Boosted Top Quarks

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Outline

- Introduction & Motivation
- Run1 Summary
  - Boosted Measurements
  - Systematic Uncertainties
- Run2 Outlook
  - Future Developments

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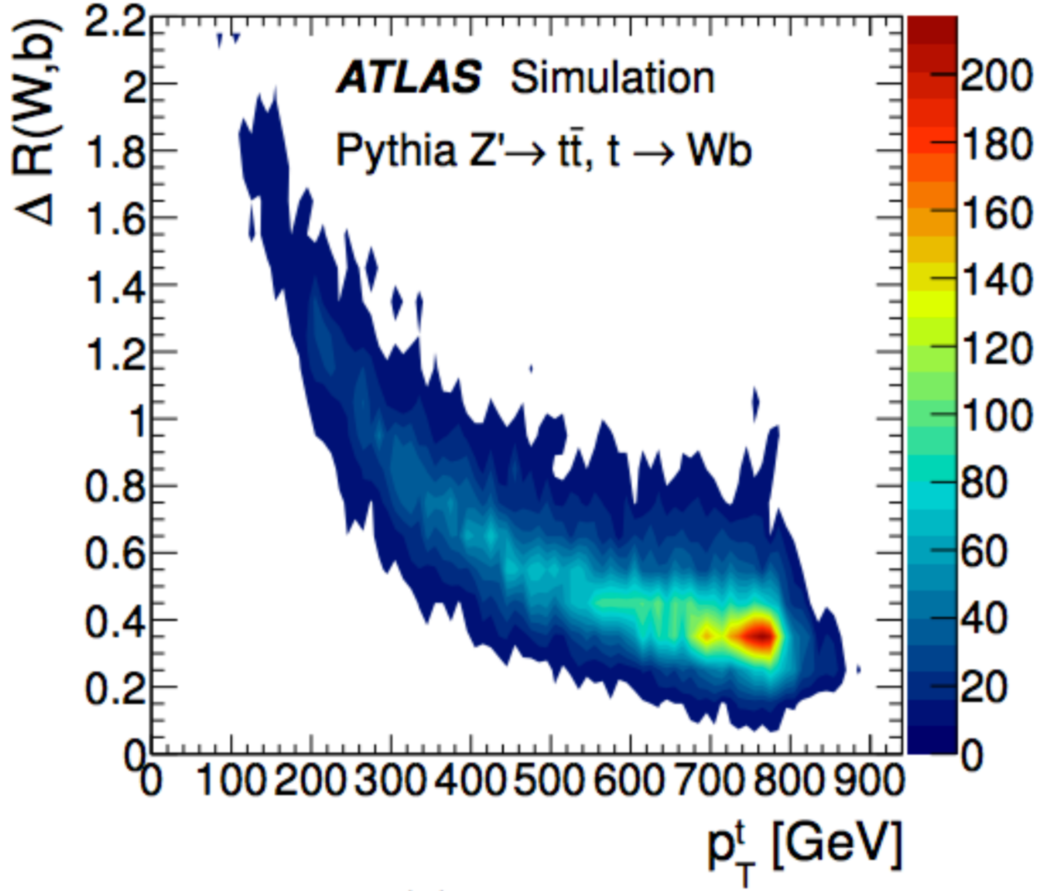
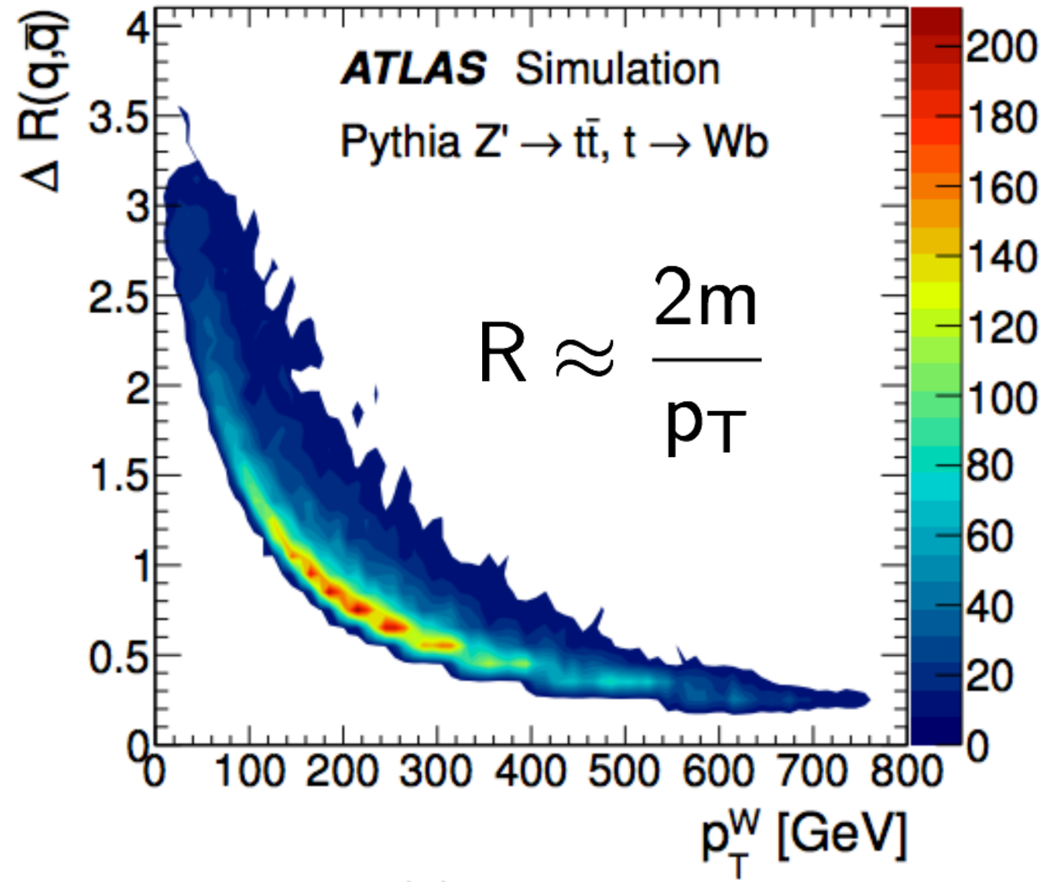


(a) $t \rightarrow Wb$



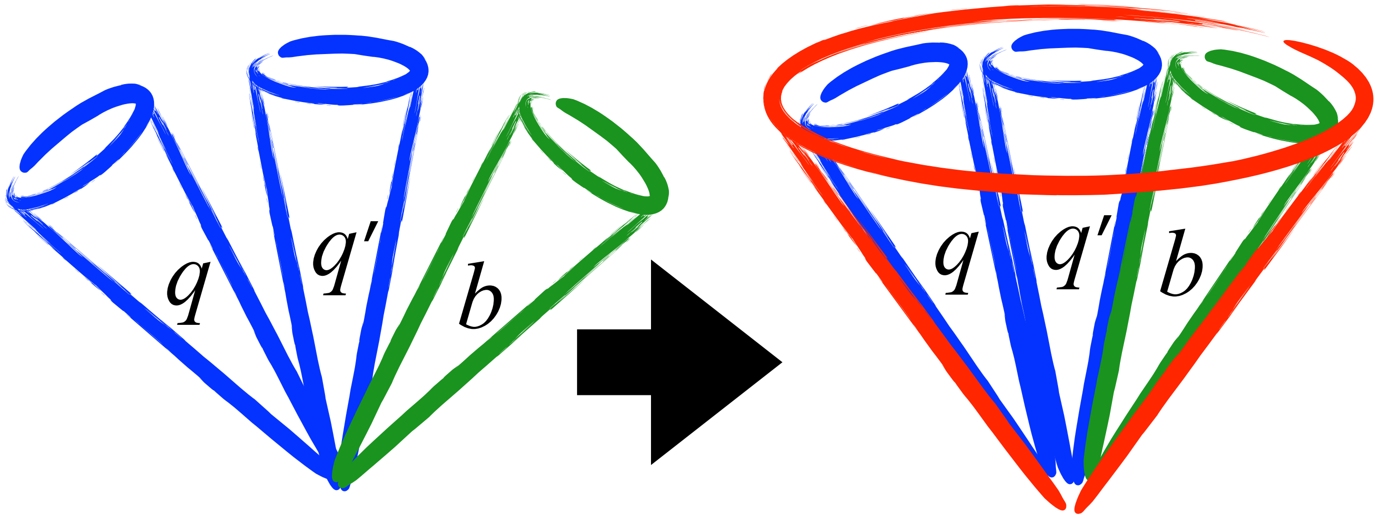
$$R \approx \frac{2m}{p_T}$$

(b) $W \rightarrow q\bar{q}$

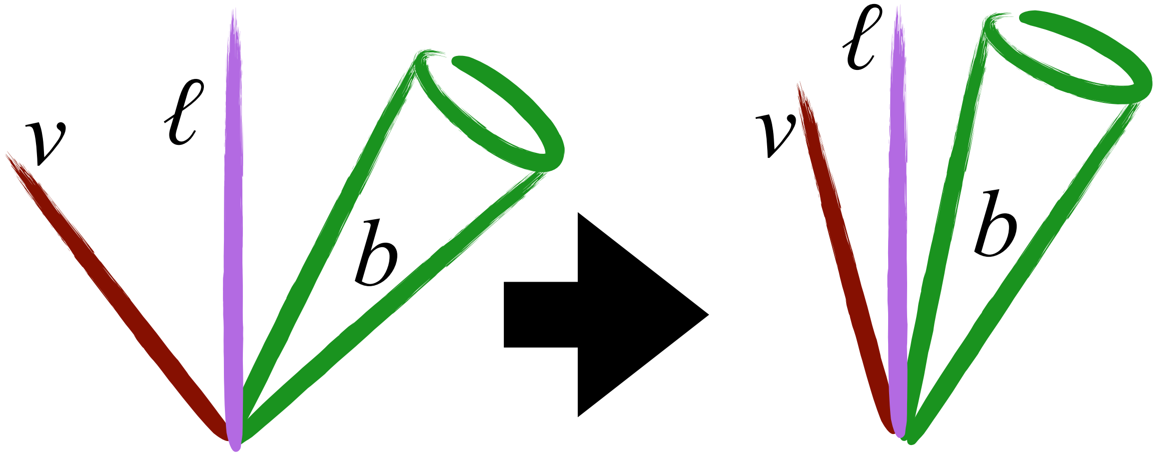
More info: L. Skinnari talk at Top2015

Boosted Tops

- Top-quarks that are produced with high-p_T ($p_T \gtrsim 300$ GeV) are considered *boosted* & have collimated decay products
  - New techniques for boosted top-quark reconstruction!
- Boosted top-quarks are useful for studying high-p_T top properties & searching for heavy resonances*



Large-radius jets +
Jet Substructure



Special isolation +
lepton-jet overlap removal

*Only discussing SM aspects here

Motivation

- Why use boosted top-quarks?
  - Traditional methods of reconstructing top-quarks begin to deteriorate when jets merge & leptons/jets overlap!
  - If using a method such as a Likelihood fitter or χ^2 algorithm, you will not use the appropriate jets
  - Boosted events may not pass common resolved event selections that require ≥4 jets
- High-p_T region: Largest discrepancies between Data and prediction can be readily studied using boosted tops

Boosted Leptonic Tops

- Consider small-radius (r=0.4,0.5) jets near lepton
  Special techniques developed to recover events where the lepton and jet begin to overlap

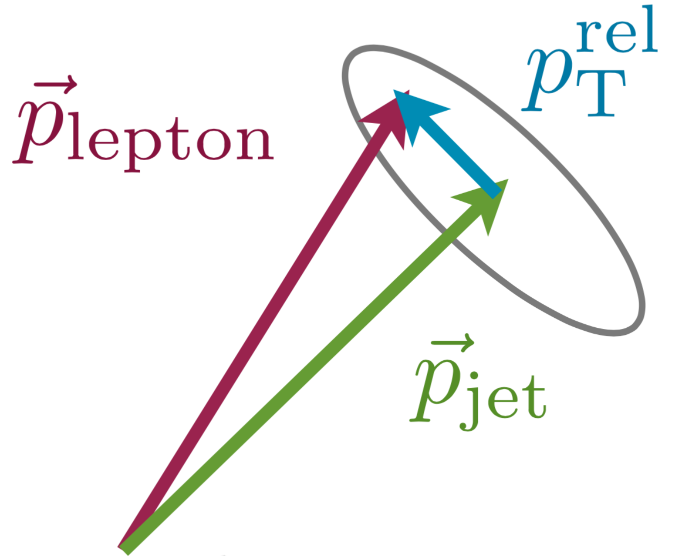
- ATLAS

$$I_{\mathrm{mini}} = \sum_{\mathrm{tracks}} \frac{p_T^{\mathrm{track}}}{p_T^{\ell}}$$

