A Brief, But Biased History of Jets and Jet Substructure (including at the LHC) Part 2

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Steve Ellis

(The oldest person in the room)

Department of Physics
University of Washington

Issues for the LHC (~2005):

- Realized that familiar particles (W,Z,Top) can be boosted enough at the LHC that hadronic decays may be observed as single jet. Want to ID this jets! → TAGGERS
- Finding the Higgs – Are decays into photons and leptons enough? It turns out the answer is yes, but we looked for other ways, like tagged hadronic decays.
- Understood that all jet algorithms include "Uncorrelated" contributions from the underlying event, a situation that grows worse as the luminosity is increased.
- Recognized the need to deal with the underlying event (UE) contributions to jets and the also the worse problem of Pile-Up (PU) events at the eventual large luminosity –we needed GROOMERS

Learn about Substructure of the Jets!

Review:

- JETS: The shower of QCD radiation emitted by colored particles produced (initially) in isolation in momentum space – the dominant feature of hadronic final states at colliders

- JETS: Defined in detail by the specific jet algorithm, i.e., QCD jets have LITTLE INTRINSIC substructure – "everything is a smooth distribution"; plus for QCD jets there is an essential ambiguity – partons are colored while jets are not

- At the LHC "formerly" heavy objects can be boosted sufficiently to be detected as single jets with INTRINSIC substructure, which drove the development of new jet tools

- Jet Substructure Tools:

  Groomers – remove "UN-associated" hadrons from jet (including Underlying event and Pile-Up)

  Taggers – ID the "primary source" of jet, Q vs G, W, Z, H, top, sparticles (?)

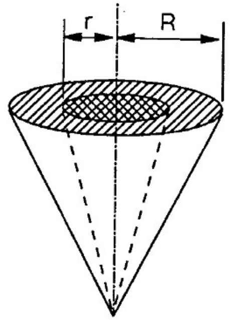
- But details tied to specific jet algorithm – relax that connection ⇒ Qjets

QCD Jets - What was once a signal is now a Bkg!

- Apply algorithm to elements in the detector (tracks, calorimeter cells) and obtain jets as list of such constituents (just partons for the theory case)
- Kinematic details shaped by details of the algorithm
- Mass $$m_{jet}^2 = p_{jet}^{\mu} p_{jet,\mu}, \quad p_{jet}^{\mu} = \sum_{\text{jet constituents } k} p_k^{\mu}$$

  (jets around for ~45 years, but jet masses only looked at seriously for last 7 years, since BOOST 2009 – see BOOST proceedings for detailed explanations)
- Groomed Mass, as above after grooming (removing some constituents)
- Simple related tagger – cut on groomed mass , e.g., jets in mass bin around M_W
- Here focus on example of pruning and pruned mass

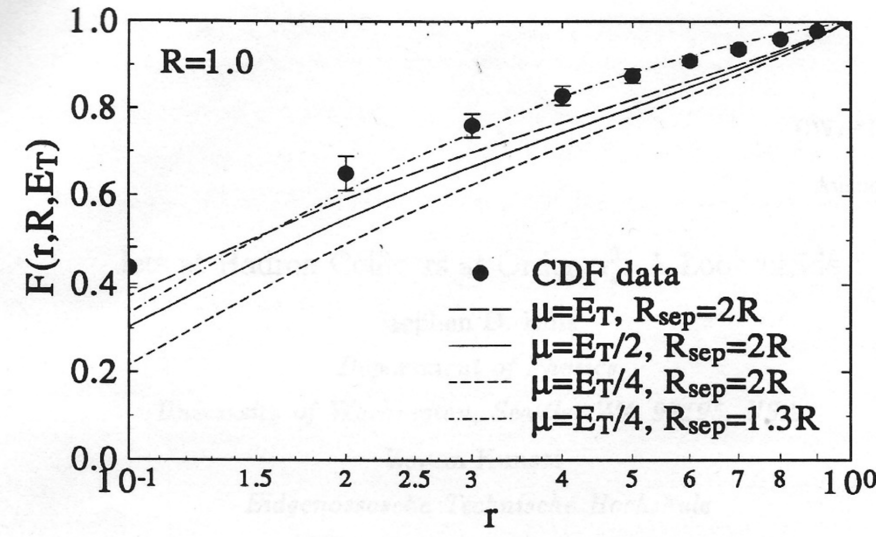
History: Early Jet Substructure



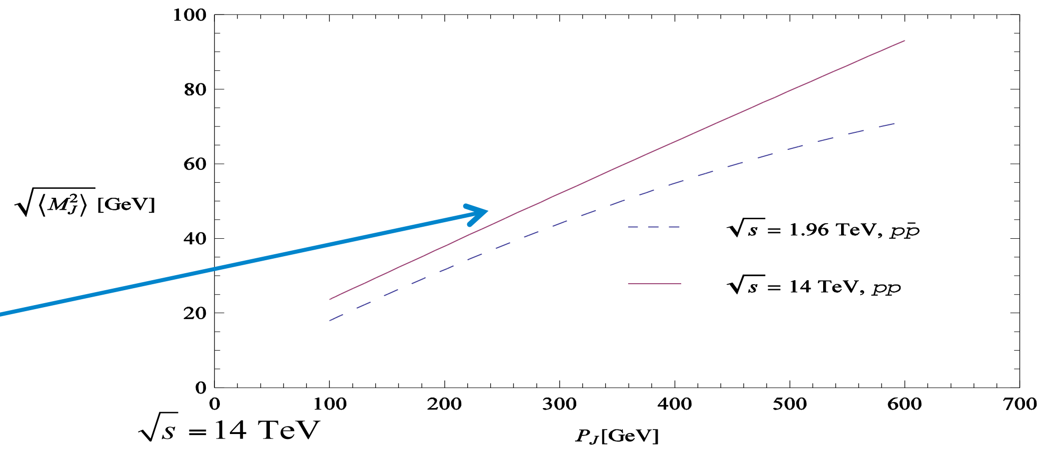
- In the Cone Jet days (1992) Ellis, Kunszt and Soper looked at the distribution of energy within the cone (r < R) at NLO (2 partons in the jet).

- The predicted distribution had more energy near the edge of the cone than the data, illustrating the merge/split issues already mentioned. "Fixed" at the time with a new (and unwanted) parameter R_{sep} (don't include 2 partons further than R_{sep} apart). Consider fraction F of jet E_T inside r. Too much energy near R without R_{sep} fix.

- In 1998 Seymour wrote a prescient paper reminding us of the problems with cones and suggested a better algorithm could allow us to use jet substructure at the LHC. E.g., the Anti-kT algorithm.



Jet Masses in NLO QCD: A Brief Review



- In NLO PertThy (EKS)

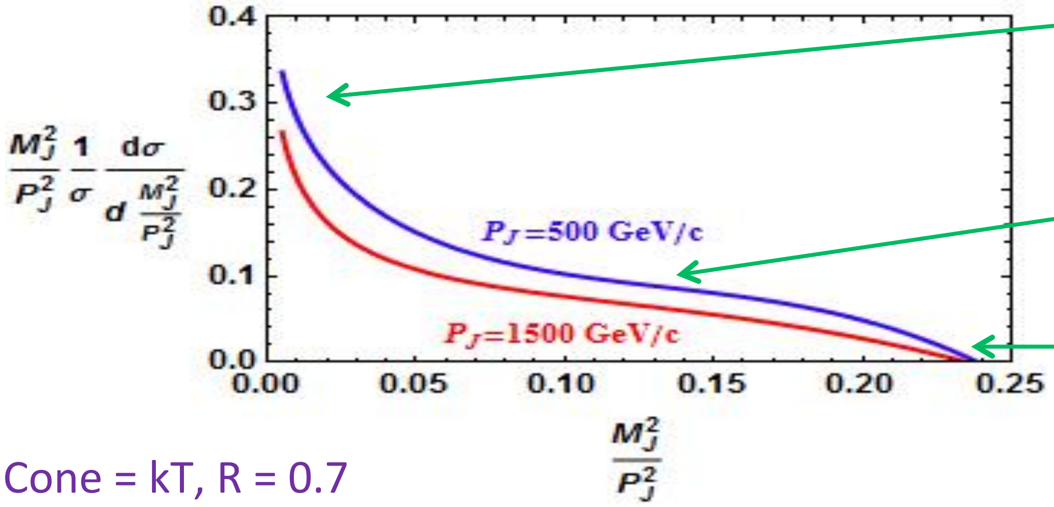
$$\sqrt{p_{J,\mu}p_J^\mu} \Rightarrow \sqrt{\langle M^2 \rangle_{NLO}} = f\left(\frac{p_J}{\sqrt{s}}\right)\sqrt{\alpha_s(p_J)}\,p_J R$$

$\sqrt{s} = 14$ TeV

Phase space from pdfs, $f \sim 1$ & const

Dimensions

Jet Size, $R \sim \Delta\theta$, determined by jet algorithm



Peaked at low mass due to soft, collinear emission (log(m)/m behavior)

"Shoulder" where mass arises from hard, large angle emission

Cuts off for $(M/P)^2 > 0.25 \sim R^2/4$
(M/P > 0.5) large mass can't fit in fixed size jet,
QCD suppressed for M/P > 0.3 ($\sim \gamma < 3$)

Cone = kT, R = 0.7

Useful QCD "Rule-of-Thumb"

$$\Rightarrow \sqrt{\langle M^2 \rangle_{NLO}} \sim 0.2\,p_J R\,(1 \pm 0.25)$$

Recombination Algorithms – focus on undoing the shower

Merge partons, particles or towers pairwise based on "closeness" defined by minimum value of k_T, *i*.e. make list of metric values
(rapidity *y* and azimuth ϕ, p_T transverse to beam)

$$\text{Pair } ij: k_{T,(ij)} \equiv \text{Min}\left[\left(p_{T,i}\right)^\alpha, \left(p_{T,j}\right)^\alpha\right] \frac{\sqrt{\left(y_i - y_j\right)^2 + \left(\phi_i - \phi_j\right)^2}}{R} \equiv \text{Min}\left[\left(p_{T,i}\right)^\alpha, \left(p_{T,j}\right)^\alpha\right] \frac{\Delta R_{ij}}{R},$$

$$\text{Single } i: k_{T,i} = \left(p_{T,i}\right)^\alpha$$

If $k_{T,(ij)}$ is the minimum, merge pair (add 4-vectors), replace pair with sum in list and redo list;

If $k_{T,i}$ is the minimum $\rightarrow$ *i* is a jet! (no more merging for *i*, it is isolated by *R*),

1 angular size parameter *R*, plus

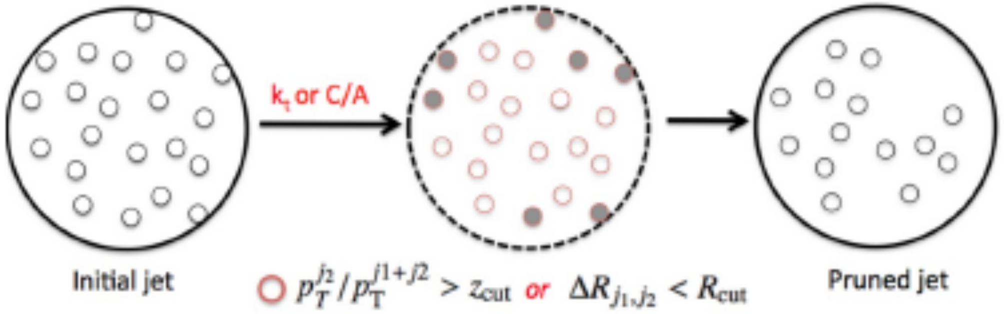
$\alpha = 1$, ordinary k_T, recombine soft stuff first

$\alpha = 0$, *Cambridge/Aachen* (CA), controlled by angles only

$\alpha = -1$, *Anti-*k_T, just recombine stuff around hard guys – cone-like (with seeds)

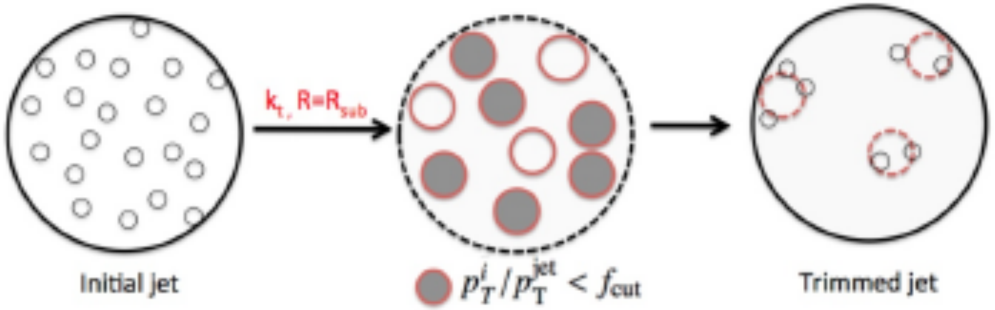
Sample Groomers – (figures from ATLAS 1306.4945)

Pruning



Based on properties at 2 → 1 mergings

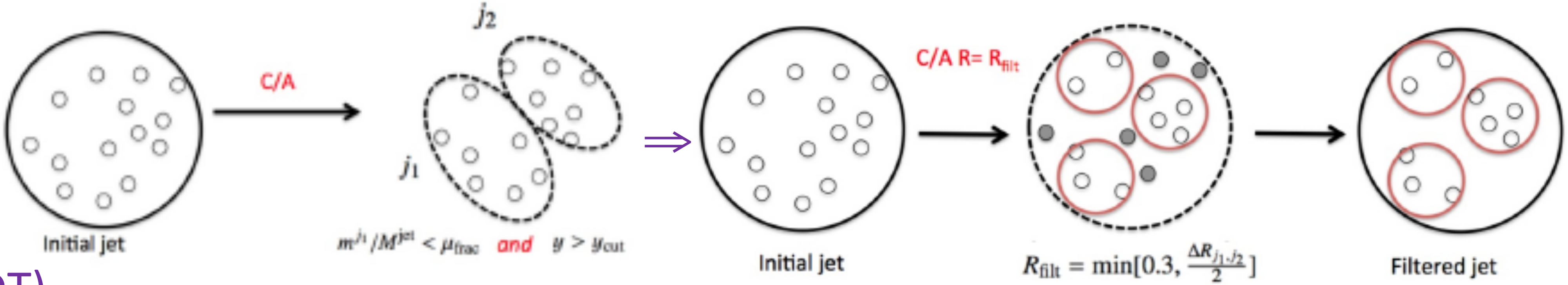
Trimming



Based on properties of subjets

Mass Drop, Filtering

Also Modified Mass Drop (mMDT)



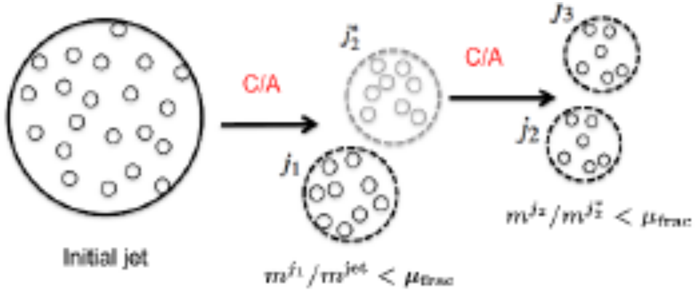
Sample Taggers -

- Simplest – Groom and cut on mass

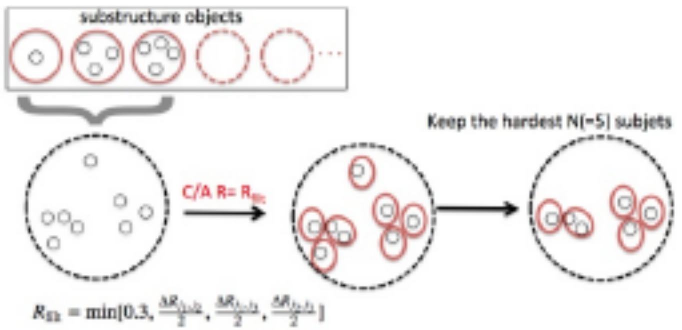
- More elaborate
  – HEP TopTagger

  look for specific number of subjets

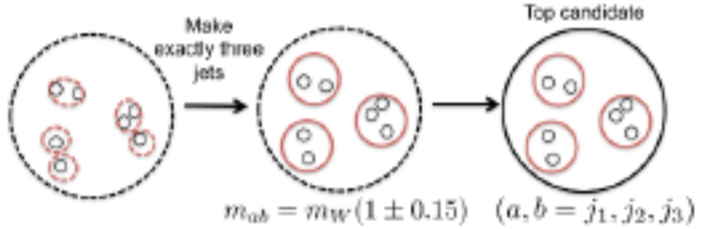
(a) Every object encountered in the declustering process is considered a 'substructure object' if it is of sufficiently low mass or has no clustering history.



(b) The mass-drop criterion is applied iteratively, following the highest subjet-mass line through the clustering history, resulting in N_i substructure objects.



(c) For every triplet-wise combination of the substructure objects found in (b), recluster the constituents into subjets and select the N_{subjet} leading-p_T subjets, with $3 \le N_{subjet} \le N_i$ (here, $N_{subjet} = 5$).



(d) Recluster the constituents of the N_{subjet} subjets into exactly three subjets to make the top candidate for this triplet-wise combination of substructure objects.

A Brief Review of Pruning (Ellis, Vermilion and Walsh, 2009)

- Like other groomers, given a jet (identified by some generic jet algorithm like AkT, kT or C/A) pruning attempts to remove from the jets those constituents that are UNlikely to be ``associated'' with the jet or at least carry no significant/useful information.

- In particular, we expect the mass of the resulting pruned jet to be small if we start with an every-day QCD jet, and near the particle mass if we start with a jet containing the decay products of a heavy particle. Thus can use in a TAGGER.

- Pruning will can remove much of the uncorrelated contributions from UE and PU that make significant contributions to the jet mass.

Basic Idea of Pruning -

- Prune (remove) those constituents of the original jet that are:
  soft
  large angle

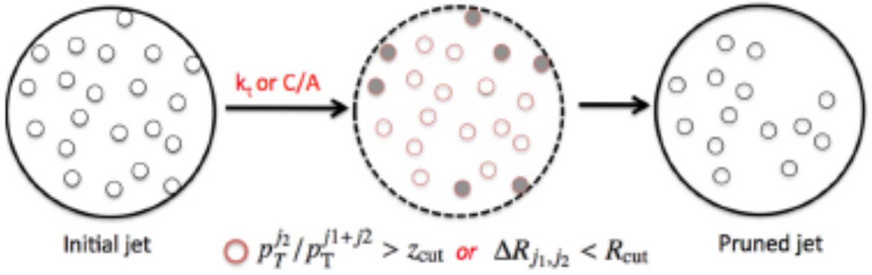
- These soft, large angle constituents are (statistically) less likely to be correlated with the energetic constituents in the jet and yet can still make measureable contributions to the mass

- Soft, small angle constituents can also be uncorrelated (UE, PU), but make a small contribution to the mass

- Most configurations that arise from actual heavy particle decay will not tend to be pruned (not all, but most).

