Summary of QCD measurements (from ATLAS, CDF, CMS and D0)

Frontiers in Particle Physics: From Dark Matter to the LHC and Beyond

Stephen Bieniek[1]

[1] University College London

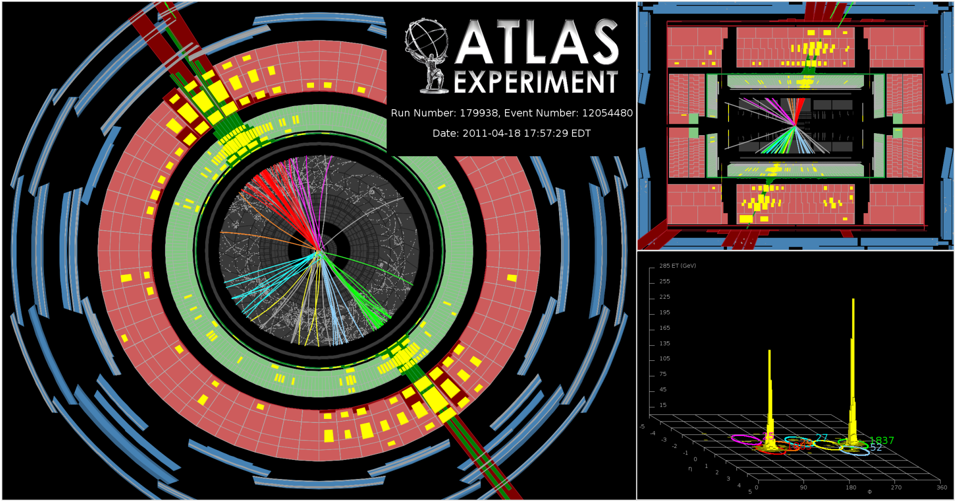
21st January 2014

Outline

1. Introduction
2. Modeling the Data
3. Measurements
4. Determination of α_s
5. Conclusions

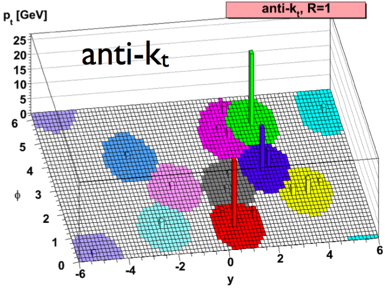
(Soft QCD is not covered in this talk)

Jets[1]



[1] Event display: https://cds.cern.ch/record/1357899/

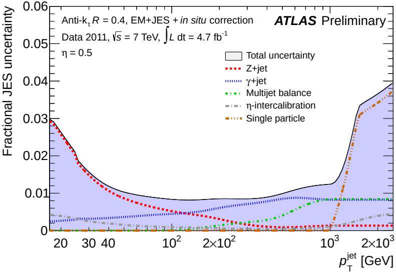
Jet Reconstruction Algorithms



JHEP 0804:063,2008

- Jet algorithms cluster a spray of particles into a single object.
- These single objects can act as a proxy for the partons from the hard process.
- CDF and D0 generally use cone algorithms.
  - Mid-point cone algorithm
- ATLAS and CMS use a sequential recombinations algorithm.
  - Anti-kt algorithm

Jet Energy Scale Uncertainty

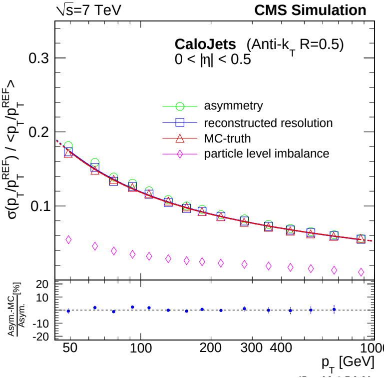


ATLAS-CONF-2013-004

- The jet energy scale uncertainty is the accuracy with which the calorimeters have been calibrated.
- Determined by:
  - looking for a jet recoiling off a EM objects (photon or Z);
  - test-beam data;
  - Monte Carlo simulation.

