Recent ATLAS measurement sensitive to PDFs

Pavel Starovoitov

DESY

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Outlook

1. Jet measurements
2. $W$-production in association with jets and $W$–jet/$Z$–jet ratios
3. Production of $Z$-boson in association with $b$-jets
4. Simultaneous measurements of the $t\bar{t}$, $WW$, and $Z \rightarrow \tau\tau$ production cross-sections: AIDA
5. PDF uncertainties in $W$-boson mass
6. Summary
Jet measurements. JES uncertainty

Calorimeter jets (EM or LCW scale)
- Pile-up offset correction
  Corrects for the energy offset introduced by pile-up. Depends on $\mu$ and $N_{PV}$. Derived from MC.
- Origin correction
  Changes the jet direction to point to the primary vertex. Does not affect the energy.
- Energy & $\eta$ calibration
  Calibrates the jet energy and pseudorapidity to the particle jet scale. Derived from MC.
- Residual in situ calibration
  Residual calibration derived using in situ measurements. Derived in data and MC. Applied only to data.
- Calorimeter jets (EM+JES or LCW+JES scale)

Three jet cross-section measurements with the same JES systematics

- Dijet production
  JHEP05(2014)059
- Inclusive jet cross-section
  arXiv:1410.8857
- Three-jet mass spectrum
  ATLAS-CONF-2014-045

Combination of in situ measurements ($Z/\gamma$–jet, multi-jet)

$\sim 5\times$ reduction in the JES uncertainty

- Dijet production
  JHEP05(2014)059
- Inclusive jet cross-section
  arXiv:1410.8857
- Three-jet mass spectrum
  ATLAS-CONF-2014-045

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PDF4LHC-Nov/2014
Jet measurements. Inclusive jet $p_T$

- $p_T > 100$ GeV, binned according to resolution
- $|y| < 3$, six rapidity bins, in steps of 0.5
- Theory:
  - NLOJET++ $\times$ NPC $\times$ EW
  - non-pert. correction:
    - Pythia/Herwig with various tunes

- theory is corrected for EW effects

Good agreement between data and theory over 7 orders of magnitude
Inclusive jets. Detailed comparison to theory (I)

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Inclusive jets. Detailed comparison to theory (II)

ATLAS
\[ \int L \, dt = 4.5 \, fb^{-1} \]
\( \overline{s} = 7 \, TeV \)
Non-pert and EW corr.

Different set of PDFs

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Recent ATLAS measurement sensitive to PDFs
Inclusive jets. Test of gaussianity of uncertainties

**ATLAS**
anti-\(k_t\) jets, \(R=0.6\)
\(|y| < 0.5\)
\(838 \leq p_T \text{ [GeV]} < 894\)

--- Nominal Quantiles
Experimental
\(\nabla\) Gaussian
\(\triangle\) LogNormal

1 \(\sigma\)
2 \(\sigma\)
3 \(\sigma\)
4 \(\sigma\)
5 \(\sigma\)

Uncertainty in the energy deposited in the EM calorimeter
Jet measurements. Dijet mass

\( m_{12} = \sqrt{p_1 + p_2} \)
\( y^* = |y_1 - y_2|/2 \)

- \( p_T^1 > 100 \text{ GeV}, p_T^2 > 50 \text{ GeV}, |y^{| < 3} \)
- \( |y^*| < 3 \), six rapidity separation bins, in steps of 0.5

Theory:
- NLOJET++ × NPC × EW
- non-pert. correction: Pythia/Herwig with various tunes

\[
\int L \, dt = 4.5 \text{ fb}^{-1} \\
\sqrt{s} = 7 \text{ TeV} \\
\text{anti-}k_T \text{ jets}, R = 0.4
\]

- theory is corrected for EW effects

Good agreement between data and theory over 7 orders of magnitude
Jet measurements. Three-jet mass

\[
\begin{align*}
\rho_T^1 & > 150 \text{ GeV}, \rho_T^2 > 100 \text{ GeV}, \rho_T^3 > 50 \text{ GeV}, \\
|y^{\text{jet}}| & < 3 \\
Y^* & = |y_1 - y_2| + |y_1 - y_3| + |y_2 - y_3| \\
|Y^*| & < 10, \text{ five rapidity separation bins, in steps of 2}
\end{align*}
\]

