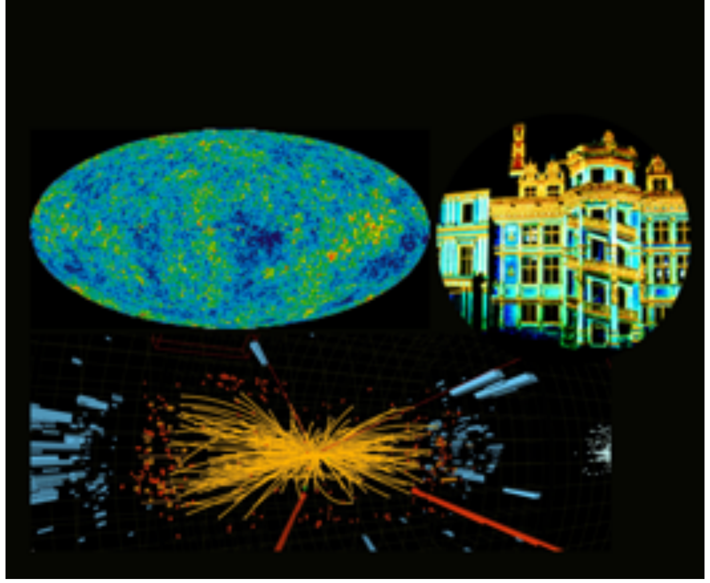
27th Rencontres de Blois



Particle Physics and Cosmology

Light Quark Composite Partners

Seung J. Lee

KAIST
한국과학기술원
Korea Advanced Institute of Science and Technology

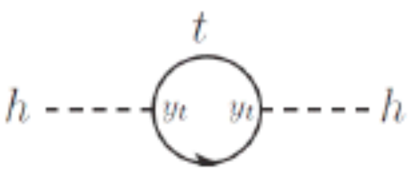
Delaunay, Fraille, Flacke, SL, Panico, Perez; JHEP 1402, 055 (2014)

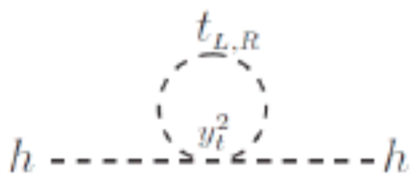
Flacke, Kim, SL, Lim; JHEP 1405, 123 (2014)

Backovic, Flacke, Kim, SL; JHEP 1504, 082 (2015)

Motivation

- Naturalness => new colored partners, potentially within the LHC reach.





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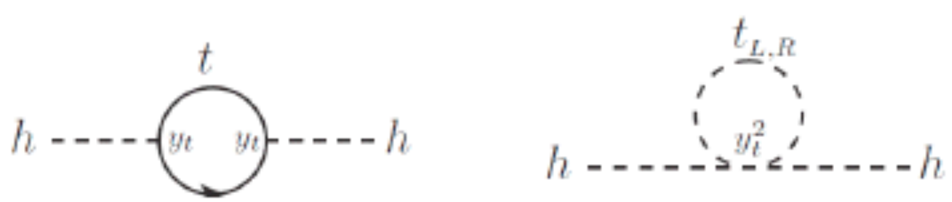

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2 leading frameworks
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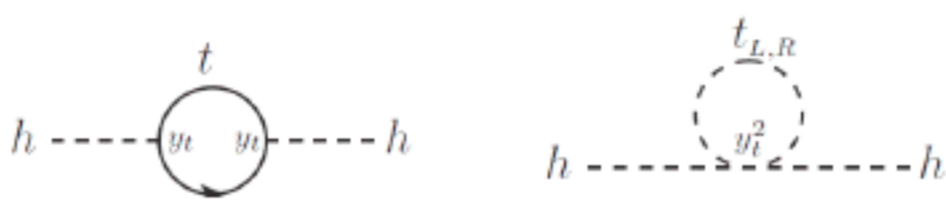

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top partners=stops

Composite Higgs
top partners = "T"

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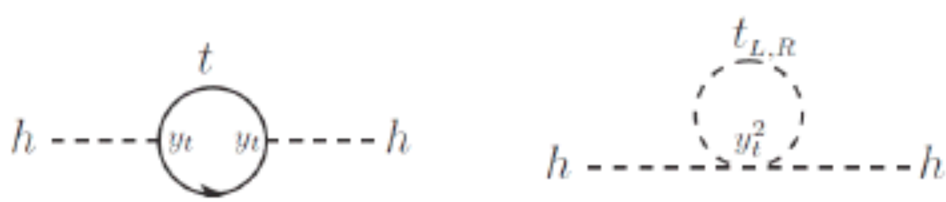

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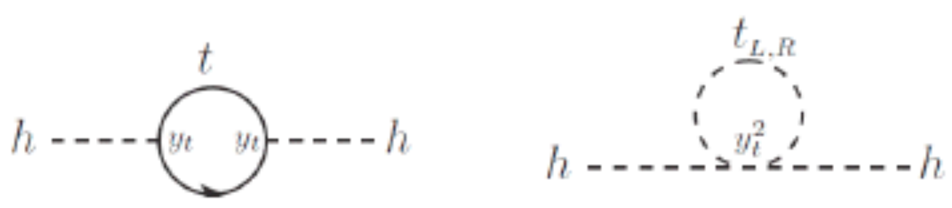

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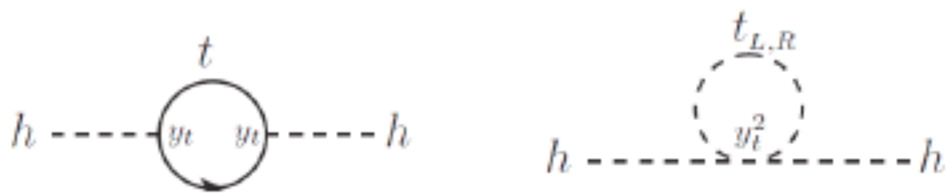
*Neutral Naturalness (a last resort…) is not discussed in this talk



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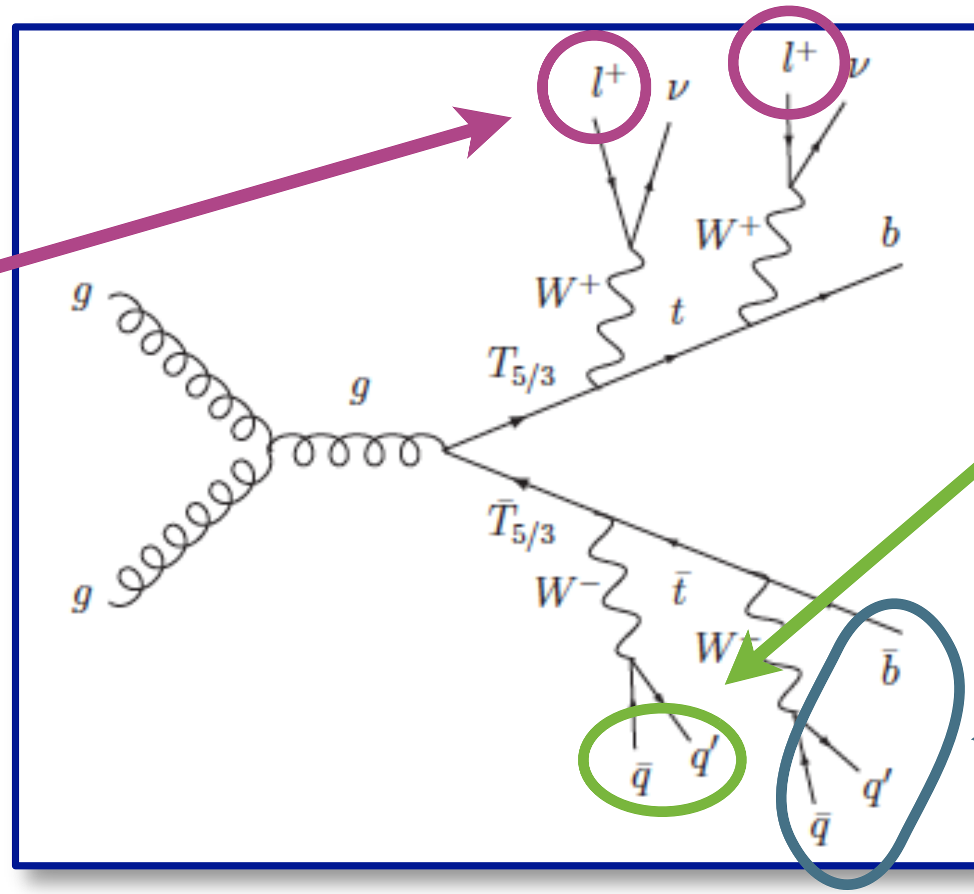
Composite Top Partner Searches @ Run 1

Simone, Matsedonski, Rattazzi, Wulzer `12
Azatov, Son, Spannowsky `13
Matsedonski, Panico, Wulzer `14

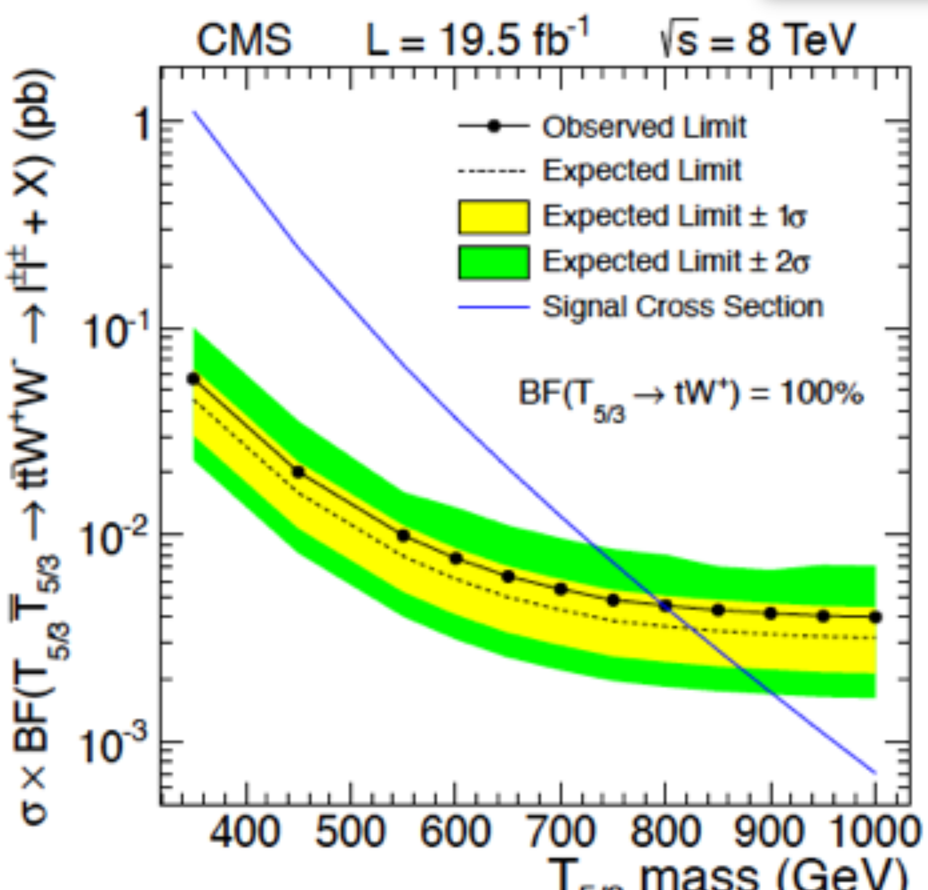
same-sign dileptons



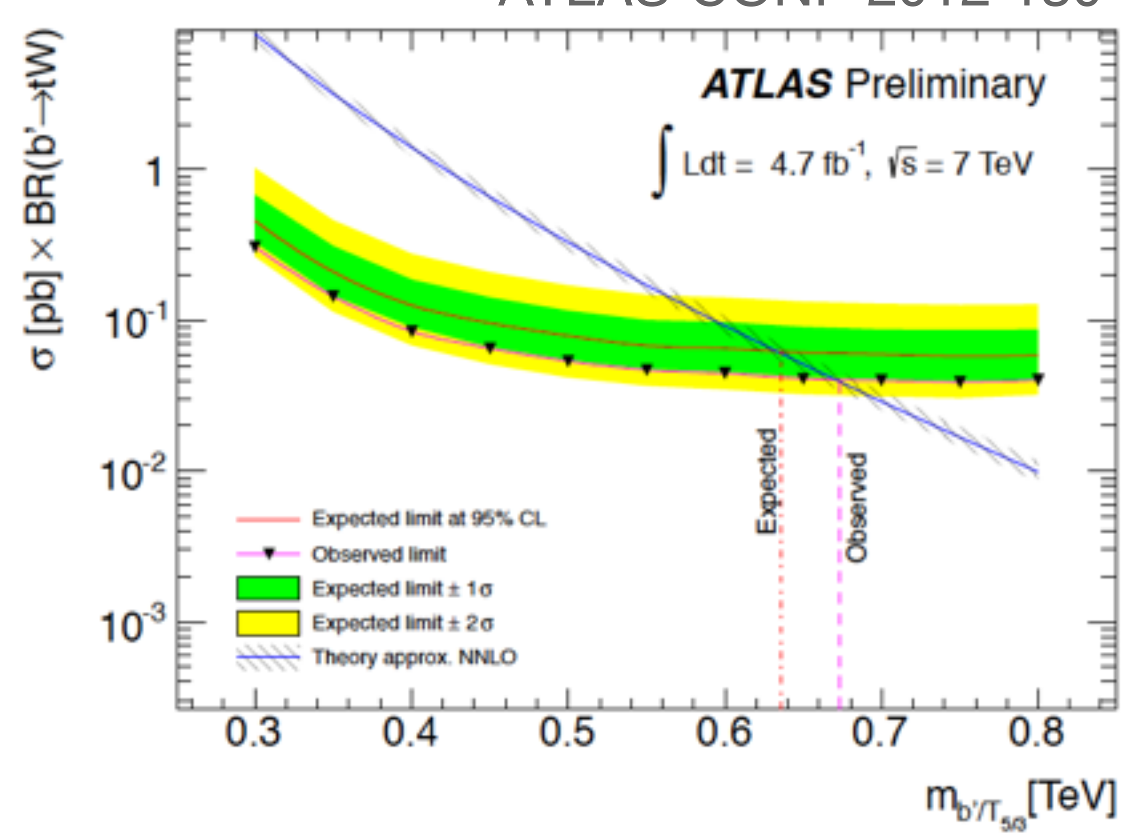
W tag:
2 subjets,
M_j[60,130]

CMS top tag

10.1103/PhysRevLett.112.171801



ATLAS-CONF-2012-130



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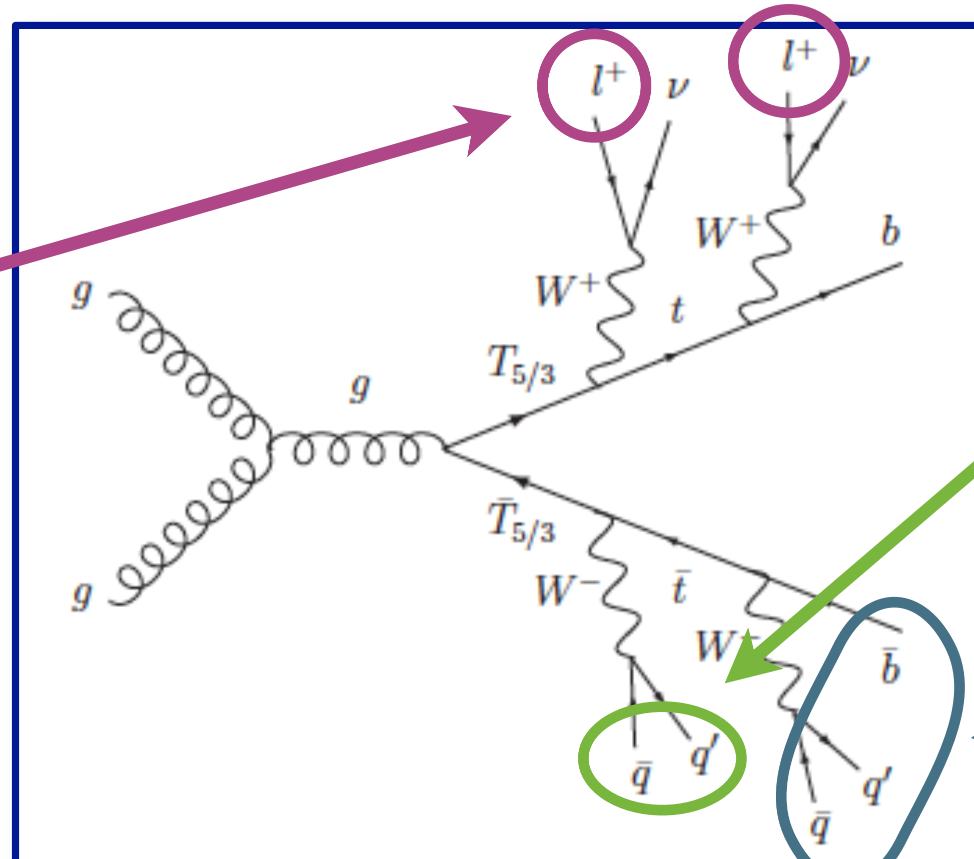

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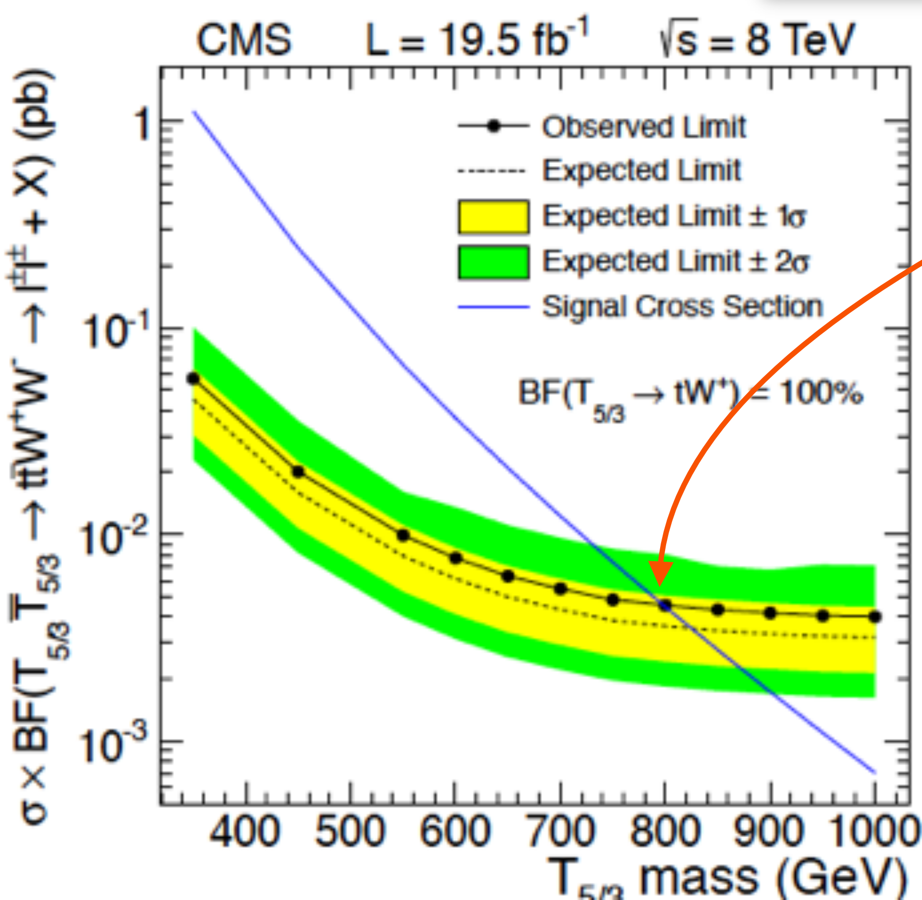

$$M_{X_{5/3}} \gtrsim 800\,\mathrm{GeV}$$

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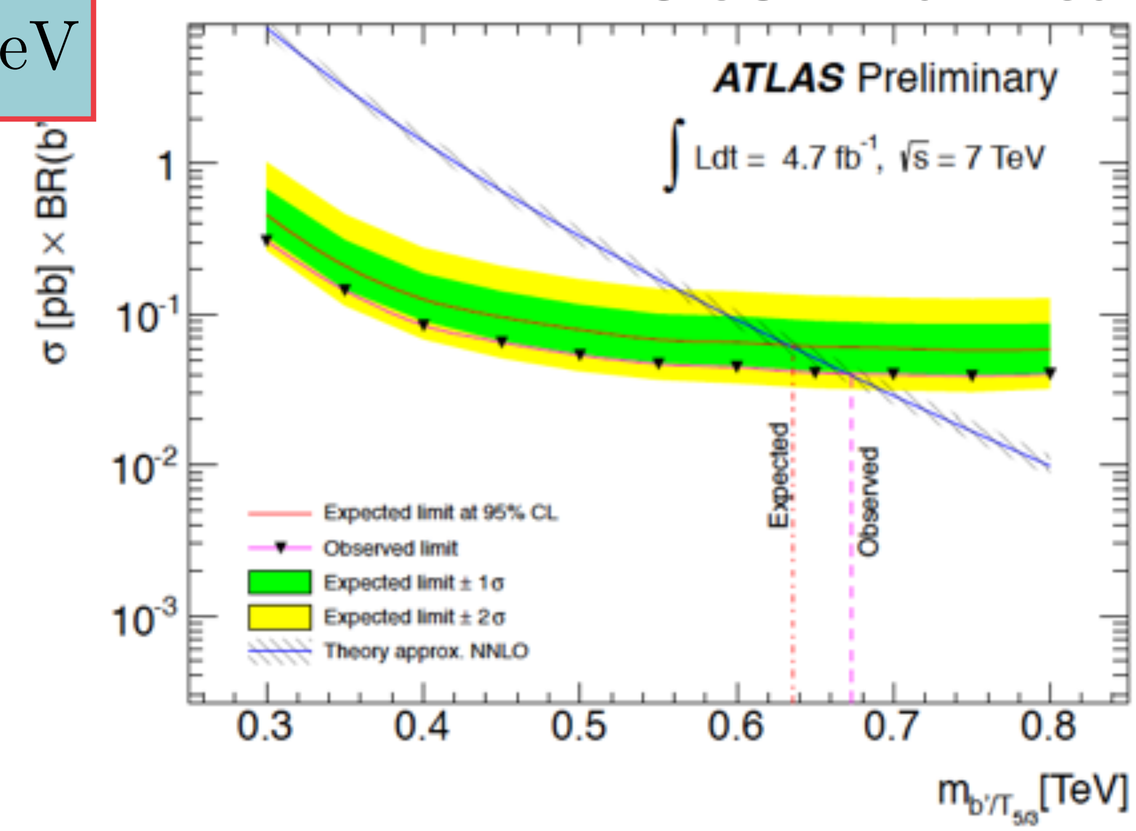

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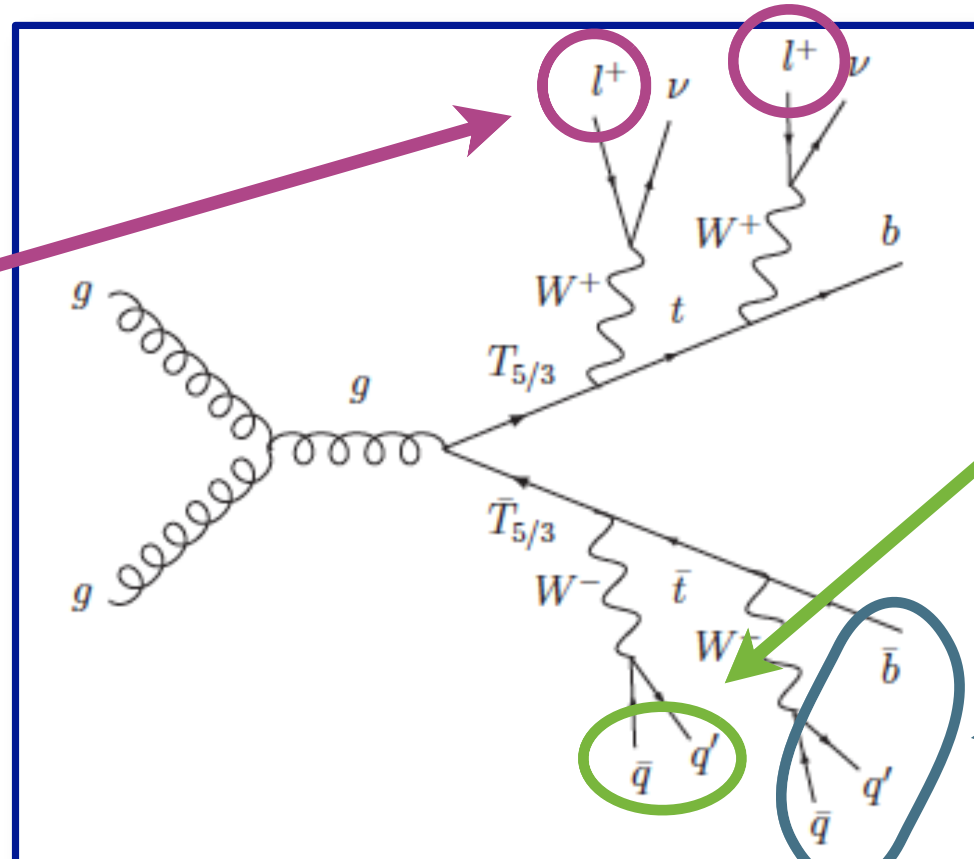

W tag:
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Oblique parameter fits of LEP & Tevatron data gave
f ≥ 800GeV

