Strategies to Identify Boosted Tops

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Based on:

1. B. Lillie, L. Randall, L. T. Wang hep-ph/0701166
2. J. Thaler and L. T. Wang, arXiv:0806.0023

Nov. 8th, BF08

- Outline

- Motivation

- Two types of variables:

  1. Substructure of hadronic top jet

  2. Kinematical features of lepton in top jet

- Conclusion

Motivation:

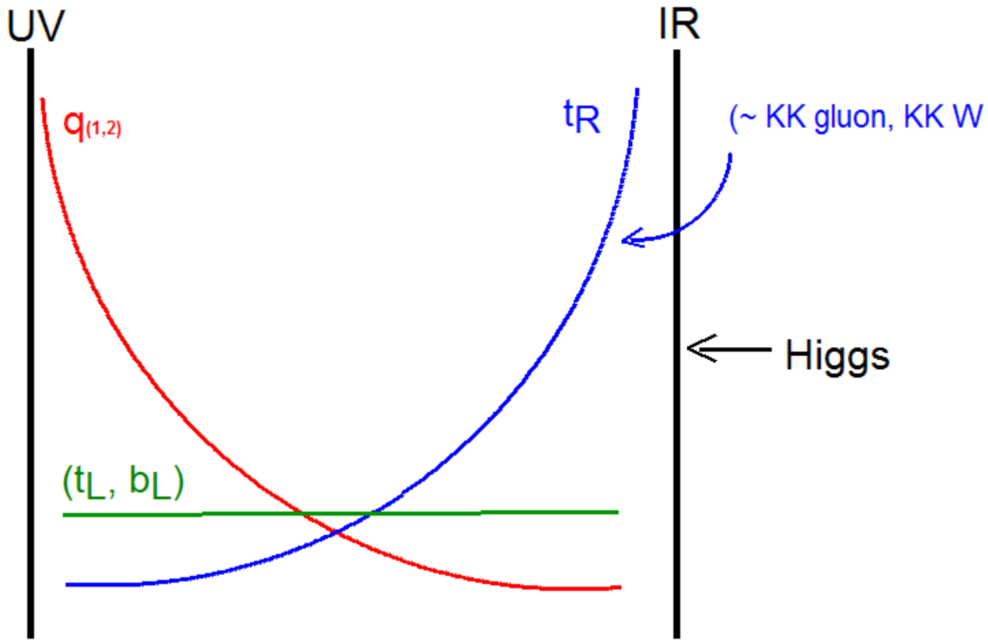
- Top is special:

Much heavier than other fermions in the SM.

Something unique (only “known” to top quark)!

$\longrightarrow$ NP signals involve top quarks

Typical example: NP resonances $\rightarrow$ $t\ \bar{t}^*$



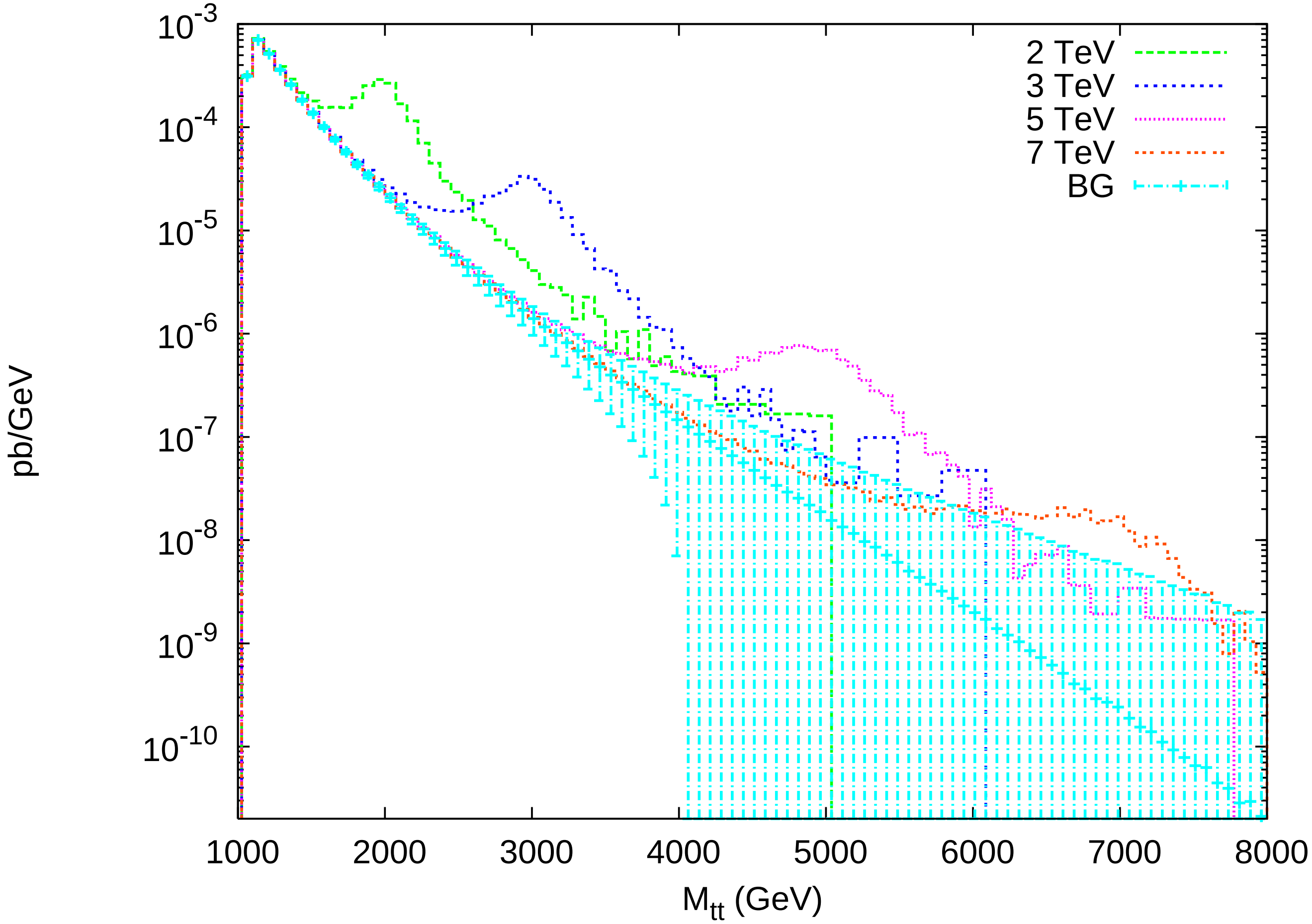
top is composite $\longrightarrow$ top is heavy

Other composite states (KK gluon, KK W) dominantly decay into $t\bar{t}$.

Bump searching.

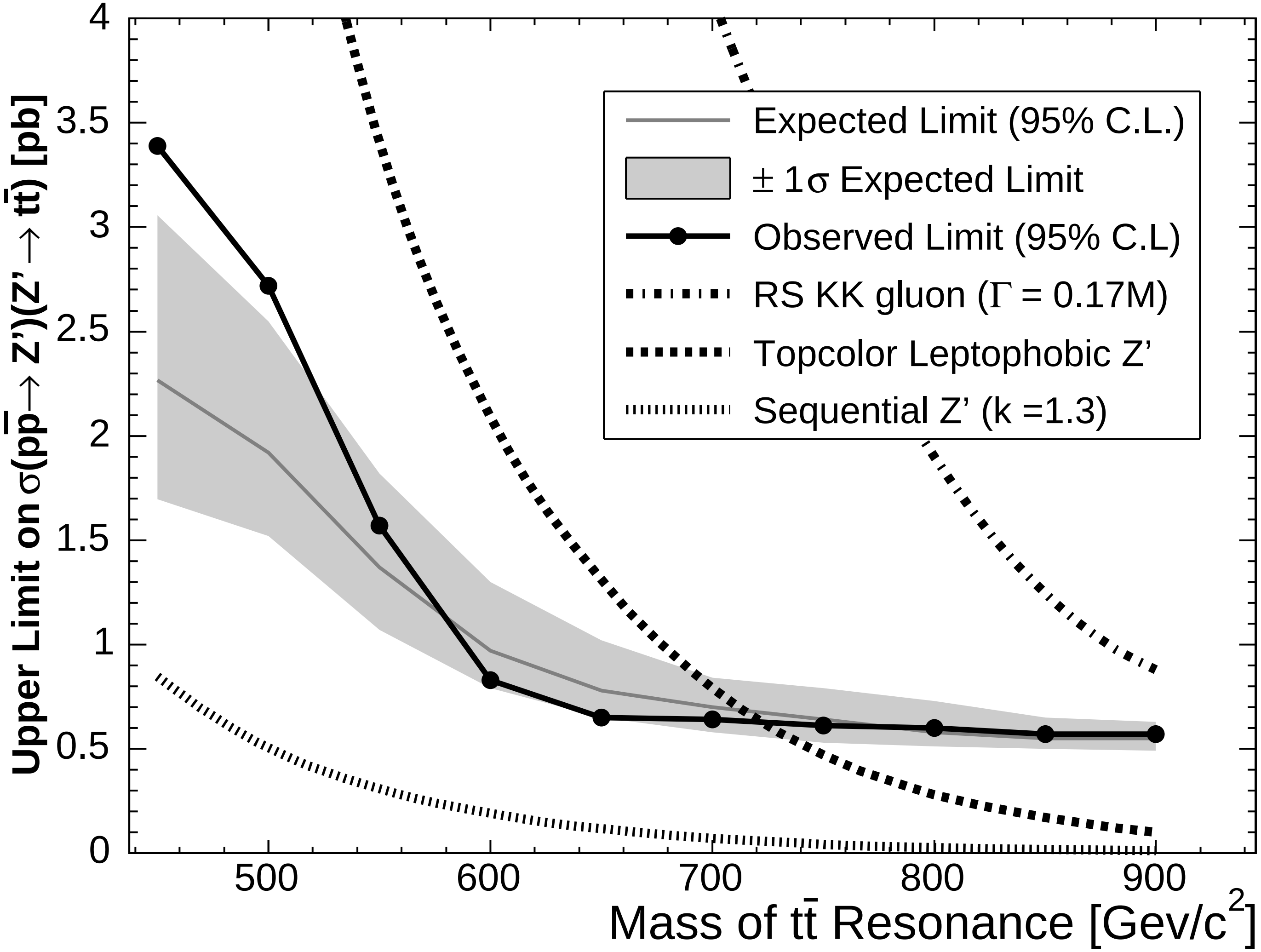
*K. Agashe, A. Delgado, M. May, R. Sundrum, hep-ph/0308036

Signal vs SM $t\bar{t}$*, $\sqrt{N}$ error bar



*R. Bonciani, S. Catani, M. L. Mangano and P. Nason, arXiv:hep-ph/9801375
Recent progresses: S. Moch and P. Uwer, arXiv:0804.1476
M. Cacciari, S. Frixione, M. M. Mangano, P. Nason and G. Ridolfi, arXiv:0804.2800.

