Composite Higgs: Principles and Applications

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SM or not ?

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

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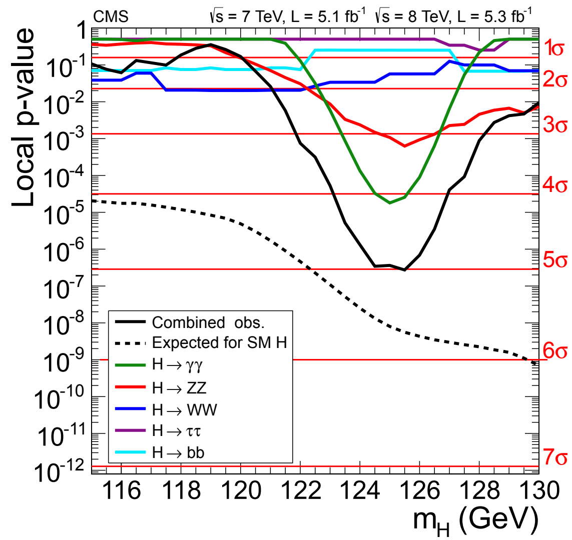
First step taken on 07/04/2012:

Higgs-like particle **exists** !

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



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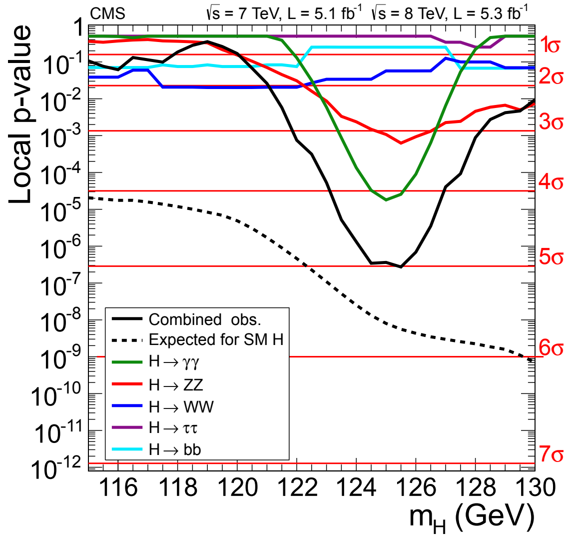


Where is BSM scale $\Lambda_{\rm UV}$?

SM or not ?

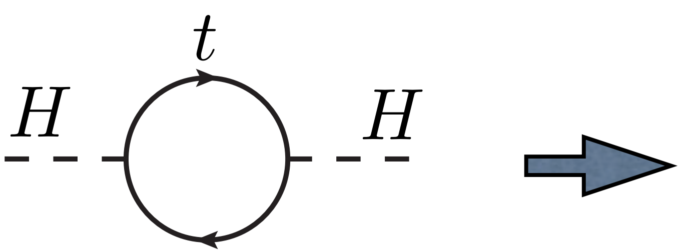
Good reasons to guess $\Lambda_{\rm UV} \gg \rm TeV$ (e.g ,$10^{16}\rm GeV$):

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

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

The Hierarchy Problem

$$\delta m_H^2 \gg m_H^2$$



$$\delta m_H^2 = \frac{y_t^2}{16\pi^2}\Lambda_{\rm UV}^2$$

SM or not ?

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

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

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 !

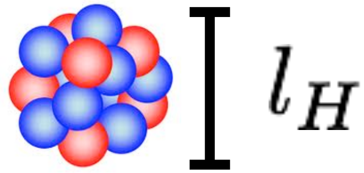
Composite Higgs

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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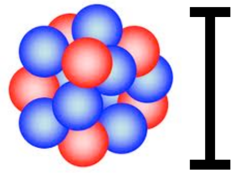

l_H

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

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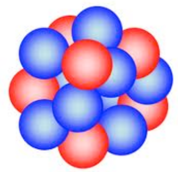

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Indirect effects from sigma-model couplings

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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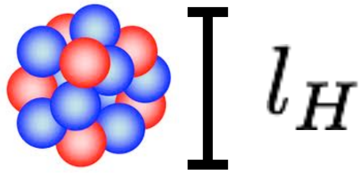

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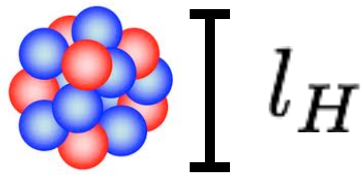

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Direct Production of new particles:

Fermion **(Top) Partners**

More promising

Goldstone Boson Higgs

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

Composite Sector

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

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

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

Elementary Sector

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

$$f_L,\ f_R$$

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 phys. 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: $v = 246\,\mathrm{GeV} = f \sin \dfrac{\langle h \rangle}{f}$

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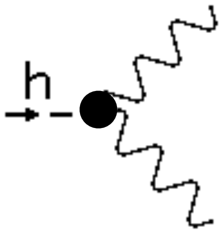
the physical Higgs coupling to W is



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

deviations from SM controlled by

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

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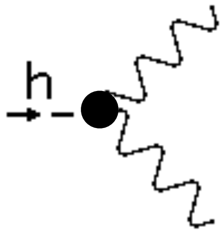

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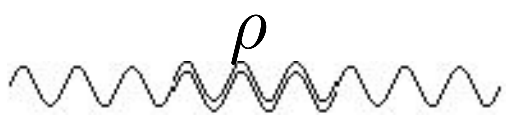
In principle, departures from SM could be huge.

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 compositenes

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

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

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

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

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

Goldstone Boson Higgs

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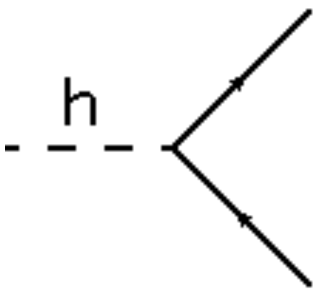
For each choice, fermion coupling fixed by symmetry



