(2) Vector Boson Production in Hadronic Collisions

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Outline

Lecture 2 : Vector Boson Production

(A) Introduction

(B) QCD and Vector Boson Production

(C) Vector Boson Production at the LHC

What is the purpose of the LHC?

Different people may have different answers, but my answer is ...
to test the Standard Model, precisely.

$SU(3) \quad \times \quad SU(2) \times U(1)$

$\leftarrow$ QCD $\mapsto$ $\quad$ $\leftarrow$ electroweak $\mapsto$

$\leftarrow$ gluons $\mapsto$ $\quad$ $\leftarrow W^{\pm}\ Z^{0}\ \gamma \mapsto$

Important: one cannot separate the interactions.
For example, QCD contributes to Drell-Yan processes.

The Higgs Boson

▪ ▪ ▪ *a triumph of physics,*
both theoretical and experimental

▪ ▪ ▪ *a hint (or even the full answer?)*
about electroweak symmetry breaking

▪ ▪ ▪ *a part of the Standard Model to be explored*

New Physics

▪ ▪ ▪ *i.e., Beyond the Standard Model,*
measure the Standard Model so precisely, that BSM emerges

Yesterday: aspects of the standard Drell-Yan process

- The experimental signal is "clean" because the underlying interaction is electroweak; at short distance ⟩~~~⟨
- The theory is known accurately.
  - *factorization of short and long distances*
  - *perturbative QCD up to NNLO*
- Historical importance
  - *discoveries of Υ, Z^0, $W^\pm$*
  - *helped to establish QCD as a quantitative theory*
    - *angular dependence* $\propto 1 + \cos^2\theta$;
    - *NLO correction explains* **the K-factor**
      expt/LO ~ 2 ; and NLO/LO ~ 2
  - *contributes to the phenomenology of PDFs*

(A) Introduction - Vector Boson Production in Hadronic Collisions

Exercise. Vector boson production is also called a Drell-Yan process. Explain why.

Today we will consider some recent applications of VBP :

- the W boson mass ;
- constraints on Parton Distribution Functions (PDFs) ;
- searching for new physics .

Measuring the W-boson mass

Why is it important?

M_W is a fundamental parameter of the Standard Model, so its value is needed to test the Standard Model precisely.

For example, to compare the ***direct measurement*** to ***indirect measurements*** based on precision experiments.

The Z^0 mass is known very precisely because the decay $Z^0 \to l^+ + l^-$ has a resonant peak at invar.mass $m_{ll} = M_Z$; for example in the process $e^+ + e^- \to Z^0 \longrightarrow l^+ + l^-$ at $\sqrt{s} \sim 90$ GeV.

Measuring the W mass

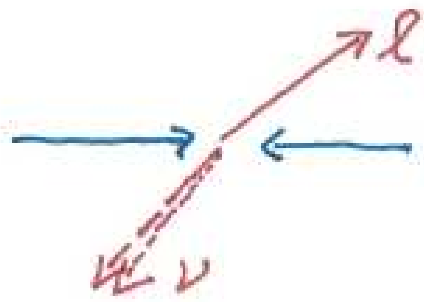
But for $W^{\pm}$ the leptonic decay is W → l ν ; the neutrino is "missing energy" so the detector cannot reconstruct the W mass peak.

V boson	Mass	Decay width	lBR
Z0	91.1876±0.0021 GeV/c	2.4952±0.0023 GeV/c	0.068
W±	80.379±0.012 GeV/c	2.085±0.042 GeV/c	0.210

However, there is a ***Jacobian peak*** in the distribution of the transverse momentum of the charged lepton, $p_T^{(\text{lepton})}$. The shape of that peak depends on M_W.

The lowest-order calculation

W rest frame



$$|\vec{p}_\ell| = |\vec{p}_\nu| = \frac{M_W}{2}$$

$$p_{\ell T} \le \frac{M_W}{2}$$

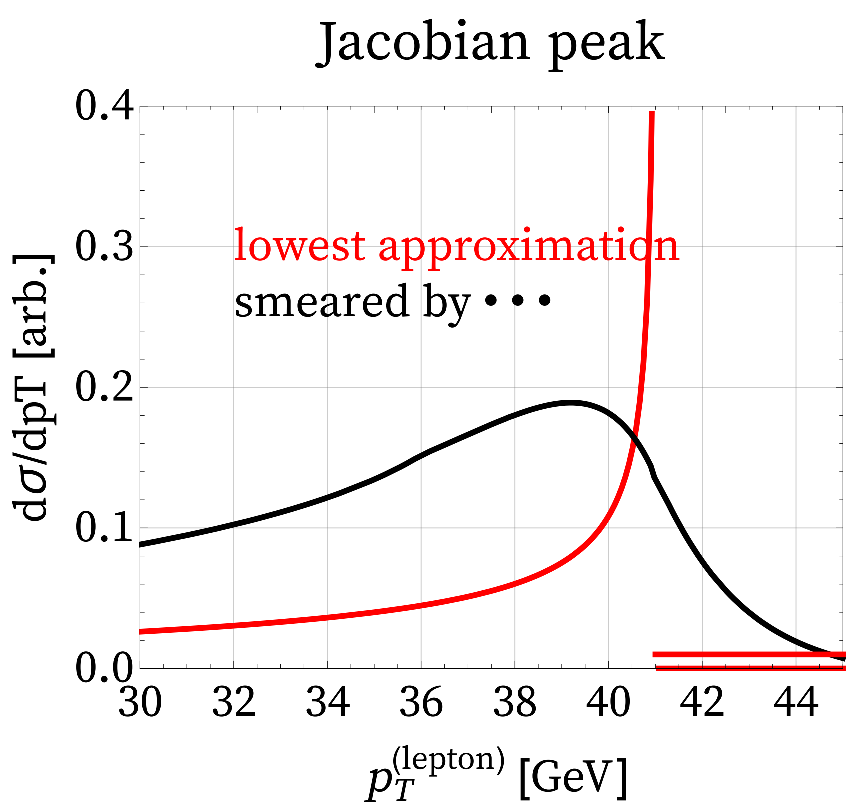
$$\frac{d\sigma}{dp_T^e} = \frac{d\sigma/d\cos\theta_*}{|dp_T^e/d\cos\theta_*|} = \frac{4p_T^e/M_W^2}{\sqrt{1-(2p_T^e/M_W)^2}}\,\frac{d\sigma}{d\cos\theta_*}$$

the Jacobian produces a "peak" at $p_T^e = \frac{M_W}{2}$

or use transverse mass $M_T = \sqrt{2E_{T\ell}E_{T\nu}(1-\cos\theta)}$

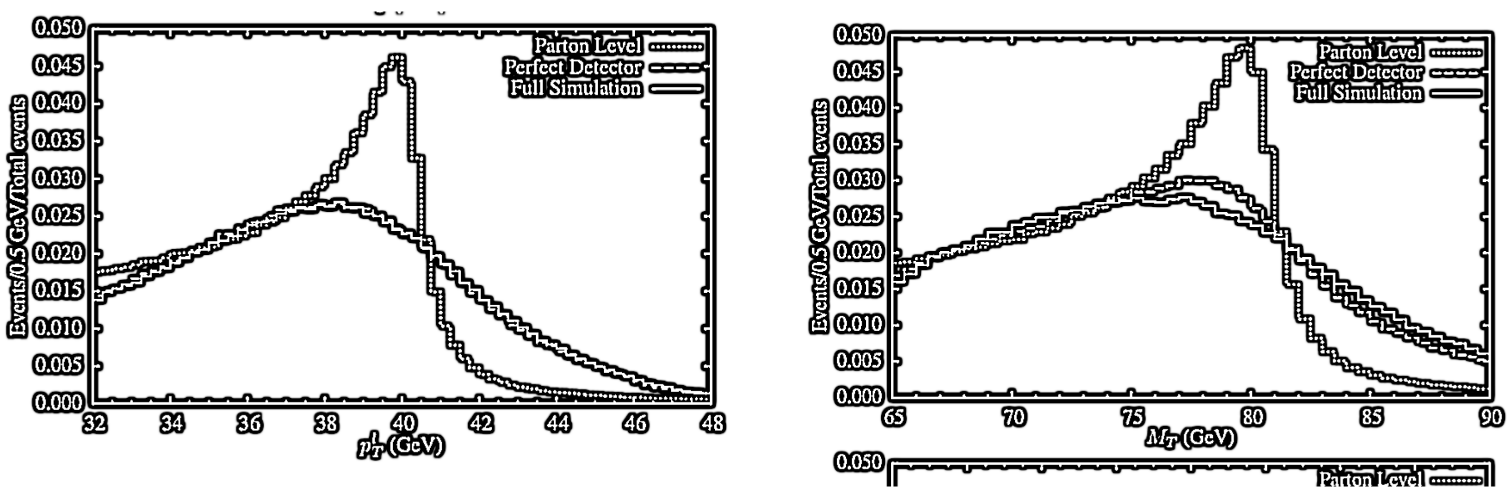
However, the sensitivity to M_W is reduced because of several effects

- Γ_W ;
- QCD radiation (which makes $p_{TW} \neq 0$) ;
- detector smearing.



Transverse Momentum p_T and Transverse Mass M_T

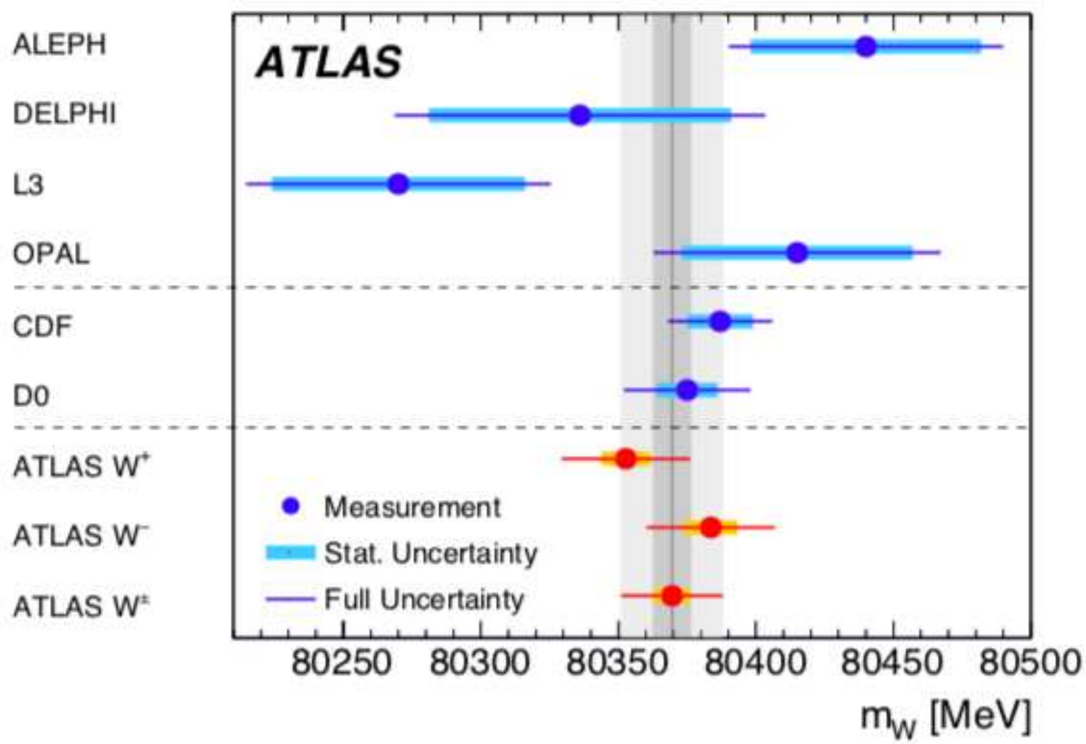
Quackenbush and Sullivan [hep-ph/1502.04671] studied in detail the detector limits for measuring the p_T or M_T Jacobian peak to deterine M_W.



Importantly, they studied the effect of ***PDF uncertainty*** in the measurement of M_W. The goal is to measure M_W to an accuracy of 10 MeV.

Today: 80.379 GeV ± 12 MeV.

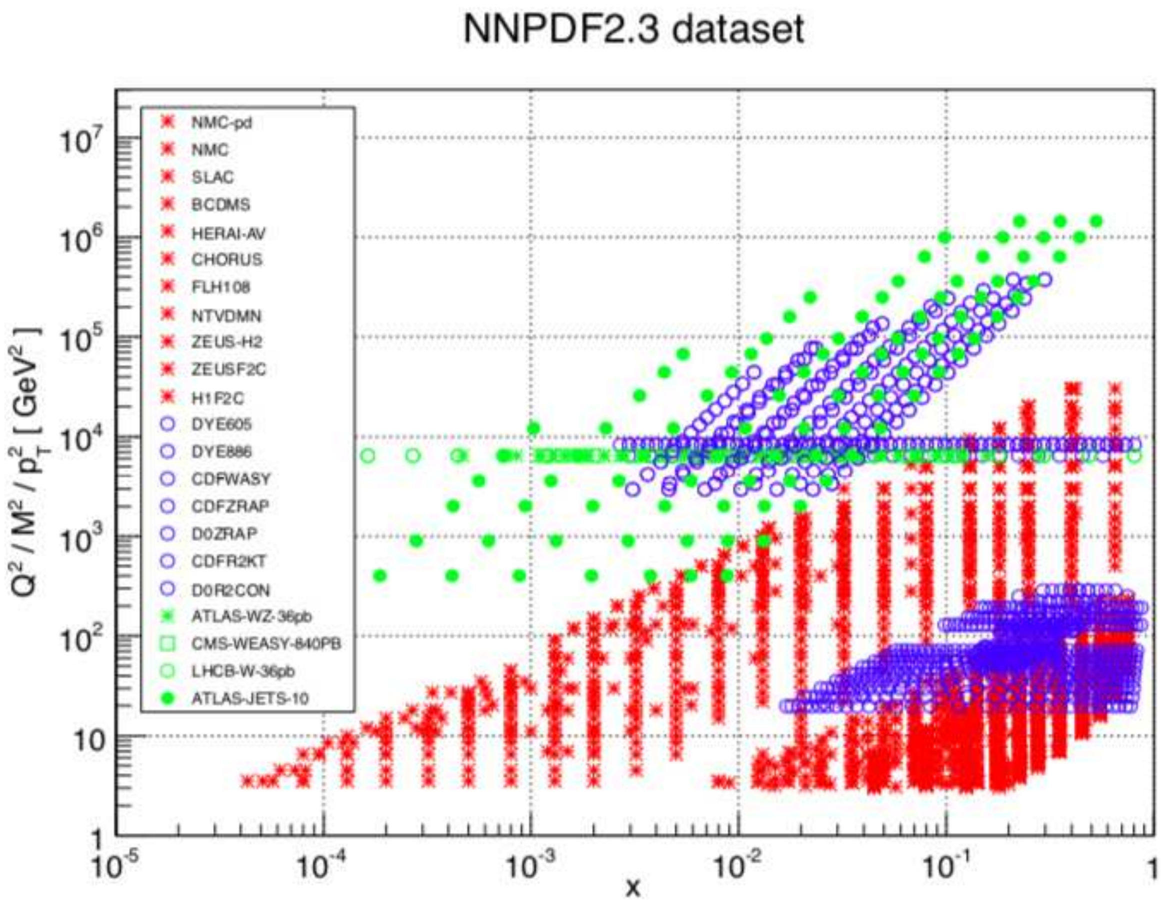
From ATLAS publication
hep-ex/1701.07240



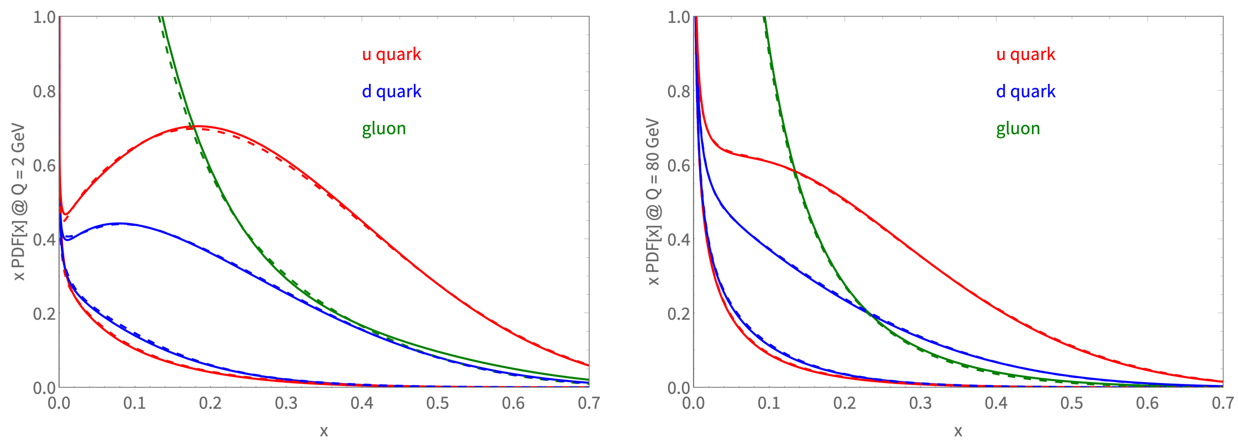
(B) Constraints on PDFs from Vector Boson Pproduction (VBP)

Recall … "Global Analysis of QCD must be global."

