Substructure Performance in Boosted Objects at ATLAS

Chris Pollard
On behalf of the ATLAS Collaboration

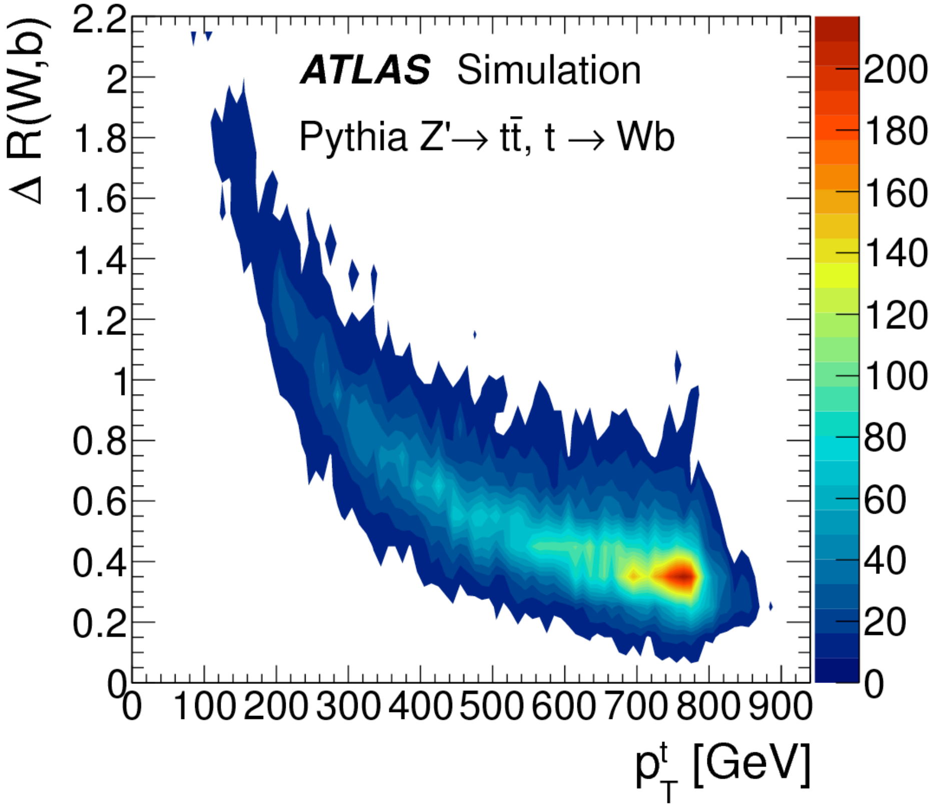
Duke University

Outline

- Motivation
- Jet mass scale validation
- Substructure studies with top jets
  - Jet mass
  - k_t splitting scales
  - N-subjettiness
  - HEPTopTagger
- Conclusions and outlook

Motivation

- At high p_T, heavy objects which decay hadronically are difficult to distinguish from background jets.
- The internal structure of a jet gives us useful tools for testing QCD and for searches for new physics.
- Several of these tools have been validated with 2011 data, and many are currently being validated with data from 2012.



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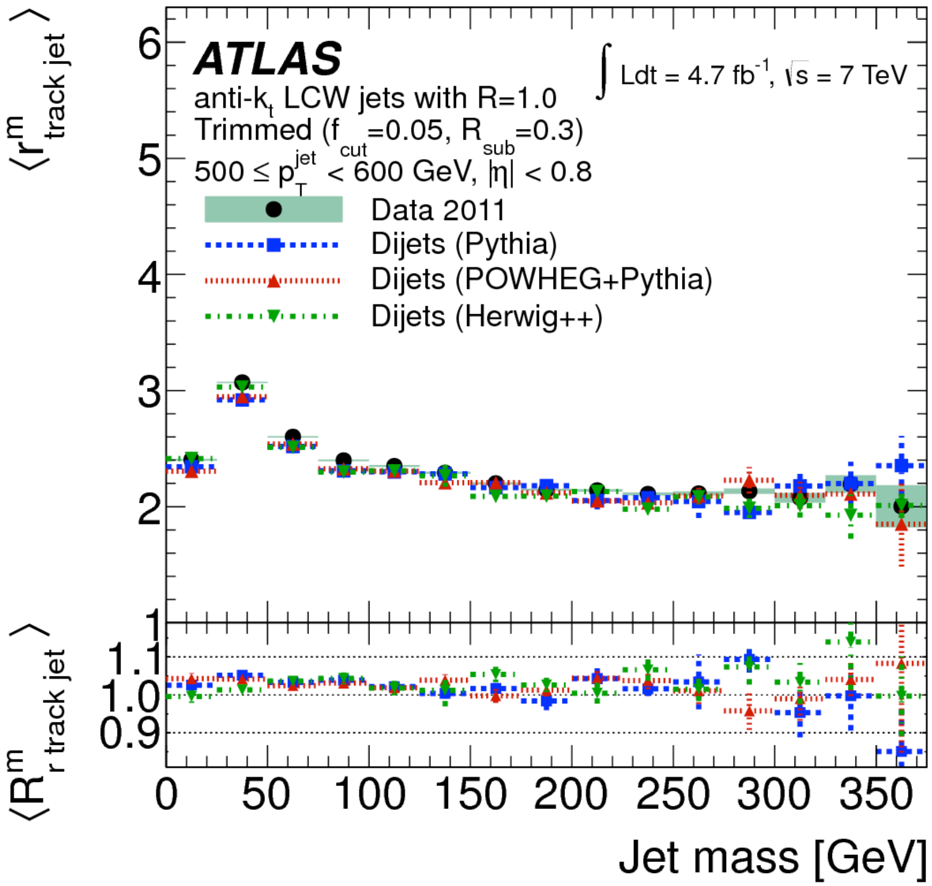
(arXiv:1306.4945)

Why is JMS Important?

- Many exotic models predict heavy particles which decay to tops, Ws, and Zs
- Jet mass is a very good discriminating variable → need good handle on JMS!
- How can we measure it? Use ratio of track jet mass to calo jet mass.
- Inner detector and calorimeter have uncorrelated uncertainties → probe detector modeling effects.



5-8% uncertainty

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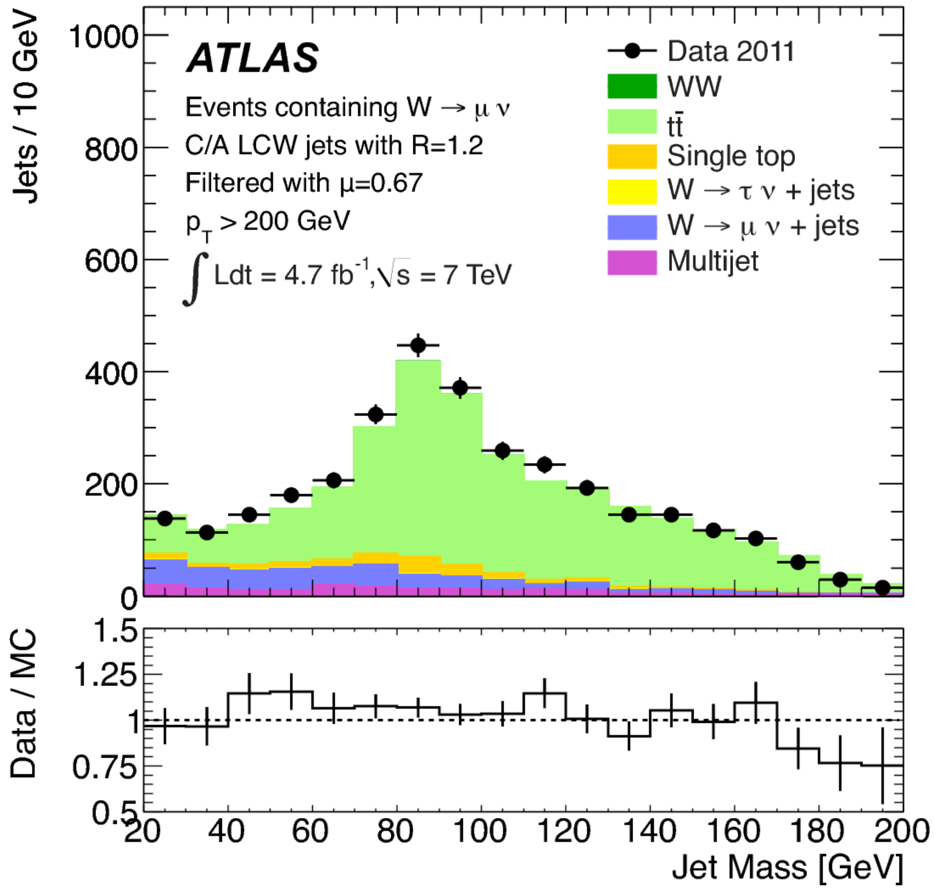
Recently accepted by JHEP

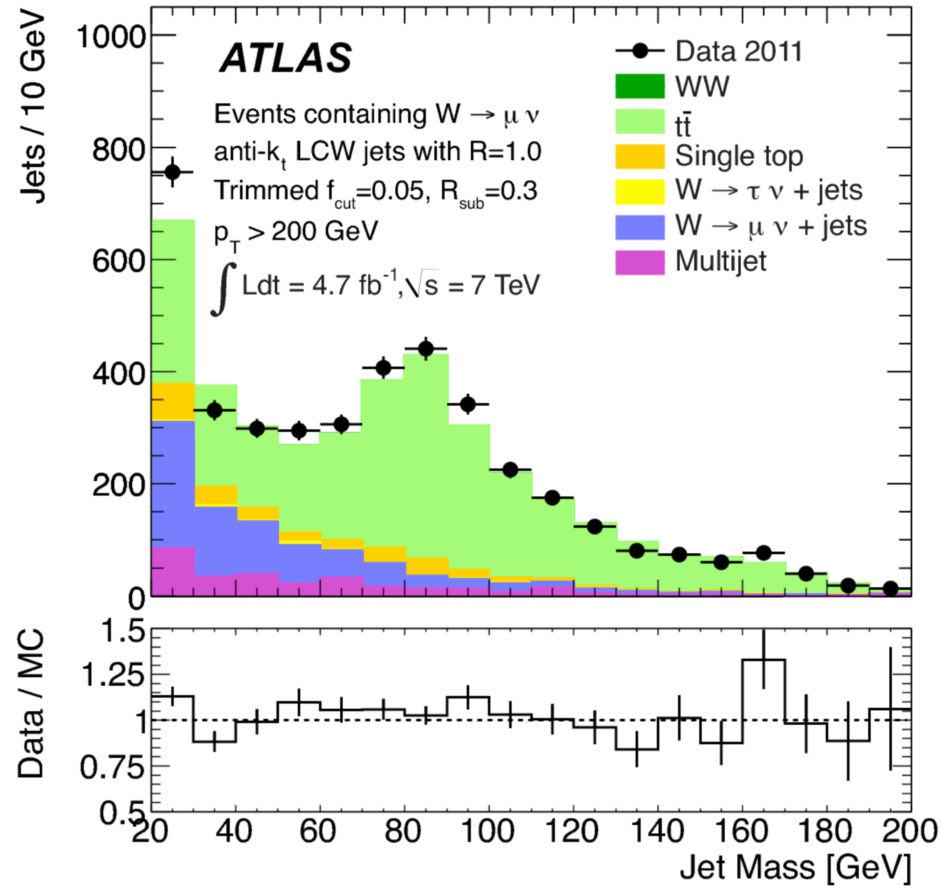
2011 Results

Validation of Jet Mass Scale

Filtered C/A 1.2; p_T > 200 GeV



Trimmed anti-k_t 1.0; p_T > 200 GeV



Mass distribution for jets with
p_T > 200 GeV after μ+jets tt selection
(W → μν candidate and a b-tagged anti-k_t 0.4 jet)

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Validation of Jet Mass Scale

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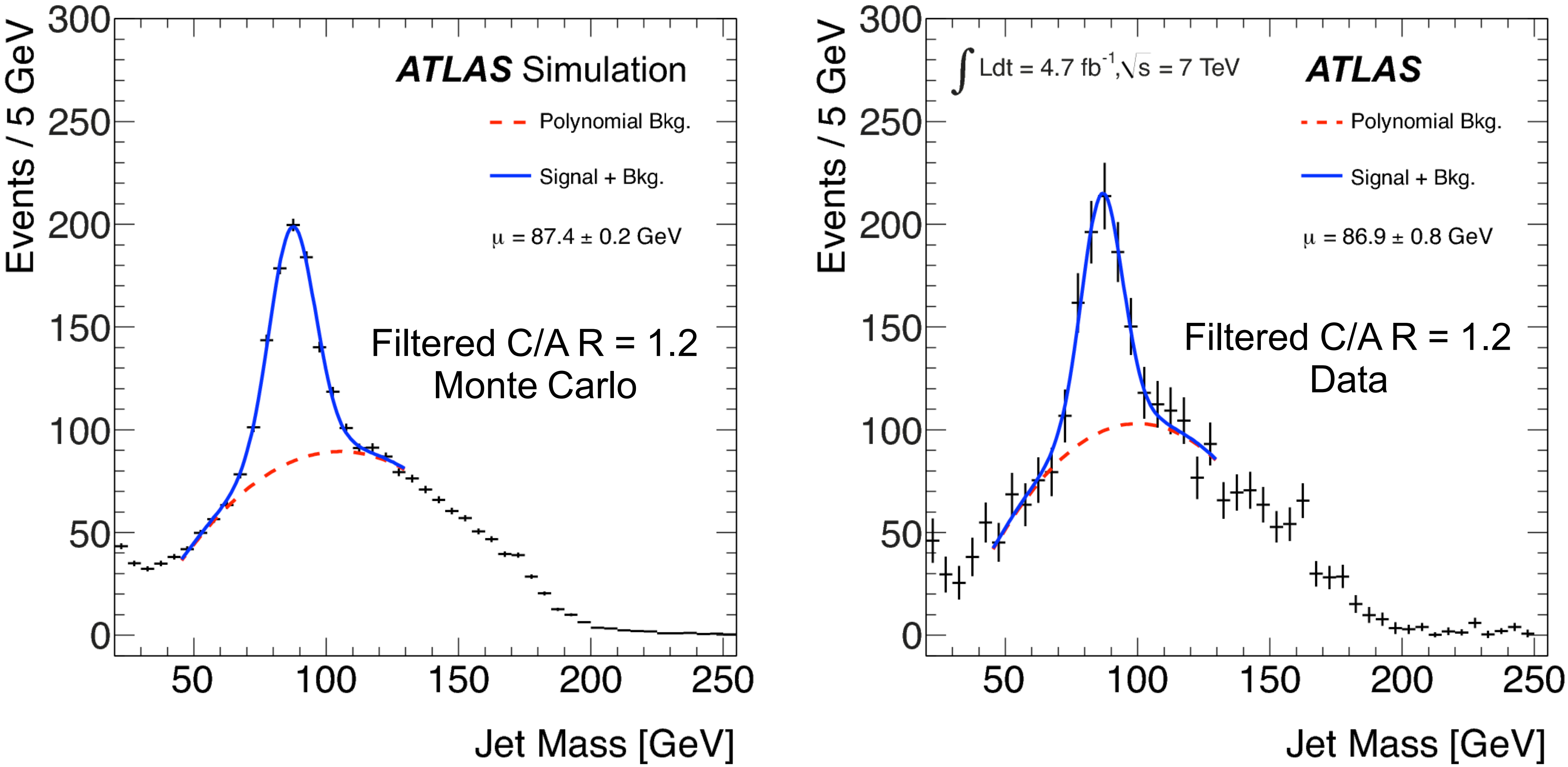

Fit signal (W jets) + background (after subtracting W+jets, multijet).
Extract mean W jet mass: μ_{MC} = 87.4 GeV, μ_{data} = 86.9 GeV.