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

MCHM_5 $\quad c = \dfrac{1-2\xi}{\sqrt{1-\xi}}$

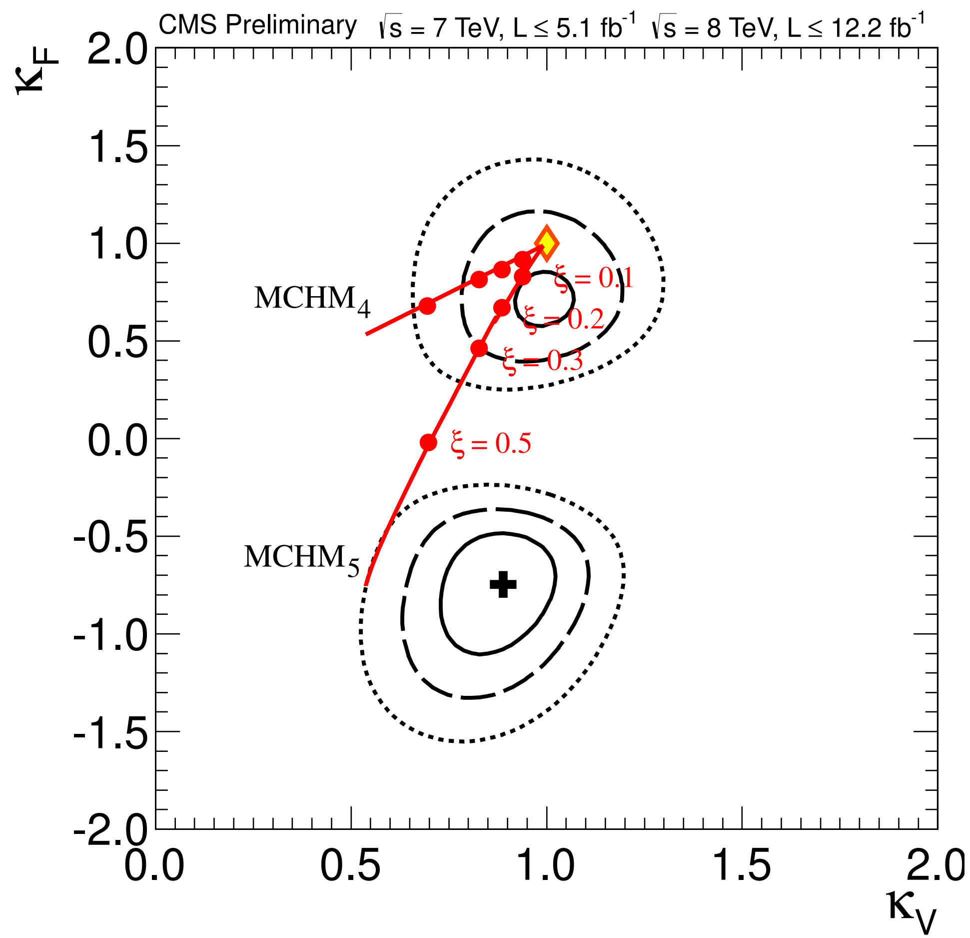
MCHM_4 $\quad c = \sqrt{1-\xi}$

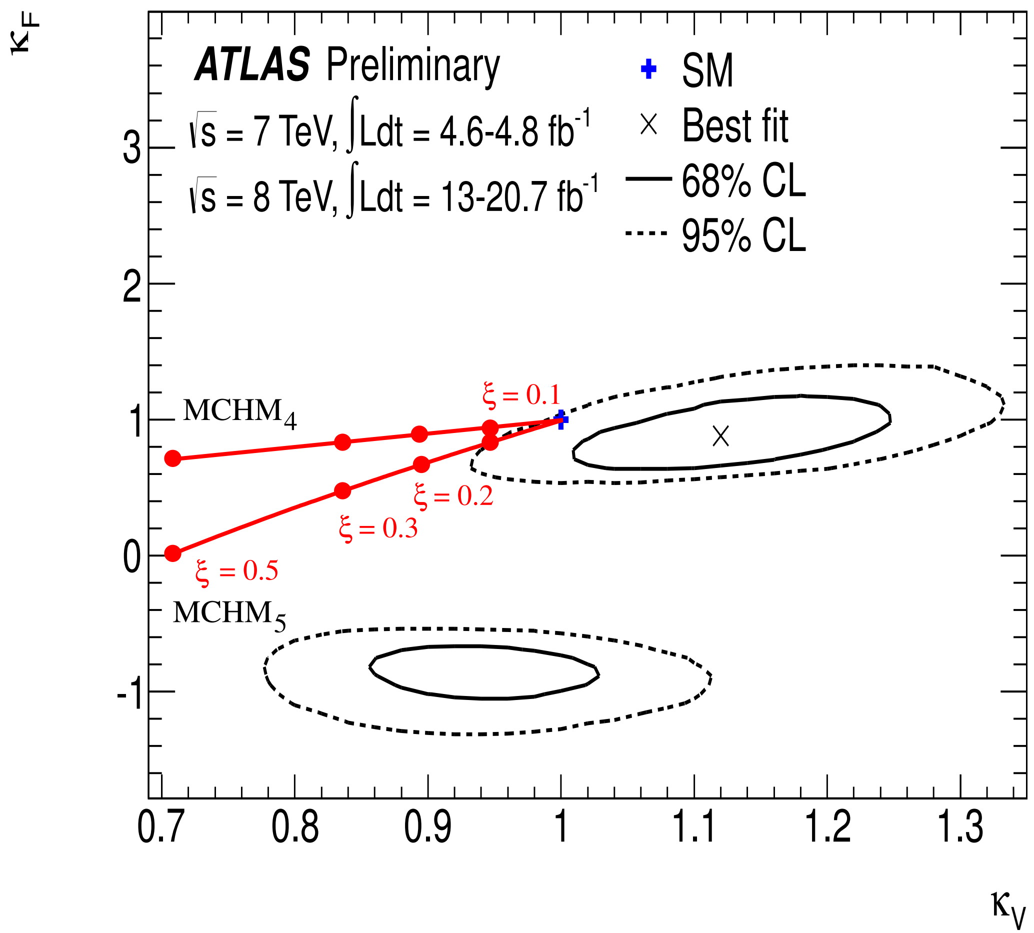
MCHM_{10} $\quad \cdots$

Goldstone Boson Higgs

courtesy of G. Panico

Some (not so) 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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In the IR operators correspond to particles:

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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:

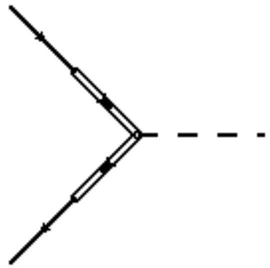
$$\mathcal{L}_{mass} = m_Q^* \overline{Q} Q + y\, f \overline{q} Q$$

physical particles are **partially composite**

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

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

Partial Compositeness

Yukawa couplings: $y_f =$  $= g_\rho \sin\phi_L \sin\phi_R$

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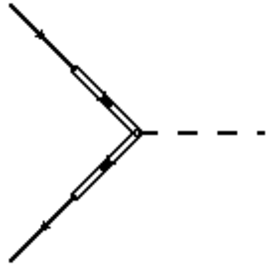
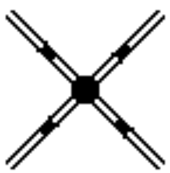
Yukawa couplings: $y_f =$  $= g_\rho \sin\phi_L \sin\phi_R$

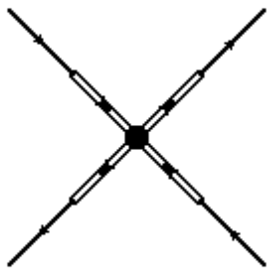
Light fermions are mostly **elementary**

Extremely helpful in suppressing Flavor violation



$\sim g_\rho^2$

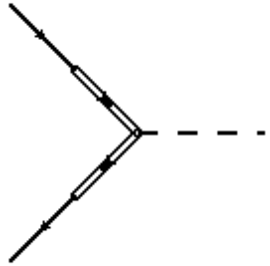
anarchic strong sector couplings



$\sim g_\rho^2 \sin^2\phi_d \sin^2\phi_s \simeq y_d y_s$

suppressed FCNC

Partial Compositeness

Yukawa couplings: $y_f =$  $= g_\rho \sin\phi_L \sin\phi_R$

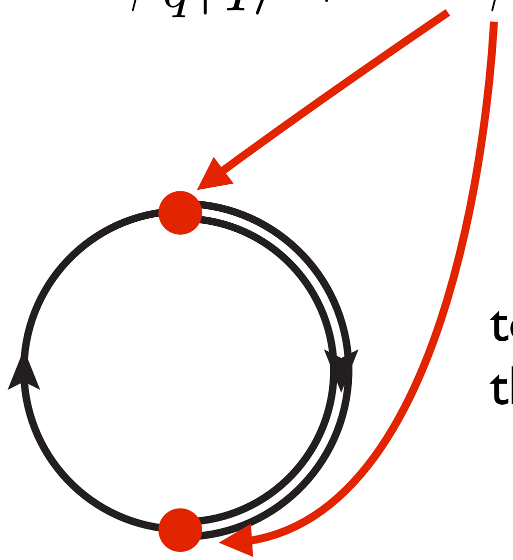
Light fermions are mostly **elementary**

Top quark is **largely composite**

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

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

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

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

Top Partners

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

Natural SUSY:

light stops

Natural CH:

