Higgs Compositeness from Direct Searches

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Natural or Not ?

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Light Higgs plus **Low Tuning** need **Light Partners**

SUSY:	**Composite Higgs:**
light stops	**light fermionic partners**

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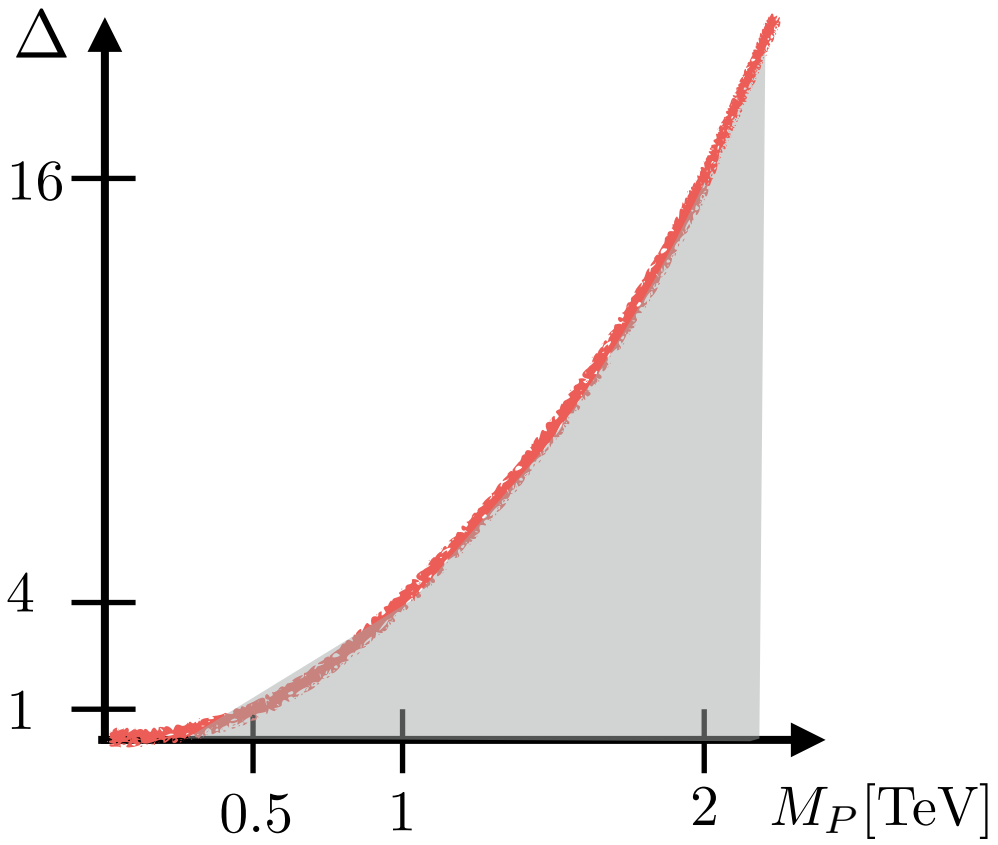

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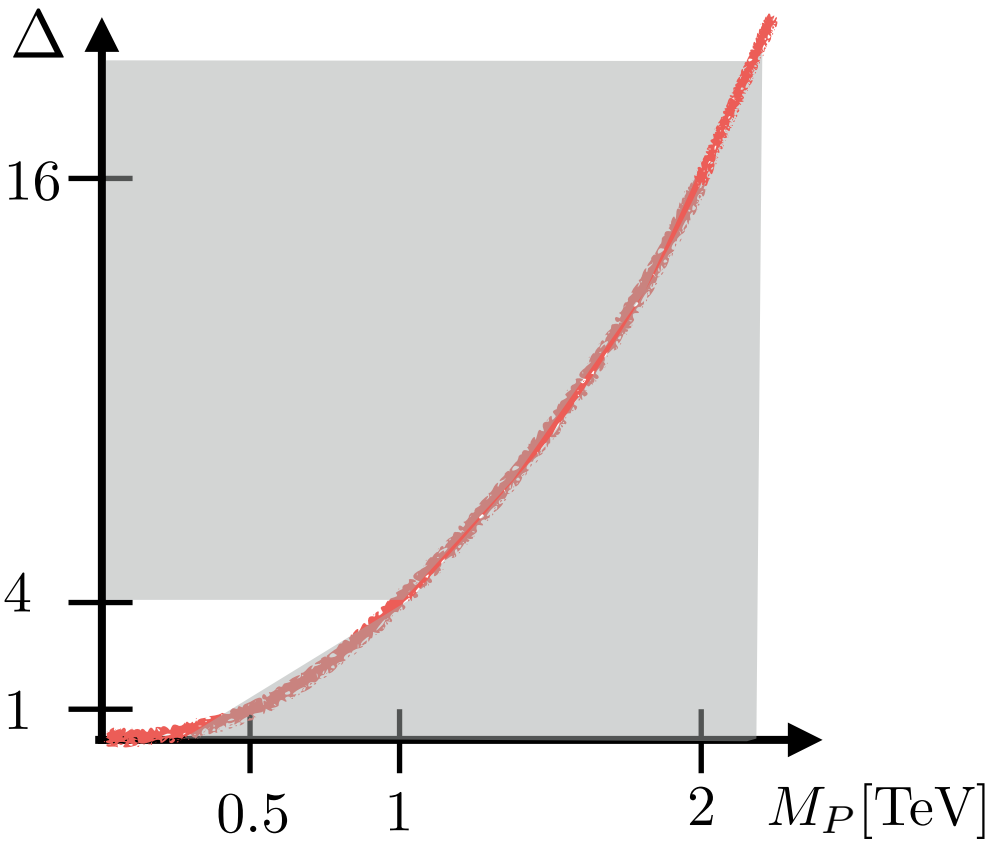

Optimistic Interpretation:

Fine tuning must be small thus we discover Partners

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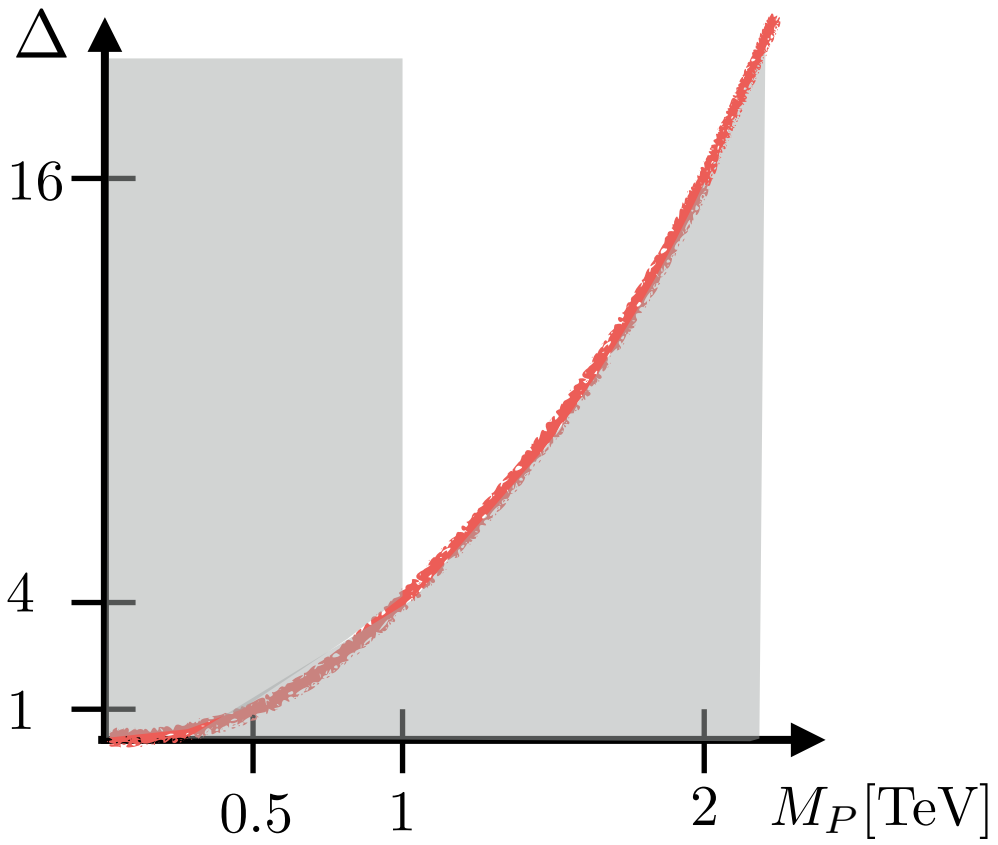

