Prospects and Precision at the Large Hadron Collider at 14 TeV

Searches for composite partners at the LHC: status and prospects

Seung J. Lee

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Delaunay, Fraille, Flacke, SL, Panico, Perez `13
Flacke, Kim, SL, Lim `13
Backovic, Flacke, SL, Perez `14
Backovic, Flacke, Kim, SL in preparation `14
Blum, Cliche, Csaki, SL `14

Outline

- Introduction (Composite Higgs Model)
- Top partner Searches
- Flavorful naturalness (hiding top partners): Light Composite partner searches
- Vector resonance searches
- Composite WIMP Dark Matter (through Dilaton Portal)
- Summary

Motivation

* The discovery of a SM-like Higgs boson at the LHC is a great victory

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Is SM complete with no definite new scale (modulo gravity)?

- It's too early to give up (e.g. naturalness paradigm)

We are still in the early stage (less than half way through) of LHC era.

(The Higgs mass is subject to additive renormalization => EW scale is technically unnatural. The solution of this UV sensitivity problem requires new dynamics characterized by energy scale close to the weak scale.)

Motivation

We Might be this Close!

* The discovery … at
victory

* So far nothing … lings

Is SM comple…

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(The Higgs mass is subj… The solution
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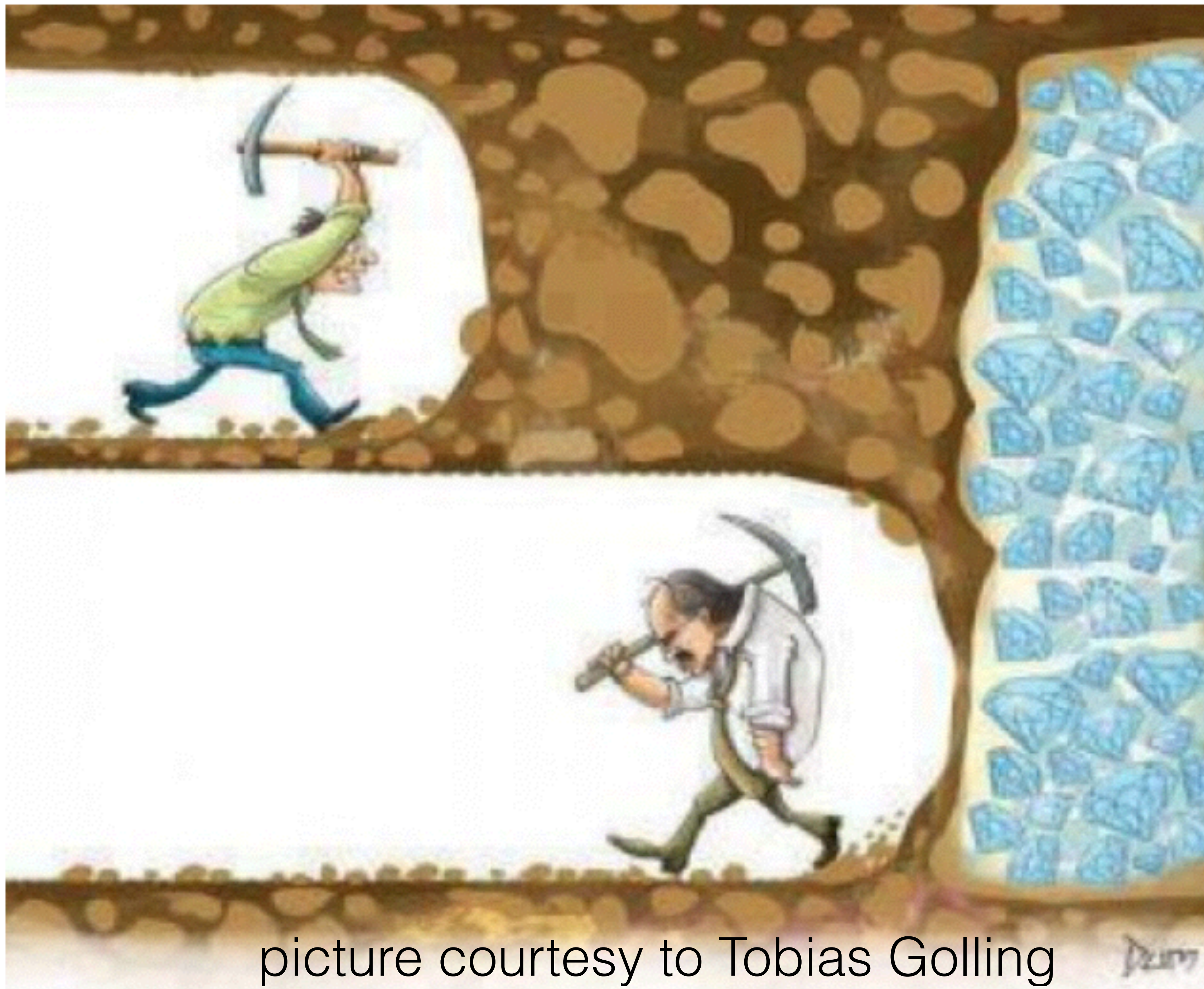
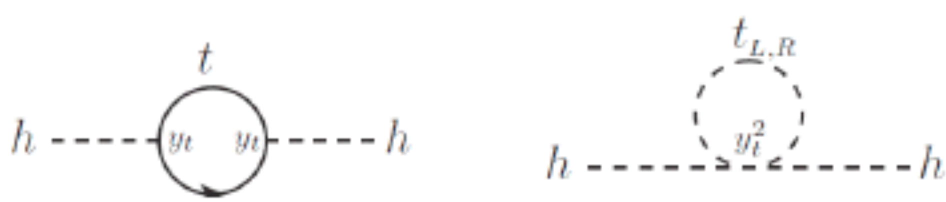


picture courtesy to Tobias Golling

Motivation

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



$$\frac{\delta m_h^2}{m_h^2} \sim \left(\frac{\tilde{m}_t}{400\,\mathrm{GeV}}\right)^2$$

2 leading frameworks
of naturalness

Supersymmetry
top partners=stops

Composite Higgs
top partners = "T"

Composite Higgs

- Just as pion (PGB) is the lightest states in QCD, Higgs is a PGB of a new strong sector (with symmetry breaking scale f) => Higgs is lighter than other resonances

  Georgi & Kaplan '84

- Warped XD models: 5D dual (AdS/CFT correspondence) of Composite Higgs: nice frame work, providing explicit realization of 4D composite Higgs models

  Randall & Sundrum,... '90s

  GUT works just as good as in SUSY

- Little Higgs: collective symmetry breaking

  Arkani-Hamed, Cohen, Georgi '00s

  -Higgs is GB under multiple symmetries
  -Two or more explicit symmetry breaking terms are needed to break all symmetries protecting the Higgs mass.
  - No quadratic divergences at one-loop.

- Holographic Higgs: Higss as a component of GB (A5)

  Contino, Nomura, Pomarol; Agashe, Contino, Pomarol; Hosotani,...

- Simple 4D effective description (Strongly-Interacting Light Higgs)

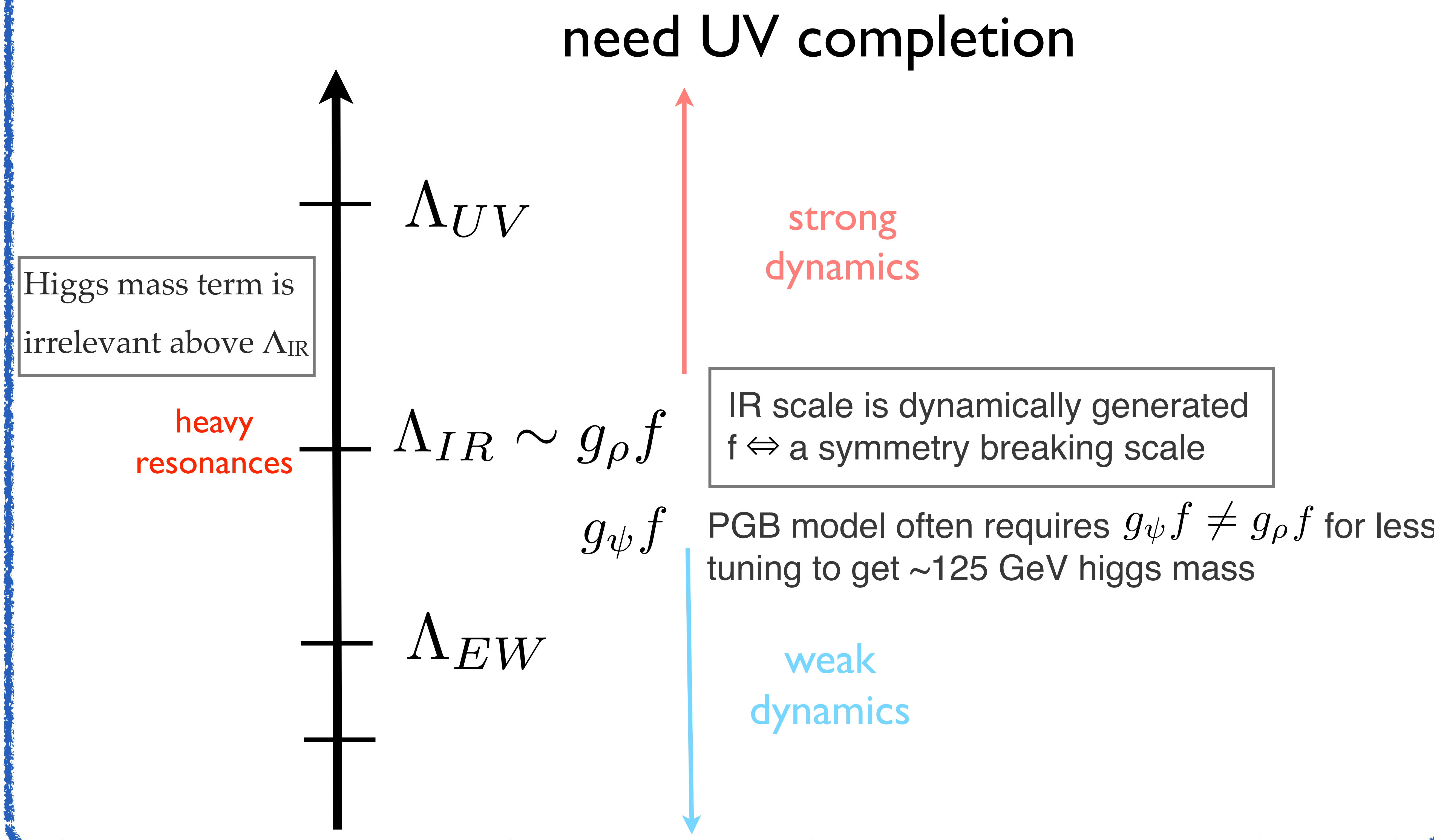
  Giudice, Grojean, Pomarol, Rattazzi '07

- NB: Higgs does not need to be a usual PGB; it can arise from other mechanisms, i.e. it can be a light dilaton

  Bellazzini, Csaki, Hubisz, Serra, Terning '12, '13

Composite Higgs

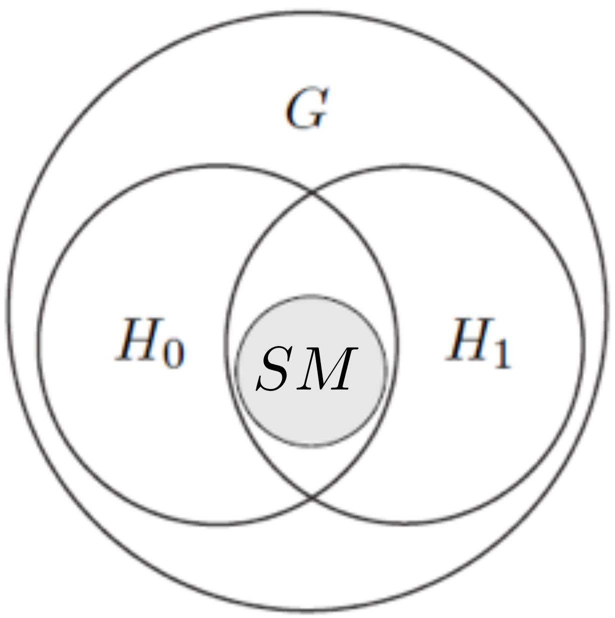
Georgi, Kaplan '84; Kaplan '91; Agashe, Contino, Pomarol '05; Agashe et al '06; Giudice et al '07; Contino et al '07; Csaki, Falkowski, Weiler '08; Contno, Servant '08; Mrazek, Wulzer '10; Panico, Wulzer '11; De Curtis, Redi, Tesi '11, Marzocca, Serone, Shu '12; Pomarol, Riva '12; Bellazini et al '12; De Simone et al '12, Grojean, Matsedonskyi, Panico `13; De Curtis, Redi, Vigiani `14,…



Minimal Composite PGB Higgs

- G/H_1: Global symmetry G is broken by strong dynamics at some scale f to a subgroup H_1.
- And a subgroup H_0 is gauged (explicit breaking of G), including $G_{SM}=SU(2)_L \times U(1)_{em}$ $\quad G_{SM} \in (H_0 \cap H_1)$

# of GB	$\dim(G) - \dim(H_1)$
# of eaten GB	$\dim(H_0) - \dim(H_0 \cap H_1)$
# of PGB	$\dim(G) - \dim(H_0 \cup H_1)$



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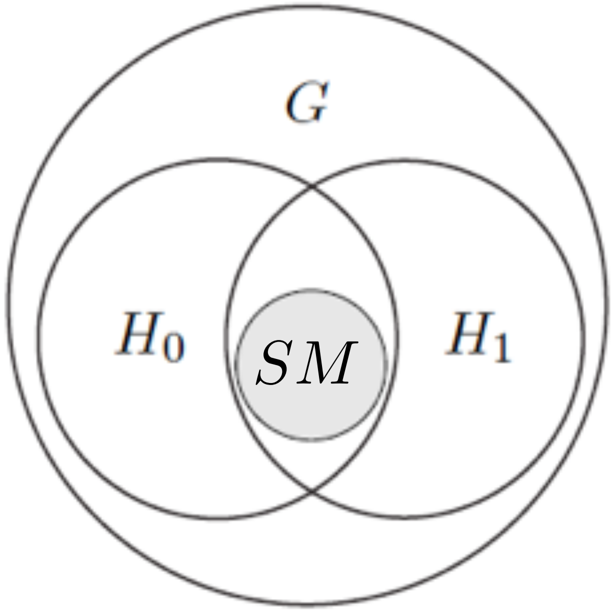

- Minimal choice: $H_0 = H_1 = G_{SM}$ and $\dim(G)-\dim(H_1) \geq 4$

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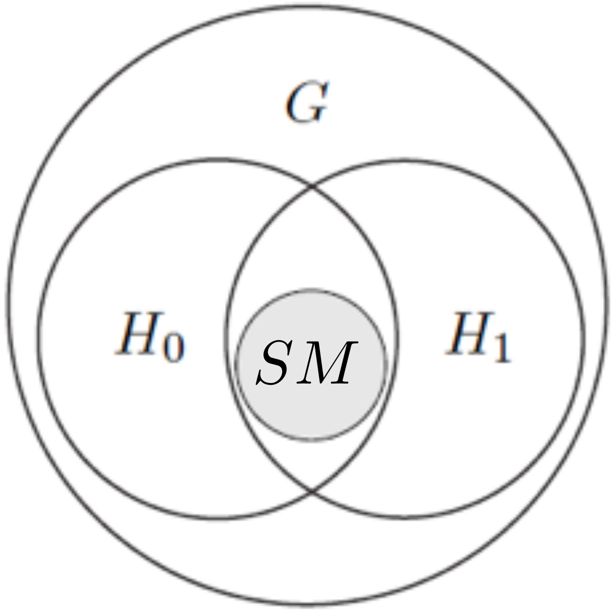

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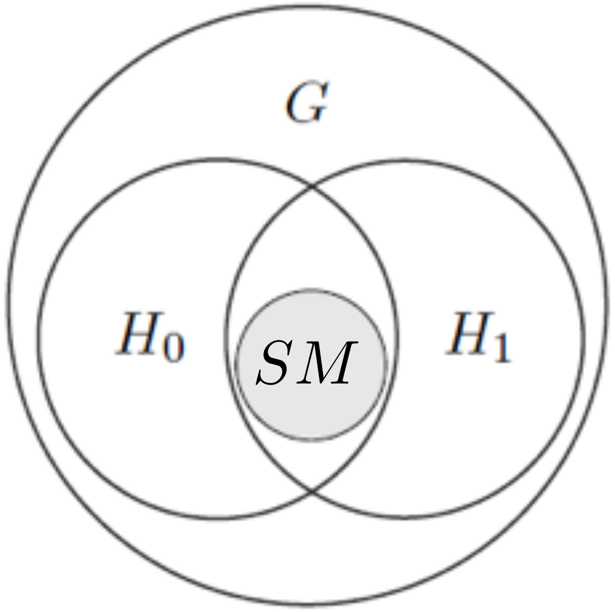

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$$H_1 = SU(2)_L \times SU(2)_R \simeq SO(4) \qquad SO(5)/SO(4)$$

Minimal Composite PGB Higgs

- Higgs potential radiatively generated by resonances loops (top is the largest contribution) Coleman Weinberg ’73

- Top contribution to the Higgs potential:

Contino et. al, Pomarol, Riva ’12

$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

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with EM charge 5/3,2/3,-1/3,...

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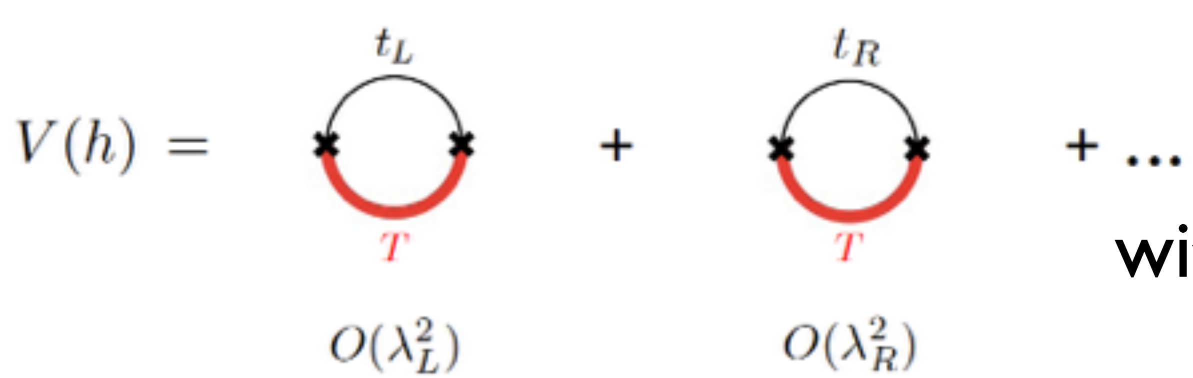
5 of SO(5) =4 + 1

=> light top partners (~1 TeV) are required to obtain 125 GeV Higgs mass to avoid large tuning



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But where are the partners @ LHC?

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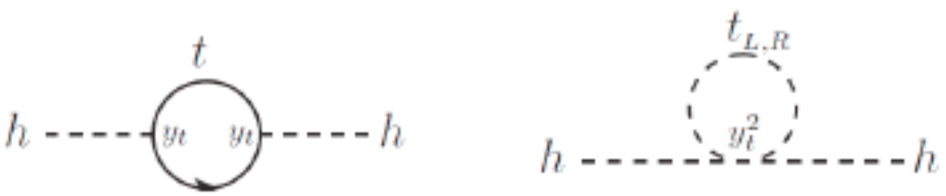

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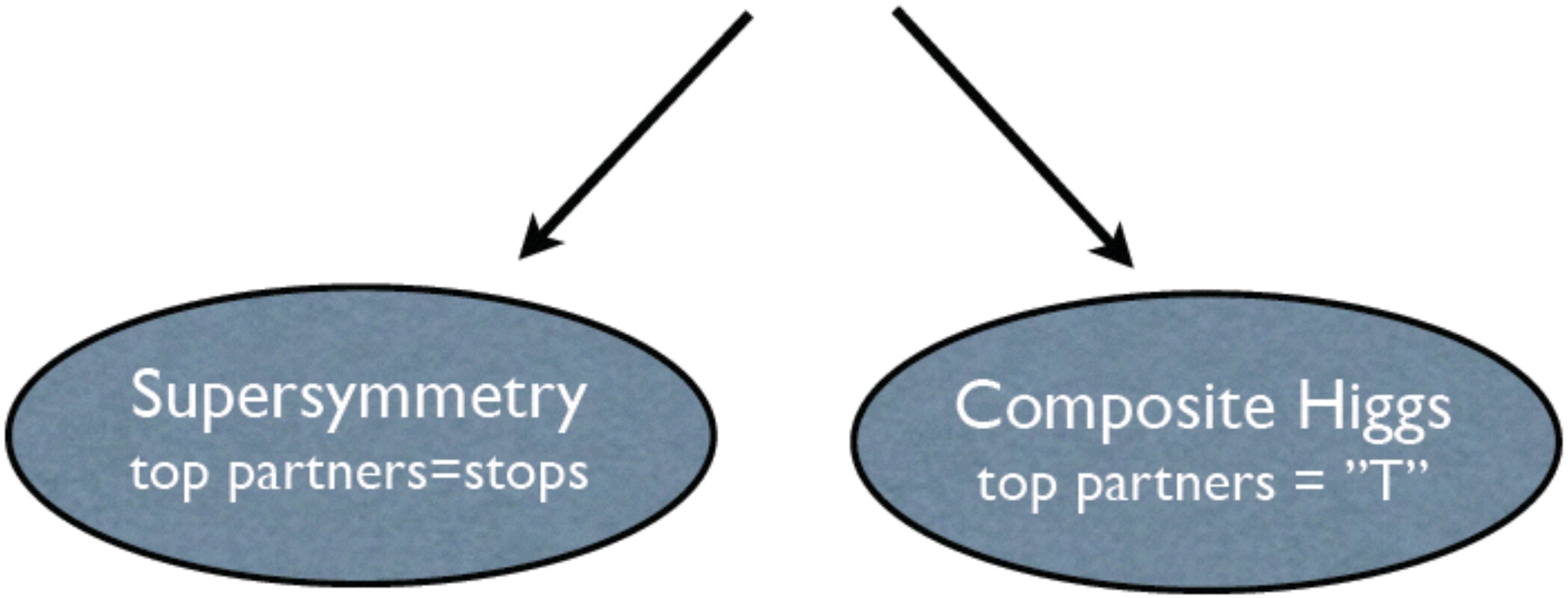
2 leading frameworks
of naturalness



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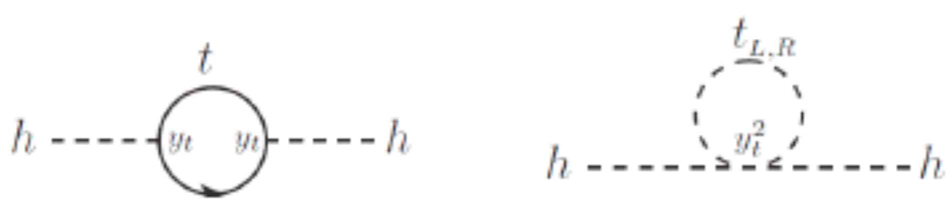

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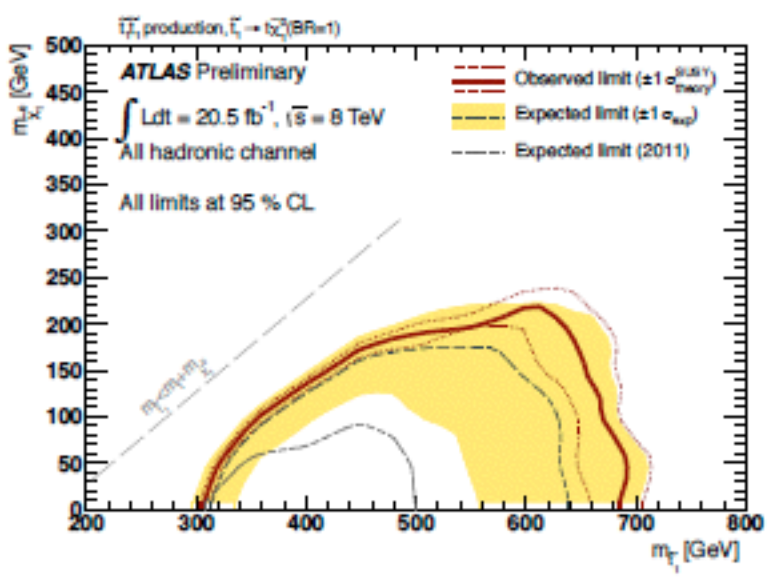
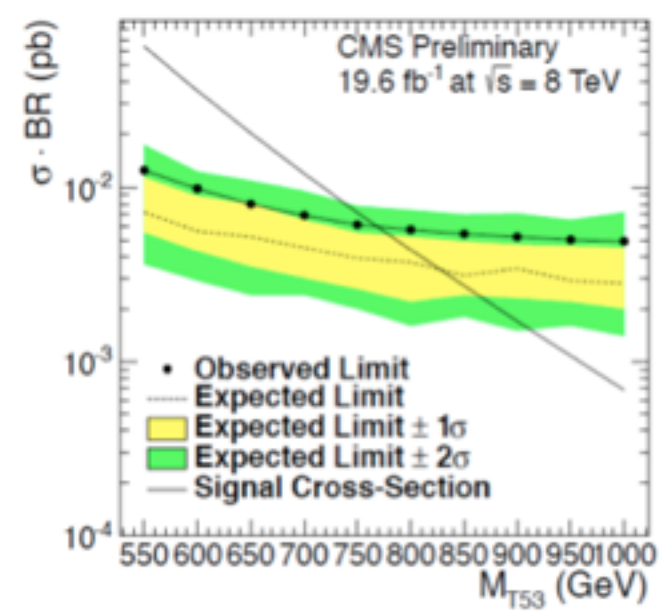
SUSY

composite Higgs



$m_{\mathrm{stop}} \gtrsim 700\,\mathrm{GeV}$



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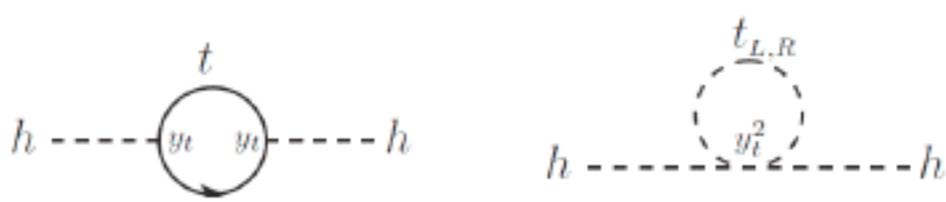

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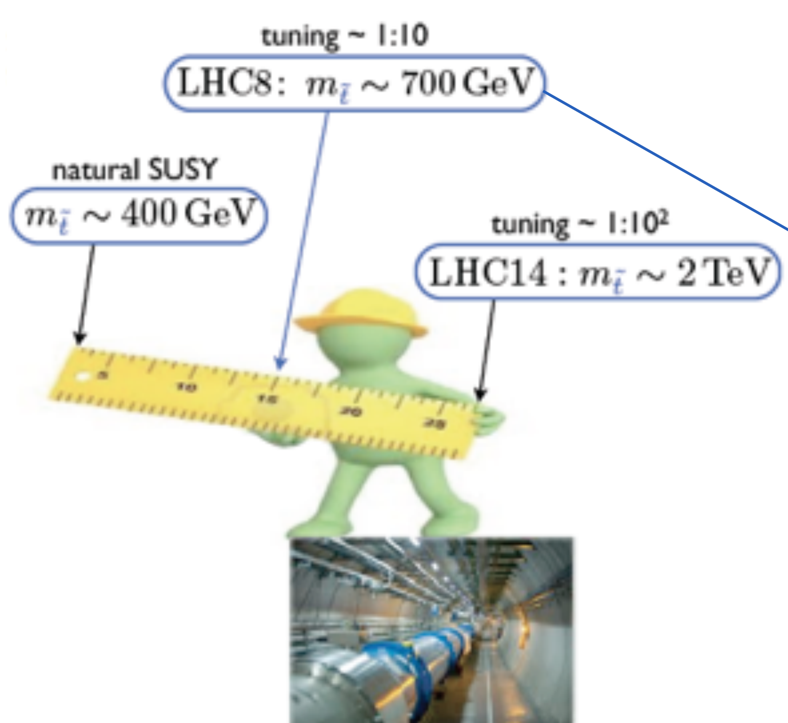

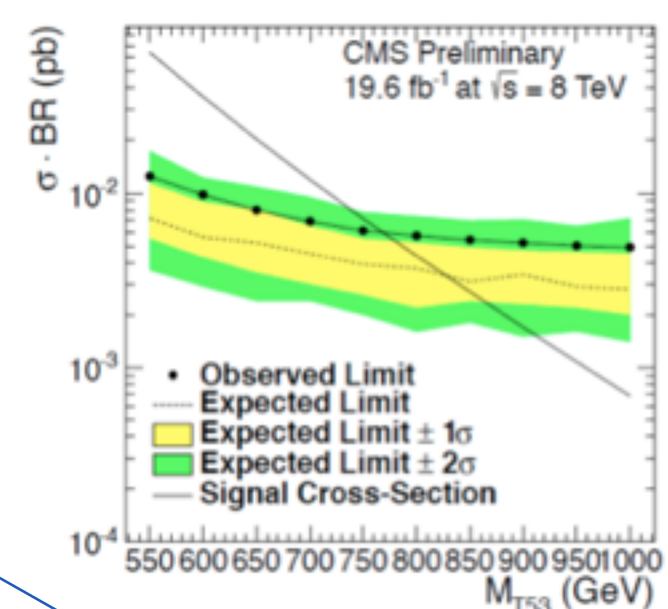

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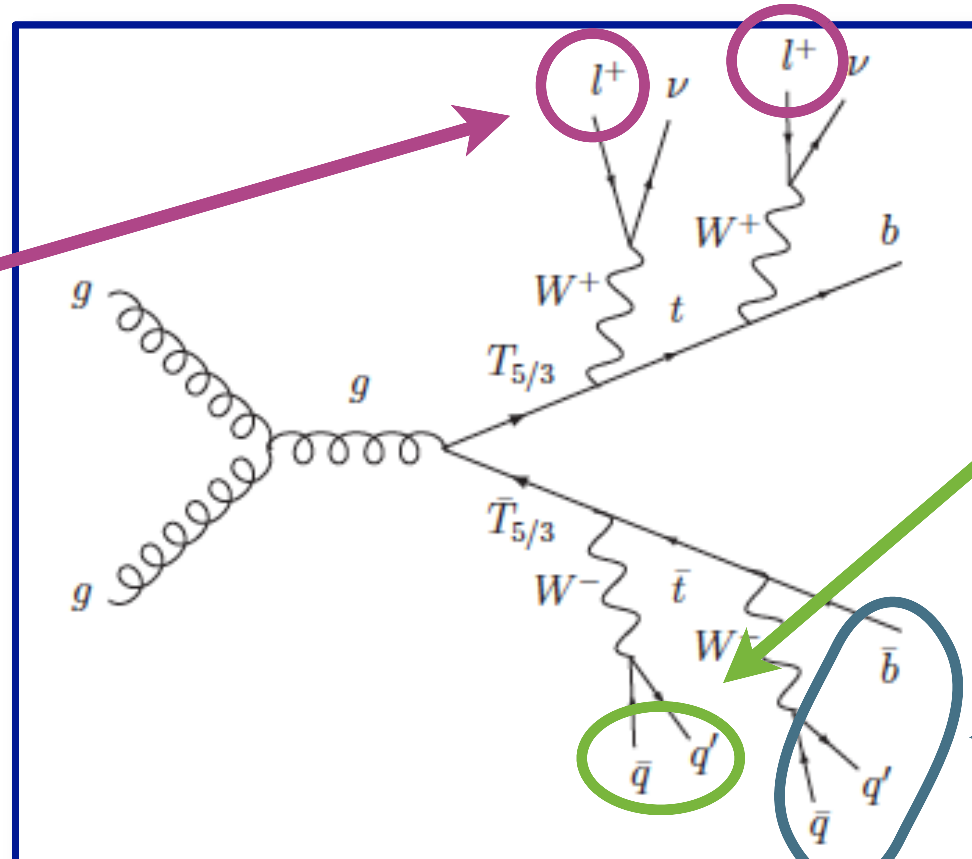
Current LHC Limit on composite Top partner

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

same-sign dileptons



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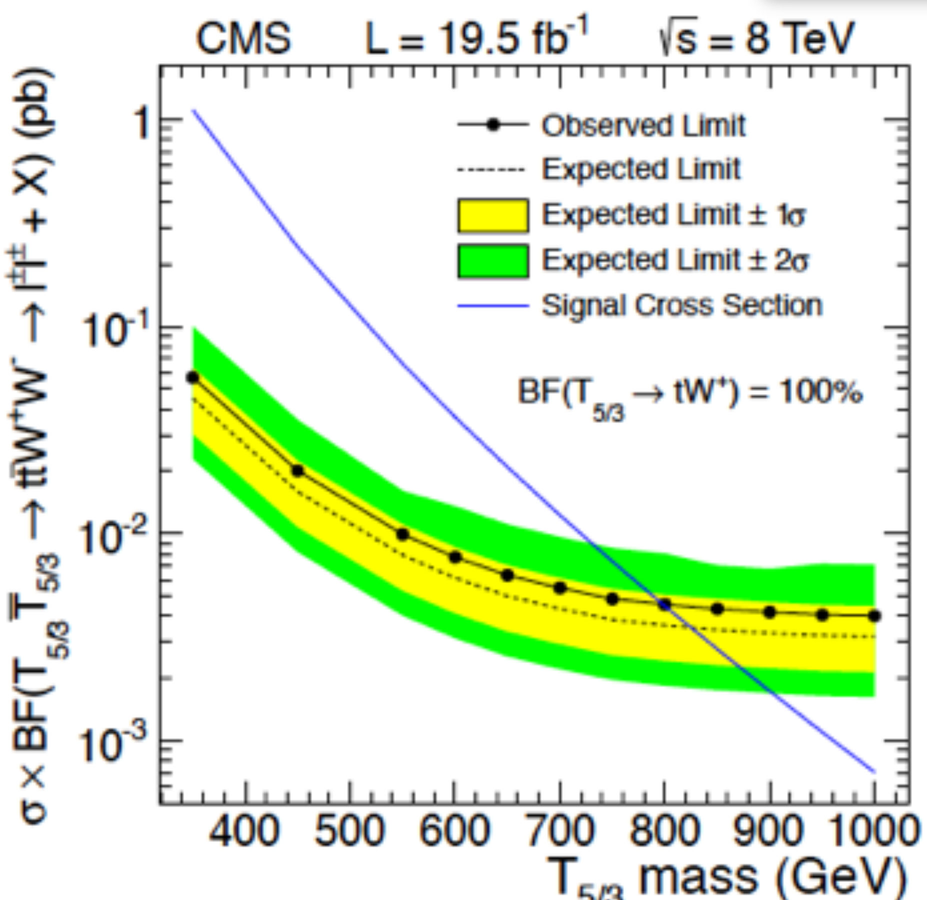
2 subjets,
M_j[60,130]

CMS top tag

10.1103/PhysRevLett.112.171801



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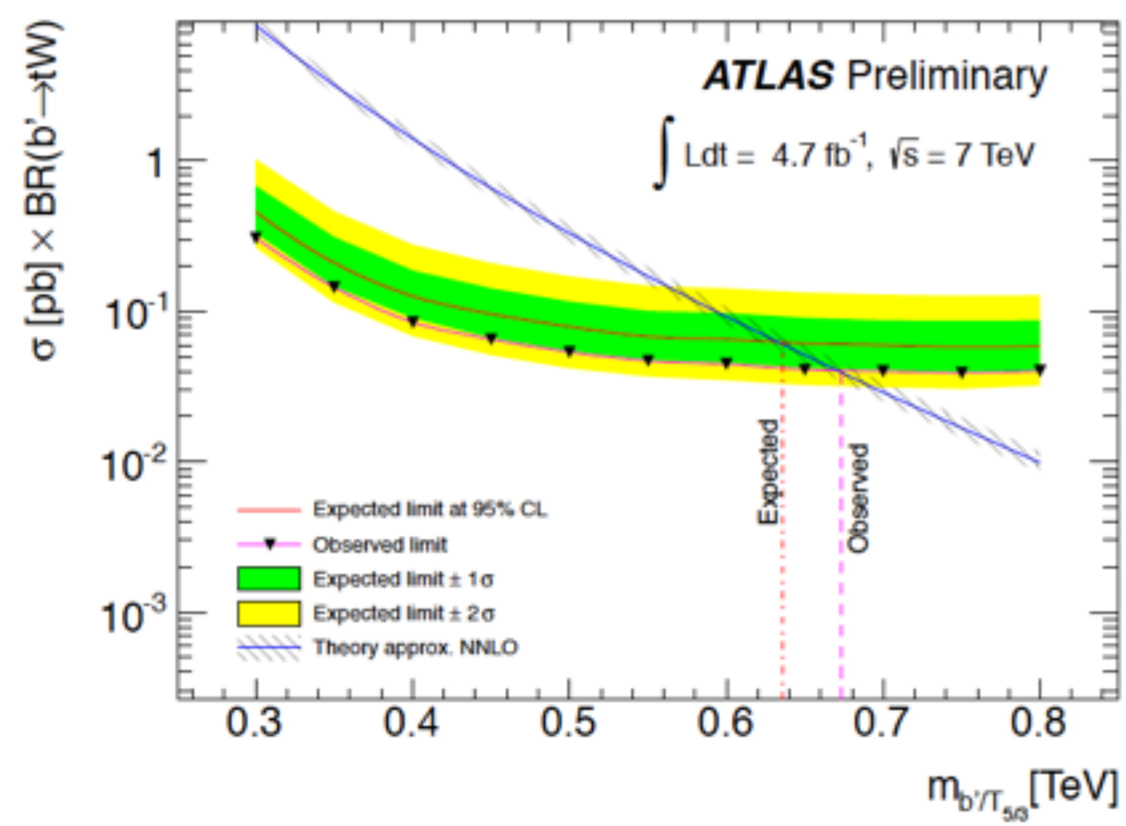

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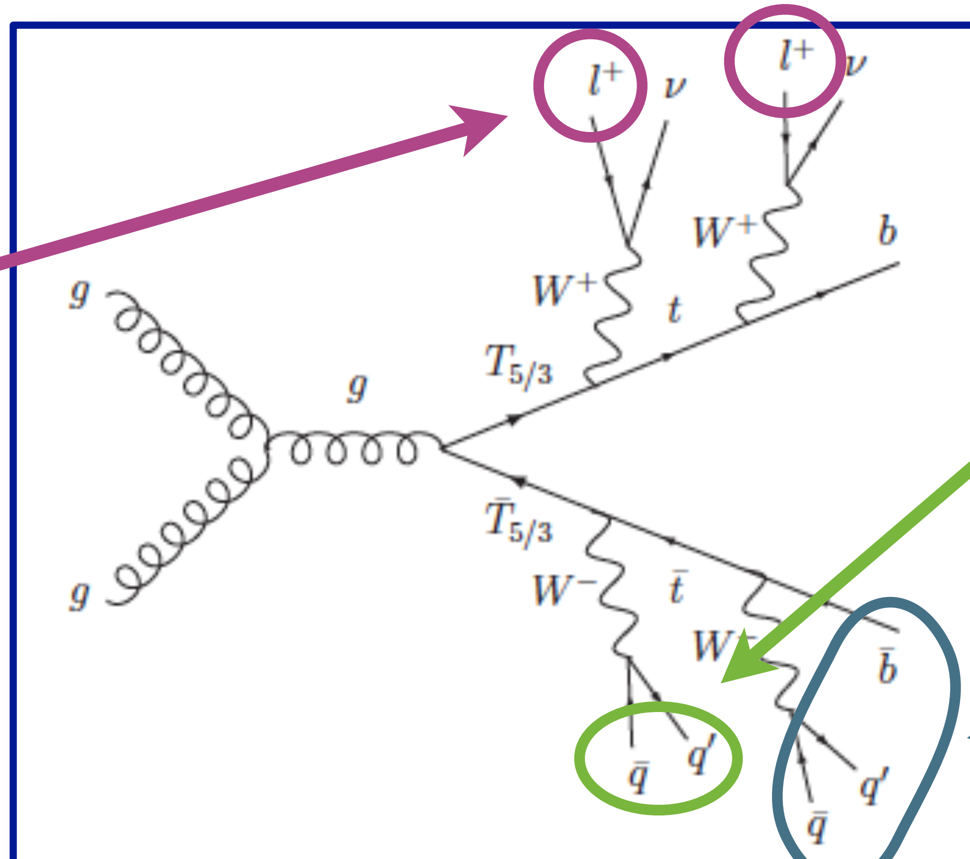

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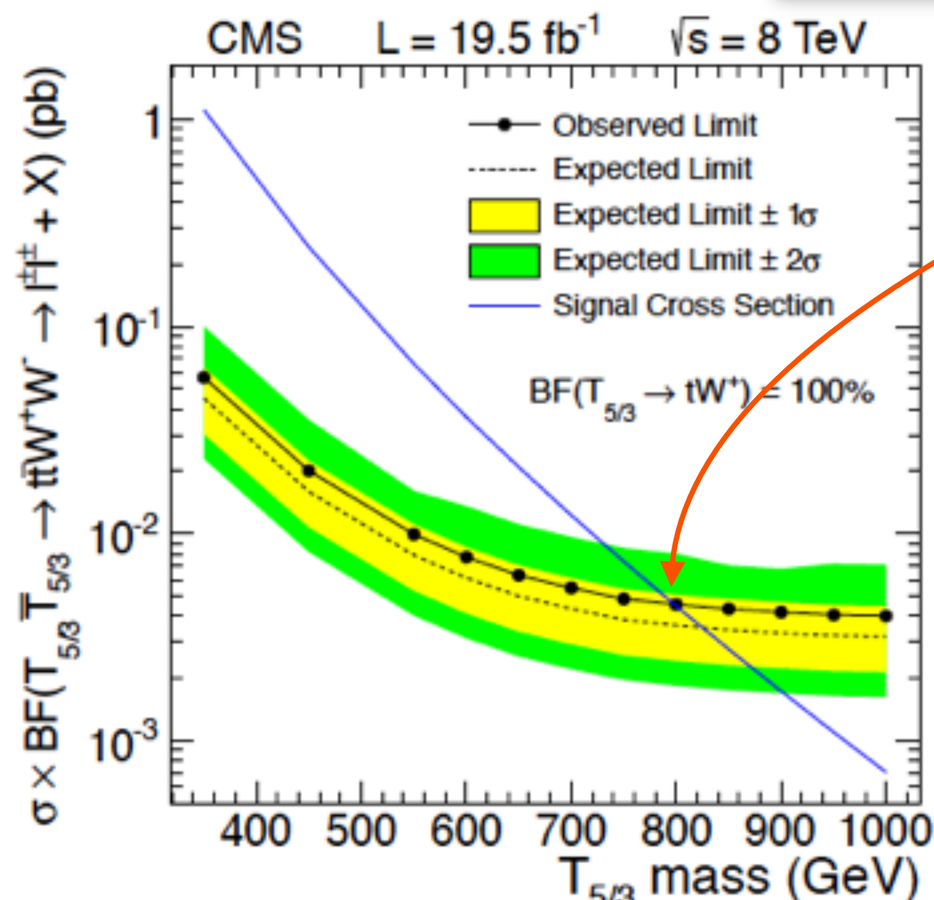
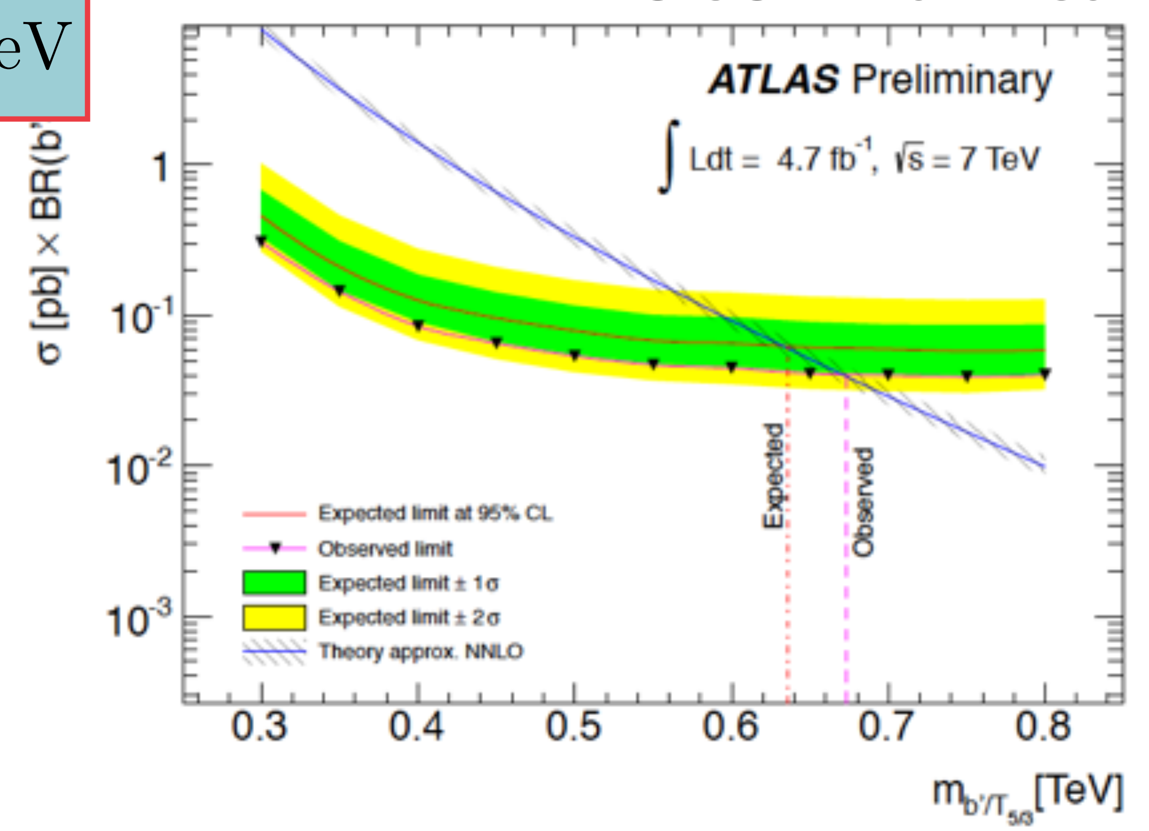


$$M_{X_{5/3}} \gtrsim 800\,\mathrm{GeV}$$

ATLAS-CONF-2012-130



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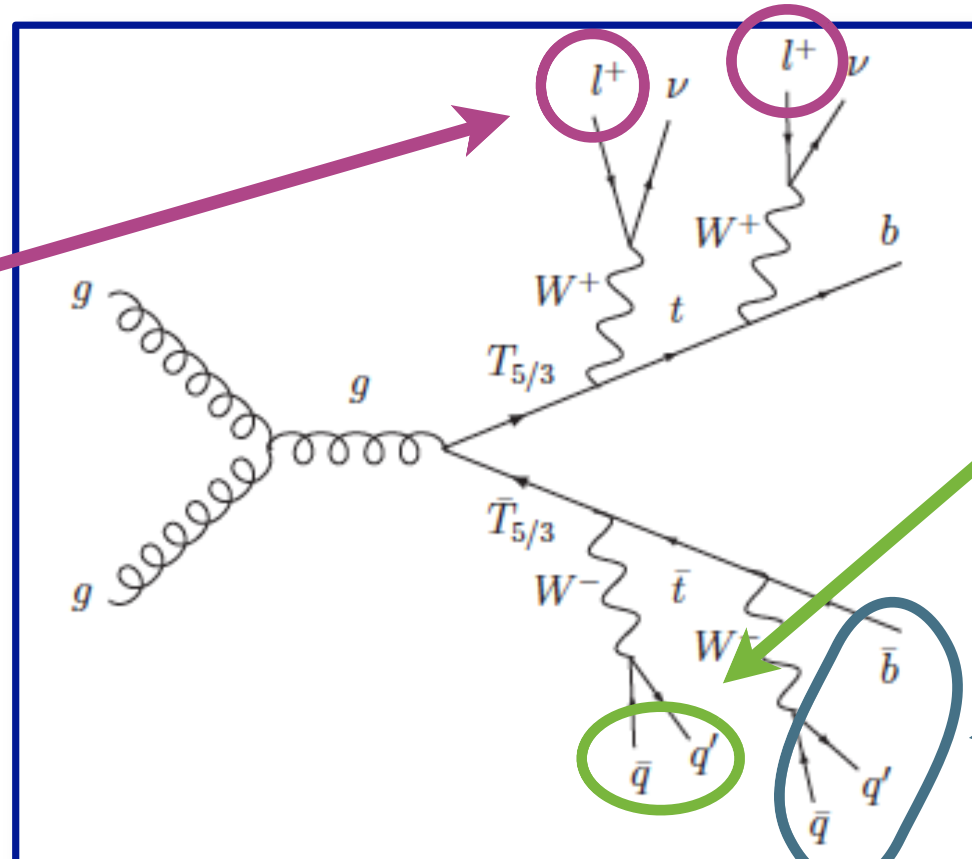

