Precision measurements of jet substructure and fragmentation at ATLAS

Jason Veatch
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(AG Lai)

on behalf of the ATLAS collaboration

Bundesministerium für Bildung und Forschung

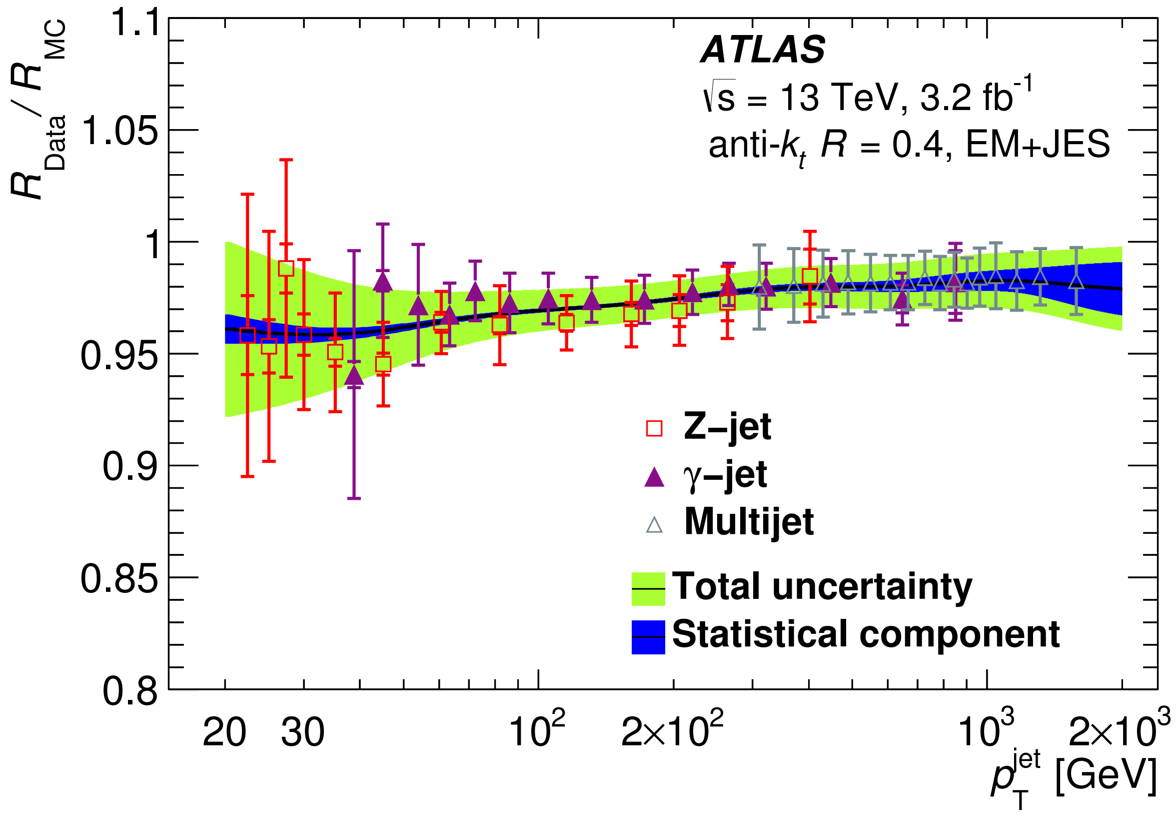
BMBF-Forschungsschwerpunkt ATLAS-EXPERIMENT
Physik bei höchsten Energien mit dem ATLAS-Experiment am LHC
FSP 103 ATLAS

Introduction

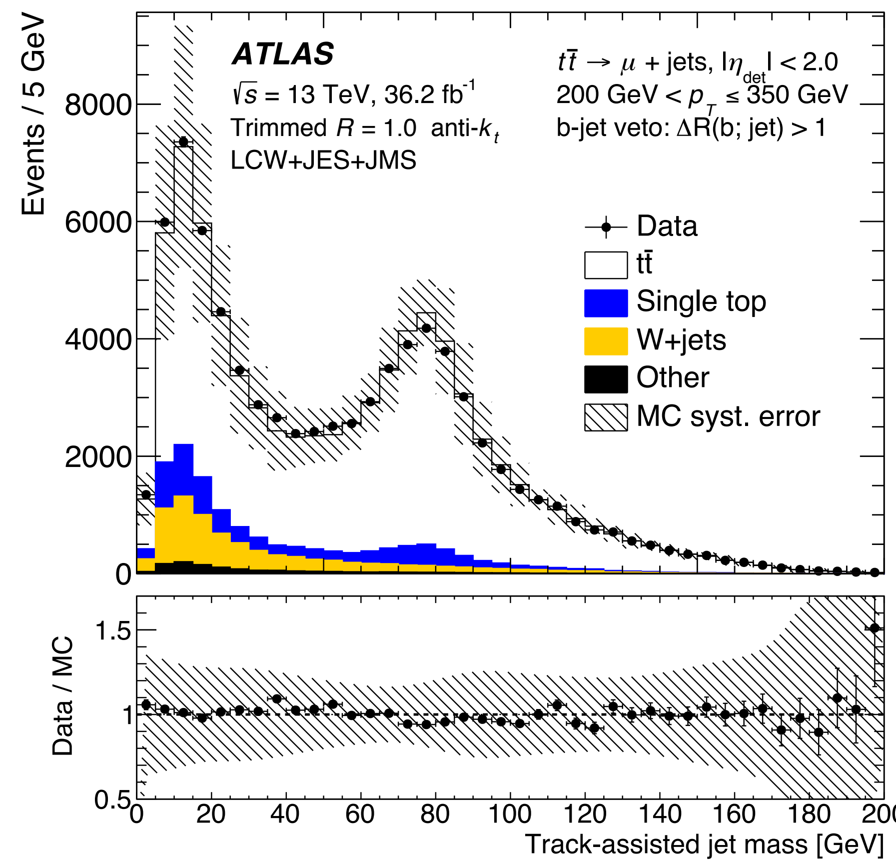
- We are in the era of precision jet property measurements
  - We can now probe QCD predictions at higher order
- Excellent jet reconstruction/calibration techniques allow precise measurements
- New techniques are available to accurately probe jet formation and shape
- Measurements in this talk:
  - Jet fragmentation: ATLAS-STDM-2017-16
  - Soft-Drop mass: Phys. Rev. Lett. 121 (2018) 092001
  - Jet shape observables: arXiv:1903.02942
  - g→bb properties: Phys. Rev. D 99 (2019) 052004

Jet calibration performance

- Jet energy scale and mass scale need to be calibrated
- In situ techniques can be used to provide great performance



Phys. Rev. D 96 (2017) 072002



Eur. Phys. J. C 79 (2019) 135

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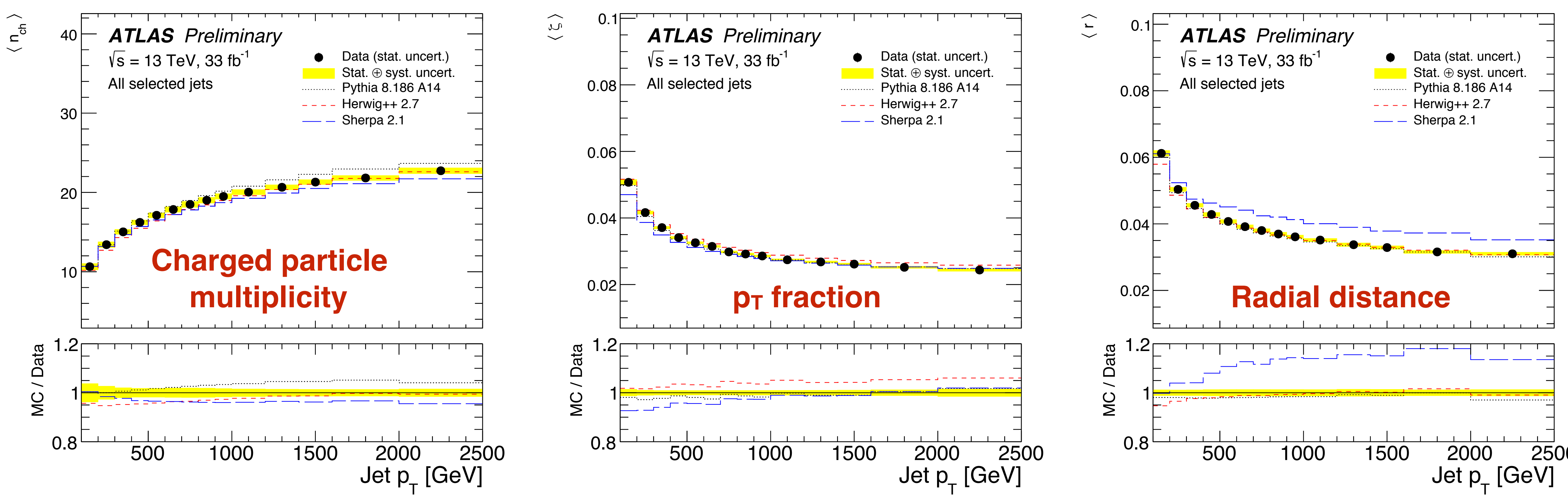
Jet fragmentation properties using charged particles

- Jet formation is complex and involves several energy scales
  - MC parameters need to be tuned to data
- Measuring quantities related to fragmentation using charged particle tracks helps us to tune MC parameters
- Predictions agree reasonably well with data
  - Sherpa needs to be better tuned



ATLAS-STDM-2017-16

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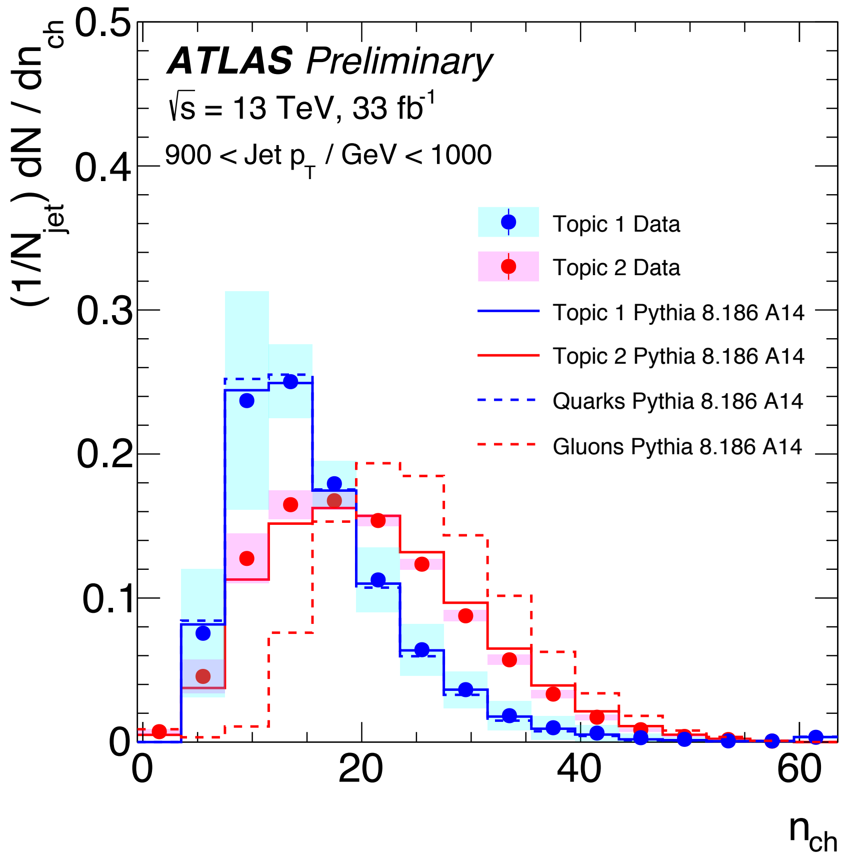
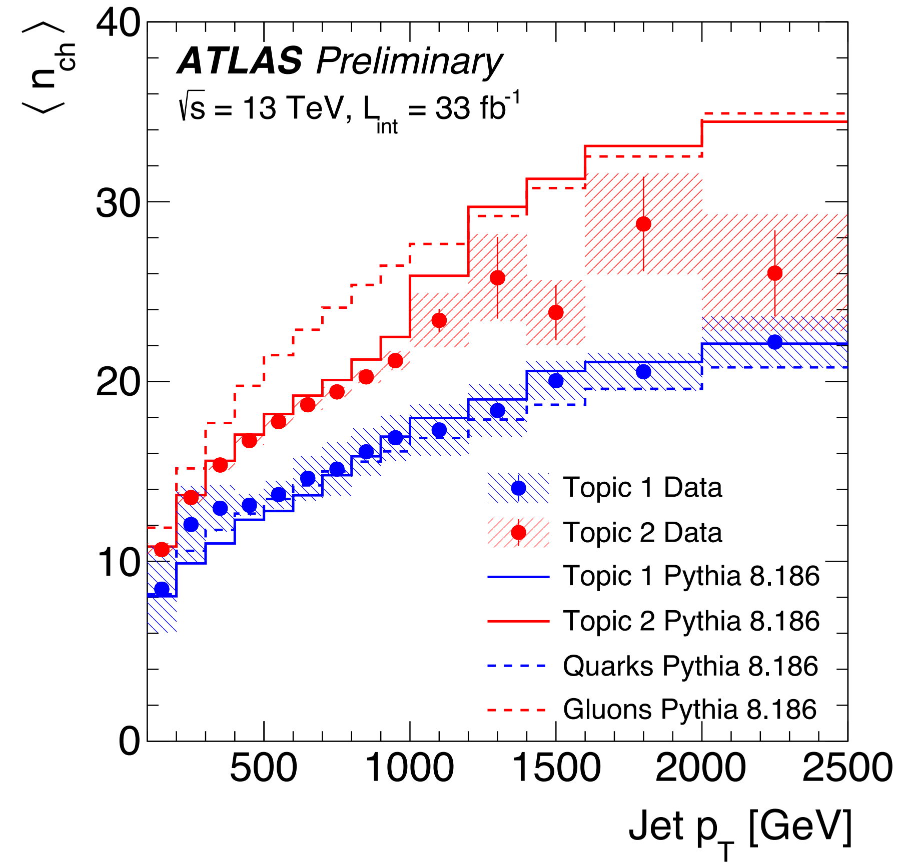
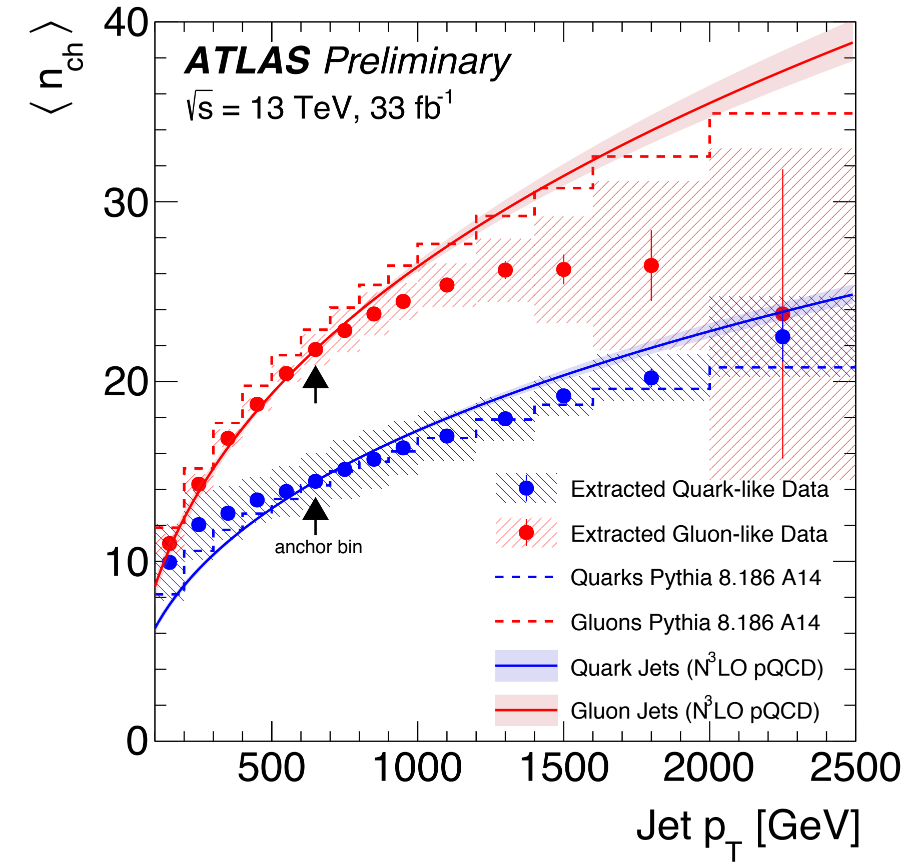
Jet fragmentation properties using charged particles

- Operational hadron-level definition of quark or gluon jets needed
  - Most jet-by-jet tagging is highly dependent on PS model
- Topics are data-driven classifications that approximately align with quark and gluon jets





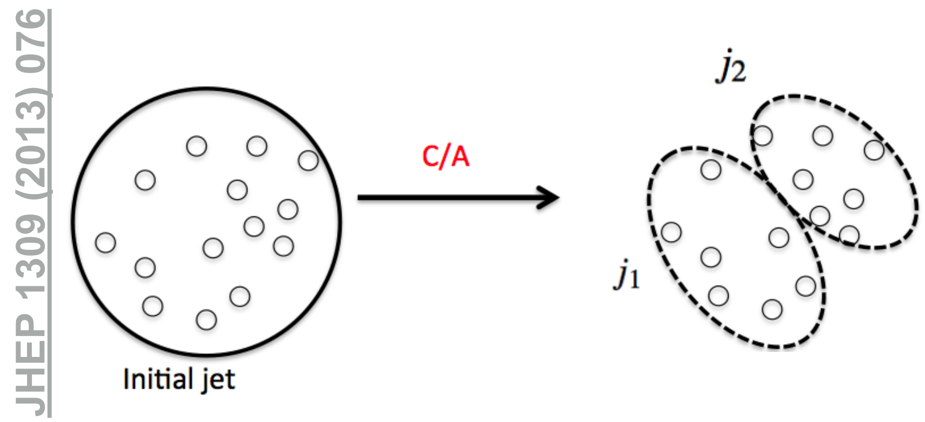


$$h_i^{T_1} = \frac{h_i^f - \left(\min_j \{h_j^f / h_j^c\}\right) \times h_i^c}{1 - \min_j h_j^f / h_j^c} \qquad h_i^{T_2} = \frac{h_i^c - \left(\min_j \{h_j^c / h_j^f\}\right) \times h_i^f}{1 - \min_j h_j^c / h_j^f}$$

ATLAS-STDM-2017-16

Soft-Drop jet mass measurements

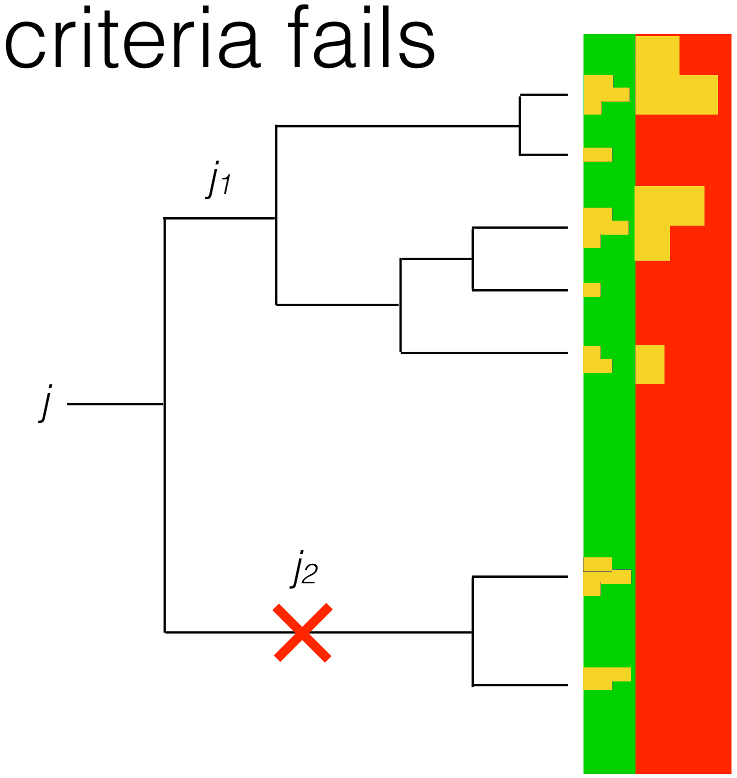
- Grooming removes soft and wide angle radiation from large-R jets
- SoftDrop designed to remove nonglobal logarithms
  - Jet reclustered using C/A



  - Softer branch removed at each node if criteria fails

$$\frac{\min(p_{T,j_1}, p_{T,j_2})}{p_{T,j_1} + p_{T,j_2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