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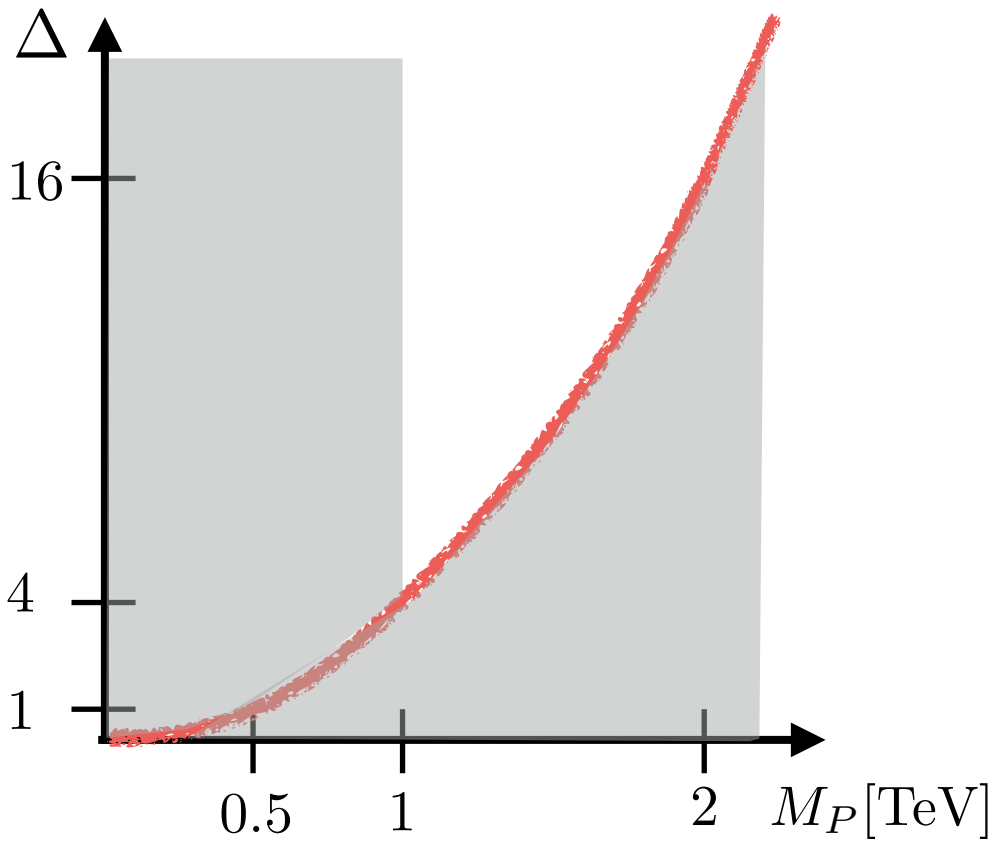

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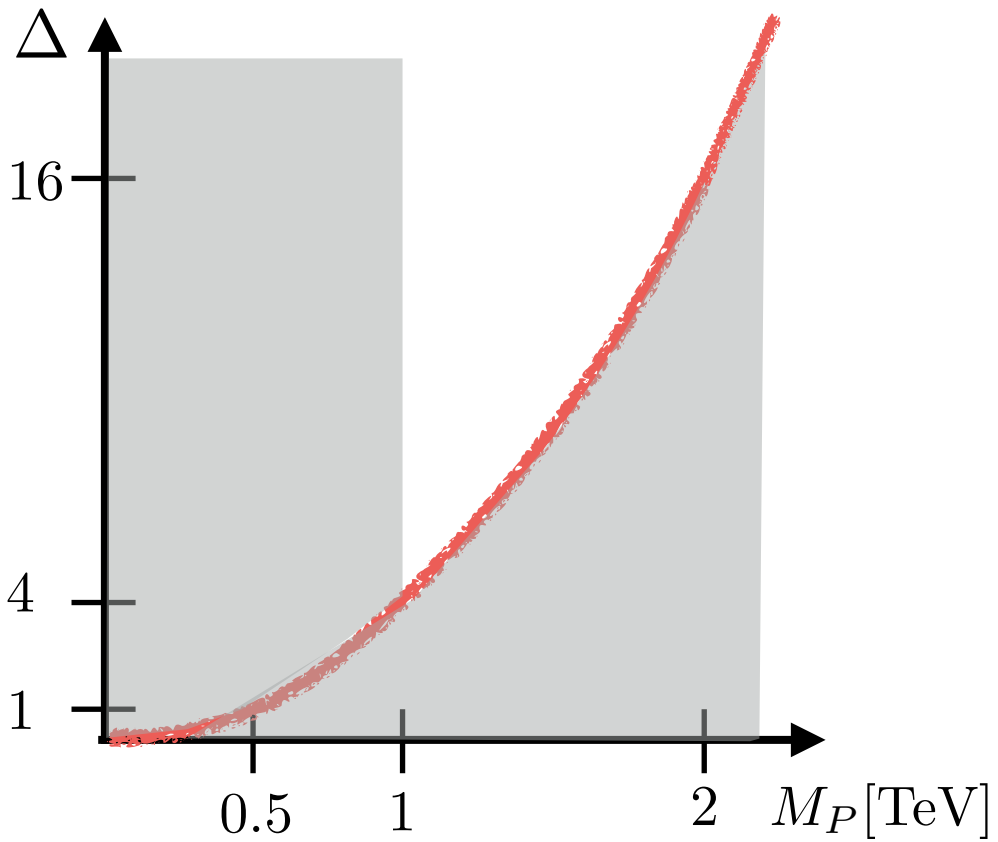

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Question: where should we stop? $\Delta = 1,\ 10,\ 100, \ldots$?

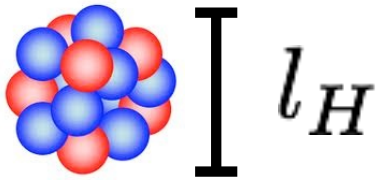
Composite Higgs

Composite Higgs scenario:

1. Higgs is **hadron** of **new strong force**

Corrections to m_H screened above $1/l_H$

The **Hierarchy Problem** is **solved**



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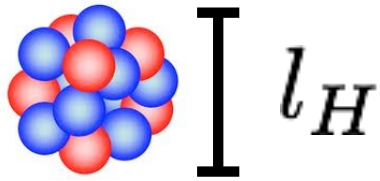

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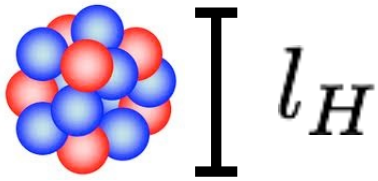

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Indirect effects from sigma-model couplings

A) Corrections to SM:

$[\mathcal{O}(v^2/f^2) \lesssim 20\%]$

- Higgs Br. Ratios
- Higgs Production

B) Non-ren. **Couplings**:

- In $WW \to hh$
- In $gg \to hh$

Indirect, but "direct" (robust) signature of compositeness

however **not easy** to see with present (and future?) data

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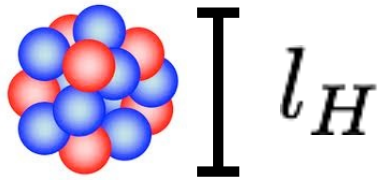

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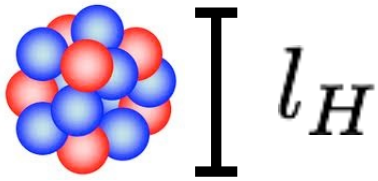

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Direct Production of new particles:

Fermionic Top Partners

More promising

Goldstone Boson Higgs

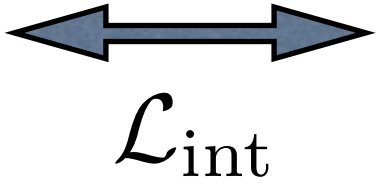
Let us focus on the **Minimal Coset** $\mathrm{SO}(5)/\mathrm{SO}(4)$

Composite Sector

Elementary Sector

$\mathrm{SO}(5) \to \mathrm{SO}(4)$

$H \in \mathrm{SO}(5)/\mathrm{SO}(4)$



$\mathcal{L}_{\mathrm{int}}$

$W_\mu^{1,2,3},\ B_\mu$

$f_L,\ f_R$

gauge couplings: $\mathcal{L}_{\mathrm{int}} = g J_\mu W^\mu$

fermion couplings: $\mathcal{L}_{\mathrm{int}} = y_L q_L \mathcal{O}_L + y_R q_R \mathcal{O}_R$

Goldstone Boson Higgs

Low energy Higgs physics from **symmetries**

One parameter: Higgs decay constant f

$$\mathcal{L}_\pi = \frac{f^2}{4} d_\mu^i d_i^\mu = \frac{1}{2}(\partial h)^2 + \frac{g^2}{4} f^2 \sin^2 \frac{h}{f} \left(|W|^2 + \frac{1}{2c_w^2} Z^2 \right)$$

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on Higgs VEV we get W/Z masses: ($\rho = 1$ thank to custodial !)

$$m_W = \frac{g}{2} f \sin \frac{\langle h \rangle}{f}\,, \qquad m_Z = m_W / c_w$$

thus the EWSB scale is: $v = 246\,\mathrm{GeV} = f \sin \frac{\langle h \rangle}{f}$

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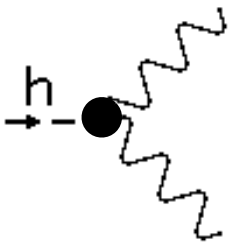
the physical Higgs coupling to W is



$$= i \frac{g^2}{4} v \sqrt{1-\xi}$$

deviations from SM controlled by

$$\xi \equiv \frac{v^2}{f^2} = \sin^2 \frac{\langle h \rangle}{f}$$

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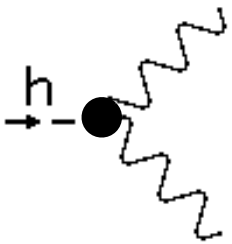

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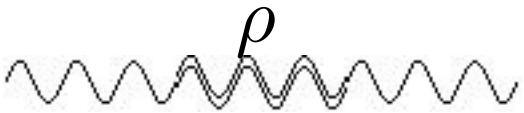
In principle, departures from SM could be huge.