Pruning in Action -

- Given the list of constituents in a jet, remerge using the kT or C/A algorithm



- At each potential merging step, j+k → l, check for soft - $p_k/p_l < z_{cut}$ ($p_k < p_j$)

  large angle - $\Delta R_{jk} > R_{cut}*(2m_{jet}/p_{jet})$,
  where $2m_{jet}/p_{jet}$ is angular scale **set by jet itself**

- If **both** cuts are satisfied, prune (remove) constituent k and proceed

- **Larger** z_{cut} and **smaller** R_{cut} values correspond to more **aggressive** pruning

- The level of pruning tends to be determined by the **LESS** aggressive of the two parameters (since we must satisfy **both** cuts)

Default Parameters

- The original studies (0912.0033) suggested

  R_{cut} = 0.5 (kT & C/A) $\Rightarrow \Delta R > m_{jet}/p_{jet}$

  z_{cut} = 0.1 (C/A)

  z_{cut} = 0.15 (kT, since nearby soft constituents are merged early and are no longer as soft)

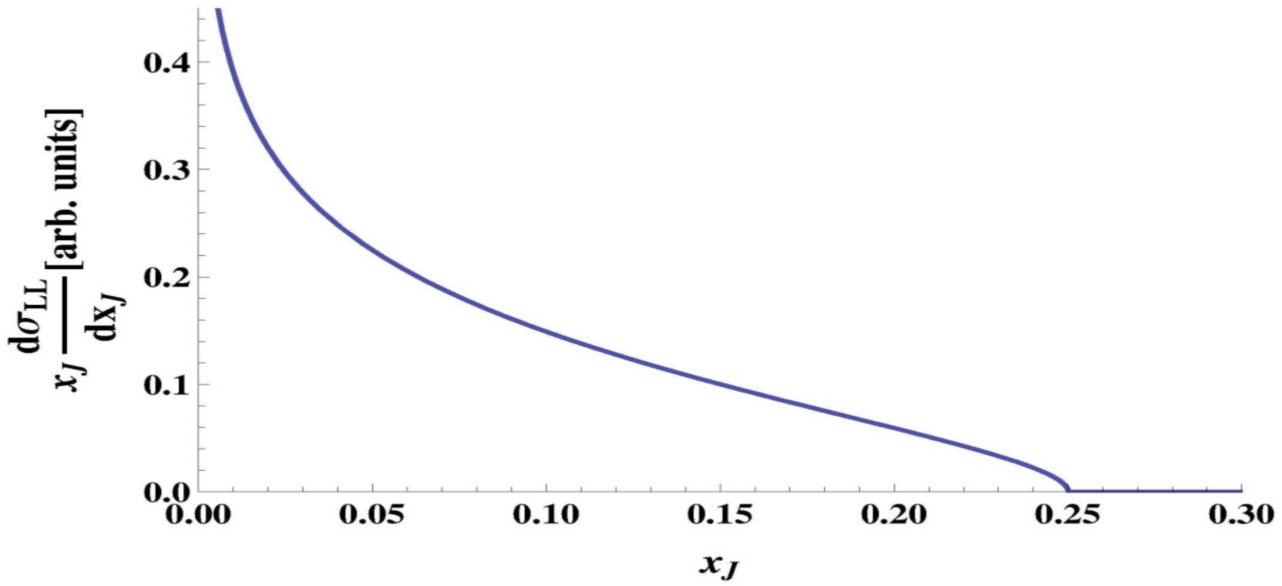
- Also, to ensure that decay products of "signal" particle "fit" in jet (size R) and are rarely pruned,

  require $m_{particle}/p_{jet}/R$ be less than 0.5

Recall Naïve NLO 2-body analysis

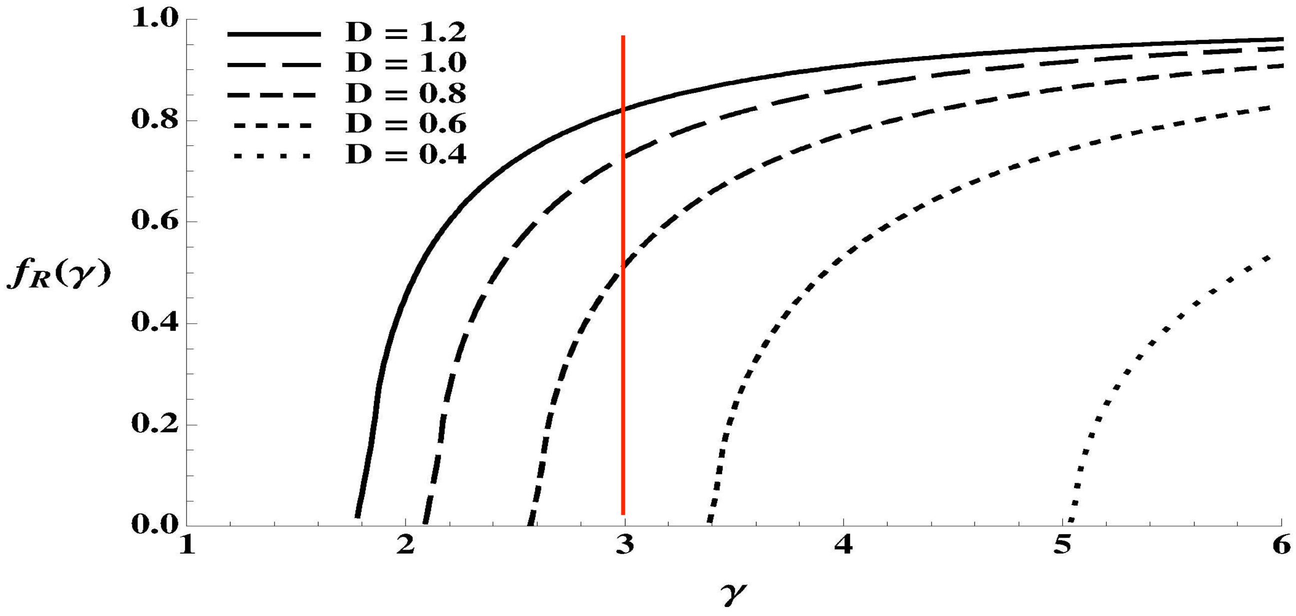
- Distribution vanishes above $x_J = (m_{particle}/p_{jet}/R)^2 = 0.25$ (from 0912.0033)

- With more complete showering the distribution goes past 0.25 but the "shoulder" is rapidly falling there



Also (more forgotten history?)

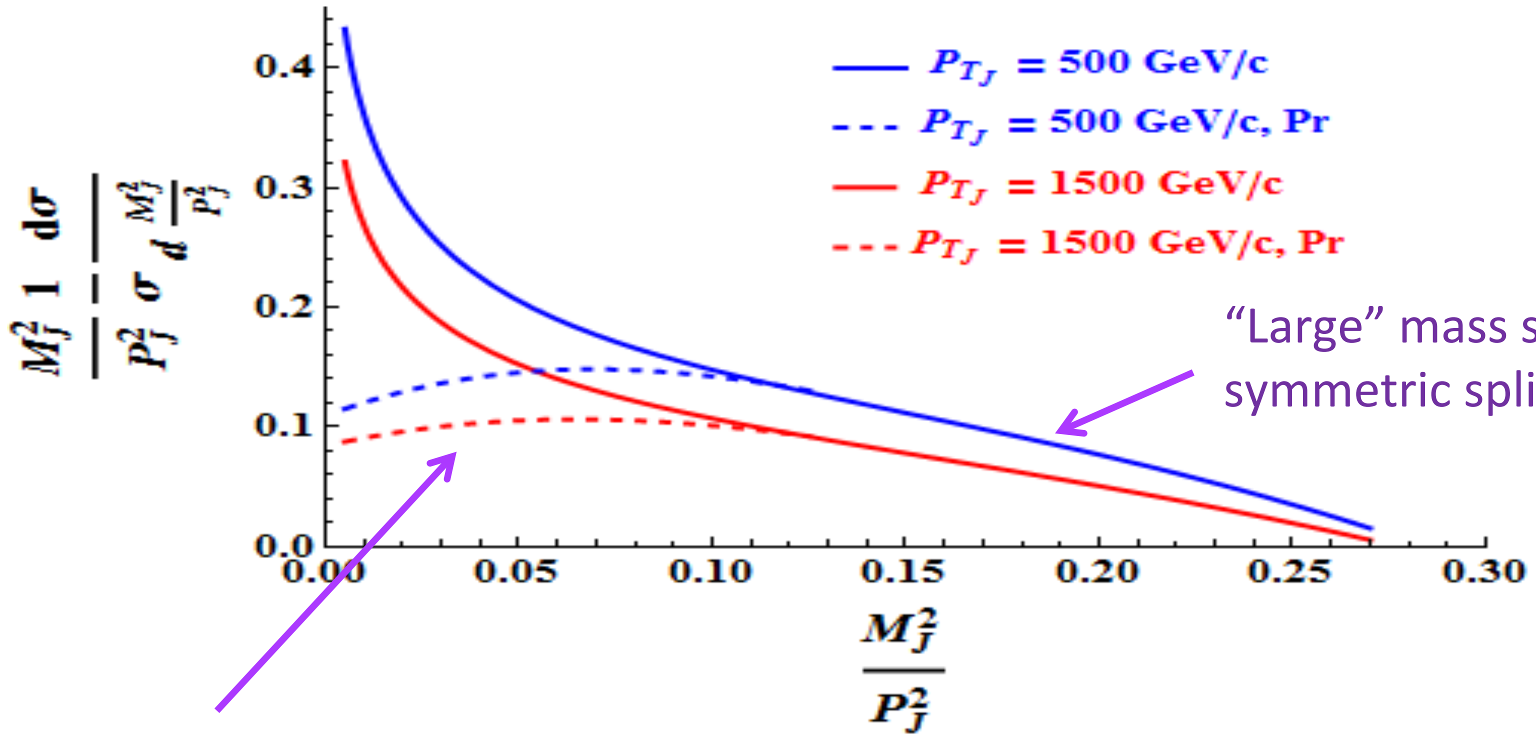
- Recall Figure 11 from 0912.0033, which shows the fraction of two-body decays that "fit" in a jet of size R (=D).



- Consider a W with pT of order 250 to 300 GeV/c, and thus a γ of about 3.
- About 50% of the W's don't fit for R = 0.8, while about 15% still don't fit for R = 1.2.
- The W's that don't fit will populate the low mass bump.
- The situation is substantially improved for larger pTs (> 450 GeV, γ > 5).

Groomed (Pruned) Fixed Order (NLO) Result (dashed):

Pruning removes, soft, wide angle constituents



"Large" mass shoulder unchanged (hard, symmetric splitting is not pruned)

Prune "small" masses to zero mass (soft, wide angle emission is pruned), only one parton remains in jet

More realistic add shower to all orders (radiation from colored partons)

- Probability of no extra emissions and zero mass goes to zero (Sudakov ~ $\exp[-(\alpha_s/2\pi)C_{A/F} \ln^2(m^2/pT^2)]$).

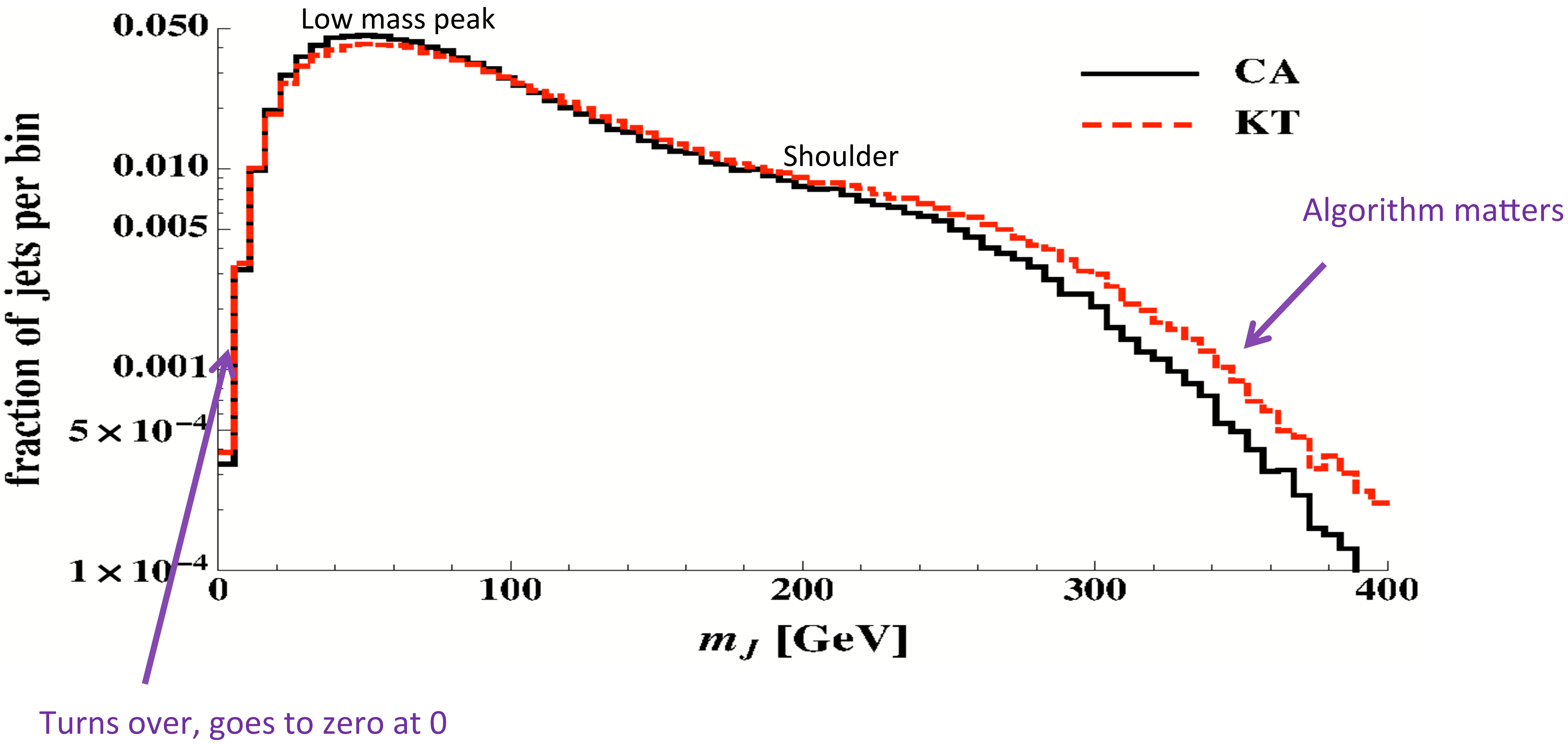
- Low mass peak moves away from origin.

- Shoulder region only slightly changed.

- Low mass peak order ~ 1, shoulder order α_s (factor ~ 1/10)

  – can use log on y-axis to resolve both.

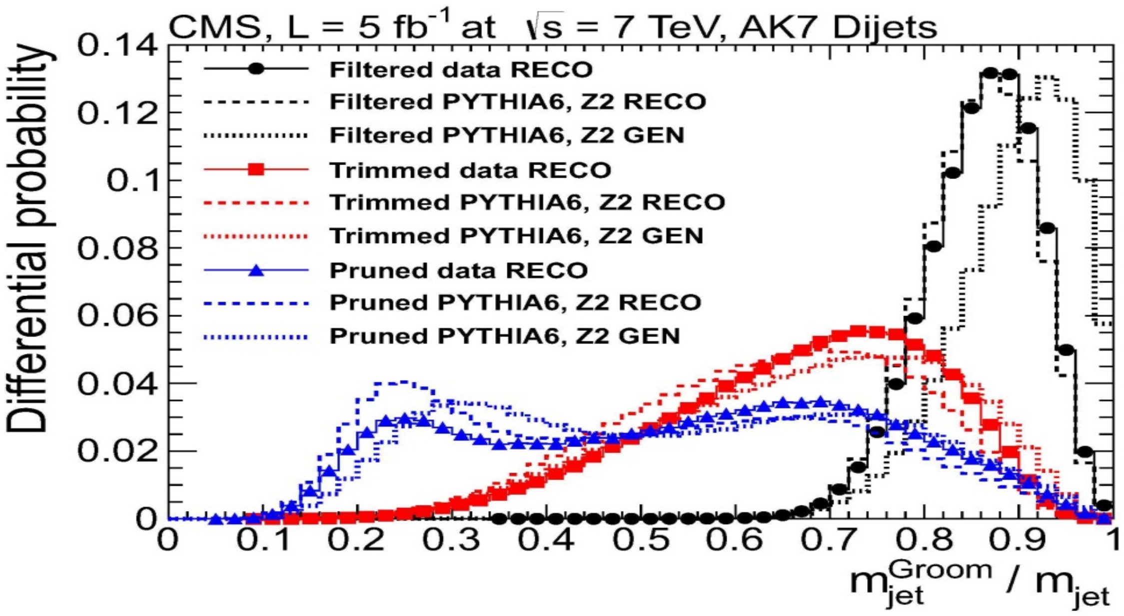
Jet Mass in PYTHIA (showered & matched set)
R = 1, 500 GeV/c < pT < 700 GeV/c

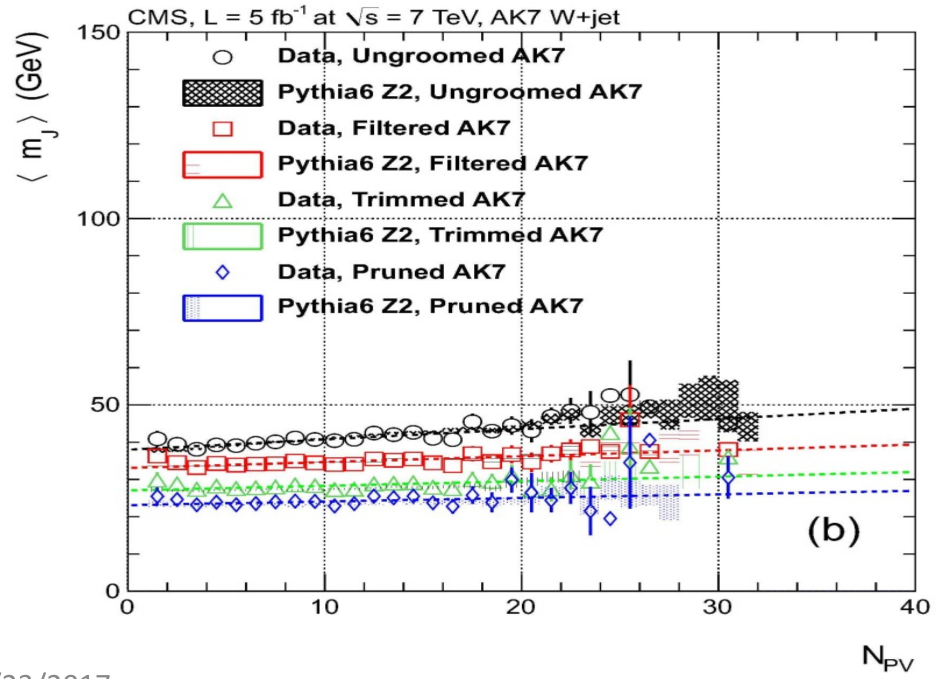


Pruning at CMS, e.g., 1303.4811

- Prune with C/A using parameters
  z_{cut} = 0.1 (default)
  R_{cut} = 0.25, $\Delta R > 0.5\ m_{jet}/p_{jet}$ (aggressive)

- Conclude that Pruning is most aggressive groomer studied -





Pruning at ATLAS – Comments/Explanations (a cautionary tale)

A dramatic contrast (to my thoroughly biased eye) between the CMS and ATLAS jet grooming/tagging analyses as reported at BOOST 2013 and the Boosted Boson Workshop (CERN, 3/25/14) –

$\Rightarrow$ CMS analyses finds jet pruning is **very** effective

$\Rightarrow$ ATLAS finds pruning is **not** very effective!