Validation of Jet Mass Scale

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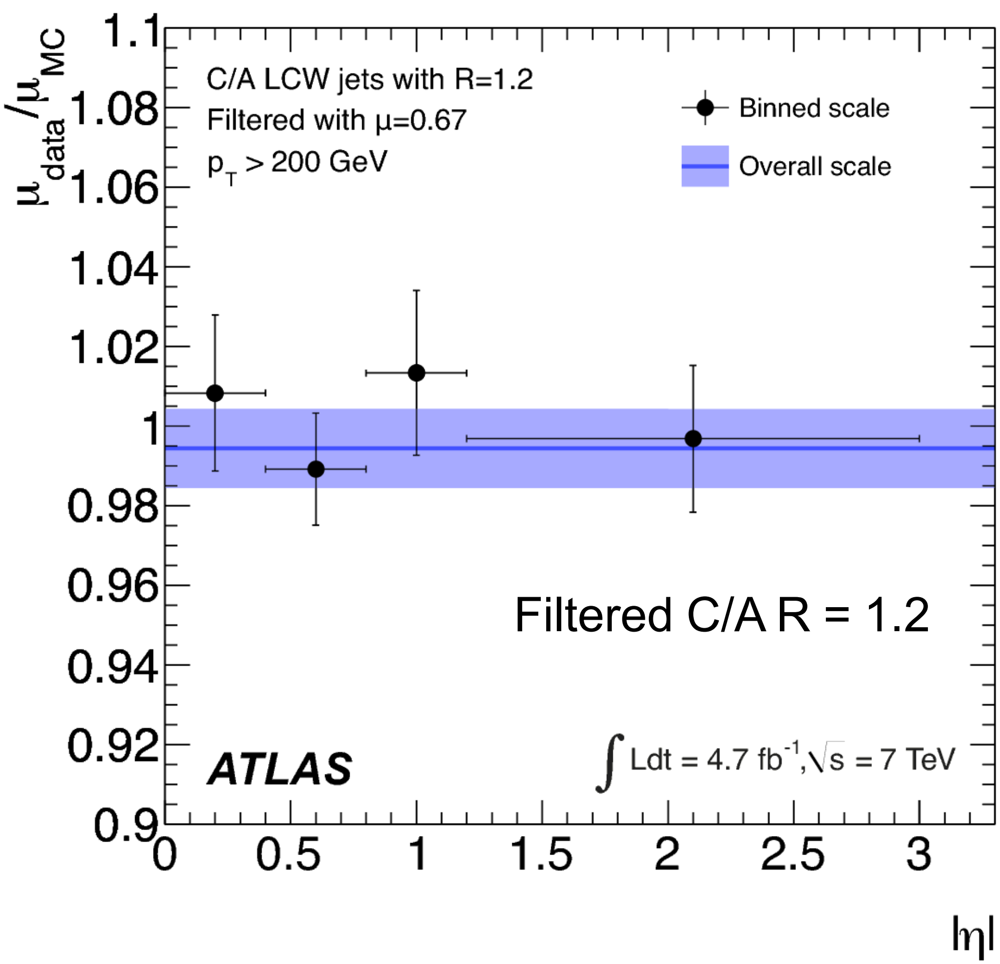
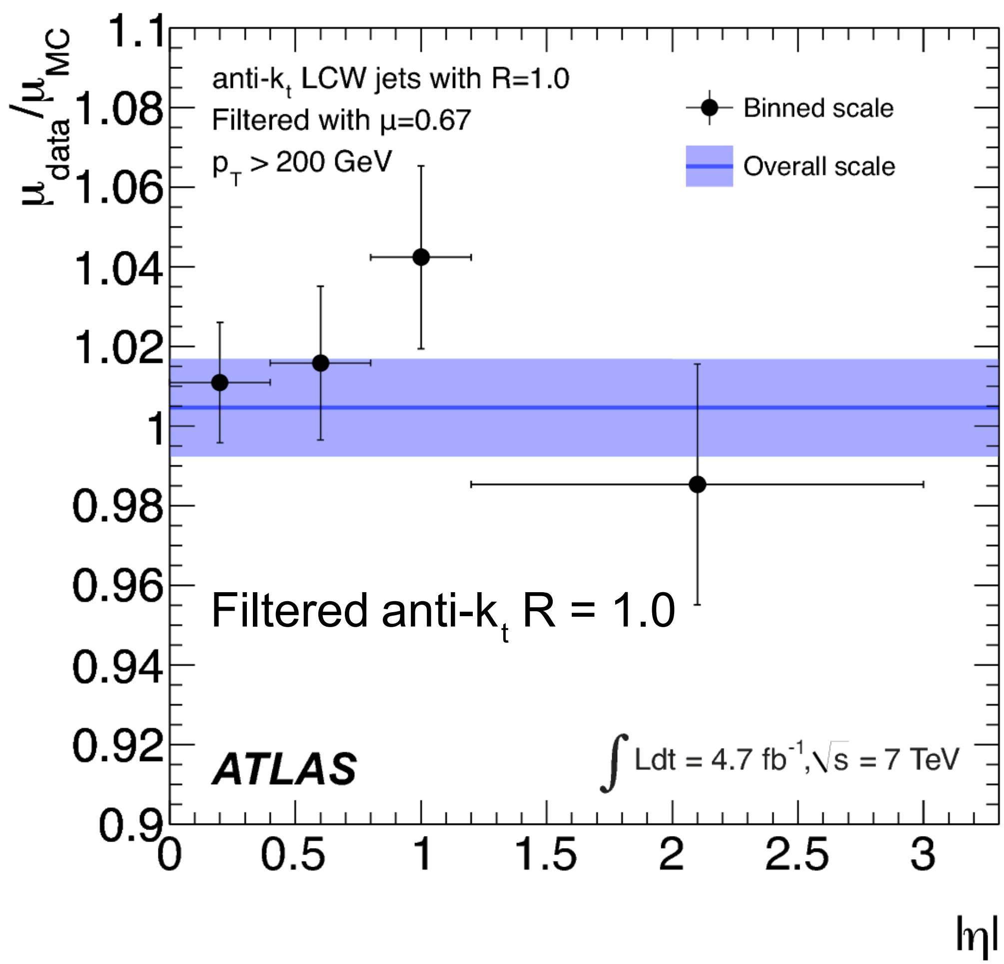




Perform the same analysis in jet |η| bins
No significant discrepancy between data and MC for W jets

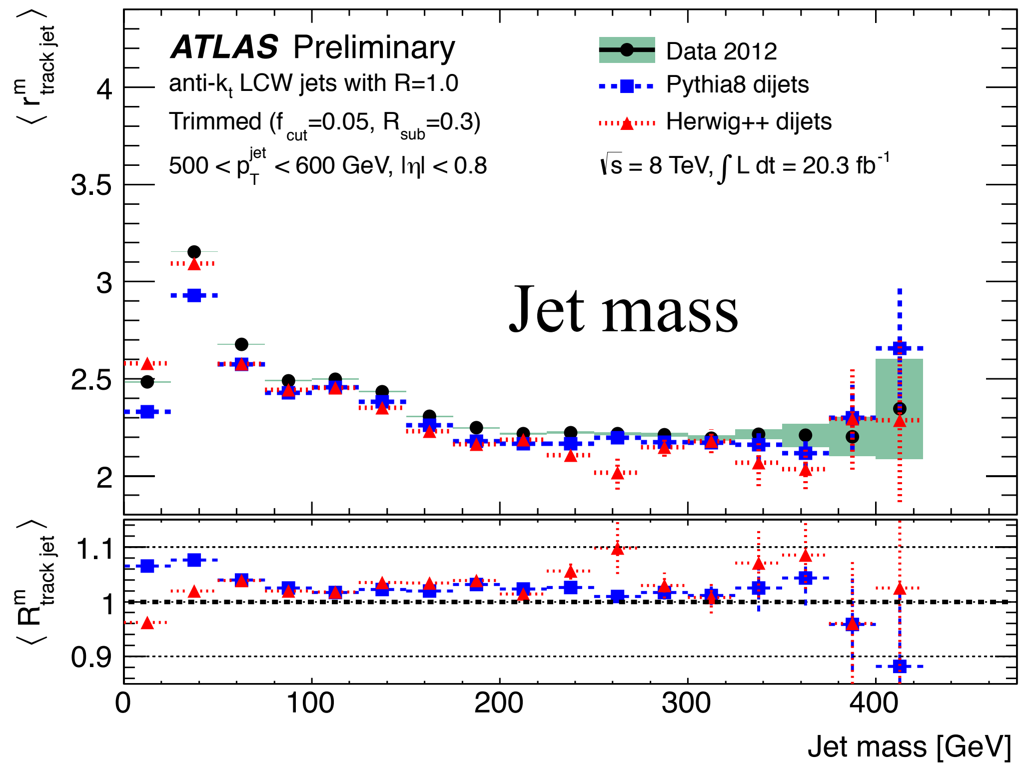
2012 Results

Jet Mass Ratios

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetEtmissApproved2013Jms

y-axis:

average $r^{m}_{\text{track jet}} = \frac{m^{\text{jet}}}{m^{\text{track jet}}}$



JMS uncertainty determination:

$$\delta_{\text{Pythia/Herwig}} = \text{abs}(R^{m}_{\text{track jet}} - 1)$$

$$\delta_{\text{track}} = \max[\delta_{\text{Pythia}}, \delta_{\text{Herwig}}]$$

$$\delta_{\text{tracking efficiency}} = 0.027$$

$$\delta_{\text{track merging}} = 0.02$$

$$\epsilon_{\text{tot}} = \sqrt{\delta^2_{\text{track}} + \delta^2_{\text{tracking eff}} + \delta^2_{\text{track merging}}}$$

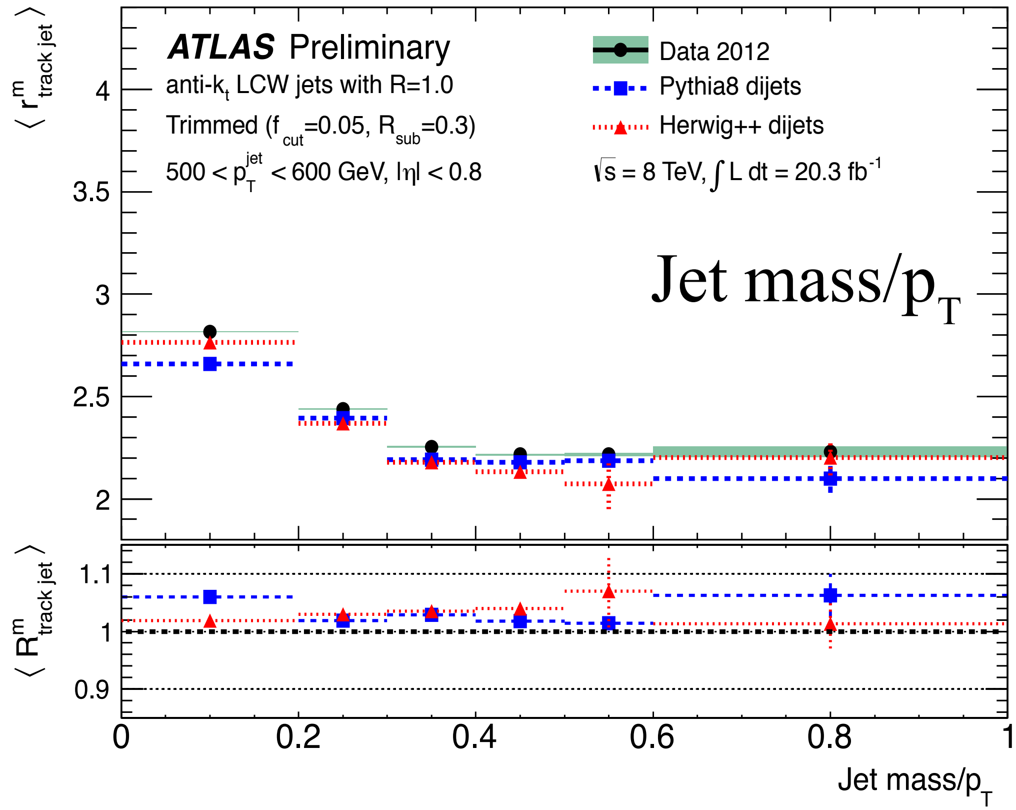
Jet Mass Ratios

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetEtmissApproved2013Jms

Why jet m/p_T?

→ less susceptible to JES

→ each bin covers a broad range of jet masses and p_Ts.



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Jet Mass Ratios

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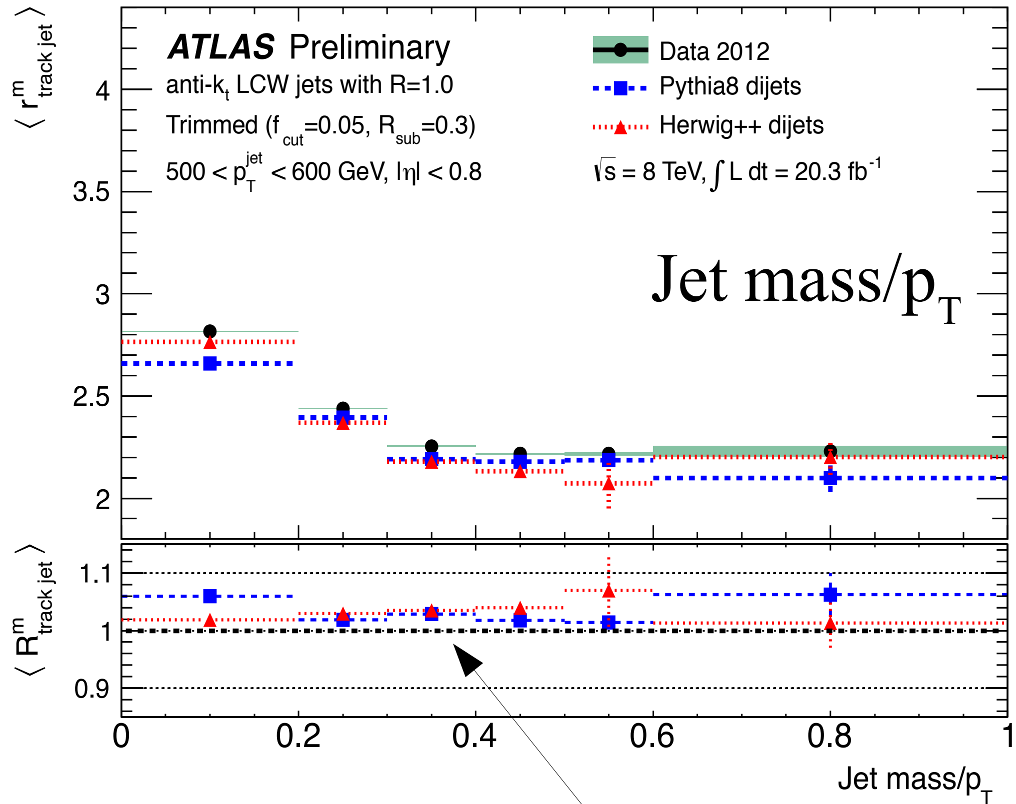

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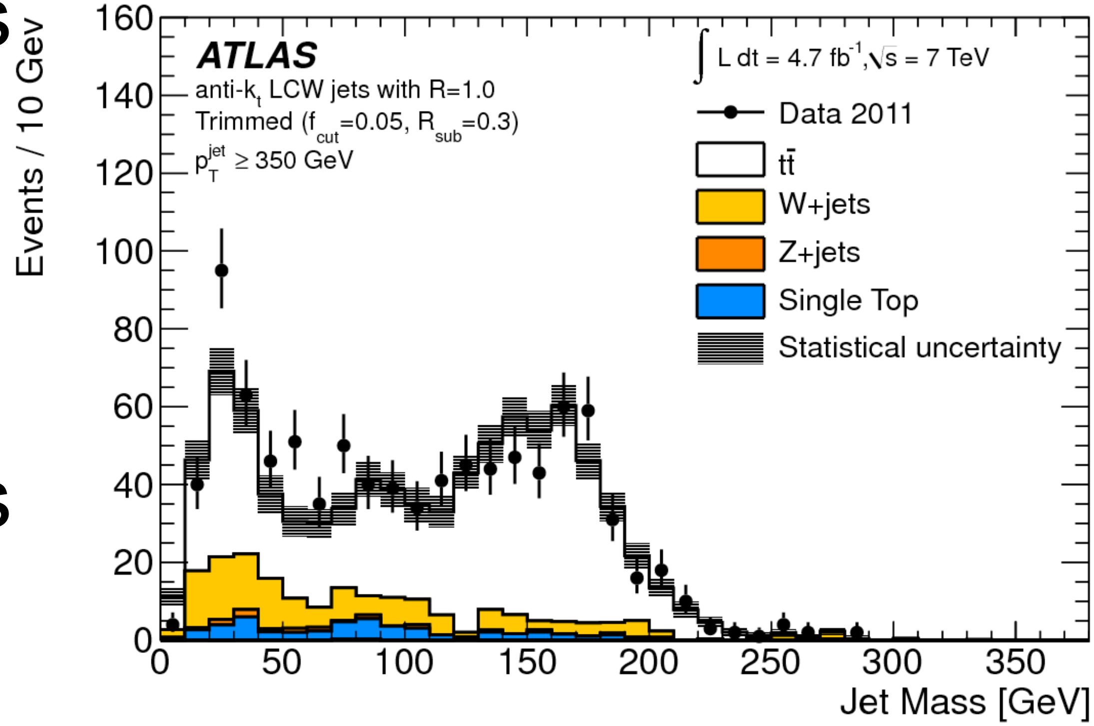
\end{aligned}$$

For a top-jet with p_T = 500 GeV, the JMS uncertainty is 4-5%

Substructure Studies with Top Jets

- Q: Does MC model substructure variables well in an interesting use case--top jets?

- Q: How do substructure variables perform if not all decay products are contained? Does MC model this well?



2011 Data/MC comparison

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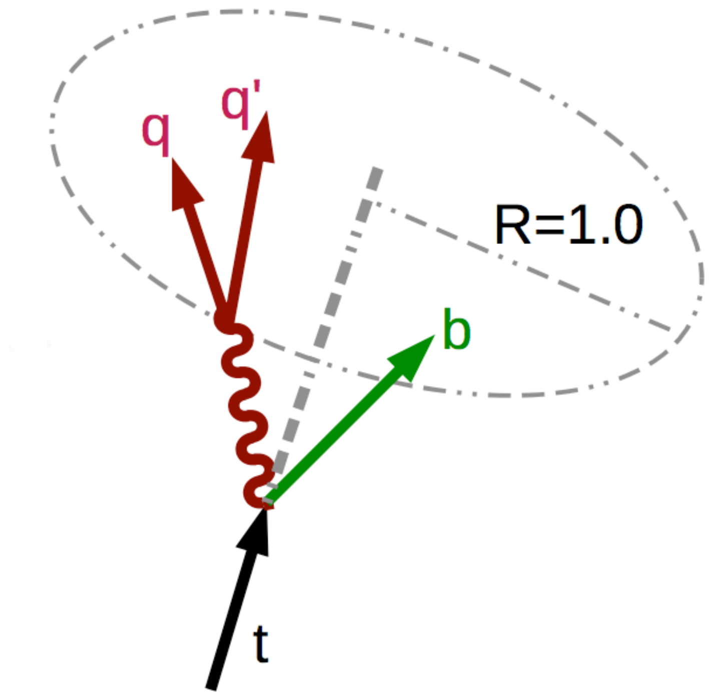
(arXiv:1306.4945)

Substructure Studies with Top Jets

- Q: Does MC model substructure variables well in an interesting use case--top jets?
  - μ+jets decay channel with a b-tagged jet to obtain a top-enriched sample
- Q: How do substructure variables perform if not all decay products are contained? Does MC model this well?
  - Split MC events into two categories: with fully-contained and non-contained top jets
  - Study substructure as a function of number of k_t subjets



Event with a fully-contained top jet:
- All three daughters within ΔR < 1.0 of truth top, before radiation
- Plots for highest p_T jet, not necessarily the top jet

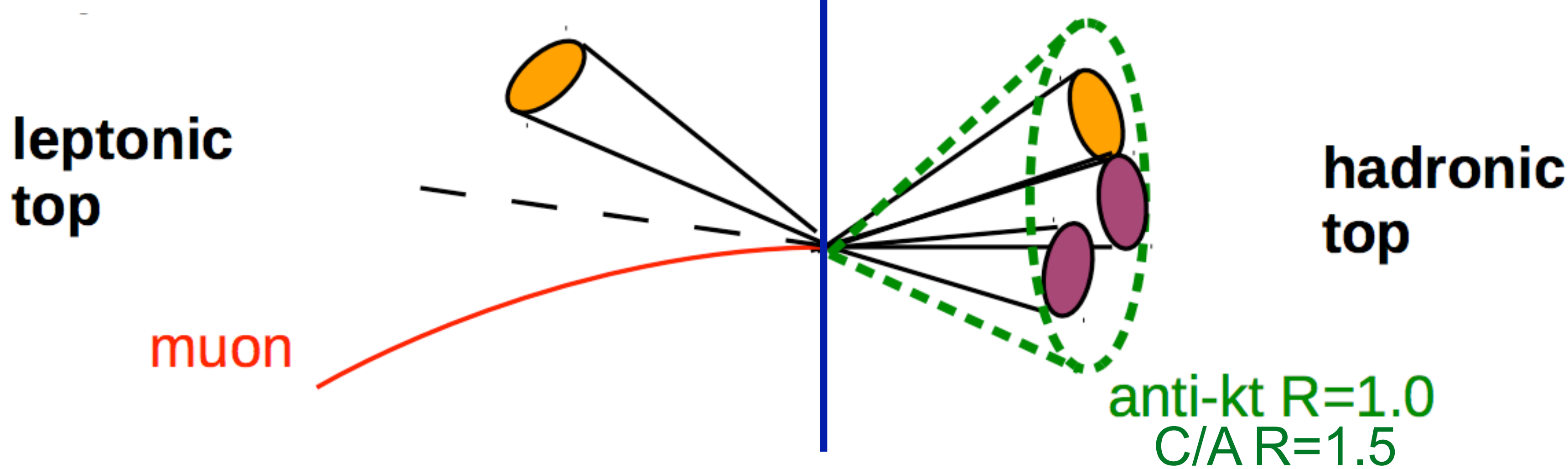
μ+jets Event Selection

- One triggered muon with p_T > 25 GeV, $|\eta|$ < 2.5, and relative miniisolation < 0.05
- $E_T^{miss} + m^W_T$ > 60 GeV
- One b-tagged anti-k_t R = 0.4 jet within ΔR < 1.5 of the selected muon