In other words we must use many experiments.



A comment on PDF uncertainty
∃ lectures by Marco Guzzi



W and Z production will be sensitive for PDFs at Q = 80 or 90 GeV, so we obtain new information about PDFs, different from fixed-target Drell-Yan experiments.

QCD and the process $pp \to W^+ + X$

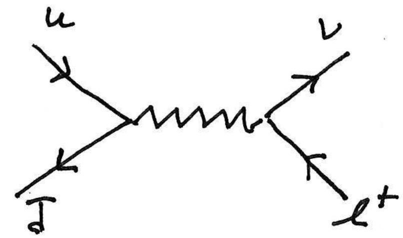
$\hookrightarrow \nu e^+$

THE BLACK BOOK OF QUANTUM CHROMODYNAMICS

Campbell, Huston, Krauss

Chaps 2, 3

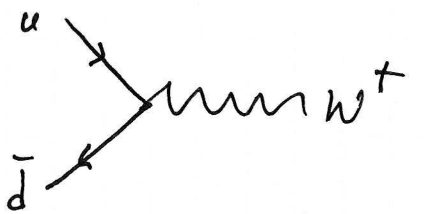
Leading Order



$$\sum |\mathcal{M}_0|^2 = \frac{g_W^2}{12} \frac{\hat{t}^2}{(Q^2 - m_W^2)^2 + m_W^2 \Gamma_W^2}$$

$\hat{s} = (p_u + p_{\bar{d}})^2$ and $\hat{t} = (p_u - p_{\ell^+})^2$

Simpler: ignore the decay (narrow width approximation)



$$|\mathcal{M}_0|^2 = \frac{g_W^2 m_W^2}{12}$$

$\sum_{u,\bar{d}}$ implied

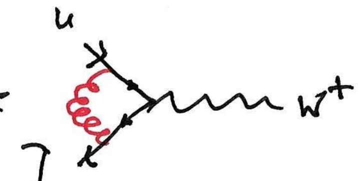
$$\sigma^{(LO)}(h_1 h_2 \to W^+ X) = \frac{\pi g_W^2}{12 s} \int_{-y_{max}}^{y_{max}} dy_W \, f_{u/h_1}(x_u) \, f_{\bar{d}/h_2}(x_{\bar{d}})$$

where $x_u = \frac{m_W}{\sqrt{s}} e^{y_W}$

$x_{\bar{d}} = \frac{m_W}{\sqrt{s}} e^{-y_W}$

$$\pm y_{max} = \pm \frac{1}{2} \ln\left(\frac{s}{m_W^2}\right)$$

QCD Virtual Correction

$\mathcal{M}_2^{(v)} =$ 

$$= \frac{g_W}{\sqrt{2}} g_s^2 \, \bar{v}(\bar{d}) \underbrace{\int \frac{d^4k}{(2\pi)^4}} \frac{1}{k^2} S_F(p_u - k) S_F(p_{\bar{d}} + k) \, u(u) \, \epsilon(W)$$

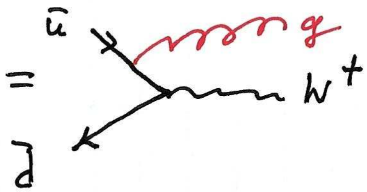
replace it by $\mu^{4-D} \int \frac{d^Dk}{(2\pi)^D}$ where $D = 4 - 2\epsilon$

later $\epsilon \to 0$

$\Rightarrow$ Eq. (2.117)

$$2 \left| \mathcal{M}_2^{(v)} \mathcal{M}_0 \right| = |\mathcal{M}_0|^2 \frac{\alpha_s}{2\pi} C_F \left(\frac{\mu^2}{Q^2} \right)^\epsilon \frac{4\pi^\epsilon}{\Gamma(1-\epsilon)}$$

$$\times \left\{ -\frac{2}{\epsilon^2} - \frac{3}{\epsilon} - 8 + \pi^2 \right\}$$

QCD Real Corrections; e.g. $\mathcal{M}_1^{(R)} =$ 

$\Rightarrow$ Eq (2.118)

$$\mu^{4-D} \int \frac{d^Dk}{(2\pi)^D} \left| \mathcal{M}_1^{(R)} \right|^2 = |\mathcal{M}_0|^2 \frac{\alpha_s}{2\pi} C_F \left(\frac{\mu^2}{Q^2} \right)^\epsilon \frac{4\pi^\epsilon}{\Gamma(1-\epsilon)}$$

$$\times \left\{ \left(\frac{2}{\epsilon^2} + \frac{3}{\epsilon} + \frac{\pi^2}{3} \right) \delta(1-z) + \text{finite distributions} \right\}$$

e.g. $P^{(1)}_{qq}(z)$

($x = m_W^2/s$ and $z = ??$)

$\therefore$ Cancellation of singularities $\Longrightarrow \hat{\sigma}^{(NLO)}$

"DIMENSIONAL TRANSMUTATION" $\frac{1}{\epsilon} \left(\frac{\mu^2}{Q^2} \right)^\epsilon = \frac{1}{\epsilon} + \ln\left(\frac{\mu^2}{Q^2} \right)$

(#0) Dzero with $\sqrt{s}$ = 1.96 TeV

lepton charge asymmetry in $W^{\pm}$ production

hep-ex/1412.2862

Information about the experiment

- "Measurement of the electron charge asymmetry in $p\,\overline{p} \to W + X \to e\nu + X$ decays in $p\,\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV" (2016)
- I believe this is the most precise lepton charge asymmetry measurement from the Tevatron Collider.

Lepton Charge Asymmetry...
... from inclusive $W^{\pm}$ production

•• the Fermilab Tevatron Collider,
a proton-antiproton collider with $\sqrt{s}$ = 1.96 TeV. The measurement of electron charge asymmetry in the process $p\,\overline{p} \to W{+}X$ provided important information about PDFs.

•• In $p\,\overline{p}$ collisions, W production is predominantly due to annihilation of valence quarks, $u\overline{d} \to W^{+}$ and $d\overline{u} \to W^{-}$.

••Think about the x dependence of PDFs, and note that $u_{\overline{p}} = \overline{u}_{p}$, etc.
$\therefore$ W^{+} bosons tend to move in the direction of the proton ($y_W > 0$) ;
W^{-} bosons tend to move in the direction of the antiproton ($y_W < 0$).

Define W-charge asymmetry by

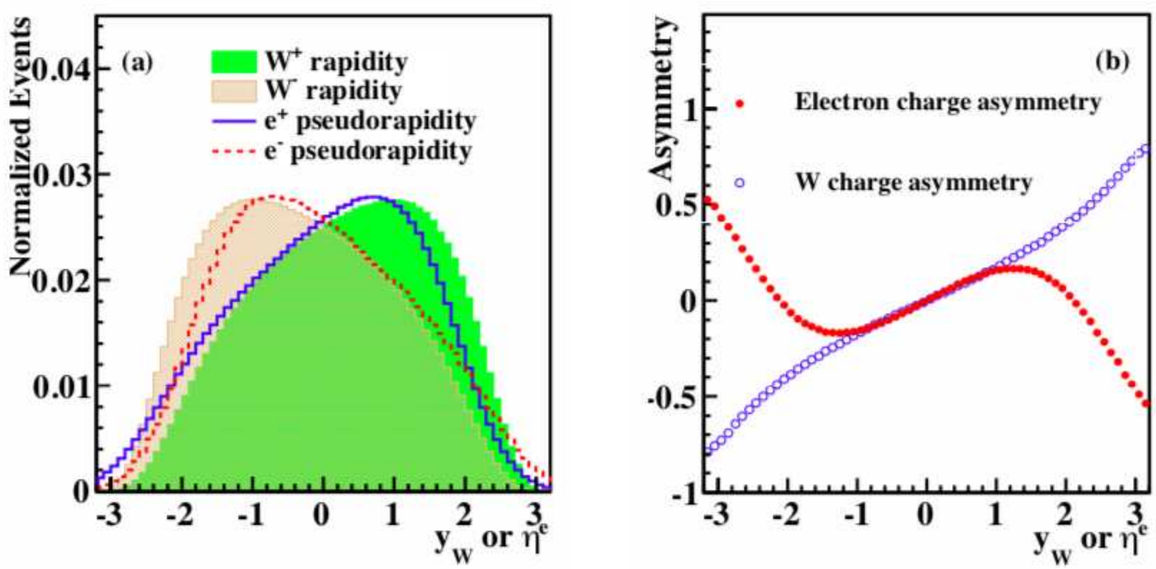
$$A_W(y_W) = \frac{(d\sigma/dy)_{W+} - (d\sigma/dy)_{W-}}{(d\sigma/dy)_{W+} + (d\sigma/dy)_{W-}} = \frac{\text{plus} - \text{minus}}{\text{plus} + \text{minus}}$$

However, we can't measure the rapidity of the W because the neutrino is "missing energy".

Instead the experiments measure ***lepton charge asymmetry,*** as a function of the ***pseudorapidity*** of the observed (charged) lepton;

$$A_l(\eta_l) = \frac{(d\sigma/d\eta)_{\eta+} - (d\sigma/d\eta)_{\eta-}}{(d\sigma/d\eta)_{\eta+} + (d\sigma/d\eta)_{\eta-}} = \frac{\text{plus} - \text{minus}}{\text{plus} + \text{minus}}$$

Behavior of W^+ and W^- inclusive production at the Tevatron collider

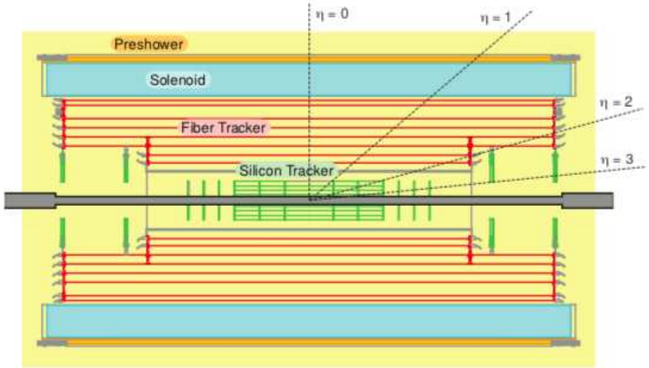


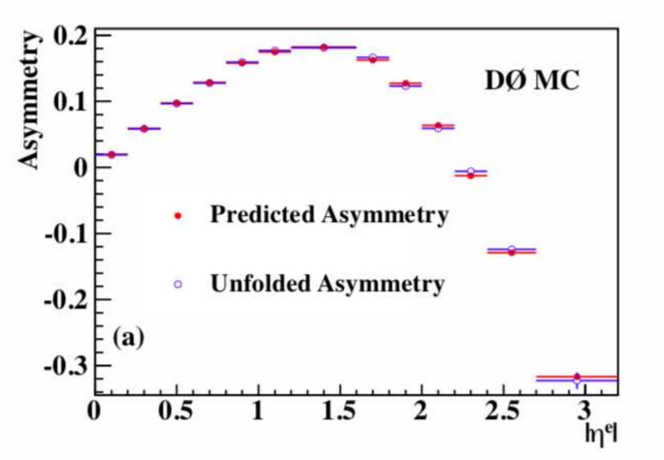
cross section versus y_W or η^e || Asymmetry = (+ − −) / (+ + −)

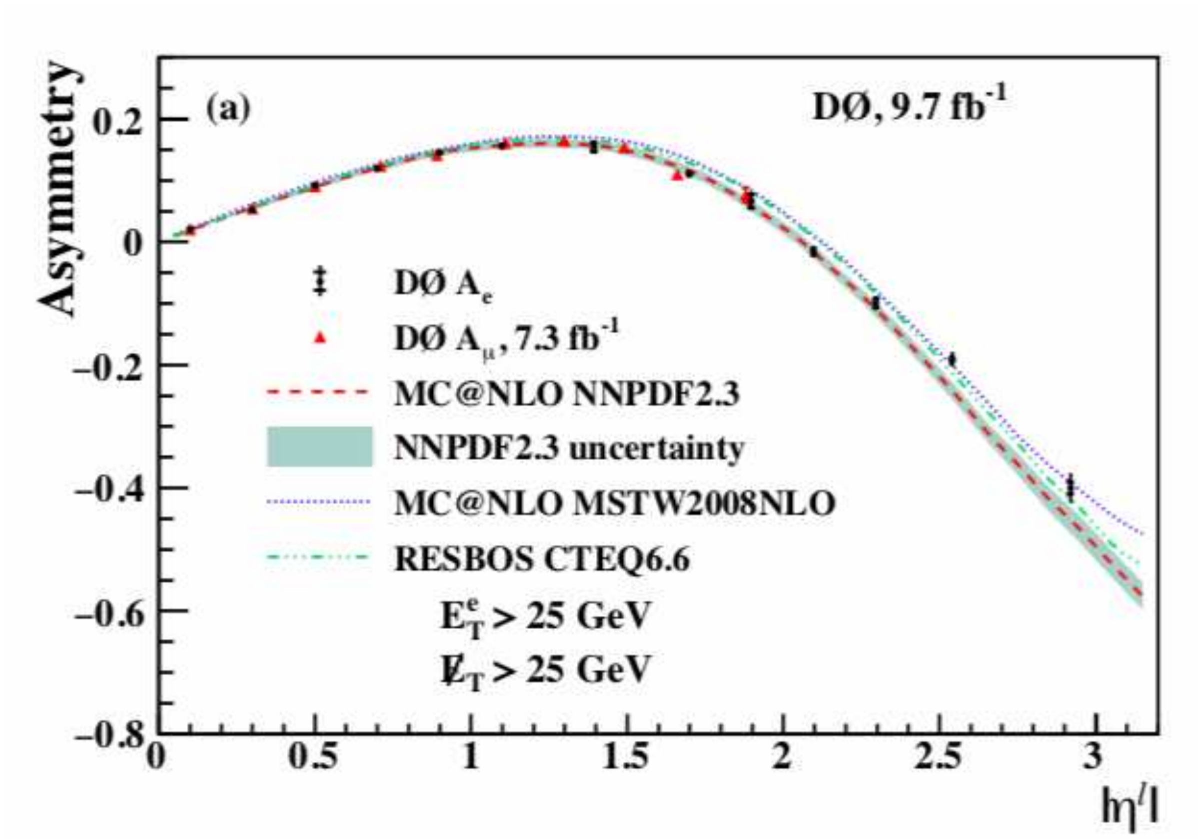
The electron asymmetry has a "turn-over" due to the convolution of the W boson asymmetry and the V−A structure of the W boson decay.

