Fermionic Partners

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Introduction

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Being QCD pair produced is the only robust feature of a VLQ
Decays and single production modes highly model-dependent

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More specific (still model-independent) phenomenology

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Two classes of Fermionic Partners
(sorted by relevance)

1. Top Partners
2. Light quarks partners

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(sorted by relevance)

1. Top Partners
2. Light quarks partners

Note: VLQs also in one MSSM extension (Martin 2010)

Top Partners

One sure goal of the LHC is to answer the question:

"Is EWSB scale Natural of Fine-tuned?"

Any of the two would be a fundamental result!

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From the top loop quadratic divergence, we estimate

$$\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{126\ \text{GeV}}{m_h}\right)^2 \left(\frac{M_P}{500\ \text{GeV}}\right)^2$$

M_P = mass of the **Top Partner** that cancels the divergence

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

SUSY:	**pNGB Higgs:**
light stops	light top partners

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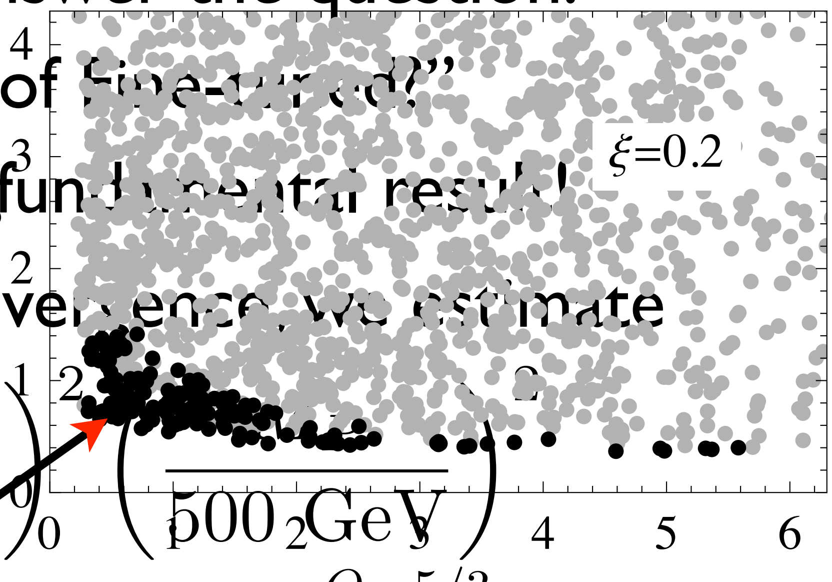
(Matsedonskyi, Panico, AW 2012)

In a class of explicit CHM models

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

$\xi = 0.2$: (low tuning)

$m_H \in [115, 130]$



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In a class of explicit CH models

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

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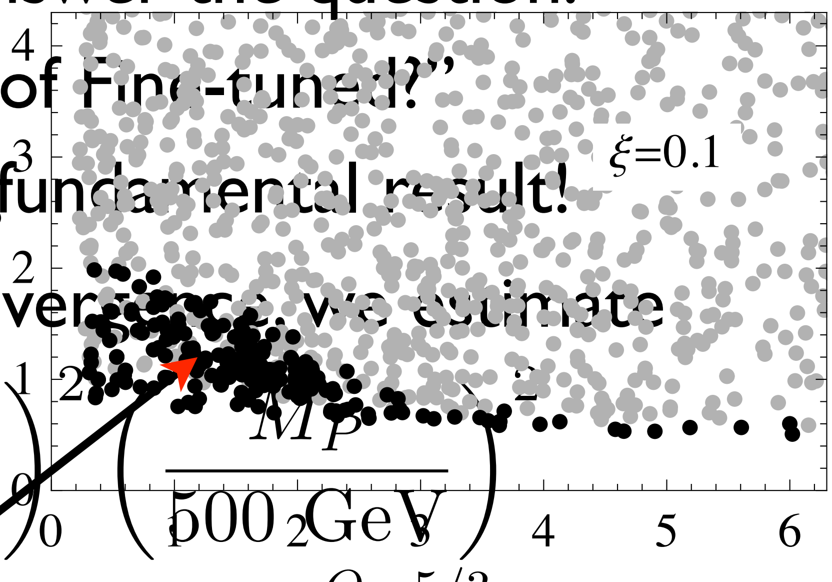


Light Higgs plus **Low Tuning** need **Light Partners**

SUSY:

light stops

pNGB Higgs:

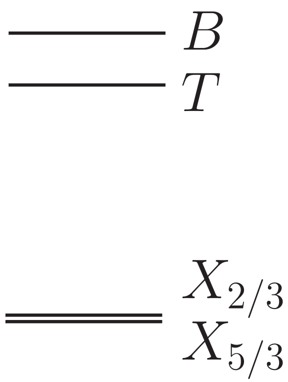
light top partners

Top Partners

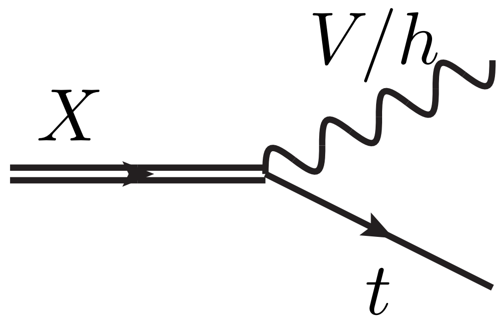
(De Simone, Matsedonsky, Rattazzi, AW, 2012)

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

Spectrum:



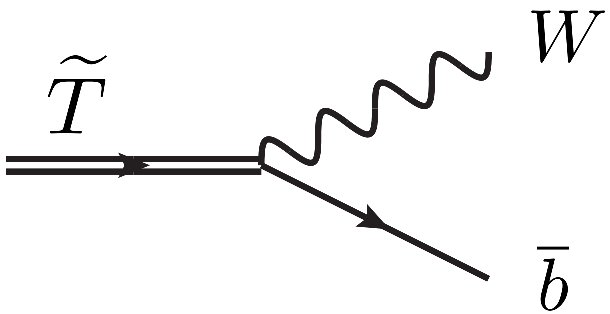
Couplings:



$\sim M_X/f$

generically large Top coupling

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



sizeable coupling with the bottom quark

Top Partners

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

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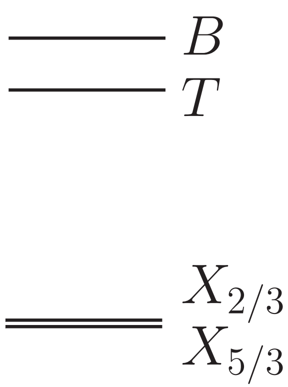

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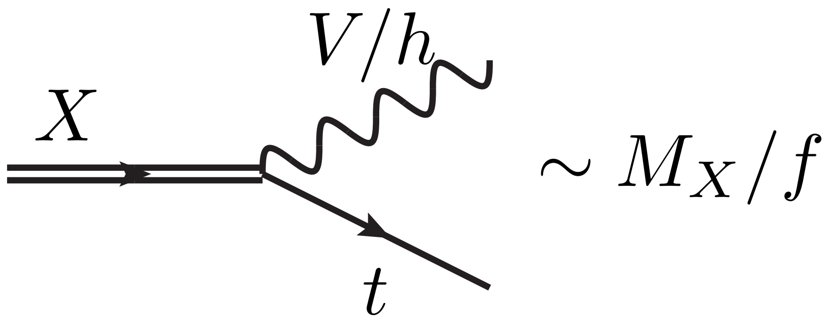


generically large Top coupling
because Goldstones are derivatively coupled

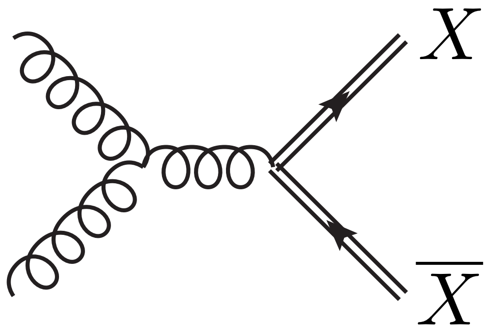
ESSENTIAL to take **GOLDSTONE** symmetry into account

Can not understand Top Partners without Goldstone Higgs

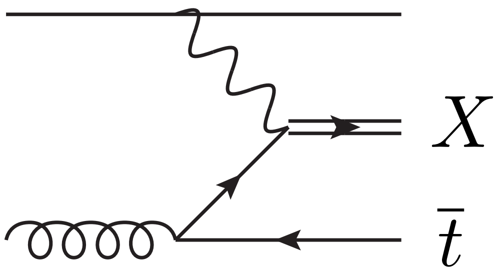
Top Partners

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

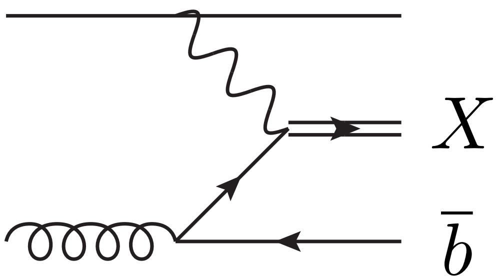
Three possible production mechanisms



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



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

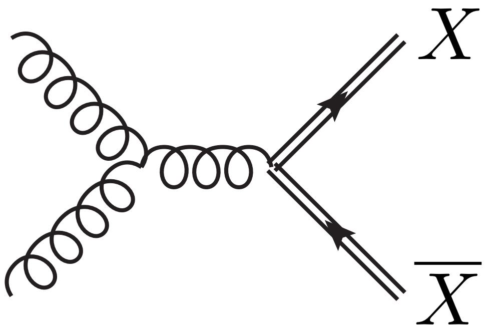


single prod. with **b**
favoured by small b mass
dominant when allowed

Top Partners

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

Three possible production mechanisms



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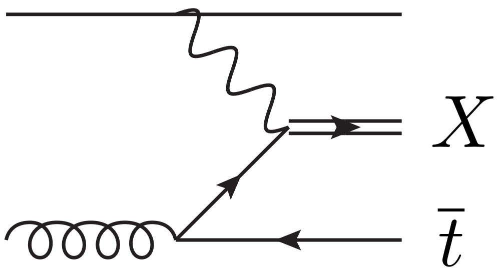