- At least one trimmed anti-k_t R=1.0 jet

- OR -

- At least one C/A R=1.5 jet which passes HEPTopTagger selection
- Both cases: p_T > 200 GeV and $|\eta|$ < 1.2



Jet Mass

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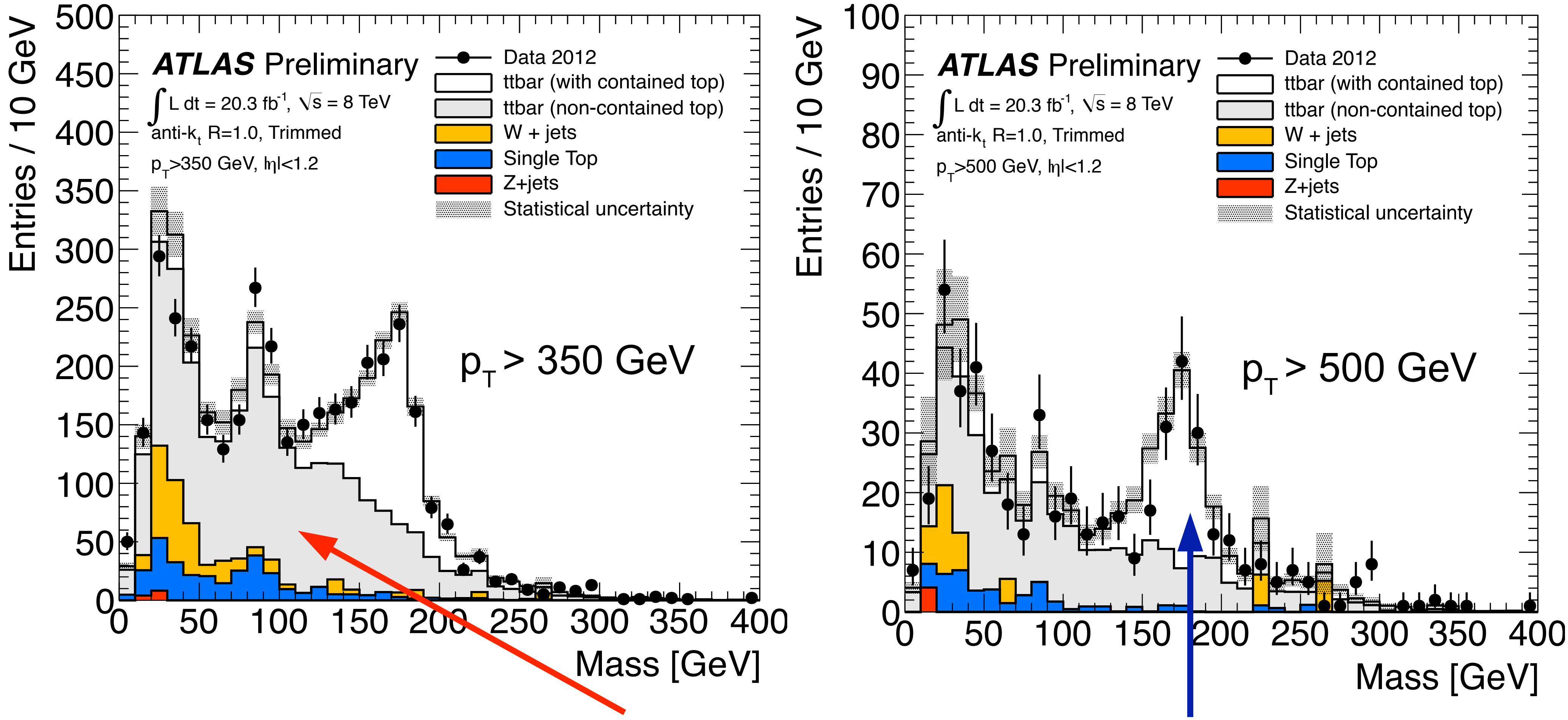
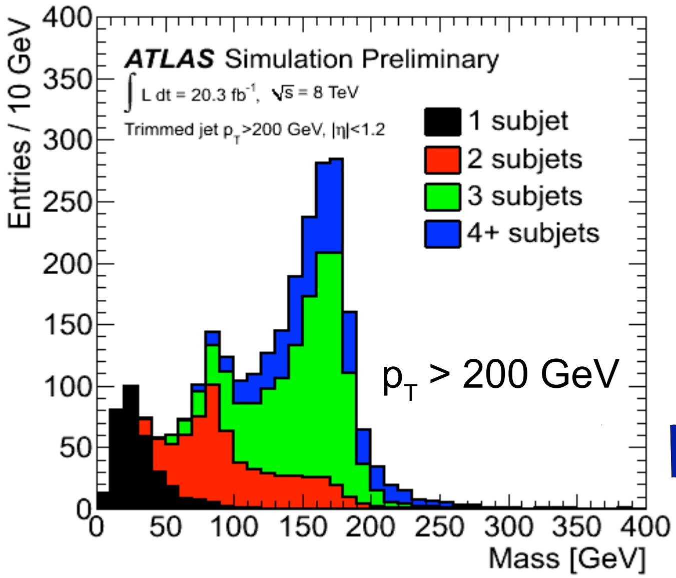
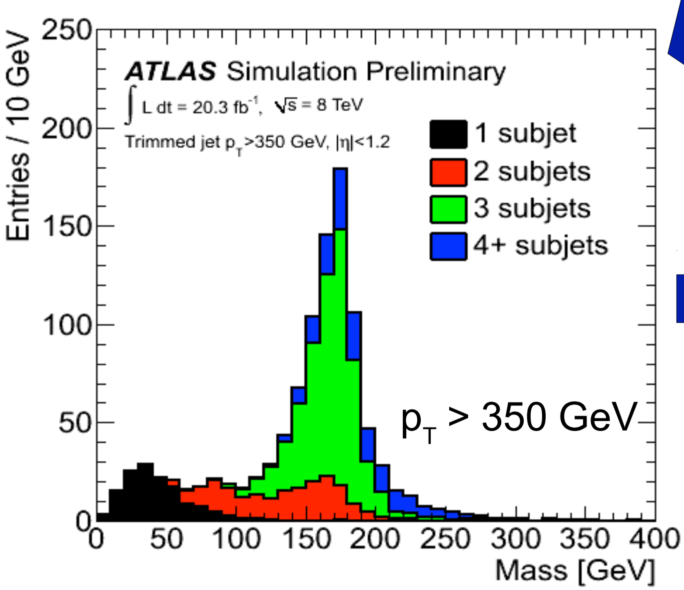


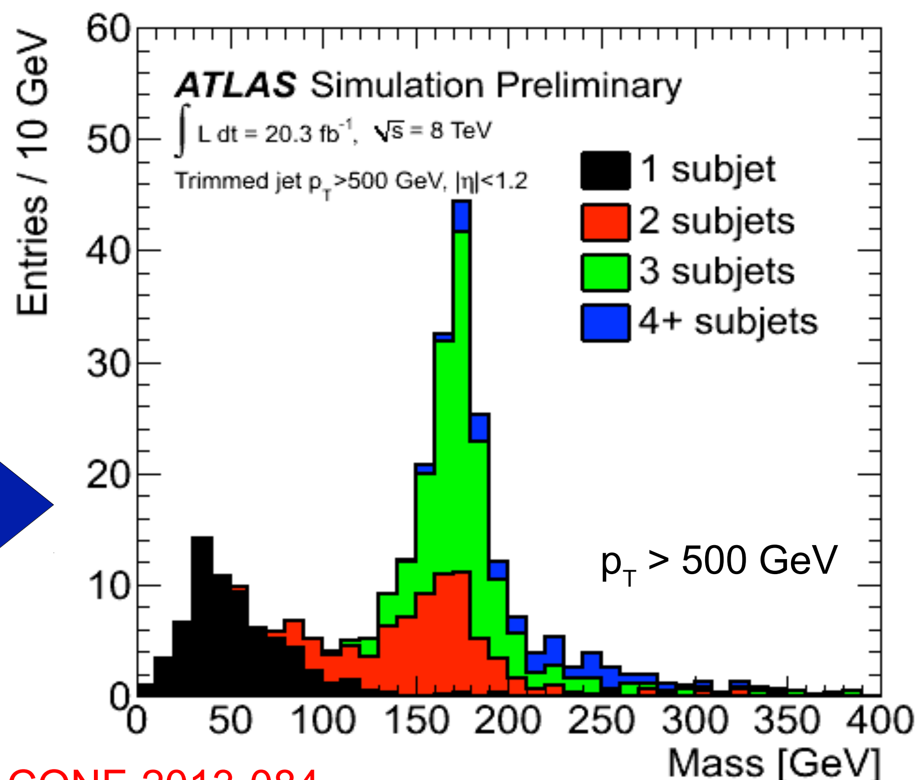
Clear peaks at m_W (non-contained), m_t (fully-contained).

Jet Mass ($n_{subjets}$)





- $n_{subjets}$ *after trimming*
- Expect distributions to be sensitive to f_{cut} (0.05) and R_{sub} (0.3)
- Top jets with three subjets have clear peak at m_t.
- At high p_T even two-subjet jets peak at m_t.



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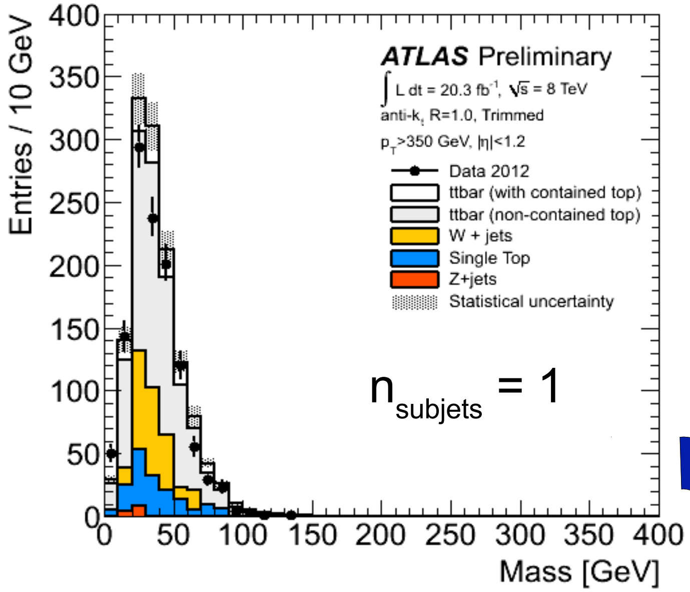
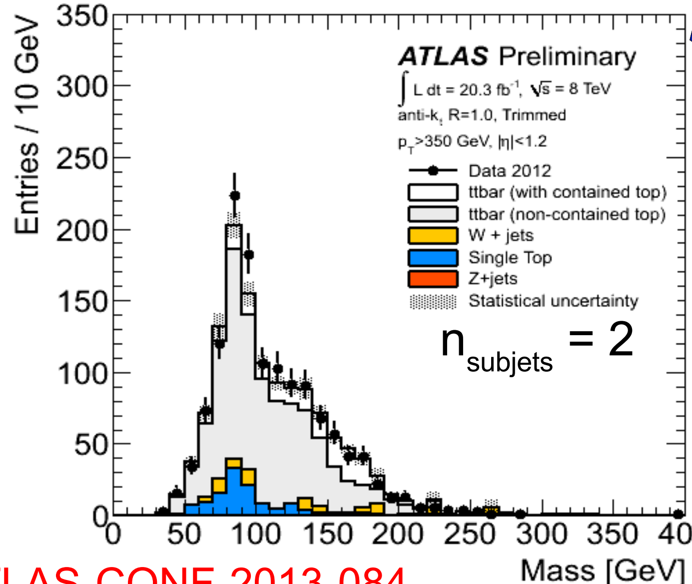
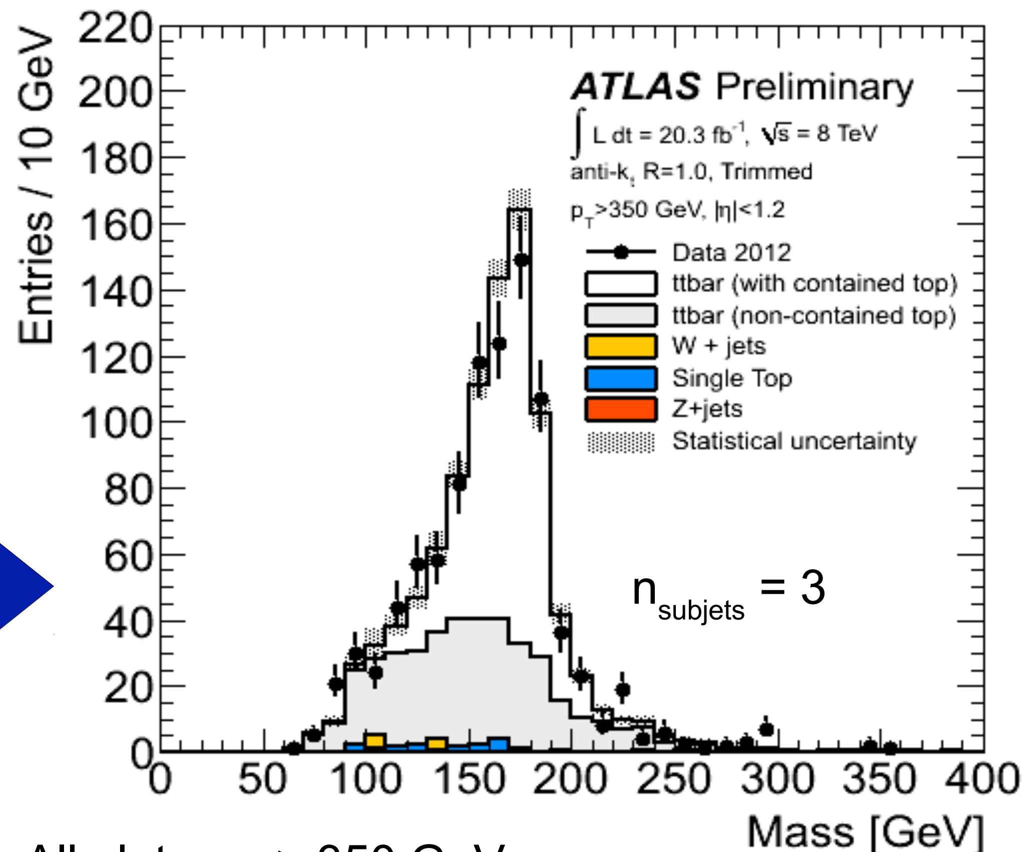
Jet Mass ($n_{subjets}$)



- Nice peak at top mass in 3 subjet bin and at W mass in 2 subjet bin.
- Backgrounds mostly in 1 subjet bin.
- Recall: JMS uncertainty 4-5%





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All plots: $p_T > 350$ GeV

k_t Splitting Scales

- k_t splitting scales are determined by reclustering jet constituents using the k_t algorithm
- $\sqrt{d_{ij}} = \min(p_{\mathrm{T}i}, p_{\mathrm{T}j}) \times \Delta R_{ij}$
- Subjets in the last step of clustering correspond to d_{12}, those in the second-to-last to d_{23}, etc.
- $d_{12} \sim (m/2)^2$