- Theory: NLOJET++ \times NPC
- non-pert. correction: Pythia/Herwig with various tunes
- no EW correction is available

Good agreement between data and theory over 6 orders of magnitude
Three-jets. Detailed comparison to theory (I)

ATLAS Preliminary

\[ \int L \, dt = 4.5 \, fb^{-1} \]

\( \sqrt{s} = 7 \, TeV \)

\( \text{anti-} k_t, R = 0.4 \)

DATA Uncert.

Total

Statistical

\( \times \) non-pert. corr.

\( \otimes \) PDF

NLO QCD

CT 10

MSTW 2008

HERAPDF 1.5

<table>
<thead>
<tr>
<th>Prediction/Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
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<td>0.6</td>
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<tr>
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| 4 | 2 |
| | |

| 2 | 6 |
| | |

| 1.4 |
| 1.2 |
| 1 |
| 0.8 |
| 0.6 |
| 0.4 |

| 4 | 2 |
| | |

| 2 | 6 |
| | |

different set of PDFs
Three-jets. Detailed comparison to theory (II)

**ATLAS** Preliminary

\[ \int L \, dt = 4.5 \, \text{fb}^{-1} \]
\[ \sqrt{s} = 7 \, \text{TeV} \]
\[ \text{anti-}k_t, \, R = 0.4 \]

\[ |Y^*| < 2 \]
\[ 2 < |Y^*| < 4 \]
\[ 4 < |Y^*| < 6 \]
\[ 6 < |Y^*| < 8 \]
\[ 8 < |Y^*| < 10 \]

Prediction/Data

0.6
0.8
1
1.2
1.4
4\times10^2
10^3
2\times10^3
m_{jjj}[\text{GeV}]\times10^2
10^3
2\times10^3
m_{jjj}[\text{GeV}]

**GJR 08**
**ABM 11**
**NNPDF 2.3**

\[ \times \text{non-perf. corr.} \]
\[ \times \text{PDF} \]
\[ \times \text{NLO QCD} \]

Different set of PDFs

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Recent ATLAS measurement sensitive to PDF
$W$-production in association with jets and $W$–jet/$Z$–jet ratios

Same systematics and binning between $W/Z$–jets measurements allows to measure cross-section ratios $\rightarrow$ reduction of exp. uncertainties

- $W$–jets cross-sections (arXiv:1409.8639)
- $R$–jets cross-sections (arXiv:1408.6510)
- $Z$–jets cross-sections (JHEP07(2013)032)

Many interesting results

Will discuss only a few examples which are the most relevant for PDFs studies
Very good agreement between NLO calculations and data for jet rapidity distribution

NLO theory undershoots data at high-$p_T$.

Interesting input for MC tuning PDF studies
Recent ATLAS measurement sensitive to PDFs
Production of $Z$-boson in association with $b$-jets

Clean experimental signature:
- leptonically decaying $Z +$ HF jet
  - Allows to test the associated heavy flavour production
  - Large uncertainties in theory calculations → measurement provides important constraints
  - Probes $b$-quark PDF (5FNS)

PDF4LHC-Nov/2014 15 / 24
Inner bar – stat. uncert.

Outer bar – total uncert.

MCFM is corrected for QED FSR, hadronisation, MPI

Theory uncert.:

PDF+scale+\(\alpha_s\)+corr. Scale is the dominant

Best PDF sensitivity from \(y_Z\) in 1\(b\)-jet channel

2\(b\)-jet channel is not very sensitive to PDFs (splitting)

\(b\)-jet \(p_T\) spectrum potentially is very interesting for PDF studies (need more precise theory . . . )
Simultaneous measurements of the $t\bar{t}$, $WW$, and $Z \rightarrow \tau \tau$ production cross-sections: AIDA

