PDF constraints using Vector Bosons at CMS

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on behalf of the CMS collaboration

Introduction

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

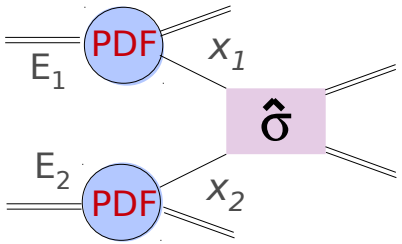
(not covered in this talk)

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.

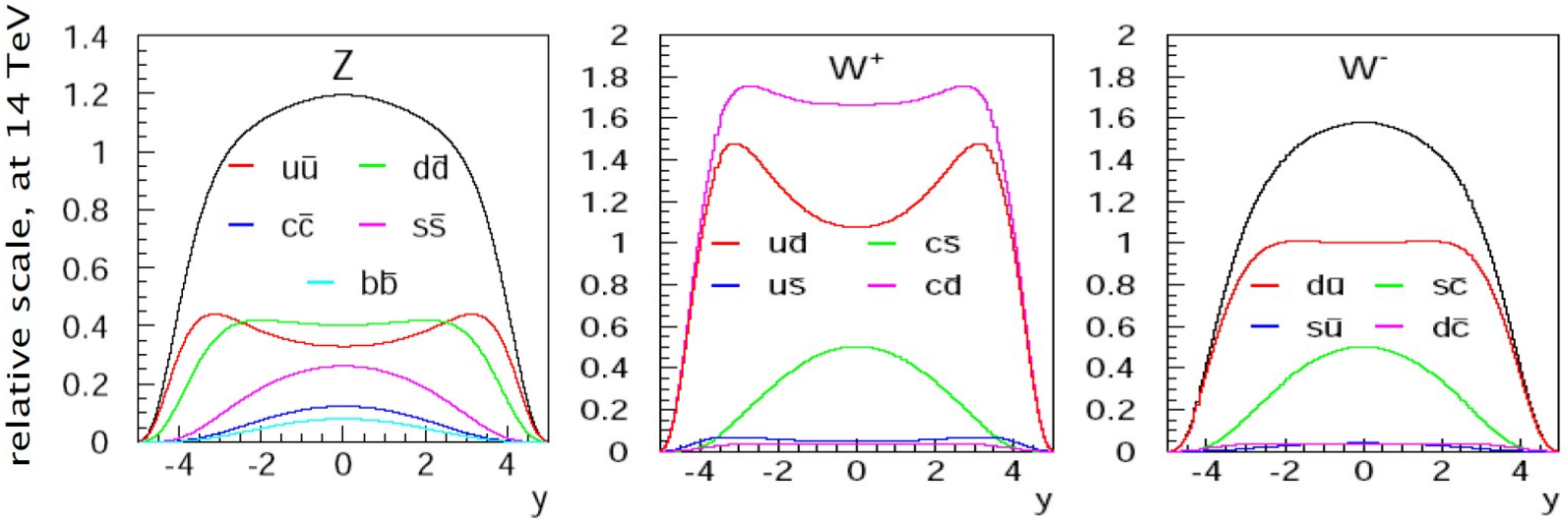
Z and W production at LHC

→ probe different flavour combinations
→ potential to improve quark PDFs



QCD factorisation:

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



→ 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 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 TeV
  Phys Lett B 749 (2015) 187

- W + charm production in pp collisions at $\sqrt{s}$ = 7 TeV
  → *included into NNPDF3.0* JHEP 02 (2014) 013

- Electron charge asymmetry in inclusive W production at $\sqrt{s}$ = 7 TeV
  → *included into CT14, NNPDF3.0* PRL 109 (2012) 111806

- Muon charge asymmetry in pp→WX production at $\sqrt{s}$ = 7 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 → 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
- **W boson production cross section in association with two b jets at $\sqrt{s}$ = 8 TeV** CMS PAS SMP-14-020
- **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
- Differential cross section of W ($\rightarrow\mu\nu$) boson in association with jets at $\sqrt{s}$ = 8 TeV CMS PAS SMP-14-023

CMS W muon charge asymmetry at 8 TeV

W lepton charge asymmetry at LHC

→ overall excess of W^+ over W^- due to presents of two valence *u* quarks in the proton