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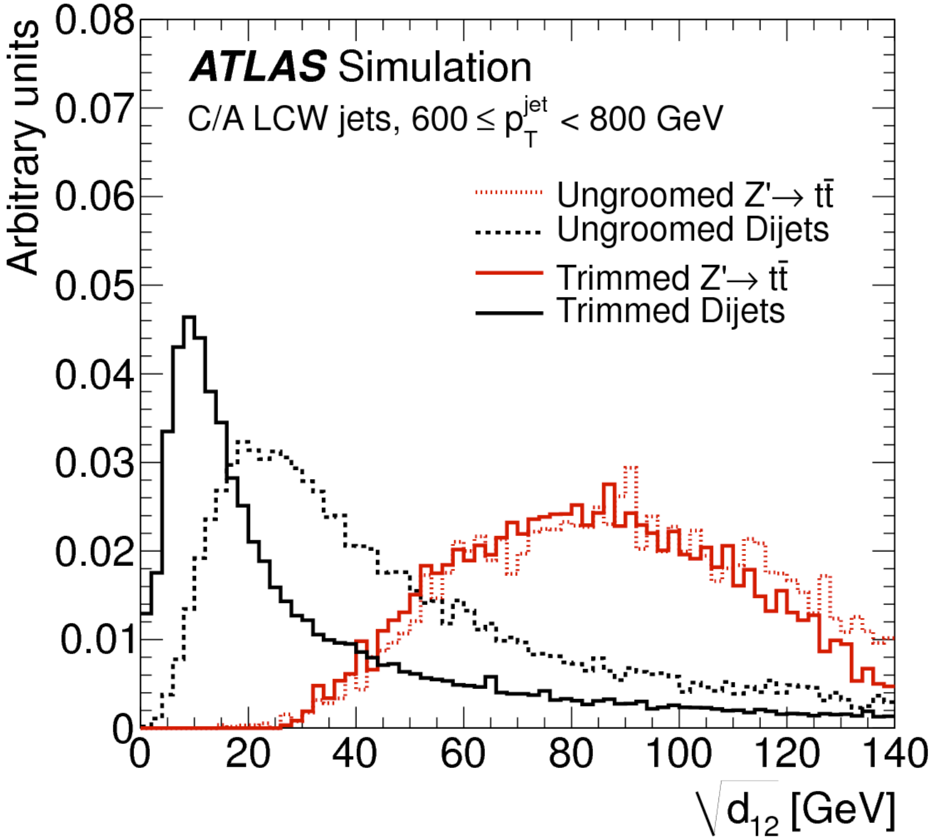
(arXiv:1306.4945)



k_t Splitting Scales

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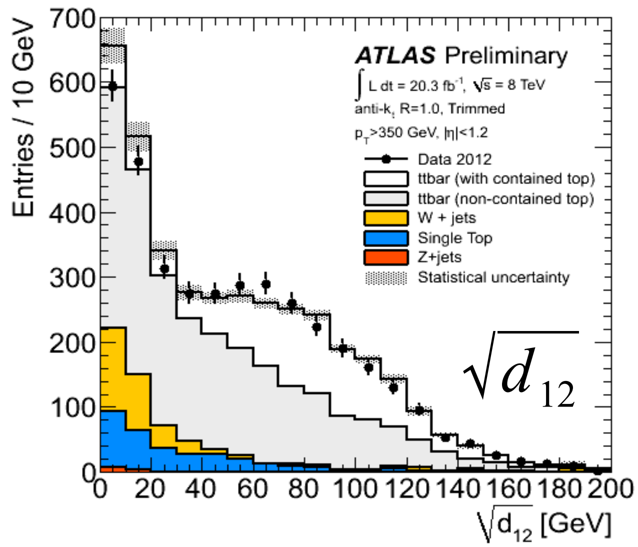
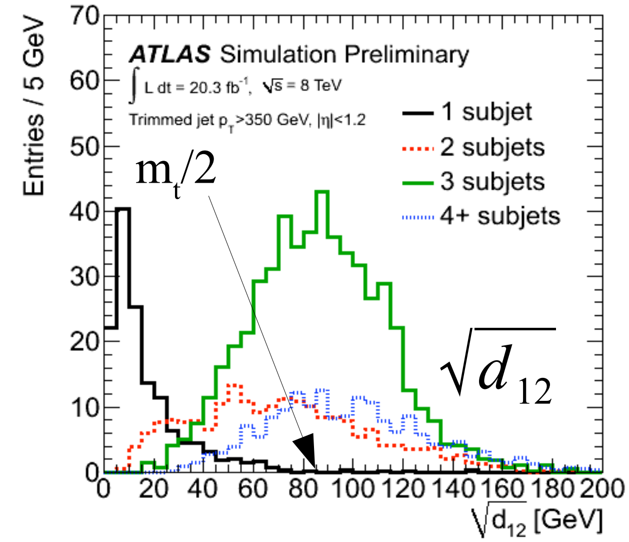
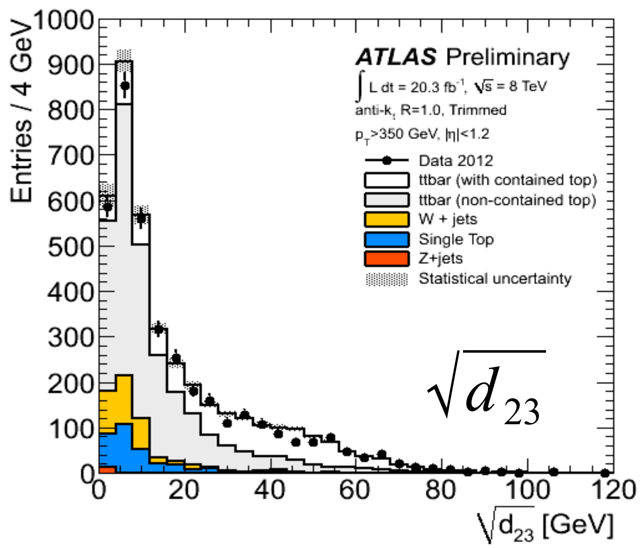
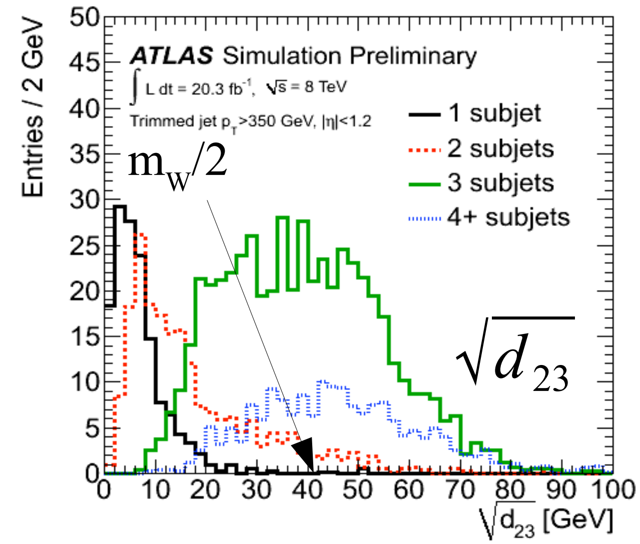




Only fully contained top events





N-subjettiness

- N-subjettiness (τ_N) corresponds to how well a jet can be described as containing N or fewer k_T subjets.
- Ratios (τ_N/τ_M) are denoted τ_{NM}.
- Ratios particularly useful for QCD discrimination

$$\tau_N = \frac{1}{d_0} \sum_k p_{Tk} \times \min(\Delta R_{1k}, \Delta R_{2k}, ..., \Delta R_{Nk})$$

$$d_0 \equiv \sum_k p_{Tk} \times R \qquad (\beta=1)$$

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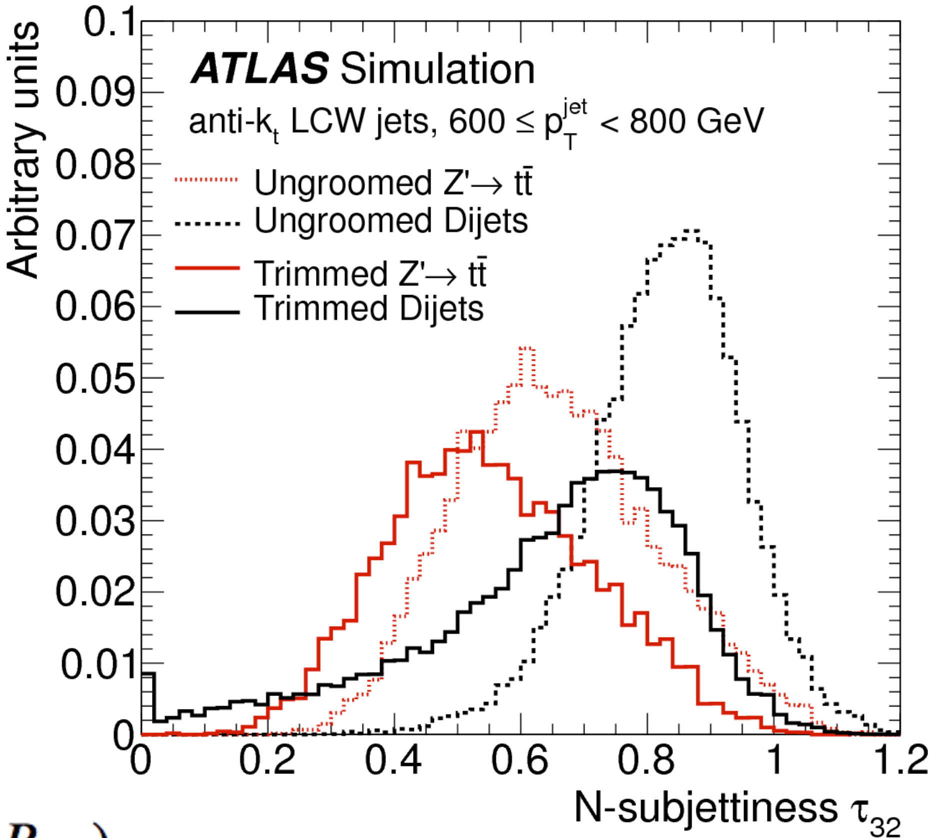

← 3 subjet-like

N-subjettiness

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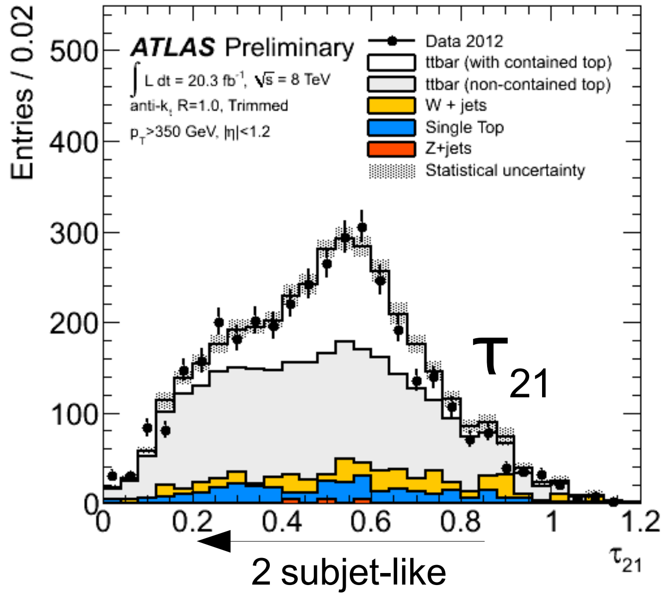

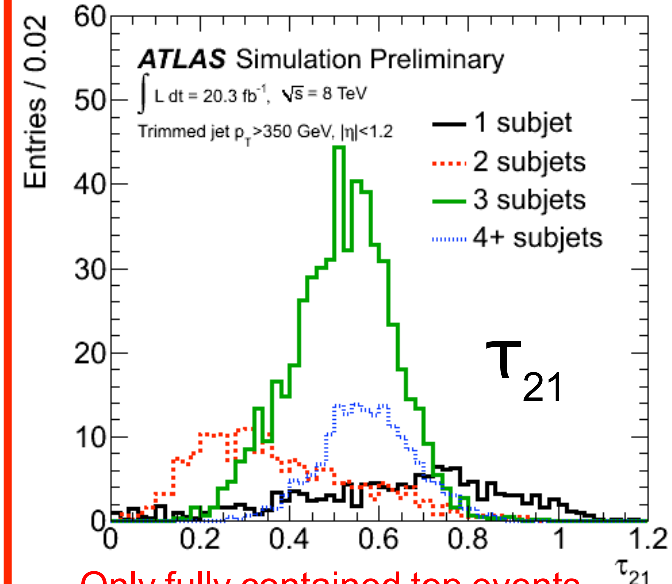

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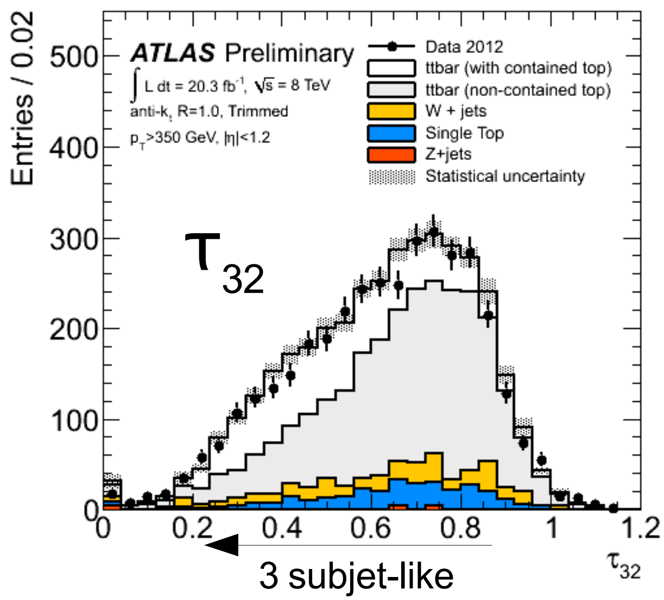

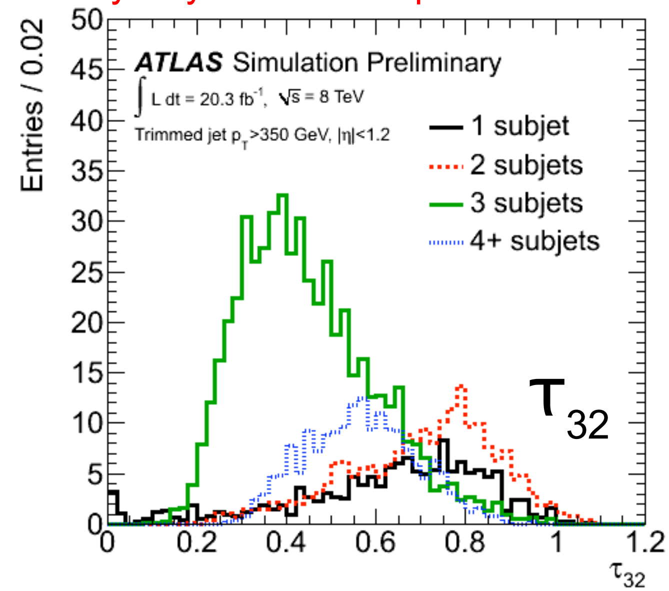

HEPTopTagger

- HTT algorithm identifies the hard substructure of a C/A jet and tests it for compatibility with top decay pattern.
- C/A R=1.5 jets with $p_T > 200$ GeV
- 3 main steps in procedure:

1) Undo C/A clustering until $m_i < m_{cut}$ or no clustering history (substructure objects)

2) Test combinations of 3 substructure objects for compatibility with a hadronic top quark decay

parameter	default value	tight	loose
m_{cut}	50 GeV	30 GeV	70 GeV
$R_{\text{filt}}^{\text{max}}$	0.3	0.2	0.5
N_{filt}	5	4	7
f_W	±15%	±10%	±20%

3) Apply kinematic cuts, e.g. W-mass window cut.

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HEPTopTagger

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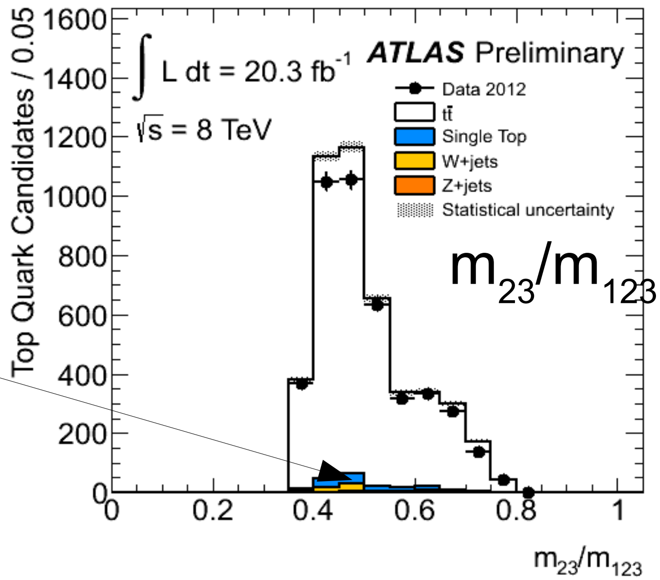
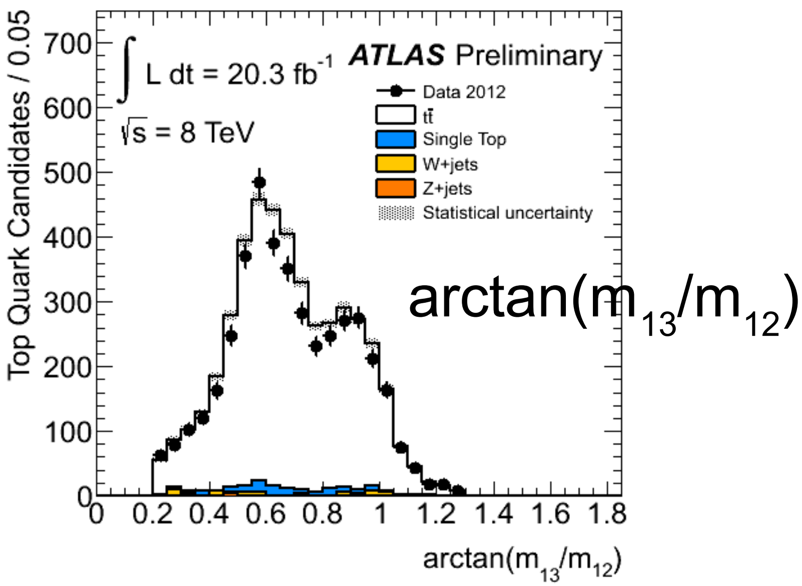
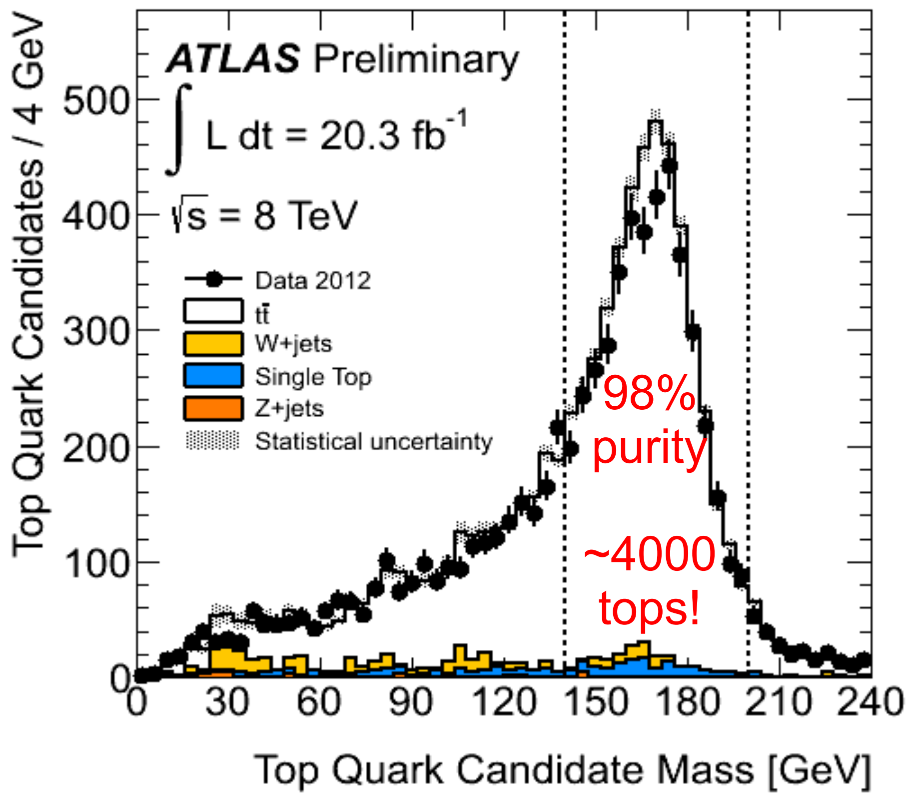
C/A R=1.5 jets with p_T > 200 GeV after $W \rightarrow \mu\nu$ preselection and default HEPTopTagger criteria