Grojean, Matsedonskyi, Panico `13

Ciuchini, Franco, Mishima, Silvestrini `13

10.1103/PhysRevLett.112.171801

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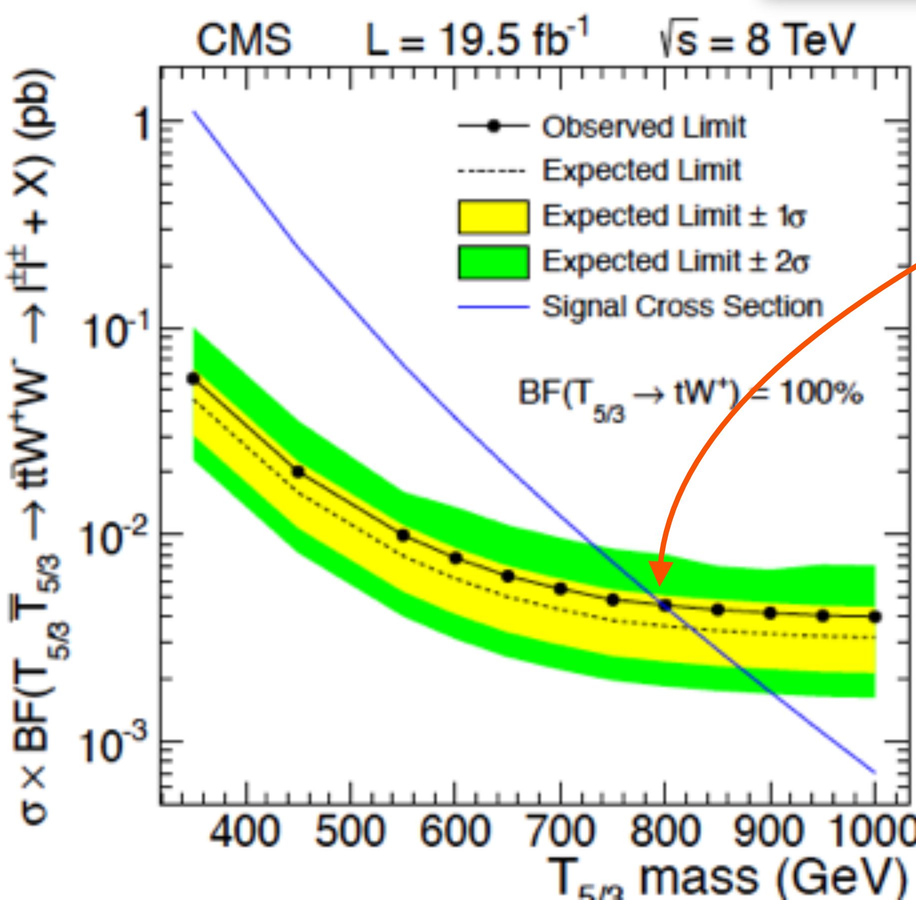

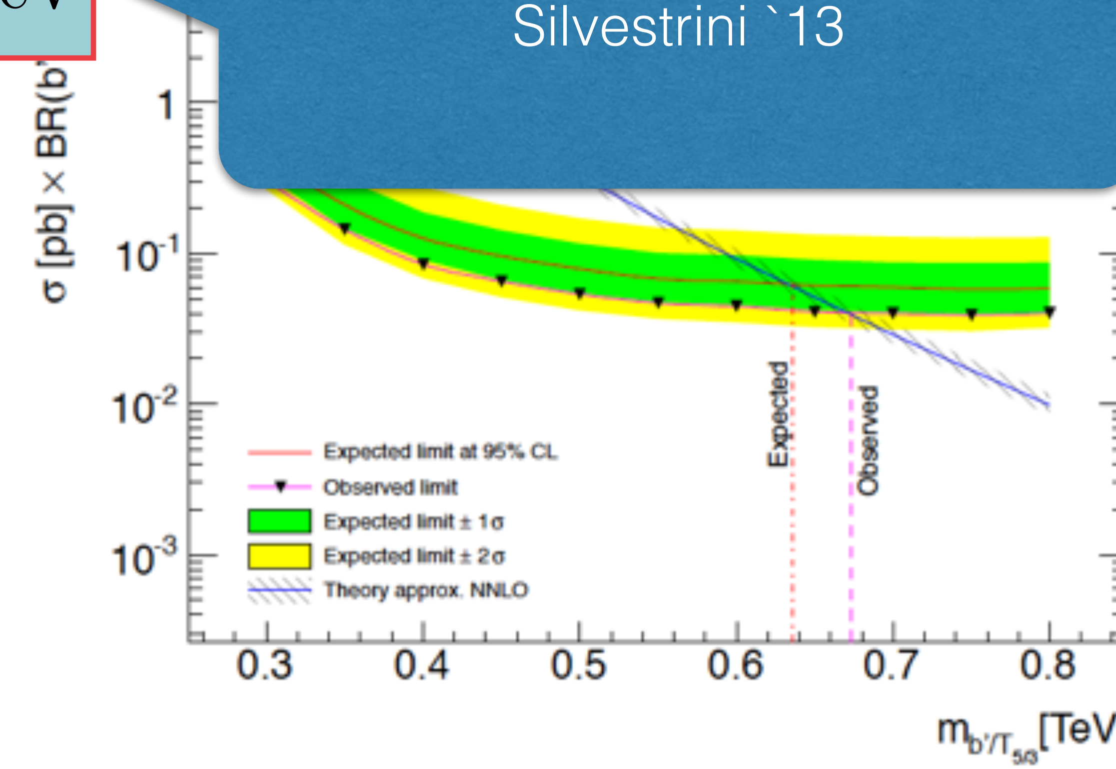

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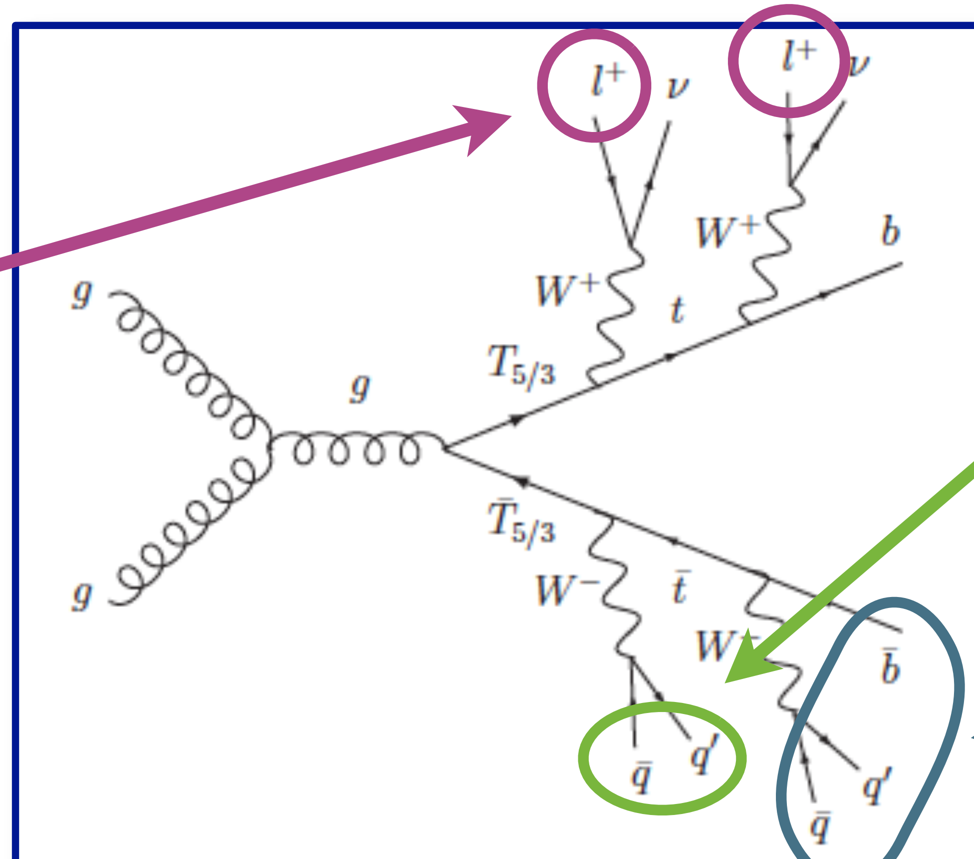

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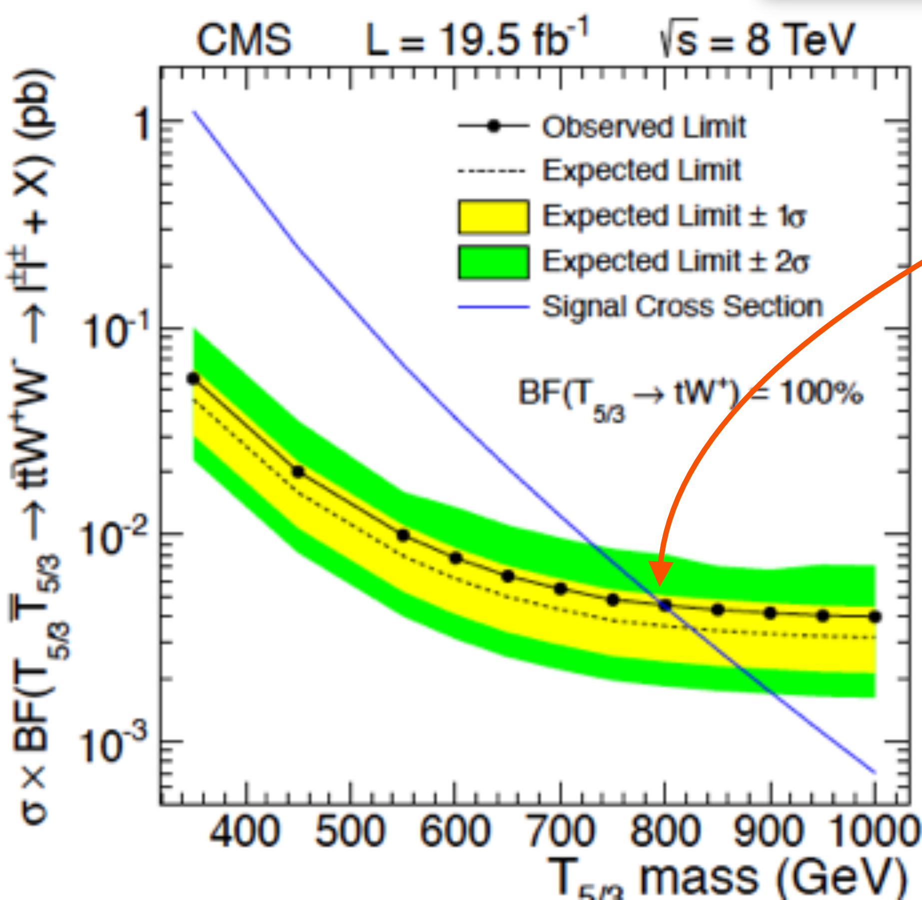

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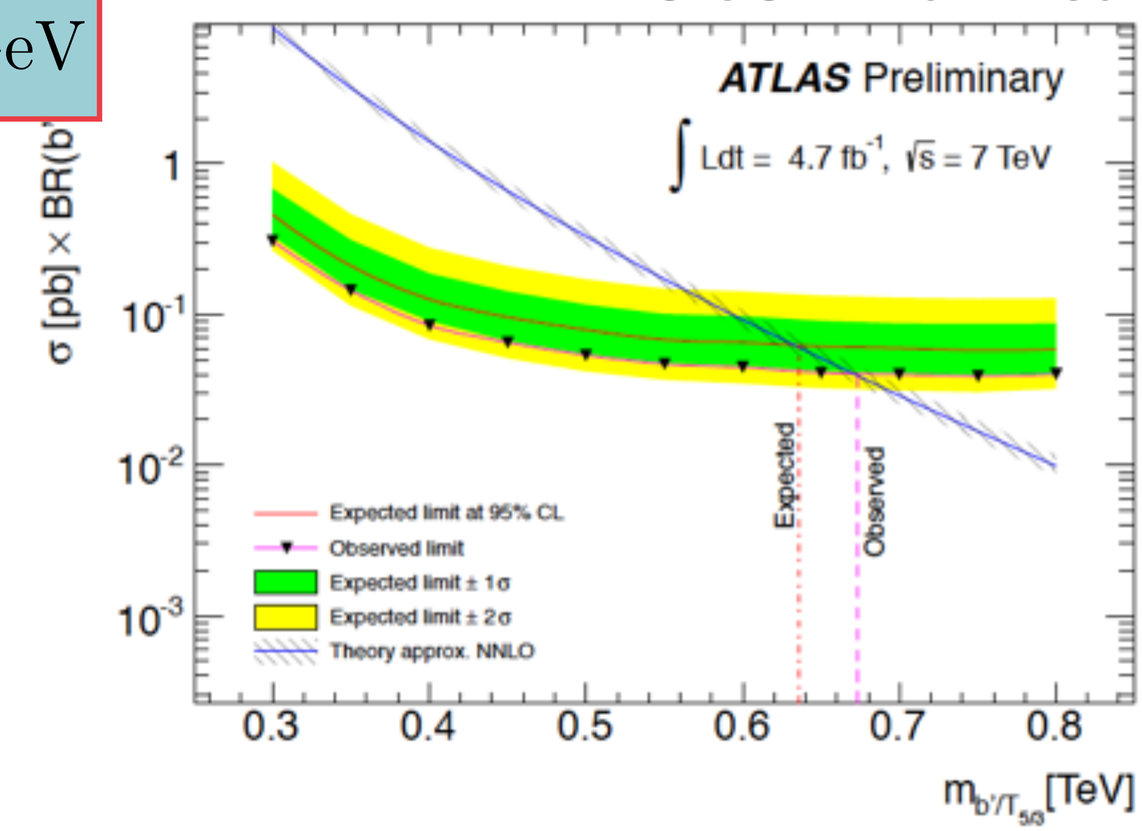

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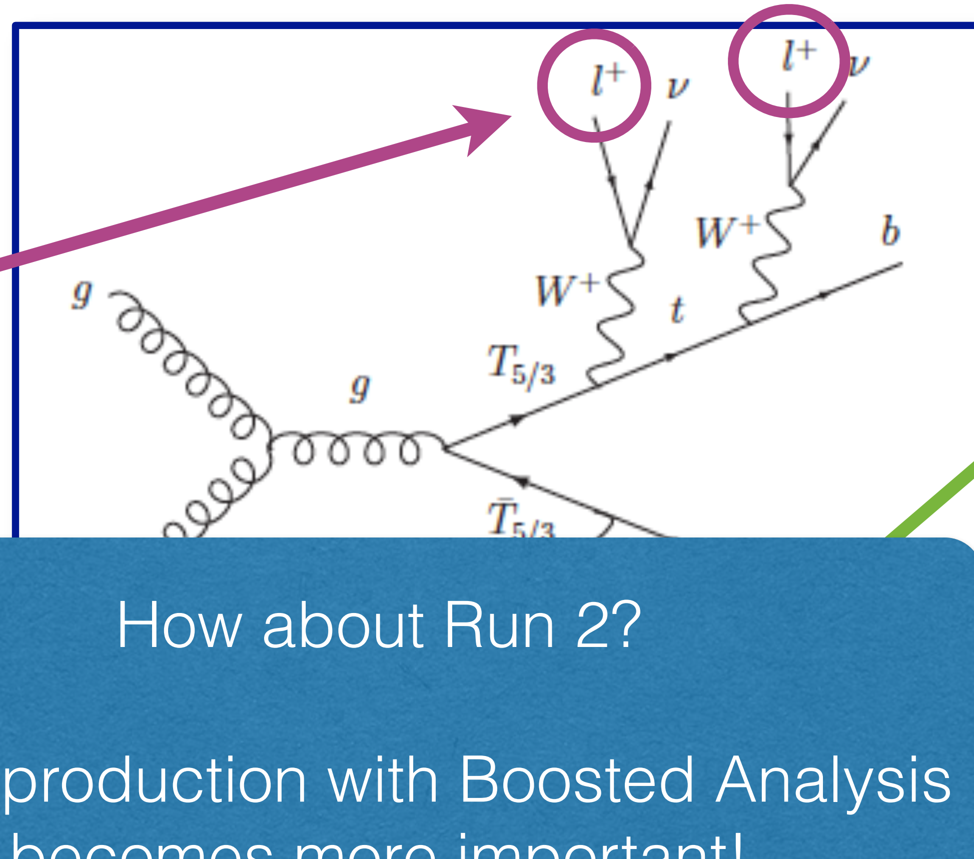

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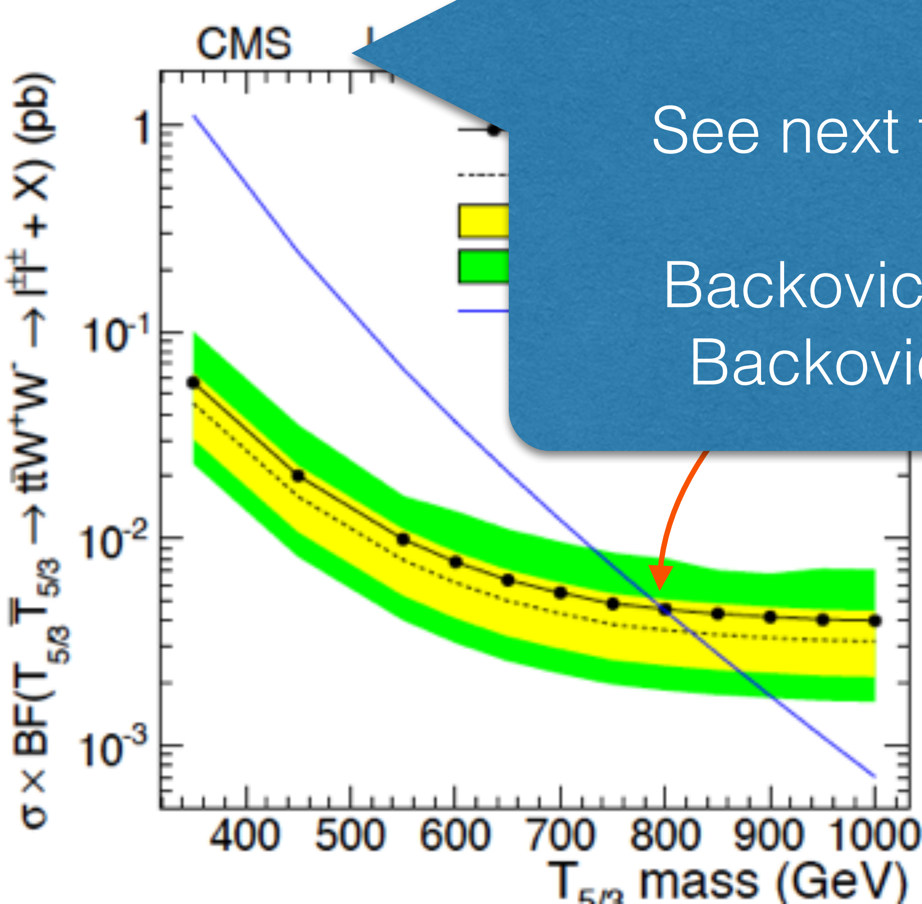
10.1103/PhysRevLett.11

How about Run 2?

Single production with Boosted Analysis becomes more important!

See next talk by Thomas Flacke!

Backovic, Flacke, SL, Perez `14
Backovic, Flacke, Kim, SL,`15



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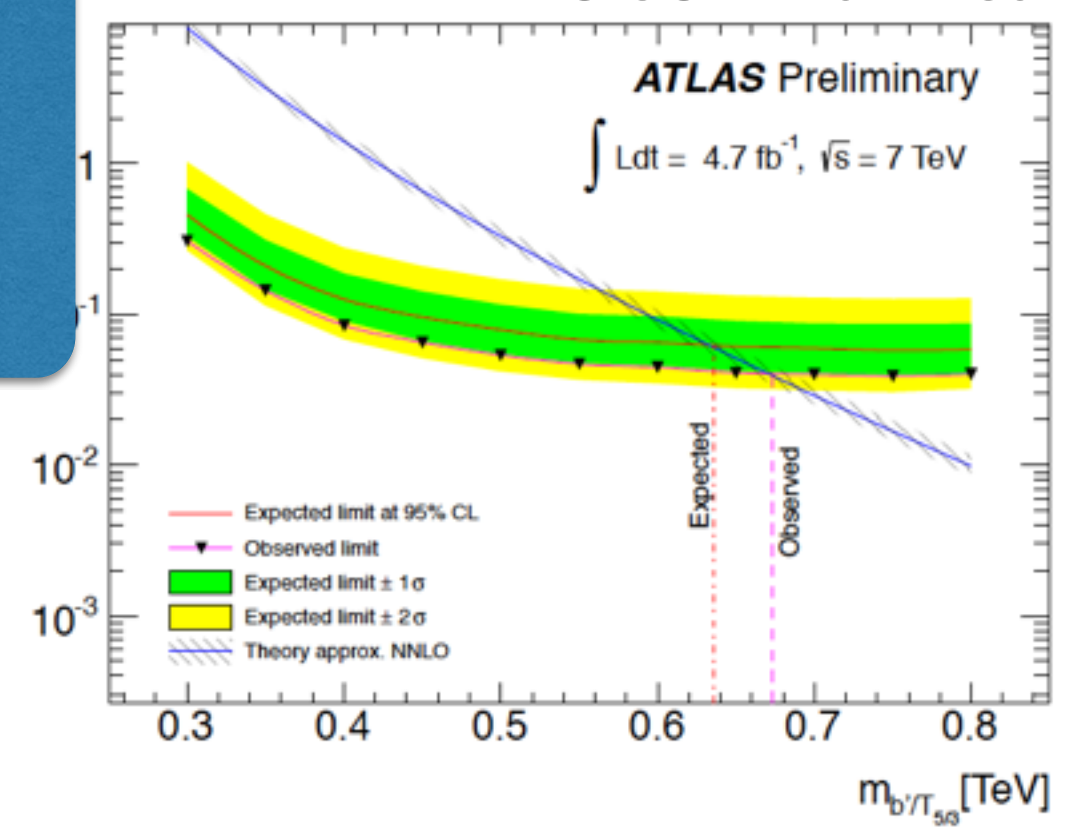

Hiding partners @LHC

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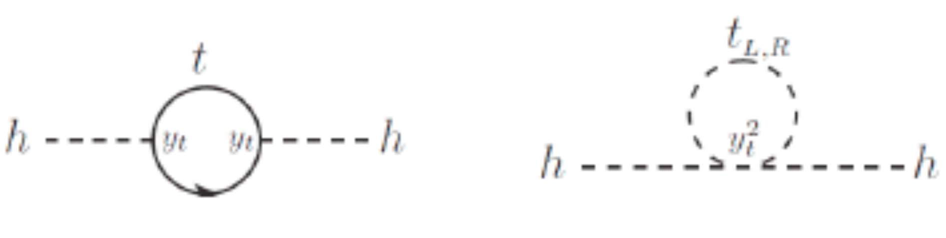

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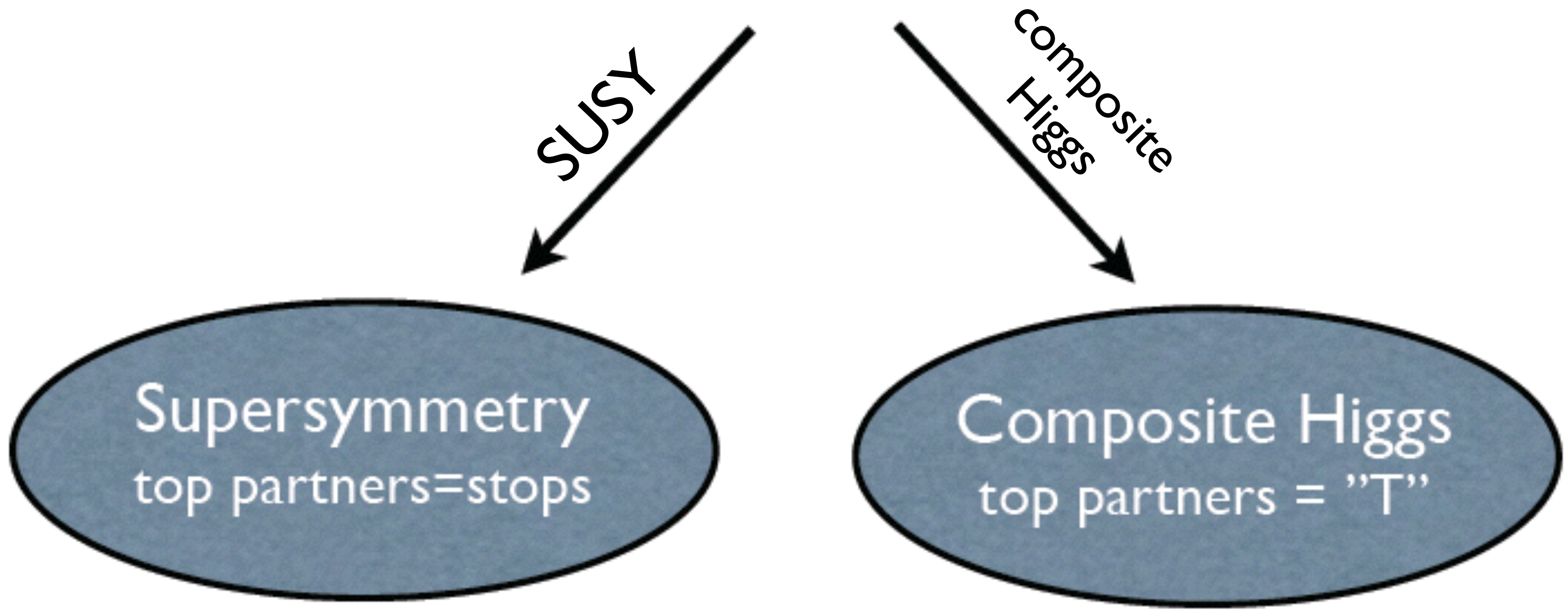