However the constraints from EWPT suggest $\xi \simeq 0.2$ or $\xi \simeq 0.1$:

direct constraint on modified W coupling

tree-level S from other resonances



Goldstone Boson Higgs

Fermion couplings from partial compositeness

$$\mathcal{L}_{\rm int} = y_L q_L \mathcal{O}_L + y_R q_R \mathcal{O}_R$$

The $\mathcal{O}_{L,R}$ can live in different representations of $\mathrm{SO}(5)$

$$\mathcal{O}_{L,R} \in \mathbf{4} \quad \Rightarrow \quad \mathrm{MCHM}_4$$

$$\mathcal{O}_{L,R} \in \mathbf{5} \quad \Rightarrow \quad \mathrm{MCHM}_5$$

$$\mathcal{O}_{L,R} \in \mathbf{10} \quad \Rightarrow \quad \mathrm{MCHM}_{10}$$

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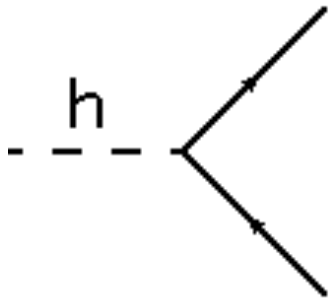
For each choice, fermion coupling fixed by symmetry



$$= i \frac{m_f}{v} c$$

$$\mathrm{MCHM}_5 \qquad c = \frac{1-2\xi}{\sqrt{1-\xi}}$$

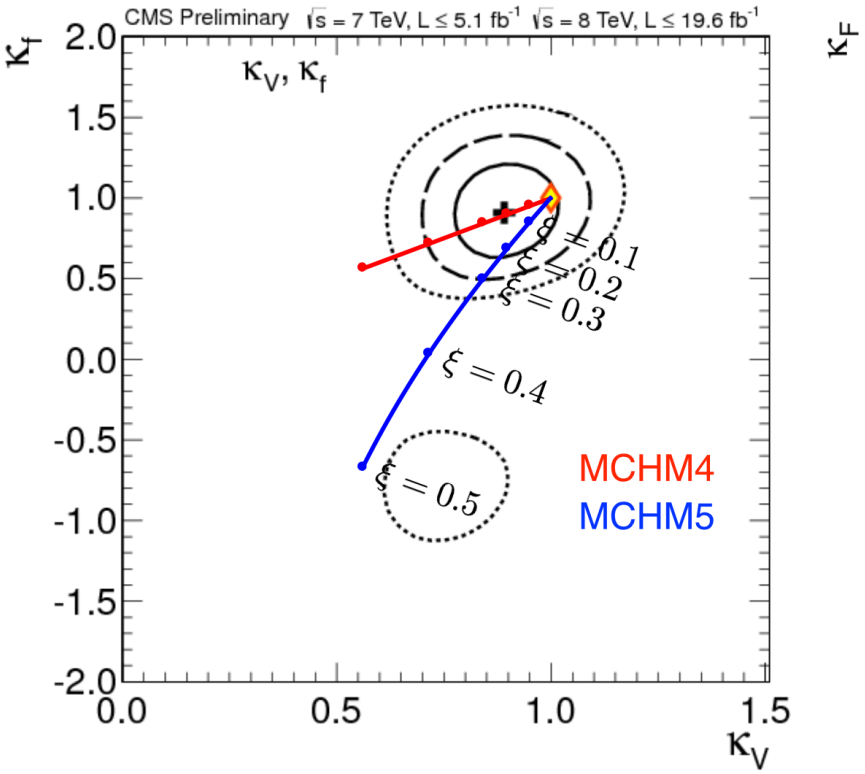
$$\mathrm{MCHM}_4 \qquad c = \sqrt{1-\xi}$$

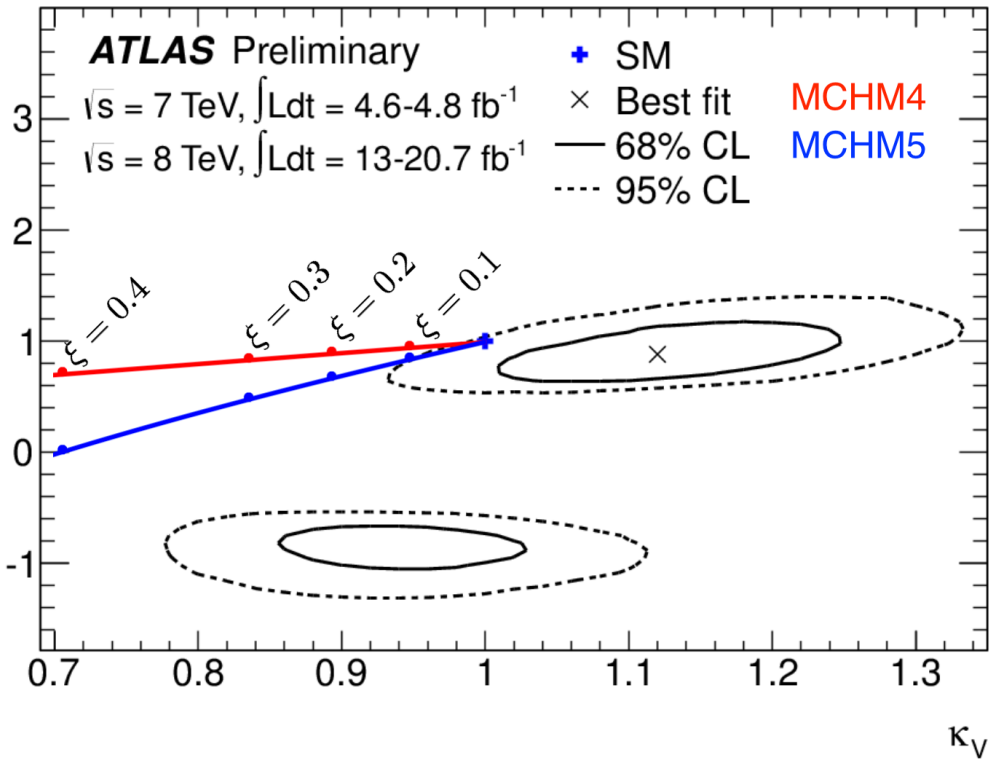
$$\mathrm{MCHM}_{10} \qquad \cdots$$

Goldstone Boson Higgs

courtesy of R. Torre

Some updated fit:





Partial Compositeness

But why is this called “Partial compositeness”?

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In the IR operators correspond to particles:

$\langle 0|\mathcal{O}|Q\rangle \neq 0$ $\qquad$ $\mathcal{O}_{L,R} \leftrightarrow Q_{L,R}$

Important Remark:

$\mathcal{O}$ and Q **carry color !**

$Q =$ "vector-like colored fermions" (partners)

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$\mathcal{L}_{\rm int} = y_L q_L \mathcal{O}_L + y_R q_R \mathcal{O}_R$ gives a **mass-mixing** in the IR:

$$\mathcal{L}_{mass} = m_Q^* \overline{Q} Q + y\, f \bar{q} Q$$

physical particles are **partially composite**

$$|SM_n\rangle = \cos\phi_n |elementary_n\rangle + \sin\phi_n |composite_n\rangle$$
$$|BSM_n\rangle = \cos\phi_n |composite_n\rangle - \sin\phi_n |elementary_n\rangle$$

$$\tan\phi_n = \frac{yf}{m_Q^*}$$

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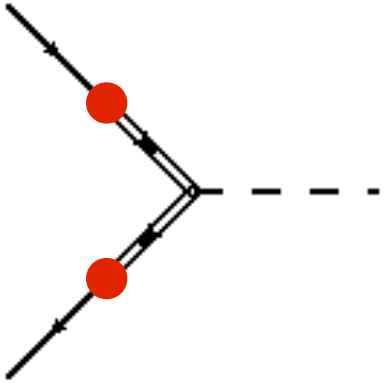
P.C. generates **Yukawas** ...

$$y_f =$$



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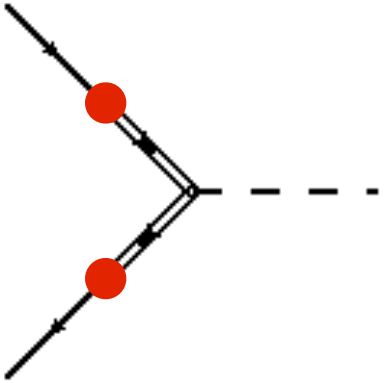
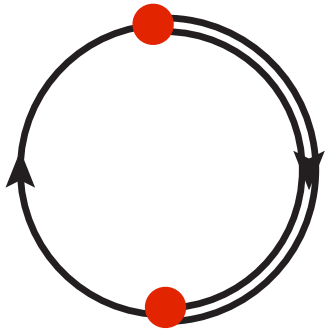


... and the **Higgs Potential**



Top loop dominate because the top is largely composite.

Partial Compositeness

Top partners cancel m_H divergence, thus are **directly bounded** by Naturalness

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(Panico, Redi, Tesi, AW 2012)

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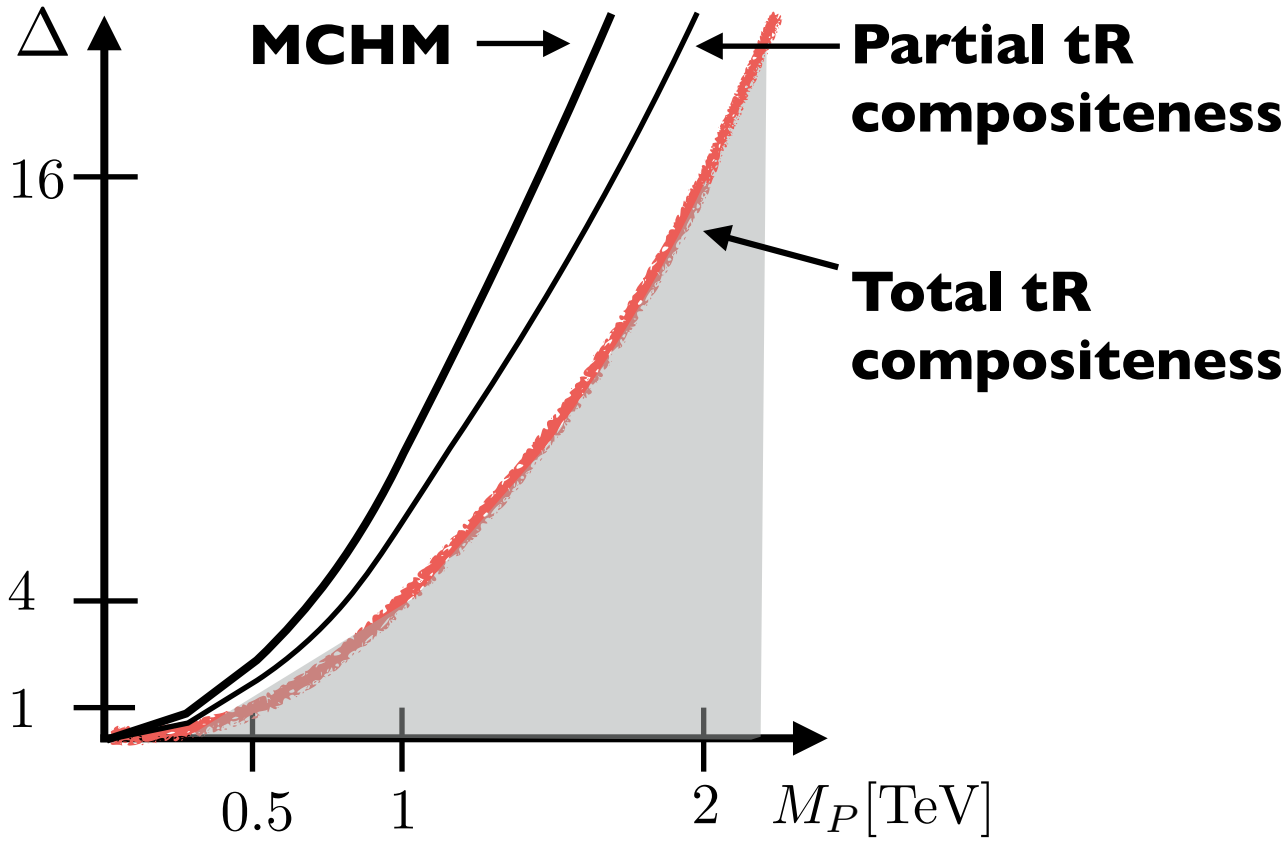


