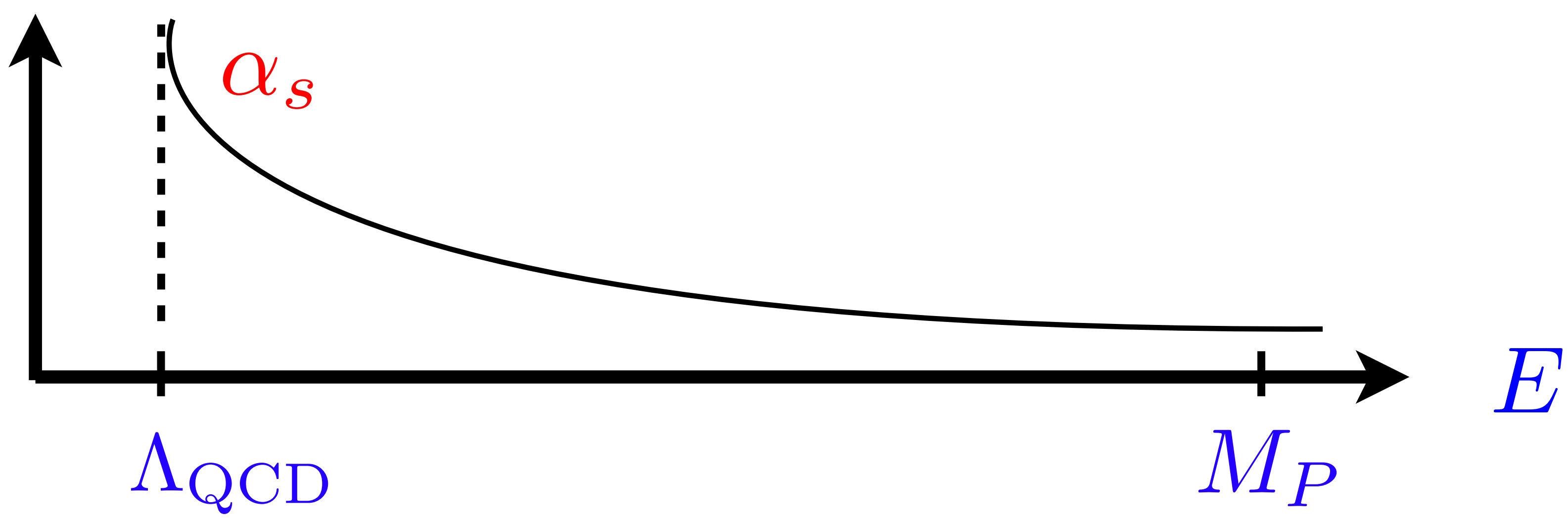
New Strong Dynamics at the TeV scale and its impact on dibosons

Alex Pomarol, UAB & IFAE (Barcelona)

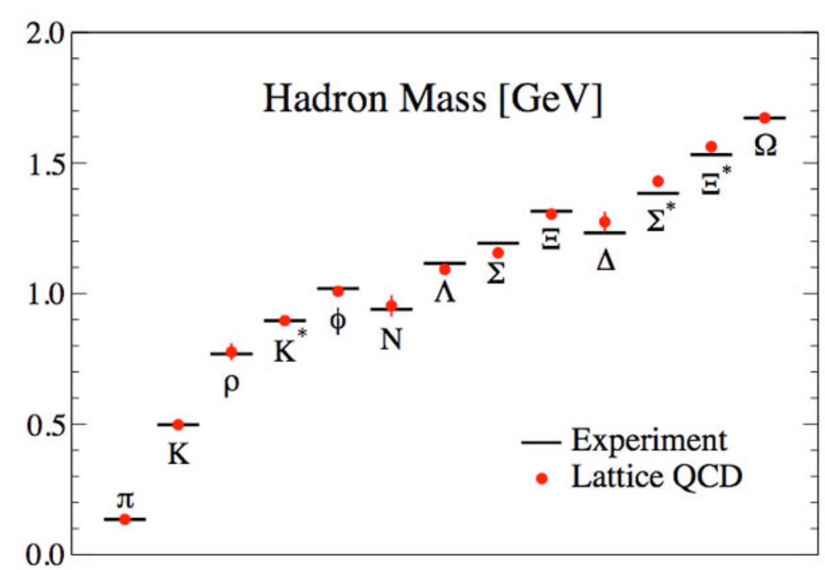
Why Strong Dynamics at Λ~TeV ?

To explain why $m_H \ll M_P \sim 10^{19}$ GeV

As in QCD:



Explains why $\Lambda_{\rm QCD} << M_P$ and the origin of most hadron masses



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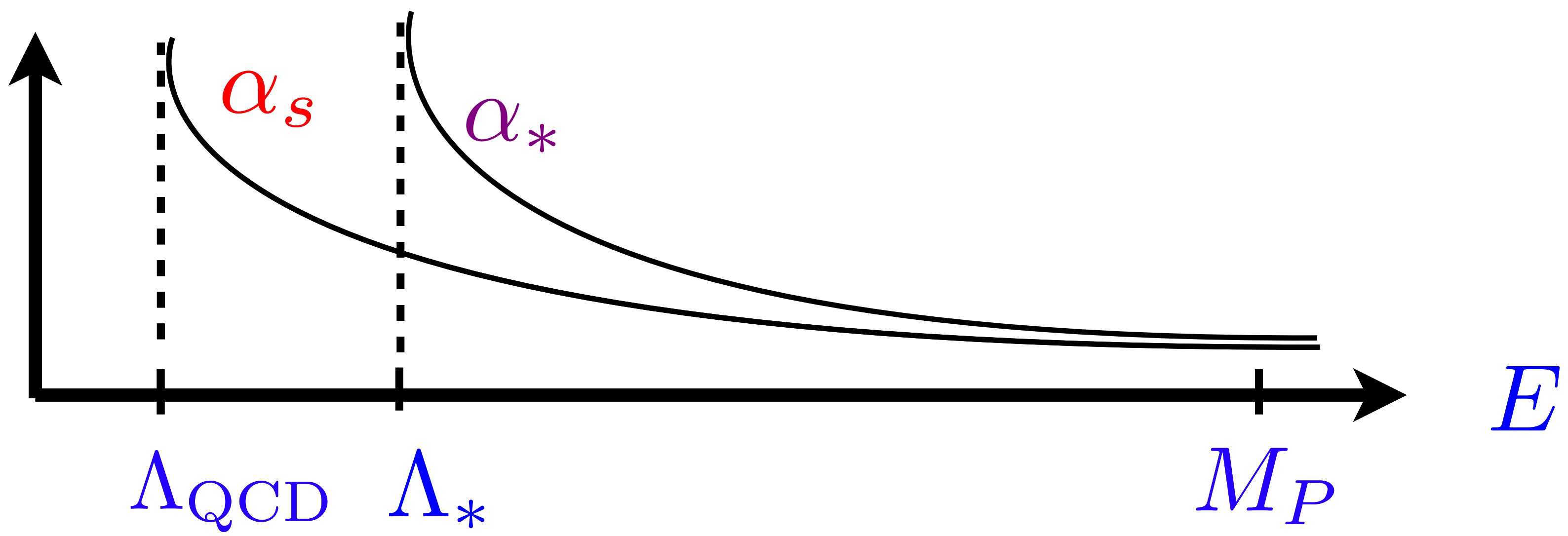
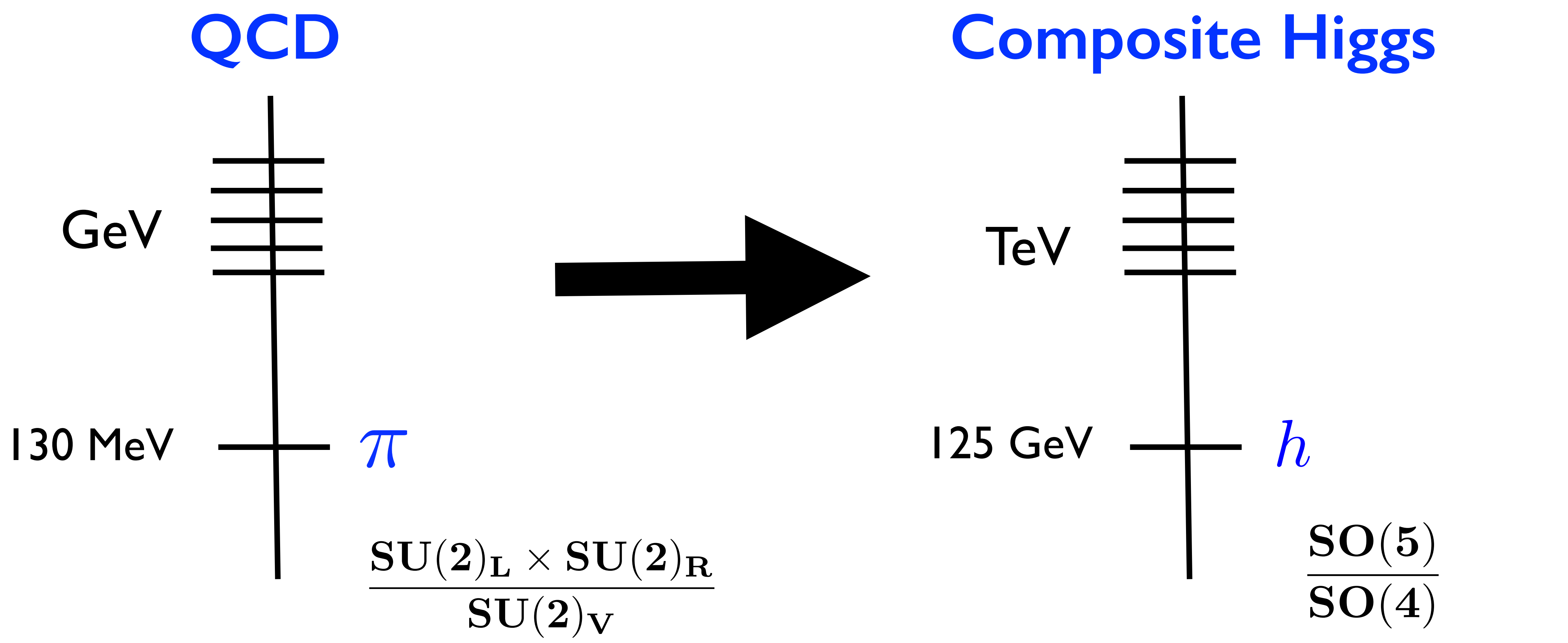


New strong dynamics at TeV

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

Composite Higgs

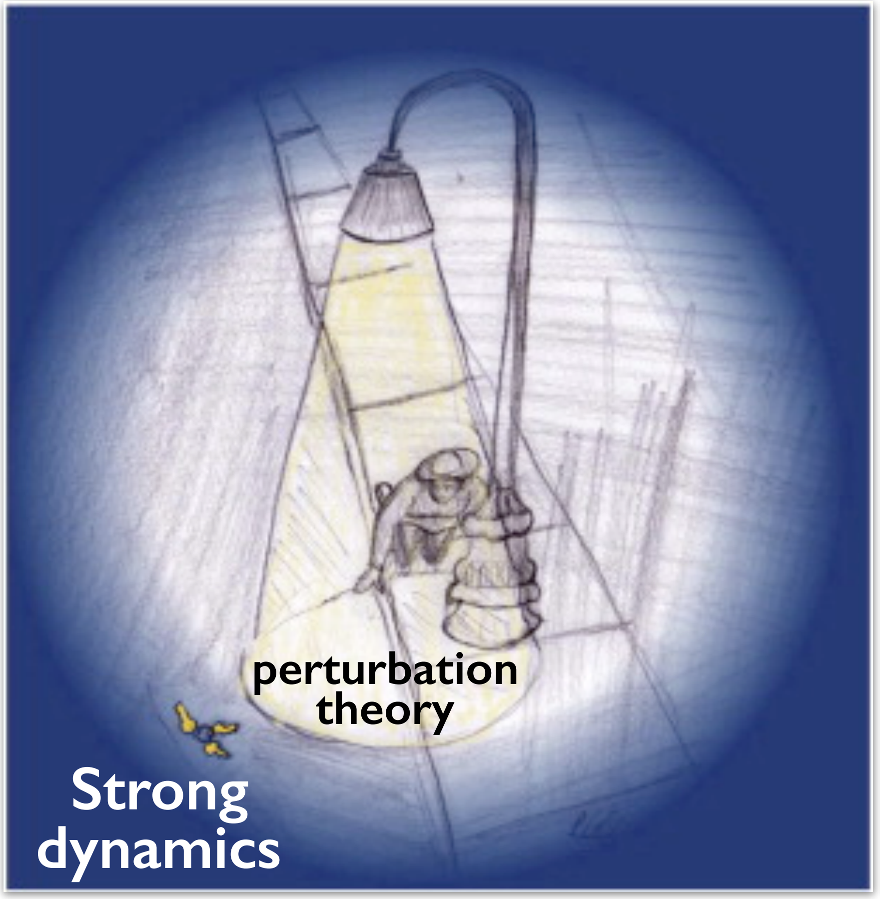
QCD → Composite Higgs



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

Dealing with strong dynamics…

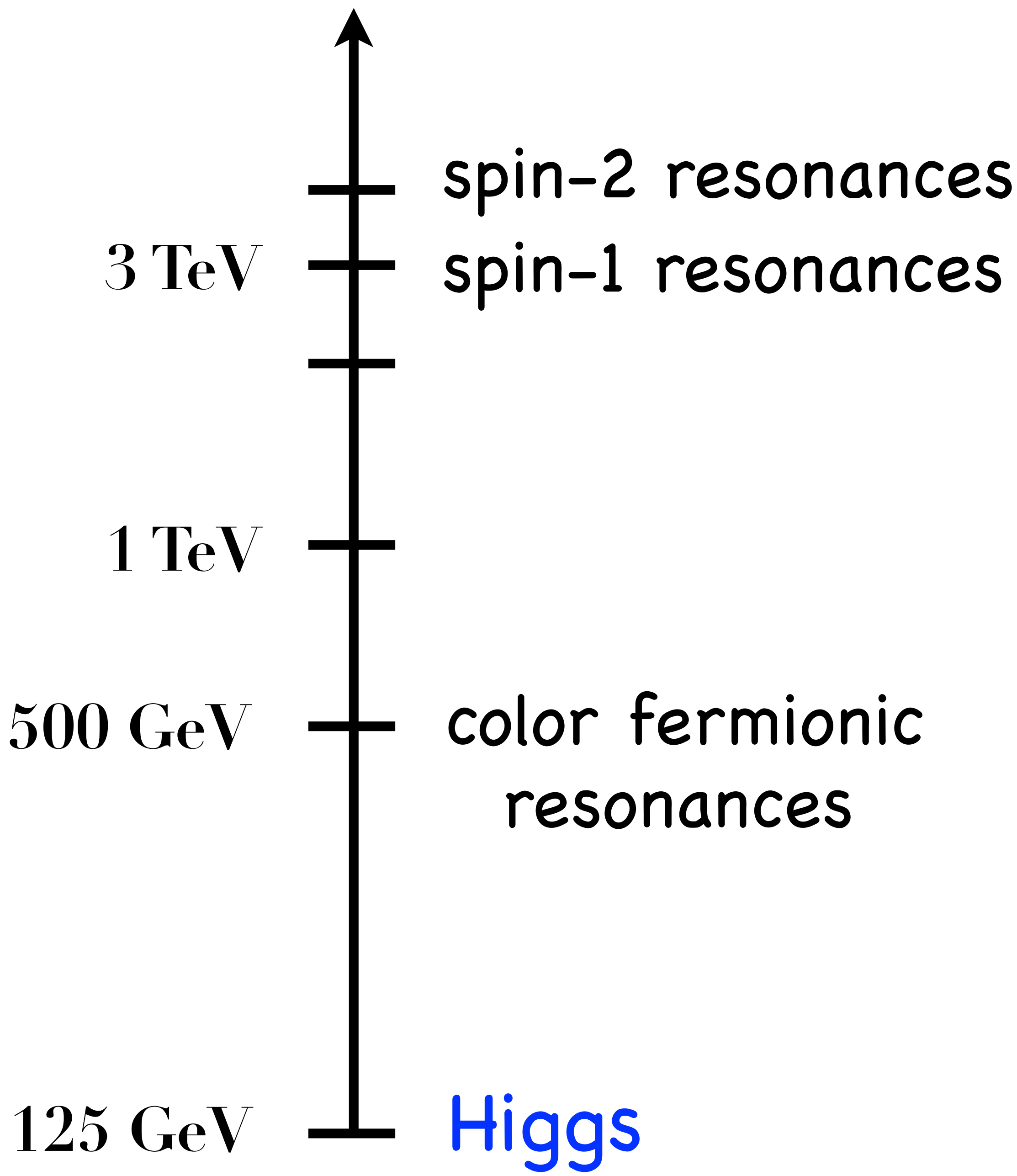
Beyond the lamp-post:



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

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

Expected spectrum in Composite Higgs Scenarios



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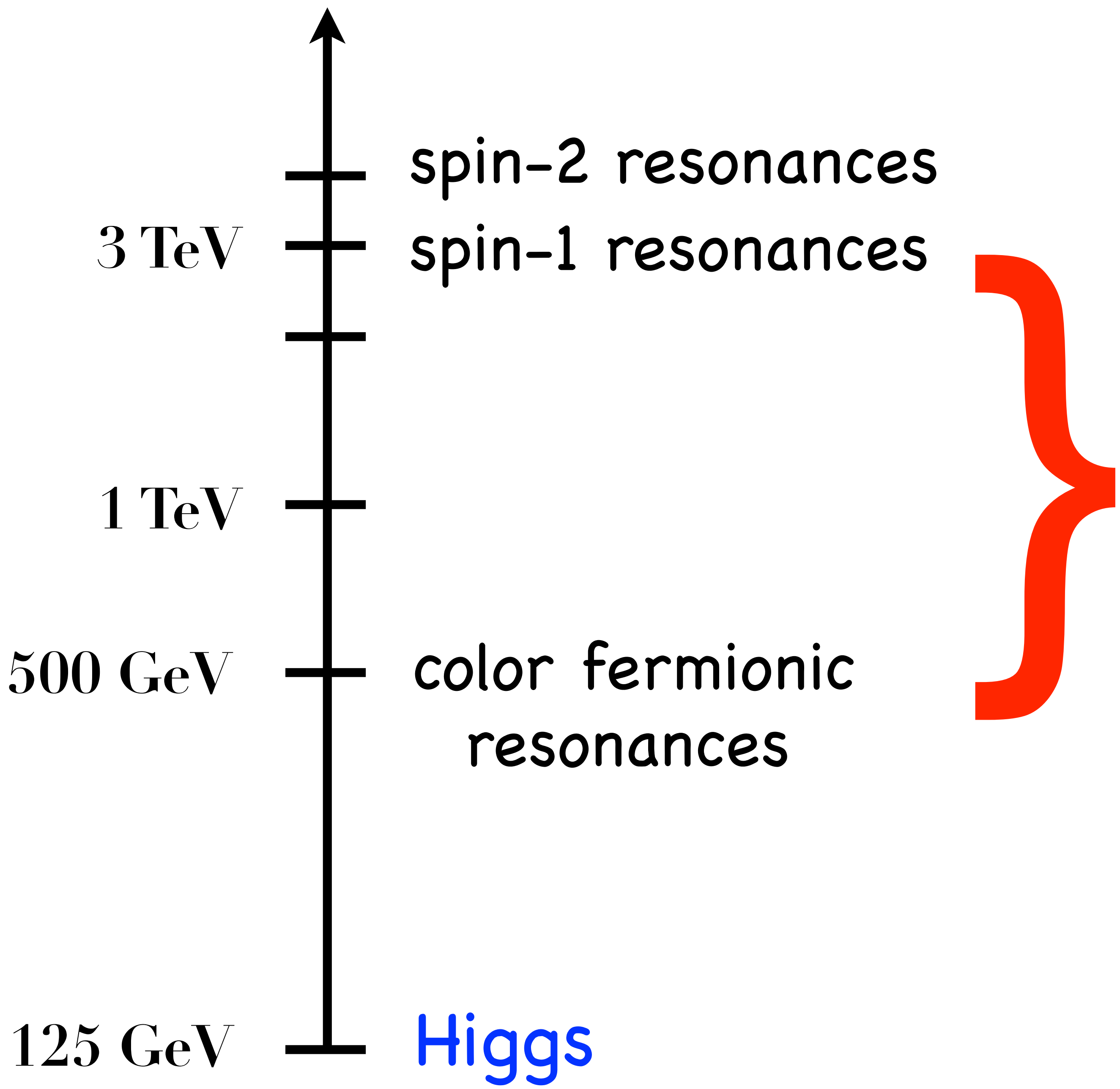
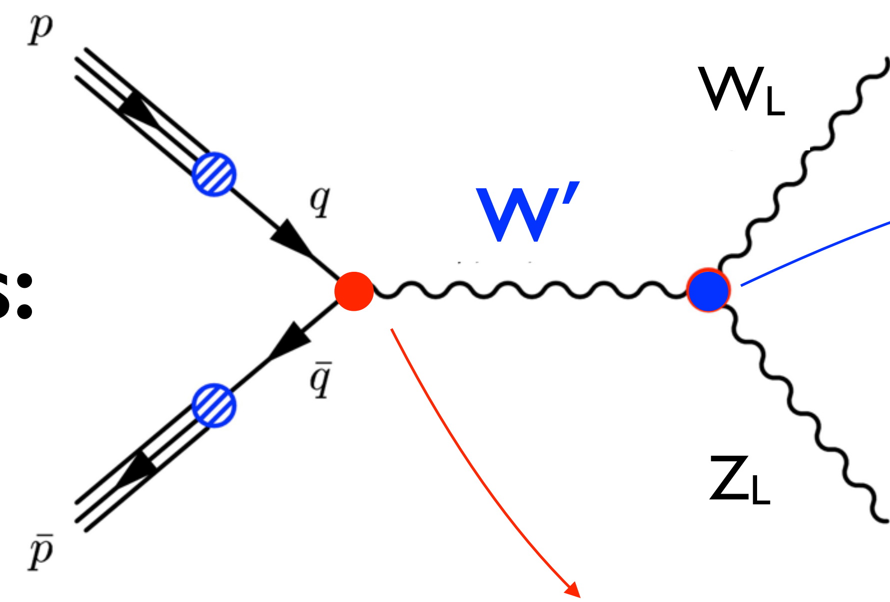


Best way to unravel new dynamics:
Discovering new resonances !

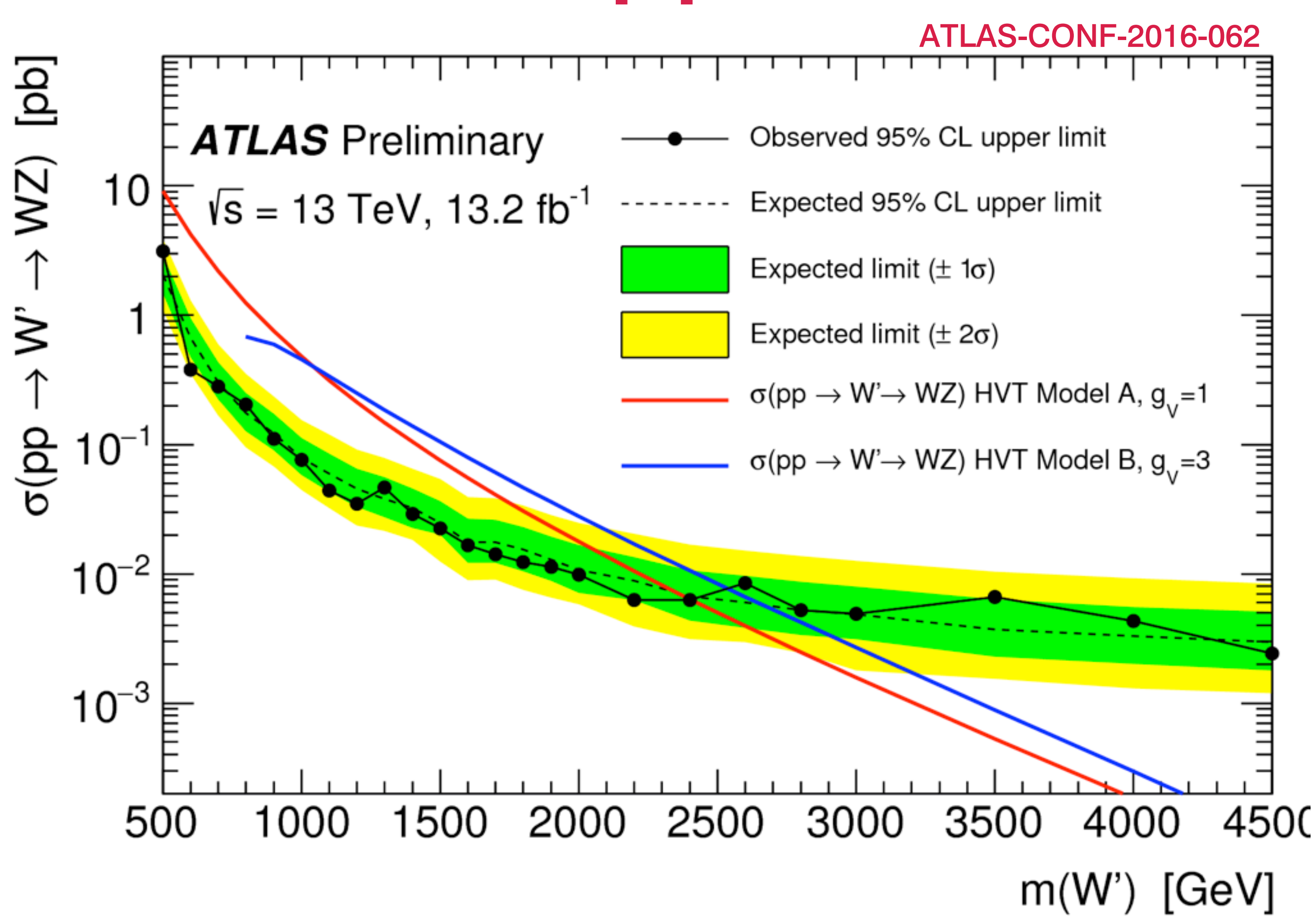
Spin-1 resonance searches:



enhanced by large couplings from the composite sector

through mixing with the SM W:
suppressed by large couplings from the composite sector

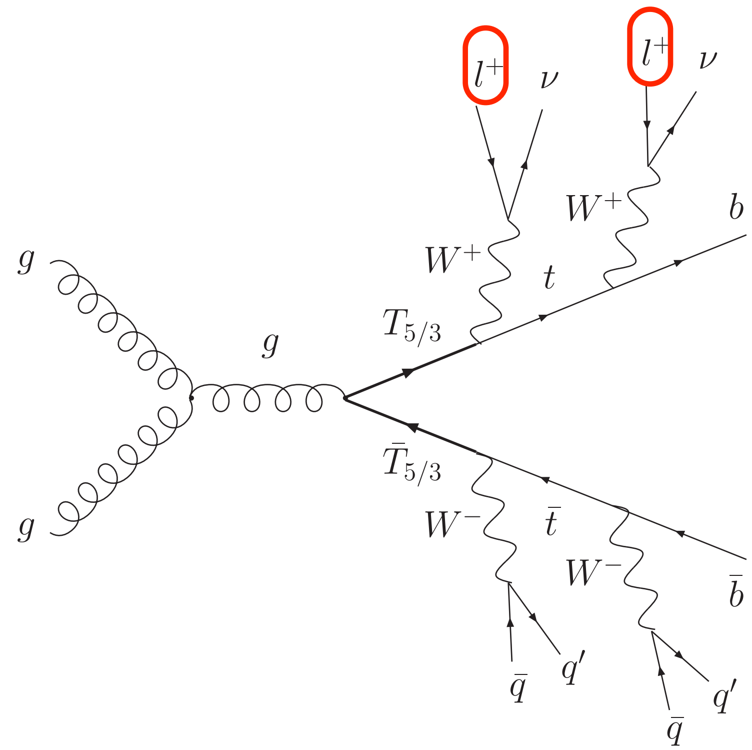
VV → ℓνqq

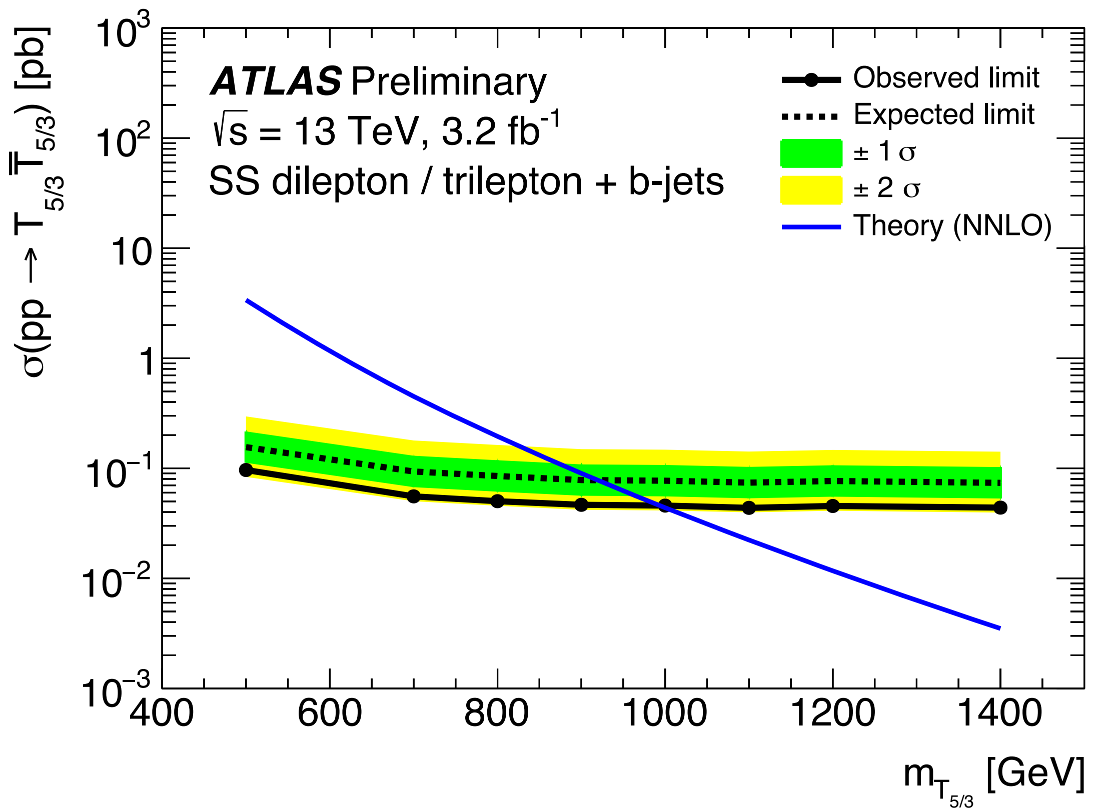


☛ $$\mathbf{m(W') \gtrsim 2.5\ TeV}$$

scratching
the interesting regions!