☹☹☹☹ at UW!!!!!

The following comments attempt to explain this difference between the two collaborations.

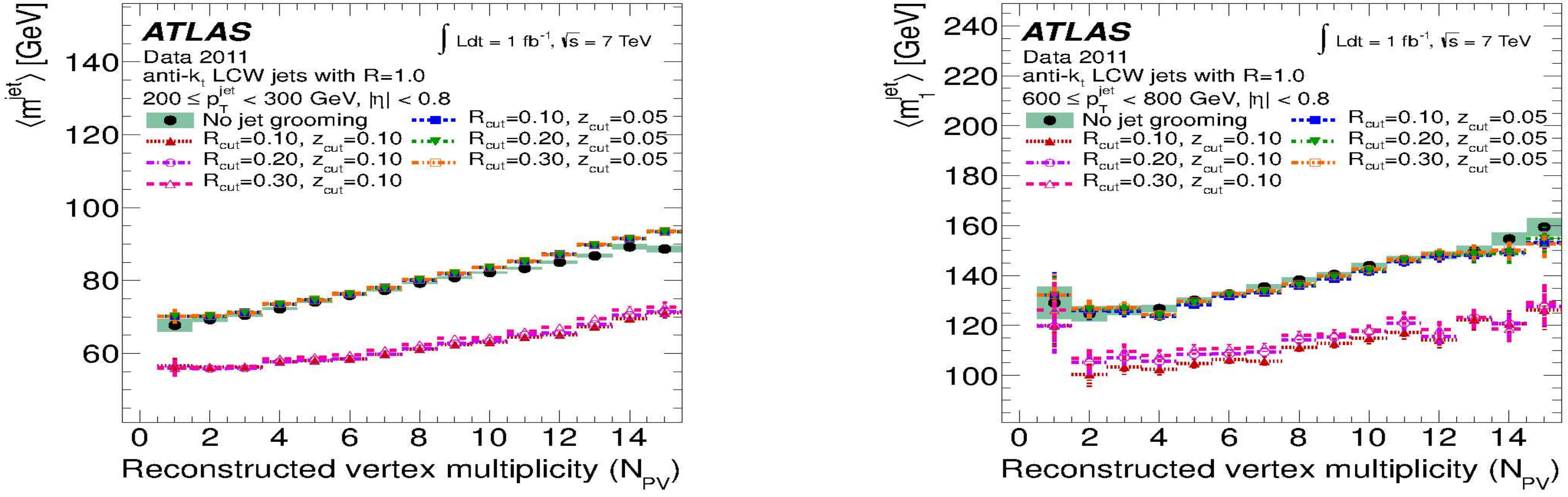
Pruning Refs: 0912.0033, 0903.5081

Compare - Pruning at ATLAS – 1306.4945

- Prune with kT using parameters

z_{cut} = 0.1, 0.05 (less aggressive than default = 0.15)

R_{cut} = 0.1, 0.2, 0.3, $\Delta R > R_{cut}\ (2m_{jet}/p_{jet})$ (more aggressive than default)



- Conclude pruning is **NOT** very effective groomer – **AS EXPECTED** due to parameter choices

ATLAS results – ATL-PHYS-PUB-2014-004 (3/26/14)

- Study 5 combinations of algorithm + groomer, :
  AK10 + trim, C/A12 + BDRS, C/A12 + BDRS-A,
  C/A8 + C/A prune (0.1,0.5 = default),
  C/A8 + kT prune (0.1,0.5 less aggressive than default as above)

  in 3 pT bins using 7 kinematic variables for W tagger

- First do ROC study of algorithm + groomer: define groomed jet mass window to keep 68% of signal (W) and check QCD fake rate (MC data, check that found jets match truth jets almost all of time)

ATL-PHYS-PUB-2014-004

- Results (Table 1) - ε_{QCD} = fake rate, $\mathcal{P}^{+\mathcal{U}}{}_{-\mathcal{L}}$= mass window

Jet collection	$200 < p_T^{turth} < 350$ GeV		$350 < p_T^{truth} < 500$ GeV		$500 < p_T^{truth} < 1000$ GeV	
	$\mathcal{P}^{+U}_{-L}$ [GeV]	ϵ_{QCD}	$\mathcal{P}^{+U}_{-L}$ [GeV]	ϵ_{QCD}	$\mathcal{P}^{+U}_{-L}$ [GeV]	ϵ_{QCD}
Trimmed	82^{+10}_{-18}	$13.6 \pm 0.1\%$	80^{+8}_{-8}	$9.9 \pm 0.2\%$	82^{+10}_{-10}	$8.4 \pm 0.5\%$
BDRS	78^{+14}_{-16}	$14.8 \pm 0.1\%$	80^{+6}_{-18}	$7.8 \pm 0.2\%$	76^{+6}_{-14}	$6.7 \pm 0.5\%$
BDRS-A	78^{+12}_{-16}	$23.2 \pm 0.1\%$	82^{+8}_{-14}	$15.9 \pm 0.3\%$	80^{+10}_{-14}	$10.0 \pm 0.6\%$
C/A-pruned	78^{+22}_{-40}	$28.9 \pm 0.1\%$	78^{+8}_{-12}	$8.0 \pm 0.2\%$	78^{+6}_{-14}	$6.5 \pm 0.5\%$
k_t-pruned	84^{+22}_{-42}	$40.7 \pm 0.2\%$	82^{+16}_{-14}	$16.9 \pm 0.3\%$	82^{+18}_{-14}	$16.4 \pm 0.7\%$

- kT-pruned performs less well (larger ε_{QCD}) than C/A pruned, **as expected** due to (poor) parameter choice

- In largest 2 pT bins C/A pruning is (effectively) tied for **most** aggressive groomer, smallest ε_{QCD} (like CMS)

What happens in the lowest pT bin?

Recall that
$\mathcal{P}^{+\mathcal{U}}_{-\mathcal{L}}$= mass window

Jet collection	$200 < p_T^{turth} < 350$ GeV		$350 < p_T^{truth} < 500$ GeV		$500 < p_T^{truth} < 1000$ GeV	
	$\mathcal{P}^{+U}_{-L}$ [GeV]	ϵ_{QCD}	$\mathcal{P}^{+U}_{-L}$ [GeV]	ϵ_{QCD}	$\mathcal{P}^{+U}_{-L}$ [GeV]	ϵ_{QCD}
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k_t-pruned	84^{+22}_{-42}	$40.7 \pm 0.2\%$	82^{+16}_{-14}	$16.9 \pm 0.3\%$	82^{+18}_{-14}	$16.4 \pm 0.7\%$

Pruned mass window
for lowest pT bin is **TWICE** the size of the other mass windows, essentially **DOUBLES** the fake rate!

Why is this large mass window needed?

Because these low pT (low boost) W's are difficult to fit in a small R (0.8) jet, i.e., we are on the **low** efficiency edge of the shoulder
– should plot the distribution versus $(m_{particle}/p_{jet}/R)^2$ to check!

Comments:

- Pruning is observed to be performant at ATLAS when **appropriate** parameter values are chosen, i.e., consistent with CMS

- Analysis of lowest pT bin needs to be clarified (boost too small for small R?)

- ATLAS study has kinematic variable correlation information, but currently difficult to interpret due to multiple “knobs” being turned at once (e.g., vary algorithm AND R values)

- **Experimental folks should talk to their Theory friends often!!**

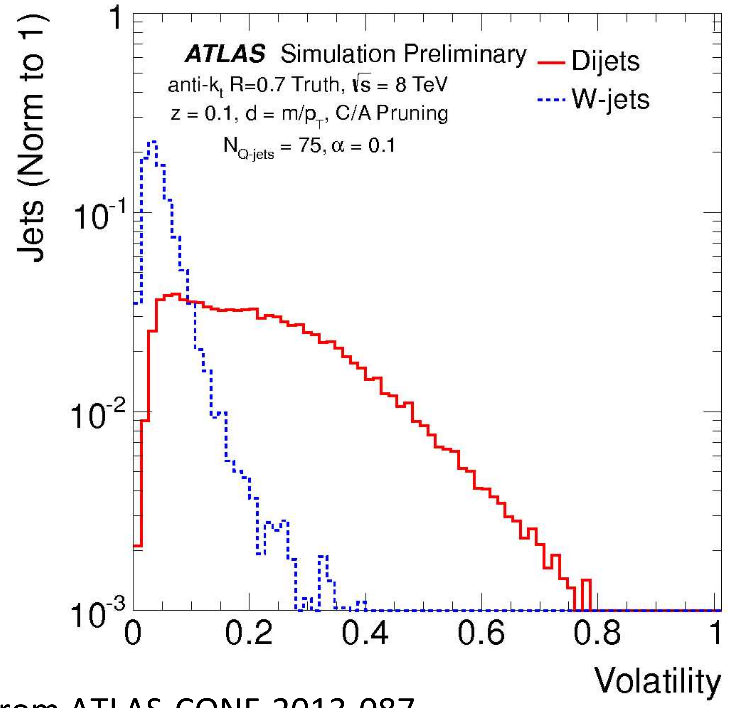
Qjets & Volatility (Γ) (Ellis, Hornig, Krohn, Roy and Schwartz, 2012)

- Qjet idea is that there is no "correct" algorithm for pruning (or grooming in general);
- So prune several times with a defined but "random" set of algorithms;
- Generates a mass DISTRIBUTION for each jet;
- The width of this distribution is the volatility Γ;
- A jet containing a real decay will exhibit small volatility, while QCD jets exhibit larger volatility;

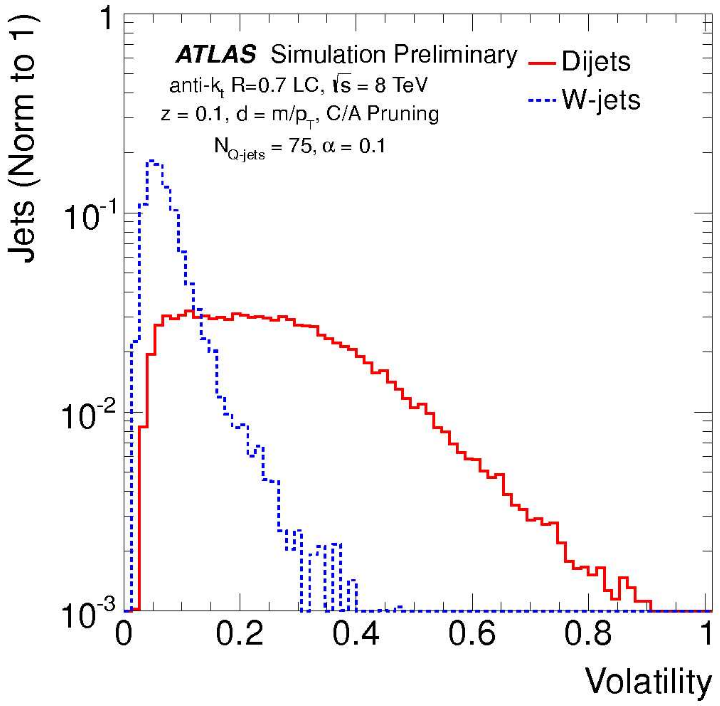
Volatility – a sophisticated Qjet variable

For jet sample make plot of Volatility values (distribution)

As expected Volatility distribution is BROADER for QCD than boosted W

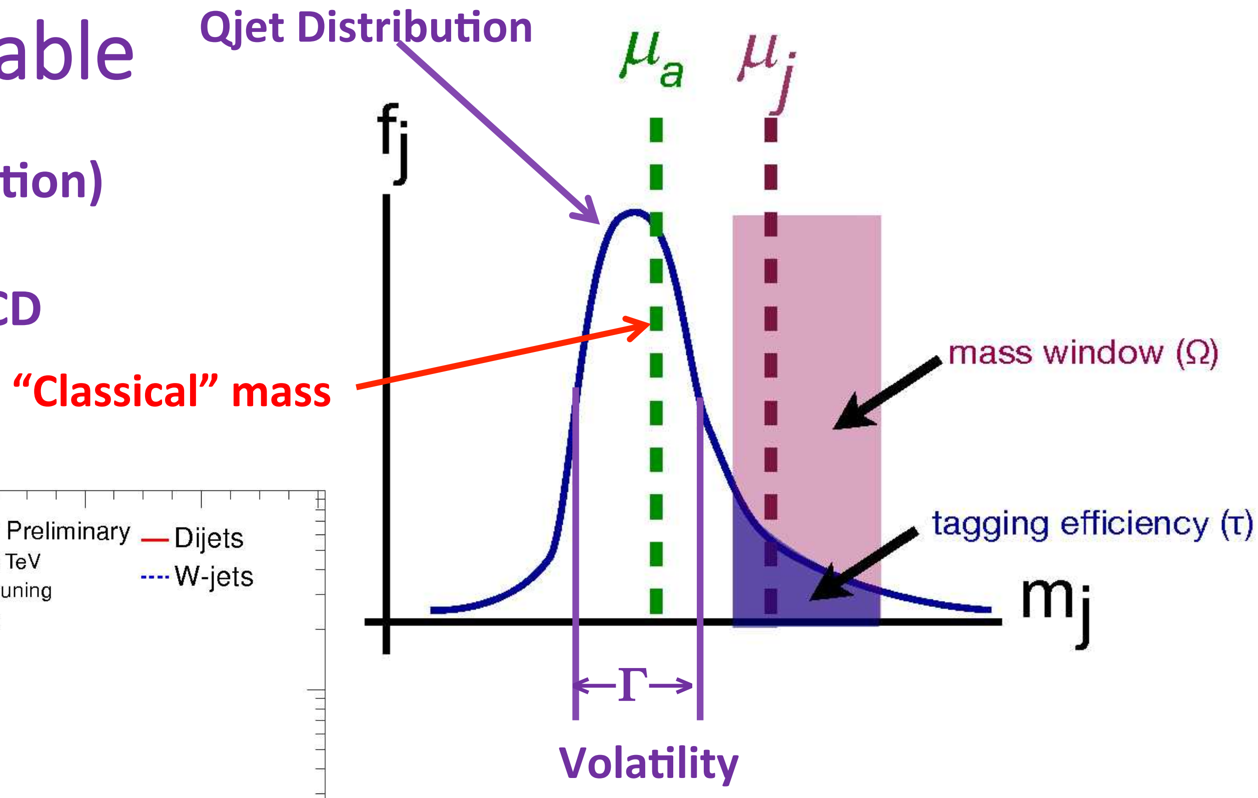


(a) Truth Jets



(b) Reconstructed Jets

From ATLAS-CONF-2013-087



$$\Gamma \equiv \frac{\sqrt{\langle m_j^2 \rangle - \langle m_j \rangle^2}}{\langle m_j \rangle}$$

Qjets details (from ATLAS-CONF-2013-87)

1. Start with a jet found by any jet algorithm and collect the constituents into a list.

2. Compute a set of weights ω_{ij}, which reflect how likely a pair of four-vectors is to be merged, for all pairs of four-vectors. Here, the weights are chosen to be defined as:

$$\omega_{ij}^{(\alpha)} = \exp\left\{-\alpha \frac{d_{ij} - d^{\min}}{d^{\min}}\right\} \quad (3)$$

   where α is the *rigidity* which controls the sensitivity of the pair selection to the random number generation, $d_{ij} \equiv \Delta R_{ij}^2 = \Delta y_{ij}^2 + \Delta\phi_{ij}^2$ the distance measure for the (i, j) pair and $d^{\min}$ the minimum of the distance between all pairs. Then the probability $\Omega_{ij} = \omega_{ij}/N$ is defined, where $N = \sum \omega_{ij}$.

3. Instead of finding the single minimum d_{ij} as in Equation 1, generate a random number, using Equation 3 as a probability density function, and choose a pair of four-vectors as above according to the probabilities Ω_{ij}.

4. Consider this pair for merging, and veto (as in normal pruning) if they fail the cuts in Equation 2.

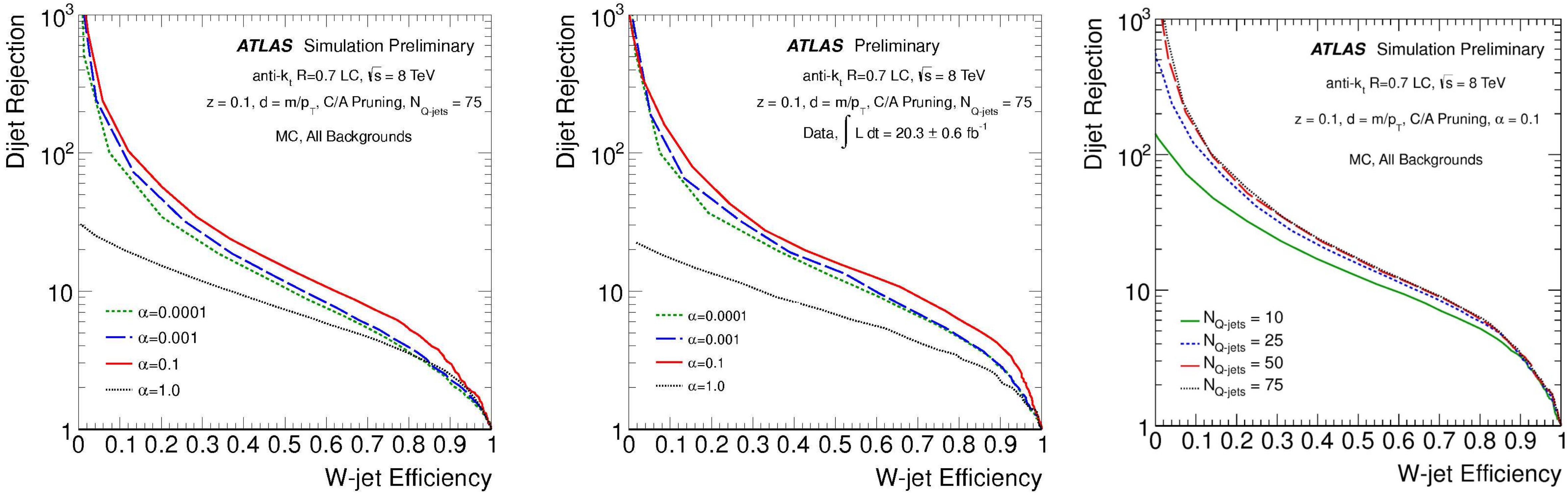
5. Continue until all pairs are merged: the result is one Q-jet. The algorithm can be repeated multiple times to generate a distribution of Q-jets for every jet.