  - $I_{\mathrm{mini}}<0.05$: p_T-dependent isolation considering all tracks (except the lepton's) with $p_T>400$ MeV and $\Delta R<(10/p_T^{\ell})$
    Overlap removal procedures described in back-up

- CMS

  - Kinematic cut on orthogonal component of p_T between lepton and jet for leptons that are within $\Delta R<0.5$ of the jet



$$p_T^{\mathrm{rel}} \gtrsim 20\ \mathrm{GeV}$$

Boosted Hadronic Tops

- For hadronically-decaying boosted tops, use *large-radius jets* and *substructure* to “tag” top-quarks

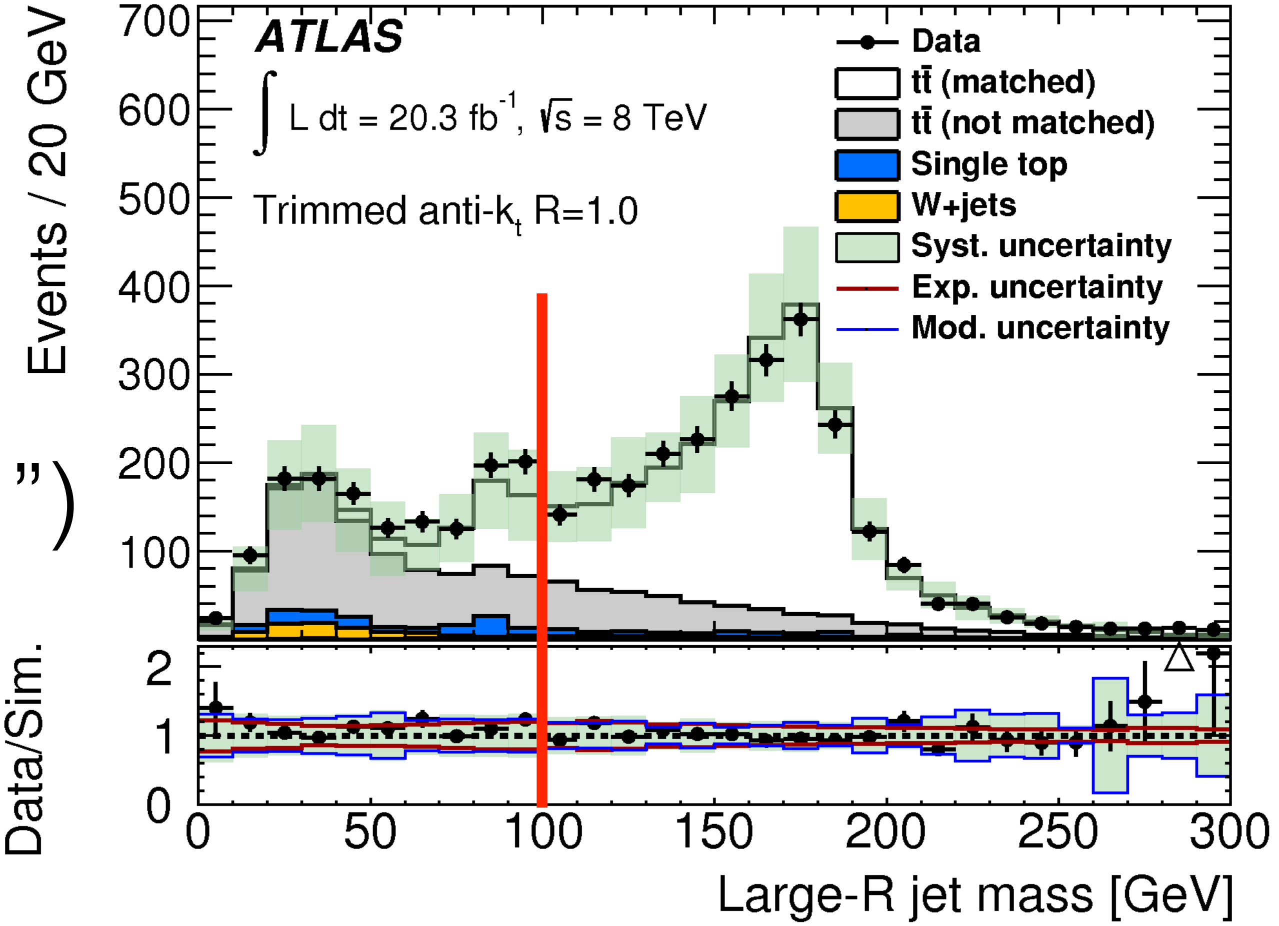
- **Grooming:** Remove soft radiation from pileup/underlying event/ISR
  - **Trimming**: Recluster jet constituents and remove subjets with p_T below some threshold
  - **Filtering**: Recluster jet constituents and keep N hardest subjets
  - **Pruning**: Remove soft and wide-angle radiation
  - **Softdrop**: Remove soft and wide-angle radiation

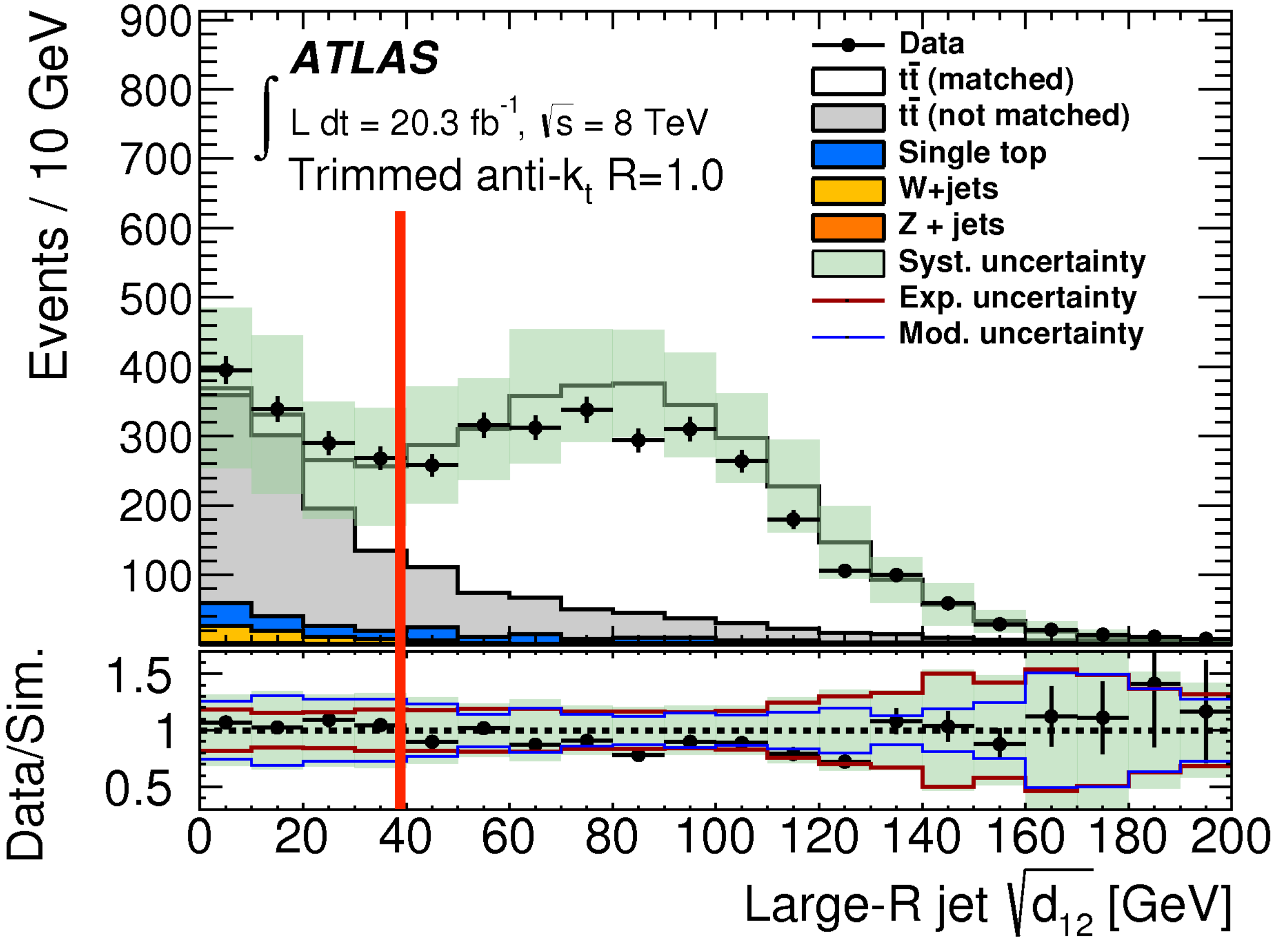
- **Substructure:** Identify top-quarks using structure in the large-R jet
  - **N-subjettiness**: How well the jet is described by N or fewer subjets
  - **k_T splitting scale**: Scale of the last recombination

- Lots of techniques have been developed to tag top-quarks, the following slides focus on those applied to top measurements

ATLAS Tagger

- Common tagger used in run1 measurements: [cds](cds) (“Tagger III”)
    - Anti-k_T R=1.0 jet trimmed: r_{sub}=0.3 & $p_{T,subjet}$ > 0.05*(large-R jet p_T)
    - large-R jet p_T > 300 GeV
    - large-R jet mass > 100 GeV
    - First splitting scale $\sqrt{d_{12}}$ > 40 GeV