- New $t\bar{t}$ resonance: A limit from Tevatron.*



Aaltonen et al. [CDF Collaboration], arXiv:0710.5335 [hep-ex].

Challenges at the LHC

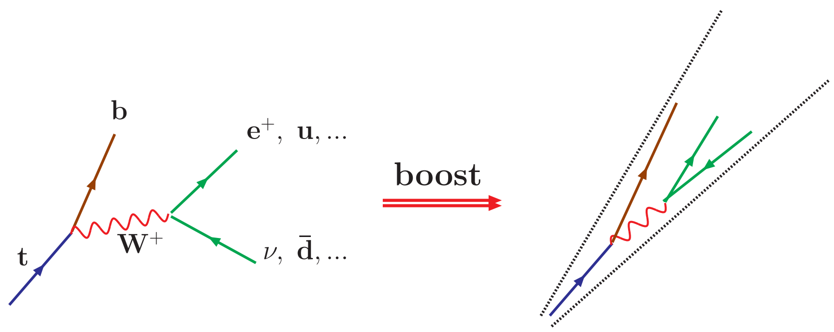
1. SM $t\bar{t}$ has long tail in $m_{t\bar{t}}$.

2. Wider resonances, $\Gamma \sim 0.2M$. PDF distorts the shape of resonances.

3. EWPT typically constrains the composites to be quite heavy $\geq$ 3TeV*.

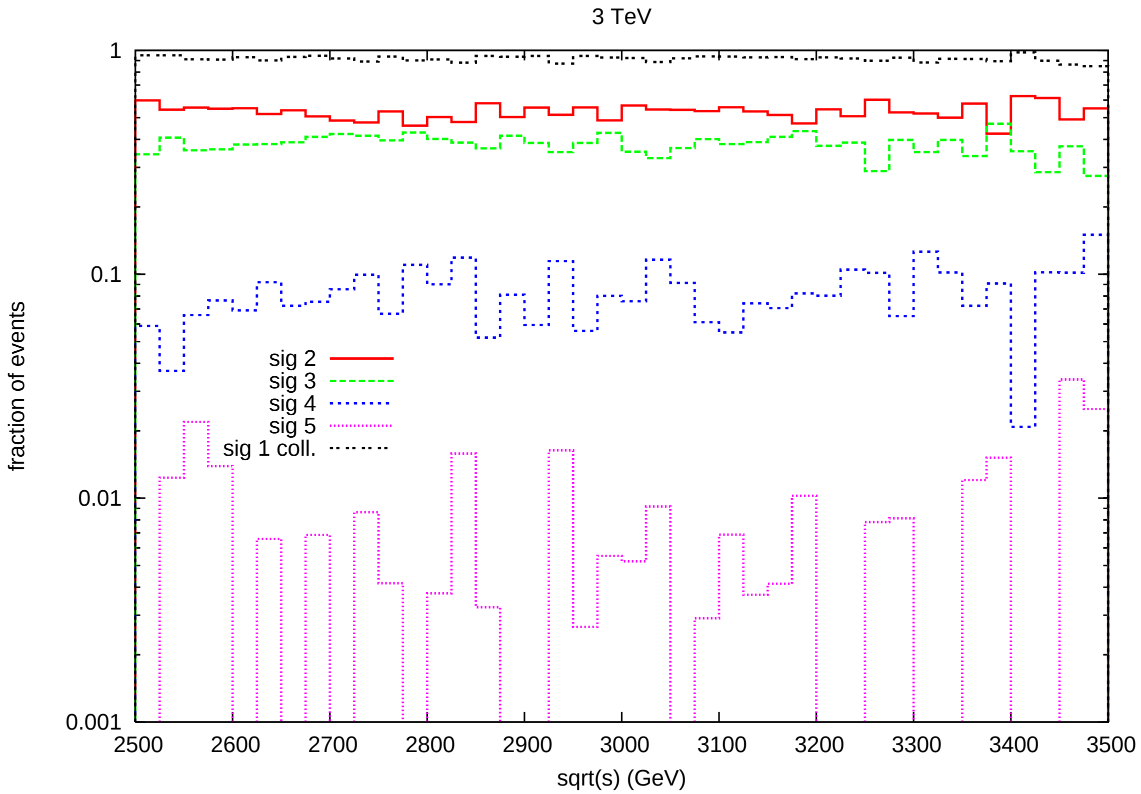
$\longrightarrow$ Very energetic tops

Reconstruction of tops based on isolated objects is likely to fail.



*K. Agashe, A. Delgado, M. May, R. Sundrum, hep-ph/0308036

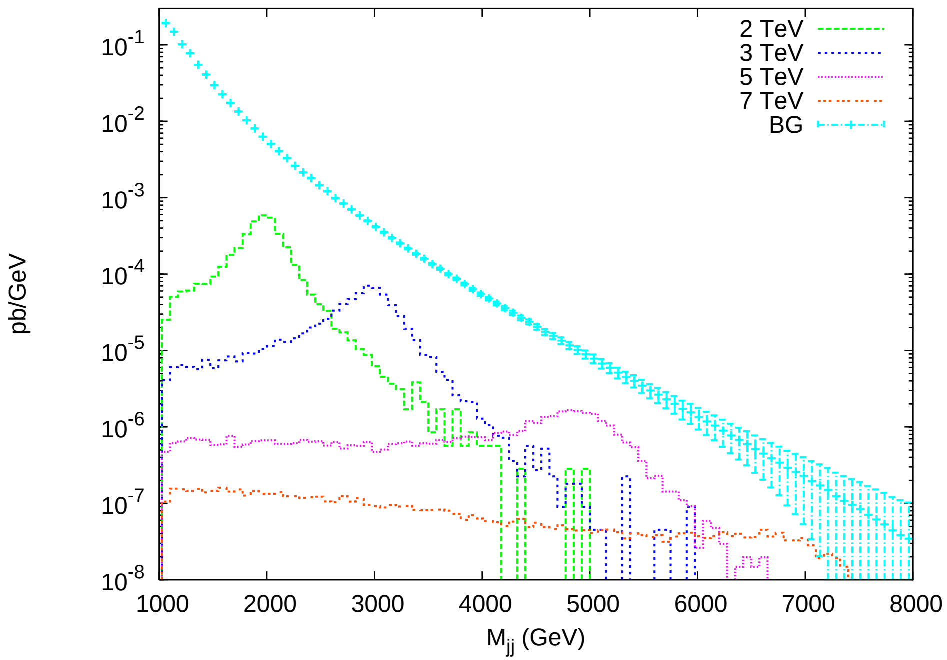
Collimation: $\Delta R = 0.4$, $m_{\rm NP} \sim 3$ TeV*



- For $m_{t\bar{t}} > 3$ TeV, $>$ 90% events with at least one top fully collimated.
- Large fraction of events "2-object"-like. QCD $b\bar{b}$, jj background.
- A few % with lepton isolation

*B. Lillie, L. Randall, LW (hep-ph/0701166)

Example: SM di-jet vs KK gluon.



New techniques of tagging highly boosted tops need to be developed.

Roughly, $\mathcal{O}(10^2)$ enhancement on S/B needed.

Studies with fewer isolated objects and/or partial reconstruction.*† ‡.

*V. Barger, T. Han and D. G. E. Walker, hep-ph/0612016

†K. Agashe, A. Belyaev, T. Krupovnickas, G. Perez and J. Virzi, hep-ph/0612015

‡U. Buar and L. Orr, arXiv:0707.2066, arXiv:0803.1160

Identifying top jets J. Thaler and LW, arXiv:0806.0023

Basic intuition:

Top decay: $t \to bW(\to qq',\ \ell\nu)$ 3 hard initial objects.

QCD: radiation

Energetic tops $\to$ massive jets, with some substructures
How well this can be distinguished from (massive) QCD jets?

Energetic muons in top jet. Compare them with muons in b-jet. more detailed study necessary.

We will study variables which explore both of these features.

Studies of jet substructures

- WW scattering: J. M. Butterworth, B. E. Cox and J. R. Forshaw, hep-ph/0201098.
- Sparticle reconstruction: J. M. Butterworth, J. R. Ellis and A. R. Raklev, hep-ph/0702150.
- Higgs search: J. M. Butterworth, A. R. Davison, M. Rubin and G. P. Salam, arXiv:0802.2470 [hep-ph].

Boosted tops:

- G. Brooijmans *et al.*, arXiv:0802.3715 [hep-ph].
- J. Thaler and LW, arXiv:0806.0023. (This talk.)
- D. E. Kaplan, K. Rehermann, M. D. Schwartz and B. Tweedie, arXiv:0806.0848 [hep-ph].
- L. G. Almeida, S. J. Lee, G. Perez, G. Sterman, I. Sung and J. Virzi, arXiv:0807.0234 [hep-ph].
- L. G. Almeida, S. J. Lee, G. Perez, I. Sung and J. Virzi, arXiv:0810.0934 [hep-ph].
- Talk by L. G. Almeida earlier in this forum.

The rest of the talk:

Study one top jet produced from the decay of some narrow resonance, $X \to t\bar{t}$, for different m_X. We will focus on top tagging efficiency and rejection against SM background.

Focusing only on the shape of the. All kin. distributions are normalized to 1.

Smaller cone?

How about shrinking the size of the cone (or other separation variables such as d_{cut} in k_T algorithm?) to see more jets?

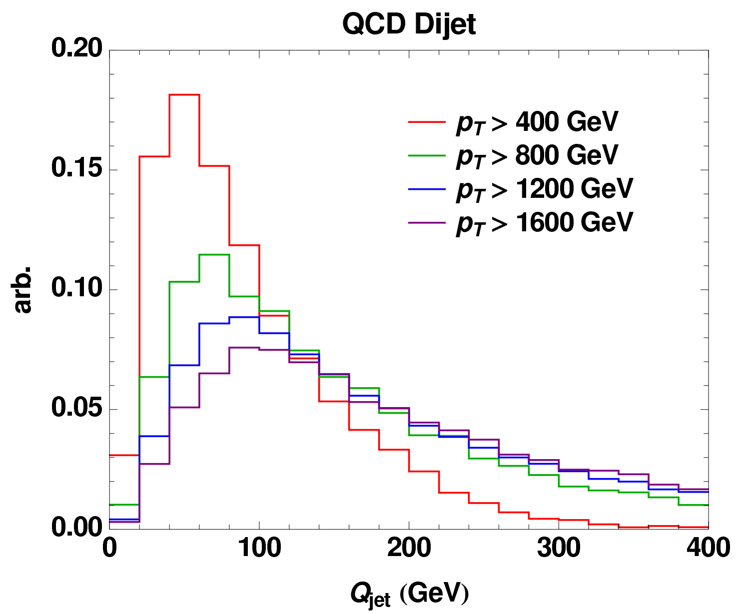
In principle, it is not different from just studying substructure variables.

