



Results on vector boson production, both inclusive and in association with jets, at the LHC

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On behalf of the ATLAS & CMS collaborations

Overview

- Motivation and Introduction
- Constraining PDFs: Inclusive and Differential Measurements
- Transverse Momentum of Vector-Bosons
- Vector Boson + Jets
- Summary and Conclusion

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Motivation and Introduction

- Motivation of the W/Z measurement at the LHC
- Transverse momentum
- ATLAS & CMS data

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Constraining PDFs: Inclusive and Differential Measurements

- CMS. $Z \rightarrow ll$ cross sections in mass bins
- ATLAS. $Z \rightarrow ee$ cross sections in mass bins
- CMS. $Z \rightarrow ll$ cross sections in mass and boson rapidity bins

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Transverse Momentum of Vector-Bosons

- Z boson transverse momentum measurement
- ATLAS: ϕ^* in Drell-Yan lepton pairs

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Vector Boson + Jets

- $Z +$ Jet measurements
- $Z + b$ Jet measurements
- $W + b$ Jet measurements
- $W +$ charm measurements

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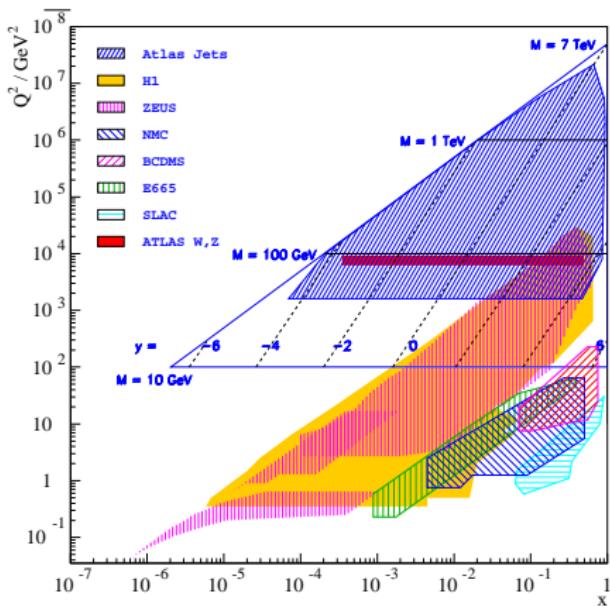
Summary

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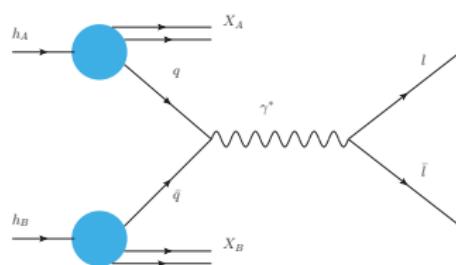
Backup

Motivation of the W/Z measurement at the LHC

- Production of W, Z bosons is theoretically well understood
- Clear experimental signature in the leptonic decay



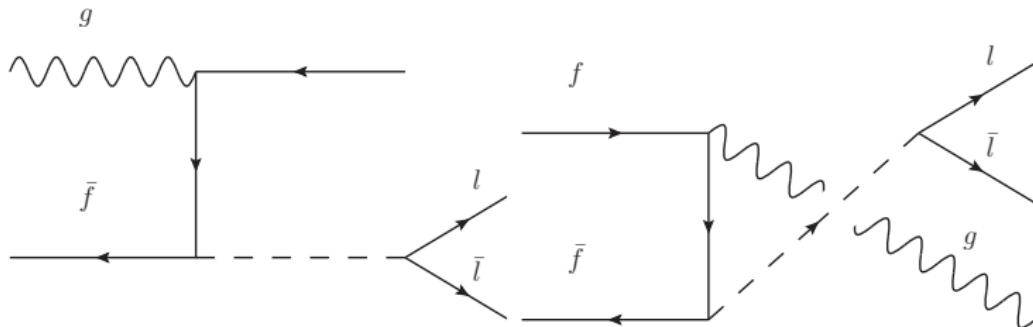
$$Q^2 = M_{W/Z}^2 \text{ and } x_{1,2} = e^{\pm y \frac{M_{W/Z}}{\sqrt{s}}}$$



Motivation:

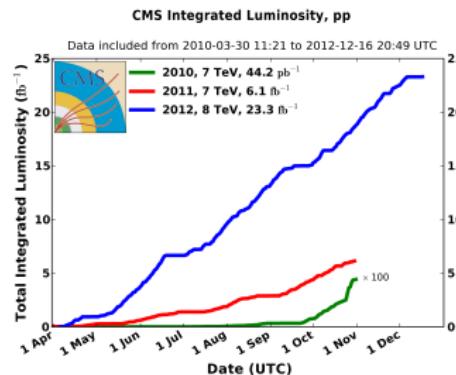
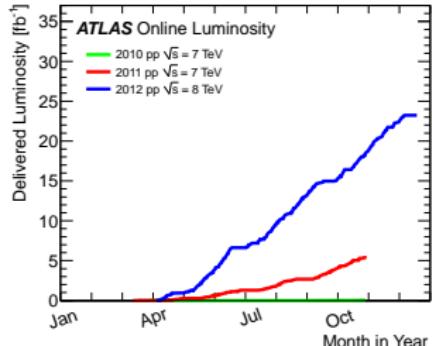
- Test of the validity of the QCD evolution into the region of high Q^2 at low Bjorken x
- Check of the PDFs estimated using HERA data

Transverse momentum



- Transverse momentum characterises the Drell-Yan process since gluon radiation leads to departures from collinear approximations.
- Measurements of the p_T and **boson + Jet** cross section help to test the perturbative QCD (higher-order corrections, resummation technique). These measurements are used to tune LO generators.
- Boson + Jet** measurements provide test of important backgrounds for searches and other SM processes.

