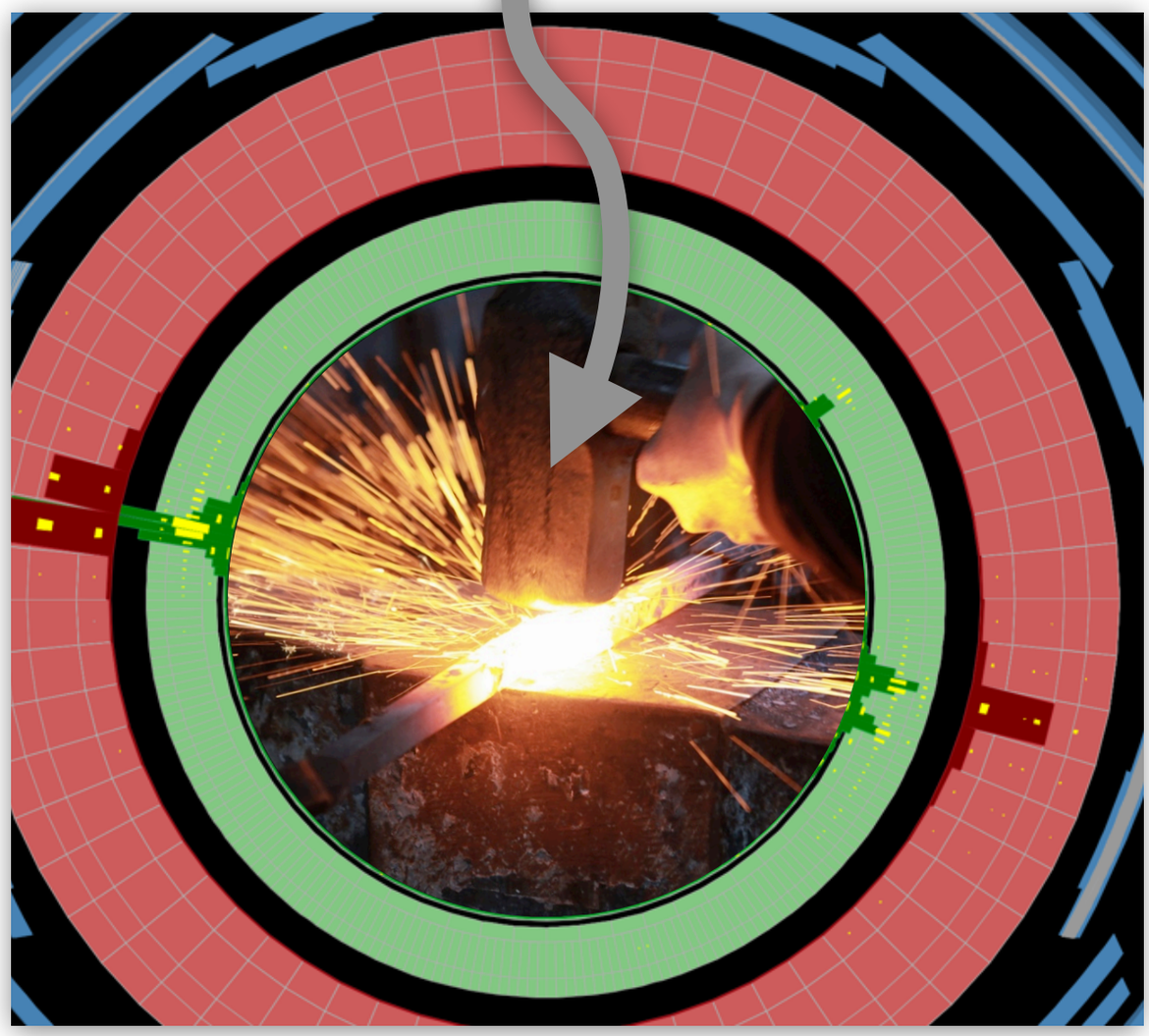
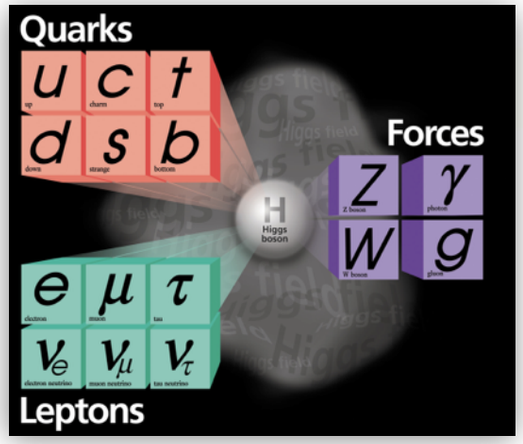
New Strong Dynamics at the TeV scale



Alex Pomarol, CERN & UAB (Barcelona)

After the Higgs discovery…



CERTIFIED

… we've moved to a different situation in particle physics:

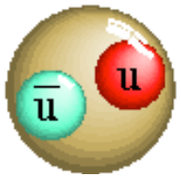
We have the theory,
but **now** we'd like to understand **why it is like it is**

In particular, we'd like to understand:

Why $m_H \ll M_P \sim 10^{19}$ GeV?

provides a (unique?) solid argument for TeV new-physics

Among the few possibilities to solve the hierarchy problem:

Compositeness: **H =** 

"dead dogs don't bite":

If no elementary Higgs, m_H is not anymore a fundamental parameter

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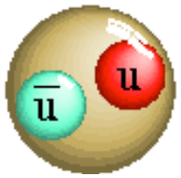
Compositeness: **H =** 

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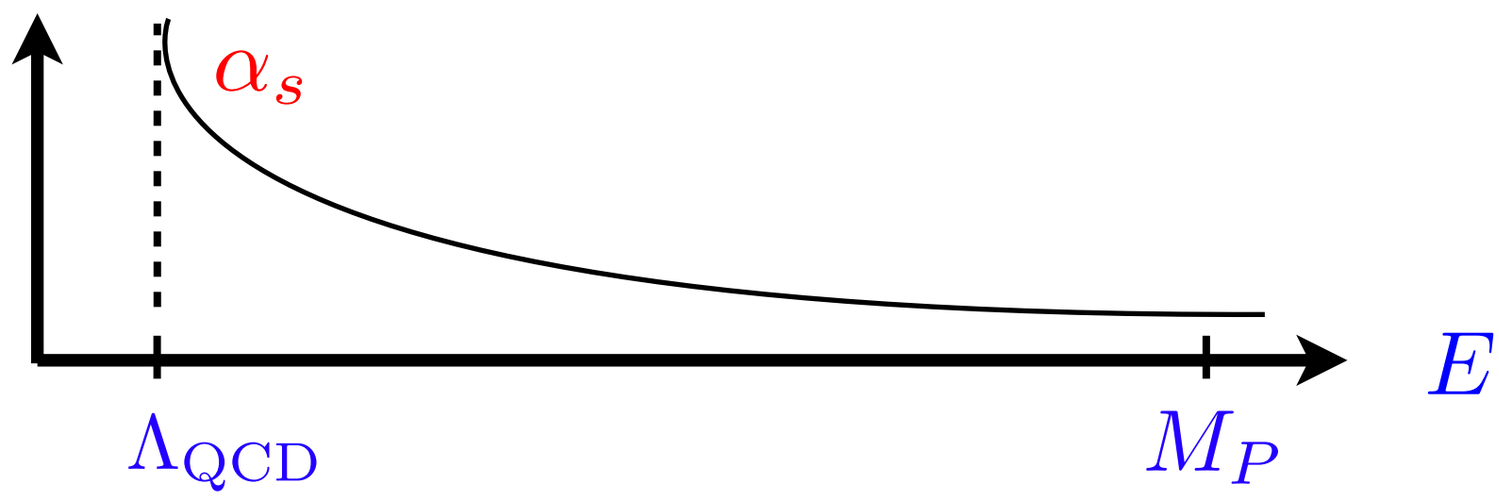

Explains why $\Lambda_{\rm QCD} << M_P$

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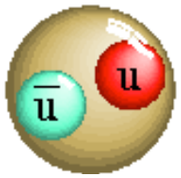
Compositeness: **H =** 

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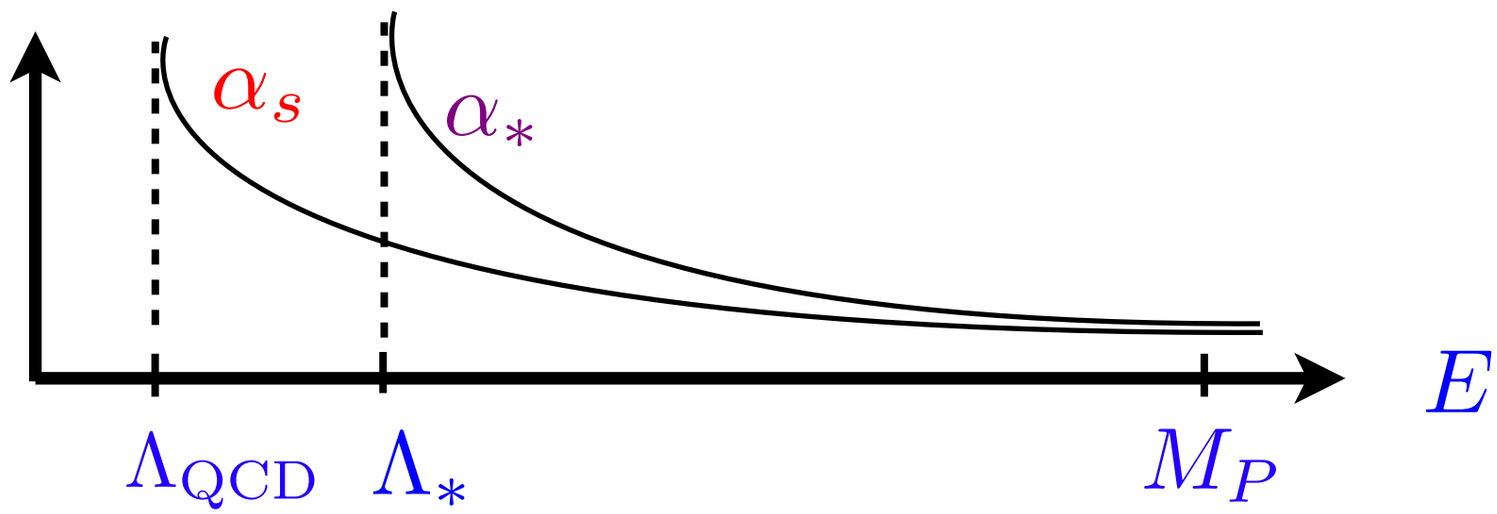
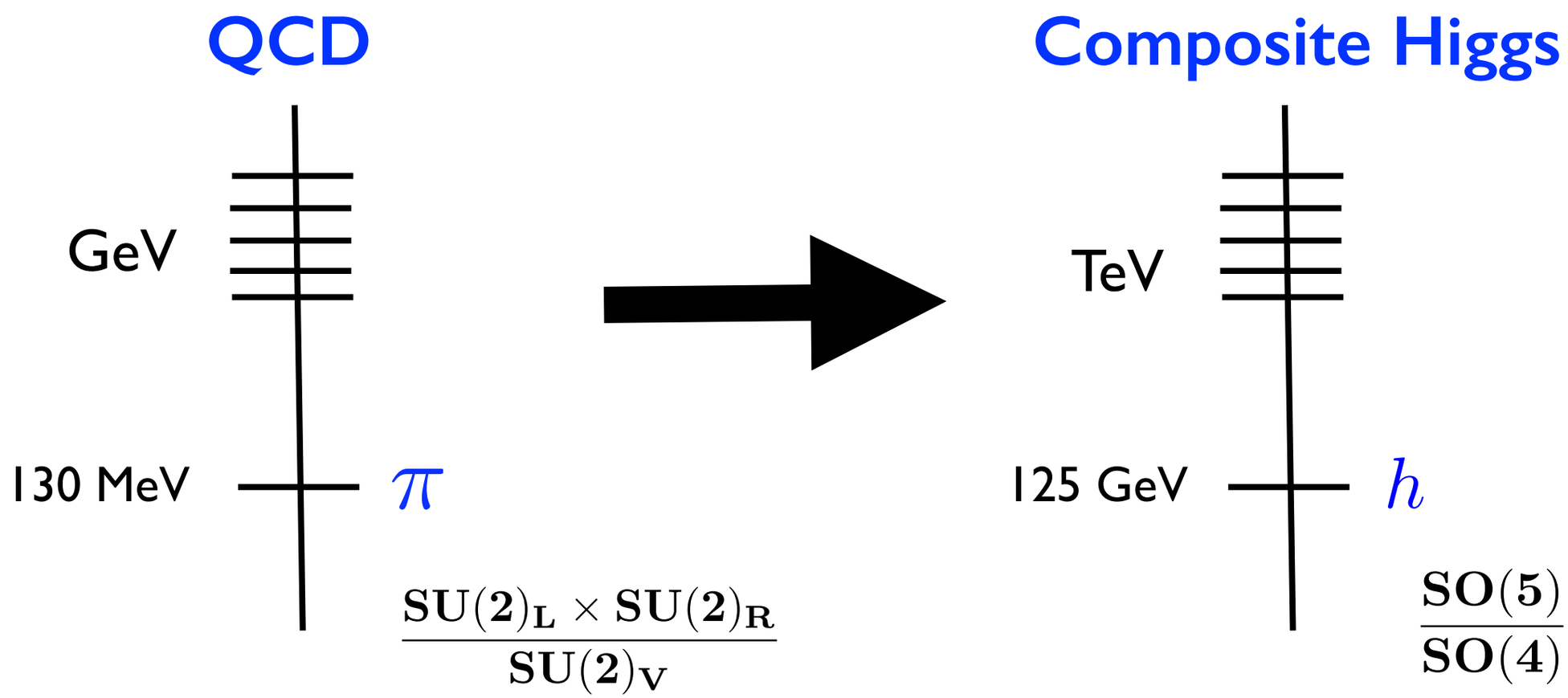


New strong dynamics at TeV

It could explain why $m_H \lesssim \Lambda_* \sim \mathrm{TeV} \ll M_P$

The **Higgs, the lightest** of the new strong resonances,
as pions in QCD: they are Pseudo-Goldstone Bosons (**PGB**)



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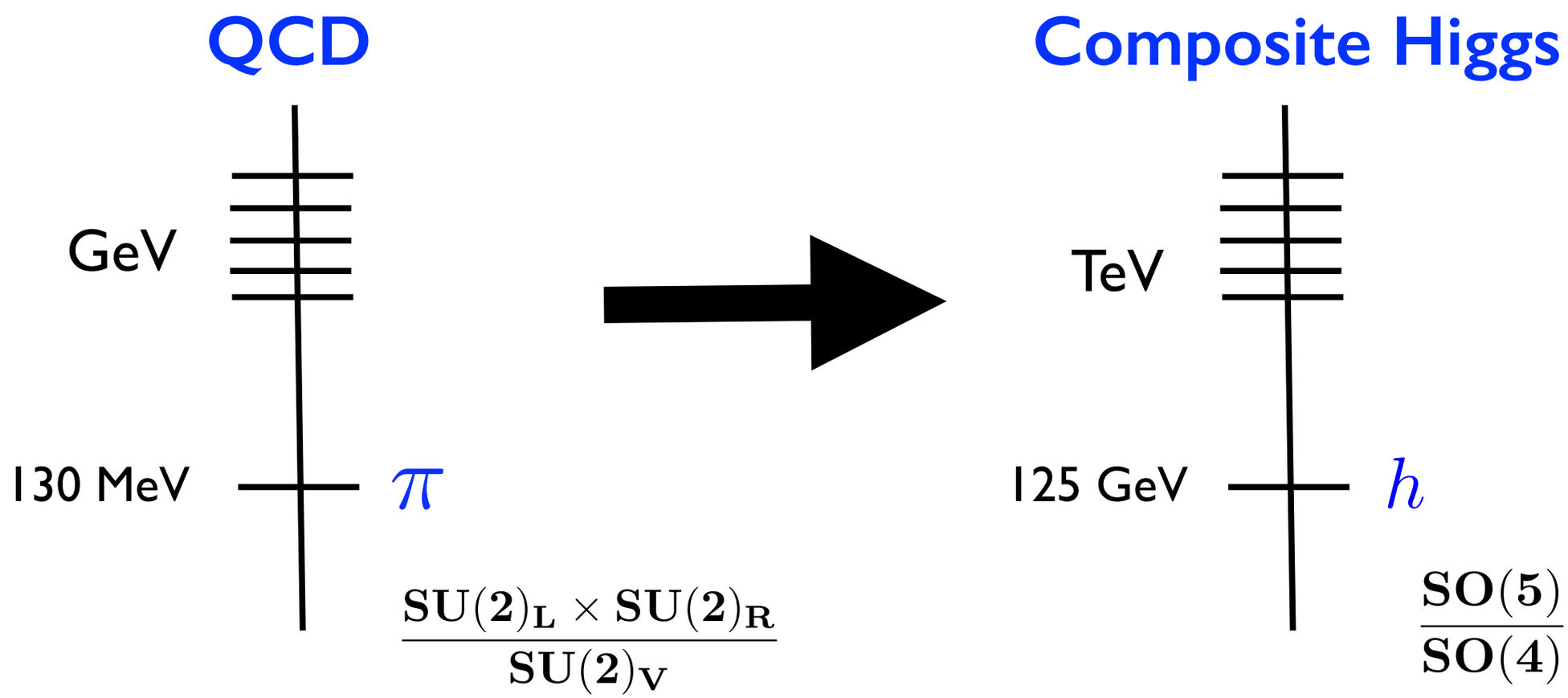


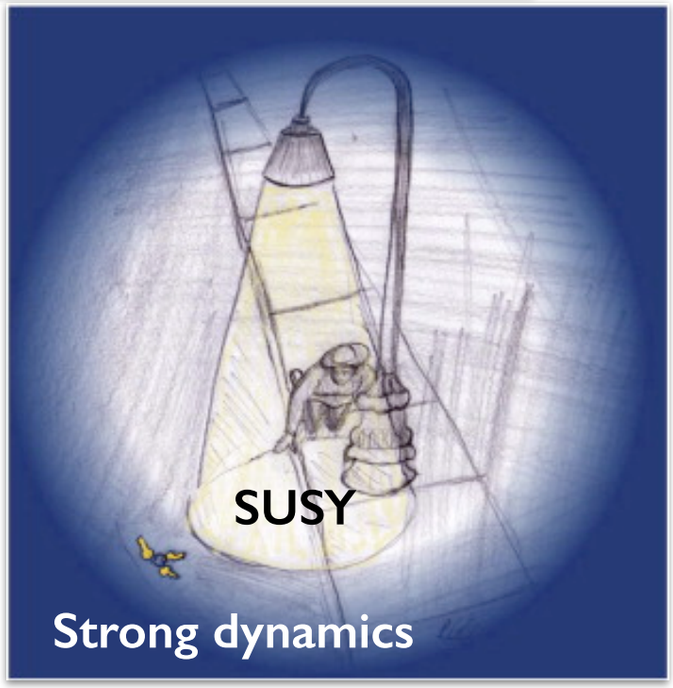
Minimality should not the guiding principle!

