Composite Higgs
vs
LHC Data

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SM or not ?

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

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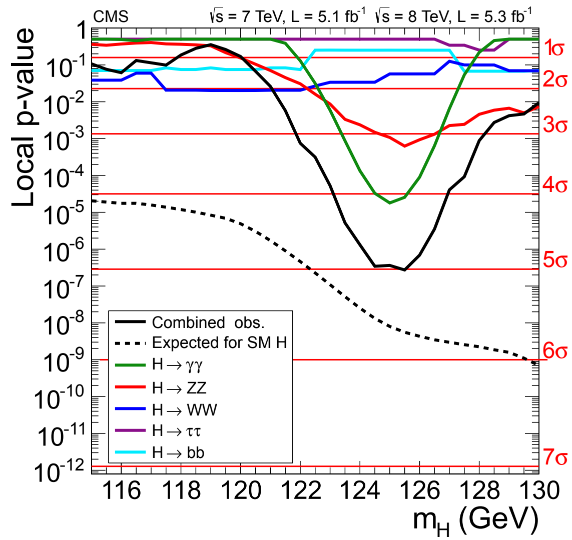
First step taken on 07/04/2012:

Higgs-like particle **exists** !

$$m_h \simeq 125\text{GeV}$$



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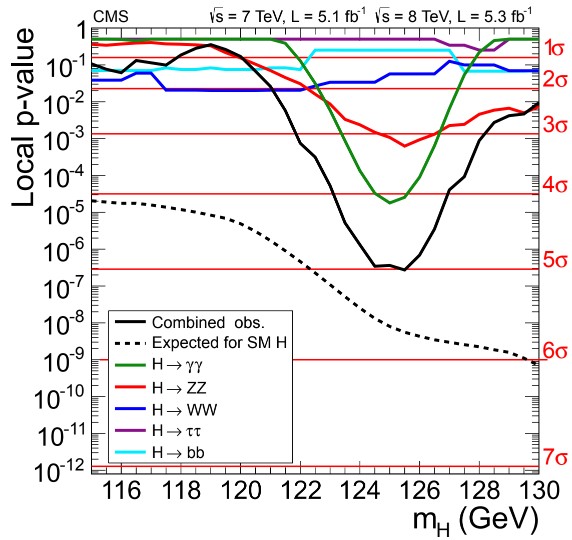


Where is BSM scale $\Lambda_{\rm UV}$?

SM or not ?

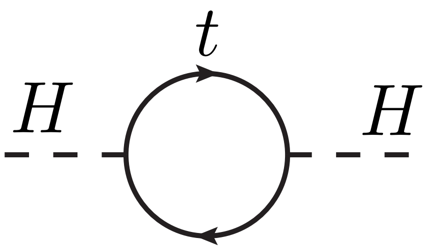
Good reasons to guess $\Lambda_{\rm UV} \gg {\rm TeV}$ (e.g ,$10^{16}{\rm GeV}$):

- **Accidental Symmetries**
- **Flavor**
- **Majorana neutrinos (?)**

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

The Hierarchy Problem

$$\delta_{\rm UV} m_H^2 = c\,\Lambda_{\rm UV}^2 \gg m_H^2$$



from top loops we estimate:

$$c \gtrsim \frac{3 G_F m_t^2}{\sqrt{2}\pi^2} \simeq 0.1$$

SM or not ?

Option #1, "**just** the **SM**": $\Lambda_{\rm UV}{\sim}10^{16}{\rm GeV}$, **huge tuning**

$$\Delta = \frac{\delta_{\rm UV} m_H^2}{m_H^2} \gtrsim \left(\frac{\Lambda_{\rm UV}}{400\,{\rm GeV}}\right)^2 \sim 10^{27}$$

Option #2, "**natural BSM**": $\Lambda_{\rm UV}{\sim}{\rm TeV}$, **moderate** tuning

$\Delta = 1$: BSM at $\Lambda_{\rm UV} \sim 400{\rm GeV}$

$\Delta = 100$: BSM at $\Lambda_{\rm UV} \sim 4{\rm TeV}$

} in LHC range

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

LHC data will answer !

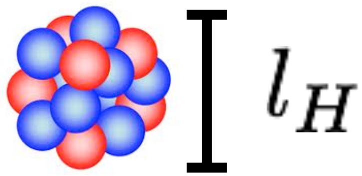
Composite Higgs

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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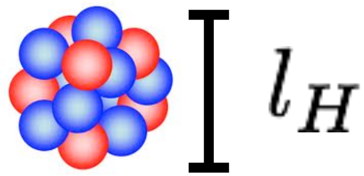

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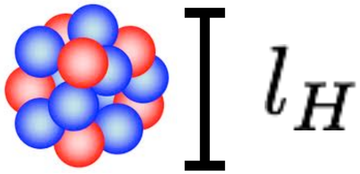

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Indirect effects from sigma-model couplings

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 $gg \to hh$

Not easy to see with present data

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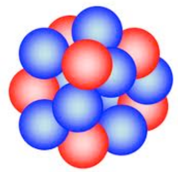

l_H

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

Composite Sector | Elementary Sector

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

gauge couplings: $\mathcal{L}_{\rm int} \propto g_W \rho_\mu W^\mu$

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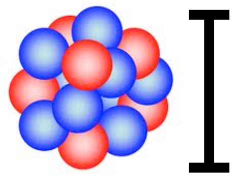

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fermion partners, among which, the **top partners**