MC event generator RESBOS with the CTEQ6 .6 central PDF set

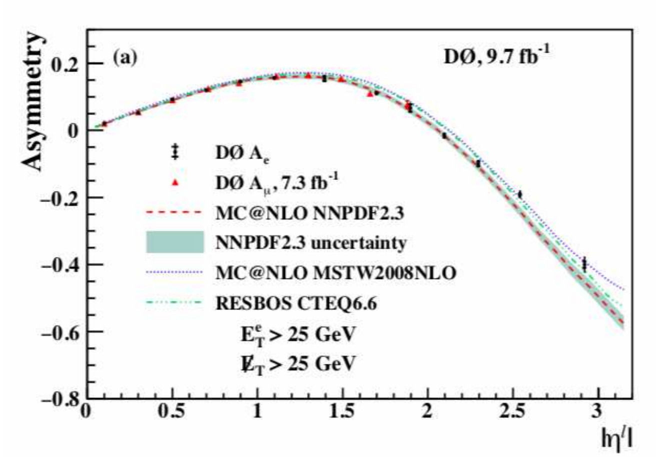
Experimental Results

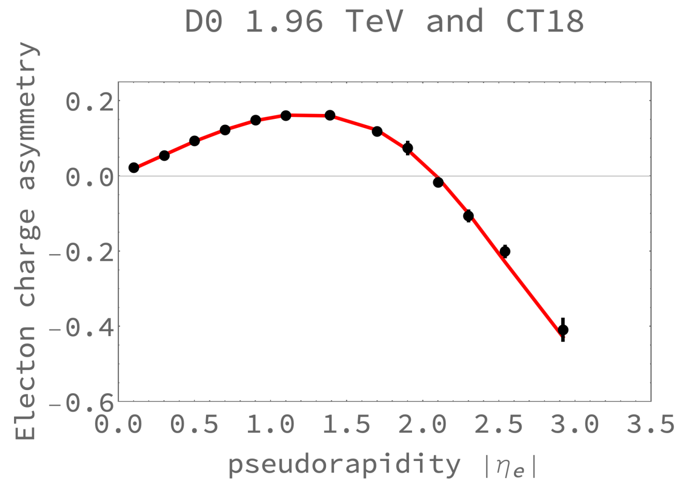





(a)
DØ, 9.7 fb-1
Asymmetry
DØ Ae
DØ Aμ, 7.3 fb-1
MC@NLO NNPDF2.3
NNPDF2.3 uncertainty
MC@NLO MSTW2008NLO
RESBOS CTEQ6.6
E_T^e > 25 GeV
E̸_T > 25 GeV
|η^l|

Compare to the CT18 global analysis,





χ^2 / N = 22.8/13 with 6 systematic errors.

(#1) ATLAS 7 TeV

inclusive W and Z production

hep-ex/1109.5141

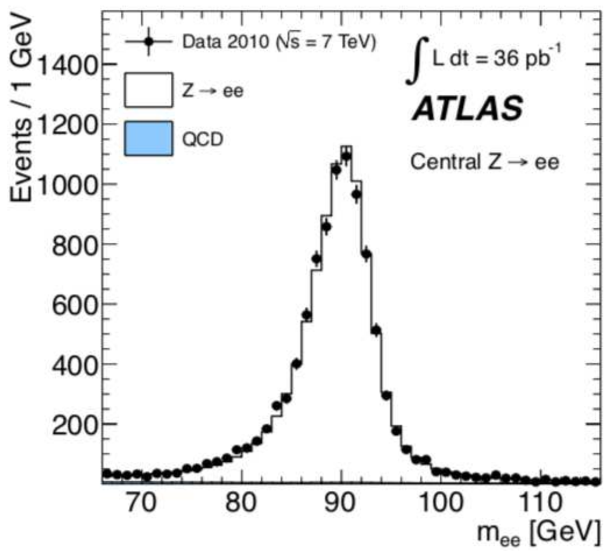
Information about the experiment

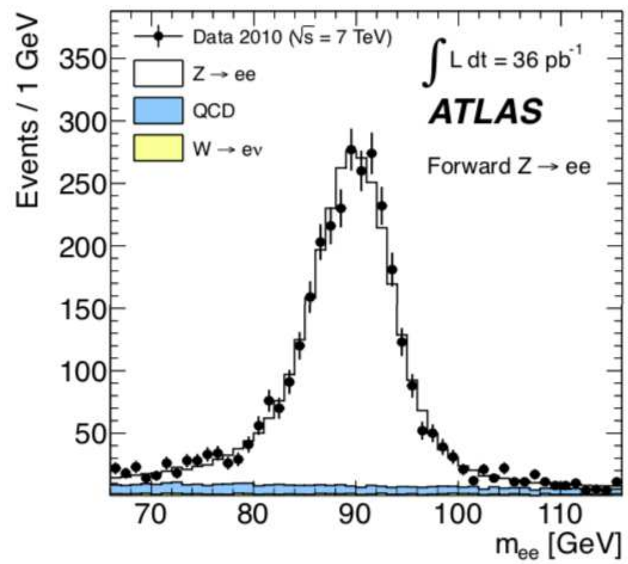
"Measurement of the inclusive $W^{\pm}$ and Z^0/γ^* cross sections in the e and μ decay channels in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector"

Number of data points = 41

Number of systematic errors = 31

What is a Z boson at the LHC?

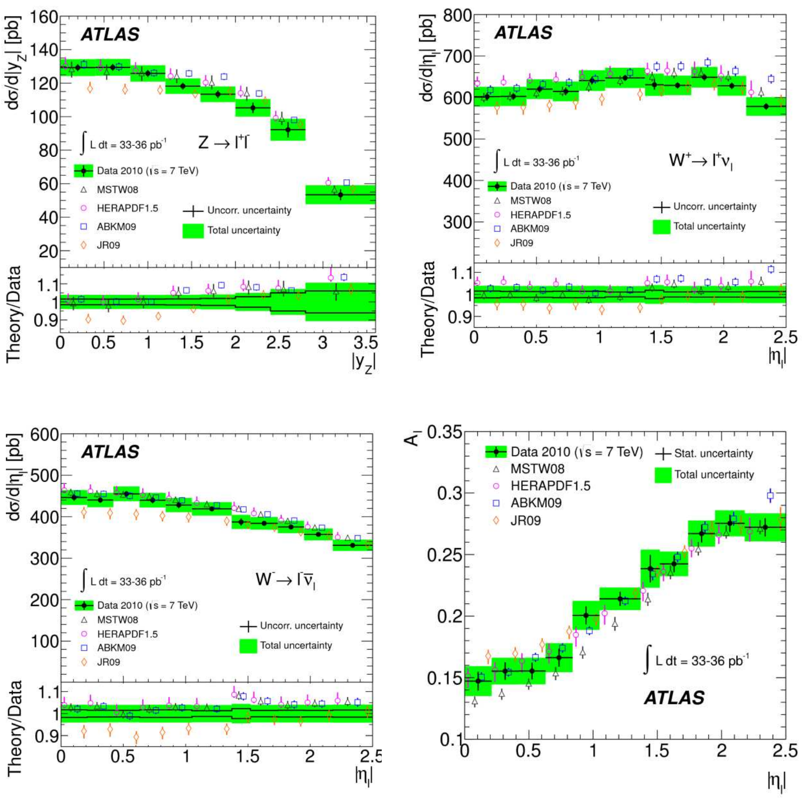




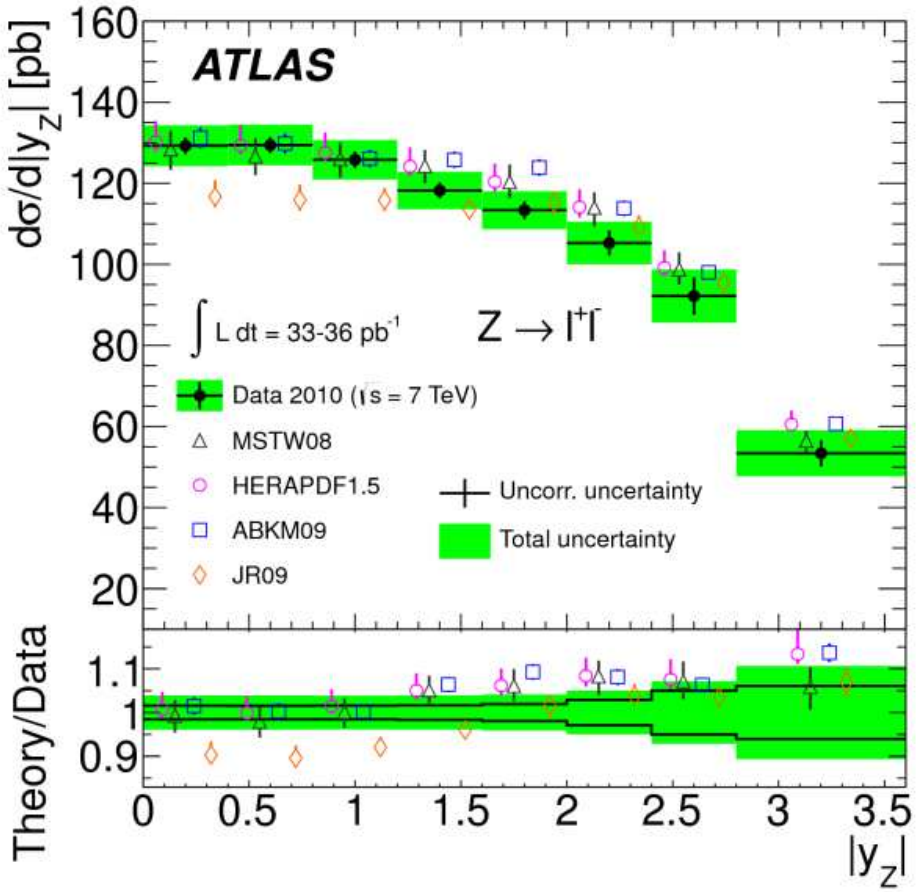
$m_{ll} \in \{ 66, 111 \}$ GeV

Results

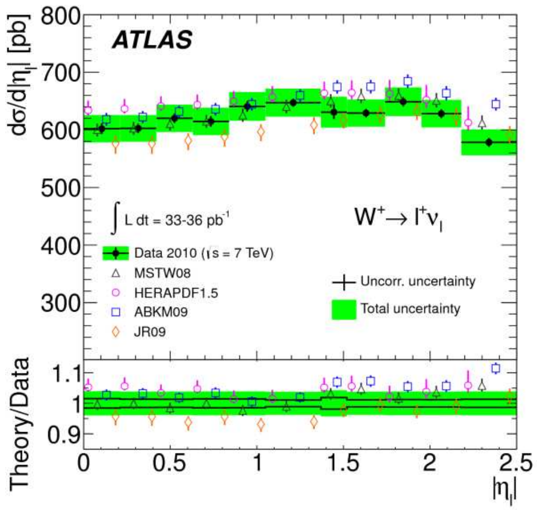
ATLAS 7 TeV; cross sections for W and Z production, versus y_Z or η_l; also lepton asymmetry