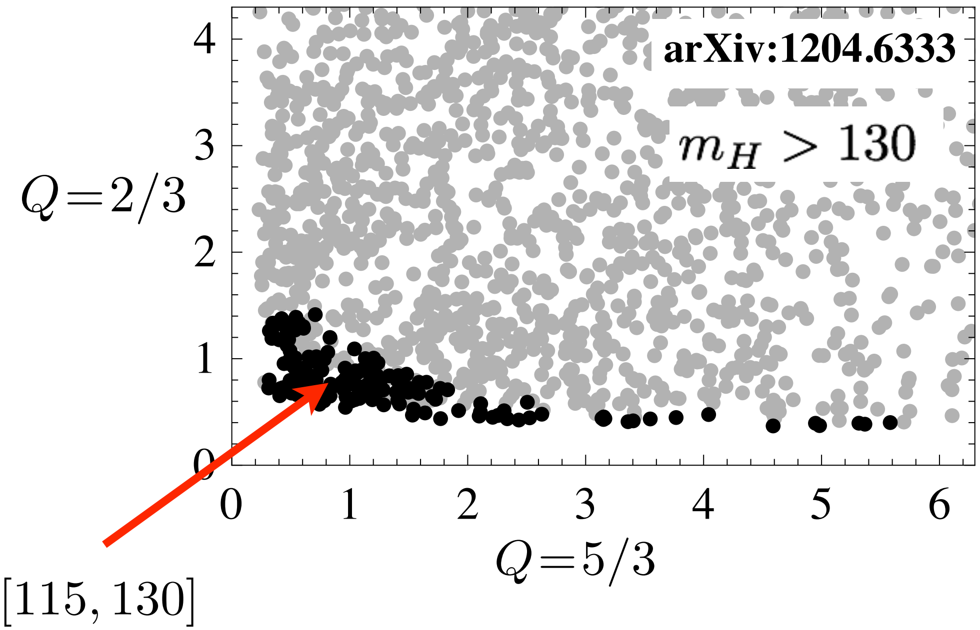
light top partners

Top Partners

Striking Example:
(Matsedonski, Panico, AW 2012)

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

$\xi = 0.2$



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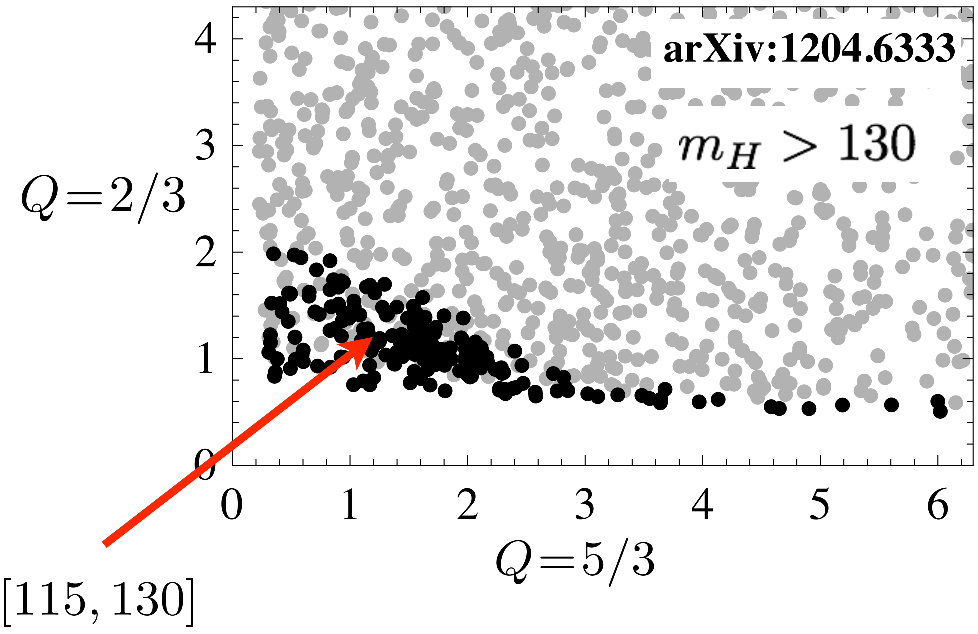
$\mathrm{MCHM}_{4,5,10}$

$\xi = 0.1:$ (larger tuning)



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

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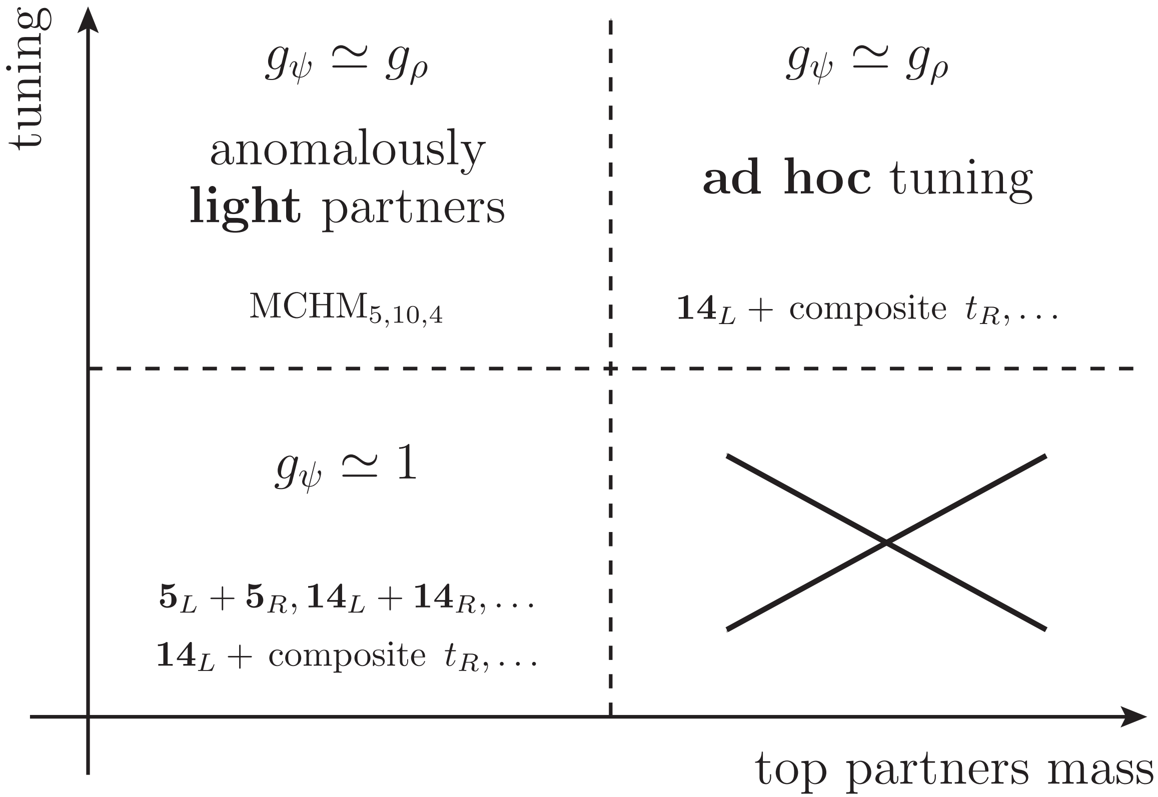
In general, taking Higgs mass into account:

(Panico, Redi, Tesi, AW 2012)

