Composite Higgs
vs
LHC Data

Andrea Wulzer

DIPARTIMENTO
DI FISICA
E ASTRONOMIA
Galileo Galilei

SM or not ?

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"Unveil the Nature of **EWSB** mechanism"

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Higgs-like particle **exists** !

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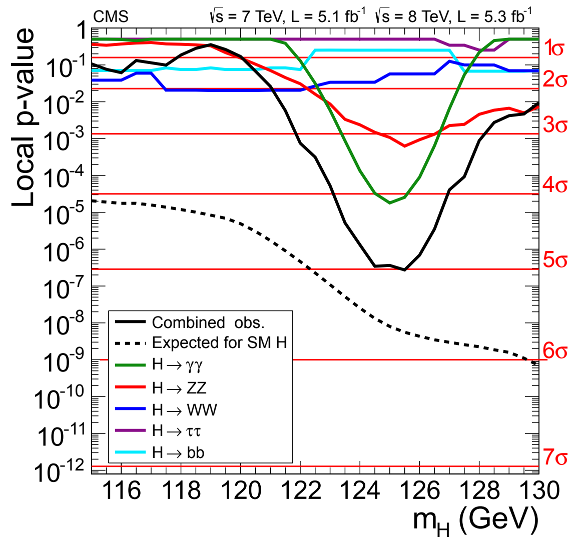

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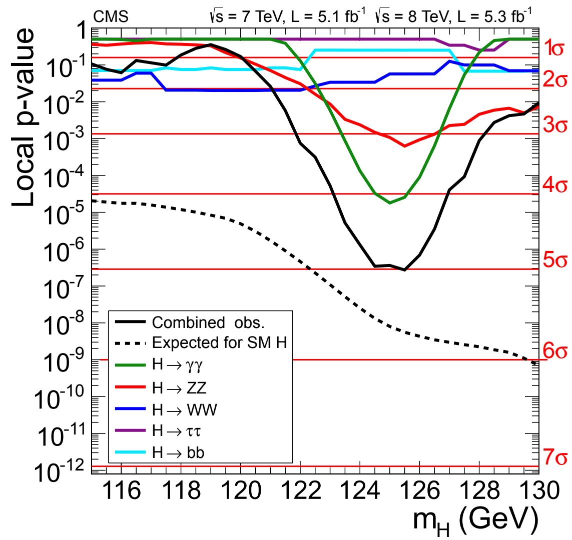


Where is BSM scale $\Lambda_{\rm UV}$?

SM or not ?

Good reasons to guess $\Lambda_{\mathrm{UV}} \gg \mathrm{TeV}$ (e.g ,$10^{16}\mathrm{GeV}$):

- **Accidental Symmetries**
- **Minimal Flavor Violation**

} deviations suppressed by $1/\Lambda_{\mathrm{UV}}^{p}$

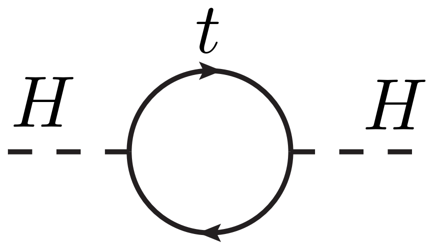
- **Majorana neutrinos (?)** ⟹ $m_\nu \sim v^2/\Lambda_{\mathrm{UV}}$

One reason to expect $\Lambda_{\mathrm{UV}} \sim \mathrm{TeV}$:

The Hierarchy Problem

$$m_H{}^2_{|pole} = c\Lambda_{\mathrm{UV}}^2 + \delta m_H^2$$

$\delta m_H^2 =$



$\simeq -\dfrac{y_t^2}{16\pi^2}\Lambda_{\mathrm{UV}}^2$

SM or not ?

Realistic Higgs requires **tuning** :

$$\Delta \geq \frac{\delta m_H^2}{m^2_{H|_{pole}}} \simeq \left(\frac{125\,\mathrm{GeV}}{m_H}\right)^2 \left(\frac{\Lambda_{\mathrm{UV}}}{400\,\mathrm{GeV}}\right)^2$$

$\Delta \lesssim 100$ ⇒ $\Lambda_{\mathrm{UV}} \lesssim 4\,\mathrm{TeV}$ ⇒ New physics in LHC range

Is Hierarchy a problem of Nature or just a problem of theory ?

LHC data will answer !

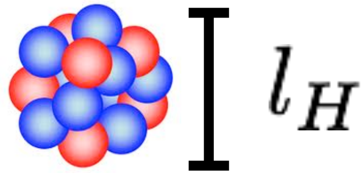
Composite Higgs

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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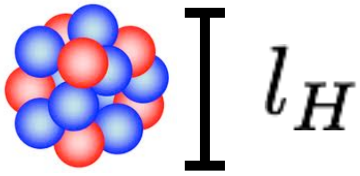

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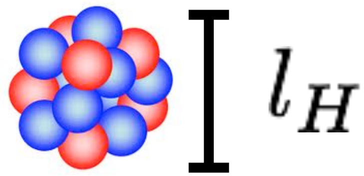

2. Higgs is a **Goldstone Boson**, this is why it is light

3. SM fermions and gauge coupled **linearly** to the strong sector

Composite Sector — Elementary Sector

Higgs + resonances $\longleftrightarrow^{\mathcal{L}_{\text{int}}}$ $W_\mu^{1,2,3},\ B_\mu\ \ f_L,\ f_R$

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

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

Composite Higgs

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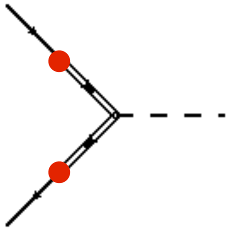
Yukawas : $y_f =$  $\sim \dfrac{y_L y_R}{g_\rho}$

2. Hig

small Yukawas $\Longrightarrow$ small mixing: $y_{L,R} \sim \sqrt{g_\rho y_f}$

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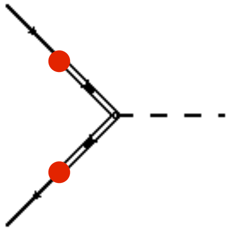
Yukawas : $y_f =$  $\sim \dfrac{y_L y_R}{g_\rho}$