m_W/m_t



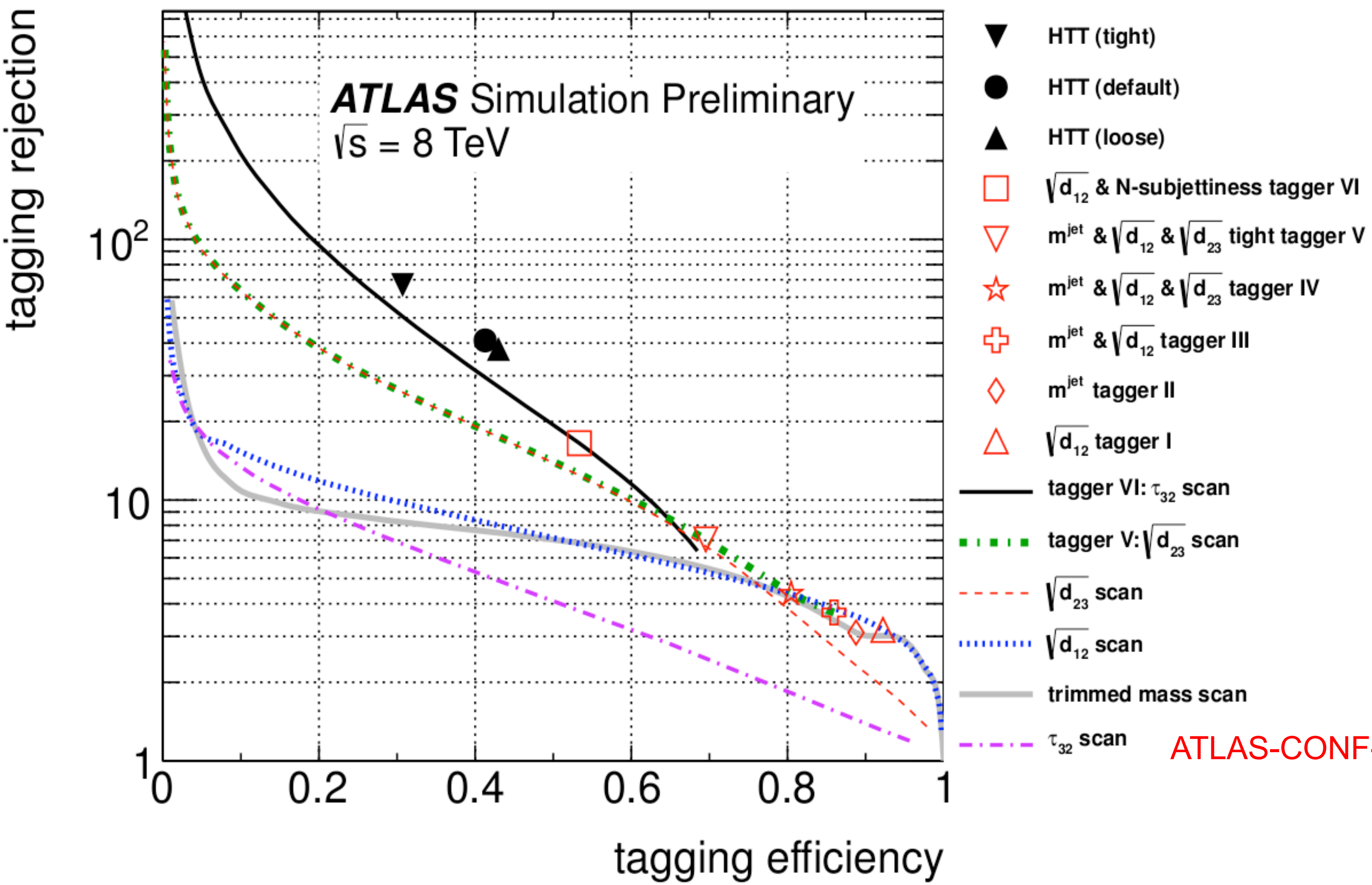




Top Tagger Comparison

- We studied top jet efficiency vs rejection for a variety of top "taggers."
  - Cuts on jet mass, k_t-splitting scales, N-subjettiness
  - HEPTopTagger
- Preselection:
  - Truth-level C/A R=1.2 jet and anti-k_t R=1.0 jet with p_T > 150 GeV and $|\eta| < 1.2$
  - Corresponding ΔR-matched reconstructed C/A and anti-k_t jets with p_T > 550 GeV
  - Reconstructed C/A and anti-k_t jets within $\Delta R < 0.75$
- Signal jets from 1.75 TeV Z' → tt
- Background jets from dijet with leading anti-k_t 0.6 jet 500 < p_T < 1000 GeV
- Efficiency/rejection curves derived on a jet-by-jet basis, **not** event-by-event.
- HTT not optimized for C/A 1.2 jets and p_T > 550 GeV!

Top Tagger Comparison



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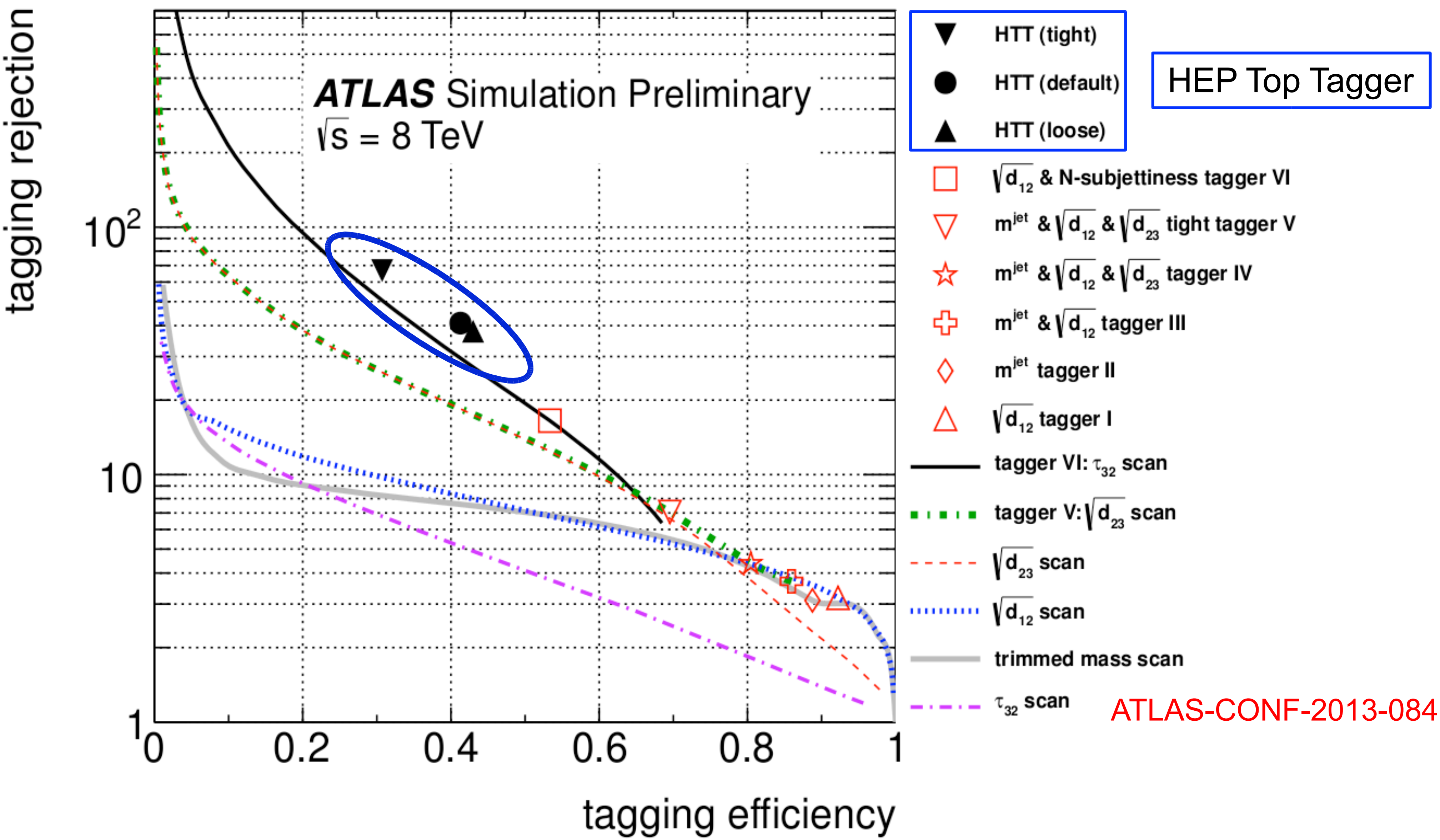
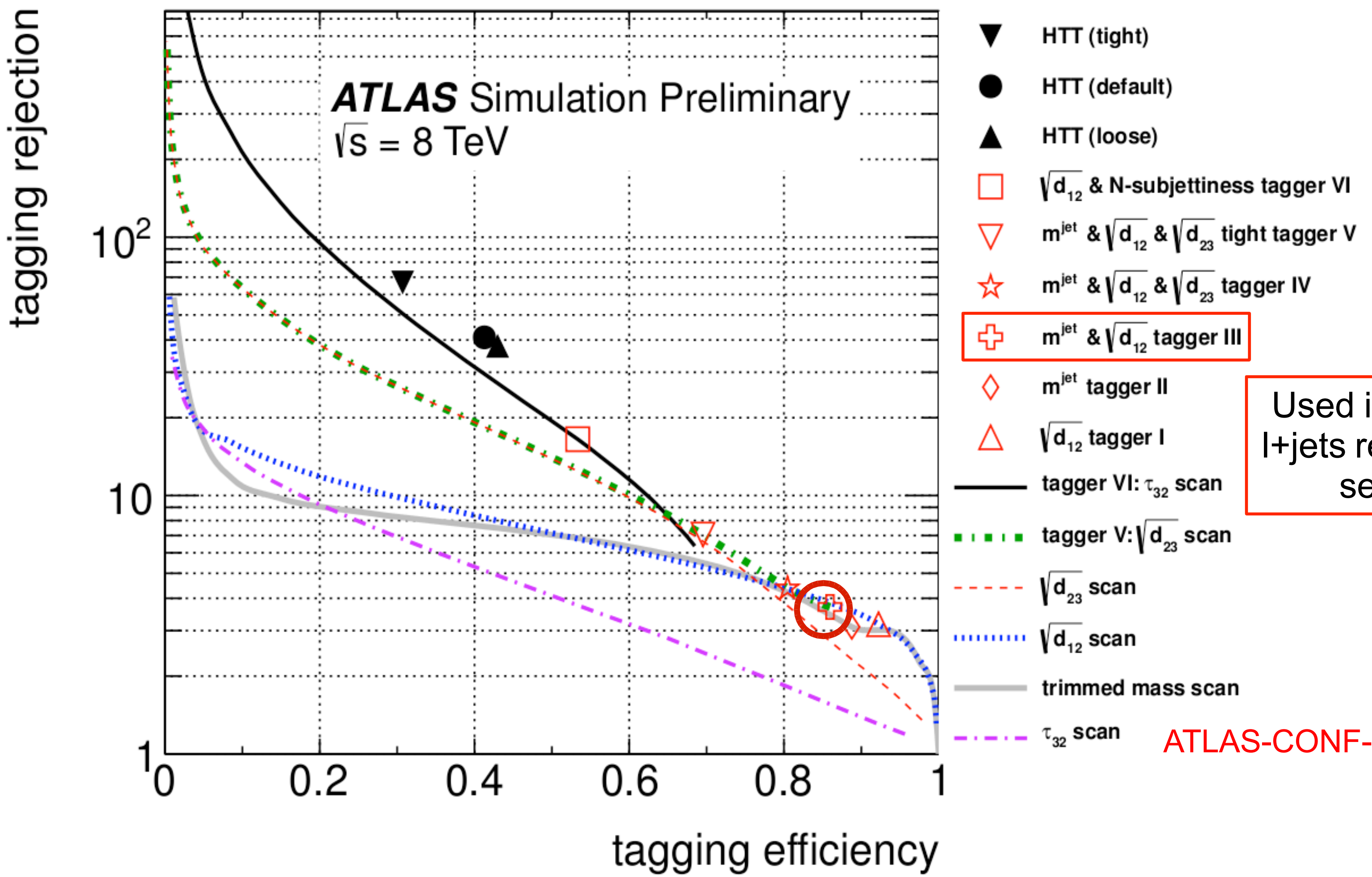
Top Taggers

- substructure tagger I: $\sqrt{d_{12}} > 40$ GeV
- substructure tagger II: trimmed anti-k_t $R = 1.0$ mass $m^{\mathrm{jet}} > 100$ GeV
- substructure tagger III: $m^{\mathrm{jet}} > 100$ GeV, $\sqrt{d_{12}} > 40$ GeV.
- substructure tagger IV: $m^{\mathrm{jet}} > 100$ GeV, $\sqrt{d_{12}} > 40$ GeV, $\sqrt{d_{23}} > 10$ GeV
- substructure tagger V: $m^{\mathrm{jet}} > 100$ GeV, $\sqrt{d_{12}} > 40$ GeV, $\sqrt{d_{23}} > 20$ GeV
- substructure tagger VI: $\sqrt{d_{12}} > 40$ GeV, $0.4 < \tau_{21} < 0.9$, $\tau_{32} < 0.65$

Top Tagger Comparison



Top Tagger Comparison



Used in current l+jets resonance search

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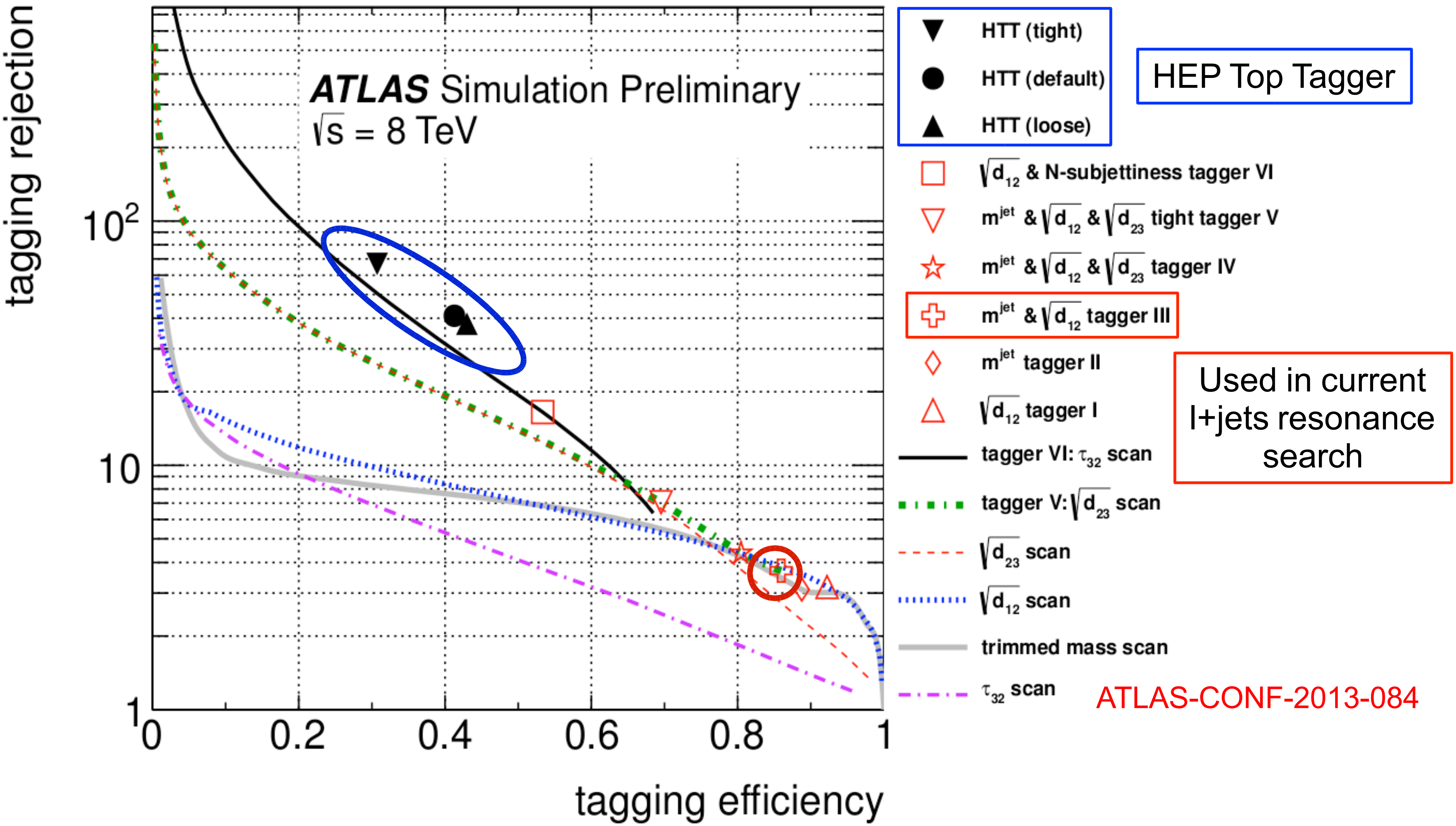
Top Tagger Comparison



We have a wide variety of taggers available for different analyses!

Conclusion and Outlook

- Jet mass, k_t splitting scales, and N-subjettiness have been studied on the full 2012 ATLAS dataset.
- There is good agreement between data and MC in a sample enriched in top quarks from the 2012 data.
- These substructure variables have been incorporated into current analyses, and new variables are being studied and validated!
- We have derived detailed systematic uncertainties using different techniques and commissioned these techniques for physics.

