BSM – LECTURE 1

TALLER DE ALTAS ENERGÍAS (TAE) 2024

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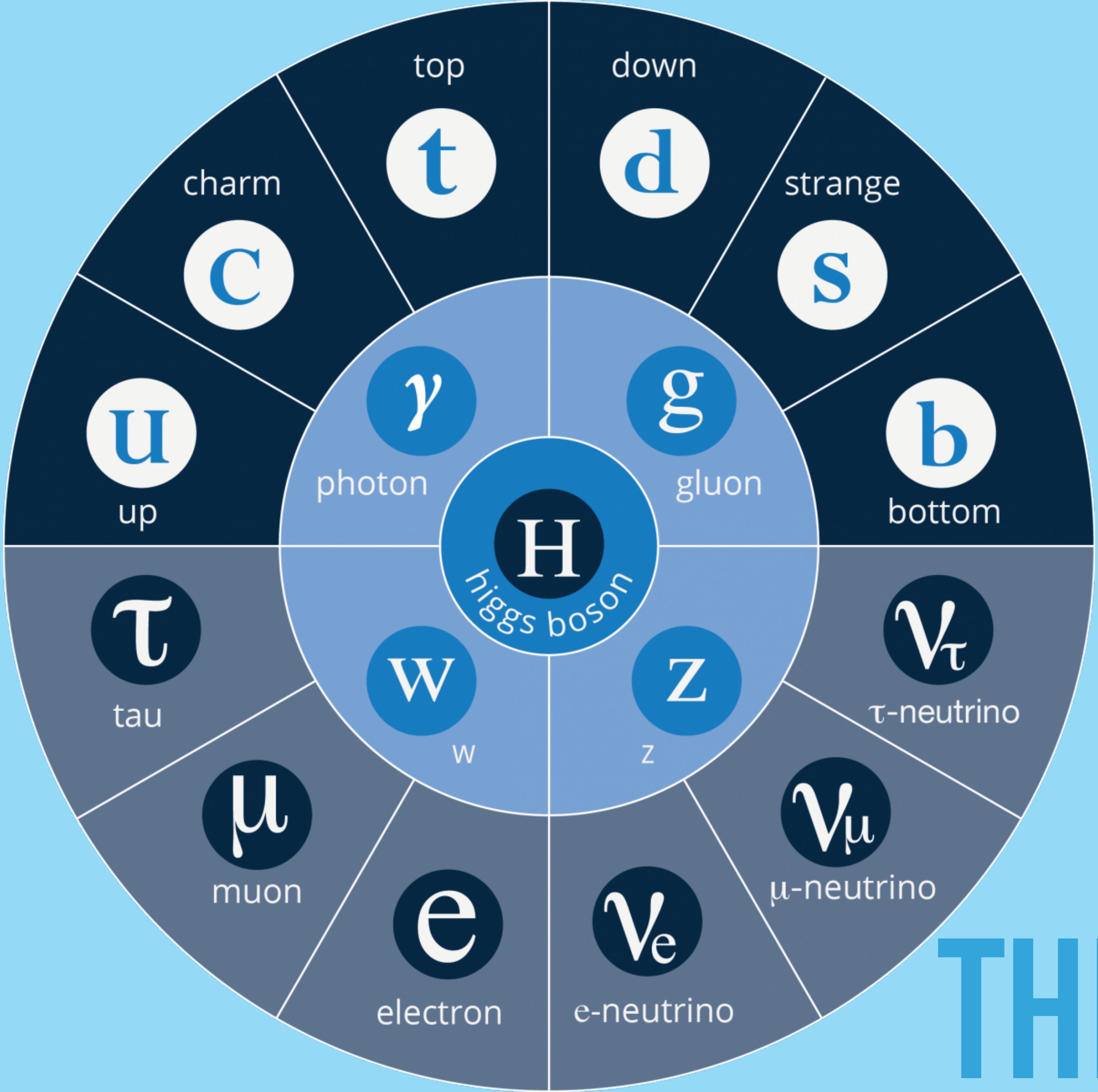
UNIVERSIDAD DE GRANADA

WHY?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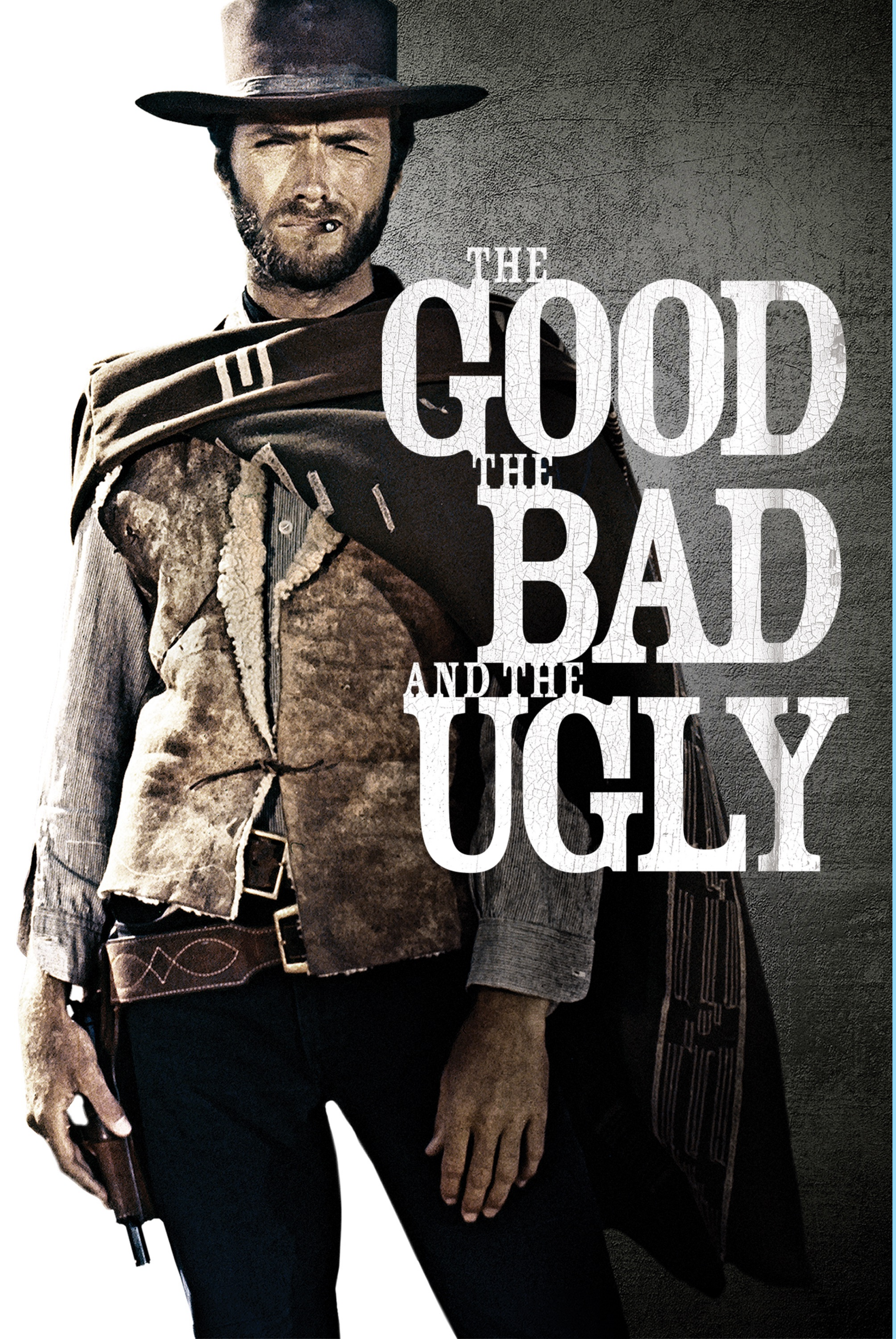
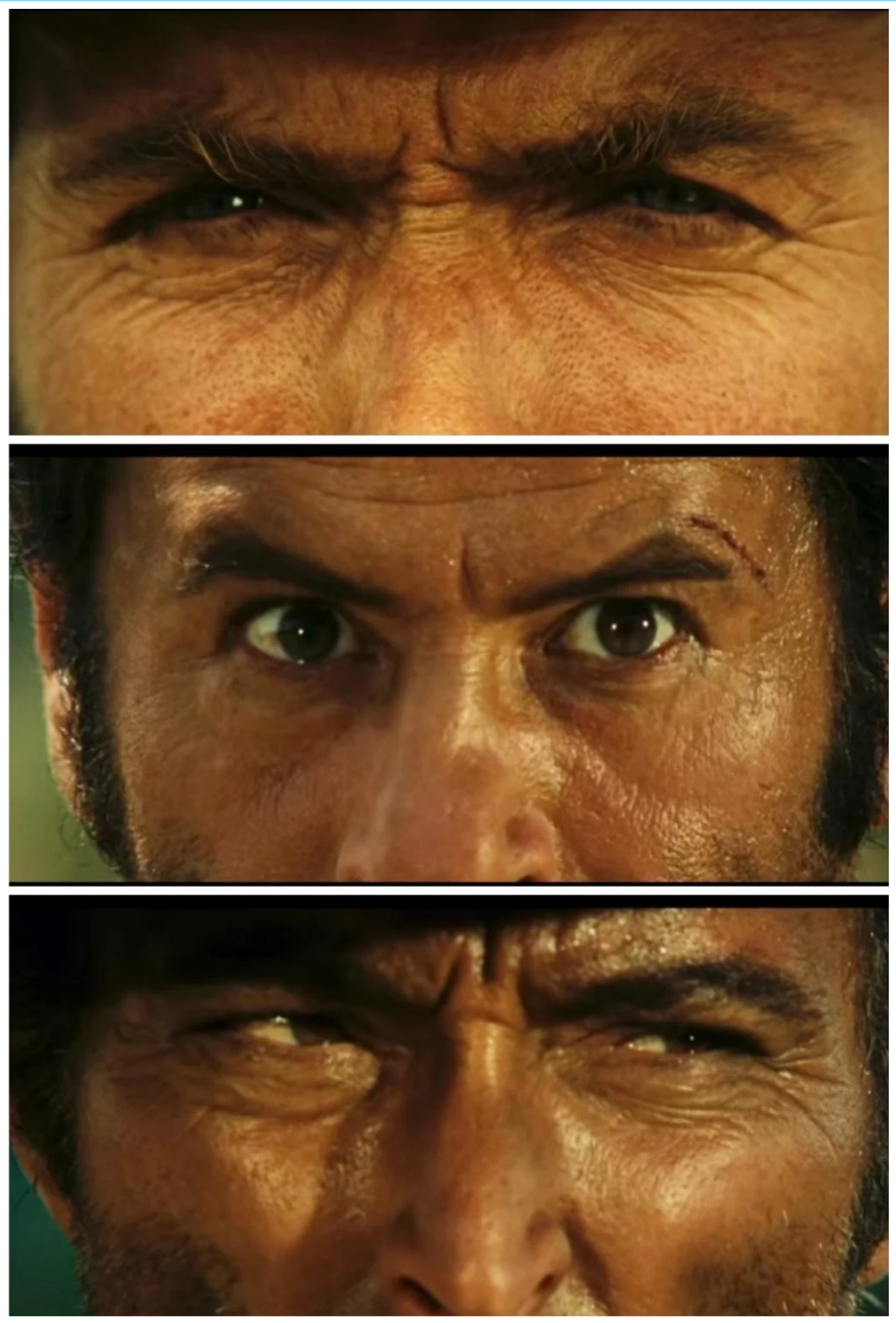
THE SM





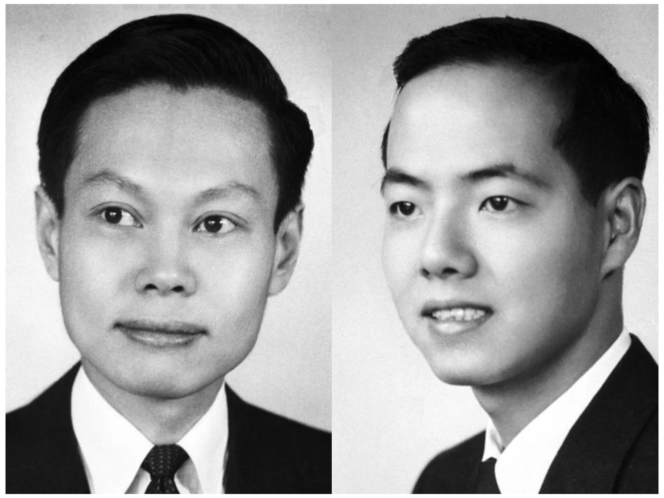
ABOUT THE STANDARD MODEL

THE GOOD

THE STANDARD MODEL. THE GOOD.

- The Standard Model (SM) of particle physics explains nature to very short distances.
- It is a local quantum field theory (QFT)
  - Renormalizable (operators up to mass dimension 4)
  - Based on the gauged global symmetry $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
  - With three families of chiral fermions $q_L^i, u_R^i, d_R^i, \ell_L^i, e_R^i$
  - And the spontaneous symmetry breaking $SU(2)_L \otimes U(1)_Y \to U(1)_Q$
- In July 2012, the last missing piece was discovered at CERN: the Higgs boson. Englert and Higgs got the nobel prize for it!

THE STANDARD MODEL. THE GOOD.



1956 – WU EXPERIMENT
– PARITY VIOLATION

1957 – YANG, LEE

1949 – QED

1965 – TOMONAGA, SCHWINGER, FEYNMANN

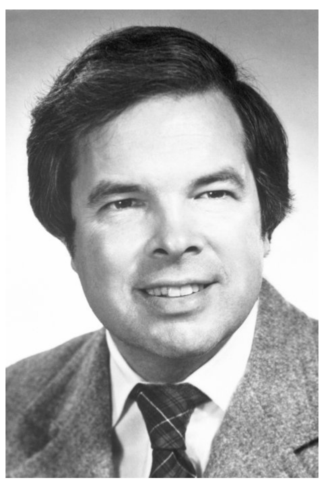
1967 – EW
THEORY

1979 – GLASHOW, SALAM, WEINBERG

THE STANDARD MODEL. THE GOOD.

1971/2- RENORMALIZATION OF YANG-MILLS THEORIES

1999 – T 'HOOFT, VELTMAN



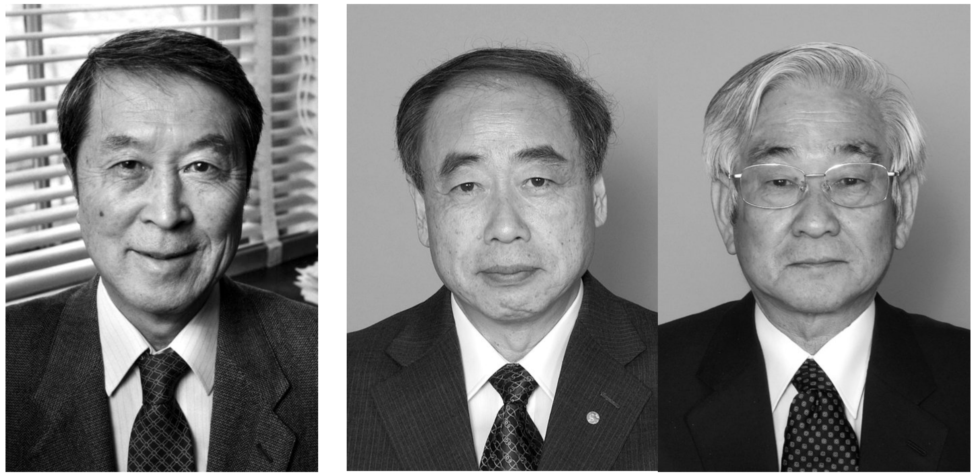
71, 75 – RENORMALIZATION GROUP

1982 – WILSON

1973 – QCD

2004 – GROSS, POLITZER, WILCZEK

THE STANDARD MODEL. THE GOOD.



1960 – SPONTANEOUS SYMMETRY BREAKING

1973 – THREE FAMILIES AND CP VIOLATION

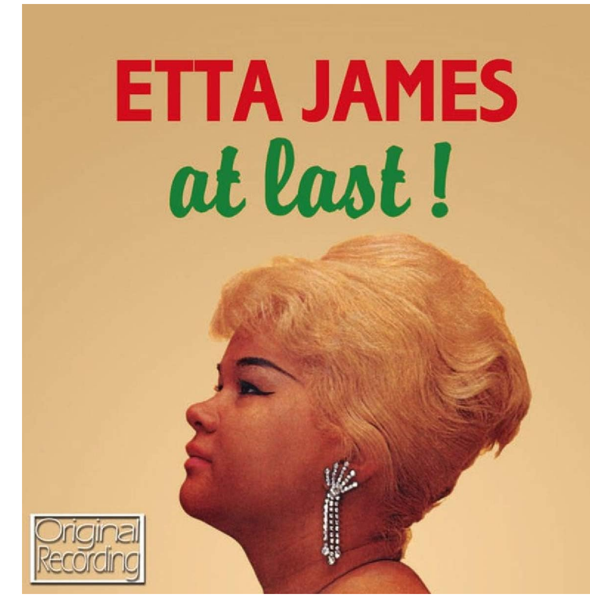
2008 – NAMBU, KOBAYASHI, MASKAWA

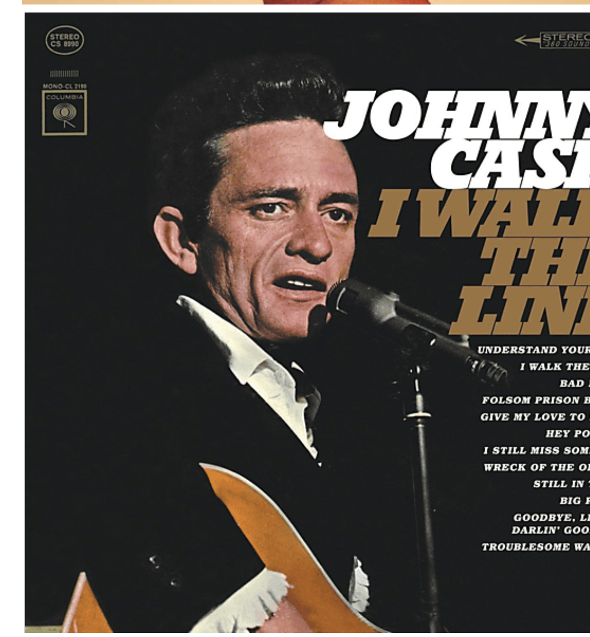
1964 – HIGGS MECHANISM

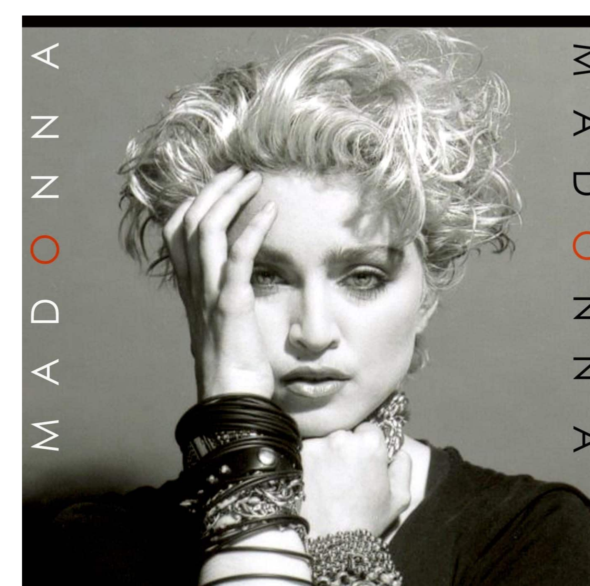
2013 – ENGLERT, HIGGS

1983 – DISCOVERY OF THE W AND Z

1984 – RUBBIA, VAN DER MEER

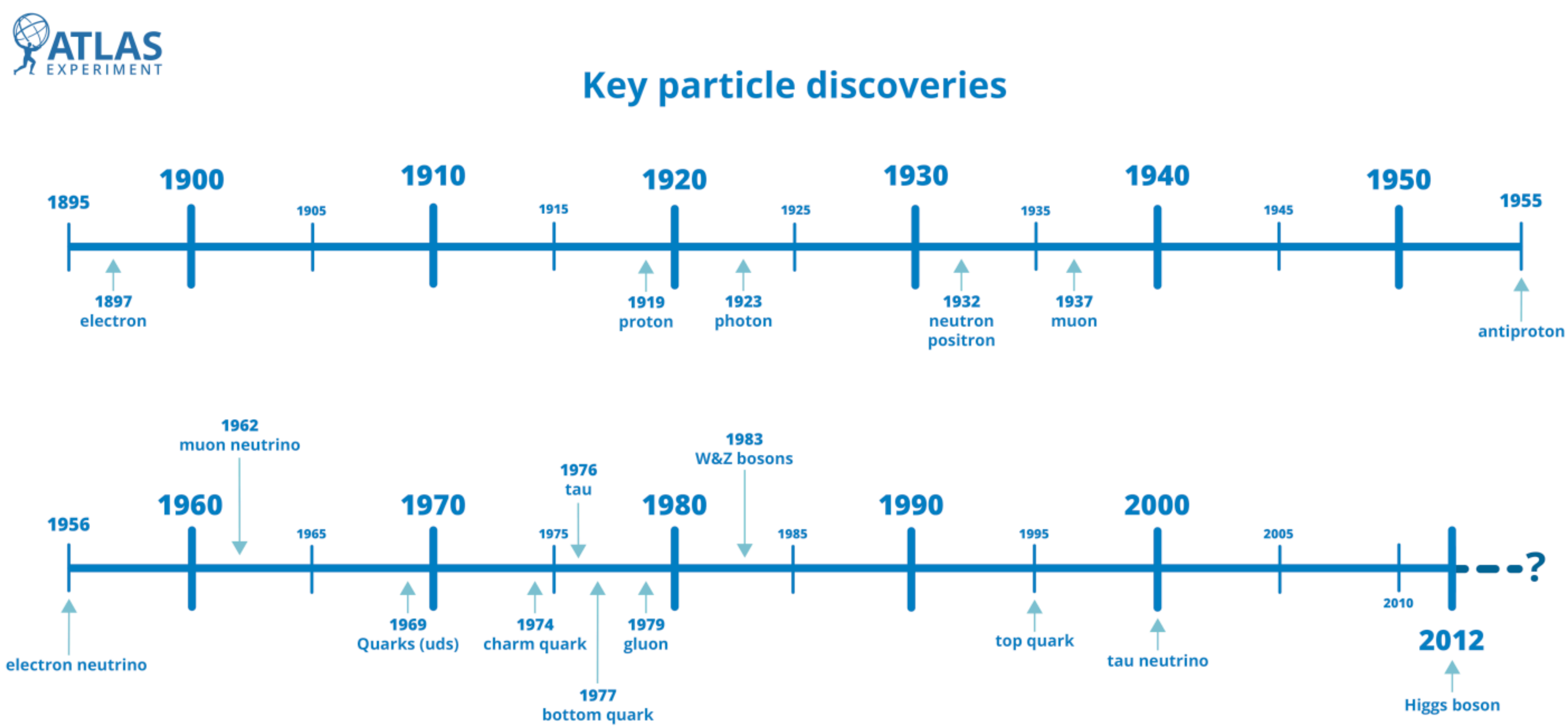






THE STANDARD MODEL. THE GOOD.

- The SM has been confirmed experimentally by a plethora of experimental data (LEP, LEP II, Tevatron, LHC, …)
- There is currently no serious anomaly that the SM fails to accommodate



THE STANDARD MODEL

THE BAD

THE STANDARD MODEL. THE BAD.

There are several observed phenomena which can not be explained within the SM. More explicitly:

- Neutrino oscillations
- Dark Matter
- Matter – antimatter asymmetry

This is not a matter of taste. These are experimental facts that can not be reproduced in the SM. This is terrible, I assure you.

THE STANDARD MODEL

THE UGLY

THE STANDARD MODEL. THE UGLY.

There are several SM ‘features’ which are kind of ugly:

1. It features an elementary scalar. This is weird (as hell) and has never been seen before.

	dof $m=0$	dof $m\neq 0$
scalar	1	1
fermion	2	4
vector	2	3

This is also known as the hierarchy problem. An elementary scalar is quadratically sensitive to mass thresholds.

Other way to put it would be: *why is the scale of gravity so much weaker than the electroweak scale?*

THE STANDARD MODEL. THE UGLY.

Let us consider the following toy model

$$\mathscr{L} = \frac{1}{2}(\partial_\mu \phi)^2 + \frac{1}{2}(\partial_\mu \Phi)^2 + \bar{\psi} i \partial\!\!\!/ \psi - \frac{1}{2} m_\phi^2 \phi^2 - \frac{1}{2} m_\Phi^2 \Phi^2 - m_\psi \bar{\psi}\psi$$

$$-\frac{1}{4}\lambda \phi^2 \Phi^2 - y_\phi \phi \bar{\psi}\psi - y_\Phi \Phi \bar{\psi}\psi$$

If we compute the one-loop corrections to m_ϕ^2 in dimrec @ MSbar

$$\delta m_\phi^2 \Big|_\psi = \frac{y_\phi^2}{4\pi^2} m_\psi^2 \left[1 - 3 \log\left(\frac{m_\psi^2}{\mu^2} \right) + \mathcal{O}\left(m_\phi^2 / m_\psi^2 \right) \right]$$

$$\delta m_\phi^2 \Big|_\Phi = -\frac{\lambda}{32\pi^2} m_\Phi^2 \left[1 - \log\left(\frac{m_\Phi^2}{\mu^2} \right) \right]$$

THE STANDARD MODEL. THE UGLY.

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$$-\frac{1}{4}\lambda \phi^2 \Phi^2 - y_\phi \phi \bar{\psi}\psi - y_\Phi \Phi \bar{\psi}\psi$$

Let us now compute the correction to the fermion mass m_ψ

$$\delta m_\psi = m_\psi \left[\frac{5}{4} - \frac{3}{2} \log\left(\frac{m_\Phi^2}{\mu^2} \right) + \mathcal{O}(m_\psi^2 / m_\Phi^2) \right] + (\Phi \to \phi)$$

This is VERY different, because the corrections to the fermion mass are proportional to the fermion mass itself

THE STANDARD MODEL. THE UGLY.

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$$\mathscr{L} = \frac{1}{2}(\partial_\mu \phi)^2 + \frac{1}{2}(\partial_\mu \Phi)^2 + \bar{\psi} i \partial\!\!\!/ \psi - \frac{1}{2} m_\phi^2 \phi^2 - \frac{1}{2} m_\Phi^2 \Phi^2 - m_\psi \bar{\psi}\psi$$

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I TOLD YOU THAT THIS WAS WEIRD!

This is related to the notion of technical naturalness:

A small value of a dimensionless parameter is said to be technically natural, if the symmetry of the theory is enhanced when the parameter goes to zero

Let us check-it with the fermion masses.

$$\mathscr{L} = \bar{\psi}_R i\partial\!\!\!/ \psi_R + \bar{\psi}_L i\partial\!\!\!/ \psi_L - \left[m\bar{\psi}_L \psi_R + \mathrm{h.c.} \right]$$

The theory is invariant under a global $U(1)_{L+R} \quad \psi_L \to e^{i\alpha}\psi_L, \quad \psi_R \to e^{i\alpha}\psi_R.$

However, in the massless case both rotations can be made independent $\psi_L \to e^{i\alpha_L}\psi_L, \quad \psi_R \to e^{i\alpha_R}\psi_R$. The symmetry is now $U(1)_L \otimes U(1)_R$

So, fermion masses are technically natural!

THE STANDARD MODEL. THE UGLY.

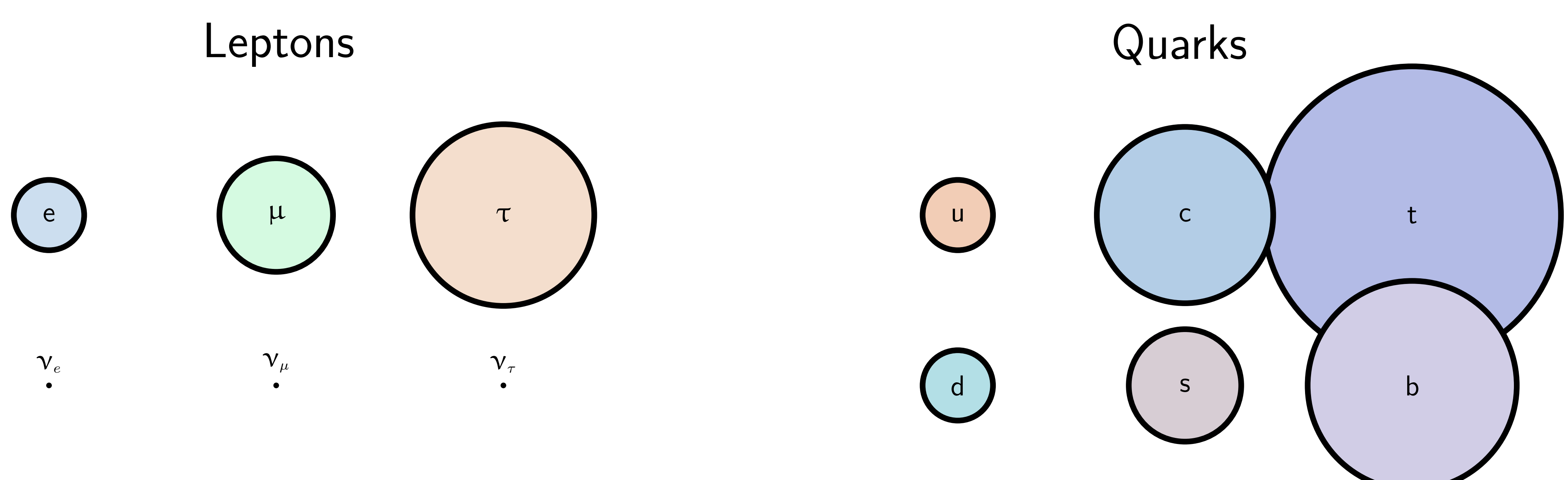
There are several SM 'features' which are kind of ugly:

2. It has another tiny parameter which is not technically natural neither:

$$\mathscr{L} \supset \frac{g_s \bar{\theta}}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \text{ where } |\bar{\theta}| \lesssim 10^{-10}$$

This is called the strong CP-problem.

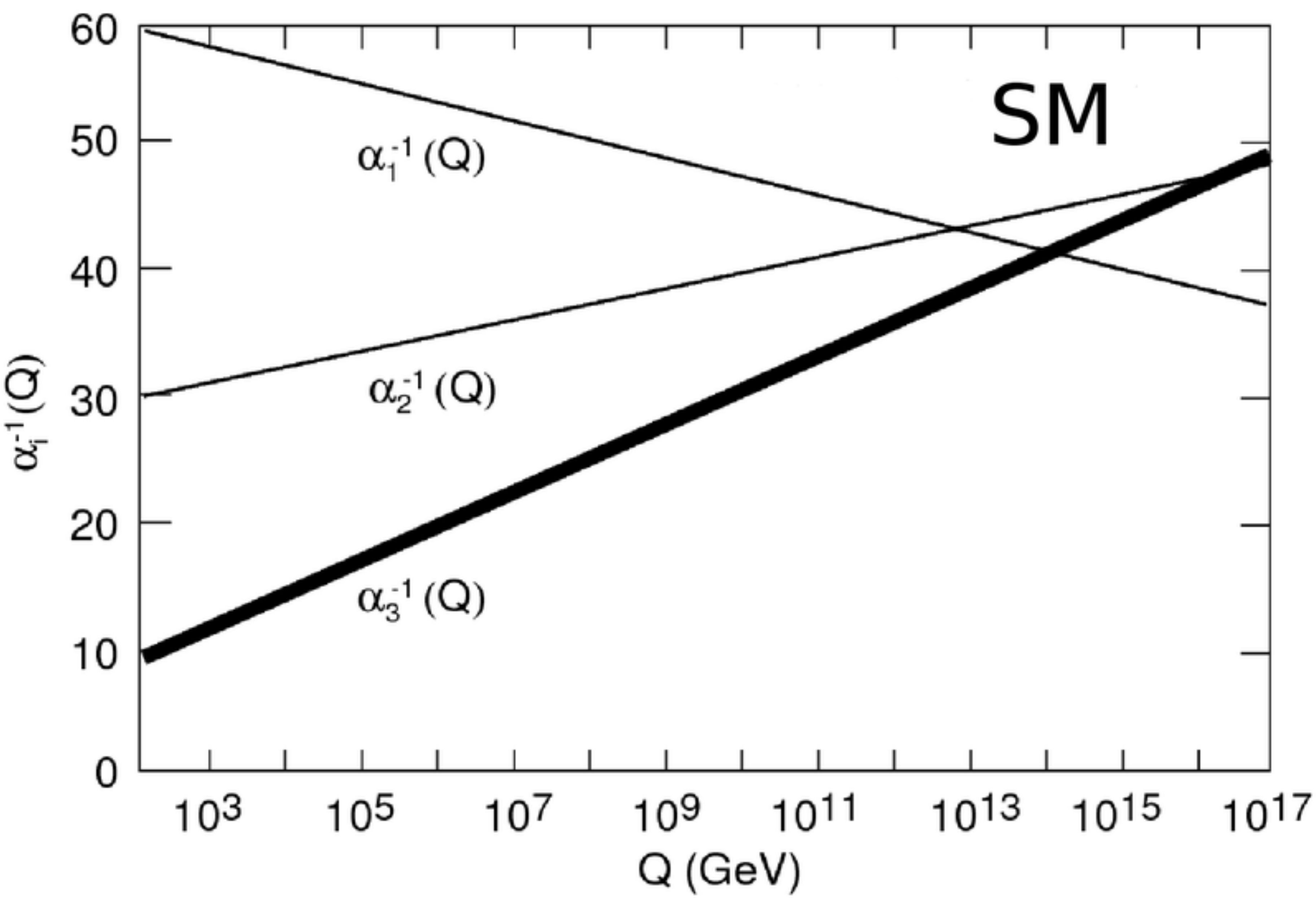
3. Although technically natural, we do not know why the fermion masses span so many orders of magnitude and why the quark masses and mixing angles are so hierarchical (the flavor puzzle)



THE STANDARD MODEL. THE UGLY.

There are several SM ‘features’ which are kind of ugly:

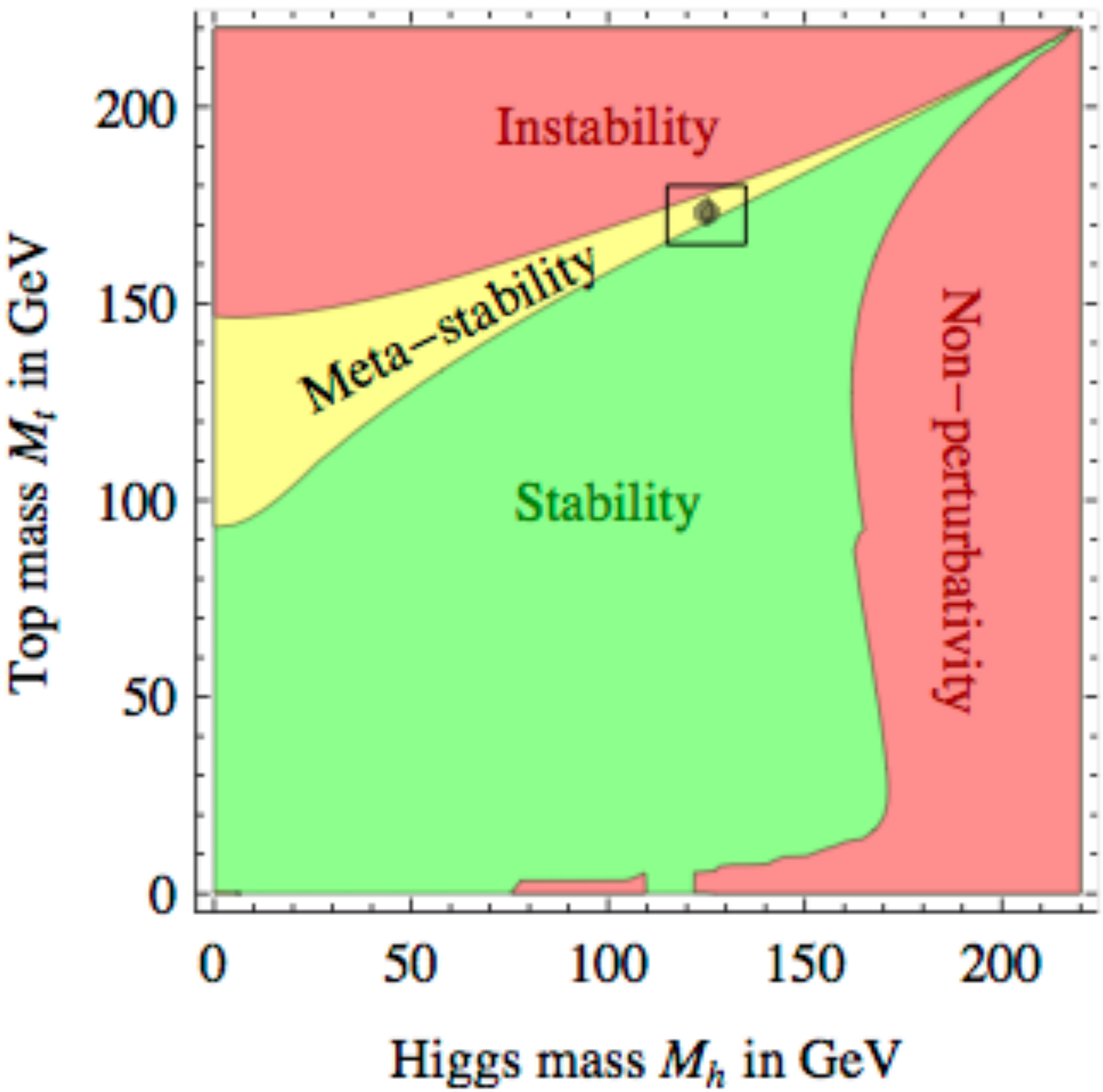
4. The SM hints to some gauge unification at higher energies



THE STANDARD MODEL. THE UGLY.