Jet Energy Resolution

- The jet energy resolution is the inherent accuracy with which a jet can be measured.
- Its measured by looking for two objects with the same transverse momentum (p_{T}) (i.e. back-to-back jets) and looking at the spread of their measured p_{T}.



CMS-PAS-JME-10-014

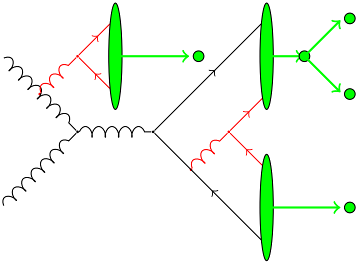
Average size of JER and JES systematic

Experiment	JES[%]	JER [%]
ATLAS	1 – 3	10 – 20
CMS	1 – 5	10 – 20
CDF	2 – 3	10 – 20
D0	1.5 – 3.5	10 – 20

- Numbers based upon best guesses from available plots.
- The range tries to indicate minimum and maximum, starting from 20 GeV.

Modeling the Data

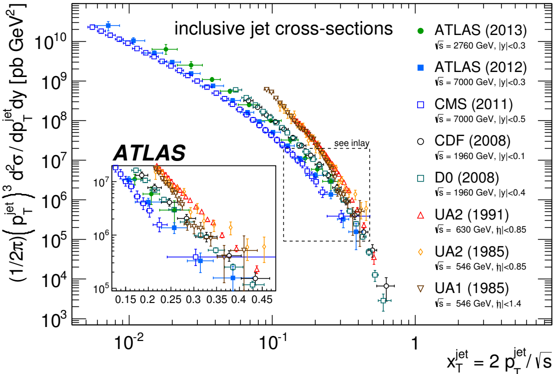
Data is modeled using Monte Carlo generators:



- Matrix Element - this is the exact part up to the stated accuracy (e.g. LO or NLO).
- Parton Shower - A good approximation to describe that QCD radiates a lot.
- Hadronization - A model to describe non perturbative effects.
- Underlying Event: this part describes how the rest of the colliding protons interact with the event and each other.

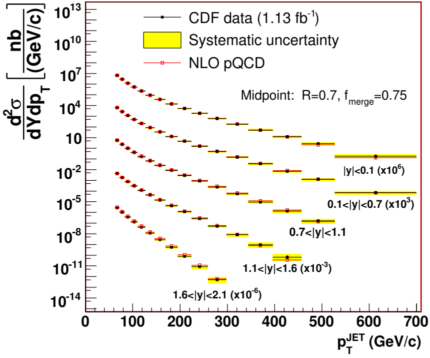
Cross Section Measurements

- The simplest way to test QCD is to count jets.
- You can count them with respect to various systems and variables.
- Comparing results to theory gives a good idea of how well we are doing.

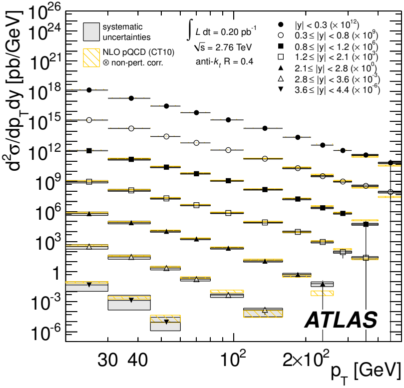


EPJC (2013) 73 2509

Inclusive-jet cross section (1)

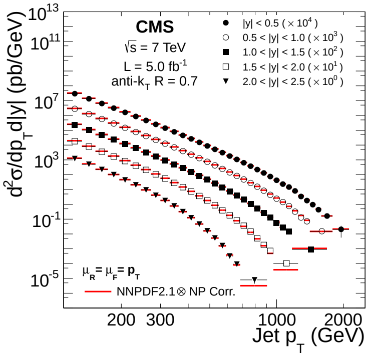


1.96 TeV - Phys.Rev.D78:052006 2008

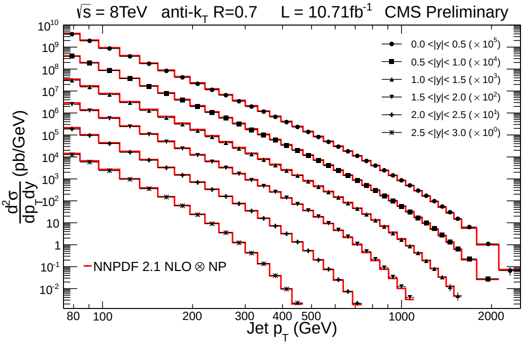


2.76 TeV - EPJC (2013) 73 2509

Inclusive-jet cross sections (2)



