

PDF constraints using Vector Bosons at CMS

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on behalf of the



collaboration



Z- and W-boson production at LHC

theoretically well understood processes with clean signatures and high rates

→ used to calibrate the detector response in experiments

→ **probe different aspects of QCD calculations**

→ test of perturbative QCD (e.g. EW parameters, play a key role in understanding backgrounds for various processes, etc)

→ tune Monte Carlo generators

→ **provide constraints to Parton Distribution Functions (PDFs)**

→ probe different flavour combinations

→ potential to improve quark PDFs

Photon measurements: sensitivity to gluon PDF, tests of pQCD

(not covered in this talk)

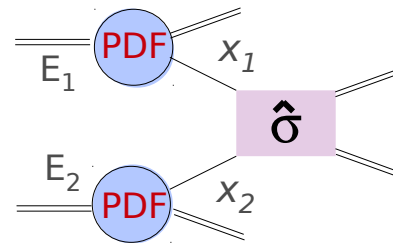
Introduction

Precise knowledge of the PDFs are essential for predictions at the LHC

→ one of main theory uncertainties in Higgs production, M_W measurement, etc.

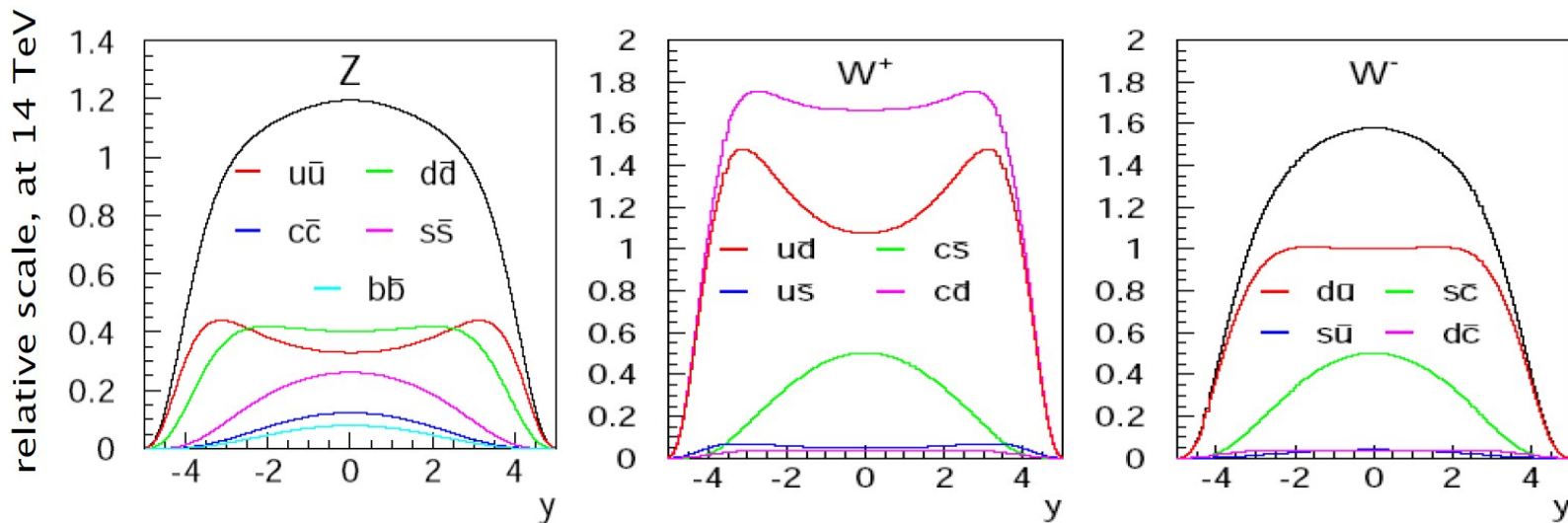
Z and W production at LHC

- probe different flavour combinations
- potential to improve quark PDFs

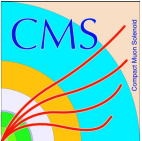


QCD factorisation:

$$\sigma \approx \hat{\sigma} \otimes \text{PDF}$$



→ u and d quarks dominate for W, all flavours contribute to Z



CMS DY Data Sensitive to PDFs (from Run I)

Main published CMS Vector Boson measurements sensitive to PDFs:

(older sets with 36 pb^{-1} are not shown here)

- Differential and double-differential Drell-Yan cross sections at $\sqrt{s} = 8 \text{ TeV}$
(measurement at 7 TeV [JHEP 12 \(2013\) 030](#)) [EPJC 75 \(2015\) 147](#)
→ 7 TeV data included into NNPDF3.0, MMHT14
 - Z boson differential cross section in q_T and y at $\sqrt{s} = 8 \text{ TeV}$
[Phys Lett B 749 \(2015\) 187](#)
 - W + charm production in pp collisions at $\sqrt{s} = 7 \text{ TeV}$
→ included into NNPDF3.0 [JHEP 02 \(2014\) 013](#)
 - Electron charge asymmetry in inclusive W production at $\sqrt{s} = 7 \text{ TeV}$
→ included into CT14, NNPDF3.0 [PRL 109 \(2012\) 111806](#)
 - Muon charge asymmetry in $pp \rightarrow WX$ production at $\sqrt{s} = 7 \text{ TeV}$ and an improved determination of light parton distribution functions
[PRD 90 \(2014\) 032004](#)
→ included into CT14, NNPDF3.0, ABMP15
- some of data sets already substituted with newer measurements (next slide)

Recent CMS DY Measurements (8 and 13 TeV)

- **Differential cross section and charge asymmetry for $pp \rightarrow WX$ production at $\sqrt{s} = 8$ TeV**
arXiv:1603.01803
- **Z + charm production in pp collisions at $\sqrt{s} = 8$ TeV**
CMS PAS SMP-15-009
- **Inclusive W and Z boson production cross sections at $\sqrt{s} = 13$ TeV**
CMS PAS SMP-15-004
- **Inclusive and differential Z boson production cross sections ($d\sigma/dy$, $d\sigma/dp_T$) at $\sqrt{s} = 13$ TeV**
CMS PAS SMP-15-011
- **Differential Drell-Yan cross section ($d\sigma/dm$) in pp collisions $\sqrt{s}=13$ TeV**
CMS PAS SMP-16-009
- **Transverse momentum spectra of weak vector bosons ($d\sigma/dp_T$) at $\sqrt{s} = 8$ TeV**
arXiv:1606.05864
- **Differential cross section for the production of a W ($\rightarrow \mu\nu$) boson in association with jets at $\sqrt{s} = 13$ TeV**
CMS PAS SMP-16-005
- **W boson production cross section in association with two b jets at $\sqrt{s} = 8$ TeV**
CMS PAS SMP-14-020



CMS W muon charge asymmetry at 8 TeV

W lepton charge asymmetry at LHC

- overall excess of W^+ over W^- due to presence of two valence u quarks in the proton
- probe valence quarks and PDFs ratios (u_v , d_v , d/u , d_v/u_v , $d\bar{u}/u\bar{u}$):

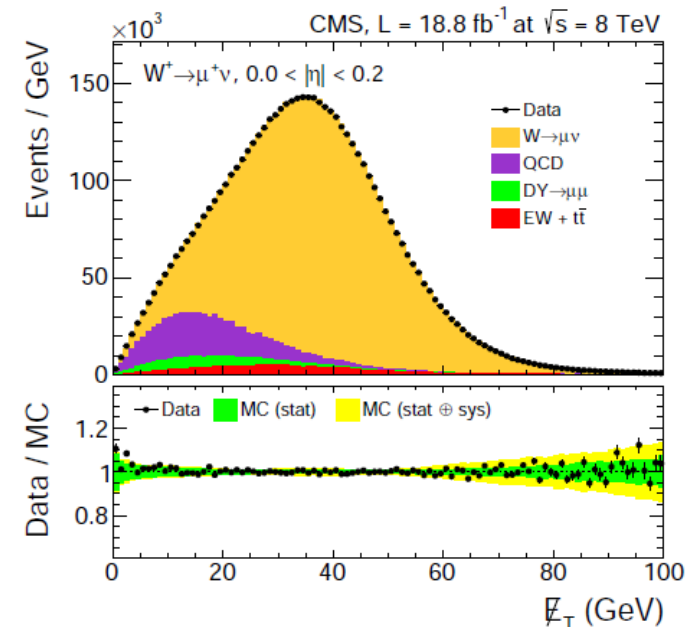
at LO:

$$A_W = \frac{W^+ - W^-}{W^+ + W^-} \approx \frac{u_v - d_v}{u_v + d_v + 2u_{sea}}$$