Let's not repeat Sakurai's mistake:

… and since any successful theory must be simple… **Sakurai**

The **rho-meson** was **not** a gauge boson! (even though was the simplest theory to built)

beyond the lamp-post:

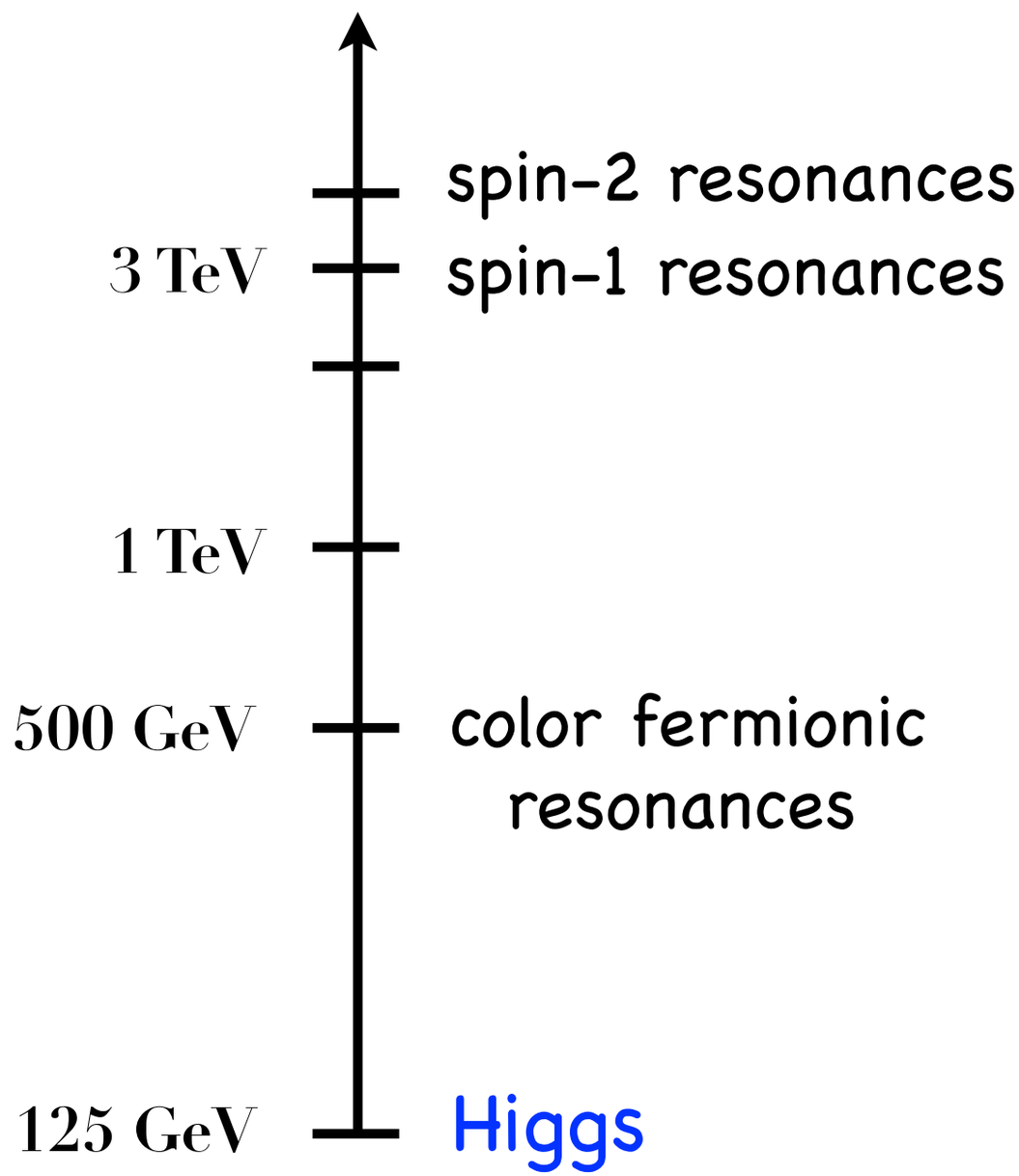


Even though <u>no possibility to calculate</u>…

it's possible provide a <u>characterization</u> of the expected signals

(as in the 60', experiments will be driving the field)

Expected spectrum in Composite Higgs Scenarios



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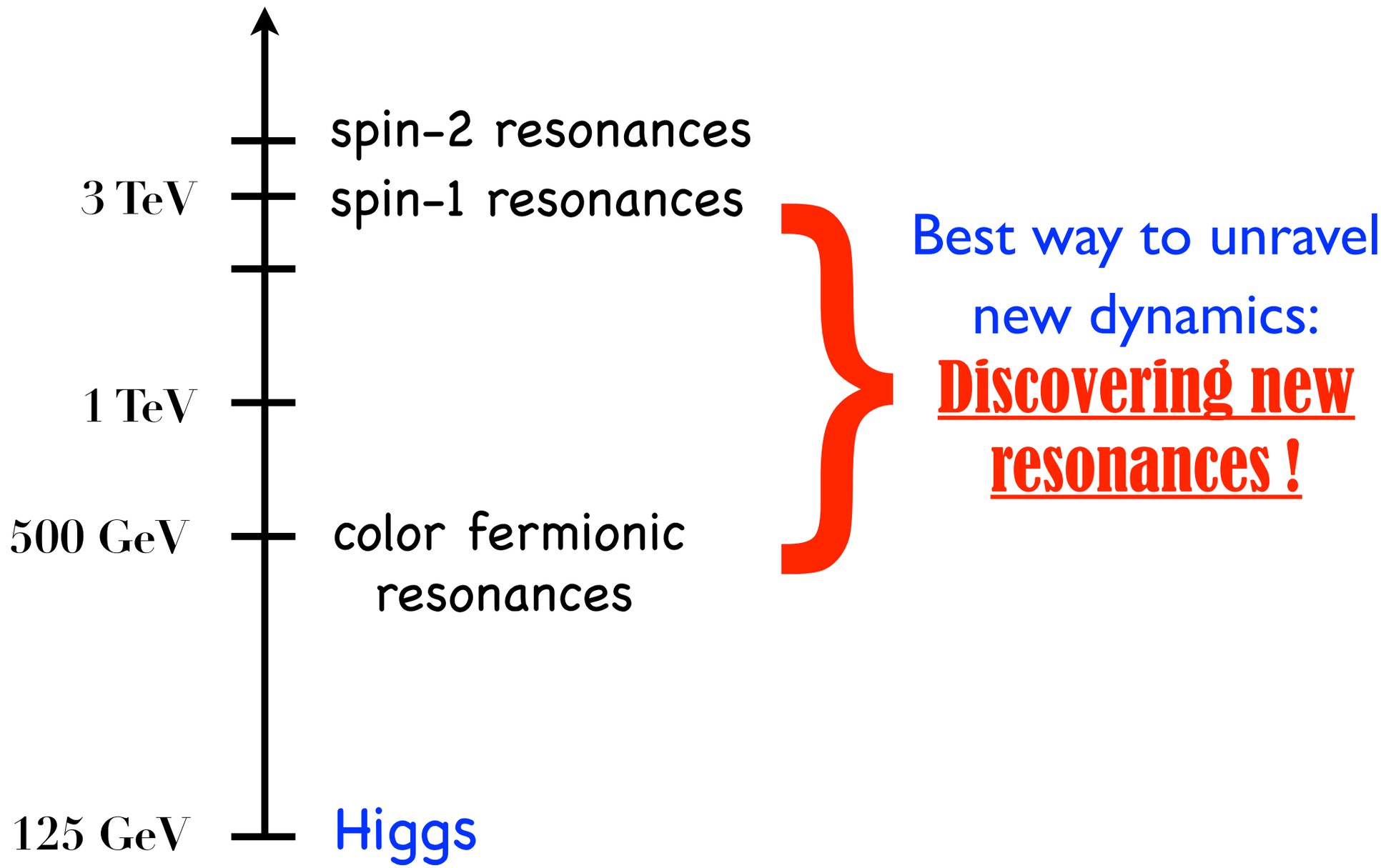

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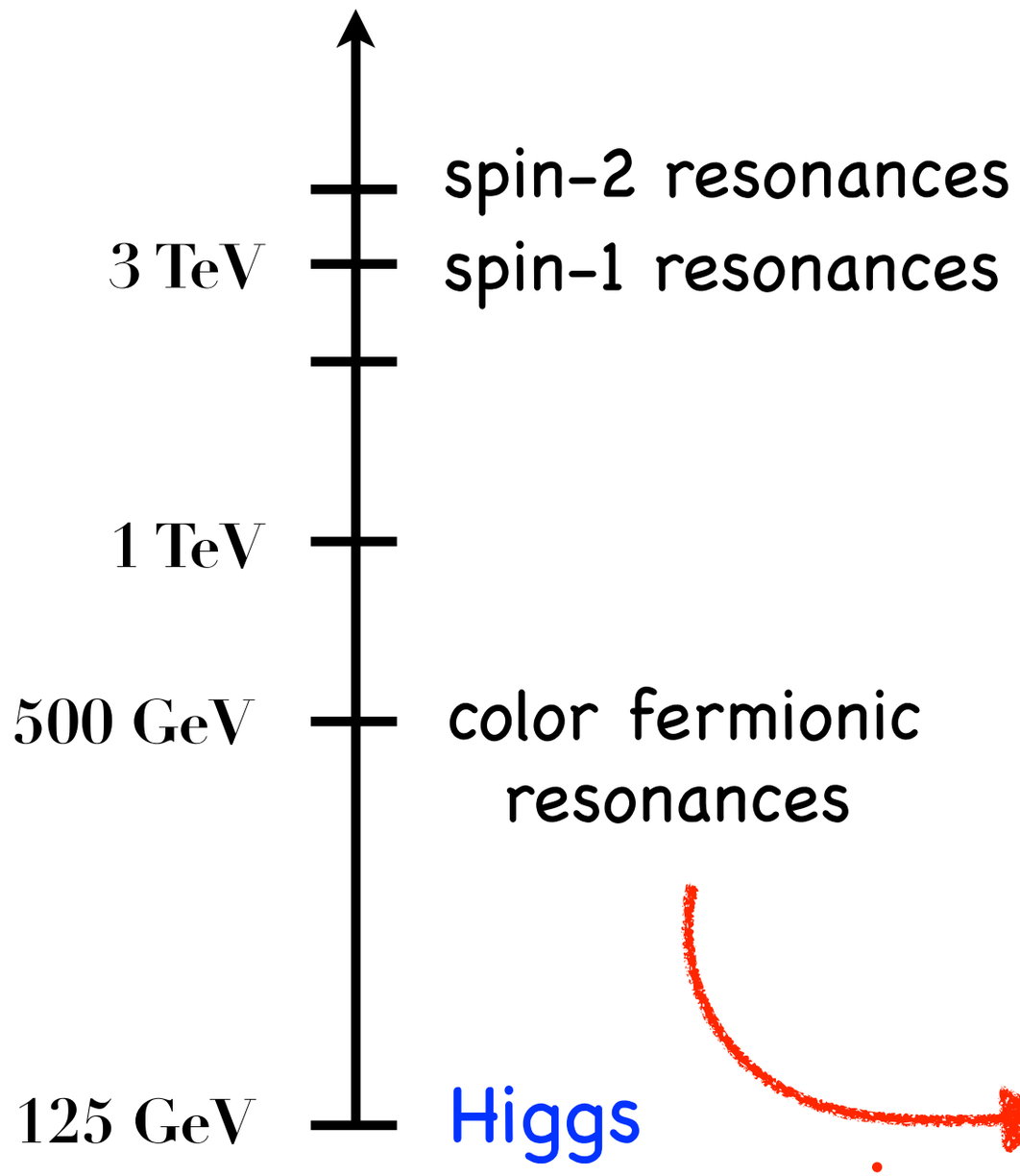
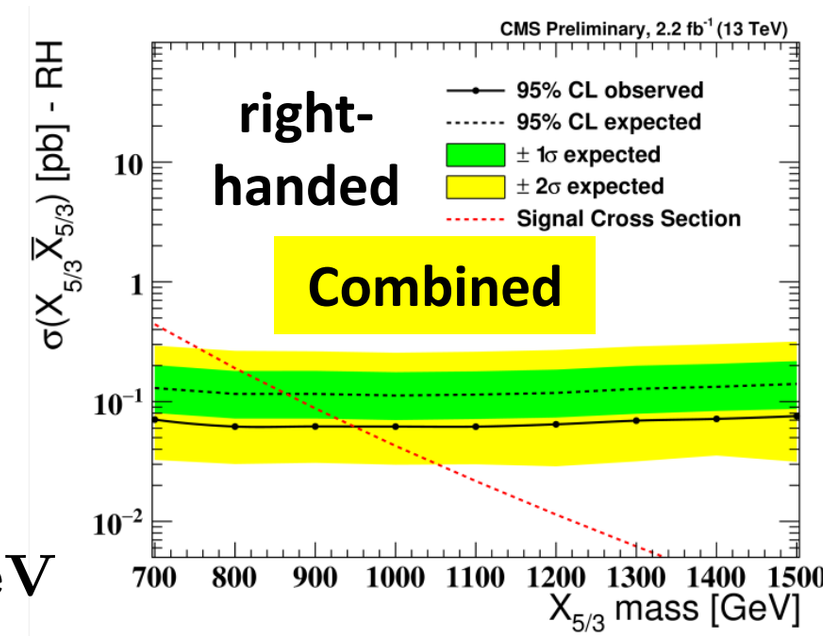


Best way to unravel new dynamics:

Discovering new resonances !

no sign at 13 TeV!

