Probing perturbative QCD using electroweak bosons

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on behalf of the ATLAS Collaboration

ICNFP 2019
Perturbative QCD at the LHC

Parton Distribution Function (PDF)
Results at four centre-of-mass energies

- Measurement of inclusive isolated photon cross-section in pp collisions at 13 TeV using 36 fb\(^{-1}\) of ATLAS data
- Measurement of the ratio of cross sections for inclusive isolated photon production in pp collisions at 13 TeV and 8 TeV with the ATLAS detector
- Measurement of the cross section and charge asymmetry of W bosons produced in pp collisions at 8 TeV with the ATLAS detector
- Measurement of W\(^\pm\) boson and Z boson production cross sections in pp collisions at 2.76 TeV with the ATLAS detector
- Measurement of W and Z boson production in pp collisions at 5.02 TeV with the ATLAS detector
- Measurement of the inclusive cross section for the production of jets in association with a Z boson in pp collisions at 8 TeV with the ATLAS detector
**Motivation**

![Graph showing evolution of strong coupling constant](image)

**Test the Renormalization Group Equation**

- New Physics contributions in the loops (not produced with on-shell particles) could cause deviations from the QCD prediction of the RGE

**Determination of strong coupling constant $\alpha_s$**

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**Fig. 1.** Evolution of the strong coupling constant (displayed as $1/\alpha_s$) in the standard and supersymmetric versions of the SU(5) unified theory, for superpartners that become active at $Q = 1$ TeV.
Motivation

Why bother with perturbative QCD?

- Constraints on the parton distribution functions (PDFs) of the content of the proton
- Inclusive W/Z boson production is highly sensitive to valence quarks PDFs
- Inclusive photon production is more sensitive to gluon PDF

Test of perturbative QCD predictions

- Colorless photon used as a probe of the hard partonic interaction

Description of background event kinematics for Monte Carlo validation that are used in several measurements (e.g., Higgs production) and different searches for New Physics
Inclusive isolated-photon cross section in pp collisions

- Prompt photon production provides a testing ground for pQCD
- Abundant photon production in hadron colliders, mostly from hadron decays

\[ pp \rightarrow \gamma + X \]

"direct" photon

\[ qg \rightarrow q\gamma \]

Matrix Element (ME)

"fragmentation" photon from high pT parton

\[ qg \rightarrow qg \]

fragmentation/parton shower (PS)

non-distinguishable processes

sensitive to the gluon density in the proton at LO
Photon identification in the ATLAS detector

Jets vs photons

hadronic calorimeter

ECAL middle layer

ECAL front layer

No energy leakage in Hadron Calorimeter

Narrow shower in ECAL 2nd layer

\[ \pi^0 \rightarrow \gamma \gamma \text{ vs photons} \]

Narrow shower in 1st layer

\( \pi^0 \text{ in strips} \)

\( \text{photon in strips} \)

Narrow shower in ECAL 2nd layer
Inclusive isolated-photon cross section in pp collisions

**arXiv:1908.02746**

**ATLAS Preliminary**

Data:
- $|\eta| < 0.6$ ($\times 10^0$)
- $0.6 < |\eta| < 1.37$ ($\times 10^1$)
- $1.56 < |\eta| < 1.81$ ($\times 10^2$)
- $1.81 < |\eta| < 2.37$ ($\times 10^3$)

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

- Observed $d\sigma/dE_T^\gamma$ in 4 $\eta$ regions
- Several theory models (hard process and PDFs)
  - JetPhox+MMHT2014
  - Sherpa NLO + NNPDF3.0
  - NNLOJet + NNPDF3.1

**scales $\mu_R=\mu_F=\mu_f=E_T^\gamma$**

The inclusion of the ATLAS data leads to a reduction in the gluon density uncertainties

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Inclusive isolated-photon cross section in pp collisions

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

- **Data** $|\eta^\gamma| < 0.6$
- **Data** $0.6 < |\eta^\gamma| < 1.37$
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- **Data** $1.81 < |\eta^\gamma| < 2.37$

**Ratio of NLO pQCD prediction of Jetphox with $\mu_R=\mu_F=\mu_t=E_T^\gamma$ using the MMHT2014 PDF set to the measured differential cross section for isolated-photon production as a function of $E_T^\gamma$ in different regions of $|\eta^\gamma|$**