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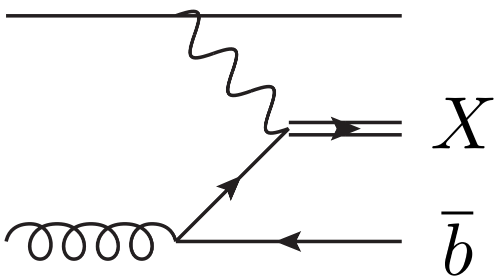

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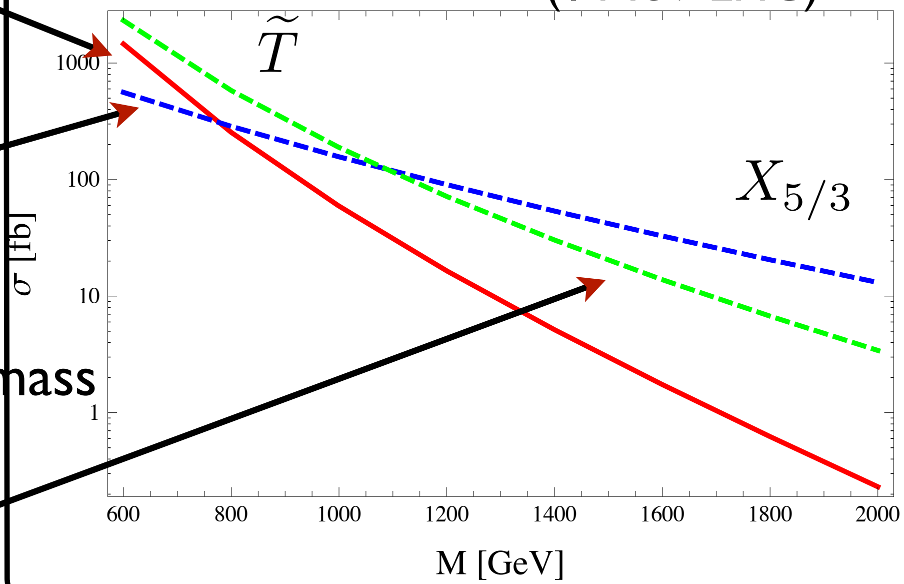
comparing production rates:
(14 TeV LHC)



Top Partners

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

Searches on a Table:

Decay

Production

	$W+t$	$W+b$	$Z/h+t$
Pair Production	$X_{5/3}, B$	$\widetilde{T}$	$X_{2/3}, T, \widetilde{T}$
Single + top	$X_{5/3}, B$		$X_{2/3}, T$
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Composite Higgs favorite channels:

(lighter and/or larger rates)

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Little Higgs favorite channels:

(see e.g. Peskin 2003)

Top Partners

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

Searches on a Table:

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Production

	$W + t$	$W + b$	$Z/h + t$
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Single + bottom		$\widetilde{T}$	$\widetilde{T}$

Infidel experimentalist's favorites:

(SM-like charges and QCD production)

Interpretation Strategy

(Matsedonsky, Panico, AW, 2014)

To interpret a search, we don't need (have!) to use a model

A non-model: all possible couplings are free parameters

(see arXiv:1211.5663, HEPMDB link: http://hepmdb.soton.ac.uk/hepmdb:0214.0153)

		couplings			
partner (MG name)	Q	$W^\pm$	Z	h	$W^\pm W^\pm$
$T_{2/3}$ (T23)	$2/3$	$c_L^{TW},\ c_R^{TW}$	$c_L^{TZ},\ c_R^{TZ}$	$c_L^{Th},\ c_R^{Th}$	—
$B_{1/3}$ (B13)	$-1/3$	$c_L^{BW},\ c_R^{TW}$	$c_L^{BZ},\ c_R^{BZ}$	$c_L^{Bh},\ c_R^{Bh}$	—
$X_{5/3}$ (X53)	$5/3$	$c_L^{XW},\ c_R^{XW}$	—	—	—
$Y_{4/3}$ (Y43)	$-4/3$	$c_L^{YW},\ c_R^{YW}$	—	—	—
$V_{8/3}$ (V83)	$8/3$	—	—	—	$c_L^{VW},\ c_R^{VW}$

Telling which one to turn on for a given search channel is what phenomenologist are (or should be) payed for!

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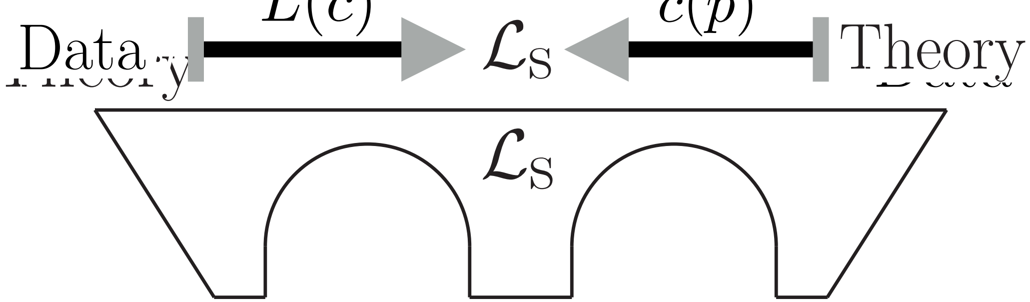
$$\begin{aligned}\mathcal{L} = \; & \frac{g_w}{2}\left[c_R^{XV}\,\overline{X}_R \not{V} t_R + c_L^{XV}\,\overline{X}_L \not{V} t_L\right] + \frac{g_w}{2}\left[c_L^{XV}\,\overline{X}_L \not{V} b_L + c_R^{XV}\,\overline{X}_R \not{V} b_R\right] \\ + \; & \left[c_R^{Xh}\, h\,\overline{X}_L t_R + c_L^{Xh}\, h\,\overline{X}_R t_L\right] + \left[c_L^{Xh}\, h\,\overline{X}_R b_L + c_R^{Xh}\, h\,\overline{X}_L b_R\right] + \mathrm{h.c.}\,,\end{aligned}$$

Explicit models cover different regions of the parameter space



Limits on "c" easily translated in any model

Interpretation Strategy

(Matsedonsky, Panico, AW, 2014)

Example: 2ssl plus jets $\left\{ \begin{array}{l} \text{CMS-B2G-12-012} \\ \text{ATLAS-CONF-2013-051} \end{array} \right.$

Potentially sensitive to pair and to single $X_{5/3}$ production

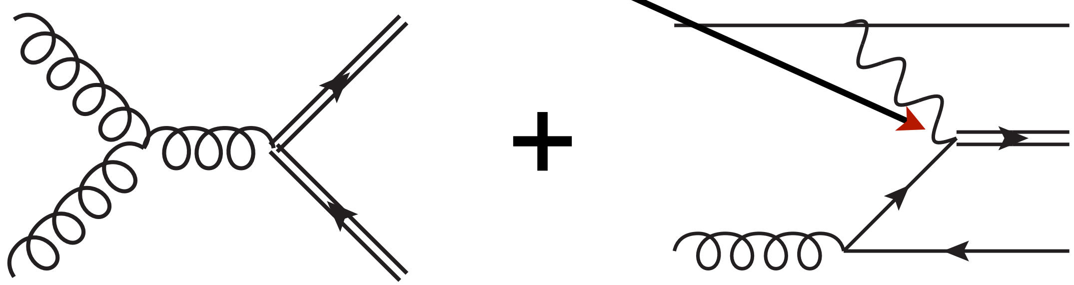
Interpretation Strategy

(Matsedonsky, Panico, AW, 2014)

Example: 2ssl plus jets { CMS-B2G-12-012 / ATLAS-CONF-2013-051

Potentially sensitive to pair and to single $X_{5/3}$ production

$$\mathcal{L}_{5/3} = \frac{g_w}{2} c_R \overline{X}_{5/3R} \not{W} t_R + \text{h.c.}$$



$$S = \mathcal{L} \sum_n \mathrm{BR}_n \, \epsilon_n \, \sigma_n(M_n)$$

Interpretation Strategy

(Matsedonsky, Panico, AW, 2014)

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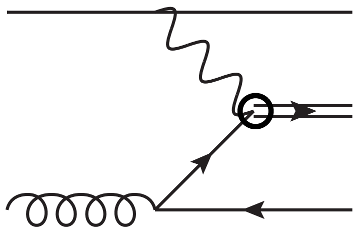
Acceptances/Efficiencies $e_n = \mathrm{BR}_{\mathrm{n}} \epsilon_n$ tot. signal eff.

Cross-Sections in **semi-analytical** form:

$\sigma_{pair}(M_X)$ Universal QCD pair from MC

$$\sigma_{\mathrm{sing}}(X\bar{t}) = c_R^2 \, \sigma_{Wt}(M_X)$$

fact. coupling



Interpretation Strategy

(Matsedonsky, Panico, AW, 2014)

Efficiencies from recasting:
(one simulation per mass point)

CMS pair [%]

M [GeV]	$Q=\frac{5}{3}$ right
700	2.27
800	2.64
900	2.85

CMS single [%]

M [GeV]	$Q=\frac{5}{3}$ right
700	0.185
800	0.269
900	0.308

ATLAS pair [%]

M [GeV]	$Q=\frac{5}{3}$ right
700	2.17
800	2.23
900	2.22
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1100	2.24
1200	2.23

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CMS loses on single prod.