ATLAS & CMS data



- Inner detector: $|\eta| < 2.5$
- Calorimeter:
 - Center: $|\eta| < 2.5$
 - Extension: $|\eta| < 4.9$
- Muon system: $|\eta| < 2.4$

- Inner detector: $|\eta| < 2.5$
- Calorimeter:
 - Center: $|\eta| < 3.0$
 - Extension: $|\eta| < 5.0$
- Muon system: $|\eta| < 2.4$

Boson	2010	2011	2012
W	~100K	>10M	>40M
Z	~10K	>1.5M	>5M

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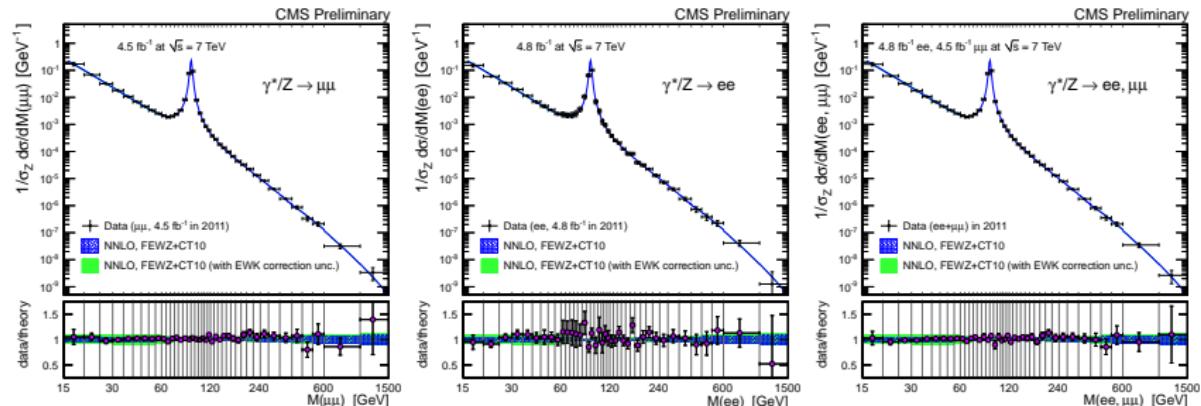
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- $Z + b$ Jet measurements
- $W + b$ Jet measurements
- $W +$ charm measurements

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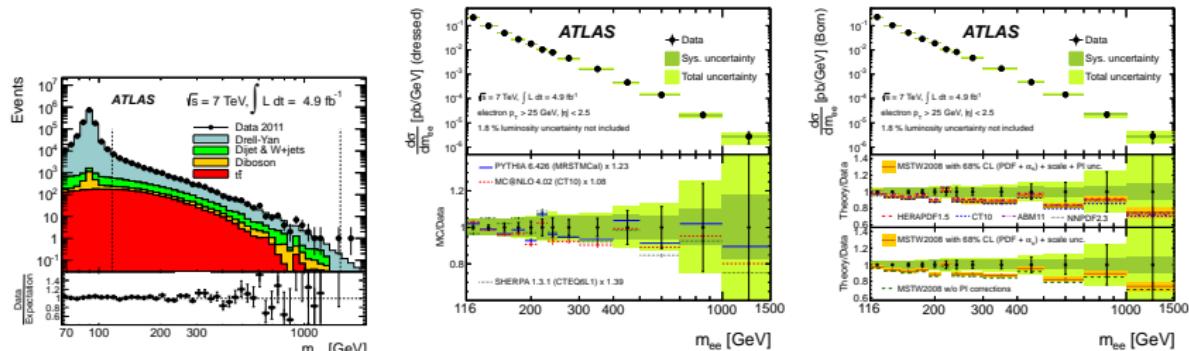
CMS. $Z \rightarrow \mu\mu$ cross sections in mass bins



- First CMS results on full 2011 dataset available
- The measurement of Z boson in bins of invariant mass is in good agreement with the NNLO theoretical predictions, as computed with FEWZ.

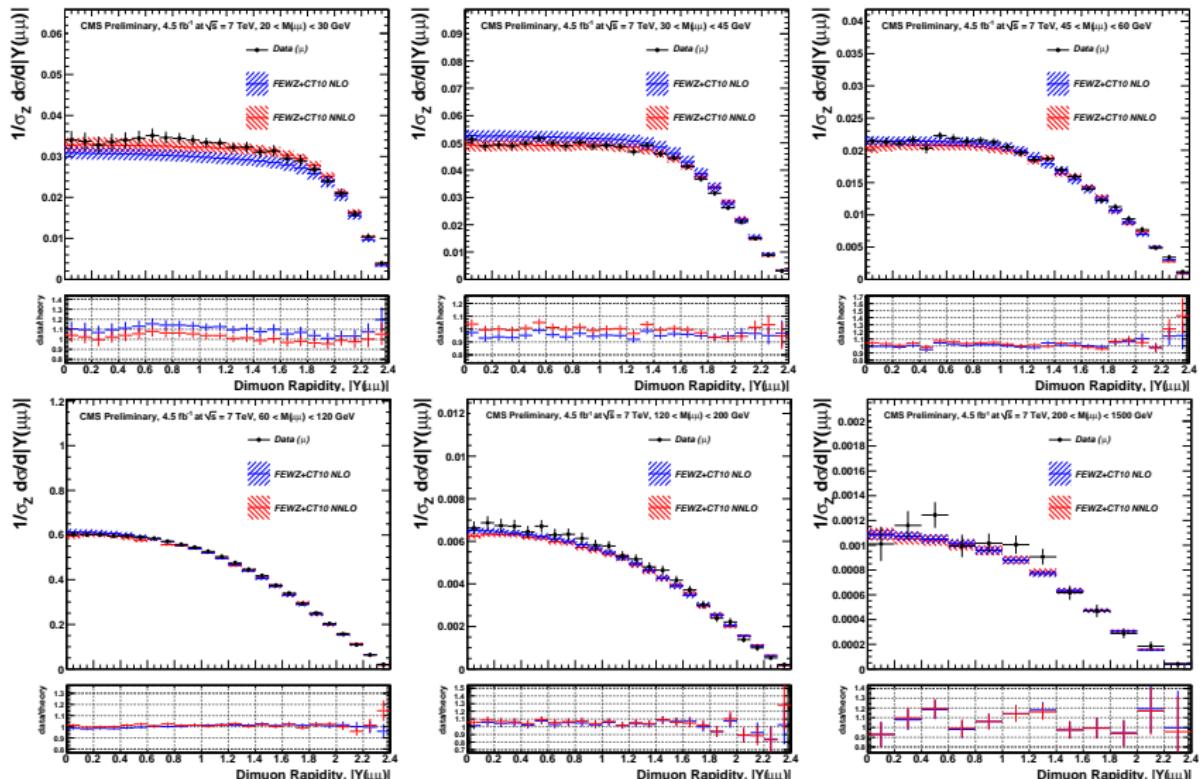
CMS-PAS-SMP-13-003;

ATLAS. Drell-Yan $Z \rightarrow ee$ cross sections in mass bins



- Comparisons have been made to the predictions of the PYTHIA, MC@NLO and SHERPA MC generators. The MC predictions are consistent with the shape of the measured m_{ee} distribution.
- The resulting predictions for all PDFs are consistent with the measured di-electron cross-section, although the data are systematically above the theory.
- Results can be used for PDF fit.