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21-29 August 2019
Cross section ratios

\[ R^\gamma \equiv \frac{d\sigma^{13\,\text{TeV}}}{d\sigma^{8\,\text{TeV}}} \quad \text{and} \]

\[ D^{\gamma/Z} \equiv \left( \frac{d\sigma^{13\,\text{TeV}}}{d\sigma^{8\,\text{TeV}}} \right) / \left( \frac{\sigma^{13\,\text{TeV}}}{Z,\,\text{fid}} \right) / \left( \frac{\sigma^{8\,\text{TeV}}}{Z,\,\text{fid}} \right) \]
Comparisons to NLO QCD limited by the size of the theoretical uncertainties (typically larger than the experimental uncertainties)

More stringent test of theory through cross section ratios at different $\sqrt{s}$

Test the evolution as a function of $\sqrt{s}$

Systematic uncertainties are correlated and would reduce in the ratio

Luminosity uncertainty - uncorrelated between $\sqrt{s}$ plays an important role
Results on $R^\gamma$

Top plots: $R^\gamma \equiv \frac{d\sigma_{13 TeV}^{13}}{d\sigma_{8 TeV}^{8}}$

— measurements and theory predictions compared to NLO QCD calculations

Bottom plots: $\frac{(R^\gamma)_{\text{theory}}}{(R^\gamma)_{\text{meas}}}$ for different PDF sets

NLO predictions agree with the measured within the reduced theoretical uncertainties (2-4%)
Results on double ratios $D_{\gamma/Z}$

- Reduce further the uncertainty by performing measurement of double ratios

\[ D^{\gamma/Z}_{13/8} = \frac{R^{\gamma}_{13/8}(E_T^\gamma)}{\sigma^{\text{fid}}_Z(13\ TeV)/\sigma^{\text{fid}}_Z(8\ TeV)} \]

- Double ratios with another final state benefit from the cancelation of the luminosity uncertainty … but…

Note: \( R^\gamma \equiv \frac{d\sigma^{13\ TeV}_Z}{d\sigma^{8\ TeV}_Z} \) is a function of \( E_T^\gamma \) in several regions of \( |\eta^\gamma| \)

\[ R^Z \equiv \frac{\sigma^{13\ TeV}_{Z,\text{fid}}}{\sigma^{8\ TeV}_{Z,\text{fid}}} \]

is a single number, measured as \( R^Z = 1.537 \pm 0.001(\text{stat}) \pm 0.010(\text{syst}) \pm 0.044(\text{lumi}) \)

*ATLAS measurement*  \[ \text{JHEP 02 (2017) 117} \]
Results on double ratios $D^{\gamma/Z}$

Top plots: $D^{\gamma/Z} \equiv \frac{R^{\gamma}}{R^{\gamma}}$ — measurements and theory predictions compared to NLO QCD calculations

Bottom plots: $\left( \frac{D^{\gamma/Z}}{D^{\gamma/Z}} \right)_{\text{theory}}$ for different PDF sets

NLO predictions agree with the measured within the reduced theoretical uncertainties (2-4%)

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W boson cross section and charge asymmetry

- W-boson production at LHC is highly sensitive to valence quarks PDFs

**main production mechanism at the LHC**

- The difference between $u_v$ and $d_v$ yields an asymmetry between $W^+$ and $W^-$ production which is a function of rapidity $y$
- ATLAS provides measurements of differential cross sections as a function of $y$ and for various $\sqrt{s}$ pp collisions to illuminate further our understanding on PDFs

**W bosons are preferentially produced with a boost in the direction of the incoming valence quark**
**W boson cross section and charge asymmetry**

**arXiv:1904.05631**

- **W**⁺ and **W**⁻ fiducial cross sections, differential in muon pseudorapidity
- Data compared with the nominal predictions based on six different PDF sets. The statistical uncertainties of the DYNNLO predictions are indicated by error bars
W boson cross section and charge asymmetry

\( \sqrt{s} = 8 \text{ TeV}, 20 \text{ fb}^{-1} \)

\[ A_\ell = \frac{dN_{W^+}\rightarrow \ell^+\nu}{d\eta_\ell} \bigg|_{\eta_\ell=0} - dN_{W^-}\rightarrow \ell^-\bar{\nu}_\ell}{d\eta_\ell} \bigg|_{\eta_\ell=0} \]

- W boson charge asymmetry as a function of absolute muon pseudo-rapidity. Data are compared with the prediction from DYNLO in which the CT14 NNLO PDF set is used and with a selection of PDFs.
- Result gives stronger support of ATLASepWZ16, consistent discrepancy between \(W^+\) and \(W^-\) for HERAPDF.
W/Z boson cross section and W charge asymmetry