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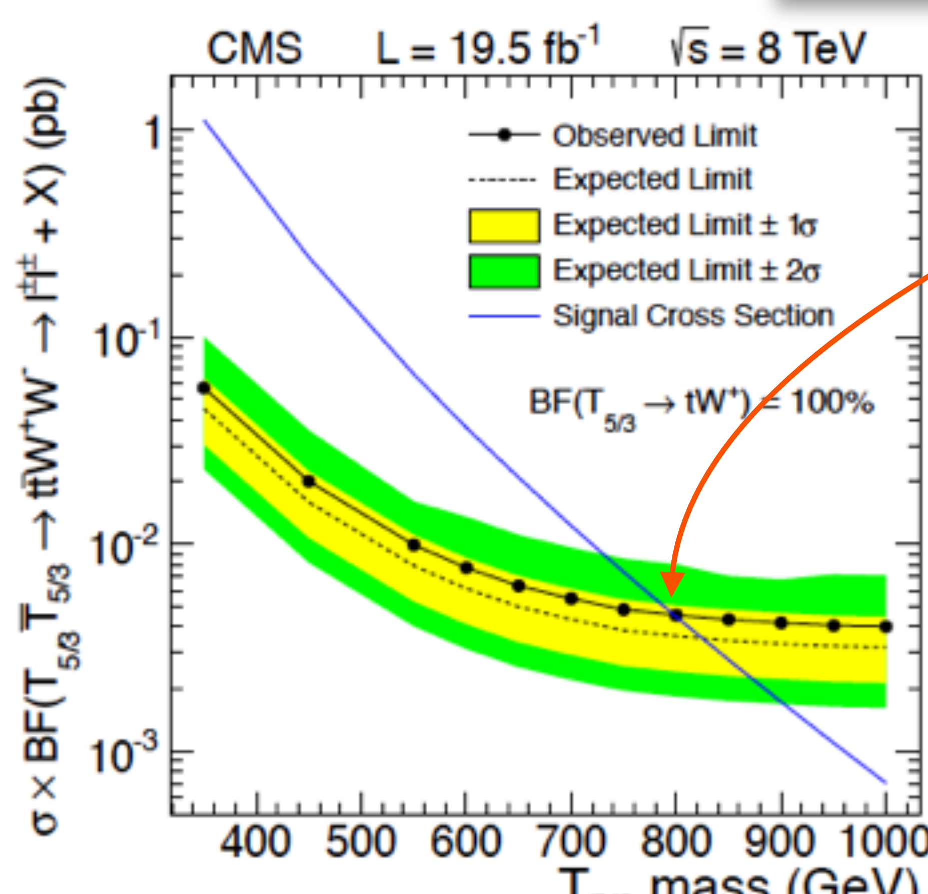
Oblique parameter fits of LEP & Tevatron data gave
f ≥ 800GeV

Grojean, Matsedonskyi, Panico `13

Ciuchini, Franco, Mishima, Silvestrini `13

10.1103/PhysRevLett.112.171801



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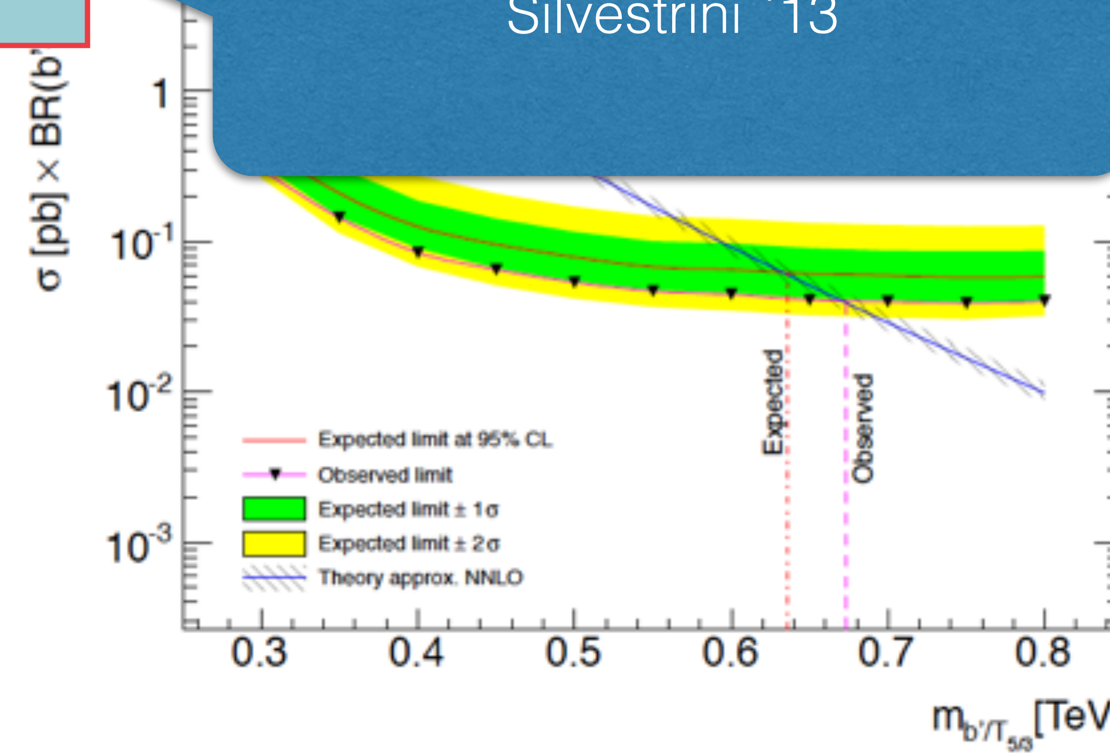

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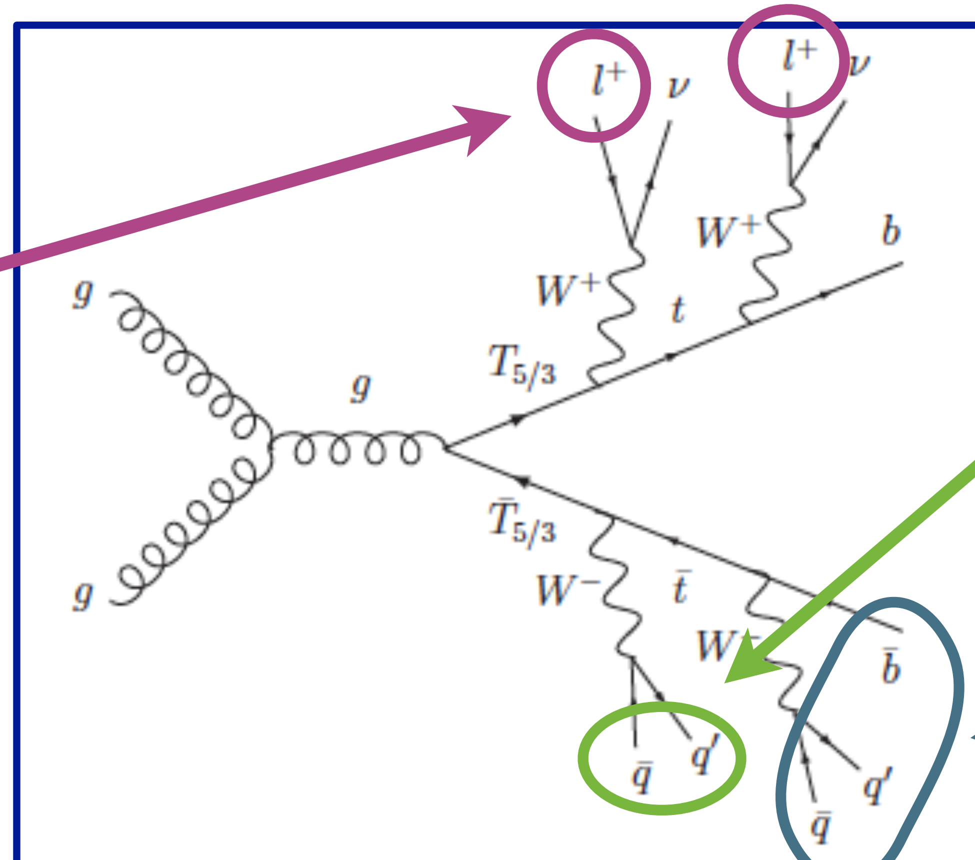

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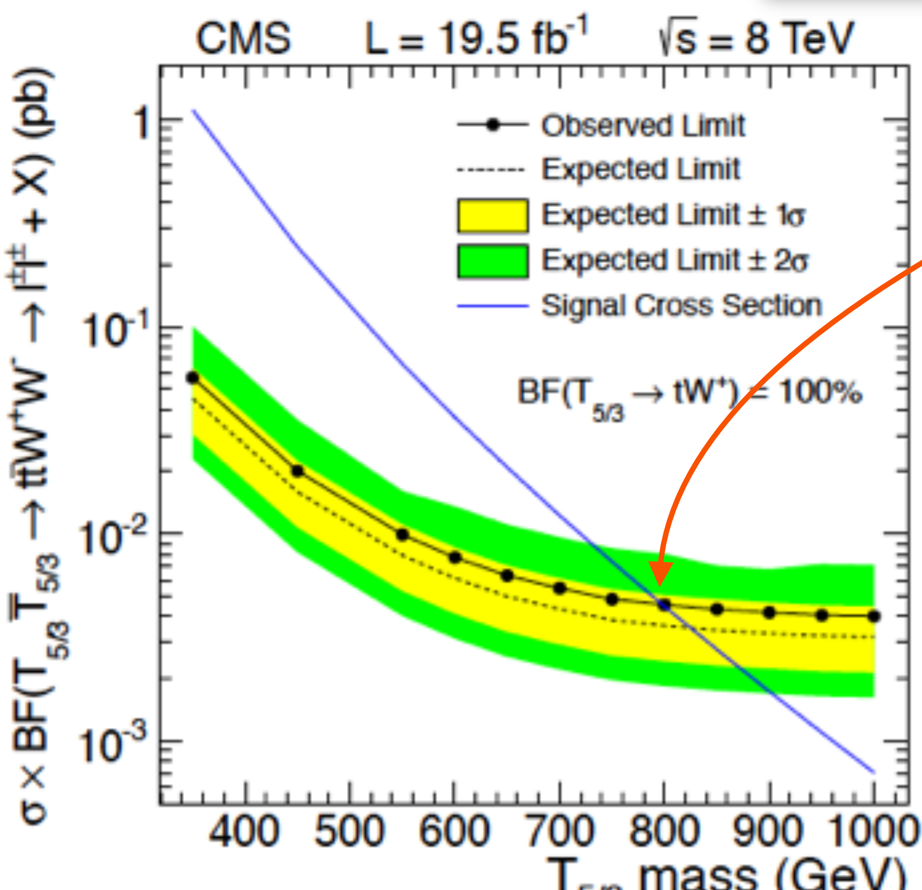

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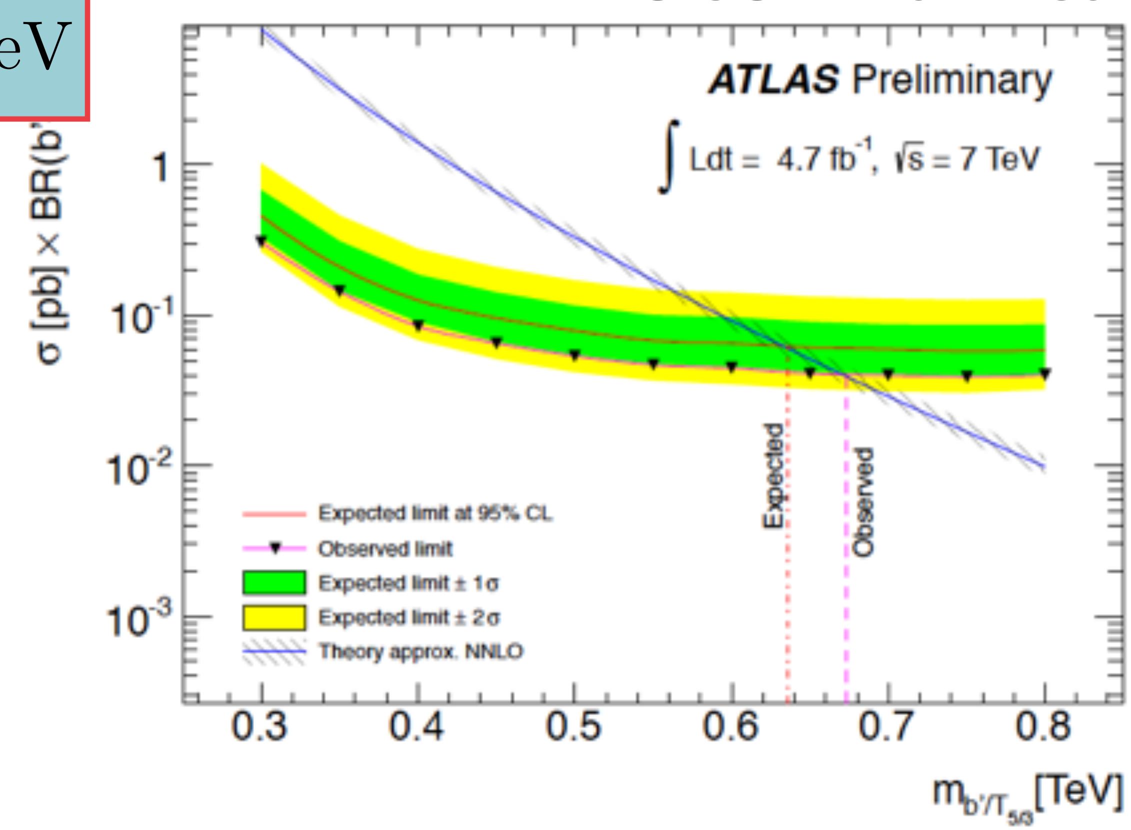

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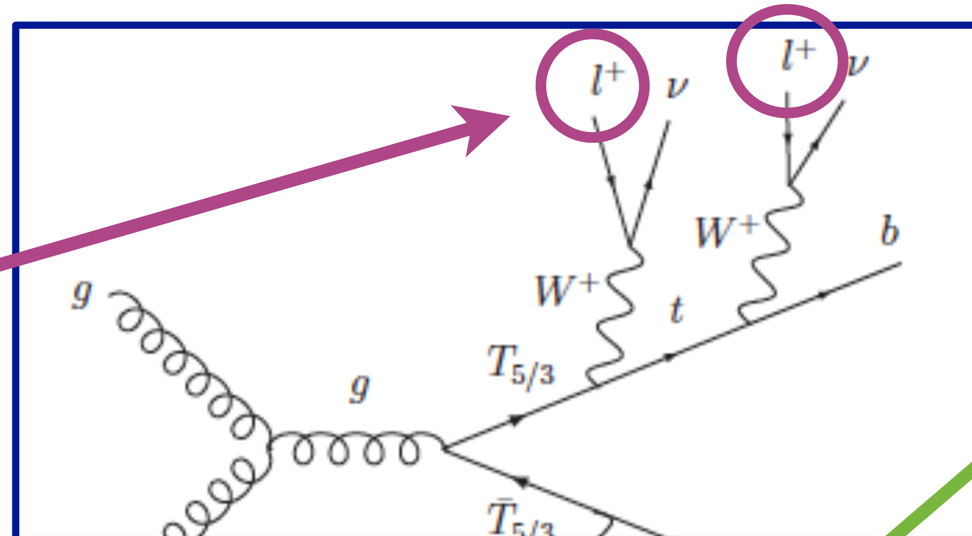

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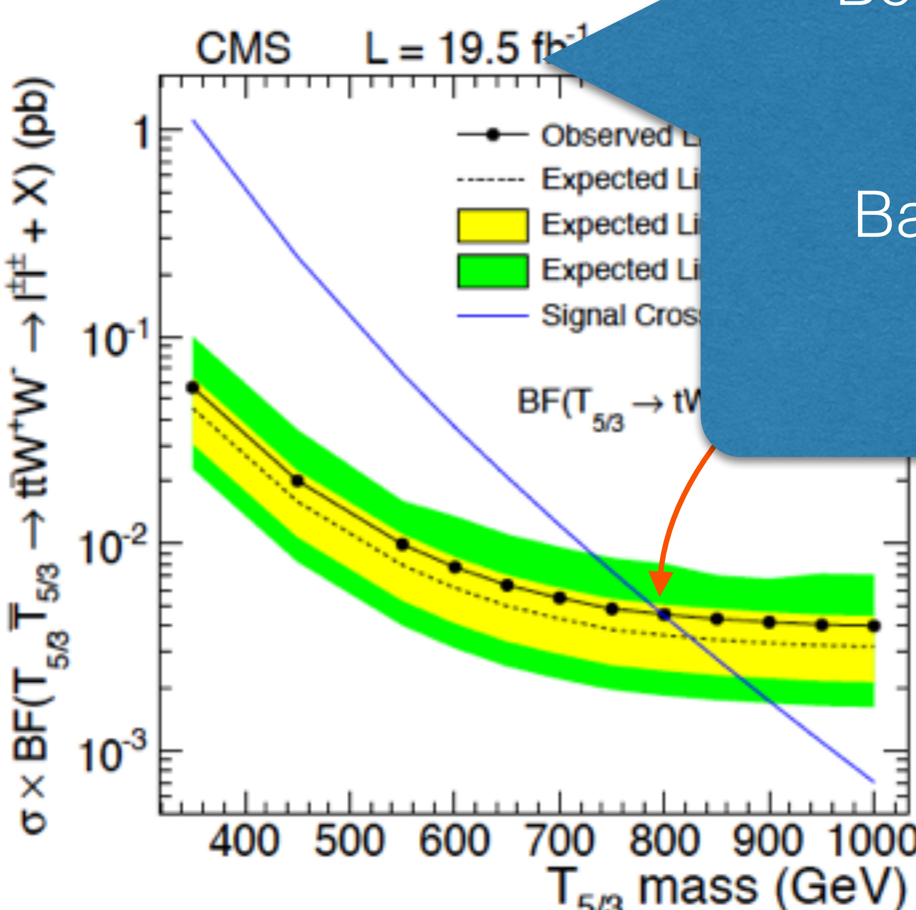
How about Run 2?

Boosted Analysis becomes more important!

Backovic, Flacke, SL, Perez `14

10.1103/PhysRevLett.112.17180



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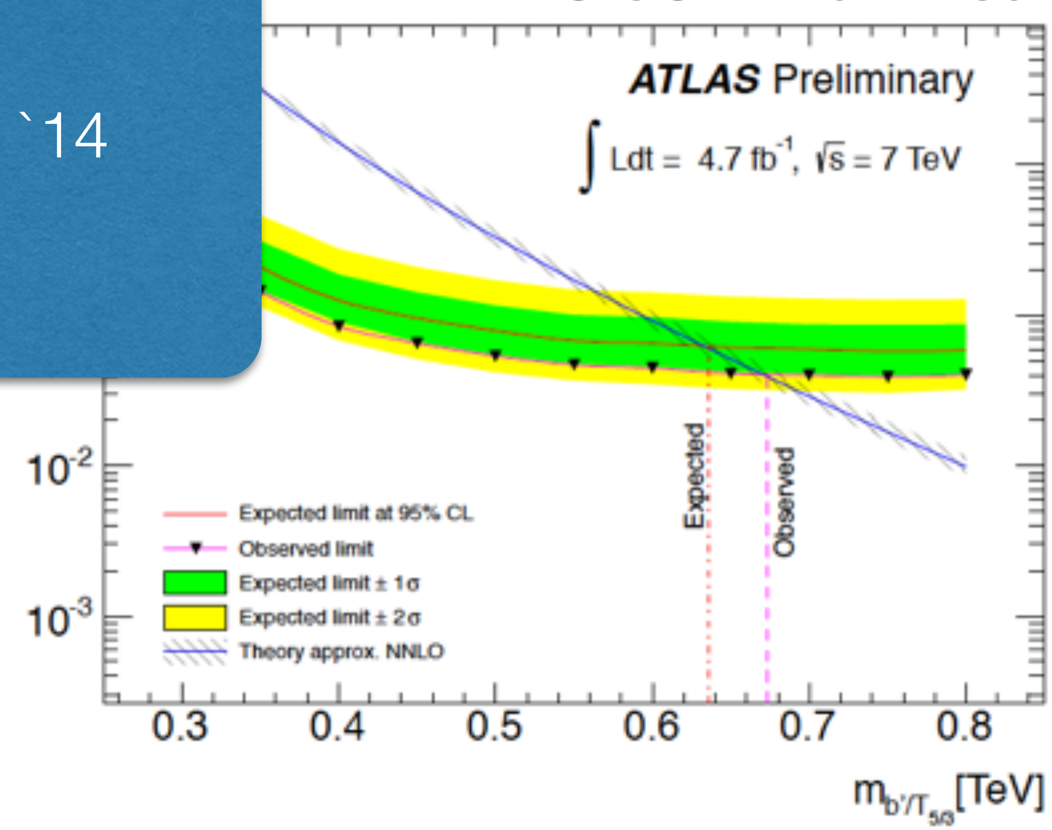


General Set-up

* 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
  Note: possible vector resonances are "integrated out" and do not appear directly in the effective description

* Central element: the Goldstone boson matrix

$$U(\Pi) = \exp\left(\frac{i}{f}\Pi_i T^i\right) = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & \cos\overline{h}/f & \sin\overline{h}/f \\ 0 & 0 & 0 & -\sin\overline{h}/f & \cos\overline{h}/f \end{pmatrix},$$

where $\Pi = (0,0,0,\overline{h})$ with $\overline{h} = <h> + h$
and T^i are the broken $SO(5)$ generators.

* From it, one can construct the CCWZ d^i_μ and e^a_μ symbols
  (roughly speaking: connections corresponding to broken / unbroken generators).
  E. g. kinetic term for the "Higgs":

$$\mathcal{L}_\Pi = \frac{f^2}{4} d^i_\mu d^{i\mu} = \frac{1}{2}(\partial_\mu h)^2 + \frac{g^2}{4} f^2 \sin^2\left(\frac{\overline{h}}{f}\right)\left(W_\mu W^\mu + \frac{1}{2c_w} Z_\mu Z^\mu\right)$$

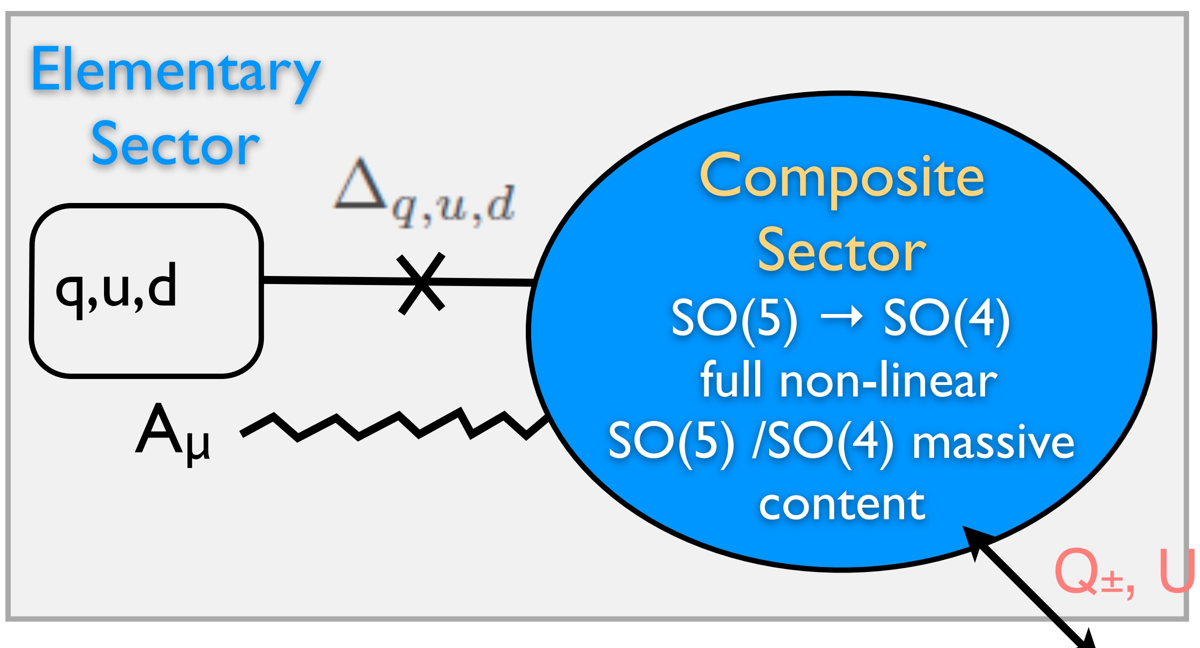
$$\Rightarrow v = 246 \text{ GeV } = f \sin\left(\frac{<\overline{h}>}{f}\right) \equiv f\sin(\epsilon).$$

General Set-up : Partial Compositeness

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

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

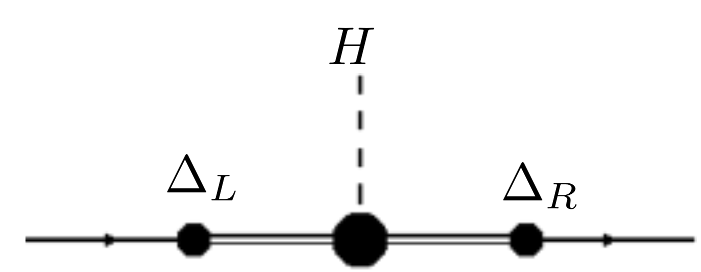
The flavor problem of theories with strong dynamics can be improved if the Yukawa couplings arise through mixings of elementary quarks with fermionic operators of the strong sector



Q±, U± + ... +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,...

...lk

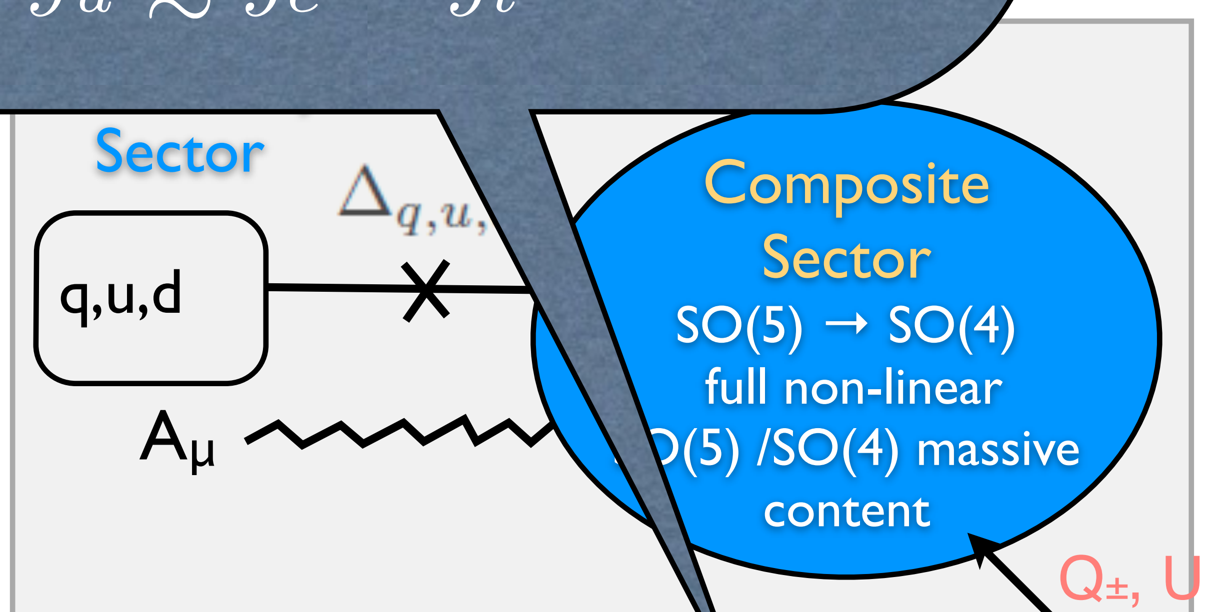
$\ldots_{mix} = \Delta_q \bar{q}_{l_{\mathcal{O}}} \mathcal{O}^{l_{\mathcal{O}}} + \text{h.c.}$

Delaunay, Gedalia, SL, Perez, Ponton `11
Redi, Sanz, de Vries, Weiler `13
Delaunay, Flacke, Fraille, SL, Perez `13

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

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

...strong dynamics can be ...e through mixings of ...erators of the strong sector



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

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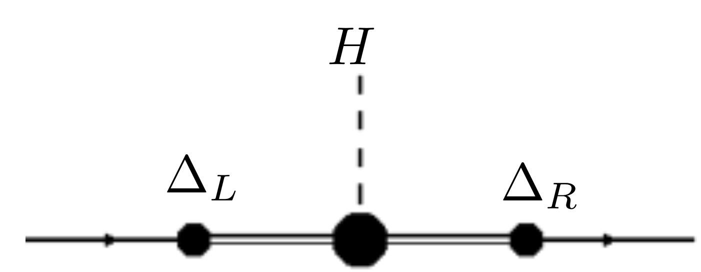

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General Set-up

* The model contains elementary fermions q and composite fermionic resonances of the strongly coupled theory, which mix via linear interactions

$$\mathcal{L}_{mix} = y\bar{q}_{I_{\mathcal{O}}}\mathcal{O}^{I_{\mathcal{O}}} + \text{h.c.}$$

where $\mathcal{O}$ is an operator of the strongly coupled theory in the rep. $I_{\mathcal{O}}$, and $\bar{q}_{I_{\mathcal{O}}}$ is an (incomplete) embedding of the elementary q into $SO(5)$.

* One common choice (partially composite quarks):

$$\begin{aligned}\bar{q}_L^5 &= \frac{1}{\sqrt{2}}\left(-i\bar{d}_L\,,\bar{d}_L\,,-i\bar{u}_L\,,-\bar{u}_L\,,0\right),\\ \bar{u}_R^5 &= (0\,,0\,,0\,,0\,,\bar{u}_R)\,,\end{aligned}$$

* This fixes composite partner quarks to be embedded as **5** reps. of $SO(5)$:

$$\psi = \begin{pmatrix} Q \\ \tilde{U} \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} iD - iX_{5/3} \\ D + X_{5/3} \\ iU + iX_{2/3} \\ -U + X_{2/3} \\ \sqrt{2}\tilde{U} \end{pmatrix} = \begin{bmatrix} \tilde{\psi}_4 \\ \tilde{\psi}_1 \end{bmatrix}_{\frac{2}{3}}$$

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

* The down-type sector can be realized analogously.

General Set-up

* BSM particle content: 5 = 4 + 1

$$Y = T^3_R + X$$

	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	$2/3$	$2/3$	$-1/3$	$5/3$	$2/3$

* Two principal ways to embed the right-handed up-type quarks:
  - In the elementary sector, which mix with their partners, (→ "partially composite quarks")
    Matsedonski, Panico, Wulzer \`14
    Backovic, Flacke, SL, Perez \`14
  - or as chiral composite states. (→ "fully composite quarks")
    Simone, Matsedonski, Rattazzi, Wulzer \`12

General Set-up

* BSM particle content: 5 = 4 + 1 $Y = T^3_R + X$

	U	X
$SO(4)$	**4**	
$SU(3)_c$	**3**	
EM charge	2/3	2

In this talk, I will focus on partially composite quarks scenario

* Two principal ways to embed the right-handed up-type quarks:
  - In the elementary sector, which mix with their partners, ($\rightarrow$ "partially composite quarks")
    Matsedonski, Panico, Wulzer \`14
    Backovic, Flacke, SL, Perez \`14
  - or as chiral composite states. ($\rightarrow$ "fully composite quarks")
    Simone, Matsedonski, Rattazzi, Wulzer \`12

Top Partner Searches Beyond the 2 TeV Mass Region

Backovic, Flacke, SL, Perez `14

$$
\begin{aligned}
\mathcal{L} = &+ i\bar{q}'_L \not{D} q'_L + i\bar{t}'_R \not{D} t'_R + i\bar{b}'_R \not{D} b'_R \\
&+ i\bar{\tilde{\psi}}_4 \not{D} \tilde{\psi}_4 + i\bar{\tilde{\psi}}_1 \not{D} \tilde{\psi}_1 - M_4 \bar{\tilde{\psi}}_4 \tilde{\psi}_4 - M_1 e^{i\phi} \bar{\tilde{\psi}}_1 \tilde{\psi}_1 \\
&+ \left(i c_L \bar{\tilde{\psi}}^i_{L4} \gamma^\mu d_{\mu i} \tilde{\psi}_{L1} + i c_R \bar{\tilde{\psi}}^i_{R4} \gamma^\mu d_{\mu i} \tilde{\psi}_{R1} + h.c. \right) \\
&- \left(y_L f \bar{q}^{t5}_L U \tilde{\psi}_R + y_R f \bar{t}^5_R U \tilde{\psi}_L + h.c. \right) .
\end{aligned}
$$

Top Partner Searches Beyond the 2 TeV Mass Region

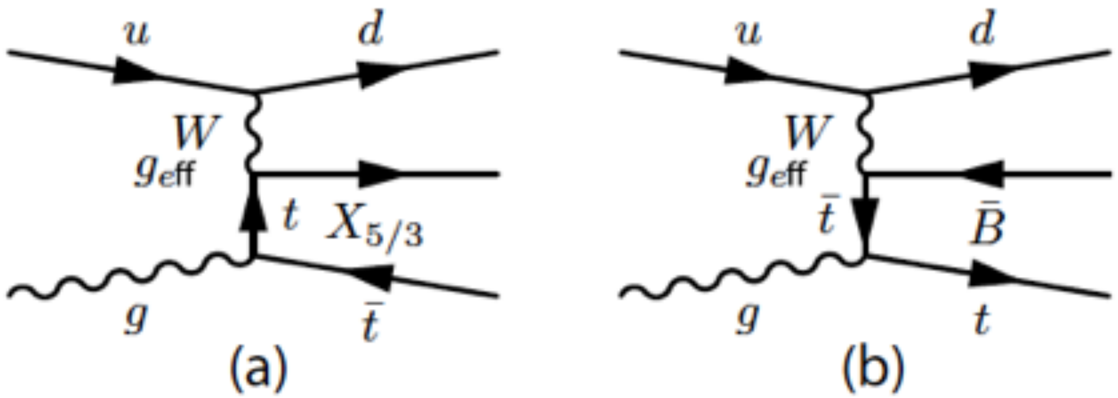
Backovic, Flacke, SL, Perez `14

$$D_\mu \tilde{\psi}_4 = (\partial_\mu + i e_\mu - i g' X B_\mu - i g_s G_\mu)\tilde{\psi}_4$$

$$\begin{aligned}\mathcal{L} = &+ i\bar{q}'_L \not{D} q'_L + i\bar{t}'_R \not{D} t'_R + i\bar{b}'_R \not{D} b'_R \\ &+ i\bar{\tilde{\psi}}_4 \not{D} \tilde{\psi}_4 + i\bar{\tilde{\psi}}_1 \not{D} \tilde{\psi}_1 - M_4 \bar{\tilde{\psi}}_4 \tilde{\psi}_4 - M_1 e^{i\phi} \bar{\tilde{\psi}}_1 \tilde{\psi}_1 \\ &+ (i c_L \bar{\tilde{\psi}}^i_{L4} \gamma^\mu d_{\mu i} \tilde{\psi}_{L1} + i c_R \bar{\tilde{\psi}}^i_{R4} \gamma^\mu d_{\mu i} \tilde{\psi}_{R1} + h.c.) \\ &- (y_L f \bar{q}^{t5}_L U \tilde{\psi}_R + y_R f \bar{t}^5_R U \tilde{\psi}_L + h.c.)\,.\end{aligned}$$

Top Partner Searches Beyond the 2 TeV Mass Region

Backovic, Flacke, SL, Perez `14

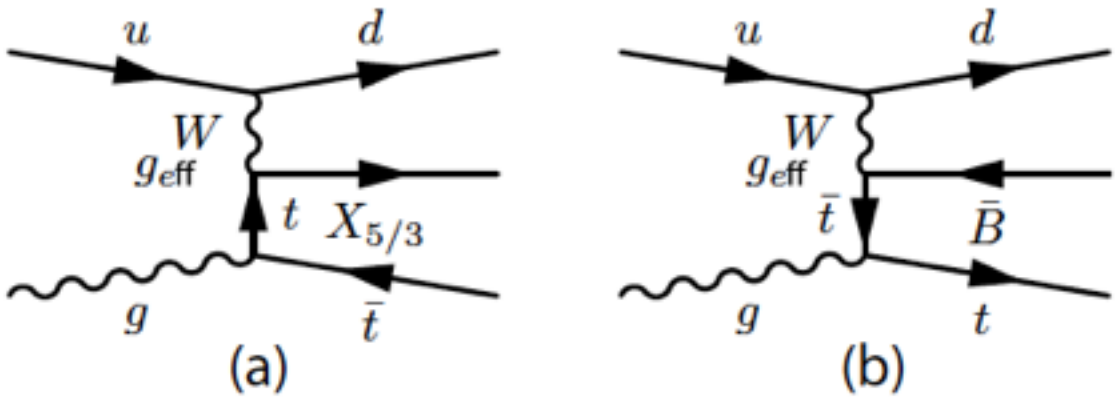


$$D_\mu \tilde{\psi}_4 = (\partial_\mu + ie_\mu - ig' X B_\mu - ig_s G_\mu)\tilde{\psi}_4$$

$$\begin{aligned}
\mathcal{L} = &+ i\bar{q}'_L \not{D} q'_L + i\bar{t}'_R \not{D} t'_R + i\bar{b}'_R \not{D} b'_R \\
&+ i\bar{\tilde{\psi}}_4 \not{D} \tilde{\psi}_4 + i\bar{\tilde{\psi}}_1 \not{D} \tilde{\psi}_1 - M_4 \bar{\tilde{\psi}}_4 \tilde{\psi}_4 - M_1 e^{i\phi} \bar{\tilde{\psi}}_1 \tilde{\psi}_1 \\
&+ (ic_L \bar{\tilde{\psi}}^i_{L4} \gamma^\mu d_{\mu i} \tilde{\psi}_{L1} + ic_R \bar{\tilde{\psi}}^i_{R4} \gamma^\mu d_{\mu i} \tilde{\psi}_{R1} + h.c.) \\
&- (y_L f \bar{q}^{t5}_L U \tilde{\psi}_R + y_R f \bar{t}^5_R U \tilde{\psi}_L + h.c.)\,.
\end{aligned}$$

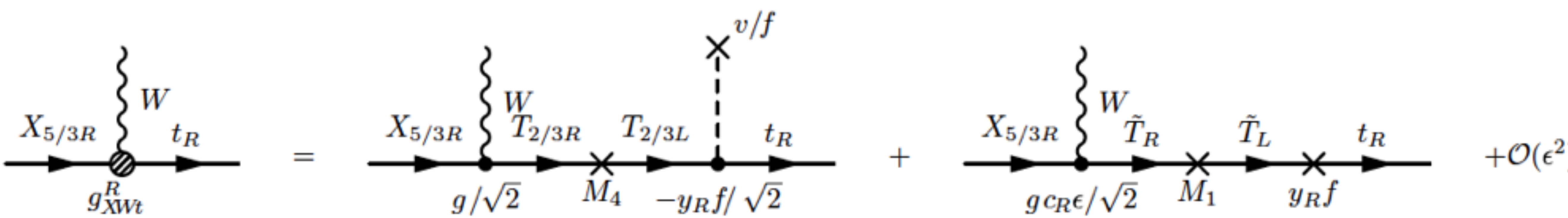
Top Partner Searches Beyond the 2 TeV Mass Region

Backovic, Flacke, SL, Perez `14



$$D_\mu\tilde{\psi}_4 = (\partial_\mu + i e_\mu - i g' X B_\mu - i g_s G_\mu)\tilde{\psi}_4$$

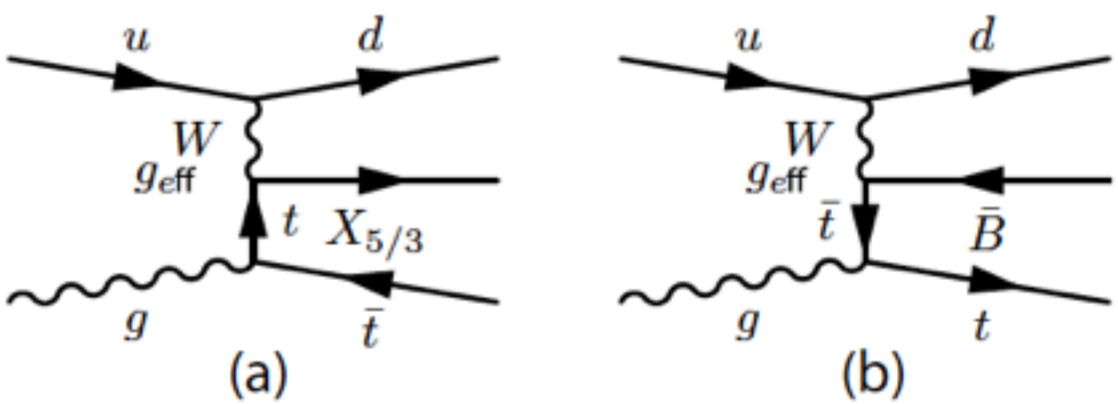
$$\begin{aligned}\mathcal{L} = &+ i\bar{q}'_L \not{D} q'_L + i\bar{t}'_R \not{D} t'_R + i\bar{b}'_R \not{D} b'_R \\ &+ i\bar{\tilde{\psi}}_4 \not{D}\tilde{\psi}_4 + i\bar{\tilde{\psi}}_1 \not{D}\tilde{\psi}_1 - M_4\bar{\tilde{\psi}}_4\tilde{\psi}_4 - M_1 e^{i\phi}\bar{\tilde{\psi}}_1\tilde{\psi}_1 \\ &+ \left(i c_L \bar{\tilde{\psi}}^i_{L4}\gamma^\mu d_{\mu i}\tilde{\psi}_{L1} + i c_R \bar{\tilde{\psi}}^i_{R4}\gamma^\mu d_{\mu i}\tilde{\psi}_{R1} + h.c.\right) \\ &- \left(y_L f \bar{q}^{t5}_L U \tilde{\psi}_R + y_R f \bar{t}^5_R U \tilde{\psi}_L + h.c.\right).\end{aligned}$$



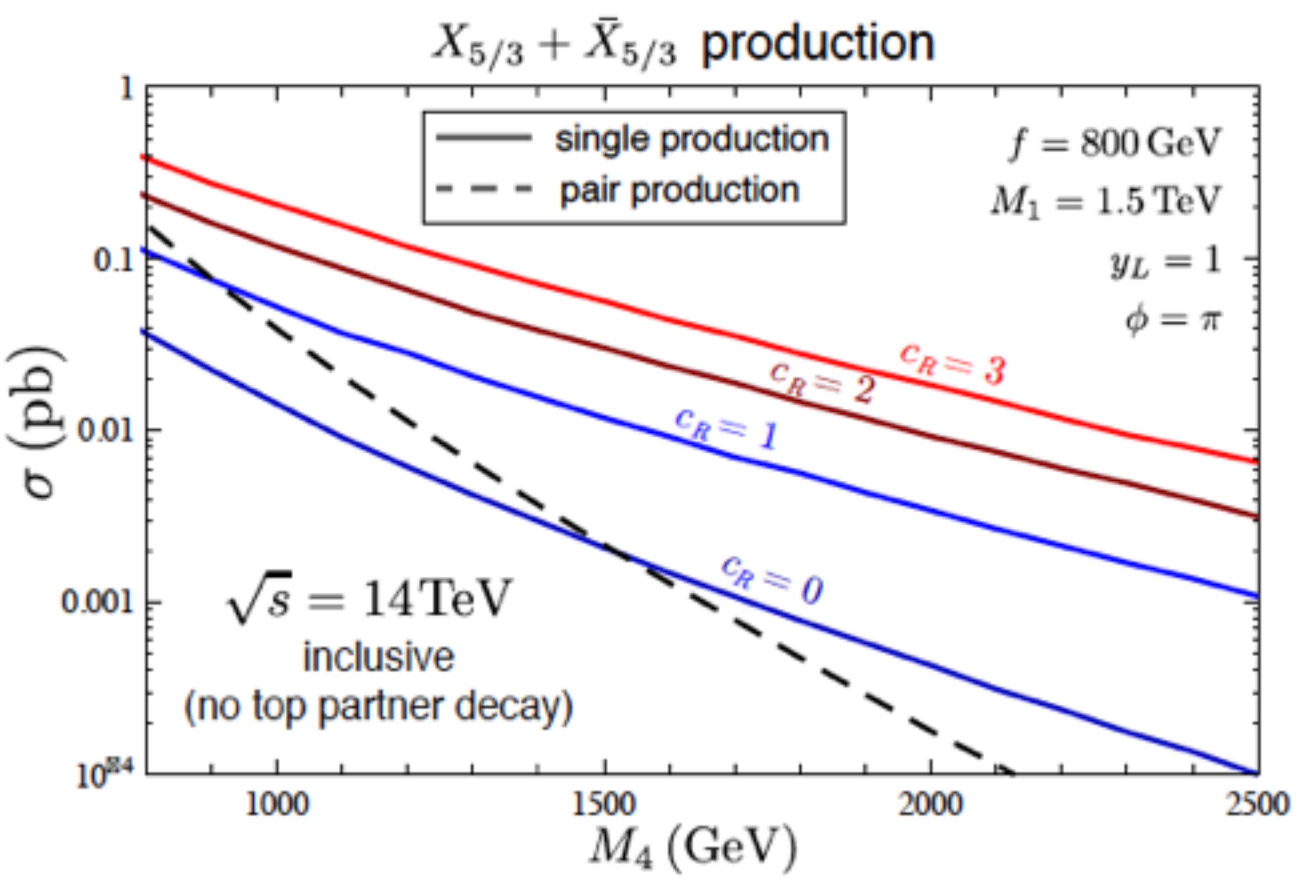
$$\begin{aligned} g^L_{XWt} &= G^X_{L\,i}\left(U^t_L\right)^\dagger_{i1} = \mathcal{O}(\epsilon^2)\,, \\ g^R_{XWt} &= G^X_{R\,i}\left(U^t_R\right)^\dagger_{i1} = \frac{g}{\sqrt{2}}\left(U^{*t}_{R\,13} + c_R\epsilon U^{*t}_{R\,14}\right) + \mathcal{O}(\epsilon^2)\,, \\ &= -\frac{g e^{-i\tilde{\phi}}}{\sqrt{2}}\frac{\epsilon}{\sqrt{2}}\left(\frac{y_R f M_1}{M_4 M_{T_s}} - \sqrt{2} c_R \frac{e^{-i\phi} y_R f}{M_{T_s}}\right) + \mathcal{O}(\epsilon^2)\,. \end{aligned}$$

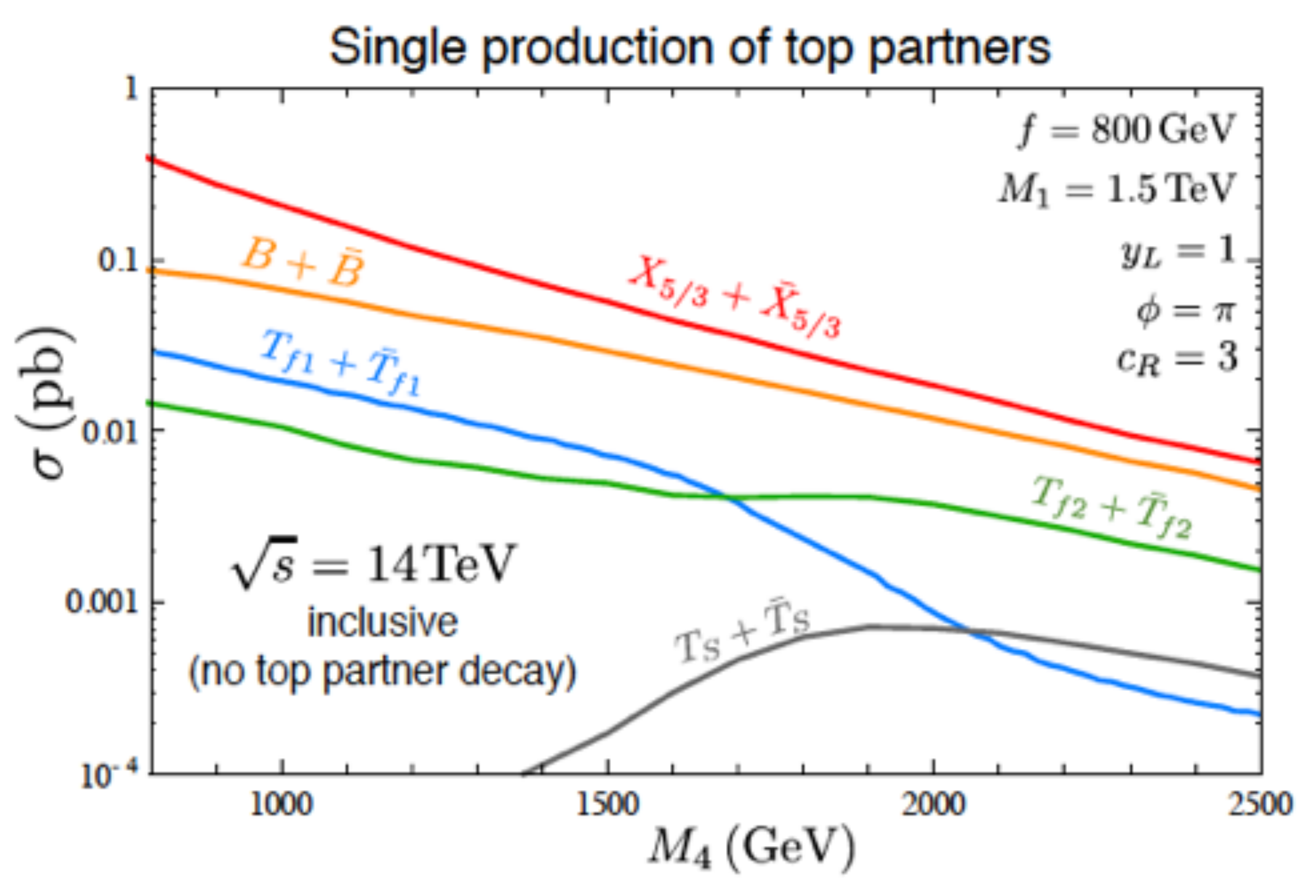
Top Partner Searches Beyond the 2 TeV Mass Region

