Kavli-IPMU-Durham-KIAS workshop: New particle searches confronting the first LHC run-2 data

7-11 September 2015
Asia/Tokyo timezone

Composite Resonances at the run-2 of the LHC

Seung J. Lee
KAIST

September 10, 2015

Backovic, Flacke, SL, Perez, arXiv:1409.0409
Backovic, Flacke, Kim, SL, arXiv:1410.8131
Backovic, Flacke, Kim, SL, arXiv:1501.07456
Cacciapaglia, Cai, Deandrea, Flacke, SL, Parolini arXiv:1507.02283
Backovic, Flacke, Kim, SL, arXiv:1507.06568

Outline

- Introduction (Composite Higgs Model)
- Main part: Top partner Searches (Status, and perspective at Run II)
- Vector resonance searches
- Composite Scalars (meson states)
- Summary

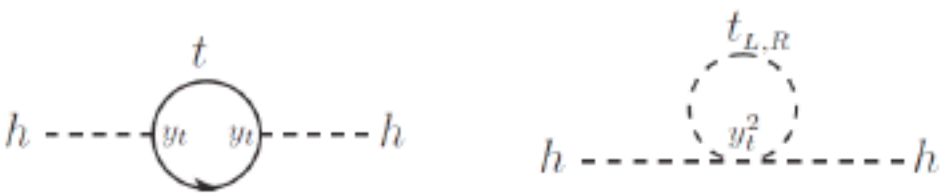
Outline

- Introduction (Composite Higgs Model)
- Main part: Top partner Searches (Status, and perspective at Run II)
- Vector resonance searches
- Composite Scalars (meson states)
- Summary

For the recent ATLAS anomaly and it's connection with composite spin-1 resonances, see LianTao's talk tommorow!

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

Well, Higgs is just another fundamental scalar bosons, and more is coming…!
$m_{stop} \gtrsim 700$ GeV

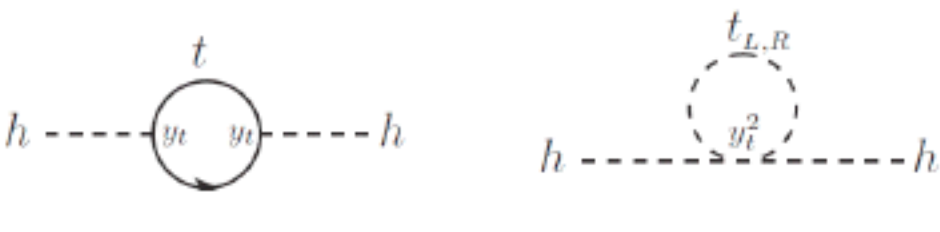
Composite Higgs
top partners = "T"

No, Higgs is just another composite resonance we are familiar with …!

Motivation

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

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



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

2 leading frameworks
of naturalness

Supersymmetry
top partners=stops

Composite Higgs
top partners = "T"

Well, Higgs is just another fundamental scalar bosons, and more is coming…!
$m_{stop} \gtrsim 700$ GeV

No, Higgs is just another composite resonance we are familiar with …!

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,...

composite sector originated at some UV scale: e.g. assuming a conformal fixed point below UV, …

$\mathcal{L}^{UV}_{comp} + \mathcal{L}^{UV}_{el,mix}$

Λ_{UV}

strong dynamics

Higgs mass term is irrelevant above Λ_{IR}

$\mathcal{L}^{IR}_{comp} + \mathcal{L}^{IR}_{el,mix}$

heavy resonances

$\Lambda_{IR} \sim g_\rho f$

IR scale is dynamically generated
f ⇔ a symmetry breaking scale

$g_\psi f$

PNGB model often requires $g_\psi f \neq g_\rho f$ for less fine-tuning to get ~125 GeV higgs

Λ_{EW}

weak dynamics

$$m_h^2 \sim \frac{N_c}{2\pi^2}\frac{v^2}{f^2}M_T$$

$\xi = \frac{v^2}{f^2}$

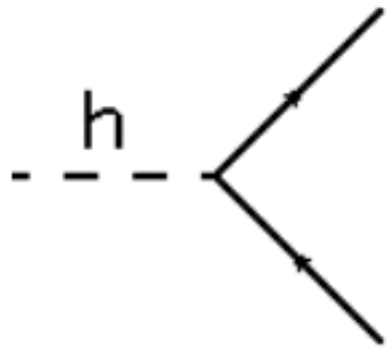
Higgs Couplings

- Low energy Higgs physics from **symmetries**

$$\mathcal{L}_\pi = \frac{f^2}{4} d^i_\mu d^\mu_i = \frac{1}{2}(\partial h)^2 + \frac{g^2}{4} f^2 \sin^2 \frac{h}{f}\left(|W|^2 + \frac{1}{2c_w^2} Z^2\right)$$

$$g_{HVV} = i\,\frac{g^2}{4} v\sqrt{1-\xi} \qquad \xi \equiv \frac{v^2}{f^2} = \sin^2\frac{\langle h\rangle}{f}$$

- Fermion couplings are less sharply predicted



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

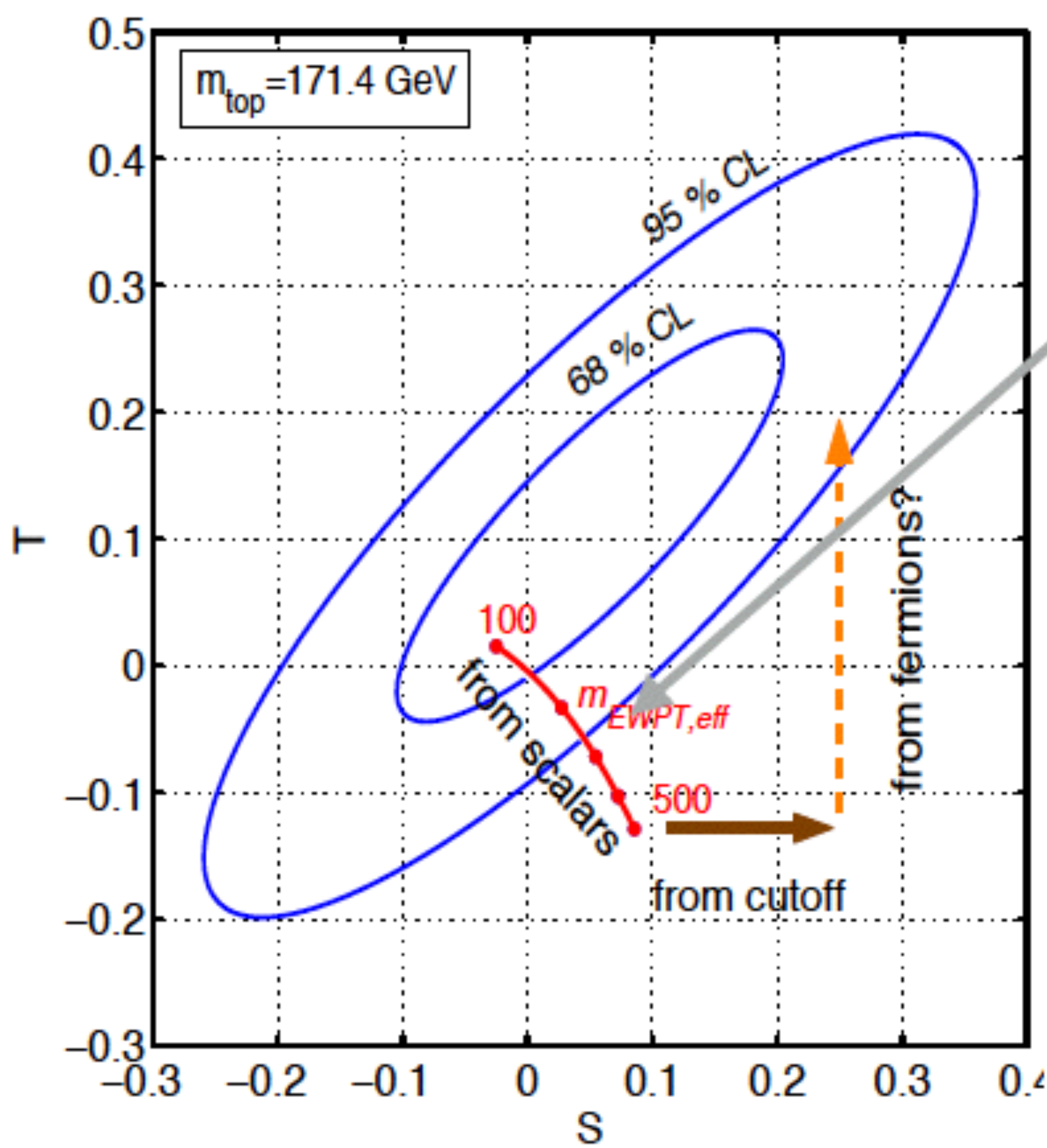
MCHM_5 $\quad c = \dfrac{1-2\xi}{\sqrt{1-\xi}}$

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

MCHM_{10} $\quad \cdots$

⇨ Do depend on fermionic operator representations

EWPT



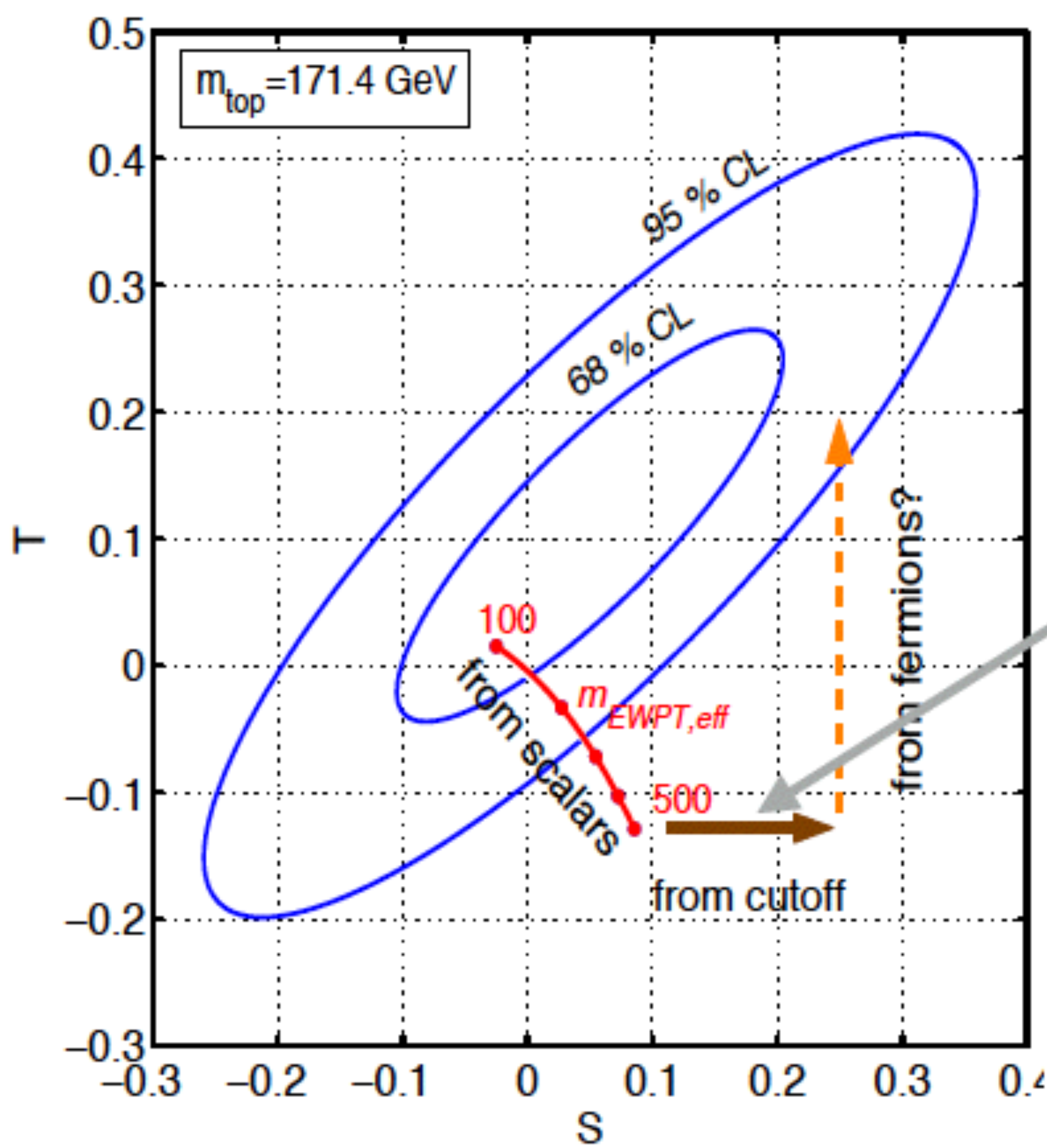
$$\Delta\hat{S} = \frac{g^2}{96\pi^2}\xi \log\left(\frac{8\pi m_W}{g m_h \sqrt{\xi}}\right)$$

$$\Delta\hat{T} = -\frac{3g'^2}{32\pi^2}\xi \log\left(\frac{8\pi m_W}{g m_h \sqrt{\xi}}\right)$$

Modified Higgs couplings go in bad direction.

Barbieri, Bellazzini, Rychkov, Varagnolo ,`07

EWPT



$$\Delta\hat{S} = \frac{g^2}{96\pi^2}\xi \log\left(\frac{8\pi m_W}{g m_h \sqrt{\xi}}\right) + \frac{m_W^2}{m_\rho^2}$$

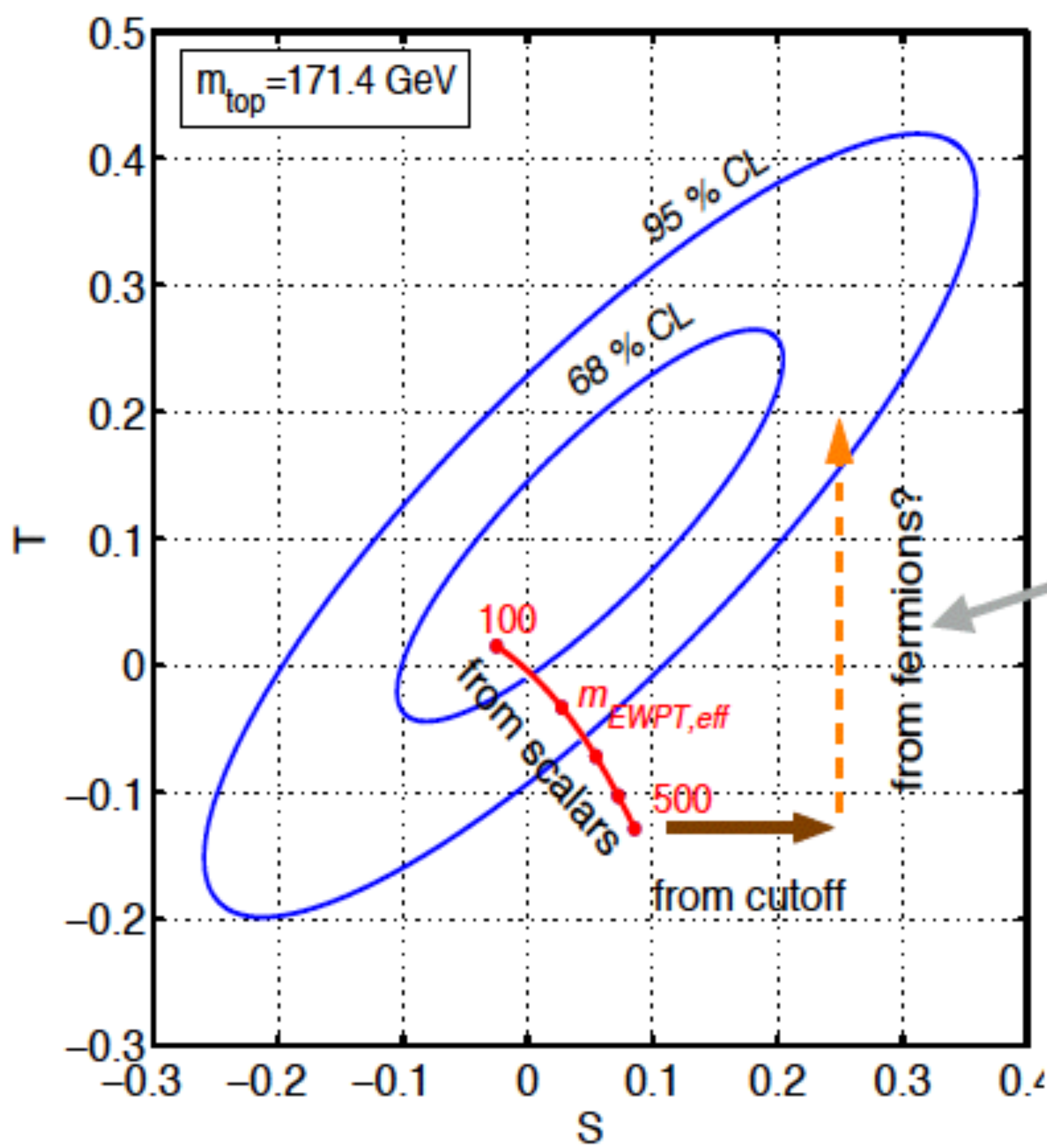
$$\Delta\hat{T} = -\frac{3g'^2}{32\pi^2}\xi \log\left(\frac{8\pi m_W}{g m_h \sqrt{\xi}}\right)$$

Modified Higgs couplings go in bad direction.

Resonance exchange as well

Barbieri, Bellazzini, Rychkov, Varagnolo ,`07

EWPT



$$\Delta\hat{S} = \frac{g^2}{96\pi^2}\xi \log\left(\frac{8\pi m_W}{g m_h \sqrt{\xi}}\right) + \frac{m_W^2}{m_\rho^2} + \alpha \frac{g^2}{16\pi^2}\xi\,,$$

$$\Delta\hat{T} = -\frac{3g'^2}{32\pi^2}\xi \log\left(\frac{8\pi m_W}{g m_h \sqrt{\xi}}\right) + \beta \frac{3y_t}{16\pi^2}\xi\,,$$

Modified Higgs couplings go in bad direction.

Resonance exchange as well

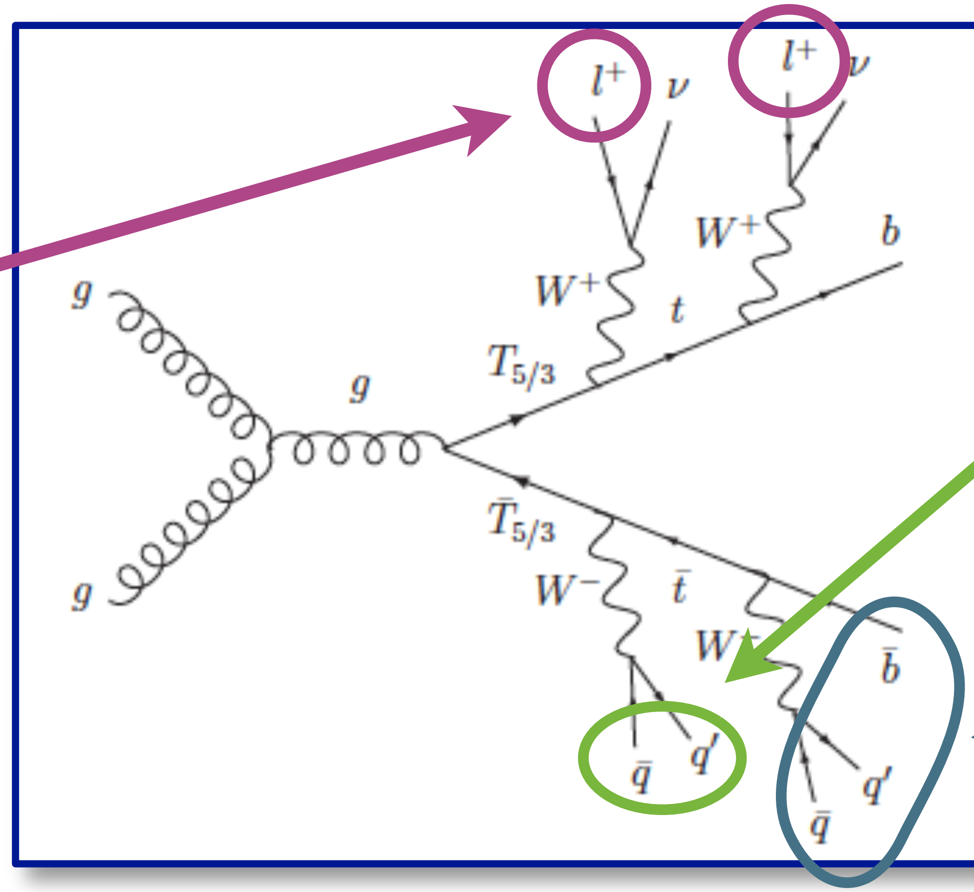
Light Top Partners come to rescue.

Barbieri, Bellazzini, Rychkov, Varagnolo ,`07

Composite Top Partner Searches @ Run 1

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

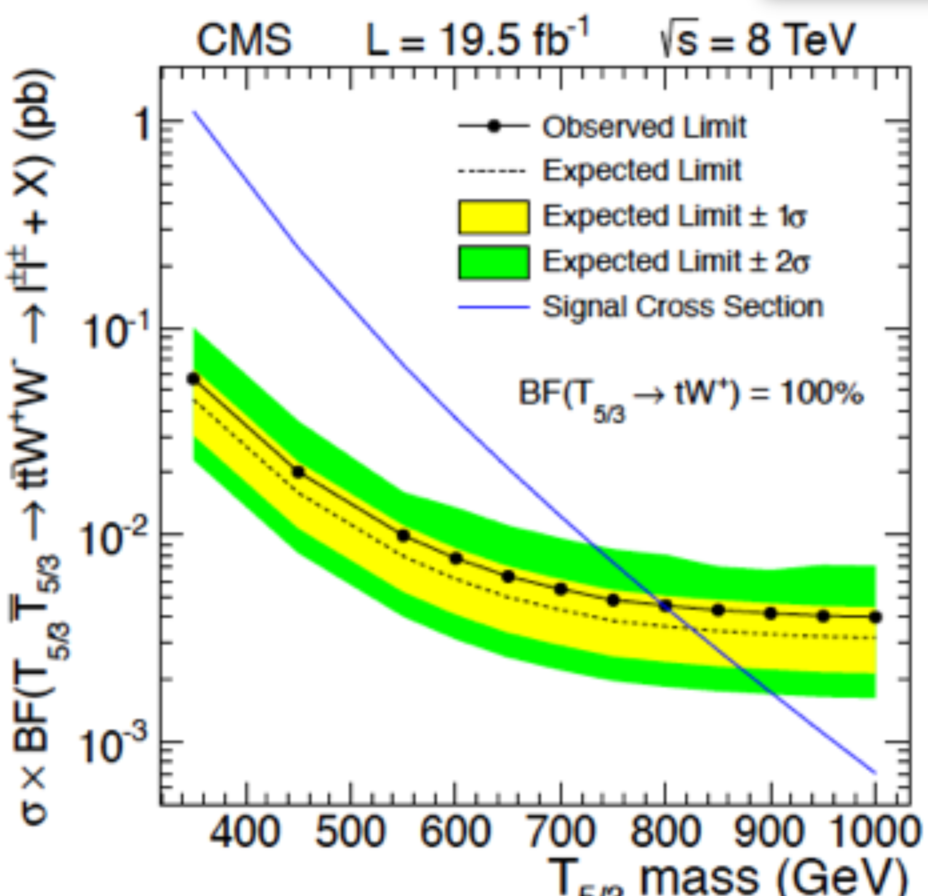
same-sign dileptons



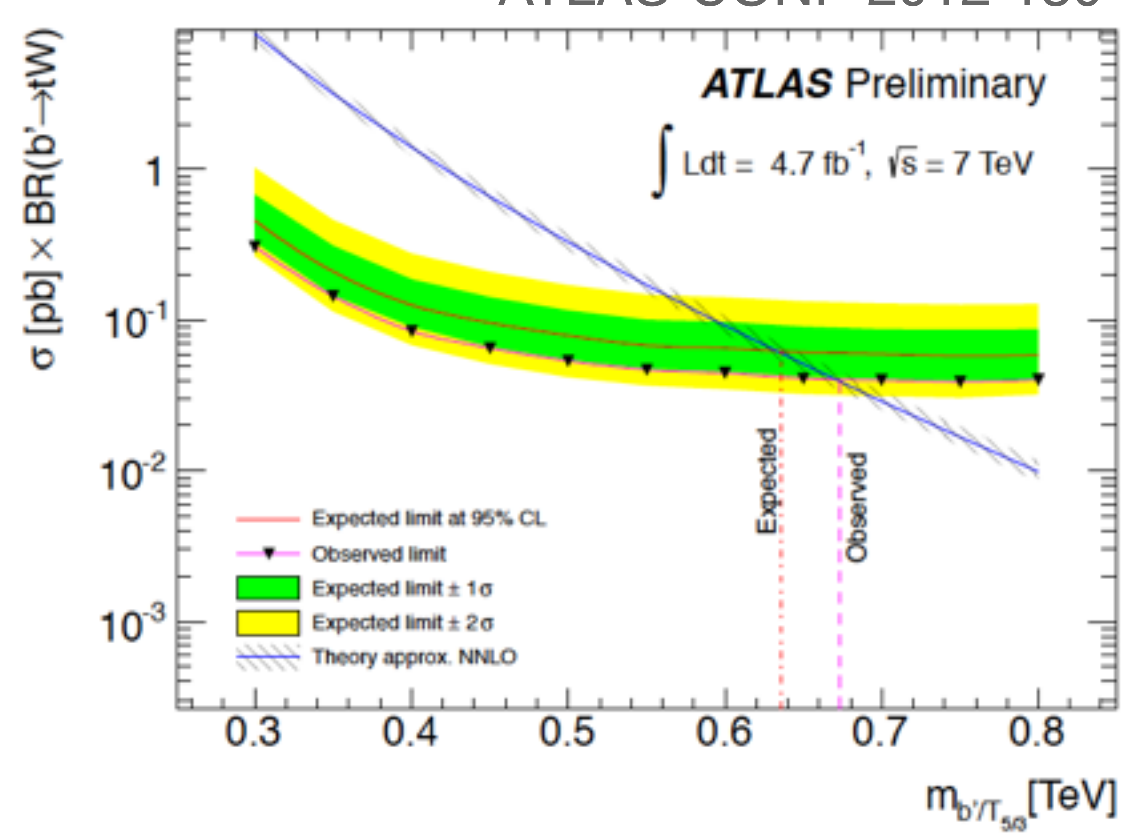
W tag:
2 subjets,
M_j[60,130]