**arXiv:1907.03567**

- \( \sigma W \times B (W \rightarrow \ell \nu) \) for W+ bosons, W- bosons and their sum

**2.76 TeV, 4 \( \text{pb}^{-1} \)**

- \( \sigma Z/\gamma^* \times B( Z/\gamma^* \rightarrow \ell \ell) \)

Theoretical calculations are performed at NNLO in QCD using DYNNLO 1.5 and FEWZ 3.1. The theoretical uncertainties are not shown.
W/Z boson cross section and W charge asymmetry

2.76 TeV, 4 pb⁻¹

- Theoretical calculations are performed at NNLO in QCD with different PDFs
- Systematic uncertainties are reduced with the ratios

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W/Z boson cross section and W charge asymmetry


5.02 TeV, 25 pb⁻¹

Combined integrated fiducial cross sections:

\[ W^+ : \quad 2266 \pm 9 \text{ (stat)} \pm 29 \text{ (sys)} \pm 43 \text{ (lumi)} \text{ pb} \]

\[ W^- : \quad 1401 \pm 7 \text{ (stat)} \pm 18 \text{ (sys)} \pm 27 \text{ (lumi)} \text{ pb} \]

\[ Z : \quad 374.5 \pm 3.4 \text{ (stat)} \pm 3.6 \text{ (sys)} \pm 7.0 \text{ (lumi)} \text{ pb} \]

Fiducial integrated and differential cross sections measured in \( pp \) collisions serve as a reference for Pb+Pb interactions.
Overall good agreement with NNLO pQCD calculations and with each PDF set

Significant tension with all sets at very low $\eta$ (low x) for $W^-$ and $Z$. Good agreement for different PDF sets except ABMP and CT14 in $W^+$
**Z plus jets inclusive cross section measurement**

**arXiv:1907.06728**

Double-differential cross-section measurement as a function of inclusive jet y and $p_T$

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**ATLAS**

$\sqrt{s}=8$ TeV, 19.9 fb$^{-1}$

$Z(\rightarrow ee) +$ jets

anti-$k_t$, $R=0.4$

Lowest $p_T$ bin

- Data
- ME+PS
- ALPGEN+PY6
- SHERPA 1.4
- SHERPA 2.2
- Fixed-order QCD
- $k_{NP} \times k_{QED}$
- CT14 PDF
- MCFM 6.8
- NNLOJET

Highest $p_T$ bin

- Data
- ME+PS
- ALPGEN+PY6
- SHERPA 1.4
- SHERPA 2.2
- Fixed-order QCD
- $k_{NP} \times k_{QED}$
- CT14 PDF
- MCFM 6.8
- NNLOJET

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**LO Alpgen+Pythia** describes well low $p_T$, but exceeds data by 20% at high $p_T$; **LO Sherpa 1.4** lower than data by 10% at low $p_T$, describes data well at high $p_T$; **NLO Sherpa 2.2** agrees well with data; **NLO MCFM** 5-10% lower than data, differences covered by uncertainties; **NNLO** shows best agreement with data in all bins of the measurement.
Data compared to NLO predictions with different PDFs

Differences among NLO predictions with different PDFs covered by the theoretical uncertainties

Data uncertainty smaller than theory uncertainty in most of the bins $\implies$ we need to go to NNLO corrections

ATLAS
$\sqrt{s}=8$ TeV, 19.9 fb$^{-1}$
anti-$k_t$ $R=0.4$
Data compared to **NNLO predictions with different PDFs**

- Difference between CT14 and NNPDF3.1 is 2-5%, comparable in some region with the size of theoretical uncertainties
Conclusions

- ATLAS performed comprehensive studies of PDF and other pQCD effects in inclusive electroweak boson production
- Measurements sensitive to various NNLO PDF predictions
- More results with the full Run 2 dataset are expected
Thank you

Summary

• Most of the active Exotic searches have already started looking at data!
• The rest are ramping up very quickly and will look at early data soon.
• Harmonisation effort has been a success. Working closely with CP groups.
• Teams are keeping a discovery-mode frame-of-mind so that we are ready to make discoveries if nature presents us with new physics.
• Many VE (<1 fb) searches are on track to produce results for EPS/LHCP.

A New Discovery Could Be Just Around The Beam Pipe..... And We’re Ready!
Inclusive isolated-photon cross section in pp collisions

$\sqrt{s} = 13\ TeV,\ 36.1\ fb^{-1}$

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NNLOQCD (NNPDF3.1)

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NLO QCD (NNPDF3.1)

NLO QCD (NNPDF3.1)

(PDF and $\alpha_s$ unc. from NLO)