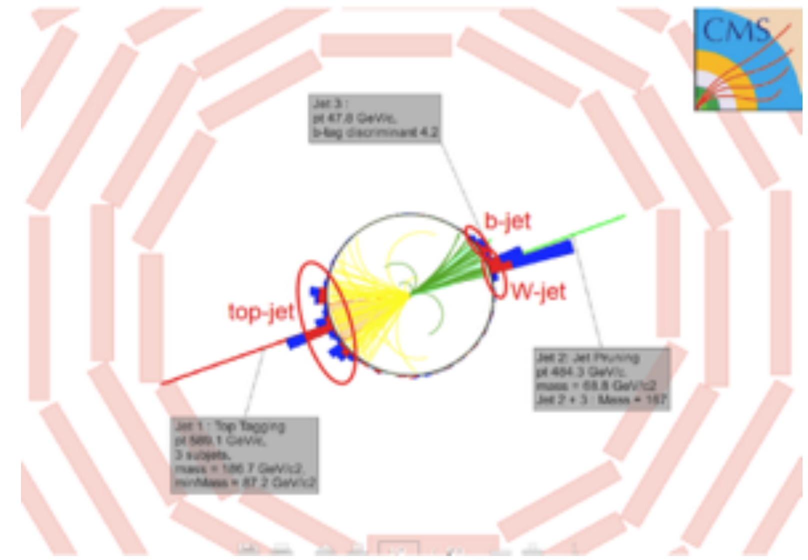
Boosted Top Tagging

Seung J. Lee

KAIST
한국과학기술원

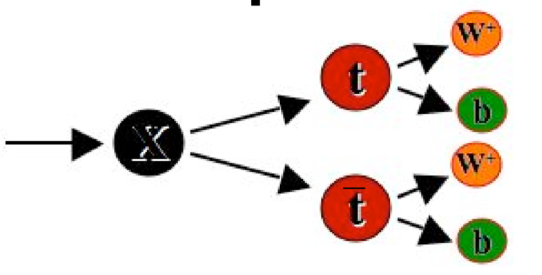
Outline

- Introduction: top jets @ LHC
- Modern boosted top tagging
  - review of existing top tagging
  - pile-up removal & mass reconstruction
- Top partners @ Run II
- Summary



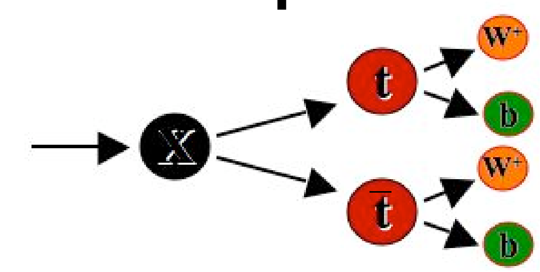
Top jets @ LHC

- Fine tuning solution => New states decay quickly into top + X



Top jets @ LHC

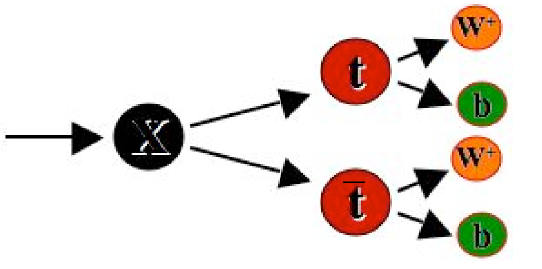
* Fine tuning solution => New states decay quickly into top + X



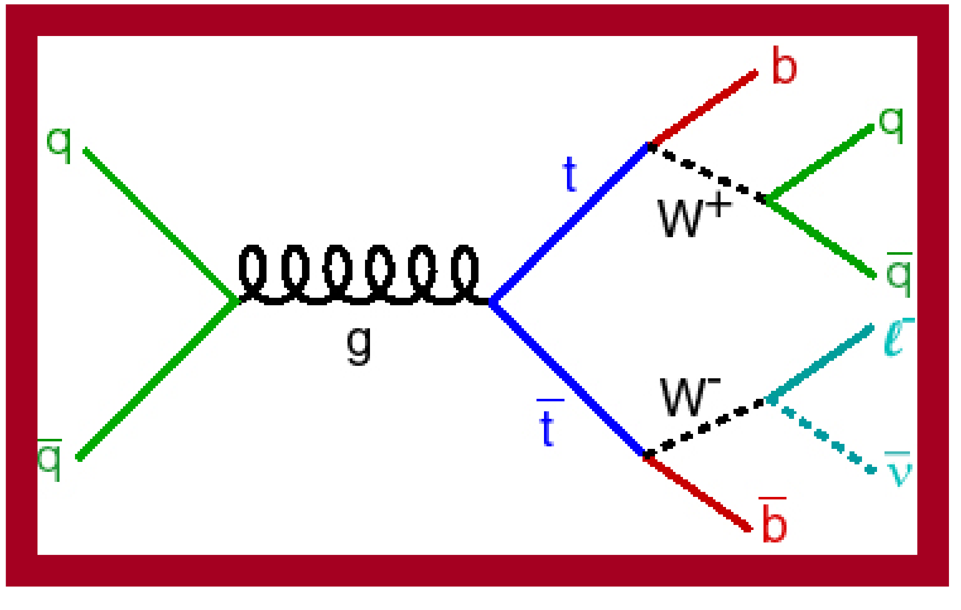
* If $m_X \gg m_t$, the outgoing tops are ultra-relativistic, their products collimate => top jets. $\Delta R \approx 2\,m / p_T$

Top jets @ LHC

- Fine tuning solution => New states decay quickly into top + X

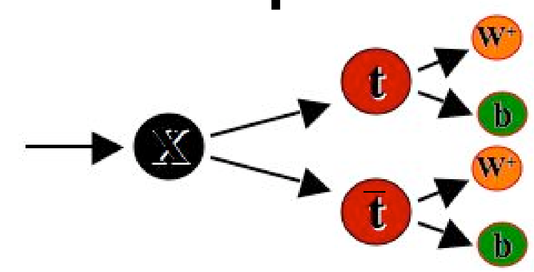


- If $m_X >> m_t$, the outgoing tops are ultra-relativistic, their products collimate => top jets. $\Delta R \approx 2\,m / p_T$

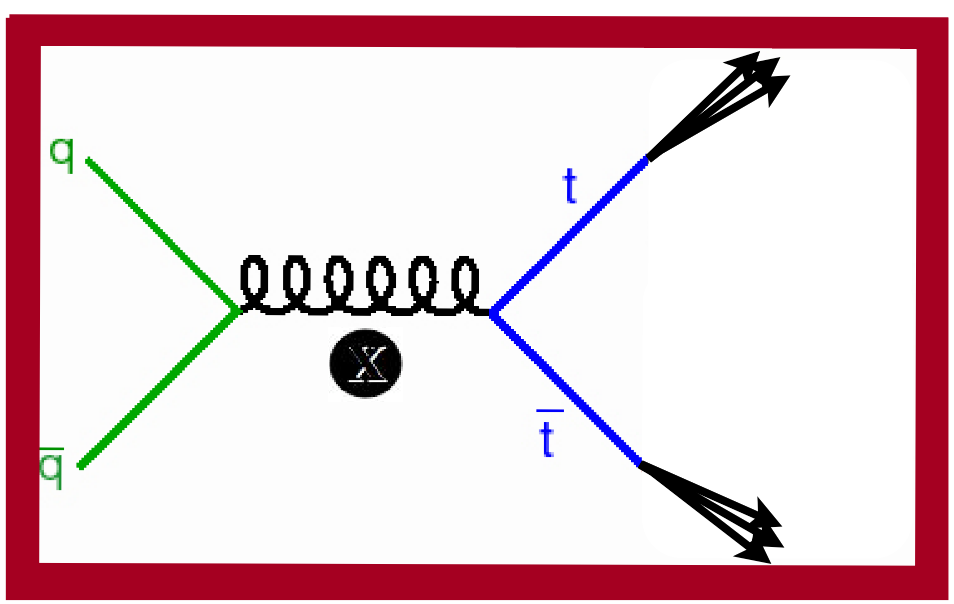


Top jets @ LHC

- Fine tuning solution => New states decay quickly into top + X

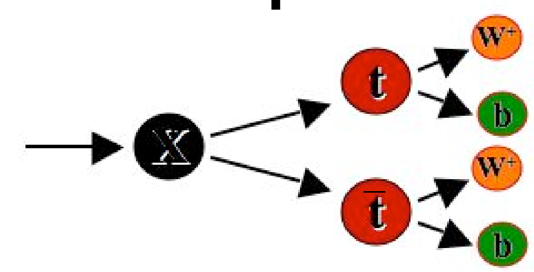


- If $m_X \gg m_t$, the outgoing tops are ultra-relativistic, their products collimate => top jets. $\Delta R \approx 2\, m / p_T$

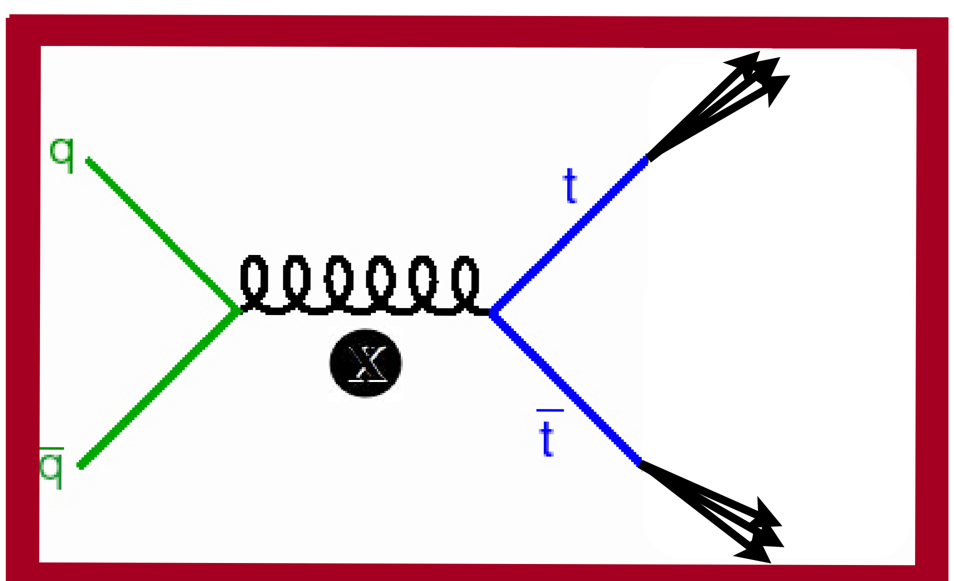


Top jets @ LHC

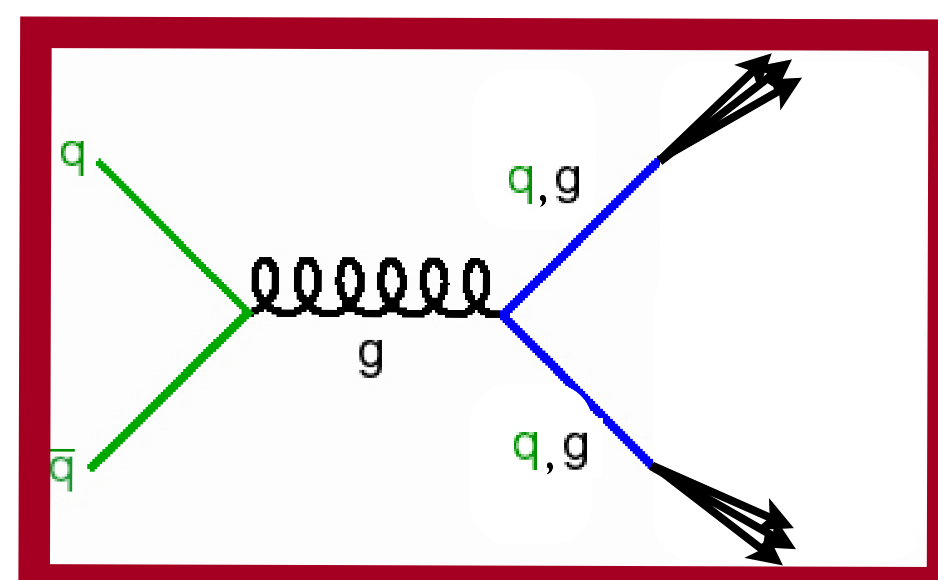
- Fine tuning solution => New states decay quickly into top + X



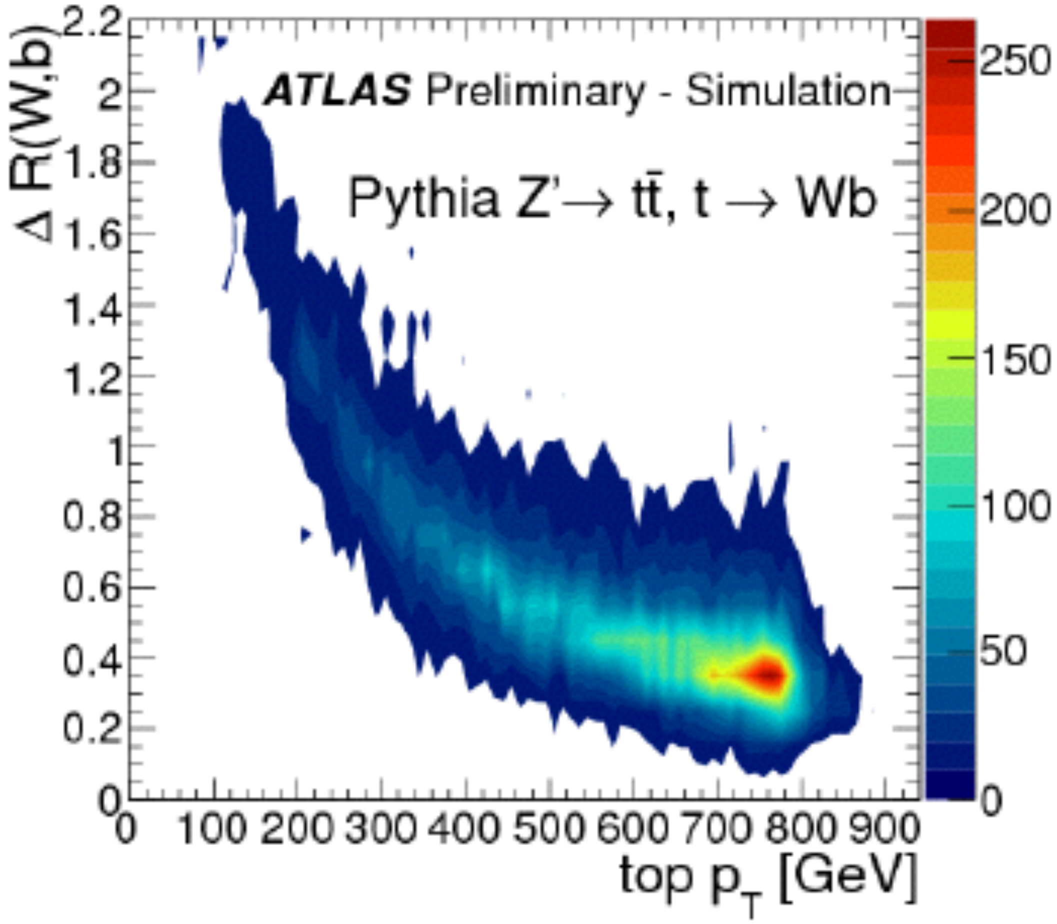
- If $m_X \gg m_t$, the outgoing tops are ultra-relativistic, their products collimate => top jets. $\Delta R \approx 2\, m / p_T$



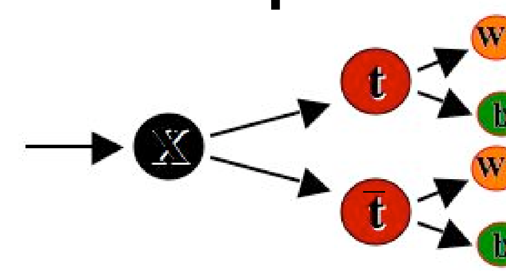
Similar to ordinary 2-jet QCD process impossible to observe ⁉



Top jets @ LHC

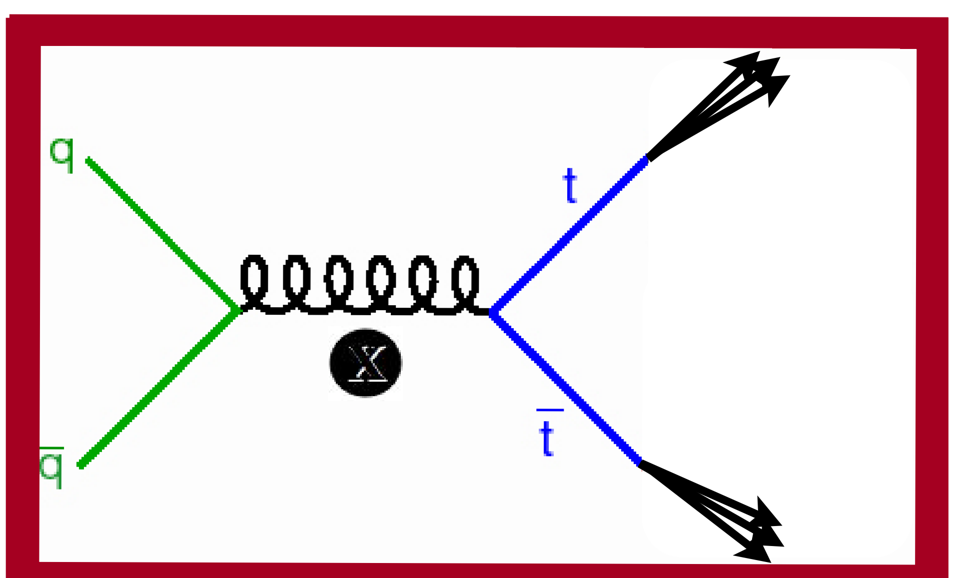


lew states decay quickly into top + X

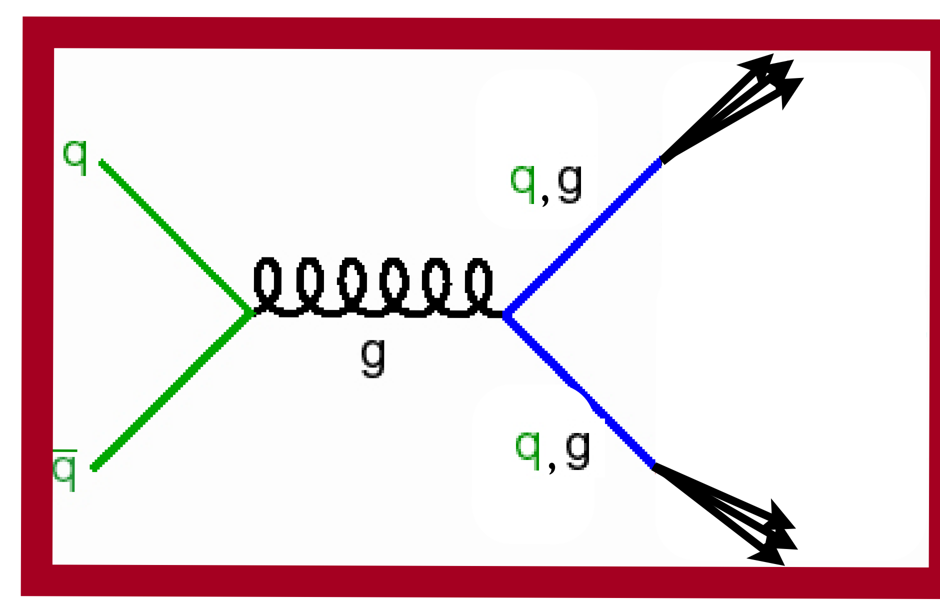


tops are ultra-relativistic, their

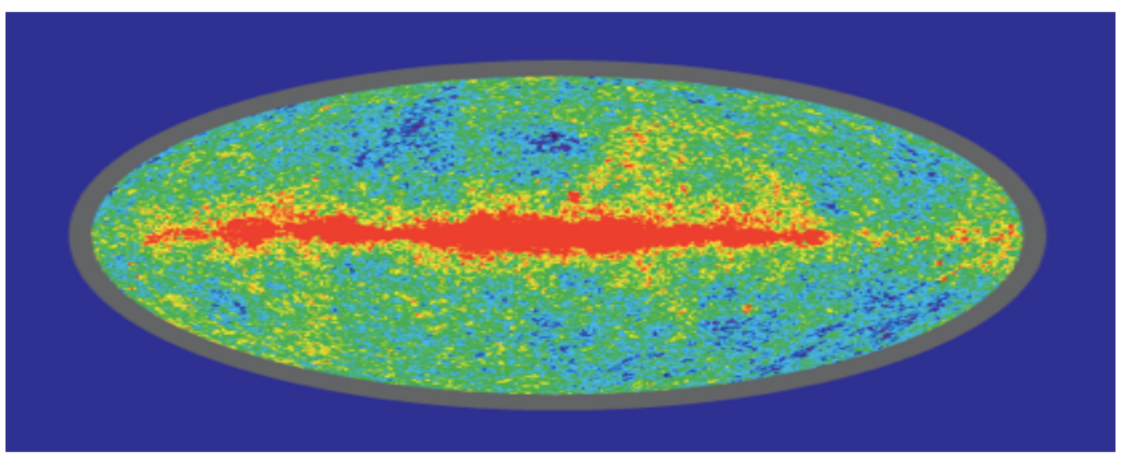
ets. $\Delta R \approx 2\, m / p_T$

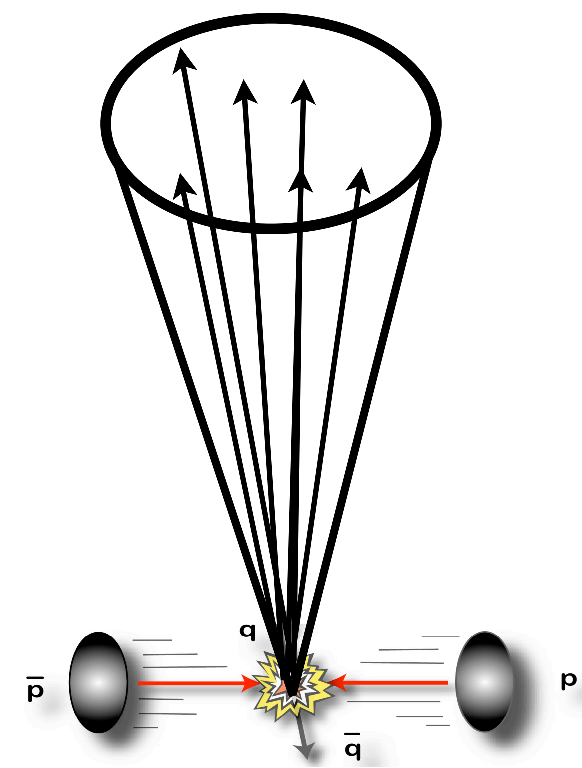


Similar to ordinary 2-jet QCD process impossible to observe ??



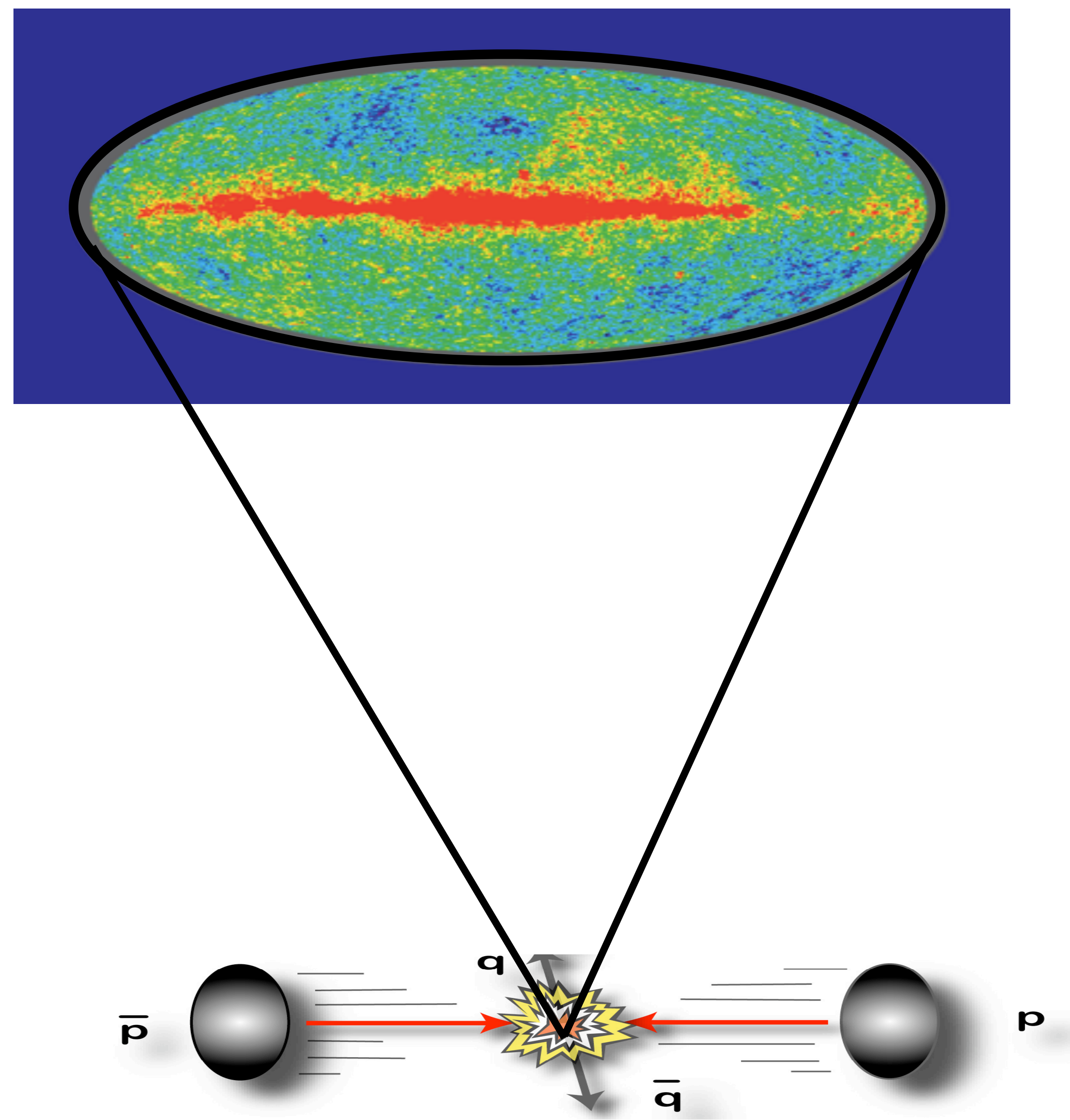
Need to understand the energy flow inside jet





Need to understand the energy flow inside jet

Jet Substructure



i)Algorithmic…
(Jet declustering)

ii)Jet Shape (calculable)