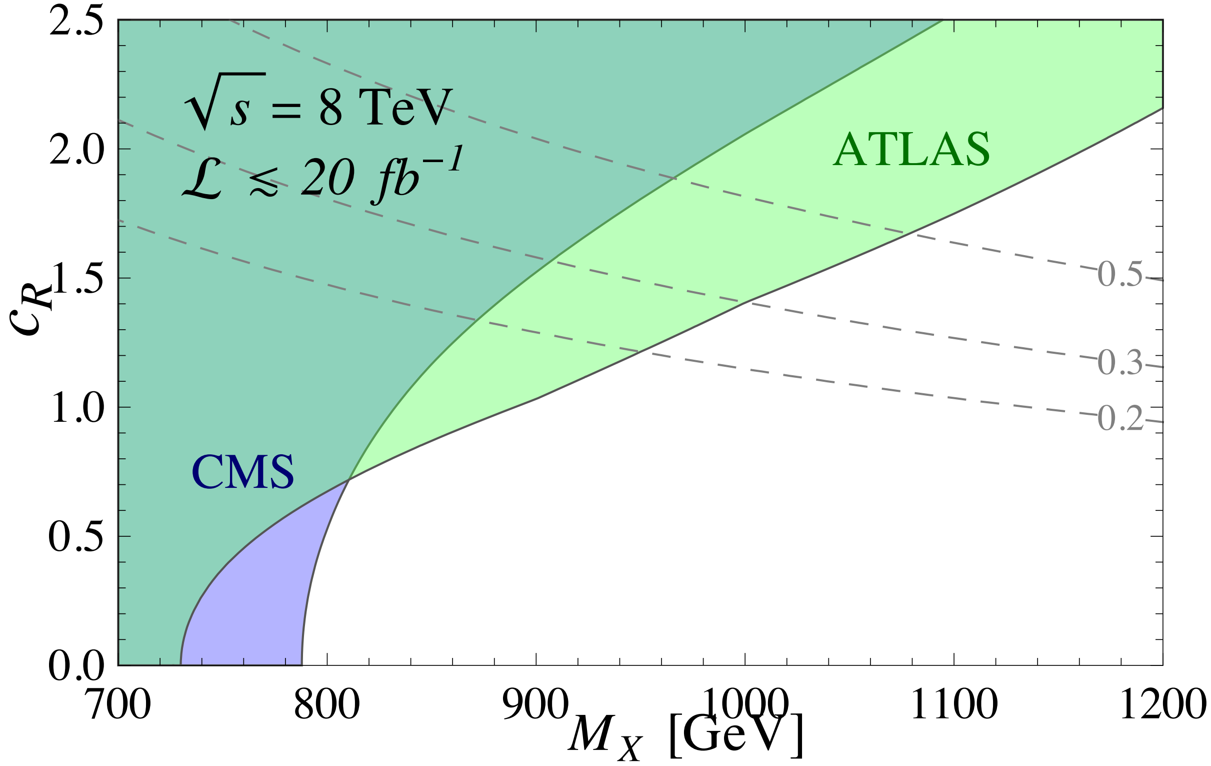
mainly due to $N_{con} \geq 5$

for ATLAS, 2 jets are enough

Interpretation Strategy

(Matsedonsky, Panico, AW, 2014)

Current Limit:



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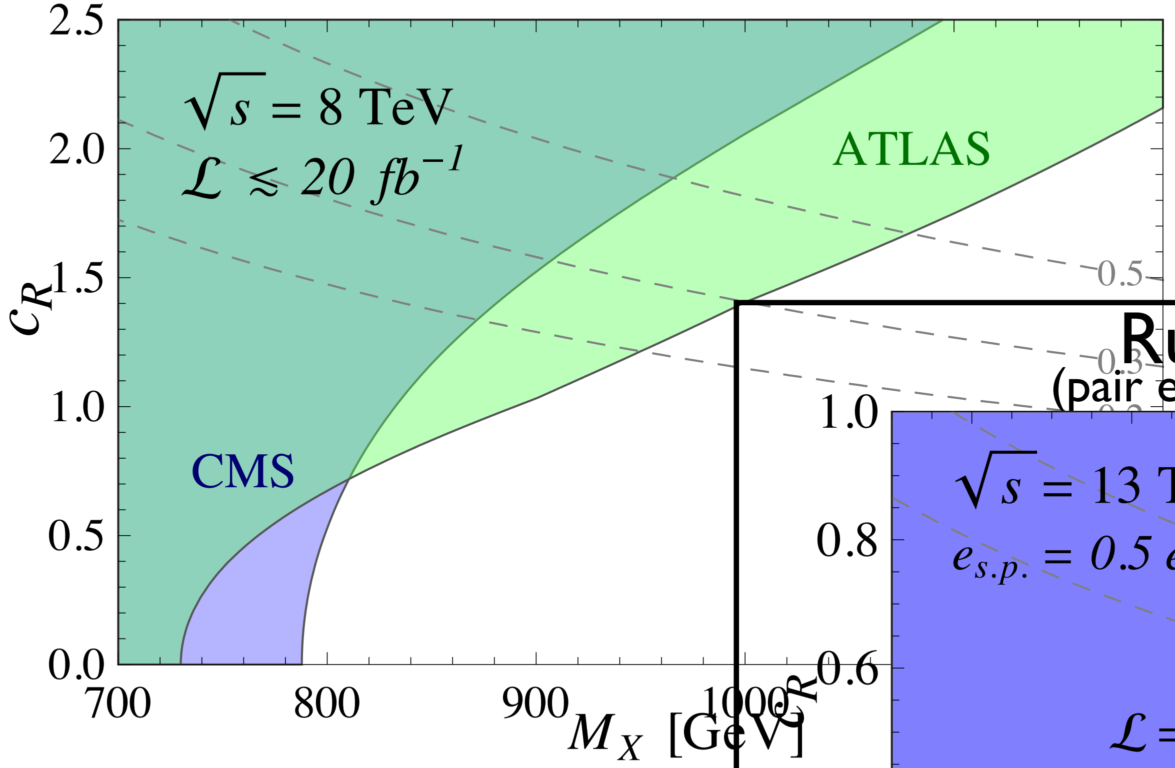
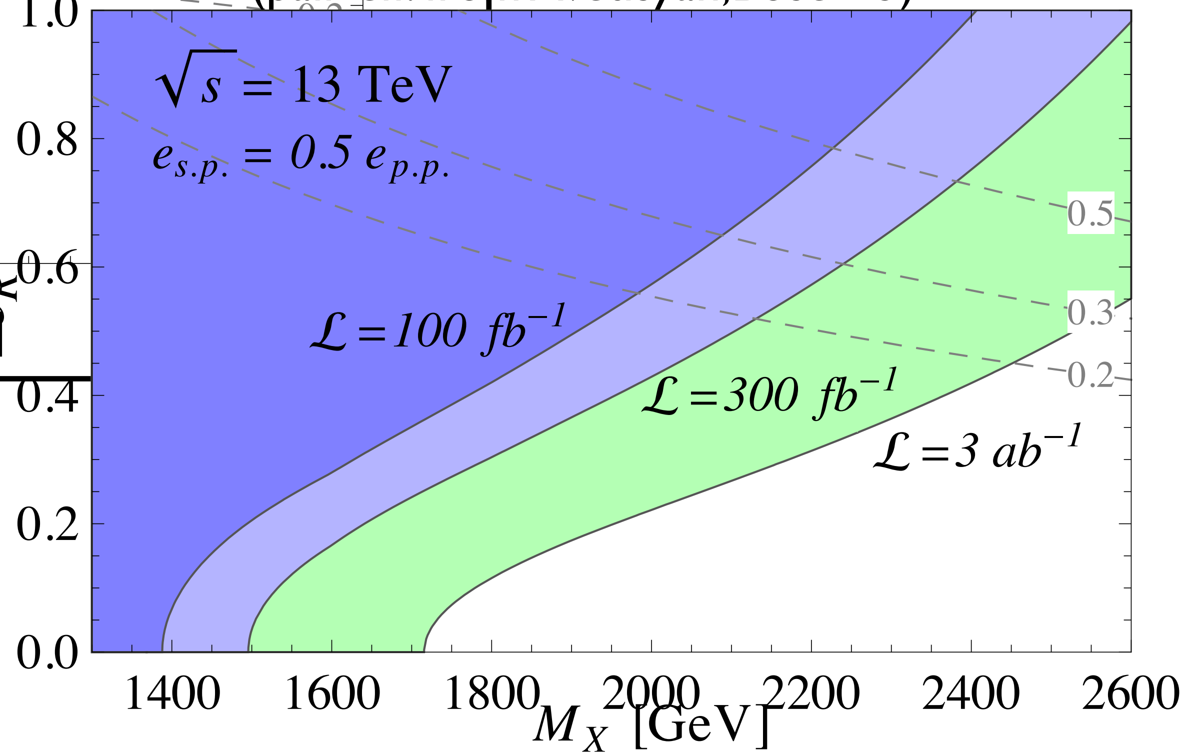


Run-2 Projection:

(pair eff. from Avetisyan, Bose '13)

