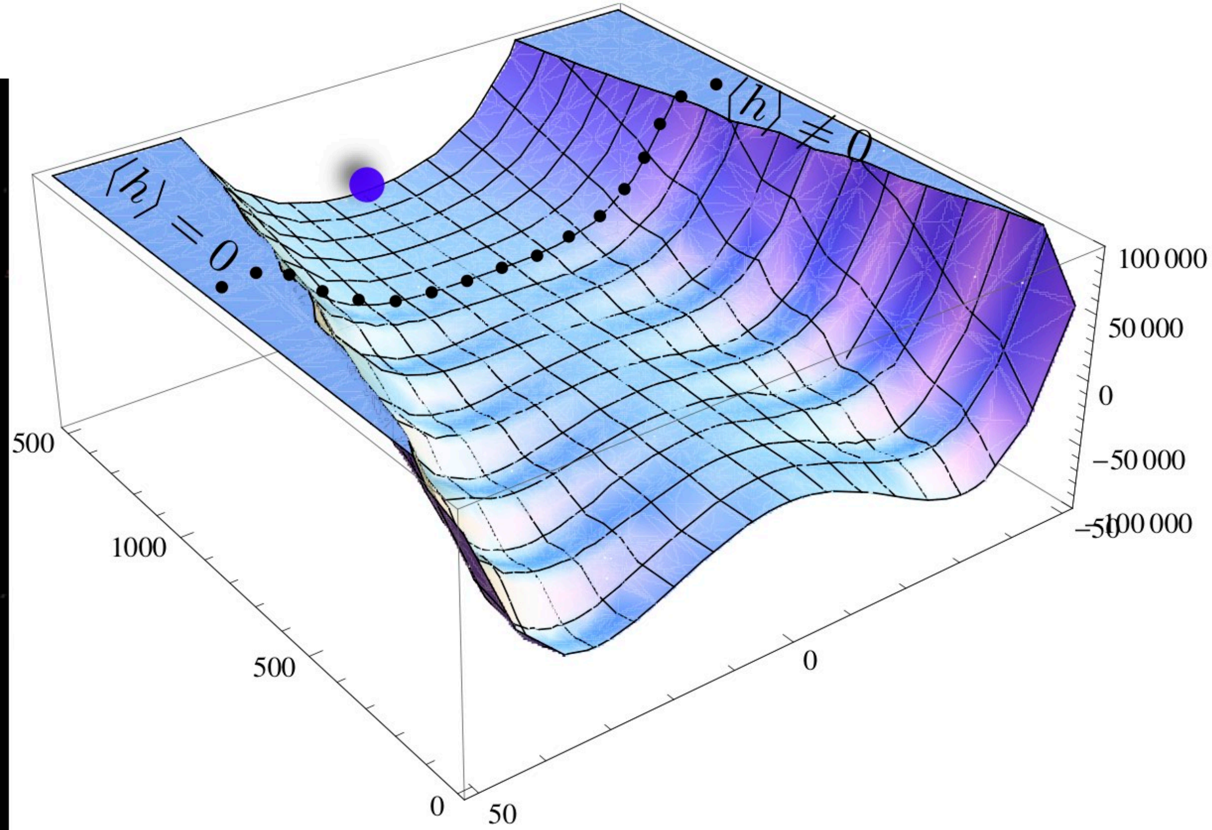
$$\Lambda_{\rm QCD}^3\, h\, \cos\frac{\phi}{f}$$

If ϕ continues rolling, the Higgs vev increases, the potential barrier increases and ultimately prevents ϕ from rolling down further

inflation = friction
to prevent overshooting the EW vacuum

Higgs-axion cosmological relaxation

ham, Kaplan, Rajendran '15



Hierarchy problem solved
by light weakly coupled new physics
and not by TeV scale physics

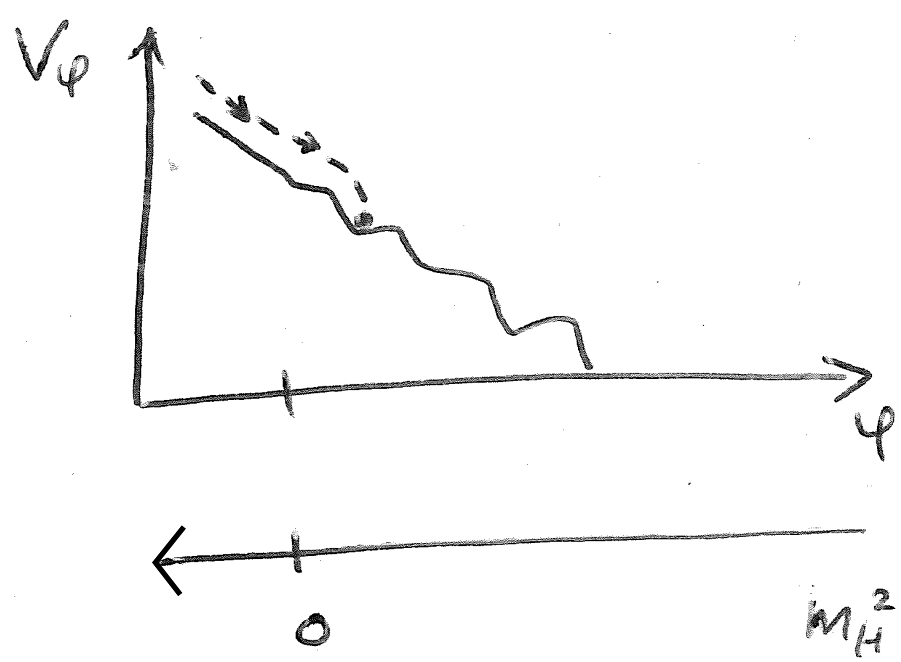
Two classes of relaxion models (so far)

- H-dependent potential barrier

Graham, Kaplan, Rajendran '15

Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

potential barriers in the relaxion potential appear soon after EWSB occurs and the relaxion gets trapped in one minimum



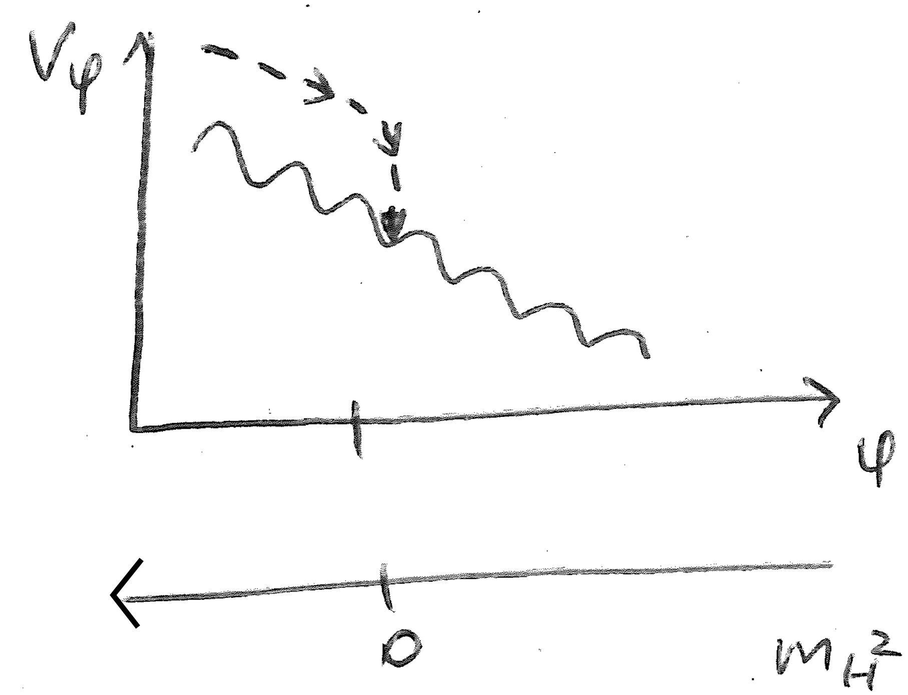
- H-dependent friction

Hook, Marques-Tavares '16

You '17

Fonseca, Morgante, Servant '18

the potential barriers in the relaxion potential always exist but there is no friction to stop the relaxion in one the minimum until the Higgs vev approaches a critical value



drawings borrowed from A. Matsedonskyi, DESY workshop seminar '17

Consistency Conditions

- **Higgs vev stops cosmological rolling**

note: v<<Λ provided that g<<1. It doesn't explain why the coupling is small (that question can be postponed to higher energies, requires more model-building engineering, relaxion=PGB?) but it ensures that the solution is stable under quantum correction.

$$\Lambda^3_{\rm QCD}\frac{v}{f} \sim \frac{\partial}{\partial\phi}\left(\Lambda^4 V(g\phi/\Lambda)\right) \simeq g\Lambda^3$$

- **Slow rolling:** $H_I > \dfrac{\Lambda^2}{M_P}$

ensures that the energy density stored in ϕ does not affect inflation

- **Classical rolling:** $H_I^3 < g\Lambda^3$

classical displacement over one Hubble time

$$\frac{1}{H_I}\frac{d\phi}{dt} = \frac{1}{H_I^2}\frac{dV}{d\phi} = \frac{g\Lambda^3}{H_I^2}$$

$>$

quantum fluctuation

$$H_I$$

$$\boxed{\frac{\Lambda^6}{M_P^3} < g\Lambda^3 = \Lambda^3_{\rm QCD}\frac{v}{f} \qquad \text{i.e.} \qquad \Lambda < 10^7\,{\rm GeV}\left(\frac{10^9\,{\rm GeV}}{f}\right)^{1/6}}$$

Pbs.

1. $\theta_{QCD} \sim 1 \gg 10^{-10}$. Can be solved but Λ < 30 TeV
2. large field excursion: $\Delta\phi \sim \Lambda/g \sim f\Lambda^3/(v\Lambda_{QCD}^3) \gg 1$, $N_e \sim \dfrac{f^2\Lambda^8}{v^2\Lambda^6_{QCD}M_P^2} \gg 1$

Quantum stability of relaxing Lagrangians...

$$V(\phi,h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2\left(1-\frac{g\phi}{\Lambda}\right)h^2 + \Lambda_B^4\cos(\phi/f) + \ldots$$

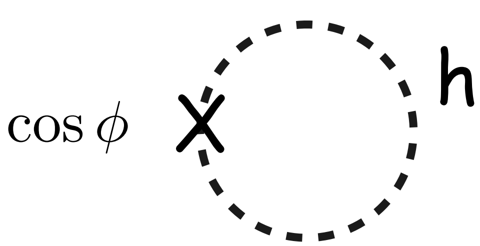
$$\Lambda_B^4 = \Lambda_{B(0)}^4 + \Lambda_{B(1)}^3 h + \Lambda_{B(2)}^2 h^2 + \ldots$$

necessary condition for the Higgs vev to stop the relaxion: $\Lambda_B^4 < v^4$

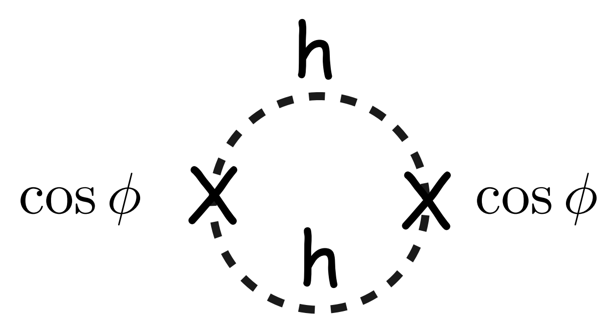
- **n=1:** need another source of EWSB
  - QCD condensate <qq>~ Λ_{QCD}
  - new strongly-coupled sector à la Technicolor

    ⊩ new physics @ TeV, coincidence problem? ⫣

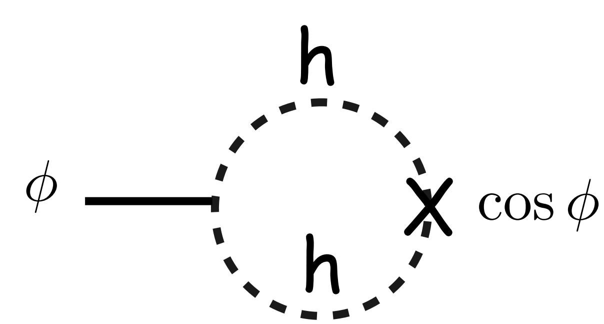
- **n=2:** no extra source of EWSB needed
  - quantum stability? h-loops generate extra interactions that will stop ϕ before the Higgs vev develops unless Λ_B<v (new physics below TeV again)



$\Lambda_{B(2)}^2\Lambda^2\cos(\phi/f)$



$\Lambda_{B(2)}^4\cos^2(\phi/f)$



$g\Lambda\Lambda_{B(2)}^2\phi\cos(\phi/f)$

Cosmological Higgs-Axion Interplay (CHAIN)

Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

introduce a second field to scan the potential barrier

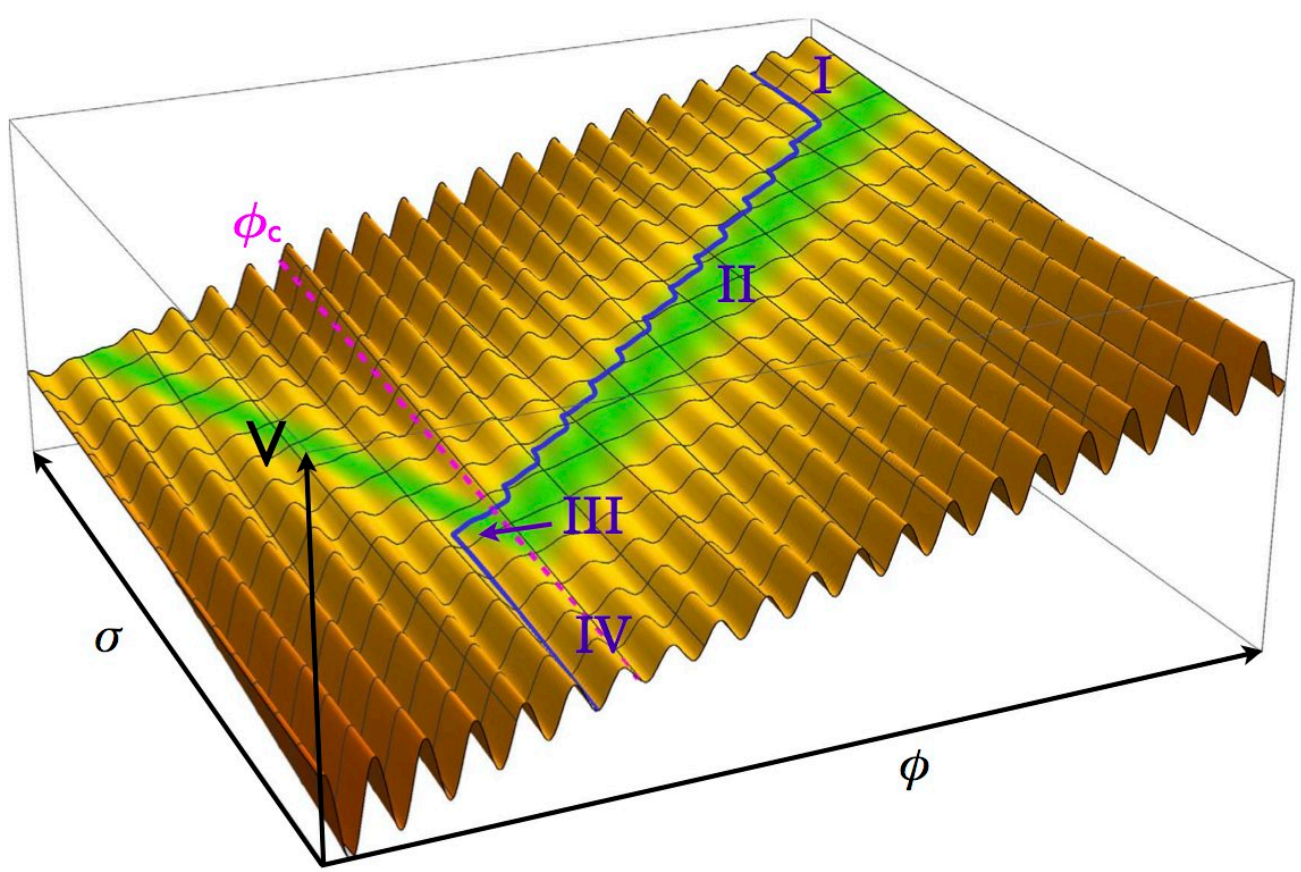
$$V(\phi,\sigma,H) = \Lambda^4\left(\frac{g\phi}{\Lambda}+\frac{g_\sigma\sigma}{\Lambda}\right) - \Lambda^2\left(\alpha-\frac{g\phi}{\Lambda}\right)|H|^2 + \frac{1}{2}\lambda|H|^4 + A(\phi,\sigma,H)\cos(\phi/f)$$

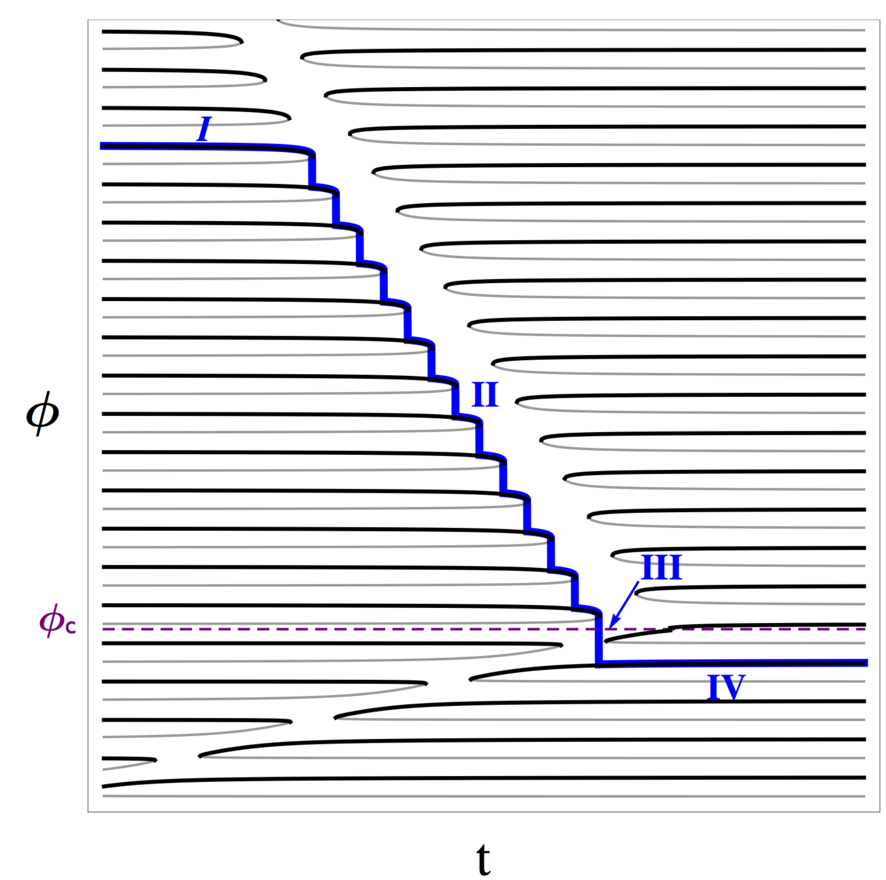
$$\epsilon = \left(\frac{\Lambda_B}{\Lambda}\right)^4 \qquad A(\phi,\sigma,H) \equiv \epsilon\Lambda^4\left(\beta + c_\phi\frac{g\phi}{\Lambda} - c_\sigma\frac{g_\sigma\,\sigma}{\Lambda} + \frac{|H|^2}{\Lambda^2}\right)$$

quantum generated new terms from the $|H|^2\cos(\phi/f)$ term

the new interaction that saves our day

original relaxion-type term





Same problem, same solution?