Low Tuning requires **Light Partners**



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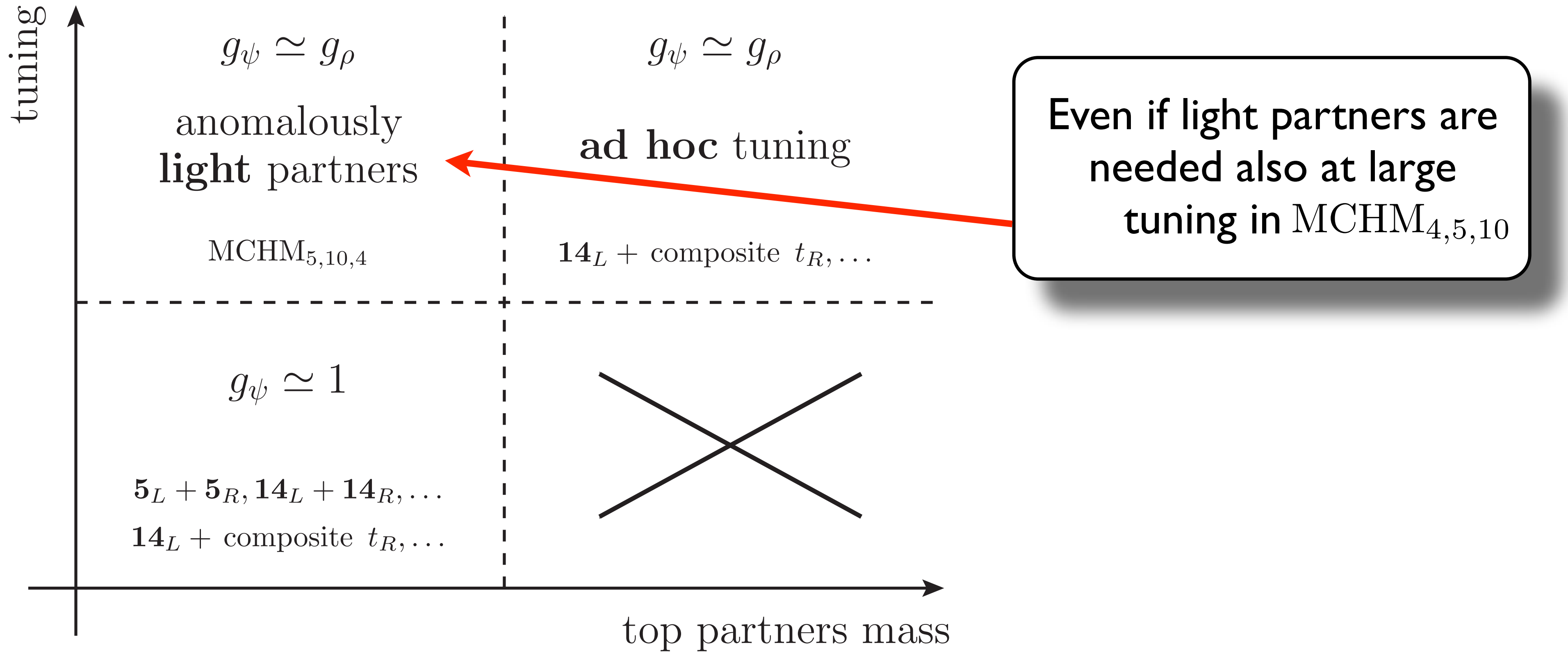

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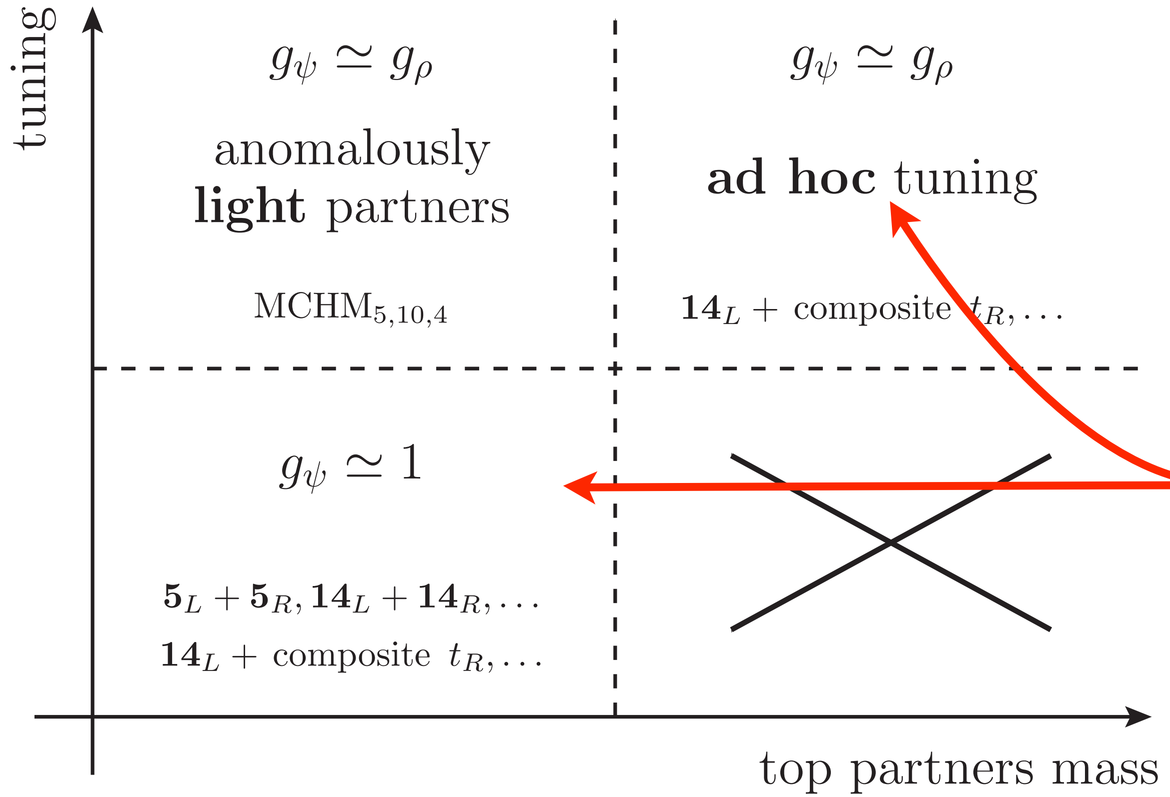


Even if light partners are needed also at large tuning in $\mathrm{MCHM}_{4,5,10}$

Totally composite and mix with **14** is promising alternative (for explicit 5d model, see **arXiv:1303.3062**)

Top Partners at the LHC

Top Partners @ LHC studied by several groups:

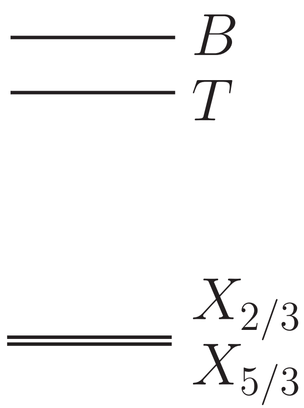
Contino, Servant 2008
Aguilar-Saavedra 2009
Mrazek, AW 2009
Dissertori, Furlan et al 2010
Barcelo, Carmona et al 2011
Vignaroli 2012
Cacciapaglia et al. 2012/2013
Santiago et. al 2013
Li, Liu, Shu 2013
Son, Spannowsky, et al, 2013

Top Partners at the LHC

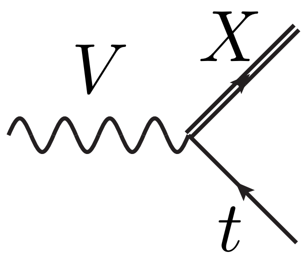
De Simone, Matsedonski, Rattazzi, AW, 2012

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

Spectrum:



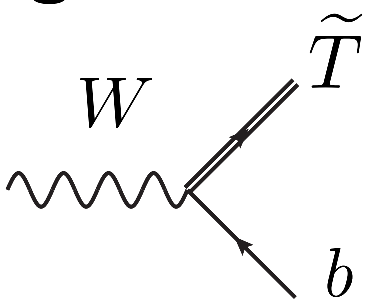
Couplings:



$\sim M_X/f$

because Goldstones are derivatively coupled

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

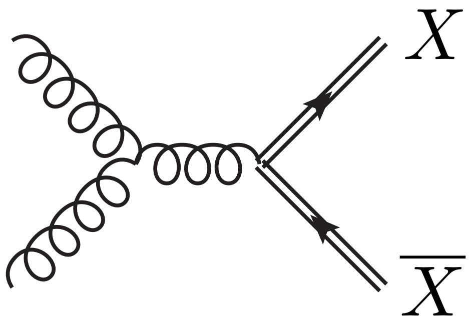


sizable coupling to bottom quark

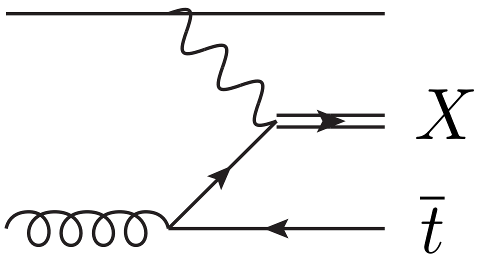
Top Partners at the LHC

De Simone, Matsedonski, Rattazzi, AW, 2012

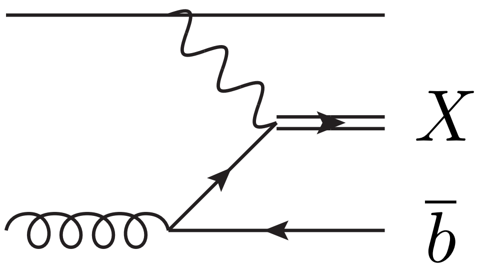
Three possible production mechanisms



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



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

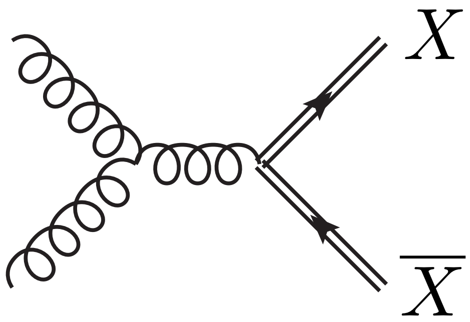


single prod. with **b**
favored by small b mass
dominant when allowed

Top Partners at the LHC

De Simone, Matsedonski, Rattazzi, AW, 2012

Three possible production mechanisms



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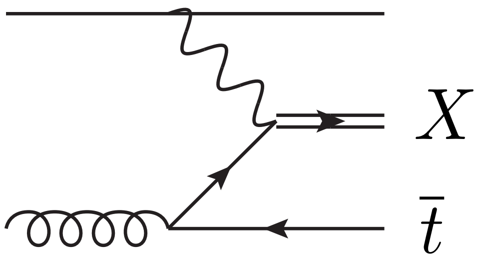

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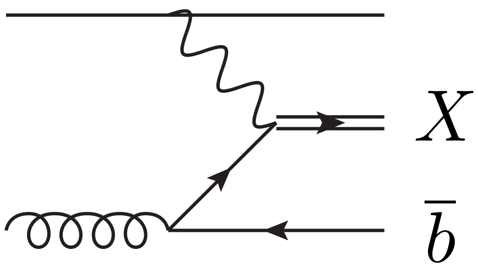

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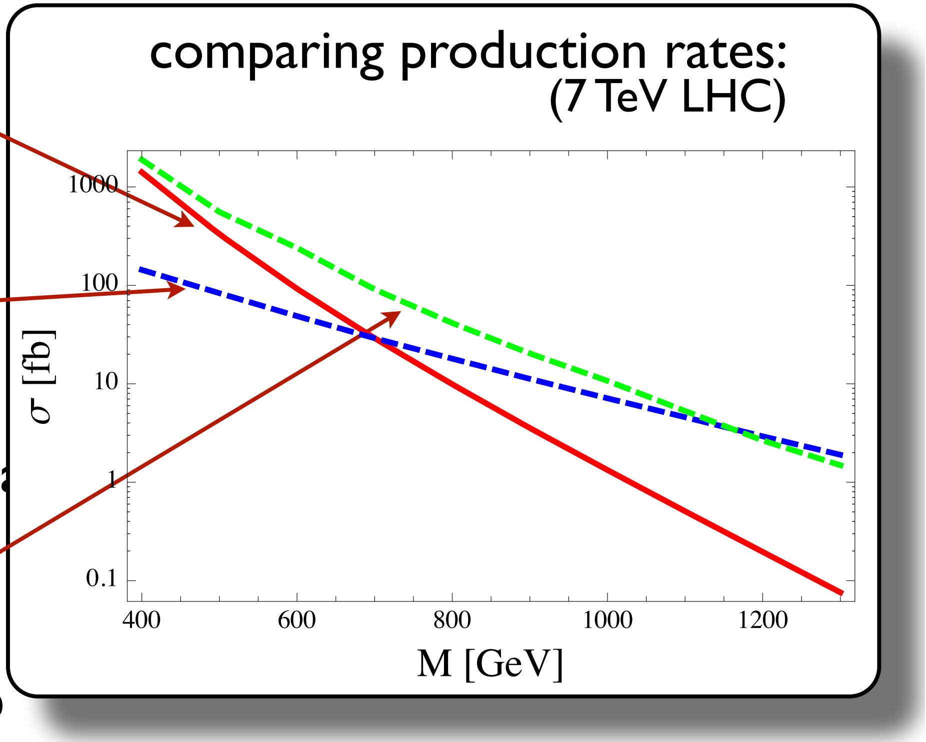


Top Partners at the LHC

De Simone, Matsedonski, Rattazzi, AW, 2012

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

Top Partners at the LHC

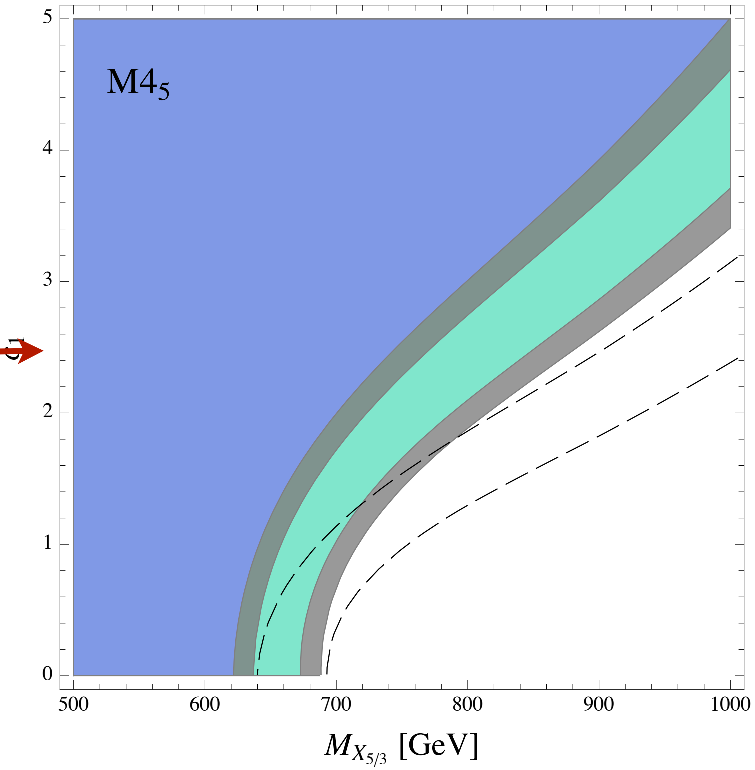
De Simone, Matsedonski, Rattazzi, AW, 2012

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, Matsedonski, Rattazzi, AW, 2012

A recent progress:

(Azatov, Salvarezza, Son, Spannowsky, 2013)

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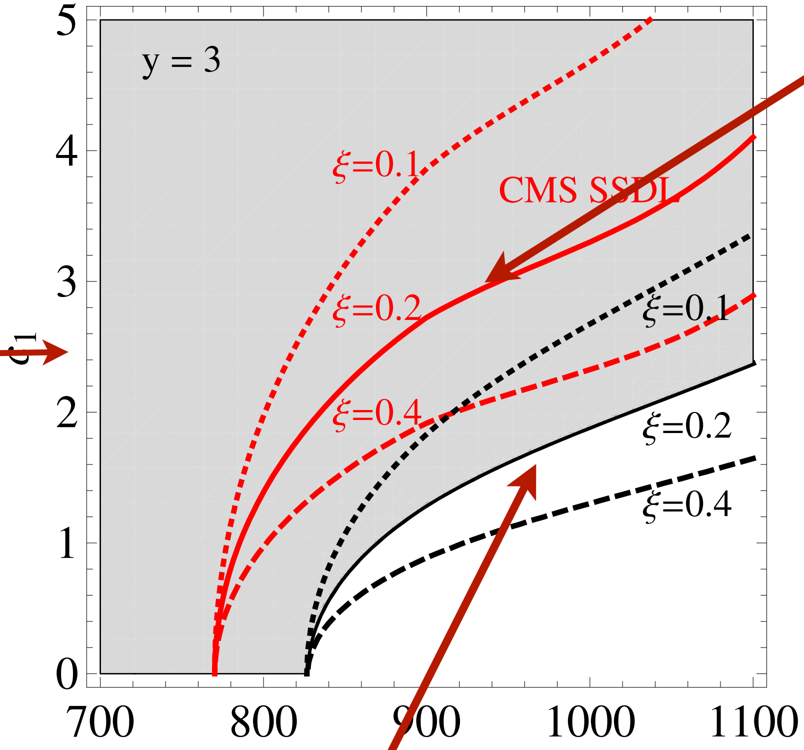