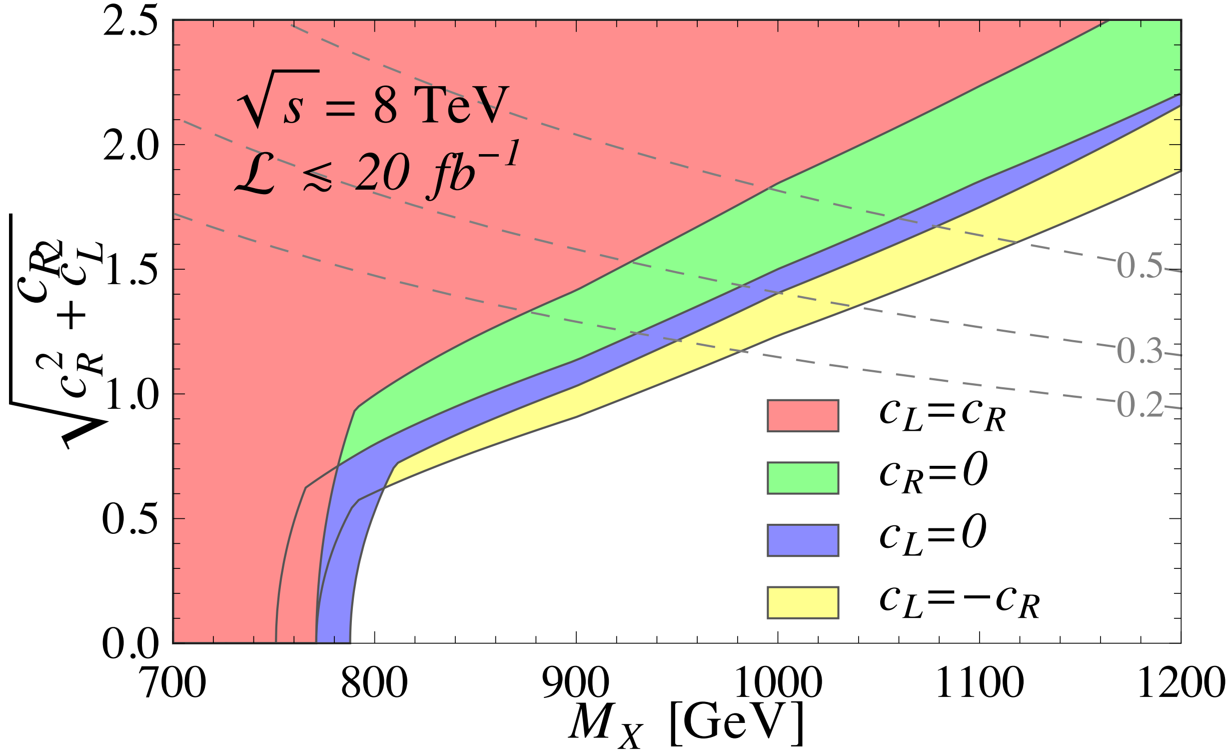


Interpretation Strategy

(Matsedonsky, Panico, AW, 2014)

Limits depend on coupling chirality:

Current Limit:



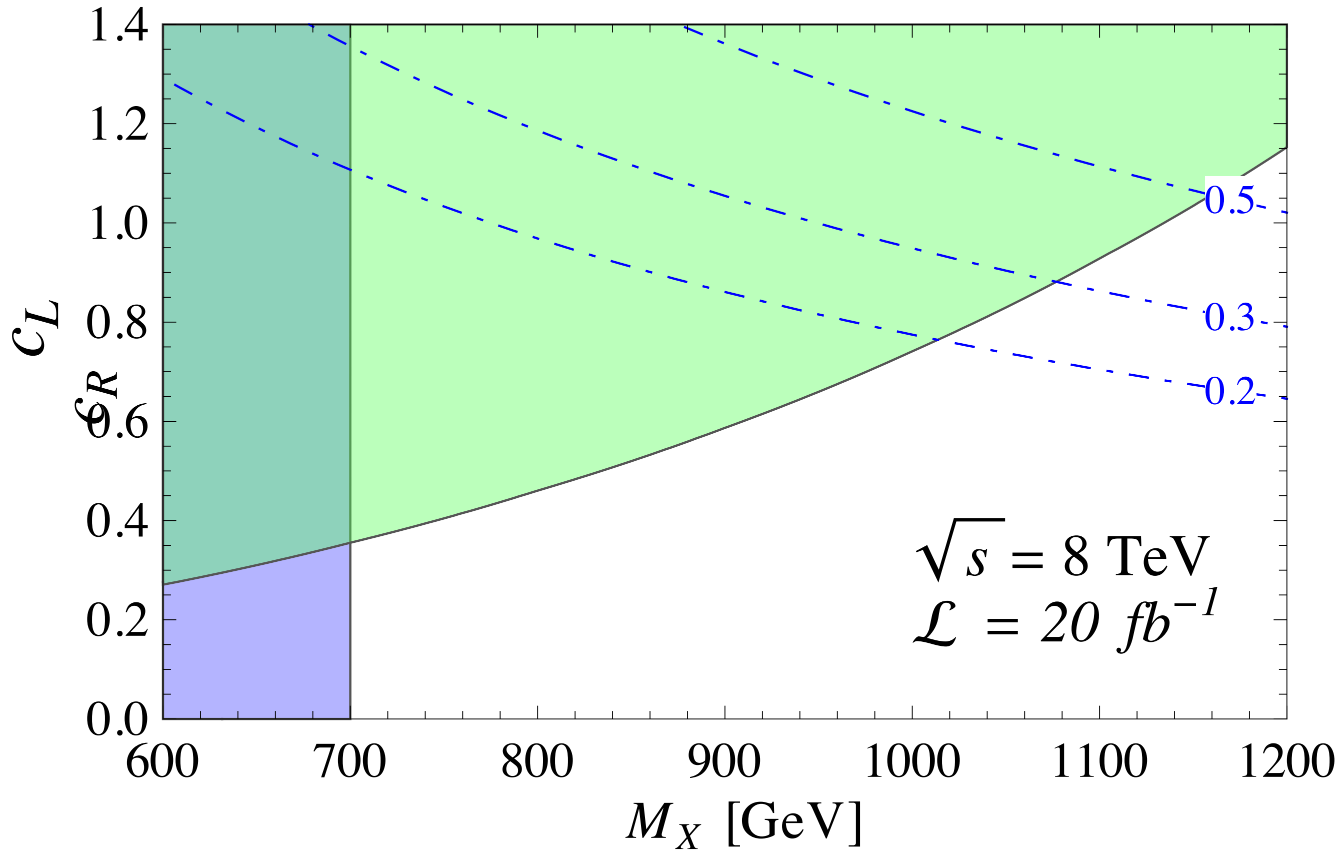
Details in Backup, ask if interested

Interpretation Strategy

(Matsedonsky, Panico, AW, 2014)

$\widetilde{T}$ searches at 8 TeV:

- pair prod. from ATLAS and CMS
- estimated single production reach from (Ortiz, Ferrando, Kar, Spannowsky, 2014)

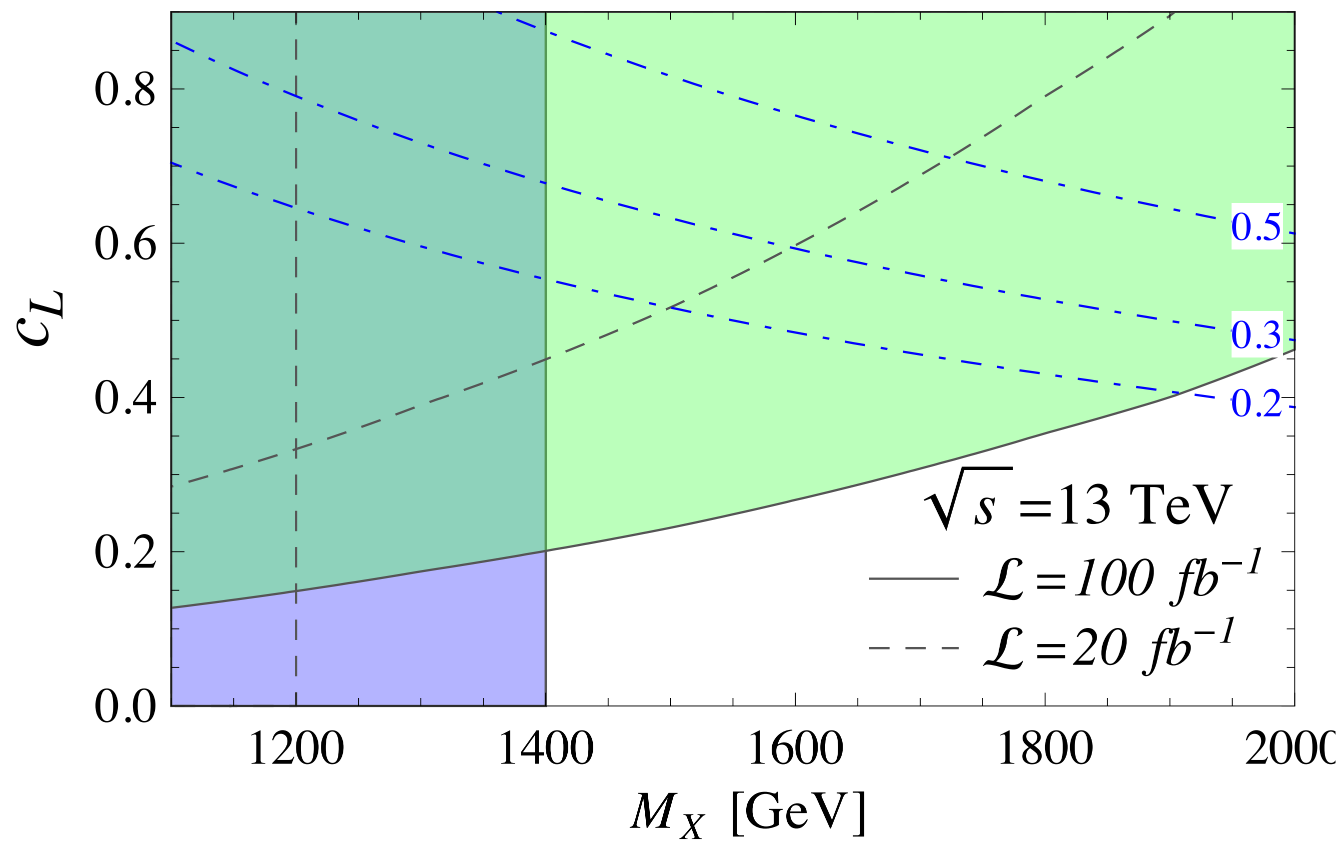


Interpretation Strategy

(Matsedonsky, Panico, AW, 2014)

Rough 13 TeV extrapolation:

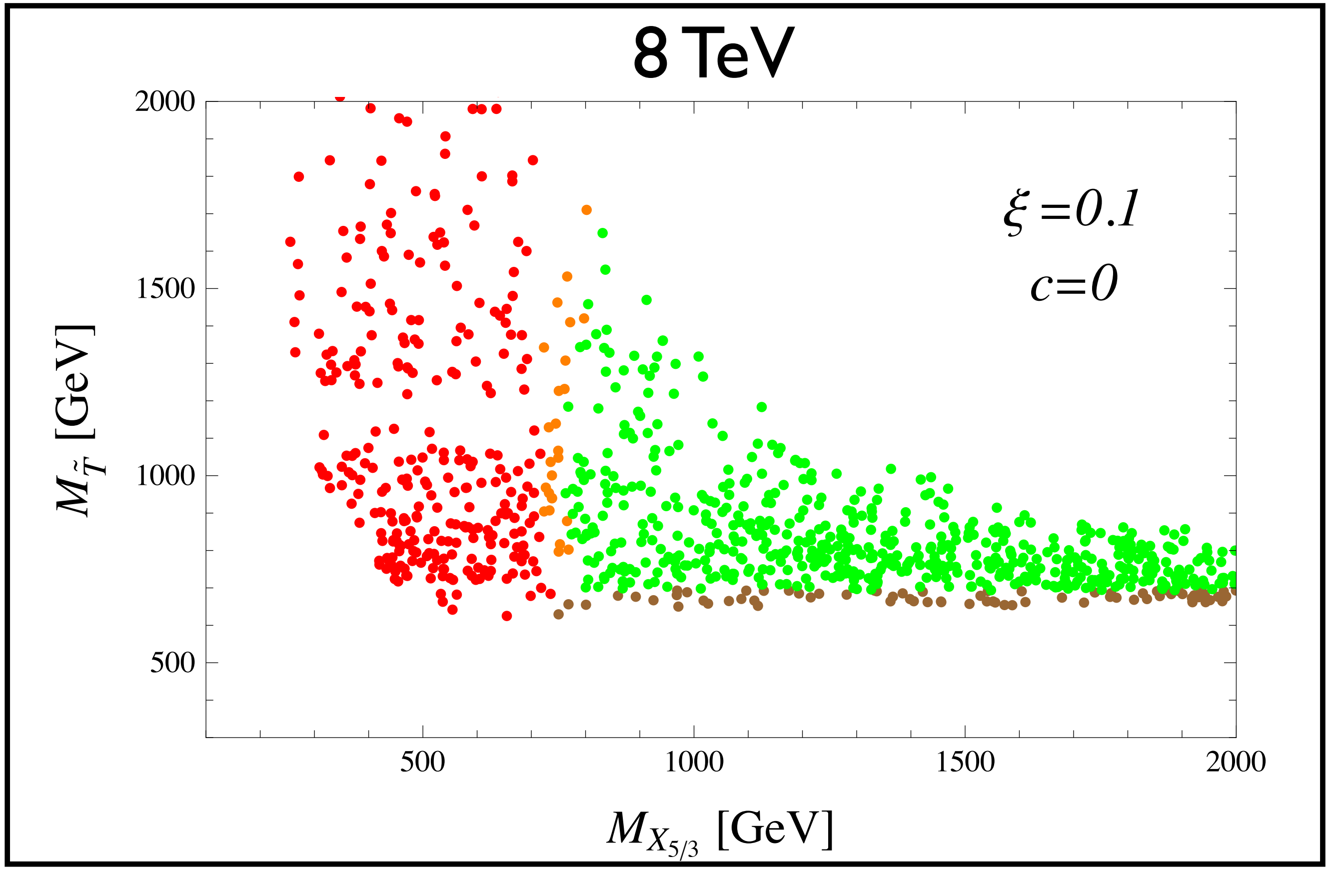
- assuming sensitivity to same number of produced Partners as at 8 TeV



Interpretation Strategy

(Matsedonsky, Panico, AW, 2014)

Impact on a concrete Composite Higgs model



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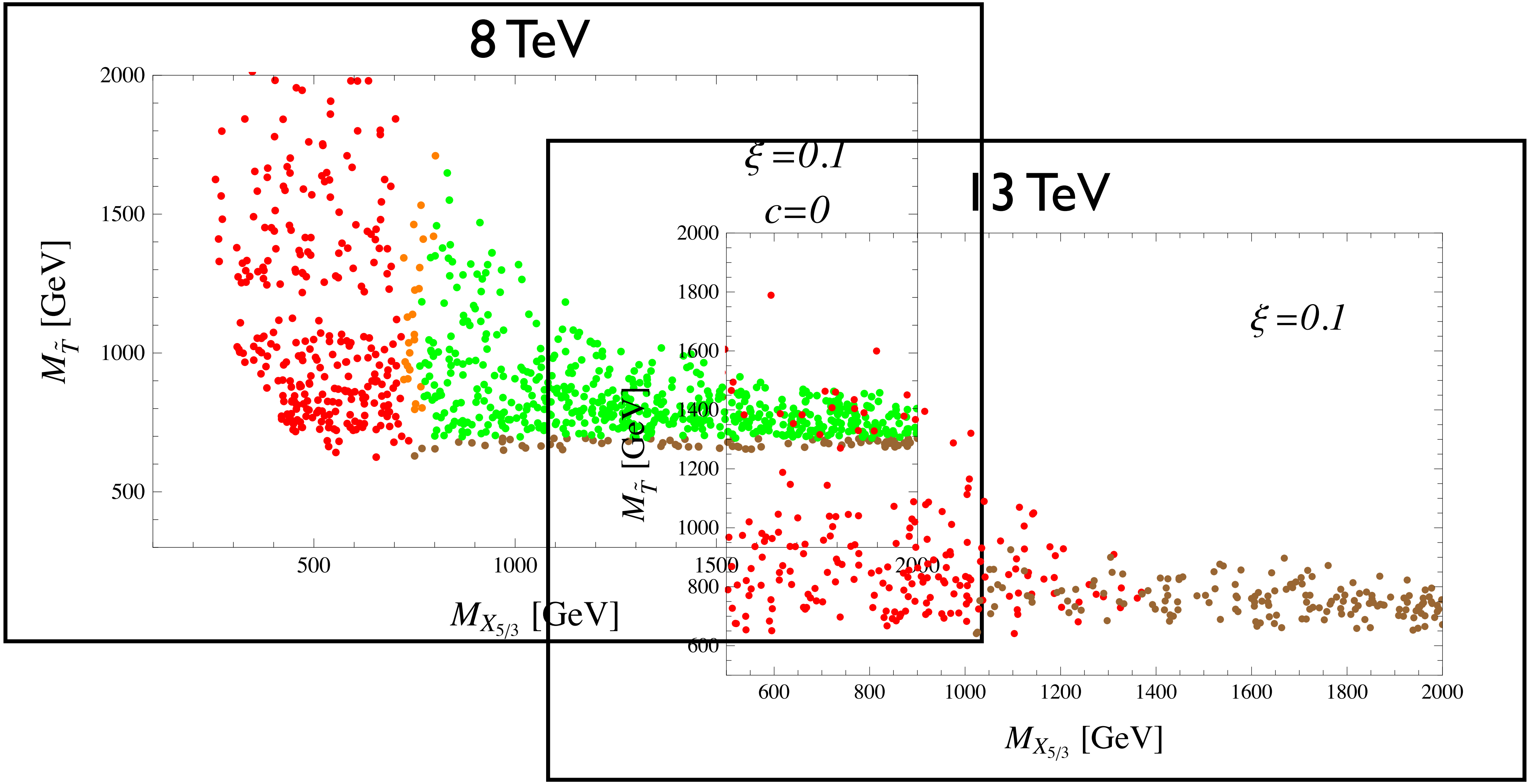
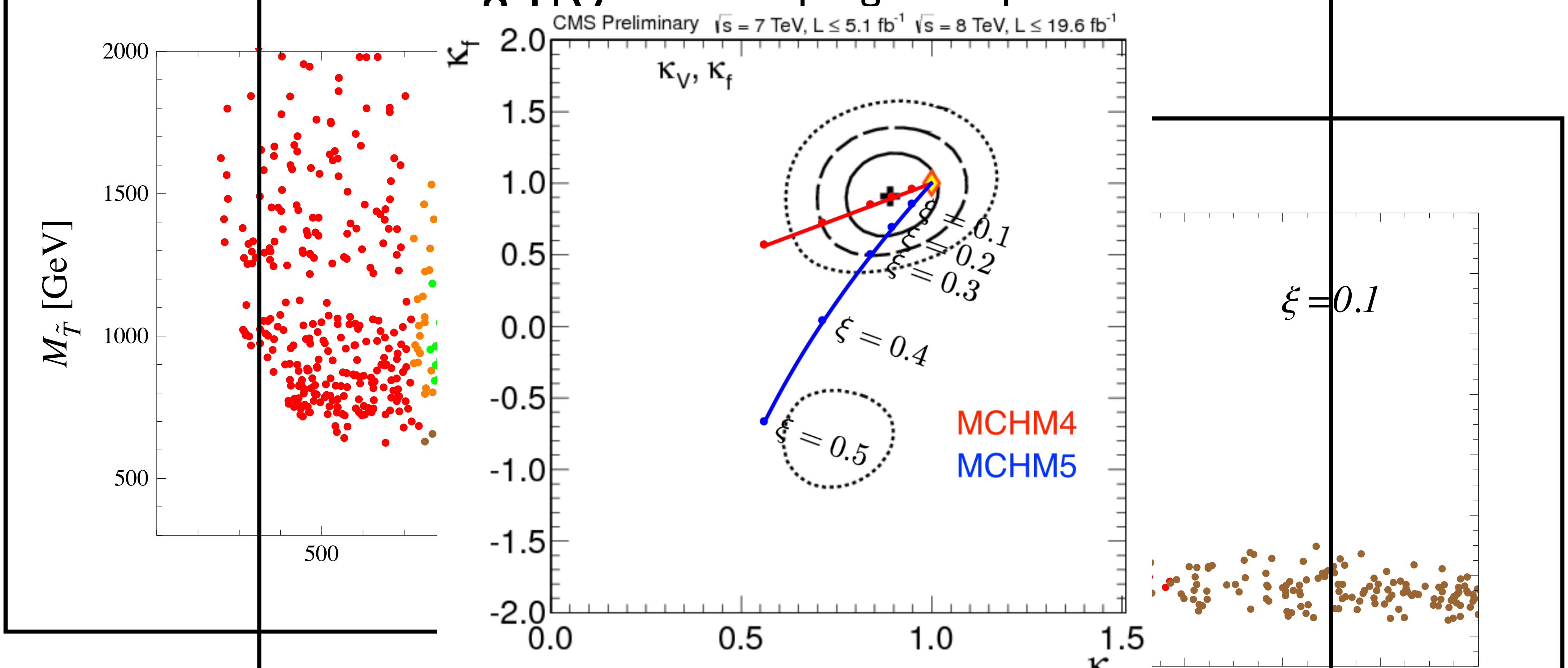


Interpretation Strategy

(Matsedonsky, Panico, AW, 2014)

Impact on a concrete Composite Higgs model

Compare with coupling deviations …



Top Partner searches are by far the most sensitive probes of CH at the LHC!