Backovic, Flacke, SL, Perez `14



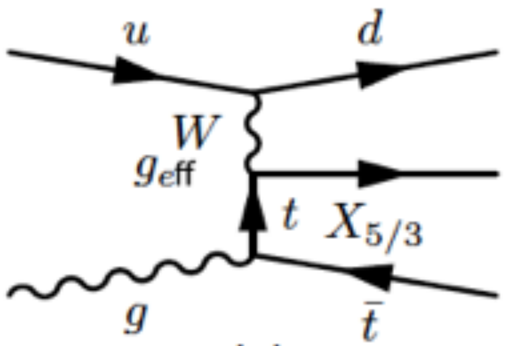
$$
\begin{aligned}
m_t &= \frac{v}{\sqrt{2}} \frac{|M_1 - e^{-i\phi} M_4|}{f} \frac{y_L f}{\sqrt{M_4 + y_L^2 f^2}} \frac{y_R f}{\sqrt{|M_1|^2 + y_R^2 f^2}} + \mathcal{O}(\epsilon^3), \\
M_B &= \sqrt{M_4^2 + y_L^2 f^2}, \\
M_{X_{5/3}} &= M_4, \\
M_{Tf1} &= M_4 + \mathcal{O}(\epsilon^2), \\
M_{Tf2} &= \sqrt{M_4^2 + y_L^2 f^2} + \mathcal{O}(\epsilon^2), \\
M_{Ts} &= \sqrt{|M_1|^2 + y_R^2 f^2} + \mathcal{O}(\epsilon^2),
\end{aligned}
$$



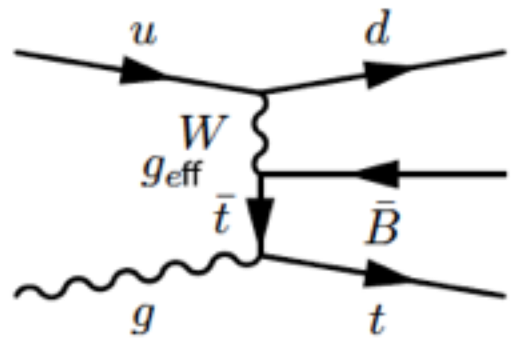


Top Partner Searches Beyond the 2 TeV Mass Region

Backovic, Flacke, SL, Perez `14

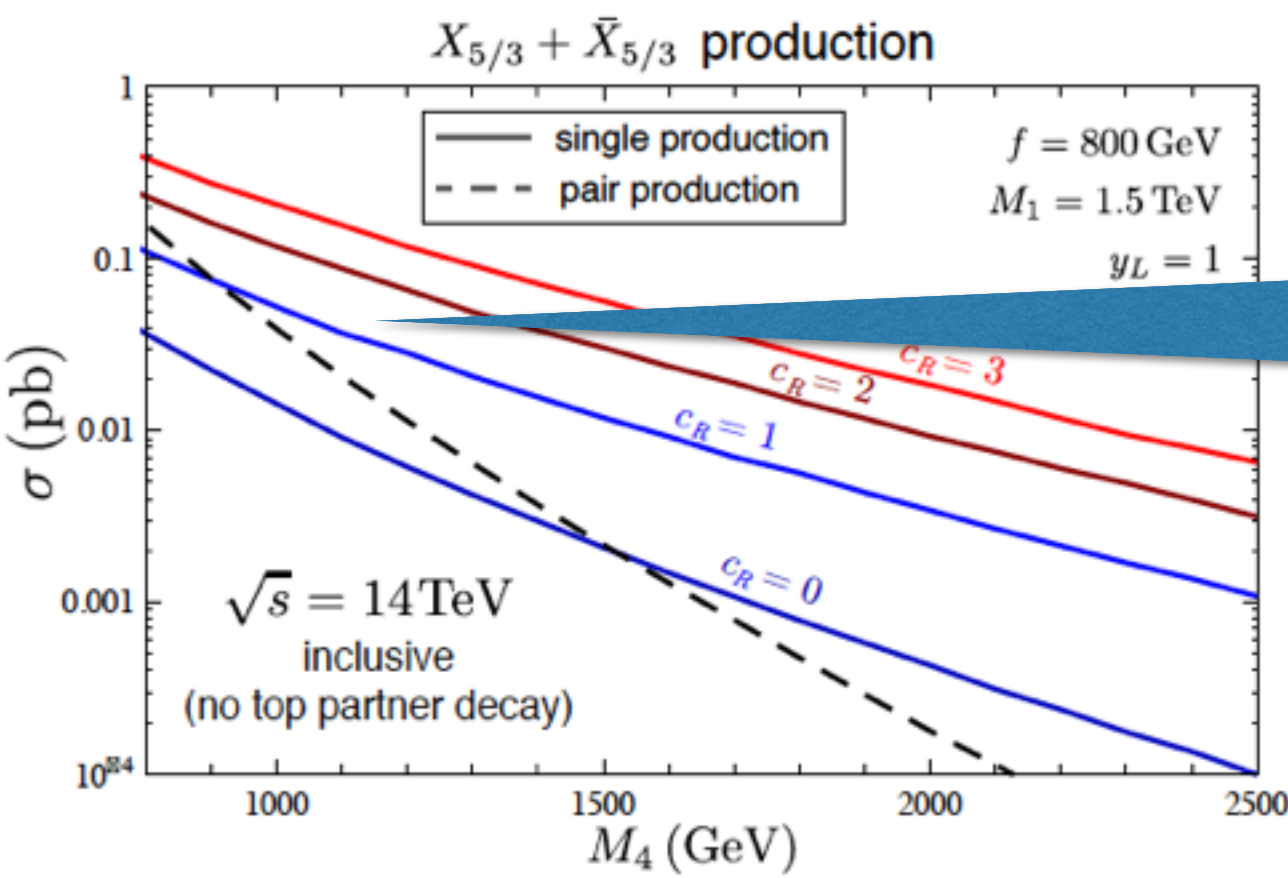


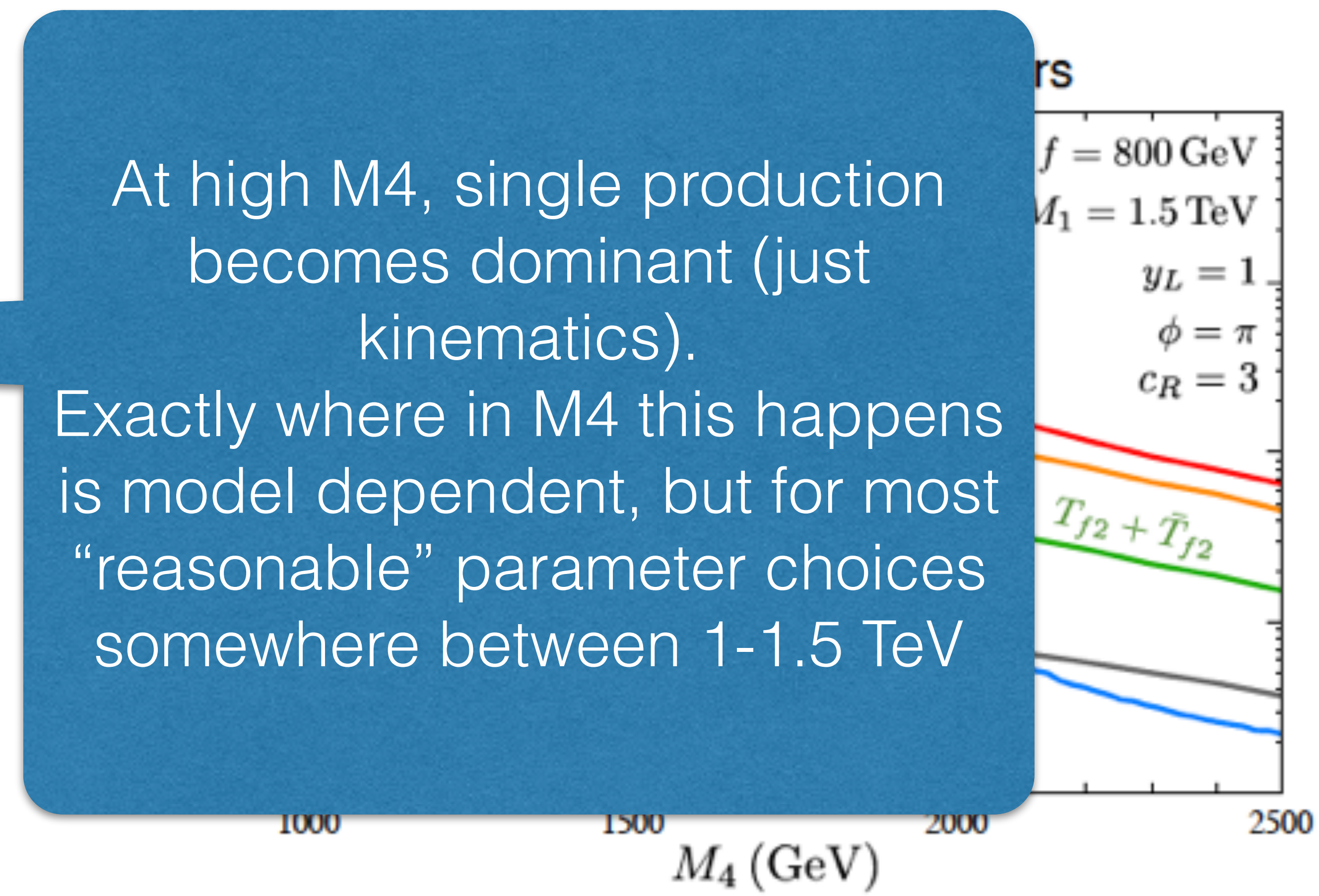
(a)



(b)

$$
\begin{aligned}
m_t &= \frac{v}{\sqrt{2}} \frac{|M_1 - e^{-i\phi} M_4|}{f} \frac{y_L f}{\sqrt{M_4 + y_L^2 f^2}} \frac{y_R f}{\sqrt{|M_1|^2 + y_R^2 f^2}} + \mathcal{O}(\epsilon^3), \\
M_B &= \sqrt{M_4^2 + y_L^2 f^2}, \\
M_{X_{5/3}} &= M_4, \\
M_{Tf1} &= M_4 + \mathcal{O}(\epsilon^2), \\
M_{Tf2} &= \sqrt{M_4^2 + y_L^2 f^2} + \mathcal{O}(\epsilon^2), \\
M_{Ts} &= \sqrt{|M_1|^2 + y_R^2 f^2} + \mathcal{O}(\epsilon^2),
\end{aligned}
$$

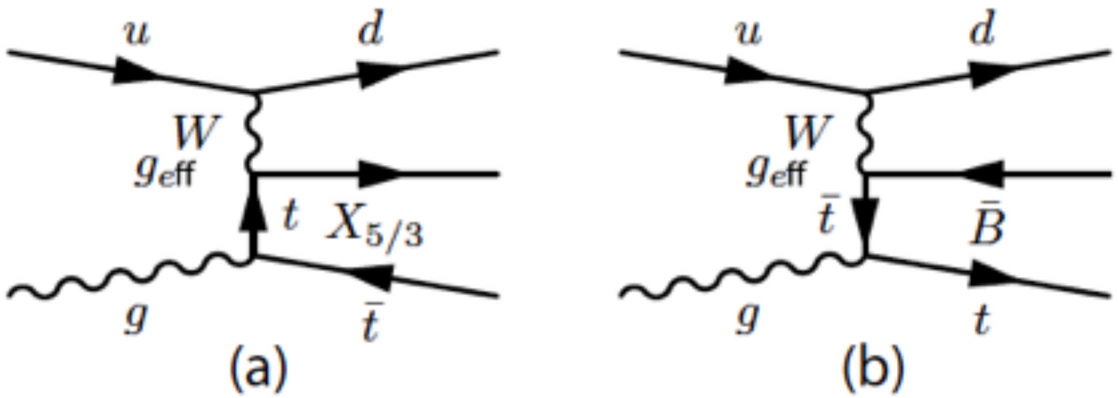




At high M4, single production becomes dominant (just kinematics).
Exactly where in M4 this happens is model dependent, but for most "reasonable" parameter choices somewhere between 1-1.5 TeV

Top Partner Searches Beyond the 2 TeV Mass Region

Backovic, Flacke, SL, Perez `14



$$
\begin{aligned}
m_t &= \frac{v}{\sqrt{2}} \frac{|M_1 - e^{-i\phi} M_4|}{f} \frac{y_L f}{\sqrt{M_4 + y_L^2 f^2}} \frac{y_R f}{\sqrt{|M_1|^2 + y_R^2 f^2}} + \mathcal{O}(\epsilon^3), \\
M_B &= \sqrt{M_4^2 + y_L^2 f^2}, \\
M_{X_{5/3}} &= M_4, \\
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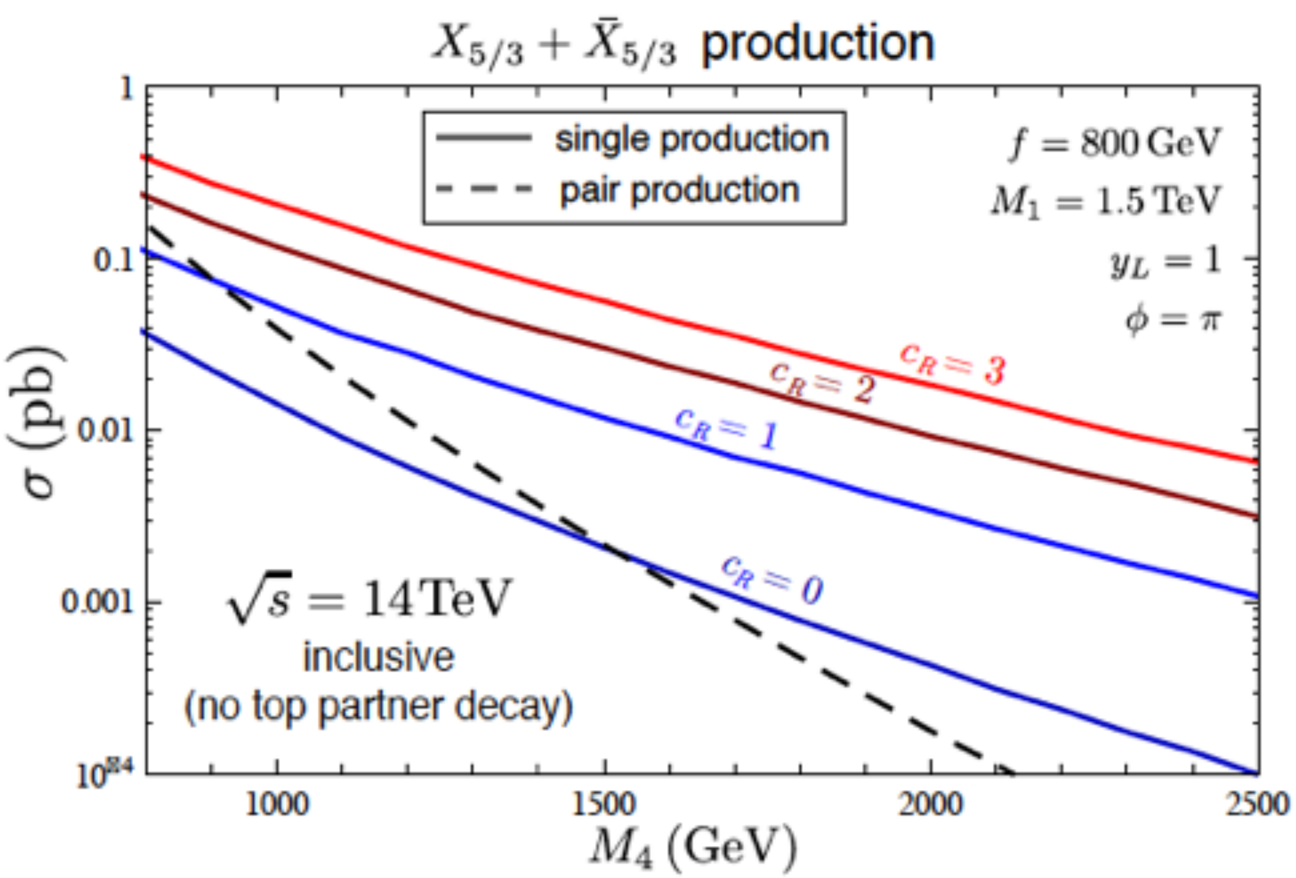
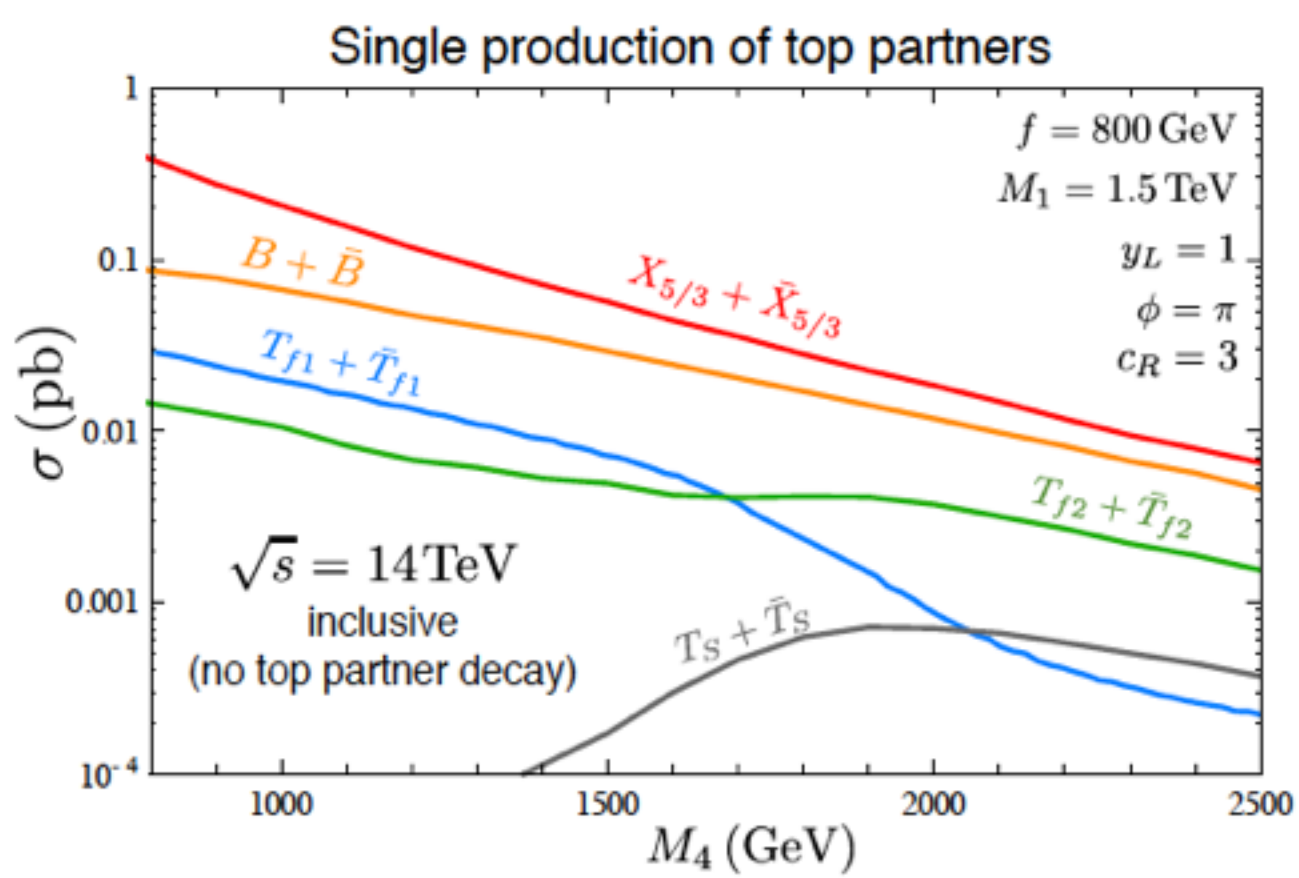
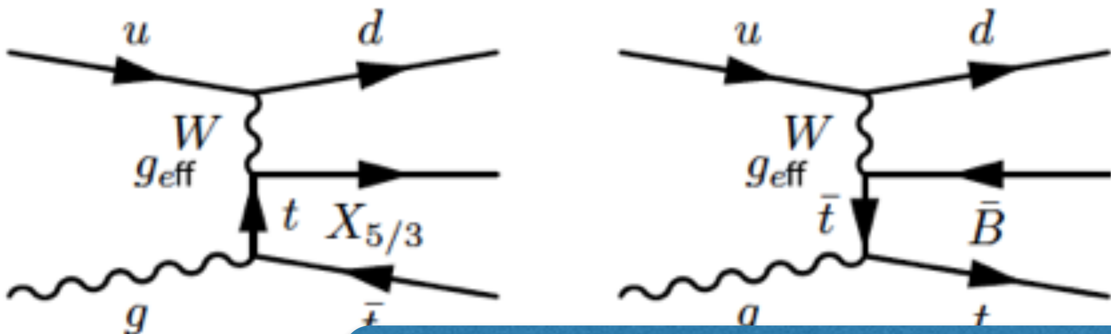
M_{Ts} &= \sqrt{|M_1|^2 + y_R^2 f^2} + \mathcal{O}(\epsilon^2),
\end{aligned}
$$





Top Partner Searches Beyond the 2 TeV Mass Region

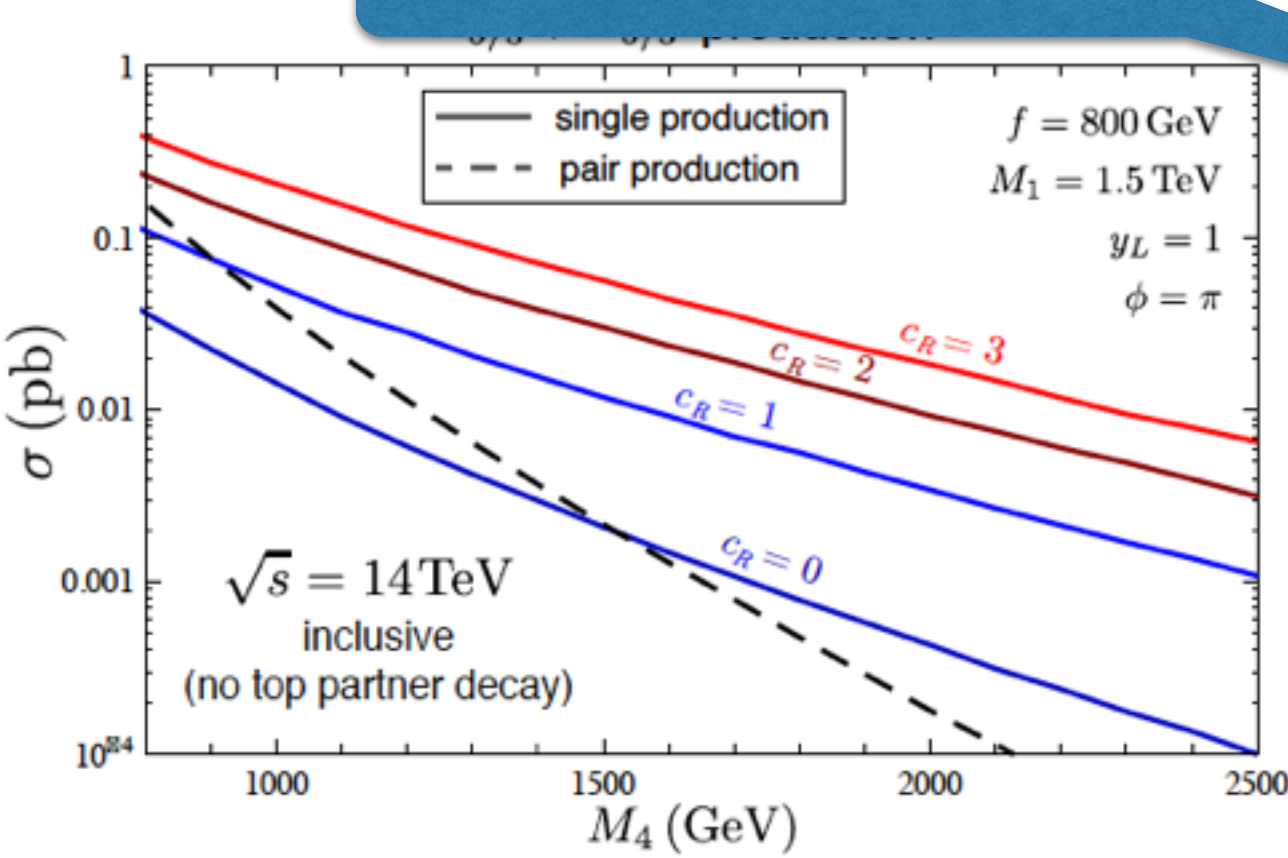
Backovic, Flacke, SL, Perez `14

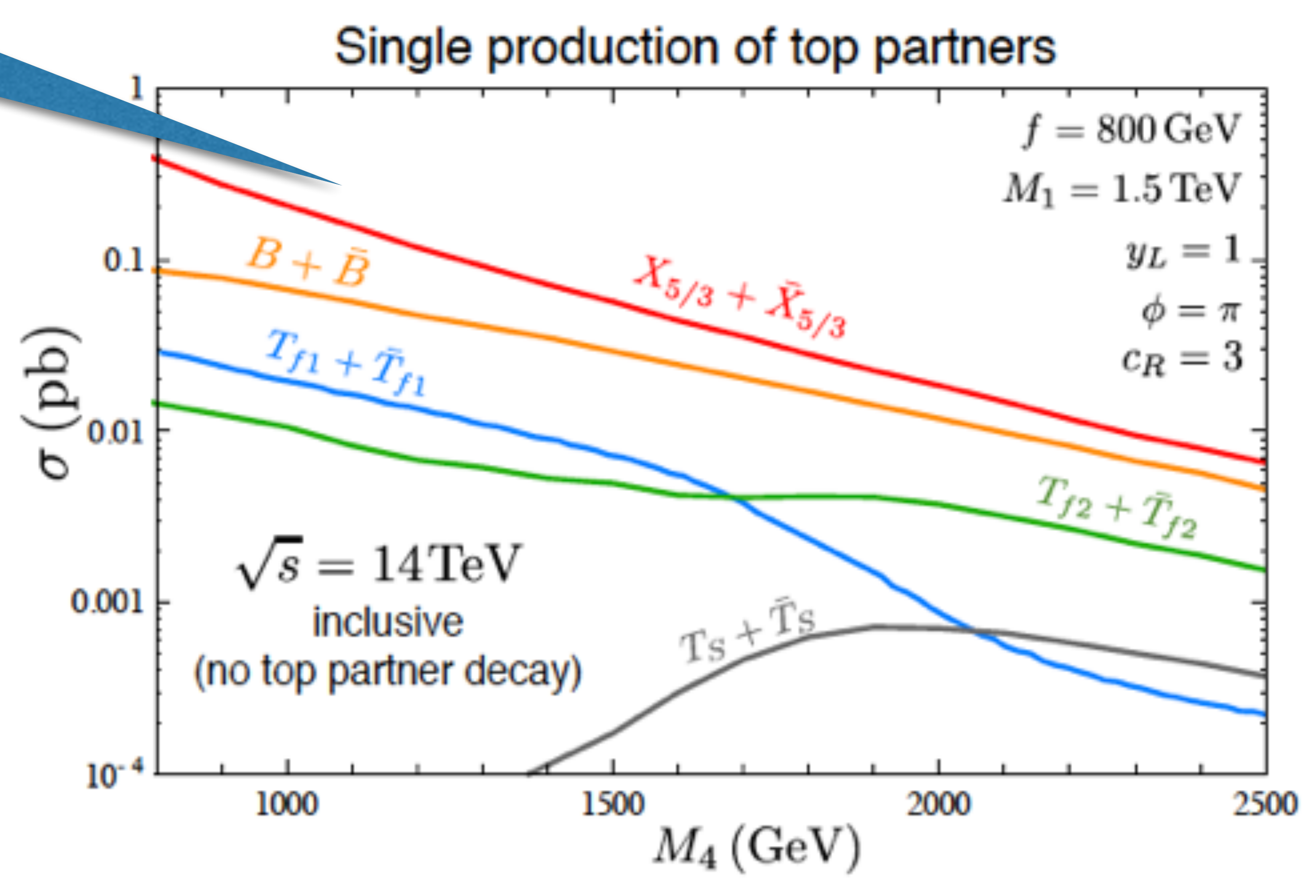


(a)

$$
\begin{aligned}
m_t &= \frac{v}{\sqrt{2}} \frac{|M_1 - e^{-i\phi} M_4|}{f} \frac{y_L f}{\sqrt{M_4 + y_L^2 f^2}} \frac{y_R f}{\sqrt{|M_1|^2 + y_R^2 f^2}} + \mathcal{O}(\epsilon^3), \\
M_B &= \sqrt{M_4^2 + y_L^2 f^2}, \\
M_{X_{5/3}} &= M_4, \\
M_{Tf1} &= M_4 + \mathcal{O}(\epsilon^2), \\
M_{Tf2} &= \sqrt{M_4^2 + y_L^2 f^2} + \mathcal{O}(\epsilon^2), \\
M_{Ts} &= \sqrt{|M_1|^2 + y_R^2 f^2} + \mathcal{O}(\epsilon^2),
\end{aligned}
$$

Single production is dominated by X5/3 and B partners.

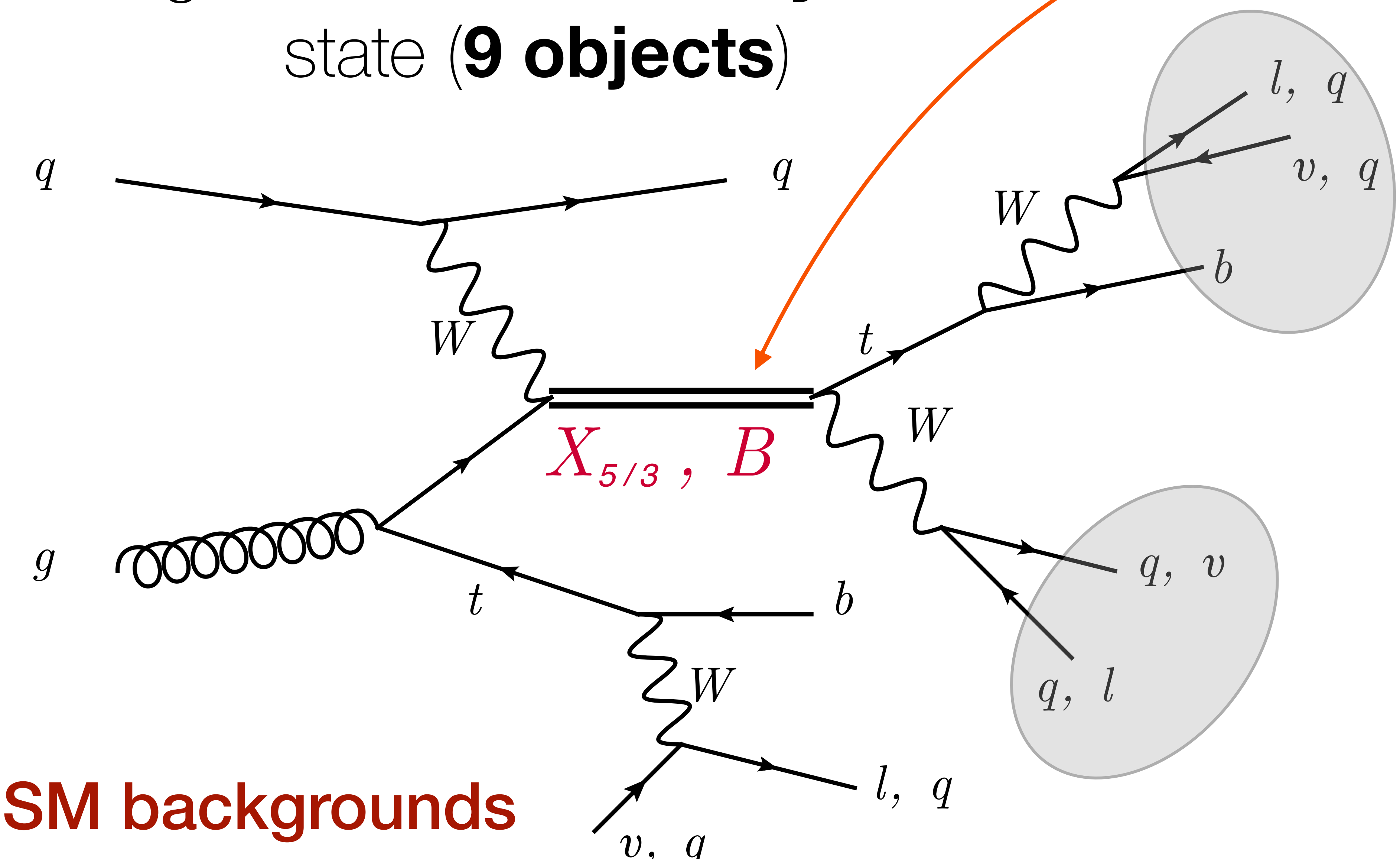




Top Partner Searches Beyond the 2 TeV Mass Region

- Single production of top partners might look like a "**messy**" final state (**9 objects**)

$M \sim O(1\,\mathrm{TeV})$



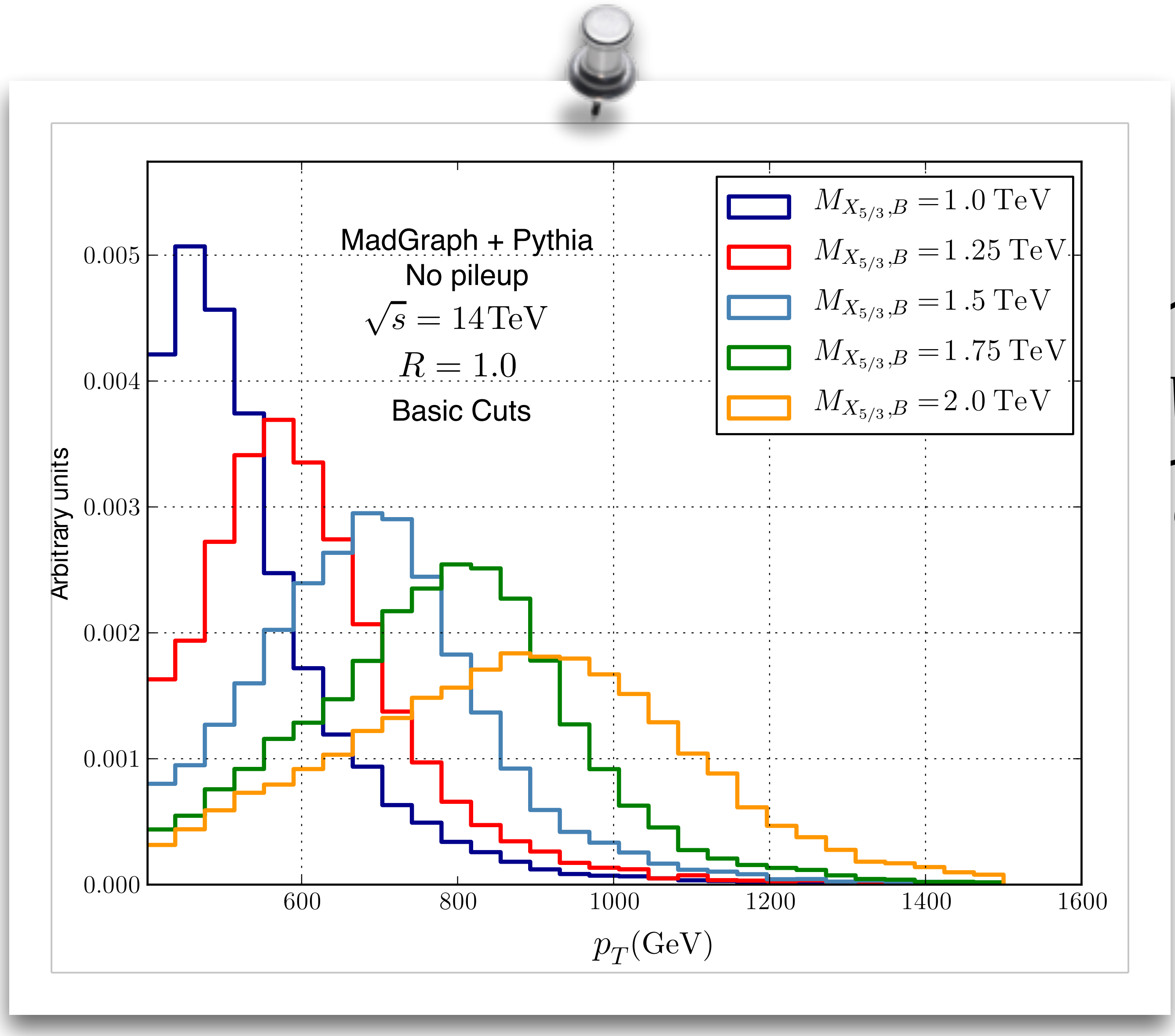
Large **SM backgrounds** (di-tops, **W**+jets, …)

Backovic, Flacke, SL, Perez `14

Top Partner Searches Beyond the 2 TeV Mass Region

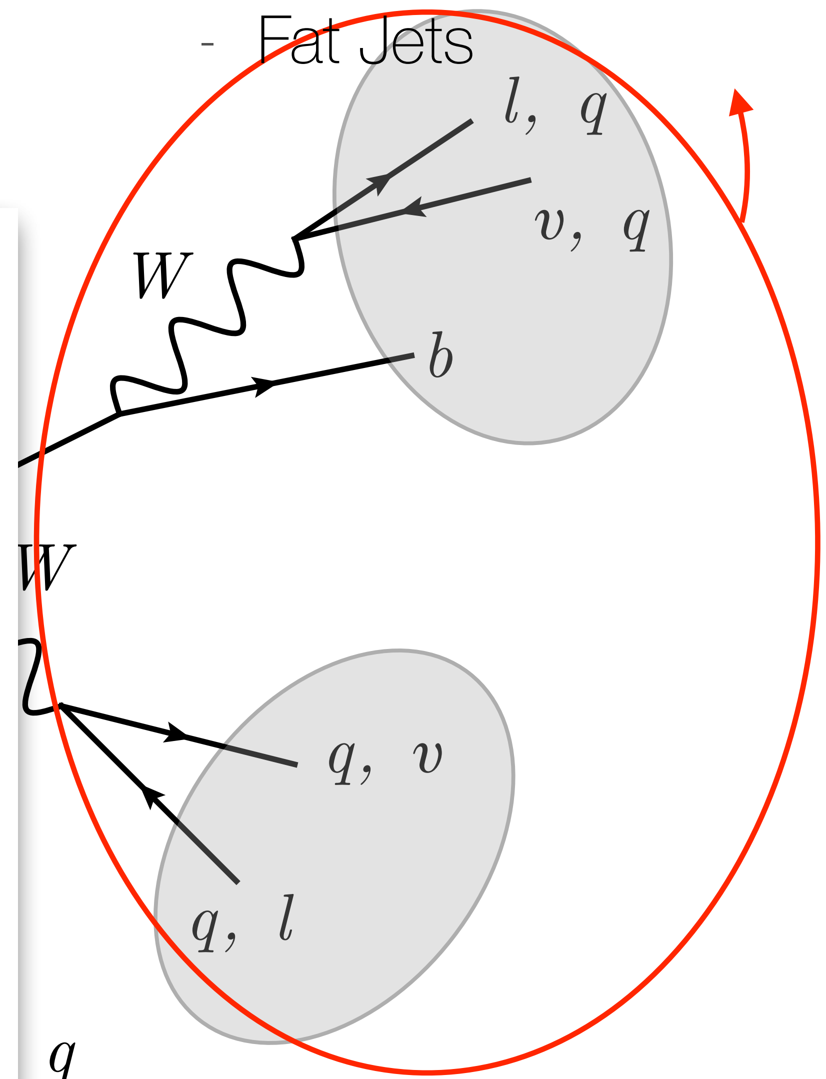
Unique event topology!

At least **three interesting handles** on the SM backgrounds



Boosted t / W

- Hard Lepton
- Missing Energy
- Fat Jets

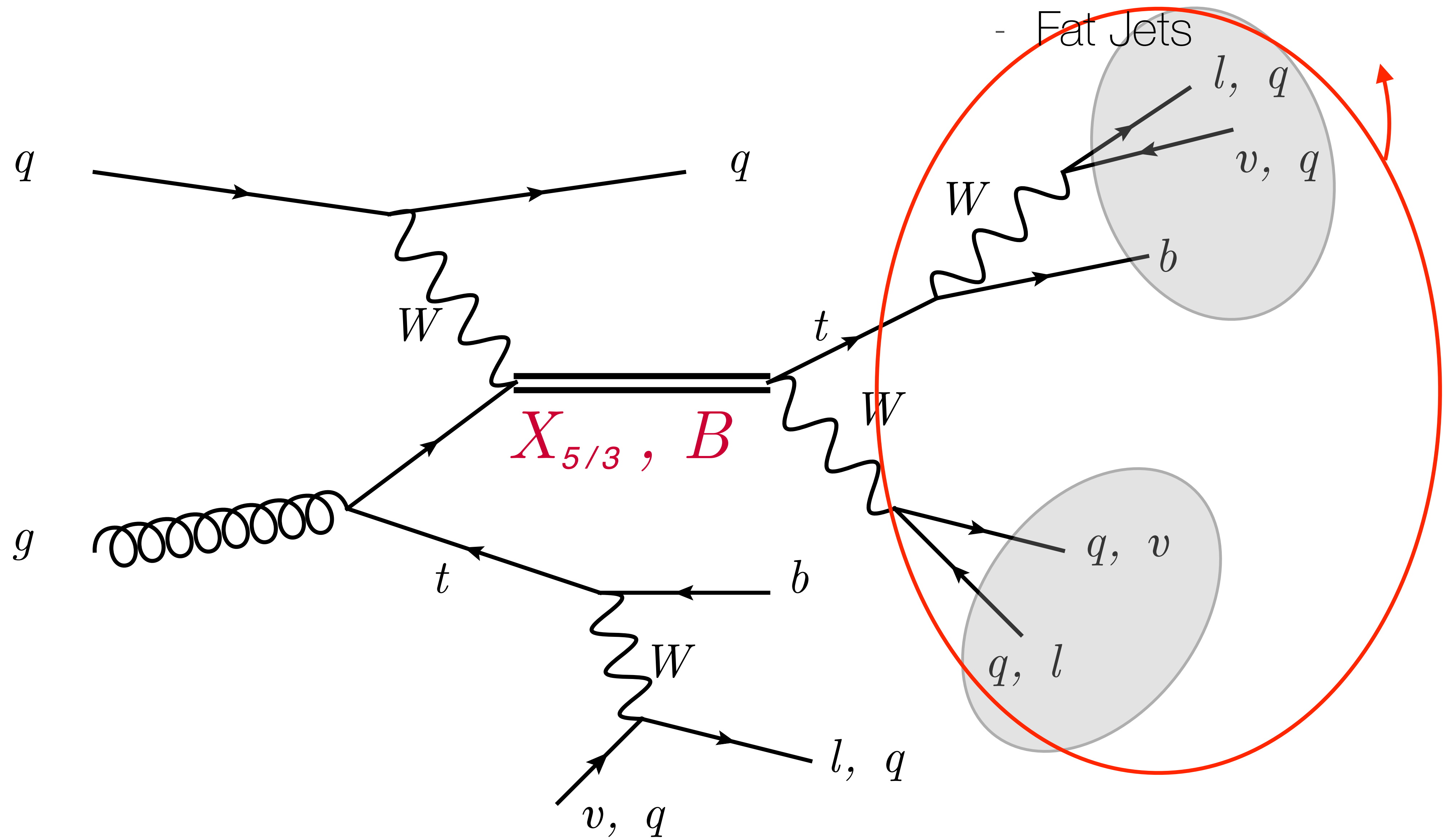


Backovic, Flacke, SL, Perez `14

Top Partner Searches Beyond the 2 TeV Mass Region

Boosted t / W

- Hard Lepton
- Missing Energy
- Fat Jets



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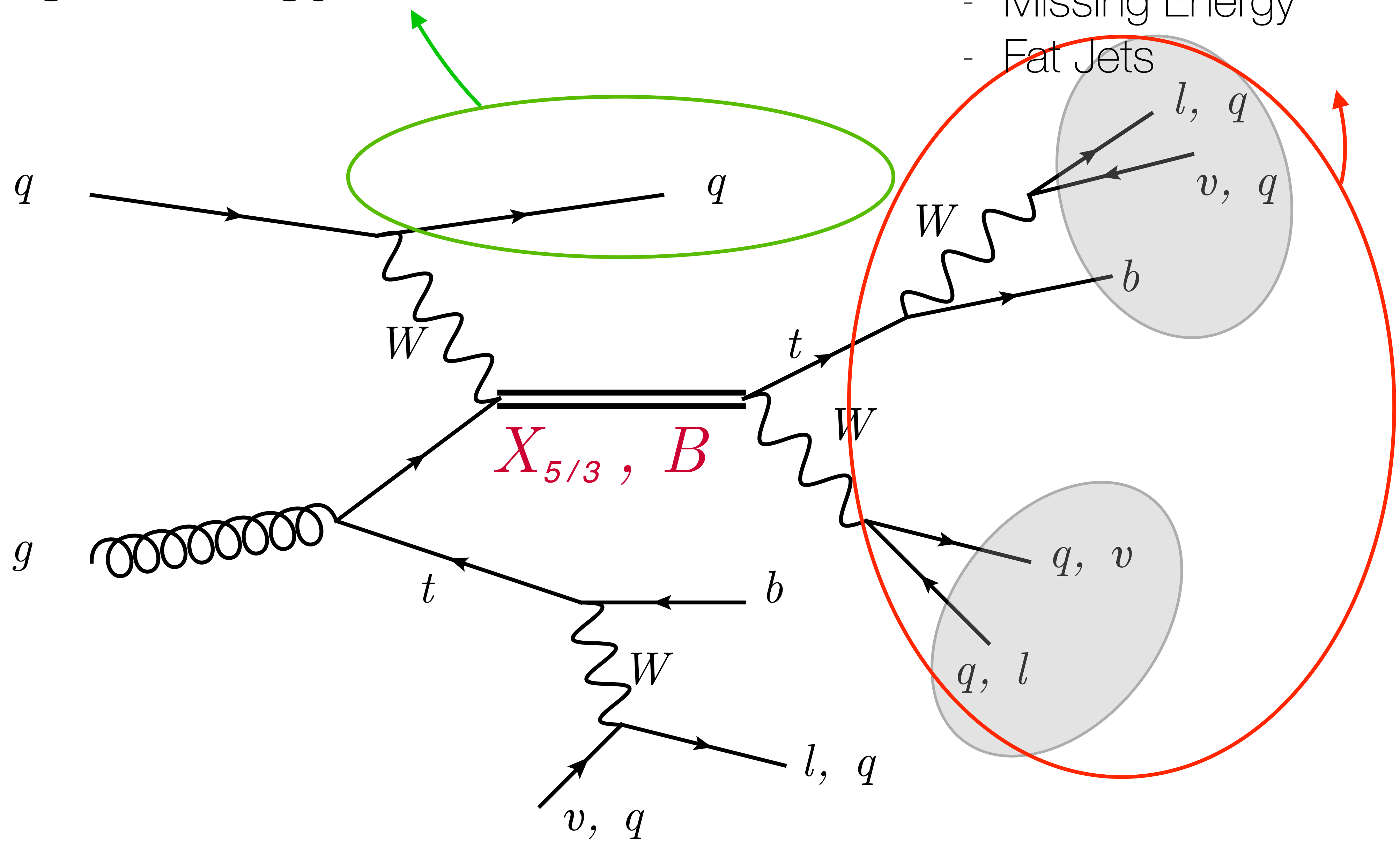
Top Partner Searches Beyond the 2 TeV Mass Region