  - Continued until criteria is passed
- Allows measurement beyond LL

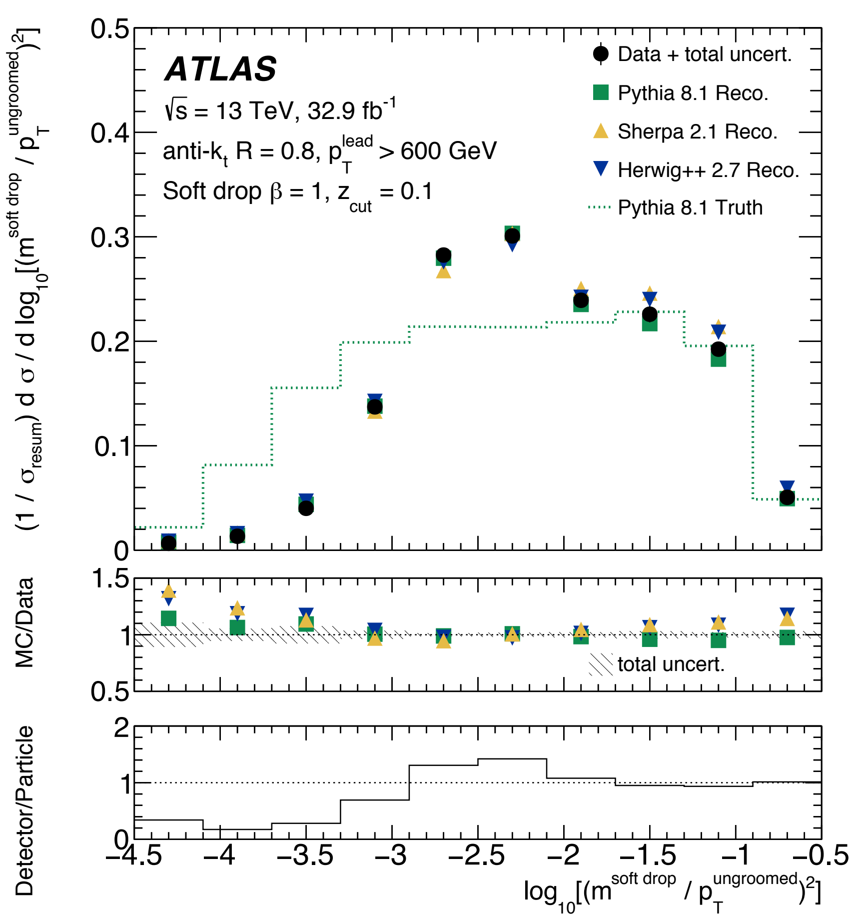


[Phys. Rev. Lett. 121 (2018) 092001]

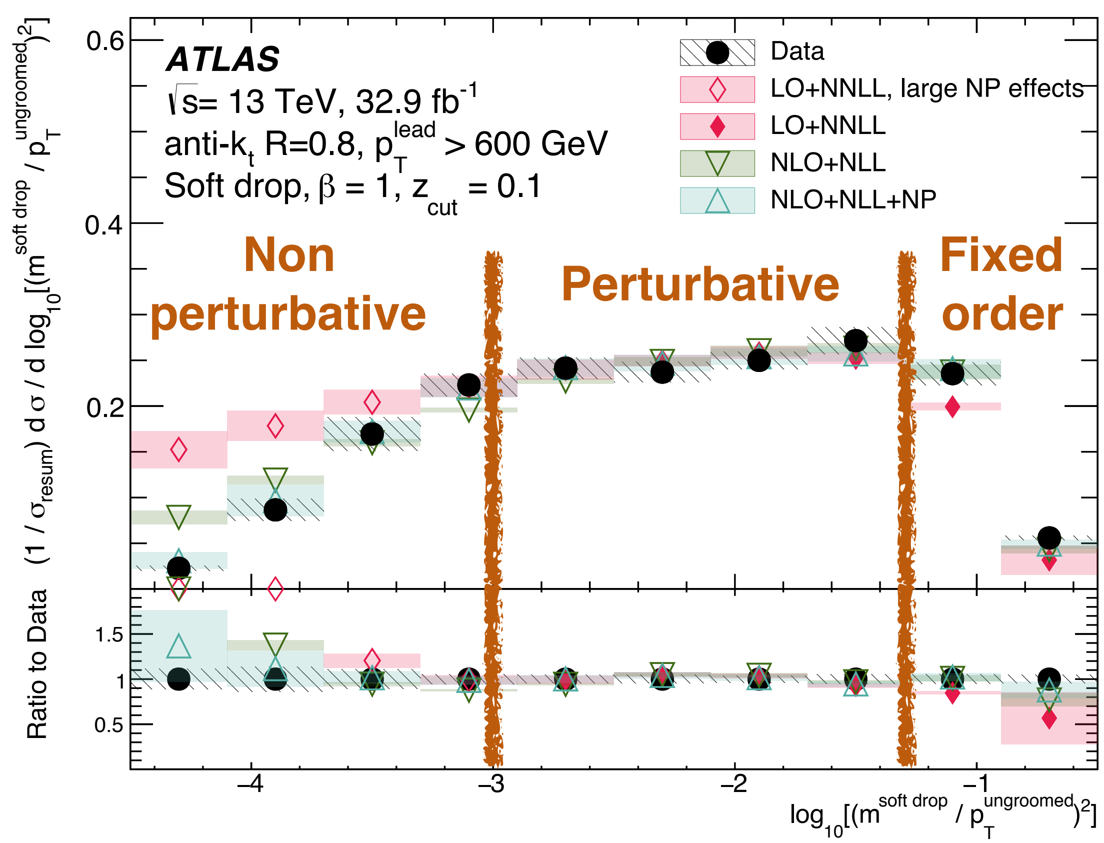
Soft-Drop jet mass measurements

- Measured in dijet events using anti-k_t R = 0.8 jets
- Scan of β values
- Excellent unfolded agreement in perturbative region

Reconstructed



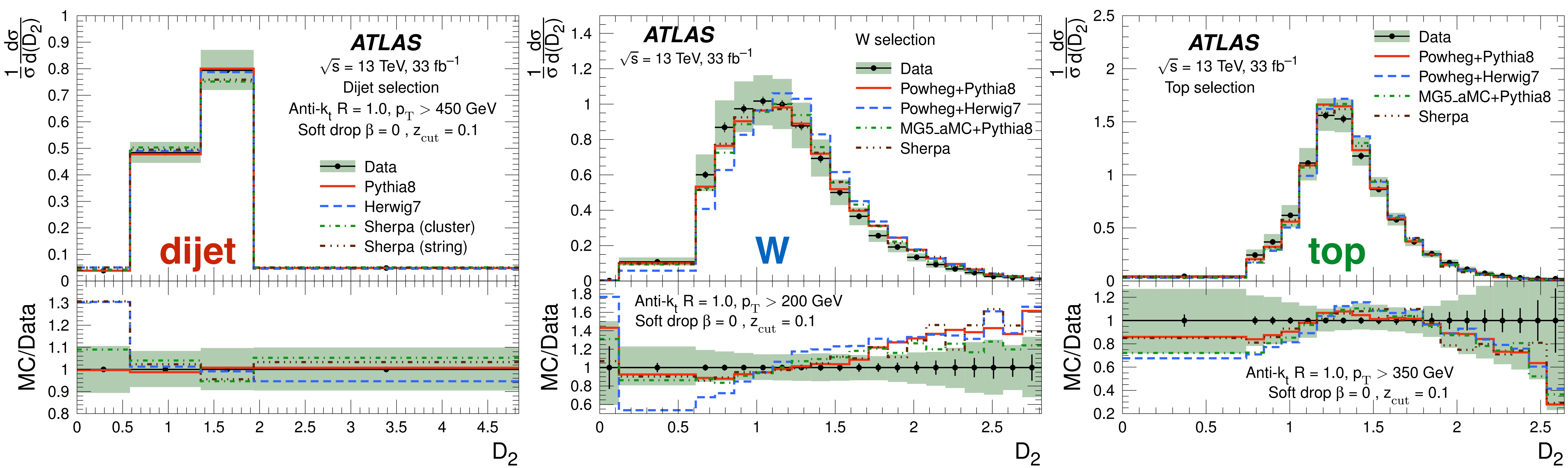
Unfolded



Phys. Rev. Lett. 121 (2018) 092001

Measurement of jet substructure observables in top quark, W boson and light jet production

- Various shape substructure observables measured in data
- Dijet, W, and top selections applied
- Distributions unfolded to remove detector effects
- ME and PS variations included in comparison
- Different mis-modeling for W and top jets



arXiv:1903.02942

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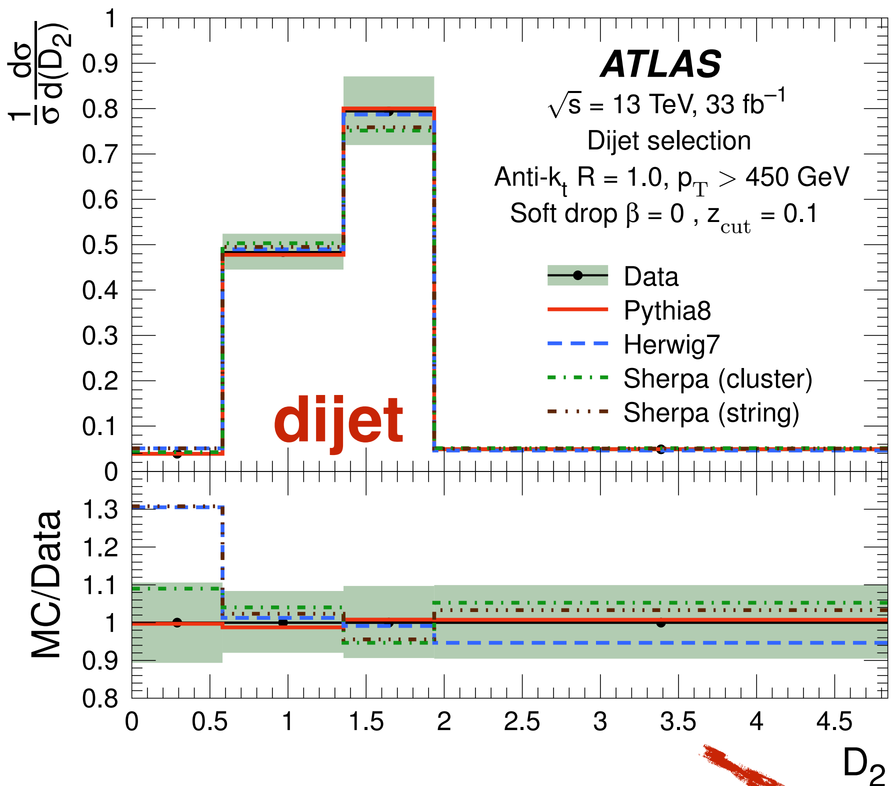
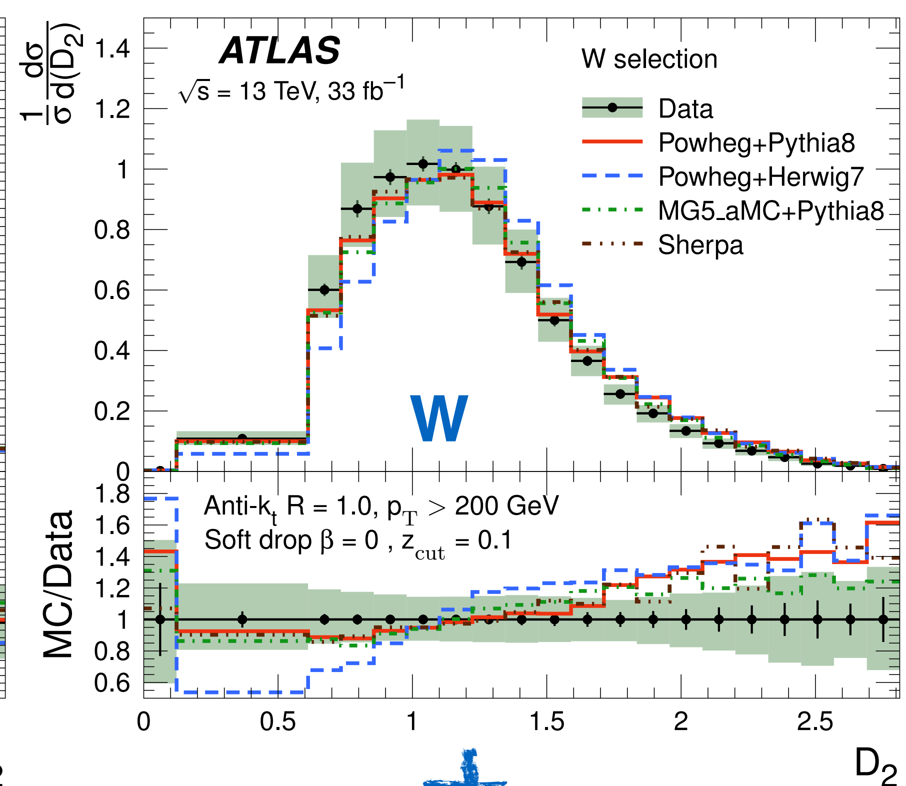
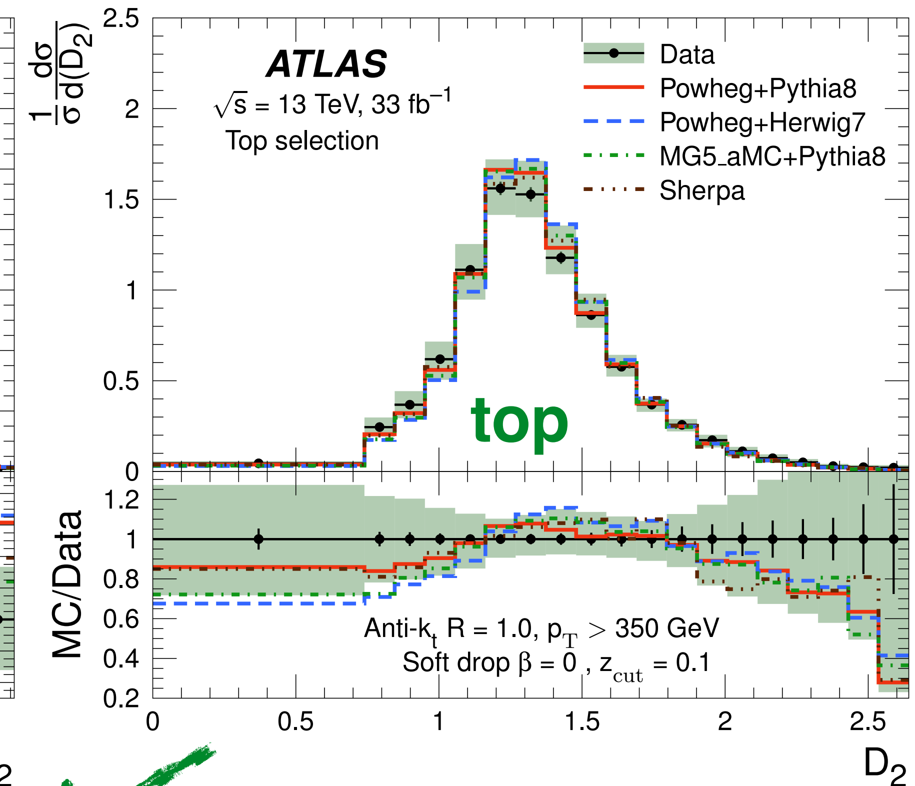
Measurement of jet substructure observables in top quark, W boson and light jet production







$$D_2 = \frac{e_3}{(e_2)^3}$$

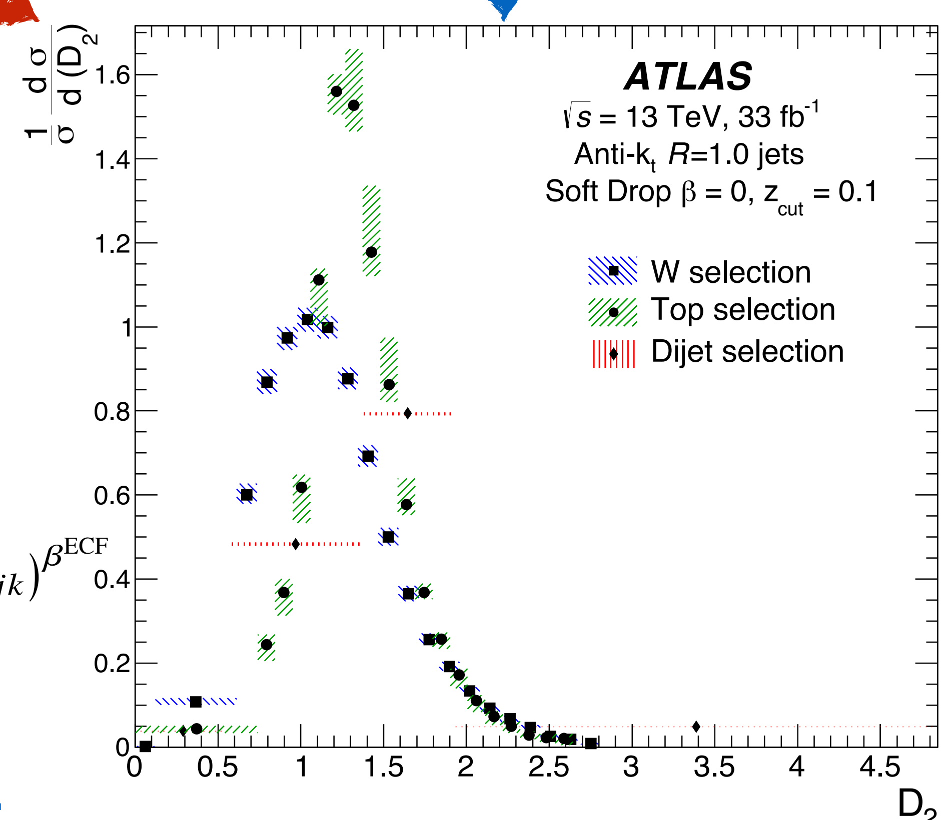
$$e_2 = \frac{\mathrm{ECF2}}{(\mathrm{ECF1})^2}$$

$$e_3 = \frac{\mathrm{ECF3}}{(\mathrm{ECF1})^3}$$

$$\mathrm{ECF1} = \sum_{i \in J} p_{\mathrm{T}_i}$$

$$\mathrm{ECF2}(\beta^{\mathrm{ECF}}) = \sum_{i<j \in J} p_{\mathrm{T}_i} p_{\mathrm{T}_j} \left(\Delta R_{ij}\right)^{\beta^{\mathrm{ECF}}}$$

$$\mathrm{ECF3}(\beta^{\mathrm{ECF}}) = \sum_{i<j<k \in J} p_{\mathrm{T}_i} p_{\mathrm{T}_j} p_{\mathrm{T}_k} \left(\Delta R_{ij} \Delta R_{ik} \Delta R_{jk}\right)^{\beta^{\mathrm{ECF}}}$$



arXiv:1903.02942

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Properties of g→bb at small opening angles

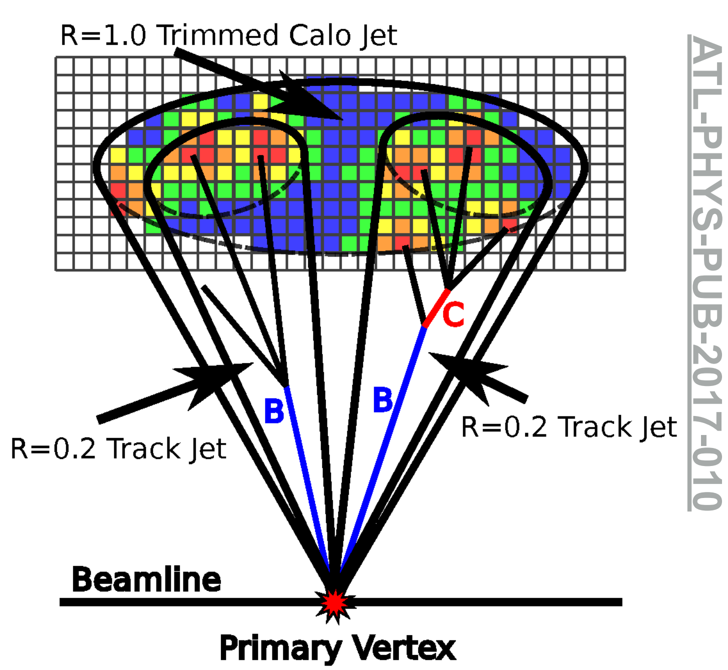
- Precision measurements of g→bb important for SM measurements and searches for BSM H production
- b-tag track jets associated to large-R calorimeter jet
- Study 4 important quantities:

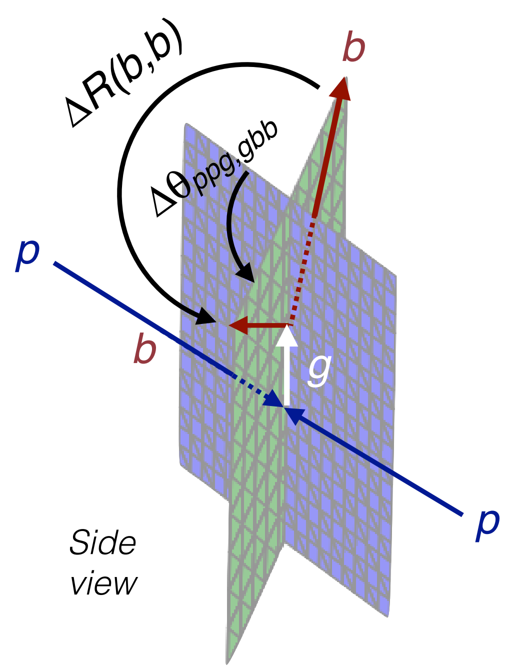
$$\Delta\theta_{\mathrm{ppg,gbb}}$$

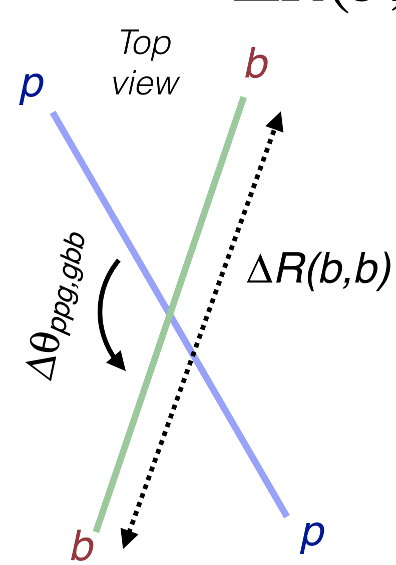
$$\log(m_{bb}/p_{\mathrm{T}})$$

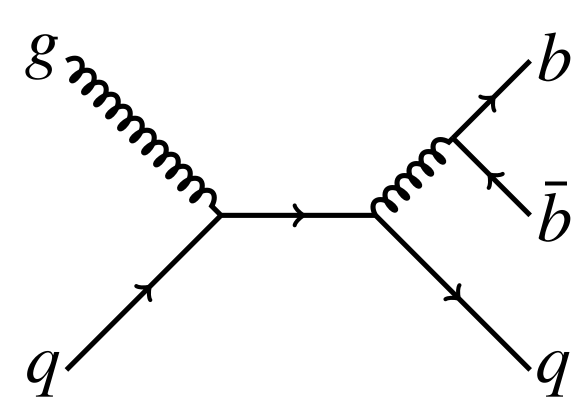
$$z(p_{\mathrm{T}}) = p_{\mathrm{T},2}/(p_{\mathrm{T},1} + p_{\mathrm{T},2})$$

$$\Delta R(b,b) = \sqrt{\Delta\phi(b,b)^2 + \Delta\eta(b,b)^2}$$





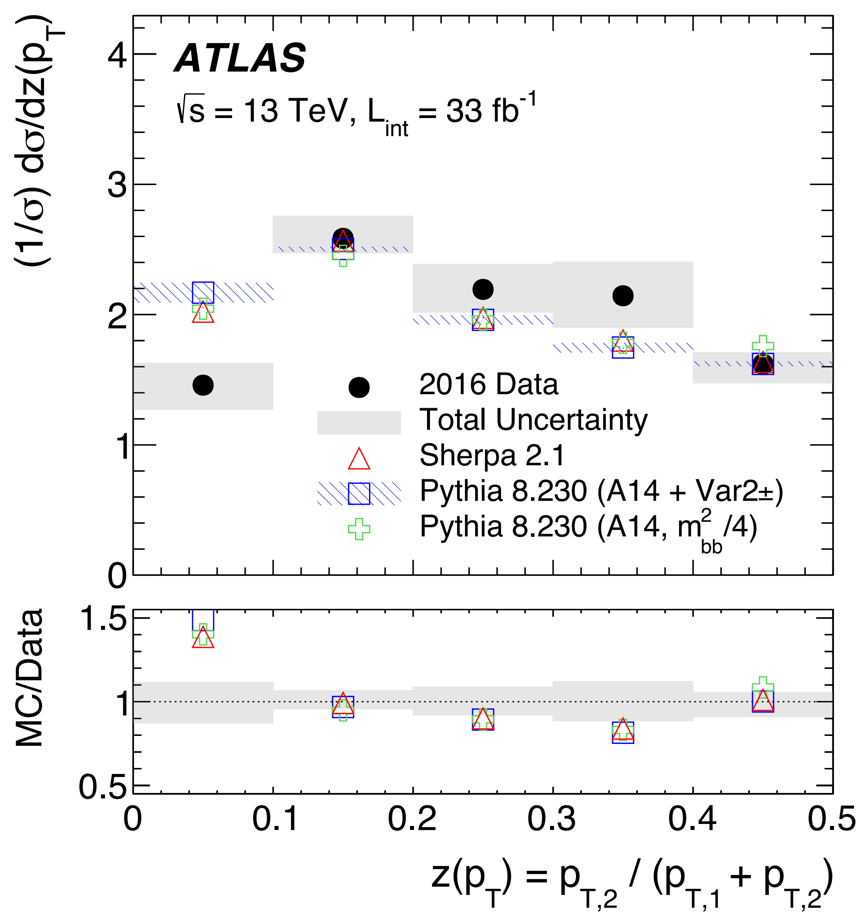


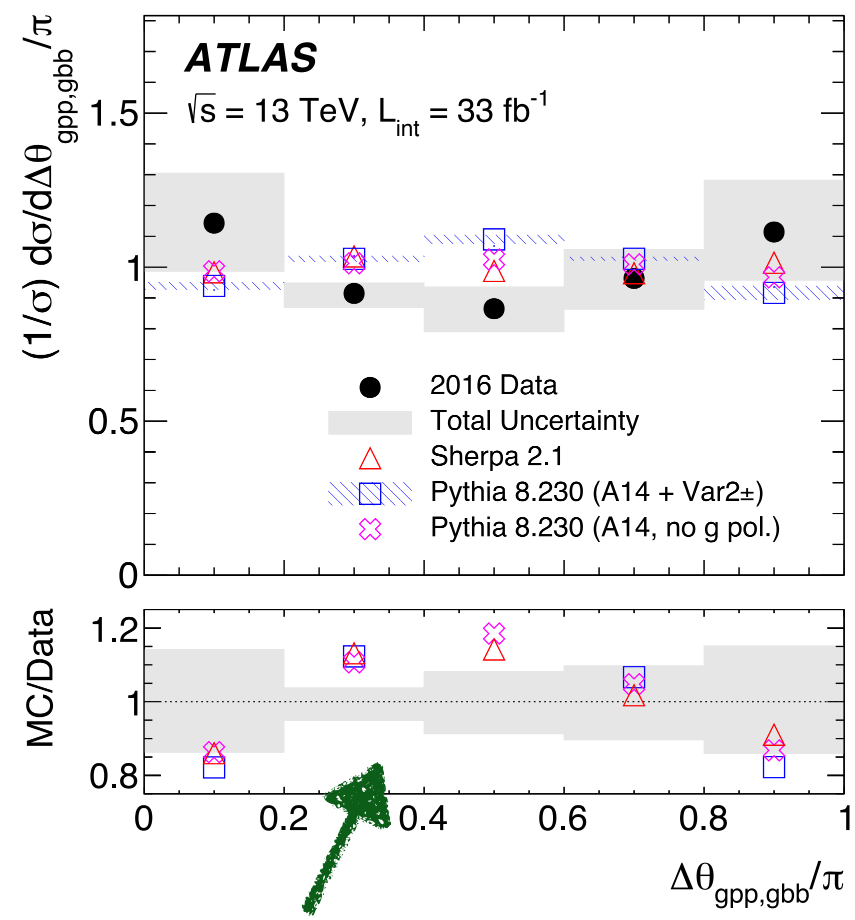


[Phys. Rev. D 99 (2019) 052004](#)

Properties of g→bb at small opening angles

- Significant differences between MC and data
- NLO predictions somewhat more accurate than LO
- Pythia8 tune variations show differences





Mismodeling of gluon polarization
in unpolarized hadrons

[Phys. Rev. D 99 (2019) 052004](#)

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Conclusions and outlook

- Precise jet property measurements test QCD predictions
- Some modeling validated, other modeling needs improvement
- New experimental techniques will further improve tests of QCD
- Stay tuned for future measurements…

Thank you for your attention

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Backup slides

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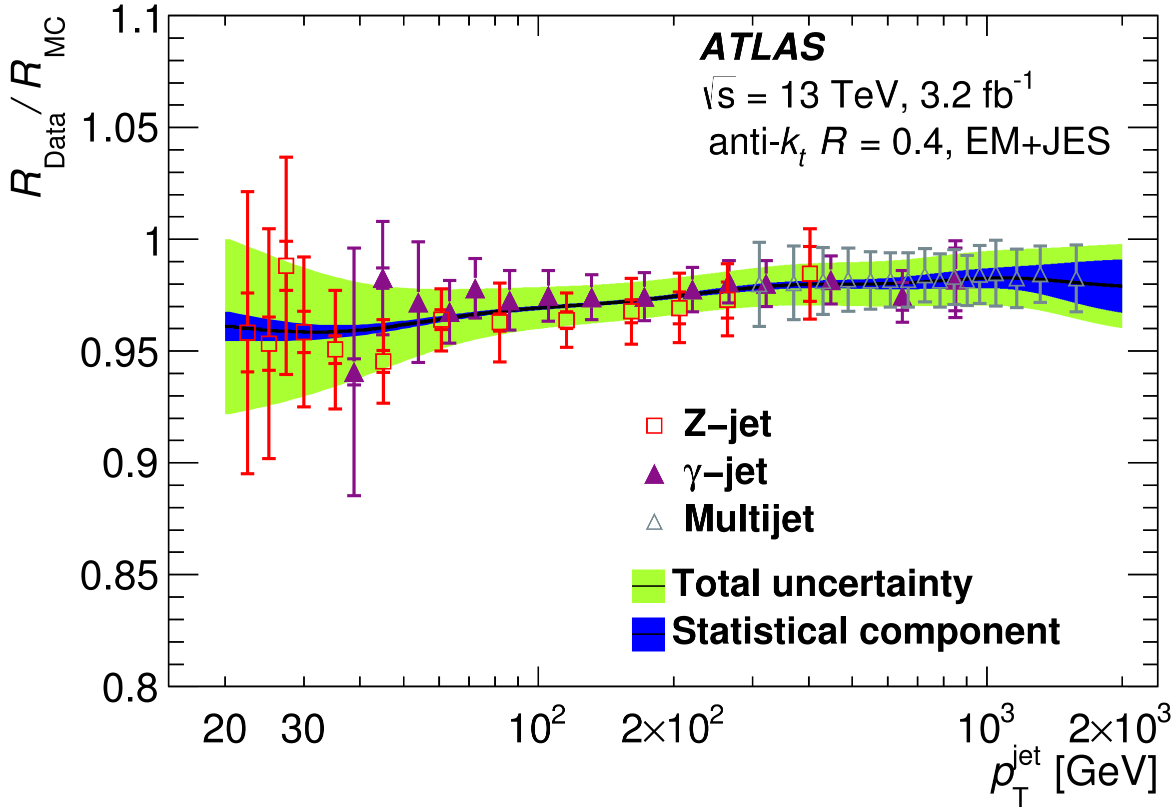
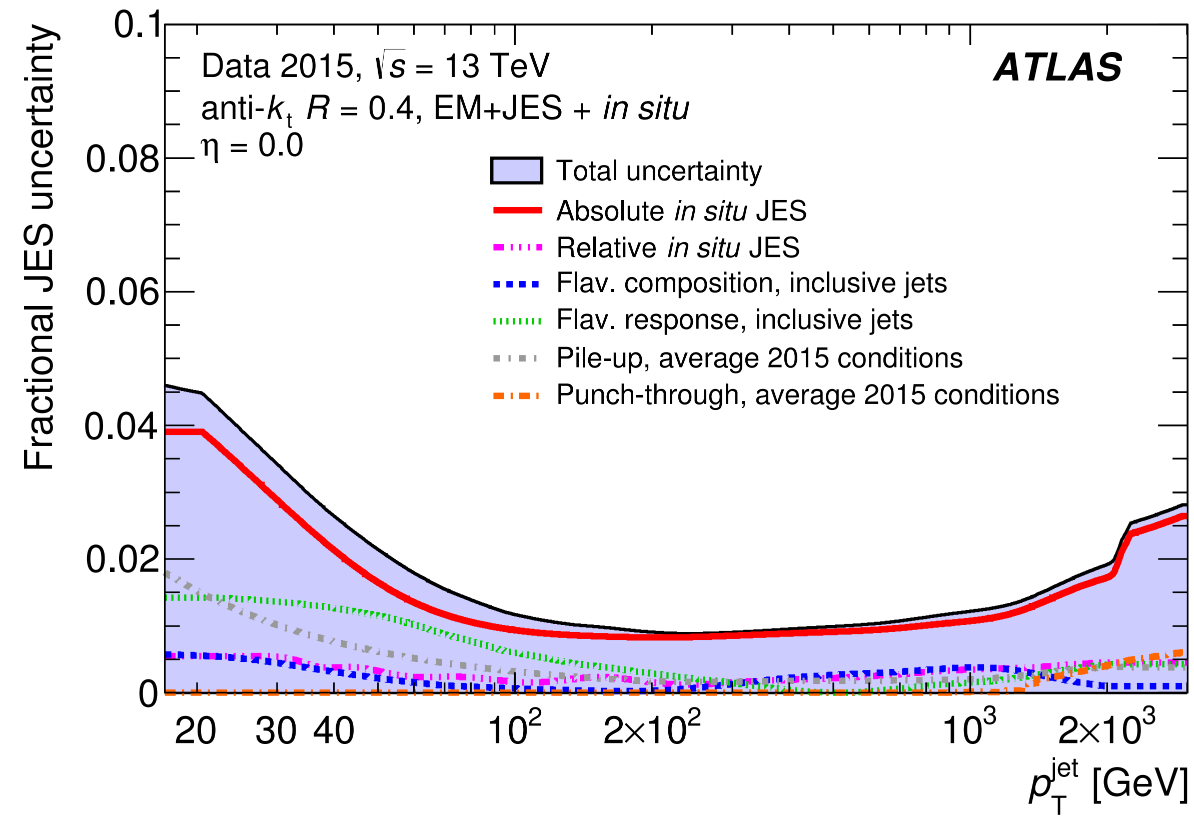
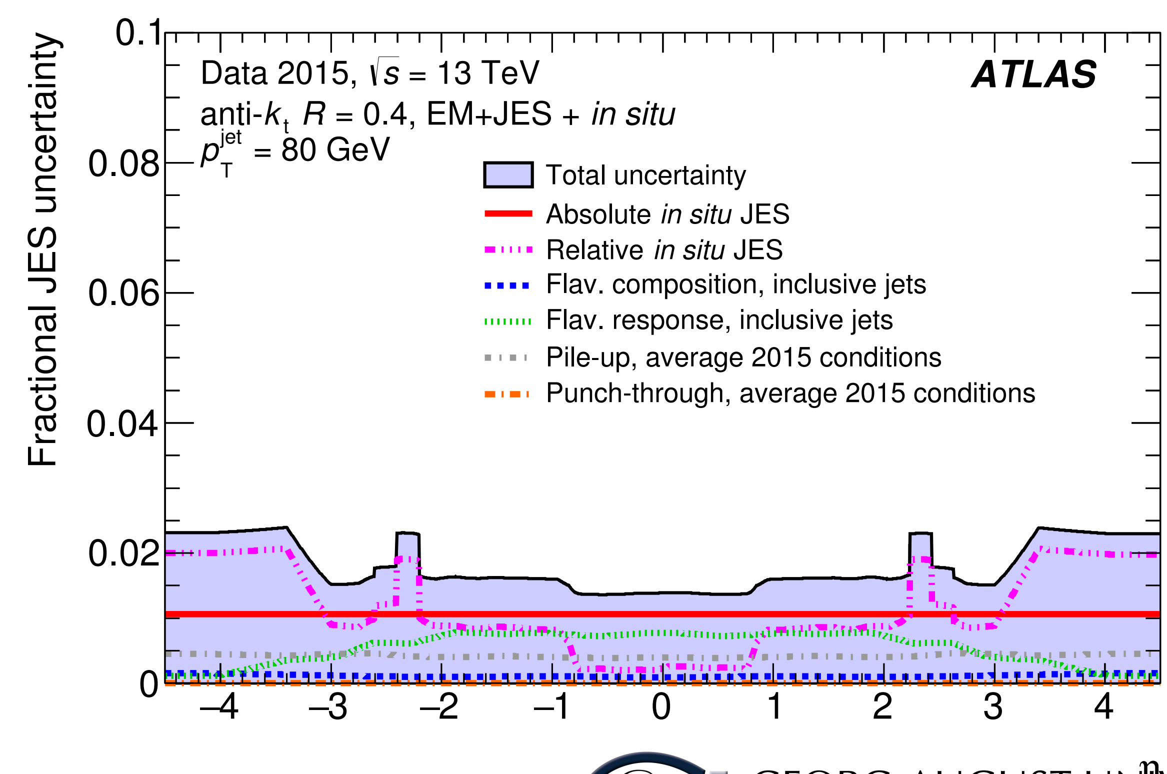
Jet calibration performance