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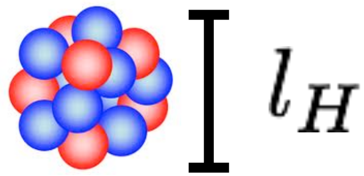

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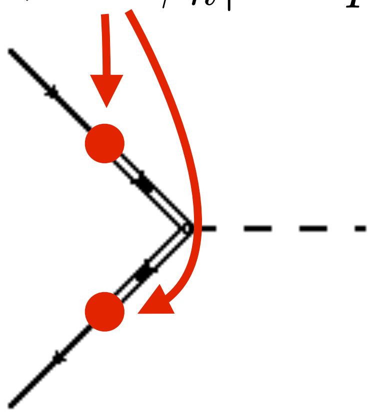
Linear coupling = **partial compositeness**:

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

PC generates **Yukawas** ...

$y_f =$



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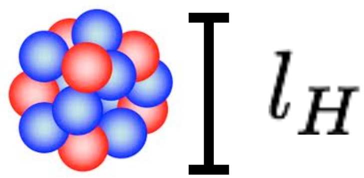

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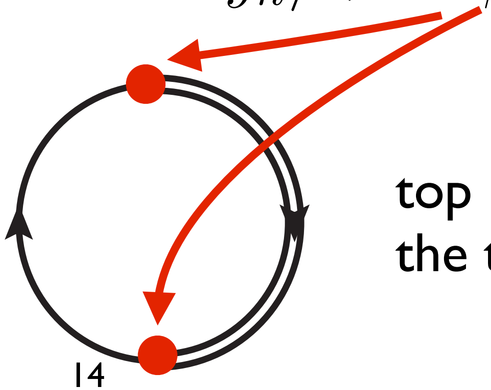
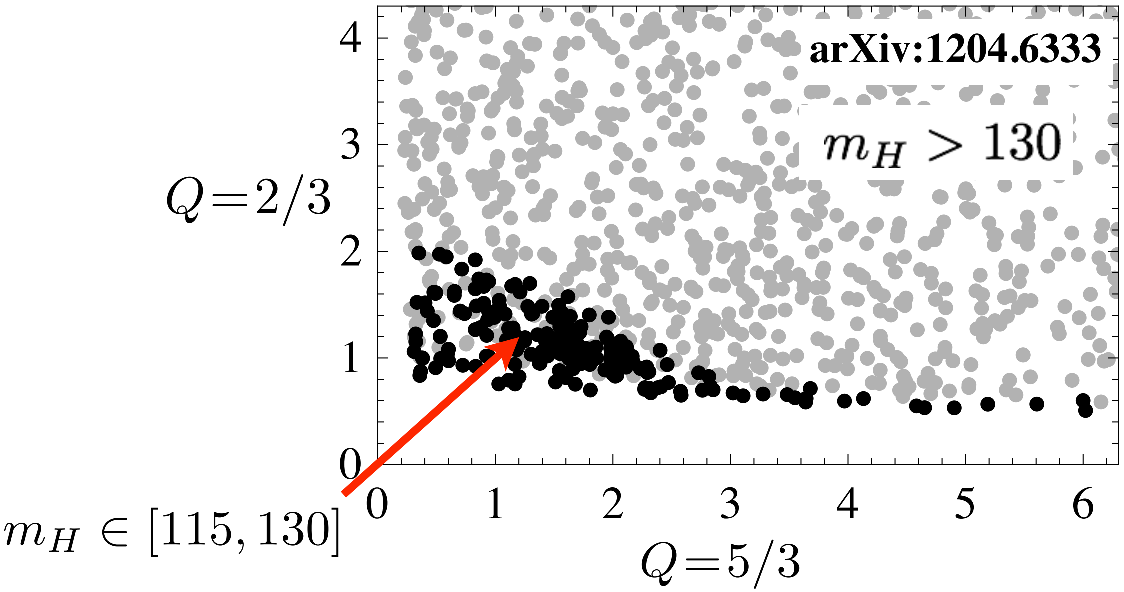


top loops dominate because the top is largely composite

Composite Higgs

Striking Higgs/top partners correlations in $\mathrm{MCHM}_{4,5,10}$



Light Higgs
wants
Light Partners

Contino et al 2007,
Matsedonski-Panico-AW 2012
Marzocca-Serone 2012
Pomarol-Riva 2012

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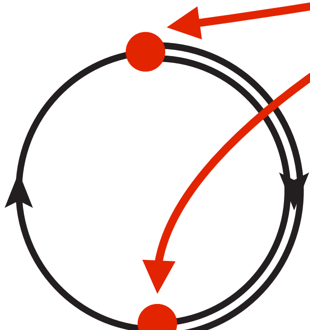

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Composite Higgs

In general, taking Higgs mass into account:

(Panico, Redi, Tesi, AW 2012 **arXiv:1210.7114**)

Low Tuning requires **Light Partners**

Simple reason for this:

$$\Delta \gtrsim \left(\frac{\Lambda_{\rm UV}}{400\,{\rm GeV}}\right)^2$$

Top partners cut off quadratic div., thus $\Lambda_{\rm UV} = M_{\rm partners}$

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A bound on the partners is a bound on the tuning.
If too high, we are left with "unnatural" SM

Natural SUSY:

light stops

Natural CH:

light top partners

Composite Higgs

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

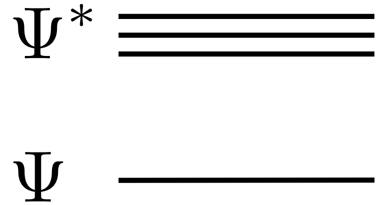
Benchmark Models

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

We consider a **totally composite top right**

We make minimal assumptions on the composite sector
(e.g., min. coset, part. comp., ...)

