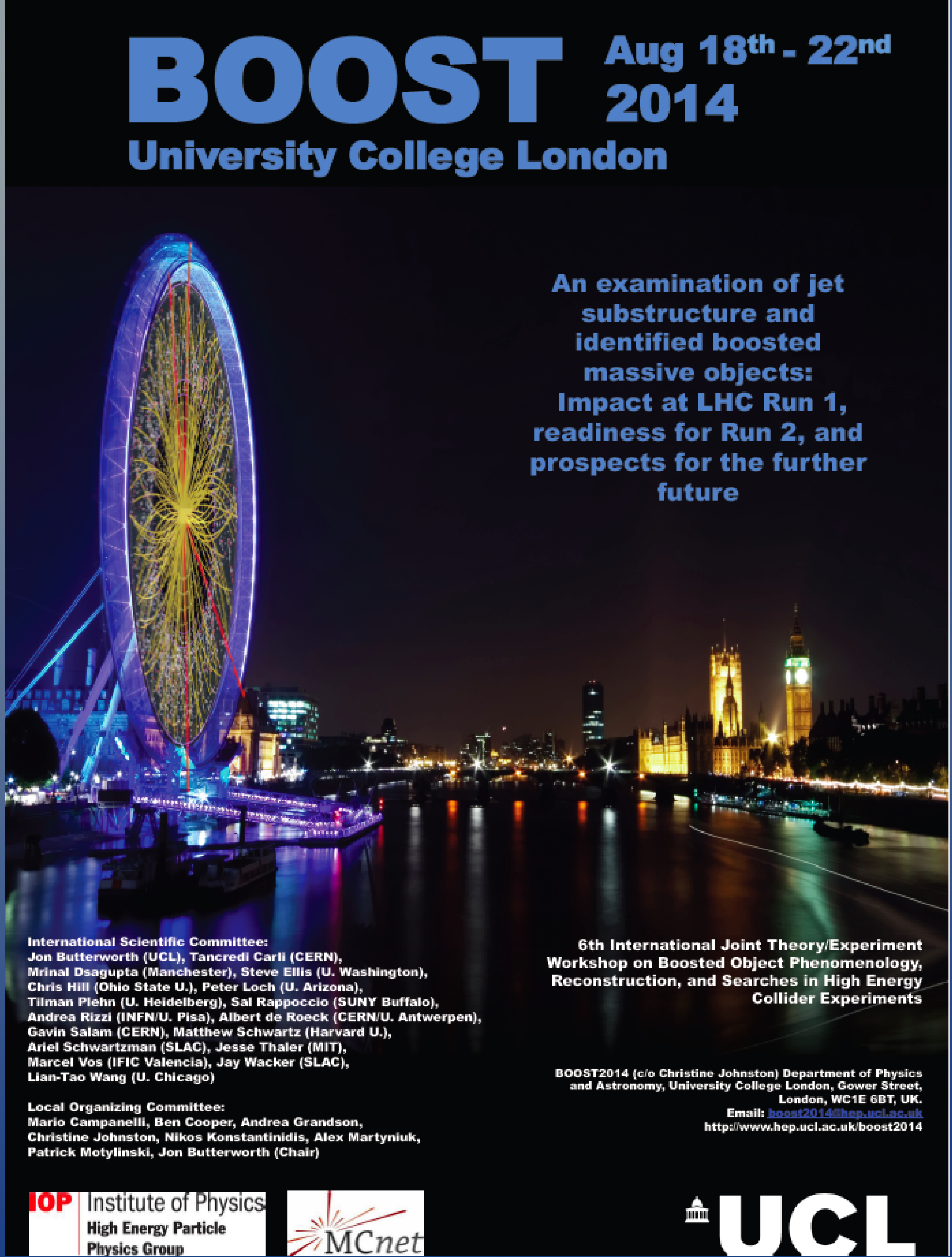
Jet substructure and boosted objects: state of the art

Mario Campanelli
UCL



BOOST

Aug 18th - 22nd
2014

University College London

An examination of jet substructure and identified boosted massive objects: Impact at LHC Run 1, readiness for Run 2, and prospects for the further future

International Scientific Committee:
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6th International Joint Theory/Experiment Workshop on Boosted Object Phenomenology, Reconstruction, and Searches in High Energy Collider Experiments

BOOST2014 (c/o Christine Johnston) Department of Physics and Astronomy, University College London, Gower Street, London, WC1E 6BT, UK.
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http://www.hep.ucl.ac.uk/boost2014

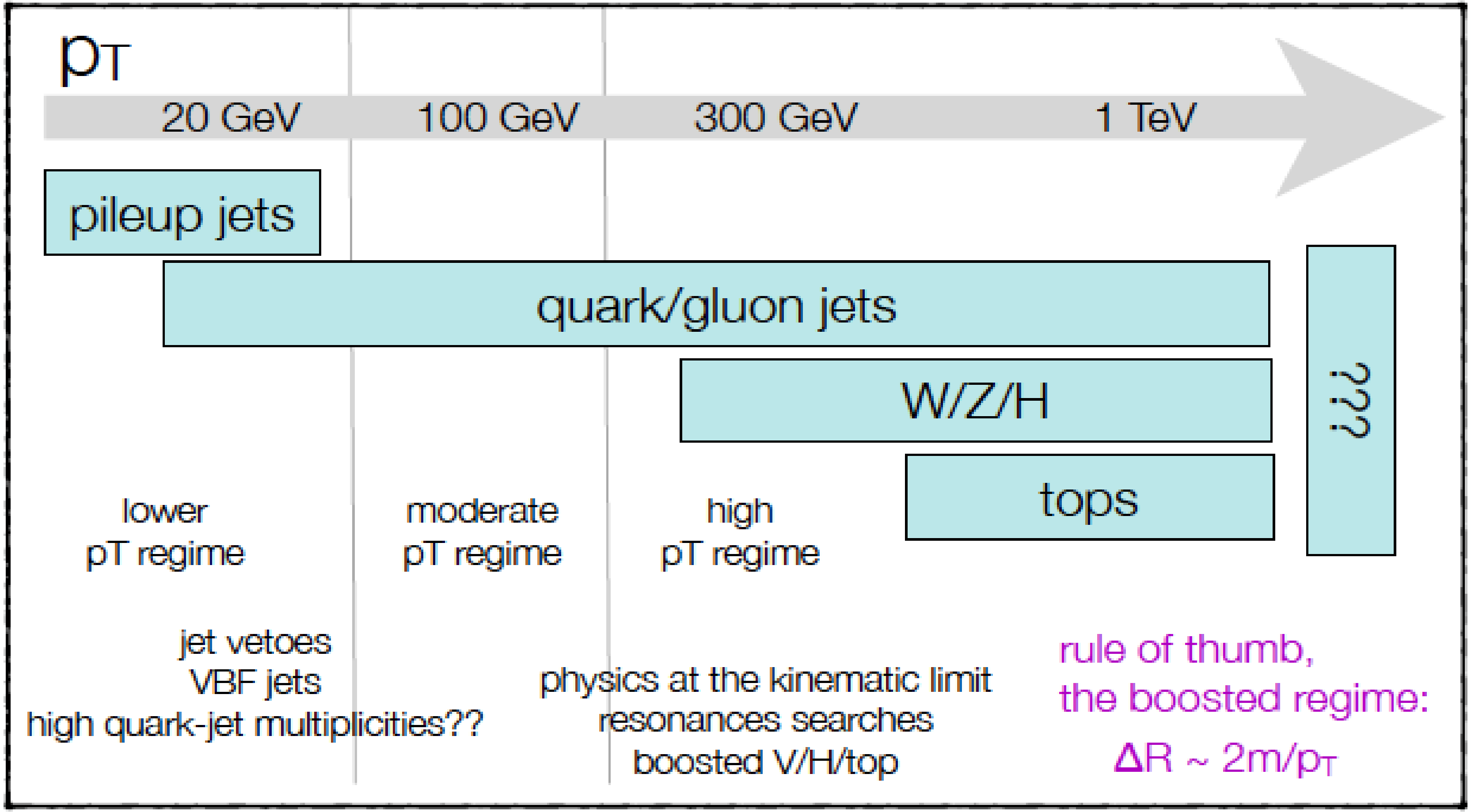
Why jet substructure at the LHC

- Widespread availability and use of infrared-safe recombination algorithms for hadron colliders

- Pileup and UE always present in with our hadronic final states, need to look inside the jets, can't treat them as just four-momenta any more

- Heavy particles can be produced with momenta large with respect to their mass, and BG falls at high-pt
  -> final states in hadronic decay modes are reconstructed as a single jet

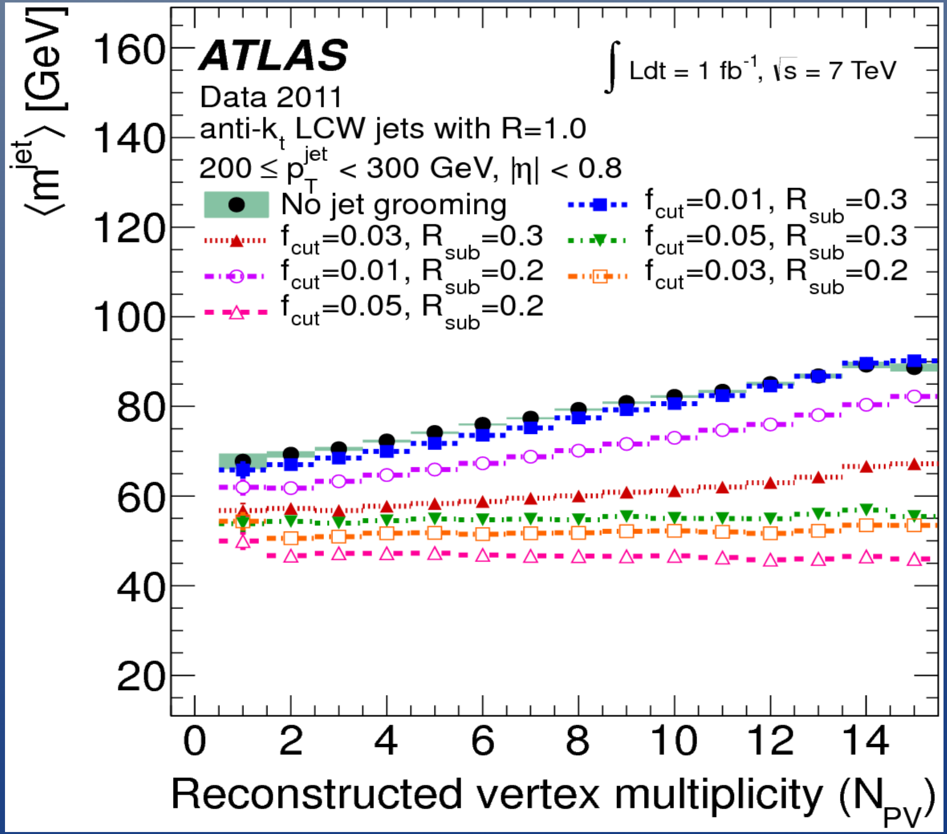
From jet substructure to Boost

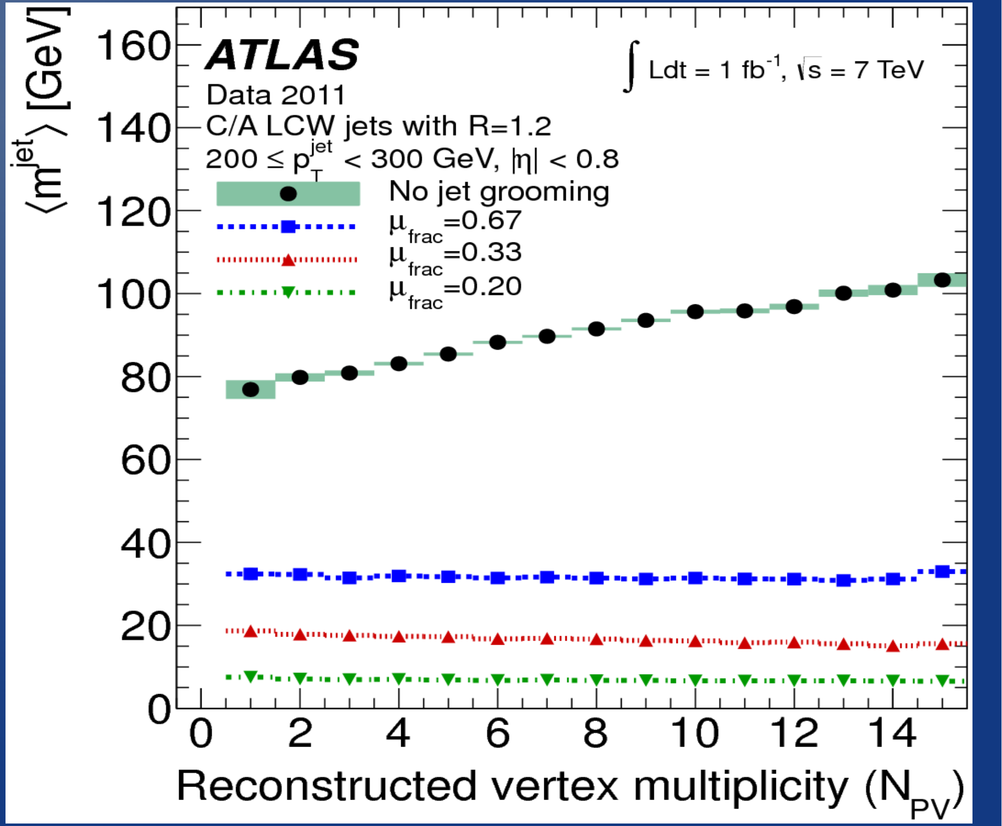


Nhan Thran, BOOST exp. summary

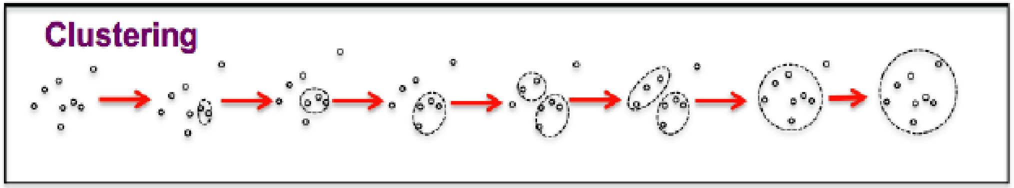
Jet grooming: removing soft components

Techniques exist since a few years to remove soft radiation from jets.
Main aim is improving mass resolution for known resonances, but they also improve jet response stability under pileup JHEP09 (2013) 076

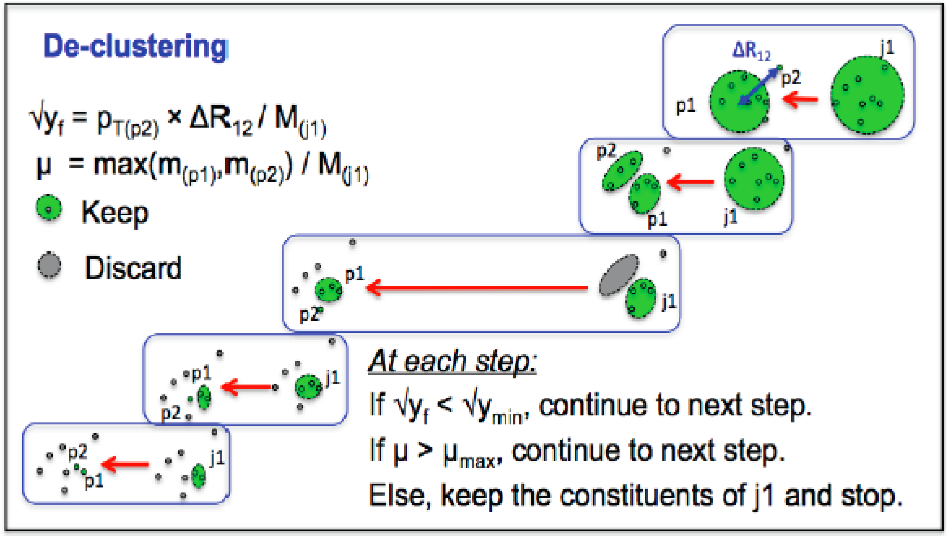




“historic” grooming techniques



(a) Reconstruction of a jet with the C/A algorithm.



$\sqrt{y_f} = p_{T(p2)} \times \Delta R_{12} / M_{(j1)}$

$\mu = \max(m_{(p1)}, m_{(p2)}) / M_{(j1)}$

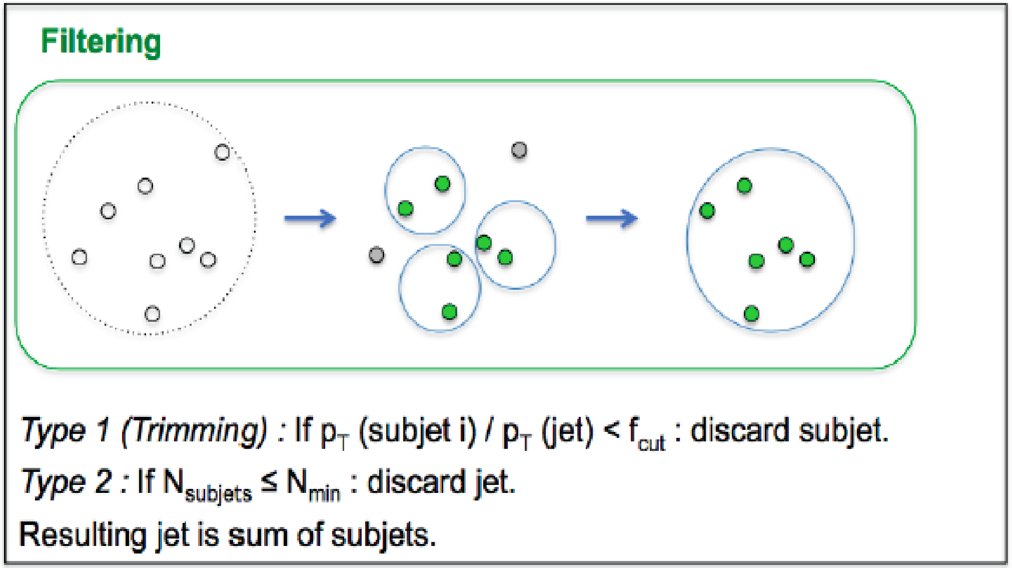
At each step:

If $\sqrt{y_f} < \sqrt{y_{min}}$, continue to next step.

If $\mu > \mu_{max}$, continue to next step.

Else, keep the constituents of j1 and stop.