Other Partners

In Composite Higgs, each quark has a Partner
(Light families partners generically unrelated with Naturalness)

- Worth searching for them?
- Exotic/enhanced signatures?

Other Partners

In Composite Higgs, each quark has a Partner
(Light families partners generically unrelated with Naturalness)

Flavour Scheme

• Worth searching for them?			
• Exotic/enhanced signatures?			

The answer crucially depends on the scheme adopted
to incorporate Flavour structure and constraints

Other Partners

Fermionic Partners come from **partial compositeness**

Elementary Sector:

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

Elementary/Composite
mixing

Composite Sector:

Higgs
+
resonances

Other Partners

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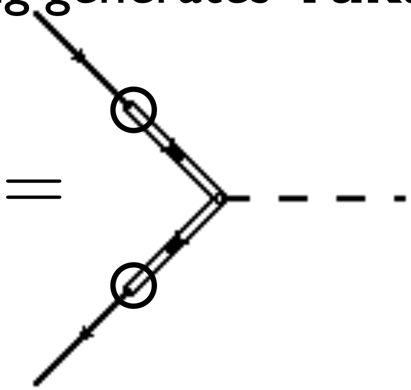
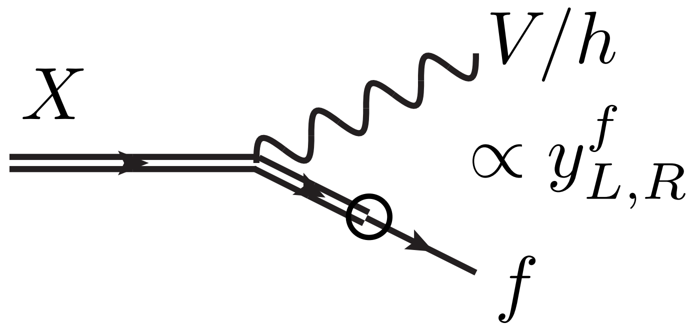
mixing generates **Yukawas...**

$y_f =$  $\propto y_L^f y_R^f$

... and **single Partner couplings**



y_{top} is large. Thus the Top **must** have large mixing.

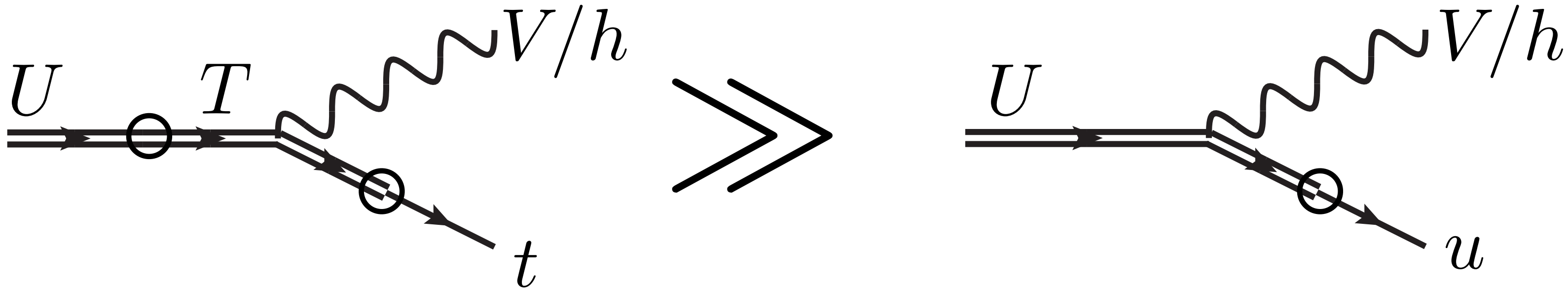
Light quarks **can** have one large mixing, but need not.

Other Partners

Anarchic Ⓐ Flavour Scheme

I: $y_L^f \simeq y_R^f \propto \sqrt{y_f}$ $\left\{ \begin{array}{l} \text{Large Top Mixing} \\ \text{Small Other Quarks Mixings} \end{array} \right.$

II: Flavour Anarchy. All Partner couplings/mixings allowed
No distinction among "Top" and "Other" Partners



Top Partner searches cover Other Partners as well

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Flavour Scheme

	Ⓐ		
• Worth searching for them?	**NO**		
• Exotic/enhanced signatures?	**NO**		

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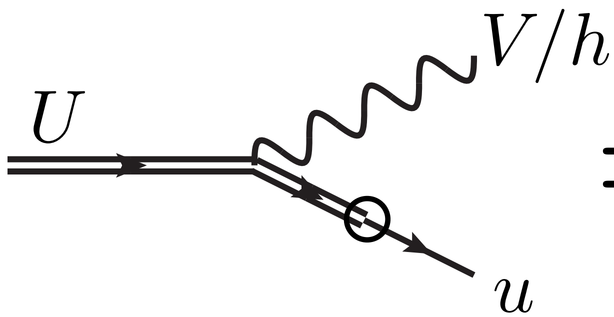
Other Partners

$U(3)^3$ Flavour Scheme

I: $y_R^u = y_R^c = y_R^t$ $\begin{cases} y_f \text{ by a very small } y_L^f \\ \text{Large } u_R, c_R, t_R \text{ Mixings} \end{cases}$

II: Flavour **Symmetry** in the Strong Sector

Distinct Phenomenology (e.g., decay to jets)



$=$ "Large"

New single production modes

Other Partners

In Composite Higgs, each quark has a Partner
(Light families partners generically unrelated with Naturalness)

Flavour Scheme

	Ⓐ	$\mathrm{U}(3)^3$	
• Worth searching for them?	**NO**	**YES**	
• Exotic/enhanced signatures?	**NO**	**YES**	

The answer crucially depends on the scheme adopted
to incorporate Flavour structure and constraints

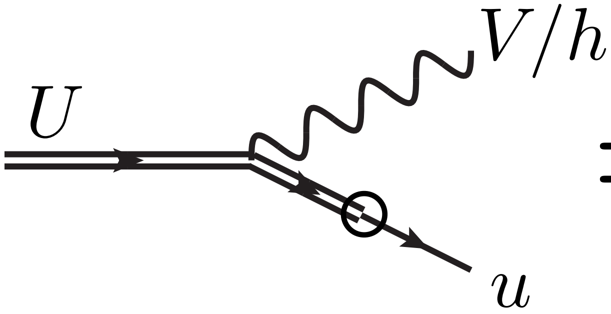
Other Partners

$U(2)^3$ Flavour Scheme

I: $\quad y_R^u = y_R^c \ll y_R^t$

II: Flavour **Symmetry** for the Light Families

Distinct Phenomenology (e.g., decay to jets)



$=$ “Small”

NO new single production modes

Other Partners

In Composite Higgs, each quark has a Partner

(Light families partners generically unrelated with Naturalness)

Flavour Scheme

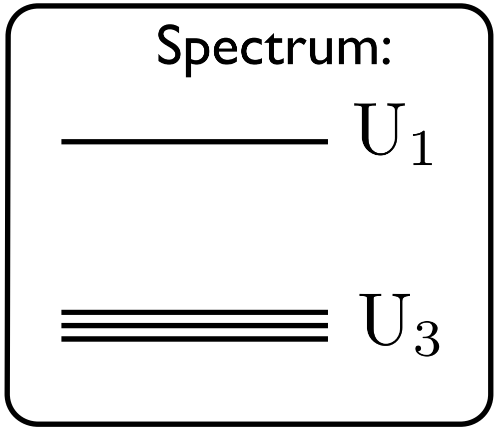
	Ⓐ	$\mathrm{U}(3)^3$	$\mathrm{U}(2)^3$
• Worth searching for them?	**NO**	**YES**	**YES**
• Exotic/enhanced signatures?	**NO**	**YES**	**NO**

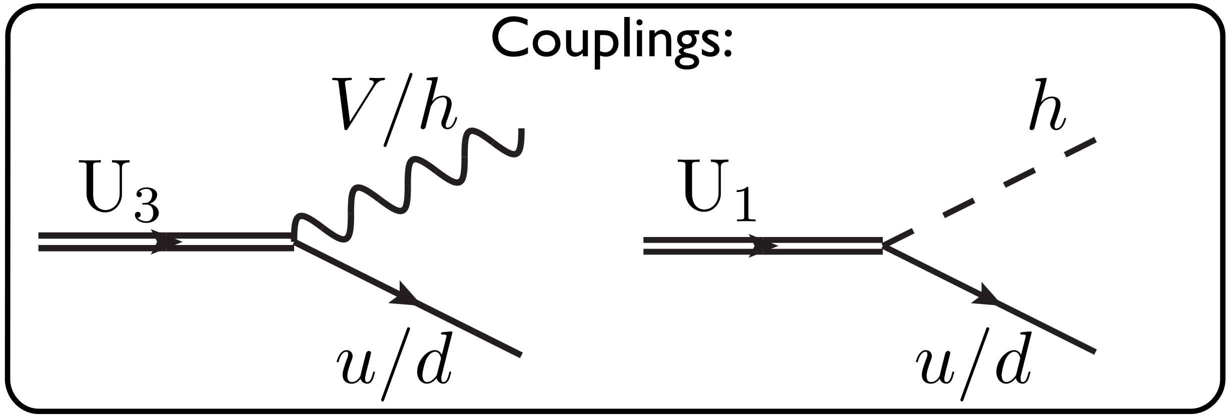
The answer crucially depends on the scheme adopted to incorporate Flavour structure and constraints