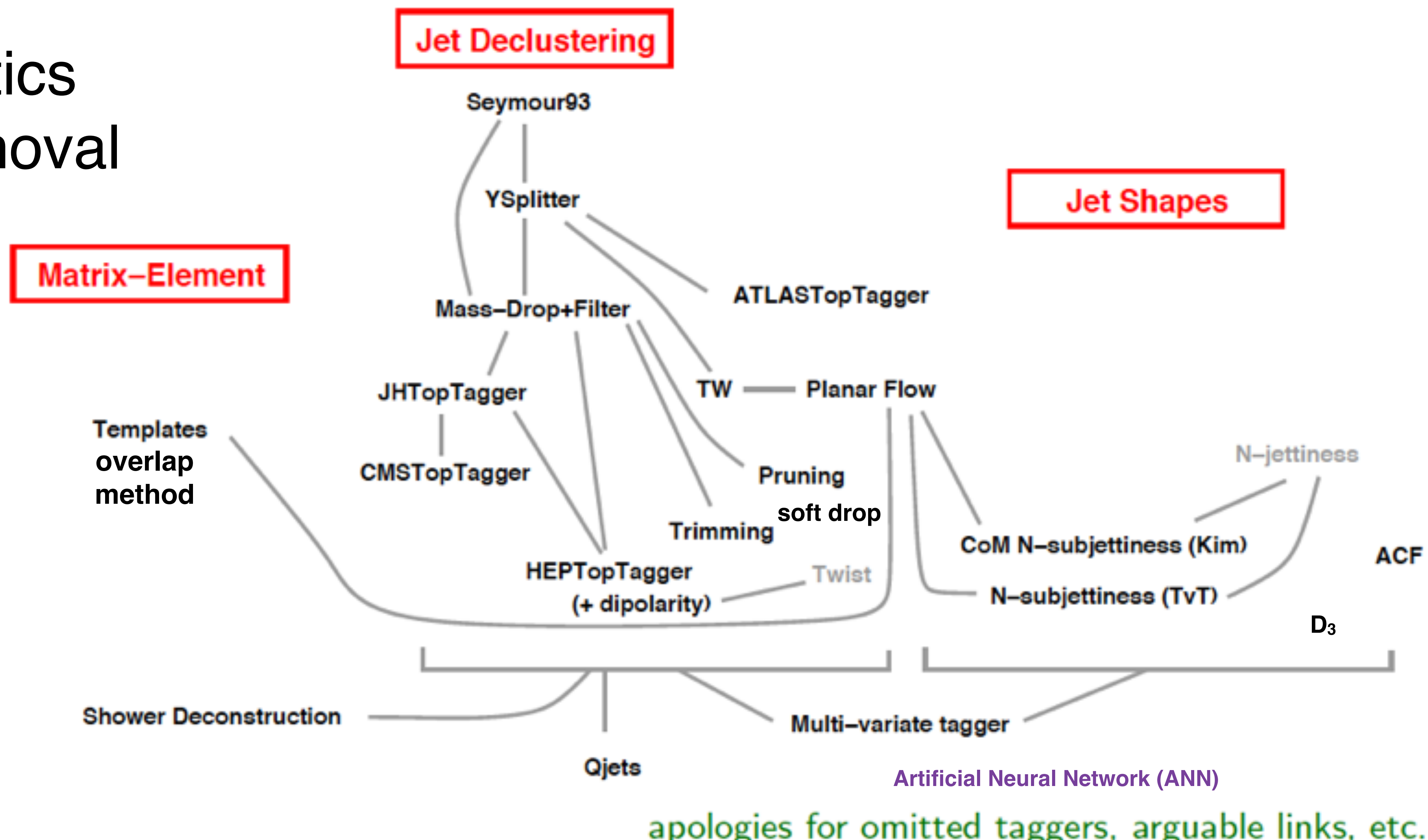
iii)Matrix-element…

iv)…

Jet substructure

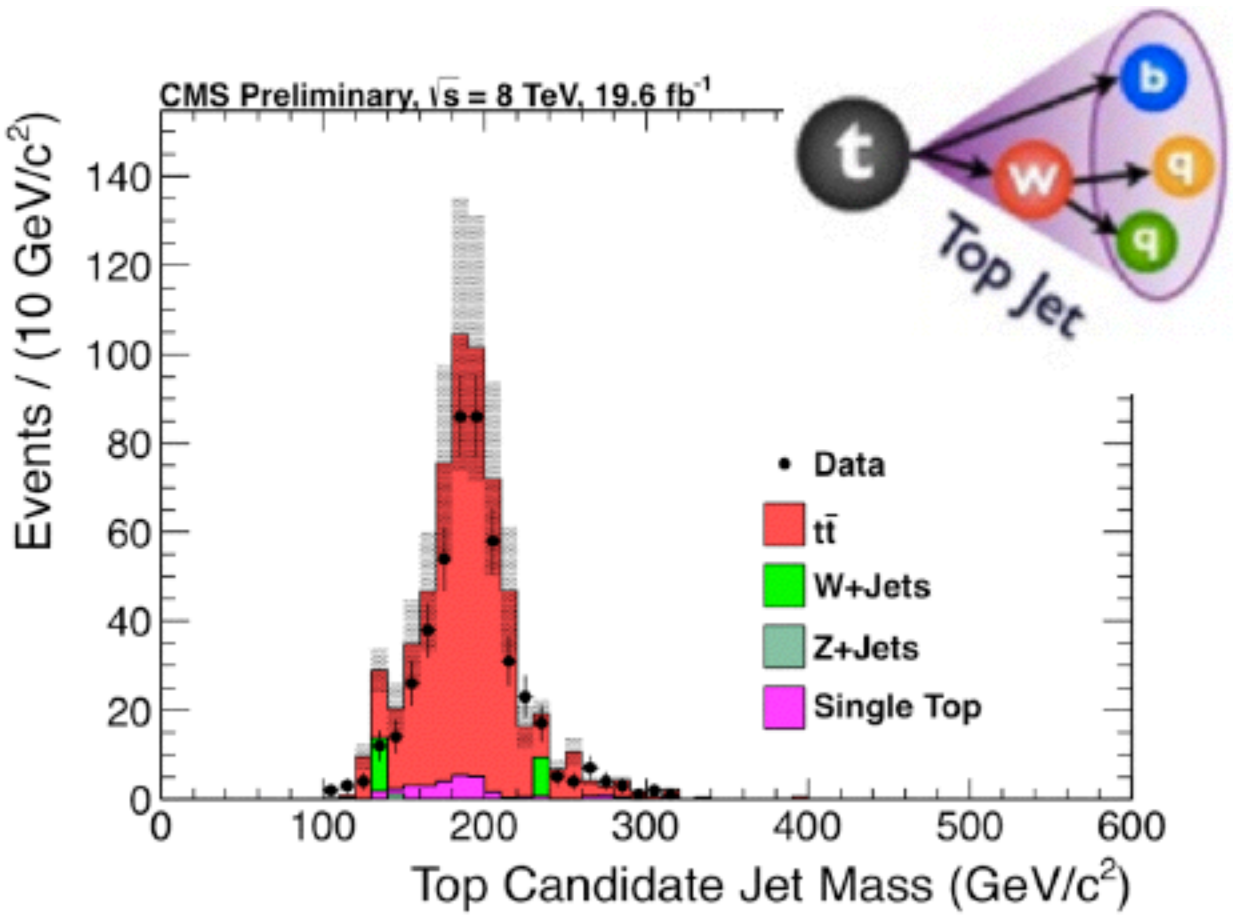
Very active research field

- Shape
- Kinematics
- Soft removal

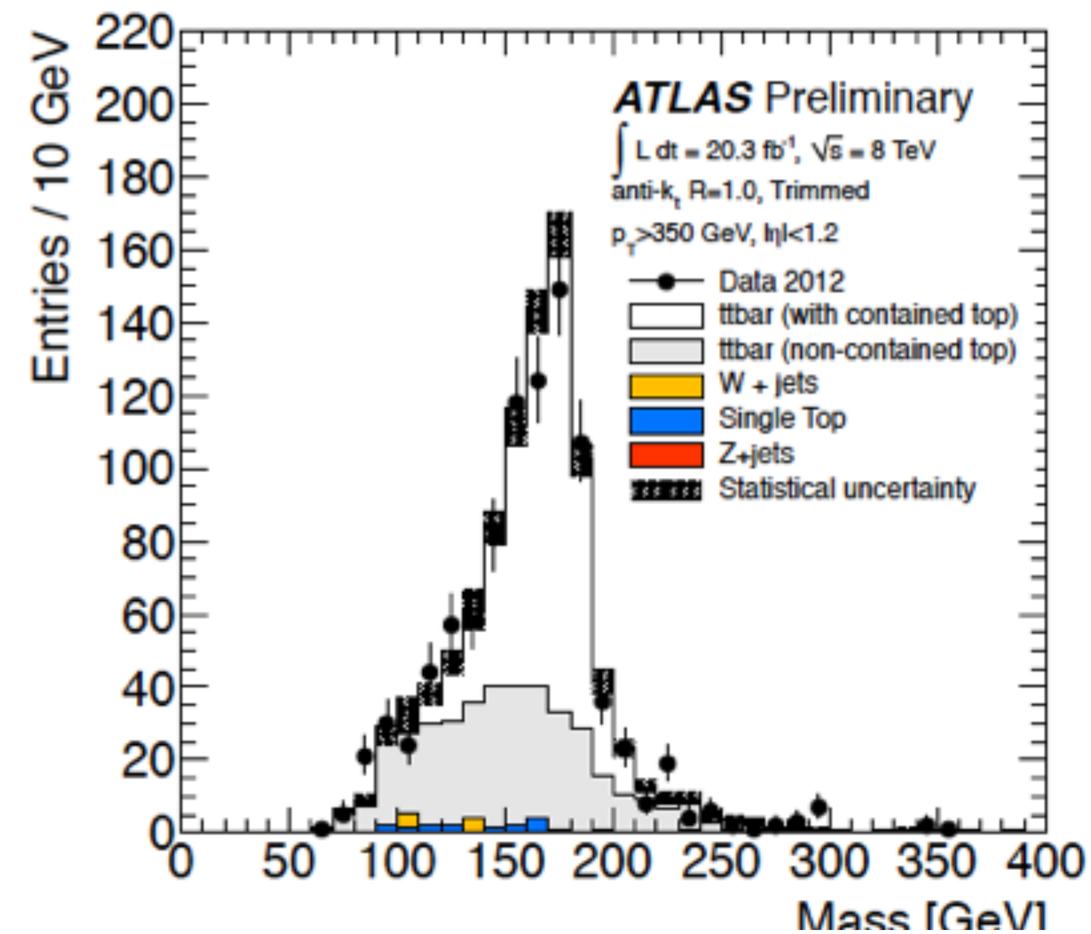


Gavin Salam

Lesson from Run I: it works!

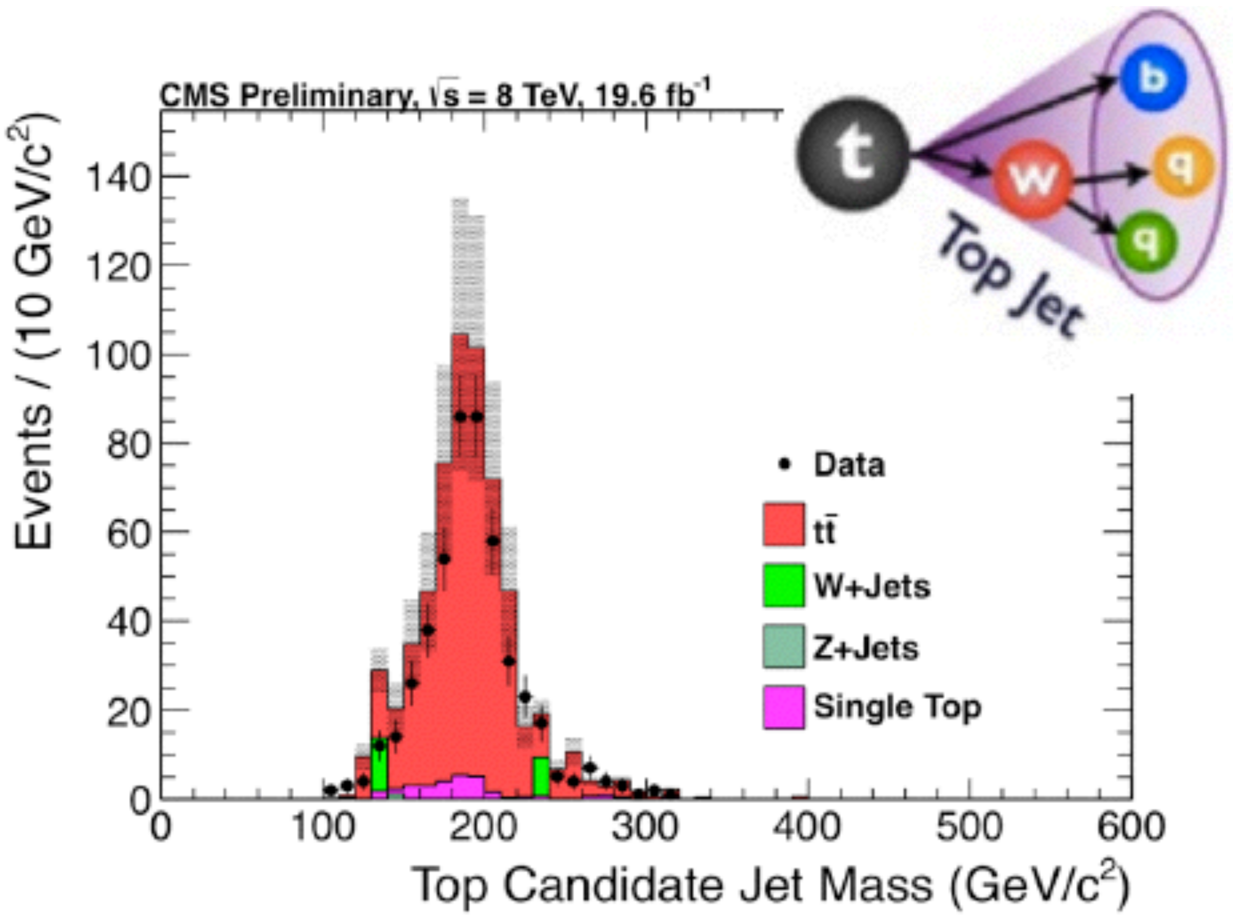


$p_T > 400$ GeV

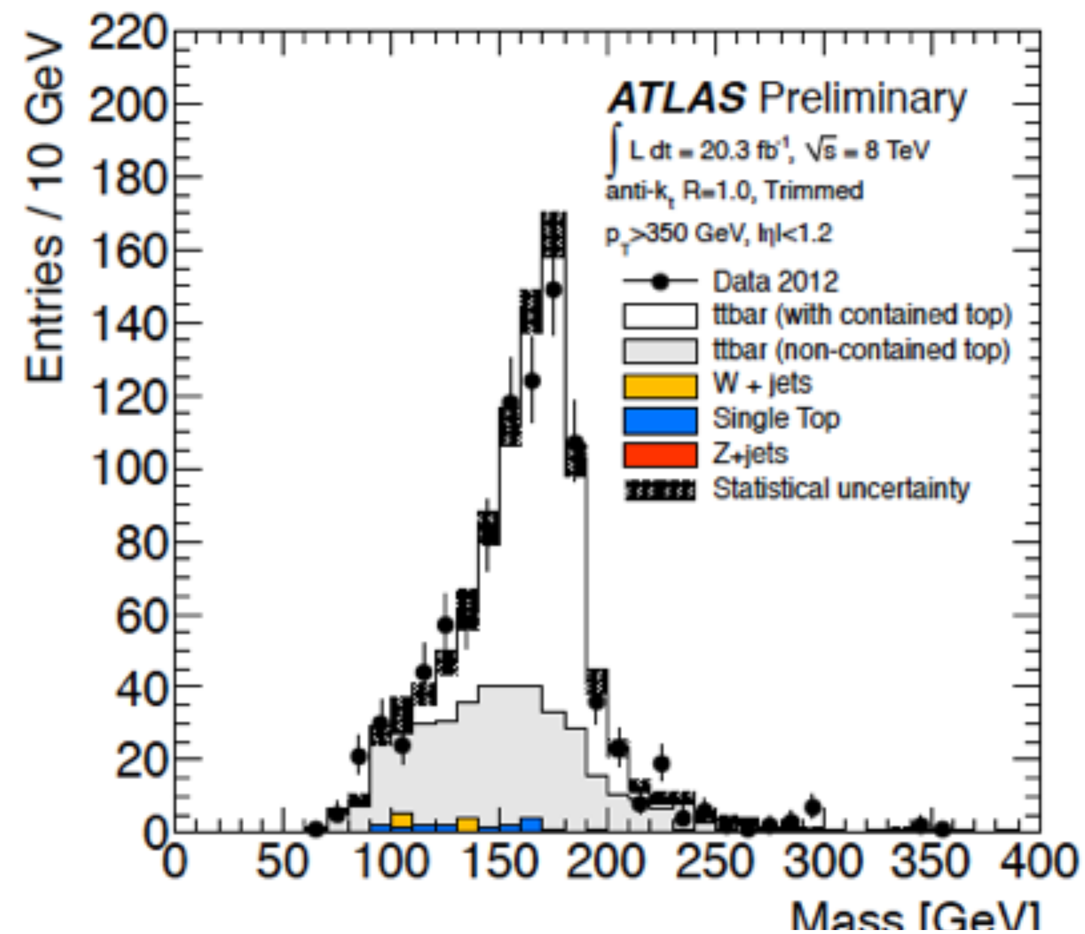


Jet p_T > 350 GeV

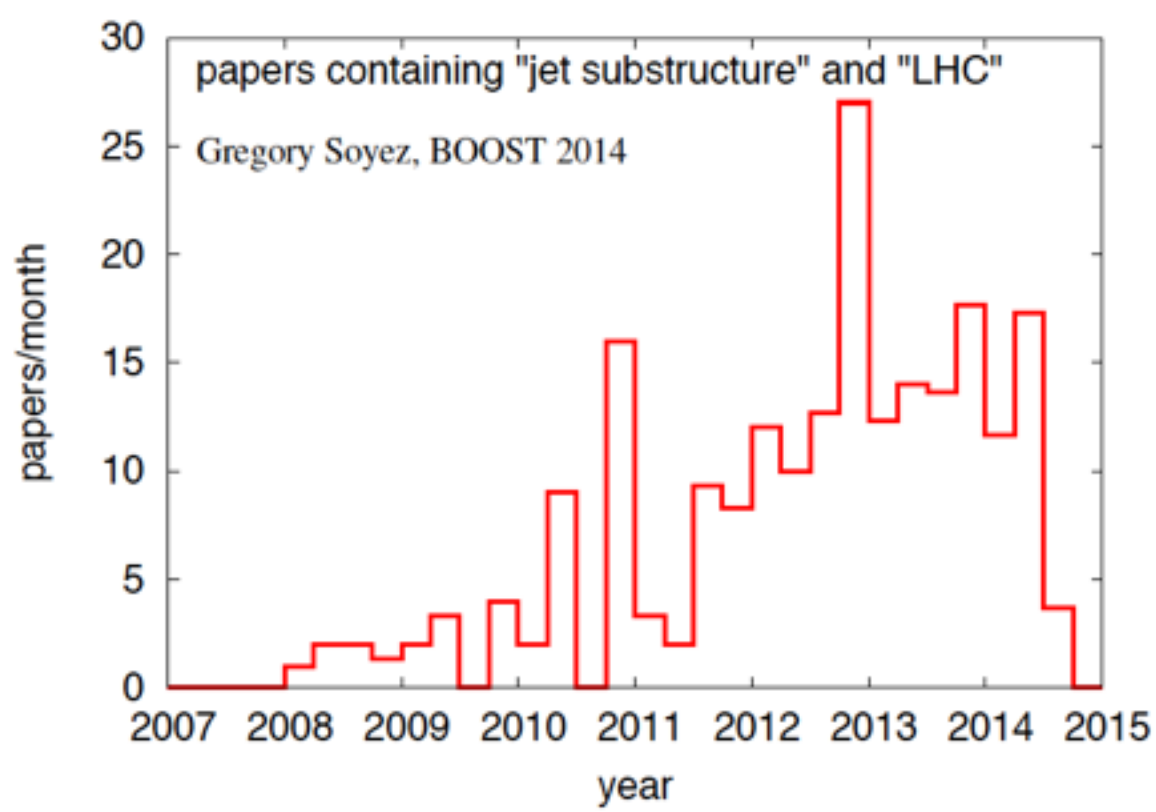
Lesson from Run I: it works!



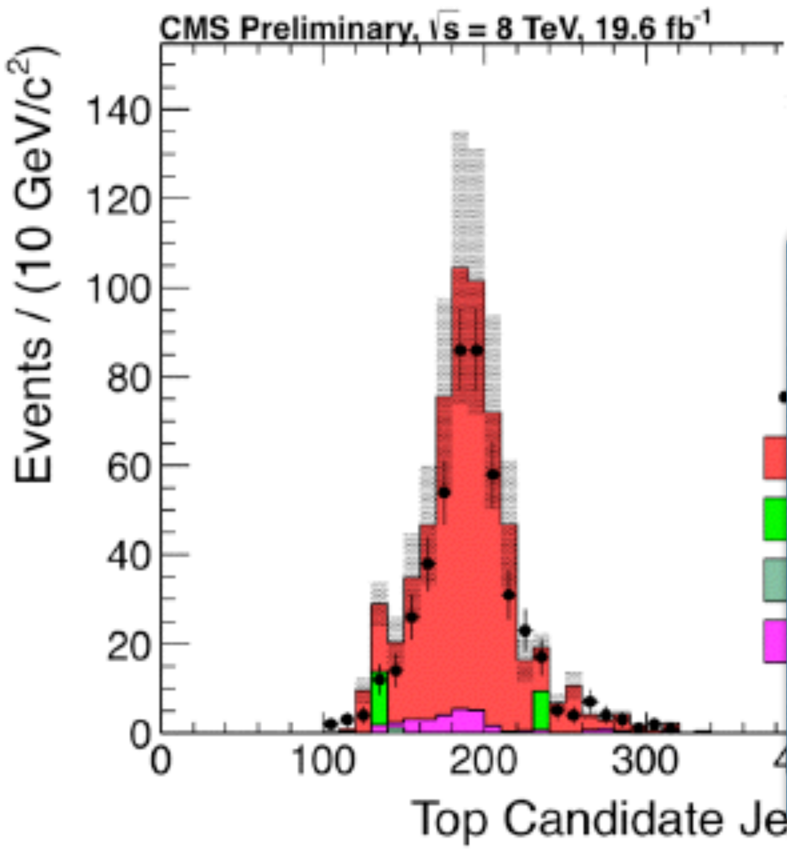
$p_T > 400$ GeV



Jet p_T > 350 GeV

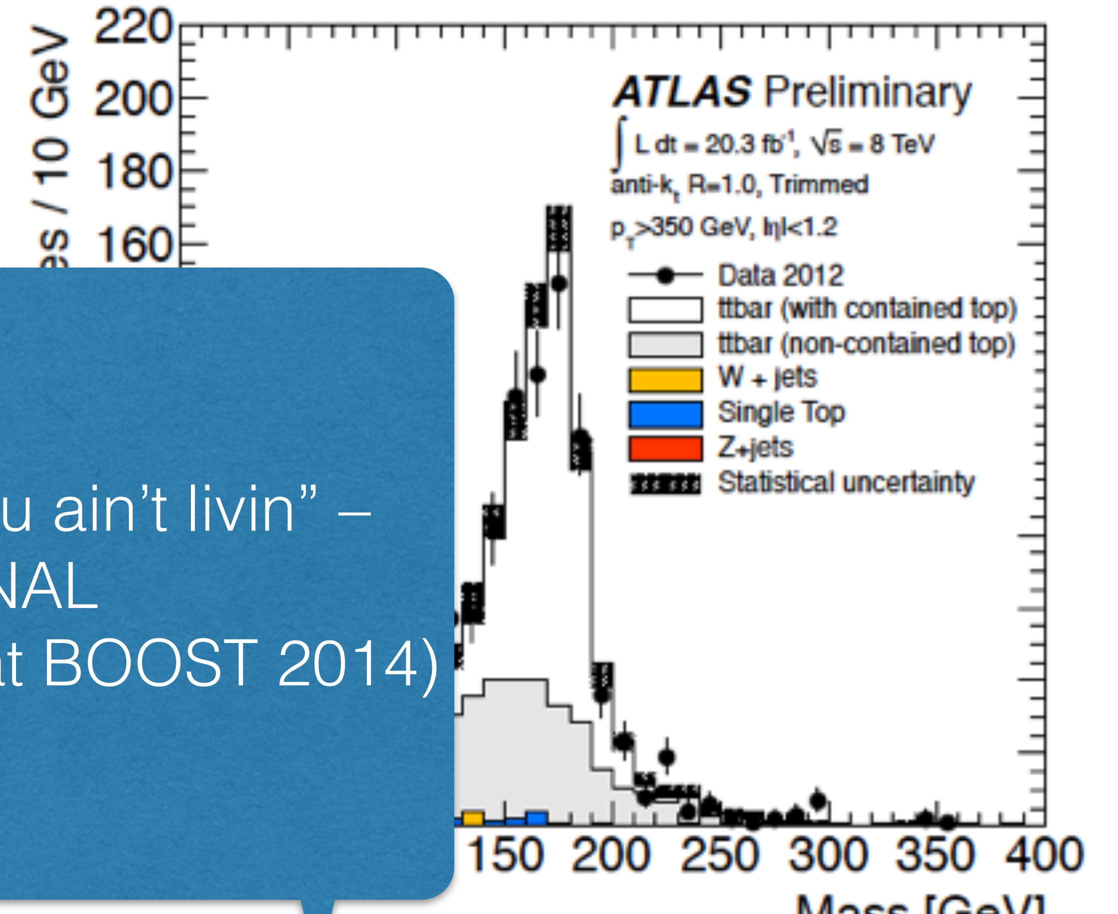


Lesson from Run I: it works!

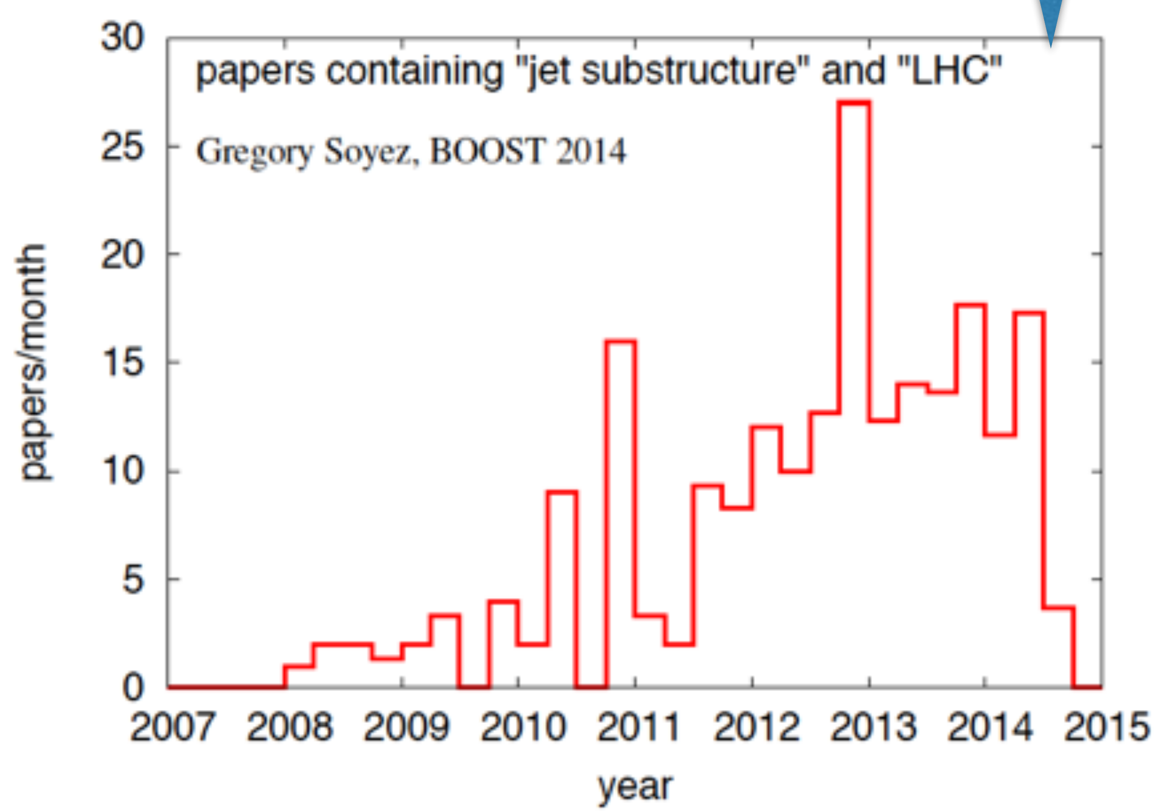


$p_T > 400$ GeV

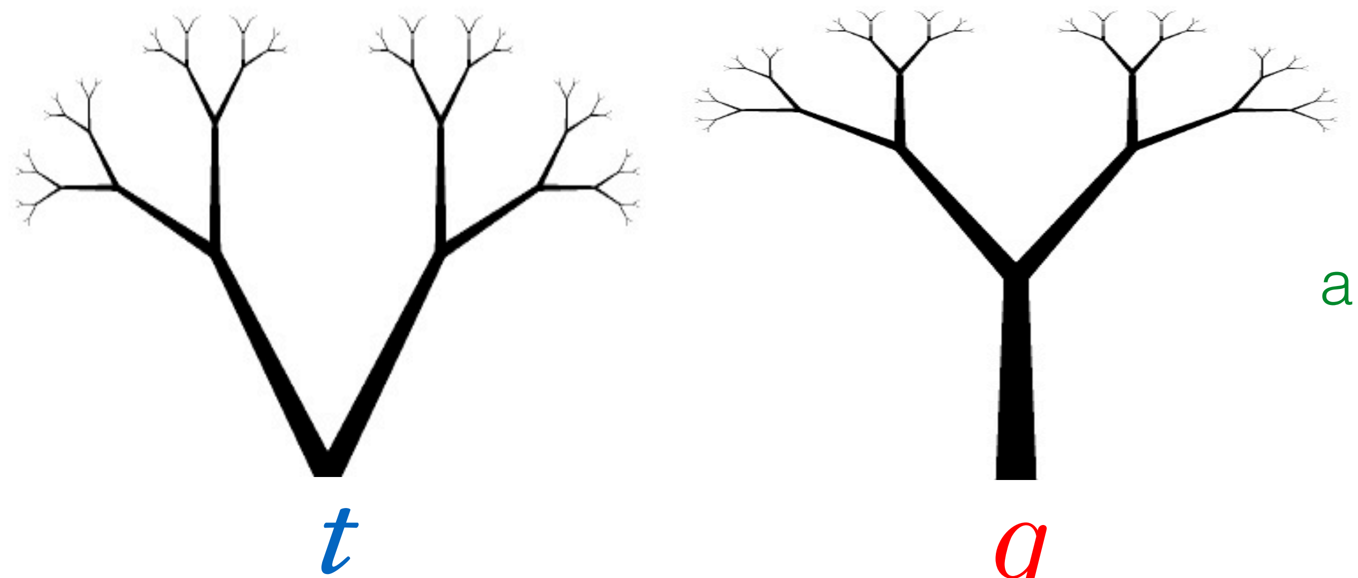
"If you ain't boostin', you ain't livin" –
Nhan Tran, FNAL
(Experimental Summary at BOOST 2014)



Jet $p_T > 350$ GeV



Modern boosted top tagging



apologies for omitted ones…

* **Algorithm:** Filtering, pruning, trimming, mass drop, soft drop, etc
(simple to implement, very successful)
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

* **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

* **Matrix element method** shower deconstruction method
Soper & Spannowsky (11,12)

* **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)

Jet Grooming

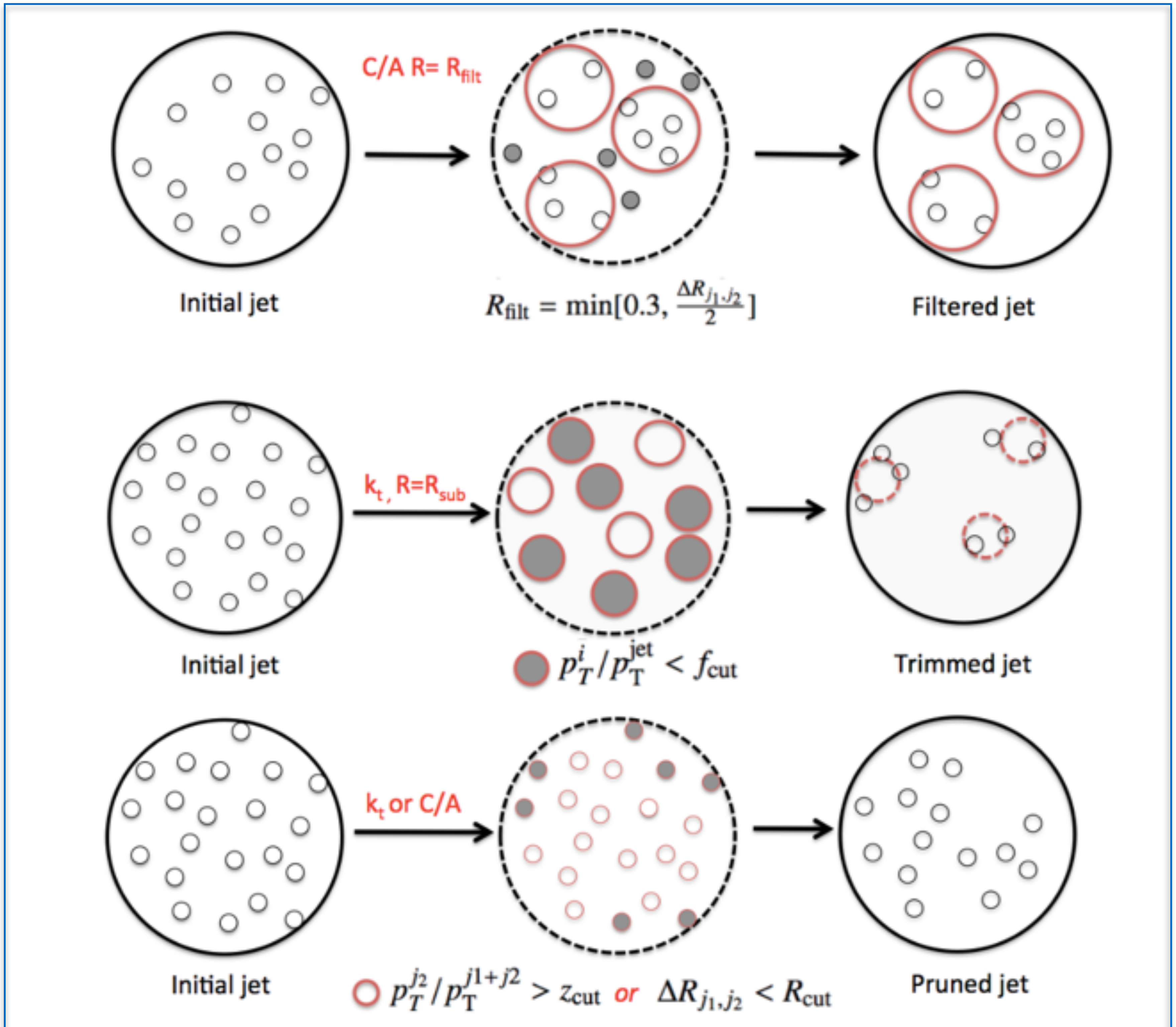
Filtering: Butterworth, Davison, Rubin, Salam 0802.2470
Pruning: Ellis, Vermilion, Walsh 0912.0033
Trimming: Krohn, Thaler, Wang 0912.1342

- Jet horticulture: soft removal

filtering

trimming

pruning

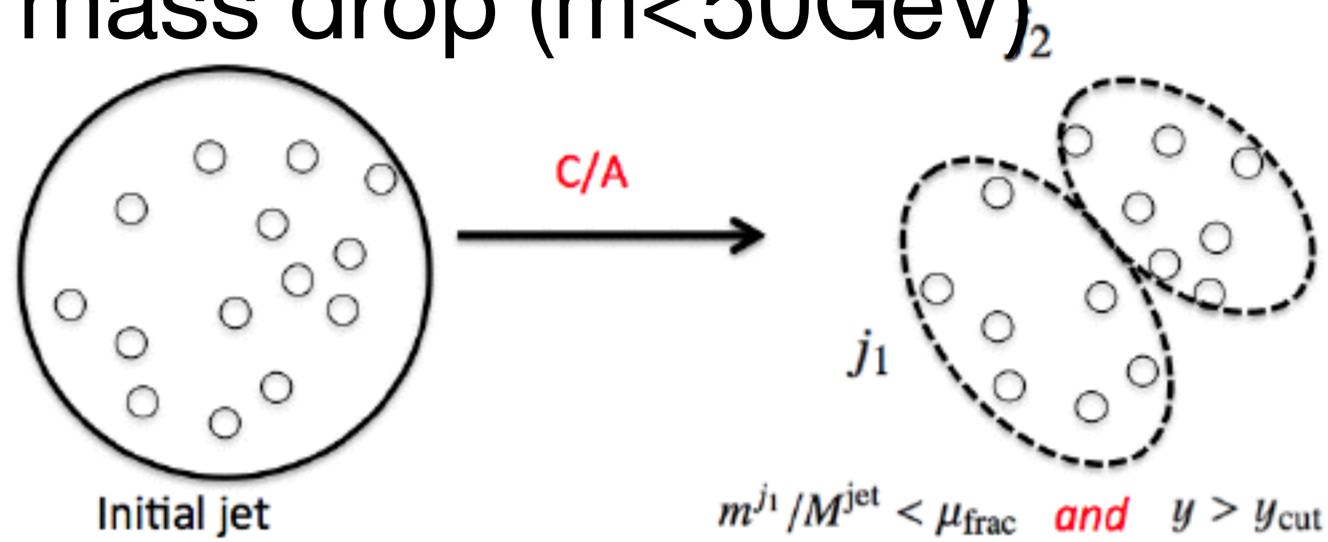


1306.4945

Jet Grooming

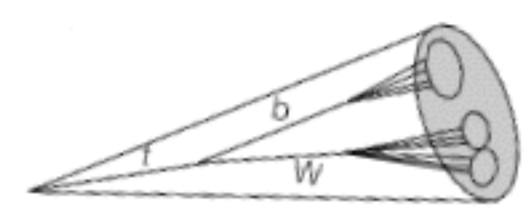
* e.g. how HepTopTagger works:

->start with a C/A fat jet (R=1.5) -> find hard jet substructure by mass drop (m<50GeV)



-> apply filtering (R_{max} =0.3, N_{fit} =5) to get top decay

->Applies kinematic cuts and demand that a pair of sub-jets falls within W-mass window



Jet shapes: Jet mass

Almeida, SL, Perez, Sung & Virzi (09)

- **Jet mass**-sum of "massless" momenta in h-cal inside the cone: $m_J^2 = (\sum_{i\in R} P_i)^2,\ {P_i}^2 = 0$

$$J^t(m_J, R, p_T) \sim \int d(\delta m_{EW}) dm_{QCD}\, \delta(m_J - m_{QCD} - \delta m_{EW}) \times J^t_{QCD}(m_{QCD}, R, p_T)\, \mathcal{F}_{EW}(\delta m_{EW}, m_{QCD}/(p_T R))$$

- In practice $m_J^t \sim m_t + \delta m_{QCD} + \delta m_{EW}$

+ pile-up effects+detector smearing.

