Latest jet cross-section measurements in proton–proton collisions by ATLAS

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9 June 2020

Overview

- Jet cross-sections provide valuable information about the strong coupling constant, α_s, and the structure of the proton
- Final states with only jets represent a background to many other processes at hadron colliders

The measurements presented here collectively probe:

- Precision QCD predictions and MC predictions
- Jet substructure (substructure observables, trimming and soft-drop)
- Jet quantities related to fragmentation
- Event shapes in multijet events

Brief introduction on jets and grooming techniques

- Jets: collimated sprays of particles initiated by high-energy partons
- Grooming techniques (soft drop, trimming) remove soft and wide-angle radiation, making jets robust against pileup, final-state radiation and underlying event

Trimming procedure: Reconstruct very-small-R jets from constituents and discard those that have very low p_{T} fraction

Soft-drop procedure:

- Jet constituents are reclustered using C/A algorithm
  - Which iteratively clusters the closest constituents in rapidity and azimuth
- Last step of clustering is undone, breaking the jet into two subjets (j_1 & j_2)
- These subjets are then used to evaluate the soft-drop condition:

$$\frac{\min\left(p_{\mathrm{T},j1}, p_{\mathrm{T},j2}\right)}{p_{\mathrm{T},j1} + p_{\mathrm{T},j2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

- z_{cut} and β regulates the sensitivity to soft and wide-angle radiation
- Failed condition: subjet w/ lower p_{T} is removed and the procedure is iterated with the remaining jet
- Satisfied condition: algorithm stops and resulting jet is the soft-drop jet

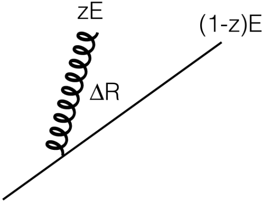
Lund Plane measurement with charged particles

[arXiv:2004.03540]

[Submitted to PRL]

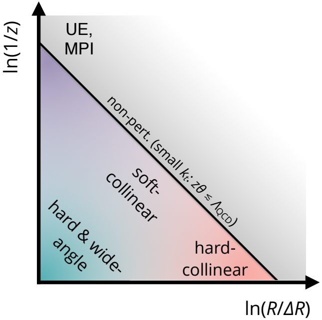
Lund plane measurement with charged particles in Full Run 2 data

- In the soft gluon ('eikonal') picture of jet formation, a quark or gluon radiates a haze of relatively low energy and statistically independent gluons
- Emission pattern is ≈ uniform in $ln(1/z)$–$ln(1/\Delta R)$
  - z: relative momentum fraction of the emitted gluon
  - ΔR: emission opening angle
- This space is called the **Lund plane**, where different physical effects factorize



- How to extract z & ΔR proxies [ref]:
  - Recluster jet's constituents w/ C/A, reverse clustering history
  - At each step in the C/A declustering sequence, Lund plane is filled w/:
  - $z = p_{\mathrm{T}}(j_2)/(p_{\mathrm{T}}(j_1) + p_{\mathrm{T}}(j_2))$ & $\Delta R = \Delta R(j_1, j_2)$
  - Where j_1 (j_2) is the hardest (softer) of the proto-jet pair

Regions of the Lund Plane



Lund plane measurement with charged particles | Selections & Results

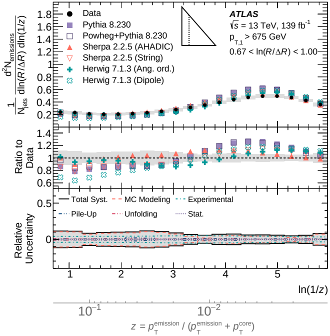
Event selection and procedure:

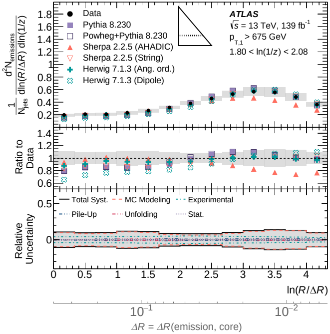
- Leading anti-k_t $R = 0.4$ jet $p_{\mathrm{T}} > 650\,\mathrm{GeV}$, $p_{\mathrm{T}}^{\text{lead}} < 1.5 \times p_{\mathrm{T}}^{\text{sublead}}$
- First two leading p_{T} jets w/ $|\eta| < 2.1$
- Tracks matched to jets ($\Delta R = 0.4$) are used to recluster C/A jets

Uncertainties:

- Jets and tracks
- Unfolding, particle-detector matching and pile-up modelling
- **Fragmentation modelling**

Slices in the plane are done to quantitatively compare with MC





No prediction describes the data in all regions, but Herwig 7.1.3 angle-ordered provides the best description across most of the plane

Measurement of Soft Drop jet Observables at 13 TeV

[Phys. Rev. D 101 (2020) 052007]

[arXiv:1912.09837]

Soft Drop Jet Observables at 13 TeV (using 2016 ATLAS data)

Jets:

- Soft drop applied to calorimeter- and track-based jets reconstructed w/ anti-k_t algorithm and $R = 0.8$
- Tracks are those that match the ungroomed jets using ghost-association

Event selection:

- At least two jets with $p_{\mathrm{T}}^{\text{lead}} > 300\,\mathrm{GeV}$ and within $|\eta| < 1.5$
- Dijet topology enhanced by requesting $p_{\mathrm{T}}^{\text{lead}}/p_{\mathrm{T}}^{\text{sublead}} < 1.5$

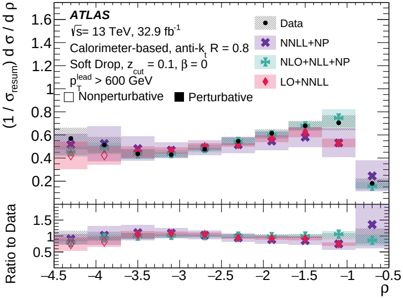
Double-differentially cross sections measured for these observables:

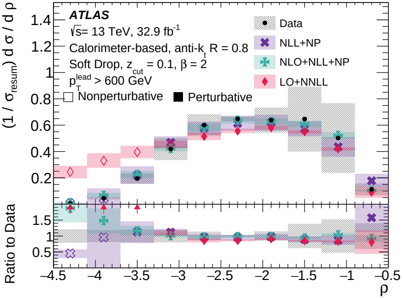
- Relative jet mass: $\rho = m^2/p_{\mathrm{T}}^2$ (m is groomed and p_{T} is ungroomed)
- p_{T} balance z$_g$ from the soft-drop condition $\left(\dfrac{\min(p_{\mathrm{T},j1}, p_{\mathrm{T},j2})}{p_{\mathrm{T},j1} + p_{\mathrm{T},j2}}\right)$
- r_g: Opening angle of the splitting (ΔR_{12})

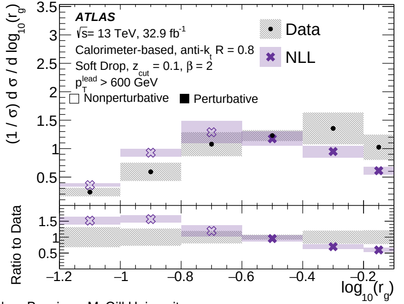
Systematics:

- Calorimeter-cell cluster uncertainties
- MC and pileup modelling and unfolding non-closure
- Tracking uncertainties are negligible