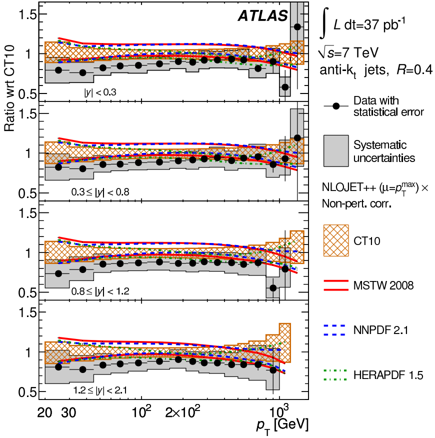
7 TeV - Phys.Rev.D 87 (2013) 112002



8 TeV - CMS-PAS-SMP-12-012

- Through inclusive cross section measurements, QCD has been tested at 4 centre of mass energies and over 7 orders of magnitudes.
- It performs very well.

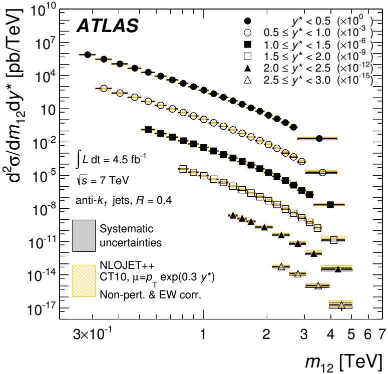
Inclusive-jet cross section (3)

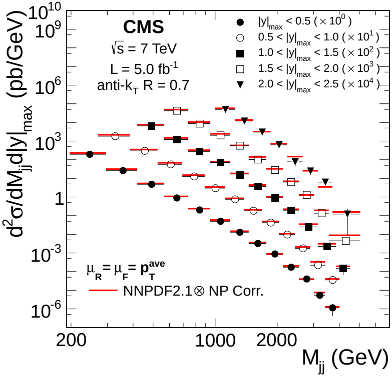


Phys.Rev. D86 (2012) 014022

- Theory predicts a larger cross section than seen in data.
- ATLAS 7 TeV data indicates the CT10 PDF description becomes worse at high p_T.
  - To some extent, MSTW 2008 predicts the trend seen in the data.
- CMS 8 TeV data favours the high p_T. description from CT10.

Dijet cross section[2]



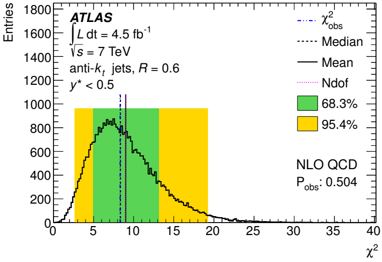


- Large uncertainty is seen in the theory predictions for high mass regions.

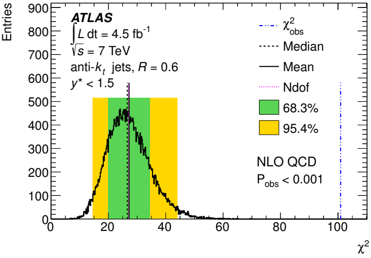
[2] arXiv:1312.3524

Accurate recording of correlations[3]

The correlations between bins in a measurement allow an easy quantification of the agreement between data and theory



HERAPDF1.5

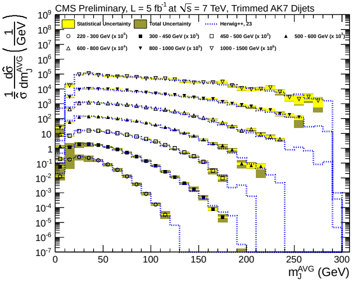


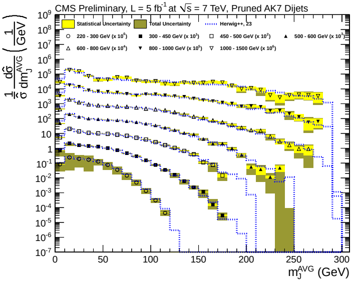
ABM11

- Making use of the covariance matrix, theory predictions are varied within their respective uncertainties to create pseudo-data.
- Different PDFs are compared here, but this method can be used for any physics model.