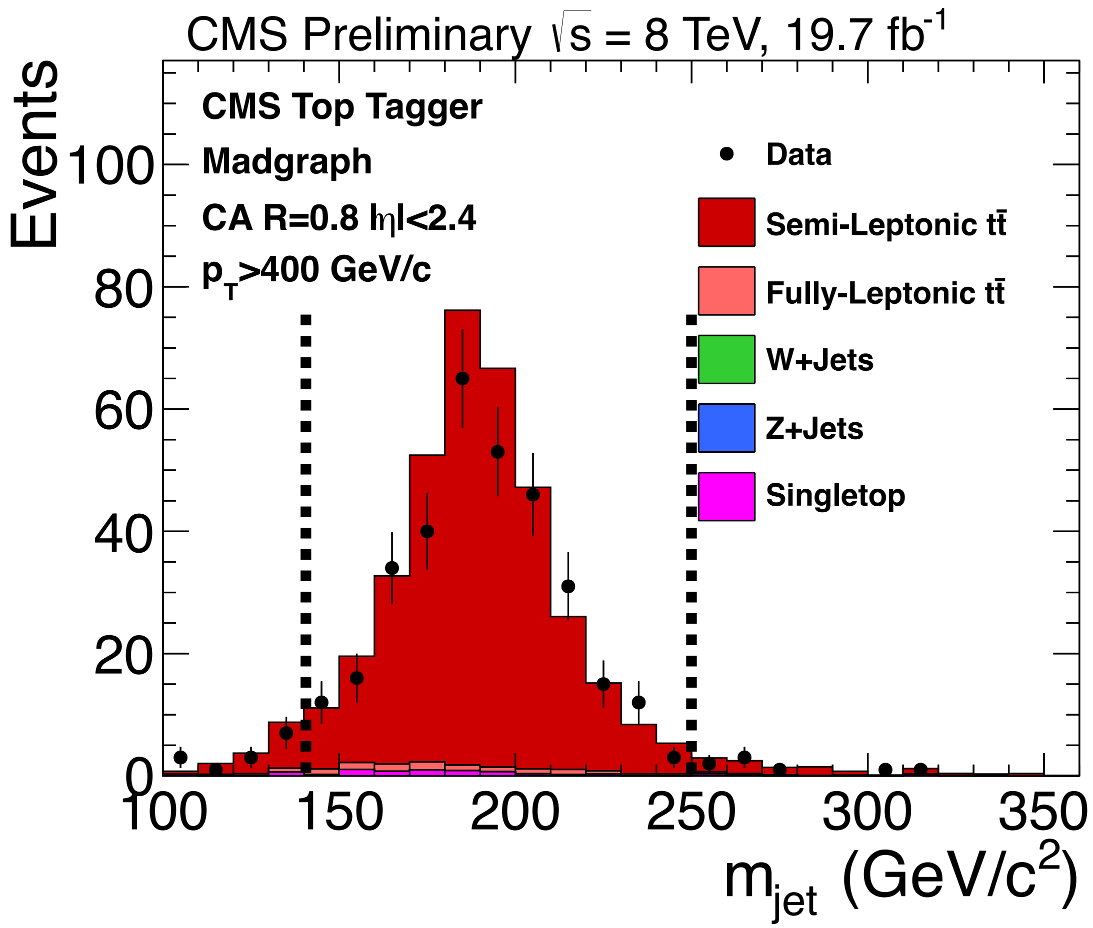
CMS Top Tagger

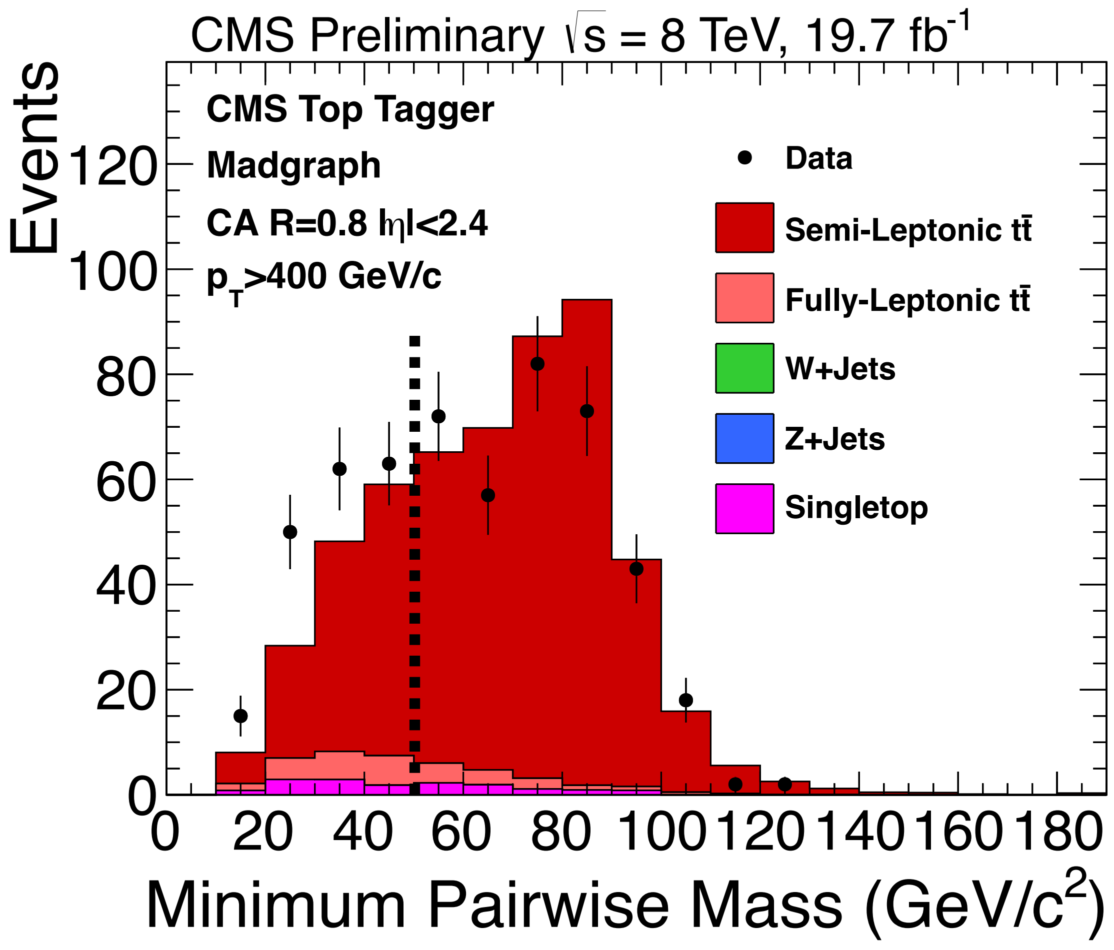
- C/A R=0.8 jet cds
  - Recursive declustering of large-R jet, $J \rightarrow j_1, j_2 \rightarrow$ etc.
  - If subjets satisfy $\Delta R(j_1, j_2) > 0.4 - 0.004 * p_T(J)$, keep subjets distinct
  - Keep subjets if they satisfy $p_{T,i} > 0.05 * p_T(J)$
  - Continue until a max. of 4 subjets

- large-R jet $p_T > 400$ GeV

- ≥3 subjets & min(pairwise subjet mass)>50 GeV

- 140 < large-R jet mass < 250 GeV



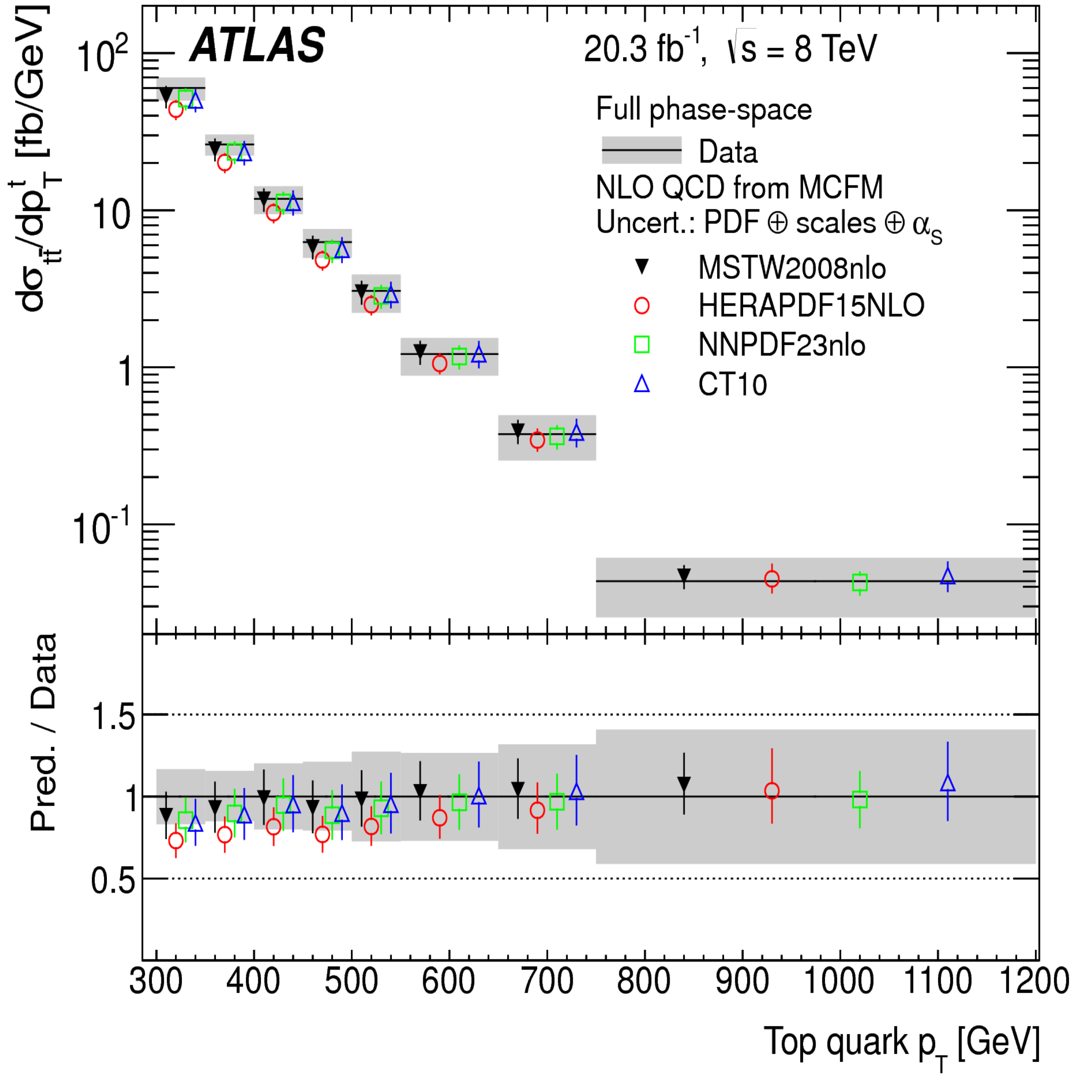


Run-1 Results

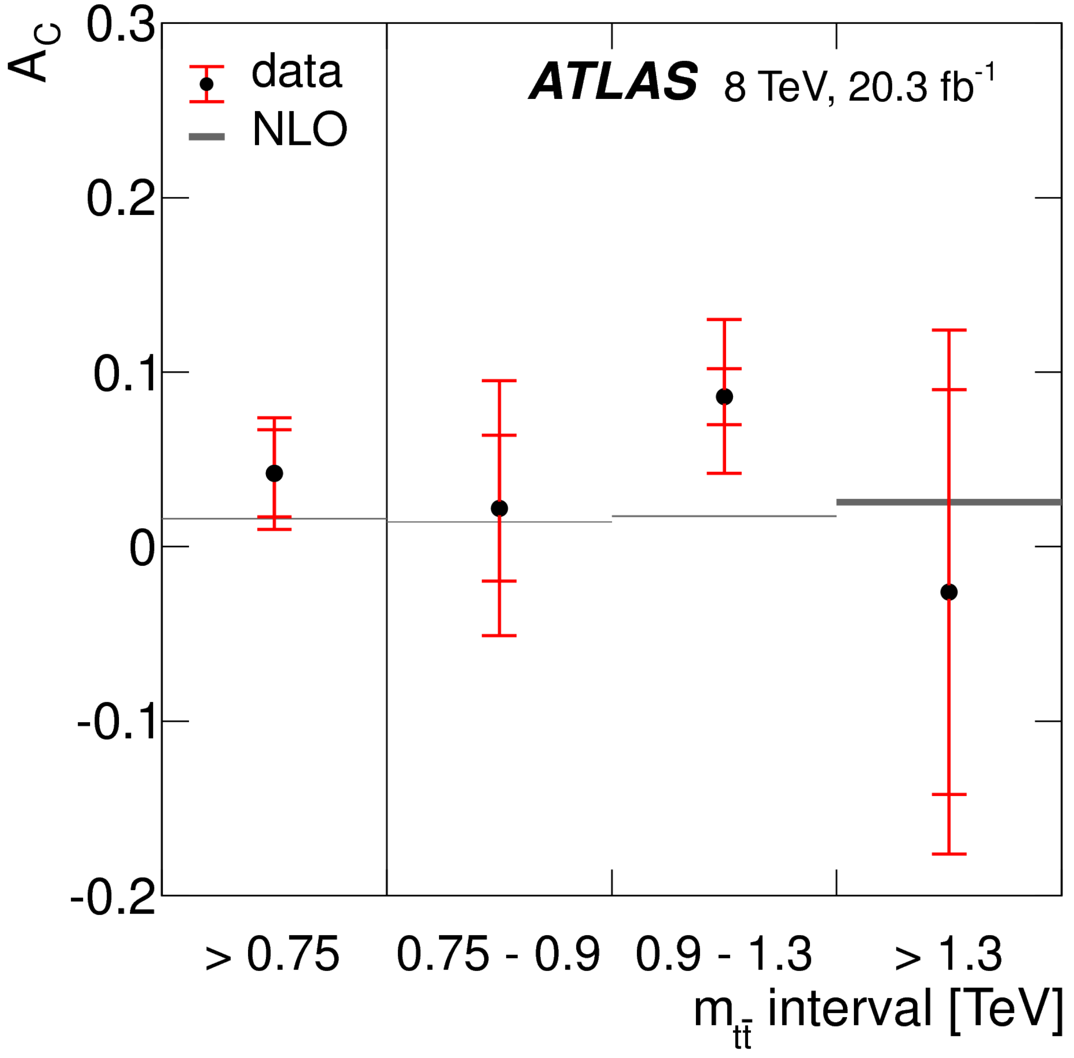
- ATLAS and CMS used boosted top-quarks in many run-1 results (primarily applied in searches)
  - Often a complementary channel to analyses that also employed *resolved* top-quark reconstruction
- (Relatively) low statistics for boosted top-quarks, but results still provide strong understanding of high-p_T region
  - These results have set a good precedent for run2 where we expect significantly more boosted top-quarks

ATLAS

- Two ATLAS measurements, the Boosted differential cross section [arXiv] & Boosted charge asymmetry [arXiv] utilized a common boosted ℓ+jets event selection (mini-isolation & ATLAS top tagger)