Soft Drop observables | Comparisons with analytical predictions

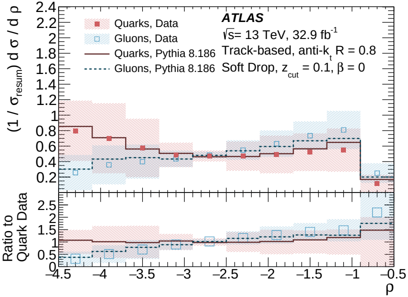


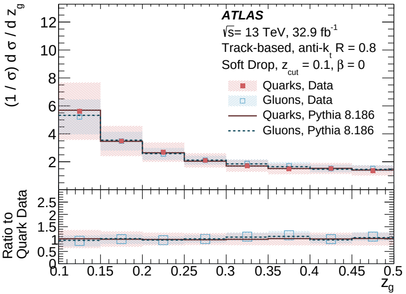


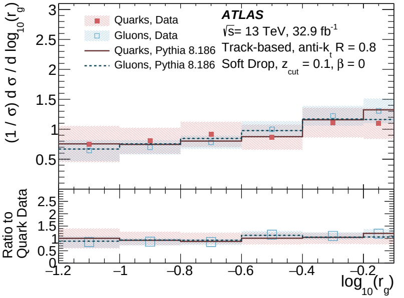


- ρ:
  - Calculations are able to model the data in the resummation region ($-3 \lesssim \rho \lesssim -1$) at the level of a 10% difference
  - NLO+NLL models well data at the high values of ρ, while LO+NLL and NNLL don't
- r_g: The prediction is systematically higher than the data in regions where nonperturbative effects are large

Soft Drop observables | Quark-gluon track-based distributions ($\beta = 0$)







- Gluon distribution tends towards higher values of ρ and larger splitting
- This becomes more apparent at larger values of β
- z_g: Very similar distributions for $\beta = 0$, while some differences begin to appear for $\beta > 0$
- In general, data distributions are in agreement with MC predictions

Properties of jet fragmentation using charged particles at $\sqrt{s} = 13\,\text{TeV}$

[Phys. Rev. D 100 (2019) 052011]

[arXiv:1906.09254]

Jet fragmentation properties (using 2016 ATLAS data)

Jets: Calorimeter-based jets reconstructed with anti-k_t and $R = 0.4$

Event selection:

- At least two jets with $p_{\mathrm{T}}^{\text{lead}} > 60\,\mathrm{GeV}$ and within $|\eta| < 2.1$
- Dijet topology enhanced by requesting $p_{\mathrm{T}}^{\text{lead}}/p_{\mathrm{T}}^{\text{sublead}} < 1.5$

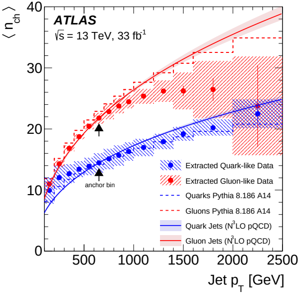
Observables: (two more were studied by are not discussed today)

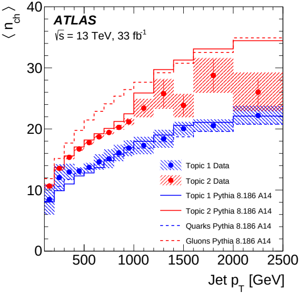
- Charged-particle multiplicity (n_{ch}): # of charged particles inside a jet
- Radial profile ($< r >$): Weighted average number of charged particles (weighted by radial distance w.r.t. jet axis)

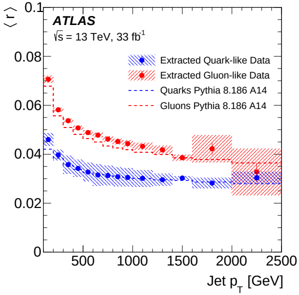
Systematics:

- Rate of fake and secondary tracks (result of interactions in detector material)
- Tracking efficiency
- MC modelling
- Unfolding uncertainty
- Jet energy scale and resolution uncertainties much smaller than the rest

Jet fragmentation properties | Data vs MC and pQCD predictions







- $< n_{\mathrm{ch}} >$:
  - Predictions describe the quark-like data, but the gluon-like data have sistematically fewer charged particles than the prediction
  - Similar conclusions from the two jet flavour labelling approches
- Radial profile:
  - Predictions describe the quark-like data, but underestimate the gluon-like data

Brand new results!

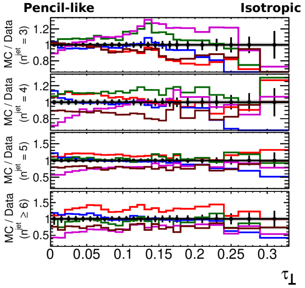
Measurement of hadronic event shapes in multijet final states at $\sqrt{s} = 13$ TeV

[ATLAS-CONF-2020-011]

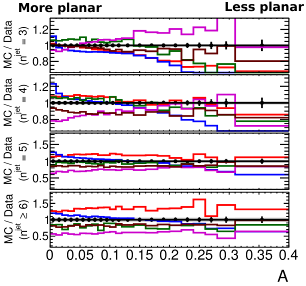
Measurement of hadronic event shapes in multije final states

- Event shapes are a family of observables which are sensitive to event-wide energy flow:
  - *Thrust*: How dijet-like is the event?
    - **Pythia (LO)** describes the data well in dijet-like topologies
    - **Sherpa** over-estimation becomes more pronounced as n^{jet} increases
    - Herwig7 (**dipole** & **ang. ord.** PS) show different trends
    - **MadGraph** underestimate the data
  - *Aplanarity*: How planar is the event?
    - Sensitivity to PS algorithm selection in Herwig7 is apparent (**dipole** & **ang. ord.** PS)
    - **Sherpa** over-predicts events at high n^{jet}
    - **Pythia** describes more-planar events best
    - **MadGraph** underestimate the data but agreement in shape

Thrust:



Aplanarity:



Conclusions

- Many great jet cross section measurements from ATLAS
- Interesting results probing new techniques and different physic effects
- Most of the results are well modelled by predictions
- But some discrepancies are observed in some results
- Giving room to improve MC event simulations and pQCD predictions

Back-up slides

Quark-gluon extraction of the observables

Following approach is used to extract the quark and gluon distributions

- Take the more forward (f) and central (c) of the two selected jets
- Using the fraction of quark jets f_q from MC we can extract the quark (h_i^q) and gluon (h_i^g) jet fragmentation properties separately by solving the following per bin i of an observable:

$$h_i^f = f_q^f h_i^q + (1 - f_q^f) h_i^g$$
$$h_i^c = f_q^c h_i^q + (1 - f_q^c) h_i^g$$

where the flavour of a jet in MC is defined as the type of the highest-E parton

An alternative approach (**topic modelling**) is used by one of the analyses:

- This does not require the input of any fractions from MC
- We can extract distributions of 'topics' T_1 and T_2 (more in back-up)
- Used only for those observables which ensures that first topic is well aligned with quarks and second one is more gluon-like

Topic modelling

In this, we can extract distributions of 'topics' T_1 and T_2

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

where:

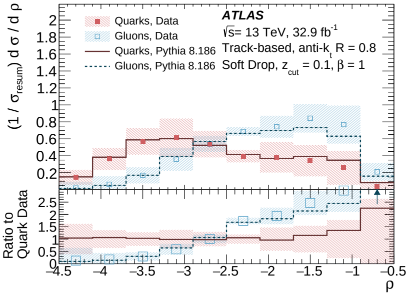
- h_i is a bin of a histogram for an observable
- f and c represent the forward and central regions
- q and g represent quark or gluon

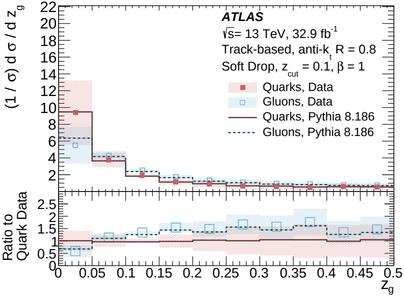
Measurement of Soft Drop jet Observables at 13 TeV