- Boosted QCD Jet mass distribution

$$\frac{d\sigma(R)}{dp_T dm_J} = \sum_c J^c(m_J, p_T, R)\, \frac{d\hat{\sigma}^c(R)}{dp_T} \qquad \int dm_J\, J^i = 1$$

Jet shapes: Jet mass

Almeida, SL, Perez, Sung & Virzi (09)

- Jet mass-sum of "massless" momenta in h-cal inside the cone: $m_J^2 = (\sum_{i\in R} P_i)^2, \quad {P_i}^2 = 0$

$$J^t(m_J, R, p_T) \sim \int d(\delta m_{EW}) dm_{QCD}\, \delta(m_J - m_{QCD} - \delta m_{EW}) \times J^t_{QCD}(m_{QCD}, R, p_T)\, \mathcal{F}_{EW}(\delta m_{EW}, m_{QCD}/(p_T R))$$

- In practice $m_J^t \sim m_t + \delta$

+ smearing.

For large jet mass & small R,
no big logs =>
can be calculated via perturbative QCD!

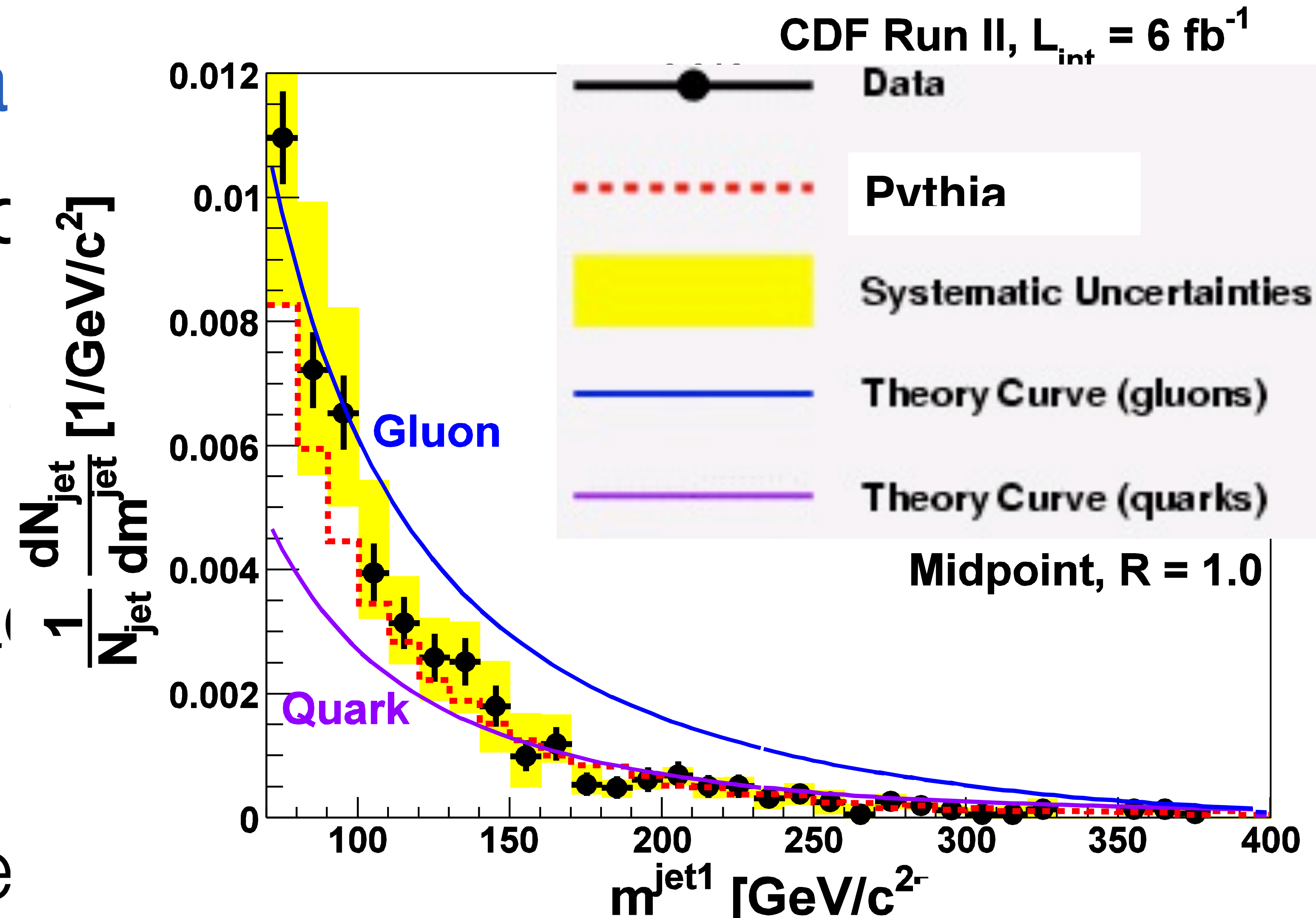
- Boosted QCD Jet mass distribution

$$\frac{d\sigma(R)}{dp_T dm_J} = \sum_c J^c(m_J, p_T, R)\, \frac{d\hat{\sigma}^c(R)}{dp_T} \qquad \int dm_J\, J^i = 1$$

Jet shapes: Jet mass

Almeida, SL, Perez, Sung & Virzi (09)

* Jet ma ... -cal
  insic ... $^2 = 0$
  $J^t(m_J,$ ... $R))$
* In prac ... earing.
* Booste



$$\frac{d\sigma(R}{dp_T dm} \quad J^{(eik),c}(m_J, p_T, R) \simeq \alpha_S(p_T)\frac{4\,C_c}{\pi m_J}\log\left(\frac{R\,p_T}{m_J}\right) \quad = 1$$

$C_F = 4/3$ for quarks, $C_A = 3$ for gluons.

Jet shapes: Jet mass

Almeida, S… (09)

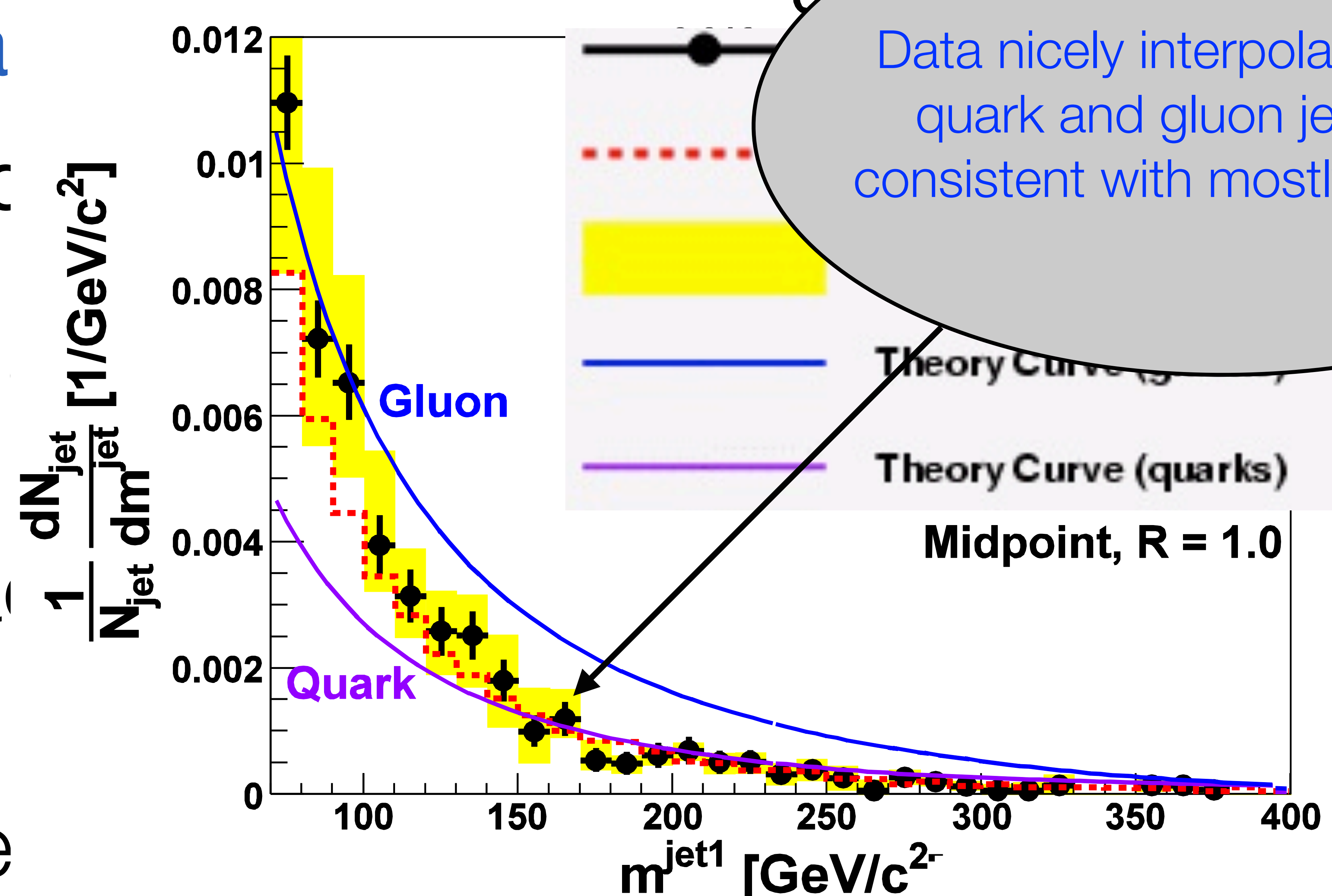
* Jet ma…

insic…

$J^t(m_J,$ … R))

* In prac… earing.

* Booste…



Data nicely interpolates between quark and gluon jet functions consistent with mostly quark case

$$\frac{d\sigma(R}{dp_T dm} \quad J^{(eik),c}(m_J, p_T, R) \simeq \alpha_S(p_T)\frac{4\,C_c}{\pi m_J}\log\left(\frac{R\,p_T}{m_J}\right) \quad = 1$$

$C_F = 4/3$ for quarks, $C_A = 3$ for gluons.

Calculable Jet shape: Planar flow

- Top-jet is 3 body vs. massive QCD jet <=> 2-body (our result)

Thaler & Wang, JHEP (08);
Almeida, SL, Perez, Stermam, Sung & Virzi, PRD (09).

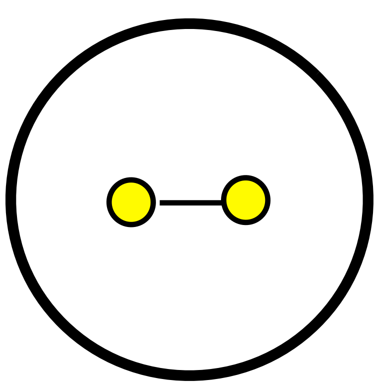
- Planar flow, *Pf*, measures the energy ratio between two primary axes of cone surface:

(i) “moment of inertia”:

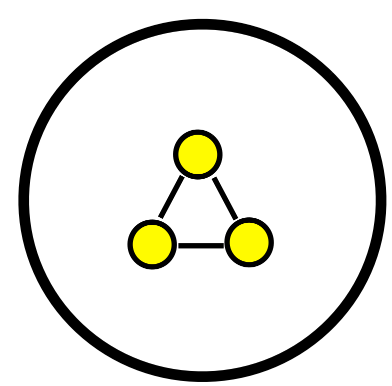
$$I_E^{kl} = \frac{1}{m_J} \sum_{i \in R} E_i \frac{p_{i,k}}{E_i} \frac{p_{i,l}}{E_i} \,,$$

(ii) Planar flow:

$$Pf = 4\,\frac{\det(\mathrm{I_E})}{\mathrm{tr}(\mathrm{I_E})^2} = \frac{4\lambda_1\lambda_2}{(\lambda_1+\lambda_2)^2}$$



leading order QCD, *Pf=0*



top jet, *Pf=1*

Calculable Jet shape: Planar flow

- Top-jet is 3 body vs. massive QCD jet <=> 2-body (our result)

Thaler & Wang, JHEP (08);
Almeida, SL, Perez, Stermam, Sung & Virzi, PRD (09).

- Planar flow, *Pf*, measures the energy ratio between two primary axes of cone surface:

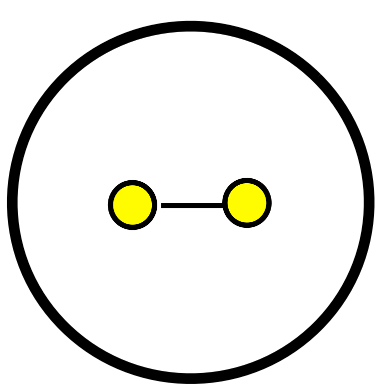
(i) "moment of inertia":

$$I_E^{kl} = \frac{1}{m_J} \sum_{i \in R} E_i \frac{p_{i,k}}{E_i} \frac{p_{i,l}}{E_i} \,,$$

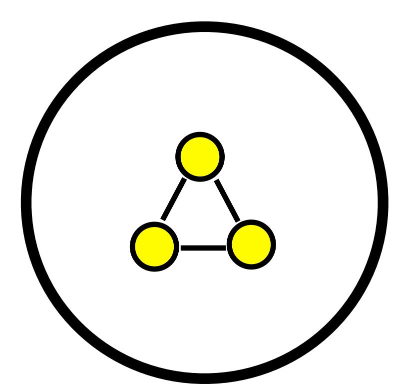
(ii) Planar flow:

$$Pf = 4\,\frac{\det(\mathrm{I_E})}{\mathrm{tr}(\mathrm{I_E})^2} = \frac{4\lambda_1\lambda_2}{(\lambda_1+\lambda_2)^2}$$

IRC safe, but sensitive to pile-up effect



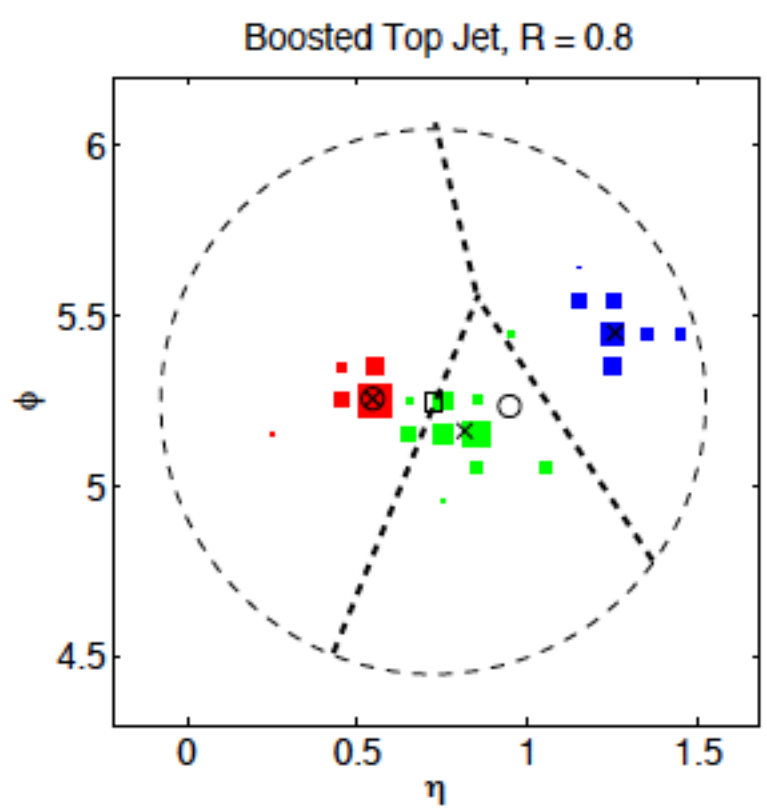
leading order QCD, *Pf=0*



top jet, *Pf=1*

Jet shape: N-subjettiness

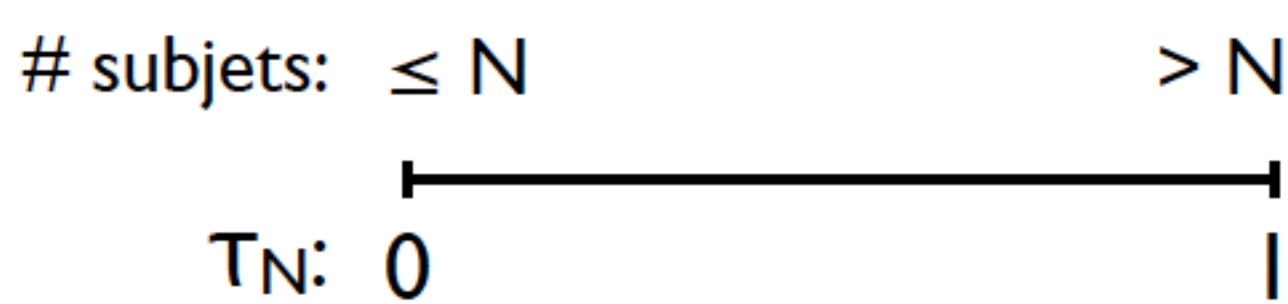
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{\Delta R_{k,1}, \Delta R_{k,2}, \ldots, \Delta R_{k,N}\}$$



Generalization of thrust to multiple (sub)jets!

(strictly speaking, generalization of jet broadening)

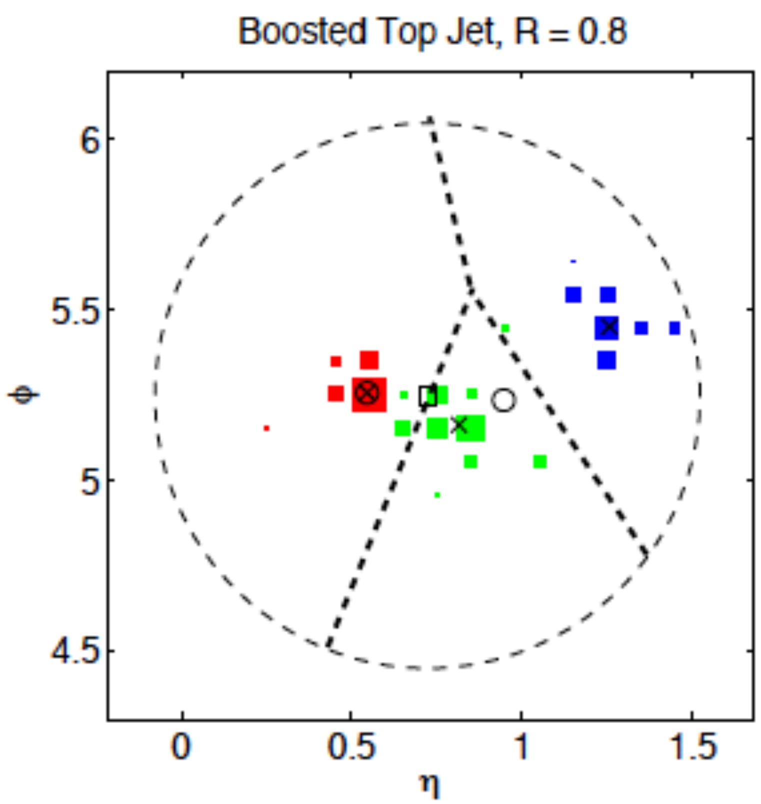
Jet shape "counts" number of subjets!



Thaler & Tilburg (10)

Jet shape: N-subjettiness

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{k,1}, \Delta R_{k,2}, \ldots, \Delta R_{k,N}\}$$



Ratio observables: IRC unsafe, but Sudakov safe:
To all-orders, singular region is exponentially suppressed by perturbative Sudakov factor (Larkoski & Thaler)

$$\tau_{2,1}^{(\beta)} = \frac{\tau_2^{(\beta)}}{\tau_1^{(\beta)}}$$

Powerful boosted *W* tagger

Selects for 2-subjet structures

$$\tau_{3,2}^{(\beta)} = \frac{\tau_3^{(\beta)}}{\tau_2^{(\beta)}}$$

Powerful boosted *t* tagger

Selects for 3-subjet structures

))

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

✦ describe jet energy flow as spikes

|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

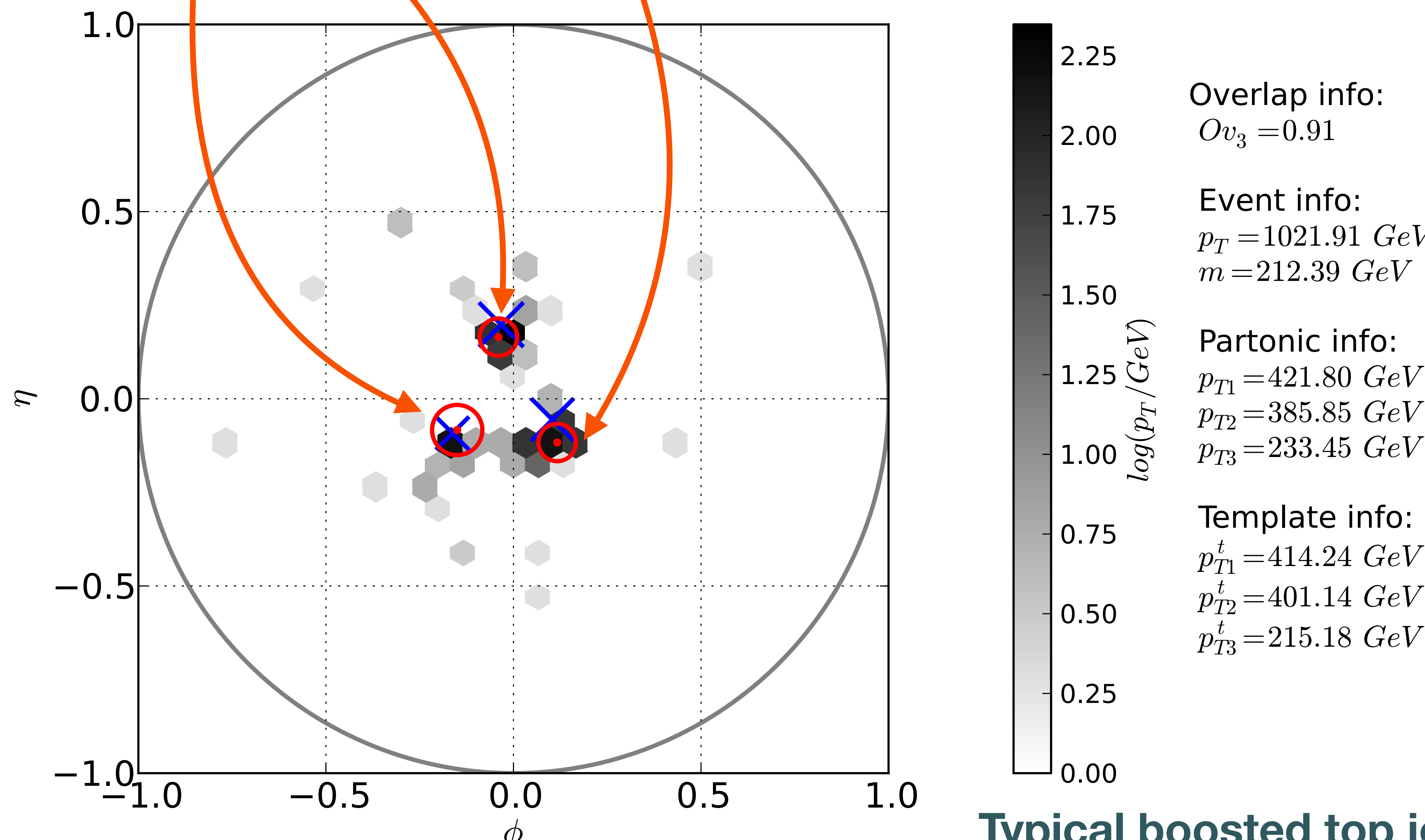
"template"

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

Template Overlap Method

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.

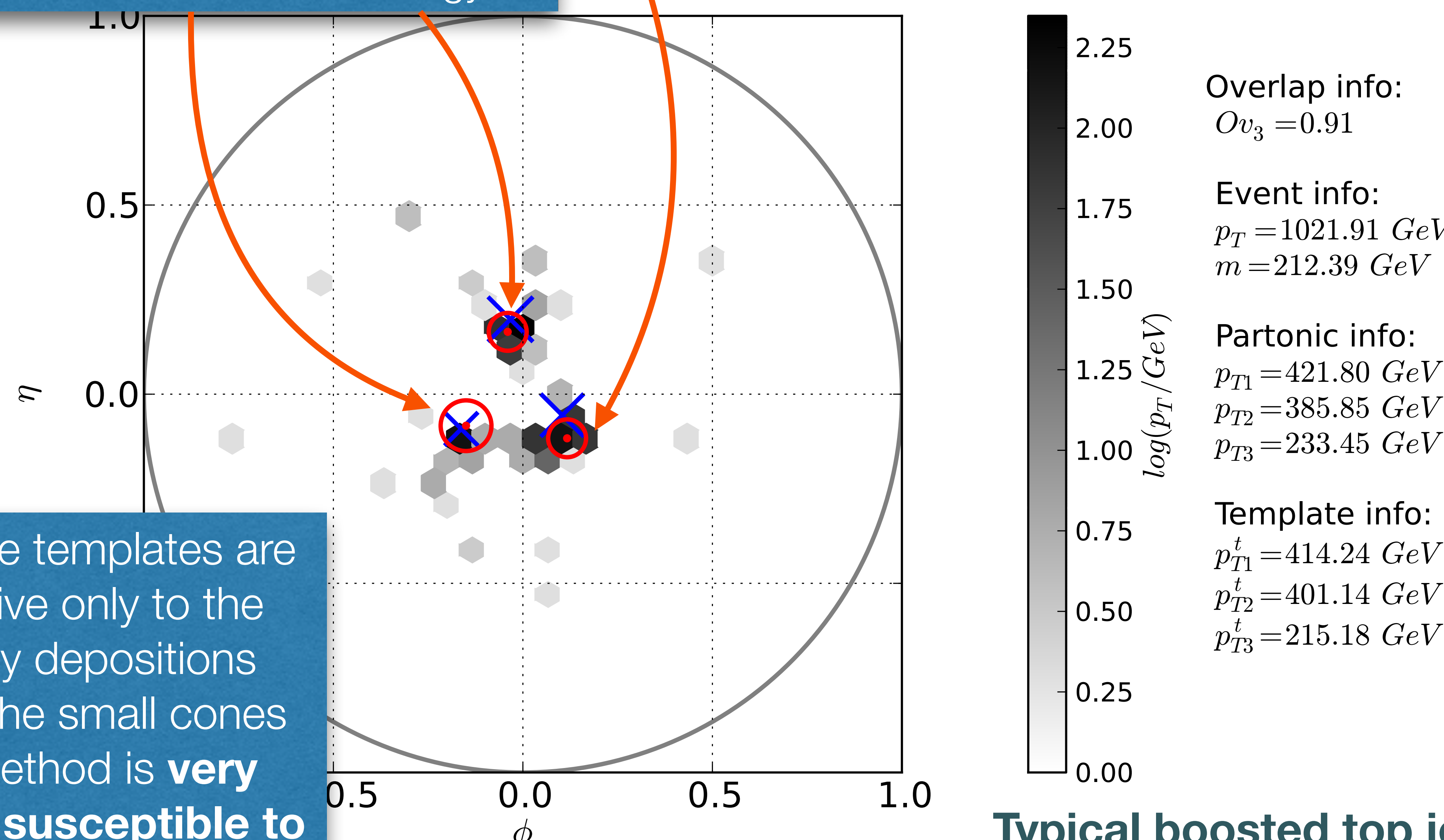


Typical boosted top jet

Template Overlap Method

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

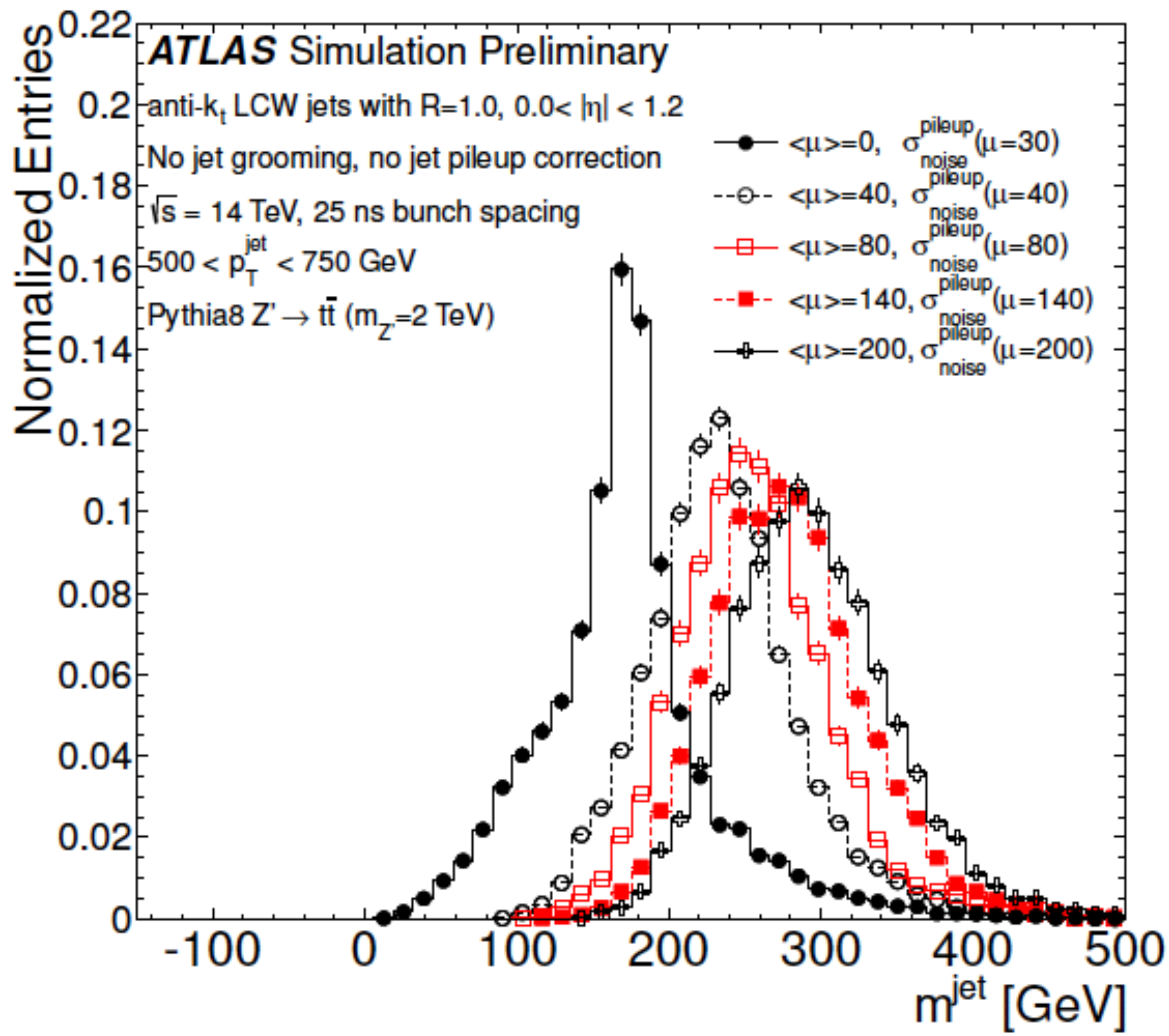
pile-up removal & mass reconstruction

Boosted top tagging and pile-up at very high luminosity

High pile-up scenarios for top tagging

David Miller, Aspen, Jan 2015

- The anti-k_t $R = 1.0$ jet mass distribution in $Z' \to t\bar{t}$ events where the mean number of interactions per bunch crossing ($\langle\mu\rangle$) is 40, 80, 140, and 200.
- The pileup correction is made to the subjets only, before their pT fraction is calculated.
- When both trimming and jet 4-vector pileup subtraction are applied, the jet mass distribution is stable even at $\langle\mu\rangle$ =200.