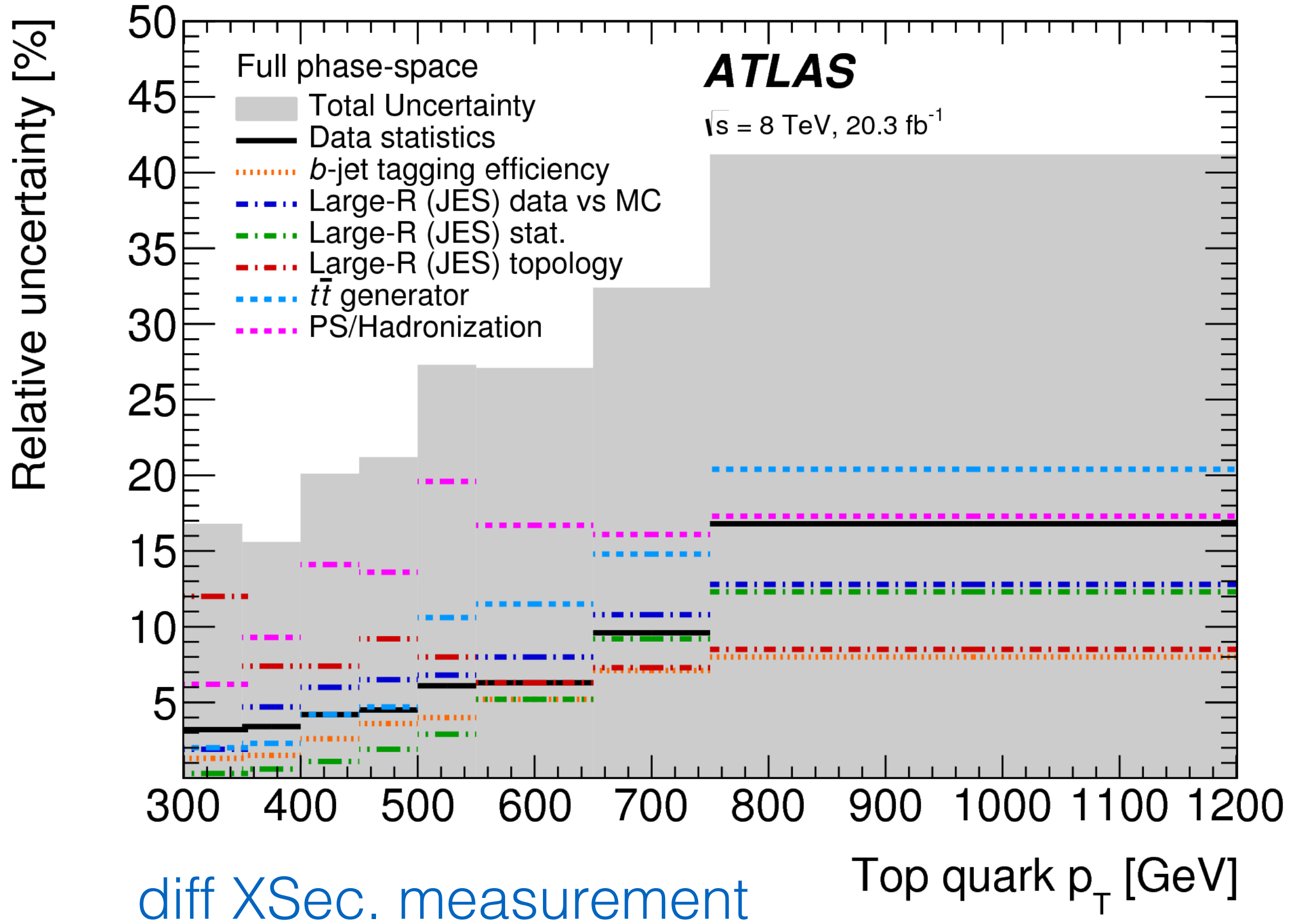
resolved final bin: >500 GeV



resolved final bin: >900 GeV

Systematics

- With the introduction of a new reconstructed object (large-R jets), there are new systematic uncertainties to consider



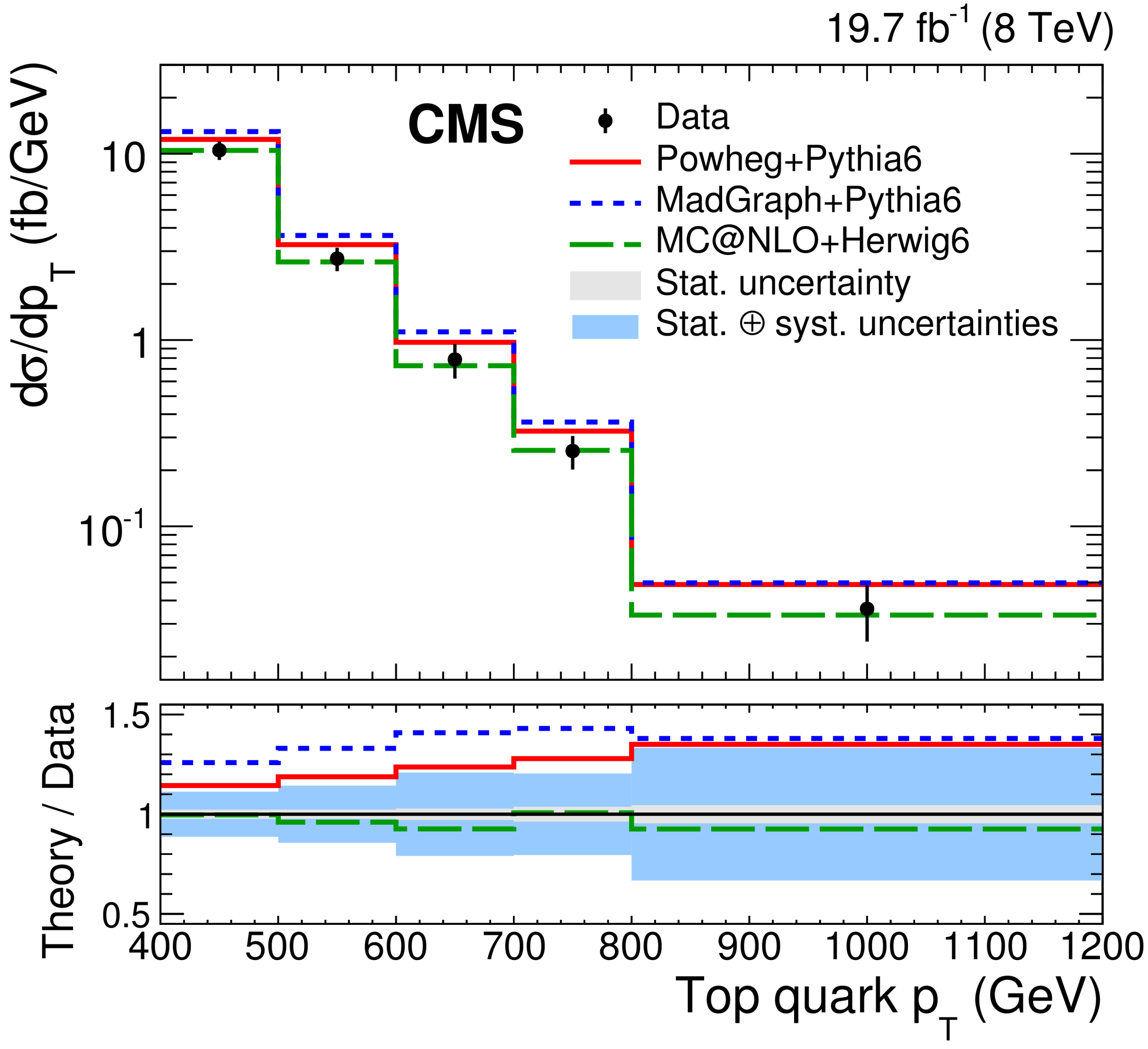
diff XSec. measurement

- Particle-level uncertainties (diff XSec only) dominated by the large-R jet uncertainties
- Parton-level uncertainties (diff XSec & A_C) dominated by ttbar modeling

*To obtain particle-level measurement, the same substructure techniques used on reco-level large-R jets are applied to truth-level large-R jets (including trimming)

CMS

- The ℓ+jets boosted differential cross-section measurement complements the resolved analysis with an extra 4 bins
  - Lepton isolation p_T^{rel} + CMS Top Tagger
- Top tagging efficiency extracted from maximum likelihood fit over multiple kinematic regions based on number of top and b-tags

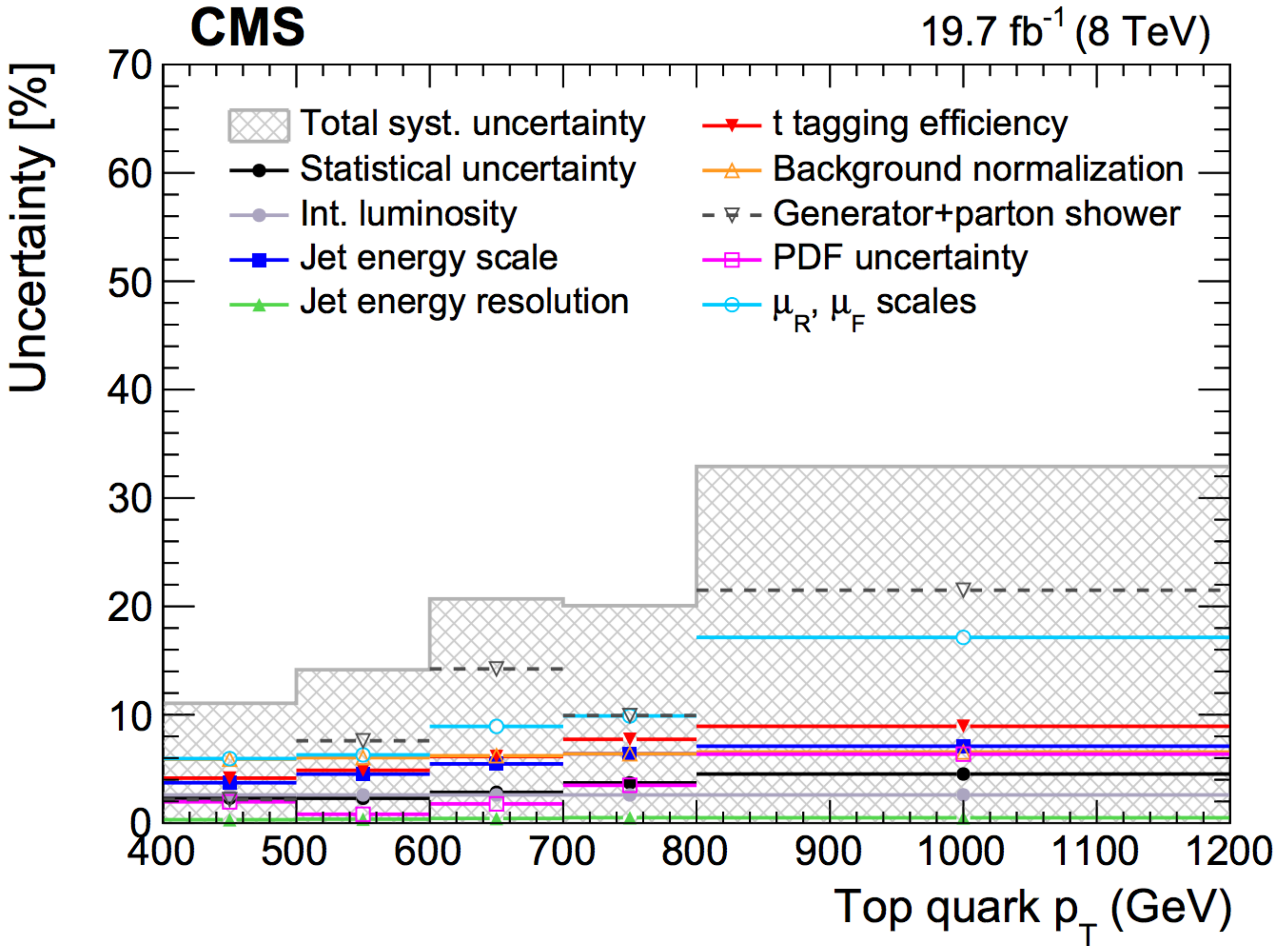


resolved final bin: >400 GeV

Systematics

- The top tagging efficiency was found to be strongly anti-correlated with the cross-section

- Dominant experimental uncertainty from top tagging uncertainty
  - More dominant at higher top-quark p_T
    p_T<600 GeV: ±5%
    p_T>600 GeV: ±18%