Other Partners Phenomenology

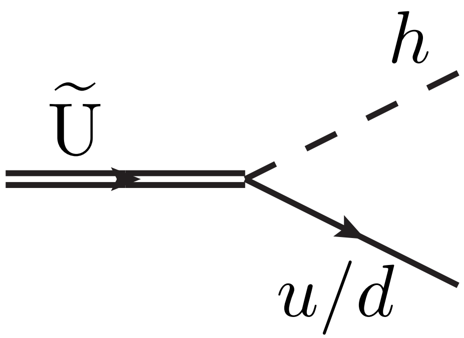
(from Panico, Perez et.al., 2013)

Fourplet of custodial $\mathrm{SO}(4)$: $\mathrm{U}_3 = \{U, D, X_{5/3}\}$ **+** $\mathrm{U}_{(1)}$





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

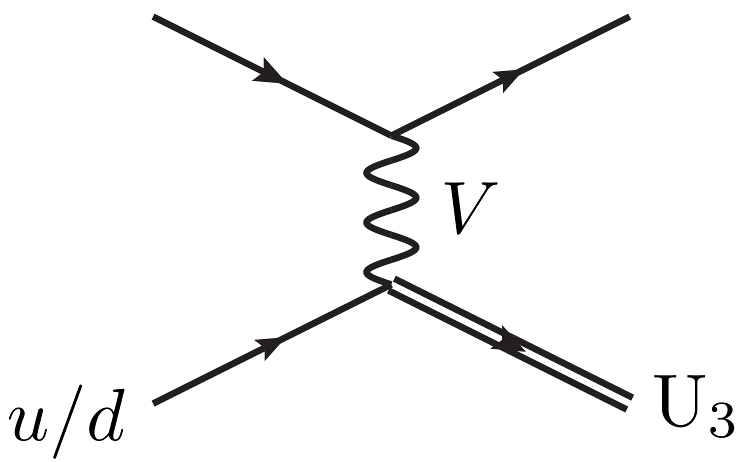


Singlets only couple to the Higgs

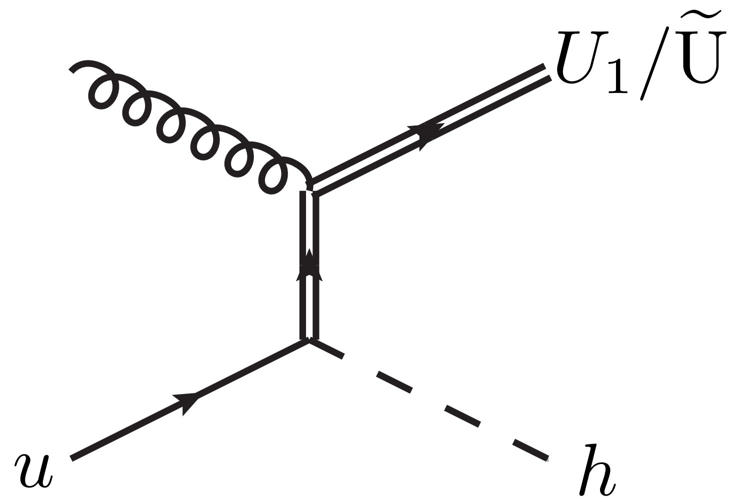
Other Partners Phenomenology

(from Panico, Perez et.al., 2013)

New Single Production channels:



Similar to Top Partners



Radically new

Other Partners Phenomenology

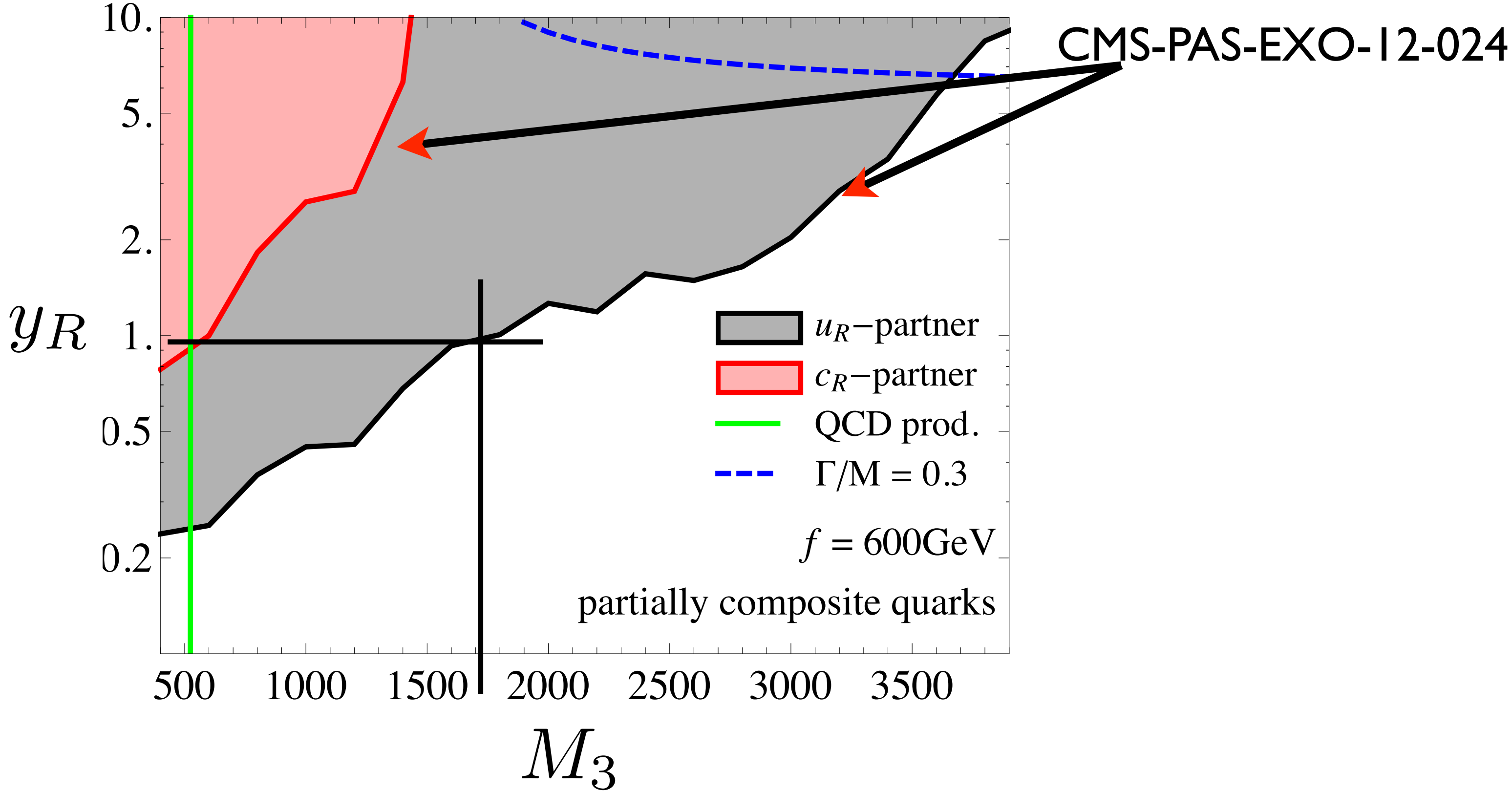
(from Panico, Perez et.al., 2013)

Triplet Mass from pair production:

$$M_3 > 530 \text{ GeV}$$

recasting CMS leptoquark (CMS-PAS-EXO-12-042)

Triplet from single production:



Other Partners Phenomenology

(from Panico, Perez et.al., 2013)

Singlet is basically unbounded!

Other Partners Phenomenology

(from Panico, Perez et.al., 2013)

Relevant channels:

Decay

Production

	$W + j$	$Z + j$	$h + j$
Pair Production	$D, X_{5/3}$	U	$U_1, \widetilde{U}$
Single + Higgs			$U_1, \widetilde{U}$
Single (+fwd jet)	$D, X_{5/3}$	U	

Conclusions and Outlook

Top Partner searches allow to test Naturalness in a non-SUSY context.

Even a negative result, discovering "Unnaturalness" would be a valuable information towards the understanding of Fundamental Interactions.

Top Partner phenomenology is simple enough to be studied in general by a Simplified Model approach. Efficient coverage of explicit models.

Other Partners can couple strongly to light quarks and display peculiar production and decay modes.

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Backup

In some corner of the par. space, $c_L \sim c_R$

$$\mathcal{L}_{5/3} = \frac{g_w}{2} c_R \, \overline{X}_{5/3R} \not{W} t_R + \frac{g_w}{2} c_L \, \overline{X}_{5/3L} \not{W} t_L + \text{h.c.}$$

New cross-section formula:

$$\sigma_{\text{sing}}(X\bar{t}) = \left(c_R^2 + c_L^2\right) \sigma_{Wt}(M_X) + c_R \, c_L \left(\frac{m_t}{M_X + m_t} \right) \sigma'_{Wt}(m_X)$$

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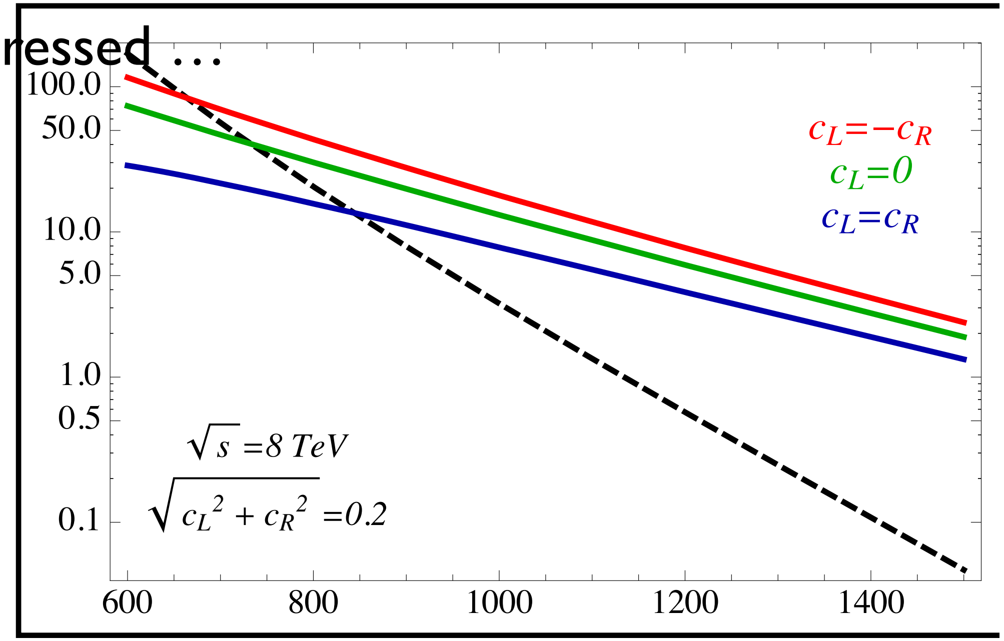
  but **numerically enhanced:**

  $\sigma'_{Wt}(M_X) \simeq -5.2\,\sigma_{Wt}(M_X)$.