Will be uploaded today



- These results provide valuable input to update the PDF sets

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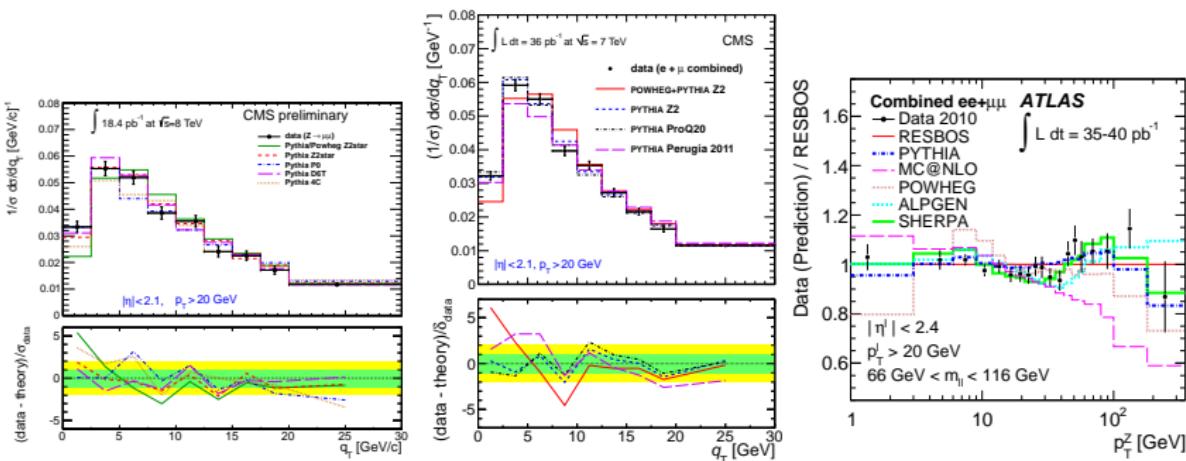
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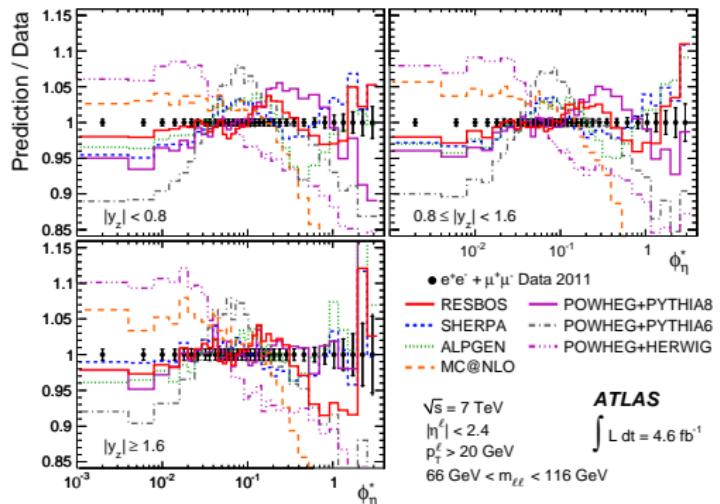
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Z boson transverse momentum measurement



- First 8 TeV result.
- Predictions of various event generators: Sherpa, Alpgen and Pythia show a good agreement with the measurement as well.
- No single model describes the normalized differential cross section of the Z transverse momentum over the full range.

ATLAS: ϕ^* in Drell-Yan lepton pairs



- $\phi^* = \tan \phi_{\text{acop}} / 2 \sin \theta^*$, $\phi_{\text{acop}} = \pi - \Delta\phi$, where θ^* is scattering angle of the leptons in the rest frame of the di-lepton system. ϕ^* was chosen as an optimal experimental observable to probe the low- $p_{T,z}$.
- Energy scale uncertainty doesn't impact here
- ResBos provide the best descriptions of the data (within 4%).

