Recent probes of perturbative QCD calculations with jets at ATLAS and CMS

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Introduction

Large momentum transfers seen at the LHC allow us to probe pQCD

- Jet final states can be sensitive to parton structure (PDFs), strong coupling, matrix elements

$$\sigma_{P_1,P_2\to X} = \sum_{ij} \int dx_1 dx_2 f_{i,P_1}(x_i,\mu_f) f_{j,P_2}(x_j,\mu_f)$$
$$\times \sigma_{ij\to X}\left(x_1 p_1, x_2 p_2, \alpha(\mu_r^2), \frac{Q^2}{\mu_f^2}\right)$$

Will discuss four recent ATLAS and CMS results, looking at jet final states sesntive to the above

- dijet and inclusive jet: probe NNLO calculation and scale choices
- triple differential dijet: constrain PDFs
- azimuthal correlations: compare MC generators
- azimuthal correlation ratio: $\alpha_s(Q)$ extraction at high Q

ATLAS: Dijet and inclusive jet

arXiv:1711.02692

measure inclusive jet and dijet double-differential cross sections:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} = \frac{N_{\mathrm{jets}}}{\mathcal{L}\Delta p_{\mathrm{T}}\Delta y} \qquad \frac{\mathrm{d}^2\sigma}{\mathrm{d}m_{\mathrm{jj}}\mathrm{d}y^*} = \frac{N_{\mathrm{dijet}}}{\mathcal{L}\Delta m_{\mathrm{jj}}\Delta y^*}$$

- Use 3.2 fb^{-1} of $\sqrt{s} = 13$ TeV data
- Compare to NLO and state of the art NNLO calculations
- Also probe how the choice of scale effects on the inclusive jet calculations

Event selection and triggering

- Use a suite of single jet triggers to select inclusive jet events
- dijet selection: use trigger pairing with σ based on pairings

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$y^* = |y_1 - y_2|/2$

Theoretical predictions

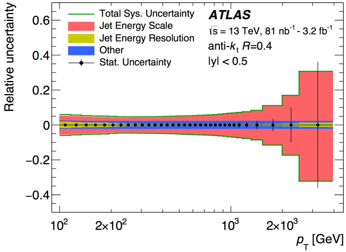
Data is corrected for detector effects using the iterative dynamically stabilised (IDS) unfolding method

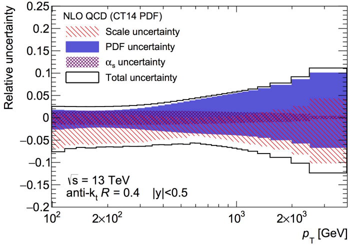
NLO calculated using NLOJET++

- Calculated using 6 different NLO PDF sets provided by LHCPDF6

NNLO calculation provided by J. Currie, E. Glover and J. Pires

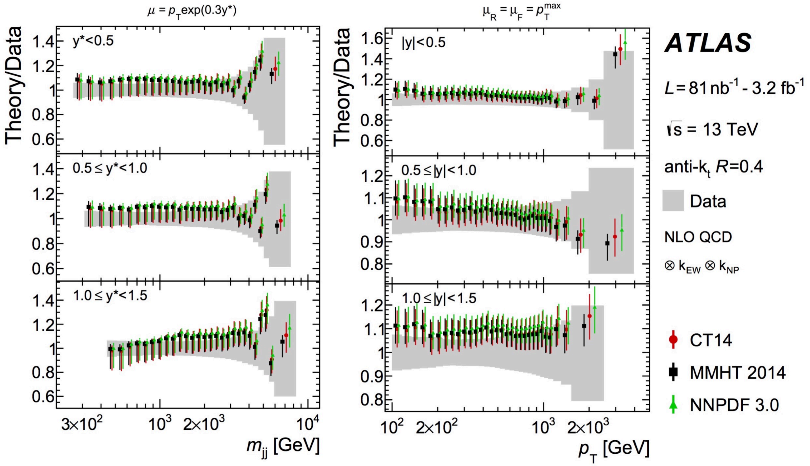
- Non perturbative correction factors are derived bin by bin, comparing a LO MC with and without showering and hadronisation
- Electroweak corrections are taken from S. Dittmaier, A. Huss and C. Speckner





