Jet substructure: back to basics

Gavin Salam (CERN)

Applications of Jet Substructure to New Physics Searches
Perimeter Institute for Theoretical Physics
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As a field we've devised O(10-20) powerful methods to tag jet substructure.

Many of the methods have been tried out in searches and work; these kinds of methods will be crucial for searches in the years to come.

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But from outside, the many methods make the field look pretty confusing.

And from inside, I get the impression we don't always know *why or how* the methods work – which is bad if we're looking for robustness.

Is it time to get back to basics?

What was the original motivation?

Normal R=0.4/0.5 jet finding fails to find one jet per prong of a boosted [W/Z/H/top/NP] hadronic decay.

We need to make sure that this doesn't prevent us from using EW-scale particles in TeV scale searches.

Question #1:

To what extent are the things we do with "normal" jets (and leptons) mirrored in the things we're doing with "fat" jets?

What have we found out in the meantime?

There's a huge number of things you can do with jet substructure.

Many of the things appear to improve mass resolution, background rejection, etc. [at least in MC simulation]

Question #2:
How should we balance improvements v. "complexity" of method?

What are we comfortable with?

Resolved Analysis

Find one jet/prong

Cut on jet p_t, Δy, ...

What are we comfortable with?

Resolved Analysis		**Fat-jet Analysis**
Find one jet/prong	→	Find subjets
Cut on jet p_t, Δy, ...	→	Cut on subjet z, ΔR, ...

[MDT/Prune/Trim/Filt/XYZTopTagger/Template ...]

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Isolation cut for colourless leptons, γ

Cut on radiation in jet for q/g discrimination

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Isolation cut for colourless leptons, γ	→	Cut on radiation for colourless W,H,...
Cut on radiation in jet for q/g discrimination	→	Cut on radiation in subjets
		[τ_{mn}, Qjets, deconstruction...]

What are we comfortable with?

Resolved Analysis

Fat-jet Analysis

Standard, well understood

Find one jet/prong → Find subjets

Cut on jet p_t, Δy, ... → Cut on subjet z, ΔR, ...

[MDT/Prune/Trim/Filt/XYZTopTagger/Template ...]

Isolation cut for colourless leptons, γ

Cut on radiation for colourless W,H,...

Less standard requires case-by-base validation

Cut on radiation in jet for q/g discrimination

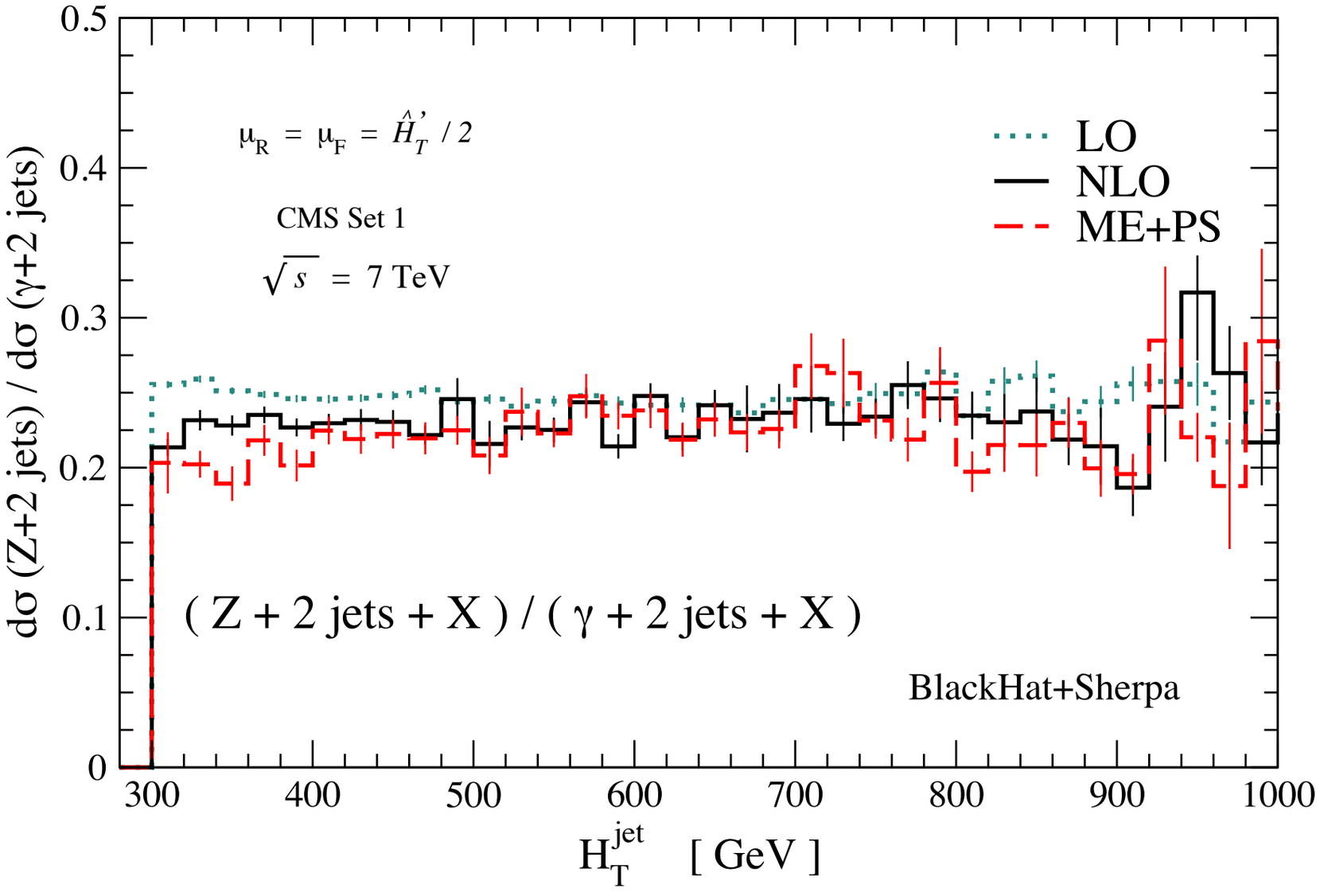
Cut on radiation in subjets

[τ_{mn}, Qjets, deconstruction...]

[Analytic] understanding

Understanding your taggers means you know what tools you can safely use with them

For robustness, you can then choose taggers whose distributions can be predicted in many ways



Just like MET($Z\to\nu\nu$) in multijets is reliably estimated from γ+jets because multiple types of calculations of the ratio agree

What do we know currently?

Boost 2010 proceedings:

The [Monte Carlo] findings discussed above indicate that while [pruning, trimming and filtering] have qualitatively similar effects, there are important differences. For our choice of parameters, pruning acts most aggressively on the signal and background followed by trimming and filtering.

At the time:

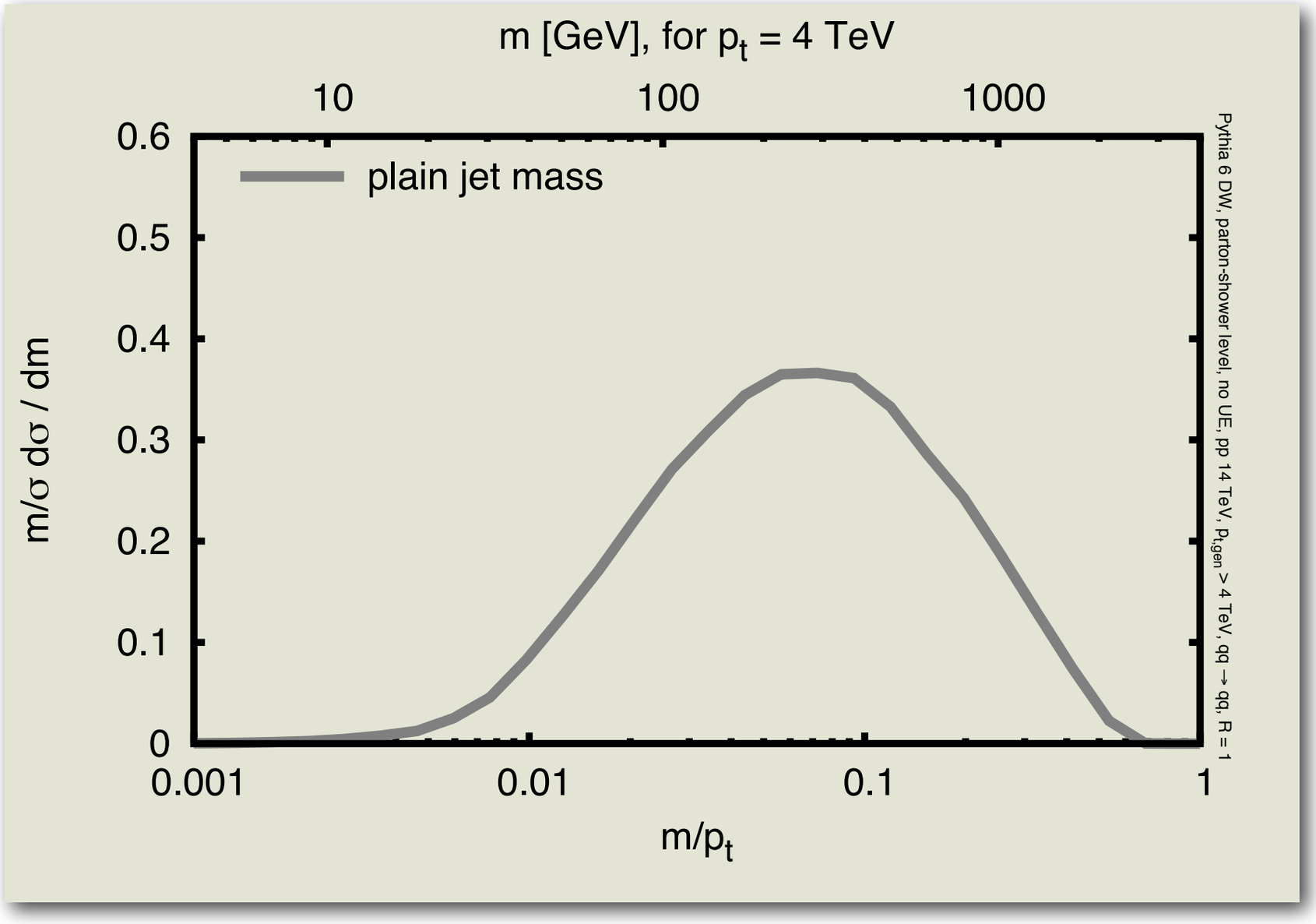
- No clear picture of why the taggers might be similar or different
- No clear picture of how the parameter choices affect the taggers

Today:

- I'll show a selection of **preliminary** lessons from studies for background jets in progress with Dasgupta, Fregoso and Marzani

The “right” MC study can already be instructive

(testing on background [quark] jets)



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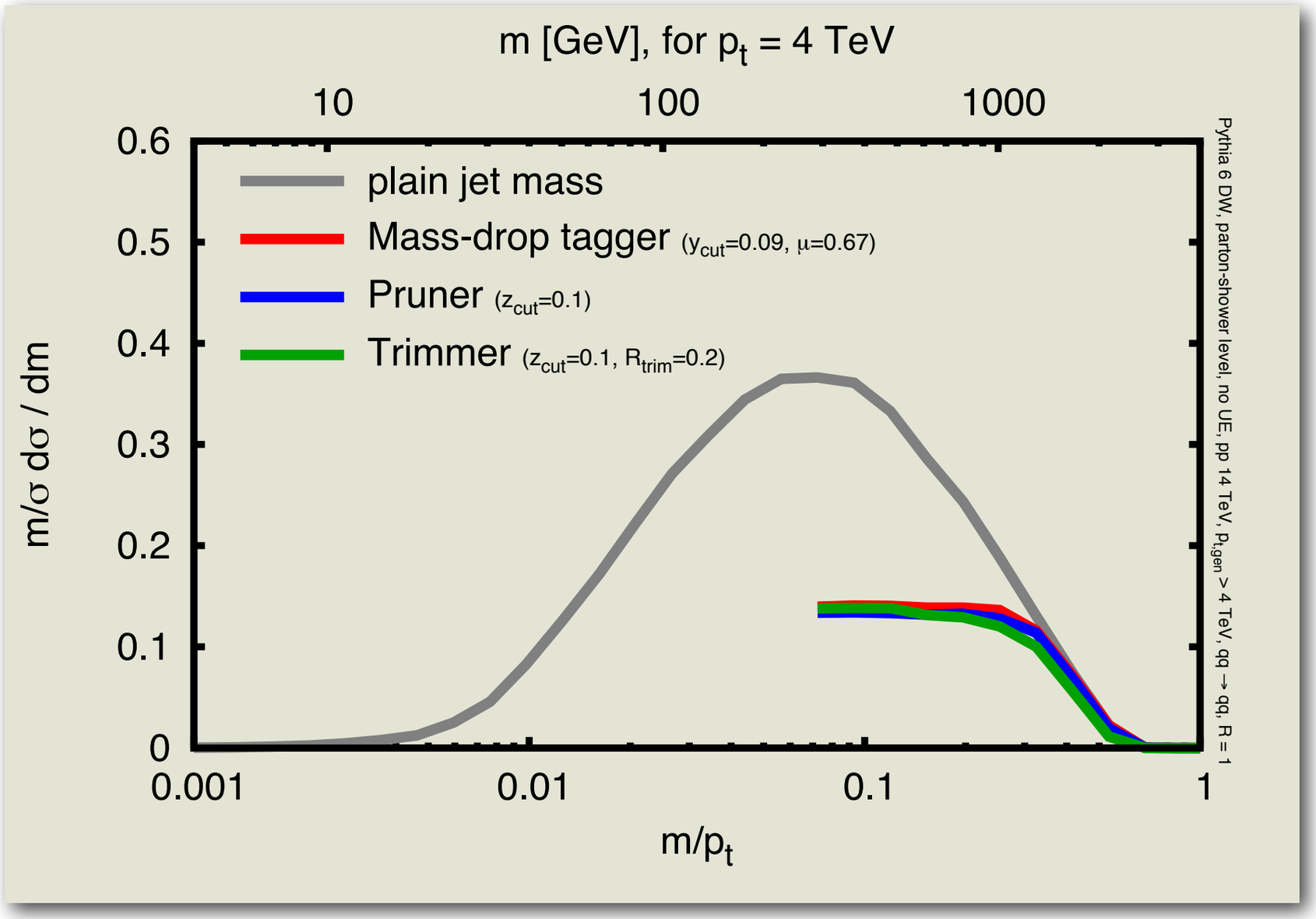
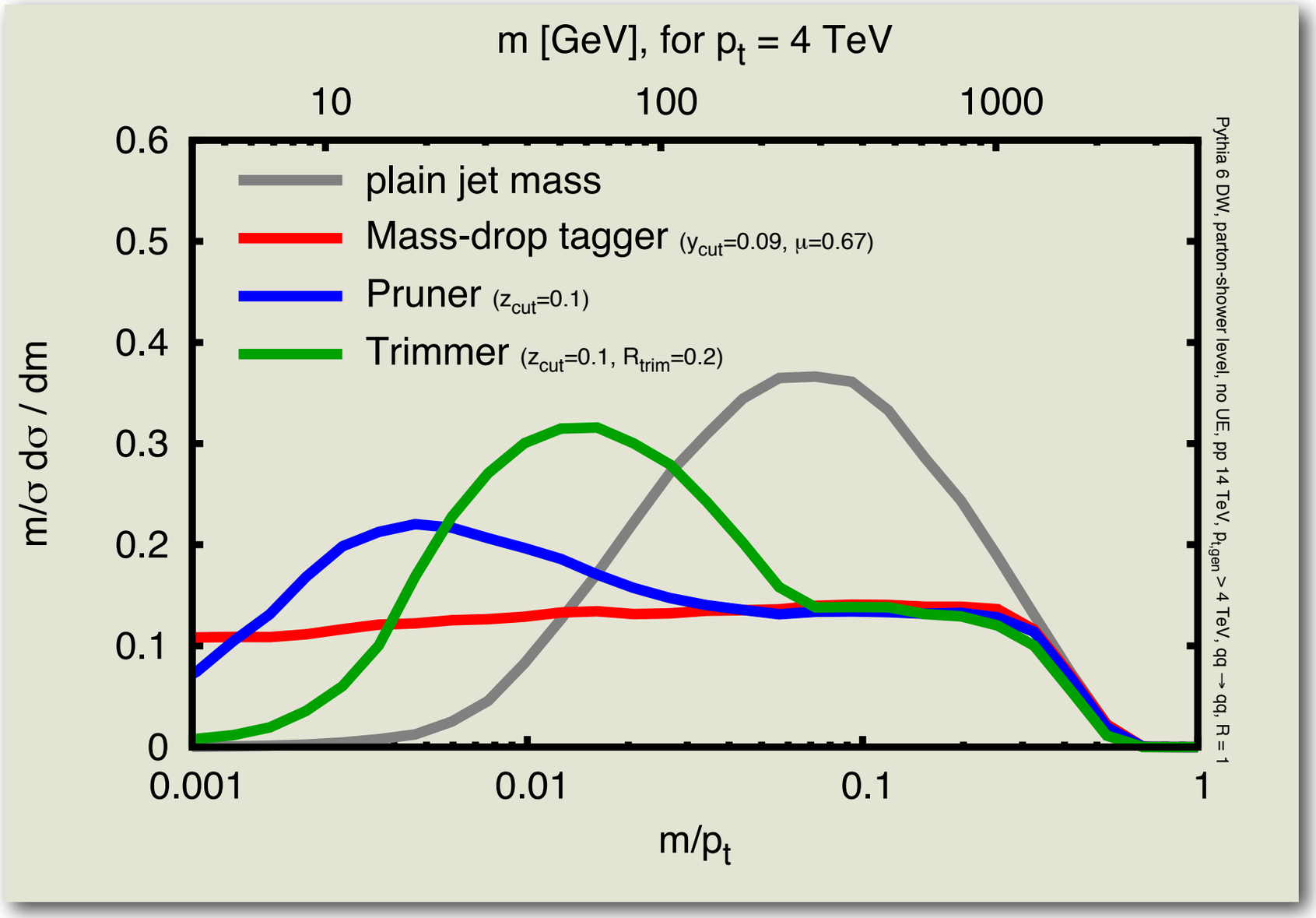