[3] arXiv:1312.3524

Jet substructure[4]



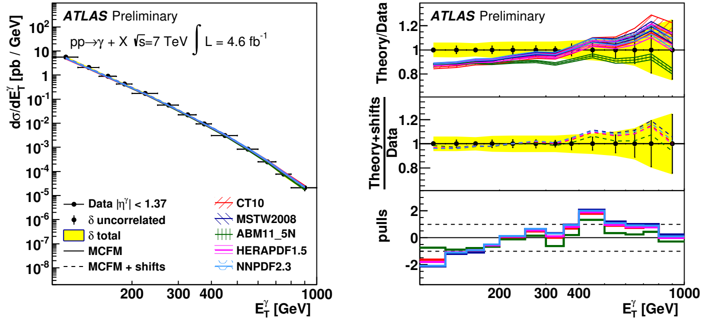


- Boosted objects and jet substructure provides a new tool to seperate QCD from the decay of heavy objects.
- There are several ways to examine jet substructure and they are all reasonable described in simulation.
- In some cases, the more aggressive the substructure techniques produce a better agreement between data and simulation

[4] J. High Energy Phys. 05 (2013) 090

PDF sensitivity to photon cross section[5]

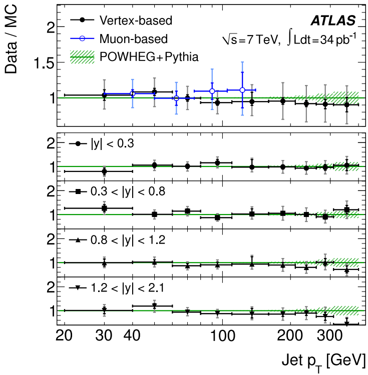
Pretty much all measurements at a hadron collider are QCD tests, its just a matter of how precise they are.



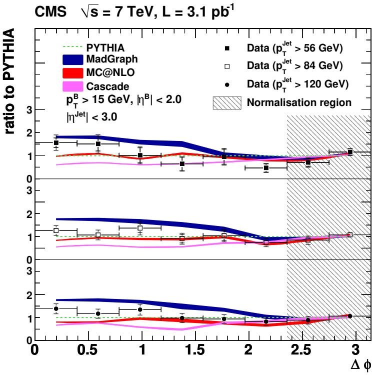
- The inclusive photon cross section provides information about the gluon PDF.

[5] arXiv:1311.1440, ATL-PHYS-PUB-2013-018

b-jet Cross Section Measurement



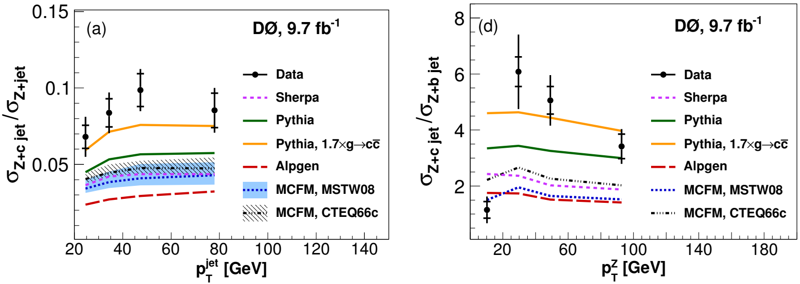
Eur.Phys.J.C 71 (2011) 1846



JHEP 1103 (2011) 136

- As b-hadrons have a sizeable lifetime, jets containing them can be identified.
- The inclusive *b*-jets cross section is described well by MC.
- Events with a small angular separation between two *b*-jets are not as well described.