NLO results

Showing a subset of $|y|$ and y^* bins and PDF sets

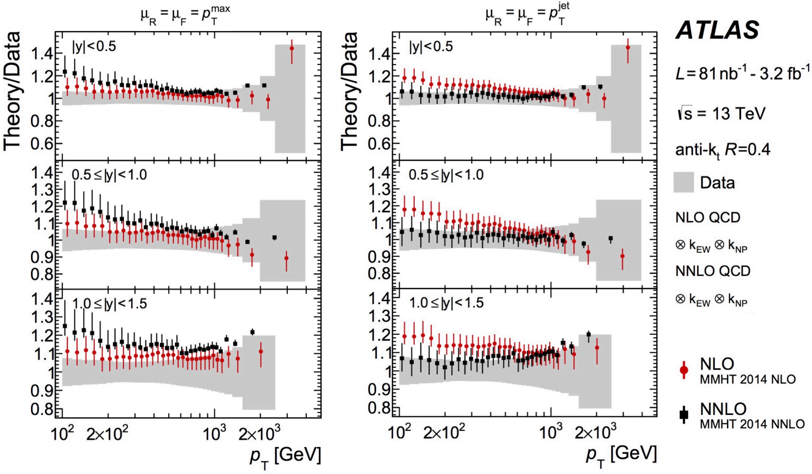


Fair agreement is seen in most of the phase space, with some tensions in the 1.5-2.5 y^* range for the dijet selection.

Tension between data and theory is observed in the inclusive measurement when considering the full phase-space

NNLO results

Showing NNLO/data comparison with different scale choices



Effects of two different scale choices considered
Either NLO or NNLO has better agreement based on choice

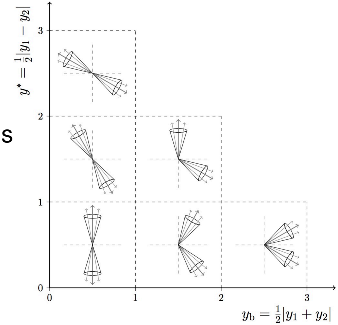
CMS: Dijet triple-differential

arXiv:1705.02628

Measure triple differential cross section using 19.7 fb^{-1} of 8 TeV data

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}p_{\mathrm{T,avg}}\mathrm{d}y^*\mathrm{d}y_{\mathrm{b}}} = \frac{1}{\epsilon\mathcal{L}^{\mathrm{eff}}}\frac{N}{\Delta p_{\mathrm{T,avg}}\Delta y^*\Delta y_{\mathrm{b}}}$$

- Comparisons made to NLO predictions
- Binning in y_{b} results in selections with different partonic subprocesses
- Data used to constrain PDFs and extract a value for α_s



Use a suite of single jet triggers and select the leading two central ($|y| < 3.0$) jets from events with at least two jets

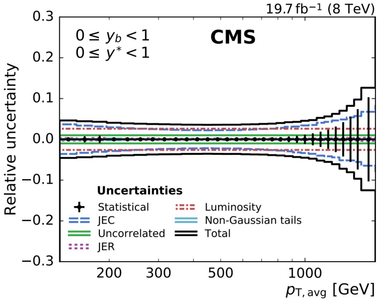
Unfolding and systematics

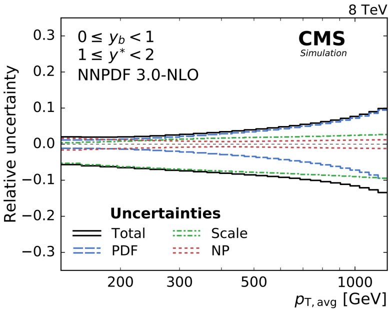
Distributions corrected to particle level using iterative D'Agostini algorithm

- Response matrix uses psuedo-events weighted to NLO prediction, smeared using the jet p_T
- Jet energy correction is the largest experimental uncertainty

NLO predictions calculated using NLOJET++

- non perturbative corrections are applied by comparing LO MC with and without hadronisation and MPI
- Electroweak correction also applied, from arXiv: 1210.0438