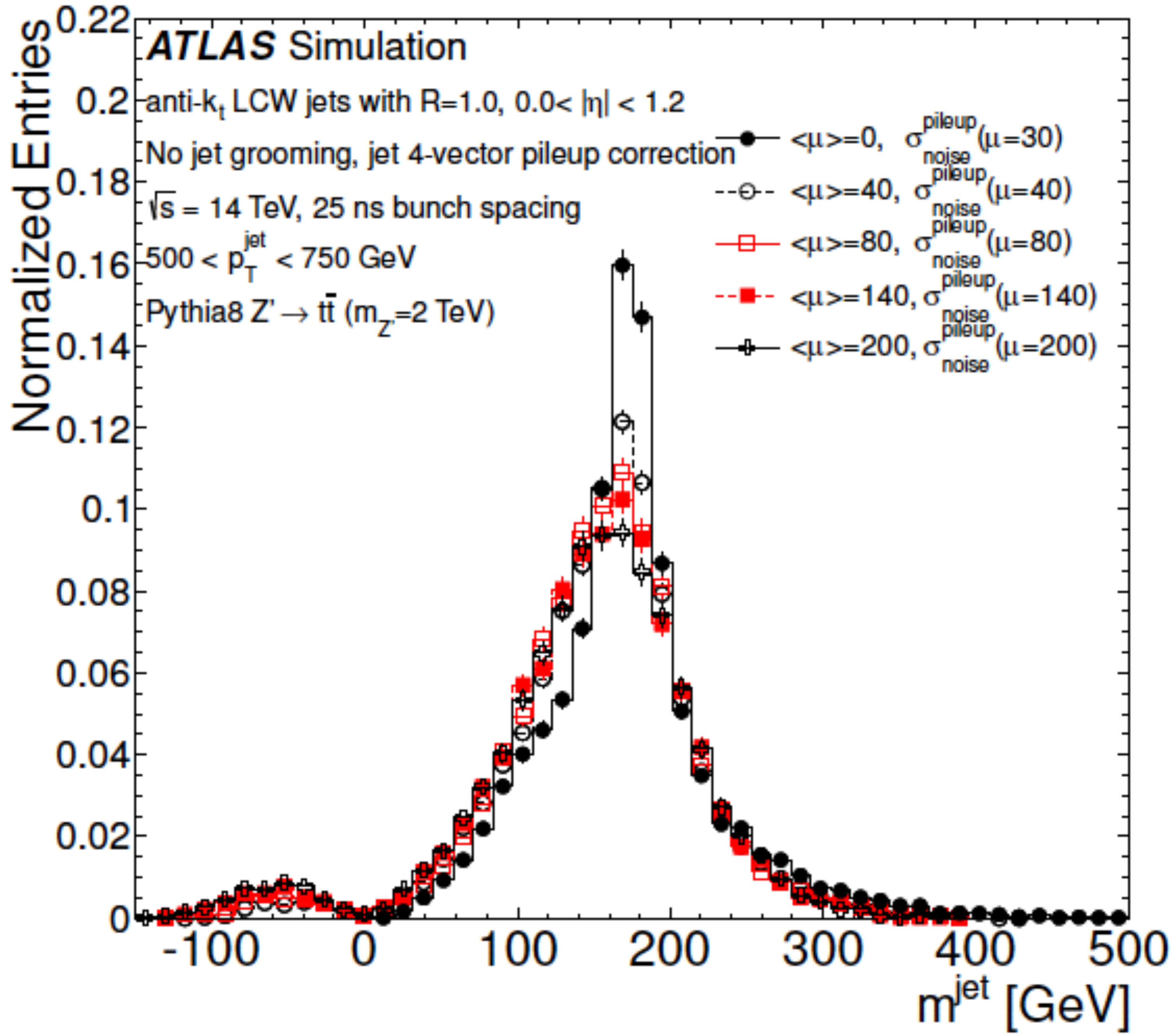
pile-up removal & mass reconstruction

Boosted top tagging and pile-up at very high luminosity

High pile-up scenarios for top tagging

David Miller, Aspen, Jan 2015

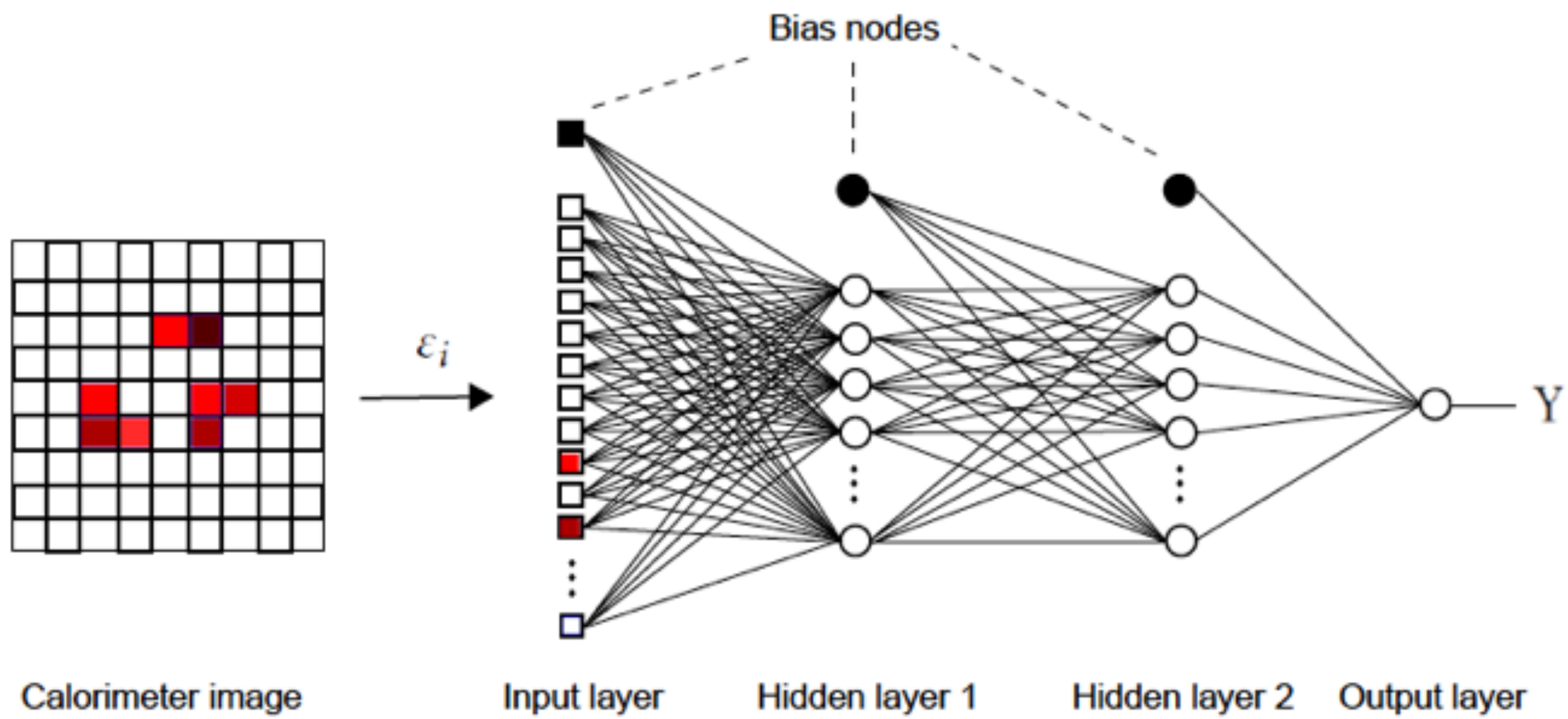
- The anti-k_t $R = 1.0$ jet mass distribution in $Z' \to t\bar{t}$ events where the mean number of interactions per bunch crossing ($\langle\mu\rangle$) is 40, 80, 140, and 200.
- The pileup correction is made to the subjets only, before their pT fraction is calculated.
- When both trimming and jet 4-vector pileup subtraction are applied, the jet mass distribution is stable even at $\langle\mu\rangle$ =200.



Jet Substructure with Artificial Neural Network (ANN)

Almeida, Backovic, Cliche, SL, Perelstein `15

✱Jet as an Image: HCAL output = digital image of the jet: each cell=pixel, energy deposit in each cell



succession of non-linear transformations:

$$\epsilon_i \to h_i^{(1)} = f(W_{ij}^{(1)}\epsilon_j + b_i^{(1)}) \to \cdots \to h_i^{(l)} = f(W_{ij}^{(l)}h_j^{(l-1)} + b_i^{(l)}) \to Y = f(W_j^{(O)}h_j^{(l)} + b^{(O)}),$$

$$f(z) = \frac{1}{1+e^{-z}}.$$ - "activation function"

- ANN is a highly non-linear map from N inputs to 1 output
- Our ANN has 30x30=900 inputs (0.1x0.1 HCAL cells); 2 hidden layers of 100 nodes each; and 1 output node
- There are ~100,000 "neurons" (connections), each with its own "weight" W

ANN

Almeida, Backovic, Cliche, SL, Perelstein `15

Network Training

- The weights W are determined through a "training" procedure:
  - Generate large MC samples of top-jets (SM ttbar) and QCD jets (dijet)
  - "Feed" these samples to ANN, record output Y_i for each jet
  - Compute the "error function" (desired outputs: y_i=1 for top, y_i=0 for QCD):

$$\text{Log-loss} = -\frac{1}{N}\sum_{i=1}^{N}\left[y_i \log(Y_i) + (1-y_i)\log(1-Y_i)\right].$$

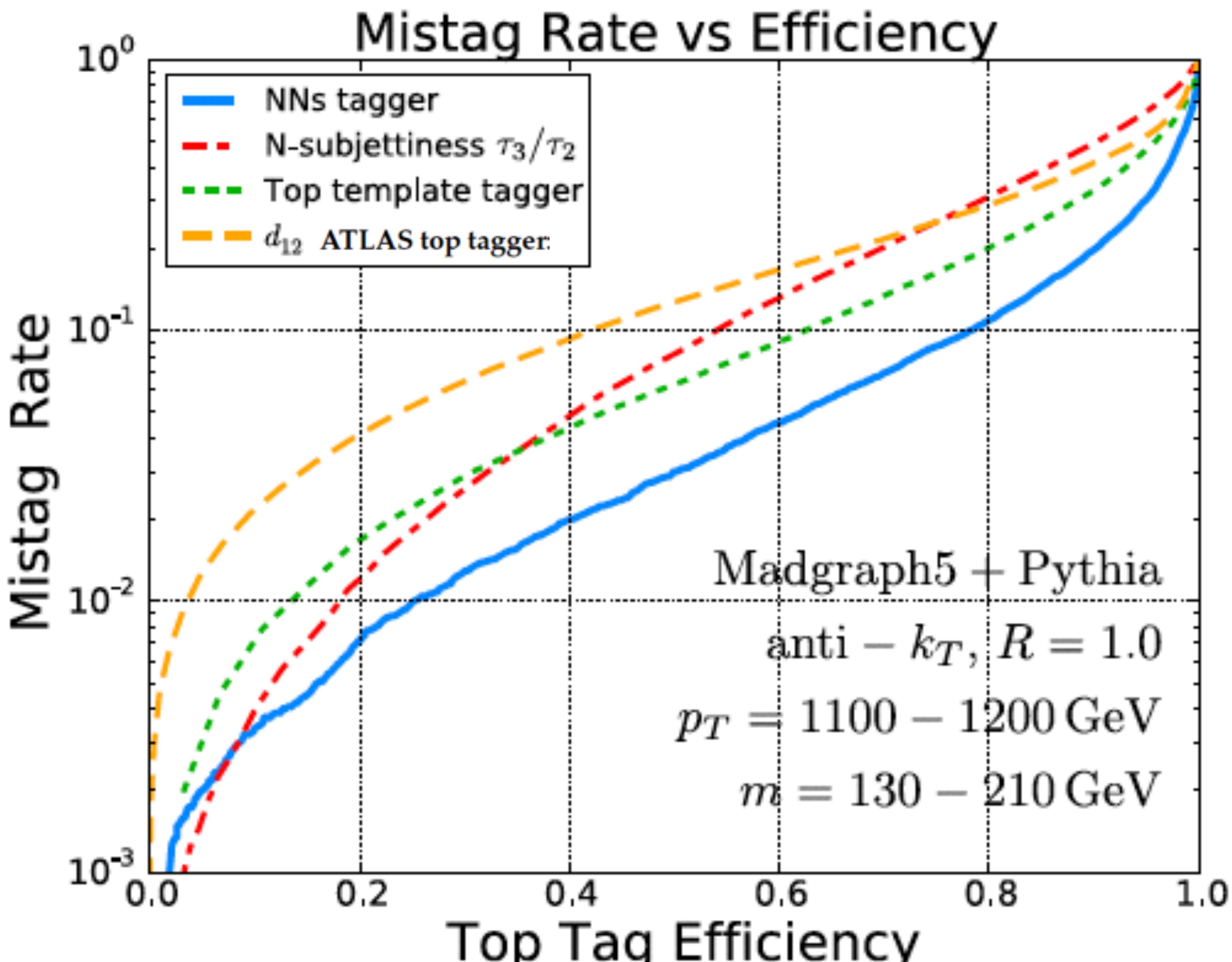
  - Adjust weights iteratively to minimize the error function
  - Minimizing a function of 100,000 variables is not trivial, but there are well-know numerical techniques for this; we use the back-propagation algorithm, with "batch gradient descent with momentum" minimization
- Outcome: a set of weights such that Y_i close to 1 for top jets, close to 0 for QCD jets
- ANN "learns" how to tell them apart, using all available info! (or: it just constructed a complicated but optimal - in some sense - observable)

ANN

Almeida, Backovic, Cliche, SL, Perelstein `15

✱ Network Training

-



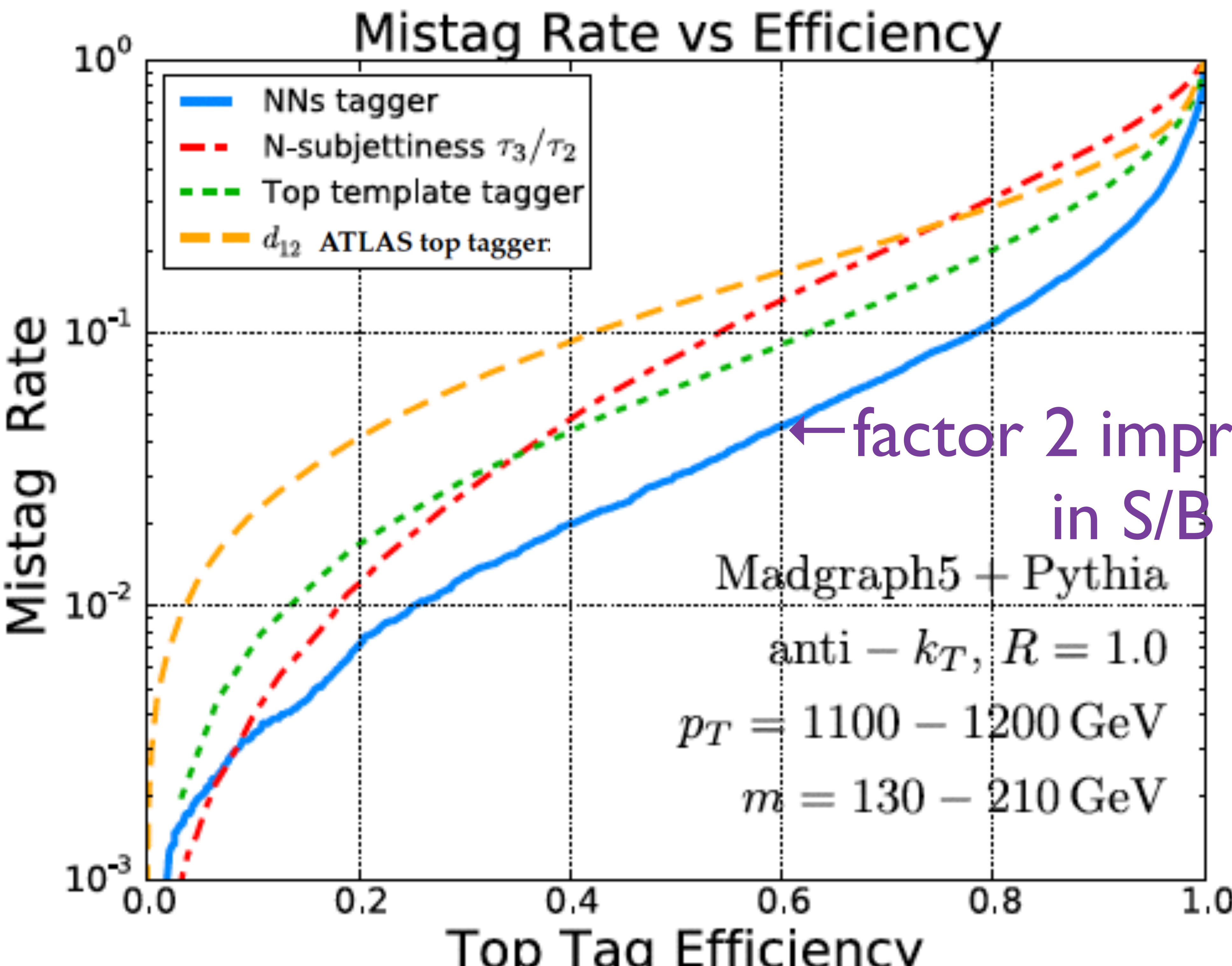
-
-

ANN

Almeida, Backovic, Cliche, SL, Perelstein `15

Network Training

-



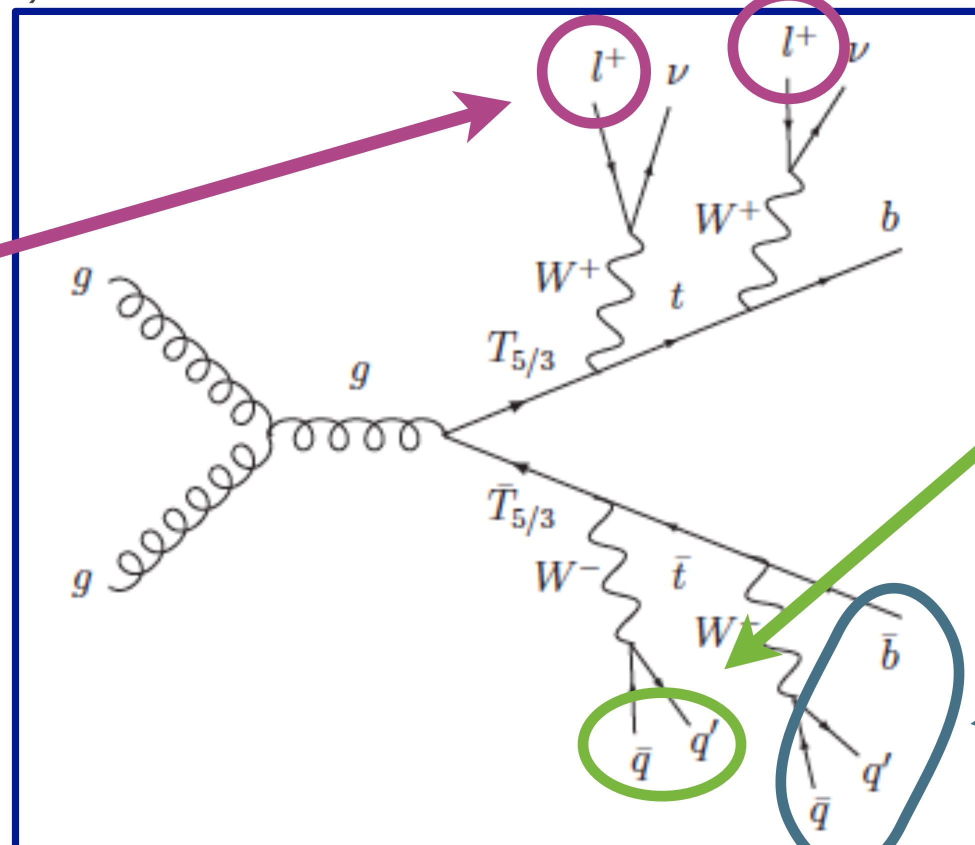
-
-

Composite Top Partner Searches @ Run 1

cf. Ennio Salvioni's talk
(and also Raman Sundrum's Review talk)
VLQ searches from ATLAS & CMS talk

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

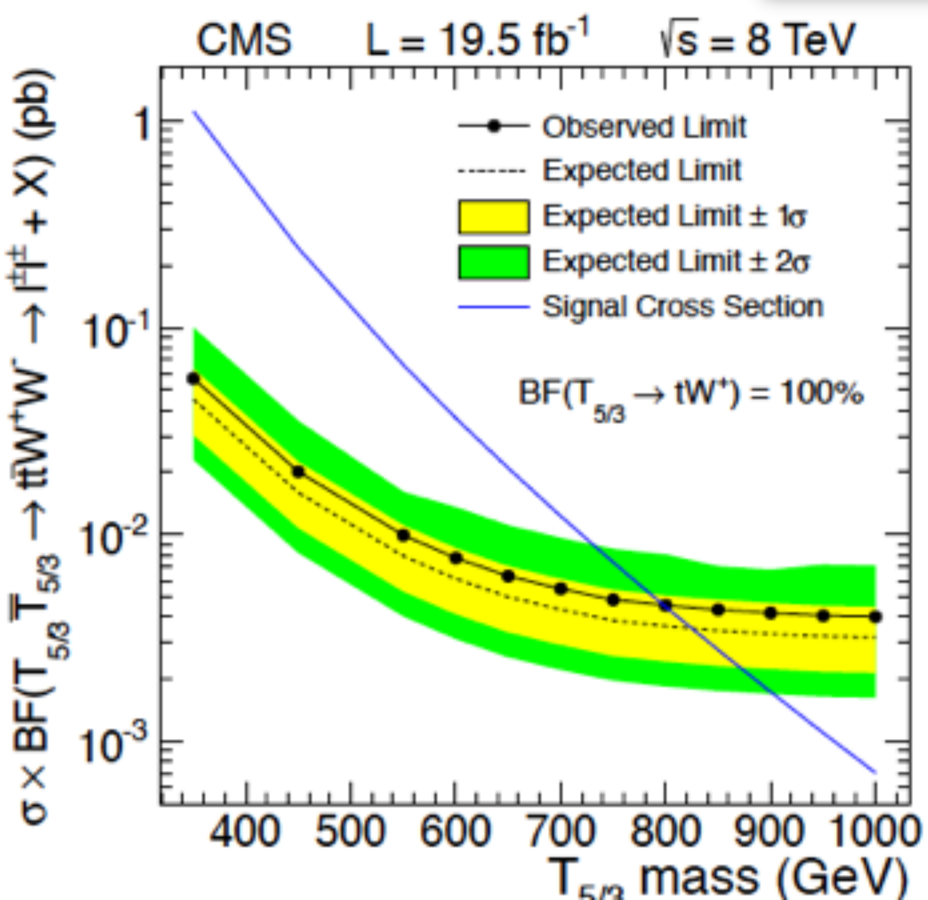
same-sign dileptons



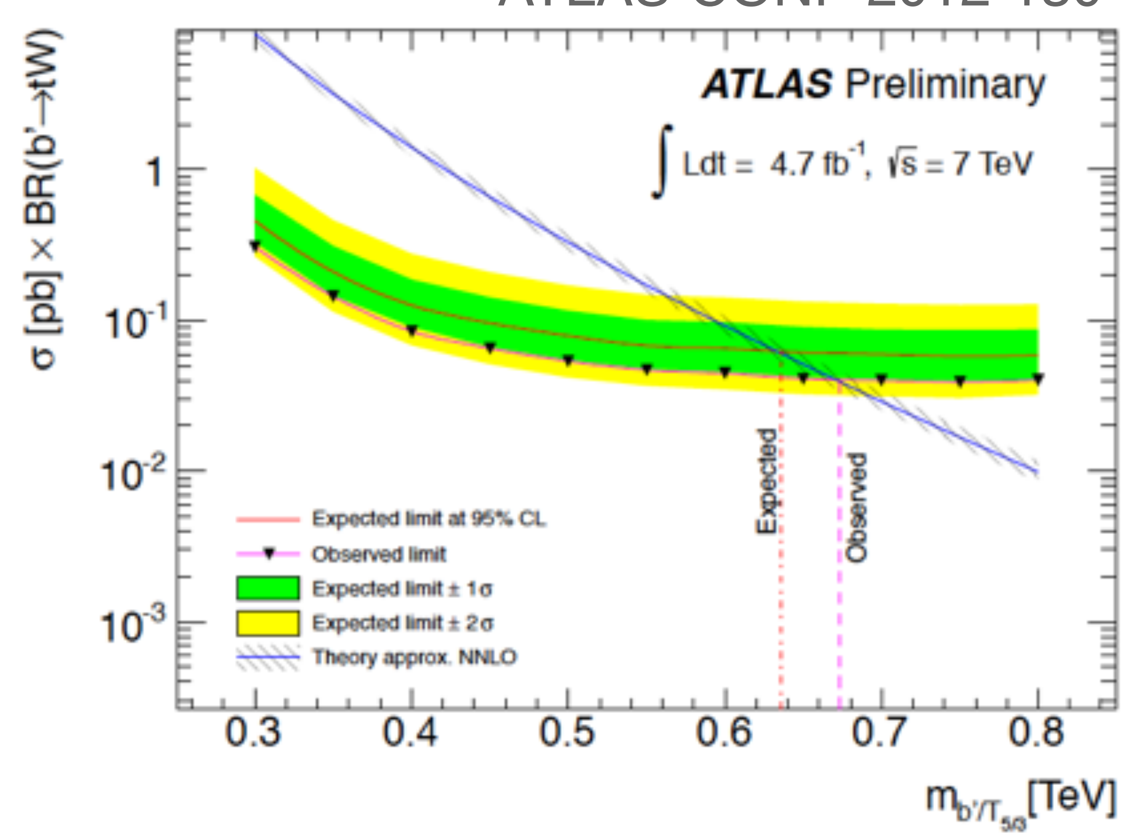
W tag:
2 subjets,
M_j[60,130]

CMS top tag

10.1103/PhysRevLett.112.171801



ATLAS-CONF-2012-130

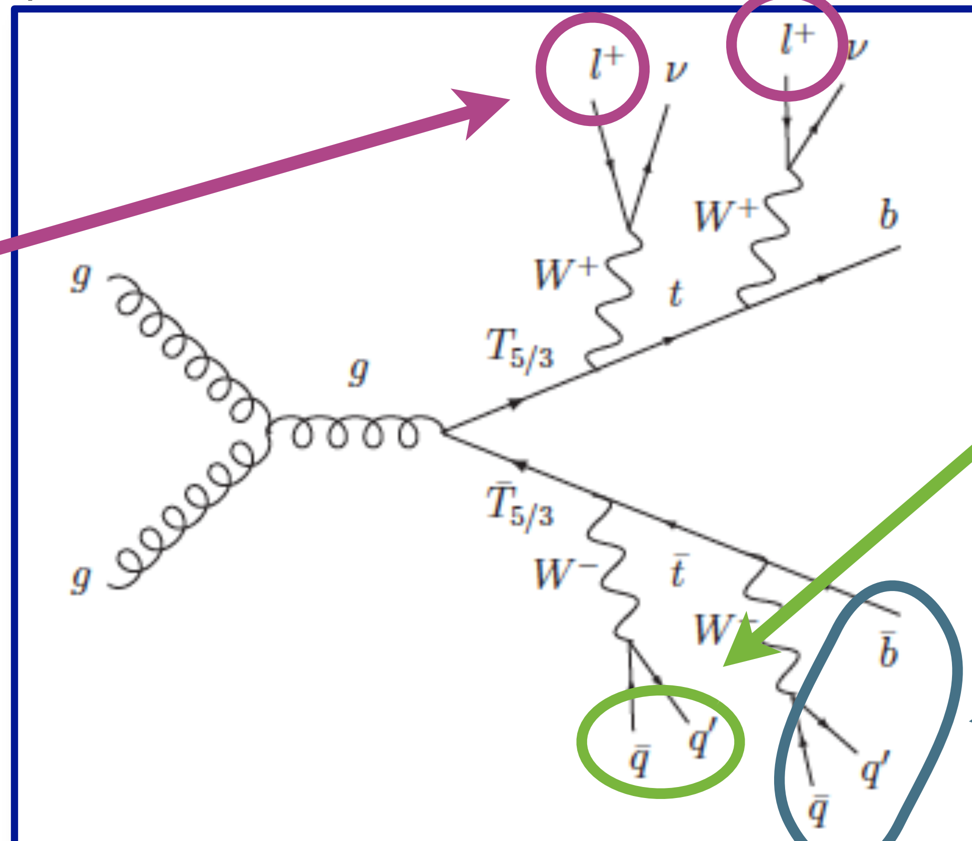


Composite Top Partner Searches @ Run 1

cf. Ennio Salvioni's talk
(and also Raman Sundrum's Review talk)
VLQ searches from ATLAS & CMS talk