Different taggers are apparently quite similar

The “right” MC study can already be instructive

(testing on background [quark] jets)

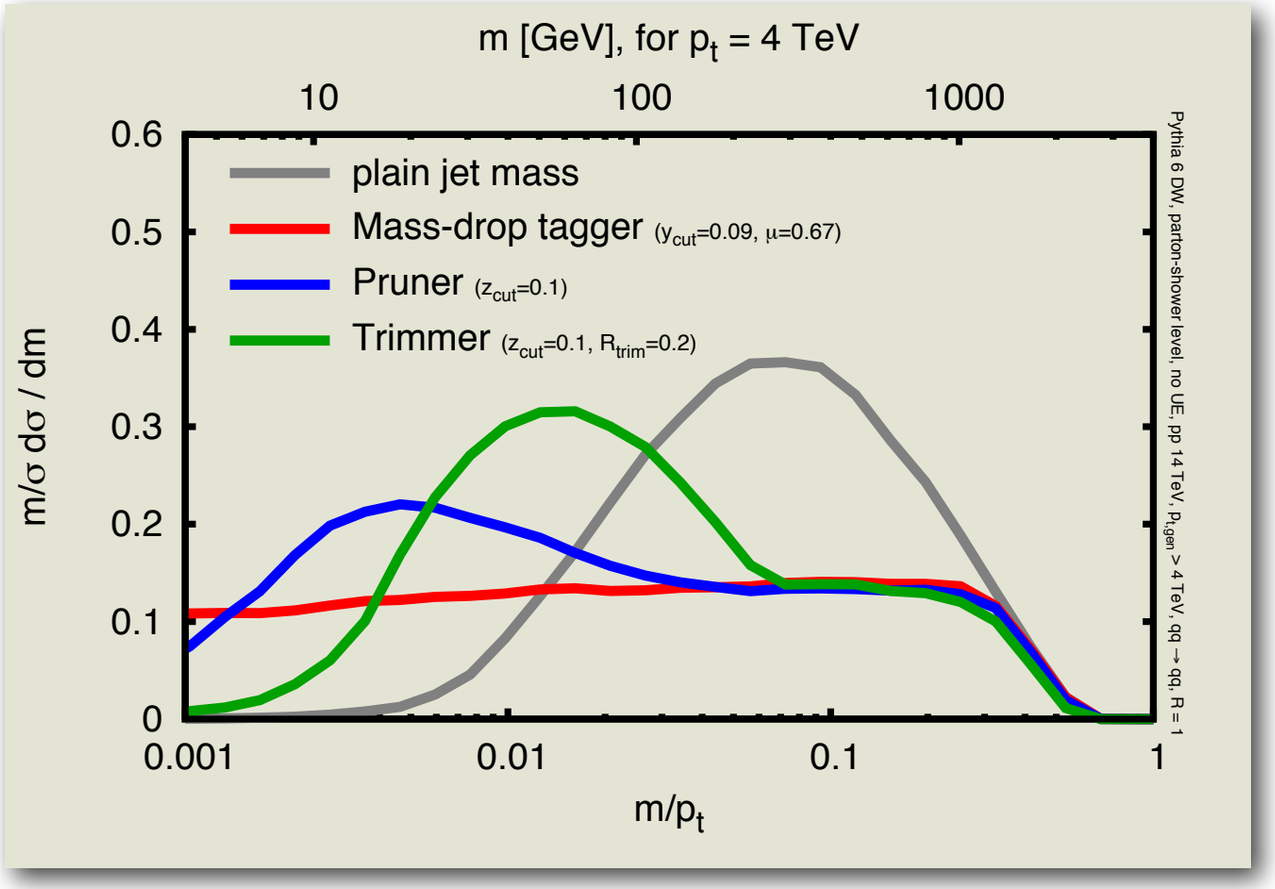


But only for a limited range of masses

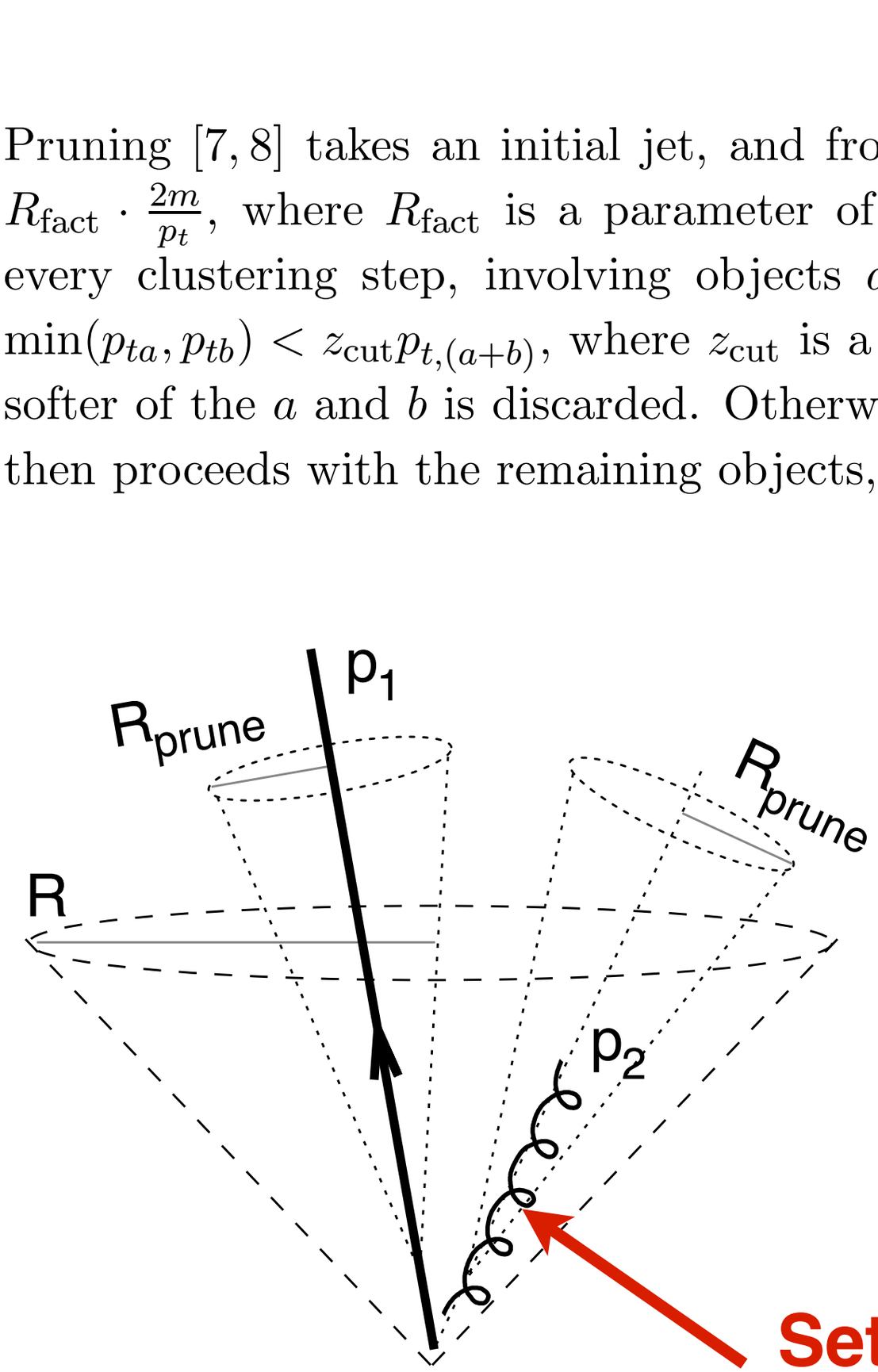
Do we care about such differences?

- Think data-driven backgrounds: kinks can seriously mess with you [especially if you got used to their being absent, e.g. from moderate p_t tests]
- How do these structures depend on the z_{cut}, y_{cut}, R_{trim}, etc. parameters?
- Are these structures telling us something we might want to know about the taggers? E.g. how to improve them?

This calls for analysis and calculation



Pruning [7, 8] takes an initial jet, and from its mass deduces a pruning radius $R_{\rm prune} = R_{\rm fact} \cdot \frac{2m}{p_t}$, where $R_{\rm fact}$ is a parameter of the tagger. It then reclusters the jet and for every clustering step, involving objects a and b, it checks whether $\Delta_{ab} > R_{\rm prune}$ and $\min(p_{ta}, p_{tb}) < z_{\rm cut} p_{t,(a+b)}$, where $z_{\rm cut}$ is a second parameter of the tagger. If so, then the softer of the a and b is discarded. Otherwise a and b are recombined as usual. Clustering then proceeds with the remaining objects, applying the pruning check at each stage.



What pruning is meant to do:

Choose an $R_{\rm prune}$ such that different hard prongs (p_1, p_2) end up in different hard subjets.

Discard any softer radiation.

Sets pruning radius, & hard enough to end up as subjet

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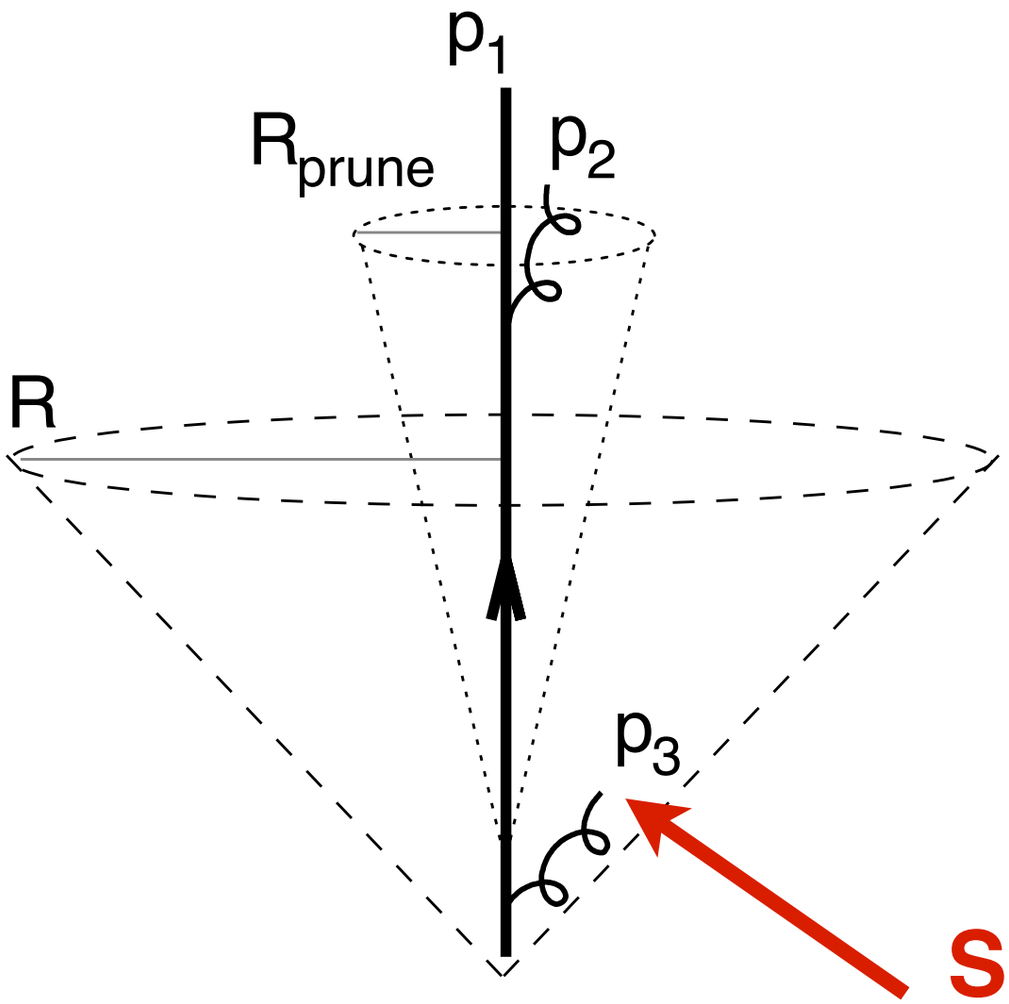