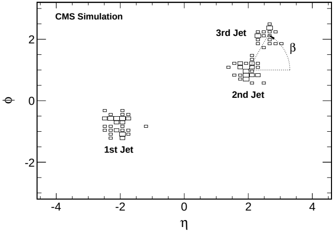
Z + heavy flavour[6]

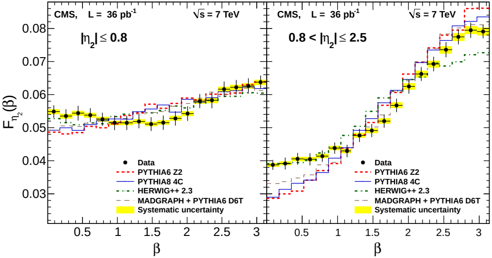


- Vector bosons plus heavy flavour measurements provide a good way to probe heavy flavour production.
- Current NLO predictions describe the total rate of production and the shape poorly.
- This is true for both the ratio of $\frac{Z+c}{Z+jet}$ and $\frac{Z+c}{Z+b}$.

[6] FERMILAB-PUB-13-329-E

Color Coherence[7]

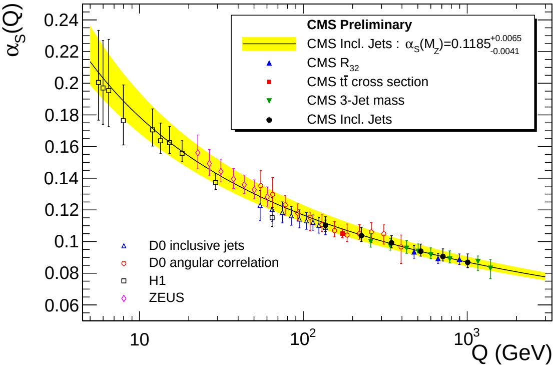




- The emission of a coloured object depends on other coloured objects in the event.
  - Color Coherence.
- The direction of emission of the third jet in a 3 jet system provides information about color coherence.
  - Quantified by the β variable.
- Non of the examined MC give a adequate description of the data.

[7] arXiv:1311.5815v1

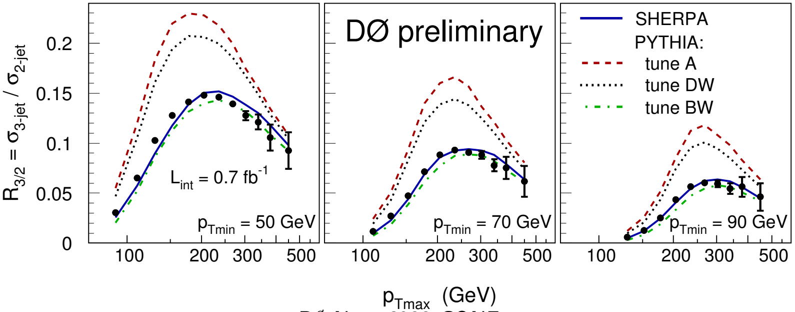
Measuring α_s



Eur.Phys.J. C73 (2013) 2604

- α_s is the only free parameter within QCD (apart from the quark masses).
- Measuring the energy scale dependence of α_s provides a very strong test of QCD.