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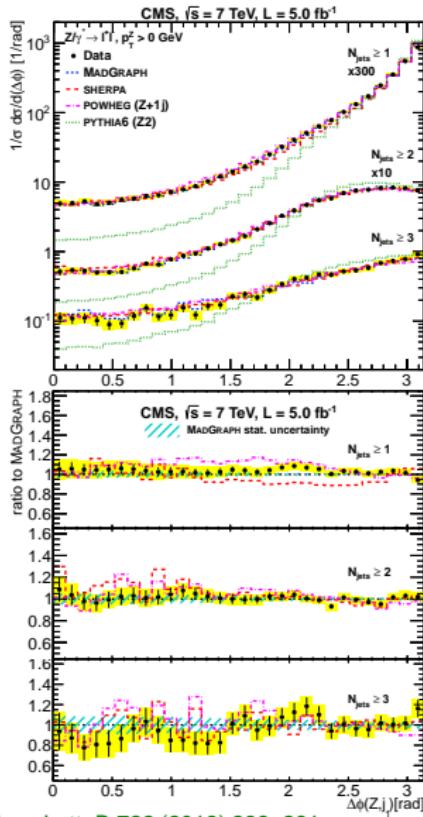
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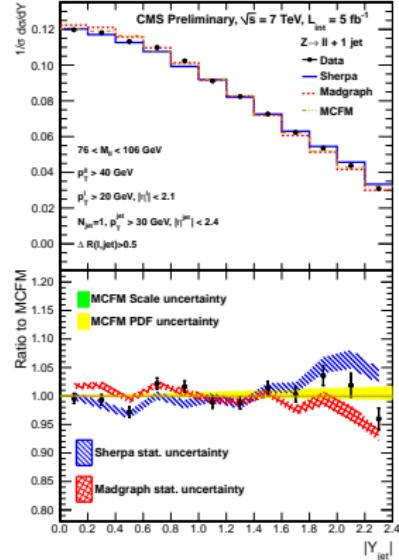
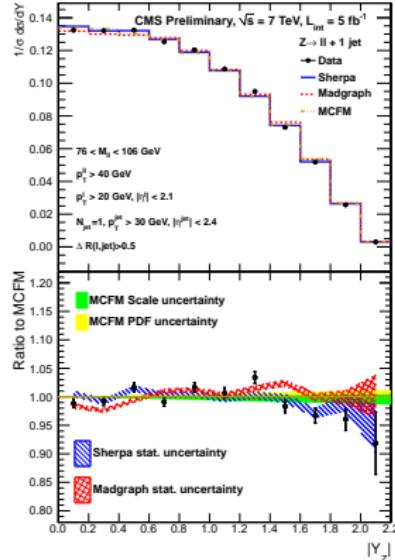
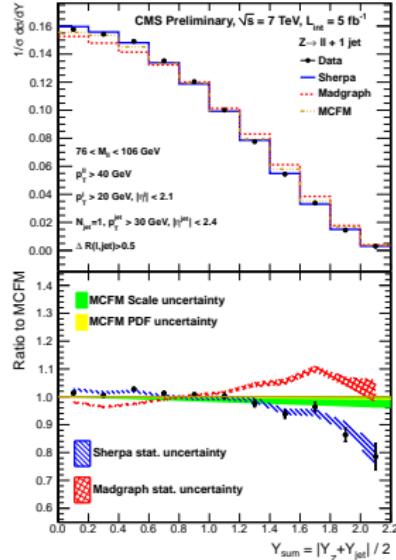
CMS: $Z +$ Jet measurements



Phys. Lett. B 722 (2013) 238–261

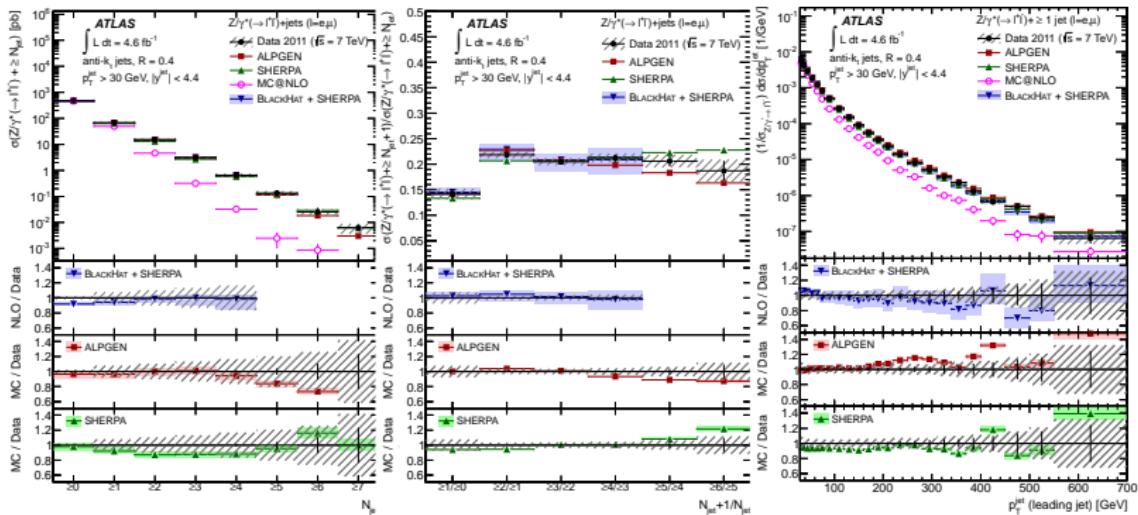
- Azimuthal correlations among the Z boson and the accompanying jets, $\Delta\phi(Z, j_1)$ are measured as functions of inclusive jet multiplicity ($N_{\text{jets}} \geq 1, 2, 3$)
- Important to test perturbative QCD.
- The data are compared with predictions from MADGRAPH, SHERPA, POWHEG $Z + 1$ -jet (at NLO), and stand-alone PYTHIA $Z + 1$ -jet (at LO).
- The MC models that combine multi-parton QCD LO ME interfaced to parton shower evolution tend to agree with the data.

CMS: $Z + \text{Jet}$ in rapidity bins



- The measurement of the rapidity distributions of $Z + \text{jet}$ events is necessary for the characterization of the Higgs boson properties.
- The basic quantities are in general agreement with predictions from Madgraph, Sherpa, and MCFM.

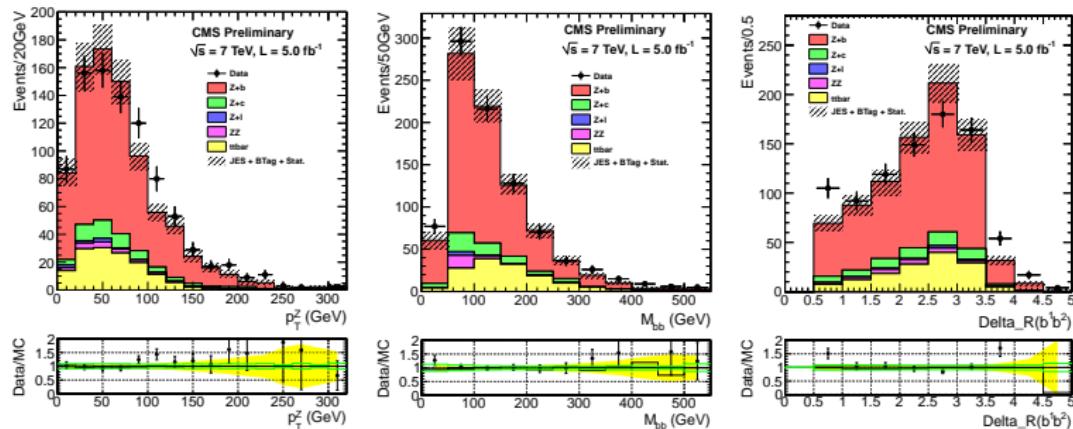
ATLAS: $Z +$ Jet measurements



- Cross sections for jets produced in association with a Z boson have been measured using electron and muon decay modes of Z boson.
- Data have been compared with predictions from the SHERPA generator, from MC@NLO interfaced with HERWIG, from the ALPGEN generator, interfaced with HERWIG, and with fixed-order calculations from Black-Hat +SHERPA.