CMS W muon asymmetry measurement at $\sqrt{s} = 8$ TeV with $\int L = 18.8 \text{ fb}^{-1}$

arXiv:1603.01803, accepted by EPJC

- with muon $P_T > 25$ GeV and pseudorapidity $|\eta| < 2.4$
- about 61M W^+ and 45M W^- candidate events





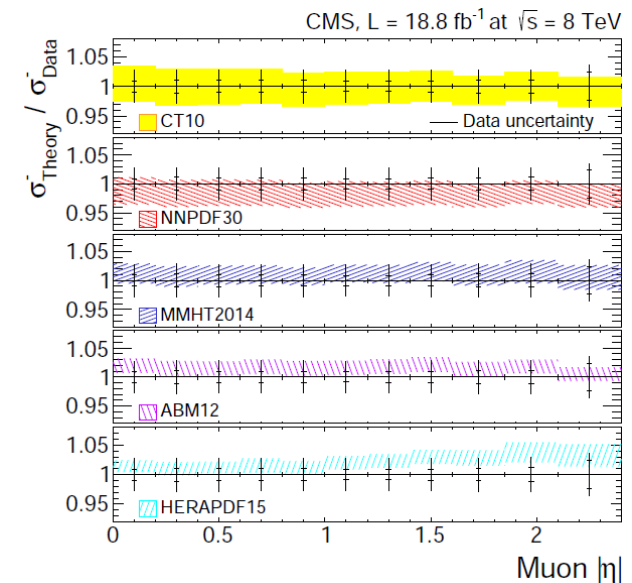
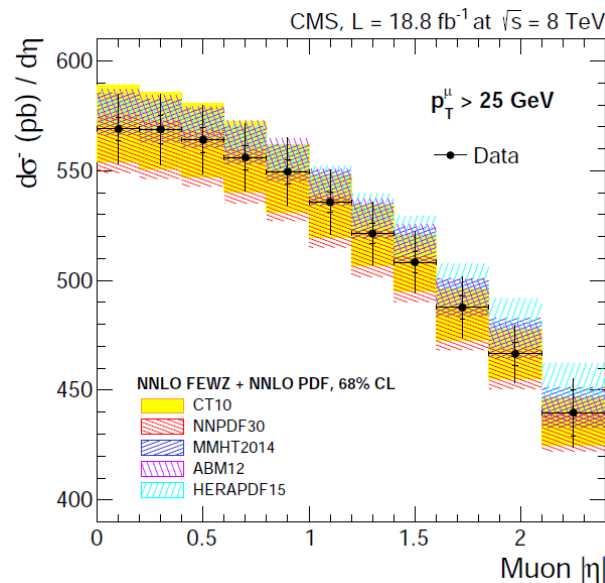
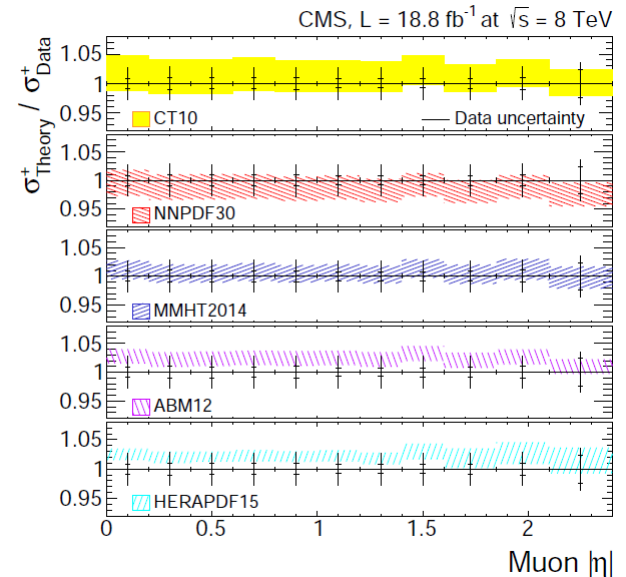
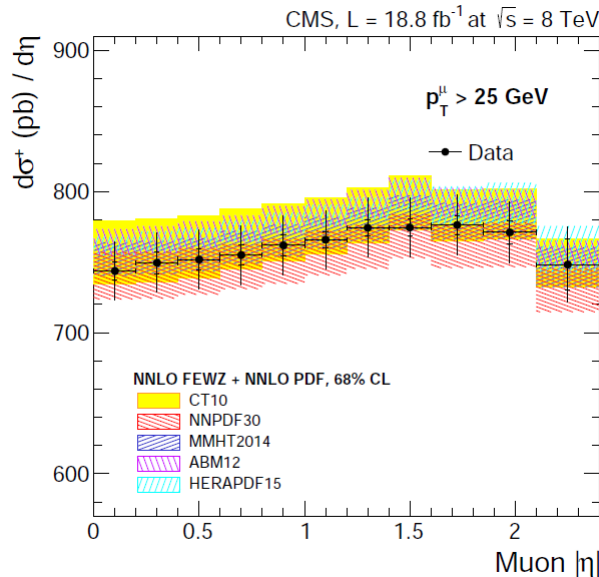
CMS W^+ and W^- distributions

arXiv:1603.01803

→ separate W^+ and W^- distributions provided

→ compared with theory predictions (FEWZ) at NNLO using different PDFs

→ good agreement predictions obtained with all PDFs



(systematic correlations provided in the paper)

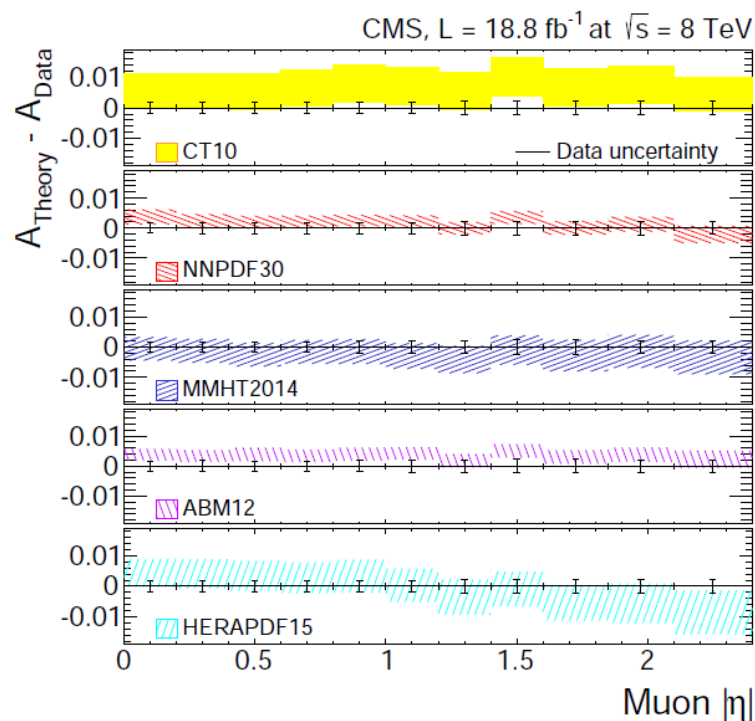
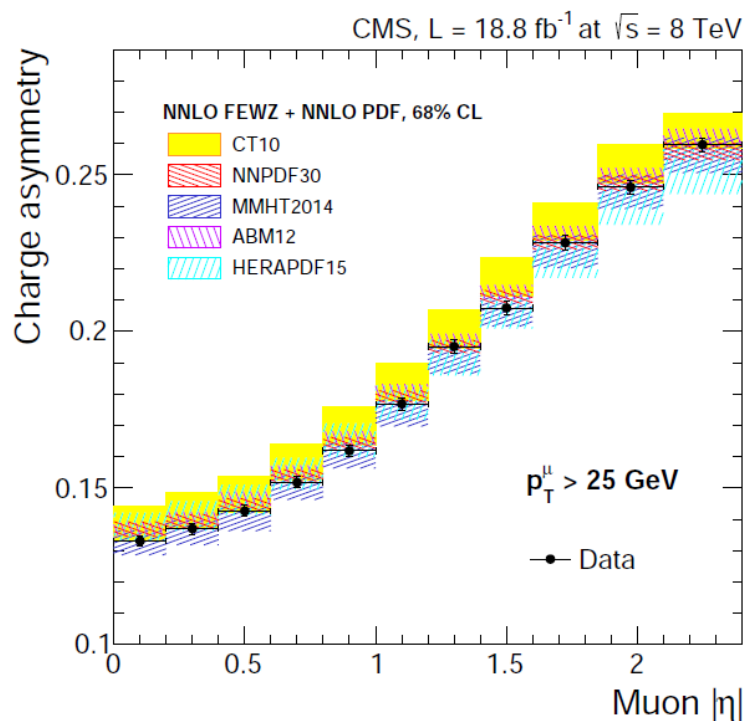