(b) The mass-drop / momentum-balance technique utilised by the BDRS and BDRS-A algorithms for identifying jets with hard substructure. The de-clustering is performed running backwards the history of the clustering algorithm. BDRS requires $\sqrt{y_f} \geq 30\%$ and $\mu_{max} = \frac{2}{3}$. BDRS-A requires $\sqrt{y_f} \geq 20\%$ and makes no requirement on the mass-drop, $\mu_{max} = 1$.

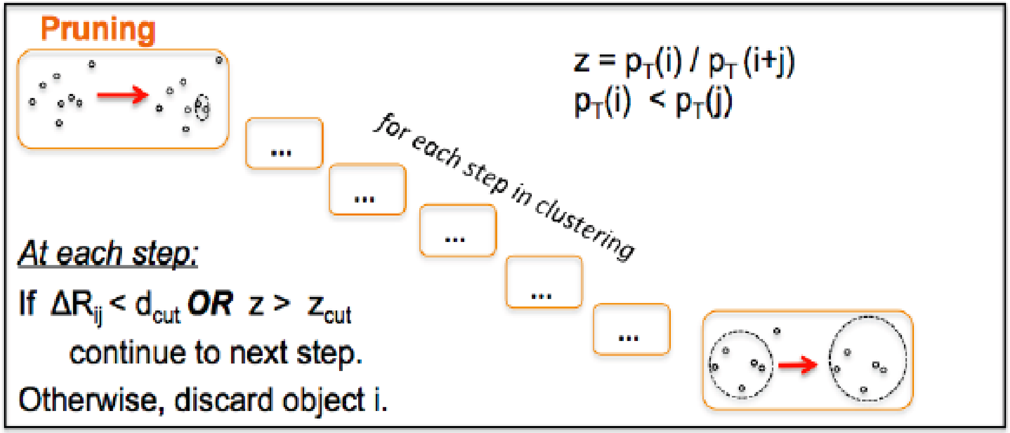


Type 1 (Trimming) : If p_T (subjet i) / p_T (jet) < f_{cut} : discard subjet.

Type 2 : If $N_{subjets} \leq N_{min}$: discard jet.

Resulting jet is sum of subjets.

(c) The filtering and trimming procedures. Filtering is used here as part of the BRDS and BDRS-A algorithms, each requiring a minimum of three subjets reconstructed with $R_{subjet} = min(0.3, \Delta R/2)$ and $R_{subjet} = 0.3$ respectively. Trimming is used here with $f_{cut} = 5\%$ and $R_{subjet} = 0.3$.



$z = p_T(i) / p_T(i+j)$

$p_T(i) < p_T(j)$

At each step:

If $\Delta R_{ij} < d_{cut}$ ***OR*** $z > z_{cut}$

continue to next step.

Otherwise, discard object i.

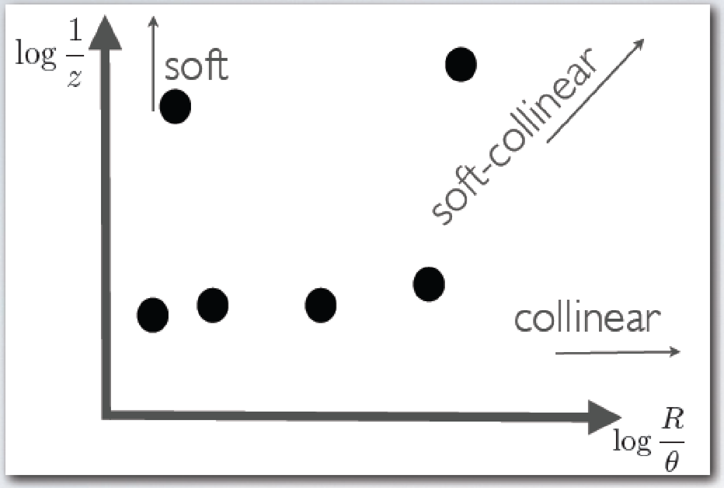
(d) Jet pruning. The re-clustering of the jet constituents can proceed via either of the C/A or k_t algorithms; both are studied here.

Split-filtering: Butterworth Davison Rubin Salam Phys. Rev. Lett 100 (2008) 242001

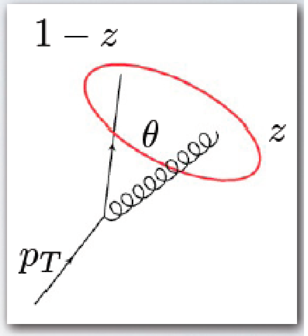
Triming: Krohn Thaler Wang JHEP 02 (2010) 84

Pruning: Ellis Vermillon Walsh Phys Rev D 81 (2010) 094023

Effects of grooming can be analytically computed



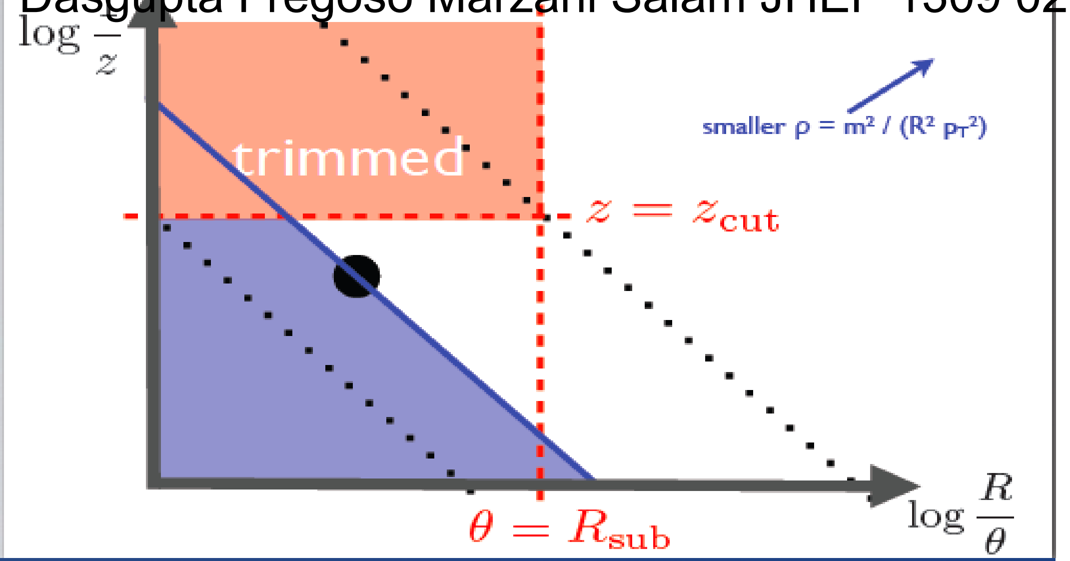
Soft gluons off a hard parton (a quark for definiteness)



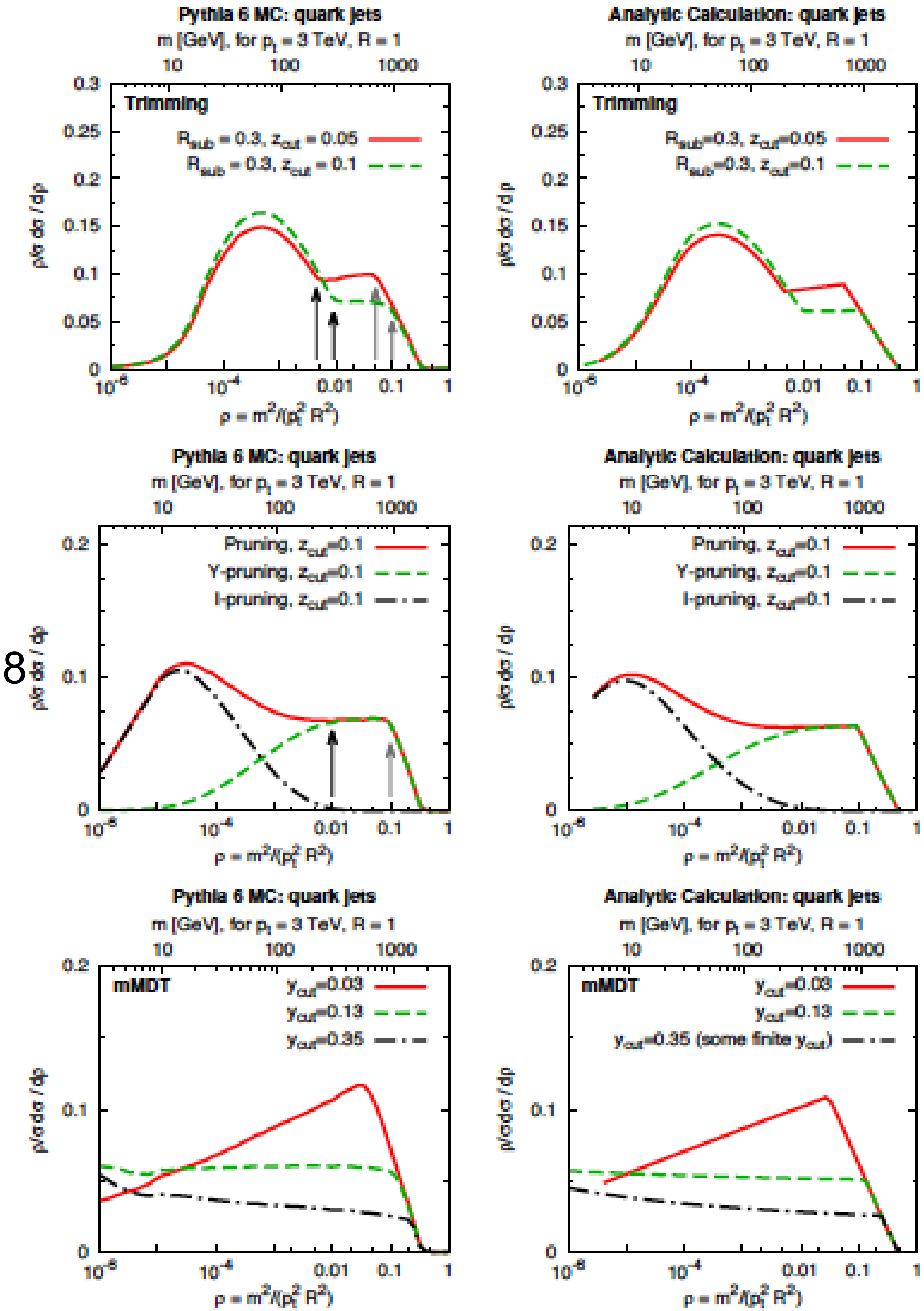
Emission probability is uniform in the (log z, log θ) plane:

$$dP_i \sim \frac{\alpha_s}{\pi} C_r \frac{dz_i}{z_i} \frac{d\theta_i}{\theta_i}$$

Dasgupta Fregoso Marzani Salam JHEP 1309 028



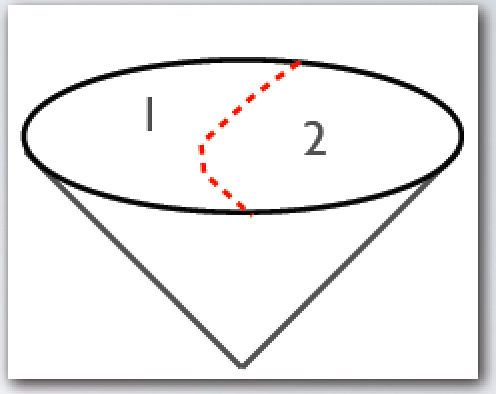
In case of grooming, areas of phase-space are removed from the integral giving the ρ distribution



Soft Drop

Larkoski, SM, Soyez and Thaler (2014)

1. Undo the last stage of the C/A clustering. Label the two subjets j_1 and j_2.



2. If

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

then deem j to be the soft-dropped jet.

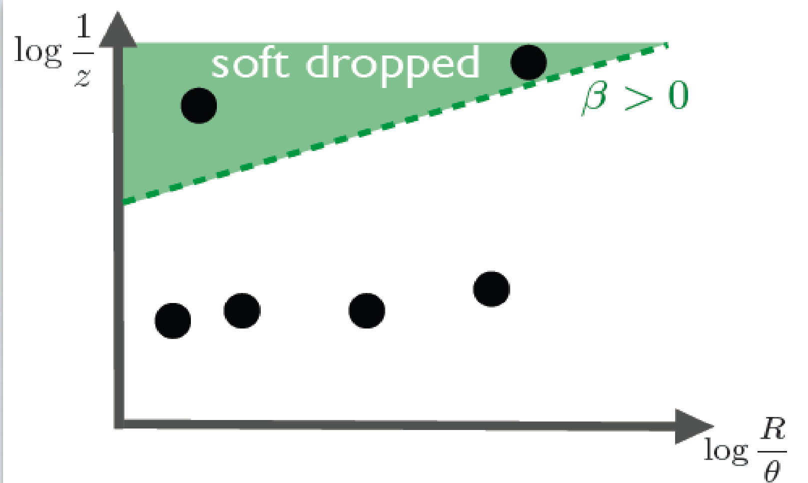
3. Otherwise redefine j to be the harder subjet and iterate.

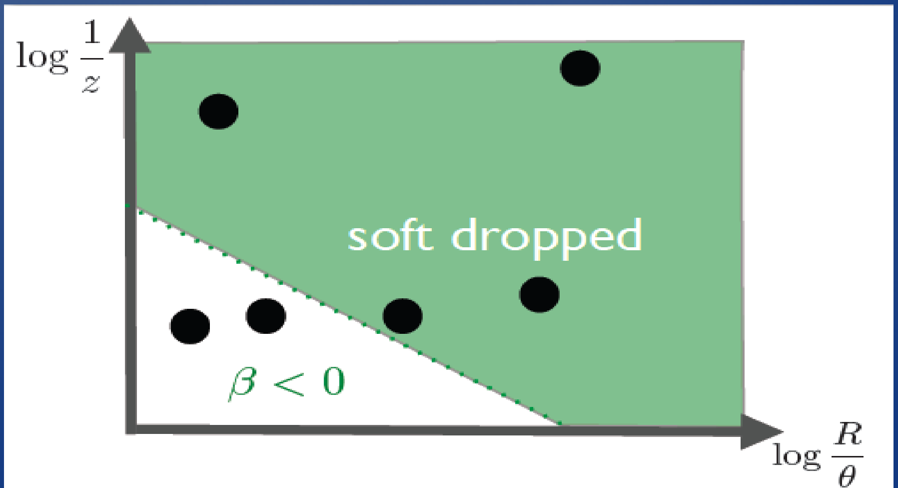
1-prong jets can be either kept (grooming mode) or discarded (tagging mode)

- Generalisation of the (modified) Mass Drop procedure
- no mass drop condition (not so important)
- mMDT recovered for β=0

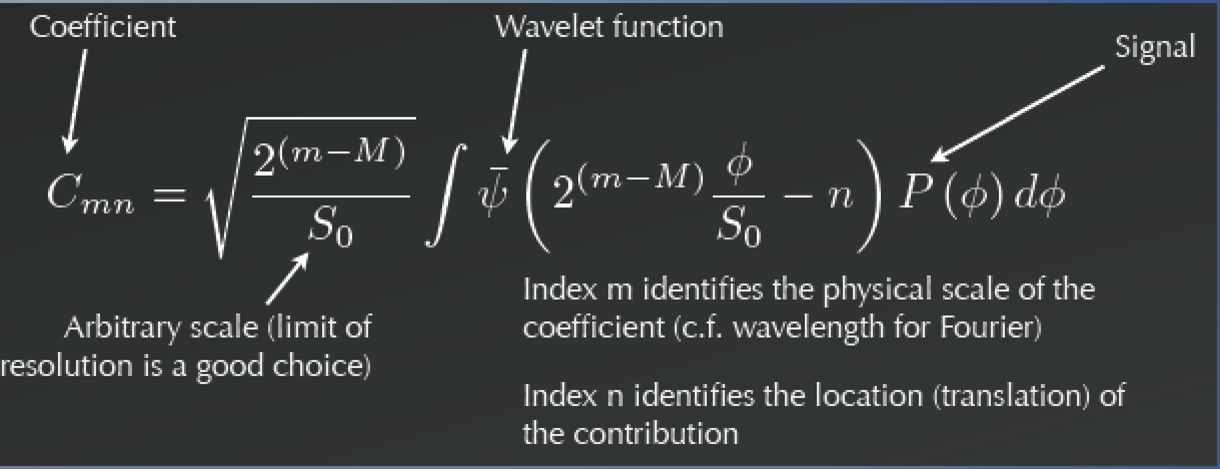
Butterworth, Davison, Rubin and Salam (2008)
Dasgupta, Fregoso, SM and Salam (2013)

For β>0 only removes soft radiation, for β<0 also some collinear





Wavelet de-noising J.Monk arxiv 1405.5008



Coefficient

Wavelet function

Signal

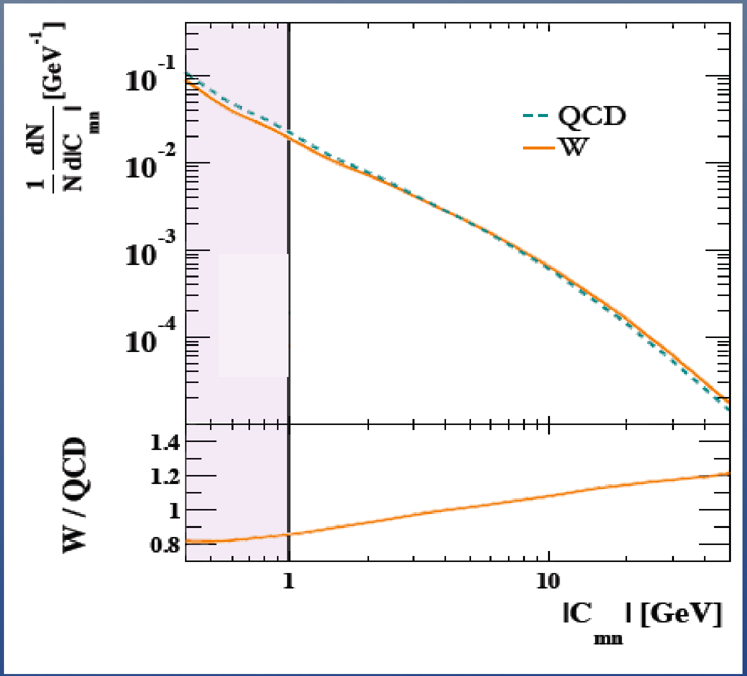
$$C_{mn} = \sqrt{\frac{2^{(m-M)}}{S_0}} \int \bar{\psi}\left(2^{(m-M)}\frac{\phi}{S_0} - n\right) P\left(\phi\right) d\phi$$