Colored fermion resonances at LHC 13 TeV





First important constraint from LHC:

$$\mathbf{m(X_{5/3}) \gtrsim 1\ TeV}$$

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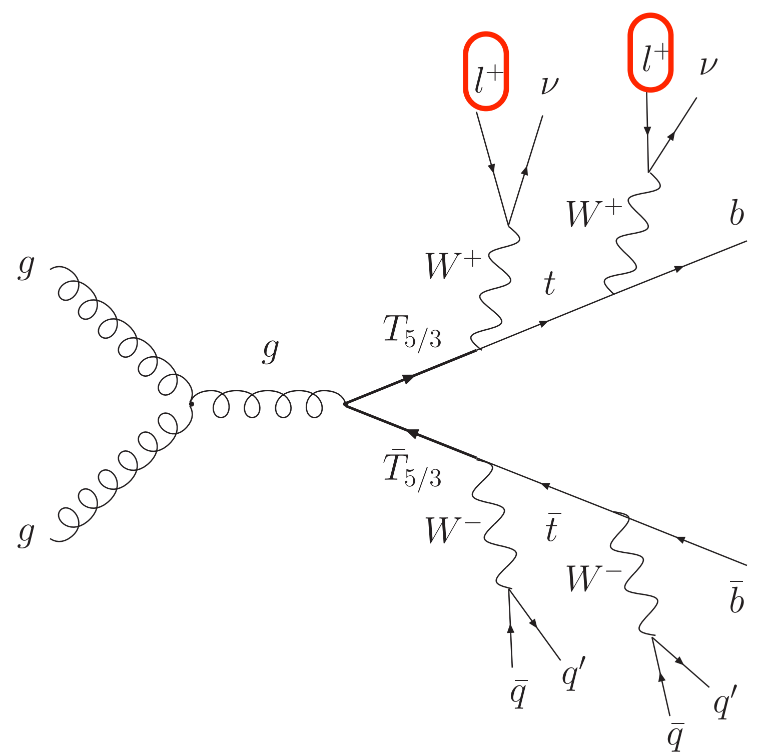

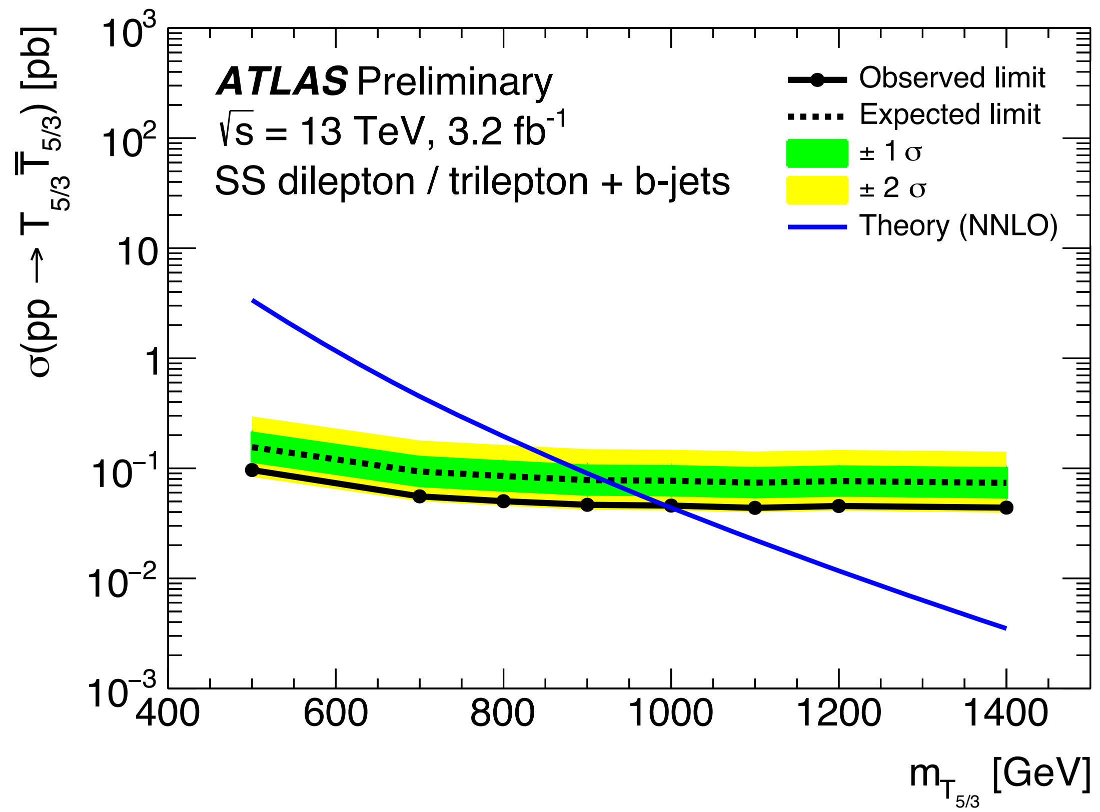

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The situation starts being worrisome..

but not yet desperate

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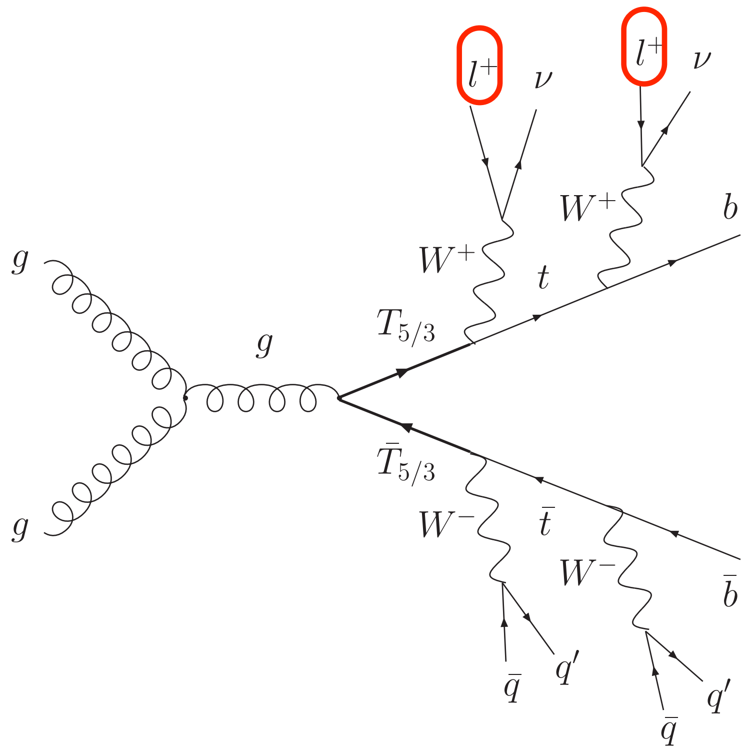

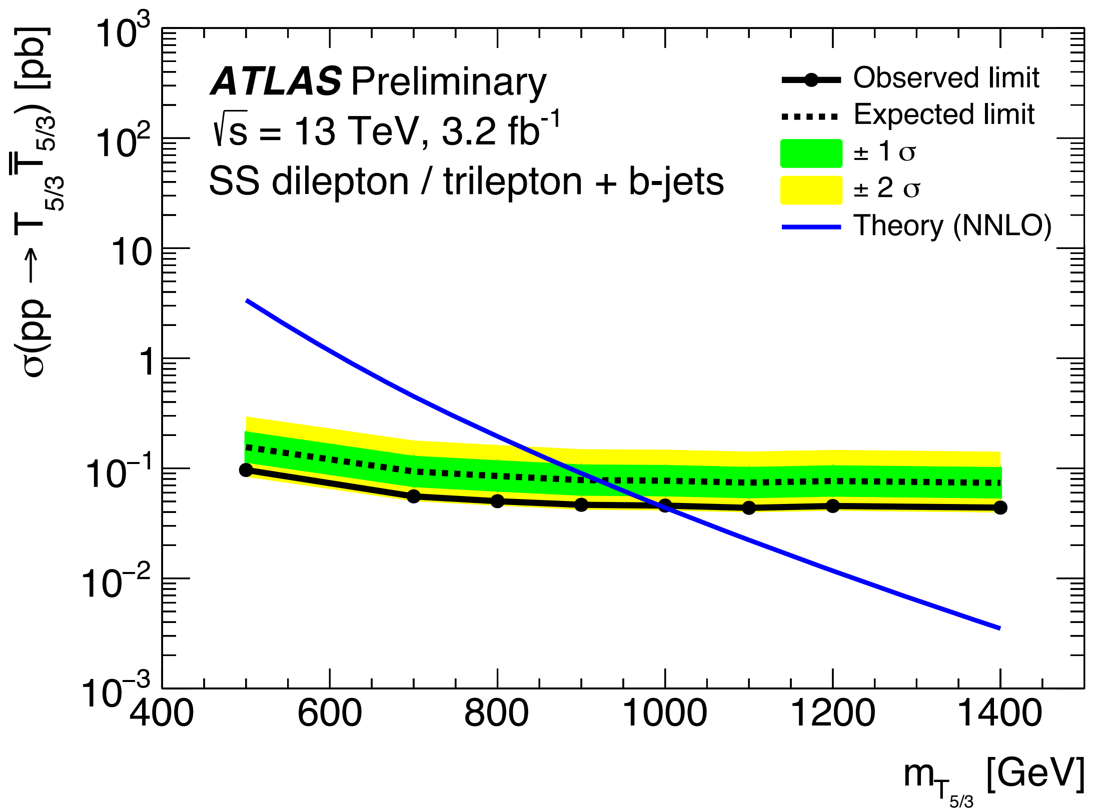

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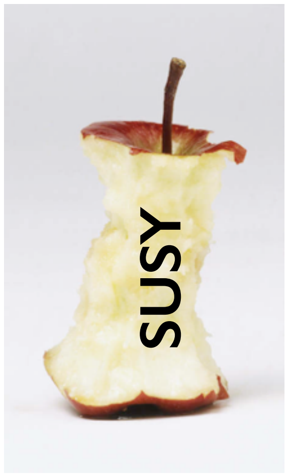
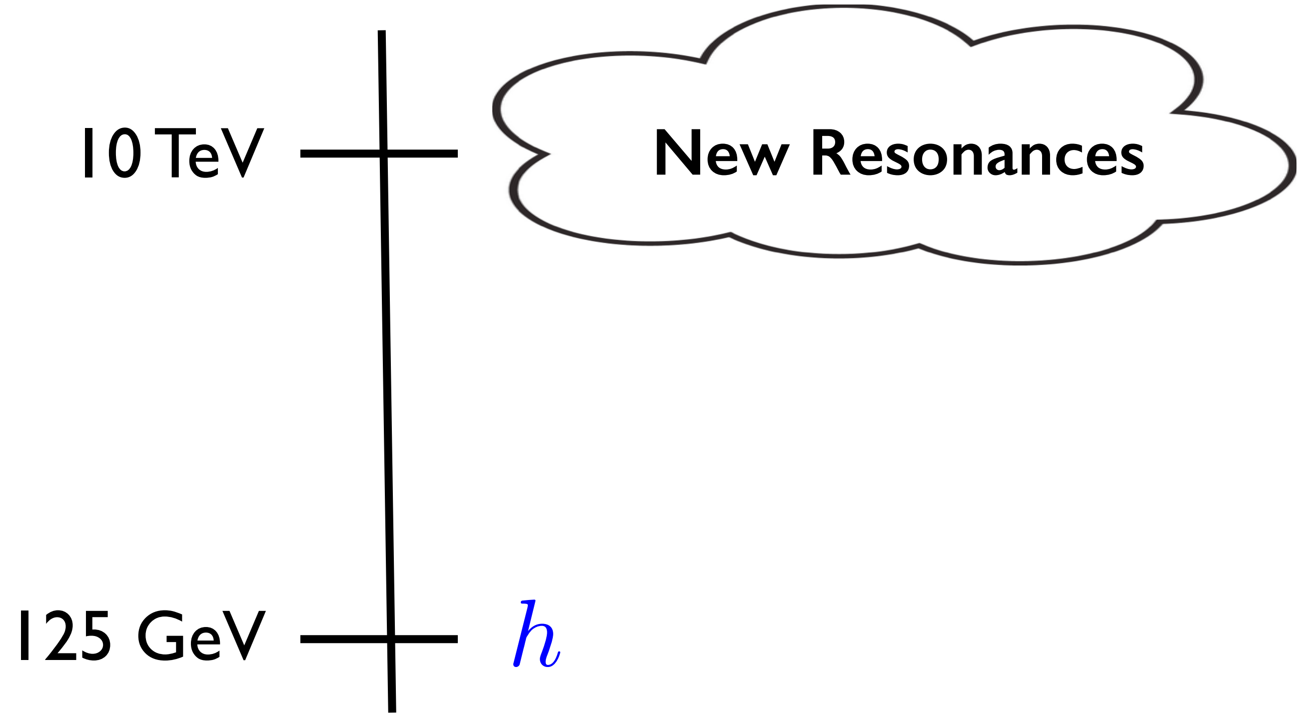


(not as bad as susy)

If the new-strong sector turns out to be too heavy to detect resonances at the LHC…