CMS W muon charge asymmetry at 8 TeV

arXiv:1603.01803

Muon charge asymmetry measurement as a function of muon pseudorapidity

→ compared with theory predictions (FEWZ) at NNLO using different PDFs



A NNLO QCD analysis performed with the CMS W muon asymmetry data

QCD analysis at NNLO performed using xFitter www.xfitter.org

→ parton evolution in Q^2 via DGLAP equations as implemented in QCDNUM

[Comp.Phys.Com.182:490,2011](#)

Data: HERA I+II combined inclusive DIS data [EPJC 75 \(2015\) 580](#)

→ uncertainty treatment follows HERAPDF1.0 prescription

CMS muon asymmetry data ($P_T^l > 25$ GeV)

→ systematic correlations included via covariance matrix

Theory: predictions from APPLGRID files obtained with MCFM (NLO) and NNLO corrections obtained with k-factors (FEWZ)

Starting scale $Q_0^2 = 1.9 \text{ GeV}^2$

$m_c = 1.43 \text{ GeV}$, $m_b = 4.5 \text{ GeV}$

heavy flavour scheme: general mass variable flavour scheme RT

scale $\mu_R^2 = \mu_F^2 = Q^2$

strong coupling $\alpha_s = 0.118$

→ *variation of parameters later considered in the PDF uncertainties*

PDF parametrisation at the starting scale ($Q_0^2=1.9 \text{ GeV}^2$):

Optimal parametrisation form determined through a *parametrisation scan* (adding additional parameters one-by-one to the basic form until χ^2 is not improving anymore)

“13p” fit: $xg(x) = A_g x^{B_g} (1-x)^{C_g} (1 + D_g x),$

$$xu_v(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + E_{u_v} x^2),$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}},$$

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}} (1 + E_{\bar{U}} x^2),$$

$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}},$$

A: normalisation
B: small x behavior
C: $x \rightarrow 1$ shape

Additional constraints applied:

$$B_{\bar{U}} = B_{\bar{D}}$$

$$A_{\bar{U}} = A_{\bar{D}}(1 - f_s)$$

$$x\bar{U} = x\bar{u} (+ x\bar{c})$$

$$x\bar{D} = x\bar{d} + x\bar{s} (+ x\bar{b})$$

$$x\bar{s} = f_s x\bar{D} \text{ with}$$

$$f_s = x\bar{s} / (x\bar{d} + x\bar{s}) = 0.31 + 0.08 \text{ (as determined in$$

EPJC 63 (2009) 189)

→ variation of parametrisation (addition of parameters) later considered in the PDF uncertainties

Resulting χ^2 obtained in the PDF fit with CMS W muon asymmetry data:

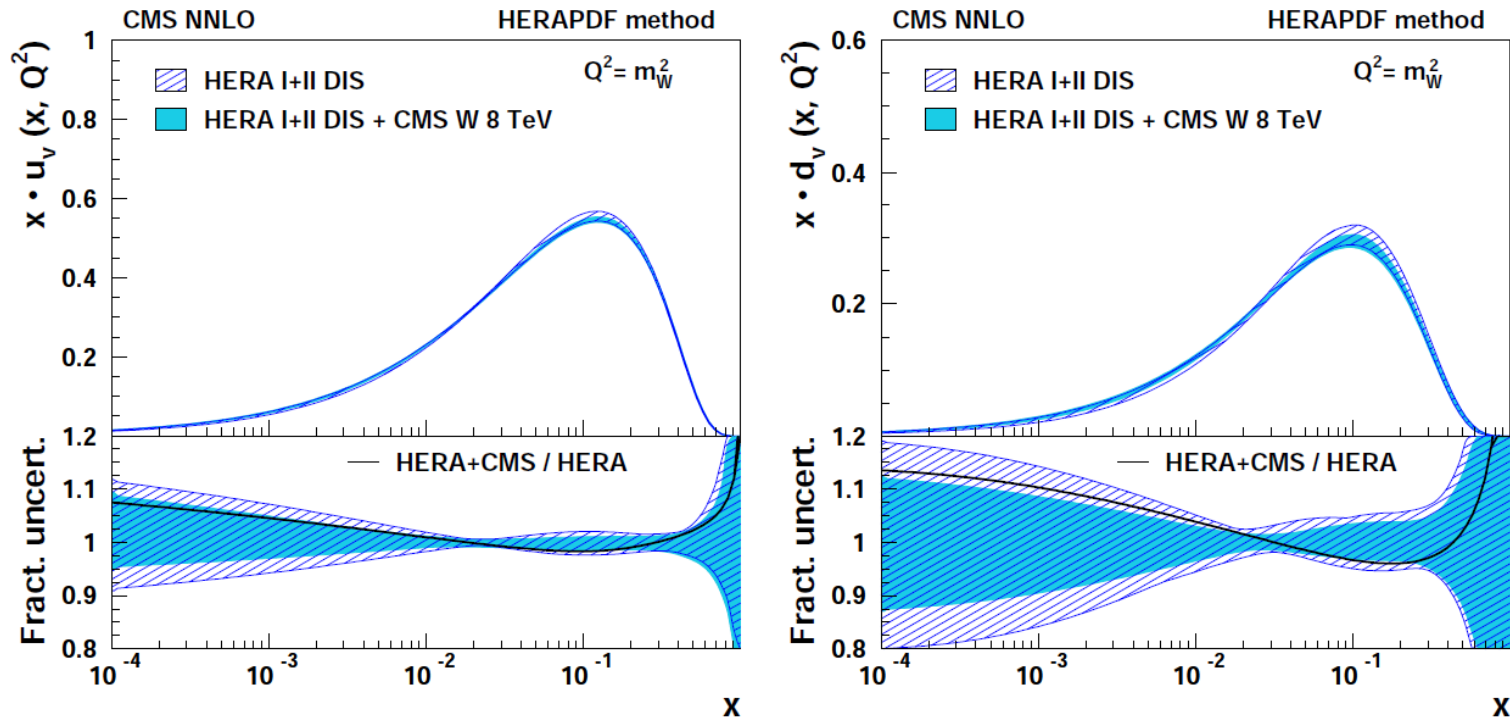
Data sets	Partial χ^2/n_{dp}
HERA1+2 neutral current, e^+p , $E_p = 920$ GeV	440/377
HERA1+2 neutral current, e^+p , $E_p = 820$ GeV	69/70
HERA1+2 neutral current, e^+p , $E_p = 575$ GeV	214/254
HERA1+2 neutral current, e^+p , $E_p = 460$ GeV	210/204
HERA1+2 neutral current, e^-p , $E_p = 920$ GeV	218/159
HERA1+2 charged current, e^+p , $E_p = 920$ GeV	46/39
HERA1+2 charged current, e^-p , $E_p = 920$ GeV	50/42
CMS $W^\pm$ muon charge asymmetry $\mathcal{A}(\eta\mu)$, $\sqrt{s} = 8$ TeV	3/11
Correlated χ^2	141
Global χ^2/n_{dof}	1391/1143

all correlated χ^2 part is from the HERA data

→ good χ^2 observed for CMS data, higher values for HERA data are consistent with the results obtained in HERAPDF2.0 analysis [EPJC 75 \(2015\) 580](#)

CMS W muon charge asymmetry measurement: QCD analysis at NNLO

with HERA I+II combined DIS data [EPJC 75 \(2015\) 580](#)



error bands represent total uncertainties, (experimental, model and parametrisation uncertainties)

Change of u and d valence quark PDF shape and improved constraints

CMS Z+charm measurement at 8 TeV

CMS PAS SMP-15-009

New measurement of the production cross section of a Z boson and at least one jet originating from a c-quark

→ can address question of the intrinsic charm quark component in the proton

8 TeV data with $\int \mathcal{L} = 19.7 \pm 0.5 \text{ fb}^{-1}$

→ Z-boson candidates are identified through their decay into a pair of electrons or muons

→ heavy flavour jets in the kinematic region $p_T^{\text{jet}} > 25 \text{ GeV}$, $|\eta^{\text{jet}}| < 2.5$

Measured the inclusive Z+c cross section and Z+c/Z+b cross sections ratio:

$$\sigma(\text{pp} \rightarrow \text{Z} + \text{c} + \text{X}) \times \mathcal{B}(\text{Z} \rightarrow \ell^+ \ell^-) = 8.6 \pm 0.5 \text{ (stat.)} \pm 0.7 \text{ (syst.) pb}$$

in agreement with prediction (MadGraph, LO): $8.14 \pm 0.03 \text{ (stat)} \pm 0.25 \text{ (PDF) pb}$

$$\sigma(\text{pp} \rightarrow \text{Z} + \text{c} + \text{X}) / \sigma(\text{pp} \rightarrow \text{Z} + \text{b} + \text{X}) = 2.0 \pm 0.2 \text{ (stat.)} \pm 0.2 \text{ (syst.)}$$

prediction (MADGRAPH5 AMC@NLO): $9.47 \pm 0.04 \text{ (stat)} \pm 0.15 \text{ (PDF)} \pm 0.50 \text{ (scales)}$