CMS top tag

10.1103/PhysRevLett.112.171801



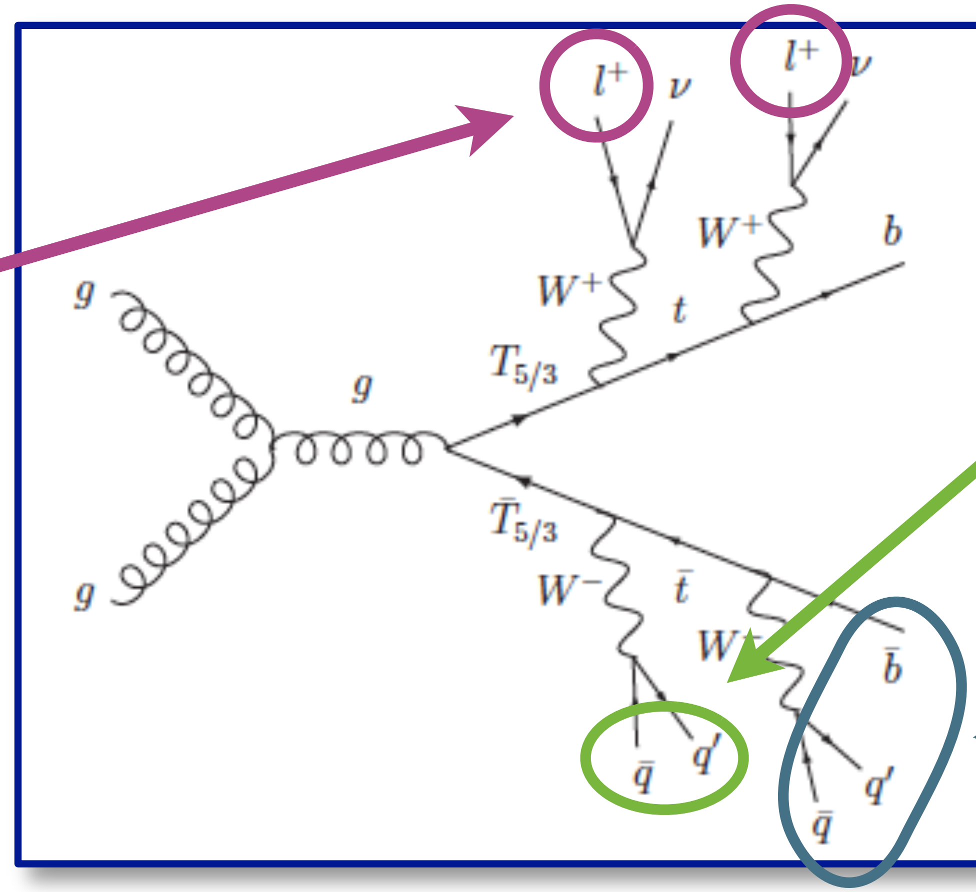
ATLAS-CONF-2012-130



Composite Top Partner Searches @ Run 1

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

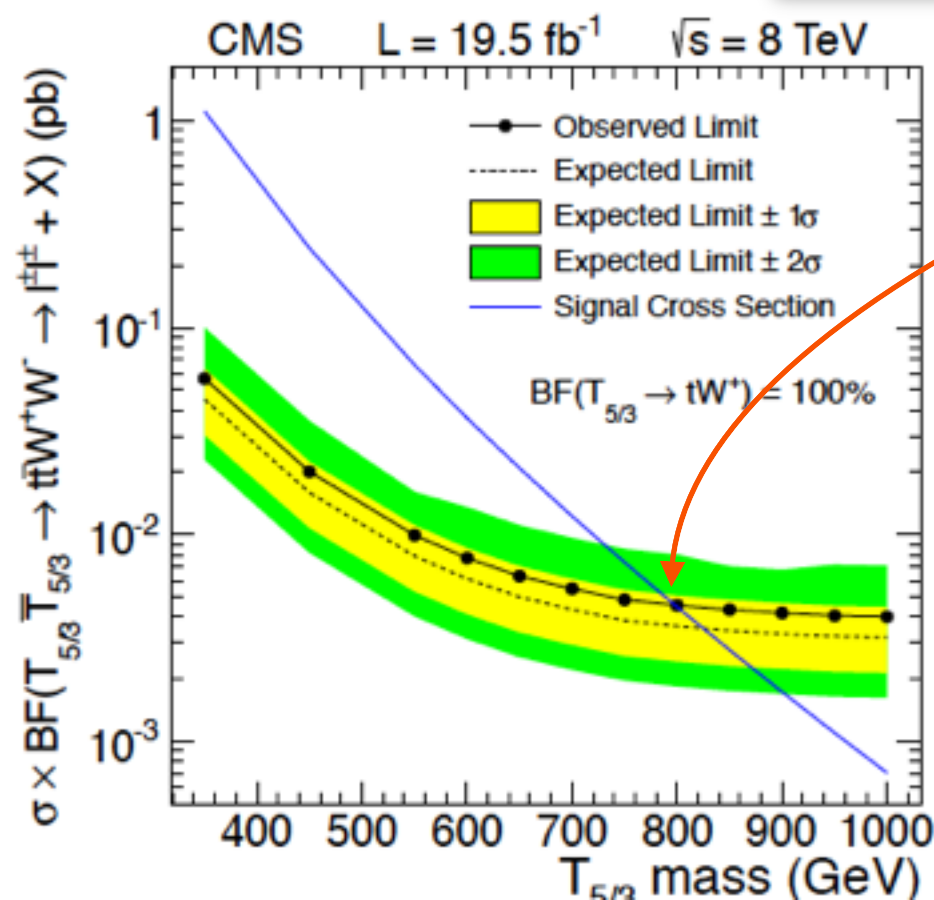
same-sign dileptons



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

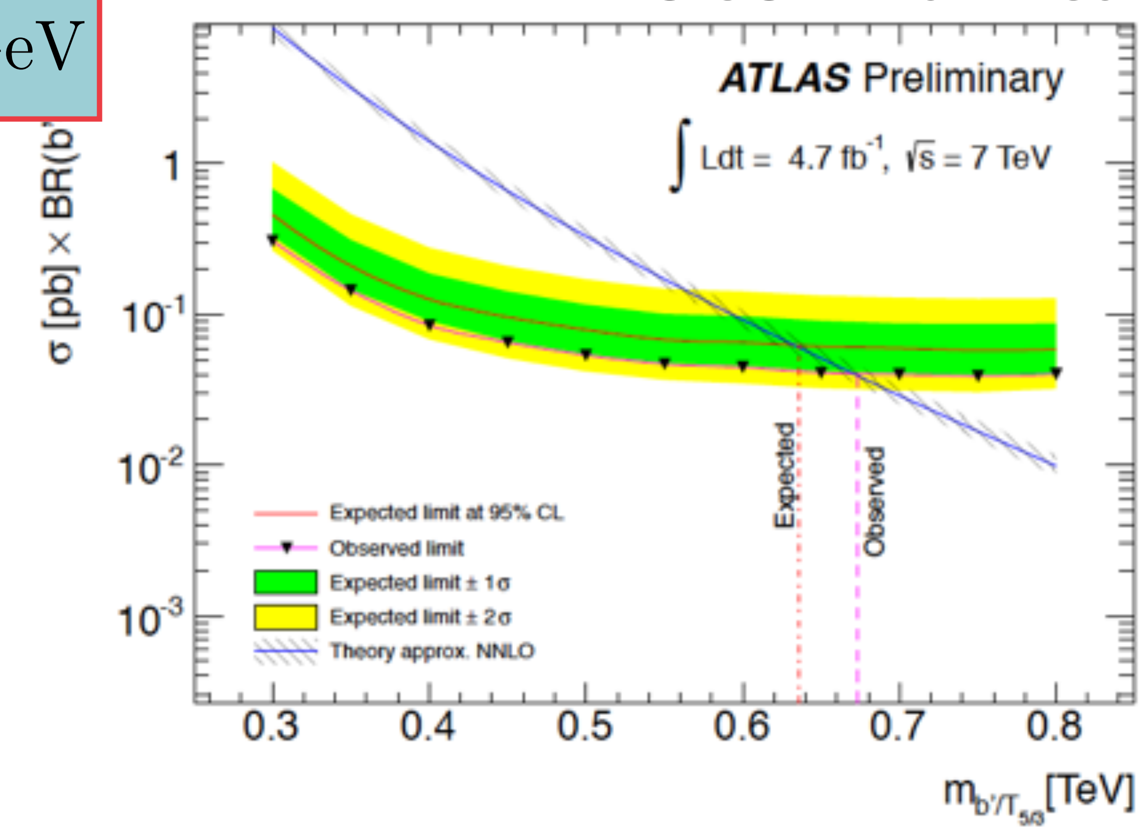
CMS top tag

10.1103/PhysRevLett.112.171801



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

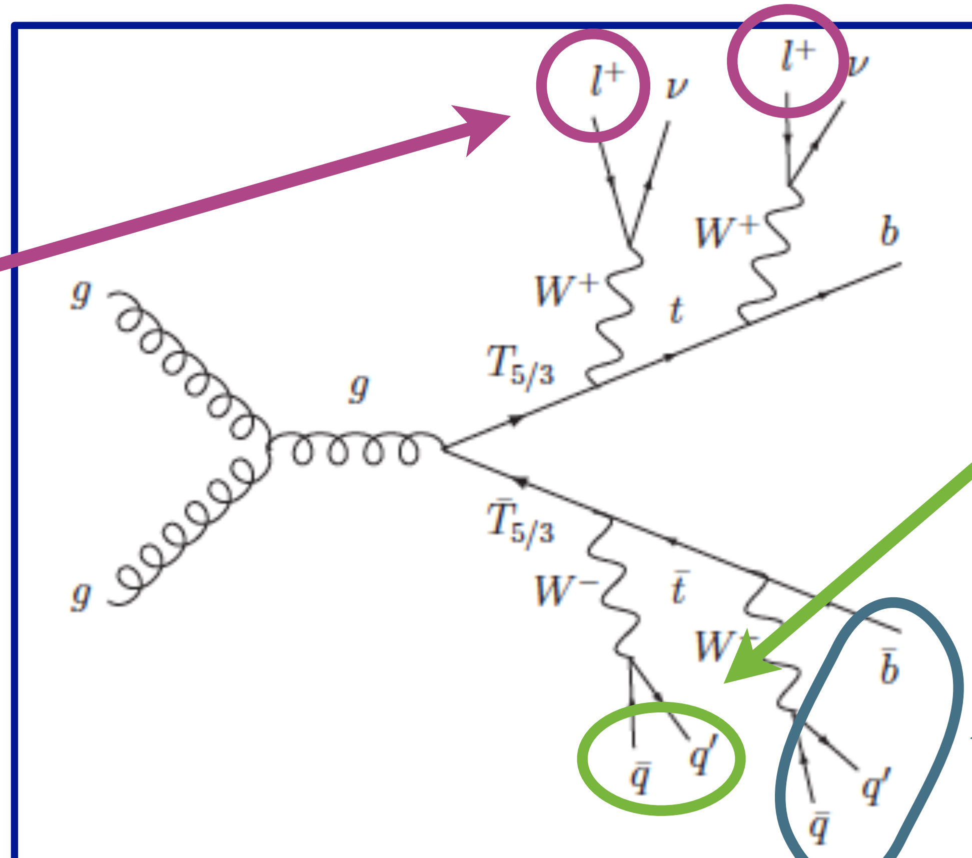
ATLAS-CONF-2012-130



Composite Top Partner Searches @ Run 1

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

same-sign dileptons



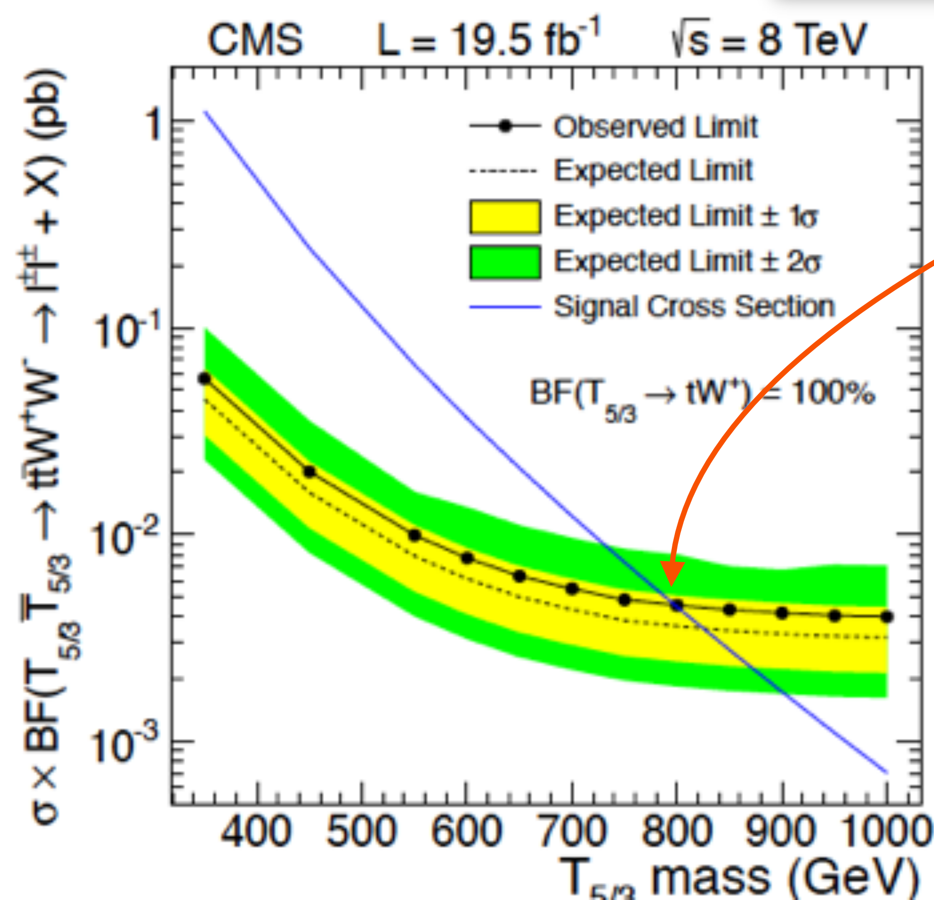
W tag:
2 subjets,

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

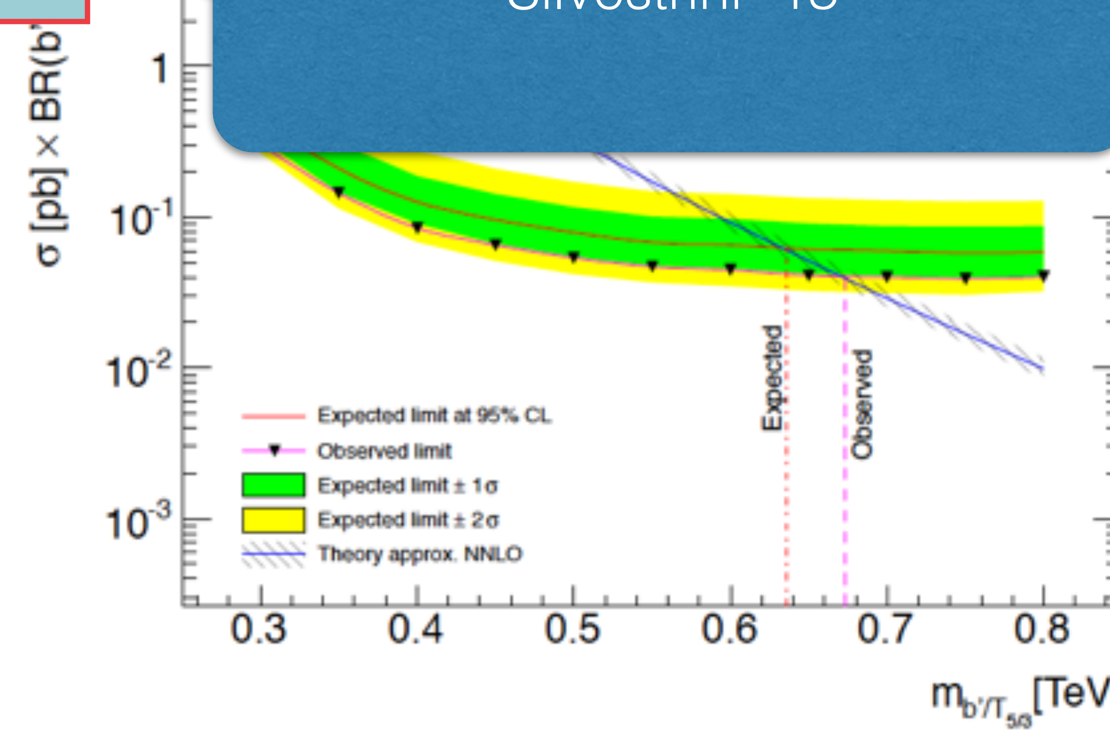
Grojean, Matsedonskyi, Panico `13

Ciuchini, Franco, Mishima, Silvestrini `13

10.1103/PhysRevLett.112.171801



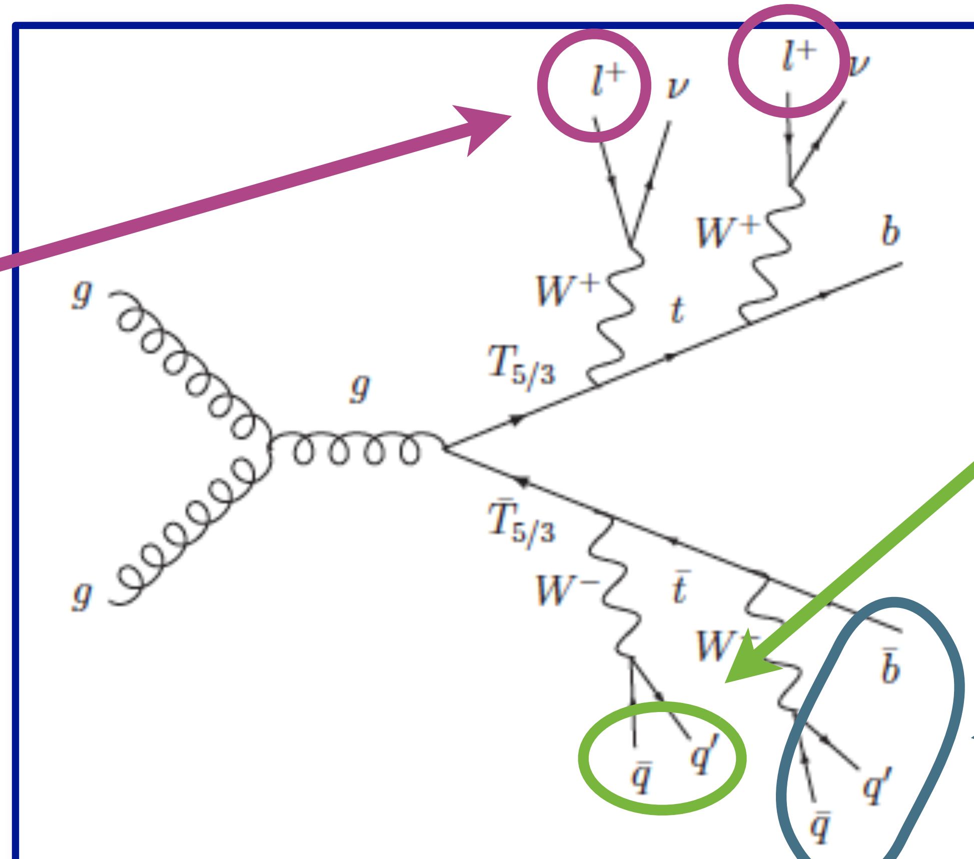
$$M_{X_{5/3}} \gtrsim 800\,\mathrm{GeV}$$



Composite Top Partner Searches @ Run 1

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

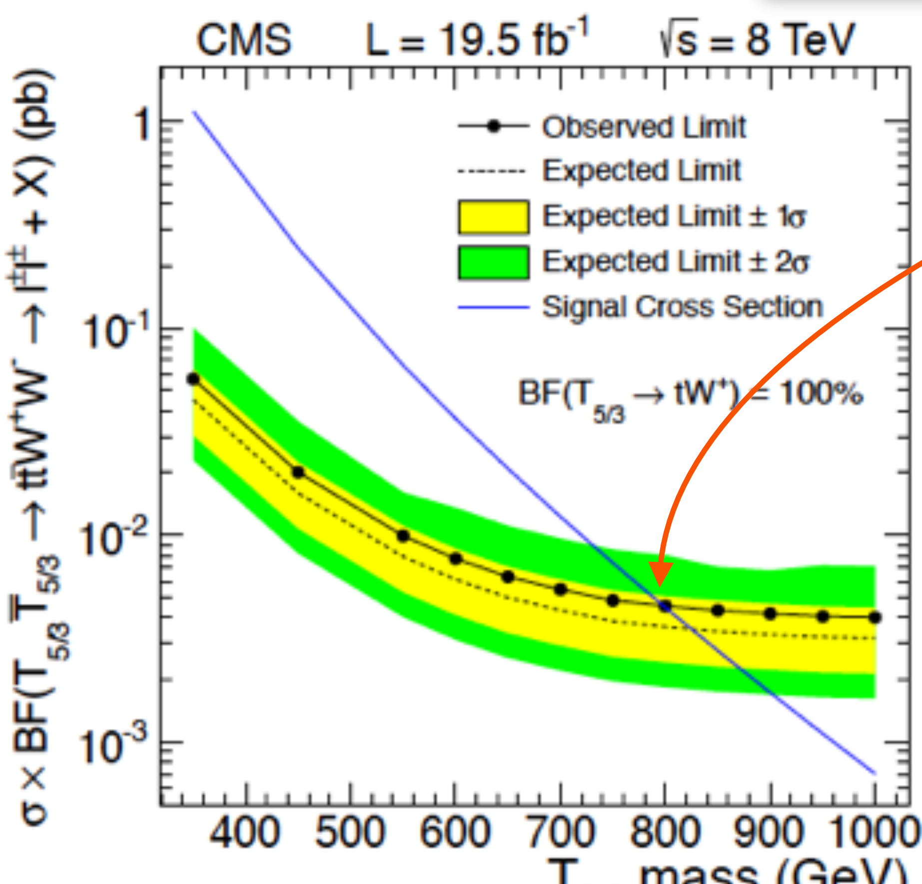
same-sign dileptons



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

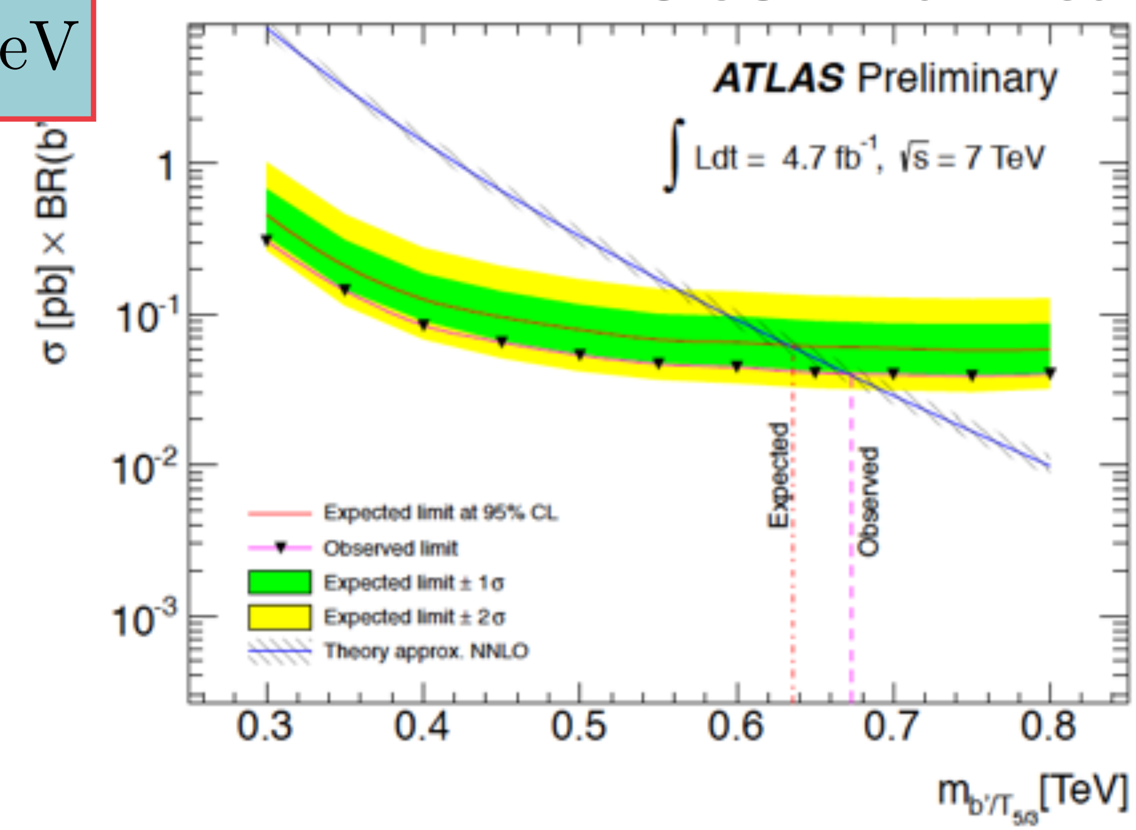
CMS top tag

10.1103/PhysRevLett.112.171801



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

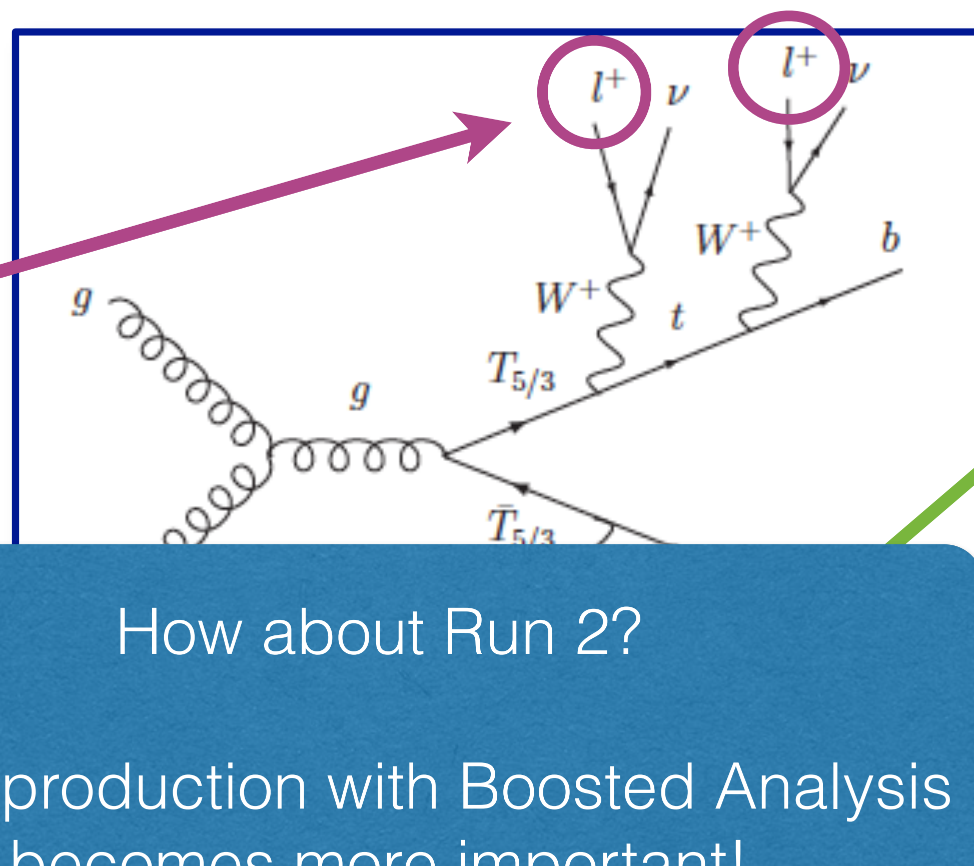
ATLAS-CONF-2012-130



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

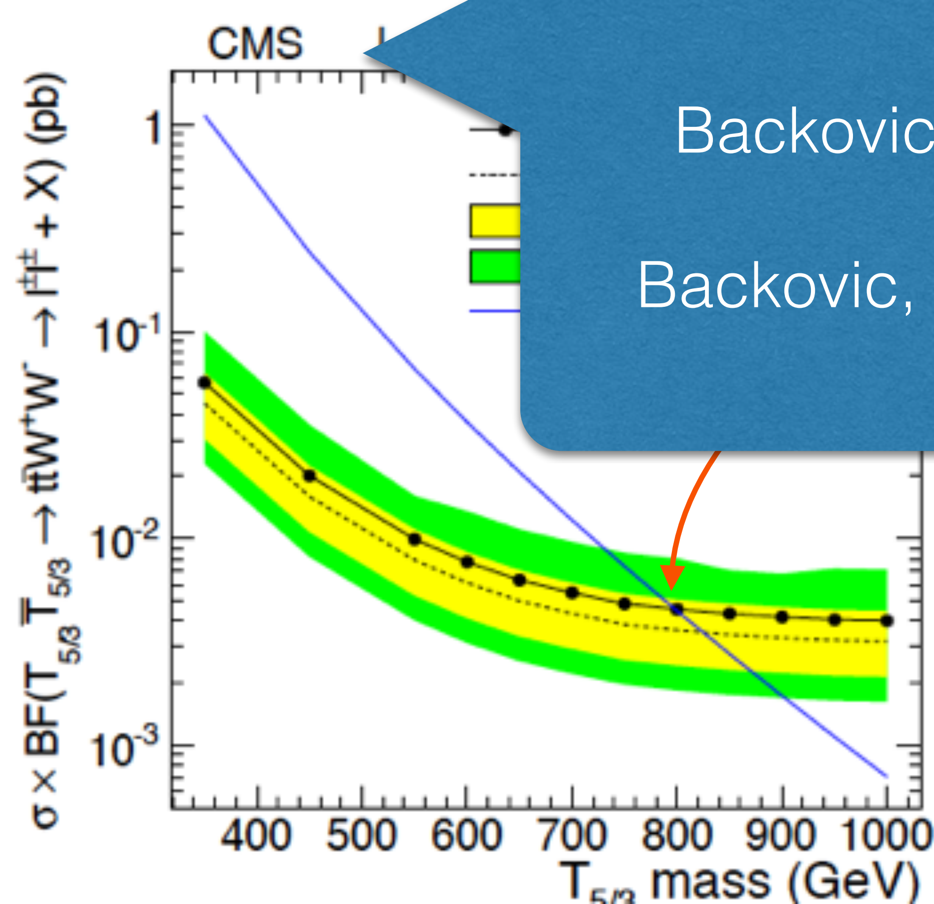
How about Run 2?

Single production with Boosted Analysis becomes more important!

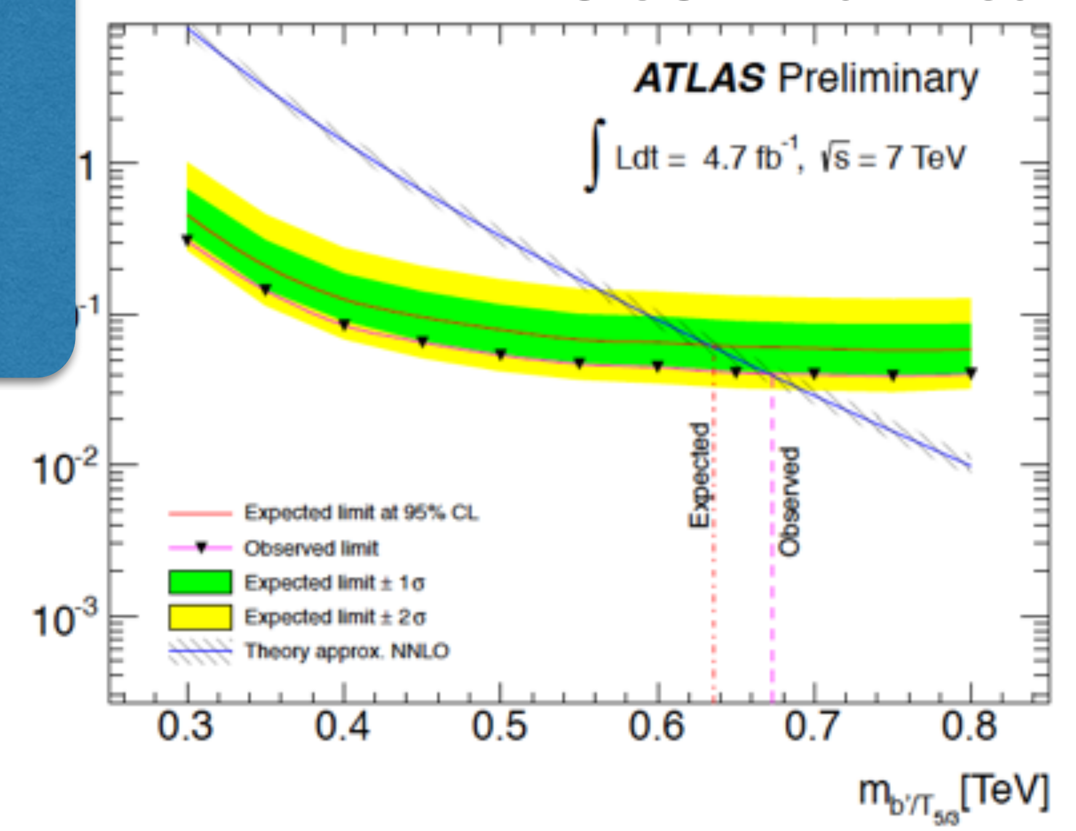
Backovic, Flacke, SL, Perez `14

Backovic, Flacke, Kim, SL (x2),`15

10.1103/PhysRevLett.11



ATLAS-CONF-2012-130



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 top quark partner resonances are assumed to be in the 5 of SO(5)

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

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 $Y = T_R^3 + X$

	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)

General Set-up

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

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

* 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

General Set-up

✱ BSM particle content: 5 = 4 + 1 $Y = T_R^3 + X$

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

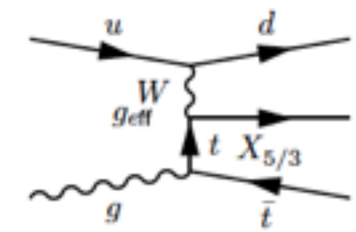
In this talk, I will focus on partially composite quarks scenario

✱ Two principal ways to embed the right-handed up-type quarks:

- In the elementary sector, which mix with their partners, (→ "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

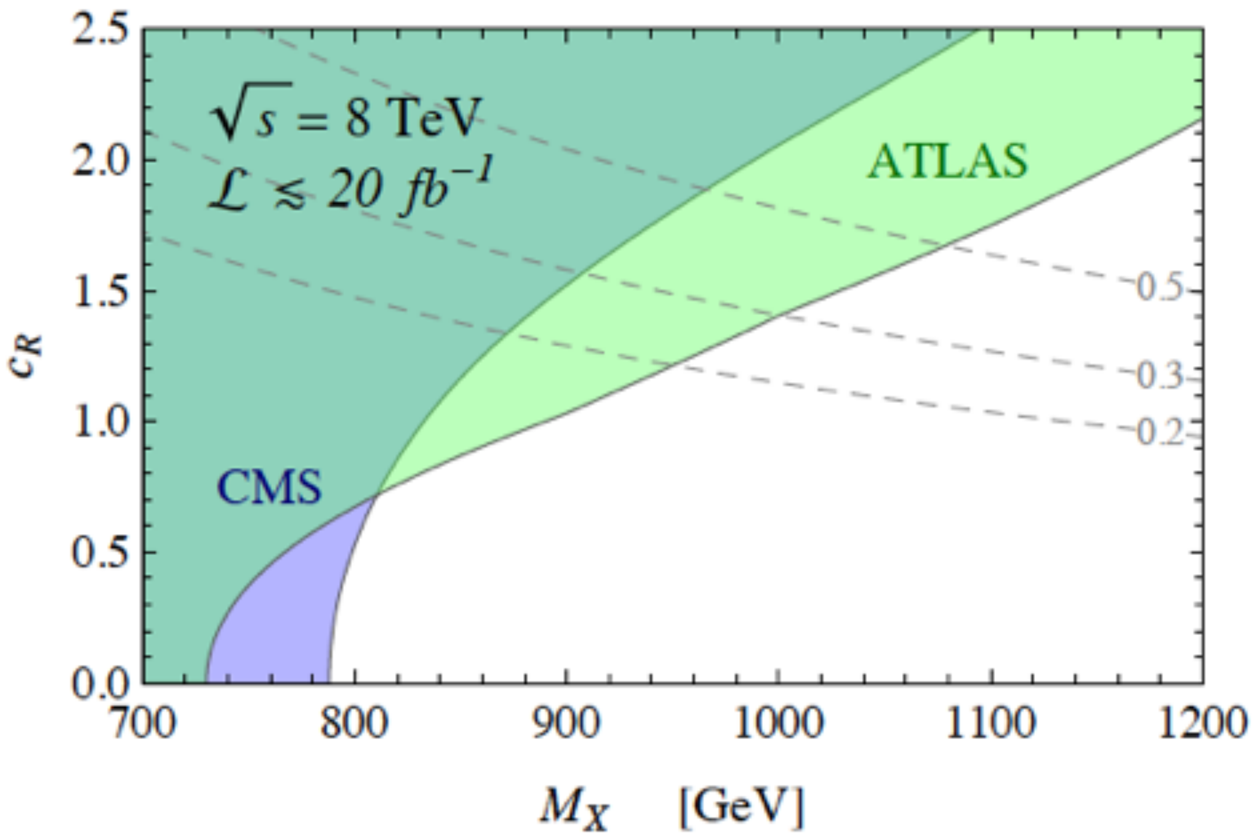
Top partners @ Run 2 of the LHC

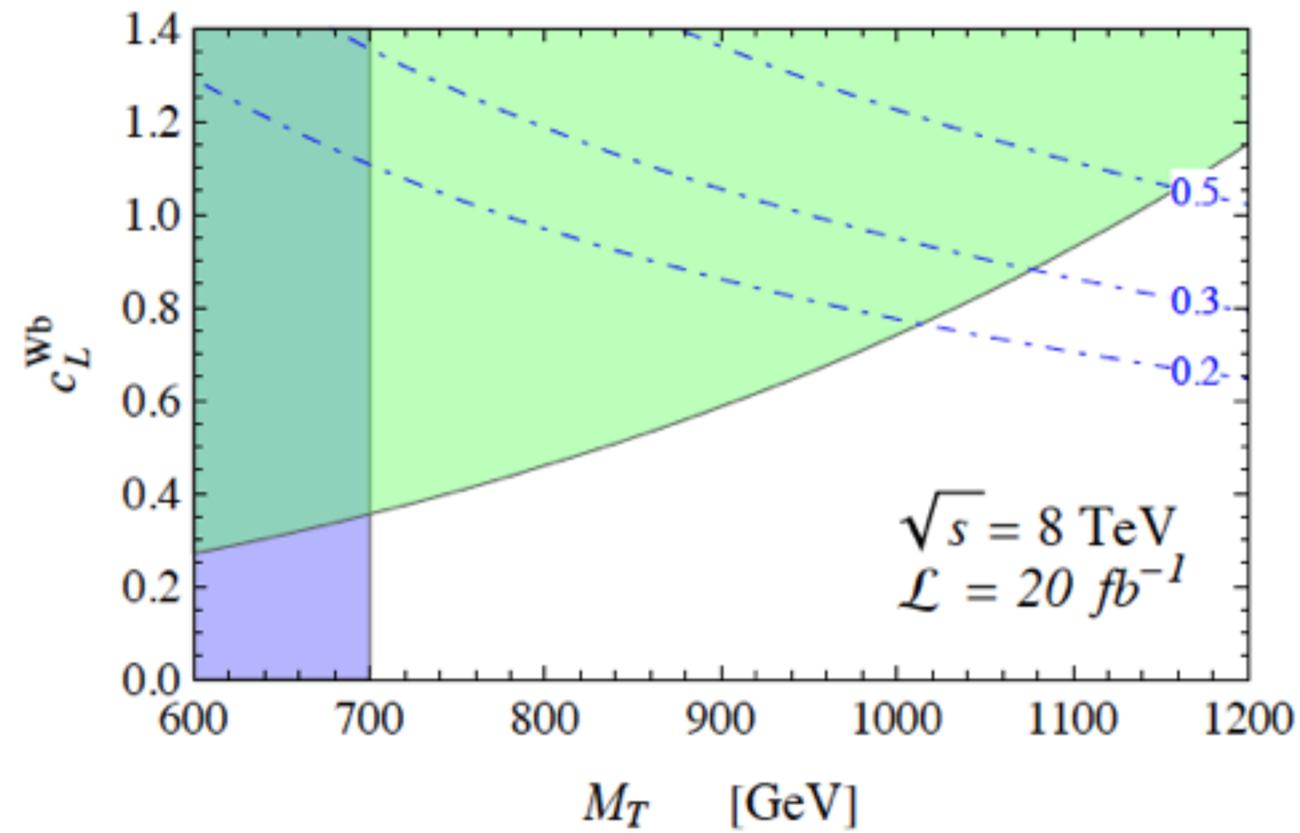
- Current bounds including single-production channels from same sign lepton searches:



Matsedonski, Panico, Wulzer `14

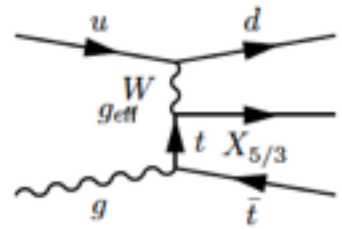
Azatov, Son, Spannowsky `13 (for boosted analysis for run I)





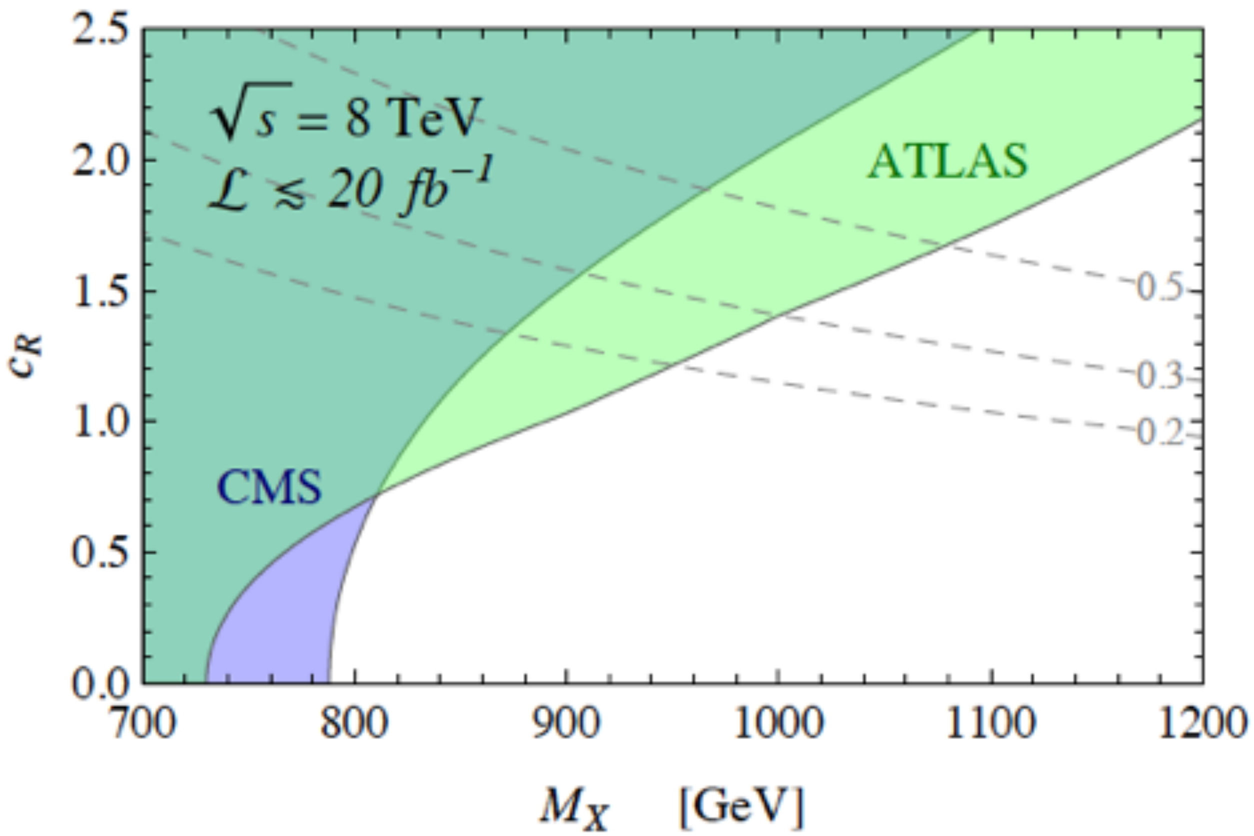
Top partners @ Run 2 of the LHC

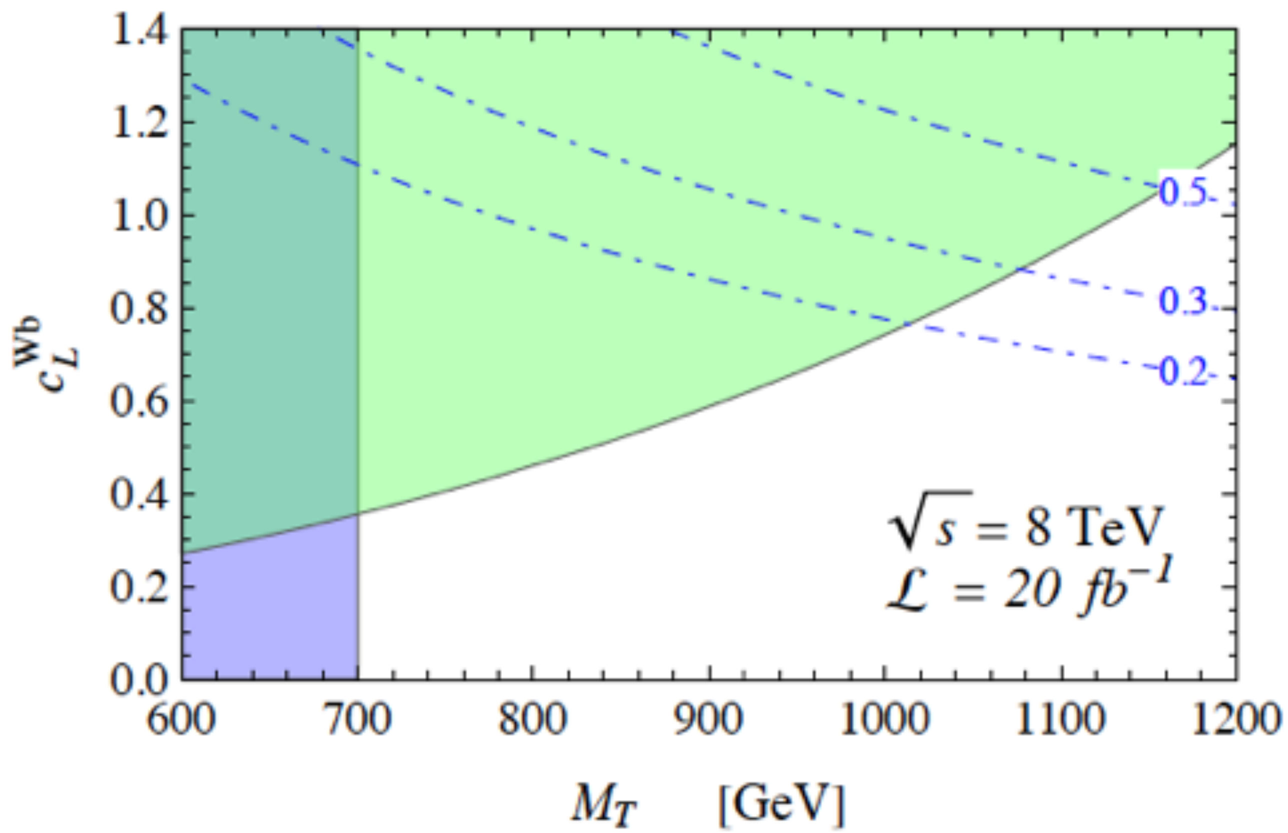
- Current bounds including single-production channels from same sign lepton searches:



Matsedonski, Panico, Wulzer `14

Azatov, Son, Spannowsky `13 (for boosted analysis for run I)

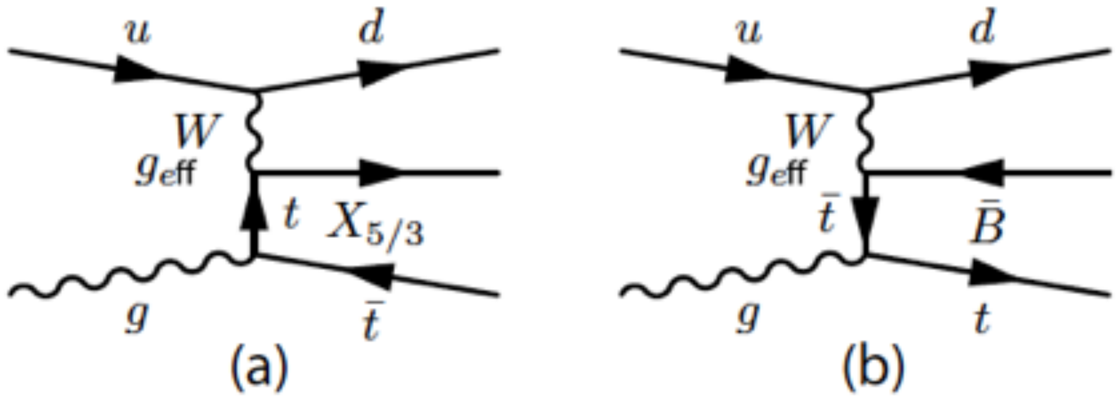




- Game changer for run II: boosted analysis for single production   Backovic, Flacke, SL, Perez `14

Top Partner Searches @ Run II

Backovic, Flacke, SL, Perez `14

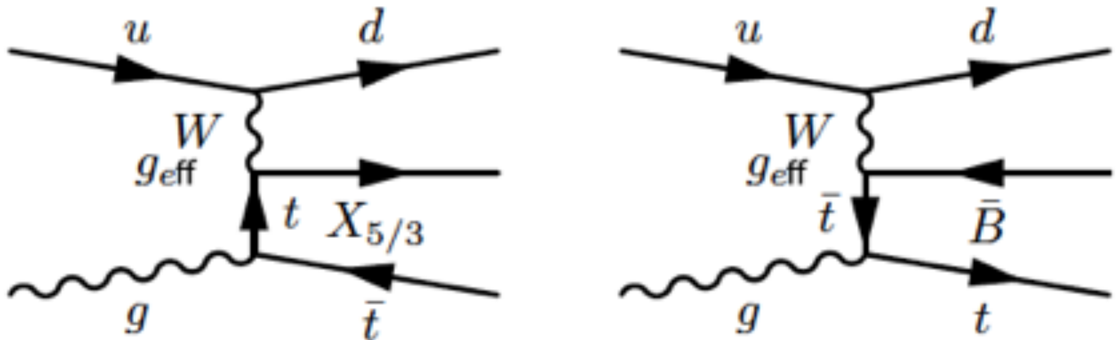


$$D_\mu \tilde{\psi}_4 = (\partial_\mu + i e_\mu - i g' X B_\mu - i g_s G_\mu)\tilde{\psi}_4$$

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

Top Partner Searches @ Run II

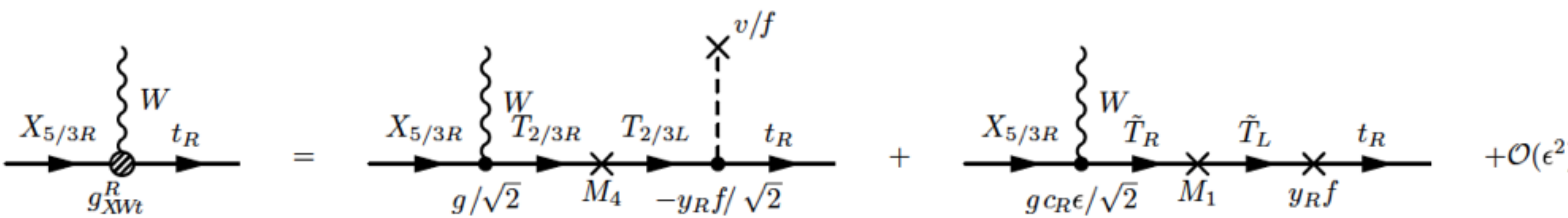
Backovic, Flacke, SL, Perez `14



(a) (b)