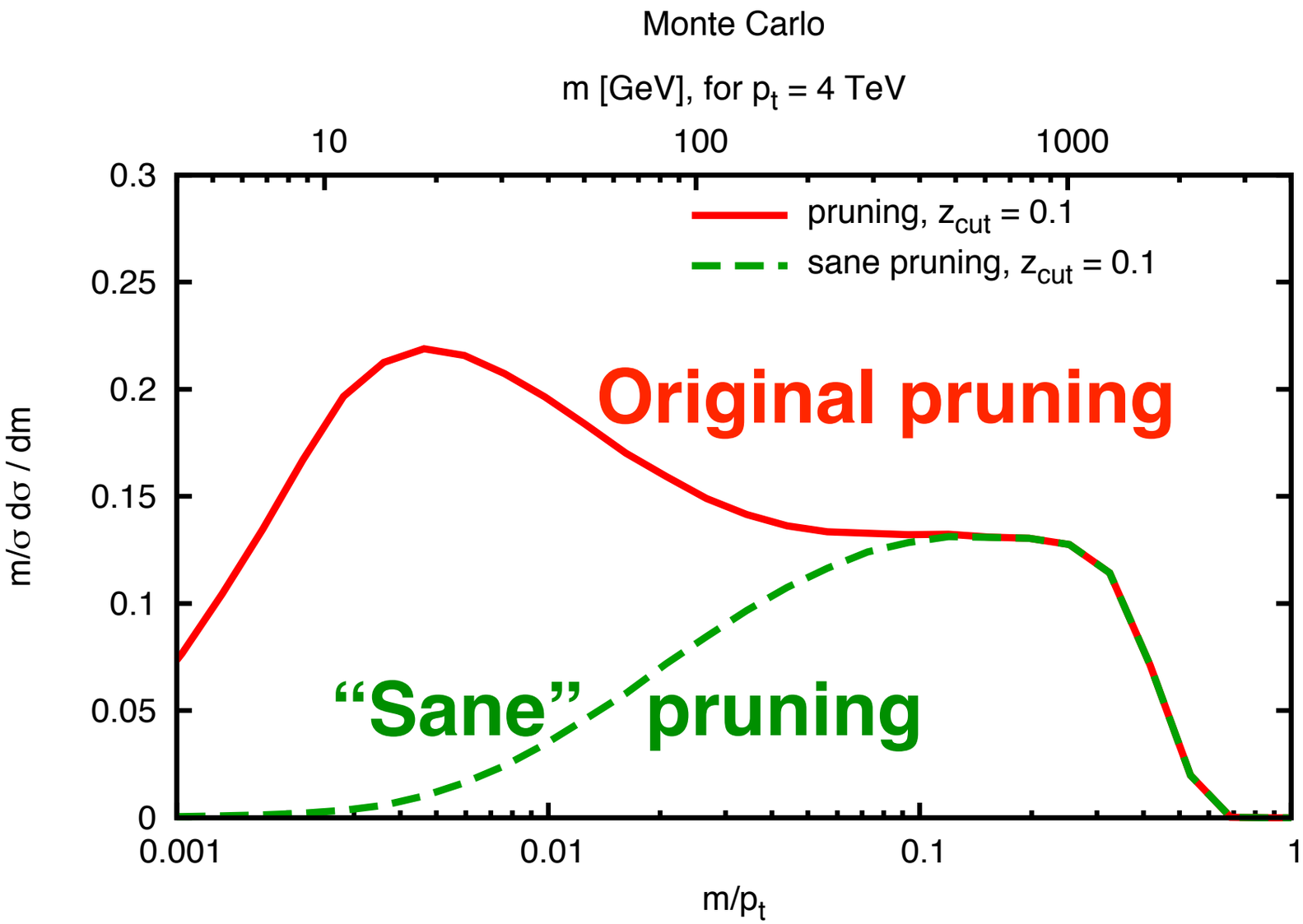
What pruning sometimes does

Chooses $R_{\rm prune}$ based on a soft p_3 (dominates total jet mass), and leads to a single narrow subjet whose mass is also dominated by a soft emission (p_2, within $R_{\rm prune}$ of p_1, so not pruned away).

Sets pruning radius, but gets pruned away

A simple fix: “sane” pruning

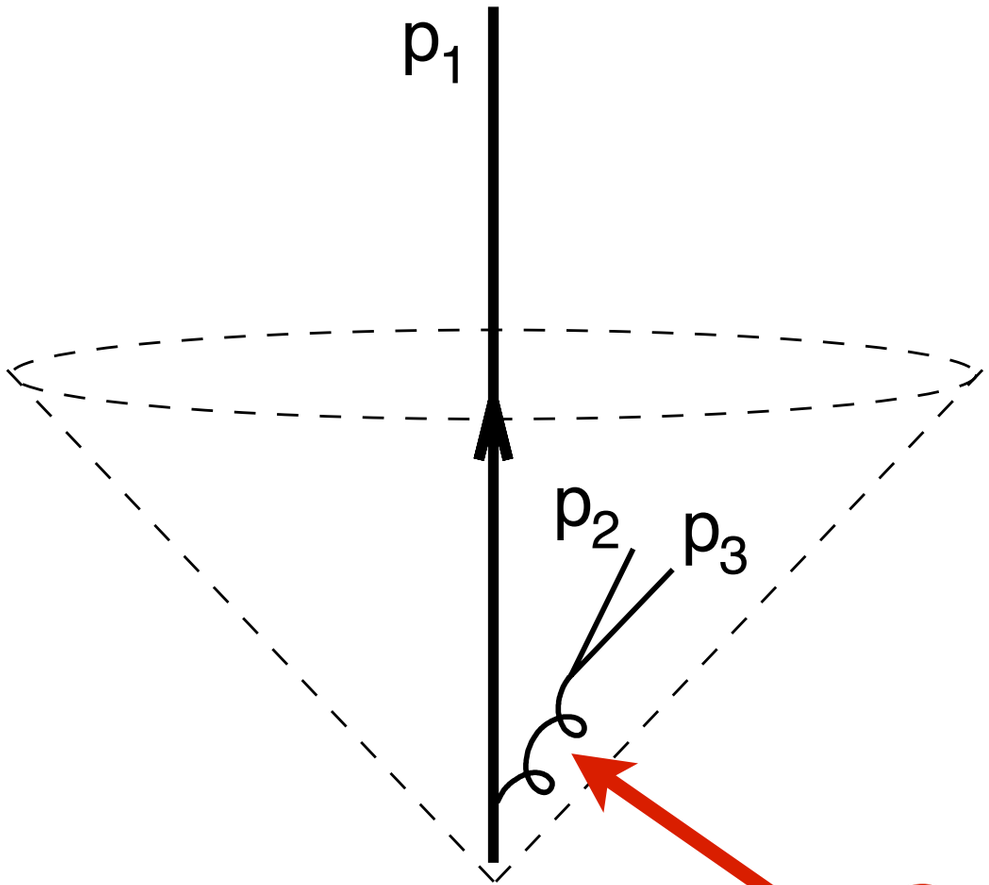
Require at least one successful merging with $\Delta R > R_{prune}$ and $z > z_{cut}$



“sane” pruning is effectively placing an isolation cut on radiation around the tagged object

Mass drop tagger

1. Break the jet j into two subjets by undoing its last stage of clustering. Label the two subjets j_1, j_2 such that $m_{j_1} > m_{j_2}$.
2. If there was a significant mass drop, $m_{j_1} < \mu m_j$, and the splitting is not too asymmetric, $y = \min(p_{tj_1}^2, p_{tj_2}^2)\Delta R_{j_1 j_2}^2 / m_j^2 > y_{\rm cut}$, then deem j to be the tagged jet.
3. Otherwise redefine j to be equal to j_1 and go back to step 1 (unless j consists of just a single particle, in which case the original jet is deemed untagged).



What MDT does wrong:

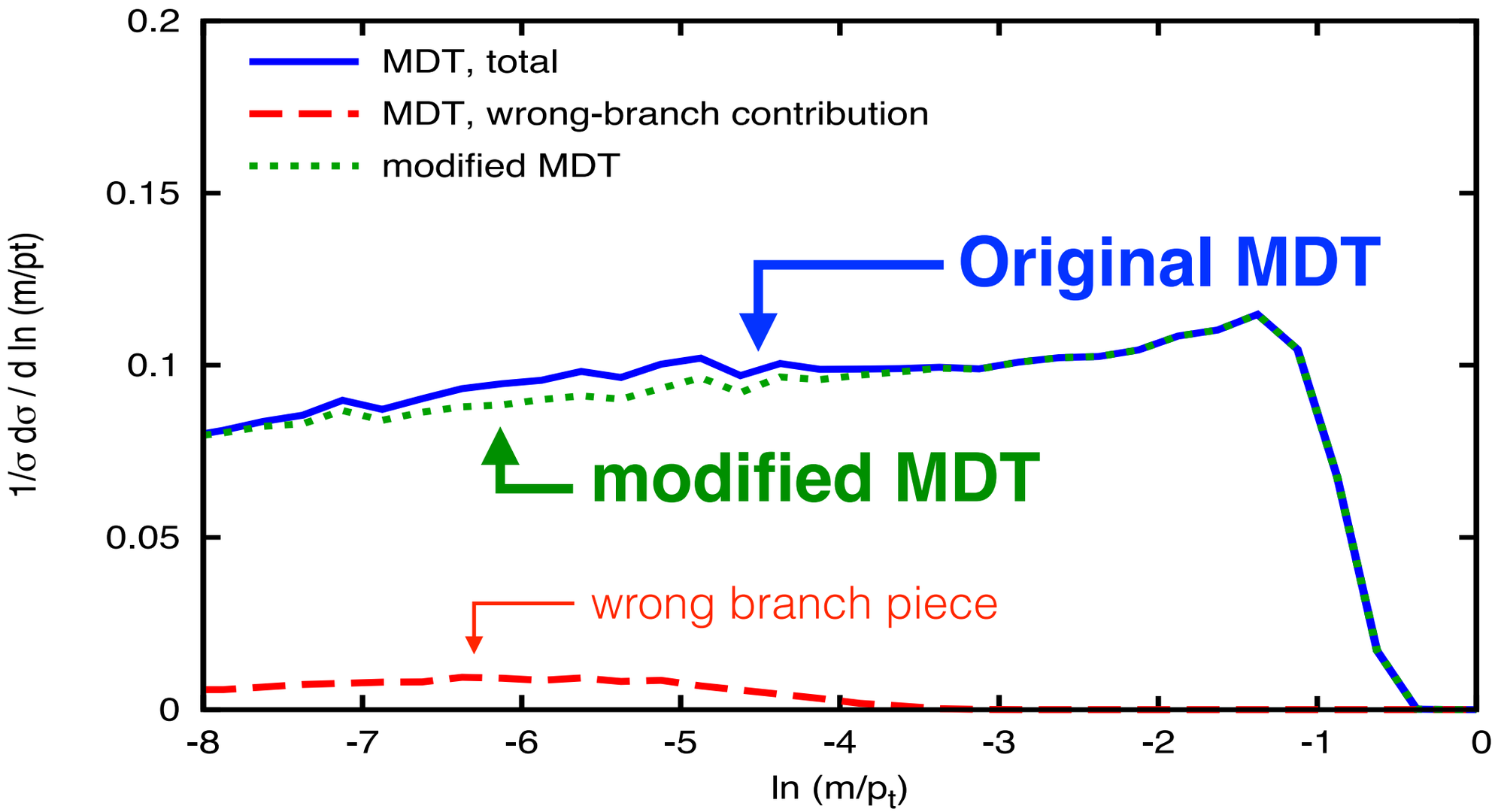
Follows a soft branch (p_2+p_3 < y_{cut} p_{jet}) with "accidental" small mass, when the "right" answer was that the (massless) hard branch had no substructure

Subjet is soft, but has more substructure than hard subjet

A simple fix for "modified" Mass Drop Tagger:

When recursing, follow branch with larger ($m^2+p_t^2$)

(rather than the one with larger m)



What about analytic calculations of the taggers?

Simpler — More complex

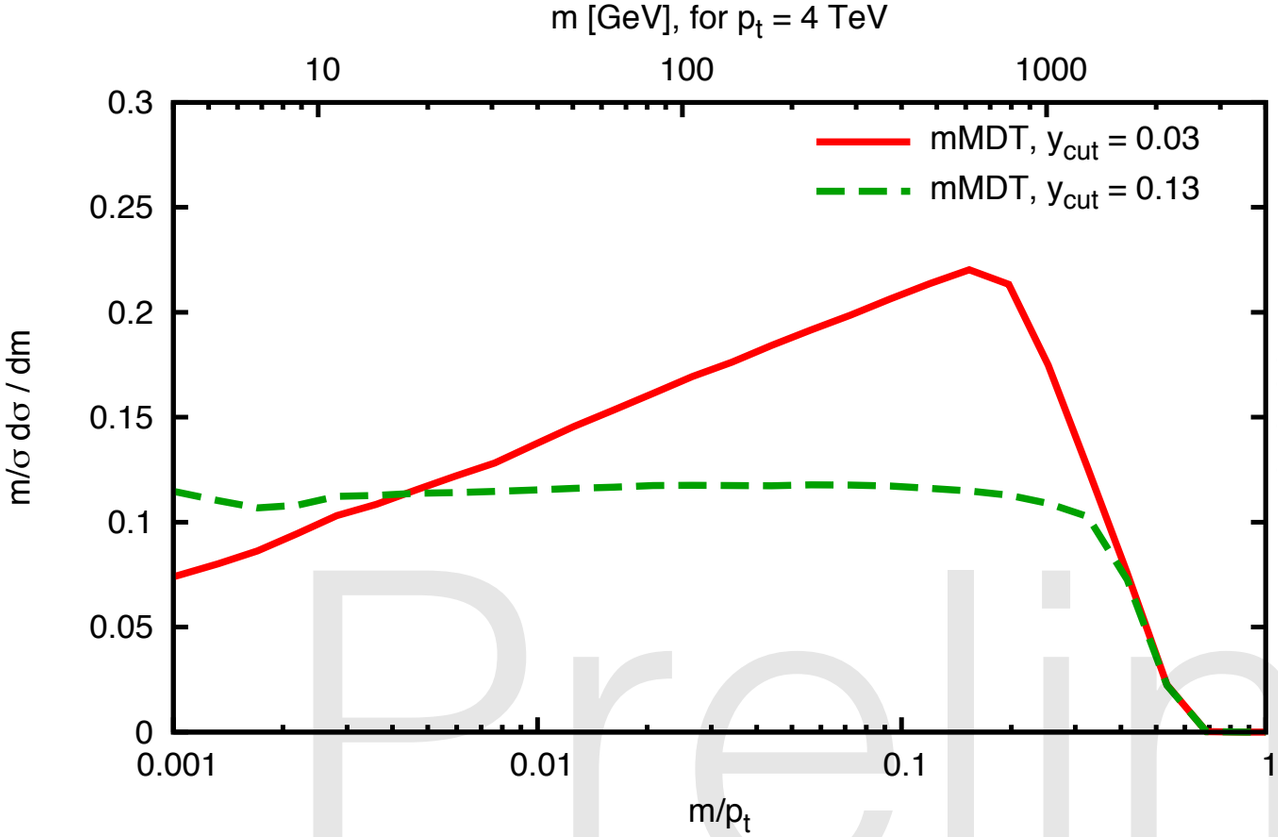
Dasgupta et al (full NLL, including non-global part)
Chien et al (partial NNLL)
Jouttenus et al (they say full NNLL; I remain to be convinced!)