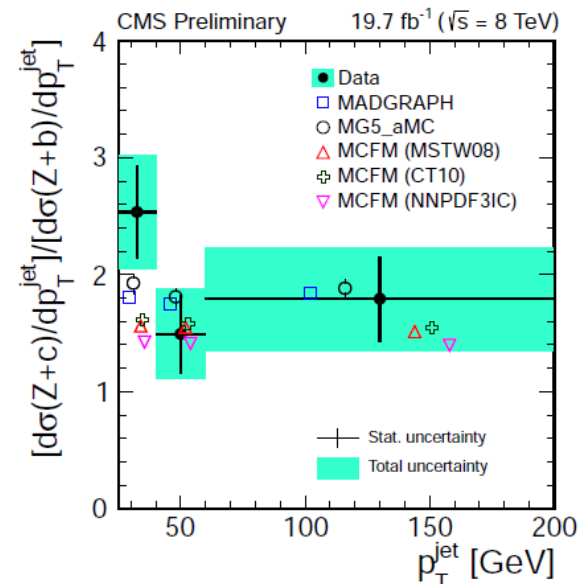
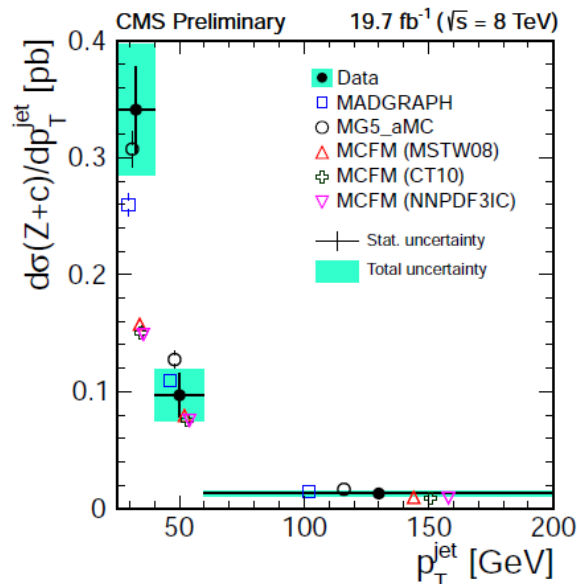
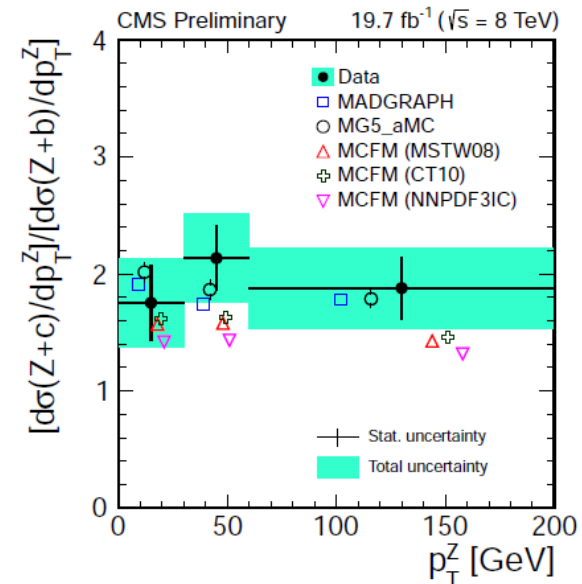
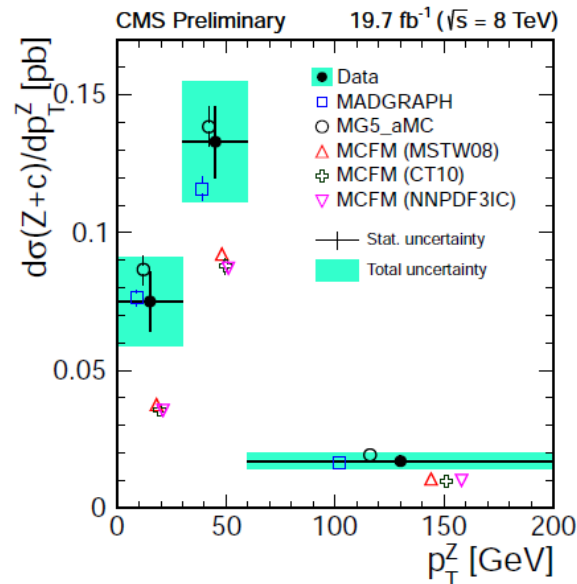
CMS Z+charm measurement at 8 TeV

CMS PAS SMP-15-009

Theoretical predictions (NLO) obtained with the MCFM using the NLO PDF sets **MSTW08**, **CT10**, **NNPDF3IC** and **NNPDF3nIC**

→ all predictions are smaller than measured cross sections

→ no significant differences in the predictions using either **NNPDF3IC** or **NNPDF3nIC** PDFs



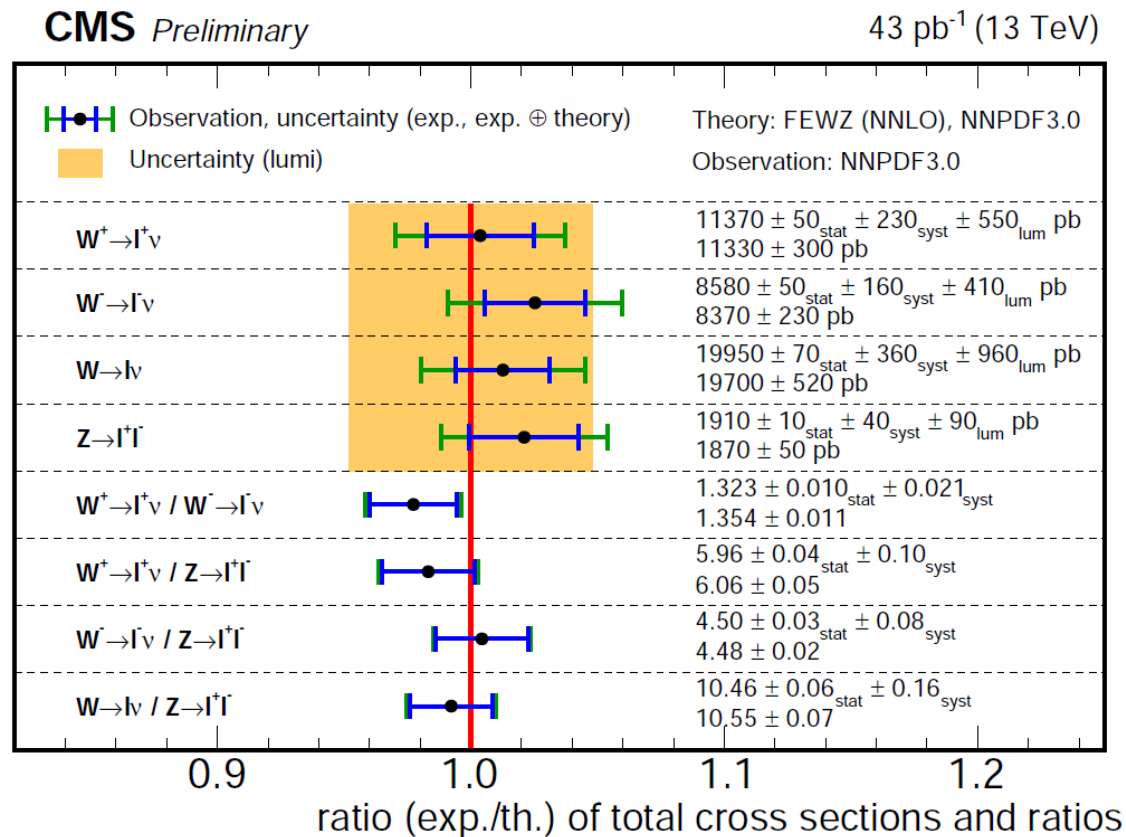


CMS inclusive W and Z production at 13 TeV

New 13 TeV measurement of W and Z boson cross sections with $\int L = 43 \pm 2 \text{ pb}^{-1}$

- measurement performed in the electron and muon decay channels (dilepton mass range of 60 to 120 GeV)
- inclusive cross sections and ratios