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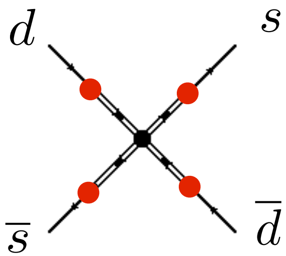
suppressed FCNC : 

$\sim \dfrac{y_L^2 y_R^2}{g_\rho^2} \sim y_d y_s$

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Higgs Couplings

The **Minimal Coset :**

- delivers **one** doublet (4 reals)
- has **custodial** symmetry

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

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

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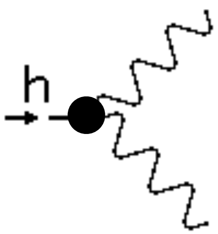
Anomalous couplings from σ-model non-linearities :

$$\mathcal{L}_\pi = \frac{f^2}{4} d^i_\mu d^\mu_i = \frac{1}{2}(\partial h)^2 + \frac{g^2}{4} f^2 \sin^2 \frac{h}{f} \left(|W|^2 + \frac{1}{2c^2_w} Z^2 \right)$$

Higgs-W couplings:



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

deviations from SM controlled by

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

EWPT suggest mild deviations: $\xi \simeq 0.2$ or $\xi \simeq 0.1$.

Higgs Couplings

Higgs-top coupling is more model-dependent

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

We have to specify $\mathrm{SO}(5)$ representations of $\mathcal{O}_{L,R}$

$\mathcal{O}_{L,R} \in \mathbf{4}$ ⇒ MCHM_4

$\mathcal{O}_{L,R} \in \mathbf{5}$ ⇒ MCHM_5

$\mathcal{O}_{L,R} \in \mathbf{10}$ ⇒ MCHM_{10}

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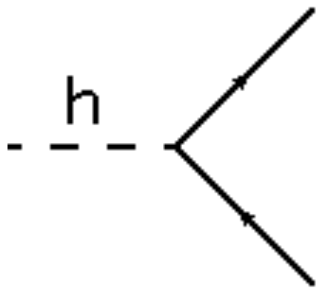
$\mathcal{O}_{L,R} \in \mathbf{4}$ $\Rightarrow$ MCHM_4 $\quad c = \dfrac{1-2\xi}{\sqrt{1-\xi}}$