- JES uncertainty contains contributions from small-r and large-R jets. C/A R=0.8 found to have similar uncertainty as anti-k_T r=0.7, within 1% (+1% uncertainty for Data/MC disagreement)

Run1 Summary

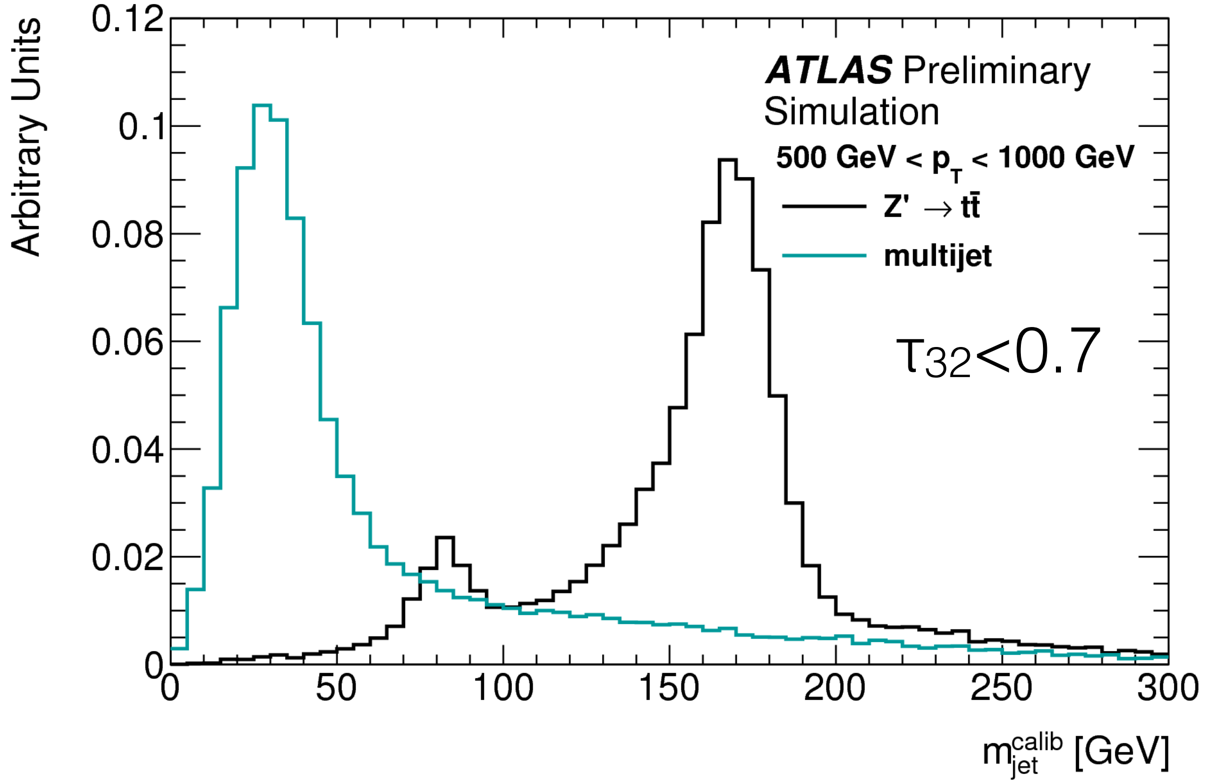
- During run1, the measurements performed offer competitive results, but they are dominated by low statistics and large systematic uncertainties
    - Able to extend resolved results by 1 or more bins into high-p_T (and high ttbar invariant mass) regions
- Simple taggers applied for measurements, following earlier use in searches (e.g., ttbar resonances), that yield high efficiencies
    - In ℓ+jets channels, simple taggers perform well due to the high signal:background ratio (more sophisticated taggers needed for all-hadronic final states, e.g., HEPTopTagger)

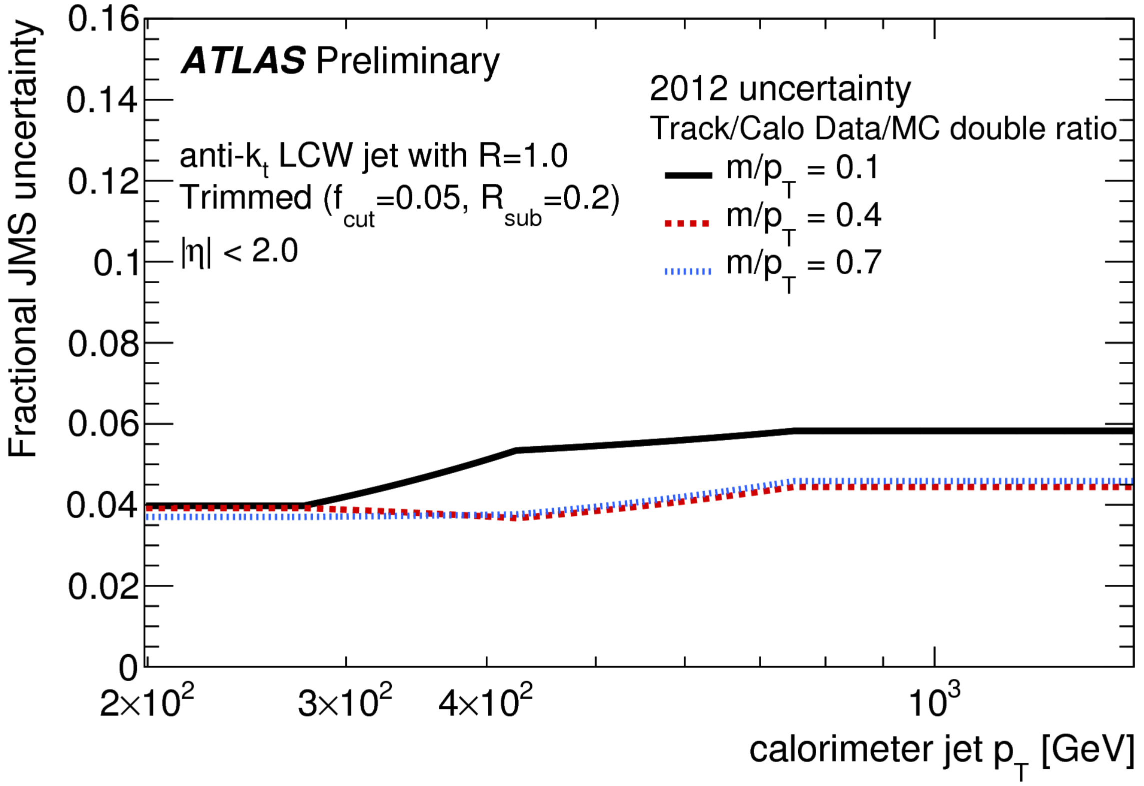
Run2 Outlook

- With the increased cross section for ttbar production at 13 TeV, many analyses have already exploited boosted top-tagging in run2
    - Thus far, these have been searches!
      (resonances, SUSY, VLQ, etc.)
- Preliminary top taggers released by collaborations are being studied for initial measurements (top taggers already applied by many searches)
    - Run1 studies were repeated using 13 TeV simulations to produce new optimized working points

Run2 Tagger

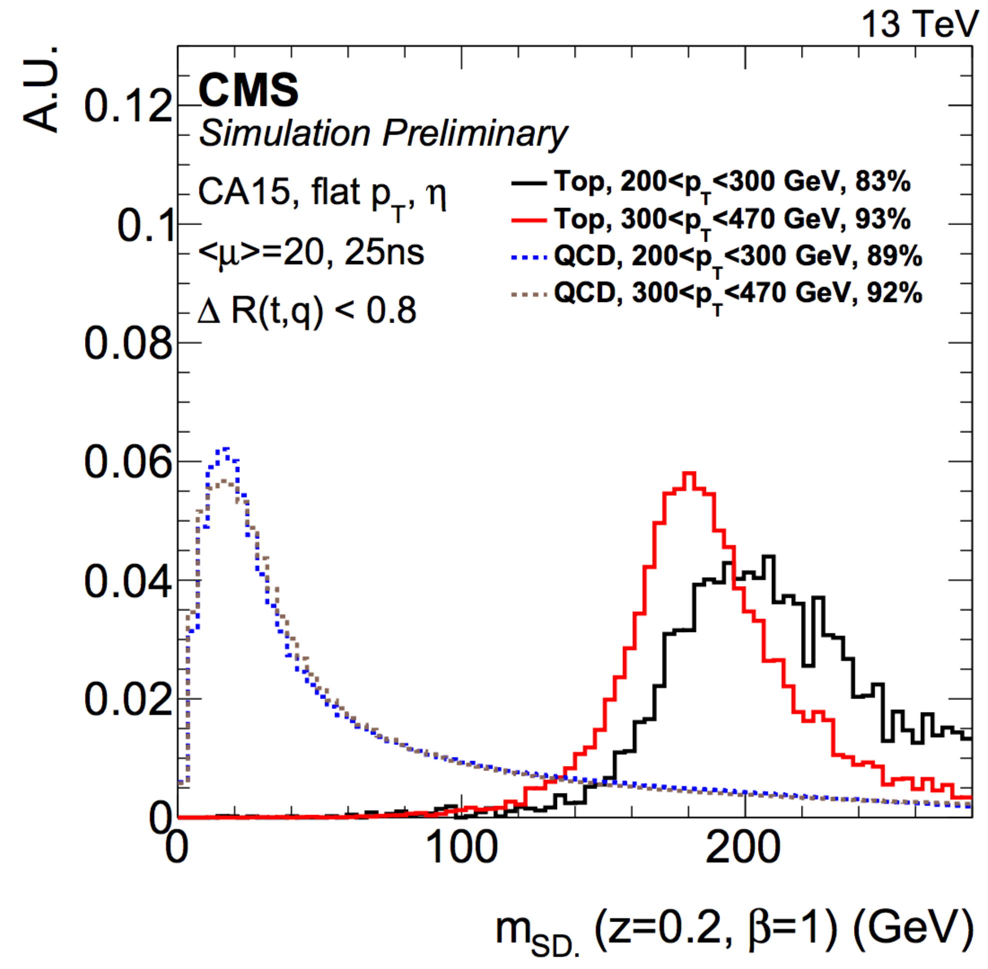
- At 13 TeV it has been determined that top tagging is improved by using the jet mass and n-subjettiness ("winner-takes-all" axis) substructure variables [cds](cds)
  - Changes to jet trimming parameters (r_{sub}=0.2) & p_T-dependent cuts
- Initial evaluations of the systematic uncertainties apply extrapolations based on run1 uncertainties & differences between run1 and run2