mMDT > plain mass ~ trimming > sane pruning > full pruning » ~~MDT~~

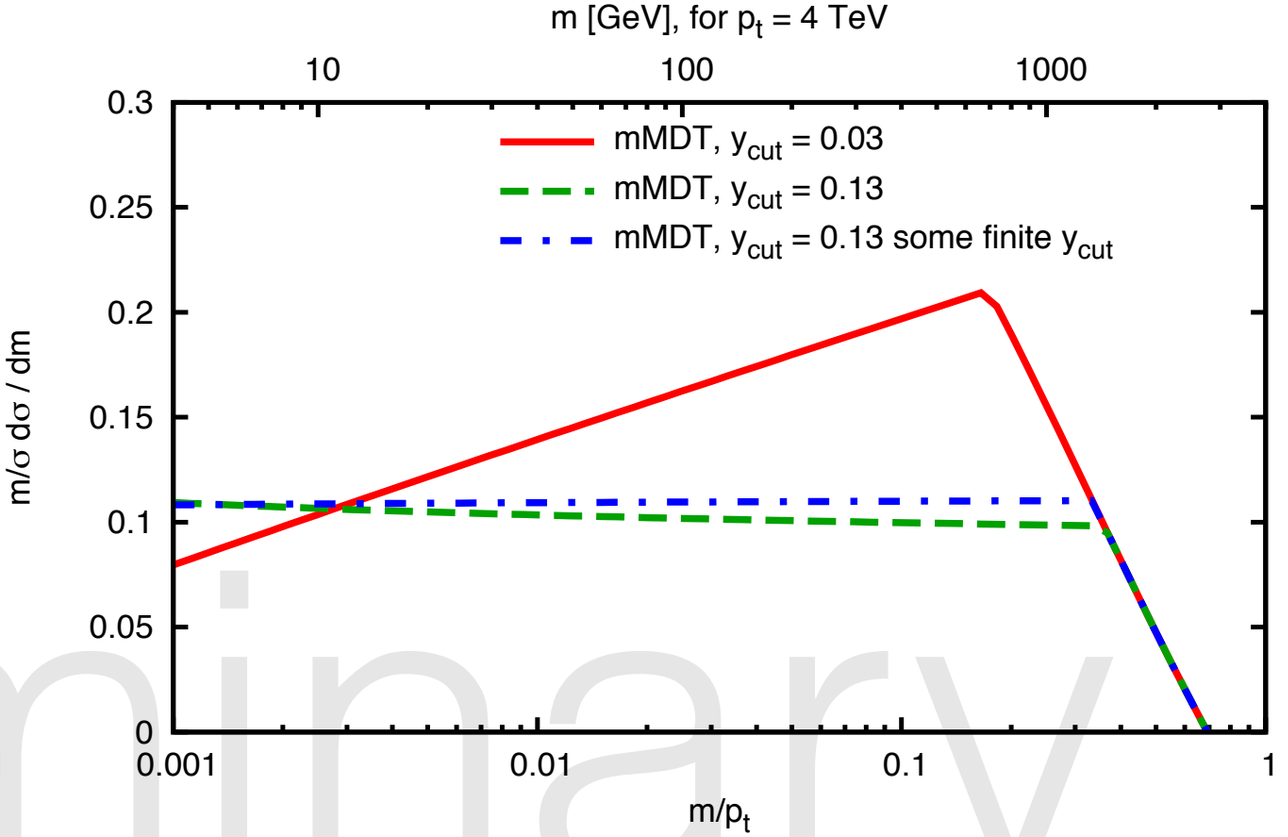
Dasgupta, Fregoso, Marzani & GPS, forthcoming:
LL in all cases, plus some subleading logs
[NB: LL doesn't mean the same thing in all cases!)

Modified Mass Drop Tagger

Monte Carlo



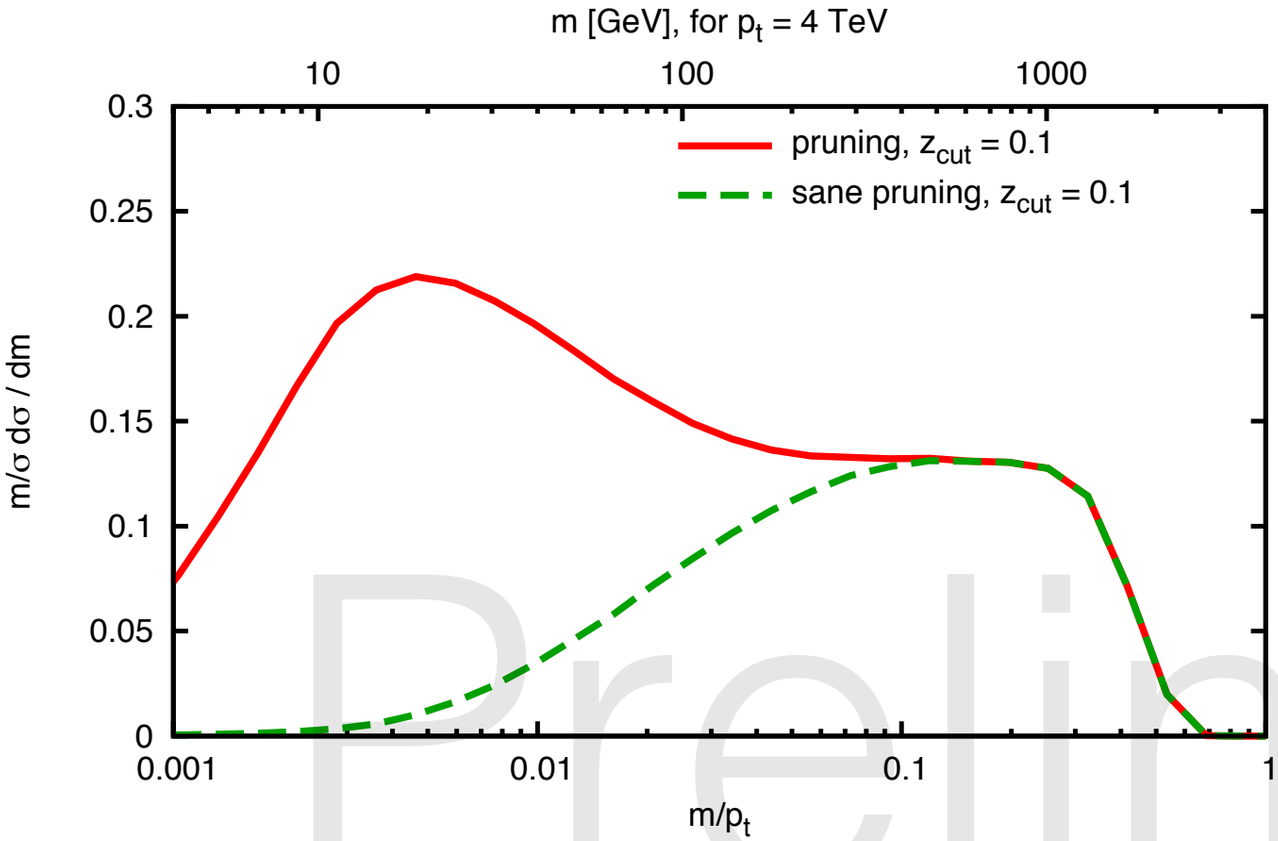
Analytic



[mMDT is closest we have to a scale-invariant tagger, though exact behaviour depends on q/g fractions]

Pruning

Monte Carlo



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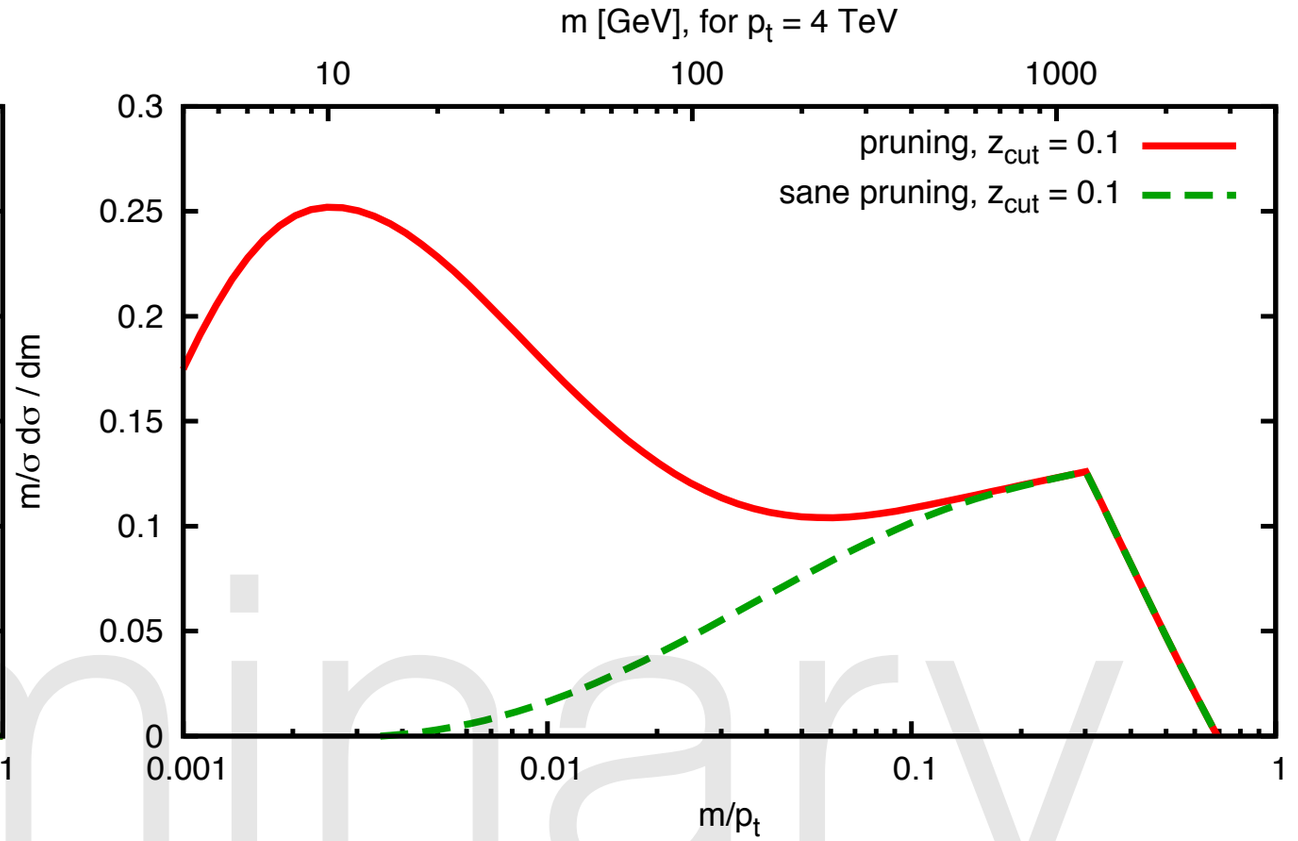
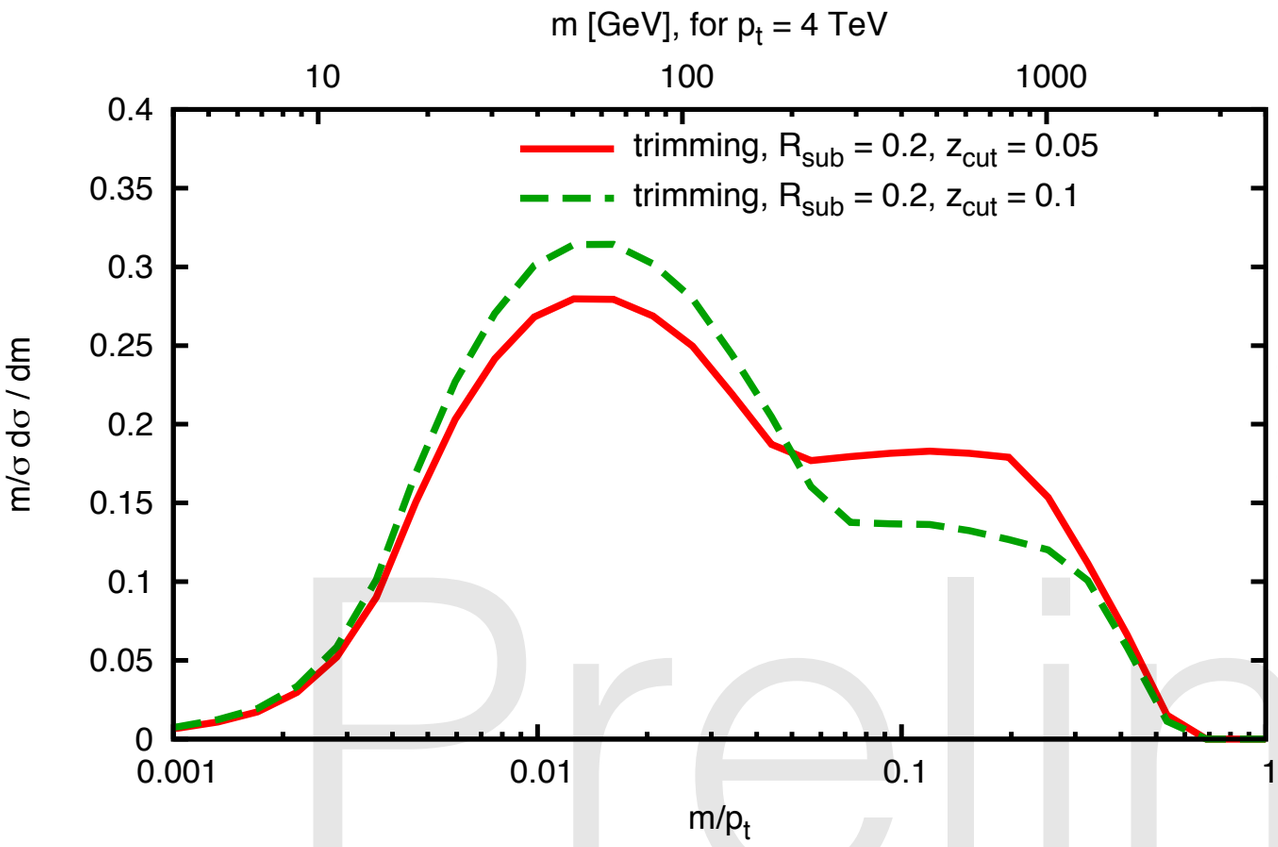
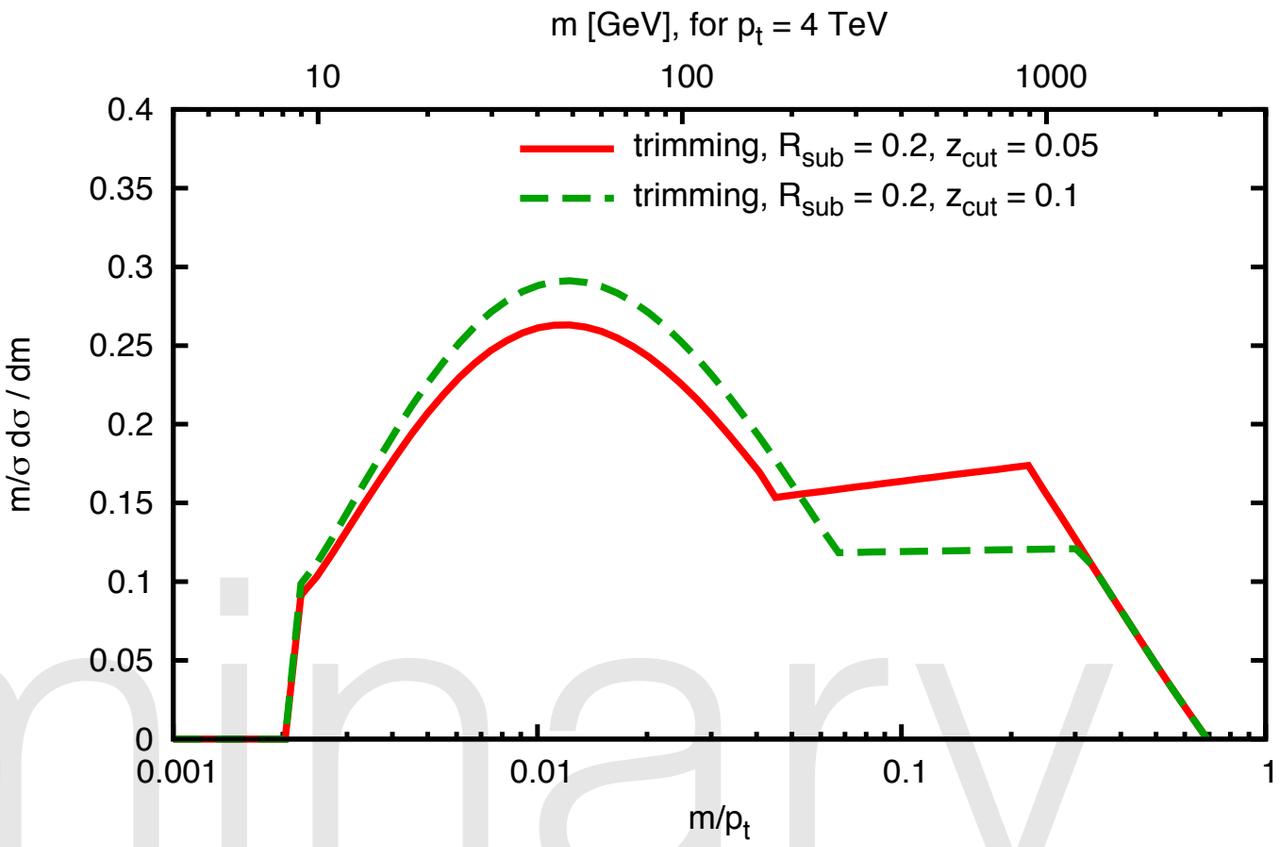