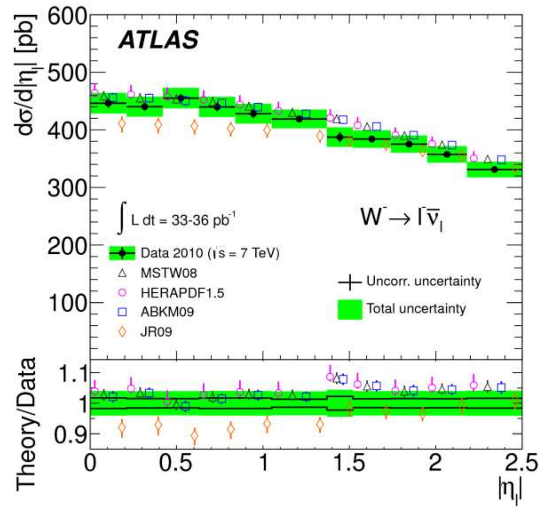


$d\sigma / d\ |y_Z|$ for Z production

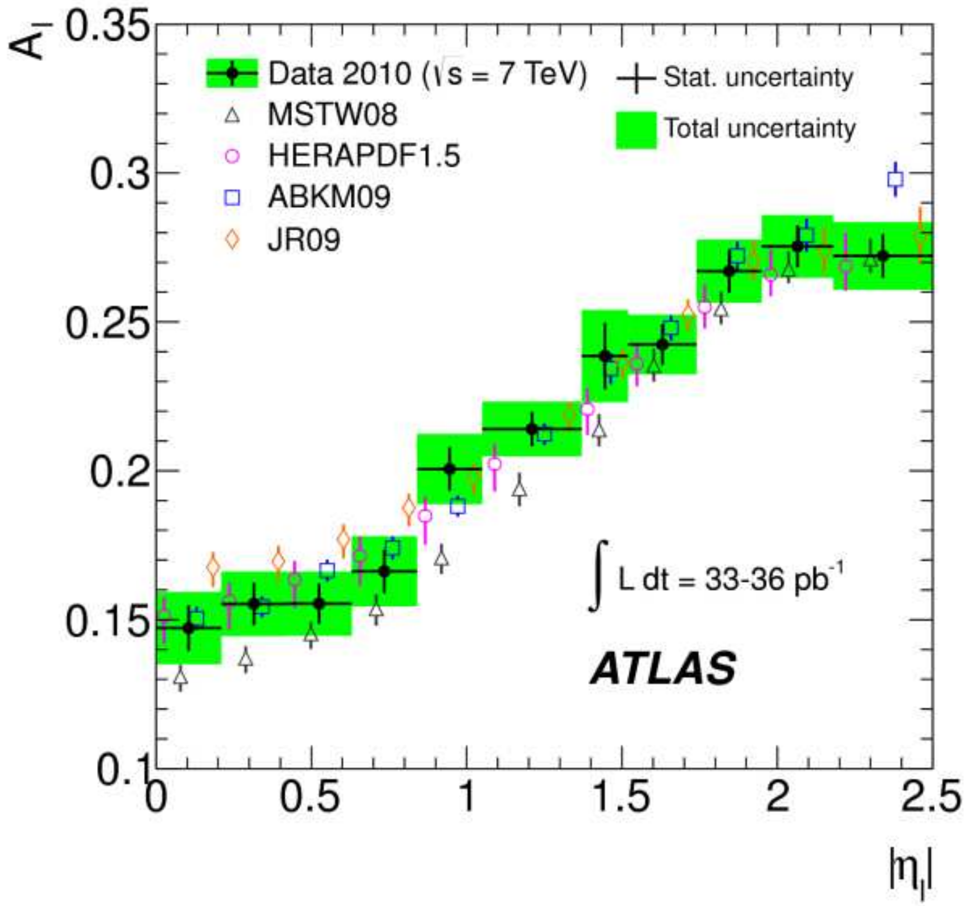


$\mathrm{d}\sigma / d\ |\eta_l|$ for W^+ and W^-



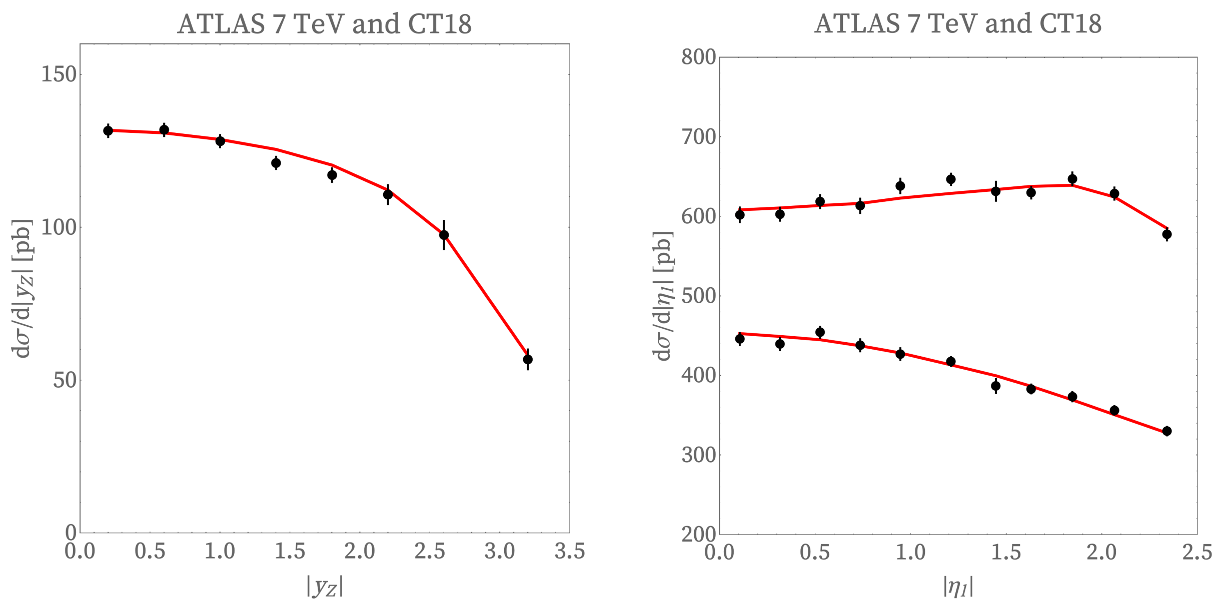


Lepton charge asymmetry for W production



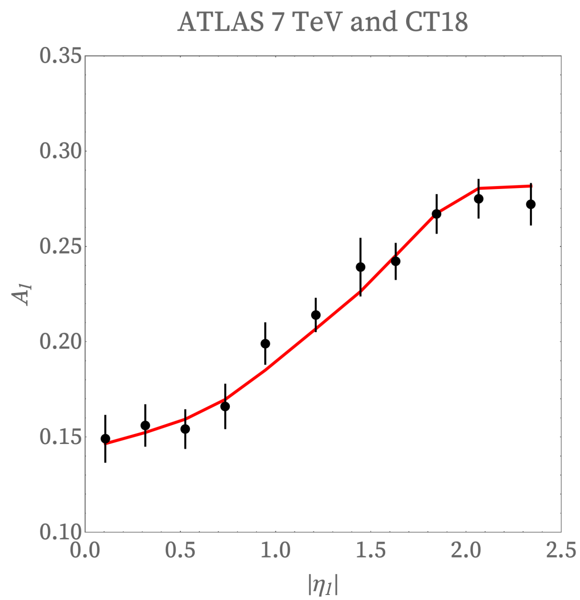
Some of the data from this experiment are being used in the 'CT18' Global Analysis of QCD.

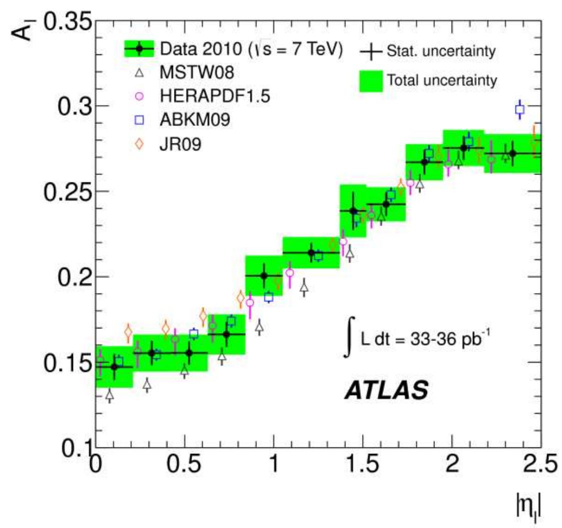
Show data compared to theory with 'CT18' PDFs



$\chi^2 / N = 1.084$

Lepton charge asymmetry : theory | data





CT18 $\Longleftrightarrow$ ATLAS data

(#2) CMS 7 TeV

Muon charge asymmetry in W production

hep-ex/1312.6283

Information about the experiment

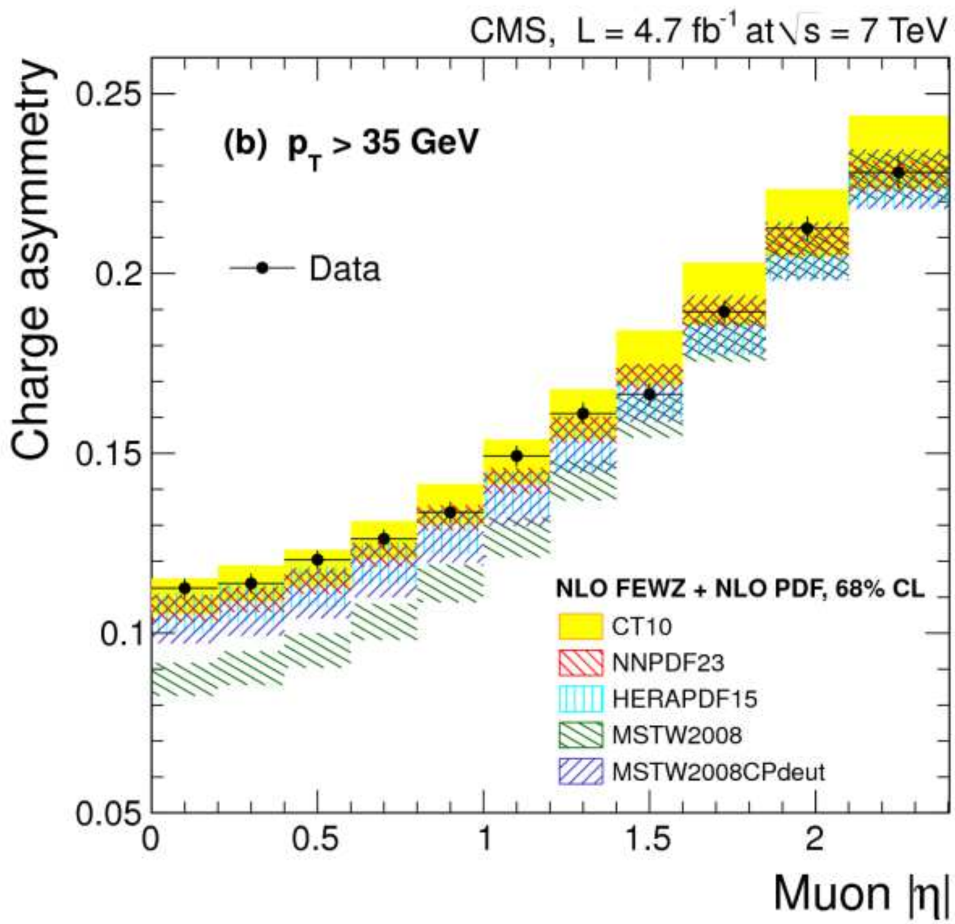
"Measurement of the muon charge asymmetry in inclusive pp $\rightarrow$ W + X production at $\sqrt{s} = 7$ TeV and an improved determination of light parton distribution functions" (2014)

Number of data points = 33

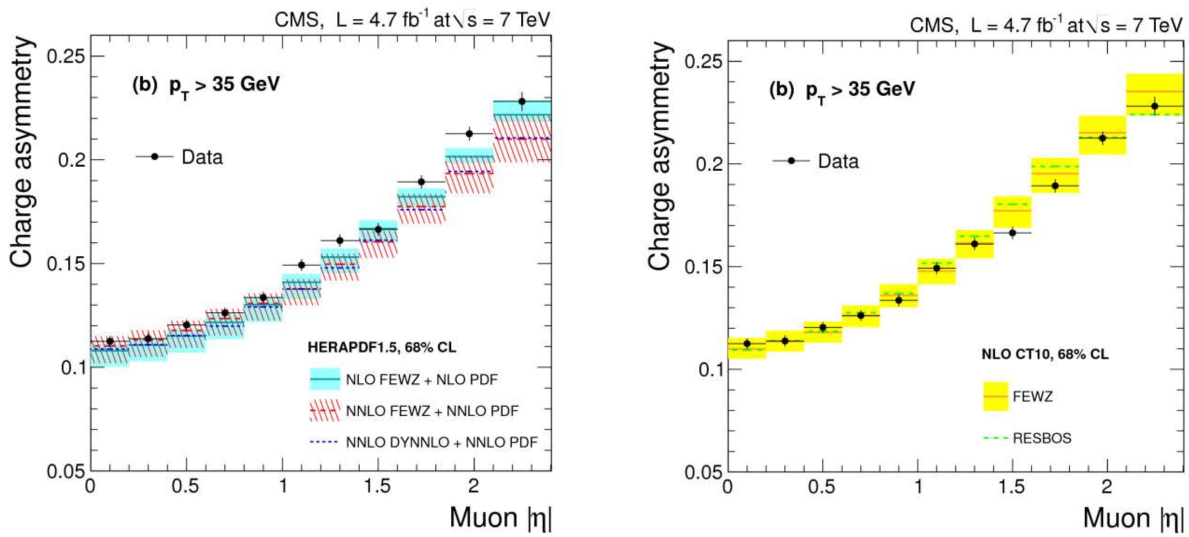
number of systematic errors = 12

Results

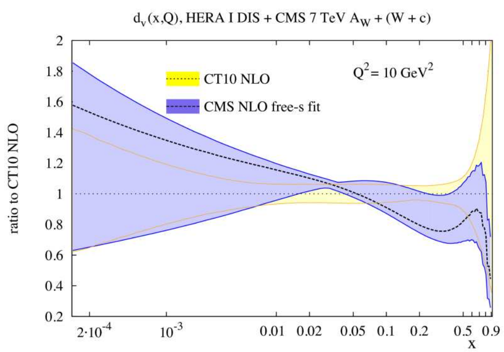
Muon charge asymmetry for W production

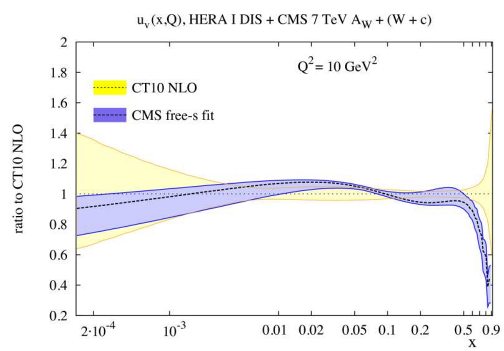


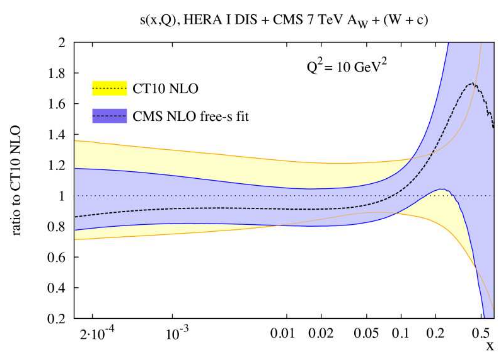
Comparisons of data to NNLO pQCD and to a resummation calculation



Light parton distribution functions "HERA+CMS" ratio to CT10 PDFs ; [d $_{valence}$, $u_{valence}$] and [strange]







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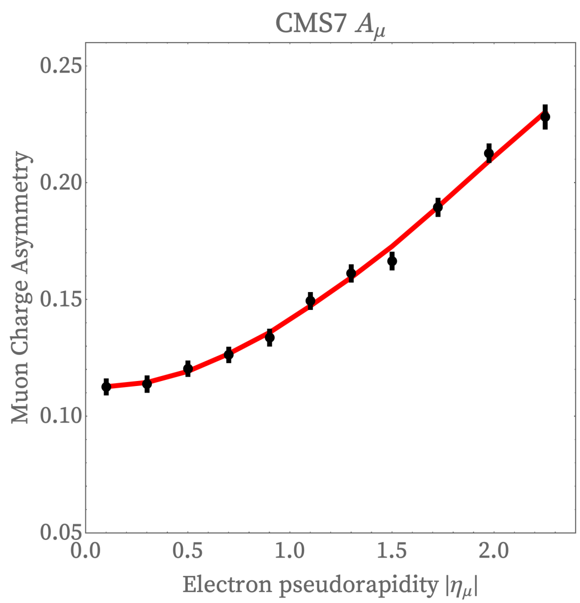
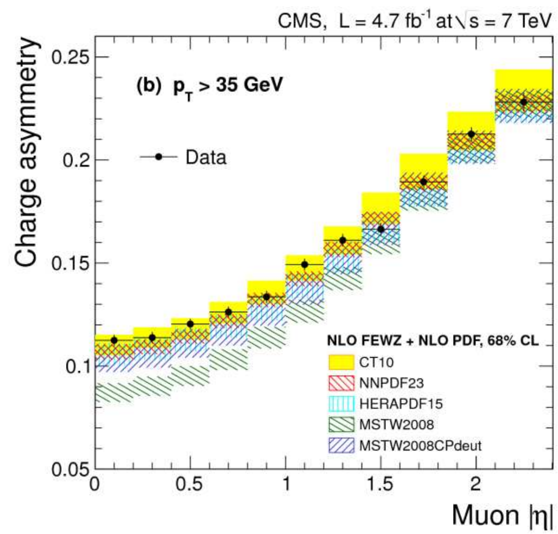




X^2 /N = 1.630

(#3) CMS 7 TeV

Electron charge asymmetry in W production

hep-ex/1206.2598

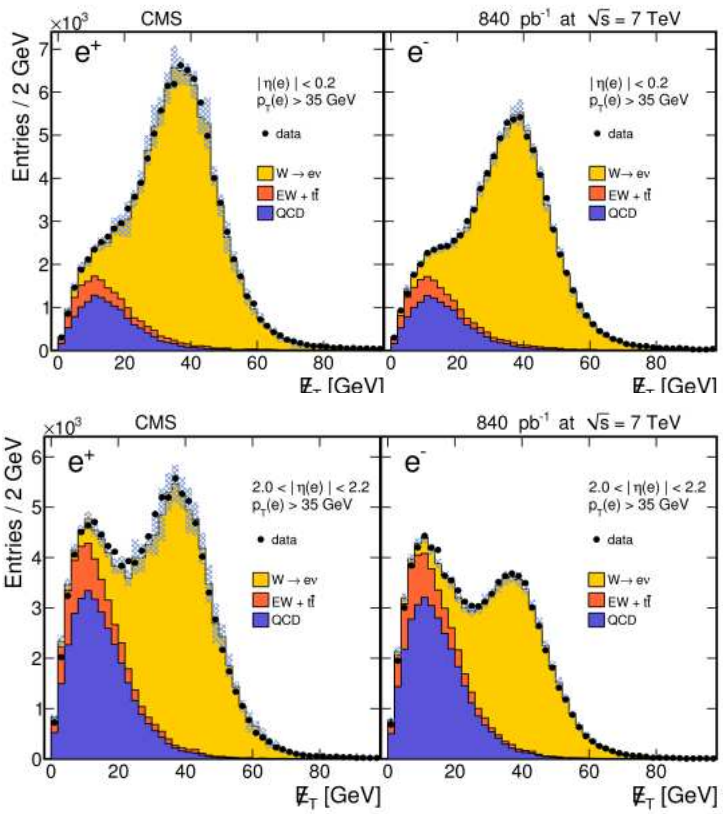
Information about the experiment

"Measurement of the electron charge asymmetry in inclusive W production in pp collisions at $\sqrt{s}$ = 7 TeV" (2013)