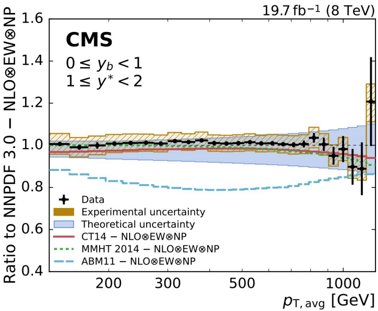




Results

good agreement between data and NLO,
expect in regions of high $p_{\mathrm{T,avg}}$ and y_b which are sensitive to high-x PDF values

ABM11 PDFs underestimate the data for $y_b < 2.0$



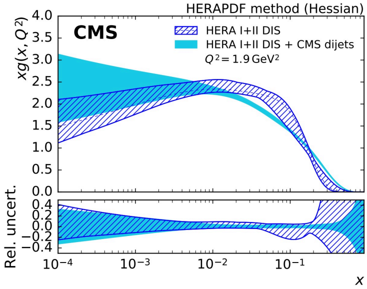
Constraints on PDFs are obtained by a fit including the results and HERA DIS data.

- Fits are performed using the XFitter framework, at NLO
- comparisons are made on the quality of the fit

Data set(s)	n_{dof}	χ^2	χ^2/n_{dof}	χ^2	χ^2/n_{dof}
HERA data	1040	1211.00	1.16	—	—
HERA & CMS data	1162	—	—	1372.52	1.18

Results

- Uncertainty in the gluon pdf significantly reduced in the high *x* region, some reduction also seen in valence and sea quarks
- Also noticeable change in the shape



By repeating the fit while leaving $\alpha_s(M_Z)$ as a free parameter, one obtains

$$\alpha_s(M_Z) = 0.1199 \pm 0.0015(\mathrm{exp})^{+0.0032}_{-0.0020}(\mathrm{mod})$$

which is in agreement with previous CMS and ATLAS measurements and the world average.

Analysis overview

CMS: Azimuthal correlations

arXiv:1712.05471

Consider leading two jets in 2,3,4 inclusive jet events and measure

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\Delta\phi_{12}} \quad \text{and} \quad \frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\Delta\phi_{2j}^{\min}}$$

- $\Delta\phi_{2j}^{\min}$ is sensitive to lower p_{T} jets and adds additional information
- Compare to various LO and NLO predictions

Used 35.9 fb^{-1} of 13 TeV data

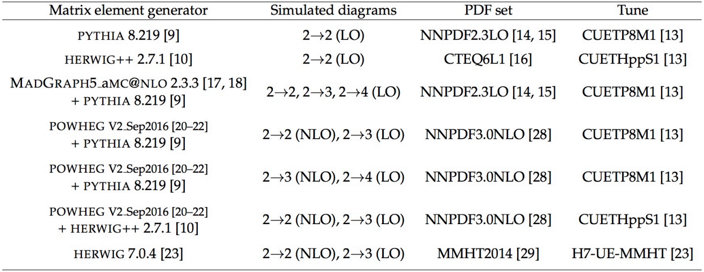
- Use a selection of five single jet triggers to select events with at least one jet with $p_{\mathrm{T}} > 200$ GeV
- Study different MC generators at different orders
- Evaluate performance of parton showers and matching