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

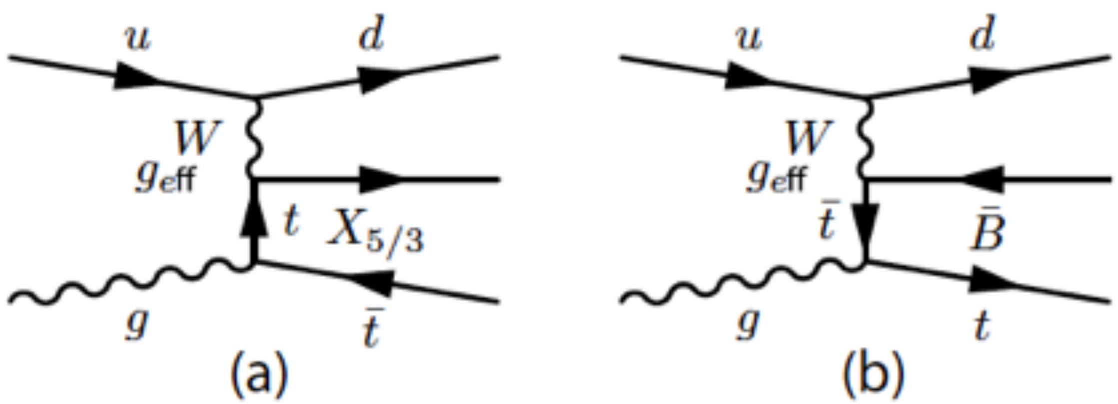
$$\begin{aligned}
\mathcal{L} = &+ i\bar{q}'_L \not{D} q'_L + i\bar{t}'_R \not{D} t'_R + i\bar{b}'_R \not{D} b'_R \\
&+ i\bar{\tilde{\psi}}_4 \not{D} \tilde{\psi}_4 + i\bar{\tilde{\psi}}_1 \not{D} \tilde{\psi}_1 - M_4 \bar{\tilde{\psi}}_4 \tilde{\psi}_4 - M_1 e^{i\phi} \bar{\tilde{\psi}}_1 \tilde{\psi}_1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



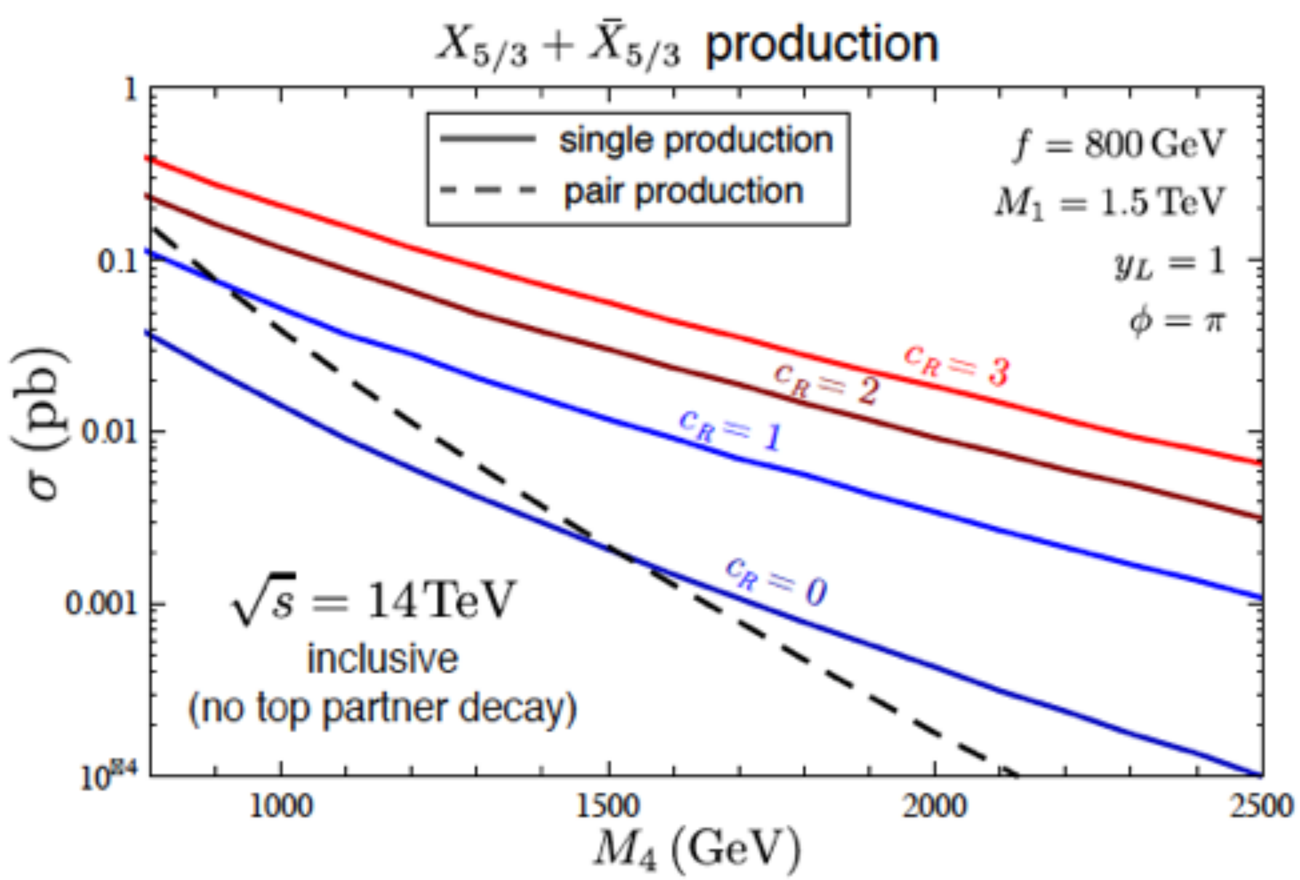
$$\begin{aligned}
g^L_{XWt} &= G^X_{L\,i}\left(U^t_L\right)^\dagger_{i1} = \mathcal{O}(\epsilon^2)\,, \\
g^R_{XWt} &= G^X_{R\,i}\left(U^t_R\right)^\dagger_{i1} = \frac{g}{\sqrt{2}}\left(U^{*t}_{R\,13} + c_R \epsilon U^{*t}_{R\,14}\right) + \mathcal{O}(\epsilon^2)\,, \\
&= -\frac{g e^{-i\tilde{\phi}}}{\sqrt{2}}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

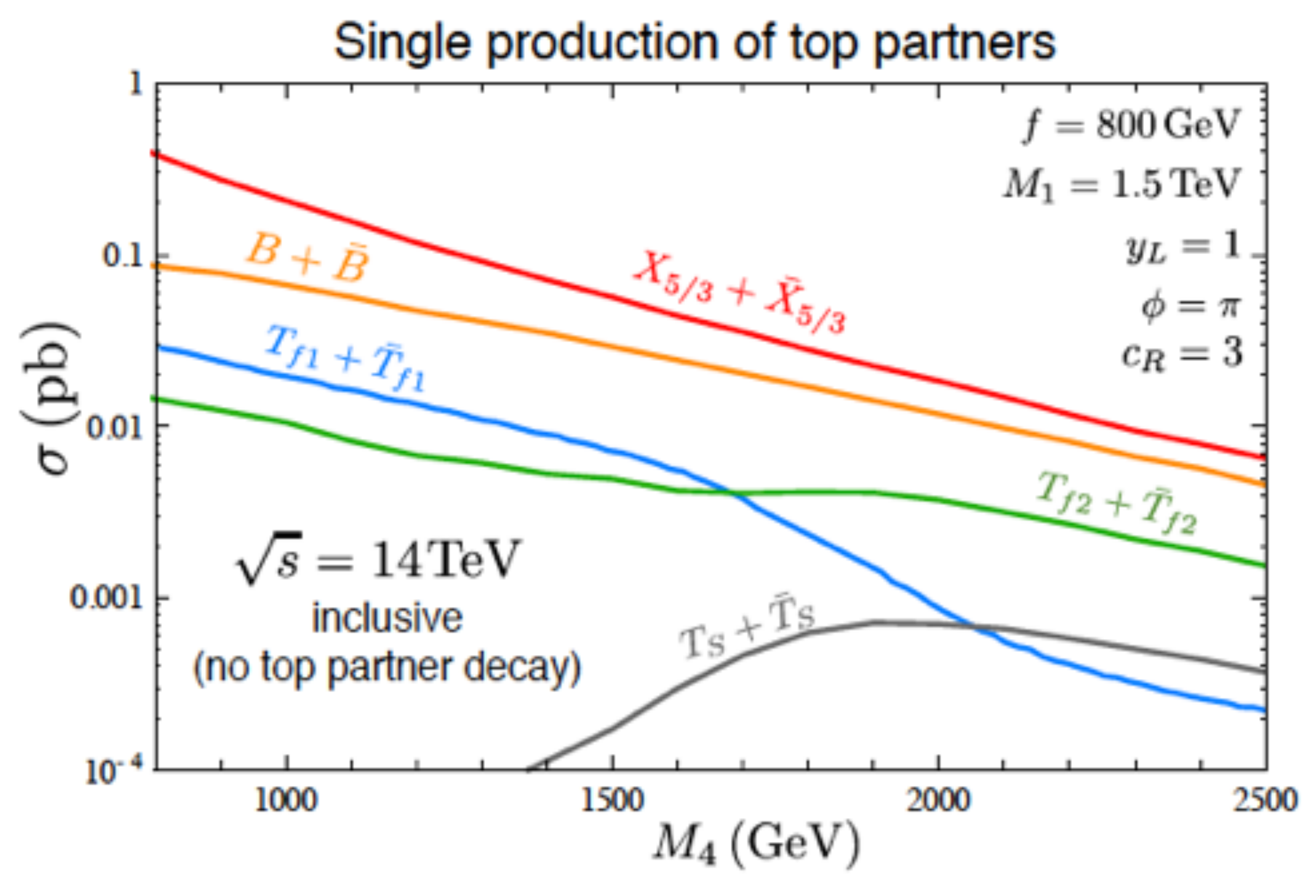
Top Partner Searches @ Run II

Backovic. Flacke. SL. Perez `14



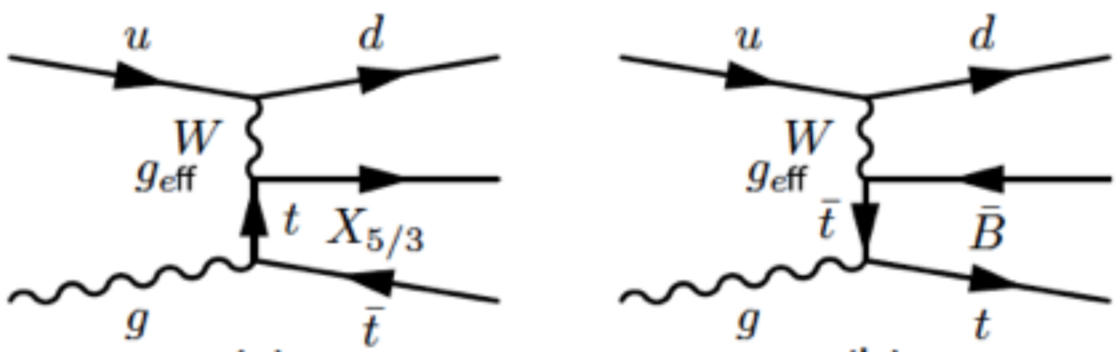
$$
\begin{aligned}
m_t &= \frac{v}{\sqrt{2}} \frac{|M_1 - e^{-i\phi} M_4|}{f} \frac{y_L f}{\sqrt{M_4 + y_L^2 f^2}} \frac{y_R f}{\sqrt{|M_1|^2 + y_R^2 f^2}} + \mathcal{O}(\epsilon^3), \\
M_B &= \sqrt{M_4^2 + y_L^2 f^2}, \\
M_{X_{5/3}} &= M_4, \\
M_{Tf1} &= M_4 + \mathcal{O}(\epsilon^2), \\
M_{Tf2} &=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





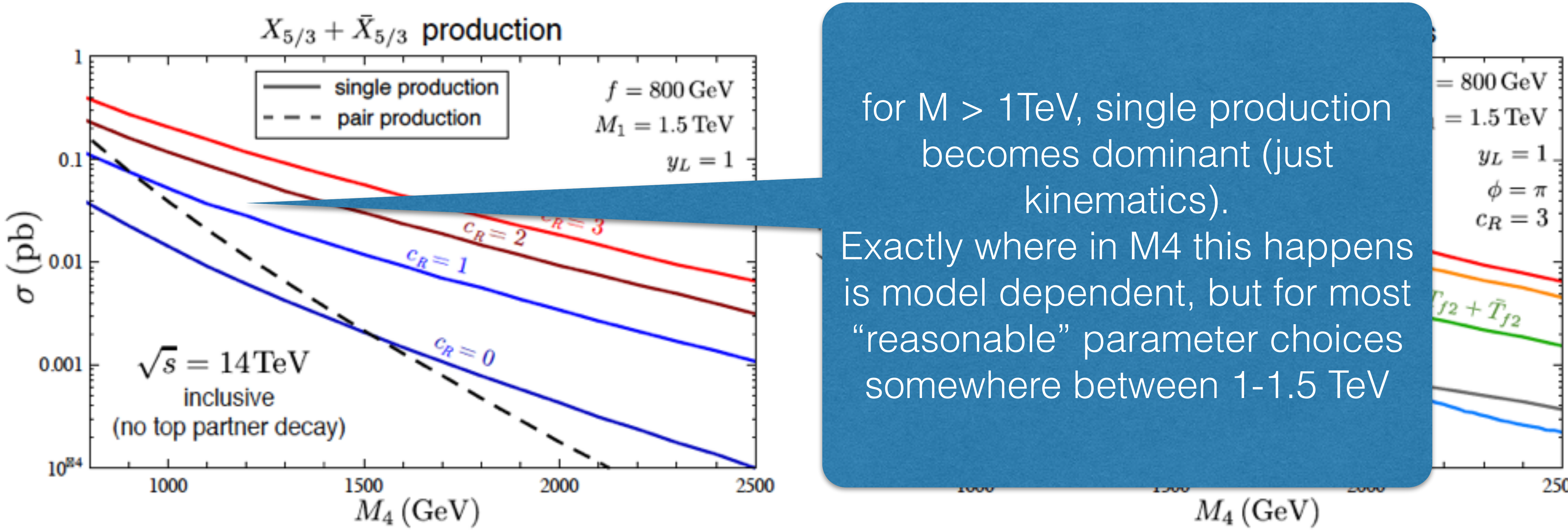
Top Partner Searches @ Run II

Backovic. Flacke. SL. Perez `14



(a) (b)

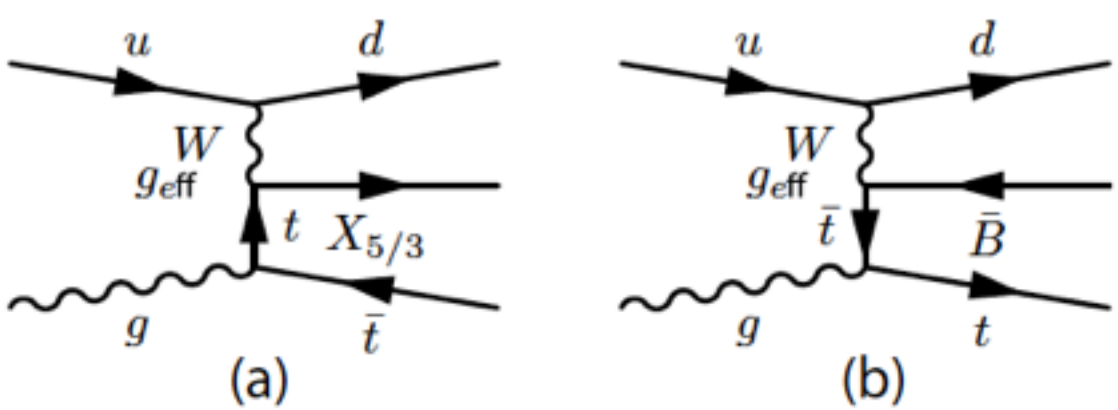
$$
\begin{aligned}
m_t &= \frac{v}{\sqrt{2}} \frac{|M_1 - e^{-i\phi} M_4|}{f} \frac{y_L f}{\sqrt{M_4 + y_L^2 f^2}} \frac{y_R f}{\sqrt{|M_1|^2 + y_R^2 f^2}} + \mathcal{O}(\epsilon^3), \\
M_B &= \sqrt{M_4^2 + y_L^2 f^2}, \\
M_{X_{5/3}} &= M_4, \\
M_{Tf1} &= M_4 + \mathcal{O}(\epsilon^2), \\
M_{Tf2} &=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



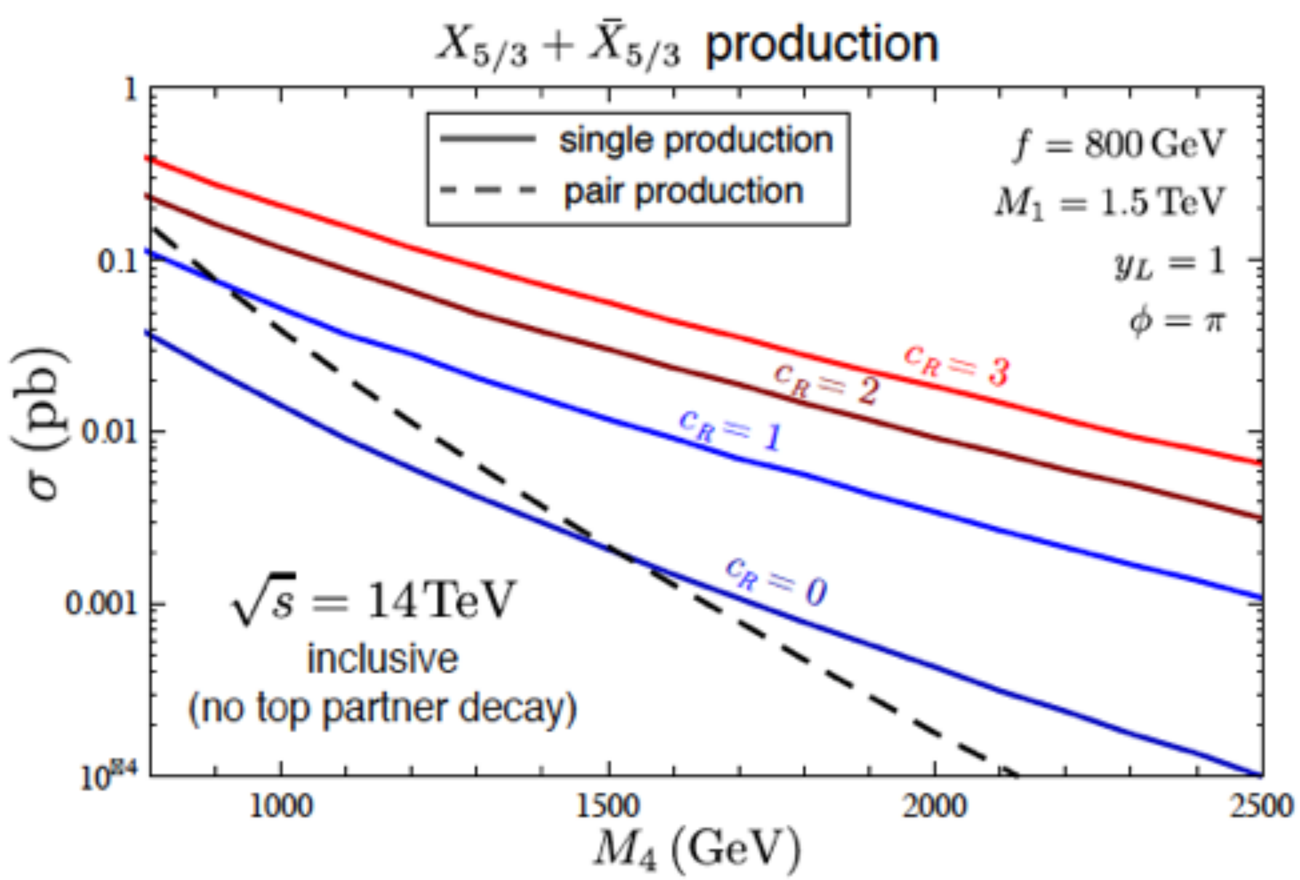
for M > 1TeV, single production becomes dominant (just kinematics).
Exactly where in M4 this happens is model dependent, but for most "reasonable" parameter choices somewhere between 1-1.5 TeV

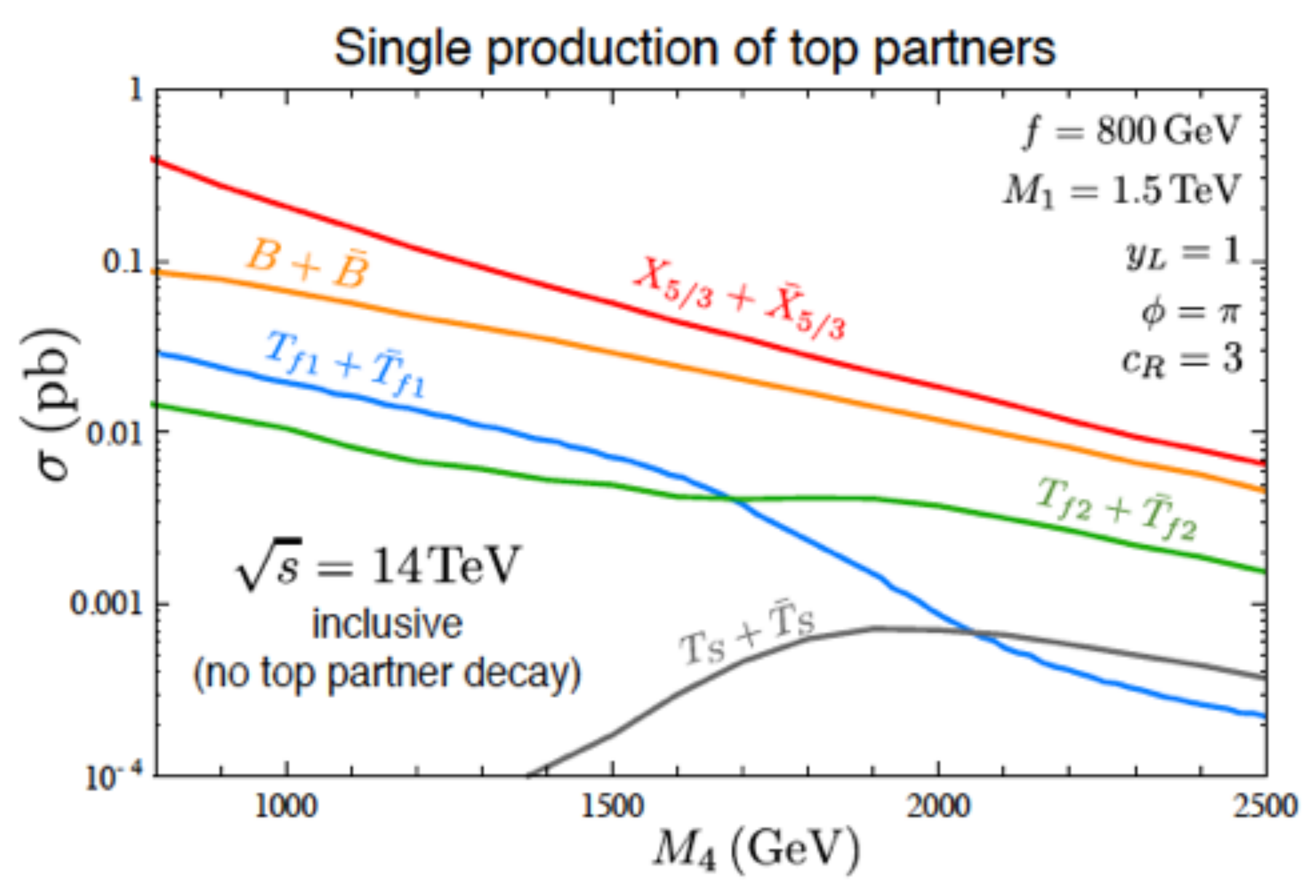
Top Partner Searches @ Run II

Backovic. Flacke. SL. Perez `14



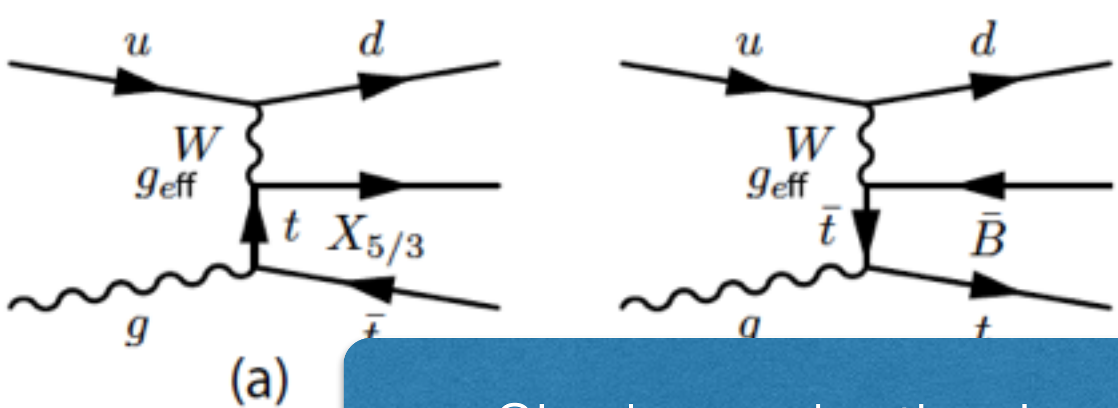
$$
\begin{aligned}
m_t &= \frac{v}{\sqrt{2}} \frac{|M_1 - e^{-i\phi} M_4|}{f} \frac{y_L f}{\sqrt{M_4 + y_L^2 f^2}} \frac{y_R f}{\sqrt{|M_1|^2 + y_R^2 f^2}} + \mathcal{O}(\epsilon^3), \\
M_B &= \sqrt{M_4^2 + y_L^2 f^2}, \\
M_{X_{5/3}} &= M_4, \\
M_{Tf1} &= M_4 + \mathcal{O}(\epsilon^2), \\
M_{Tf2} &=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





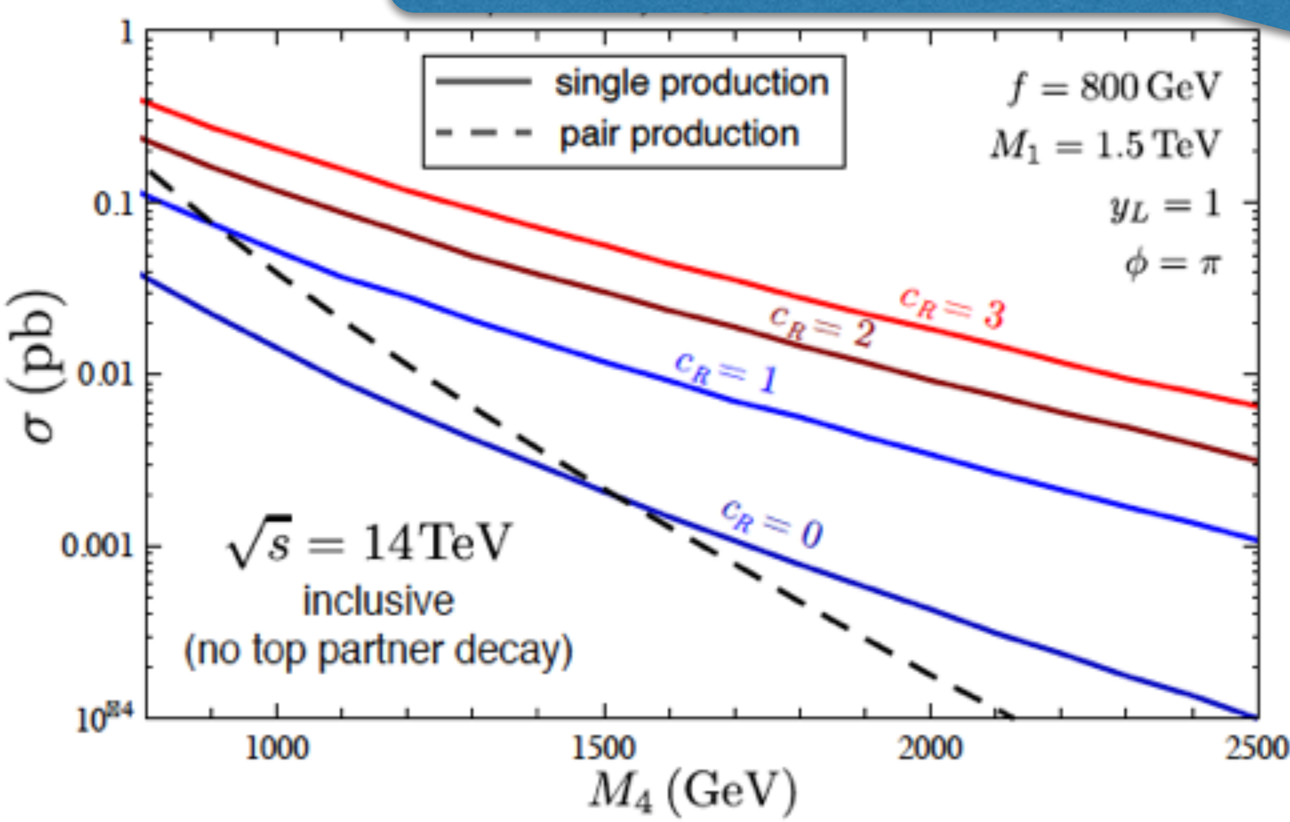
Top Partner Searches @ Run II

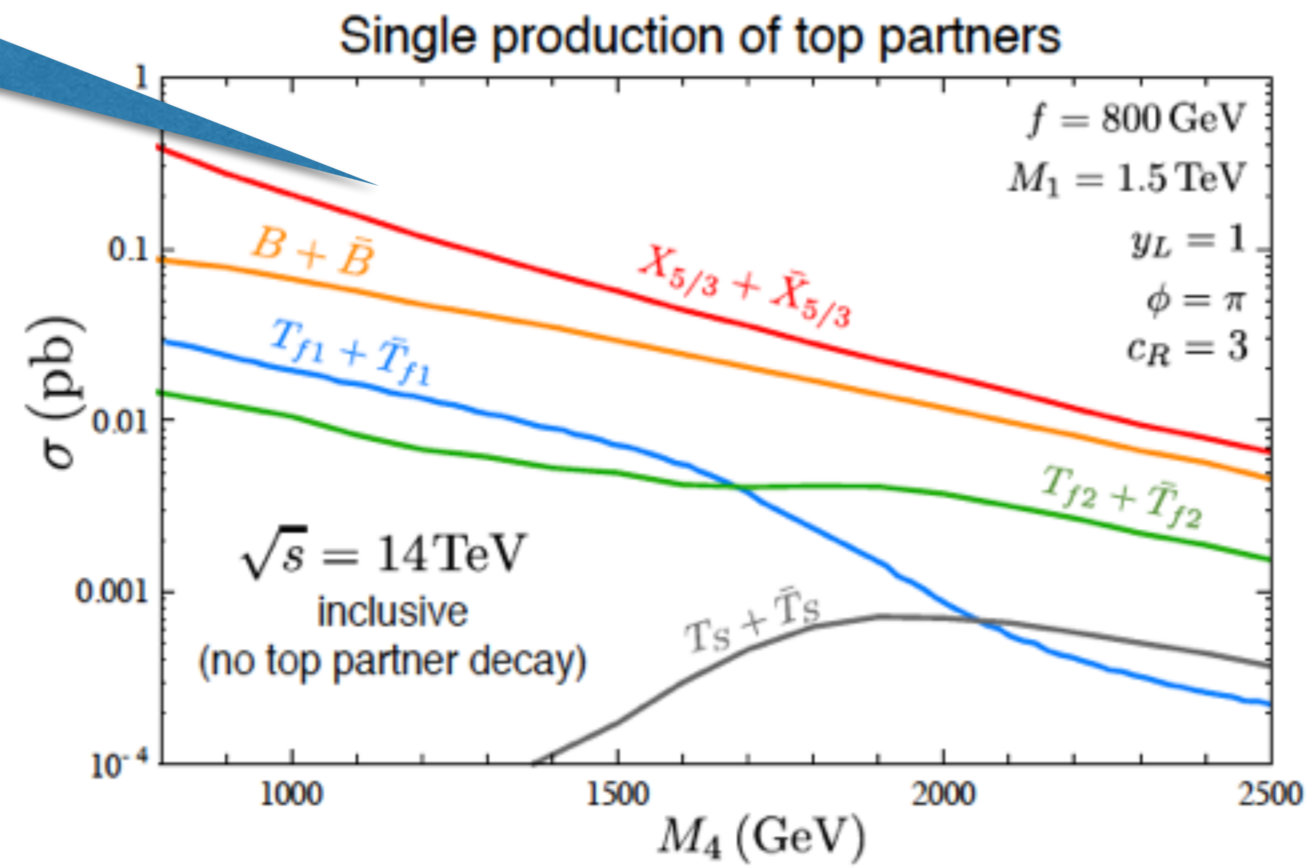
Backovic. Flacke. SL. Perez `14



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

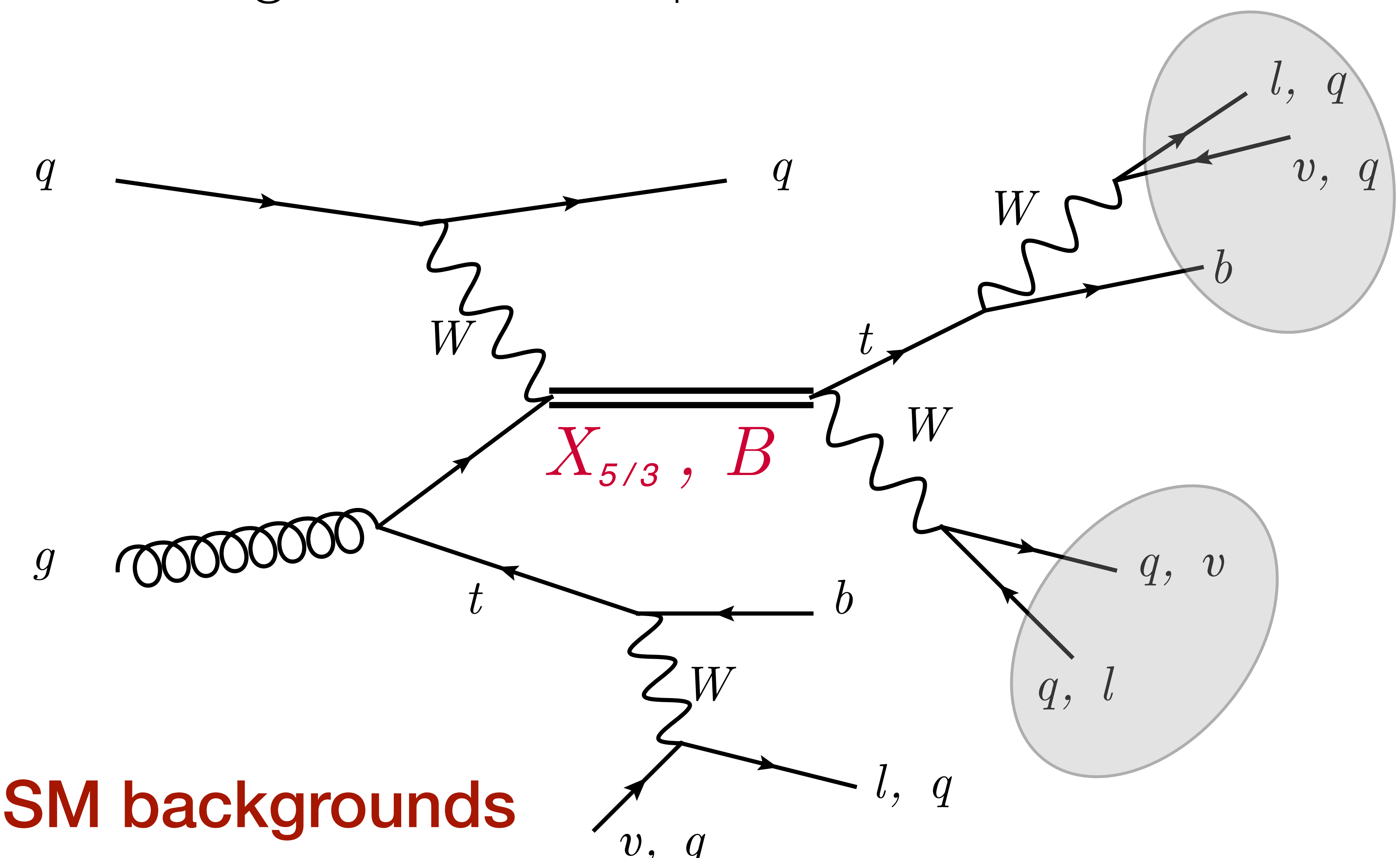
Single production is dominated by X5/3 and B partners.