We derive the **most general** top-p. Lagrangian
(rigorous for **large separation**)



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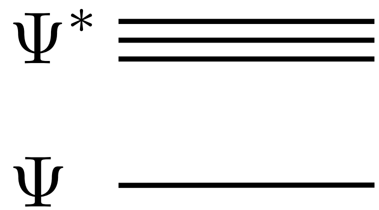

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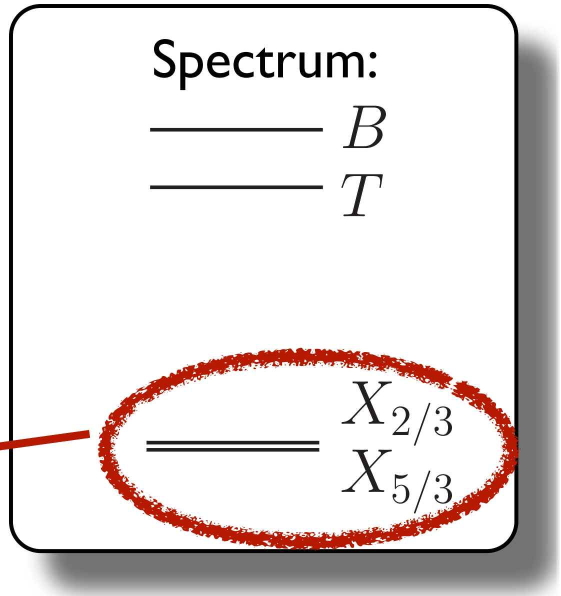
Case #1, **fourplet** of custodial $\mathrm{SO}(4)$

$$\begin{pmatrix} T & X_{5/3} \\ B & X_{2/3} \end{pmatrix}$$

two colored vect.like doublets
one exotic charge state



focus on these ones

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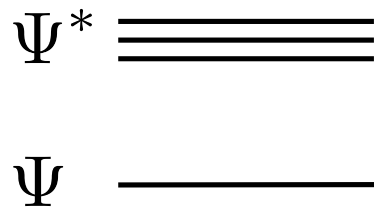

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two models, to asses dependence on mixing quantum numbers

$$\mathbf{M4_5} \quad \mathscr{L}^{\mathbf{M4_5}} = i\,\bar q_L \not{D}\, q_L + i\,\bar t_R \not{D}\, t_R + i\,\bar\Psi(\not{D}+i\not{e})\Psi - M_\Psi \bar\Psi\Psi$$
$$+ \Big[i\,c_1\,\big(\bar\Psi_R\big)_i\,\gamma^\mu d^i_\mu\, t_R + y f\,(\overline{Q}^{\mathbf{5}}_L)^I U_{I\,i}\,\Psi^i_R + y\,c_2 f\,(\overline{Q}^{\mathbf{5}}_L)^I U_{I\,5}\,t_R + \mathrm{h.c.}\Big]$$

four free parameters, c's of order one, $y \sim y_t \simeq 1$

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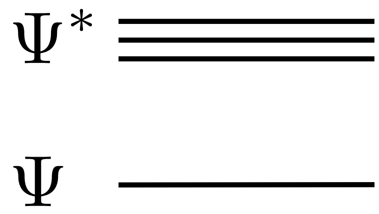

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Case #2, **singlet** of custodial $\mathrm{SO}(4)$

$\widetilde{T}$ colored vector-like singlet with charge 2/3

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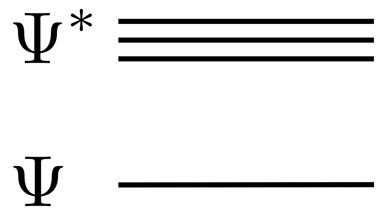

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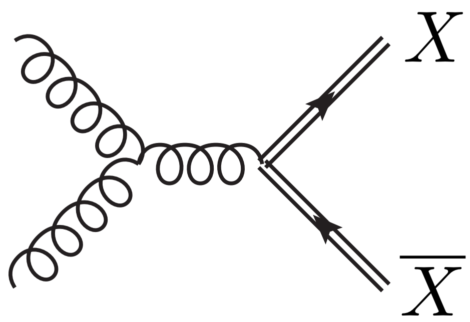
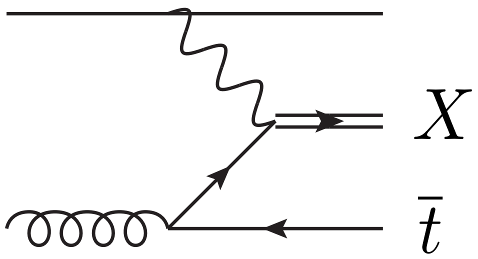
Phenomenology