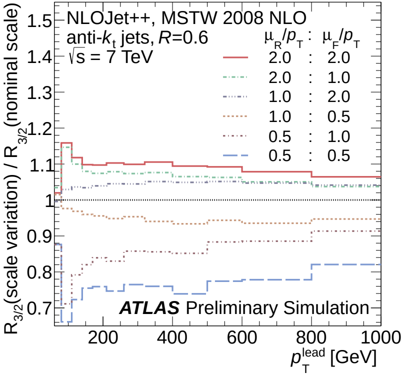
$R_{3/2}$

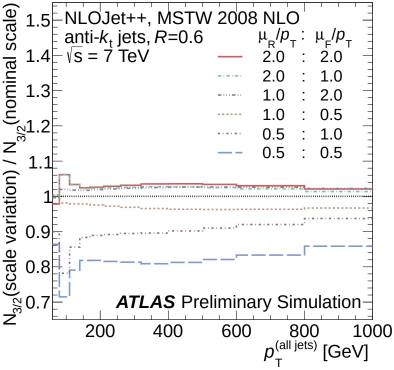


DØ Note 6032-CONF

- Ratio of events with at least 3 jets over at least 2 jets gives information about α_s.
  - Structure in plot comes from associated logarithm of the ratio of the jet p_T cut and hard scale of the event.
- $R_{3/2}$ is plotted with respect to leading jet p_T.
- The inclusion of extra parton emissions in Sherpas perturbative calculation results in good description of data.

$N_{3/2}$[8]

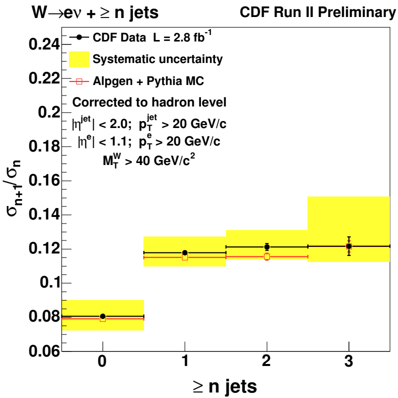




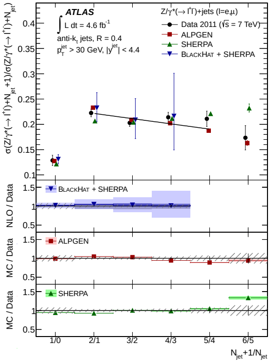
- ATLAS also uses $N_{3/2}$ as it is more stable against scale variation.
- Here, the p_T of every jet within the event is considered in the ratio.

[8] ATLAS-CONF-2013-041

Vector Boson + jets



CDF note 10423



JHEP07(2013)032

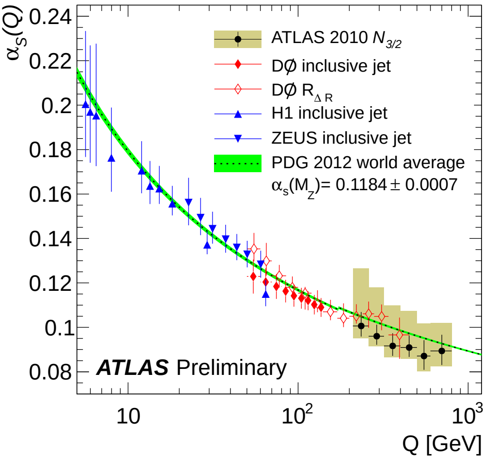
- The ratio of n+1 / n jets can be also taken in association of a vector boson.
- The step is due to new creation processes turning on.
- Good agreement between data and MC.

Conclusions

- QCD has been tested across a range of energies and phase spaces.
- Broadly speaking, it is performing remarkably well.
- Once we start looking into extreme areas of phase space we see disagreement.
  - Disagreement often comes in high multiplicity regions.
- New measurements are providing powerful constraints on PDFs.
- There are many results which I could not cover, which can be found here:
  - ATLAS https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
  - CDF http://www-cdf.fnal.gov/physics/new/qcd/QCD.html
  - CMS https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP
  - D0 http://www-d0.fnal.gov/Run2Physics/WWW/results/qcd.htm

Backup slides

ATLAS Combined α_s measurements[9]



---

[9] ATLAS-CONF-2013-041

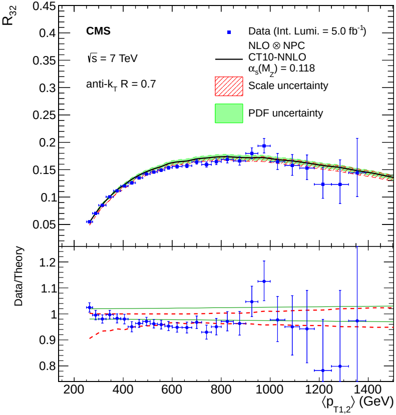
ATLAS Dijet cross-sections vs PDFs[10]