Trimming

Monte Carlo



Analytic

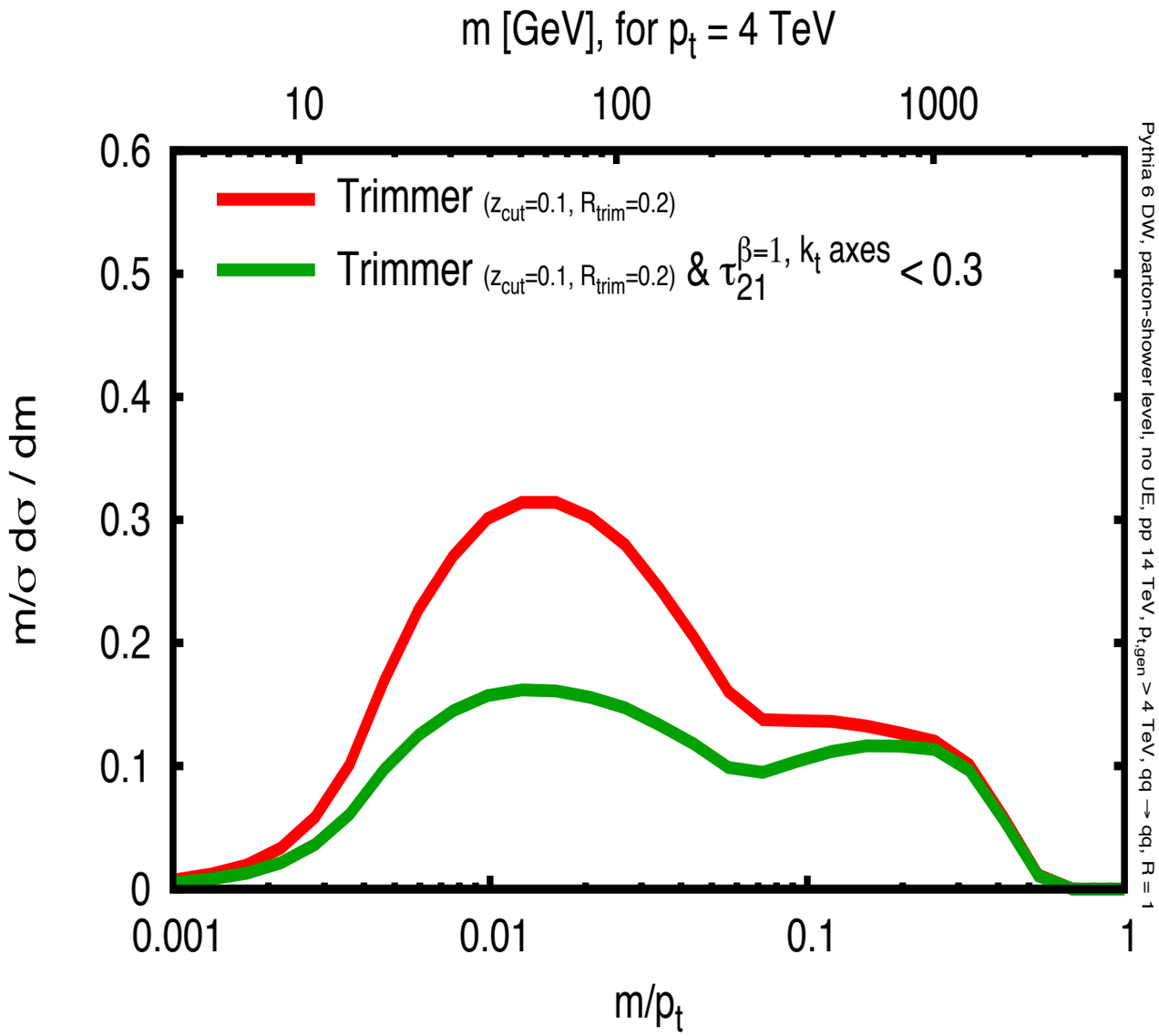


What about cuts on shapes/radiation

E.g. cuts on N-subjettiness, tight mass drop, etc.?

- These cuts are nearly always for a jet whose mass is somehow groomed. All the structure from the grooming persists.

- So grooming & shape must probably be calculated together



Bottom line on “understanding”

- Taggers may be quite simple to write, but potentially involved to understand – tiny details can lead even courageous theorists to tears.

- Contrast this with p_t cuts for standard jet analyses – (mostly) simple

- Still, many taggers/groomers are within calculational reach.

- New “modified” Mass Drop Tagger is especially simple

- New “sane” pruning is also interesting – further investigation warranted...

Infrared safety

Infrared safety:

When the addition of one soft particle with momentum **ε** changes the outcome of tagging by an amount O(1).

It means that perturbative calculations give ∞

It means that the physics of hard objects may be irremediably contaminated by non-perturbative physics – not good for robustness!

Was long an issue in hadron-collider jet-finding.
Let's make sure it doesn't come back to haunt us!

CMS's pruning followed by a mass-drop cut:

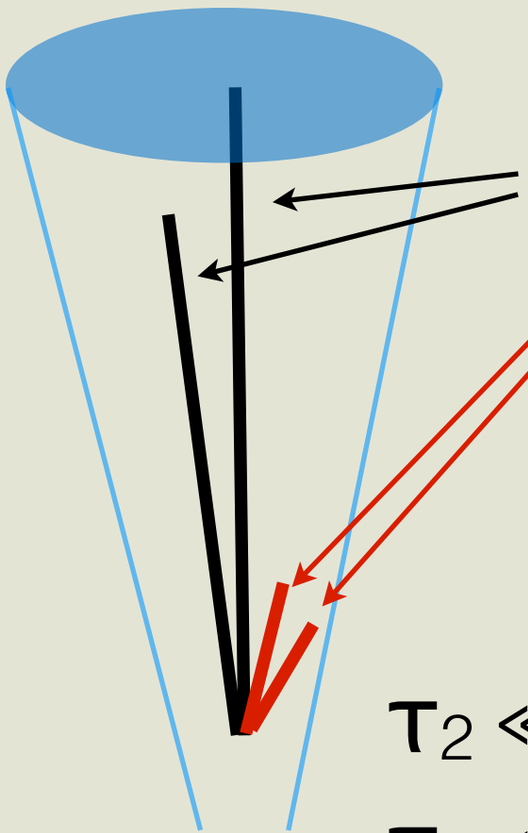
see blackboard!

IR issues in τ_{23}

N-subjettiness τ_3 / τ_2:

τ_2 measures departure from 2-parton energy flow

τ_3 measures departure from 3-parton energy flow



$\tau_2 \ll 1$

$\tau_3 \ll 1$

$\tau_3/\tau_2 \sim 1$

} However soft the two gluons, you get finite τ_3/τ_2

That's IR unsafe

Easily cured with a cut on τ_2 / τ_1, which forces 3rd prong not to be soft.

Extra cut has almost no impact on performance

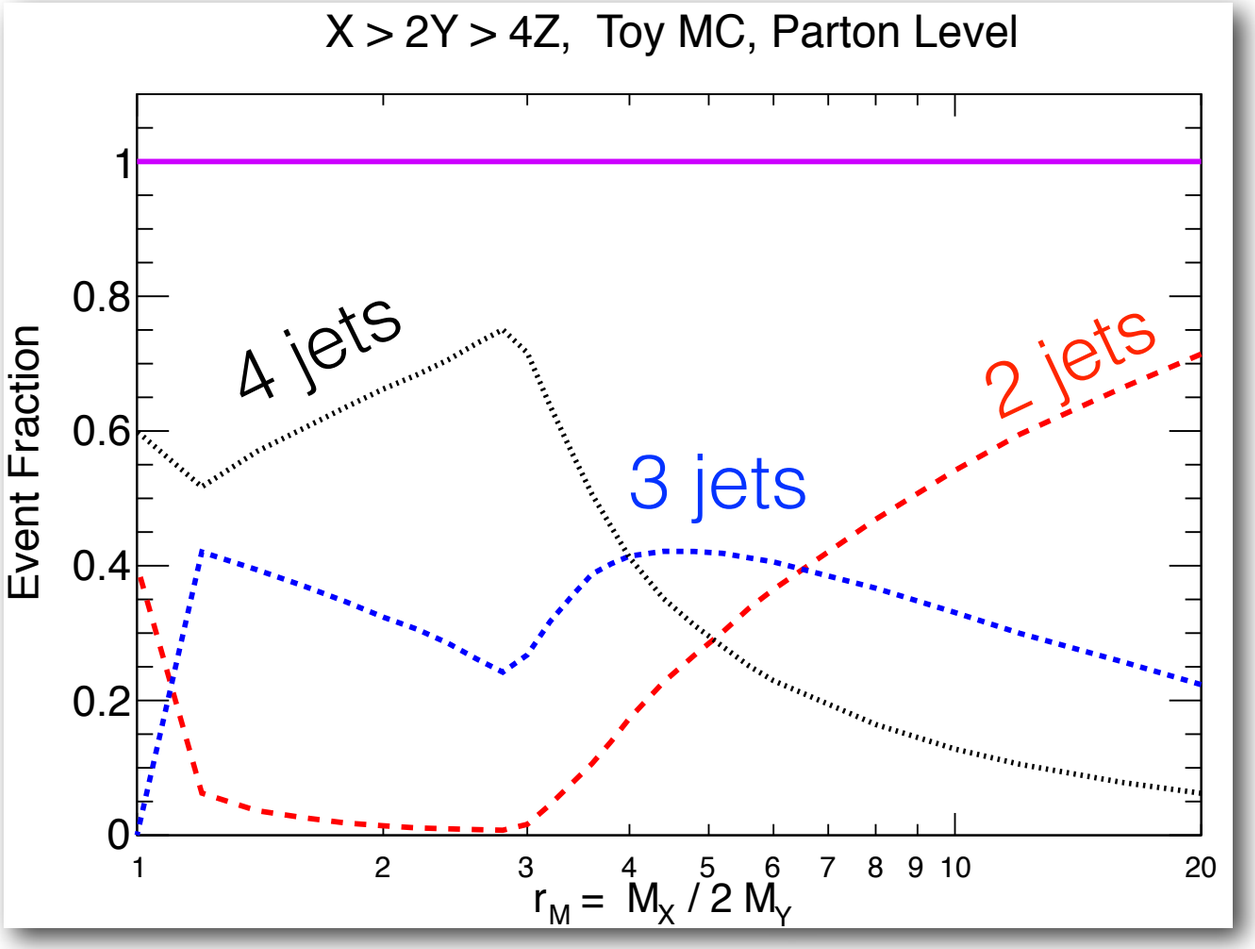
Cacciari et al '12

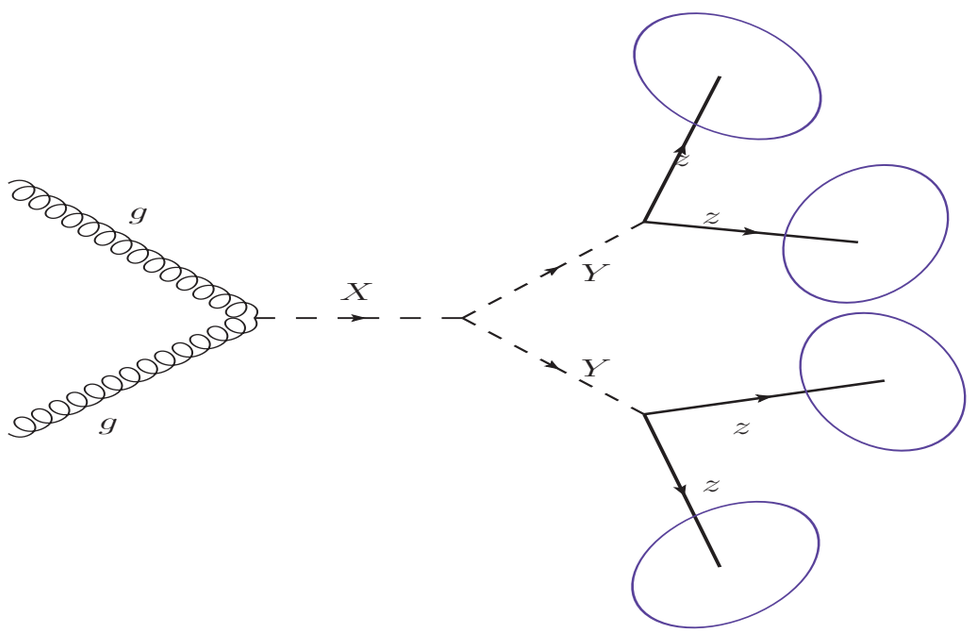
Scale invariant searches

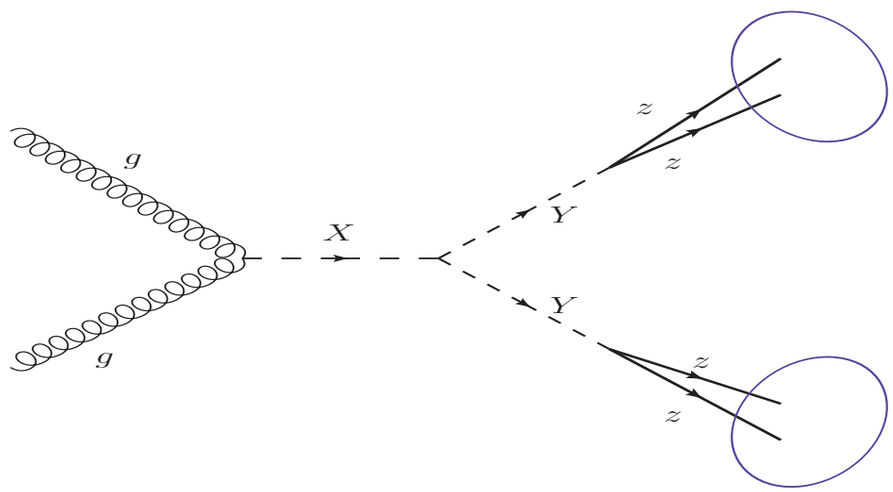
Experiments often have two distinct searches:

Resolved (small-R multi-jet)
Boosted (large-R fat-jet)

Can resolved and boosted analyses be consistently performed together?