High accuracy in theoretical prediction $\rightarrow$ good experimental test

- Study of the common final state ($e\mu$)-events
- two-dimensional parameter space ($E_{T}^{\text{miss}}$, $N_{\text{jets}}$)

Allows to "see" correlation between cross-section induced by a use of common PDFs in MC

measurements are consistent with dedicated analyses
AIDA results. Total cross-section

Fiducial results are corrected to the total phase-space

- **NNLO** calculations describe data much better than NLO
- **scale uncert.** @NLO is the dominant source
- **PDF uncert.** @NNLO is the dominant source

NLO - MCFM

NNLO - FEWZ, TOP++
The extraction of $m_W$ from the $p_T^\ell$ spectrum, is likely to be limited by theoretical uncertainties.

This study addresses:

- $u$ and $d$ PDF uncertainties on the average $W$ polarisation
- strange PDF uncertainty on the charm-initiated $W$-production
- impact of the muon momentum resolution on the PDF uncertainties

**TOOLS:**

- MCFM ($W$-jet LO, finite width, leptonic decay, spin correlations)
- CuTe (NLO+NNLL, ZWA, no decay)

→ need to combine two tools

Dedicated PDF set : HERA I data, $m_{ch} = 1.38$ GeV, $m_b = 4.75$ GeV, $m_t = 3.5$ TeV, $r_s = s/\bar{d} = 1$, $Q_0^2 = 1.7$ GeV$^2$ 13p→26 hessian errors, 4 model vars : $m_{ch} \uparrow$, $r_s \uparrow$
Methodology

Event selection

- $|\eta^\ell| < 2.4$
- $p_T^\nu > 30$ GeV
- $M_T > 60$ GeV
- $30 < p_T^\ell < 50$ GeV

Test sample: normalised $p_T^\ell$ spectrum with $M_W = 80.385$ GeV. Stat. uncert. corresponds to $5 fb^{-1}$

Set of $p_T^\ell$ templates as a function of $M_W$

calculate $\chi^2$ profile and fit it with parabolic function to get minima and uncertainty
$W$-polarisation

The uncertainty on the $u$ and $d$ valence and sea PDF translates into an uncertainty in the average $W$ polarisation, which affects the $p_T^\ell$ distribution.

Disentangle the impact of polarisation: Keep only $u$ and $d$ quarks.

- Randomise decay angle of leptons in the $W$ rest frame
- Sign flip to the lepton momentum
- Full spin correlations

Dramatic shrink of PDF uncert. with spin corr. off

- $\sim 20$ MeV in $W^+$ (mostly $r_s$);
- $\sim 25$ MeV in $W^-$ (many);
- $\sim 15$ MeV for $W^\pm$ due to some cancellations.

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Recent ATLAS measurement sensitive to PDF

PDF4LHC-Nov/2014
Charm quark and strange PDF

- A charm-initiated production changes the $W$ kinematics
- Disentangle the impact of the charm: Randomise decay angle of leptons

1. Switch between configurations with only light quarks, only charm and standard mix

- Dramatic shrink of PDF uncert. without initial state charm
  - $\sim 3(6)\text{ MeV in } W^+ (W^-)$
  - increases to $\sim 8(10)\text{ MeV in } W^+ (W^-)$. (mostly $r_s$)

Total PDF uncertainties

- $12(20)$ for $W^+ (W^-)$
- $10$ for $W^\pm$

There is some cancellation of uncertainties for the combination of polarisation and charm-induced effects.
Detector effects (muon $\rho_T$)

Muon $\rho_T$ is smeared according to (arxiv:1404.4562)

SUMMARY of PDF uncertainties

<table>
<thead>
<tr>
<th></th>
<th>MW-NLO</th>
<th>CT10nlo</th>
<th>MSTW2008CPdeutnlo</th>
<th>NNPDF30.nlo.as.118</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+$</td>
<td>+13 -12</td>
<td>+18 -22</td>
<td>+11 -10</td>
<td>+8 -10</td>
</tr>
<tr>
<td>$W^-$</td>
<td>+22 -22</td>
<td>+18 -23</td>
<td>+11 -10</td>
<td>+8 -9</td>
</tr>
<tr>
<td>$W^\pm$</td>
<td>+11 -11</td>
<td>+14 -18</td>
<td>+7 -7</td>
<td>+6 -5</td>
</tr>
</tbody>
</table>

