Jet substructure measurements sensitive to soft QCD with the ATLAS detector

Trisha Farooque[1] on behalf of the ATLAS collaboration

[1] Michigan State University

April 17, 2018

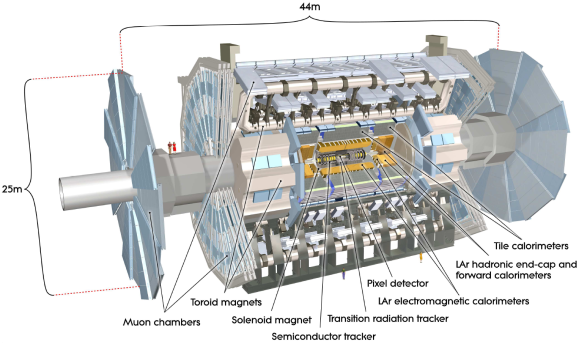
Overview

Introduction

- Study of energy flow **within** the body of hadronic jets
  - Useful in identification of boosted heavy particles
  - Important probe of perturbative QCD and also sensitive to soft QCD effects

- Three recent ATLAS results on **substructure measurements sensitive to soft QCD**:
  1. Measurement of the k_T splitting scales in $Z \to ll$ events in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector
     JHEP08 (2017) 26 arXiv:1704.01530
  2. A measurement of the soft-drop jet mass in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
     (*Submitted to PRL*) arXiv:1711.08341
  3. Measurement of colour flow using jet-pull observables in $t\bar{t}$ events with the ATLAS experiment at $\sqrt{s} = 13$ TeV ATLAS-CONF-2017-069

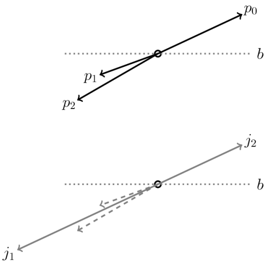
The ATLAS Experiment



- General purpose detector with multi-layer detection chambers
- Charge particle tracks reconstructed in **Inner Detector (ID)**
- Hadronic jets reconstructed from **topological clusters** of energy deposits in calorimeter cells
  - Sequence of calibrations applied to correct jet to hadron level

Overview of jet reconstruction algorithms

- Cluster any set of four-momenta (charged tracks, calorimeter energy deposits) into collimated "jets"
- ATLAS uses infra-red- and collinear-safe **sequential recombination algorithms**
  - Iteratively combine pair with min. d_{ij} until $d_{ib} < d_{ij}$
- $d_{ij} = \min(p^n_{T,i},\ p^n_{T,j}) \times \frac{\Delta R^2_{ij}}{R^2};\ d_{ib} = p^n_{T,i}$



k$_T$ (n=2)

- Softest pair of constituents clustered first
- Follows IR and collinear splittings

anti-k$_T$ (n=-2)

- Hardest constituent clustered with closest neighbour
- Regularly shaped jets

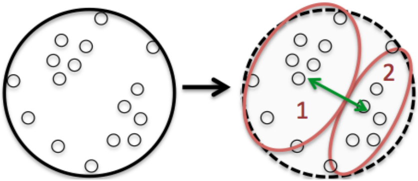
Cambridge-Aachen (n=0)

- Closest pair of constituents clustered first
- Mimics angular-ordered parton showers

ATLAS measurement of k_T splitting scales in $Z \longrightarrow ll$ events

k_T splitting scales

- $\sqrt{d_0} = p_T$ of final jet
- $\sqrt{d_1} = min(p_{T,1}, p_{T,2}) \times \frac{\Delta R_{12}}{R}$, etc.
- Small $\sqrt{d_k} \Rightarrow$ soft/collinear splitting
- Large $\sqrt{d_k} \Rightarrow$ hard splitting