Boosted t / W

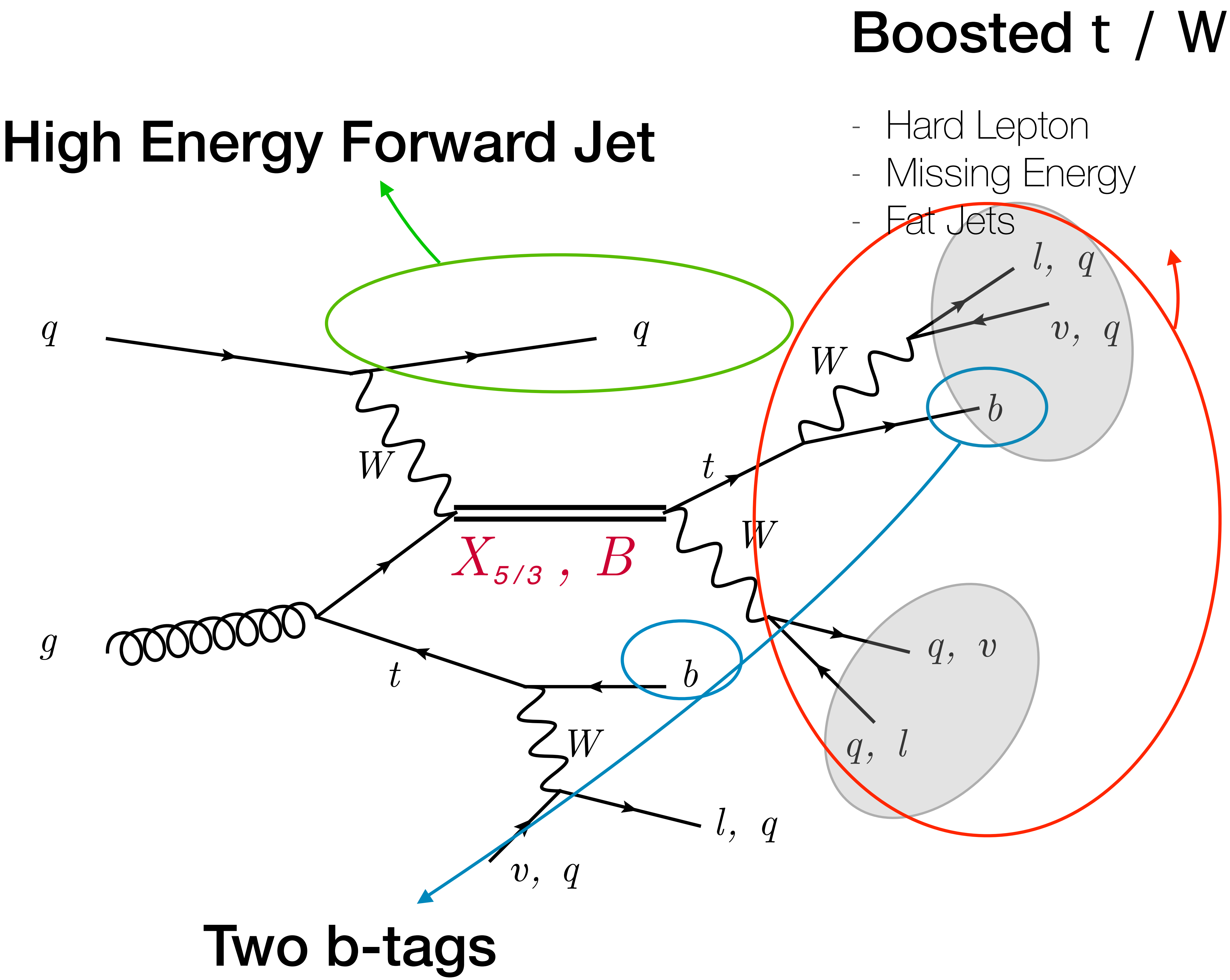
- Hard Lepton
- Missing Energy
- Fat Jets

High Energy Forward Jet



Backovic, Flacke, SL, Perez `14

Top Partner Searches Beyond the 2 TeV Mass Region



Backovic, Flacke, SL, Perez `14

Tagging of **Boosted Objects**

* We use the **Template Overlap Method (TOM)**

  - Low susceptibility to pileup.
  - Good rejection power for light jets.
  - Flexible Jet Substructure framework
    (**can tag tops, Higgses, Ws …**)

* For a gruesome amount of detail on TOM see:

Almeida, SL, Perez, Sterman, Sung '10
Almeida, Erdogan, Juknevich, SL, Perez, Sterman '12
Agashe, et al (SL), Snowmass studies (top & RS benchmark) '13
Backovic, Juknevich, Perez '13
Backovic, Gabizon, Juknevich, Perez, Soreq '14

Template Overlap Method

- Template overlaps: functional measures that quantify how well the energy flow of a physical jet matches the flow of a boosted partonic decay

|j>=set of particles or calorimeter towers that make up a jet. e.g.
|j>=|t>,|g>,etc, where:

$$
\begin{aligned}
|t > &= \text{top distribution} \\
|g > &= \text{massless QCD distribution}
\end{aligned}
$$

Lunch table discussion with Juan Maldacena

We need a probe distribution, $|f>$, such that

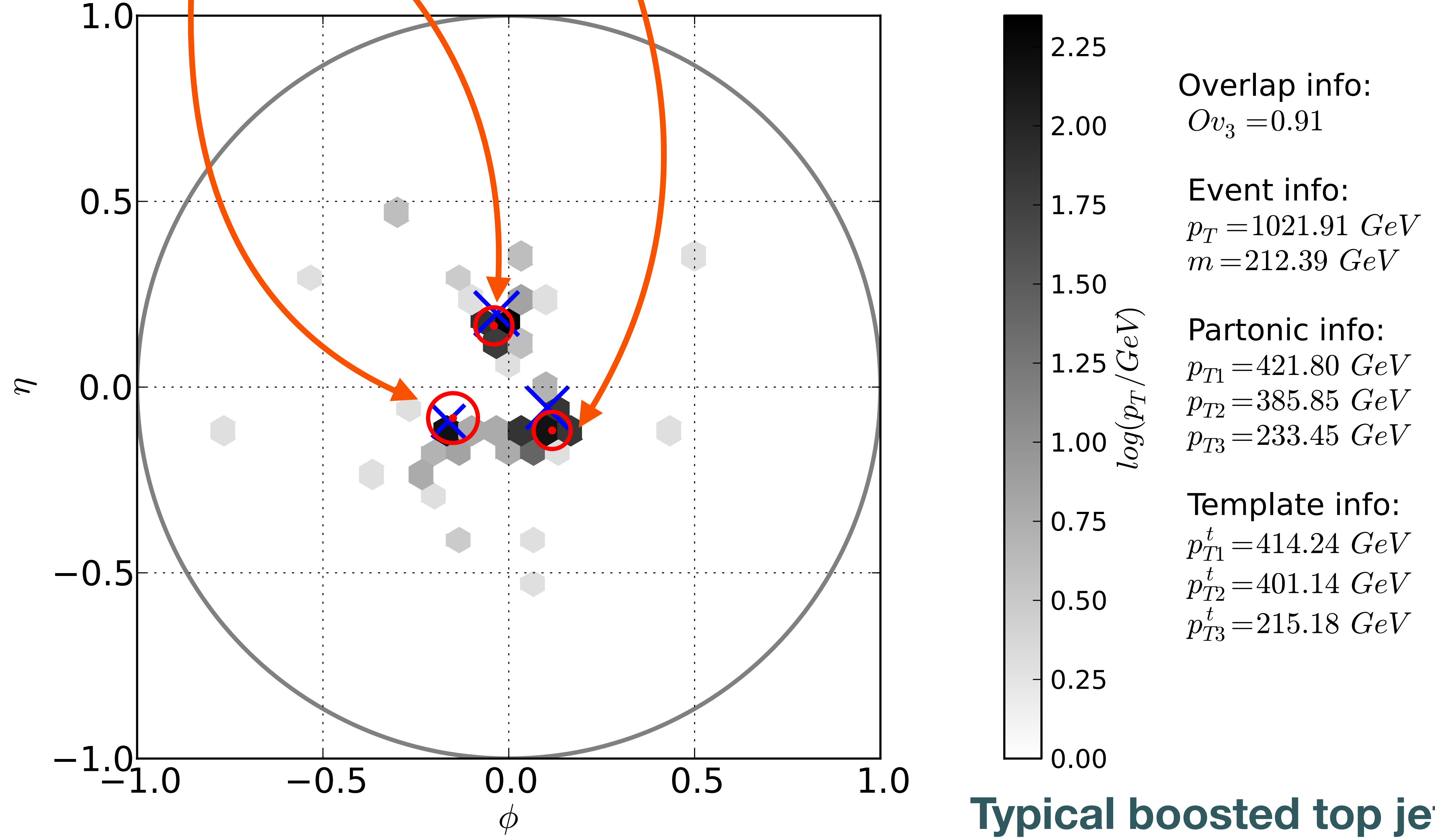
"template"

$$R = \left(\frac{< f|t >}{< f|g >} \right) \text{ is maximized.}$$

Tagging of **Boosted Objects**

Blue - positions of truth level top decay products.
Gray - Calorimeter energy depositions.
Red - Peak template positions.

The red dots with circles are **peak template momenta.** They represent the "most likely" top decay configuration at a parton level.

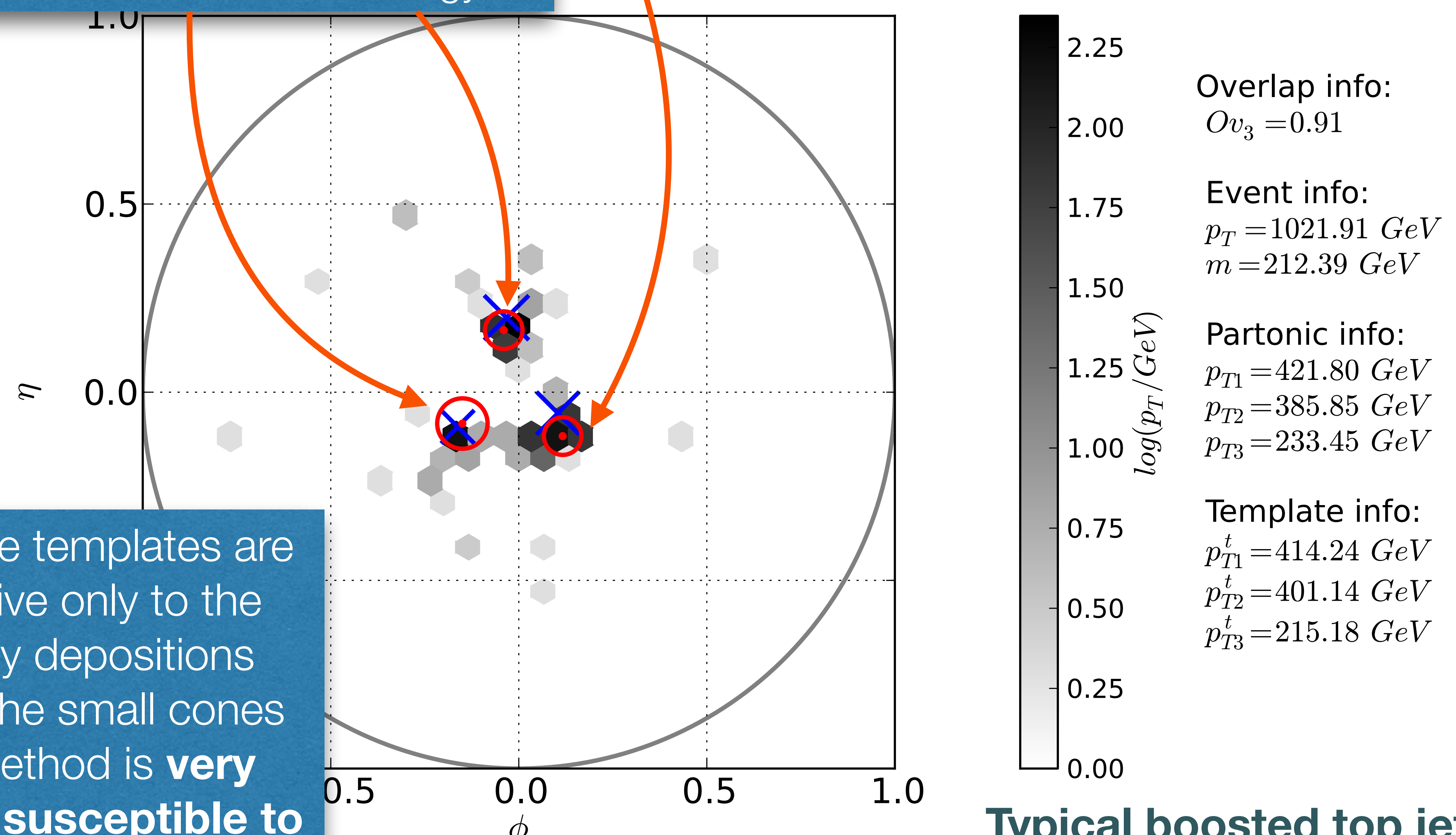


Typical boosted top jet

Tagging of **Boosted Objects**

Blue - positions of truth level top decay products.
Gray - Calorimeter energy depositions.
Red - Peak template positions.

Templates are matched to jet energy distribution **by collecting radiation within some small cone around each parton and minimizing the difference** between the energy of the parton and the collected energy.



Typical boosted top jet

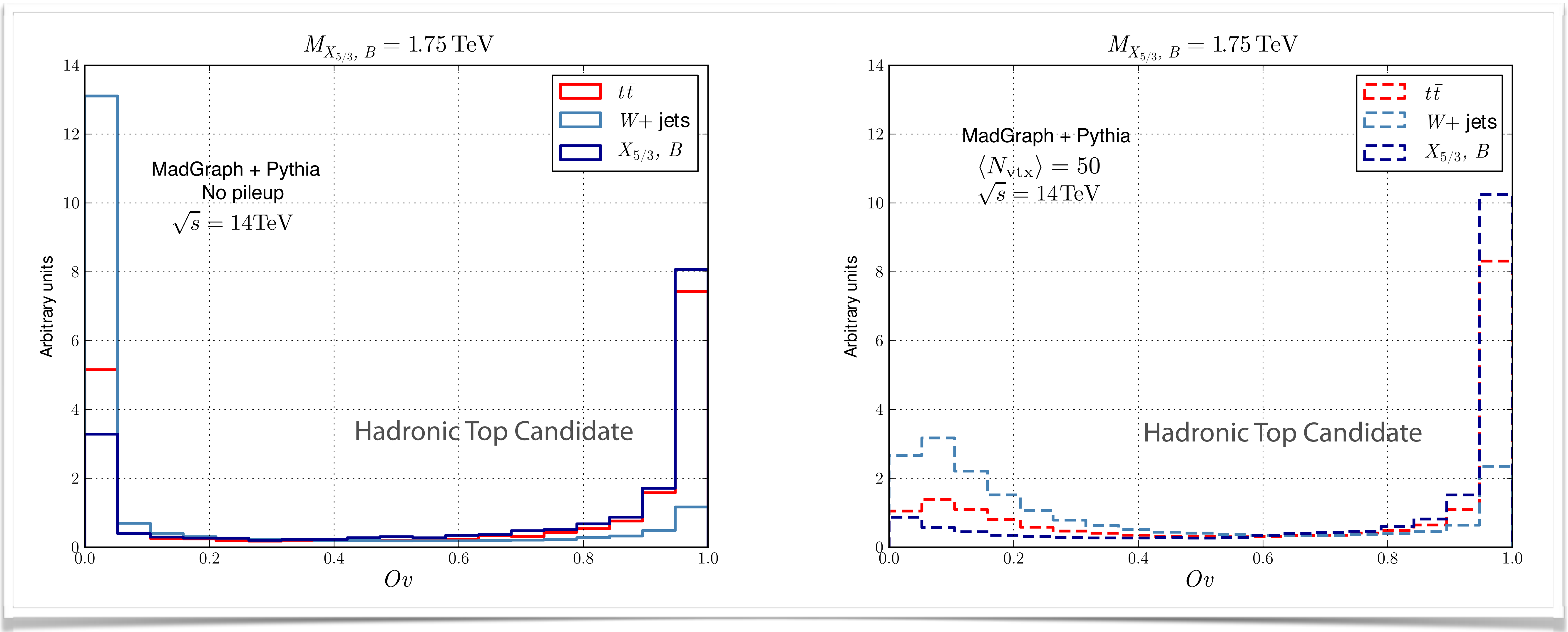
Because templates are sensitive only to the energy depositions within the small cones the method is **very weakly susceptible to pileup.**

Tagging of **Boosted Objects**

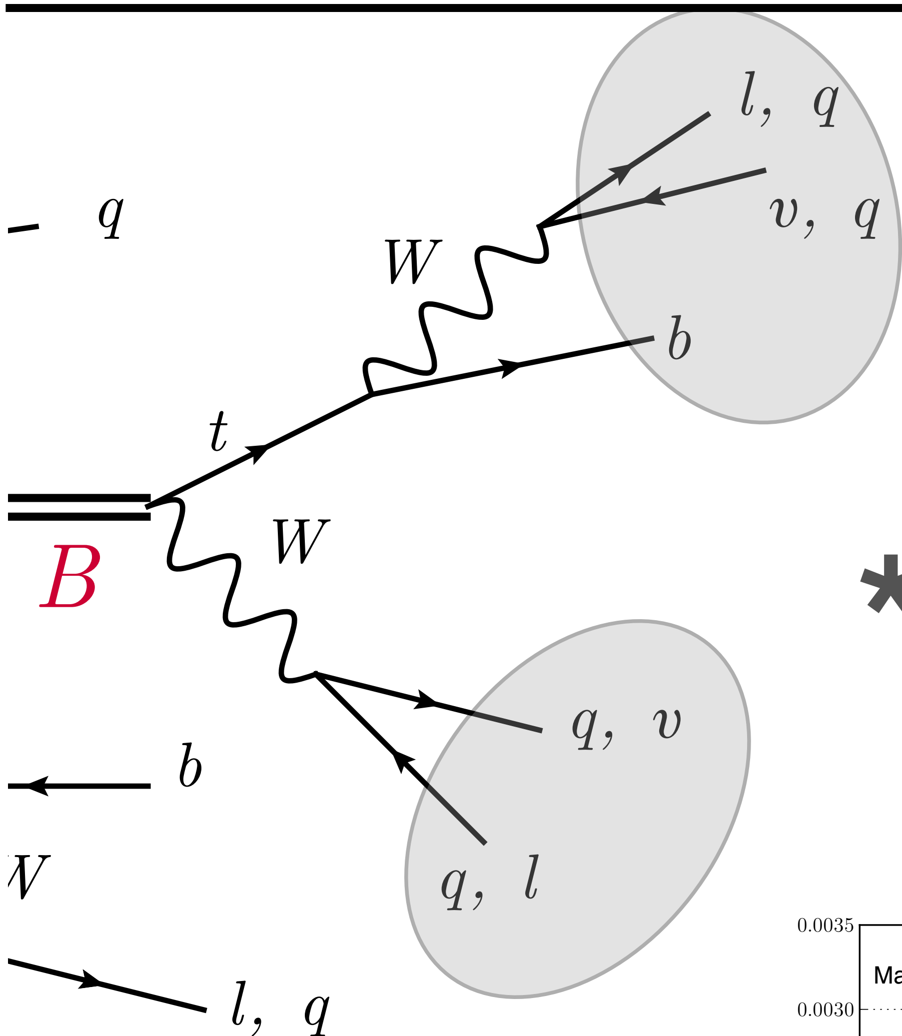
Template Overlap Method

- Good rejection power for light jets.
- Flexible Jet Substructure framework (**can tag t, h, W ...**)

No Pileup | 50 avg. pileup



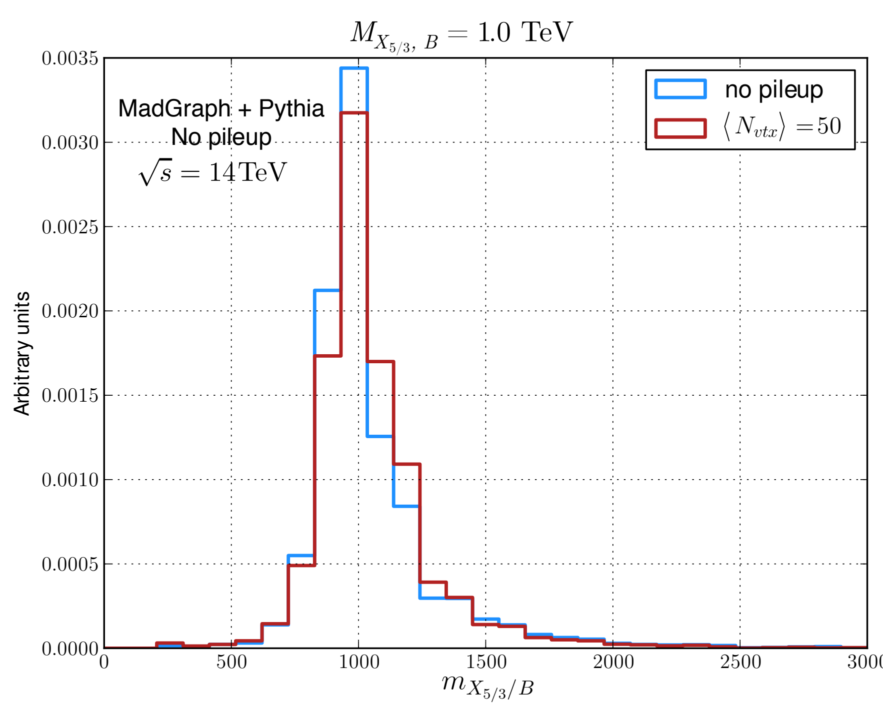
We can reconstruct the **resonance mass**

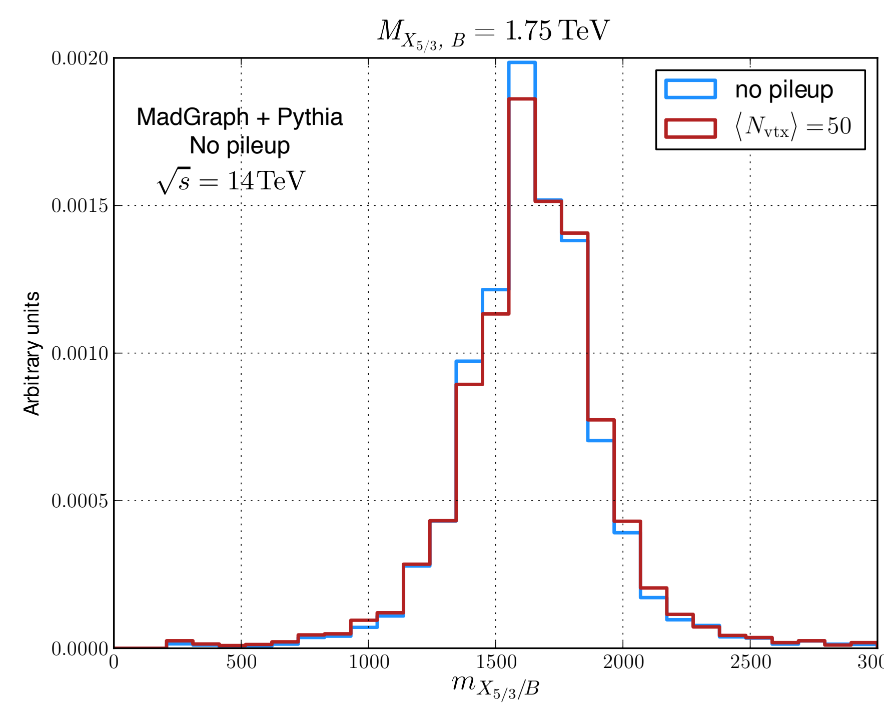


- Use the peak template (pileup insensitive)*****:
  - **hadronic top:** $m_X^2 = (p^{\text{temp}} + p^l + p^\nu)^2$
  - **hadronic W:** $m_X^2 = (p^{\text{temp}} + p^l + p^\nu + p^b)^2$

***** because of a **boosted topology**, assigning $\eta_\nu = \eta_l$ works well for the purpose of resonance reconstruction.

red - pileup blue - no pileup





Note: very **difficult to reconstruct the resonance mass** with same sign **di-leptons**!

Can we break on through to **2 TeV**?

Possible additional handle:

$$M_B = \sqrt{M_4^2 + y_L^2 f^2}$$

$$M_{X_{5/3}} = M_4$$

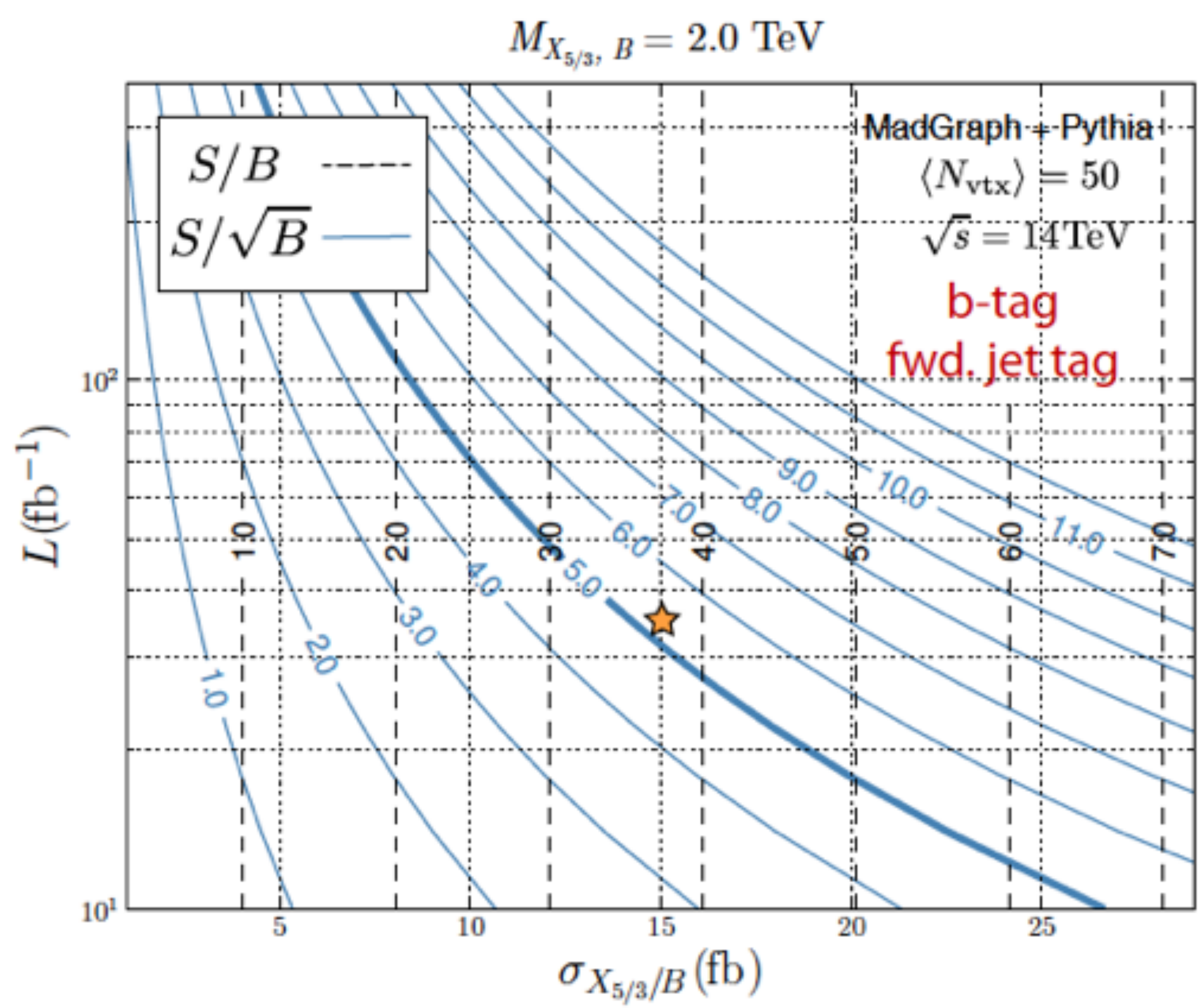
For large **M4**, 5/3 and *B* partners are becoming **mass degenerate**

Production cross section **nearly doubles**, but only if the event selections are **sensitive to both 5/3 and *B* partner**

Clear advantage over same sign di-lepton channels!

Backovic, Flacke, SL, Perez `14

✱Template Overlap Method w/ forward jet tagging & b-tagging



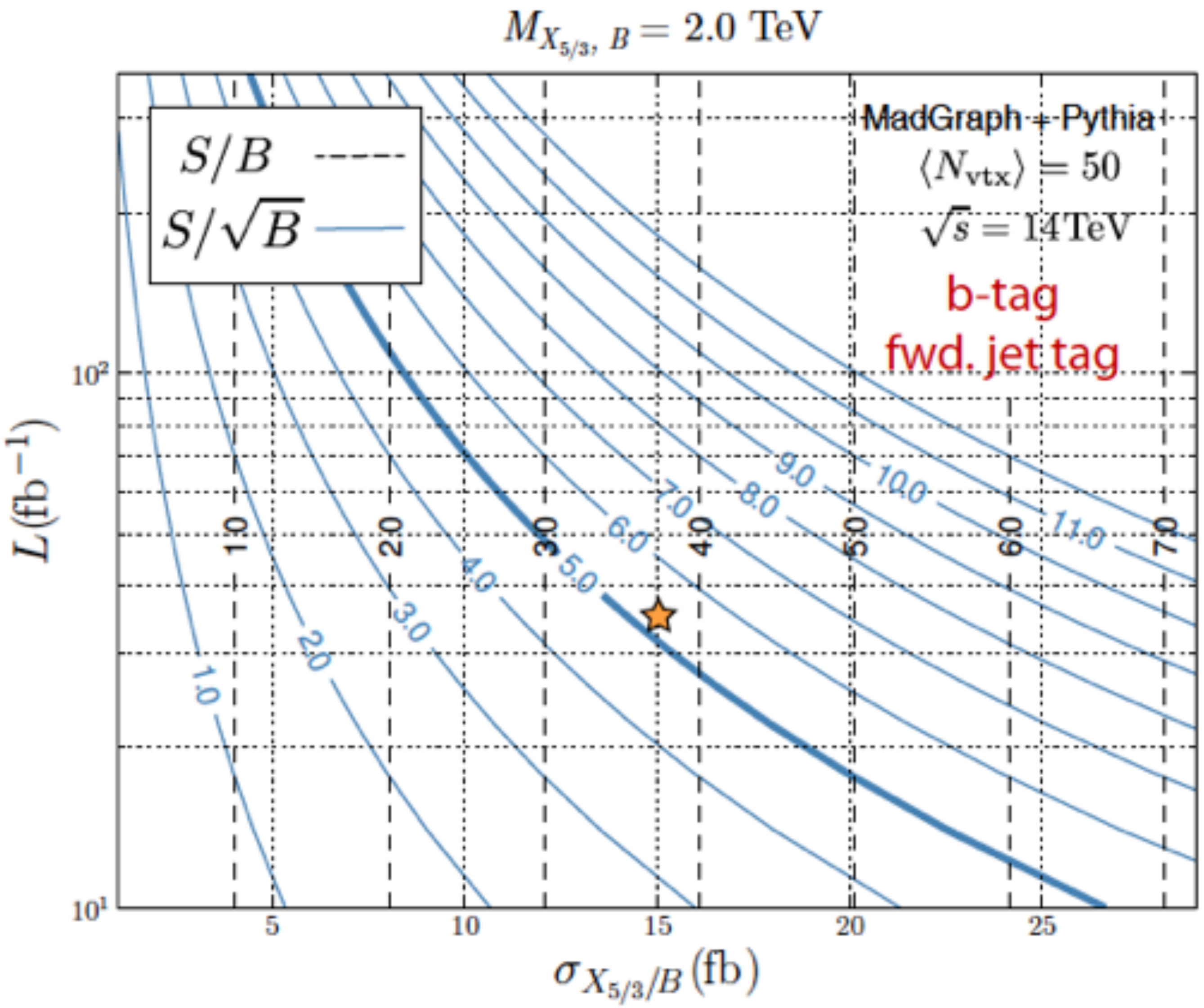
Top Partner Searches Beyond the 2 TeV Mass Region

Backovic, Flacke, SL, Perez `14

Template Overlap Method w/ forward jet tagging & b-tagging

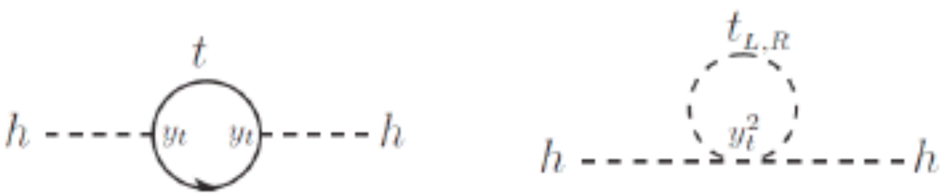
- We showed that Run 2 of the LHC at 14 TeV can detect and measure 2 TeV top partners in a lepton-jet final state, with almost 5 sigma signal significance and S/B > 1 at 35 fb^{-1}

- A sizeable part of the model parameter space parts which result in a 2 TeV top partner can be ruled at 2 sigma with as little as 10 fb^{-1}



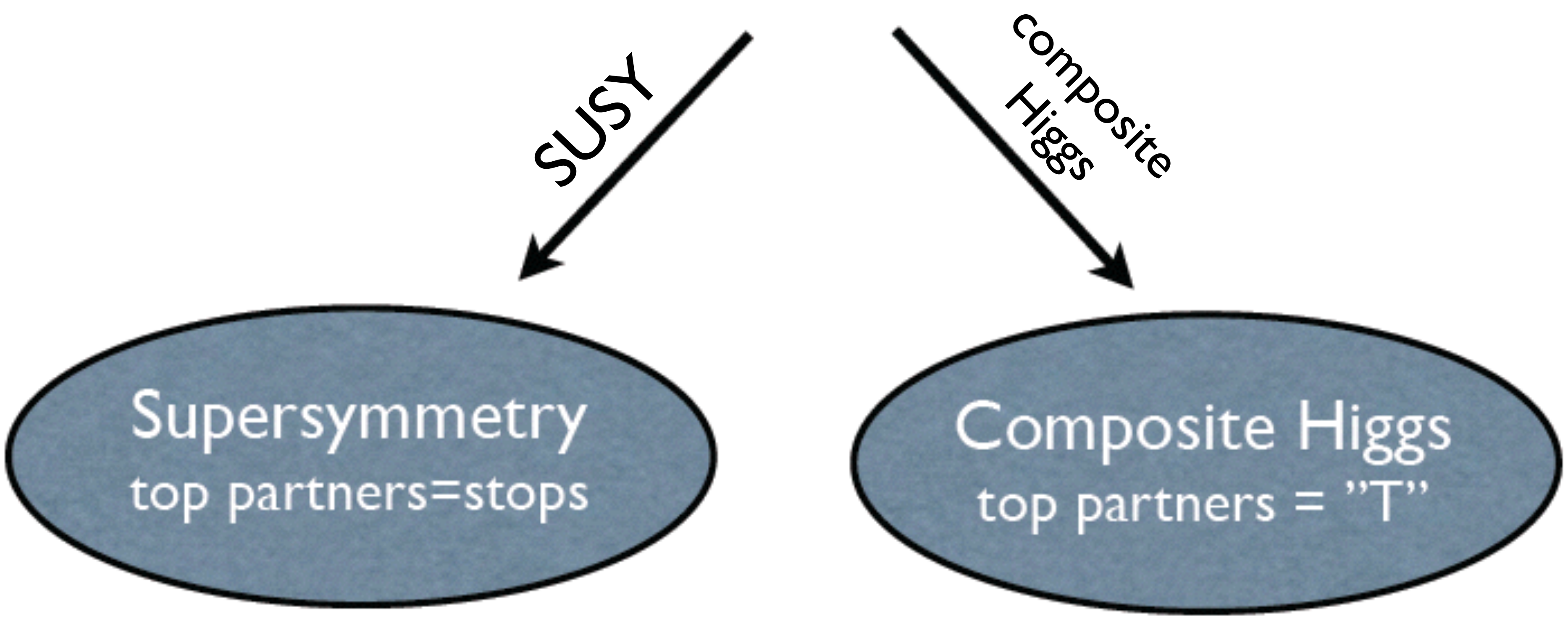
Hiding partners @LHC

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



$$\frac{\delta m_h^2}{m_h^2} \sim \left(\frac{\tilde{m}_t}{400\,\mathrm{GeV}}\right)^2$$

2 leading frameworks
of naturalness



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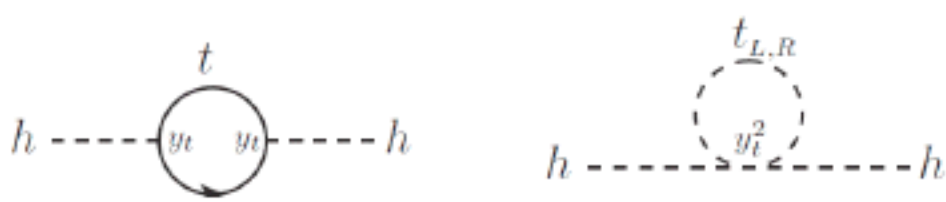

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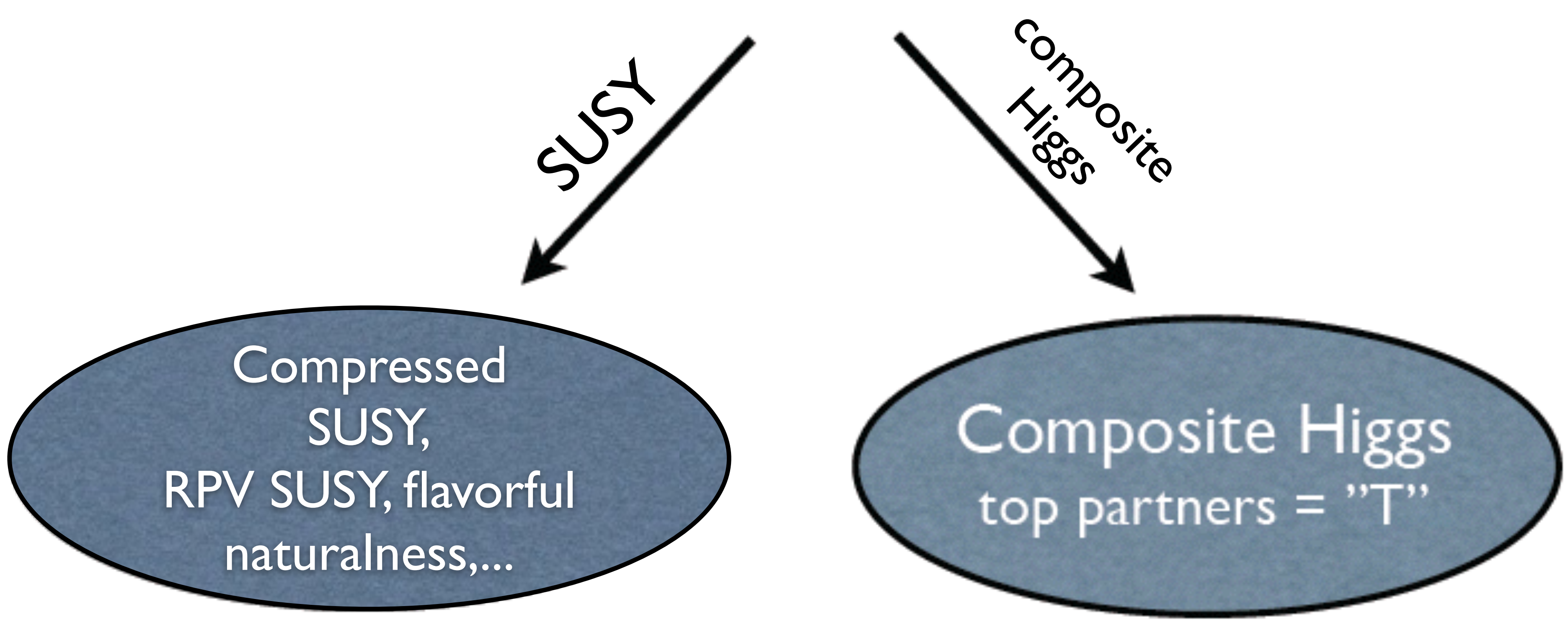

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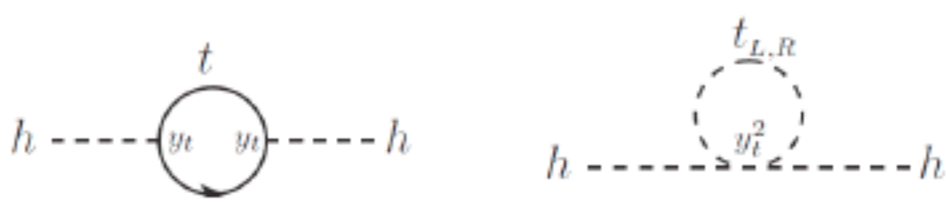

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2 leading frameworks
of naturalness

SUSY

composite
Higgs

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

increase tuning
or,...

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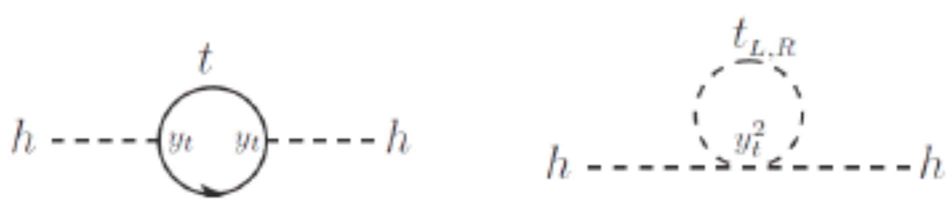

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2 leading frameworks of naturalness

SUSY

composite Higgs

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

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

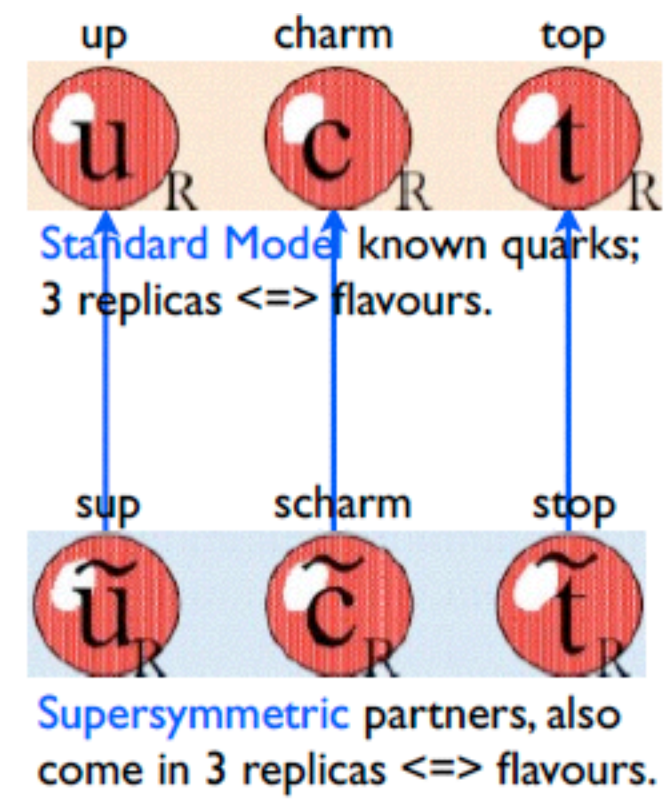
Partners are hiding due to non-trivial flavor physics effects

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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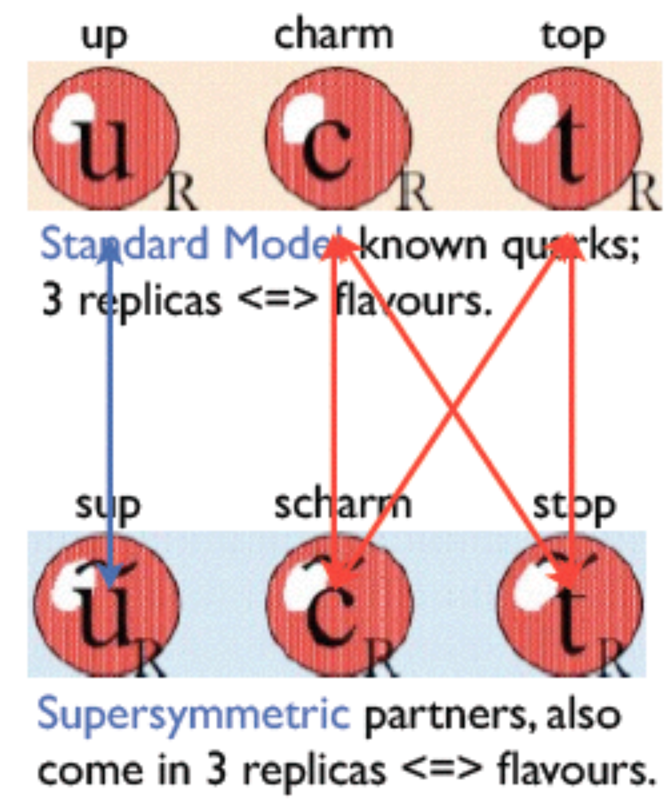

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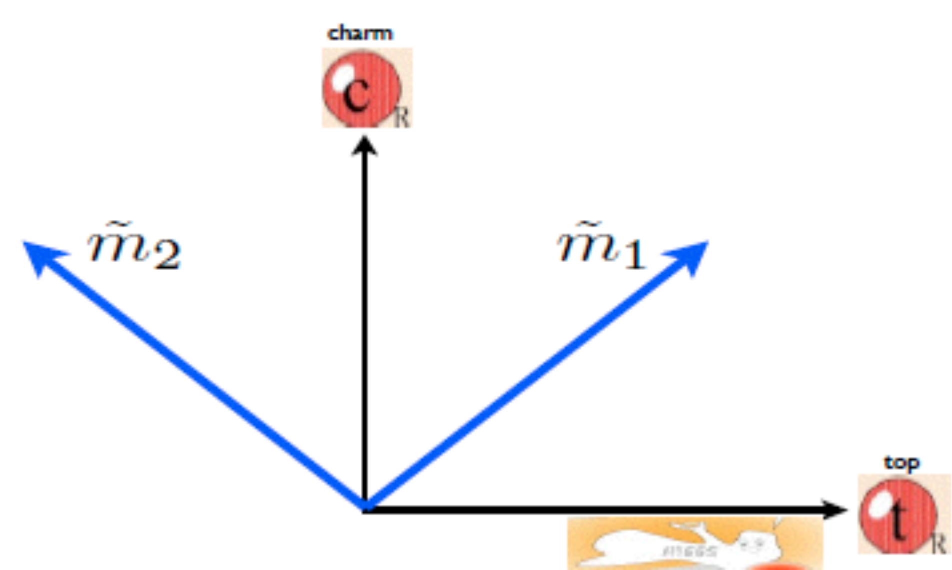

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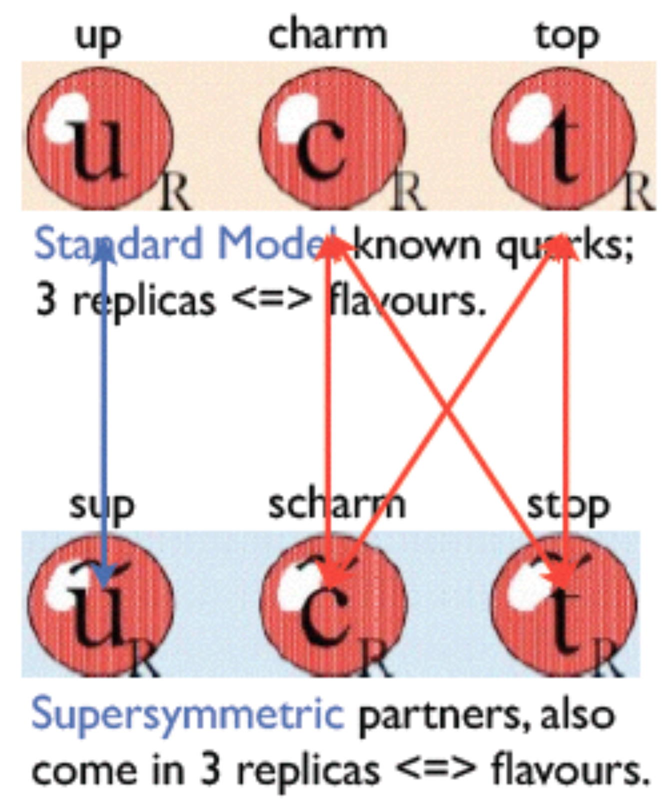

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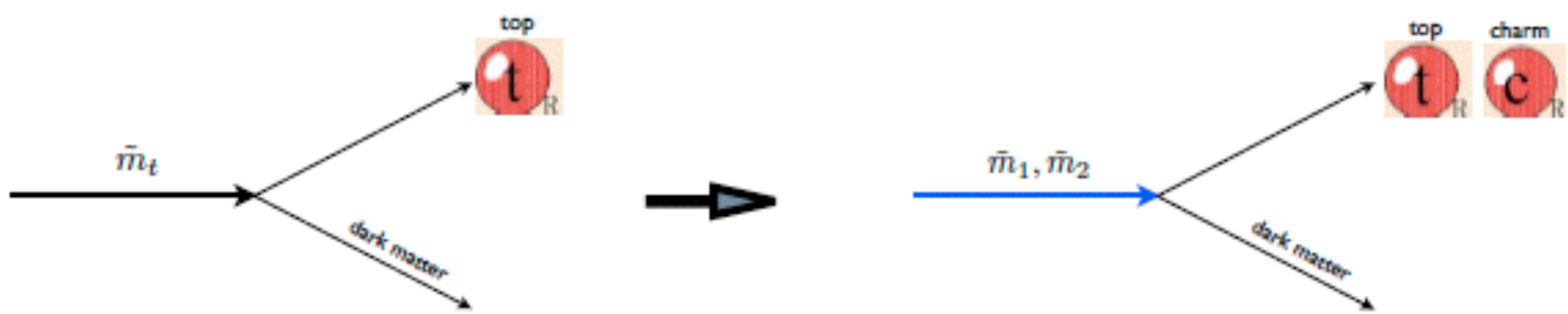

SUSY Flavorful Naturalness

Mahbubani, Papucci, Perez, Ruderman, Weiler '
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- It was demonstrate that in SUSY, the RH top squark flavor eigenstate can consist of an admixture of would be stop-like and scharm-like mass eigenstate.