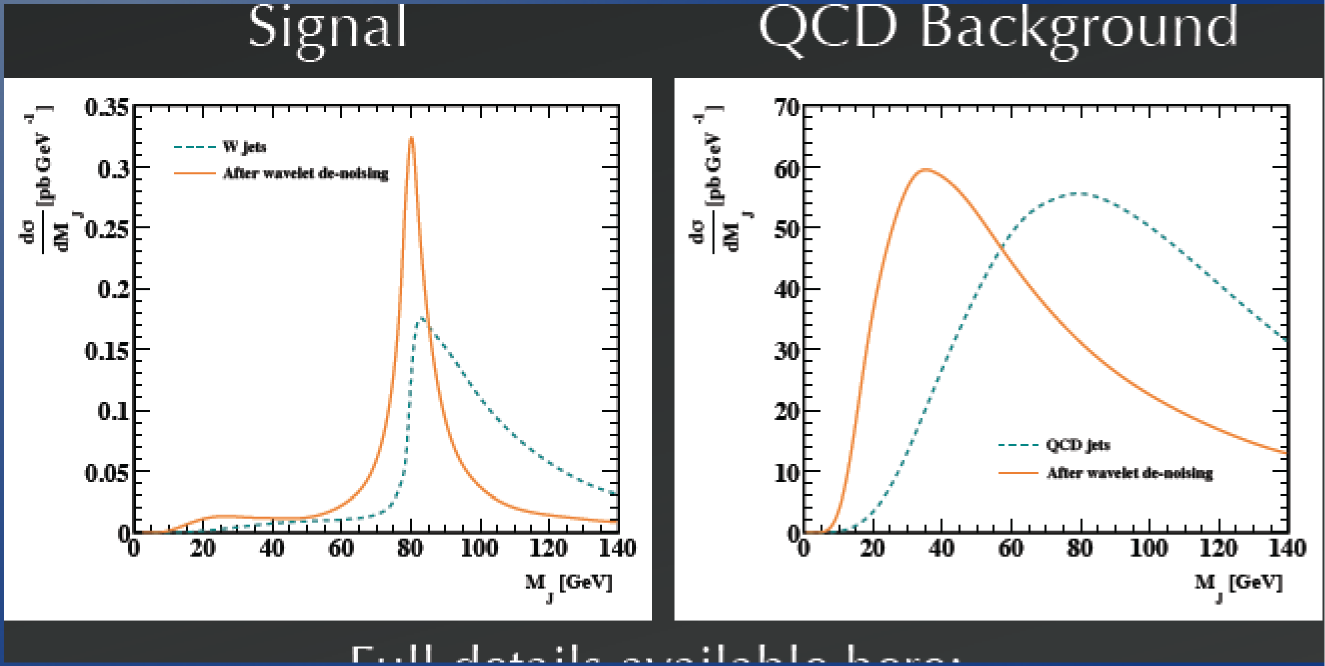
Arbitrary scale (limit of resolution is a good choice)

Index m identifies the physical scale of the coefficient (c.f. wavelength for Fourier)

Index n identifies the location (translation) of the contribution

Similar to Fourier transforms, but also account for translation, and use more complex function as basis

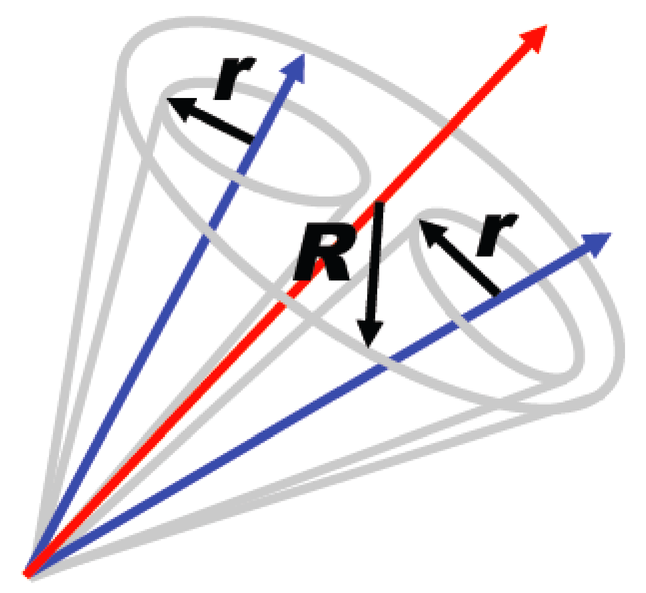


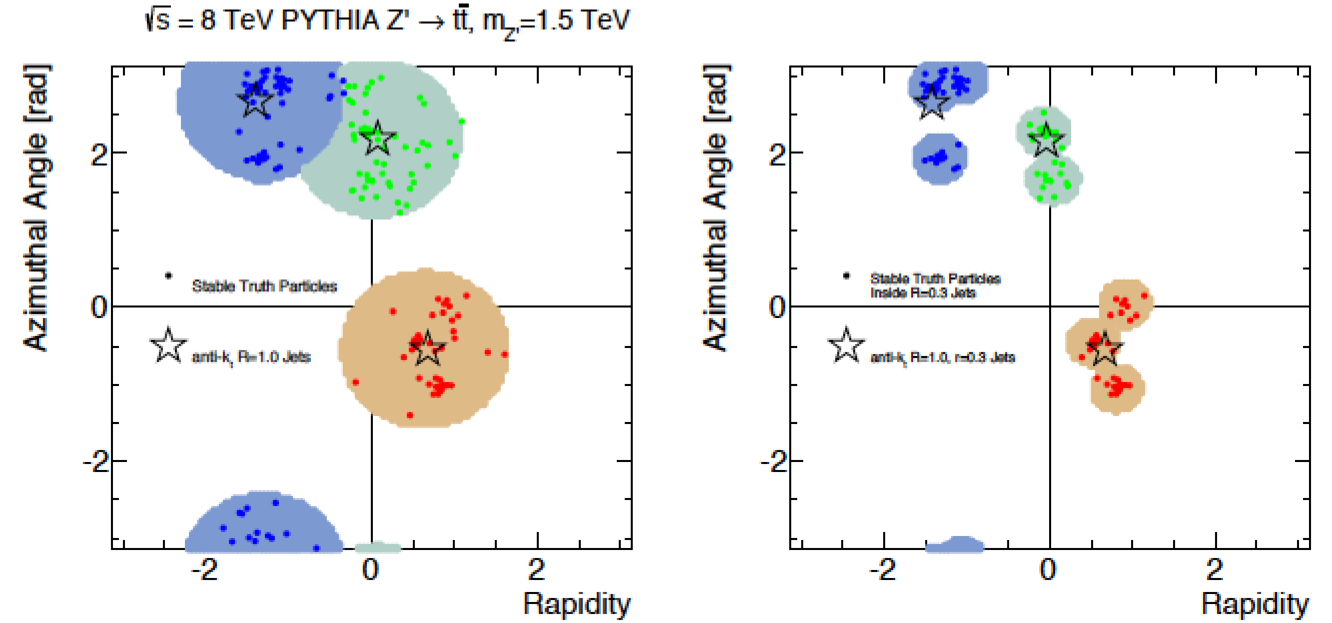


Much improved mass behaviour once coefficients corresponding to scales < 1 GeV are dropped

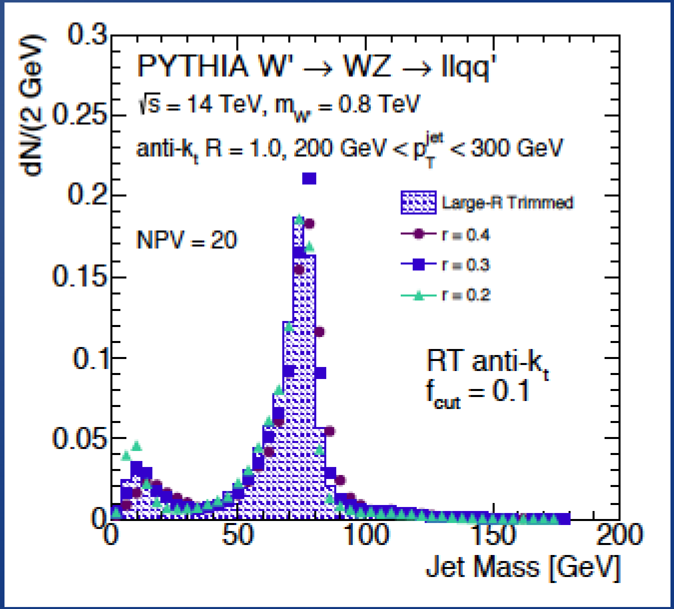
Jets from jets B.Nachmann et al. arxiv 1407.2922

Calibrate jets with a small radius r, and from them build large R jets. Basically, a bottom-up trimming





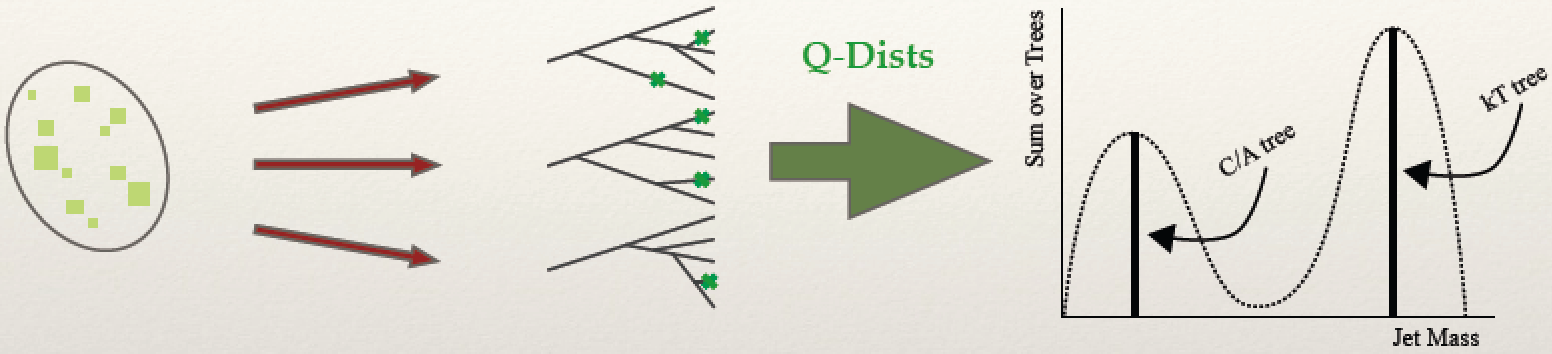
Can have slightly better performance than standard trimming for the right choice of the r and R parameters; easier calibration?



Q-jets Ellis Hornig Roy Schwartz 1201.1914

Use all clusterings and get a mass distribution for each jet

- different for different algorithms :

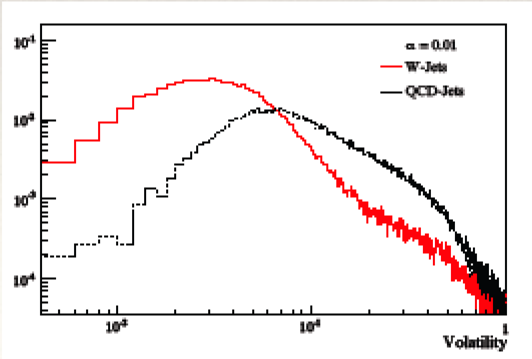


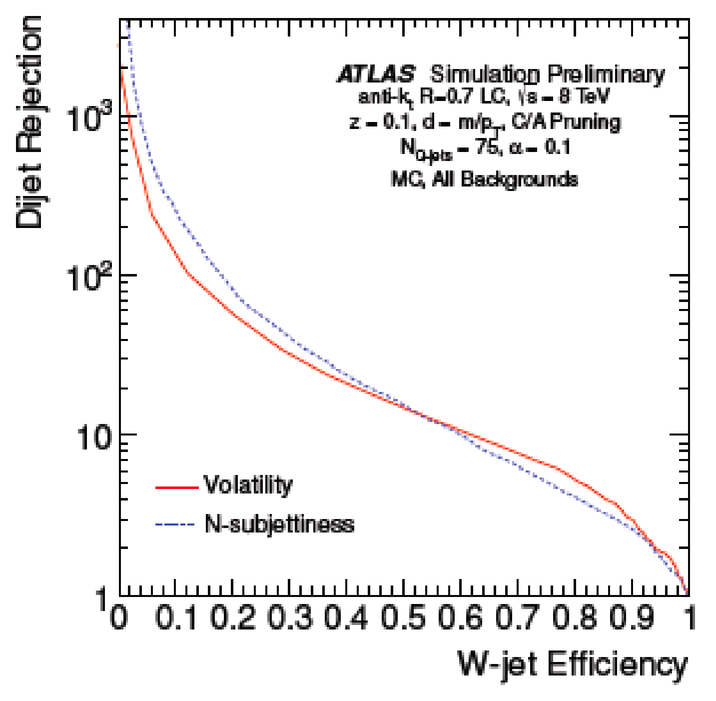
- Variation larger for QCD jets (no real m_J scale)

⇒ “Volatility”:

$$\mathcal{V} = \Gamma/\langle m \rangle$$

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





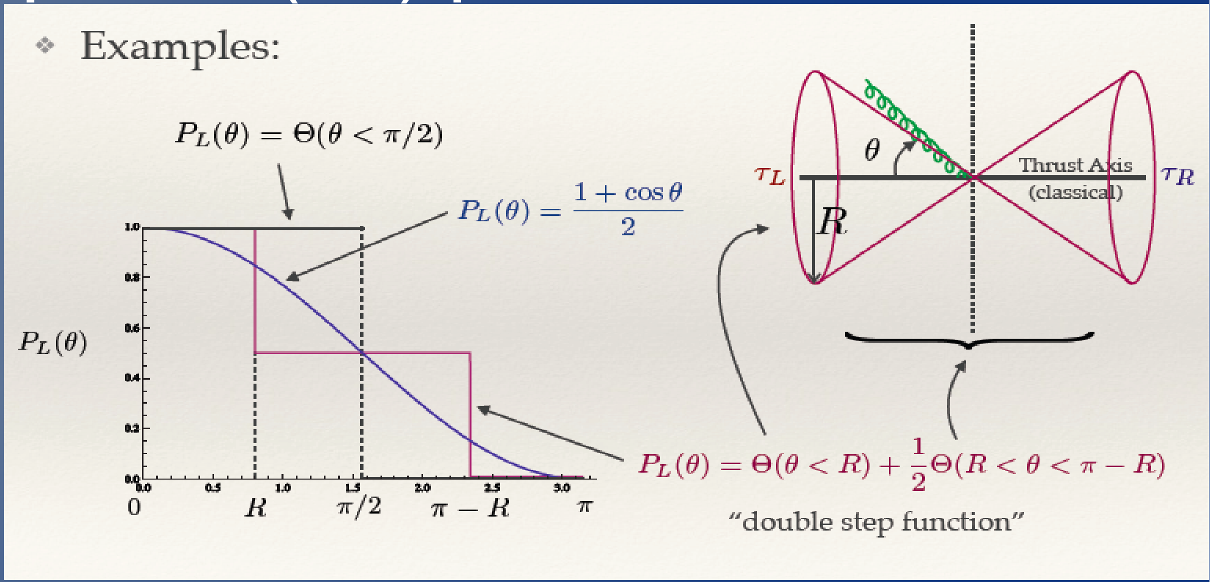
Volatility can be used to discriminate W-jets from QCD giving similar/better results than e.g. n-subjettiness

What can be calculated for Q-jets?

Not volatility- it would require O(10) particles

Q-Thrust

Generalises easily to Q-subjettiness



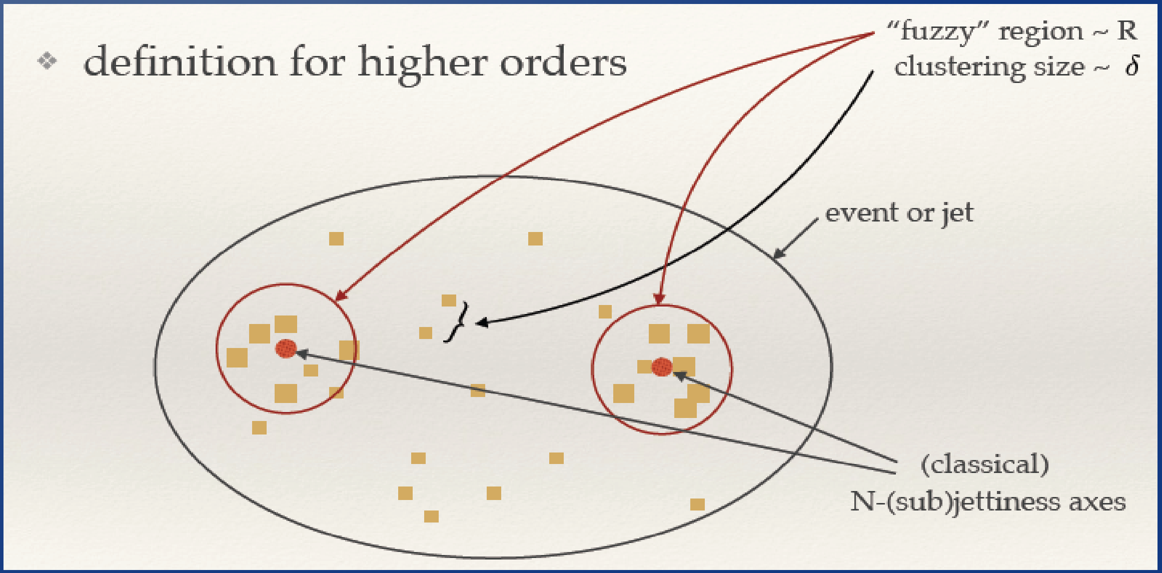
- Examples:

$P_L(\theta) = \Theta(\theta < \pi/2)$

$P_L(\theta) = \frac{1 + \cos\theta}{2}$

$P_L(\theta) = \Theta(\theta < R) + \frac{1}{2}\Theta(R < \theta < \pi - R)$

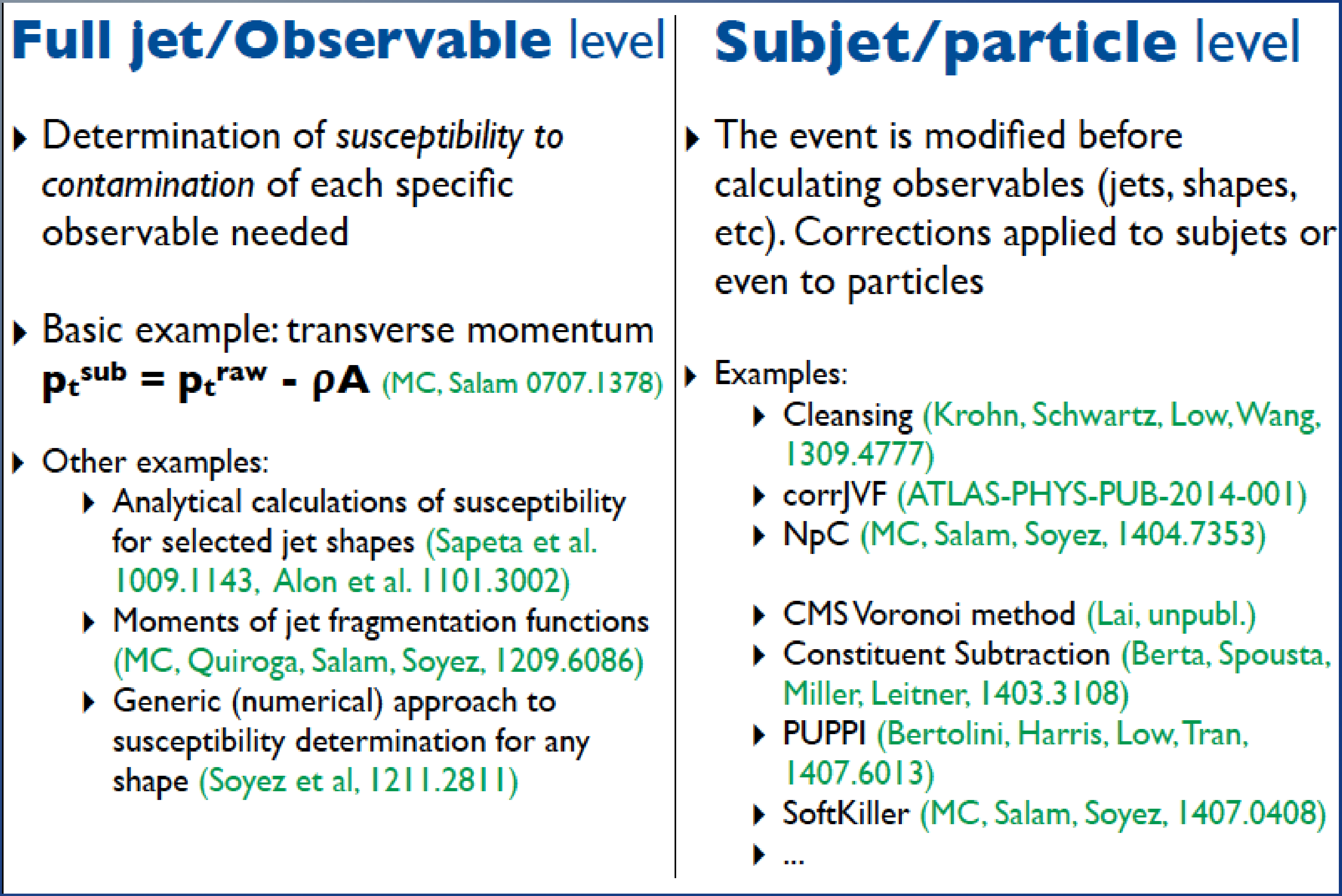
"double step function"



- definition for higher orders

Pileup control

Jet grooming improves stability wrt pileup, but it is not its main focus. Dedicated pileup subtraction techniques:



Full jet/Observable level

- Determination of *susceptibility to contamination* of each specific observable needed
- Basic example: transverse momentum
  $p_t^{sub} = p_t^{raw} - \rho A$ (MC, Salam 0707.1378)
- Other examples:
  - Analytical calculations of susceptibility for selected jet shapes (Sapeta et al. 1009.1143, Alon et al. 1101.3002)
  - Moments of jet fragmentation functions (MC, Quiroga, Salam, Soyez, 1209.6086)
  - Generic (numerical) approach to susceptibility determination for any shape (Soyez et al, 1211.2811)

Subjet/particle level

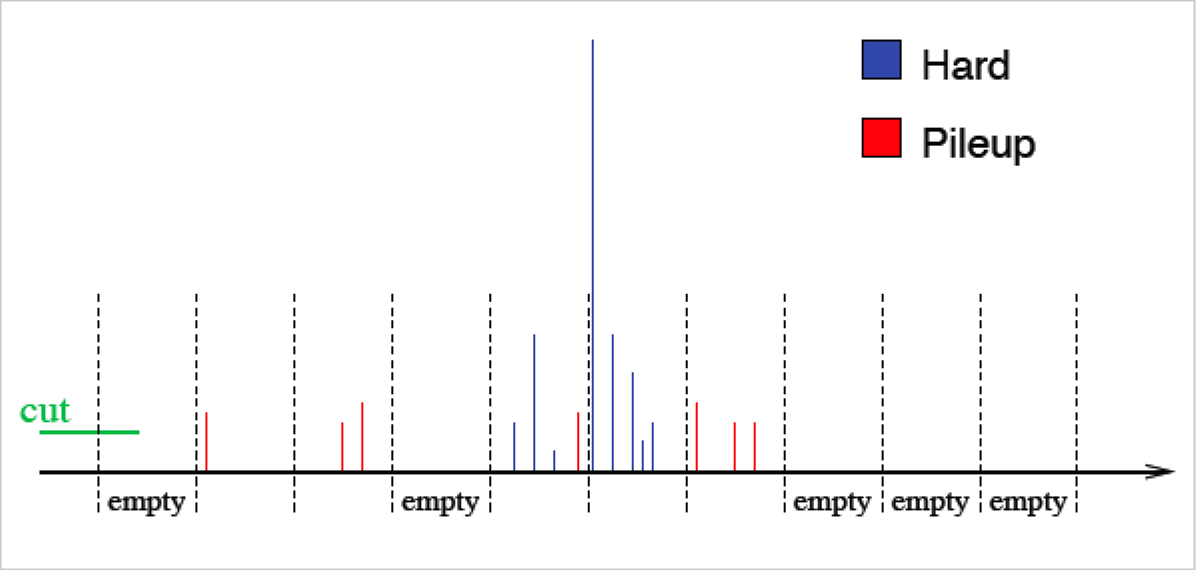
- The event is modified before calculating observables (jets, shapes, etc). Corrections applied to subjets or even to particles
- Examples:
  - Cleansing (Krohn, Schwartz, Low, Wang, 1309.4777)
  - corrJVF (ATLAS-PHYS-PUB-2014-001)
  - NpC (MC, Salam, Soyez, 1404.7353)

  - CMS Voronoi method (Lai, unpubl.)
  - Constituent Subtraction (Berta, Spousta, Miller, Leitner, 1403.3108)
  - PUPPI (Bertolini, Harris, Low, Tran, 1407.6013)
  - SoftKiller (MC, Salam, Soyez, 1407.0408)
  - ...

SoftKiller Cacciari Salam Soyez arXiv 1407.0408

Divide event into regions, and tune the threshold until half the event is empty (median is zero!)

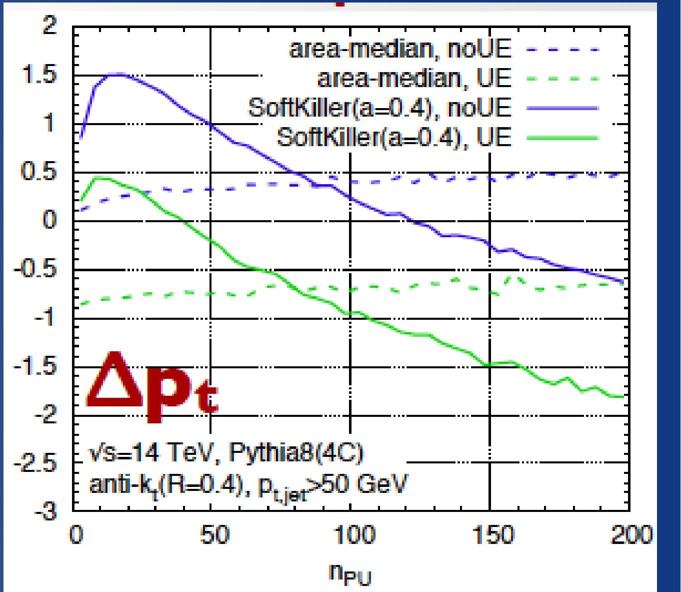
$$p_t^{\text{cut}} = \underset{i \in \text{patches}}{\text{median}} \{p_{ti}^{\text{max}}\}$$

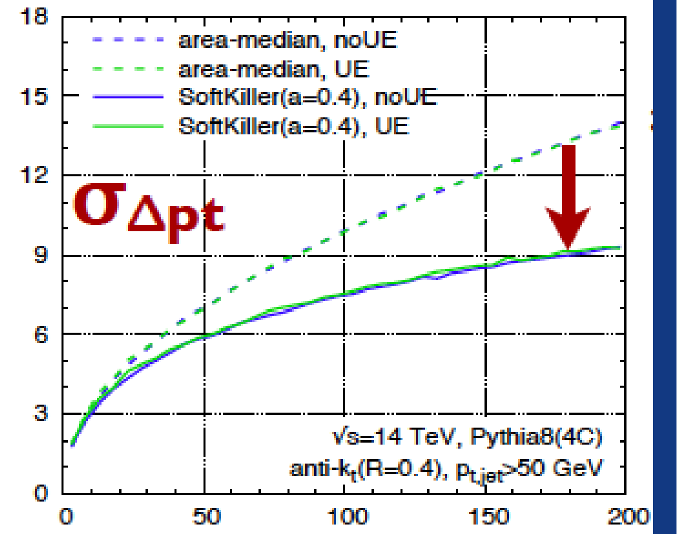


G. Soyez

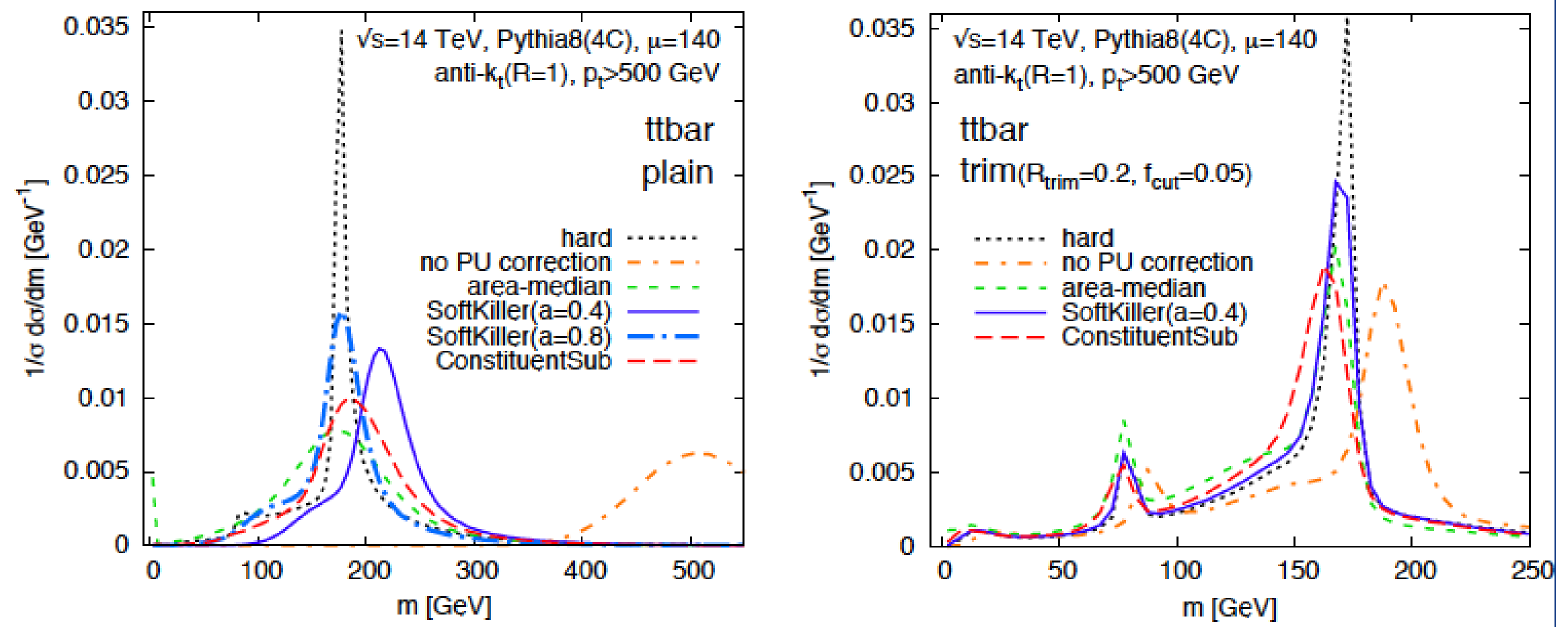
Half of the event is empty ⇒ **ρ = 0** (because it's the median)

NB. SK needs tuning of the size of the patches used to calculate ρ.
0.4 was found to be a good choice for R=0.4 jets





SoftKiller with trimming or thresholds

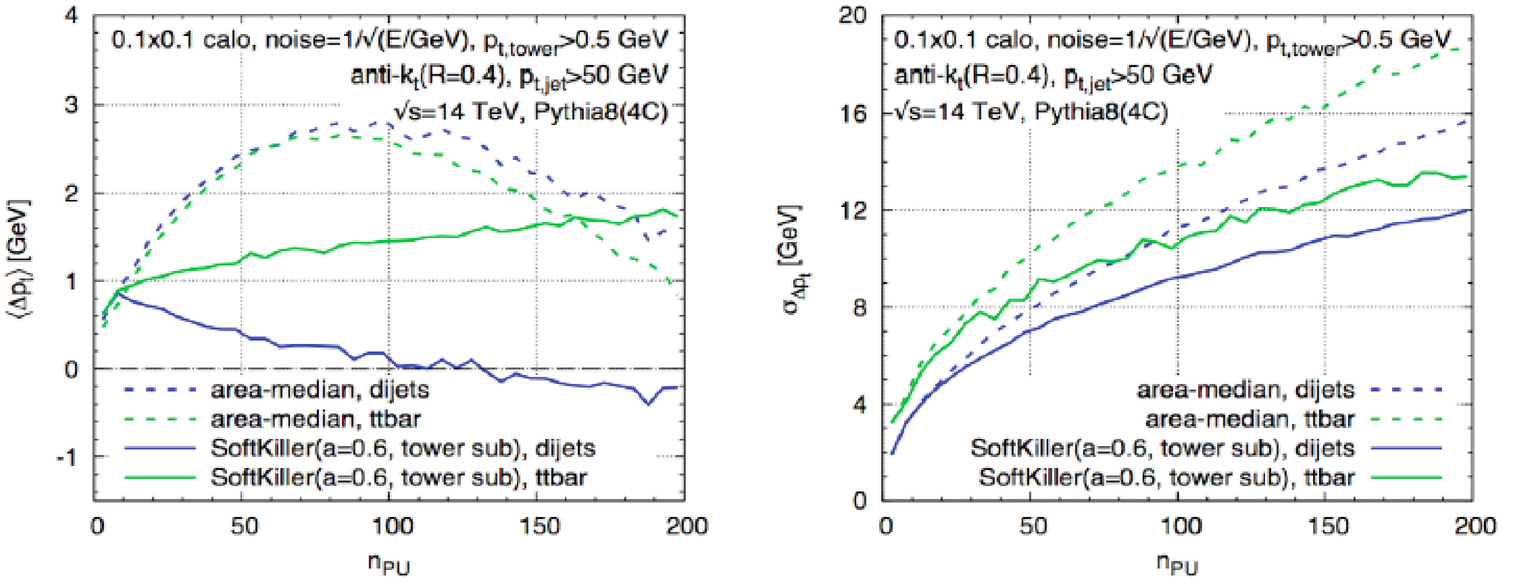


No trimming

Trimming (R$_{sub}$=0.2, f=0.05)

$$p_t^{\text{tower,sub}} = \max\left(0,\ p_t^{\text{tower}} - \rho A^{\text{tower}}\right)$$

$$p_t^{\text{cut,sub}} = \underset{i\in\text{patches}}{\text{median}} \left\{ p_{ti}^{\text{tower,sub, max}} \right\}$$

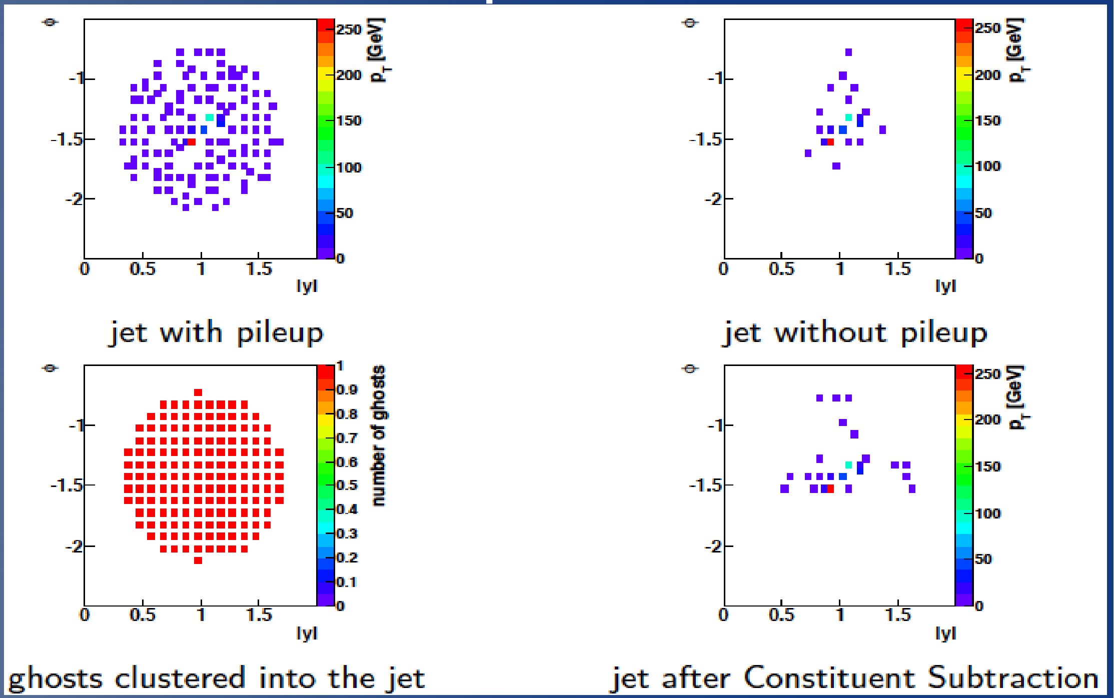


Constituent subtraction Berta Spousta Miller Leitner

Fill jets with ghosts with pTg = **ρ Ag** and associate them with particles according to

$$\Delta R_{i,k} = p_{Ti}^{\alpha} \cdot \sqrt{(y_i - y_k^g)^2 + (\phi_i - \phi_k^g)^2}.$$