Partial Compositeness

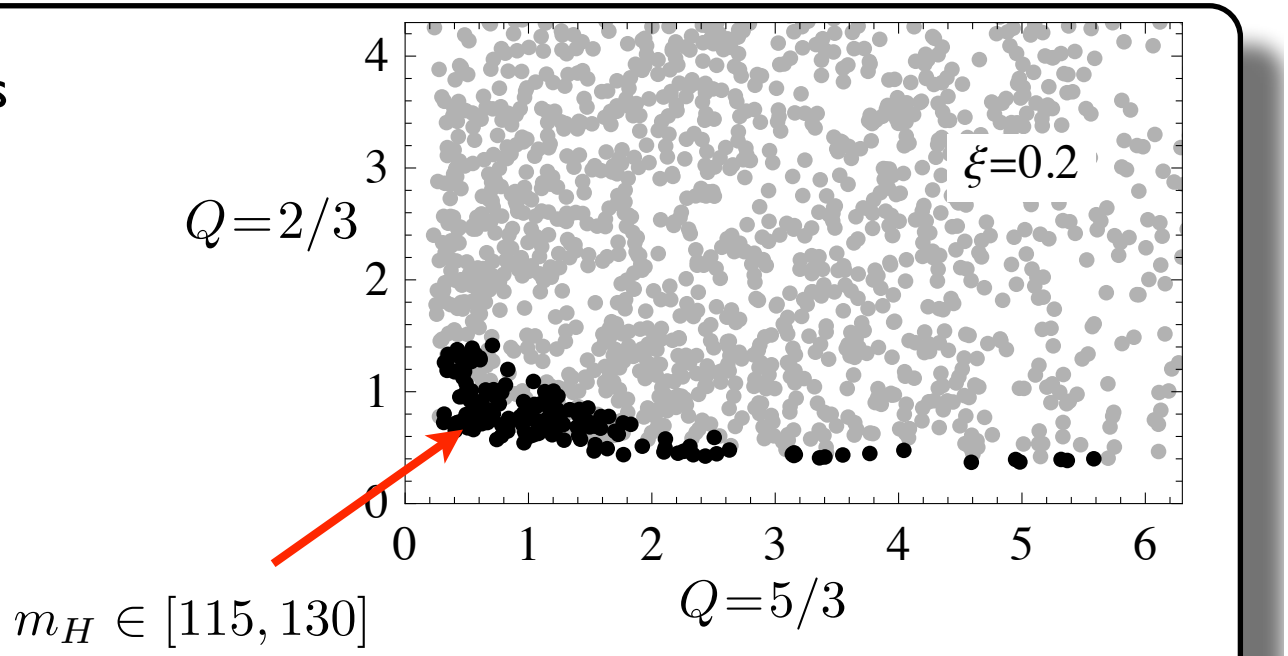
A more pragmatic illustration

(Matsedonsky,i Panico, AW 2012)

In a class of explicit CH models

$$\mathrm{MCHM}_{4,5,10}$$

$\xi = 0.2$: (low tuning)



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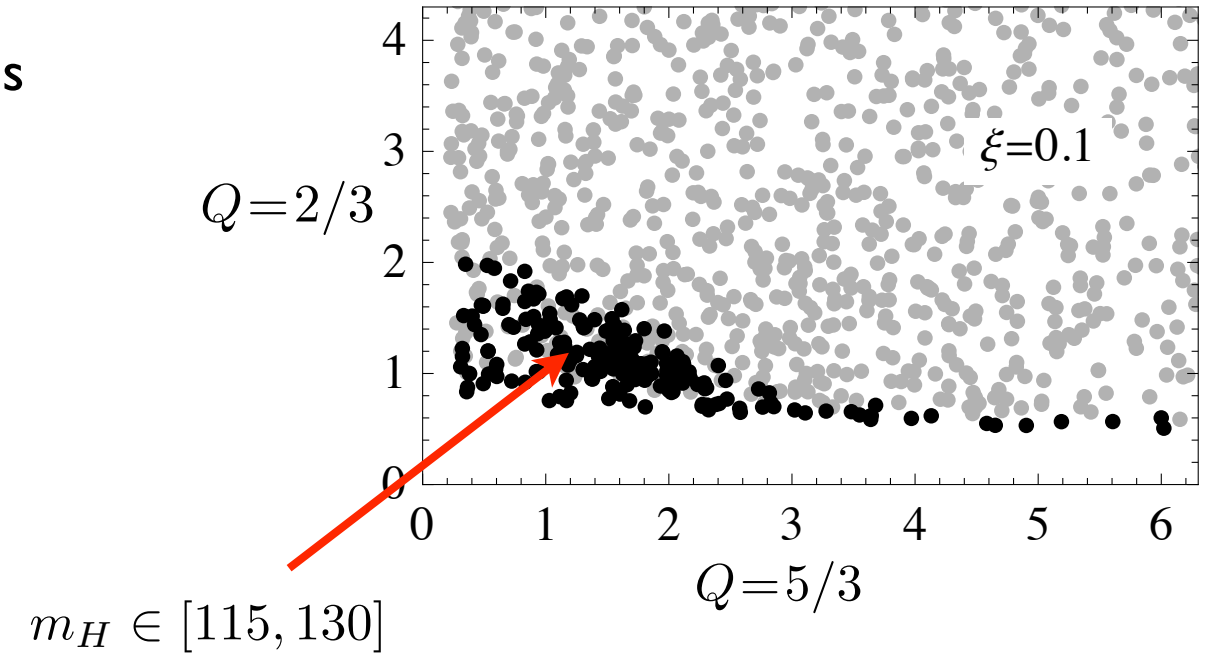

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(De Simone, Matsedonsky, Rattazzi, AW, 2012)

A simple, but general model for the Top Partners

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Write down the most general Effective Field Theory Lagrangian.
Within the assumptions, rigorous description of any explicit model

Top Partners at the LHC

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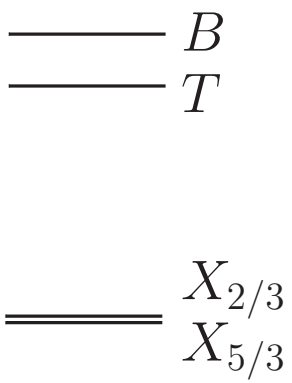
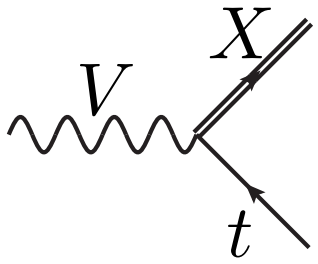
Fourplet of custodial $\mathrm{SO}(4)$ $\begin{pmatrix} T & X_{5/3} \\ B & X_{2/3} \end{pmatrix}$

Spectrum:



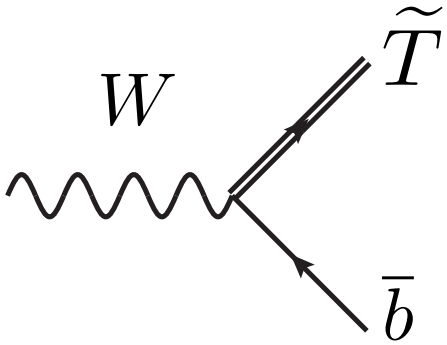
Couplings:



$\sim M_X / f$

because Goldstones are derivatively coupled

Singlet of custodial $\mathrm{SO}(4)$ $\widetilde{T}$



sizeable coupling to bottom quark

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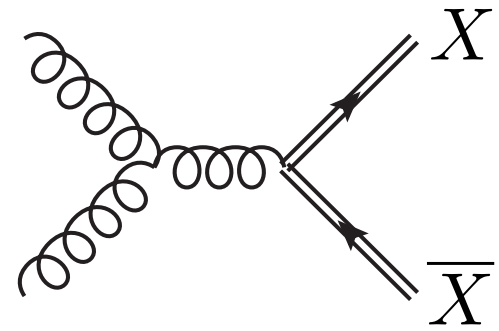
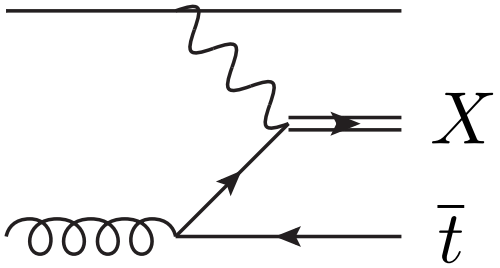
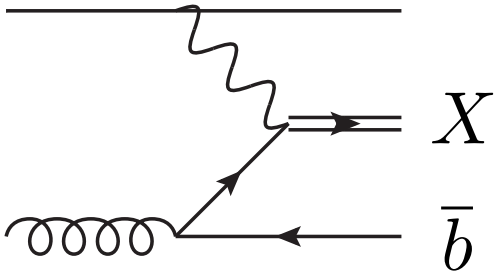
Three possible production mechanisms