Theoretical predictions

Use a matrix inversion algorithm to correct for detector effects

JES, JER and unfolding systematics are the largest experimental uncerts

There were a number of event generators used for comparison

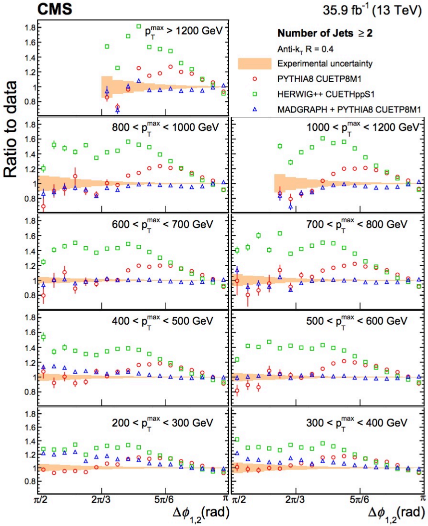


Matrix element generator	Simulated diagrams	PDF set	Tune
Pythia 8.219 [9]	2→2 (LO)	NNPDF2.3LO [14, 15]	CUETP8M1 [13]
Herwig++ 2.7.1 [10]	2→2 (LO)	CTEQ6L1 [16]	CUETHppS1 [13]
MadGraph5_aMC@NLO 2.3.3 [17, 18] + Pythia 8.219 [9]	2→2, 2→3, 2→4 (LO)	NNPDF2.3LO [14, 15]	CUETP8M1 [13]
POWHEG V2_Sep2016 [20–22] + Pythia 8.219 [9]	2→2 (NLO), 2→3 (LO)	NNPDF3.0NLO [28]	CUETP8M1 [13]
POWHEG V2_Sep2016 [20–22] + Pythia 8.219 [9]	2→3 (NLO), 2→4 (LO)	NNPDF3.0NLO [28]	CUETP8M1 [13]
POWHEG V2_Sep2016 [20–22] + Herwig++ 2.7.1 [10]	2→2 (NLO), 2→3 (LO)	NNPDF3.0NLO [28]	CUETHppS1 [13]
Herwig 7.0.4 [23]	2→2 (NLO), 2→3 (LO)	MMHT2014 [29]	H7-UE-MMHT [23]

Largest theoretical uncertainty comes from parton showering

- Evaluated using Pythia8 by scaling renormalisation scale for ISR and FSR independently up and down
- For $\Delta\phi_{12}$ range from $< 5\%$ at π upto 40-60% at ($\approx \pi/2$) for greater $p_{\mathrm{T}}^{\mathrm{max}}$ in the 2-jet case. Don't exceed 20% for the 3,4-jet case

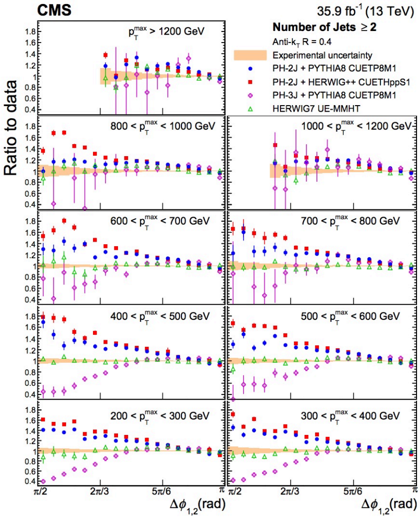
Results, $\Delta\phi_{12}$



LO results

- MadGraph+Pythia8 provides the best description of the data
- Pythia8 performs better than Herwig++

Results, $\Delta\phi_{12}$



NLO results

- HERWIG7 provides the best description of the data
- PowHeg 2j and 3j have large deviations from the measured data
- Herwig++ and Pythia8 use different α_s values for (I)FSR and have a different upper scale for PS emissions
- HERWIG 7 uses MC@NLO method of combining PS with particle level, which here seems to perform better than the POWHEG method

ATLAS: Azimuthal decorrelations

arXiv:1805.04691

Measure the following ratio:

$$R_{\Delta\phi}(H_{\mathrm{T}}, y^*, \Delta\phi_{\mathrm{max}}) = \frac{\frac{\mathrm{d}^2\sigma_{\mathrm{dijet}}(\Delta\phi_{\mathrm{dijet}} < \Delta\phi_{\mathrm{max}})}{\mathrm{d}H_{\mathrm{T}}\,\mathrm{d}y^*}}{\frac{\mathrm{d}^2\sigma_{\mathrm{dijet}}(\mathrm{inclusive})}{\mathrm{d}H_{\mathrm{T}}\,\mathrm{d}y^*}}$$

- Ratio has smaller dependance on PDFs in α_s extraction and running studies

Additional cuts applied on y^*_{max}, $y^{\mathrm{b}}_{\mathrm{max}}$ and $p_{\mathrm{T}1}/H_{\mathrm{T}}$