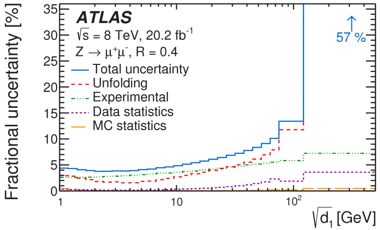
- k_T clustering sequence run in reverse
- $d_{ij} = \min(p^n_{T,i},\ p^n_{T,j}) \times \frac{\Delta R^2_{ij}}{R^2}$; $d_{ib} = p^n_{T,i}$
- Splitting scale $\sqrt{d_k} = min(\sqrt{d_{ij}}, \sqrt{d_{ib}})$ for k^{th} iteration step

Overview of measurement

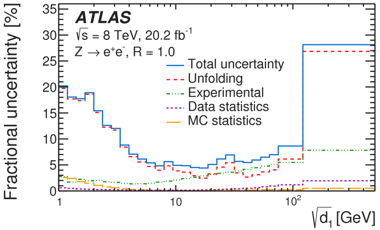
- Measurement of k_T splitting scale in Z+jets events with charged particle tracks at $\sqrt{s} = \mathbf{8}$ **TeV**
- $Z \rightarrow ll$ events provides clean environment
- Smaller experimental uncertainties from charged tracks compared to calorimeter clusters
- Separate measurements for R =0.4 and R =1.0 jet radius parameters
  - Different sensitivity to hadronisation and underlying event
- **Iterative Bayesian Unfolding** of measured distributions based on Sherpa LO predictions
- Results also extrapolated to include neutral particles

Uncertainties

R=0.4, $\mu\mu$ channel; charged-only



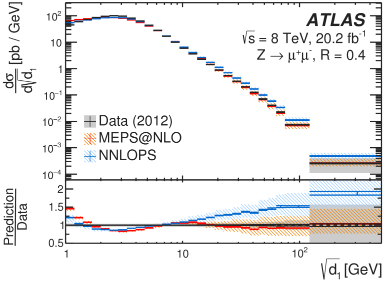
R=1.0, *ee* channel; charged+neutral



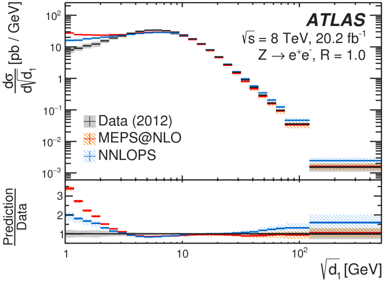
- Modelling uncertainties are dominant
- Experimental uncertainties are mostly related to track reconstruction and measurement
- Larger uncertainties in charged+neutral results due to sensitivity to hadronisation model
  - Mostly affects small values of $\sqrt{d_k}$ (soft and collinear regime)

Unfolded distributions

R=0.4 $\mu\mu$ channel; charged-only



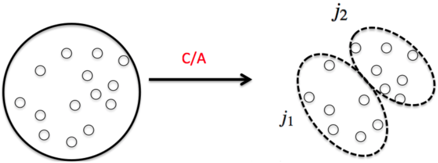
R=1.0 *ee* channel; charged+neutral



- Large discrepancies to both NLO MEPS and NNLO predictions at low values of $\sqrt{d_k}$
  - Estimated modelling uncertainties mostly dominated by perturbative QCD
  - Results can be used for generator tuning for non-perturbative effects
- NLO Sherpa+OpenLoops (MEPS@NLO) describes data better in high $\sqrt{d_k}$ tail compared to Powheg(DYNNLO)+Pythia8 NNLO (NNLOPS) predictions