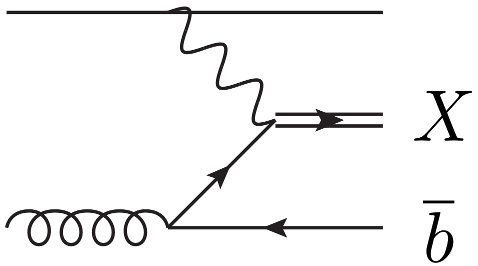
Three possible production mechanisms



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

Phenomenology

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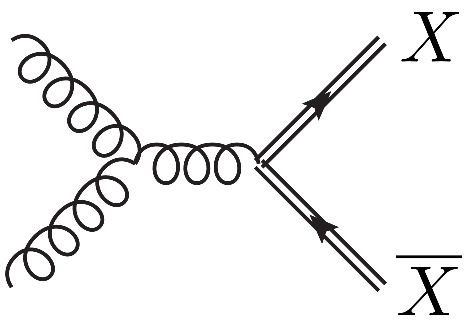

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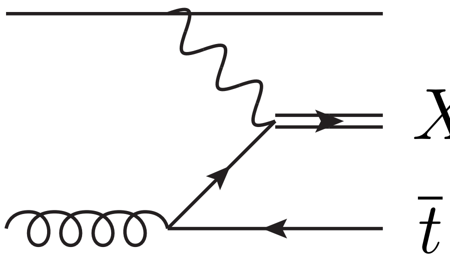

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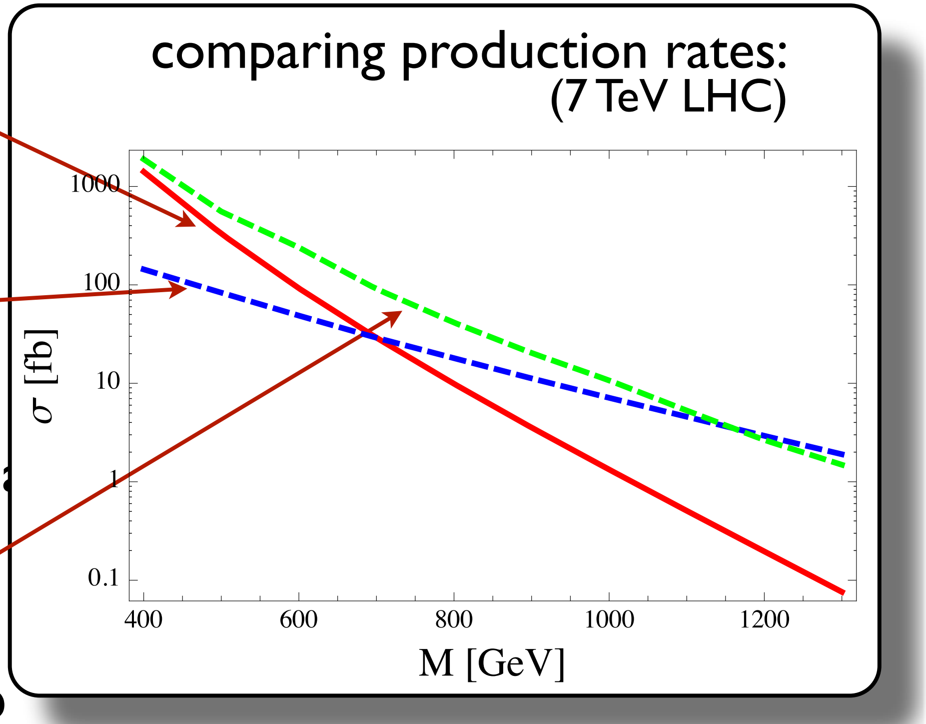

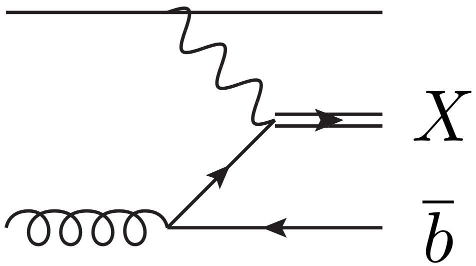

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Phenomenology

Summary of production/decay: $X_{5/3}$

Production: QCD or single+t, comparable at $M \sim 700\,\mathrm{GeV}$

Decay: $BR(Wt) = 1$

Final states: $t\bar{t}W + \begin{cases} W & \text{in QCD prod.} \\ \text{fwd jet in sing. prod.} \end{cases}$

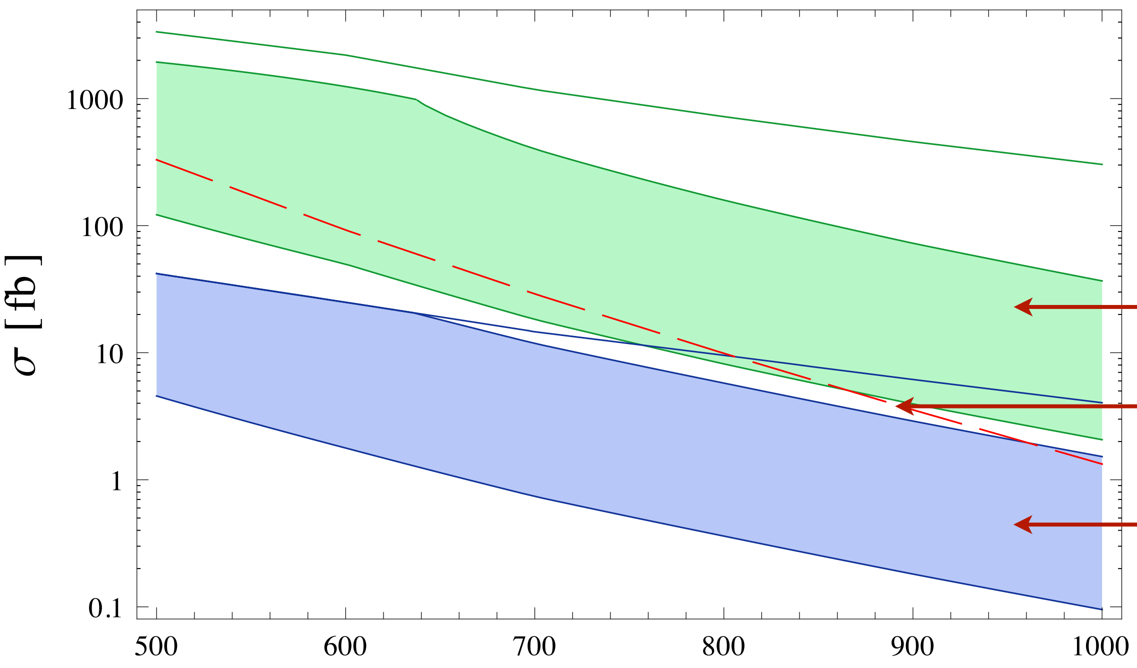
Good channel is **same-sign di-(tri-)leptons** plus jets:

ATLAS-CONF-2012-130
CMS-PAS-B2G-12-003
CMS-PAS-EXO-11-036

Phenomenology

Summary of production/decay: $\widetilde{T}$

Production: sing.+b typically dominant



bands from varying param.

single+b

pair

single+t

Phenomenology

Summary of production/decay: $\widetilde{T}$

Production: sing.+b typically dominant

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

Plenty of possible final states, **rich phenomenology**

Wb mode studied in one/two lep + one/two b + jets:

ATLAS **arXiv:1210.5468**

CMS **arXiv: 1203.5410**

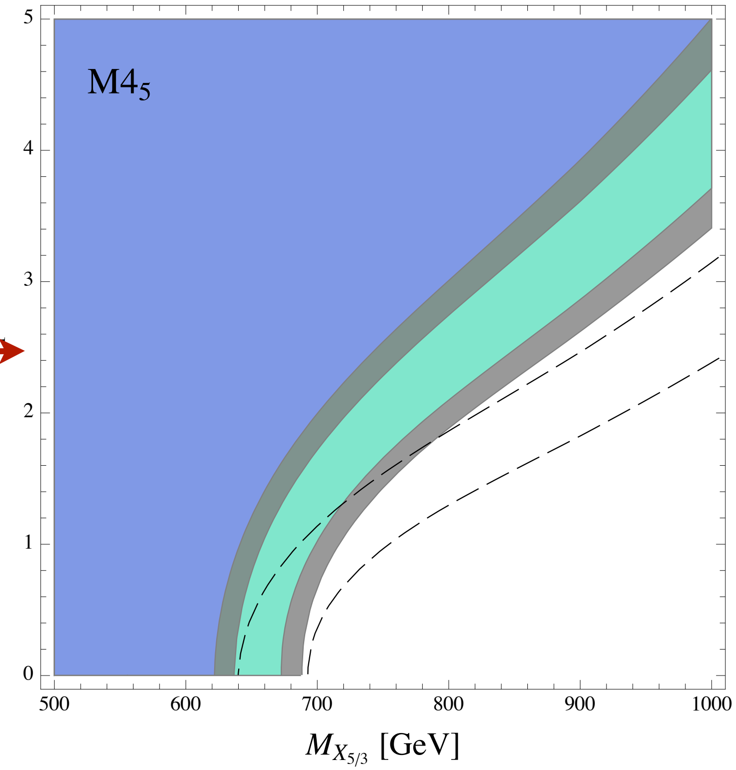
Models vs Data

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

Models vs Data

Example II: recasting CMS t' to Zt

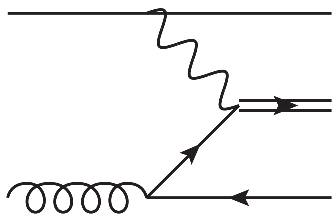
(arXiv:1109.4985)

Sensitive to $\widetilde{T}$ pair and single+top, but **not to single + bottom**

	pair prod. eff. [%]			single prod. eff. [%]	
M [GeV]	$T\bar{T} \to Zt\,Z\bar{t}$	$T\bar{T} \to Zt\,W\bar{b}$	$T\bar{T} \to Zt\,h\bar{t}$	$T\,\bar{t}\,j$	$T\,\bar{b}\,j$
300	1.78	1.22	1.51	1.13	0.03
350	1.93	1.47	1.64	1.17	0.03
450	2.21	1.81	1.81	1.25	0.05
550	2.34	1.93	1.95	1.30	0.06
650	2.40	2.12	1.96	1.35	0.08