EW SCALE AS COSMOLOGICAL ERRATIC

courtesy to J.R. Espinosa

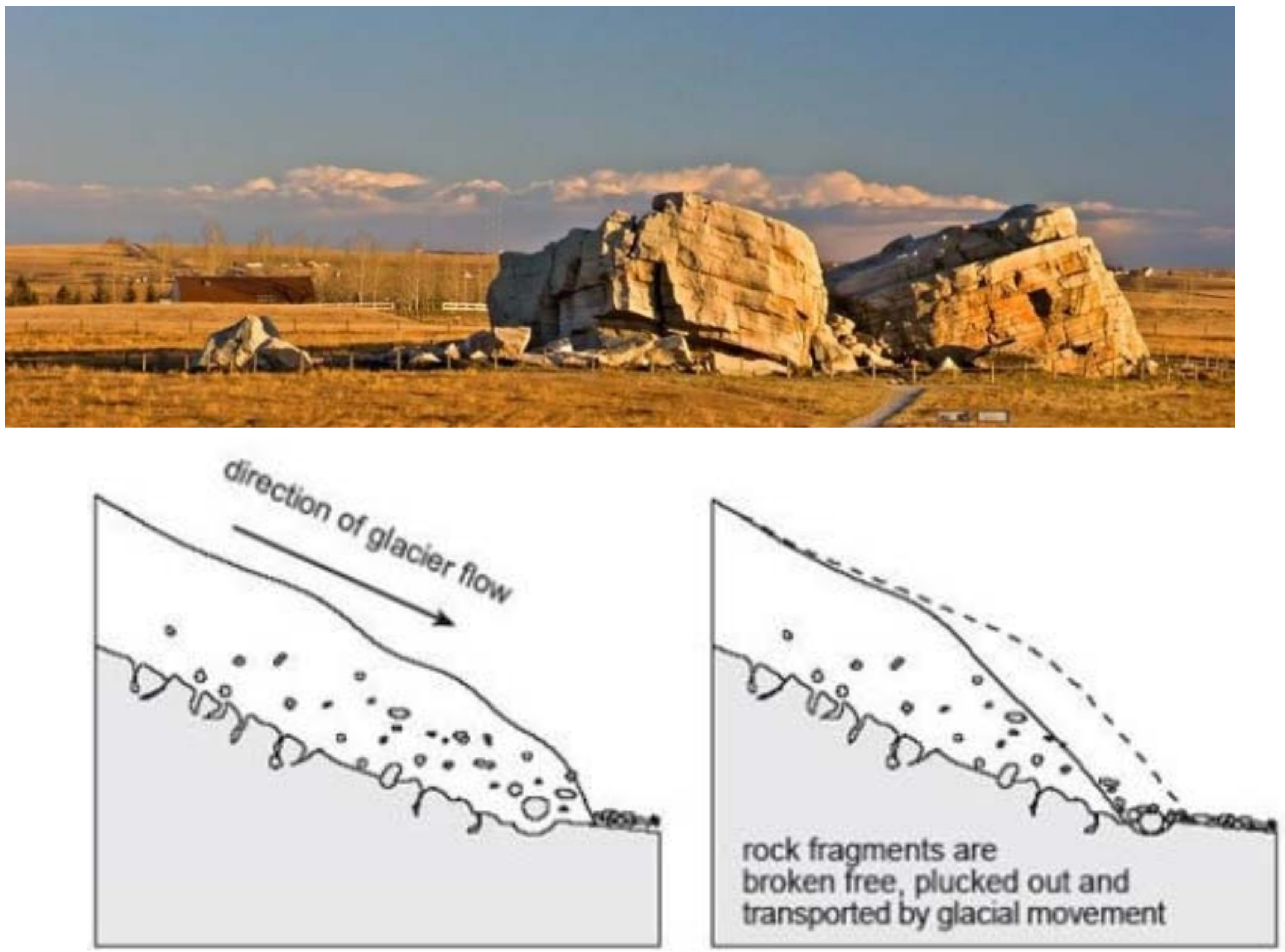
Okotoks glacial erratic,
Alberta, Canada

Unnatural large rocks differing in composition from the typical surrounding ones

Same problem, same solution?

EW SCALE AS COSMOLOGICAL ERRATIC

courtesy to J.R. Espinosa



Standard geological history:
they were transported by ancient glaciers over hundreds of kilometers

Consistency conditions

- Quantum stability of the potential $\epsilon \lesssim v^2/\Lambda^2$

ensures that terms $\epsilon^2\Lambda^4\cos^2(\phi/f)$ don't affect the tracking solution

Ex. $\cos(\phi/f)$ 

$\cos(\phi/f)$ $\qquad \epsilon^2\Lambda^4\cos^2(\phi/f)$

should be subleading compared to $\epsilon\Lambda^2 h^2\cos(\phi/f)$

Requires $\epsilon \lesssim v^2/\Lambda^2$

courtesy to JR Espinosa

large potential barrier allowed: $\Lambda_B^4 < v^2\Lambda^2$

Consistency conditions

- Quantum stability of the potential $\epsilon \lesssim v^2/\Lambda^2$

  ensures that terms $\epsilon^2\Lambda^4\cos^2(\phi/f)$ don't affect the tracking solution

- Higgs vev stops cosmological rolling $\frac{\epsilon\Lambda^2 v^2}{f} \sim \frac{\partial}{\partial\phi}\left(\Lambda^4 V(g\phi/\Lambda)\right) \simeq g\Lambda^3$

- Slow rolling: $H_I > \frac{\Lambda^2}{M_P}$ ensures that the energy density stored in σ and ϕ does not affect inflation

- Classical rolling: $H_I^3 < g_\sigma\Lambda^3$

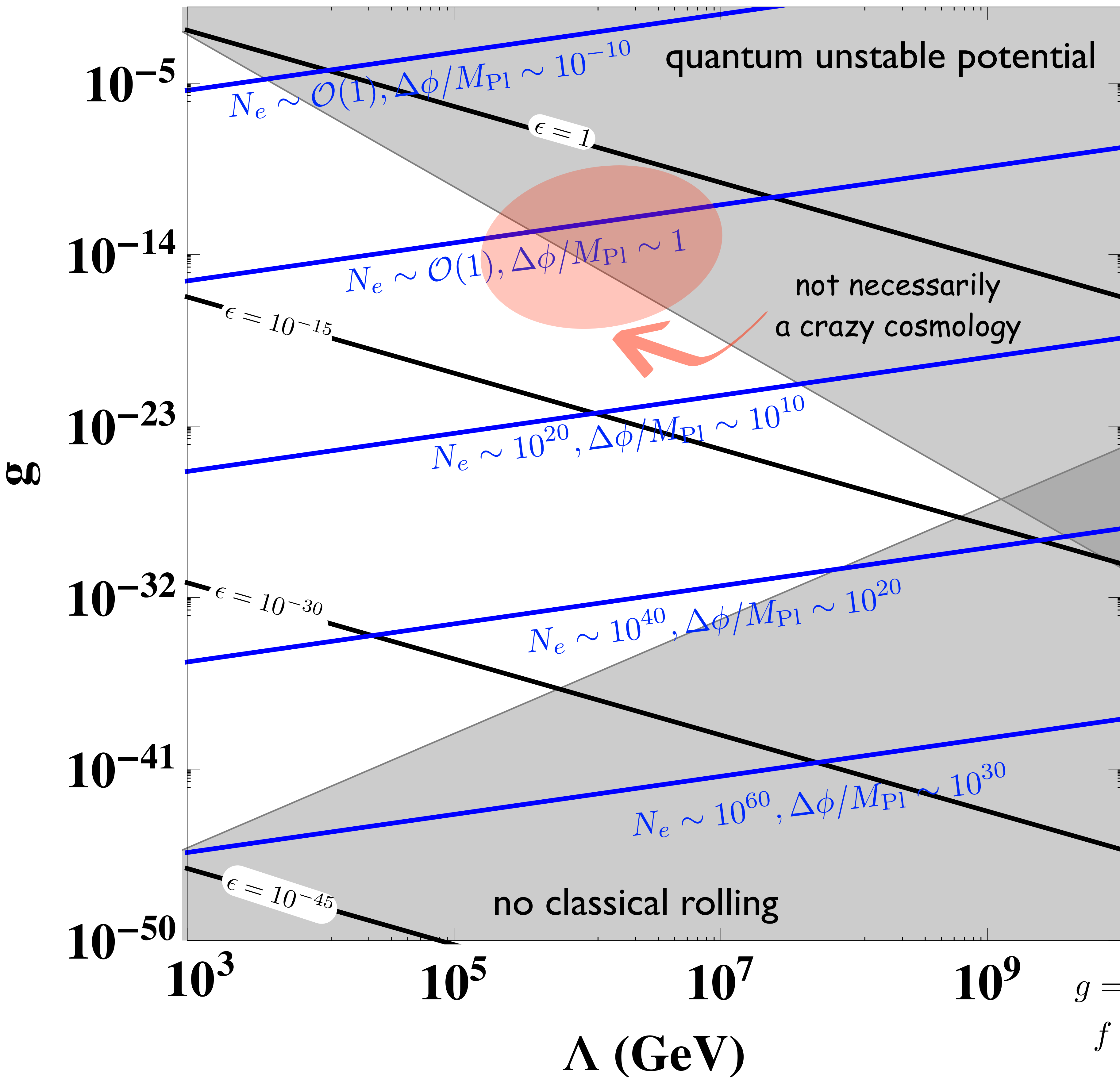
- ϕ tracks σ in the barrier-free valley before EWSB: $c_\phi g^2 > c_\sigma g_\sigma^2$

- ϕ exits the barrier-free valley after EWSB: $(c_\phi - \frac{1}{2\lambda})g^2 < c_\sigma g_\sigma^2$

- large field excursions: $\Delta\phi, \Delta\sigma > \Lambda/g$ to ensure that the Higgs mass scans from Λ to the weak scale

$$\boxed{\frac{\Lambda^3}{M_{\rm Pl}^3} \lesssim g_\sigma \lesssim g \lesssim \frac{v^4}{f\Lambda^3}} \Rightarrow \boxed{\Lambda \lesssim \left(v^4 M_{\rm Pl}^3\right)^{1/7} \simeq 2\times 10^9\ {\rm GeV}}$$

Consistency conditions



$g = 10 g_\sigma$

$f = \Lambda$

Best solution to little hierarchy pb?

Long epoch of **inflation** to allow the field to explore large range values and reach the critical point without fine-tuning

$$\Delta\sigma \sim N_e \left(\frac{g_\sigma \Lambda^3}{H_I^2}\right) > \Lambda / g_\sigma$$

Phenomenological signatures

Nothing to be discovered at the LHC/ILC/CLIC/CepC/SppC/FCC!

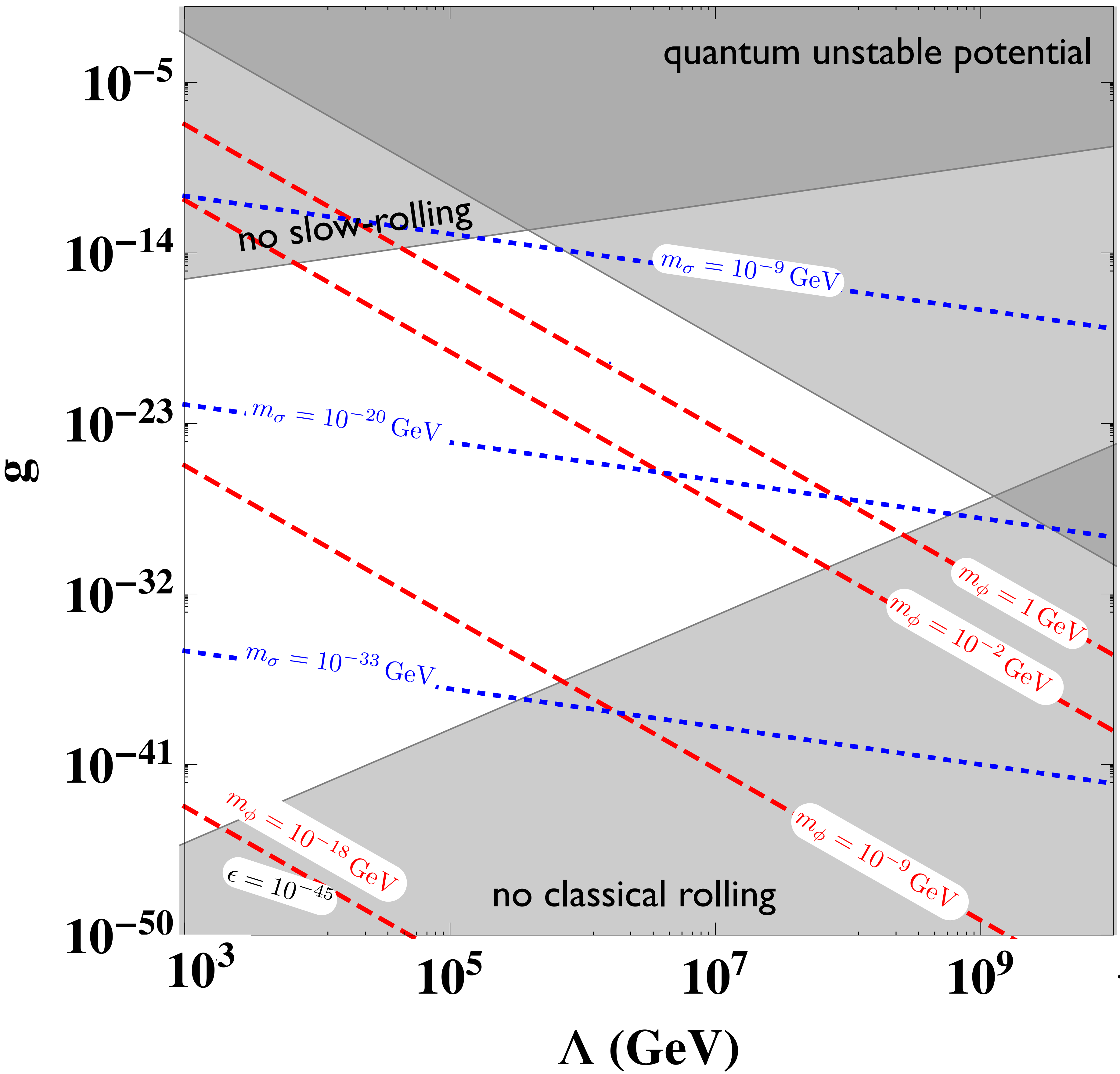
only BSM physics below Λ

two (very) light and very weakly coupled axion-like scalar fields

$$m_\phi \sim \left(\frac{g\,\Lambda^5}{f\,v^2}\right)^{1/2} \sim (10^{-20} - 10^2)\,\mathrm{GeV}$$

$$m_\sigma \sim g_\sigma \Lambda \sim (10^{-45} - 10^{-2})\,\mathrm{GeV}$$

Phenomenological signatures



$g = 10 g_\sigma$

$f = \Lambda$

Phenomenological signatures

A QFT rationale for light and weakly coupled degrees of freedom

Espinosa et al '15

Flacke et al '16

~interesting cosmology signatures~

◎ BBN constraints

◎ decaying DM signs in γ-rays background

◎ ALPs

◎ superradiance

Choi and Im '16

~interesting signatures @ SHiP~

◎ production of light scalars by B and K decays

~interesting atomic physics~

◎ change of atom sizes

G. Perez et al 'in progress

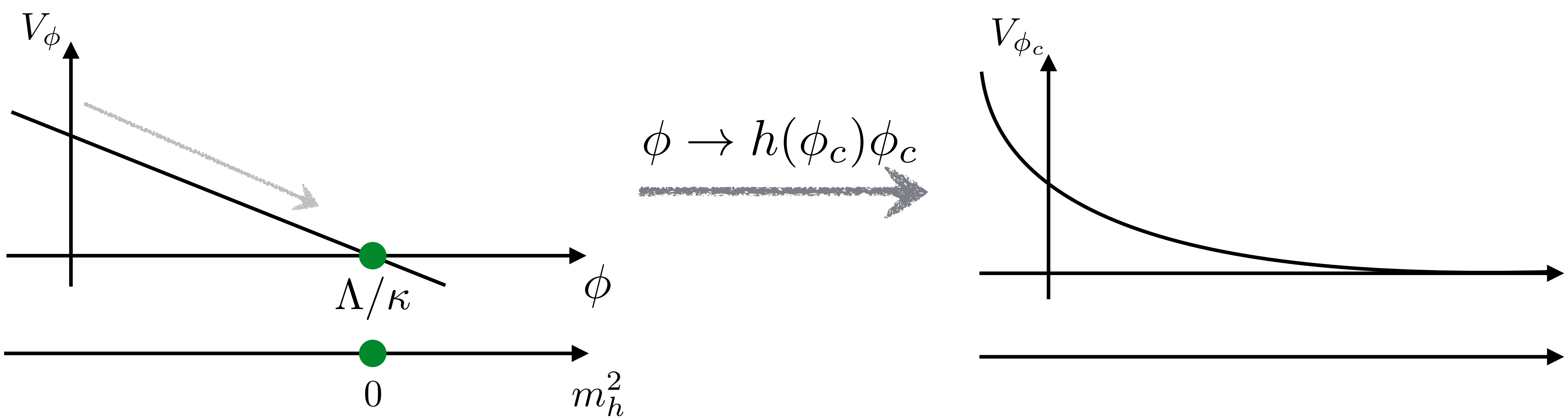
Relaxing without multiple vacua: pole attractors

Matsedonskyi, Montull ‘17

- The Higgs mass is scanned by the relaxion field ϕ

$$V_h \supset (-\Lambda^2 + \kappa\Lambda\phi)\, h^2 \qquad\qquad (V_\phi = -\kappa\Lambda^3\phi)$$

- The relaxion has a non canonical kinetic term $\frac{1}{h^{2n}}(\partial_\mu\phi)^2$
- When $\phi \to \Lambda/\kappa$ then $h \to 0$ and the kinetic term grows.

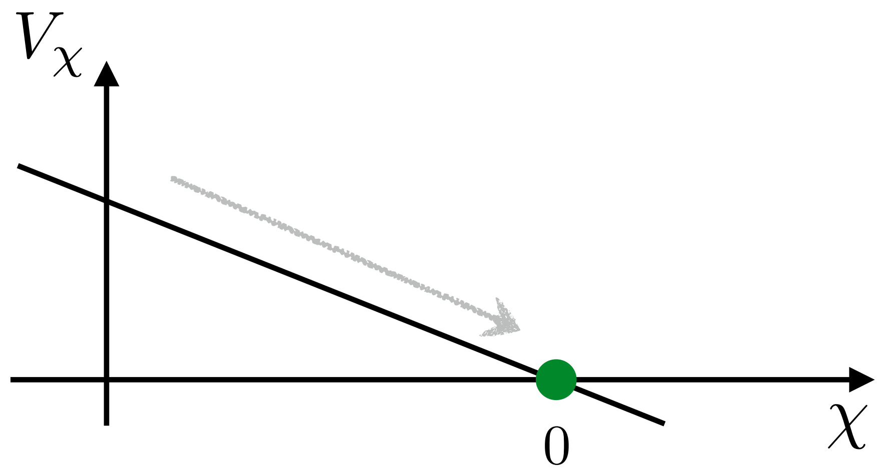


- The slope of the relaxion potential and coupling to the Higgs decrease and the scanning effectively stops.