  => Direct experimental bounds on the second generation squarks are rather weak, of O(400-500) GeV, since the associated searches are mainly sensitive to "valence" squark masses (masses of the first generation squarks) and are optimized for heavy squarks: To constrain, look for: tt, cc & tc + MET channels

- Non-degenrate RH first 2 generation squarks is consistent with flavor constraints Galon, Perez, Shadmi '13

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

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

Galon, Perez, Shadmi '13

Composite Light Quark

- 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;
  Redi, Sanz, de Vries, Weiler '13; Da Rold, Delaunay, Grojean, Perez '13;
  Atre, Chala, Santiago '13
- And LHC implications for non-degenerate first 2-generation partners.
  Delaunay, Fraille, Flacke, SL, Panico, Perez `13
  Kim, Flake, SL, Lim '13
  Backovic, Kim, Flake, SL '14

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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 (just as in 3rd generation)

- The model contains elementary fermions q and composite fermionic resonances of the strongly coupled theory, which mix via linear interactions

$$\mathcal{L}_{mix} = y\bar{q}_{I_{\mathcal{O}}}\mathcal{O}^{I_{\mathcal{O}}} + \text{h.c.}$$

where $\mathcal{O}$ is an operator of the strongly coupled theory in the rep. $I_{\mathcal{O}}$, and $\bar{q}_{I_{\mathcal{O}}}$ is an (incomplete) embedding of the elementary q into $SO(5)$.

- One common choice (partially composite quarks):

$$\begin{aligned} \bar{q}_L^5 &= \frac{1}{\sqrt{2}}\left(-i\bar{d}_L\,, \bar{d}_L\,, -i\bar{u}_L\,, -\bar{u}_L\,, 0\right), \\ \bar{u}_R^5 &= (0\,, 0\,, 0\,, 0\,, \bar{u}_R)\,, \end{aligned}$$

- This fixes composite partner quarks to be embedded as **5** reps. of $SO(5)$:

$$\psi = \begin{pmatrix} Q \\ \tilde{U} \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} iD - iX_{5/3} \\ D + X_{5/3} \\ iU + iX_{2/3} \\ -U + X_{2/3} \\ \sqrt{2}\tilde{U} \end{pmatrix}.$$

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

- The down-type sector can be realized analogously.

Partial Composite light quarks

Delaunay, Fraille, Flacke, SL, Panico, Perez `13
Flacke, Kim, SL, Lim `13

* 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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wh… …stone 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…

- expand d_μ, e_μ, U_{gs} around $\langle h \rangle$, $\quad m_u \simeq \frac{\ldots}{\sqrt{2}f} \times |\ldots| \times \frac{y_L f}{\sqrt{(M_4^2 + y_L^2 f^2)}} \times \frac{y_R f}{\sqrt{(M_1^2 + y_R^2 f^2)}}$
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Partners in Singlet

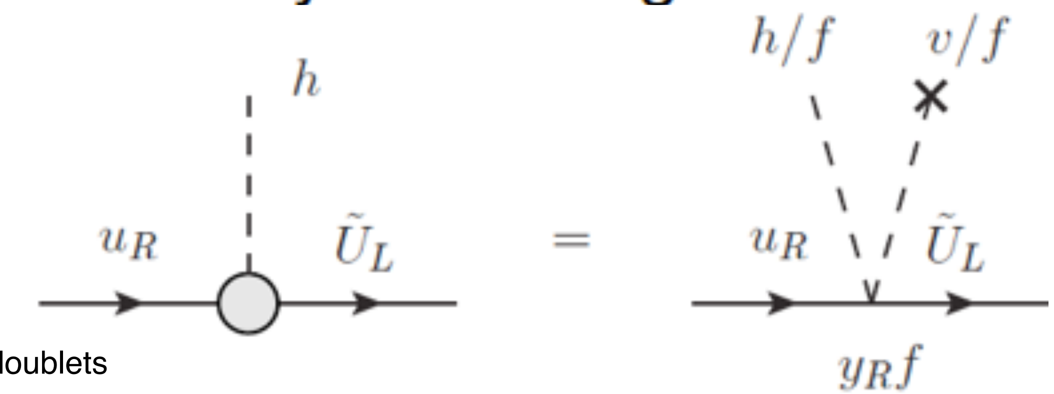
Delaunay, Fraille, Flacke, SL, Panico, Perez `13

Flacke, Kim, SL, Lim `13    Backovic, Flacke, Kim, SL `14

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

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

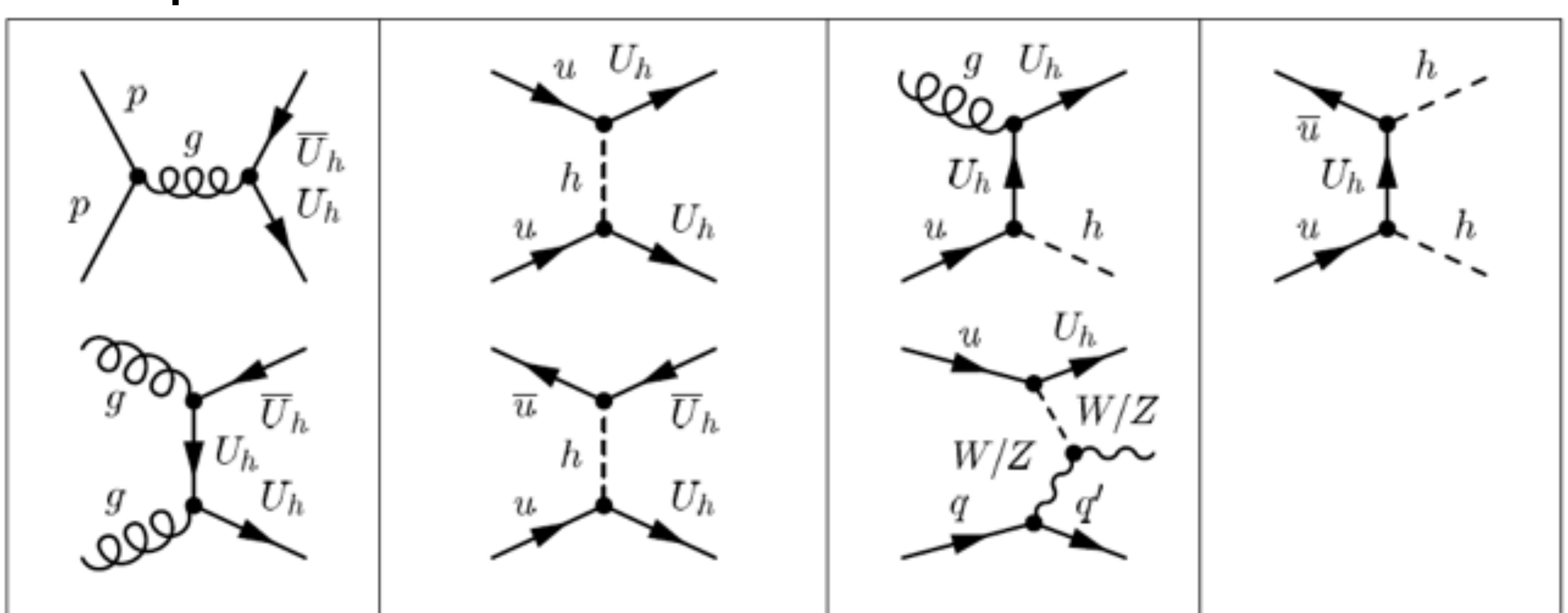
- Now lets look at the singlet limit: M_1 finite and $M_4 \to \infty$.
  Then, all fourplet states decouple, and the only remaining BSM state is $\tilde{U}$.
- Mass: $m_{\tilde{U}} = \sqrt{M_1^2 + (y_R f \cos(\epsilon))^2}$
- only "mixing" coupling:
  u and $\tilde{U}$, being both SO(4) singlets, can only couple to an even number of Higgs doublets



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

- main production channels:

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



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

Partners in Singlet

Flacke, Kim, SL `13

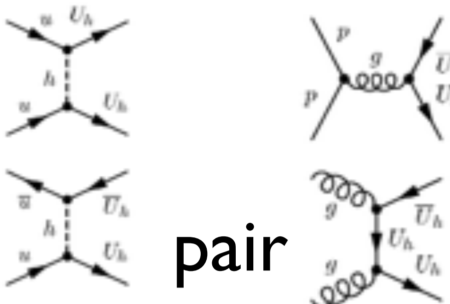
Backovic, Flacke, Kim, SL `14

$$\mathcal{L} = i\overline{\tilde{U}}\not{D}\tilde{U} - M_1\overline{\tilde{U}}\tilde{U} + i\,\overline{q}_L\not{D}q_L + i\,\overline{u}_R\not{D}u_R$$
$$- \left[\frac{y_L}{\sqrt{2}} f \overline{u}_L F\left(\frac{h+v}{f}\right)\tilde{U}_R + y_R f \overline{\tilde{U}}_L G\left(\frac{h+v}{f}\right) u_R + \text{h.c.}\right]$$

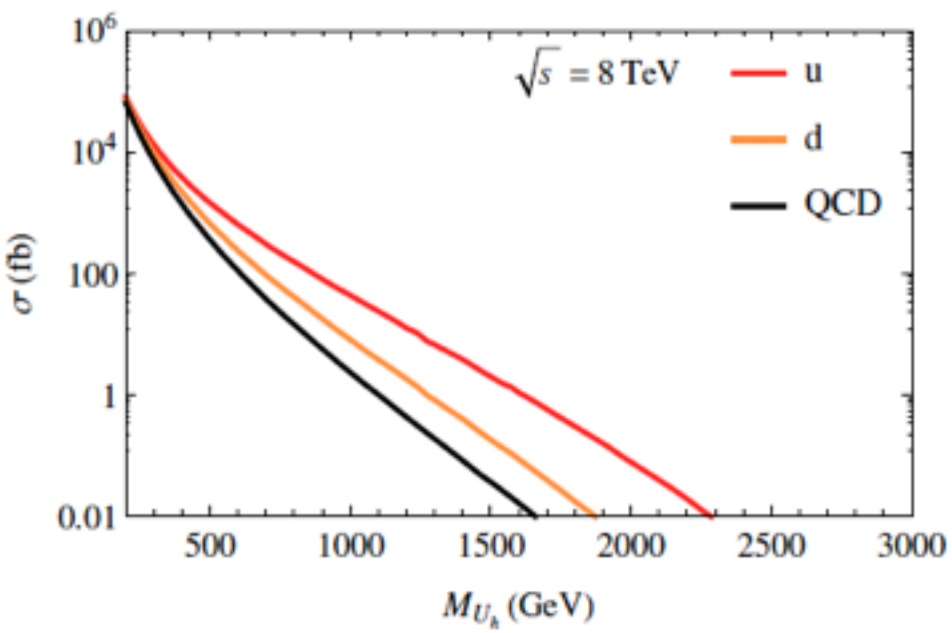
5 rep'

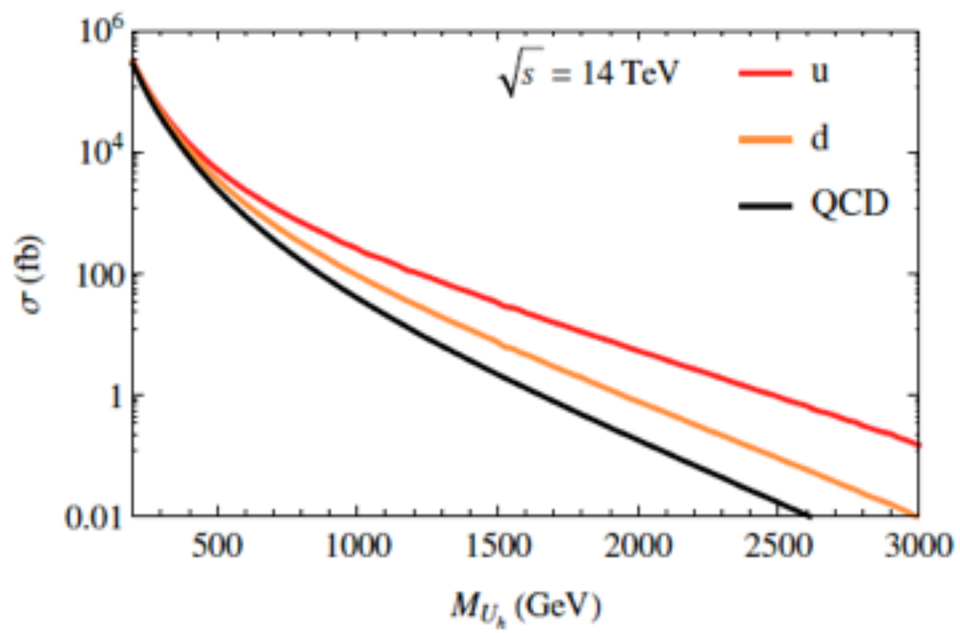
$$= i\overline{\tilde{U}}\not{D}\tilde{U} - M_1\overline{\tilde{U}}\tilde{U} + i\,\overline{q}_L\not{D}q_L + i\,\overline{u}_R\not{D}u_R$$
$$- \left[m_2\overline{u}_L\tilde{U}_R + m_3\overline{\tilde{U}}_L u_R + \lambda_2 h\overline{u}_L\tilde{U}_R + \lambda_3 h\overline{\tilde{U}}_L u_R + \text{h.c.} + \mathcal{O}(\epsilon^2)\right]$$

	$\mathcal{F}(U_{gs})$	$\mathcal{G}(U_{gs})$	$F(\frac{h+v}{f})$	$G(\frac{h+v}{f})$	$\lambda^{\rm eff}_{\rm mix}$
$q_L \in \mathbf{5}$ $\psi \in \mathbf{5}$	U^{i5}_{gs}	U^{i5}_{gs}	$-\sin(\frac{h+v}{f})$	$\cos(\frac{h+v}{f})$	$-\frac{y_R^2}{2}\sin(2\epsilon)\frac{f}{M_{U_h}}$ $= -y_R^2\frac{v}{M_{U_h}}[1+\mathcal{O}(\epsilon^2)]$
$q_L \in \mathbf{14}$ $\psi \in \mathbf{5}$	$U^{i5}_{gs}U^{j5}_{gs}$	$U^{i5}_{gs}U^{j5}_{gs}$	$\frac{1}{\sqrt{2}}\sin(2\frac{h+v}{f})$	$\frac{1}{\sqrt{2}}\sin(2\frac{h+v}{f})$	$-\frac{y_R^2}{2}\sin(4\epsilon)\frac{f}{M_{U_h}}$ $= 2y_R^2\frac{v}{M_{U_h}}[1+\mathcal{O}(\epsilon^2)]$

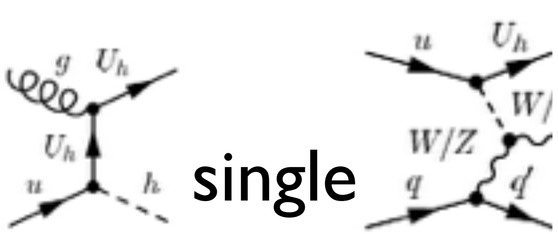


pair production

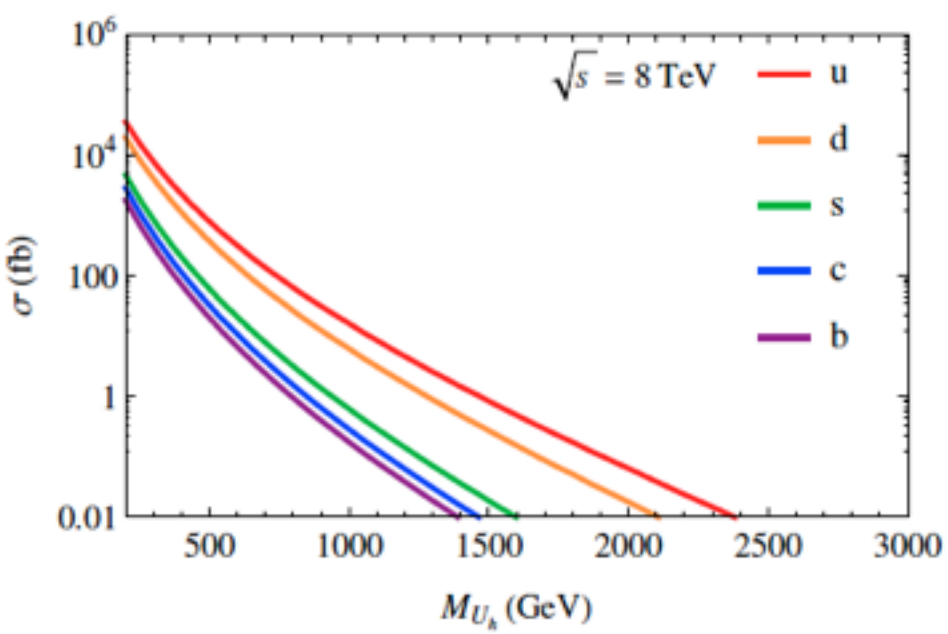


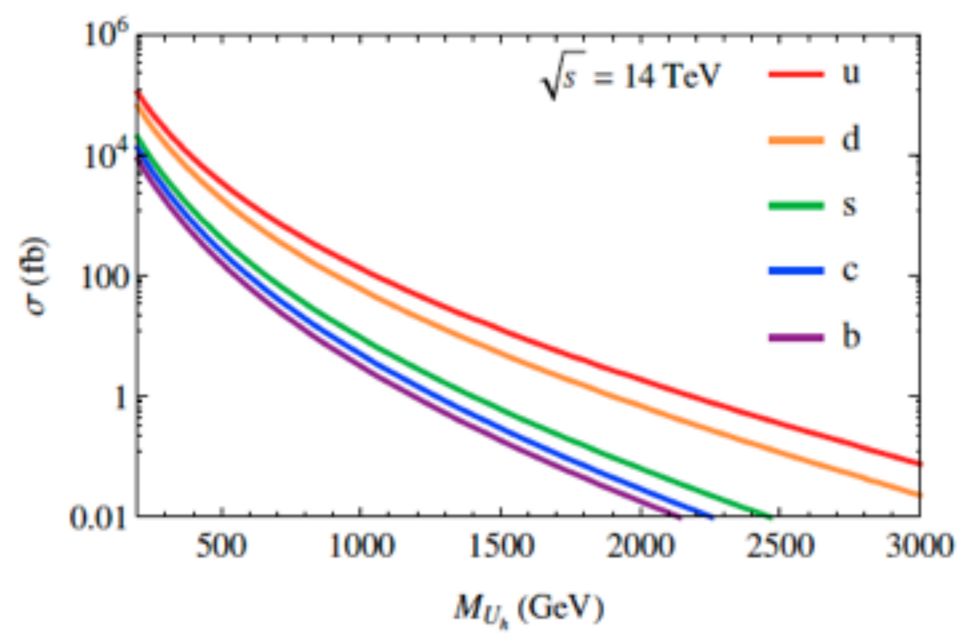


$$\lambda^{\rm eff}_{\rm mix} = 1$$



single production





... Singlet

Flacke, Kim, SL, Lim `13

Backovic, Flacke, Kim, SL `14

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

boosted analysis needed (no LHC bounds yet)

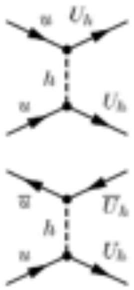
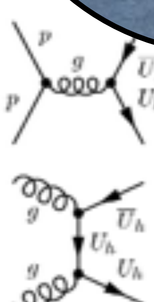
$\mathcal{L} = i\bar{\tilde{U}}\not{D}$ ...

$- \Big[$ ...

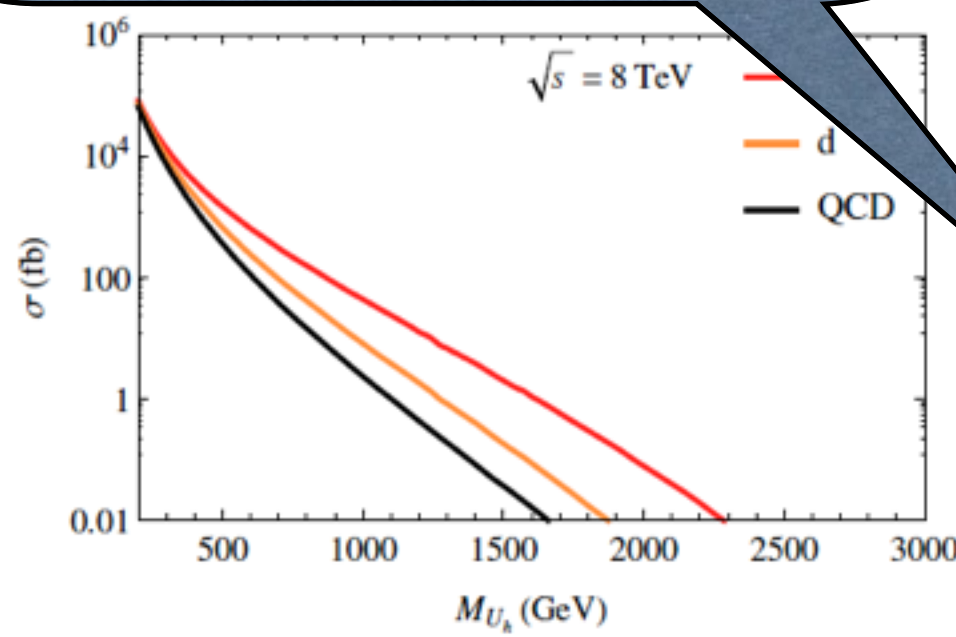
5 rep' $= i\bar{\tilde{U}}\not{D}$ ...

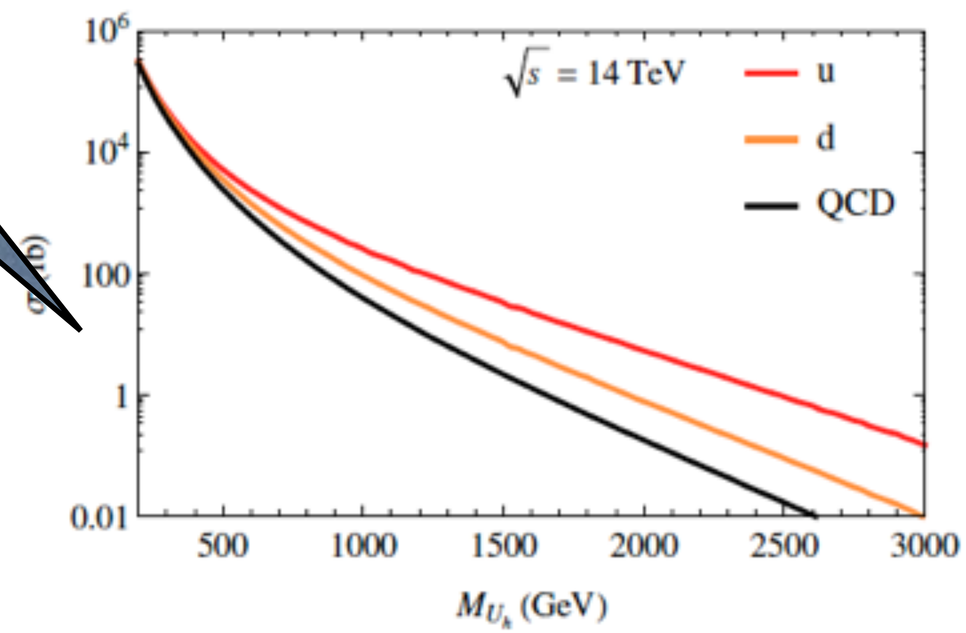
$- \Big[m$ ... $\mathcal{O}(\epsilon^2)\Big]$

	$\mathcal{F}(U_{gs})$	$\mathcal{G}(U_{gs})$	$F(\frac{h+v}{f})$	$G(\frac{h+v}{f})$	$\lambda^{\rm eff}_{\rm mix}$
$q_L \in 5$ $\psi \in 5$	U^{i5}_{gs}	U^{i5}_{gs}	$-\sin(\frac{h+v}{f})$	$\cos(\frac{h+v}{f})$	$-\frac{y_R^2}{2}\sin(2\epsilon)\frac{f}{M_{U_h}}$ $= -y_R^2\frac{v}{M_{U_h}}[1+\mathcal{O}(\epsilon^2)]$
$q_L \in 14$ $\psi \in 5$	$U^{i5}_{gs}U^{j5}_{gs}$	$U^{i5}_{gs}U^{j5}_{gs}$	$\frac{1}{\sqrt{2}}\sin(2\frac{h+v}{f})$	$\frac{1}{\sqrt{2}}\sin(2\frac{h+v}{f})$	$-\frac{y_R^2}{2}\sin(4\epsilon)\frac{f}{M_{U_h}}$ $= 2y_R^2\frac{v}{M_{U_h}}[1+\mathcal{O}(\epsilon^2)]$

pair production





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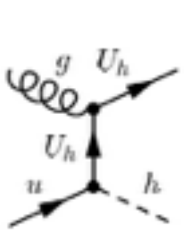
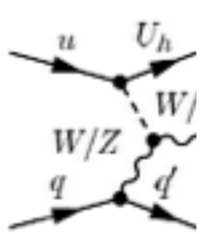
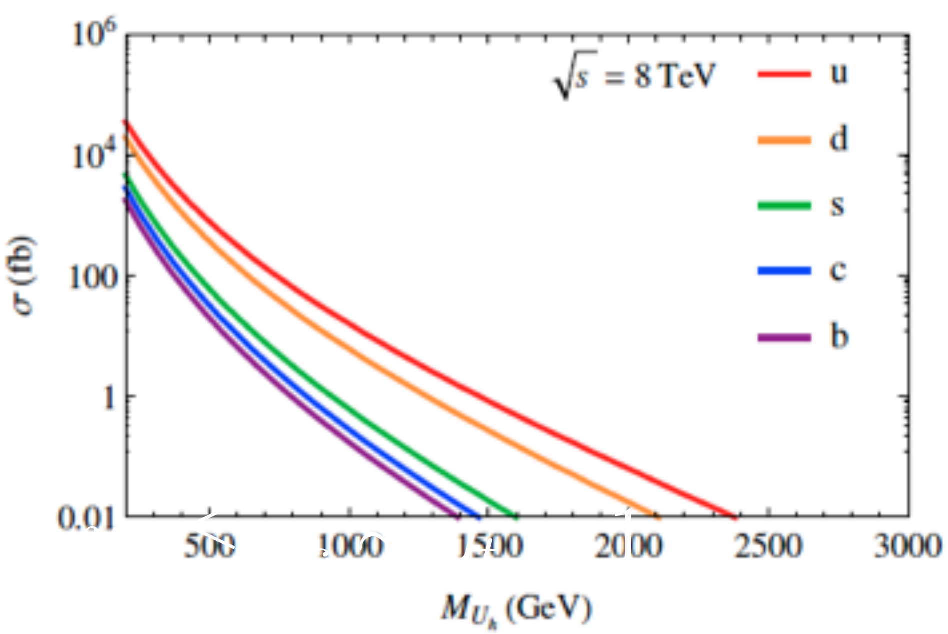
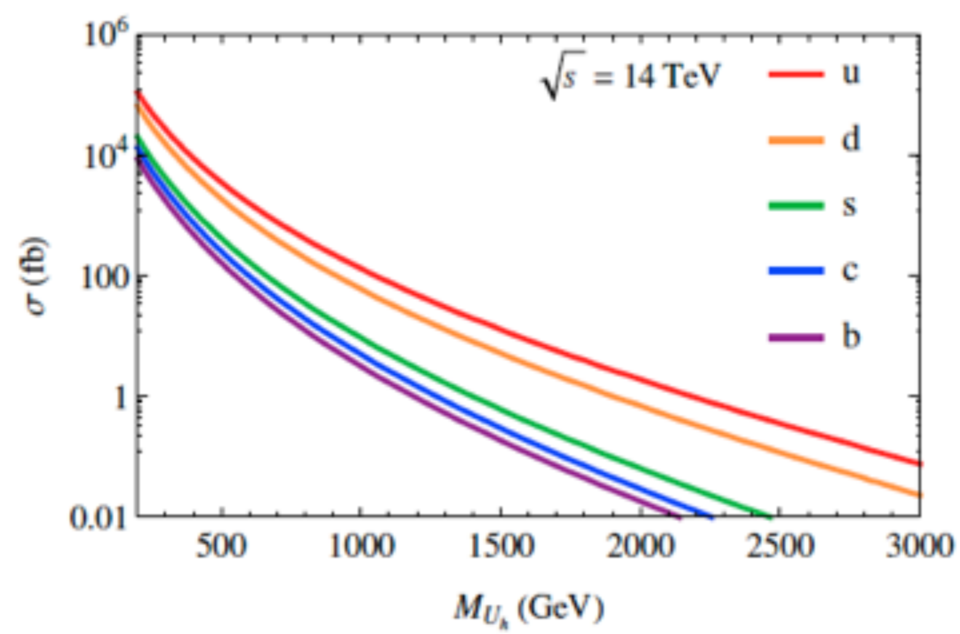



single production





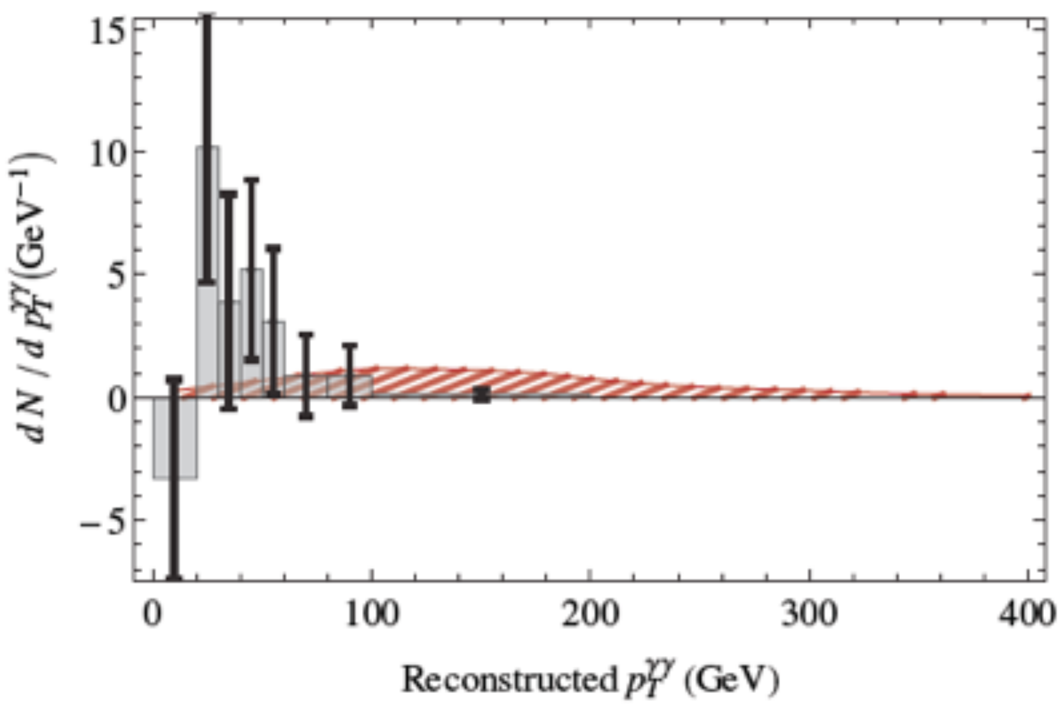
Partners in Singlet

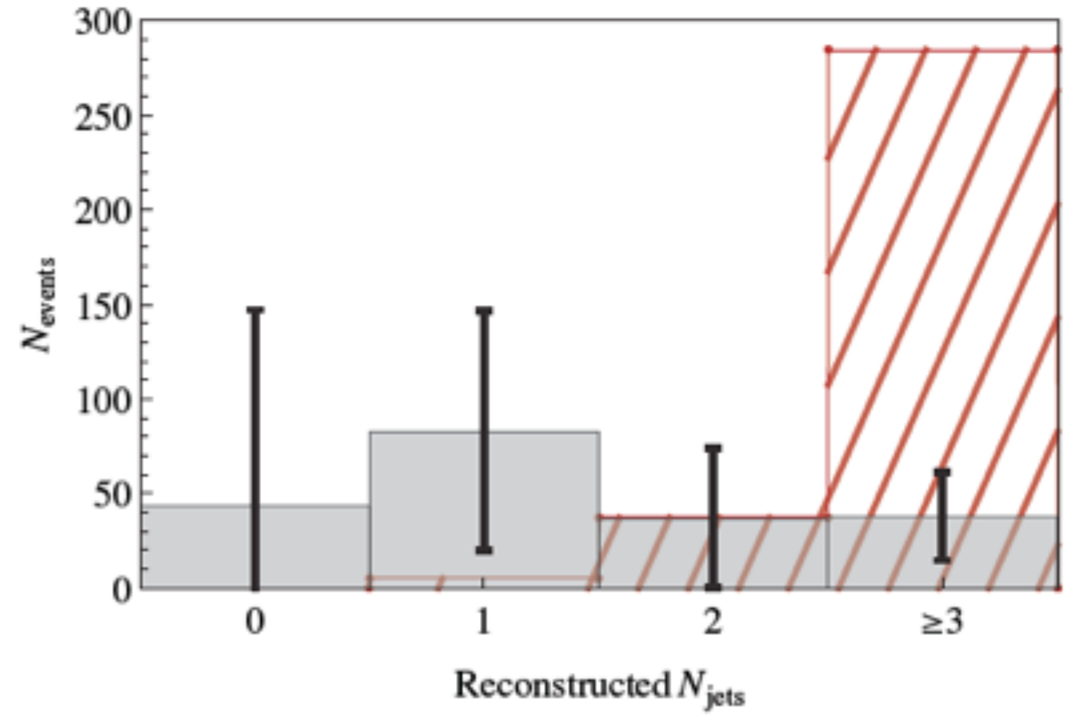
Flacke, Kim, SL, Lim `13

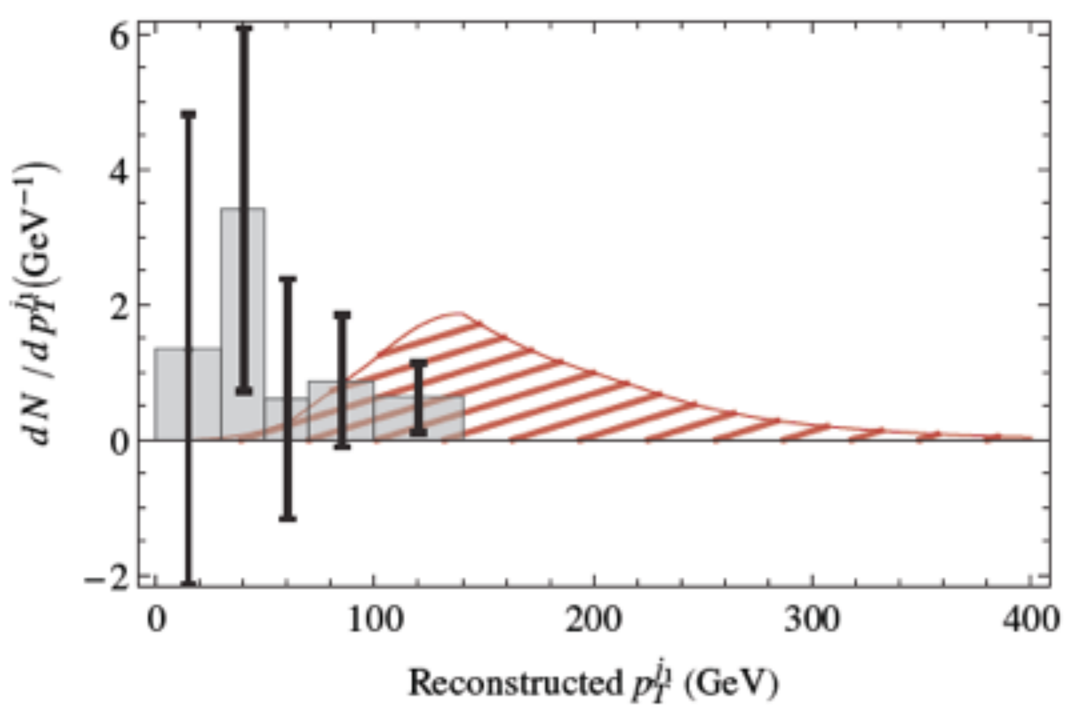
* LHC bounds comes mostly from $h \to \gamma\gamma$ ATLAS-CONF-2013-072

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

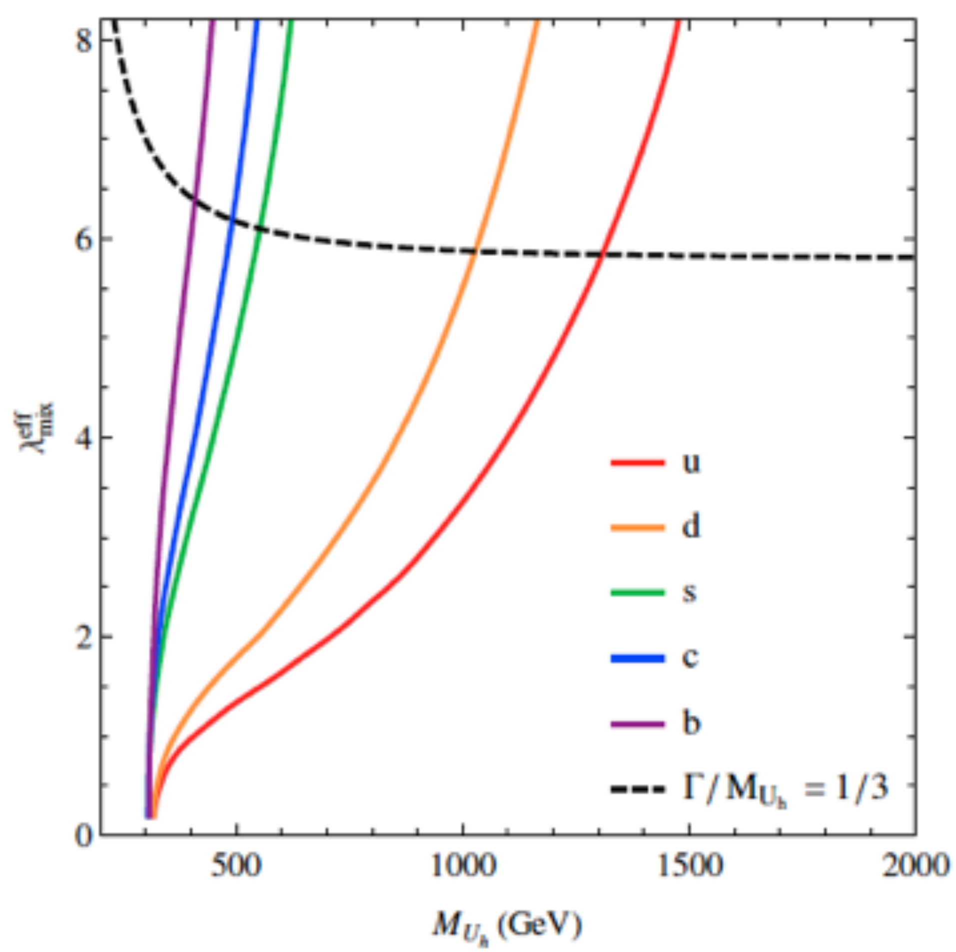
Flacke, Kim, SL, Lim `13

* LHC bounds comes from QCD pair production:

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

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

* LHC bounds for single production (partially composite):



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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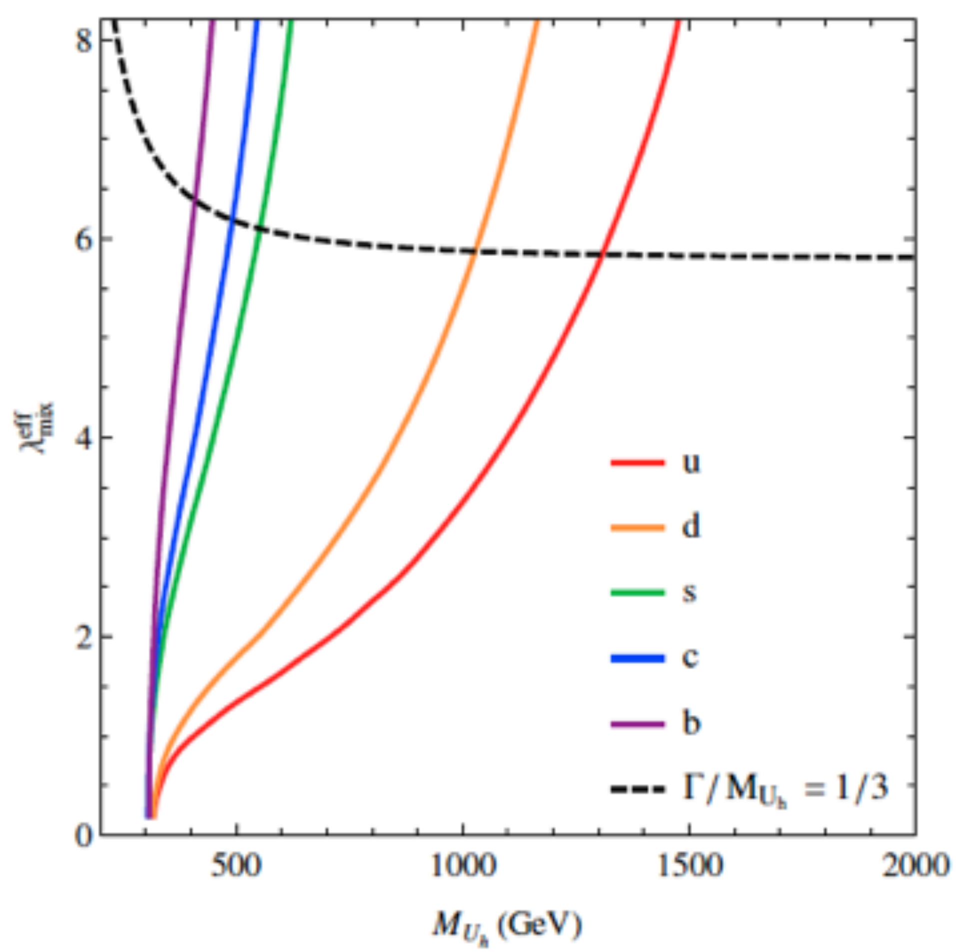

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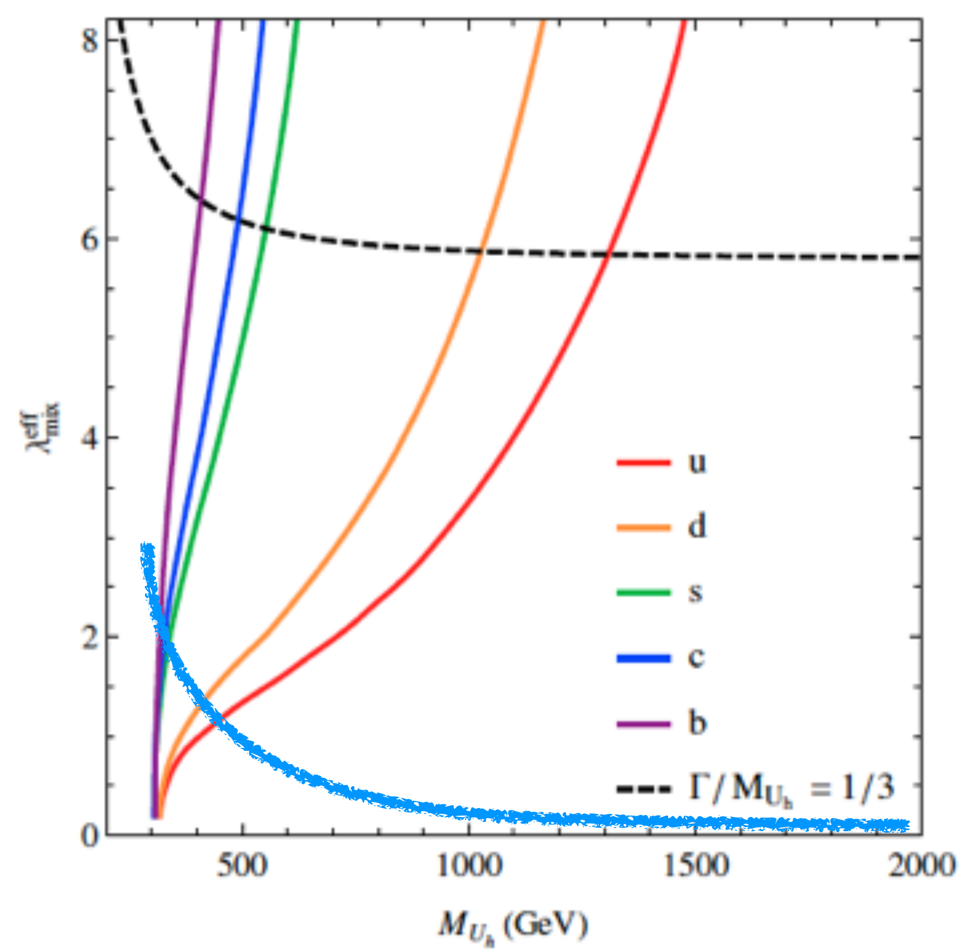
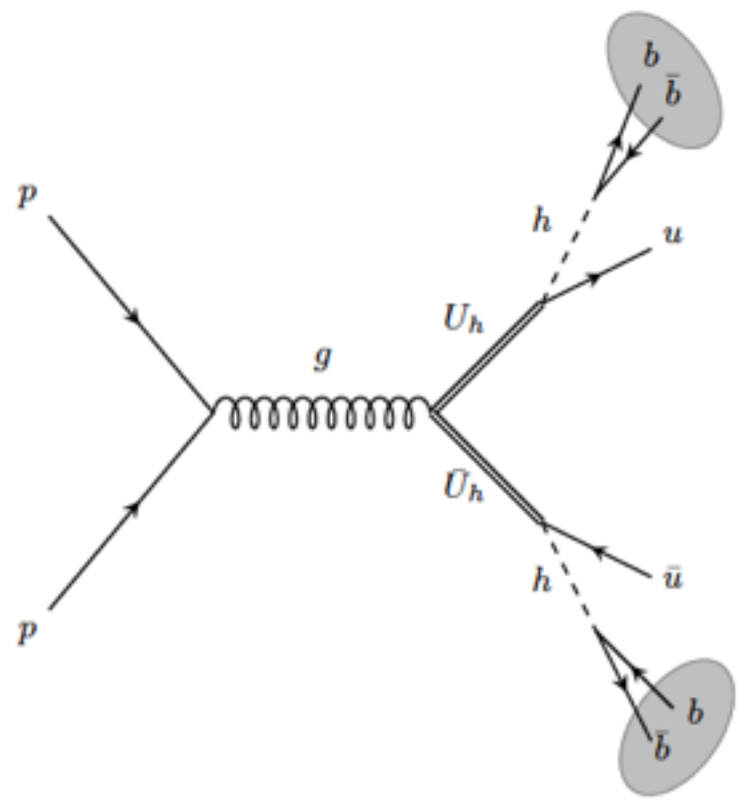


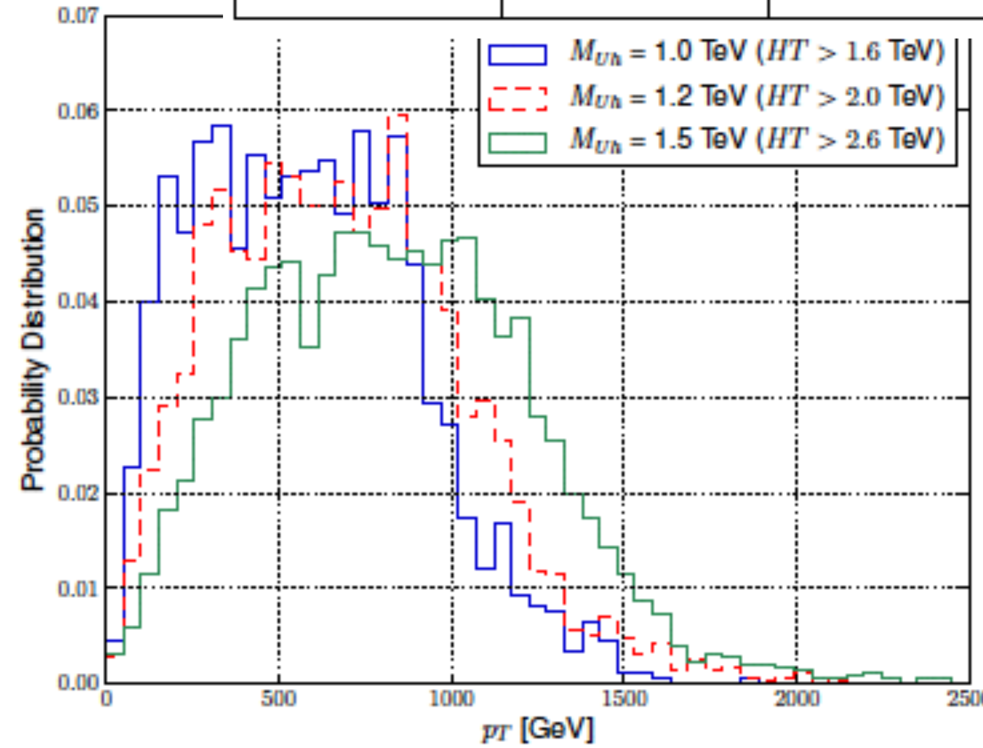
Performing a bin-by-bin χ^2 test on the BSM distributions, we obtain a bound on the composite quark parameter space.