- ensure that jets are within $|y| < 2.5$ and are thus well measured
- Reduces contributions from events with 4 or more jets, less sensitive to higher orders in α_s

Use a set of single and multi jet triggers in each H_{T} bin

$y^*_{\mathrm{max}} < 2.0$, $y^{\mathrm{b}}_{\mathrm{max}} < 0.5$, $p_{\mathrm{T}1}/H_{\mathrm{T}} > 1/3$

Theoretical predictions

pQCD calculations at fixed order in α_s with NP corrections

- Calculations carried out using NLOJET++
- predictions for $R_{\Delta\phi}$ are calculated at NLO, expect for $\Delta\phi_{\mathrm{max}} = 2\pi/3$ (4 jet quantity)
- evolution of α_s computed at a NLL approximation

A set of various PDF sets were used

- Sets obtained for a series of discrete α_s values with $\Delta\alpha_s = 0.001$
- continuous dependance obtained by interpolation
- MMHT2014 used as nominal: largest range of values (0.108 - 0.128)

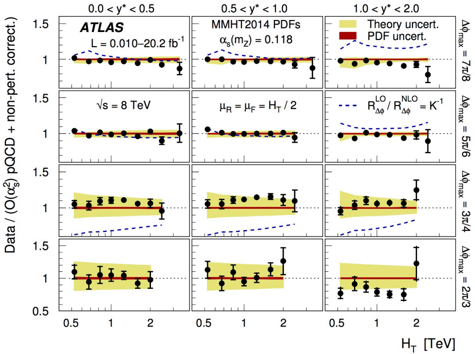
uncertainties

- Uncertainties on pQCD by varying μ_f and μ_r
- MMHT2014 PDF uncertainties used, an envelope of the results obtained with other sets is also used
- NP corrections obtained from M. Wobisch, *et al.*

Results

All predictions (including LO) are consistent with the data

A subset of the datapoints are used for the α_s extraction



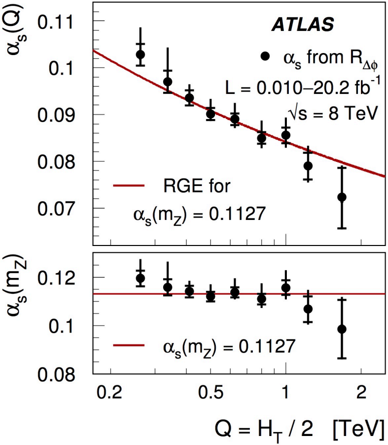
- points where calculation is most reliable (scale dependance)
- data points are combined if their phase space is orthogonal
- largest cancellation of PDF uncertainty
- smallest stat uncertainty

The datapoints from the region $0 < y^* < 0.5$ and $0.5 < y^* < 1$ for $\Delta\phi_{\max} = 7\pi/8$ are used
Scale uncertainties are the largest sytematic

Results

α_s extracted as a function of $Q = H_\mathrm{T}/2$

- the results are extracted from a Minuit χ^2 fit
- Nine $\alpha_s(Q)$ values are extracted $262 < Q \leq 1675$ GeV
- Separate χ^2 fits are made for scale variations and also for CT14, NNPDF2.3, ABMP16, HERAPDF 2.0
- Biggest difference of +0.0029 observed with HERAPDF 2.0
- A series of systematic studied also investigated the effect of other analyses choices (suggest result is rather independent of the analysis choice)



Final value: $\alpha_s(m_\mathrm{Z}) = 0.1127^{+0.0063}_{-0.0027}$, consistent with global value

Summary

Large scope for doing precision measurements at the LHC

- Tensions seen in some region of phase space
- New complimentary measurements of α_s
- Help reduce PDF uncertainty in certain regions of phase space

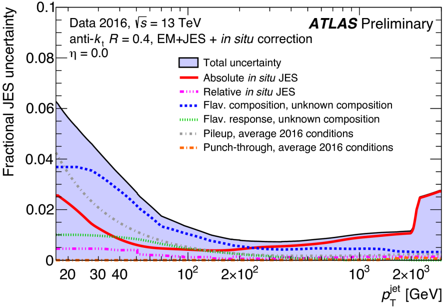
BACKUP

ATLAS: Jet calibration and systematics

Multi-step Jet energy calibration

1. Pile up correction: Based on jet area, μ and N_{PV}
2. Jet energy Scale: Energy corrected for mean detector response in η, p_{T}
3. Global sequential: Based on topology and associated tracks
4. In situ calibration: measurements used to correct remaining data/MC difference