- derivative Higgs-relaxion couplings becomes non-perturbative
- UV completions unknown

Pole attractors: minimal realistic model

Matsedonskyi, Montull '17

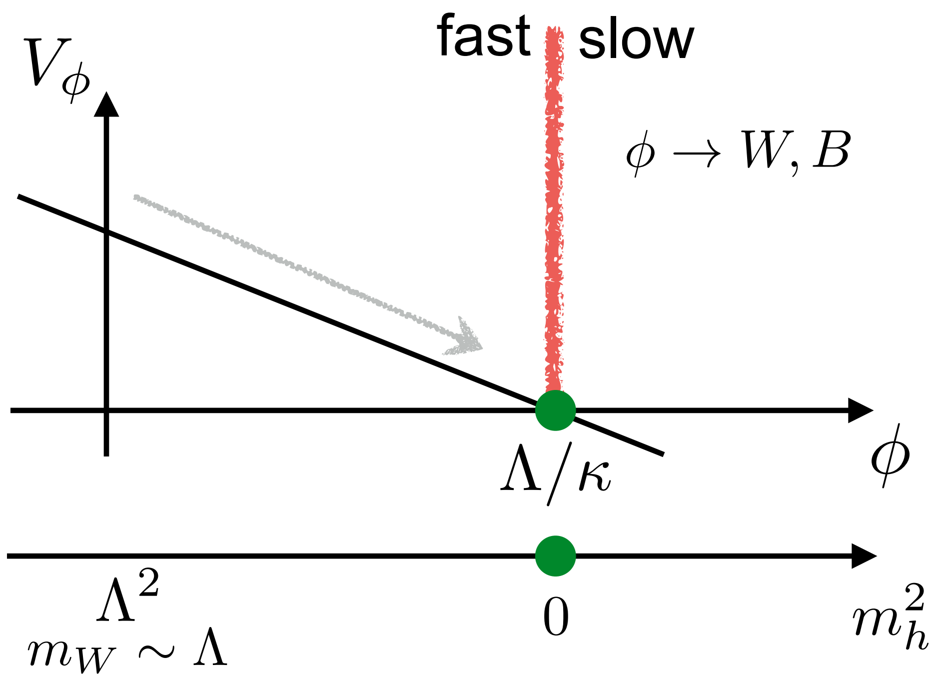


1) kinetic terms controlled by a new field χ

$$\frac{1}{\chi^2}\left\{(\partial\chi)^2 + (\partial\phi)^2\right\}$$

motivated by SUSY-based inflation models

2) χ provides a limited time for a scan until it gets to zero and blocks all the evolution



3) ϕ moves quickly before reaching h~0, and after it's slowed down by particle friction provided

$$\dot\phi \gtrsim m_W\, f$$

* f controls particle friction

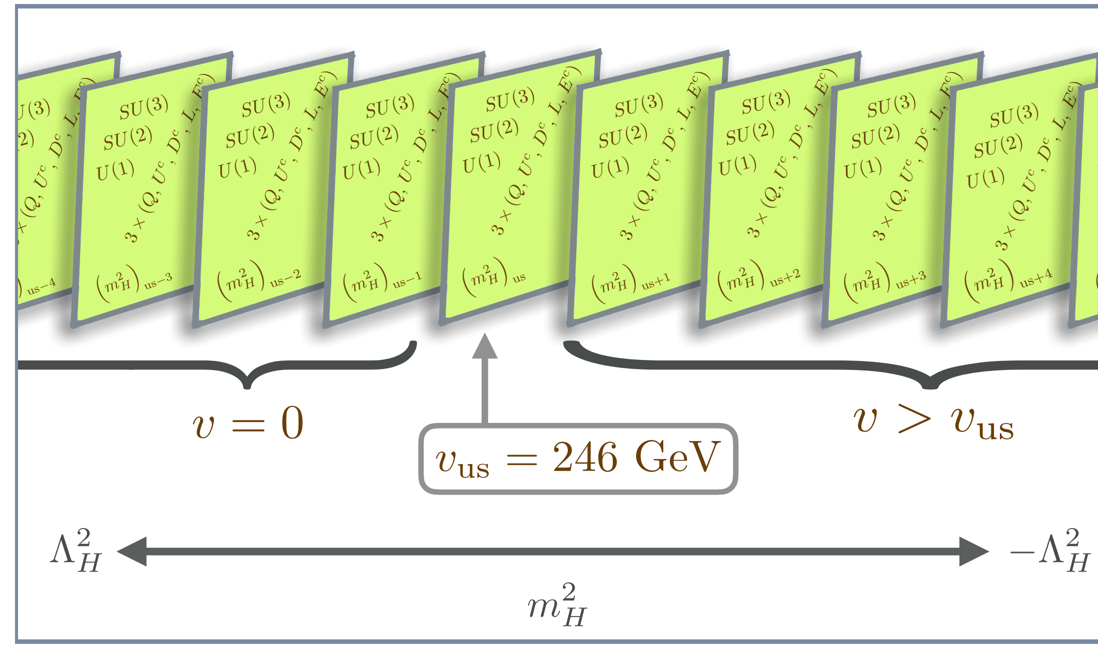
4) remaining part of the <u>limited</u> time relaxion is very slow, almost no scan is possible

NNaturalness

or another way to select our vacuum

[Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner '16]

NNaturalness



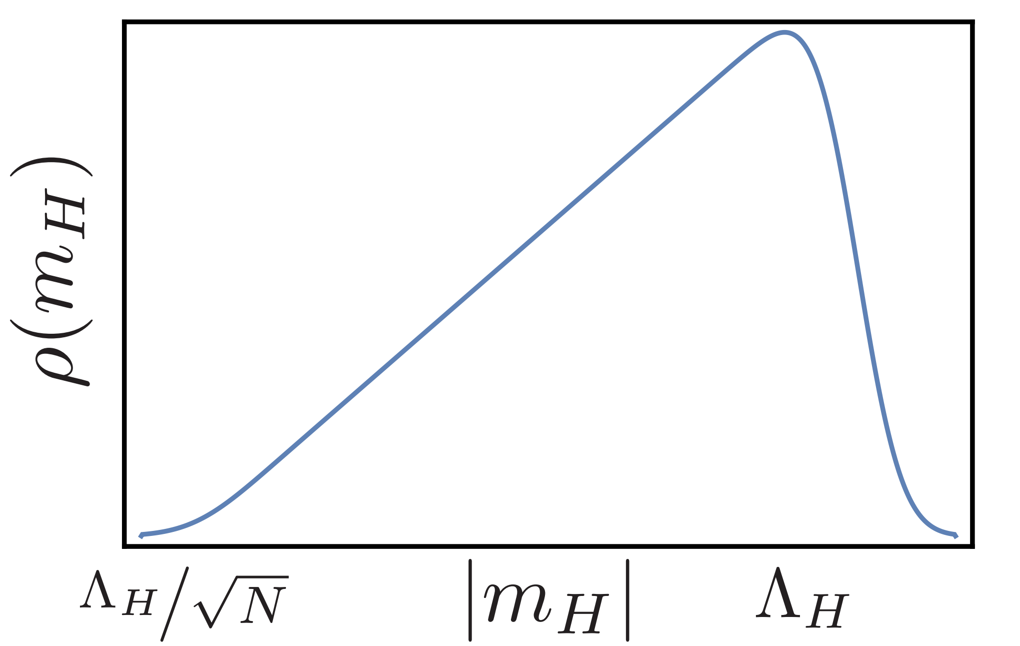
N copies of the SM

High Higgs cutoff Λ_H, high gravity cutoff Λ_G

Two effects:

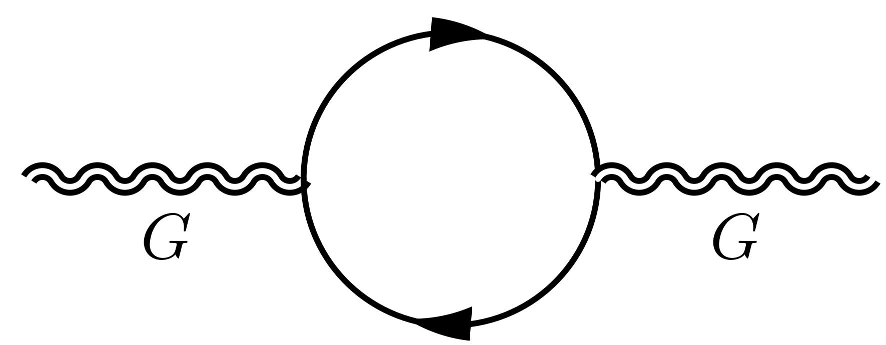
(N. Craig @ Paris'18)

1. Random UV contributions → flat distribution of m_H^2 between $\pm\Lambda_H^2$



At least 1 copy w/ $|m_H| \sim \Lambda_H/\sqrt{N}$

2. Large number of species renormalizes Planck scale (e.g. graviton wavefunction renorm.)



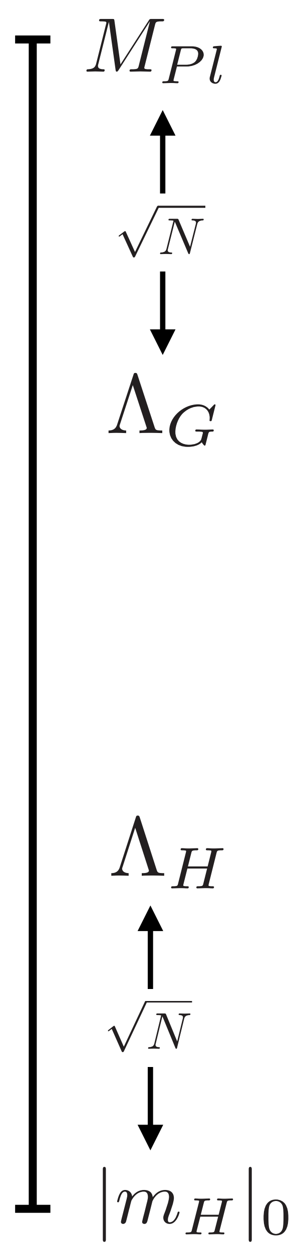
Gravitational strong coupling scale Λ_G below M_{Pl}

$$M_{Pl}^2 \sim N\Lambda_G^2$$

NNaturalness

(N. Craig @ Paris'18)

Scale separation from large N:



For example:
One copy w/ weak-scale Higgs for

N=10^{16}:
Λ_H=10^{10} GeV
Λ_G=10^{10} GeV
(That's it.)

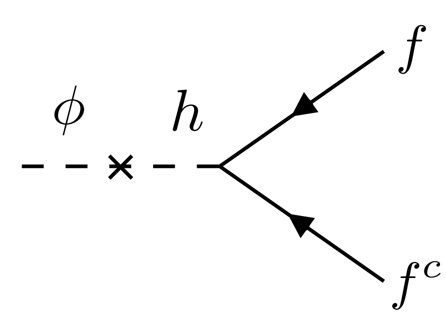
N=10^{4}:
Λ_H=10^{4} GeV
Λ_G=10^{16} GeV
(SUSY or compositeness at Λ_H)

Now…why does the copy with the smallest m_H dominate? *Cosmology*.

Reheaton ϕ starts universe via ϕ $|H_i|^2$ couplings

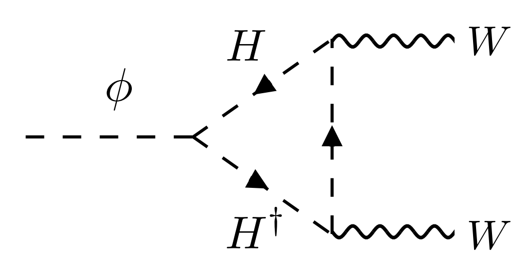
Decays (provided $m_\phi < |m_{H_i}|$)

$$m^2_{H,i} < 0$$



$$\Gamma \propto \frac{1}{m^2_{H,i}}$$

$$m^2_{H,i} \geq 0$$



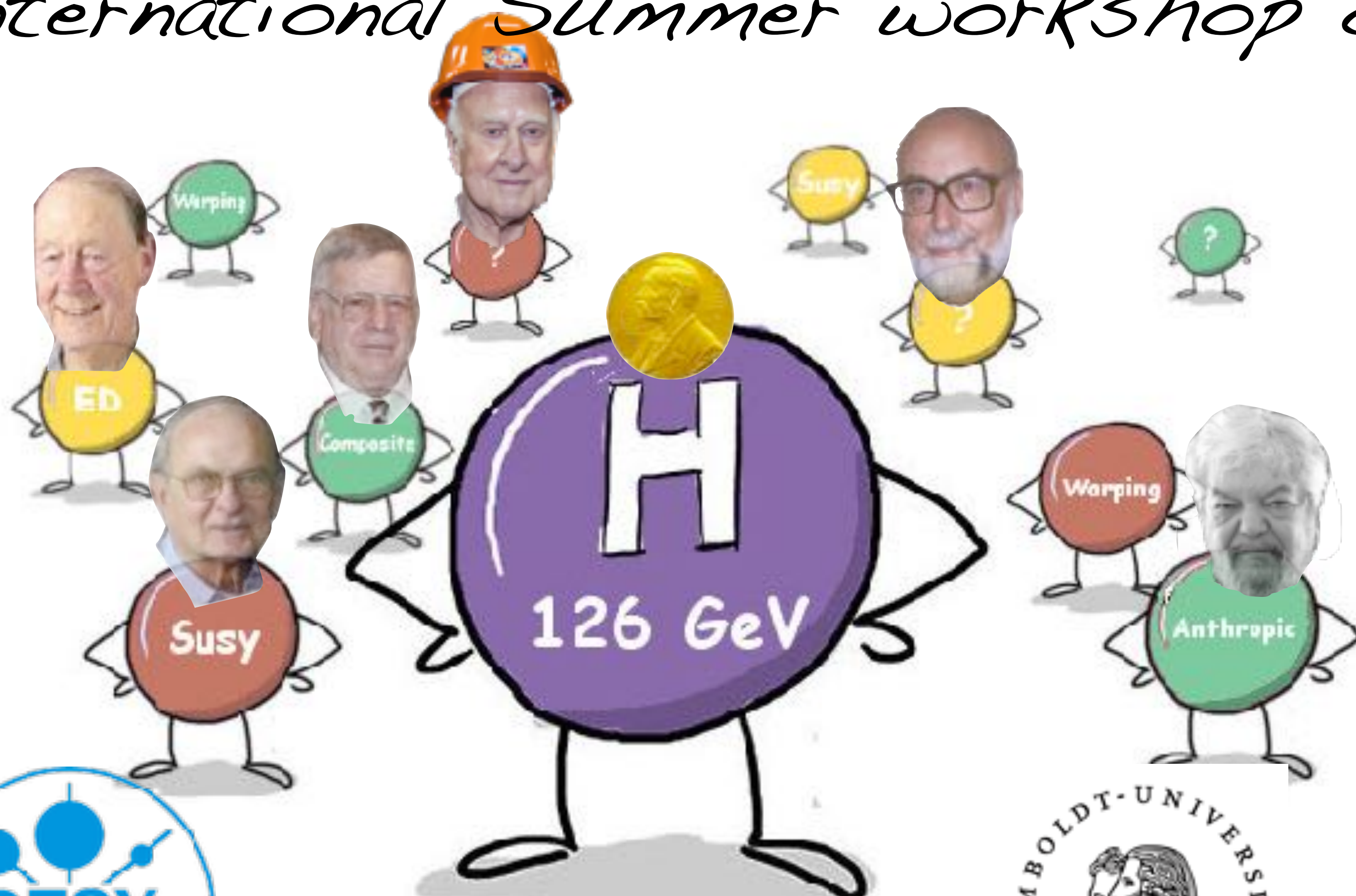
$$\Gamma \propto \frac{1}{m^4_{H,i}}$$

Preferentially reheats copy w/ smallest $|m_H|$ & $m_H^2<0$

Beyond the Standard Model

TAE 2018 @ Benasque

International Summer workshop on High Energy Physics



Lecture 3/3

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Humboldt University (Berlin)
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Outline

Lecture #1

- General introduction: From Fermi theory to the Standard Model
- Higgs physics as a door to BSM
- Naturalness and the weak scale hierarchy problem
- Supersymmetry

Lecture #2

- Composite Higgs
- Extra dimensions
- Cosmological relaxation: a concrete example of different energy frontier
- NNaturalness

Lecture #3

- Weak gravity conjecture and the swampland
- Beyond colliders searches for new physics
  - Gravitational waves
  - AMO: isotope spectroscopy
  - Electric dipole moment
  - Neutron-antineutron oscillations
  - Primordial black holes

The Standard Model: Matter

~~The particles seen in a detector~~

Absolutely stable particles	Collider stable particles	Sort of stable particles	Displaced vertex particles
γ (m=0) (G (m=0)) (ν (m~0)) e^- (m=511keV) p (m=938MeV)	n (m=940MeV, ct=10^{14}mm) μ (m=940MeV, ct=10^6mm) K_L (m=500MeV, ct=10^4mm) $\pi^\pm$ (m=140MeV, ct=10^4mm) $K^\pm$ (m=500MeV, ct=10^3mm)	Ξ, Λ, Σ, Ω (m=1-2GeV, ct=10-100mm) K_S (m=500MeV, ct=30mm)	B, D $\Xi_{c,b}$, $\Lambda_{c,b}$ (m=2-5GeV, ct=0.1-0.5mm)

You don't "see" most of the SM particles!
You have to infer their existence

Test: have you ever seen dinosaurs? You "reconstruct" them from their decay products

Physics probed at Colliders

Colliders are best places to search for

Heavy objects
With short lifetime
That are rarely produced
That have a direct coupling to quarks/gluons or electrons

Are we sure that BSM falls in this category?
No, and actually, we only have evidence that BSM has gravitational interactions
Nonetheless there are compelling arguments that BSM can be seen at colliders

Swampland: UV/IR mixing

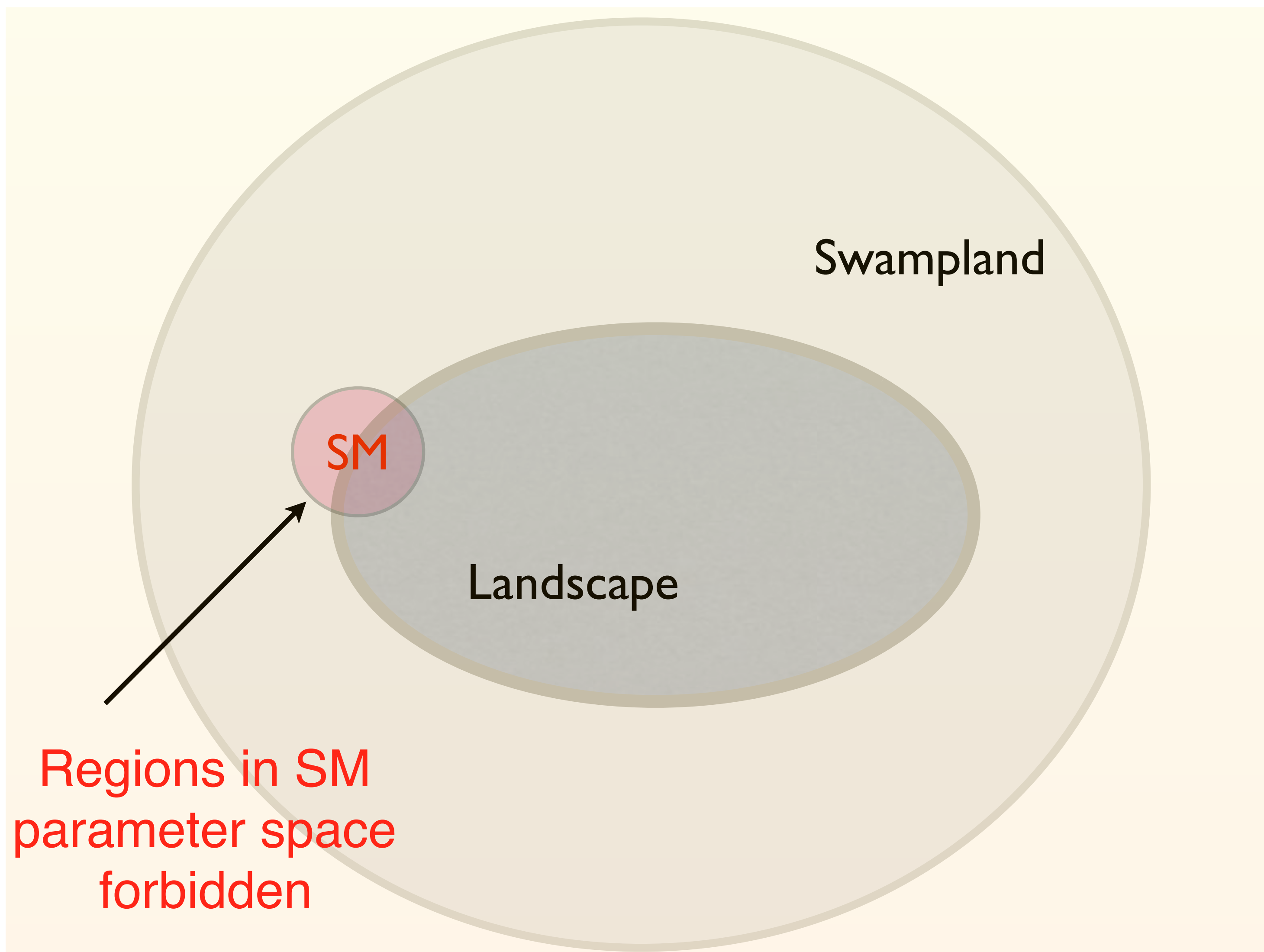
Particle Physics & Quantum Gravity

Can the SM be embedded in a theory of quantum gravity at the Planck scale?
Can QG be really decoupled at low energy?