ATLAS measurement of the soft-drop jet mass

Soft-drop algorithm



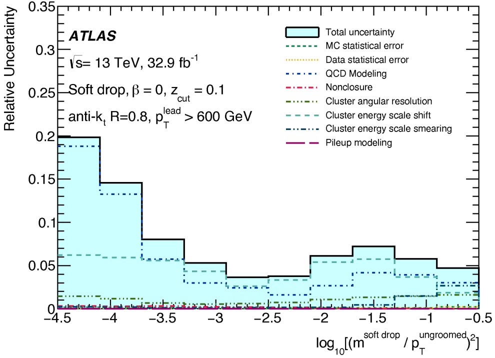
- Cluster input constituents with Cambridge-Aachen algorithm
- Apply **soft-drop** criterion at each step of clustering sequence, in reverse order
- $\frac{\min(p_{T,1},p_{T,2})}{p_{T,1}+p_{T,2}} > z_{cut}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$
- Remove softer of two branches if criterion not satisfied
- Higher z_{cut} $\Rightarrow$ more energy removed by algorithm
- β: Tunes sensitivity to wide-angle radiation

- Jet substructure calculations beyond leading log accuracy problematic due to non-global logarithms (NGLs)
  - Related to particles radiating out of and then into jet
- **Soft drop** grooming makes jet substructure insensitive to NGLs
  - Removes energy in jet related to soft QCD processes and pile-up

Overview of measurement

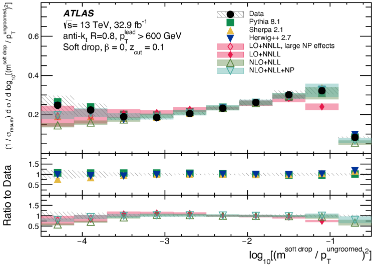
- Measurement of soft-drop jet mass for anti-k_T R=0.8 jets built from topological calorimeter-cell clusters at $\sqrt{s}$ = **13 TeV**
- Events with dijet topologies selected
  $\Rightarrow p_{T,1}/p_{T,2}$ <1.5 for two leading jets
- Distribution of $\log_{10}(\rho^2)$ studied for β =0,1,2
  - Dimensionless mass parameter $\rho = m^{\mathrm{softdrop}}/p_T^{\mathrm{ungroomed}}$
- Iterative Bayesian unfolding applied simultaneously to $\log_{10}(\rho^2)$ and jet p_T distributions using Pythia LO predictions
- Three distinct regions:
  - **Non-perturbative region** $\log_{10}(\rho^2) <$ -3.7 (soft and collinear emissions)
  - **Resummation region** -3.7 $< \log_{10}(\rho^2) <$ -1.7 (resummation dominates)
  - **Fixed-order region** $\log_{10}(\rho^2) <$ -3.7 (wide-angle hard gluon emissions)

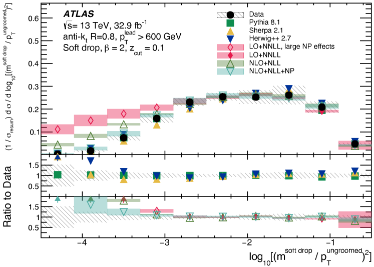
Uncertainties



- QCD modelling uncertainty dominant in non-perturbative regime
- Experimental uncertainties on energy scale of calorimeter clusters dominate in perturbative region

Unfolded distributions





- Distributions normalised to σ_{resum}
- Largest difference between Monte Carlo and analytic predictions in non-perturbative regime
  - Effect larger for higher β (smaller fraction of soft energy removed)
- NLO+NLL calculation included non-perturbative corrections $\Rightarrow$ better agreement at low $\log_{10}(\rho^2)$
- Good agreement between data and analytic calculations in resummation and fixed-order regions

ATLAS measurement of colour flow using jet-pull observables in $t\bar{t}$ events

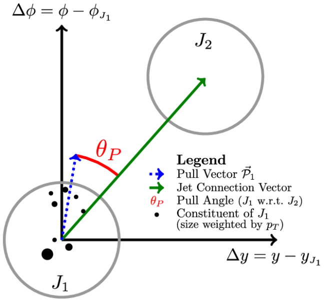
Jet pull observables

Coloured partons

$$\xrightarrow[\text{DGLAP evolution}]{\text{Jet algorithm}}$$

Jets of colour singlet hadrons

- Colour connections between high-p_T particles affects structure of emitted radiation
- Colour flow in QCD is poorly constrained by current data
- **Jet pull angle** $\theta_{\mathcal{P}}$ measures colour connection between jets
  - $\theta_{\mathcal{P}} \sim 0$ for colour connected jets
  - Uniform distribution when no colour connection exists