1) $$d_{ij} = \min\left(p_{\mathrm{Ti}}^{\beta}, p_{\mathrm{Tj}}^{\beta}\right) \frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = p_{\mathrm{Ti}}^2$$

2) $$z_{ij} = \frac{\min(p_{\mathrm{T},i}, p_{\mathrm{T},j})}{|\vec{p_{\mathrm{T},i}} + \vec{p_{\mathrm{T},j}}|} < z_{\mathrm{cut}} \text{ and } \Delta R_{ij} > d_{\mathrm{cut}}.$$

Cut on Γ as tagger – from same ATLAS analysis ("ROC" curves)



Good basic Tagger! Even with just 25 iterations per jet

From ATLAS-CONF-2013-087

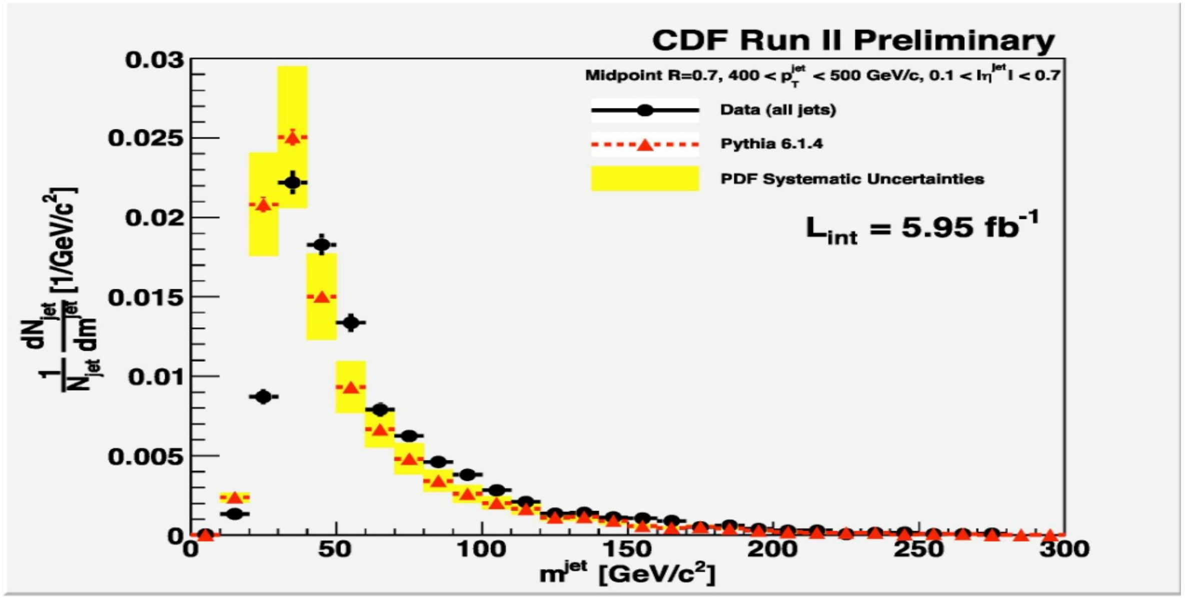
Conclusions (2017):

- Jets are an extremely useful feature of the final states in high energy hadronic collisions.
- QCD and modern calculational techniques allow us to understand, with good precision, the production rates of jets as defined by modern jet algorithms.
- Progress in the last 10 years, both theoretical and experimental, provide us with techniques to TAG jets resulting from the production of heavy particles (vs those from light partons).
- Likewise we have techniques to GROOM and to control the impact of uncorrelated contributions from Pile Up.
- JETS ARE GREAT!!

Hear the latest results this week!
Learn how to use them.

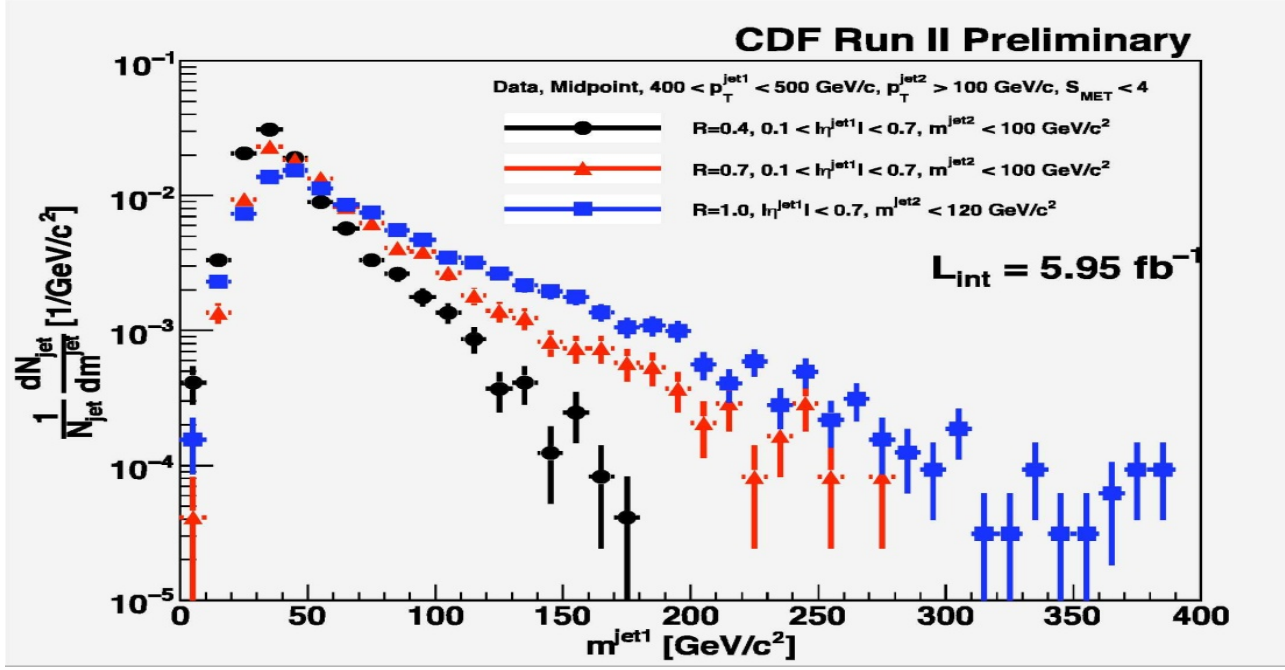
Extras

Jet Mass – CDF Data (CDF/PUB/JET/PUBLIC/10199 7/19/10)

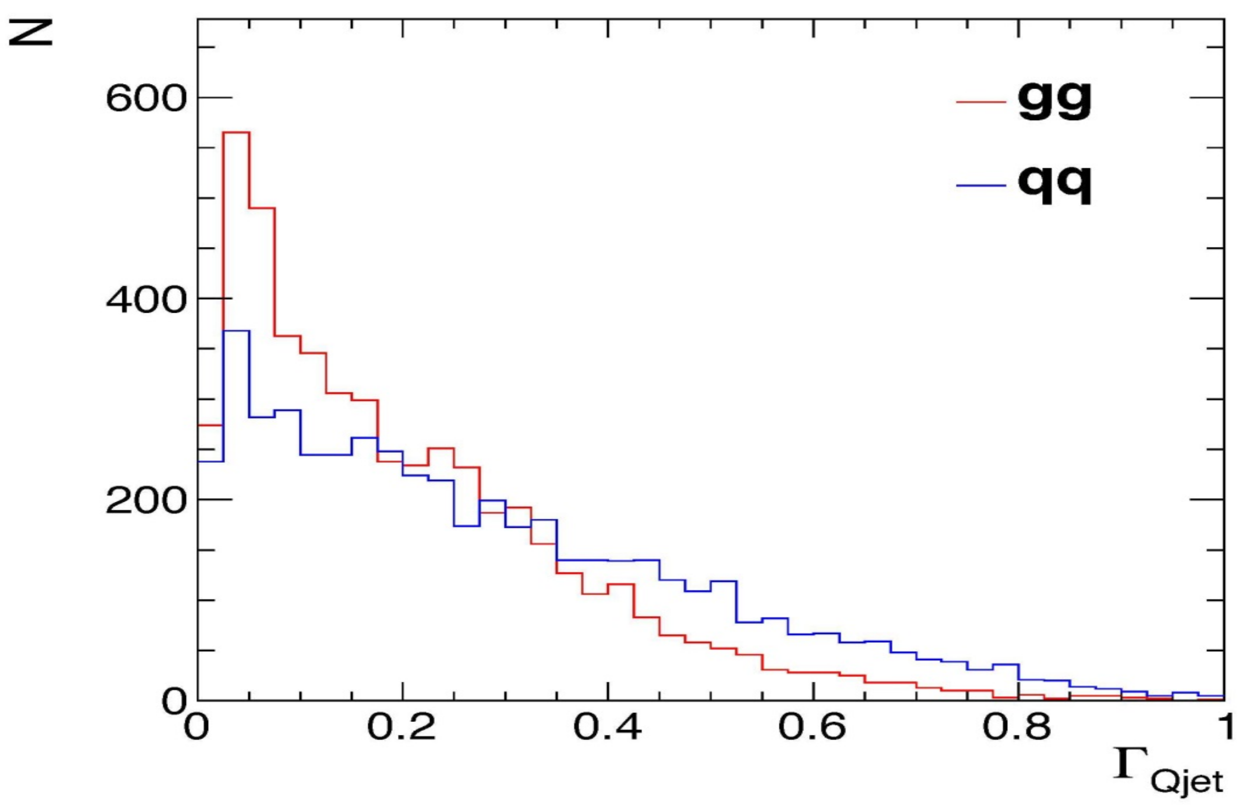


At least qualitatively the expected shape – masses slightly larger than MC – need the true hard emissions (as in matched sets)

Large mass tail grows, as expected, with jet size parameter in the algorithm - You find what you look for!



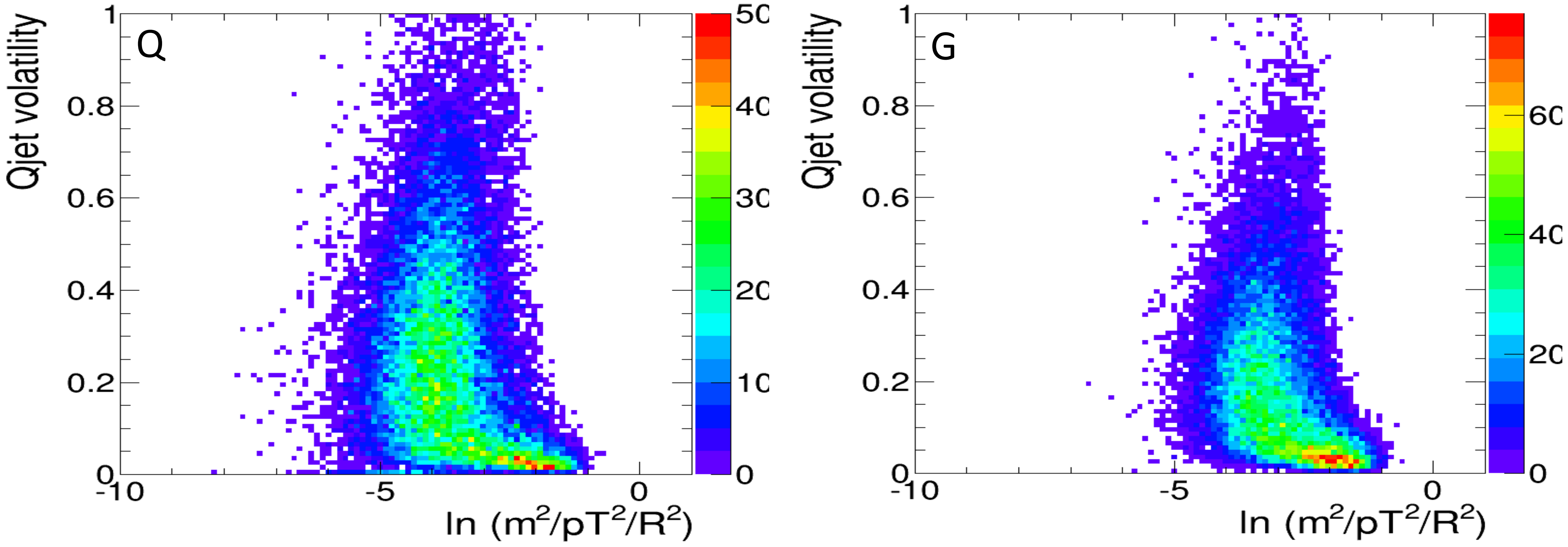
Gluons are LESS volatile! Why??



1) Shoulder region is higher and peak is lower for gluons, so gluon jets have larger fraction in shoulder;
2) Shoulder region jets have mass from energetic, wide angle emission;
3) Shoulder region jets exhibit smaller volatility;
4) Gluons jets are LESS volatile.

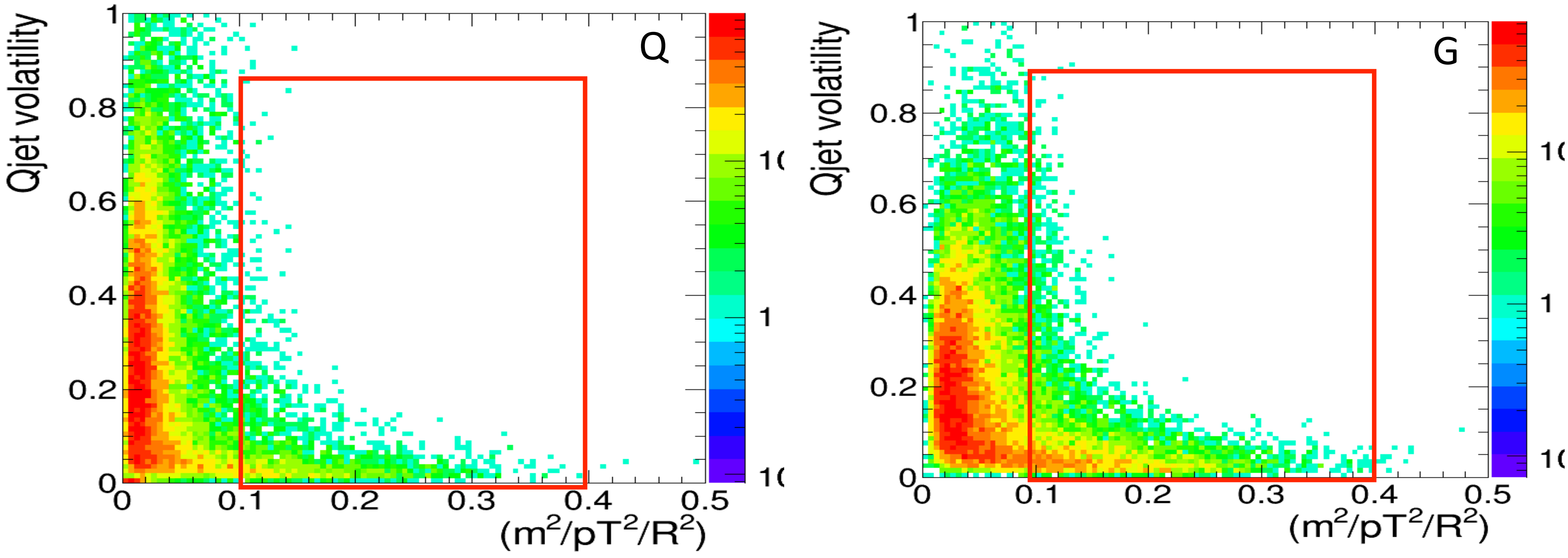
Look at this correlation in detail with 2-D scatter plots

UNpruned Γ_{Qjet} versus Ln m/pT/R (focus on small values)



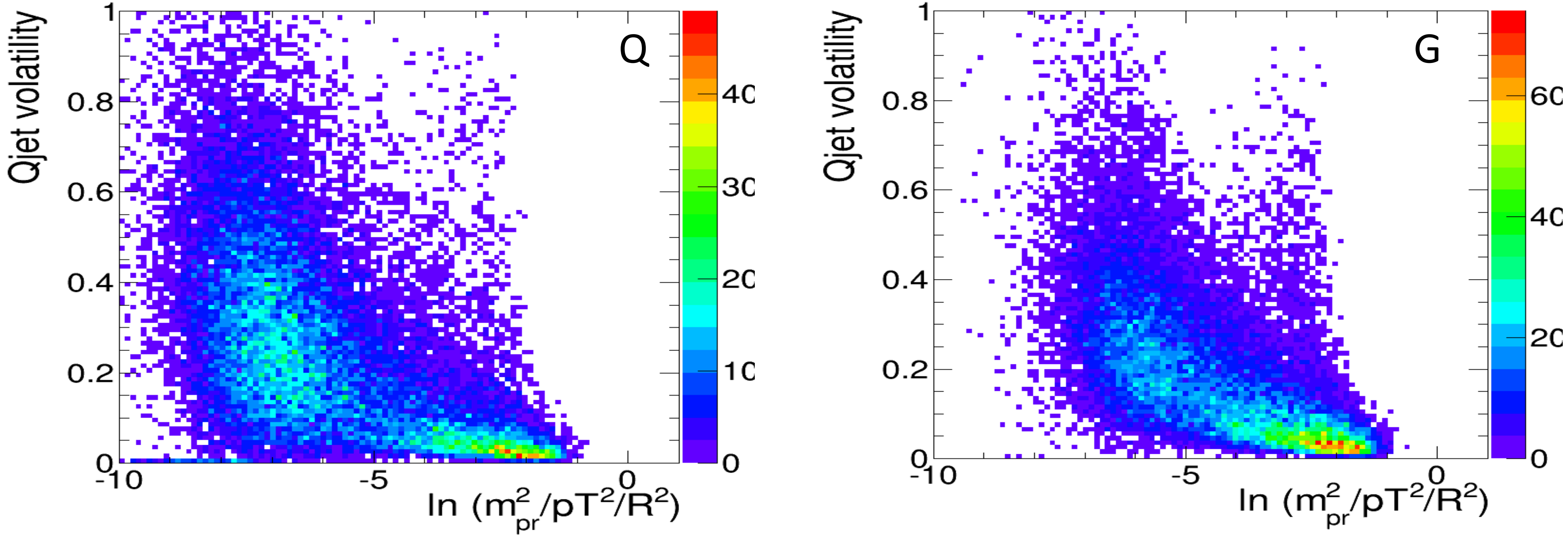
In both cases larger volatility is associated with smaller m/pT, where mass is generated by many soft emissions → different pruning yields different masses

UNpruned Γ_{Qjet} versus $(m/pT/R)^2$ (focus on larger values)



In both cases larger volatility is associated with smaller m/pT, and smaller volatility with the shoulder region , the small but hard-to-beat BKG.