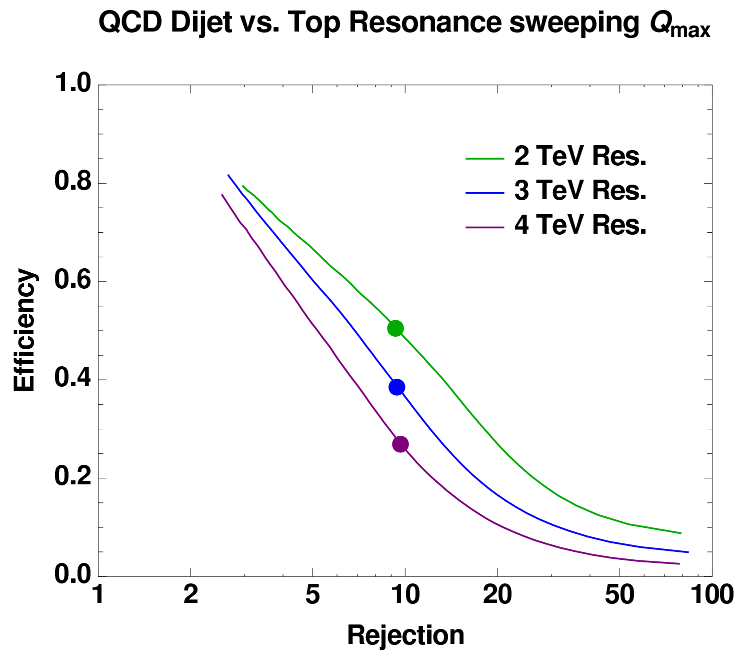
Same issue of QCD background:

Several smaller and closer jets vs several sub-jets in a fat jet.

• Top jets vs QCD jets

Jet mass. $m_{\text{top jet}} \sim m_t$. $< m_{j\text{QCD}} > \sim 0.07 - 0.1 \times p_T^{j}$ * †





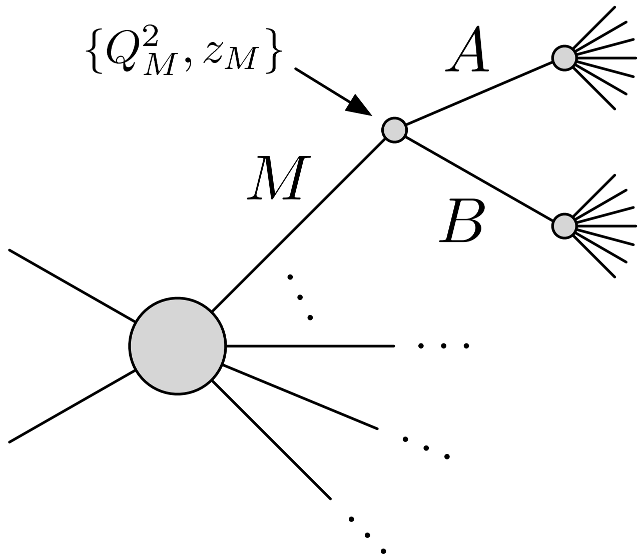
ref points: 160 GeV $< Q_{\text{jet}} <$ 200 GeV

Useful. Additional variable?

*Recent study on jet mass: L. G. Almeida, S. J. Lee, G. Perez, I. Sung and J. Virzi, arXiv:0810.0934 [hep-ph]

†Parton shower: PYTHIA 6 (8) T. Sjostrand, S. Mrenna and P. Skands, hep-ph/0603175, arXiv:0710.3820, →FASTJET, M. Cacciari and G. P. Salam, hep-ph/0512210.

- QCD jets: robust feature at leading log



Parton $\rightarrow$ radiation/branching $\rightarrow$ shower

Consider branching $M \rightarrow A + B$

A shower history is characterized by

t: evolution variable, such as virtuality Q_M, p_T...

virtuality at first branching $\rightarrow$ jet mass.

z: energy fraction of branching $\min(E_A, E_B)/E_M$

QCD parton shower

Branching probability for given t and z

$$dP = dt\frac{\alpha_s(t)}{t}\, dz f(z)\ \Delta(t_0, t)$$

$\Delta(t_0, t)$ Sudakov form factor. (resuming the leading log, collinear + IR)

$f(z)$ Altarelli-Parisi splitting function. Singularity at $z \to 0$ for gluon radiation.

Top jets:

First branching: top $\to bW$. z finite.

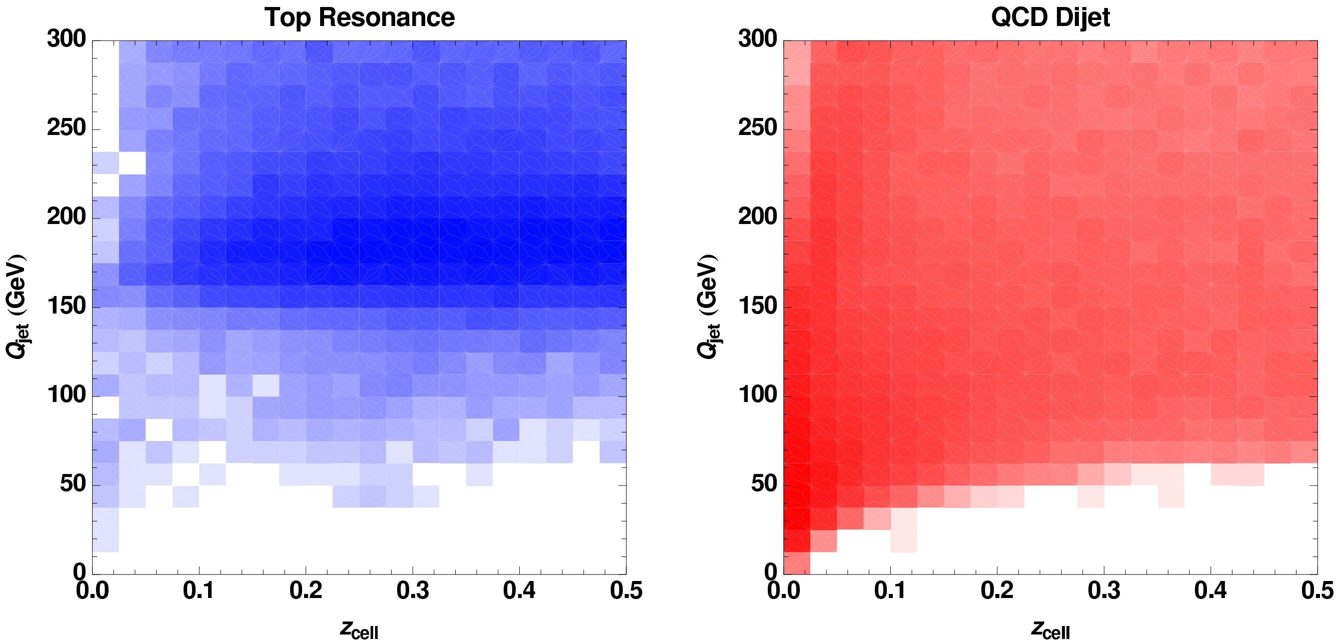
z variable at the first branching should be a useful discriminant between QCD and top jets.

• Top jets vs QCD jets*

"Following" the branching History

Recursive algorithm, e.g., $k_T{}^*$. k_T close to an evolution variable.

k_T clustering history $\sim$ inverse branching history.



Rough approximation of finite calorimetry: $\delta\eta \times \delta\phi = 0.1 \times 0.1$.

*J. Thaler, LW, arxiv:0806.0023

*S. Catani, Y. L. Dokshitzer, M. H. Seymour and B. R. Webber, Nucl. Phys. B **406**, 187 (1993).

z-type variables.

Many possible choices to preserve the structure of AP:

$z \to \min(\mathrm{E_A}, \mathrm{E_B})/\mathrm{E_M}$ in collinear on-shell limit.

For example

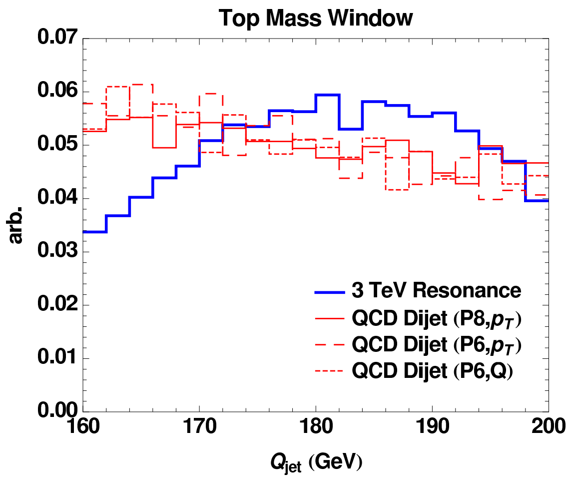
1. $z_{\text{cell}} = \frac{\min(E_A, E_B)}{E_A + E_B}, \qquad E_X \equiv \sum_{i \in X} E_i,$

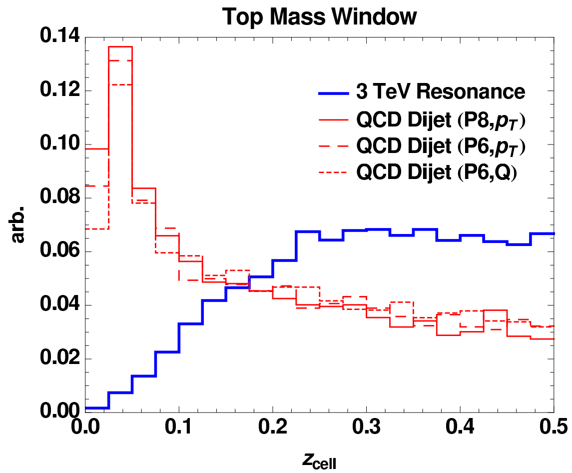
2. $z_{\text{cut}} \equiv \frac{d_{\text{cut}}}{d_{\text{cut}} + Q_M^2} \to \frac{\min(E_A, E_B)}{E_A + E_B}$ where

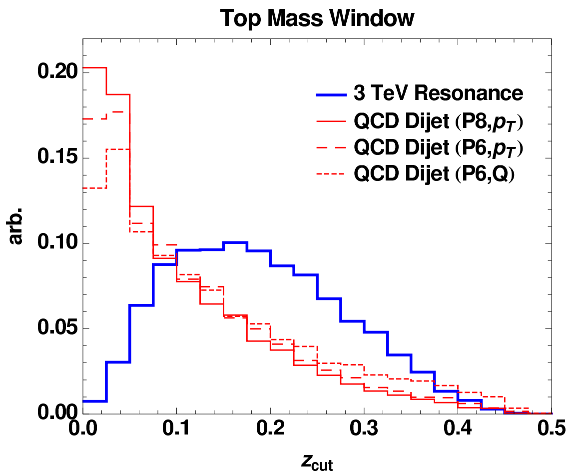
$$d_{\text{cut}} = \min(p_{TA}^2, p_{TB}^2)\Delta R_{AB}^2, \qquad \Delta R_{AB}^2 \equiv (\phi_A - \phi_B)^2 + (\eta_A - \eta_B)^2$$

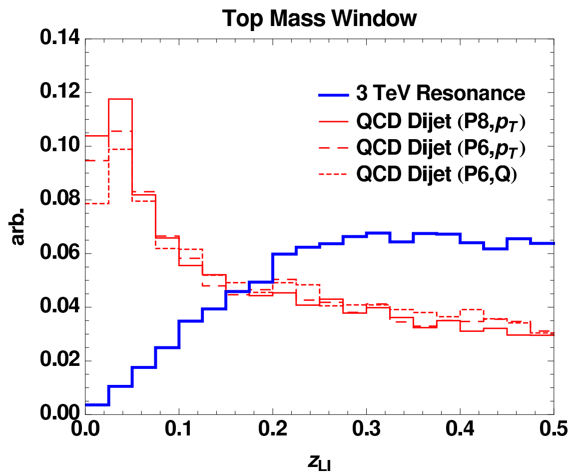
3. $z_{\text{LI}} = \frac{\min(p_{\text{ref}} \cdot p_A, p_{\text{ref}} \cdot p_B)}{p_{\text{ref}} \cdot (p_A + p_B)}$, with any p_{ref}

Studies of different variables.