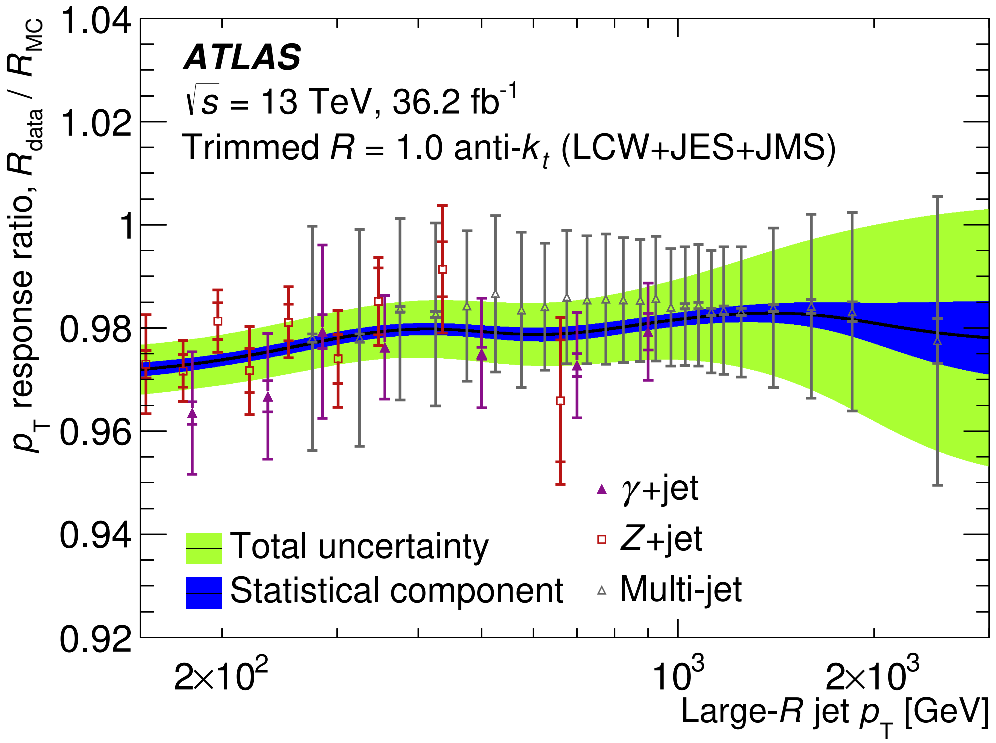


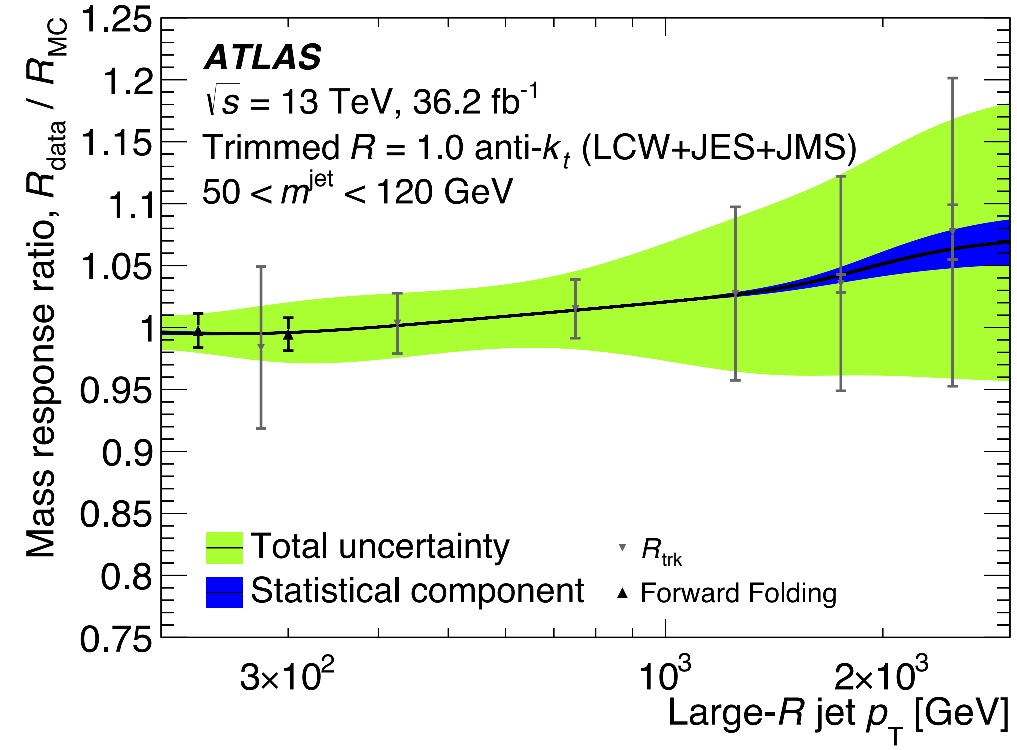


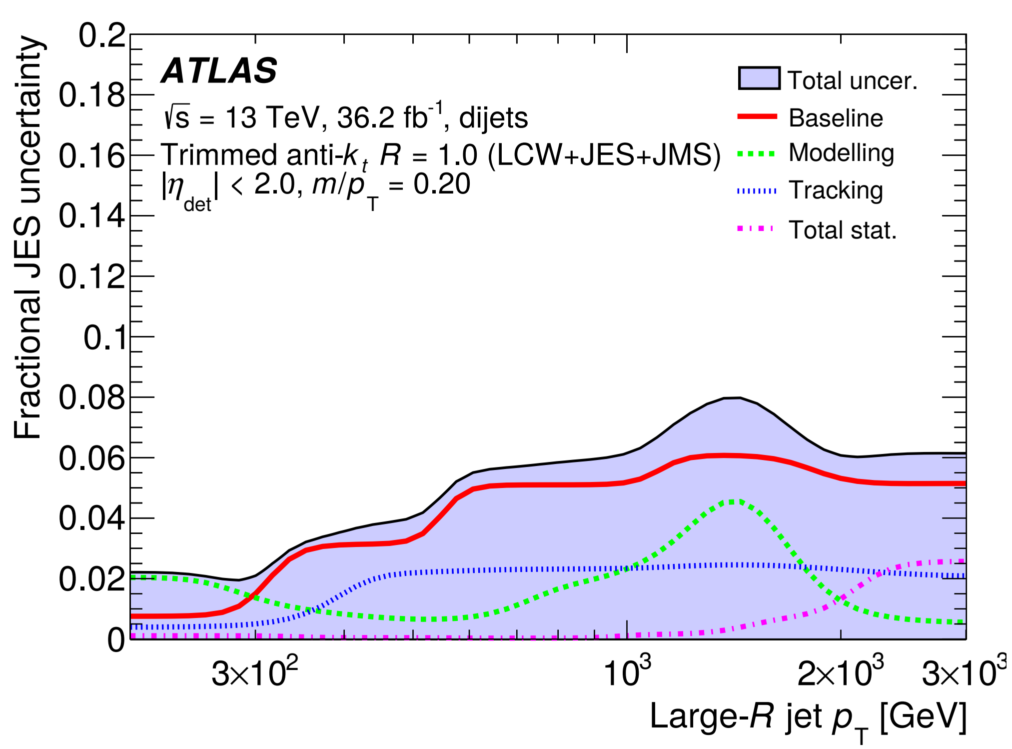


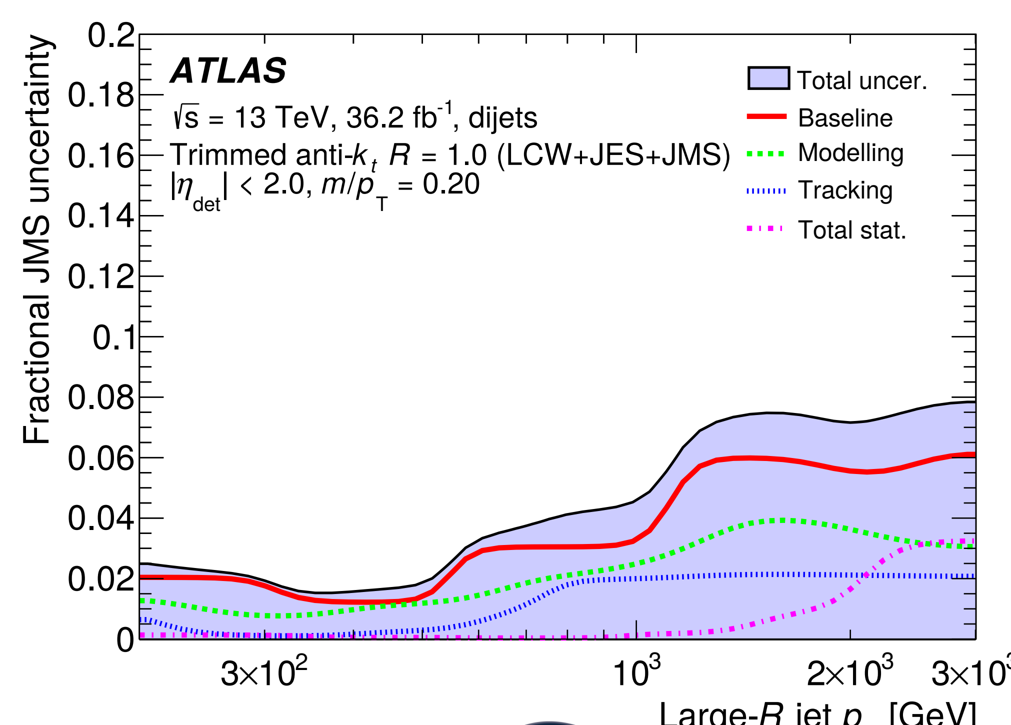
Phys. Rev. D 96 (2017) 072002

Jet calibration performance









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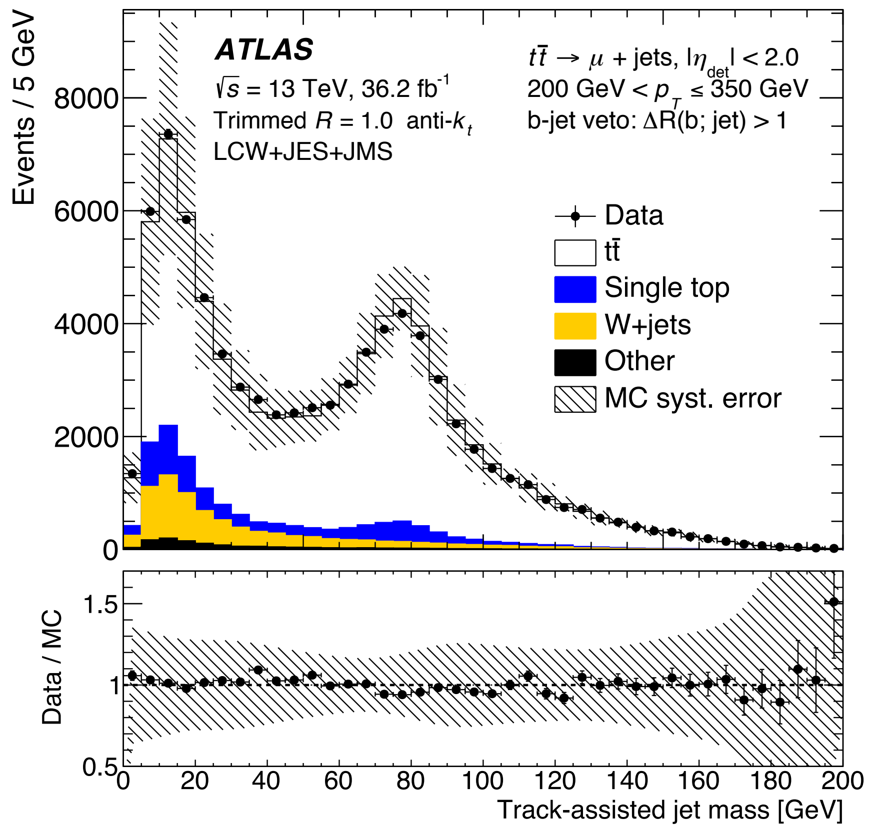
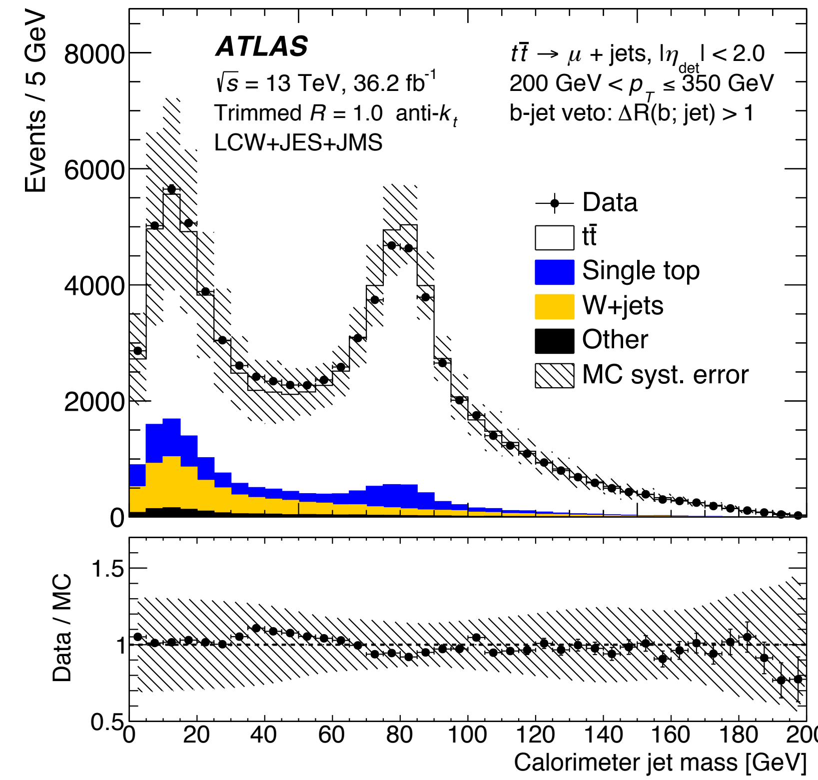
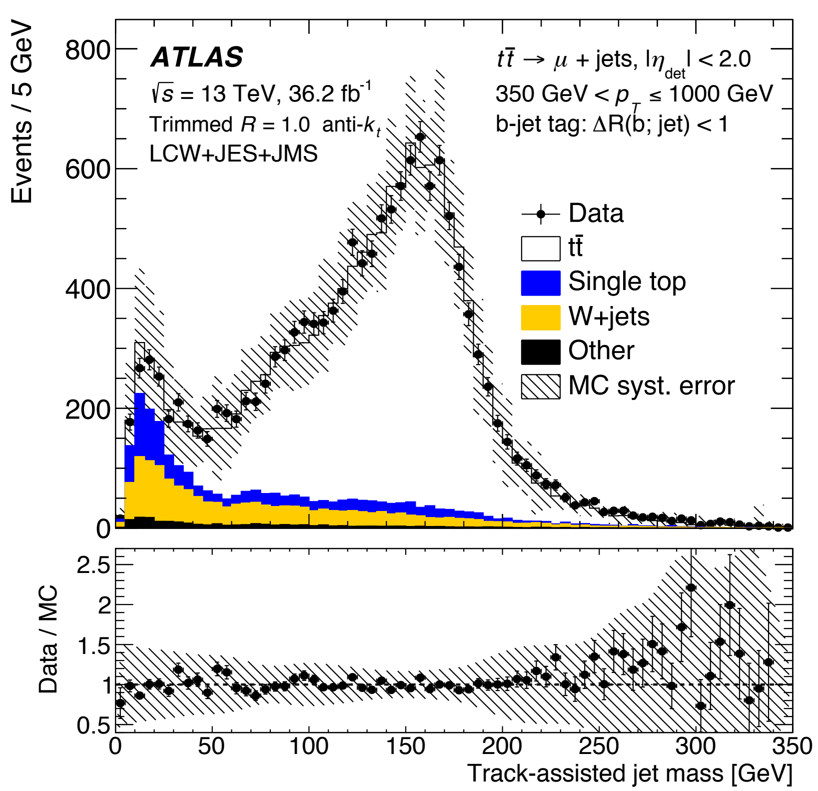
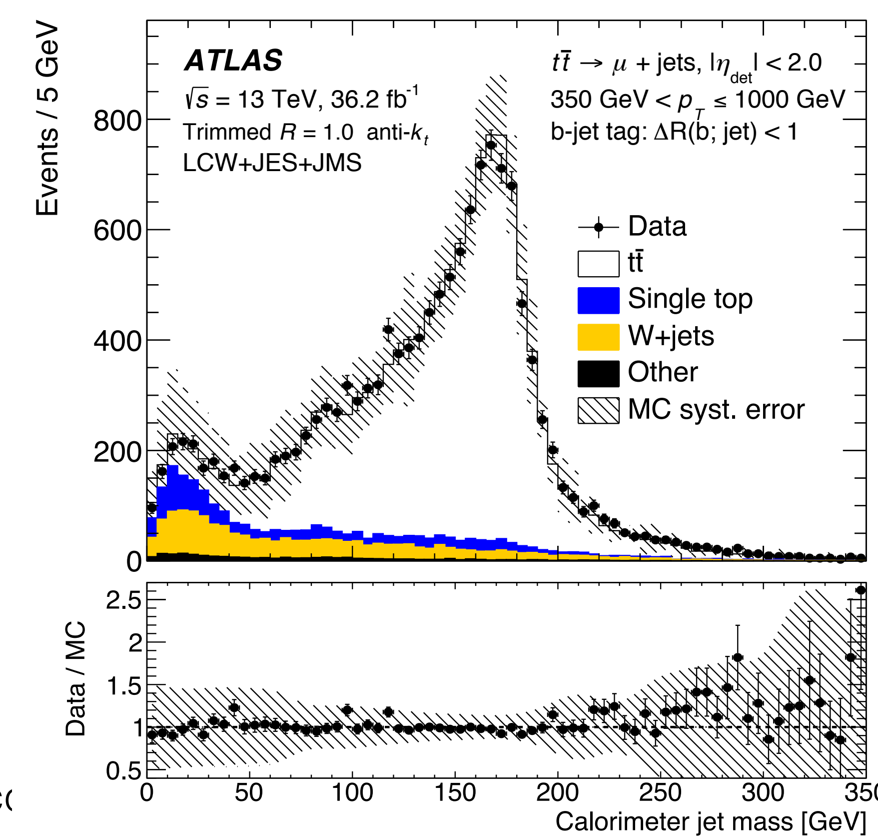
Jet calibration performance









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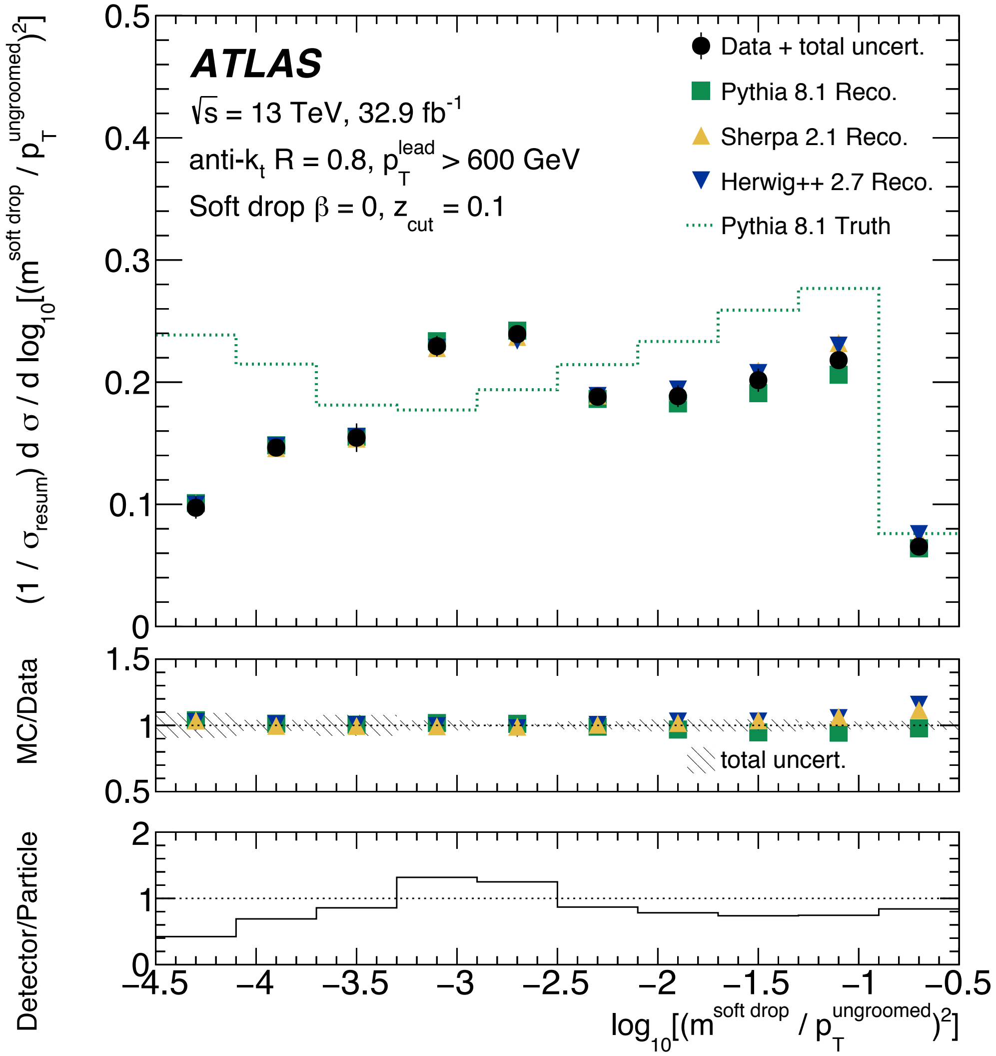
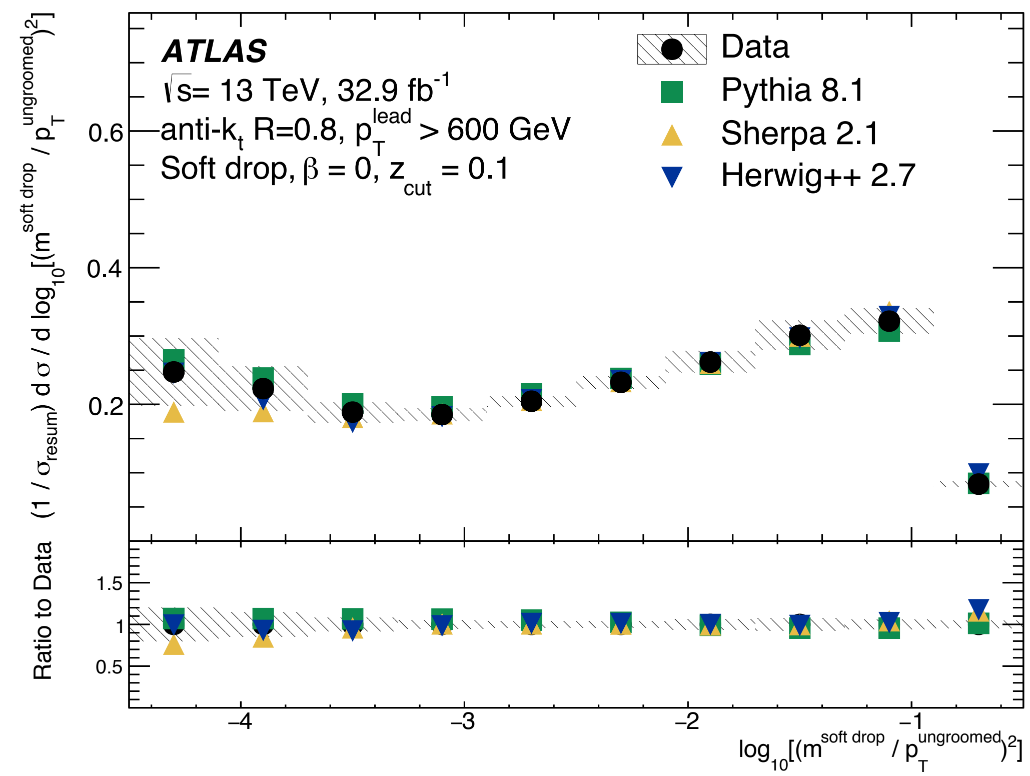
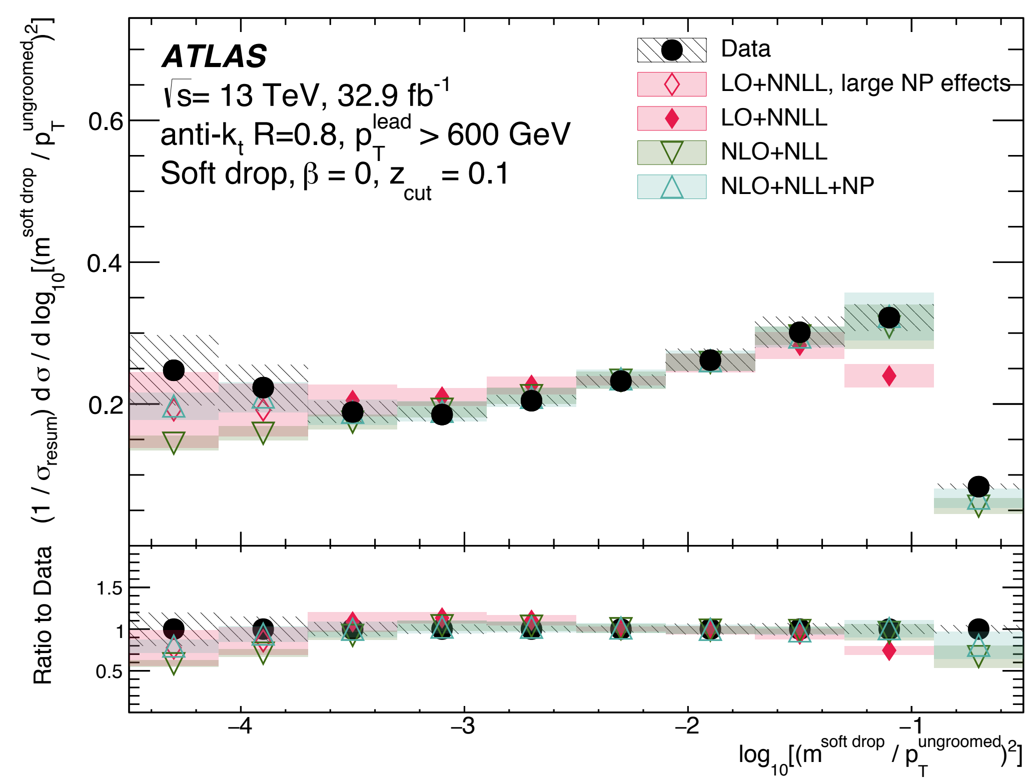
Soft-Drop β = 0