There are several SM 'features' which are kind of ugly:

5. The vacuum of the universe seems to be meta-stable



WHY?

SM

BSM

SM

GOOD OLD DAYS

BSM

SM

NOWDAYS **BSM**

SM

HOW I
SEE IT

BSM

HOW?

BEYOND THE STANDARD MODEL

Going beyond the SM implies doing any of these things:

1. Changing the matter content (aka ‘adding new particles’)
2. Enlarging the gauge group (aka ‘adding new interactions’)
3. Adding operators with mass dimension bigger than four (aka ‘let’s not care about renormalizability’)

Model builders typically do #1 and/or #2. Other approach is just go for the #3 the SMEFT.

NEW THEORIES

SMEFT

BEYOND THE STANDARD MODEL. AN EXAMPLE.

Let us consider e.g. neutrino oscillations. One easy way to explain neutrino oscillations is via neutrino masses.

However, in the SM we only have LH neutrinos in $\ell_L^i = (\nu_L^i, e_L^i)^T$.

- With just one Weyl spinor we can just build Majorana masses but with the fields and the symmetries of the SM we need to go to (mass) dim 5

$$\mathscr{L} \supset \frac{c_{ij}}{M_N}(\bar{\ell}_L^i \tilde{H})(\tilde{H}^\dagger \ell_L^{jC}), \qquad \text{with} \qquad \tilde{H} = i\sigma_2 H^* \qquad (\#3)$$

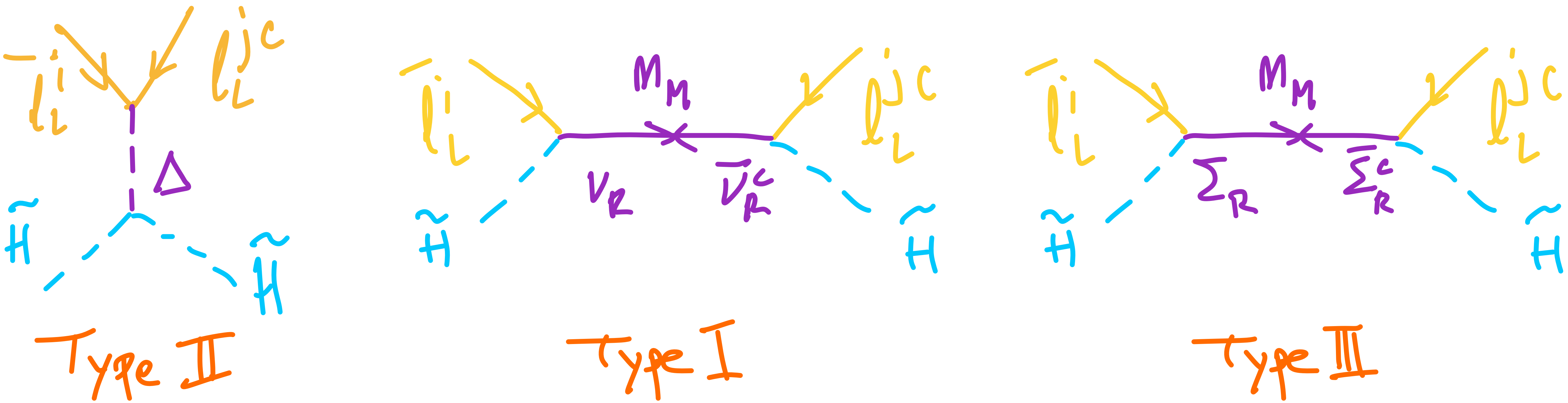
- If we want to generate such operator at tree-level with heavy fields (#1) we need to add heavy fermions or scalars. Since

$$\bar{\ell}_L^i \ell_L^{jC},\ \tilde{H}^\dagger \ell_L^{jC} \in \mathbf{2} \otimes \mathbf{2} = \mathbf{1} \oplus \mathbf{3}$$

we can add a singlet or a triplet.

BEYOND THE STANDARD MODEL. AN EXAMPLE.

$\bar{\ell}^i_L \ell^{jC}_L,\ \tilde{H}^\dagger \ell^{jC}_L \in \mathbf{2} \otimes \mathbf{2} = \mathbf{1} \oplus \mathbf{3}.$ We should add a singlet or a triplet:



- Singlet. We can add RH neutrinos which are full singlets of the SM $\mathscr{L} \supset -\left[(y_D)_{ij}\bar{\ell}^i_L \tilde{H} \nu^j_R + \mathrm{h.c.}\right] - \frac{1}{2}(m_M)^{ij}\bar{\nu}^{iC}_R \nu^j_R$ which leads after EWSB to $\mathscr{L} \supset -\frac{1}{2}\bar{N}_L \mathscr{M} N^C_L$ where $N_L = (\nu_L, \nu^C_R)^T$, $\mathscr{M} = \begin{pmatrix} 0 & m_D \\ m_D^T & m_M \end{pmatrix}$, $m_D = \frac{v}{\sqrt{2}} y_D$. If we assume that $m_M \gg m_D$ we get the type-I seesaw.

- Triplet. We can add a scalar or a fermion triplet (type-II or III seesaw)

BEYOND THE STANDARD MODEL

- We just saw that the EFT approach can be complementary to the model building one. It gives you insights about what to do.
- Some UV theories are not renormalizable neither.
- Specific UV models will lead to correlations between Wilson coefficients.
- The EFT approach can be useful to know if a model is viable quickly.

BEYOND THE SM

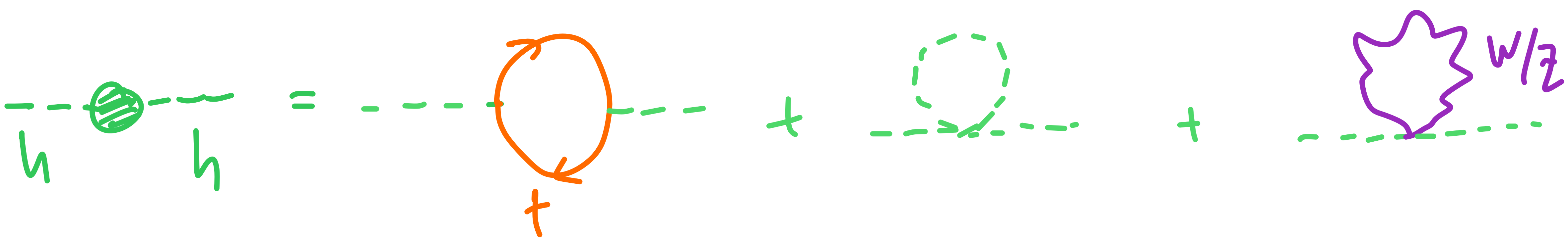
BEYOND THE UGLY

THE HIERARCHY PROBLEM

Let us come back to the hierarchy problem for a while. Let us consider

$$\mathscr{L} = |D_\mu H|^2 - V(H) - \left[y_t \bar{q}_L H t_R + \mathrm{h.c.}\right], \quad \text{with } V(H) = -\mu^2 |H|^2 + \lambda |H|^4,$$

and $H = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\phi^+ \\ v + h + i\phi^0 \end{pmatrix}$.



We will compute the top contributions as an exercise

$$-i\,\delta m_h^2\Big|_{\mathrm{top}} = (-1)N_c \int \frac{d^4k}{(2\pi)^4} \mathrm{Tr}\left[\left(-i\frac{y_t}{\sqrt{2}}\right)\frac{i}{\not{k} - m_t}\left(-i\frac{y_t}{\sqrt{2}}\right)\frac{i}{\not{k} - m_t}\right] = (-1)N_c \frac{y_t^2}{2}\int \frac{d^4k}{(2\pi)^4}\mathrm{Tr}\left[\frac{(\not{k}+m_t)(\not{k}+m_t)}{(k^2 - m_t^2)^2}\right] = -2N_c y_t^2 \int \frac{d^4k}{(2\pi)^4}\left[\frac{k^2 + m_t^2}{(k^2 - m_t^2)^2}\right]$$

After performing a Wick rotation $k_0 = ik_E^0, \mathbf{k} = \mathbf{k}_E, k^2 = -k_E^2$ the above integral becomes

$$-i\,\delta m_h^2\Big|_{\mathrm{top}} = 2iN_c y_t^2 \int d\Omega \int_0^\infty \frac{dk_E}{(2\pi)^4} k_E^3 \left[\frac{k_E^2 - m_t^2}{(k_E^2 + m_t^2)^2}\right] = 2iN_c y_t^2\,(2\pi^2)\int_0^\infty \frac{dk_E^2}{2(2\pi)^4} k_E^2 \left[\frac{k_E^2 - m_t^2}{(k_E^2 + m_t^2)^2}\right]$$

THE HIERARCHY PROBLEM

After simplifying and setting a hard cut-off Λ, we get

$$-i\,\delta m_h^2\Big|_{\text{top}} = \frac{iN_c y_t^2}{8\pi^2}\int_0^{\Lambda^2} dk_E^2 \left[\frac{k_E^2(k_E^2 - m_t^2)}{(k_E^2 + m_t^2)^2}\right]$$

Finally, changing variables to $x = k_E^2 + m_t^2$ results in

$$\delta m_h^2\Big|_{\text{top}} = -\frac{N_c y_t^2}{8\pi^2}\int_{m_t^2}^{\Lambda^2+m_t^2} dx\left(1 - \frac{3m_t^2}{x} + \frac{2m_t^4}{x^2}\right) = -\frac{N_c y_t^2}{8\pi^2}\left[\Lambda^2 - 3m_t^2\log\left(\frac{\Lambda^2 + m_t^2}{m_t^2}\right) + \frac{2m_t^2\Lambda^2}{m_t^2 + \Lambda^2}\right]$$

We still see that the Higgs mass is quadratically sensitive to the high scales.

Depending on the regulator used, the hierarchy problem will show up differently but it will always be there (for you).

Let me show you a possible solution.

Let us focus on the top contribution to the Higgs mass. Imagine that we have N scalars particles ϕ_L and ϕ_R with the following interactions

$$\mathscr{L} \supset -\frac{\lambda}{2}h^2(|\phi_L|^2 + |\phi_R|^2) - h\left(\mu_L|\phi_L|^2 + \mu_R|\phi_R|^2\right) - m_L^2|\phi_L|^2 - m_R^2|\phi_R|^2$$

We will get tadpole and bubble contributions. The tadpole correction reads:

$$-i\delta m_h^2\Big|^{\text{tad}} = (-i\lambda)\,N\sum_{X=L,R}\int\frac{d^4k}{(2\pi)^4}\frac{i}{k^2-m_X^2} = -\,i\lambda N\sum_{X=L,R}\int\frac{d^4k_E}{(2\pi)^4}\frac{1}{k_E^2+m_X^2}$$

$$= -\,i\lambda N(2\pi^2)\sum_{X=L,R}\int_0^{\Lambda^2}\frac{dk_E^2}{2(2\pi)^4}\frac{k_E^2}{k_E^2+m_X^2} = -\,i\lambda N\sum_{X=L,R}\frac{1}{(4\pi)^2}\int_{m_X^2}^{\Lambda^2+m_X^2}dx\left(1-\frac{m_X^2}{x}\right)$$

leading to

$$\delta m_h^2\Big|^{\text{tad}} = \lambda N\frac{1}{(4\pi)^2}\left[2\Lambda^2 - m_L^2\log\left(\frac{\Lambda^2+m_L^2}{m_L^2}\right) - m_R^2\log\left(\frac{\Lambda^2+m_R^2}{m_R^2}\right)\right]$$

On the other hand, the bubble correction leads to

$$\delta m_h^2\Big|_h^{\text{bubble}} = -N\frac{1}{(4\pi)^2}\left[\mu_L^2\log\left(\frac{\Lambda^2+m_L^2}{m_L^2}\right)+\mu_R^2\log\left(\frac{\Lambda^2+m_R^2}{m_R^2}\right)+\ldots\right].$$

Summing the contributions to the one of the top, we obtain

$$\delta m_h^2 = \frac{\Lambda^2}{16\pi^2}\left[-2N_c y_t^2 + 2N\lambda\right]$$

$$+\frac{1}{16\pi^2}\left[-N\left(\lambda m_L+\mu_L^2\right)\log\left(\frac{\Lambda^2+m_L^2}{m_L^2}\right)+(L\leftrightarrow R)+6Ny_t^2m_t^2\log\left(\frac{\Lambda^2+m_t^2}{m_t^2}\right)\right]+\ldots$$

- The quadratic piece vanishes if $N = N_c$ and $\lambda = y_t^2$
- The logarithmic piece vanishes if on top of that $m_L = m_R = m_t$ and $\mu_L = \mu_R = 2\lambda m_t$

THE HIERARCHY PROBLEM

We have just seen that

- The quadratic piece vanishes if $N = N_c$ and $\lambda = y_t^2$
- The logarithmic piece vanishes if on top of that $m_L = m_R = m_t$ and $\mu_L = \mu_R = 2\lambda m_t$

There is a symmetry that guarantees this to happen. It is called

We have just seen that

- The quadratic piece vanishes if $N = N_c$ and $\lambda = y_t^2$
- The logarithmic piece vanishes if on top of that $m_L = m_R = m_t$ and $\mu_L = \mu_R = 2\lambda m_t$

There is a symmetry that guarantees this to happen. It is called

SUPERSYMMETRY

Roughly speaking, supersymmetry relates fermions and bosons. These scalars are called stops (s - supersymmetric partner) and they appear from supermultiplets.

So we have just saw one way of solving the hierarchy problem: using symmetries.

SUPERSYMMETRY

Susie
Q
Creedence
Clearwater-Revival
Visadisc
M. 8 0 - 0 1 3

WEYL SPINORS. VAN DER WÆRDEN NOTATION

It will be useful to remind you of Weyl spinors. Let us introduce

$$\text{right}-\text{handed}: \quad \bar{\eta}^{\dot{\alpha}}, \quad \dot{\alpha}=1{,}2. \quad \text{left}-\text{handed}: \quad \chi_{\alpha}, \quad \alpha=1{,}2.$$

Lorentz scalars are build of $\chi^{\alpha}\xi_{\alpha}$ or $\bar{\psi}^{\dot{\alpha}}\bar{\eta}_{\dot{\alpha}}$ where

$\chi^{\alpha}=\varepsilon^{\alpha\beta}\chi_{\beta}, \quad \left(\chi_{\alpha}=\varepsilon_{\alpha\beta}\chi^{\beta}\right), \quad \bar{\psi}_{\dot{\alpha}}=\varepsilon_{\dot{\alpha}\dot{\beta}}\bar{\psi}^{\dot{\beta}}, \quad \left(\bar{\psi}^{\dot{\alpha}}=\varepsilon^{\dot{\alpha}\dot{\beta}}\bar{\psi}_{\dot{\beta}}\right),$ with

$$\varepsilon^{\alpha\beta}=-\varepsilon^{\beta\alpha}, \quad \varepsilon^{12}=-\varepsilon_{12}=1, \quad \varepsilon^{\dot{\alpha}\dot{\beta}}=-\varepsilon^{\dot{\beta}\dot{\alpha}}, \quad \varepsilon^{\dot{1}\dot{2}}=-\varepsilon_{\dot{1}\dot{2}}=1, \quad \varepsilon^{\alpha\beta}\varepsilon_{\beta\rho}=\delta^{\alpha}{}_{\rho}.$$

We introduce the standard shorthand notation

$$\eta\chi \equiv \eta^{\alpha}\chi_{\alpha}=\chi^{\alpha}\eta_{\alpha}, \qquad \bar{\eta}\bar{\chi} \equiv \bar{\eta}_{\dot{\alpha}}\bar{\chi}^{\dot{\alpha}}=\bar{\chi}_{\dot{\alpha}}\bar{\eta}^{\dot{\alpha}},$$

so that $(\eta\chi)^{\dagger}=(\eta^{\alpha}\chi_{\alpha})^{\dagger}=(\chi_{\alpha})^{*}(\eta^{\alpha})^{*}=\bar{\chi}_{\dot{\alpha}}\bar{\eta}^{\dot{\alpha}}=\bar{\chi}\bar{\eta}$ with $\bar{\chi}_{\dot{\alpha}} \equiv (\chi_{\alpha})^{*}$, $\bar{\eta}^{\dot{\alpha}}=(\eta^{\alpha})^{*}$.

WEYL SPINORS. VAN DER WÆRDEN NOTATION

We will also introduce

$$(\sigma^\mu)_{\alpha\dot\beta} = \left(1,\vec\sigma\right)_{\alpha\dot\beta},\ (\bar\sigma^\mu)^{\dot\beta\alpha} = (1,-\vec\sigma)_{\dot\beta\alpha}$$

and $A_{\alpha\dot\beta} = A_\mu(\sigma^\mu)_{\alpha\dot\beta}$, such that $A^\mu = \frac{1}{2}A_{\alpha\dot\beta}(\bar\sigma^\mu)^{\dot\beta\alpha}$.

One can also define

$$\sigma^{\mu\nu} \equiv \frac{1}{4}\left(\sigma^\mu\bar\sigma^\nu - \sigma^\nu\bar\sigma^\mu\right), \qquad \bar\sigma^{\mu\nu} \equiv \frac{1}{4}\left(\bar\sigma^\mu\sigma^\nu - \bar\sigma^\nu\sigma^\mu\right).$$

Dirac fields can be written as

$$\Psi_D = \begin{pmatrix} \chi_\alpha \\ \bar\psi^{\dot\alpha} \end{pmatrix}$$

With kinetic terms $i\bar\chi_{\dot\beta}(\bar\sigma^\mu)^{\dot\beta\alpha}\partial_\mu\chi_\alpha + i\psi^\alpha(\sigma^\mu)_{\alpha\dot\beta}\partial_\mu\bar\psi^{\dot\beta}$.

SUPERSYMMETRY

Supersymmetry (SUSY) is interesting *per se*. People became interested in extending the Poincaré symmetries in the 60s.

$$\left[P^\mu, P^\nu\right] = 0, \quad [P^\mu, J^{\rho\sigma}] = i\left(g^{\mu\rho}P^\sigma - g^{\mu\sigma}P^\rho\right),$$

$$\left[J^{\mu\nu}, J^{\rho\sigma}\right] = i\left(g^{\nu\rho}J^{\mu\sigma} - g^{\mu\rho}J^{\nu\sigma} - g^{\nu\sigma}J^{\mu\rho} + g^{\mu\sigma}J^{\nu\rho}\right)$$

P^μ is the generator of translations while $J^k = \frac{1}{2}\epsilon^{klm}J^{lm}$ generate the group of rotations and $K^k = J^{0k} = - J^{k0}$ the boosts. There are two Casimir invariants

$$m^2 = P_\mu P^\mu, \quad W^2 = W^\mu W_\mu = - m^2\vec{J}^2, \quad W^\mu = - \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}J_{\nu\rho}P_\sigma\,.$$

Coleman and Mandula proved that, under certain assumptions, the only symmetry of the S-matrix that included the Poincaré symmetry was the direct product of the Poincaré symmetry with some internal symmetry group.

This was a no-go theorem, but …

One of the assumptions of the Coleman-Mandula theorem is that the generators of the symmetry formed a Lie algebra. In the case where they formed a graded-Lie algebra (or superalgebra) one could allow for a symmetry between bosons and fermions.

In addition to the usual Poincaré generators we add complex, anticonmuting Weyl spinors Q_α and their conjugates $\bar{Q}^{\dot{\alpha}}$ (where $\bar{Q}^{\dot{\alpha}} = (Q^\alpha)^\dagger = (\varepsilon^{\alpha\beta} Q_\beta^\dagger)$):

$$\{Q_\alpha, Q_\beta\} = \{\bar{Q}^{\dot{\alpha}}, \bar{Q}^{\dot{\beta}}\} = 0, \quad \{Q_\alpha, \bar{Q}_{\dot{\alpha}}\} = 2\sigma^\mu_{\alpha\dot{\alpha}} P_\mu, \quad [P_\mu, Q_\alpha] = [P_\mu, \bar{Q}^{\dot{\alpha}}] = 0$$

$$[J^{\mu\nu}, Q_\alpha] = i(\sigma^{\mu\nu})_\alpha{}^\beta Q_\beta, \quad [J^{\mu\nu}, \bar{Q}^{\dot{\alpha}}] = i(\bar{\sigma}^{\mu\nu})^{\dot{\alpha}}{}_{\dot{\beta}} \bar{Q}^{\dot{\beta}}.$$

We can express

$$H = P^0 = \frac{1}{4}\left(Q_1 Q_1^\dagger + Q_1^\dagger Q_1 + Q_2 Q_2^\dagger + Q_2^\dagger Q_2\right)$$

If SUSY is unbroken, $Q_\alpha|0\rangle = (Q_\alpha)^\dagger|0\rangle = 0$ and $E_{\rm vac} = 0$. Otherwise $E_{\rm vac} > 0$.

Single particles fall into irreps of the SUSY algebra - supermultiplets.

- Since $m^2 = P_\mu P^\mu$ commutes with Q_α and $\bar{Q}^{\dot{\alpha}}$ all the states contained in the supermultiplets share the same mass.
- Since the gauge generators also commute, all these states also have the same gauge charge.
- However, since $\left[W^2, Q_\alpha\right] \neq 0$ massive irreducible superalgebra representations must contain particles different spins.
- Q_α and $\bar{Q}_{\dot{\alpha}}$ change fermion number by one unit $(-1)^{N_f} Q_\alpha = -Q_\alpha (-1)^{N_f}$ Then $\mathrm{Tr}\left((-1)^{N_f}\{Q_\alpha, \bar{Q}_{\dot{\alpha}}\}\right) = 0 \Rightarrow \mathrm{Tr}\left((-1)^{N_f} P_\mu\right) = 0$ and $\mathrm{Tr}\left((-1)^{N_f}\right) = 0$ for the states of the supermultiplet with fixed P_μ. Then $n_B = n_F$, each supermultiplet contains the same amount of bosons and fermions.

In SUSY we introduce the concept of superspace. Consider one supercharge ($\mathcal{N} = 1$ SUSY). Any finite element of the group can be written as

$G(x^\mu, \theta, \bar{\theta}) = \exp\left[i(\theta^\alpha Q_\alpha + \bar{\theta}^{\dot{\beta}} \bar{Q}_{\dot{\beta}} - x^\mu P_\mu \right]$, where θ^α and $\bar{\theta}^{\dot{\beta}} = (\theta^\beta)^*$ are Grassmann variables $\{\theta^\alpha, \theta^\beta\} = \{\bar{\theta}^{\dot{\alpha}}, \bar{\theta}^{\dot{\beta}}\} = \{\theta^\alpha, \bar{\theta}^{\dot{\beta}}\} = 0.$

One can prove that

$$G\left(x^\mu, \theta, \bar{\theta}\right) G\left(a^\mu, \epsilon, \bar{\epsilon}\right) = G\left(x^\mu + a^\mu + i\epsilon\sigma^\mu\bar{\theta} - i\theta\sigma^\mu\bar{\epsilon}, \theta + \epsilon, \bar{\theta} + \bar{\epsilon}\right)$$

Therefore, the superspace transformations

$$\left(x^\mu, \theta^\alpha, \bar{\theta}^{\dot{\alpha}}\right) \to \left(x^\mu + \delta x^\mu, \theta^\alpha + \delta^\alpha, \bar{\theta}^{\dot{\alpha}} + \delta\bar{\theta}^{\dot{\alpha}}\right)$$

$$\delta\theta^\alpha = \epsilon^\alpha, \quad \delta\bar{\theta}^{\dot{\alpha}} = \bar{\epsilon}^{\dot{\alpha}}, \quad \delta x^\mu = i\epsilon\sigma^\mu\bar{\theta} - i\theta\sigma^\mu\bar{\epsilon},$$

add supersymmetry to the Poincaré transformations (translations and Lorentz)..

The most general superfield with no external indices looks like

$$S(x,\theta,\bar\theta) = \phi + \theta\psi + \bar\theta\bar\psi + \theta^2 F + \bar\theta^2 G + \theta^\alpha A_{\alpha\dot\beta}\bar\theta^{\dot\beta} + \theta^2(\bar\theta\bar\lambda) + \bar\theta^2(\theta\rho) + \theta^2\bar\theta^2 D$$

These superfields are not irreducible representations of the superalgebra. We should impose constraints:

- Vector superfields $S = S^\dagger$
- Chiral superfields $\bar D_{\dot\alpha}\Phi = 0$ (or anti-chiral $D_\alpha\bar\Phi = 0$)

where

$$D_\alpha = \frac{\partial}{\partial\theta^\alpha} - i\bar\theta^{\dot\alpha}\partial_{\alpha\dot\alpha}, \quad \bar D_{\dot\alpha} = -\frac{\partial}{\partial\bar\theta^{\dot\alpha}} + i\theta^\alpha\partial_{\alpha\dot\alpha}, \quad \left\{D_\alpha, \bar D_{\dot\alpha}\right\} = 2i\partial_{\alpha\dot\alpha}\,.$$

Vector superfields read:

$$V(x,\theta,\bar\theta) = C + i\theta\chi - i\bar\theta\bar\chi + \frac{i}{\sqrt{2}}\theta^2 M - \frac{i}{\sqrt{2}}\bar\theta^2\bar M - 2\theta^\alpha\bar\theta^{\dot\alpha}v_{\alpha\dot\alpha}$$

$$+\left[2i\theta^2\bar\theta^2\left(\bar\lambda^{\dot\alpha} - \frac{i}{4}\partial^{\dot\alpha\alpha}\chi_\alpha\right) + \mathrm{h.c.}\right] + \theta^2\bar\theta^2\left(D - \frac{1}{4}\partial^2\right)$$

with

- C, D and $v_\mu = \frac{1}{2}(\sigma^\mu)^{\dot\alpha\alpha}v_{\alpha\dot\alpha}$ are real bosonic fields, while M is complex.
- χ and λ are fermions.

Only orange fields are physical: v_μ, λ_α (a vector and a fermion). For instance, from the same vector superfield we get the W and wino (fermion).

Defining x_L^μ, x_R^μ by

$$(x_L)_{\alpha\dot\alpha} = x_{\alpha\dot\alpha} - 2i\theta_\alpha\bar\theta_{\dot\alpha}, \quad x_L^\mu = x^\mu - i\theta^\alpha(\sigma^\mu)_{\alpha\dot\alpha}\bar\theta^{\dot\alpha}$$

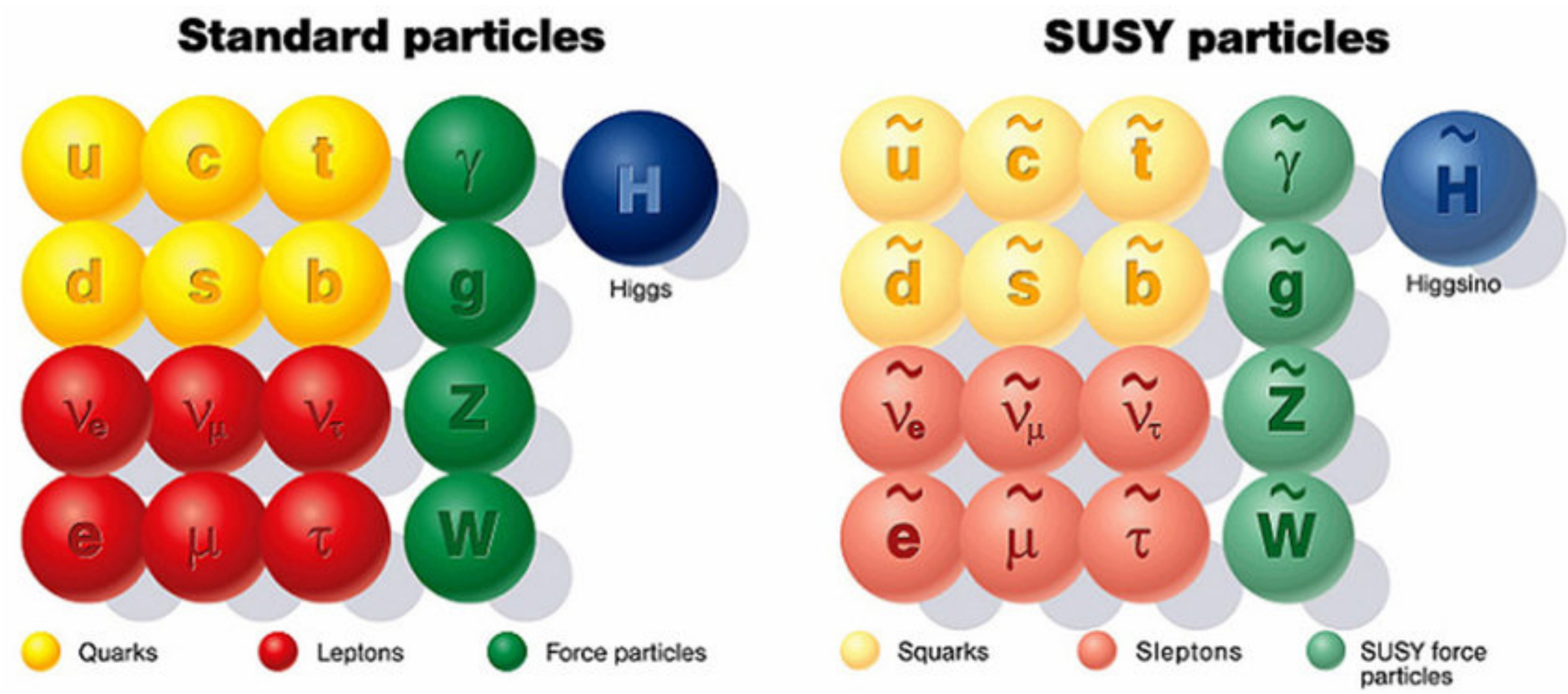
$$(x_R)_{\alpha\dot\alpha} = x_{\alpha\dot\alpha} + 2i\theta_\alpha\bar\theta_{\dot\alpha}, \quad x_R^\mu = x^\mu + i\theta^\alpha(\sigma^\mu)_{\alpha\dot\alpha}\bar\theta^{\dot\alpha}$$

the condition for chiral superfields will be easier to impose since $\bar D_{\dot\alpha} x_L^\mu = 0,\ D_\alpha x_R^\mu = 0$. Then chiral superfields read

$$\Phi(x_L, \theta) = \phi(x_L) + \sqrt{2}\theta^\alpha\psi_\alpha(x_L) + \theta^2 F(x_L)$$

- It contains real scalars ϕ and F (this not propagating) and a fermion ψ_α
- For instance, we get the top and the stop (scalar), …

THE MSSM


Standard particles
SUSY particles
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Higgs
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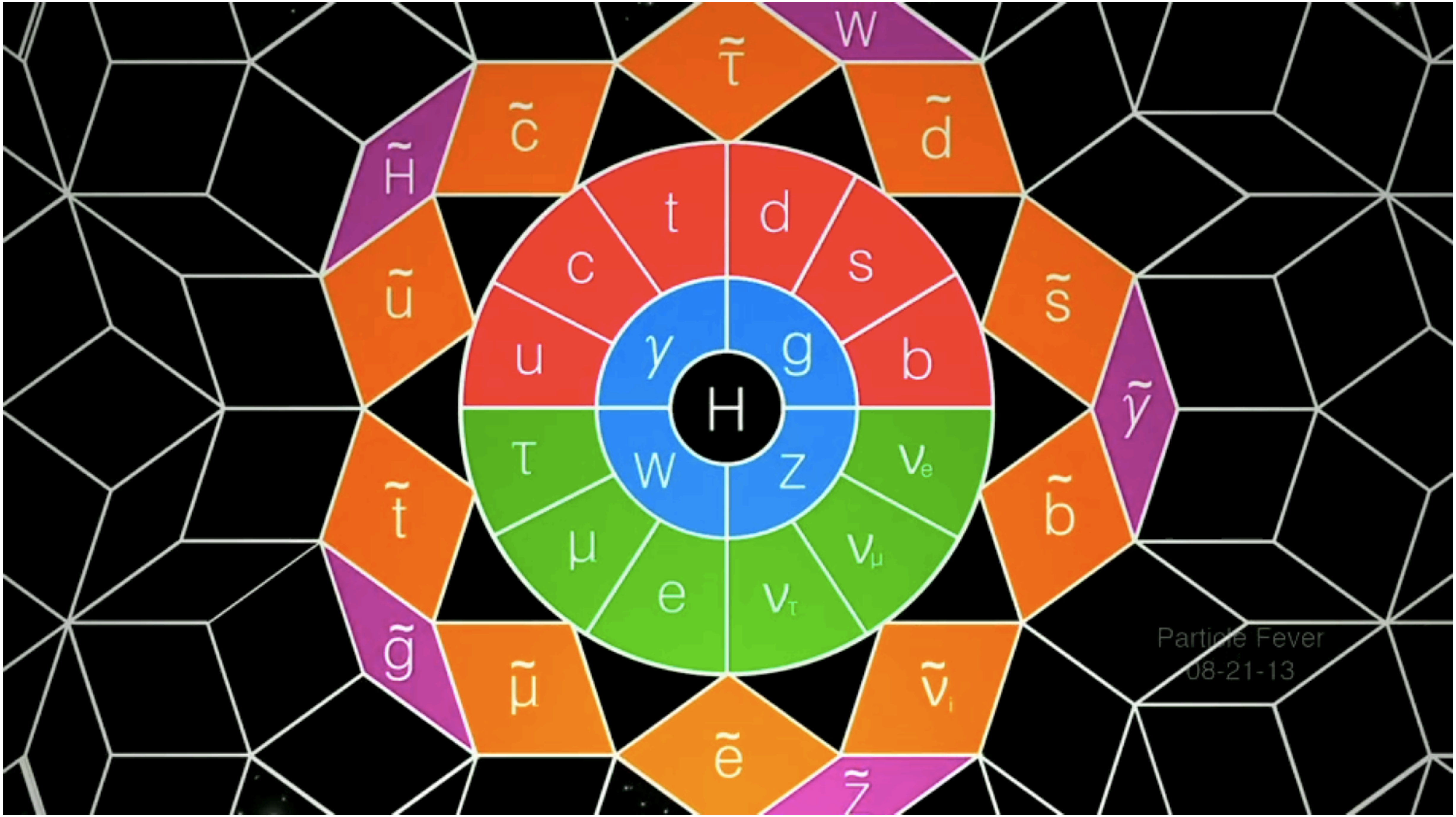
Quarks
Leptons
Force particles
Squarks
Sleptons
SUSY force particles

THE MSSM


H
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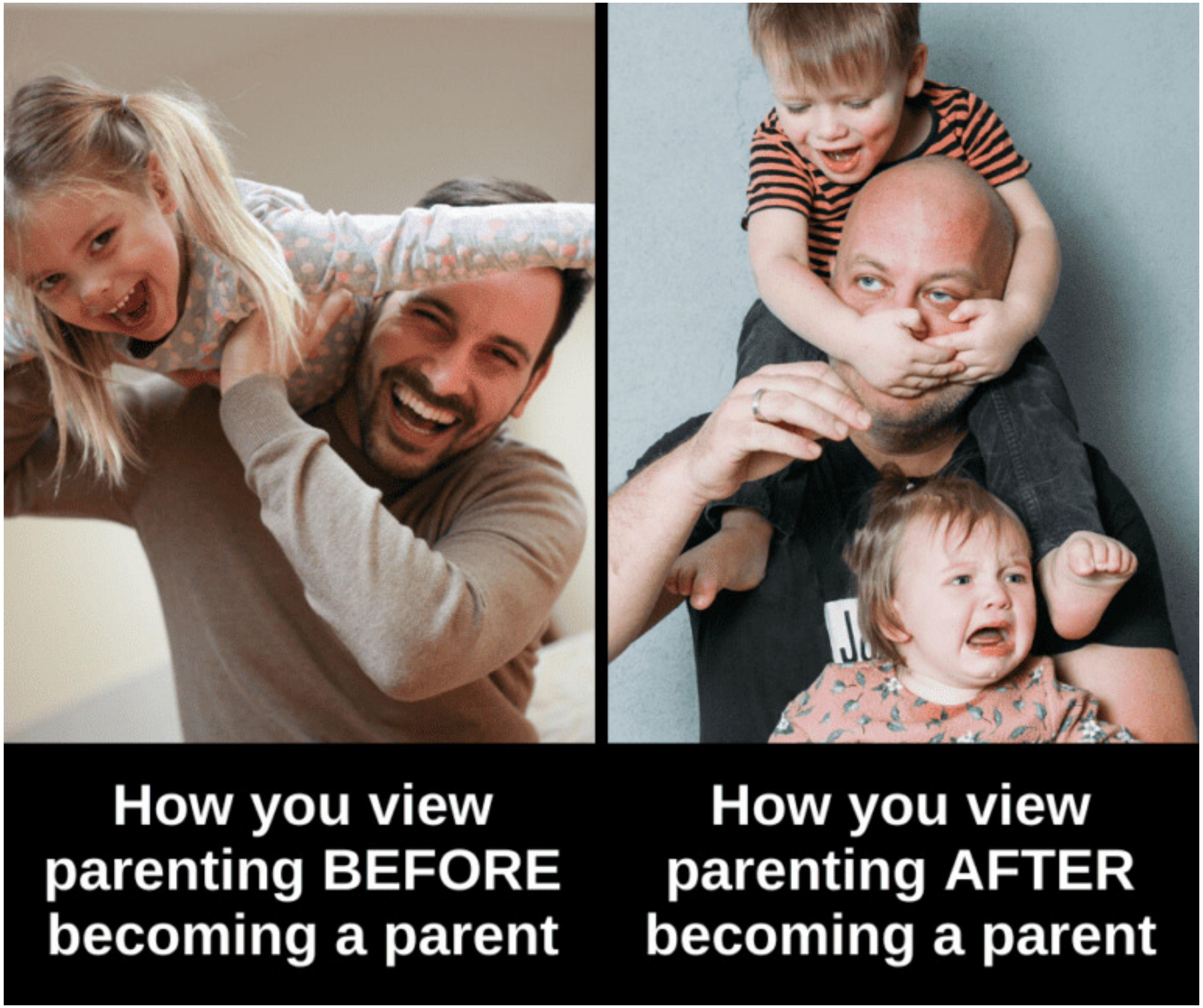
Particle Fever
08-21-13