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



single prod. with **t**
model dep. coupling
pdf-favoured at high mass



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

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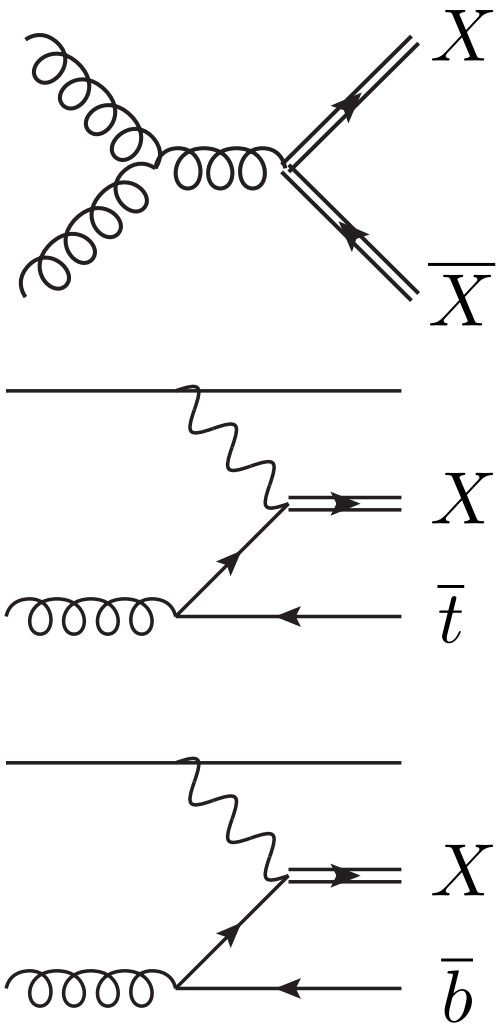
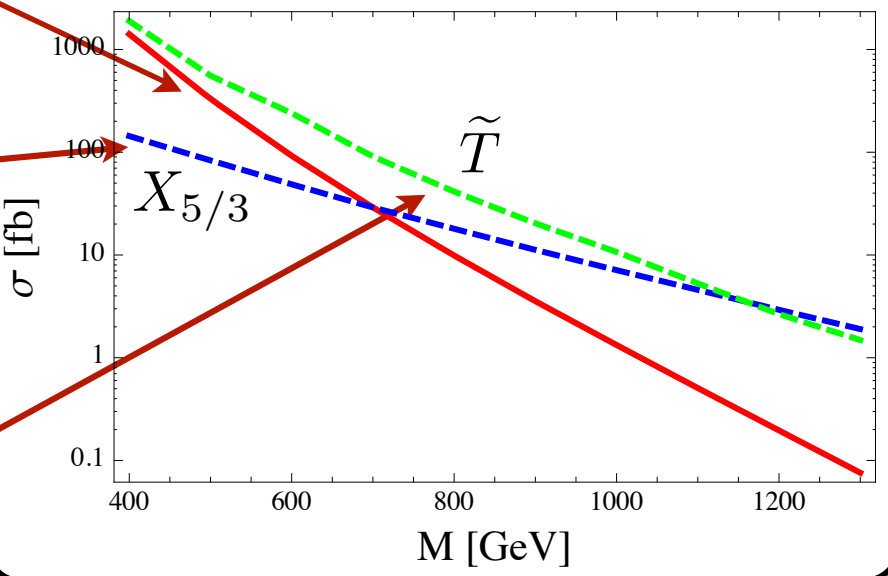


QCD **pair prod**.
model indep.,
relevant at low mass

single prod. with **t**
model dep. coupling
pdf-favoured at high m

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

comparing production rates:
(7 TeV LHC)



Top Partners at the LHC

(De Simone, Matsedonsky, Rattazzi, AW, 2012)

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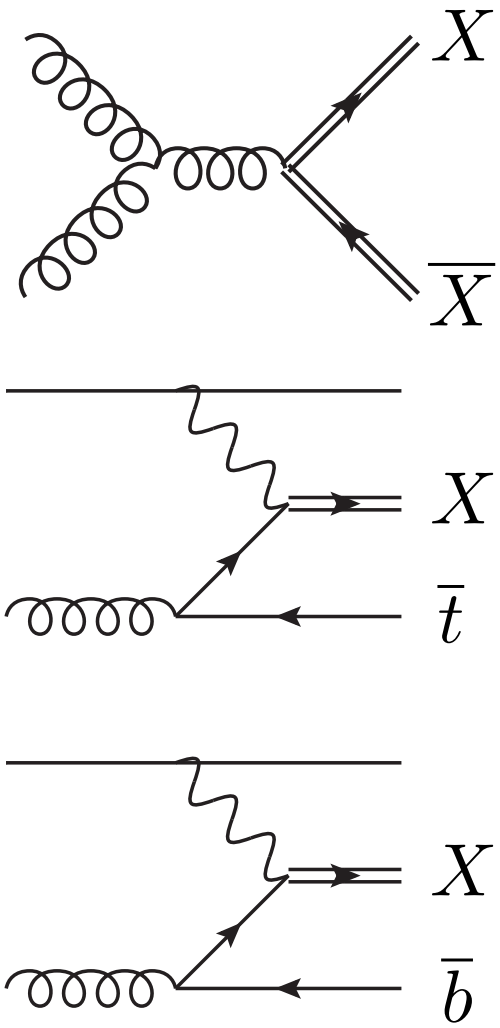

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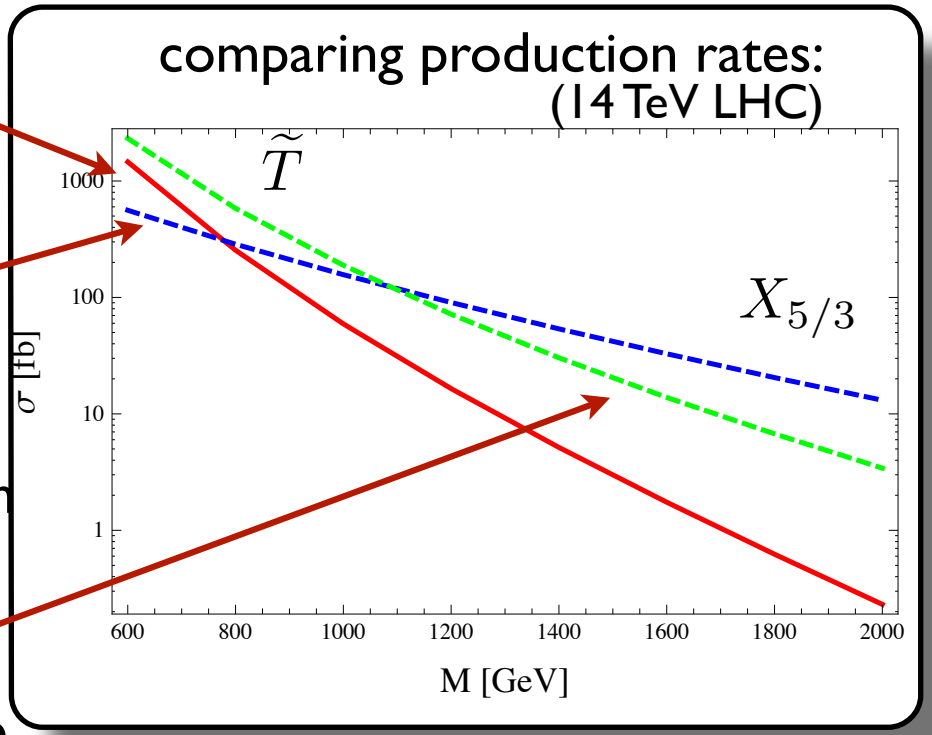

Top Partners at the LHC

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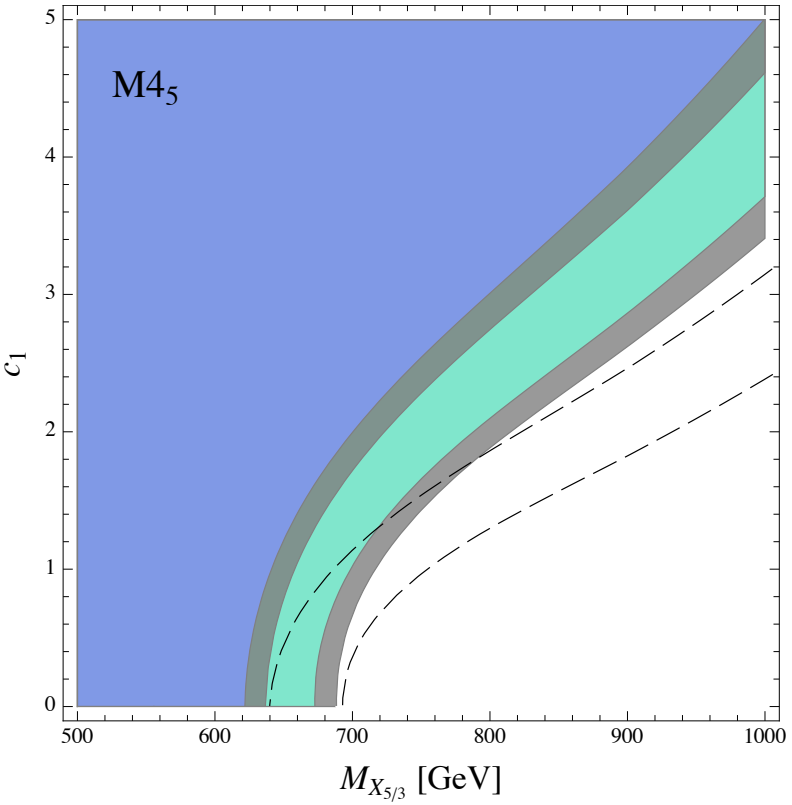
$X_{5/3}$: pair or single+t production, decay to Wt.