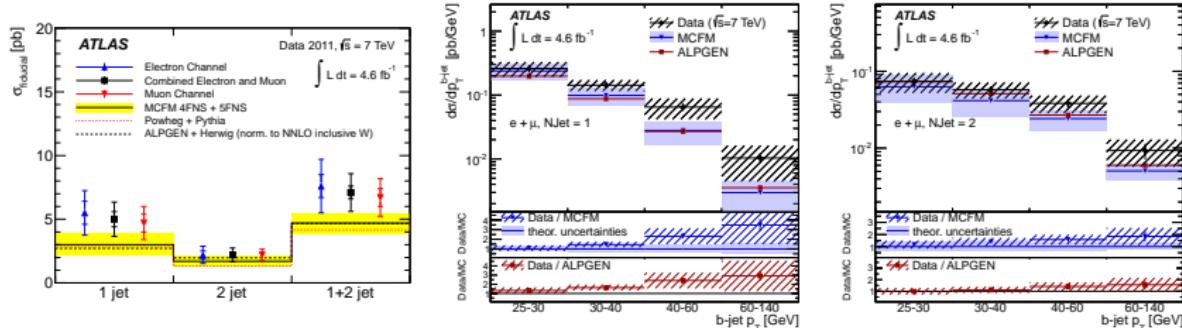
arXiv:1304.7098

CMS: $Z + b$ Jet measurements



- The results found to be in agreement with the expectations from MadGraph.
- Comparisons of the kinematic properties with simulations show potential limitations of the MC event generator, which employs the Matrix Element + Particle Shower approach at leading order with massless b quarks. Next-to-leading order simulations and/or simulations with massive quarks could possibly do better.
- Understanding the details of the kinematics is important for searches for yet undiscovered particles in similar topologies

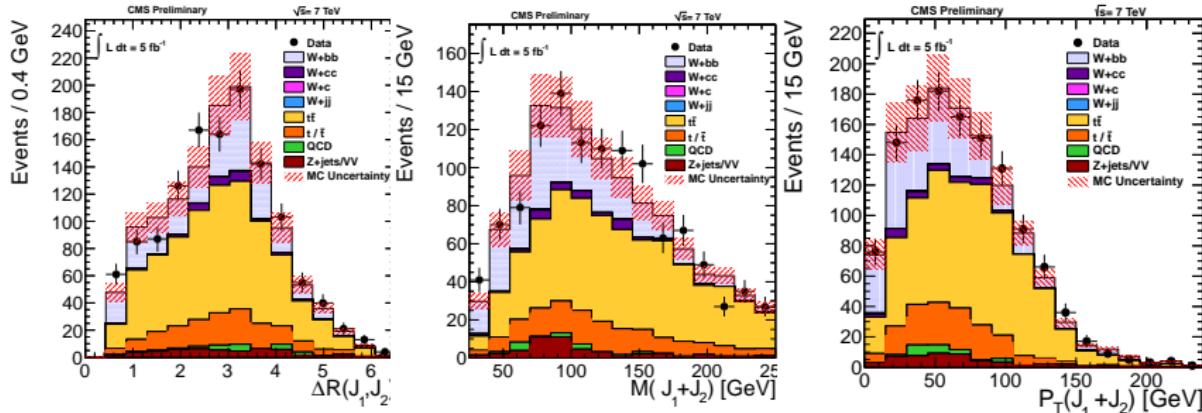
ATLAS: $W + b$ Jet measurements



- The measurement is performed with a single b-tagged jet requirement in the $W + 1\text{-jet}$ and $W + 2\text{-jets}$ samples.
- As a result, the combined 1+2-jet measurement is found to be consistent within $\sigma = 1.5$ with the MCFM NLO prediction, corrected for hadronization and DPI effects.

arXiv:1302.2929

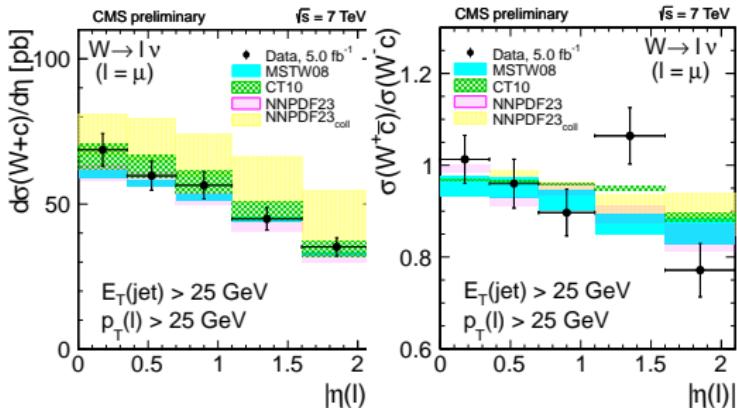
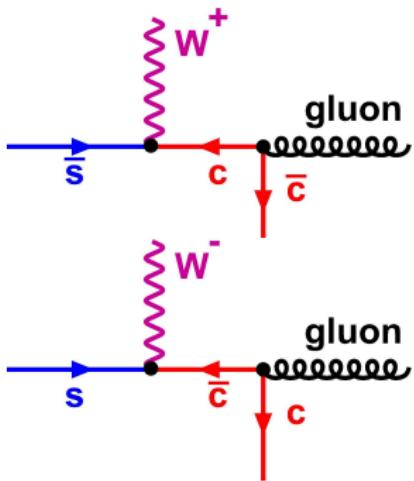
CMS: $W + b\bar{b}$ measurements



- The cross section was measured in $W \rightarrow \mu\nu$ channel with 2011 data
- This result is approaching the precision of theoretical predictions at NNLO, allowing a sensitive test of perturbative calculations in the SM.