Would certainly be true if any QFT can be consistently coupled to QG

Instead Vafa conjectured in 2005 that there exists a **swampland**

Ibanez @ SUSY'18



This conjecture has potentially far-reaching implications for phenomenology

Swampland Conjectures

0) No exact global symmetry

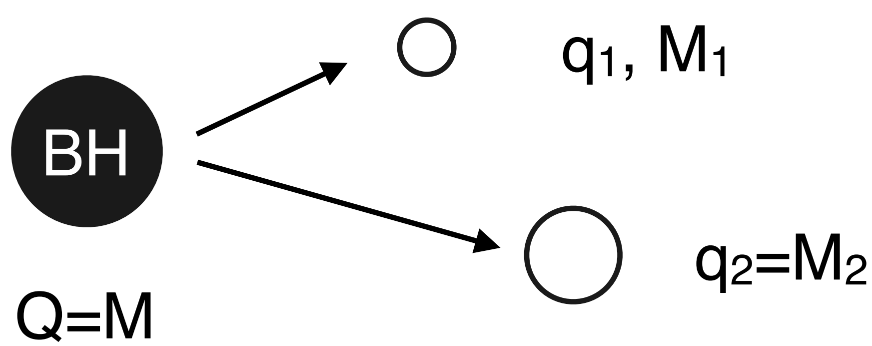
For a review, see Banks, Seiberg '10

1) Gravity is the weakest force

Arkani-Hamed, Motl, Nicolis, Vafa '06

In any UV complete U(1) gauge theory there must exist at least one charged particle with mass M such that: $M/M_P < g \cdot q$

Why? otherwise extremal charged BH cannot decay!



BH can decay iff $M_1+M_2<M$, i.e. $M_1<M-M_2=Q-q_2=q_1$

Swampland Conjectures

2) non-susy AdS vacua (Vmin<0) are unstable

Ooguri, Vafa '16

Consider the SM (with cc) compactified on a circle of radius R

Ibanez, Martin-Lozano, Valenzuela '17

$$V(R) \simeq \frac{2\pi r^3 \Lambda_4}{R^2} - 4\left(\frac{r^3}{720\pi R^6}\right) + \sum_i (2\pi R)(-1)^{s_i} n_i \rho_i(R)$$

From 4D c.c.

$\gamma, g_{\mu\nu}$

ν_i

$$\rho(R) = \mp \sum_{n=1}^{\infty} \frac{2m^4}{(2\pi)^2} \frac{K_2(2\pi Rmn)}{(2\pi Rmn)^2}$$

Heavier particles have exponentially small contribution

Majorana neutrinos leads to an AdS vacuum ⇒ in swampland

Dirac neutrinos avoid AdS vacuum iif $m_\nu^4 < \Lambda_4$

$\langle H \rangle < 1.6 \frac{\Lambda_4^{1/4}}{Y_\nu}$ ⇒ Large quantum corrections end up in swampland (for fixed Λ_4 and Y_ν)

SM with 3 families but without Higgs also develops AdS vacuum ⇒ in swampland

Ibanez @ SUSY'18

Swampland Conjectures

3) $M_P \parallel \vec{\nabla}_{\phi_i} V(\phi_i) \parallel > c\, V(\phi_i)$ with c is O(1) for any field configuration

Obied, Ooguri, Spodyneiko, Vafa '18

- Pure positive cosmological constant, i.e. vacuum energy, (dS vacuum) is forbidden

- Quintessence: Agrawal, Obied, Steinhart, Rafa '18

$$V(\phi) = \Lambda^4 e^{-\kappa\phi/M_P}$$

$$0.6 > \kappa > c$$

Planck data

swampland conjecture

- Quintessence + Higgs: Denef, Hebecker, Wrase '18

$$V(H,\phi) = \Lambda^4 e^{-\kappa\phi/M_P} + \lambda(|H|^2 - v^2)^2 + V_0$$

$$M_P \parallel \vec{\nabla}_{\phi_i} V(\phi_i) \parallel = \begin{array}{ll} \dfrac{\kappa\Lambda^4}{\Lambda^4 + \lambda v^4 + V_0} & @(H=0, \phi=0) \\ \dfrac{\kappa\Lambda^4}{\Lambda^4 + V_0} & @(H=v, \phi=0) \end{array}$$

at least one of them is as small as

$$\mathcal{O}\left(\frac{\text{cc}}{\text{EW}^4}\right) \sim \frac{(10^{-3}\,\text{eV})^4}{(100\,\text{GeV})^4} \sim 10^{-56}$$

- Quintessence + axion: Murayama, Yamazaki, Yanagida '18

$$V(\theta,\phi) = \Lambda^4 e^{-\kappa\phi/M_P} + \Lambda^4_{QCD}(1 - \cos(\theta/f)) + V_0$$

$$M_P \parallel \vec{\nabla}_{\phi_i} V(\phi_i) \parallel = \begin{array}{ll} \dfrac{\kappa\Lambda^4}{\Lambda^4 + V_0} & @(\theta=0, \phi=0) \\ \dfrac{\kappa\Lambda^4}{\Lambda^4 + \Lambda^4_{QCD} + V_0} & @(\theta=\pi f, \phi=0) \end{array}$$

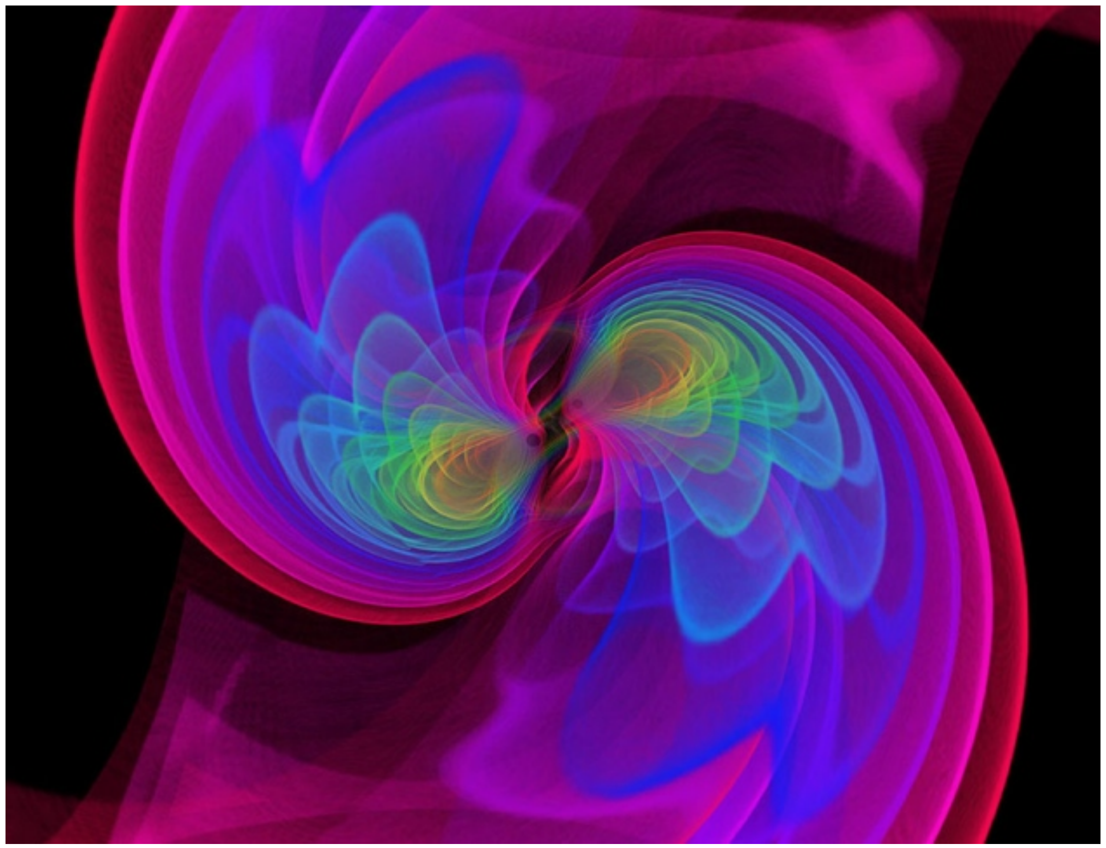
at least one of them is as small as

$$\mathcal{O}\left(\frac{\text{cc}}{\text{QCD}^4}\right) \sim \frac{(10^{-3}\,\text{eV})^4}{(200\,\text{MeV})^4} \sim 10^{-44}$$

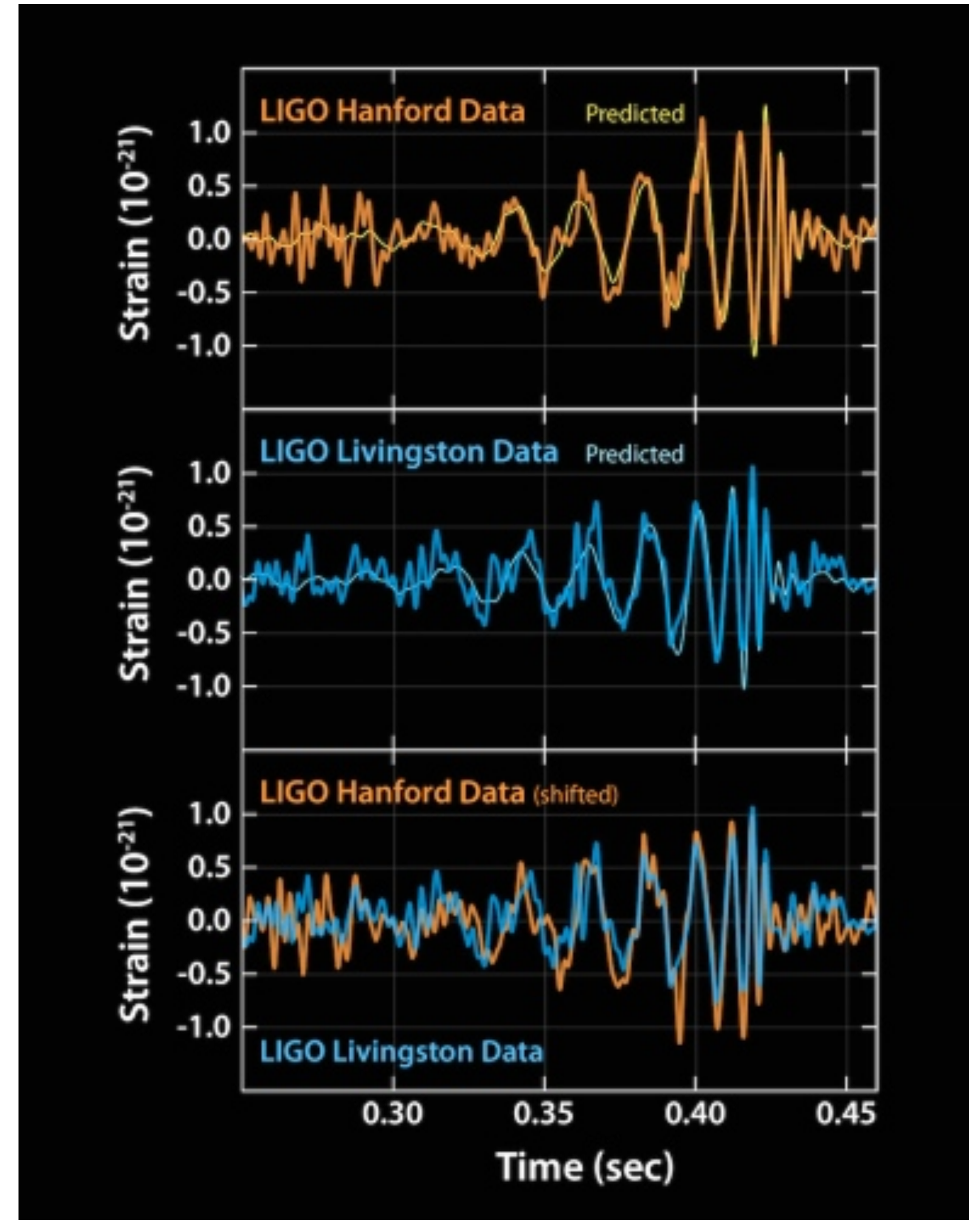
Gravitational waves

The pictures that shook the Earth

GW150914



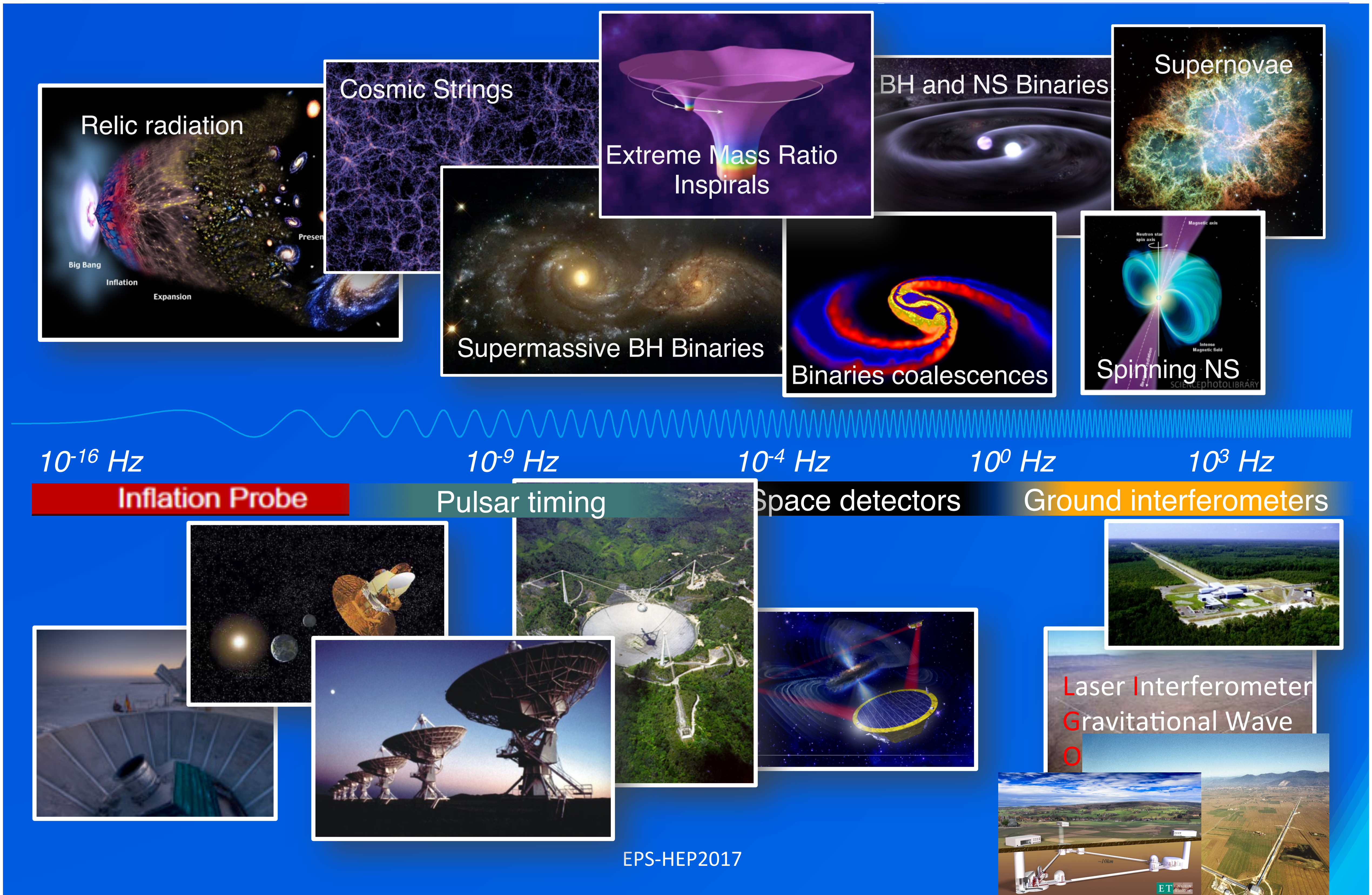
1.3 billion years later on earth



what did it teach us?

- never give up against strong background when you know you are right
- $m_g < 10^{-22}$ eV ($c_g - c_\gamma < 10^{-17}$ GRB observed together with GW with the same origin?)
- no spectral distortions: scale of quantum gravity > 100 keV

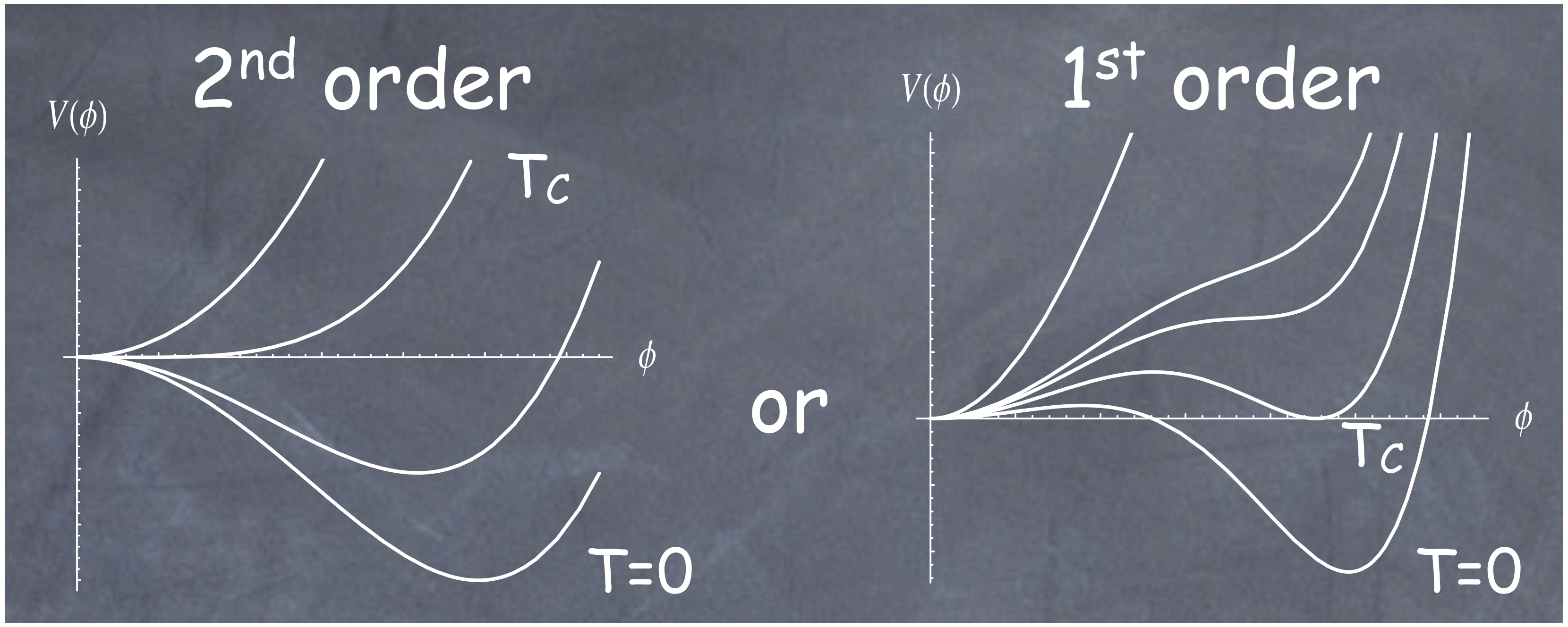
GW and astrophysics/cosmology



Dynamics of EW phase transition

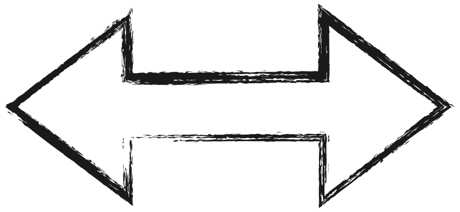
The asymmetry between matter-antimatter can be created dynamically
it requires an out-of-equilibrium phase in the cosmological history of the Universe

An appealing idea is EW baryogenesis associated to a first order EW phase transition



the dynamics of the phase transition is determined by Higgs effective potential at finite T
which we have no direct access at in colliders (LHC≠Big Bang machine)

finite T
Higgs potential



Higgs couplings
at T=0

SM: first order phase transition iff mH < 47 GeV
BSM: first order phase transition needs some sizeable deviations in Higgs couplings

GW and the ElectroWeak Phase Transition

GW interact very weakly and are not absorbed

direct probe of physical process of the very early universe

possible cosmological sources:

inflation, vibrations of topological defects, excitations of xdim modes, 1st order phase transitions...