CMS PAS SMP-15-004

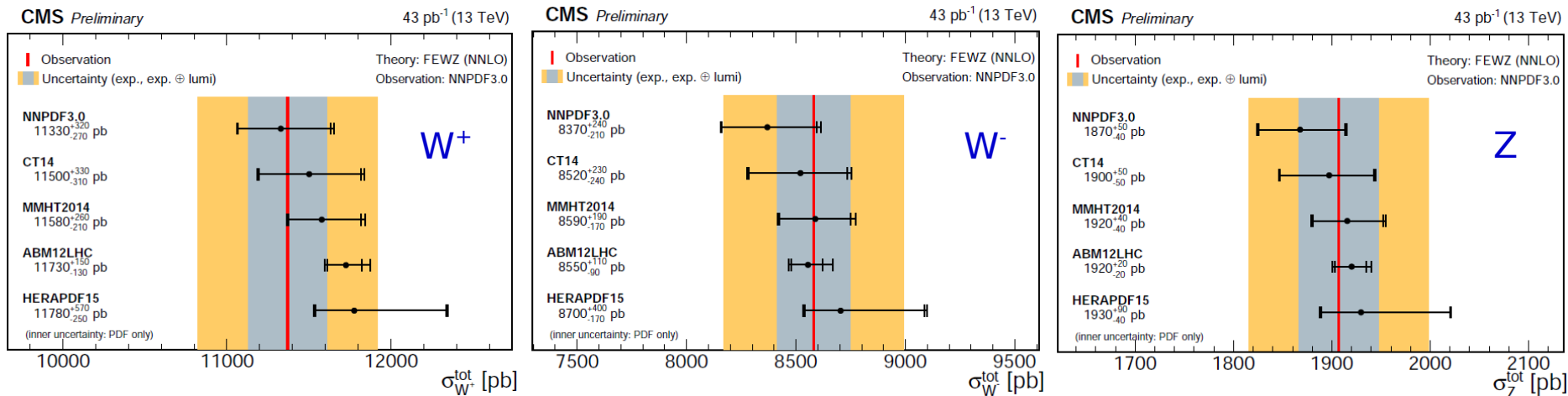




W and Z cross sections at 13 TeV

CMS PAS SMP-15-004

Dominant systematic uncertainty: luminosity

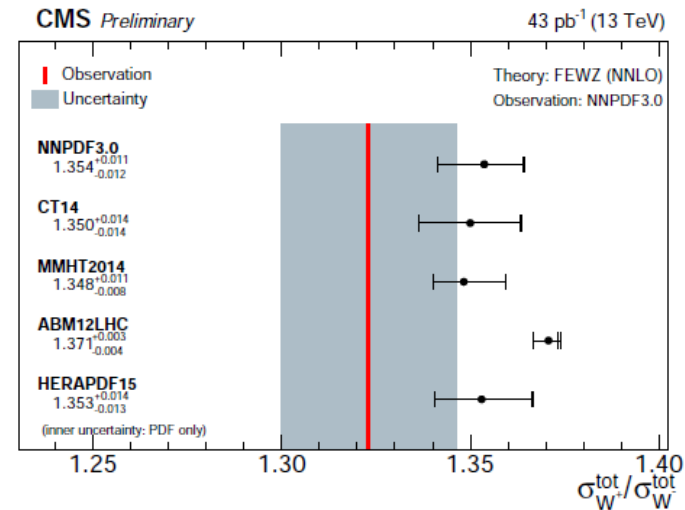
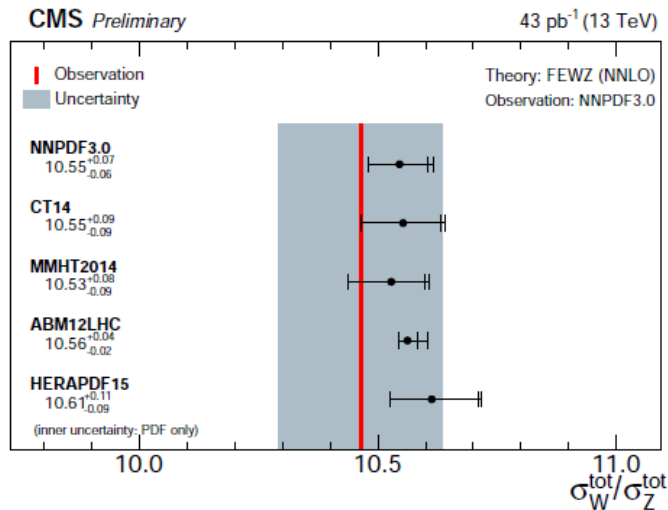
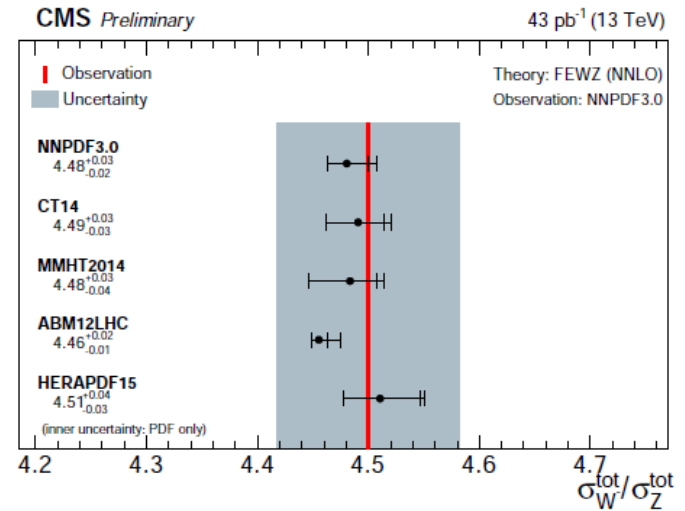
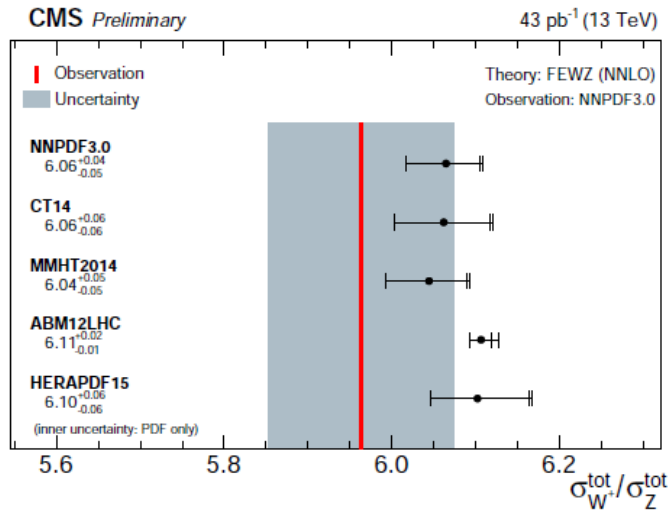


Compared with FEWZ (NNLO QCD and NLO order EW calculations) with various PDFs:

	NNPDF3.0	CT14	MMHT2014	ABM12LHC	HERAPDF15
$\sigma_{W^+}^{tot}$ [pb]	11330^{+320}_{-270}	11500^{+330}_{-310}	11580^{+260}_{-210}	11730^{+150}_{-130}	11780^{+570}_{-250}
$\sigma_{W^-}^{tot}$ [pb]	8370^{+240}_{-210}	8520^{+230}_{-240}	8590^{+190}_{-170}	8550^{+110}_{-90}	8700^{+400}_{-170}
σ_W^{tot} [pb]	19700^{+560}_{-470}	20020^{+560}_{-550}	20170^{+430}_{-390}	20280^{+260}_{-220}	20480^{+960}_{-410}
σ_Z^{tot} [pb]	1870^{+50}_{-40}	1900^{+50}_{-50}	1920^{+40}_{-40}	1920^{+20}_{-20}	1930^{+90}_{-40}
$\sigma_{W^+}^{tot} / \sigma_{W^-}^{tot}$	$1.354^{+0.011}_{-0.012}$	$1.350^{+0.014}_{-0.014}$	$1.348^{+0.011}_{-0.008}$	$1.371^{+0.003}_{-0.004}$	$1.353^{+0.014}_{-0.013}$
$\sigma_{W^+}^{tot} / \sigma_Z^{tot}$	$6.06^{+0.04}_{-0.05}$	$6.06^{+0.06}_{-0.06}$	$6.04^{+0.05}_{-0.05}$	$6.11^{+0.02}_{-0.01}$	$6.10^{+0.06}_{-0.06}$
$\sigma_{W^-}^{tot} / \sigma_Z^{tot}$	$4.48^{+0.03}_{-0.02}$	$4.49^{+0.03}_{-0.03}$	$4.48^{+0.03}_{-0.04}$	$4.46^{+0.02}_{-0.01}$	$4.51^{+0.04}_{-0.03}$
$\sigma_W^{tot} / \sigma_Z^{tot}$	$10.55^{+0.07}_{-0.06}$	$10.55^{+0.09}_{-0.09}$	$10.53^{+0.08}_{-0.09}$	$10.56^{+0.04}_{-0.02}$	$10.61^{+0.11}_{-0.09}$