$m(X_{5/3}) > 960$ GeV



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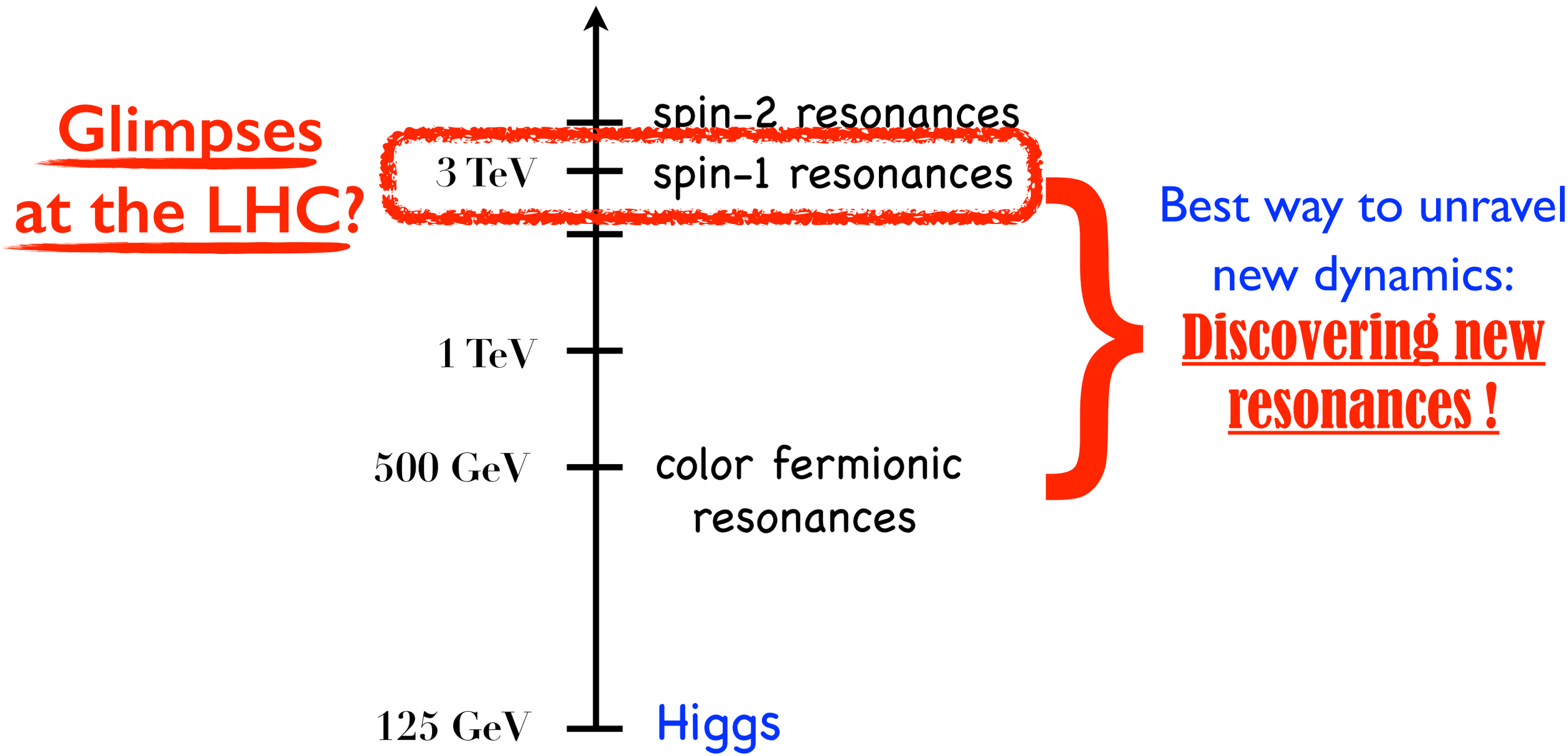
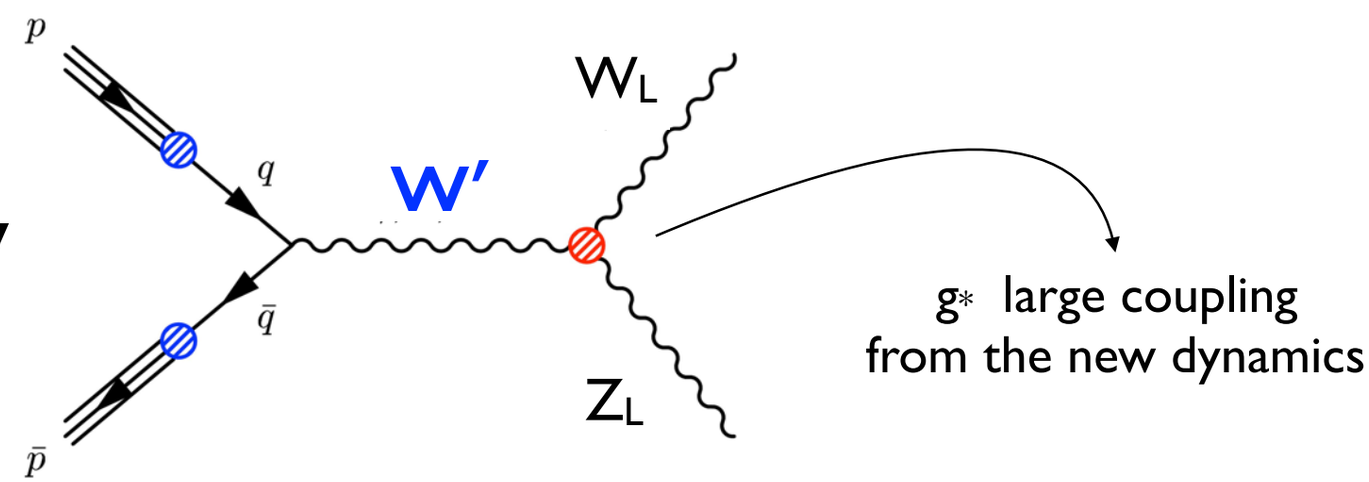
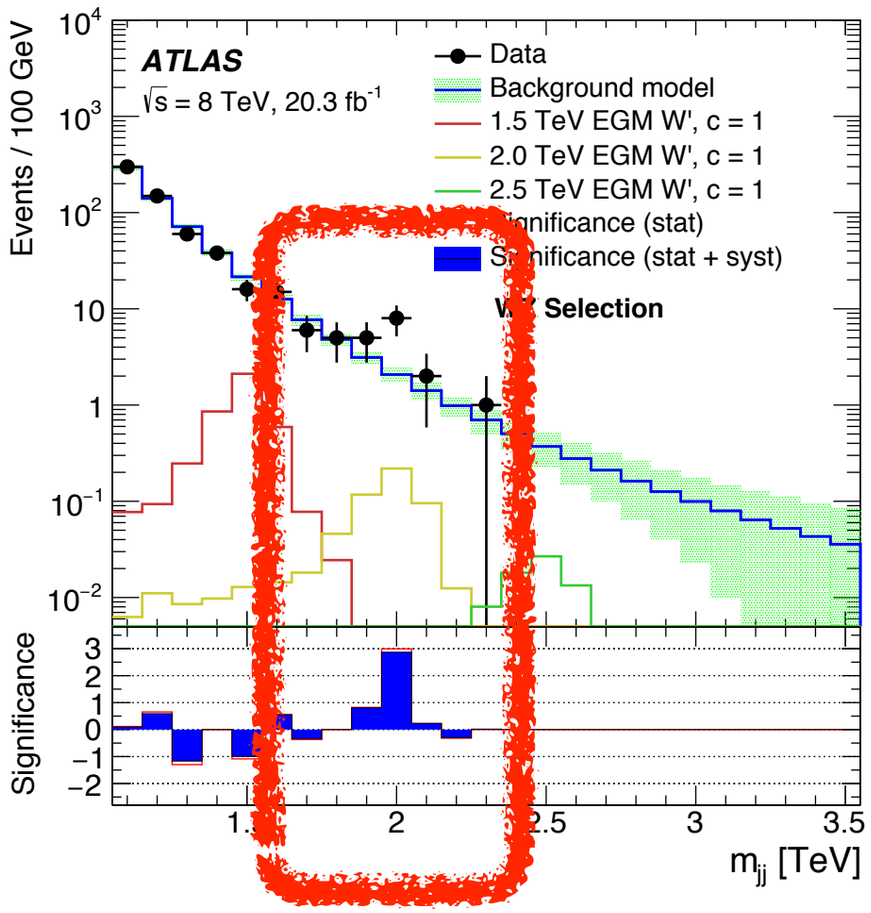


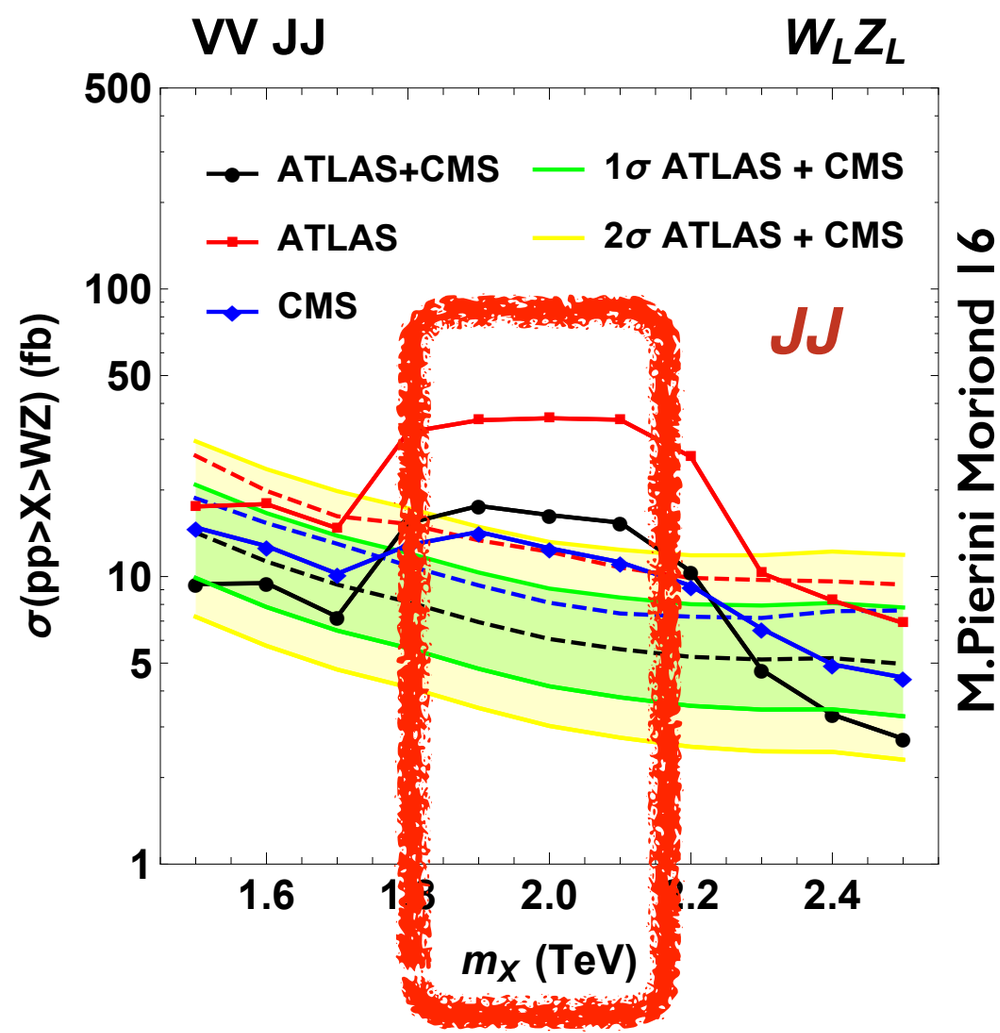
Glimpses at the LHC?

$M_{W'}$ expected at 2-3 TeV



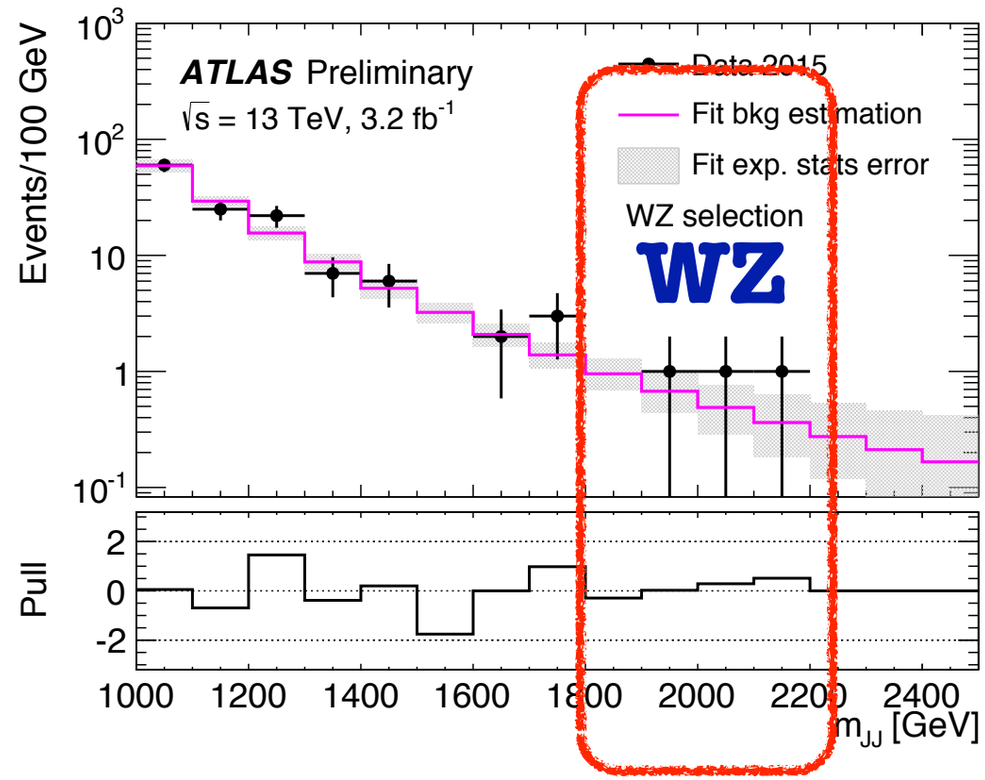
At 8 TeV, some excess in ZW decays (in jets) mostly in ATLAS:





M.Pierini Moriond 16

At the LHC 13…



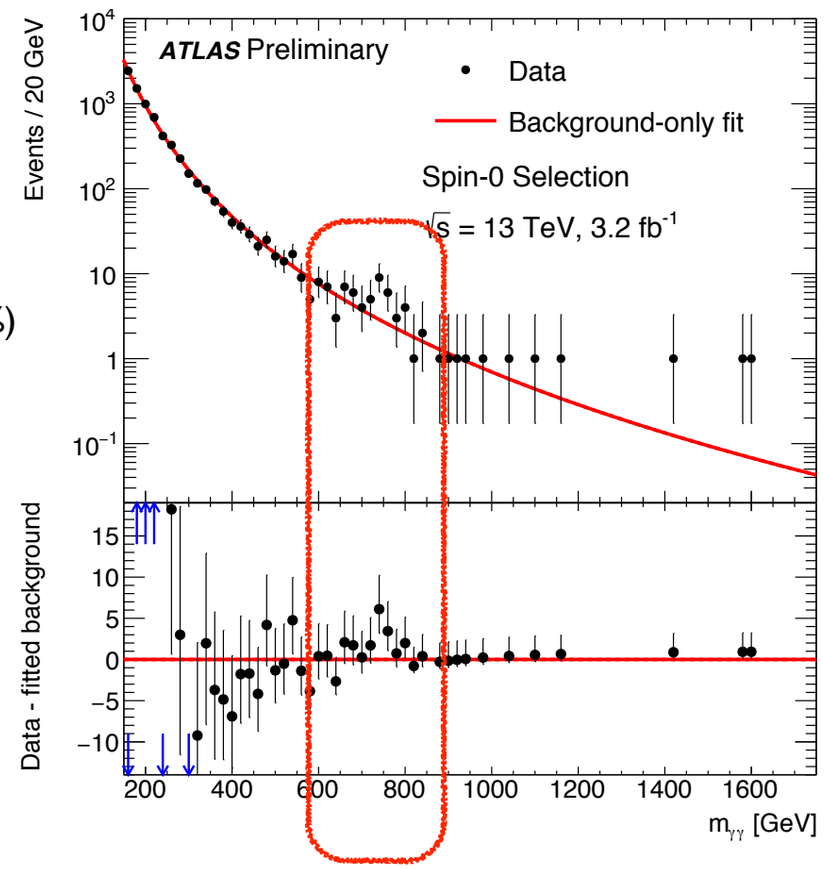
Not much of di-Boson excess…

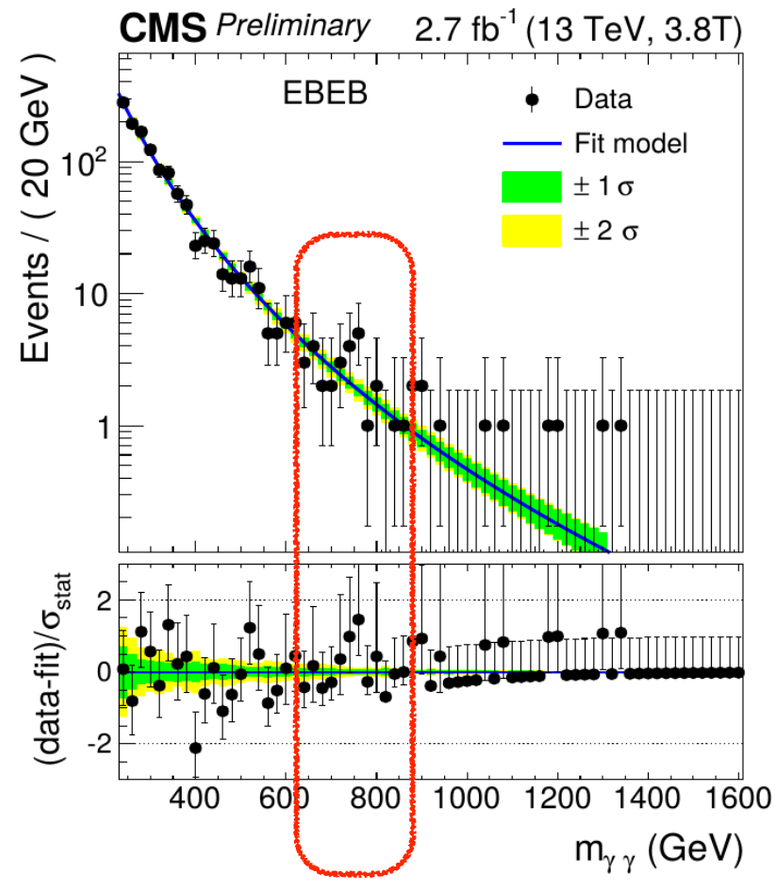
M.Pierini's talk at Moriond 16:

Still, not enough lumi to exclude the Run I excess or to confirm it

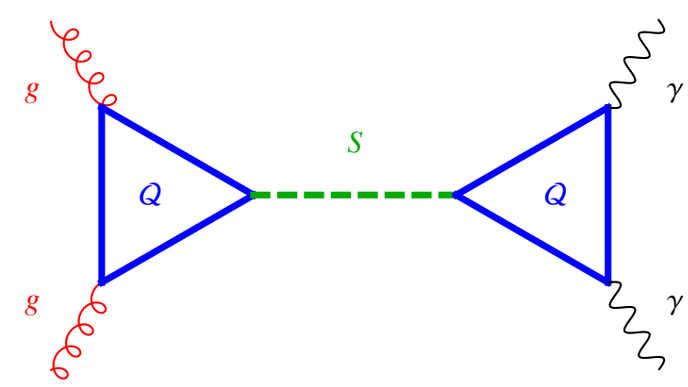
Glimpses? Di-photon excess:

- ✓ $m_X \sim 750$ GeV, $\Gamma_X \sim 45$ GeV (6%)
- ✓ Local Z = **3.9 σ**
- ✓ Global Z = **2.0 σ**





Pointing towards…
a (pseudo)-scalar of mass **750 GeV**
with a sizable **BR to photons & gluons**



a width Γ/M of 6% slightly favored!