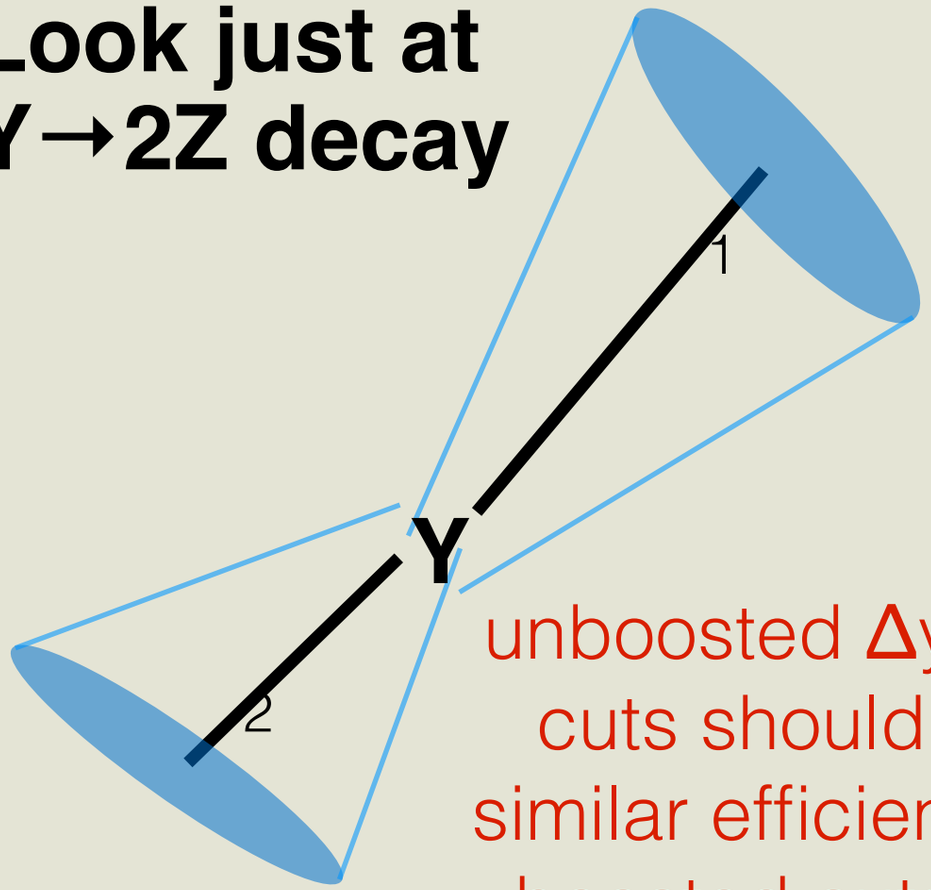






Work in progress with Gouzevitch, Oliveira, Rojo, Rosenfeld & Sanz

Look just at Y→2Z decay

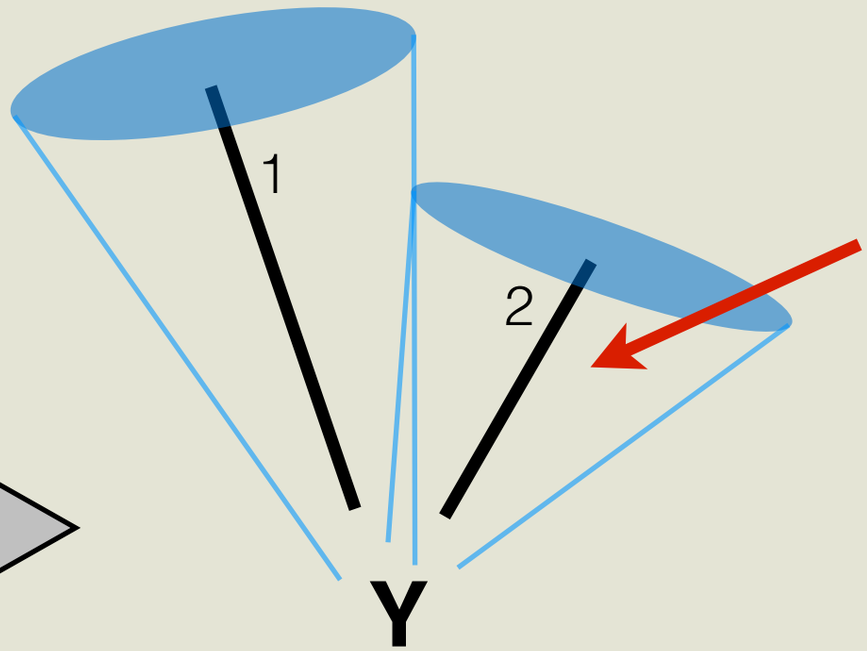


unboosted Δy_{12} & p_t cuts should have similar efficiencies to boosted cuts (y_{cut})

Key [simple] **idea:**

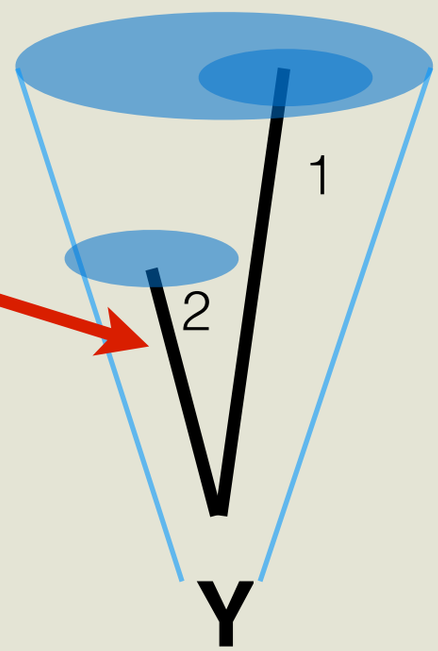
Cuts on resolved jets should mirror those on subjets inside fat jets

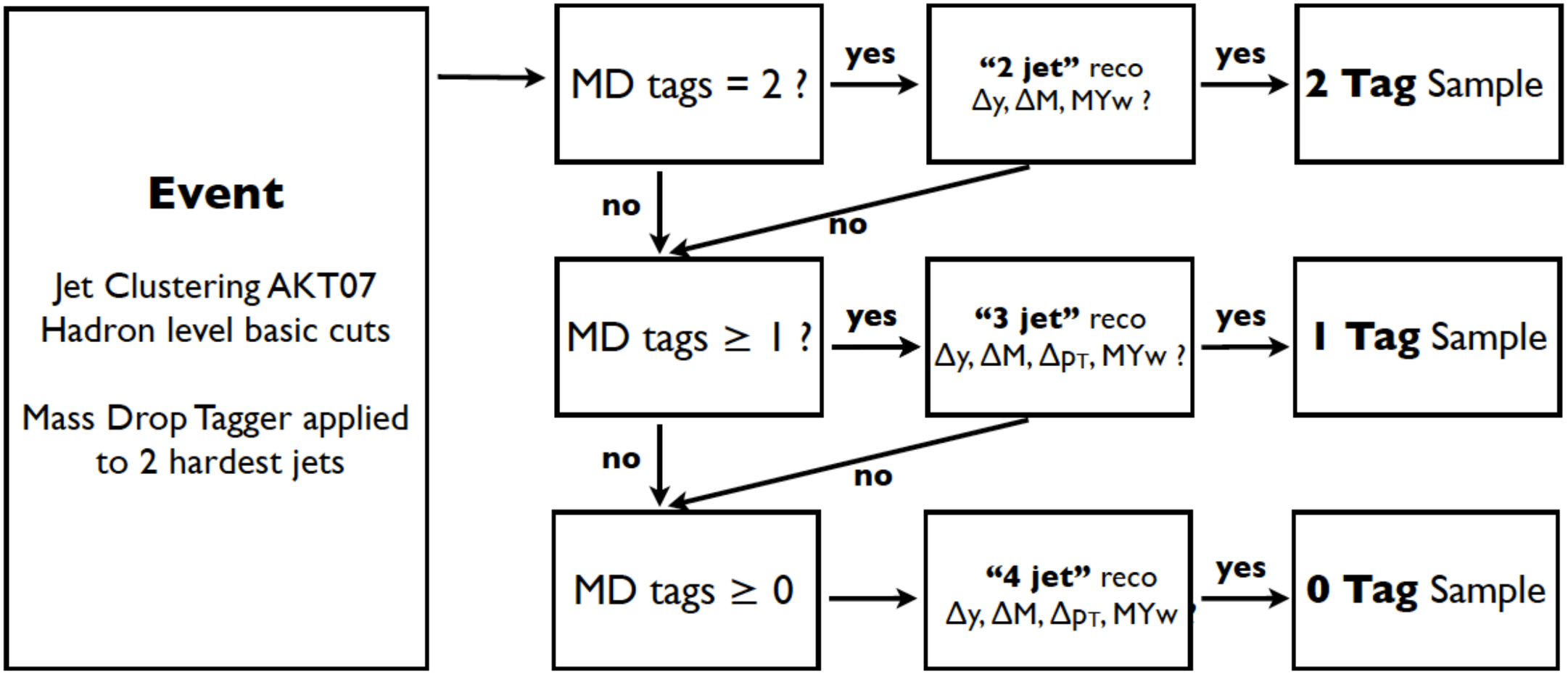
Increasing boost



cuts on nearby jets should mirror subjets cuts,

$p_{t2} \lesssim y_{cut}\, p_{t1}$





$$\left|\frac{2\,(m_{Y1}-m_{Y2})}{m_{Y1}+m_{Y2}}\right| \leq f_m \qquad M_Y\,(1-f_m) \leq m_{Y1}, m_{Y2} \leq M_Y\,(1+f_m)$$

$$\Delta y \equiv |y_{Y1}-y_{Y2}| \leq \Delta y_{\max} \qquad \Delta y \equiv |y_{Yi,1}-y_{Yi,2}| \leq \Delta y^{\rm res}_{\max}$$

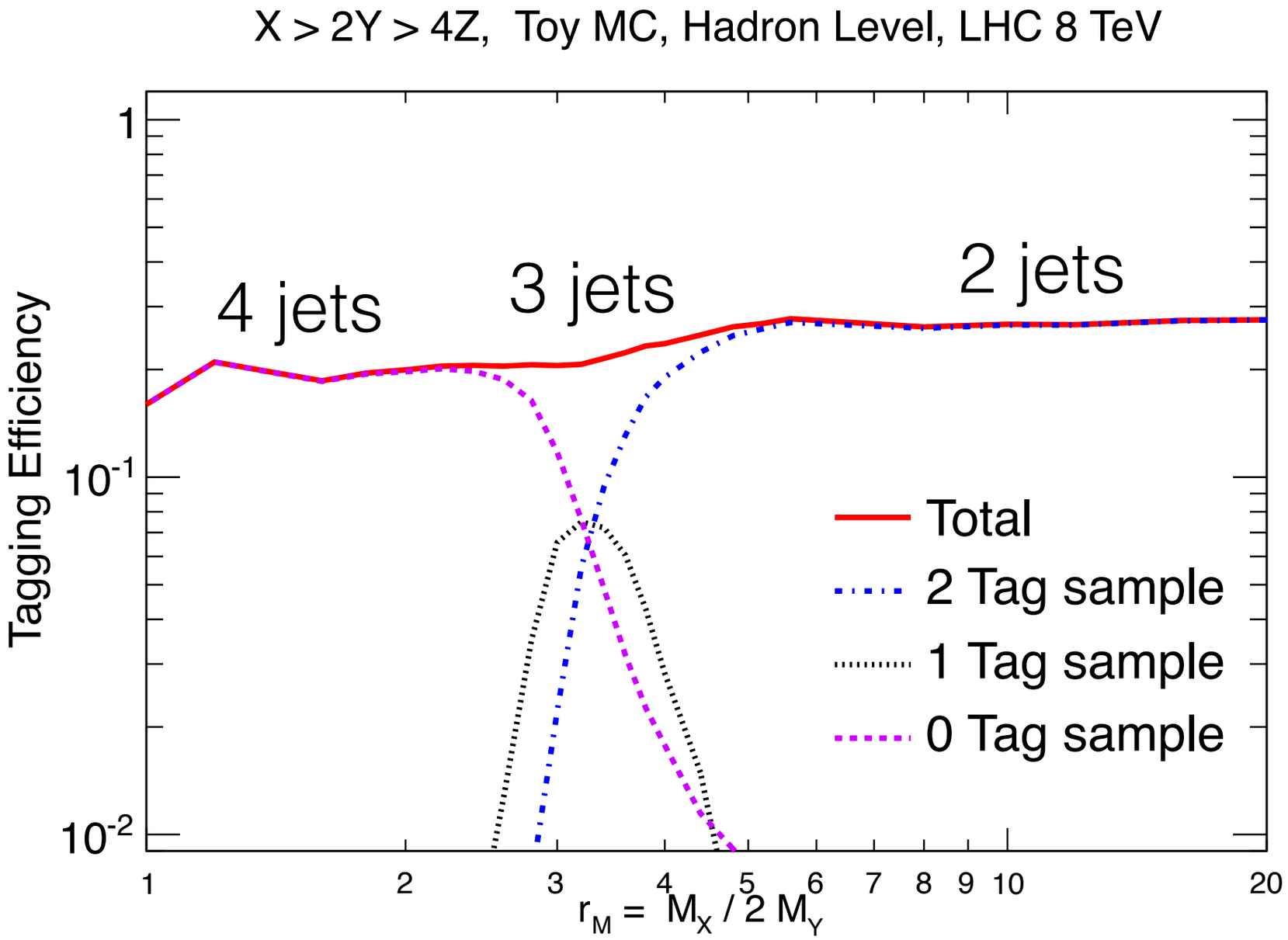
$$\Delta p_T \equiv p_T^{(1)} - p_T^{(2)} \geq (1-y_{\rm cut})\,p_T^{(1)} \qquad \max\left(m_{Y,1}, m_{Y,2}\right) \leq \mu \cdot m_Y$$