Partners in Singlet: boosted analysis for run 2

Backovic, Flacke, Kim, SL `14



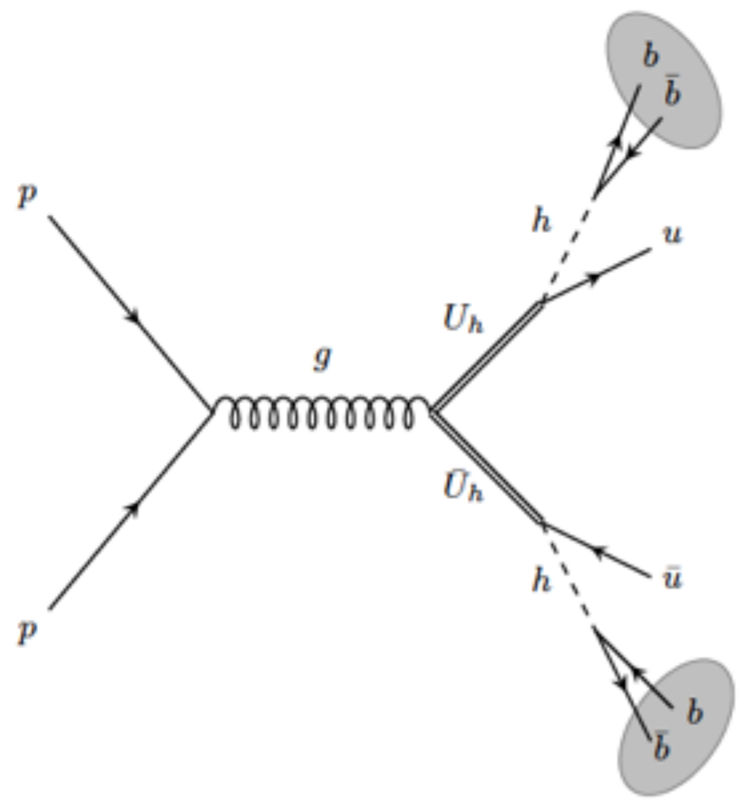
σ_s^{LO} [pb]	$\sigma_{t\bar{t}}^{NLO}$ [pb]	$\sigma_{b\bar{b}}^{NLO}$ [pb]	$\sigma_{\text{multi-jet}}^{NLO}$ [pb]
6.8×10^{-3}	4.6×10^{-1}	8.4	282.2



Preliminary

Partners in Singlet: boosted analysis for run 2

Backovic, Flacke, Kim, SL `14



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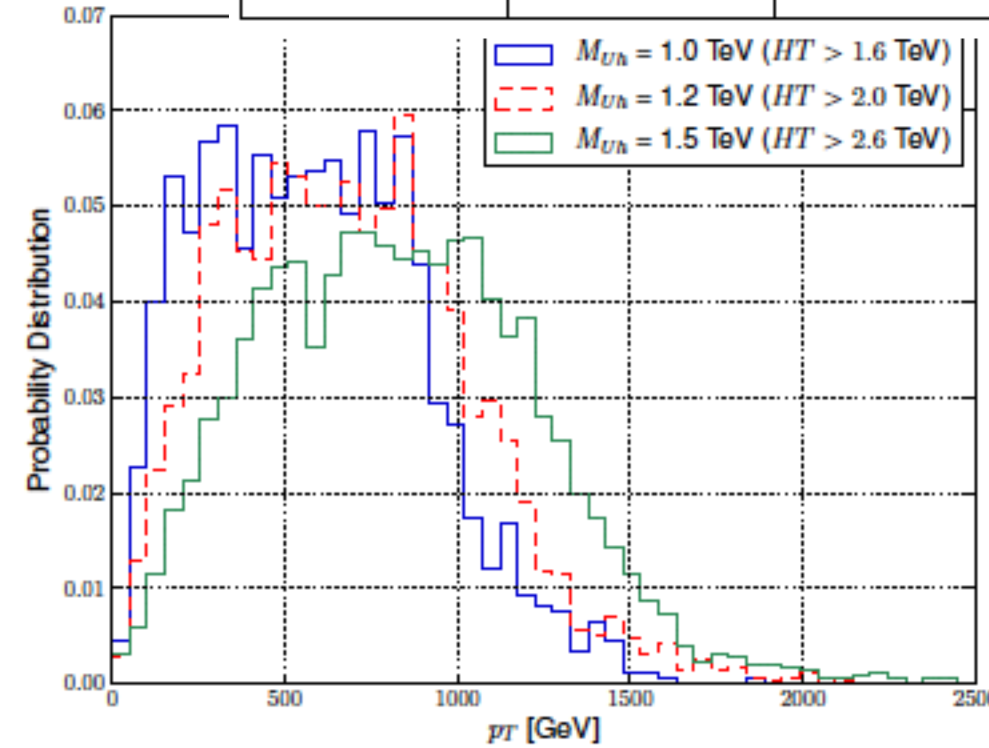
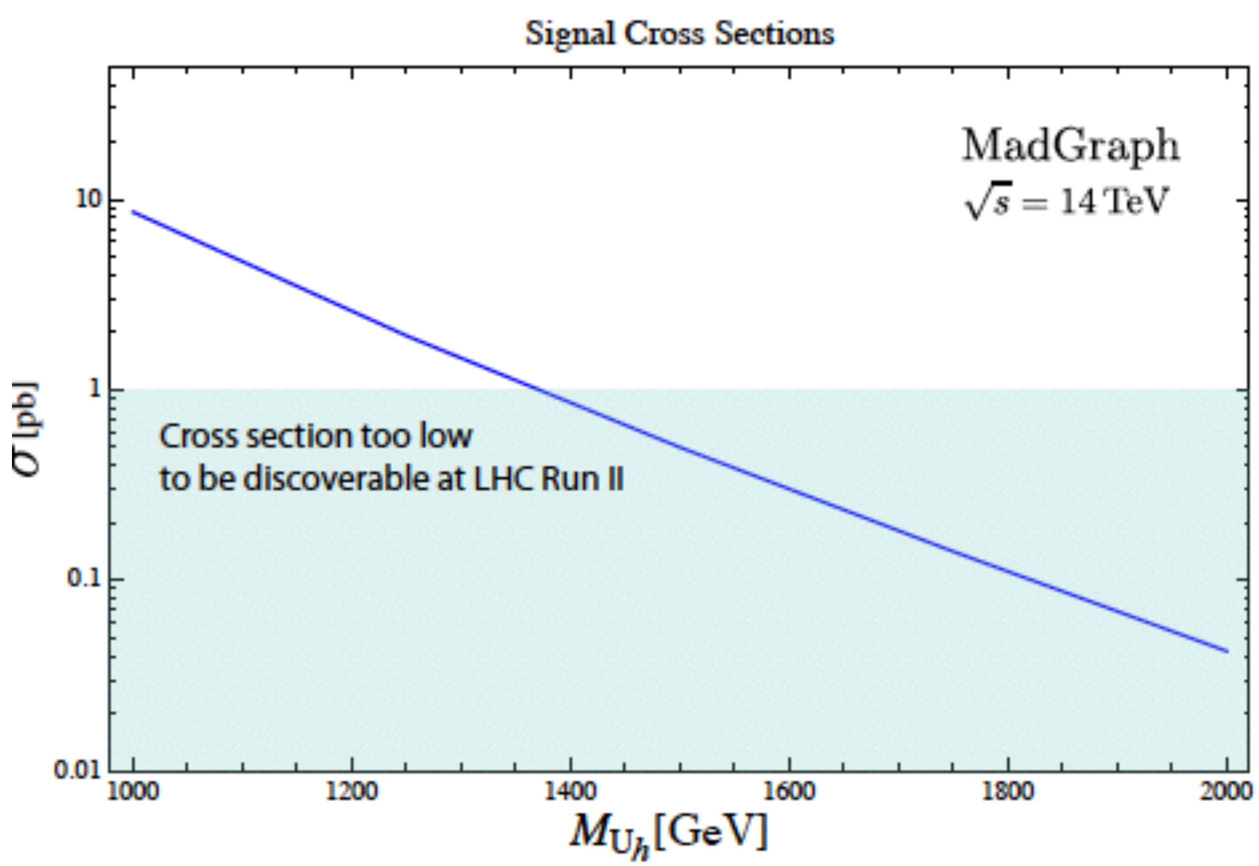
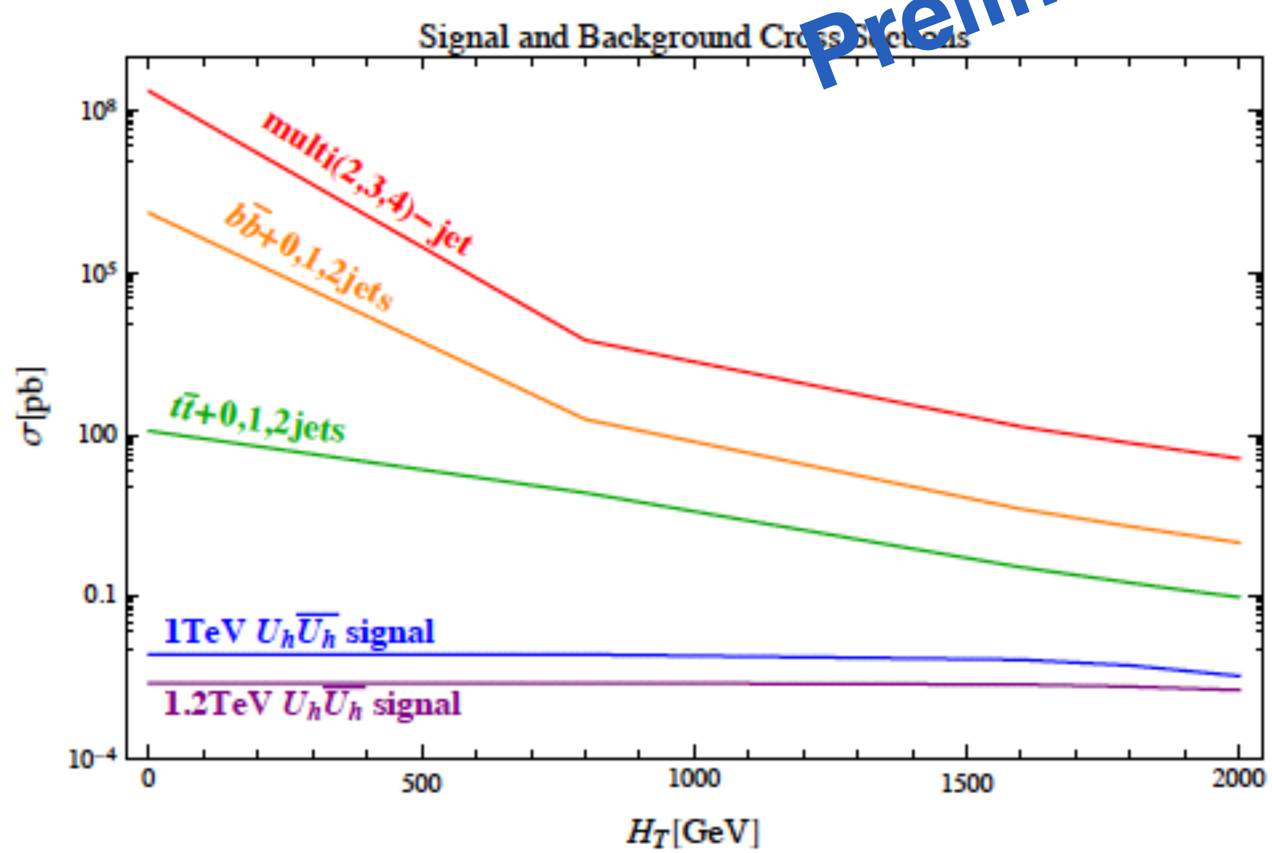


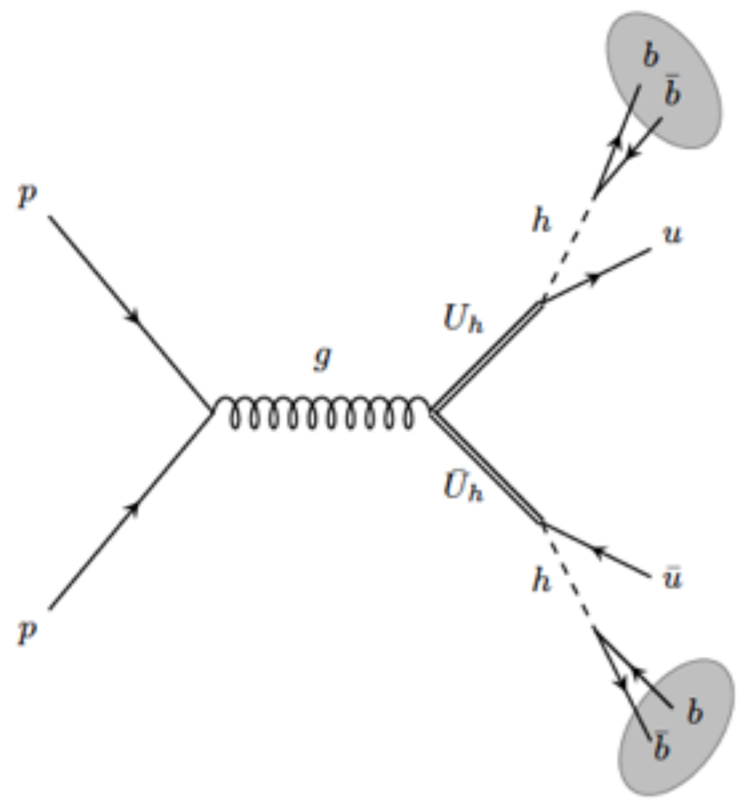


Preliminary



Partners in Singlet: boosted analysis for run 2

Backovic, Flacke, Kim, SL `14



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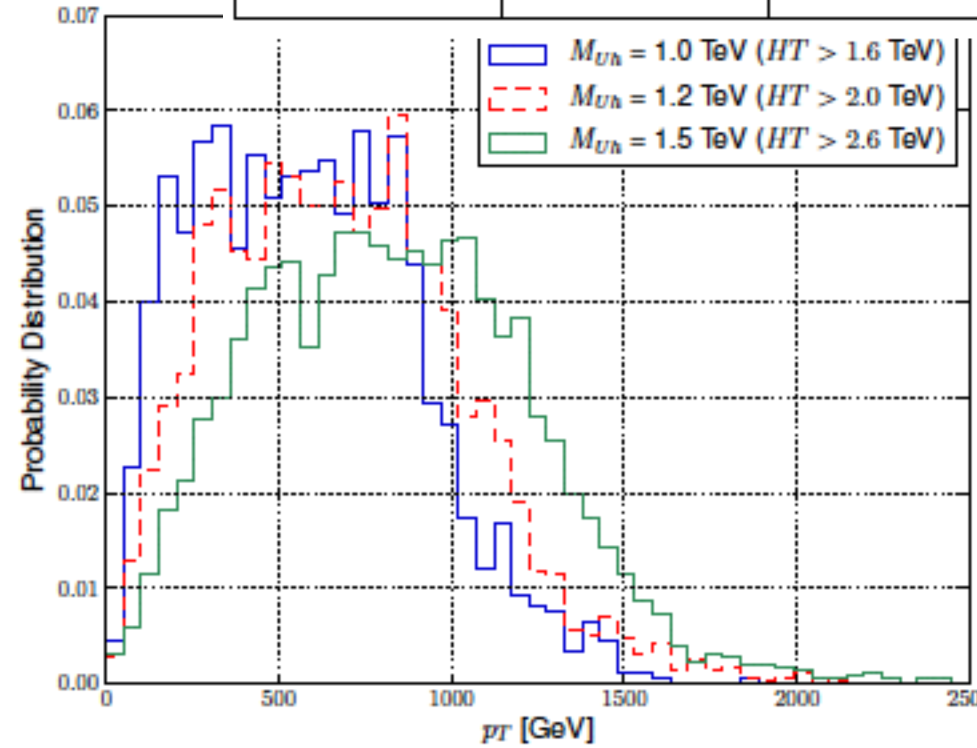


Table V: $m_{U_h} = \boxed{1.2\ \text{TeV}}$, $\sigma_s = 2.4$ fb , $\mathcal{L} = 35\ \text{fb}^{-1}$

Preliminary

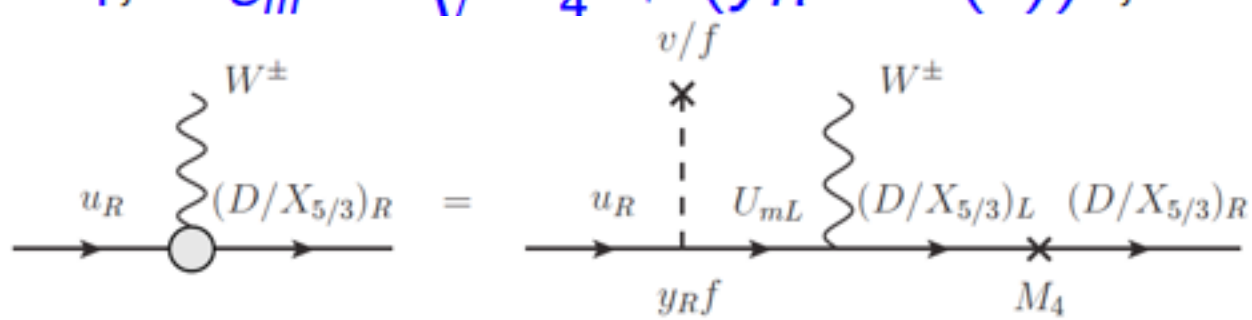
	σ_s [fb]	$\sigma_{t\bar{t}}$ [fb]	$\sigma_{b\bar{b}}$ [fb]	$\sigma_{\text{multi-jet}}$ [fb]	S/B	$S/\sqrt{B}$
Preselection Cuts	2.3713	463.053	8428	282200	8.15×10^{-6}	0.026
Basic Cuts	0.5601	4.6491	15.162	650.9413	0.0008	0.1279
$\lvert\Delta_{mh}\rvert < 0.1$	0.3472	1.6763	5.8322	259.8121	0.0013	0.1256
$\lvert\Delta_{mU}\rvert < 0.1$	0.2333	0.5376	1.8626	82.7787	0.0027	0.1496
$m_{U_{h1,2}} > 1000$ GeV	0.1897	0.1931	0.9102	42.5181	0.0043	0.1699
b-tag	0.1135	0.0284	0.0082	0.0116	2.3533	3.0578

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

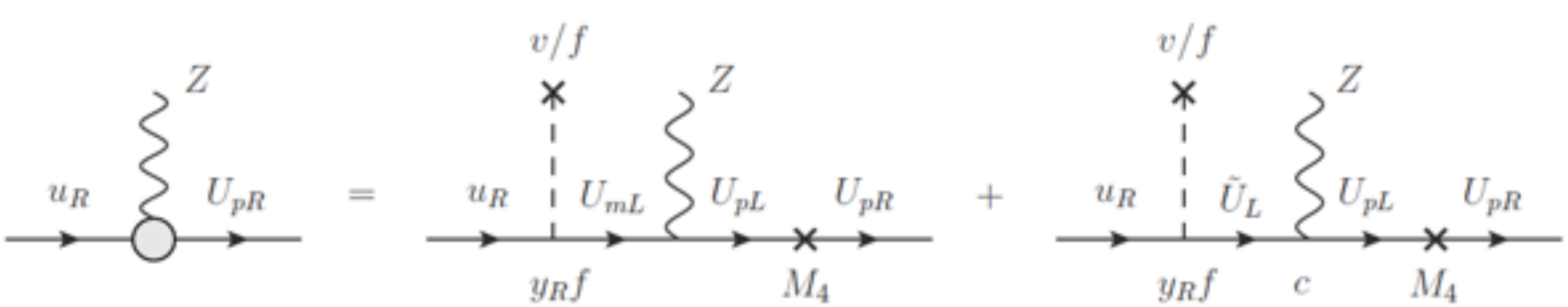
Delaunay, Fraille, Flacke, SL, Panico, Perez `13

- 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:
  $U_{p/m} = (1/\sqrt{2})\left(U \pm X_{2/3}\right)$, 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:



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

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

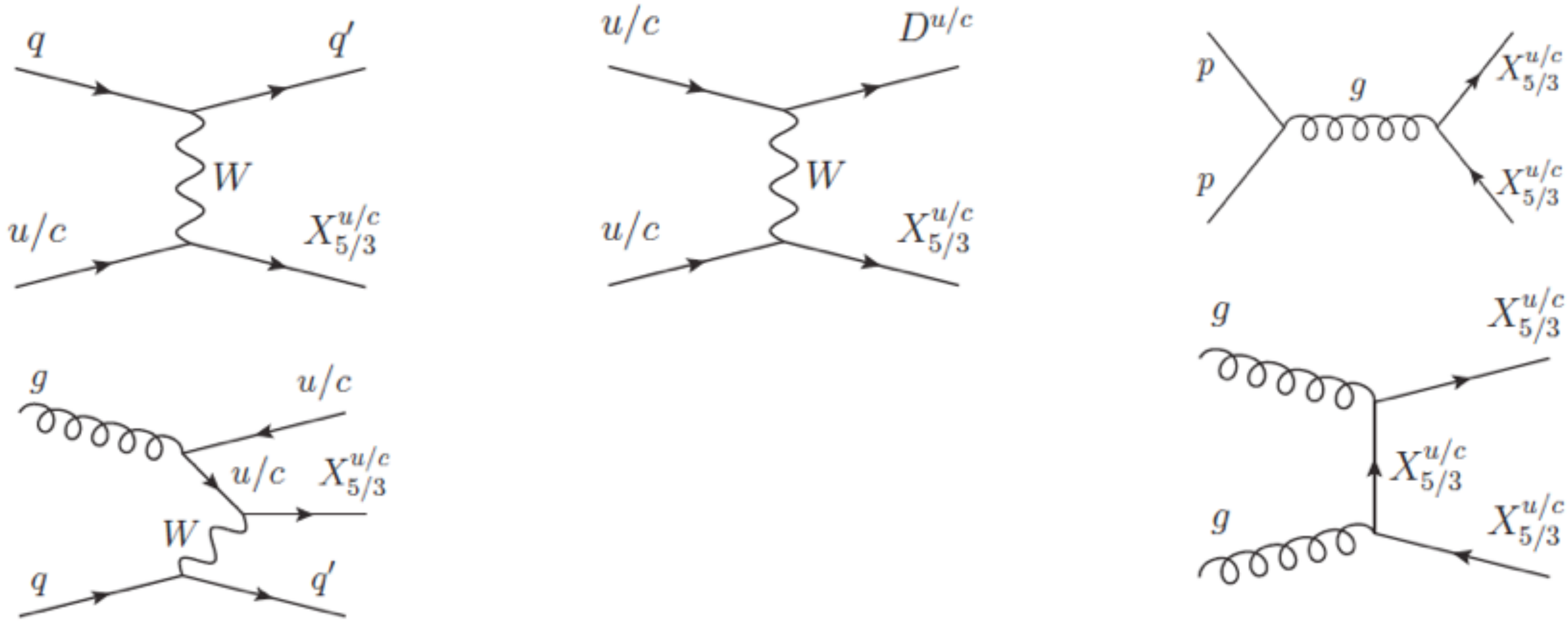


$$\tan\varphi_4 \equiv \frac{y_R f \sin\epsilon}{M_4}\,.$$

Partners in 4-plet

Delaunay, Fraille, Flacke, SL, Panico, Perez `13

- 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

Delaunay, Fraille, Flacke, SL, Panico, Perez `13

- 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 $\to$ jets.
  - 2nd generation partners: $c, s \to$ jets, potentially tagable c in the future
  - 3nd generation partners: $t, b \to$ well distinguishable from jets

We focus on 1st and 2nd family partners
$\to$ relevant measured final states:

- Single production: Wjj, Zjj

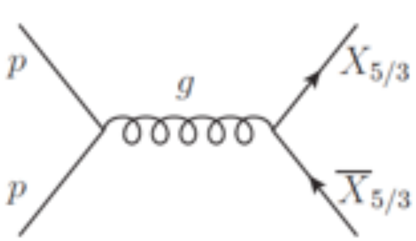
[D0 Collaboration], Phys. Rev. Lett. 106, 081801 (2011)
[CDF Collaboration], CDF/PUB/EXOTIC/PUBLIC/1026
[ATLAS Collaboration], ATLAS-CONF-2012-137 (4.64 fb^{-1} 7 TeV)
[CMS Collaboration],CMS-PAS-EXO-12-024 (19.8 fb^{-1} 8 TeV)

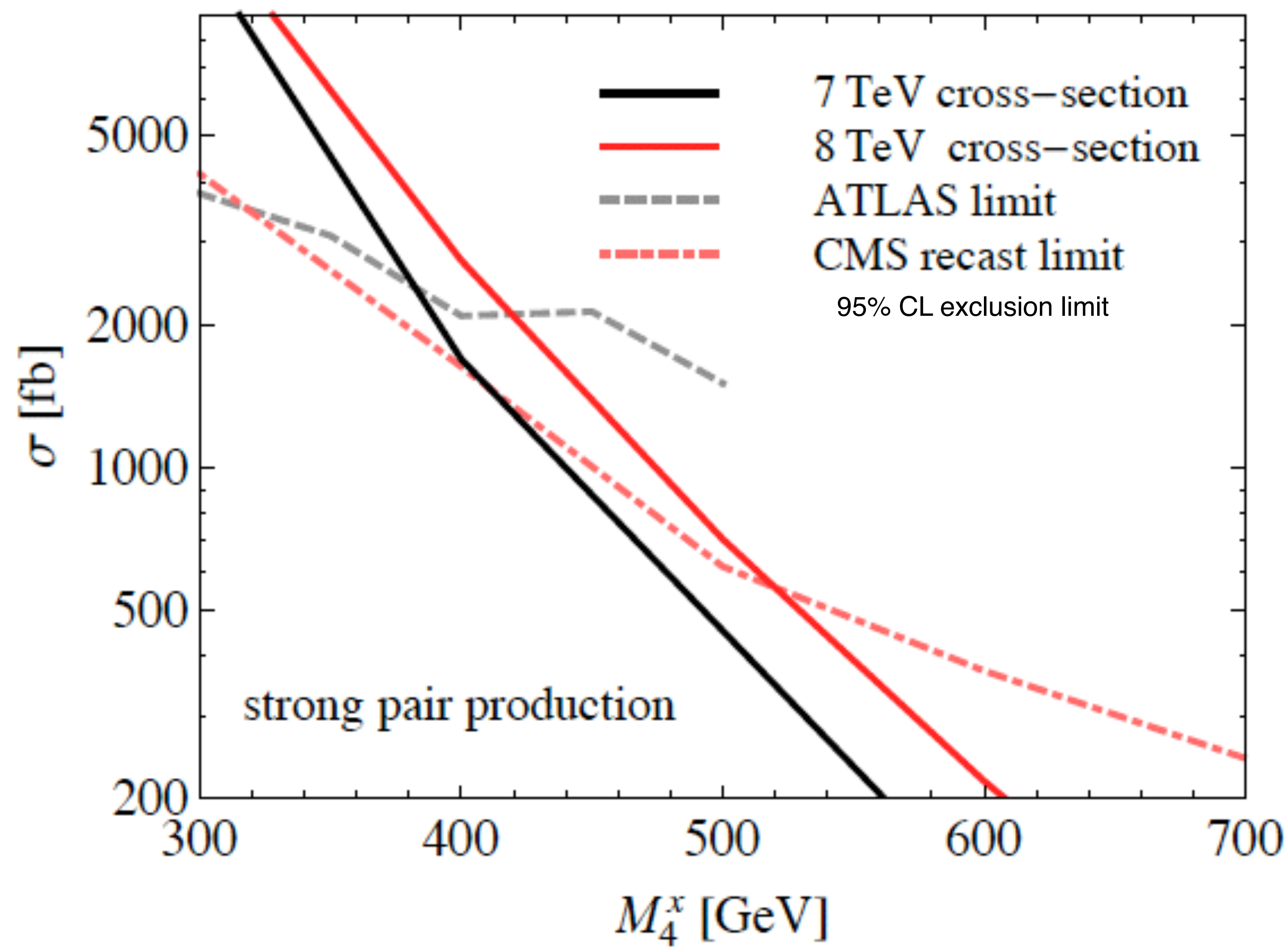
- Pair production: WWjj, ZZjj, hhjj

[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)

Bounds on u/c partner from Run 1, LHC

Delaunay, Fraille, Flacke, SL, Panico, Perez `13

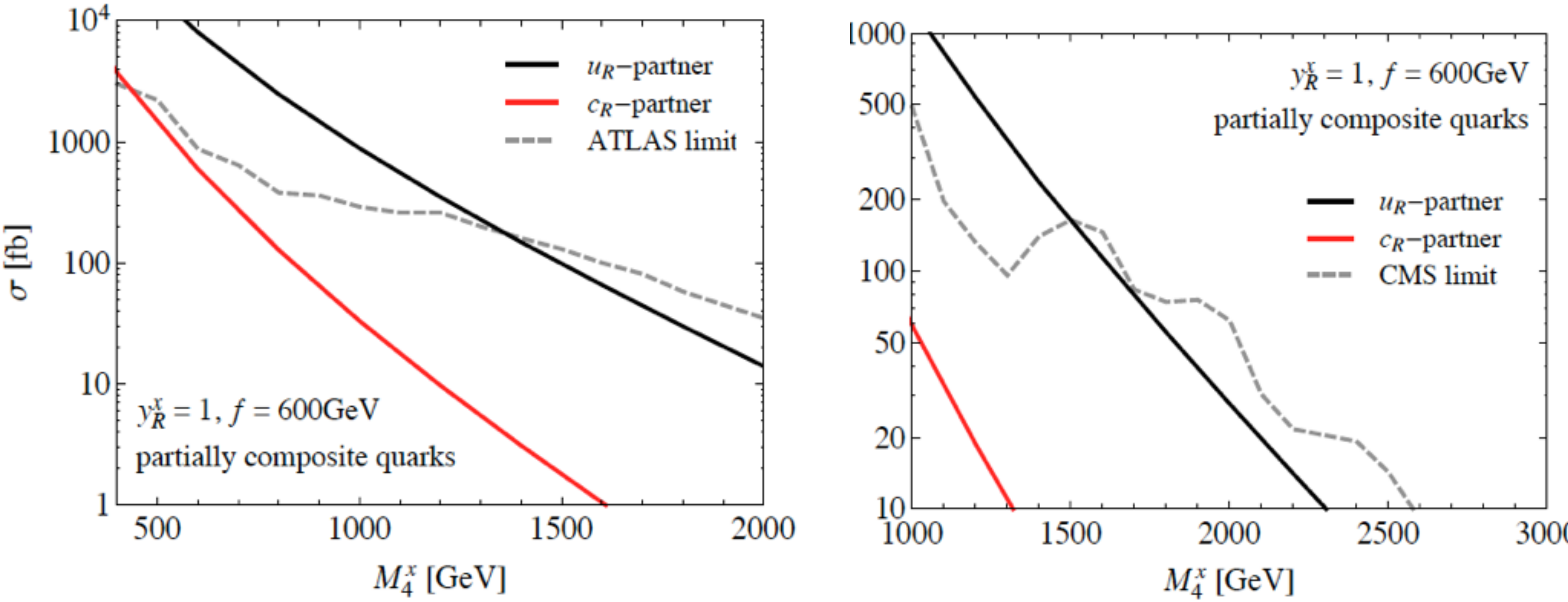


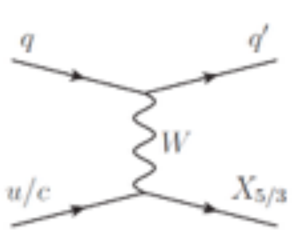


Model Independent predictions for WWjj cross sections through QCD pair production of –1/3 and 5/3 charge partners of the composite right-handed up and charm quarks. The solid black (red) line stands for the 7TeV (8TeV) cross section. They are the same for the first two generations and in both partially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

Bounds on u/c partner from Run 1, LHC

Delaunay, Fraille, Flacke, SL, Panico, Perez `13



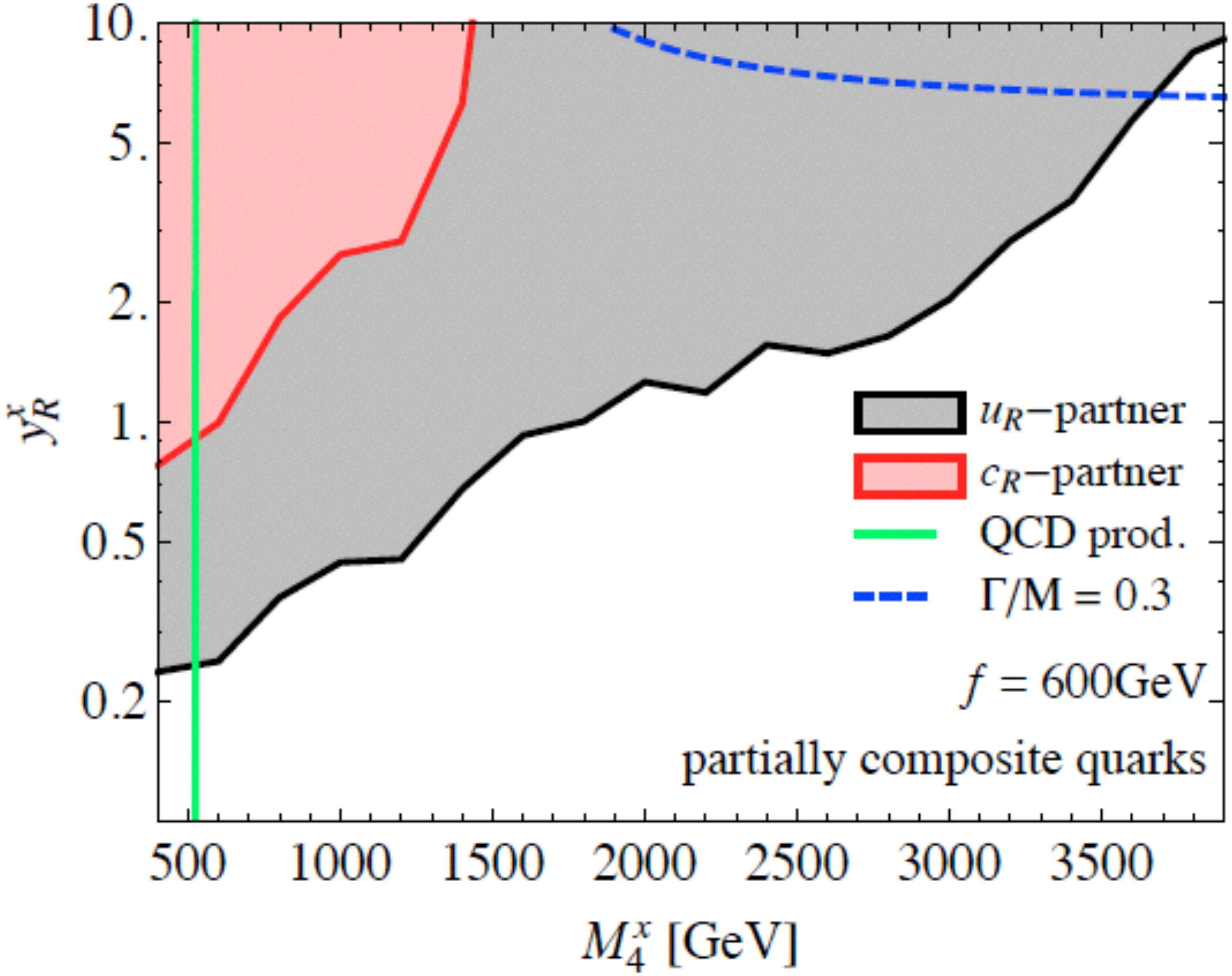


Predictions for Wjj cross sections of function of the fourplet partner mass M_4^x ,x = u, c, in the partially composite right-handed for two generation quarks. dashed curve is the 95% CL exclusion limit from the ATLAS and CMS searches at the 7TeV LHC run

Partners in 4-plet

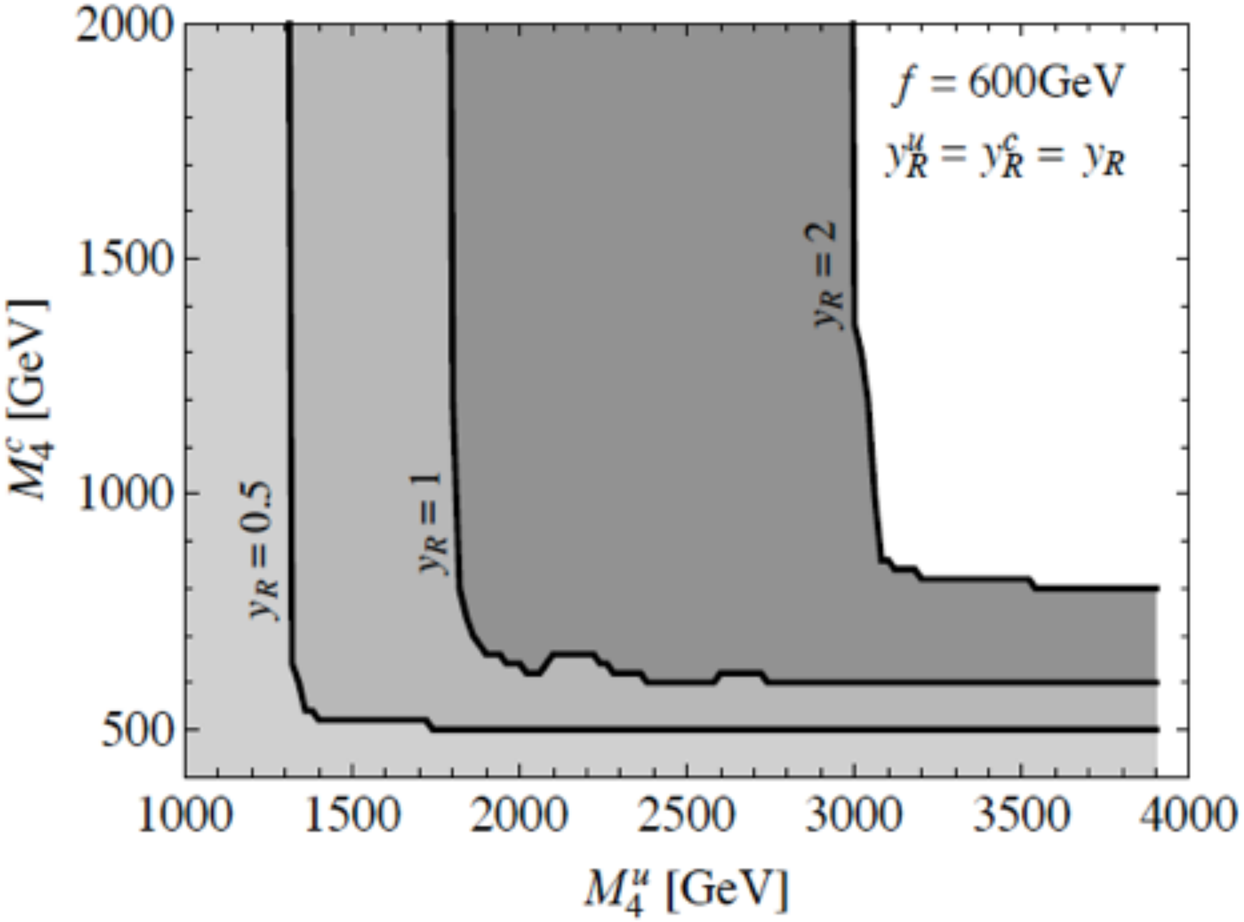
Delaunay, Fraille, Flacke, SL, Panico, Perez `13

95% CL exclusion limits



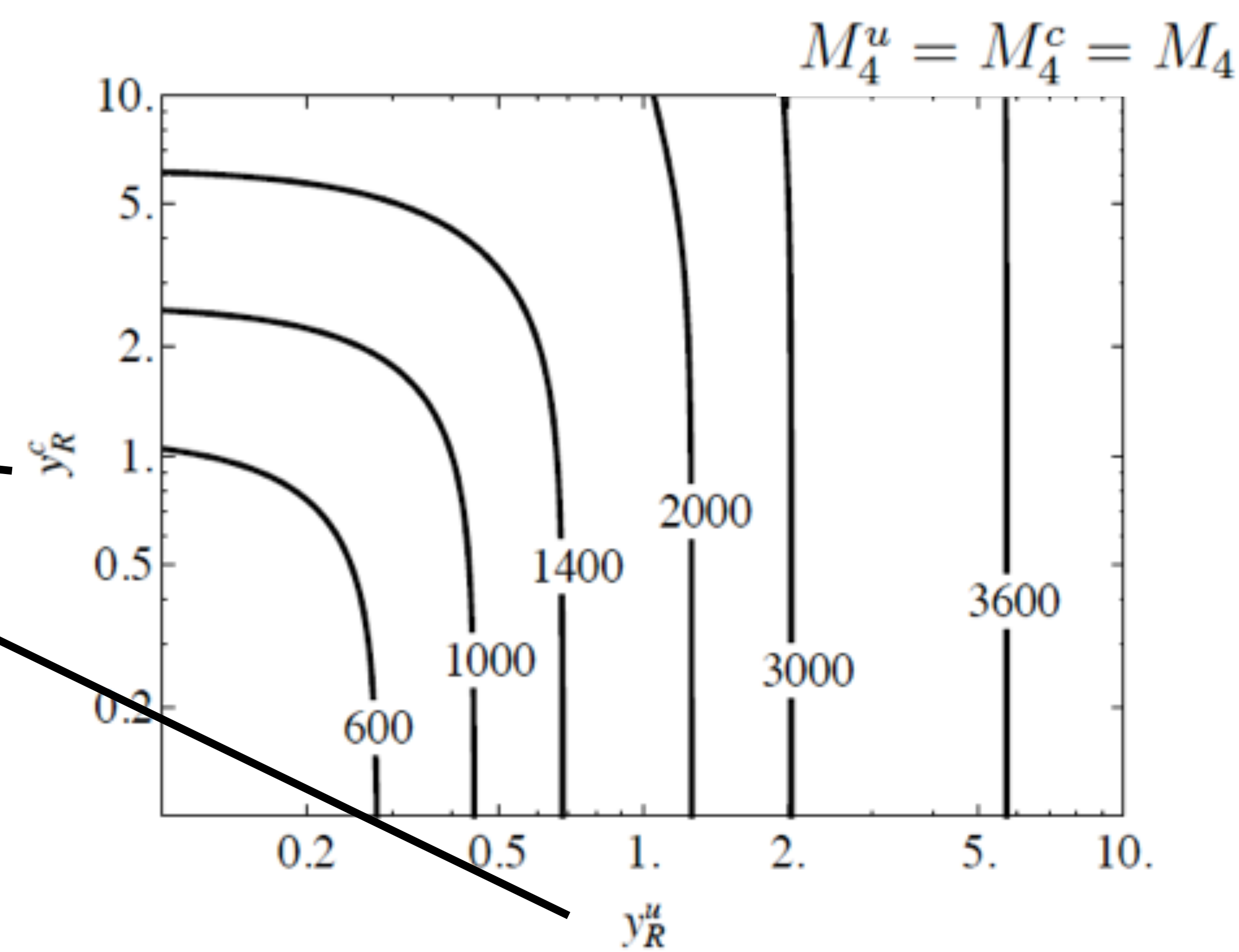
Collider implications for split 2 generations (similar to SUSY case)

Delaunay, Fraille, Flacke, SL, Panico, Perez `13

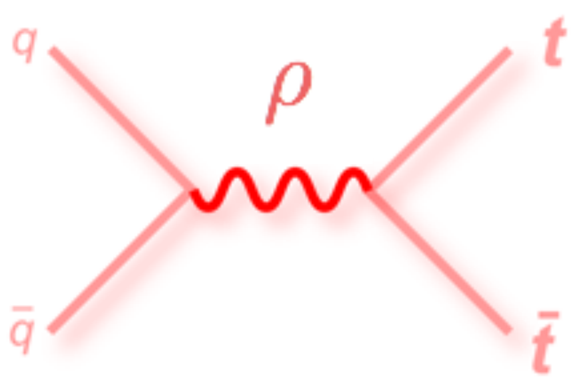


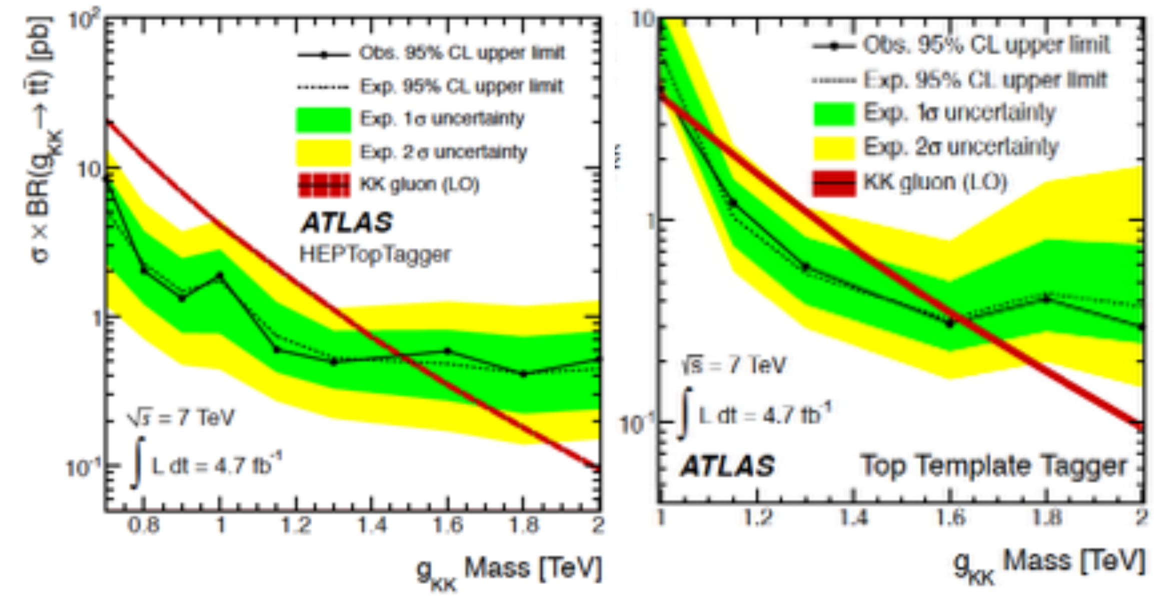
$$M_c \ll M_U$$

$$y_c \gg y_u$$

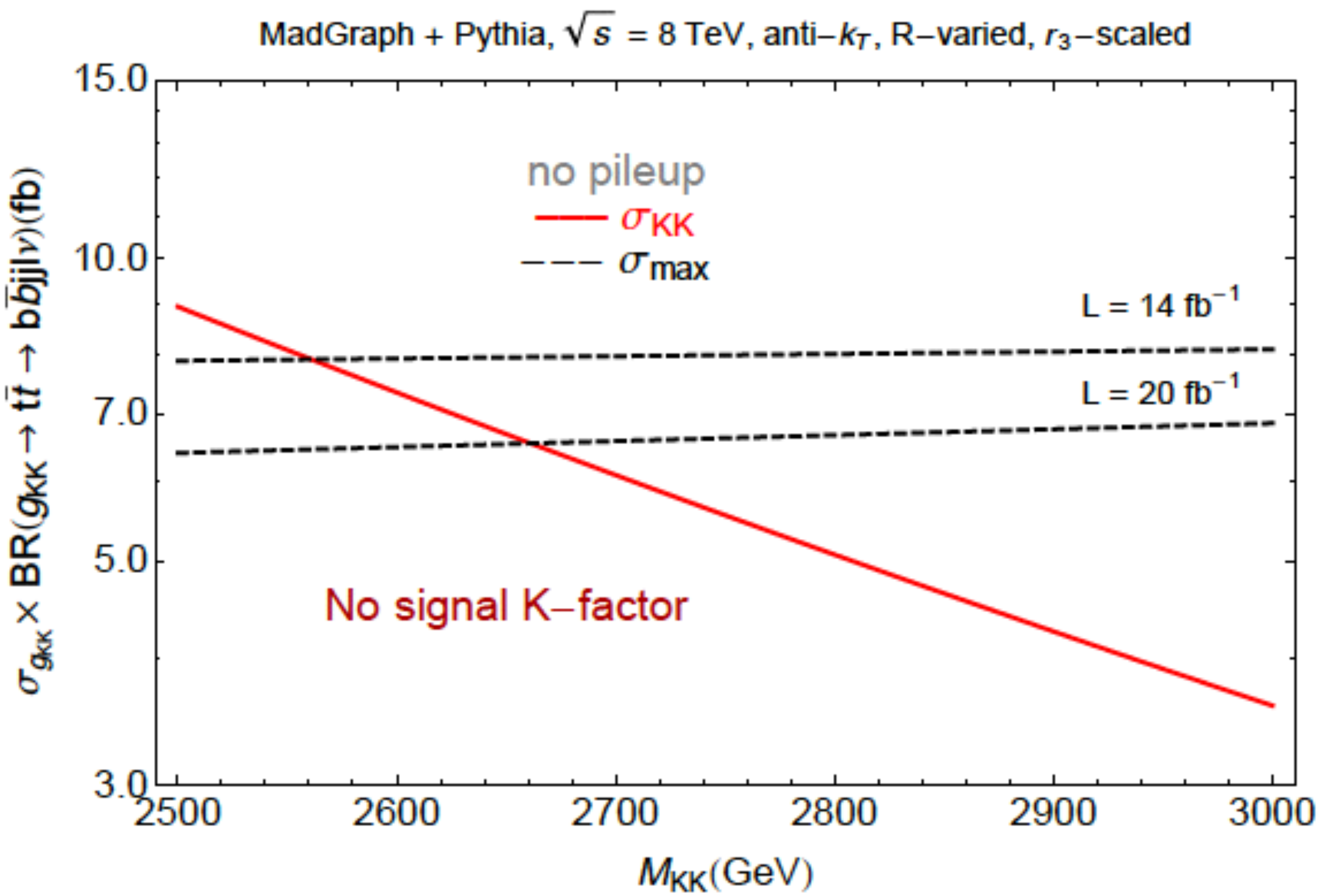


Vector resonances

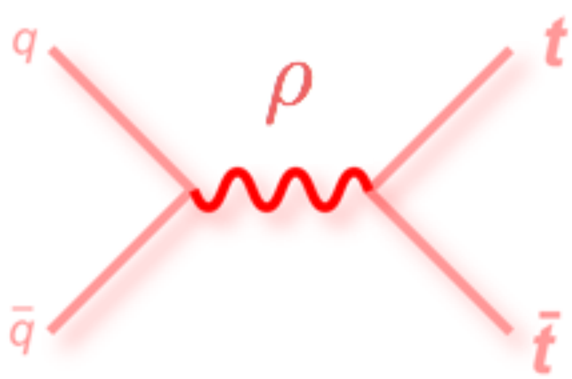


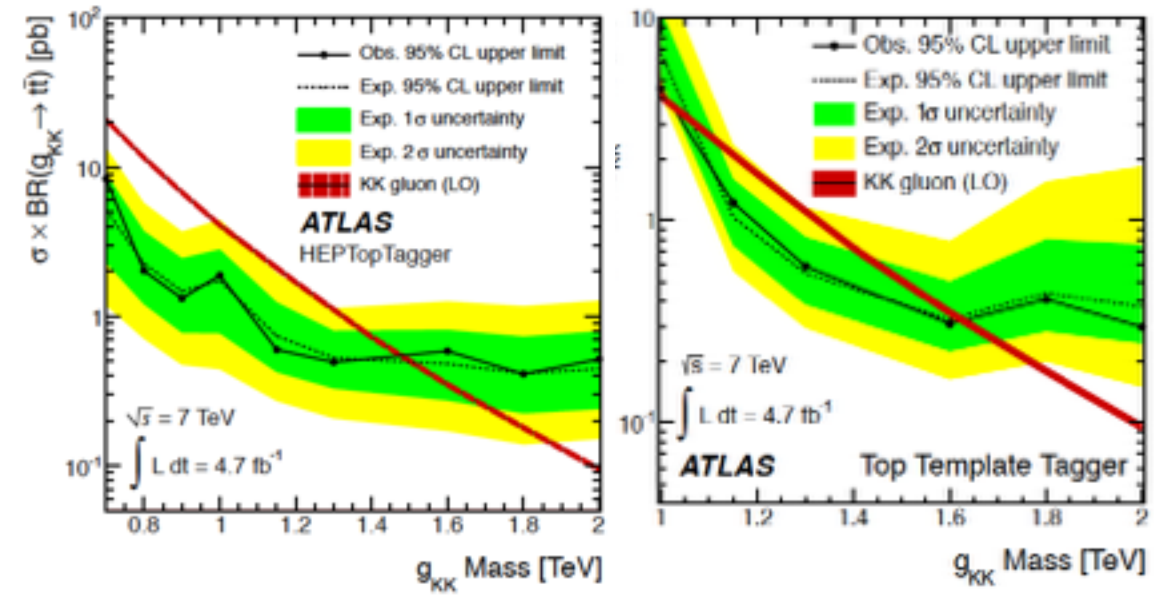


Backovic, Gabizon, Juknevic, Perez, Soreq `13



Vector resonances





Snowmass top quark working group report `13

Backovic, Gabizon, Juknevic, Perez, Soreq `13

Warped Extra Dimensional Benchmarks for Snowmass `13

Collider	Luminosity	Pileup	95 % exclusion for Z'	95 % exclusion for KK gluon
LHC 14 TeV	300 fb^{-1}	50	3.3 TeV	4.3 TeV
LHC 14 TeV	3 ab^{-1}	140	5.5 TeV	6.7 TeV