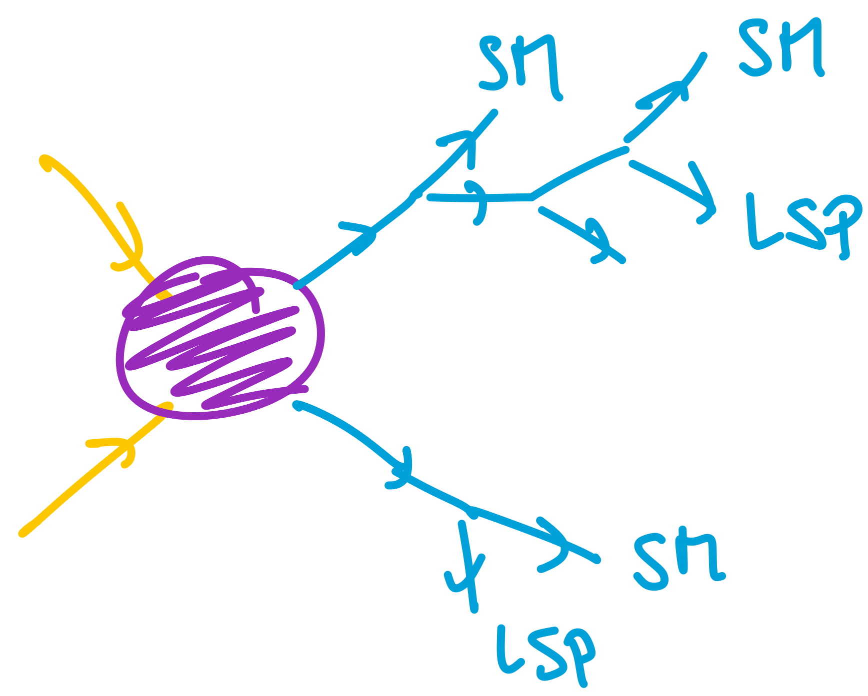
Supersymmetry is a brilliant idea but once you start model building, things become ugly. It is a bit like parenting:



THE MSSM

Some features of the MSSM:

- SUSY has to be broken softly.
- Two Higgs multiplets: anomaly cancellation + holomorphic Yukawas
- R-parity to avoid proton decay ⇒ LSP stable ⇒ DM candidate
- Usual pheno consequences:
    - Pair production
    - Cascades
    - Missing energy



ATLAS SUSY Searches* - 95% CL Lower Limits

July 2024

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	140	$\tilde{q}$ [1×, 8× Degen.]	1.0 / 1.85	m($\tilde{\chi}_1^0$)<400 GeV	2010.14293
		mono-jet	1-3 jets	E_T^{miss}	140	$\tilde{q}$ [8× Degen.]	0.9	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	2102.10874
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	140	$\tilde{g}$	2.3	m($\tilde{\chi}_1^0$)=0 GeV	2010.14293
						$\tilde{g}$ Forbidden	1.15-1.95	m($\tilde{\chi}_1^0$)=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}W\tilde{\chi}_1^0$	1 e,μ	2-6 jets		140	$\tilde{g}$	2.2	m($\tilde{\chi}_1^0$)<600 GeV	2101.01629
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee,\mu\mu$	2 jets	E_T^{miss}	140	$\tilde{g}$	2.2	m($\tilde{\chi}_1^0$)<700 GeV	2204.13072
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qqWZ\tilde{\chi}_1^0$	0 e,μ	7-11 jets	E_T^{miss}	140	$\tilde{g}$	1.97	m($\tilde{\chi}_1^0$) <600 GeV	2008.06032
		SS e,μ	6 jets		140	$\tilde{g}$	1.15	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	2307.01094
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	E_T^{miss}	140	$\tilde{g}$	2.45	m($\tilde{\chi}_1^0$)<500 GeV	2211.08028
		SS e,μ	6 jets		140	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1909.08457
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	E_T^{miss}	140	$\tilde{b}_1$	1.255	m($\tilde{\chi}_1^0$)<400 GeV	2101.12527
						$\tilde{b}_1$	0.68	10 GeV<Δm($\tilde{b}_1$,$\tilde{\chi}_1^0$)<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow b\tilde{\chi}_2^0\rightarrow bh\tilde{\chi}_1^0$	0 e,μ	6 b	E_T^{miss}	140	$\tilde{b}_1$ Forbidden	0.23-1.35	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=100 GeV	1908.03122
		2 τ	2 b	E_T^{miss}	140	$\tilde{b}_1$	0.13-0.85	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=0 GeV	2103.08189
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	0-1 e,μ	$\geq$ 1 jet	E_T^{miss}	140	$\tilde{t}_1$	1.25	m($\tilde{\chi}_1^0$)=1 GeV	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow Wb\tilde{\chi}_1^0$	1 e,μ	3 jets/1 b	E_T^{miss}	140	$\tilde{t}_1$ Forbidden	1.05	m($\tilde{\chi}_1^0$)=500 GeV	2012.03799, 2401.13430
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\rightarrow\tau\tilde{G}$	1-2 τ	2 jets/1 b	E_T^{miss}	140	$\tilde{t}_1$ Forbidden	1.4	m($\tilde{\tau}_1$)=800 GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\rightarrow c\tilde{\chi}_1^0$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$	0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	140	$\tilde{t}_1$	0.55	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow t\tilde{\chi}_2^0$, $\tilde{\chi}_2^0\rightarrow Z/h\tilde{\chi}_1^0$	1-2 e,μ	1-4 b	E_T^{miss}	140	$\tilde{t}_1$	0.067-1.18	m($\tilde{\chi}_2^0$)=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1+Z$	3 e,μ	1 b	E_T^{miss}	140	$\tilde{t}_2$ Forbidden	0.86	m($\tilde{\chi}_1^0$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 40 GeV	2006.05880
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	Multiple ℓ/jets		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	0.96	m($\tilde{\chi}_1^0$)=0, wino-bino	2106.01676, 2108.07586
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	0.205	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=5 GeV, wino-bino	1911.12606
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via WW	2 e,μ		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}$	0.42	m($\tilde{\chi}_1^0$)=0, wino-bino	1908.08215
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh	Multiple ℓ/jets		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ Forbidden	1.06	m($\tilde{\chi}_1^0$)=70 GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}$	1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\rightarrow\tau\tilde{\chi}_1^0$	2 τ		E_T^{miss}	140	$\tilde{\tau}$ [$\tilde{\tau}_R\tilde{\tau}_R$]	0.35 / 0.5	m($\tilde{\chi}_1^0$)=0	2402.00603
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\rightarrow\ell\tilde{\chi}_1^0$	2 e,μ	0 jets	E_T^{miss}	140	$\tilde{\ell}$	0.7	m($\tilde{\chi}_1^0$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	140	$\tilde{\ell}$	0.26	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}$, $\tilde{H}\rightarrow h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	E_T^{miss}	140	$\tilde{H}$	0.94	BR($\tilde{\chi}_1^0\rightarrow h\tilde{G}$)=1	2401.14922
		4 e,μ	0 jets	E_T^{miss}	140	$\tilde{H}$	0.55	BR($\tilde{\chi}_1^0\rightarrow Z\tilde{G}$)=1	2103.11684
		0 e,μ	$\geq$ 2 large jets	E_T^{miss}	140	$\tilde{H}$	0.45-0.93	BR($\tilde{\chi}_1^0\rightarrow Z\tilde{G}$)=1	2108.07586
		2 e,μ	$\geq$ 2 jets	E_T^{miss}	140	$\tilde{H}$	0.77	BR($\tilde{\chi}_1^0\rightarrow Z\tilde{G}$)=BR($\tilde{\chi}_1^0\rightarrow h\tilde{G}$)=0.5	2204.13072
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	E_T^{miss}	140	$\tilde{\chi}_1^{\pm}$	0.66	Pure Wino	2201.02472
						$\tilde{\chi}_1^{\pm}$	0.21	Pure higgsino	2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		E_T^{miss}	140	$\tilde{g}$	2.05		2205.06013
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\rightarrow qq\tilde{\chi}_1^0$	pixel dE/dx		E_T^{miss}	140	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns]	2.2	m($\tilde{\chi}_1^0$)=100 GeV	2205.06013
	$\tilde{\ell}\tilde{\ell}$, $\tilde{\ell}\rightarrow\ell\tilde{G}$	Displ. lep		E_T^{miss}	140	$\tilde{e},\tilde{\mu}$	0.74	$\tau(\tilde{\ell})$ = 0.1 ns	ATLAS-CONF-2024-011
						$\tilde{\tau}$	0.36	$\tau(\tilde{\ell})$ = 0.1 ns	ATLAS-CONF-2024-011
		pixel dE/dx		E_T^{miss}	140	$\tilde{\tau}$	0.36	$\tau(\tilde{\ell})$ = 10 ns	2205.06013
RPV	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_1^0$, $\tilde{\chi}_1^{\pm}\rightarrow Z\ell\rightarrow\ell\ell\ell$	3 e,μ			140	$\tilde{\chi}_1^{\mp}/\tilde{\chi}_1^0$ [BR($Z\tau$)=1, BR(Ze)=1]	0.625 / 1.05	Pure Wino	2011.10543
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0\rightarrow WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$]	0.95 / 1.55	m($\tilde{\chi}_1^0$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow qqq$		$\geq$8 jets		140	$\tilde{g}$ [m($\tilde{\chi}_1^0$)=50 GeV, 1250 GeV]	1.6 / 2.34	Large λ''_{112}	2401.16333
	$\tilde{t}\tilde{t}$, $\tilde{t}\rightarrow t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow tbs$		Multiple		36.1	$\tilde{t}$ [λ''_{323}=2e-4, 1e-2]	0.55 / 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\rightarrow b\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^{\pm}\rightarrow bbs$		$\geq$ 4b		140	$\tilde{t}$ Forbidden	0.95	m($\tilde{\chi}_1^{\pm}$)=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs]	0.42 / 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow q\ell$	2 e,μ	2 b		140	$\tilde{t}_1$	0.4-1.85	BR($\tilde{t}_1\rightarrow be/b\mu$)>20%	2406.18367
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9]	1.0 / 1.6	BR($\tilde{t}_1\rightarrow q\mu$)=100%, cos$\theta_t$=1	2003.11956
	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0/\tilde{\chi}_1^0$, $\tilde{\chi}_{1,2}^0\rightarrow tbs$, $\tilde{\chi}_1^+\rightarrow bbs$	1-2 e,μ	$\geq$6 jets		140	$\tilde{\chi}_1^0$	0.2-0.32	Pure higgsino	2106.09609

10^{-1} 1 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Bottom line. On paper, SUSY has a lot of nice features:

- It is a renormalizable theory.
- It provides the more general way of extending the symmetries of the Poincaré algebra.
- It contains an U(1) symmetry, called R-parity, that can give you a dark matter candidate.
- It is required for some string theories.
- It helps with gauge unification
- It solves the hierarchy problem.

But unfortunately, data suggests that the symmetry is broken and that the SUSY breaking scale is rather heavy.

THE HIERARCHY PROBLEM

Another way of solving the hierarchy problem is by *lowering* the cut-off of the theory:

- In composite Higgs models, the Higgs is not an elementary particle but the (pseudo)Nambu-Goldstone boson of some spontaneously broken global symmetry. Like e.g. the pions in QCD.
- This models have an holographic dual where the Higgs is the scalar component of a five-dimensional gauge field (a five dimensional Lorentz vector is equal to a four dimensional Lorentz vector and a scalar)

$$\mathbb{A}^a_M = (\mathbb{A}^a_\mu, \mathbb{A}^a_5)$$

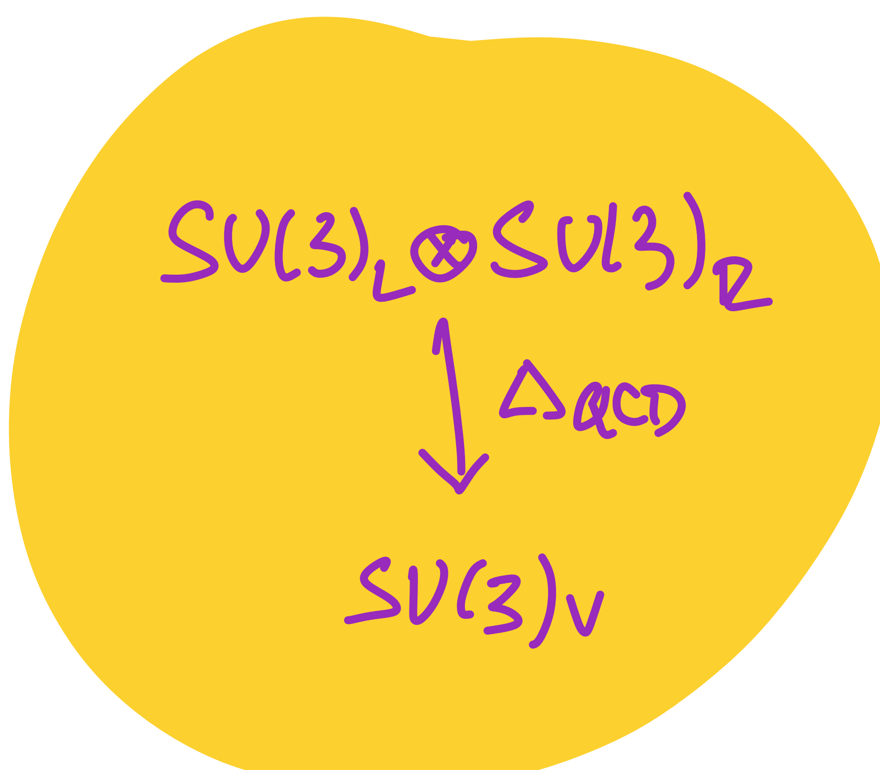
- In this picture, the Higgs can not get a mass due to the 5D gauge invariance. They are thus called models of gauge-Higgs unification. They can help with calculability.

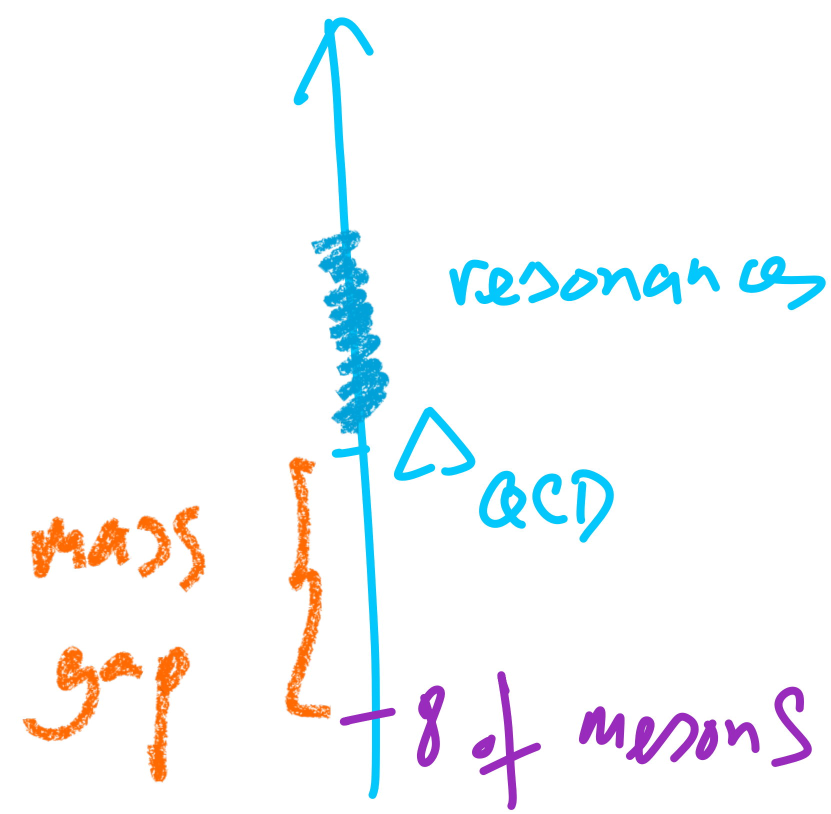
COMPOSITE HIGGS MODELS

Rationale: *elementary scalars are weird and should not exist*. Scalars should only be composite objects: (pseudo-)Nambu-Goldstone bosons (like in condense matter). We will call them (p)NGBs.

Goldstone theorem: in a theory with spontaneous symmetry breaking there are as many massless scalar bosons as generators of the Lie group 'broken'.

Consider the example of QCD:





COMPOSITE HIGGS MODELS

Non-linear realizations of the spontaneous symmetry breaking of a global symmetry are very helpful to build an EFT for the pNGBs.

Imaging n scalar fields transforming linearly and globally under some global group G, $\Phi(x) \to D(g)\Phi(x)$, acquiring a VEV $\langle \Phi \rangle = \Sigma_0$ only invariant under $H \subset G$. We can trade Φ by

- A field Φ_0 that under $g \in G$ transforms linearly but locally on $H \subset G$

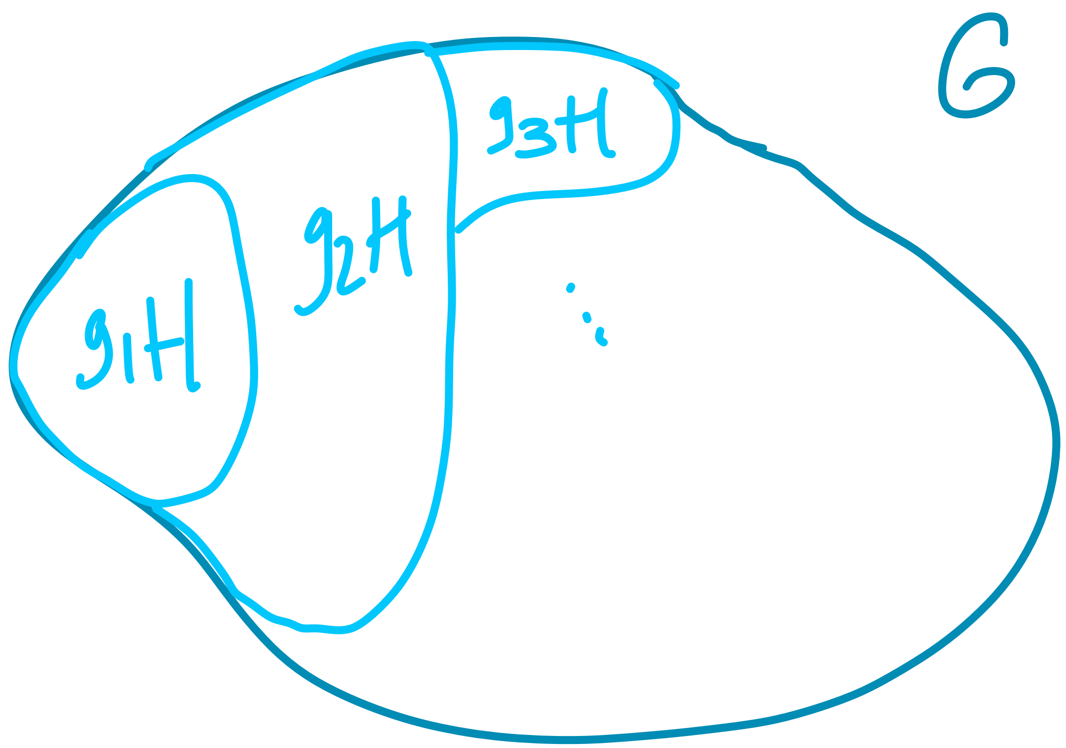
$$\Phi_0 \to D\big(h(g, \xi(x))\big)\Phi_0$$

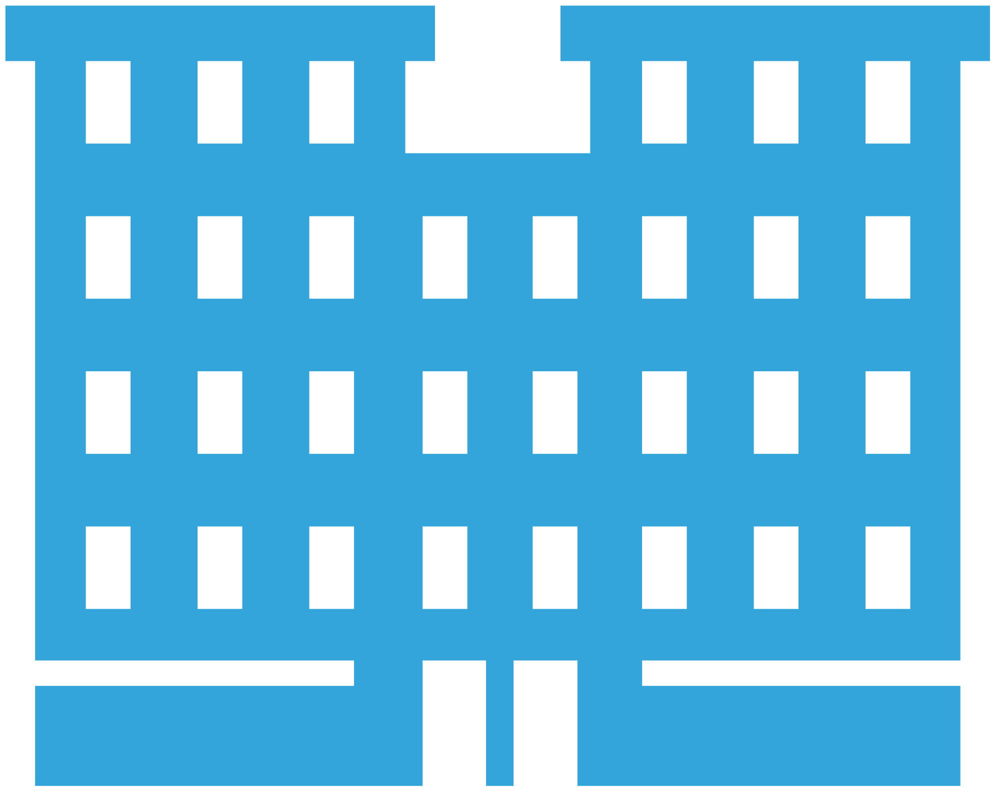
- Goldstone bosons $\xi(x)$ transforming globally but non-linearly. If we define the matrix $U(\chi) = \exp\left(2i\frac{\xi^a(x)T^{\dot{a}}}{f}\right)$, under $g \in G$ it transforms

$$U(\xi) \to D(g)U(\xi)D^{-1}\big(h(g, \xi(x))\big)$$

If we do a transformation $h \in H$, $\Phi_0 \to D(h)\Phi_0$, $U(\xi) \to D(h)U(\xi)D^{-1}(h)$.

Left cosets G/H are defined by $gH = \{gh \ : \ h \in H\}$. Two cosets are either identical or disjoint. At the end of the day we can divide the elements of G





Every element $g_1, g_2, \ldots$ is a representative of the corresponding left coset. Any element of G can be pin-pointed by specifying a representative and its coordinates within the coset $\xi^{\dot{a}}$. To know anyone on a building you just need to know the flats in the building and who lives in each flat (e.g. the son of Pedro's from the 3rd right).

COMPOSITE HIGGS MODELS

One can see that if we define $\omega_\mu = -iU^{-1}\partial_\mu U = d_\mu^{\dot a}T^{\dot a} + E_\mu^i T^i = d_\mu + E_\mu$, where $T^{\dot a} \notin \mathfrak{h}$, $T^i \in \mathfrak{h}$, we obtain

$\Phi_0 \to D\big(h(g,\xi(x))\big)\Phi_0$,

$d_\mu \to D(h(g,\xi(x)))\, d_\mu\, D^{-1}(h(g,\xi(x)))$, $\quad d_\mu^{\dot a} \approx \dfrac{2}{f}\partial_\mu \xi^{\dot a}(x) + \mathcal{O}(\partial_\mu \xi / f \cdot \xi^2/f^2)$,

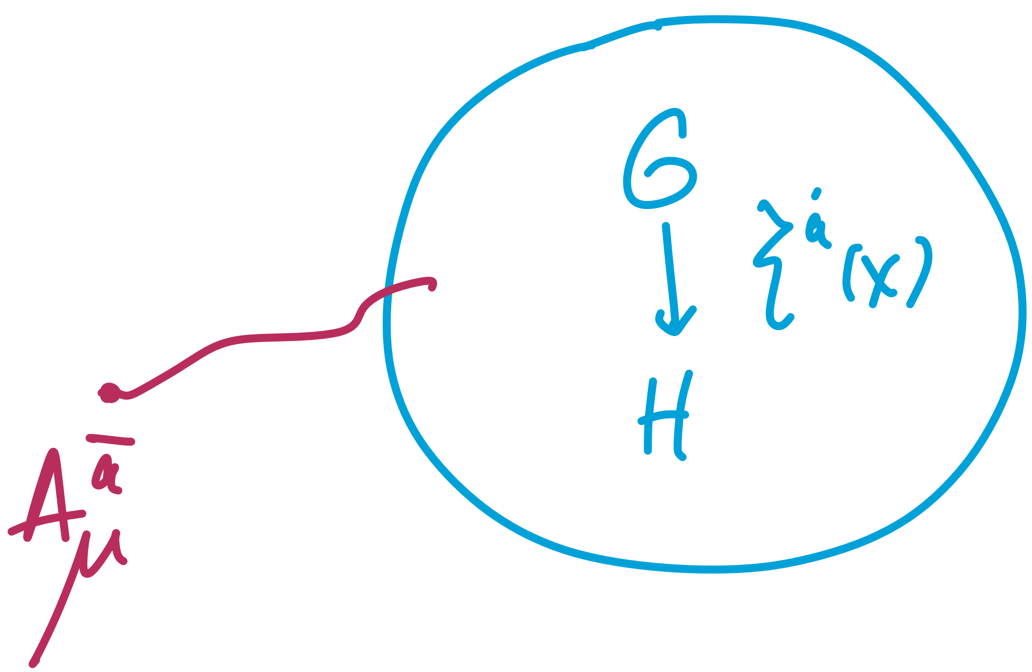
$E_\mu \to D\big(h(g,\xi(x))\big)\, E_\mu\, D^{-1}\big(h(g,\xi(x))\big) + iD\big(h(g,\xi(x))\big)\big[\partial_\mu D^{-1}\big(h(g,\xi(x))\big)\big]$.

Notice that $\mathscr{E}_\mu \equiv \partial_\mu - iE_\mu$ is a H-covariant derivative. We can write H-invariant Lagrangians with all these symbols. The leading term is $-\operatorname{Tr}\big(T^a \cdot T^b\big) = \dfrac{1}{2}\delta^{ab}$

$$\mathscr{L}_\xi = \frac{f^2}{4}\operatorname{Tr}\big(d_\mu d^\mu\big) = \frac{f^2}{8} d_\mu^{\dot a} d^{\dot a \mu} = \frac{f^2}{2}\operatorname{Tr}\big(-iU^{-1}\partial_\mu U T^{\dot a}\big)\operatorname{Tr}\big(-iU^{-1}\partial^\mu U T^{\dot a}\big)$$

$$= \frac{1}{2}\partial_\mu \xi^{\dot a}\partial^\mu \xi^{\dot a} + \sum_n \mathcal{O}((\partial_\mu \xi)^2 \xi^n / f^n)$$

Sometimes, we want to couple this strongly interacting sector to some external gauge fields (aka, weakly gauge some subgroup $M \subset G$)



$$T^i \in \mathfrak{h}, T^{\bar{a}} \in \mathfrak{m}, T^{\dot{a}} \notin \mathfrak{h}$$

Then, we need to replace ∂_μ by $\mathscr{D}_\mu = \partial_\mu - igA_\mu^{\bar{a}}T^{\bar{a}}$ in the definition of ω_μ

$$\bar{\omega}_\mu = -iU^{-1}\mathscr{D}_\mu U = \bar{d}_\mu^{\dot{a}}T^{\dot{a}} + \bar{E}_\mu^i T^i = \bar{d}_\mu + \bar{E}_\mu$$

The leading effective Lagrangian is then

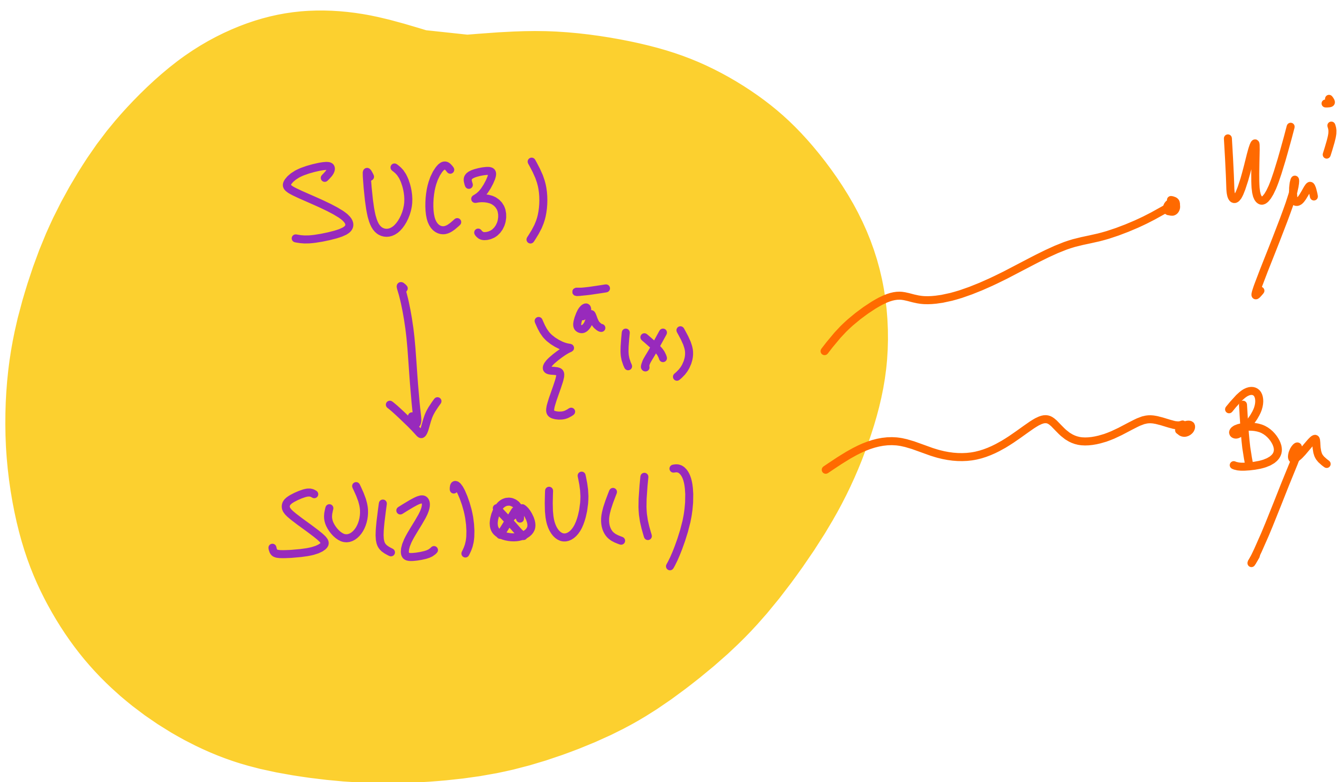
$$\mathscr{L}_{\xi,A_\mu} = \frac{f^2}{8}\mathrm{Tr}\left(\bar{d}_\mu \bar{d}^\mu\right)$$

COMPOSITE HIGGS MODELS. A MINIMAL EXAMPLE.

Let us consider a minimal example:

$$G \equiv SU(3) \to H \equiv SU(2) \otimes U(1)$$

- There are four generators $T^{\dot{a}} \notin \mathfrak{h} \Rightarrow$ We expect four pNGBs
- We will weakly gauge the subgroup H



COMPOSITE HIGGS MODELS. A MINIMAL EXAMPLE.

Consider the usual Gell-Mann representation of $SU(3)$: $T^a = \dfrac{\lambda_a}{2}$, $a = 1,\ldots,8$.

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}, \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}, \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}$$

They satisfy commutation relations $\left[T^a, T^b\right] = i f_{abc} T^c$, with

$$f_{123} = 1, \quad f_{458} = f_{678} = \frac{\sqrt{3}}{2}, \quad f_{147} = f_{165} = f_{246} = f_{257} = f_{345} = f_{376} = \frac{1}{2}$$

We can see that in particular $\left[T^i, T^j\right] = i\epsilon^{ijk} T^k,\ \left[T^i, T^8\right] = 0,\ i,j,k \in \{1,2,3\}$:

$$SU(2) \otimes U(1) \subset SU(3)$$

COMPOSITE HIGGS MODELS. A MINIMAL EXAMPLE.

We can define $T_\phi = \begin{pmatrix} T^+ \\ T^0 \end{pmatrix}$, with $T^+ \equiv \frac{T^4 - iT^5}{\sqrt{2}}$, $T^0 \equiv \frac{T^6 - iT^7}{\sqrt{2}}$. One gets

$$\left[T^i, T_\phi\right] = -\frac{\sigma^i}{2} T_\phi, \ \left[Y, T_\phi\right] = -\frac{1}{2} T_\phi$$

where $Y \equiv \frac{1}{\sqrt{3}} T^8$. Then, defining $\xi^+(x)$ and $\xi^0(x)$ analogously we obtain that

$$\phi(x) = \begin{pmatrix} \xi^+(x) \\ \xi^0(x) \end{pmatrix} \sim \mathbf{2}_{1/2}$$

We have therefore the right quantum numbers to get the SM Higgs doublet. In the unitary gauge, $\xi^6 \equiv h$, $\xi^{4,5,7} = 0$, we obtain

$$U(x) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(h/f) & i\sin(h/f) \\ 0 & i\sin(h/f) & \cos(h/f) \end{pmatrix}$$

COMPOSITE HIGGS MODELS. A MINIMAL EXAMPLE.

The pNGB EFT reads

$$\mathscr{L} = \frac{f^2}{8}\mathrm{Tr}\left(\bar{d}_\mu \bar{d}^\mu\right) = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{g^2}{4} f^2 \sin^2\left(\frac{h}{f}\right) W^+_\mu W^{-\mu} + \frac{g^2}{32 c_W^2} f^2 \sin^2\left(\frac{2h}{f}\right) Z_\mu Z^\mu + \ldots$$

At this point the Higgs is massless. However, the weakly gauging of the EW group will generate a Higgs potential at the loop level and, together with the fermion contributions (partial compositeness), will trigger EWSB.

After the Higgs get a VEV, $\langle h \rangle = v$, we obtain the W and Z masses

$$m_W^2 = \frac{g^2}{4} f^2 \sin^2\left(\frac{v}{f}\right) = \frac{g^2}{4} v^2 \left(1 - \frac{v^2}{3f^2} + \mathcal{O}\left(v^4/f^4\right)\right)$$

$$m_Z^2 = \frac{g^2}{16 c_W^2} f^2 \sin^2\left(\frac{2v}{f}\right) = \frac{g^2}{4 c_W^2} v^2 \left(1 - \frac{4}{3}\frac{v^2}{3f^2} + \mathcal{O}\left(v^4/f^4\right)\right)$$

It leads to $\rho \equiv \dfrac{m_W^2}{m_Z^2 c_W^2} = 1 + \dfrac{v^2}{f^2} + \mathcal{O}\left(v^4/f^4\right)$ – it does not have Custodial Symmetry

COMPOSITE HIGGS MODELS. A MINIMAL EXAMPLE.

For simplicity we define $\Sigma = U(\xi)\Sigma_0 U(\xi)^{-1}$, with $\Sigma_0 \equiv T^8/\sqrt{3}$ the H-preserving vacuum.

This object transform as

$$\Sigma \to D(g)U(\xi)D^{-1}\big(h(g,\xi(x))\big)\Sigma_0 D\big(h(g,\xi(x))\big)D^{-1}(g)$$

Since Σ_0 is invariant under $h \in H$, $D\big(h(g,\xi(x))\big)\Sigma_0 D^{-1}\big(h(g,\xi(x))\big) = \Sigma_0$ and

$$\Sigma \to D(g)U(\xi)\Sigma_0 U^{-1}(\xi)D^{-1}(g) = D(g)\Sigma D^{-1}(g)$$

The gauge boson matrix $A_\mu = W_\mu^i T^i + \frac{1}{\sqrt{3}} B_\mu T^8 + A_\mu^{\dot{a}} T^{\dot{a}}$ transforms the same

$$A_\mu \to D(g)A_\mu D^{-1}(g)$$

For convenience we add an spectator group $U(1)_X$ with gauge boson $X_\mu = B_\mu$

COMPOSITE HIGGS MODELS. A MINIMAL EXAMPLE.