Recasting an old CMS b' search we found …

single prod. coupling



Sensitive to $X_{5/3}$ pair and **single**, though not optimised for the latter one

Top Partners at the LHC

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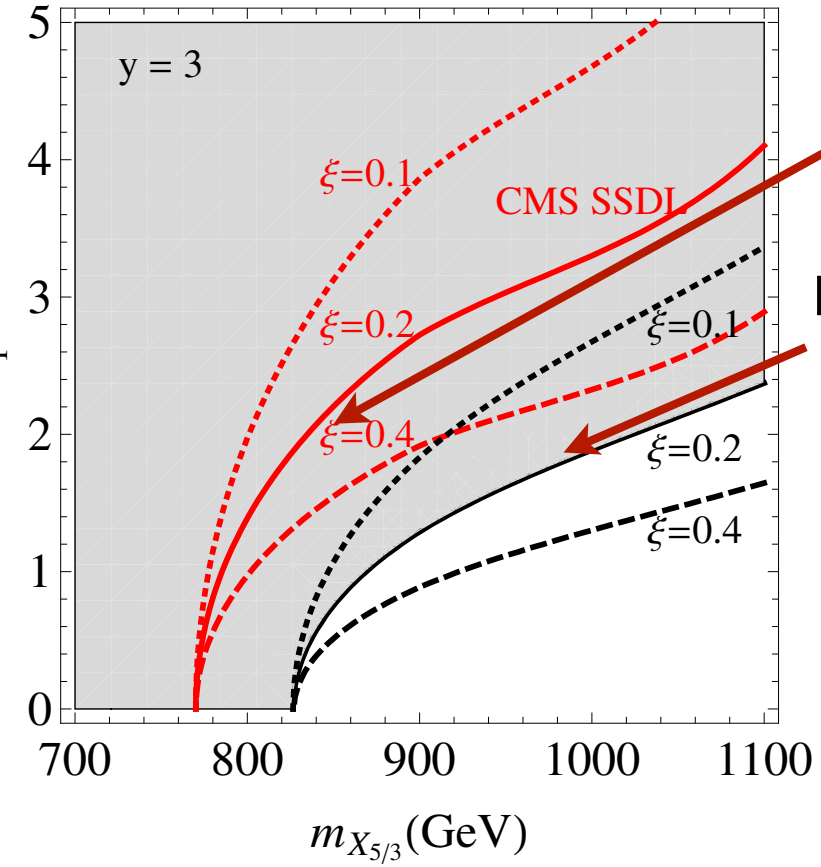
A more recent study
(Azatov, Salvarezza, Son, Spannowsky, 2013)



single prod. coupling

NEW BOUND
(CMS PAS B2G-12-012)

Expected 8 TeV reach by boosted W techniques

CMS is now studying single production, at 8 and 14 TeV. ATLAS?

Top Partners at the LHC

(De Simone, Matsedonsky, Rattazzi, AW, 2012)

$\widetilde{T}$: **dominant single+b** production.

democratic decays

$$BR(tZ) \simeq BR(ht) \simeq 0.5 BR(Wb)$$

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(CMS PAS B2G-12-015)

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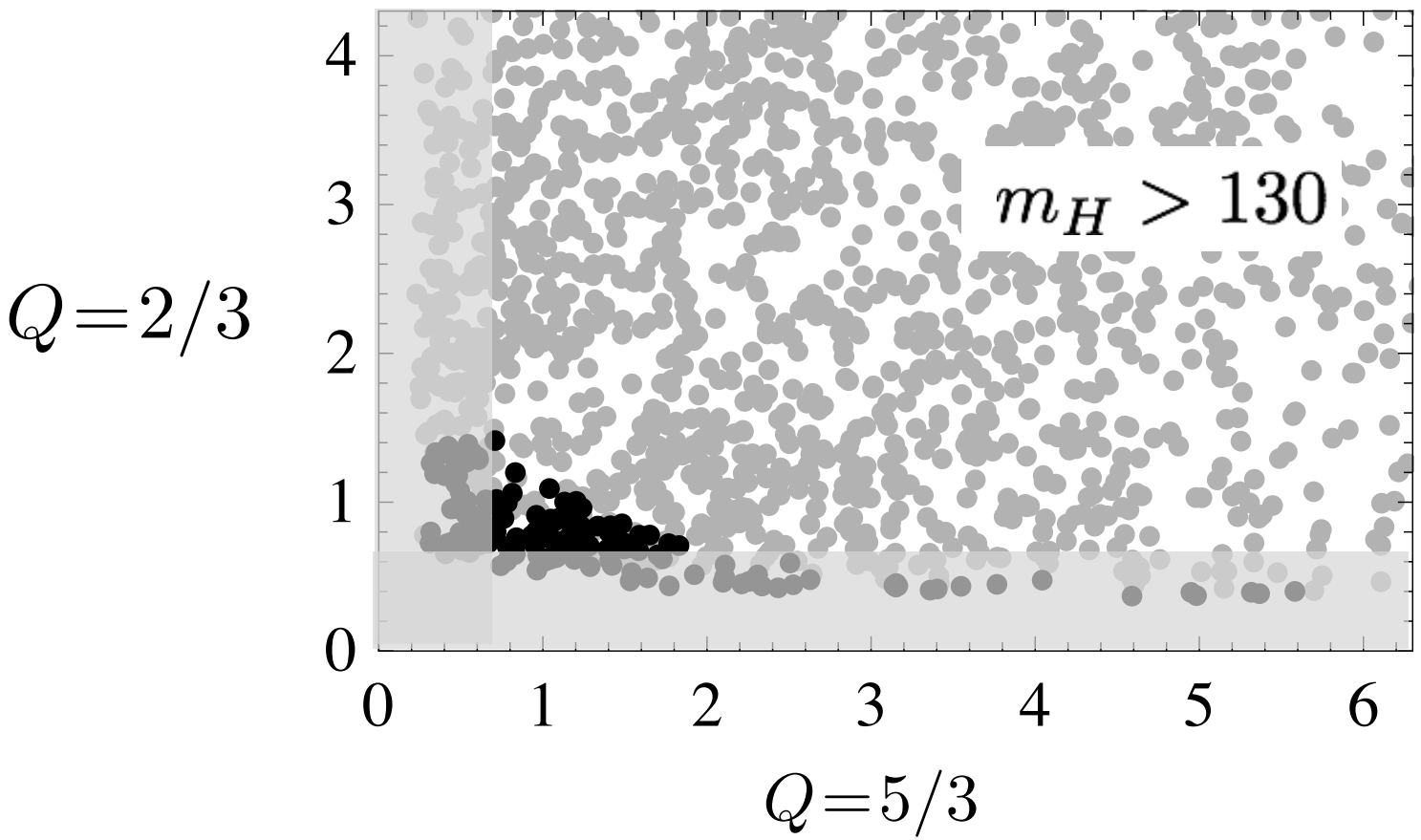
$\widetilde{T}$ searches are **insensitive** to single production.
Better reach need dedicated single production studies.

Top Partners at the LHC

(De Simone, Matsedonsky, Rattazzi, AW, 2012)

Impact on a concrete model (roughly):
(to be refined, work in progress)

$\xi = 0.2$



Top Partners at the LHC

(De Simone, Matsedonsky, Rattazzi, AW, 2012)

Impact on a concrete model (roughly):
(to be refined, work in progress)

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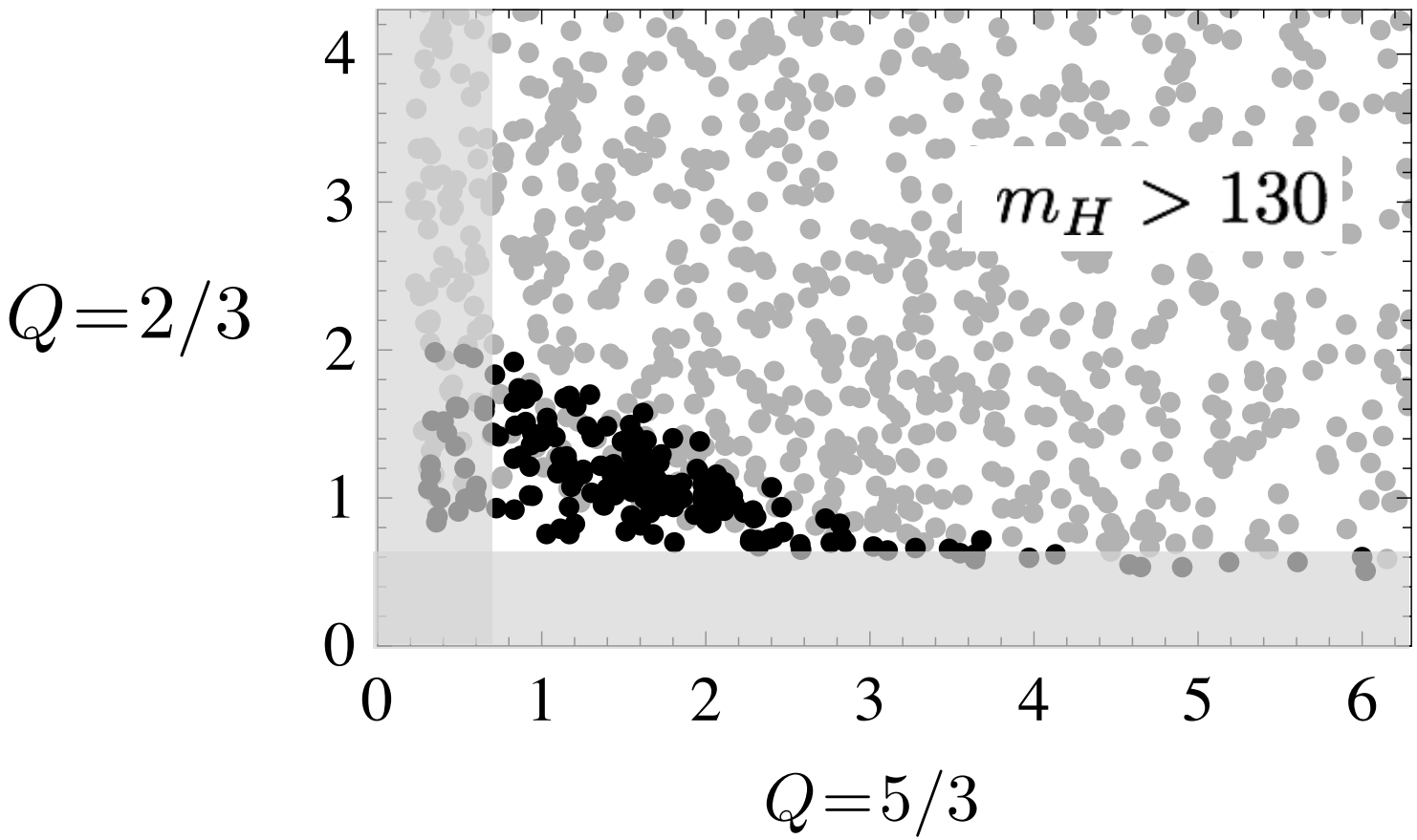