☛ strong dynamics at TeV ?

Was this resonance expected/predicted?

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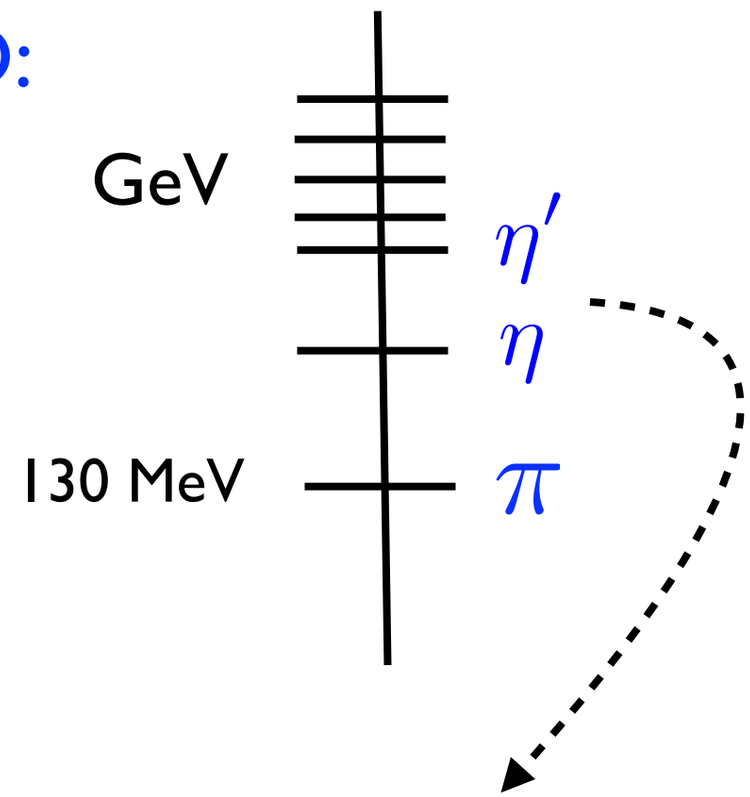
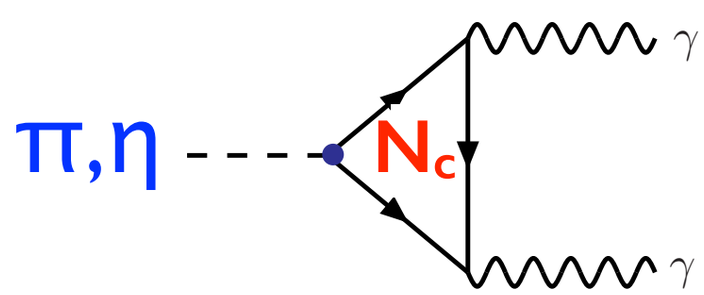
Lessons from QCD:



Lighter as they are Pseudo-Goldstone bosons (PGB)

☛ pseudo-scalars with sizable couplings to photons:



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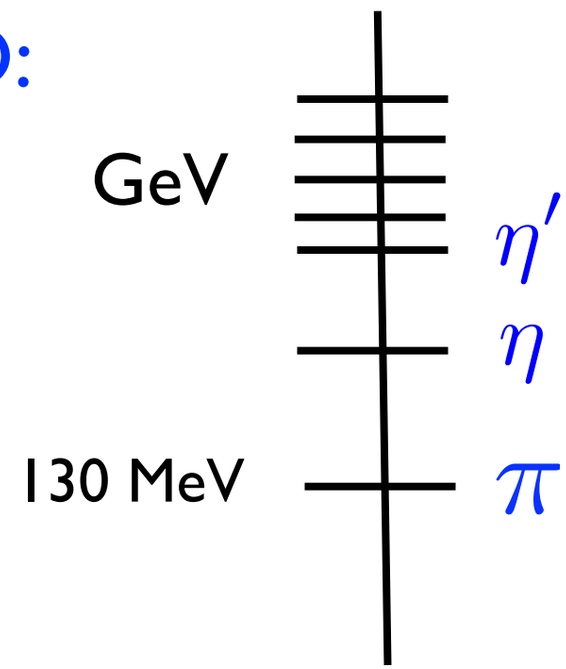
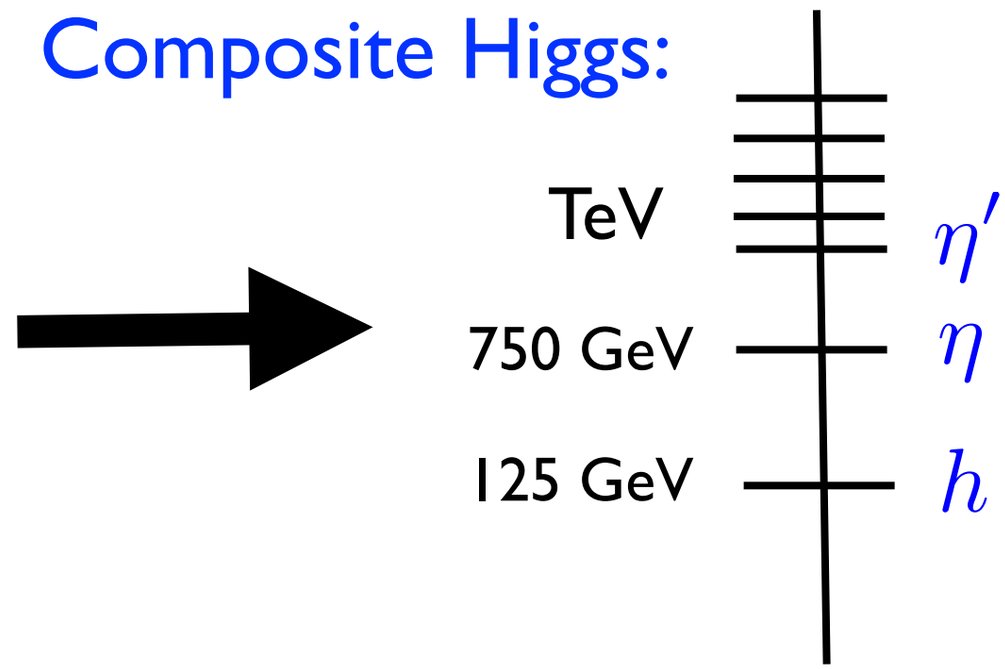


Composite Higgs:



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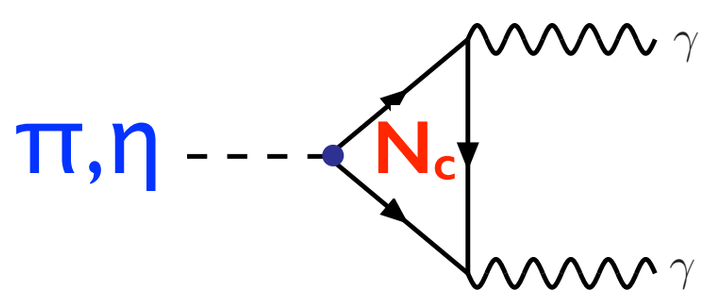
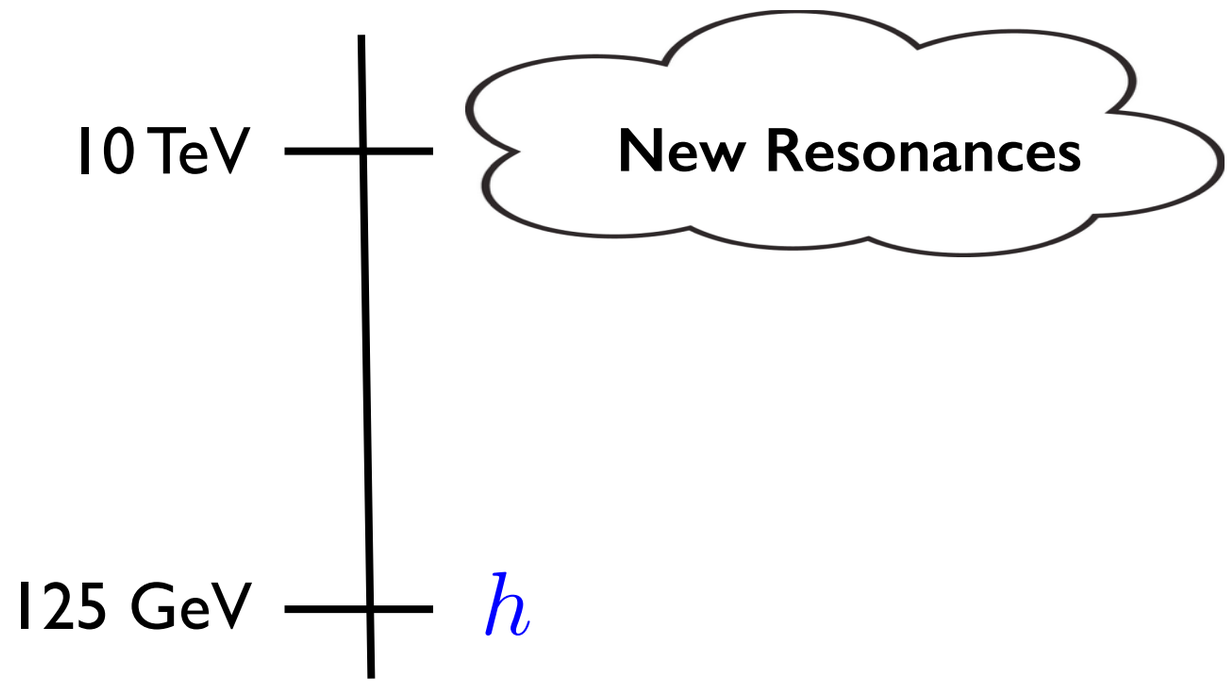


If these excesses are not confirmed…
and the new-strong sector turns out to be too heavy…



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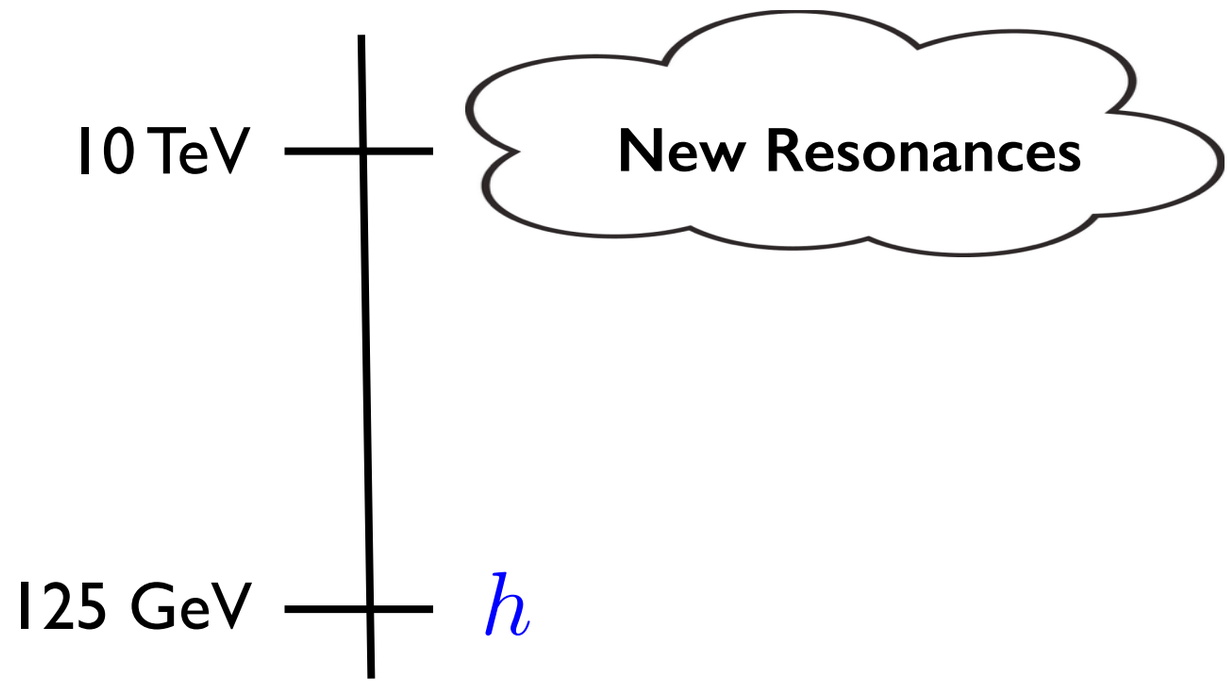
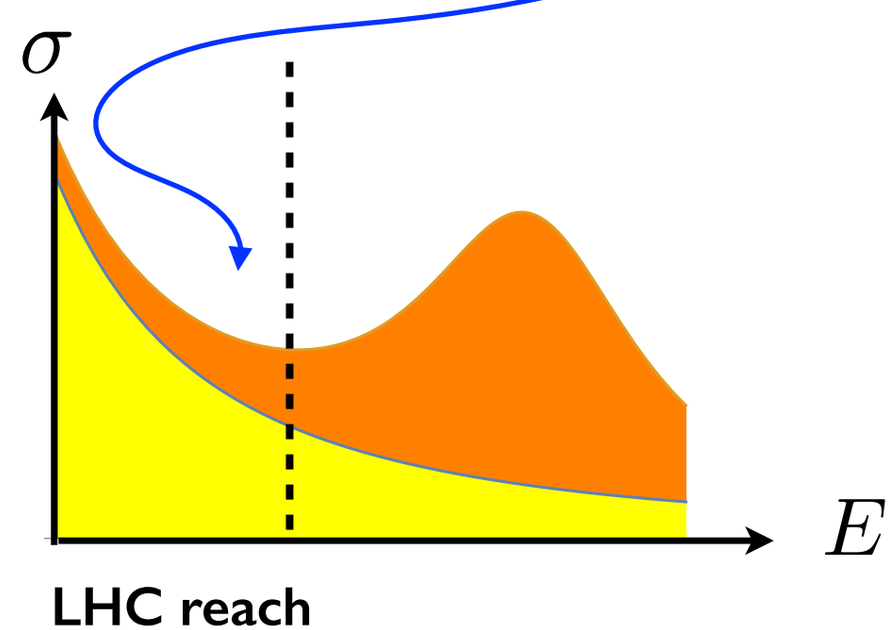


LHC still <u>offers</u> the possibility to see new-physics in deviations in 2→2 SM processes:



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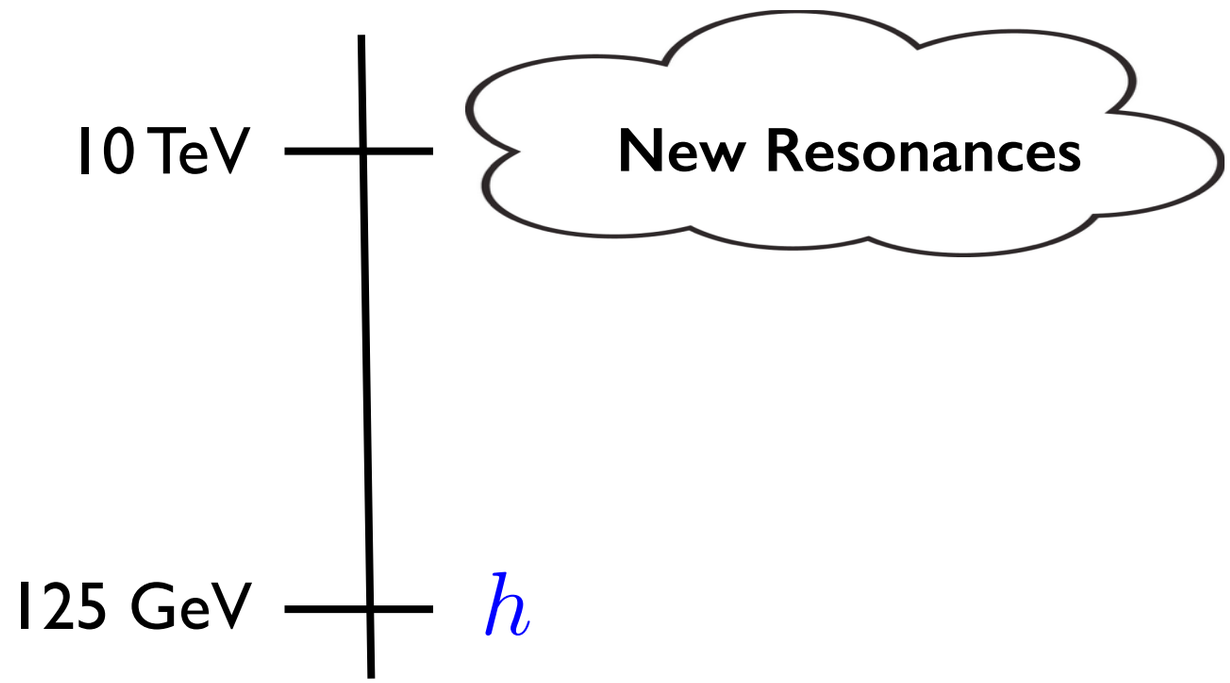