At the quadratic level in the gauge fields and in momentum space, the most general H-invariant Lagrangian is

$$\mathscr{L} = (\mathscr{P}_T)^{\mu\nu}\left[\frac{1}{2}\Pi_0^X(q^2)X_\mu X_\nu + \Pi_0(q^2)\mathrm{Tr}\big(A_\mu \cdot A_\nu\big) + \Pi_1(q^2)\mathrm{Tr}\big(\left[A_\mu, \Sigma\right]^\dagger\left[A_\nu, \Sigma\right]\big)\right]$$

with $(\mathscr{P}_T)^{\mu\nu} = \eta_{\mu\nu} - \dfrac{p_\mu p_\nu}{p^2}$. The form factors $\Pi_0^X(q^2), \Pi_0(q^2), \Pi_1(q^2)$ encode the dynamics of the strong sector. After making $A_\mu^{\dot{a}} \equiv 0$ we obtain

$$\mathscr{L} = (\mathscr{P}_T)^{\mu\nu}\left[\left(\Pi_0(q^2) + \frac{\Pi_1(q^2)s_h^2}{4}\right)W_\mu^+W_\nu^- + \frac{1}{2}\left(\Pi_0(q^2) + \frac{\Pi_1(q^2)s_h^2c_h^2}{4}\right)W_\mu^3W_\nu^3\right.$$

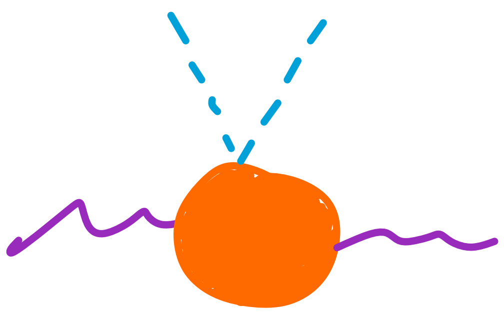
$$\left.+\frac{1}{2}\left(\frac{\Pi_0(q^2)}{3} + \Pi_0^X(q^2) + \frac{\Pi_1(q^2)s_h^2c_h^2}{4}\right)B_\mu B_\nu - \frac{\Pi_1(q^2)s_h^2c_h^2}{4}W_\mu^3B_\nu\right]$$

where $s_h = \sin(h/f)$, $c_h = \cos(h/f)$.

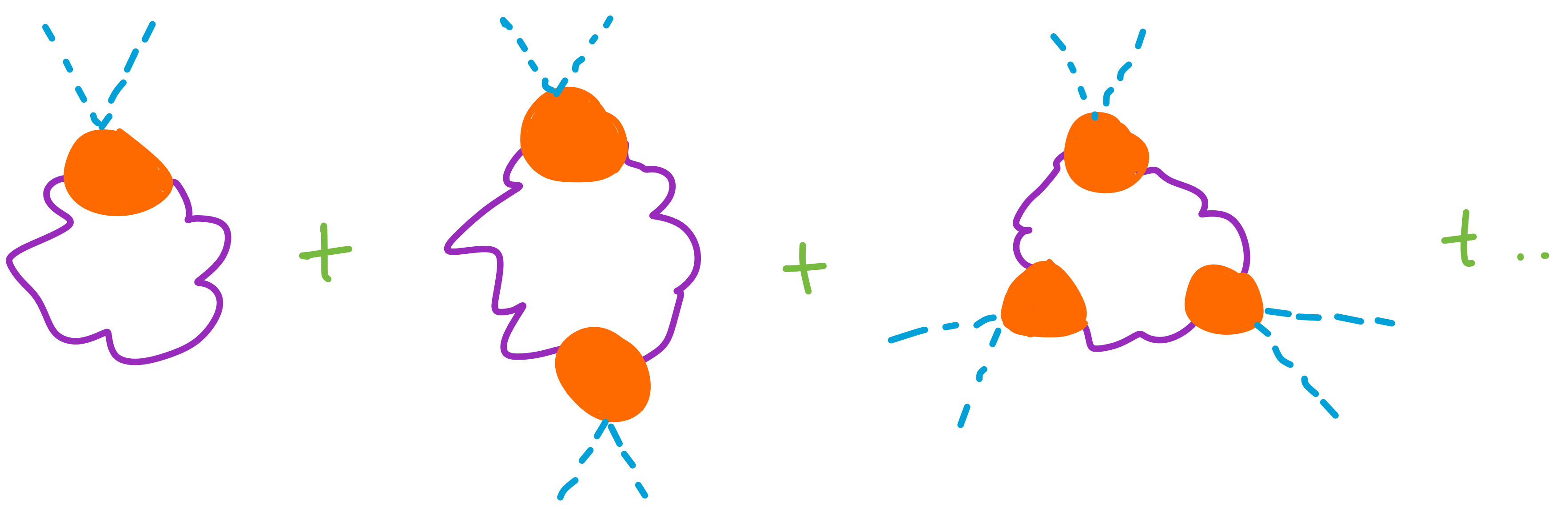
COMPOSITE HIGGS MODELS. A MINIMAL EXAMPLE.

For simplicity, let us forget right now about the hypercharge. Then

$$F_{\mu\nu} = \frac{i}{\Pi_0(q^2)}(P_T)_{\mu\nu} - \xi\frac{ig^2}{q^2}(P_L)_{\mu\nu}$$



$$i\Gamma_{\mu\nu} = \frac{i\,\Pi_1(q^2)}{4}\sin^2(h/f)\,(P_T)_{\mu\nu}$$



$$V(h) = \frac{6}{2}\int_0^\infty \frac{d^4p_E}{(2\pi)^4}\log\left(1 + \frac{1}{4}\frac{\Pi_1(-p_E^2)}{\Pi_0(-p_E)^2}\sin^2(h/f)\right)$$

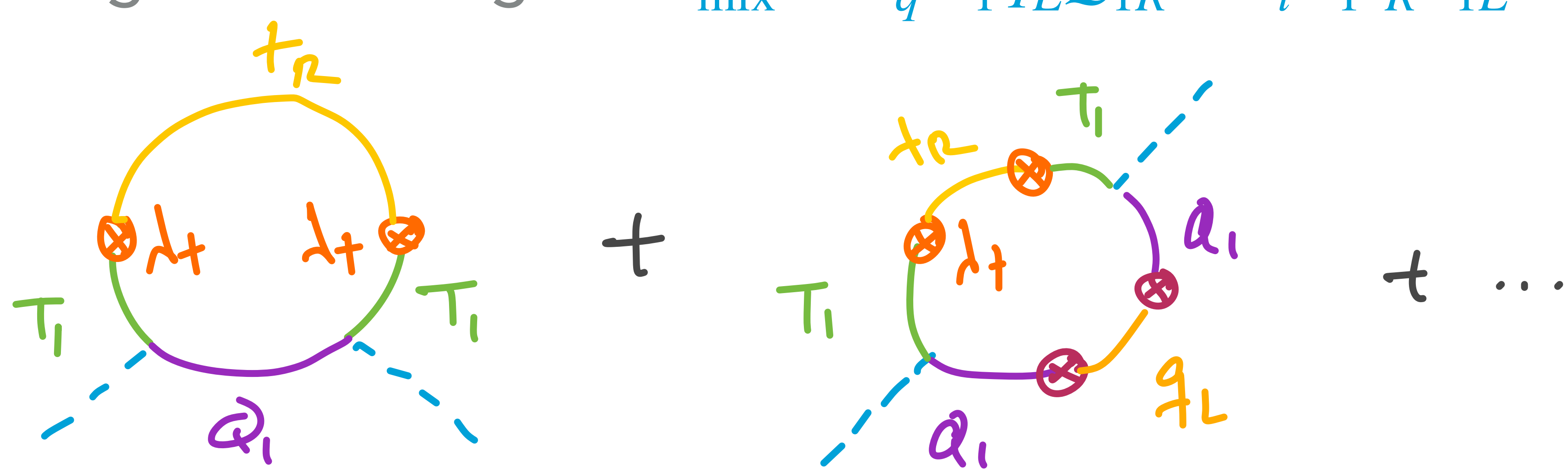
COMPOSITE HIGGS MODELS. PARTIAL COMPOSITENESS.

- Weakly gauging $SU(2) \otimes U(1)$ generates a potential at one loop.
- However, as pointed out by Witten, gauge contributions alone can not trigger EWSB.
- We need thus something else. What can it be? We still need to give masses to fermions!

The solution to all our problems is called partial compositeness:

$\mathscr{L}_{\text{mix}} = \lambda_q \bar{q}_L \mathcal{O}_q + \lambda_t \bar{t}_R \mathcal{O}_t + \text{h.c.},$ with $\langle 0 | \mathcal{O}_q | Q_n \rangle = \Delta_n, \langle 0 | \mathcal{O}_t | T_n \rangle = \Gamma_n$

inducing at low energies $\mathscr{L}_{\text{mix}} = \lambda_q \Delta_1 \bar{q}_L Q_{1R} + \lambda_t \Gamma_1 \bar{t}_R T_{1L} + \text{h.c.} + \ldots$



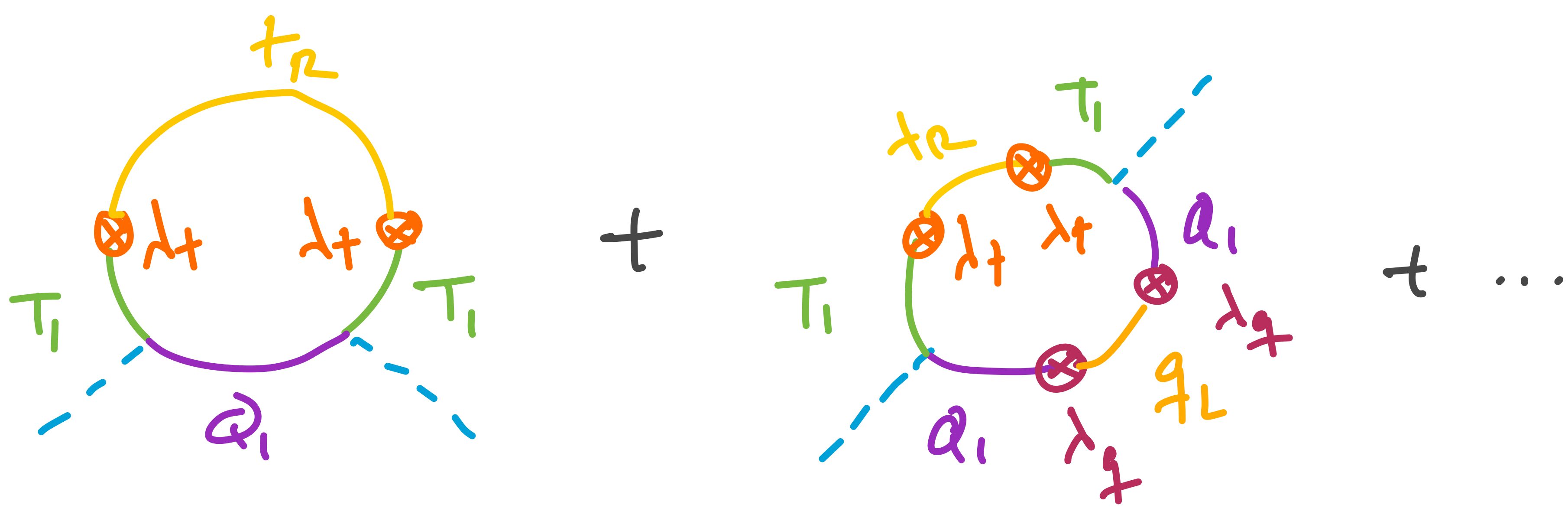
COMPOSITE HIGGS MODELS. PARTIAL COMPOSITENESS.

The solution to all our problems is called partial compositeness:

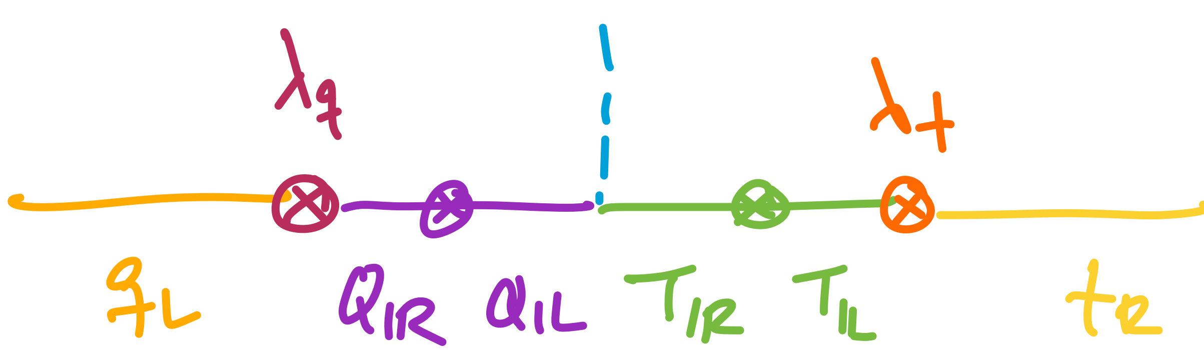
$$\mathscr{L}_{\rm mix} = \lambda_q \bar{q}_L \mathcal{O}_q + \lambda_t \bar{t}_R \mathcal{O}_t + \mathrm{h.c.}, \quad \text{with } \langle 0 | \mathcal{O}_q | Q_n \rangle = \Delta_n, \langle 0 | \mathcal{O}_t | T_n \rangle = \Gamma_n$$

inducing at low energies $\mathscr{L}_{\rm mix} = \lambda_q \Delta_1 \bar{q}_L Q_{1R} + \lambda_t \Gamma_1 \bar{t}_R T_{1L} + \mathrm{h.c.} + \ldots$

They contribute to the Higgs potential



And generate the light fermion masses



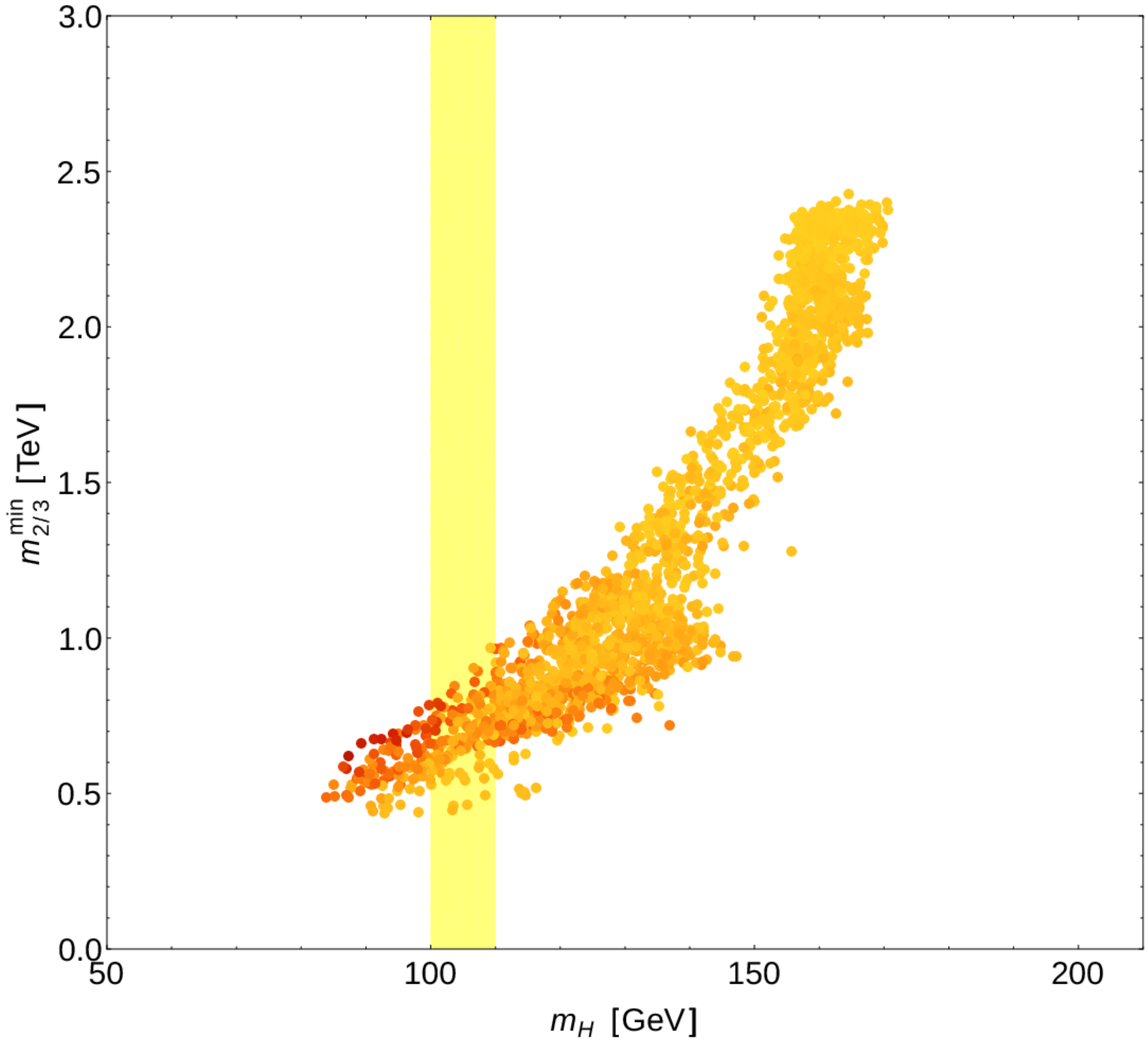
$$m_t \sim \frac{v}{\sqrt{2}} \frac{\lambda_q \Delta_1}{m_{Q_1}} \frac{\lambda_t \Gamma_1}{m_{T_1}} \frac{Y}{f}$$

COMPOSITE HIGGS MODELS. PARTIAL COMPOSITENESS

The solution to all our problems is called partial compositeness:

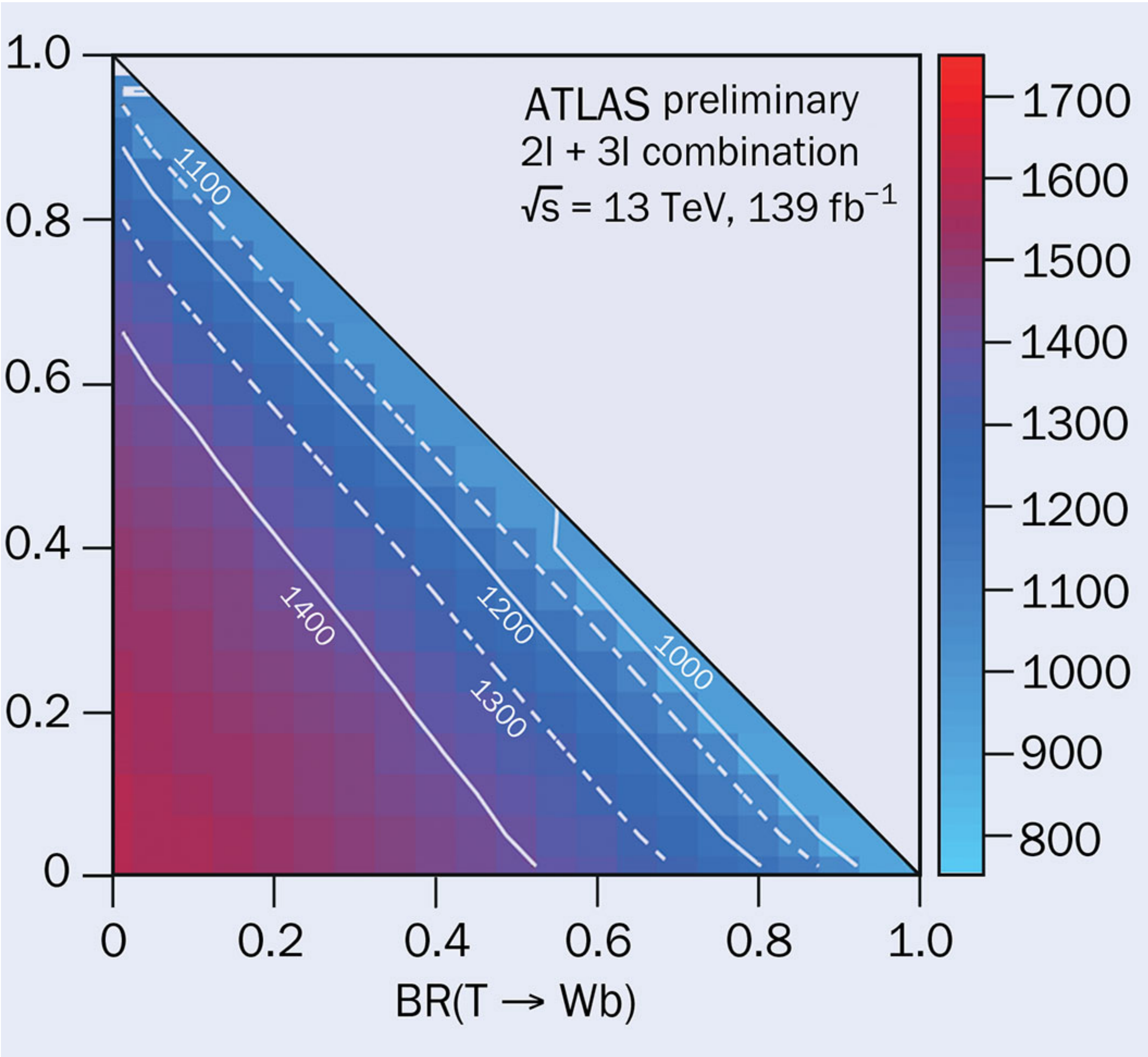
- It gives a contribution to the Higgs quartic with the opposite sign to that of the gauge bosons!
- It correlates the Higgs mass with the top one. Indeed, the top mass triggers EWSB.
- The Higgs potential is dynamically generated, not postulated as in the SM
- It helps with the flavor puzzle.
- Due to the large top mass, one typically expects light fermionic resonances, aka top partners.

COMPOSITE HIGGS MODELS. TOP PARTNERS.



Taken from 1410.8555, **JHEP 05 (2015) 022**

COMPOSITE HIGGS MODELS. TOP PARTNERS.



Taken from **ATLAS-CONF-2021-024**

COMPOSITE HIGGS MODELS. PARTIAL COMPOSITENESS

Partial compositeness solves the flavor puzzle

$\mathscr{L}_{\text{int}} = \frac{\lambda_q}{\Lambda_{\text{UV}}^{\gamma_q}} \bar{q}_L \mathcal{O}_q + \frac{\lambda_t}{\Lambda_{\text{UV}}^{\gamma_t}} \bar{t}_R \mathcal{O}_t$, with $\left[\mathcal{O}_{q,t}\right] = 5/2 + \gamma_{q,t}$ $\quad \mathcal{O}_{q,t} \sim \Psi\Psi\Psi$

The naive estimate of the quark masses read

$m_q \sim g_* v \frac{N_{TC}}{16\pi^2} \lambda_q(\Lambda_{\text{IR}}) \lambda_t(\Lambda_{\text{IR}})$, with $m_* \sim g_* f \sim \frac{4\pi}{\sqrt{N_{\text{TC}}}} \sim \Lambda_{\text{IR}}$

Therefore,

$$m_q \sim v \frac{\sqrt{N_{TC}}}{4\pi} \lambda_q(\Lambda_{\text{IR}}) \lambda_t(\Lambda_{\text{IR}})$$

The RGE of $\lambda_{q,t}$ reads

$$\mu \frac{d}{d\mu} \lambda = \gamma \lambda + c \frac{N_{\text{TC}}}{16\pi^2} \lambda^3$$

Partial compositeness solves the flavor puzzle

$$m_q \sim v \frac{\sqrt{N_{TC}}}{4\pi} \lambda_q(\Lambda_{\rm IR}) \lambda_t(\Lambda_{\rm IR})$$

The RGE of $\lambda_{q,t}$ reads

$$\mu \frac{d}{d\mu} \lambda = \gamma \lambda + c \frac{N_{\rm TC}}{16\pi^2} \lambda^3$$

- $\gamma_{q,t} > 0$: (Useful for light fermions)

$$\lambda_{q,t}(\mu) = \lambda_{q,t}(\Lambda) \left(\frac{\mu}{\Lambda} \right)^{\gamma_{q,t}} \Rightarrow m_q \sim v \frac{\sqrt{N_{\rm TC}}}{4\pi} \left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm UV}} \right)^{\gamma_q + \gamma_t}$$

- $[\gamma_{q,t} < 0] \wedge [c > 0]$: the RGE goes to an IR fixed point. (Useful for the top)

$$\lambda_* \cong \sqrt{\frac{-\gamma}{c}} \frac{4\pi}{\sqrt{N_{\rm TC}}} \Rightarrow m_q \sim v \frac{4\pi}{\sqrt{N_{\rm TC}}} \sqrt{\gamma_q \gamma_t}$$

COMPOSITE HIGGS MODELS. EXTRA SCALARS.

As we have seen, the minimal non-custodial model is $SU(3)/\left[SU(2) \otimes U(1)\right]$.

The minimal custodial model is $SO(5)/SO(4)$.

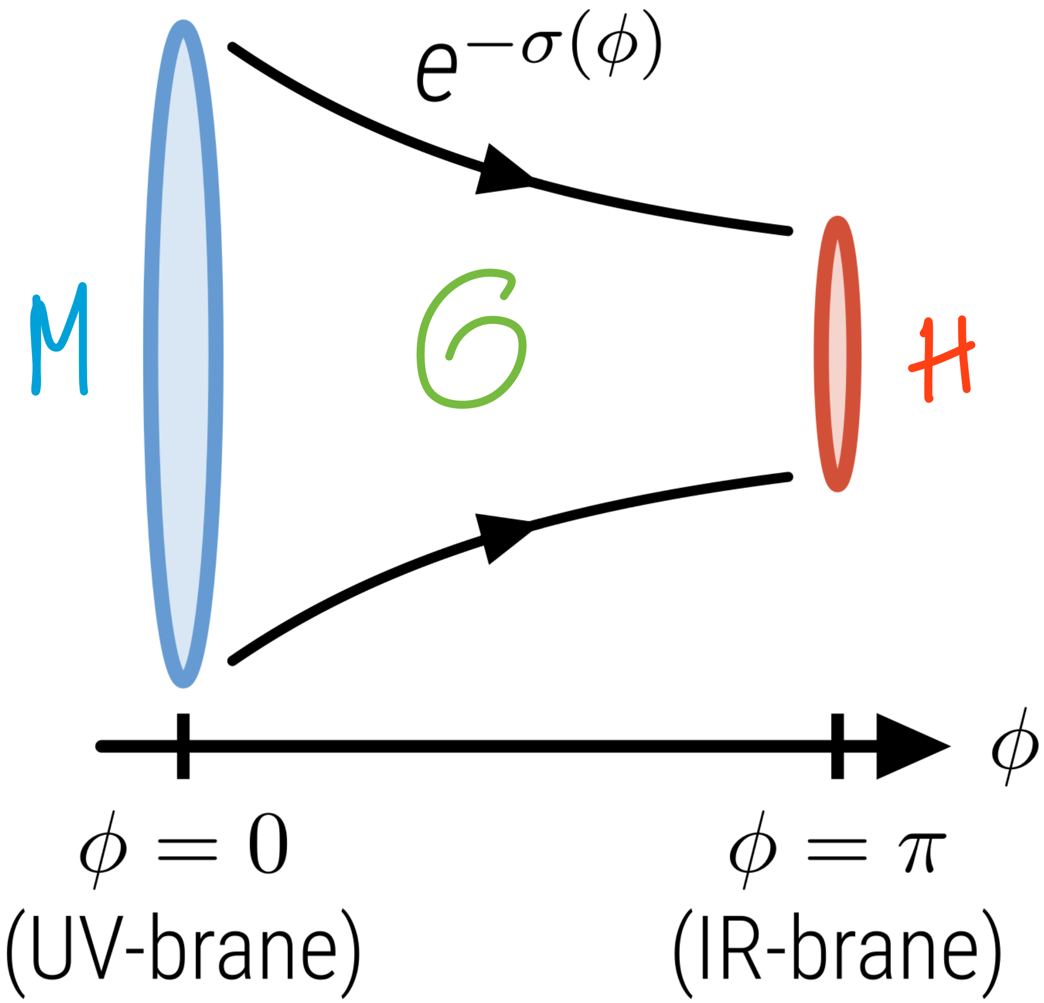
Models that can be UV completed in 4D with new fermions (under some reasonable assumptions) require bigger cosets:

- $SU(5)/SO(5) : \mathbf{14} = \mathbf{3}_1 \oplus \mathbf{3}_0 \oplus \mathbf{2}_{1/2} \oplus \mathbf{1}_0$. under $SU(2) \otimes U(1)$
- $SU(4)/Sp(4) : \mathbf{5} = \mathbf{2} \oplus \mathbf{1}_0$
- $\left[SU(4) \otimes SU(4)\right]/SU(4) : \mathbf{15} = \mathbf{3}_0 \oplus \mathbf{2}_{1/2} \oplus \mathbf{2}'_{1/2} \oplus \mathbf{1}_1 \oplus \mathbf{1}_0 \oplus \mathbf{1}'_0$
- …

So, light pNGBs which are singlets under the EW group a natural expectation in these scenarios (aka axion-like particles)

HOLOGRAPHY

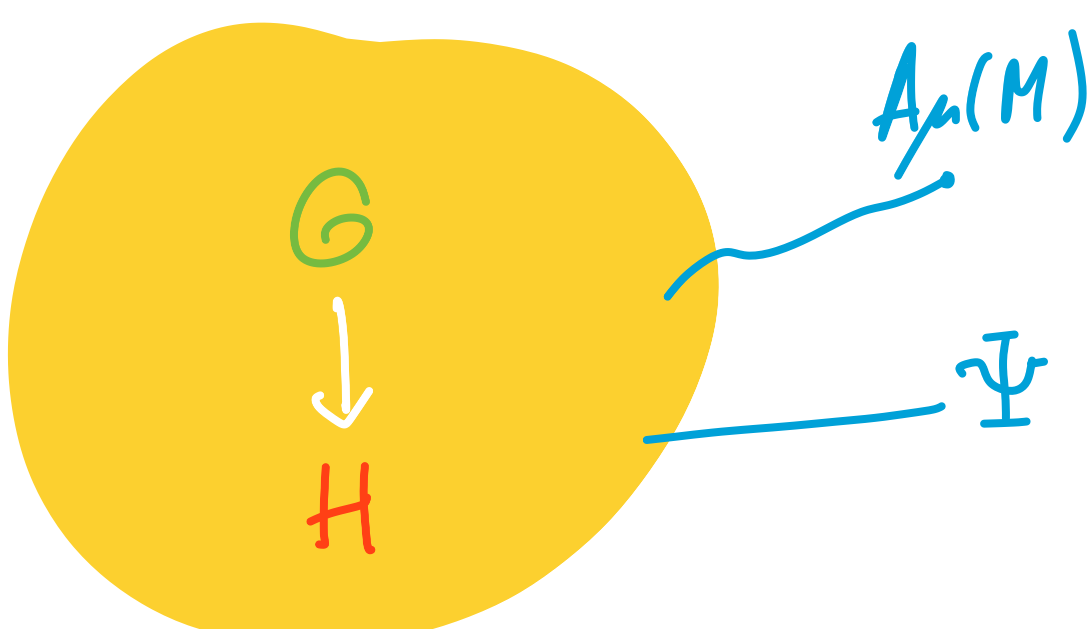
HOLOGRAPHY

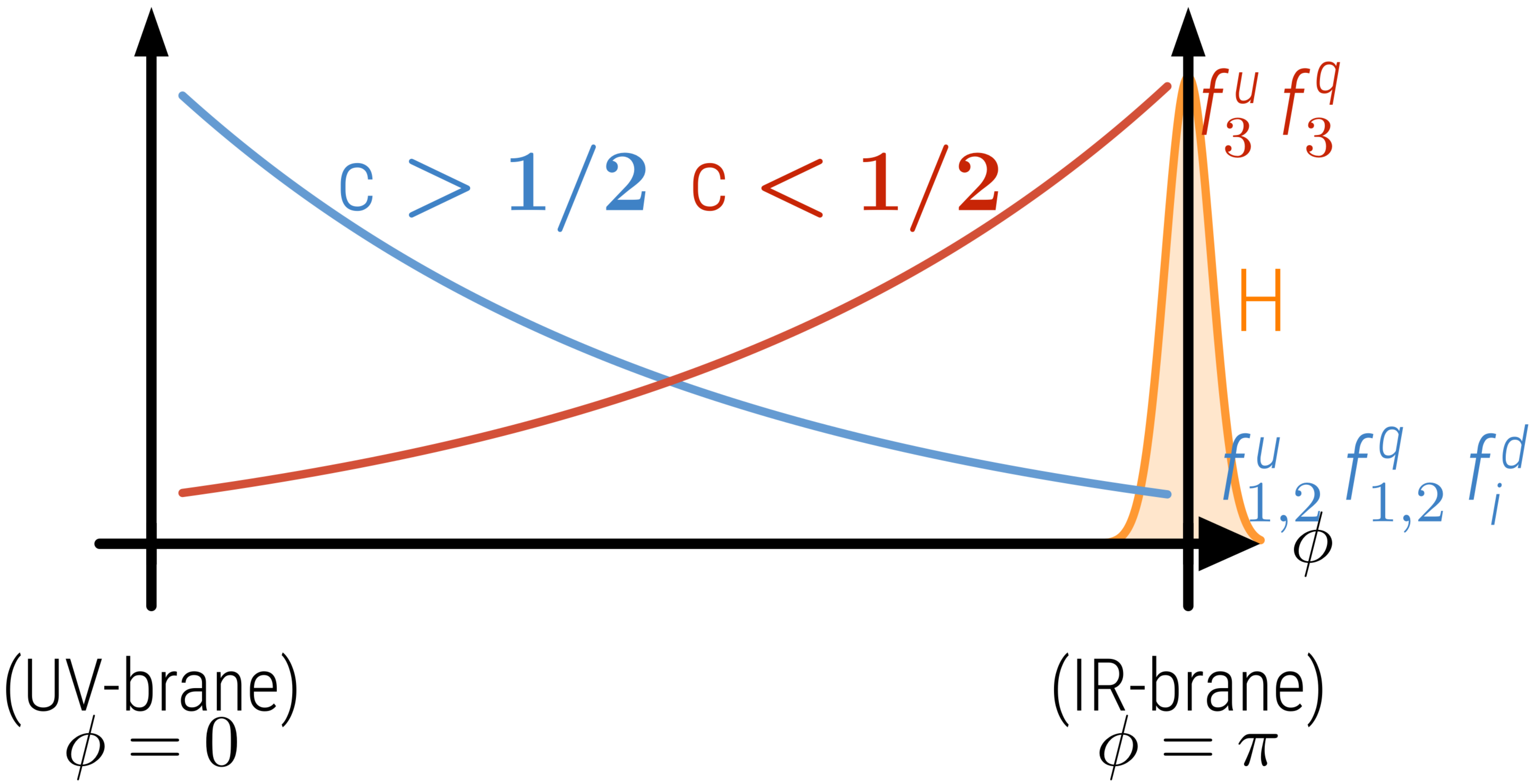


$$ds^2 = e^{-2\sigma(\phi)}\,\eta_{\mu\nu}dx^\mu dx^\nu - r^2\,d\phi^2$$

UV: $m \sim M_{\mathrm{Pl}} = 2 \cdot 10^{15}$ TeV

IR: $m \sim M_{\mathrm{Pl}} \cdot e^{-\sigma(\pi)} \sim$ TeV





$c > 1/2$
$c < 1/2$
$f^u_3\ f^q_3$
H
$f^u_{1,2}\ f^q_{1,2}\ f^d_i$
ϕ
(UV-brane)
$\phi = 0$
(IR-brane)
$\phi = \pi$

Sorry but they only gave me two hours.

BSM – LECTURE 2

TALLER DE ALTAS ENERGÍAS (TAE) 2024

Adrián Carmona Bermúdez. Universidad de Granada.

UNIVERSIDAD DE GRANADA

BEYOND THE SM

BEYOND THE BAD

NEW PHYSICS AFTER THE LHC NULL RESULTS

The LHC has not yet observed any sign of new physics (NP):

- Naturalness might not be the lighthouse we thought it was.
- There seems to be a significant mass gap between the EW scale and the scale of NP ⇒ Ideal for effective field theories (EFTs).
- It is still possible for NP to be light but it would need to be very weakly couple ⇒ Searches for long-lived particles (LLP).

We will see a few examples during this lecture. Since we have very limited time, we will just consider very few cases:

Apologies if your favorite NP model is not mentioned!

LONG-LIVED PARTICLES

LONG-LIVED PARTICLES

Most of LHC experimental searches assume prompt decays of the particles involved or a sizable amount of missing energy.