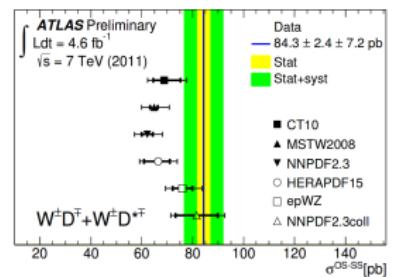
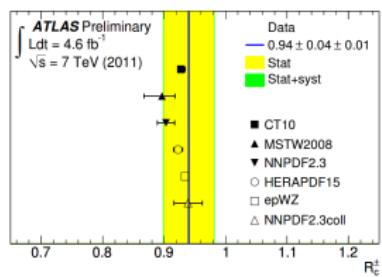
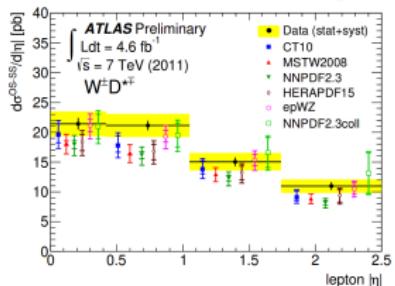
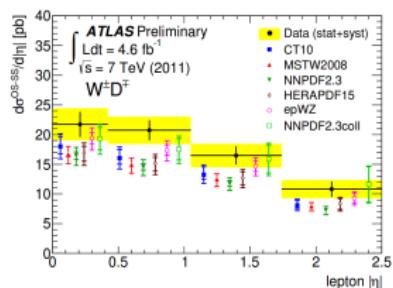
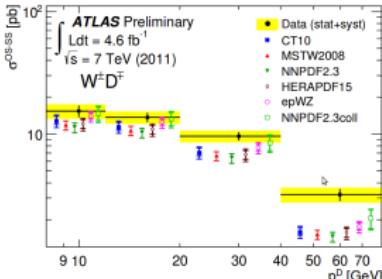
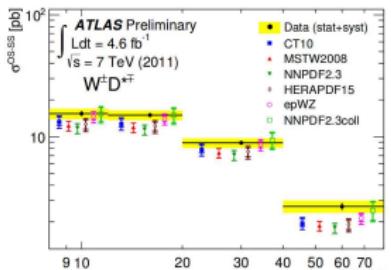
CMS-PAS-SMP-12-026

CMS: $W +$ charm measurements



- Main diagrams at the hard scattering level for associated $W +$ charm production at the LHC.
- Differential measurements of $W + c$ production are calculated as a function of the pseudo-rapidity of the lepton from the W decay.
- Predictions for W^+/W^- ratios are specially sensitive to the assumptions applied by the several PDF groups in the global fits about the s and \bar{s} quark content.
- Theoretical predictions are in good agreement with s measurements.

ATLAS. $W + D$



- The shapes of these distributions agree well with the predictions of NLO QCD calculations.
- The data agree with predictions for the epWZ and NNPDF2.3coll PDFs and lie about $1.1(1.7\sigma)$ above the central value of the CT10 PDF for $D^{*+}(D^+)$.

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Summary

- Inclusive and differential W/Z cross-section measurement was performed in e and μ decay channels using 2010 data. The total experimental uncertainty is around 1.2%.
- Treatment of the 2011 data is close to finish. Several analysis are waiting for approval.
- Inclusive and differential cross-section measurement are sensitive to PDFs and will provide new constraints for future PDF-sets
- Cross-section measurement in bins of boson transverse momentum provides excellent test for Soft-QCD calculations
- So far a very good agreement between data and N(N)LO QCD calculations in $W/Z+jets$ measurements
- **We seem to understand the Standard Model to a very high precision!**

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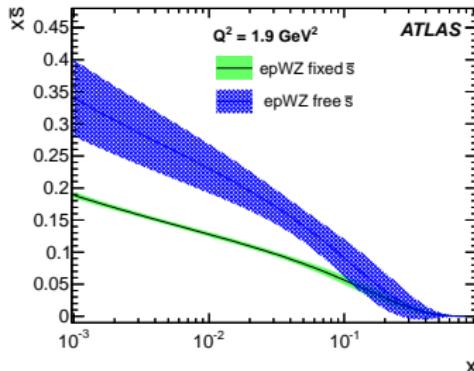
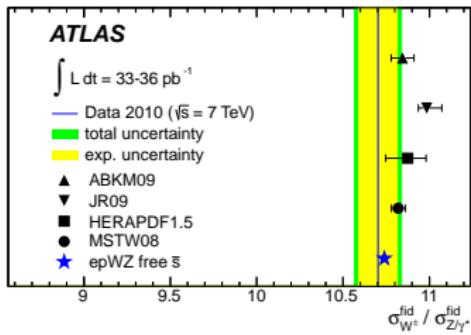
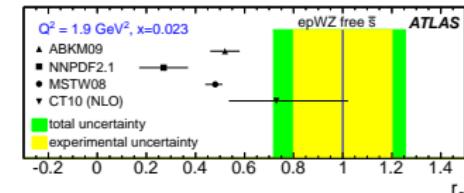
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Strange quark density. Result.