Table 1-18. *Expected mass sensitivity for a leptophobic Z' and KK gluon decaying into semileptonic $t\bar{t}$ [140].*

Collider	Luminosity	Pileup	3 σ evidence	5 σ discovery
LHC 14 TeV	300 fb^{-1}	50	3.8 TeV	3.2 TeV
LHC 14 TeV	3 ab^{-1}	50	4.4 TeV	3.5 TeV

Table 1-19. *Expected mass sensitivity for a KK gluon decaying into semileptonic $t\bar{t}$, based on a study for the Snowmass process using the template overlap method.*

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

- Top partner will be probed beyond the 2 TeV mass region at the Run 2 of LHC

- The phenomenology of composite light quarks differs from top partner phenomenology, and may hide 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 light => Flavorful Naturalness

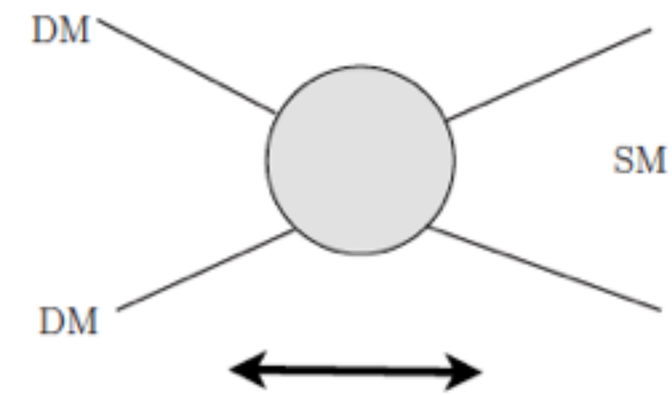
- Analysis for boosted Higgs /VB/top will be improved the reach at Run2

COMPOSITE WIMP DM THROUGH THE DILATON PORTAL

BLUM, CLICHE, CSAKI, SL
ARXIV:1410.1873V1

WIMP DARK MATTER

- Original idea of WIMP Miracle



Rate in thermal eq. $\langle \sigma v \rangle \sim \frac{g_{\mathrm{D}}^4}{m_{\mathrm{DM}}^2}$

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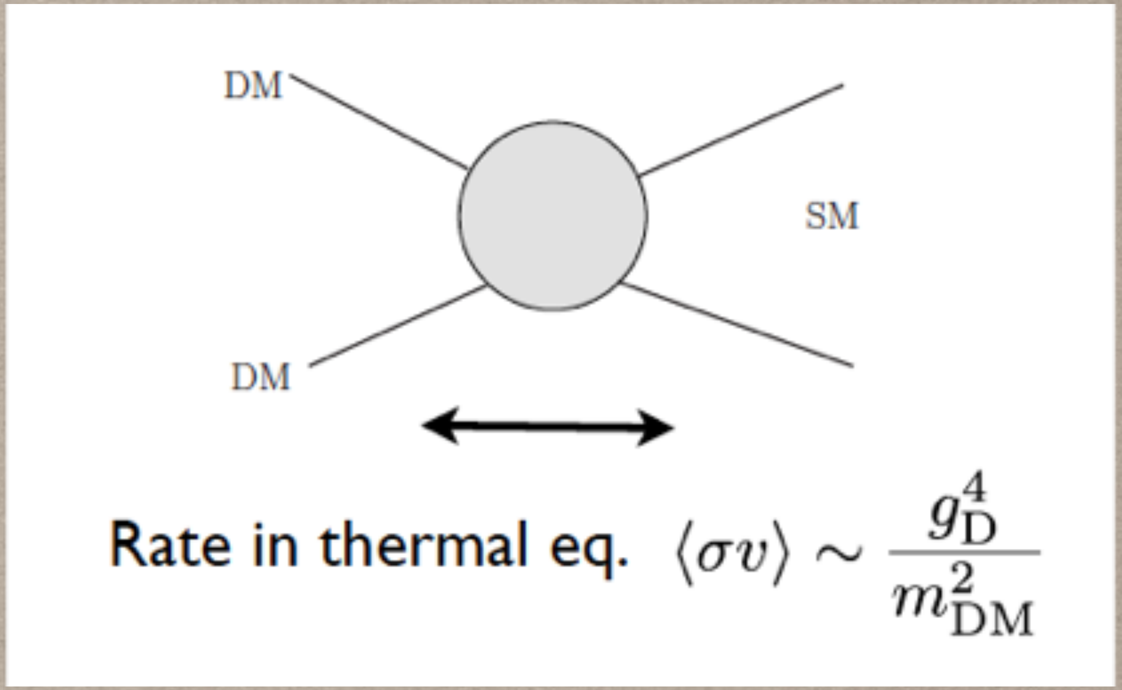
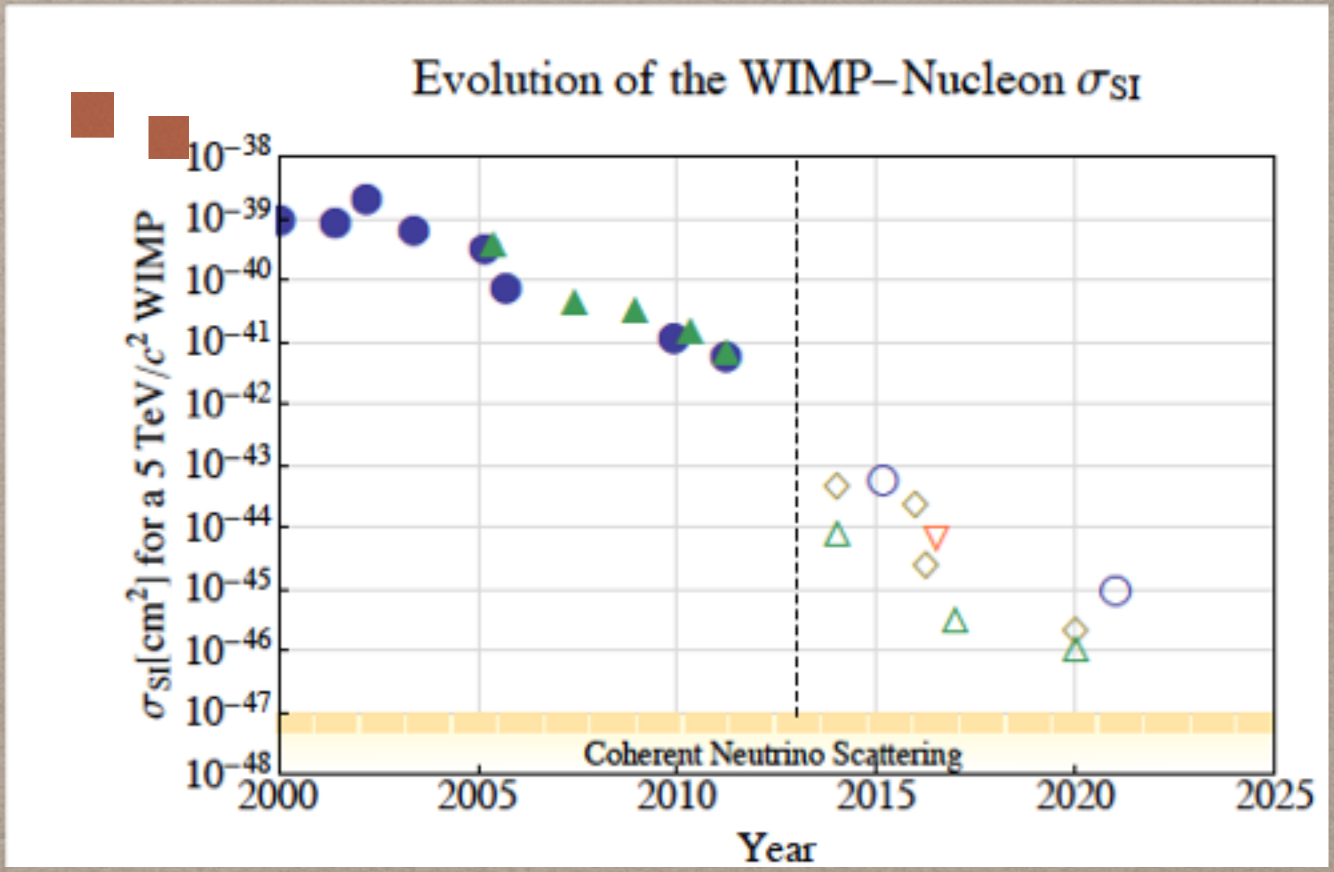
- => now pushed to a conner by the null results from DM direct detection experiments

Moore's Law works in DM!



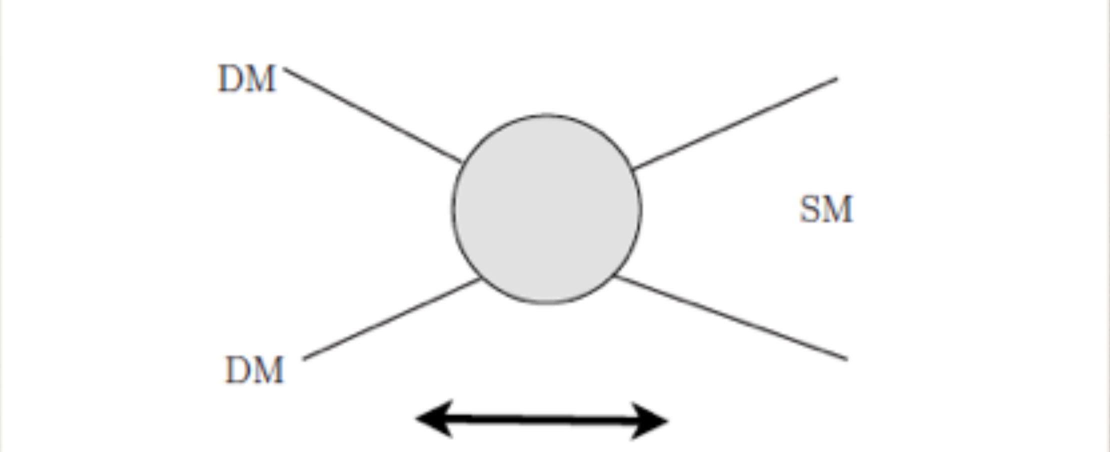


WIMP DARK MATTER

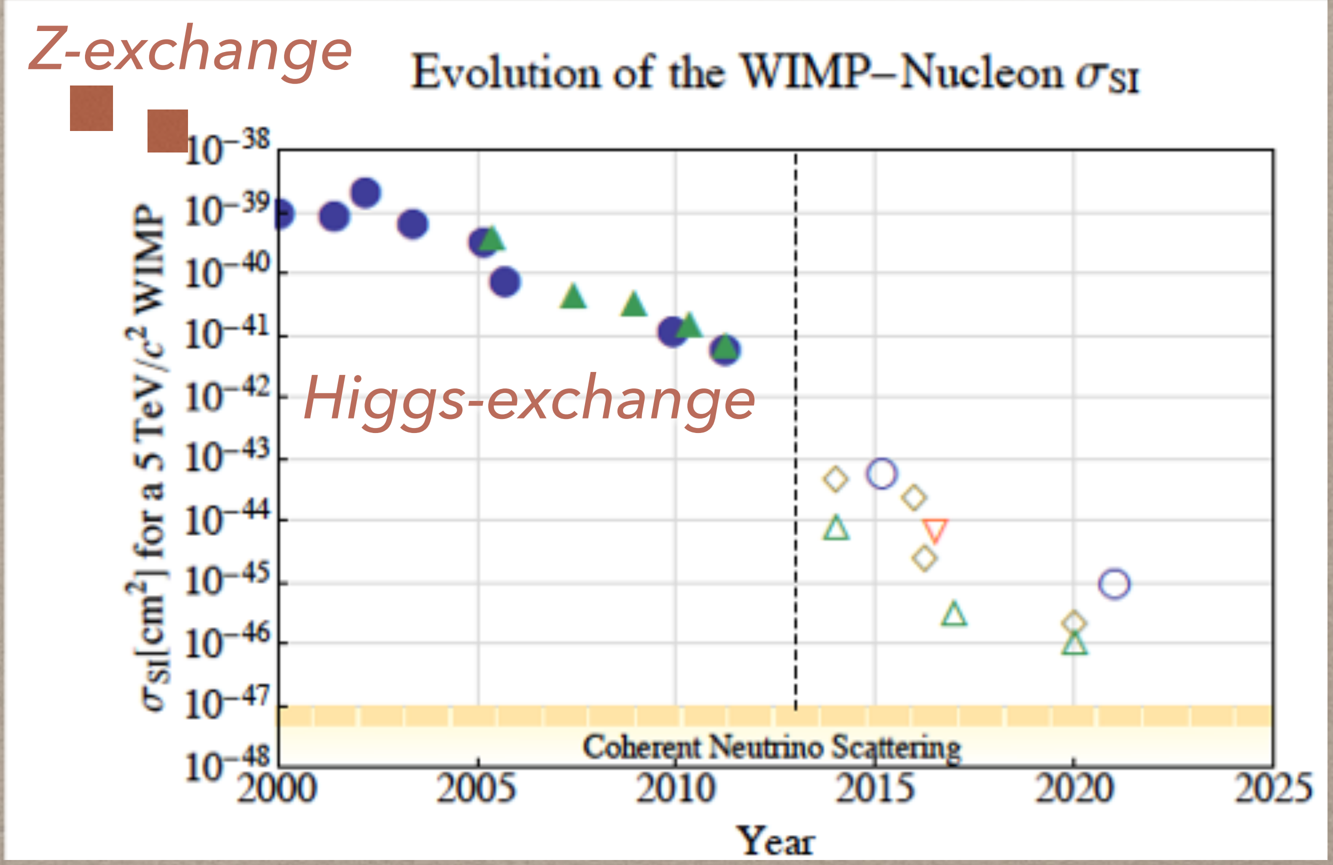
- Original idea of WIMP Miracle
- => now pushed to a conner by the null results from DM direct detection experiments

Moore's Law works in DM!

- Z boson exchange excluded except for fine-tuned corners of parameter space, and requiring tuning for Higgs mediation as well



Rate in thermal eq. $\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$



THE DILATON MEDIATED DARK MATTER MODEL

Bai, Careba, Lykken 09'

Agashe, Blum, S.L., Perez 09'

- Embedding the SM partially or completely in a composite sector can solve the hierarchy problem, by making the Higgs boson composite.

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- Often such a composite sector arises as the low-energy limit of an approximately scale invariant theory, where scale invariance is broken somewhere above the weak scale.

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- Embedding the SM partially or completely in a composite sector can solve the hierarchy problem, by making the Higgs boson composite.
- Often such a composite sector arises as the low-energy limit of an approximately scale invariant theory, where scale invariance is broken somewhere above the weak scale.
- If the breaking of scale invariance is spontaneous, then it is accompanied by a dilaton (corresponding GB) that couples to the fields in the composite sector through $\boxed{-\frac{\sigma}{f}\mathrm{Tr}T}$

THE DILATON MEDIATED DARK MATTER MODEL

- For massive particles, coupling to dilaton is proportional to ~M/f
    1. A very economic way to couple the SM to the dark sector (singlet under SM gauge symmetry)
    2. DM coupling to SM resembles Higgs portal, but with an extra suppression of order $(v/f)^2\ (m_h/m_\sigma)^4$
- In the minimal set-up, basically three parameters determine the dynamics of thermal freeze-out in the early universe: f, m_χ, m_σ (all three around 1-10 TeV)

THE DILATON MEDIATED DARK MATTER MODEL

- Effective theory describing an approximately scale invariant sector, with dilaton, σ (GB from SSB at scale f) parametrized by spurion:

$$\Phi(x) \equiv f e^{\sigma(x)/f}$$

$x \to xe^{\lambda}$ we have $\Phi(x) \to e^{\lambda}\Phi(e^{\lambda}x)$ and $\langle \Phi \rangle = f$

- After EWSB,

$1 + \gamma = c_L - c_R$

$$\begin{aligned}
\mathcal{L}_\sigma &= \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{5}{6}\frac{m_\sigma^2}{f}\sigma^3 - \frac{11}{24}\frac{m_\sigma^2}{f^2}\sigma^4 + \ldots - \left(\frac{\sigma}{f}\right)\left[\sum_\psi (1+\gamma_\psi) m_\psi \bar{\psi}\psi\right] + \\
&+ \left(\frac{2\sigma}{f} + \frac{\sigma^2}{f^2}\right)\left[m_W^2 W^{+\mu}W_\mu^- + \frac{1}{2}m_Z^2 Z^\mu Z_\mu - \frac{1}{2}m_h^2 h^2\right] + \frac{\alpha_{\rm EM}}{8\pi f}c_{\rm EM}\sigma F_{\mu\nu}F^{\mu\nu} + \\
&+ \frac{\alpha_s}{8\pi f}c_G \sigma G_{a\mu\nu}G^{a\mu\nu}.
\end{aligned}$$

Csaki, S.L., Hubisz 07',
Goldberg, Grinshtein, Skiba 08'
Bellazzini, Csaki, Hubisz, Sera, Terning 12'

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$$\Phi(x) \equiv f e^{\sigma(x)/f}$$

$$x \to x e^{\lambda} \text{ we have } \Phi(x) \to e^{\lambda}\Phi(e^{\lambda}x) \text{ and } \langle \Phi \rangle = f$$

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$$1 + \gamma = c_L - c_R$$

$$\begin{aligned}
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& + \left(\frac{2\sigma}{f} + \frac{\sigma^2}{f^2}\right)\left[m_W^2 W^{+\mu}W^-_\mu + \frac{1}{2}m_Z^2 Z^\mu Z_\mu - \frac{1}{2}m_h^2 h^2\right] + \frac{\alpha_{\rm EM}}{8\pi f}c_{\rm EM}\sigma F_{\mu\nu}F^{\mu\nu} + \\
& + \boxed{\frac{\alpha_s}{8\pi f}c_G \sigma G_{a\mu\nu}G^{a\mu\nu}}
\end{aligned}$$

Csaki, S.L., Hubisz 07',
Goldberg, Grinshtein, Skiba 08'
Bellazzini, Csaki, Hubisz, Sera, Terning 12'

BENCHMARK MODEL

$$+ \quad \frac{\alpha_s}{8\pi f} c_G \sigma G_{a\mu\nu} G^{a\mu\nu}$$

loop contribution + trace anomaly

$$c_G = b_{\rm IR}^{(3)} - b_{\rm UV}^{(3)} + \frac{1}{2} F_{1/2}(x_t)$$

Csaki, S.L., Hubisz 07'

BENCHMARK MODEL

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Csaki, S.L., Hubisz 07'

Model A: This is the well-studied case proposed in [5] where the entire SM is composite, corresponding to $b_{UV} = 0, b_{IR} = b_{SM}$, giving rise to the parameters $b^3_{UV} - b^3_{IR} = -7$, $b^{EM}_{UV} - b^{EM}_{IR} = 11/3$. Note that for a light dilaton these b's depend somewhat on the dilaton mass: for example $b^3_{UV} - b^3_{IR} = -11 + 2n/3$, with n denoting the number of quarks whose mass is smaller than $m_\sigma/2$.

BENCHMARK MODEL

$$+\ \frac{\alpha_s}{8\pi f} c_G \sigma G_{a\mu\nu} G^{a\mu\nu}$$

loop contribution + trace anomaly

$$c_G = b_{\rm IR}^{(3)} - b_{\rm UV}^{(3)} + \frac{1}{2} F_{1/2}(x_t)$$

Csaki, S.L., Hubisz 07'

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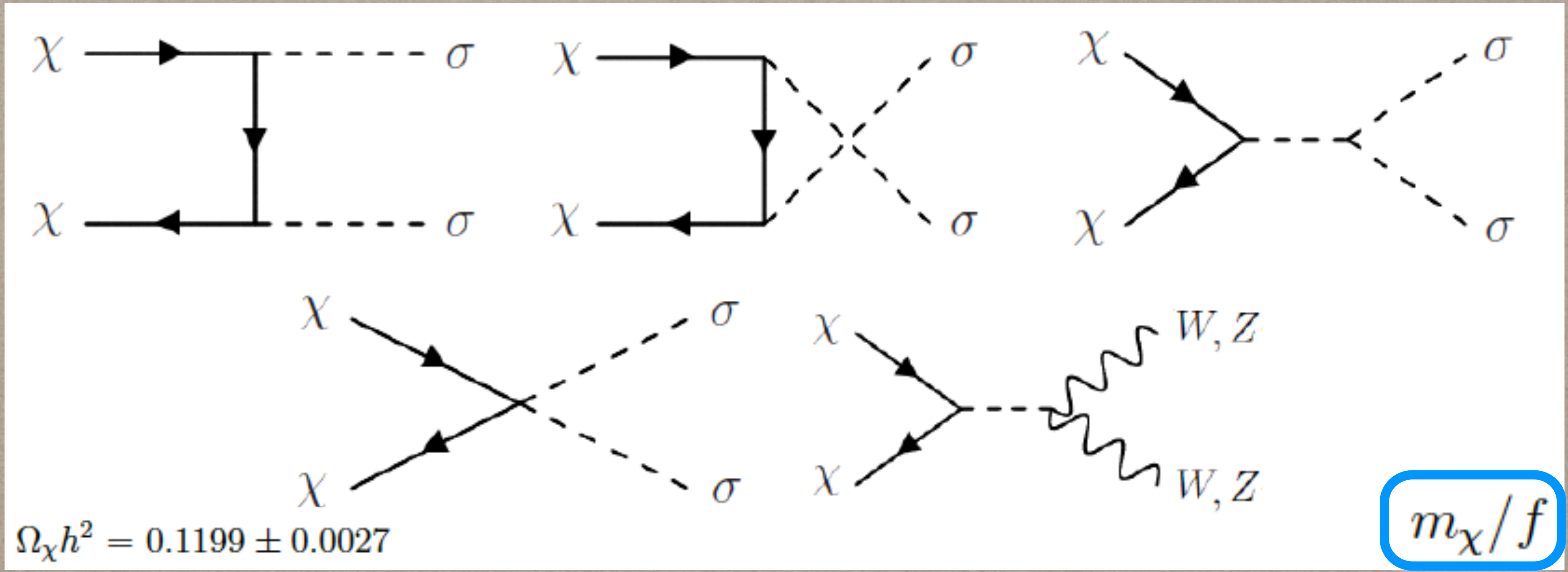
DM = a composite of the conformal sector

$$\mathcal{L}_{\rm DM} \supset \begin{cases} -\left(1 + \frac{2\sigma}{f} + \frac{\sigma^2}{f^2}\right) \frac{1}{2} m_\chi^2 \chi^2 & \text{Scalar} \\ -\left(1 + \frac{\sigma}{f}\right) m_\chi \bar{\chi}\chi & \text{Fermion} \\ \left(1 + \frac{2\sigma}{f} + \frac{\sigma^2}{f^2}\right) \frac{1}{2} m_\chi^2 \chi_\mu \chi^\mu & \text{Gauge boson.} \end{cases}$$

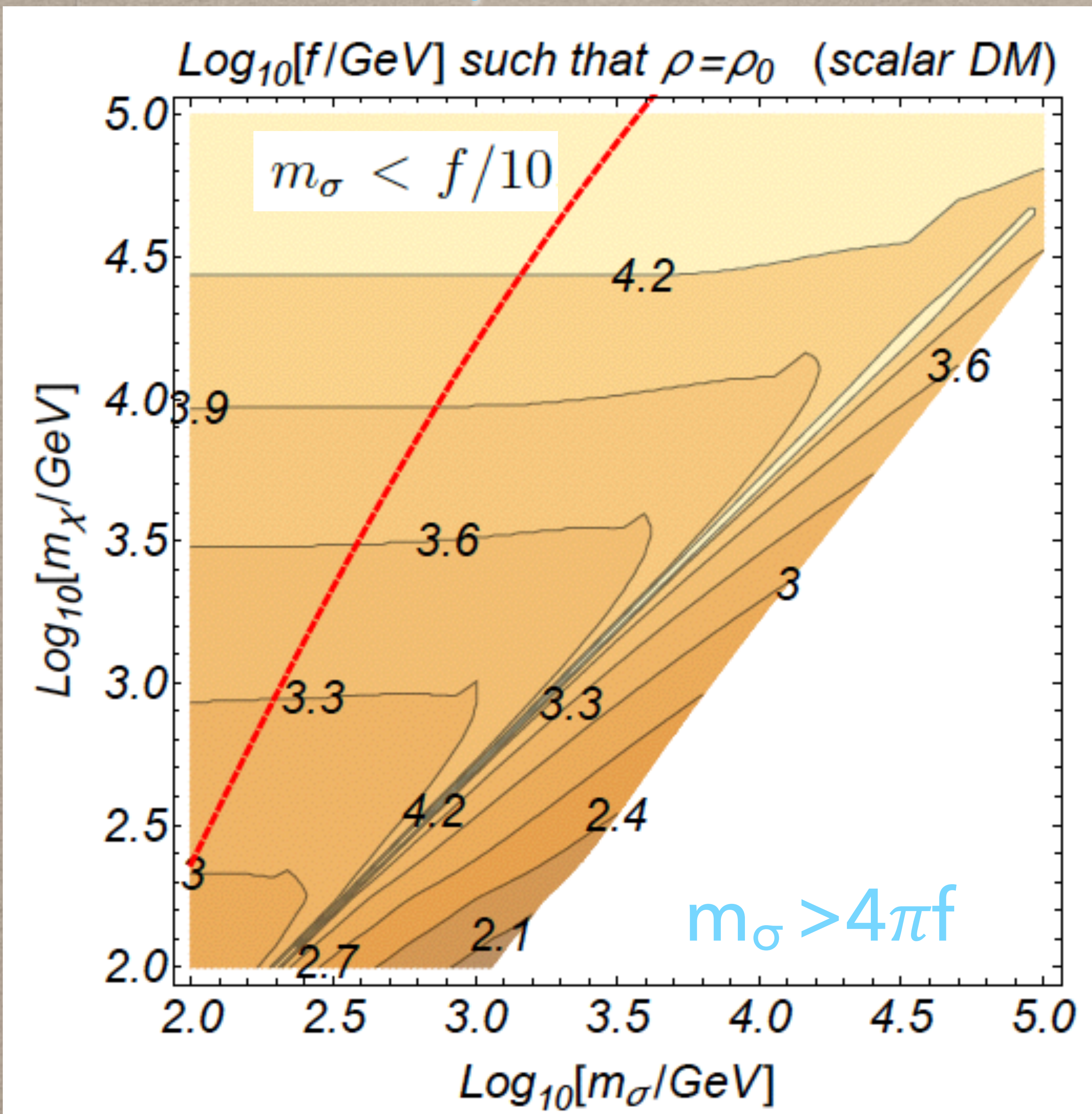
RELIC ABUNDANCE

- Annihilations into SM states are assumed to proceed via dilaton exchange.
- The dominant DM annihilation channel for $M_{DM} >> m_t$:



RELIC ABUNDANCE: EXAMPLE- SCALAR DM

- Assume: $f, m_\chi, m_\sigma \gg m_Z$ WW,ZZ and, if kinematically allowed, $\sigma\sigma$ dominates.



- $m_\chi > m_\sigma$ $\quad m_\chi = f^2/(6\text{TeV})$

$$\langle \sigma v \rangle \approx \frac{m_\chi^2}{4\pi f^4} \approx 3\times 10^{-26} \left(\frac{f}{6\ \text{TeV}}\right)^{-2} \left(\frac{m_\chi}{f}\right)^2$$

- $m_\chi << m_\sigma$

$$\langle \sigma v \rangle \sim \frac{3 m_\chi^6}{\pi f^4 m_\sigma^4} \approx 2{\cdot}10^{-26} \left(\frac{m_\chi}{350\ \text{GeV}}\right)^6 \left(\frac{\text{TeV}}{f}\right)^4 \left(\frac{\text{TeV}}{m_\sigma}\right)^4$$

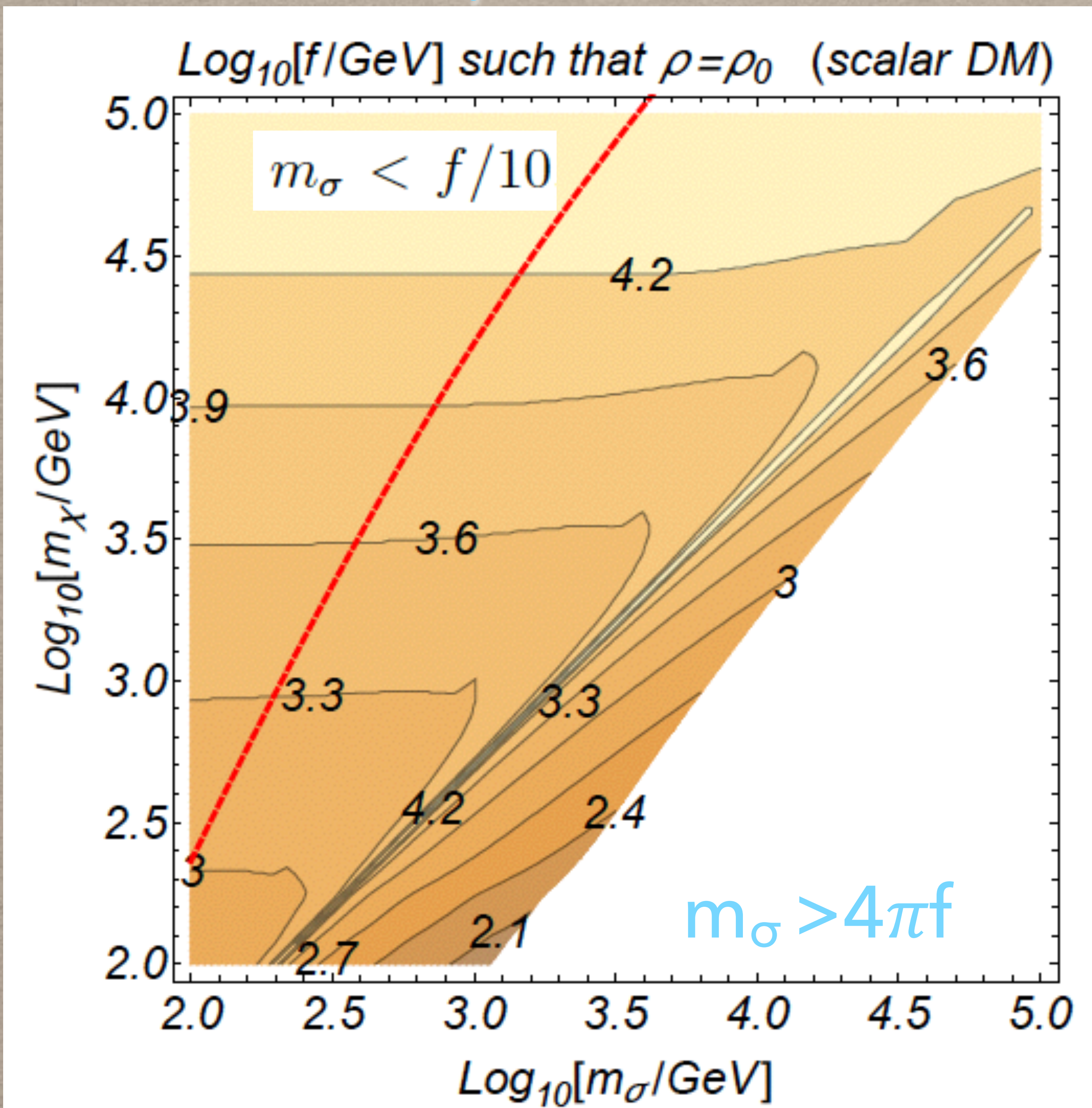
- $2m_\chi = m_\sigma$

$$\langle \sigma v \rangle \sim \frac{3 m_\chi^6}{\pi \left[(\Delta m)^4 f^4 + \frac{9 m_\chi^8}{4\pi^2}\right]},$$

$$\Delta m^2 = 4m_\chi^2 - m_\sigma^2$$

RELIC ABUNDANCE: EXAMPLE- SCALAR DM

- Assume: f, m_χ, $m_\sigma \gg m_Z$ WW,ZZ and, if kinematically allowed, $\sigma\sigma$ dominates.



- $m_\chi > m_\sigma$

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$$\langle \sigma v \rangle \approx \frac{m_\chi^2}{4\pi f^4} \approx 3\times 10^{-26}\left(\frac{f}{6\ \text{TeV}}\right)^{-2}\left(\frac{m_\chi}{f}\right)^2$$

Assuming no DM co-annihilation with extra particles in dark sector, unitarity bound combined with relic abundance gives:

$$f < 30\ \text{TeV}$$

$$m_\chi \lesssim 100\ \text{TeV}$$

DIRECT DETECTION

- Relevant dilaton effective Lagrangian:

$$\mathcal{L} \supset -\sum_q \frac{\sigma}{f}(1+\gamma_q) m_q q\bar{q} + \frac{\alpha_s}{8\pi f} c_G G^2$$

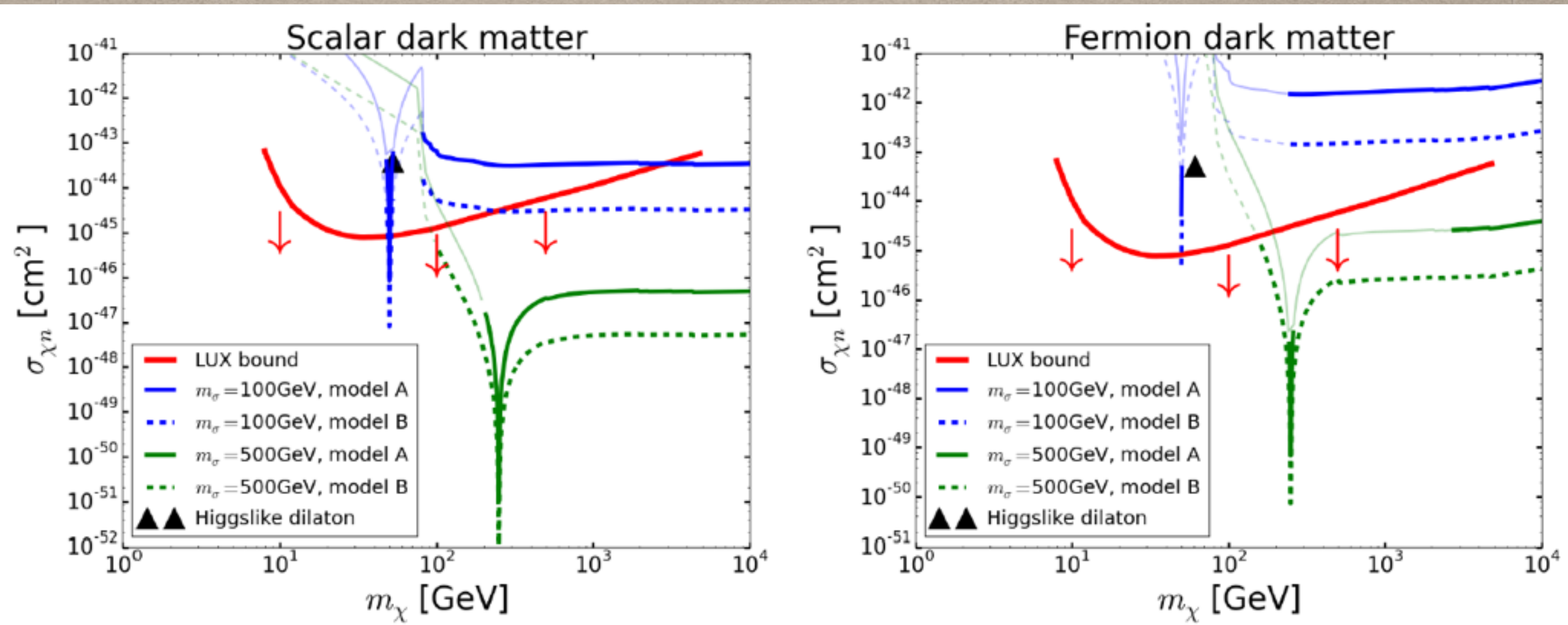
$$\mathcal{L}_{\sigma nn} \;=\; y_n \sigma n \bar{n}$$

$$y_n \equiv -\sum_q f_q^n \frac{m_n}{f} + R^n \frac{c_G}{8\pi f}$$

$$\begin{aligned}
f_q^n &= \langle n|\bar{q}q|n\rangle \frac{m_q}{m_n} \\
f_u^n &\simeq f_d^n \simeq 0.022 \\
f_s^n &\simeq 0.043 \\
f_c^n &\simeq 0.0814 \\
f_b^n &\simeq 0.0785 \\
f_t^n &\simeq 0.0820 \\
R^n &= \alpha_s \langle n|G^a_{\mu\nu} G^{a\mu\nu}|n\rangle \simeq -2.4\mathrm{GeV}
\end{aligned}$$

$$\boxed{\sigma_{\chi,n} \;\approx\; \frac{y_n^2}{\pi}\left(\frac{m_\chi}{f}\right)^2 \frac{m_n^2}{m_\sigma^4}}$$

DIRECT DETECTION



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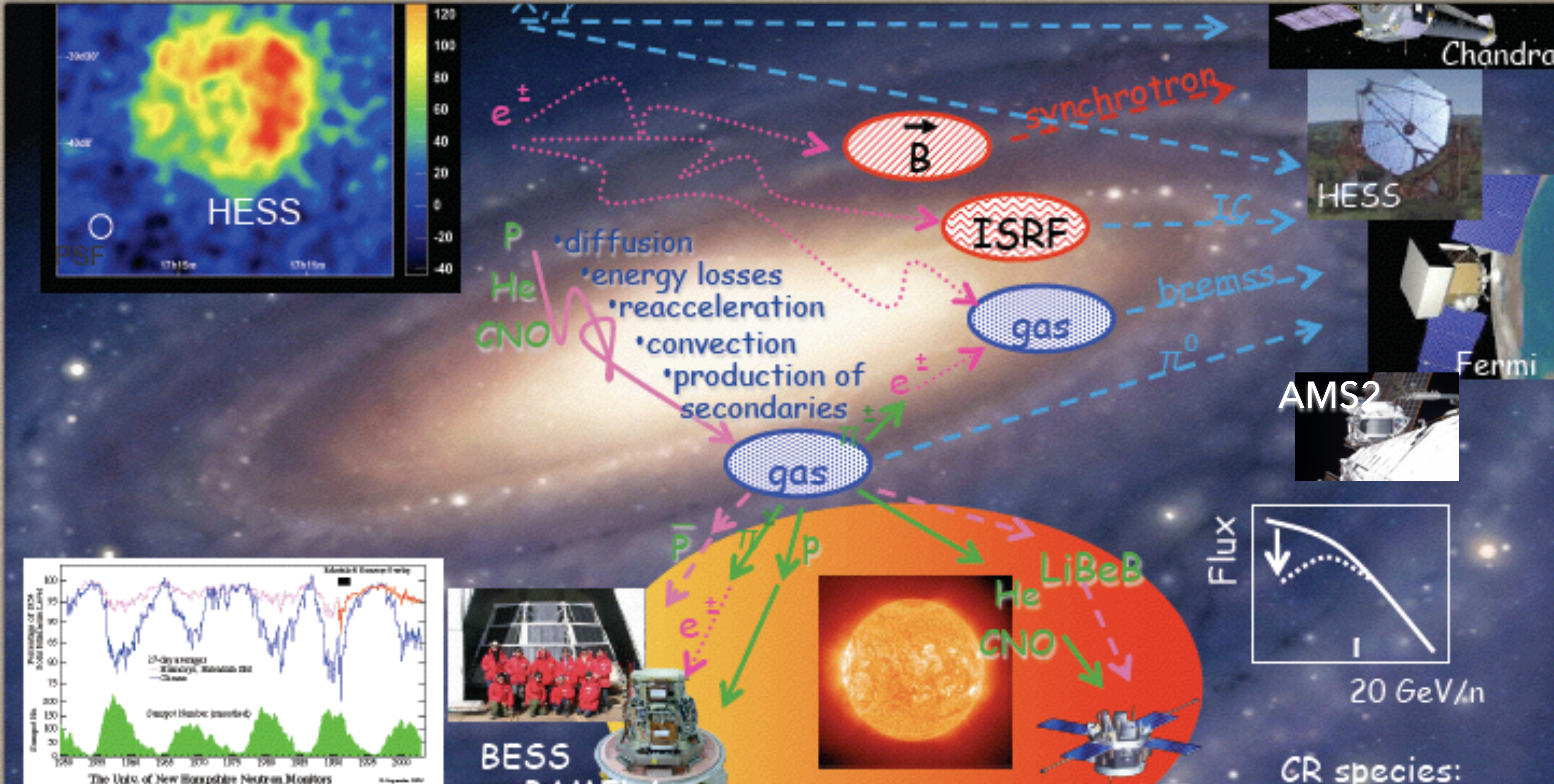


INDIRECT DETECTION: SIGNATURE IN GCRS

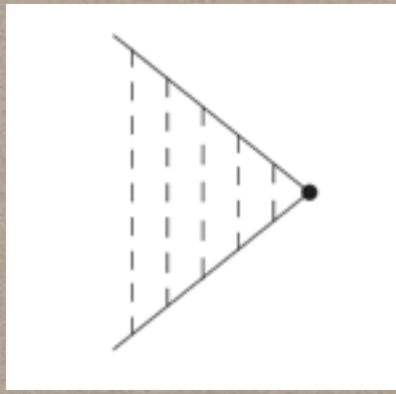
SOMMERFELD ENHANCEMENT & INDIRECT DETECTION

- The parameter space of interest for the model includes the regime where $m_\chi > m_\sigma$.
- In this regime, dilaton exchange produces an attractive Yukawa potential $-\frac{\alpha}{r}e^{-m_\sigma r}$ $\alpha = \frac{m_\chi^2}{4\pi f^2}$

Agashe, Blum, S.L., Perez 09'

=>Sommerfeld Enhancement

$$SE \approx \frac{\pi}{\epsilon_v} \frac{\sinh\left(\frac{12\epsilon_v}{\pi\epsilon_\phi}\right)}{\cosh\left(\frac{12\epsilon_v}{\pi\epsilon_\phi}\right) - \cos\left[2\pi\sqrt{\frac{6}{\pi^2\epsilon_\phi} - \left(\frac{12\epsilon_v}{\pi\epsilon_\phi}\right)^2}\right]},$$

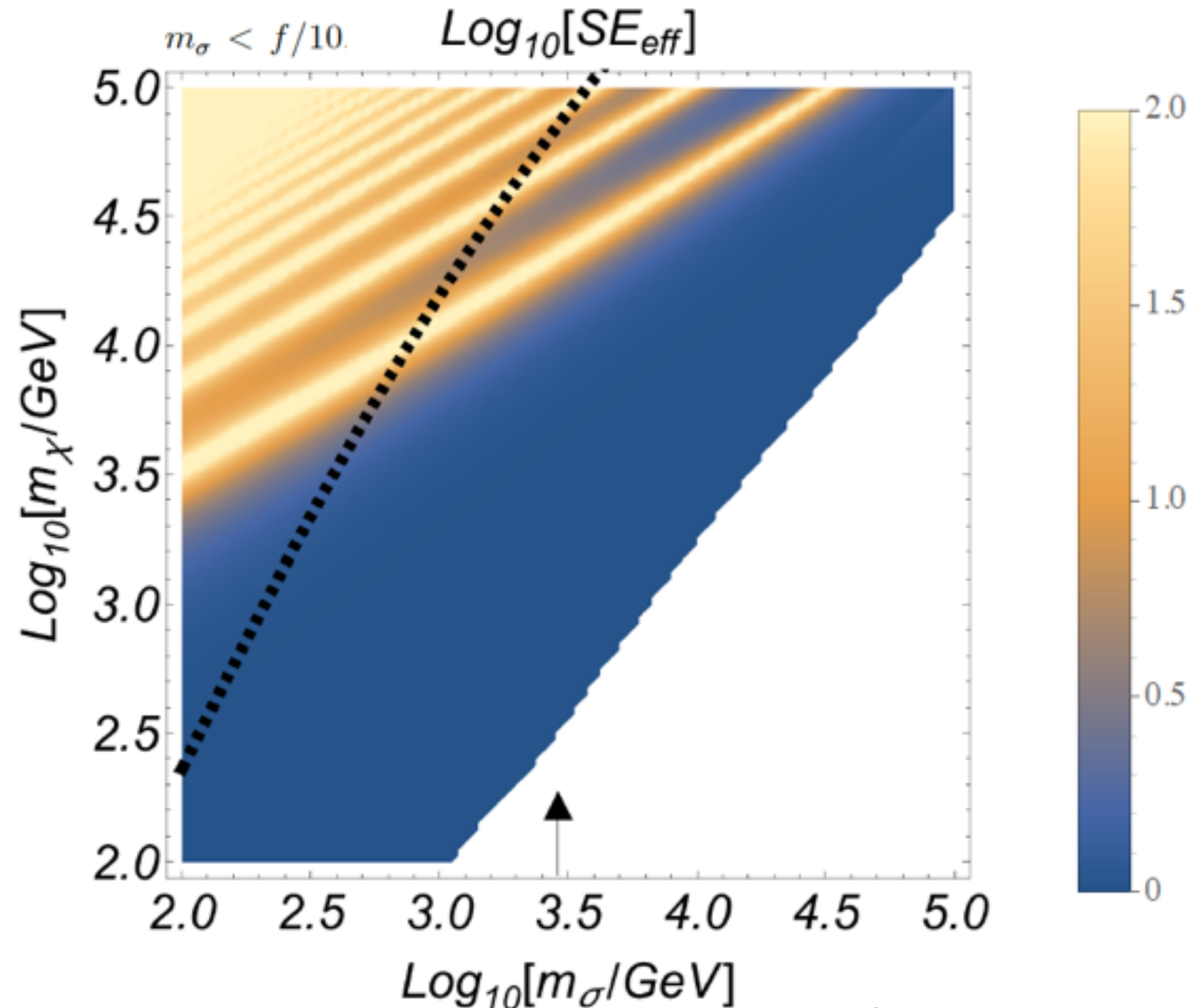


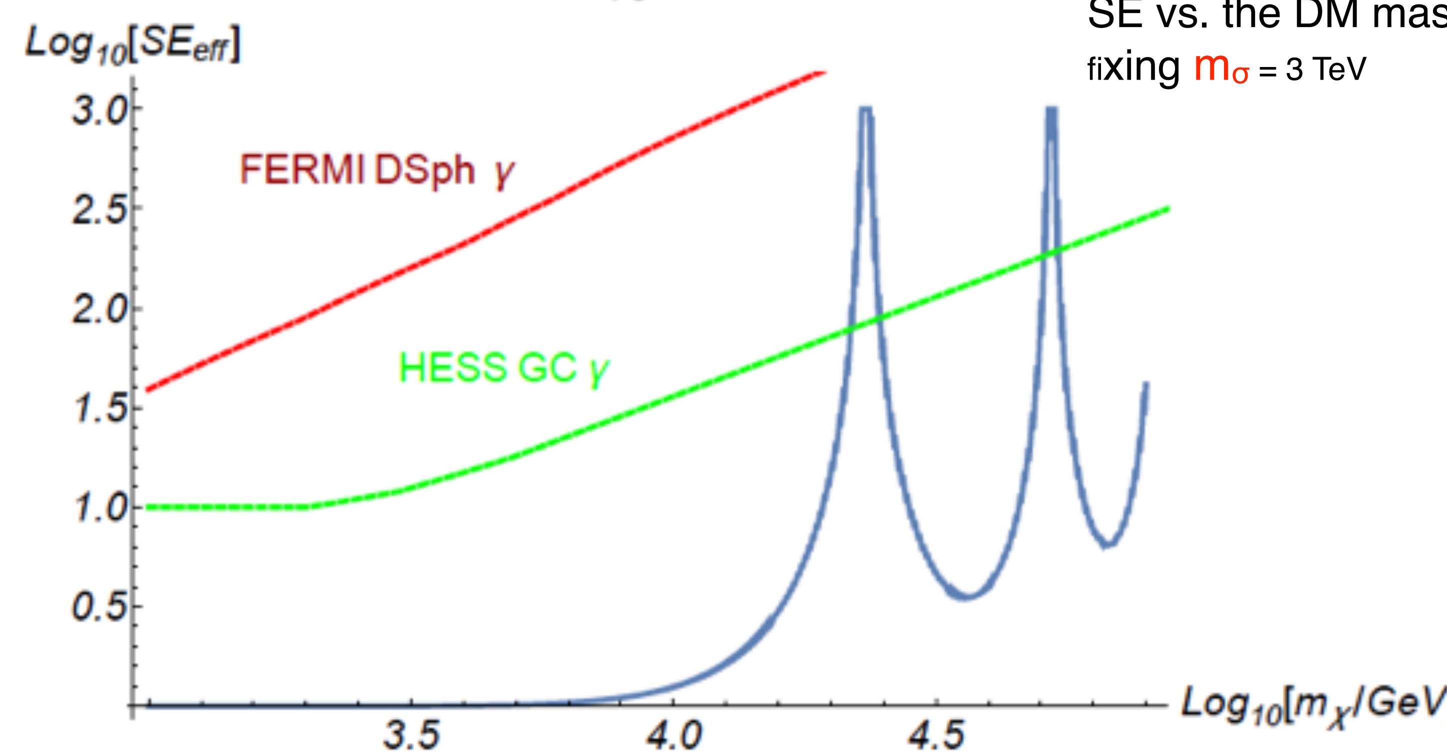
$$\epsilon_v \equiv \frac{v}{2\alpha} = \frac{2\pi v f^2}{m_\chi^2} \text{ and } \epsilon_\phi \equiv \frac{m_\sigma}{\alpha m_\chi} = \frac{4\pi m_\sigma f^2}{m_\chi^3}$$ $v = 10^{-3}$

SOMMERFELD ENHANCEMENT

& INDIRECT DETECTION

FOR DM MASS ABOVE A FEW TEV, LARGE VALUES OF THE SE FACTOR ARE POSSIBLE WITH SE LARGER THAN 100 IN RESONANCE REGIONS.