$\mathcal{O}_{L,R} \in \mathbf{5}$ $\Rightarrow$ MCHM_5 $\quad c = \sqrt{1-\xi}$

$\mathcal{O}_{L,R} \in \mathbf{10}$ $\Rightarrow$ MCHM_{10} $\quad \cdots$

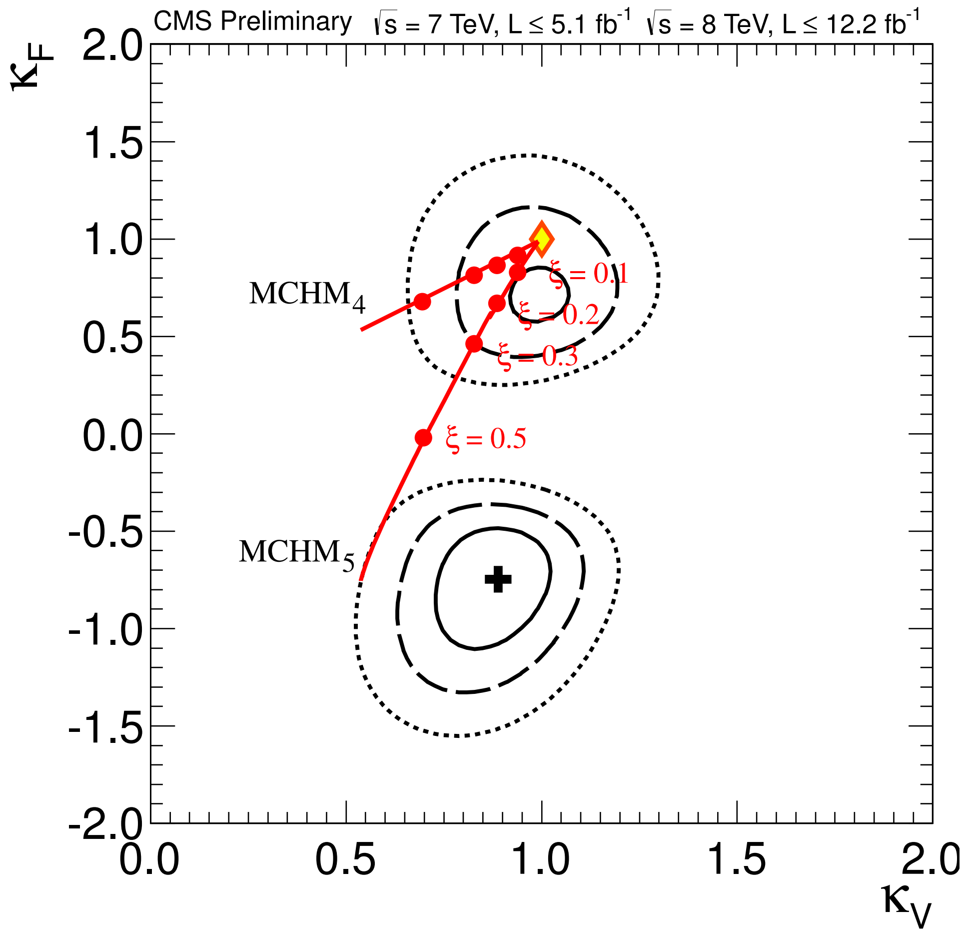


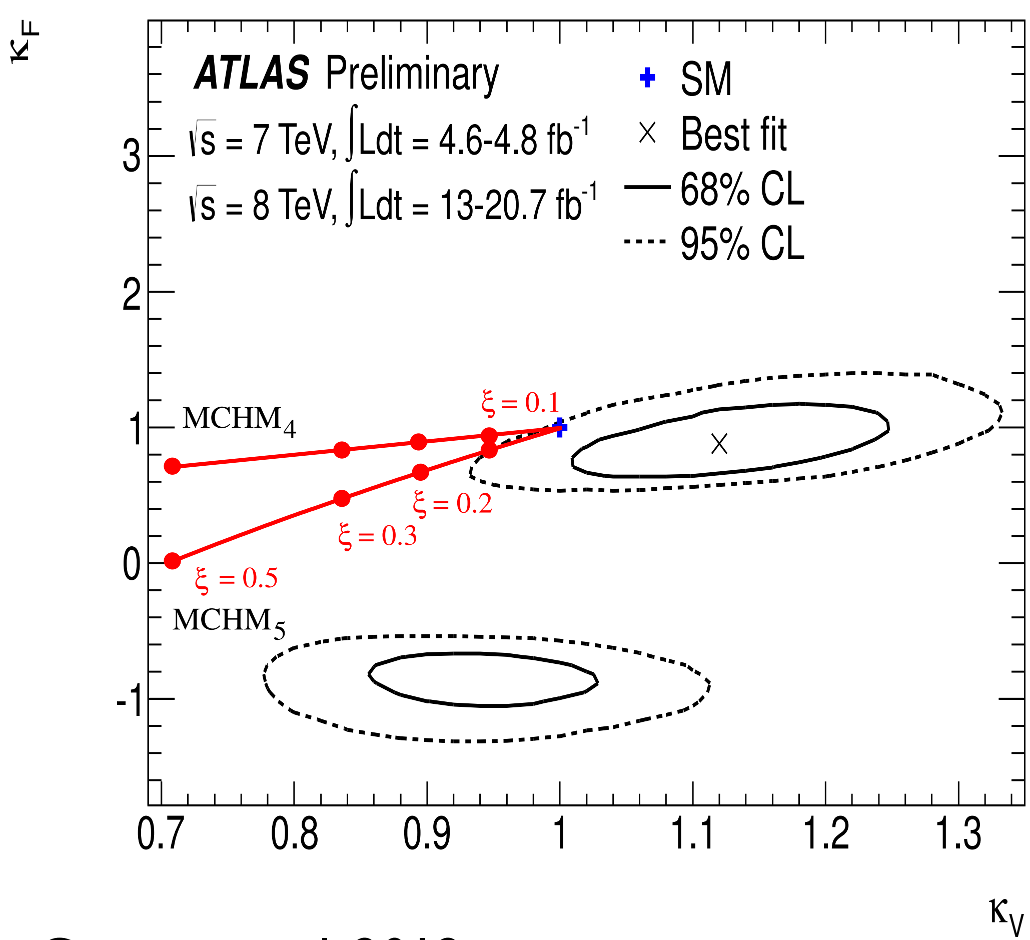
$$= i\,\frac{m_f}{v}\,c$$

Goldstone Boson Higgs

courtesy of G. Panico

Some updated fit:





Refs.: Contino et al., Grojean et al. 2012,
see also talks by C.Delaunay and D.Barducci

Top Partners

Linear interaction is **partial compositeness**:

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

In the IR, operators correspond to particles:

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

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Important Remark:

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

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

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Mass-mixing at low energy:

$$\mathcal{L}_{\rm int} \propto y_L q_L Q_L + y_L q_R Q_R$$

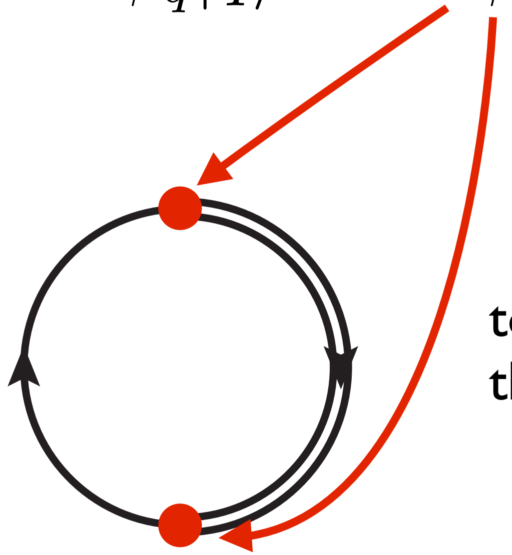
physical particles are **partially composite:**

$$|SM_q\rangle = \cos\phi_q |q\rangle + \sin\phi_q |Q\rangle$$

Top Partners

Elementary/composite mixing breaks Goldstone symmetry.
Thus generates **Higgs potential**. (like pion mass from QED)

$$|SM_q\rangle = \cos\phi_q|q\rangle + \sin\phi_q|Q\rangle$$



top loops dominate because the top is largely composite

Expected connection among **top partners** physics, Higgs mass and VEV

Top Partners

$$\Delta \geq \frac{\delta m_H^2}{m_{H|_{pole}}^2} \simeq \left(\frac{125\,\mathrm{GeV}}{m_H}\right)^2 \left(\frac{\Lambda_{\mathrm{UV}}}{400\,\mathrm{GeV}}\right)^2$$

Top partners cancel top quark divergence $\Rightarrow \quad \Lambda_{\mathrm{UV}} \geq M_T$

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

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Natural SUSY:

light stops

Natural CH:

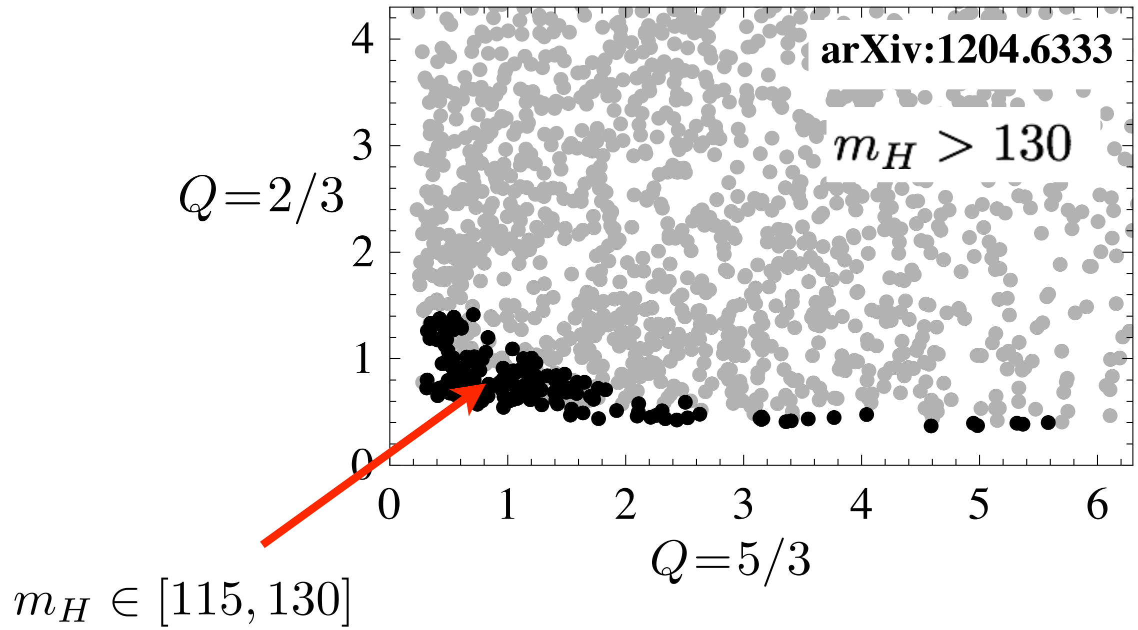
light top partners

Top Partners

Striking Example:

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

$\xi = 0.2$



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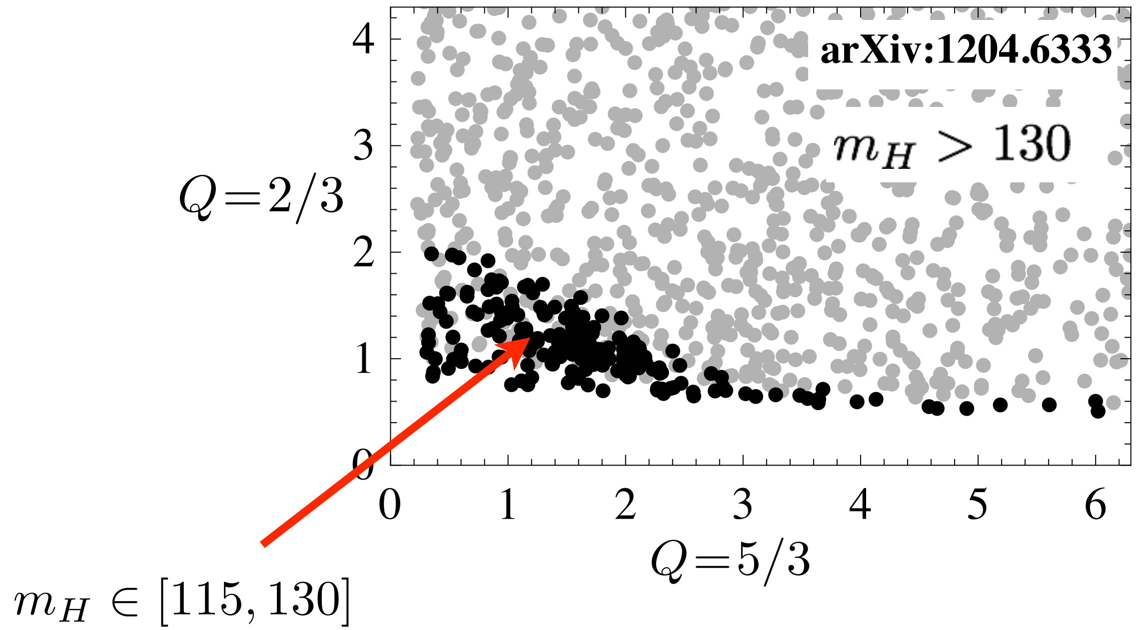

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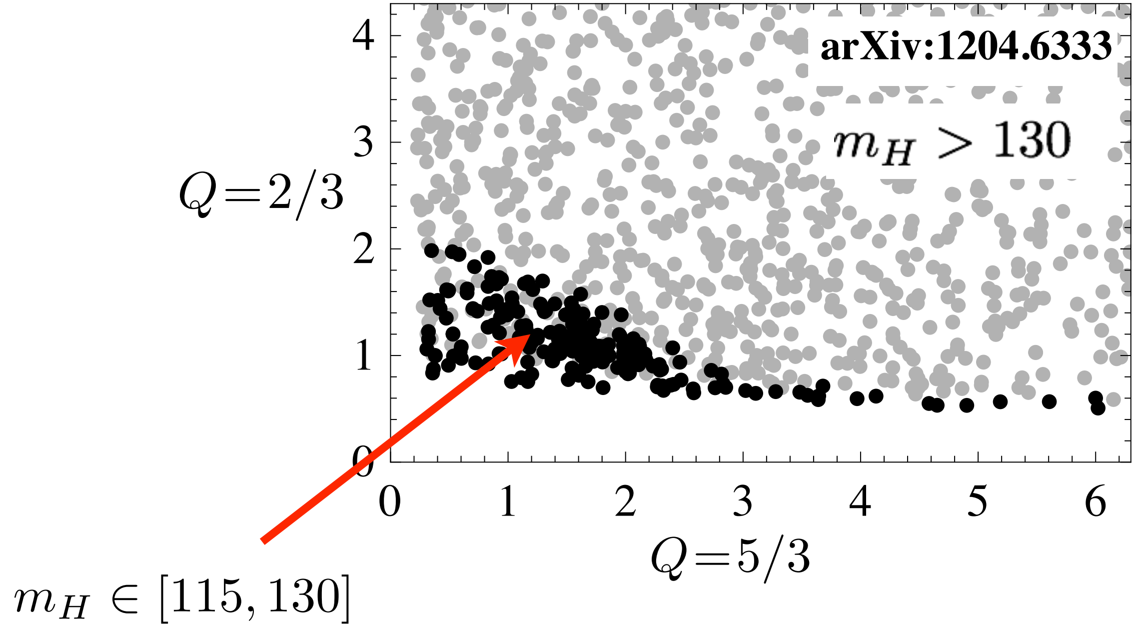


Result confirmed in many ways: Contino et al 2007, Marzocca-Serone 2012 → (see talk by D.Marzocca) Pomarol-Riva 2012

We find the same from general analysis (Panico, Redi, Tesi, AW 2012)

e.g. MCHM_{14}: $\mathcal{O}_L \in \mathbf{14}$ and **composite** t_R

Embedded in promising explicit 5d model (Pappadopulo, Torre, Thamm 2013).
(see talk by A.Thamm)

Top Partners

Top Partners @ LHC studied by several groups:

Contino, Servant 2008
Aguilar-Saavedra 2009
Mrazek, AW 2009
Dissertori, Furlan et al 2010
Barcelo, Carmona et al 2011
Vignaroli 2012
Cacciapaglia et al. 2012/2013
Santiago et al. 2013