- Jet pull vector $\vec{\mathcal{P}} = \sum_{i \in J} \frac{|\vec{\Delta r_i}|.p_T^i}{p_T^J} \vec{\Delta r_i}$

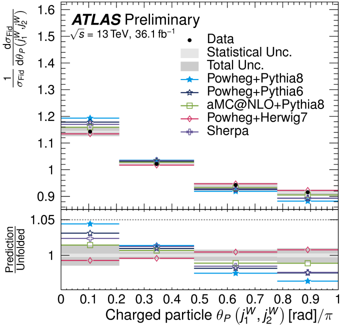
Overview of measurement

- Jet pull angle measured in $t\bar{t}$ events at $\sqrt{s}$ =13 TeV for:
  - Jets originating from colour singlet W (colour connected)
  - *b*-jets coming from the two top quarks (no colour connection)
- Magnitude of pull vector also measured
- Calculation based on charged particle tracks to improve spatial resolution of measurement
- Dominant uncertainty in measurement from $t\bar{t}$ modelling
- Largest experimental uncertainty comes from *b*-tagging
- Iterative Bayesian unfolding with predictions from Powheg+Pythia8 simulations

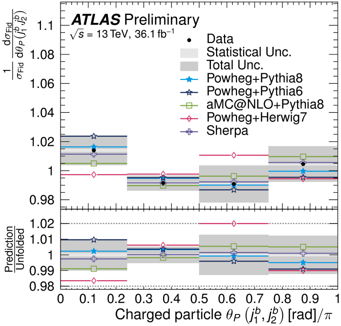
Target colour flow	**Signal colour flow** (j_1 and j_2 are colour connected)	**Spurious colour flow** (j_1 and j_2 are not colour connected)
Jet assignment	j_1^W : leading p_{T} non-b-tagged jet j_2^W : 2$^{\mathrm{nd}}$ leading p_{T} non-b-tagged jet	j_1^b : leading p_{T} b-tagged jet j_2^b : 2$^{\mathrm{nd}}$ leading p_{T} b-tagged jet
Observables	$\theta_{\mathcal{P}}\left(j_1^W, j_2^W\right)$: *"forward pull-angle"* $\theta_{\mathcal{P}}\left(j_2^W, j_1^W\right)$: *"backward pull-angle"* $\lvert\vec{\mathcal{P}}\left(j_1^W\right)\rvert$: *"pull-vector magnitude"*	$\theta_{\mathcal{P}}\left(j_1^b, j_2^b\right)$: *"forward di-b-jet-pull angle"*

Unfolded distributions

$\theta_{\mathcal{P}}(j_1^W, j_2^W)$



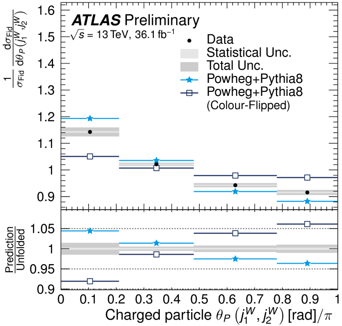
$\theta_{\mathcal{P}}(j_1^b, j_2^b)$



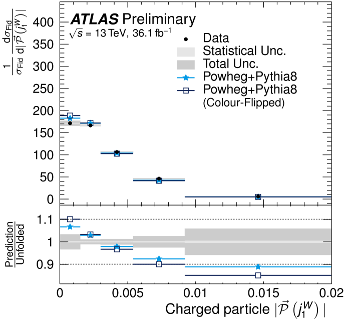
- Various hadronisation models tested (Pythia6, Pythia8, Herwig7, Sherpa)
  - All predict smaller jet pull (stronger colour flow effect) than data
- Signal jet pull modelled best by Powheg+Herwig7; but spurious jet pull modelled poorly
- Pythia6 describes data better than Pythia 8
  - Differenes between the two models not limited to hadronisation