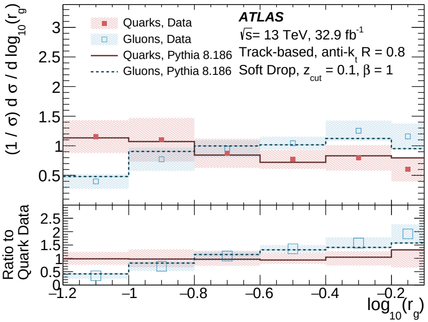
[Phys. Rev. D 101 (2020) 052007]

[arXiv:1912.09837]

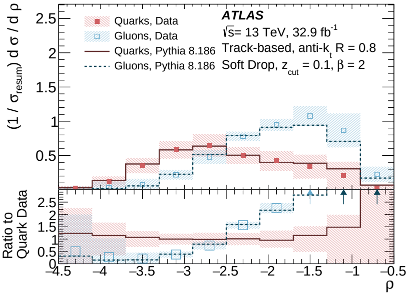
Soft Drop observables | Quark-gluon track-based distributions ($\beta = 1$)

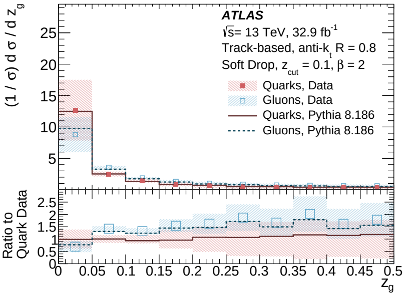


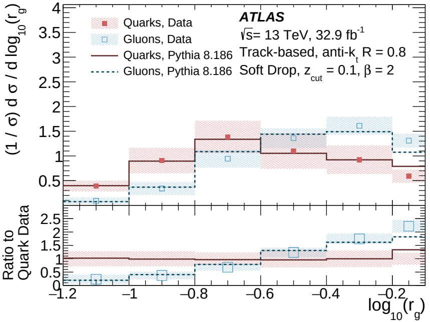




Soft Drop observables | Quark-gluon track-based distributions ($\beta = 2$)

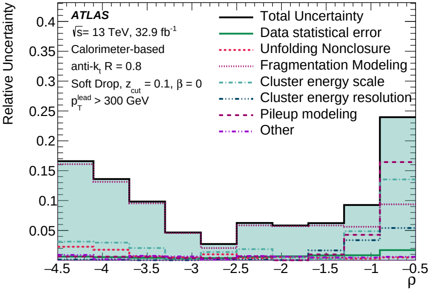


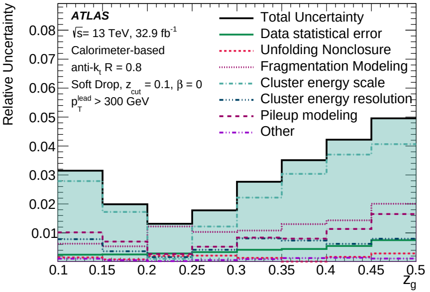




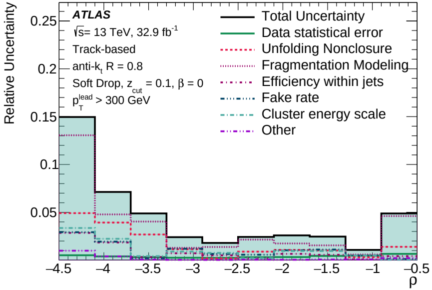
Soft Drop observables | Systematics

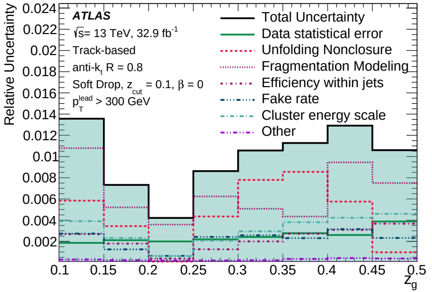
Calorimeter-based





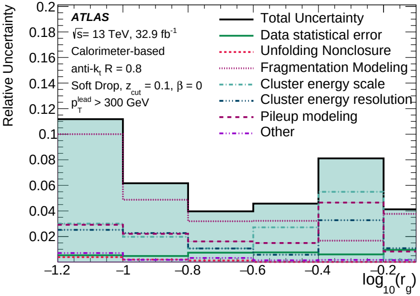
Track-based



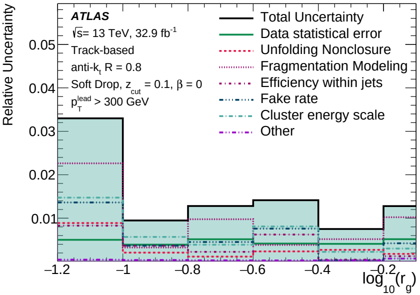


Soft Drop observables | Systematics

Calorimeter-based



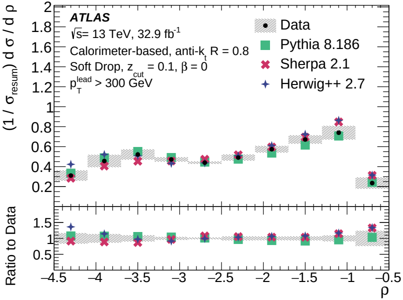
Track-based

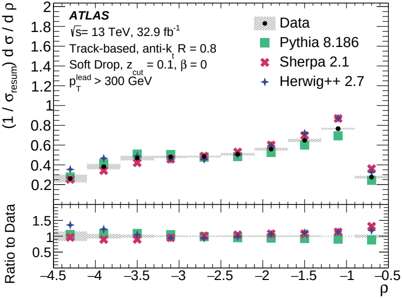


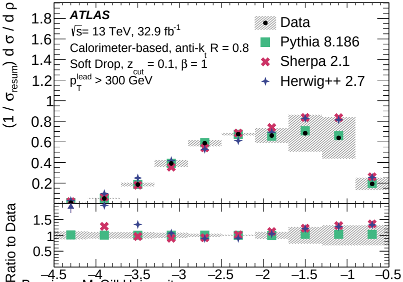
Soft Drop observables | MC/data plots for ρ

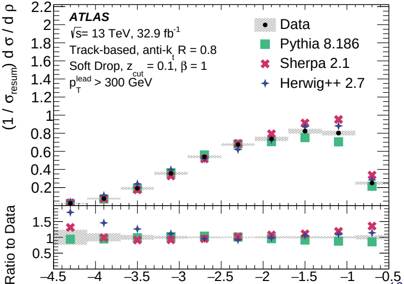
Calorimeter-based

Track-based

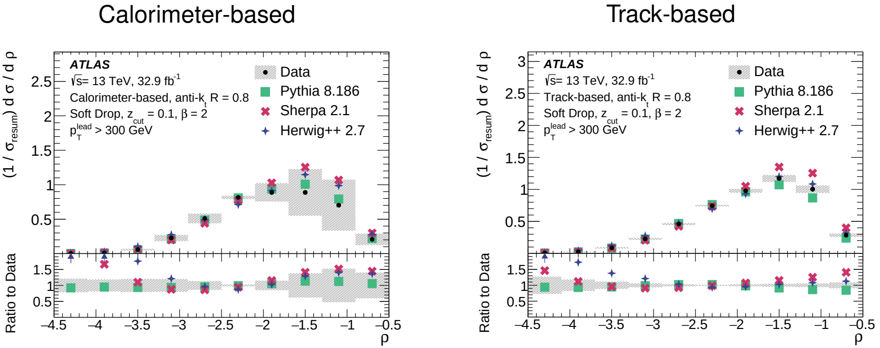








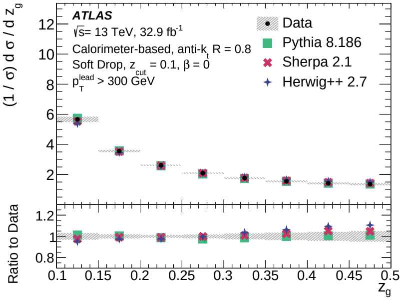
Soft Drop observables | MC/data plots for z_g