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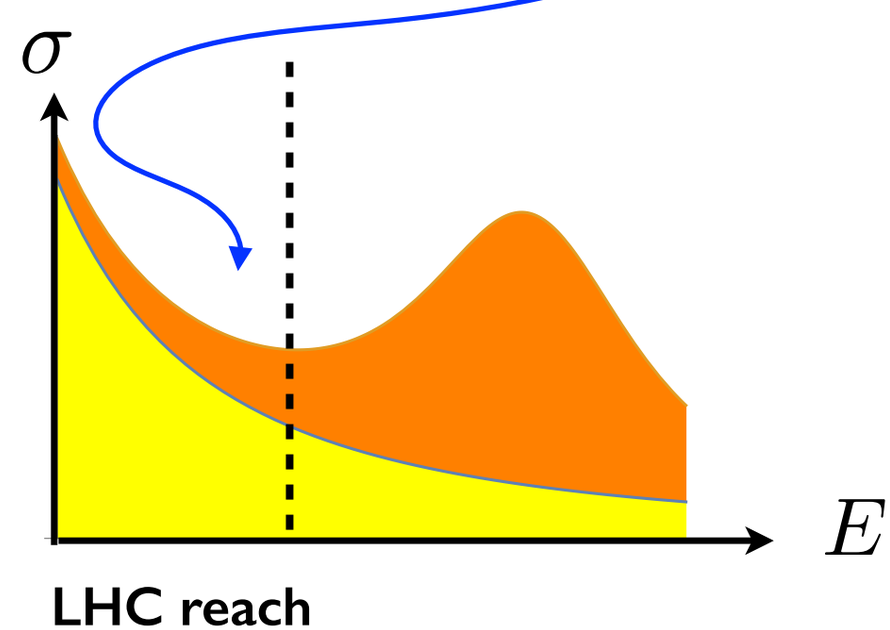
Even if we cannot get the resonance, we could get its tail



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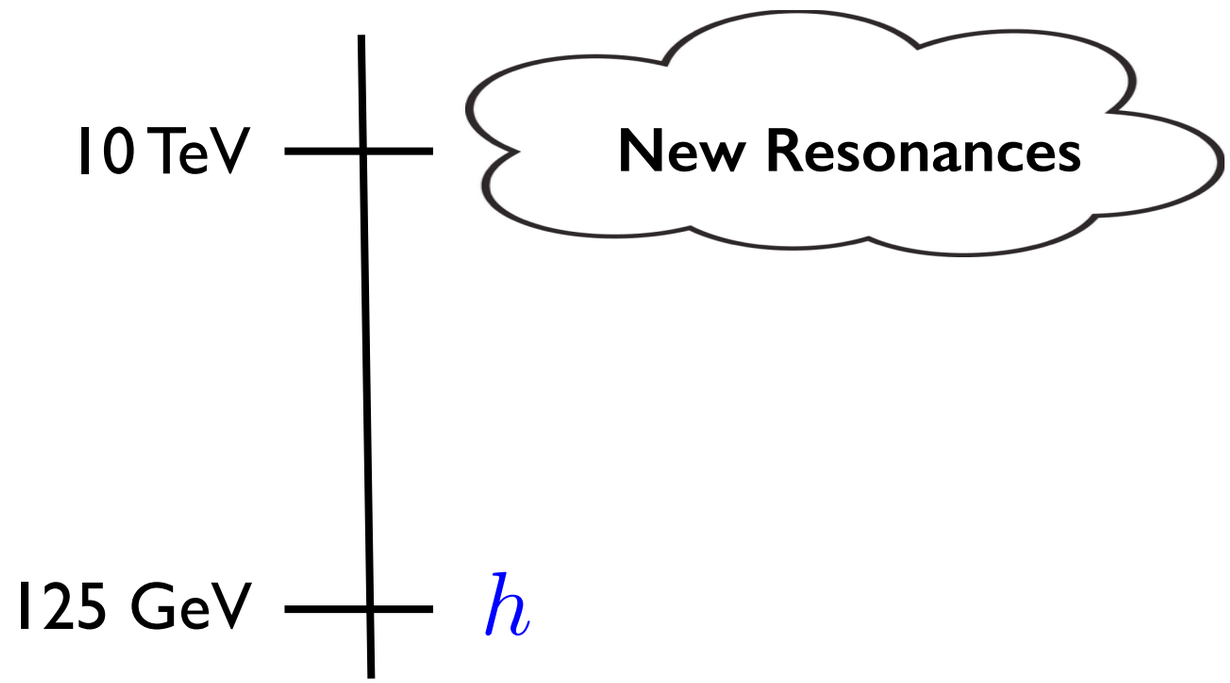

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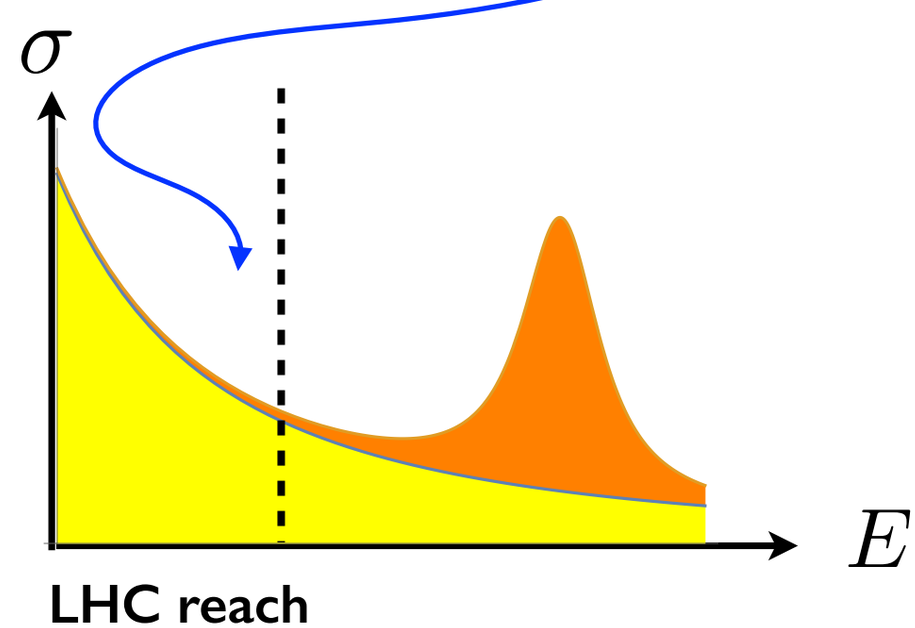
Not possible for weakly-coupled BSM
as LHC is not a **precise** machine:
either we find the resonance
or wait for future ee-colliders



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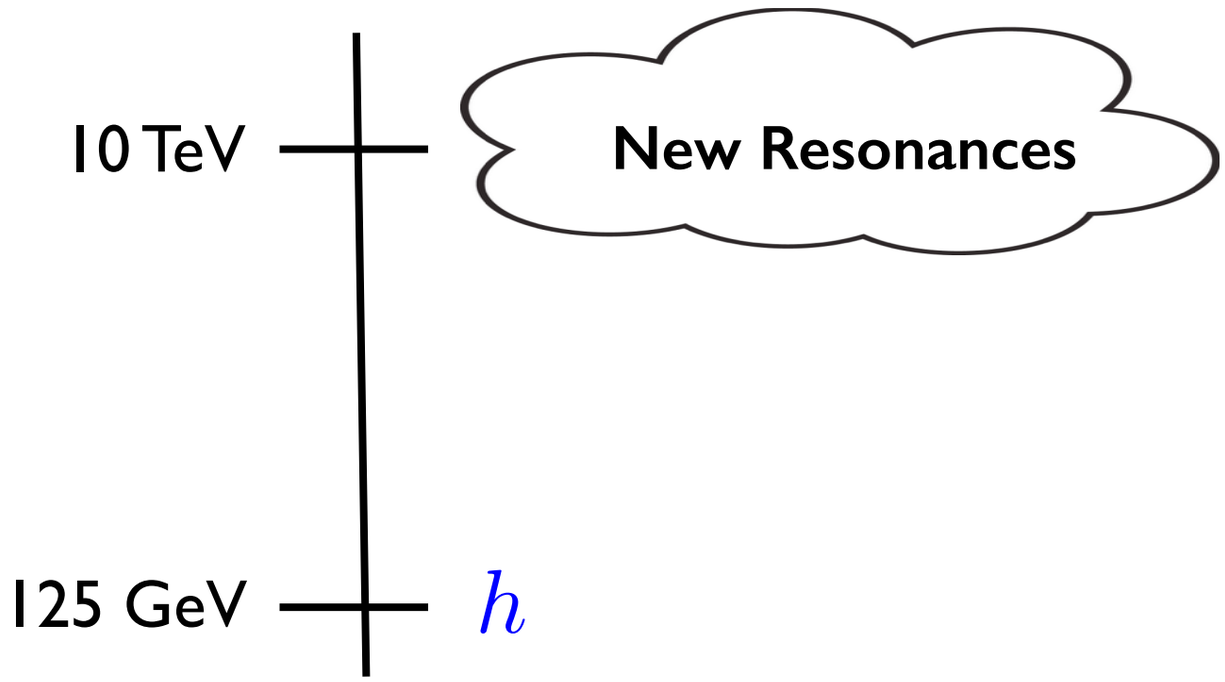

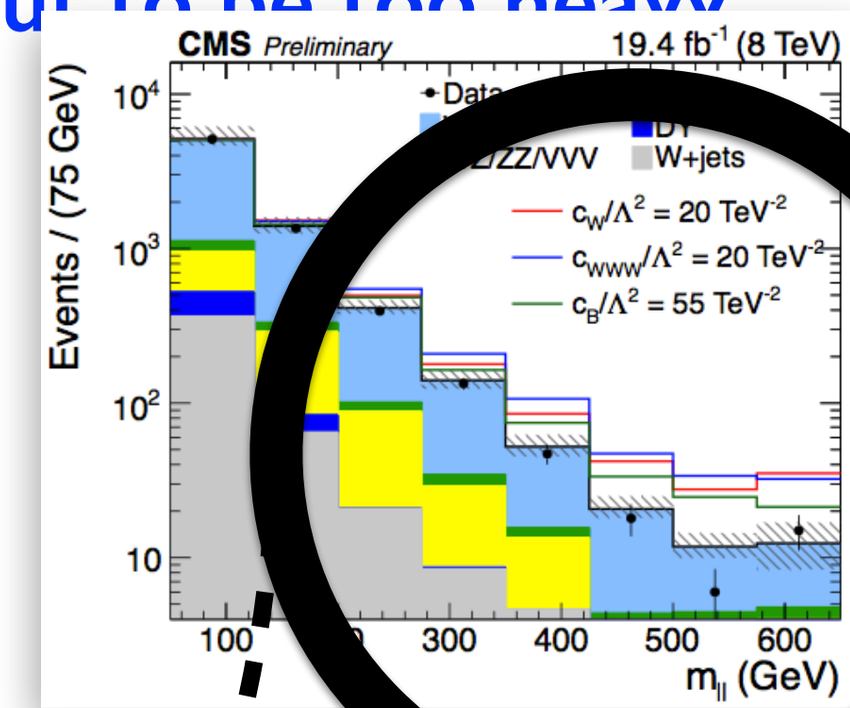

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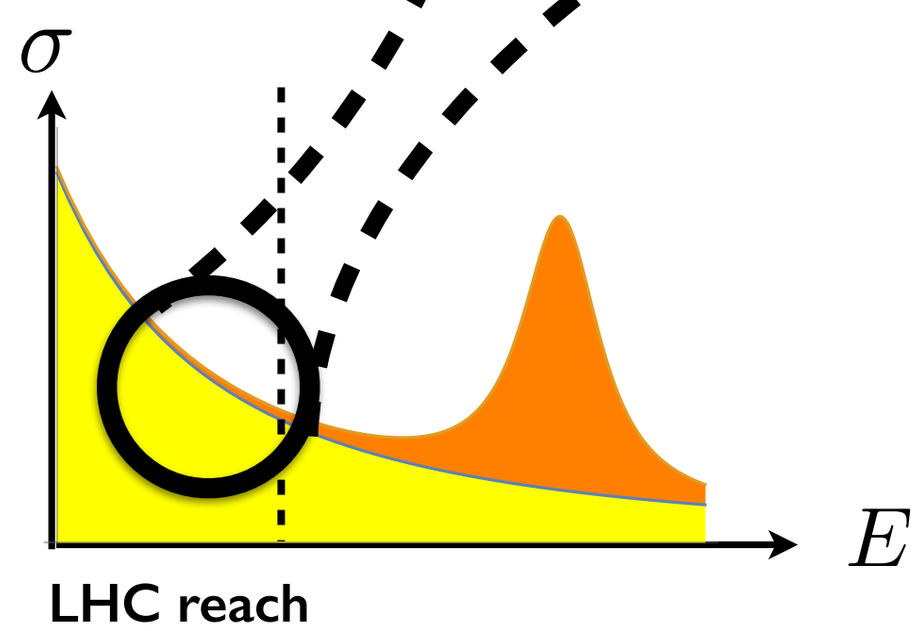

Effects of the resonance "tails"

Encoded in **Higher-dimensional operators,**

e.g. $(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$, $W^{a\,\nu}_{\mu} W^{b}_{\nu\rho} W^{c\,\rho\mu}$, ...

generated after integrating out new-physics

Goal: Recognize the relevant effects

e.g. those that make the

2→2 amplitudes grow with E

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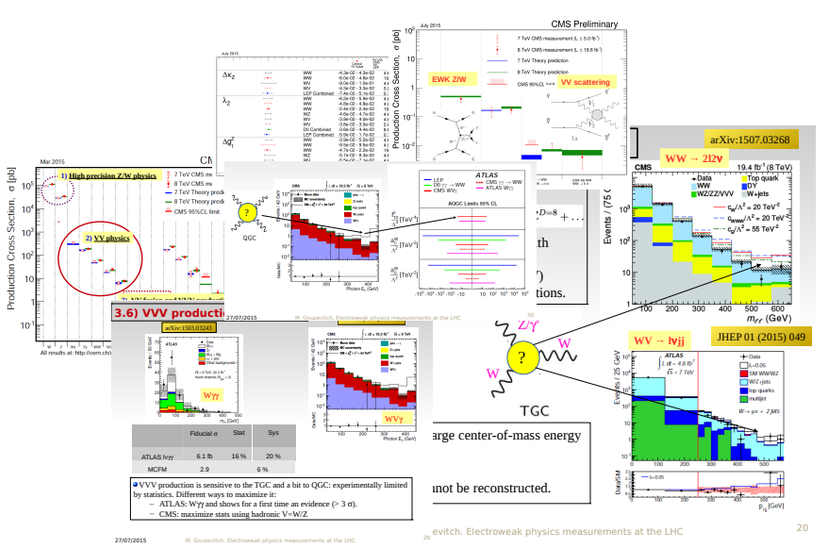
EX

TH

e.g. those that make the
2→2 amplitudes grow with E

Plenty of LHC data:

qq→VV/h, qq→qq, VV→VV



Plenty of higher-dim operators:

$$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2$$
$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
$$\mathcal{O}_6 = \lambda |H|^6$$

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$$
$$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$$
$$\mathcal{O}_{2G} = -\frac{1}{2}(D^\mu G^A_{\mu\nu})^2$$

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$

$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^{b}_{\nu\rho} W^{c\,\rho\mu}$$
$$\mathcal{O}_{3G} = \frac{1}{3!} g_s f_{ABC} G^{A\,\nu}_{\mu} G^{B}_{\nu\rho} G^{C\,\rho\mu}$$