PDF set	y^* ranges	mass range (full/high)	P_{obs} $R = 0.4$	P_{obs} $R = 0.6$
CT10	$y^* < 0.5$	high	0.742	0.785
	$y^* < 1.5$	high	0.080	0.066
	$y^* < 1.5$	full	0.324	0.168
HERAPDF1.5	$y^* < 0.5$	high	0.688	0.504
	$y^* < 1.5$	high	0.025	0.007
	$y^* < 1.5$	full	0.137	0.025
MSTW 2008	$y^* < 0.5$	high	0.328	0.533
	$y^* < 1.5$	high	0.167	0.183
	$y^* < 1.5$	full	0.470	0.352
NNPDF2.1	$y^* < 0.5$	high	0.405	0.568
	$y^* < 1.5$	high	0.151	0.125
	$y^* < 1.5$	full	0.431	0.242
ABM11	$y^* < 0.5$	high	0.024	$< 10^{-3}$
	$y^* < 1.5$	high	$< 10^{-3}$	$< 10^{-3}$
	$y^* < 1.5$	full	$< 10^{-3}$	$< 10^{-3}$

Table 1. Sample of observed probabilities obtained in the comparison between data and the NLO QCD predictions using the CT10, HERAPDF1.5, MSTW 2008, NNPDF2.1 and ABM11 PDF sets, with values of the jet radius parameter $R = 0.4$ and $R = 0.6$. Results are presented for the range $y^* < 0.5$, as well as the combination of the first three ranges of $y^* < 1.5$, performing the test in the full dijet-mass range or restricting it to the high dijet-mass subsample. The full information on uncertainties, including their asymmetries and correlations, is used for both the pseudo-experiments and the χ^2 calculation.

[10] arXiv:1312.3524

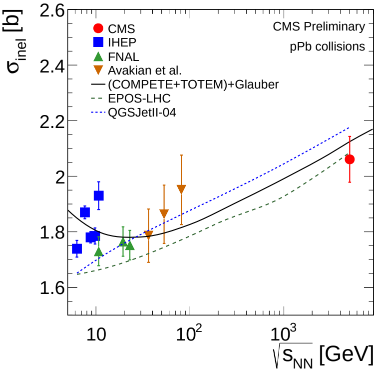
CMS Result for $N_{3/2}$[11]



- First measurment of $R_{3/2}$ at the TeV scale.
- Measured for jets with $p_T > 150\,\text{GeV}$ between $250 < p_{T1,2} < 1390$.
- $\alpha_s(M_Z) = 0.1148 \pm 0.0014$ (exp.) $\pm\ 0.0018$ (PDF) $\pm\ 0.0050$ (theory) $= 0.1148 \pm 0.0055$.
- Dominant uncertainty from theory.

[11] Eur. Phys. J. C (2013) 73:2604

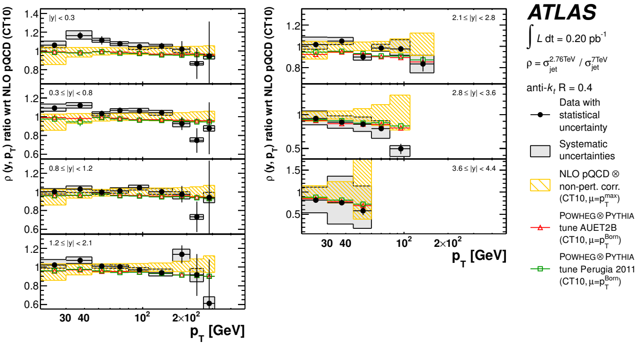
Proton-Lead Cross Section[12]



- The LHC also collides beams of heavy ions.
- Measuring the cross section inelastic p-Pb cross section provide another QCD test in a much more complicated environment.

[12] CMS-PAS-FSQ-13-006

Ratio of inclusive jet cross section results at $\sqrt{s} = 2.76$ and $\sqrt{s} = 7$ TeV results[13]



- By performing a ratio of results from the same detector uncertainties can be significantly reduced.
- There is disagreement between data and theory for $y < 0.3$.

[13] EPJC (2013) 73 2509