ElectroWeak Phase Transition (if 1st order)

typical freq. ~ (size of the bubble)$^{-1}$ ~ (fraction of the horizon size)$^{-1}$

$$@\ T = 100\ \mathrm{GeV}, \qquad H = \sqrt{\frac{8\pi^3}{45}\frac{T^2}{M_{Pl}}} \sim 10^{-15}\ \mathrm{GeV}$$

redshifted freq.

~ today ~

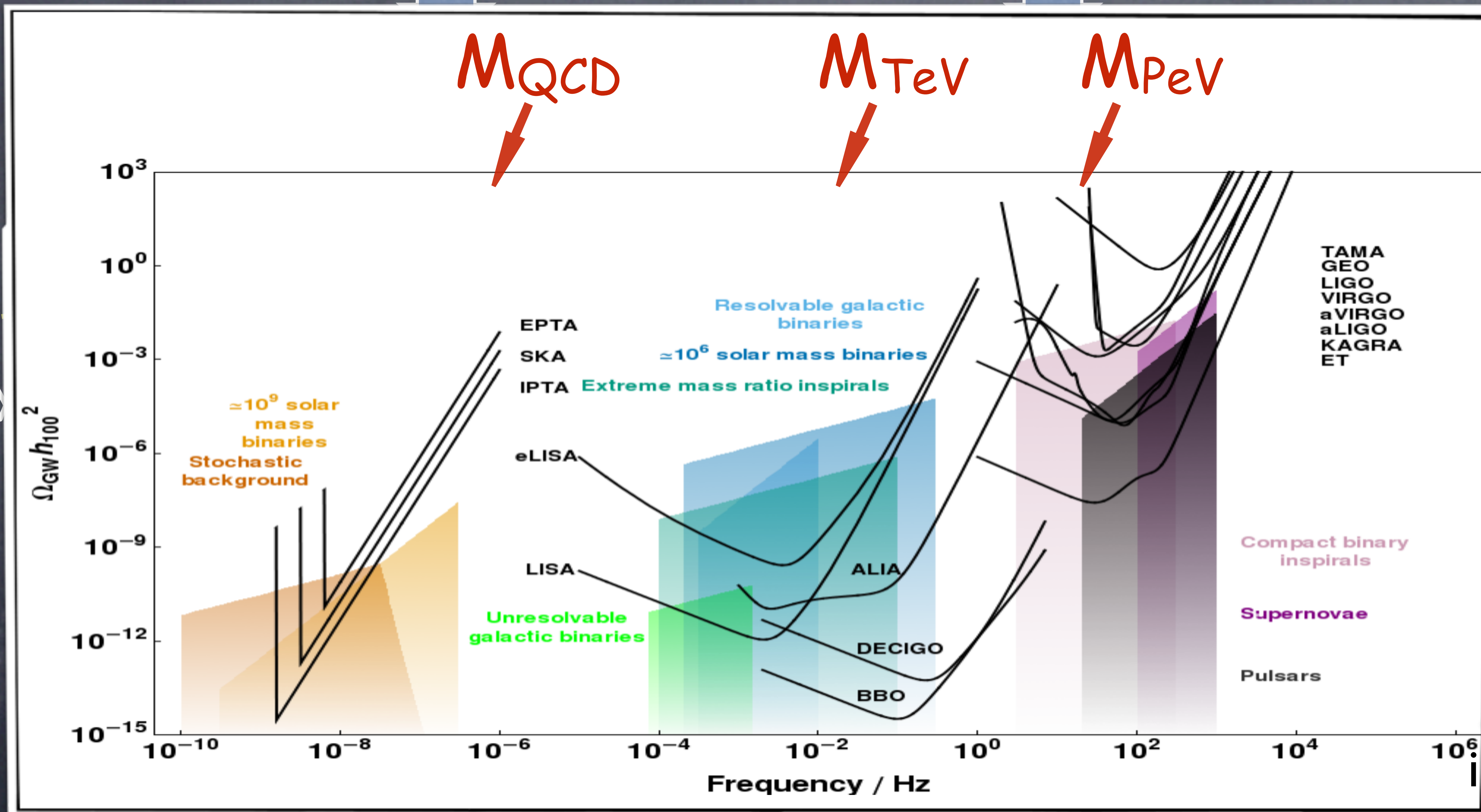
$$f \sim \# \frac{2 \cdot 10^{-4}\ \mathrm{eV}}{100\ \mathrm{GeV}}\ 10^{-15}\ \mathrm{GeV} \sim \# \, 10^{-5}\ \mathrm{Hz}$$

Grojean, Servant '06

The GW spectrum from a 1st order electroweak PT is peaked around the milliHertz frequency

GW and the ElectroWeak Phase Transition

GW interact very weakly and are not absorbed

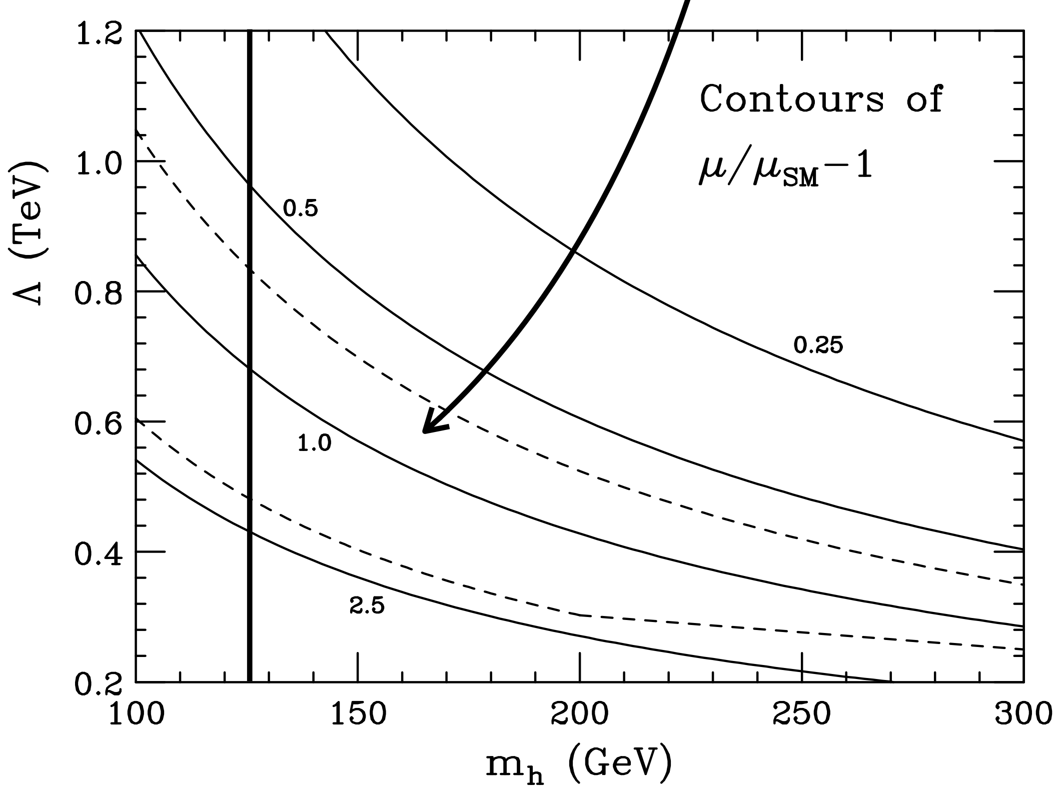


Grojean, Servant '06

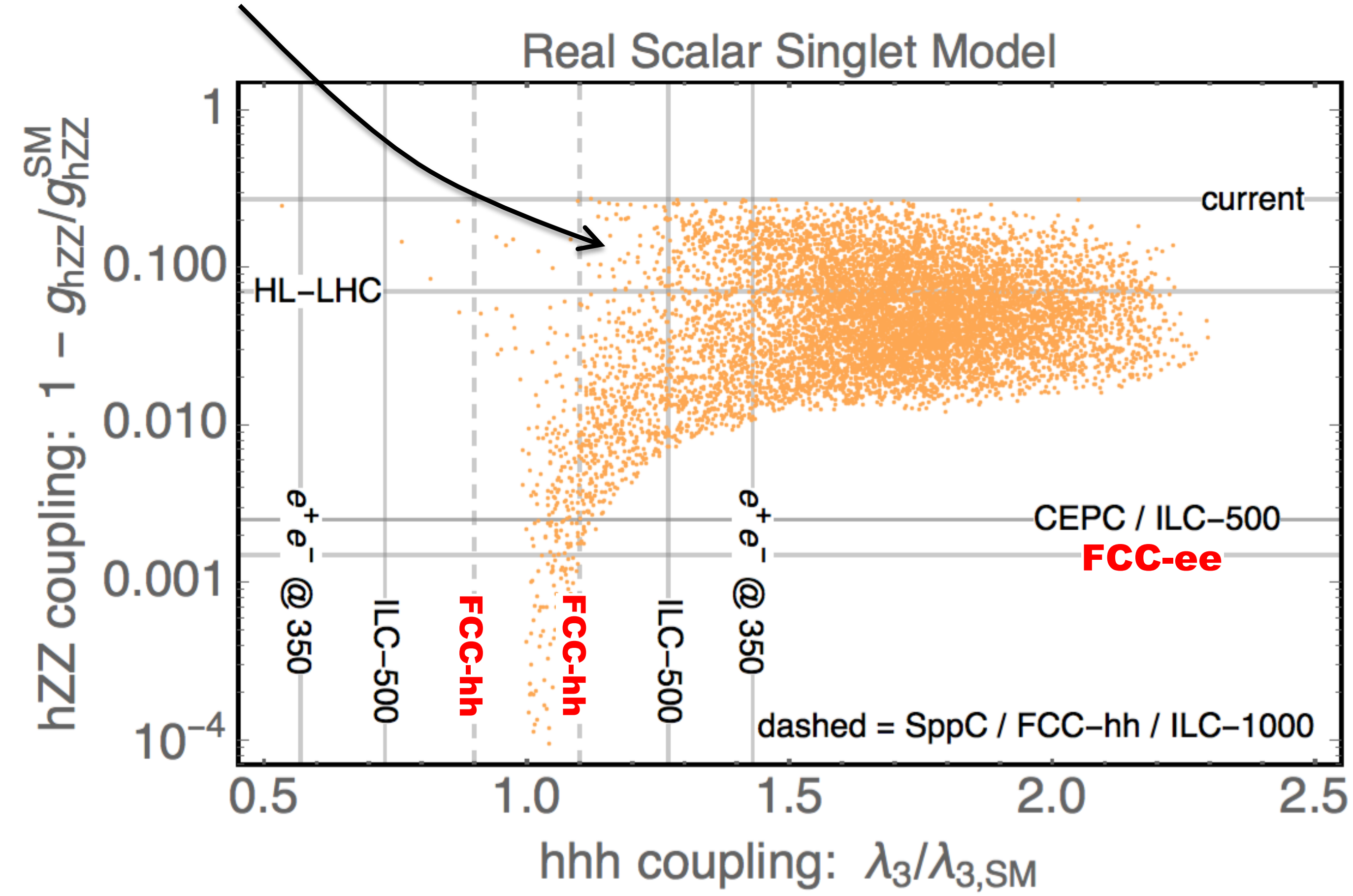
The GW spectrum from a 1st order electroweak PT
is peaked around the milliHertz frequency

Complementary GW - Colliders

EWPT is 1st order and gives rise to GW stochastic background



Grojean, Servant, Wells '04

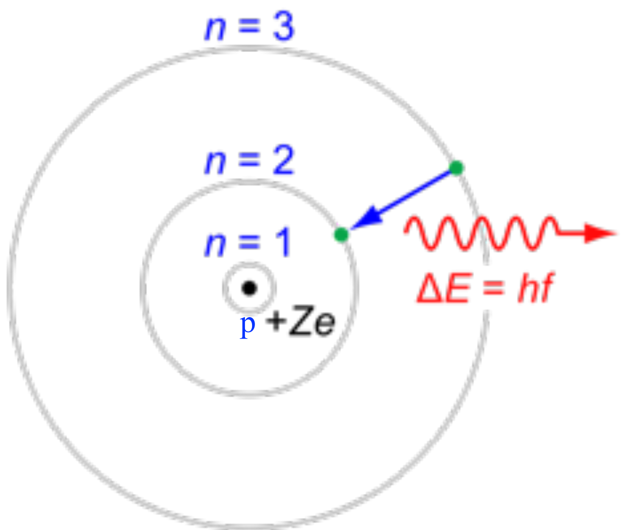


Huang, Long, Wang '16

"Large" deviations of the Higgs (self-)couplings expected to obtain a 1st order phase transition

BSM and Atomic Physics

Atomic Clocks as a BSM probe



Physics beyond QED contributes to the frequency of the radiation

$$\frac{1}{\lambda} = R\,Z^2 \left(\frac{1}{n^2} - \frac{1}{n'^2} \right)$$

$|\psi(0)|^2/n^3$ is the wave-function-density at the origin.

$$V_{\rm weak}(r) = -\frac{8 G_{\rm F} m_{Z^0}^2}{\sqrt{2}} \frac{g_e g_A}{4\pi} \frac{e^{-r m_{Z^0}}}{r} \quad \Longrightarrow \quad \delta E_{nlm}^{\rm weak} = -\frac{8 G_F m_Z^2}{\sqrt{2}} \frac{g_e g_A}{4\pi m_Z^2} |\psi(0)|^2 \frac{\delta_{l,0}}{n^3}$$

fifth force ⟹ ?

Exp sensitivity in atomic clock measurements $O(10^{-18})$

(ms over one billon years)

Not all transitions can be used (yet) for BSM

frequency shifts O(1-100 Hz) over frequencies O(1THz): still a sensitivity $O(10^{-6:-9})$

can be used to detect new (long range) forces

Isolating the signal: isotope shifts

$$\nu_i^{AA'} = \nu_i^A - \nu_i^{A'}$$

$$\delta\nu^i_{AA'} = \underbrace{K_i\,\mu_{AA'}}_{\text{mass shift}} + \underbrace{F_i\delta\langle r^2\rangle_{AA'}}_{\text{field shift}} + \underbrace{H_i(A-A')}_{\text{BSM or NLO SM/QED}}$$

K_i and F_i are difficult to compute to the accuracy needed but they are the same for different isotopes

The King Plot

W. H. King, *J. Opt. Soc. Am.* 53, 638 (1963)

- First, define modified IS as $m\delta\nu^i_{AA'} \equiv \delta\nu^i_{AA'}/\mu_{AA'}$
- Measure IS in two transitions. Use transition 1 to set $\delta\langle r^2\rangle_{AA'}/\mu_{AA'}$ and substitute back into transition 2:

$F_{21} \equiv F_2/F_1$
$K_{21} \equiv K_2 - F_{21}K_1$
$H_{21} \equiv H_2 - F_{21}H_1$

$$m\delta\nu^2_{AA'} = K_{21} + F_{21}m\delta\nu^1_{AA'} - AA'H_{21}$$

- Plot $m\delta\nu^1_{AA'}$ vs. $m\delta\nu^2_{AA'}$ along the isotopic chain

Isolating the signal: isotope shifts

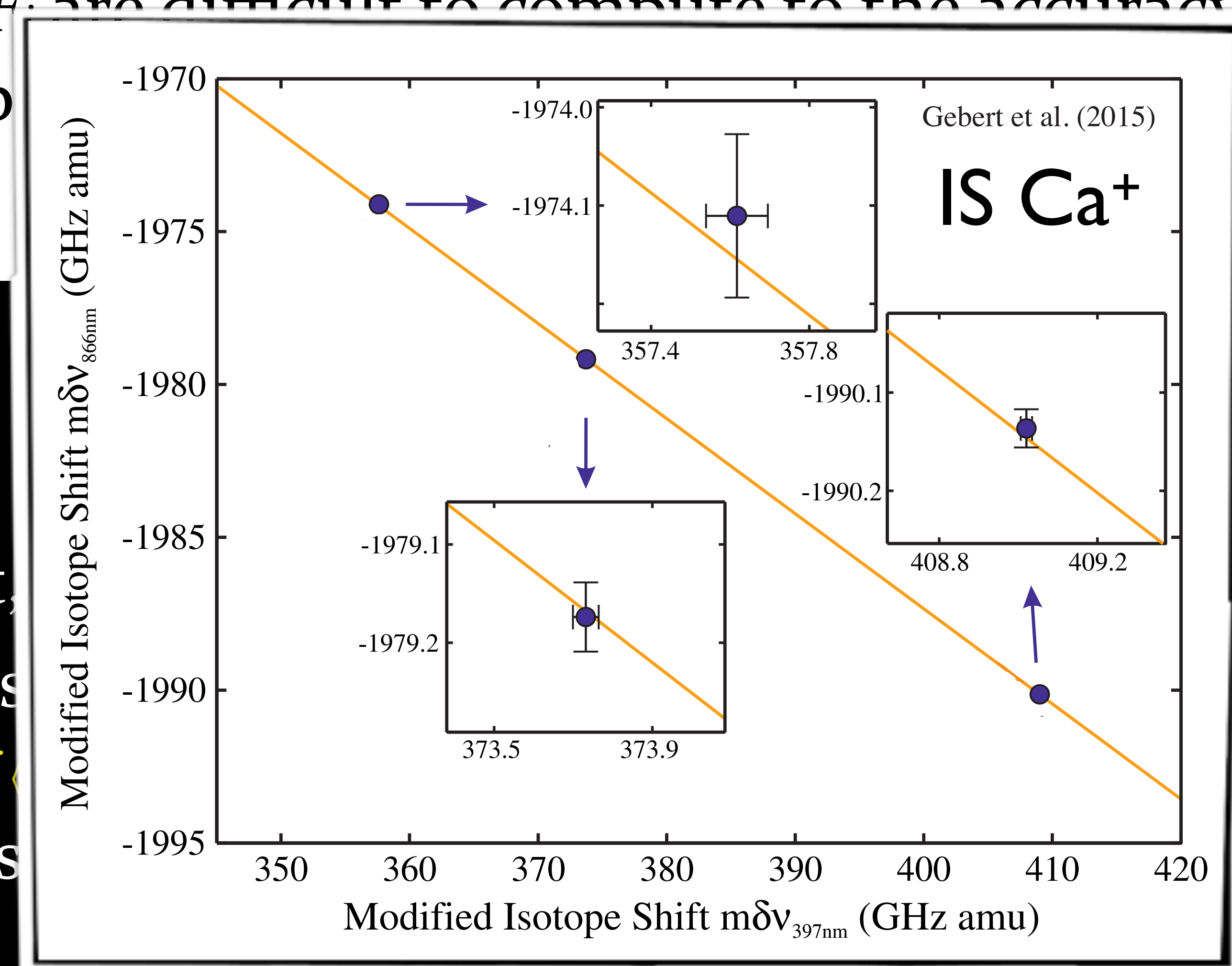
$$\nu_i^{AA'} = \nu_i^{A} - \nu_i^{A'}$$

$$\delta\nu^i_{AA'} = K_i\,\mu_{AA'} + F_i\delta\langle r^2\rangle_{AA'} + H_i(A-A')$$

mass shift field shift BSM or NLO SM/QED

K_i and F_i are difficult to compute to the accuracy needed

b ... es



The ... . H. King, ... 638 (1963)

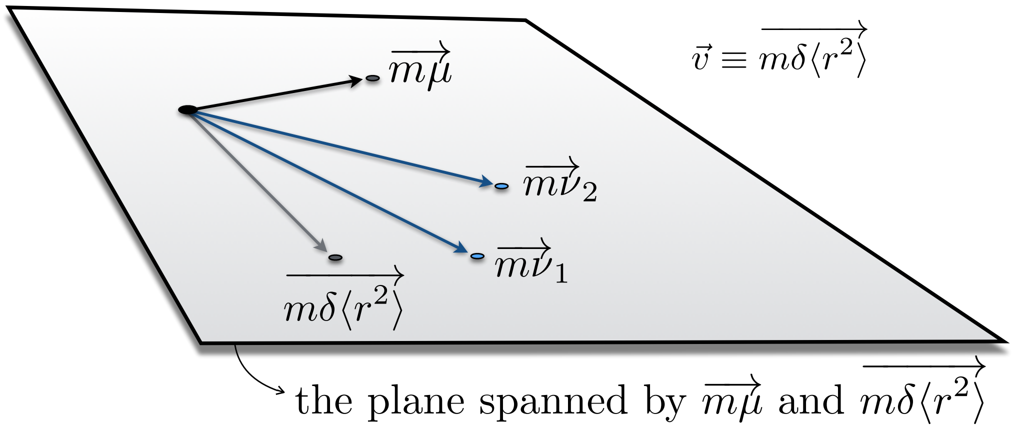
- First, ... AA'
- Meas ... 1 to set δ ... trans ...