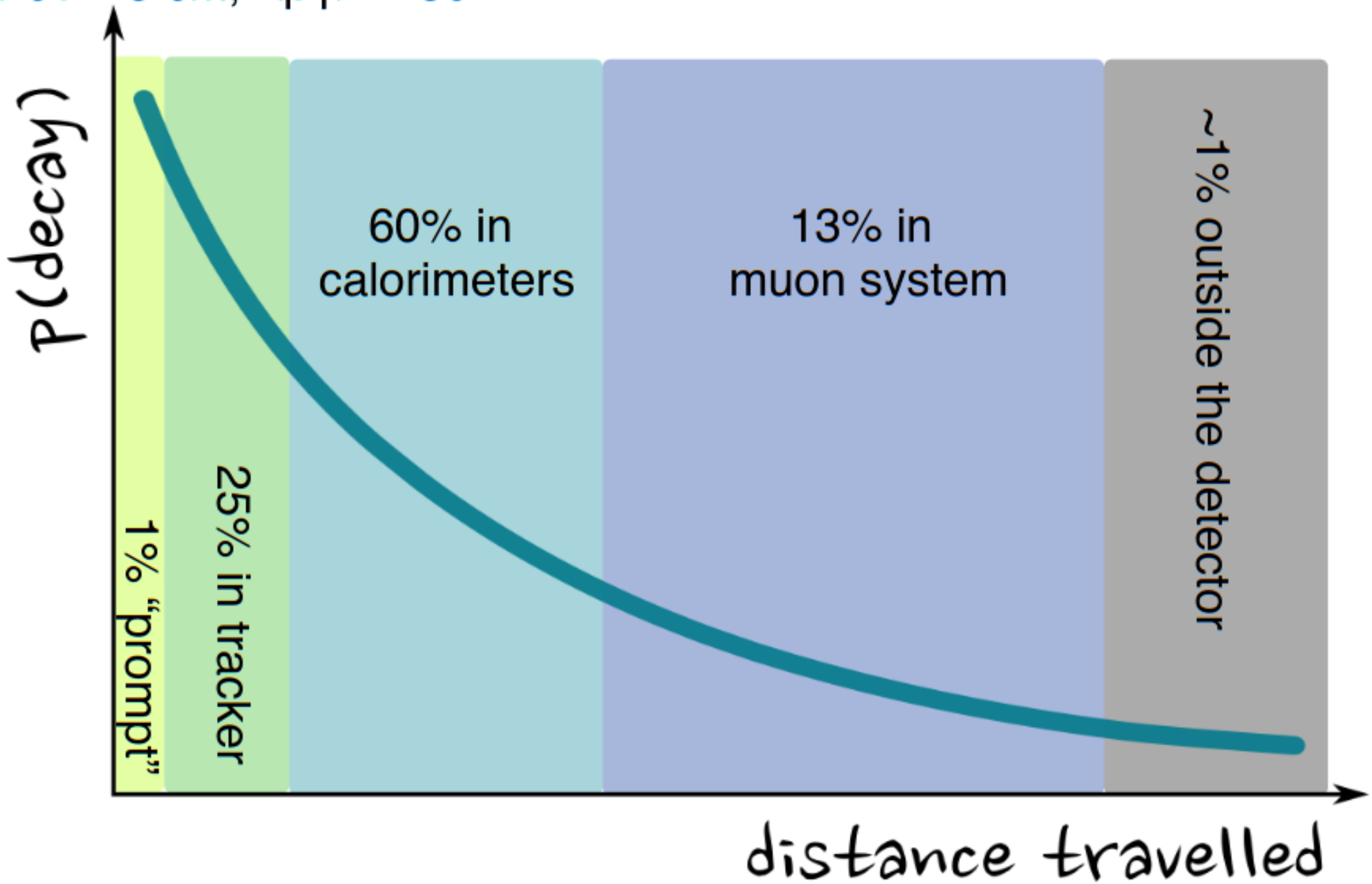
But life is not black and white, there are a lot of grays! Long-lived particles (LLPs) are **predicted in many BSM scenarios**

- Particle decays mediated via heavy virtual mediators (e.g. heavy neutral leptons) – $m \ll M$
- Nearly mass degenerate states (e.g. compressed SUSY)
- Small couplings to SM particles (e.g. dark mediators) – g small

$$\frac{1}{\tau} = \Gamma = \frac{1}{2m} \int \mathrm{d}\Phi \, |\mathscr{M}|^2 \sim \frac{g^2}{(8\pi)^{a-1}} \frac{m^2}{M^{n-1}}$$

LONG-LIVED PARTICLES

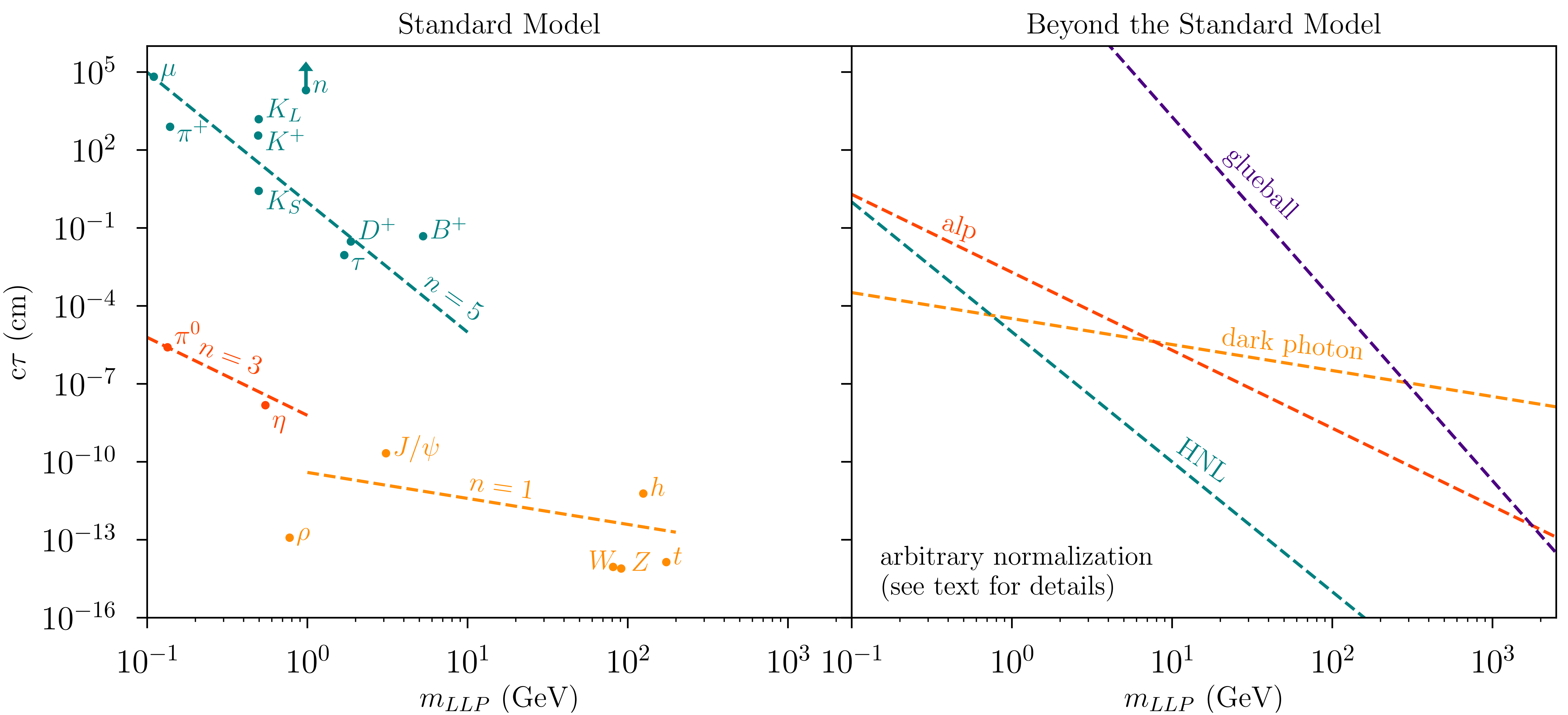
e.g. for $c\tau$ = 5 cm, $\langle\beta\gamma\rangle \sim 30$



Taken from **Heather Russel**

LONG-LIVED PARTICLES

Taken from **2212.03883**



There are plenty of possible LLPs, some of them in the SM. For instance

$$c\tau(K^+) = 3.71\,\text{m},\; c\tau(D^+) = 311.78\,\mu\text{m},\; c\tau(B^+) = 491.06\,\mu\text{m},\; \ldots$$

The CMS collaboration at CERN presents its latest search for new exotic particles

This search for exotic long-lived particles looks at the possibility of "dark photon" production, which would occur when a Higgs boson decays into muons displaced in the detector

10 NOVEMBER, 2023

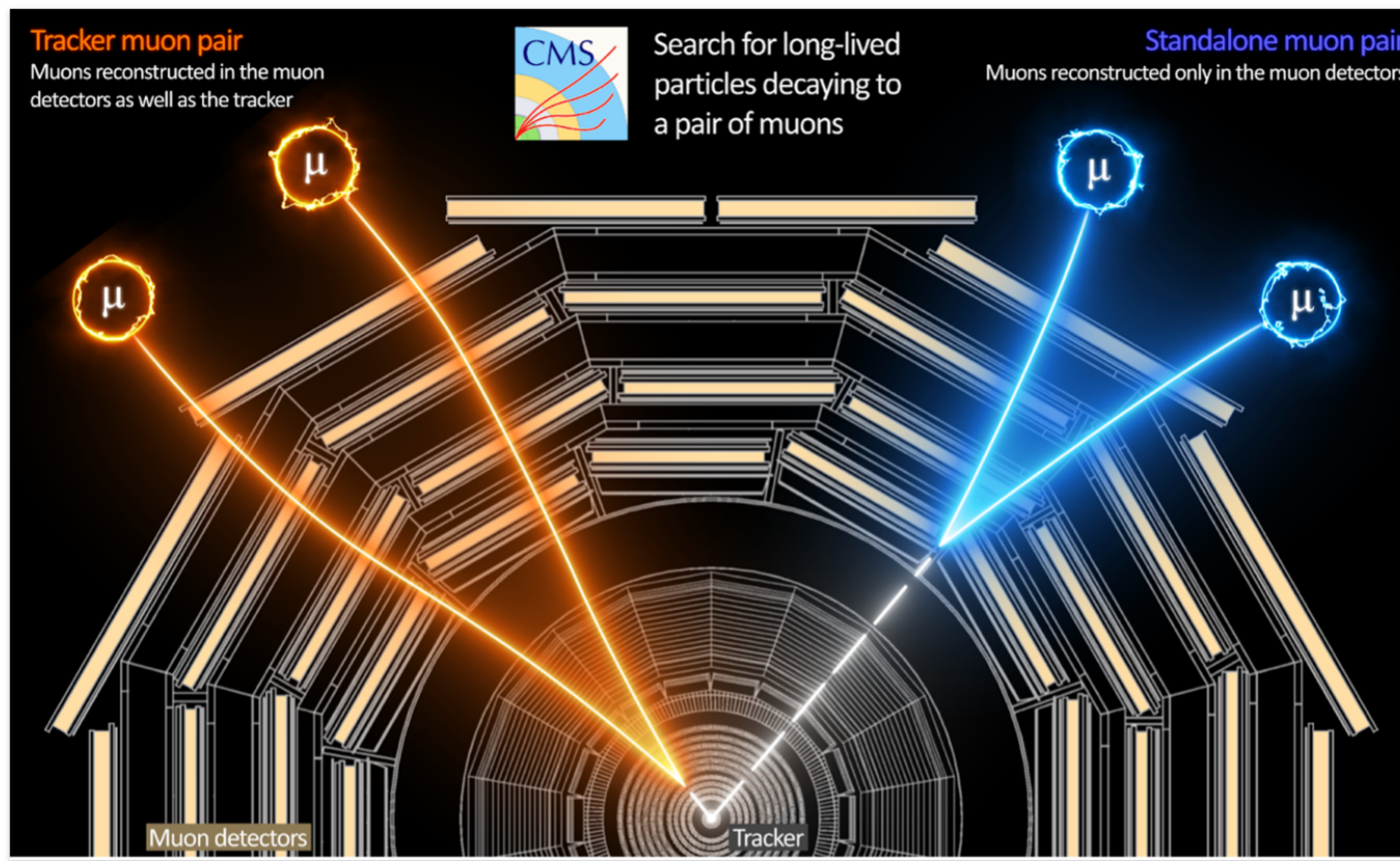


Illustration of two types of long-lived particles decaying into a pair of muons, showing how the signals of the muons can be traced back to the long-lived particle decay point using data from the tracker and muon detectors. (Image: CMS/CERN)

The CMS experiment has presented its first search for new physics using data from Run 3 of the Large Hadron Collider. The new study looks at the possibility of "dark photon" production in the decay of Higgs bosons in the detector. Dark photons are exotic long-lived particles: "long-lived" because they have an average lifetime of more than a tenth of a billionth of a second – a very long lif[redacted] – and

A QCD-LIKE DARK SECTOR

DARK SECTORS

STANDARD MODEL

↕ PORTAL

DARK SECTOR

$$m_N \approx 1\,\mathrm{GeV}$$
$$n_B/n_\gamma \approx 6 \cdot 10^{-10}$$
$$\Omega_B \approx 0.046$$

COULD THE OBSERVED BARYONIC ABUNDANCE BE A THERMAL RELIC?

$$\frac{\rho_{\mathrm{DM}}}{\rho_\gamma} \sim \frac{M}{T_0}\frac{n_{\mathrm{DM}}}{n_\gamma} \sim \frac{1}{M_{\mathrm{Pl}}\sigma T_0}$$

If we plug $M = m_N$ and $\sigma \sim m_\pi^{-1}$ we get something 10^{-8} times smaller than the observed abundance. Baryons are not thermal relic.

Why should DM be a thermal relic then?

ASYMMETRIC DARK MATTER

If you look at baryons:

$$m_N \approx 1\,\mathrm{GeV}$$
$$n_B/n_\gamma \approx 6 \cdot 10^{-10}$$
$$\Omega_B \approx 0.046$$

BARYONS ARE NOT THERMAL RELICS

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.15 \pm 0.25) \cdot 10^{-10}$$

We know that a small primordial excess of baryons over anti-baryons η_B was preserved until today because baryon number is conserved.

Below $T \sim m_N$ the protons and anti-protons annihilate efficiently and only the small excess remains!

ASYMMETRIC DARK MATTER

If you look at baryons:

$$m_N \approx 1\,\mathrm{GeV}$$
$$n_B/n_\gamma \approx 6 \cdot 10^{-10}$$
$$\Omega_B \approx 0.046$$

BARYONS ARE NOT THERMAL RELICS

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.15 \pm 0.25) \cdot 10^{-10}$$

The primordial asymmetry requires Sakarov conditions:

- Violation of B number
- Violation of CP
- Out-of-equilibrium dynamics

ASYMMETRIC DARK MATTER

If you look at baryons:

$$m_N \approx 1\,\mathrm{GeV}$$
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BARYONS ARE NOT THERMAL RELICS

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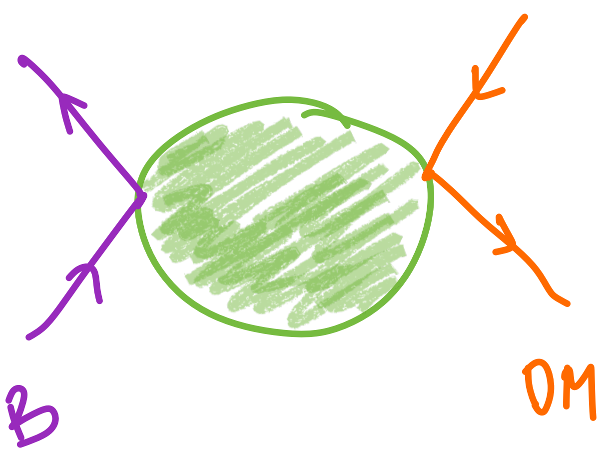
Let us apply the baryon example to DM ⇒ asymmetric dark matter.

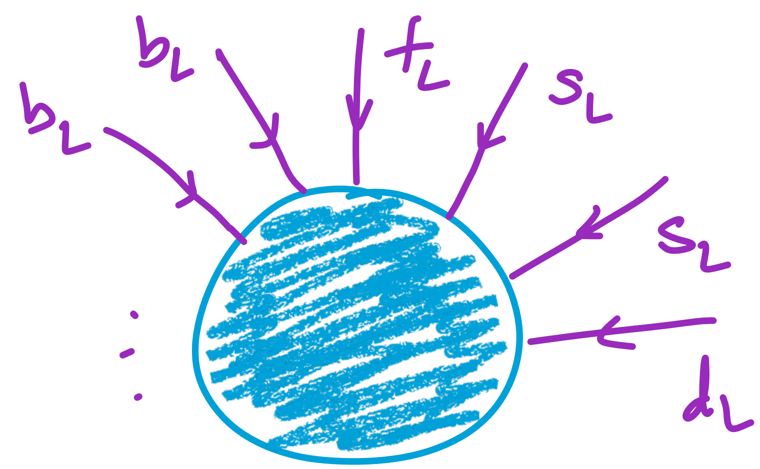
If $\eta_{\mathrm{DM}}/\eta_B = \mathcal{O}(1)$,

$$\frac{\Omega_{\mathrm{DM}}}{\Omega_B} = \frac{m_{\mathrm{DM}}}{m_N}\frac{\eta_{\mathrm{DM}}}{\eta_B} \Rightarrow m_{\mathrm{DM}} \approx 5 m_N \approx 5\,\mathrm{GeV}$$

ASYMMETRIC DARK MATTER

A DM candidate of $m_{\rm DM} = \mathcal{O}(5\,{\rm GeV})$ is not the only possibility. If $\eta_B \sim \eta_{\rm DM}$ is the consequence of weak sphalerons instead of some new interaction.





sphalerons

If $m_{\rm DM} \gtrsim T_{\rm EW}$, with $T_{\rm EW}$ the critical temperature below which sphalerons turn off the asymmetric DM abundance is Boltzmann suppressed:

$$\Omega_{\rm DM}/\Omega_B \approx e^{-T_{\rm EW}/m_{\rm DM}} m_{\rm DM}/m_N \Rightarrow m_{\rm DM} \approx 8T_{\rm EW} \approx 2\,{\rm TeV}$$

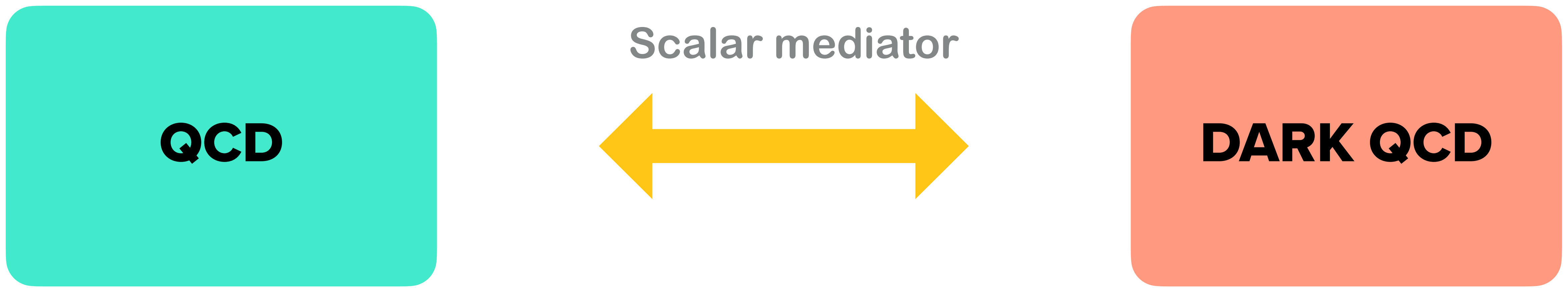
Example: DM is a bound state of fermions chiral under $SU(2)_L$.

ASYMMETRIC DARK MATTER

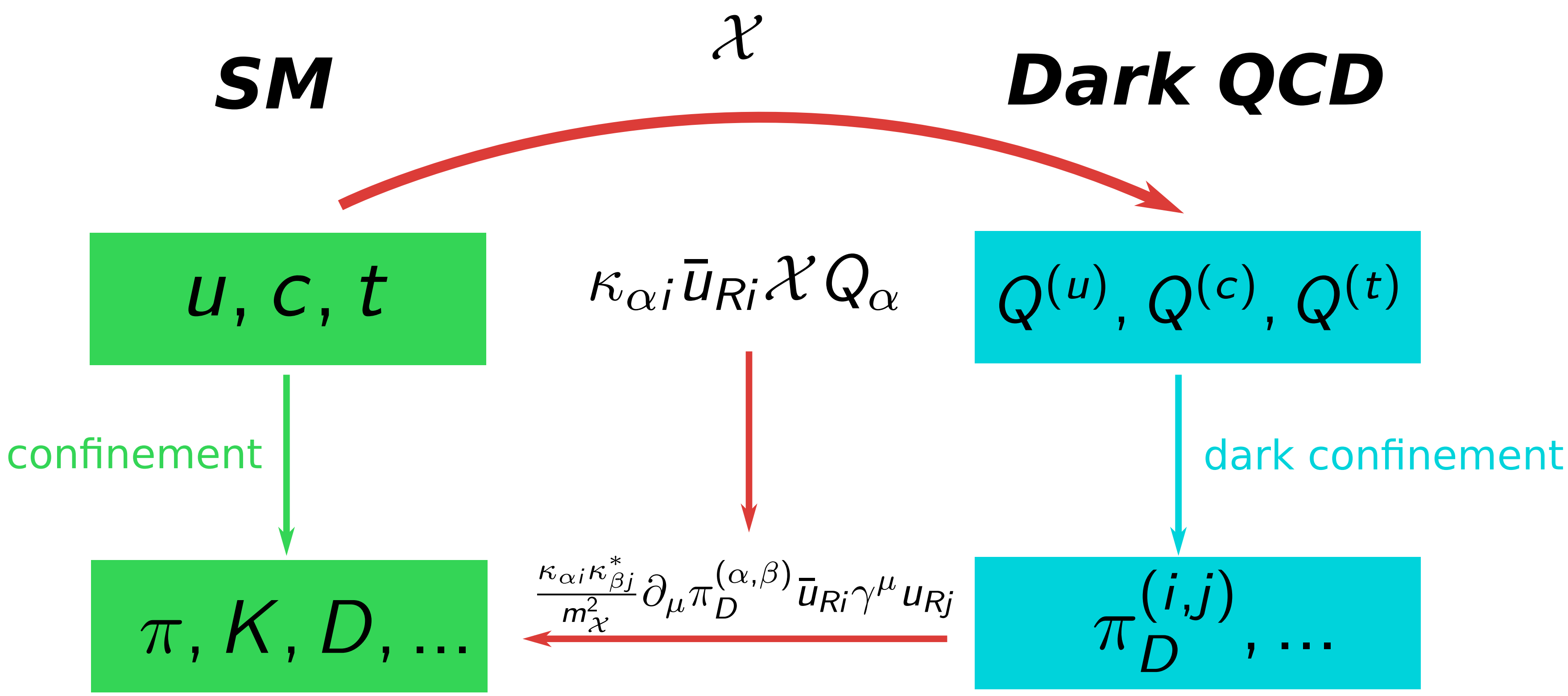
ADM models present several advantages over the WIMP paradigm:

- Alternative explanation of the relic density
- Avoids stringent direct/indirect limits (absence of $\overline{\mathrm{DM}}$ to co-annihilate)
- Self interaction solves small scale structure problems
- They show a different phenomenology

There are plenty of ADM models. We will examine in more detail the example of a QCD-like dark sector (without entering into details of the asymmetry generation, asymmetry transfer, …).



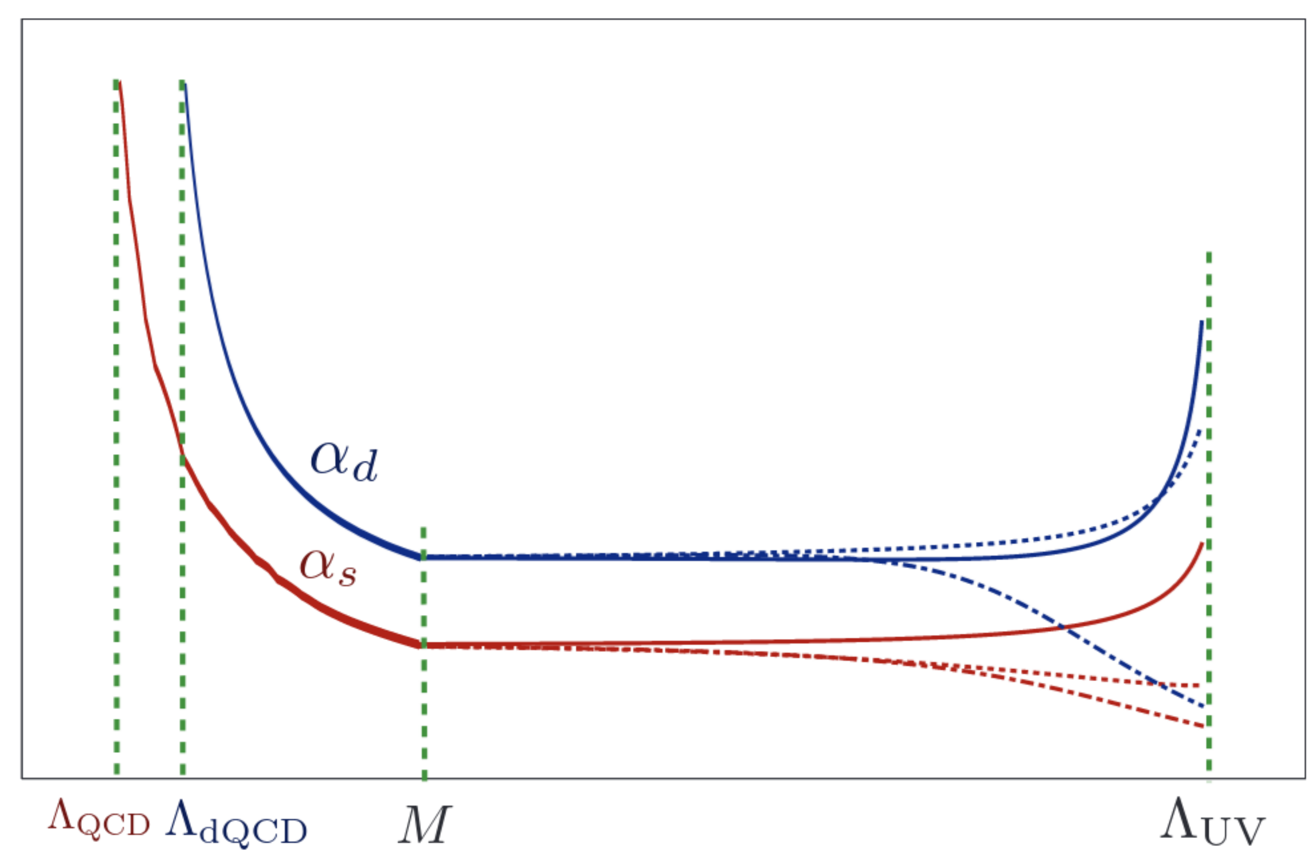
A QCD-LIKE DARK SECTOR



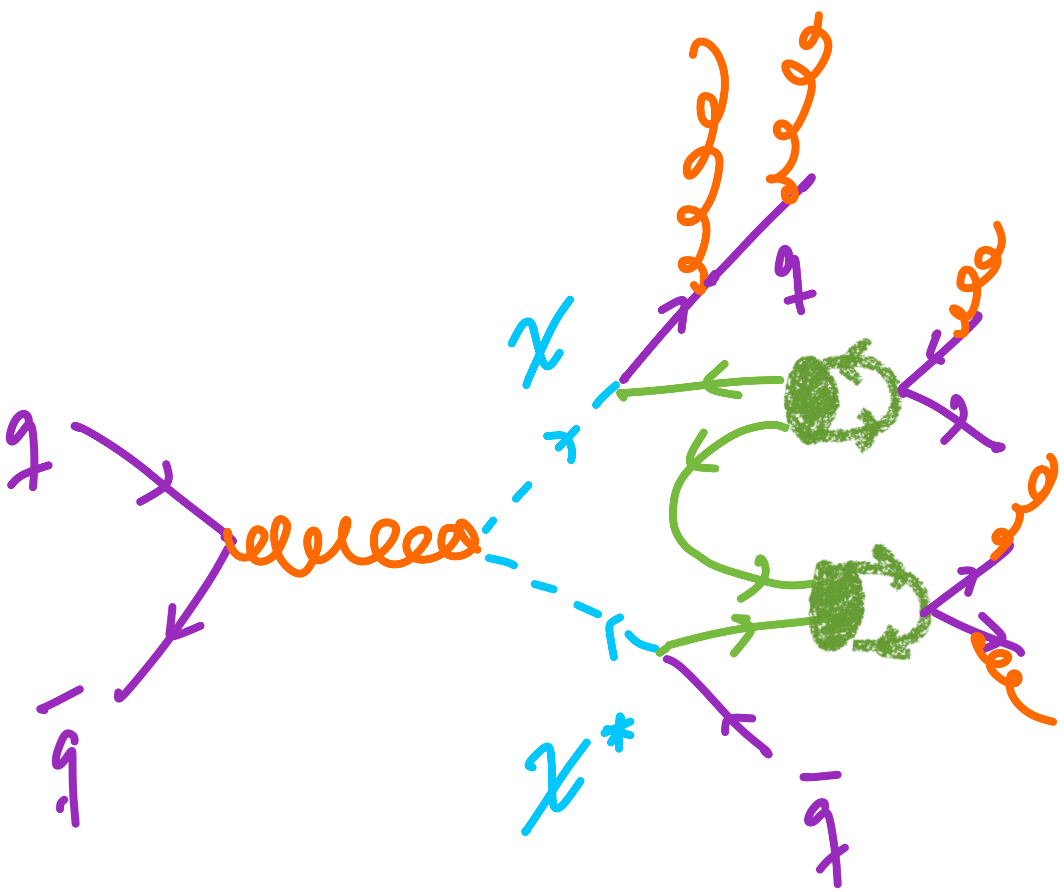
We expect efficient annihilation via

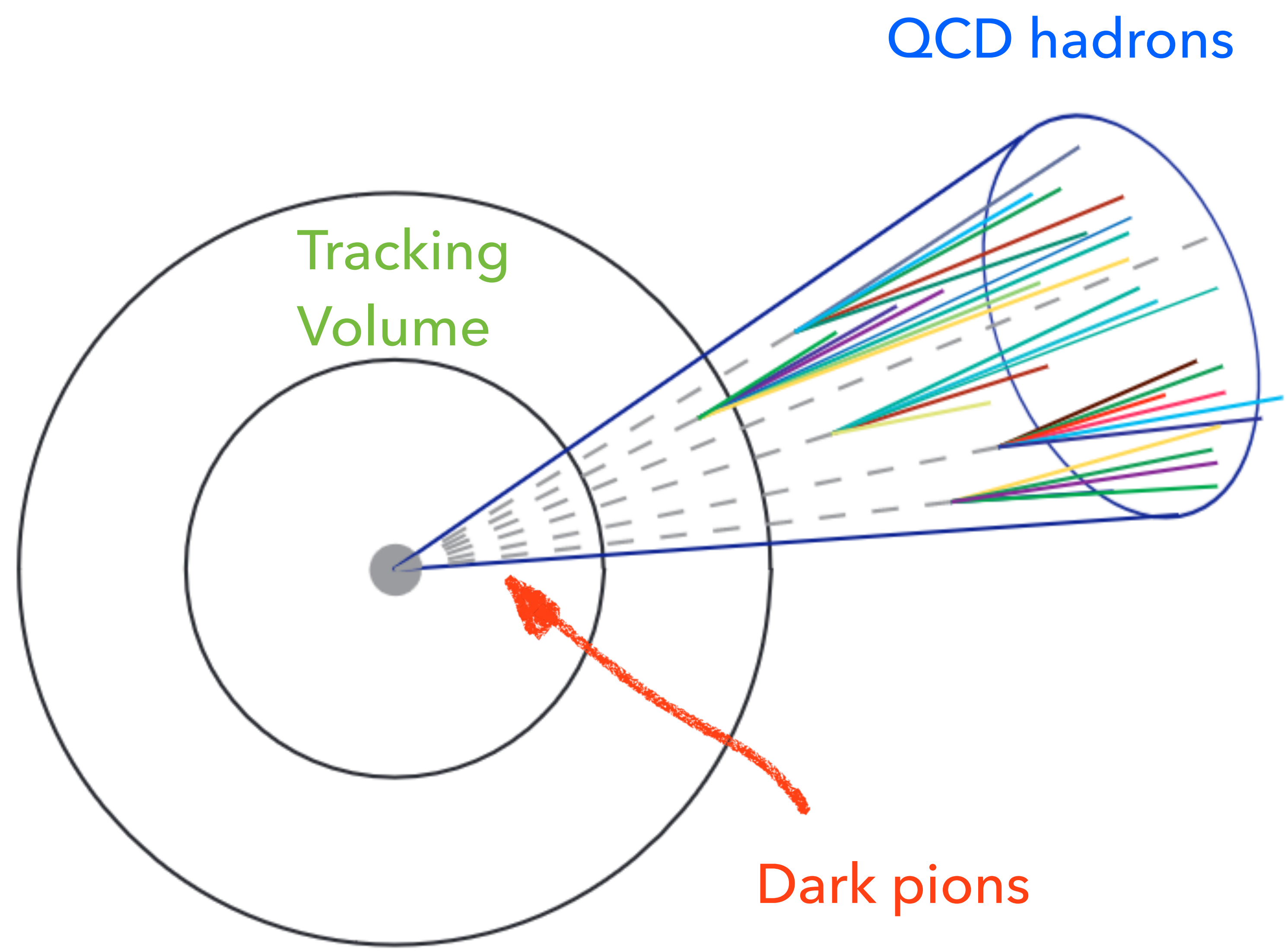
$$p_D \bar{p}_D \rightarrow \pi_D \pi_D$$

- $SU(N_D)$ gauge group, with $N_D \geq 3$
- n_{df} dark fermions
- $m_Q \ll \Lambda_{dQCD}$
- $SU(n_f)_L \otimes SU(n_f)_R \rightarrow SU(n_f)_V$



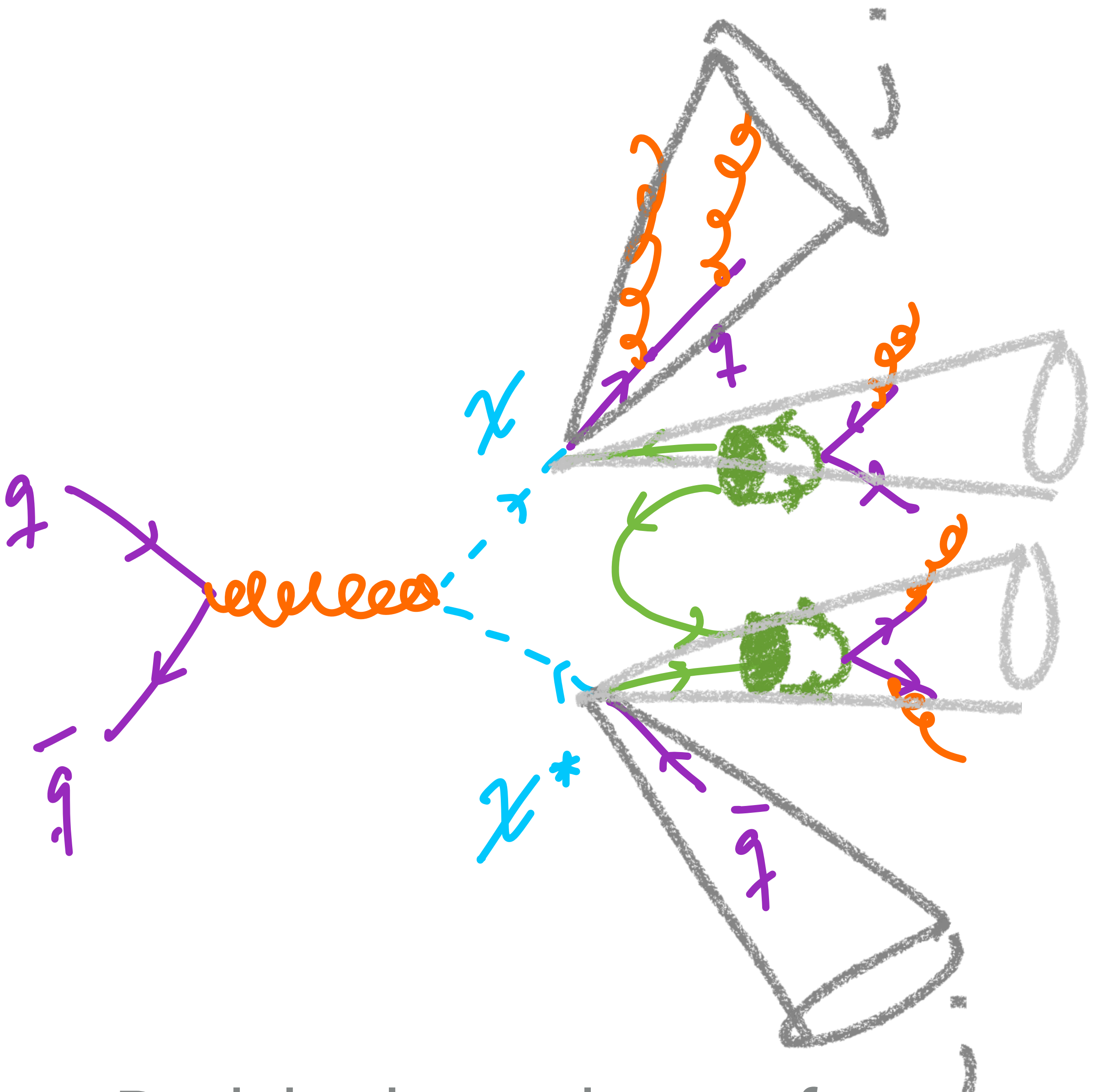
A QCD-LIKE DARK SECTOR. A VERY DIFFERENT PHENO.