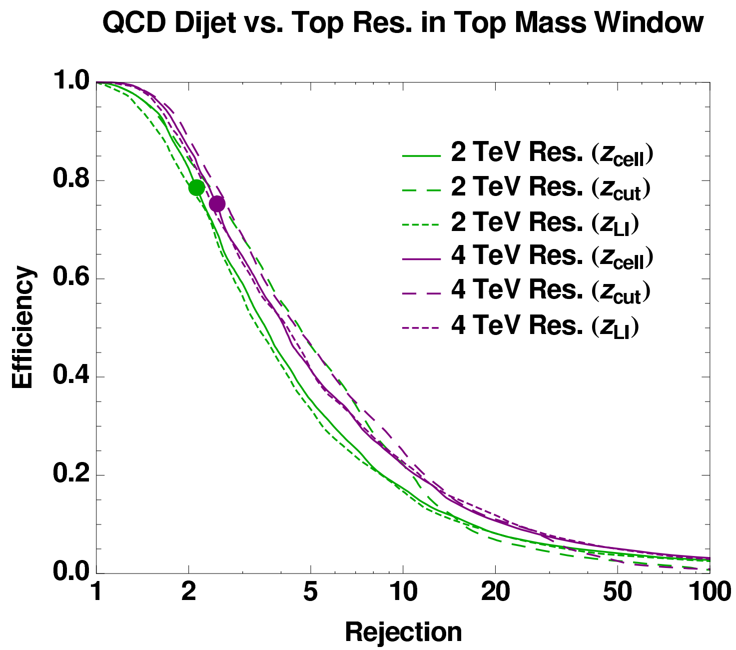




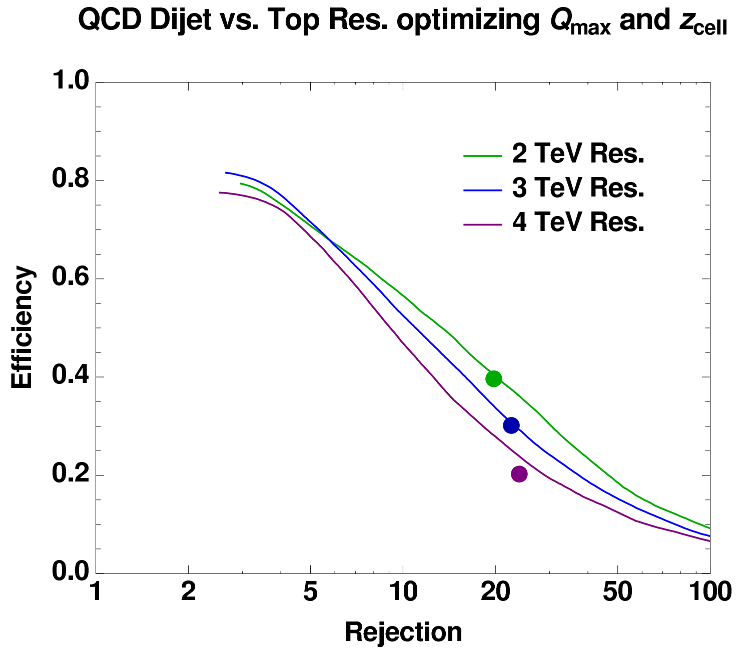




Efficiency vs rejection (against QCD jets)



optimizing with z



optimizing with jet mass and z

Sideband potential

Parton shower modeling is not perfect.

We will have to train variables on real QCD jets at the LHC.

Study it in a sideband where top does not change the shape of the background, and the background has similar shape as in the signal region.

$\longrightarrow$ Looking for a variable which is maximally "orthogonal" to jet mass.

z variable motivated since it is "factorized" at leading order

$$dP \propto \frac{dt}{t} \times dz f(z)$$

Other possibilities: Ysplitter $p_T^2 dy$ [*] [†‡], ...

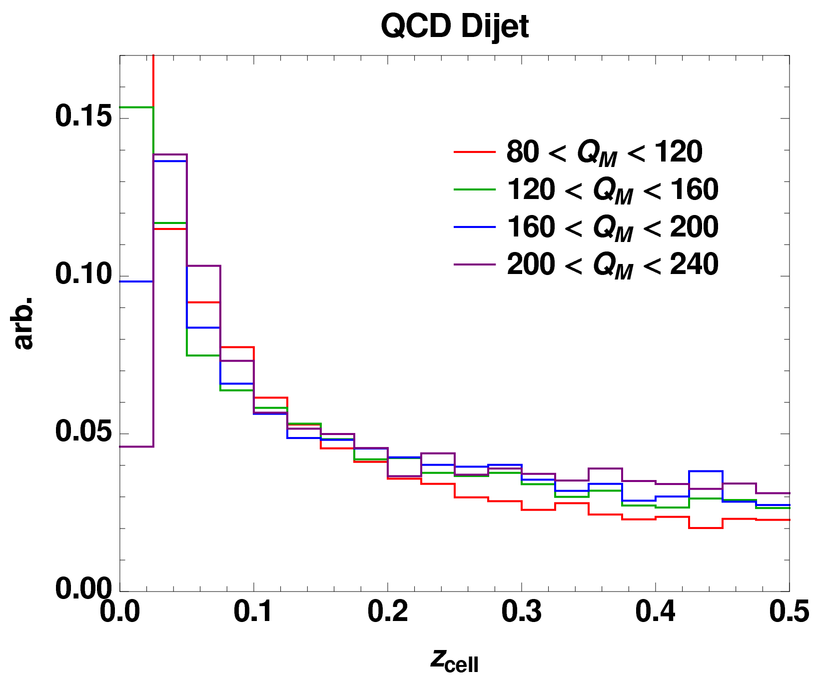
[*] WW scattering. J. M. Butterworth, B. E. Cox and J. R. Forshaw, hep-ph/0201098

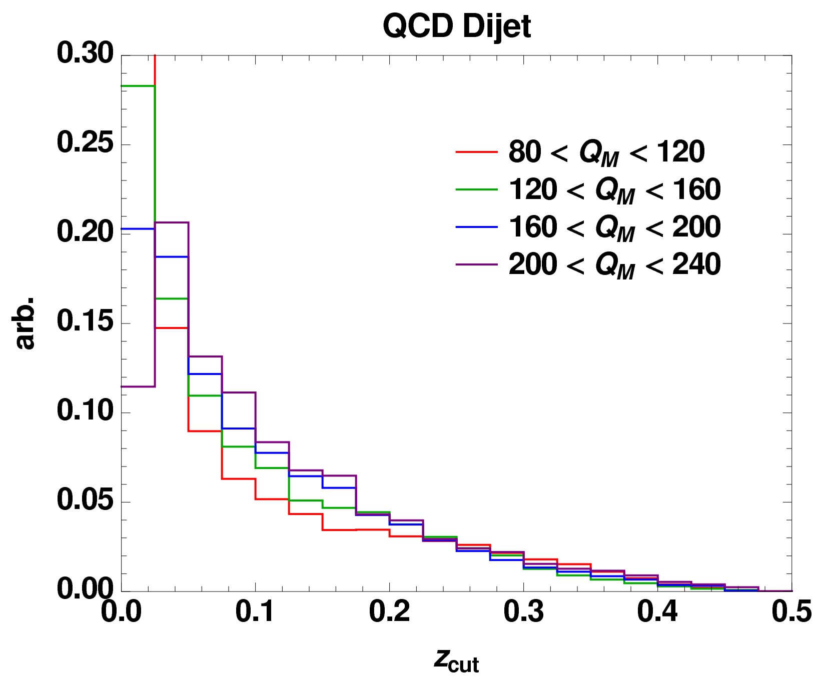
[†] J. M. Butterworth, A. R. Davison, M. Rubin and G. P. Salam, arXiv:0802.2470 [hep-ph].

[‡] G. Brooijmans *et al.*, arXiv:0802.3715 [hep-ph].

Sideband potential:

Parton shower approximation (PYTHIA 6 (Q-shower))





Better understanding will have to come from higher order knowledge and measurement at the LHC.

Multiple objects substructure?[*] [†] .

Top decay looks more like $1 \rightarrow 3$.

Not very well understood in the parton shower approximation.

Still useful if properly trained.

[*]D. E. Kaplan, K. Rehermann, M. D. Schwartz and B. Tweedie, arXiv:0806.0848 [hep-ph].

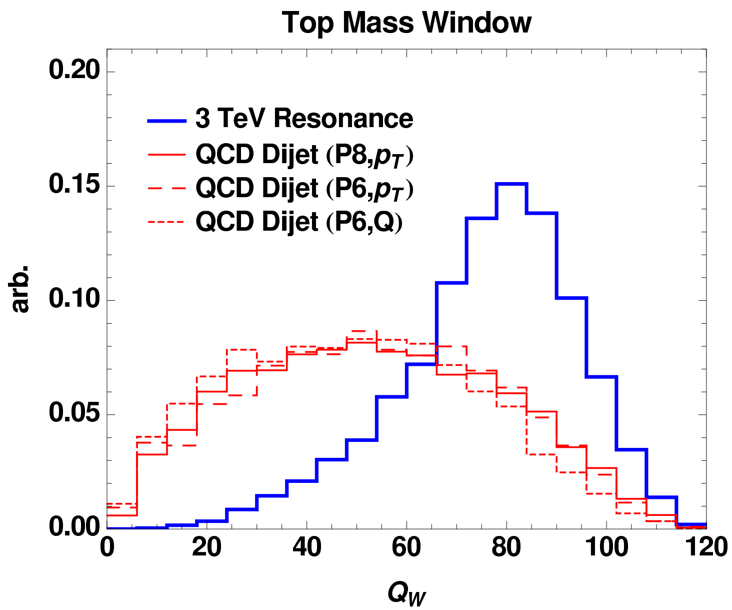
[†]L. G. Almeida, S. J. Lee, G. Perez, G. Sterman, I. Sung and J. Virzi, arXiv:0807.0234 [hep-ph].