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

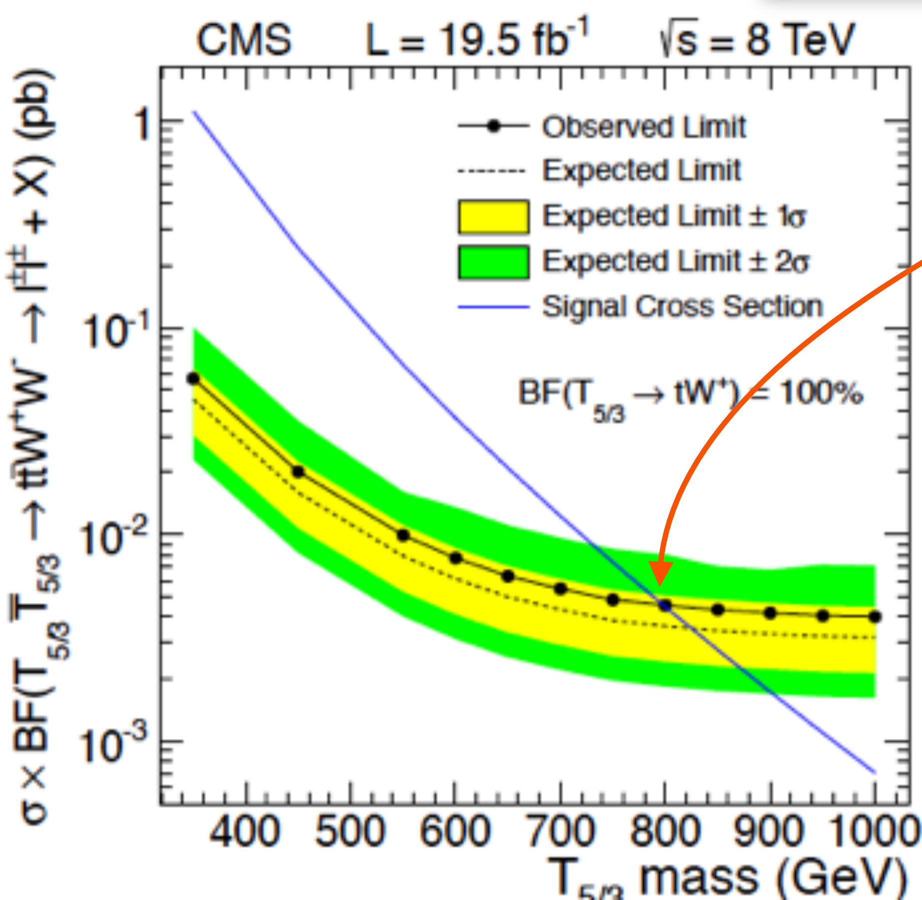
same-sign dileptons



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

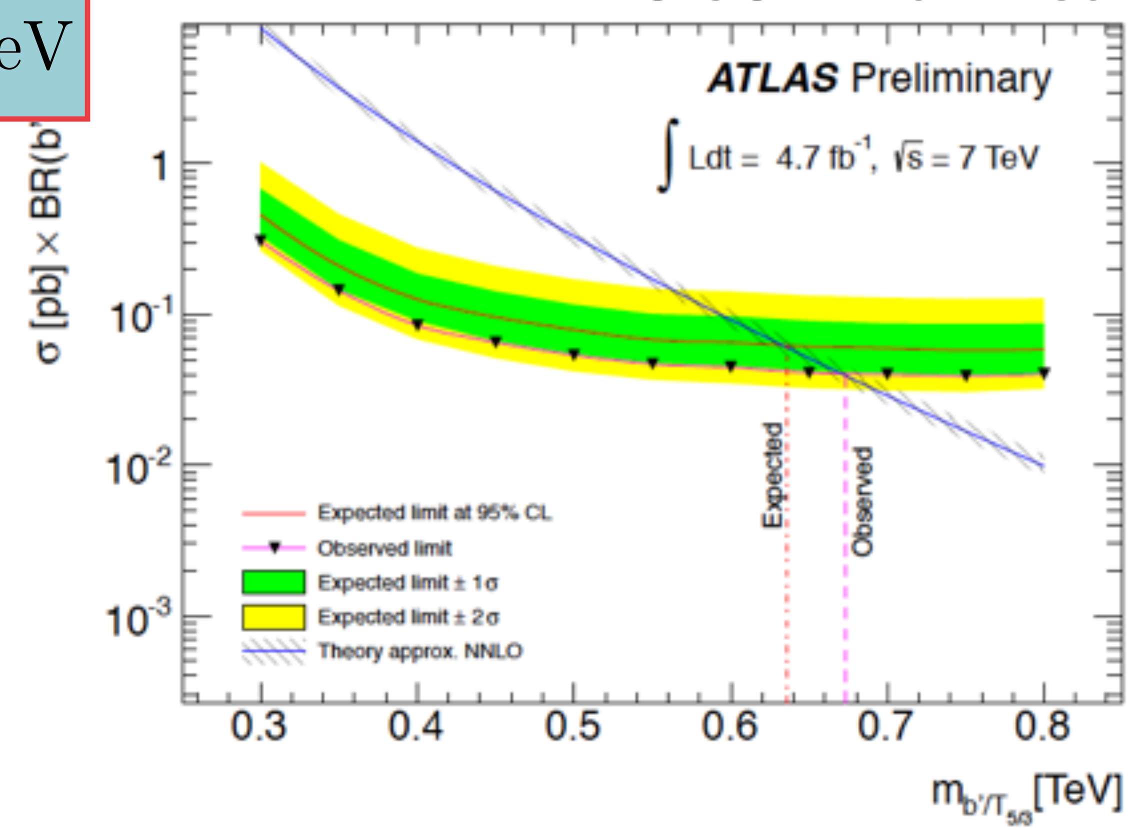
CMS top tag

10.1103/PhysRevLett.112.171801



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

ATLAS-CONF-2012-130

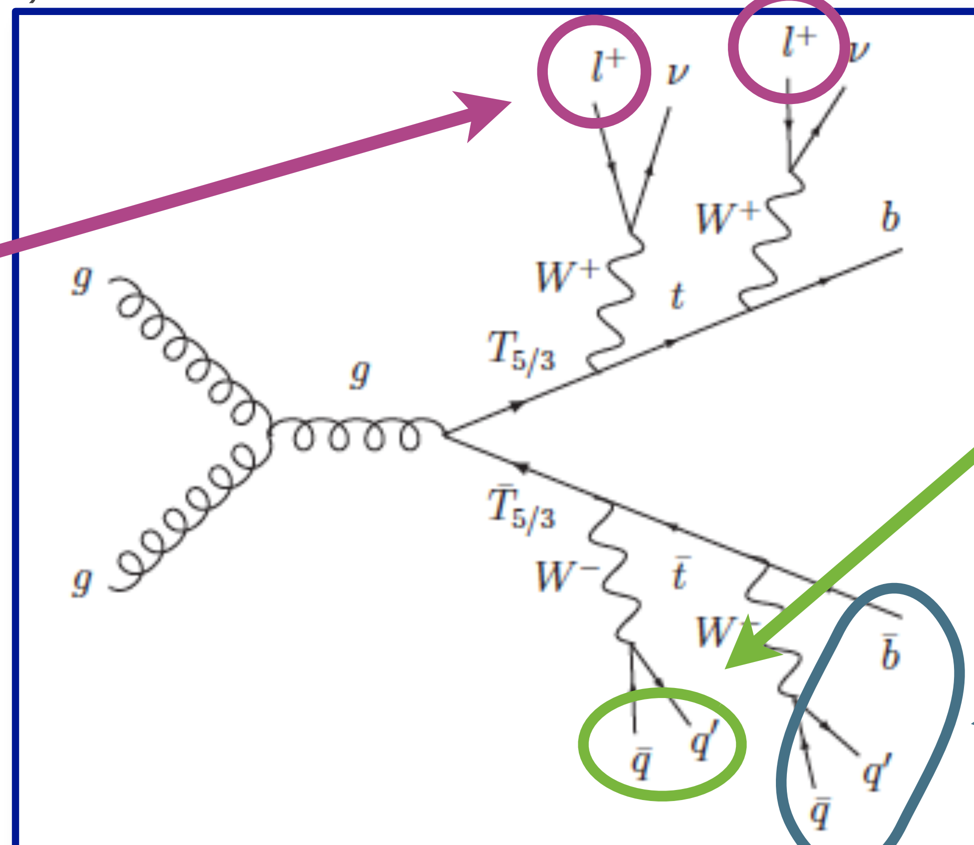


Composite Top Partner Searches @ Run 1

cf. Ennio Salvioni's talk
(and also Raman Sundrum's Review talk)
VLQ searches from ATLAS & CMS talk

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

same-sign dileptons



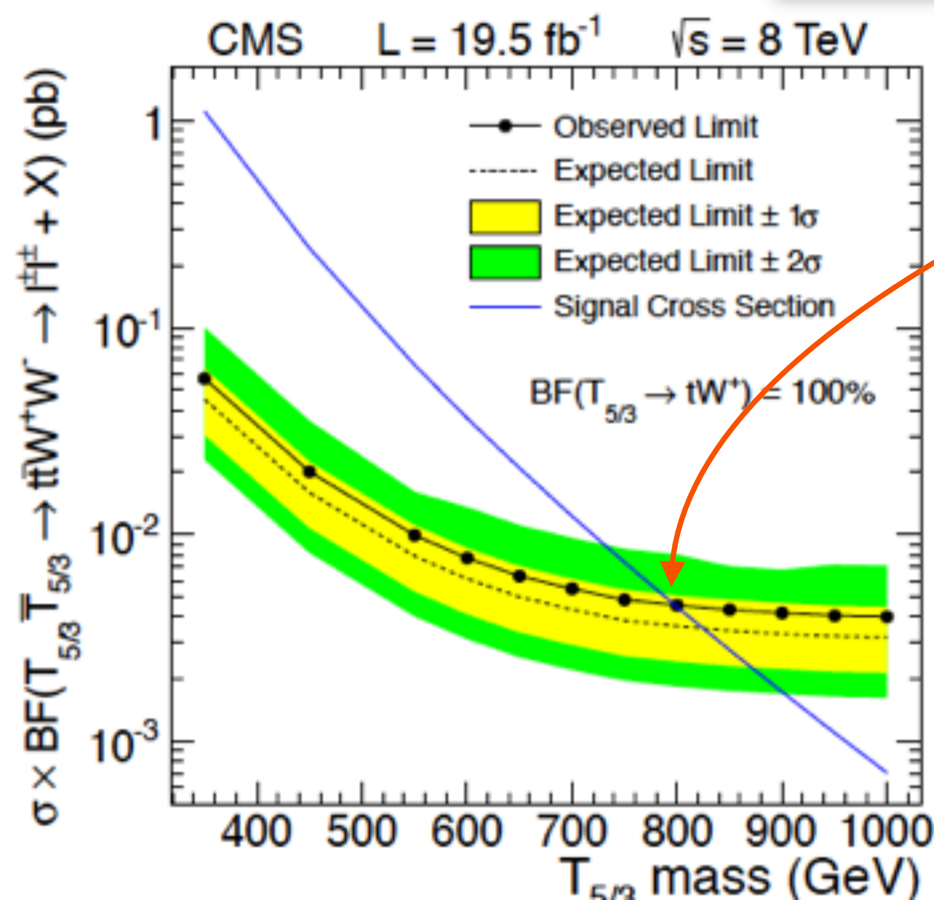
W tag:
2 subjets,

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

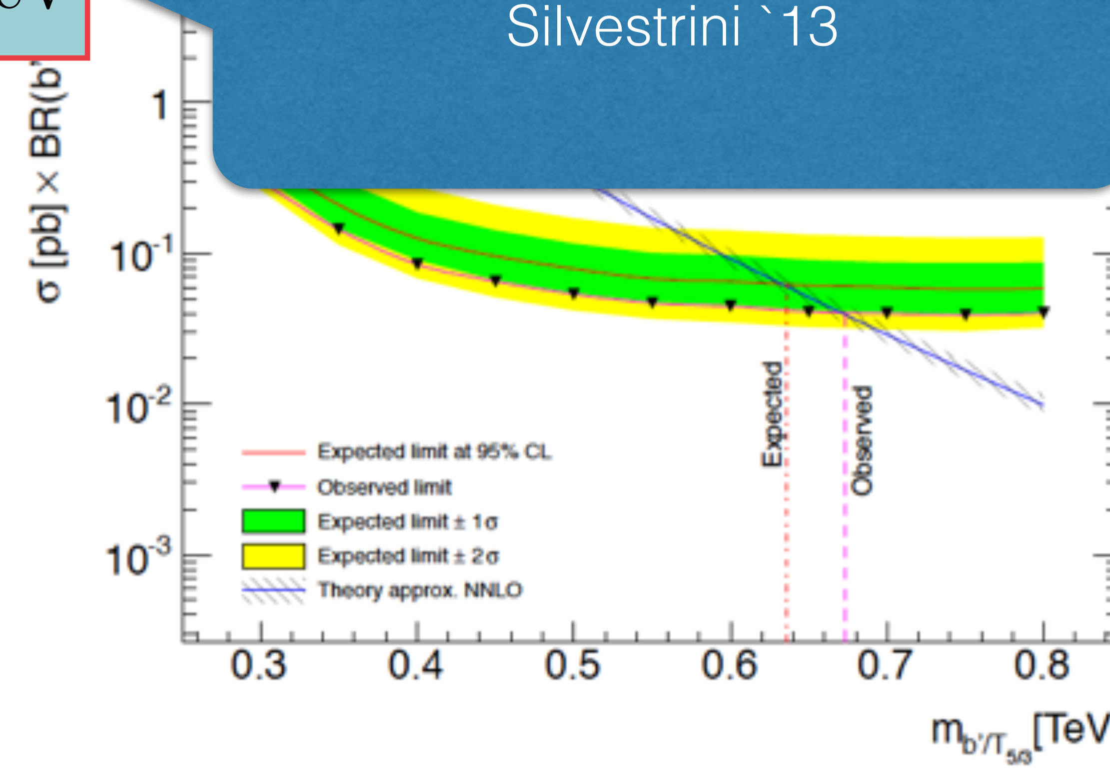
Grojean, Matsedonskyi, Panico `13

Ciuchini, Franco, Mishima, Silvestrini `13

10.1103/PhysRevLett.112.171801



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

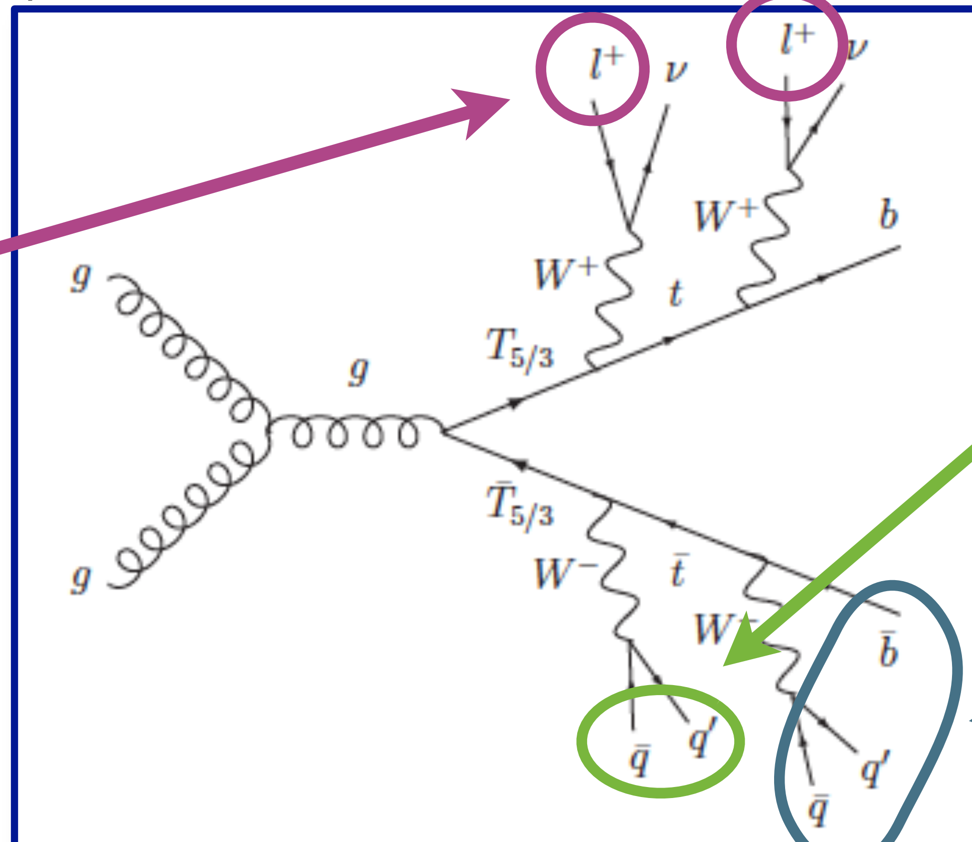


Composite Top Partner Searches @ Run 1

cf. Ennio Salvioni's talk
(and also Raman Sundrum's Review talk)
VLQ searches from ATLAS & CMS talk

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

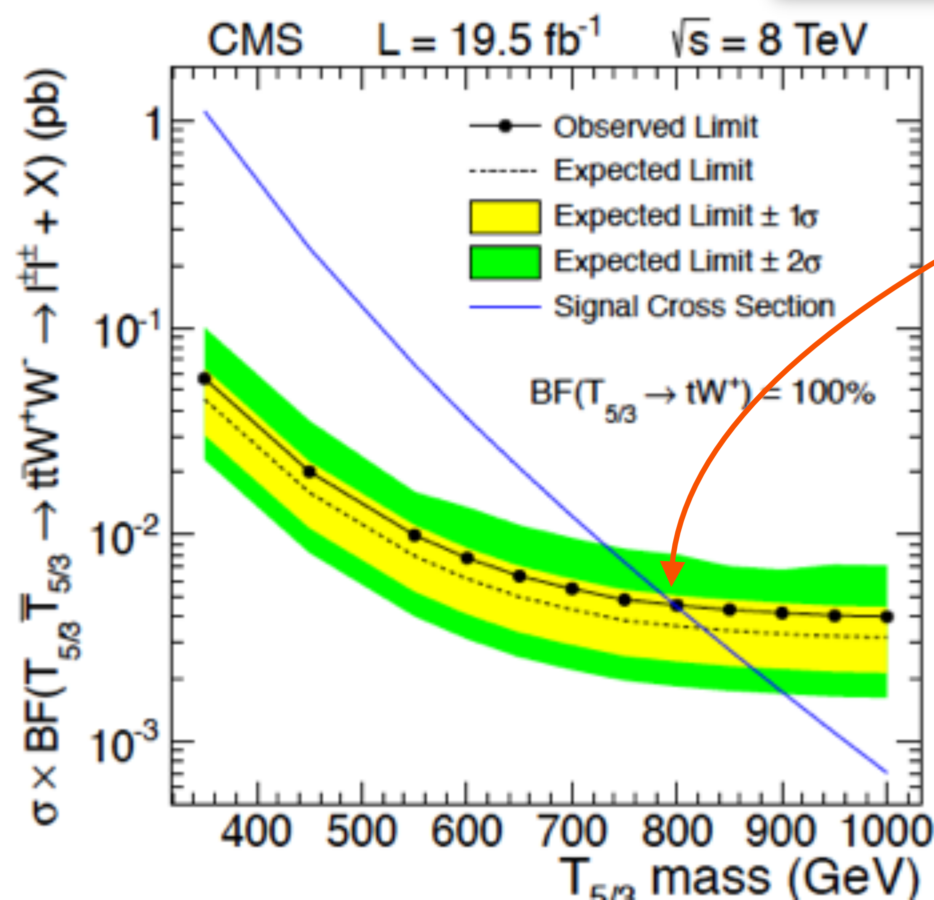
same-sign dileptons



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

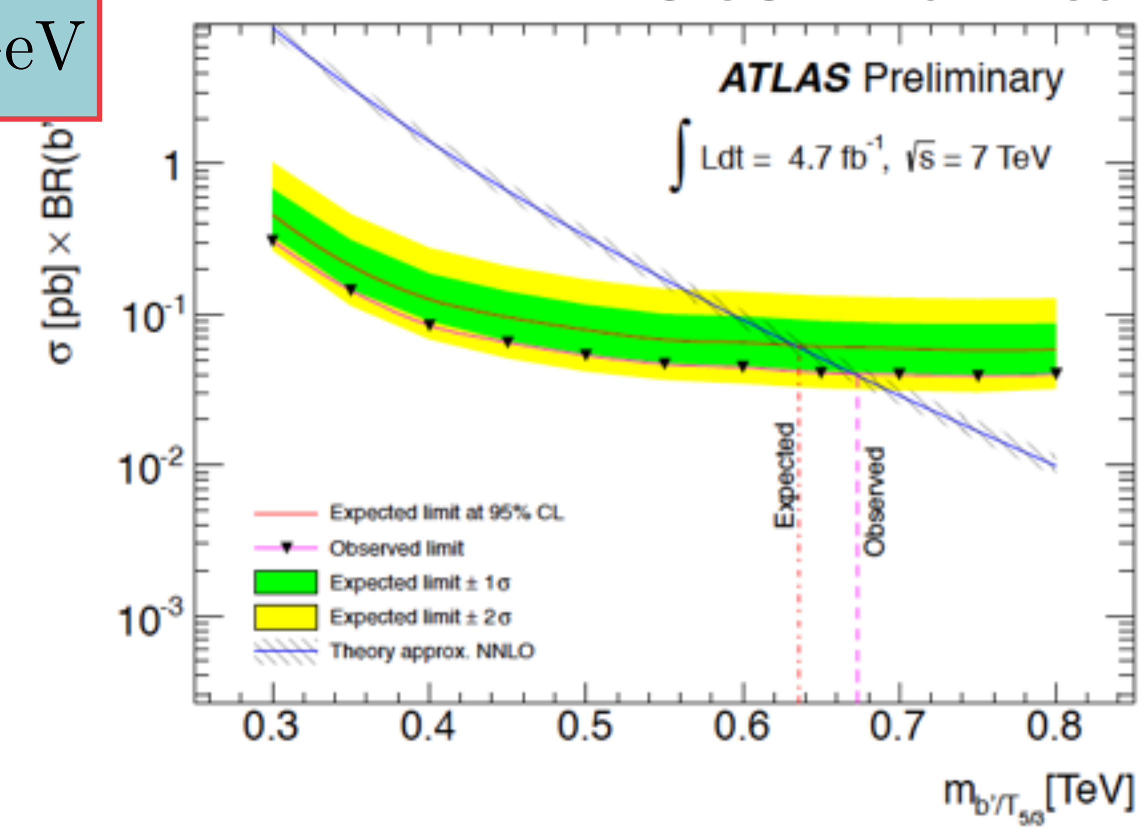
CMS top tag

10.1103/PhysRevLett.112.171801



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

ATLAS-CONF-2012-130

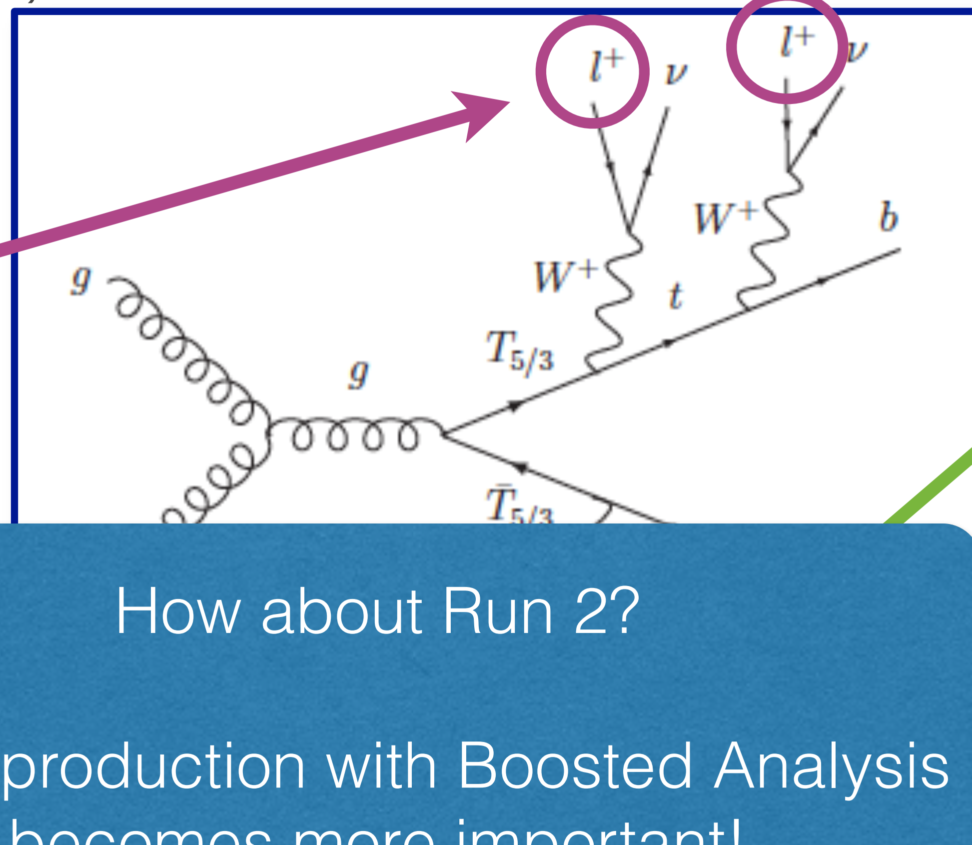


Composite Top Partner Searches @ Run 1

cf. Ennio Salvioni's talk
(and also Raman Sundrum's Review talk)
VLQ searches from ATLAS & CMS talk

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

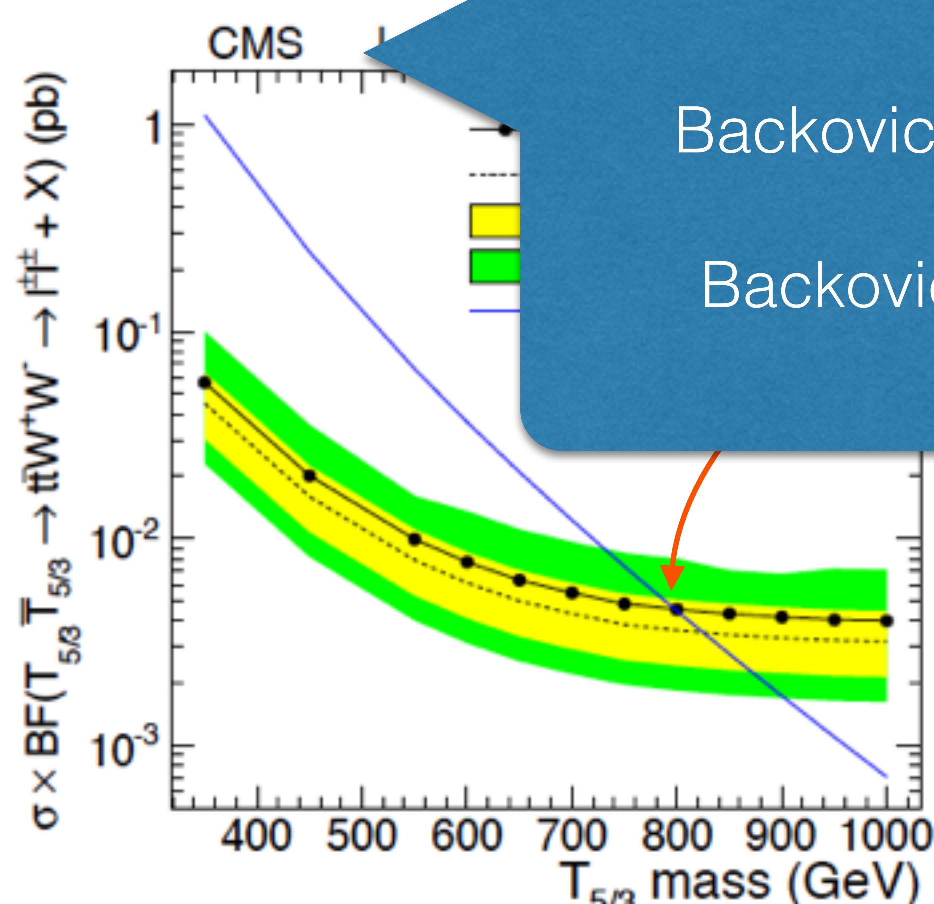
10.1103/PhysRevLett.11

How about Run 2?

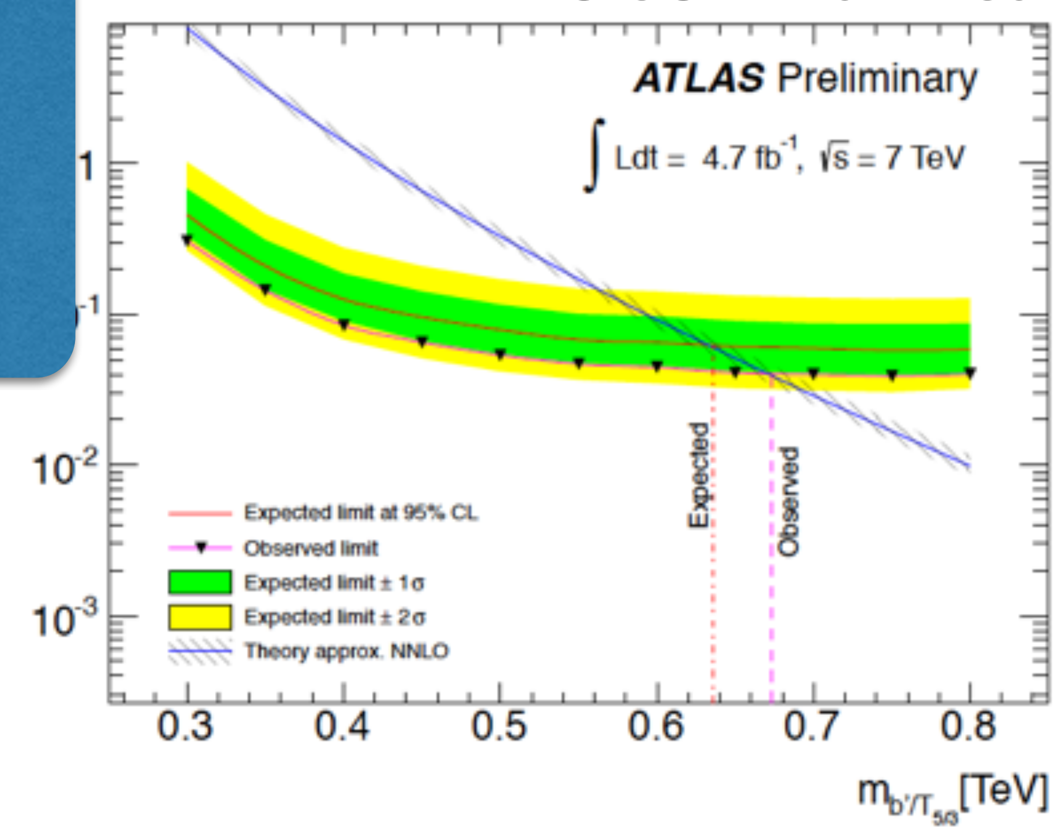
Single production with Boosted Analysis becomes more important!