W and Z cross section ratios at 13 TeV

CMS PAS SMP-15-004



The measured ratio values agree with theory predictions at NNLO
W⁺ cross section tends to be slightly below the predictions

CMS differential Z measurement at 13 TeV

CMS PAS SMP-15-011

Inclusive and differential Z production at 13 TeV in the μ final state with $\int \mathcal{L} = 2.3 \text{ fb}^{-1}$

Inclusive cross section (in the dilepton mass range of 60 to 120 GeV) and comparison with NNLO predictions (FEWZ) using different PDFs

$$\sigma(pp \rightarrow ZX) \times \mathcal{B}(Z \rightarrow \ell^+ \ell^-) = 1870 \pm 2 \text{ (stat)} \pm 35 \text{ (syst)} \pm 51 \text{ (lumi)} \text{ pb}$$

	$\sigma_Z^{\text{tot}} [\text{pb}]$
NNPDF3.0	1870^{+50}_{-40}
CT14	1900^{+50}_{-50}
MMHT2014	1920^{+40}_{-40}
ABM12LHC	1920^{+20}_{-20}
HERAPDF15	1930^{+90}_{-40}

Inclusive and **differential** Z production at 13 TeV in the μ final state with $\int \mathcal{L} = 2.3 \text{ fb}^{-1}$

- measurement as a function of p_T , angular variable ϕ^* , $y^{\mu+\mu-}$ and $p_T^{\mu+\mu-}$
- quark-gluon scattering dominates at high p_T (low p_T range is governed by ISR and the transverse momentum of the initial-state parton inside the proton)
- angular variable ϕ^* is expressed via pseudo-rapidity of muon pair

$$\phi_\eta^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \cdot \sin(\theta_\eta^*) \quad \cos(\theta_\eta^*) = \tanh\left(\frac{\eta^- - \eta^+}{2}\right)$$

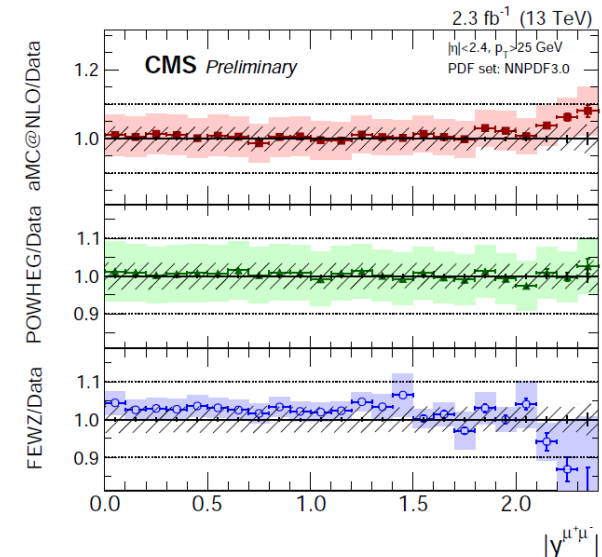
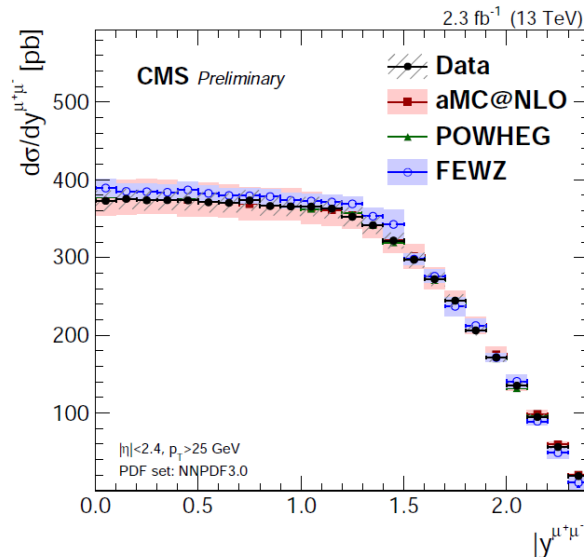
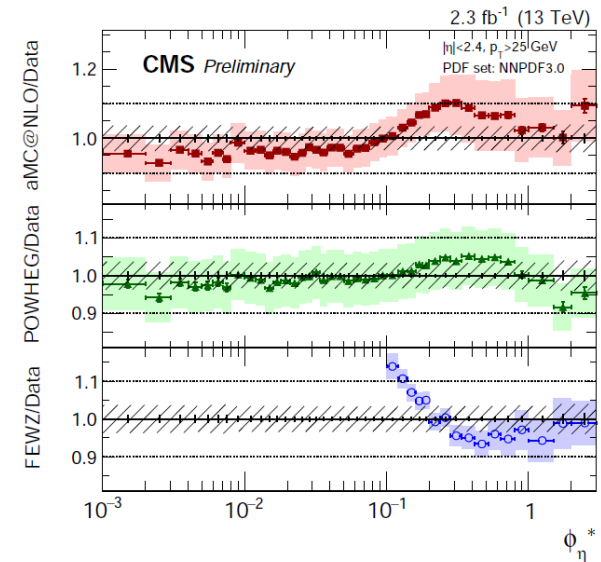
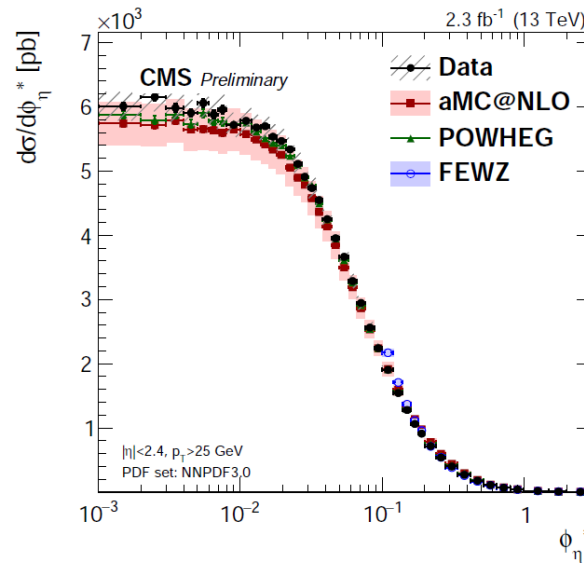
probes Z boson p_T but depends on direction of muon → smaller exp. uncertainty

CMS differential Z measurement at 13 TeV

CMS PAS SMP-15-011

Data compared to
MADGRAPH5_AMC@NLO,
POWHEG, and FEWZ

→ no generator is able to
describe the data in all of
the studied phase-space



W- and Z-boson production measurements at CMS

- provide valuable input and constraints to PDFs
- used by many PDF fitting groups (7 TeV data)
- many new measurements (8 and 13 TeV) available
- will provide further constraints to PDFs
 - illustration: CMS W muon asymmetry data at 8 TeV
- also can probe other QCD and EW aspects (e.g. boson polarisation, A_{FB} asymmetry, angular coefficients, MC tuning, ..)



Back-up slides

Strange quark density determination

Strange quark density in the proton is still poorly known

→ mainly constrains come from fixed target data (NuTeV, HERMES, NOMAD)

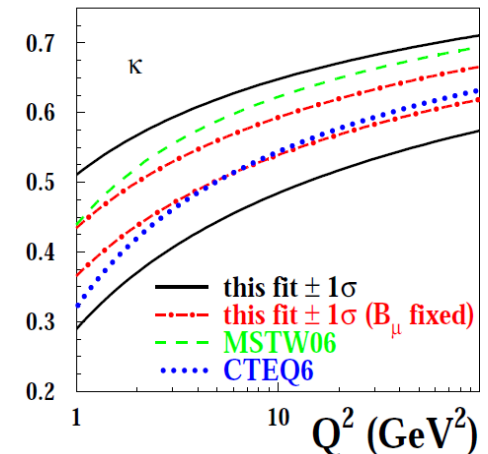
Nucl.Phys. B876(2013) 339

NOMAD measurement

$$K_s(20 \text{ GeV}^2) = 0.59 \pm 0.019$$

$$\kappa_s(Q^2) = \frac{\int_0^1 x [\bar{s}(x, Q^2) + s(x, Q^2)] dx}{\int_0^1 x [\bar{u}(x, Q^2) + \bar{d}(x, Q^2)] dx}$$

Phys. Lett. B 675, 433 (2009)



→ LHC Z,W and W+charm data sensitive to strange quark density

The differential ATLAS $W^\pm$, Z data used to measure strange quark density

→ data suggest that light quark sea at low x is flavor symmetric

Phys.Rev.Lett.109(2012)012001

$$r_s = 0.5(s + \bar{s})/\bar{d} = 1.00 \pm 0.20_{\text{exp}} \pm 0.07_{\text{mod}} {}^{+0.10}_{-0.15}_{\text{par}} {}^{+0.06}_{-0.07} \alpha_s \pm 0.08_{\text{th}} \quad \text{at } Q_0^2 \text{ and } x = 0.023$$