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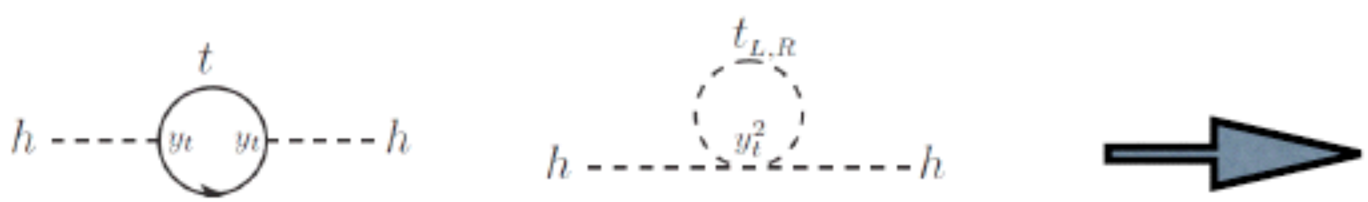

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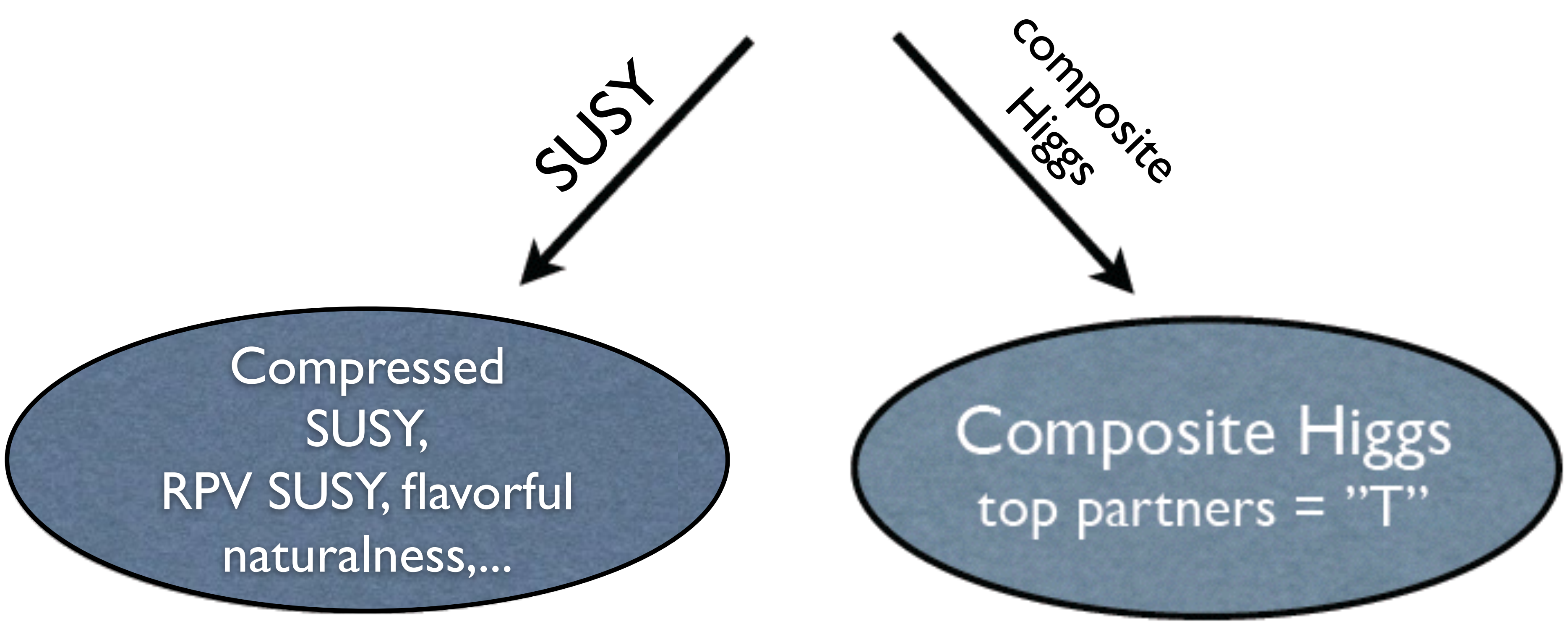

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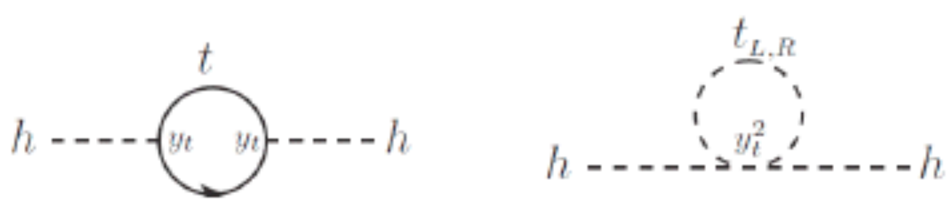

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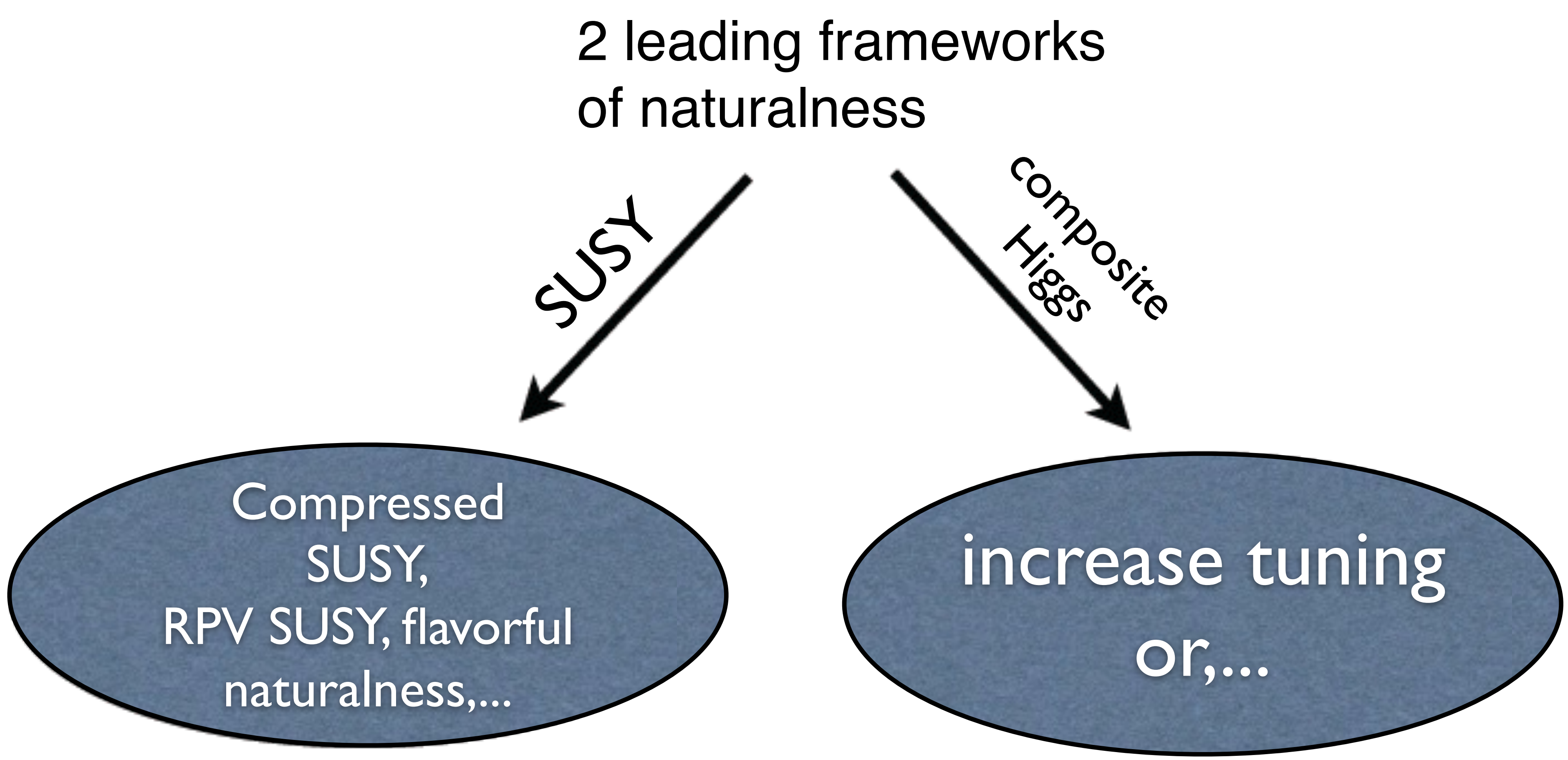

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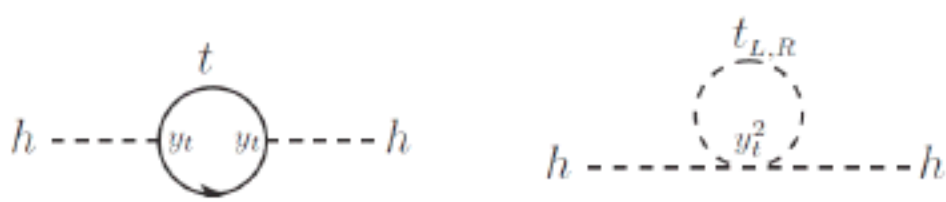

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2 leading frameworks
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SUSY

composite
Higgs

Compressed
SUSY,
RPV SUSY, flavorful
naturalness,...

discovery @ run2, or
increase tuning or, flavorful
naturalness,...

Partners are hiding due to non-trivial flavor physics effects

Flavorful Naturalness

Mahbubani, Papucci, Perez, Ruderman, Weiler '12
Blanke, Giudice, Paradisi, Perez, Zupan '13

- Standard model: 3 copies (flavours) of quarks; same holds for new physics. (e.g. SUSY)

- Hard-wired" assumption:

  top partner (stop) is mass eigenstate.

  Dine, Leigh, Kagan '93;
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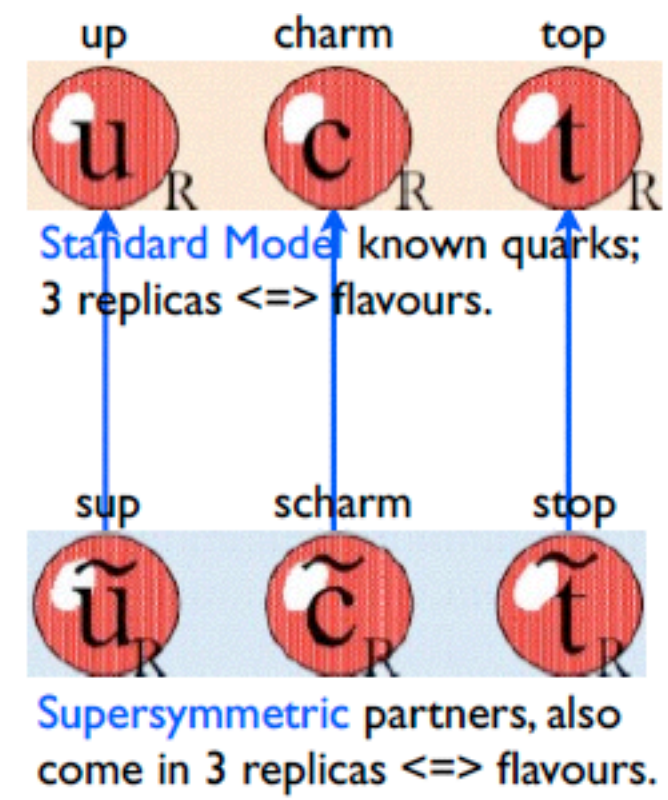
  Cohen, Kaplan, Nelson '96



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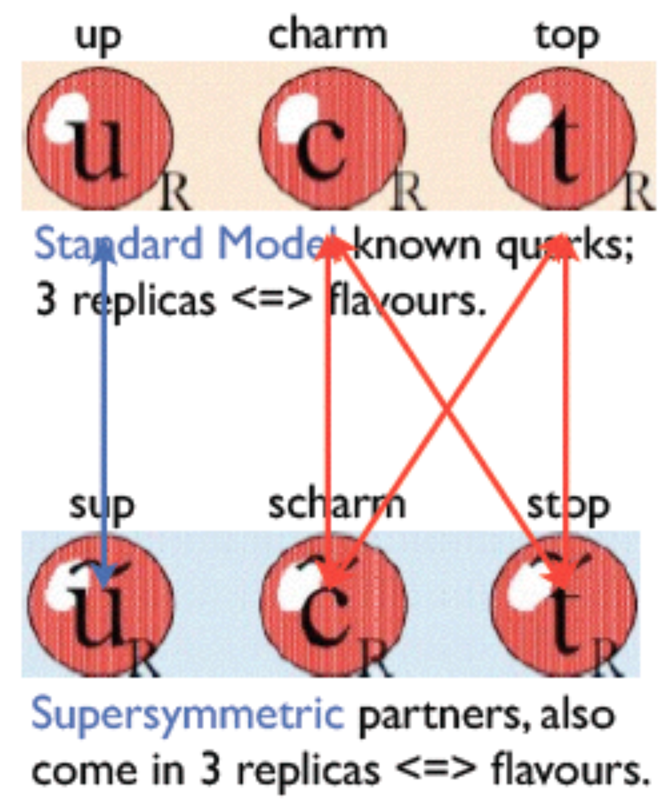

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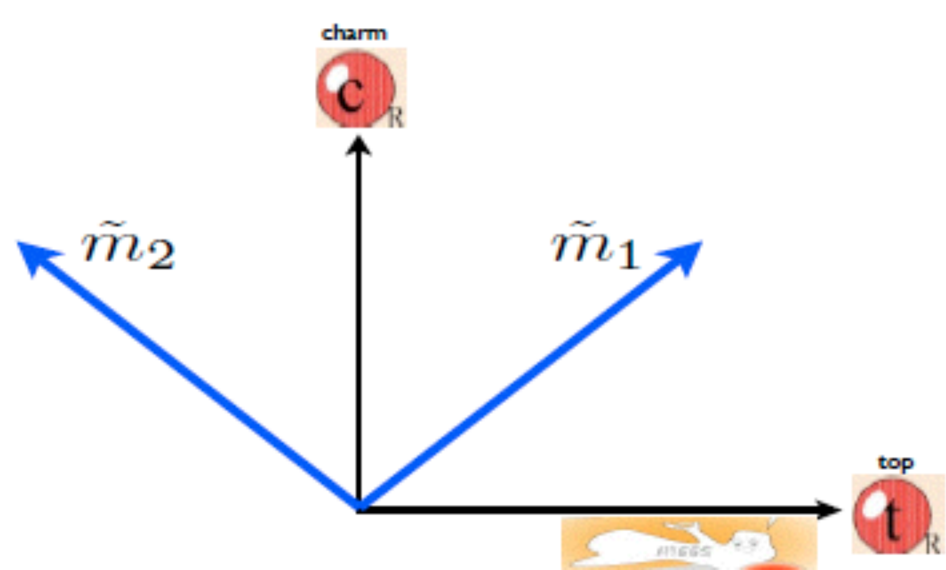

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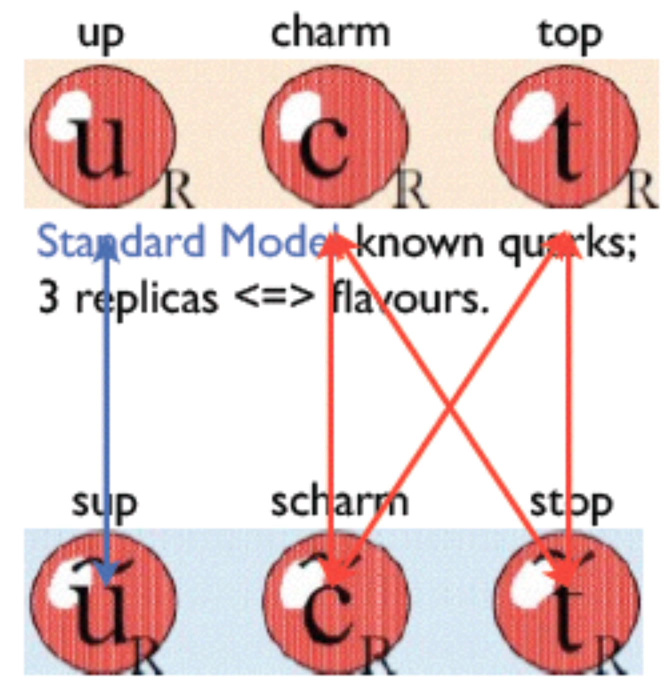

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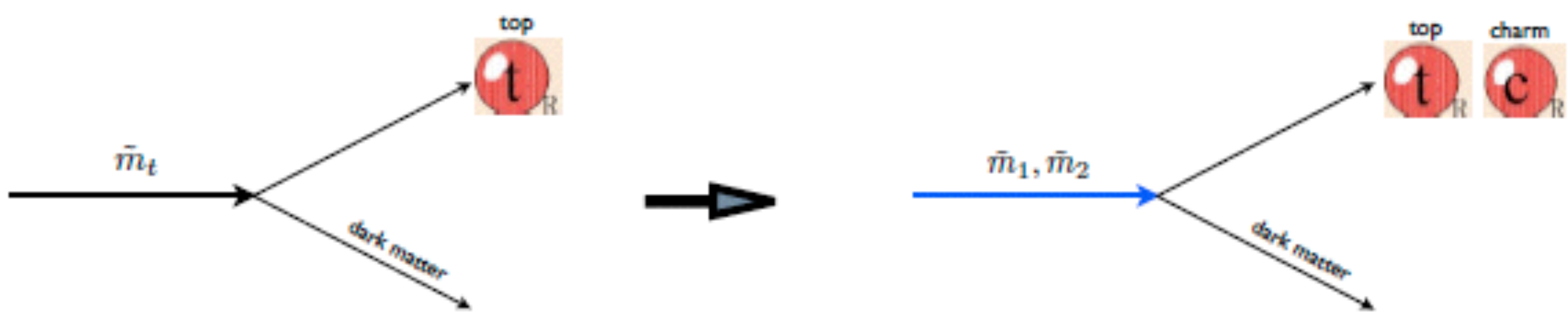

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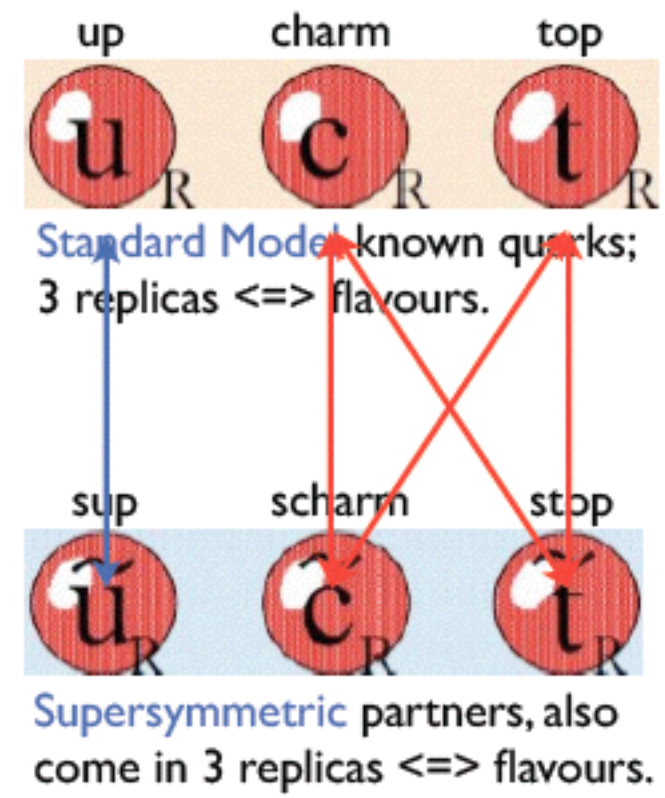

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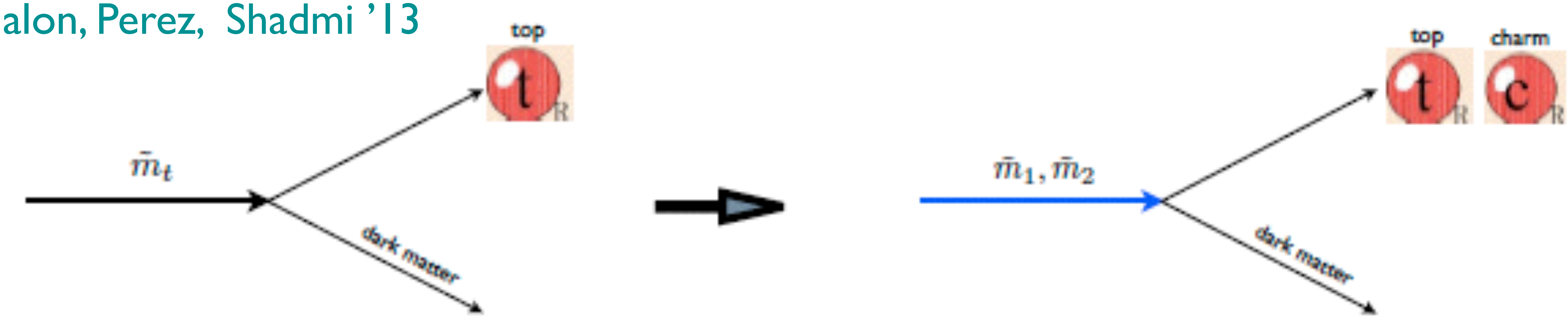
  Non-degenerate RH first 2 generation squarks is consistent with flavor constraints

  Galon, Perez, Shadmi '13



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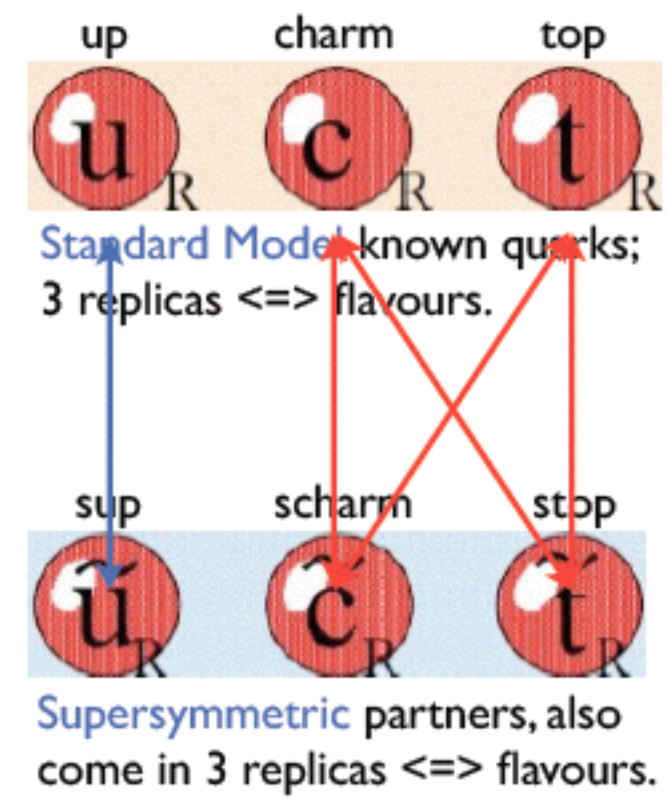

* Hard-

top p ate.

Dine,

Dimopou

Cohen, Kaplan,

Can we use this trick to hide the top partner in composite Higgs models?

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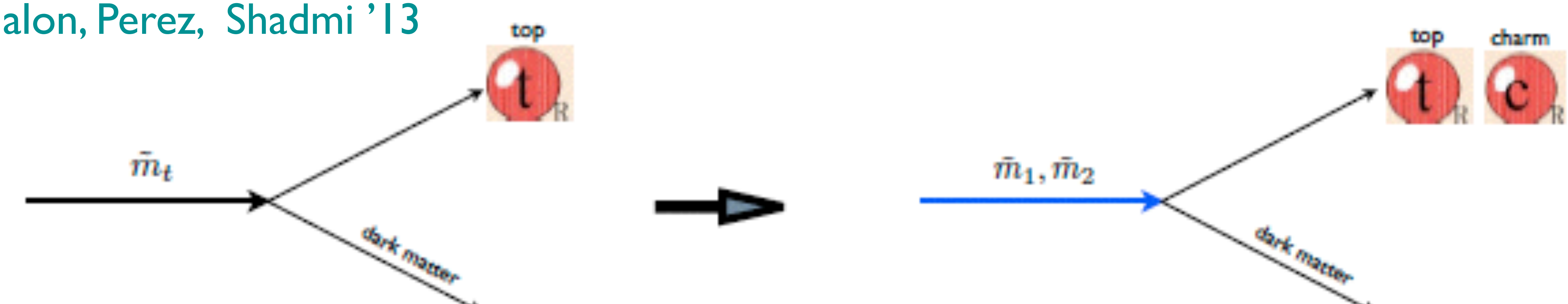

Light Quark Composite Partners

- Custodial symmetry for Z->bb Agashe, Contino, Da Rold, Pomarol '12
  => allow for composite light quark without tension with precision tests
  Cacciapaglia, Csaki, Galloway, Marandella, Terning, Weiler '07
  Delaunay, Gedalia, SL, Perez, Ponton (x2) '10;
  Redi, Weiler '11 MFV
  Flavor problems in composite Higgs models can be solved if the composite sector has flavor symmetries, and light compositeness is allowed/ preferred /or even require

- Drastic change to phenology: large production rates, top forward-backward asymmetry, non-standard flavor signals ...
  Delaunay, Gedalia, SL, Perez, Ponton (x2) '10; Redi, Weiler '11;
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- And LHC implications for non-degenerate first 2-generation partners.