Heavy Vectors

(Pappadopulo, Thamm, Torre, AW, 2014)

A "more direct" direct signature:

$$J_\mu^{SO(4)} = (\mathbf{3},\mathbf{1}) \oplus (\mathbf{1},\mathbf{3})$$

The W partners

Not strongly bounded by Naturalness, by why should they be much heavier than the Top Partners?

Need a model, but which one?

- P.C. models
- H.L.S. approach
- Deconstructed DCHM
- 5d Holographic

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Not the way to go

We construct a "Unified" Simplified Model

Describes **weakly-coupled** V as well (say, sequential W')

Heavy Vectors

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SM triplet with zero Hypercharge: $V^a \to \{V^+, V^-, V^0\}$

$$\mathcal{L}_S = -\frac{1}{4} D_{[\mu} V^a_{\nu]} D^{[\mu} V^{\nu]\, a} + \frac{m_V^2}{2} V^a_\mu V^{\mu\, a}$$
$$+ i\, g_V c_H V^a_\mu H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V^a_\mu J_F^{\mu\, a}$$
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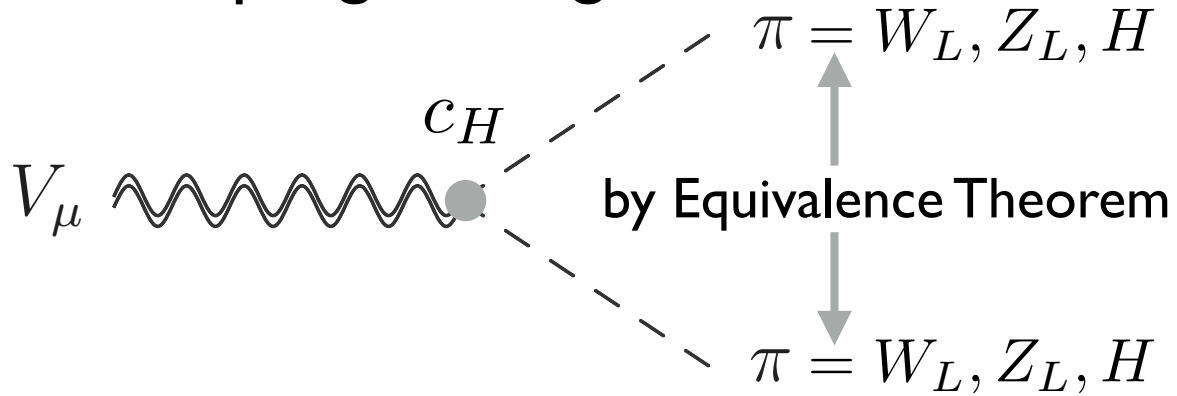
Direct coupling to longitudinal W,Z and Higgs:



Correlated VB and Higgs channels

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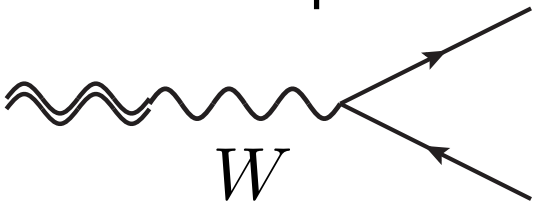
Direct couplings to fermions

partial W compositeness



$$\sim g\, \frac{g}{g_V}$$

Reduced at strong g_V.
Suppress DY production

In general, we consider $c_F \to \{c_l, c_q, c_3\}$

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Indirect effects, after V-W mixing
Typically give **small contributions**,
could be fixed to benchmark values

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For this particular problem, differently from Top Partners, the pNGB nature of the Higgs can be safely ignored for $\xi \lesssim 0.2$

Explicit models can be mapped to different regions of the par. space

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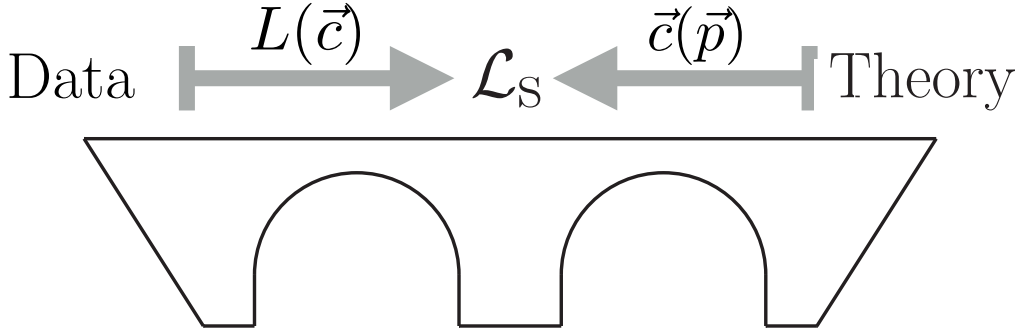

THE BRIDGE METHOD

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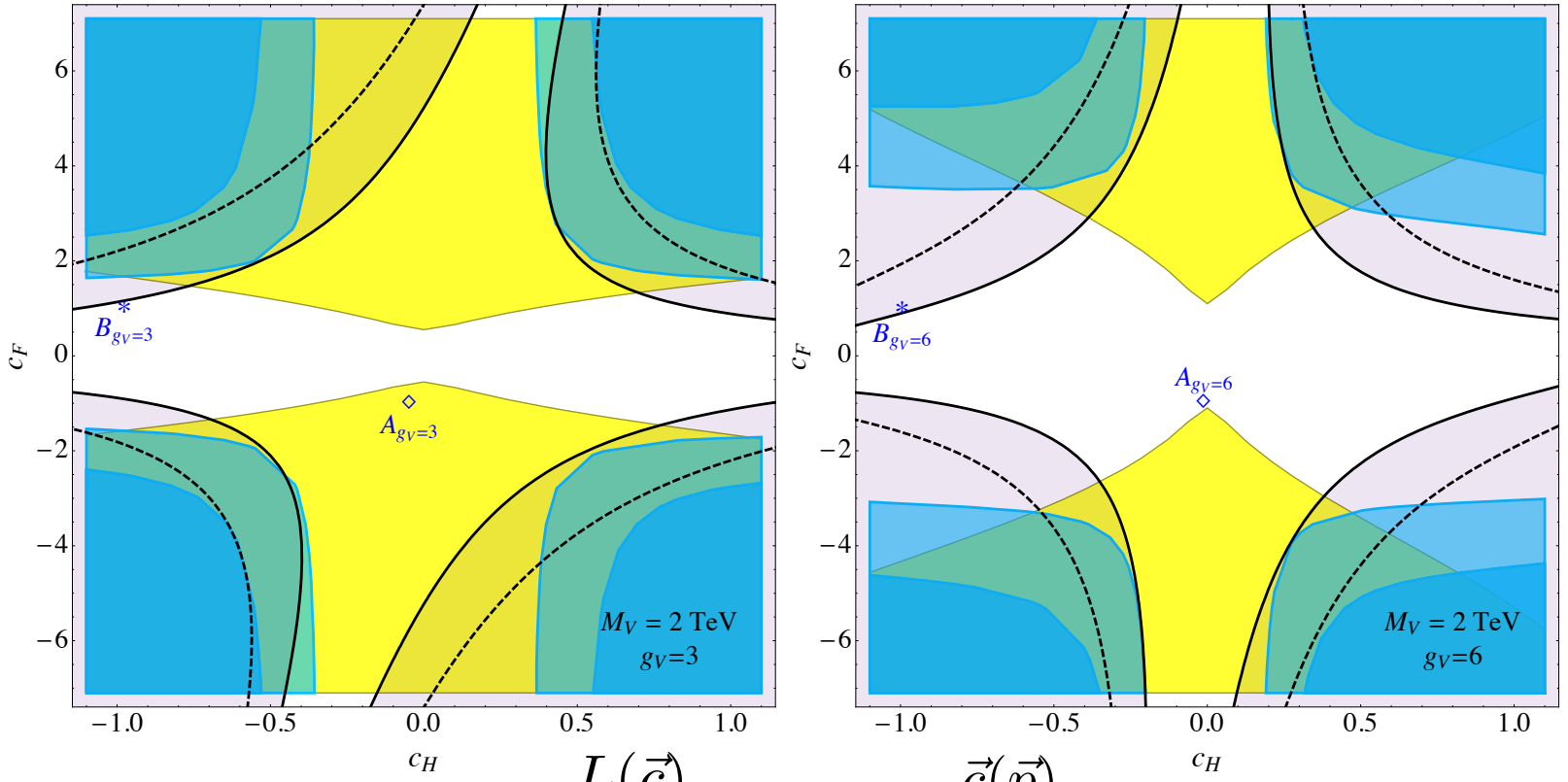