Top Partner Searches @ Run II

- Single production of top partners might looks complicated



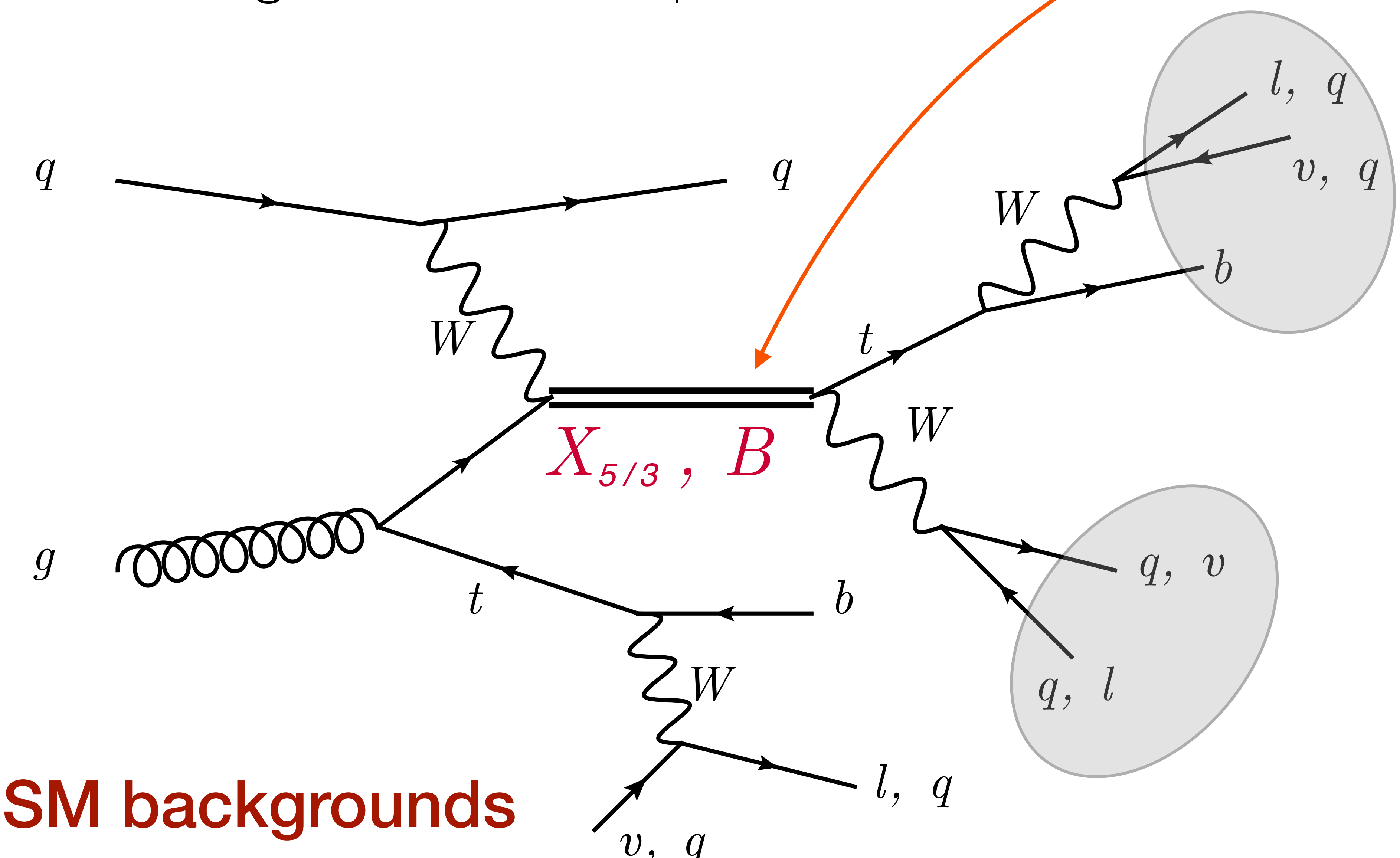
Large **SM backgrounds** (di-tops, **W**+jets, …)

Backovic, Flacke, SL, Perez `14

Top Partner Searches @ Run II

- Single production of top partners might looks complicated

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



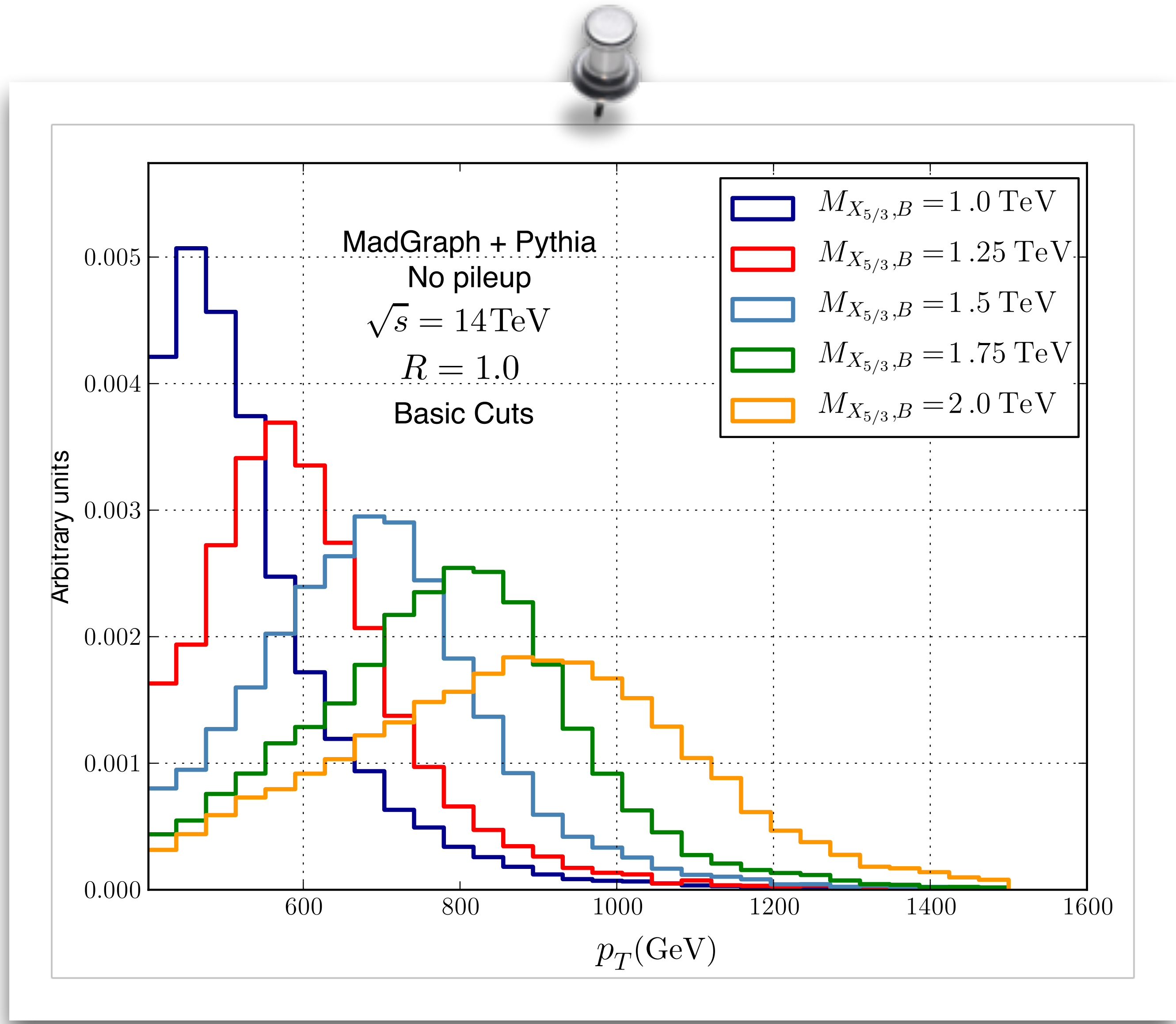
Large **SM backgrounds**
(di-tops, **W**+jets, …)

Backovic, Flacke, SL, Perez `14

Top Partner Searches Beyond the 2 TeV Mass Region

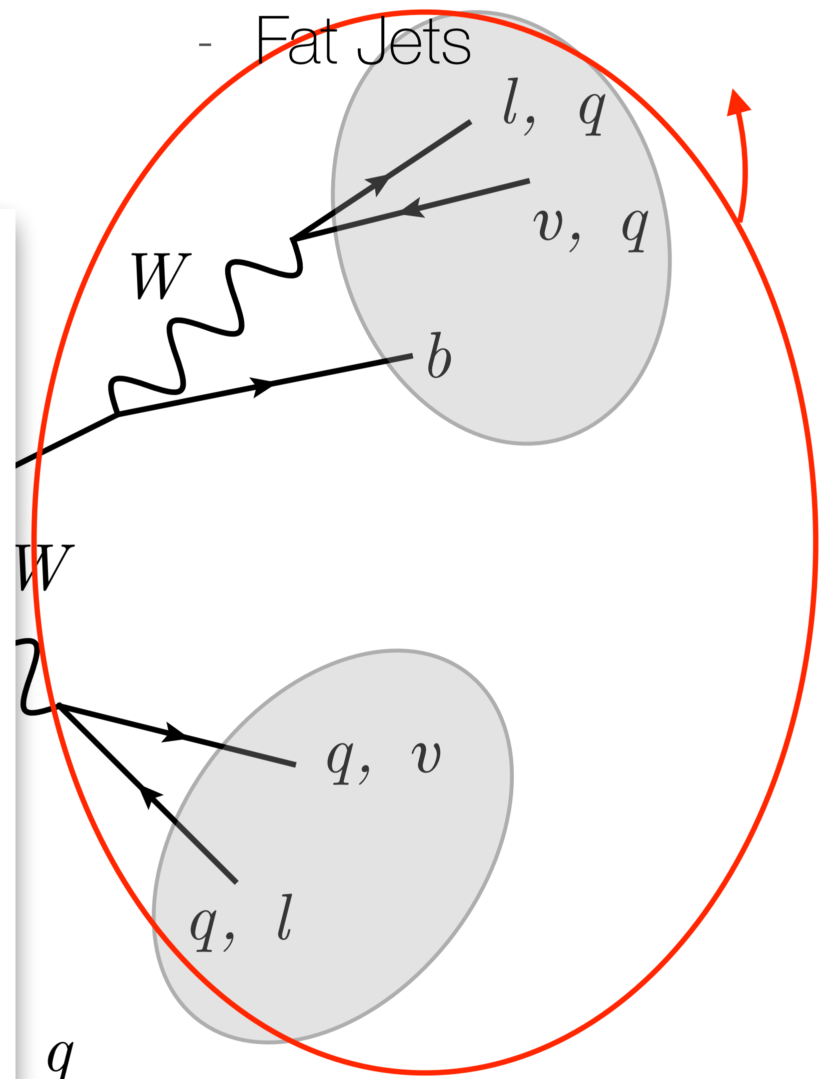
Unique event topology!

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



Boosted t / W

- Hard Lepton
- Missing Energy
- Fat Jets

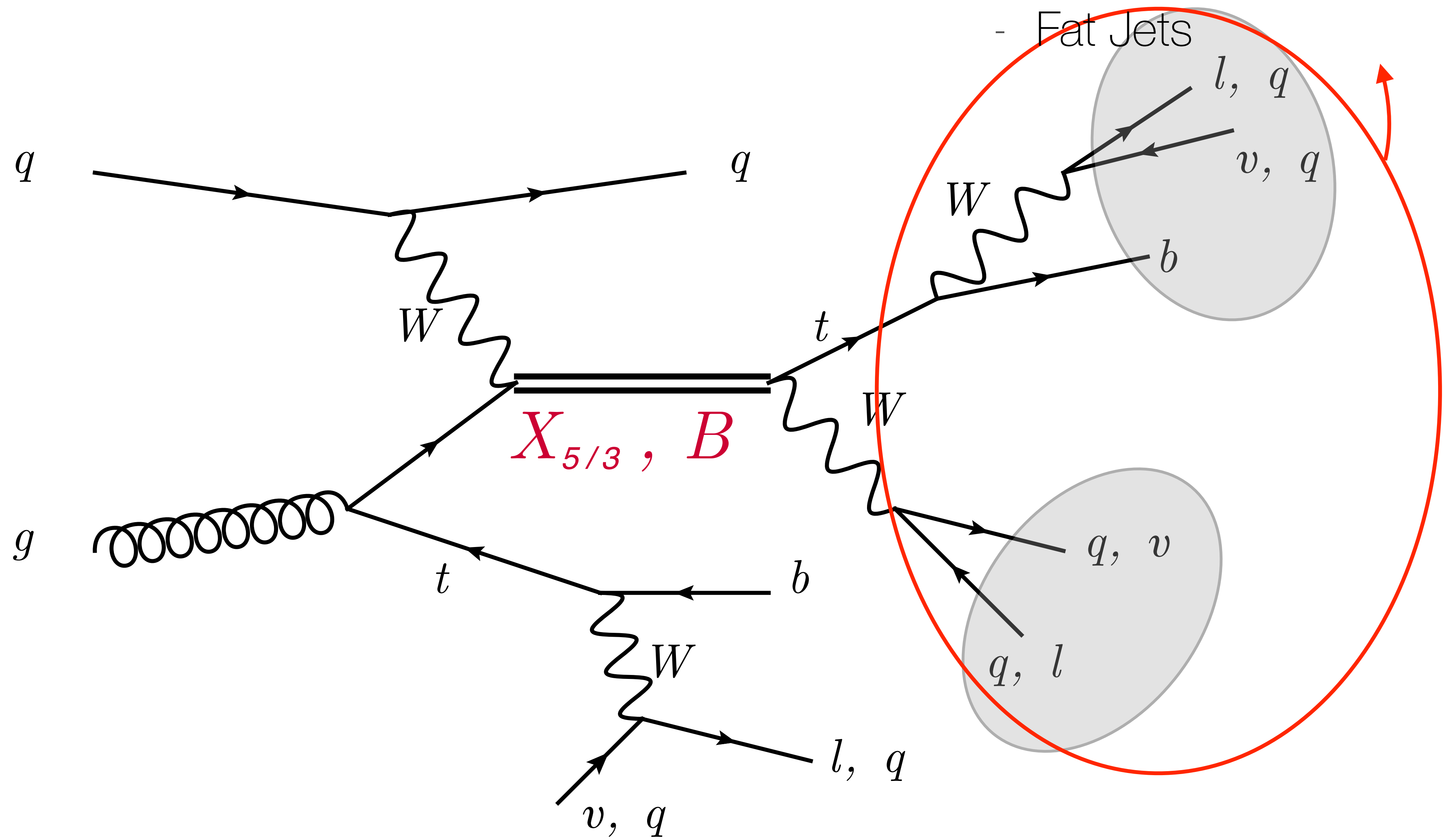


Backovic, Flacke, SL, Perez `14

Top Partner Searches Beyond the 2 TeV Mass Region

Boosted t / W

- Hard Lepton
- Missing Energy
- Fat Jets



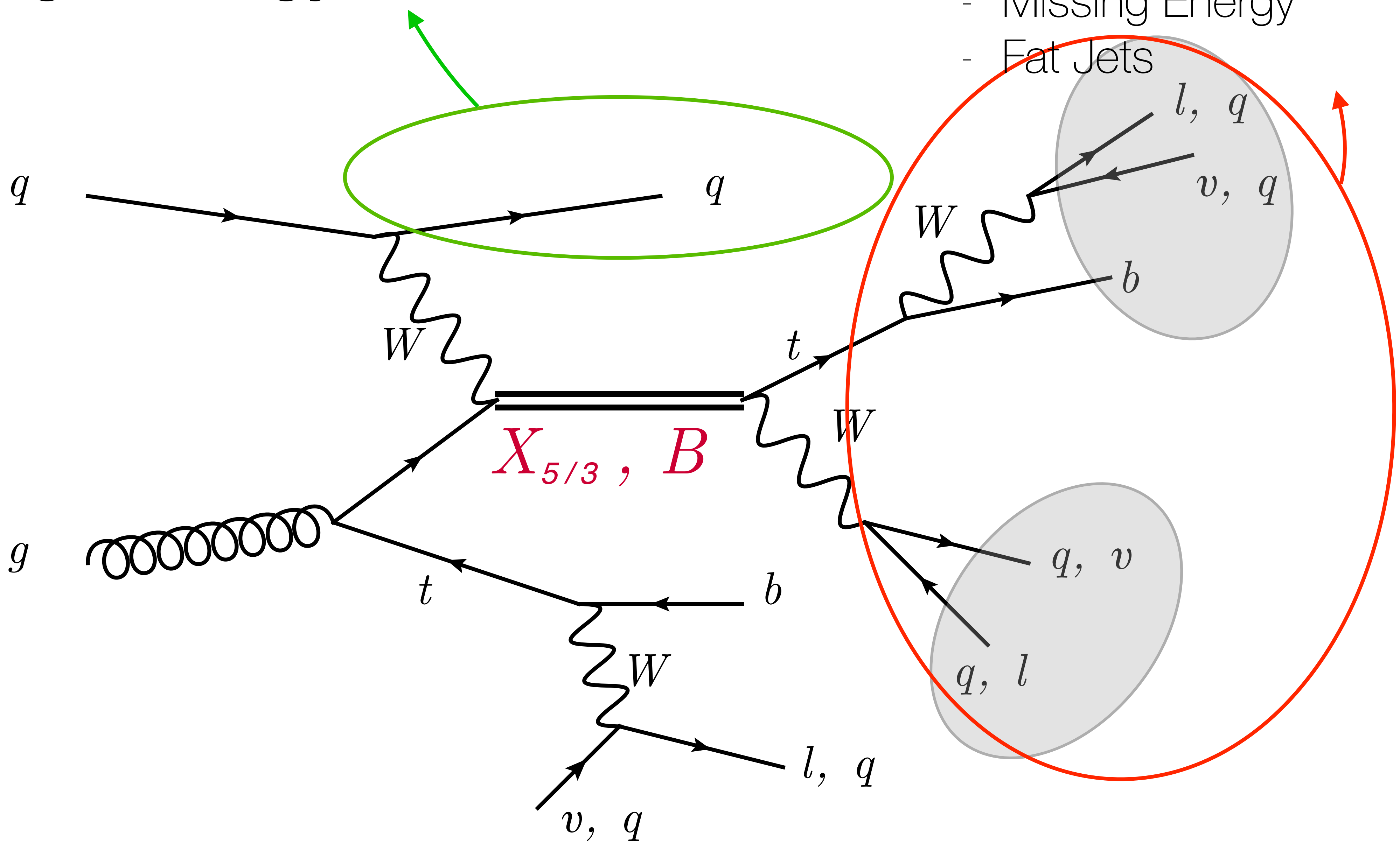
Backovic, Flacke, SL, Perez `14

Top Partner Searches Beyond the 2 TeV Mass Region

Boosted t / W

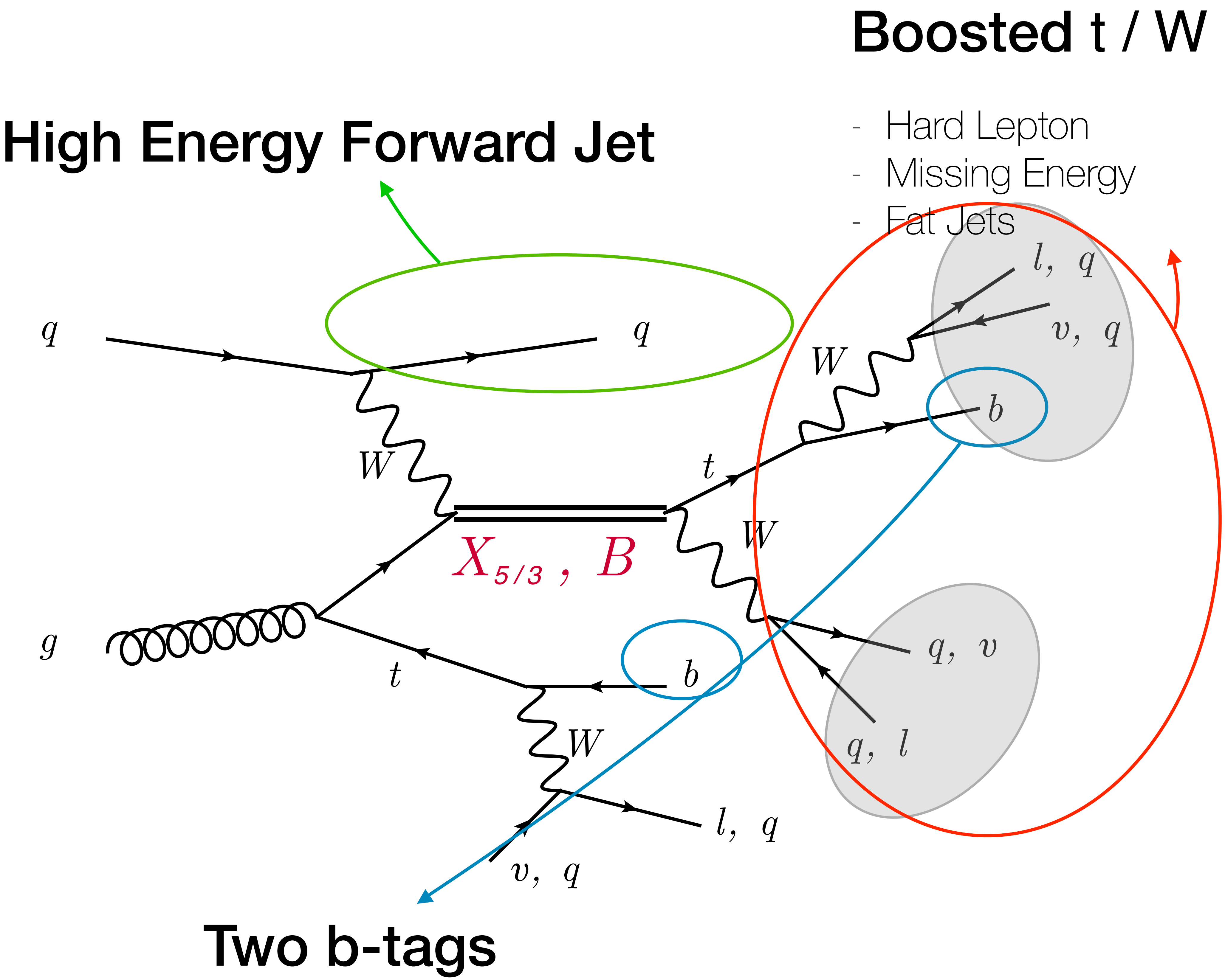
- Hard Lepton
- Missing Energy
- Fat Jets

High Energy Forward Jet



Backovic, Flacke, SL, Perez `14

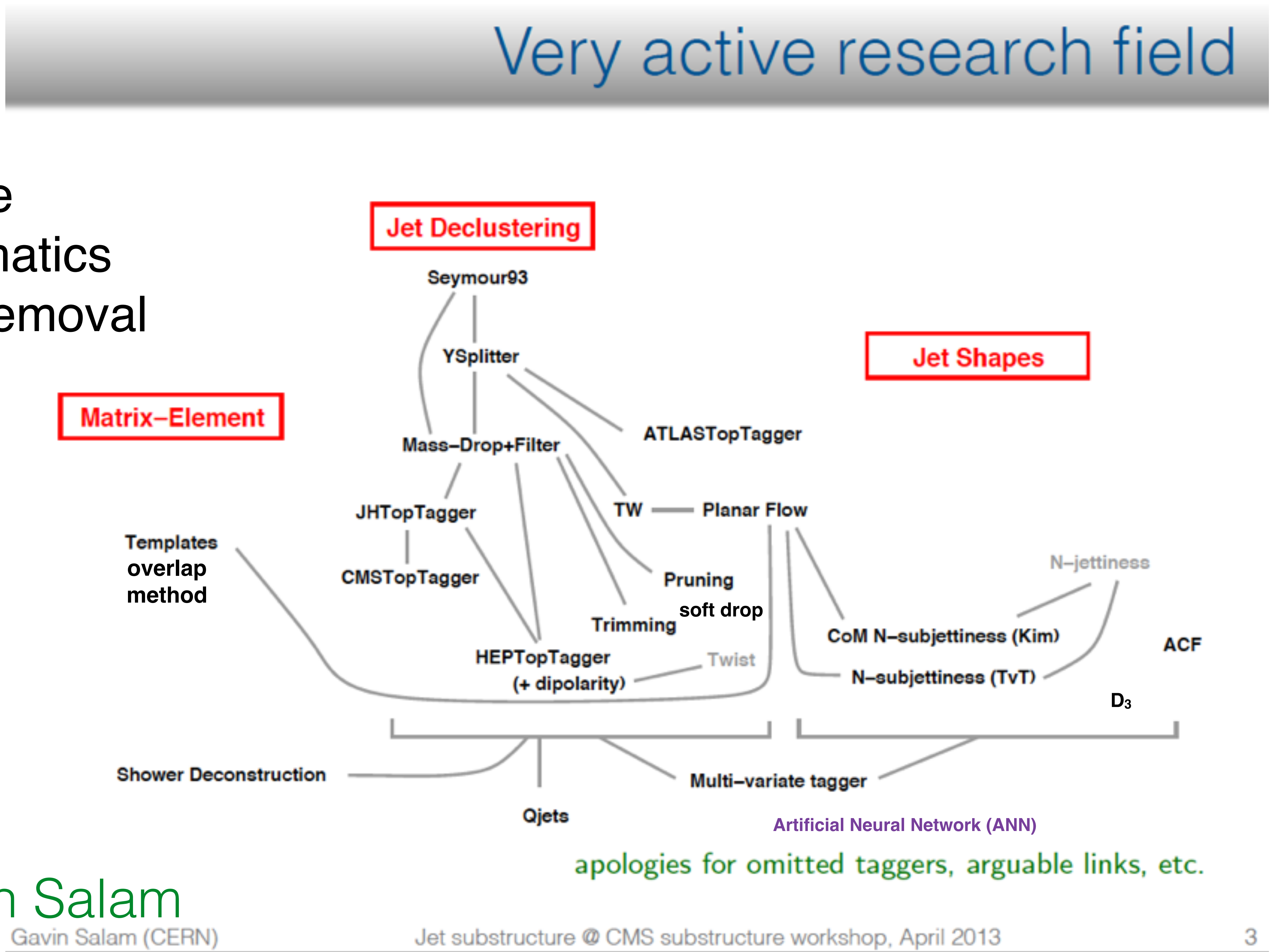
Top Partner Searches Beyond the 2 TeV Mass Region



Backovic, Flacke, SL, Perez `14

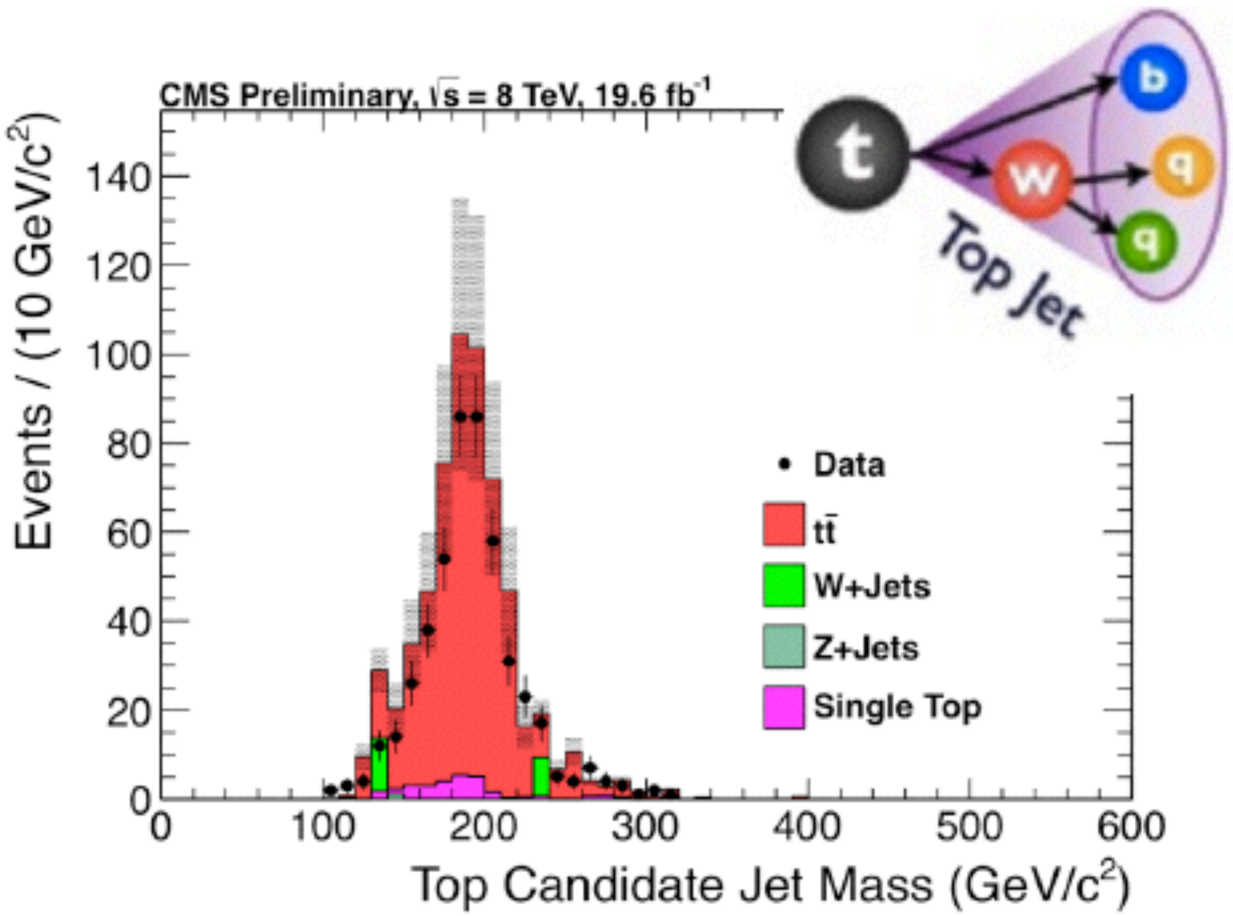
Boosted top tagging: Jet substructure

- Shape
- Kinematics
- Soft removal

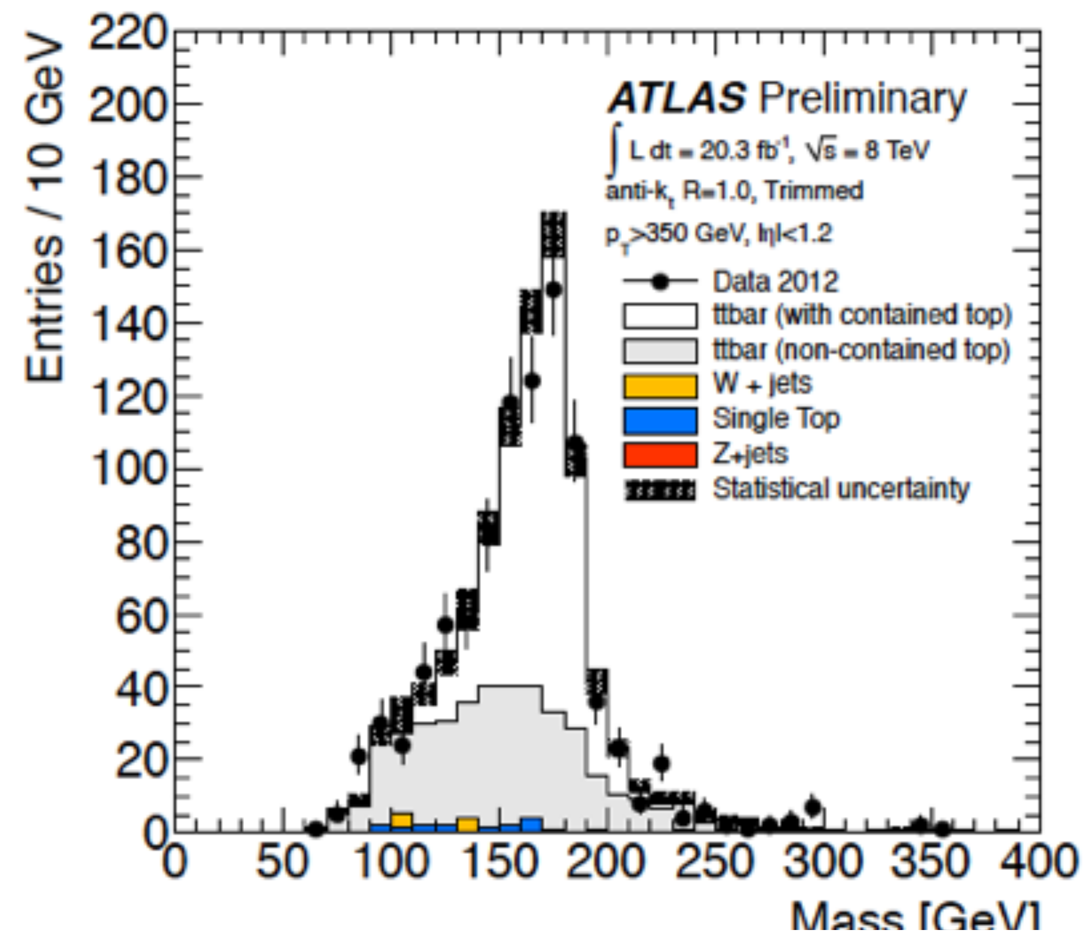


Gavin Salam

Lesson from Run I: it works!

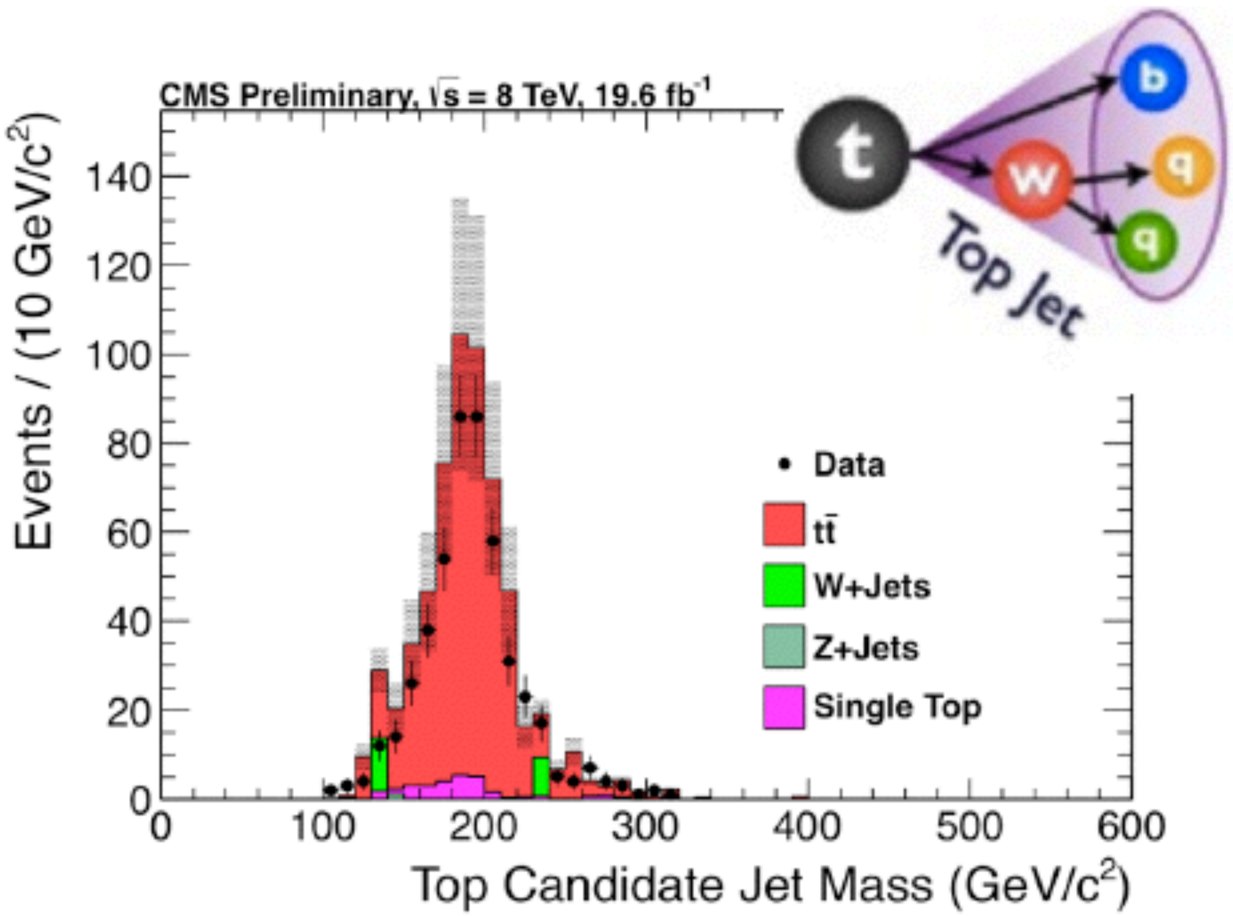


$p_T > 400$ GeV

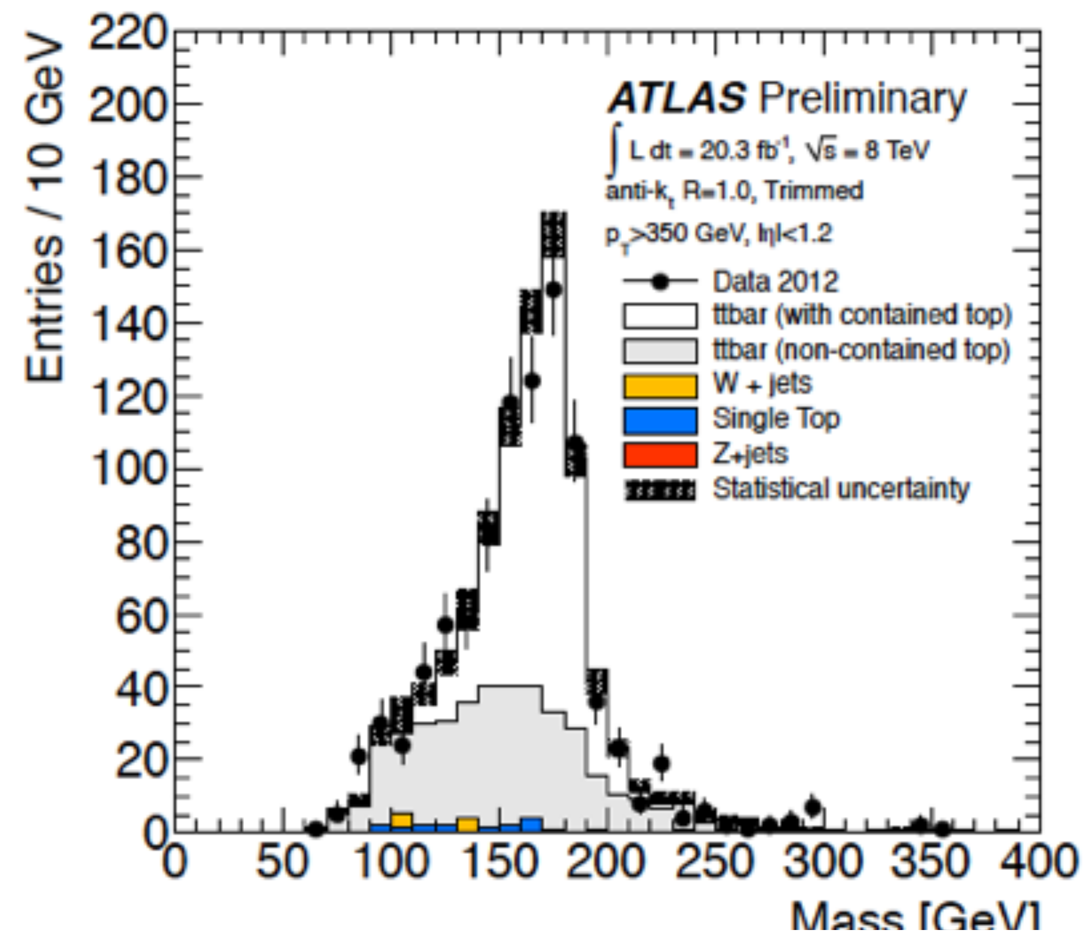


Jet $p_T > 350$ GeV

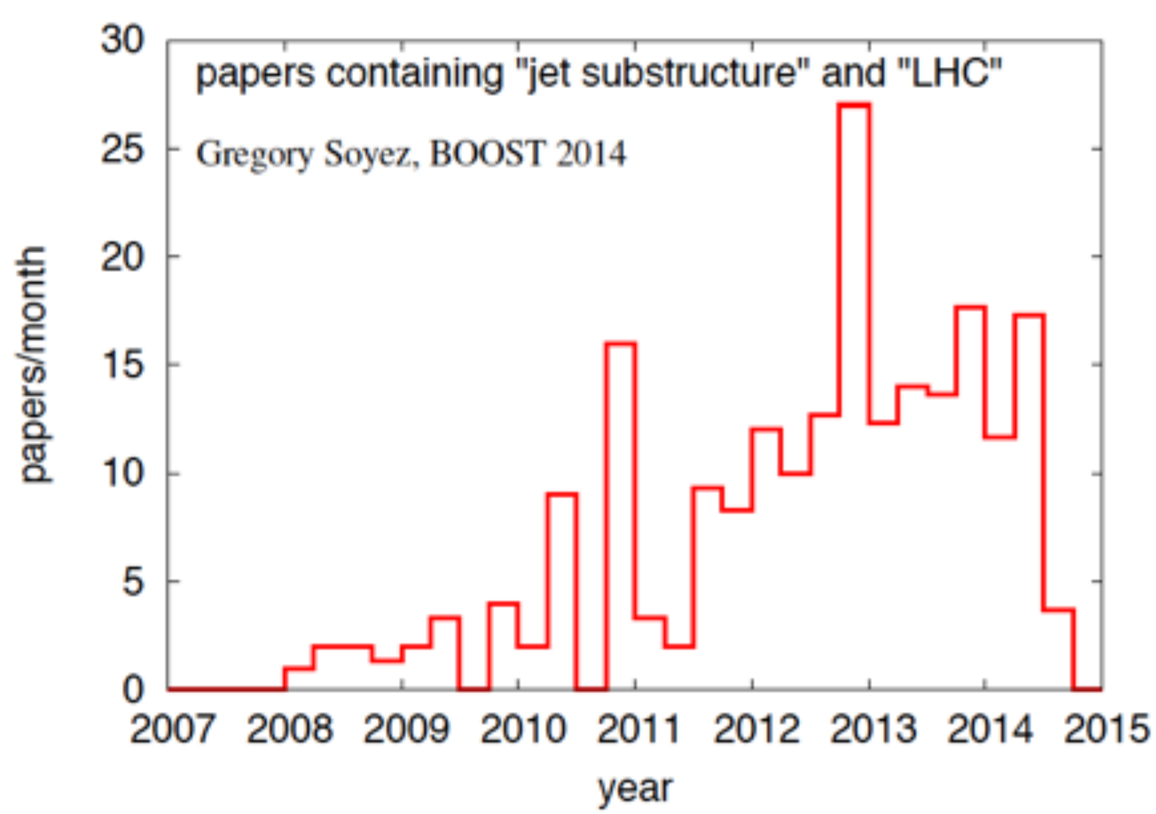
Lesson from Run I: it works!