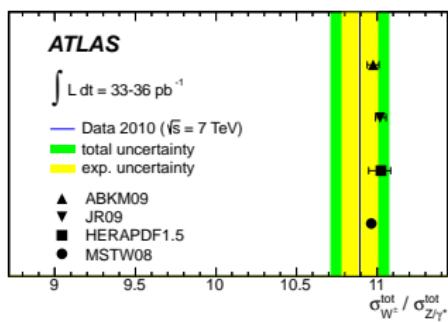
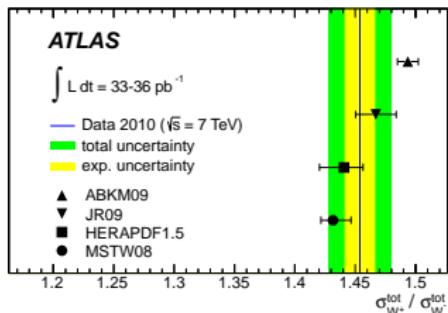
$$r_s = \frac{s(x) + \bar{s}(x)}{2d(x)} = 1.00 \pm 0.20_{\text{exp}} \pm 0.07_{\text{mod}} \pm ^{+0.10}_{-0.15} \pm ^{+0.06}_{-0.07} \pm ^{+0.08}_{\text{th}}$$



Phys.Rev.Lett. 109 (2012) 012001

- total sea is enhanced by 8%
- \bar{u}, \bar{d} decrease by 10%
- better agreement found in ratio $\sigma_{W^\pm}^{\text{fid}} / \sigma_Z^{\text{fid}}$

ATLAS: Ratio of fiducial cross-sections

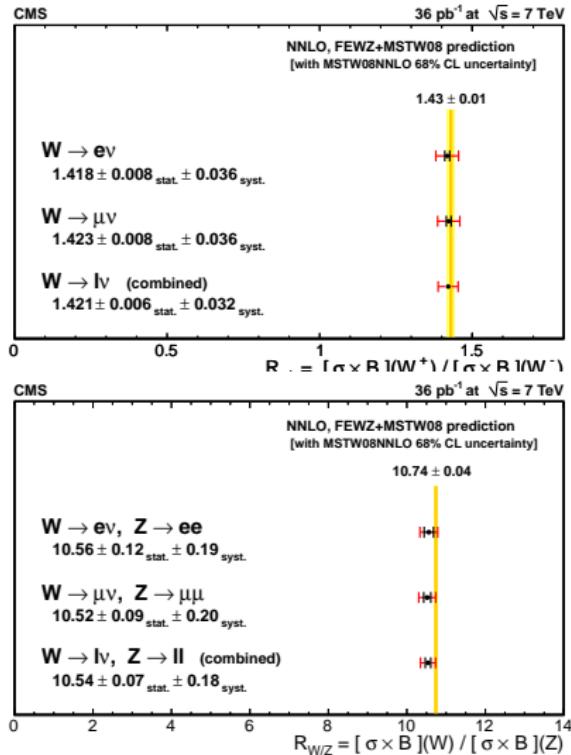


Phys. Rev. D85 (2012) 072004

- Broad agreement with NNLO predictions, different PDF dependences:
 - ▶ W/Z – sensitive to sea quarks,
 - ▶ W^+/W^- – sensitive to up-down PDF differences.
- Ratio is obtained in the fiducial regions and combining the electron and muon final states.
- Fiducial volume is defined by the following requirements:

- ▶ $p_{T,I} > 20$ GeV
- ▶ $\eta_I < 2.5$
- ▶ $66 < M_{II} < 116$ GeV
- ▶ $M_{T,W} > 40$ GeV
- ▶ $E_T^{\text{miss}} > 25$ GeV

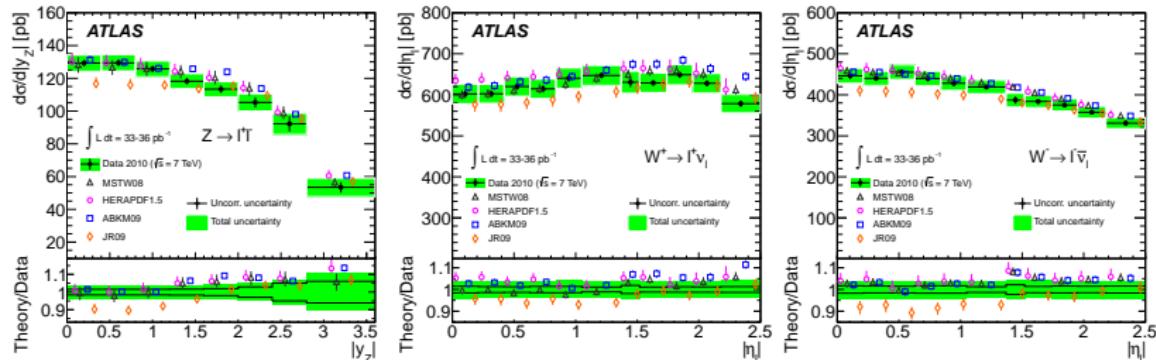
CMS: Ratio of fiducial cross-sections



- Similar tension for W/Z ratio as it is in ATLAS measurement.
- (Combined) measurements are compared to the theoretical predictions computed at the NNLO in QCD with recent PDF sets.
- Kinematic cuts are defined by the following requirements:
 - $p_{T,e} > 25$ GeV, $p_{T,\mu} > 20$ GeV
 - $\eta_e < 2.5$, $\eta_\mu < 2.1$
 - $60 < M_{ll} < 120$ GeV

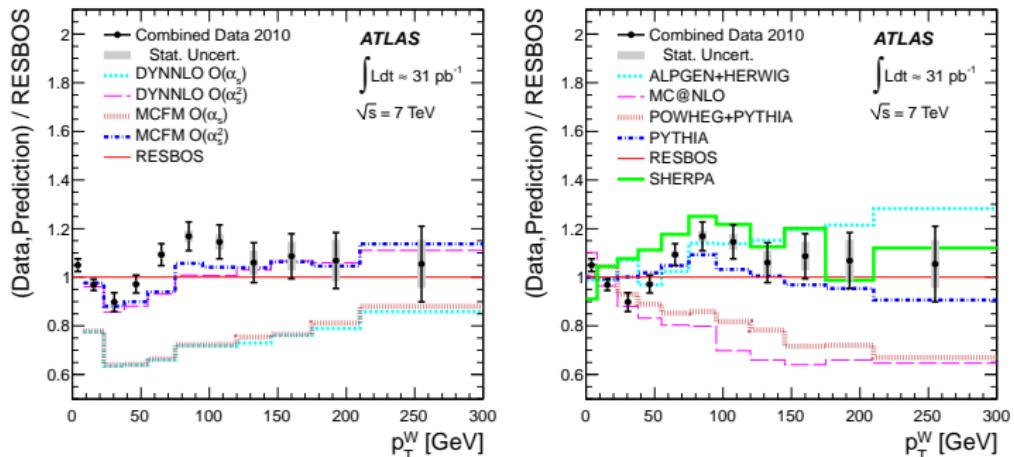
J. High Energy Phys. 10 (2011) 132

ATLAS. Differential W/Z measurement



- Reasonable agreement in comparison to theoretical calculations performed with FEWZ and DYNNLO programs using recent NNLO PDFs (JR09, ABKM09, HERAPDF1.5 and MSTW08).
- None of the PDF sets describe all features of the ATLAS data → Differential cross sections will reduce the uncertainties of PDFs and also influence the central values
- Stat. unc. dominating; new measurement of full data-set will come soon!