Small efficiency due to asking extra hard activity besides Z and top

Signal, instead, has fwd jet plus soft b

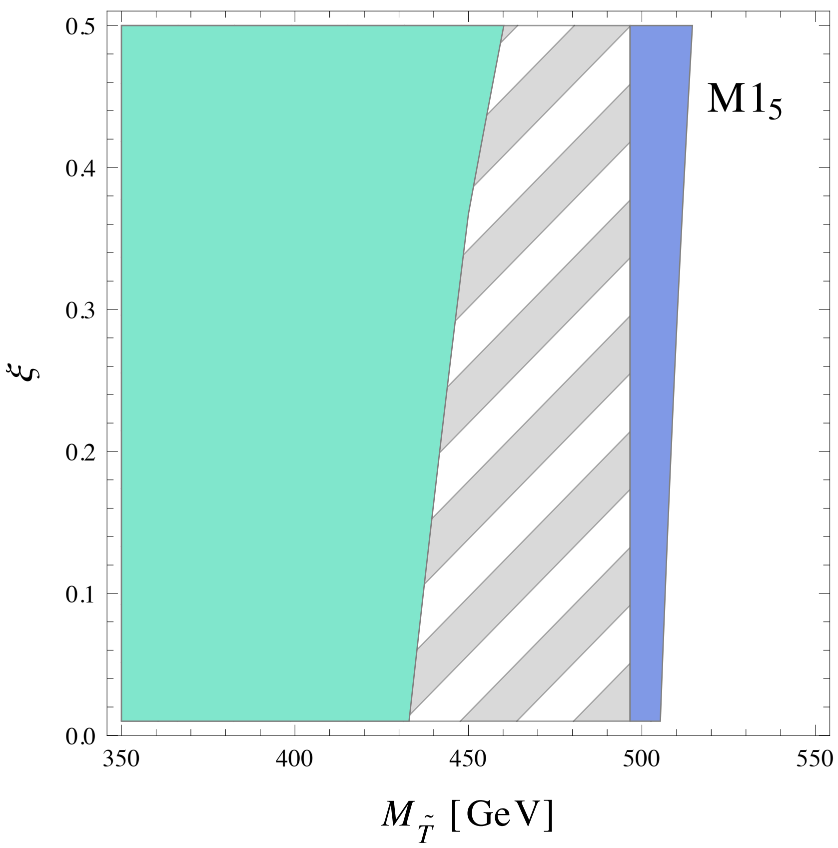


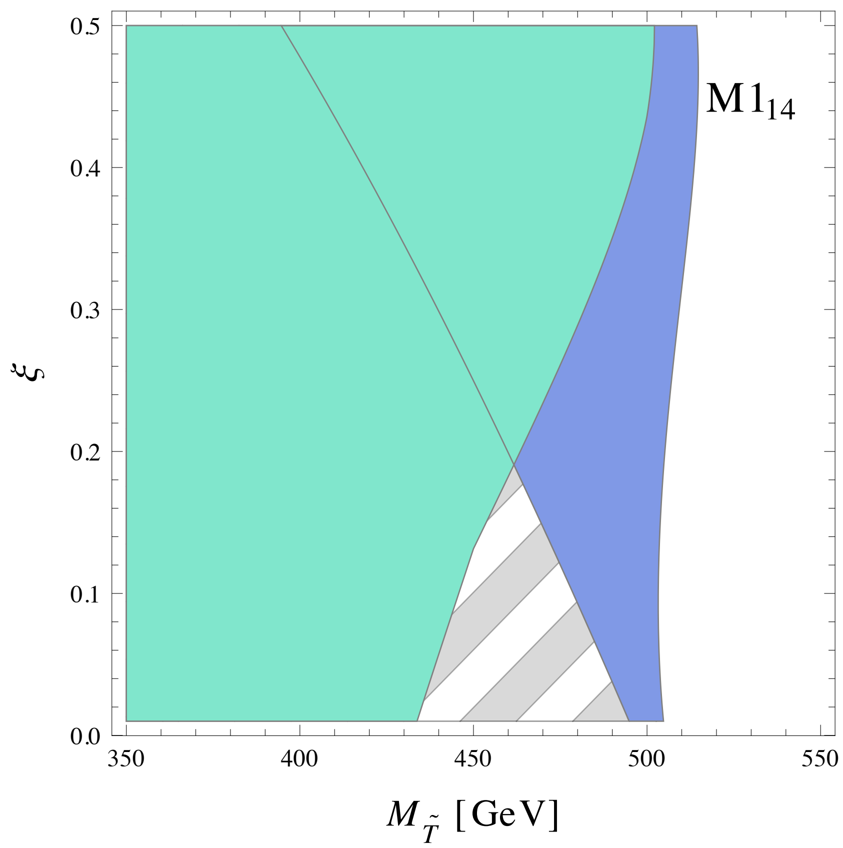
Having lost the main production signal, the bound is weak, $300\,\mathrm{GeV}$ or less

Models vs Data

Example III: recasting the CMS t' Wb search

(arXiv:1203.5410)