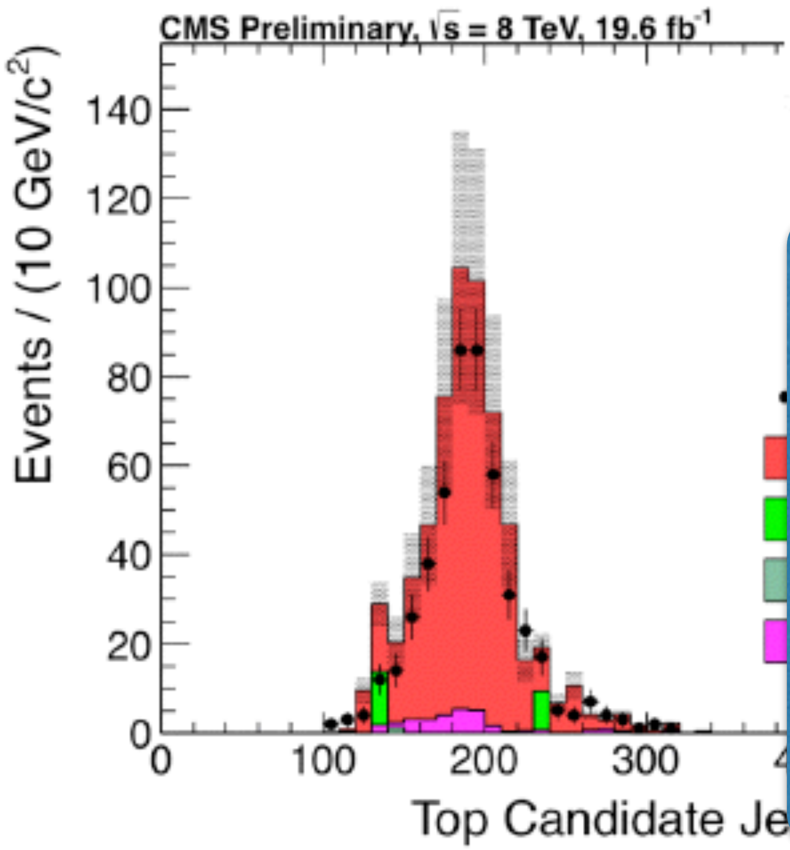
$p_T > 400$ GeV

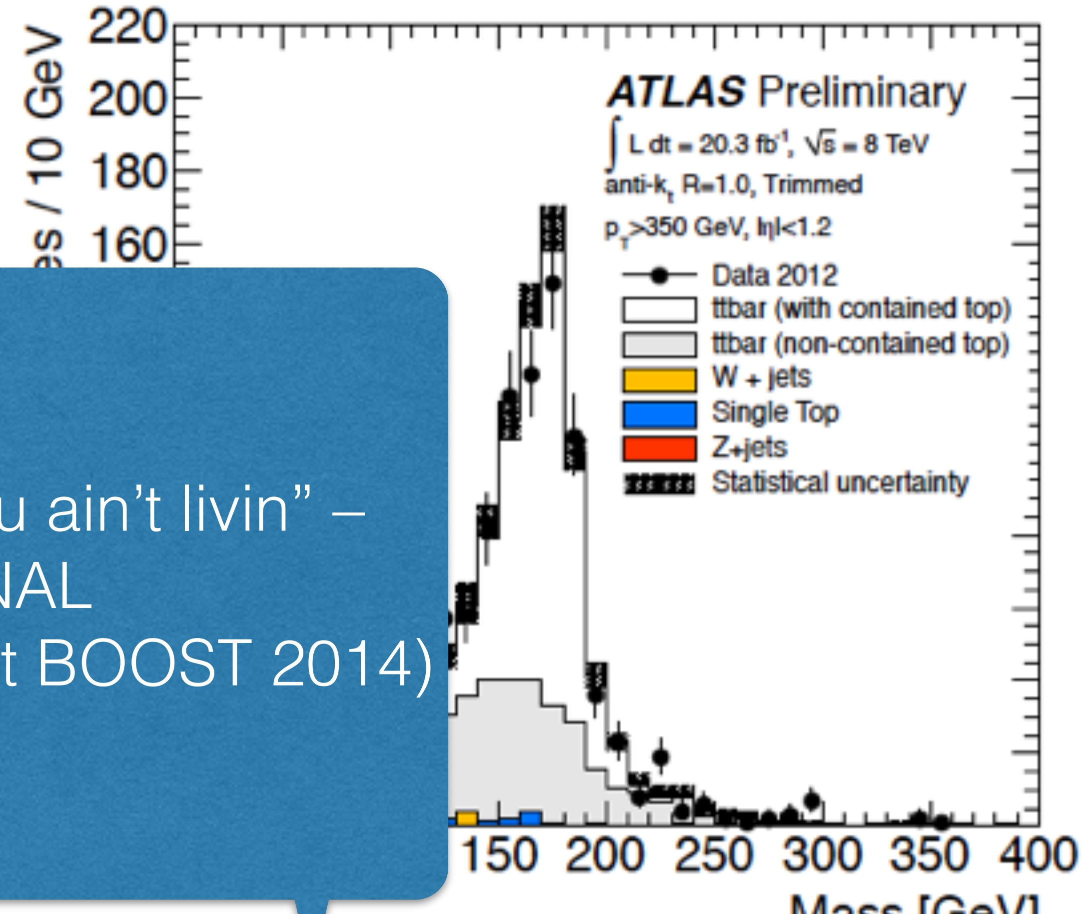


Jet p_T > 350 GeV



Lesson from Run I: it works!

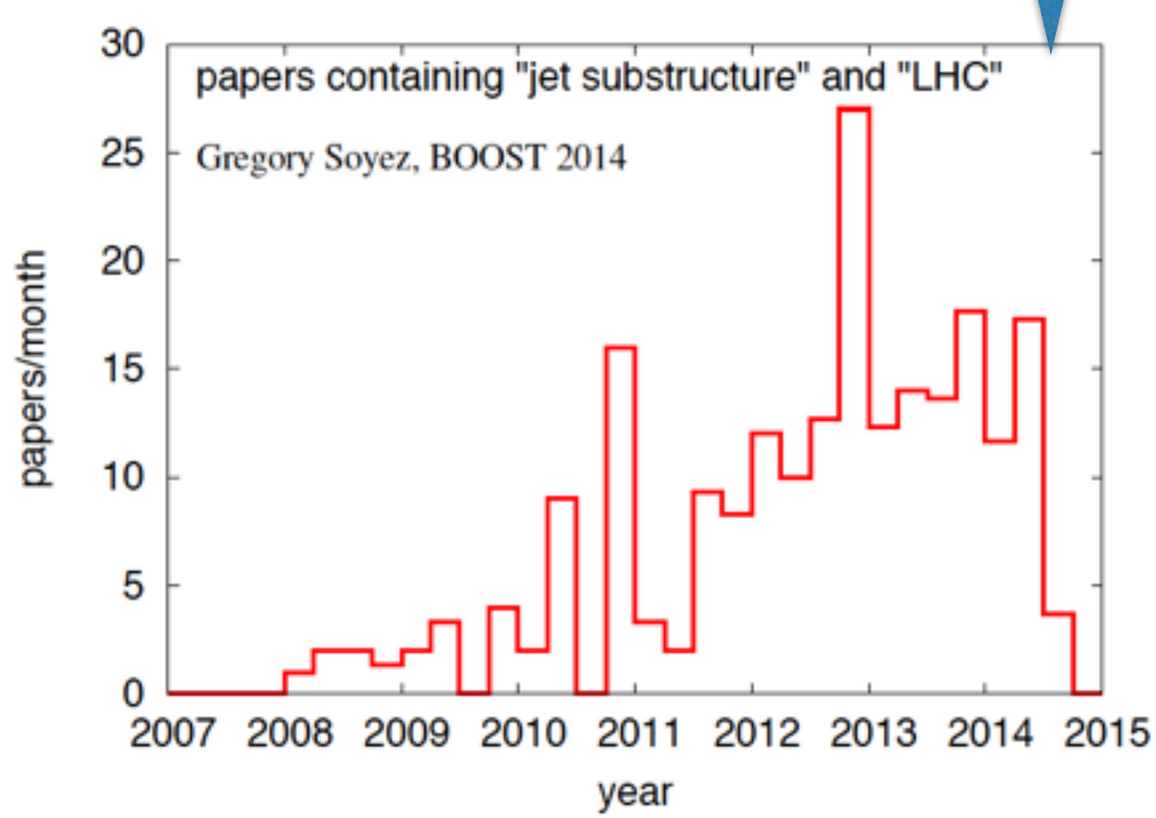




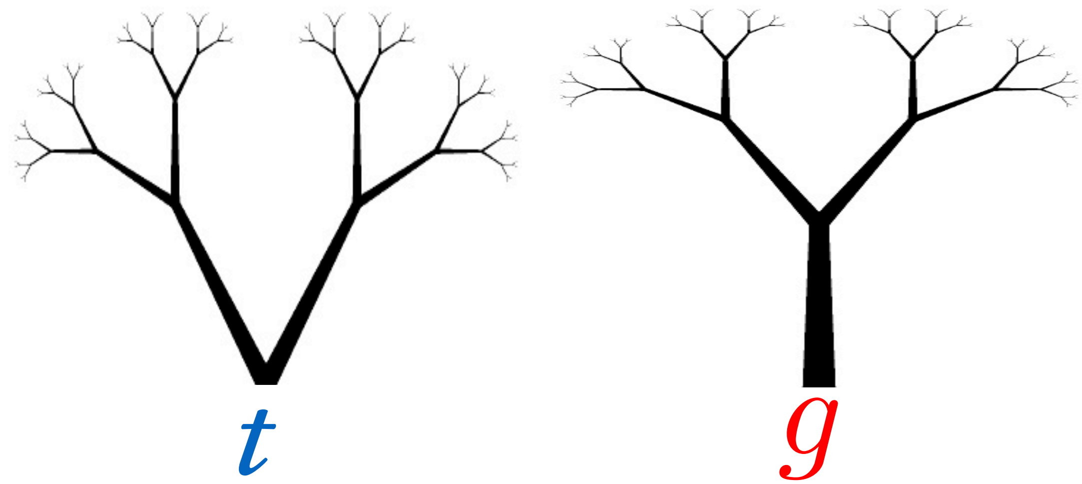
$p_T > 400$ GeV

Jet $p_T > 350$ GeV

"If you ain't boostin', you ain't livin" – Nhan Tran, FNAL
(Experimental Summary at BOOST 2014)



How do we know it's top jet?
Boosted top tagging (jet substructure)



apologies for omitted ones…

1) Algorithm: Filtering, pruning, trimming, mass drop, soft drop, etc

Seymour (93); Butterworth, Cox, Forshaw (02); Butterworth, Davison, Rubin & Salam (08); Kaplan, Rehermann, Schwartz, Tweedie (08); Krohn, Thaler & Wang (10); Ellis, Vermilion & Walsh (09); T. Plehn, G. P. Salam, & M. Spannowsky (09),Larkoski, Marzani,Soyez,Thaler (14),etc

2) JetShape: Moments. (easy to get LO PQCD, weak jet finder dependence, etc)

Almeida, SL, Perez, Sterman, Sung & Virzi; Thaler & Wang (08); Thaler & Tilburg (10), Gallichio & Schwartz (10), Hook, Jankowiak & Wacker (11), etc

3)Matrix element method shower deconstruction method

Soper & Spannowsky (11,12)

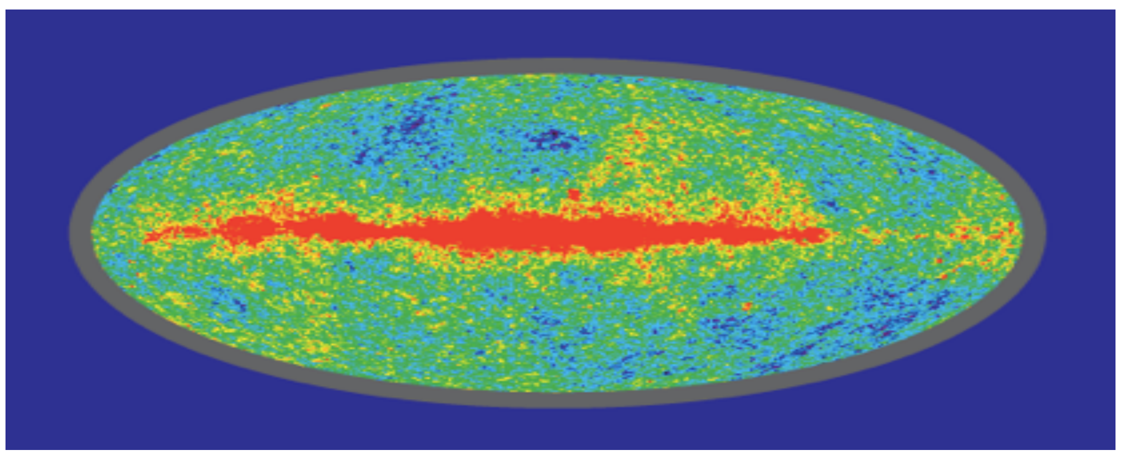
4)Template Overlap. (easy to get LO PQCD, weak jet finder dep'& beyond, fits the spiky nature of signals)

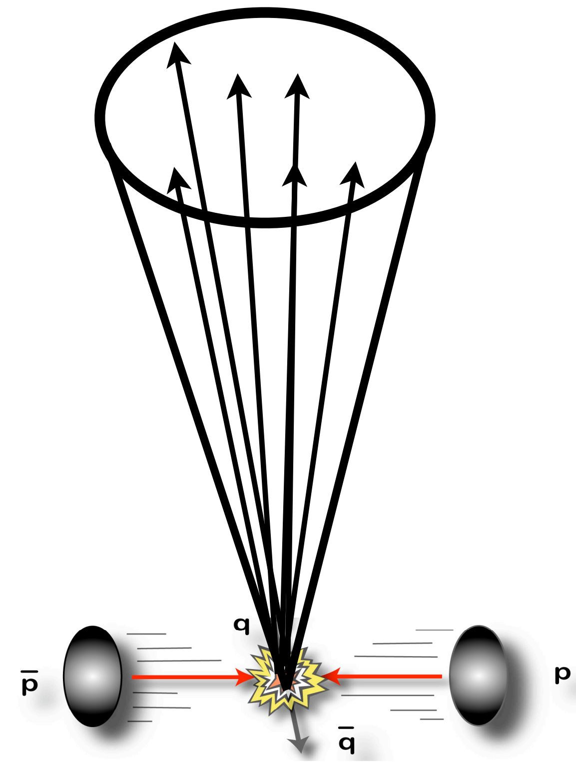
Almeida, SL, Perez, Sterman & Sung (10); Almeida, Erdogan, Juknevich, SL, Perez, Sterman (11);Backovic, Juknevich, Perez (13); Backovic, Gabizon, Juknevich, Perez, Soreq (14)

5)ANN: new method

Almeida,Clich,SL, Perelstien (15)

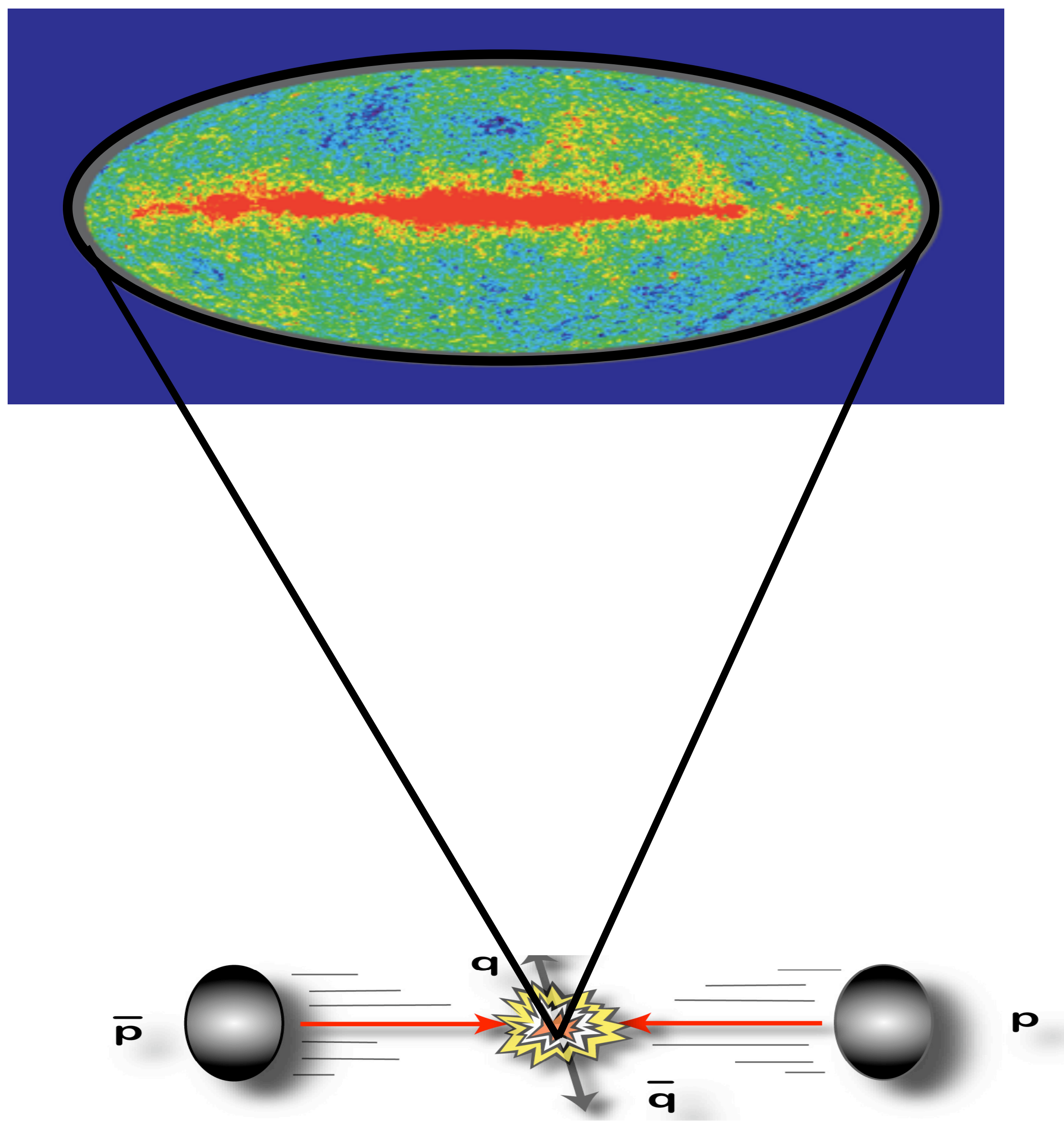
Need to understand the energy flow inside jet
jet shapes or jet substructure





Need to understand the energy flow inside jet
jet shapes or jet substructure

Template Overlap Method



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

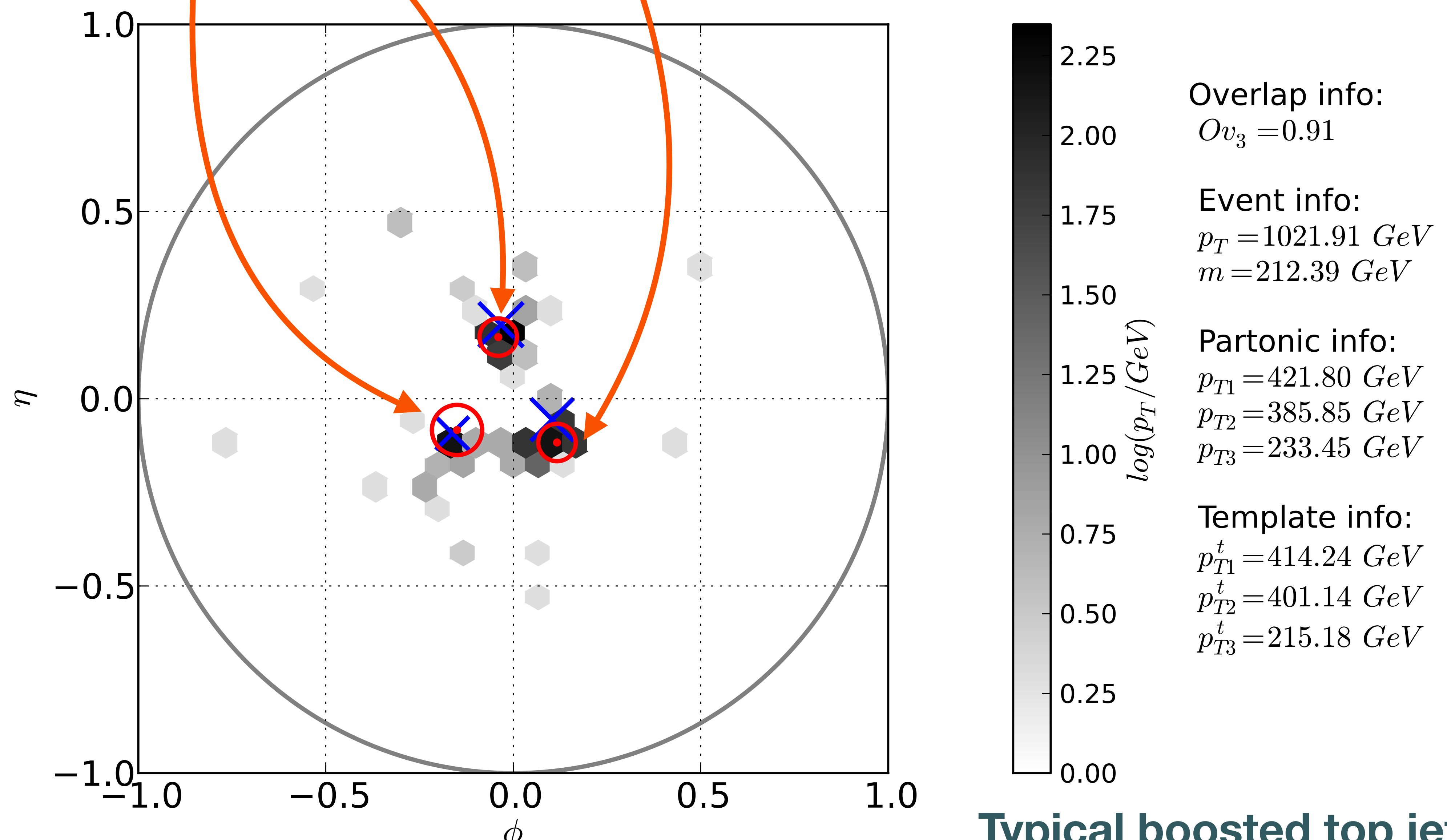
"template"

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

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.

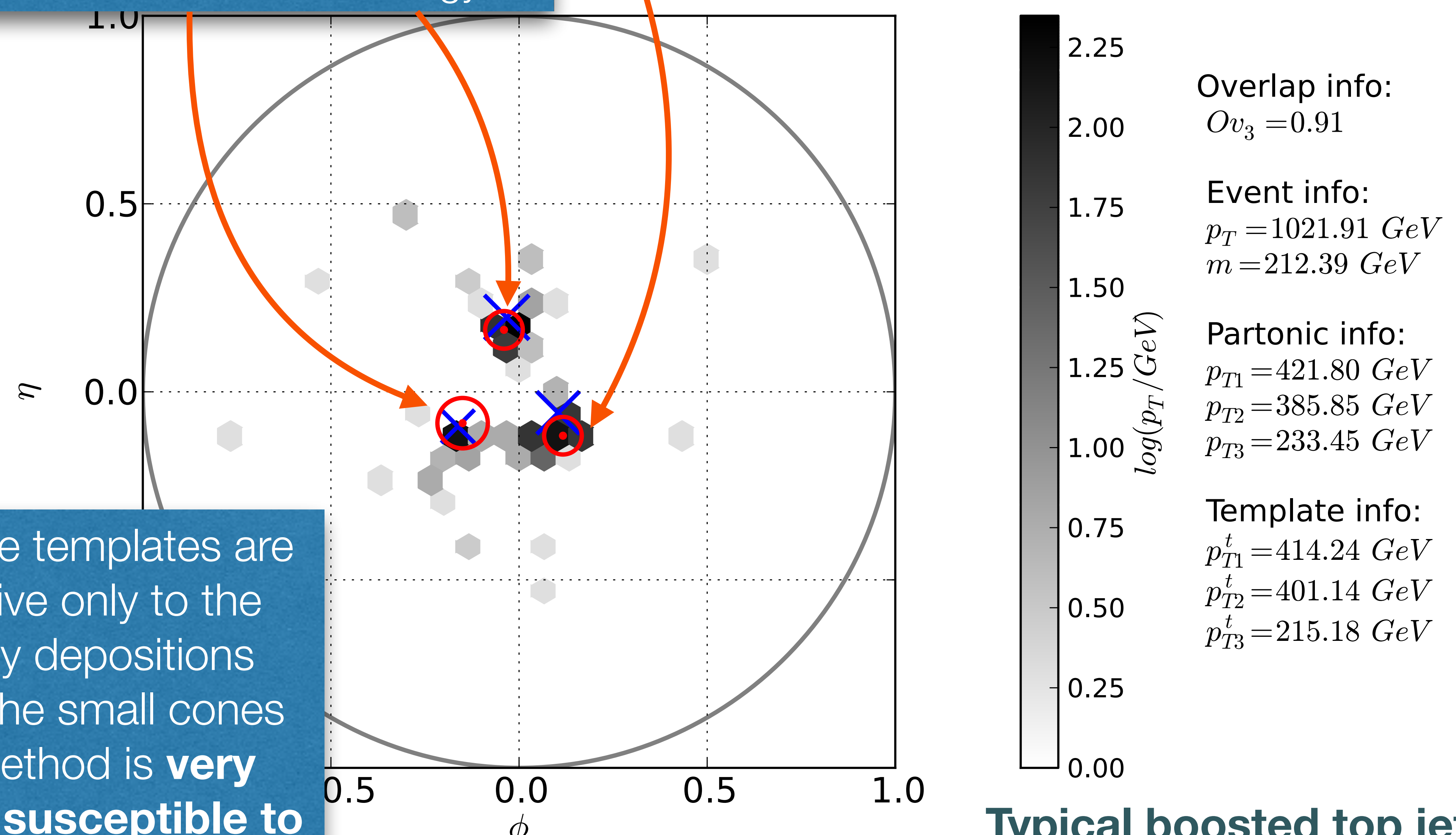


Typical boosted top jet

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.



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

Typical boosted top jet

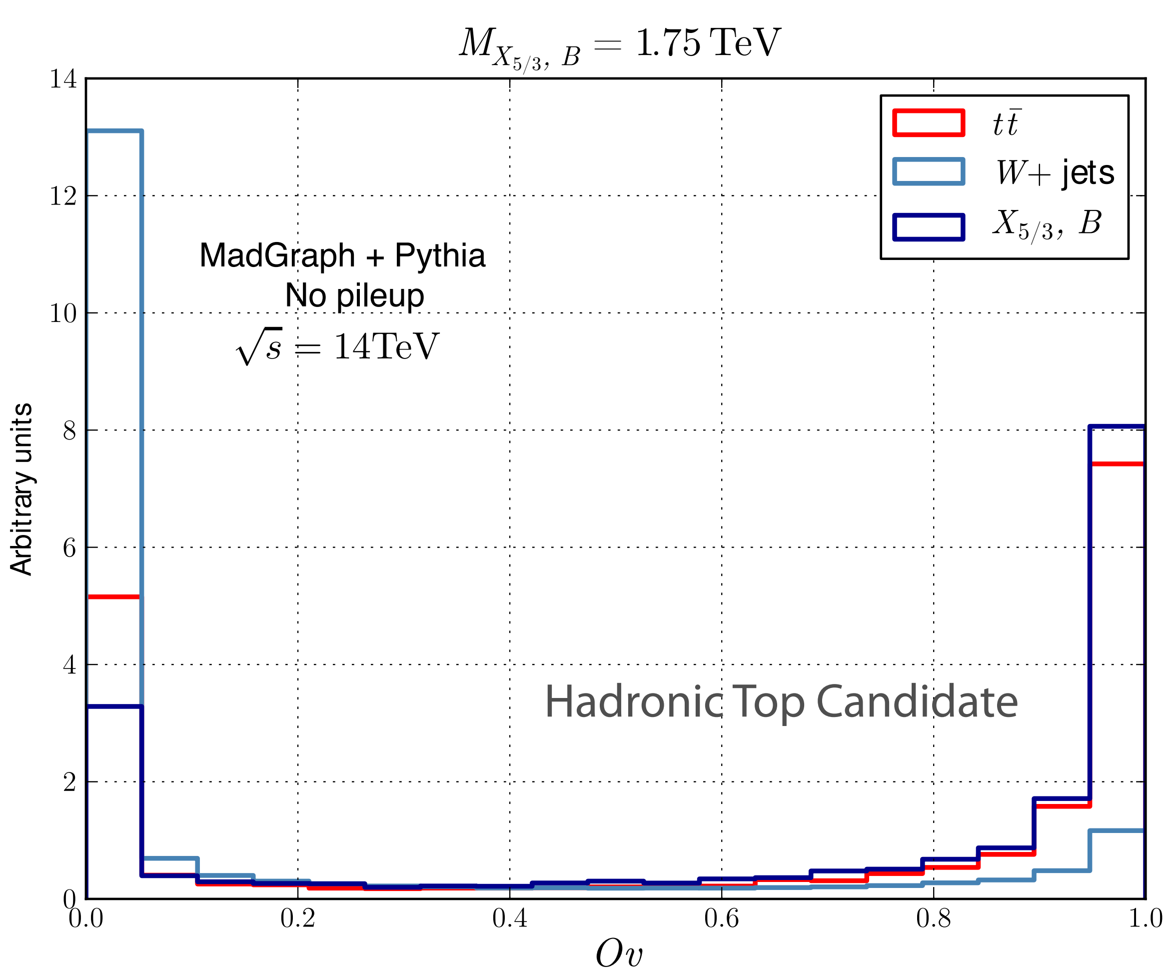
Tagging of **Boosted Objects**

Template Overlap Method

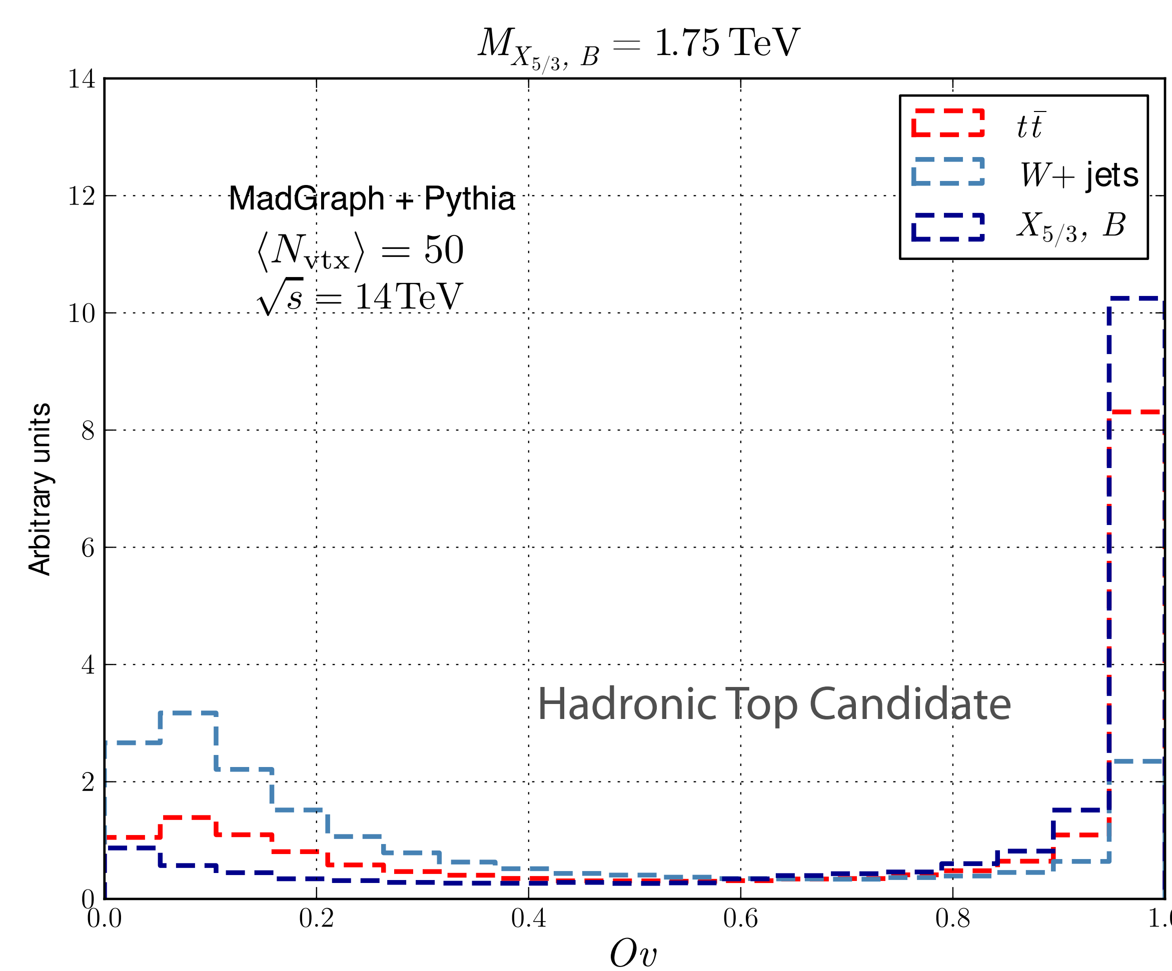
- Good rejection power for light jets.
- Flexible Jet Substructure framework

(can tag t, h, W ...)

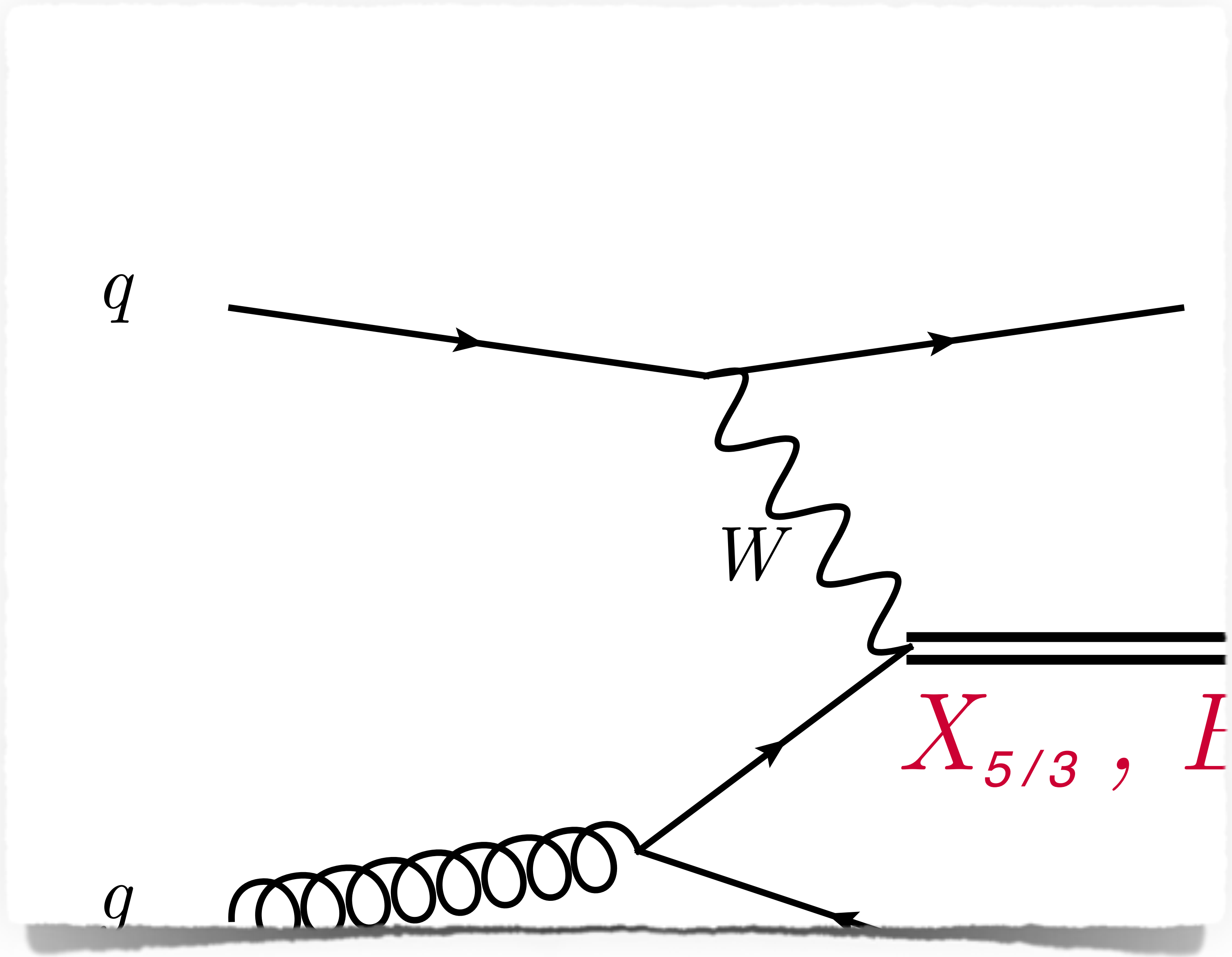
No Pileup



50 avg. pileup



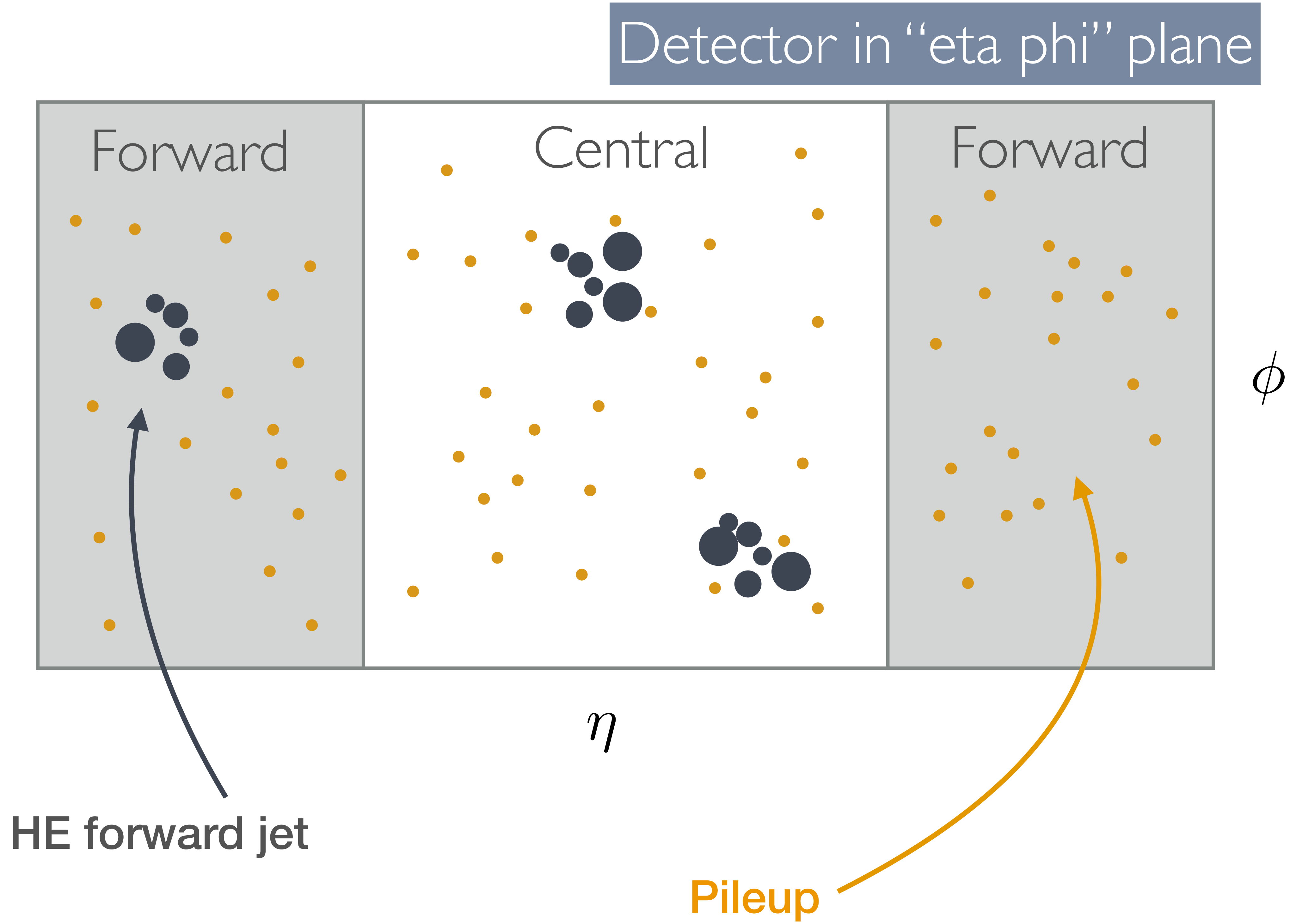
Forward Jet Tagging



Forward Jets as useful tags of top partner production also proposed in:

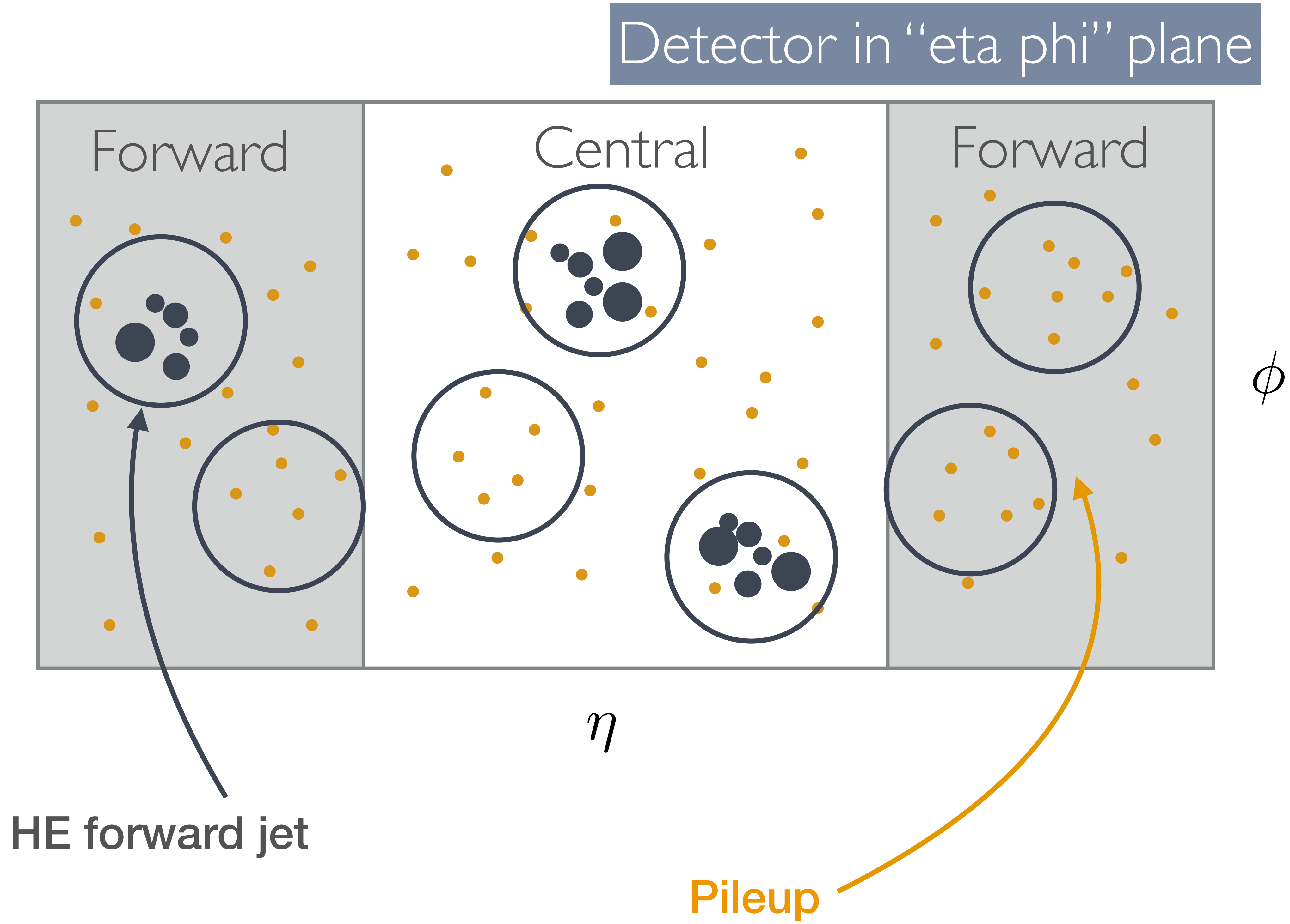
De Simone, Matsedonskyi, Rattazzi Wulzer JHEP 1304 (2013) 004

Forward Jet Tagging



Seems easy, but actually quite difficult!

