Probing QCD with the ATLAS detector

XXIV International Baldin Seminar on High Energy Physics
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Grazia Cabras
on behalf of the ATLAS Collaboration
University of Bologna and INFN
**Anatomy of a Collision**

**QCD** describes what goes on at high-energy accelerators.
- Interacting protons act as composite objects: **partons** (quarks and gluons)

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Parton Distribution Functions (PDFs) model parton composition and momentum distribution. PDF shapes from fit to data. QCD does not predict proton content.

Described by perturbative QCD (Matrix element)

Additional QCD radiation

Initial State Radiation

Final State Radiation

Hard Scattering

Interacting Proton
Anatomy of a Collision

Hadrons decay in other stable particle disclosed by the detector

Secondary partons interacts and fragment in other detectable hadrons

Hadron Decays

Fragmentation

Underlying Event

Modelling of the transition from partons to collimated particle systems: JETS
QCD and High Energy Accelerators

- **Jets** are reconstructed from the event and describe the **fragmentation** of quarks and gluons:
  - distinctive signature of short-distance interactions between partons

**Latest Run2 results**

- **QCD measurements** represent an extensive part of the **ATLAS** physics program:
  - soft QCD: all processes with low momentum transfer
  - hard QCD: jets physics
  - Comparison with pQCD theoretical predictions
  - Main background for Standard Model and Beyond Standard Model measurements

**Probing perturbative QCD with Jets!**
**ATLAS @ LHC**

- **LHC** (Large Hadron Collider) is the world’s largest accelerator.
  - 27 km ring of superconducting magnets, 100 m underground
  - proton-proton collisions
  - 4 big experiments: ATLAS, CMS, ALICE and LHCb

- **ATLAS (A Toroidal LHC ApparatuS)** is a general purpose experiment:
  - Standard Model and new physics measurements
  - 44 m long, with 25 m diameter and 7000 tons weight.

“*The ATLAS Experiment at the CERN Large Hadron Collider*”
Jets in ATLAS

- **Charged tracks** in the Inner Detector (track jets)
- Clusters of topologically connected calorimeter (both electromagnetic and hadronic) deposits (topo-clusters)

Need of a proper way to link jets to partons to understand their properties
Jet Reconstruction and Calibration

- **Jet reconstruction algorithm** to cluster objects into a jet
- ATLAS choice is **anti-kt algorithm**: sequential recombination algorithm based on **minimum distance**
  - Depends on jet $p_T$ and angular distance ($\eta$, $\varphi$)
- It must be:
  - **Collinear safe**, insensitive to splitting of a hard particle
  - **Infrared safe**, insensitive to the emission of a soft gluon

- Energy of the reconstructed jet is not the energy of partons due to detector effects

- **Strategy**: combine Monte Carlo studies, information from track jets and in situ measurements

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**Jet Calibration**

**STEP-BY-STEP**

1. **EM-scale jets**: Jet finding applied to topological clusters at the EM scale.
2. **Origin correction**: Changes the jet direction to point to the hard-scatter vertex. Does not affect $E$.
3. **Jet area-based pile-up correction**: Applied as a function of event pile-up $p_T$ density and jet area.
4. **Residual pile-up correction**: Removes residual pile-up dependence, as a function of $\mu$ and $N_{\mu}$

- **Absolute MC-based calibration**: Corrects jet 4-momentum to the particle-level energy scale. Both the energy and direction are calibrated.
- **Global sequential calibration**: Reduces flavor dependence and energy leakage effects using calorimeter, track, and muon-segment variables.
- **Residual in situ calibration**: A residual calibration is derived using in situ measurements and is applied only to data.

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ATL-PHYS-PUB-2015-036
Jet Physics @ ATLAS

**Jet cross-section measurements:**
- Probe proton substructure
- Test of Monte Carlo pQCD predictions
- Study of the strong coupling constant
- Constrain to PDF fits

Strong constraint at high momentum fraction!