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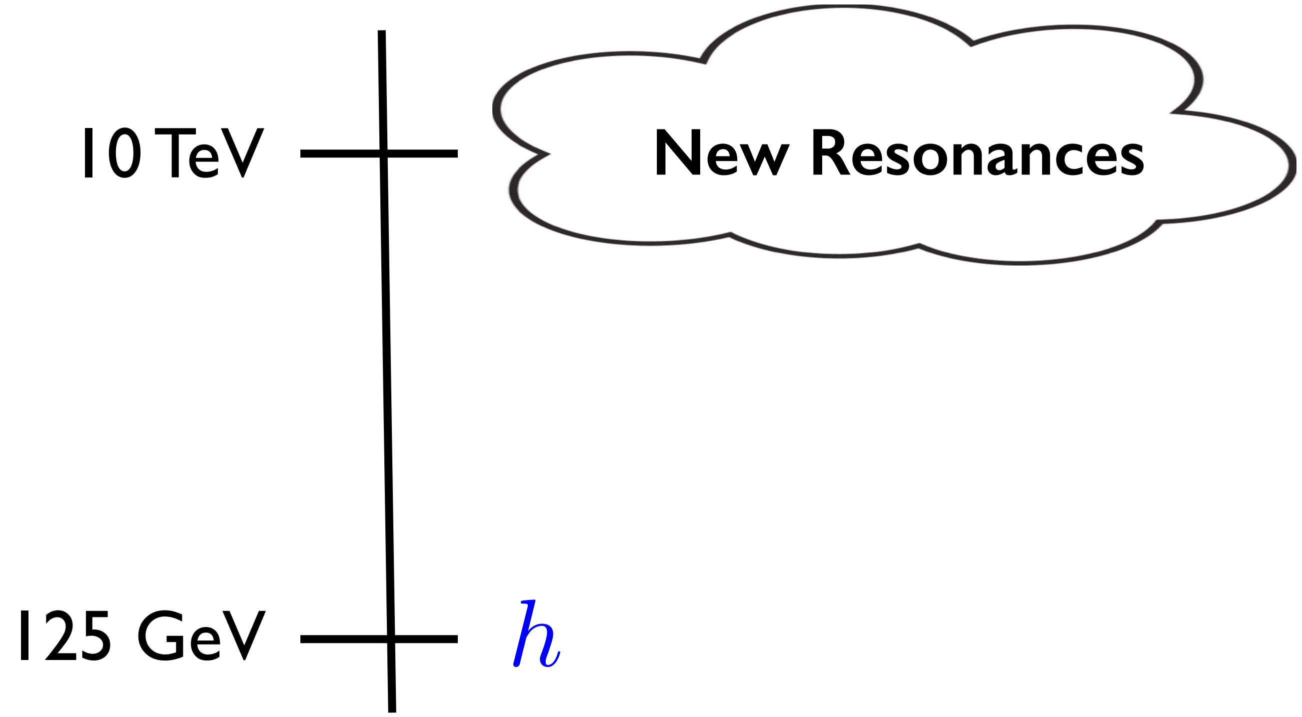
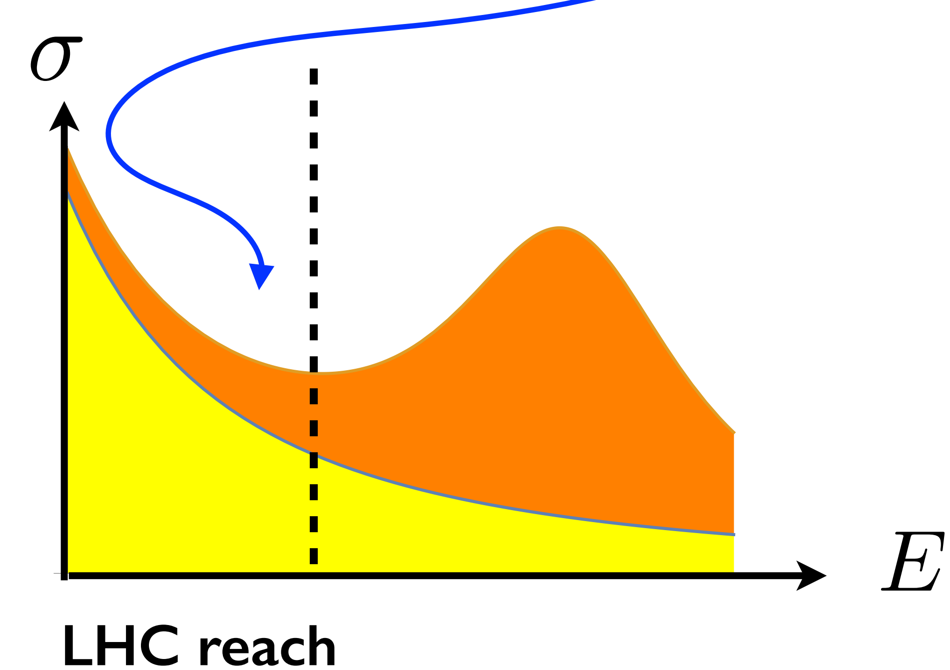


LHC still <u>offers</u> the possibility to see new-physics in deviations in 2→2 SM processes:



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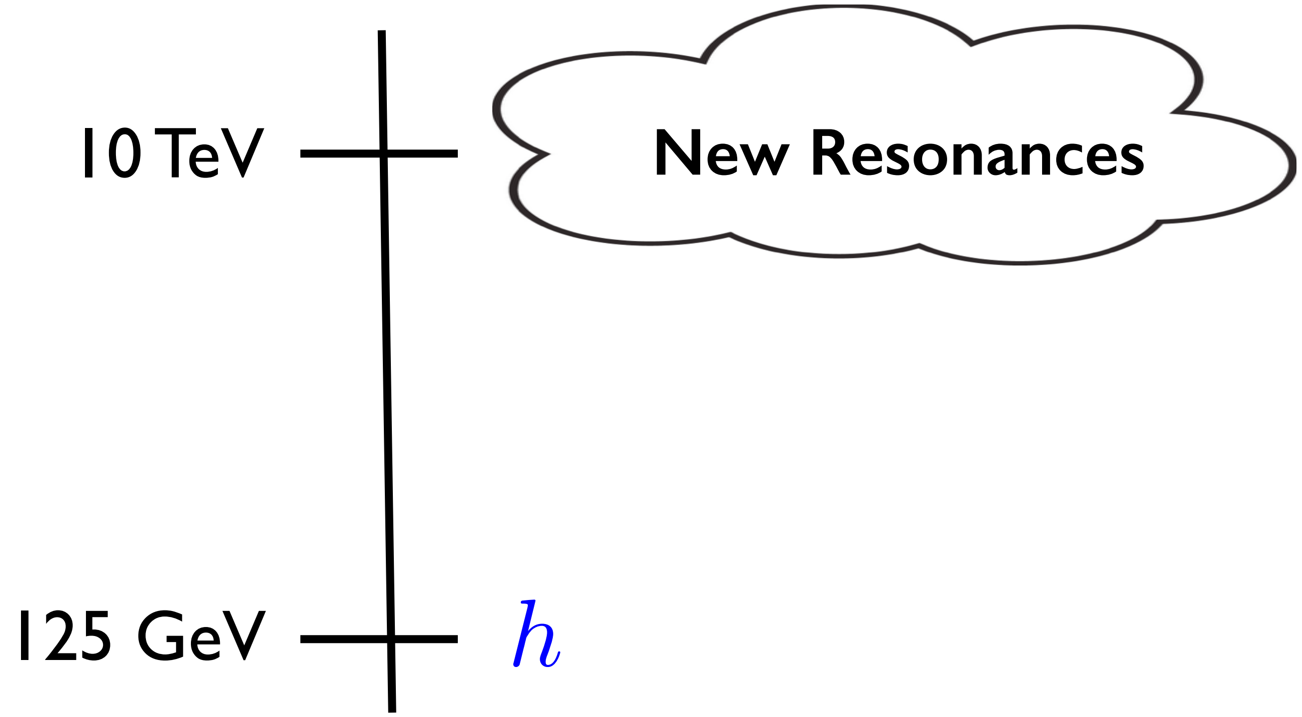
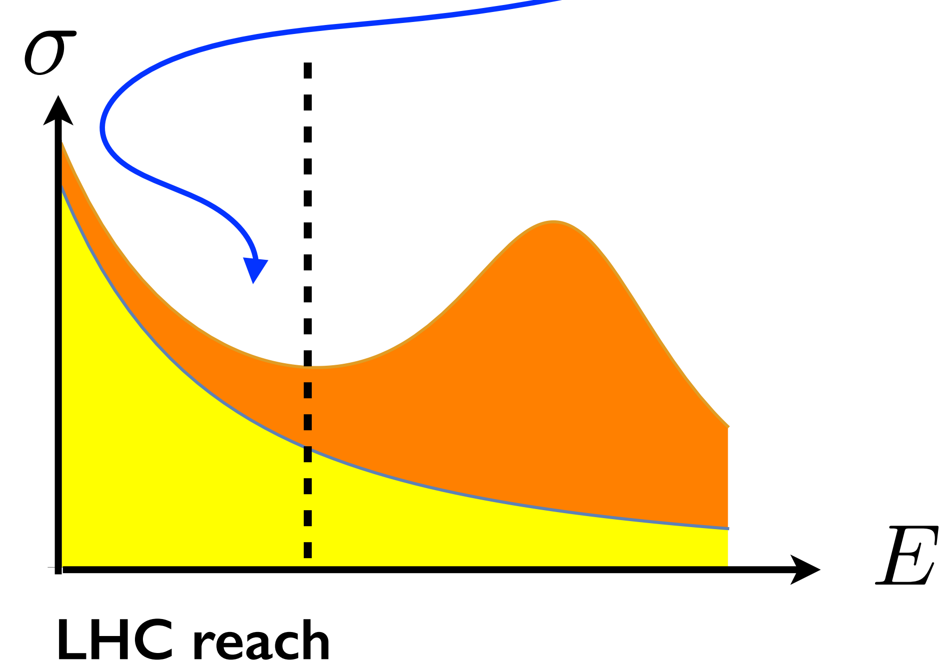


LHC still offers the possibility to see new-physics in deviations in 2→2 SM processes:

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



Effects of the resonance "tails"

Encoded in **Higher-dimensional operators,**

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

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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Restrict only to dimension-6 operators?

W. Buchmuller and D. Wyler 86

& thousands more…

Be careful that this could either be…

Redundant: Missing correlations

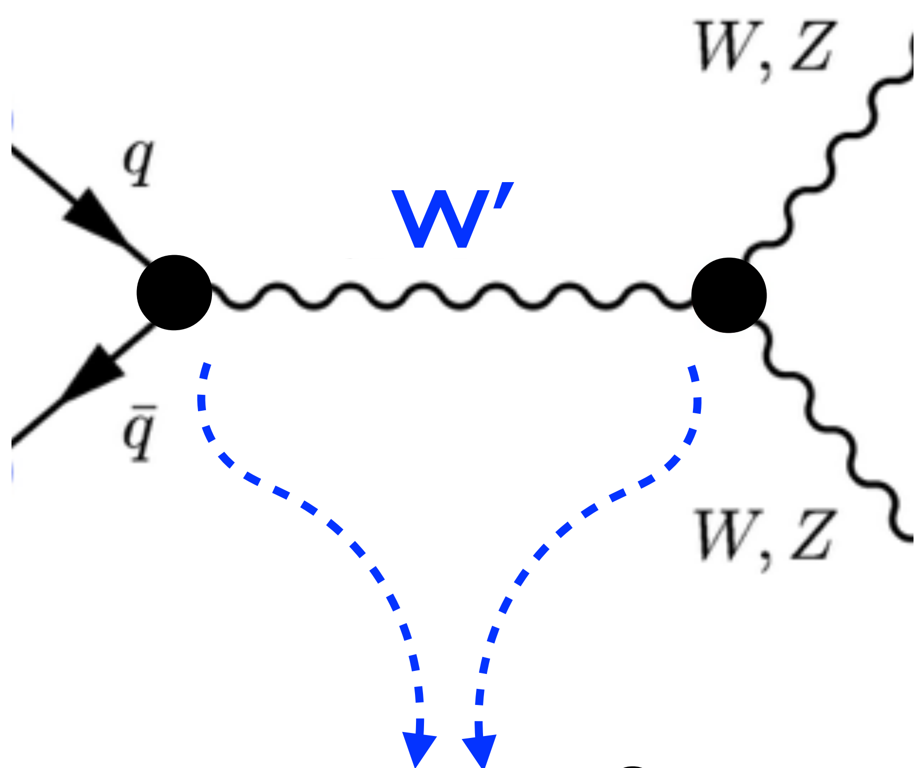
Incomplete: Dimension-8 operator also relevant in certain BSMs

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

e.g.



$$\mathbf{g}_*^{\mathbf{2}} \frac{\mathbf{E^2}}{\mathbf{\Lambda^2}}$$

Large effect: $\mathbf{1} \ll \frac{\mathbf{g}_*^{\mathbf{2}}}{\mathbf{g^2}} \lesssim \mathbf{16}\pi^{\mathbf{2}} \sim \mathbf{160!}$

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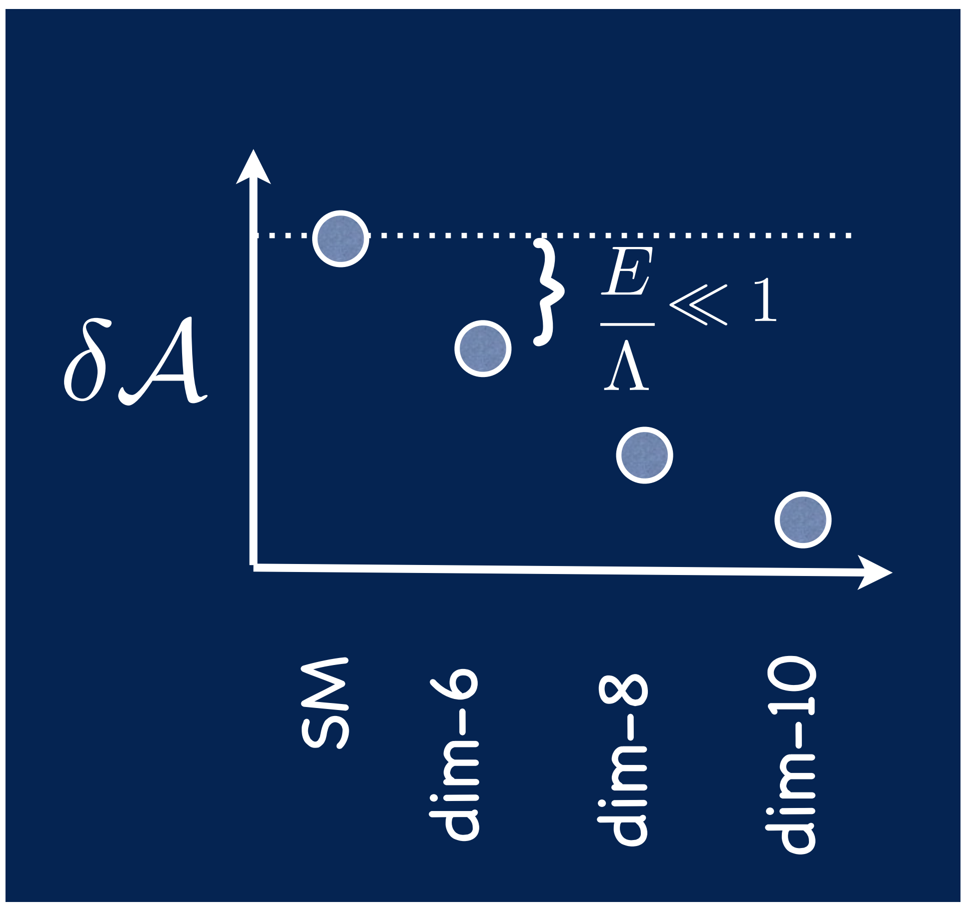