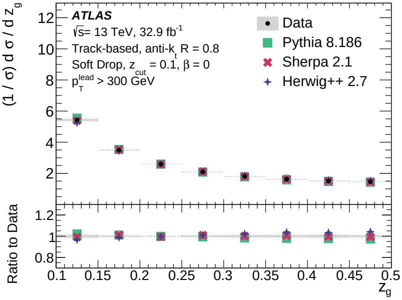


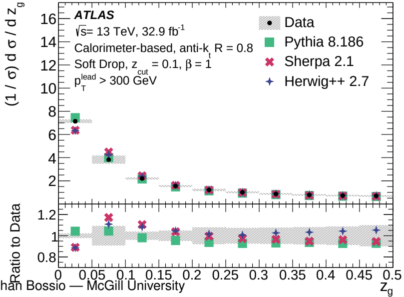
Soft Drop observables | MC/data plots for z_g

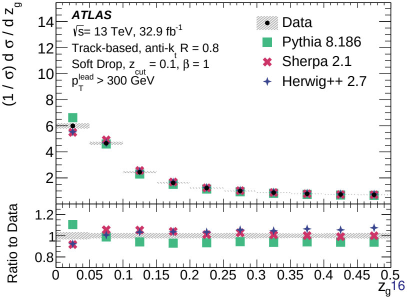
Calorimeter-based

Track-based

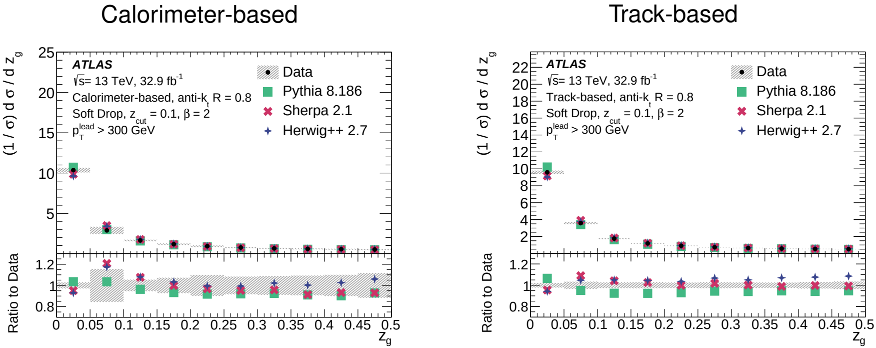








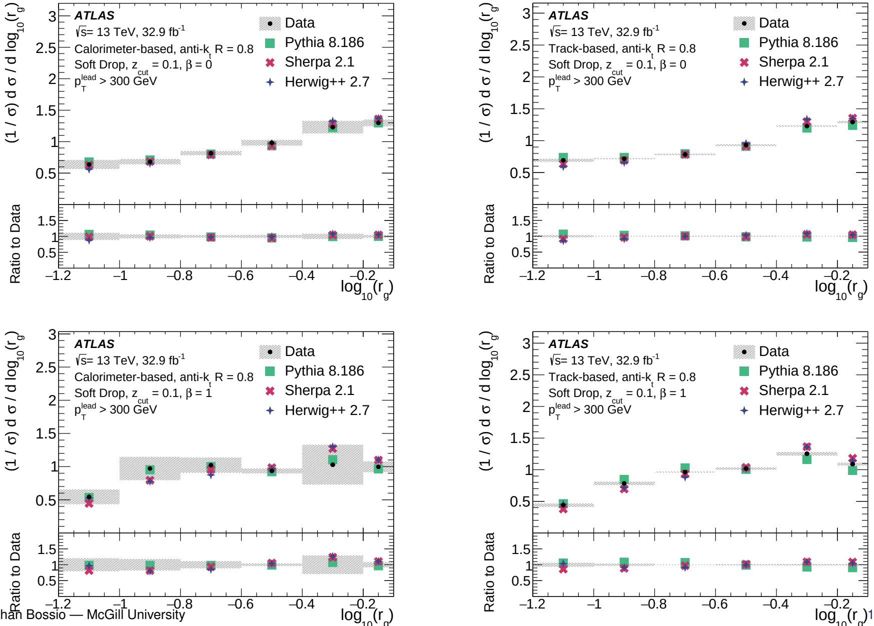
Soft Drop observables | MC/data plots for z_g



Soft Drop observables | MC/data plots for r_g

Calorimeter-based

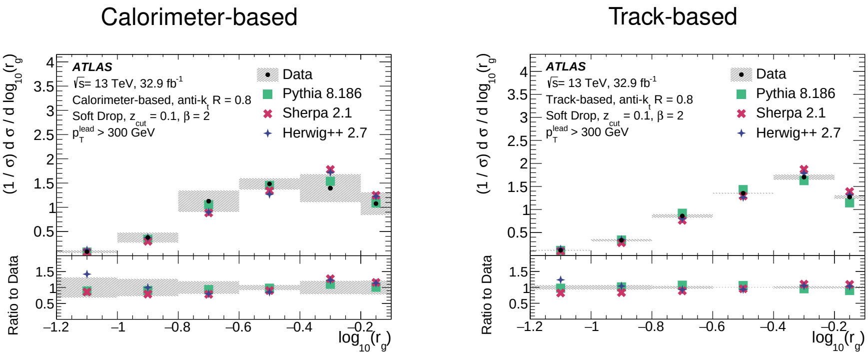
Track-based



Soft Drop observables | MC/data plots for r_g

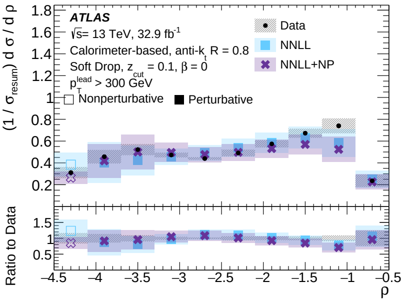
Calorimeter-based

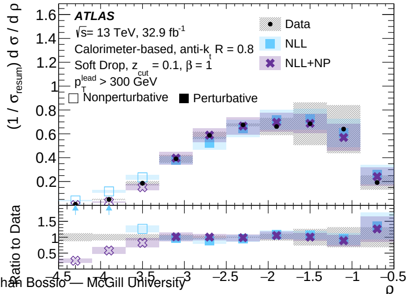
Track-based



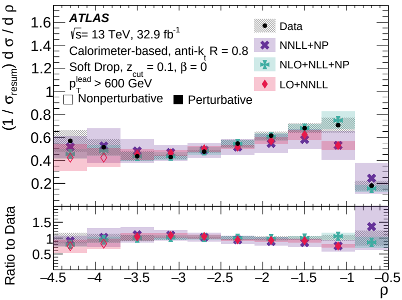
Soft Drop observables | Comparisons to analytical predictions