Thank You

Backup Slides

Mass-drop filtering: step 1

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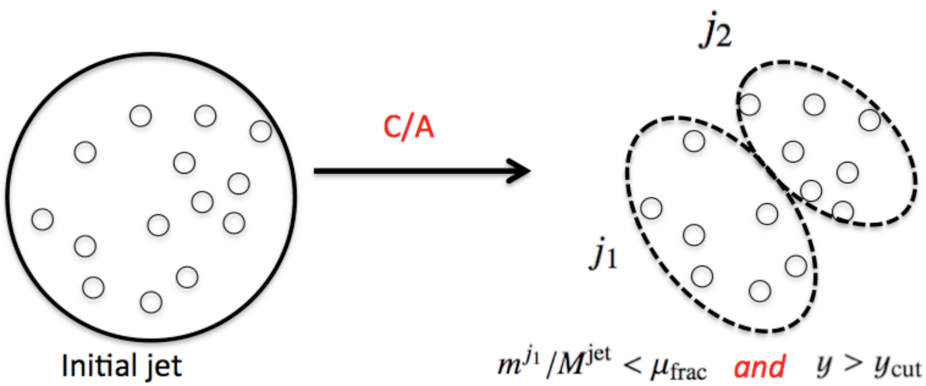
- Undo last stage of C/A clustering and order subjets by mass



- Require:
  - $m^{j_1}/m^{\rm jet} < \mu_{\rm frac}$
  - $\dfrac{\min[(p_{\rm T}^{j_1})^2, (p_{\rm T}^{j_2})^2]}{(m^{\rm jet})^2} \times \Delta R^2_{j_1,j_2} > y_{\rm cut}$
- Discard jet otherwise

Mass-drop Filtering: step 2

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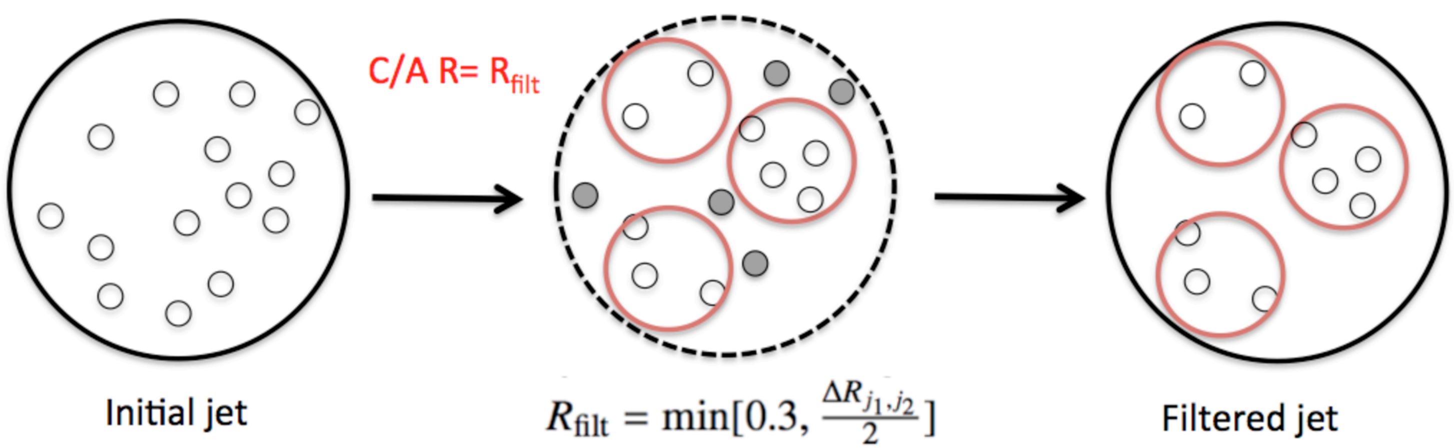
- j_1 and j_2 are reclustered using the C/A algorithm with radius parameter

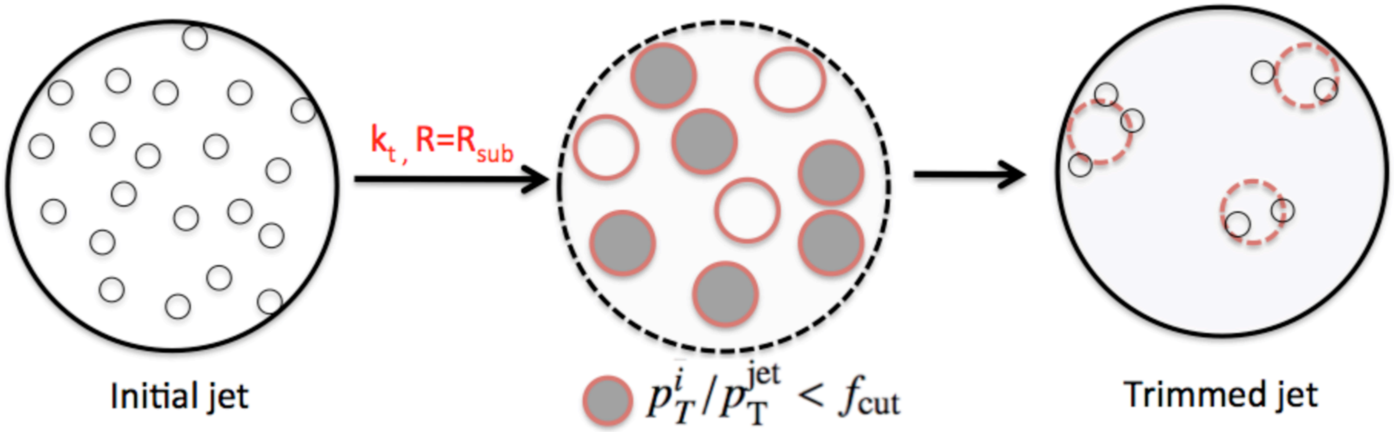
$$R_{\text{filt}} = \min[0.3, \Delta R_{j_1,j_2}/2]$$

- All but the three hardest subjets are discarded.
- This allows for a two-body decay + radiation in the jet



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

Trimming



- Recluster the jet using the k_t algorithm with R parameter R_{sub}.
- Any subjet whose p_T is less than f_{cut} times the jet's total p_T is removed.

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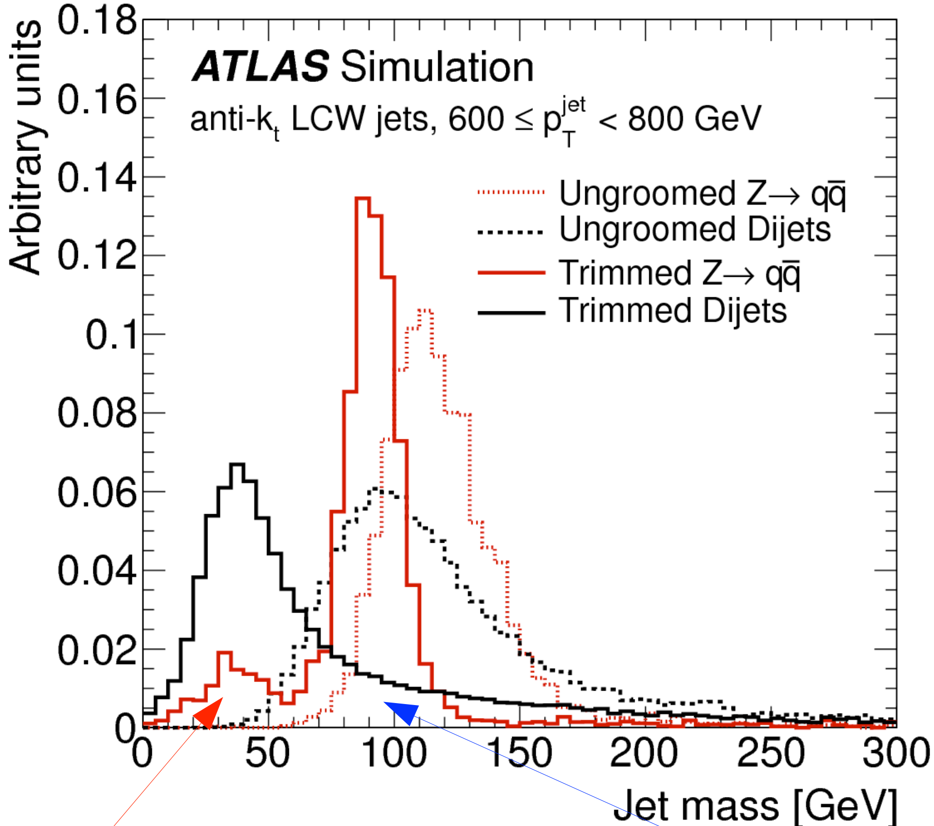
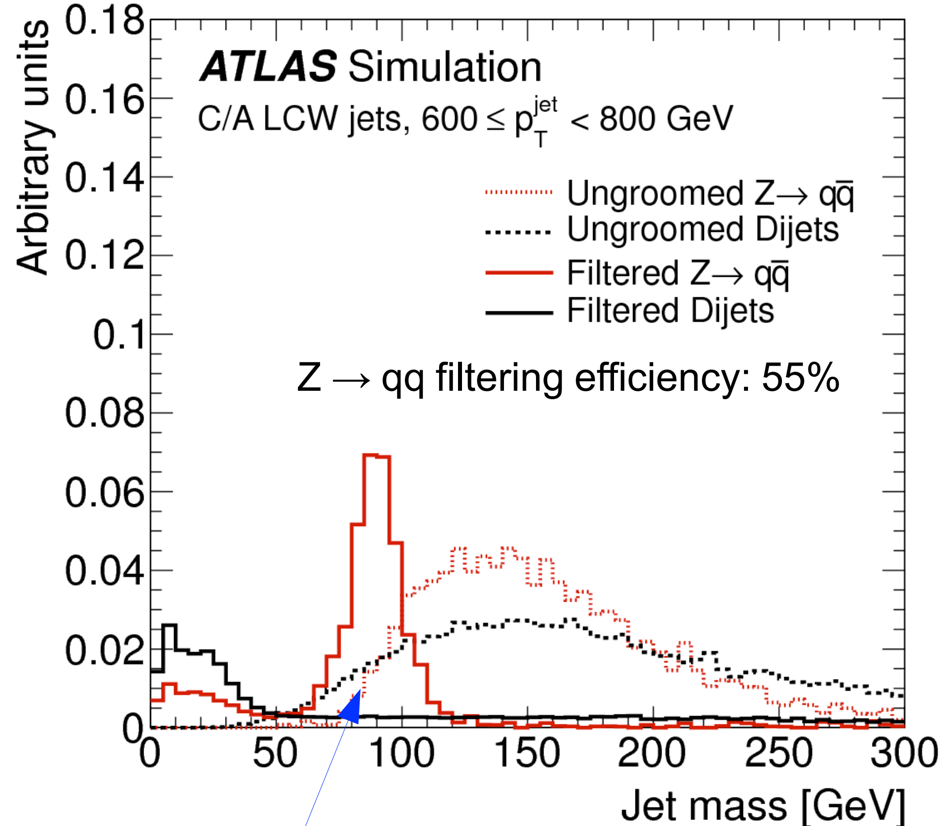
Jet Grooming

ATLAS-PERF-2012-02
(arXiv:1306.4945)

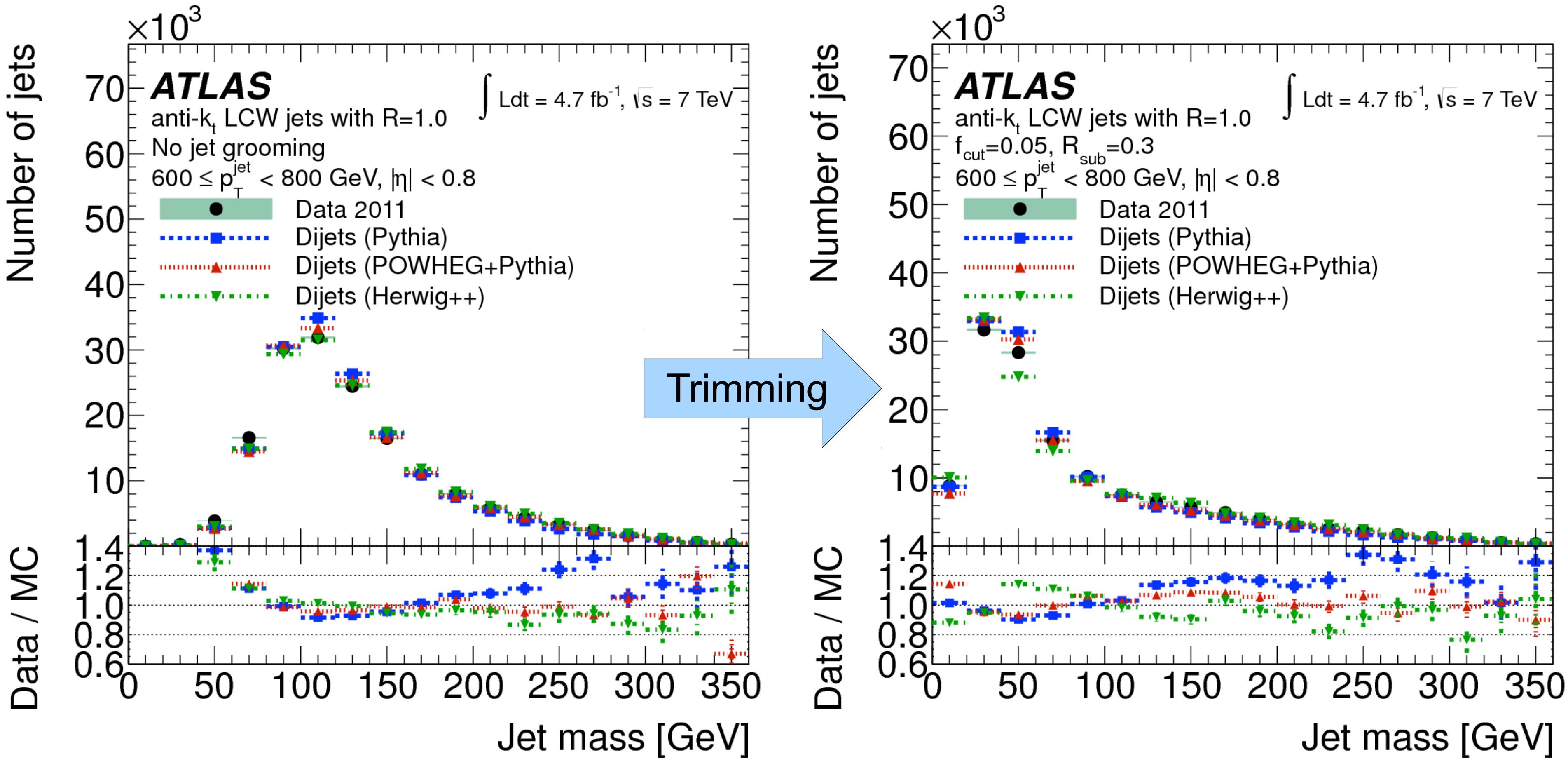




One quark removed
by grooming

Clear Z peak!

Jet Mass
Data/MC Comparison



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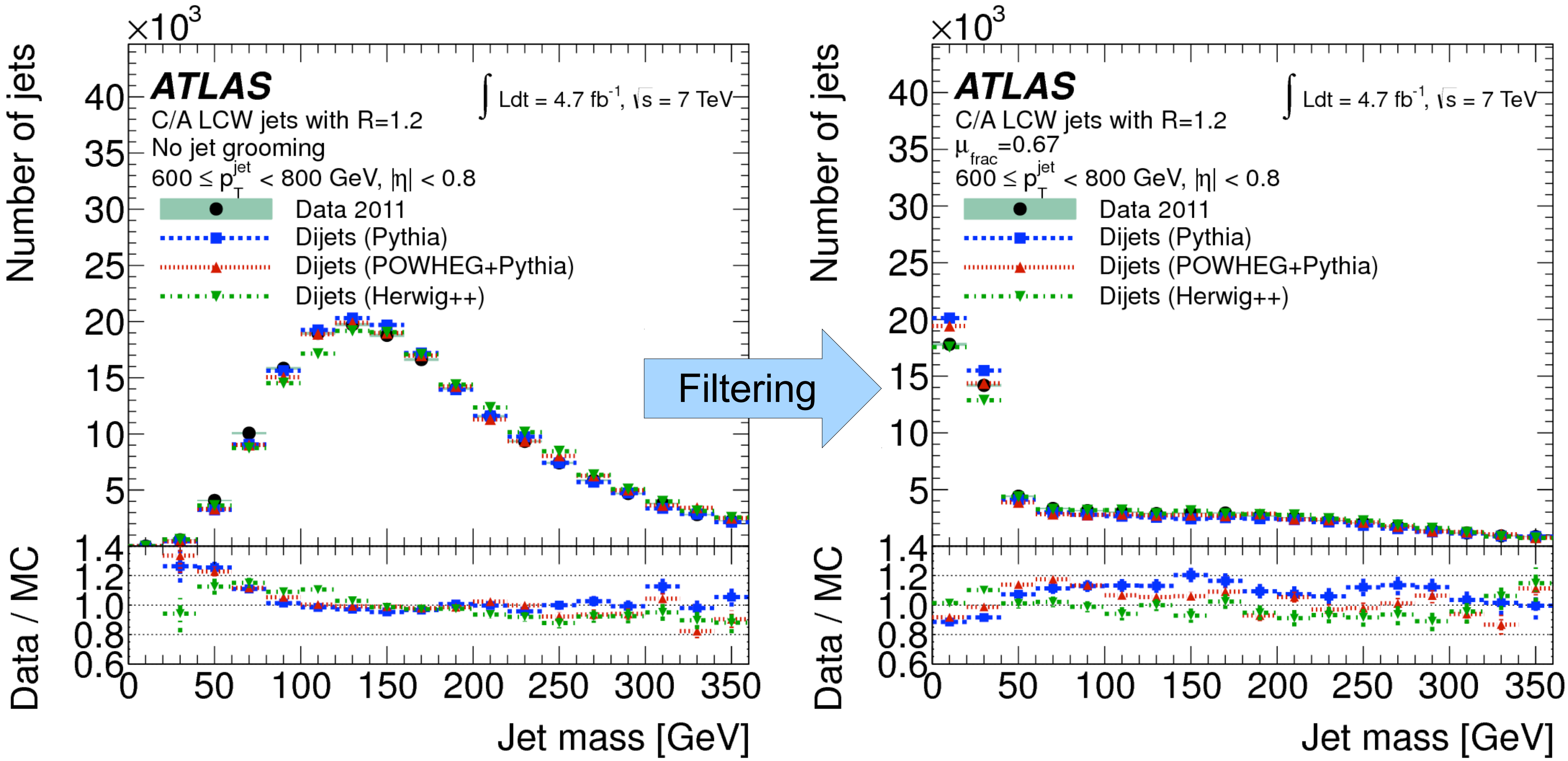
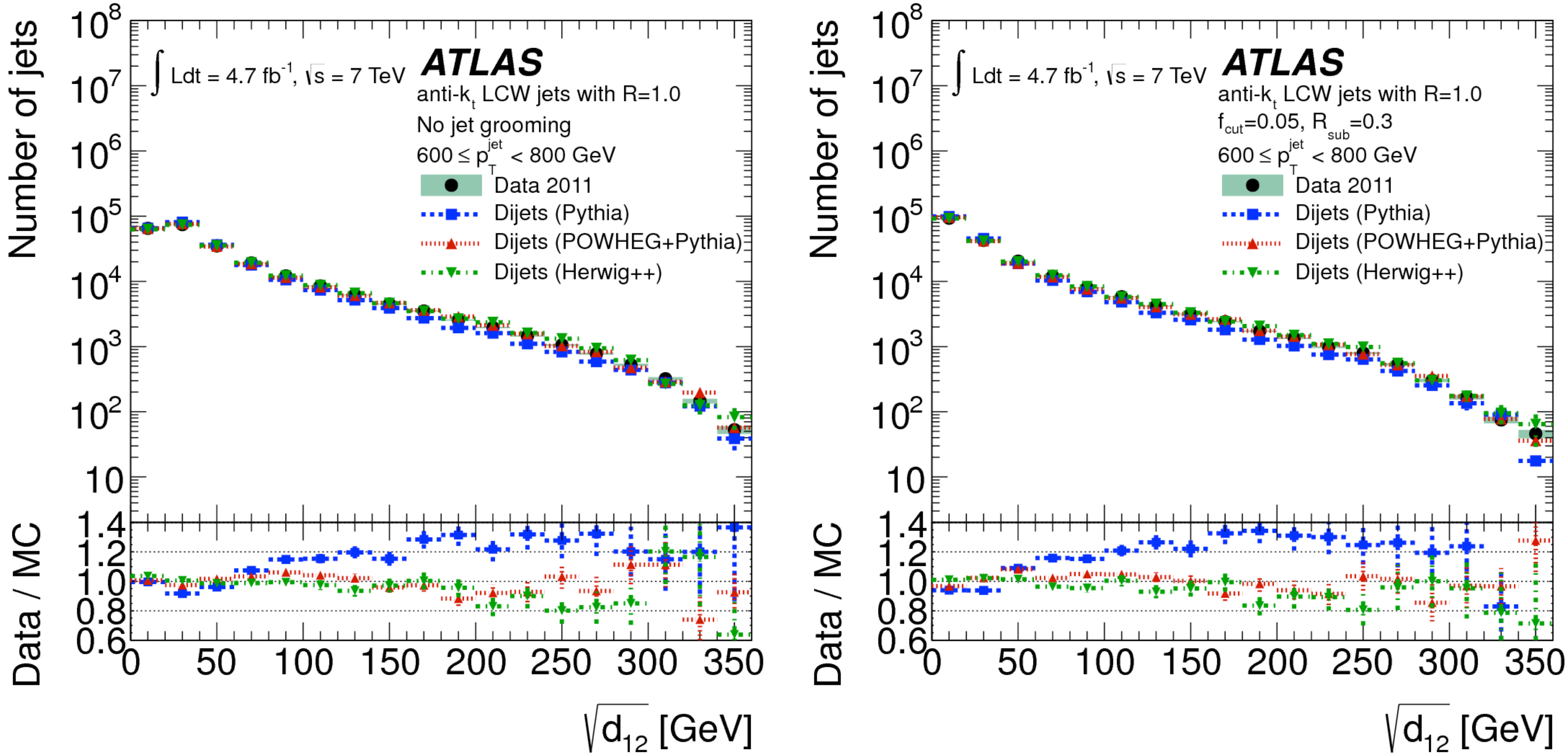
Jet Mass
Data/MC Comparison