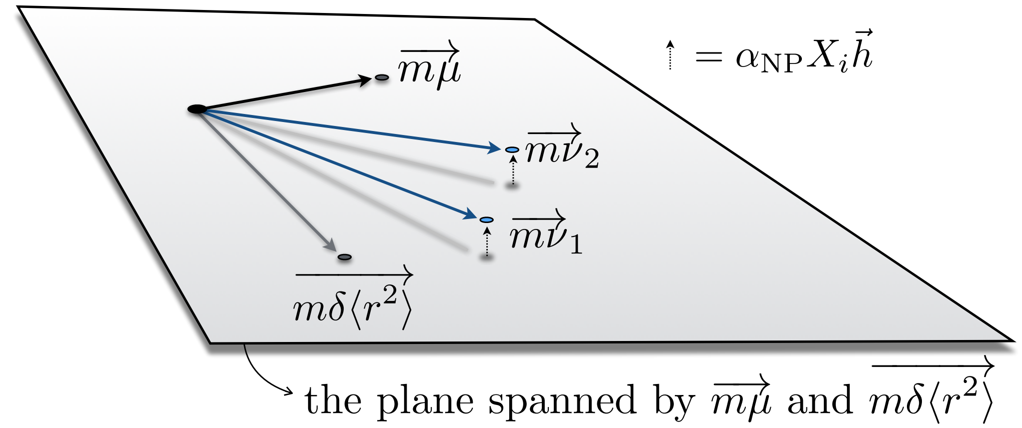
$\equiv F_2/F_1$
$\equiv K_2 - F_{21}K_1$
$\equiv H_2 - F_{21}H_1$

$$m\delta\nu^2_{AA'} = K_{21} + F_{21}m\delta\nu^1_{AA'} - AA'H_{21}$$

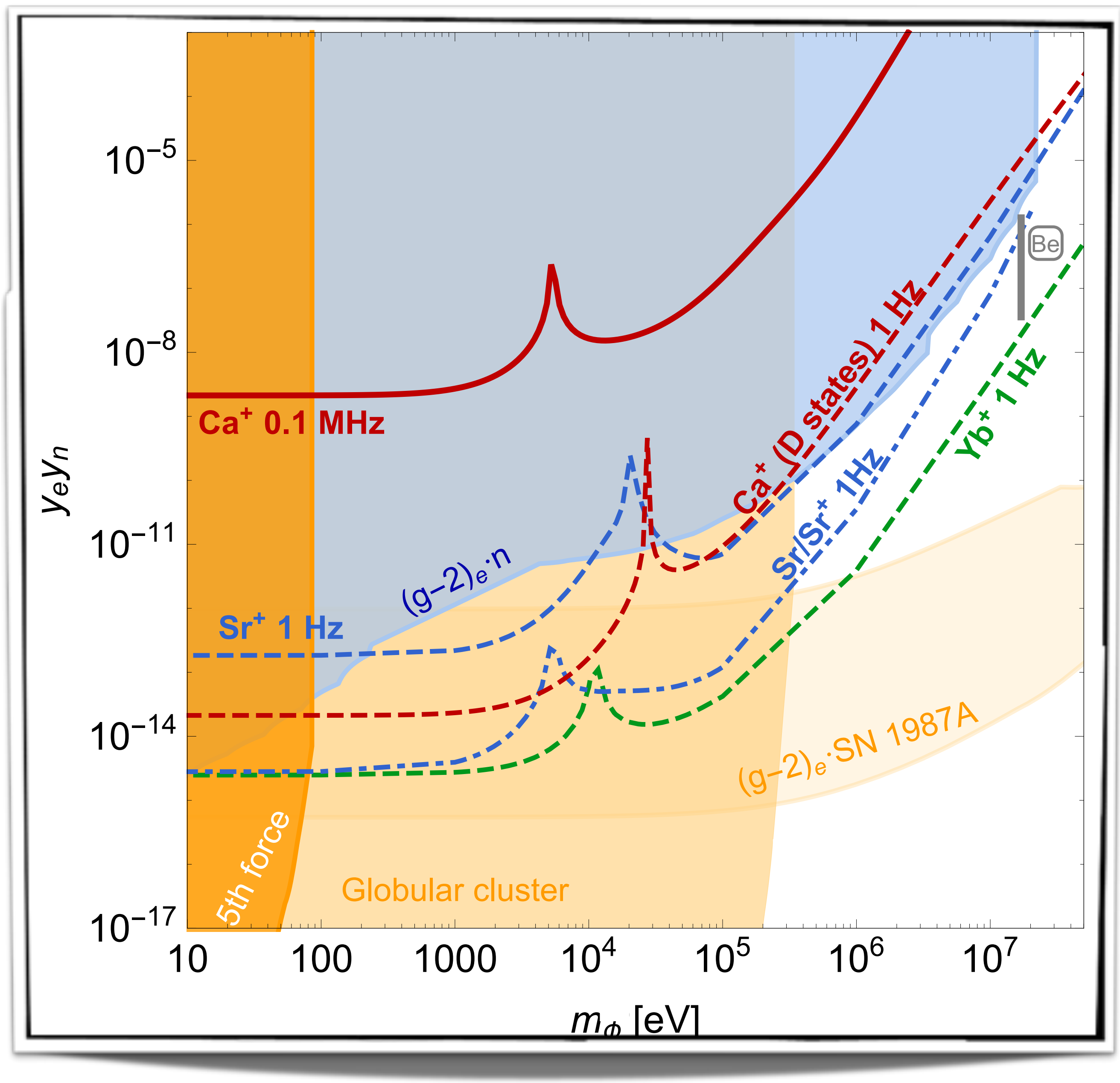
- Plot $m\delta\nu^1_{AA'}$ vs. $m\delta\nu^2_{AA'}$ along the isotopic chain

Constraining light NP





As long as
King linearity deviation
is not observed,
one can bound
new physics sources
More tricky to interpret
if a signal is observed



arXiv:1704.05068v1 [hep-ph]

EDM

Electric Dipole Moment

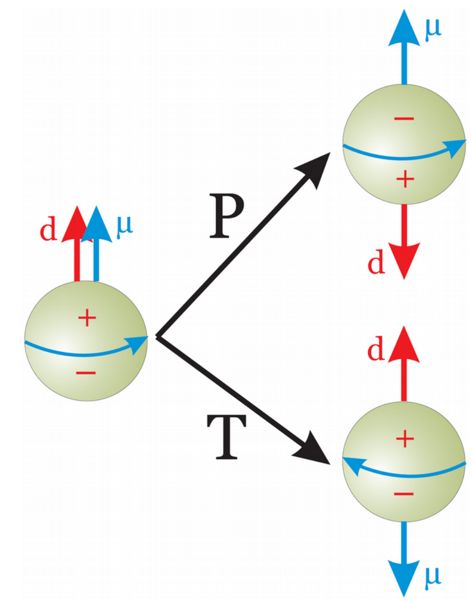
(M. Riembau, PhD defense '18)

$$\mathcal{L}_{dipole} = -\frac{\mu}{2}\bar{\Psi}\sigma^{\mu\nu}F_{\mu\nu}\Psi - \frac{d}{2}\bar{\Psi}\sigma^{\mu\nu}i\gamma^5 F_{\mu\nu}\Psi$$

Non-relativistic limit

$$H = -\mu\,\vec{B}\cdot\frac{\vec{S}}{S} - d\,\vec{E}\cdot\frac{\vec{S}}{S}$$

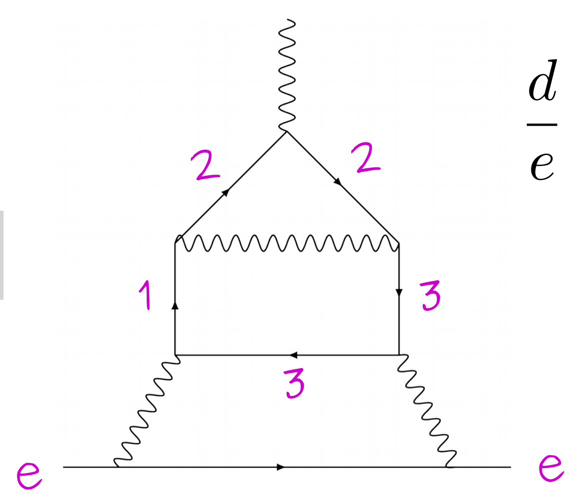
Nonvanishing EDM breaks CP



Nonvanishing d breaks CP

SM predictions

3-loop since needs to involve 3 family to break CP



$$\frac{d}{e} \sim \left(\frac{g^2}{16\pi^2}\right)^3 \frac{m_e J}{m_W^{14}}\mathcal{N}$$

Jarsklog invariant
$\sim 10^{-4}\, m_t^4 m_b^4 m_c^2 m_s^2$

Integral factor
$\sim 10^{10}$

$$\to d_e/e \sim 10^{-40}\ cm$$

SM contribution is ridiculously small
EDM is clear signal of New Physics

EDMs violate chirality, so putting in the electron mass a spurion, we expect an effect of order:

$$d_e \sim \delta_{\rm CPV}\left(\frac{\lambda}{16\pi^2}\right)^k \frac{m_e}{M^2}$$

Then dimensional analysis tells us that the experiment probes masses **Preliminary: experimental result not yet known**

0-loop	1-loop	2-loop
800 TeV	40 TeV	2 TeV

(M. Reece, SUSY '18)

EDM - experimental status

Science 343, p. 269-272 (2014)

$$|d_e| < 9.4 \cdot 10^{-29}\, e\,\mathrm{cm} \qquad \text{at} \;\; 90\%\ \mathrm{CL}$$

$$|d_e| \lesssim 0.5 \cdot 10^{-29}\, e\,\mathrm{cm} \qquad (\mathrm{ACME\ II})$$

$$|d_e| \lesssim 0.3 \cdot 10^{-30}\, e\,\mathrm{cm} \qquad (\mathrm{ACME\ III})$$

$$|d_e| \lesssim 10^{-30}\ e\ cm$$ arXiv:1704.07928

$$|d_e| \lesssim 5 \cdot 10^{-30}\ e\ cm$$ arXiv:1804.10012

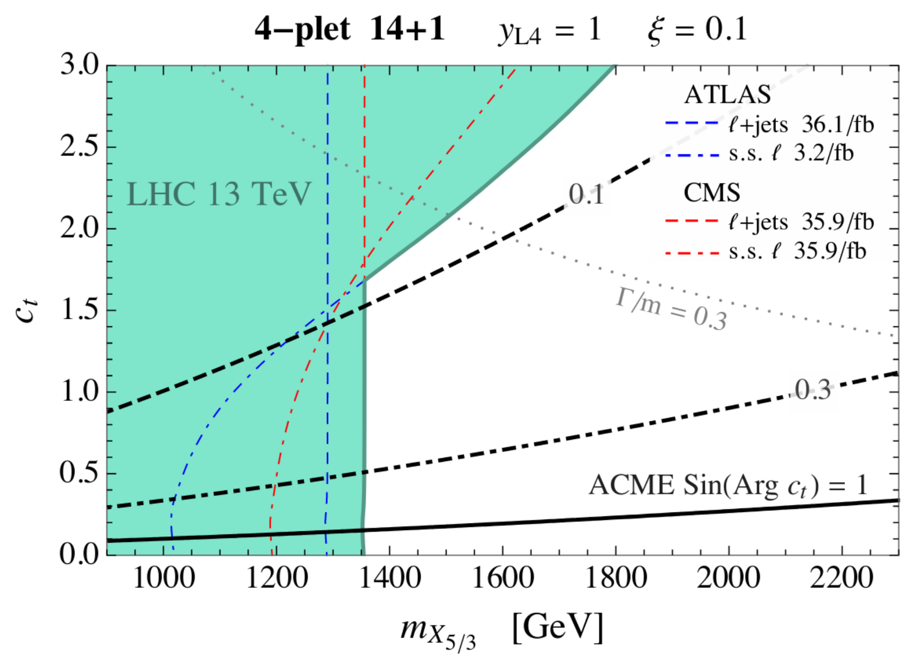
$$|d_e| \lesssim 10^{-35}\ e\ cm$$ arXiv:1710.08785

EDM as a BSM probe

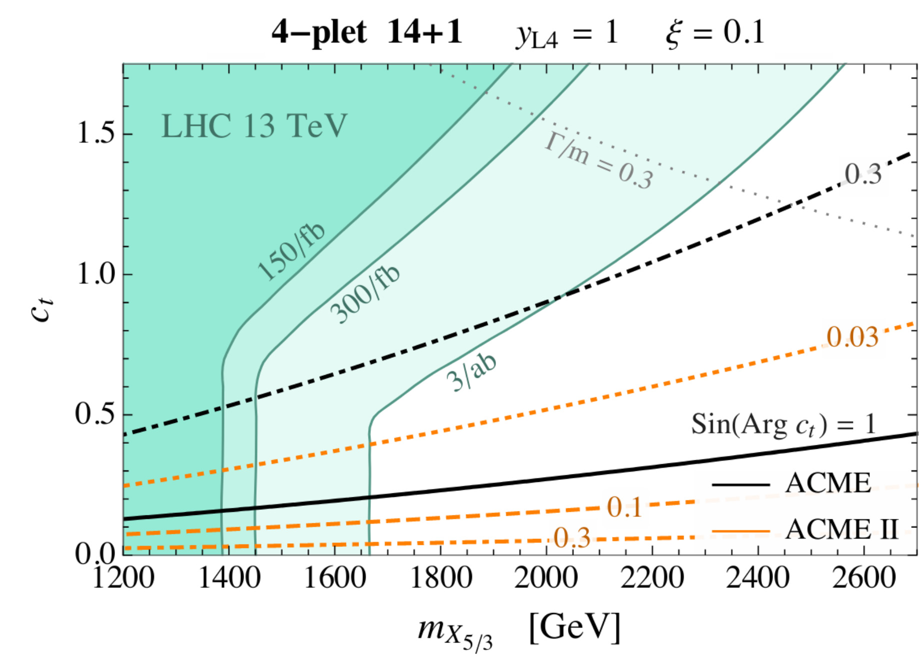
Panico, Riembau, Vantalon '17

e.g., EDM can help testing the presence of top partners in composite Higgs models