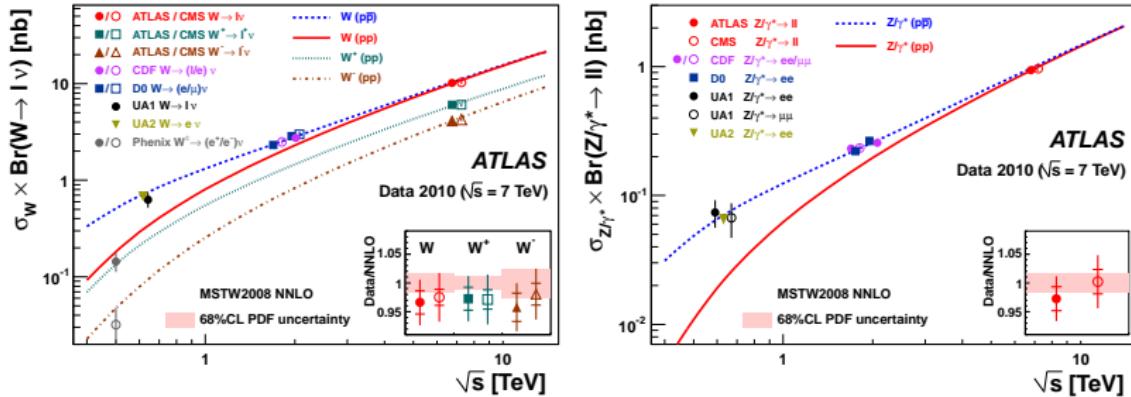
W boson transverse momentum measurement



- Very challenging measurement due to Recoil resolution; crucial for W -mass measurement.
- The Alpgen+Herwig, Pythia, Resbos, and Sherpa predictions match the $W \rightarrow l\nu$ cross section in $p_{T,W}$ bins within 20%.
- MC@NLO provides the closest description of the data for $p_{T,W} < 38 GeV$
- measurement agrees with Z-Pt measurement

Lepton universality

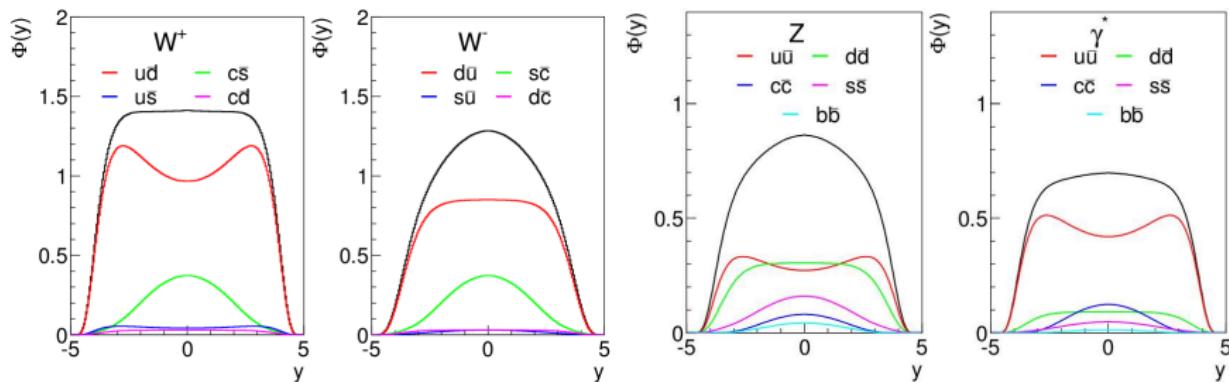
The correlated measurement of the electron-to-muon cross section ratios in the W and the Z channels.



- The inclusive measurements were performed with a few % uncertainties ($\sim 35\text{pb}^{-1}$, 2010 data)

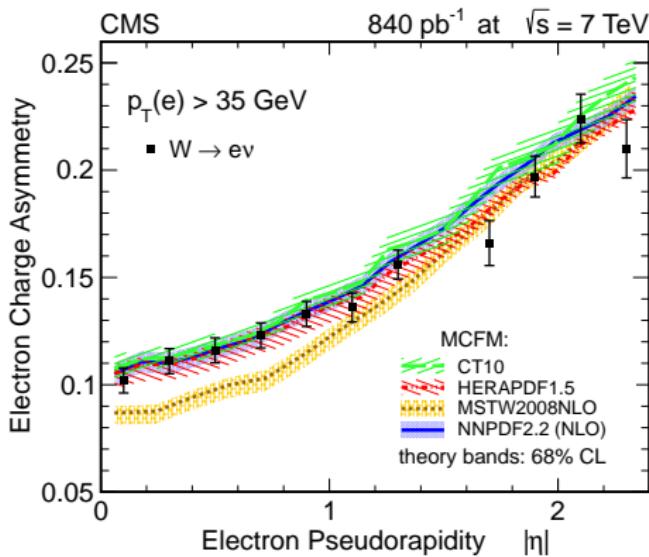
Phys. Rev. D85 (2012) 072004

PDFs sensitivity



- For the Z exchange the d -quark distribution is higher than u for the central rapidity region
- A contribution of s quarks to the Z cross section for the central rapidity is not negligible
- W^+ cross section is dominated by the $u\bar{d}$ contribution and expected to exceed the W^- cross section, which is dominated by the $\bar{u}d$ part
- Measurements of the W/Z production at the LHC in bins of invariant mass and rapidity are sensitive to PDFs.

CMS. W charge asymmetry



- The experimental data of W charge asymmetry are in agreement with the predictions from CT10, NNPDF, and HERAPDF

Phys. Rev. Lett. 109 (2012) 111806;