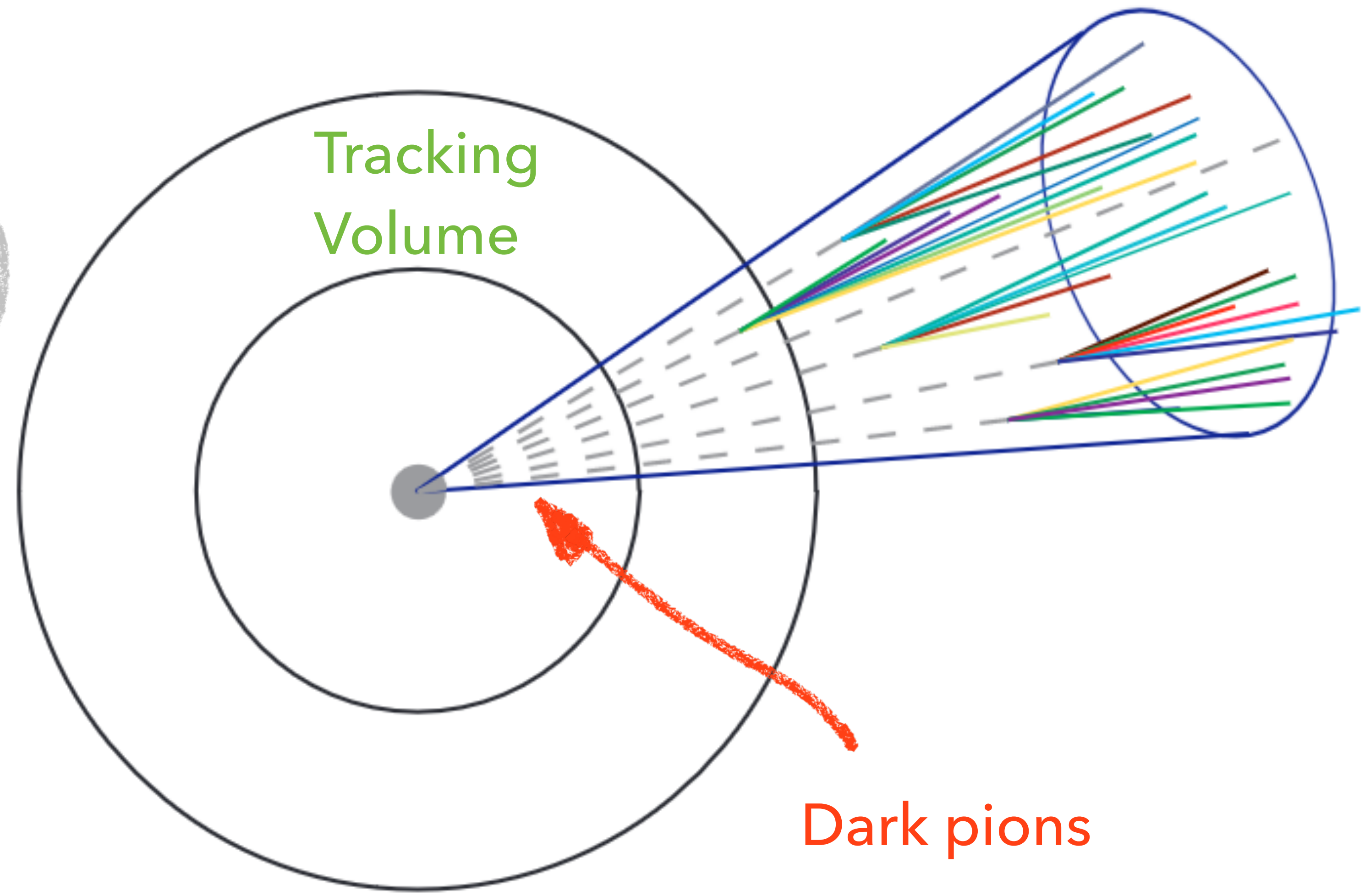




- Dark hadrons decay after some lifetime
- We end up with multiple displaced vertices within each jet
- This is called an emerging jet

A QCD-LIKE DARK SECTOR. A VERY DIFFERENT PHENO.





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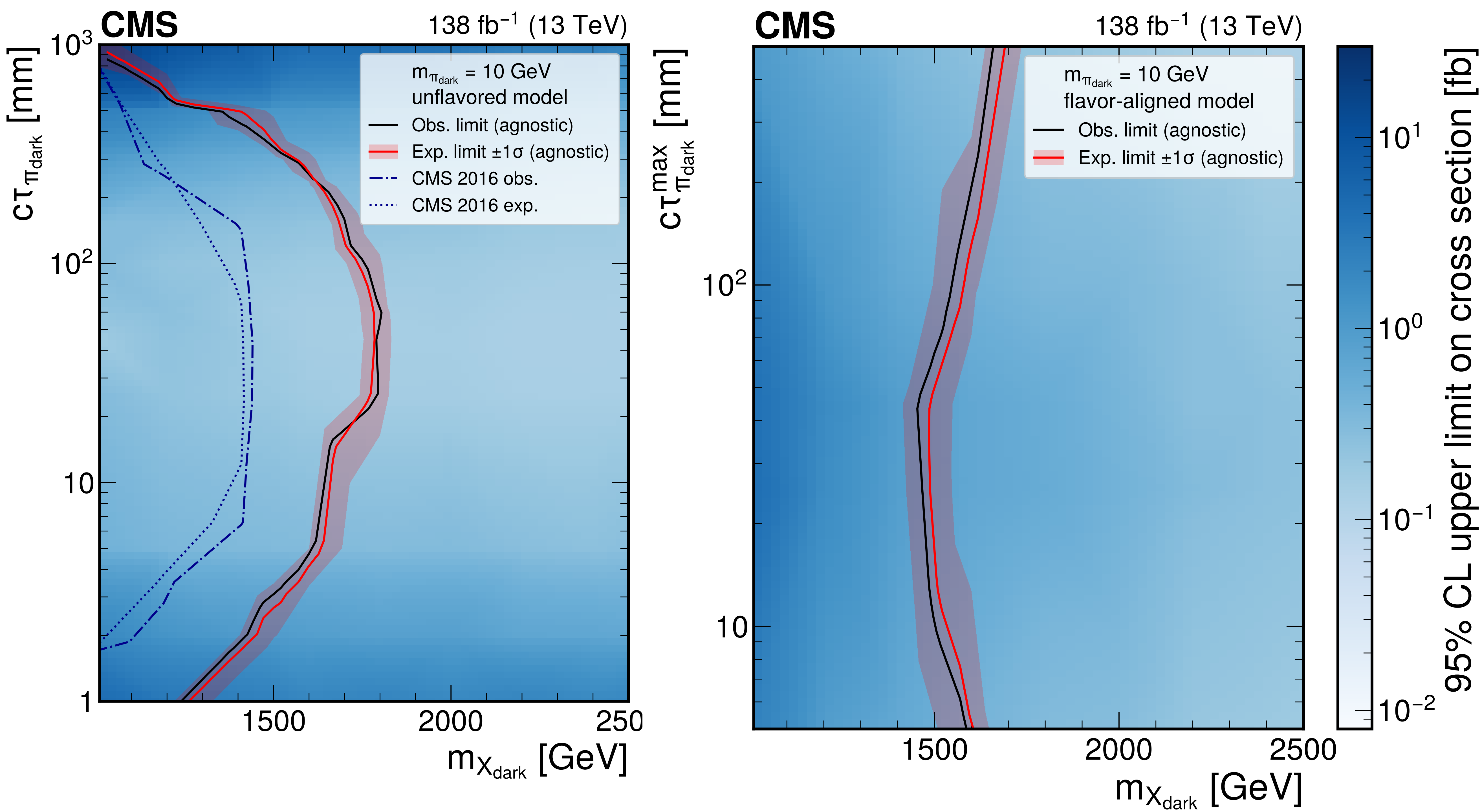

Taken from **JHEP 07 (2024) 142**

A QCD-LIKE DARK SECTOR

In the $n_{df} = 3 = N_D$ case, when $m_Q \to 0, m_\chi \to \infty$, we have

$$SU(3)_L \otimes SU(3)_R \to SU(3)_V$$

by $\langle \bar{Q}_\alpha Q_\beta \rangle = \delta_{\alpha\beta} \Lambda^3_{dQCD}$, delivering 8 pNGBs

Dark Pions	Dark Quark content
$\pi_D^{(1,2)}$	$\bar{Q}_2 Q_1$
$\pi_D^{(1,3)}$	$\bar{Q}_3 Q_1$
$\pi_D^{(2,3)}$	$\bar{Q}_3 Q_2$
π_{D3}	$1/\sqrt{2}\,[\bar{Q}_1 Q_1 - \bar{Q}_2 Q_2]$
π_{D8}	$1/\sqrt{6}\,[\bar{Q}_1 Q_1 + \bar{Q}_2 Q_2 - 2\bar{Q}_3 Q_3]$

A QCD-LIKE DARK SECTOR

Depending on the quantum numbers of the mediator we will have different phenomenology for the '[dark pions]' (note that they are not really dark since they are unstable and decay into SM fermions).

$$SU(3)_c \otimes SU(3)_D \otimes SU(2)_L \otimes U(1)_Y \equiv \mathcal{G}_{gauge}$$

$$\chi \sim (3, \bar{3}, 1, 1/3) \qquad \mathcal{L}_{int} \supset -\kappa_{\alpha i} \overline{d_{Ri}} Q_{L\alpha} \chi + h.c$$

Schwaller, Renner '18

$$\chi \sim (3, \bar{3}, 1, -2/3) \qquad \mathcal{L}_{int} \supset -\kappa_{\alpha i} \overline{u_{Ri}} Q_{L\alpha} \chi + h.c$$

AC, Scherb, Schwaller '21

A QCD-LIKE DARK SECTOR

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$$SU(3)_c \otimes SU(3)_D \otimes SU(2)_L \otimes U(1)_Y \equiv \mathcal{G}_{gauge}$$

$$\chi \sim (3, \bar{3}, 1, 1/3) \qquad \mathcal{L}_{eff} \supset \frac{f_D^2}{m_\chi^2} \kappa_{\alpha i} \kappa^*_{\beta j} \partial_\mu \pi_D^{(\alpha,\beta)} \bar{d}_{Ri} \gamma^\mu d_{Rj}$$

Schwaller, Renner '18

$$\chi \sim (3, \bar{3}, 1, -2/3) \qquad \mathcal{L}_{eff} \supset \frac{f_D^2}{m_\chi^2} \kappa_{\alpha i} \kappa^*_{\beta j} \partial_\mu \pi_D^{(\alpha,\beta)} \bar{u}_{Ri} \gamma^\mu u_{Rj}$$

AC, Scherb, Schwaller '21

After dark confinement

A QCD-LIKE DARK SECTOR

Depending on the quantum numbers of the mediator we will have different phenomenology for the 'dark pions' (note that they are not really dark since they are unstable and decay into SM fermions).

Dark Pions	Dark Quark content
$\pi_D^{(1,2)}$	$\bar{Q}_2 Q_1$
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π_{D3}	$1/\sqrt{2}\,[\bar{Q}_1 Q_1 - \bar{Q}_2 Q_2]$
π_{D8}	$1/\sqrt{6}\,[\bar{Q}_1 Q_1 + \bar{Q}_2 Q_2 - 2\bar{Q}_3 Q_3]$

A QCD-LIKE DARK SECTOR

We can study e.g. the phenomenology of these two. We can treat the matrix $\kappa^T_{\alpha i} \sim (\mathbf{3}, \bar{\mathbf{3}})$ as a spurion of the flavor group $SU(3)_q \otimes SU(3)_Q$. In the alignment limit, its vev lead to the breaking $SU(3)_q \otimes SU(3)_Q \to SU(3)_{q+Q}$.

Dark Pions	Dark Quark content
$\pi_D^{(1,2)}$	$\bar{Q}_2 Q_1$
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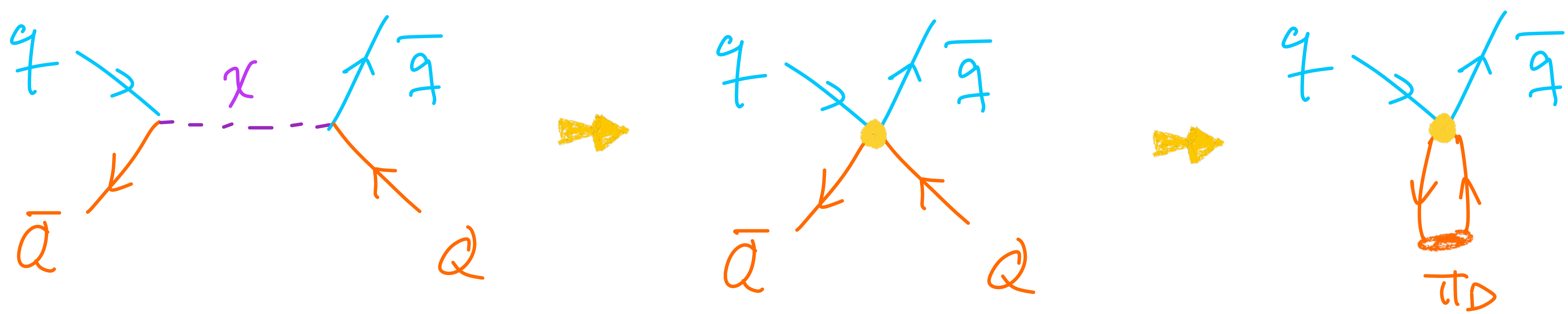
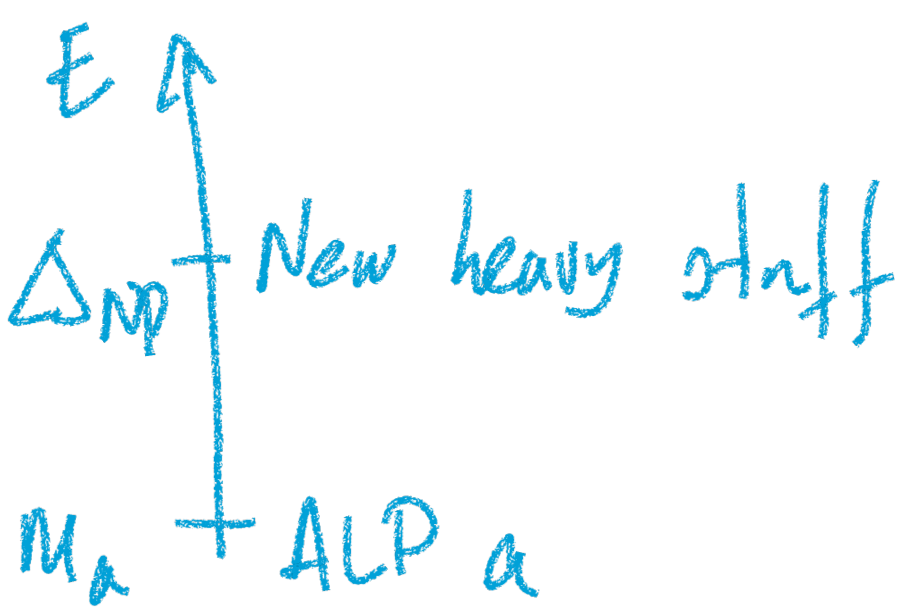
π_{D8}	$1/\sqrt{6}\,[\bar{Q}_1 Q_1 + \bar{Q}_2 Q_2 - 2\bar{Q}_3 Q_3]$

A QCD-LIKE DARK SECTOR

These dark mesons are essentially flavored axion-like particles (ALPs).

ALPs = CP-odd pNGBs of a spontaneously broken global symmetry





$a \longrightarrow a + \theta$

Shift symmetry

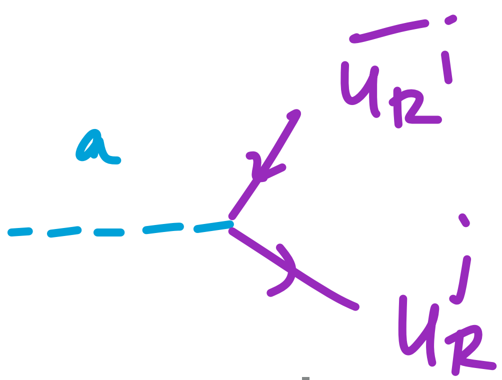
FLAVORED ALPS

The EFT for ALPs above the EW scale is

$$\mathscr{L} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{f_a}\sum_\psi \left(c_\psi\right)_{ij} \bar{\psi}_i \gamma^\mu \psi_j$$
$$-\frac{a}{f_a}\left[c_{GG}\frac{g_3^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} + c_{WW}\frac{g_2^2}{32\pi^2}W^I_{\mu\nu}\tilde{W}^{I\,\mu\nu} + c_{BB}\frac{g_1^2}{32\pi^2}B_{\mu\nu}\tilde{B}^{\mu\nu}\right]$$

Dark QCD will typically give rise to ALPs with only couplings to fermions (at tree-level). For instance, in the case where $\chi \sim (\mathbf{3}, \bar{\mathbf{3}}, 1, -2/3)$, we obtain

$$\mathscr{L} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{f_a}(c_{uR})_{ij}\left(\bar{u}_{Ri}\gamma^\mu u_{Rj}\right)$$

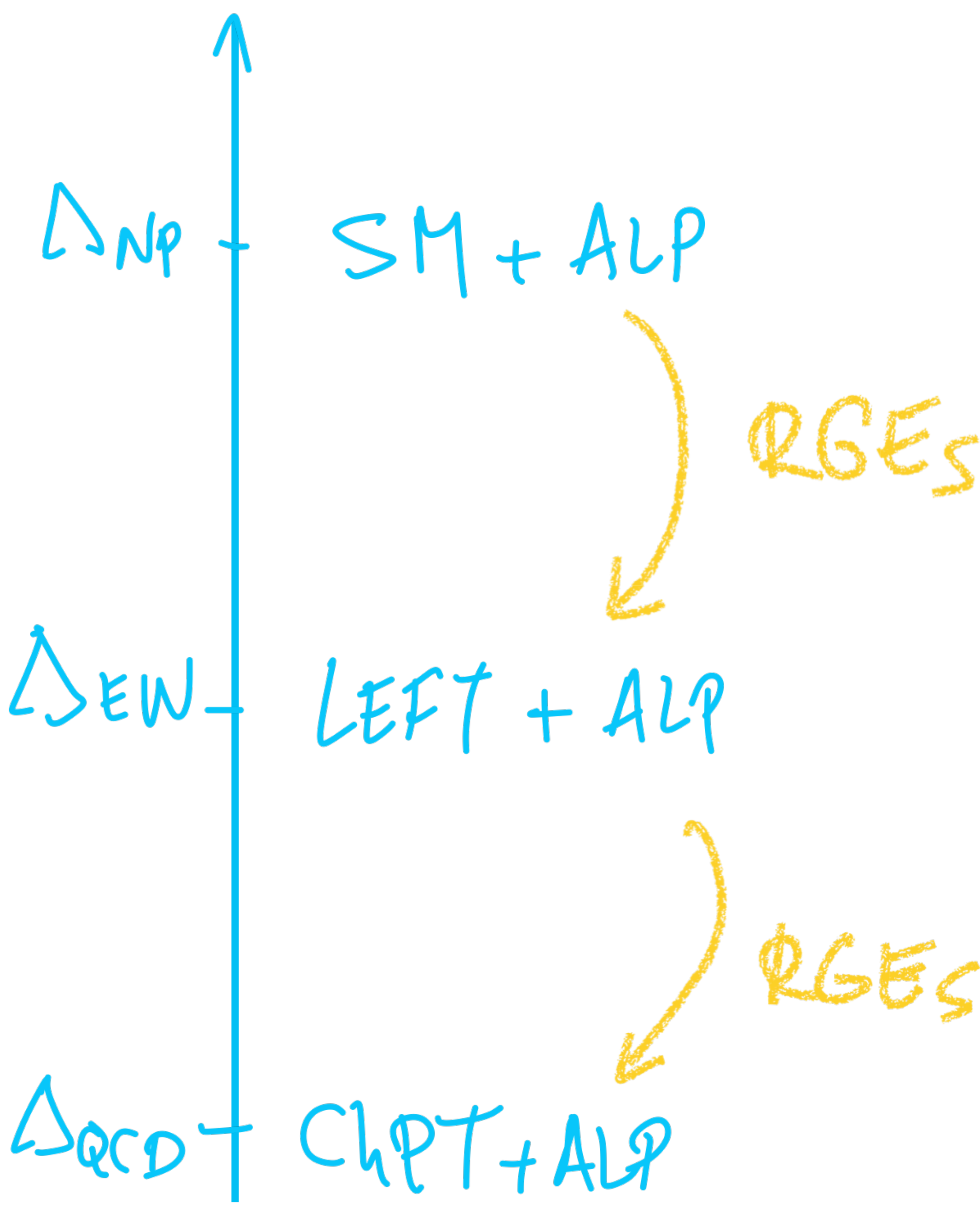


However, even if some Wilson coefficients are zero at the UV scale, they will be generated by the running.

RUNNING UP THAT COUPLING

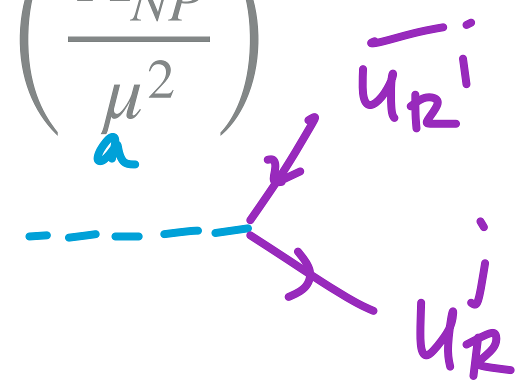
FLAVORED ALPS. RUN THROUGH THE HEP JUNGLE.

$$\left(\mathcal{O}_{q_L}\right)_{ij} = \frac{\partial_\mu a}{\Lambda_{NP}} \left(\bar{q}_{Li}\gamma^\mu q_{Lj}\right), \qquad \mathcal{O}_H = \frac{\partial_\mu a}{\Lambda_{NP}} \left(H^\dagger i \overleftrightarrow{D}^\mu H\right)$$



$$c_H = \frac{3}{8\pi^2} \mathrm{Tr}\left(Y_u c_{u_R} Y_u\right) \ln\left(\frac{\Lambda_{NP}}{\mu^2}\right)$$

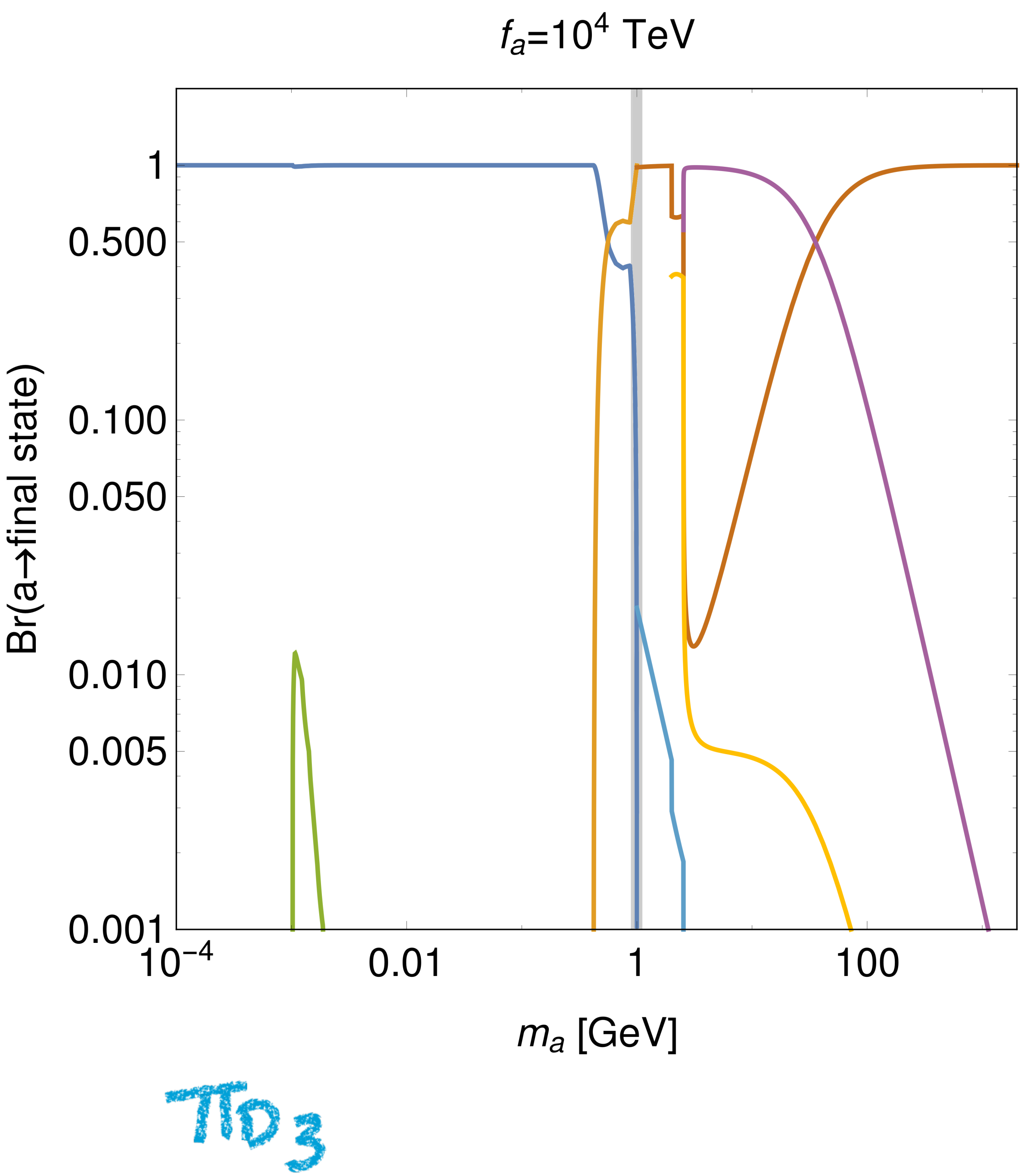
$$c_{q_L} = \frac{Y_u c_{u_R} Y_u}{32\pi^2} \ln\left(\frac{\Lambda_{NP}}{\mu^2}\right)$$

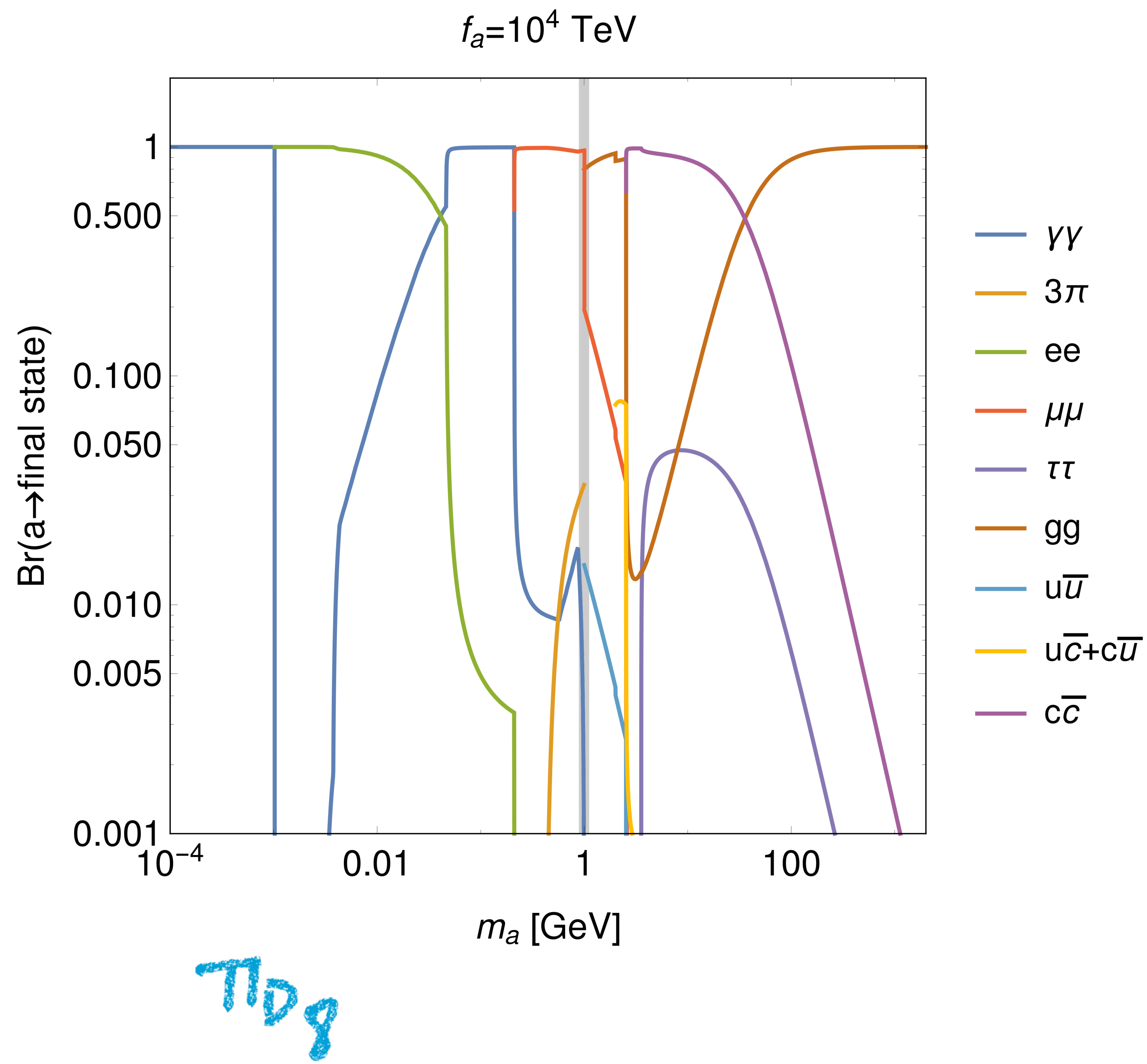


Top couplings will make a difference!

FLAVORED ALPS

The ADM paradigm fixes $\Lambda_{dQCD} \sim 5\Lambda_{QCD}$ and thus $m_a \lesssim \Lambda_{dQCD}$. But we want to be a bit more general here (e.g. DM could be made of dark pions).

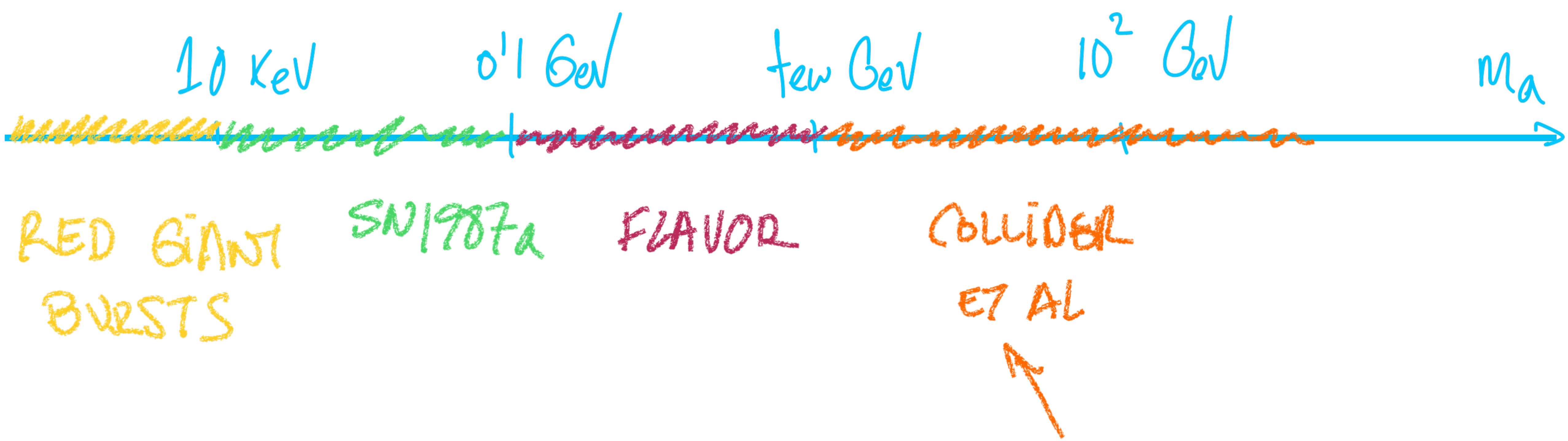




FLAVORED ALPS

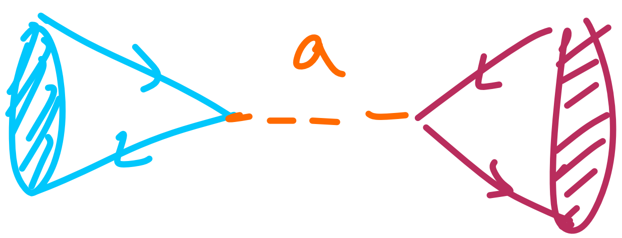
The ADM paradigm fixes $\Lambda_{dQCD} \sim 5\Lambda_{QCD}$ and thus $m_a \leq \Lambda_{dQCD}$. But we want to be a bit more general here (e.g. DM could be made of dark pions).

Flavor probes will compete or be complemented by astrophysical or cosmological bounds as well as by collider or fixed target experiments.



FLAVORED ALPS. FLAVOR BOUNDS.

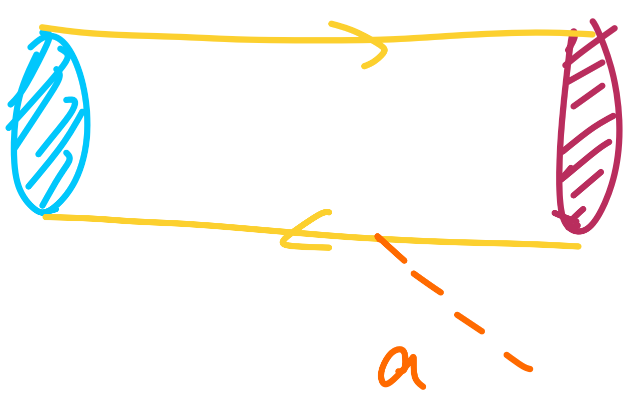
ΔF=2 Neutral meson mixing



$B-\bar{B}$ mixing / $K-\bar{K}$ mixing / $D-\bar{D}$ mixing

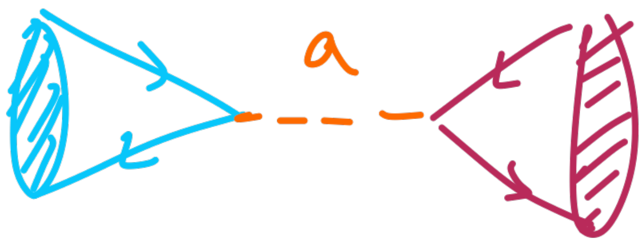
Depending on $m_a/m_{c,b}$ we might need to use OPE

ΔF=1 Rare meson decays

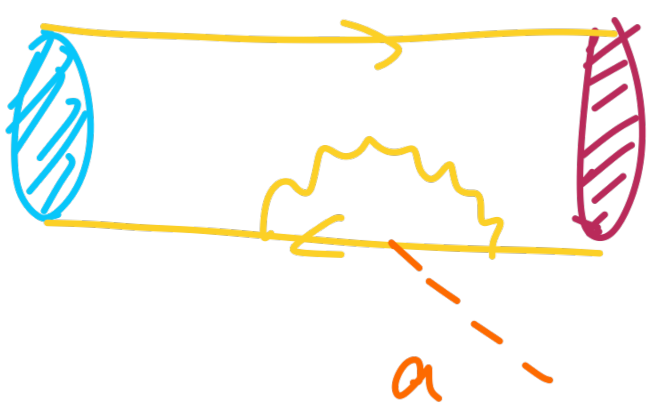


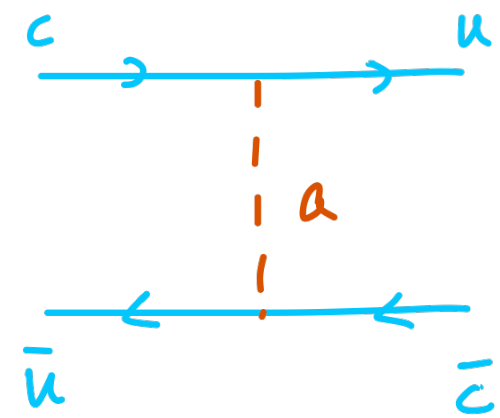
$D \to \pi a$, $B \to K a$, $B \to \pi a$, $K \to \pi a$, ...

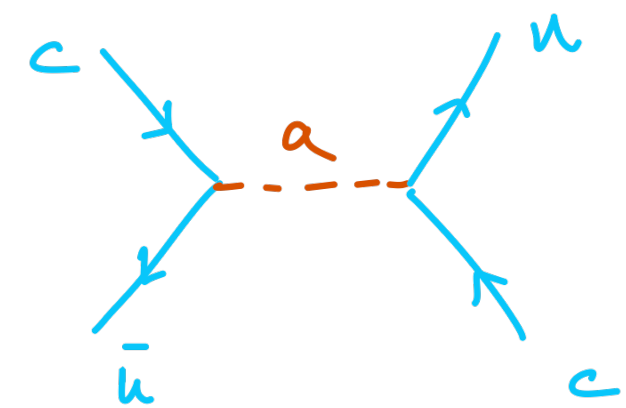
FLAVORED ALPS. FLAVOR BOUNDS.