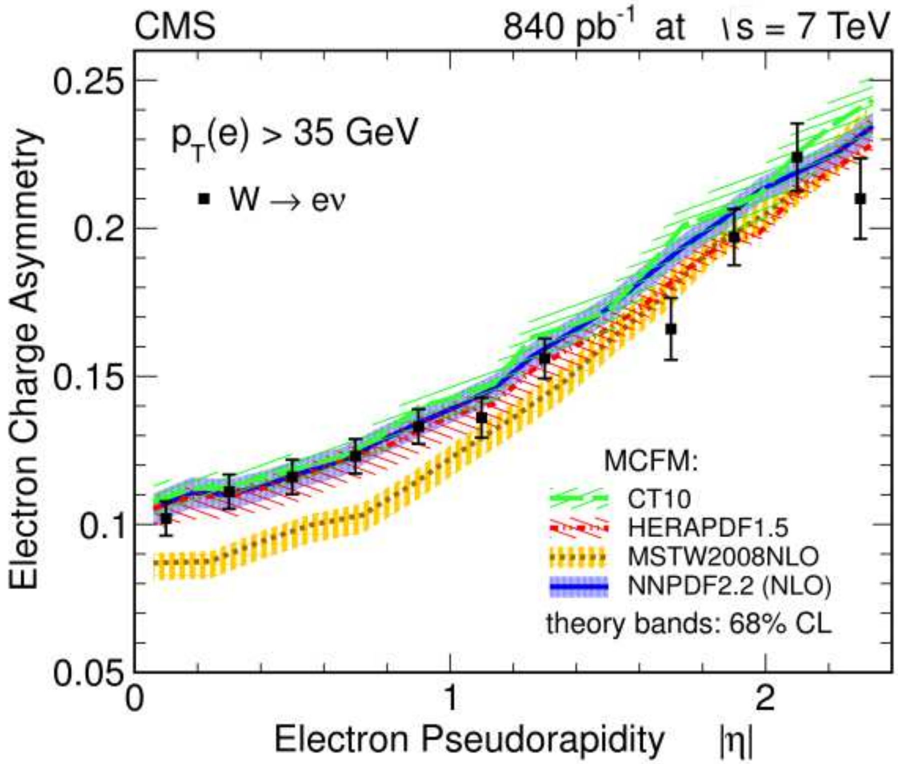
Number of points = 11;
systematic errors = 0

Results

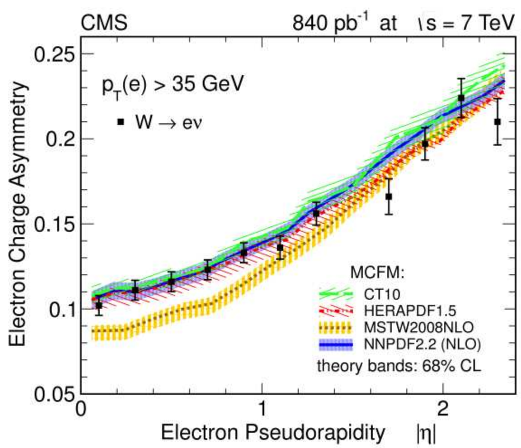
I' m not sure what to say about this…

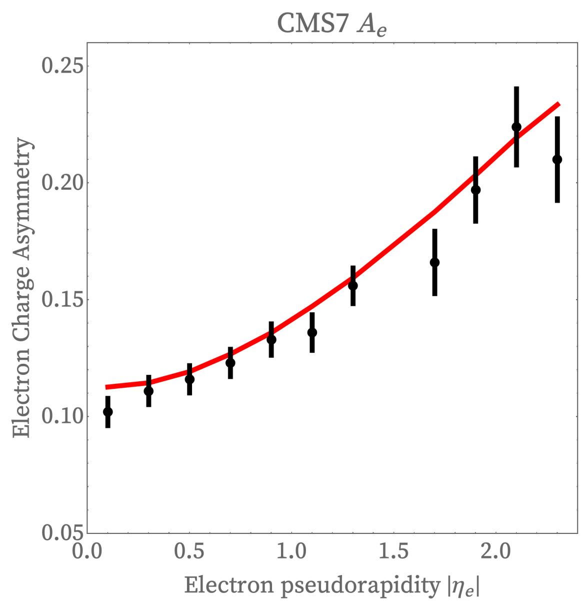


This shows the electron charge asymmetry for W production at $\sqrt{s}$ = 7 TeV; the data is compared to MCFM calculations with various parton distribution functions, showing that this data imposes constraints on PDFs



Data from this experiment are being used in the 'CT18' Global Analysis of QCD. Show the data compared to NNLO theory with 'CT18' PDFs …





$X^2/N = 1.070$

(#4) LHCb 7 TeV

W and Z production

hep-ex/1505.07024

Information about the experiment

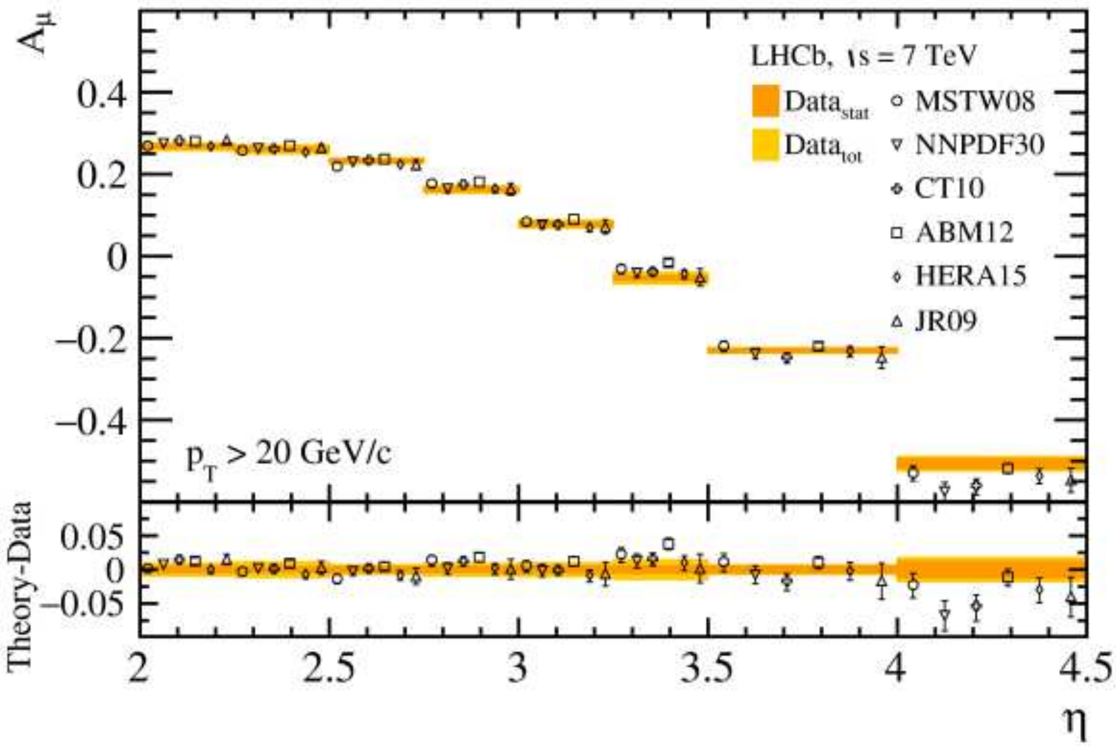
"Measurement of the forward Z boson production cross section in pp collisions at $\sqrt{s}$ = 7 TeV" (2015)

The number of data points = 33;

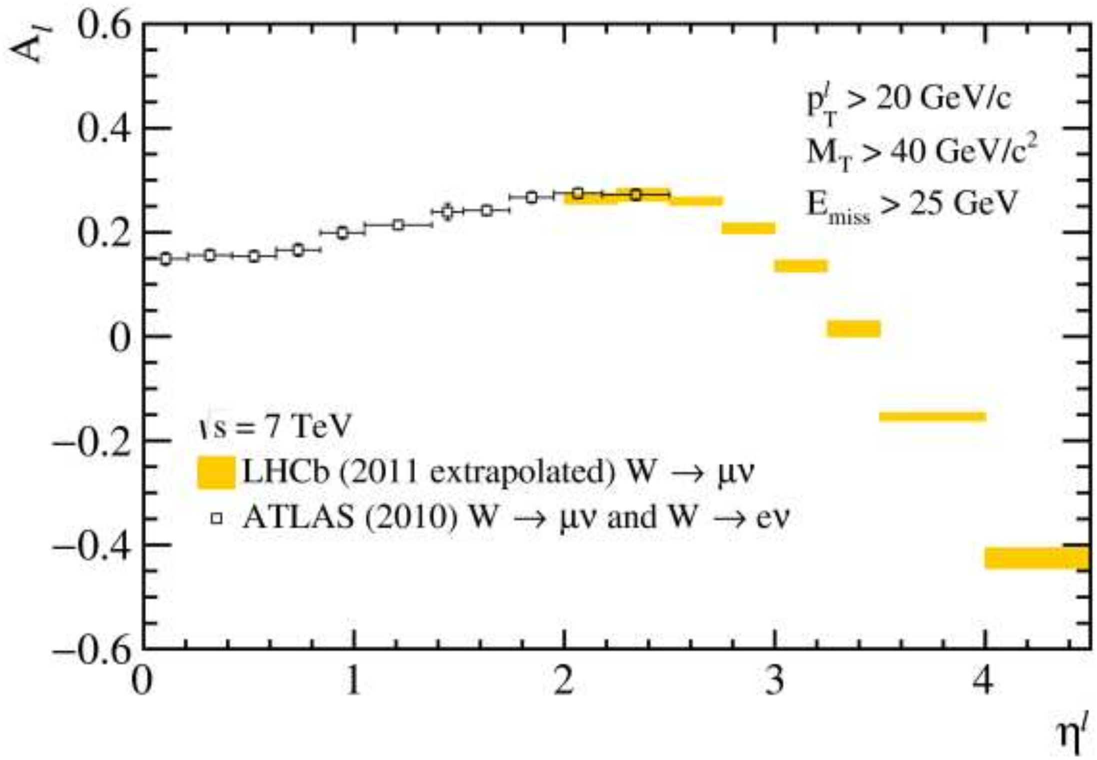
the number of systematic errors = 12

Results

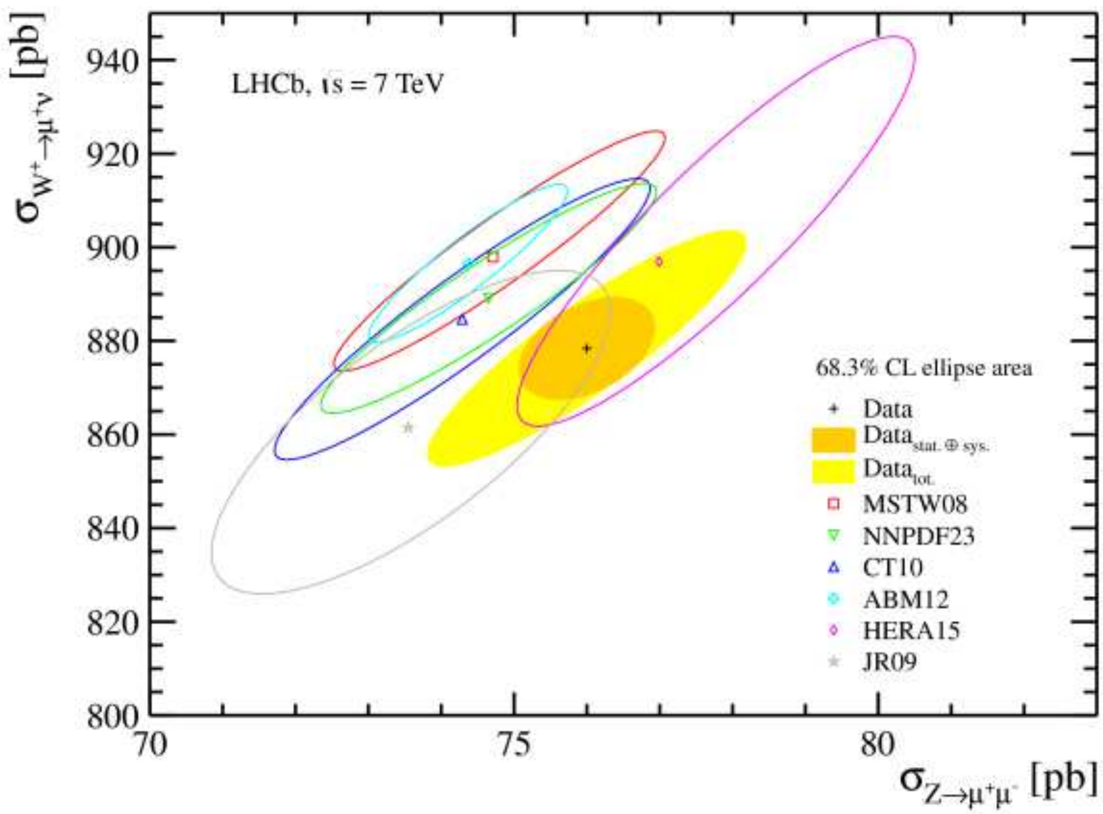
Muon charge asymmetry for forward W production



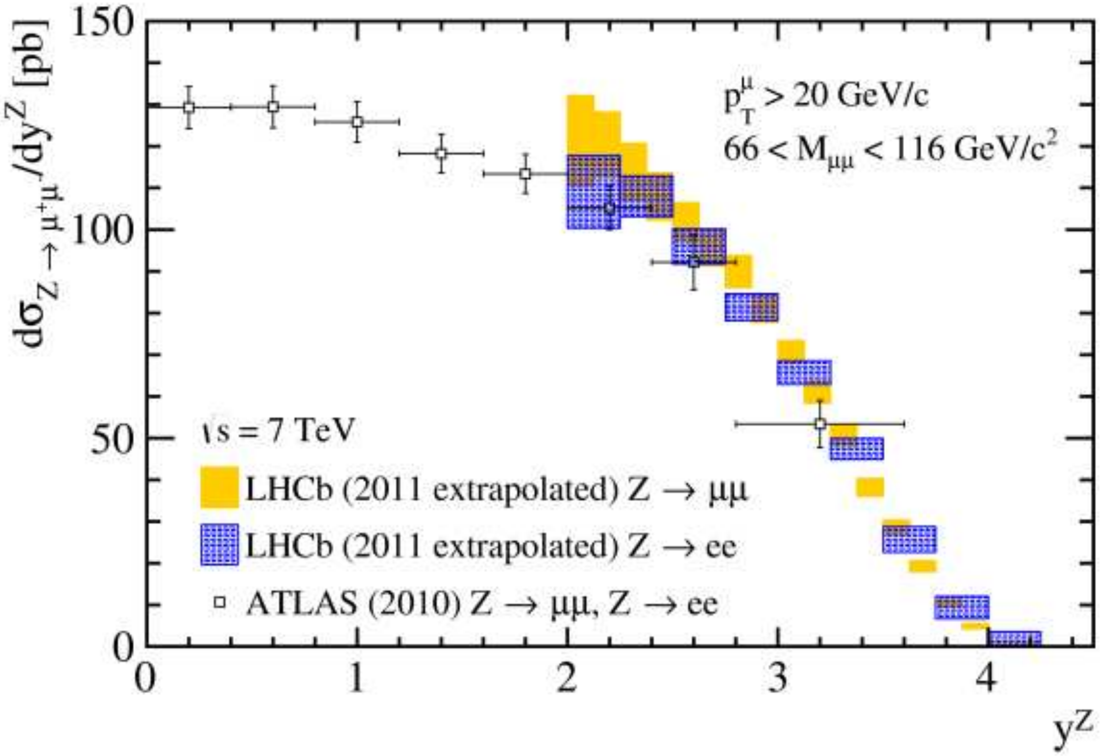
Lepton charge asymmetry, comparing LHCb and ATLAS

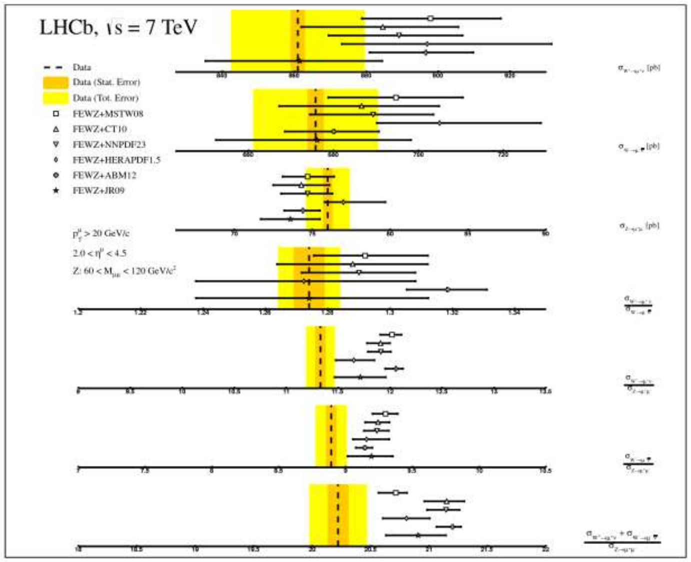


Integrated cross sections, comparing W^+ and Z^0 production in the forward direction; apparently these cross sections can constrain PDFs.