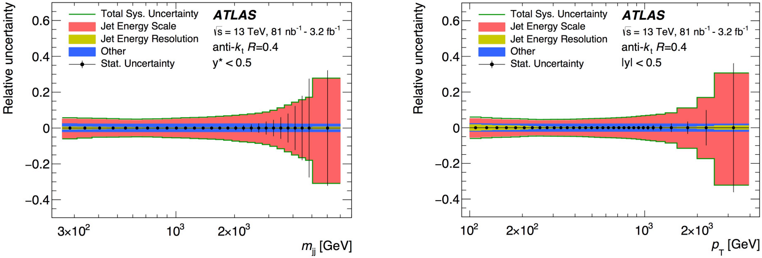
Energy scale uncertainties
The systematic uncertainties of the above steps are combined as independent components



ATLAS multijet: Unfolding and uncertainties

Data is corrected for detector effects using the iterative dynamically stabilised (IDS) unfolding method

- statistical uncertainties are propagated through the unfolding using an ensemble of pseudo-experiments (bootstrap method)
- the various JES uncertainties are propagated through the unfolding using ±1 sigma variations and pseudo data (bootstrap method) to evaluate statistical significance



ATLAS multijet: *P* values

P values from the comparison between data and the NLO predictions for inclusive jet selection

	P_{obs}				
Rapidity ranges	CT14	MMHT 2014	NNPDF 3.0	HERAPDF 2.0	ABMP16
$p_{\mathrm{T}}^{\mathrm{max}}$					
$\lvert y\rvert < 0.5$	67%	65%	62%	31%	50%
$0.5 \leq \lvert y\rvert < 1.0$	5.8%	6.3%	6.0%	3.0%	2.0%
$1.0 \leq \lvert y\rvert < 1.5$	65%	61%	67%	50%	55%
$1.5 \leq \lvert y\rvert < 2.0$	0.7%	0.8%	0.8%	0.1%	0.4%
$2.0 \leq \lvert y\rvert < 2.5$	2.3%	2.3%	2.8%	0.7%	1.5%
$2.5 \leq \lvert y\rvert < 3.0$	62%	71%	69%	25%	55%
$p_{\mathrm{T}}^{\mathrm{jet}}$					
$\lvert y\rvert < 0.5$	69%	67%	66%	30%	46%
$0.5 \leq \lvert y\rvert < 1.0$	7.4%	8.9%	8.6%	3.4%	2.0%
$1.0 \leq \lvert y\rvert < 1.5$	69%	62%	68%	45%	54%
$1.5 \leq \lvert y\rvert < 2.0$	1.3%	1.6%	1.4%	0.1%	0.5%
$2.0 \leq \lvert y\rvert < 2.5$	8.7%	6.6%	7.4%	1.0%	3.6%
$2.5 \leq \lvert y\rvert < 3.0$	65%	72%	72%	28%	59%

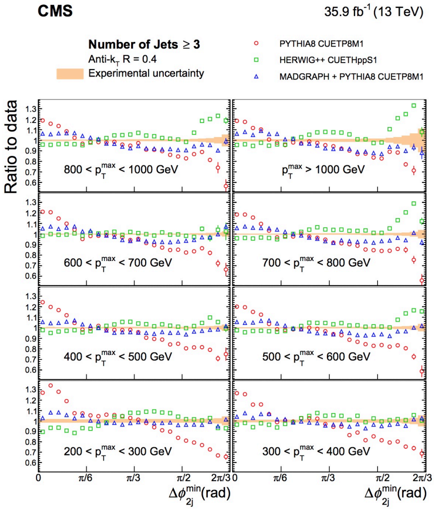
χ^2/dof all $\lvert y\rvert$ bins	CT14	MMHT 2014	NNPDF 3.0	HERAPDF 2.0	ABMP16
$p_{\mathrm{T}}^{\mathrm{max}}$	419/177	431/177	404/177	432/177	475/177
$p_{\mathrm{T}}^{\mathrm{jet}}$	399/177	405/177	384/177	428/177	455/177