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But what are the bounds on 1st and 2nd generation partners?

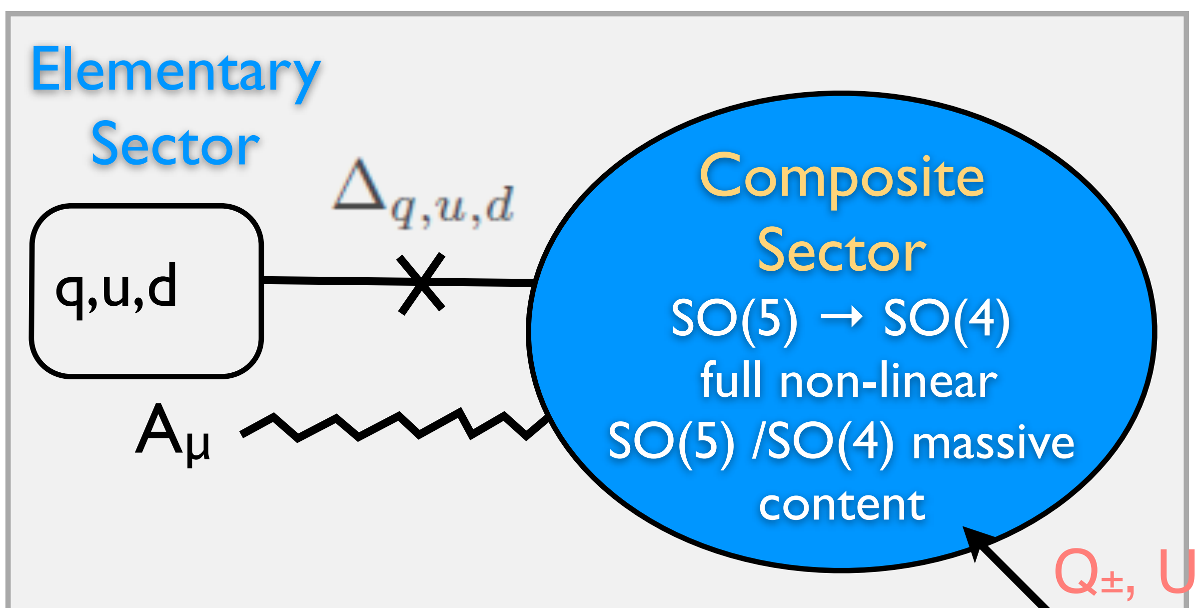
...And how much do *u* and *c* partner bounds differ?

General Set-up : Partial Compositeness

* Partial Compositeness: D.B. Kaplan; Gorssman & Neubert; Huber,...

Elementary-composite states talk through linear couplings. $\mathcal{L}_{mix} = \Delta_q \bar{q}_{l_\mathcal{O}} \mathcal{O}^{l_\mathcal{O}} + \mathrm{h.c.}$

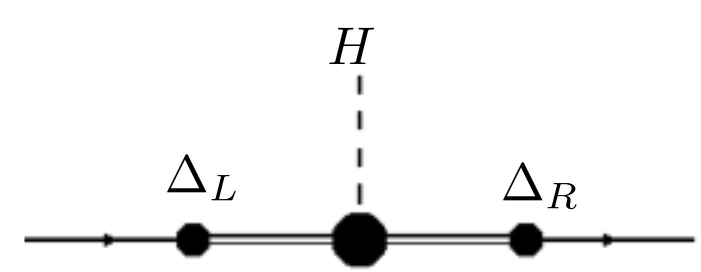
The flavor problem of theories with strong dynamics can be improved if the Yukawa couplings arise through mixings of elementary quarks with fermionic operators of the strong sector



$Q_\pm$, $U_\pm$ + ... +EW + H

$$m_\Psi \simeq g_\Psi f$$

$$y_{SM} = \frac{\Delta_L \Delta_R}{m_\Psi} \simeq \frac{y_L y_R}{g_\Psi}$$



Typically (anarchy): $\Delta_i \ll \Delta_{q3,u3} \sim M$, i = 1, 2 .

$\Delta_i = y_i f$ (f ⇔ decay constant for the SO(5)/SO(4) breaking)

General Set-up : Partial Compositeness

* **Partial Compositeness**: D.B. Kaplan; Gorssman & Neubert; Huber,...

Elementary-composite states talk

$_{ix} = \Delta_q \bar{q}_{l_{\mathcal{O}}} \mathcal{O}^{l_{\mathcal{O}}} + \text{h.c.}$

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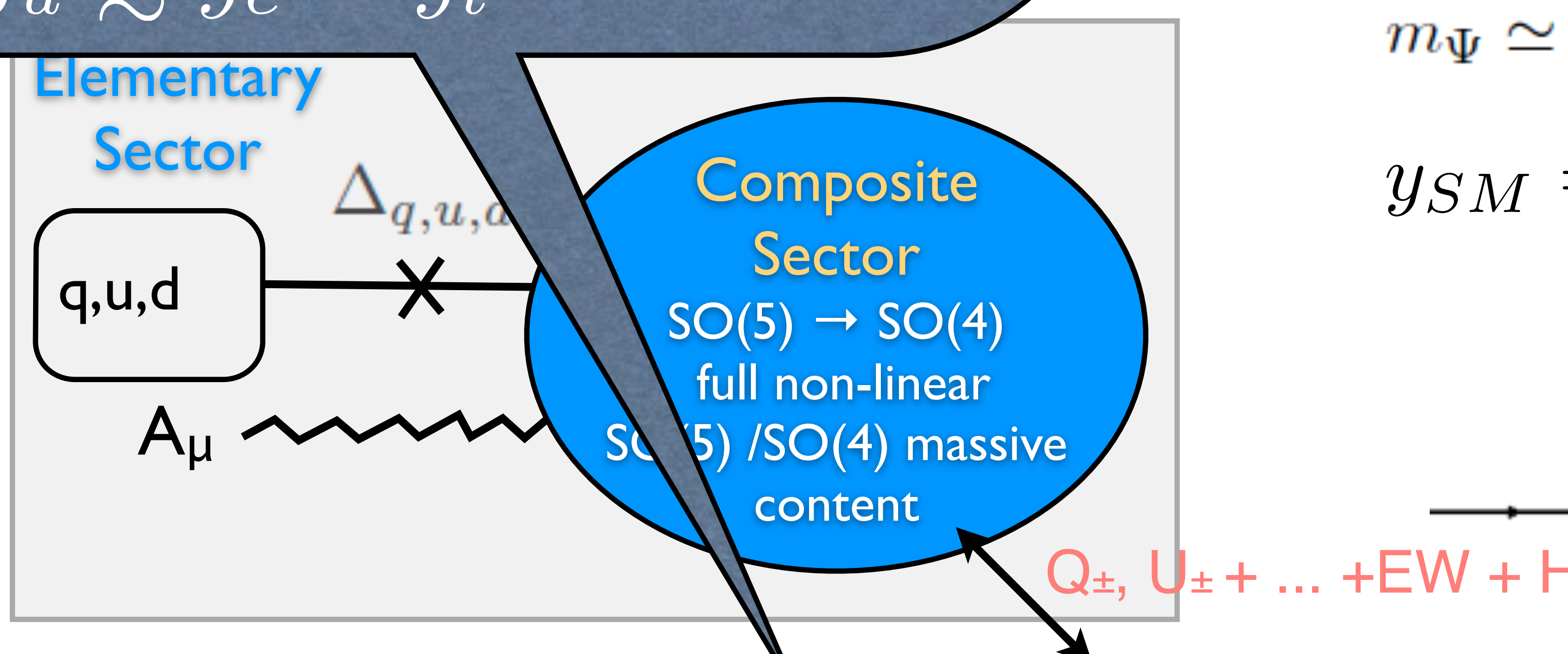
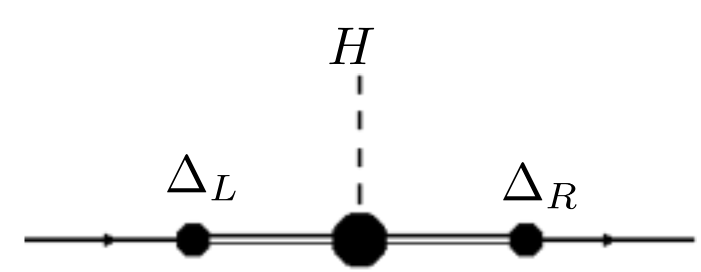
What if the first two generations of RH quarks are composite but not at the same level, for instance:

$$y_u \lesssim y_c \sim y_t \sim 1$$

$m_\Psi \simeq g_\Psi f$

$$y_{SM} = \frac{\Delta_L \Delta_R}{m_\Psi} \simeq \frac{y_L y_R}{g_\Psi}$$





Typically (anarchy): $\Delta_i \ll \Delta_{q3,u3} \sim M$, i = 1, 2 .

$\Delta_i = y_i f$ (f ⇔ decay constant for the SO(5)/SO(4) breaking)

General Set-up

- As a setup we choose the minimal composite Higgs model based on SO(5)/SO(4). We use the CCWZ construction in order to write down $\mathcal{L}_{eff}$ in a nonlinearly invariant way under SO(5) Coleman, Wess, Zumino '69, Callan, Coleman '69

- The lightest composite quark partner resonances are assumed to be in the 5 of SO(5)

$$\psi^U = \begin{pmatrix} Q^U \\ \tilde{U} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} iD^u - iX_{5/3} \\ D^u + X_{5/3} \\ iU^u + iX_{2/3} \\ -U^u + X_{2/3} \\ \sqrt{2}\tilde{U} \end{pmatrix}, \qquad \psi^D = \begin{pmatrix} Q^D \\ \tilde{D} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} -iU^d + iX_{-4/3} \\ U^d + X_{-4/3} \\ iD^d + iX_{-1/3} \\ -D^d + X_{-1/3} \\ \sqrt{2}\tilde{D} \end{pmatrix}$$

elementary quarks: $q_L^5 \equiv \frac{1}{\sqrt{2}}(id_L\,, d_L\,, iu_L\,, -u_L\,, 0)^T \qquad u_R^5 \equiv (0\,, 0\,, 0\,, 0\,, u_R)^T$

- BSM particle content: 5 = 4 + 1 $\qquad Y = T_R^3 + X$

	U	$X_{2/3}$	D	$X_{5/3}$	$\tilde{U}$
$SO(4)$	**4**	**4**	**4**	**4**	**1**
$SU(3)_c$	**3**	**3**	**3**	**3**	**3**
EM charge	$2/3$	$2/3$	$-1/3$	$5/3$	$2/3$

the strong sector resonances are classified in terms of irreducible representations of the unbroken global $SO(4)$

Partial Composite light quarks

- Fermion Lagrangian:

$$\mathcal{L}_{comp} = i\,\overline{Q}(D_\mu + ie_\mu)\gamma^\mu Q + i\overline{\tilde{U}}\not{D}\tilde{U} - M_4\overline{Q}Q - M_1\overline{\tilde{U}}\tilde{U} + \left(ic\overline{Q}^i\gamma^\mu d^i_\mu \tilde{U} + \text{h.c.}\right)$$

$$\mathcal{L}_{el,mix} = i\,\overline{q}_L\not{D}q_L + i\,\overline{u}_R\not{D}u_R - y_L f\overline{q}^5_L U_{gs}\psi_R - y_R f\overline{u}^5_R U_{gs}\psi_L + \text{h.c.},$$

where d^i_μ, e_μ are the CCWZ "connections", and U_{gs} is the Goldstone matrix

$$U_{gs} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & \cos\overline{h}/f & \sin\overline{h}/f \\ 0 & 0 & 0 & -\sin\overline{h}/f & \cos\overline{h}/f \end{pmatrix},$$

with $\overline{h} = \langle h\rangle + h$.

- Derivation of Feynman rules:
  - expand d_μ, e_μ, U_{gs} around $\langle h\rangle$,
  - diagonalize the mass matrices,
  - match the lightest up-type mass with the SM quark mass (m_u or m_c)
    $\rightarrow$ this fixes y_L in terms of the other parameters ($y_R \sim 1 \Rightarrow y_L \ll 1$)
  - calculate the couplings in the mass eigenbasis.

$$m_u \simeq \frac{v}{\sqrt{2}f} \times |M_1 - M_4| \times \frac{y_L f}{\sqrt{(M_4^2 + y_L^2 f^2)}} \times \frac{y_R f}{\sqrt{(M_1^2 + y_R^2 f^2)}}$$

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whe… …lstone matrix

$y_L \ll 1$, the Lagrangian for the composite states and the right-handed up quark becomes invariant under the custodial symmetry $SO(3)_c$ subgroup of SO(4)

=> u_R, higgs, $\tilde{U}$, and one comb. of 4-plet are singlet, while GB, and three comb. of 4-plet are triplet under $SO(3)_c$

w…

- De…
  - exp…

$$m_u \simeq \frac{\ldots}{\sqrt{2}f} \times |\ldots| \times \frac{y_L f}{\sqrt{(M_4^2 + y_L^2 f^2)}} \times \frac{y_R f}{\sqrt{(M_1^2 + y_R^2 f^2)}}$$

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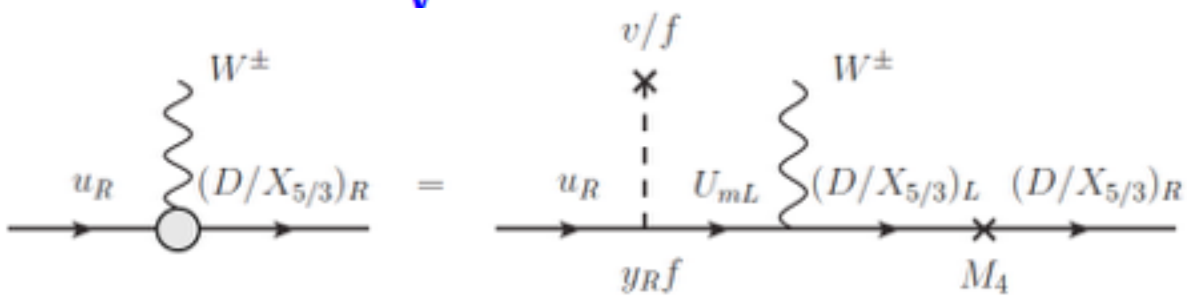
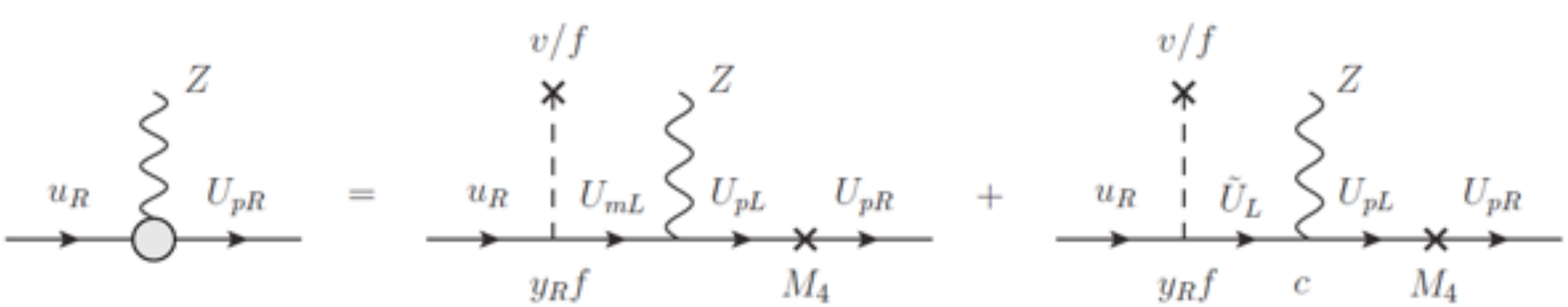
Partners in 4-plet

$SO(3)_C$ singlet: u_R, $\tilde{U}$, U_m,h
$SO(3)_C$ triplet: U_p, D, $X_{5/3}$, EW Goldstones

- Let's now consider the limit $M_1 \to \infty$.
  $\tilde{U}$ decouples, and the remaining quark partners form a **4** of $SO(4)$.
- Mass eigenstates:
  $U_{p/m} = (1/\sqrt{2})\,(U \pm X_{2/3})$, D, $X_{5/3}$.
- Masses:
  $m_{U_p} = m_D = m_{X_{5/3}} = M_4$, $m_{U_m} = \sqrt{M_4^2 + (y_R f \sin(\epsilon))^2}$, with $\epsilon = \langle h \rangle / f$.
- "Mixing" couplings:



$$g_{WuX} = -g_{WuD} = -c_w\, g_{ZuU_p} = \frac{g}{2} \cos\epsilon \sin\varphi_4 ,$$

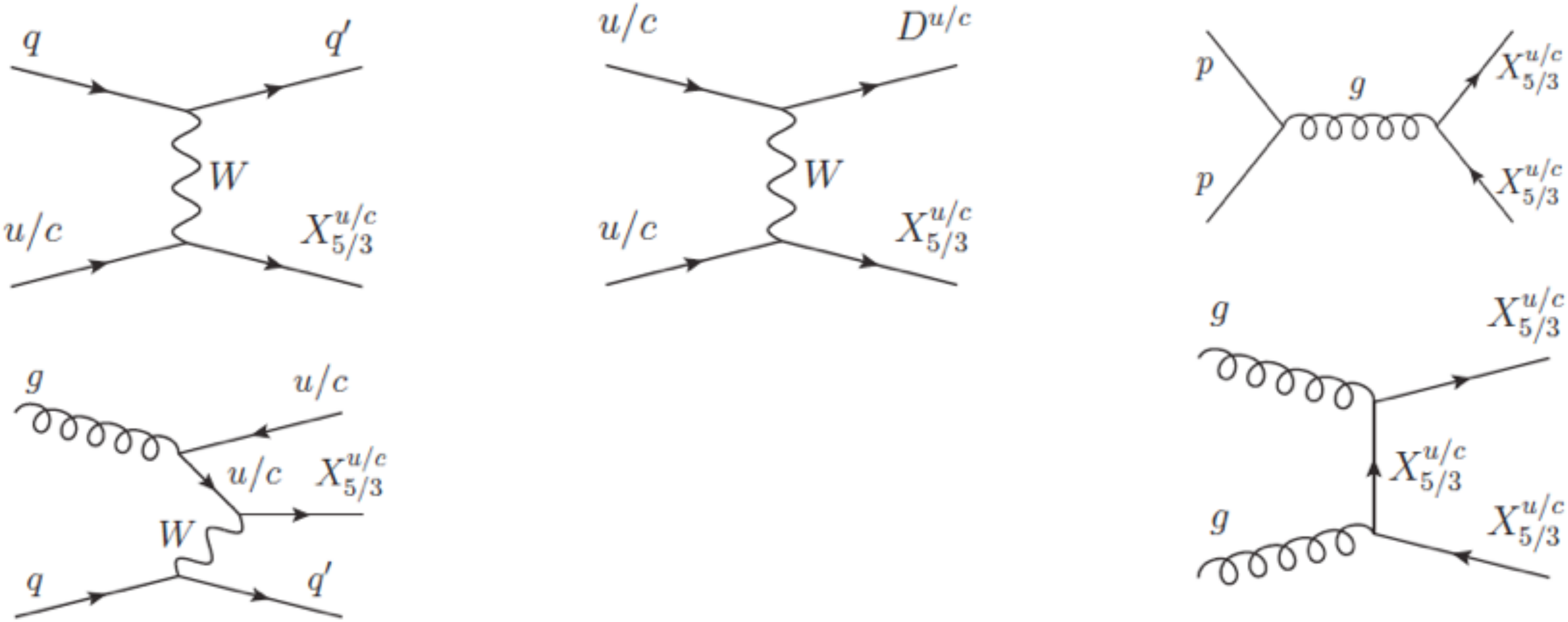


$$\lambda_{huU_m} = y_R \cos\epsilon \cos\varphi_4 ,$$

$$\tan\varphi_4 \equiv \frac{y_R f \sin\epsilon}{M_4} .$$

Partners in 4-plet

* Production mechanisms (shown here: $X_{5/3}$ production)



(a) EW single production (b) EW pair production (c) QCD pair production

* Decays:
  - $X_{5/3} \to W^+ u$ (100%),
  - $D \to W^- u$ (100%),
  - $U_p \to Zu$ (100%),
  - $U_m \to hu$ (100%).

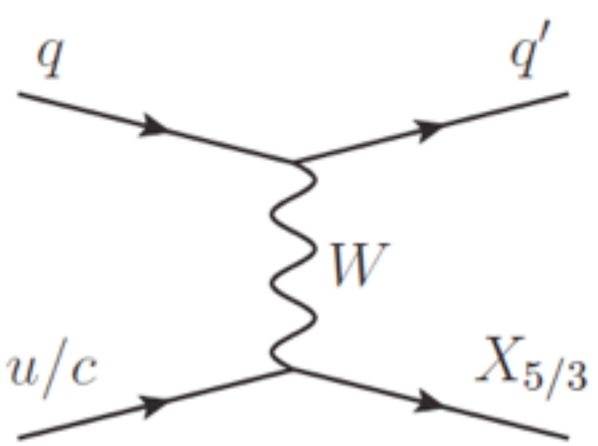
Partners in 4-plet

- The EW production mechanisms strongly differs for 1st, 2nd, and 3rd generation partners due to the differing PDFs for *u*, *c*, *t* in the proton.
- The final states (search signatures) differ:
  - 1st generation partners: *u*, *d* quarks in the final state → jets.
  - 2nd generation partners: *c*, *s* → jets, potentially tagable *c* in the future
  - 3nd generation partners: *t*, *b* → well distinguishable from jets

We focus on 1st and 2nd family partners
→ relevant measured final states:

•Single production: Wjj, Zjj

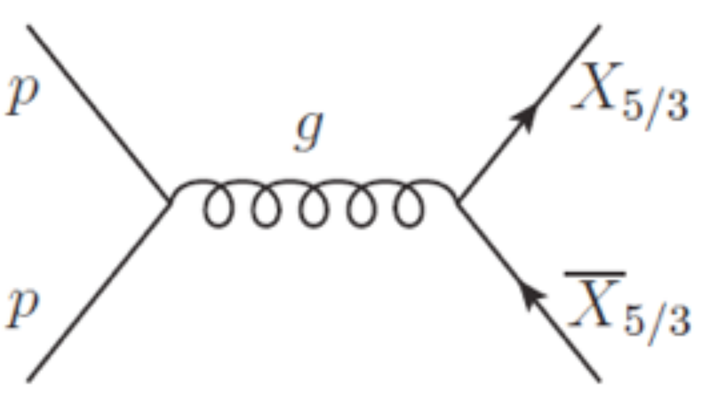
[D0 Collaboration], Phys. Rev. Lett. 106, 081801 (2011)
[CDF Collaboration], CDF/PUB/EXOTIC/PUBLIC/1026
[ATLAS Collaboration], ATLAS-CONF-2012-137 (4.64 fb^{-1} 7 TeV)
[CMS Collaboration],CMS-PAS-EXO-12-024 (19.8 fb^{-1} 8 TeV)



, . . .