Traditional cuts on resolved jets

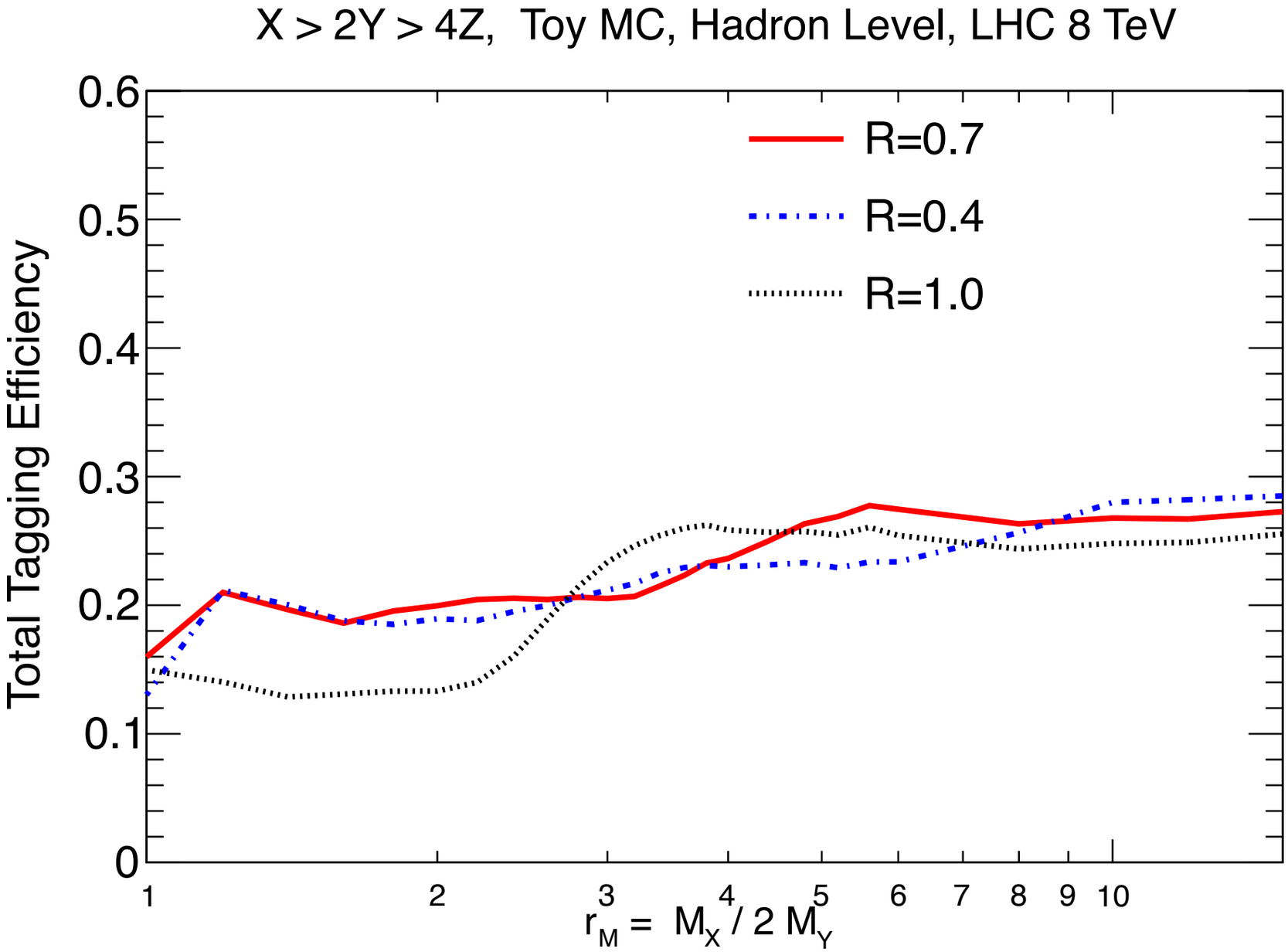
Boosted cuts on resolved jets

Jet Reconstruction					
R	$R_{\rm sj}$	$R_{\rm f}$	$n_{\rm filt}$	μ	$y_{\rm cut}$
0.7	1.3	0.3	3	0.67	0.9

Analysis cuts						
M_Y	$\Delta y_{\max}$	$\Delta y^{\rm res}_{\max}$	$p_T^{\min}$	$\lvert y_{\max}\rvert$	$H_T^{\min}$	f_m
125 GeV	1.3	0.8	25 GeV	5.0	100 GeV	0.10



Efficiency roughly stable as X→2Y→4Z goes from 4→3→2 jets



Efficiency roughly independent of R used in clustering

Pileup in the boosted regime

Pronged top taggers

Some have pileup-***reduction*** built in (HEPTopTagger, Template), essentially by using small (R~0.2–0.3) sub-cones, sometimes dynamically adjusted to the top p_t

For heavy pileup you will need to supplement them with full pileup ***subtraction*** (e.g. area-based).

[Technically trivial, but so far studied only for filtering & trimming]

Shape-based taggers

Until recently, no clear way of subtracting pileup.

Pileup subtraction for shapes

Cacciari, Dutta, JH Kim, GPS & Soyez '12

n^{th} **derivative of shape** wrt ghost momenta

Shape as a function of particle momenta in jet

$$V_{\text{jet}}^{[n]} \equiv A_g^n \frac{d^n}{dr_{t,g}^n} V(\{p_i\}_{\text{jet}})$$

Ghost area

Pileup subtraction for shapes

Cacciari, Dutta, JH Kim, GPS & Soyez '12

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Shape as a function of particle momenta in jet

$$V_{\rm jet}^{[n]} \equiv A_g^n \, \frac{d^n}{dr_{t,g}^n} V(\{p_i\}_{\rm jet})$$

Ghost area

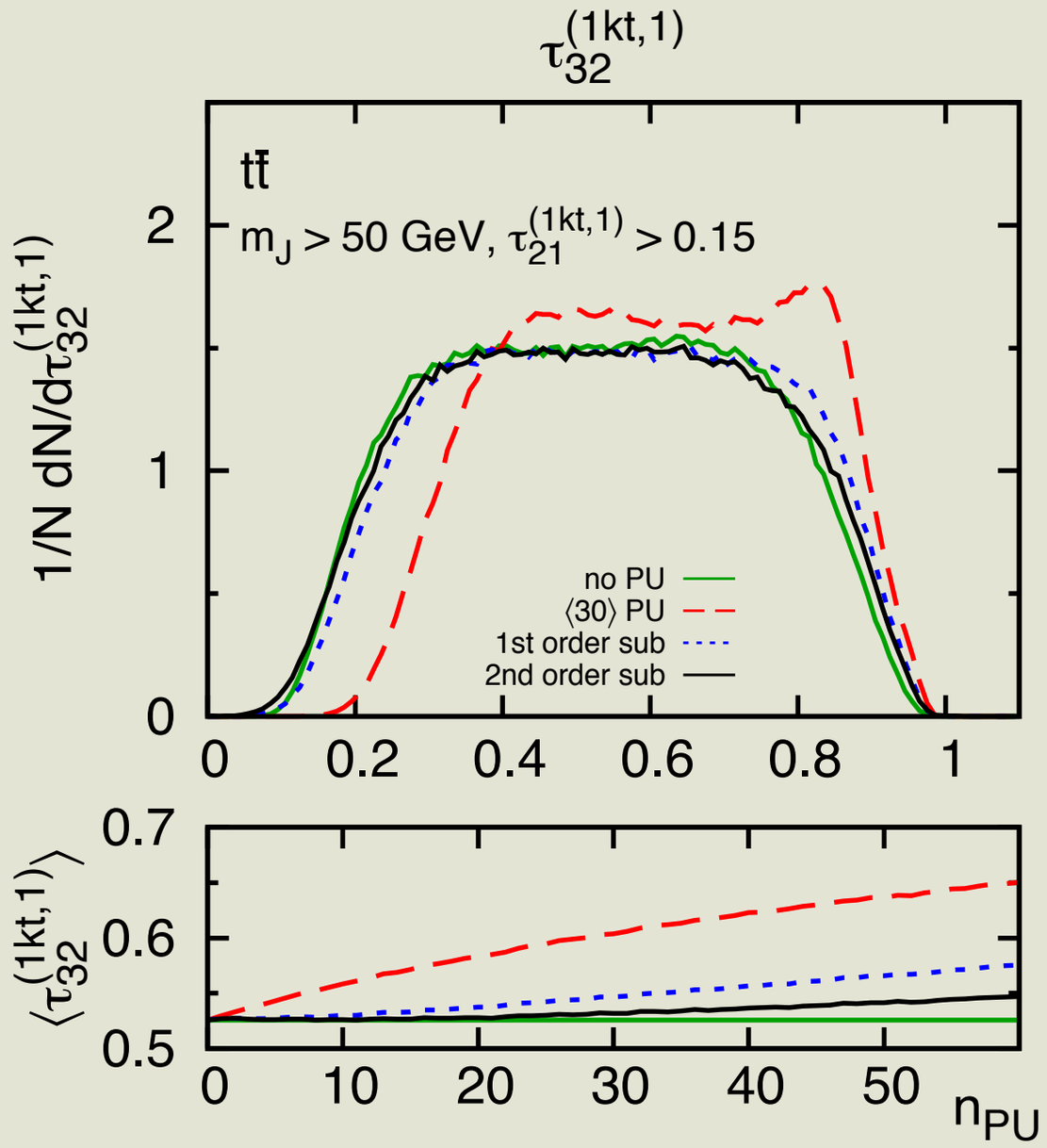
$$V_{\rm jet,sub} = V_{\rm jet} - \rho V_{\rm jet}^{[1]} + \frac{1}{2}\rho^2 V_{\rm jet}^{[2]} + \cdots$$

Subtracted shape

pileup density

Practical test: τ_{32} and top tagging

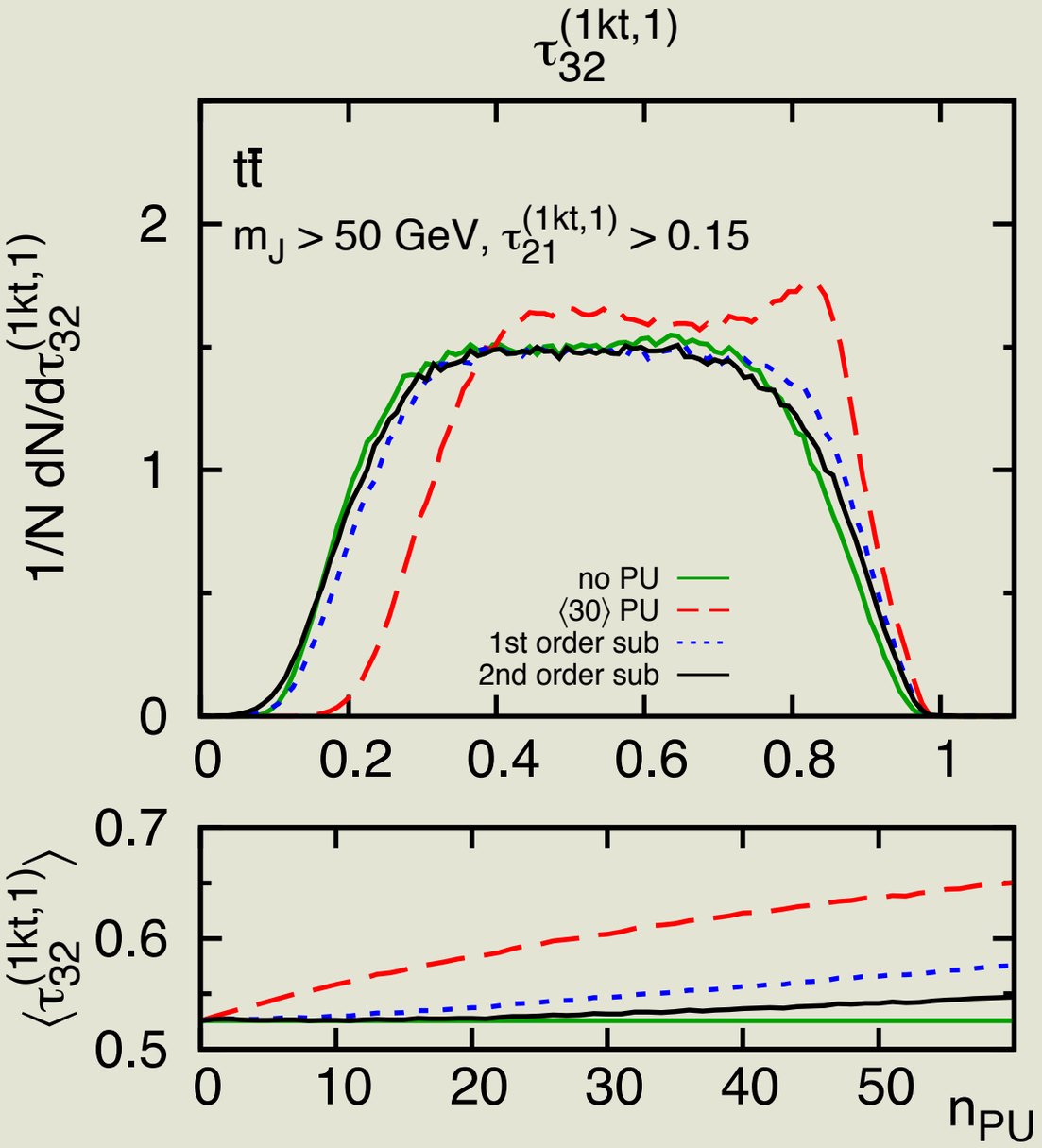
Correcting the τ_{32} distribution



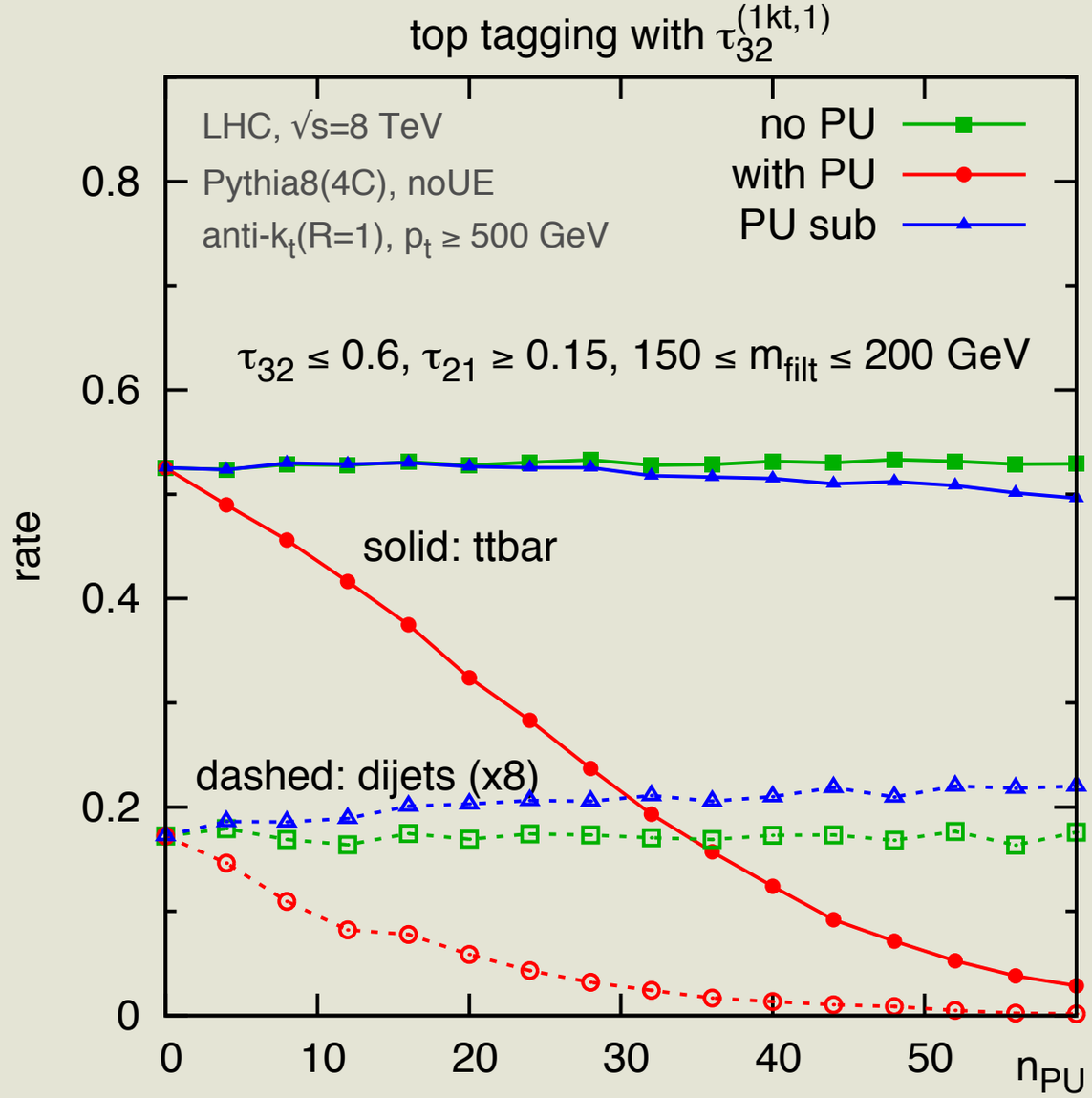
Green: no PU **Red: with PU** **Blue/Black: subtracted**

Practical test: τ_{32} and top tagging

Correcting the τ_{32} distribution



Tagging efficiency



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Summary [and points for discussion]

It's time to make the transition to a deep understanding of our tools, the only way of guaranteeing robustness

- Analytical control of "pronged" taggers now seems to be possible

  [though still early days]

- Taggers can have surprises in store for us – especially when we explore full LHC14 p_t range.