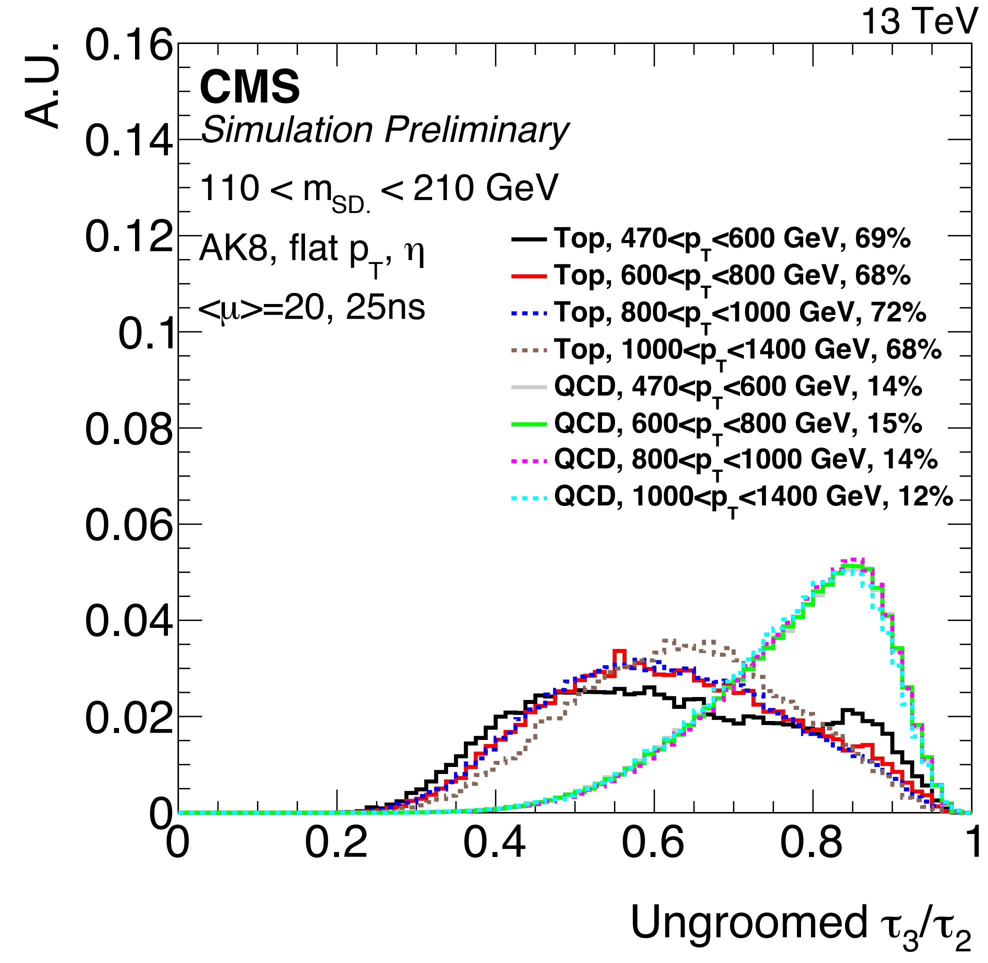




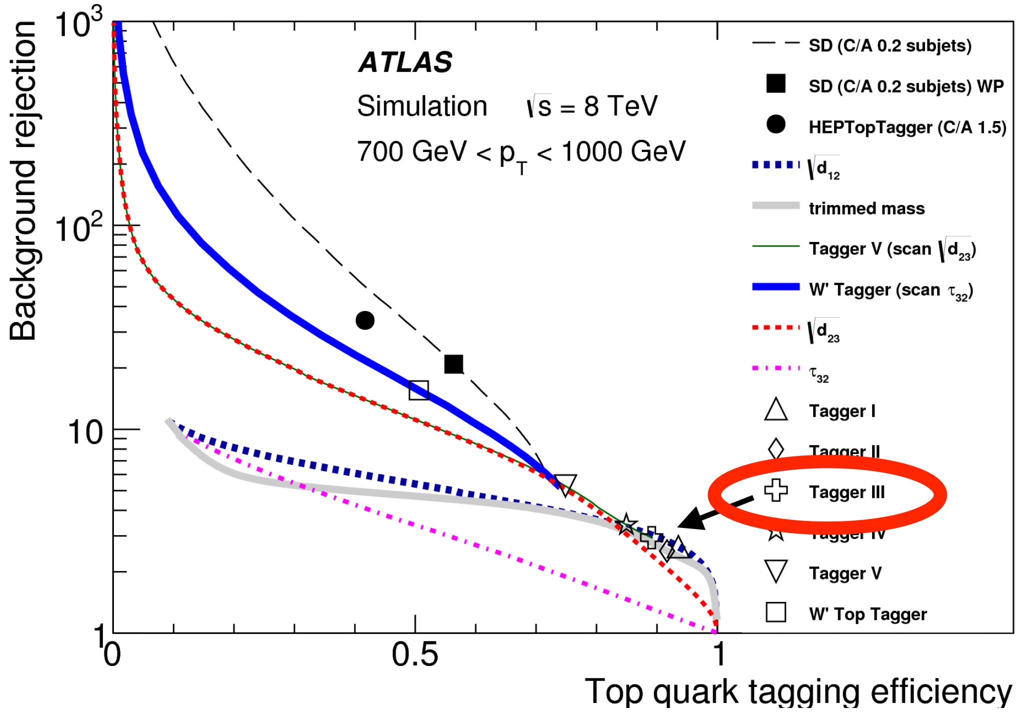
Run2 Tagger

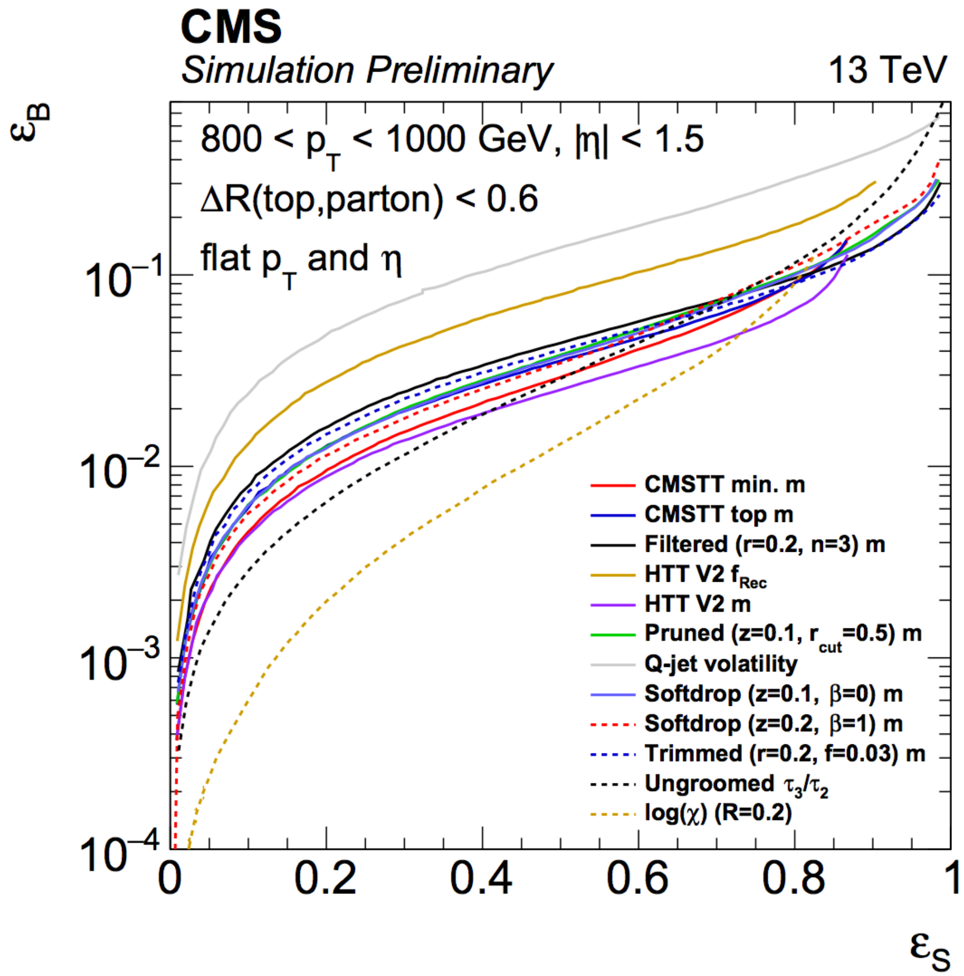
- At 13 TeV, it has been determined that the optimal run2 tagger utilizes the soft drop mass and n-subjettiness variables to tag top-quarks. cds
  - At low-p_T, the groomed n-subjettiness variable is recommended with the C/A R=1.5 jet
  - At high-p_T, the un-groomed n-subjettiness variables is recommended with the Anti-k_T R=0.8 jet





Future Developments





- Building off of run1 “capstone” papers [ATLAS, CMS], more sophisticated taggers are being explored for future results
  - Lower efficiency taggers, but better signal efficiency to background rejection
- Most importantly, with a much larger dataset, the magnitude of the systematic uncertainties should be reduced

Future Developments

- Some examples of future developments on top taggers and jet reconstruction. If interested, please visit the BOOST2015 indico page and review work presented there: BOOST2015
- Top Taggers
  - **Shower Deconstruction**: Likelihoods that large-R jet originates from signal or background (ATLAS, CMS)
  - **Machine Learning**: Use deep learning to identify boosted top-quarks (talk)
- Jet Reconstruction
  - **Variable-R Jets**: Instead of fixed-radius jets, use variable-R jets that are built to contain the particle of interest (arxiv)
  - **Re-clustering**: Use existing small-r jet collections to build large-R jets with standard jet reconstruction algorithms (anti-kT) (arxiv)

BOOST 2016

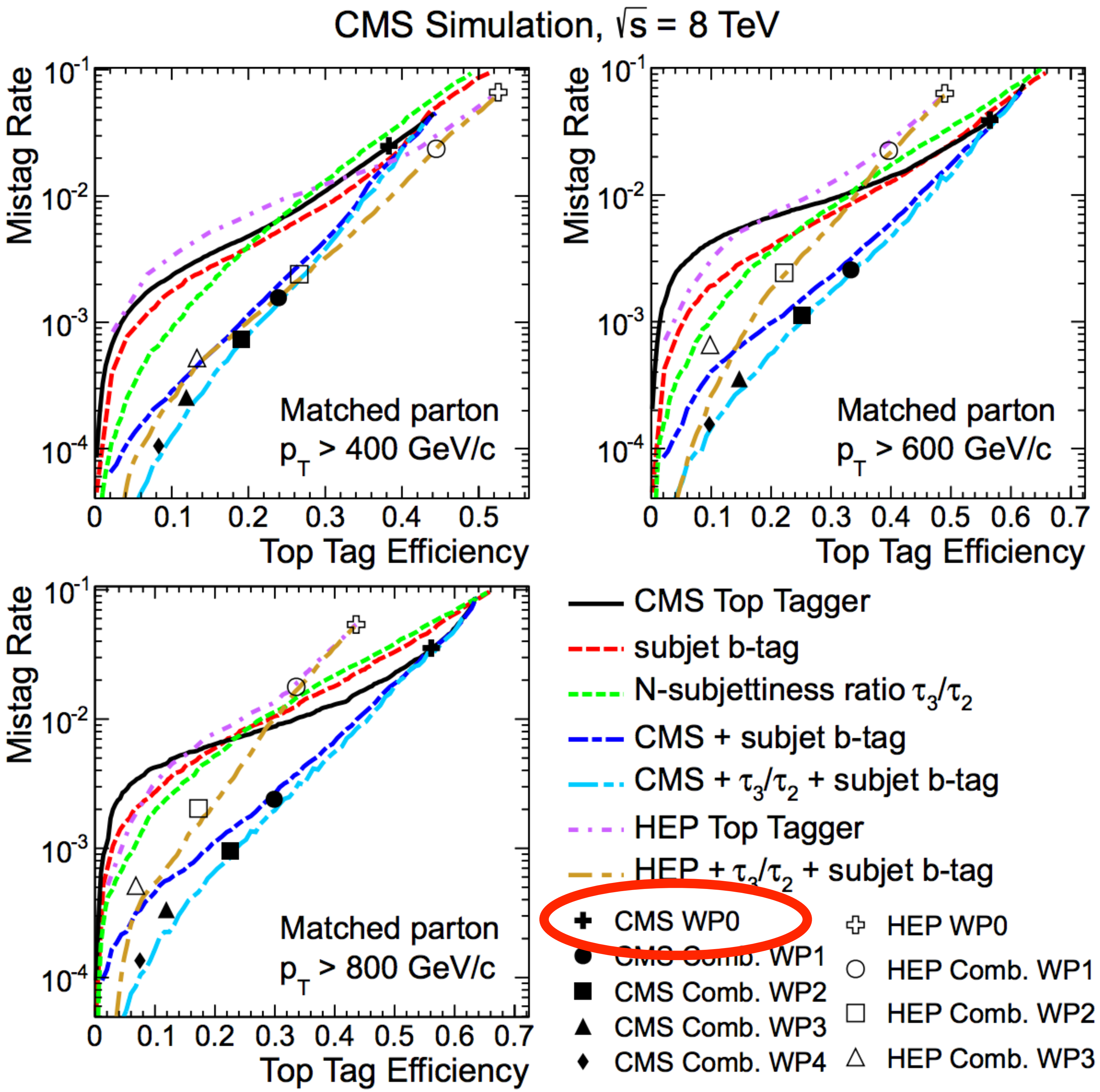
- From 18-22 July 2016 the BOOST conference will be held in Zurich
- Lots of studies will be presented from both collaborations regarding boosted top tagging
    - Results from early run2 data will be presented!
- Attend or follow online if interested in applying more sophisticated taggers, or learning what techniques exist & are under development

Conclusions

- Boosted top-quarks are necessary to make measurements in the high-pT regime and compliment the corresponding resolved analyses
  - Look for largest discrepancies between Data & predictions and look for hints of new physics!
- Run2 will see a significant increase in boosted top-quark statistics and improves reconstruction methods
  - Improved systematic uncertainties with increase in dataset