Present Talk ~ ATLAS Results:
- Inclusive jet cross-section at 8 TeV
- Inclusive jet and dijet cross-section at 13 TeV
- Strong coupling from transverse energy-energy correlation at 8 TeV
- Strong coupling from dijet azimuthal decorrelation at 8 TeV

Theoretical Predictions

- **Theoretical predictions**:
  - pQCD predictions from NLOJET++ with different sets of PDFs
  - *Non perturbative corrections* for hadronisation and underlying events from Pythia8 and Herwig+ (spread between them taken as *uncertainty*)
  - *Electroweak corrections* are applied for the effects of $\gamma$ and $W^{\pm}/Z$

**Corrections at 13TeV for inclusive jet jet cross-section**

- **NNLO pQCD** corrections became available for qualitative comparisons (not all uncertainties available yet to perform quantitative studies)

**JHEP 05 (2018) 195**
Theoretical Uncertainties

- Main uncertainties in NLO predictions (common to the three analyses)
  - PDF: uncertainty propagated for each PDF set (prescription PDF4LHC)
  - Factorisation and Renormalisation scales: varied up and down of a factor 2 (-0.5<\(\mu_R,\mu_F\)<2)
  - \(\alpha_s\), strong coupling constant: comparing two PDF sets that differ in the value of \(\alpha_s\)

**SCALE UNCERTAINTY IS DOMINANT!**

JHEP 05 (2018) 195
Inclusive Cross-section at 8 TeV

- Anti-kt clustering algorithm with R = 0.4 and R = 0.6 (Backup)
- Double differential cross-section measured as a function of jet transverse momentum $p_T$ in bins of rapidity $y$:
  - $70 \text{ GeV} \leq p_T \leq 2.5 \text{ TeV}$ and $|y| < 3$
  - $\mu_{R,F} = p_{T\text{max}}$

\[ \frac{d^2\sigma}{dp_Tdy} = \frac{N_{jets}}{\mathcal{L}\Delta p_T \Delta y} \]

- Dominant experimental uncertainty related to jet calibration ($\sim 5\%$)

**Systematics on Cross-Section at 8 TeV (R=0.4)**

- Data compared with NLO prediction with MMHT2014 PDF
- JHEP 09 (2017) 020
Inclusive Cross-section at 8 TeV

Qualitative comparison of data to NLO Calculation

Central Region

Forward Region

• All PDF sets behave similarly
• NLO QCD prediction 20% above the data both in low and high $p_T$

PDFs: CT14, HERAPDF2.0, NNPDF3.0, MMHT2014

• Overall:
  ✦ CT14 prediction gives best qualitative agreement,
  HERAPDF2.0 the worst
  ✦ Sensitivity to constrain PDFs

• Predictions close to data at low $p_T$
• At high $p_T$, CT14, NNPDF3.0 and MMHT2014 have predictions higher than data

JHEP 09 (2017) 020
Inclusive Cross-section at 13 TeV

- Same approach of 8 TeV, except for the selection:
  - R=0.4
  - 100 GeV \leq p_T \leq 3.5 TeV and |y| < 3
  - \mu_{R,F} = p_T^{\text{max}}

\[
\frac{d^2\sigma}{dp_T dy} = \frac{N_{\text{jets}}}{\mathcal{L}\Delta p_T \Delta y}
\]

**Inclusive jet cross-section (R = 0.4)**

![Inclusive jet cross-section plot](image1)

**Systematics on Cross-Section at 13 TeV (R=0.4)**

- Jet Calibration dominant experimental uncertainty (~ 5%)

![Systematics plot](image2)

Data compared with NLO prediction with CT14 PDF

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XXIV International Baldin Seminar on HEP

Grazia Cabras
Inclusive Cross-section at 13 TeV

Qualitative comparison of data to NLO Calculation

PDFs: CT14, MMHT2014, NNPDF3.0

Overall:
- No significant deviation of the data points from the predictions
- Behaviour compatible with 8 TeV results
- NLO pQCD prediction overestimate data in forward region but not exceeding uncertainty