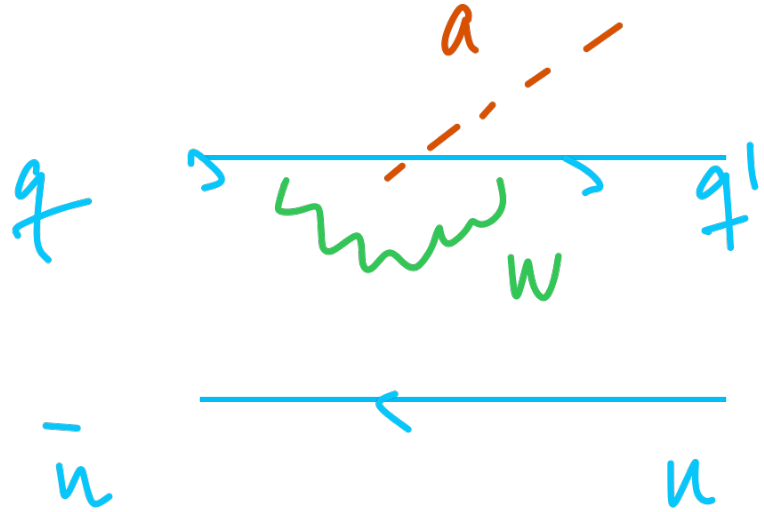


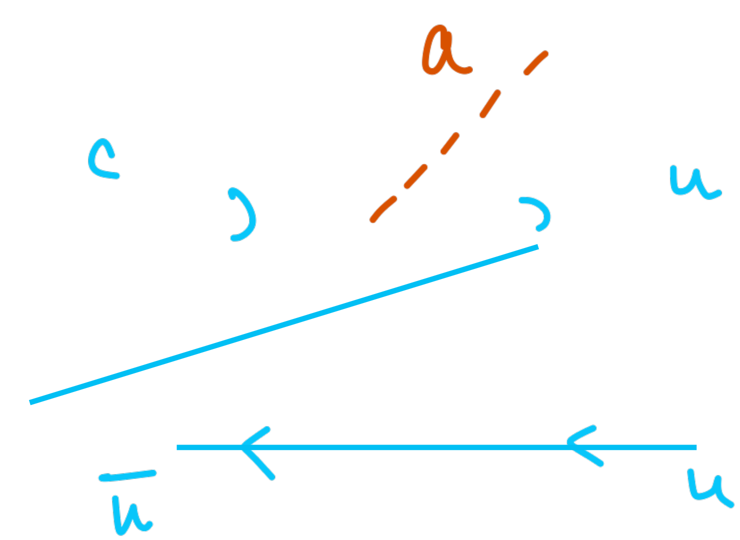
$D-\bar{D}$ mixing





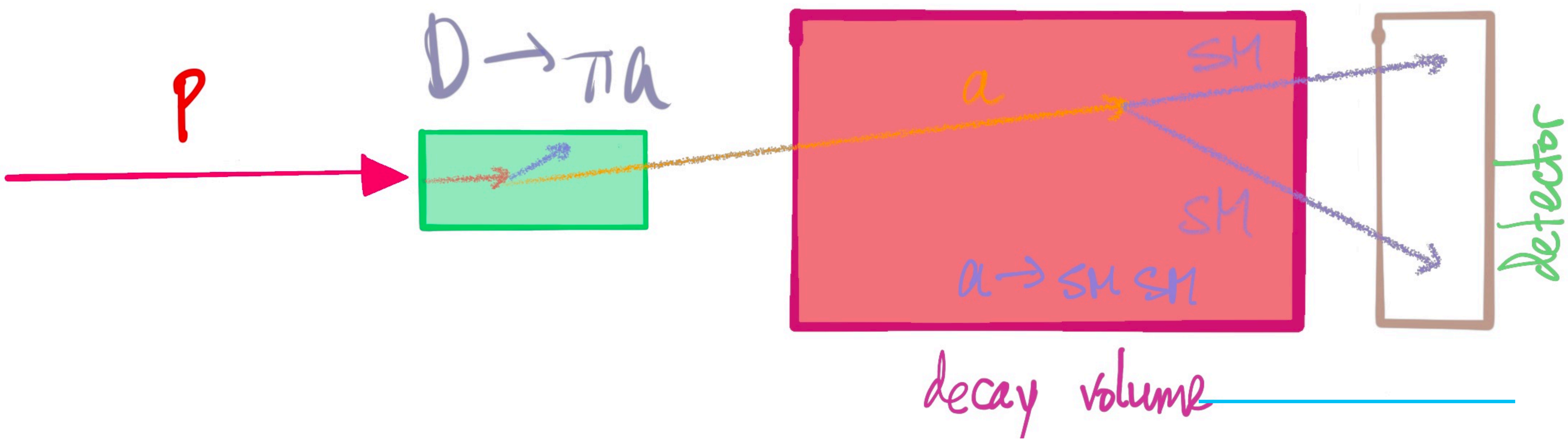






$B \to Ka$, $B \to \pi a$, $K \to \pi a$ $\qquad$ $D \to \pi a$

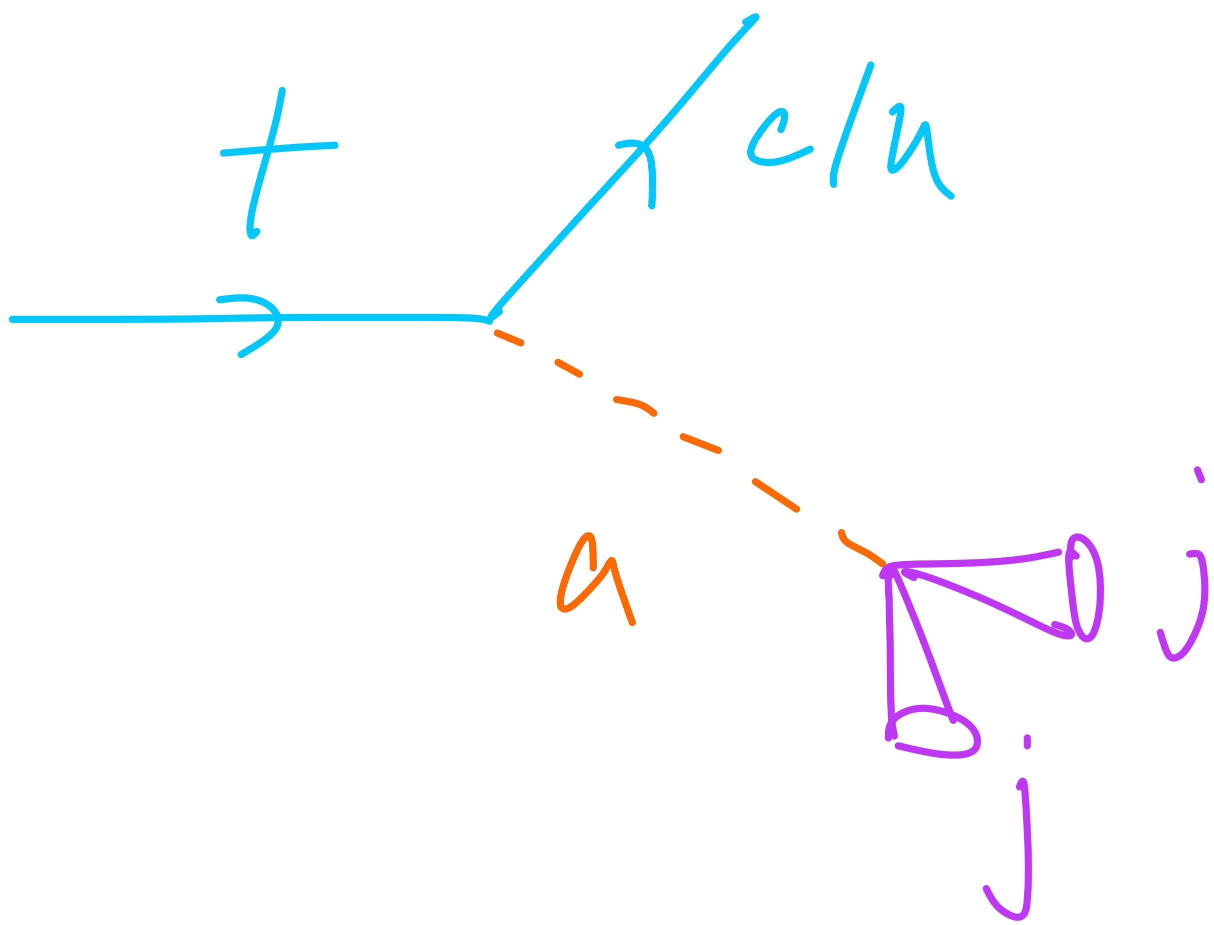
FLAVORED ALPS. FIXED TARGET EXPERIMENTS.

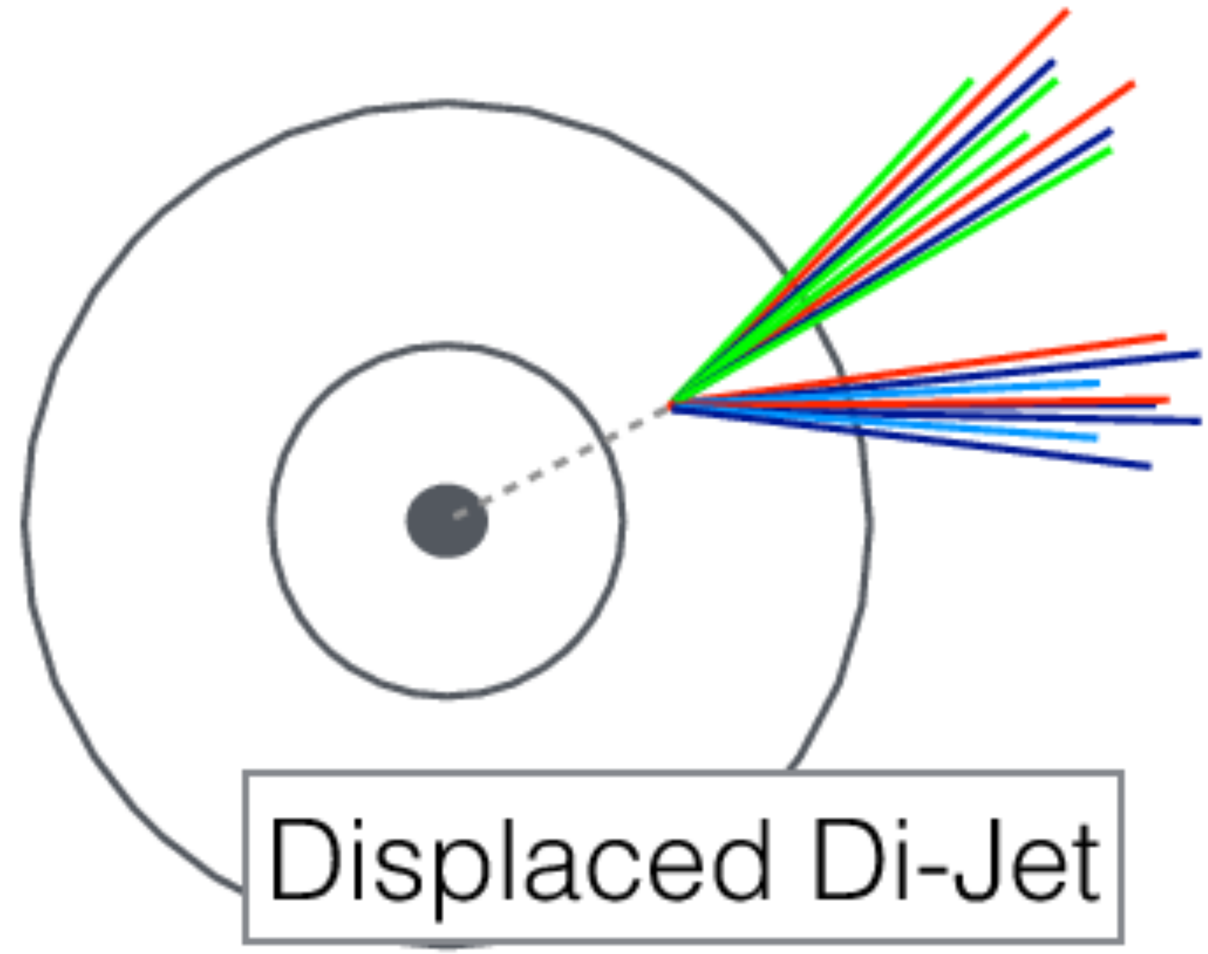


Fixed target experiments: NA62, SHiP, CHARM.

LHC forward detectors: FASER, FASER II, MATUSHLA.

FLAVORED ALPS. COLLIDER BOUNDS.

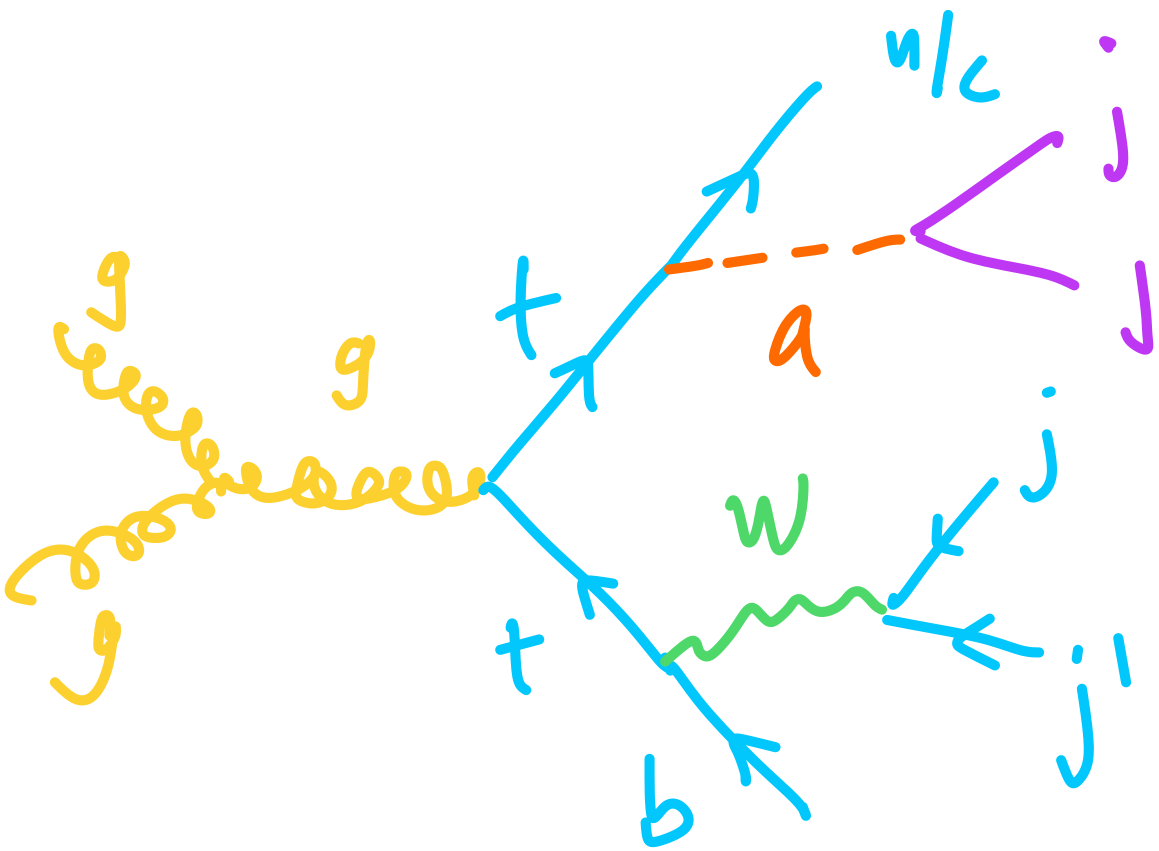


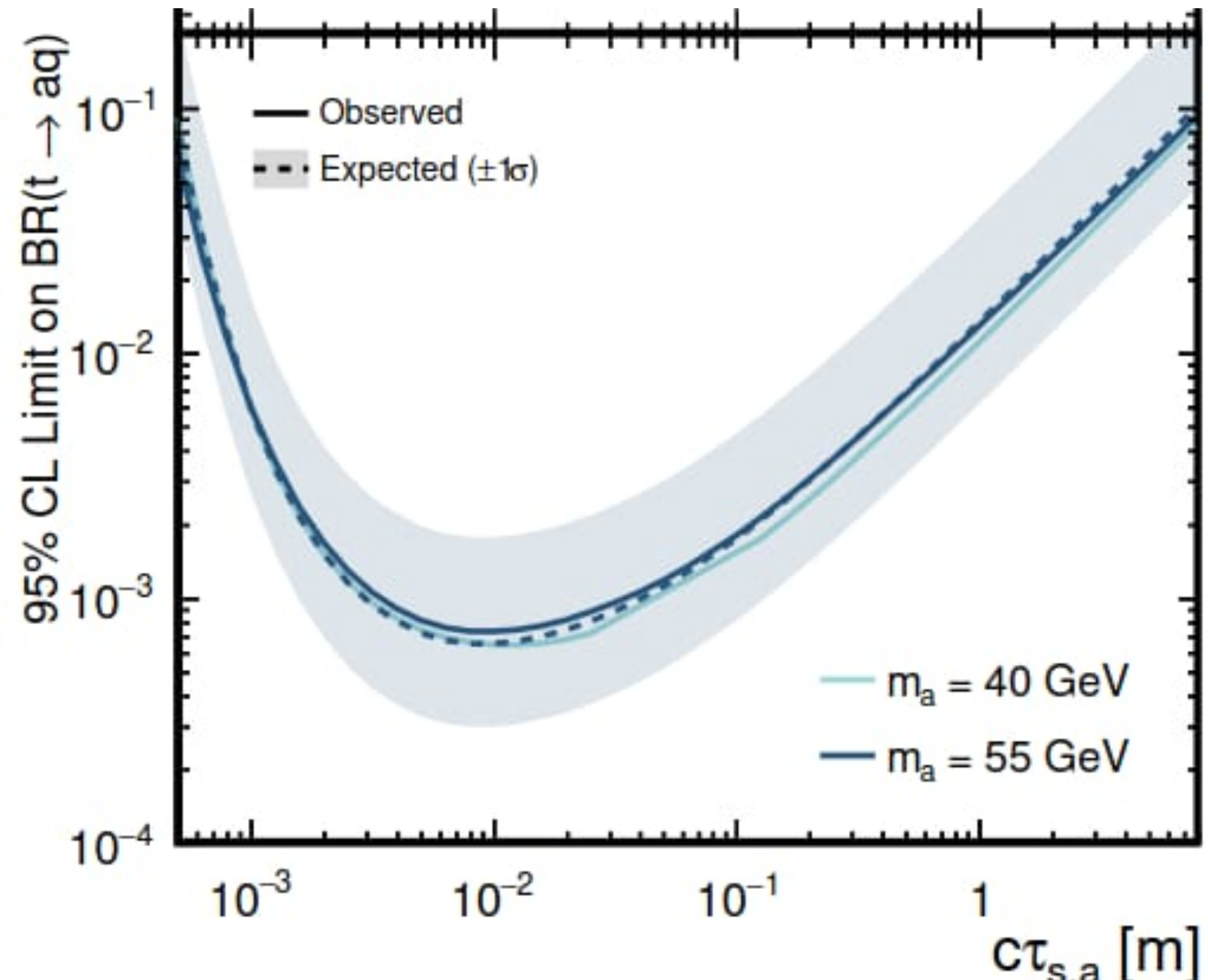


- We can probe charming ALPs above charm threshold.
- Depending on the ALP lifetime we will go from 'prompt decays' to 'displaced vertices'.

FLAVORED ALPS. COLLIDER BOUNDS.

Taken from **CERN-EP-2024-086**





- We can probe charming ALPs above charm threshold.
- Depending on the ALP lifetime we will go from 'prompt decays' to 'displaced vertices'.

DARK PIONS AS DARK MATTER

We are not forced to have ADM. Dark pions can also be DM.

Since $\mathscr{L}_{\text{int}} = -\kappa_{\alpha i}\bar{\psi}_i Q_\alpha + \text{h.c.}$, the matrix $\kappa^T_{\alpha i}$ can be seen as the vev of an spurion transforming as $\kappa^T_{\alpha i} \sim (\mathbf{3}, \bar{\mathbf{n}}_{df})$ under the group $SU(3)_\psi \otimes SU(n_{df})_Q$. The vev breaks $SU(3)_\psi \otimes SU(n_{df})_Q \to U(1)^{n_{df}-3}$.

If $n_{df} \geq 4$, there is some conserved $U(1)^{n_{df}-3}$ symmetry. We have $n_{df} - 3$ conserved flavor numbers and $n^2_{df} - 9 - (n_{df} - 3)$ stable dark mesons.

For instance, let us focus on the $n_{df} = 4$ case. The pNGBs are a $\mathbf{15}$ of $SU(4)$. We know that under $SU(3) \otimes U(1) \subset SU(4)$,

$$\mathbf{15} = \mathbf{8}_0 \oplus \mathbf{3}_{\sqrt{2/3}} \oplus \mathbf{1}_0$$

This $U(1)$ is conserved by the vev of κ^T and all SM fields are singlets. Therefore, the six pNGBs in $\mathbf{3}_{\sqrt{2/3}}$ can not decay into any SM particle.

DARK PIONS AS DARK MATTER

Let us focus on the $n_{df} = 4$ case. The pNGBs are a $\mathbf{15}$ of $SU(4)$, decomposing under $SU(3) \otimes U(1) \subset SU(4)$ as

$$\mathbf{15} = \mathbf{8}_0 \oplus \mathbf{3}_{\sqrt{2/3}} \oplus \mathbf{1}_0$$

- The $\mathbf{3}_{\sqrt{2/3}}$ can not decay into any SM particles and are thus stable.
- The $\mathbf{8}_0 \oplus \mathbf{1}_0$ will be able to decay into SM fields
- Since there is a unique $U(1) \subset SU(4)$, the stable mesons $\mathbf{3}_{\sqrt{2/3}}$ will always appear in pairs in the dark ChPT interactions.
- In some basis, one can identify SM flavors with the first three dark ones:

$$\left.\begin{array}{cccc} Q^1 & Q^2 & Q^3 & Q^4 \\ | & | & | & \\ u_R^1 & u_R^2 & u_R^3 & ? \end{array}\right\} \Rightarrow$$

Dark pions with Q^4 content can not decay!

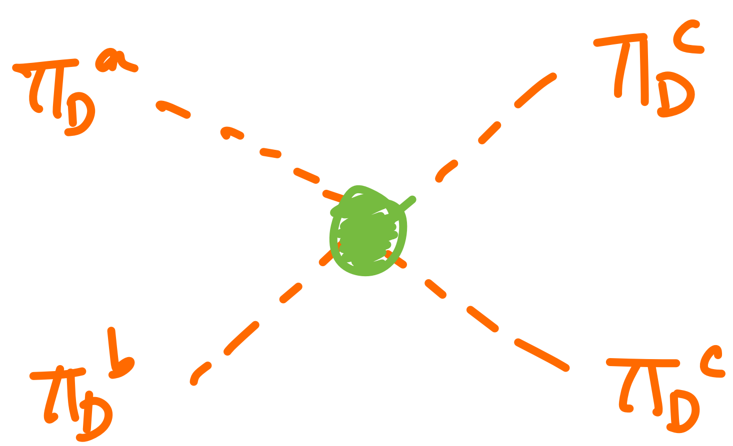
DARK PIONS AS DARK MATTER

The interactions among the different dark mesons come through the dark ChPT Lagrangian:

$$\mathscr{L}_{\mathrm{dChPT}} = \frac{f_D^2}{4}\mathrm{Tr}\left(\partial_\mu U_D^\dagger \partial^\mu U_D\right) + \frac{f_D^2 B_D}{2} m_Q \mathrm{Tr}\left(U_D^\dagger + U_D\right)$$

where $U_D = \exp\left(2i\Pi_D/f_D\right)$ and $\Pi_D = \pi_D^a T^a$. After expanding in power of Π_D

$$\mathscr{L}_{\mathrm{dChPT}} \supset \frac{2}{3f_D^2}\mathrm{Tr}\left(\Pi_D^2 \partial_\mu \Pi_D \partial^\mu \Pi_D - \Pi_D \partial_\mu \Pi_D \Pi_D \partial^\mu \Pi_D\right) + \frac{m_{\pi_D}^2}{3f_D^2}\mathrm{Tr}\left(\Pi_D^4\right)$$



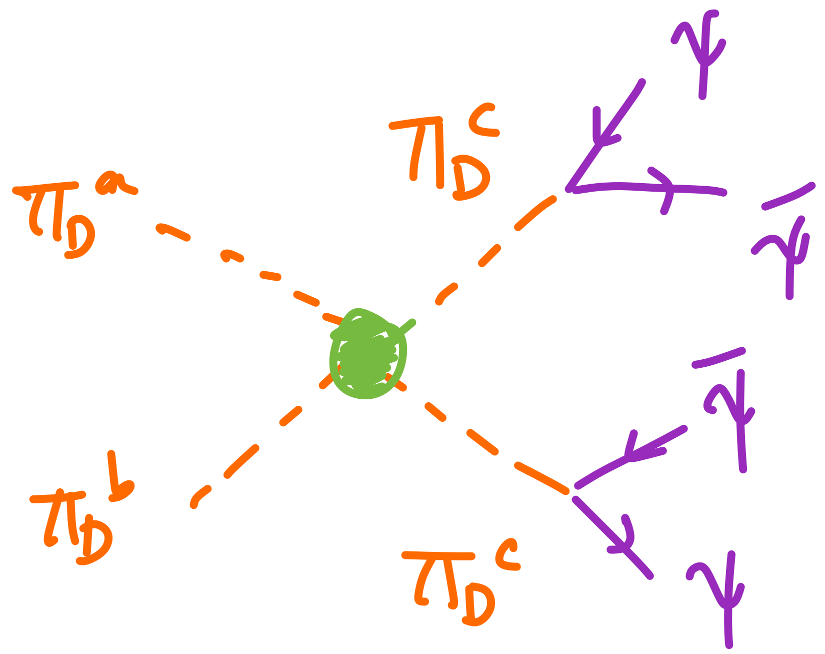
$$(\sigma v)_{\mathrm{lab}} = \sigma_0 \epsilon^{1/2}$$

$$\epsilon = (s - 4m_{\pi_D}^2)/(4m_{\pi_D}^2)$$

$$\sigma_0 \propto m_{\pi_D}^2/(f_D^4 n_{df}^2)$$

DARK PIONS AS DARK MATTER

Remember that stable dark pions need to appear in pairs. Coannihilation and indirect detection goes via cascade decay.



$$\langle \sigma v \rangle_{2_{\rm DM} \to 2_{\rm dec}} \approx \frac{2 m_{\pi_D}^2}{\pi^{3/2} f_D^4 \sqrt{m_{\pi_D}/T}}$$

The coannihilation cross-section is velocity suppressed $\langle \sigma v \rangle_{2_{DM} \to 2_{\rm dec}} \sim \sigma_0 v$. This leads to weaker signals from objects with low DM velocity, such as dwarf galaxies. Good for indirect detection and CMB!

DARK PIONS AS DARK MATTER

Direct detection goes through

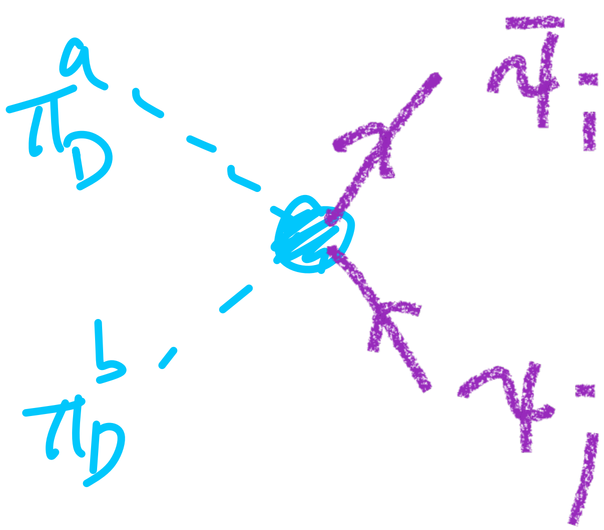
$$\mathscr{L}^{\text{portal}}_{\text{dChPT}} = i\frac{f_D^2}{4m_X^2}\kappa_{\alpha i}\kappa^*_{\beta j}\left\{\text{Tr}(c_{\beta\alpha}U_D^\dagger\partial_\mu U_D)(\bar{\psi}_i\gamma^\mu P_R\psi_j) + \text{Tr}(c_{\beta\alpha}U_D\partial_\mu U_D^\dagger)(\bar{\psi}_i\gamma^\mu P_L\psi_j)\right\}$$

where $(c_{\beta\alpha})_{\rho\lambda} = \delta^\rho_\alpha\delta^\lambda_\beta$. After expanding in powers of Π_D we obtain,

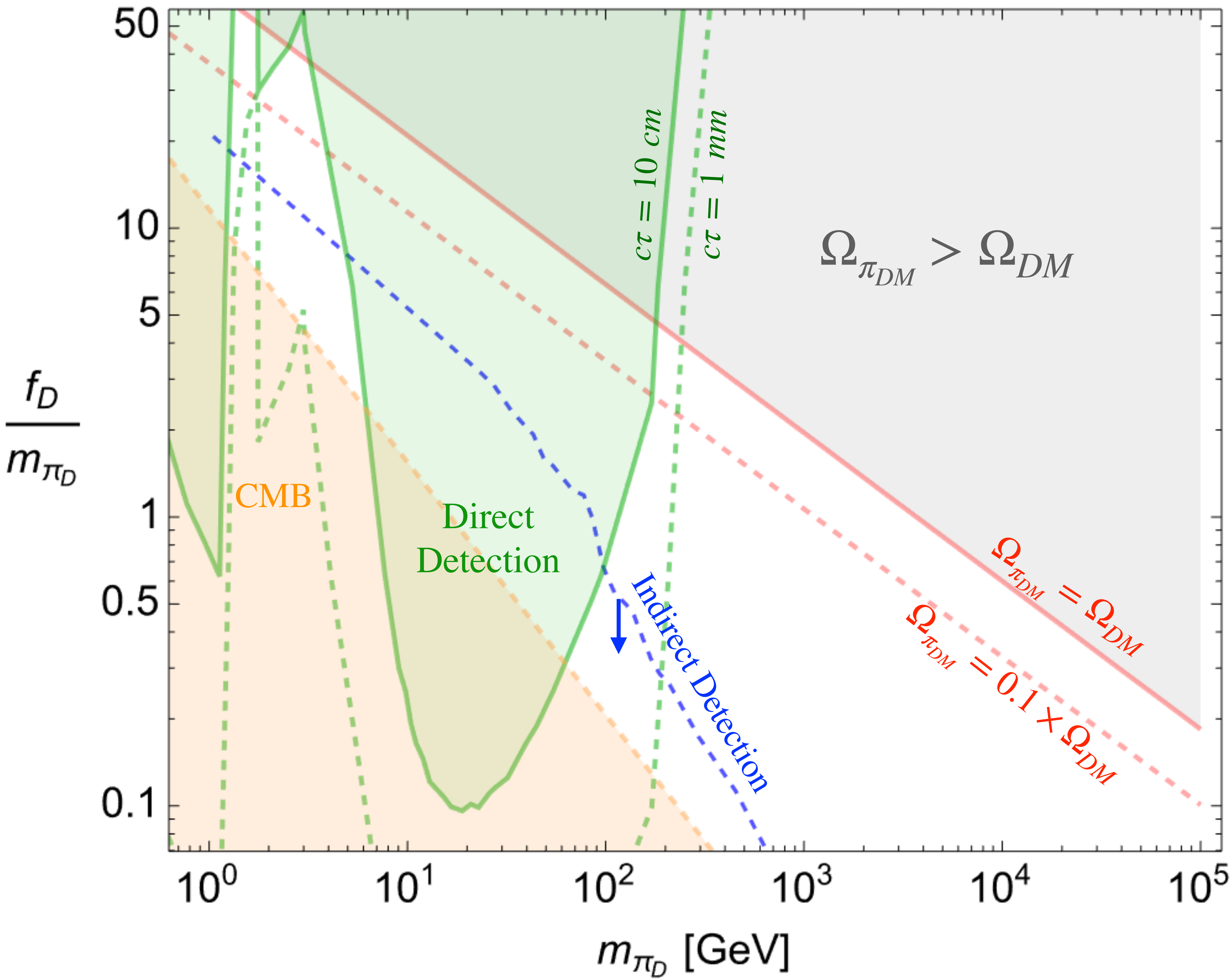
$$\mathscr{L}^{\text{portal}}_{\text{dChPT}} \supset -\frac{1}{2m_X^2}\kappa_{\alpha i}\kappa^*_{\beta j}(T^c)_{\alpha\beta}f^{abc}\pi^a_D\partial_\mu\pi^b_D(\bar{\psi}_i\gamma^\mu\psi_j),$$

If we organize the stable dark pions into a $SU(3)$ triplet φ, we can write

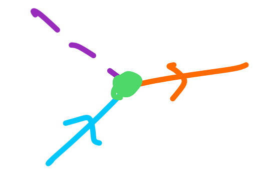
$$\mathscr{L} \supset \mp\frac{1}{8m_\chi^2}\kappa_{m1}\kappa^*_{n1}\left[\varphi^\dagger_n i\overleftrightarrow{\partial}_\mu\varphi_m\right]\left[\bar{q}\gamma^\mu(\gamma_5)q\right]$$

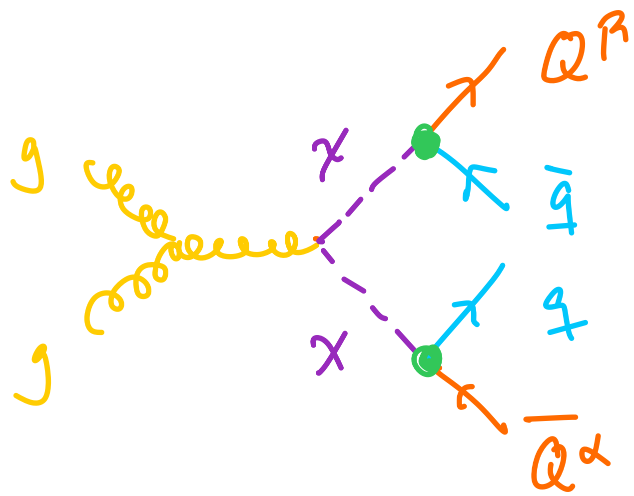


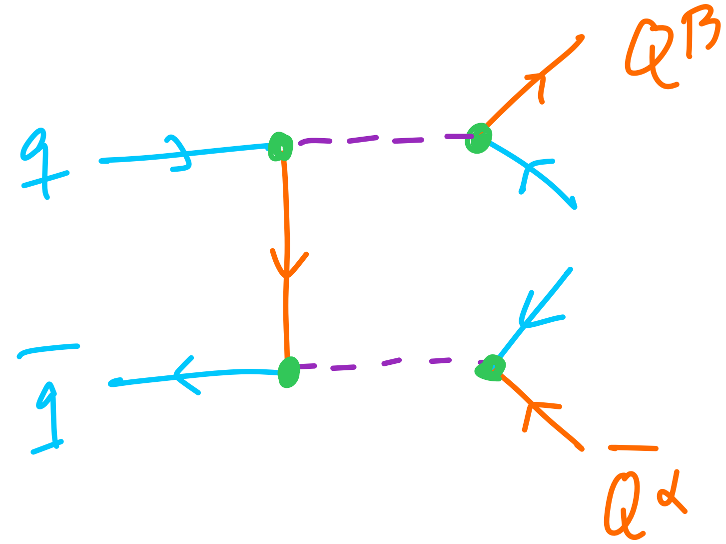
DARK PIONS AS DARK MATTER

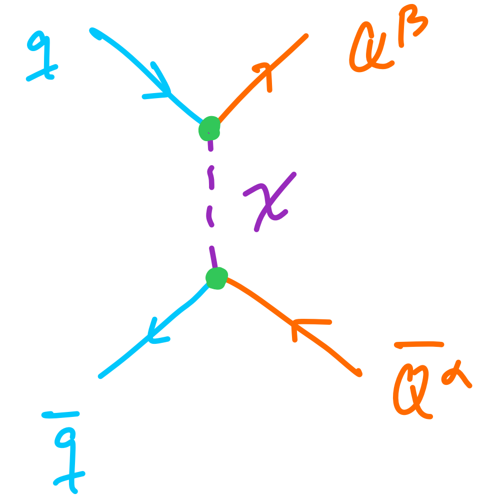


DARK PIONS AS DARK MATTER







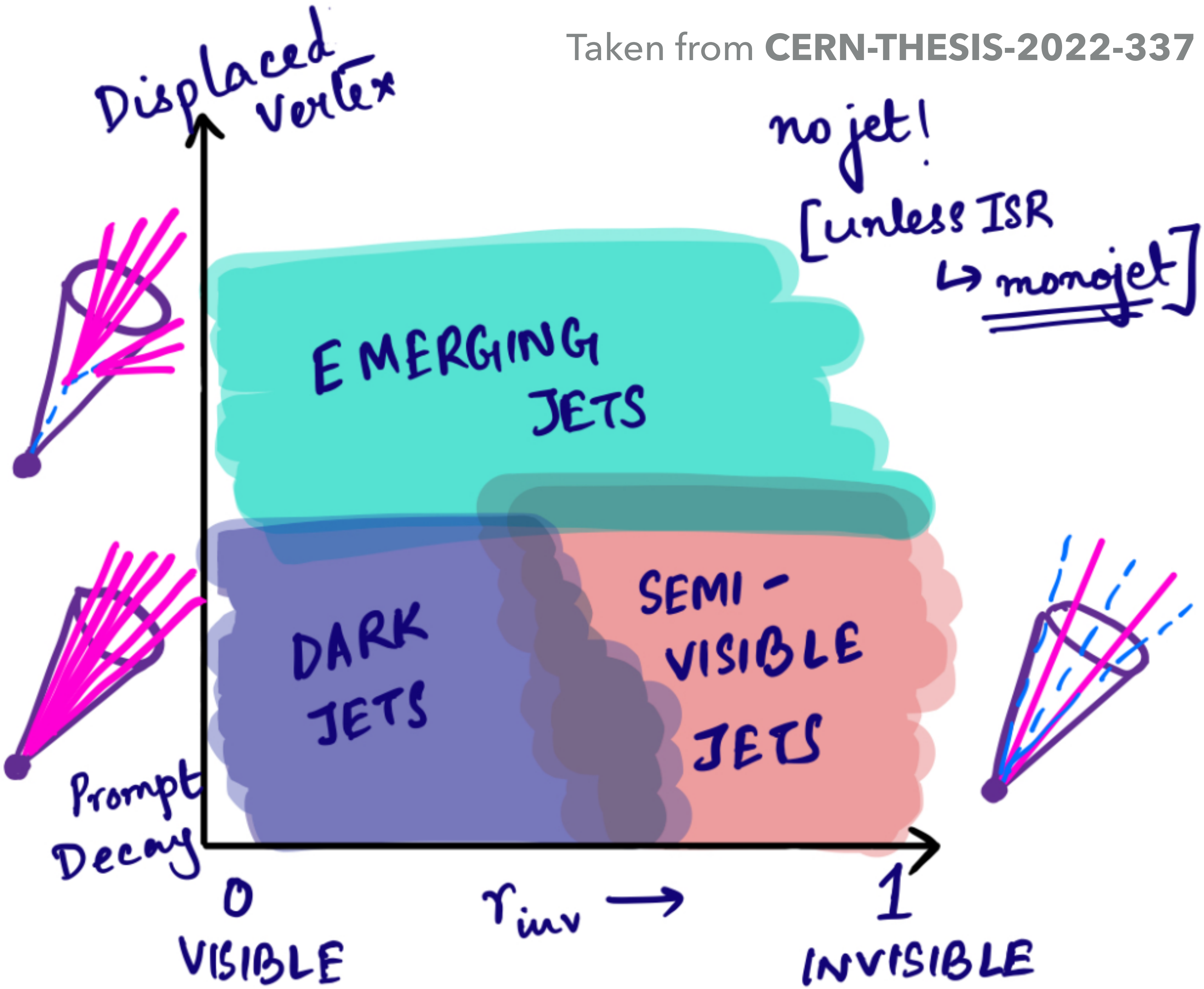


Collider Pheno: we consider the production of two dark quarks and up to two SM quarks. Depending on the unstable dark mesons lifetime we get:

- 4 prompt jets
- Two jets + two emerging jets
- Two jets + MET
- Two semi-visible jets

LLP MAYHEM

Taken from **CERN-THESIS-2022-337** [S. Sinha]

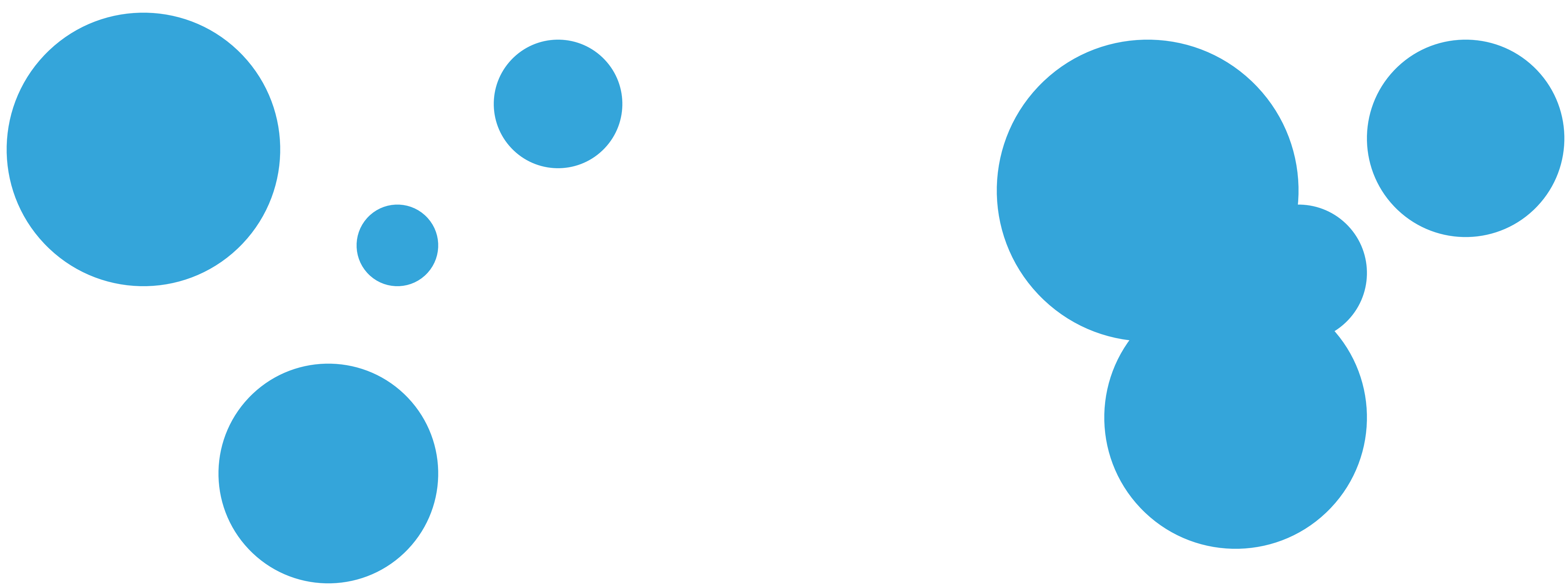


GW FROM DARK SECTORS

Dark Sectors with $SU(N_D)$ gauge group and $n_{df} \geq 3$ dark fermions experience a first order phase transition (FOPT).