ATLAS
√s = 13 TeV, 32.9 fb-1
anti-kt R = 0.8, pT lead > 600 GeV
Soft drop β = 0, zcut = 0.1
Data + total uncert.
Pythia 8.1 Reco.
Sherpa 2.1 Reco.
Herwig++ 2.7 Reco.
Pythia 8.1 Truth
total uncert.
MC/Data
Detector/Particle
(1 / σresum) d σ / d log10[(msoft drop / pTungroomed)2]
log10[(msoft drop / pTungroomed)2]

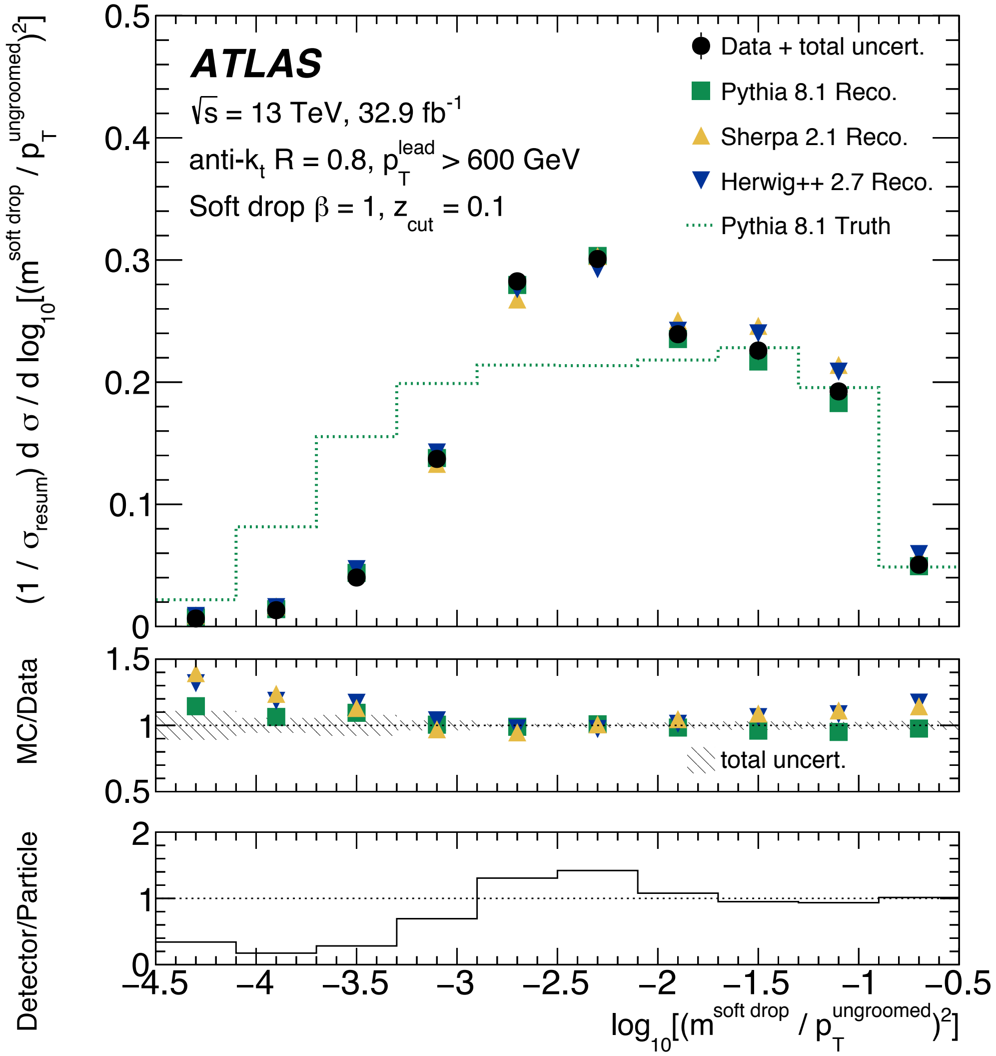


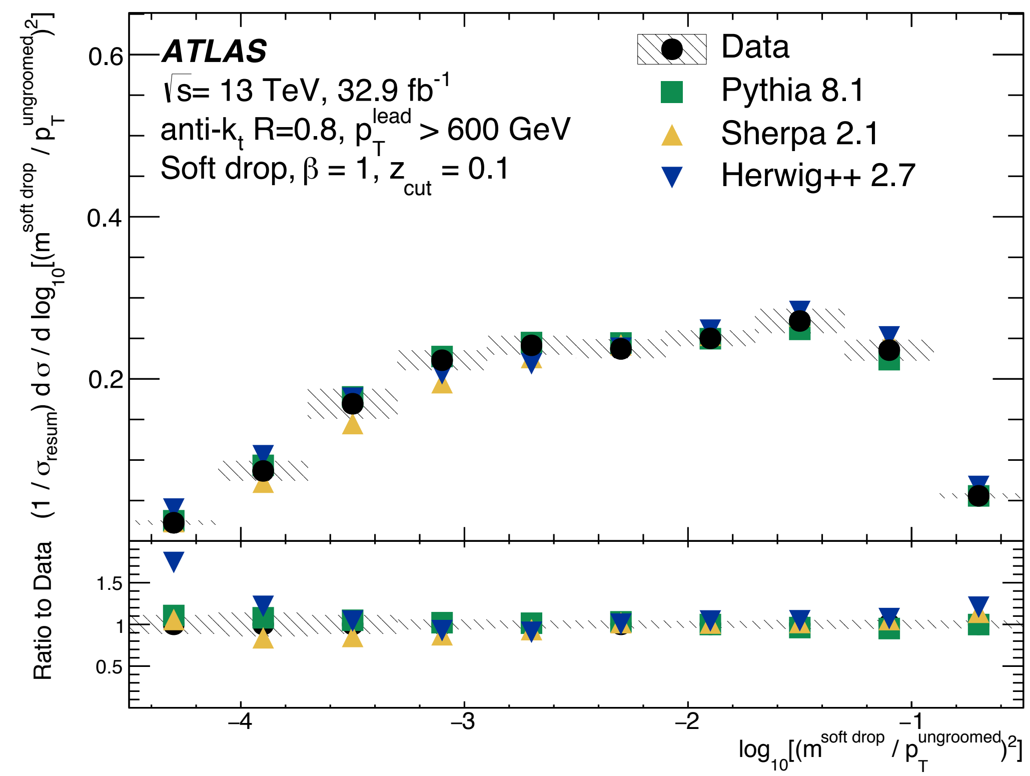
ATLAS
√s= 13 TeV, 32.9 fb-1
anti-kt, R=0.8, pT lead > 600 GeV
Soft drop, β = 0, zcut = 0.1
Data
Pythia 8.1
Sherpa 2.1
Herwig++ 2.7
Ratio to Data
(1 / σresum) d σ / d log10[(msoft drop / pTungroomed)2]
log10[(msoft drop / pTungroomed)2]

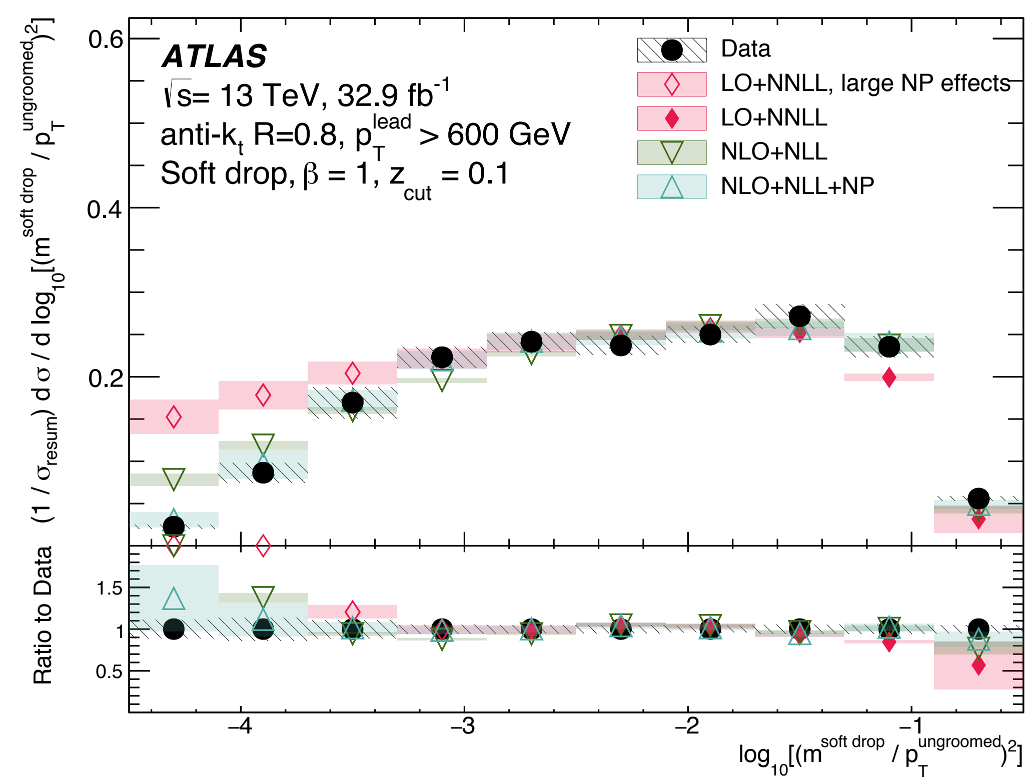


ATLAS
√s= 13 TeV, 32.9 fb-1
anti-kt, R=0.8, pT lead > 600 GeV
Soft drop, β = 0, zcut = 0.1
Data
LO+NNLL, large NP effects
LO+NNLL
NLO+NLL
NLO+NLL+NP
Ratio to Data
(1 / σresum) d σ / d log10[(msoft drop / pTungroomed)2]
log10[(msoft drop / pTungroomed)2]

Soft-Drop β = 1







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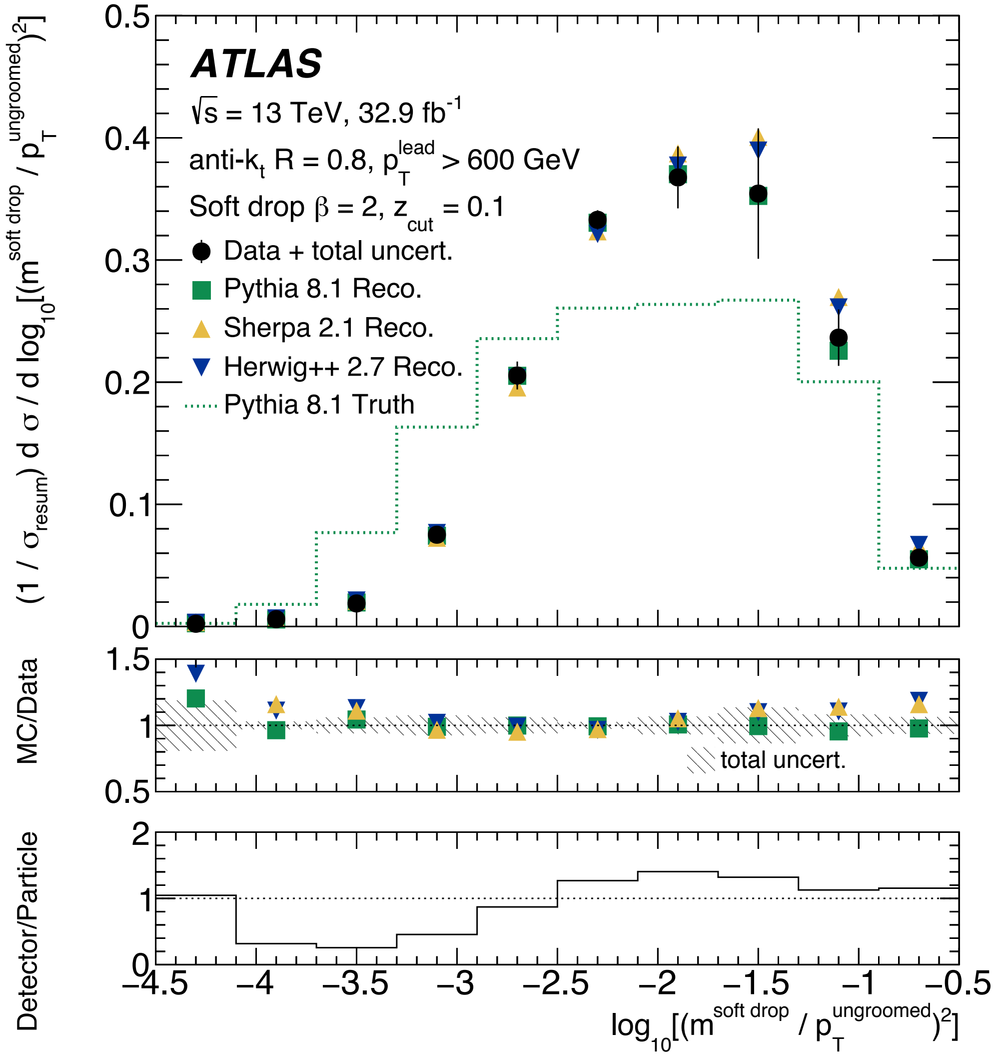
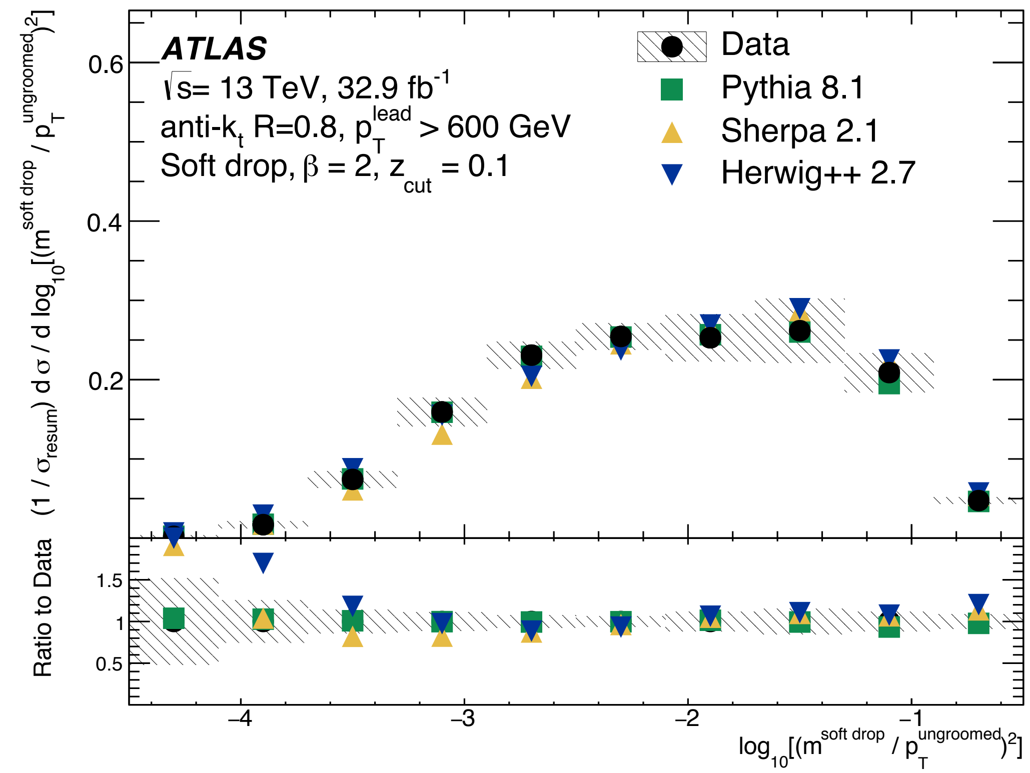
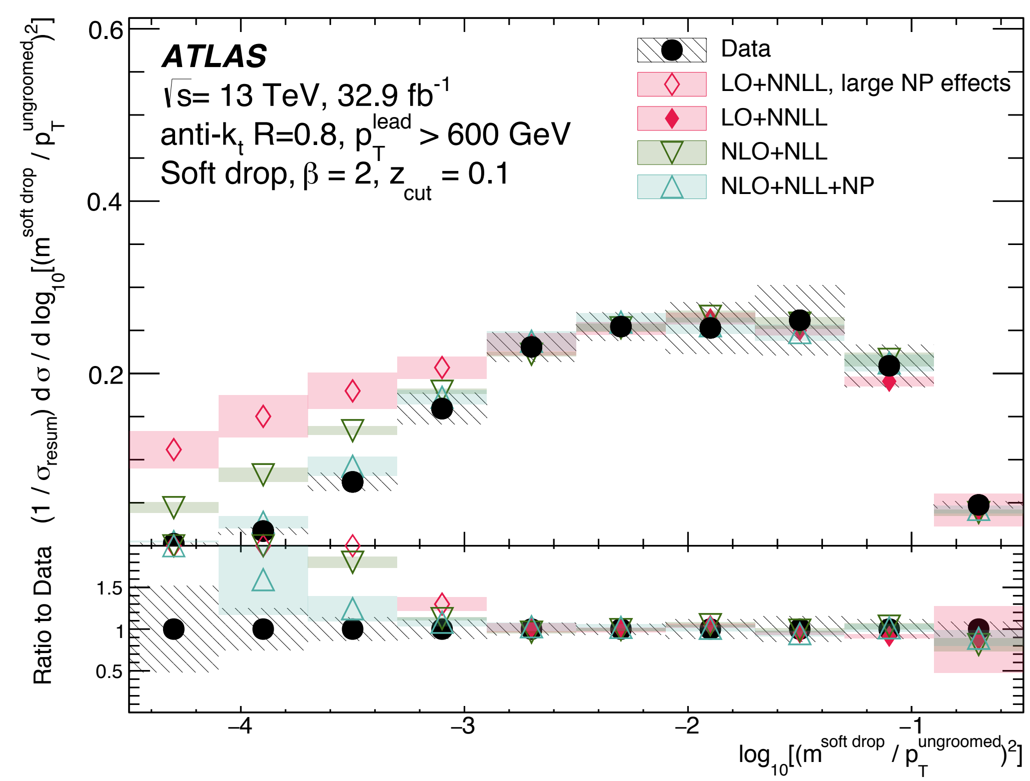
Soft-Drop β = 2







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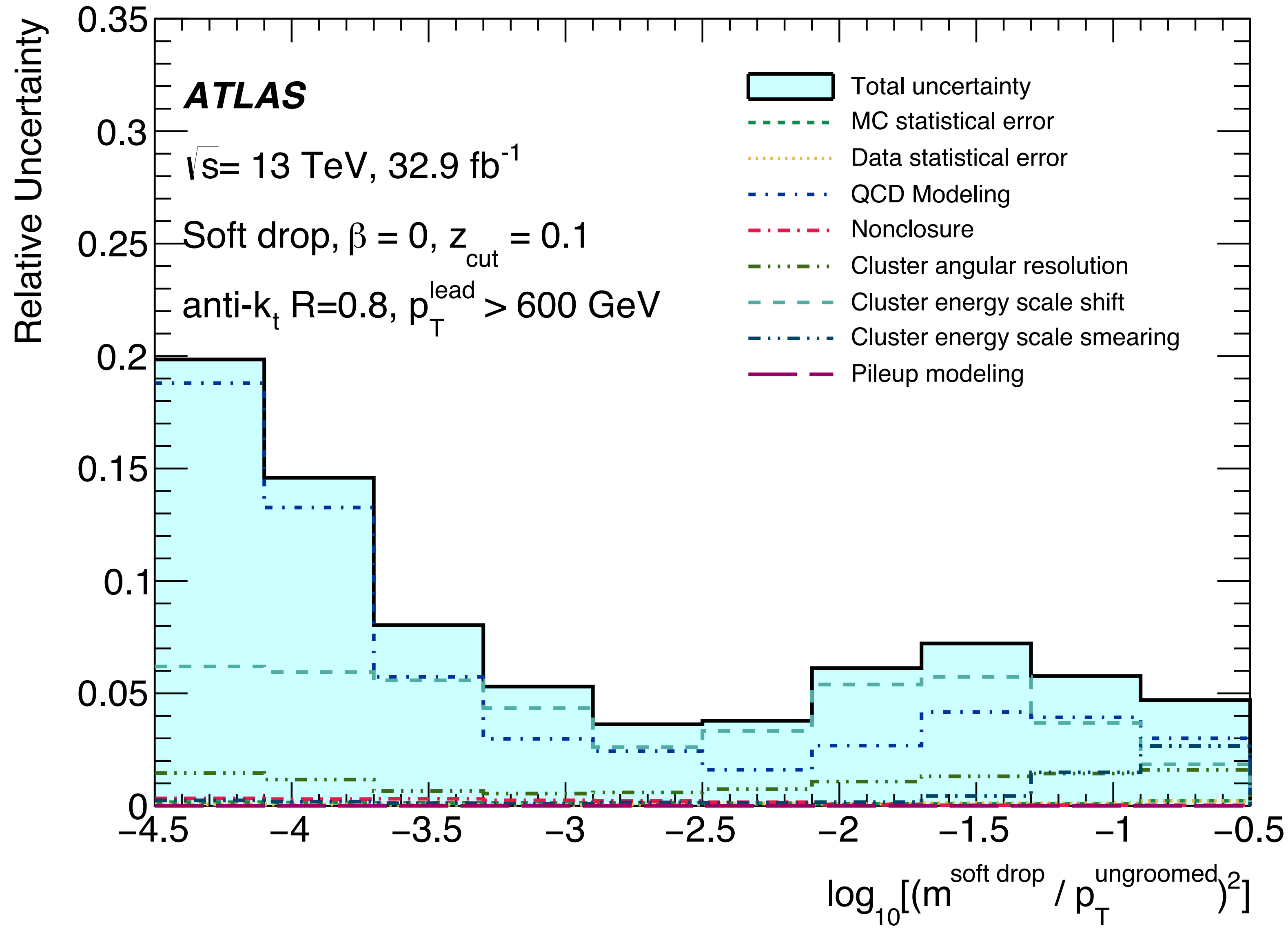
Soft-Drop systematics