(see talk by J.Santiago)

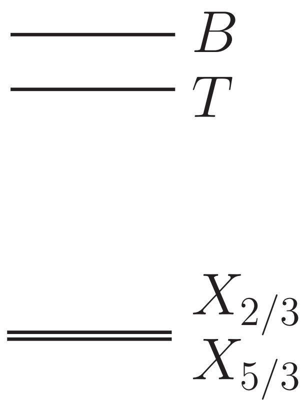
Don’t forget other resonances
(see talk by A.Kaminska)

Top Partners at the LHC

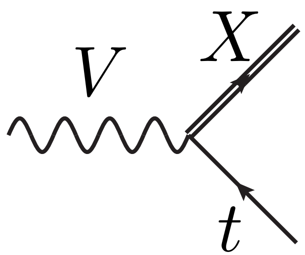
(De Simone, Matsedonsky, Rattazzi, AW, 2012 **arXiv:1211.5663**)

Case #1, **fourplet** of custodial $\mathrm{SO}(4)$ $\begin{pmatrix} T & X_{5/3} \\ B & X_{2/3} \end{pmatrix}$

Spectrum:



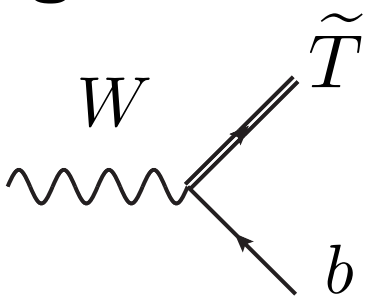
Couplings:



$\sim M_X/f$

because Goldstones are derivatively coupled

Case #2, **singlet** of custodial $\mathrm{SO}(4)$ $\widetilde{T}$



sizable coupling to bottom quark

Top Partners at the LHC

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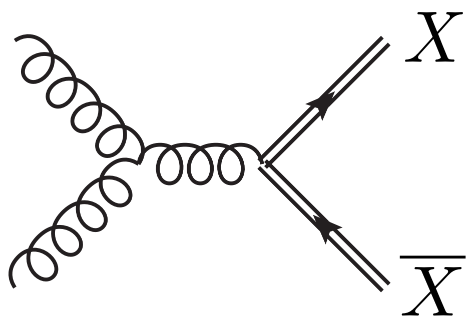
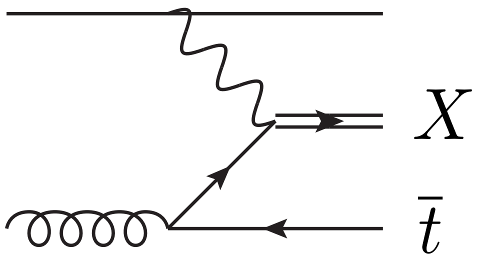
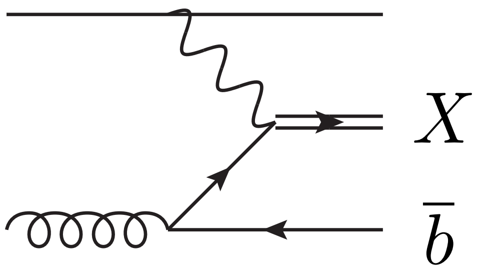
Three possible production mechanisms



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



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



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

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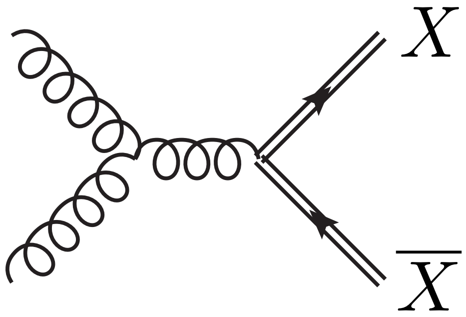

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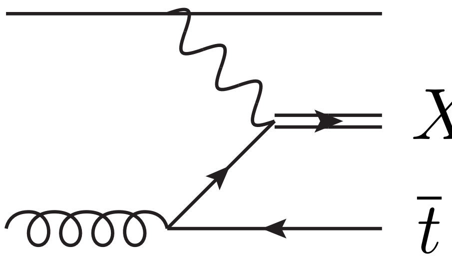

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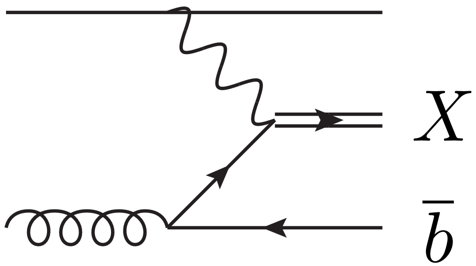

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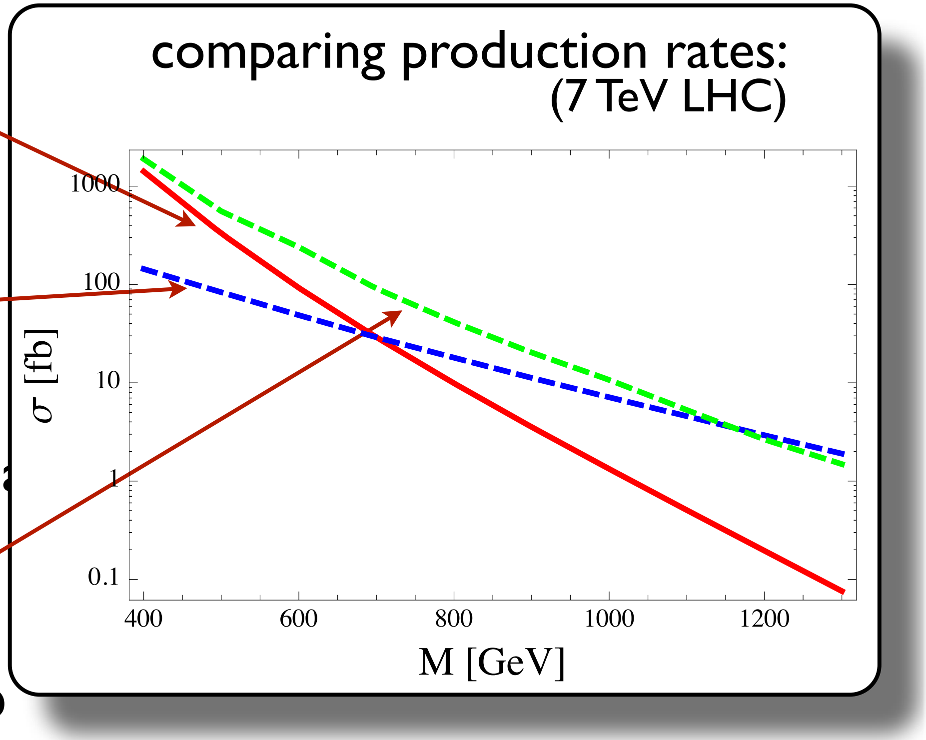