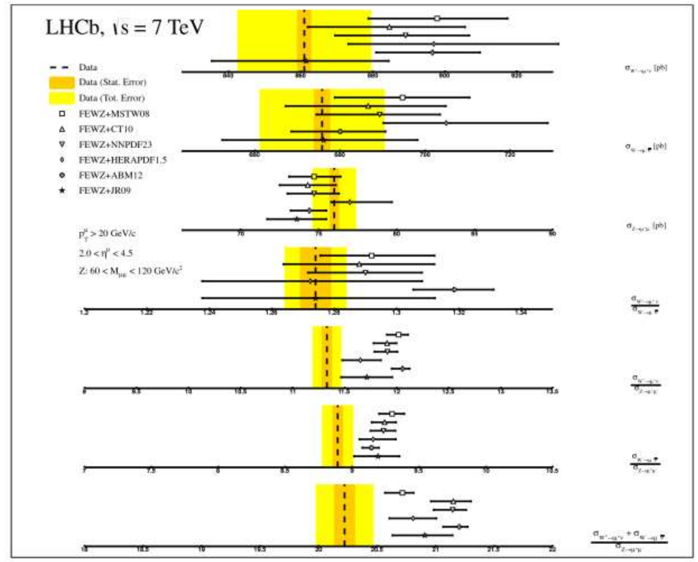


Comparing $d\sigma/dy_Z$ from LHCb and ATLAS experiments



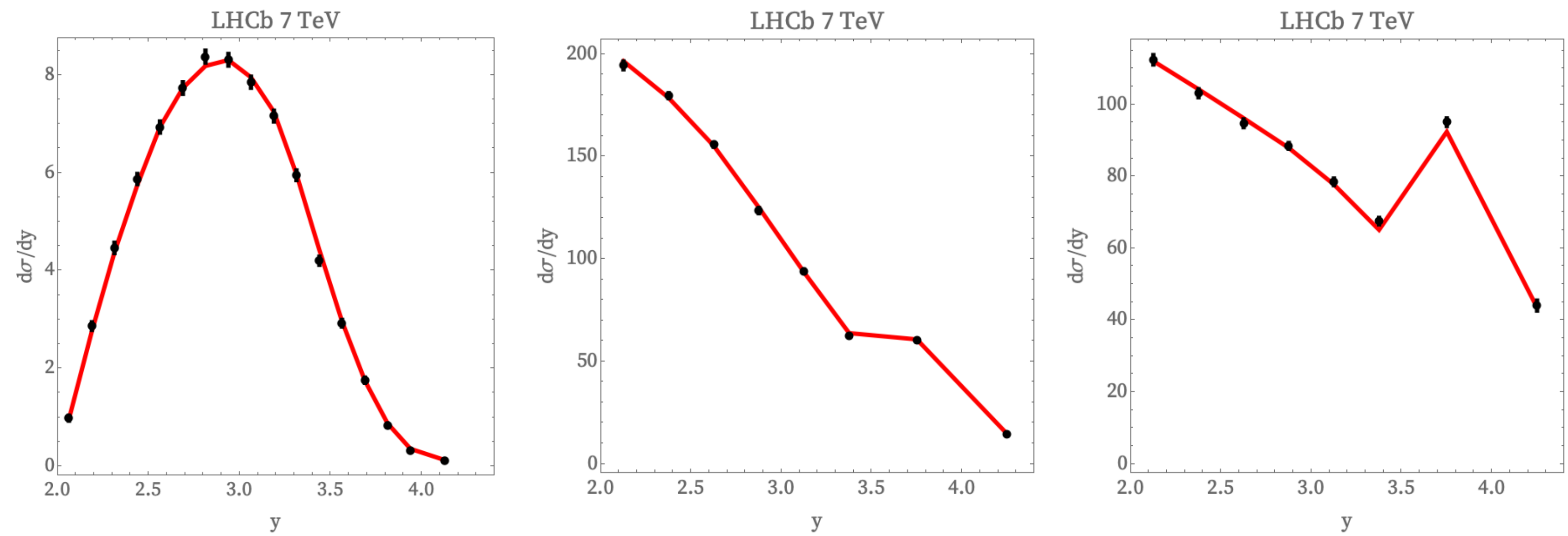


LHCb, √s = 7 TeV
Data
Data (Stat. Error)
Data (Tot. Error)
FEWZ+MSTW08
FEWZ+CT10
FEWZ+NNPDF23
FEWZ+HERAPDF1.5
FEWZ+ABM12
FEWZ+JR09
$p_T^\mu > 20$ GeV/c
$2.0 < \eta^\mu < 4.5$
Z: $60 < M_{\mu\mu} < 120$ GeV/c^2



LHCb, √s = 7 TeV
Data
Data (Stat. Error)
Data (Tot. Error)
FEWZ+MSTW08
FEWZ+CT10
FEWZ+NNPDF23
FEWZ+HERAPDF1.5
FEWZ+ABM12
FEWZ+JR09
$p_T^\mu > 20$ GeV/c
$2.0 < \eta^\mu < 4.5$
Z: $60 < M_{\mu\mu} < 120$ GeV/c^2

The LHCb 7 TeV data for forward VBP is used in the 'CT18' Global Analysis of QCD; compare the data to the theory.



$Z^0 \quad \longrightarrow \; W^+ \quad \longrightarrow \; W^-$

$\chi^2/\mathrm{N} = 1.630$

(#5) ATLAS 8 TeV : "P T Z"

$Z \to e^+ e^-$; pT cross section

hep-ex/1512.02192

Information about the experiment

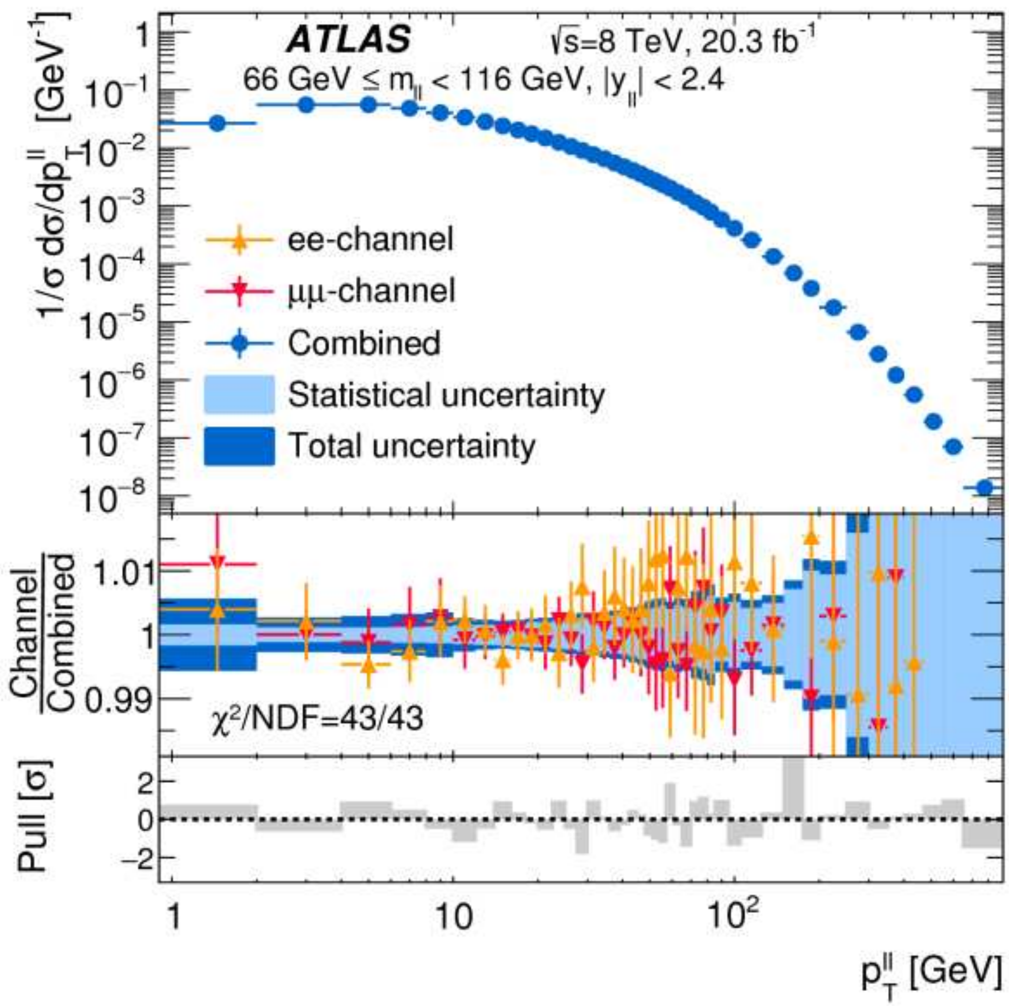
"Measurement of the transverse momentum and $\varphi * \eta$ distributions of Drell–Yan lepton pairs in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector" (2016)

Number of data points = 27;

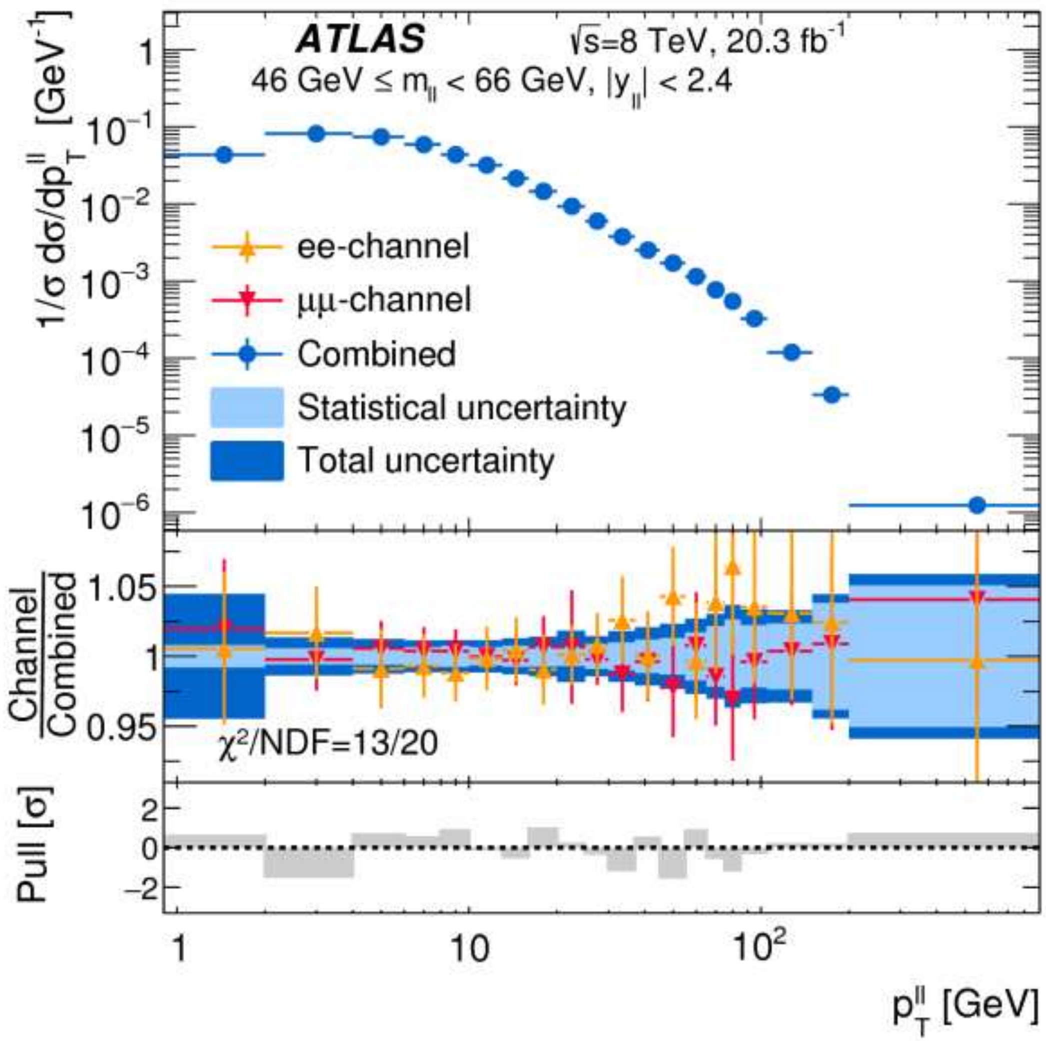
number of systematric errors = 88

Results

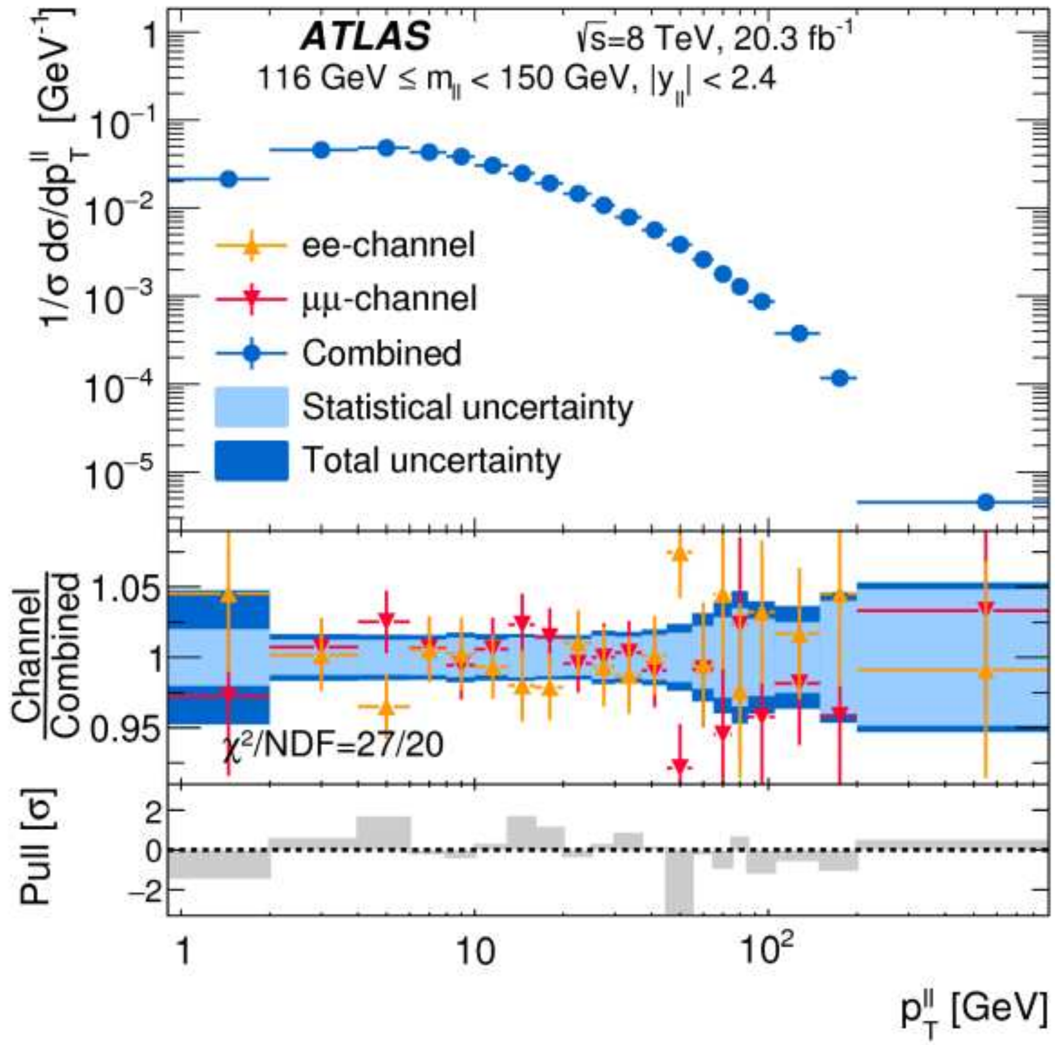
Z^0 production as a function of pT; $m_{ll} \in \{66,116\}$ GeV