•Pair production: WWjj, ZZjj, hhjj

[D0 Collaboration], Phys. Rev. Lett. 107, 082001 (2011)
[CDF Collaboration], Phys. Rev. Lett. 107, 261801 (2011)
[ATLAS Collaboration], Phys. Rev. D 86, 012007 (2012) (1.04 fb^{-1} 7 TeV)
[CMS Collaboration], CMS-PAS-EXO-12-042 (19.6 fb^{-1} 8 TeV); Leptoquark search, final state: μμjj)



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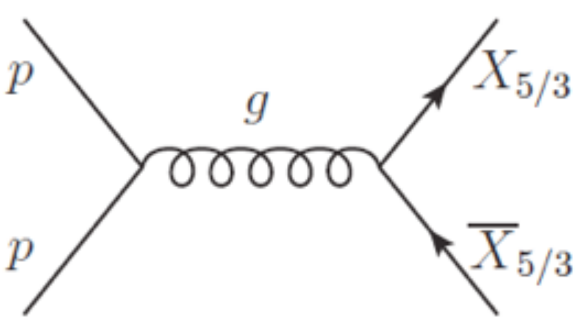
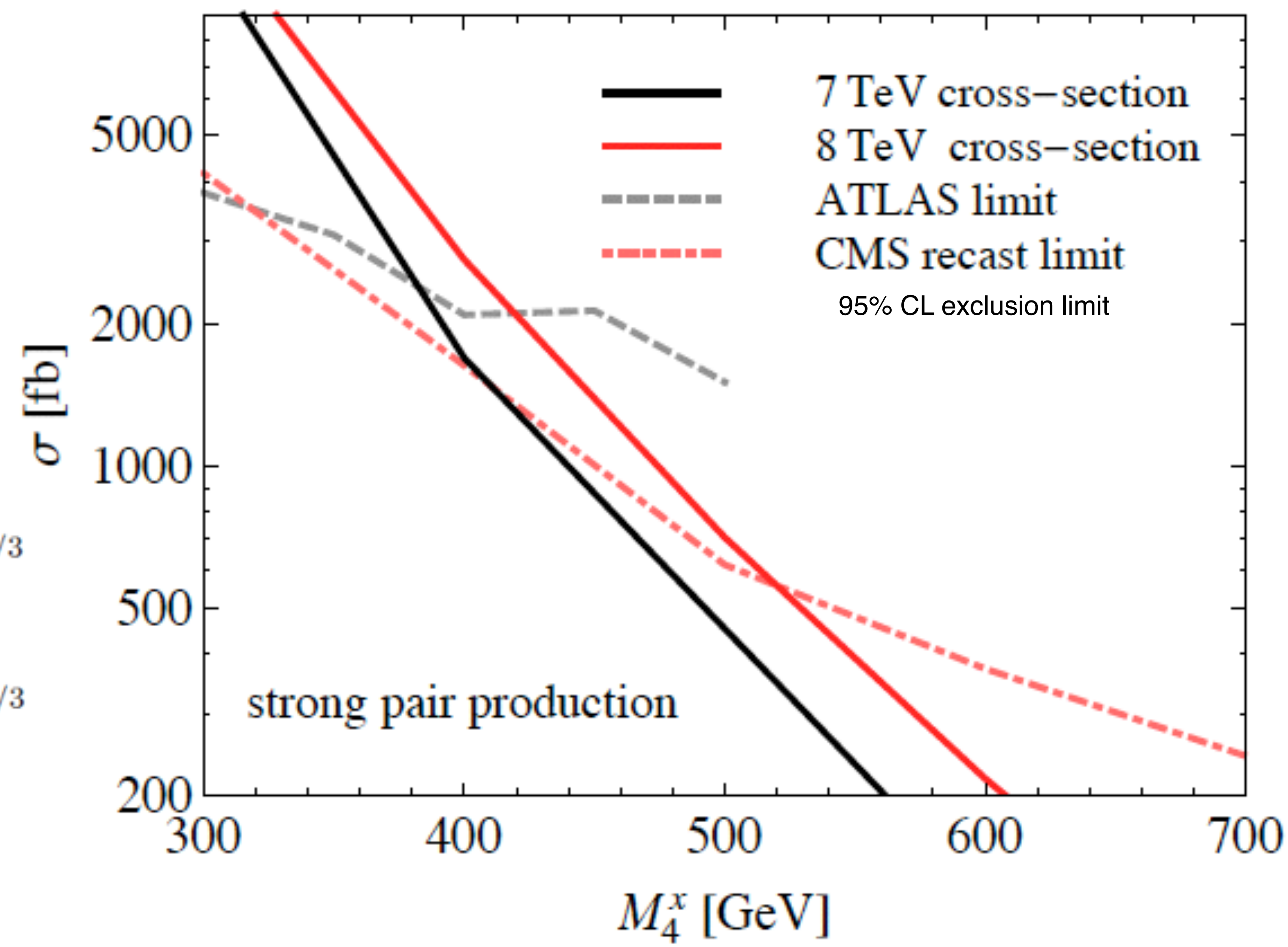
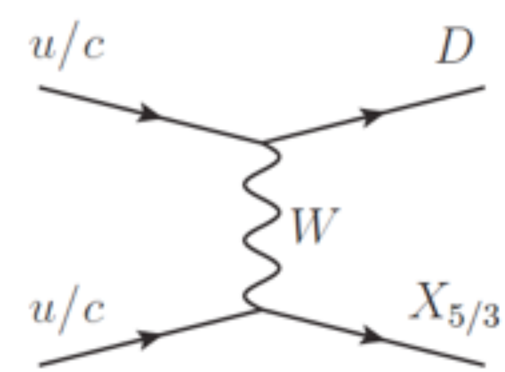
Bounds on u/c partner from 7TeV LHC

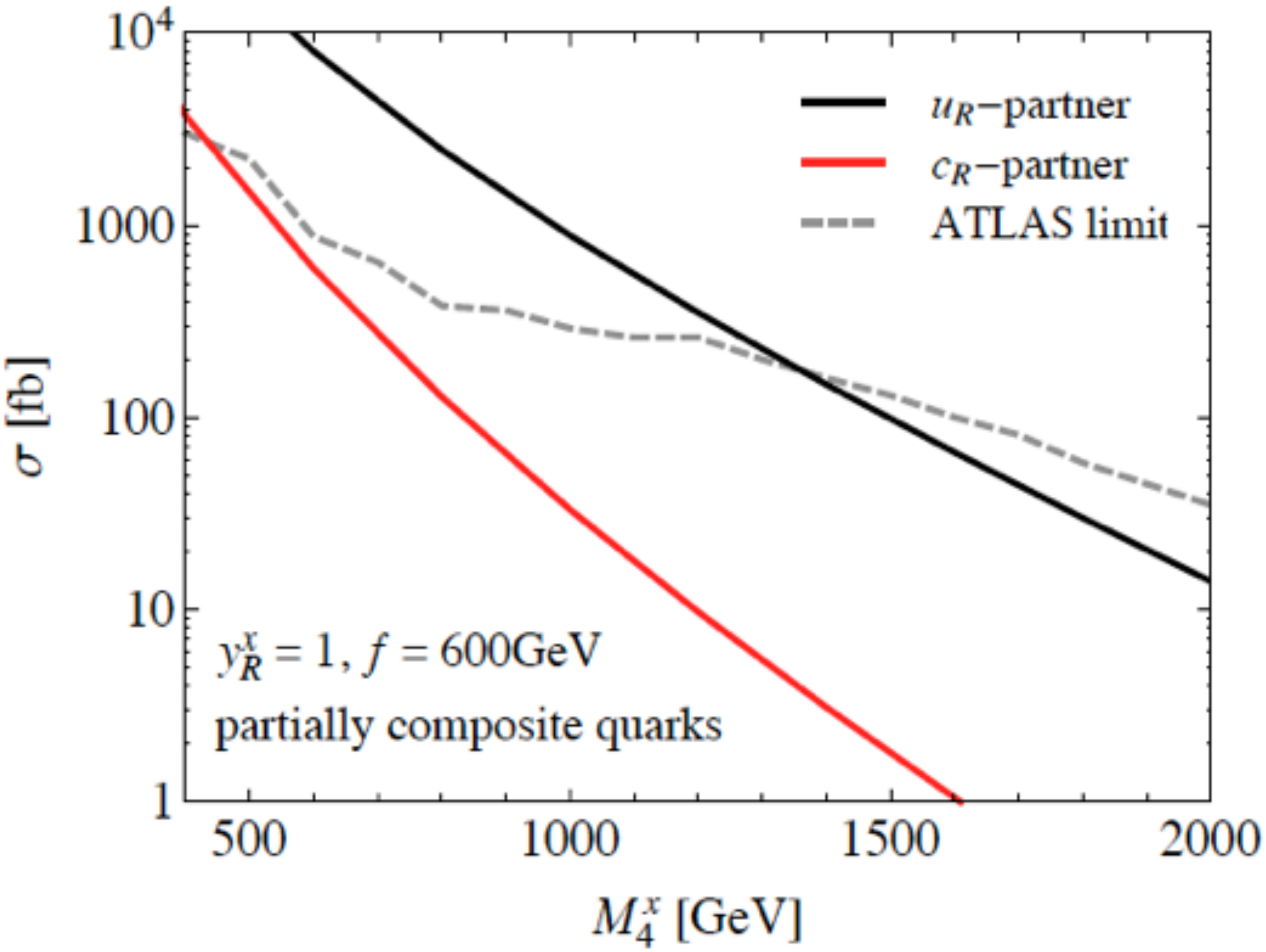


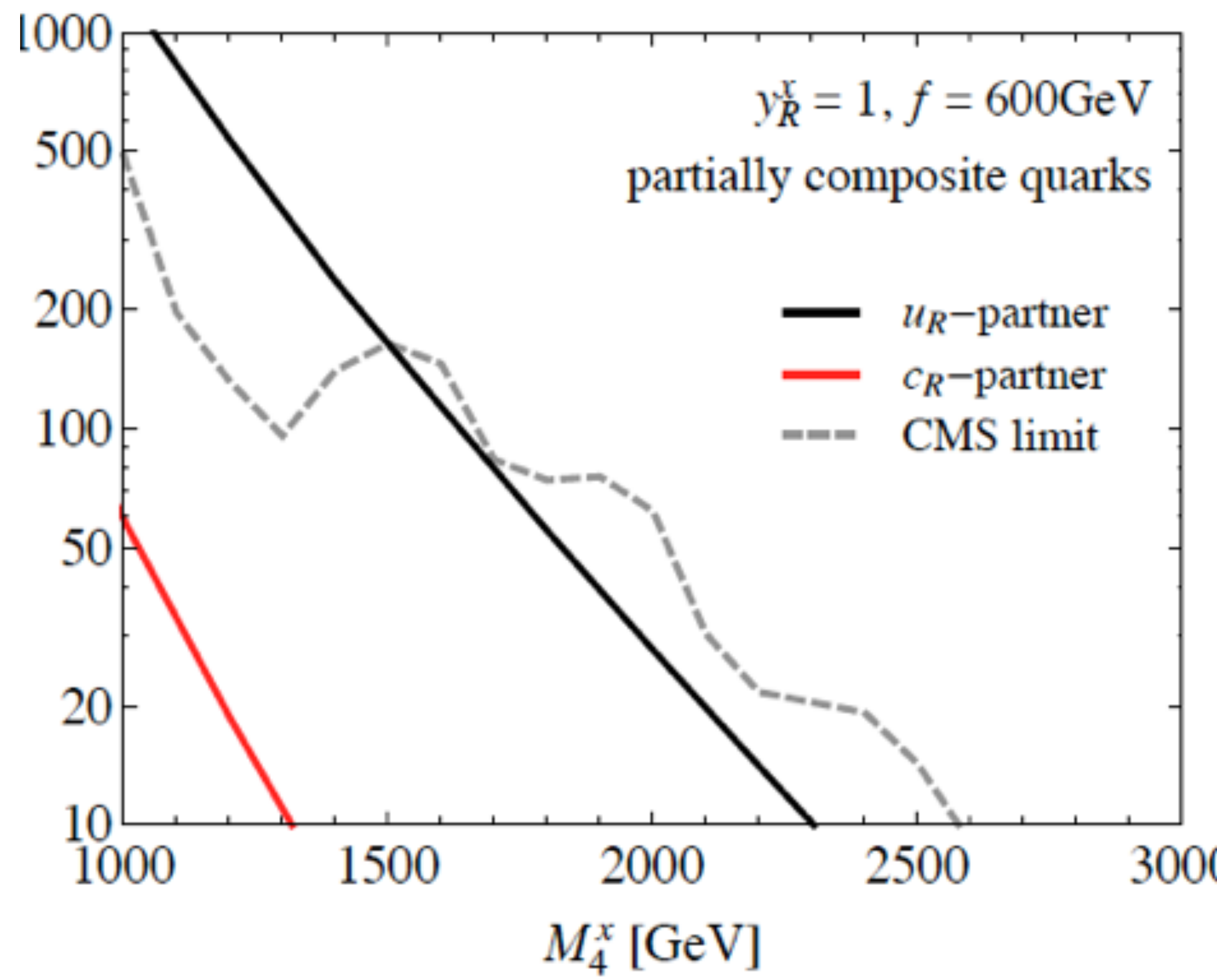


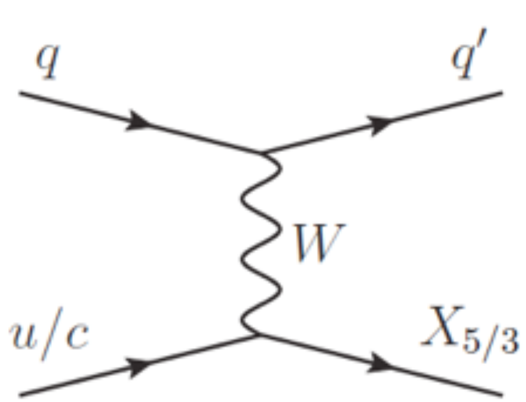


Model Independent predictions for WWjj cross sections through QCD pair production of –1/3 and 5/3 charge partners of the composite right-handed up and charm quarks. The solid black (red) line stands for the 7TeV (8TeV) cross section. They are the same for the first two generations and in both partially and fully quark scenarios.

Bounds on u/c partner from 7TeV LHC



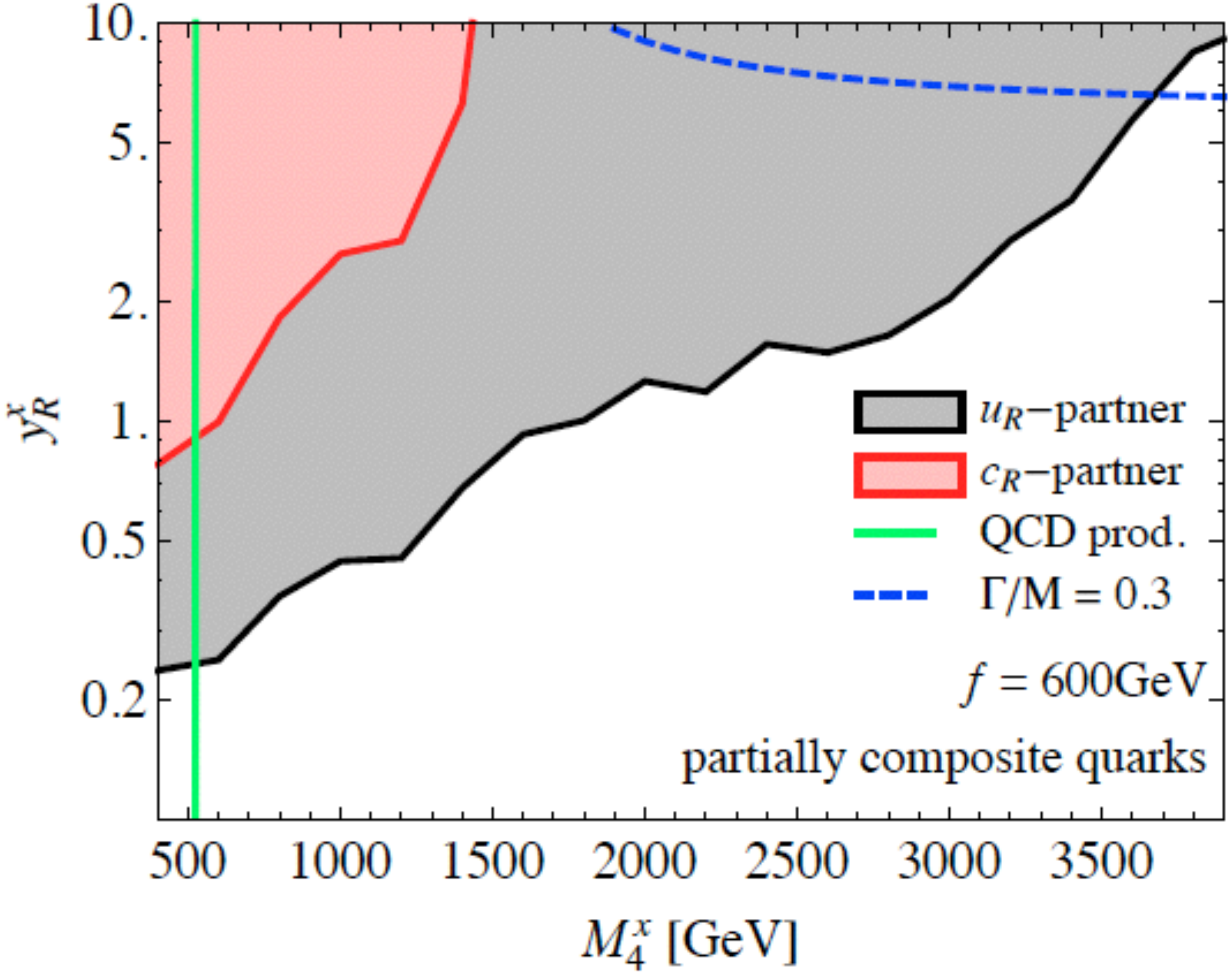




Predictions for Wjj cross sections of function of the fourplet partner mass M_4^x ,x = u, c, in the partially composite right-handed for two generation quarks. dashed curve is the 95% CL exclusion limit from the ATLAS and CMS searches at the 7TeV LHC run

Partners in 4-plet @ Run I

95% CL exclusion limits



Partners in Singlet

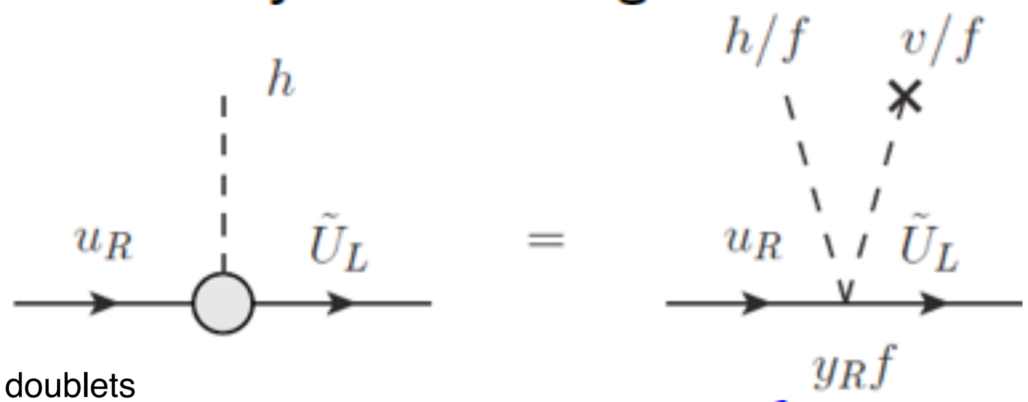
fourplet/singlet splitting is dominantly
induced by the SO(5) breaking of the strong dynamics

$$m_u \simeq \frac{v}{\sqrt{2}f} \times |M_1 - M_4| \times \frac{y_L f}{\sqrt{(M_4^2 + y_L^2 f^2)}} \times \frac{y_R f}{\sqrt{(M_1^2 + y_R^2 f^2)}}$$

- Now lets look at the singlet limit: M_1 finite and $M_4 \to \infty$.
  Then, all fourplet states decouple, and the only remaining BSM state is $\tilde{U}$.

- Mass: $m_{\tilde{U}} = \sqrt{M_1^2 + (y_R f \cos(\epsilon))^2}$

- only "mixing" coupling:

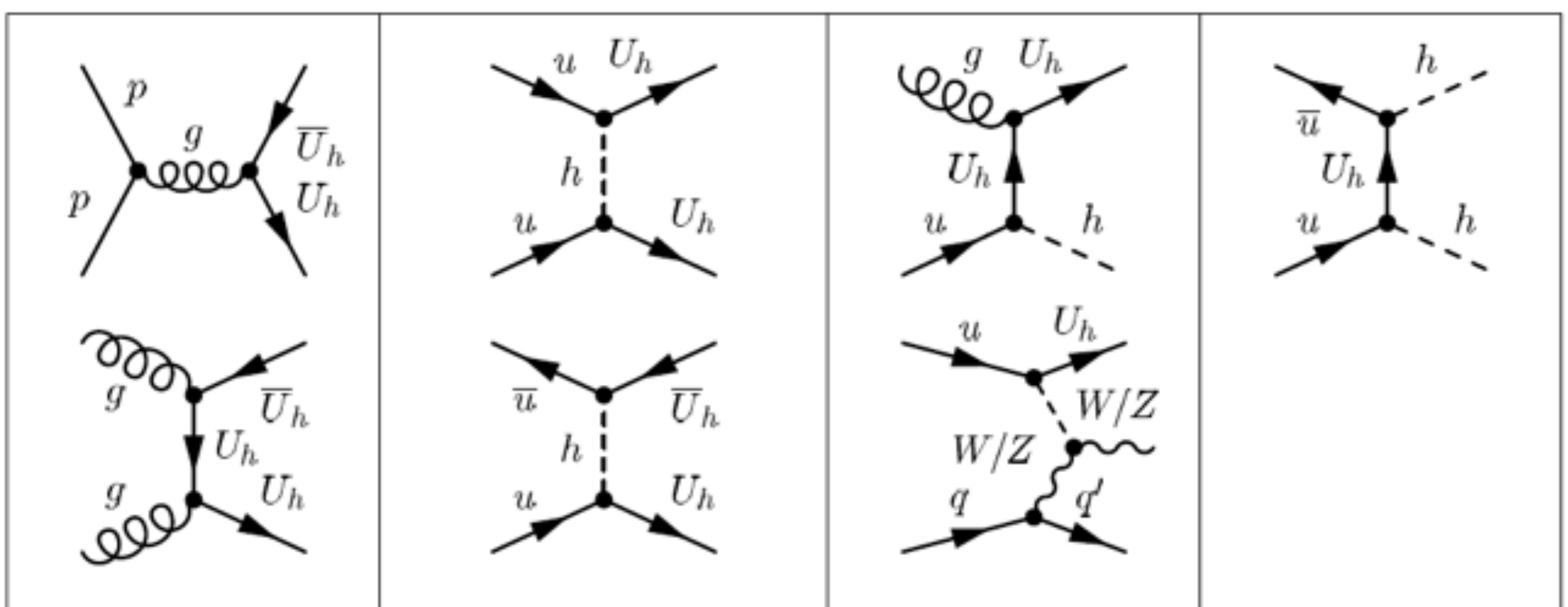


u and $\tilde{U}$, being both SO(4) singlets, can only couple to an even number of Higgs doublets

$$\lambda_{hu\tilde{U}} = y_R \sin\epsilon \cos\varphi_1 , \qquad \text{with} \qquad \tan\varphi_1 \equiv \frac{y_R f \cos\epsilon}{M_1} .$$

$$\epsilon \equiv \frac{v}{f}$$

- main production channels:



(a) QCD pair prod. | (b) non-QCD pair prod. | (c) single prod. | (d) t-channel

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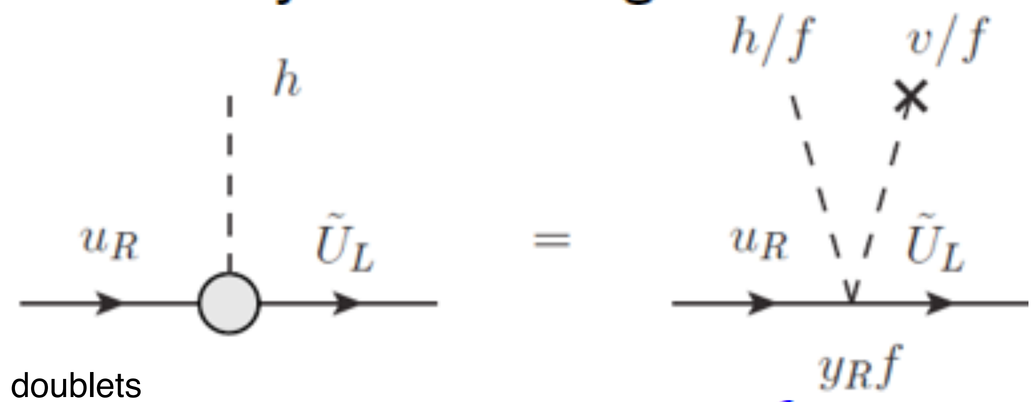

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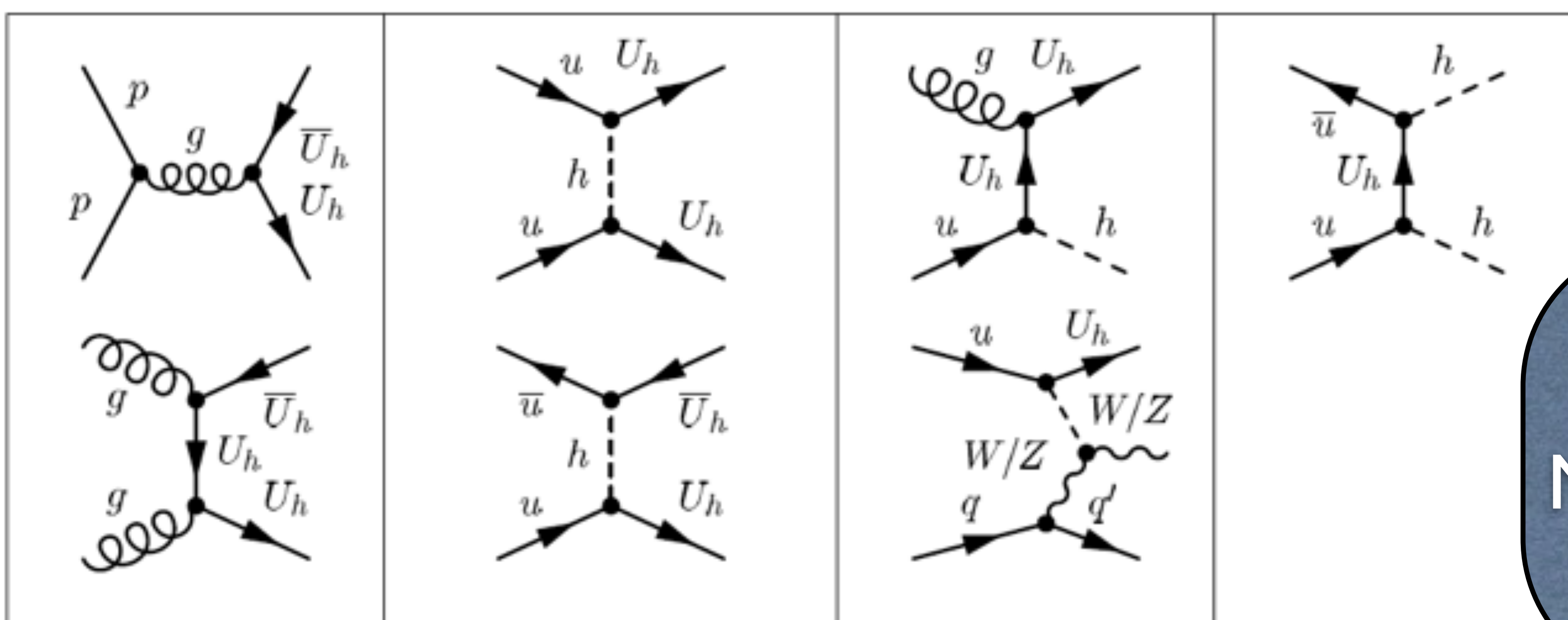