NEW BOUND:
(CMS PAS B2G-12-012)

Estimated reach by boosted W techniques

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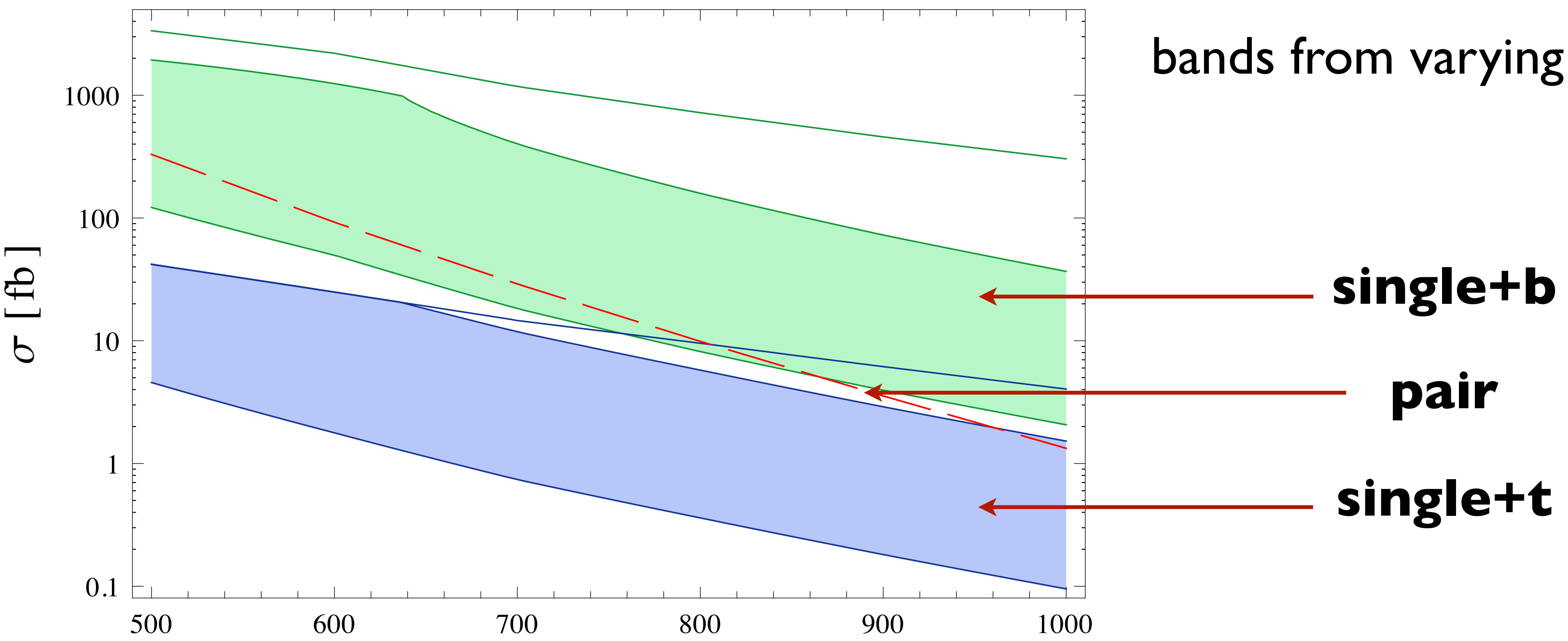
Summary of production/decay: $\widetilde{T}$

Production: sing.+b typically dominant

bands from varying param.



Top Partners at the LHC

De Simone, Matsedonski, Rattazzi, AW, 2012

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**

More recently, other modes have been considered

Top Partners at the LHC

De Simone, Matsedonski, Rattazzi, AW, 2012

Example II: recasting CMS t' to Zt

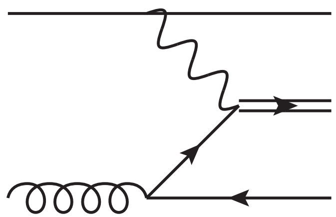
(arXiv:1109.4985)

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



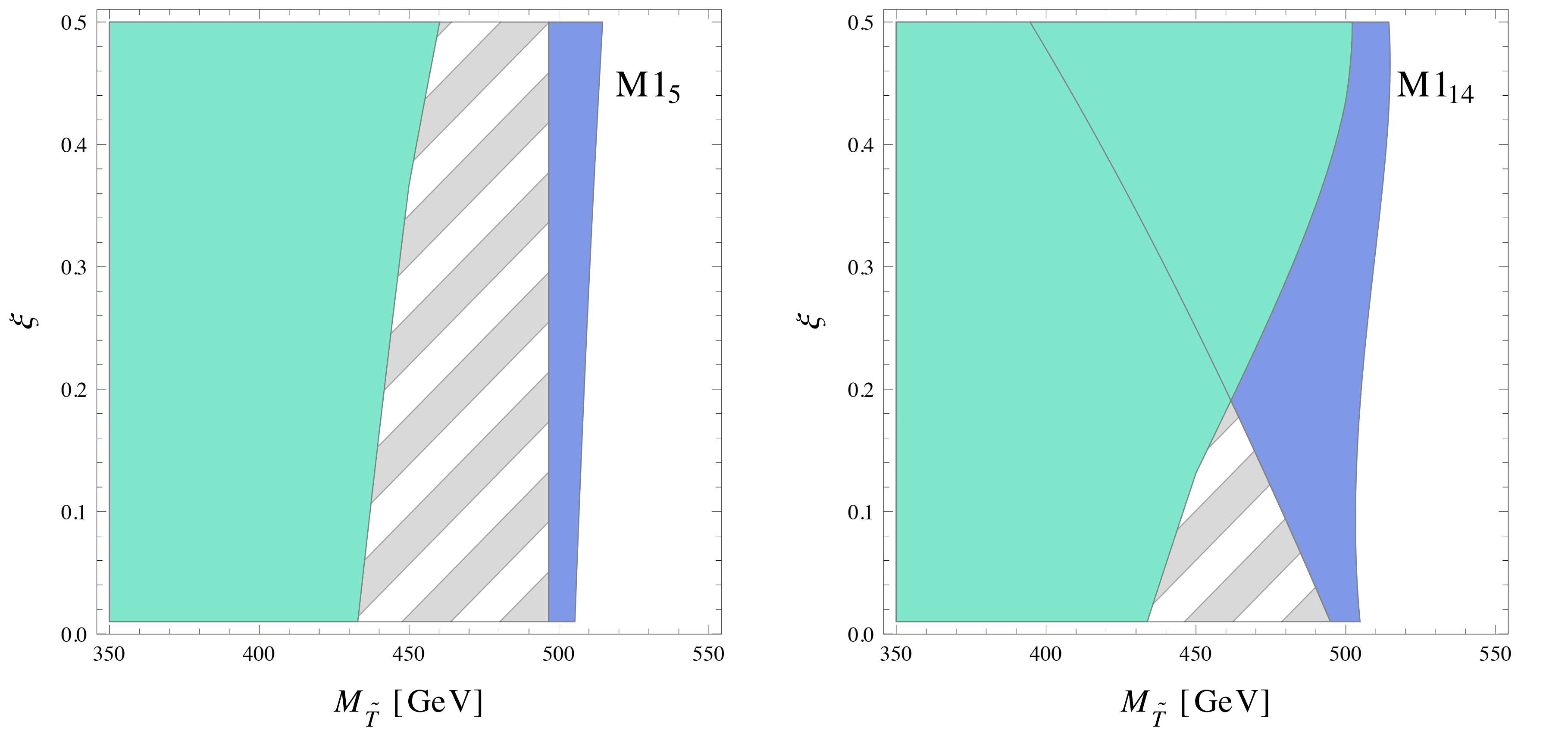
Having lost the main production signal, the bound is weak, $300\,\mathrm{GeV}$ or less