Comparison to exotic colour-flow model

$\theta_{\mathcal{P}}(j_1^W, j_2^W)$



$|\mathcal{P}(j_1^W)|$



- "Colour flip" model tested replacing colour singlet W with a colour octet
- Both pull angle and pull vector able to discriminate such exotic colour flow from Standard Model
- Data agrees better with SM predictions

Summary

- Presented three recent ATLAS measurements of substructure observables sensitive to soft QCD
  - k_T splitting scales for charged track jets in $Z \rightarrow ll$+jets events
  - Soft-drop jet mass in dijet events
  - Jet-pull observables in $t\bar{t}$ events
- Results can constrain both analytic calculations in perturbative regime and soft hadronic activity in non-perturbative region
- Useful for tuning of MC simulation of non-perturbative QCD

Backup slides

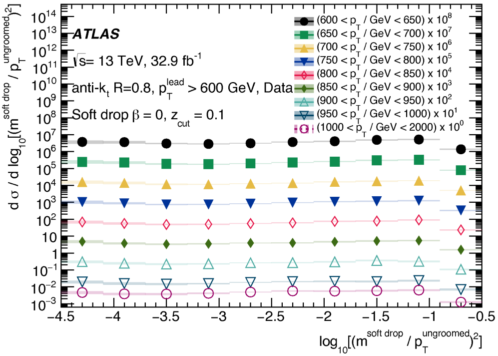
ATLAS measurement of k_T splitting scales in $Z \longrightarrow ll$ events

Signal and background yields

	$Z \to e^+e^-$		$Z \to \mu^+\mu^-$	
Process	Events	Contribution [%]	Events	Contribution [%]
QCD Z + jets	5 090 000	98.93 %	7 220 000	99.40 %
Multijet	42 000	0.81 %	25 000	0.34 %
Electroweak Z + jets	5 350	0.10 %	7 340	0.10 %
Top quarks	6 190	0.12 %	8 440	0.12 %
$W(W)$	1 100	0.02 %	1 460	0.02 %
$Z \to \tau^+\tau^-$	1 100	0.02 %	1 700	0.02 %
Total expected	5 150 000	100.00 %	7 260 000	100.00 %
Total observed	5 196 858		7 349 195	

ATLAS measurement of the soft-drop jet mass

Unfolded $\log_{10}(\rho^2)$ across p_T



ATLAS measurement of colour flow using jet-pull observables in $t\bar{t}$ events

Signal and background yields

Sample	Yield		
$t\bar{t}$	1 026 000	±	95 000
$t\bar{t}V$	3270	±	250
$t\bar{t}H$	1700	±	100
Single-top	48 400	±	5500
Diboson	1440	±	220
W + jets	27 700	±	4700
Z + jets	8300	±	1400
NP/Fake leptons	53 000	±	30 000
Total Expected	1 170 000	±	100 000
Observed	1 153 003		

Uncertainties

$\Delta\theta_P\left(j_1^W, j_2^W\right)$ [%]	$\theta_P\left(j_1^W, j_2^W\right)$			
	0.0 – 0.21	0.21 – 0.48	0.48 – 0.78	0.78 – 1.0
Hadronisation	0.63	0.22	0.27	0.09
Generator	0.37	0.24	0.50	0.06
Colour Reconnection	0.11	0.26	0.03	0.53
b-Tagging	0.35	0.12	0.20	0.31
Non-Closure	0.25	0.07	0.08	0.30
ISR / FSR	0.32	0.12	0.15	0.01
Other	0.25	0.20	0.11	0.18
JER	0.12	0.13	0.21	0.03
JES	0.13	0.06	0.13	0.07
Tracks	0.09	0.04	0.05	0.07
Syst.	0.97	0.52	0.68	0.72
Stat.	0.22	0.18	0.17	0.26
Total	0.99	0.55	0.71	0.76