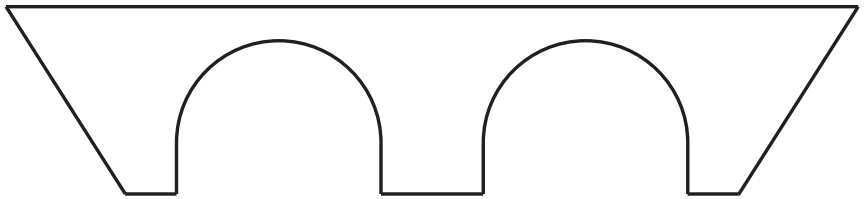

THE BRIDGE METHOD

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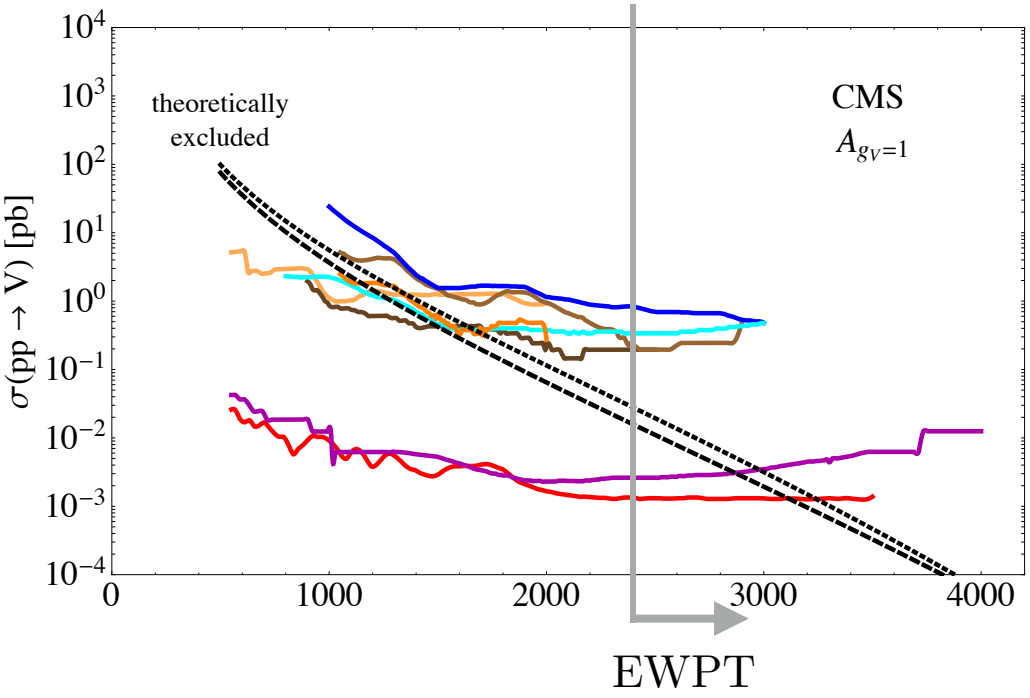
Present limits, rescaled by BR

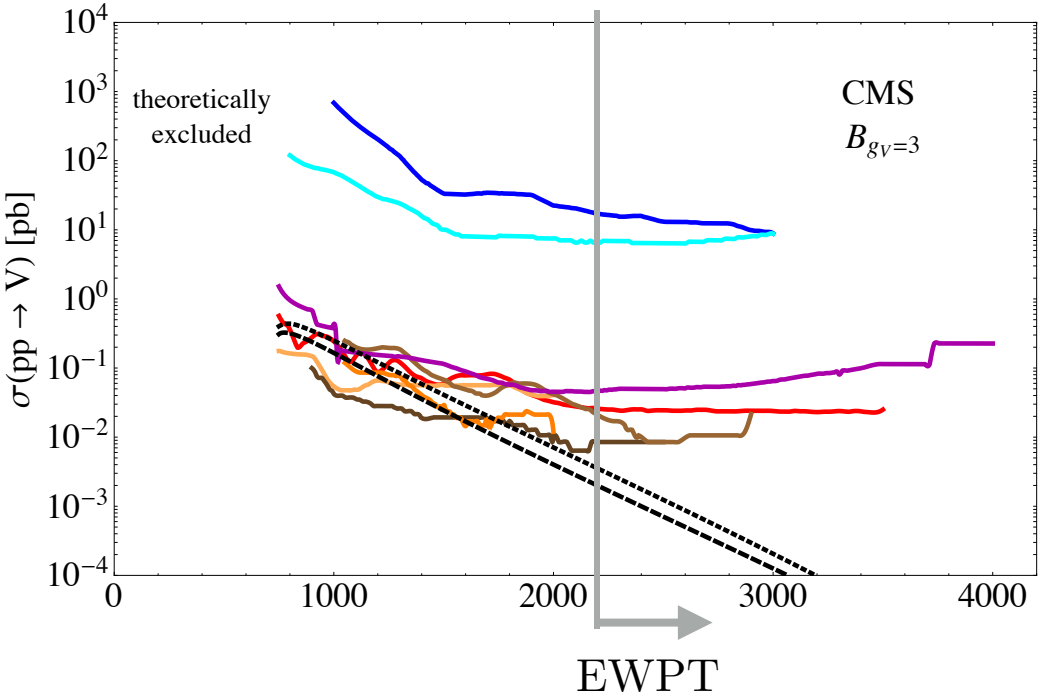
Weak: $g_V = 1$

leptons dominate, ~ 3TeV is excluded



Moderately Strong: $g_V = 3$

competitive dibosons, 1.5 TeV exclusion



Heavy Vectors

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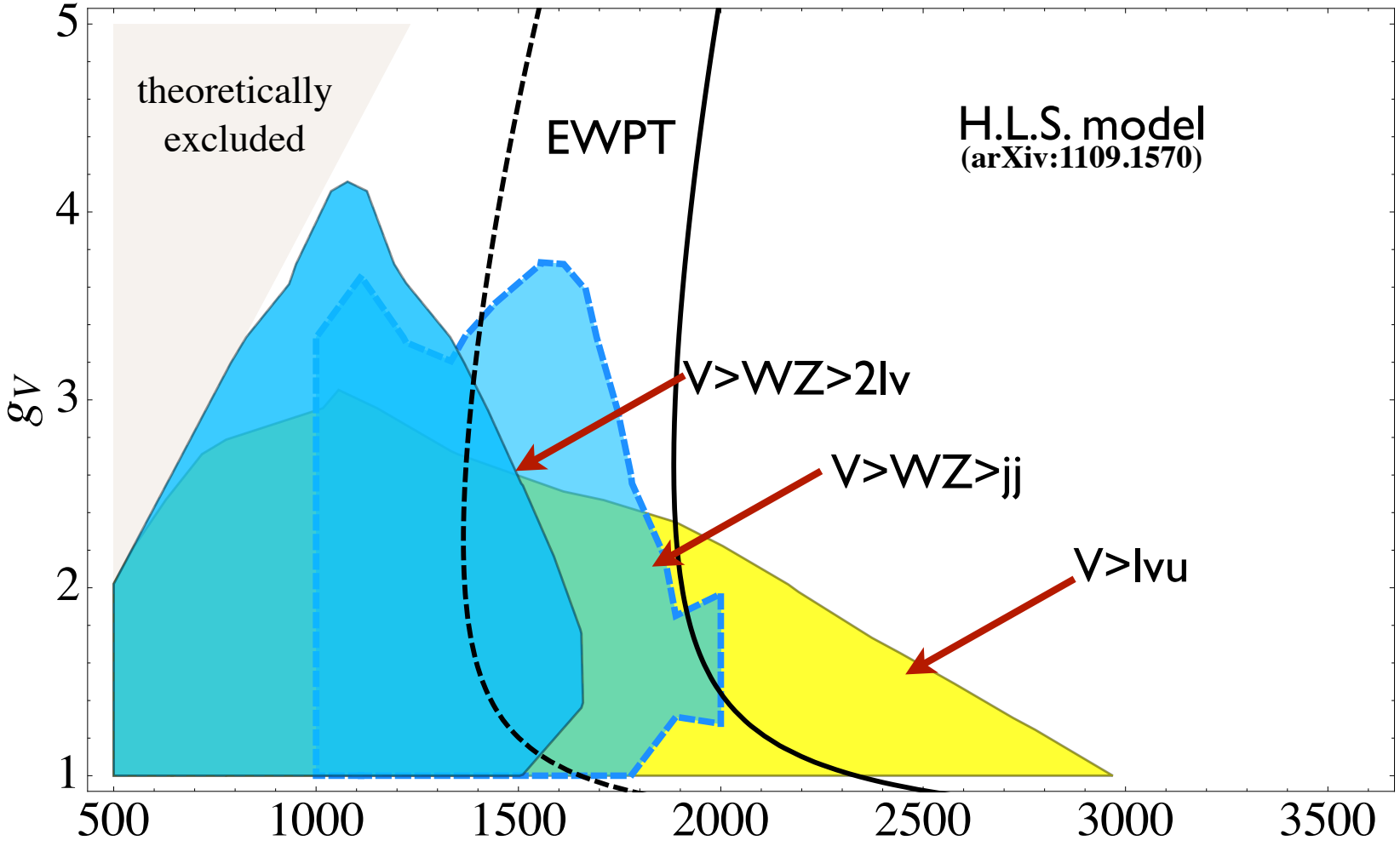
Limits on the W partners:



Conclusions and Outlook

Natural models of EWSB will be tested at the LHC, even a negative result would change our perspective on Fundamental Interactions.

A pNGB Higgs with P.C. could work, robust visible signatures are:

- Higgs couplings modifications (not yet significant)
- Direct observation of Top Partners (already effective)
- Heavy Vectors (we might do 3 or 4TeV at LHC14)

Present data are already probing part of the natural par. space.

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Significant improvements are possible with new channels (for Top.P.) and by combining different channels (for Heavy Vectors).