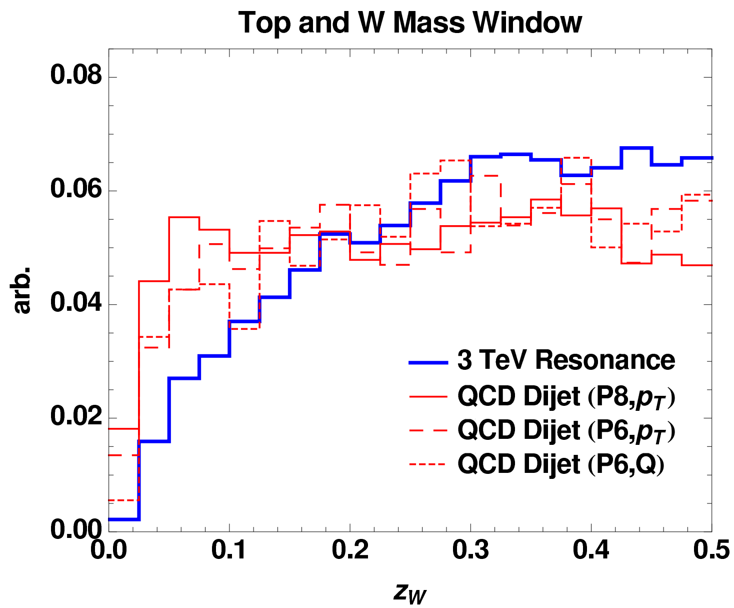
W-reconstruction

Take 3 clusters from $M \to ABC$.

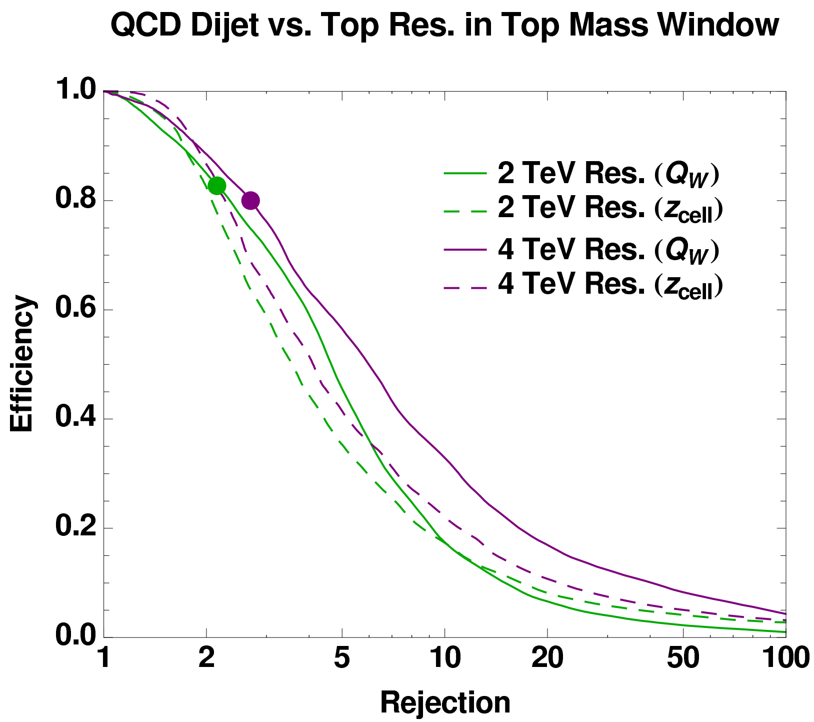
Take the pair with smallest invariant mass Q_W.

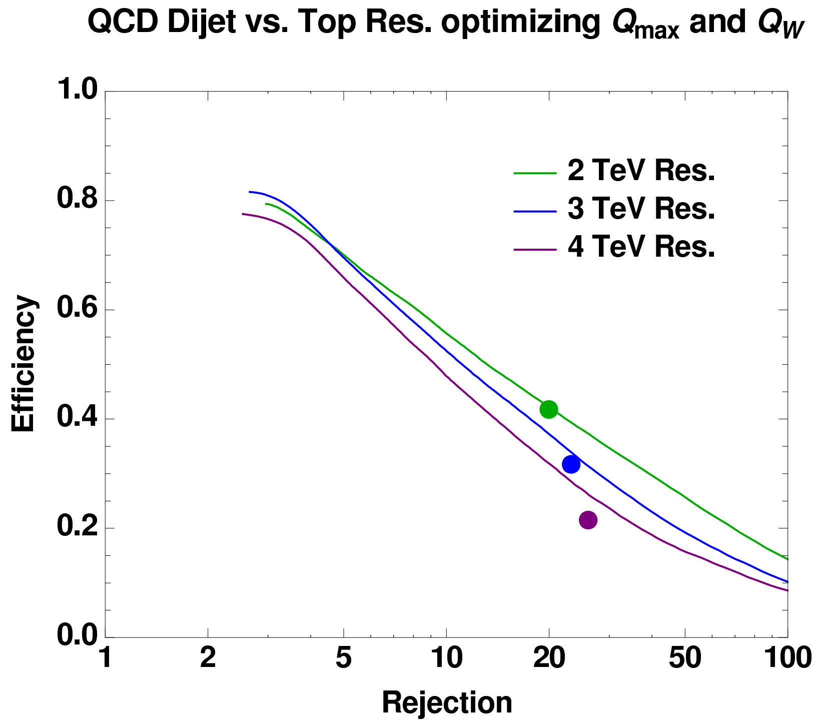
Can also define z_W within candidate W decay pair of objects.





Combining 2-body and 3-body





Q_W performs as well as z_{cell}.

Q_W and z_{cell} have correlated rejection rates.

No significant gain by using both of them.

Another multi-body variable

Consider 3-body decay M $\to$ ABC.
A, B and C defines a plane in the rest frame of M.
This planar feature is invariant under boost perpendicular to this plane.

Define: (boost inv. along jet axis)

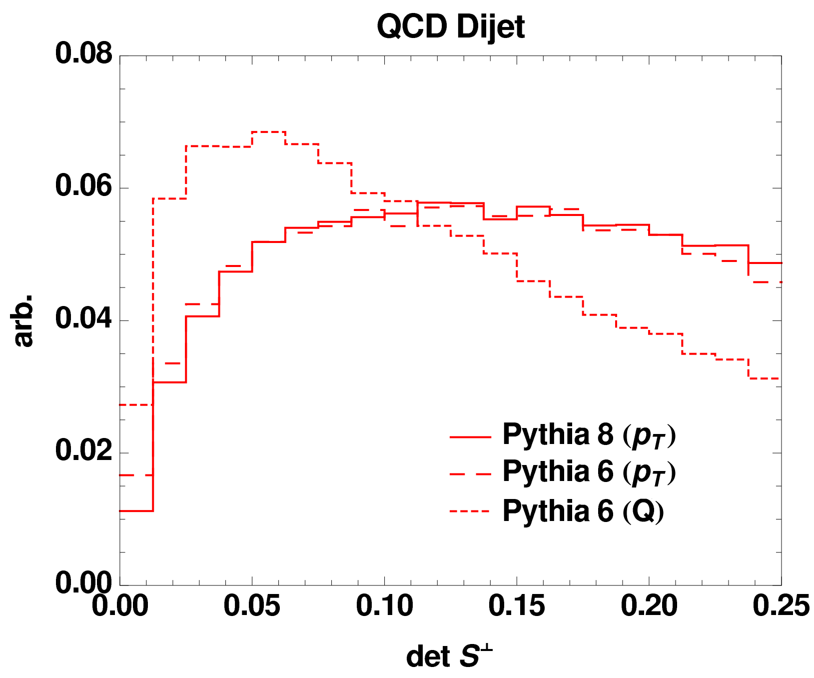
$$S^{\perp ij} = \frac{\sum_{\alpha \in \text{jet}} \frac{\vec{p}_\alpha^{\perp i} \vec{p}_\alpha^{\perp j}}{|\vec{p}_\alpha^{\perp}|}}{\sum_{\alpha \in \text{jet}} |\vec{p}_\alpha^{\perp}|}.$$

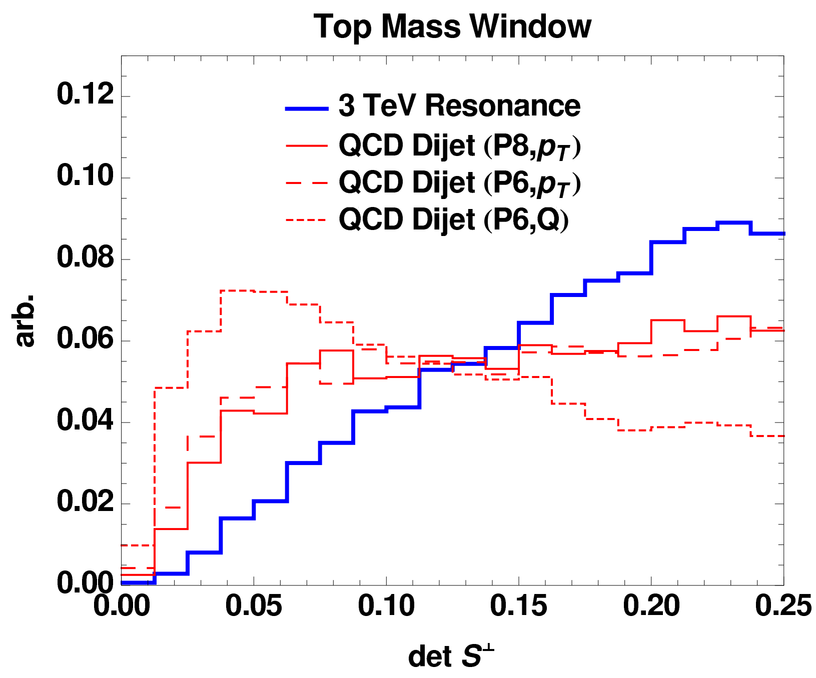
$\det S^{\perp}$ (since Tr$S^{\perp}$=1.)

$\det S^{\perp}$ vanishes in 2-body limit. True multi-body variable.

A similar variable was considered recently in
L. G. Almeida, S. J. Lee, G. Perez, G. Sterman, I. Sung and J. Virzi, arXiv:0807.0234 [hep-ph]; L. G. Almeida, S. J. Lee, G. Perez, I. Sung and J. Virzi, arXiv:0810.0934 [hep-ph]

Study of $\det S^{\perp}$





Again, useful, can improve results by another factor of several.