Remove particles with pT-pTg<0

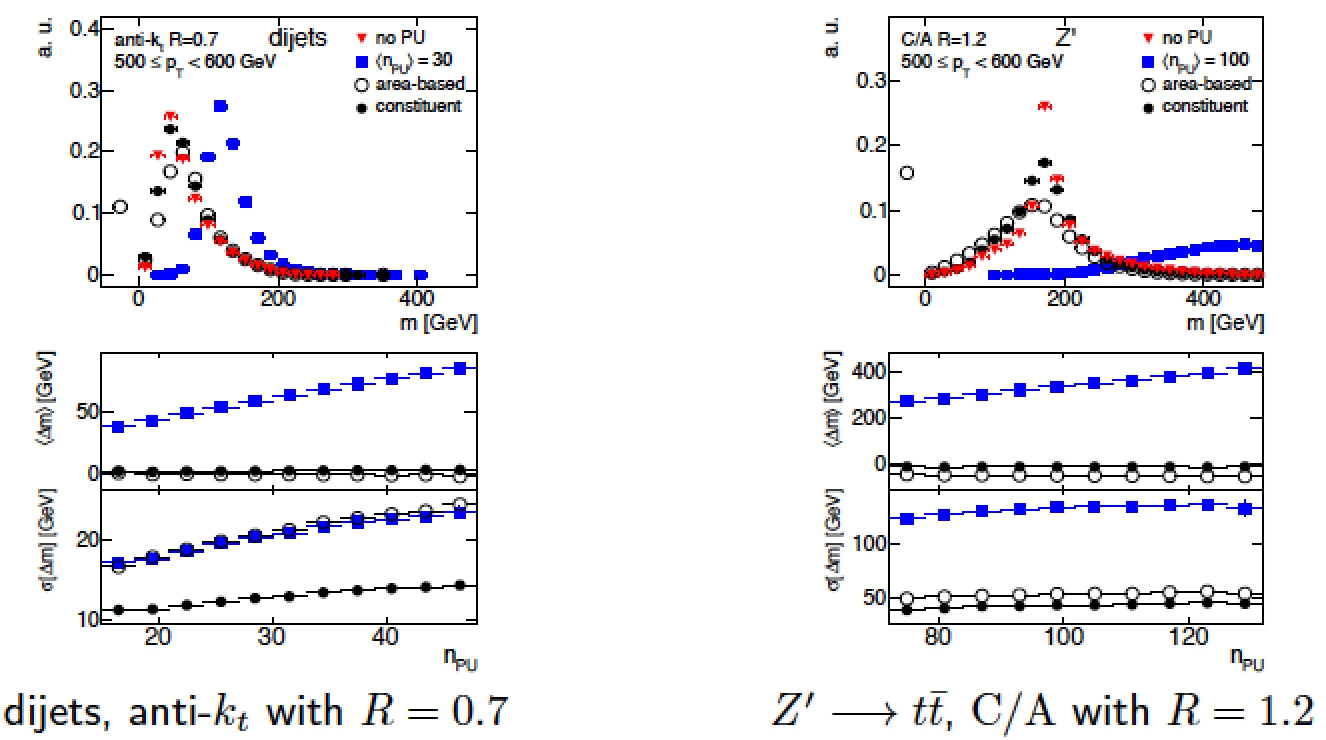


jet with pileup

jet without pileup

ghosts clustered into the jet

jet after Constituent Subtraction

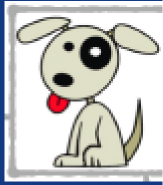


dijets, anti-k_t with $R = 0.7$

$Z' \longrightarrow t\bar{t}$, C/A with $R = 1.2$

Better performance than simple area subtraction

PUPPI Harris Tran Bertolini Low arxiv 1407.6013



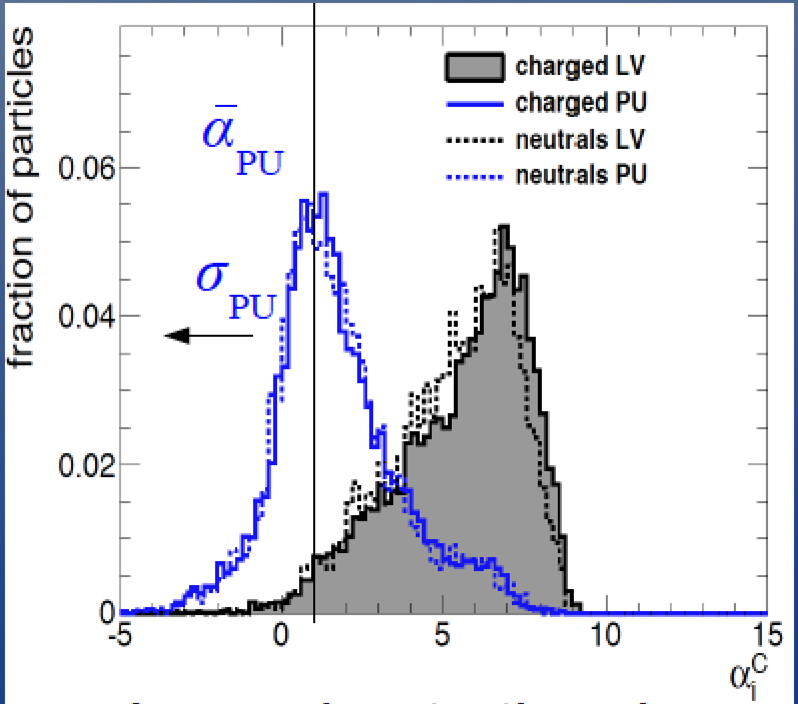
In jet-without-jet framework: draw a cone around each particle

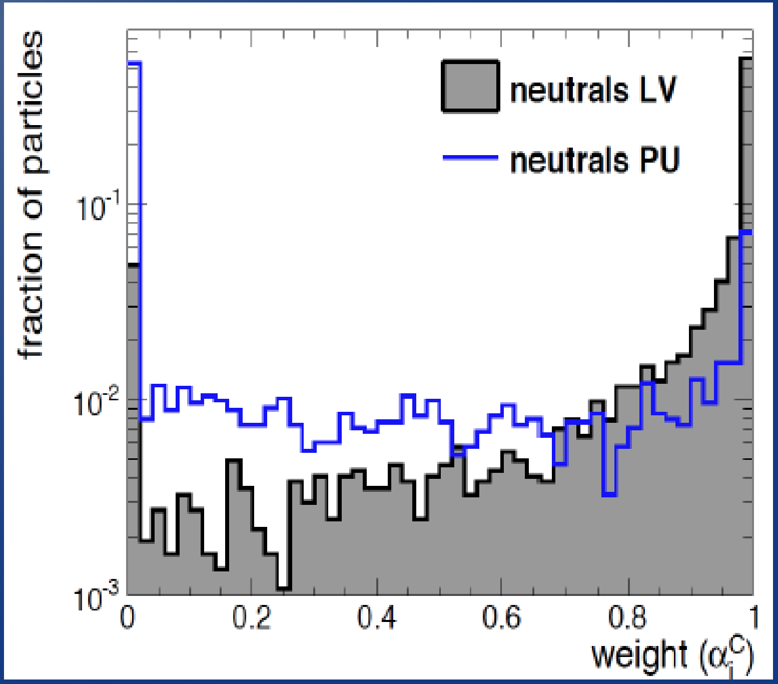
Compute metric **α** to distinguish PU from HS:

Central: $\log \sum_{j \in \text{Charged Leading Vertex}} \frac{p_{Tj}}{\Delta R_{ij}}$ Forward: $\log \sum_{j \in \text{event}} \frac{p_{Tj}}{\Delta R_{ij}}$

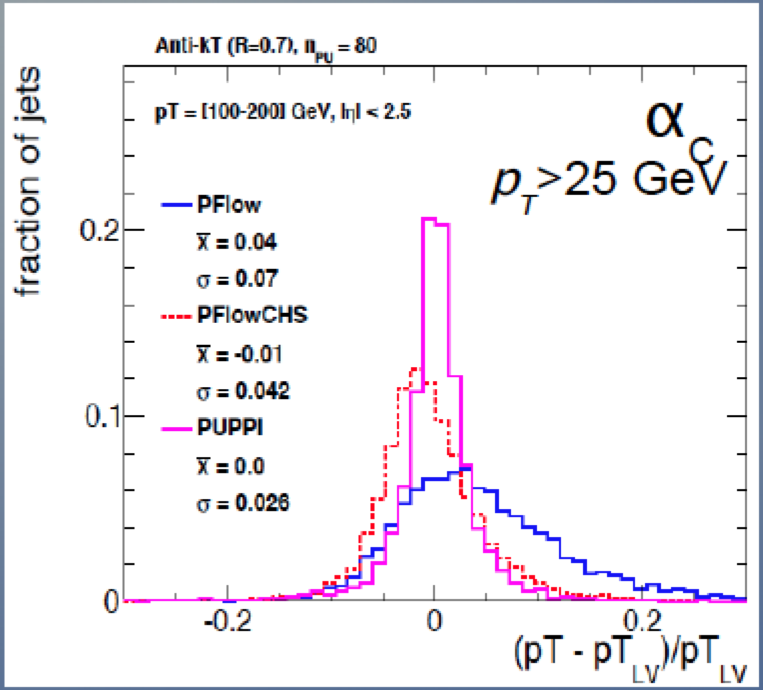
Calculate median and RMS for **α**

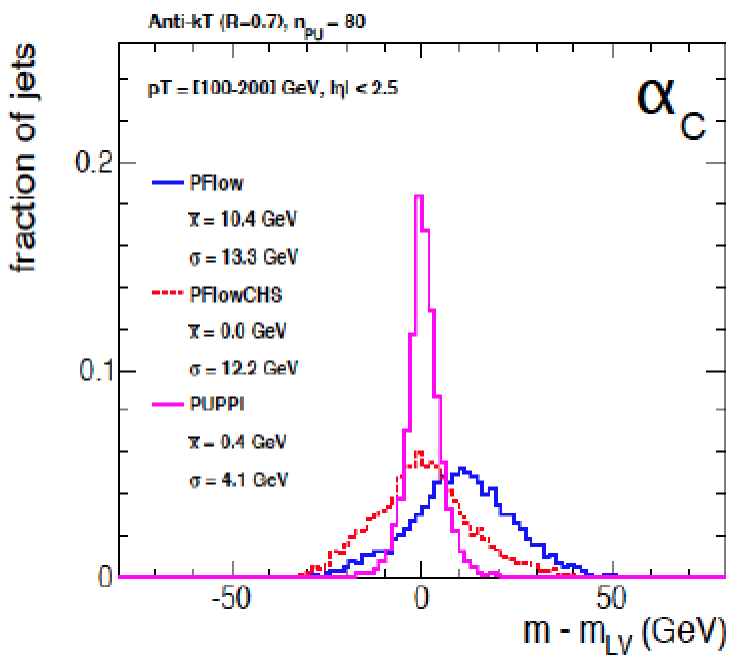
Use it to compute a particle weight, and recluster

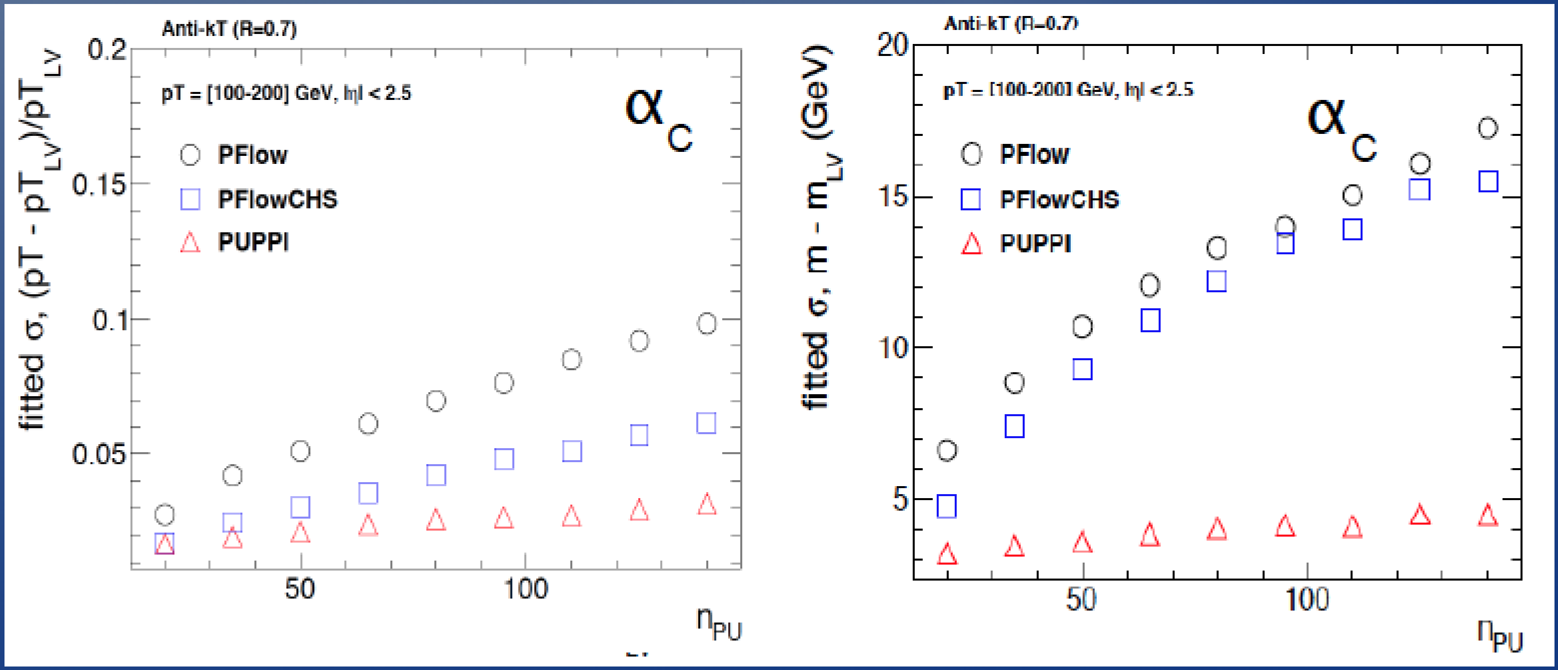




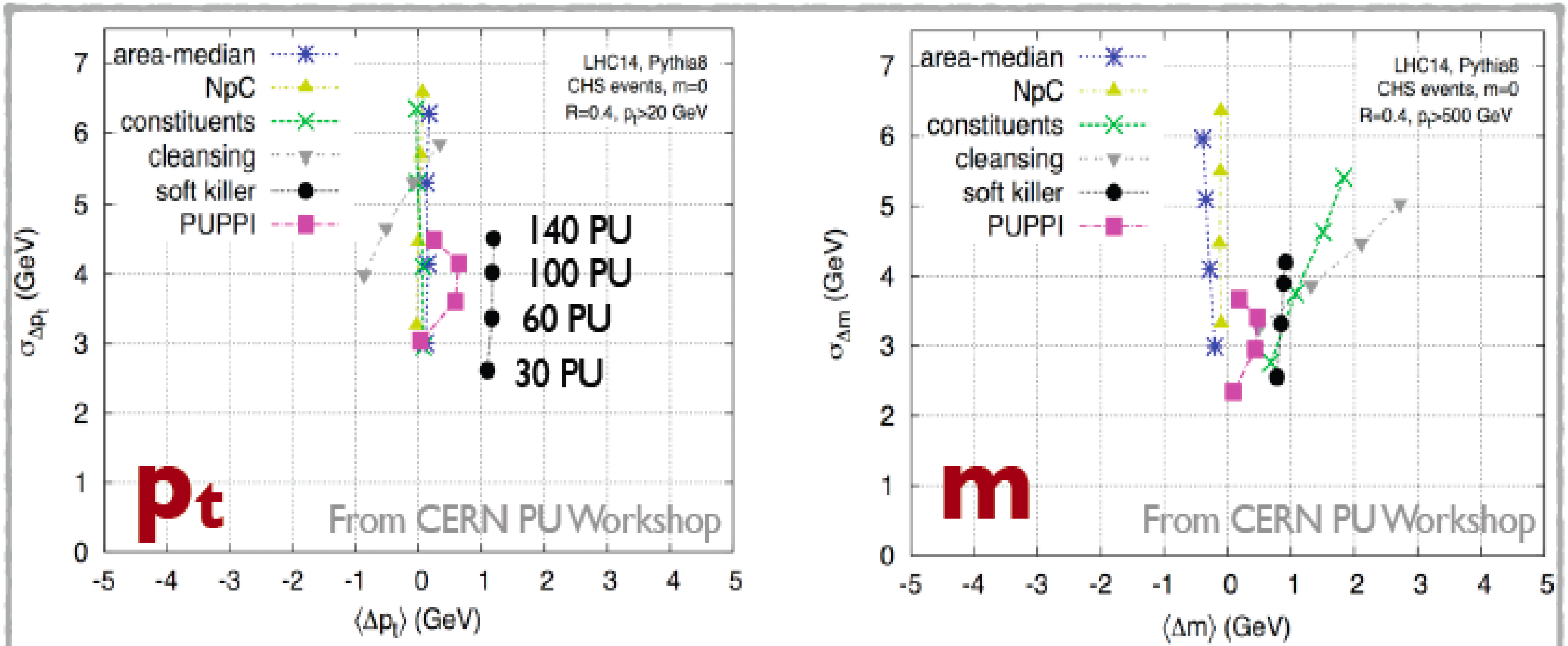
PUPPI performance







Pileup subtraction summary



- Subjet/particle-based background subtraction methods tend to perform better in terms of dispersion than full jet-based ones
  - can be made reasonably unbiased and robust
  - can be fast
  - allow one to calculate any observable
- Many tools are already public and available in FastJet Contrib

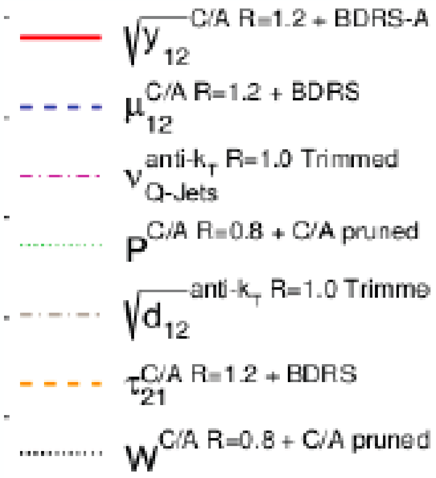
It will be interesting to see all these methods tested in the experiments!