PDFs: CT14, HERAPDF2.0, ABMP16
Results at 8 TeV and 13 TeV

Quantitative comparison of data to NLO Calculation

- $\chi^2$ goodness of the fit in each rapidity bin
- $p$-values observed

### 8 TeV

<table>
<thead>
<tr>
<th>Rapidity ranges</th>
<th>$P_{\text{obs}}$</th>
<th>$P_{\text{NNPDF3.0}}$</th>
<th>$P_{\text{HERAPDF2.0}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anti-$k_t$, jets $R = 0.4$</td>
<td>44%</td>
<td>28%</td>
<td>25%</td>
</tr>
<tr>
<td>$</td>
<td>y</td>
<td>&lt; 0.5$</td>
<td>43%</td>
</tr>
<tr>
<td>$0.5 \leq</td>
<td>y</td>
<td>&lt; 1.0$</td>
<td>44%</td>
</tr>
<tr>
<td>$1.0 \leq</td>
<td>y</td>
<td>&lt; 1.5$</td>
<td>3.7%</td>
</tr>
<tr>
<td>$1.5 \leq</td>
<td>y</td>
<td>&lt; 2.0$</td>
<td>92%</td>
</tr>
<tr>
<td>$2.0 \leq</td>
<td>y</td>
<td>&lt; 2.5$</td>
<td>4.5%</td>
</tr>
</tbody>
</table>

### 13 TeV

<table>
<thead>
<tr>
<th>Rapidity ranges</th>
<th>$P_{\text{obs}}$</th>
<th>$P_{\text{NNPDF3.0}}$</th>
<th>$P_{\text{HERAPDF2.0}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{T}}^{\text{max}}$</td>
<td>CT14</td>
<td>MMHT 2014</td>
<td>NNPDF 3.0</td>
</tr>
<tr>
<td>$</td>
<td>y</td>
<td>&lt; 0.5$</td>
<td>67%</td>
</tr>
<tr>
<td>$0.5 \leq</td>
<td>y</td>
<td>&lt; 1.0$</td>
<td>5.8%</td>
</tr>
<tr>
<td>$1.0 \leq</td>
<td>y</td>
<td>&lt; 1.5$</td>
<td>65%</td>
</tr>
<tr>
<td>$1.5 \leq</td>
<td>y</td>
<td>&lt; 2.0$</td>
<td>0.7%</td>
</tr>
<tr>
<td>$2.0 \leq</td>
<td>y</td>
<td>&lt; 2.5$</td>
<td>2.3%</td>
</tr>
<tr>
<td>$2.5 \leq</td>
<td>y</td>
<td>&lt; 3.0$</td>
<td>62%</td>
</tr>
</tbody>
</table>

- Satisfactory description of the data by the NLO QCD prediction in all the rapidity bins
  - except for one $y$-bin
- Fitting in all the rapidity bins together, $P_{\text{obs}} \ll 10^{-3}$: tension between data and theory

Possible explanation: some unknown correlation between systematics or incomplete theoretical description

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Dijet Cross-section at 13 TeV

- Anti-kt clustering algorithm with R = 0.4
- Dijet Double differential cross-section measured as a function of the invariant mass dijet system $m_{jj}$ in 6 bins of centrality $y^*$:
  1. $300 \text{ GeV} \leq p_T \leq 9 \text{ TeV}$ and $|y| < 3$
  2. $\mu_{R,F} = p_T^{\text{max}}$

\[
\frac{d^2\sigma}{dm_{jj}dy^*} = \frac{N_{\text{jets}}}{\mathcal{L}\Delta m_{jj}\Delta y^*}
\]

**Dijet cross-section (R = 0.4)**

**Systematics on Cross-Section at 13 TeV (R=0.4)**

- Jet Calibration dominant experimental uncertainty ($\sim 5\%$)