- reasonable uncert. for the dedicated PDF set
- $W^-$: larger uncert. due to limited constraining power of HERA I data

SUMMARY of biases

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</thead>
<tbody>
<tr>
<td>$W^+$</td>
<td>-9</td>
<td>-0.1</td>
<td>-20</td>
<td>-1.2</td>
</tr>
<tr>
<td>$W^-$</td>
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<td>+0.2</td>
<td>+13</td>
<td>+12</td>
</tr>
<tr>
<td>$W^\pm$</td>
<td>+16</td>
<td>0.0</td>
<td>-6</td>
<td>+5</td>
</tr>
</tbody>
</table>

- very large bias for the dedicated PDF set
- charge dependent analysis brings considerable improvement in the PDF uncertainties

PDF uncert. increases by $\sim 10\%$
Summary

- Three new jet cross-section measurements at 7 TeV are presented: provide constraints on gluon PDF and $\alpha_s$
- $W$–jets and $R$–jets: new observables for MC tuning and PDF analysis
- $Z$-b-jets: provide constraints on the $b$-quark PDF
- AIDA analysis: broader test of the Standard Model
- Theoretical uncertainties in $W$-boson mass are studied
Back-up
Inclusive jets. Detailed comparison to theory (I)

Recent ATLAS measurement sensitive to PDFs

ATLAS

\[ \int L \, dt = 4.5 \text{ fb}^{-1} \]
\[ \sqrt{s} = 7 \text{ TeV} \]

anti-k jets, \( R=0.4 \)

Data

NLOJET++
\( \mu_F = \mu_R = p_T^\text{max} \)

Non-pert and EW corr.

CT10

MSTW 2008

NNPDF 2.1

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Inclusive jets. Detailed comparison to theory (II)

Different set of PDFs
Inclusive jets. Detailed comparison to theory (I)

Recent ATLAS measurement sensitive to PDFs

ATLAS
\[ \int L \, dt = 4.5 \, fb^{-1} \]
\[ \sqrt{s} = 7 \, TeV \]
anti-k_\text{j} jets, \( R=0.4 \)

Data

NLOJET++
\( \mu_F = \mu_R = p_T^{\text{max}} \)
Non-pert and EW corr.

Theory / data

\[ 0.6 < |\gamma| < 0.8 \]
\[ 1 \]
\[ 1.2 < |\gamma| < 2 \]
\[ 2.5 < |\gamma| < 3 \]

\[ 10^2 \] \[ p_T \, [GeV] \] \[ 10^3 \]
different set of PDFs
Recent ATLAS measurement sensitive to PDFs

\[ \int L \, dt = 4.5 \text{ fb}^{-1} \]
\[ \sqrt{s} = 7 \text{ TeV} \]
\[ \text{anti-}k_t \text{ jets, } R = 0.4 \]

- Statistical uncertainty
- Systematic uncertainties

NLOJET++
\[ \mu = p_T \exp(0.3 \, y^*) \]
Non-pert. & EW corr.

ATLAS

\begin{align*}
1.0 & \leq y^* < 1.5 \\
\text{ATLAS} & \\
\text{CT10} & \\
\text{HERAPDF1.5} & \\
\text{epATLJet13} & \\
\text{exp. only} & \\
\text{HERAPDF1.5} & \\
\text{exp. only} & 
\end{align*}
Dijets. Detailed comparison to theory (II)

\[ y^* < 0.5 \]
\[ P_{\text{CT}}^{\text{obs}} = 0.616 \quad P_{\text{HERA}}^{\text{obs}} = 0.271 \]

\[ 0.5 \leq y^* < 1.0 \]
\[ P_{\text{CT}}^{\text{obs}} = 0.153 \quad P_{\text{HERA}}^{\text{obs}} = 0.009 \]

\[ 1.0 \leq y^* < 1.5 \]
\[ P_{\text{CT}}^{\text{obs}} = 0.523 \quad P_{\text{HERA}}^{\text{obs}} = 0.269 \]

\[ 2.0 \leq y^* < 2.5 \]
\[ P_{\text{CT}}^{\text{obs}} = 0.925 \quad P_{\text{HERA}}^{\text{obs}} = 0.880 \]

\[ 2.5 \leq y^* < 3.0 \]
\[ P_{\text{CT}}^{\text{obs}} = 0.060 \quad P_{\text{HERA}}^{\text{obs}} = 0.060 \]