Back-up

CMS 8 TeV Taggers

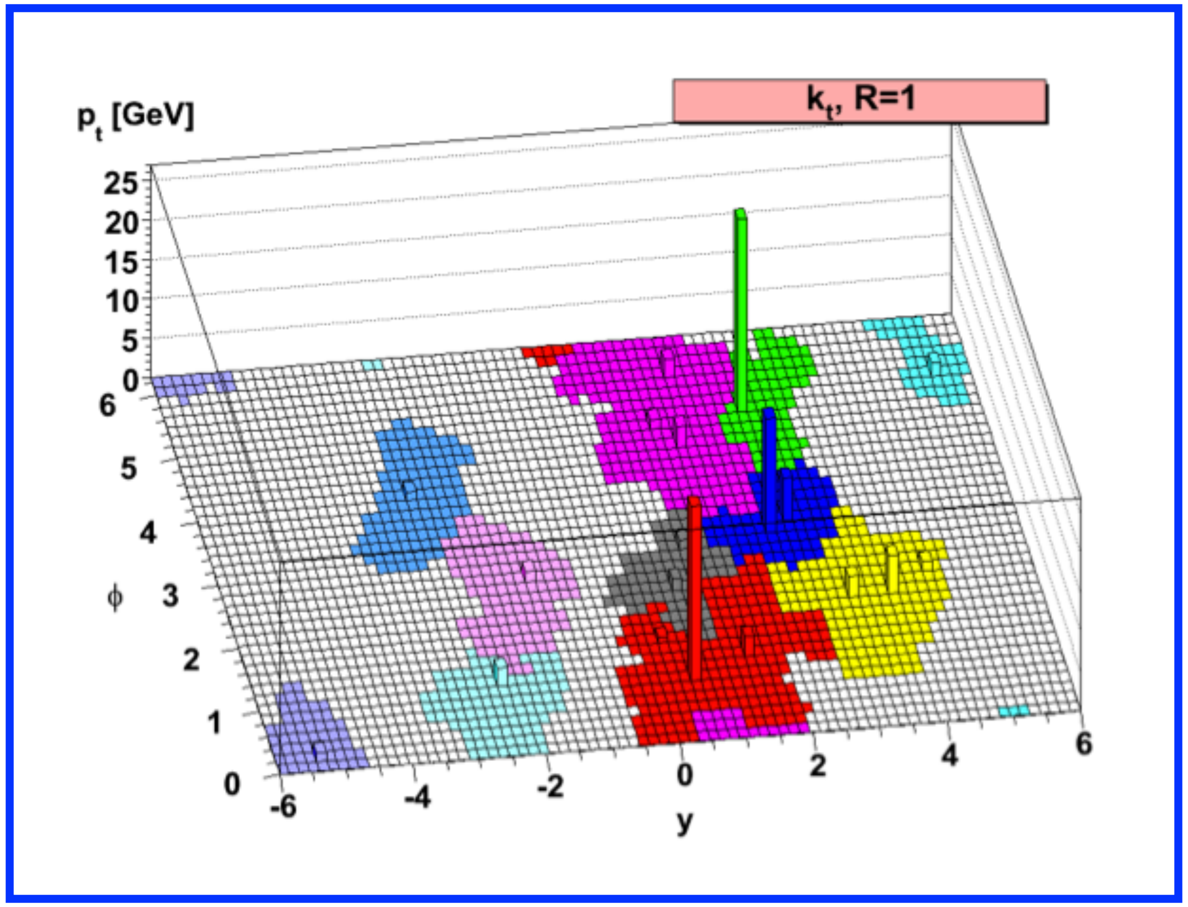


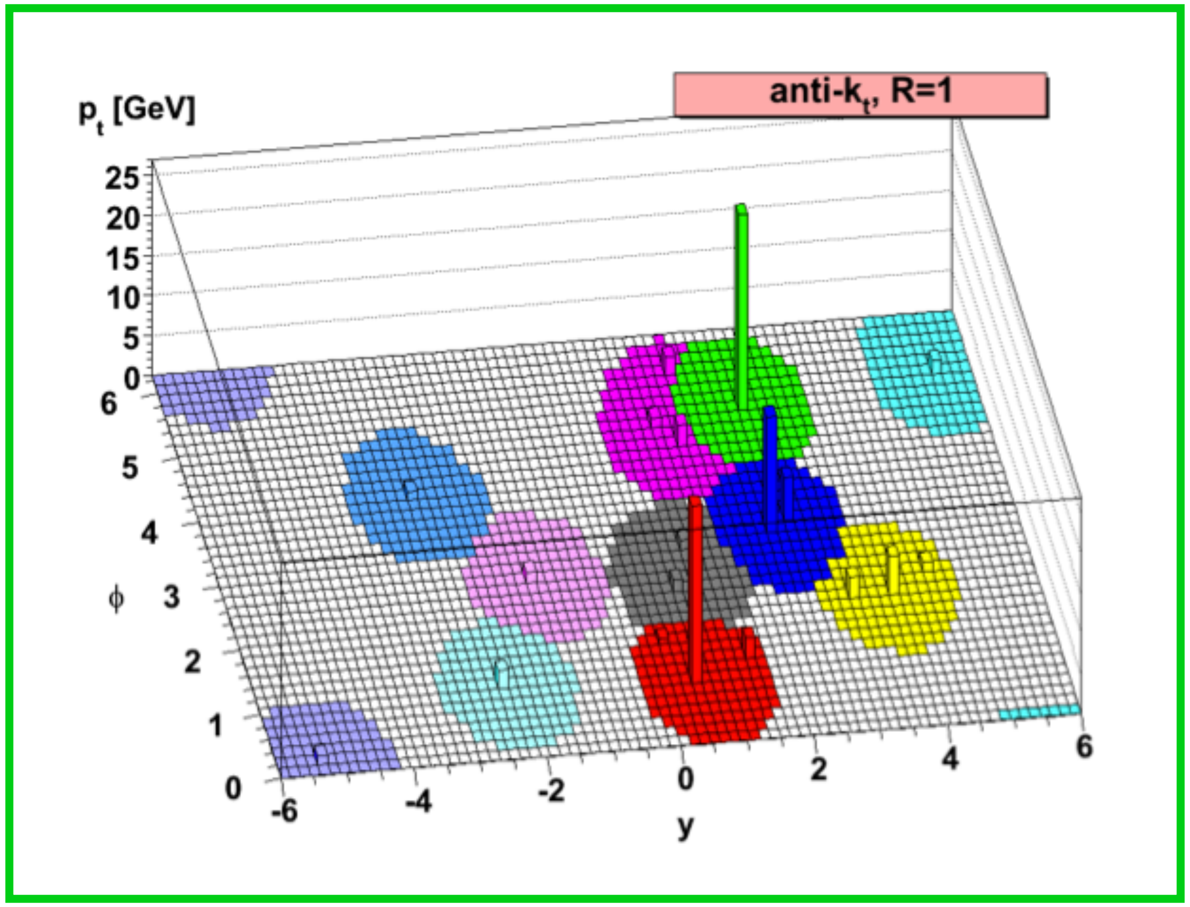
Jet Clustering

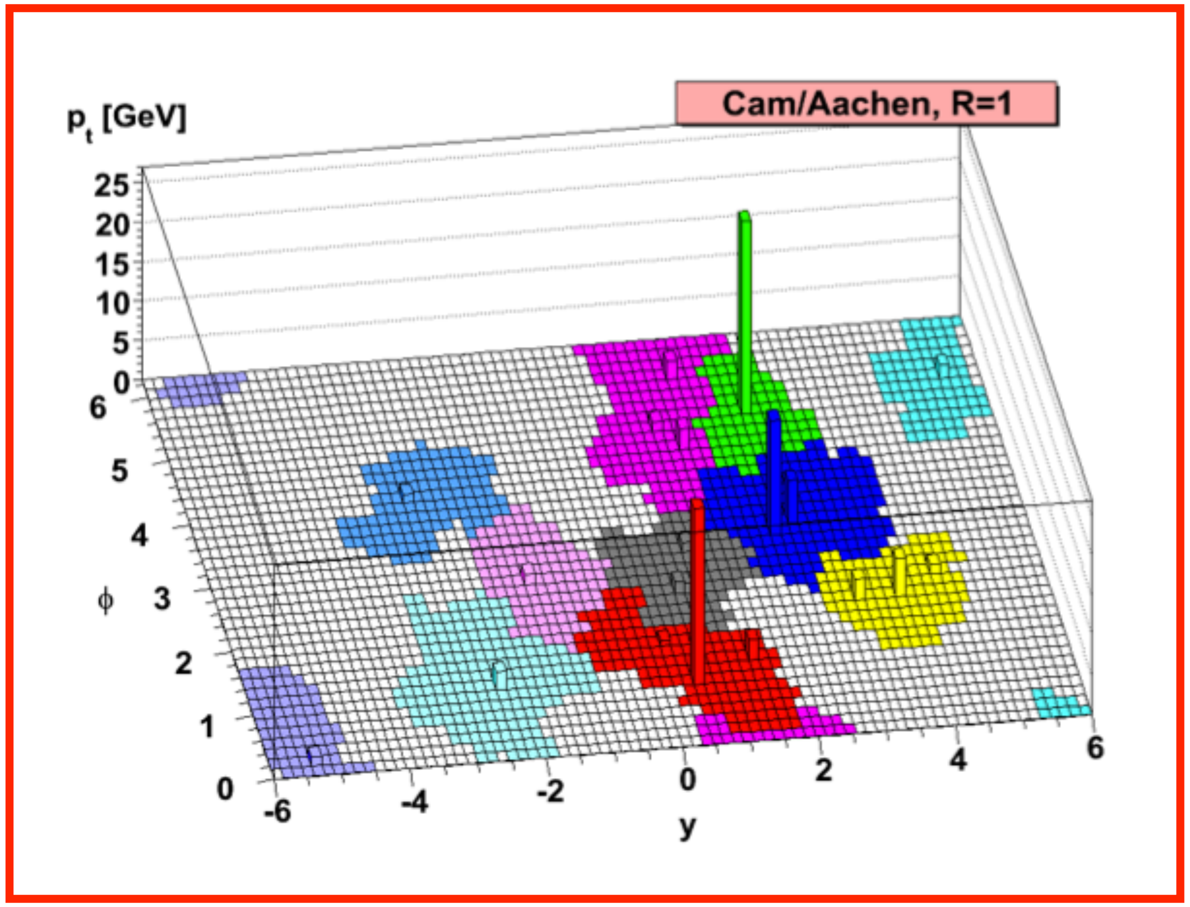
$$d_i = p_{T_i}^{2a}$$

$$d_{ij} = \frac{\Delta R_{ij}^2}{R^2} \min(p_{T_i}^{2a}, p_{T_j}^{2a})$$

a = 1 : k$_T$
a = 0 : C/A
a = -1 : anti-k$_T$







Jet Clustering

1. Define the splitting scales for each input and pairs of inputs (Topoclusters or PF objects).

2. Find min{d_q}, where d_q includes all of the distance scales d_i and d_{ij}

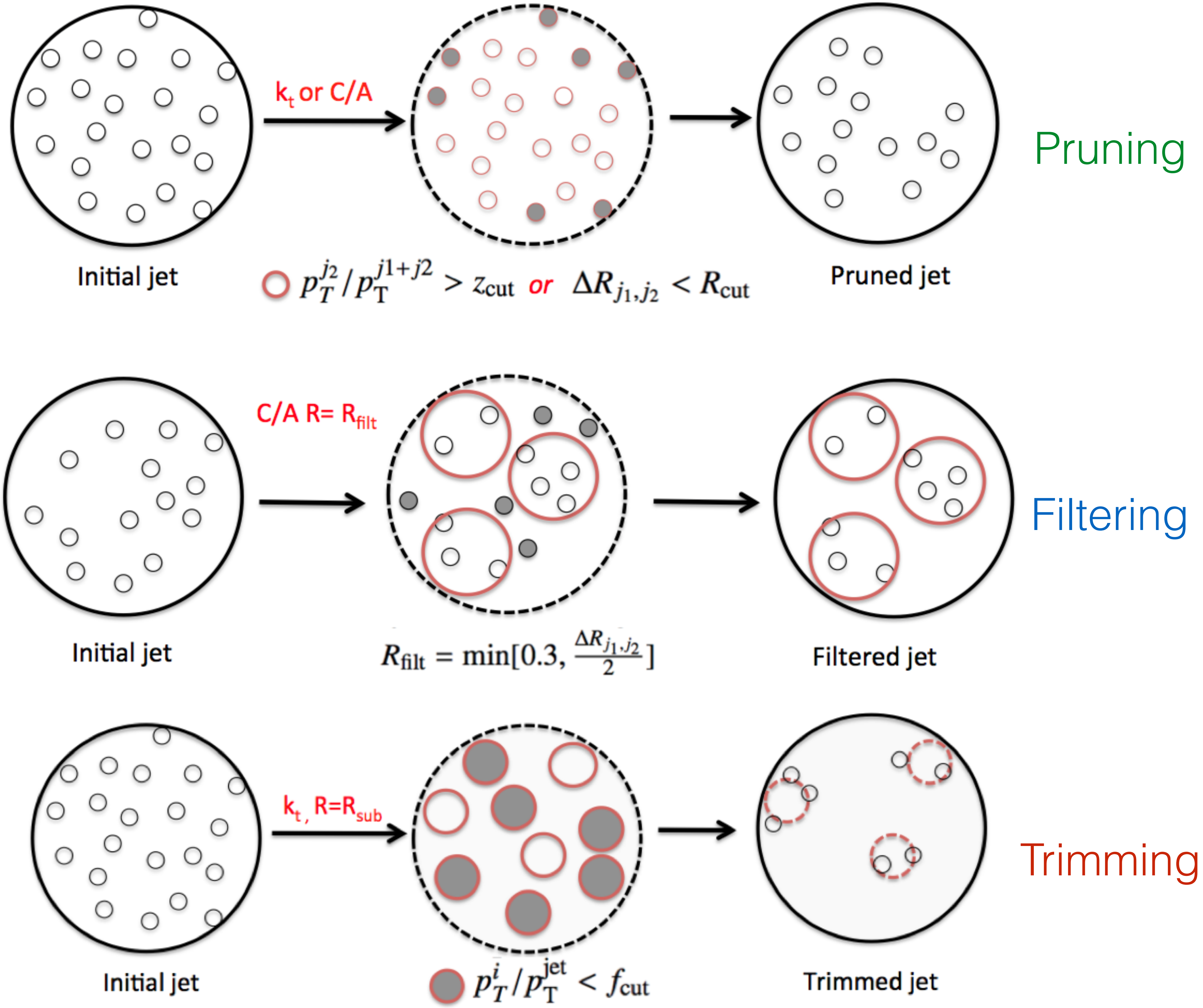
3.(a) If min is a d_{ij}: redefine as d_k.

$$\begin{aligned} p_{T_k} &= p_{T_i} + p_{T_j} \\ \eta_k &= (p_{T_i}\eta_i + p_{T_j}\eta_j)/p_{T_k} \\ \phi_k &= (p_{T_i}\phi_i + p_{T_j}\phi_j)/p_{T_k} \end{aligned}$$

3.(b) If min is a d_i: Remove from list and move to JET list

4. Repeat until all JETs formed

Jet Grooming



k_t or C/A

Initial jet

○ $p_T^{j2}/p_T^{j1+j2} > z_{\mathrm{cut}}$ *or* $\Delta R_{j_1,j_2} < R_{\mathrm{cut}}$

Pruned jet

Pruning

C/A R= R_{filt}

Initial jet

$R_{\mathrm{filt}} = \min[0.3, \frac{\Delta R_{j_1,j_2}}{2}]$

Filtered jet

Filtering

k_t, R=R_{sub}

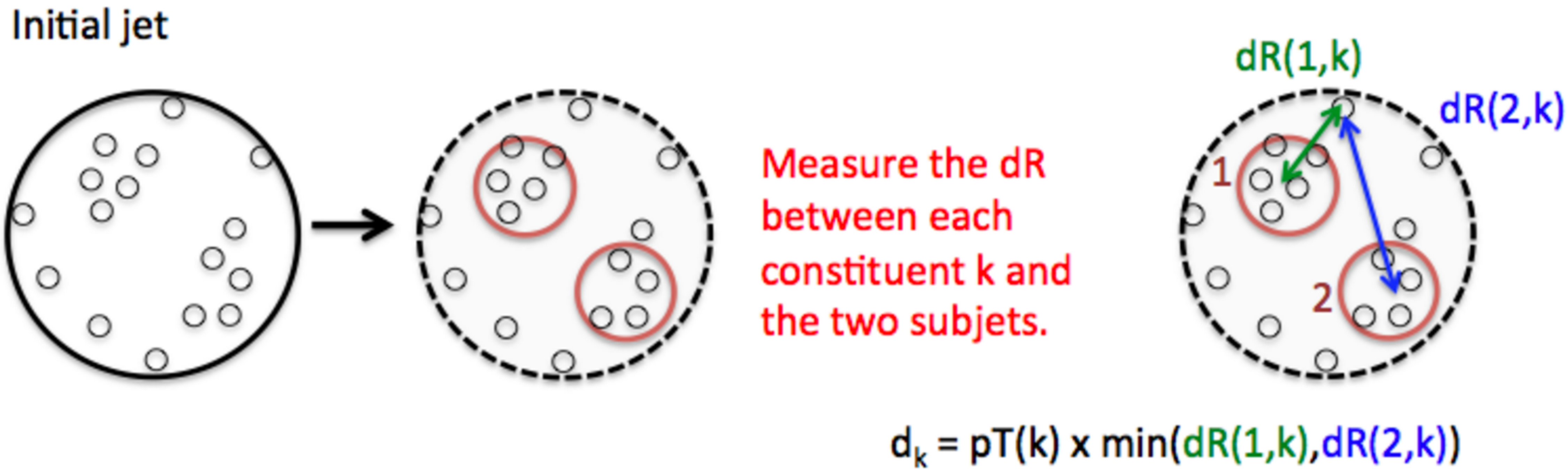
Initial jet

● $p_T^i/p_T^{\mathrm{jet}} < f_{\mathrm{cut}}$

Trimmed jet

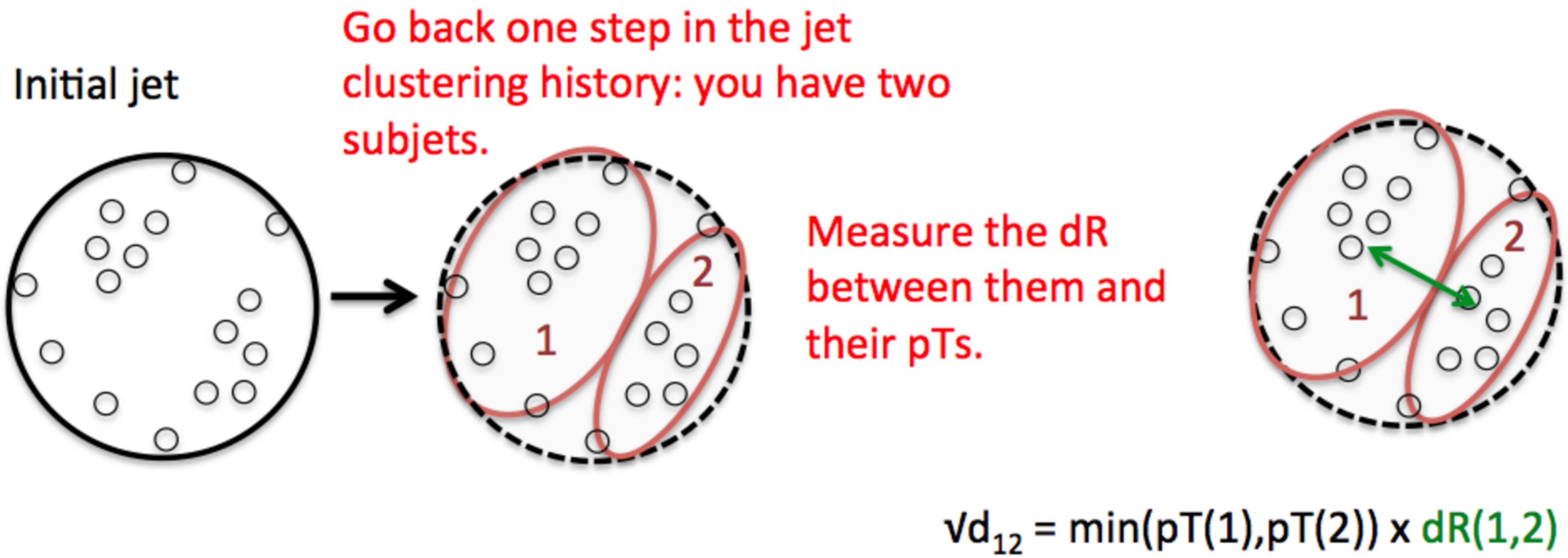
Trimming

Jet Substructure



Measure the dR between each constituent k and the two subjets.

$d_k = pT(k) \times \min(dR(1,k), dR(2,k))$



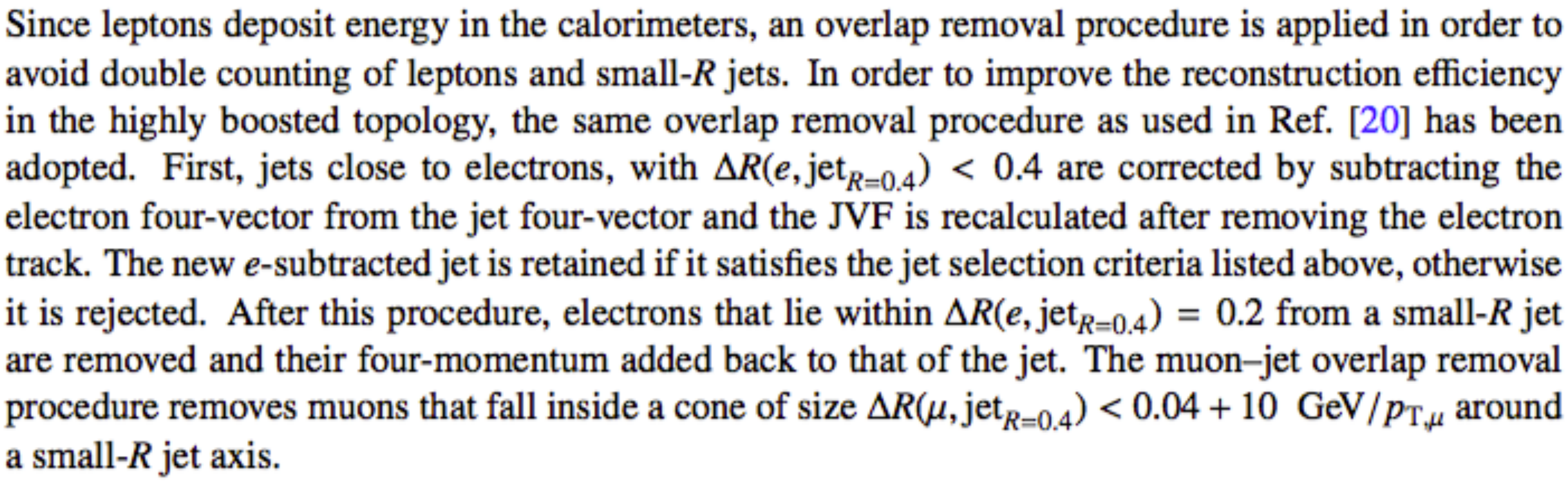