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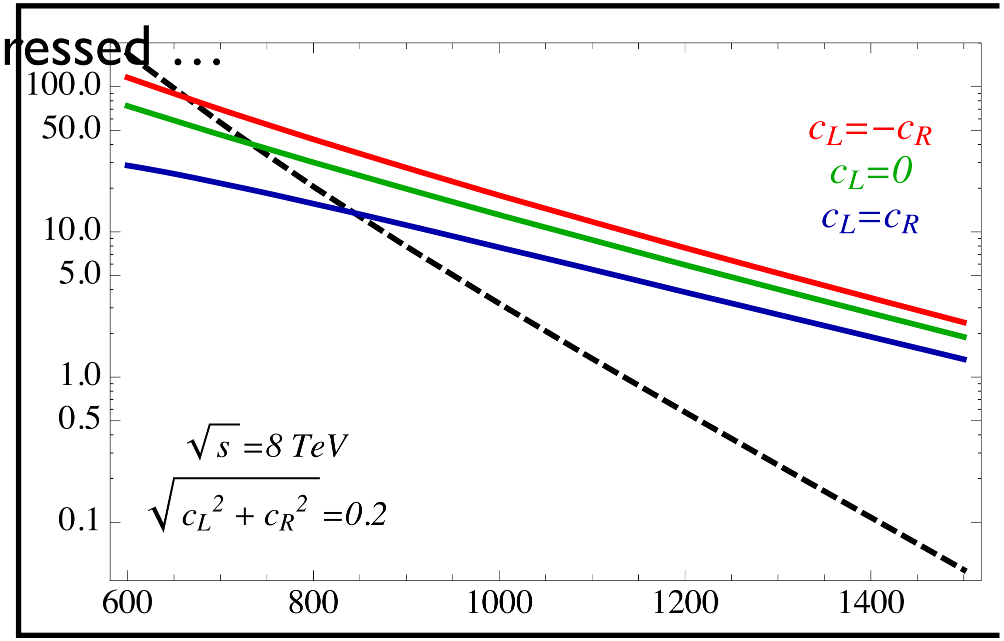
  $\sigma'_{Wt}(M_X) \simeq -5.2\, \sigma_{Wt}(M_X)$

- use full formula



Backup

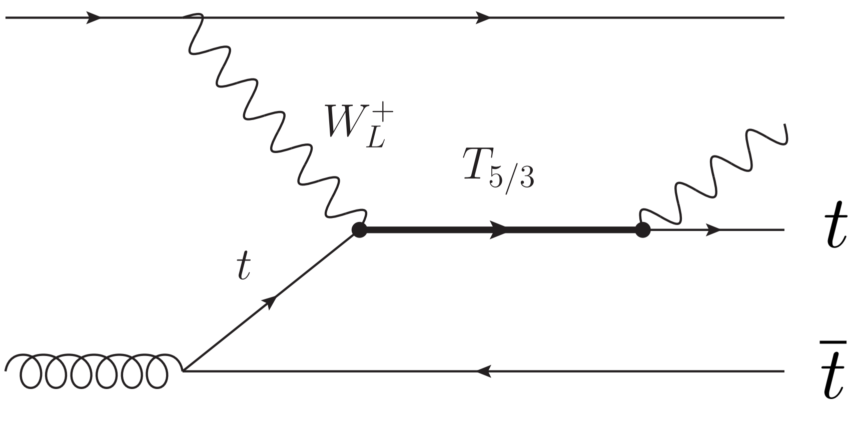
Mild changes in efficiencies:

ATLAS, single prod. eff. [%]

M [GeV]	$Q=\frac{5}{3}$ right	$Q=\frac{5}{3}$ left
700	1.14	0.952
800	1.26	1.01
900	1.31	1.10
1000	1.23	1.09
1100	1.26	1.13
1200	1.25	1.19

ATLAS, pair prod. eff. [%]

M [GeV]	$Q=\frac{5}{3}$ right	$Q=\frac{5}{3}$ left	$Q=-\frac{1}{3}$ (b') left [24]
700	2.17	1.87	1.84
800	2.23	1.95	2.03
900	2.22	2.00	2.06
1000	2.23	2.03	–
1100	2.24	2.07	–
1200	2.23	2.06	–



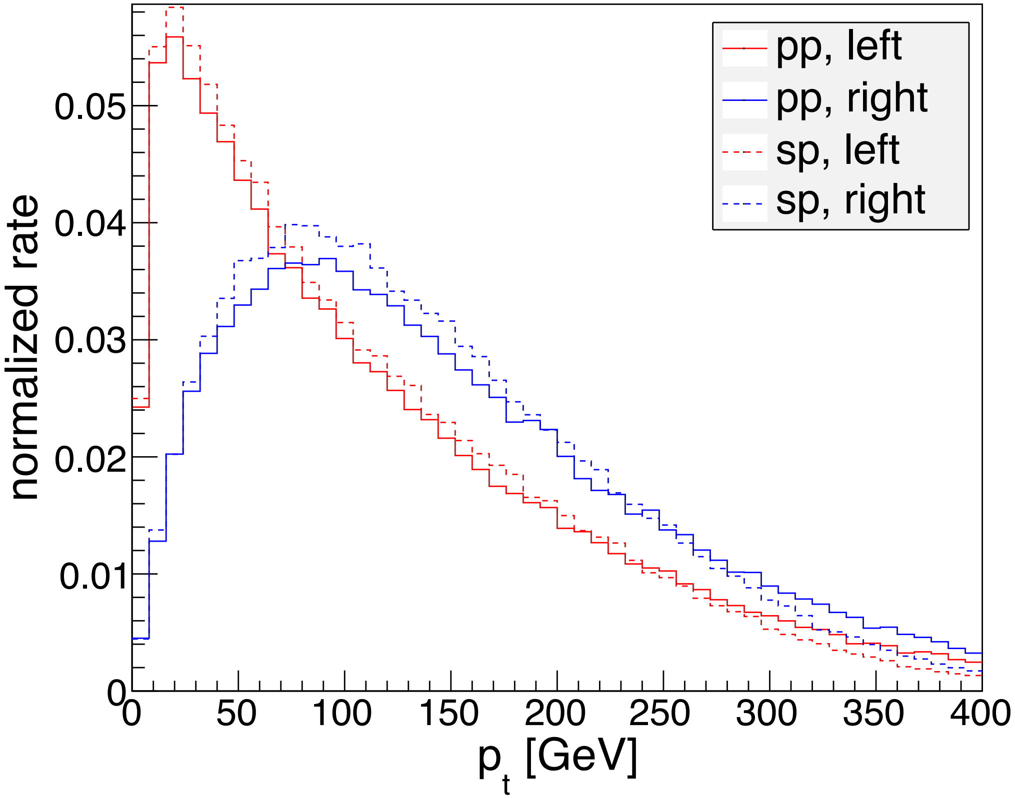
- chirality of boosted t modifies shape, lepton cut eff changes (20%)
- unboosted associated Top chirality has no impact

$$e_n = \frac{c_L^2}{c_L^2+c_R^2} e_n^L + \frac{c_R^2}{c_L^2+c_R^2} e_n^R$$

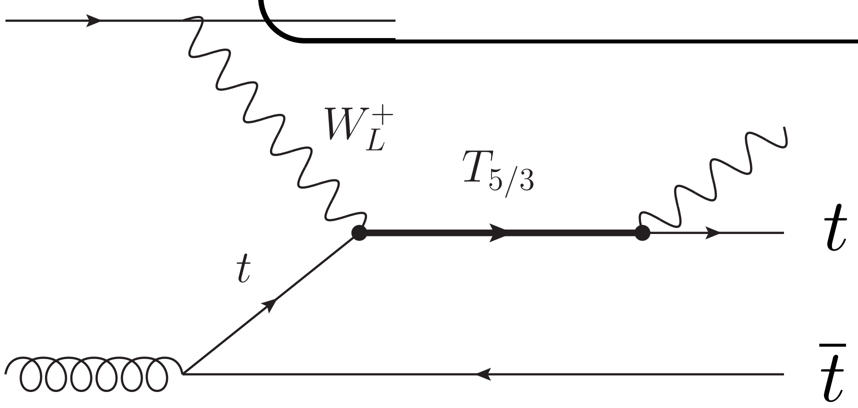
Backup

Mild changes ir

ssl distribution, pair and single production



ATLAS, s	od. eff. [%]	
M [GeV]	$= \frac{5}{3}$ t	$Q = -\frac{1}{3}$ (b') left [24]
700	7	1.84
800	5	2.03
900	0	2.06
1000	3	–
1100	7	–
1200	6	–



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$$e_n = \frac{c_L^2}{c_L^2 + c_R^2} e_n^L + \frac{c_R^2}{c_L^2 + c_R^2} e_n^R$$