Top Partners at the LHC

De Simone, Matsedonski, Rattazzi, AW, 2012

Example III: recasting the CMS t' Wb search

(arXiv:1203.5410)



Top Partners at the LHC

De Simone, Matsedonski, Rattazzi, AW, 2012

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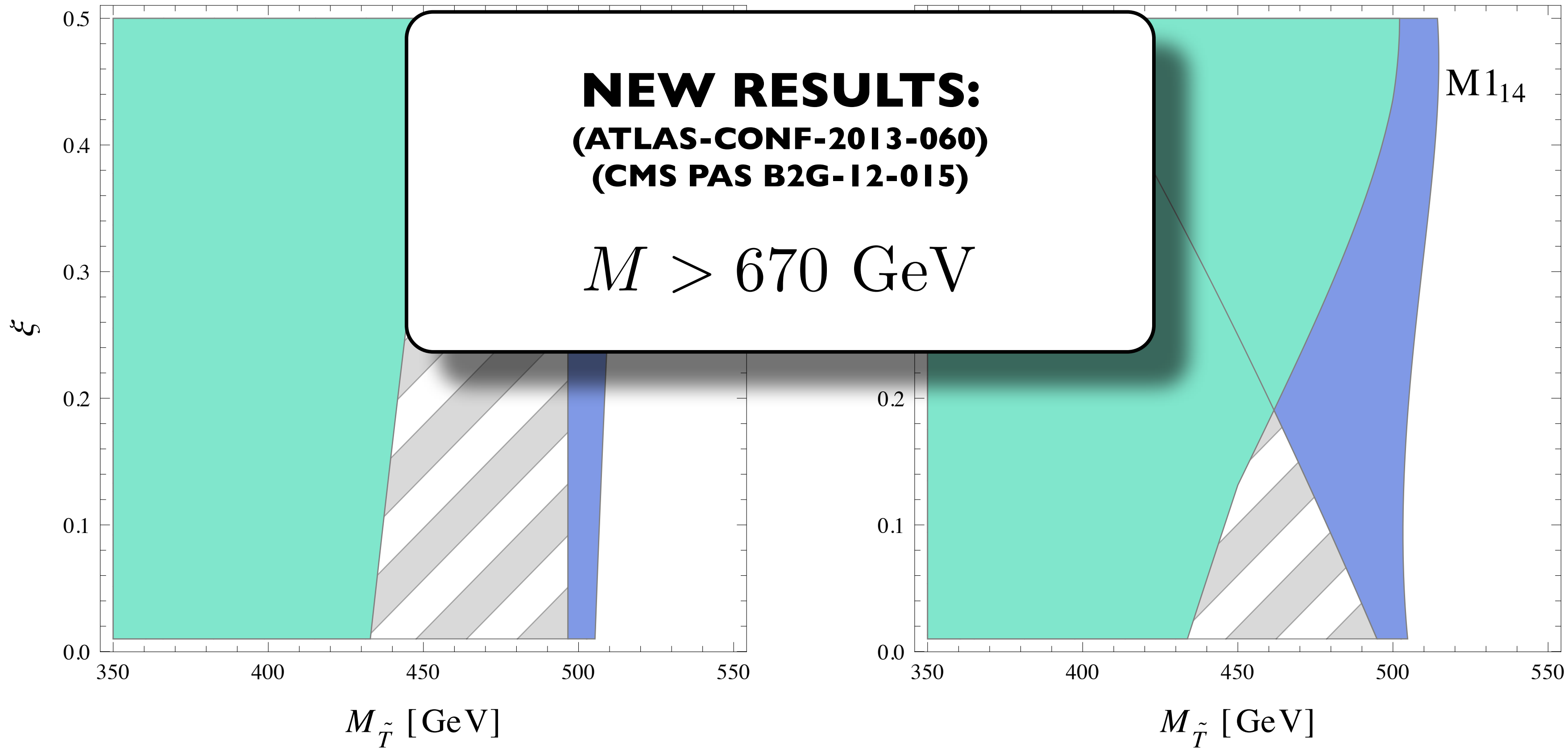
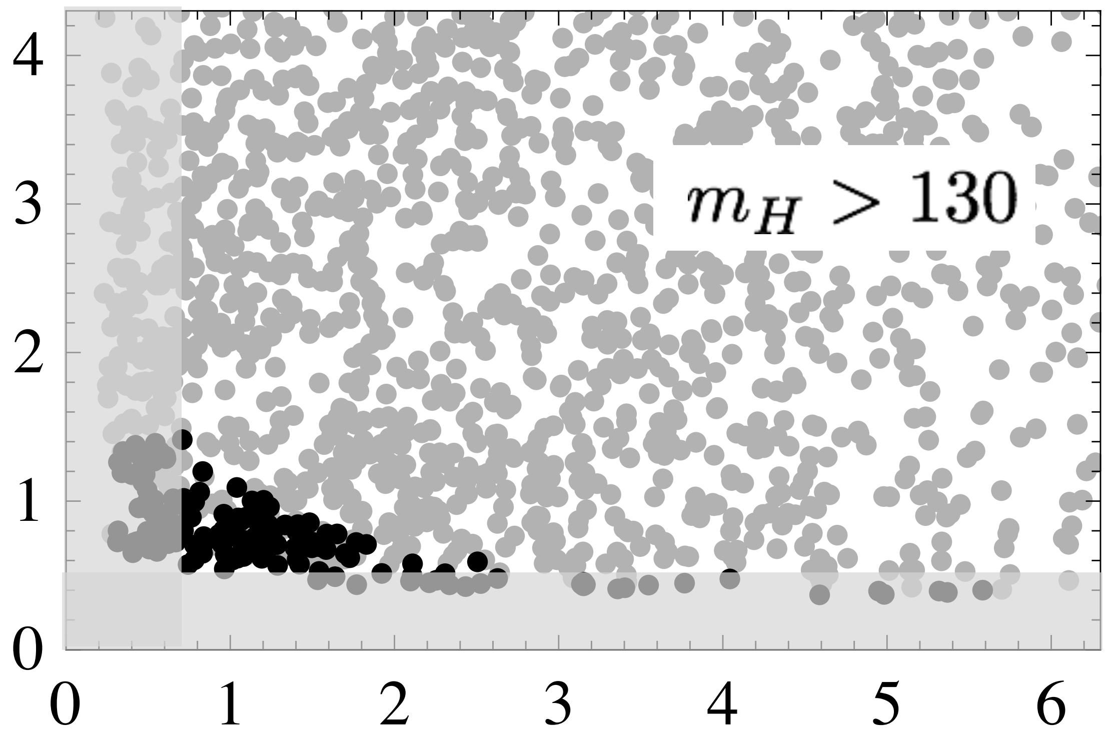


Top Partners at the LHC

Impact on a concrete model (roughly):