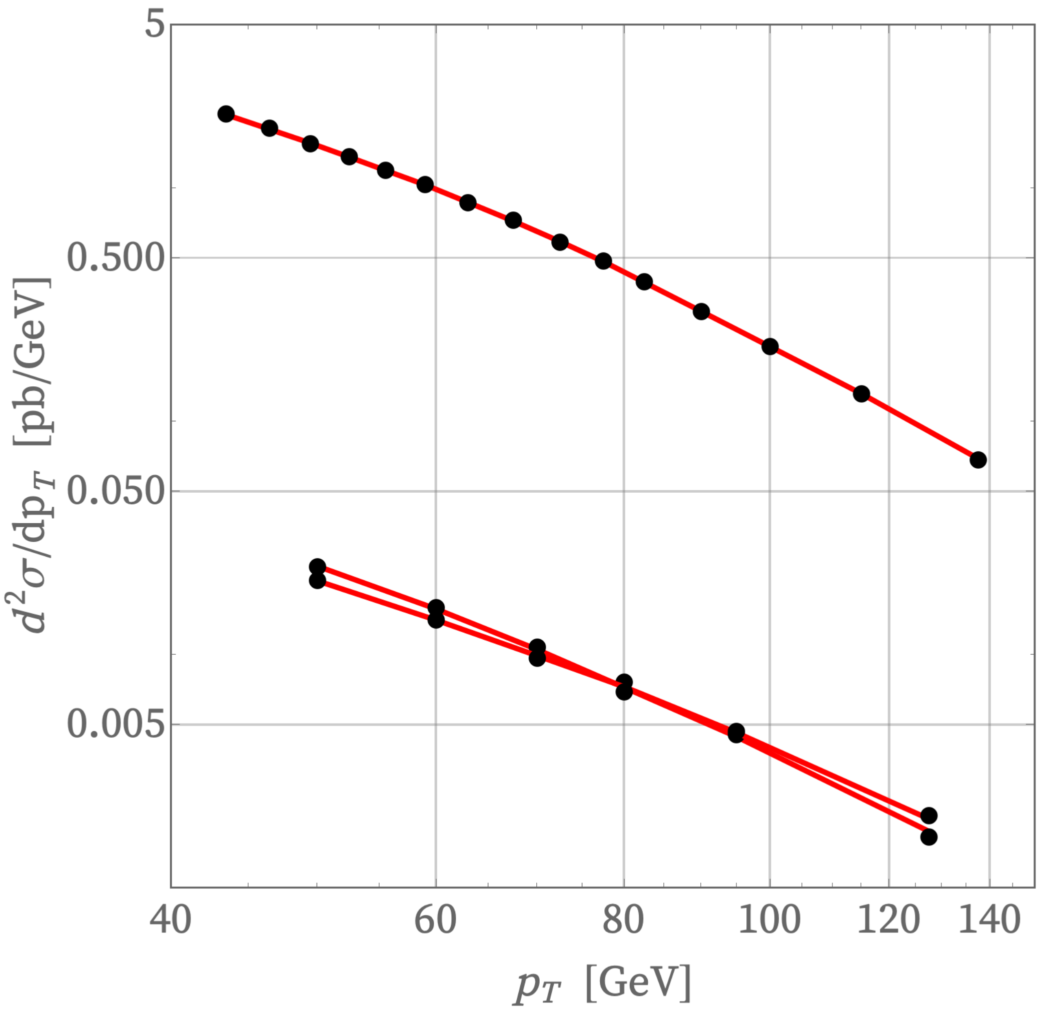
Low-mass Drell-Yan process as a function of pT; $m_{ll} \in \{46,66\}$ GeV



High-mass Drell-Yan process as a function of pT; $m_{ll} \in \{116,150\}$ GeV



Use of this data in the 'CT18' Global Analysis of QCD; show the data compared to theory $[\chi^2/N = 1.118]$



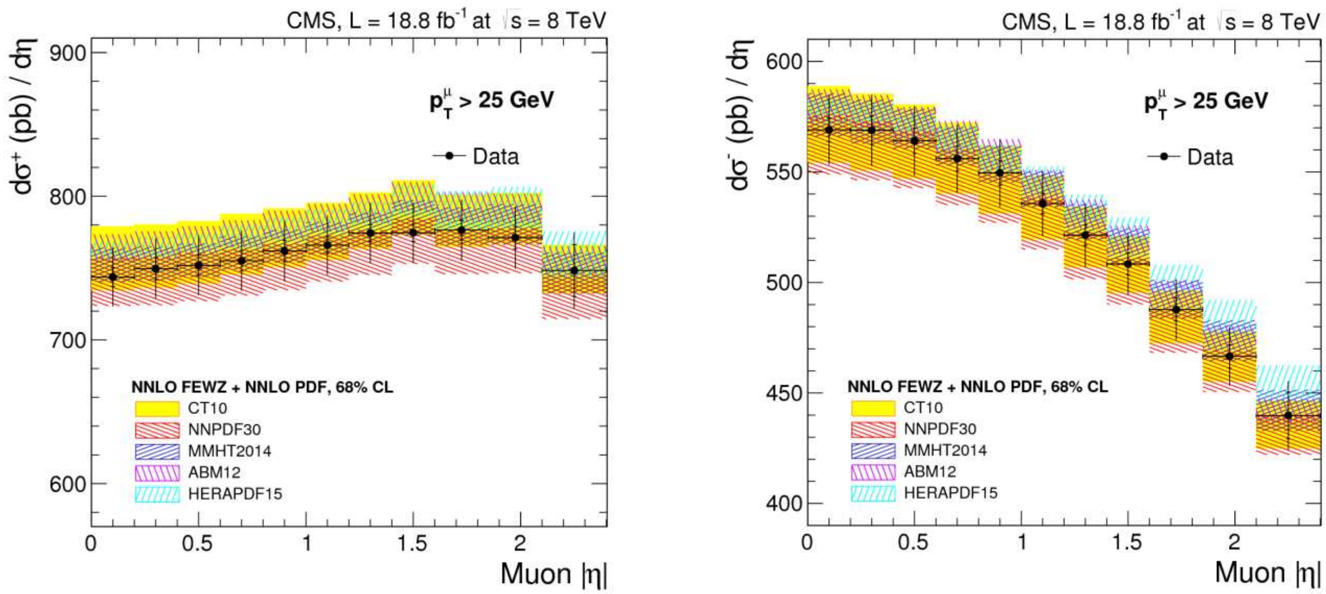
(#6) CMS 8 TeV
$W^{\pm}$ production
hep-ex/1603.01803

Information about the experiment

"Measurement of the differential cross section and charge asymmetry for inclusive pp → W± + X production at $\sqrt{s}$ = 8 TeV" (2016)

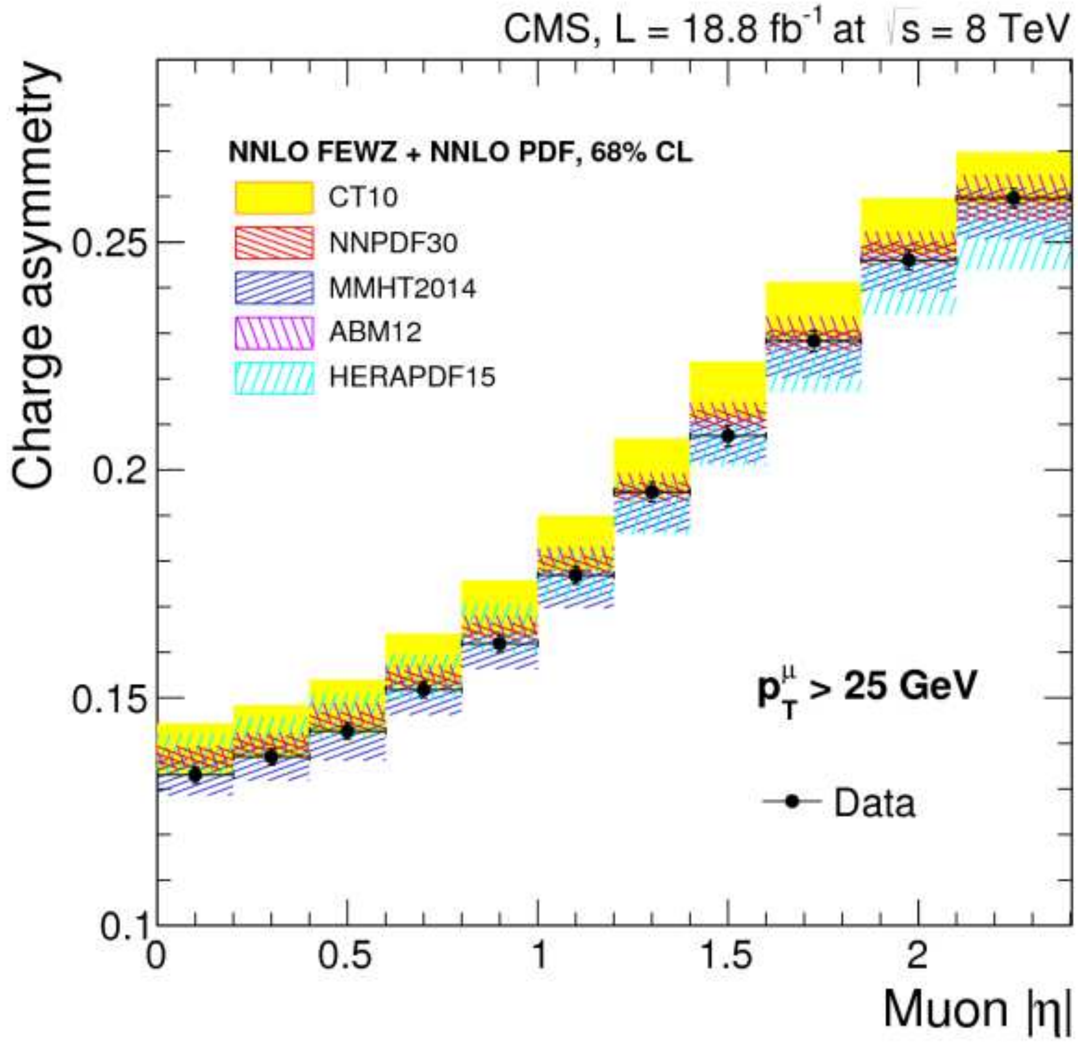
$N_{\mathrm{dpt}} = 33$; $N_{\mathrm{sys}} = 12$

Results

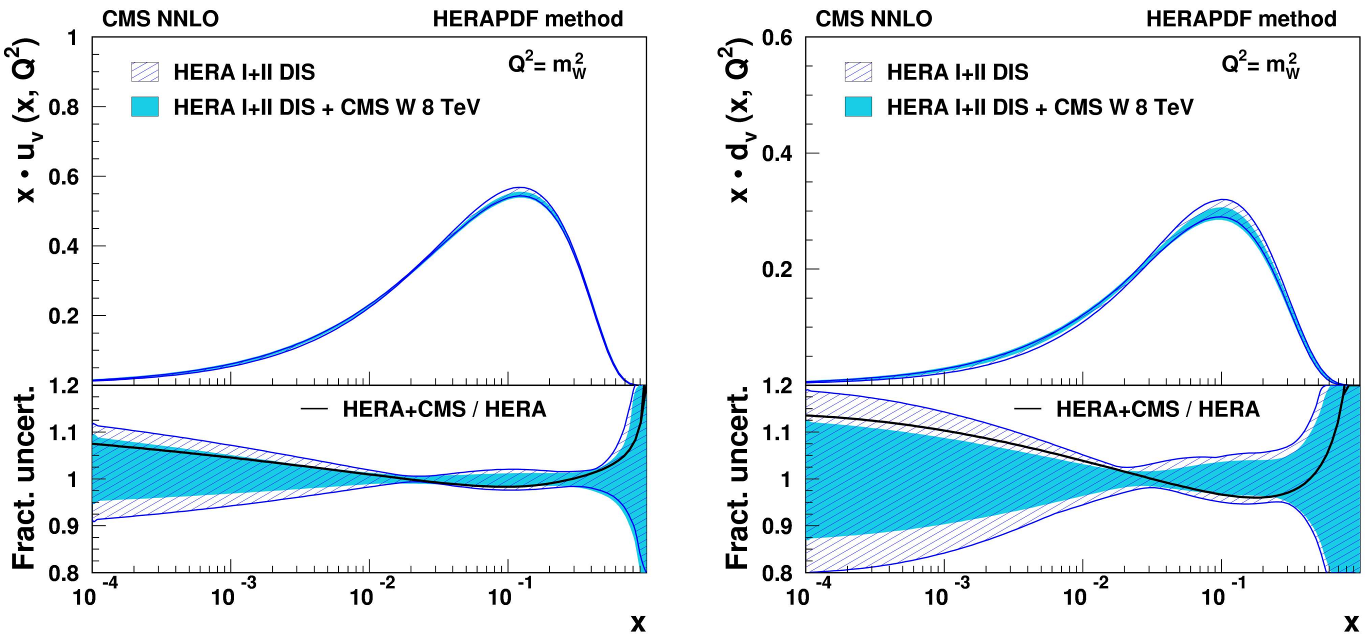


$$(\mathrm{d}\sigma / \mathrm{d}\eta_\mu)_+ \longrightarrow (\mathrm{d}\sigma / \mathrm{d}\eta_\mu)_-$$