Backovic, Flacke, SL, Perez `14

Backovic, Flacke, Kim, SL,`15

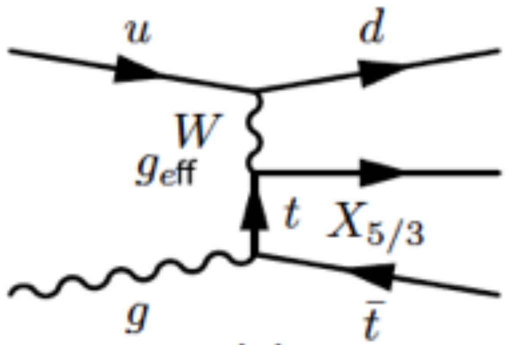


ATLAS-CONF-2012-130

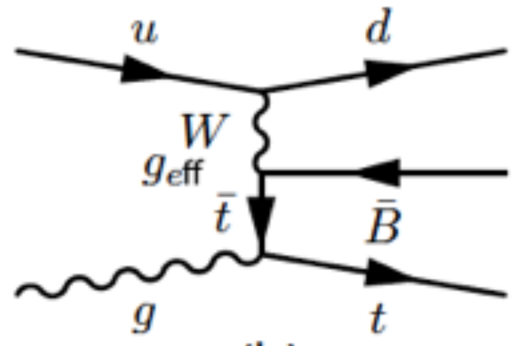


Top Partner Searches @ Run II

Backovic, Flacke, SL, Perez `14



(a)



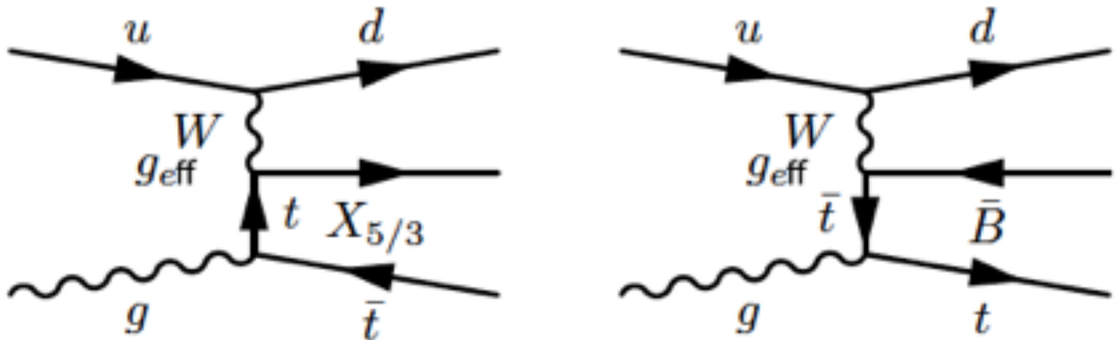
(b)

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

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

Top Partner Searches @ Run II

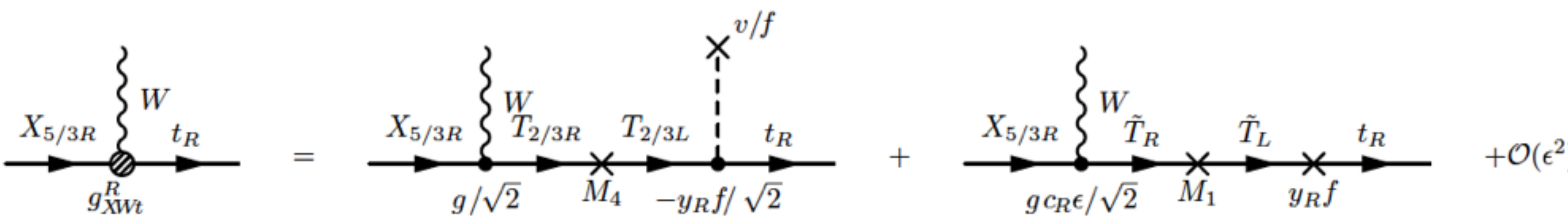
Backovic, Flacke, SL, Perez `14



(a) (b)

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

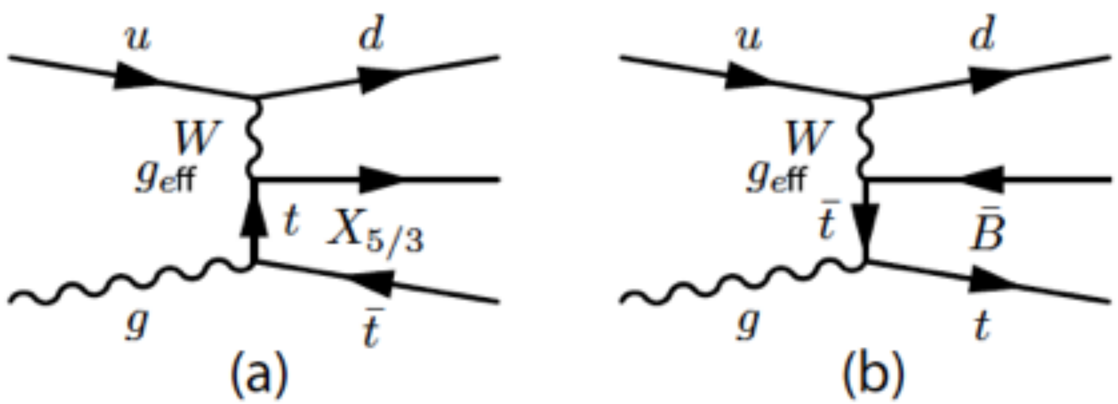
$$\begin{aligned}\mathcal{L} = &+ i\bar{q}'_L \not{D} q'_L + i\bar{t}'_R \not{D} t'_R + i\bar{b}'_R \not{D} b'_R \\ &+ i\bar{\tilde{\psi}}_4 \not{D}\tilde{\psi}_4 + i\bar{\tilde{\psi}}_1 \not{D}\tilde{\psi}_1 - M_4 \bar{\tilde{\psi}}_4\tilde{\psi}_4 - M_1 e^{i\phi}\bar{\tilde{\psi}}_1\tilde{\psi}_1 \\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



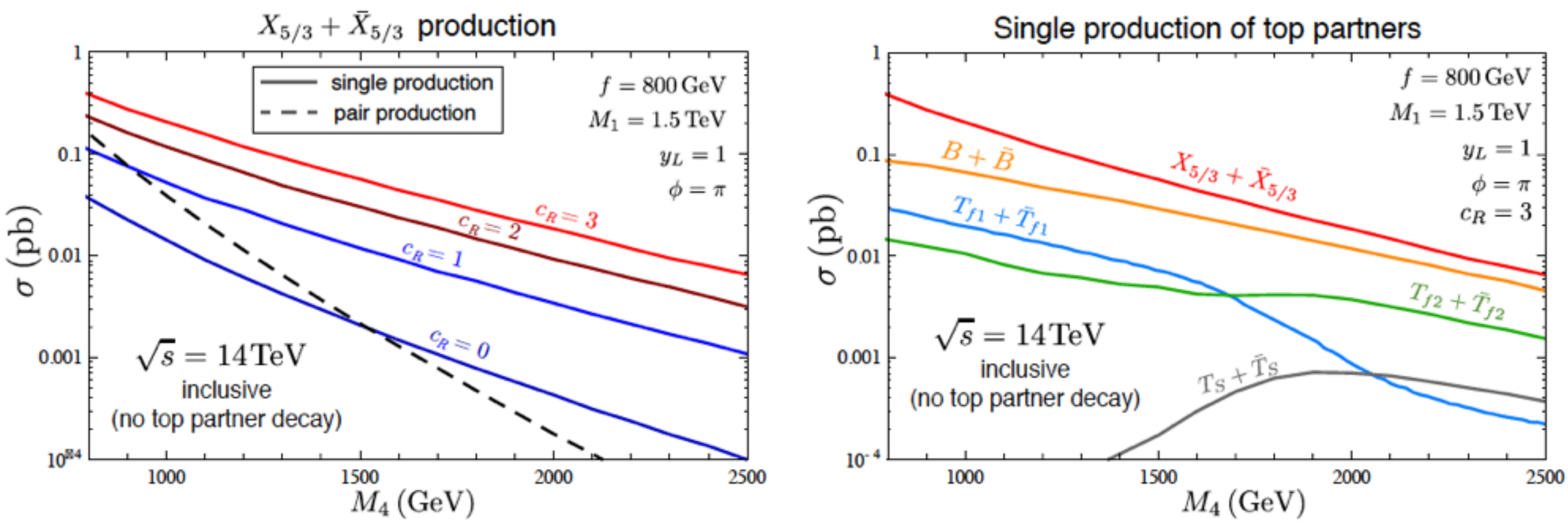
$$\begin{aligned} g^L_{XWt} &= G^X_{L\,i}\,(U^t_L)^\dagger_{\ i1} = \mathcal{O}(\epsilon^2)\,, \\ g^R_{XWt} &= G^X_{R\,i}\,(U^t_R)^\dagger_{\ i1} = \frac{g}{\sqrt{2}}\left(U^{*t}_{R\,13} + c_R \epsilon U^{*t}_{R\,14}\right) + \mathcal{O}(\epsilon^2)\,, \\ &= -\frac{g e^{-i\tilde{\phi}}}{\sqrt{2}}\frac{\epsilon}{\sqrt{2}}\left(\frac{y_R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

Top Partner Searches @ Run II

Backovic. Flacke. SL. Perez `14

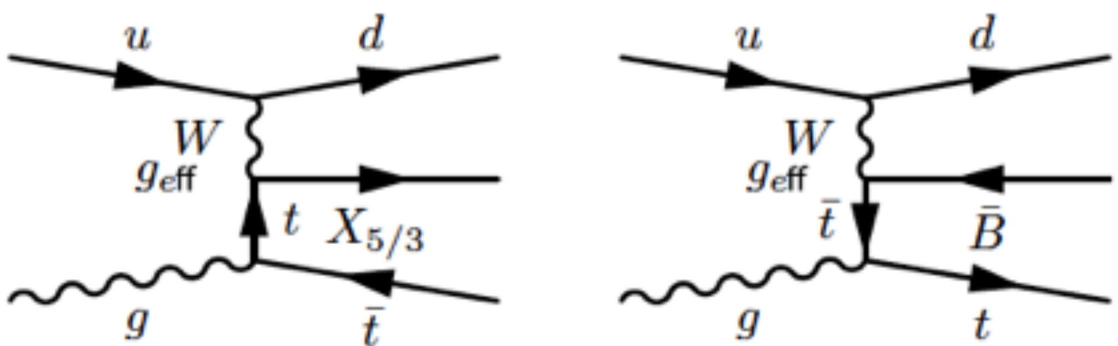


$$
\begin{aligned}
m_t &= \frac{v}{\sqrt{2}}\frac{|M_1 - e^{-i\phi}M_4|}{f}\frac{y_L f}{\sqrt{M_4 + y_L^2 f^2}}\frac{y_R f}{\sqrt{|M_1|^2 + y_R^2 f^2}} + \mathcal{O}(\epsilon^3),\\
M_B &= \sqrt{M_4^2 + y_L^2 f^2},\\
M_{X_{5/3}} &= M_4,\\
M_{Tf1} &= M_4 + \mathcal{O}(\epsilon^2),\\
M_{Tf2} &= \sqrt{M_4^2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



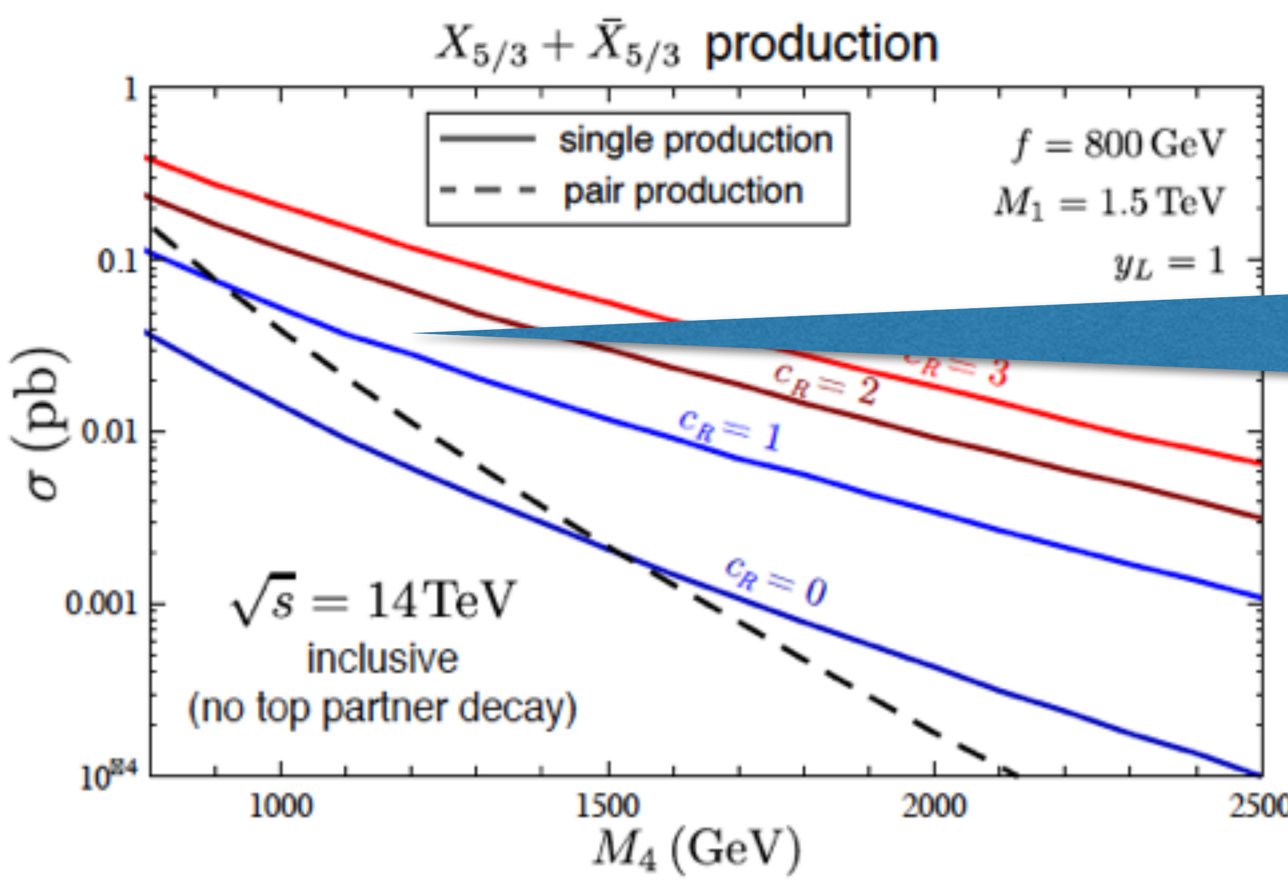
Top Partner Searches @ Run II

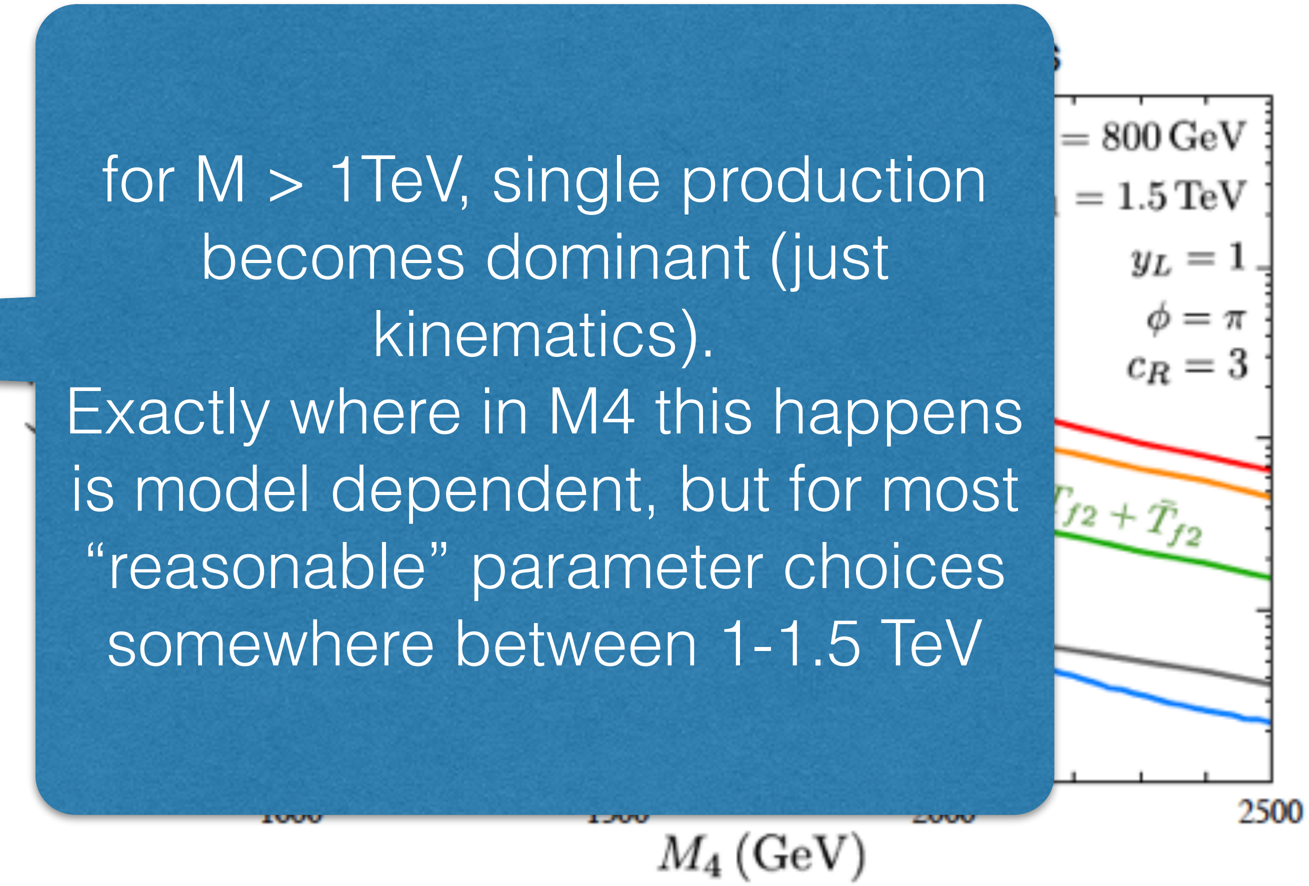
Backovic. Flacke. SL. Perez `14



(a) (b)

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

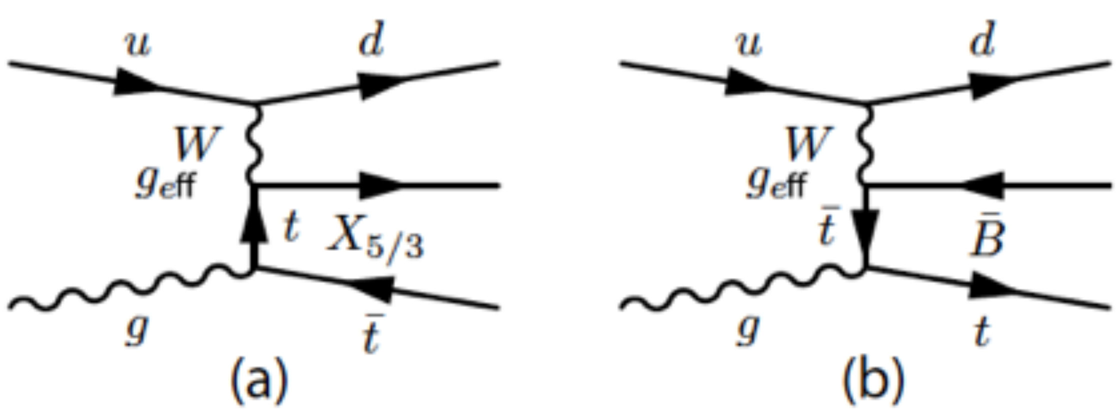




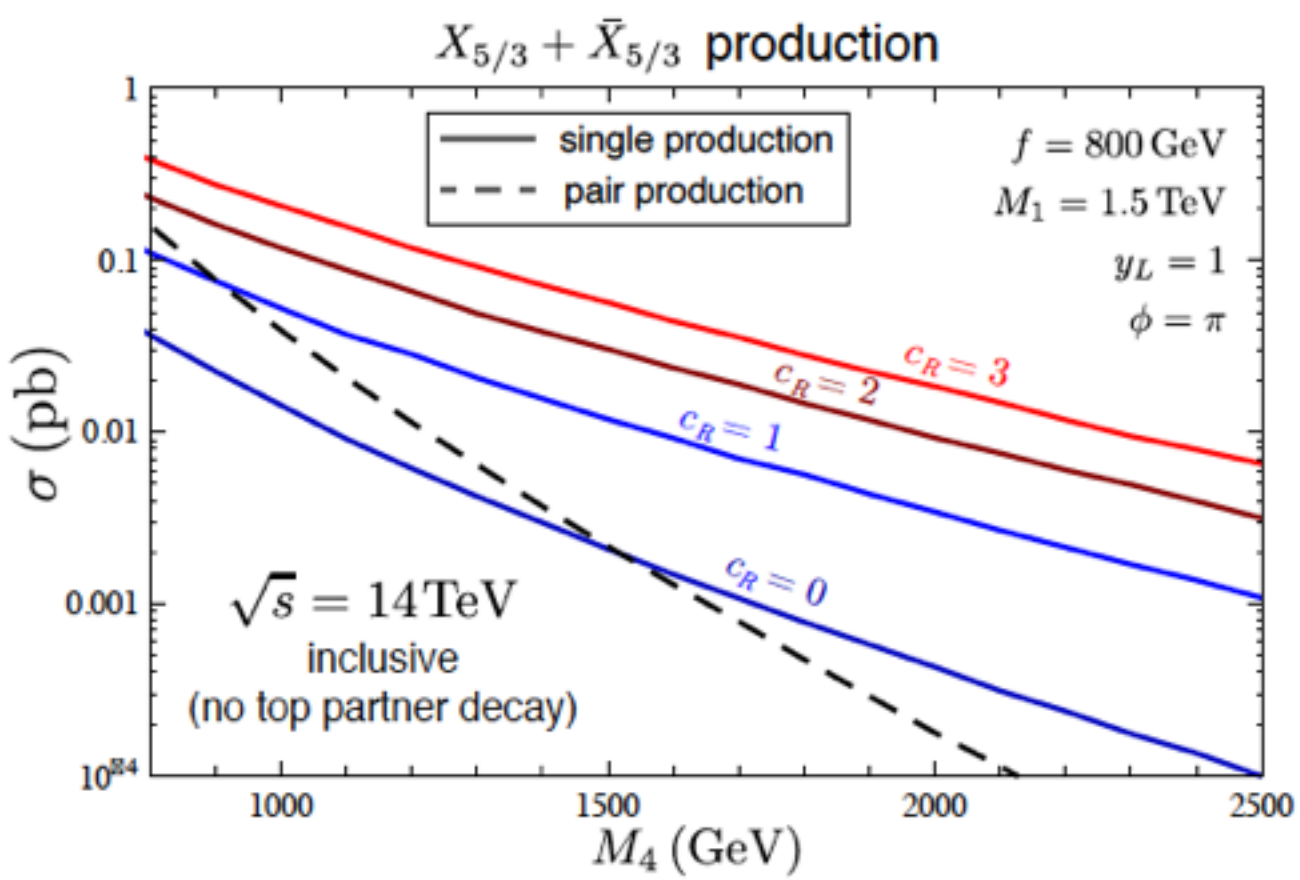
for M > 1TeV, single production becomes dominant (just kinematics).
Exactly where in M4 this happens is model dependent, but for most “reasonable” parameter choices somewhere between 1-1.5 TeV

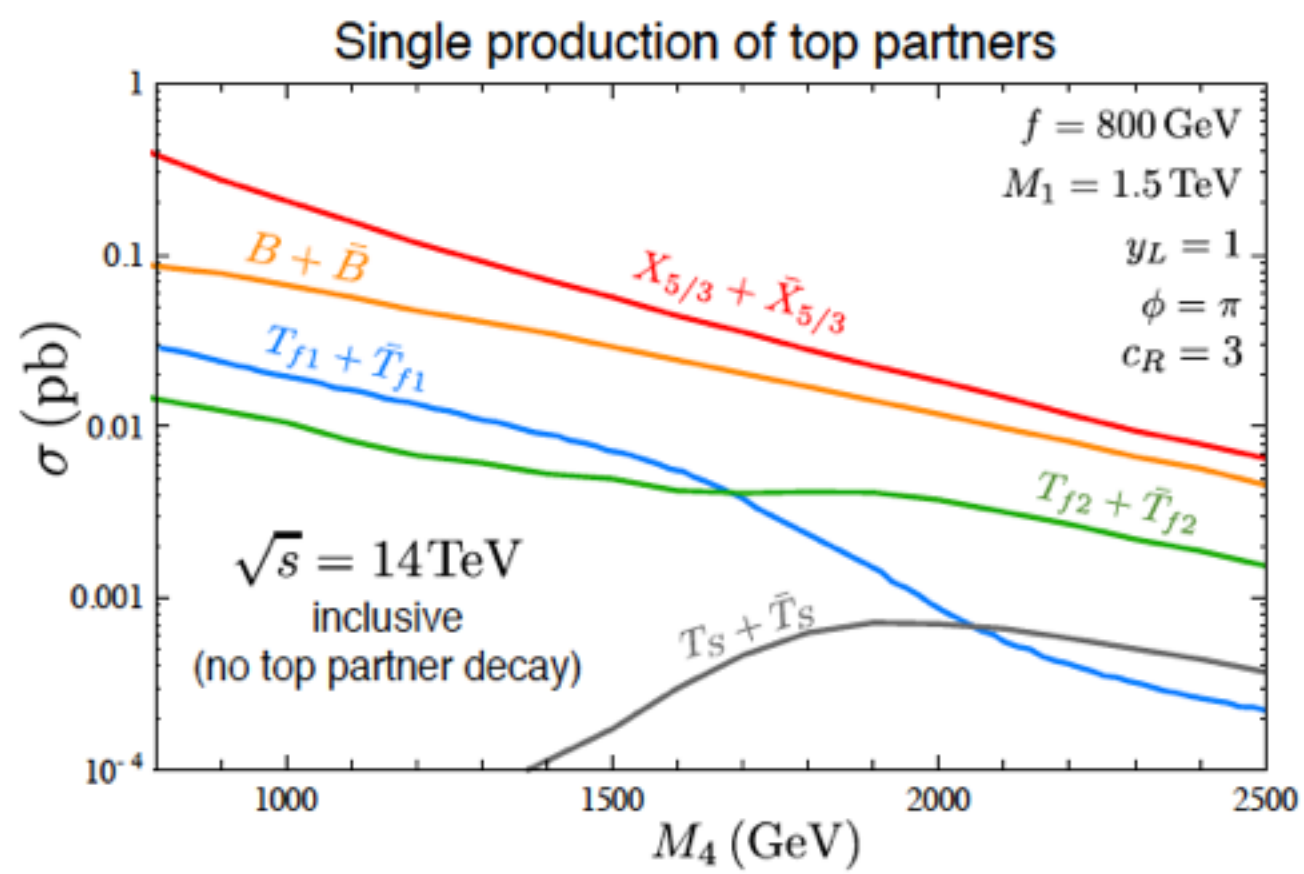
Top Partner Searches @ Run II

Backovic. Flacke. SL. Perez `14



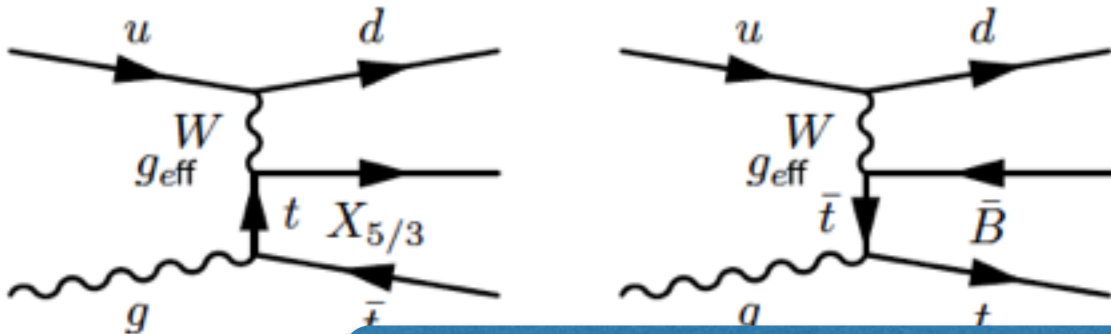
$$
\begin{aligned}
m_t &= \frac{v}{\sqrt{2}} \frac{|M_1 - e^{-i\phi} M_4|}{f} \frac{y_L f}{\sqrt{M_4 + y_L^2 f^2}} \frac{y_R f}{\sqrt{|M_1|^2 + y_R^2 f^2}} + \mathcal{O}(\epsilon^3), \\
M_B &= \sqrt{M_4^2 + y_L^2 f^2}, \\
M_{X_{5/3}} &= M_4, \\
M_{Tf1} &= M_4 + \mathcal{O}(\epsilon^2), \\
M_{Tf2} &=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





Top Partner Searches @ Run II

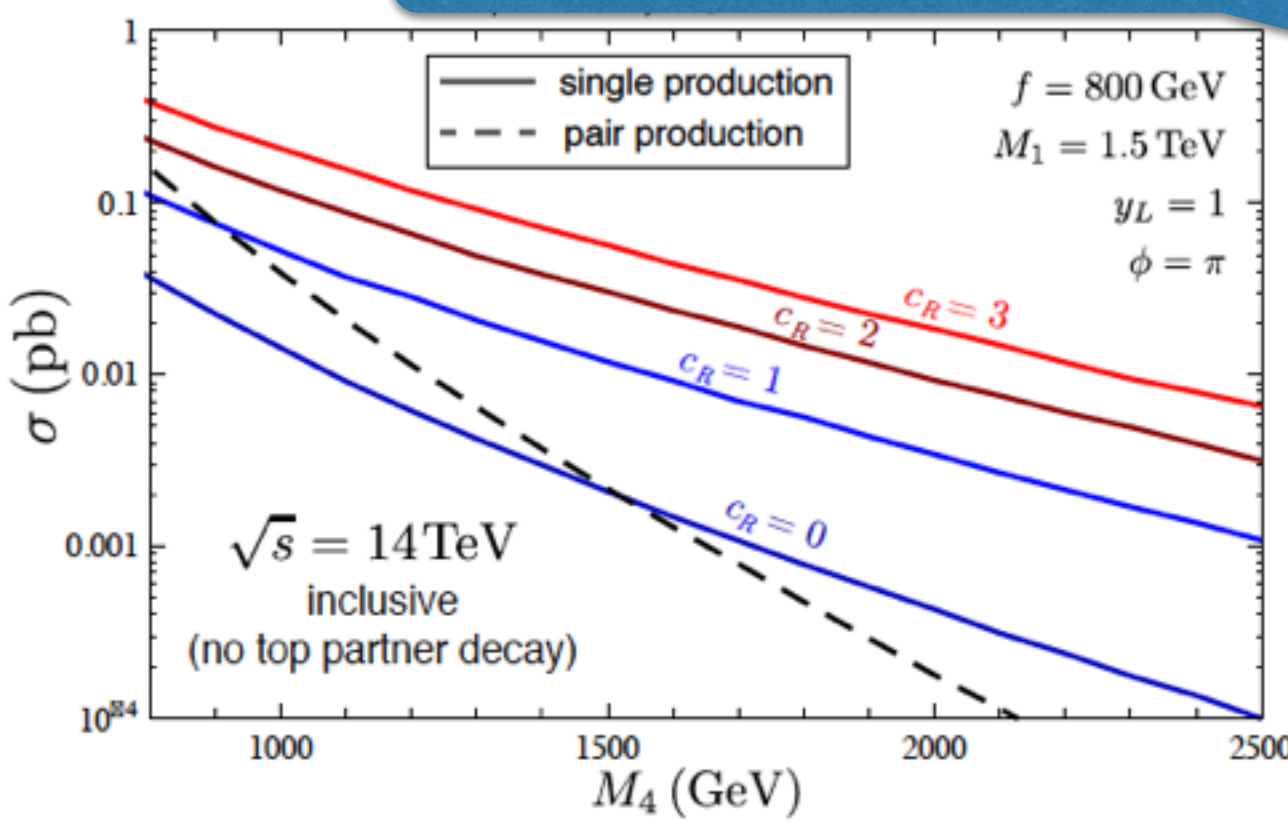
Backovic. Flacke. SL. Perez `14

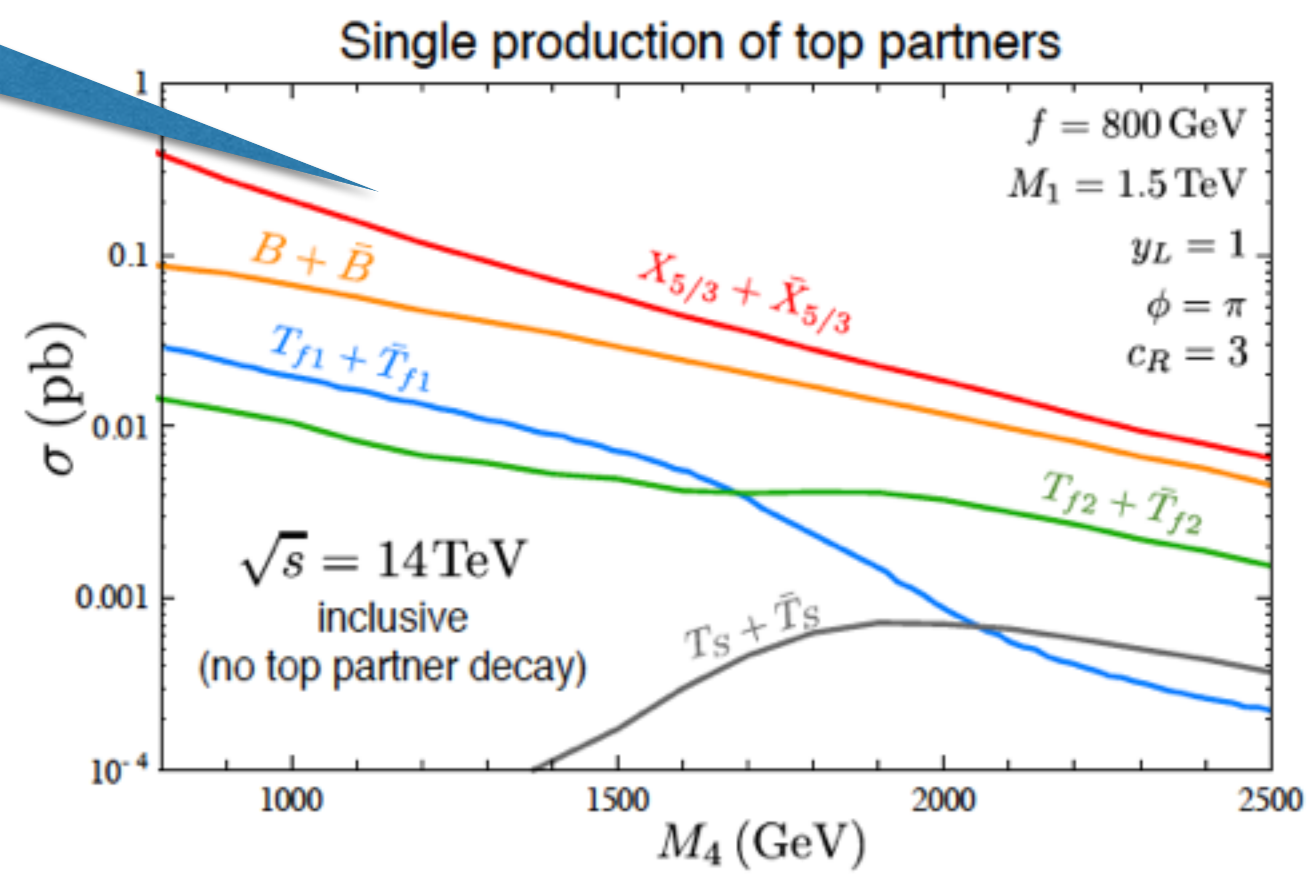


(a)