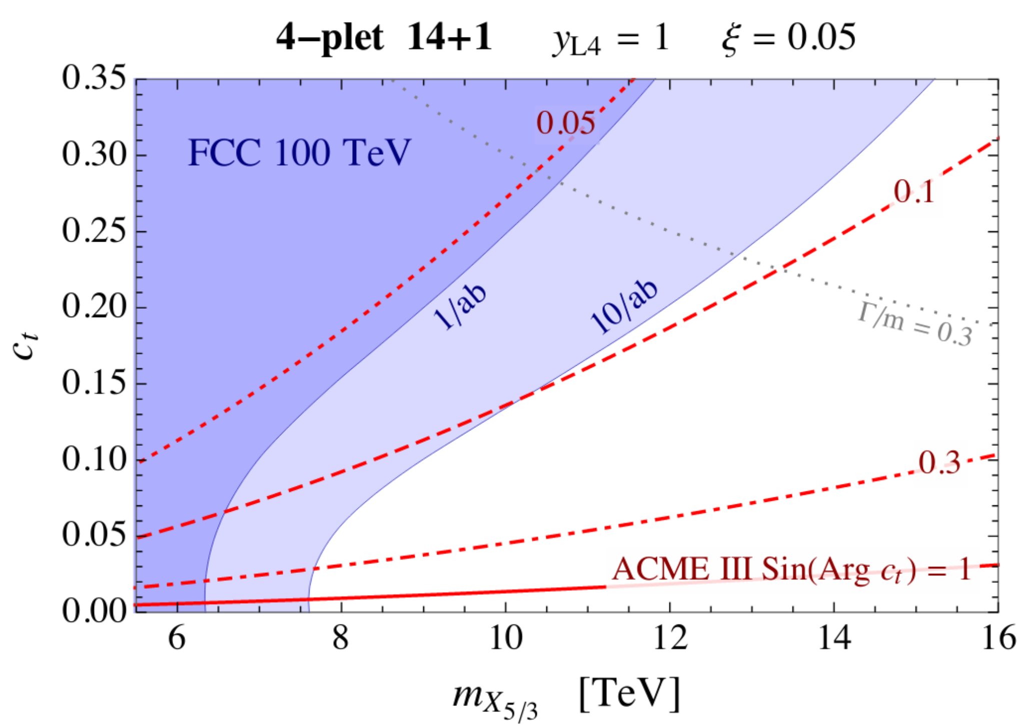
LHC



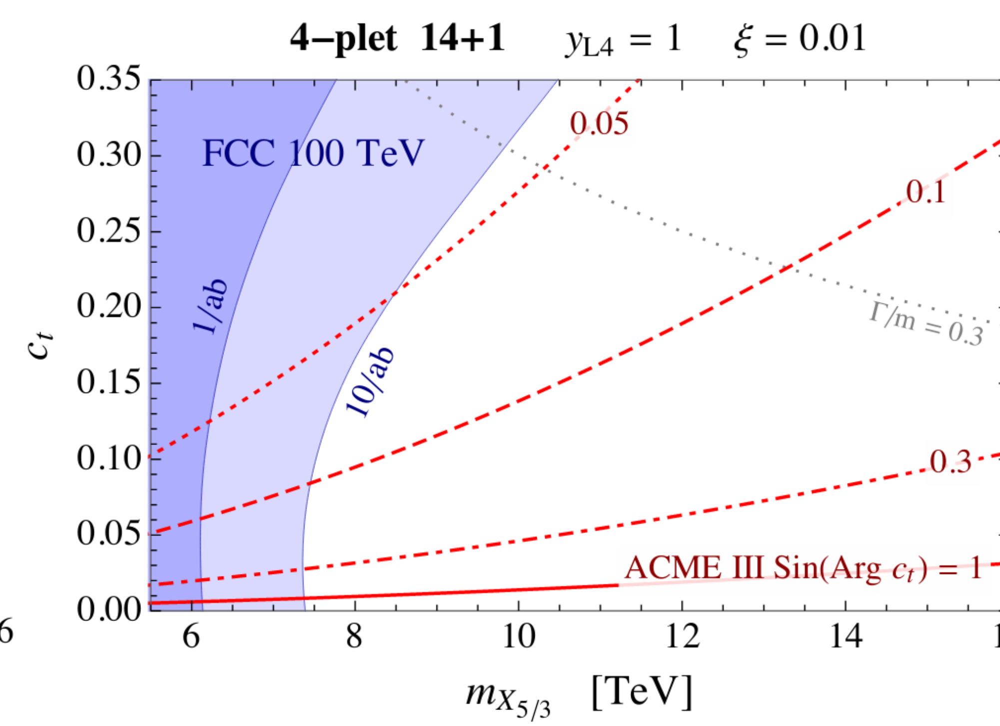
HL-LHC



FCC-hh



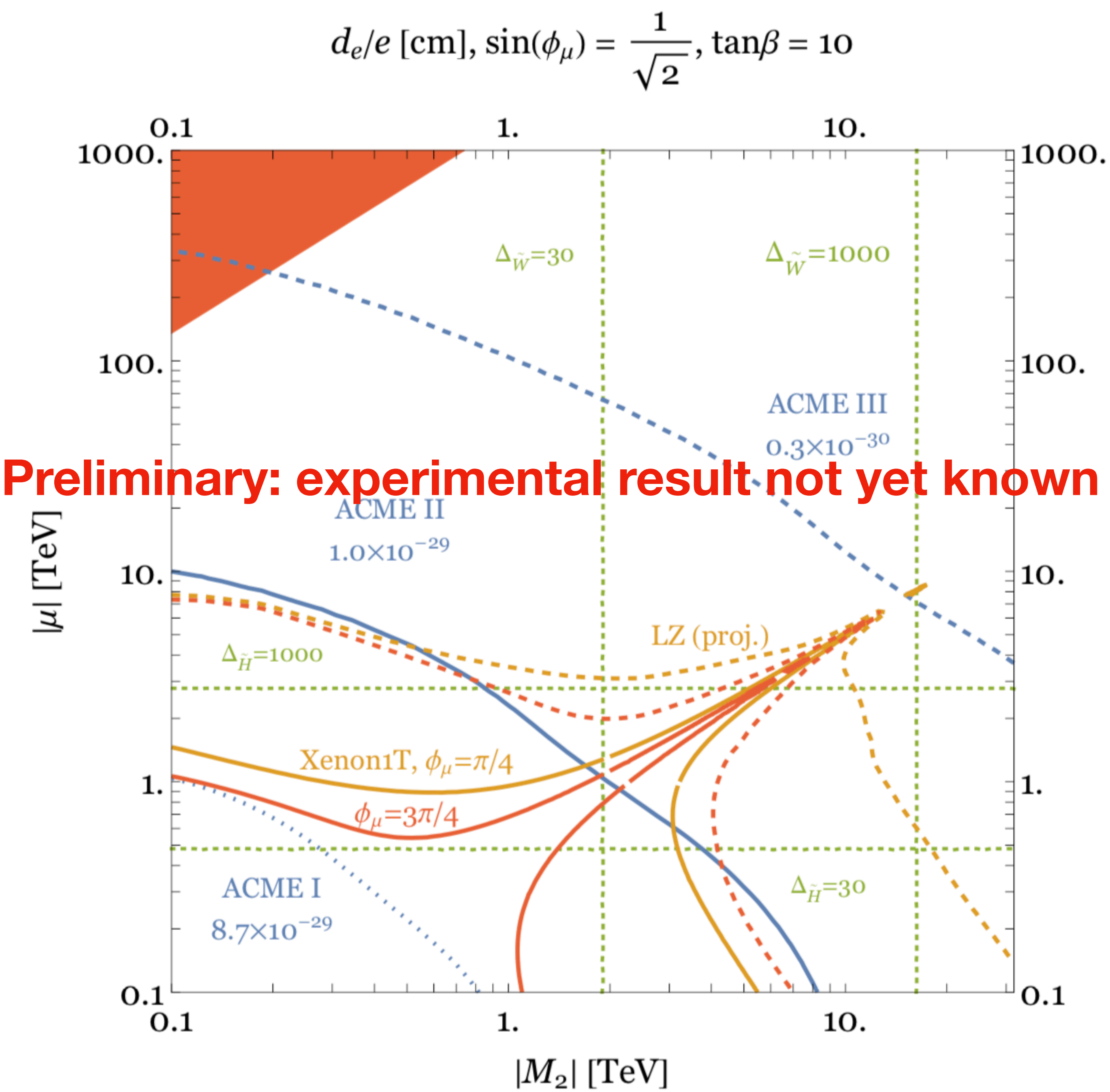
FCC-hh



EDM as a BSM probe

(M. Reece, SUSY '18)

Powerful split SUSY constraints (forecast) from ACME 2!



Preliminary: experimental result not yet known

Heavy Baryogenesis Models

& Neutron-antineutron oscillations

Baryon number violation(s)

Why are we expecting B violation(s)?

1) Neutral meson oscillations, neutral lepton oscillations (very likely), why not neutral baryon oscillations?

2) Global symmetry are not consistent with quantum gravity

3) Need to generate matter-antimatter imbalance

Selection rule

conservation of angular momentum ⇒ spin of nucleon should be transferred to another fermion

1) $\Delta B = \Delta L$ (nucleon → antilepton)
2) $\Delta B = -\Delta L$ (nucleon → lepton)
3) $\Delta L = \pm 2$ ($0\nu\beta\beta$)
4) $\Delta B = \pm 2$ ($n\bar{n}$ oscillations, dinucleon decays)

Proton stability doesn't exclude baryogenesis!

If h3 coupling is SM-like, unlikely that baryogenesis occurs at weak scale
Large scale baryogenesis requires B-L violation
otherwise any B asymmetry created above EWSB scale is wiped out by active EW sphalerons

Constraints on Baryon # violation

	Mode	Partial mean life (10^{30} years)	Confidence level
	Antilepton + meson		
τ_1	$N \to e^+\pi$	> 2000 (n), > 8200 (p)	90%
τ_2	$N \to \mu^+\pi$	> 1000 (n), > 6600 (p)	90%
τ_3	$N \to \nu\pi$	> 1100 (n), > 390 (p)	90%
τ_4	$p \to e^+\eta$	> 4200	90%
τ_5	$p \to \mu^+\eta$	> 1300	90%
τ_6	$n \to \nu\eta$	> 158	90%
τ_7	$N \to e^+\rho$	> 217 (n), > 710 (p)	90%
τ_8	$N \to \mu^+\rho$	> 228 (n), > 160 (p)	90%
τ_9	$N \to \nu\rho$	> 19 (n), > 162 (p)	90%
τ_{10}	$p \to e^+\omega$	> 320	90%
τ_{11}	$p \to \mu^+\omega$	> 780	90%
τ_{12}	$n \to \nu\omega$	> 108	90%
τ_{13}	$N \to e^+K$	> 17 (n), > 1000 (p)	90%
τ_{14}	$p \to e^+K^0_S$		
τ_{15}	$p \to e^+K^0_L$		
τ_{16}	$N \to \mu^+K$	> 26 (n), > 1600 (p)	90%
τ_{17}	$p \to \mu^+K^0_S$		
τ_{18}	$p \to \mu^+K^0_L$		
τ_{19}	$N \to \nu K$	> 86 (n), > 5900 (p)	90%
τ_{20}	$n \to \nu K^0_S$	> 260	90%
τ_{21}	$p \to e^+K^*(892)^0$	> 84	90%
τ_{22}	$N \to \nu K^*(892)$	> 78 (n), > 51 (p)	90%
	Antilepton + mesons		
τ_{23}	$p \to e^+\pi^+\pi^-$	> 82	90%
τ_{24}	$p \to e^+\pi^0\pi^0$	> 147	90%
τ_{25}	$n \to e^+\pi^-\pi^0$	> 52	90%
τ_{26}	$p \to \mu^+\pi^+\pi^-$	> 133	90%
τ_{27}	$p \to \mu^+\pi^0\pi^0$	> 101	90%
τ_{28}	$n \to \mu^+\pi^-\pi^0$	> 74	90%
τ_{29}	$n \to e^+K^0\pi^-$	> 18	90%

ΔB=ΔL=1 decay bounds

	Mode	Partial mean life (10^{30} years)	Confidence level
	Lepton + meson		
τ_{30}	$n \to e^-\pi^+$	> 65	90%
τ_{31}	$n \to \mu^-\pi^+$	> 49	90%
τ_{32}	$n \to e^-\rho^+$	> 62	90%
τ_{33}	$n \to \mu^-\rho^+$	> 7	90%
τ_{34}	$n \to e^-K^+$	> 32	90%
τ_{35}	$n \to \mu^-K^+$	> 57	90%
	Lepton + mesons		
τ_{36}	$p \to e^-\pi^+\pi^+$	> 30	90%
τ_{37}	$n \to e^-\pi^+\pi^0$	> 29	90%
τ_{38}	$p \to \mu^-\pi^+\pi^+$	> 17	90%
τ_{39}	$n \to \mu^-\pi^+\pi^0$	> 34	90%
τ_{40}	$p \to e^-\pi^+K^+$	> 75	90%
τ_{41}	$p \to \mu^-\pi^+K^+$	> 245	90%

ΔB=-ΔL=1 decay bounds

	Mode	Partial mean life (10^{30} years)	Confidence level
τ_{66}	$pp \to \pi^+\pi^+$	> 72.2	90%
τ_{67}	$pn \to \pi^+\pi^0$	> 170	90%
τ_{68}	$nn \to \pi^+\pi^-$	> 0.7	90%
τ_{69}	$nn \to \pi^0\pi^0$	> 404	90%
τ_{70}	$pp \to K^+K^+$	> 170	90%
τ_{71}	$pp \to e^+e^+$	> 5.8	90%
τ_{72}	$pp \to e^+\mu^+$	> 3.6	90%
τ_{73}	$pp \to \mu^+\mu^+$	> 1.7	90%
τ_{74}	$pn \to e^+\overline{\nu}$	> 260	90%
τ_{75}	$pn \to \mu^+\overline{\nu}$	> 200	90%
τ_{76}	$pn \to \tau^+\overline{\nu}_\tau$	> 29	90%
τ_{77}	$nn \to \nu_e\overline{\nu}_e$	> 1.4	90%
τ_{78}	$nn \to \nu_\mu\overline{\nu}_\mu$	> 1.4	90%
τ_{79}	$pn \to$ invisible	$> 2.1 \times 10^{-5}$	90%
τ_{80}	$pp \to$ invisible	$> 5 \times 10^{-5}$	90%

ΔB=2/ΔL=0 decay bounds*

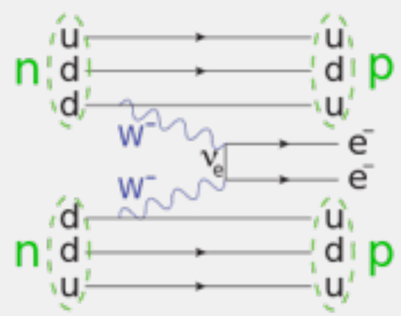
*For flavour universal models, nn gives the strongest constraints. For other flavour setups (e.g. MFV-RPV susy), dinucleon decays might be win

Pattern of B violation in SM(EFT)

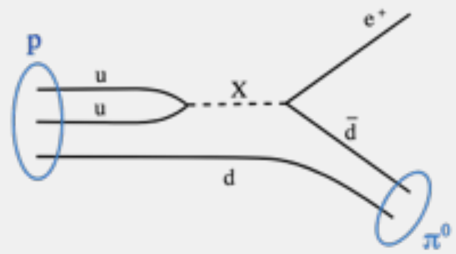
$\mathcal{L}$ =	$\mathcal{L}_{SM}$	+ dim-5	+ dim-6	+ dim-7	+ dim-8	+ dim-9 + …
allowed $(\Delta B, \Delta L)$	(0, 0)	**(0, 2)**	(0, 0), **(1, 1)**	(0, 2), (1, -1)	(0, 0), (1, 1)	**(2, 0)**, (1, -1), (0, 2), (1, 3)

A. Kobach '16

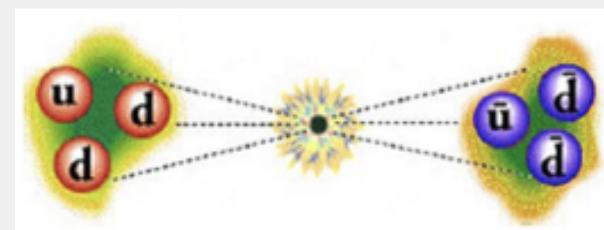
$0\nu\beta\beta$ decay



proton decays



neutron-antineutron oscillation

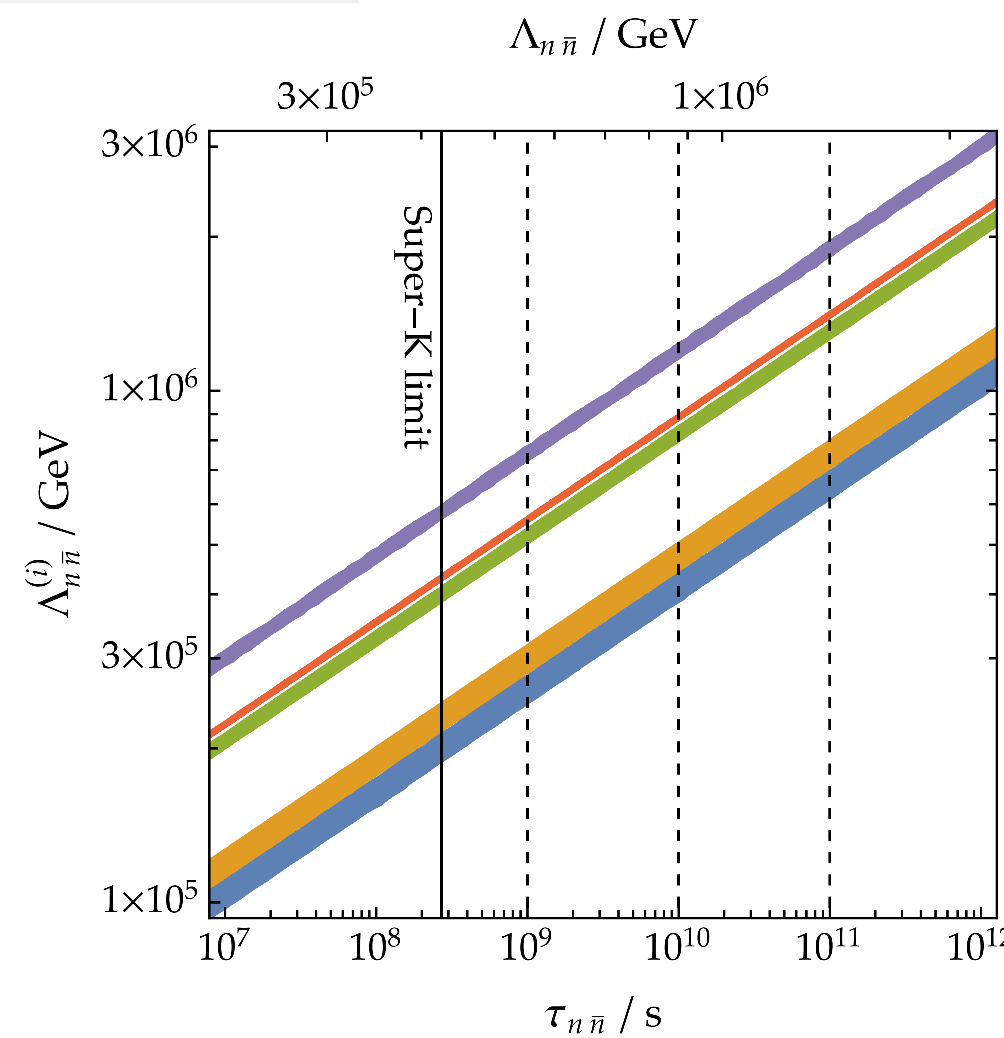


Slide stolen to Z. Zhang @ Pascos'18

12 operators (of the type 'uudddd')

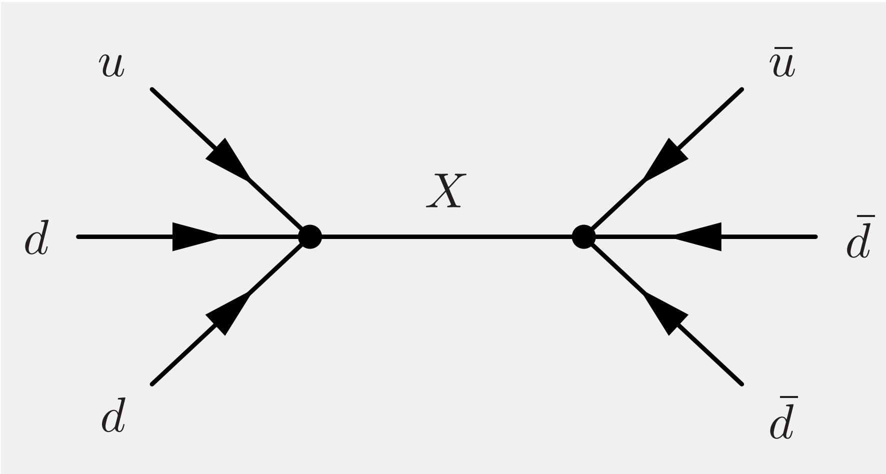
$$\tau_{n\bar{n}}^{-1} = \left|\langle \bar{n}|\mathcal{H}_{\rm eff}|n\rangle\right|$$

SuperK/ESS, DUNE is/will probe scales 10^5-10^6 GeV



$n\bar{n}$ oscillations and baryogenesis

Grojean, Shakya, Wells, Zhang '18



Mediator X

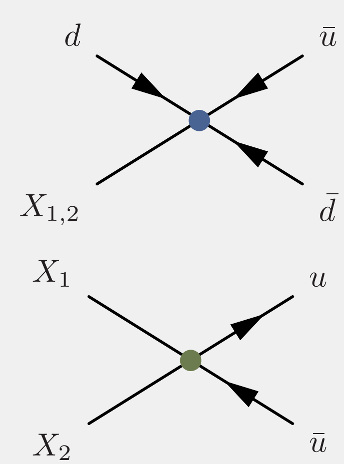
Single mediator X decays cannot generate a baryon asymmetry at leading order in the B violating coupling (Nanopoulos-Weinberg theorem '1979)

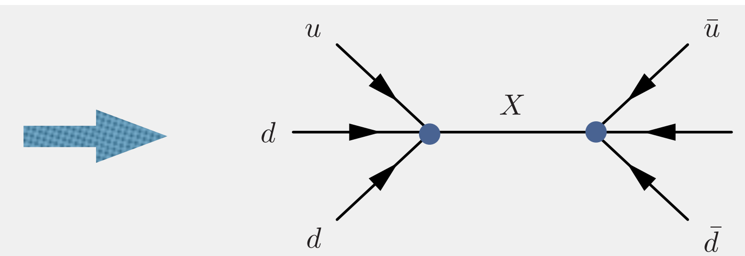
Two mediators X_1, X_2 ($M_{X1}<M_{X2}$)

$$\begin{aligned}\mathcal{L} \supset\ & \eta_{X_1}\, \epsilon^{ijk}(\bar{u}_i^c P_R d_j)(\bar{d}_k^c P_R X_1) \\ & + \eta_{X_2}\, \epsilon^{ijk}(\bar{u}_i^c P_R d_j)(\bar{d}_k^c P_R X_2) \\ & + \eta_c\, (\bar{u}^i P_L X_1)(\bar{X}_2 P_R u_i) + \text{h.c.}\end{aligned}$$

$$|\eta_{X_1}| \equiv \Lambda_{X_1}^{-2}\,,\ |\eta_{X_2}| \equiv \Lambda_{X_2}^{-2}\,,\ |\eta_c| \equiv \Lambda_c^{-2}\,.$$