**ATLAS**
\[ \int L \, dt = 4.5 \, \text{fb}^{-1} \]
\[ \sqrt{s} = 7 \, \text{TeV} \]
anti-\(k_t\) jets, \(R = 0.6\)

- Statistical uncertainty
- Systematic uncertainties

NLOJET++
\[ \mu = p_T \exp(0.3 \, y^*) \]
Non-pert. & EW corr.

- CT10
- HERAPDF1.5
- exp. only
- HERAPDF1.5

- different set of PDFs

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Dijets. Detailed comparison to theory (I)

\[
\begin{align*}
&\text{Theory/data} & \text{Theory/data} \\
&y^* < 0.5 & 1.5 \leq y^* < 2.0 \\
&P_{\text{MSTW}}^{\text{obs}} = 0.276 & P_{\text{MSTW}}^{\text{obs}} = 0.307 \\
&P_{\text{NNPDF2.1}}^{\text{obs}} = 0.189 & P_{\text{NNPDF2.1}}^{\text{obs}} = 0.383 \\
&P_{\text{ABM}}^{\text{obs}} < 0.001 & P_{\text{ABM}}^{\text{obs}} = 0.169 \\
&0.5 \leq y^* < 1.0 & 2.0 \leq y^* < 2.5 \\
&P_{\text{MSTW}}^{\text{obs}} = 0.930 & P_{\text{MSTW}}^{\text{obs}} = 0.656 \\
&P_{\text{NNPDF2.1}}^{\text{obs}} = 0.873 & P_{\text{NNPDF2.1}}^{\text{obs}} = 0.640 \\
&P_{\text{ABM}}^{\text{obs}} < 0.001 & P_{\text{ABM}}^{\text{obs}} = 0.009 \\
&1.0 \leq y^* < 1.5 & 2.5 \leq y^* < 3.0 \\
&P_{\text{MSTW}}^{\text{obs}} = 0.066 & P_{\text{MSTW}}^{\text{obs}} = 0.965 \\
&P_{\text{NNPDF2.1}}^{\text{obs}} = 0.068 & P_{\text{NNPDF2.1}}^{\text{obs}} = 0.964 \\
&P_{\text{ABM}}^{\text{obs}} < 0.001 & P_{\text{ABM}}^{\text{obs}} = 0.909 \\
&2.0 \leq y^* < 2.5 & & \\
&P_{\text{MSTW}}^{\text{obs}} = 0.930 & P_{\text{MSTW}}^{\text{obs}} = 0.965 \\
&P_{\text{NNPDF2.1}}^{\text{obs}} = 0.873 & P_{\text{NNPDF2.1}}^{\text{obs}} = 0.964 \\
&P_{\text{ABM}}^{\text{obs}} < 0.001 & P_{\text{ABM}}^{\text{obs}} = 0.909 \\
&y^* \leq 0.5 & & \\
&P_{\text{MSTW}}^{\text{obs}} = 0.276 & P_{\text{MSTW}}^{\text{obs}} = 0.930 \\
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&P_{\text{NNPDF2.1}}^{\text{obs}} = 0.189 & P_{\text{NNPDF2.1}}^{\text{obs}} = 0.873 \\
&P_{\text{ABM}}^{\text{obs}} < 0.001 & P_{\text{ABM}}^{\text{obs}} = 0.009 \\
\end{align*}
\]
Dijets. Detailed comparison to theory (II)