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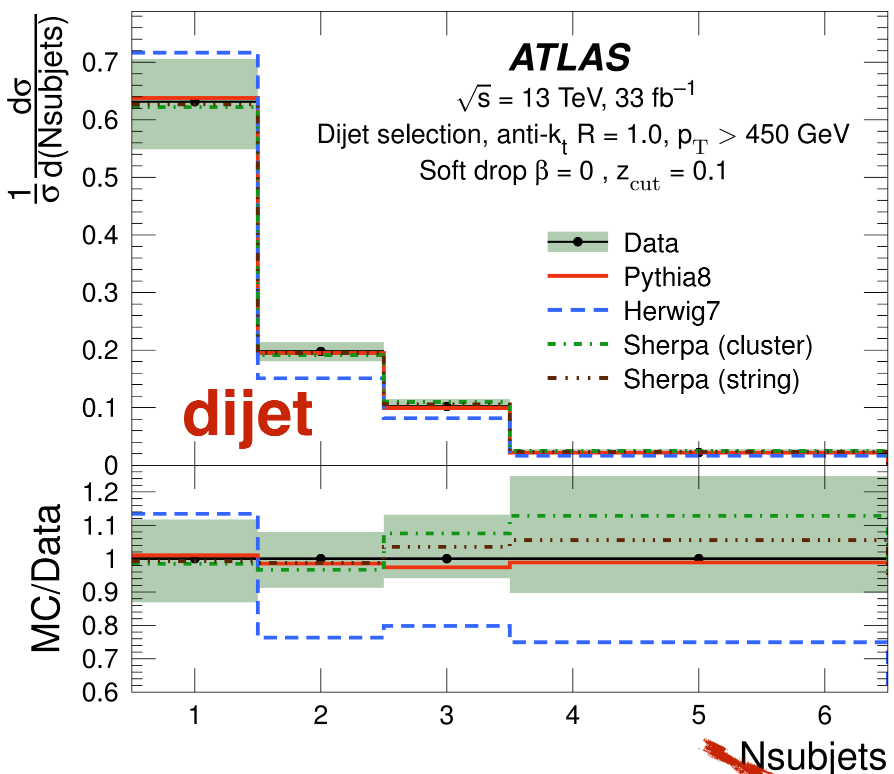
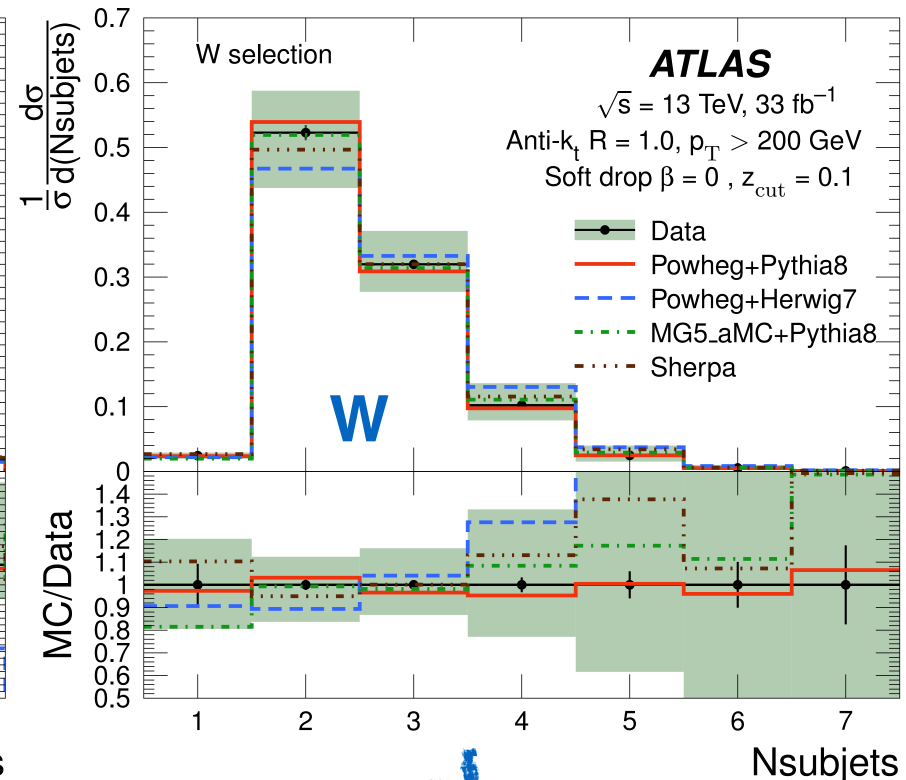
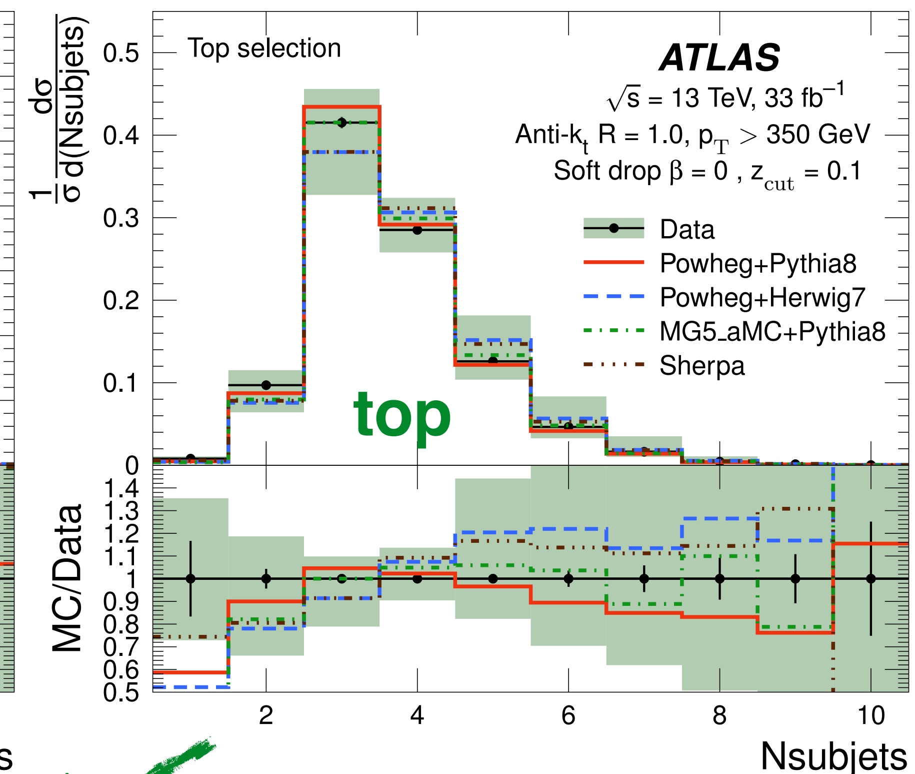
Measurement of jet substructure observables in top quark, W boson and light jet production



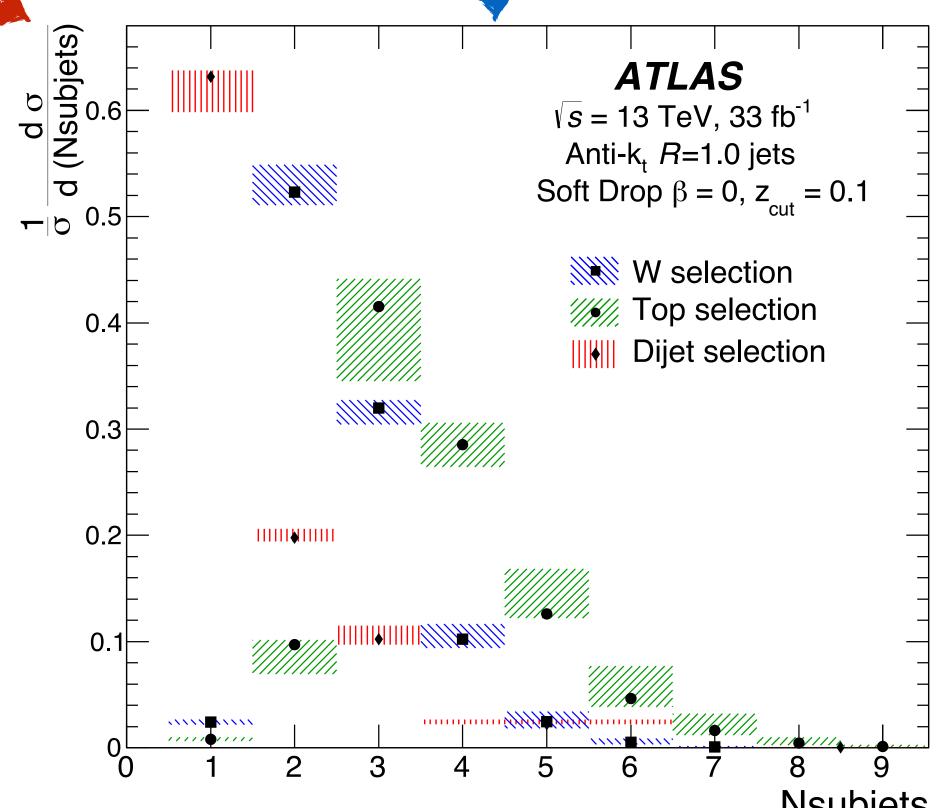




Subjet multiplicity

k_t R = 0.2

p_T > 10 GeV



arXiv:1903.02942

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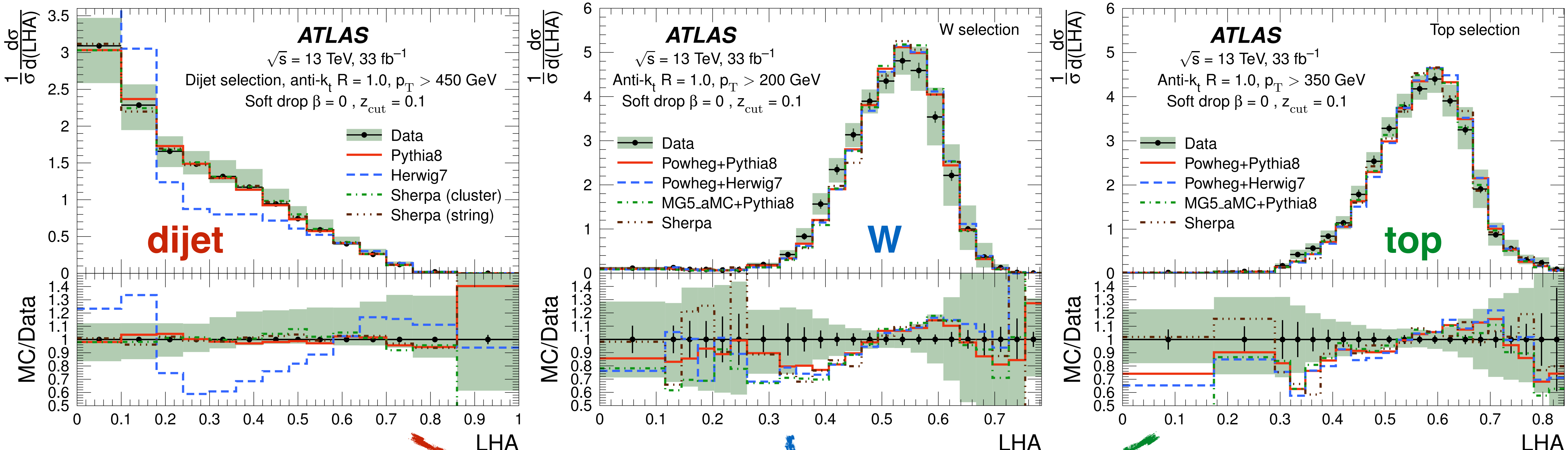
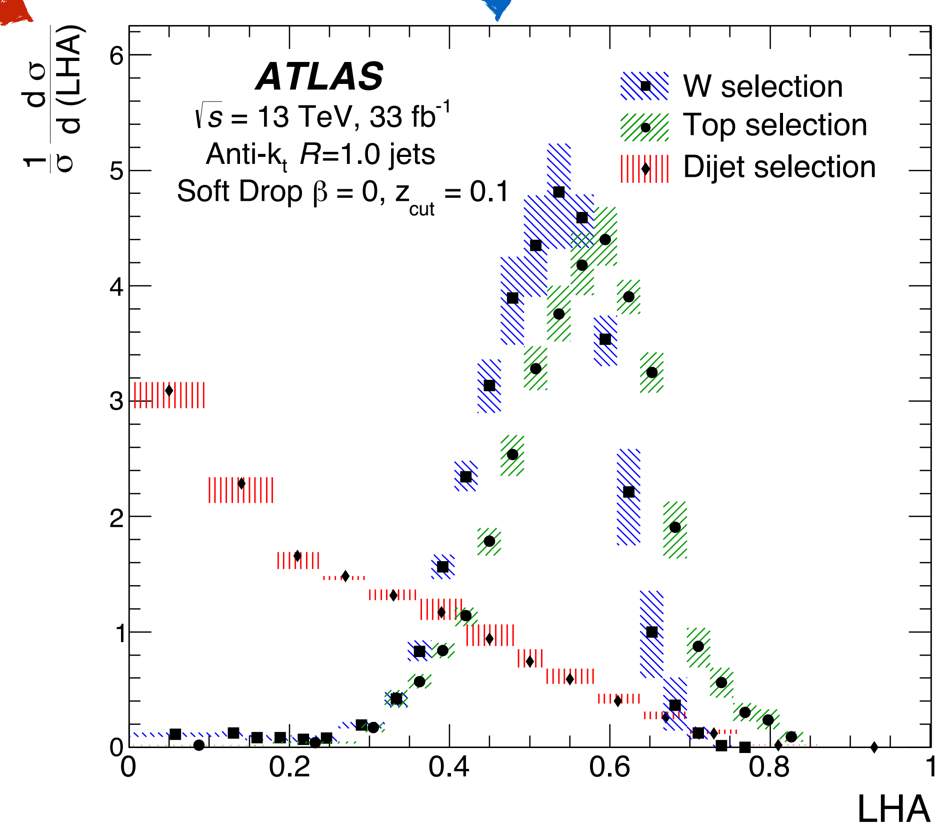
Measurement of jet substructure observables in top quark, W boson and light jet production





Les Houches Angularity

$$\lambda^{\kappa}_{\beta^{\mathrm{LHA}}} = \sum_{i \in J} z_i^{\kappa} \theta_i^{\beta^{\mathrm{LHA}}}$$

arXiv:1903.02942

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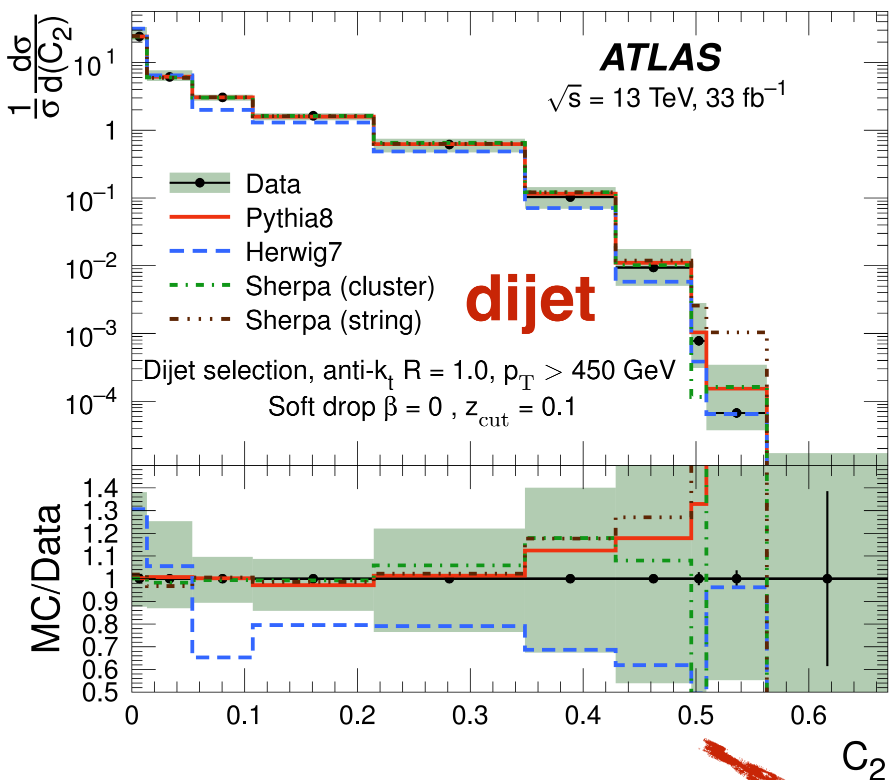
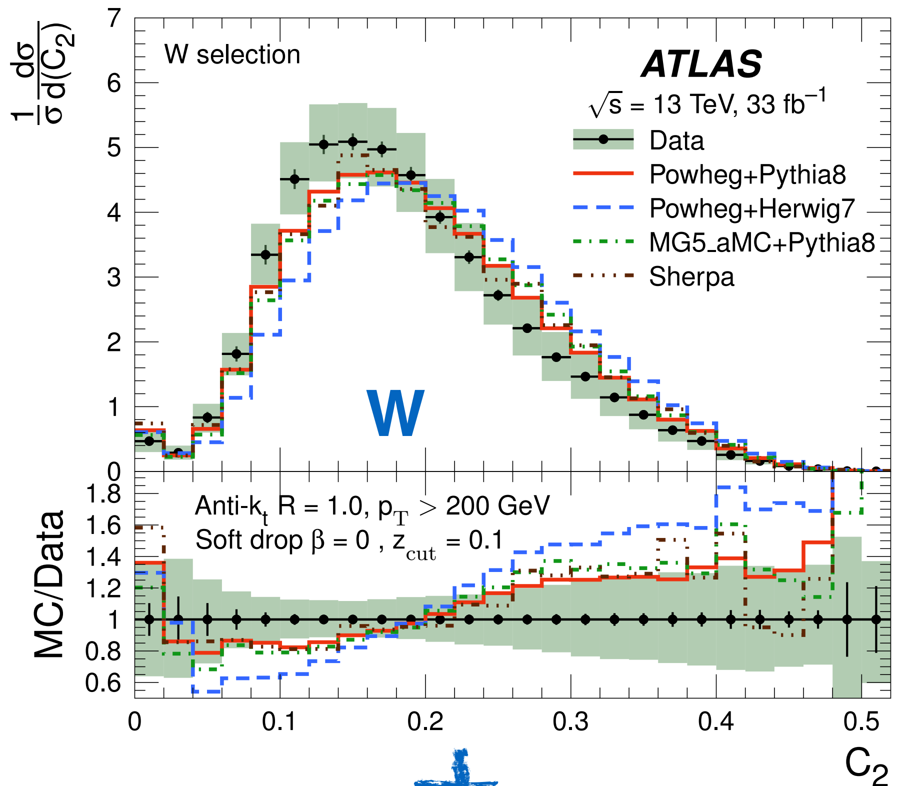
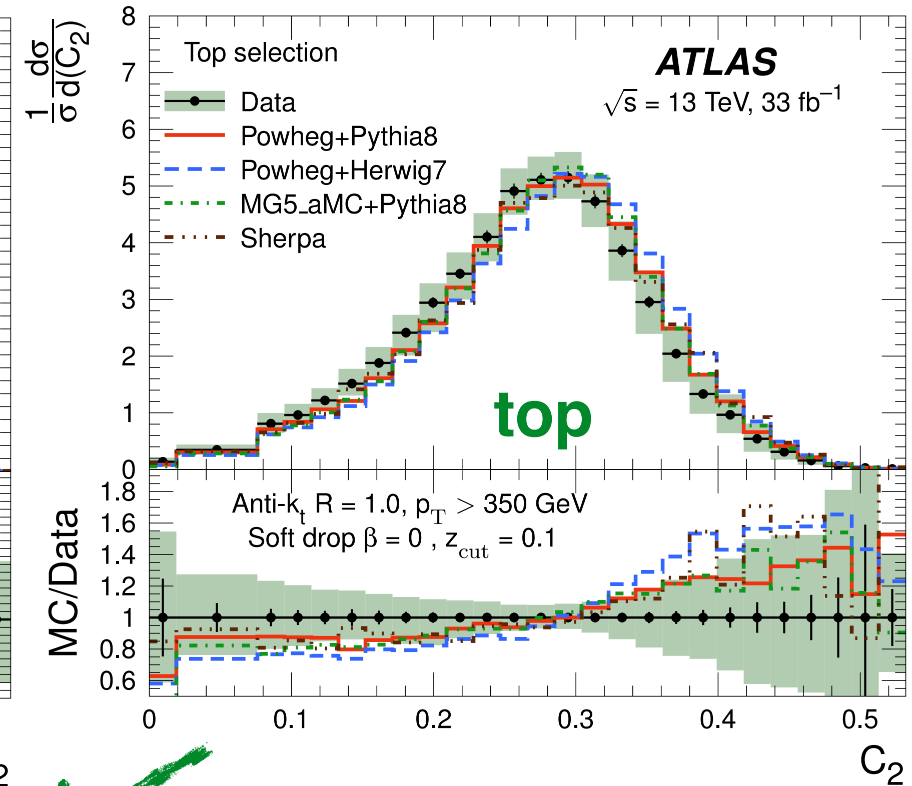
Measurement of jet substructure observables in top quark, W boson and light jet production