Weakly-coupled BSM

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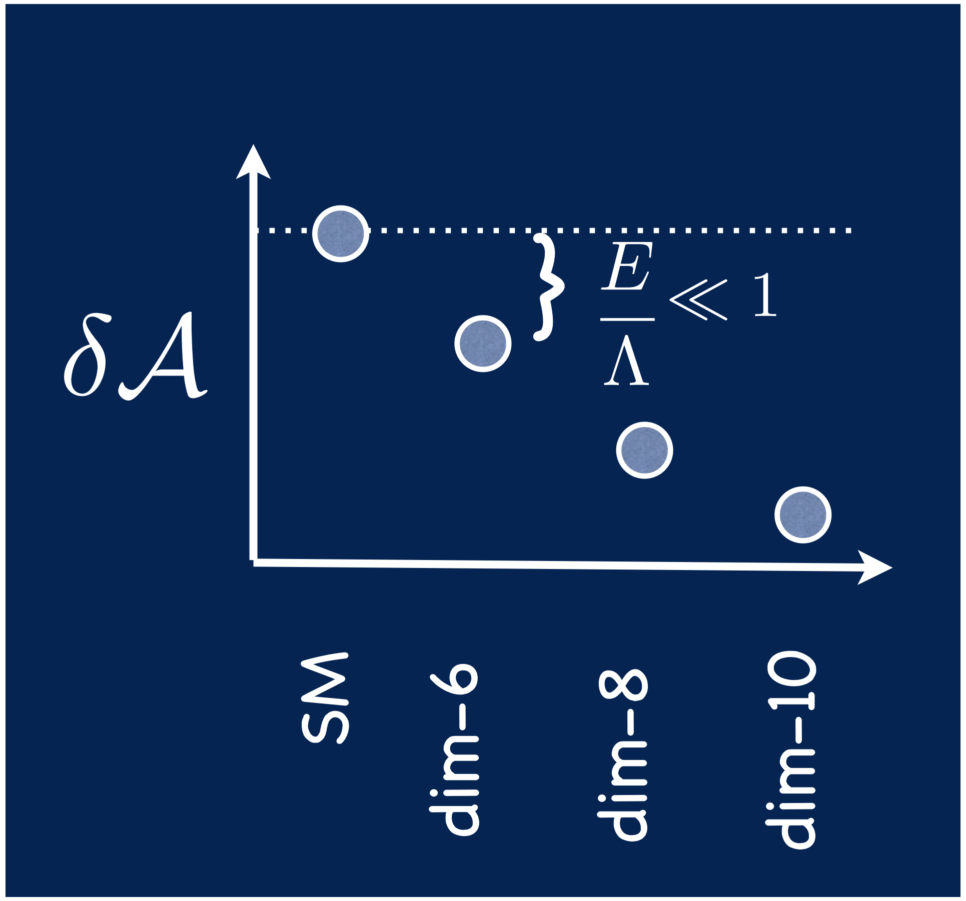

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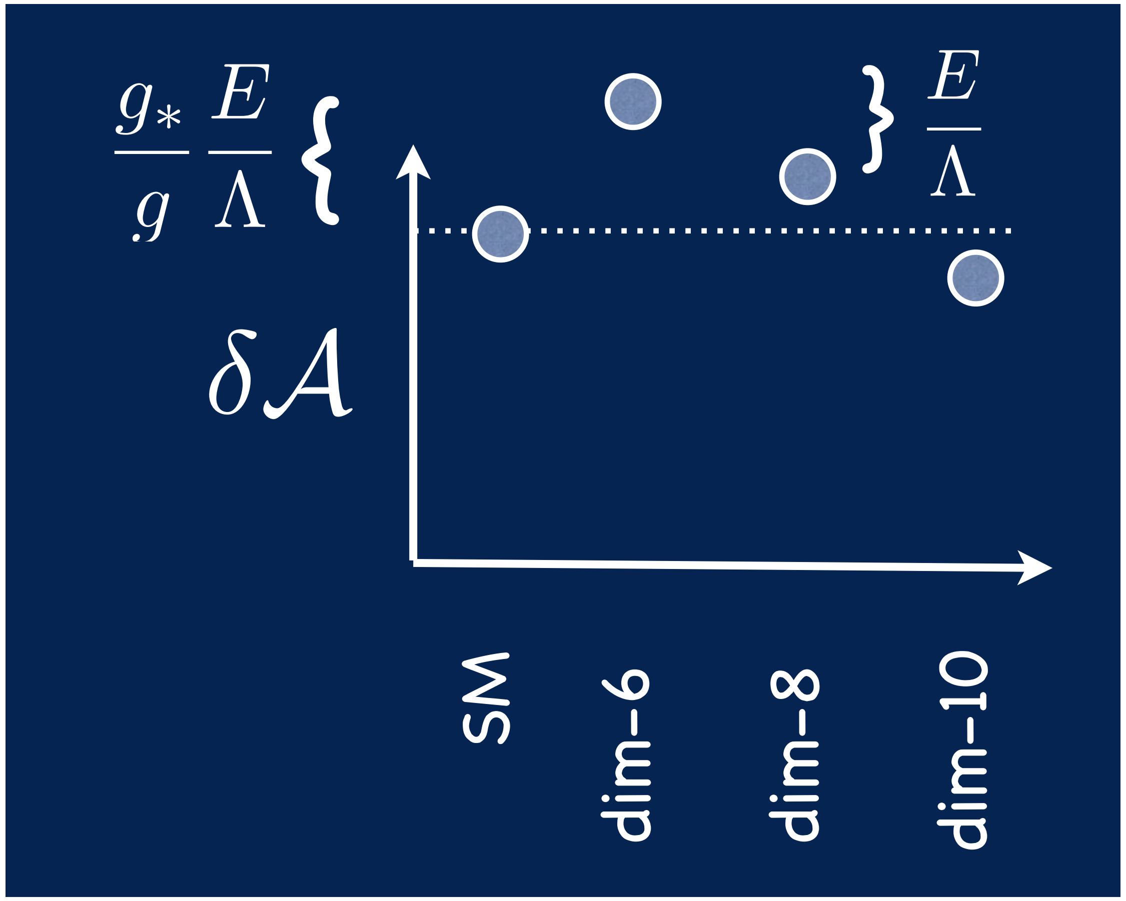

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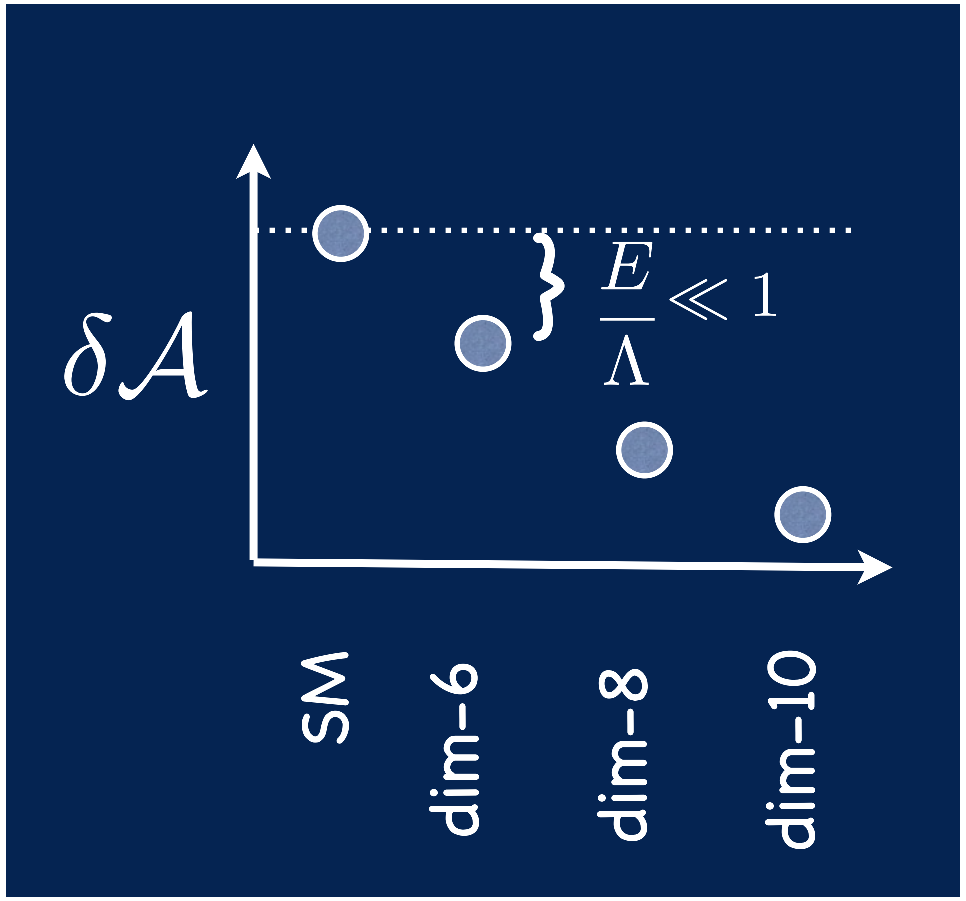

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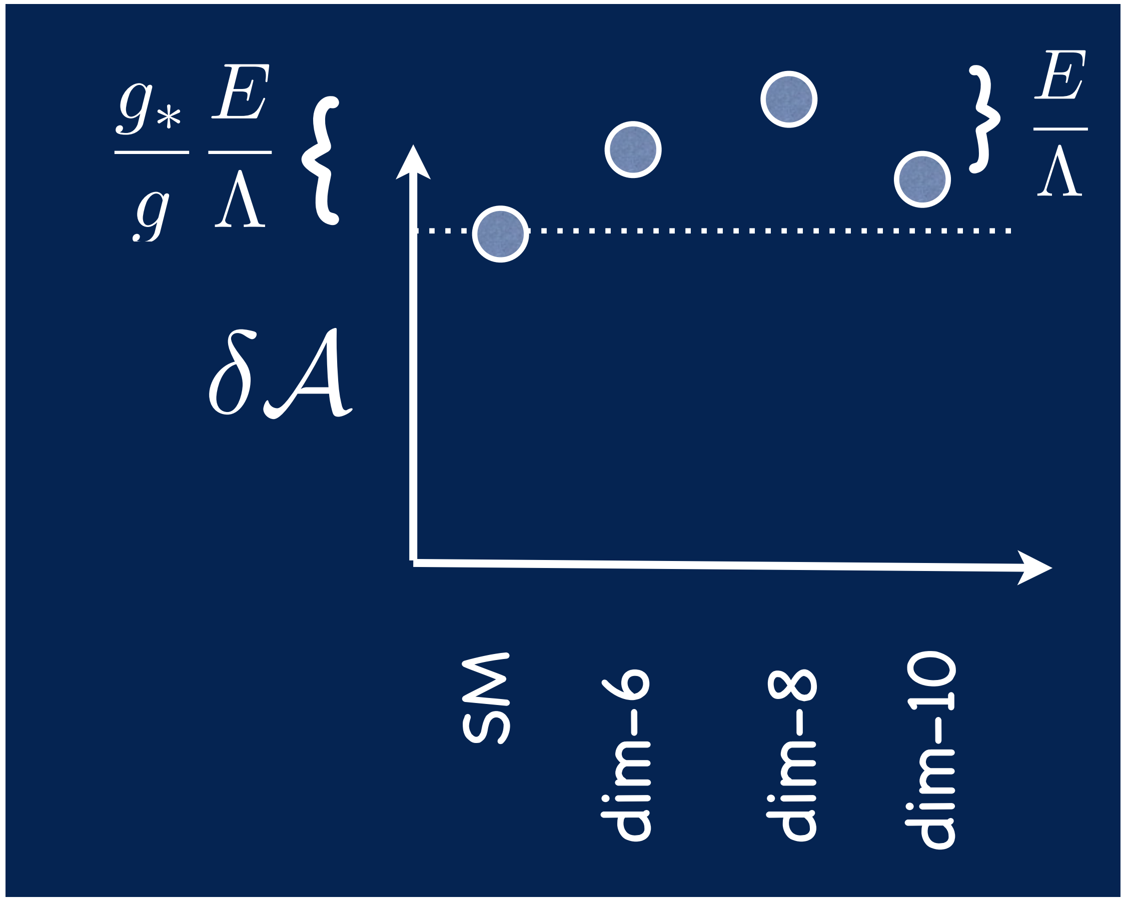
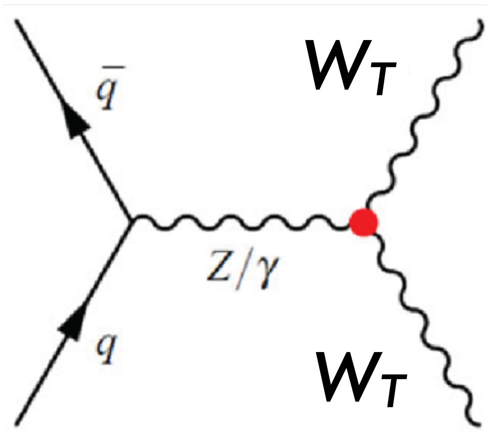


Strongly-coupled BSM

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

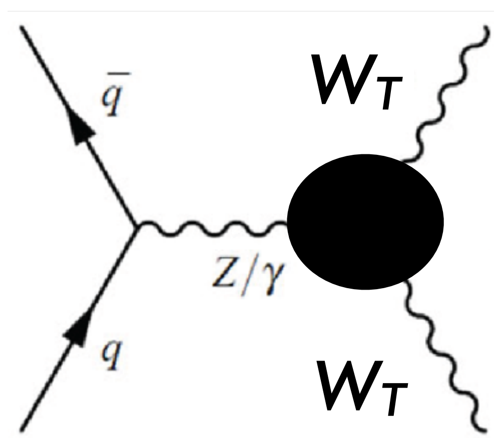
Example:

Dim-4:



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

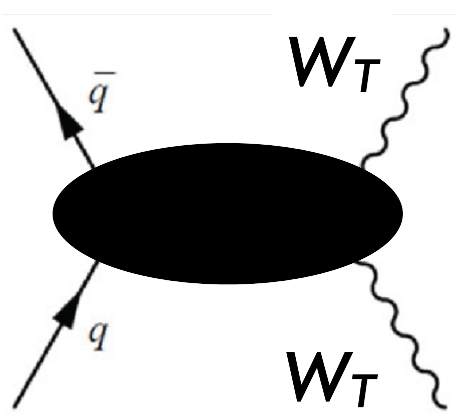
Dim-6:



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

number of couplings dictated by the number of fields: Max of 2 in 2→2 scattering ($\hbar$-counting)

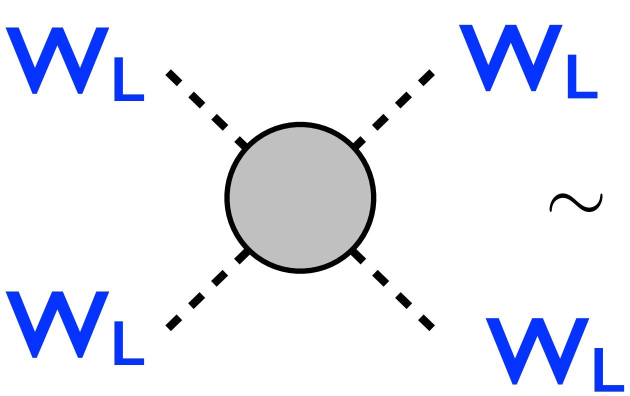
Dim-8:



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

In the simplest Composite Higgs Models

Apart from Higgs physics, **only** WW-scattering is expected to grow sizably with the energy & new strong-coupling:

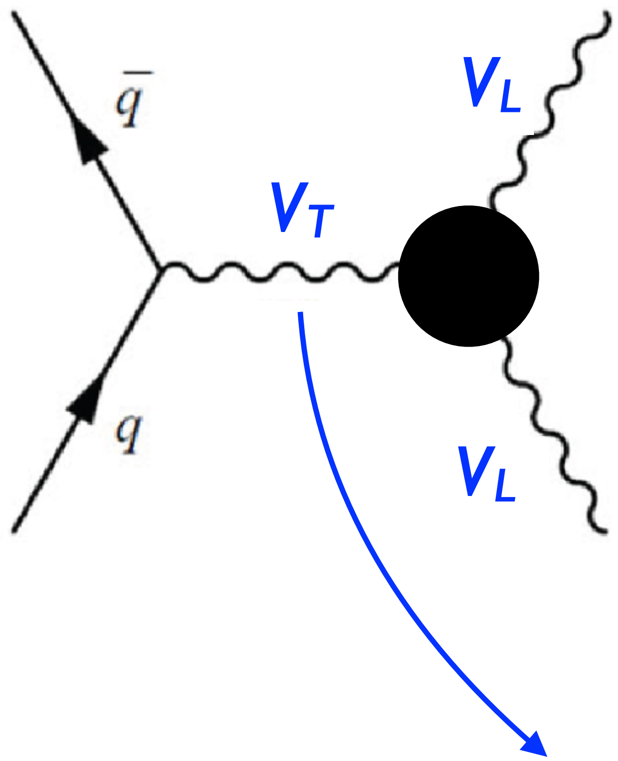


$$\sim \frac{g_*^2 E^2}{m_*^2}\left(1+\frac{E^2}{m_*^2}+\dots\right)$$

But small cross-sections at the LHC!

For the case for $\mathbf{qq \rightarrow V_T V_T}$:

TGC:



always involve a V_T that is weakly coupled

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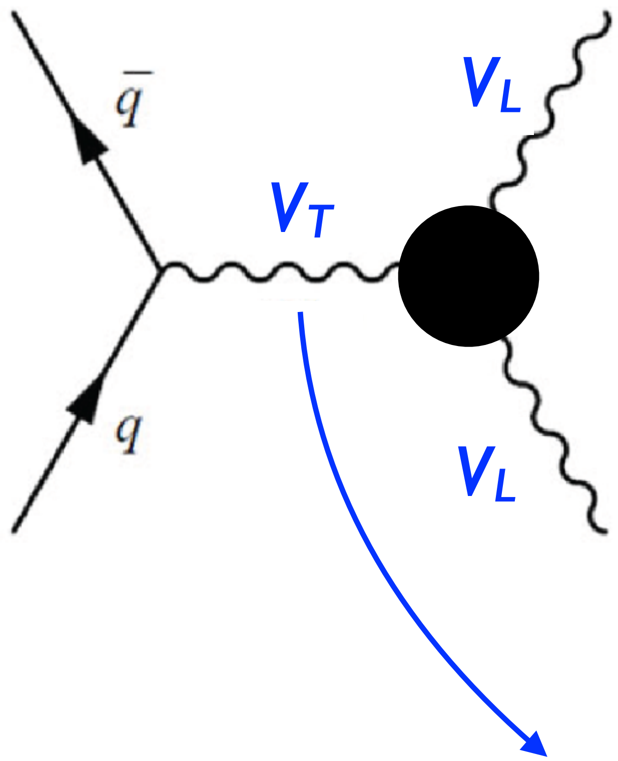


$$\sim \mathbf{g^2 \frac{E^2}{\Lambda^2} \ll 1}$$

Accuracy is needed to probe it!

always involve a V_T that is weakly coupled

But cross-sections dominated by the **transverse** components:

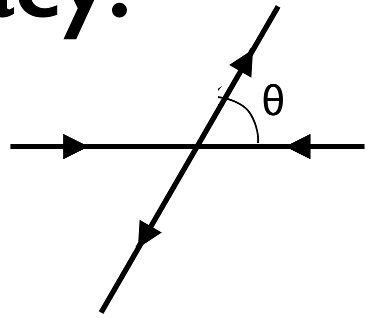
$q\bar{q} \to WZ$:

	σ_{tot}	σ_{LL}	σ_{LL}/σ_{tot}
8 TeV	12 pb	0.73 pb	6%
13 TeV	25 pb	1.5 pb	

its a background for the longitudinals!

WZ production give the only chance to get accuracy:

- **Symmetries force $W_T Z_T$ go to zero for $\theta \to 90^\circ$**
- **Small background in their leptonic decays**



Franceschini, Panico, AP, Riva, Wulzer, in preparation

See A. Wulzer's talk

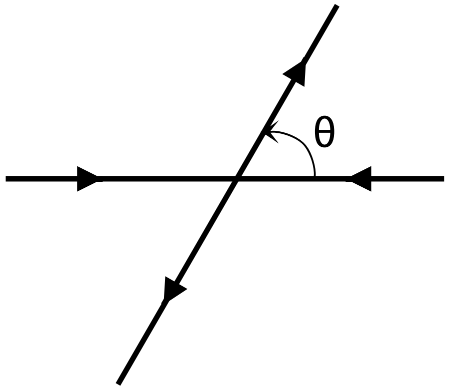
Transverse components of the SU(2) gauge bosons

$q\bar{q} \rightarrow V_1 V_2$

SU(2)-decomposition

- singlet: $W^a W_a$ — Sym. $V_1 \leftrightarrow V_2$
- triplet: $\epsilon_{abc} W^b W^c$ — Antisym. $V_1 \leftrightarrow V_2$

odd under interchange final states: $\hat{u} \leftrightarrow \hat{t}$ $\Rightarrow$ zero at $\theta \rightarrow 90^\circ$

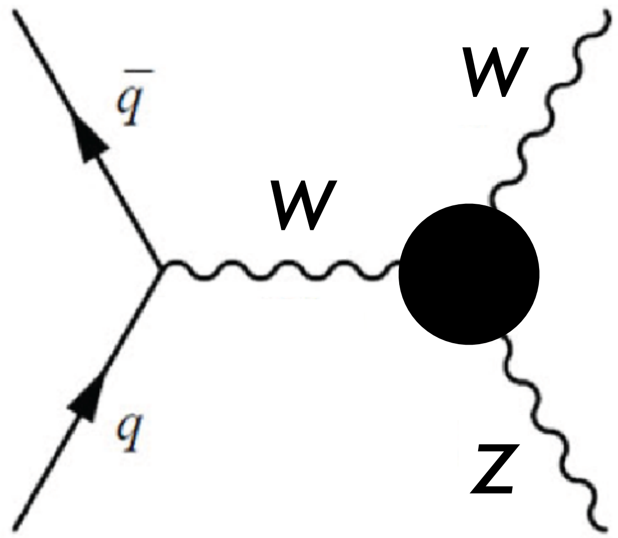


$V_1 V_2 =$ $W^+W^- \in \mathbf{1} + \mathbf{3}$

$W^+Z \in \mathbf{3}$ $\Rightarrow$ zero at $\theta \rightarrow 90^\circ$

up to small effects from
the $U(1)_Y$ gauge boson $\subset Z_\mu$ $\propto Y_L \sin^2\theta_W \sim 0.04$

How much accuracy and energy is needed?



$$\frac{\delta\mathcal{M}_{00}}{\mathcal{M}_{00}^{\rm SM}} = 1 - \frac{\hat{s}}{m_Z^2}\delta g_1^Z$$

Shift of the SM **WWZ-coupling**

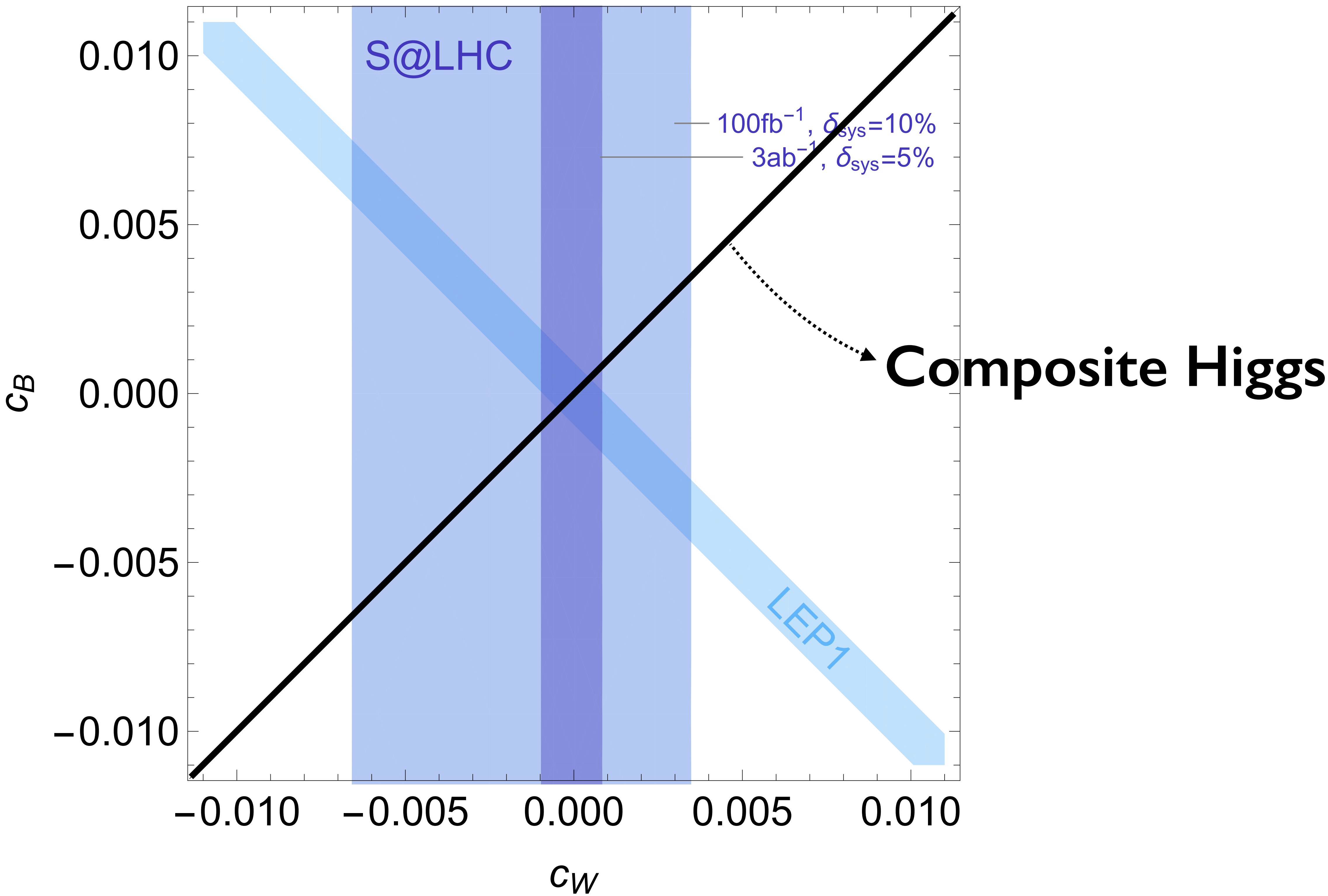
Franceschini,Panico,AP,Riva,Wulzer

It size similar to the S-parameter bound at LEP at the per-mille:

$$-g^2 c_{\theta_W}^2 \delta g_1^Z \simeq \frac{g^2}{2}\hat{S}$$

To test $\delta g_1^Z \sim 3\times10^{-3}$ ☛ We must be able to see a 10 % deviation of WZ-production at m_{WZ} >300 GeV ($\cos\theta$<0.5)

Franceschini,Panico,AP,Riva,
Wulzer, in preparation



What else can we learn from di-bosons?