→ same results confirmed by the ATLAS W+charm data (obtained from the χ^2 minimisation procedure)

arXiv:1402:6263

$$r_s = 0.96 {}^{+0.16}_{-0.18} {}^{+0.21}_{-0.24} \quad \text{at } Q^2 = 1.9 \text{ GeV}^2$$



W+charm measurement at CMS

W+charm data → direct sensitivity to the strange quark

Identification:

→ W decays to charged leptons (e or μ) and neutrino

→ c: charm-quark jets with $p_{\text{jet}}^T > 25 \text{ GeV}$, $|\eta_{\text{jet}}| < 2.5$

jets identified: secondary vertex $D^+ \rightarrow K^- \pi^+ \pi^+$ ($D^- \rightarrow K^+ \pi^- \pi^-$)

$D^{*+}(2010) \rightarrow D^0 \pi^+$ ($D^{*-}(2010) \rightarrow \bar{D}^0 \pi^-$)

$D^0 \rightarrow K^- \pi^+$ ($\bar{D}^0 \rightarrow K^+ \pi^-$)

arXiv:1310.1138

semileptonic decay with well identified muon

Background subtraction:

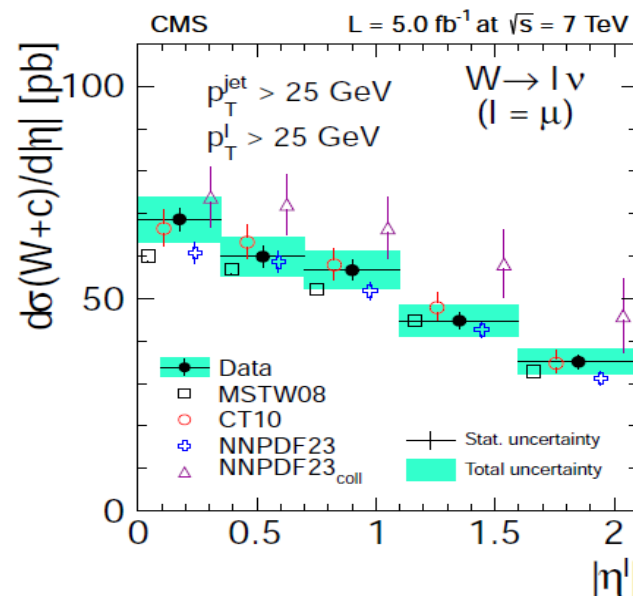
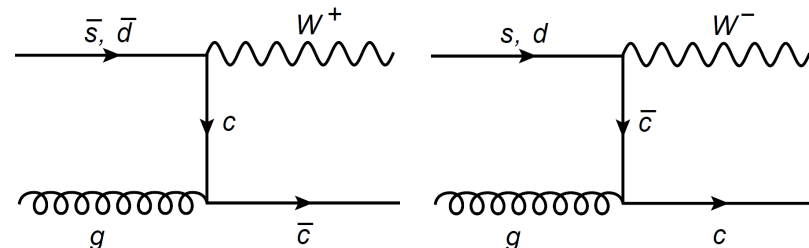
perform by subtracting the Same Sign (SS) from the Opposite Sign (OS) distributions

Total and differential cross sections

$p_{\text{jet}}^T > 25 \text{ GeV}$ ($W \rightarrow \mu \nu$)

$p_{\text{jet}}^T > 35 \text{ GeV}$ ($W \rightarrow \mu \nu$, $W \rightarrow e \nu$)

Ratios $(W^+ + c\bar{c})/(W^- + c)$





Parametrisation

PDF parametrisation at the starting scale ($Q^2_0=1.9 \text{ GeV}^2$):

“13p”:

$$xg(x) = A_g x^{B_g} \cdot (1-x)^{C_g} - A'_g x^{B'_g} \cdot (1-x)^{C'_g},$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}} \cdot (1-x)^{C_{u_v}} \cdot (1 + E_{u_v} x^2),$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}} \cdot (1-x)^{C_{d_v}},$$

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} \cdot (1-x)^{C_{\bar{U}}},$$

$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} \cdot (1-x)^{C_{\bar{D}}}.$$

A: normalisation
B: small x behavior
C: $x \rightarrow 1$ shape

$$x\bar{U} = x\bar{u} (+ x\bar{c})$$

$$x\bar{D} = x\bar{d} + x\bar{s} (+ x\bar{b})$$

$$x\bar{s} = f_s x\bar{D} \text{ with}$$

$$f_s = x\bar{s} / (x\bar{d} + x\bar{s}) = 0.31$$

“15p” or
“free-s”:

$$xg(x) = A_g x^{B_g} \cdot (1-x)^{C_g} - A'_g x^{B'_g} \cdot (1-x)^{C'_g},$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}} \cdot (1-x)^{C_{u_v}} \cdot (1 + E_{u_v} x^2),$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}} \cdot (1-x)^{C_{d_v}},$$

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} \cdot (1-x)^{C_{\bar{U}}},$$

$$\cancel{x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} \cdot (1-x)^{C_{\bar{D}}}.}$$

$$\left. \begin{array}{l} x\bar{d}(x) = A_{\bar{d}} x^{B_{\bar{d}}} (1-x)^{C_{\bar{d}}} \\ x\bar{s}(x) = A_{\bar{s}} x^{B_{\bar{s}}} (1-x)^{C_{\bar{s}}} \end{array} \right\}$$

$$A_{\bar{u}} = A_{\bar{d}} ; B_{\bar{u}} = B_{\bar{d}}$$

$$B_{\bar{s}} = B_{\bar{d}} \text{ for the central fit, } A_s \text{ and } C_s \text{ are free parameter of the fit, assumed } s = s\text{bar}$$

$$B_{\bar{s}} \neq B_{\bar{d}} \text{ fit included into parametrisation uncertainty}$$

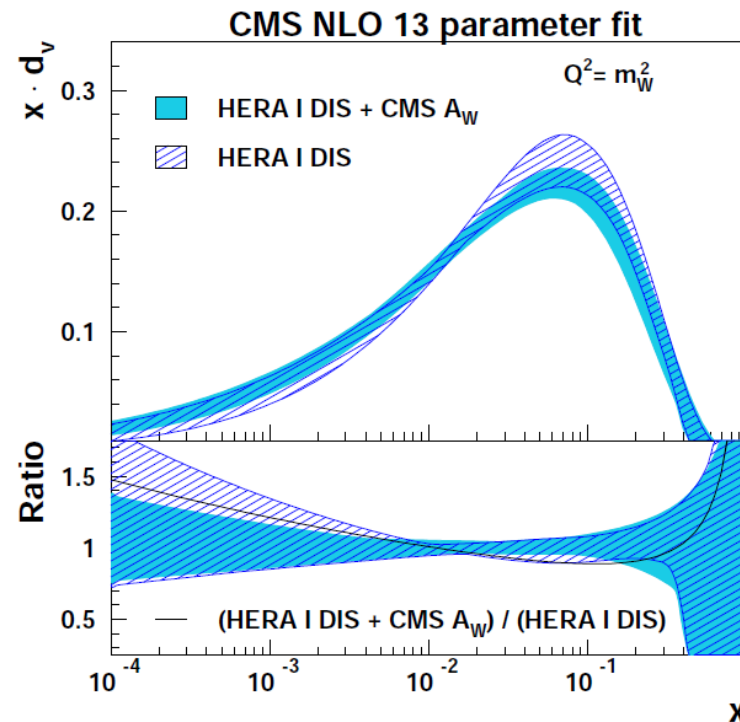
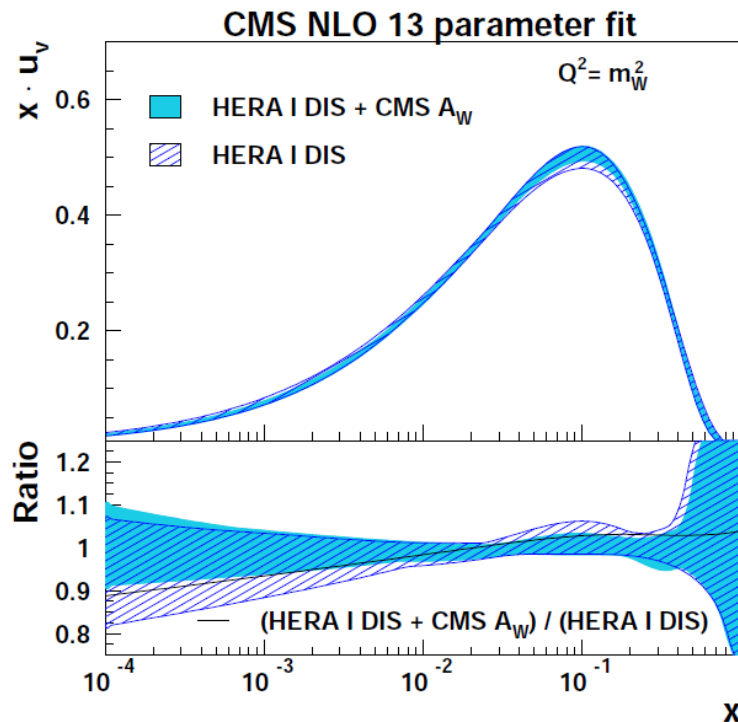
HERA data alone cannot be fitted with this parametrisation because has no sensitivity to s