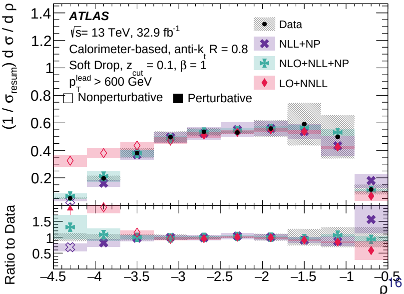
Low p_T





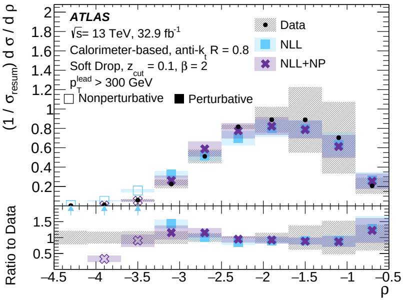
High p_T



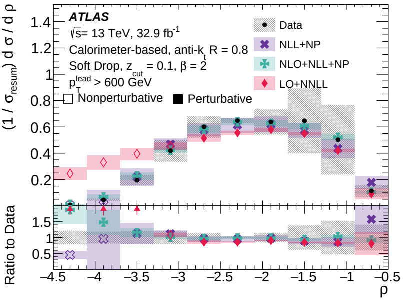


Soft Drop observables | Comparisons to analytical predictions

Low p_T

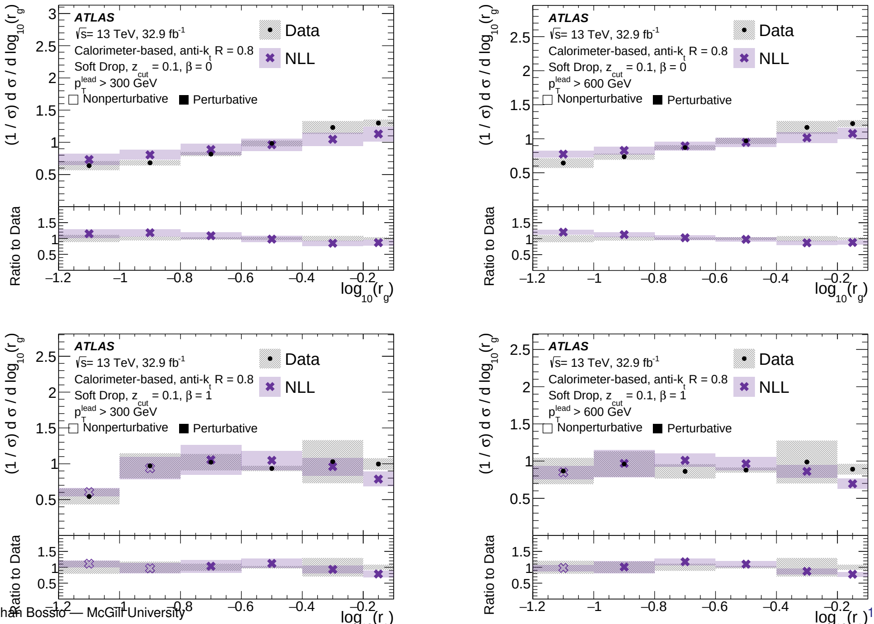


High p_T

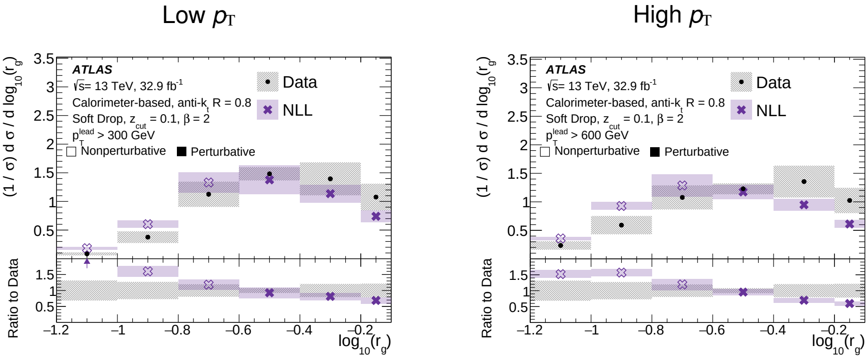


Soft Drop observables | Comparisons to analytical predictions

Low p_T High p_T



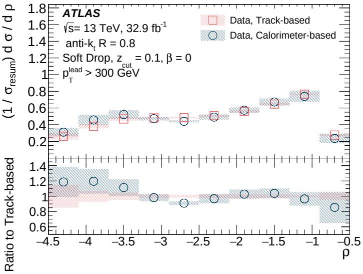
Soft Drop observables | Comparisons to analytical predictions


Low p_T

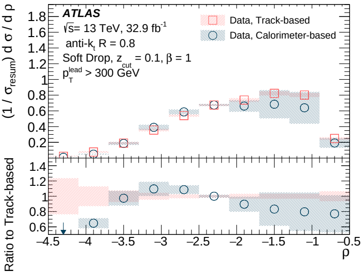
High p_T

Soft Drop observables | Calorimeter- vs track-based ρ

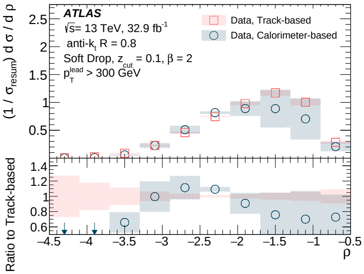
$\beta = 0$



$\beta = 1$

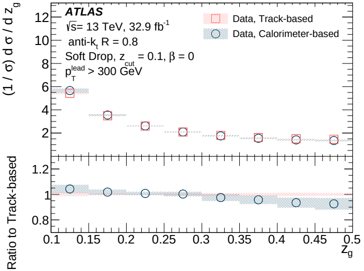


$\beta = 2$



Soft Drop observables | Calorimeter- vs track-based z_g

$\beta = 0$



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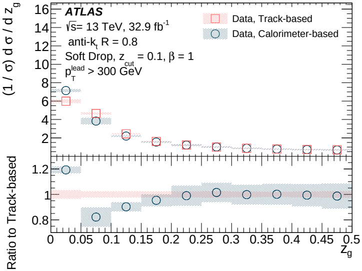
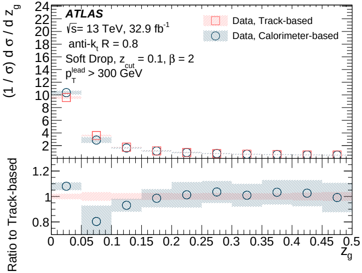
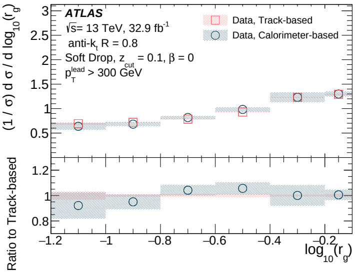


$\beta = 2$

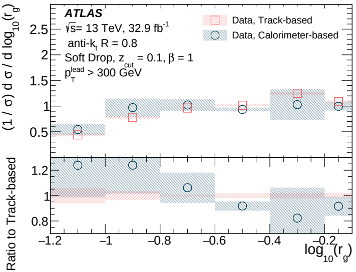


Soft Drop observables | Calorimeter- vs track-based r_g

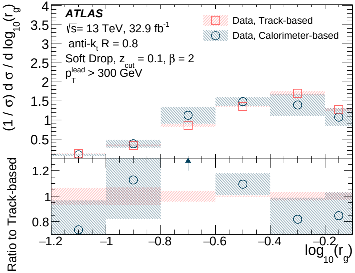
$\beta = 0$



$\beta = 1$



$\beta = 2$



Properties of jet fragmentation using charged particles at $\sqrt{s} = 13\,\textbf{TeV}$

[Phys. Rev. D 100 (2019) 052011]

[arXiv:1906.09254]