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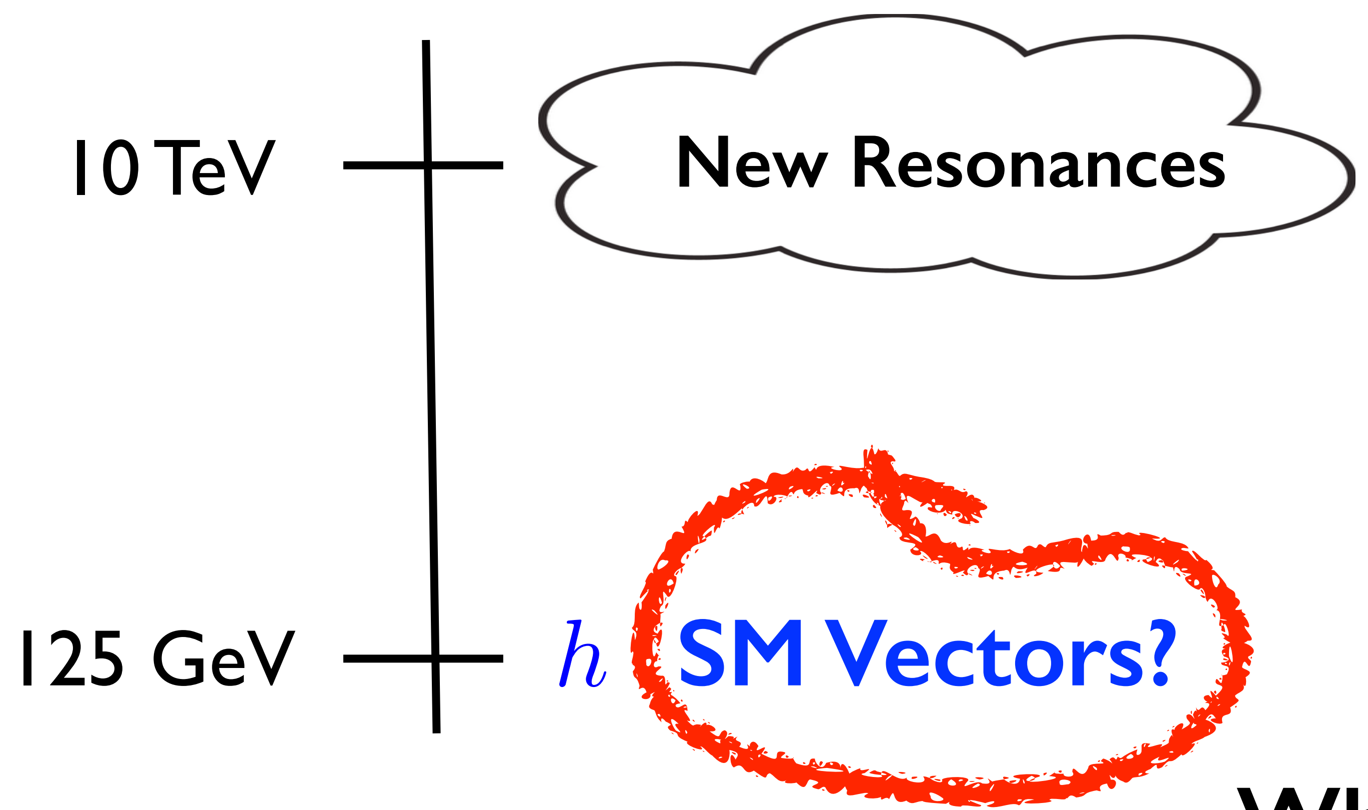
New possibilities if other SM states
arise from the new strong TeV-dynamics:



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)

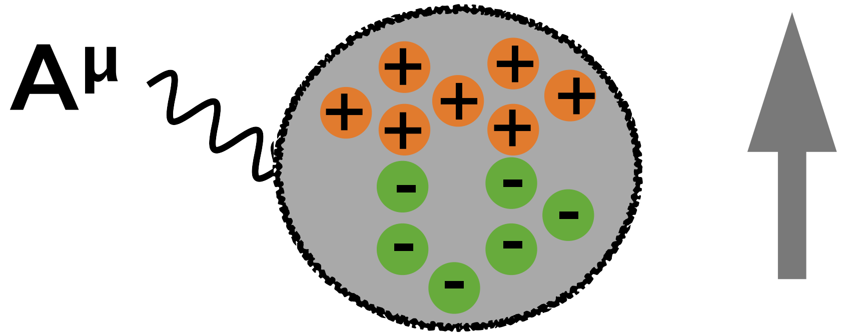
But remember pions (PGB) have two different type of couplings:

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

Small gauge 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

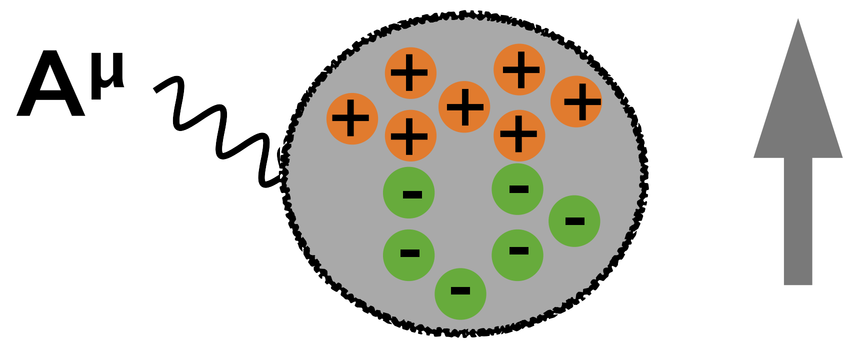


dipole $\gg 1/\Lambda$

Q=1

Example: QED at $E<m_e$ = Euler-Heisenberg EFT (only dipole int.)

Effective Theory of Strong Dipole Interactions



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Example: QED at $E<m_e$ = Euler-Heisenberg EFT (only dipole int.)

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

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

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→

Smoothly deformed by g

$SU(2)_{local}$

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The inverse of a *Inonu-Wigner contraction*:

Galilei Group ⟵ Poincare Group

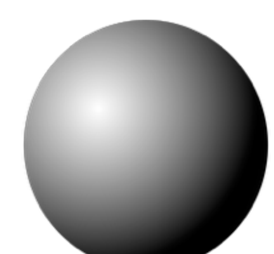
$1/c \to 0$

U(1)xU(1)xU(1)

⟵

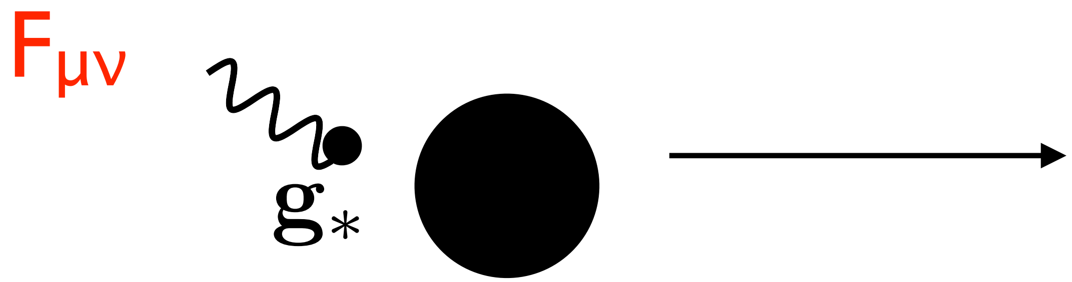
$g \to 0$

SU(2)



Remedios

Effects:



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

Remedios

Effects:

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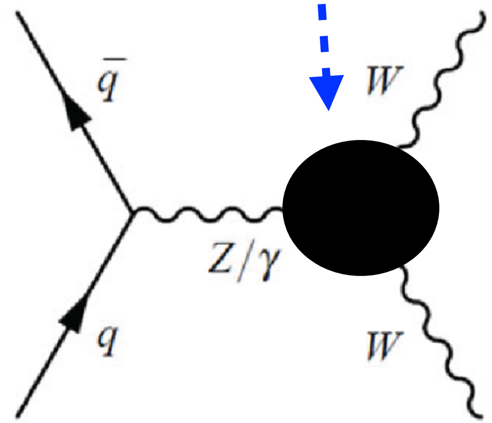

$$\lambda_\gamma\left[\frac{(q_1-q_2)^\mu}{m_W^2}\left(\frac{s}{2}g^{\alpha\beta}-p^\alpha p^\beta\right)+p^\alpha g^{\mu\beta}-p^\beta g^{\mu\alpha}\right]$$

Remedios

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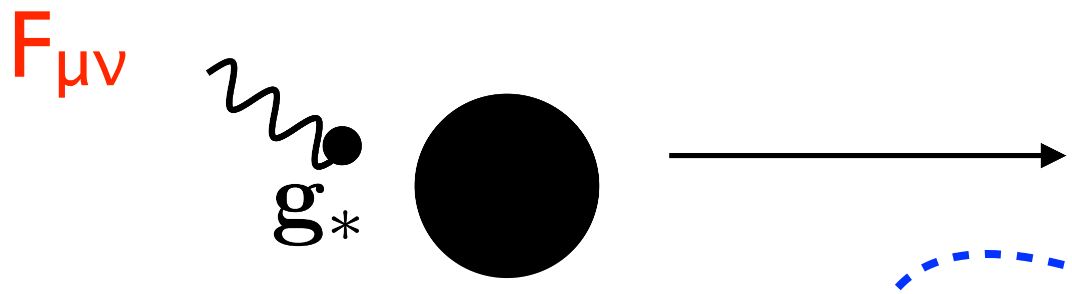

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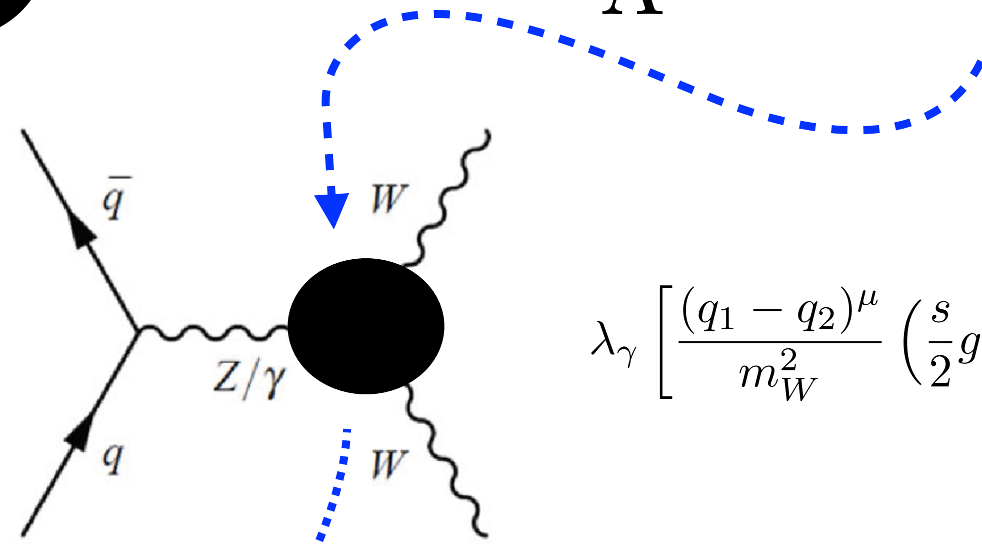
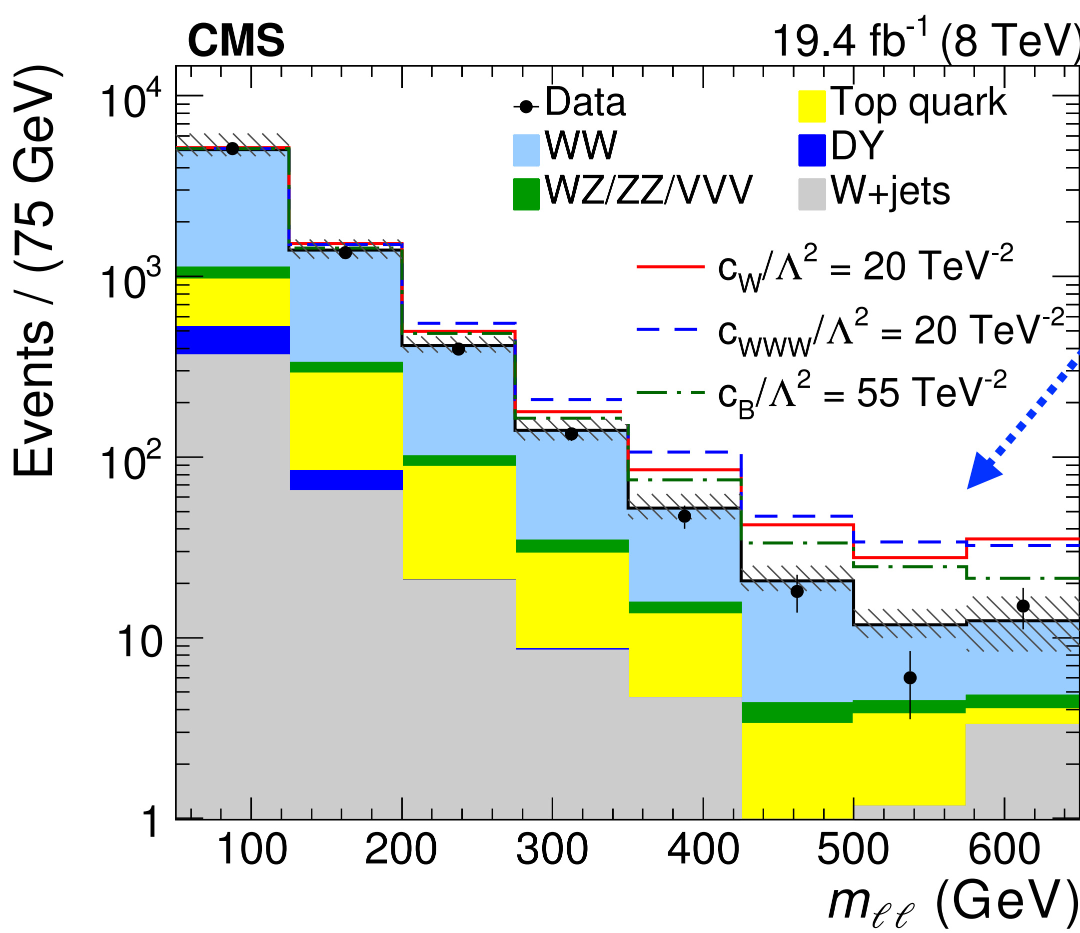


$$\lambda_\gamma\left[\frac{(q_1-q_2)^\mu}{m_W^2}\left(\frac{s}{2}g^{\alpha\beta}-p^\alpha p^\beta\right)+p^\alpha g^{\mu\beta}-p^\beta g^{\mu\alpha}\right]$$

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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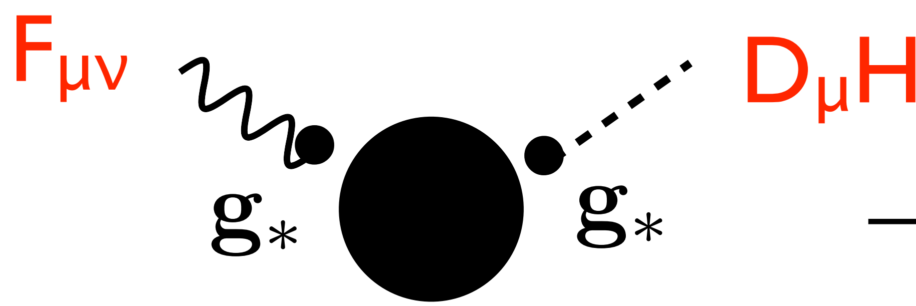

$$\longrightarrow \quad \frac{g_*}{\Lambda^2}\, i(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$