Go back one step in the jet clustering history: you have two subjets.

Measure the dR between them and their pTs.

$\sqrt{d_{12}} = \min(pT(1), pT(2)) \times dR(1,2)$

Overlap Removal: ATLAS

- Muons that fall within $\Delta R<(0.04+10/p_T^{\ell})$ are removed from the event
- Electrons
    - run1 (boosted diff. XSec):



Since leptons deposit energy in the calorimeters, an overlap removal procedure is applied in order to avoid double counting of leptons and small-*R* jets. In order to improve the reconstruction efficiency in the highly boosted topology, the same overlap removal procedure as used in Ref. [20] has been adopted. First, jets close to electrons, with $\Delta R(e, \mathrm{jet}_{R=0.4}) < 0.4$ are corrected by subtracting the electron four-vector from the jet four-vector and the JVF is recalculated after removing the electron track. The new *e*-subtracted jet is retained if it satisfies the jet selection criteria listed above, otherwise it is rejected. After this procedure, electrons that lie within $\Delta R(e, \mathrm{jet}_{R=0.4}) = 0.2$ from a small-*R* jet are removed and their four-momentum added back to that of the jet. The muon–jet overlap removal procedure removes muons that fall inside a cone of size $\Delta R(\mu, \mathrm{jet}_{R=0.4}) < 0.04 + 10\ \mathrm{GeV}/p_{\mathrm{T},\mu}$ around a small-*R* jet axis.

    - run1 (boosted A_C): If an electron is within $0.2<\Delta R<0.4$ of small-r jet, the electron is removed. If the electron is within $\Delta R<0.2$, the jet is removed