Data compared with NLO prediction with CT14 PDF
Dijet Cross-section at 13 TeV

Qualitative comparison of data to NLO Calculation

**ATLAS**

$\sqrt{s} = 13$ TeV

*PDFs:* CT14, MMHT2014, NNPDF3.0

\[ \mu = p_t \exp(0.3y^*) \]

- **Overall:** No significant deviation of the data points from the predictions
Dijet Cross-section at 13 TeV

Quantitative comparison of data to NLO Calculation

<table>
<thead>
<tr>
<th>$y^*$ ranges</th>
<th>CT14</th>
<th>MMHT 2014</th>
<th>NNPDF 3.0</th>
<th>HERAPDF 2.0</th>
<th>ABMP16</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y^* &lt; 0.5$</td>
<td>79%</td>
<td>59%</td>
<td>50%</td>
<td>71%</td>
<td>71%</td>
</tr>
<tr>
<td>$0.5 \leq y^* &lt; 1.0$</td>
<td>27%</td>
<td>23%</td>
<td>19%</td>
<td>32%</td>
<td>31%</td>
</tr>
<tr>
<td>$1.0 \leq y^* &lt; 1.5$</td>
<td>66%</td>
<td>55%</td>
<td>48%</td>
<td>66%</td>
<td>69%</td>
</tr>
<tr>
<td>$1.5 \leq y^* &lt; 2.0$</td>
<td>26%</td>
<td>26%</td>
<td>28%</td>
<td>9.9%</td>
<td>25%</td>
</tr>
<tr>
<td>$2.0 \leq y^* &lt; 2.5$</td>
<td>41%</td>
<td>34%</td>
<td>29%</td>
<td>3.6%</td>
<td>20%</td>
</tr>
<tr>
<td>$2.5 \leq y^* &lt; 3.0$</td>
<td>45%</td>
<td>46%</td>
<td>40%</td>
<td>25%</td>
<td>38%</td>
</tr>
<tr>
<td>all $y^*$ bins</td>
<td>9.4%</td>
<td>6.5%</td>
<td>11%</td>
<td>0.1%</td>
<td>5.1%</td>
</tr>
</tbody>
</table>

- Fair agreement between data and theory in single $y^*$ bins and when considering all events (last row)
\( \alpha_s \) from TEEC at 8 TeV

- Another way to probe pQCD:
  - Event shape variables \( \rightarrow \) measurements of the geometry of hadronic energy flow.
- **Transverse energy-energy correlation** (TEEC) and its asymmetry (ATEEC) measurements:
  - Event shape variable infrared safe and with small NLO corrections (both perturbative and EWK).
  - Transverse energy - weighted distribution of differences in azimuth between jets i and j.

\[
\frac{1}{\sigma'} \frac{d\Sigma'}{d\phi} = \frac{1}{N \Delta \cos \phi} \sum_{A=1}^{N} \sum_{ij} \frac{E_{T_i}^A E_{T_j}^A}{(\sum E_{T_k}^A)^2} \delta(\cos \phi - \cos \phi_{ij})
\]

- Number of events (index A)
- \( \phi_{ij} \): azimuthal angle between i and j
- i and j run over all the jets in a given event

**TEEC distribution example**

αs from TEEC at 8 TeV

- **Theoretical predictions:**
  - pQCD predictions from NLOJET++ with different sets of PDFs
    - MMHT2014, CT14, NNPDF3.0 and HERAPDF2.0
  - Non perturbative correction for hadronisation and underlying events from Pythia8 and Herwig++
  - Dominant related systematic uncertainty: $\mu_{R,F}$

![Graph showing data vs. theory for TEEC theoretical uncertainty at different energy bins](image-url)
\( \alpha_s \) from TEEC at 8 TeV

- **Multijet systems**: jet multiplicity \(< N_{\text{jets}} > = 2,3\)
  - \( p_T > 100 \text{ GeV} \) and \( |y| < 2.5 \)
- \( R = 0.4 \)
- \( H_{T2} = P_{T1} + P_{T2} \) (sum of the transverse momentum of the two leading jets)
  - \( H_{T2} > 800 \text{ GeV} \) for the two leading jets
- **6 \( H_{T2} \) bins**
  - Scale \( Q = \langle H_{T2} \rangle / 2 \)