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

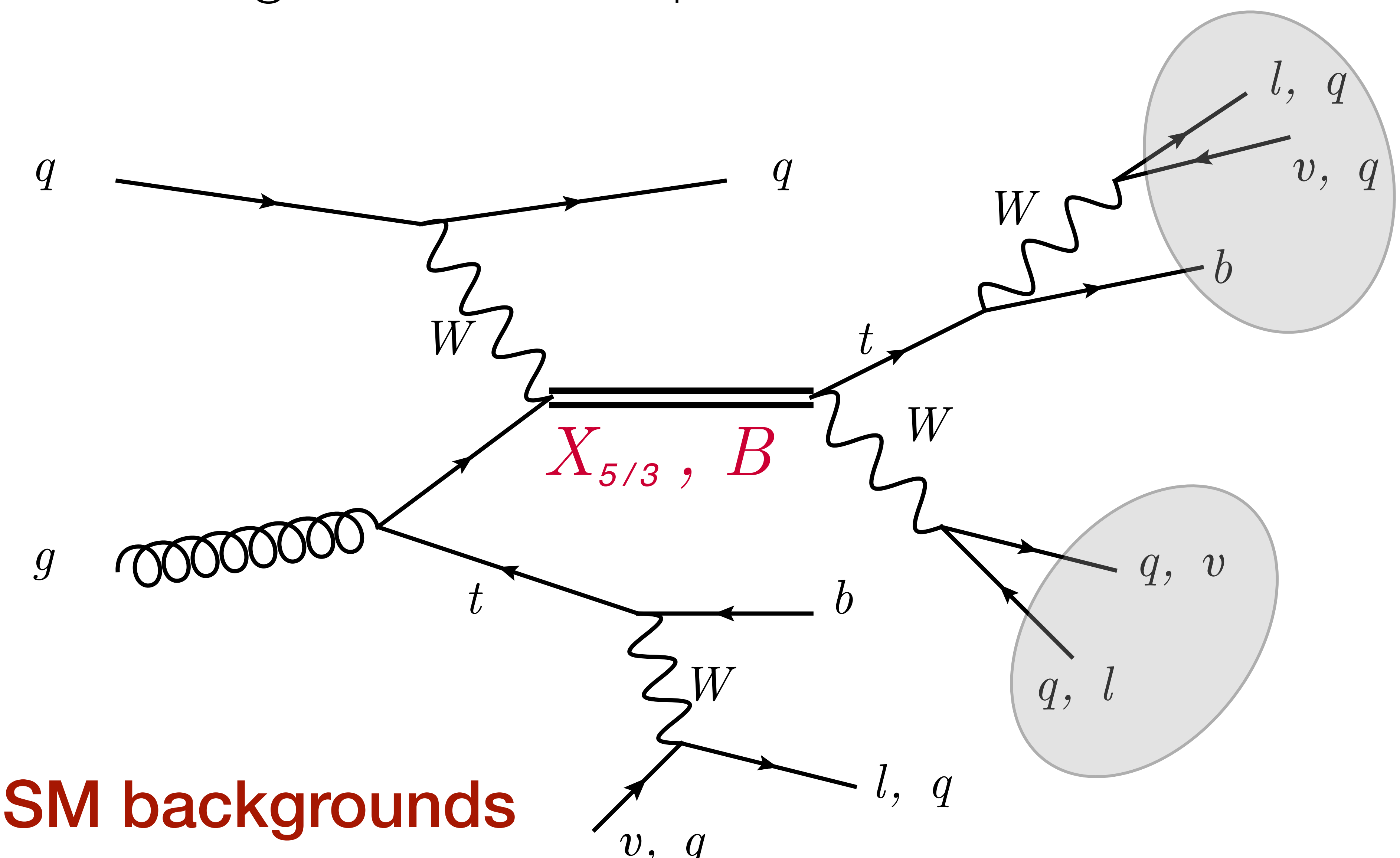
Single production is dominated by X5/3 and B partners.





Top Partner Searches @ Run II

* Single production of top partners might looks complicated



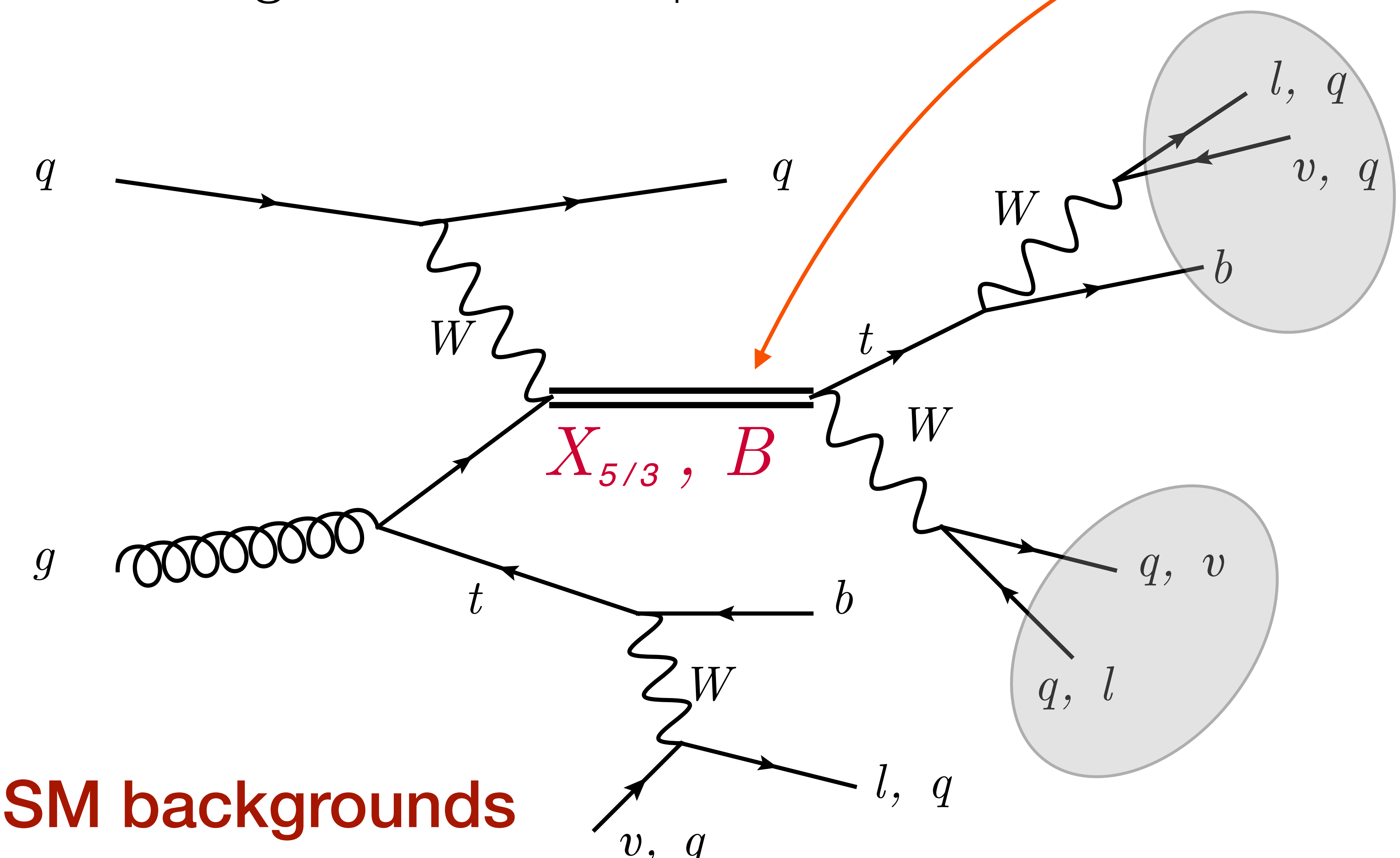
Large **SM backgrounds** (di-tops, **W**+jets, ...)

Backovic, Flacke, SL, Perez `14

Top Partner Searches @ Run II

- Single production of top partners might looks complicated

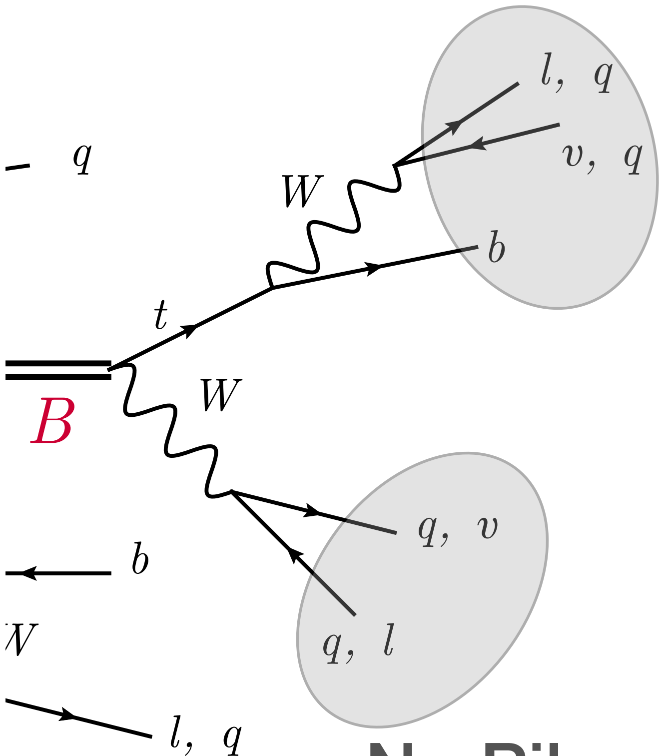
$M \sim O(1\,\mathrm{TeV})$



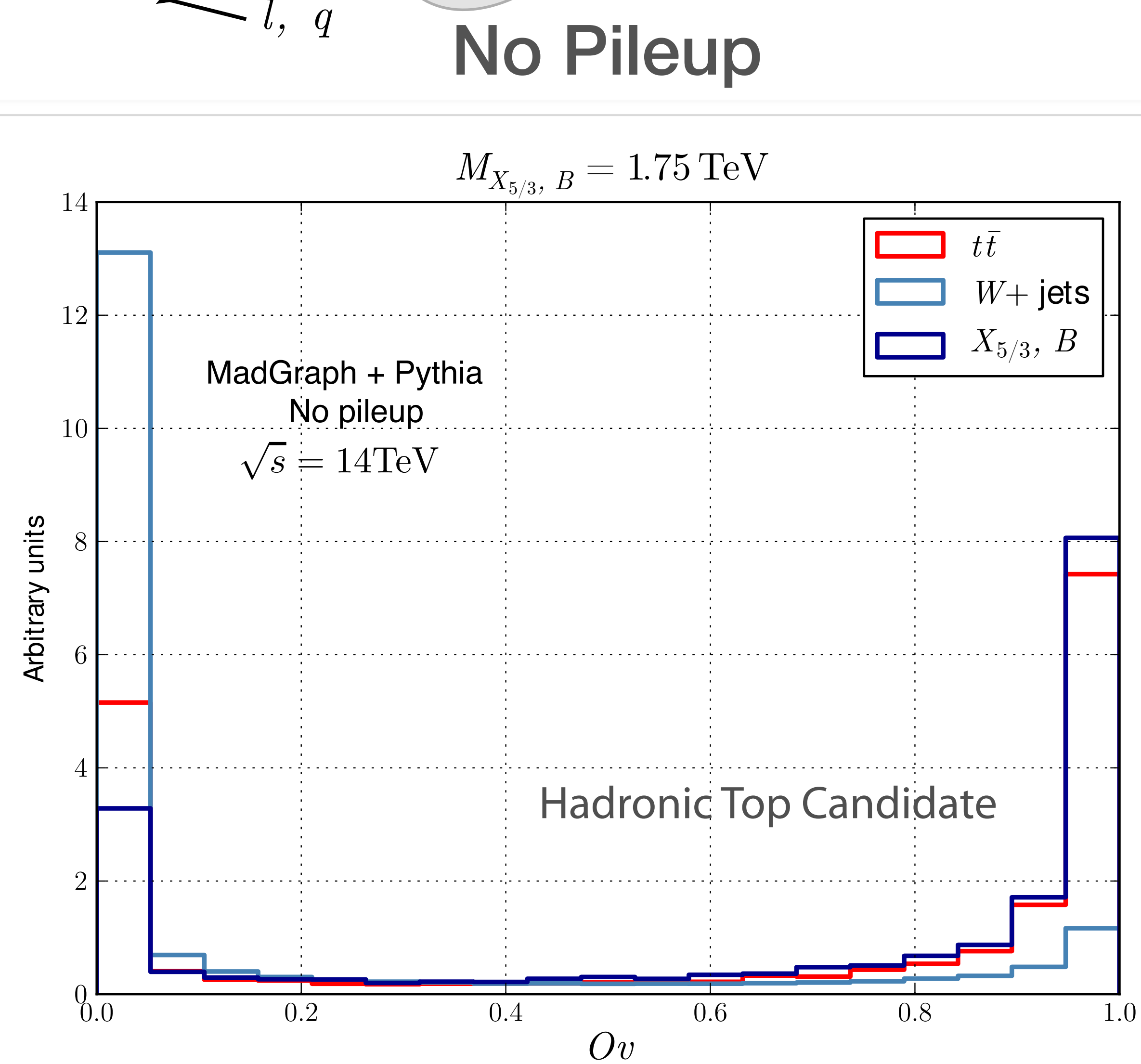
Large **SM backgrounds**
(di-tops, **W**+jets, …)

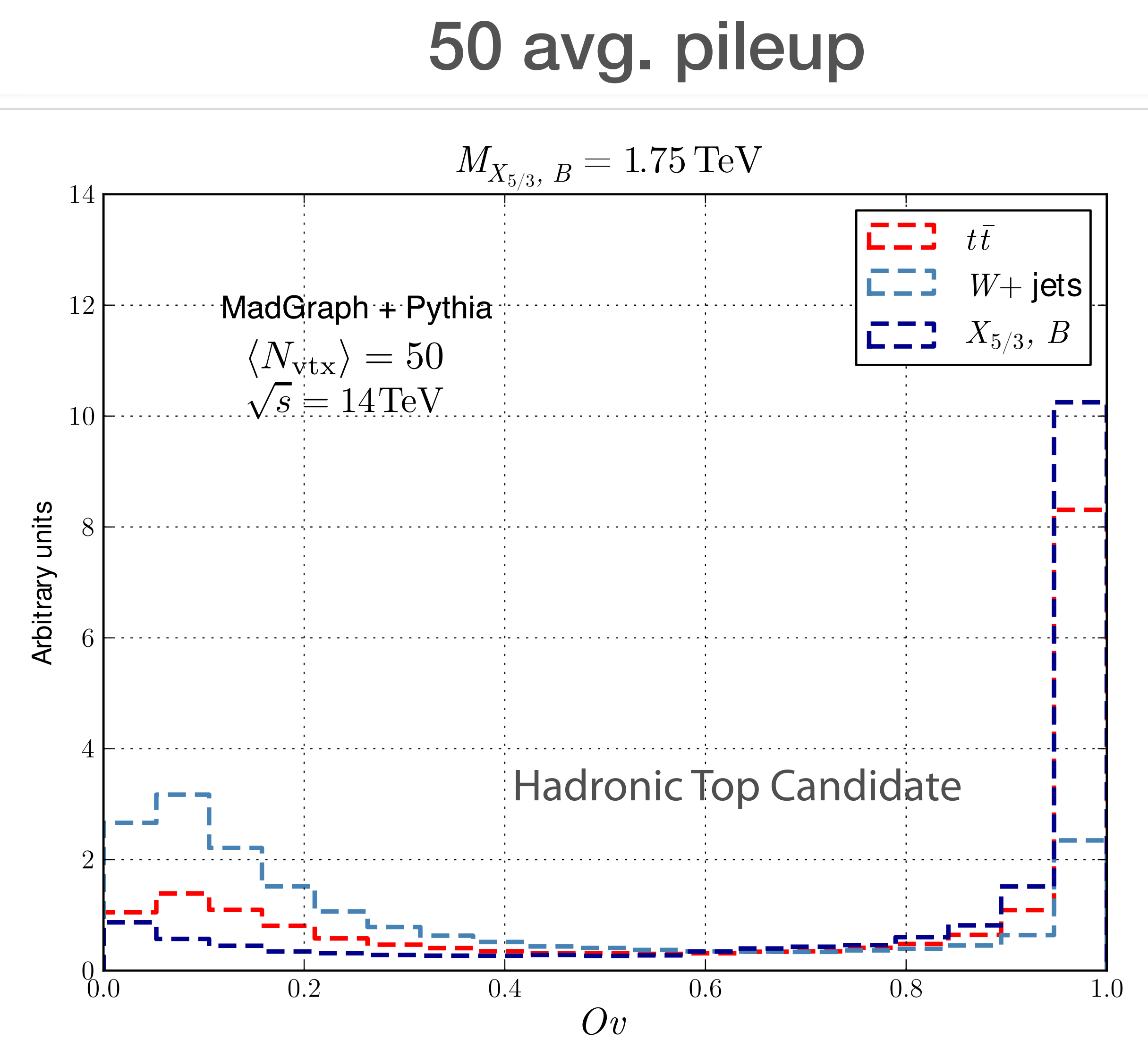
Backovic, Flacke, SL, Perez `14

jet substructure method necessary!

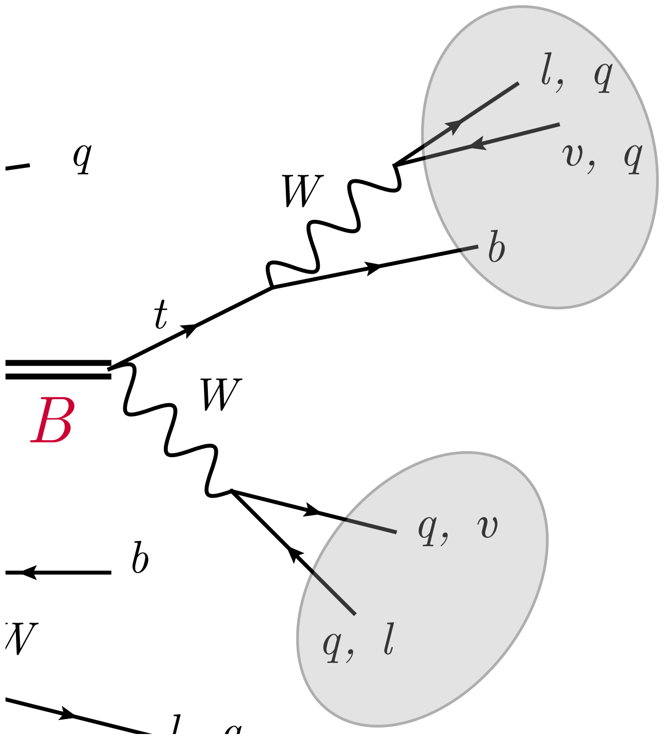


✱ Template Overlap Method



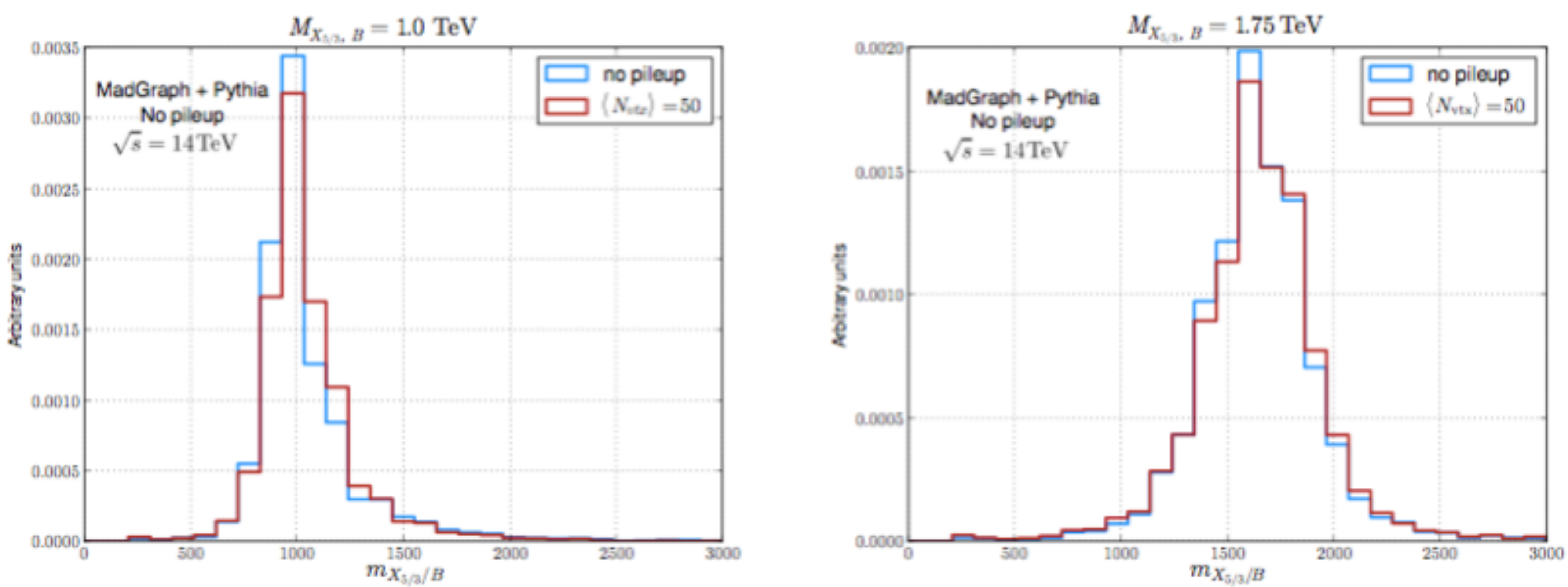


jet substructure method necessary!



✱ Template Overlap Method

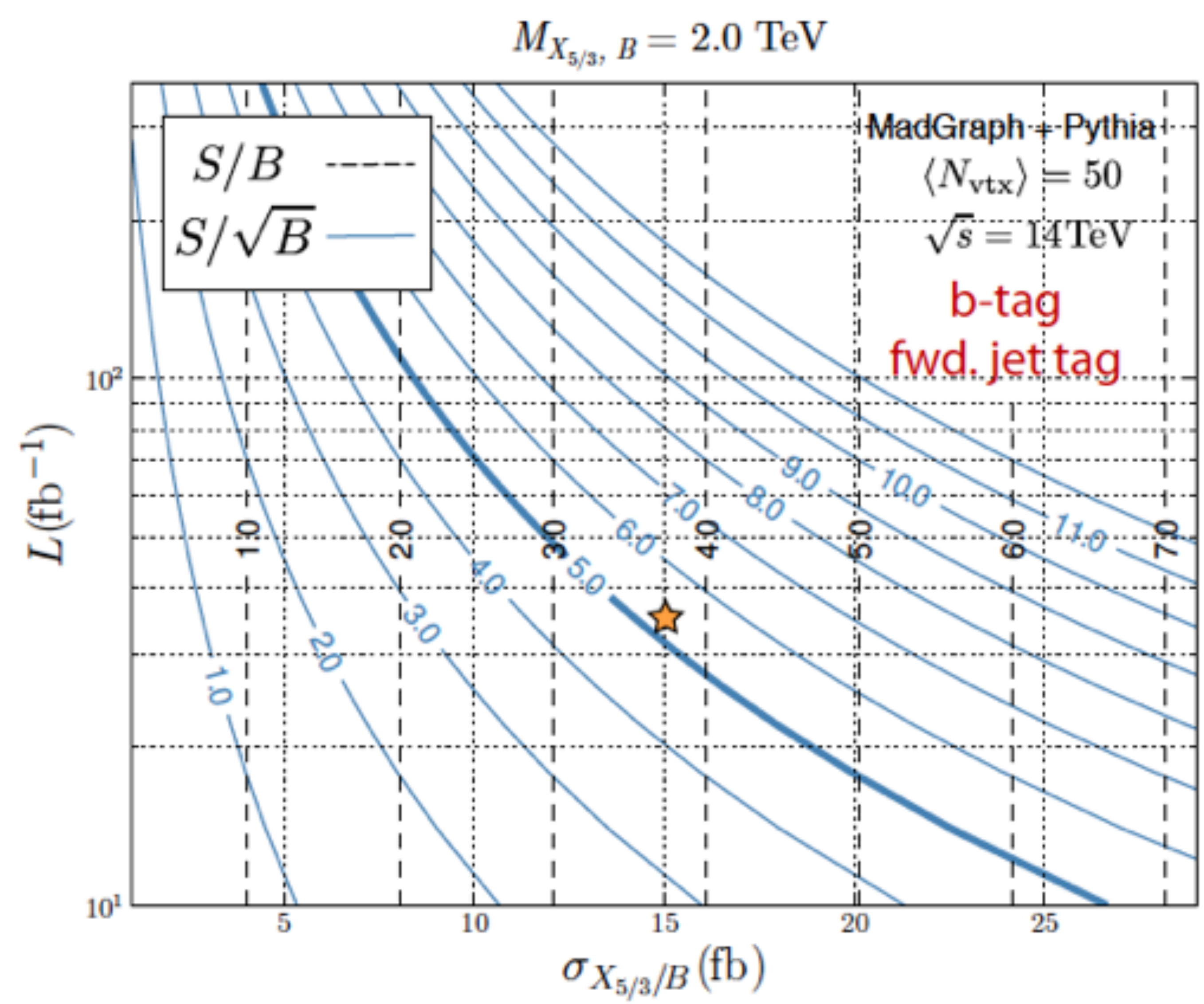
red - pileup   blue - no pileup



Note: very **difficult to reconstruct the resonance mass** with

Backovic, Flacke, SL, Perez `14

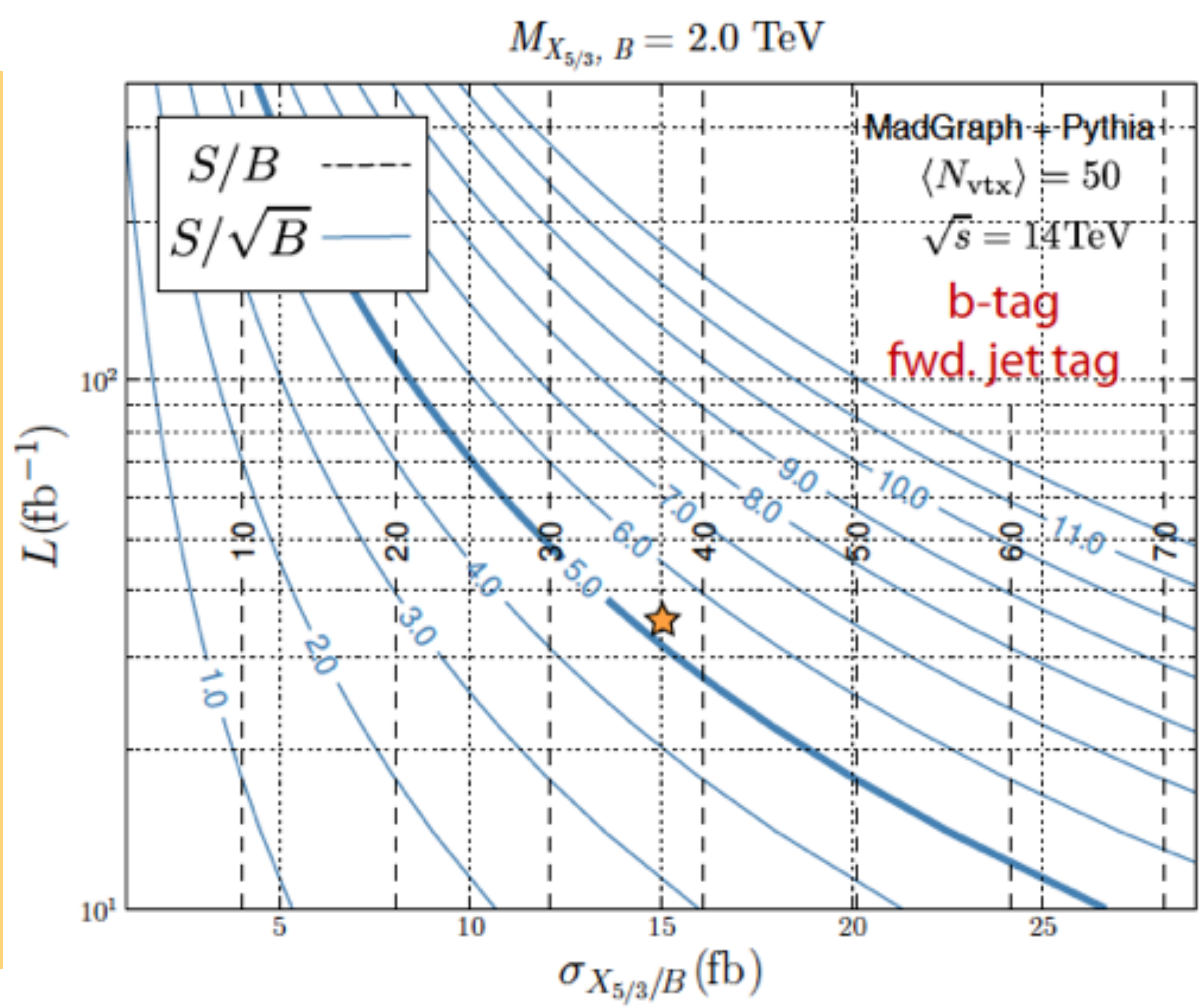
✱Template Overlap Method w/ forward jet tagging & b-tagging