Boosted boson tagging

Trimmed
BDRS
BDRS-A
C/A-pruned
k_t-pruned

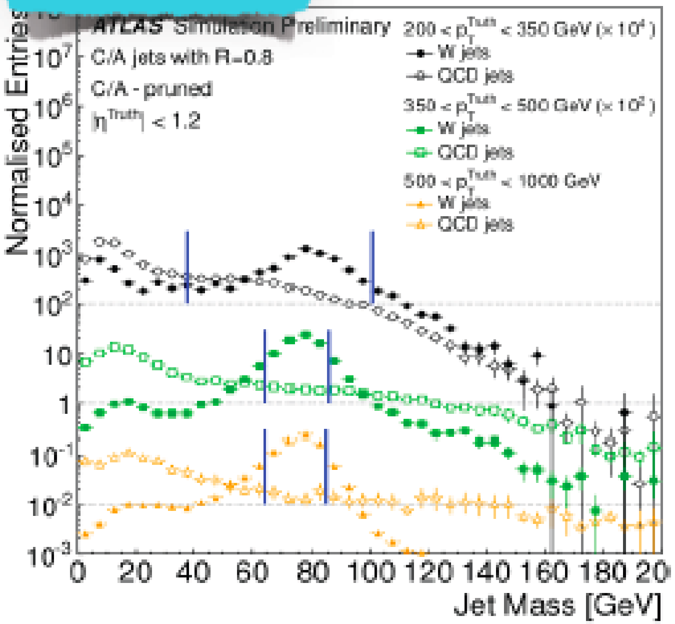
Jet grooming techniques
Filtering [1]
Trimming [2]
Pruning [3]
Soft-Drop [4]

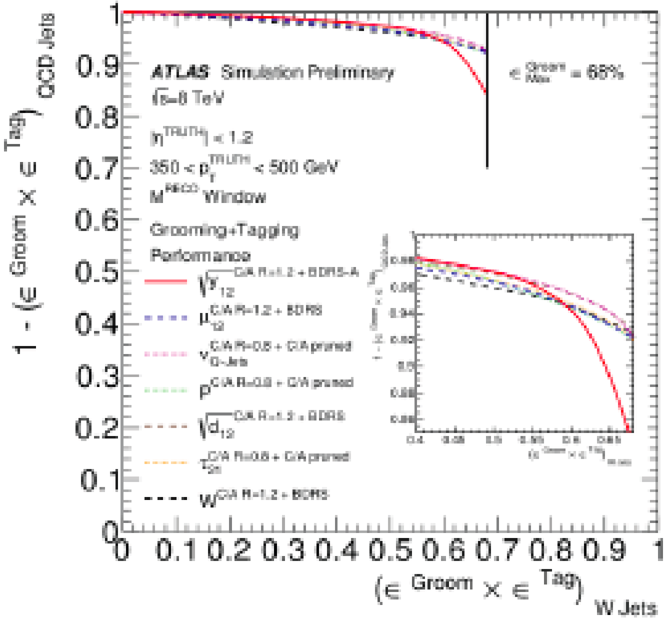
Variable
Gluon/Quark Likelihood [5]
Subjet Gluon/Quark Likelihood [5]
Energy Correlation Functions [6]
N-subjettiness
Qjet volatility [7]

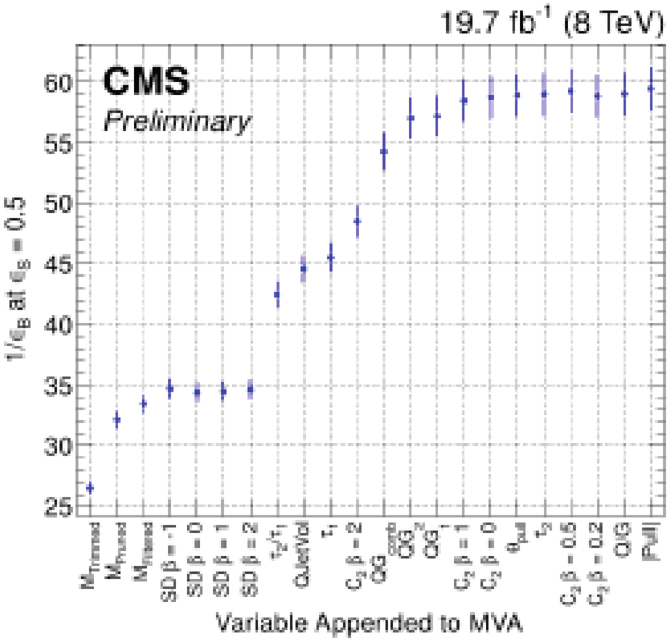


As methods mature, it becomes natural to push the bounds of performance

look here Steve!



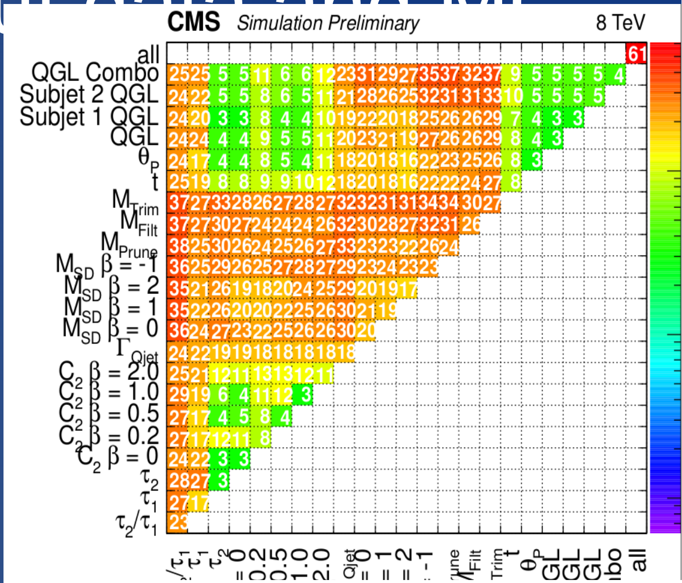


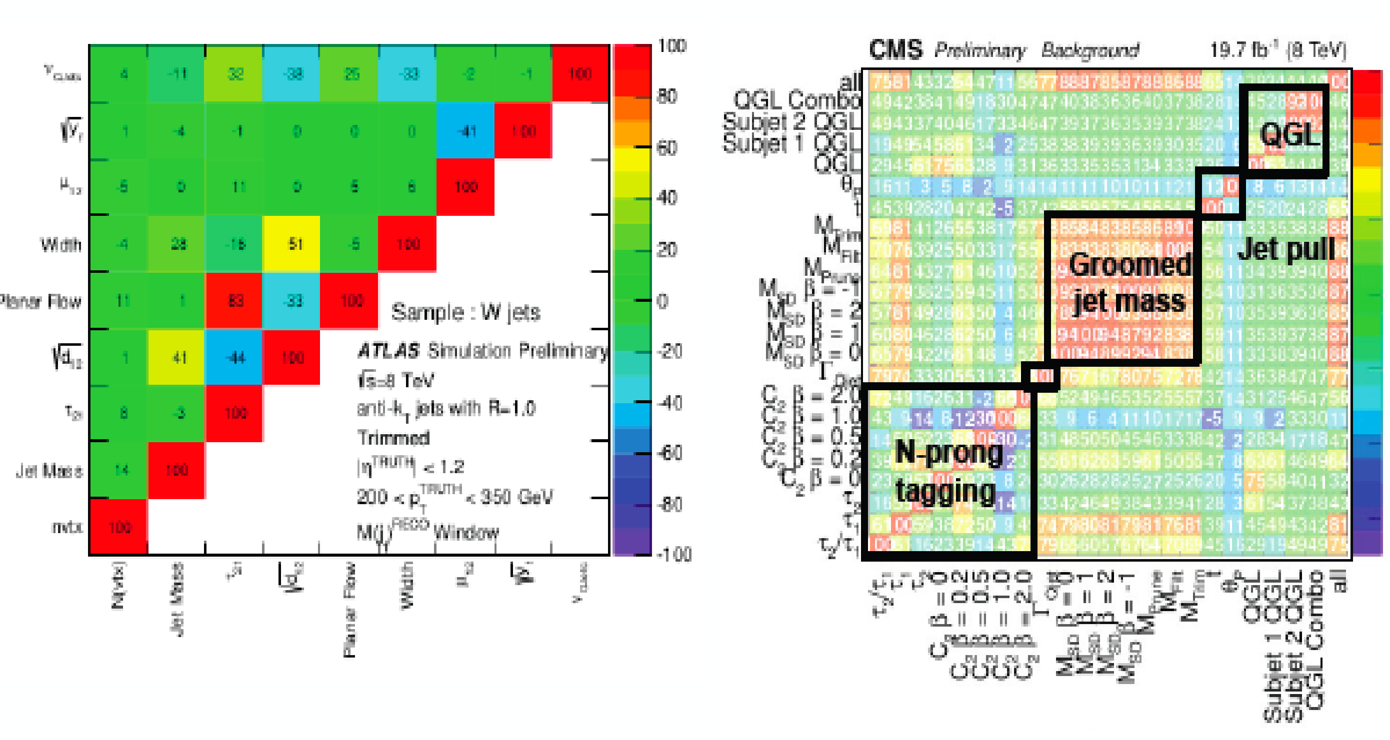


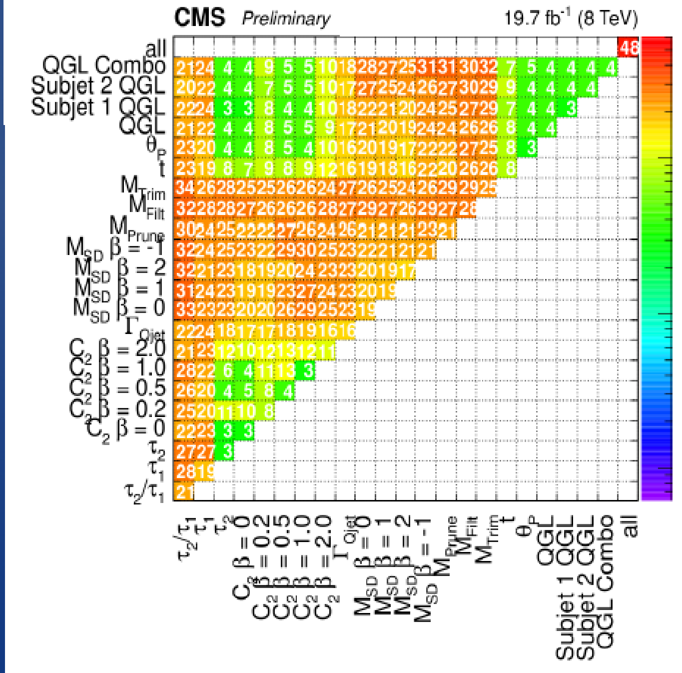
broadly speaking, groomed mass + shape is near optimal, nice to see confirmation by ATLAS, CMS and at particle level (boost 13 report)

Variable correlations

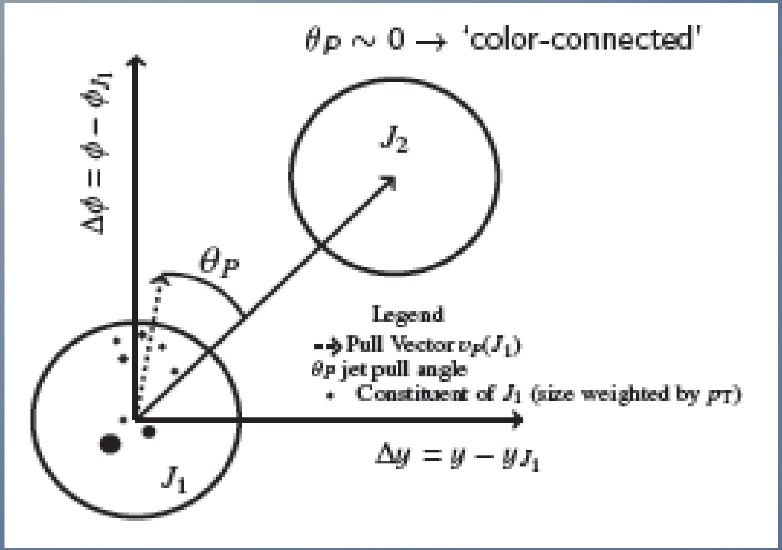
Studied in ATLAS and CMS, with the aim of combining them in a likelihood; CMS has BDT, but data and MC performance do not match very well..



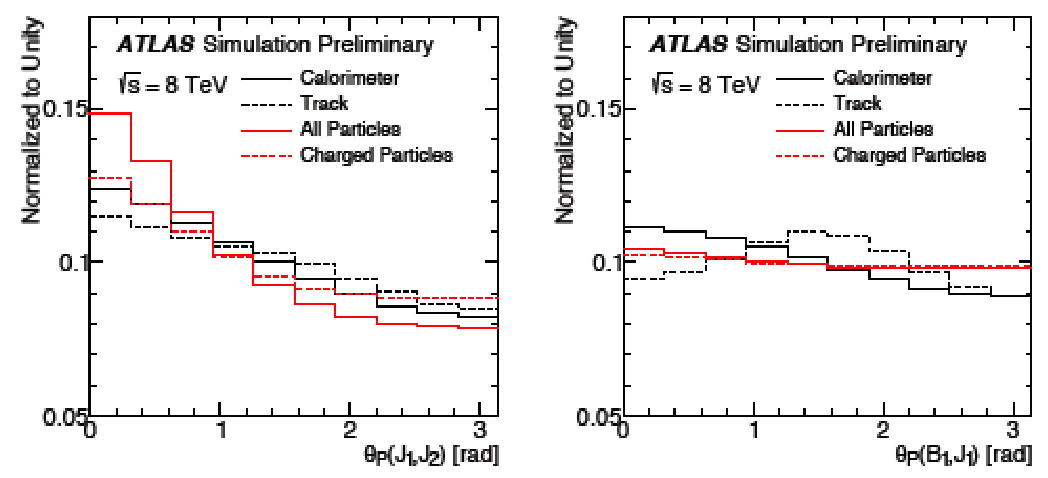


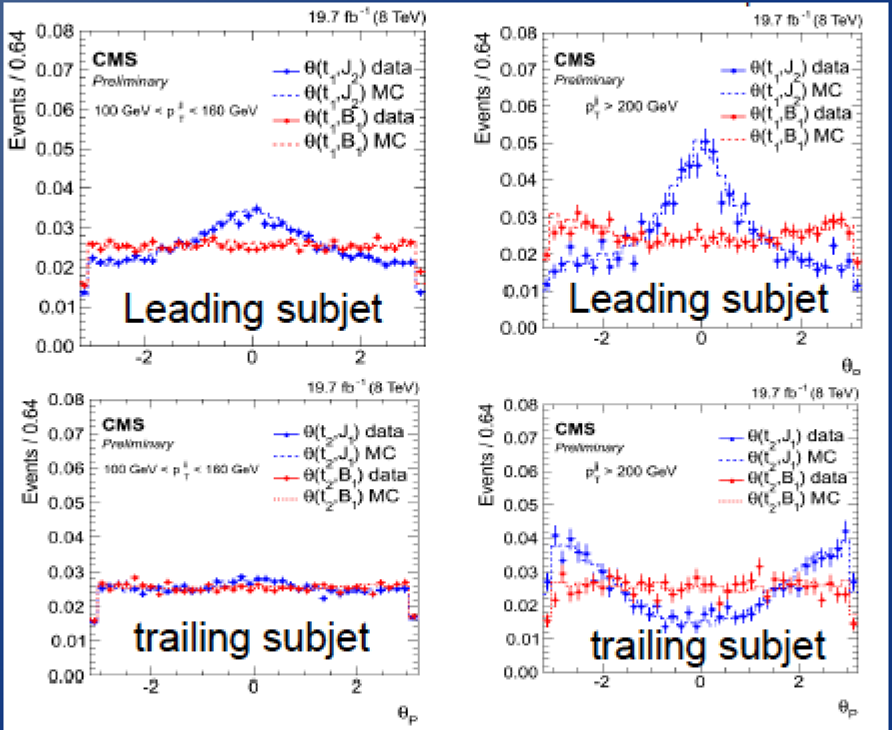


Jet pull Gallicchio Schwartz 1001.5027v3

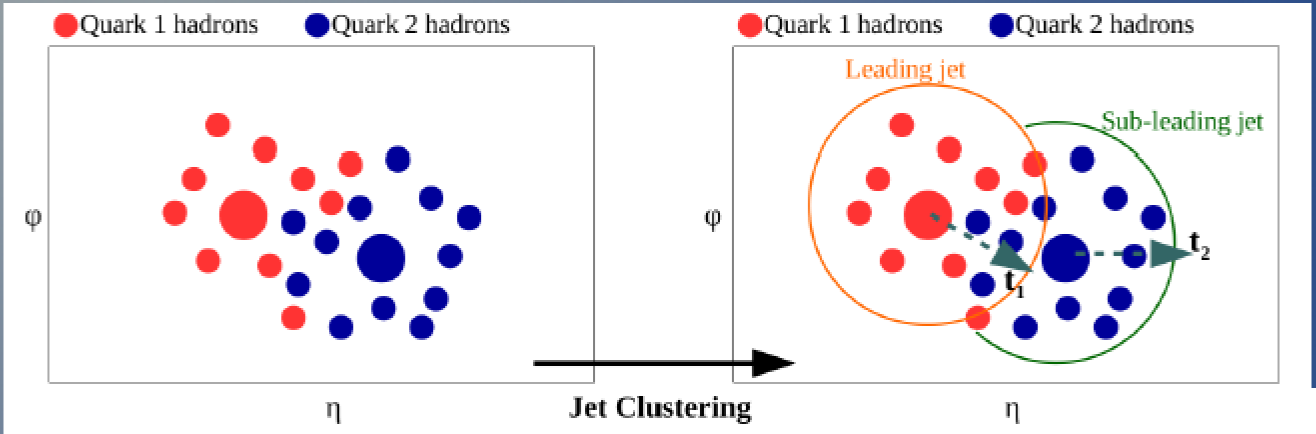


Define y axis as weighted sum of constituents wrt jet axis, and pull angle the angle wrt the closest jet. Should peak at zero for interconnected jets