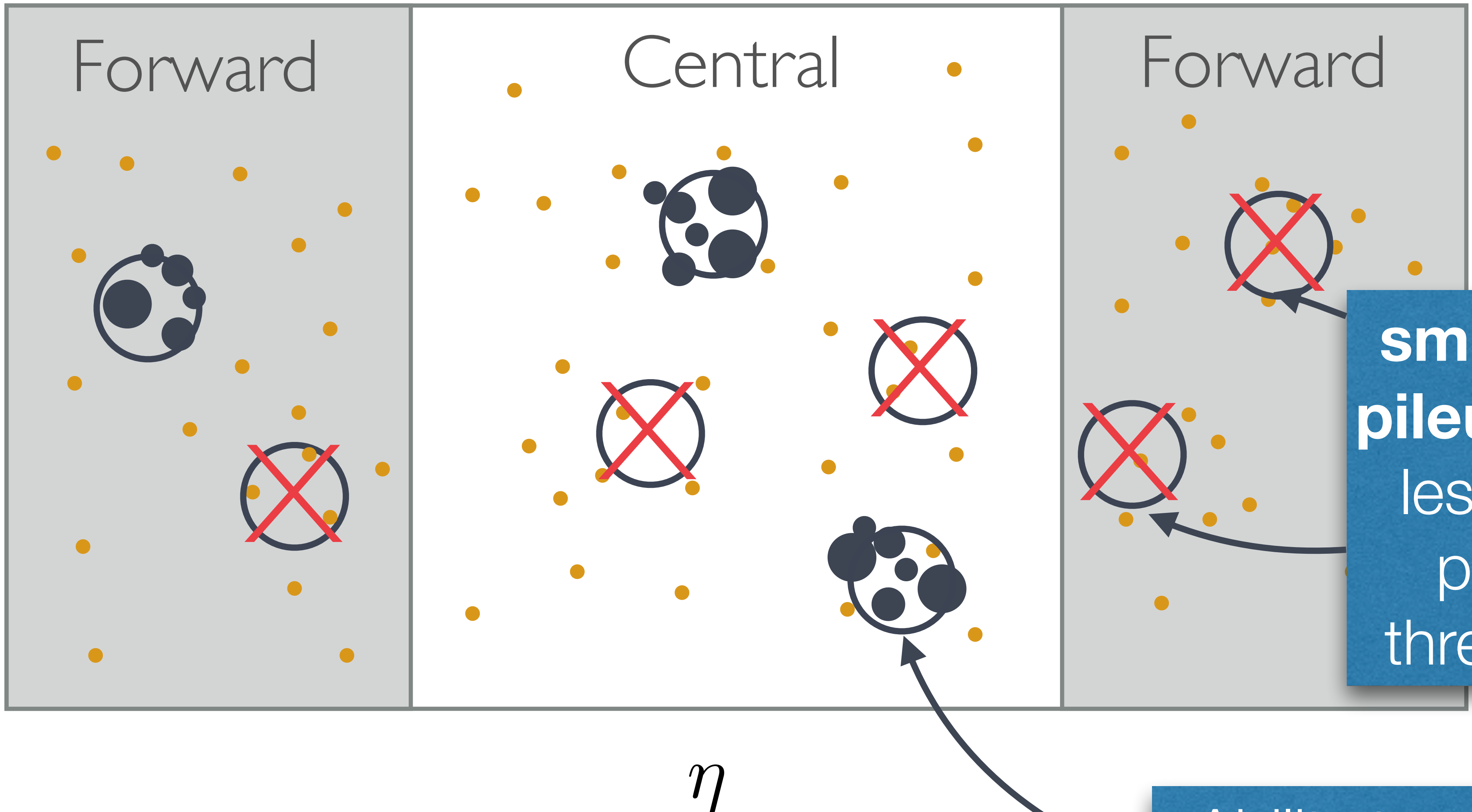
Forward Jet Tagging



Complicated at high pileup (**fake jets appear**)

Forward Jet Tagging

Detector in “eta phi” plane



small radius pileup jets are less likely to pass a p_T threshold cut

Ability to reco. the jet energy/p_T is diminished, but we are interested **in tagging the forward jet, not measuring it**

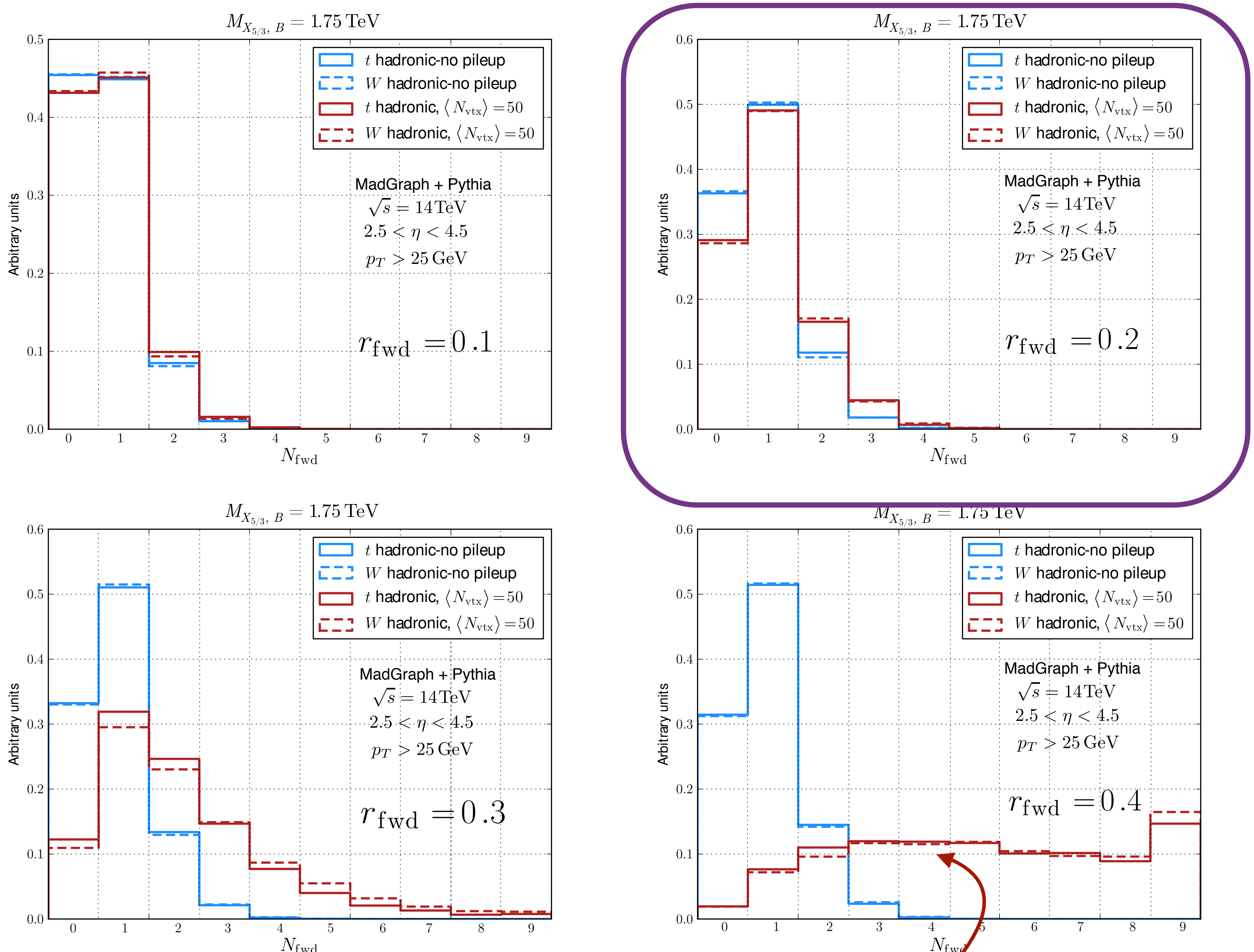
(Simple) Solution:

Define forward jets as (say) r = 0.2 jets with

$$p_T^{\mathrm{fwd}} > 25\ \mathrm{GeV}, \quad 2.5 < \eta^{\mathrm{fwd}} < 4.5\,,$$

Forward Jet Tagging

r = 0.2 - good compromise between pileup insensitivity and signal efficiency

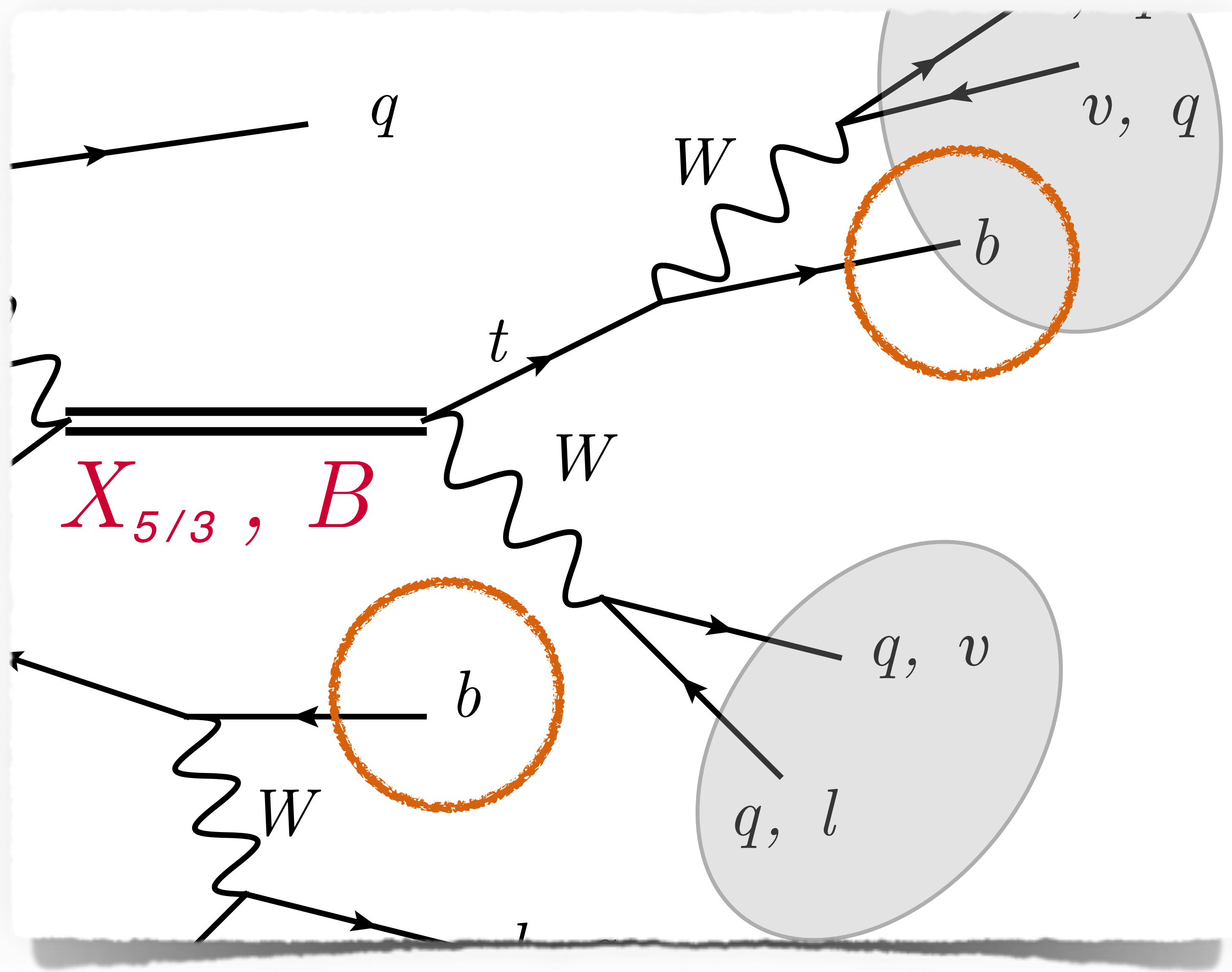


Blue - No Pileup

Red - 50 Pileup Events

Standard ATLAS *r* = 0.4 **forward jet will not work** without some aggressive pileup subtraction technique (**open problem!**)

b-tagging Strategy



b-tagging Strategy

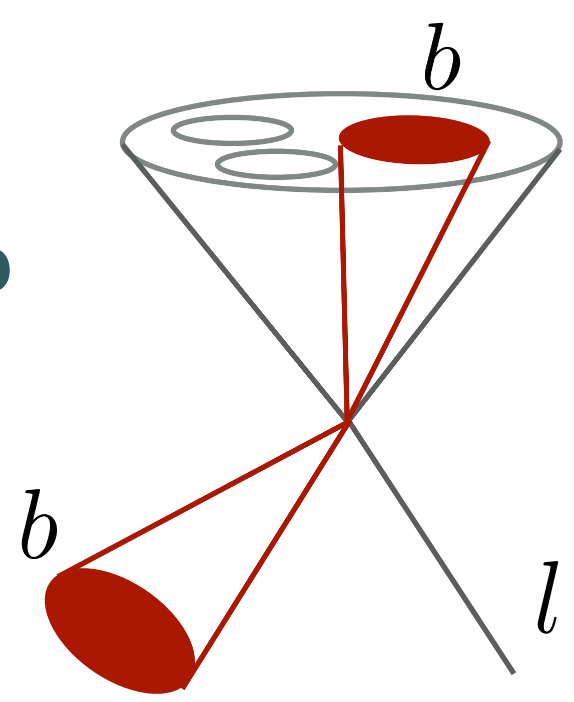
- Full simulation of b-tagging requires consideration of complex detector effects (e.g. tracking info).
- We use a **simplified approach**:

Assign a "*b*-tag" to every $r = 0.4$ jet which has a truth level b or c jet within $dr = 0.4$ from the jet axis.

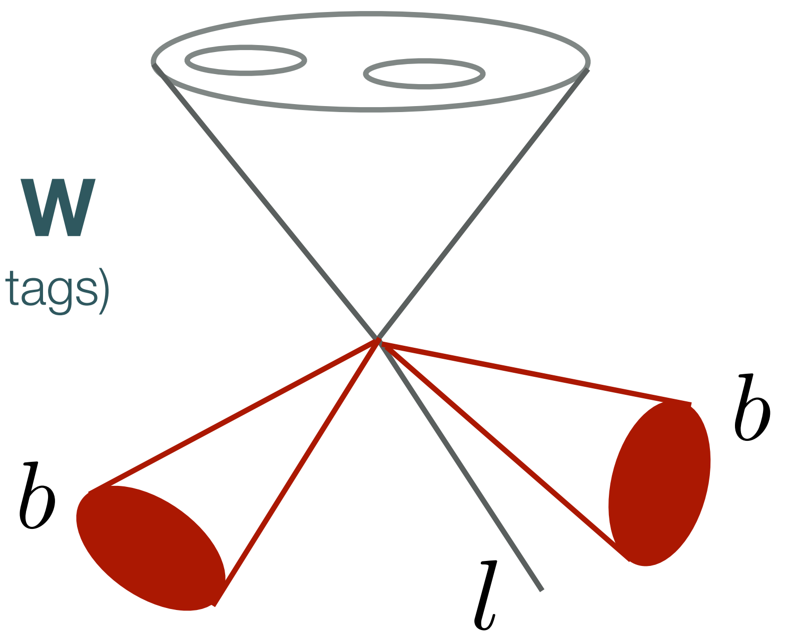
- For each "**b**-tag" we use the benchmark efficiencies:

$$\epsilon_b = 0.75, \;\; \epsilon_c = 0.18, \;\; \epsilon_l = 0.01$$

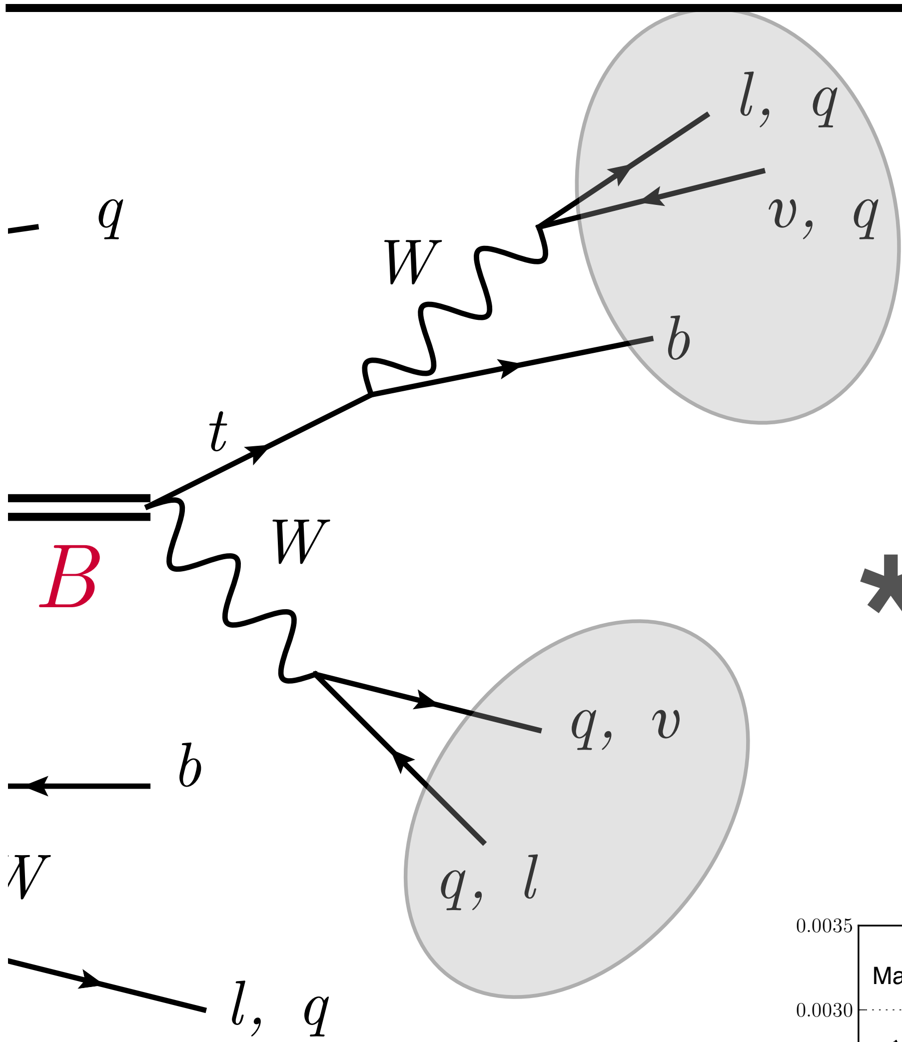
hadronic top
(one b inside fat jet, one isolated)



hadronic W
(two isolated b tags)



We can reconstruct the **resonance mass**

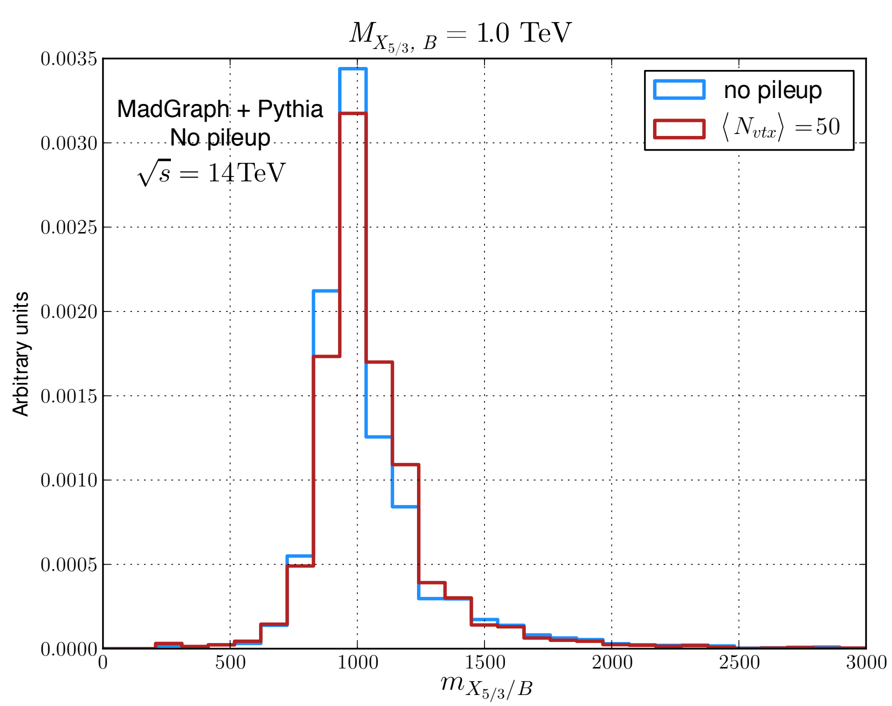


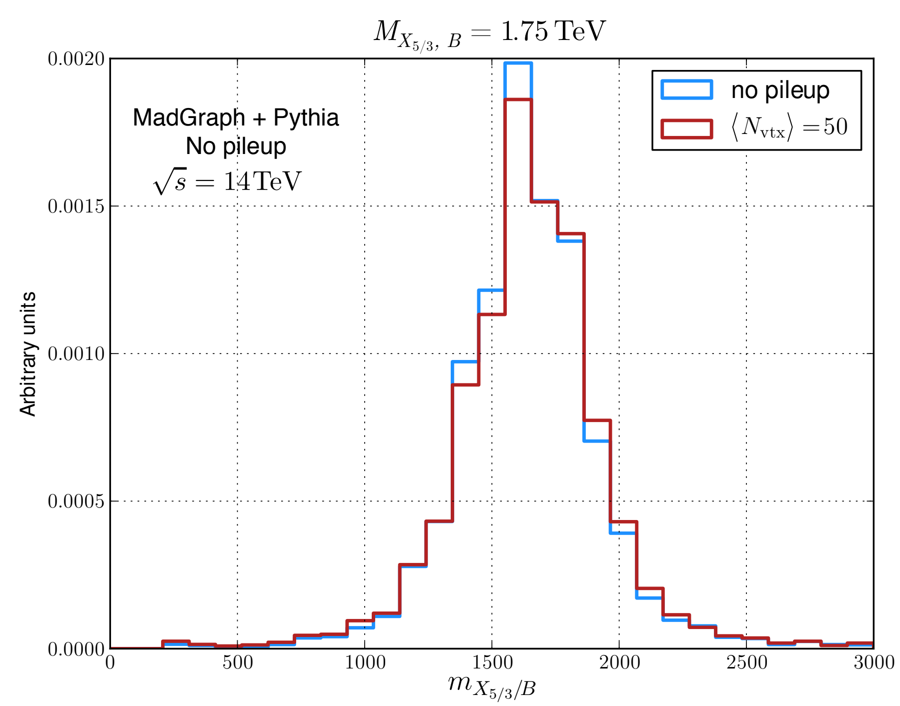
Use the peak template (pileup insensitive)*:

- **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 $\boldsymbol{M_4}$, 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!

Top Partner Searches Beyond the 2 TeV Mass Region

Backovic, Flacke, SL, Perez `14

$M_{X_{5/3}/B} = 2.0$ TeV, $\sigma_{X_{5/3}+B} = 15\,\text{fb}$, $L = 35\,\text{fb}^{-1}$

$X_{5/3}+B$	σ_s [fb]		$\sigma_{t\bar{t}}$ [fb]		$\sigma_{W+\text{jets}}$ [fb]		ϵ_s		$\epsilon_{t\bar{t}}$		$\epsilon_{W+\text{jets}}$		S/B		$S/\sqrt{B}$	
Fat jet candidate	t	W	t	W	t	W	t	W	t	W	t	W	t	W	t	W
Basic Cuts	1.7	1.9	144.0	487.0	3807.0	2301.0	0.38	0.42	0.12	0.41	0.12	0.08	4×10^{-4}	6×10^{-4}	0.2	0.2
$p_T > 600$ GeV	1.4	1.6	117.0	430.0	1045.0	747.0	0.31	0.37	0.10	0.36	0.035	0.02	0.001	0.001	0.2	0.2
$p_T^l > 100$ GeV	1.3	1.5	61.0	300.0	715.0	502.0	0.30	0.35	0.05	0.25	0.02	0.02	0.002	0.002	0.3	0.3
$Ov > 0.5$	1.0	1.1	25.0	150.0	131.0	172.0	0.22	0.22	0.02	0.13	0.004	0.006	0.006	0.003	0.5	0.3
$m_{X_{5/3}/B} > 1.5$ TeV	0.9	1.0	2.4	91.0	55.0	118.0	0.19	0.22	0.002	0.08	0.002	0.004	0.01	0.004	0.7	0.4
$m_{j'l} > 200$ GeV	0.8	0.3	0.9	11.0	45.0	37.0	0.18	0.07	8×10^{-4}	0.009	0.001	0.001	0.02	0.02	0.7	0.7
b-tag & no fwd. tag	**0.3**	0.1	**0.04**	2.0	**0.08**	0.6	0.07	0.03	4×10^{-5}	0.002	2×10^{-6}	2×10^{-5}	**2.5**	0.1	**5.2**	1.0
fwd. tag & no b-tag	**0.5**	0.2	**0.2**	2.5	8.0	5.0	0.11	0.05	2×10^{-4}	0.002	3×10^{-4}	2×10^{-4}	**0.06**	0.07	**1.0**	1.0
b-tag and fwd. tag	**0.2**	0.1	**0.01**	0.5	**< 0.01**	0.07	0.04	0.02	1×10^{-5}	4×10^{-4}	$< 10^{-6}$	2×10^{-6}	**15.7**	0.3	**10.2**	1.5

Table II: Example cutflow for signal and background events for $M_{X_{5/3}/B} = 2.0$ TeV and inclusive cross sections $\sigma_{X_{5/3}+B}$. $\sigma_{s,t\bar{t},W+\text{jets}}$ are the signal/background cross sections including all branching ratios, whereas ϵ are the efficiencies of the cuts relative to the generator level cross sections. The results assume no pileup contamination. The signal cross section assumes both $X_{5/3}$ and B production.

$f = 800$ GeV, $M_1 = 1.5$ TeV, $\phi = \pi$, $c_R = 3$, $y_L = 1$, and $M_4 = 2$ TeV. $|g^R_{XWt}| = \frac{g}{\sqrt{2}} \cdot 0.66$ and $|g^R_{BWt}| = \frac{g}{\sqrt{2}} \cdot 0.63$,

Top Partner Searches Beyond the 2 TeV Mass Region

hadronic candidate

Backovic, Flacke, SL, Perez `14

$M_{X_{5/3}/B} = 2.0$ TeV, $\sigma_{X_{5/3}+B} = 15\,\text{fb}$, $L = 35\,\text{fb}^{-1}$

$X_{5/3}+B$	σ_s [fb]		$\sigma_{t\bar{t}}$ [fb]		$\sigma_{W+\text{jets}}$ [fb]		ϵ_s		$\epsilon_{t\bar{t}}$		$\epsilon_{W+\text{jets}}$		S/B		$S/\sqrt{B}$	
Fat jet candidate	t	W	t	W	t	W	t	W	t	W	t	W	t	W	t	W
Basic Cuts	1.7	1.9	144.0	487.0	3807.0	2301.0	0.38	0.42	0.12	0.41	0.12	0.08	4×10^{-4}	6×10^{-4}	0.2	0.2
$p_T > 600$ GeV	1.4	1.6	117.0	430.0	1045.0	747.0	0.31	0.37	0.10	0.36	0.035	0.02	0.001	0.001	0.2	0.2
$p_T^l > 100$ GeV	1.3	1.5	61.0	300.0	715.0	502.0	0.30	0.35	0.05	0.25	0.02	0.02	0.002	0.002	0.3	0.3
$Ov > 0.5$	1.0	1.1	25.0	150.0	131.0	172.0	0.22	0.22	0.02	0.13	0.004	0.006	0.006	0.003	0.5	0.3
$m_{X_{5/3}/B} > 1.5$ TeV	0.9	1.0	2.4	91.0	55.0	118.0	0.19	0.22	0.002	0.08	0.002	0.004	0.01	0.004	0.7	0.4
$m_{j'l} > 200$ GeV	0.8	0.3	0.9	11.0	45.0	37.0	0.18	0.07	8×10^{-4}	0.009	0.001	0.001	0.02	0.02	0.7	0.7
b-tag & no fwd. tag	**0.3**	0.1	**0.04**	2.0	**0.08**	0.6	0.07	0.03	4×10^{-5}	0.002	2×10^{-6}	2×10^{-5}	**2.5**	0.1	**5.2**	1.0
fwd. tag & no b-tag	**0.5**	0.2	**0.2**	2.5	8.0	5.0	0.11	0.05	2×10^{-4}	0.002	3×10^{-4}	2×10^{-4}	**0.06**	0.07	**1.0**	1.0
b-tag and fwd. tag	**0.2**	0.1	**0.01**	0.5	**< 0.01**	0.07	0.04	0.02	1×10^{-5}	4×10^{-4}	$< 10^{-6}$	2×10^{-6}	**15.7**	0.3	**10.2**	1.5

Table II: Example cutflow for signal and background events for $M_{X_{5/3}/B} = 2.0$ TeV and inclusive cross sections $\sigma_{X_{5/3}+B}$. $\sigma_{s,t\bar{t},W+\text{jets}}$ are the signal/background cross sections including all branching ratios, whereas ϵ are the efficiencies of the cuts relative to the generator level cross sections. The results assume no pileup contamination. The signal cross section assumes both $X_{5/3}$ and B production.

$f = 800$ GeV, $M_1 = 1.5$ TeV, $\phi = \pi$, $c_R = 3$, $y_L = 1$, and $M_4 = 2$ TeV. $|g^R_{XWt}| = \frac{g}{\sqrt{2}} \cdot 0.66$ and $|g^R_{BWt}| = \frac{g}{\sqrt{2}} \cdot 0.63$,

Top Partner Searches Beyond the 2 TeV Mass Region

hadronic candidate

Backovic, Flacke, SL, Perez `14

$M_{X_{5/3}/B} = 2.0$ TeV, $\sigma_{X_{5/3}+B} = 15\,\mathrm{fb}$, $L = 35\,\mathrm{fb}^{-1}$

$X_{5/3} + B$	σ_s [fb]		$\sigma_{t\bar{t}}$ [fb]		$\sigma_{W+\text{jets}}$ [fb]		ϵ_s		$\epsilon_{t\bar{t}}$		$\epsilon_{W+\text{jets}}$		S/B		$S/\sqrt{B}$	
Fat jet candidate	t	W	t	W	t	W	t	W	t	W	t	W	t	W	t	W
Basic Cuts	1.7	1.9	144.0	487.0	3807.0	2301.0	0.38	0.42	0.12	0.41	0.12	0.08	4×10^{-4}	6×10^{-4}	0.2	0.2
$p_T > 600$ GeV	1.4	1.6	117.0	430.0	1045.0	747.0	0.31	0.37	0.10	0.36	0.035	0.02	0.001	0.001	0.2	0.2
$p_T^l > 100$ GeV	1.3	1.5	61.0	300.0	715.0	502.0	0.30	0.35	0.05	0.25	0.02	0.02	0.002	0.002	0.3	0.3
$Ov > 0.5$	1.0	1.1	25.0	150.0	131.0	172.0	0.22	0.22	0.02	0.13	0.004	0.006	0.006	0.003	0.5	0.3
$m_{X_{5/3}/B} > 1.5$ TeV	0.9	1.0	2.4	91.0	55.0	118.0	0.19	0.22	0.002	0.08	0.002	0.004	0.01	0.004	0.7	0.4
$m_{j'l} > 200$ GeV	0.8	0.3	0.9	11.0	45.0	37.0	0.18	0.07	8×10^{-4}	0.009	0.001	0.001	0.02	0.02	0.7	0.7
b-tag & no fwd. tag	**0.3**	0.1	**0.04**	2.0	**0.08**	0.6	0.07	0.03	4×10^{-5}	0.002	2×10^{-6}	2×10^{-5}	**2.5**	0.1	**5.2**	1.0
fwd. tag & no b-tag	**0.5**	0.2	**0.2**	2.5	8.0	5.0	0.11	0.05	2×10^{-4}	0.002	3×10^{-4}	2×10^{-4}	**0.06**	0.07	**1.0**	1.0
b-tag and fwd. tag	**0.2**	0.1	**0.01**	0.5	**< 0.01**	0.07	0.04	0.02	1×10^{-5}	4×10^{-4}	$< 10^{-6}$	2×10^{-6}	**15.7**	0.3	**10.2**	1.5

Table II: Example cutflow for signal and background events for $M_{X_{5/3}/B} = 2.0$ TeV and inclusive cross sections $\sigma_{X_{5/3}+B}$. $\sigma_{s,t\bar{t},W+\text{jets}}$ are the signal/background cross sections including all branching ratios, whereas ϵ are the efficiencies of the cuts relative to the generator level cross sections. The results assume no pileup contamination. The signal cross section assumes both $X_{5/3}$ and B production.

$f = 800$ GeV, $M_1 = 1.5$ TeV, $\phi = \pi$, $c_R = 3$, $y_L = 1$, and $M_4 = 2$ TeV. $|g^R_{XWt}| = \frac{g}{\sqrt{2}} \cdot 0.66$ and $|g^R_{BWt}| = \frac{g}{\sqrt{2}} \cdot 0.63$.

Top Partner Searches Beyond the 2 TeV Mass Region

hadronic candidate

Backovic, Flacke, SL, Perez `14

$M_{X_{5/3}/B} = 2.0$ TeV, $\sigma_{X_{5/3}+B} = 15\,\text{fb}$, $L = 35\,\text{fb}^{-1}$

$X_{5/3}+B$	σ_s [fb]		$\sigma_{t\bar{t}}$ [fb]		$\sigma_{W+\text{jets}}$ [fb]		ϵ_s		$\epsilon_{t\bar{t}}$		$\epsilon_{W+\text{jets}}$		S/B		$S/\sqrt{B}$	
Fat jet candidate	t	W	t	W	t	W	t	W	t	W	t	W	t	W	t	W
Basic Cuts	1.7	1.9	144.0	487.0	3807.0	2301.0	0.38	0.42	0.12	0.41	0.12	0.08	4×10^{-4}	6×10^{-4}	0.2	0.2
$p_T > 600$ GeV	1.4	1.6	117.0	430.0	1045.0	747.0	0.31	0.37	0.10	0.36	0.035	0.02	0.001	0.001	0.2	0.2
$p_T^l > 100$ GeV	1.3	1.5	61.0	300.0	715.0	502.0	0.30	0.35	0.05	0.25	0.02	0.02	0.002	0.002	0.3	0.3
$Ov > 0.5$	1.0	1.1	25.0	150.0	131.0	172.0	0.22	0.22	0.02	0.13	0.004	0.006	0.006	0.003	0.5	0.3
$m_{X_{5/3}/B} > 1.5$ TeV	0.9	1.0	2.4	91.0	55.0	118.0	0.19	0.22	0.002	0.08	0.002	0.004	0.01	0.004	0.7	0.4
$m_{j'l} > 200$ GeV	0.8	0.3	0.9	11.0	45.0	37.0	0.18	0.07	8×10^{-4}	0.009	0.001	0.001	0.02	0.02	0.7	0.7
b-tag & no fwd. tag	**0.3**	0.1	**0.04**	2.0	**0.08**	0.6	0.07	0.03	4×10^{-5}	0.002	2×10^{-6}	2×10^{-5}	**2.5**	0.1	**5.2**	1.0
fwd. tag & no b-tag	**0.5**	0.2	**0.2**	2.5	8.0	5.0	0.11	0.05	2×10^{-4}	0.002	3×10^{-4}	2×10^{-4}	**0.06**	0.07	**1.0**	1.0
b-tag and fwd. tag	**0.2**	0.1	**0.01**	0.5	**< 0.01**	0.07	0.04	0.02	1×10^{-5}	4×10^{-4}	$< 10^{-6}$	2×10^{-6}	**15.7**	0.3	**10.2**	1.5

Table II: Example cutflow for signal and background events for $M_{X_{5/3}/B} = 2.0$ TeV and inclusive cross sections $\sigma_{X_{5/3}+B}$. $\sigma_{s,t\bar{t},W+\text{jets}}$ are the signal/background cross sections including all branching ratios, whereas ϵ are the efficiencies of the cuts relative to the generator level cross sections. The results assume no pileup contamination. The signal cross section assumes both $X_{5/3}$ and B production.