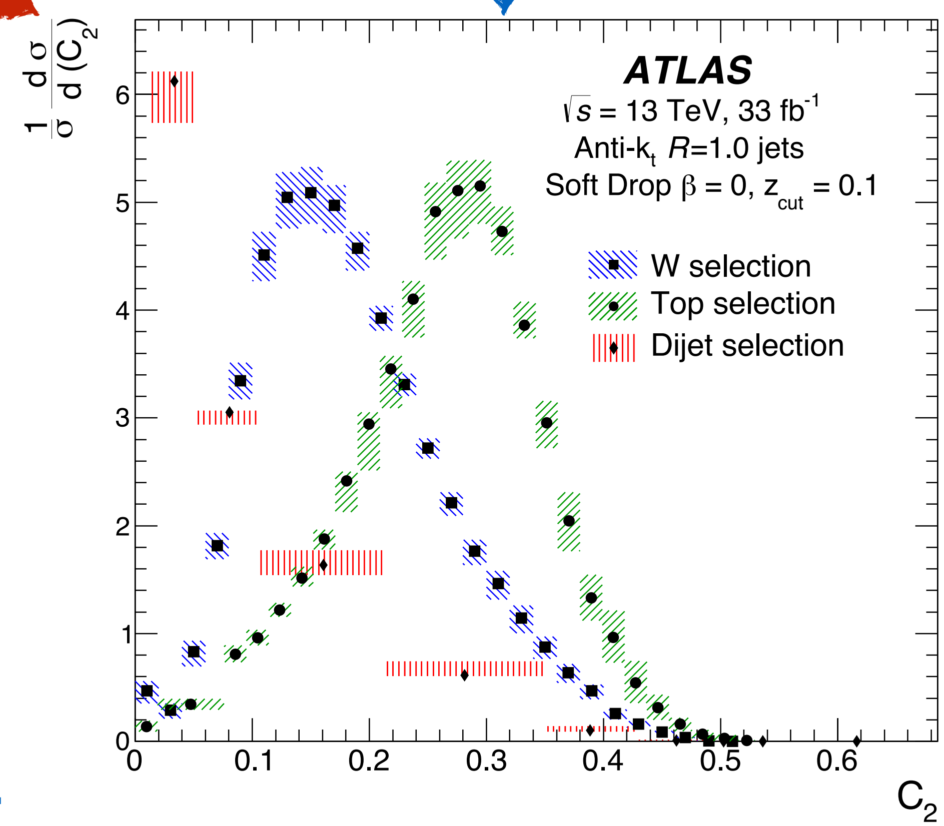






C2

$$C_2 = \frac{e_3}{(e_2)^2}$$



$$e_2 = \frac{\mathrm{ECF2}}{(\mathrm{ECF1})^2}$$

$$e_3 = \frac{\mathrm{ECF3}}{(\mathrm{ECF1})^3}$$

$$\mathrm{ECF1} = \sum_{i \in J} p_{\mathrm{T}_i}$$

$$\mathrm{ECF2}(\beta^{\mathrm{ECF}}) = \sum_{i<j \in J} p_{\mathrm{T}_i} p_{\mathrm{T}_j} \left(\Delta R_{ij}\right)^{\beta^{\mathrm{ECF}}}$$

$$\mathrm{ECF3}(\beta^{\mathrm{ECF}}) = \sum_{i<j<k \in J} p_{\mathrm{T}_i} p_{\mathrm{T}_j} p_{\mathrm{T}_k} \left(\Delta R_{ij} \Delta R_{ik} \Delta R_{jk}\right)^{\beta^{\mathrm{ECF}}}$$

[arXiv:1903.02942](https://arxiv.org/abs/1903.02942)

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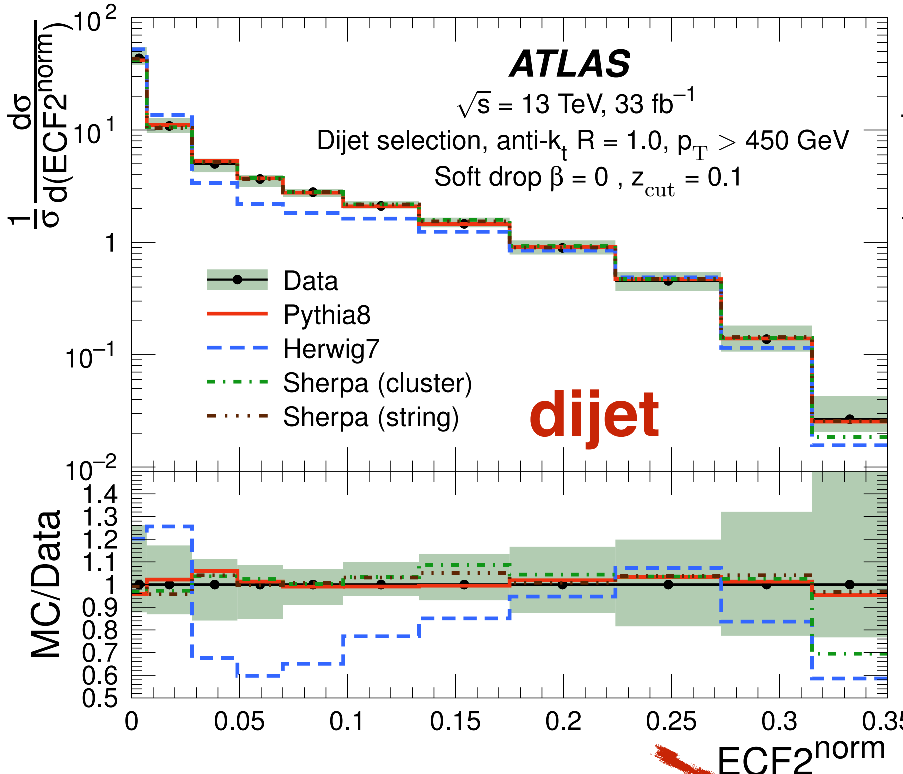
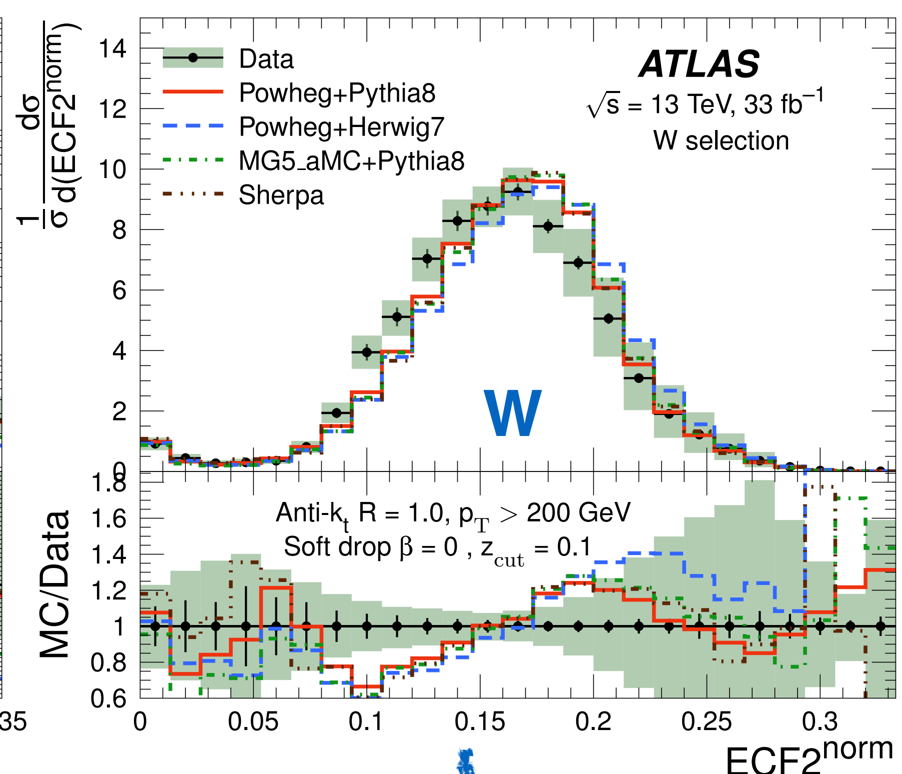
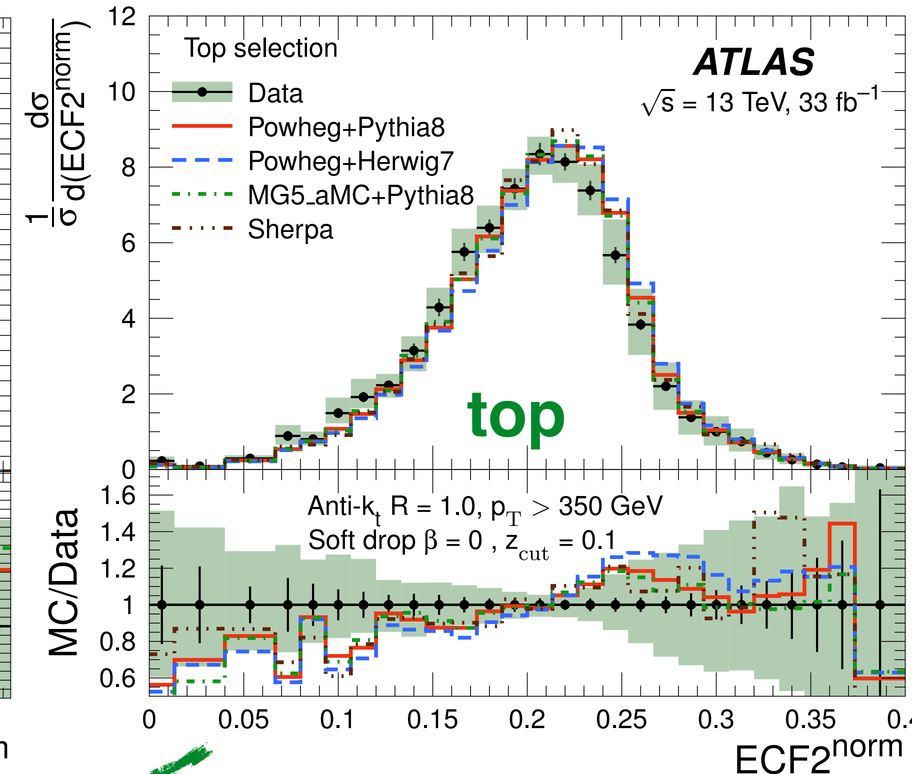
Measurement of jet substructure observables in top quark, W boson and light jet production

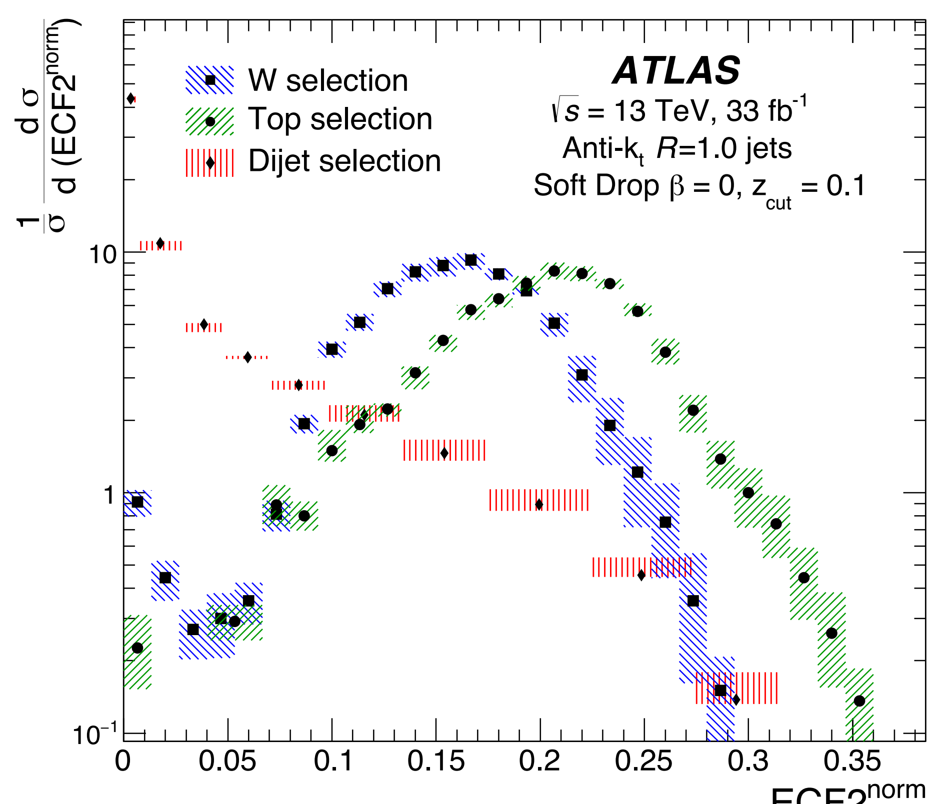






ECF2

$$\mathrm{ECF2}(\beta^{\mathrm{ECF}}) = \sum_{i<j\in J} p_{\mathrm{T}_i} p_{\mathrm{T}_j} \left(\Delta R_{ij}\right)^{\beta^{\mathrm{ECF}}}$$



arXiv:1903.02942

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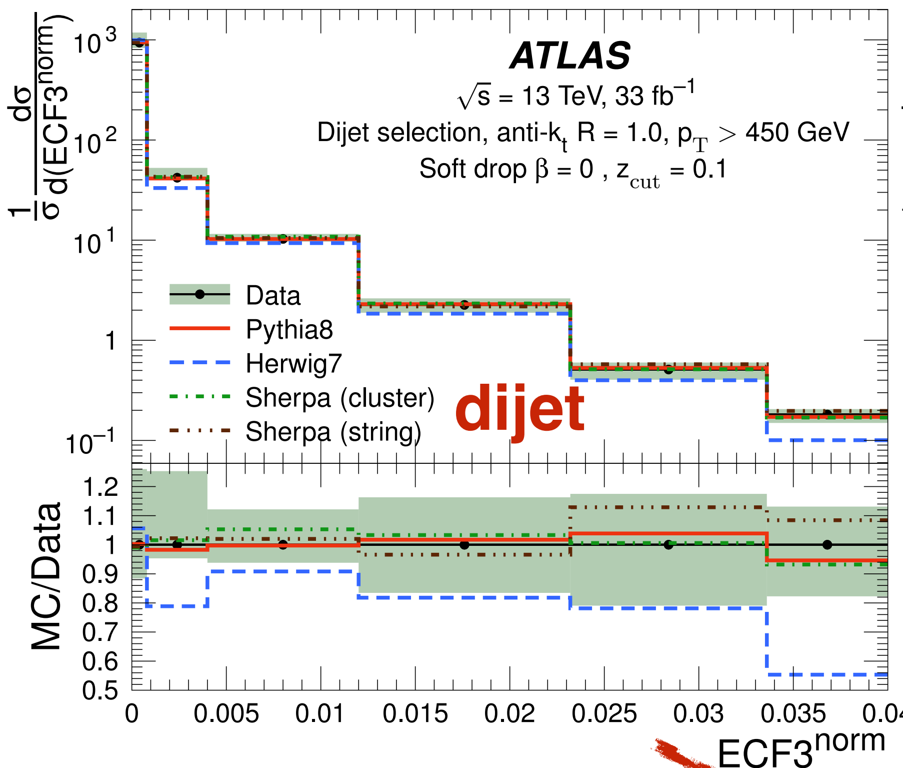
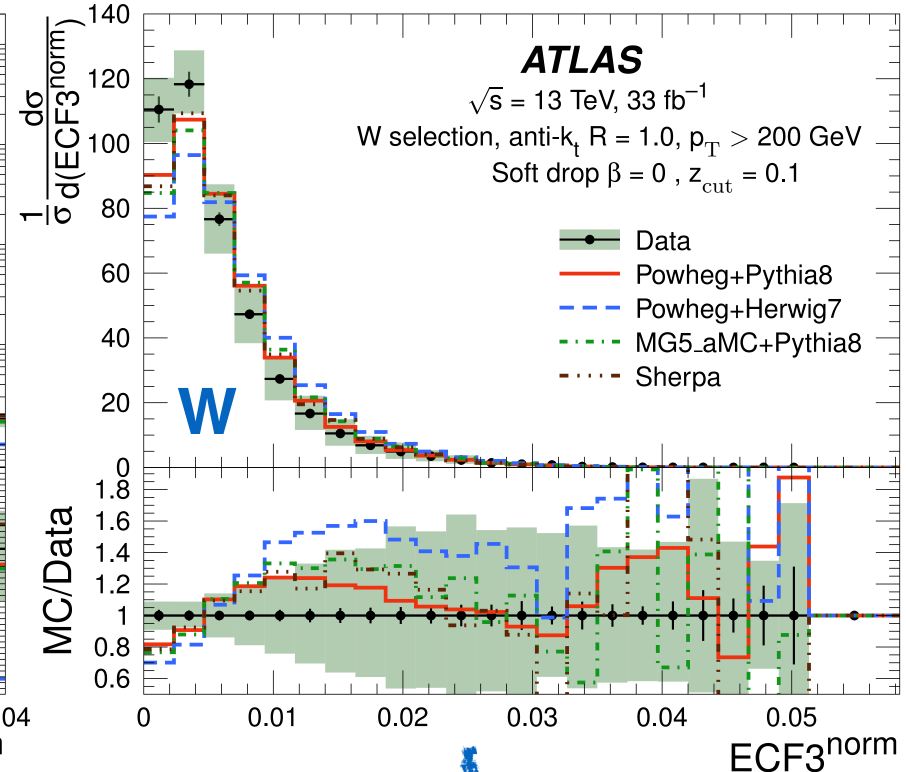
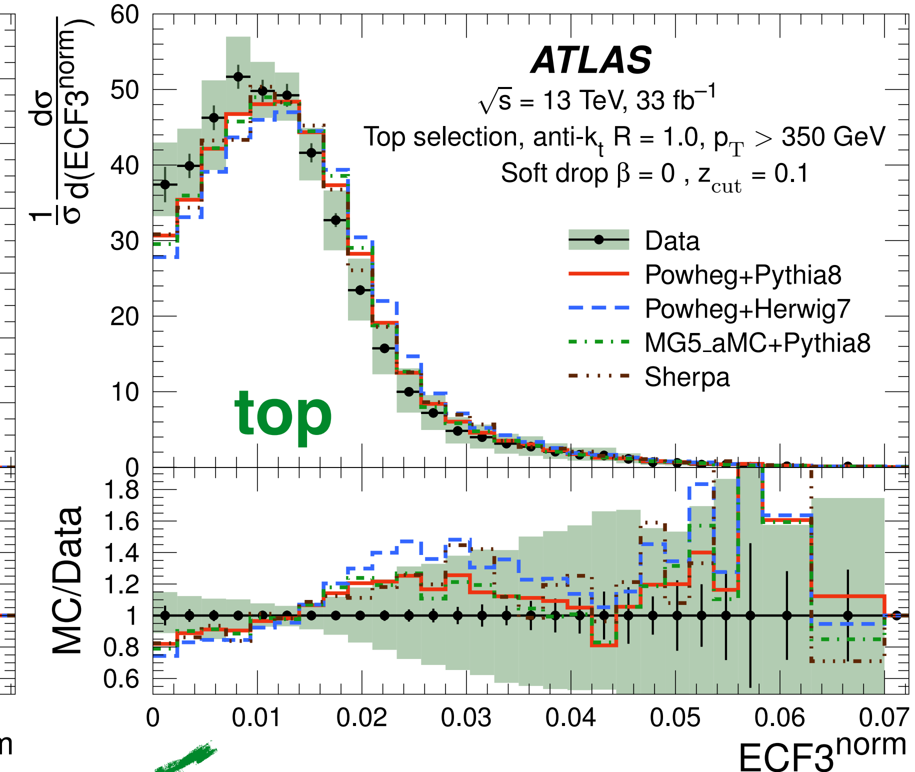
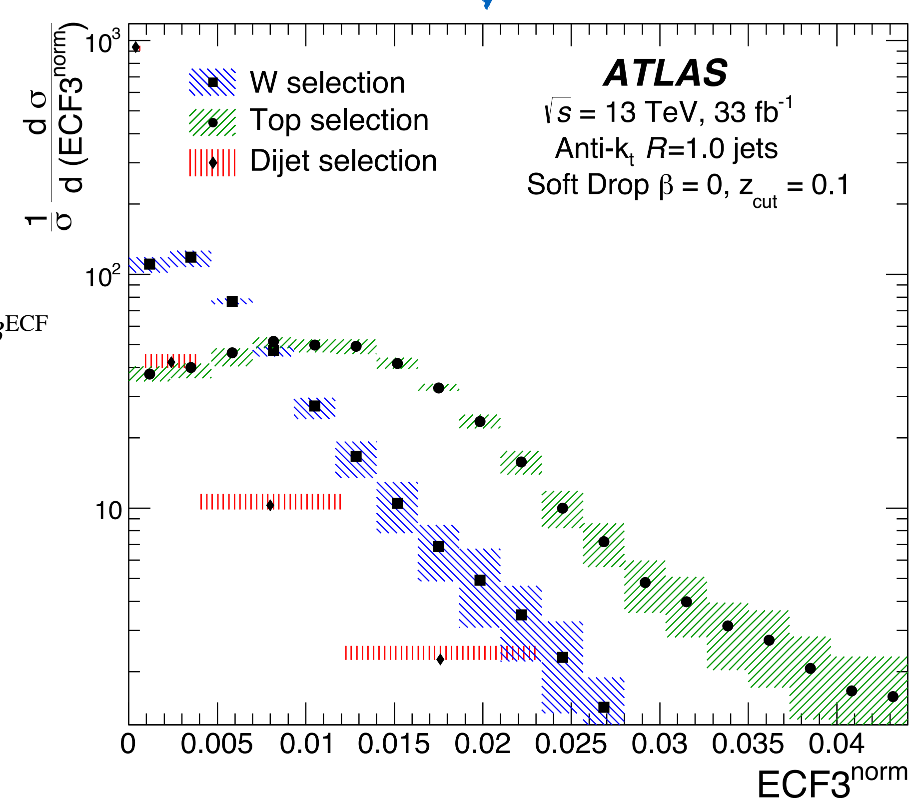