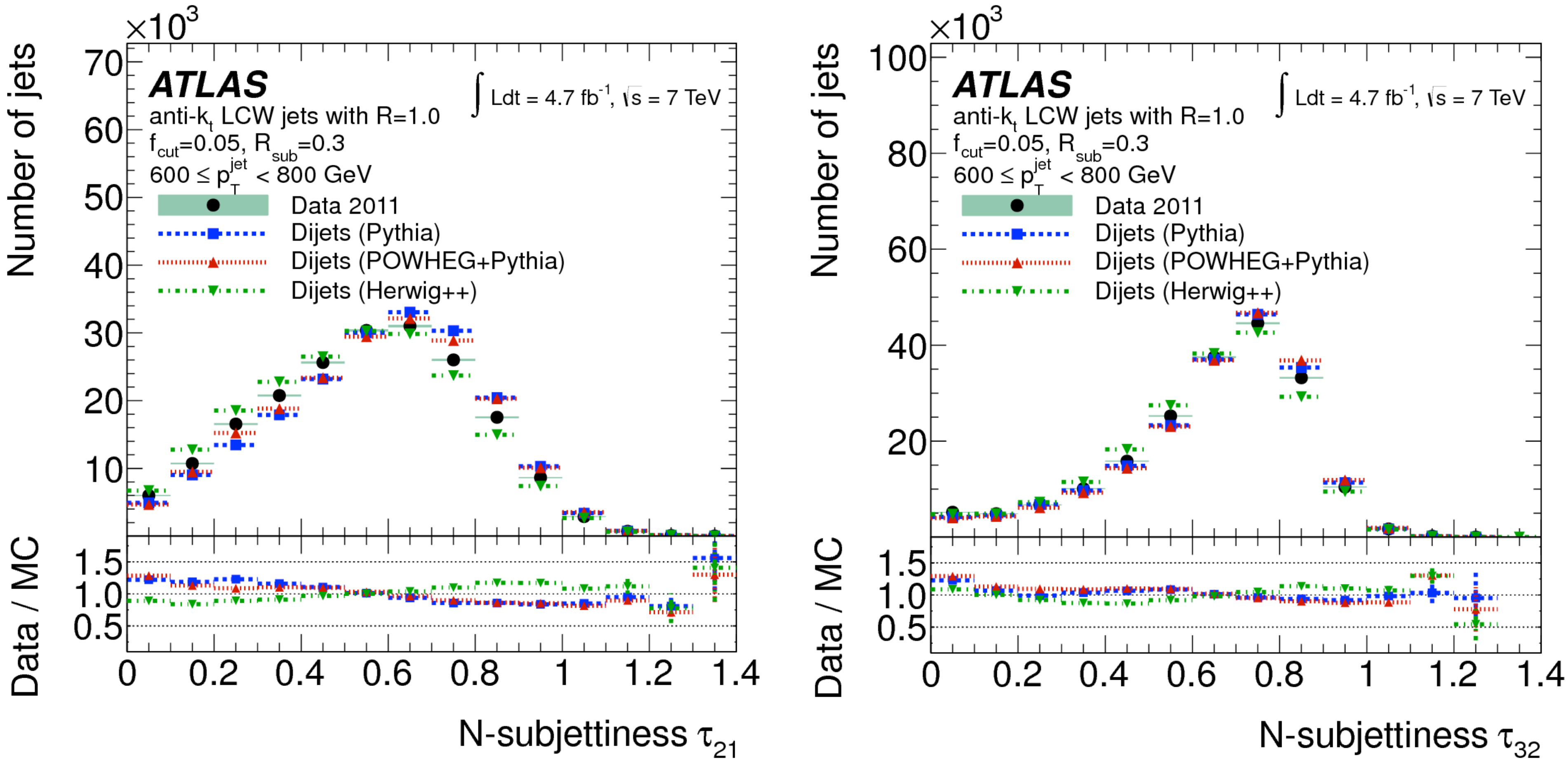
ATLAS-PERF-2012-02
(arXiv:1306.4945)

Splitting Scale $\sqrt{d_{12}}$ Data/MC Comparison



ATLAS-PERF-2012-02
(arXiv:1306.4945)

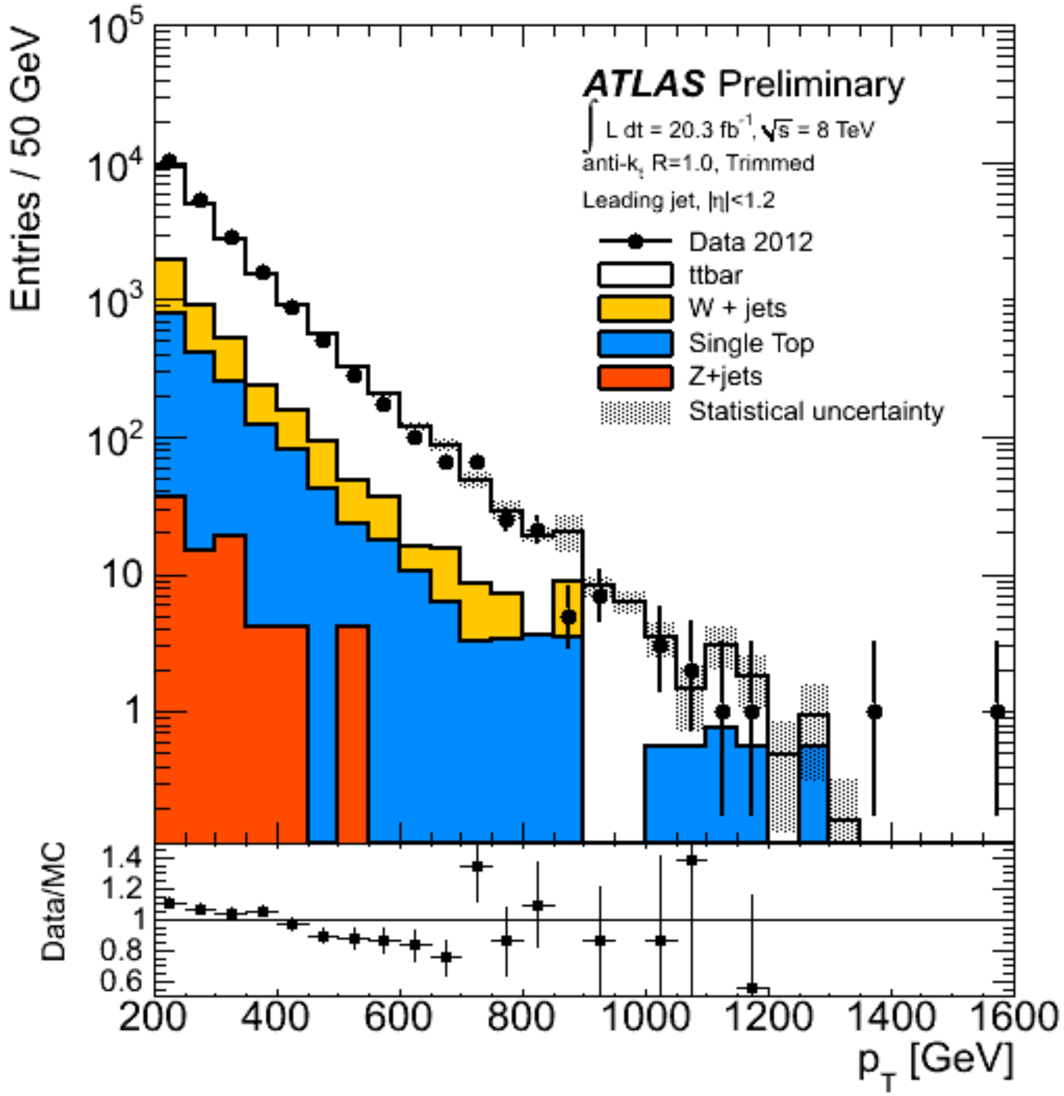
N-subjettiness Data/MC Comparison



ATLAS-PERF-2012-02
(arXiv:1306.4945)

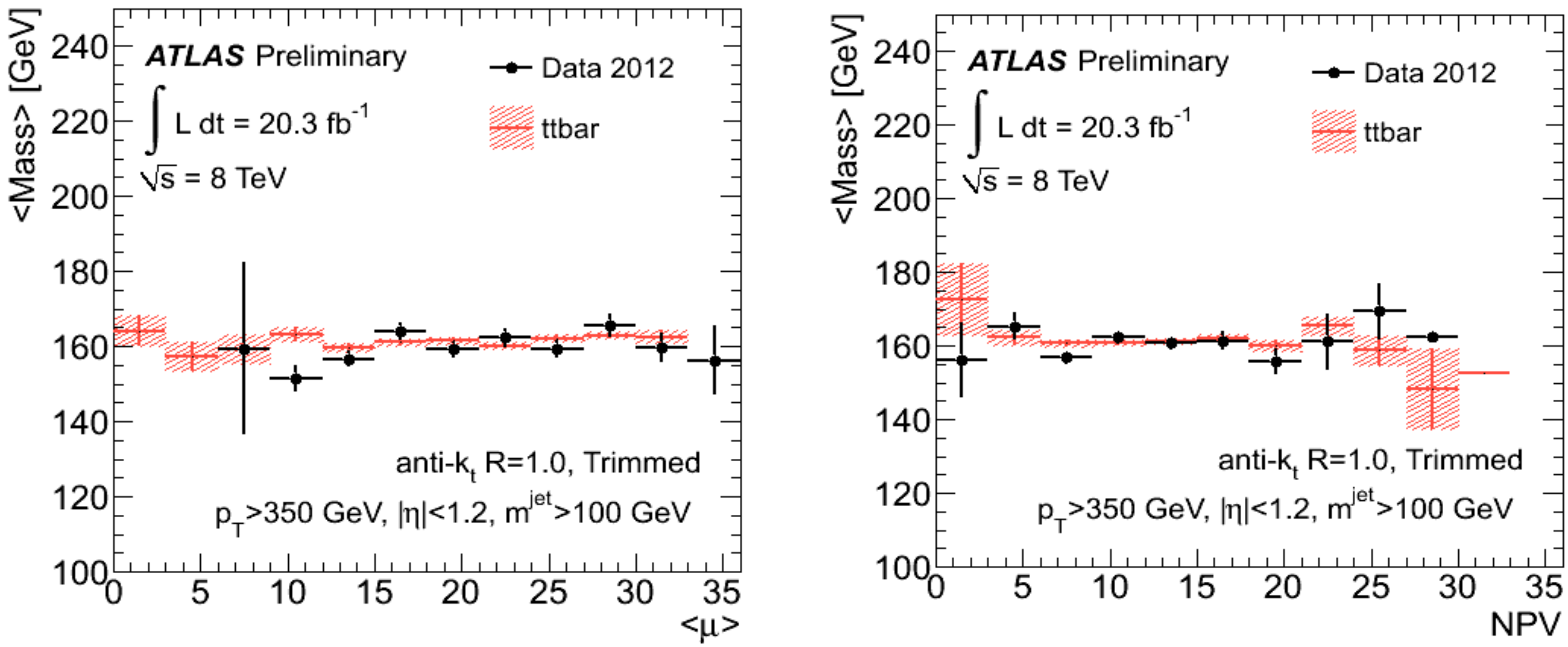
Jet p_T Spectrum

ATLAS-CONF-2013-084



Jet Mass (<μ> and NPV)

ATLAS-CONF-2013-084

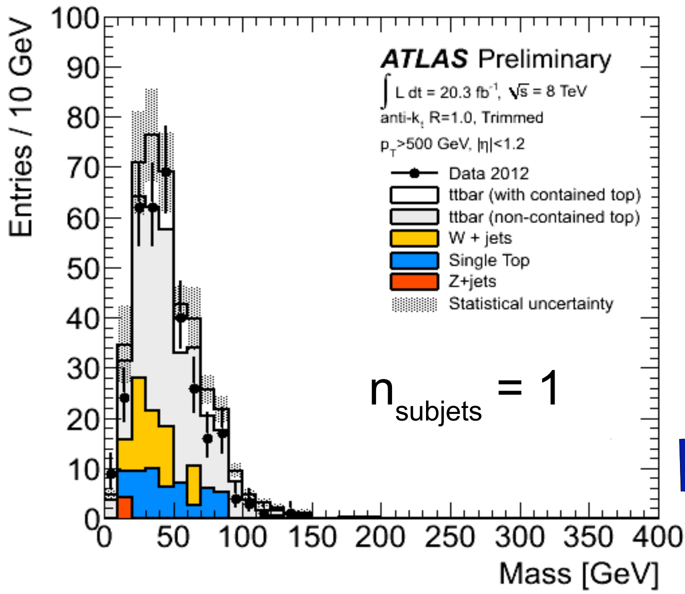


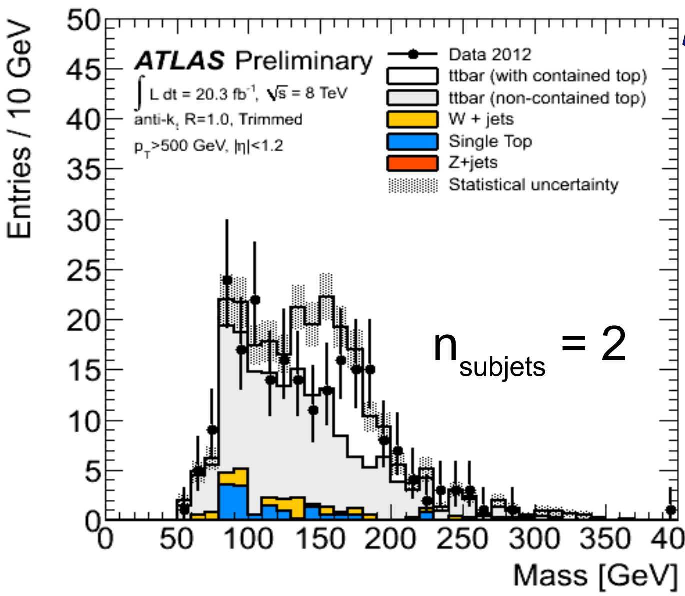
Response fairly flat in both <μ> and NPV

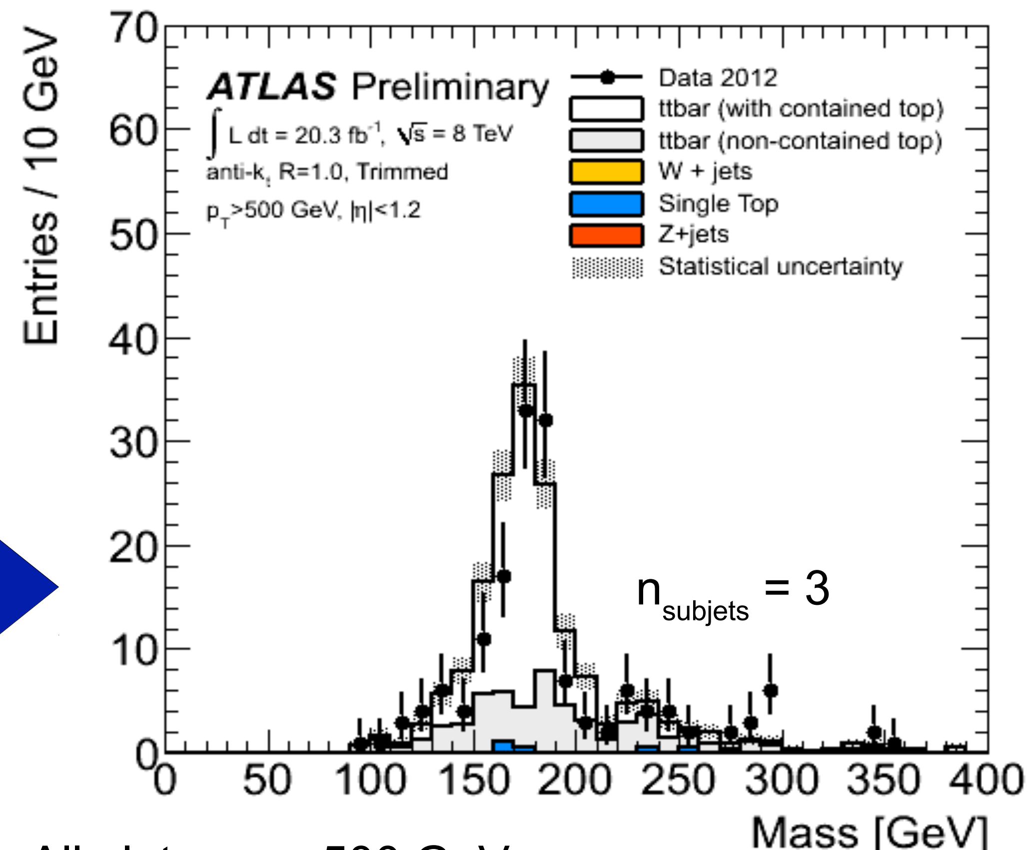
Data and MC in ~good agreement

Jet Mass ($n_{subjets}$)