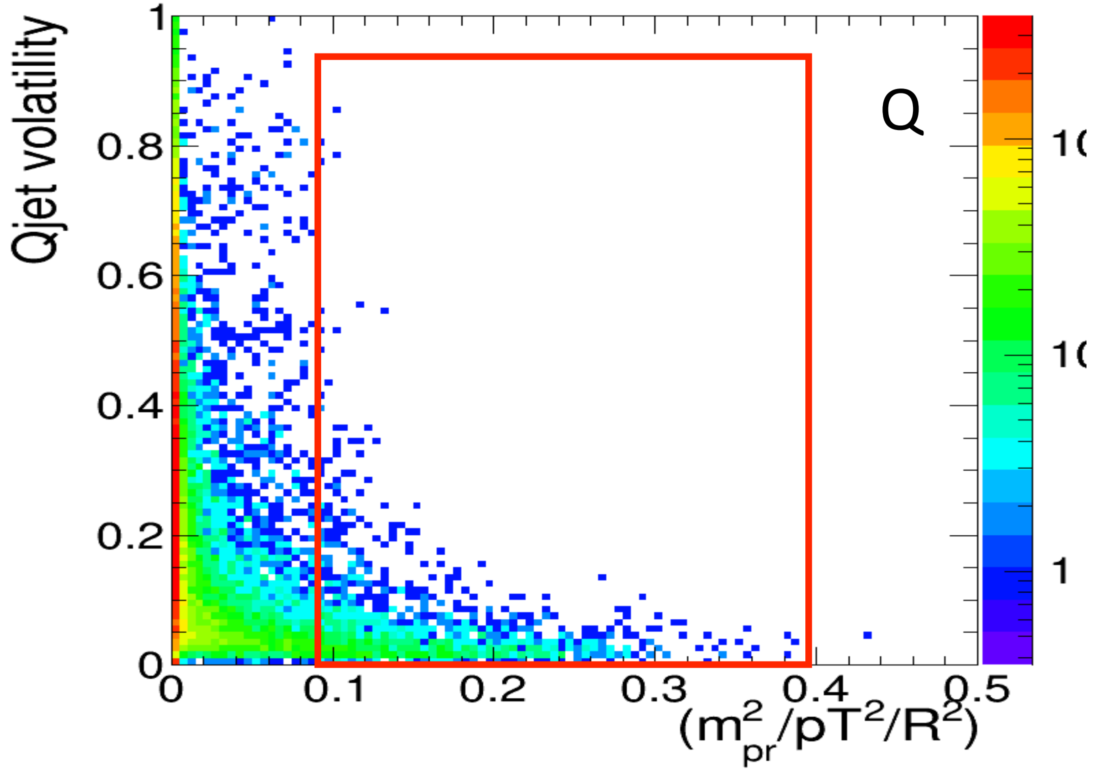
Pruned Γ_{Qjet} versus Ln m_{pr}/pT/R (focus on smaller values)

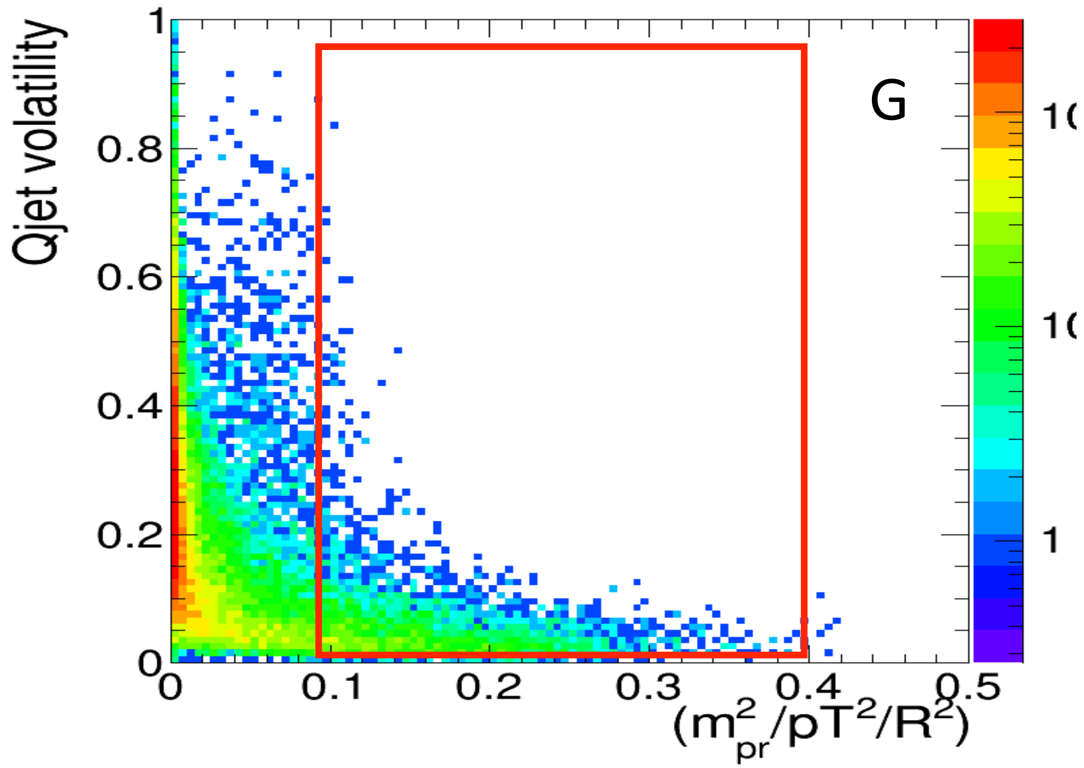


Pruned masses are smaller.

In both cases larger volatility is associated with smaller m/pT, i.e., with low mass peak; lower volatility in shoulder.

Pruned Γ_{Qjet} versus $(m_{pr}/pT/R)^2$ (focus on larger values)





In both cases larger volatility is associated with smaller m/pT, i.e., with low mass peak; lower volatility in shoulder ☐.

Comments:

- Gluons exhibit smaller volatility due to

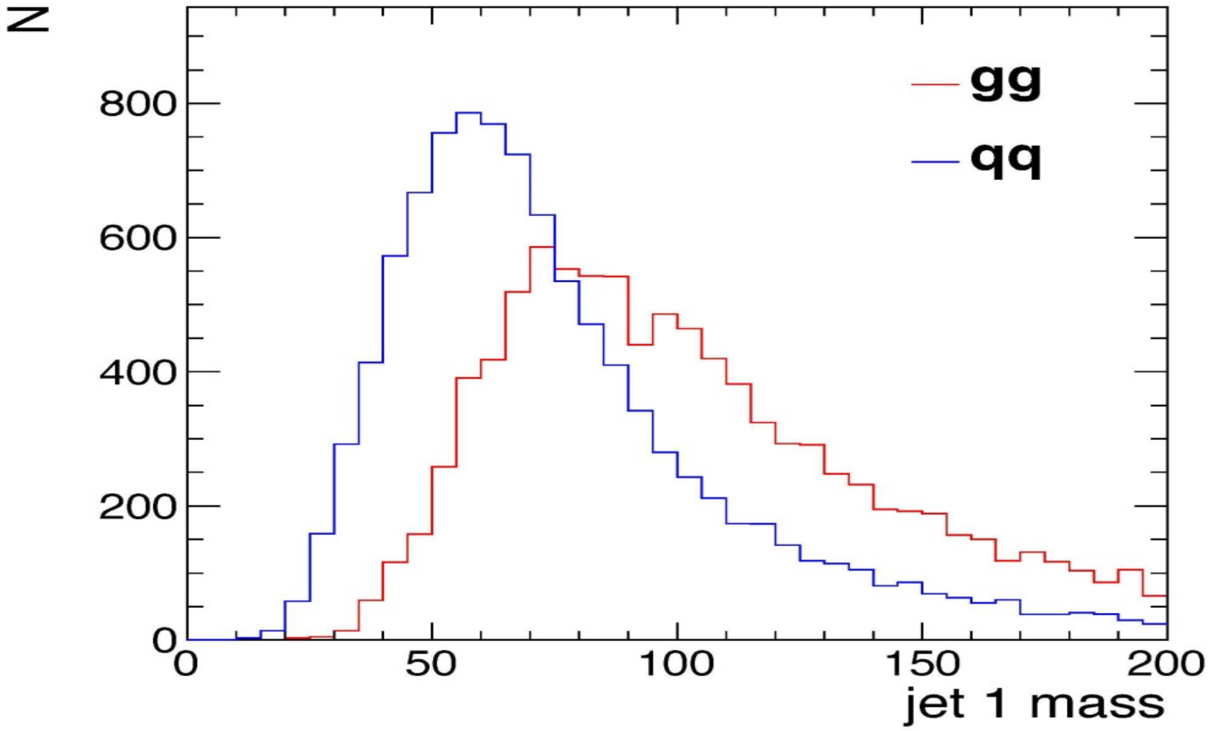
  larger fraction of jets in shoulder,
  smaller volatility in shoulder;

Suggestions:

- Recommend using linear m/pT/R axis (although shoulder is probably most obvious in pruned log case).
- Recommend using log y-axis for jet counting distributions to see both low mass peak and shoulder.

BOOST 2013 (Nhan Tran) results : Q vs G, QQ & GG samples at 8 TeV

- AkT8
- pT ~ 500 to 600 GeV



Q → G change described primarily by charge C_F (= 4/3) → C_A (= 3):

⇒ (perturbative) shoulder is higher for gluons, more "hard" radiation,

⇒ more Sudakov suppression at small masses pushes peak further from origin and to smaller value for gluons,

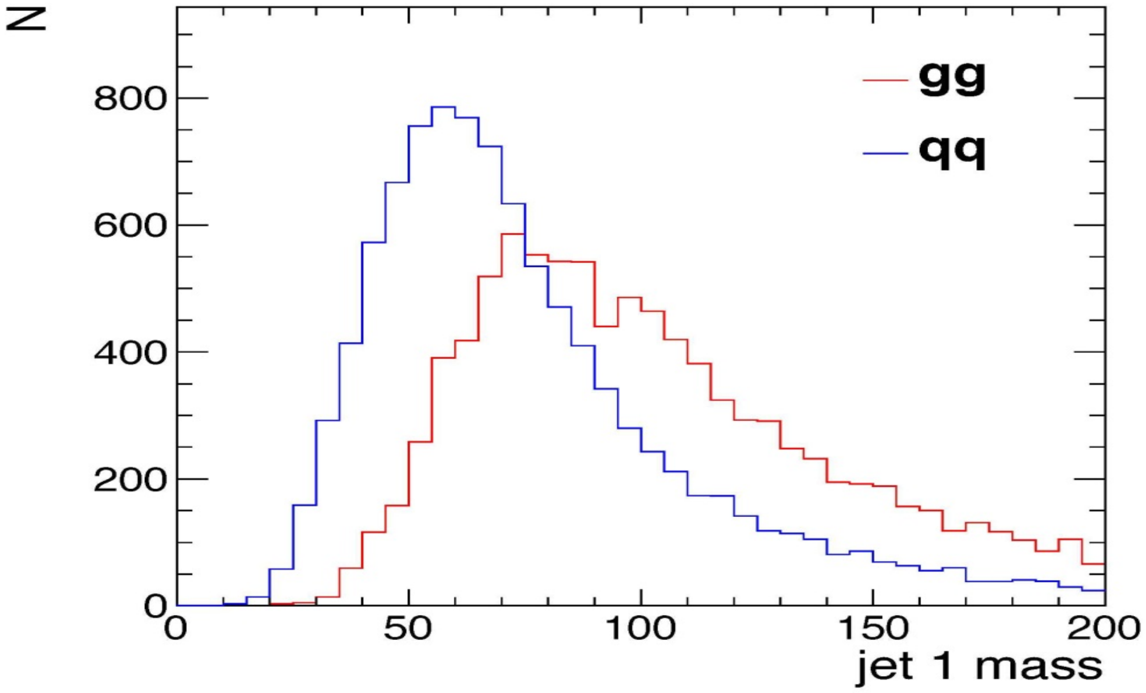
⇒ a larger fraction of gluon jets (than quark jets) are in the shoulder (small pruning) region of jet mass distribution!

⇒ gluons have larger average mass.

Leading Jet mass: Before & after grooming (pruning)

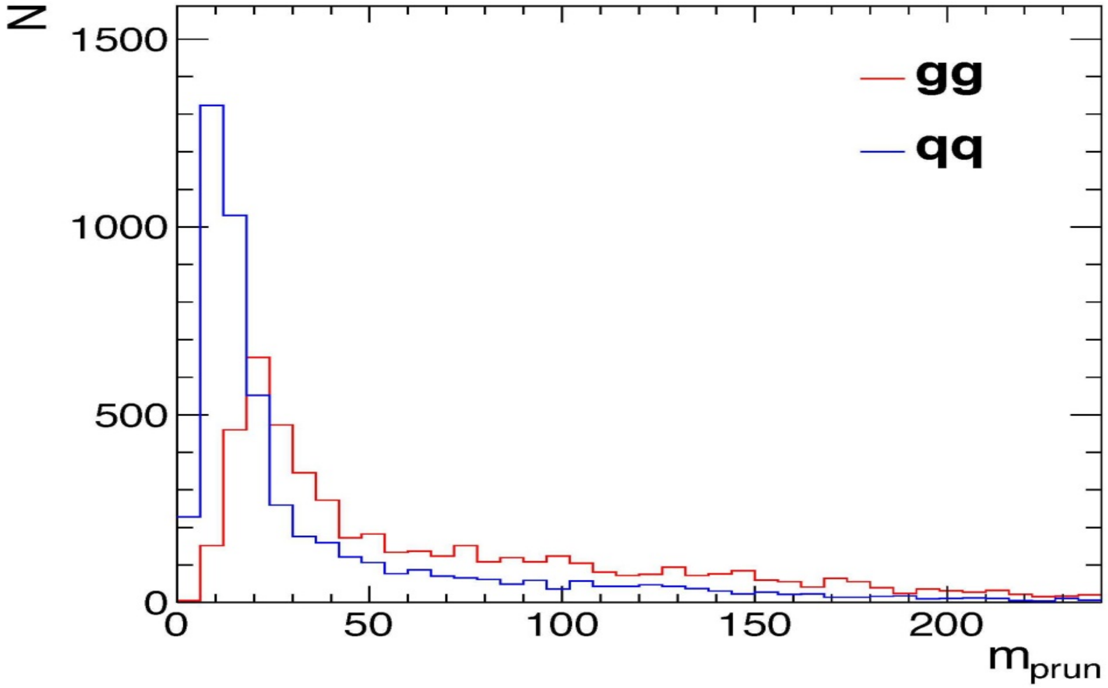
Pruning pushes low mass peak to lower mass and leaves height of shoulder largely unchanged

UNpruned



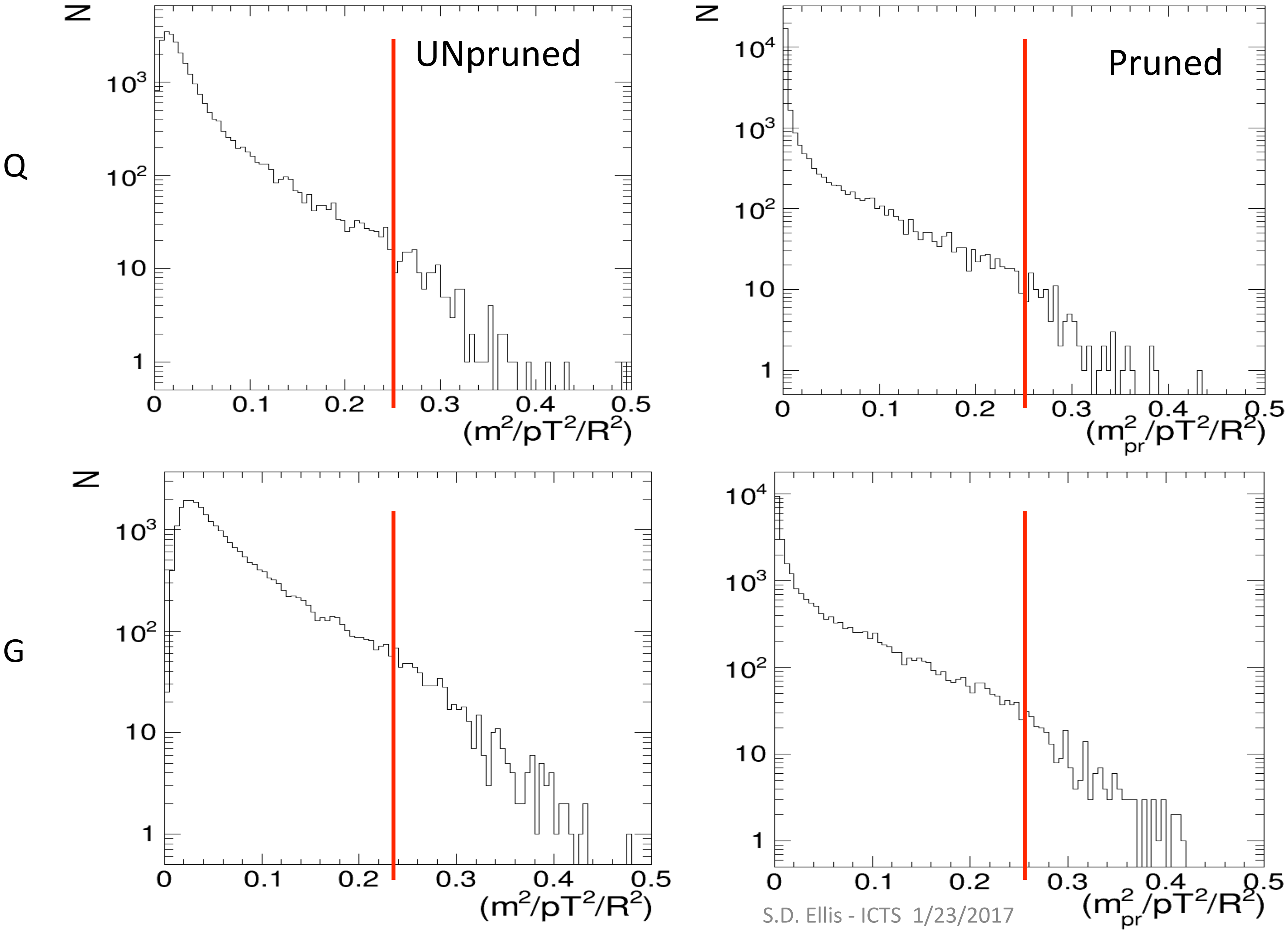
G has larger average mass

Pruned



G has higher shoulder

Jet mass distributions - Linear on x-axis, Log on y-axis (focus on large values)