(a) QCD pair prod. | (b) non-QCD pair prod. | (c) single prod. | (d) t-channel

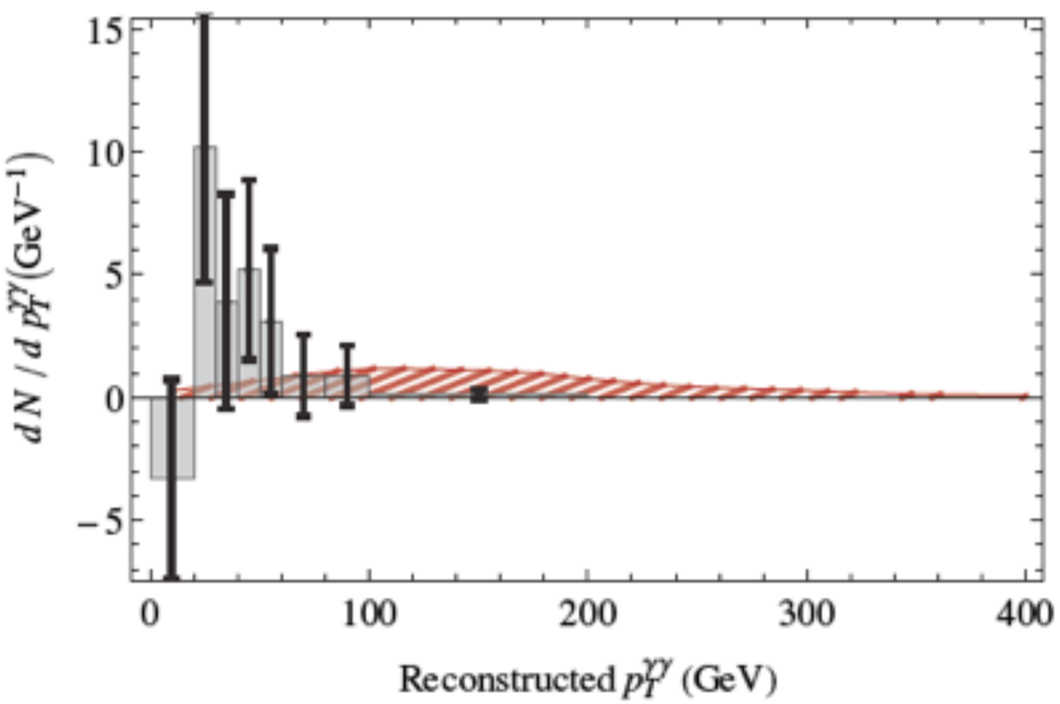
Decay: $\hat{U} \to$ hj (100%)
Most promising signal: pp $\to$ hhjj

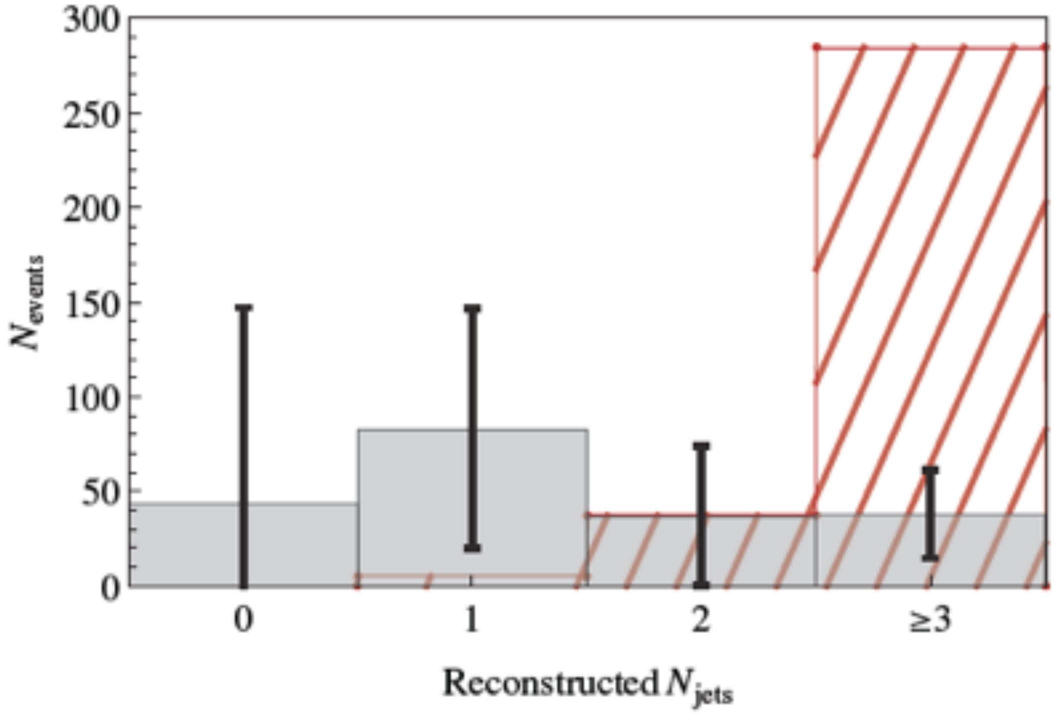
Partners in Singlet @ Run I

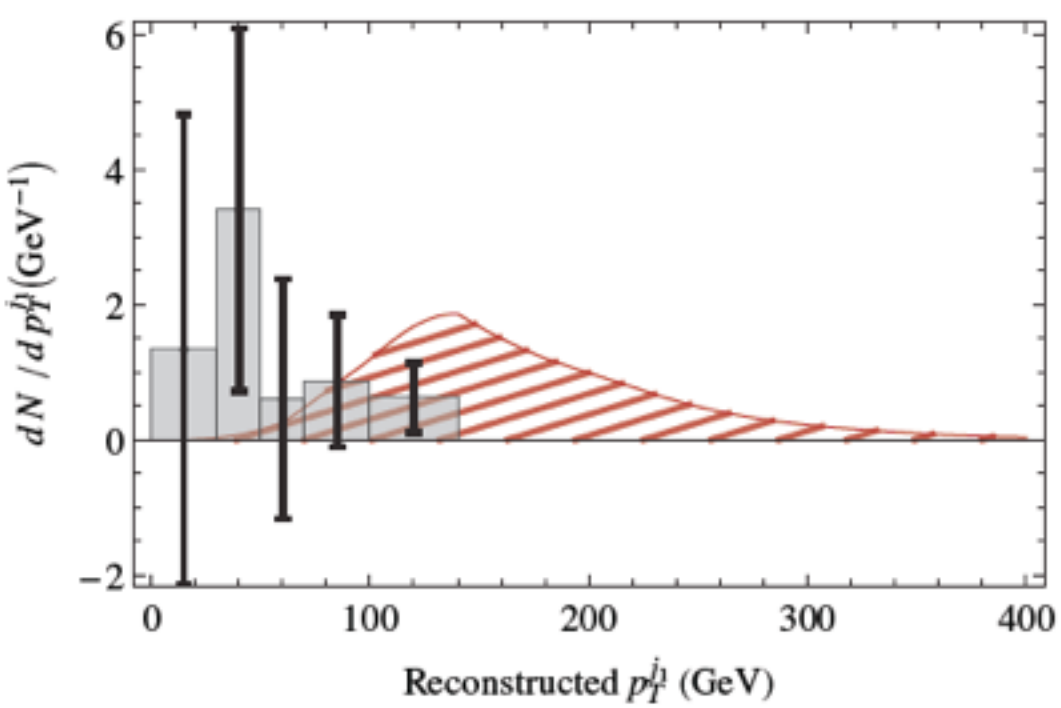
- **LHC bounds comes mostly from $h \to \gamma\gamma$** ATLAS-CONF-2013-072

Look for a deviations in pp → h(hjj) → $\gamma\gamma$ X or bbX

i.e. modifications to SM Higgs signals and their angular and p_T distributions







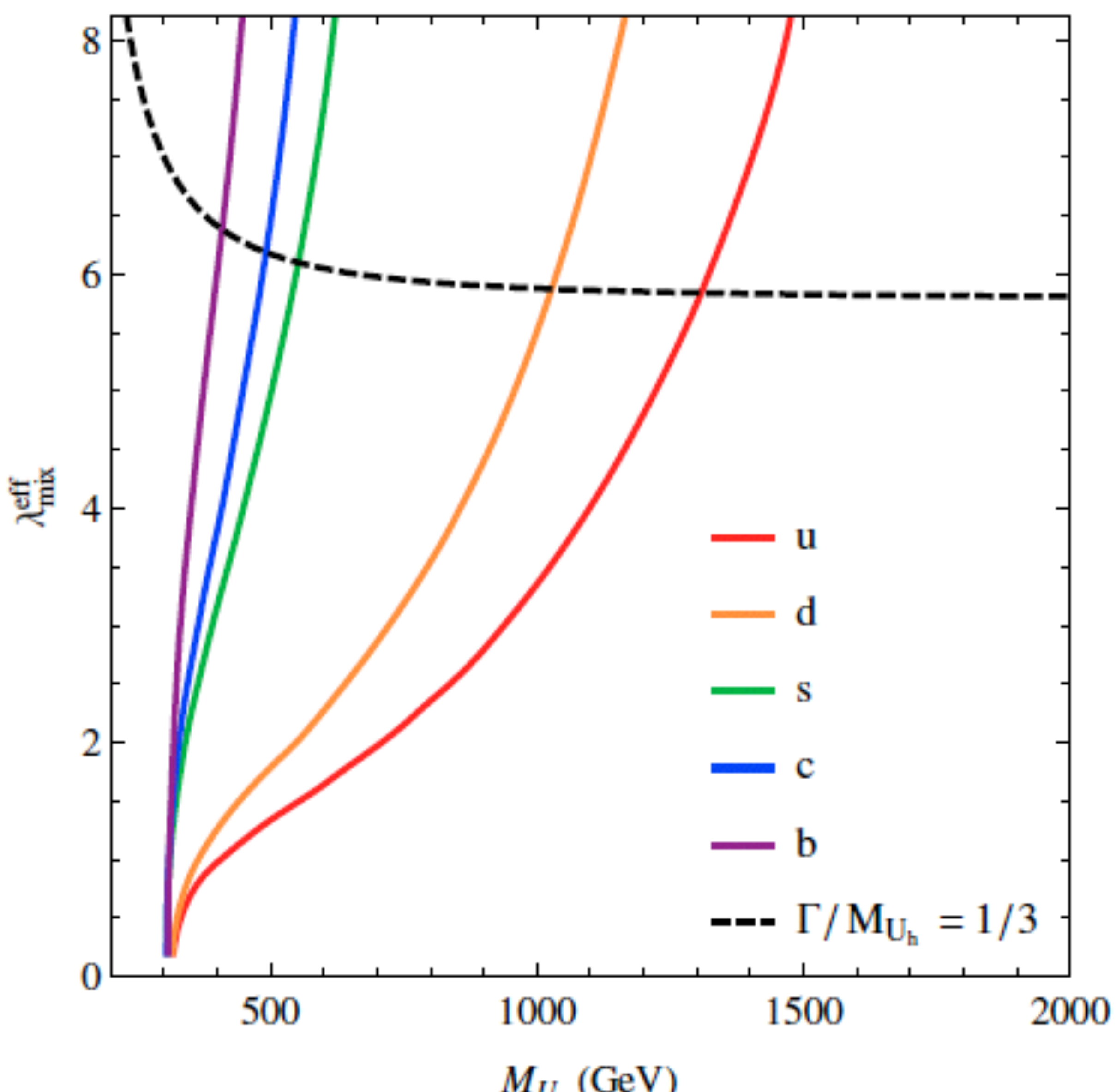
The distributions shown result from a partially composite down-quark model with a partner mass of M_{U_h} = 300 GeV and effective coupling =1(red striped region).

Partners in Singlet @ Run I

- LHC bounds comes from QCD pair production:

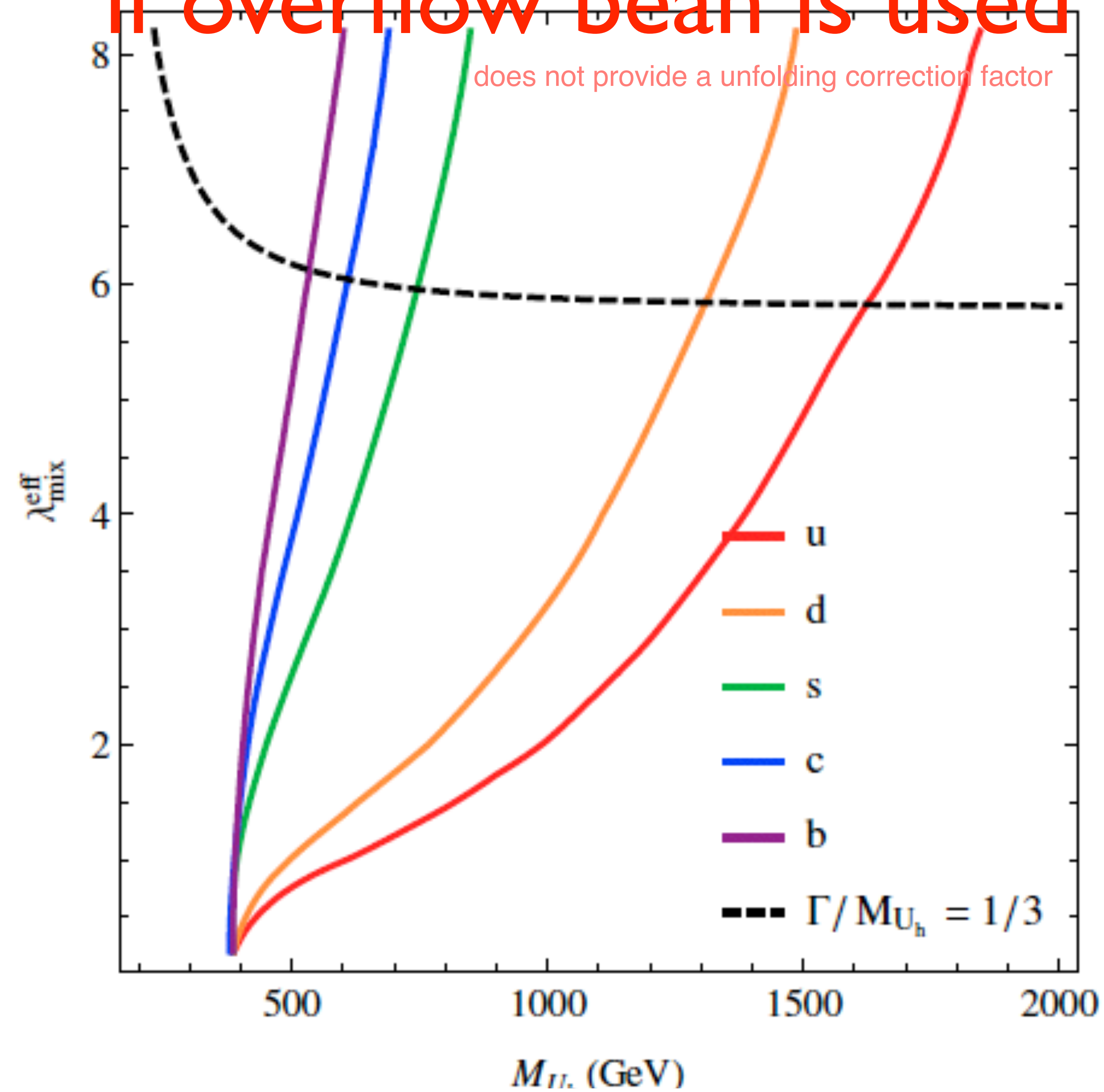
partially composite: $M_{U_h} \gtrsim 310$ GeV fully composite: $M_{U_h} \gtrsim 212$ GeV

- LHC bounds for single production (partially composite):



if overflow bean is used

does not provide a unfolding correction factor



Performing a bin-by-bin χ^2 test on the BSM distributions, we obtain a bound on the composite quark parameter space.

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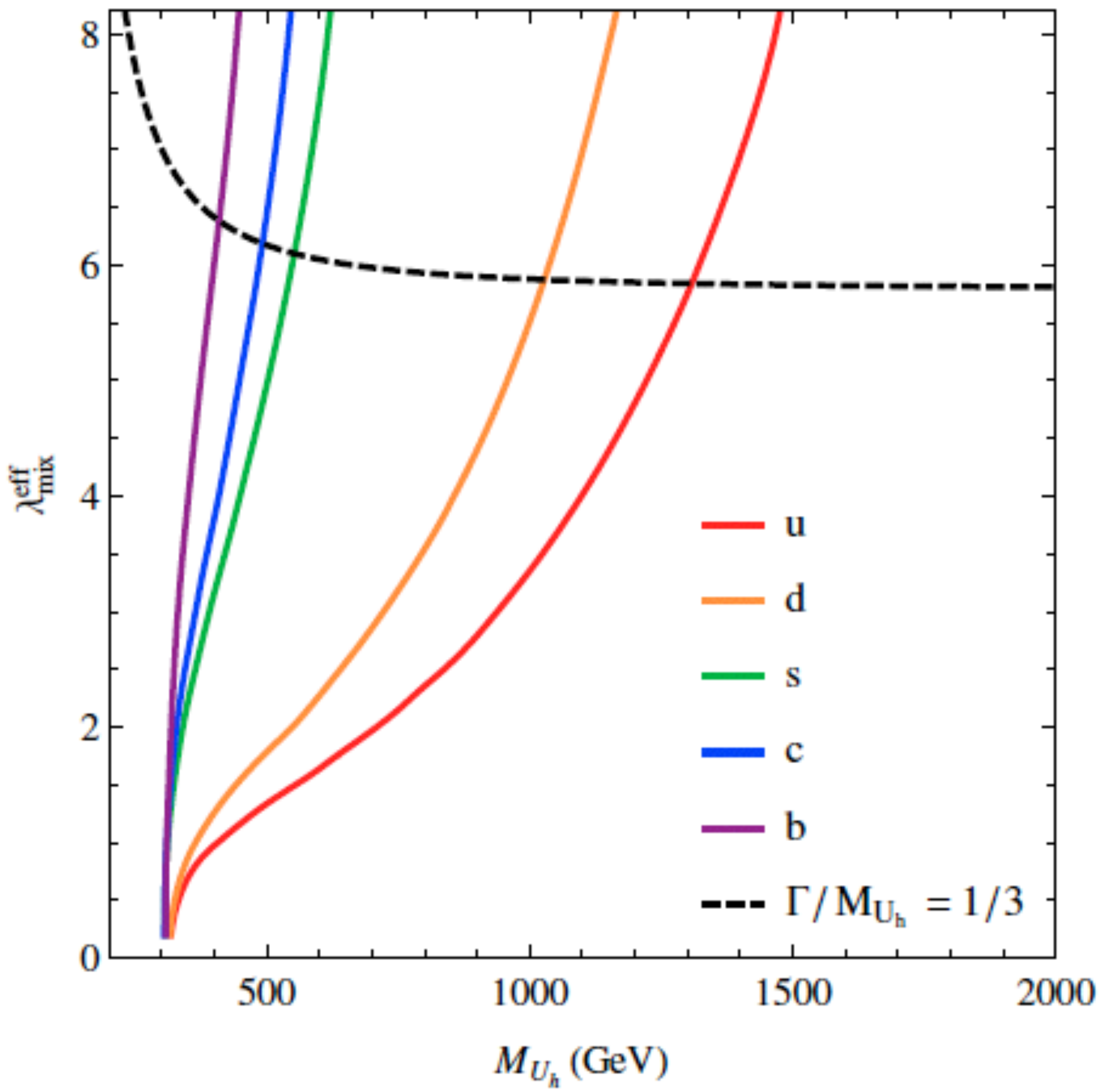

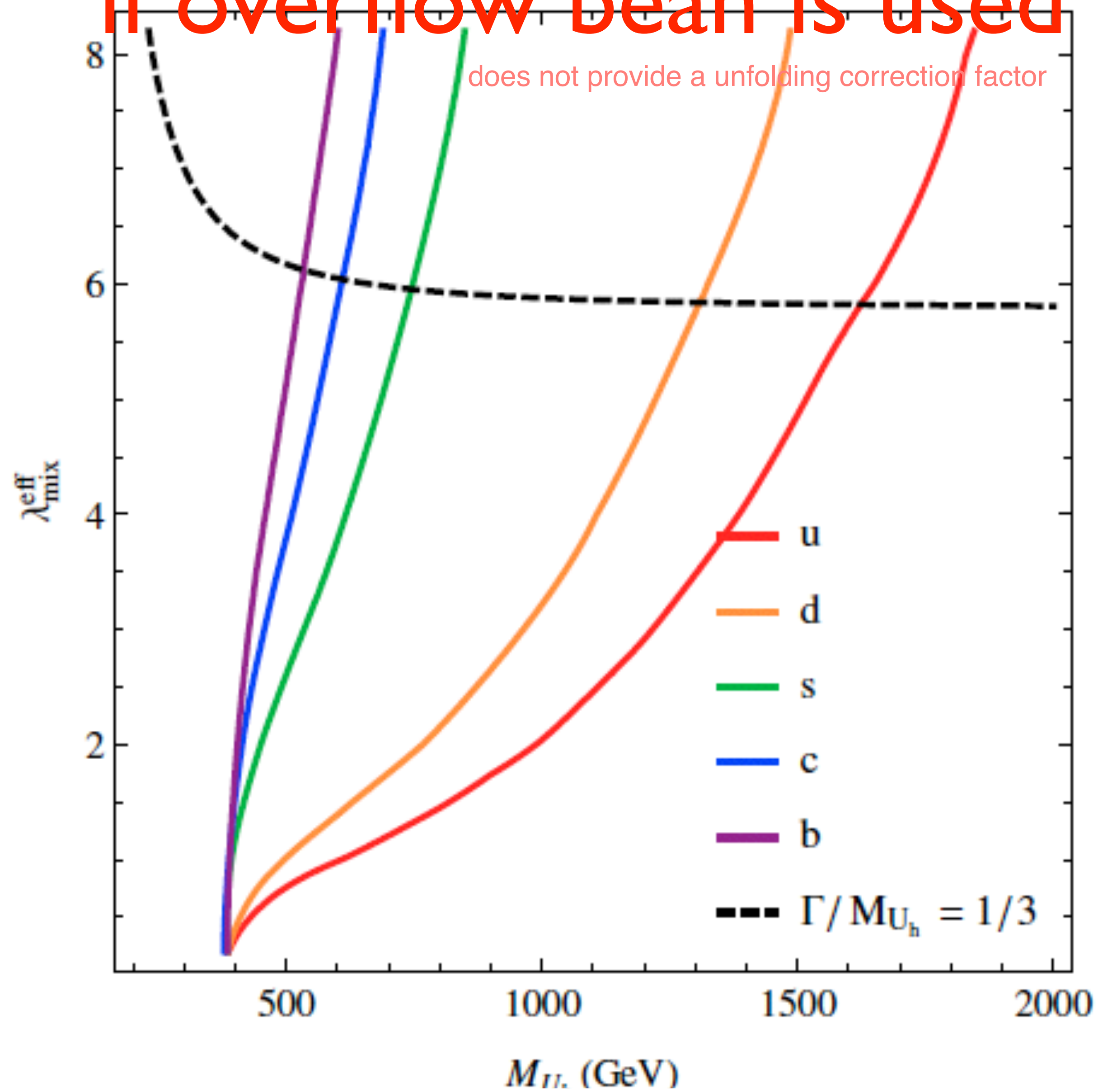

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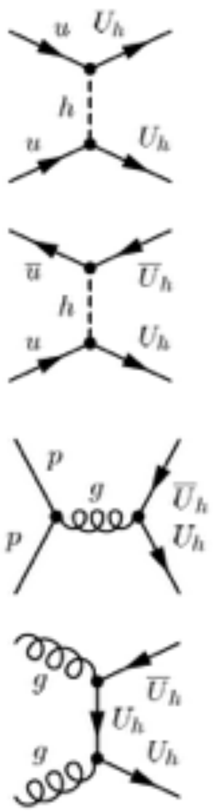
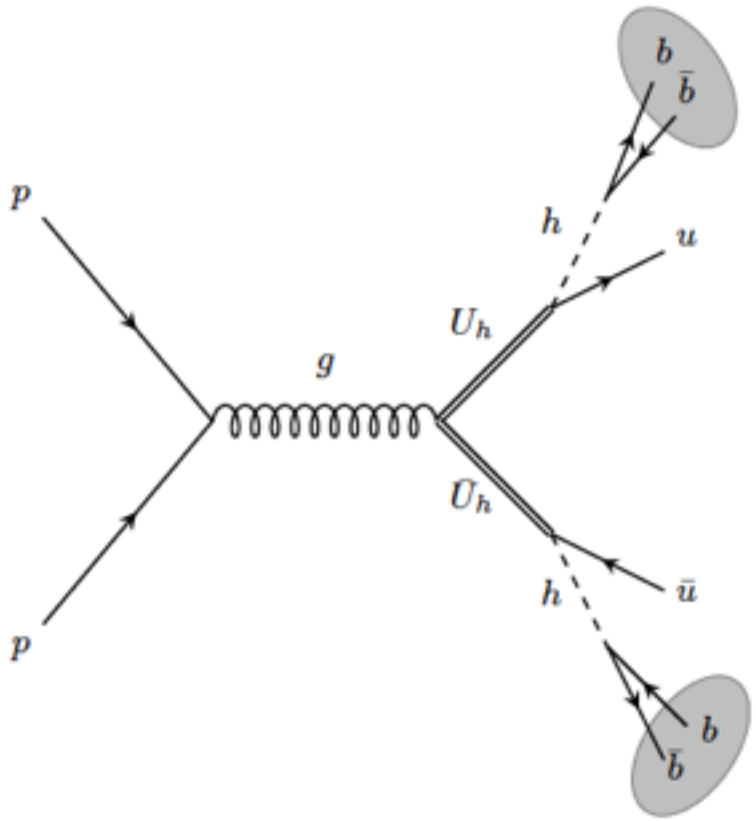
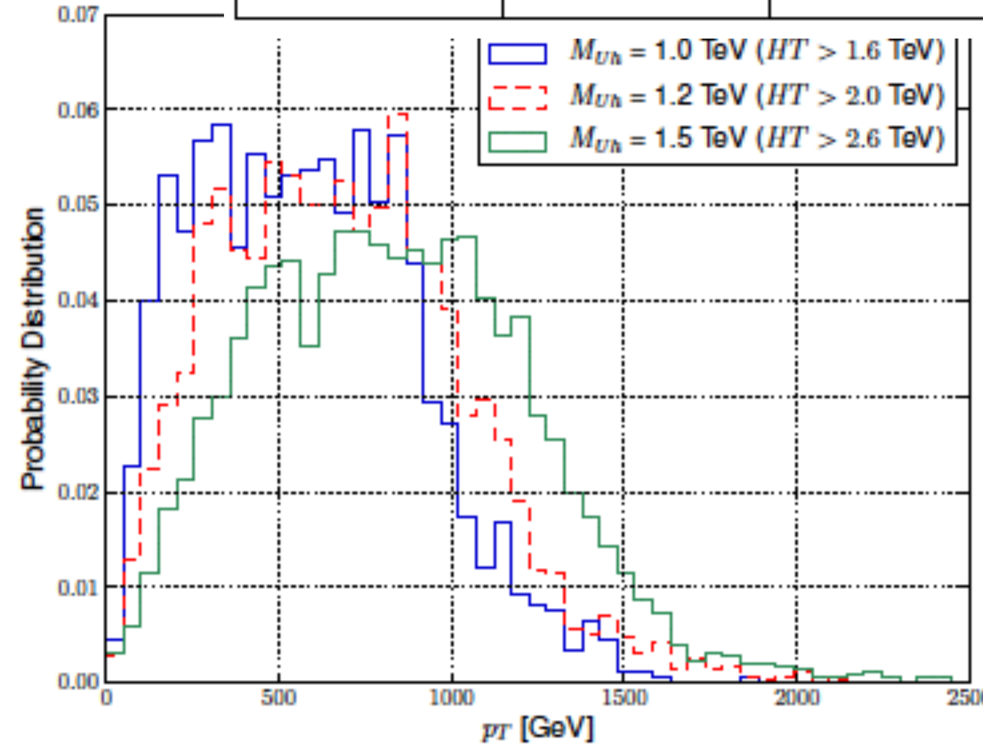
Partners in Singlet: boosted analysis @ Run 2