Larger theoretical uncertainty, should be trained by real QCD jets.

“Stuck” lepton in leptonic top decays, e.g., muon

Basic intuition: $t \to b\ell\nu$, ℓ hard, separated $p_\perp \sim m_t$

Backgrounds for lepton in jets

1. Heavy flavors, $b, c \to \ell + ...$

   b, c radiate most of its energy before decay, $E_{\ell \to 0}$

2. $W+$jets where jet accidentally overlap with lepton

   Less often. kinematical difference.

3. $t \to b(\to \ell ...) + jj$, similar to the lepton in heavy flavor decay.

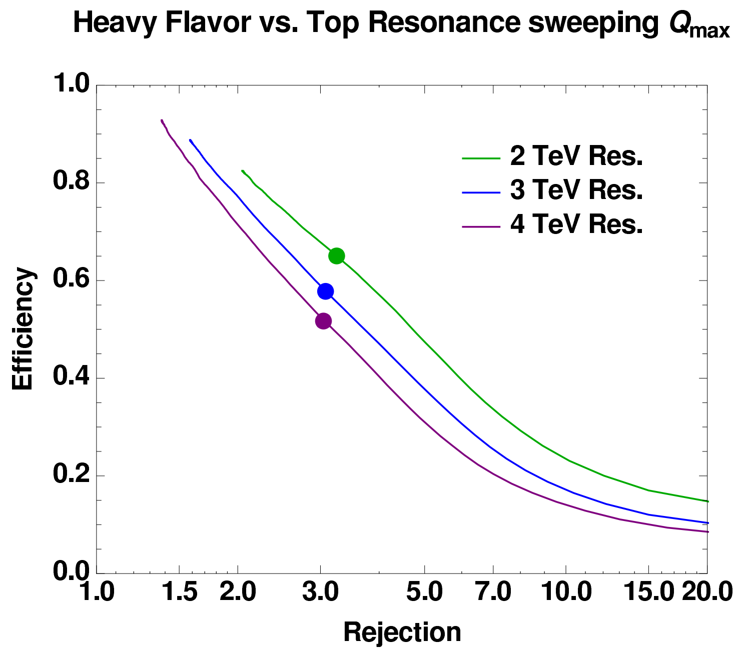
   Not very useful in picking up these tops.

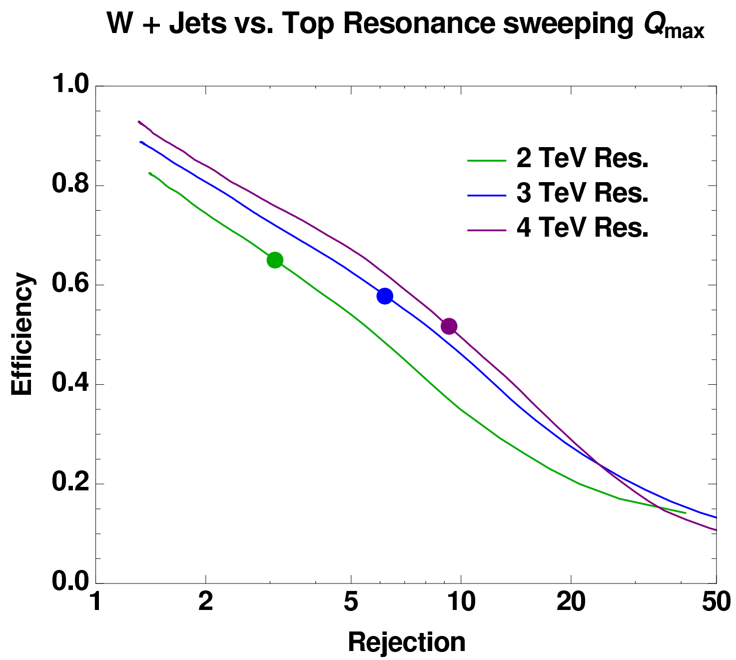
Leptonic variables

Visible mass

$$Q^2_{\text{visible}} = (p_\ell + p_b)^2; \quad \frac{m_t^2 m_b^2}{m_t^2 - m_W^2} + \mathcal{O}(m_b^4) < Q^2_{\text{visible}} < m_t^2 - m_W^2 + \mathcal{O}(m_b^2)$$

Useful. Extended distribution, good to have other separation variables.

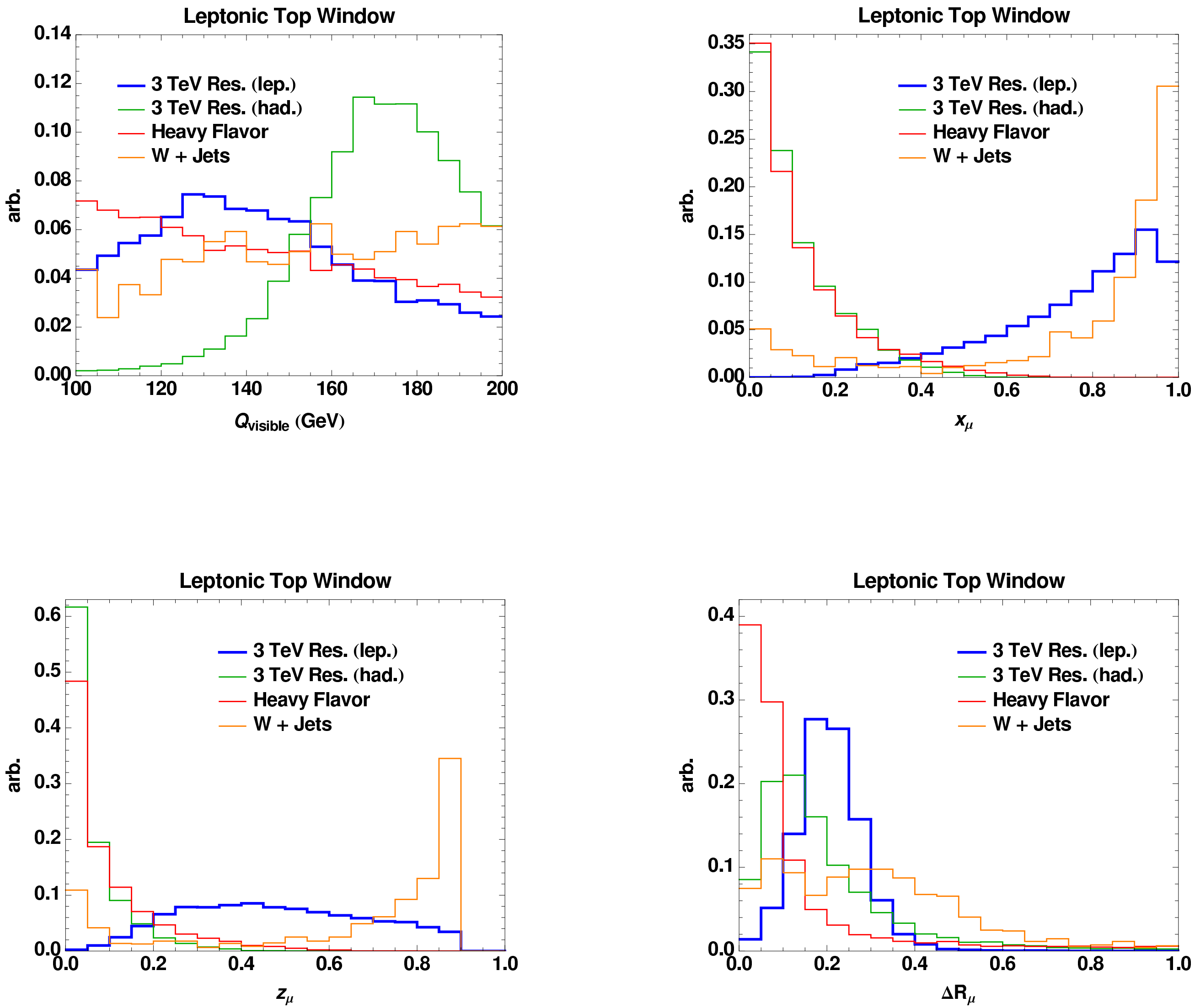




“Separation variables”

p_b: rest of the hadronic activity.

$$z_\mu = \frac{E_\mu}{E_\mu + E_b}, \qquad \Delta R = \Delta R(p_\mu, p_b), \qquad x_\mu = \frac{2 p_\mu \cdot p_b}{(p_\mu + p_b)^2}.$$