Gluon jets are a bit more massive, i.e., a broader distribution;

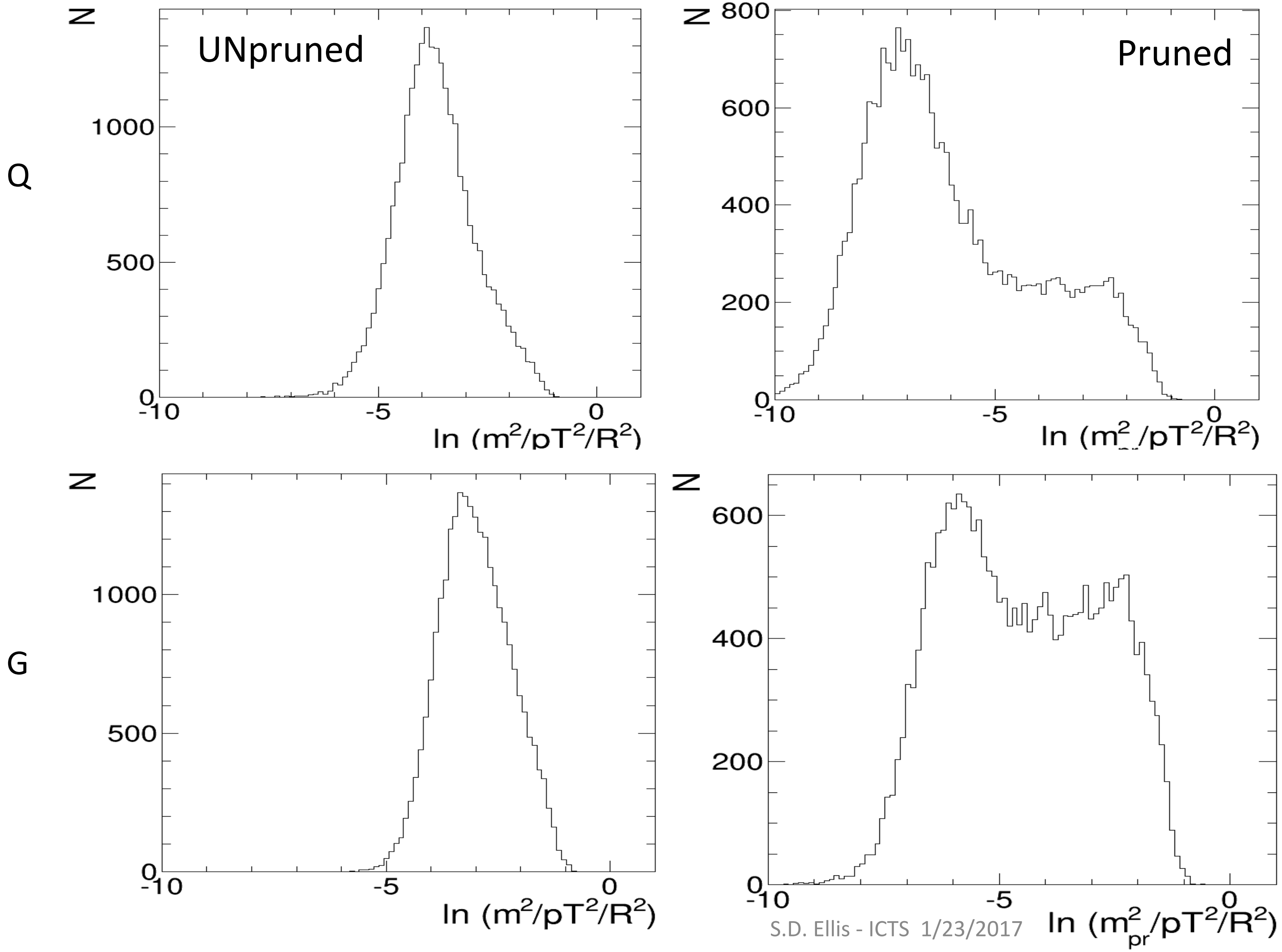
Shoulder clear (> 0.1) before and after pruning, falls off above 0.25;

Low mass peak very narrow after pruning;

Shoulder little changed by pruning;

Shoulder higher for gluons, ~ by CA/CF = 9/4;

Jet Mass distributions - Ln on x-axis, Linear on y-axis (focus on small values)



Gluon jets are a bit more massive;

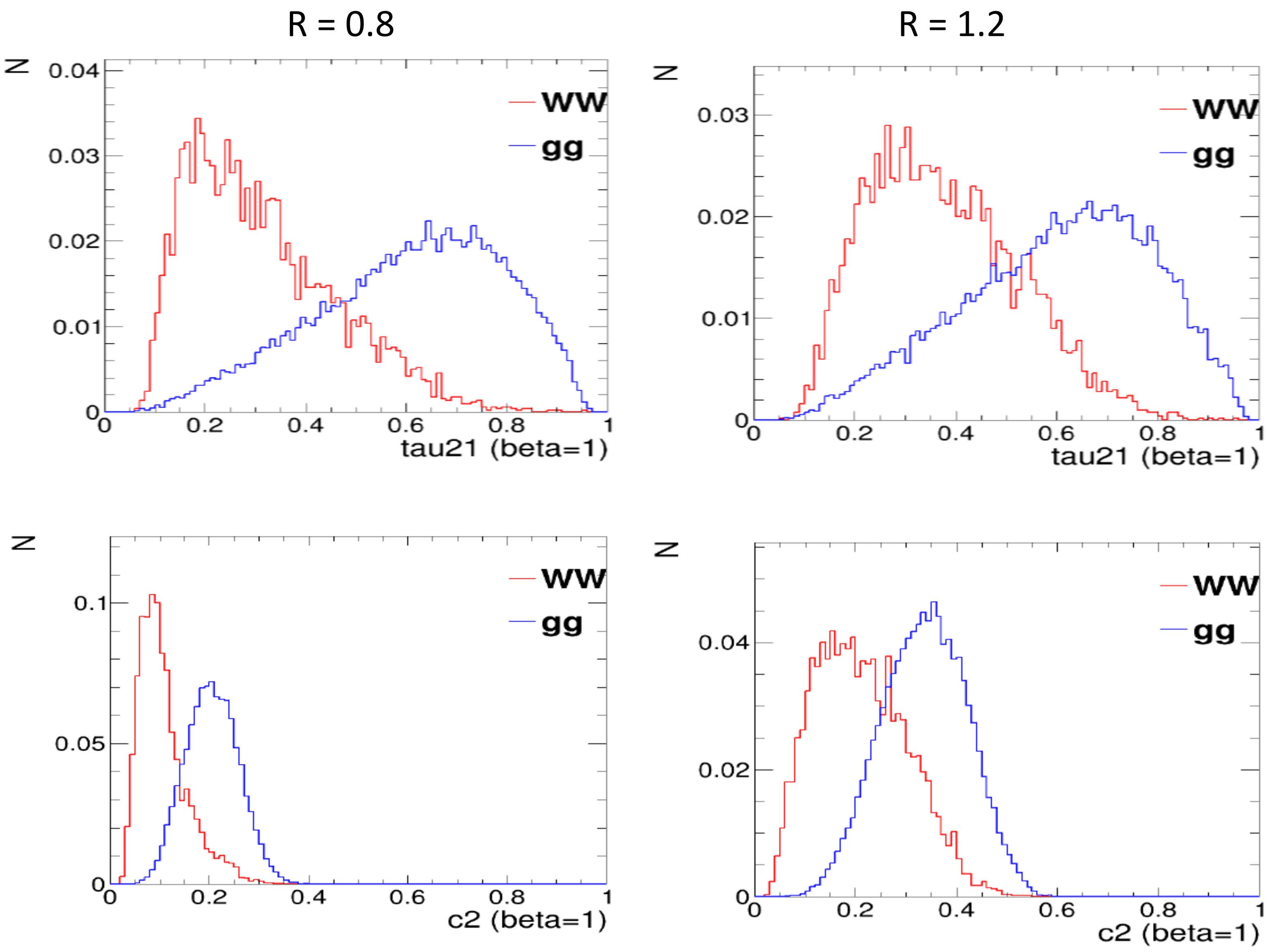
Pruning moves peak to lower mass;

Shoulder very clear after pruning;

Shoulder higher for gluons, ~ by CA/CF = 9/4;

m/pT/R is good variable for comparing distributions, removes the common kinematics;

R dependence: pT = 500 GeV (AktTR jets)

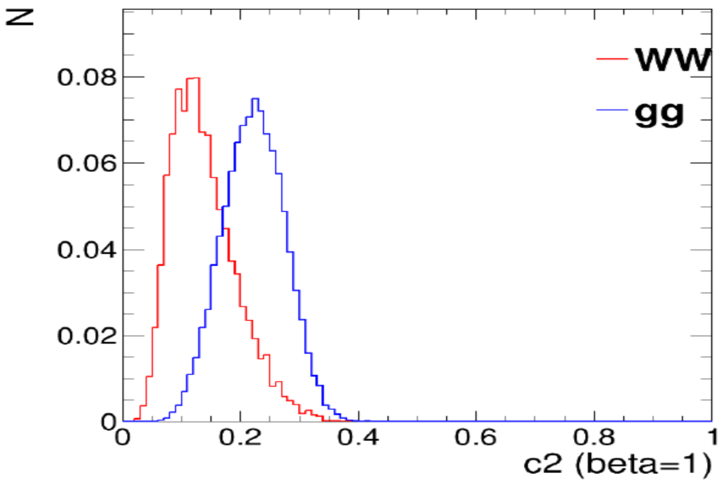


Only a slight shift to larger values, and similar for both samples. Slight degradation of separation, since W peaks broadens a bit more.

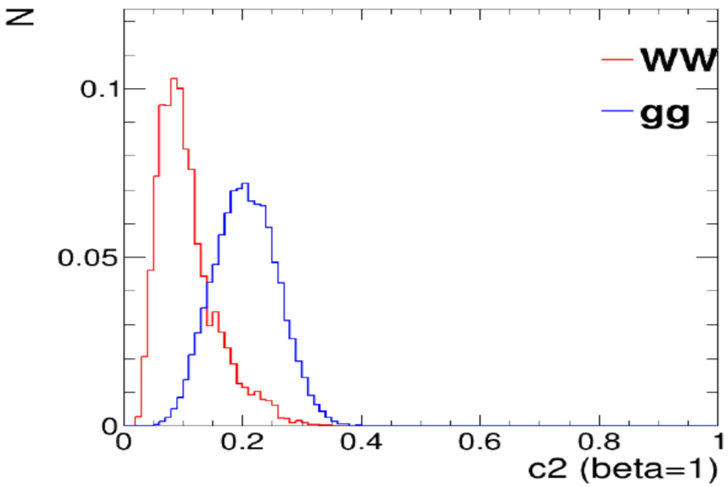
Much narrower distributions than for tau21 and at smaller R values. Shift with R is approximately linear as expected (Eq. 2.27 in 1305.0007). Broadening of peaks leads to slight degradation of separation.

pT Dependence, R = 0.8: $C_2(\beta=1)$

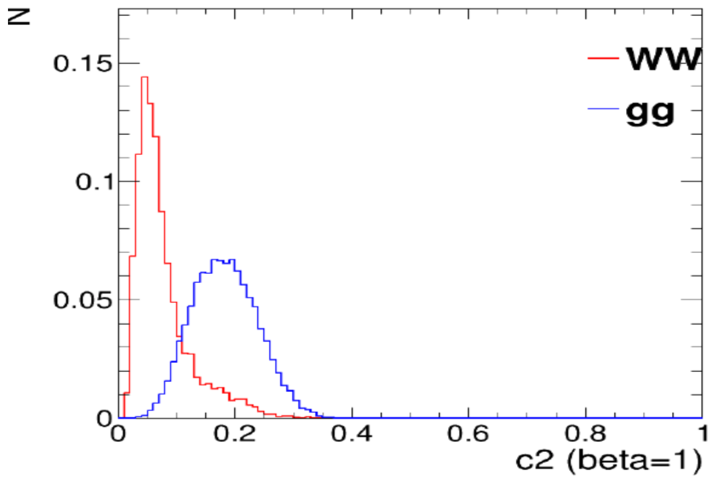
300 GeV



500 GeV



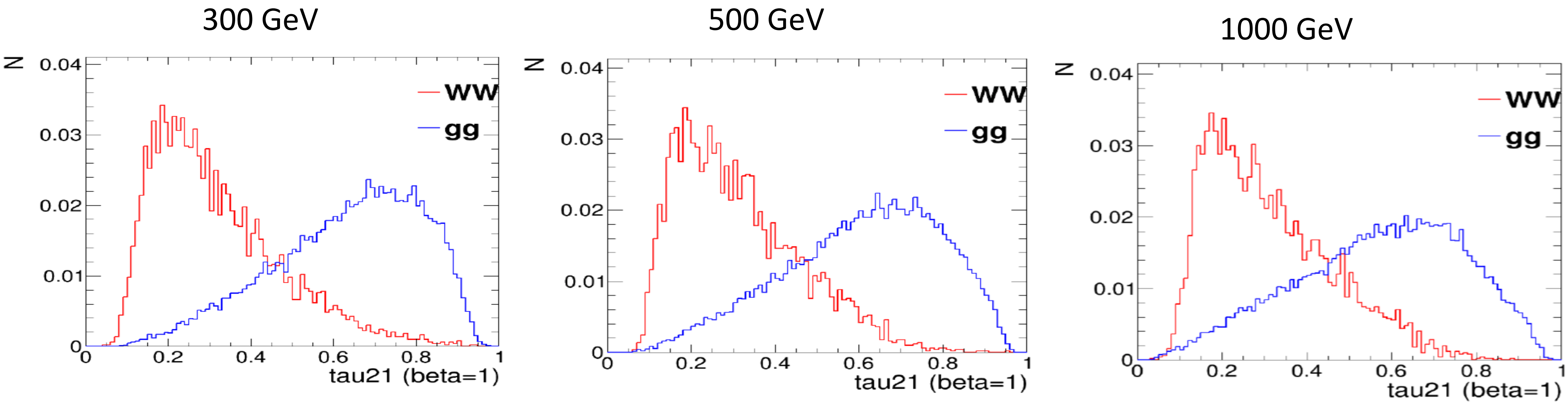
1000 GeV



The $C_2(\beta=1)$ gluon distribution shifts slightly to smaller values, and broadens slightly. Overall the $C_2(\beta=1)$ change with pT is quite small.

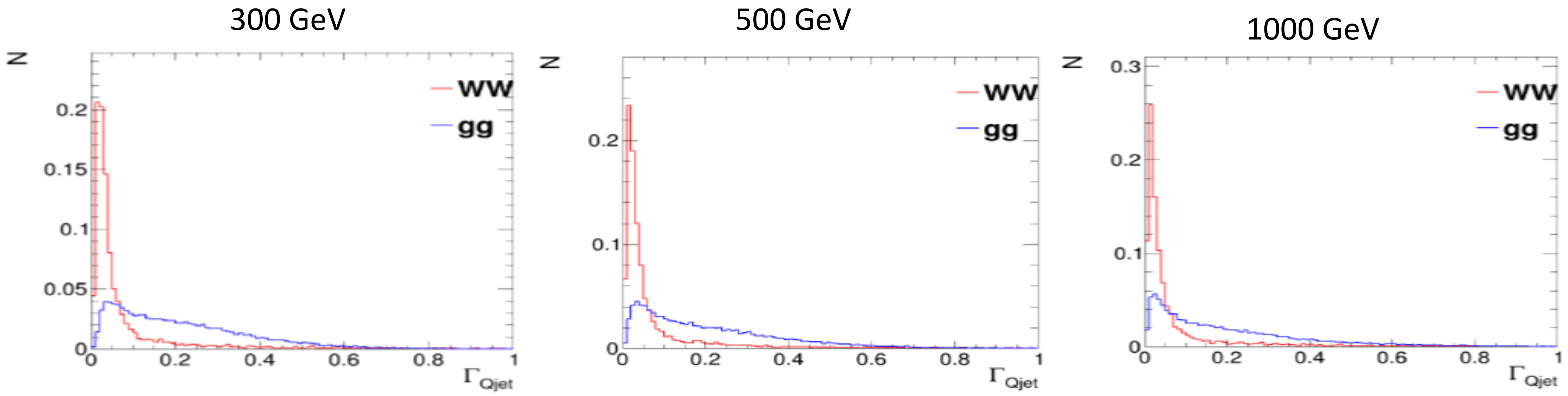
The $C_2(\beta=1)$ W distribution also shifts to slightly smaller values, but becomes substantially narrower, with an increase of about a factor of 2 in the peak value. This narrowing is presumably due to the fact that the angular size is driven by m_W/pT, which decreases as pT increases, and that $C_2(\beta=1)$ is linearly sensitive to this angle (compared to τ_{21}).

pT Dependence, R = 0.8: τ_{21}



In contrast to the $C_2(\beta=1)$ case, for τ_{21} there is very little variation of the distributions with pT. As already noted a large part of the difference is the extra angular dependence in $C_2(\beta=1)$ compared to τ_{21} (see Eq. 2.27 in 1305.0007). In τ_{21} essentially all of the kinematic and non-scaling dependence on pT cancels out.