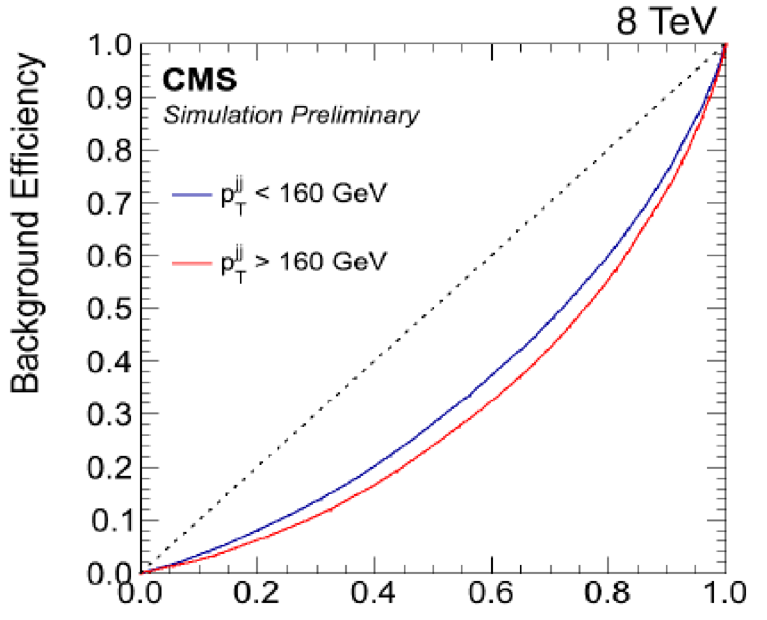




Not-so-boosted bosons



Jet pull, Q/G discrimination and dijet charge used in a BDT

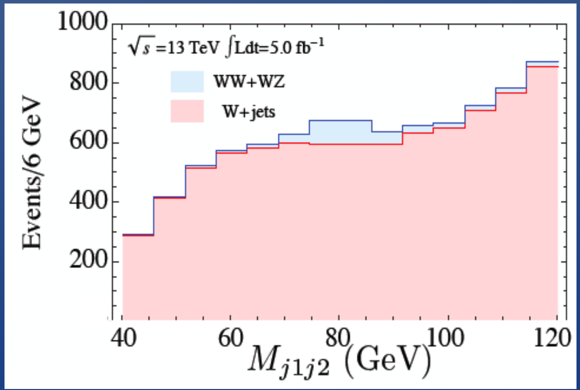


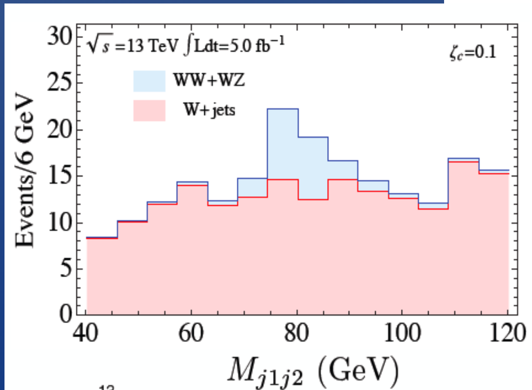
Mass ratios: Izaguirre Shuve Yavin 1407.7037

Since for a resonance $M_{12} = M_R$

While for hard splitting $<M^2_{12}> \sim R^2_{12}p^2_T$

Cut on $\zeta \equiv \frac{m_{j_1}}{m_{j_1 j_2}} R_{12}$



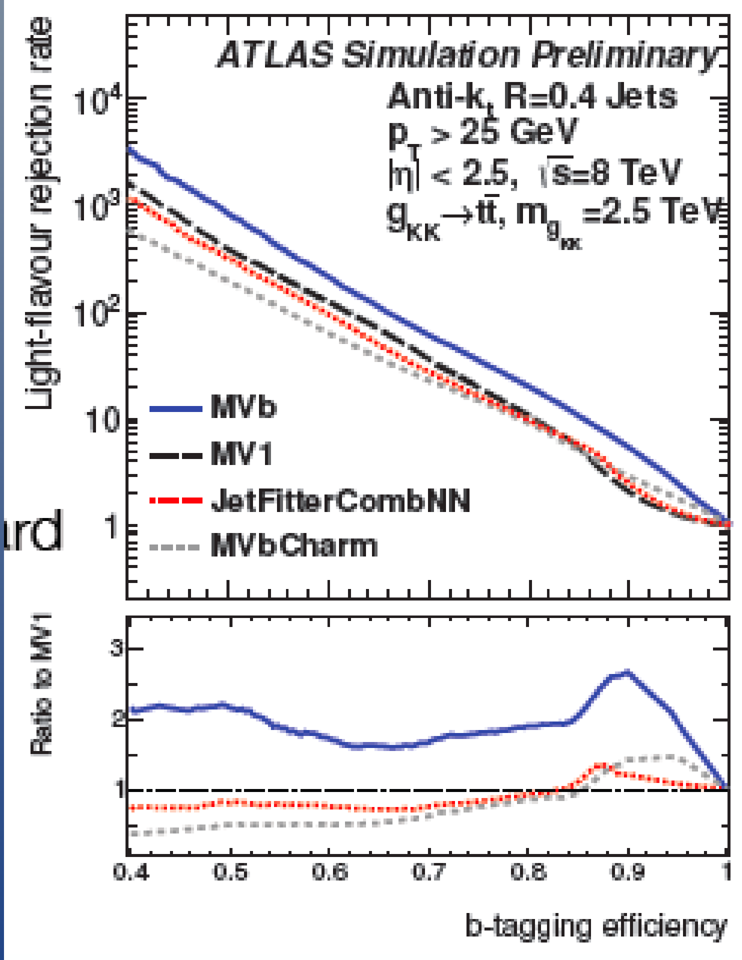


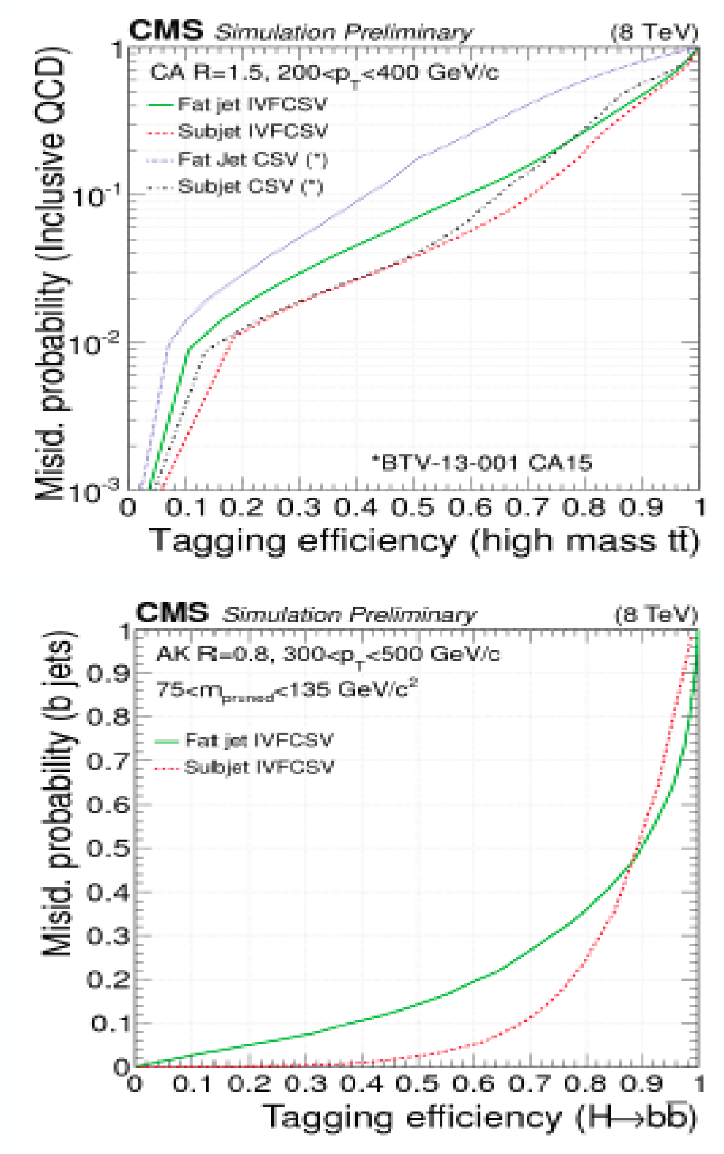
Boosted b tagging

Needed for H->bb, important for boosted top

Re-optimise b-tagging, or b-tag track jets with smaller R

Eventually combine with 2-body taggers

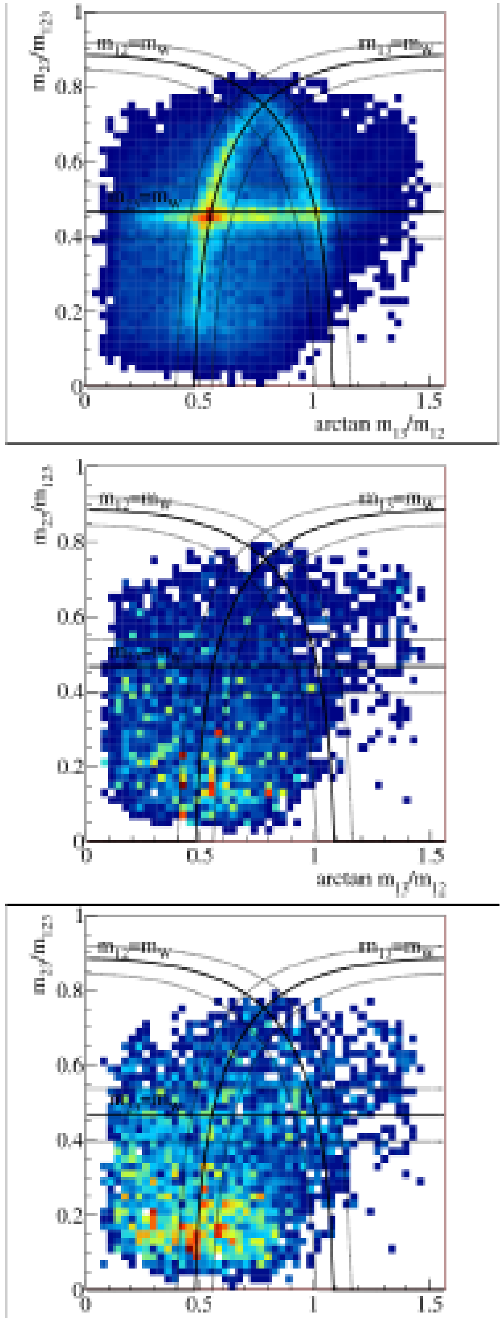




HEPTopTagger

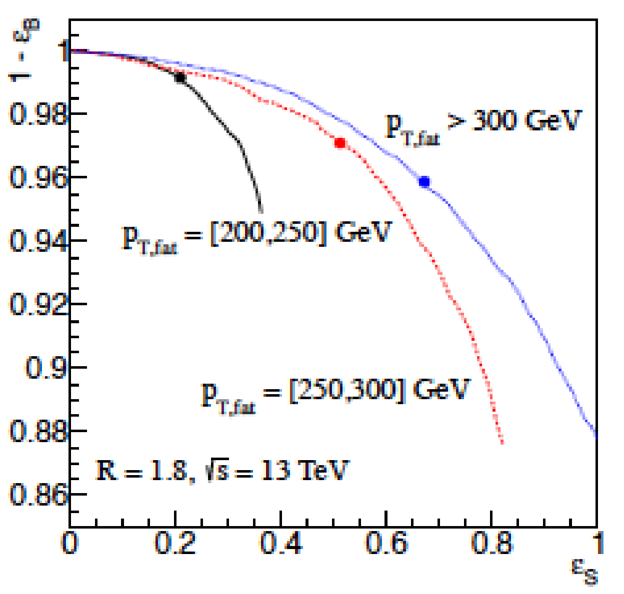
[arXiv:1006.2833]

0. **fat jet**: C/A $R = 1.5$, $p_T > 200$ GeV
1. **hard substructures**:
   mass drop $f_{\text{drop}} = 0.8$, $m_i < m_{sub} = 30$ GeV
2. **filtering**:
   filter a triple of hard substructures → 3 jets (j_1, j_2, j_3)
3. **mass window**: 150 GeV $< m_{123} <$ 200 GeV
4. **mass plane cuts**: $0.85\frac{m_W}{m_t} < \frac{m_{ij}}{m_{123}} < 1.15\frac{m_W}{m_t}$
   $m_{23} \approx m_W$: $0.2 < \arctan\frac{m_{13}}{m_{12}} < 1.3$; else $\frac{m_{23}}{m_{123}} > 0.35$
5. **consistency:** $p_T^{(\text{tag})} > 200$ GeV

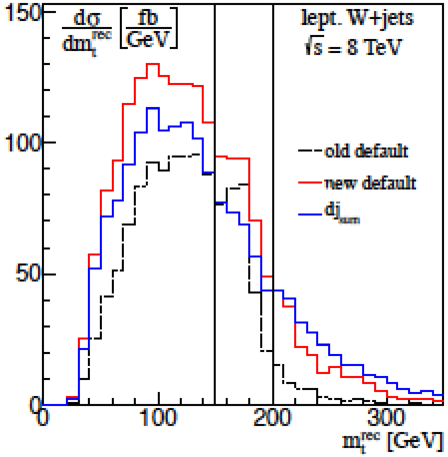


[arXiv:1006.2833]

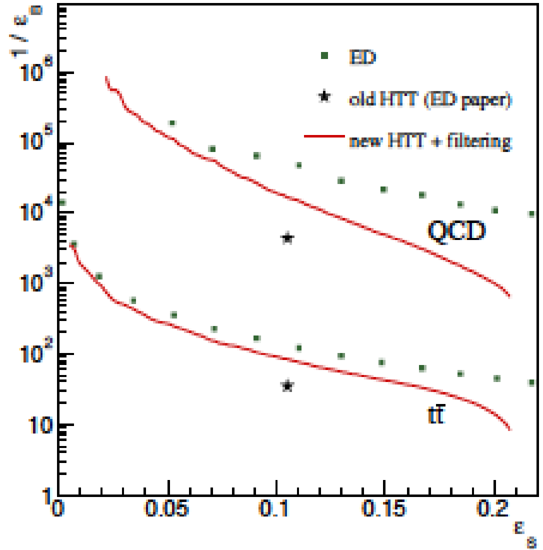
Recent improvements arXiv 1312.1504



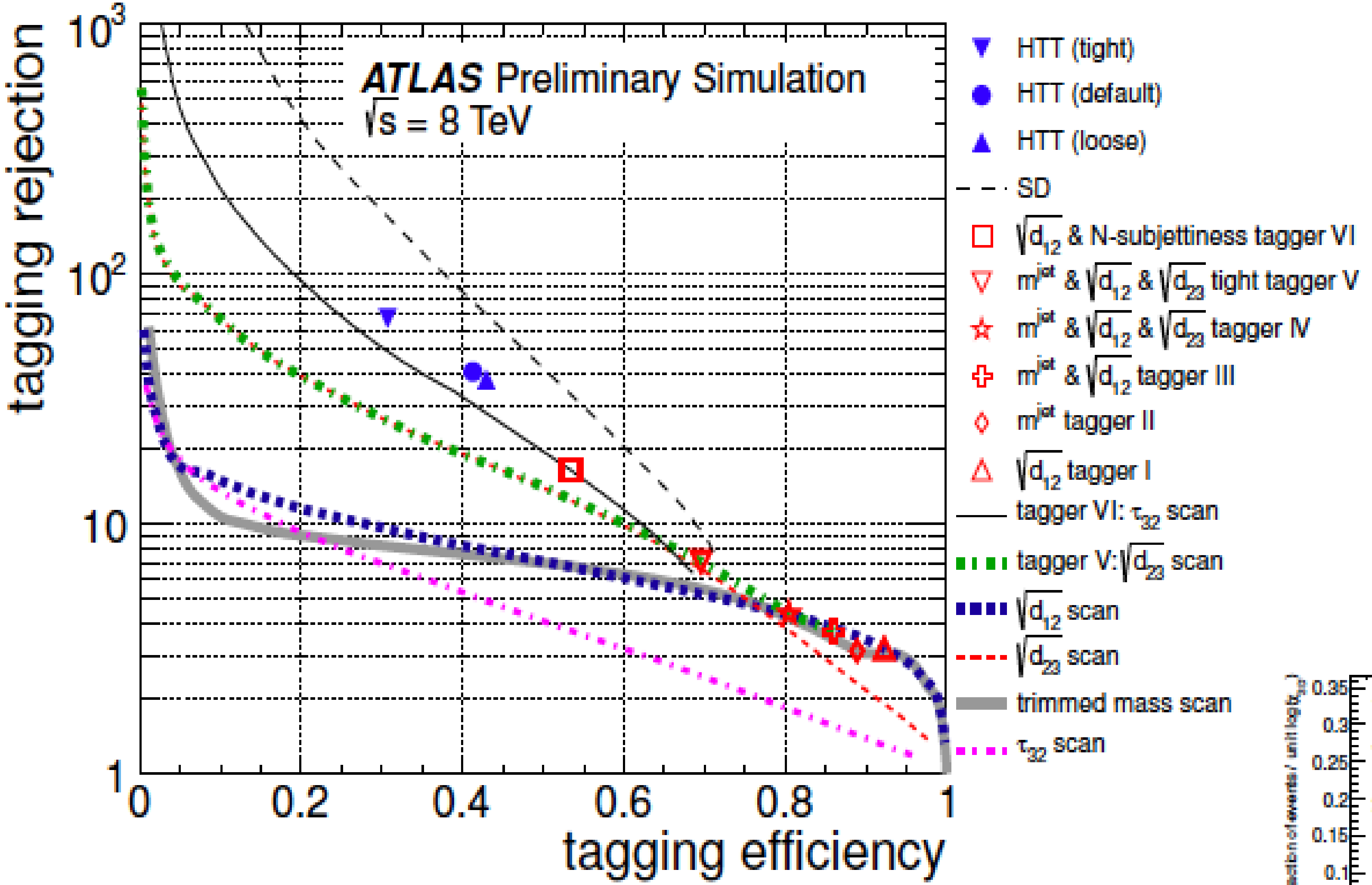
- signal efficiency ✓
  $\rightarrow$ $R = 1.8$, inverted cut order, BDTs

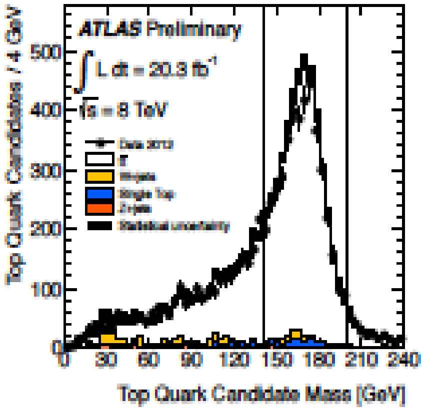


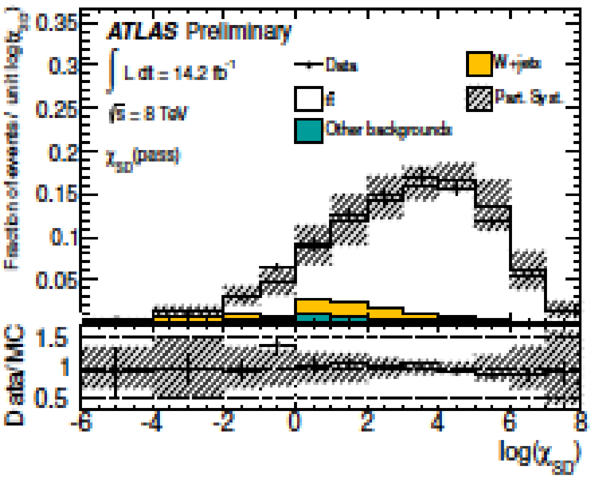
- background sculpting ✓
  $\rightarrow$ alternative triplet selections
- p_T range ✓
  $\rightarrow$ low–p_T mode
  $\rightarrow$ high p_T: MultiR, N–Subjettiness HEPTopTagger
- resonance reconstruction ✓
  $\rightarrow$ account for final state radiation, MultiR