and the charge asymmetry $A_\mu\,(\,\eta_\mu\,)$

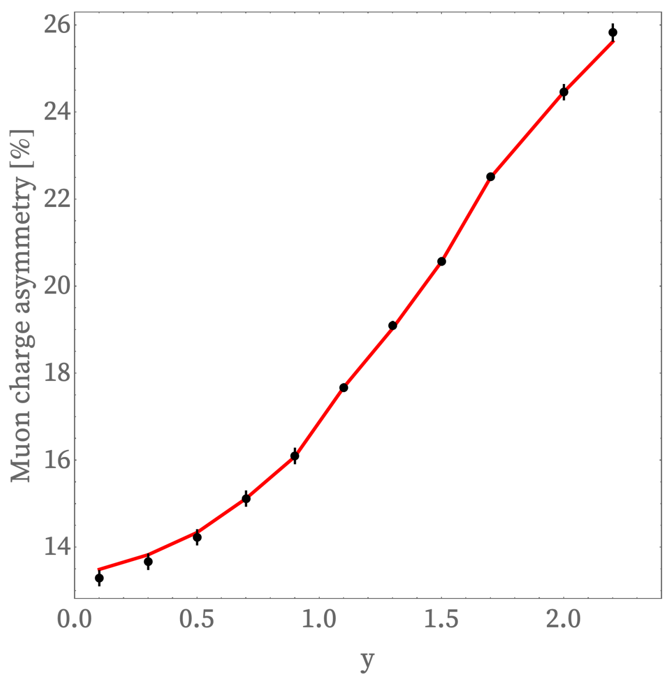


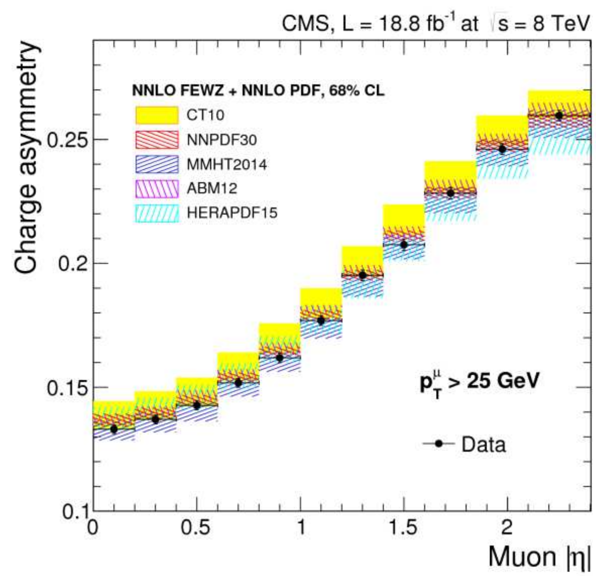
HERA + CMS parton distribution functions



$$u_{\text{valence}}(x) \longrightarrow d_{\text{valence}}(x)$$

Compare the data to the CT18 global analysis





$\chi^2/\mathrm{N} = 1.630$

(#7) LHCb 8 TeV

$Z \longrightarrow e+ e-$ production

hep-ex/1503.00963

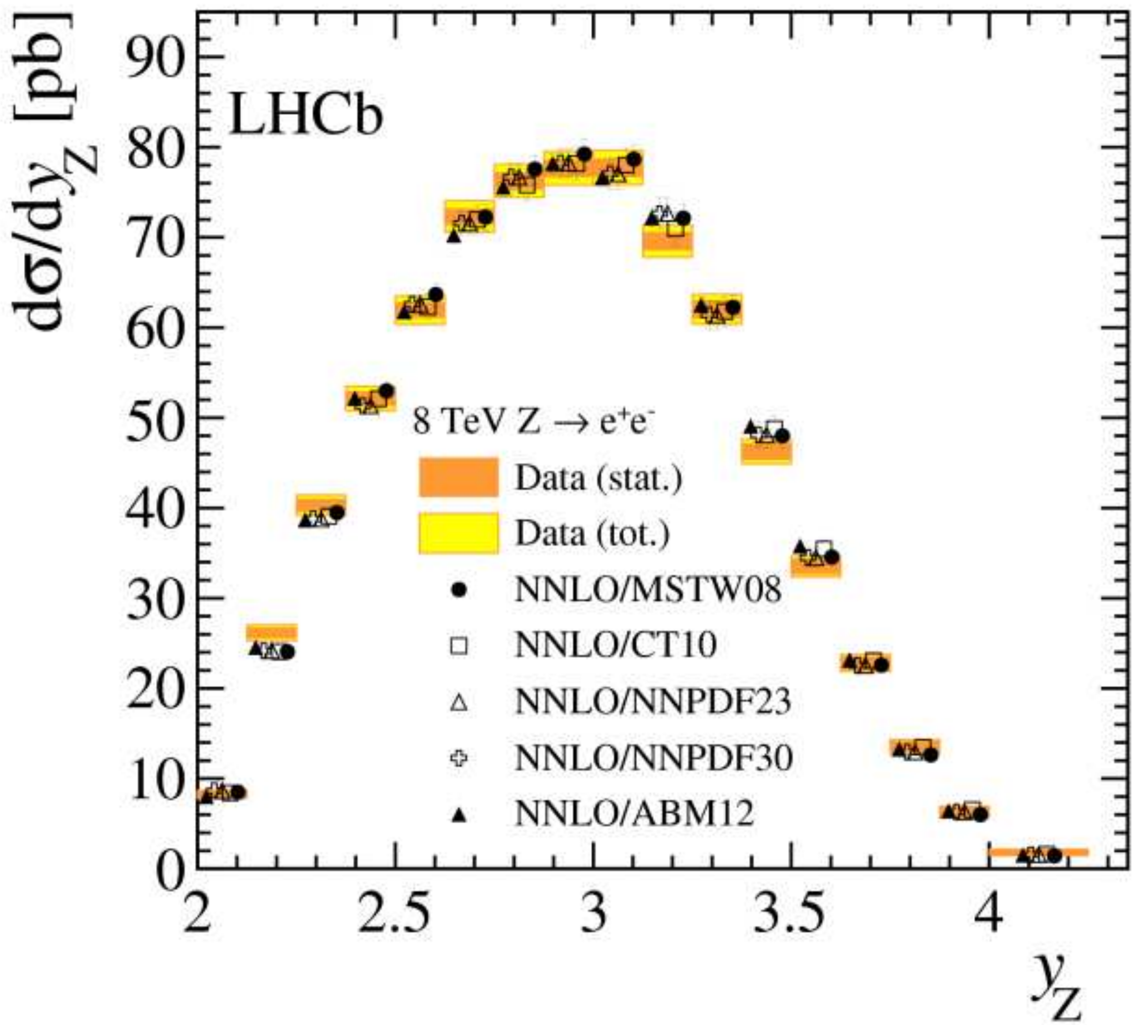
Information about the experiment

"Measurement of forward $Z \to e + e -$ production at $\sqrt{s}$ = 8 TeV" (2015)

$N_{\text{dpt}} = 17$; $N_{\text{sys}} = 1$

Results

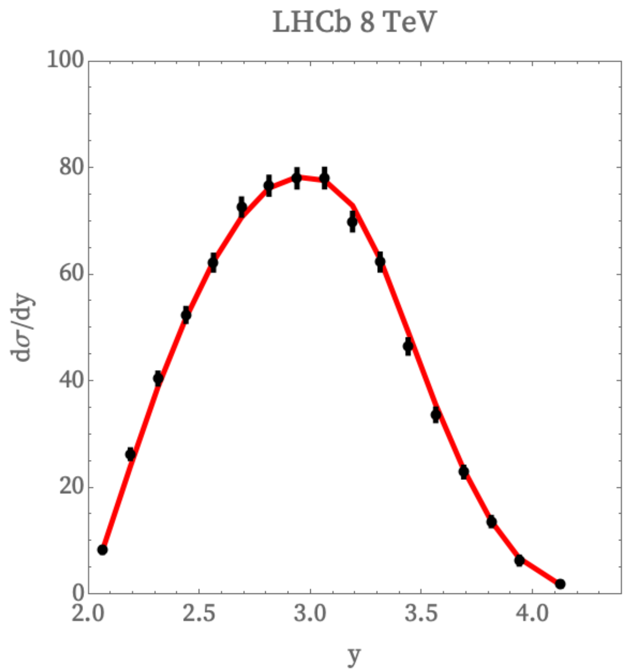
ρ3

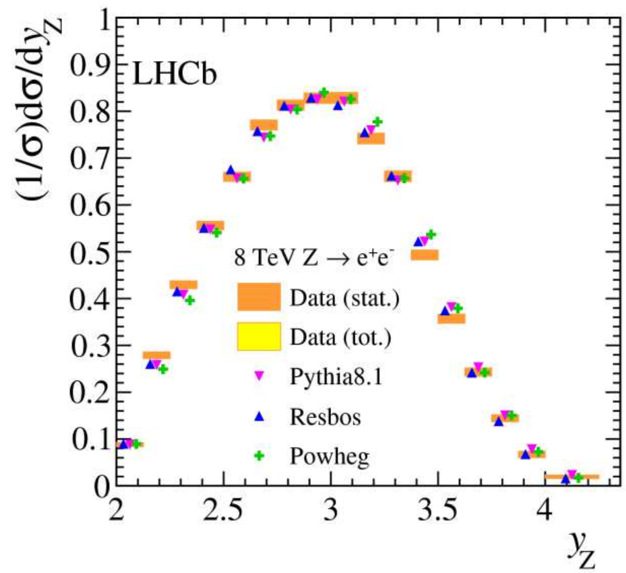


LHCb
dσ/dy_Z [pb]
y_Z
8 TeV Z → e⁺e⁻
Data (stat.)
Data (tot.)
NNLO/MSTW08
NNLO/CT10
NNLO/NNPDF23
NNLO/NNPDF30
NNLO/ABM12

Some data from this experiment are being used in the 'CT18' Global Analysis of QCD [$\chi^2/N = 1.519$]

ρ4





(#8) LHCb 8 TeV

W and Z forward production

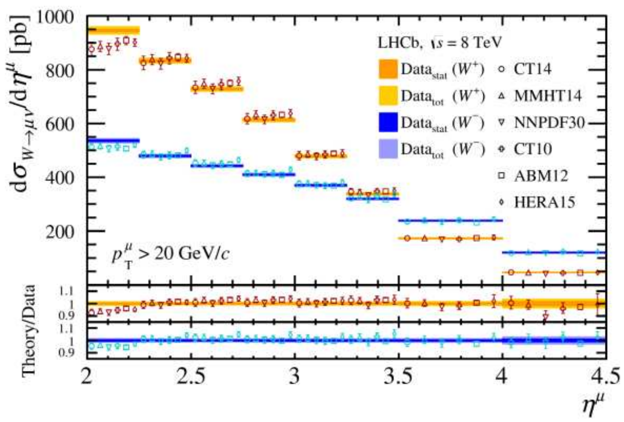
hep-ex/1512.08039

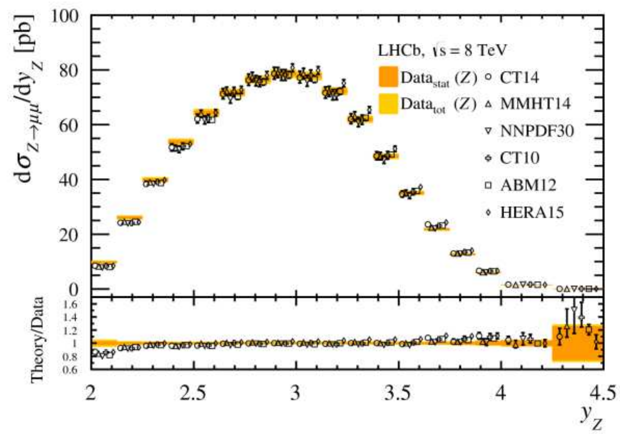
Information about the experiment

"Measurement of forward W and Z boson production in pp collisions at $\sqrt{s}$ = 8 TeV" (2016)

Ndpt = 34 ; $N_{\rm sys} = 9$

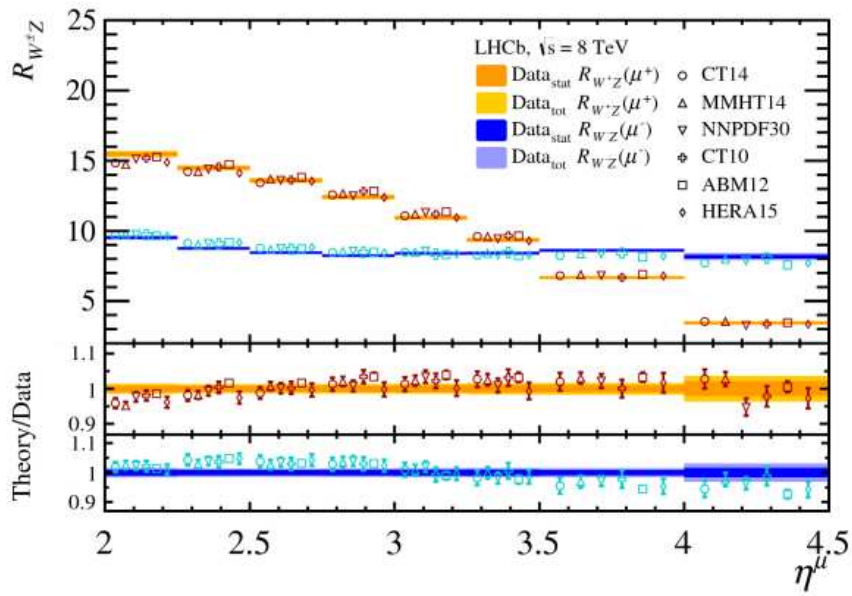
Results





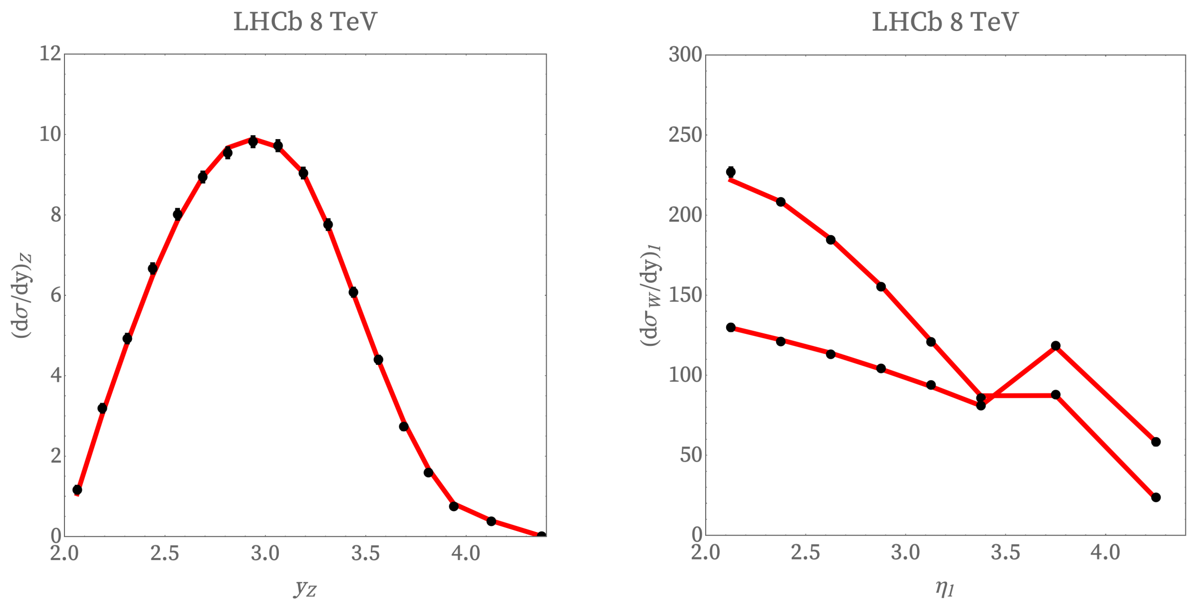
$$\mathrm{d}\sigma_W / \mathrm{d}\eta_\mu \quad \longrightarrow \quad \mathrm{d}\sigma_Z \,/\, \mathrm{d}y_Z$$

Ratio $W^{\pm} / Z^0$



LHCb, √s = 8 TeV
Data_stat R_W+Z(μ+)
Data_tot R_W+Z(μ+)
Data_stat R_W−Z(μ−)
Data_tot R_W−Z(μ−)
CT14
MMHT14
NNPDF30
CT10
ABM12
HERA15
R_W±Z
Theory/Data
η^μ

Use of this data in the ‘CT18’ Global Analysis of QCD



$$(\mathrm{d}\sigma/\mathrm{dy})_Z \quad \longrightarrow \quad (\mathrm{d}\sigma/\mathrm{d}\eta)_{W^\pm} \quad ; [\ \chi^2/N = 2.167\ ]$$