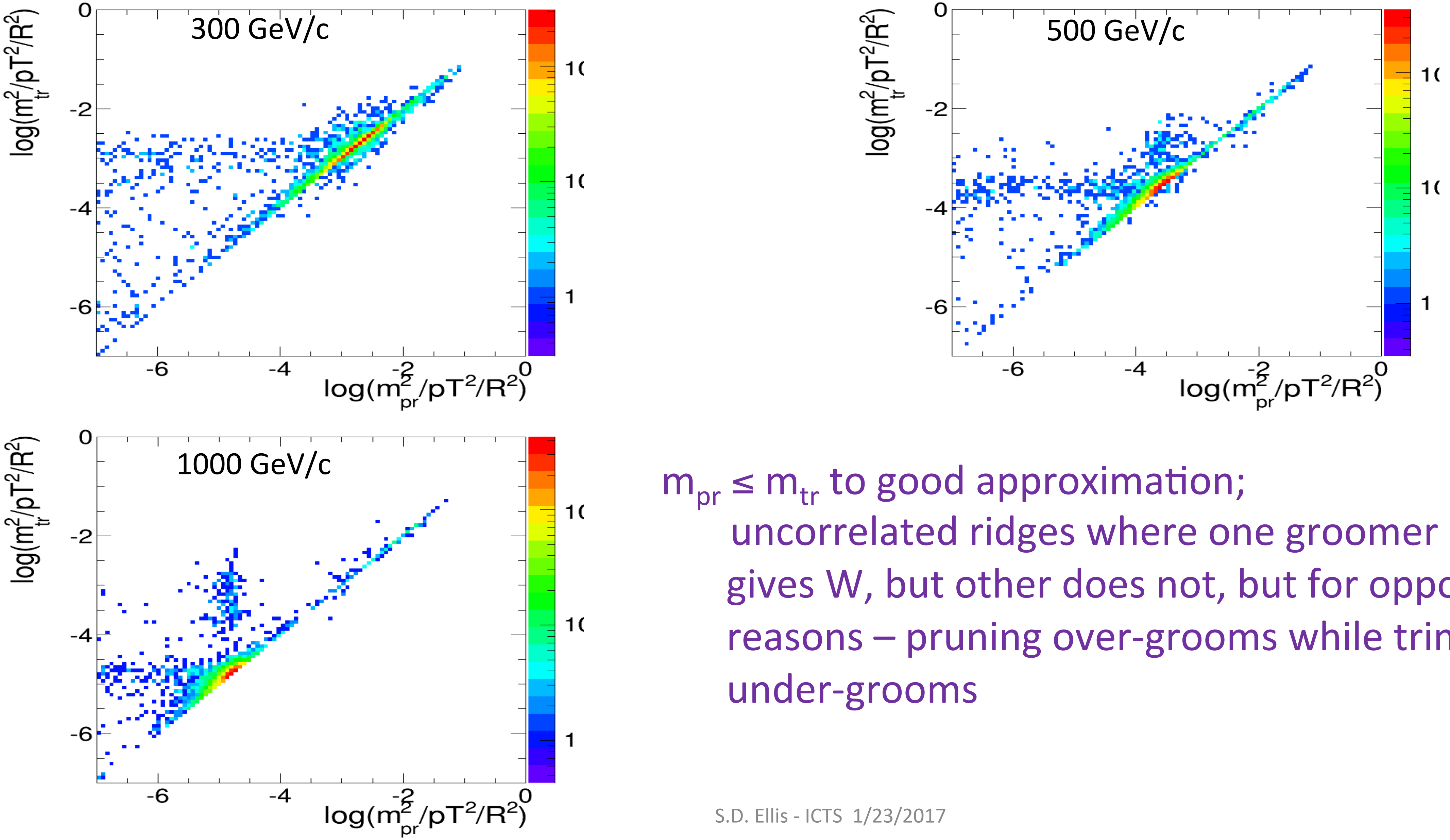
pT Dependence, R = 0.8: Γ_{Qjet}



Here the impact of increasing pT is to lower the volatility for both QCD (g) and W jets. This is most dramatic for the gluon jets, which exhibit a slowly dropping large Γ_{Qjet} tail while the peak at small Γ_{Qjet} values (< 0.1) clearly increases. Overall the Γ_{Qjet} distributions for the two samples become more similar.

$\Rightarrow$ The (single variable) ROC curves for Γ_{Qjet} exhibit a small degradation with increasing pT.

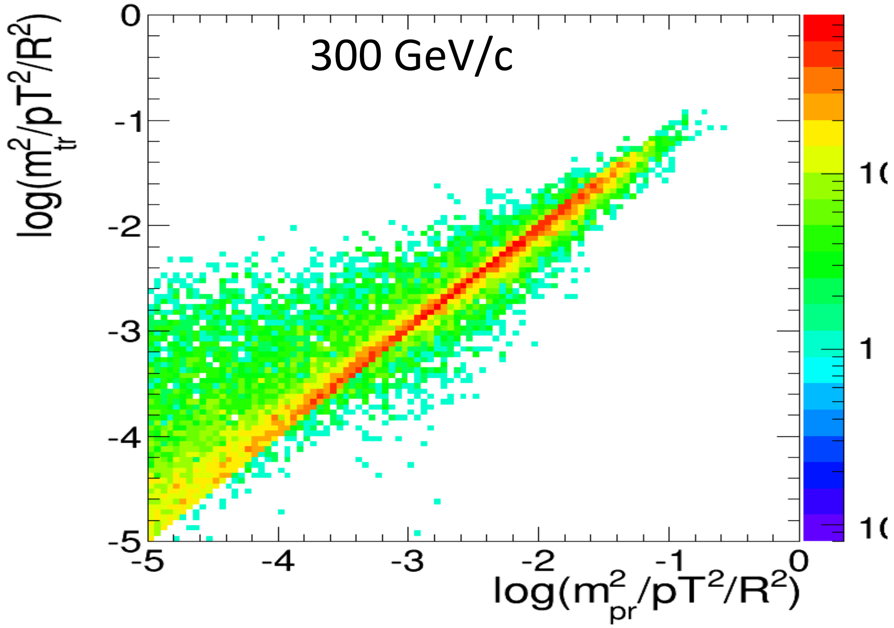
Prune vs Trim vs pT for Ws (Correlations)

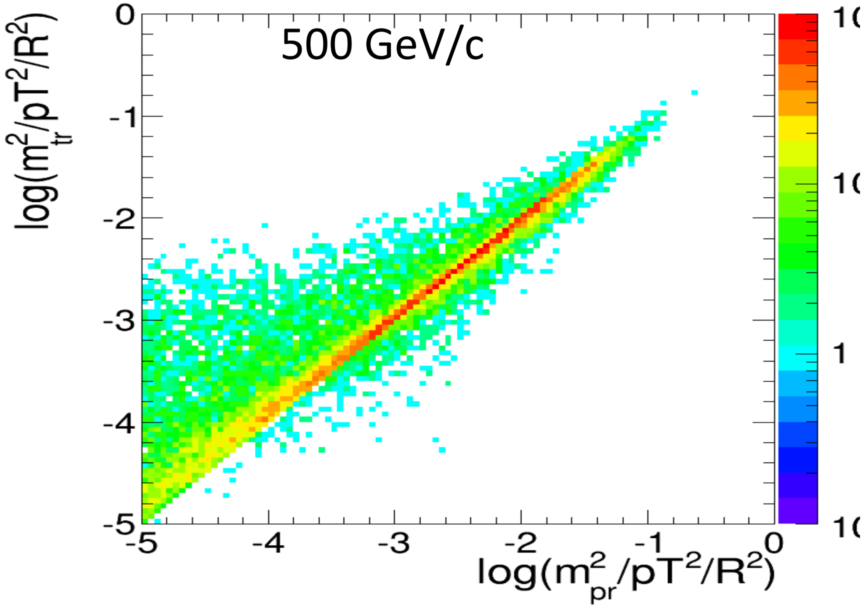


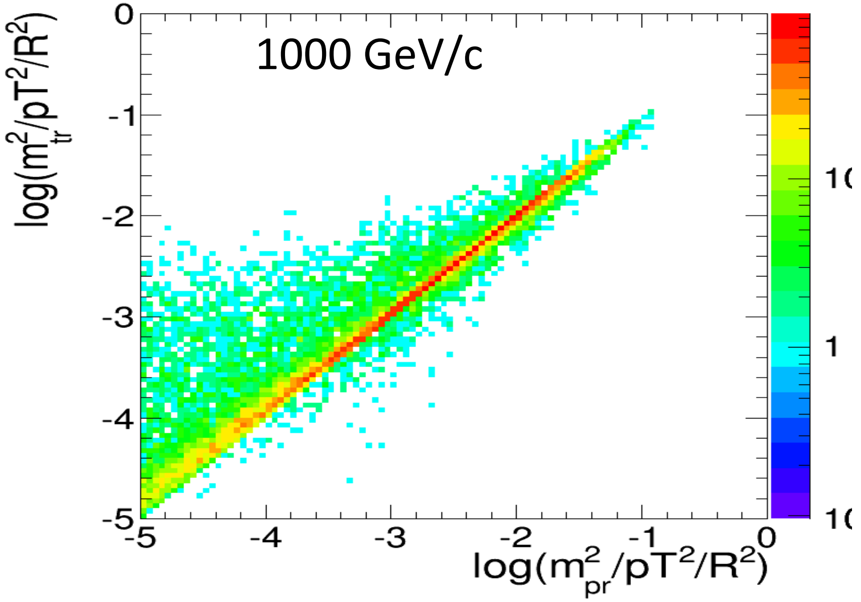
$m_{pr} \leq m_{tr}$ to good approximation;

uncorrelated ridges where one groomer gives W, but other does not, but for opposite reasons – pruning over-grooms while trimming under-grooms

Prune vs Trim vs pT for QCD



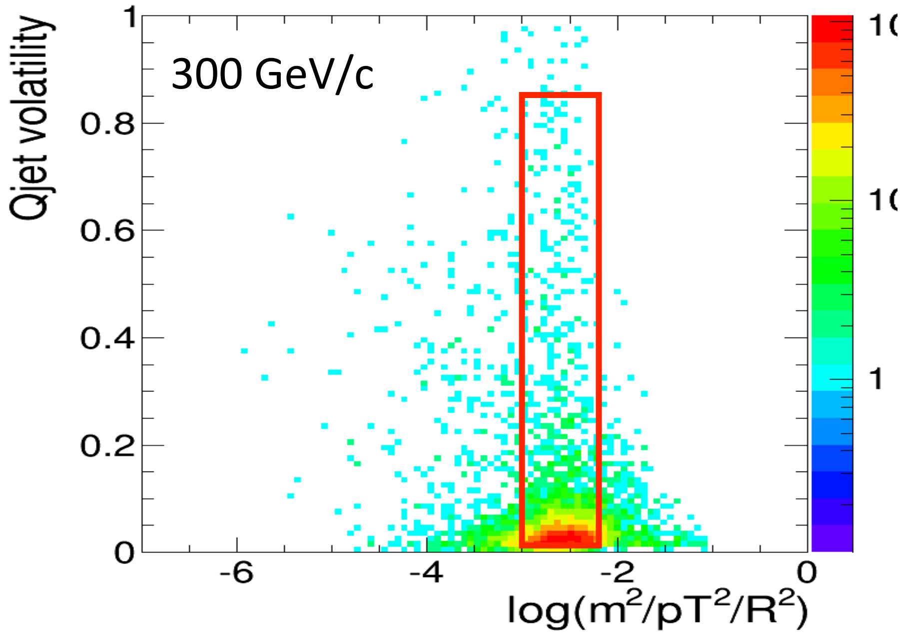


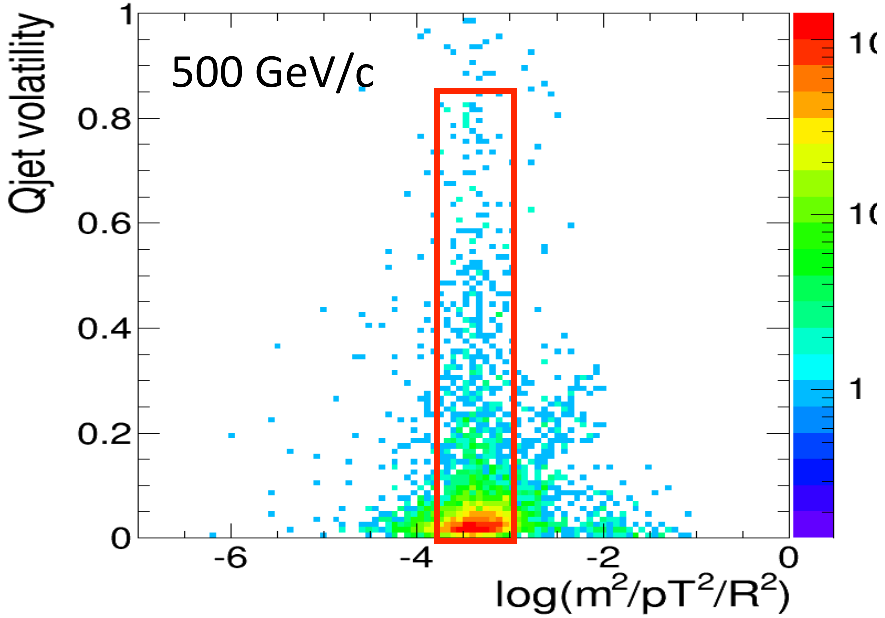


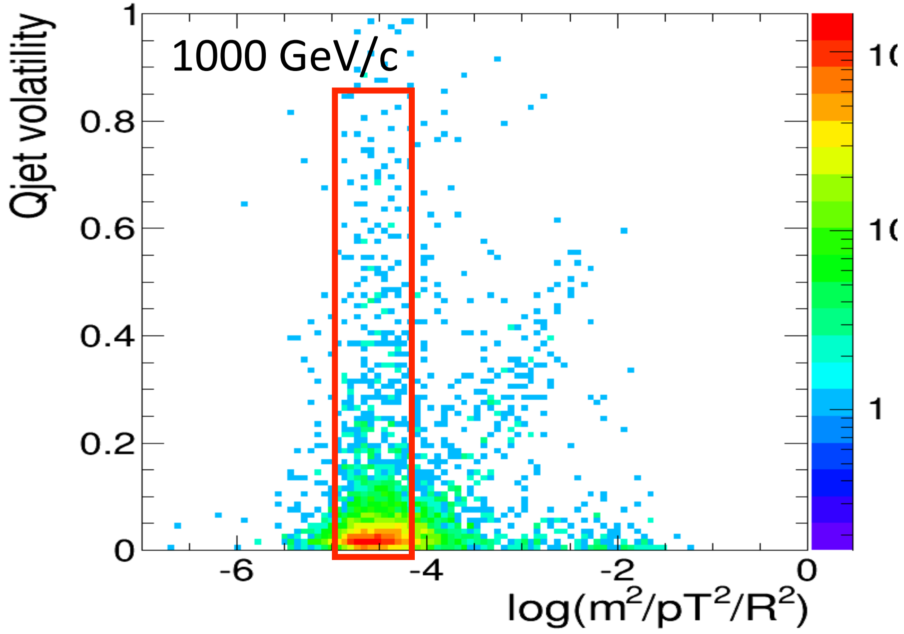
Still largely $m_{pr} \leq m_{tr}$ to good approximation;
– pruning over-grooms while trimming under-grooms;

little change with pT

W volatility vs pT, unpruned mass

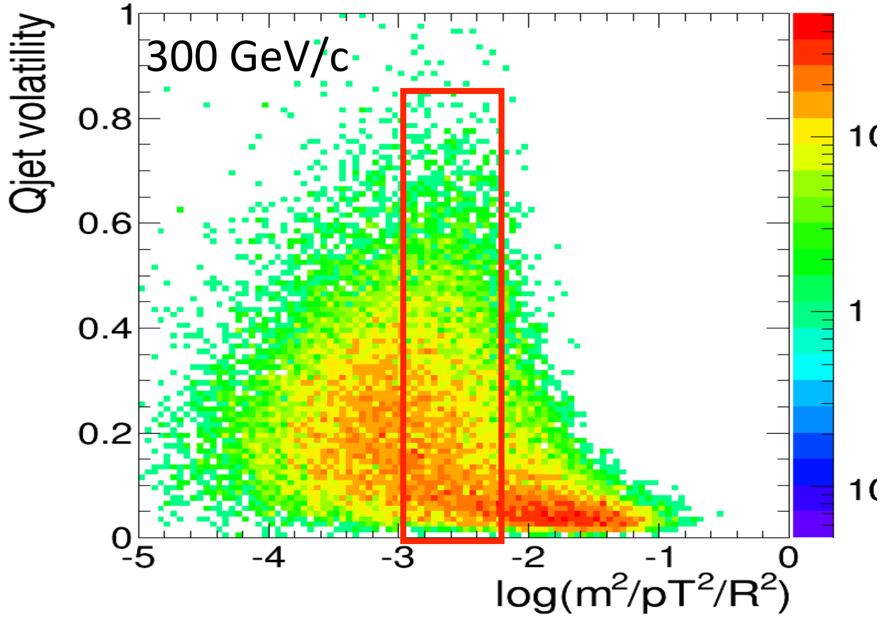


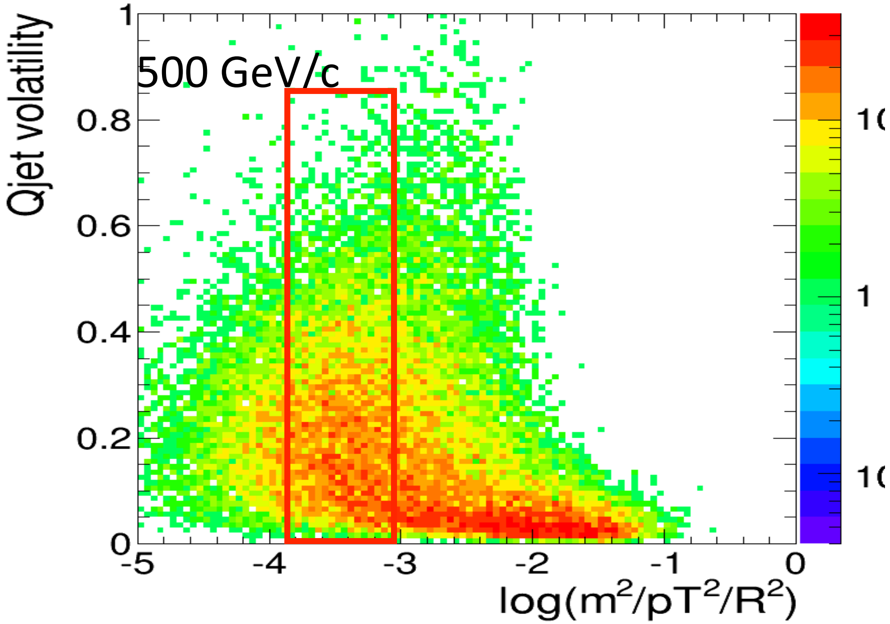


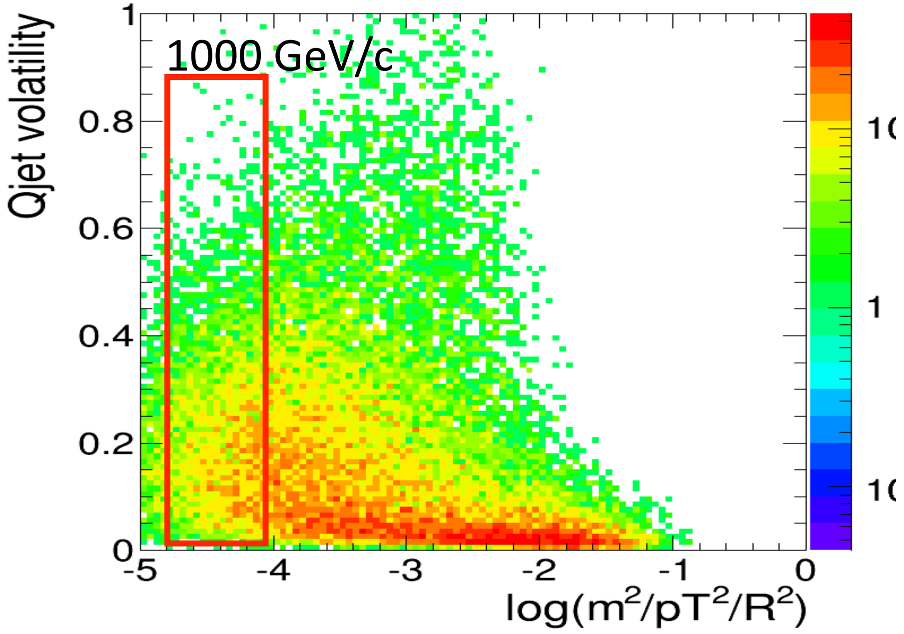


Volatility distribution broadens a little with pT generally, not so clear in peak region (= ▭)