**STRATEGY**

- Measurement of TEEC (ATEEC) distribution in different energy regimes (\( = H_{T2} \) bins)
- Fit of individual distribution
- Determination of \( \alpha_s (m_Z) \) in each energy regime
- Renormalisation Group Equation
- Test the running of \( \alpha_s \)

**Dominant experimental systematic uncertainties**

**MC model and Jet Calibration**

\( \alpha_s \) from TEEC at 8 TeV

- **How to extract \( \alpha_s \)?**
  - TEEC (and ATEEC) observables are fitted to the NLOJET++ theoretical predictions, in each \( H_{T2} \) bin, singularly
  - \( \alpha_s \) (mz) value for each bin
  - Each value is evolved to the corresponding energy scale using RGE
  - Final value of \( \alpha_s \) (mz) obtained merging all the bins together (NNPDF3.0 has the largest PDF uncertainty: related determination quoted as result to be conservative)

\( \alpha_s \) from Dijet Azimuthal Decorrelations at 8 TeV

- \( \Delta \phi_{\text{dijet}} \): azimuthal separation between the two leading jets
  - = \( \pi \) for exclusive high-\( p_T \) final states
  - <\( \pi \) due to additional activity in final states
  - <\( \pi \) and >\( 2\pi/3 \) for 3 jets in final states
  - < \( 2\pi/3 \) for 4 jets in final states

Test of pQCD for 3 or 4 jet production: probing higher order \( \alpha_s \)

Fraction of inclusive jet events with \( \Delta \phi < \Delta \phi_{\text{max}} \):

\[
R_{\Delta \phi}(H_T, y^*, \Delta \phi_{\text{max}}) = \frac{\frac{d^2 \sigma_{\text{dijet}}(\Delta \phi_{\text{dijet}} < \Delta \phi_{\text{max}})}{dH_T dy^*}}{\frac{d^2 \sigma_{\text{dijet}}(\text{inclusive})}{dH_T dy^*}}
\]

- Binned in \( \Delta \phi_{\text{max}} \): 7\( \pi/8 \), 5\( \pi/6 \), 3\( \pi/4 \) (three jets, NLO predictions) and 2\( \pi/3 \) (four jets, LO predictions)
- Binned in \( H_T \) and \( y^* \)

arXiv:1805.04691
Theoretical predictions:

- NLOJET++ for pQCD calculation
- $\mu_{R,F} = H_T/2$
- PDFs: MMHT2014, CT14, NNPDF2.3

Data described by theoretical description in all kinematic regions:

- 5% for $7\pi/8$ and $5\pi/6$: most stringent tests of theoretical prediction
- 10-15% for $3\pi/4$: large scale dependence
- 20% uncertainty dominated by scale variation for $2\pi/3$

7\pi/8 chosen for $\alpha_s$ determination:

- reliable pQCD prediction
- data points from different $y^*$ regions can be combined
- smallest statistical uncertainties
  - excluding $1<y^*<2$ region due to high NLO correction

5\pi/6 also a good choice but higher statistical uncertainty!
\( \alpha_s \) from Dijet Azimuthal Decorrelations at 8 TeV

- \( \chi^2 \) fit of 7π/8 points in two \( y^* \) regions
- Nine values of \( \alpha_s(Q) \) in Q-range 262 < \( Q \leq 1675 \) GeV
- Combine fit to extract \( \alpha_s(m_Z) \) (evolving \( \alpha_s(Q) \) using RGE)

![\( \alpha_s(Q) \) measurement](image)

\( \alpha_s(m_Z) = 0.1127 \pm 0.0063 \pm 0.0027 \)