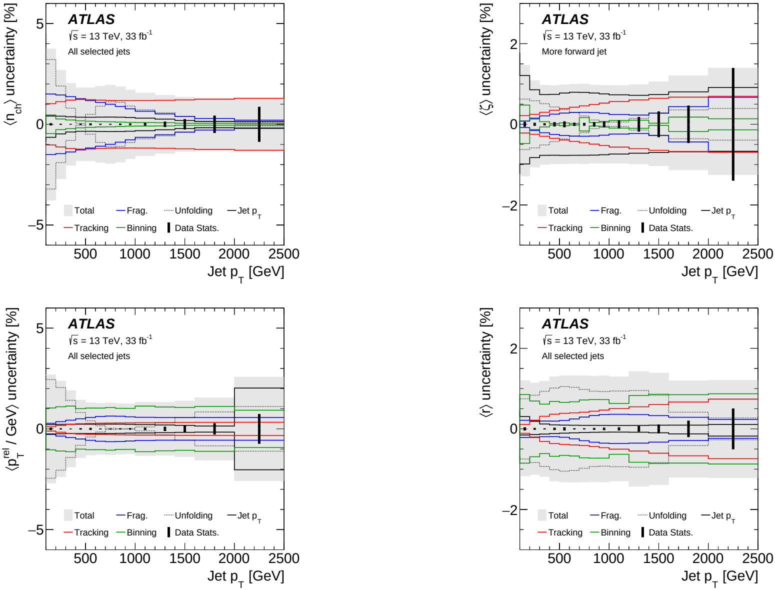
Jet fragmentation properties | Other observables

Summed fragmentation function: The distribution of the fragmentation fraction is studied inside jets summed over charged-hadron types

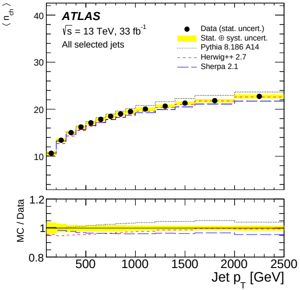
Where the fragmentation function describes the probability of finding a hadron *h* with energy fraction *z* of the parton *p* that has energy *E*.

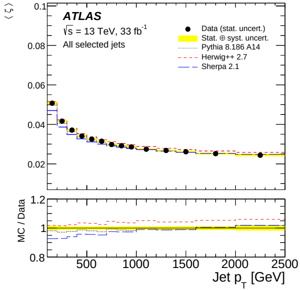
Transverse momentum: $p_{\mathrm{T}}^{\mathrm{rel}} = p_{\mathrm{T}}^{\text{charged particle}} sin\Delta\phi$, where $\Delta\phi$ is the angle b/w the charged particle and the jet axis in the transverse plane

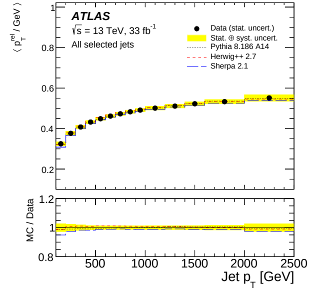
Jet fragmentation properties | Uncertainties

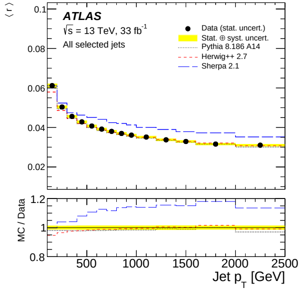


Jet fragmentation properties | Unfolded data vs MC

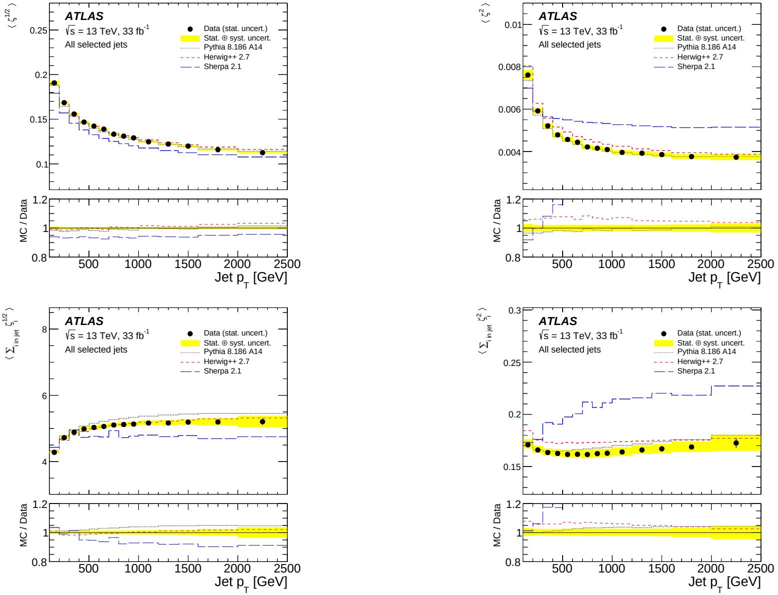




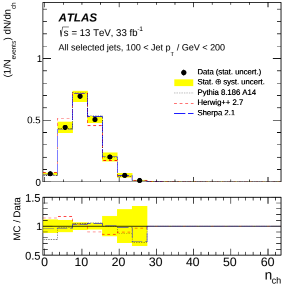


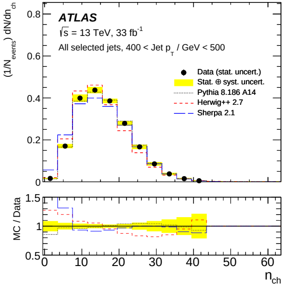


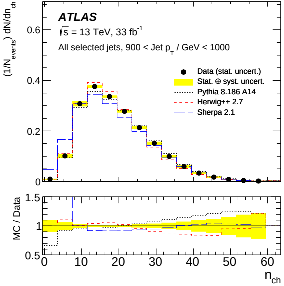
Jet fragmentation properties | Unfolded data vs MC