FOPT ⇒ Bubbles nucleate and expand.

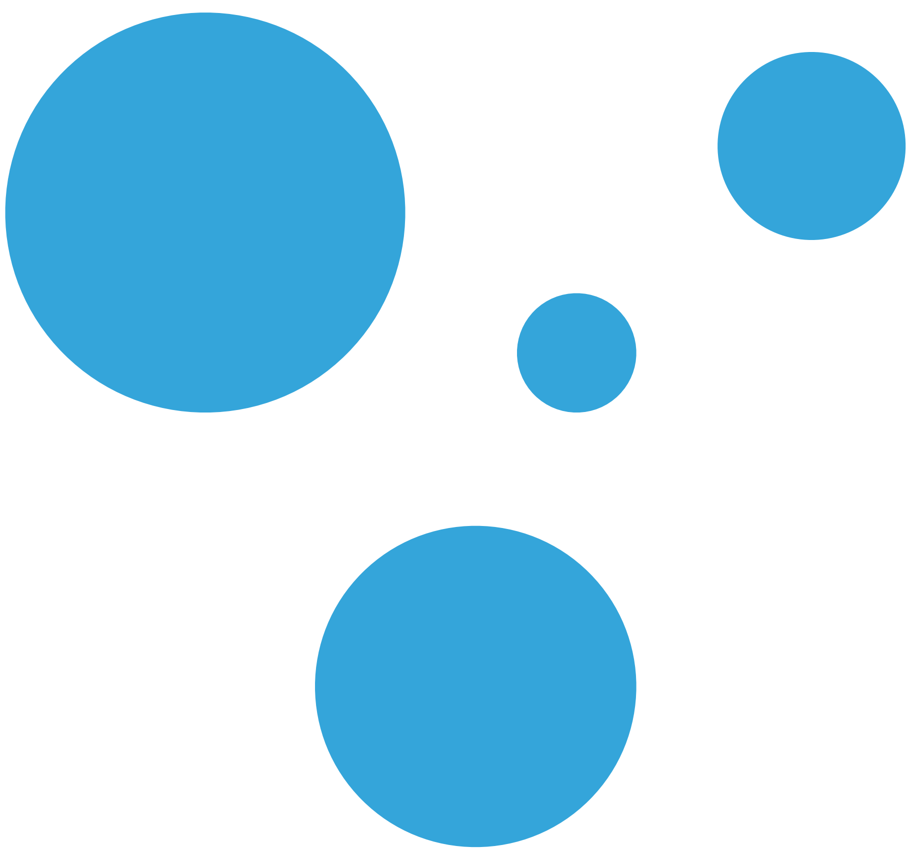
Bubble collisions ⇒ Gravitation waves.

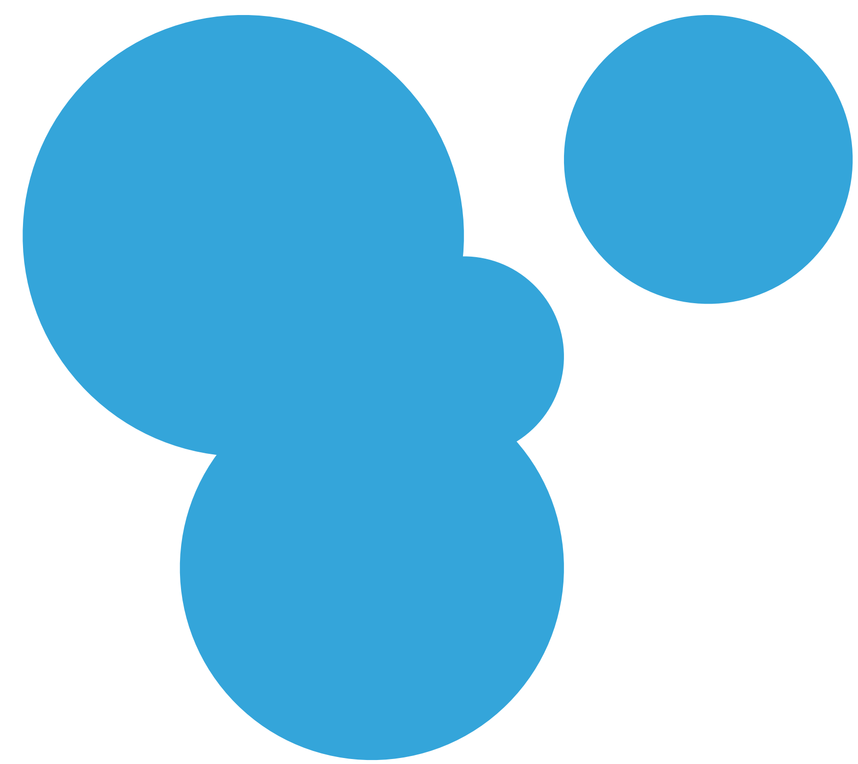


GW FROM DARK SECTORS

PT controlled by few parameters:

- Latent heat $\alpha \approx \frac{\Omega_{\mathrm{vacuum}}}{\Omega_{\mathrm{rad}}}$
- Bubble wall velocity
- Bubble nucleation rate β
- PT temperature T_*





EFFECTIVE FIELD THEORIES

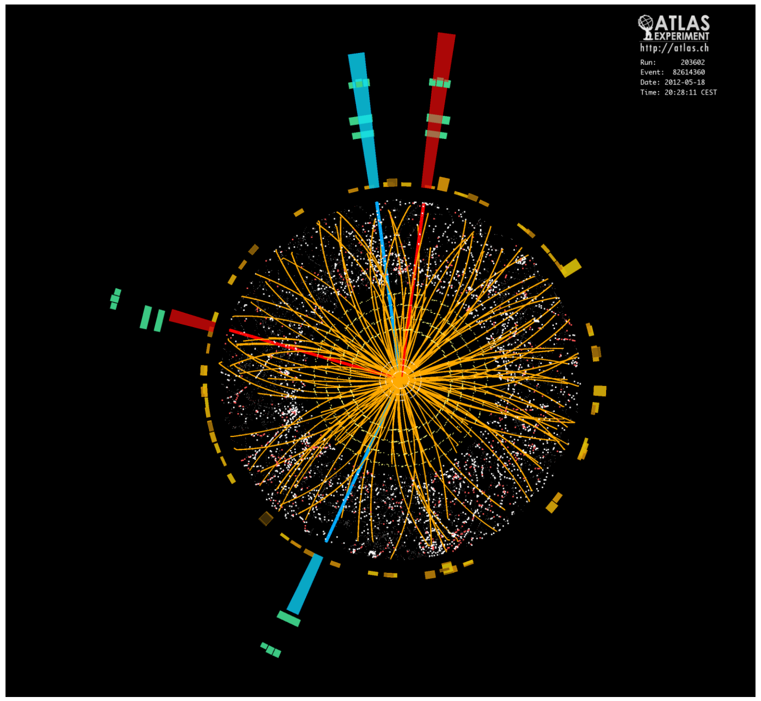
LIFE AFTER THE LHC

- The negative results at LHC strongly suggest that

$$v, m_H, m_t, m_W, m_Z \ll \Lambda_{\mathrm{NP}}$$

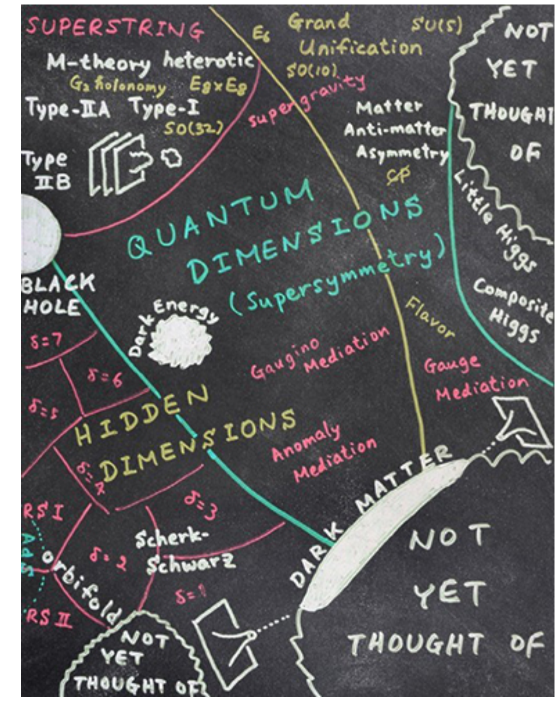
- The field is demanding more and more precision since if there is NP is going to be a matter of small deviations.
- We need some way of ranking the ever-increasing amount of data and effectively connect it with new theories.

EFT AS A DISCOVERY TOOL



X^3		φ^6 and $\varphi^4 D^2$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^* \left(\varphi^\dagger D_\mu\varphi\right)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$		

$X^2\varphi^2$		$\psi^2 X\varphi$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p'\sigma^{\mu\nu}e_r')\tau^I\varphi W_{\mu\nu}^I$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p'\sigma^{\mu\nu}e_r')\varphi B_{\mu\nu}$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p'\sigma^{\mu\nu}T^A u_r')\widetilde{\varphi}\, G_{\mu\nu}^A$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p'\sigma^{\mu\nu}u_r')\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p'\sigma^{\mu\nu}u_r')\widetilde{\varphi}\, B_{\mu\nu}$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p'\sigma^{\mu\nu}T^A d_r')\varphi\, G_{\mu\nu}^A$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p'\sigma^{\mu\nu}d_r')\tau^I\varphi\, W_{\mu\nu}^I$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p'\sigma^{\mu\nu}d_r')\varphi\, B_{\mu\nu}$



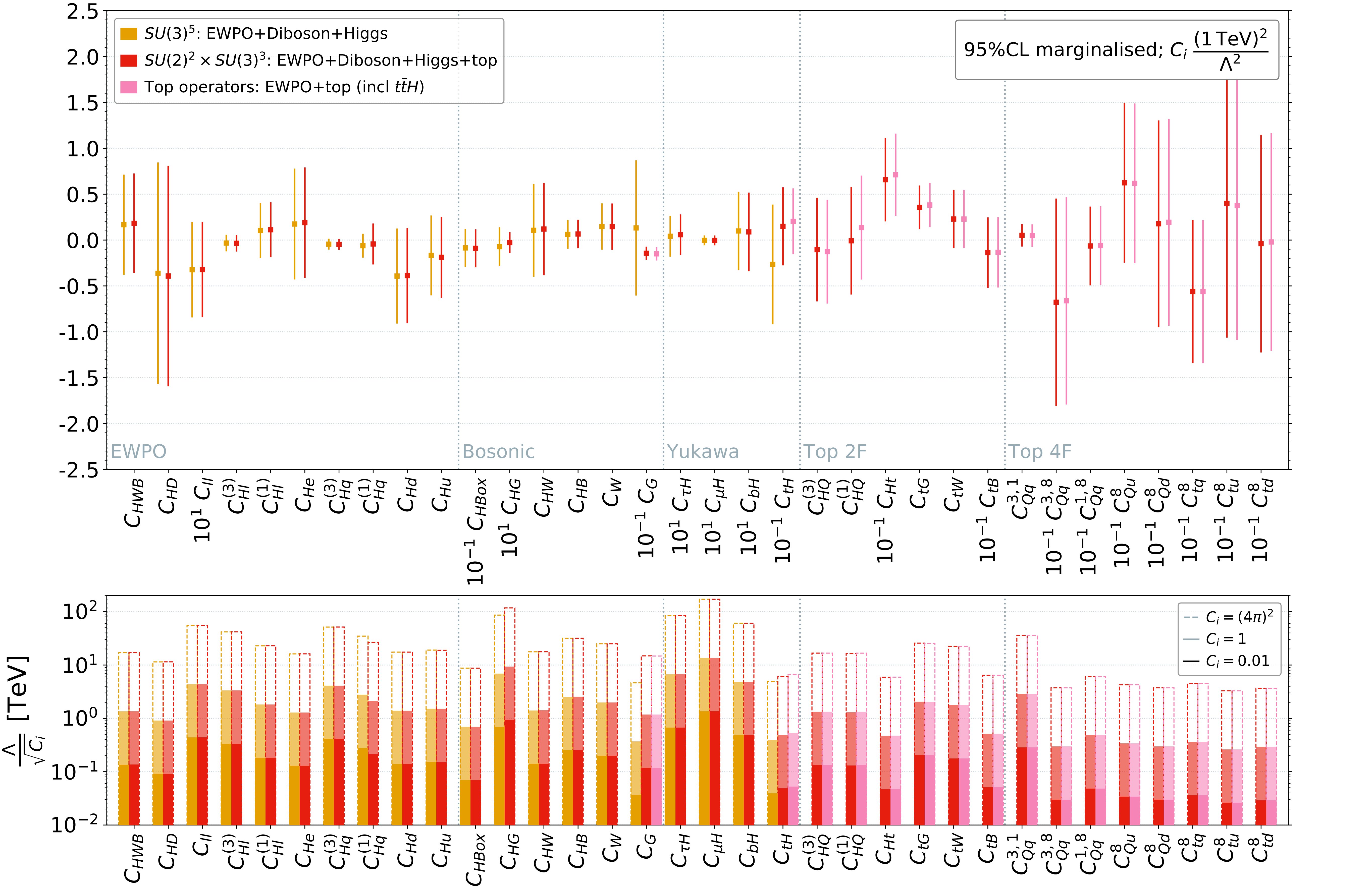
DATA **EFT** **BSM**

EFTs are THE tool to parametrize in a model-independent way new physics and shed light on what is possible beyond the SM.

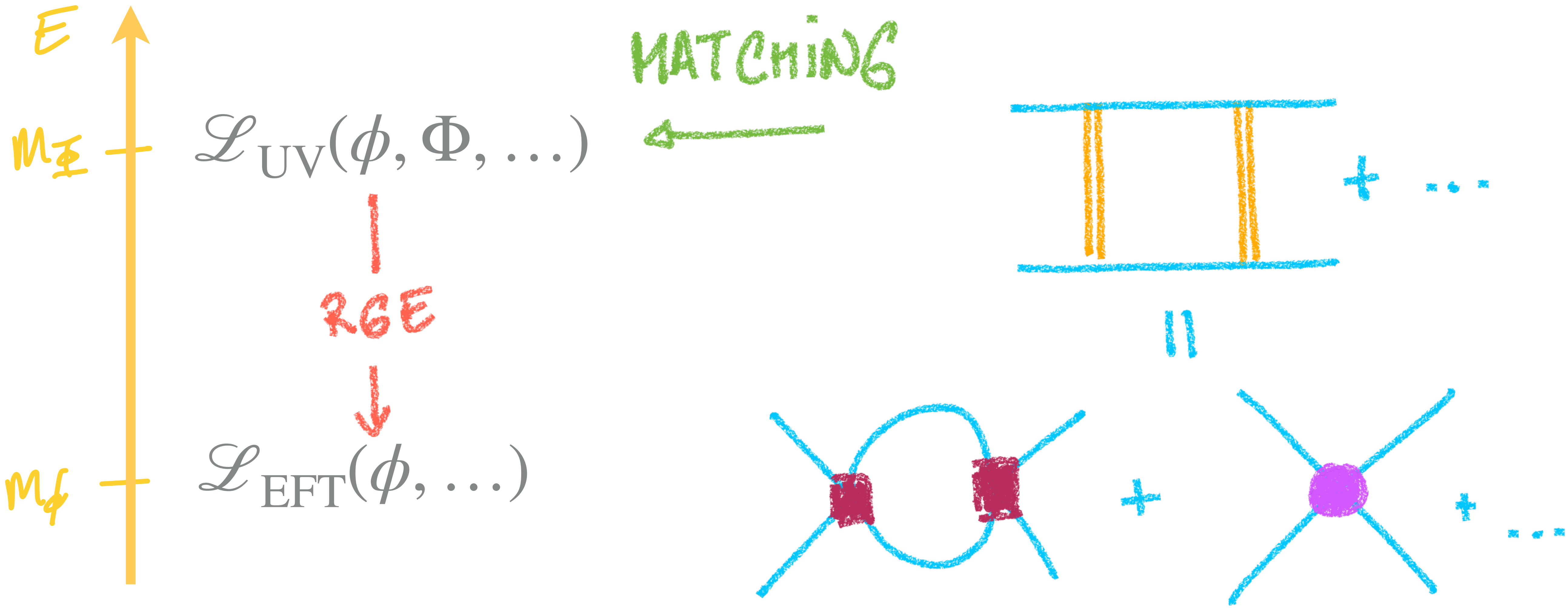
- Data → EFT : It allows to interpret data in a consistent way [Bottom-up]
- EFT ← BSM : It allows to confront any new theory with data [Top-down]

BOTTOM-UP APPROACH

Taken from **2105.14942**



TOP-DOWN APPROACH: MATCHING



where $c^{(0)}$  , $c^{(1)}$ 

TREE LEVEL MATCHING

We can perform the tree-level matching for the following Lagrangian

$$\mathscr{L}_{\mathrm{UV}}(\phi,\Phi)=\mathscr{L}_{\mathrm{SM}}(\phi)+\left[\Phi^\dagger F(\phi)+\mathrm{h.c.}\right]+\Phi^\dagger\left[-D^2-m_\Phi^2-U(\phi)\right]\Phi+\mathcal{O}(\Phi^3)$$

by using equations of motion

$$\left[D^2+m_\Phi^2+U(\phi)\right]\Phi_c=F(\phi)+\mathcal{O}(\Phi_c^2)$$

which leads to

$$\Phi_c=\left[D^2+m_\Phi^2+U(\phi)\right]^{-1}F(\phi)=m_\Phi^{-2}\left[1+m_\Phi^{-2}\left(D^2+U(\phi)\right)\right]^{-1}F(\phi)$$

$$=\frac{1}{m_\Phi^2}-\frac{1}{m_\Phi^2}\left[D^2+U(\phi)\right]\frac{1}{m_\Phi^2}F(\phi)+\dots$$

and

$$\mathscr{L}_{\mathrm{EFT}}^{(0)}=\mathscr{L}_{\mathrm{UV}}(\phi,\Phi_c(\phi))$$

TREE LEVEL MATCHING

Tree-level matching is not very tough and can be easily automated (see e.g. MatchingTools by J.C. Criado).

Actually, one can classify all possible renormalizable BSM models that contribute to the SMEFT at the **tree-level**.

$Q^{(m)}$	U	D	$\begin{pmatrix} U \\ D \end{pmatrix}$	$\begin{pmatrix} X \\ U \end{pmatrix}$	$\begin{pmatrix} D \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ U \\ D \end{pmatrix}$	$\begin{pmatrix} U \\ D \\ Y \end{pmatrix}$
Irrep	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(3,3)_{-\frac{1}{3}}$

New Quarks: del Aguila, Perez-Victoria, Santiago, '00

Leptons	N	E	$\begin{pmatrix} N \\ E^- \end{pmatrix}$	$\begin{pmatrix} E^- \\ E^{--} \end{pmatrix}$	$\begin{pmatrix} E^+ \\ N \\ E^- \end{pmatrix}$	$\begin{pmatrix} N \\ E^- \\ E^{--} \end{pmatrix}$
Irrep	$(1,1)_0$	$(1,1)_{-1}$	$(1,2)_{-\frac{1}{2}}$	$(1,2)_{-\frac{3}{2}}$	$(1,3)_0$	$(1,3)_{-1}$
Spinor	Dirac/Majorana	Dirac	Dirac	Dirac	Dirac/Majorana	Dirac

New Leptons: del Aguila, de Blas, Perez-Victoria, '08

TREE LEVEL MATCHING

Vector	$\mathcal{B}_\mu$	$\mathcal{B}^1_\mu$	$\mathcal{W}_\mu$	$\mathcal{W}^1_\mu$	$\mathcal{G}_\mu$	$\mathcal{G}^1_\mu$	$\mathcal{H}_\mu$	$\mathcal{L}_\mu$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,\text{Adj})_0$	$(1,\text{Adj})_1$	$(\text{Adj},1)_0$	$(\text{Adj},1)_1$	$(\text{Adj},\text{Adj})_0$	$(1,2)_{-\frac{3}{2}}$

Vector	$\mathcal{U}^2_\mu$	$\mathcal{U}^5_\mu$	$\mathcal{Q}^1_\mu$	$\mathcal{Q}^5_\mu$	$\mathcal{X}_\mu$	$\mathcal{Y}^1_\mu$	$\mathcal{Y}^5_\mu$
Irrep	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,\text{Adj})_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

New Vectors: del Aguila, de Blas, Perez-Victoria, '10

Colorless Scalars	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ_0	Ξ_1	Θ_1	Θ_3
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,1)_2$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{\frac{1}{2}}$	$(1,4)_{\frac{3}{2}}$

Colored Scalars	ω_1	ω_2	ω_4	Π_1	Π_7	ζ
Irrep	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$

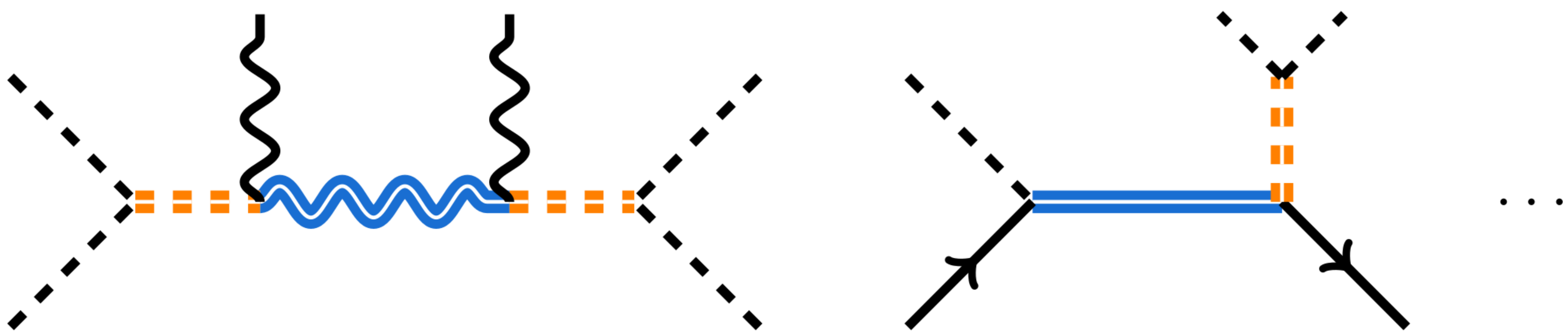
Colored Scalars	Ω_1	Ω_2	Ω_4	Υ	Φ
Irrep	$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$

New Scalars: de Blas, Chala, Perez-Victoria, Santiago, '15

TREE LEVEL MATCHING

- Dimensionful couplings imply that particles with different spin can simultaneously contribute to $\mathscr{L}_{\rm EFT}^{d=6}$ at tree-level

$$\mathscr{L}_{\rm NP} = \kappa \phi_1 \phi_2 \phi_3 + \kappa' V^\mu D_\mu \phi + \kappa'' V^\mu V'_\mu + \ldots$$



- Only a subset of the irreps in the previous lists contribute

- These mixed contributions complete the tree-level UV/IR dictionary. [Blas, Criado, Perez-Victoria, Santiago, '17]

ONE LOOP MATCHING

Doing the same at one-loop is an extremely difficult task since:

- It involves relatively complicated calculations
- It has to be done for any renormalizable UV model

As an example, the calculation of the arguably most simple case (SM+scalar singlet, [Jiang, Craig, Li, Sutherland, **JHEP 2019**]) involved more than 4000 diagrams and required four authors.

Eventually, we want to do something along these lines also for other EFTs, like the ALP EFT or the SMEFT at dimension 8.

All of these requires automation.

ONE LOOP MATCHING

There are currently (almost) two computer tools to perform this task:

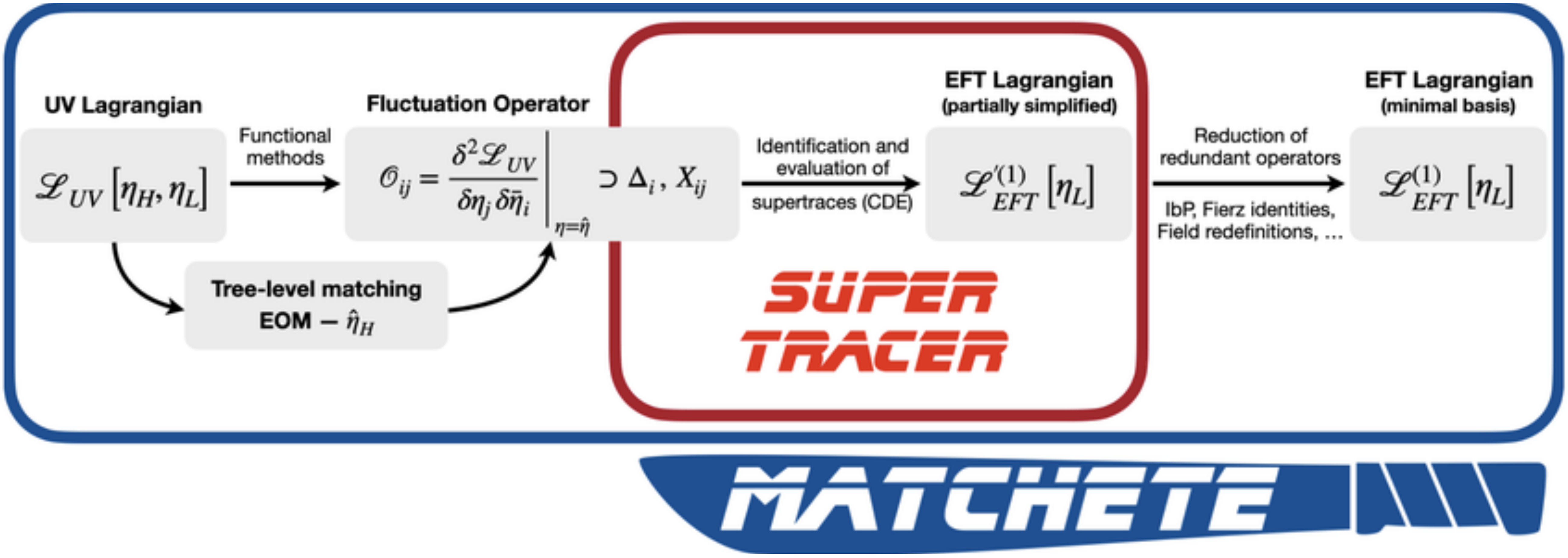
1. **MatchMakerEFT** *AC, Lazopoulos, Olgoso, Santiago,* **SciPost Phys. 12, 198 (2022).** https://ftae.ugr.es/matchmakereft/

It performs tree-level and one-loop matching between arbitrary models and arbitrary EFTs. It also computes the one-loop RGEs. It follows the diagrammatic approach.

ONE LOOP MATCHING

There are currently (almost) two computer tools to perform this task:

2. **Matchete**, *Fuentes-Martin, König, Pagès, Eller Thomsen, Wilsch*, **Eur. Phys. J. C 83 (2023) 7, 662**



It performs tree-level and one-loop matching between arbitrary models and arbitrary EFTs (at the moment without vector bosons). It follows the functional approach.

MATCHMAKEREFT: THE BASICS

- Matching is performed off-shell & diagrammatically
  - Off-shell matching involves less diagrams (only 1LPI diagrams contribute – i.e., no bridges of light particles)
  - However, we need to work with the so-called Green basis, where one needs to include redundant operators (related by EOMs).
- We use the background field method. We split the gauge fields into classical backgrounds and quantum fluctuations, fixing the gauge just for the latter. Off-shell Green functions are then gauge invariant.
- EFT amplitude computed at tree-level and solved for the Wilson coefficients.
- We compute the hard region of the UV amplitude.

A lot here taken from **P. Olgoso**

MATCHMAKEREFT: THE BASICS

- Model creation (FeynRules):
  - Particle content

model.fr

```
F[105] == {
  ClassName          -> HL,
  Indices            -> {Index[SU2D]},
  SelfConjugate      -> False,
  QuantumNumbers -> {Y -> -1/2},
  FullName           -> "heavy",
  Mass               -> ML,
  Width              -> 0
},

S[108] == {
  ClassName          -> HT,
  Indices            -> {Index[SU2W]},
  SelfConjugate      -> False,
  QuantumNumbers -> {Y -> -1},
  FullName           -> "heavy",
  Mass               -> MS,
  Width              -> 0
}
```

- Model creation (FeynRules):
  - Particle content
  - Lagrangian

```
yD[ff1] HLbar[sp1,ii].LR[sp1,ff1] Phi[ii]
+ yT[ff1] HLbar[sp1,ii].LL[sp1,ii,ff1] HT;
```

- Model creation (FeynRules):
  - Particle content
  - Lagrangian
  - Feynman rules

```
qLbar  dR  Phi  (-I/2)*deltaF[ll1,ll3]*deltaF[mm1,mm2]*gam[yy1,SIX,yy2]*yd[flfl1,flfl2]
HLbar  eR  Phi  (I/2)*deltaF[ll1,ll3]*gam[yy1,SIX,yy2]*yD[flfl2]
lLbar  eR  Phi  (-I/2)*deltaF[ll1,ll3]*gam[yy1,SIX,yy2]*yl[flfl1,flfl2]
HLbar  lL  HT  (I/2)*deltaF[ll1,ll2]*gam[yy1,SEVEN,yy2]*yT[flfl2]
qLbar  uR  Phibar  (-I/2)*deltaF[mm1,mm2]*eps[ll1,ll3]*gam[yy1,SIX,yy2]*yu[flfl1,flfl2]
lLbar  lL  B  (-I/4)*g1*deltaF[flfl1,flfl2]*deltaF[ll1,ll2]*gam[yy1,mumu3,SEVEN,yy2]
lLbar  lL  BQuantum  (-I/4)*g1*deltaF[flfl1,flfl2]*deltaF[ll1,ll2]*gam[yy1,mumu3,SEVEN,yy2]
lLbar  lL  Wi  (I/2)*g2*deltaF[flfl1,flfl2]*gam[yy1,mumu3,SEVEN,yy2]*Ta[nn3,ll1,ll2]
```

MATCHMAKEREFT: THE BASICS

- Model creation (FeynRules).
- Generation of diagrams (QGRAF).

```
(-1)*
 cpol(lLbar(-1,p1))*
 cpol(lL(-3,p2))*
 cpol(lL(-5,p3))*
 cpol(lLbar(-7,p4))*

 prop(HL(1,-k1),HLbar(2,-k1))*
 prop(HT(3,k1-p1),HT(4,k1-p1))*
 prop(HT(5,-k1-p2),HT(6,-k1-p2))*
 prop(HL(7,-k1+p1+p3),HLbar(8,-k1+p1+p3))*
 v3(lLbar(-1,p1),HL(1,-k1),HT(3,k1-p1))*
 v3(HLbar(2,k1),lL(-3,p2),HT(5,-k1-p2))*
 v3(HLbar(8,k1-p1-p3),lL(-5,p3),HT(4,-k1+p1))*
 v3(lLbar(-7,p4),HL(7,-k1+p1+p3),HT(6,k1+p2)),
```

MATCHMAKEREFT: THE BASICS

- Model creation (FeynRules).
- Generation of diagrams (QGRAF).
- Amplitude calculation (FORM).

```
 esfull(1)=yT[fl93]*yT[fl99]*yTbar[fl95]*yTbar[fl97];
 esfull(2)=G[3*DEN[ML,MS]^3*gam[y93,FIVE,mu1,y95]*gam[y99,FIVE,mu1,
y97]*FourPi^(-2)*I*MS^4*esfull(1) - 3*DEN[ML,MS]^3*gam[y93,FIVE,mu1,
y95]*gam[y99,FIVE,mu1,y97]*FourPi^(-2)*I*ML^4*esfull(1) + 2*DEN[ML,
MS]^3*gam[y93,FIVE,mu1,y95]*gam[y99,FIVE,mu1,y97]*FourPi^(-2)*I*
invepsilonbar*MS^4*esfull(1) - 2*DEN[ML,MS]^3*gam[y93,FIVE,mu1,y95]*
gam[y99,FIVE,mu1,y97]*FourPi^(-2)*I*invepsilonbar*ML^4*esfull(1) - 2
*DEN[ML,MS]^3*gam[y93,FIVE,mu1,y95]*gam[y99,FIVE,mu1,y97]*Log[MS^2]*
FourPi^(-2)*I*MS^4*esfull(1) + 2*DEN[ML,MS]^3*gam[y93,FIVE,mu1,y95]*
gam[y99,FIVE,mu1,y97]*Log[ML^2]*FourPi^(-2)*I*ML^4*esfull(1) + 3*
DEN[ML,MS]^3*gam[y93,FIVE,mu1,y95]*gam[y99,mu1,y97]*FourPi^(-2)*I*
MS^4*esfull(1) - 3*DEN[ML,MS]^3*gam[y93,FIVE,mu1,y95]*gam[y99,mu1,
y97]*FourPi^(-2)*I*ML^4*esfull(1) + 2*DEN[ML,MS]^3*gam[y93,FIVE,mu1,
y95]*gam[y99,mu1,y97]*FourPi^(-2)*I*invepsilonbar*MS^4*esfull(1) - 2
*DEN[ML,MS]^3*gam[y93,FIVE,mu1,y95]*gam[y99,mu1,y97]*FourPi^(-2)*I*
invepsilonbar*ML^4*esfull(1) - 2*DEN[ML,MS]^3*gam[y93,FIVE,mu1,y95]*
gam[y99,mu1,y97]*Log[MS^2]*FourPi^(-2)*I*MS^4*esfull(1) + 2*DEN[ML,
MS]^3*gam[y93,FIVE,mu1,y95]*gam[y99,mu1,y97]*Log[ML^2]*FourPi^(-2)*I
*ML^4*esfull(1) + 3*DEN[ML,MS]^3*gam[y93,mu1,y95]*gam[y99,FIVE,mu1,
```

MATCHMAKEREFT: THE BASICS

- Model creation (FeynRules).
- Generation of diagrams (QGRAF).
- Amplitude calculation (FORM).
- Solution ⊕ Canonical Normalization ⊕ Reduction to the physical basis (Mathematica)

Out[15]= $\left\{\text{alphaO3Gt} \to 0,\ \text{alphaO3W} \to -\frac{\text{g2}^3\ \text{onelooporder}}{2880\ \text{ML}^2\ \pi^2},\ \ldots\right\}$