ATLAS-CONF-2013-084



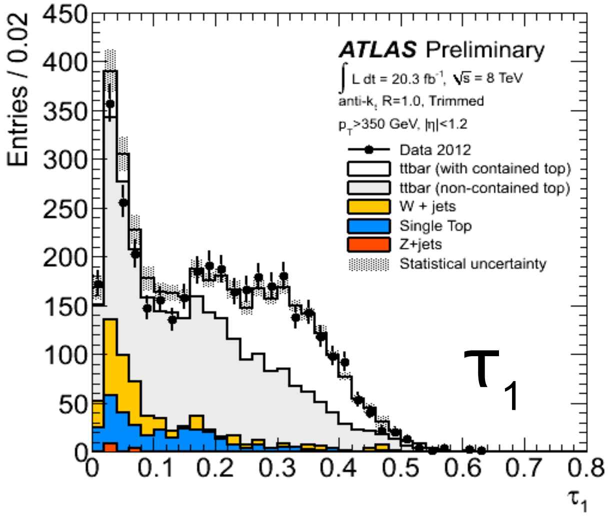


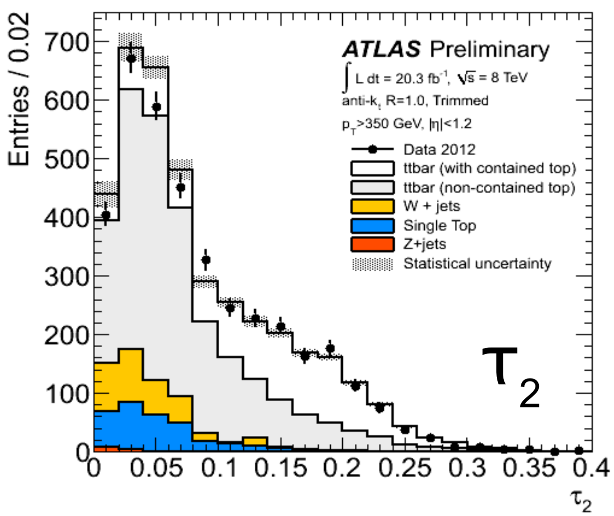


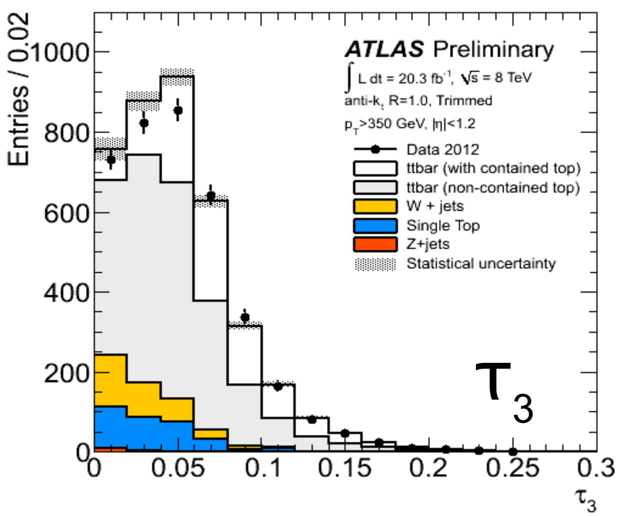
All plots: p_T > 500 GeV

N-subjettiness

ATLAS-CONF-2013-084

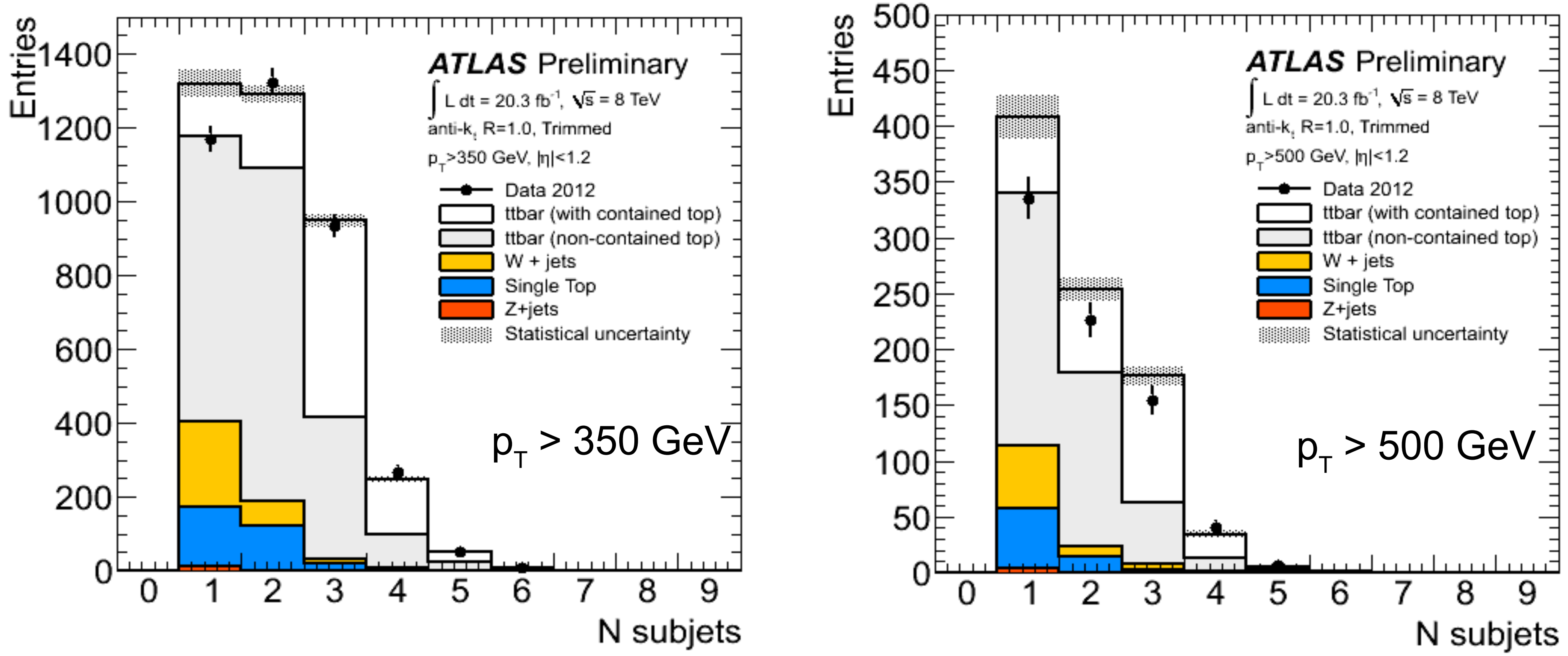






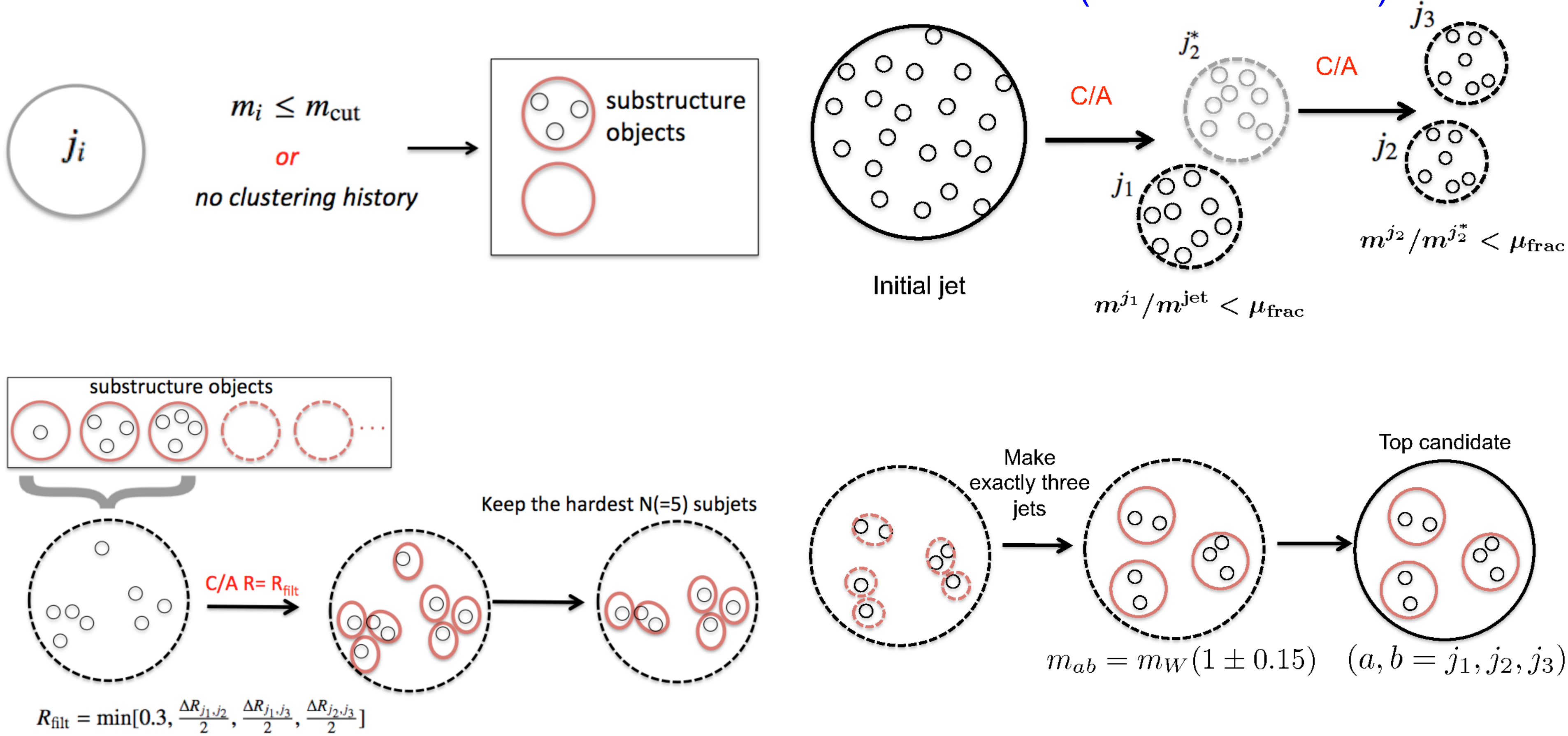
$n_{subjets}$

ATLAS-CONF-2013-084



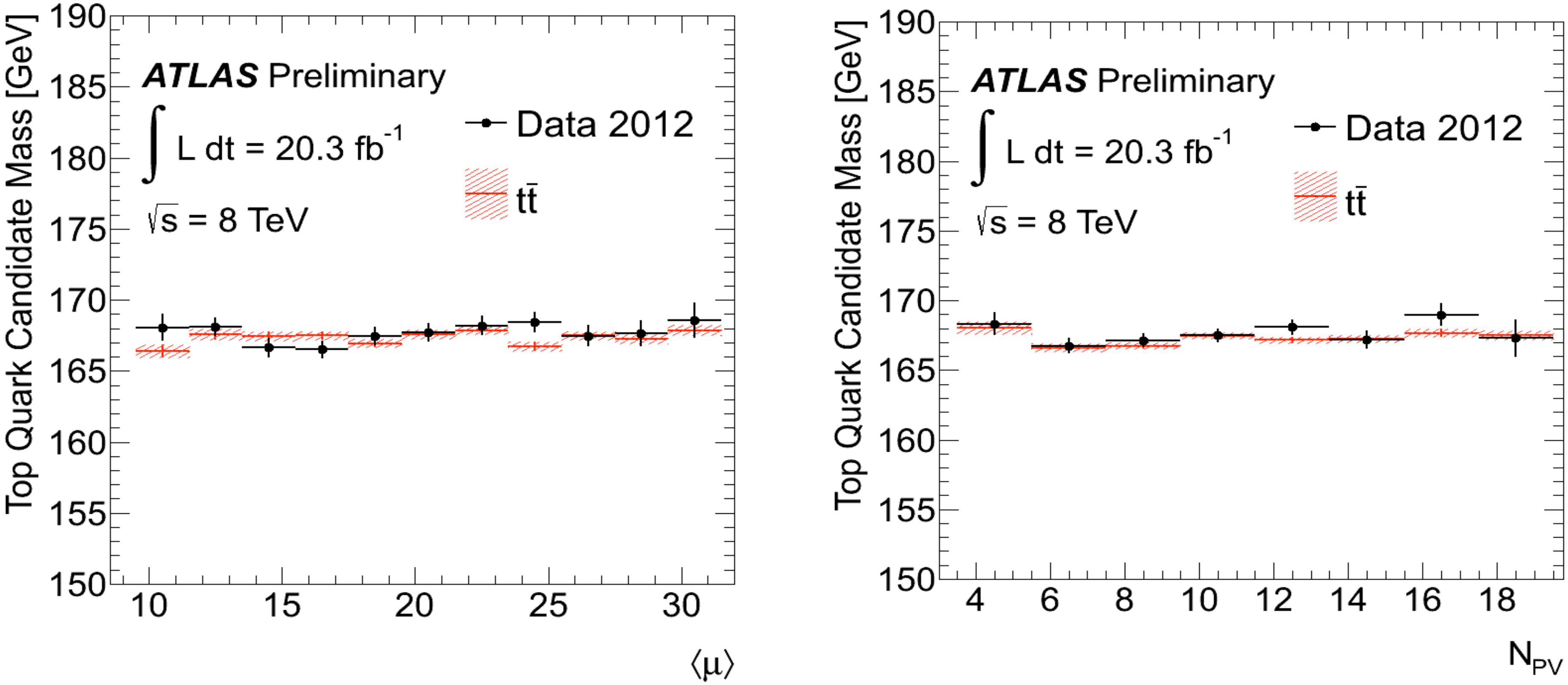
HEP Top Tagger

ATLAS-PERF-2012-02
(arXiv:1306.4945)



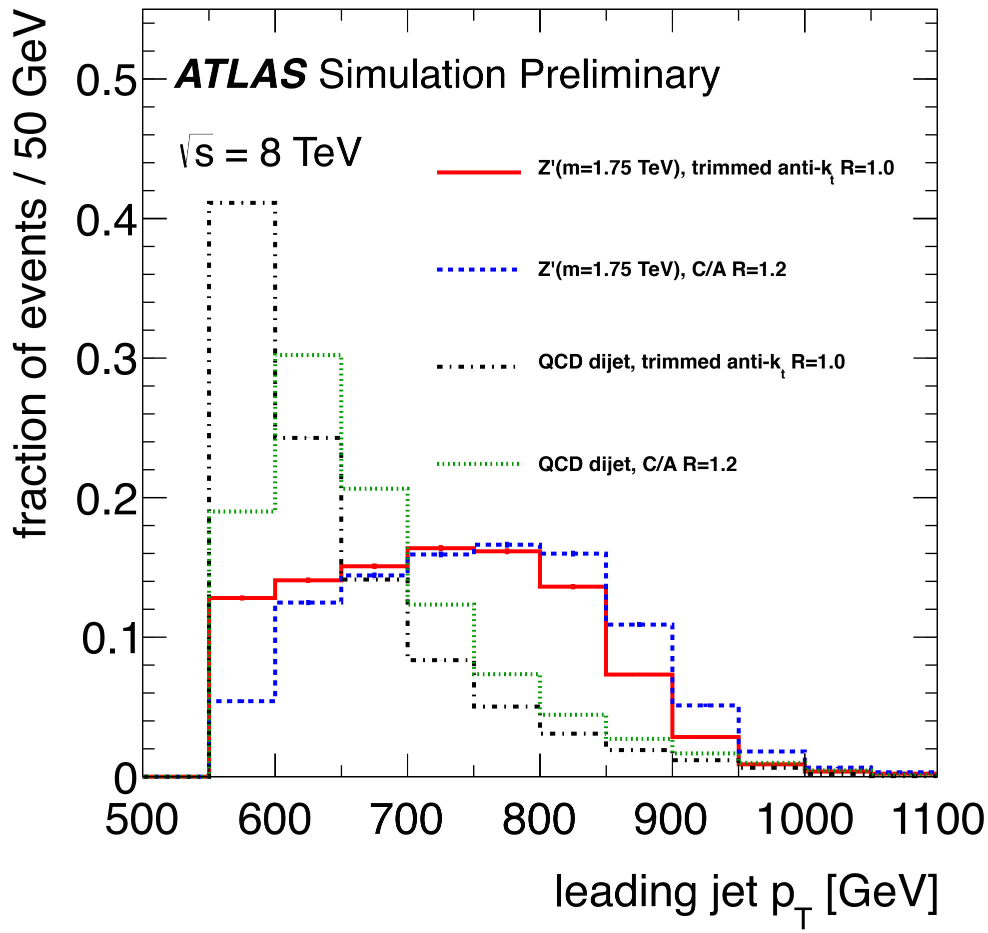
Jet Mass (<μ> and NPV) HEPTopTagger

ATLAS-CONF-2013-084



Response fairly flat in both <μ> and NPV
Data and MC in ~good agreement

Top Taggers



ATLAS Simulation Preliminary
√s = 8 TeV
Z'(m=1.75 TeV), trimmed anti-k$_t$ R=1.0
Z'(m=1.75 TeV), C/A R=1.2
QCD dijet, trimmed anti-k$_t$ R=1.0
QCD dijet, C/A R=1.2
fraction of events / 50 GeV
0
0.1
0.2
0.3
0.4
0.5
500
600
700
800
900
1000
1100
leading jet p$_T$ [GeV]