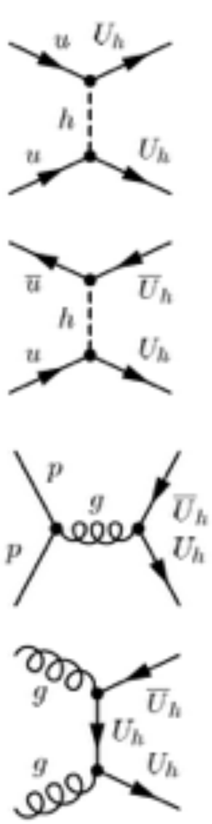


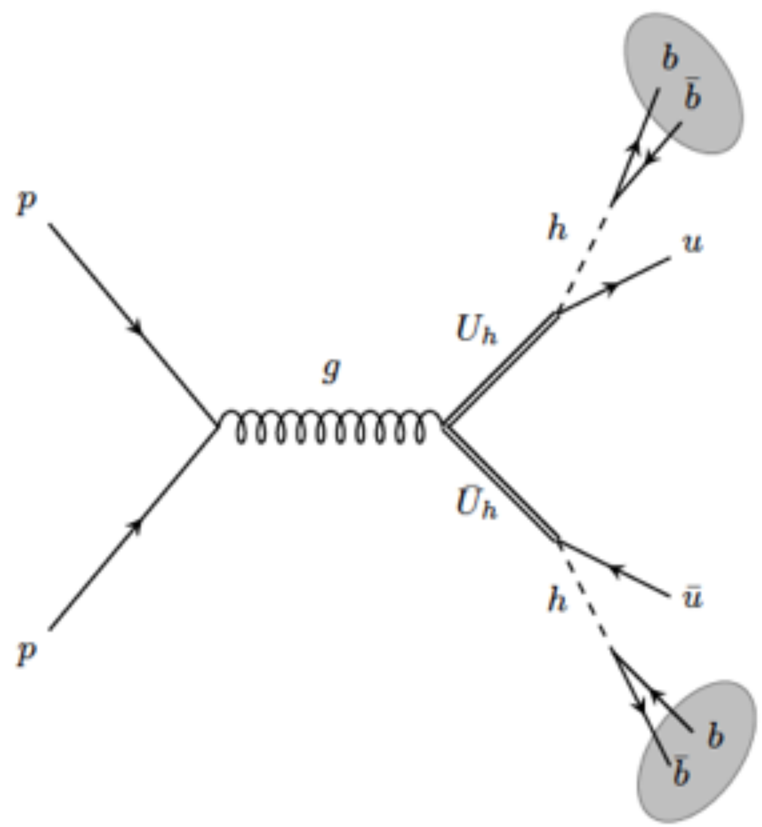


σ_s^{LO} [pb]	$\sigma_{t\bar{t}}^{NLO}$ [pb]	$\sigma_{b\bar{b}}^{NLO}$ [pb]	$\sigma_{\text{multi-jet}}^{NLO}$ [pb]
6.8×10^{-3}	4.6×10^{-1}	8.4	282.2



Partners in Singlet: boosted analysis @ Run 2





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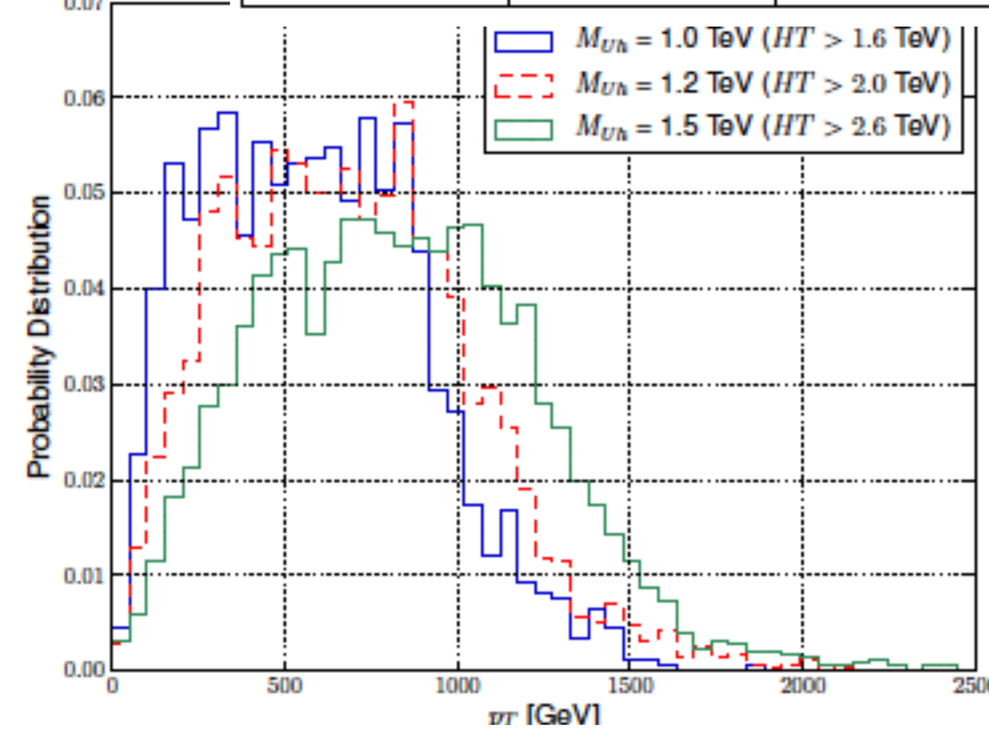
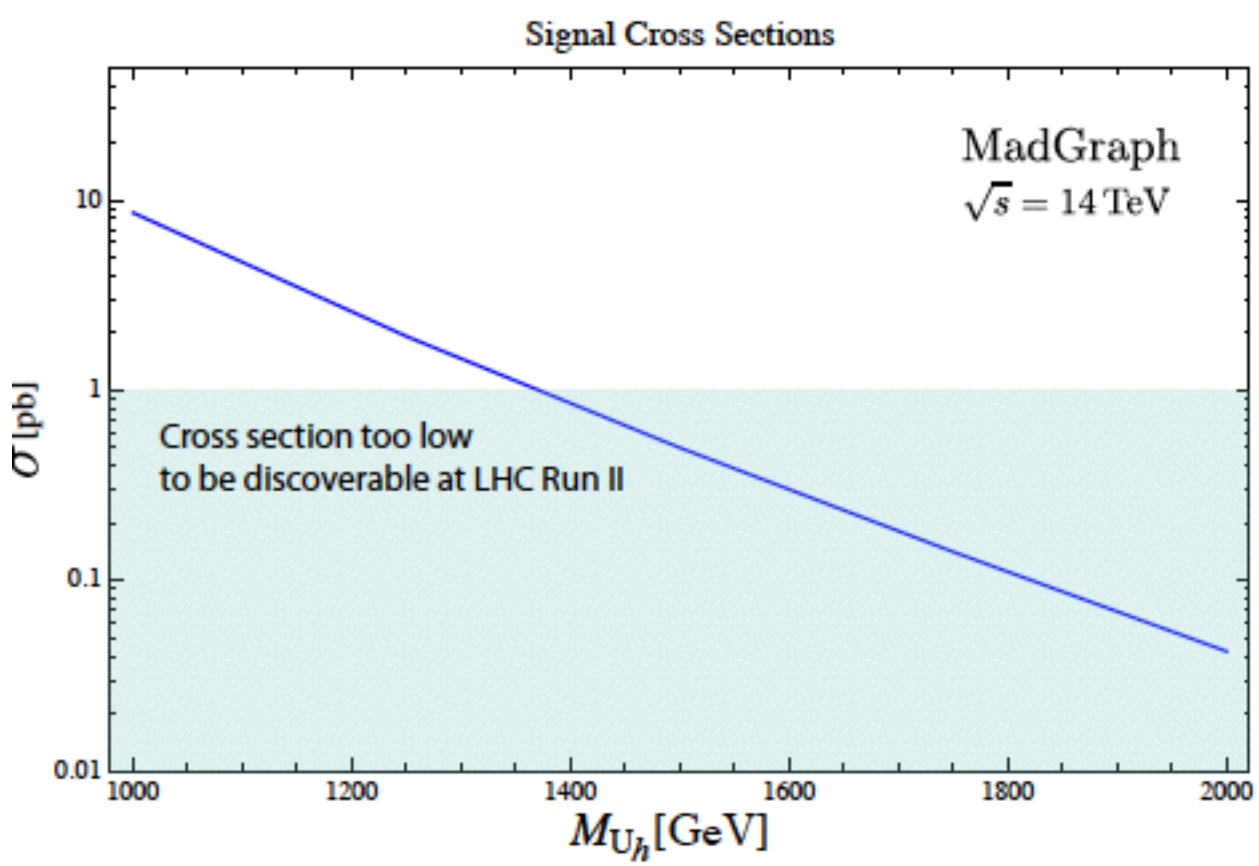
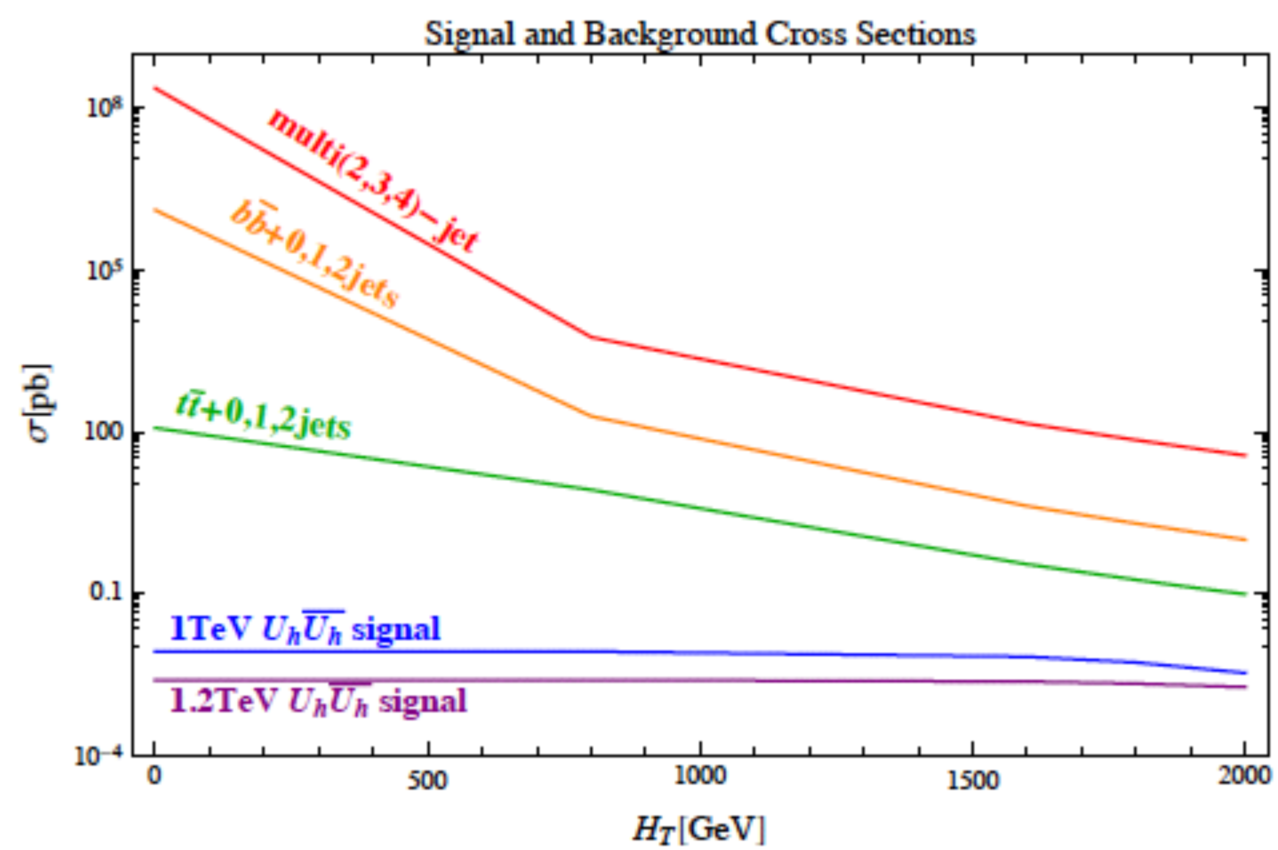
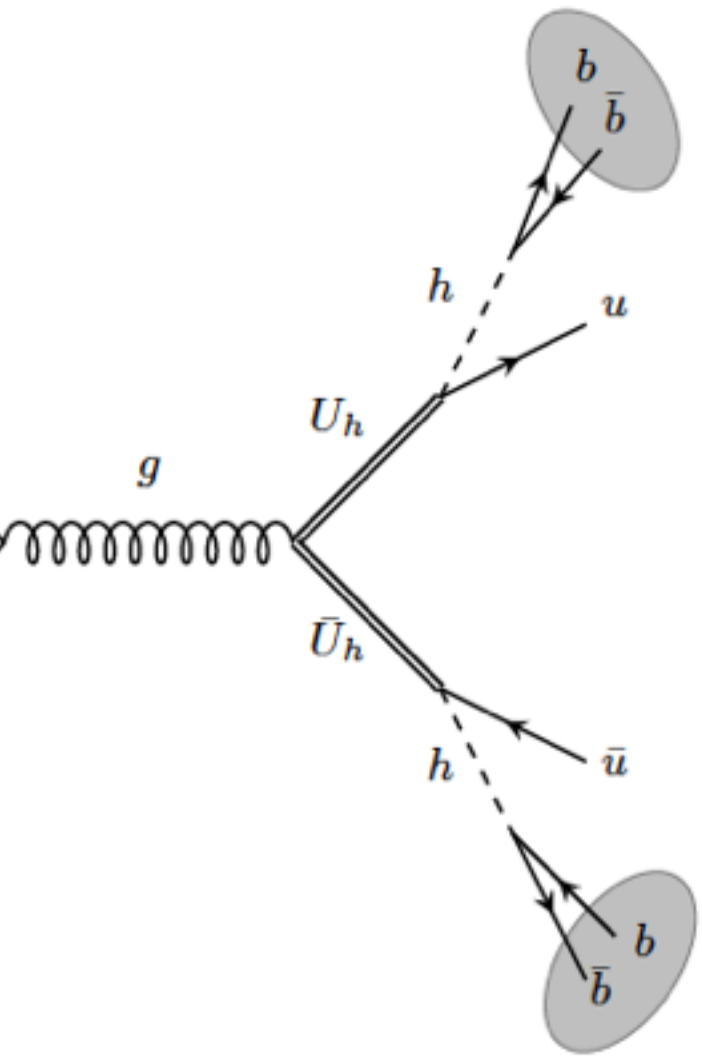
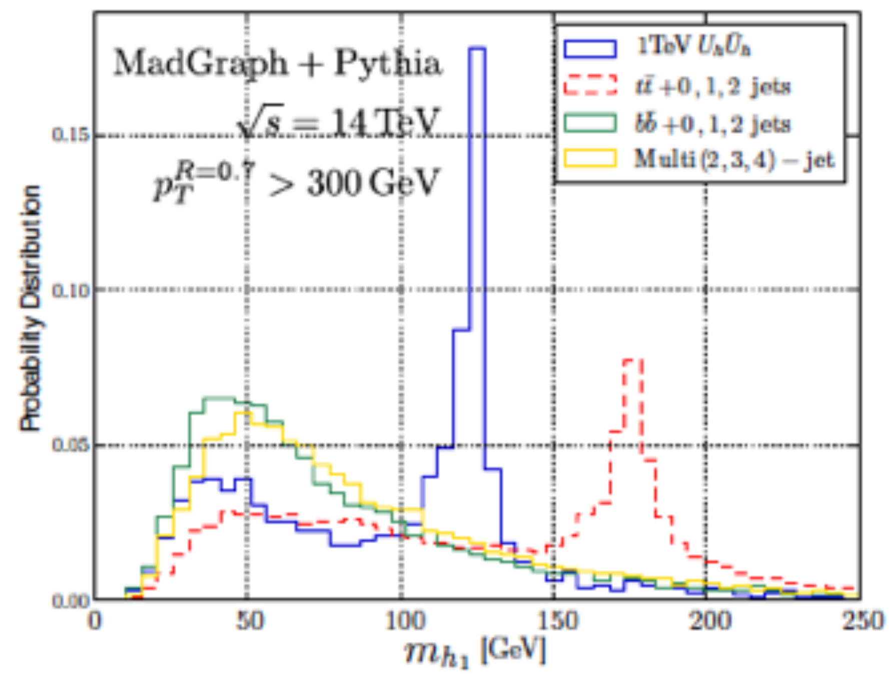


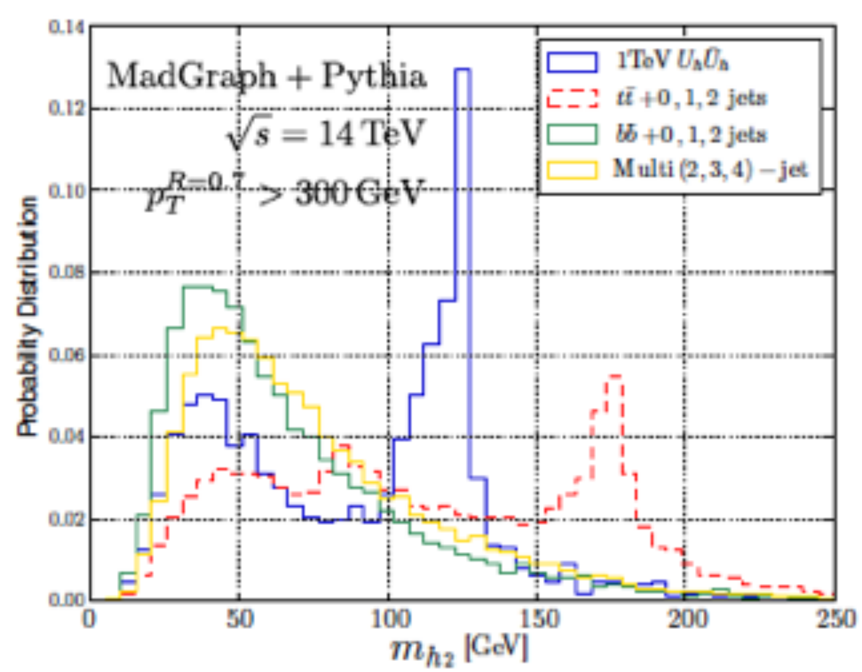




Partners in Singlet: boosted analysis @ Run 2







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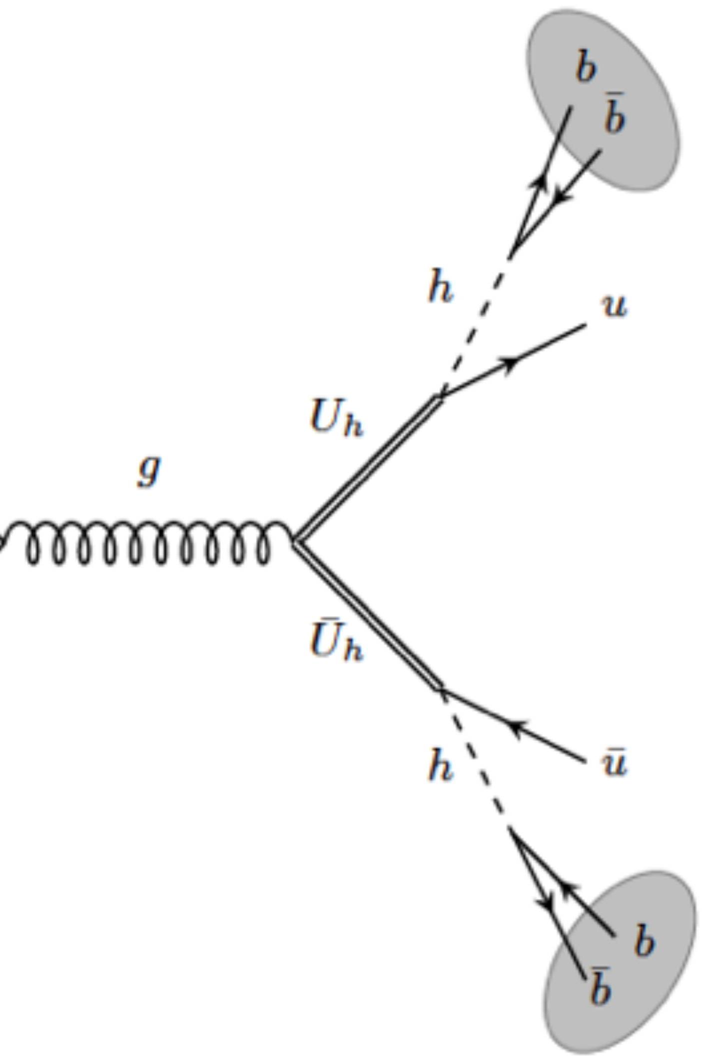
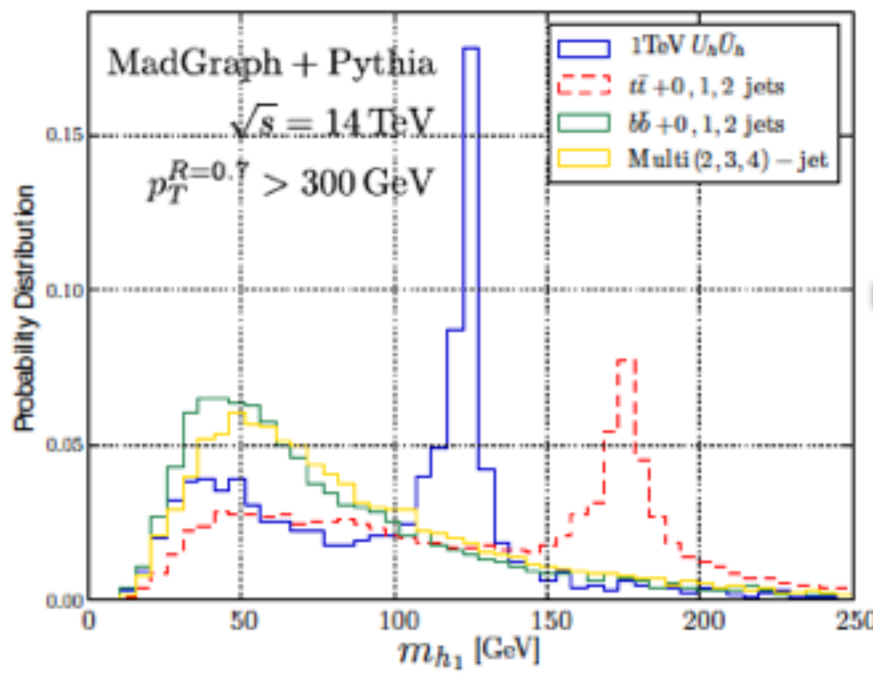
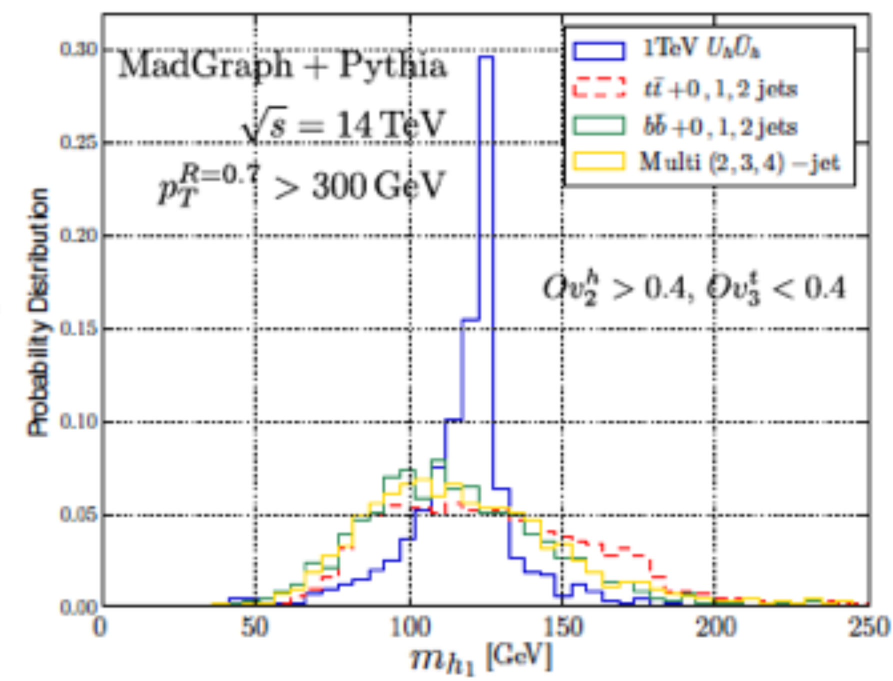
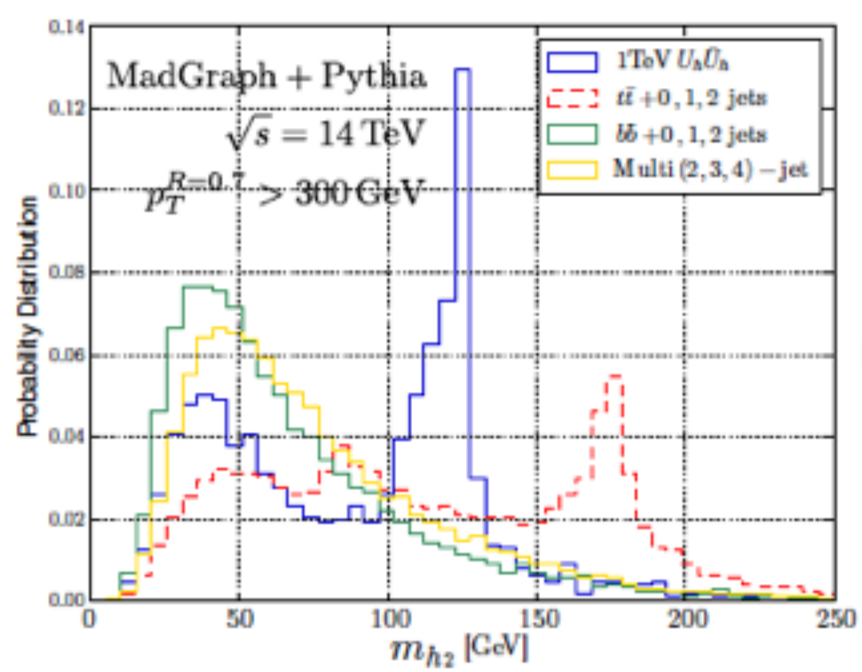