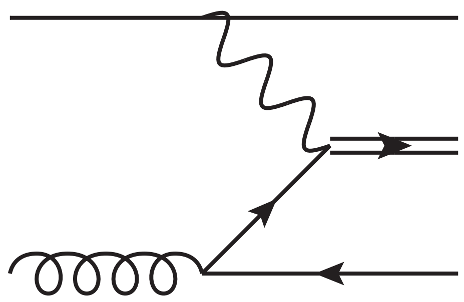


Conclusions

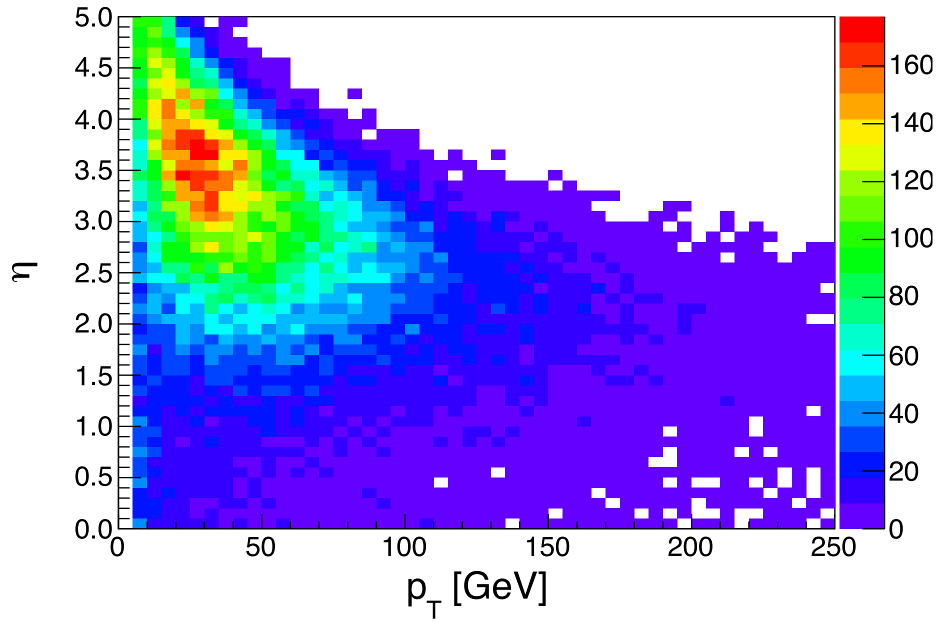
✦ **Light top partners** are essential ingredients of **Natural composite Higgs** scenario. We can(must) look for these particles

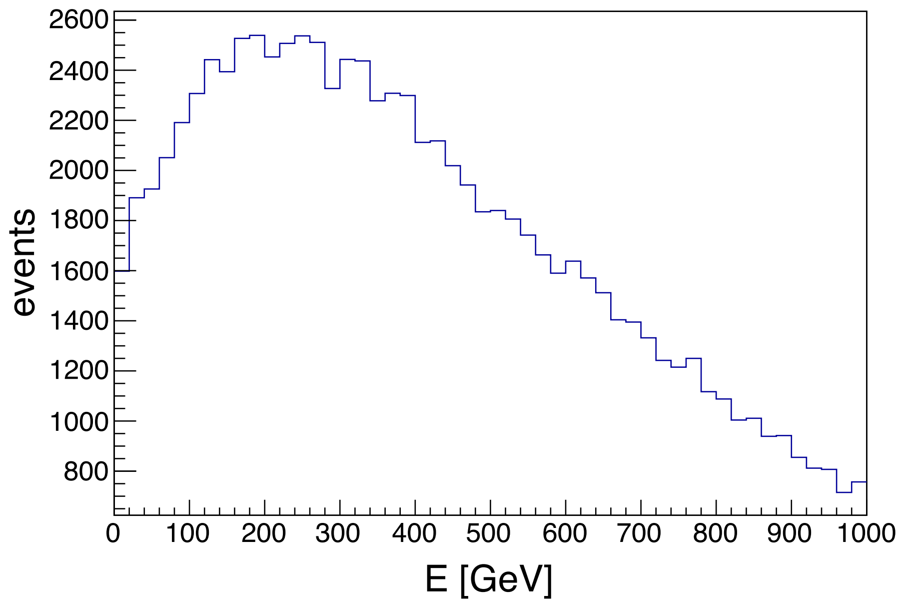
✦ We construct general benchmark models, aim is to study expected signal and to draw bounds/(discoveries?) in th. motivated par. space. First approach taking **Goldstone symmetry** into account.

✦ **Single production** can be sizable or dominant, **however** current searches are **optimized for pair prod.** (ask extra hard objects) sing. prod. instead characterized by **fwd jet** tag.



fwd jet, similar to VBF tag jets





searches are **optimized for pair prod.** (ask extra hard objects)

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Conclusions

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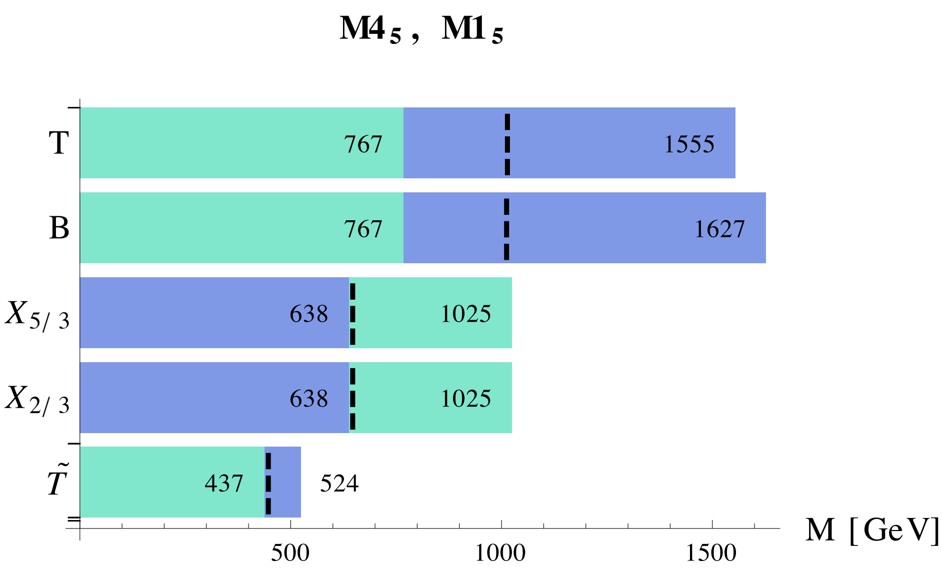
- ✦ We construct general benchmark models, aim is to study expected signal and to draw bounds/(discoveries?) in th. motivated par. space. First approach taking **Goldstone symmetry** into account.