ATLAS multijet: *P* values

P values from the comparison between data and the NLO predictions for the dijet selection

	P_{obs}				
y^* ranges	CT14	MMHT 2014	NNPDF 3.0	HERAPDF 2.0	ABMP16
$y^* < 0.5$	79%	59%	50%	71%	71%
$0.5 \leq y^* < 1.0$	27%	23%	19%	32%	31%
$1.0 \leq y^* < 1.5$	66%	55%	48%	66%	69%
$1.5 \leq y^* < 2.0$	26%	26%	28%	9.9%	25%
$2.0 \leq y^* < 2.5$	43%	35%	31%	4.2%	21%
$2.5 \leq y^* < 3.0$	45%	46%	40%	25%	38%
all y^* bins	8.1%	5.5%	9.8%	0.1%	4.4%

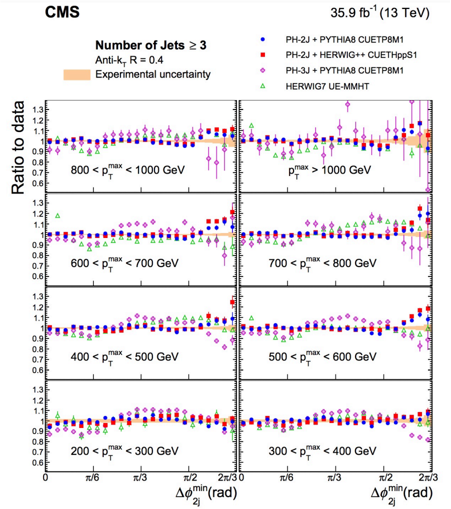
CMS: Results, $\Delta\phi_{2j}$



LO results

- Pythia8 has a larger deviation from the data than Herwig++
- MADGRAPH has reasonable agreement, but gets worse in the 4-jet case

CMS: Results, $\Delta\phi_{2j}$



NLO results

- PowHeg 2j with either Pythia8 or Herwig++ provides the best agreement with data
- PowHeg 3j results are stat limited at high $p_{\mathrm{T}}^{\max}$ but have a worse agreement

ATLAS $\Delta\phi$: Unfolding and systematics

Consider anti-k_t R=0.6 jets within detector acceptance ($|\eta| < 4.9$)

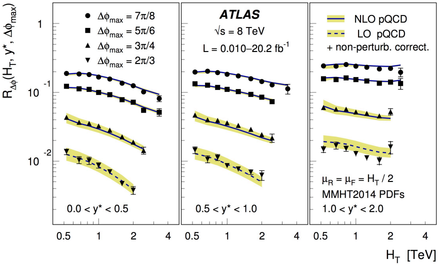
- multijet jet energy calibration is applied (pile up, area, JES, residual)
- Jet quality cuts applied to remove remaining pile up jets

The $R_{\Delta\phi}$ distributions are unfolded bin-by-bin to correct for detector effects

- Bin width is set be larger than $\Delta\phi$ resolution
- Cross checked using iterative unfolding procedure
- Corrections are small, uncertainties typically below 1%

62 sources of systematic uncertainty considered

- Mainly from the jet energy calibration
- Also includes angular and energy resolution
- typically between 1% and 1.5%



CMS $\Delta\phi$: Unfolding

Use a matrix inversion algorithm to correct for detector effects

- Reponse matrix created by the convolution of the generator level observables with the $\Delta\phi$ resolution
- Cross checked using samples will full detector sim
- Bin width set to be between 5 to 10 times $\Delta\phi$ resolution

Consider three main sources of systematic uncertainty

JES: 3% (at $\pi/2$) to 0.1% (at π) $\Delta\phi_{12}$ uncertainty and a 0.1% to 2% $\Delta\phi_{2j}^{\mathrm{min}}$