- 2 *B-violating* operators
- 1 *B-conserving* operator





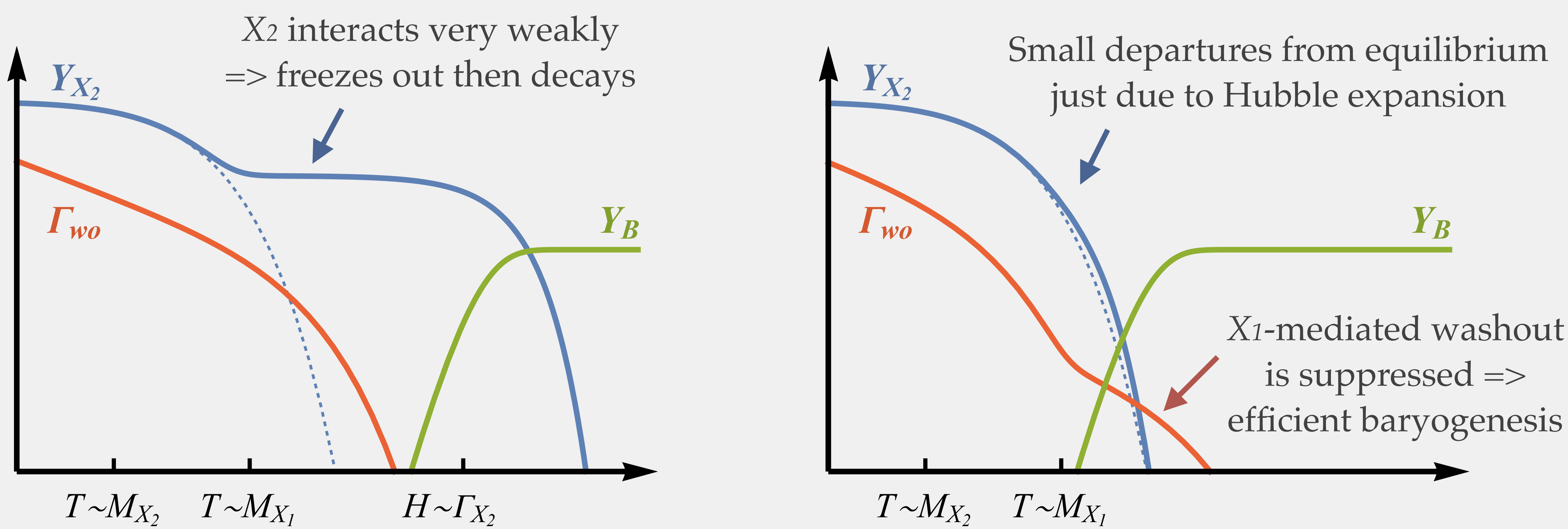
$$c_1 = \frac{1}{(\Lambda_{n\bar{n}}^{(1)})^5} = \frac{1}{M_{X_1}\Lambda_{X_1}^4} + \frac{1}{M_{X_2}\Lambda_{X_2}^4}$$

Two mediators with both B and $\cancel{B}$ couplings are enough to evade Nanopoulos-Weinberg

Baryogenesis

Grojean, Shakya, Wells, Zhang '18

Late decay scenario	Early decay scenario
$\Lambda_{X_2} \sim \Lambda_c \gg \Lambda_{X_1}$	$\Lambda_{X_1} \gg \Lambda_{X_2} \gtrsim \Lambda_c$



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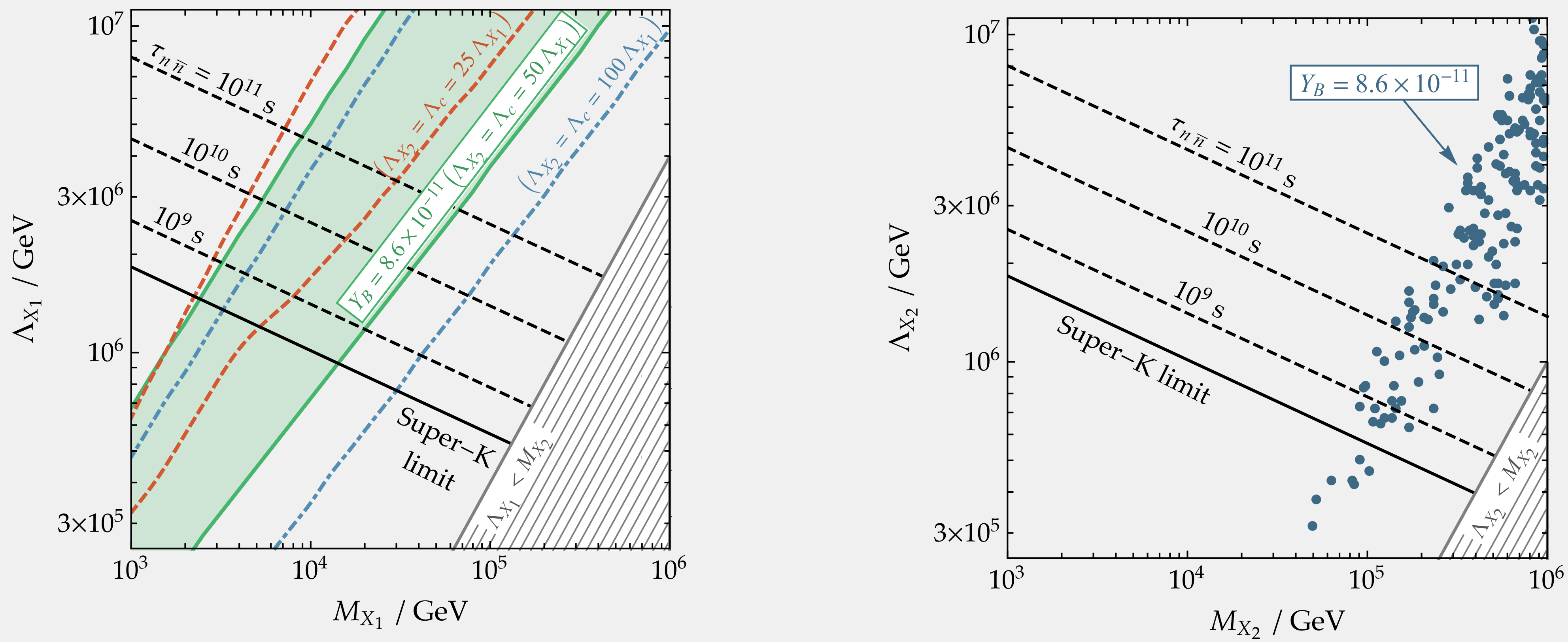


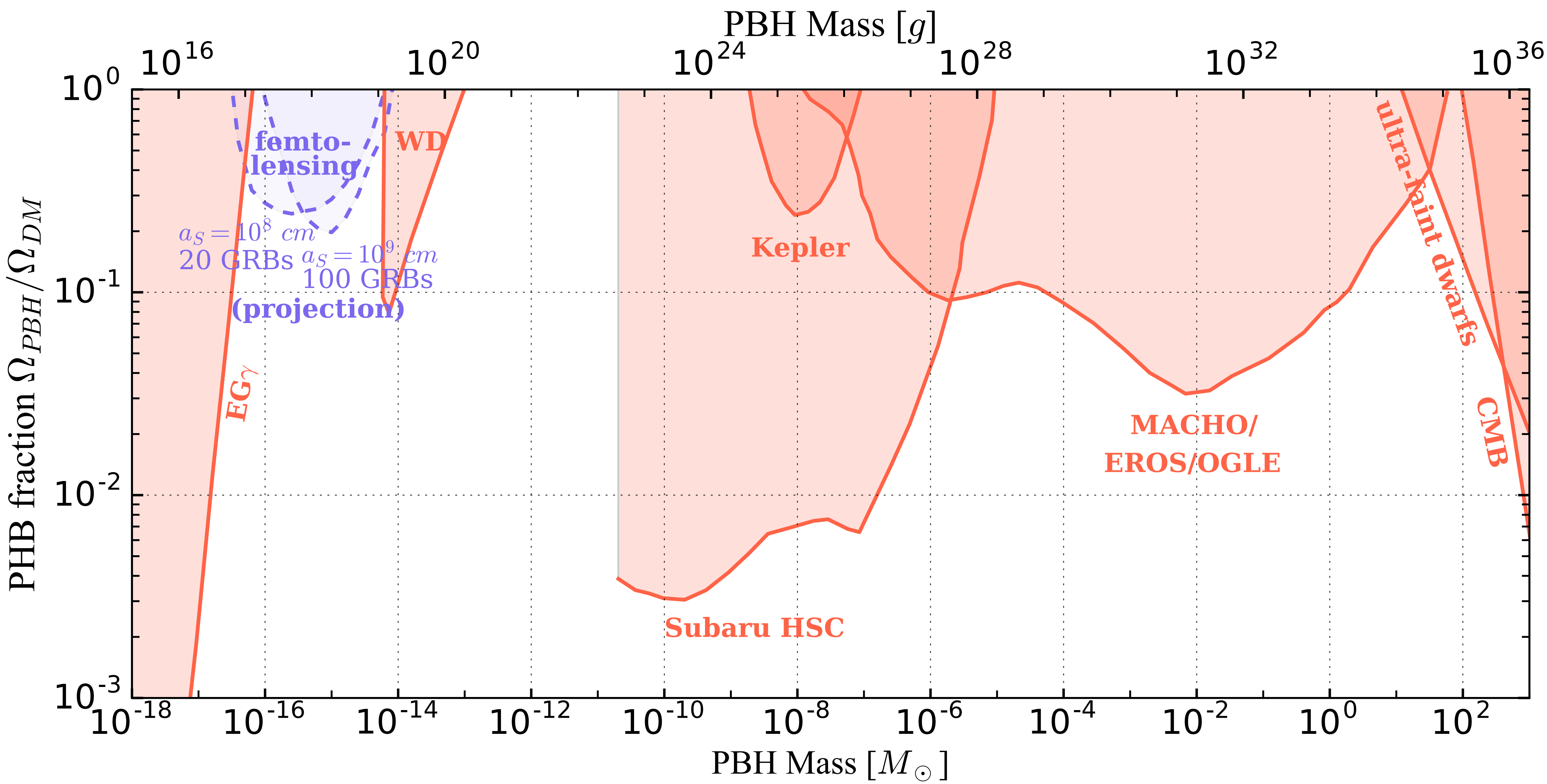
Explicit realisation of late decay scenario:
RPV SUSY with late decays of the bino in presence of a wino/gluino
[F.Rompineve, 1310.0840] [Y.Cui, 1309.2952] [G.Arcadi, L.Covi, M.Nardecchia, 1507.05584]

$n\bar{n}$ oscillations can probe direct baryogenesis scenarios @ $10^{5\text{-}6}$ GeV

Searching for a black moon

PBHs as DM

$$t_{\text{evaporation}} > 10^{64} \left(\frac{M_{BH}}{M_\odot}\right)^3 \text{ year} \quad \Rightarrow \quad M_{PBH} > 10^{-17} M_\odot$$



Katz+ 1807.11495

PBH abundance

Production of PBH is still subject to research and debates (gravitational collapse of large over-densities during inflation? Topological defects?...)

JR Espinosa @ Benasque 2018

$$\rho_{DM} \sim 0.3\,\mathrm{GeV/cm^3} \sim 10^{-15} M_\odot / V_{\text{Solar system}}$$

If

$$M_{\text{PBH}}\ 10^{-16} M_\odot,\ \text{i.e.,}\ R_{\text{Sch}}\ 10^{-13}\,\mathrm{cm}$$

We expect a few in the Solar system

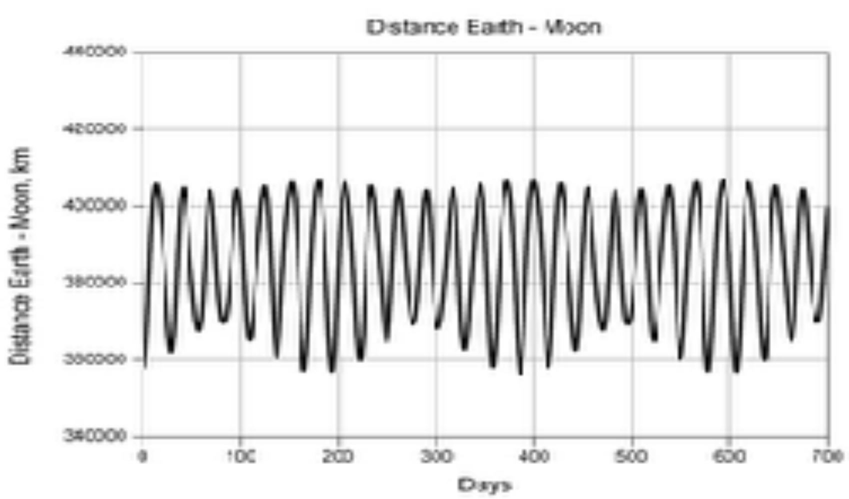
How can we detect such PBHs living in the Solar system?

A PBH orbiting around Earth

Grojean, Ruderman et al, in progress

Is there a black moon around Earth and interacting only gravitationally?

A black moon between the Earth and the Moon will induce a variation of the distance Earth-Moon, which is measured with an accuracy of 1mm (10^{-11} relative accuracy)



$$\Delta d_{\oplus-\circ} = \frac{d_{\oplus-\mathrm{PBH}} M_{\mathrm{PBH}}}{M_\oplus}$$

numerically

$$1\,\mathrm{mm} = \frac{1000\,\mathrm{km} \times 10^{-16} M_\odot}{M_\oplus}$$

A PBH orbiting around Earth

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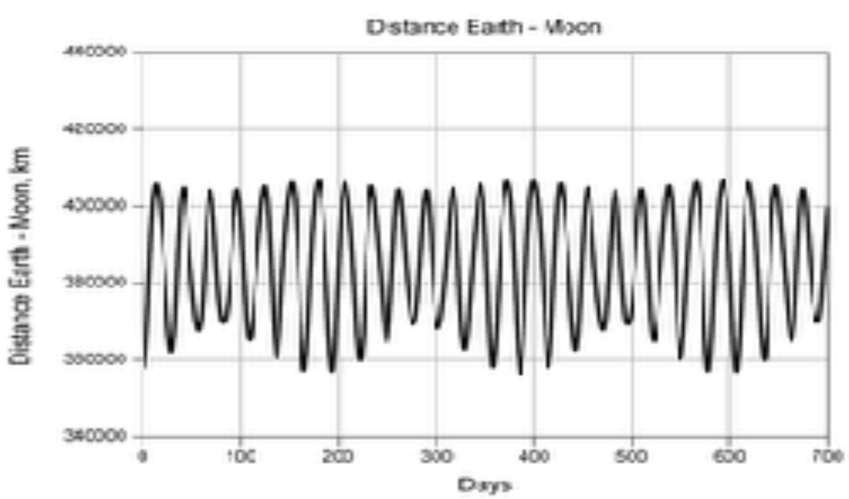

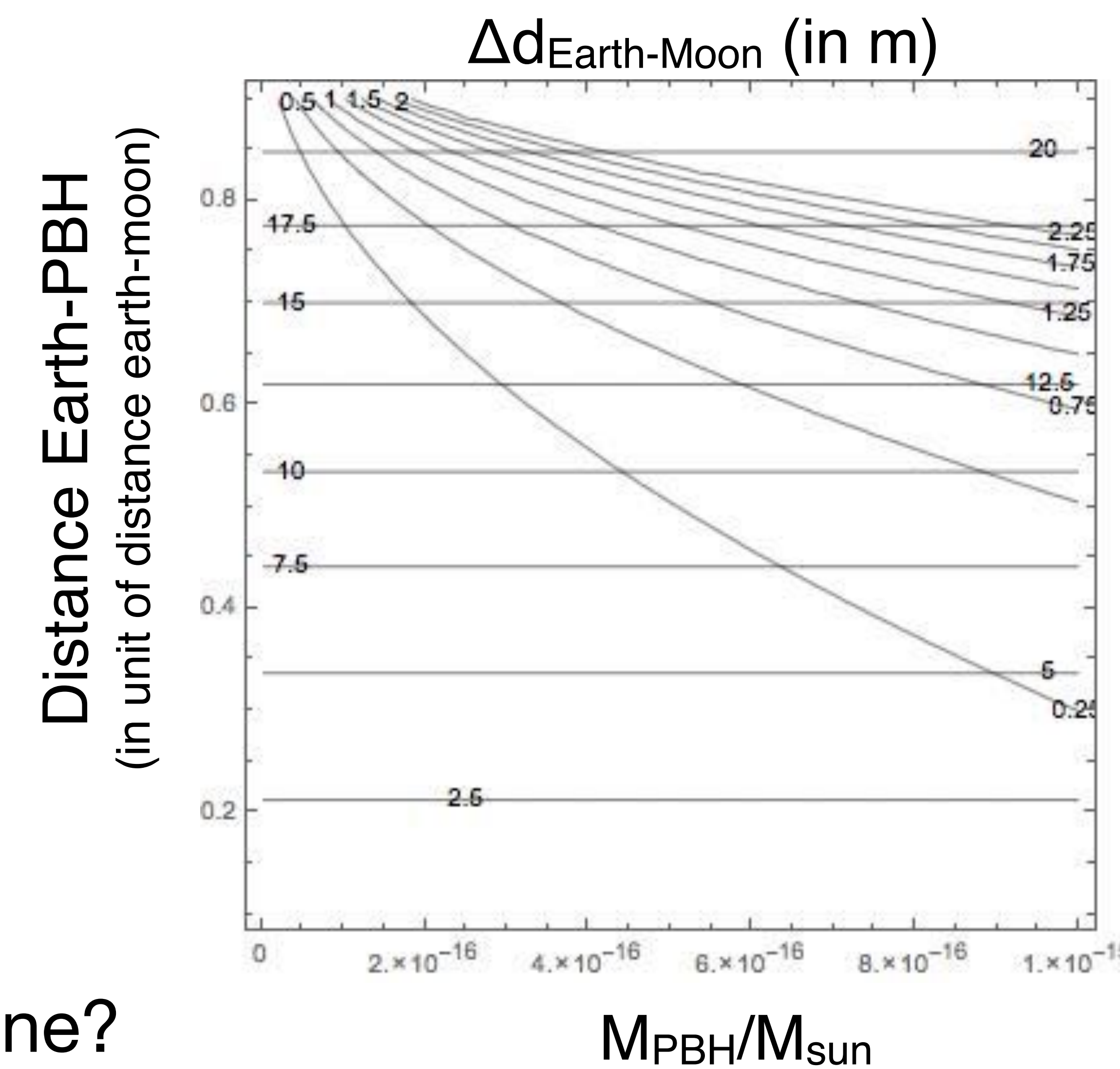

Can also use GPS measurements…
Looking for a black moon with your cell-phone?

Conclusion(s)

Executive summary on status of BSM

BAD NEWS

Experimentalists haven’t found (yet)
what theorists told them they will find

GOOD NEWS

There are rich opportunities
for mind-boggling signatures
@ colliders and beyond

Sailing to India with the right tool...

Once upon a time...

Columbus had a great proposal: "reaching India by sailing towards the West"

He had a theoretical model

- the Earth is round,
- Eratosthenes of Cyrene first estimated its circumference to be 250'000 stadia
- other measurements later found smaller values ☞Toscanelli's map
- lost in unit-conversion or misled by post-truth statements, Columbus thought it was only 70'000 stadia, so he believed he could reach India in 4 weeks

He had the right technology

- Caravels were the only ships at that time to sail against the wind, necessary tool to fight the prevailing winds, aka Alizée. Actually, the Vikings had the right technology too but the knowledge was lost

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His proposal was scientifically rejected twice (by Portuguese's & Salamanca U.)
by the decision was overruled by Isabel ... and America became great (already)

Moral(s)

"if your proposal is rejected, submit it again"

"you need the right technology to beat your competitors"

"theorists don't need to be right!
but progress needs theoretical models to motivate exploration"

Knowledge is power

B. Clinton, Davos 2011

ippog.web.cern.ch/resources/2011/bill-clinton-davos-2011

Homework:
imagine what the current US president could say about science and HEP

Thank you for your attention.
Good luck for your studies!

if you have question/want to know more

do not hesitate to send me an email

christophe.grojean@desy.de