Backovic, Flacke, SL, Perez `14

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

- Run 2 of the LHC at 13 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}

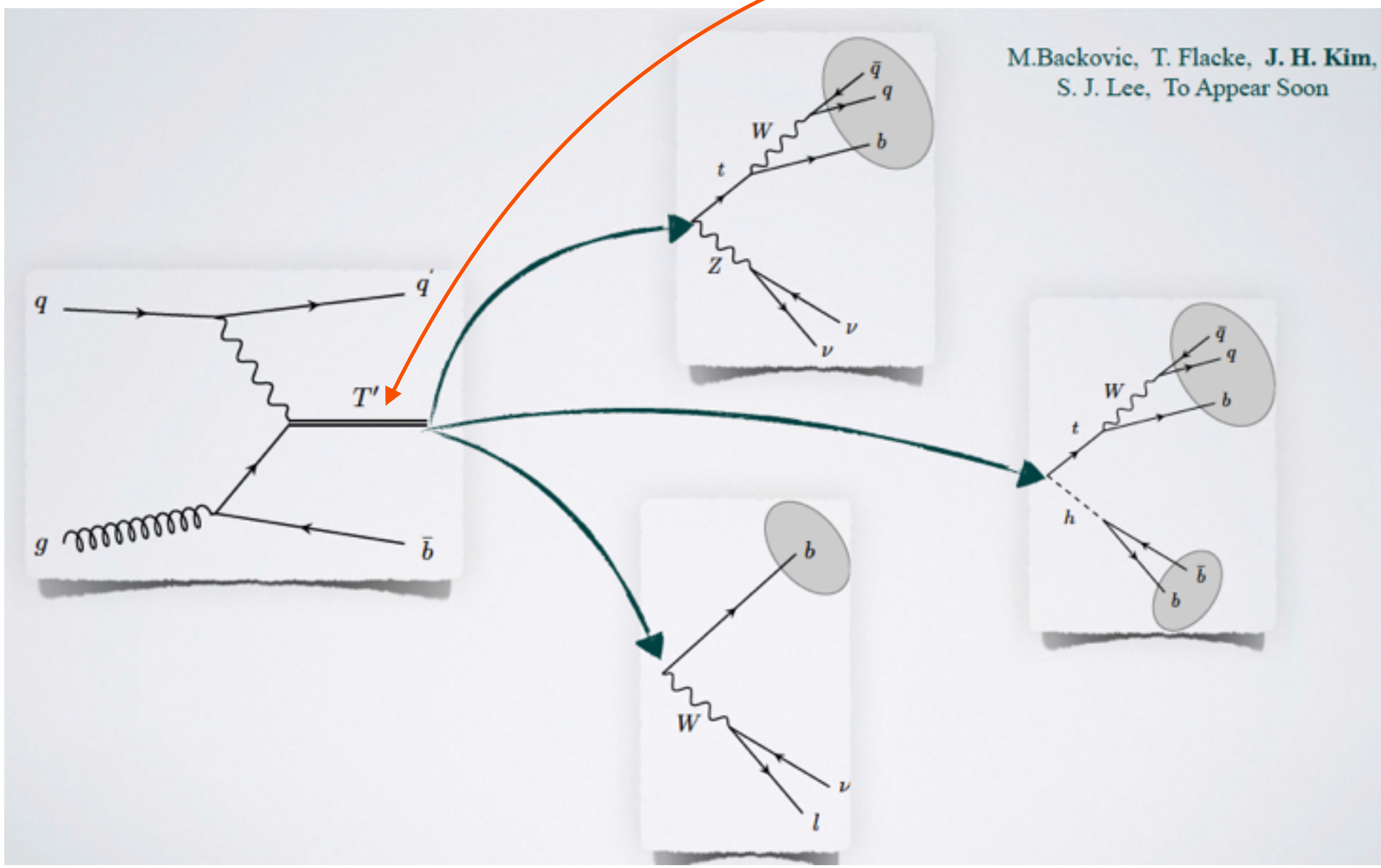


2/3 charged Top Partner Searches Beyond the 1 TeV Mass Region

Backovic, Flacke, Kim, SL, `15
Backovic, Flacke, Kim, SL, `(to appear)

- Single production of top partners

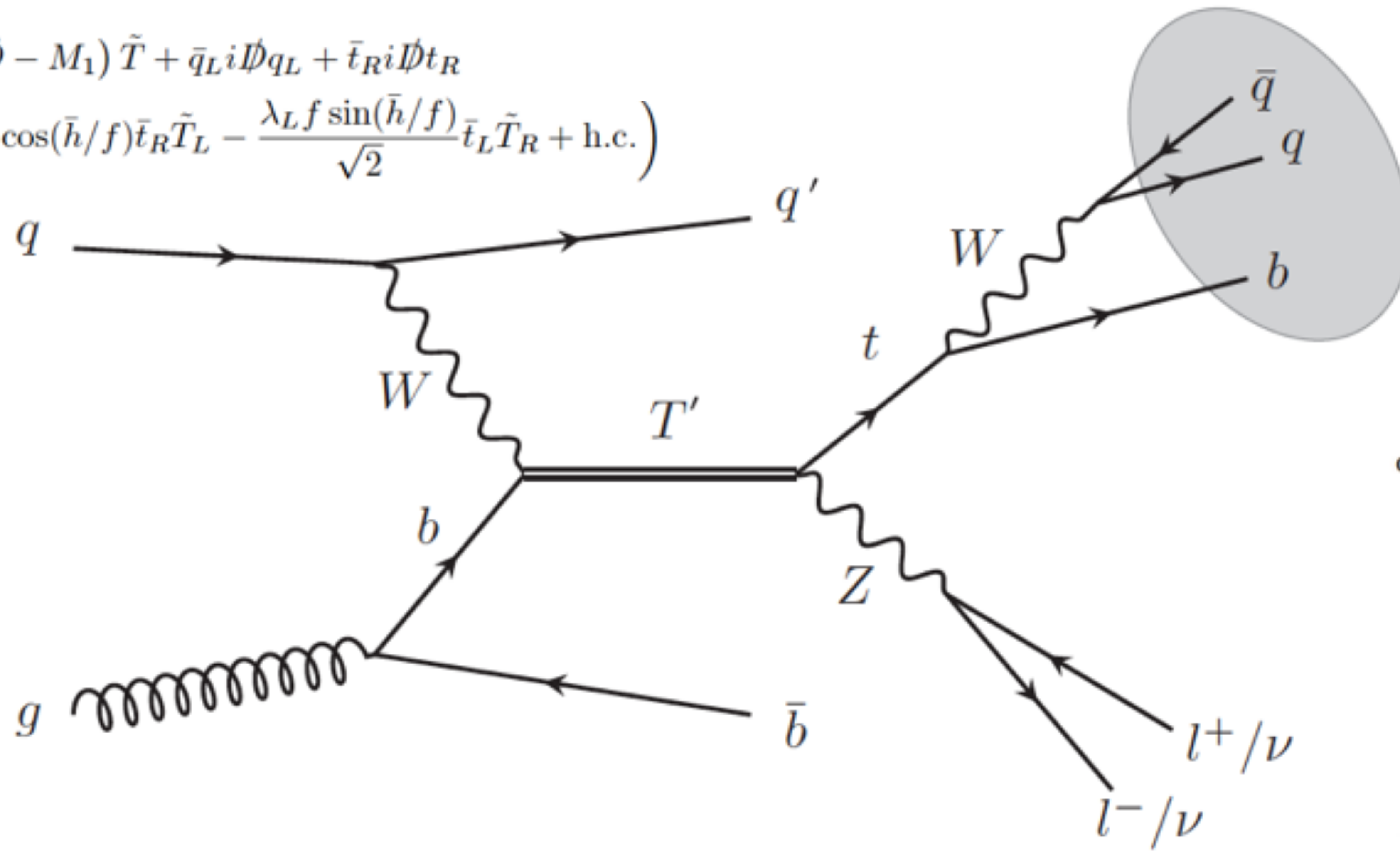
$M \sim O(1\,\mathrm{TeV})$

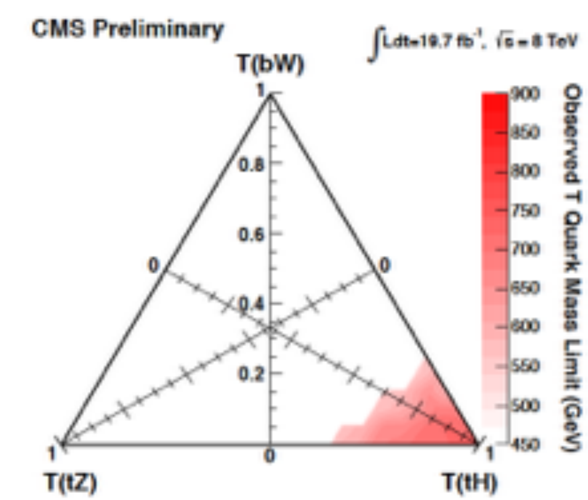


2/3 charged Top Partner Searches Beyond the 1 TeV Mass Region

- 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

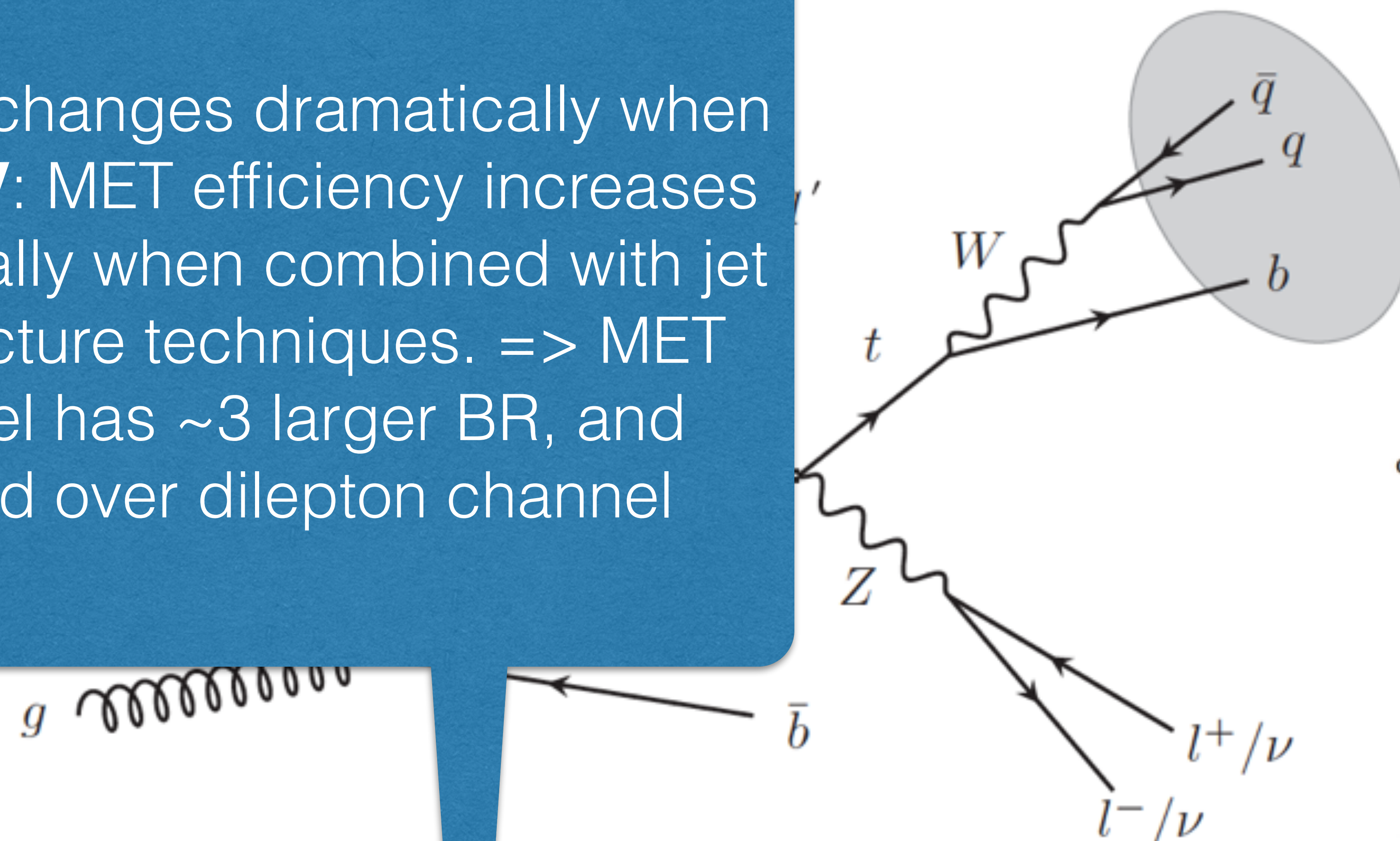
Backovic, Flacke, Kim,SL `15
Backovic, Flacke, Kim,SL to appear

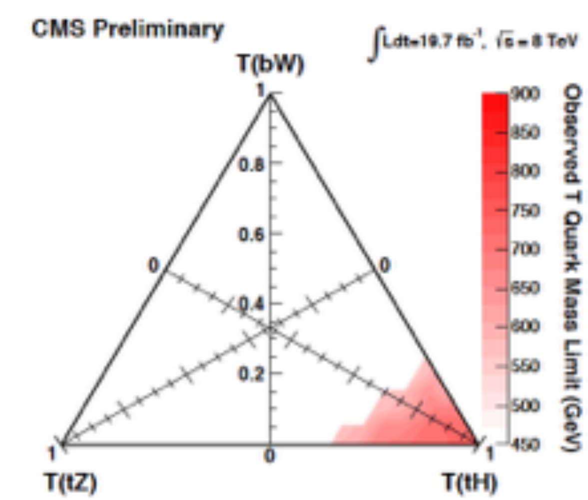
2/3 charged Top Partner Searches Beyond the 1 TeV Mass Region

- For simple study we chose 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





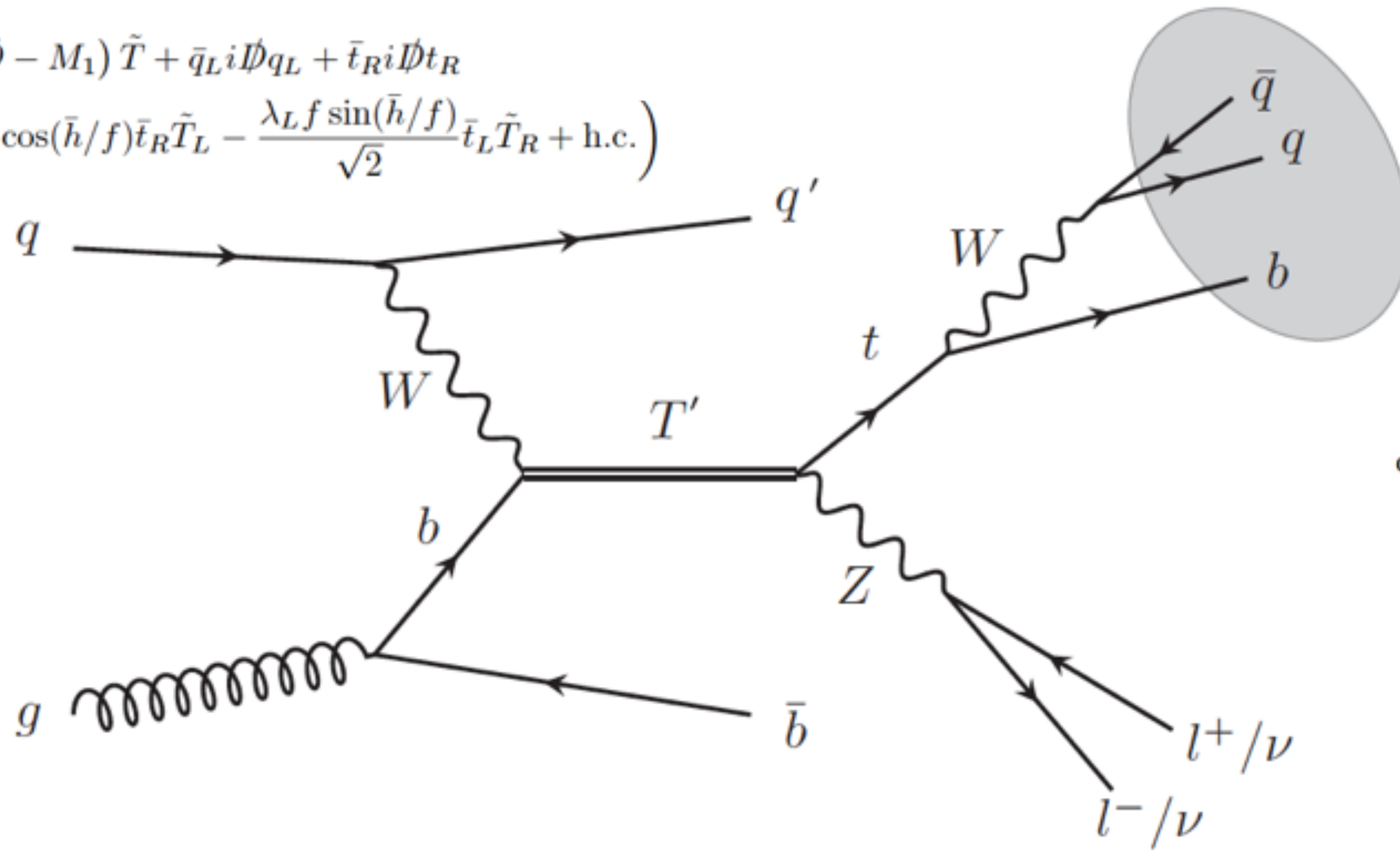
- For **Run I**, **(Z → MET)+hadronic** channel was not utilized due to large SM background (e.g. t+MET): **(Z → dilepton)+hadronic channel** has been the golden channel

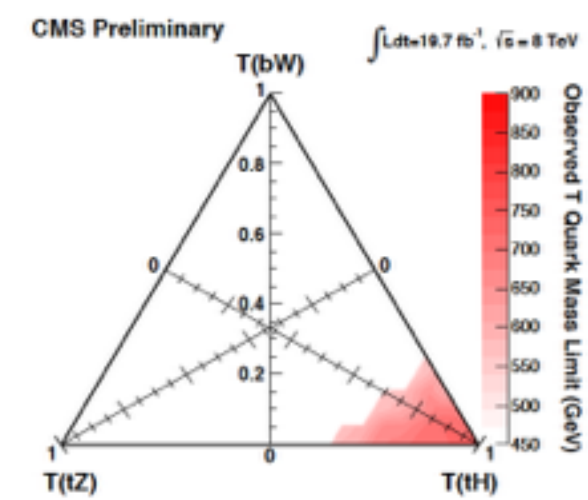
Backovic, Flacke, Kim,SL `15
Backovic, Flacke, Kim,SL to appear

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

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)

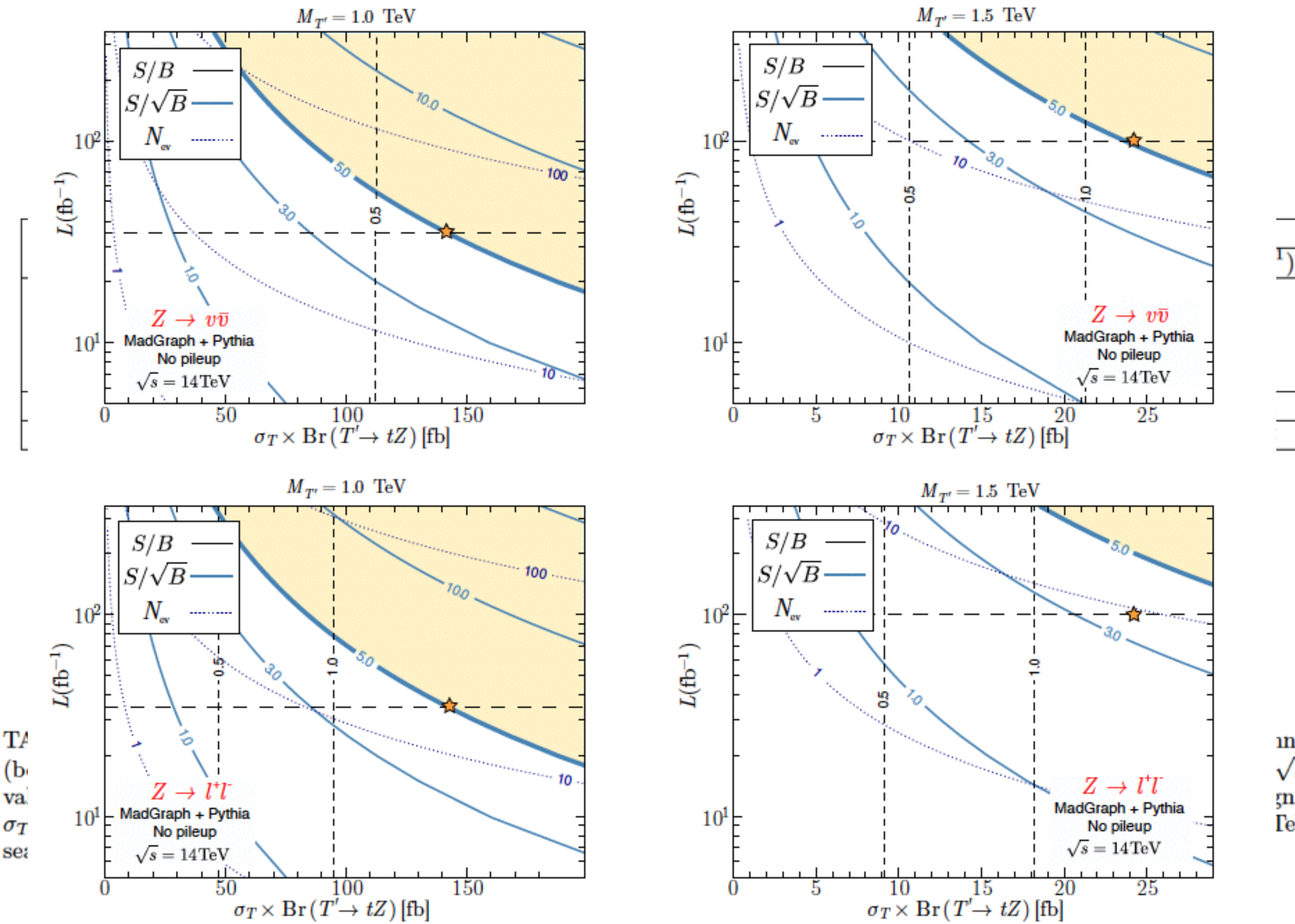
$Z \to \nu\bar{\nu}$	$M_{T'} = 1.0$ TeV search						$M_{T'} = 1.5$ TeV search					
	signal	$t\bar{t}$	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}\,(35\,\text{fb}^{-1})$	signal	$t\bar{t}$	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}\,(100\,\text{fb}^{-1})$
basic cuts	5.7	900	6100	11	0.00082	0.40	1.0	140	1200	2.4	0.00074	0.27
$Ov_3^t > 0.6$	4.6	510	840	6.5	0.0034	0.73	0.87	81	230	1.6	0.0028	0.49
b-tag	3.2	320	16	4.3	0.0094	1.0	0.54	45	3.2	0.94	0.011	0.77
$\not{E}_T$-cut	**2.2**	13	5.3	0.89	**0.11**	**2.9**	**0.41**	1.00	0.78	0.14	**0.21**	**3.0**
$N_{\text{fwd}} \geq 1$	**1.4**	2.6	0.74	0.27	**0.37**	**4.2**	**0.28**	0.20	0.11	0.041	**0.80**	**4.7**
$\Delta\phi_{\not{E}_T,j} > 1.0$	**1.1**	0.94	0.58	0.22	**0.63**	**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	$S/\sqrt{B}\,(35\,\text{fb}^{-1})$	signal	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}\,(100\,\text{fb}^{-1})$
basic cuts	1.7	750	1.3	0.0023	0.37	0.30	170	0.36	0.0018	0.23
$Ov_3^t > 0.6$	1.2	71	0.61	0.017	0.83	0.24	19	0.14	0.012	0.54
b-tag	0.85	1.6	0.42	0.41	3.5	0.15	0.36	0.086	0.33	2.2
$\Delta R_{ll} < 1.0$	0.85	1.6	0.41	0.42	3.5	0.15	0.36	0.086	0.33	2.2
$\lvert m_{ll} - m_Z \rvert < 10$ GeV	**0.78**	1.5	0.37	**0.43**	**3.4**	**0.13**	0.33	0.078	**0.32**	**2.1**
$N_{\text{fwd}} \geq 1$	**0.49**	0.23	0.11	**1.5**	**5.0**	**0.088**	0.051	0.019	**1.3**	**3.3**

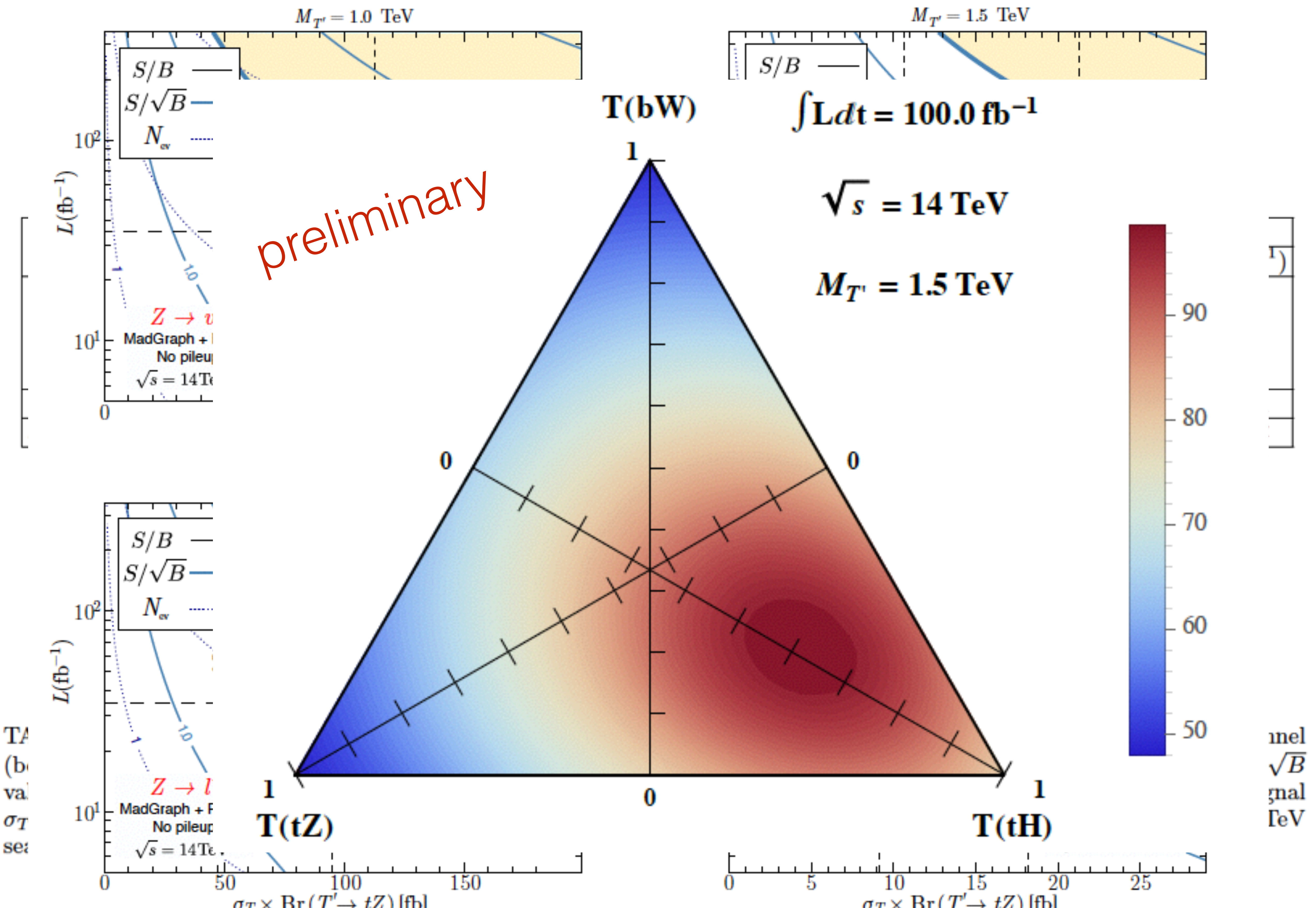
TABLE I: Example-cutflow for signal- and background events in the $Z_{\text{inv}}+t+j$ search (top table) and in the $Z_{ll}+t+j$ channel (bottom table) for $\sqrt{s} = 14\,\text{TeV}$. Cross sections after the respective cuts for signal and backgrounds are given in fb. The $S/\sqrt{B}$ values are given for a luminosity of $35\,\text{fb}^{-1}$ $(100\,\text{fb}^{-1})$ for the $M_{T'} = 1.0$ TeV ($M_{T'} = 1.5$ TeV) search. The example signal $\sigma_{T'} \equiv \sigma(pp \to T'/\bar{T}' + X) \times BR(T' \to tZ)$ displayed here are 142 fb for $M_T' = 1.0$ TeV searches and 24.1 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



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



Summary

a lot of development in boosted top taggers over last ~7 years

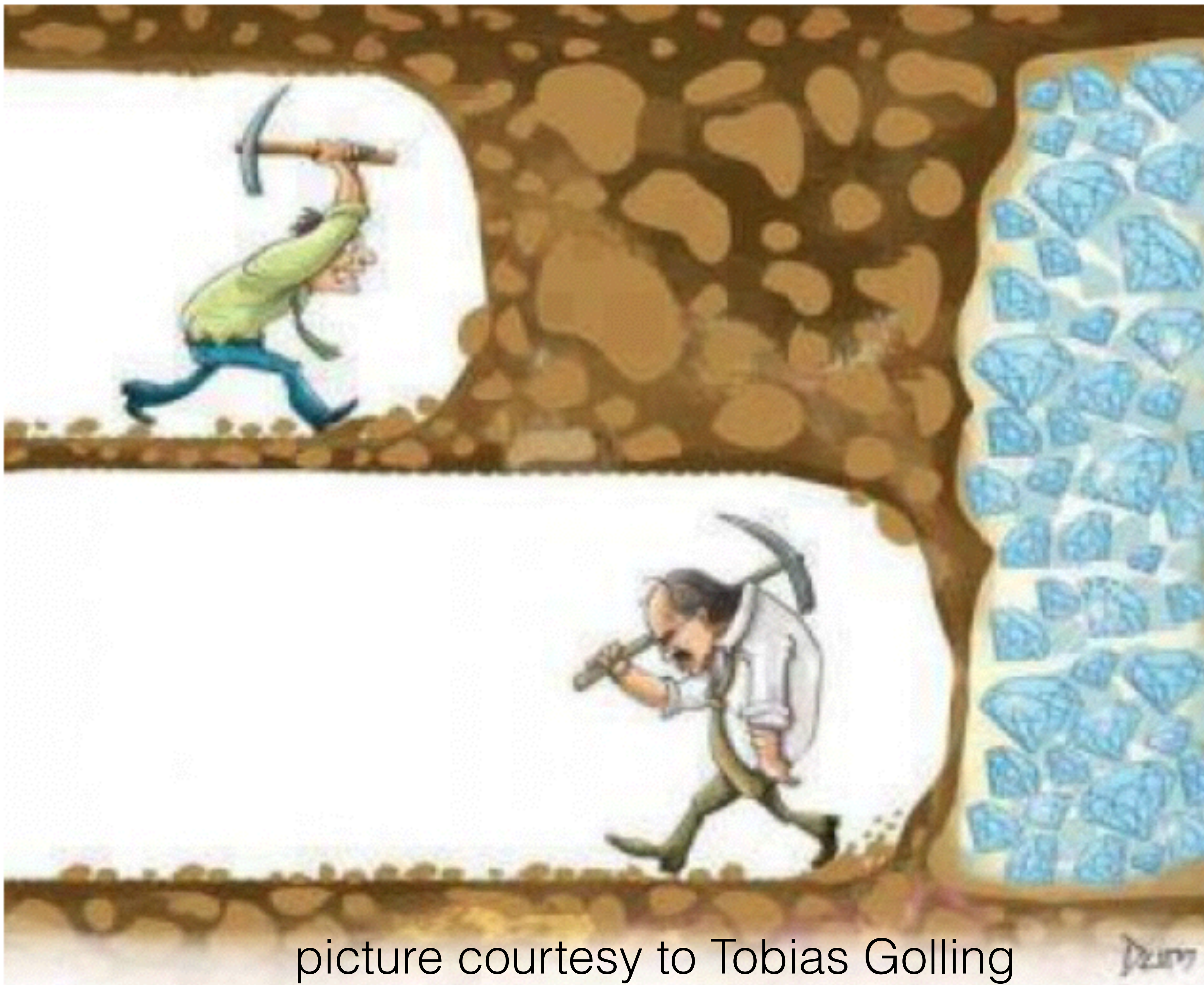
(for high p_T top)
top-tagging becomes like b-tagging?
i.e for MC study, not bothering to decaying top, but use efficiency @ fake rate?

Top partners @ Run II

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

Top partners @ Run II

We Might be this Close!



picture courtesy to Tobias Golling