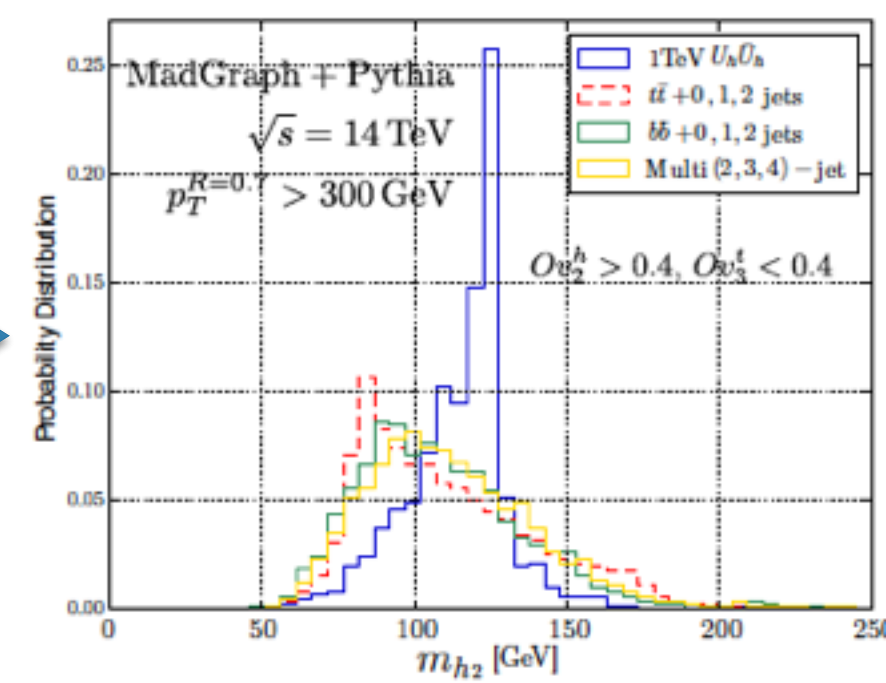




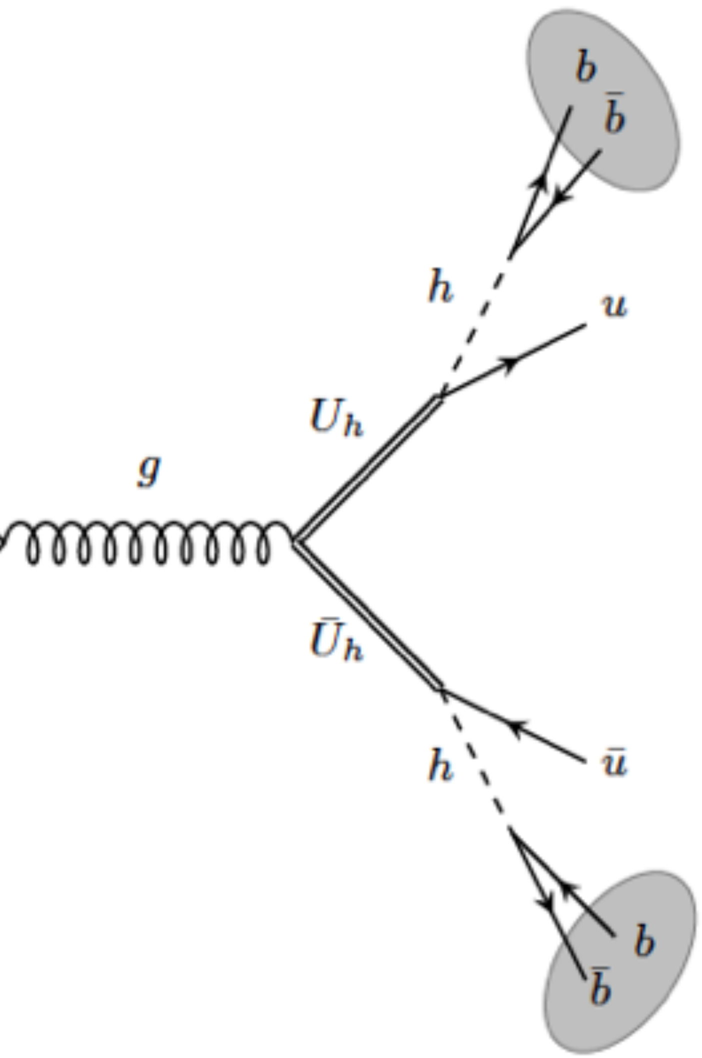
Boosted Higgs Tagging

+ anti-top tagging: **Template Overlap Method**



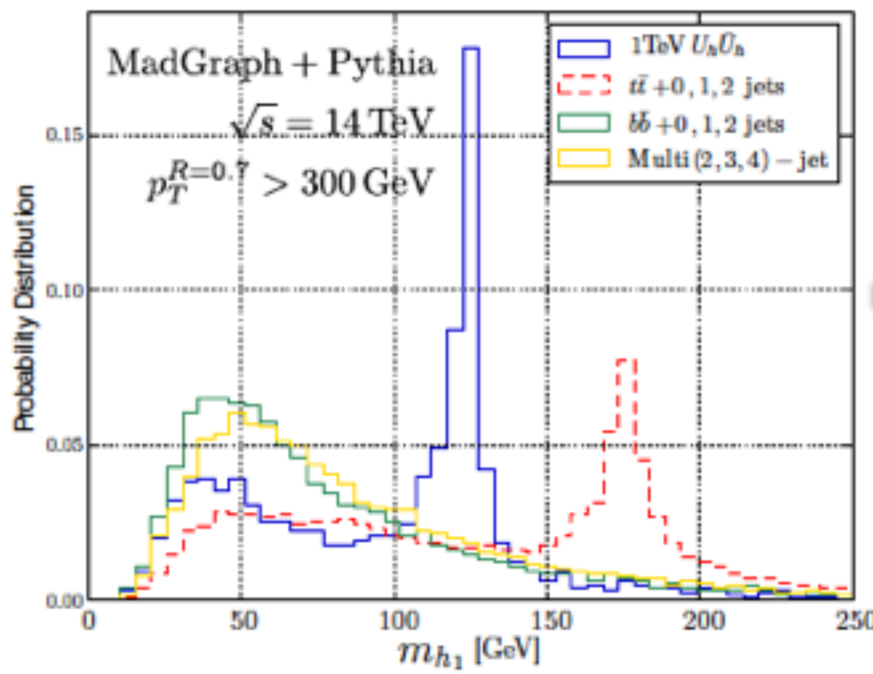


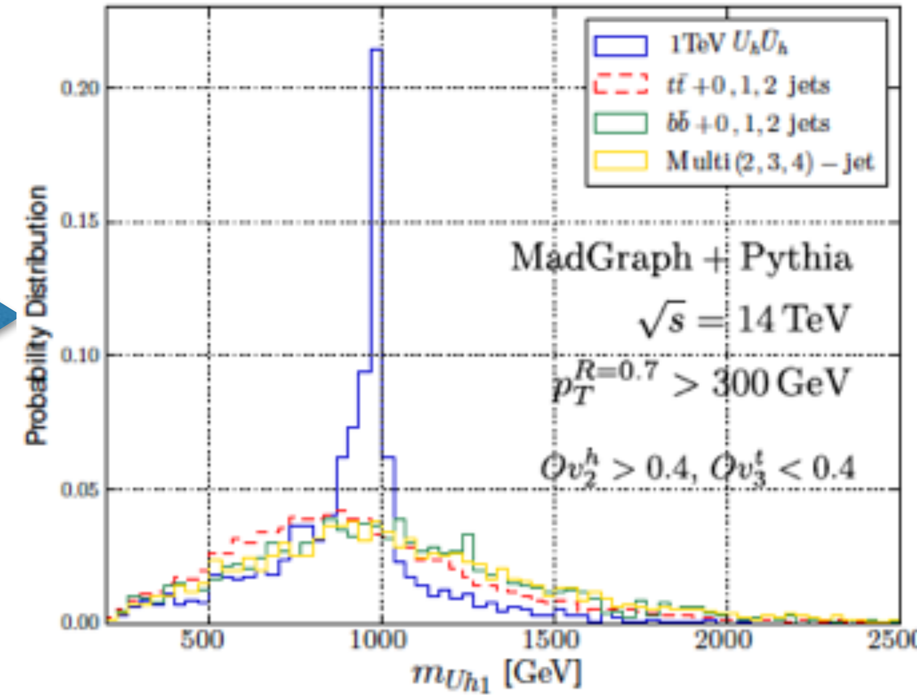
Partners in Singlet: boosted analysis @ Run 2



$$\Delta_{U_h} = \min\left[|m_{11}^{U_h} - m_{22}^{U_h}|, |m_{12}^{U_h} - m_{21}^{U_h}|\right]$$

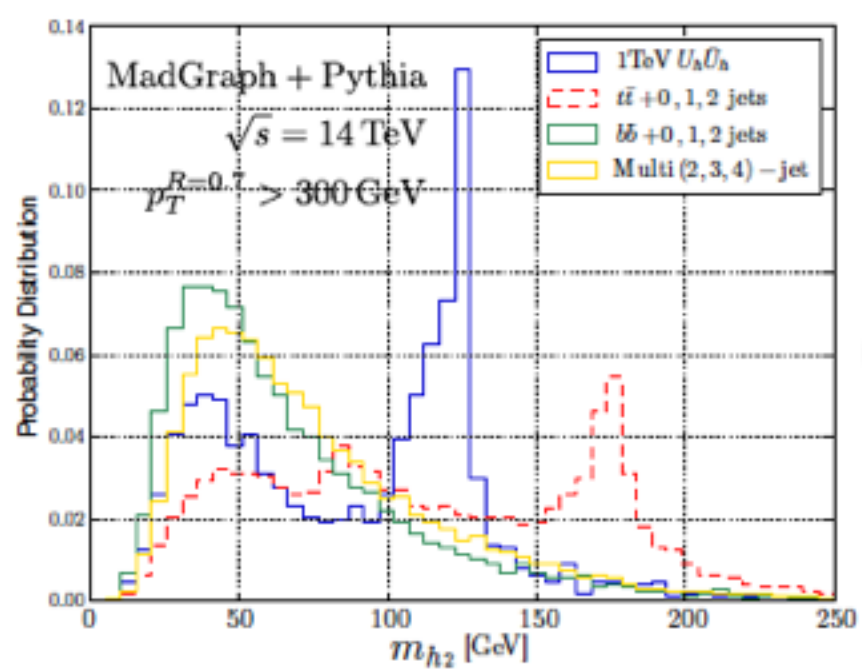
$$|\Delta_{U_h}| < 0.1$$

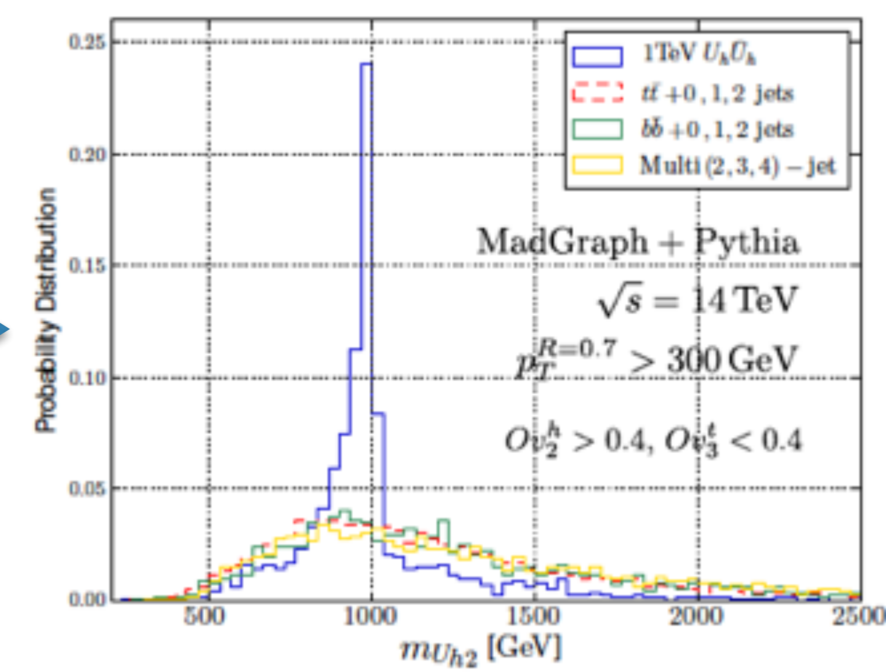




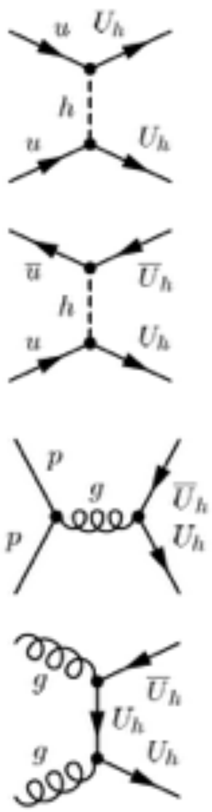
Boosted Higgs Tagging

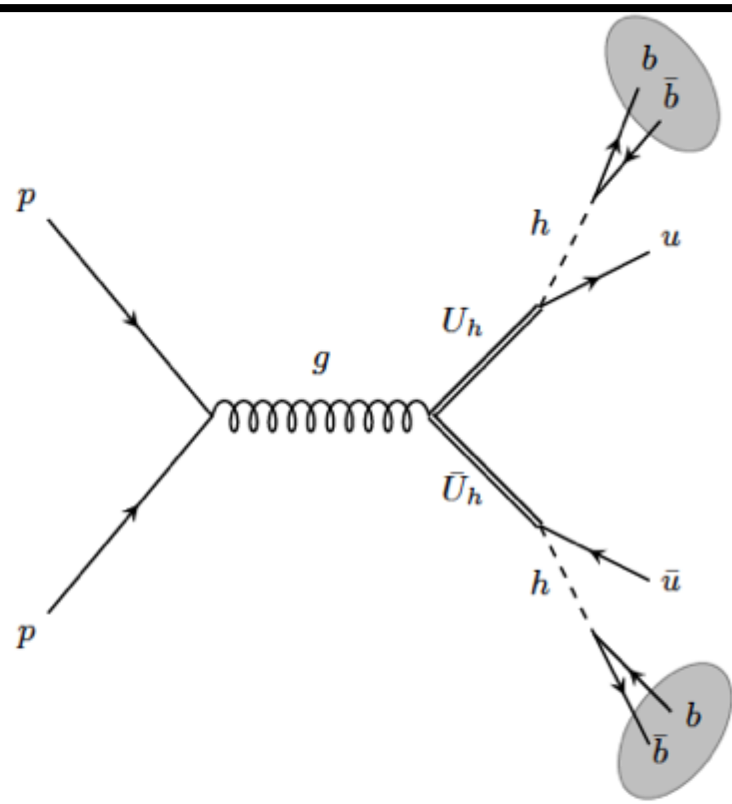
+ anti-top tagging: **Template Overlap Method**





Partners in Singlet: boosted analysis @ Run 2





σ_s^{LO} [pb]	$\sigma_{t\bar{t}}^{NLO}$ [pb]	$\sigma_{b\bar{b}}^{NLO}$ [pb]	$\sigma_{\text{multi-jet}}^{NLO}$ [pb]
6.8×10^{-3}	4.6×10^{-1}	8.4	282.2

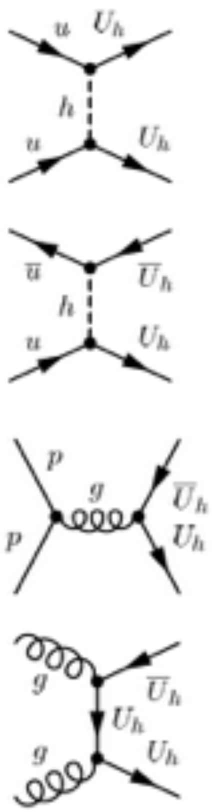
14 TeV, $M_{U_h} = 1$ TeV , $\sigma_s = 6.8$ fb , $\mathcal{L} = 35$ fb^{-1}

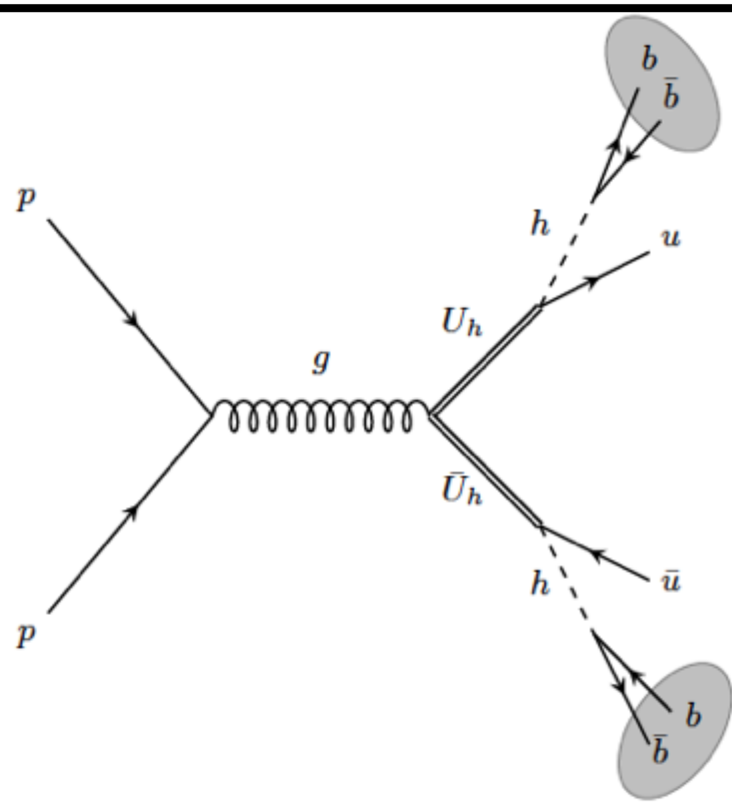
	σ_s [fb]	$\sigma_{t\bar{t}}$ [fb]	$\sigma_{b\bar{b}}$ [fb]	$\sigma_{\text{multi-jet}}$ [fb]	S/B	$S/\sqrt{B}$
Preselection Cuts	6.8	4.6×10^2	8.4×10^3	2.8×10^5	2.4×10^{-5}	7.5×10^{-2}
Basic Cuts	1.2	4.6	16.0	6.8×10^2	1.7×10^{-3}	2.7×10^{-1}
$\lvert\Delta_h\rvert < 0.1$	0.82	1.7	6.5	2.8×10^2	2.9×10^{-3}	2.9×10^{-1}
$\lvert\Delta_{U_h}\rvert < 0.1$	0.56	5.5×10^{-1}	2.0	87.0	6.3×10^{-3}	3.5×10^{-1}
$m_{U_{h1,2}} > 800$ GeV	0.50	3.6×10^{-1}	1.6	67.0	7.3×10^{-3}	3.6×10^{-1}
b-tag	0.34	4.4×10^{-2}	1.1×10^{-2}	1.5×10^{-2}	**4.8**	**7.5**

Template Overalp Method

b-tagging

Partners in Singlet: boosted analysis @ Run 2





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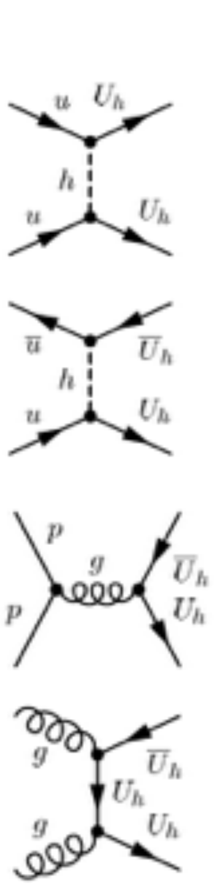
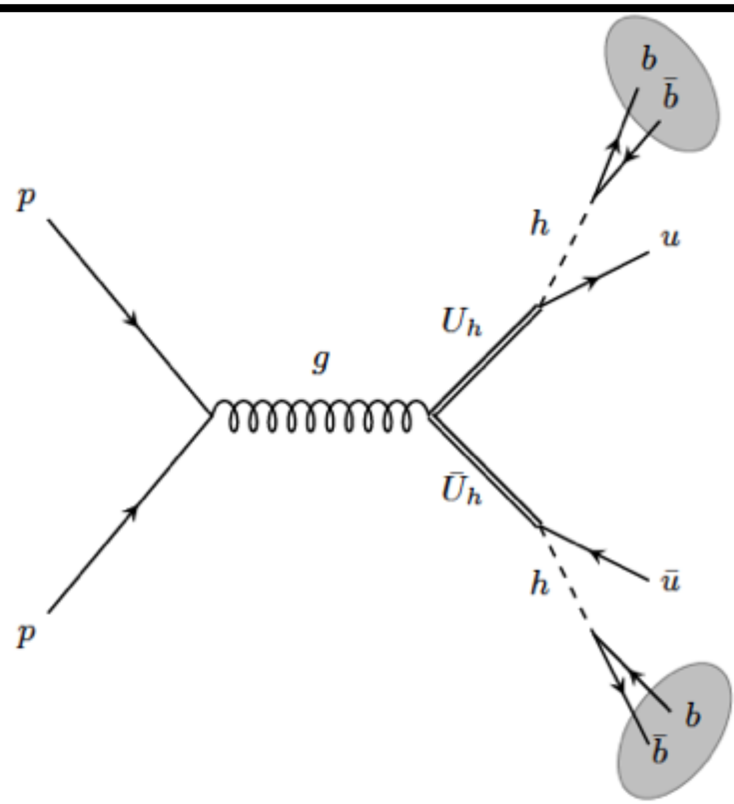
Template Overalp Method

b-tagging

Partners in Singlet: boosted analysis @ Run 2





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Run 2 of the LHC at 13 TeV can detect and measure 1TeV composite light quark partners via boosted higgs pair +jets in less than 35 fb^{-1}!

14 TeV, $\boxed{M_{U_h} = 1 \text{ TeV}}$, $\sigma_s = 6.8$ fb , $\mathcal{L} = 35$ fb^{-1}

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Template Overalp Method

b-tagging

Summary / Outlook

- Composite Higgs model (with H as PGB) provides a viable solution to the hierarchy problem and generically predict partner states to the fermions

- Light quark composite partners are interesting on its own, and also for flavorful naturalness, and have different phenomenology than that of top partners

- In the limit of first two generation degeneracy (as in MFV or U(2)-symmetric flavor models), fourplet partners need to be heavy (>1.8TeV), but for non-degenerate case, charm partner can be allowed to be very light => Flavorful Naturalness

- Singlet Partner has not been constrained much, but it will be probed much better @ Run 2

- Dedicated analysis for boosted Higgs/VB/top is required