Top Partners at the LHC

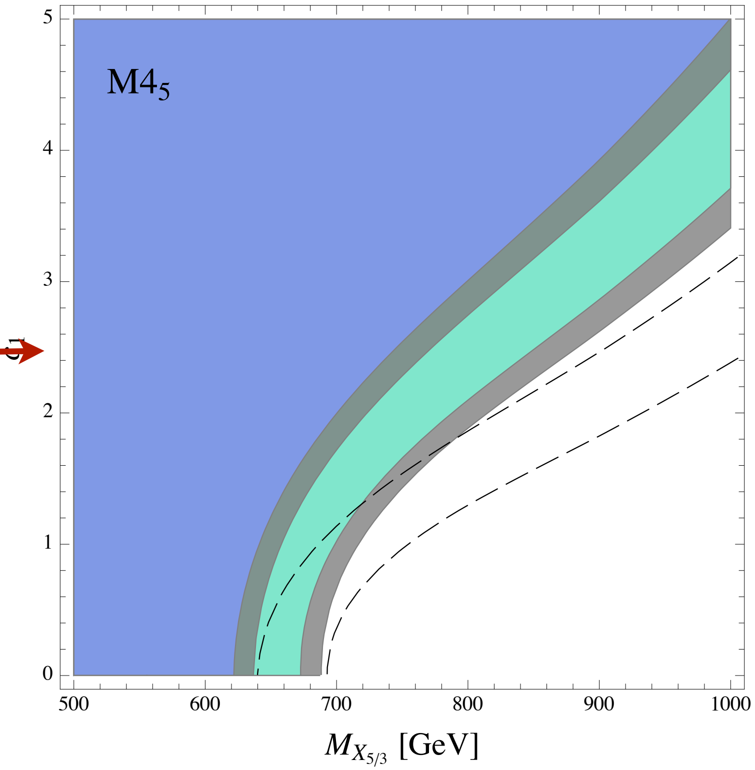
(De Simone, Matsedonsky, Rattazzi, AW, 2012 **arXiv:1211.5663**)

Example I: recasting the CMS b’ search

(CMS-PAS-EXO-11-036)

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

single prod. coupling

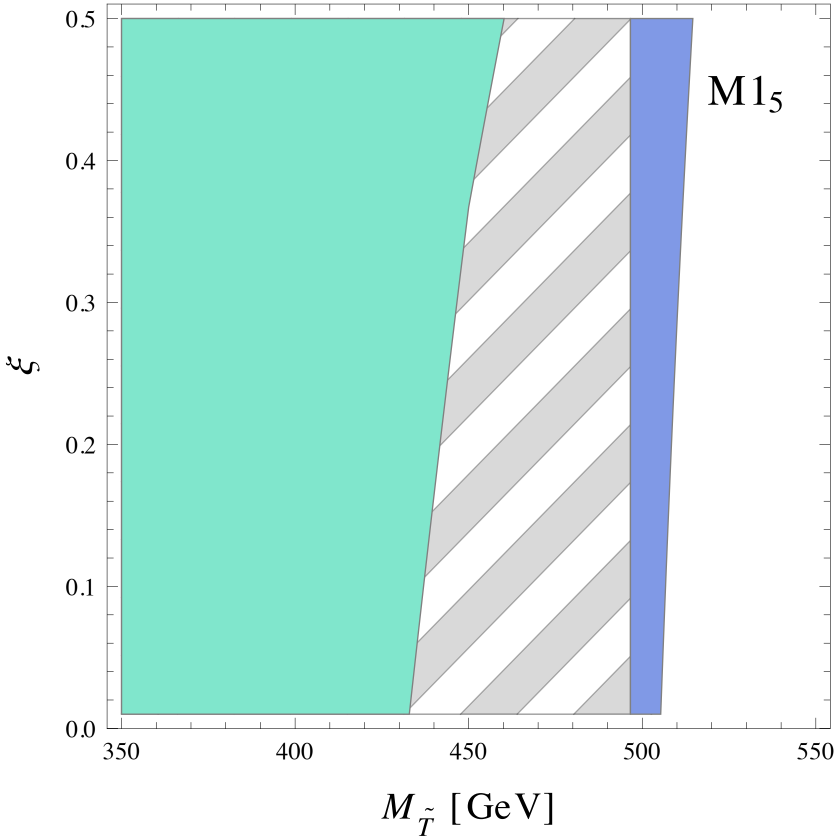


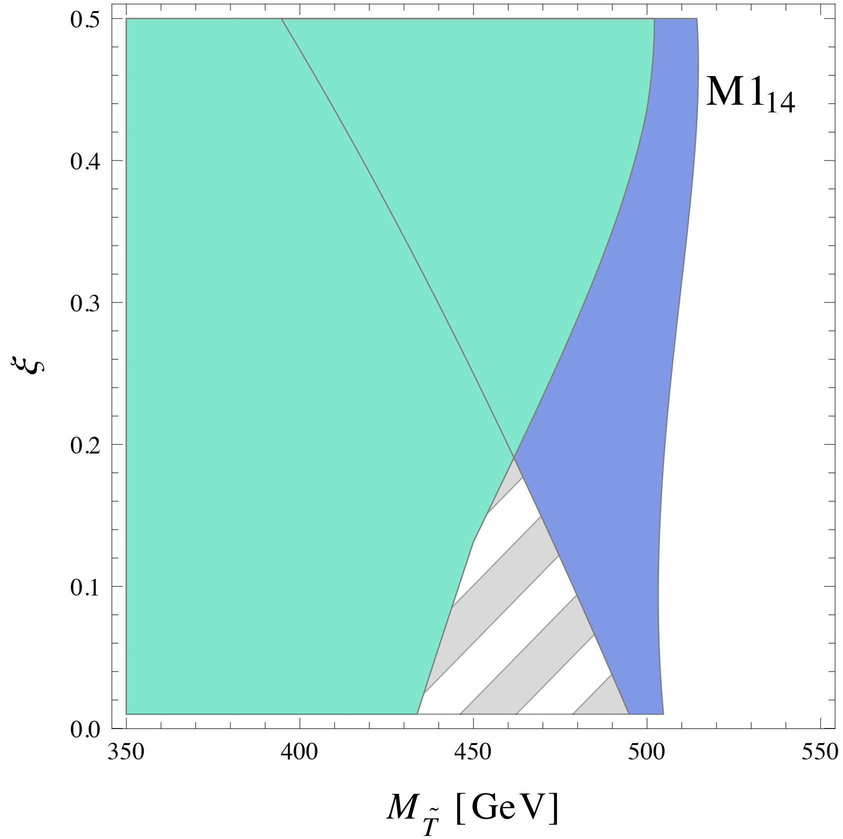
Significant improvement of the bound from single production