  [They can also be "fixed up", e.g. sane pruning, modified MDT]

- When do we want want to use "radiation-based" taggers?
- Do we need/want continuous resolved–fat-jet analyses?
- Pileup: it's time to start dealing with it systematically in our taggers

  [beyond just grooming, even as part of grooming]

EXTRAS

Different fat-jet tagger types

Prong based

(e.g. HEPTopTagger, Template Tagger)

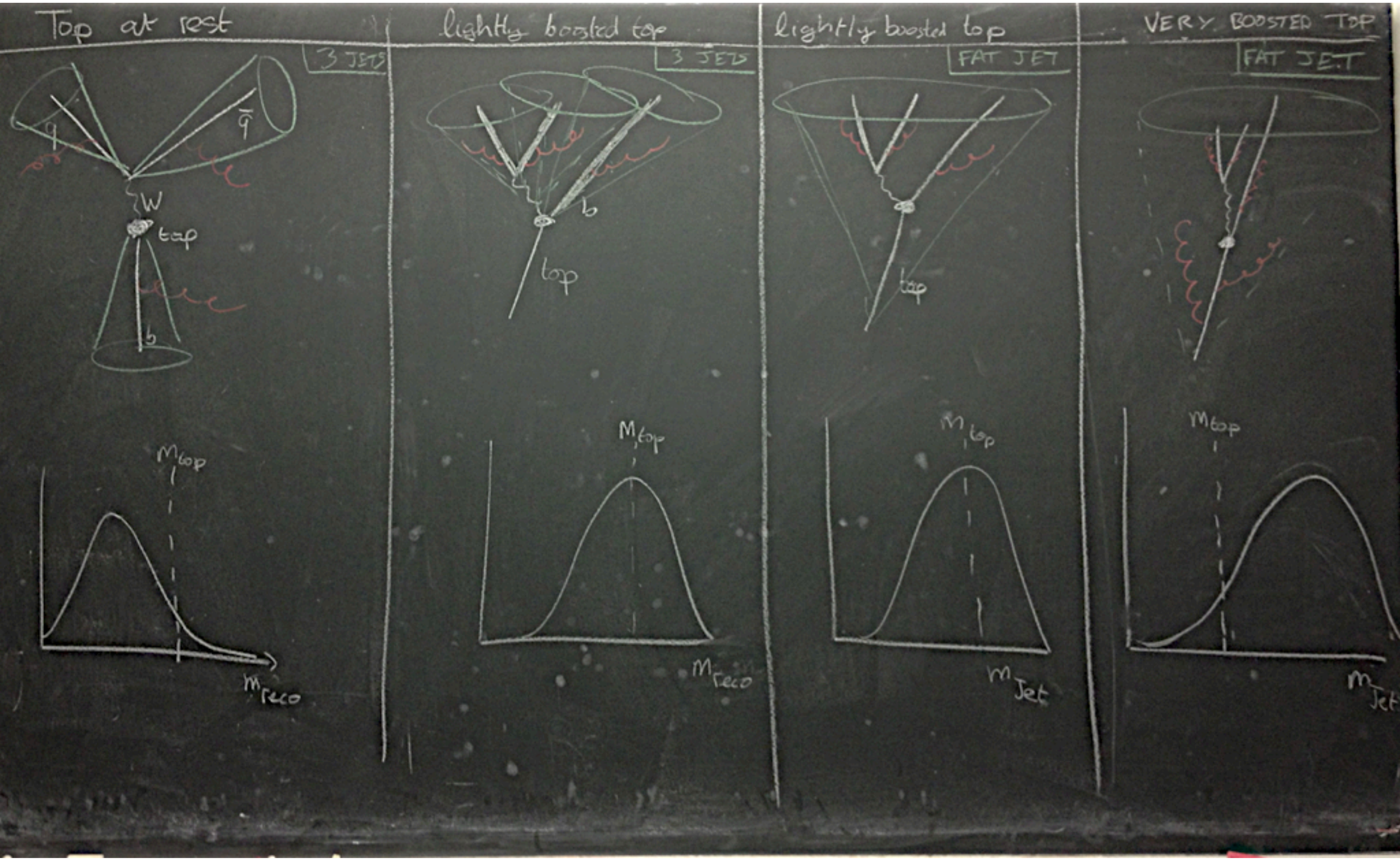
- Identifies prongs
- Requires prongs be consistent with kinematics of $t \to Wb \to$ 3 quarks

Radiation based

(e.g. N-subjettiness = τ_3/τ_2 + mass cut)

- Requires top-mass consistency (maybe with some grooming)
- Exploits weaker radiation from top (3 quarks) than background (1q+2g or 3g)

Top quarks, Tops from quark-jets &Top fat-jets
[and their radiation pattern]



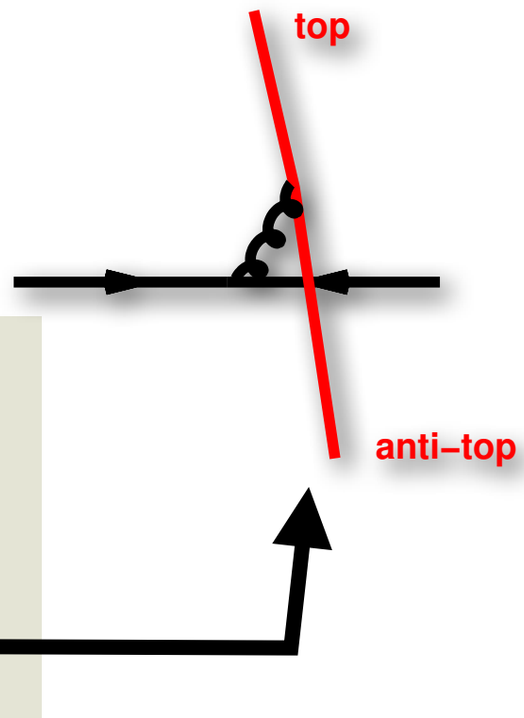
Are top pairs in high-p_t events always back-to-back?

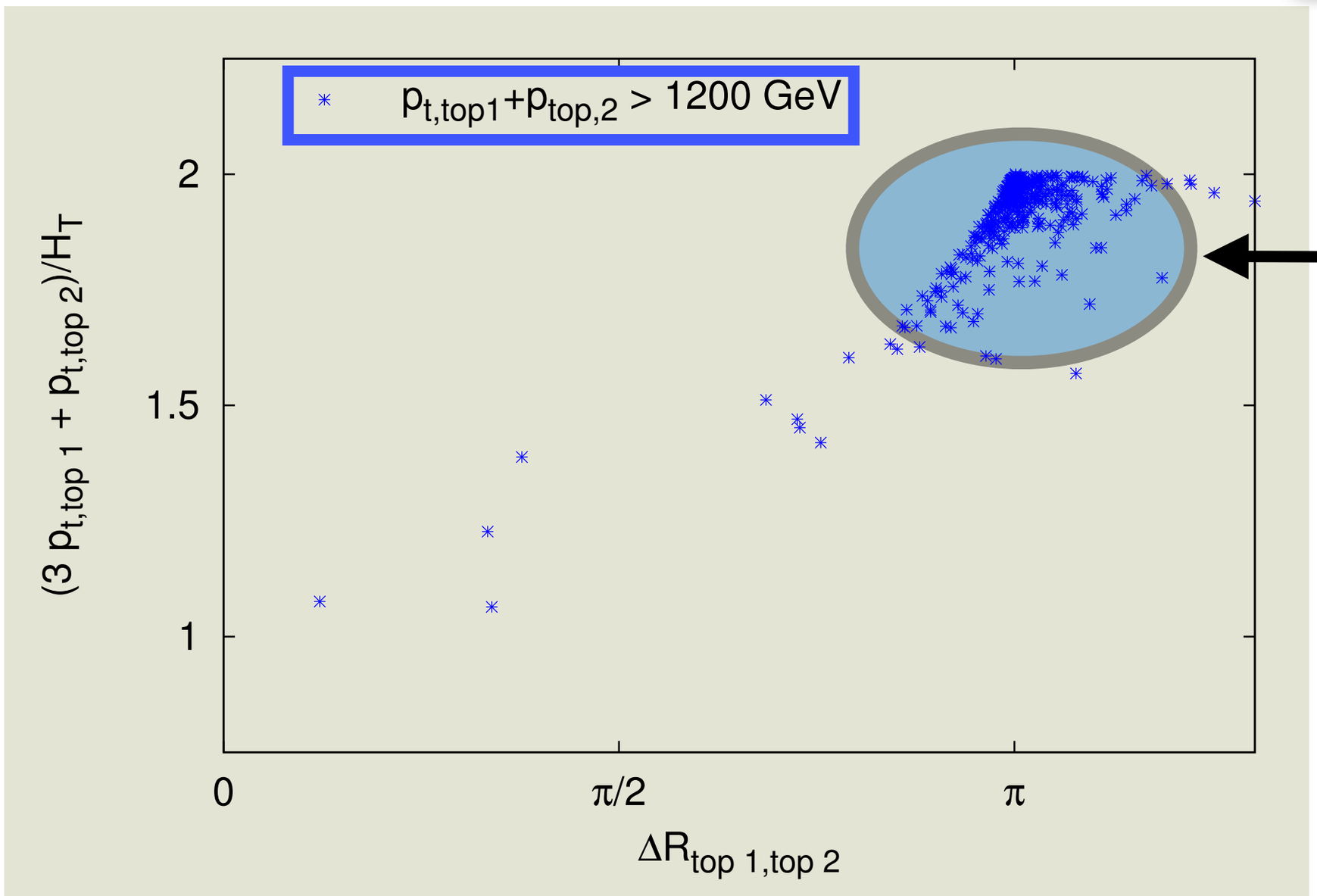
A reminder that top-quarks at LHC are almost “light”

An 8 TeV study with POWHEG, top-pair production, no decay and no parton showering (to keep things simple)

top topology v. cuts

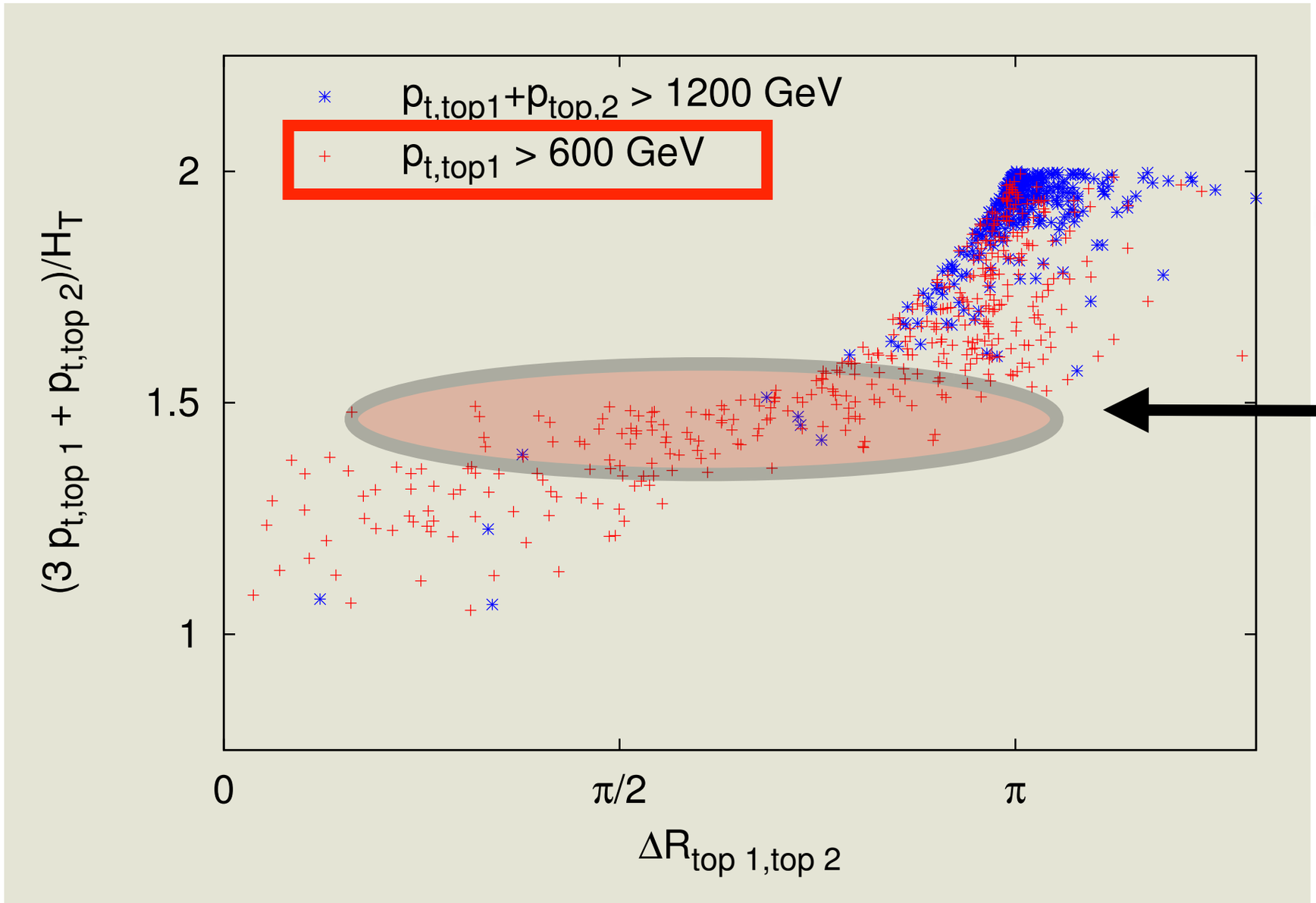
Flavour Creation

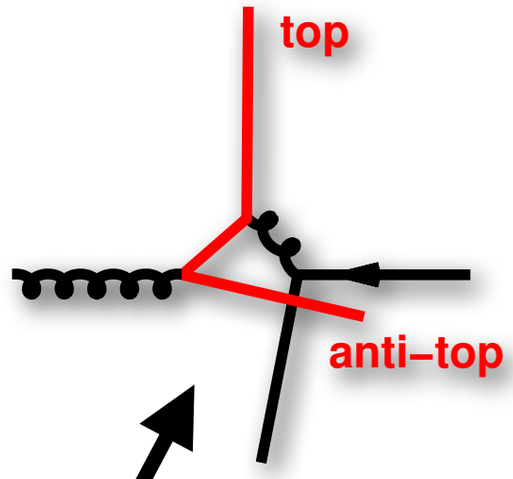




top topology v. cuts

Flavour Excitation – tops inside your PDFs





top topology v. cuts

Gluon Splitting