\[ y^* < 0.5 \]
\[ P_{\text{MSTW}}^{\text{obs}} = 0.365 \quad P_{\text{NNPDF2.1}}^{\text{obs}} = 0.304 \]
\[ P_{\text{ABM}}^{\text{obs}} < 0.001 \]

\[ 0.5 \leq y^* < 1.0 \]
\[ P_{\text{MSTW}}^{\text{obs}} = 0.255 \quad P_{\text{NNPDF2.1}}^{\text{obs}} = 0.091 \]
\[ P_{\text{ABM}}^{\text{obs}} < 0.001 \]

\[ 1.0 \leq y^* < 1.5 \]
\[ P_{\text{MSTW}}^{\text{obs}} = 0.534 \quad P_{\text{NNPDF2.1}}^{\text{obs}} = 0.494 \]
\[ P_{\text{ABM}}^{\text{obs}} < 0.001 \]

\[ 1.5 \leq y^* < 2.0 \]
\[ P_{\text{MSTW}}^{\text{obs}} = 0.299 \quad P_{\text{NNPDF2.1}}^{\text{obs}} = 0.326 \]
\[ P_{\text{ABM}}^{\text{obs}} = 0.046 \]

\[ 2.0 \leq y^* < 2.5 \]
\[ P_{\text{MSTW}}^{\text{obs}} = 0.984 \quad P_{\text{NNPDF2.1}}^{\text{obs}} = 0.984 \]
\[ P_{\text{ABM}}^{\text{obs}} = 0.356 \]

\[ 2.5 \leq y^* < 3.0 \]
\[ P_{\text{MSTW}}^{\text{obs}} = 0.086 \quad P_{\text{NNPDF2.1}}^{\text{obs}} = 0.081 \]
\[ P_{\text{ABM}}^{\text{obs}} = 0.053 \]

\[ \int L \, dt = 4.5 \, \text{fb}^{-1} \]
\[ \langle \sqrt{s} \rangle = 7 \, \text{TeV} \]
\[ \text{anti}-k_t \, \text{jets, } R = 0.6 \]

Statistical uncertainty
Systematic uncertainties
NLOJET++
\[ \mu = p_T \exp(0.3 \, y^*) \]
Non-pert. & EW corr.

MSTW 2008
NNPDF2.3
ABM11

different set of PDFs
Three-jets. Detailed comparison to theory (I)

\[ \int L \, dt = 4.5 \, fb^{-1} \]
\[ \sqrt{s} = 7 \, TeV \]
\[ R = 0.4 \]

ATLAS Preliminary

\[ |Y^*| < 2 \]
\[ 2 < |Y^*| < 4 \]
\[ 4 < |Y^*| < 6 \]
\[ 6 < |Y^*| < 8 \]
\[ 8 < |Y^*| < 10 \]

Prediction/Data

0.6
0.8
1
1.2
1.4

\[ |Y^*| < 2 \]
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different set of PDFs
Three-jets. Detailed comparison to theory (II)

**ATLAS Preliminary**
\[ \int L \, dt = 4.5 \, fb^{-1} \]
\[ \sqrt{s} = 7 \, TeV \]
\[ \text{anti-}k_t, R = 0.6 \]

**DATA Uncert.**
- Total
- Statistical

**Different set of PDFs**
- CT 10
- MSTW 2008
- HERAPDF 1.5

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Three-jets. Detailed comparison to theory (I)

ATLAS Preliminary

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\[ \sqrt{s} = 7 \, TeV \]
anti-\( k_t \), \( R = 0.4 \)

Different set of PDFs

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Three-jets. Detailed comparison to theory (II)

\[ \int L \, dt = 4.5 \text{ fb}^{-1} \]
\[ \sqrt{s} = 7 \text{ TeV} \]
\[ R = 0.6 \]
\[ \text{anti-}k_t, \text{ } R = 0.6 \]

\[ \text{DATA Uncert.} \]
\[ \text{Total} \]
\[ \text{Statistical} \]

\[ \times \text{non-pert. corr.} \]
\[ \otimes \text{PDF} \]

NLO QCD

\[ \text{different set of PDFs} \]

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