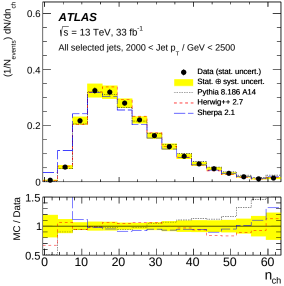


Jet fragmentation properties | Distribution of the observables

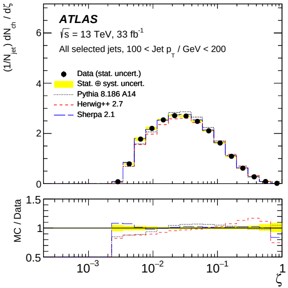


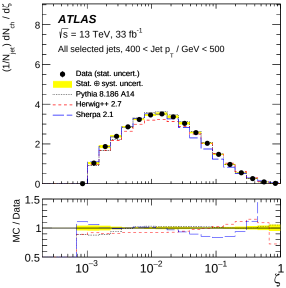


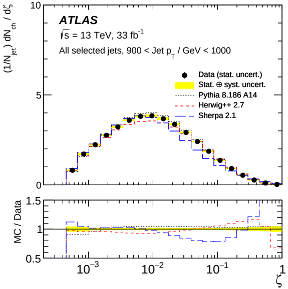


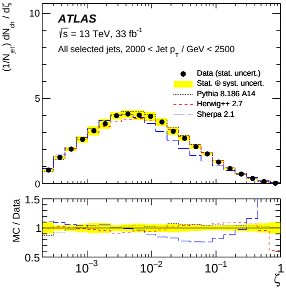


Jet fragmentation properties | Distribution of the observables

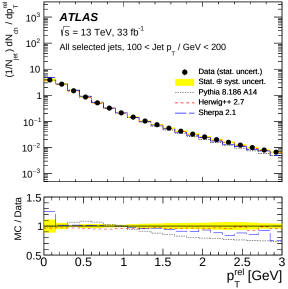


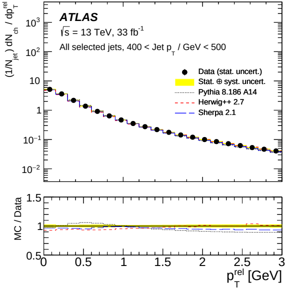


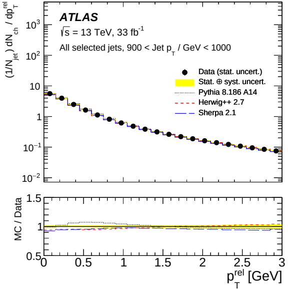


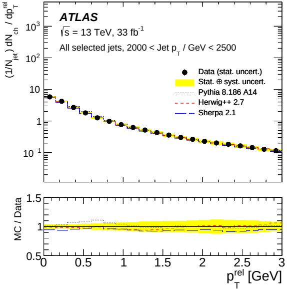


Jet fragmentation properties | Unfolded data vs MC

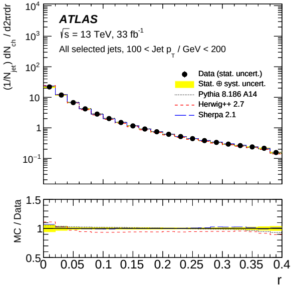


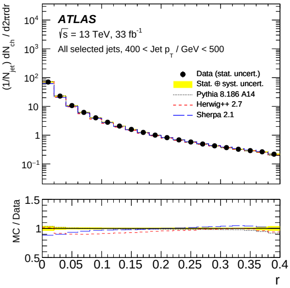


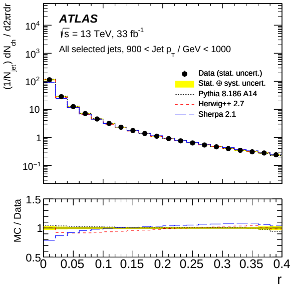


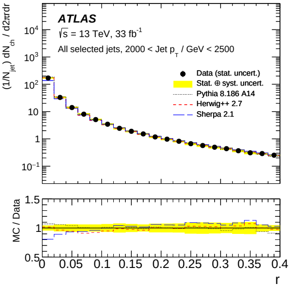


Jet fragmentation properties | Unfolded data vs MC

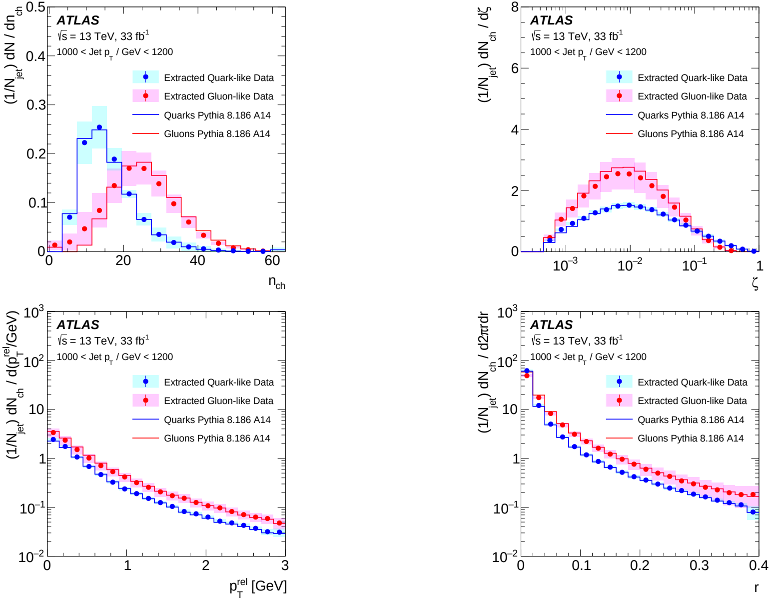




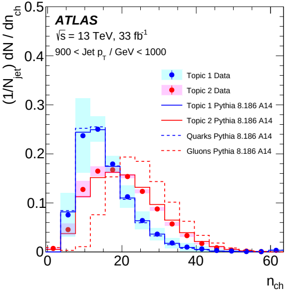


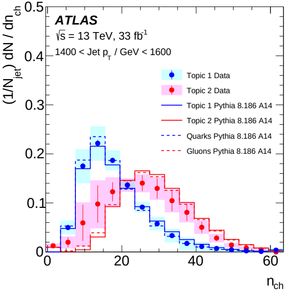


Jet fragmentation properties | Topic distributions



Jet fragmentation properties | Uncertainties



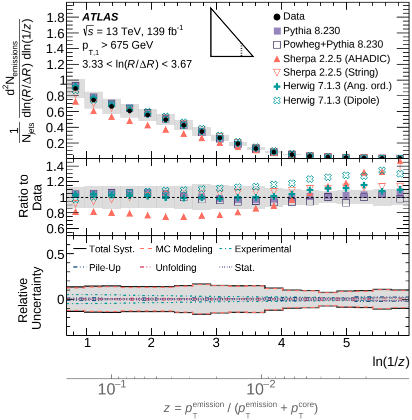


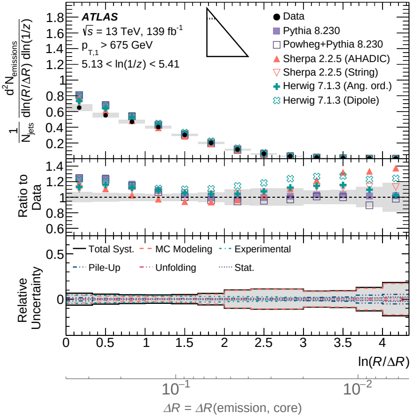
Lund Plane measurement with charged particles

[arXiv:2004.03540]

[Submitted to PRL]

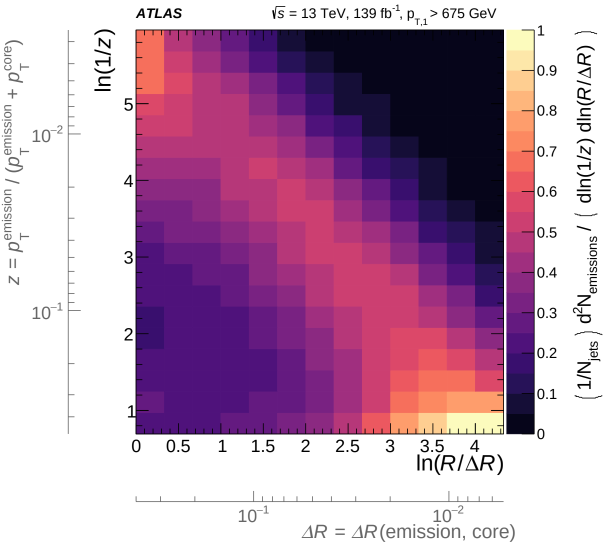
Lund plane measurement with charged particles





Lund plane measurement with charged particles

Unfolded Lund jet plane in data

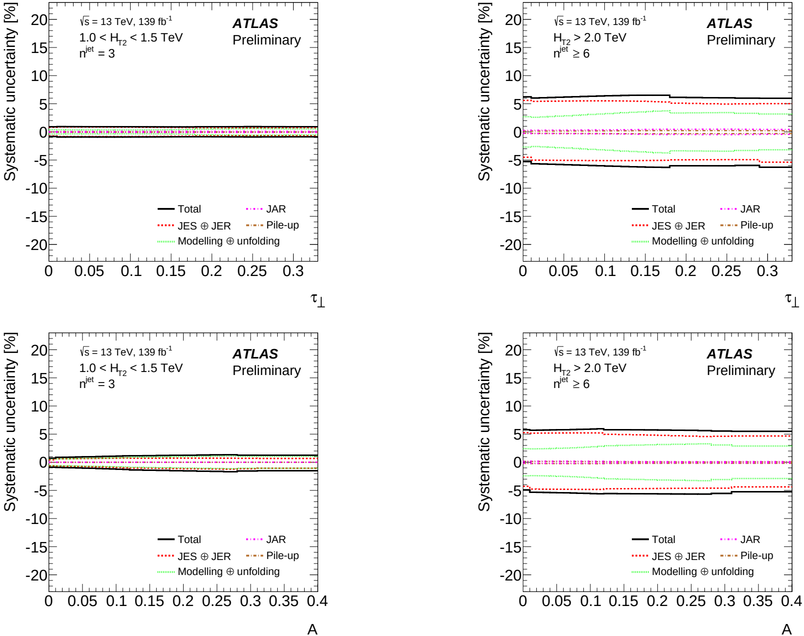


Brand new results!