<table>
<thead>
<tr>
<th>( \alpha_s(m_Z) )</th>
<th>Total</th>
<th>Statistical</th>
<th>Experimental</th>
<th>Non-perturb.</th>
<th>MMHT2014</th>
<th>PDF set</th>
<th>( \mu_{R,F} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1127</td>
<td>+6.3</td>
<td>±0.5</td>
<td>+1.8</td>
<td>+0.3</td>
<td>+0.6</td>
<td>+2.9</td>
<td>+5.2</td>
</tr>
<tr>
<td></td>
<td>−2.7</td>
<td></td>
<td>−1.7</td>
<td>−0.1</td>
<td>−0.6</td>
<td>−0.0</td>
<td>−1.9</td>
</tr>
</tbody>
</table>

arXiv:1805.04691

\( \alpha_s \) from Dijet Azimuthal Decorrelations at 8 TeV
Conclusions

• LHC is the ideal playground for extensive tests of QCD

• Jets are powerful tools for such goal also thanks to the excellent ATLAS performance in jet reconstruction

• ATLAS has wide physics program in the QCD field with jet cross-section, both inclusive and in association with $\gamma$ and vector bosons

• ATLAS latest results on pQCD shows generally good theory-data agreement
  • investigating some tension between data and theory in inclusive jet cross-section measurements both at 8 and 13 TeV
  • determination of $\alpha_s (m_Z)$ from transverse energy-energy correlation in dijet events and from dijet azimuthal decorrelation compatible with World Average
Backup
QCD

- **QCD** (Quantum ChromoDynamics) is the theory of strong interactions:
  - 3 color charges (red, blue and green)
  - 8 colored of gluons: gluons interact with each others!

- No free quarks observed: **confinement**
- At high momentum transfer, quarks **behave** as free particles: **asymptotic freedom**

- **Running** coupling constant:
  - increasing with energy decrease: perturbative QCD (**pQCD**)
  - decreasing with energy increase: phenomenological approach (perturbative one no longer reliable)
Particles in ATLAS

• **ATLAS** particle reconstruction:

  - Muon spectrometer
  - Hadronic calorimeter
  - Electromagnetic calorimeter
  - Solenoid magnet
  - Tracking
    - Transition radiation tracker
    - Pixel/SCT detector
  - Neutrino
  - Proton
  - Neutron
  - Electron
  - Photon

  Inside a 2 T solenoid

  **Calorimeters**
  - Tile barrel
  - Tile extended barrel
  - LAr hadronic end-cap (HEC)
  - LAr electromagnetic end-cap (EEMC)
  - LAr forward (FCal)

  **Inner Detector**
  - TRT
  - SCT
  - Pixels
  - IBL

  The dashed tracks are invisible to the detector.
Jet Reconstruction

- Jet reconstruction algorithm to cluster objects into a jet
- ATLAS choice is anti-kt algorithm: sequential recombination algorithm based on minimum distance
- Depends on jet $p_T$ and angular distance ($\eta$, $\phi$)
- Procedure:
  ✦ Find local cell $i$ with $E_{\text{max}}$
  ✦ $j$ is the neighboring cell
  ✦ Find $\min\{d_{ij}, d_{iB}\}$
  ✦ If $d_{ij} = \min$, then recluster
  ✦ Otherwise label $i$ as final jet

**Ingredients**

- $d_{ij} = \min \left( \frac{1}{p_{ti}^2}, \frac{1}{p_{tj}^2} \right) \cdot \frac{R_{ij}^2}{R}$
- $d_{iB} = \frac{1}{p_{ti}^2}$
- $R_{ij}^2 = (\phi_i - \phi_j)^2 + (\eta_i - \eta_j)^2$
- $R$ is the radius parameter (range 0.4 - 1)
Jet Calibration