$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \tilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$		$\mathcal{O}^l_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$
$\mathcal{O}^{(3)q}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu \sigma^a Q_L)$		$\mathcal{O}^{(3)l}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu \sigma^a L_L)$
$\mathcal{O}^u_{LR} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}^d_{LR} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_{LR} = (\bar{L}_L \gamma^\mu L_L)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}^{(8)u}_{LR} = (\bar{Q}_L \gamma^\mu T^A Q_L)(\bar{u}_R \gamma^\mu T^A u_R)$	$\mathcal{O}^{(8)d}_{LR} = (\bar{Q}_L \gamma^\mu T^A Q_L)(\bar{d}_R \gamma^\mu T^A d_R)$	
$\mathcal{O}^u_{RR} = (\bar{u}_R \gamma^\mu u_R)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}^d_{RR} = (\bar{d}_R \gamma^\mu d_R)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_{RR} = (\bar{e}_R \gamma^\mu e_R)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}^q_{LL} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{Q}_L \gamma^\mu Q_L)$		$\mathcal{O}^l_{LL} = (\bar{L}_L \gamma^\mu L_L)(\bar{L}_L \gamma^\mu L_L)$
$\mathcal{O}^{(8)q}_{LL} = (\bar{Q}_L \gamma^\mu T^A Q_L)(\bar{Q}_L \gamma^\mu T^A Q_L)$		
$\mathcal{O}^q_{RR} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{L}_L \gamma^\mu L_L)$		
$\mathcal{O}^{(3)ql}_{LL} = (\bar{Q}_L \gamma^\mu \sigma^a Q_L)(\bar{L}_L \gamma^\mu \sigma^a L_L)$		
$\mathcal{O}^{qe}_{LR} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{e}_R \gamma^\mu e_R)$		
$\mathcal{O}^{lu}_{LR} = (\bar{L}_L \gamma^\mu L_L)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}^{ld}_{LR} = (\bar{L}_L \gamma^\mu L_L)(\bar{d}_R \gamma^\mu d_R)$	
$\mathcal{O}^{ud}_{RR} = (\bar{u}_R \gamma^\mu u_R)(\bar{d}_R \gamma^\mu d_R)$		
$\mathcal{O}^{(8)ud}_{RR} = (\bar{u}_R \gamma^\mu T^A u_R)(\bar{d}_R \gamma^\mu T^A d_R)$		
$\mathcal{O}^{eu}_{RR} = (\bar{u}_R \gamma^\mu u_R)(\bar{e}_R \gamma^\mu e_R)$	$\mathcal{O}^{ed}_{RR} = (\bar{d}_R \gamma^\mu d_R)(\bar{e}_R \gamma^\mu e_R)$	
$\mathcal{O}^{ud}_R = y^1_u y_d (i\tilde{H}^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu d_R)$		
$\mathcal{O}_{y_u y_d} = y_u y_d (\bar{Q}^r_L u_R)\epsilon_{rs}(\bar{Q}^s_L d_R)$		
$\mathcal{O}^{(8)}_{y_u y_d} = y_u y_d (\bar{Q}^r_L T^A u_R)\epsilon_{rs}(\bar{Q}^s_L T^A d_R)$		
$\mathcal{O}_{y_u y_e} = y_u y_e (\bar{Q}^r_L u_R)\epsilon_{rs}(\bar{L}^s_L e_R)$		
$\mathcal{O}^r_{y_u y_e} = y_u y_e (\bar{Q}^r_L e_R)\epsilon_{rs}(\bar{L}^s_L u^c_R)$		
$\mathcal{O}_{y_u y_d} = y_e y^1_d (\bar{L}_L e_R)(\bar{d}_R Q_L)$		
$\mathcal{O}^u_{DB} = y_u Q_L \sigma^{\mu\nu} u_R \tilde{H} g' B_{\mu\nu}$	$\mathcal{O}^d_{DB} = y_d Q_L \sigma^{\mu\nu} d_R H g' B_{\mu\nu}$	$\mathcal{O}^e_{DB} = y_e \bar{L}_L \sigma^{\mu\nu} e_R H g' B_{\mu\nu}$
$\mathcal{O}^u_{DW} = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \sigma^a \tilde{H} g W^a_{\mu\nu}$	$\mathcal{O}^d_{DW} = y_d \bar{Q}_L \sigma^{\mu\nu} d_R \sigma^a H g W^a_{\mu\nu}$	$\mathcal{O}^e_{DW} = y_e \bar{L}_L \sigma^{\mu\nu} e_R \sigma^a H g W^a_{\mu\nu}$
$\mathcal{O}^u_{DG} = y_u \bar{Q}_L \sigma^{\mu\nu} T^A u_R \tilde{H} g_s G^A_{\mu\nu}$	$\mathcal{O}^d_{DG} = y_d \bar{Q}_L \sigma^{\mu\nu} T^A d_R H g_s G^A_{\mu\nu}$	

How to extract the relevant information?

Restrict to dimension-6 operators?

W. Buchmuller and D. Wyler 86
& thousands more…

This can either be…

Redundant: Missing correlations

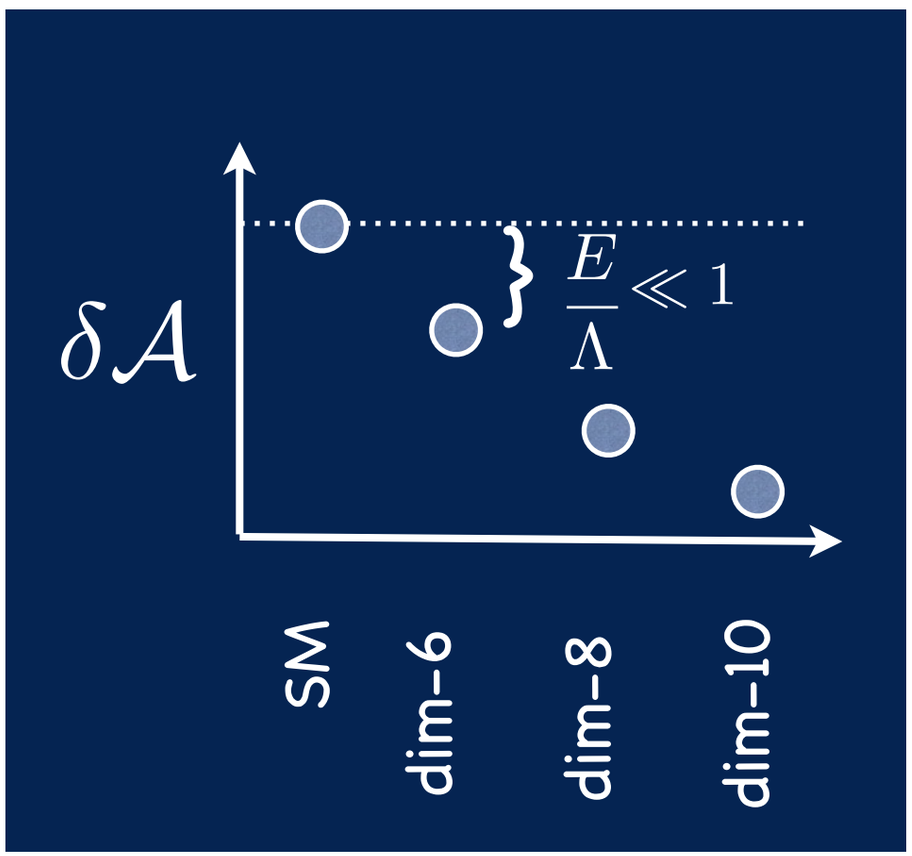
Incomplete: Dimension-8 operator also relevant in certain BSMs

The energy expansion parameter:

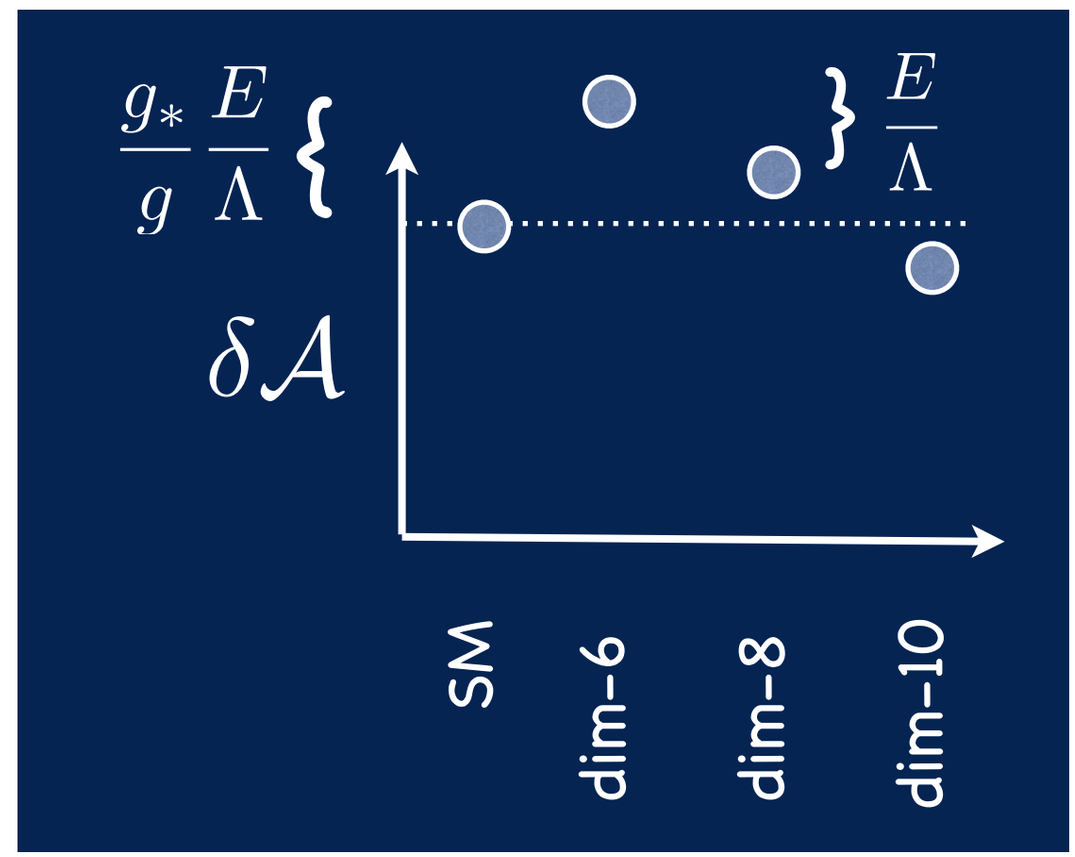
$$\frac{\mathbf{E^2}}{\mathbf{\Lambda^2}} \ll \mathbf{1}$$

can be **overcomed** by strong couplings: $\mathbf{g_*}$ = coupling of the BSM

$$\mathbf{1} \ll \frac{\mathbf{g_*^2}}{\mathbf{g^2}} \lesssim \mathbf{16\pi^2} \sim \mathbf{160!}$$



Weakly-coupled BSM



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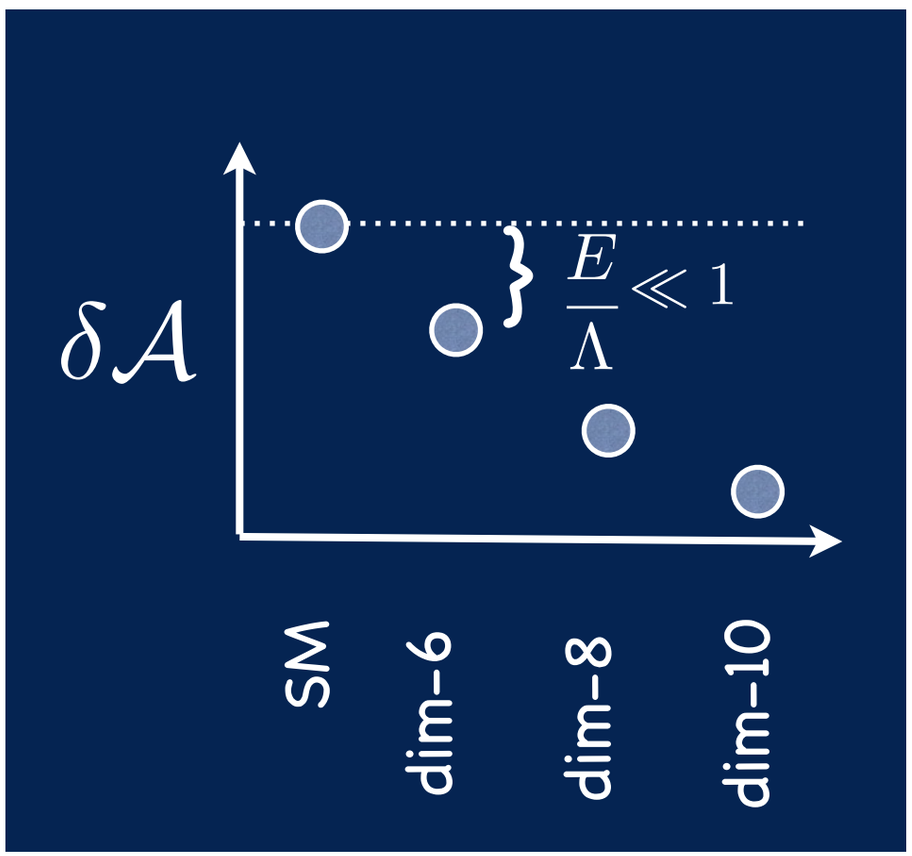
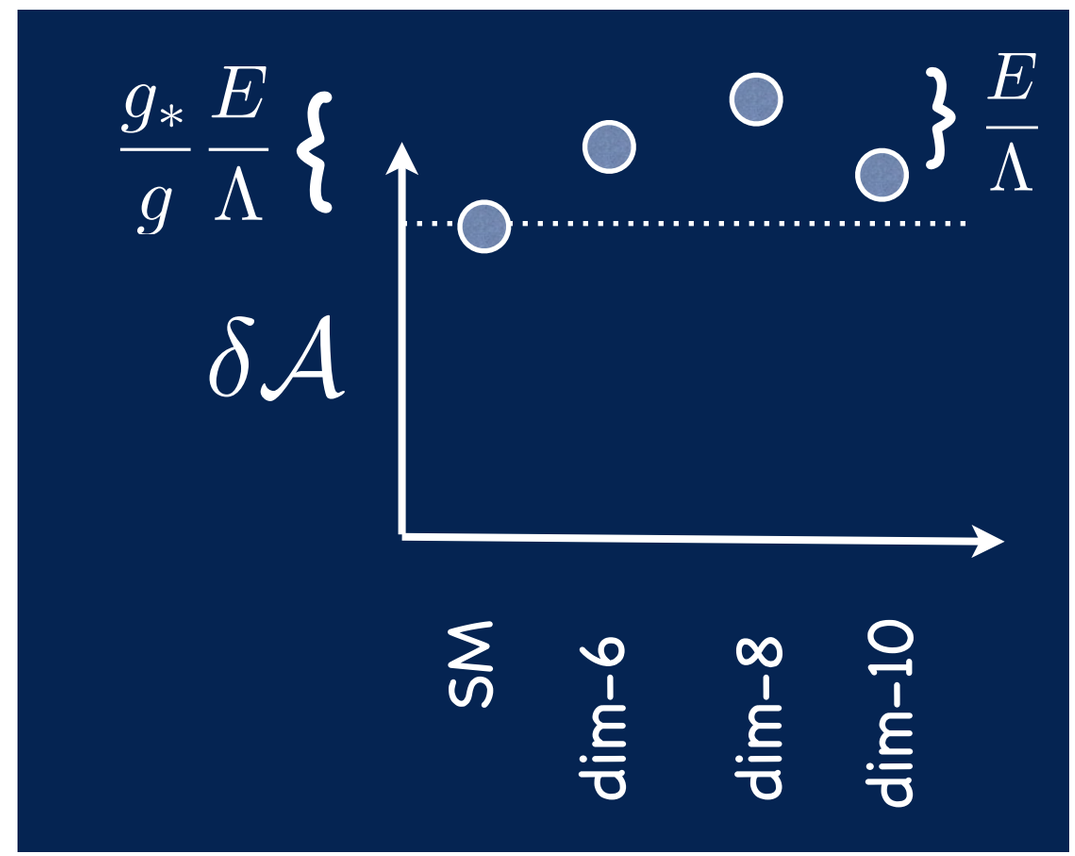


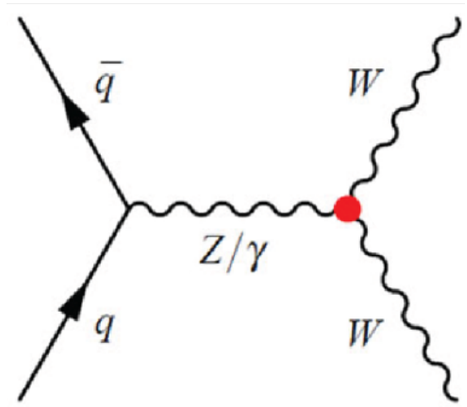
Weakly-coupled BSM



Strongly-coupled BSM

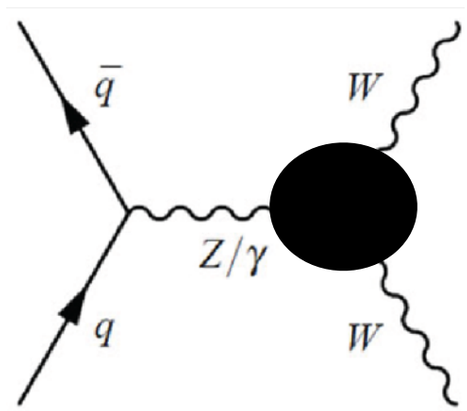
Example:

Dim-4:



$$\mathcal{A}_{\rm SM} \sim g^2$$

Dim-6:

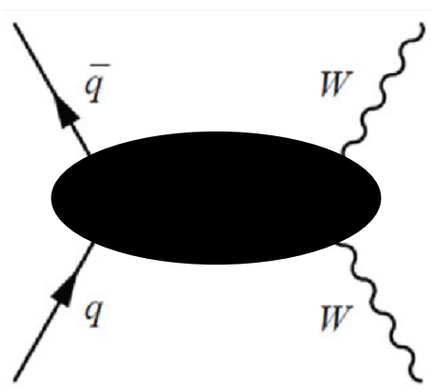


$$\frac{\delta\mathcal{A}}{\mathcal{A}_{\rm SM}} \sim \frac{g_*}{g}\frac{E^2}{\Lambda^2}$$

number of couplings dictated by the number of fields: Max of 2 in 2→2 scattering

($\hbar$-counting)

Dim-8:



$$\frac{\delta\mathcal{A}}{\mathcal{A}_{\rm SM}} \sim \left(\frac{g_*}{g}\frac{E^2}{\Lambda^2}\right)^2$$

At the LHC only models with large deviations $g_* E^2/g\Lambda^2 \gg 1$ can be probed, therefore dim-8 can dominate!