JER: 1% (at $\pi/2$) to 0.1% (at π) $\Delta\phi_{12}$ uncertainty and $<$ 0.5% $\Delta\phi_{2j}^{\mathrm{min}}$ uncertainty

unfolding Tested by changing choice of generator and varying the $\Delta\phi$ resolution. Total uncertainty 0.2%

ATLAS: Softdrop mass

arXiv:1711.08341

New grooming techniques allow for more precise calculations

$$\text{measure } \frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\log_{10}\rho^2}, \text{ where } \rho = m^{\text{softdrop}}/p_{\mathrm{T}}^{\text{ungroomed}}$$

- Jet substructure techniques have been widely used for tagging
- General procedures now exist for understanding IR an collinear safe observables at LL accuracy
- softdrop: removes NGLs, allow predictions beyond LL
- softdrop mass has been calculated at both NLO with NLL and LO NNLL accuracy

Measure for three different softdrop parameters (β = 0,1,2)
The ungroomed jet p_{T} is used since, in some cases (β = 0), its collinear unsafe

softdrop and systematics

softdrop grooming: start with a Cambridge/Aachen (angular) jet

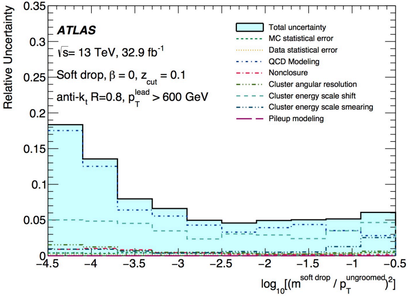
- un-do the clustering, at each step check the following (soft drop) condition for the protojets, j_i and j_2

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

- if the condition passes passes, terminate the agorithm, else discard discard the branch with the lowest p_{T} and iterate

Use a single jet trigger and select leading two Anti-*kt* jets with $|\eta| < 1.5$

- Use iterative bayesian method to correct for detector effects
- experimental uncertainties, apply variations to calo-cell clusters
- QCD fragmentation, compare Pythia, Sherpa and Herwig++



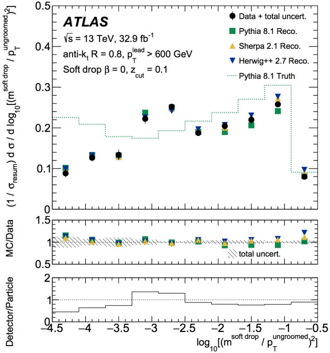
Theoretical predictions

Results compared to

- Predictions from Pythia, Sherpa, Herwig++ generators
- NLO+NLL predictions taken from S. Marzani, L. Schunk and G. Soyez arXiv:1704.02210
- LO+NNLL prediction from C. Frye et al. arXiv:1704.02210, arXiv:0808.1269

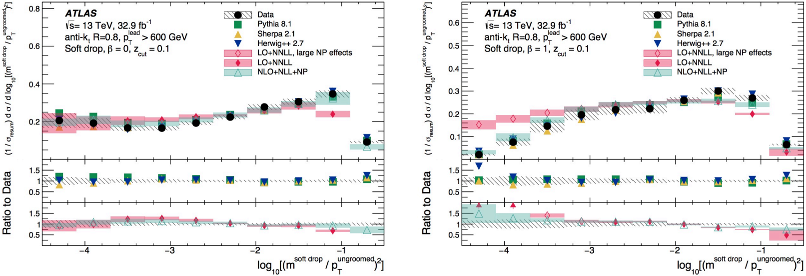
expect accuracies to differ in different regions of $\log_{10}(\rho^2)$

- resummation dominates: $-3.7 < \log_{10}(\rho^2) < -1.7$
- soft and collinear emissions $\log_{10}(\rho^2) < -3.7$ NP effects are larger
- Fixed order region: $\log_{10}(\rho^2) > -1.7$ Wide angle emissions



Results

MC generators and LO+NNLL prediction should be most accurate in the resummation region
NLO+LL should be more accurate at $\log_{10}(\rho^2) > -1.7$



As β increases, soft drop removes less radiation so NP corrections become more important

- good agreement for all predictions and MC within the resummation region
- at large β values, larger difference between MC and LO+NLL
- at low $\log_{10}(\rho^2)$ the LO+NLL starts to over predict the data