Top Partners at the LHC

(De Simone, Matsedonsky, Rattazzi, AW, 2012 **arXiv:1211.5663**)

Bounds on $\widetilde{T}$:



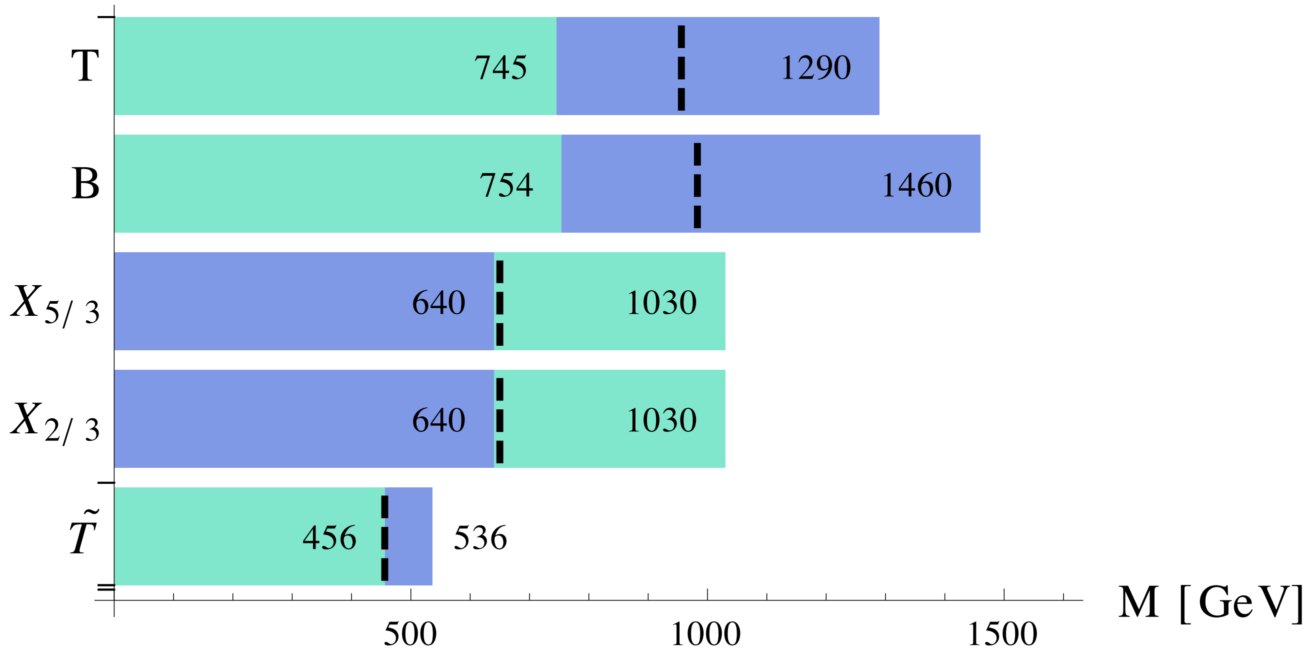


Weaker because current searches are not sensitive to sing. prod with b

Top Partners at the LHC

(De Simone, Matsedonsky, Rattazzi, AW, 2012 **arXiv:1211.5663**)

Present searches test already part of the natural par. space



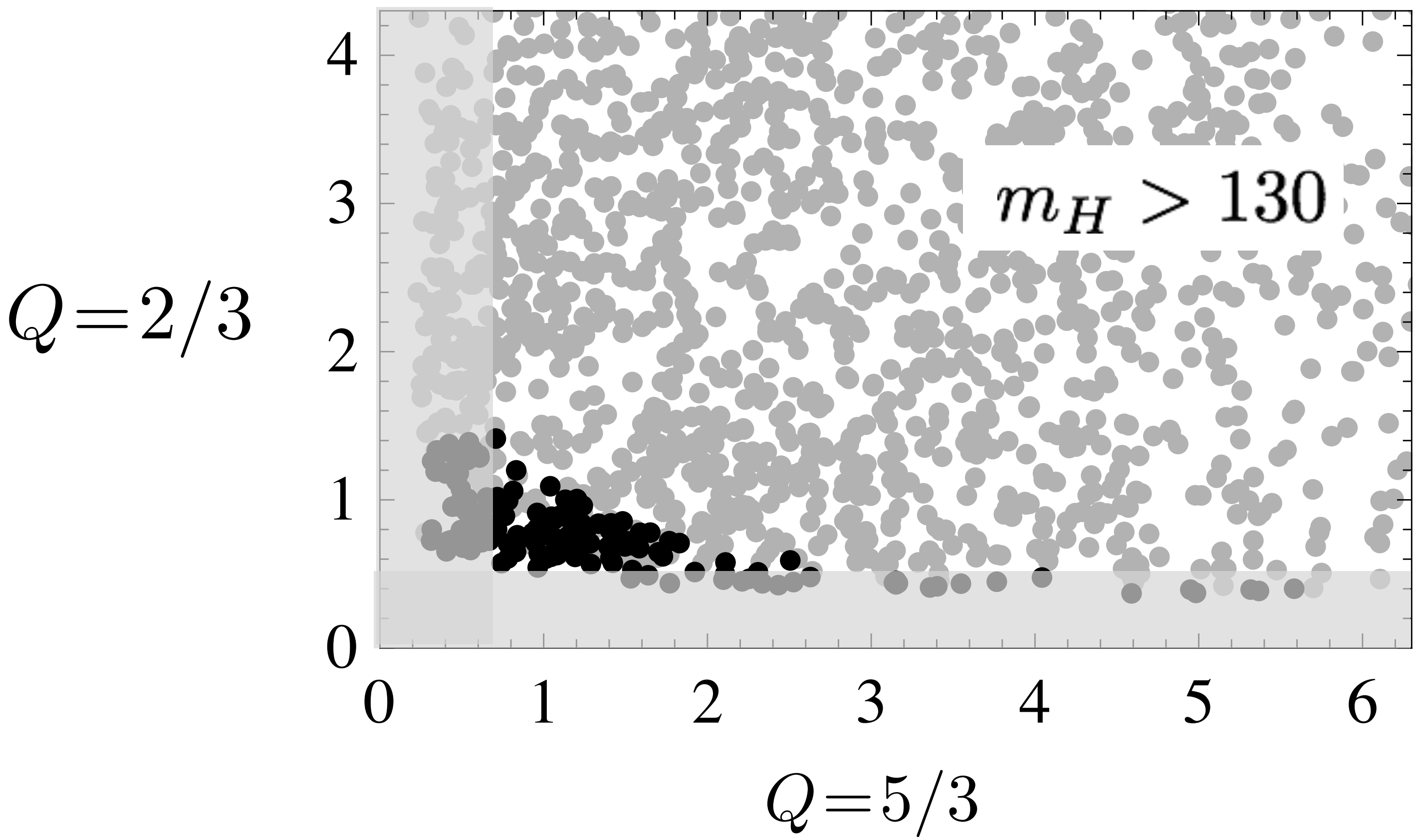
However some tuning was expected already from EWPT