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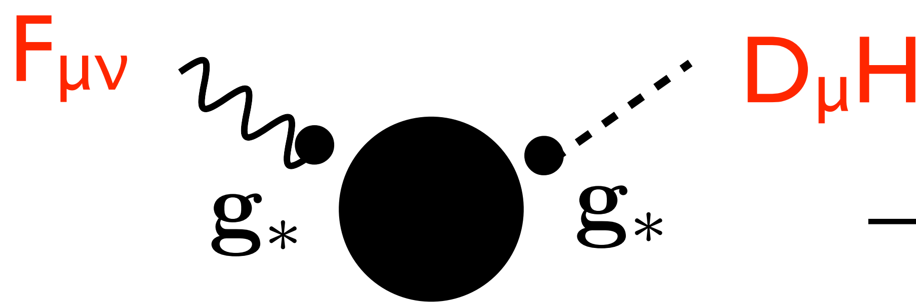
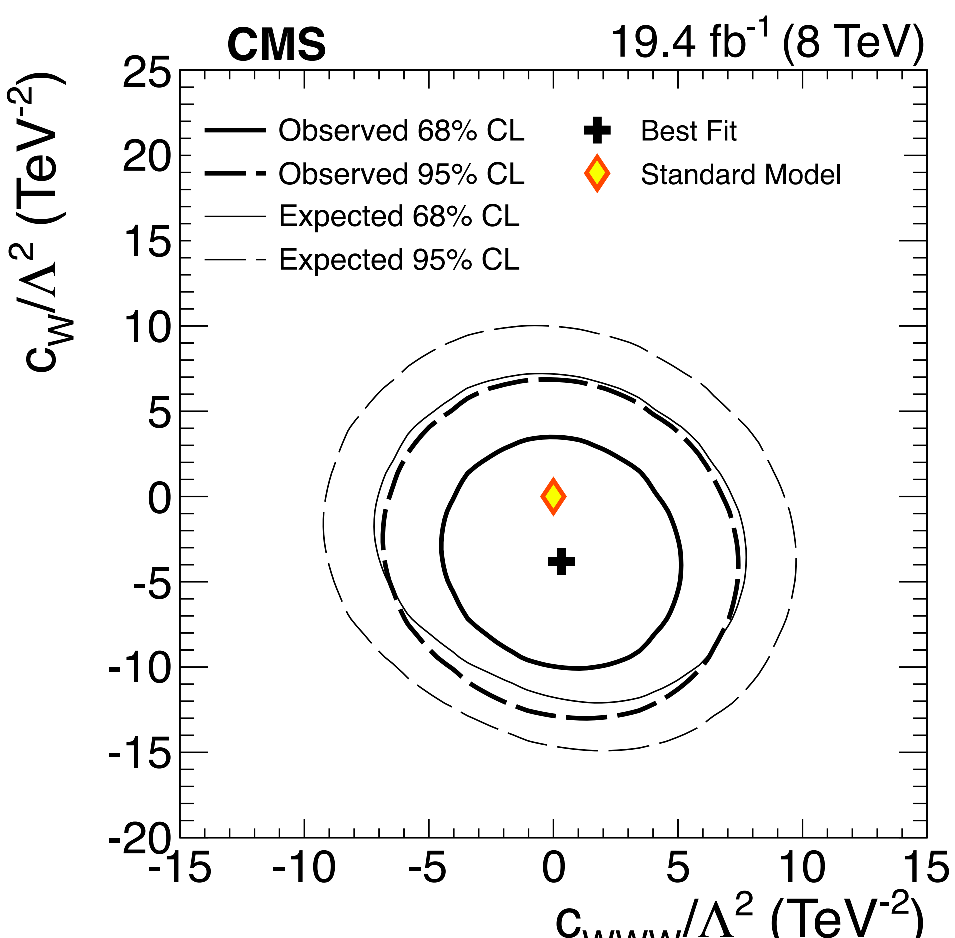


$$\longrightarrow \frac{g_*}{\Lambda^2} i(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$

qq→VV



Remedios + Composite PGB Higgs

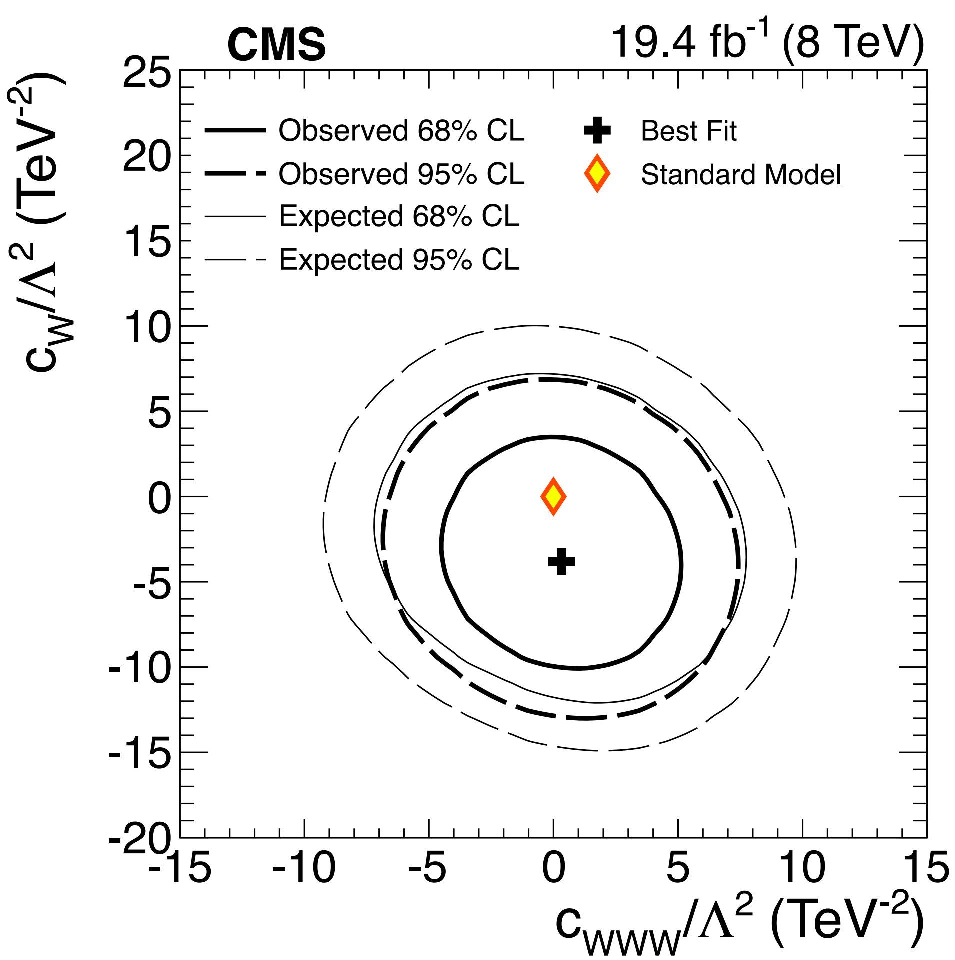
For concreteness: **H→H+c** preserving SO(4) custodial

Effects:

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

qq→VV

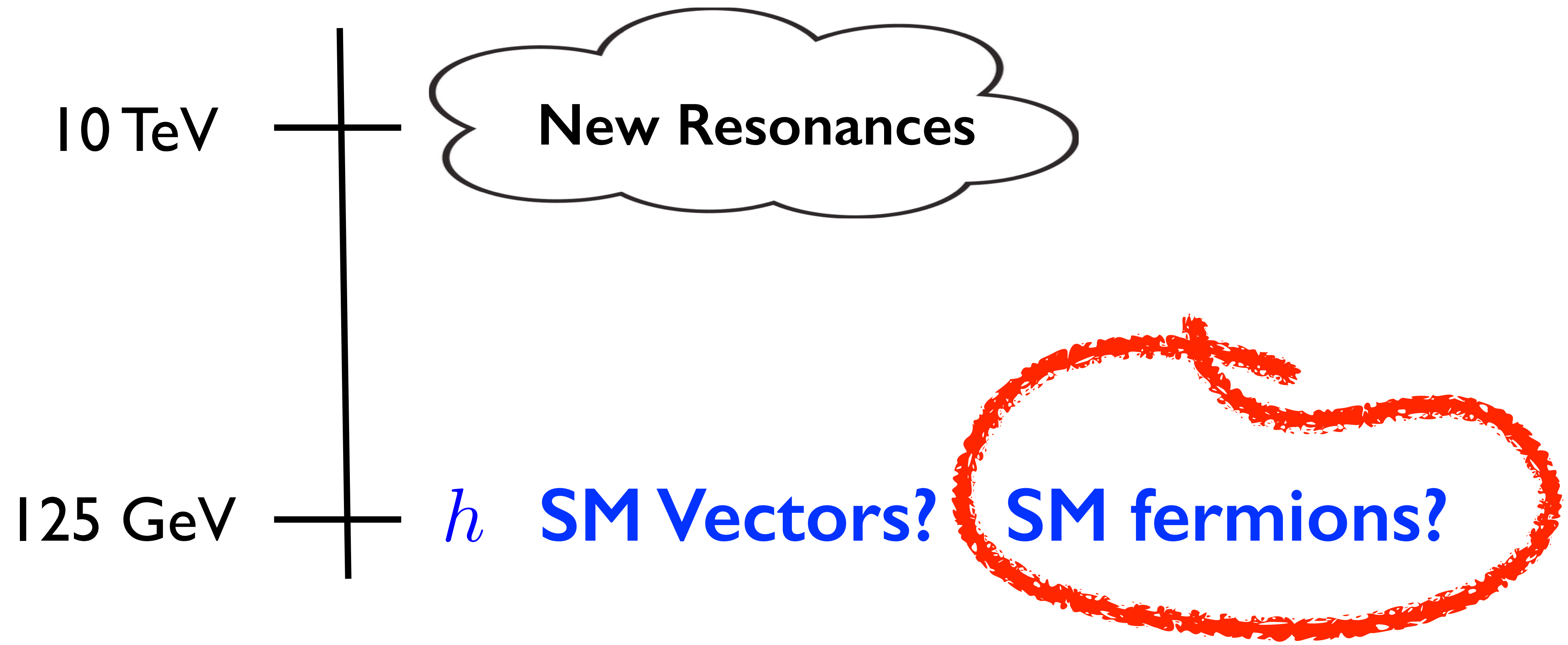
h→γZ



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 can we learn from di-bosons?



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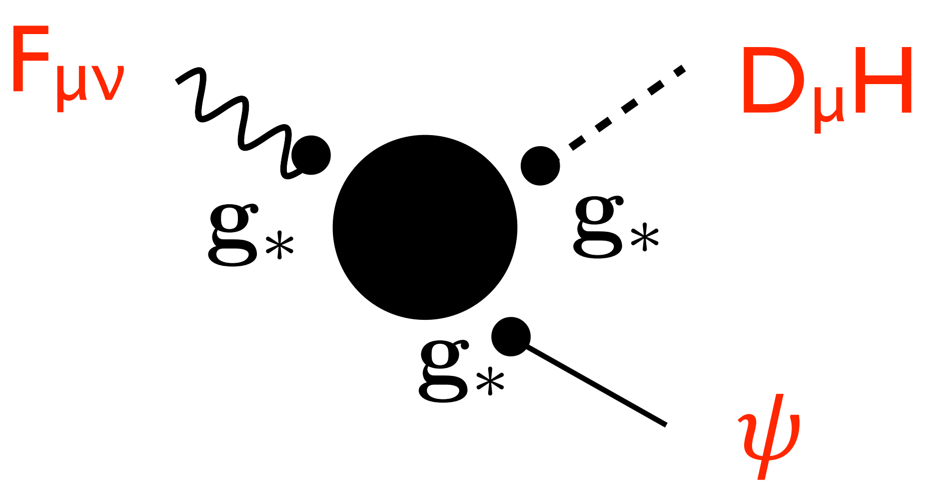
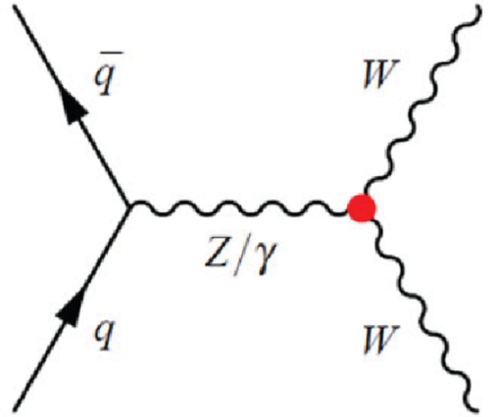
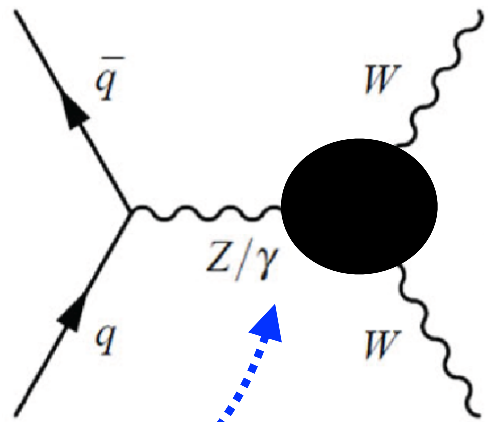


Implications in $qq \to V_T V_T$:

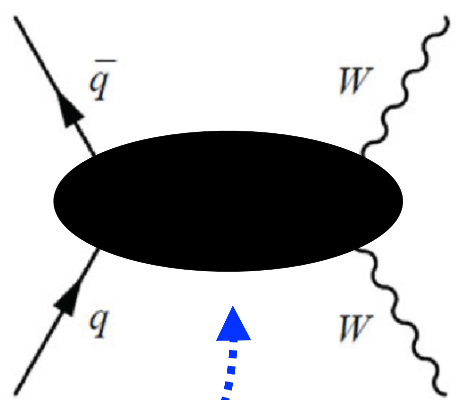


$$\mathcal{A}_{\rm SM} \sim g^2$$



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

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



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

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

work in progress!

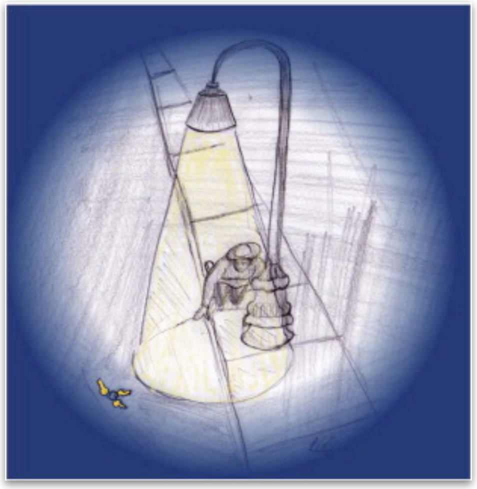
A model-independent analysis must include dim-8 operators

Conclusions

- **New Strong dynamics at the TeV** is still one of the best options for TeV-BSM:

  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 <u>di-boson production</u> at the LHC at the high-energy regime!**
  - In particular, **pp→ $W_L Z_L$** the most promising

    (reduced $W_T Z_T$ in central region, but Jet veto needed)

    possibility to achieve EWSB SM-tests below 1%
  - Other more exotic possibilities: <u>Gauge boson composite at TeV</u>:

Also **pp→ $W_T W_T$** important

(but dim-8 operators could be as important as dim-6)