Measurement of hadronic event shapes in multijet final states at $\sqrt{s} = 13\,$TeV

[ATLAS-CONF-2020-011]

Measurement of hadronic event shapes in multije final states



Measurement of the jet substructure observables at 13 TeV

[JHEP 08 (2019) 033]

[arXiv:1903.02942]

Measurement of jet substructure observables at $\sqrt{s} = 13$ TeV

Jet substructure observables in $t\bar{t}$, W boson and dijet events

- anti-k_t $R = 1.0$ jets groomed using trimming ($R_{\text{sub}} = 0.2$, $f_{\text{cut}} = 5\%$) and soft-drop ($\beta = 0, \zeta_{\text{cut}} = 0.1$)
- Unfolded data distributions are compared to various MC event generators
- Cluster-level uncertainties on the overall shape and scale of the observables

Observable: $D_2^{(\beta)} \equiv \dfrac{e_3^{(\beta)}}{\left(e_2^{(\beta)}\right)^3}$

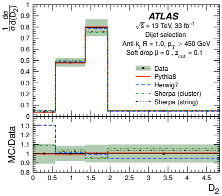
$$e_n^{(\beta)} \equiv \frac{E_{\text{CF}n}(\beta)}{E_{\text{CF1}}(\beta)^n} \quad ; \quad E_{\text{CF1}}(\beta) \equiv \sum_{i\in J} p_{\text{T}i}$$

$$E_{\text{CF2}}(\beta) \equiv \sum_{i<j\in J} p_{\text{T}i} p_{\text{T}j} (\Delta R_{ij})^\beta$$

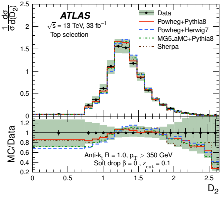
$$E_{\text{CF3}}(\beta) \equiv \sum_{i<j<k\in J} p_{\text{T}i} p_{\text{T}j} p_{\text{T}k} (\Delta R_{ij} \Delta R_{ik} \Delta R_{jk})^\beta$$

In general, reasonable agreement within uncertainties, with some discrepancies

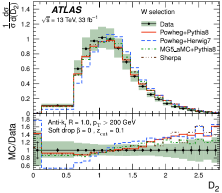
Dijet selection



$t\bar{t}$ selection



W selection



Measurement of jet substructure observables at $\sqrt{s} = 13$ TeV

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$$E_{\text{CF}3}(\beta) \equiv \sum_{i<j<k \in J} p_{\mathrm{T}\,i} p_{\mathrm{T}\,j} p_{\mathrm{T}\,k} (\Delta R_{ij} \Delta R_{ik} \Delta R_{jk})^{\beta}$$

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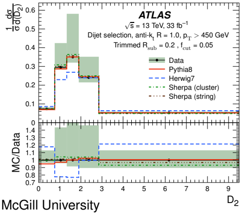
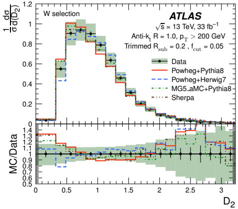


W selection



Properties of $g \to b\bar{b}$ at small opening angles at $\sqrt{s} = 13\ \mathrm{TeV}$

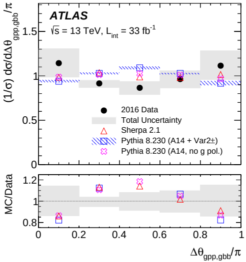
[Phys. Rev. D 99 (2019) 052004]

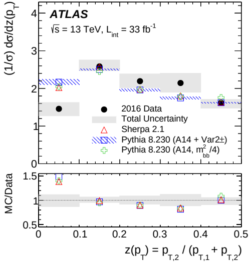
[arXiv:1812.09283]

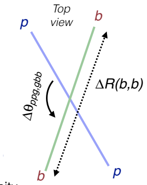
Properties of $g \to b\bar{b}$ at small opening angles at $\sqrt{s} = 13$ TeV

Main background in analyses involving boosted Higgs decaying into *b*-quarks

- $R = 1$ anti-k_t trimmed jets w/ $p_{\mathrm{T}} > 450\,\mathrm{GeV}$ and $|\eta| < 2$
- At least two $R = 0.2$ anti-k_t jets from tracks ghost-matched to $R = 1.0$ jets
- Leading track-jet b-tagged by MV2c10 algorithm (60% efficiency)
- The contribution from $R = 1.0$ jets that don't have 2 b-tagged jets is subtracted from data using template fits
- Systematics: Jet energy scale, unfolding and theoretical modeling uncertainties dominate
- Significant differences observed b/w data and MC predictions







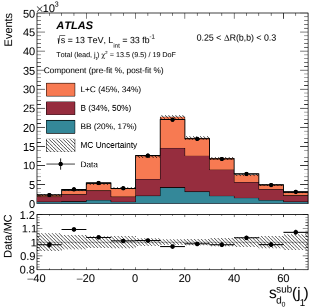
Properties of $g \to b\bar{b}$ at small opening angles at $\sqrt{s} = 13$ TeV

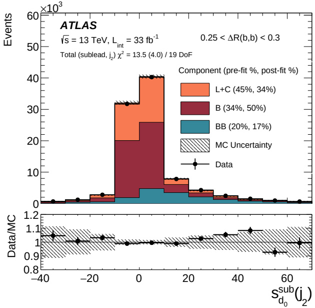
Summary of systematic uncertainty sizes for each observable for the normalized differential cross sections

	$\Delta R(b,b)$	$\Delta\theta_{\text{ppg,gbb}}$	$z(p_{\text{T}})$	$\log(m_{bb}/p_{\text{T}})$
Calorimeter jet energy	2–3%	2–3%	2–6%	2–4%
Flavor tagging	<1%	<1%	<1%	<1%
Tracking	1–2%	1–2%	2–4%	1–2%
Background fit	1%	1%	1–2%	2%
Unfolding method	2–3%	2%	2–4%	2–5%
Theoretical modeling	3–10%	2–13%	3–10%	4–11%
Statistical	1%	1%	2%	1%
Total	3–10%	3–10%	3–14%	4–12%

Properties of $g \to b\bar{b}$ at small opening angles at $\sqrt{s} = 13$ TeV

- The contribution from large-R jets that do not have two associated track-jets containing B-hadrons is subtracted from data, before correcting for detector effects
- Correction factors are determined from data template fits to the signed impact parameter distribution (s_{d_0}) and applied for each bin of the four observables
- In each bin, the distribution of s_{d_0} is fitted to data using templates from simulation while letting the fraction of each flavor component float in the fit.
- For a given track, $s_{d_0} = s_j|d_0|/\sigma(d_0)$, where d_0 is the transverse impact parameter relative to the beam-line, $\sigma(d_0)$ is the uncertainty in d_0 from the track fit, and the variable s_j is the sign of d_0 with respect to the jet axis: $s_j = +1$ if $\sin(\phi_{\text{jet}} - \phi_{\text{track}}) \cdot d_0 > 0$ and $s_j = -1$ otherwise.





Properties of $g \to b\bar{b}$ at small opening angles at $\sqrt{s} = 13$ TeV

Main background source in analyses involving boosted Higgs decaying into *b*-quarks

- $R = 0.2$ anti-k_t jets from tracks are ghost-matched to $R = 1.0$ anti-k_t trimmed jets
- The contribution from $R = 1.0$ jets that don't have 2 track-jets containing B-hadrons is subtracted from data using template fits
- Unfolding to the particle level
- **Significant differences observed b/w data and MC predictions**