Top Partners at the LHC

(De Simone, Matsedonsky, Rattazzi, AW, 2012 **arXiv:1211.5663**)

Impact on a concrete model (roughly):

$$\xi = 0.2$$



Top Partners at the LHC

(De Simone, Matsedonsky, Rattazzi, AW, 2012 **arXiv:1211.5663**)

Impact on a concrete model (roughly):

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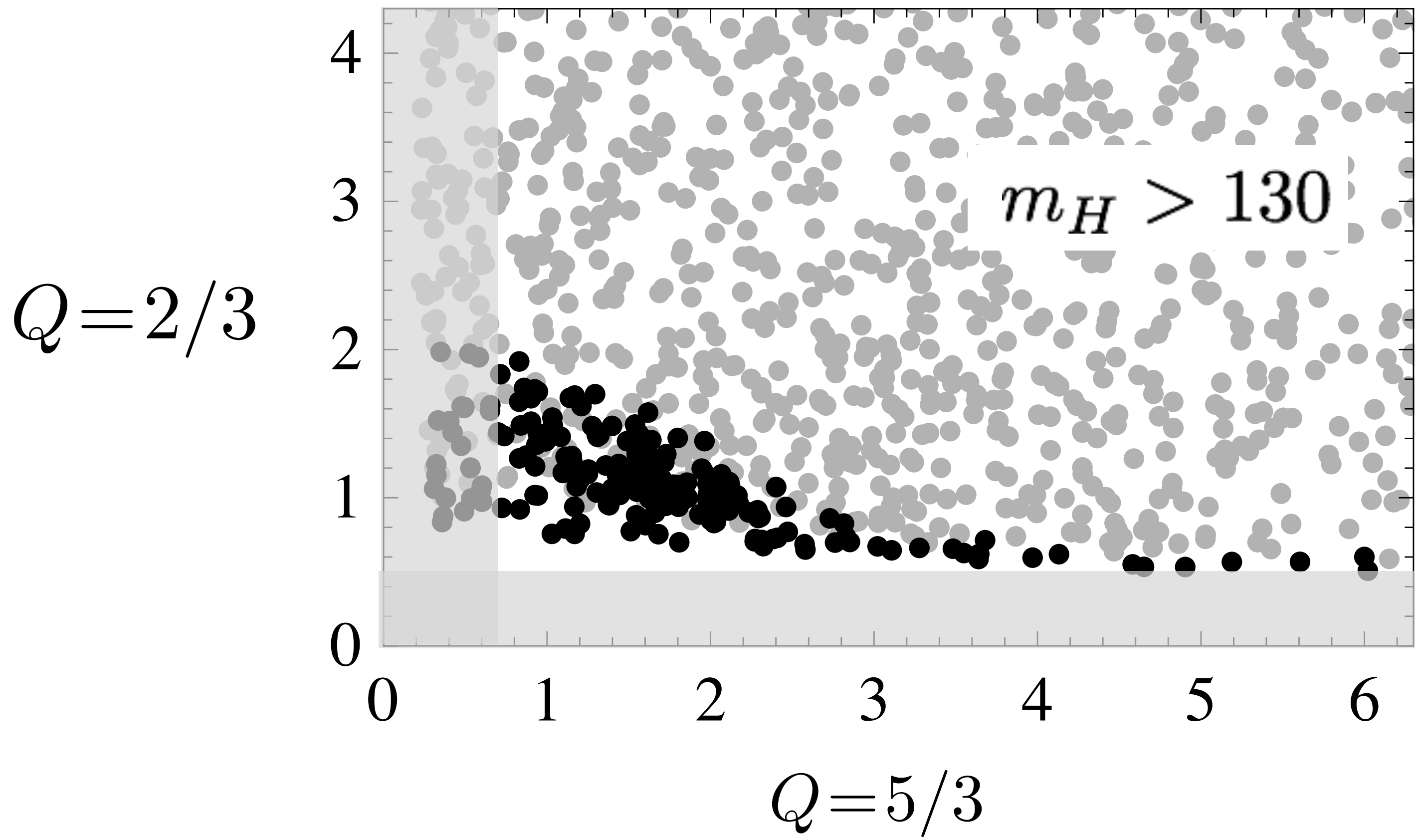

Conclusions and Outlook

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 (difficult)
- Direct observation of Top Partners (simpler)

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

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

Top partner searches are still at a primitive stage, needs work from both the th. and exp. community.

Many aspects of model-building understood only recently, further thinking might lead to further surprises

Effects of top partners on EWPT needs to be reassessed

(see talk by O. Matsedonski)