* Better sensitivity in the **hadronic top** channel for high masses

It is possible to achieve $S/\sqrt{B} > 5$ even without a forward jet tag

$f = 800$ GeV, $M_1 = 1.5$ TeV, $\phi = \pi$, $c_R = 3$, $y_L = 1$, and $M_4 = 2$ TeV. $|g^R_{XWt}| = \frac{g}{\sqrt{2}} \cdot 0.66$ and $|g^R_{BWt}| = \frac{g}{\sqrt{2}} \cdot 0.63$,

Top Partner Searches Beyond the 2 TeV Mass Region

hadronic candidate

$M_{X_{5/3}/B} = 2.0$ TeV, $\sigma_{X_{5/3}+B} = 15\,\text{fb}$, $L = 35\,\text{fb}^{-1}$

Backovic, Flacke, SL, Perez `14

$X_{5/3}+B$	σ_s [fb]		$\sigma_{t\bar{t}}$ [fb]		$\sigma_{W+\text{jets}}$								B		$S/\sqrt{B}$	
Fat jet candidate	t	W	t	W	t									W	t	W
Basic Cuts	1.7	1.9	144.0	487.0	3807.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	$\times 10^{-4}$	0.2	0.2
$p_T > 600$ GeV	1.4	1.6	117.0	430.0	1045.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.001	0.2	0.2
$p_T^l > 100$ GeV	1.3	1.5	61.0	300.0	715.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.002	0.3	0.3
$Ov > 0.5$	1.0	1.1	25.0	150.0	131.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.003	0.5	0.3
$m_{X_{5/3}/B} > 1.5$ TeV	0.9	1.0	2.4	91.0	55.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.004	0.7	0.4
$m_{j'l} > 200$ GeV	0.8	0.3	0.9	11.0	45.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.02	0.7	0.7
b-tag & no fwd. tag	**0.3**	0.1	**0.04**	2.0	**0.08**	0.6	0.07	0.03	4×10^{-5}	0.002	2×10^{-6}	2×10^{-5}	**2.5**	0.1	**5.2**	1.0
fwd. tag & no b-tag	**0.5**	0.2	**0.2**	2.5	8.0	5.0	0.11	0.05	2×10^{-4}	0.002	3×10^{-4}	2×10^{-4}	**0.06**	0.07	**1.0**	1.0
b-tag and fwd. tag	**0.2**	0.1	**0.01**	0.5	$<$ **0.01**	0.07	0.04	0.02	1×10^{-5}	4×10^{-4}	$< 10^{-6}$	2×10^{-6}	**15.7**	0.3	**10.2**	1.5

Table II: Example cutflow for signal and background events for $M_{X_{5/3}/B} = 2.0$ TeV and inclusive cross sections $\sigma_{X_{5/3}+B}$. $\sigma_{s,t\bar{t},W+\text{jets}}$ are the signal/background cross sections including all branching ratios, whereas ϵ are the efficiencies of the cuts relative to the generator level cross sections. The results assume no pileup contamination. The signal cross section assumes both $X_{5/3}$ and B productio

Cutflow efficiency for same SSDL ~ 50%, implying that the **final signal SSDL efficiency is 2-3% (including the BR).**

For $\sigma_{X_{5/3}} = 8\,\text{fb}$ **you then get**

$$\sigma_{2l} = 0.15 - 0.25\,\text{fb}$$

- signal cross section **>** same sign di-leptons
- **10 signal events** $L = 20 - 35\,\text{fb}^{-1}$
- $S/B > 1$
- $S/\sqrt{B} > 5$

Better sens ... gh masses

It is possible ... ward jet tag

$f = 800$ GeV, $M_1 = 1.5$ TeV, $\phi = \pi$, $c_R = 3$, $y_L = 1$, and $M_4 = 2$ TeV. $|g^R_{XWt}| = \frac{g}{\sqrt{2}} \cdot 0.66$ and $|g^R_{BWt}| = \frac{g}{\sqrt{2}} \cdot 0.63$,

Top partner models tend to have **many parameters**.

Event kinematics largely determined by the **mass of the partner.** (assuming we fix the width to about 15-20%)

Production Cross Section depends on all other parameters

Keep M, σ, L
as free parameters *

* We make sure that our event selections are weakly sensitive to chiral couplings

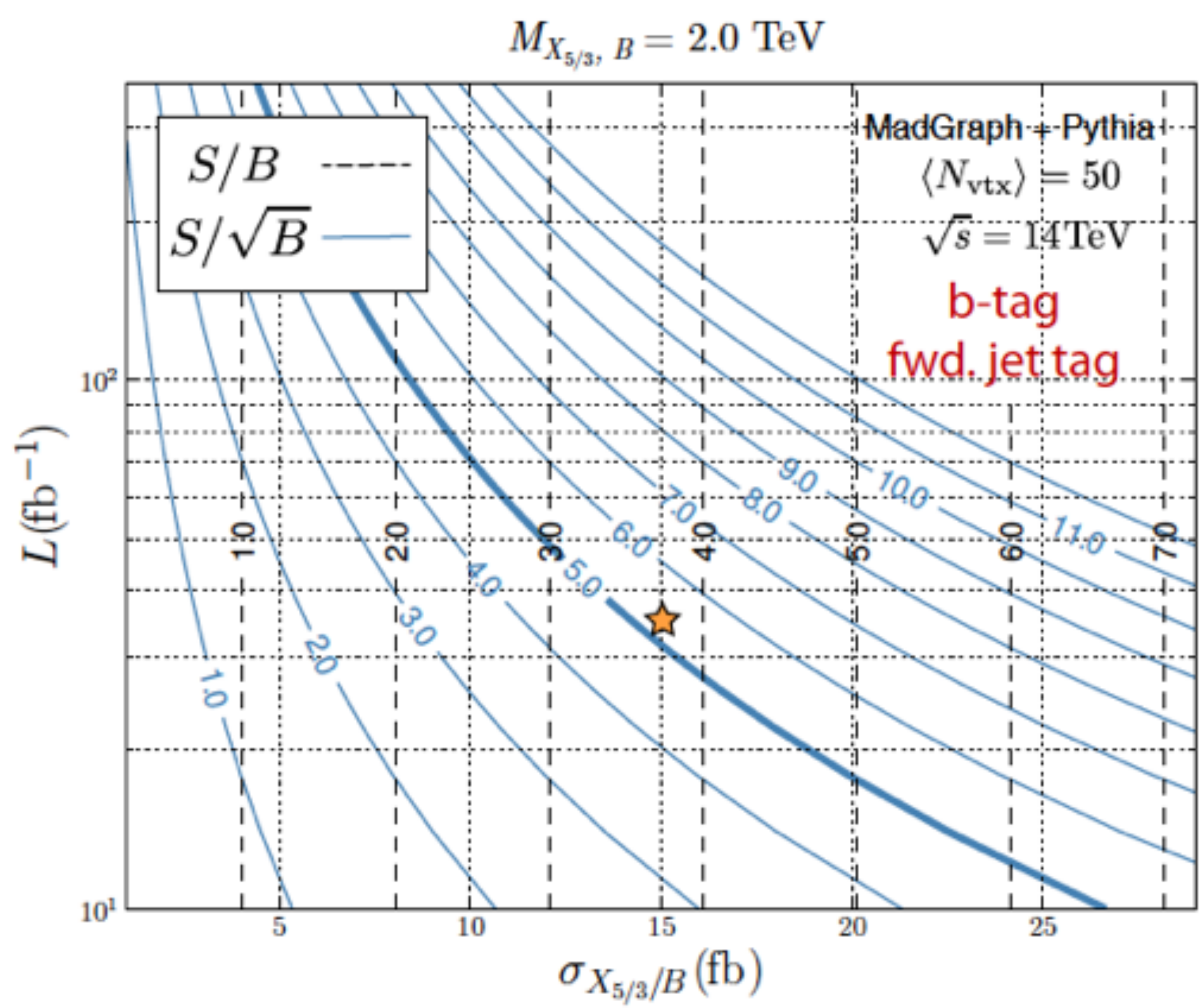
i.e.

$$g^R_{XWt} \sim O(v/f)$$
$$g^L_{XWt} \sim O((v/f)^2)$$

Top Partner Searches Beyond the 2 TeV Mass Region

Backovic, Flacke, SL, Perez `14

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



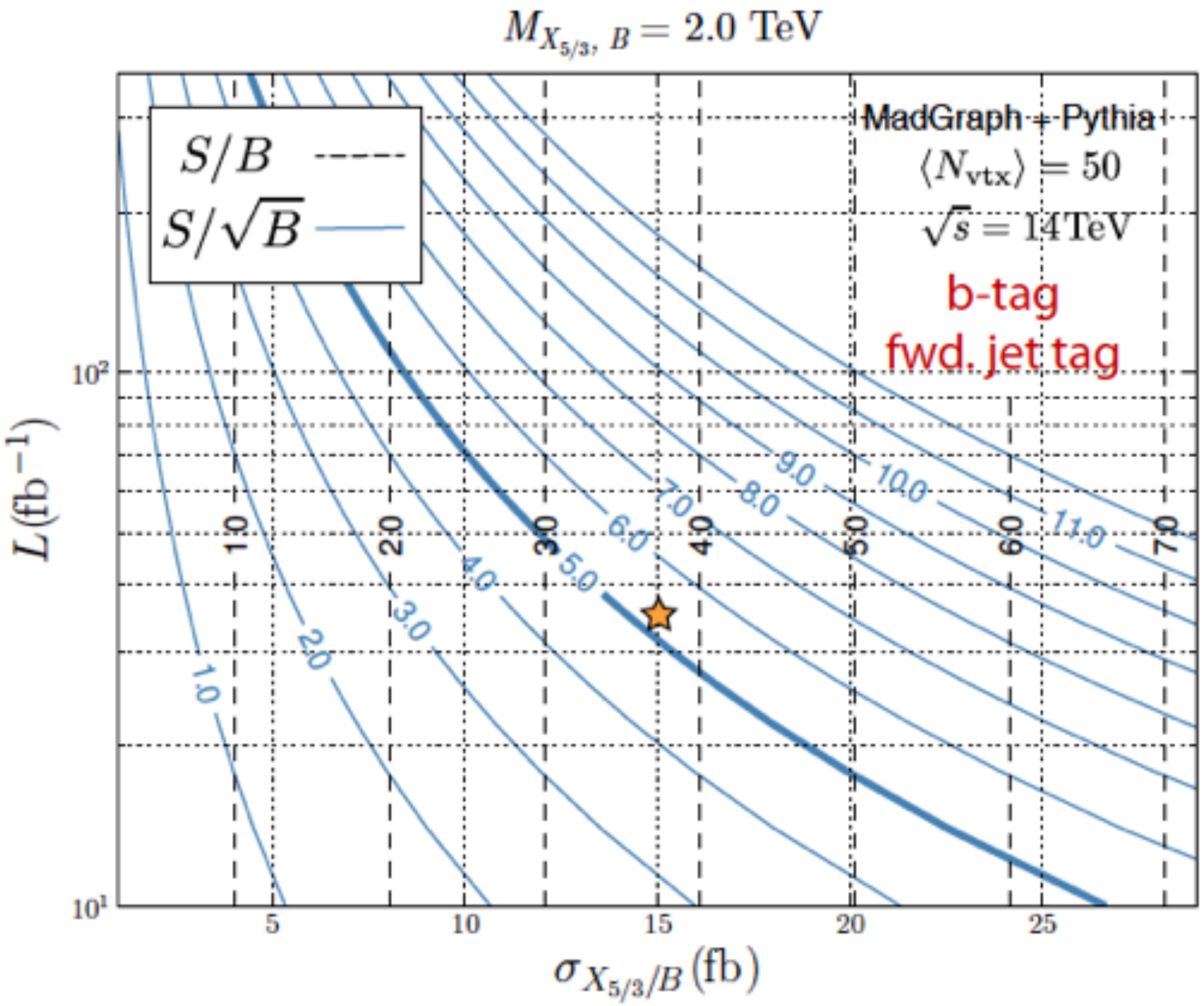
$f = 800$ GeV, $M_1 = 1.5$ TeV, $\phi = \pi$, $c_R = 3$, $y_L = 1$, and $M_4 = 2$ TeV. $|g^R_{XWt}| = \frac{g}{\sqrt{2}} \cdot 0.66$ and $|g^R_{BWt}| = \frac{g}{\sqrt{2}} \cdot 0.63$,

Top Partner Searches Beyond the 2 TeV Mass Region

Backovic, Flacke, SL, Perez `14

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

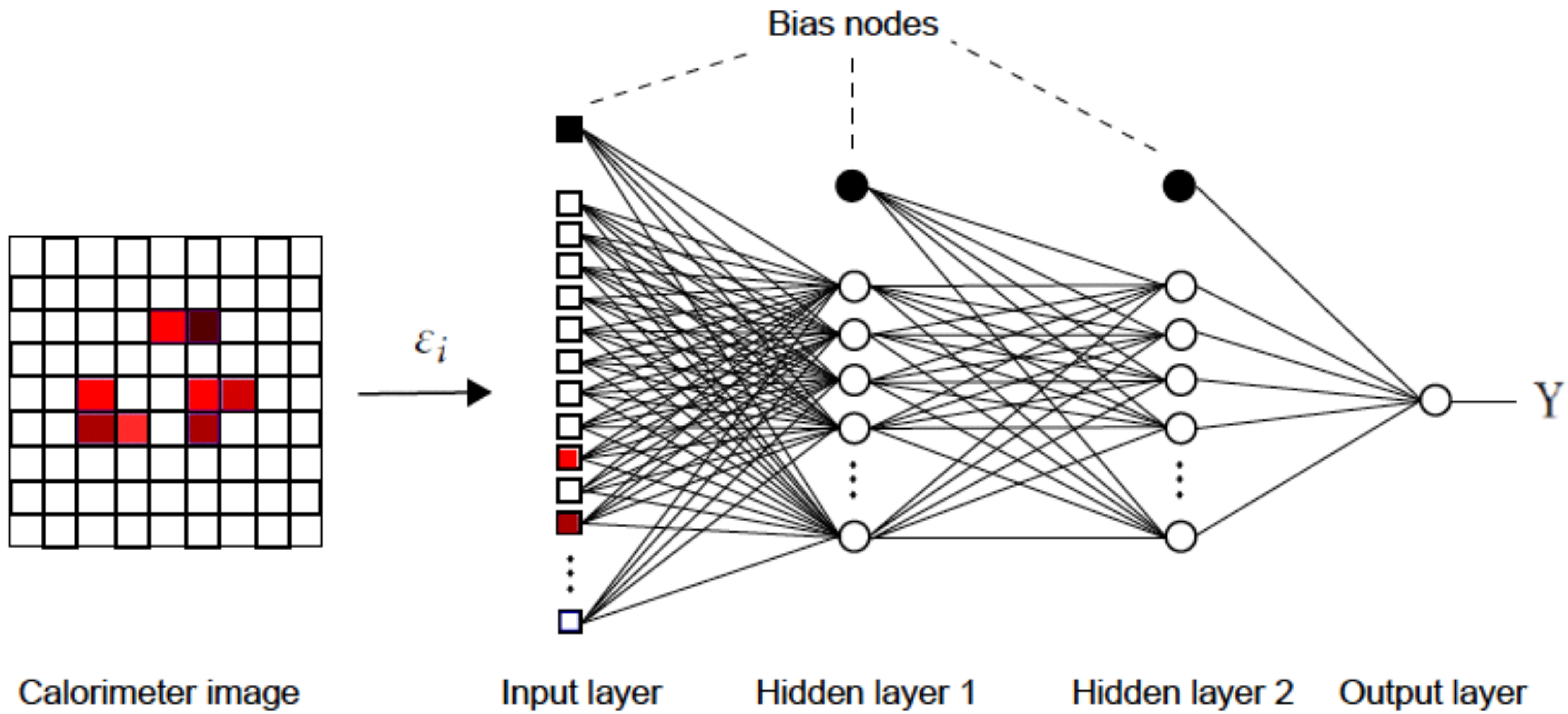
- We showed that Run 2 of the LHC at 14 TeV can detect and measure 2 TeV top partners in a lepton-jet final state, with almost 5 sigma signal significance and S/B > 1 at 35 fb^{-1}
- A sizeable part of the model parameter space parts which result in a 2 TeV top partner can be ruled at 2 sigma with as little as 10 fb^{-1}



$f = 800$ GeV, $M_1 = 1.5$ TeV, $\phi = \pi$, $c_R = 3$, $y_L = 1$, and $M_4 = 2$ TeV. $|g^R_{XWt}| = \frac{g}{\sqrt{2}} \cdot 0.66$ and $|g^R_{BWt}| = \frac{g}{\sqrt{2}} \cdot 0.63$,

Almeida, Backovic, Cliche, SL, Perelstein `15

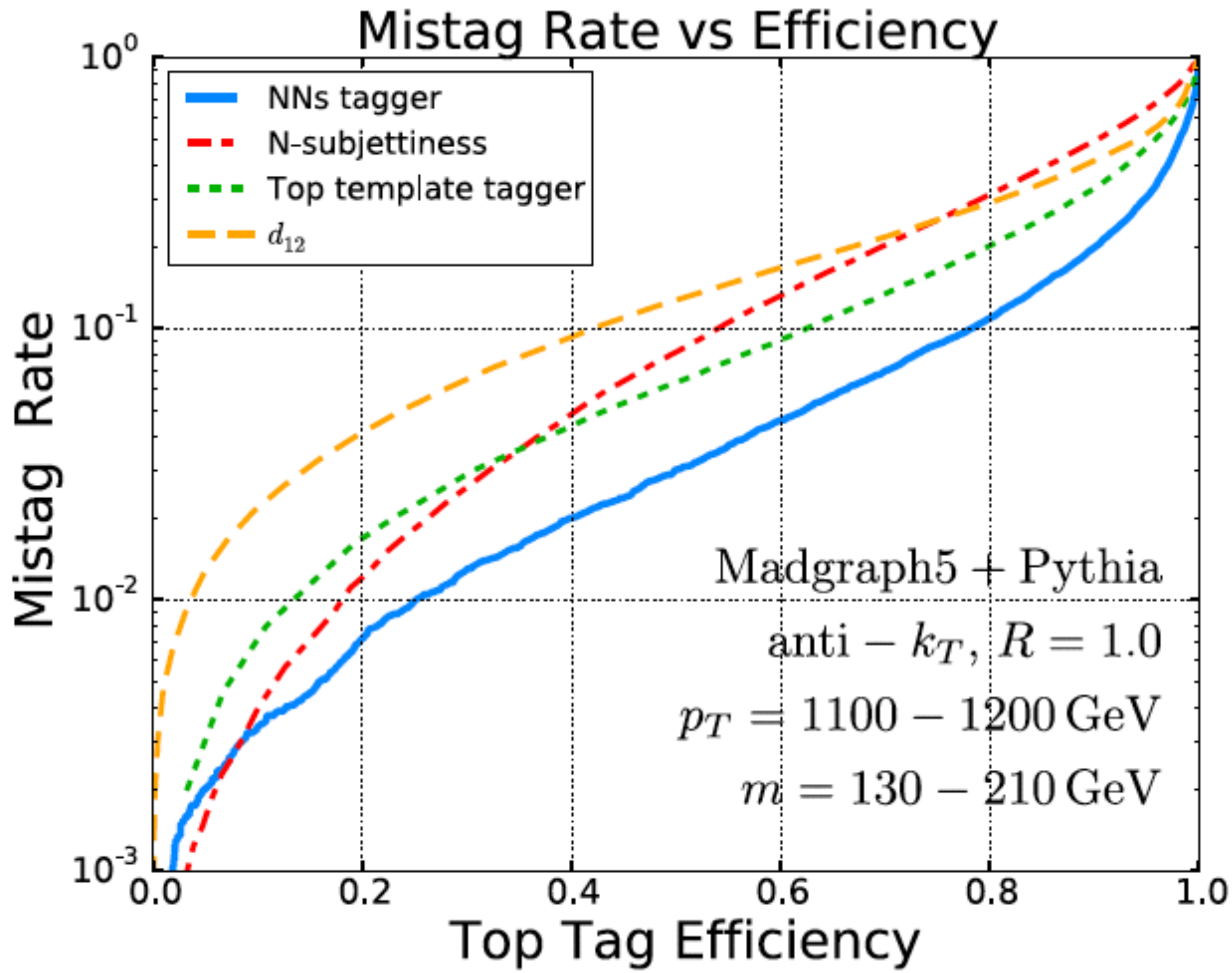
Jet Substructure with Artificial Neural Network (ANN)



Top Partner Searches Beyond the 2 TeV Mass Region

Almeida, Backovic, Cliche, SL, Perelstein `15

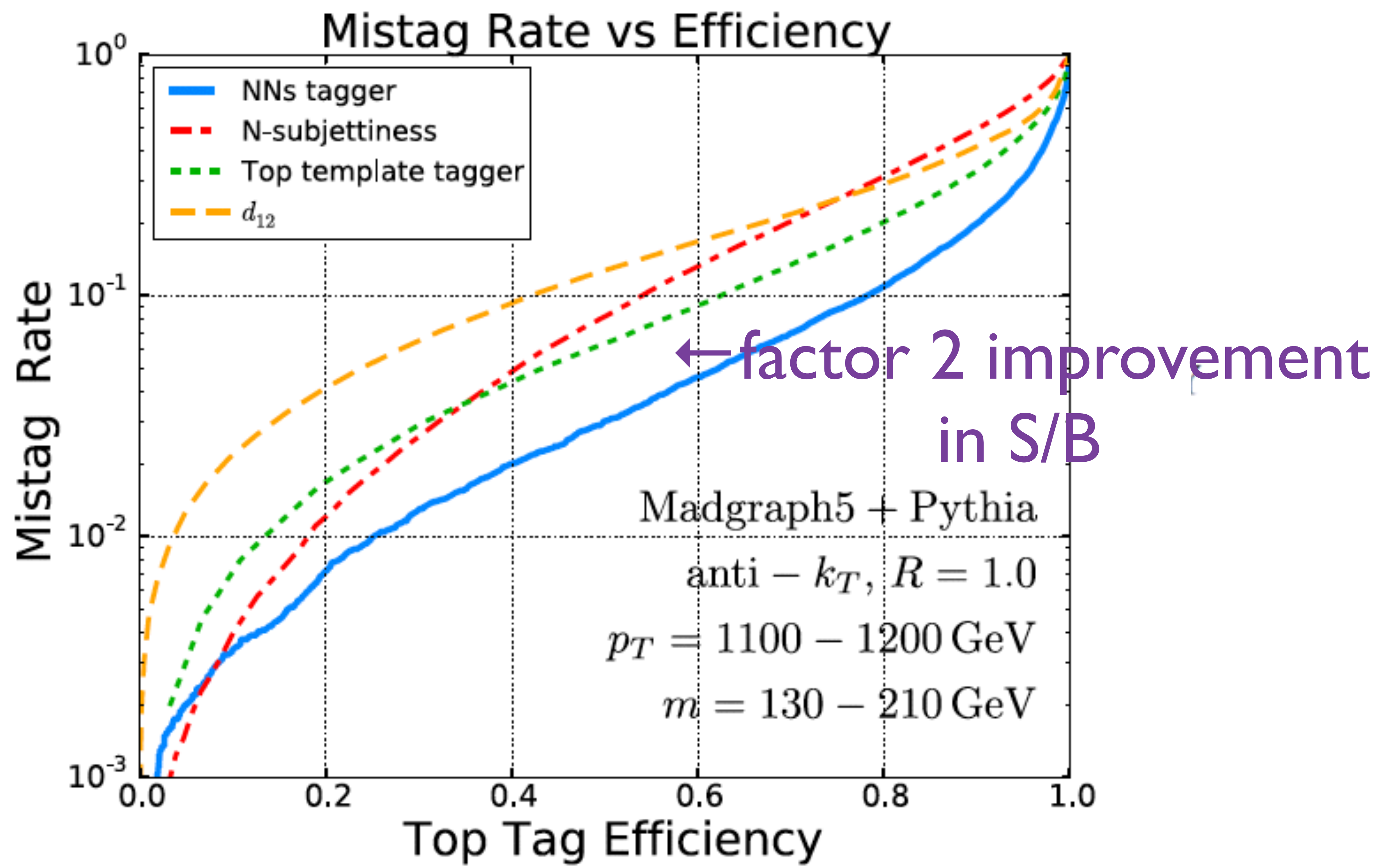
✱ Jet Substructure with Artificial Neural Network (ANN)



Top Partner Searches Beyond the 2 TeV Mass Region

Almeida, Backovic, Cliche, SL, Perelstein `15

Jet Substructure with Artificial Neural Network (ANN)

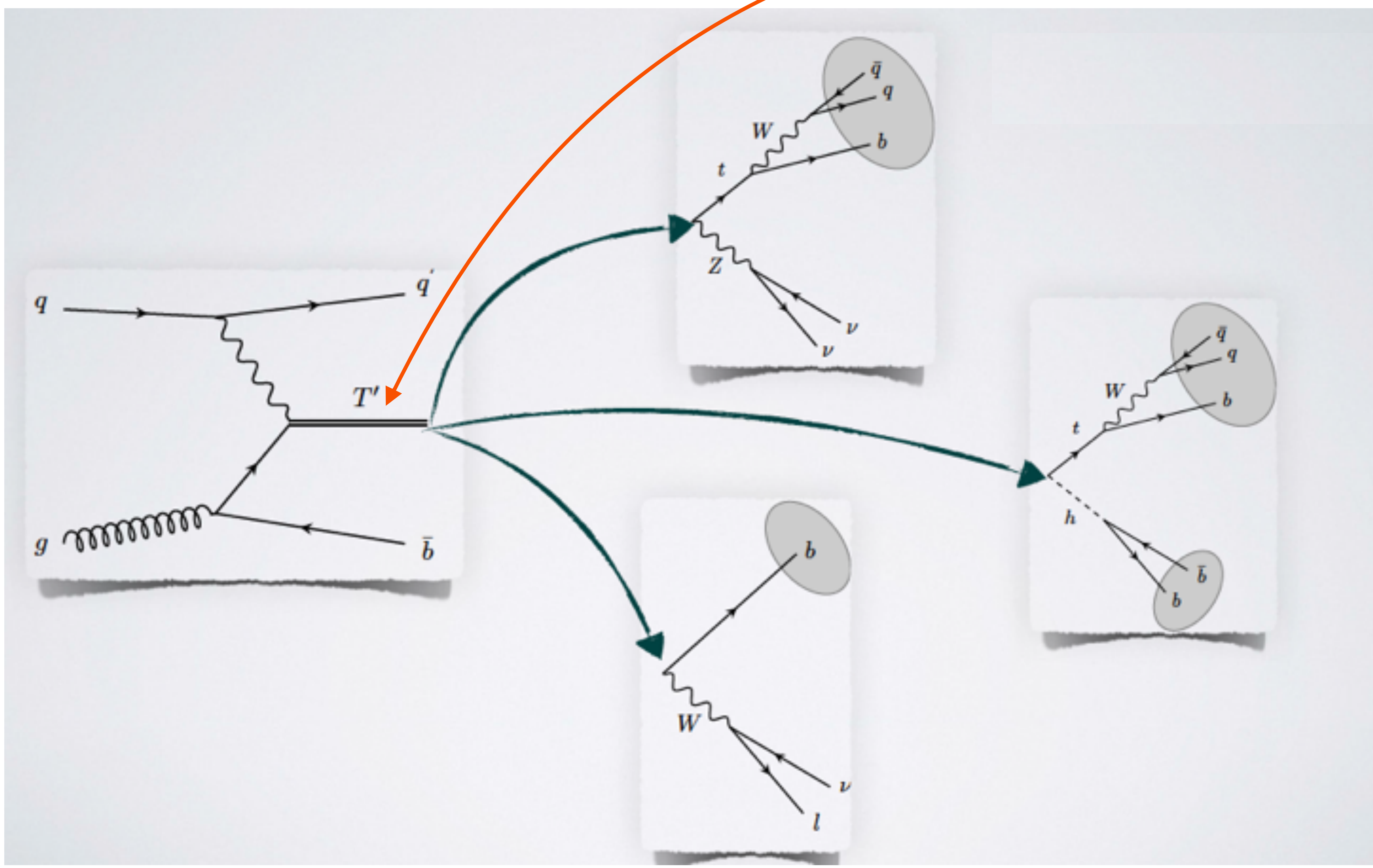


2/3 charged Top Partner Searches Beyond the 1 TeV Mass Region

- Single production of top partners

Backovic, Flacke, Kim, SL (x2), `15

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



2/3 charged Top Partner Searches Beyond the 1 TeV Mass Region

- Single production of top partners

Backovic, Flacke, Kim, SL (x2), `15

$$\mathcal{L} \supset \bar{T}\left(i\not{D} - M_1\right)T + \bar{q}_L i\not{D} q_L + \bar{t}_R i\not{D} t_R - \left(\lambda_R f \cos(\bar{h}/f)\bar{t}_R T_L - \frac{\lambda_L f \sin(\bar{h}/f)}{\sqrt{2}}\bar{t}_L T_R + \text{h.c.}\right)$$

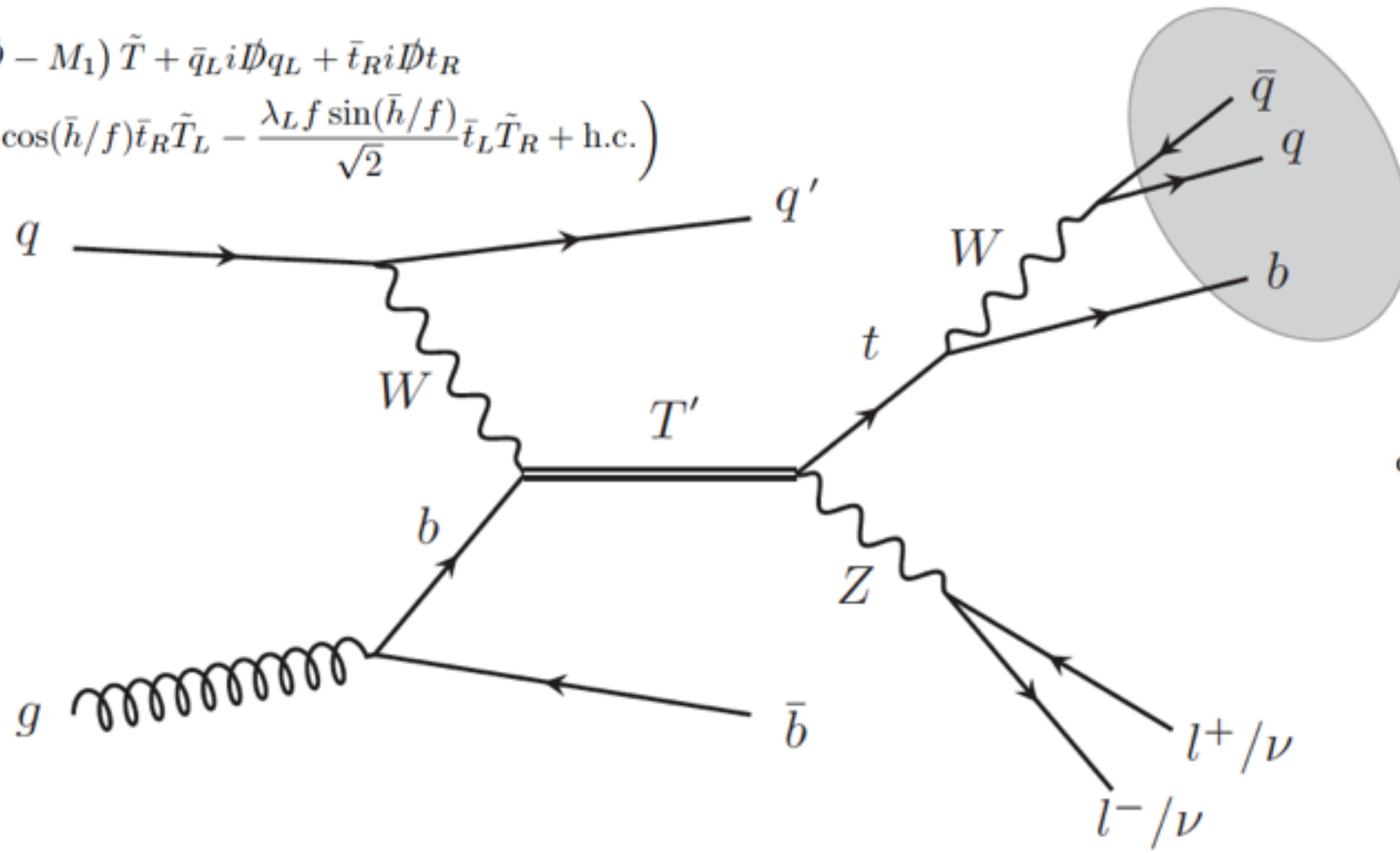
$$m_{t,\text{phys}} \equiv m_{t'} = \frac{v}{\sqrt{2}}\frac{\lambda_L \lambda_R f}{\sqrt{M_1^2 + \lambda_R^2 f^2}} + \mathcal{O}\left(\frac{v^3}{f^3}\right) \quad \text{and} \quad M_{T'} = \sqrt{M_1^2 + \lambda_R^2 f^2} + \mathcal{O}\left(\frac{v^2}{f^2}\right)$$

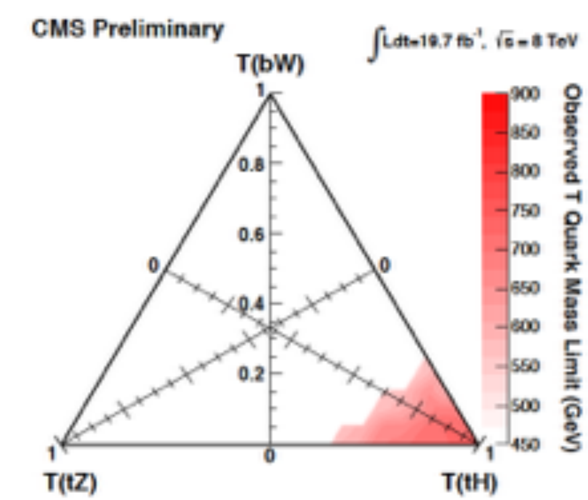
$$\begin{aligned}\mathcal{L} = \mathcal{L}_{SM,t,b} &- c_L^{ttZ}\frac{g\cos(\theta_w)}{\sqrt{2}}\bar{t}'_L \not{Z} t_L - \left(c_L^{tbW}\frac{g}{2}\bar{t}'_L \not{W} b_L + \text{h.c.}\right) + c^{tth}\frac{m'_t}{v} h\bar{t}' t' \\ &+ \bar{T}'\left(i\not{\partial} - m_{T'} + g_3 \not{G} + \frac{2}{3}e\not{A} + c_L^{T'T'Z}\frac{g\cos(\theta_w)}{\sqrt{2}}\not{Z}P_L + c^{T'T'h}h\right)T' \\ &+ \left(c_L^{T'bW}\frac{g}{2}\bar{T}'_L \not{W} b_L + c_L^{T'tZ}\frac{g\cos(\theta_w)}{\sqrt{2}}\bar{T}'_L \not{Z} t_L - c_{L,R}^{T'th} h\bar{T}'_{L,R} t'_{R,L} + \text{h.c.}\right)\end{aligned}$$

2/3 charged Top Partner Searches Beyond the 1 TeV Mass Region

- For simple study we chose $SU(2)_L$ singlet top partners (with charge 2/3) **(BR(t+h)~25%, BR(t+Z)~25%, BR(b+W)~50%)**

$$\mathcal{L} \supset \bar{\tilde{T}}' \left(i\not{D} - M_1\right)\tilde{T} + \bar{q}_L i\not{D} q_L + \bar{t}_R i\not{D} t_R - \left(\lambda_R f \cos(\bar{h}/f)\bar{t}_R \tilde{T}_L - \frac{\lambda_L f \sin(\bar{h}/f)}{\sqrt{2}}\bar{t}_L \tilde{T}_R + \text{h.c.}\right)$$



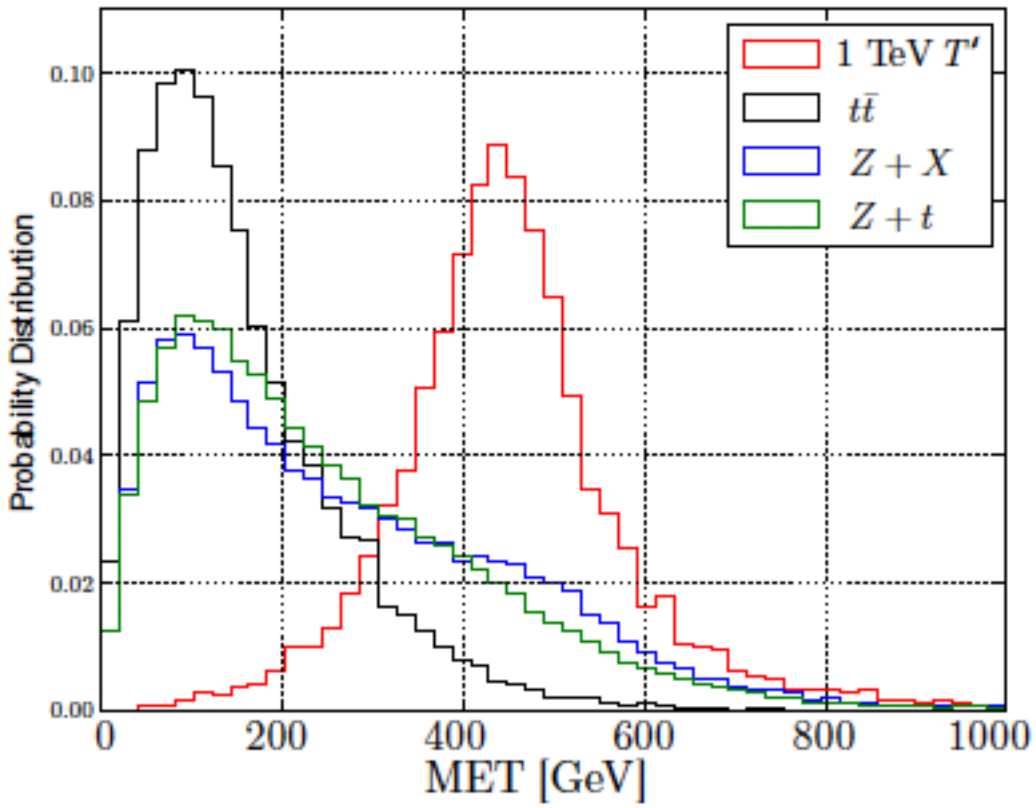


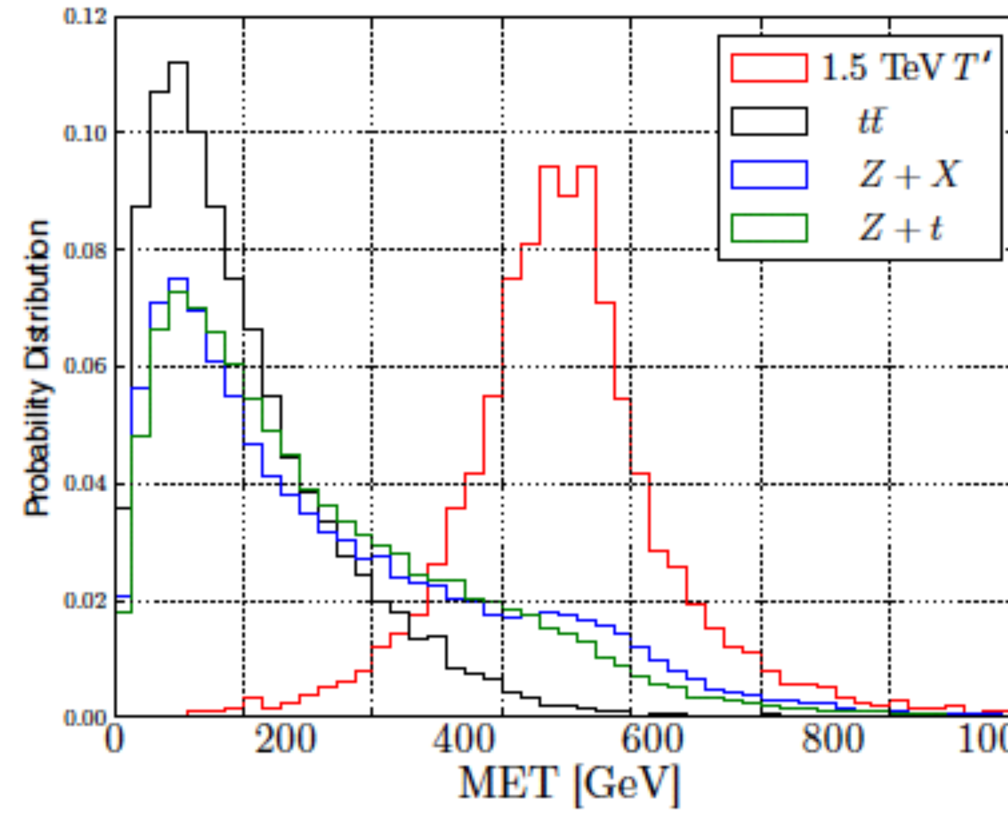
- For **Run I**, **(Z → MET)+hadronic** channel was not utilized due to large SM background (e.g. t+MET): **(Z → dilepton)+hadronic channel** has been the golden channel