QCD volatility vs pT, unpruned mass

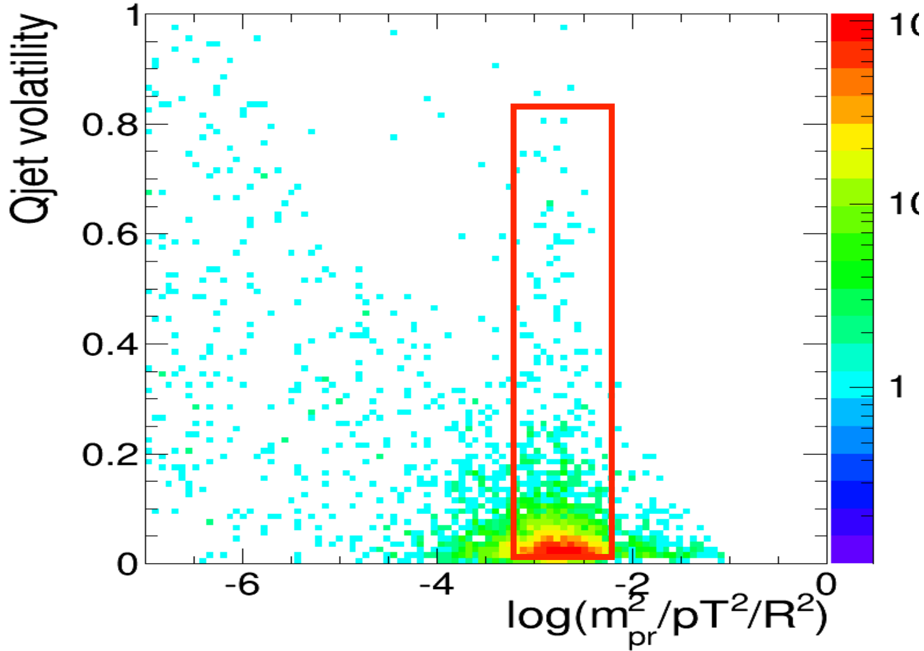


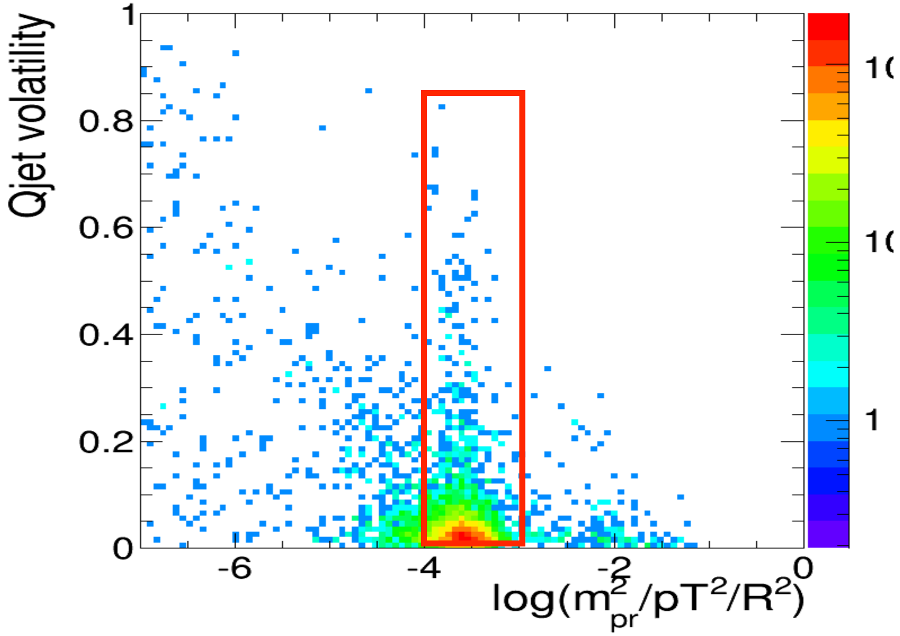


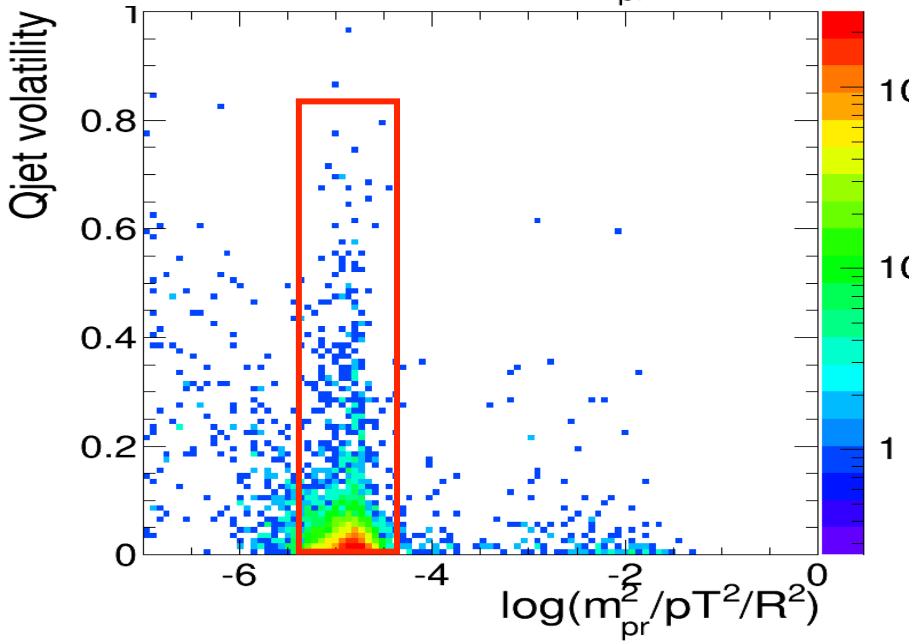


Generally QCD Volatility distribution sharpens with pT as observed in the volatility alone plots – presumably due to growing contribution of 1 "hard" emission with low volatility;
Combined pair actually improves with pT since QCD volatility distribution becomes flatter in the W mass bin

W volatility vs pT, pruned mass

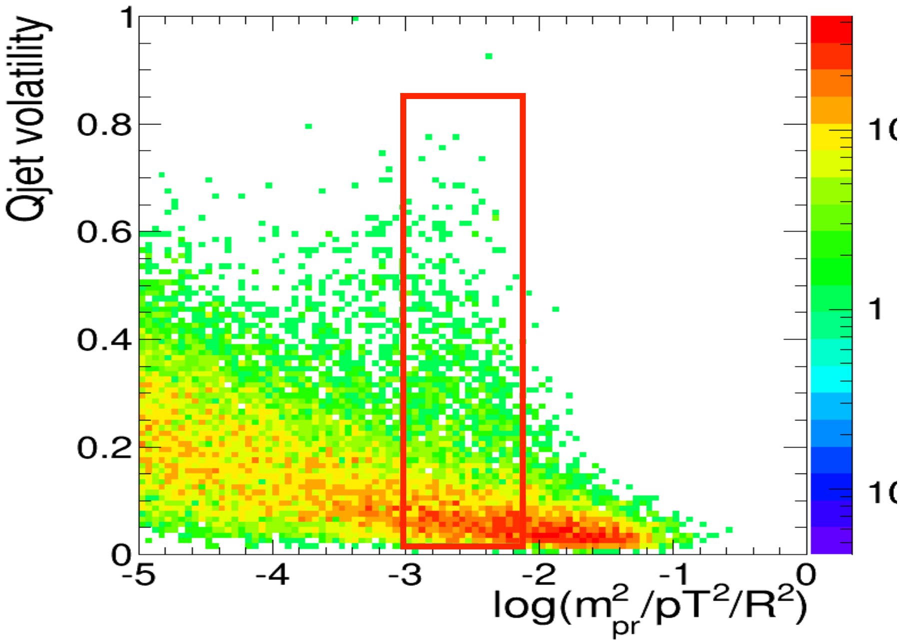


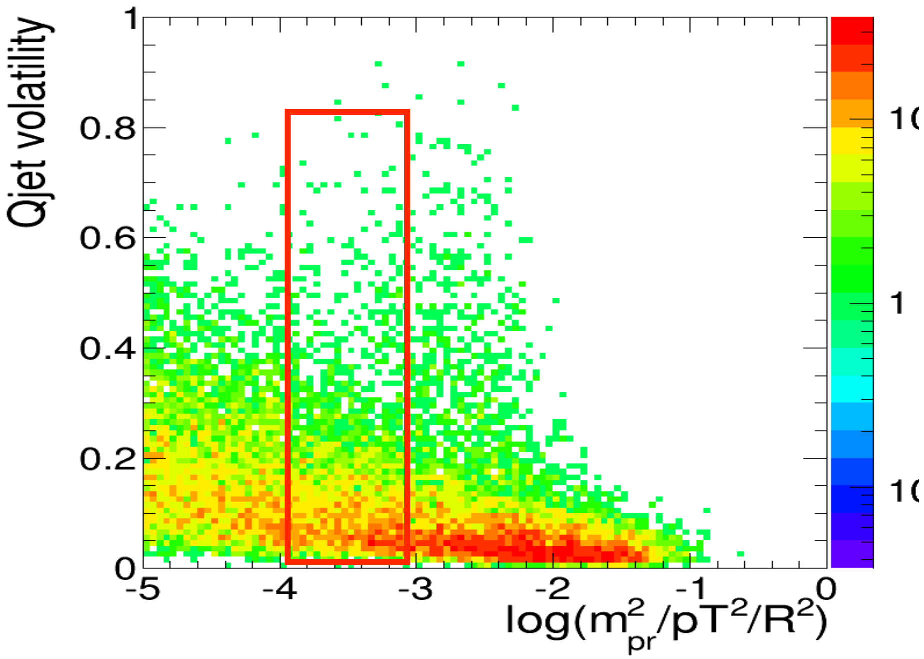


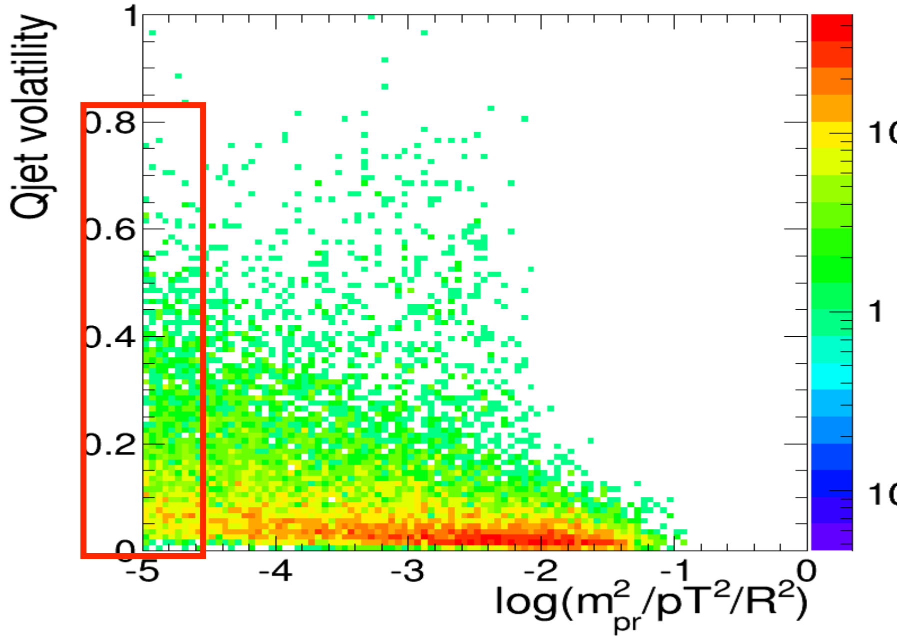


Distribution becomes more peaked at W mass

QCD volatility vs pT, pruned mass

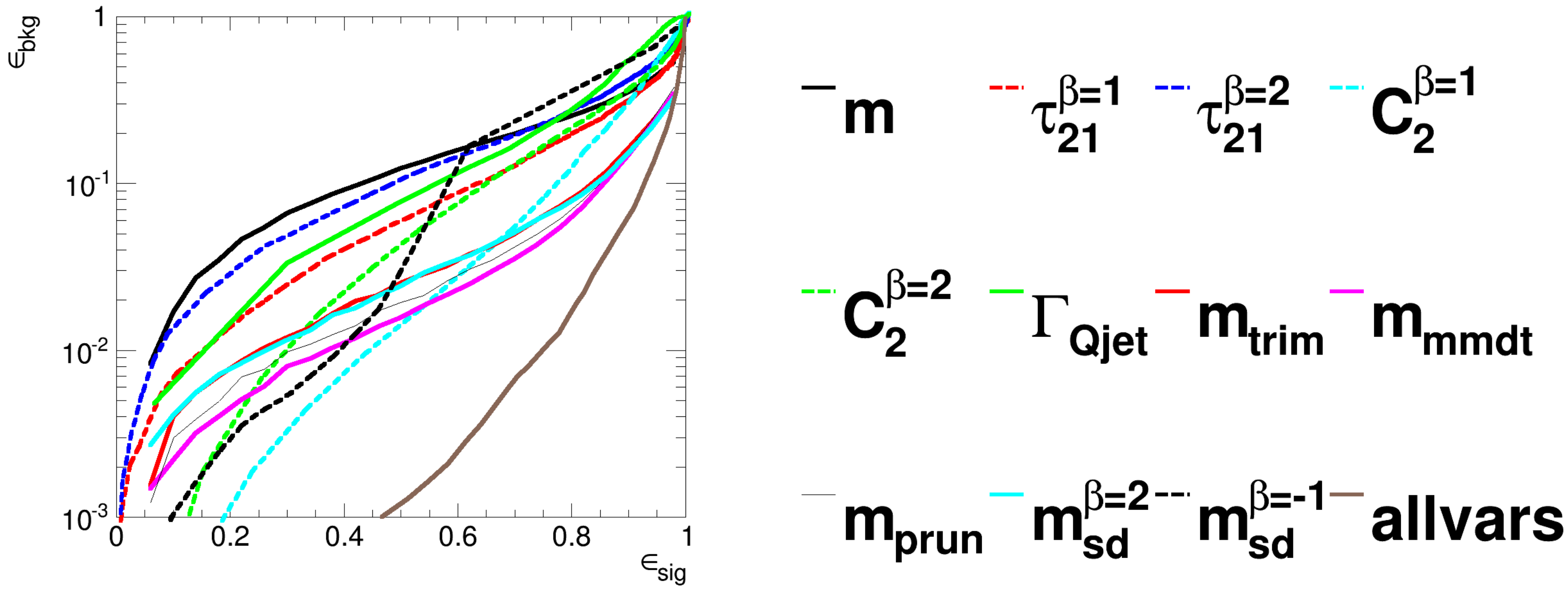






Correlated case should see larger improvement for volatility plus m_{pr}, as volatility distribution seems to be flatter in m_{pr} bin compared to m bin

ROC curves – single variable, W vs G jets, AkT8, 500 GeV

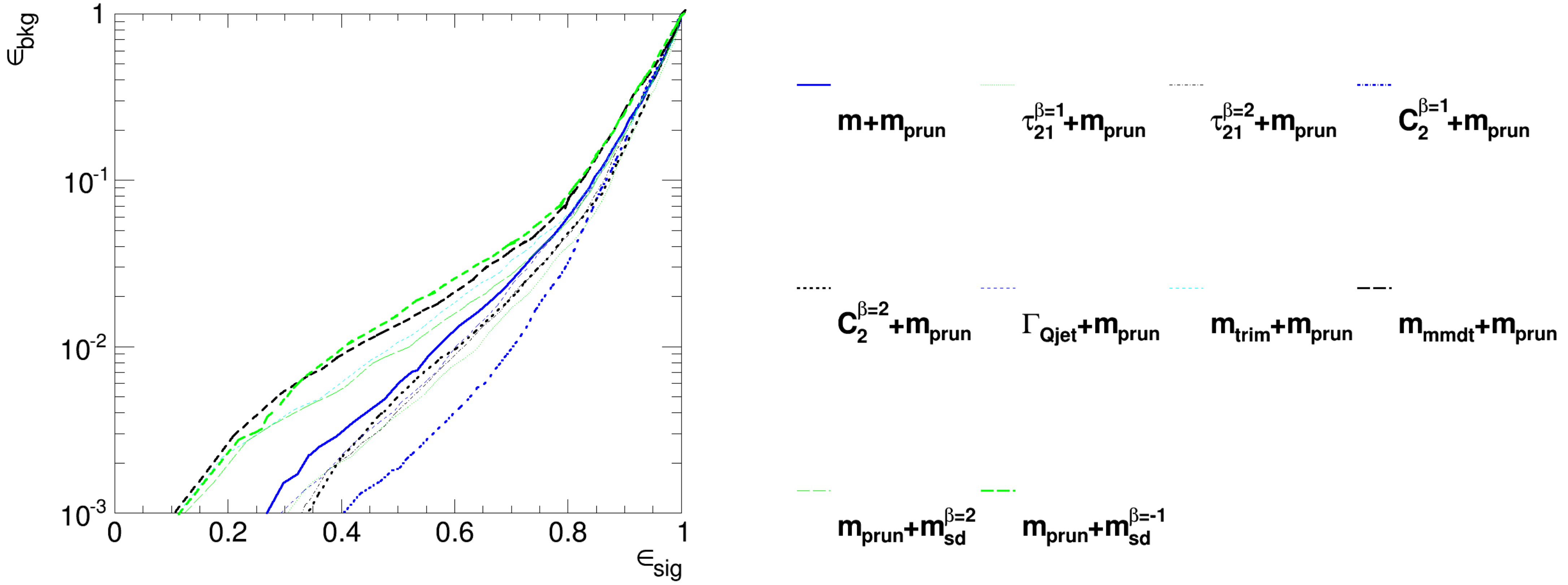


"Similar" curves for all

All better than just ungroomed mass

Improved by combining variables

Combine variables, e.g., m_{prun} +X



Discrimination improves on using two variables, especially a groomed mass plus a shape

Comments:

- Broad features of performance of groomers and taggers relatively insensitive to pT and R

- Details of performance of groomers and taggers depend on R and PT

  and on the correlations between the variables

- The BOOST 2013 report provides many details and explanations on Q vs G, Q vs G and top vs QCD