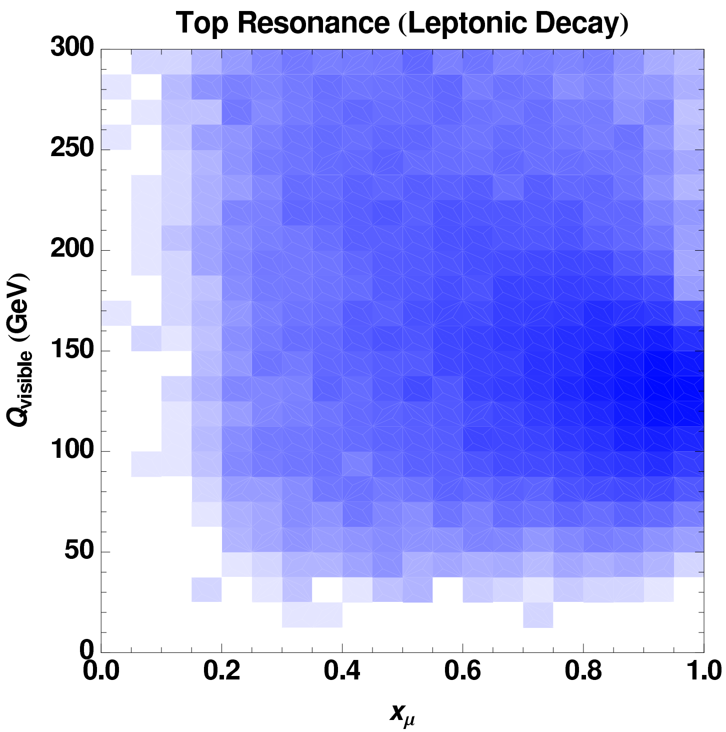


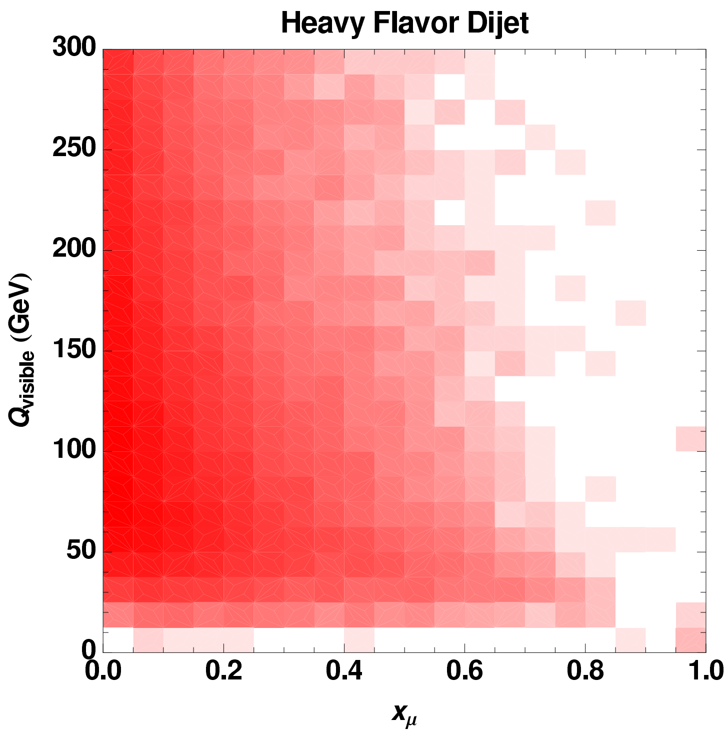
Understanding x_μ

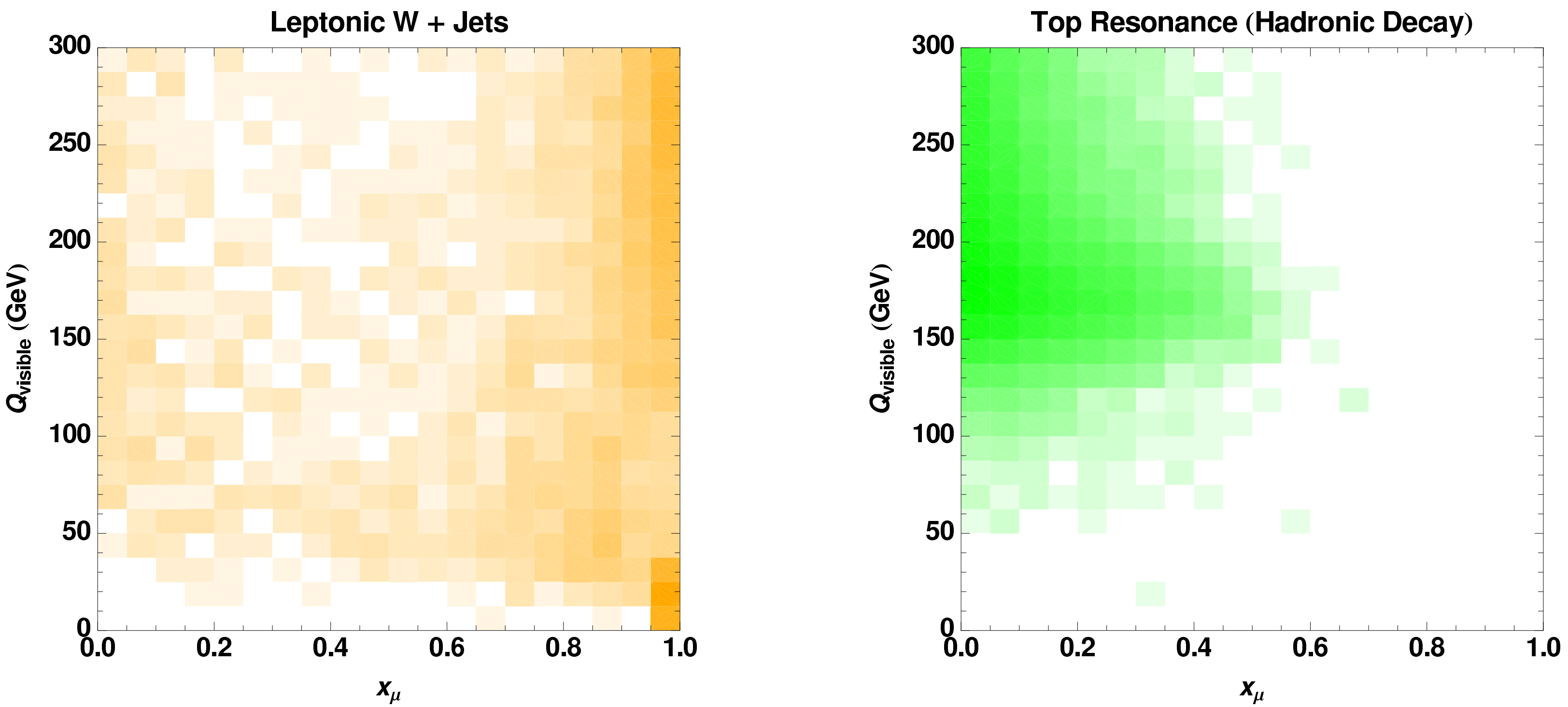
$$1 - x_\mu = \frac{m_b^2}{Q^2_{\text{visible}}}. \quad m_b^2: \text{ mass of the rest of had.}$$

Top decay: m_b^2 a fraction of m_t, $x_\mu \to 1$.

b, c decay: m_b^2 all hadronic energy ($\sim$ jet mass). $x_\mu \to 0$.



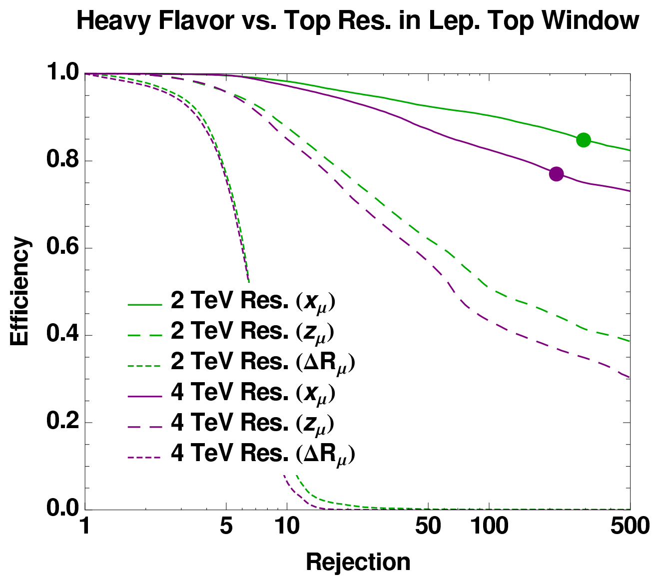


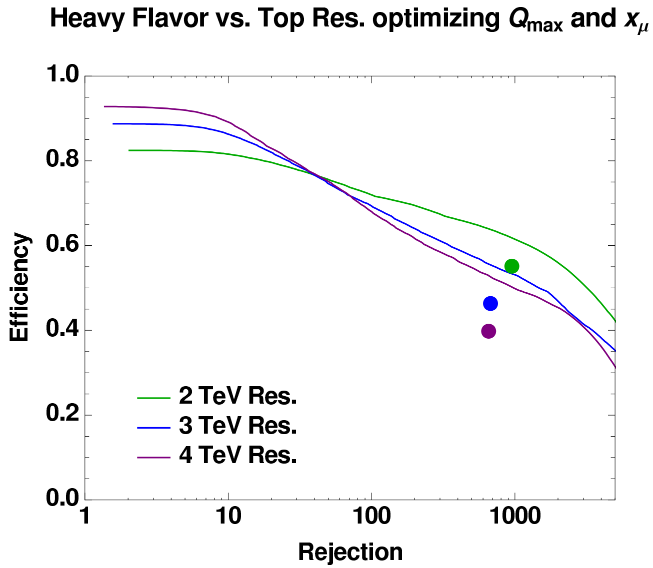


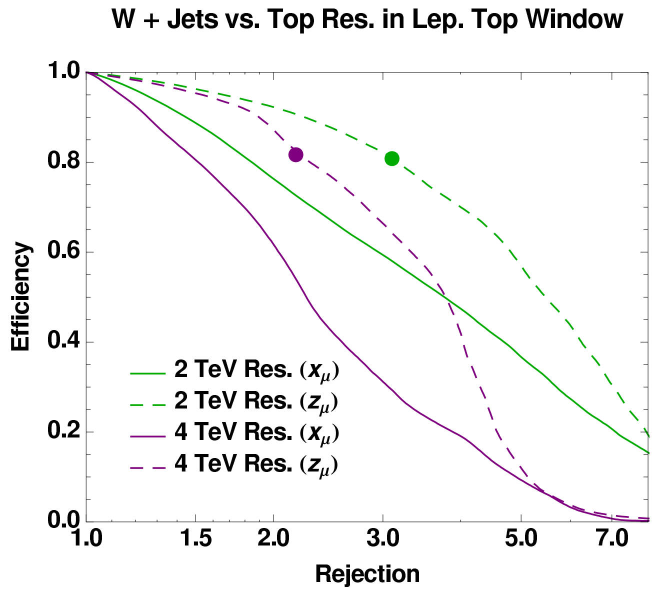
W+jets: x_μ even larger. Accidental. No correlation. Even more separated.

$t \to b(\to \ell ...) + jj...$: lepton only carries very small amount of energy of b, $x_\mu \to 0$, Q_{vis} reconstruct top.

Eff. vs Rej.


Heavy Flavor vs. Top Res. in Lep. Top Window
Efficiency
Rejection
2 TeV Res. (x_μ)
2 TeV Res. (z_μ)
2 TeV Res. (ΔR_μ)
4 TeV Res. (x_μ)
4 TeV Res. (z_μ)
4 TeV Res. (ΔR_μ)


Heavy Flavor vs. Top Res. optimizing Q_{max} and x_μ
Efficiency
Rejection
2 TeV Res.
3 TeV Res.
4 TeV Res.


W + Jets vs. Top Res. in Lep. Top Window
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2 TeV Res. (z_μ)
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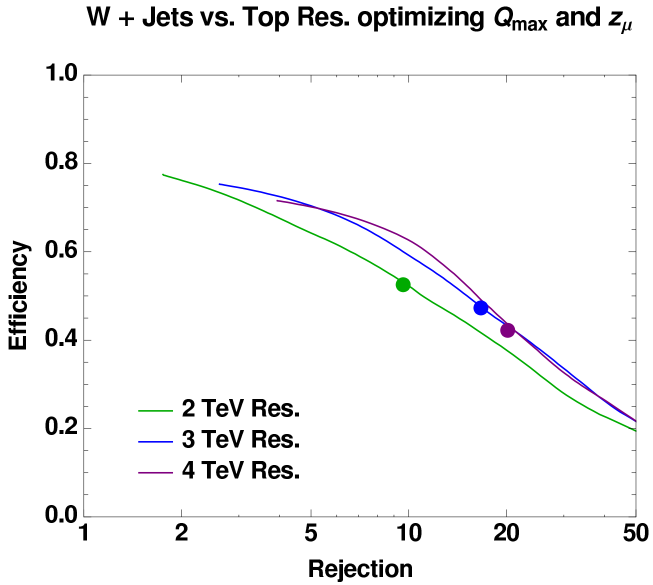

W + Jets vs. Top Res. optimizing Q_{max} and z_μ
Efficiency
Rejection
2 TeV Res.
3 TeV Res.
4 TeV Res.