We need a different rational!

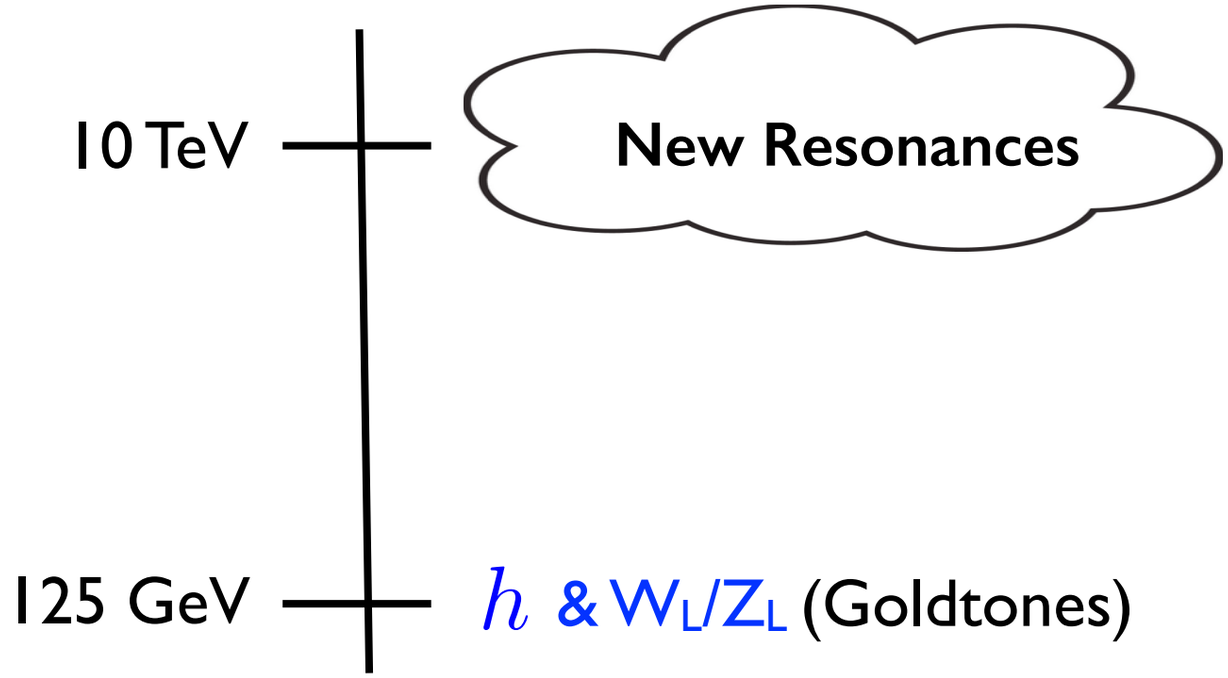
Crucial first to recognize the **different BSM scenarios classified** at least by either **symmetries** or **dynamical structure**

↳ Useful to characterize the possible

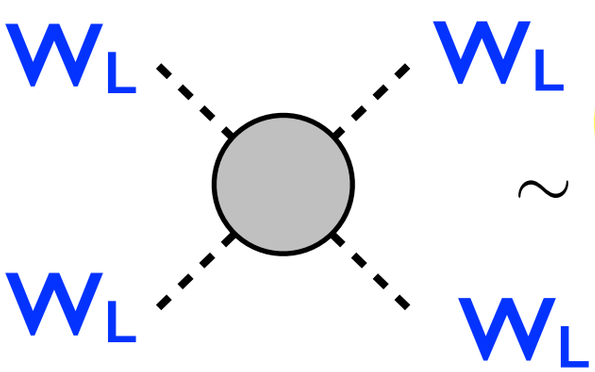
<u>patterns of Strong coupling for LHC searches</u>:

D. Liu, A.P., R. Rattazzi, F.Riva arXiv:1603.03064

In the simplest Composite Higgs Models



Apart from Higgs physics,
only WW-scattering is expected to grow sizably with the energy:

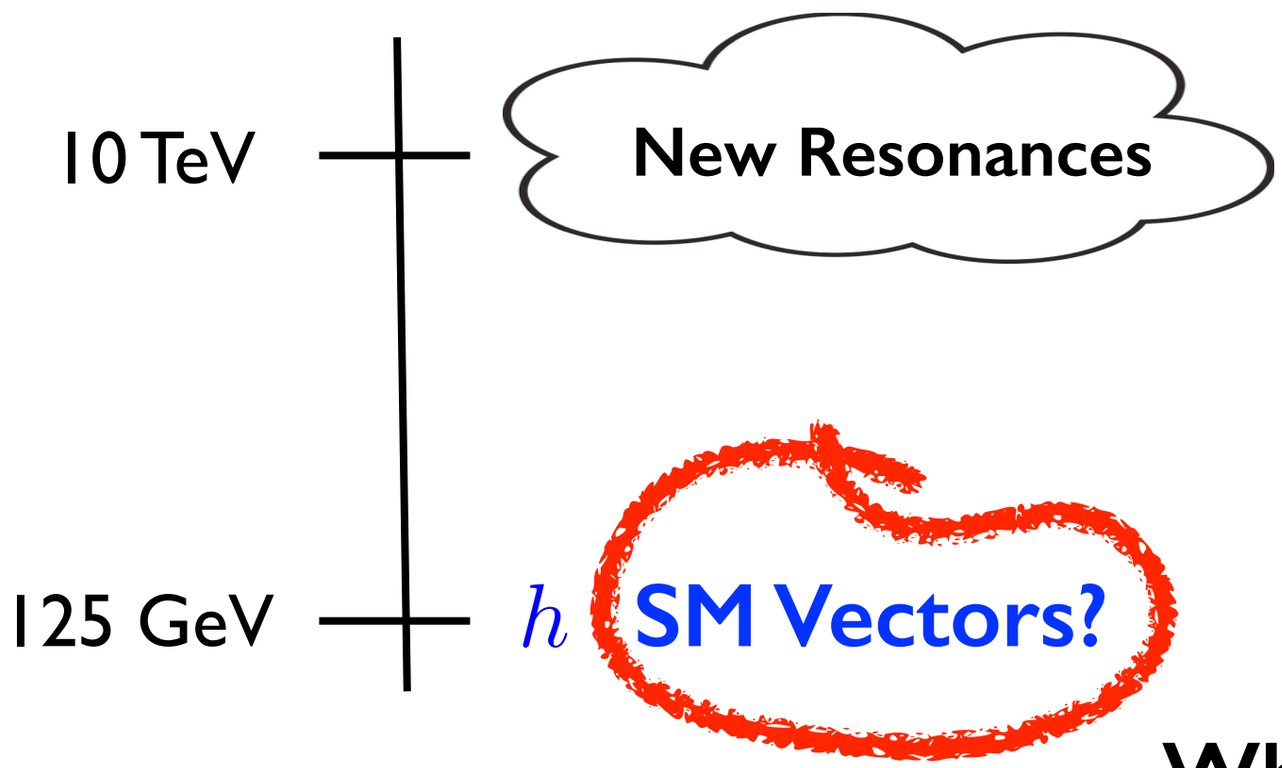


$$\sim \frac{g_*^2 E^2}{m_*^2}\left(1+\frac{E^2}{m_*^2}+\ldots\right)$$

But small cross-sections at the LHC!

What else?

New possibilities if other SM states arise from the new strong TeV-dynamics:



What to expect?

Composite SM Vectors?

Really? Their (gauge) coupling g is small $(g/4\pi \ll 1)$

& corrections to their propagators small (from LEP)

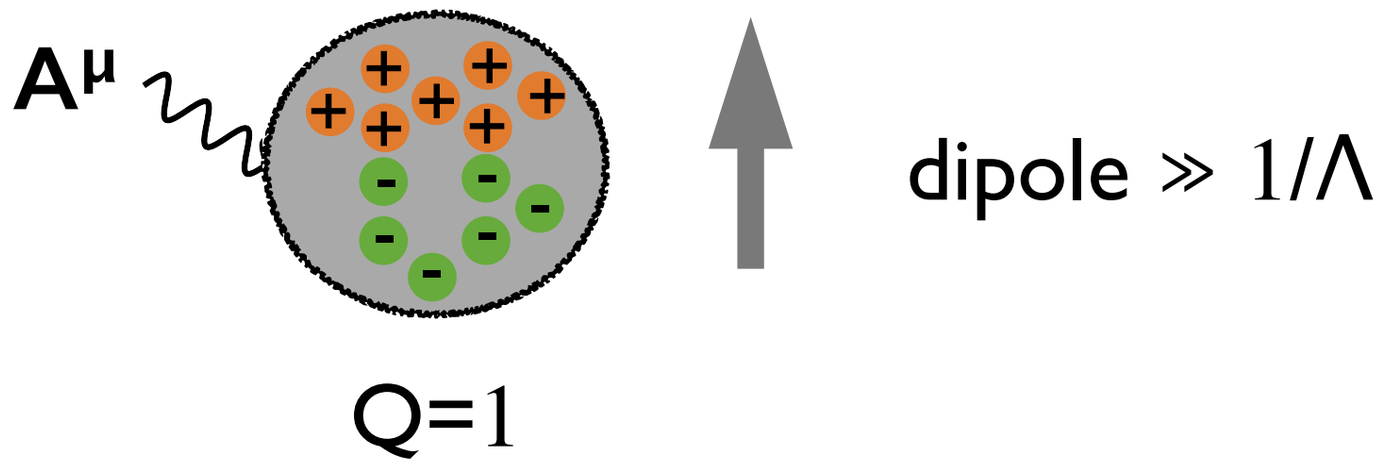
But remember pions (PGB) have two different type of couplings:

Large derivative-couplings: $(\pi\partial_\mu\pi)^2$ (preserve $\pi \to \pi + c$)

Small couplings: $(\pi\partial_\mu\pi)A^\mu$ (break $\pi \to \pi + c$)

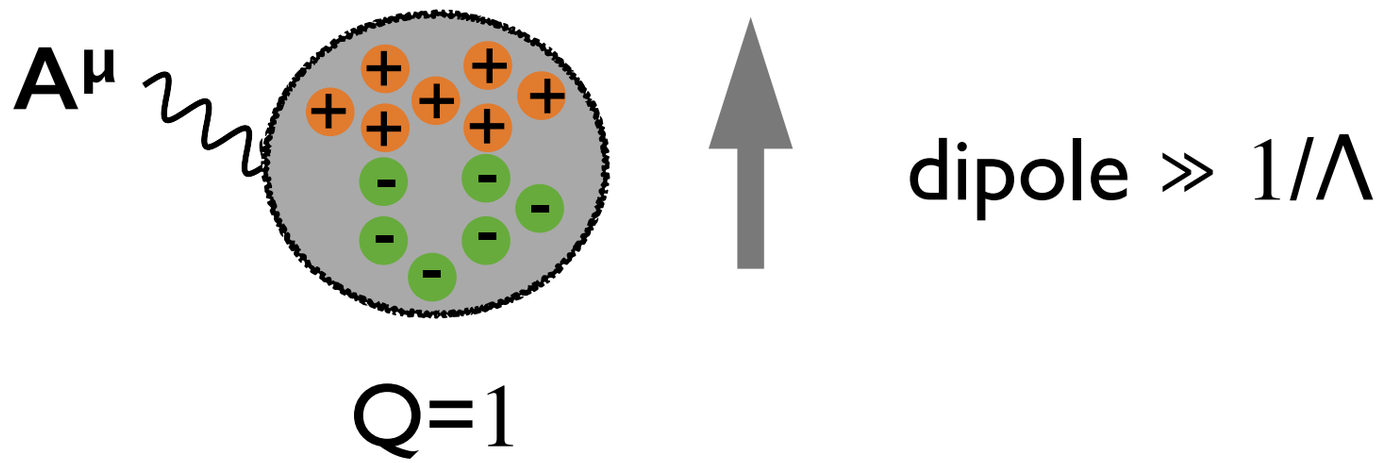
Possibility: Composite SM vector only with sizable field-strength interactions $F_{\mu\nu}$

Effective Theory of Strong Dipole Interactions



Example: QED at $E<m_e$ = Euler-Heisenberg EFT

Effective Theory of Strong Dipole Interactions



Example: QED at $E<m_e$ = Euler-Heisenberg EFT

We cannot provide a real model…
but a consistent (stable!) low-energy description
as charge is not renormalized:

$$\mathcal{L} = \frac{M^4}{g_*^2} L\left(\frac{\partial_\mu + igA_\mu}{M}, g_* \frac{F_{\mu\nu}}{M^2}, \Phi\right)$$

We named these scenarios *Remedios*[*]

[*] *Remedios the Beauty was not a creature of this world* - Gabriel Garcia Marquez.

SYMMETRY PATTERNS

In the non-abelian case, e.g. $SU(2)_L$:

Strong sector symmetry

$[U(1)_{local}]^3 \rtimes SU(2)_{global}$

Smoothly deformed by g

$SU(2)_{local}$

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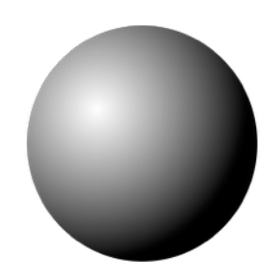
The inverse of a *Inonu-Wigner contraction*:

Galilei Group $\xleftarrow{\quad 1/c \to 0 \quad}$ Poincare Group

U(1)xU(1)xU(1) $\xleftarrow{\quad g \to 0 \quad}$ SU(2)



Remedios

Effects:

$$\frac{g_*}{\Lambda^2}\,\mathrm{Tr}\big[W_{\mu\nu}W^{\nu\rho}W_{\rho}{}^{\mu}\big]$$

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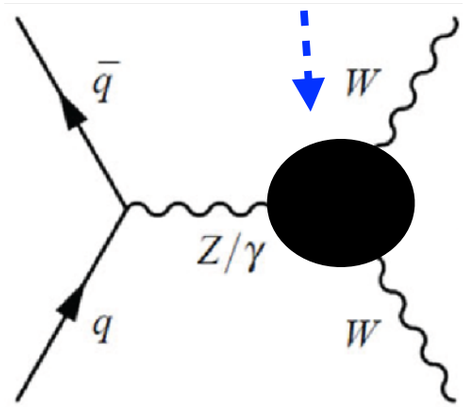

$$\lambda_\gamma\left[\frac{(q_1-q_2)^\mu}{m_W^2}\left(\frac{s}{2}g^{\alpha\beta}-p^\alpha p^\beta\right)+p^\alpha g^{\mu\beta}-p^\beta g^{\mu\alpha}\right]$$

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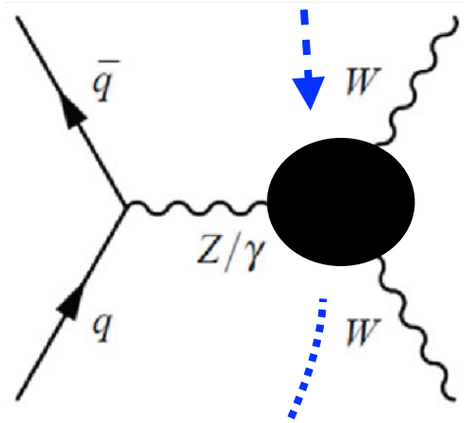

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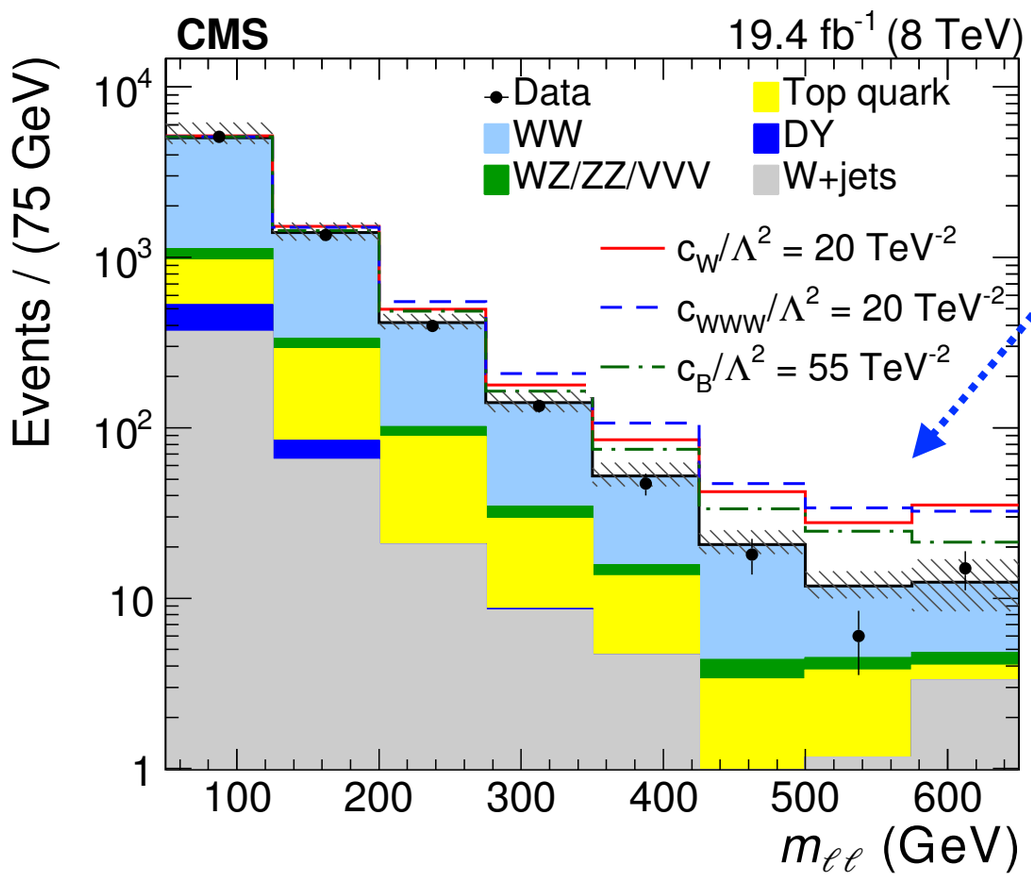
arXiv:1507.03268



effect that grows with the energy

LHC8: $\Lambda \gtrsim$ 8.5 TeV (for $g_* \sim 4\pi$)

Better than LEP!