- Effects to be corrected:
  - Calorimeter non compensation: partial measurement of the energy deposited
  - Dead material: energy losses in inactive areas of the detector
  - Leakage: energy of the particles out of the calorimeters
  - Out of calorimeter radiation: energy deposit of the particles from shower not included in reconstructed jet
  - Noise threshold and particle reconstruction efficiency: electronics losses in calorimeter clustering and jet reconstruction.
  - Pile up: taking into account energy due to additional $pp$ interactions
  - Jet origin correction: correct the direction of the jet to originate from primary vertex (no effects on energy)
Inclusive Cross-section at 8 TeV: R=0.6

Inclusive jet cross-section (R = 0.6)

ATLAS
\[ \sqrt{s} = 8 \text{ TeV}, \ 20.2 \text{ fb}^{-1} \]
anti-\(k_t\) R= 0.6

Systematics on Cross-Section at 13 TeV (R=0.6)
Inclusive Cross-section at 8 TeV: R=0.6

Qualitative comparison of data to NLO Calculation

Quantitative comparison of data to NLO Calculation

<table>
<thead>
<tr>
<th>Rapidity ranges</th>
<th>CT14</th>
<th>MMHT2014</th>
<th>$P_{\text{obs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anti-k$_t$ jets $R = 0.6$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>y</td>
<td>&lt; 0.5$</td>
<td>6.7%</td>
</tr>
<tr>
<td>$0.5 \leq</td>
<td>y</td>
<td>&lt; 1.0$</td>
<td>1.3%</td>
</tr>
<tr>
<td>$1.0 \leq</td>
<td>y</td>
<td>&lt; 1.5$</td>
<td>30%</td>
</tr>
<tr>
<td>$1.5 \leq</td>
<td>y</td>
<td>&lt; 2.0$</td>
<td>12%</td>
</tr>
<tr>
<td>$2.0 \leq</td>
<td>y</td>
<td>&lt; 2.5$</td>
<td>94%</td>
</tr>
<tr>
<td>$2.5 \leq</td>
<td>y</td>
<td>&lt; 3.0$</td>
<td>13%</td>
</tr>
</tbody>
</table>
Inclusive Cross-section at 8 TeV

- Theoretical Uncertainties in NLO predictions:
  - CT14 PDF
NNLO Calculation at 13 TeV

- NNLOJET with MMHT2014 NNLO PDF:
  - two $\mu_{R,F}$ scales: $p_T^{\text{max}}$ (leading jet) and $p_T$
$\alpha_s$ from ATEEC at 8 TeV

ATEEC systematic experimental uncertainties

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{ATEEC_systematic.png}
\caption{ATEEC systematic uncertainties for different mass bins.}
\end{figure}

ATEEC theoretical uncertainties

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{ATEEC_theoretical.png}
\caption{ATEEC theoretical uncertainties for different mass bins.}
\end{figure}
\( \alpha_s \) from ATEEC at 8 TeV

ATEEC Fit Results compared to World Average

\[ \alpha_s (Q) \]

ATLAS

<table>
<thead>
<tr>
<th>PDF</th>
<th>( \alpha_s (m_Z) ) value</th>
<th>( \chi^2/N_{\text{dof}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMHT 2014</td>
<td>0.1185 ( \pm ) 0.0012 (exp.) ( \pm 0.0010 ) (PDF) ( \pm 0.0004 ) (NP)</td>
<td>57.0 / 65</td>
</tr>
<tr>
<td>CT14</td>
<td>0.1203 ( \pm ) 0.0013 (exp.) ( \pm 0.0015 ) (PDF) ( \pm 0.0004 ) (NP)</td>
<td>55.4 / 65</td>
</tr>
<tr>
<td>NNPDF 3.0</td>
<td>0.1196 ( \pm ) 0.0013 (exp.) ( \pm 0.0017 ) (PDF) ( \pm 0.0004 ) (NP)</td>
<td>60.3 / 65</td>
</tr>
<tr>
<td>HERAPDF 2.0</td>
<td>0.1206 ( \pm ) 0.0012 (exp.) ( \pm 0.0005 ) (PDF) ( \pm 0.0002 ) (NP) ( \pm 0.0007 ) (mod)</td>
<td>54.2 / 65</td>
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