Backovic, Flacke, Kim,SL `15
Backovic, Flacke, Kim,SL to appear today

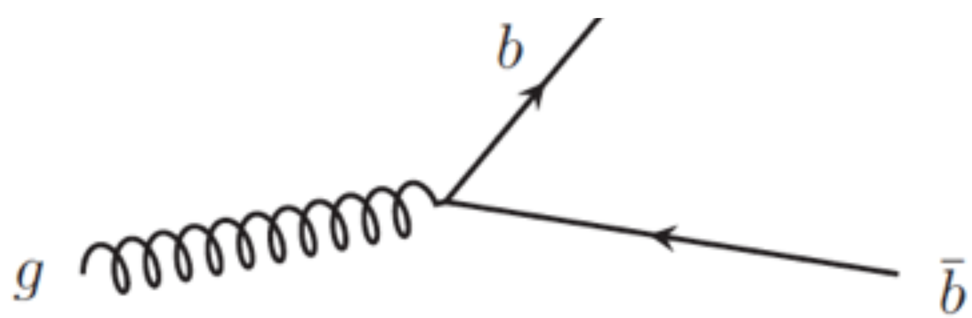
2/3 charged Top Partner Searches Beyond the 1 TeV Mass Region

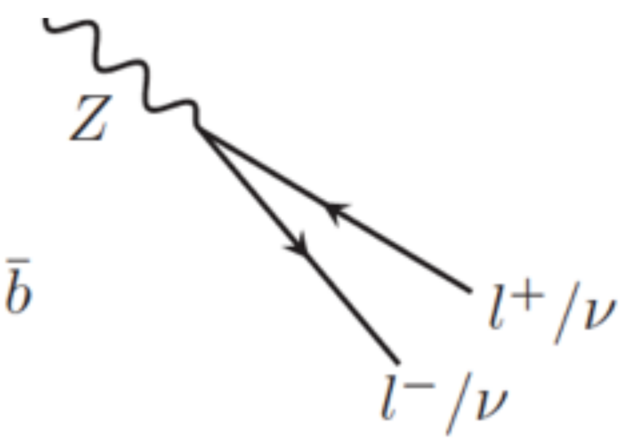
$\mathcal{L}$

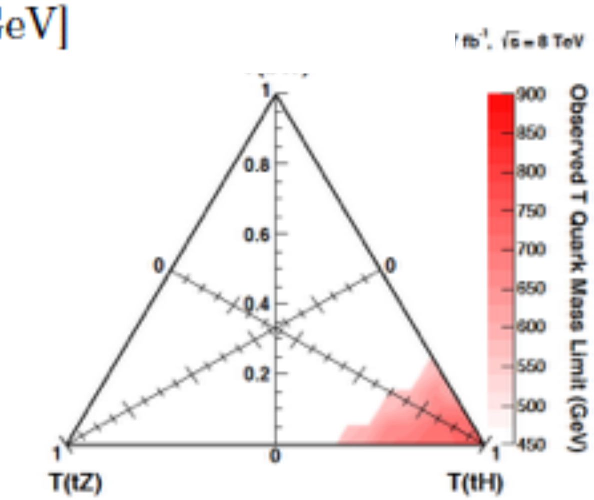




0%)







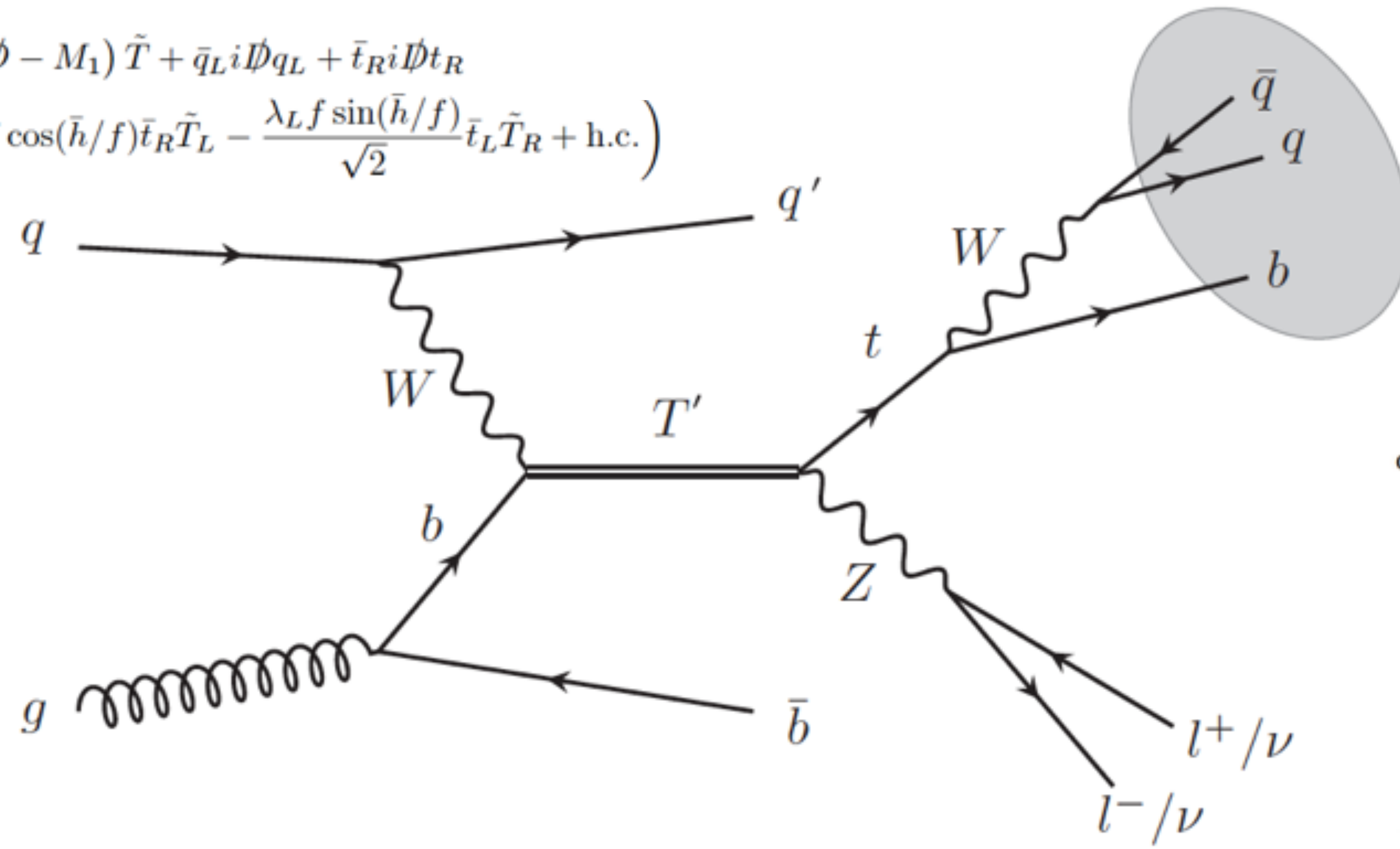
- For **Run I**, **(Z → MET)+hadronic** channel was not utilized due to large SM background (e.g. t+MET): **(Z → dilepton)+hadronic channel** has been the golden channel

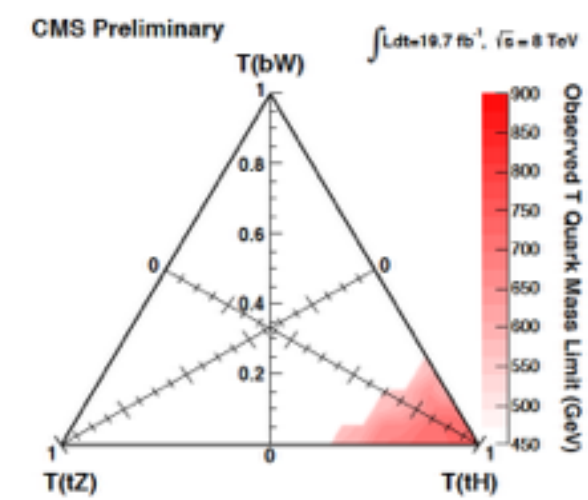
Backovic, Flacke, Kim,SL `15
Backovic, Flacke, Kim,SL to appear today

2/3 charged Top Partner Searches Beyond the 1 TeV Mass Region

- For simple study we chose $SU(2)_L$ singlet top partners (with charge 2/3) **(BR(t+h)~25%, BR(t+Z)~25%, BR(b+W)~50%)**

$$\mathcal{L} \supset \bar{\tilde{T}}' (i\not{D} - M_1)\tilde{T} + \bar{q}_L i\not{D} q_L + \bar{t}_R i\not{D} t_R - \left(\lambda_R f \cos(\bar{h}/f)\bar{t}_R \tilde{T}_L - \frac{\lambda_L f \sin(\bar{h}/f)}{\sqrt{2}} \bar{t}_L \tilde{T}_R + \text{h.c.}\right)$$





- For **Run I**, **(Z → MET)+hadronic** channel was not utilized due to large SM background (e.g. t+MET): **(Z → dilepton)+hadronic channel** has been the golden channel

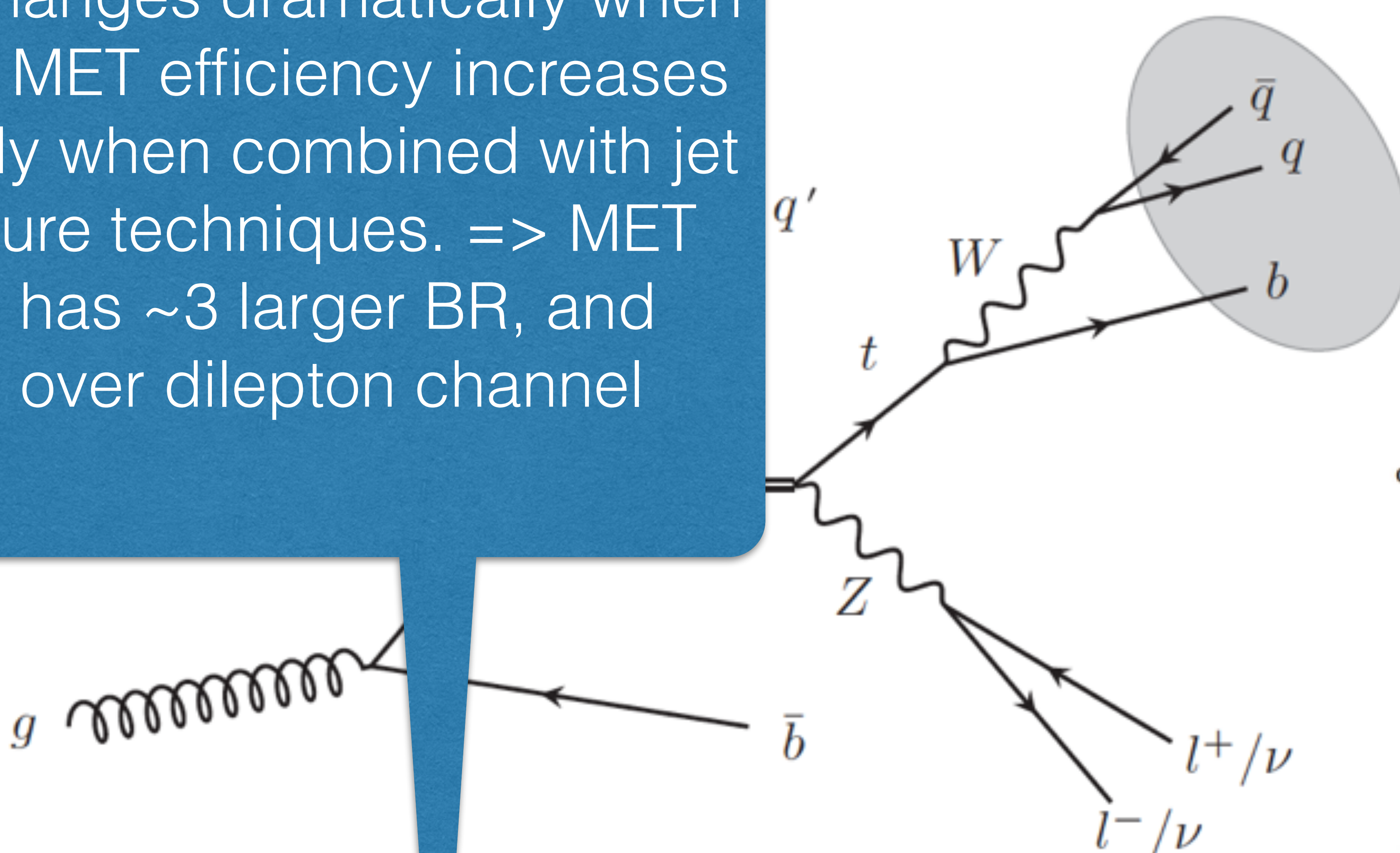
Backovic, Flacke, Kim,SL `15
Backovic, Flacke, Kim,SL to appear today

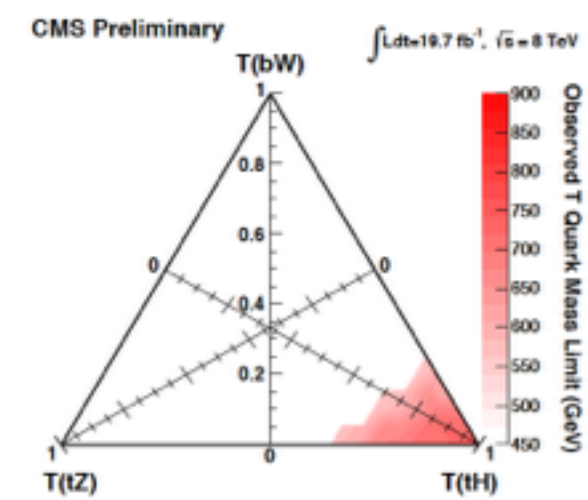
2/3 charged Top Partner Searches Beyond the 1 TeV Mass Region

se $SU(2)_L$ singlet top

(BR(t+h)~25%, BR(t+Z)~25%, BR(b+W)~50%)

Situation changes dramatically when **M > 1TeV**: MET efficiency increases dramatically when combined with jet substructure techniques. => MET channel has ~3 larger BR, and favored over dilepton channel





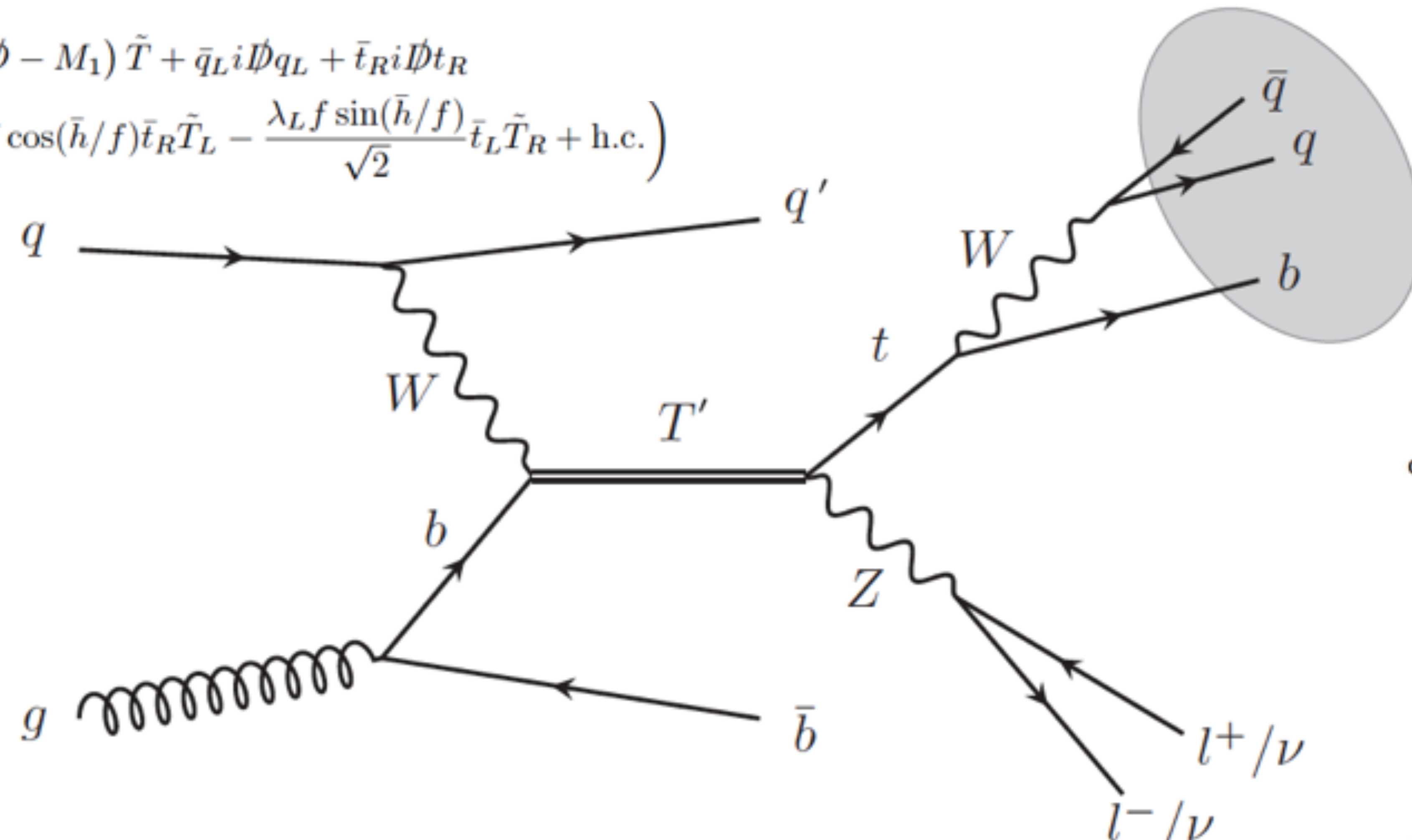
* For **Run I**, **(Z → MET)+hadronic** channel was not utilized due to large SM background (e.g. t+MET): **(Z → dilepton)+hadronic channel** has been the golden channel

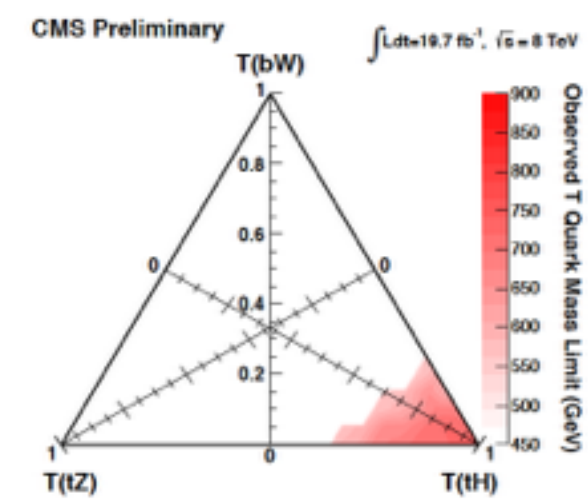
Backovic, Flacke, Kim,SL `15
Backovic, Flacke, Kim,SL to appear today

2/3 charged Top Partner Searches Beyond the 1 TeV Mass Region

- For simple study we chose $SU(2)_L$ singlet top partners (with charge 2/3) **(BR(t+h)~25%, BR(t+Z)~25%, BR(b+W)~50%)**

$$\mathcal{L} \supset \bar{\tilde{T}}' \left(i\not{D} - M_1\right)\tilde{T} + \bar{q}_L i\not{D} q_L + \bar{t}_R i\not{D} t_R - \left(\lambda_R f \cos(\bar{h}/f)\bar{t}_R \tilde{T}_L - \frac{\lambda_L f \sin(\bar{h}/f)}{\sqrt{2}}\bar{t}_L \tilde{T}_R + \text{h.c.}\right)$$





- For **Run I**, **(Z → MET)+hadronic** channel was not utilized due to large SM background (e.g. t+MET): **(Z → dilepton)+hadronic channel** has been the golden channel

Backovic, Flacke, Kim,SL `15
Backovic, Flacke, Kim,SL to appear today

2/3 charged Top Partner Searches Beyond the 1 TeV Mass Region

- For simple study we chose SU(2)L singlet top partners (with charge 2/3)

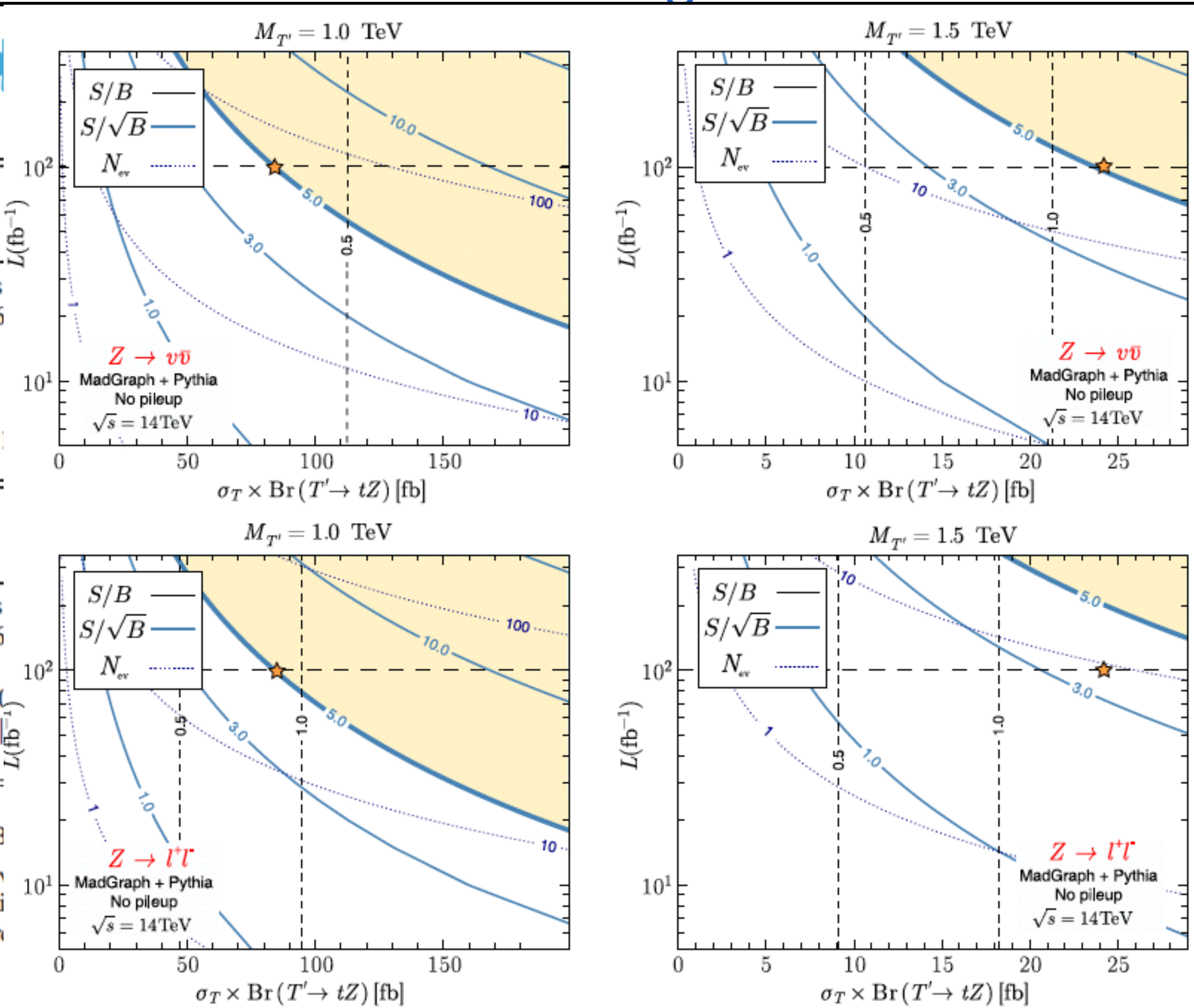
$Z \to \nu\bar{\nu}$	$M_{T'} = 1.0$ TeV search						$M_{T'} = 1.5$ TeV search					
	Signal	$t\bar{t}$	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}(100\ \text{fb}^{-1})$	Signal	$t\bar{t}$	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}(100\ \text{fb}^{-1})$
Basic cuts	3.5	900	6100	11	0.00050	0.42	1.0	140	1200	2.4	0.00074	0.27
$Ov_3^t > 0.6$	2.7	510	840	6.5	0.0020	0.75	0.87	81	230	1.6	0.0028	0.49
b-tag	2.0	320	16	4.3	0.0057	1.1	0.54	45	3.2	0.94	0.011	0.77
$\not{E}_T$-cut	**1.3**	13	5.3	0.89	**0.065**	**2.9**	**0.41**	1.00	0.78	0.14	**0.21**	**3.0**
$N_{\text{fwd}} \geq 1$	**0.79**	2.6	0.74	0.27	**0.22**	**4.1**	**0.28**	0.20	0.11	0.041	**0.80**	**4.7**
$\Delta\phi_{\not{E}_T,j} > 1.0$	**0.66**	0.94	0.58	0.22	**0.38**	**5.0**	**0.22**	0.076	0.083	0.033	**1.2**	**5.1**

$Z \to l^+l^-$	$M_{T'} = 1.0$ TeV search					$M_{T'} = 1.5$ TeV search				
	Signal	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}(100\ \text{fb}^{-1})$	Signal	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}(100\ \text{fb}^{-1})$
Basic cuts	1.1	750	1.3	0.0014	0.39	0.30	170	0.36	0.0018	0.23
$Ov_3^t > 0.6$	0.71	71	0.61	0.010	0.85	0.24	19	0.14	0.012	0.54
b-tag	0.52	1.6	0.42	0.25	3.6	0.15	0.36	0.086	0.33	2.2
$\Delta R_{ll} < 1.0$	0.52	1.6	0.41	0.26	3.6	0.15	0.36	0.086	0.33	2.2
$\lvert m_{ll} - m_Z \rvert < 10$ GeV	**0.47**	1.5	0.37	**0.26**	**3.5**	**0.13**	0.33	0.078	**0.32**	**2.1**
$N_{\text{fwd}} \geq 1$	**0.29**	0.23	0.11	**0.88**	**5.1**	**0.088**	0.051	0.019	**1.3**	**3.3**

TABLE I. Example-cutflow for signal- and background events in the $Z_{\text{inv}} + t + j$ search (top) and in the $Z_{ll} + t + j$ channel (bottom) for $\sqrt{s} = 14$ TeV. Cross sections after the respective cuts for signal and backgrounds are given in fb. The $S/\sqrt{B}$ values are given for a luminosity of 100 fb^{-1}. The example signal $\sigma_{T'} \equiv \sigma(pp \to T'/\bar{T}' + X) \times \text{BR}(T' \to tZ)$ displayed here are 80 fb for $M'_T = 1.0$ TeV searches and 24 fb for $M'_T = 1.5$ TeV searches. The corresponding parameter points of our sample model are given in the text.

Backovic, Flacke, Kim, SL `15

2/3 charged Top Partner Searches Beyond the 1 TeV Mass Region



$Z \to \nu\bar{\nu}$	100 fb^{-1})
Basic cuts	.27
$Ov_3^t > 0.6$	.49
b-tag	.77
E_T-cut	.0
$N_{\text{fwd}} \geq 1$	.7
$\Delta\phi_{E_T,j} >$	.1

$Z \to l^+l^-$	100 fb^{-1})
Basic cuts	.23
$Ov_3^t > 0.6$	.54
b-tag	.2
$\Delta R_{ll} < 1.($	.2
$\|m_{ll} - m_Z\|$	.1
$N_{\text{fwd}} \geq 1$	.3

TAB … hannel (bottom) for … s are given for a lumi … $M_T' = 1.0$ TeV sear… n in the text.

2/3 charged Top Partner Searches Beyond the 1 TeV Mass Region

- Combined results (using likelihood ratio)

$$\mathcal{LR}_{\rm dis} \equiv \sqrt{-2\ln\left(\frac{L(B|\mu S+B)}{L(\mu S+B|\mu S+B)}\right)} \qquad \mathcal{LR}_{\rm dis} \geq 5$$

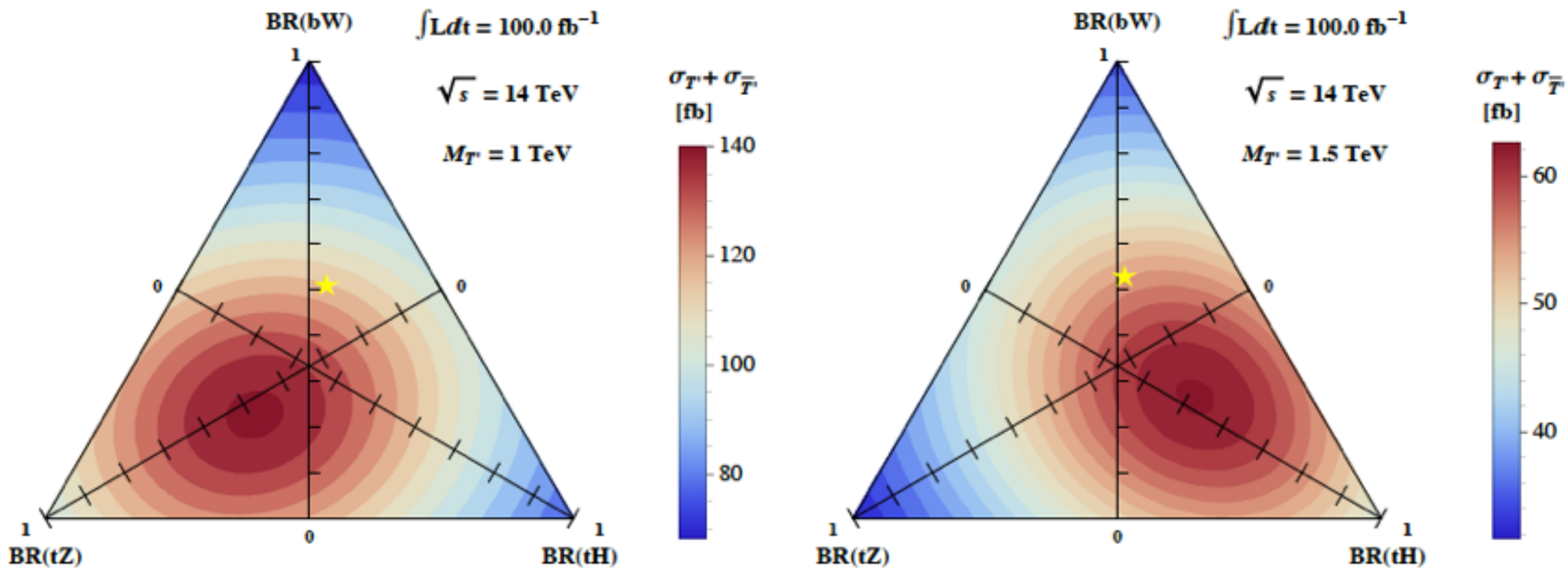


Figure 10: Signal cross section $\sigma_{T'} + \sigma_{\bar{T}'}$ required to obtain 5σ using 100 fb^{-1} of data with a fixed $M_{T'} = 1$ TeV (left) 100 fb^{-1} of data with a fixed $M_{T'} = 1.5$ TeV (right). The yellow stars mark the branching fractions at the sample points in our simulations ($c_L^{T'bW} = 0.3$ with $M_{T'} = 1.0$ TeV and $M_{T'} = 1.5$ TeV).

2/3 charged Top Partner Searches Beyond the 1 TeV Mass Region

- Combined results (using likelihood ratio)

$$\mathcal{LR}_{\rm exc} \equiv \sqrt{-2\ln\left(\frac{L(\mu S+B|B)}{L(B|B)}\right)} \qquad \mathcal{LR}_{\rm exc} \geq 2$$

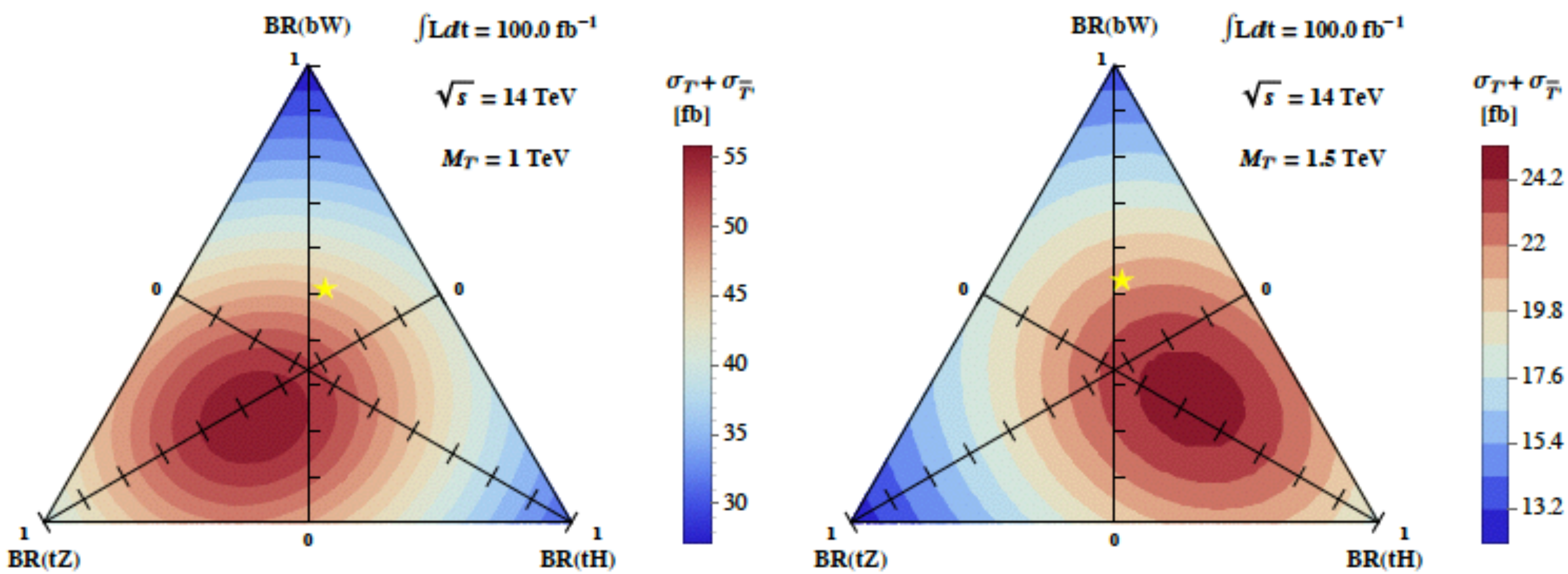


Figure 11: Signal cross section $\sigma_{T'} + \sigma_{\bar{T}'}$ which can be excluded with 100 fb^{-1} of data with a fixed $M_{T'} = 1$ TeV (left) and 100 fb^{-1} of data with a fixed $M_{T'} = 1.5$ TeV (right). The yellow stars mark the branching fractions at the sample points used in our simulations.

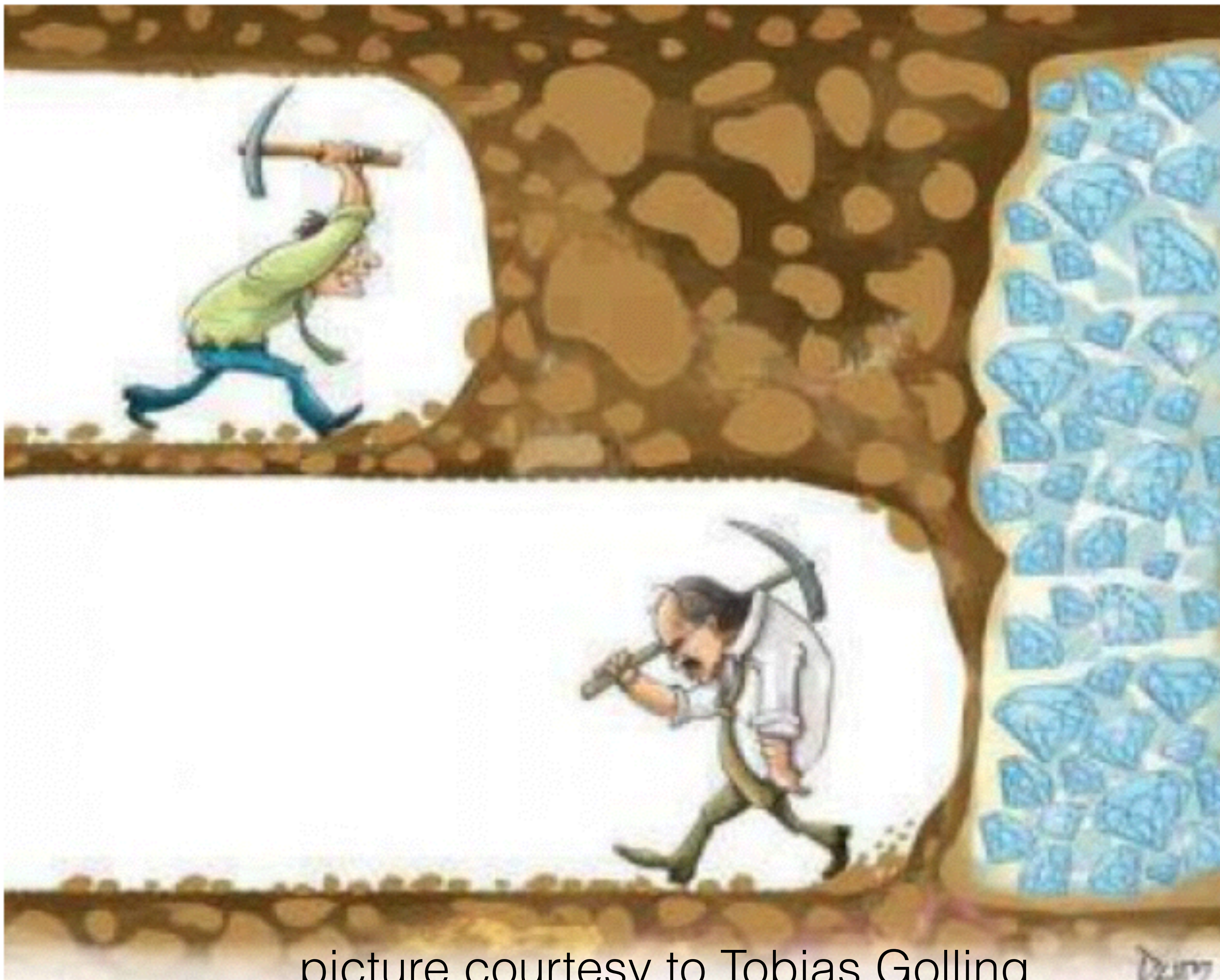
Top partners @ Run II

Boosted jet-substructure is a must tool for RUN II physics!

Composite Top Partners will be probed beyond 2 TeV!

Top partners @ Run II

We Might be this Close!



picture courtesy to Tobias Golling