$\xi = 0.2$



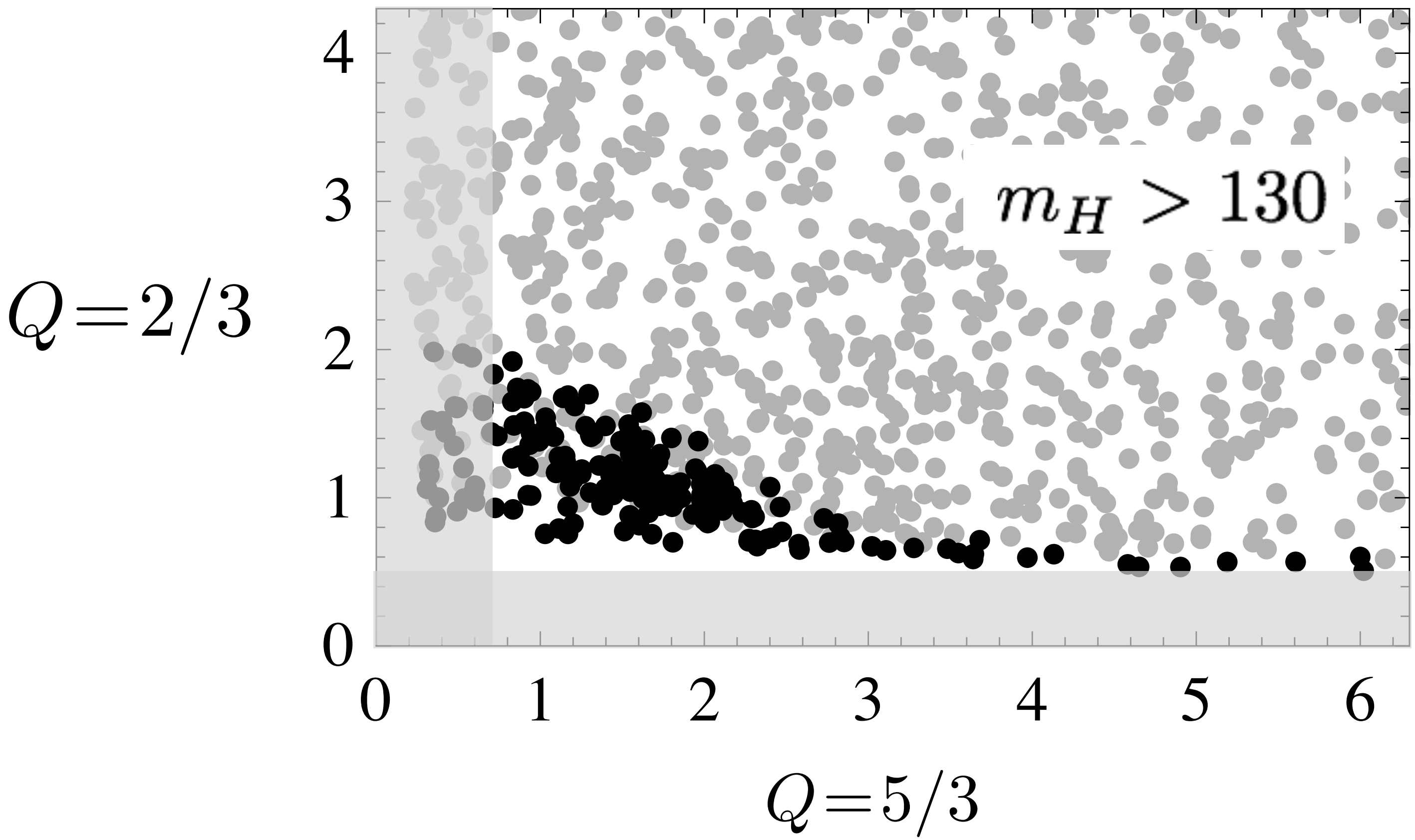
$Q = 2/3$

$Q = 5/3$

Top Partners at the LHC

Impact on a concrete model (roughly):

$$\xi = 0.1$$



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
- Direct observation of Top Partners
- Don't forget spin one resonances (good for 14 TeV)

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

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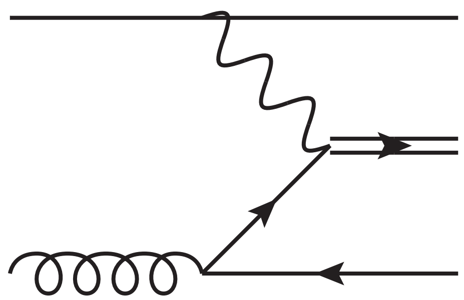
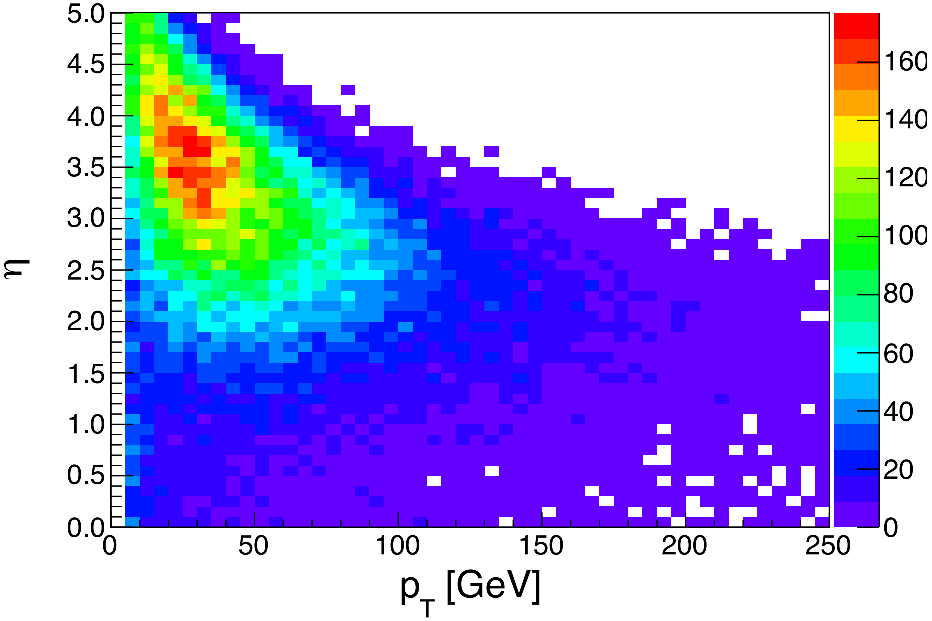
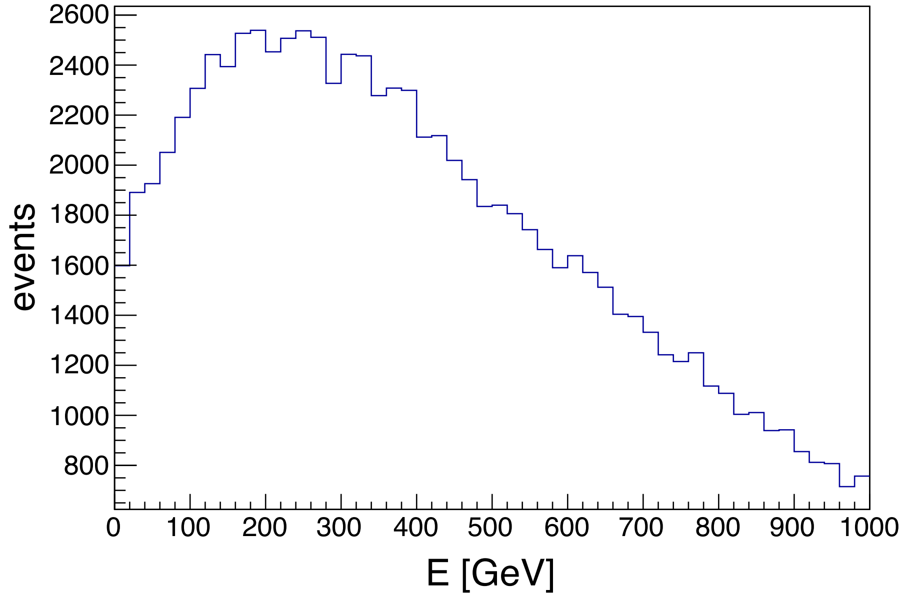
Single production sizable or dominant, **however** searches for **pair prod.** ask extra hard objects sing. prod. instead leads to **fwd jet**



fwd jet, similar to VBF tag jets





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Significant improvements are possible in top partners bounds