→ variation of parametrisation (addition of parameters) later considered in the PDF uncertainties

Results: CMS W asymmetry data

QCD analysis at NLO, 13 parameter (fixed-s fit)

- HERA I combined DIS data [JHEP 1001:109 \(2010\)](#)
- Muon charge asymmetry in W production at 7 TeV [arXiv:1312:6283](#)

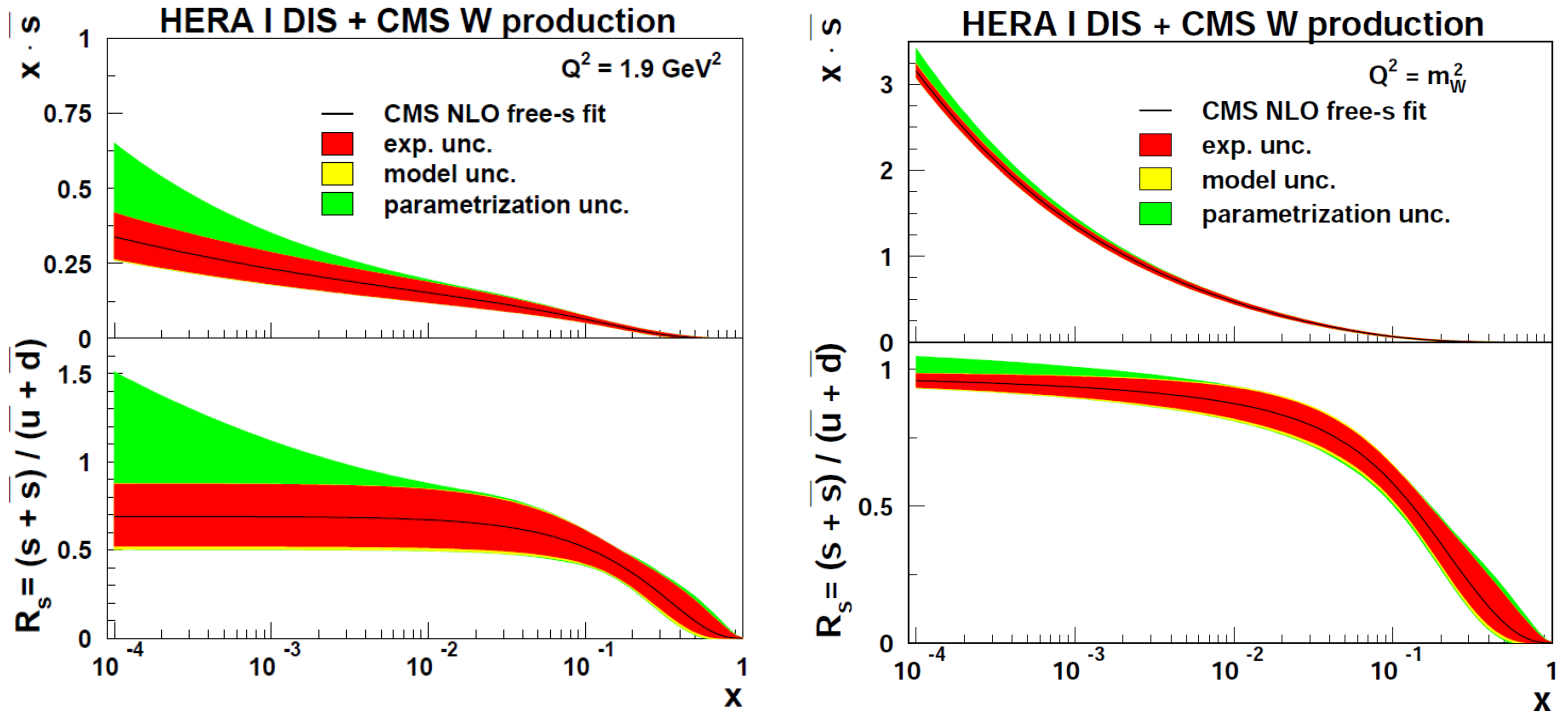


error bands represent total uncertainties, (experimental, model and parametrisation uncertainties)

Change of PDF shape, improved constraints on the valence distributions

Results: s quark density

Determination of s quark density in the proton by using W production at CMS



The determined strangeness suppression K_s (20 GeV^2):

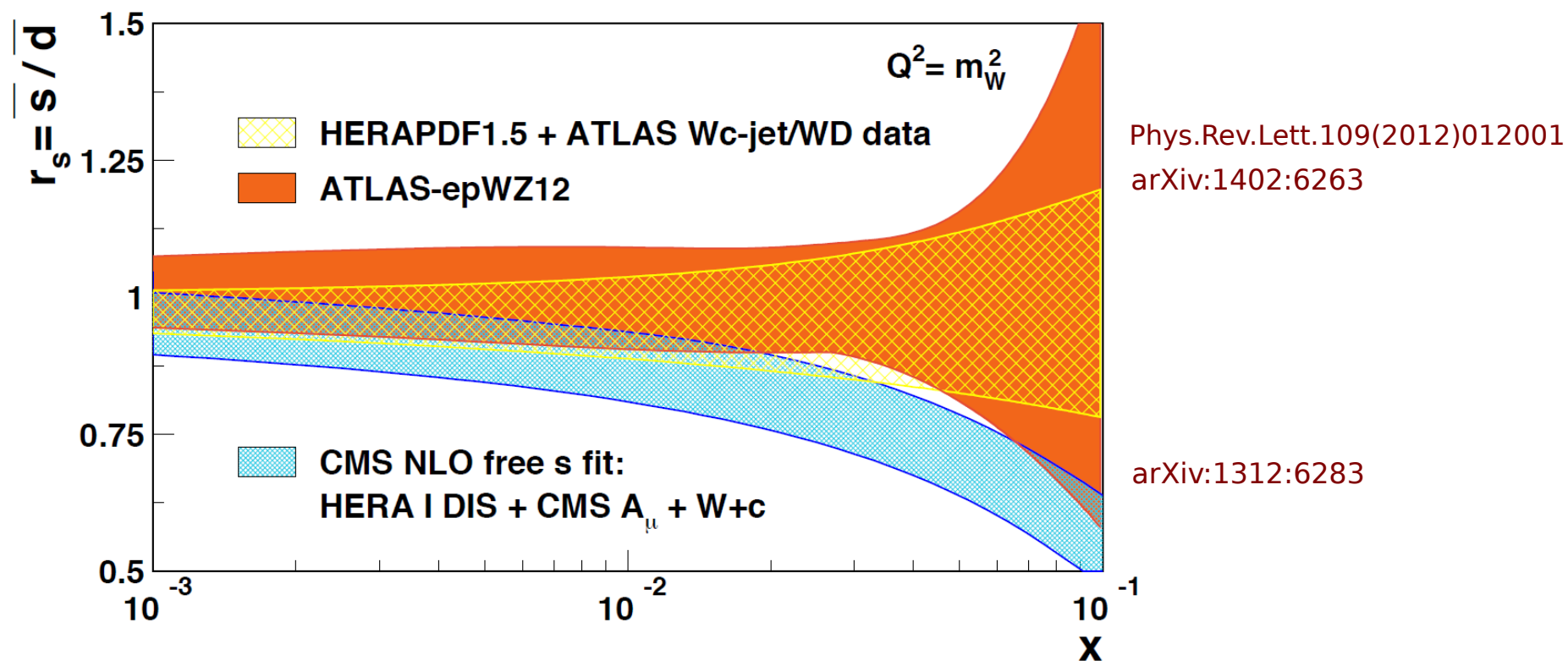
$$\kappa_s = 0.52^{+0.12}_{-0.10} (\text{exp.})^{+0.05}_{-0.06} (\text{model})^{+0.13}_{-0.10} (\text{parametrization})$$

NOMAD K_s (20 GeV^2) = 0.59 ± 0.019 Nucl.Phys. B876(2013) 339

Determined strange fraction is consistent with NOMAD results

Comparison with ATLAS results

Comparison of the ratio of s over d determined by ATLAS and CMS



Strange fraction determined in CMS is lower than in ATLAS but results are still consistent