SE vs. the DM mass fixing m_σ = 3 TeV

ANTIPROTON

- CR injection rate density for antiproton:

$$Q_{\bar{p},DM}(E) = \frac{1}{2} n_\chi^2 \langle \sigma v \rangle \frac{dN_{\bar{p}}}{dE} \approx 5 \times 10^{-36} \mathrm{cm}^{-3} \mathrm{s}^{-1} \mathrm{GeV}^{-1} \times \left(\frac{\rho_\chi}{0.4 \ \mathrm{GeV cm}^{-3}} \right)^2 \left(\frac{\langle \sigma v \rangle}{3 \times 10^{-26} \ \mathrm{cm}^3 \mathrm{s}^{-1}} \right) \left(\frac{m_\chi}{1 \ \mathrm{TeV}} \right)^{-3} \left(m_\chi \frac{dN_{\bar{p}}}{dE} \right)$$

$\left[\frac{dN_{\bar{p}}}{dE}(E) \right]_{\sigma \to \bar{p} X}$ *from PPPC 4 DM ID, Cirelli, Corcella, Hektor, Hutsi, Kadastik et al.*

Particle Physics input:
Energy dependent BR
into stable final state pbar
at dilaton rest frame

$$\left[\frac{dN_{\bar{p}}}{dE}(E) \right]_{\chi\chi \to \sigma\sigma} = \frac{1}{\gamma_\sigma \beta_\sigma} \int_{\beta_\sigma^{-1} - 1}^{\beta_\sigma^{-1} + 1} \frac{dx}{x} \left[\frac{dN_{\bar{p}}}{dE} \left(\frac{E}{x \gamma_\sigma \beta_\sigma} \right) \right]_{\sigma \to \bar{p} X}$$

$\gamma_\sigma = m_\chi / m_\sigma$ and $\beta_\sigma = \sqrt{1 - \gamma_\sigma^{-2}}$

ANTIPROTON

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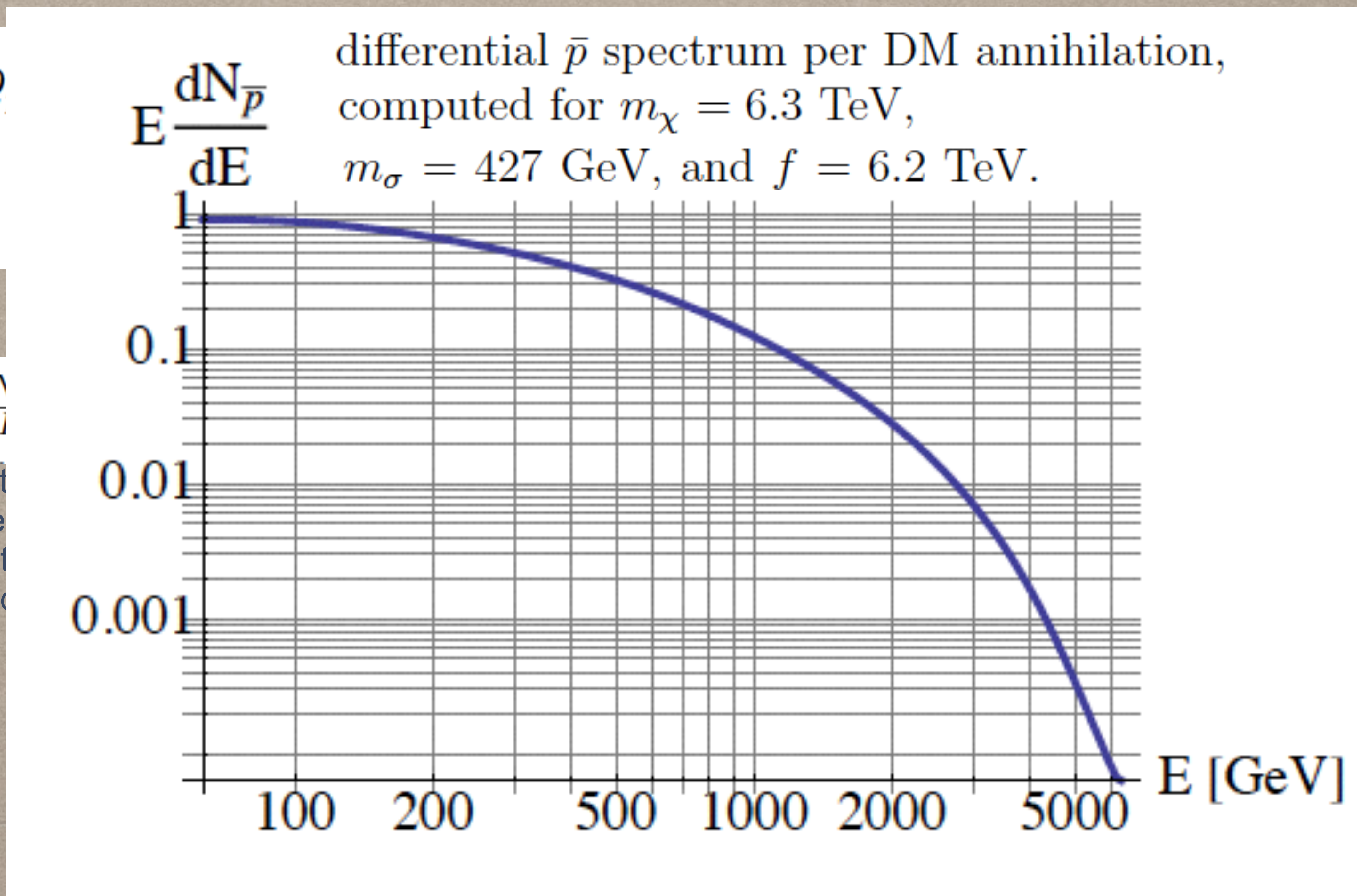
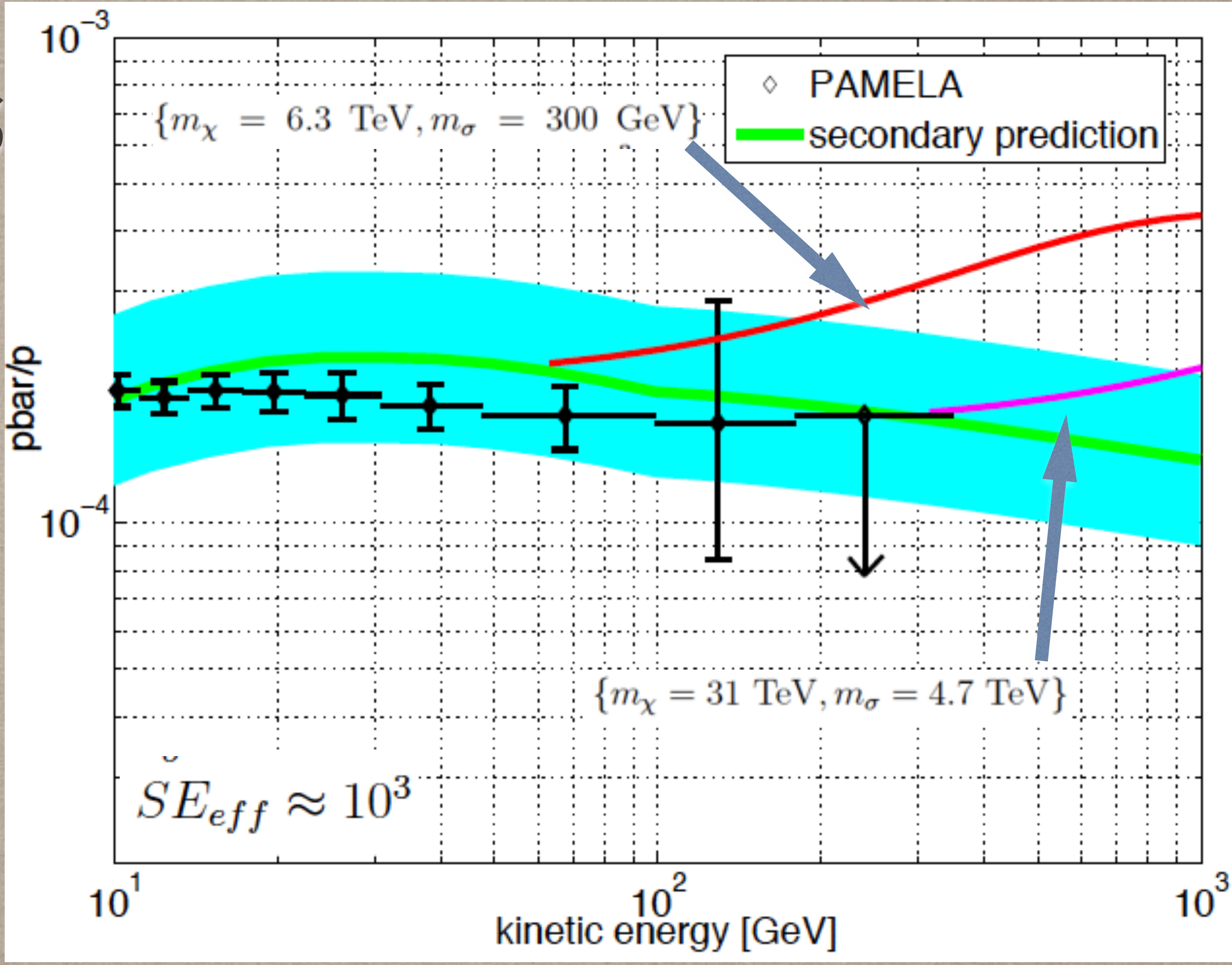


Hutsi,

ANTIPROTONS

- The basic result we find: the model survives our antiproton constraint by a large margin, unless it lives right on top of an SE resonance.
- If the model is near an SE resonance, then a detectable rise in the antiproton flux at high energy is predicted.

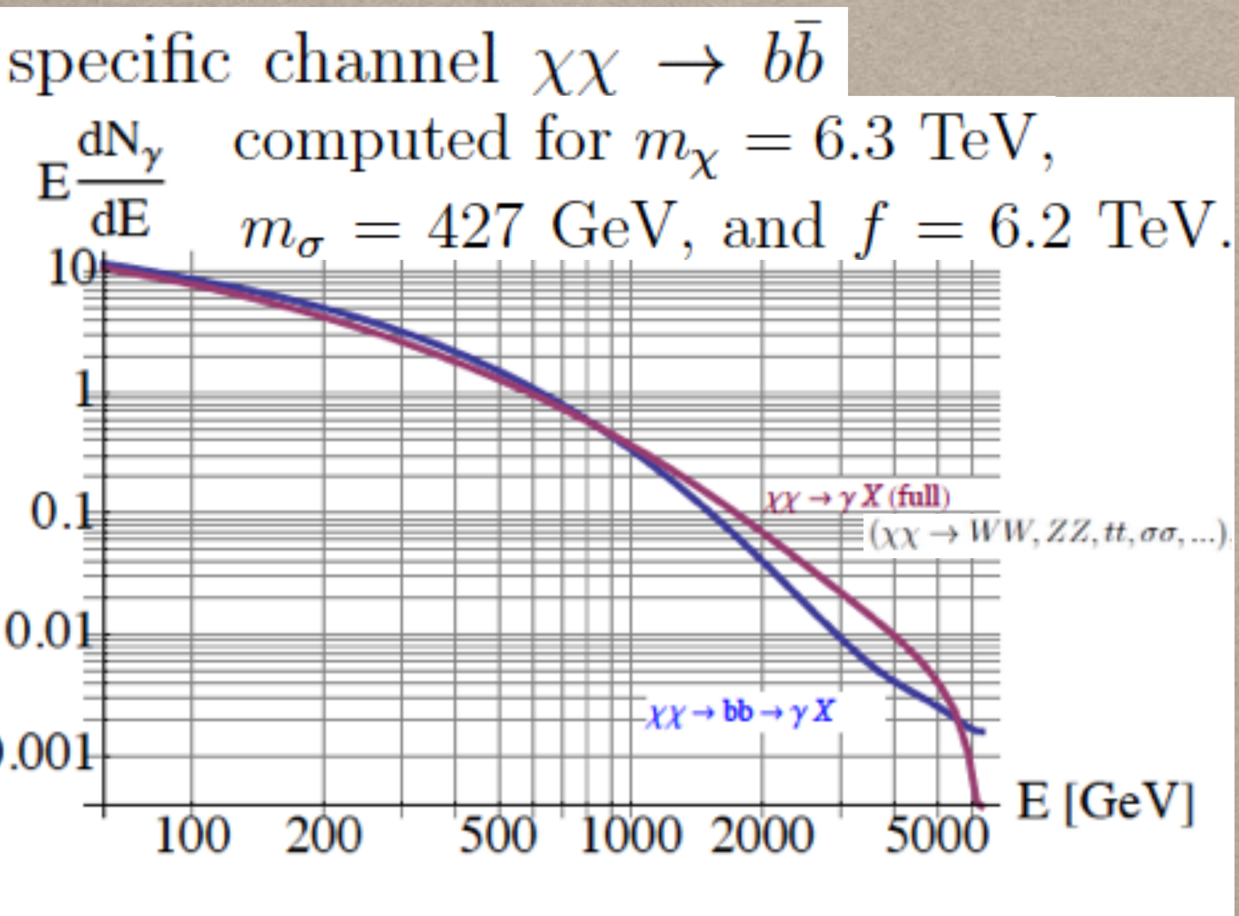


1. For DM mass below ~10 TeV, the rise would be in tension with current pbar data.

2. For DM mass above 10 TeV, there is no tension with current data, and future measurements may detect the model in antiproton flux

GAMMA RAYS

- Limit on DM annihilation from thehe FERMI gamma ray telescope (dwarf spheroidal galaxies)



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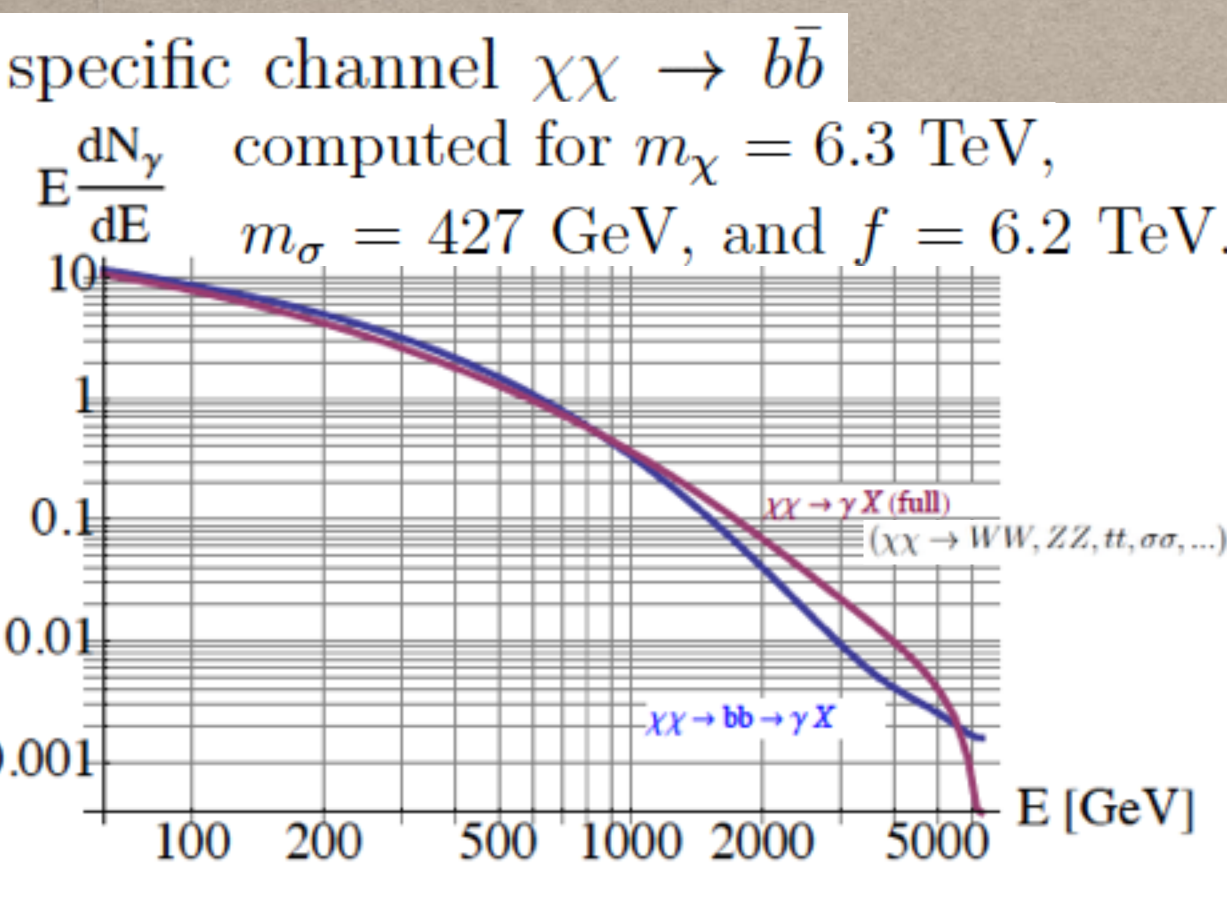

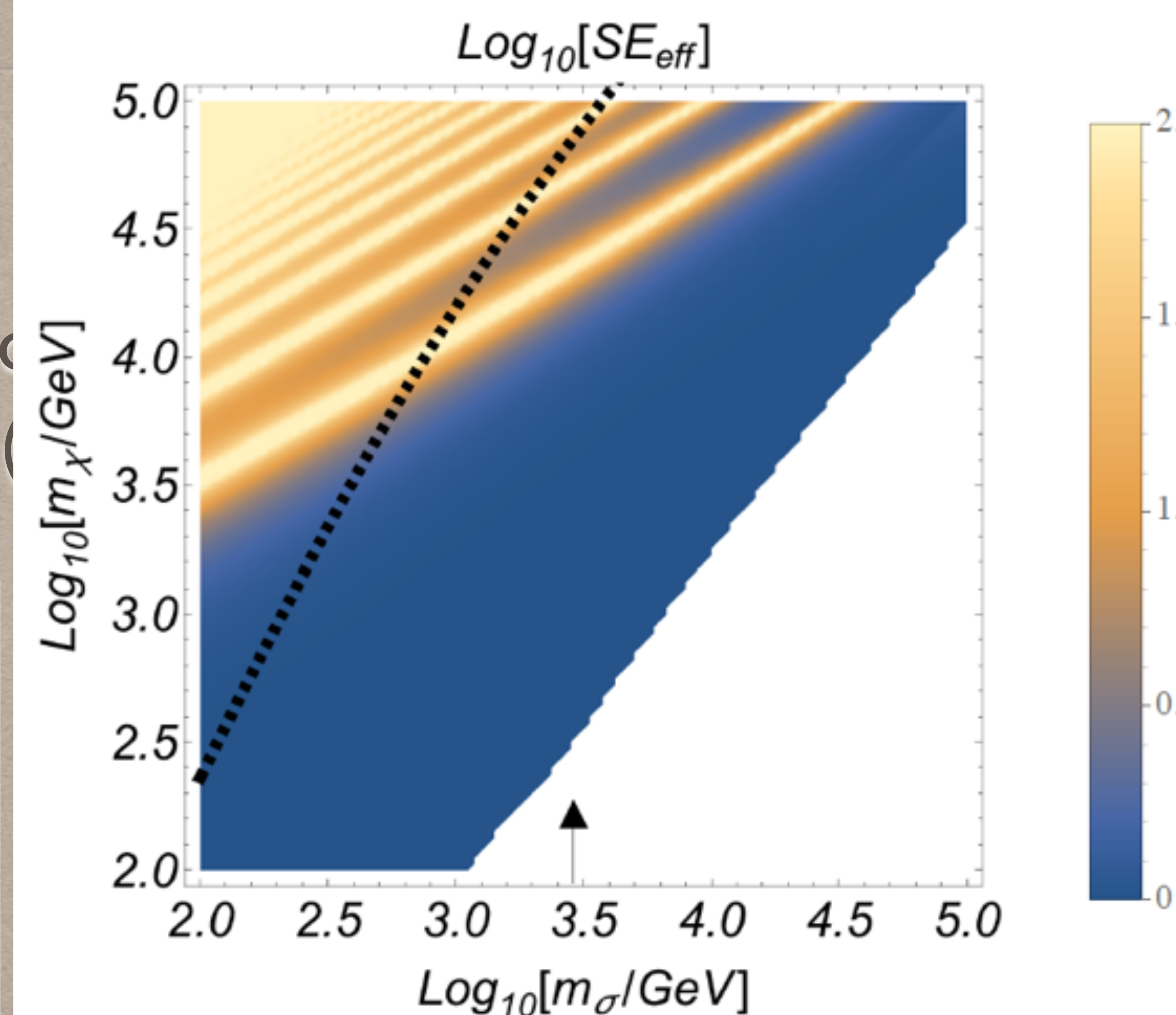

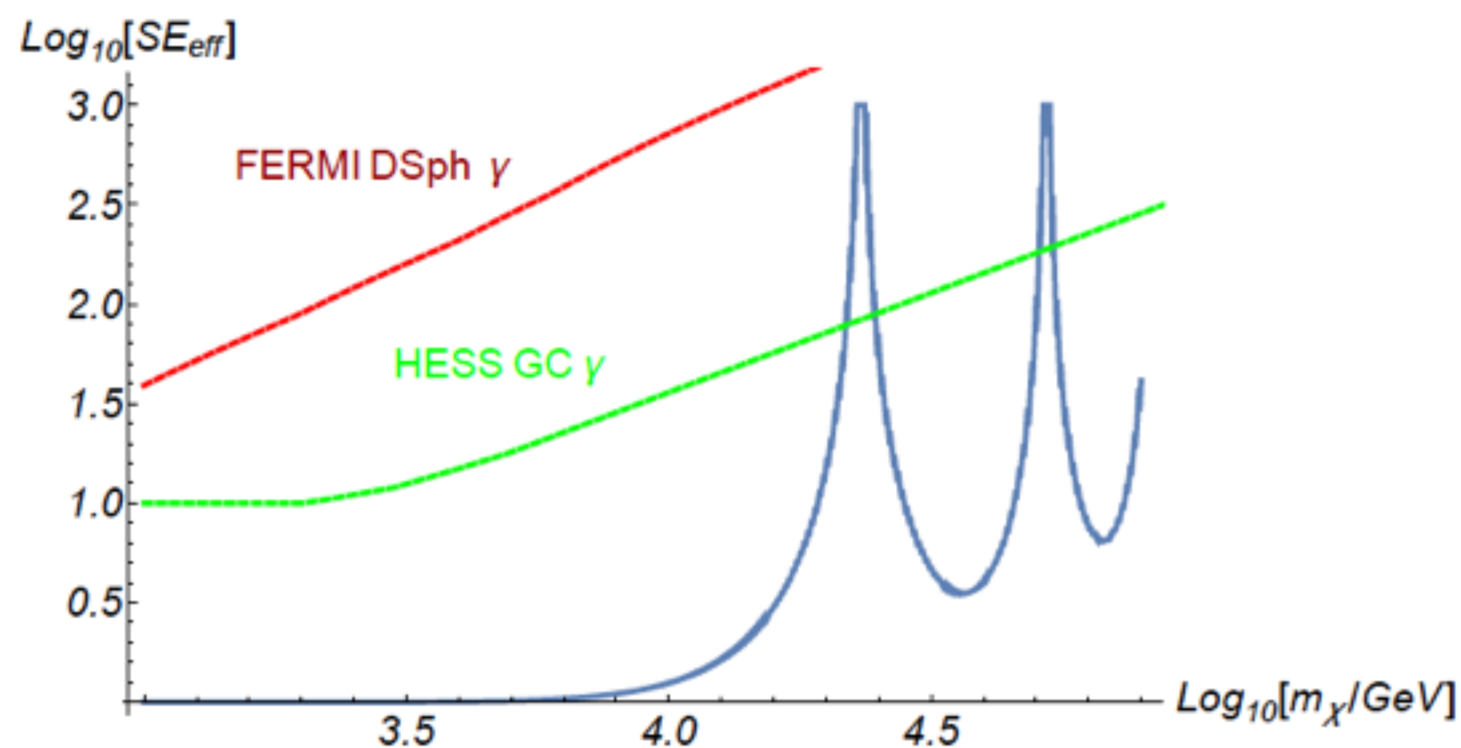

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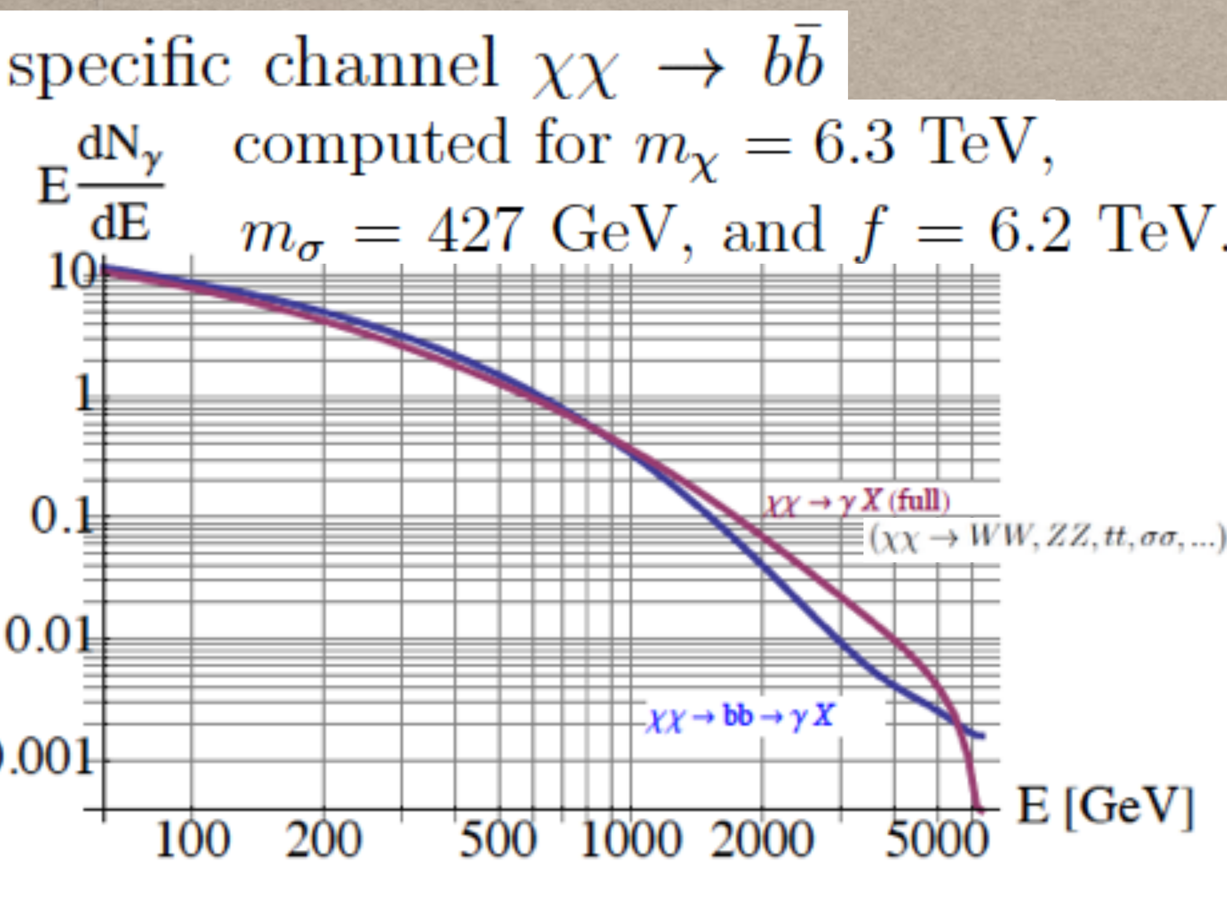
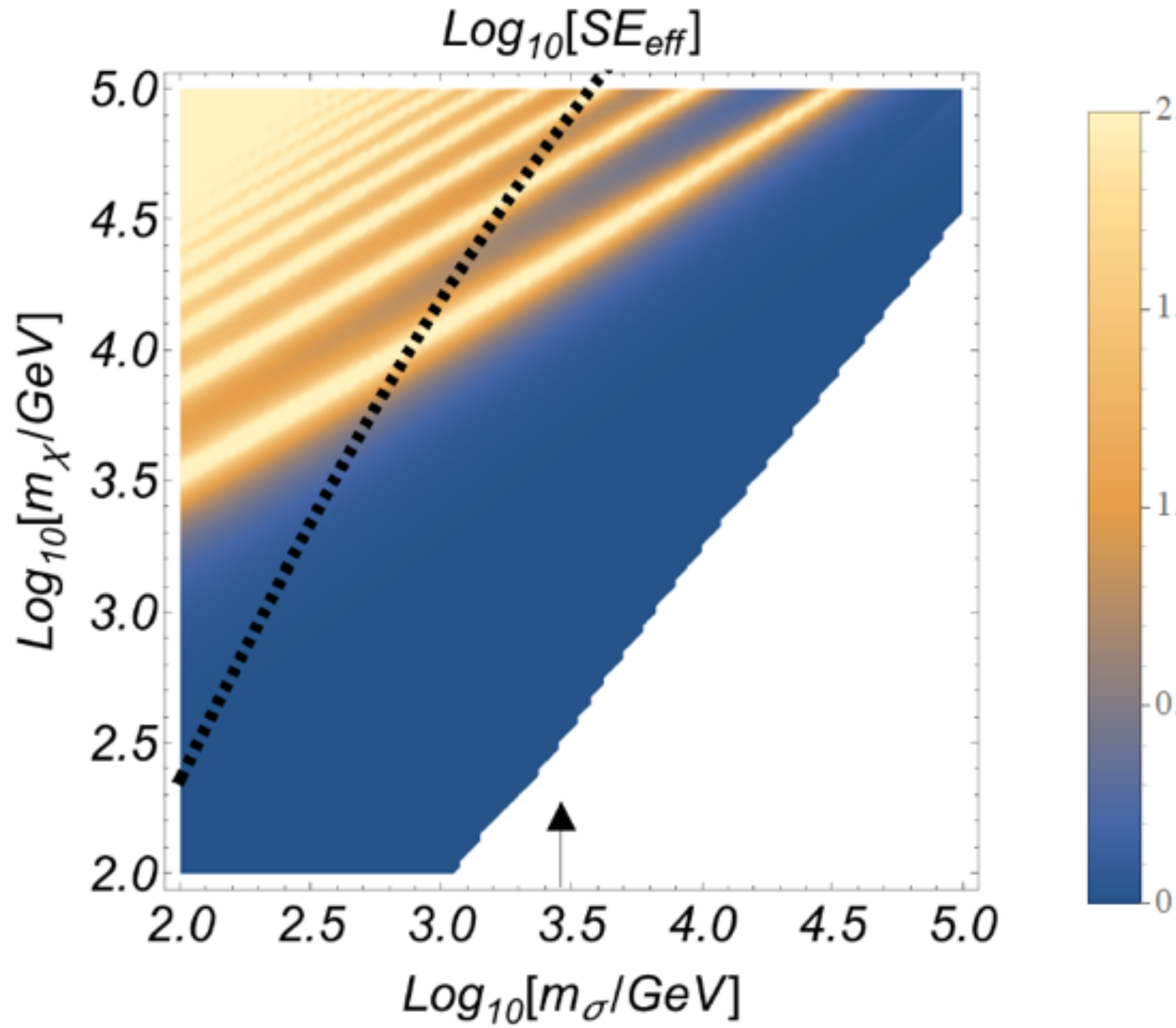
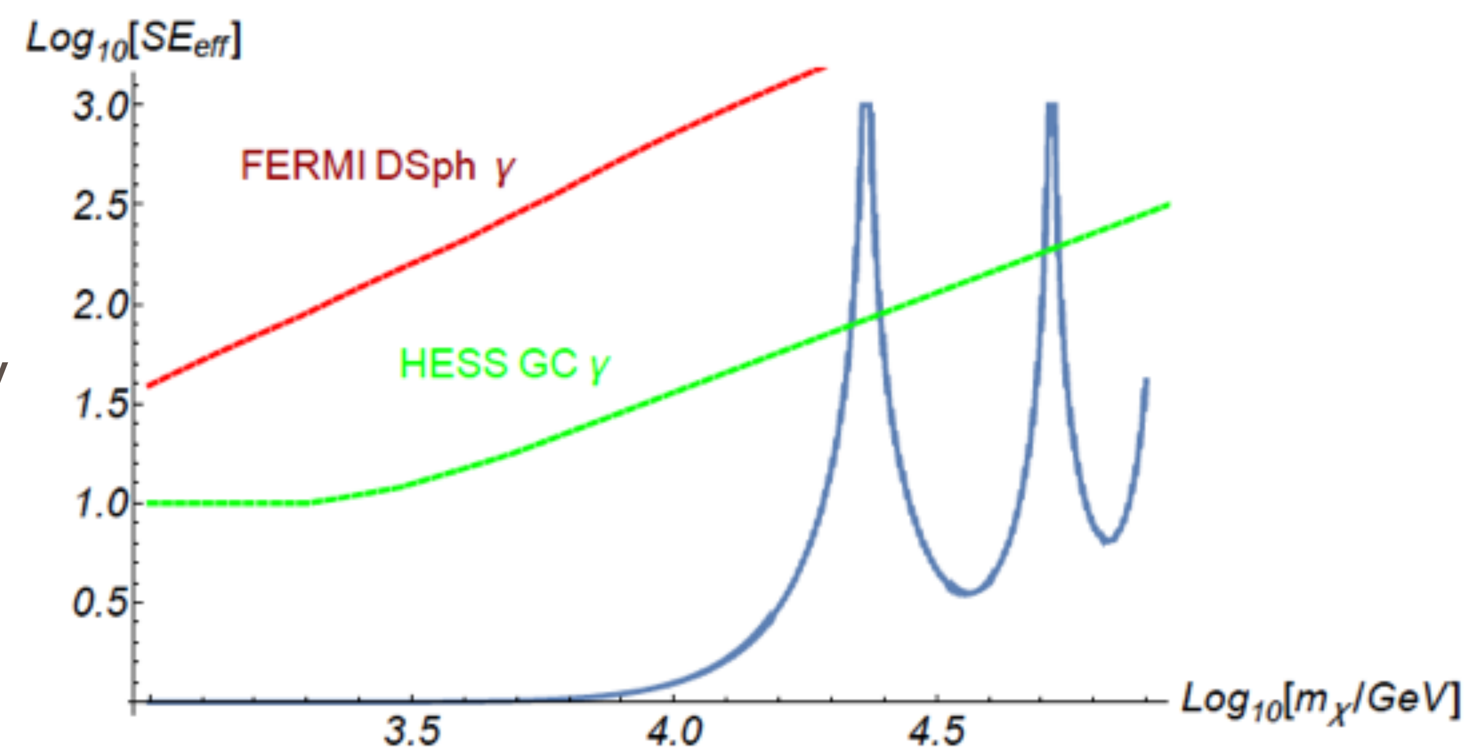


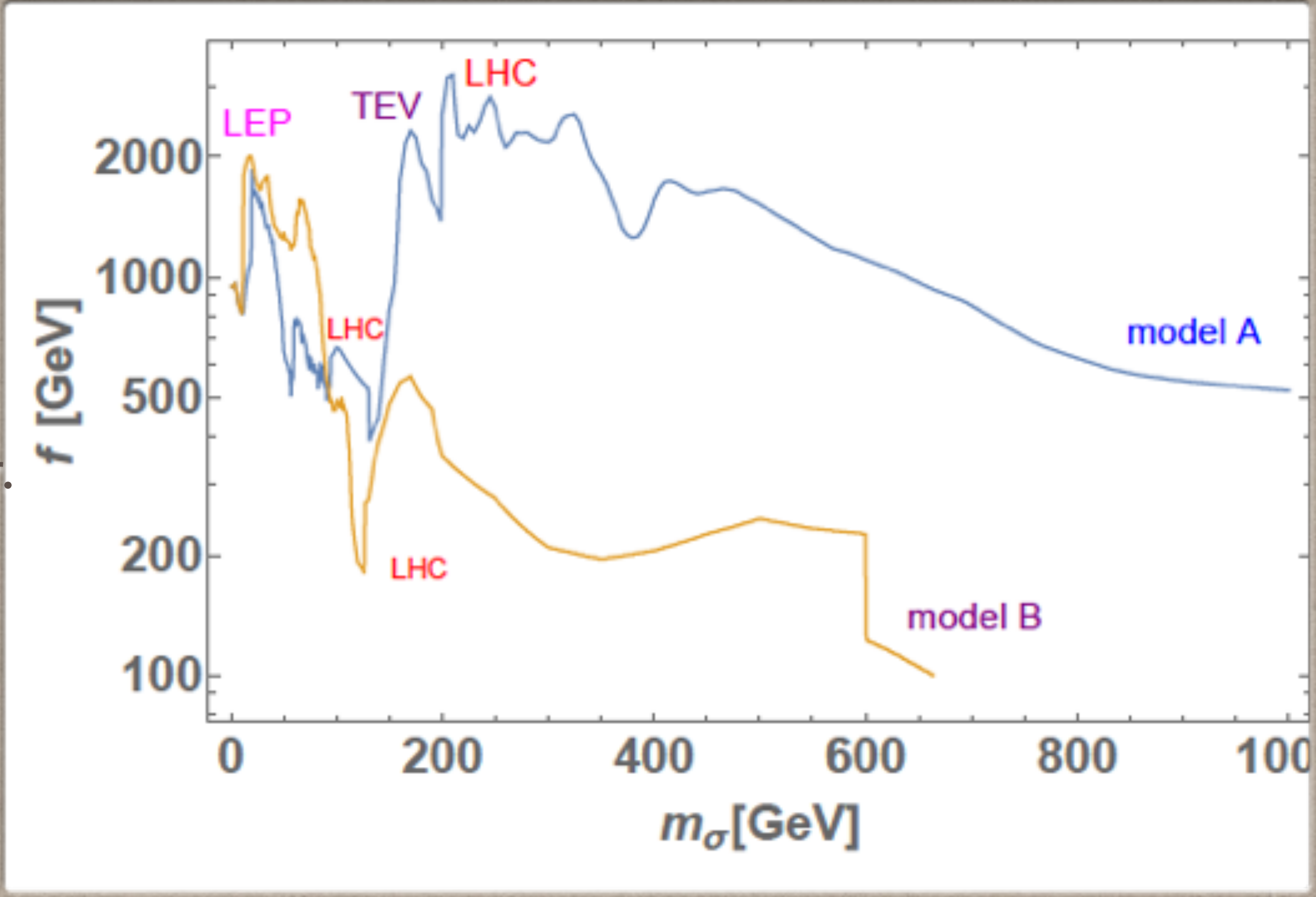




- Limit from the HESS gamma ray observatory reported limits based on Galactic Center observations: Stronger, but more model-dependent limits are obtained from ground-based air-Che-renkov telescopes.

COLLIDER BOUNDS

- The dilaton (roughly) mimics a Higgs boson, with couplings to massive SM fields suppressed by the factor v/f compared to that of the Higgs and couplings to massless gauge bosons that involve contributions from the matter content of the conformal sector.
- Collider bounds on the dilaton can thus be obtained by recasting the results of direct production limits from Higgs boson searches.
- We use the HiggsBound code version 4.1.2, that incorporates all the currently available experimental analyses from LEP, the Tevatron, and the LHC.



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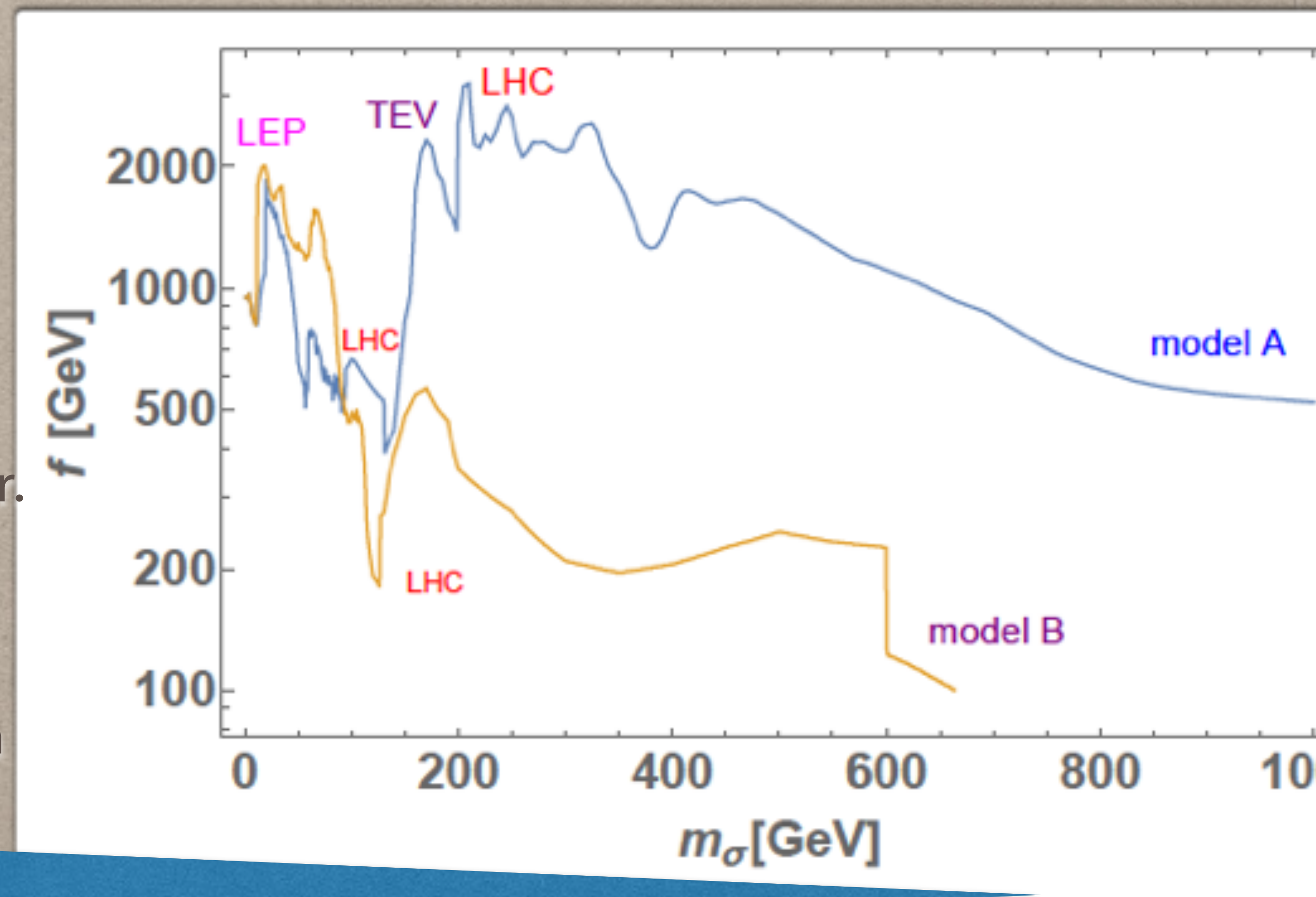
Run 2 will probe higher dilaton mass ranges, and maybe DM can be produced at the LHC



SUMMARY

- Dilaton portal provides an interesting composite WIMP DM scenario where dilaton couplings to the SM and DM field are determined by scale invariance
- The breaking scale of scale invariance f is fixed by requiring that the relic abundance matches the observed value, leaving the dark matter and dilaton masses as the main theory parameters
- Collider searches for Higgs-like particle put model dependent lower bounds on f for dilaton masses up to 1 TeV, and exclude dilaton-mediated DM for m_χ <300 GeV
- Current direct detection experiment allows the most of the parameter space, except for m_χ <300 GeV if m_σ <300 GeV
- Our analysis of indirect detection including antiproton and gamma ray data shows that the bulk of the parameter space is consistent with the current constraints.
- Upcoming direct detection experiments will probe our model, and if DM is heavy (above 10 TeV), we may still see them through indirect detection, e.g. antiproton flux and gamma rays, with Sommerfeld Enhancement via dilaton exchange