Remember: Only valid for this type of strongly-coupled models!

Remedios + Composite PGB Higgs

For concreteness: **H→H+c** preserving SO(4) custodial

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Effects:

$$\longrightarrow \quad \frac{g_*}{\Lambda^2}\, i(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$

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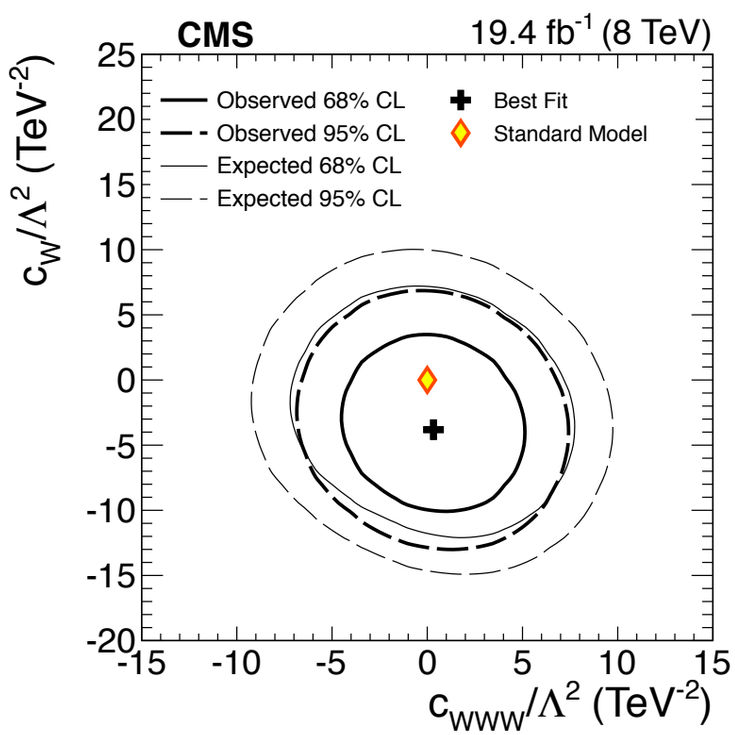
qq→VV



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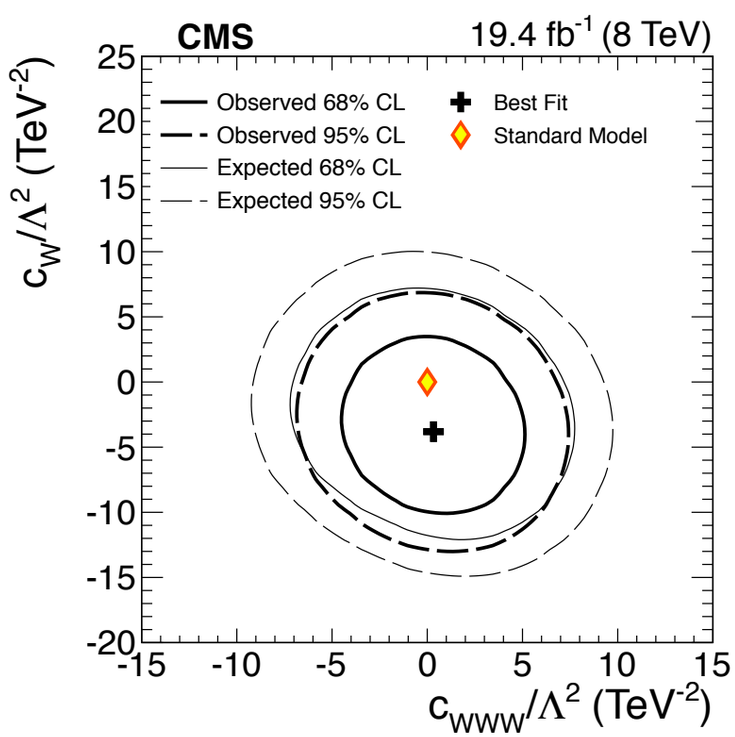
qq→VV

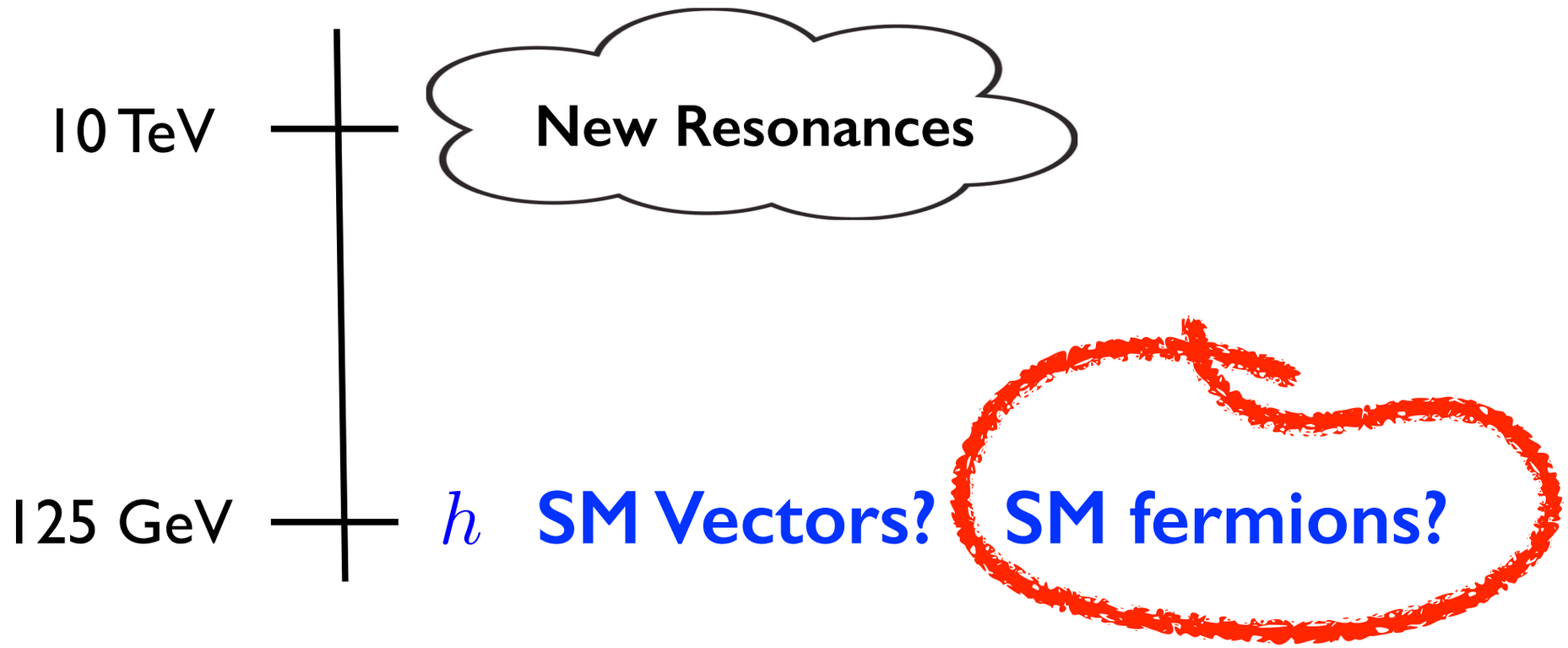
h→γZ



correlated:

$$\delta g_1^Z = \frac{\delta\kappa_\gamma}{\cos^2\theta_W} = \frac{\delta g_{hZ\gamma}}{\sin\theta_W \cos\theta_W}$$

What else?



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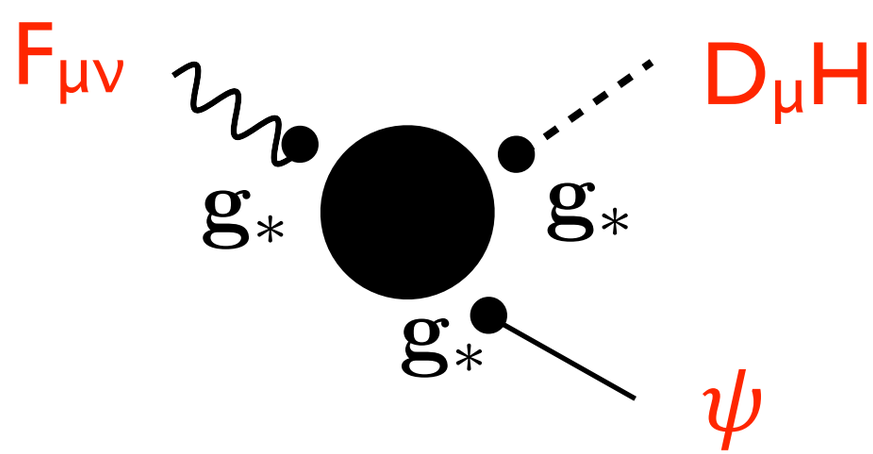
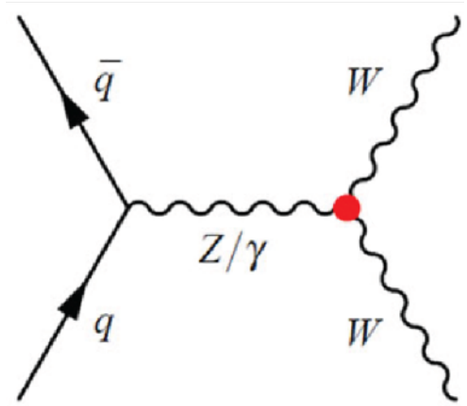
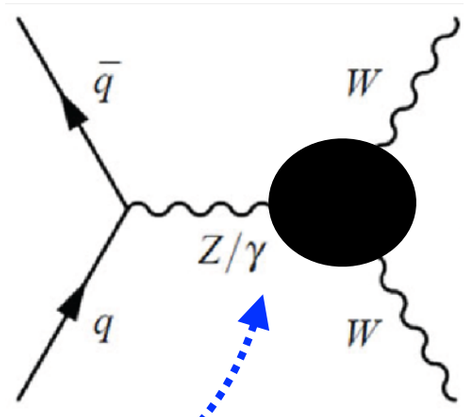


Implications in qq→VV:

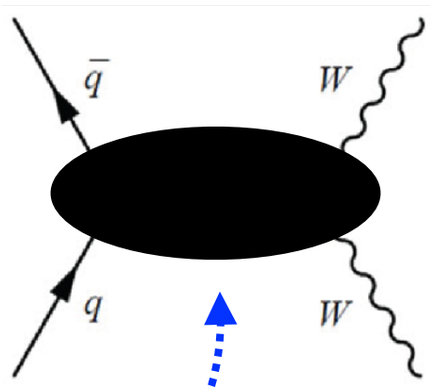


$$\mathcal{A}_{\rm SM} \sim g^2$$



$$\frac{\delta\mathcal{A}}{\mathcal{A}_{\rm SM}} \sim \frac{g_*}{g}\frac{E^2}{\Lambda^2}$$

$\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho^{\ \mu}]$



$$\frac{\delta\mathcal{A}}{\mathcal{A}_{\rm SM}} \sim \left(\frac{g_*}{g}\frac{E^2}{\Lambda^2}\right)^2$$

$\bar{\psi}(\gamma^\mu \overleftrightarrow{D}^\nu + \gamma^\nu \overleftrightarrow{D}^\mu)\psi' W^a_{\mu\rho} W^{a\,\rho}_\nu$

work in progress!

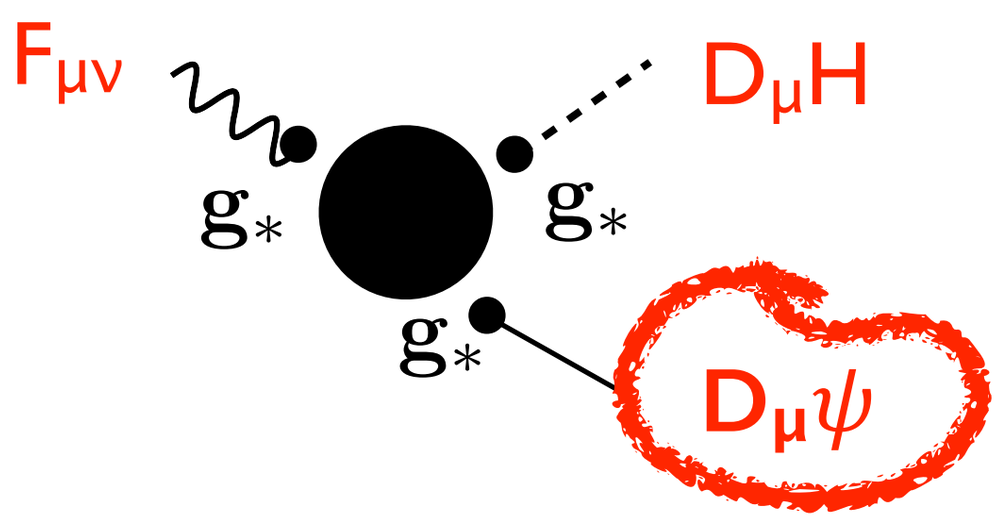
A model-independent analysis must include dim-8 operators

What else?

10 TeV — **New Resonances**

125 GeV — h **SM Vectors? SM fermions ~ Goldstini?**

Effects:



Strong sector invariant under supersymmetry:

$$\delta\psi = \xi + \frac{i}{2F^2}\partial_\mu\psi(\bar{\psi}\gamma^\mu\xi - \bar{\xi}\gamma^\mu\psi)$$

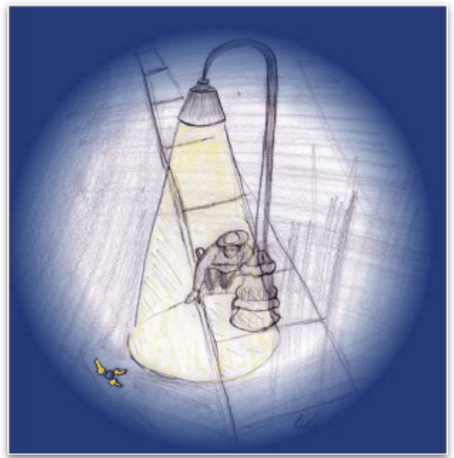
work in progress!

Conclusions

- **New Strong dynamics at the TeV** is still one of the best options for TeV-BSM: Glimpses already (750 GeV)?

Don't be afraid to pursue it, even without full knowledge of the theory

Nature does not care about our limitations!



- These BSMs can also **be probed** (possibly, the only ones!) **in 2→2 scatterings at the LHC at the high-energy regime!**

A **different parametrization** of the effects was proposed to optimize these searches, **based on** a proper power-counting of the different strongly-coupled scenarios

Crucial to understand in the absence (presence) of new-physics **which BSM are disfavored** (favored)!