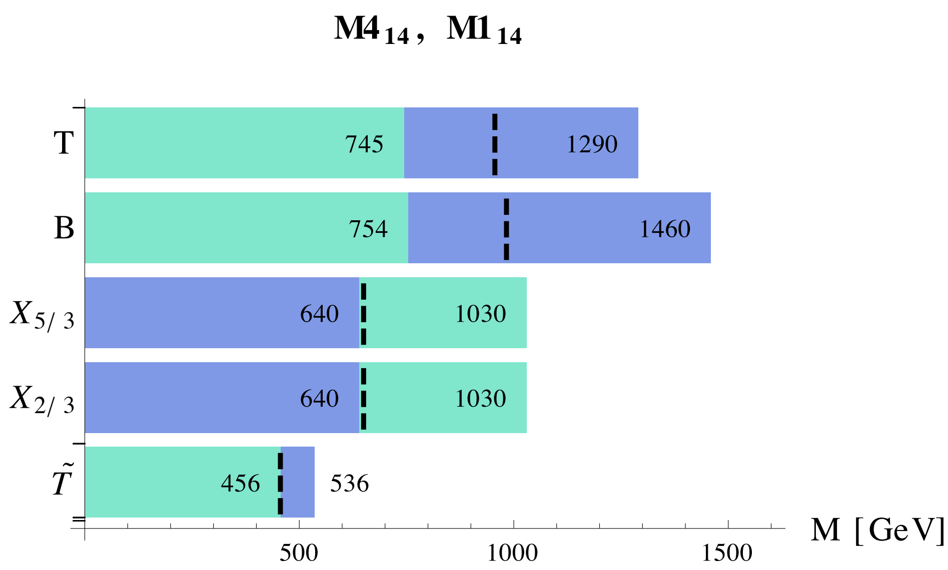
- ✦ **Single production** can be sizable or dominant, **however** current searches are **optimized for pair prod.** (ask extra hard objects) sing. prod. instead characterized by **fwd jet** tag.

- ✦ Significant improvements are possible in top partners bounds.

Conclusions

Present searches test already part of the natural par. space





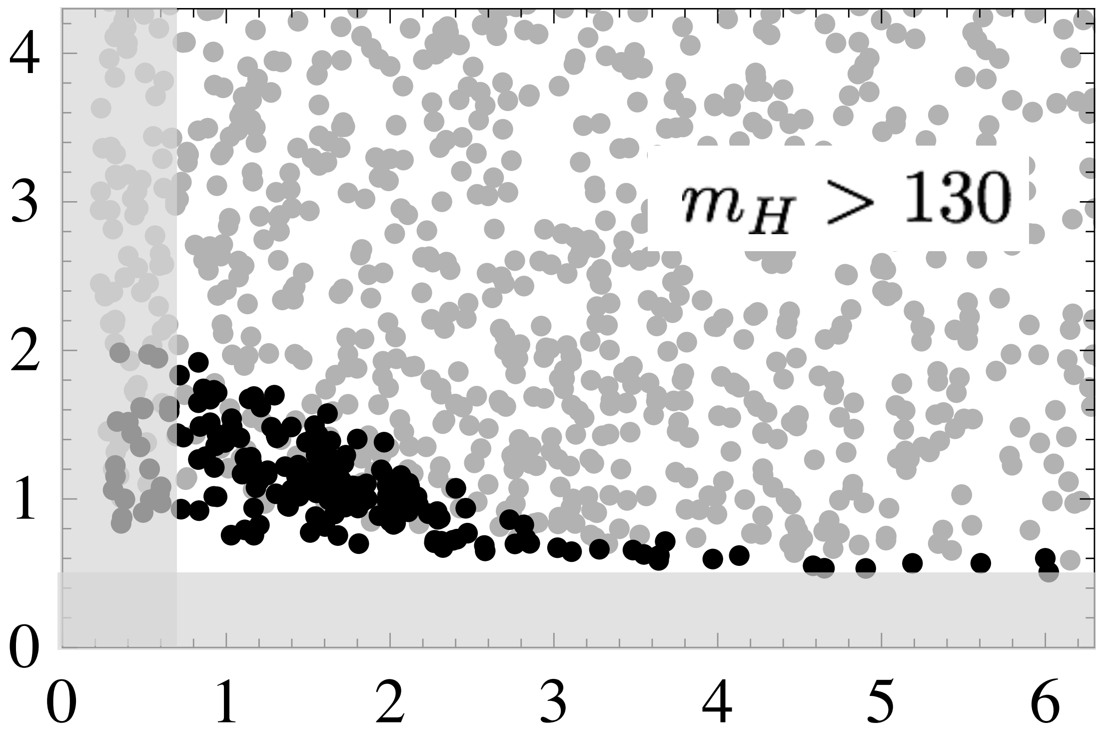
However some tuning was expected already from EWPT

Conclusions

Impact on a concrete model (roughly):

$\xi = 0.1$

$Q = 2/3$



$Q = 5/3$

Conclusions

Impact on a concrete model (roughly):

$\xi = 0.2$