Summary of top tagging

Hadronic top $t \to bjj$

$\hat{s} \sim 3$ TeV. Eff: $\sim 40\%$, Rej: ~ 20

SM $t\bar{t}$, RS KK gluon vs SM di-jet, need about several $\times 10^2$

Leptonic top $t \to b\mu\nu$

$\hat{s} \sim 3$ TeV. Eff: $\sim 40\%$, Rej: close to 10^3

Better even after 3% BR. Less reconstruction power.

More detailed study necessary.

- Conclusion:

Top sector is one of the most probable places for new physics to show up.

Important to study top as part of the final states from NP, both for discovery and interpretation.

Top with other stuff: $t\bar{t}\,\not{E}$, $t\bar{t}+$ (leptons, jets...)

Energetic tops, $m_{t\bar{t}} \sim$ several TeV

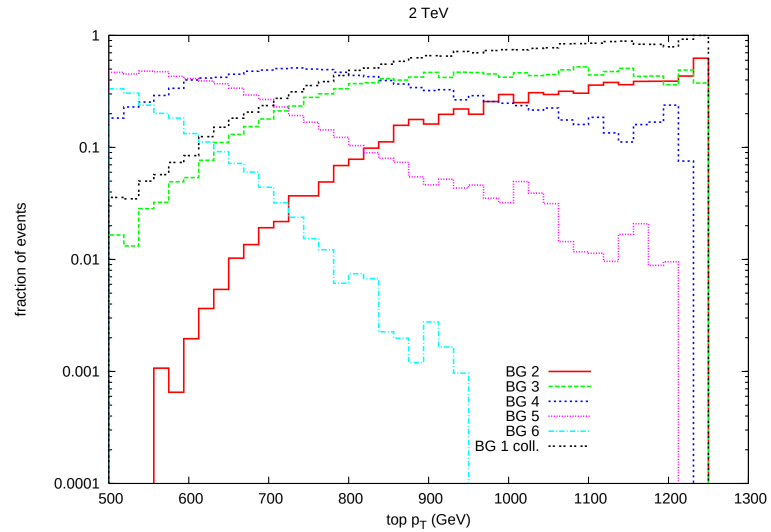
$pp \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t},\ t\bar{t}b\bar{b},\ t\bar{t}bt.$

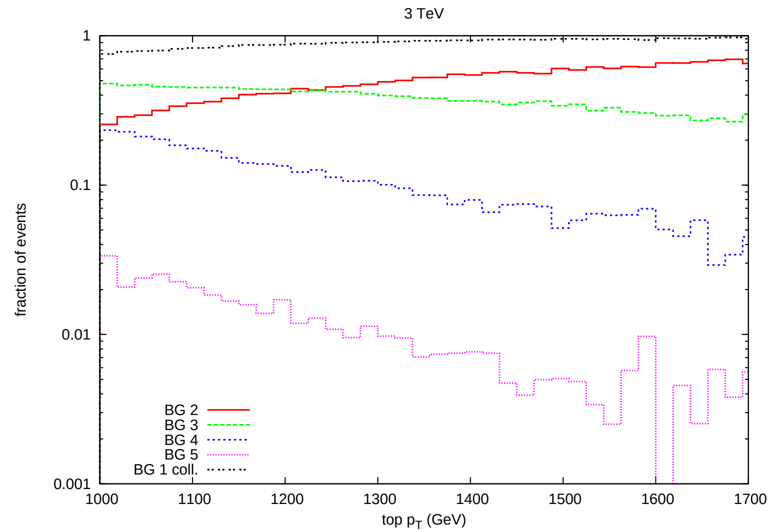
....

More studies necessary for more top finders!

- backup

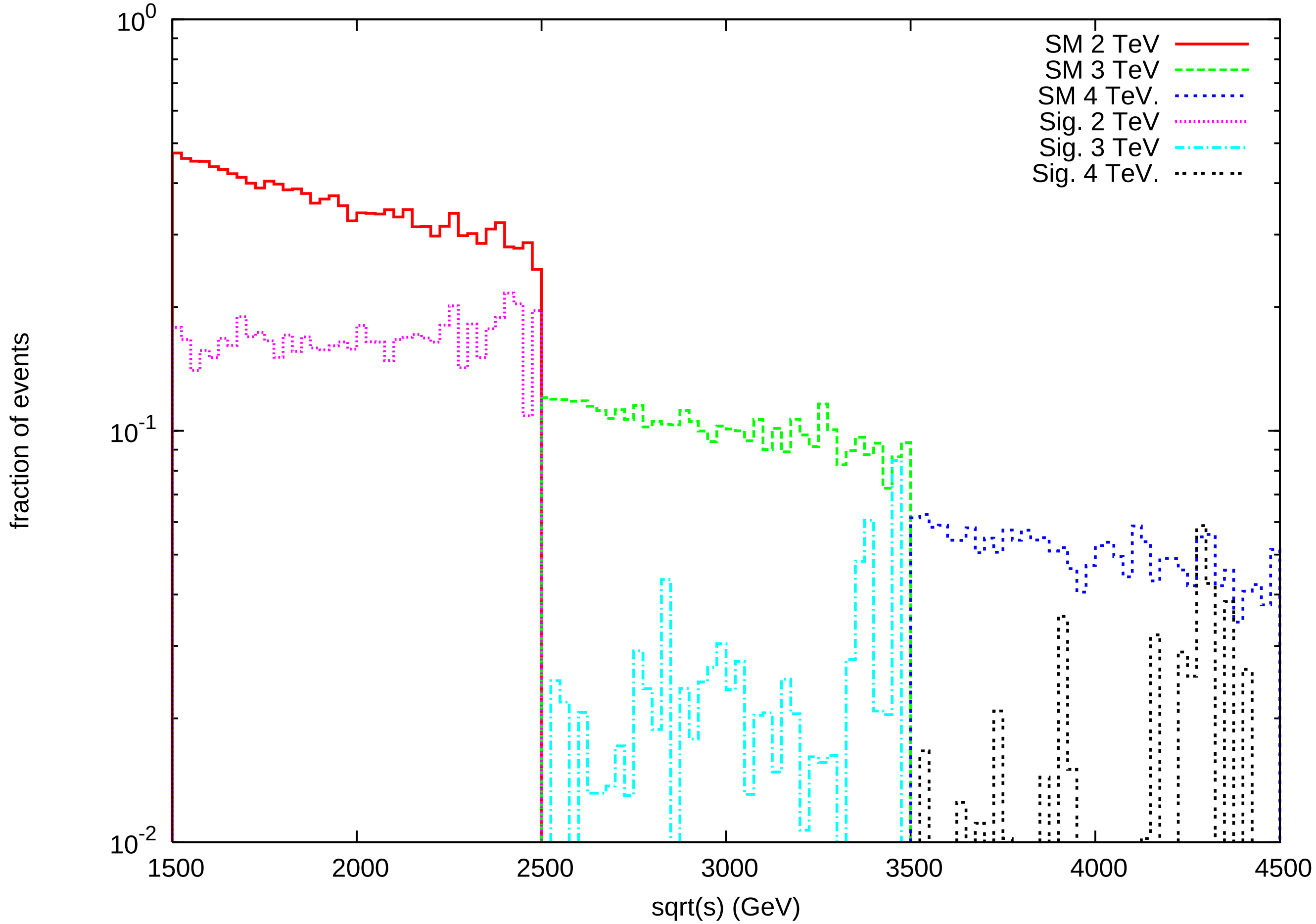
Collimation as a function of p_T





• p_T cut forces tops to be more central.

Lepton isolation?



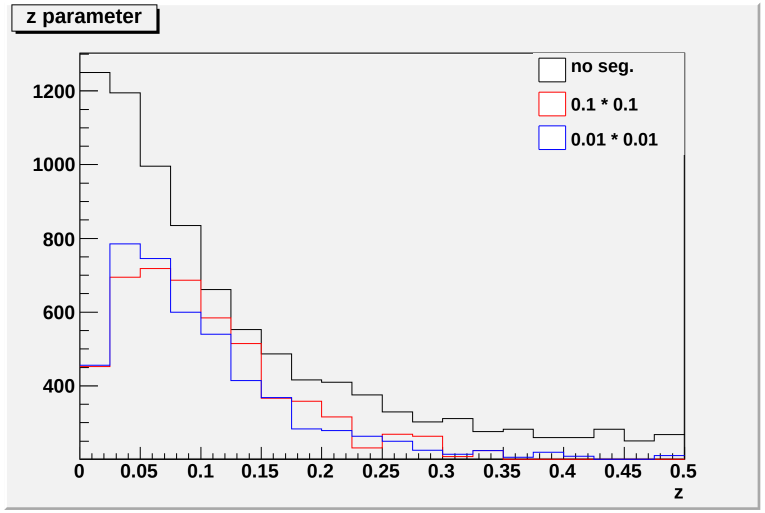
For $M_{t\bar{t}} \geq 3$ TeV, a few % with lepton isolation.

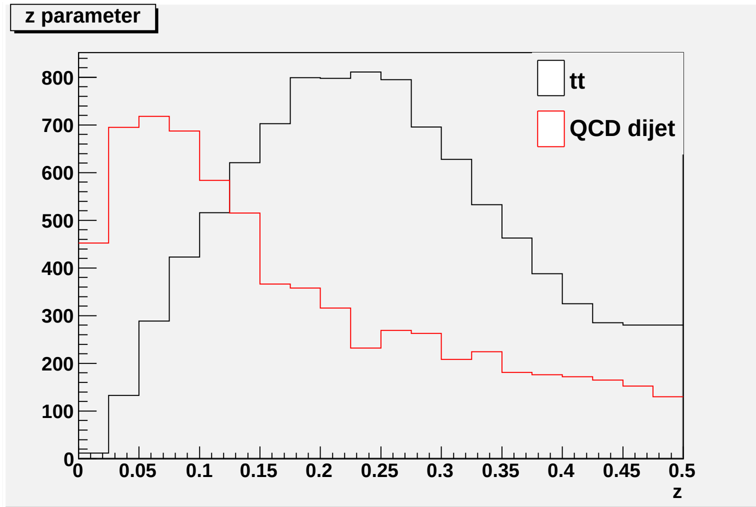
• A More important effect: granularity of the detector

$$\cos\theta_0 = \frac{1}{\beta_0}\frac{2(1-z)-(1+t_1/t_0-t_2/t_0)}{\lambda(t_0,t_1,t_2)}$$

$\beta_0 \to 1,\ t_i \to 0,\ z \to 0,\ \cos\theta_0 \to 0.$

Suppression at $z \sim 0$ due to finite granularity of the detector.





More important than the subleading log effects.

Still peak towards 0. different from top