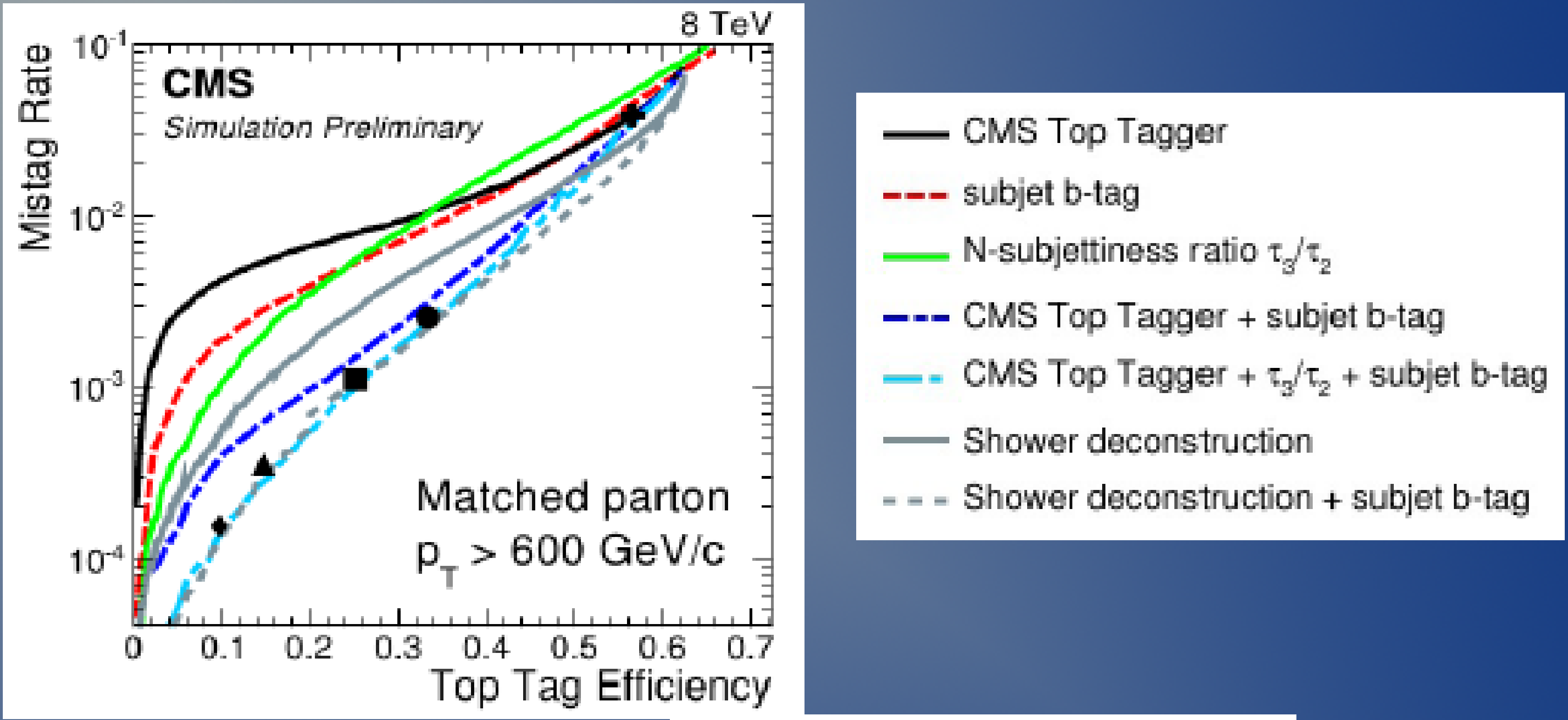
ATLAS Top tagging



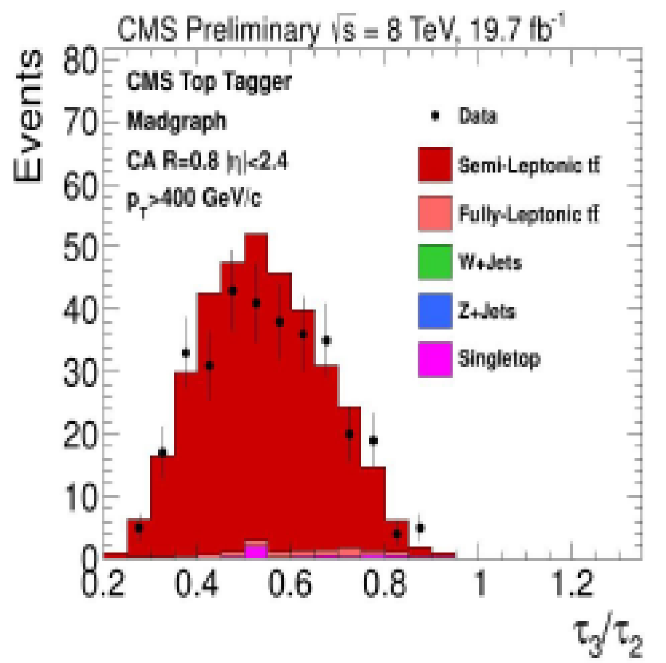


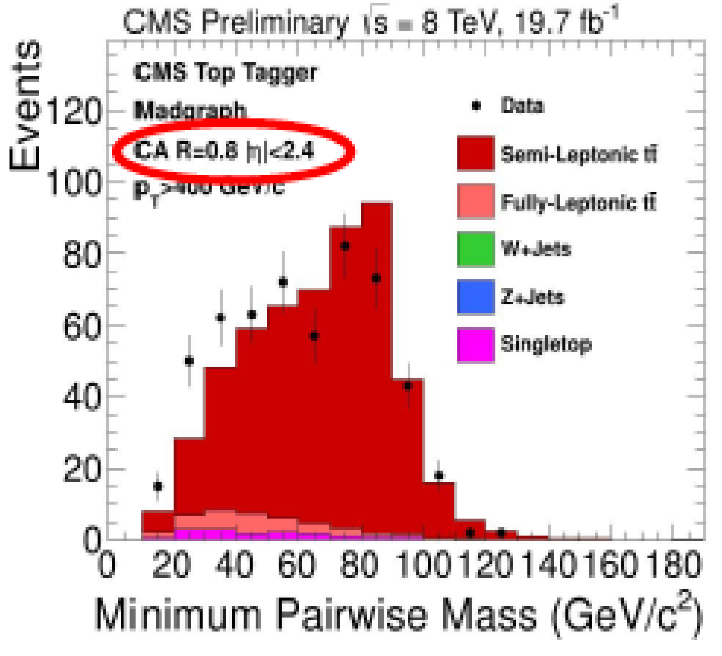


Top tagging in CMS



However, discrepancies found in some variables





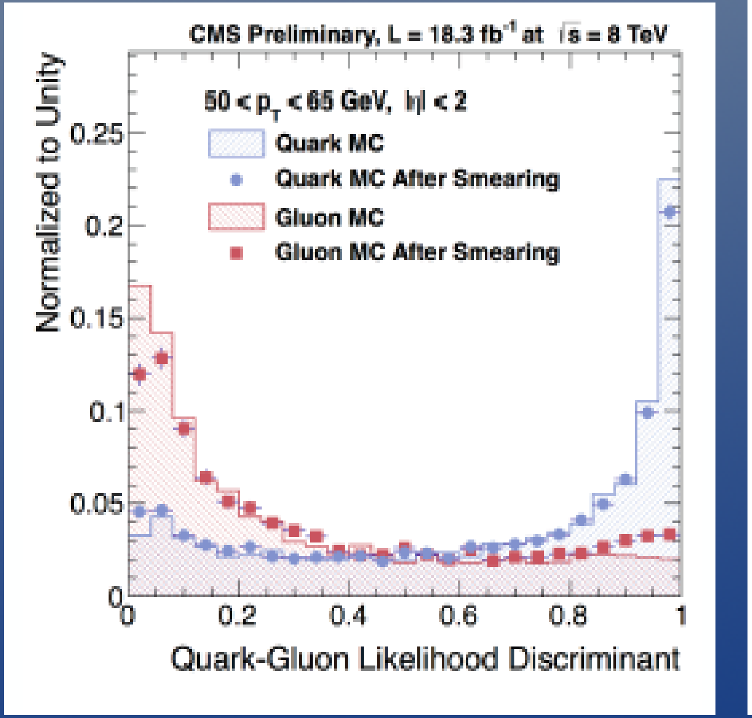
Quark/gluon discrimination

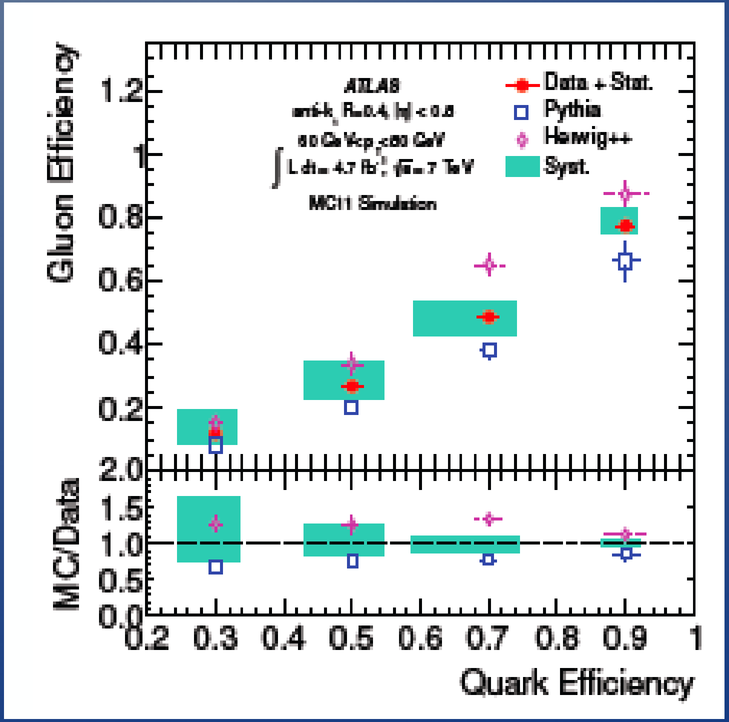
Definition of q/g jet not obvious- only LO definitions currently used, prone to be MC-dependent

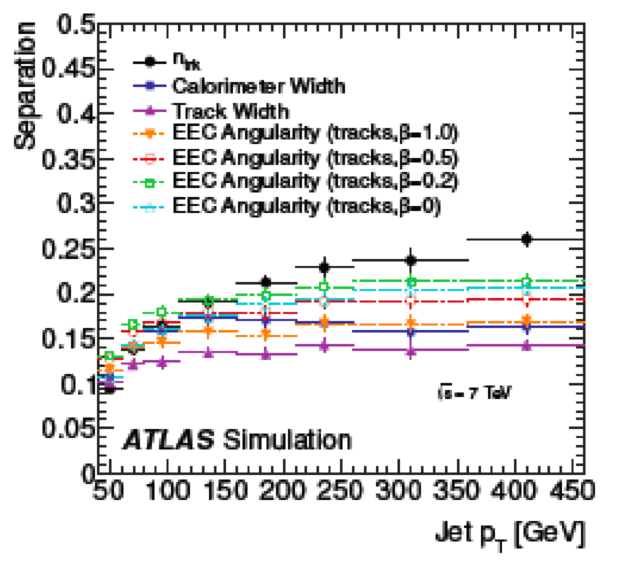
Both experiments use combinations of variables:

ATLAS: charged track multiplicity and width

CMS: pTD, n(constituents), **σ**(minor)

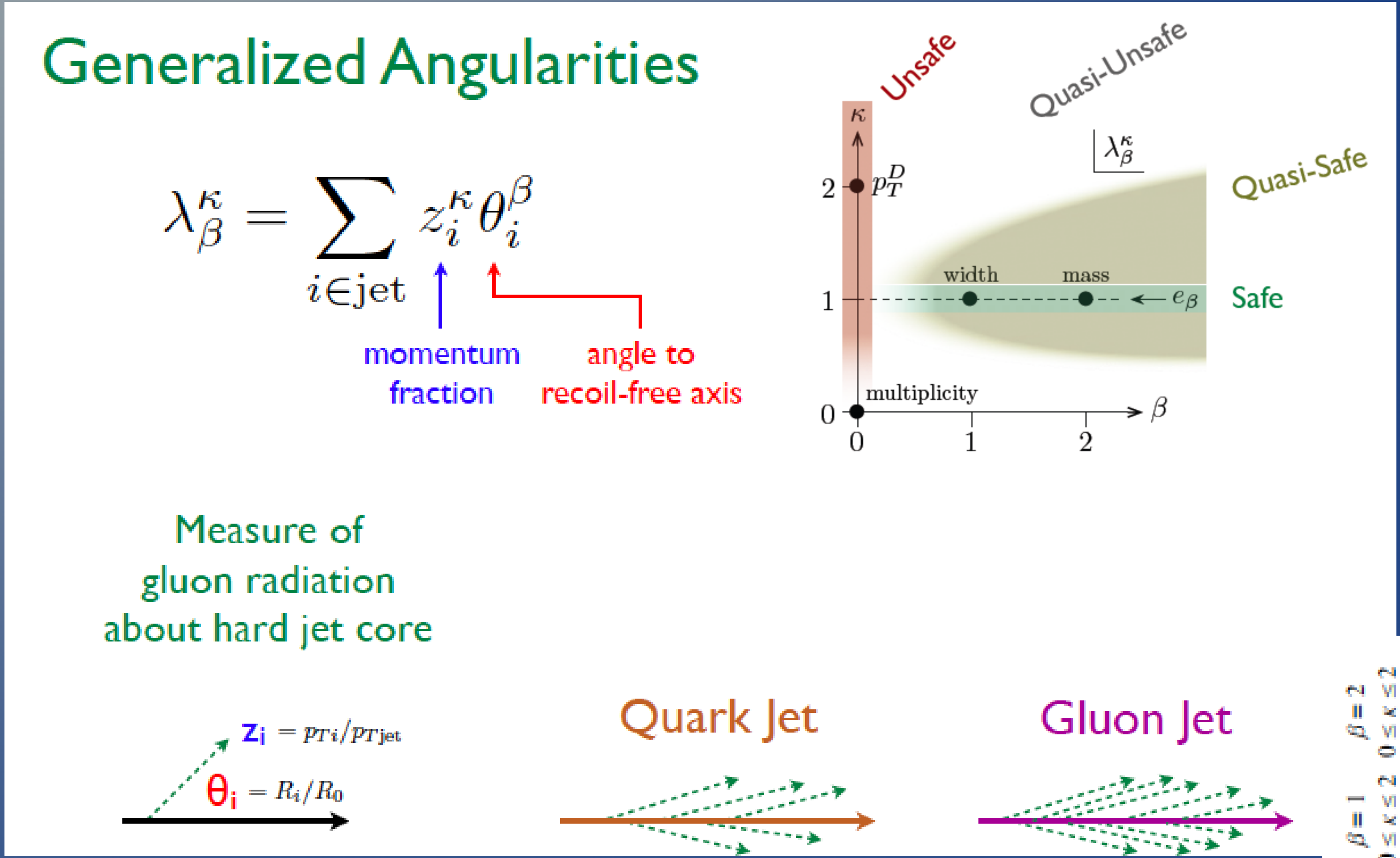






Some more variables?

Larkoski Thaler Waalewijn 1408.3122



Generalized Angularities

$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \theta_i^\beta$$

momentum fraction

angle to recoil-free axis

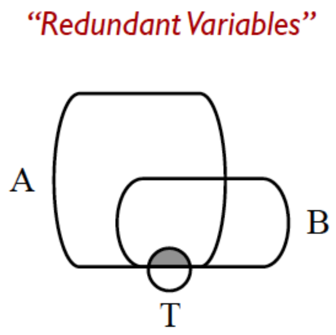
Measure of gluon radiation about hard jet core

$z_i = p_{Ti}/p_{T\text{jet}}$

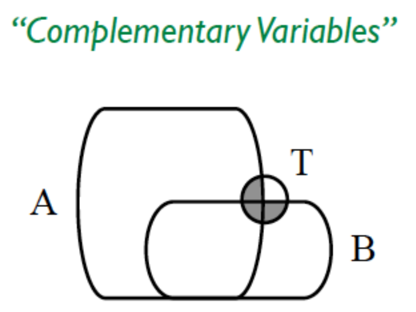
$\theta_i = R_i/R_0$

Quark Jet

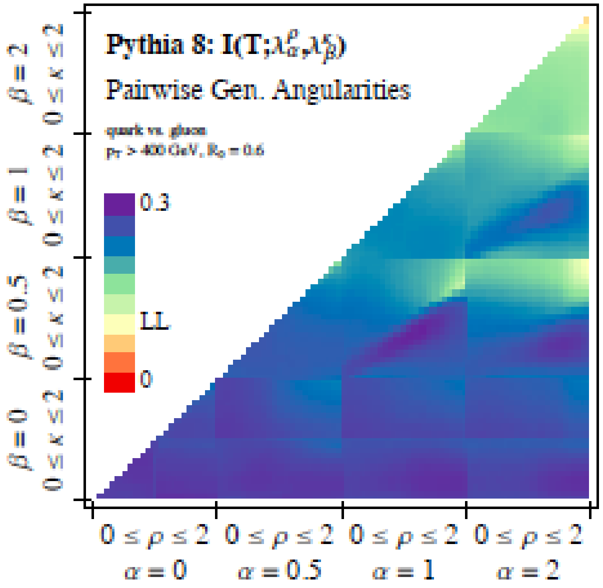
Gluon Jet



“Redundant Variables”



“Complementary Variables”



Look at two angularities and overlap with truth

Conclusions

If substructure studies were an interesting and fun new thing in Run-1, their importance will grow with beam energy and intensity

Extremely active field, with rapid developments from theorists and experimentalists alike (good ideas can come without too many involved technicalities)

In Run-2 and beyond...

if you ain't boosting, you ain't living...