ECF3

$$\mathrm{ECF3}(\beta^{\mathrm{ECF}}) = \sum_{i<j<k\in J} p_{\mathrm{T}_i} p_{\mathrm{T}_j} p_{\mathrm{T}_k} \left(\Delta R_{ij}\Delta R_{ik}\Delta R_{jk}\right)^{\beta^{\mathrm{ECF}}}$$



arXiv:1903.02942

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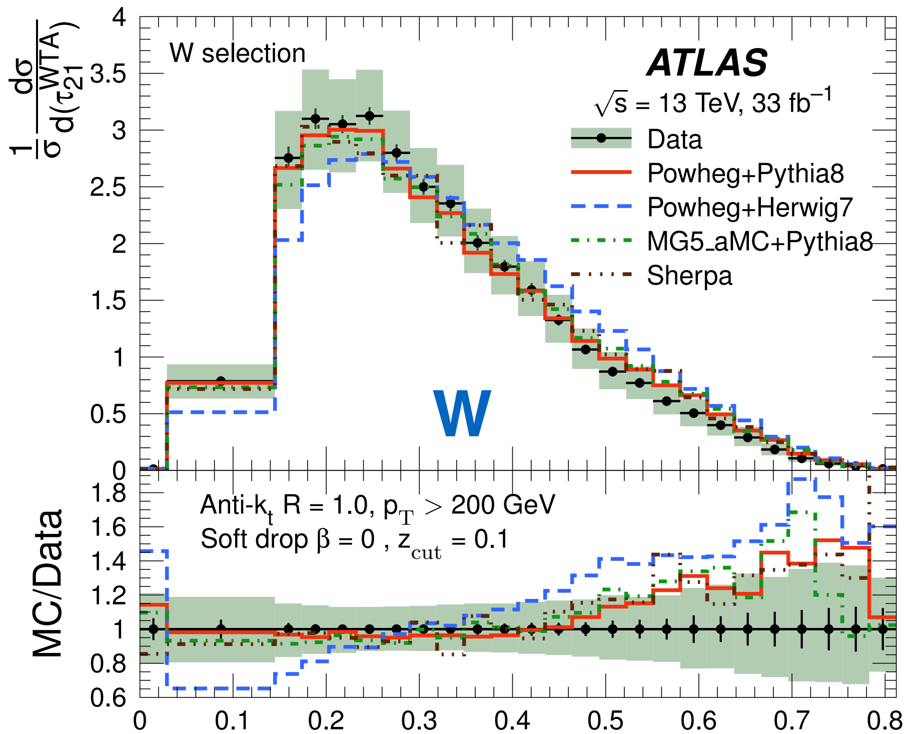
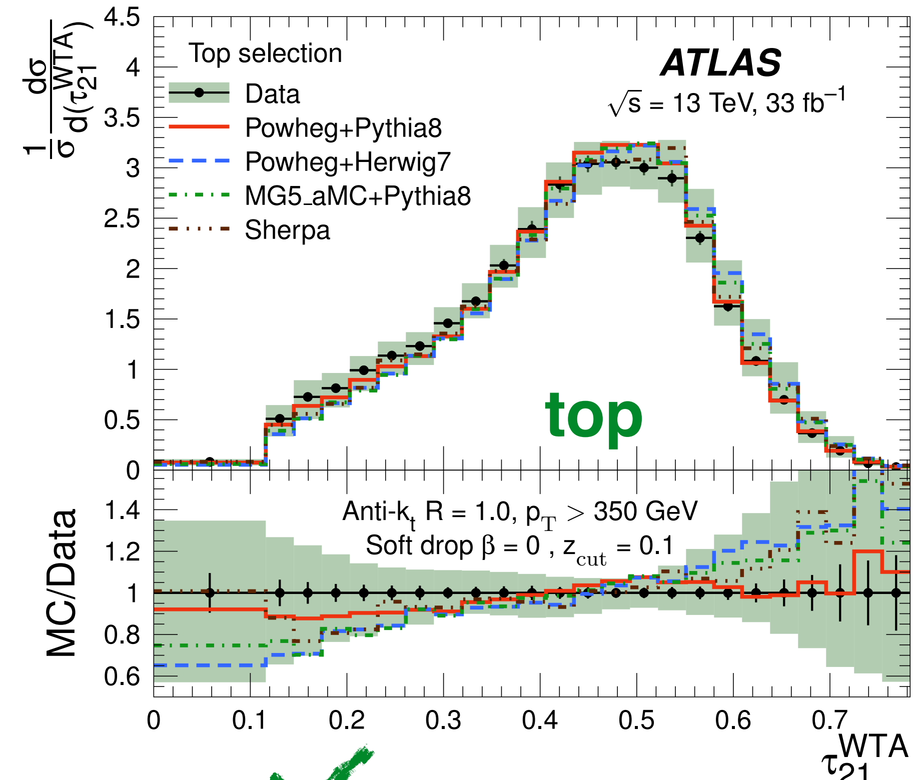
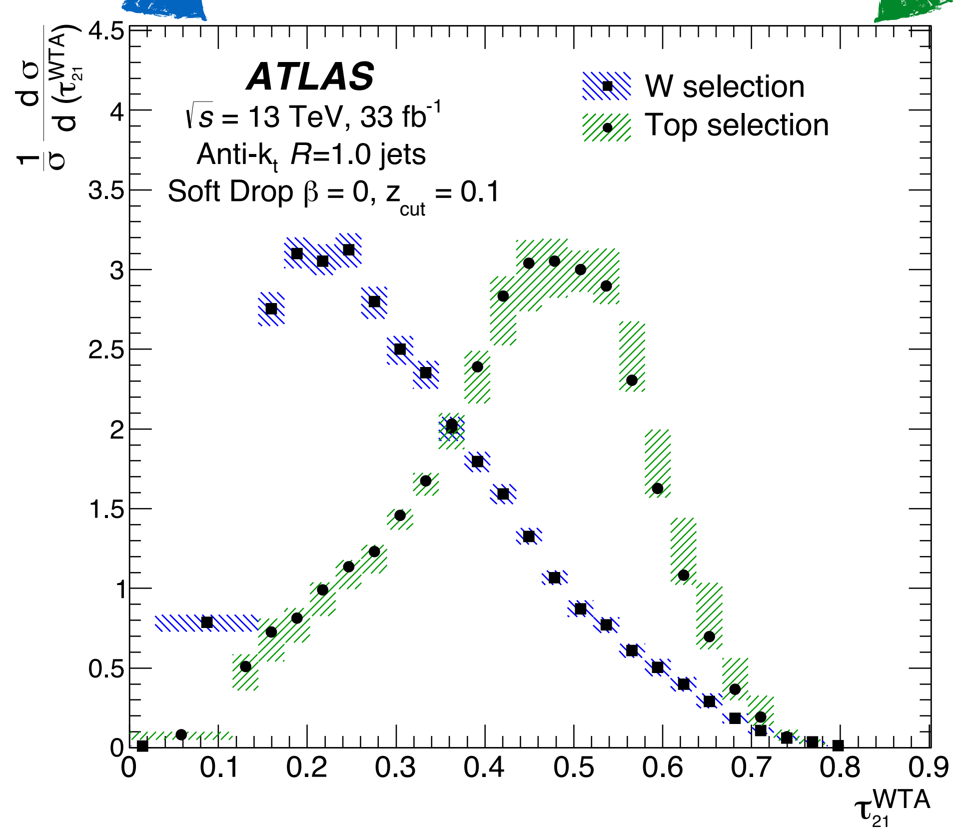
Measurement of jet substructure observables in top quark, W boson and light jet production







τ21

$$\tau_1(\beta^{NS}) = \frac{1}{\tau_0(\beta^{NS})} \sum_{i \in J} p_{T_i} \Delta R_{a_1,i}^{\beta^{NS}}$$

$$\tau_2(\beta^{NS}) = \frac{1}{\tau_0(\beta^{NS})} \sum_{i \in J} p_{T_i} \min(\Delta R_{a_1,i}^{\beta^{NS}}, \Delta R_{a_2,i}^{\beta^{NS}})$$

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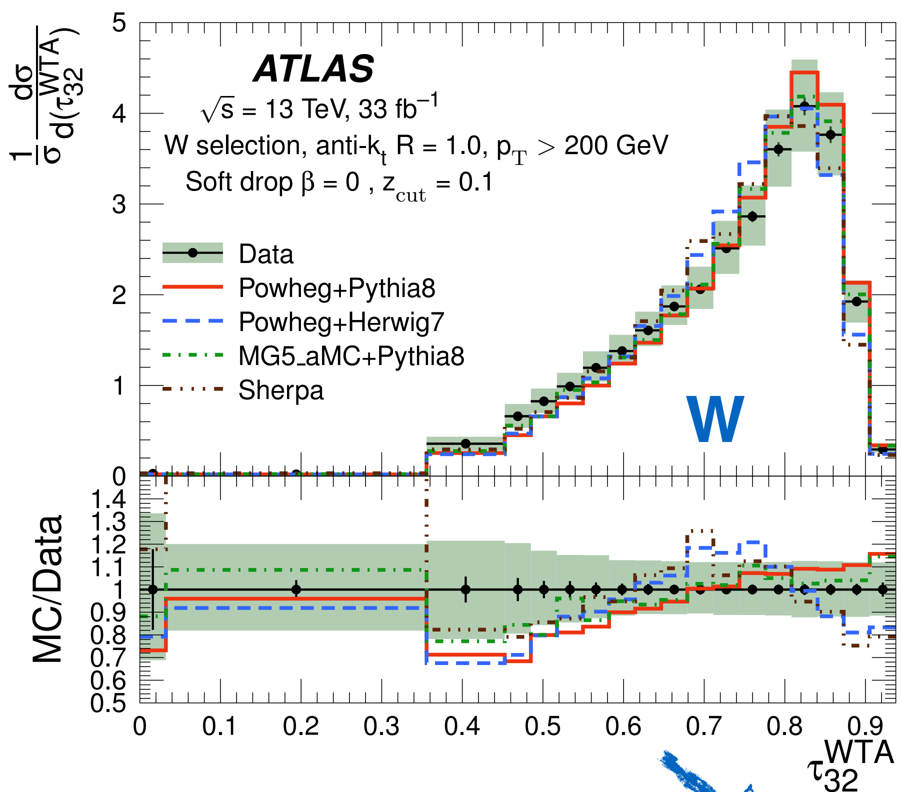
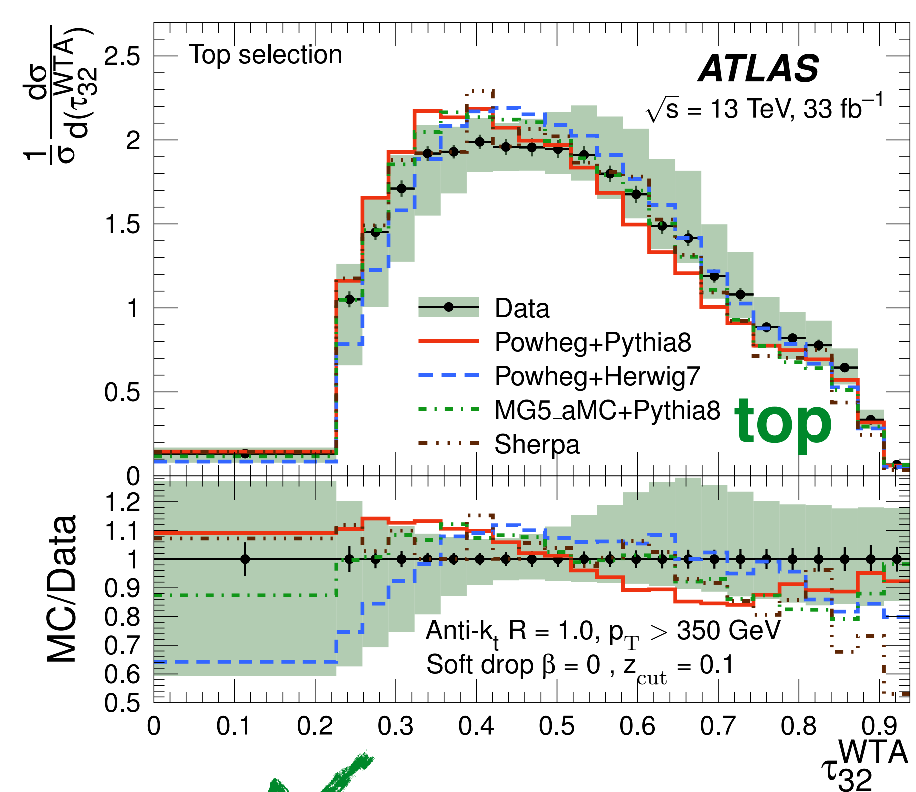
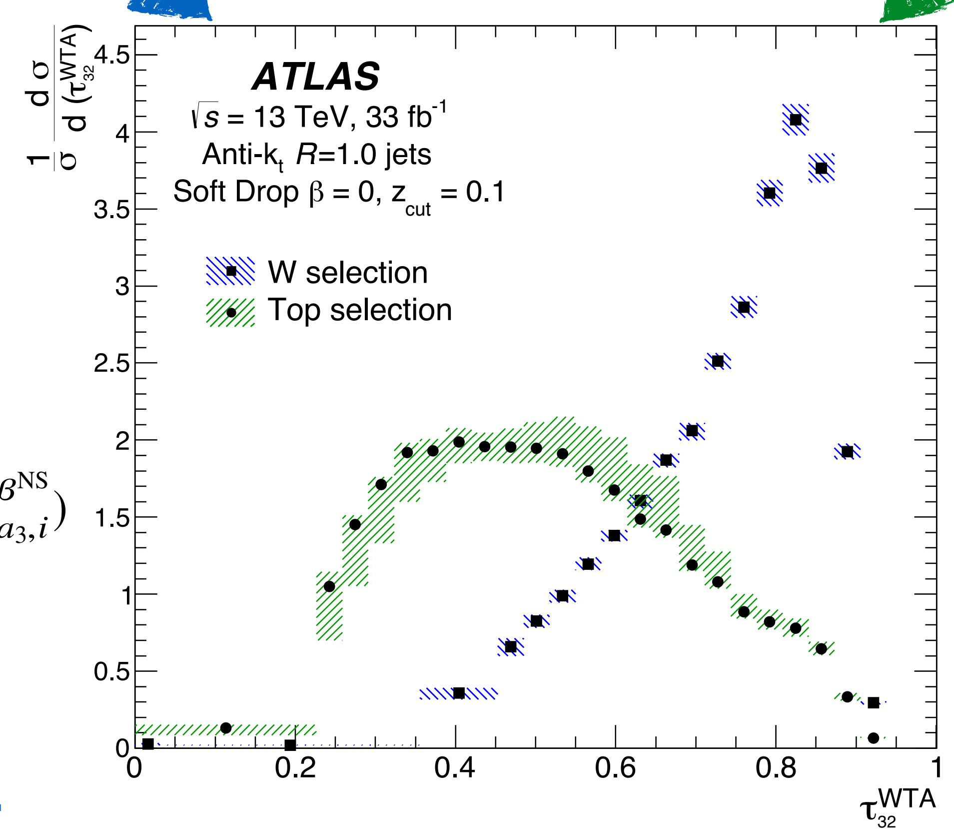




τ32

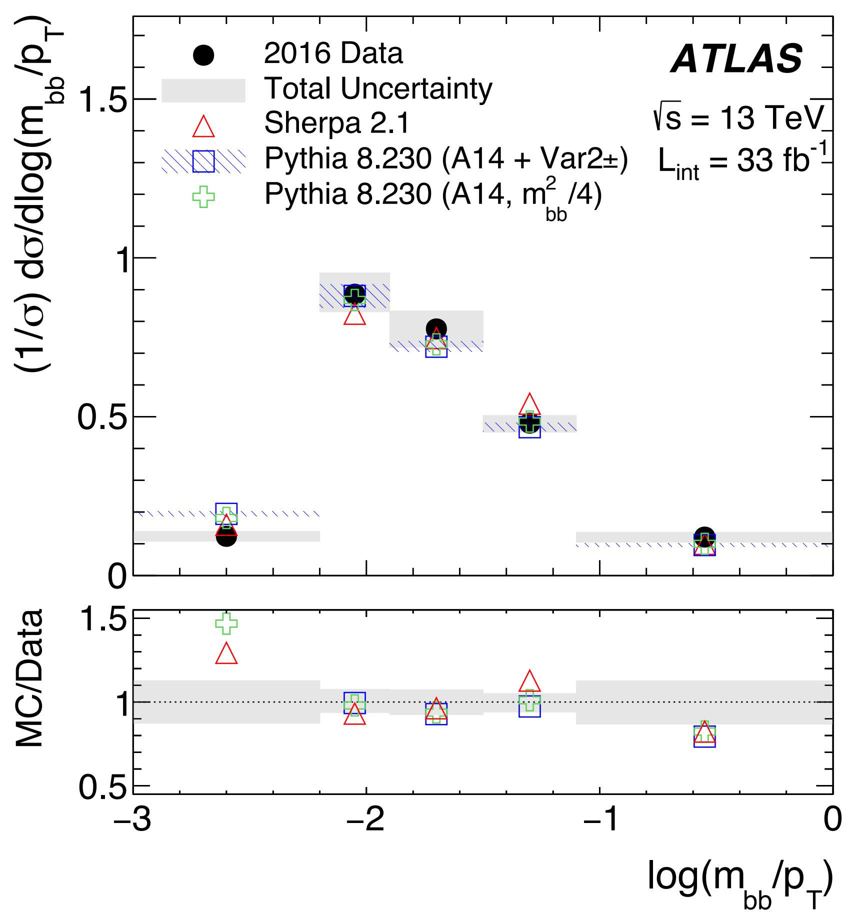
$$\tau_2(\beta^{\mathrm{NS}}) = \frac{1}{\tau_0(\beta^{\mathrm{NS}})} \sum_{i \in J} p_{\mathrm{T}_i} \min(\Delta R_{a_1,i}^{\beta^{\mathrm{NS}}}, \Delta R_{a_2,i}^{\beta^{\mathrm{NS}}})$$

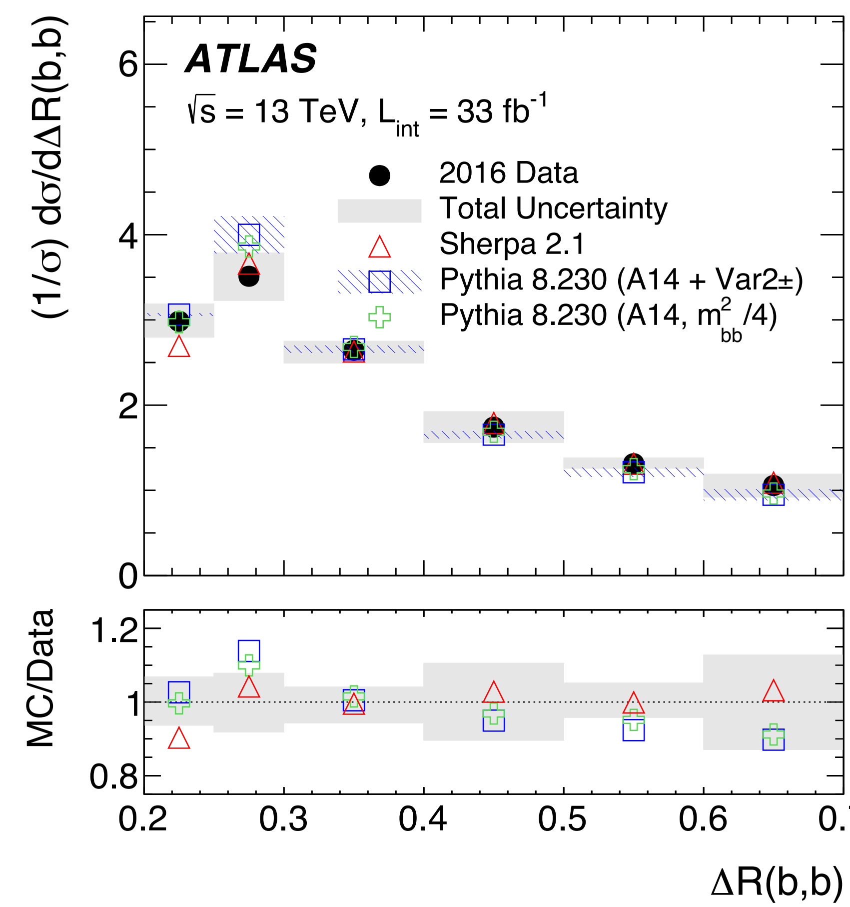
$$\tau_3(\beta^{\mathrm{NS}}) = \frac{1}{\tau_0(\beta^{\mathrm{NS}})} \sum_{i \in J} p_{\mathrm{T}_i} \min(\Delta R_{a_1,i}^{\beta^{\mathrm{NS}}}, \Delta R_{a_2,i}^{\beta^{\mathrm{NS}}} \Delta R_{a_3,i}^{\beta^{\mathrm{NS}}})$$



[arXiv:1903.02942](https://arxiv.org/abs/1903.02942)

Properties of g→bb at small opening angles





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Substructure systematics