→ probe valence quarks and PDFs rations (u_v, d_v, d/u, d_v/u_v, dbar/ubar):

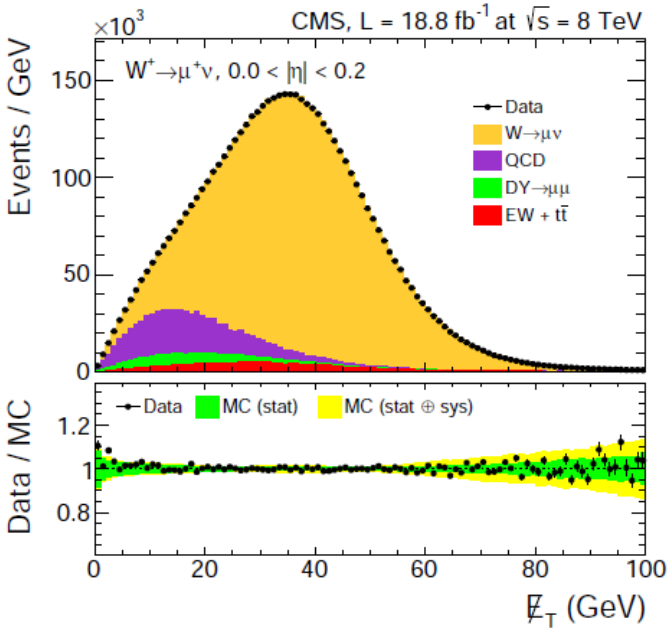
at LO: $$A_W = \frac{W^+ - W^-}{W^+ + W^-} \approx \frac{u_v - d_v}{u_v + d_v + 2u_{sea}}$$

CMS W muon asymmetry measurement at $\sqrt{s}$ = 8 TeV with $\int L$ = 18.8 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

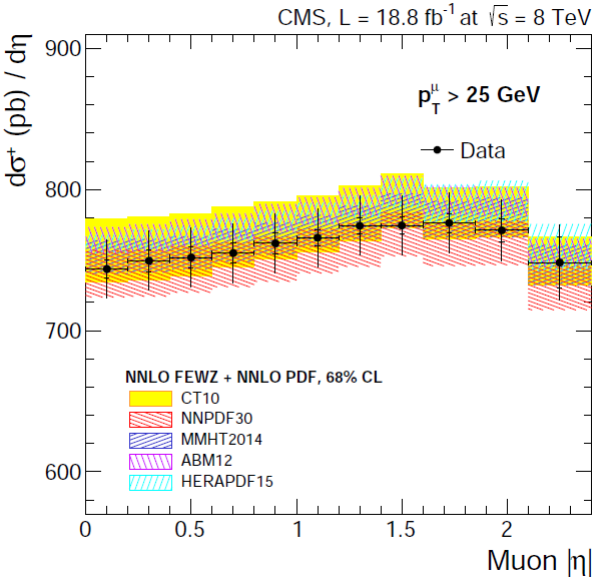
arXiv:1603.01803

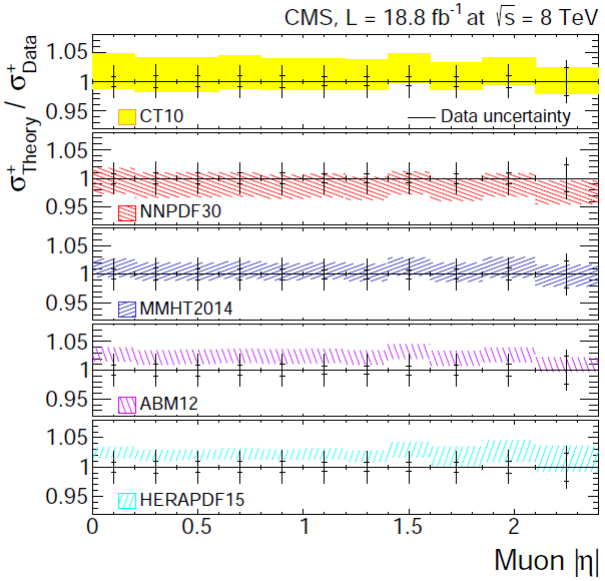
→ separate W^+ and W^- distributions provided

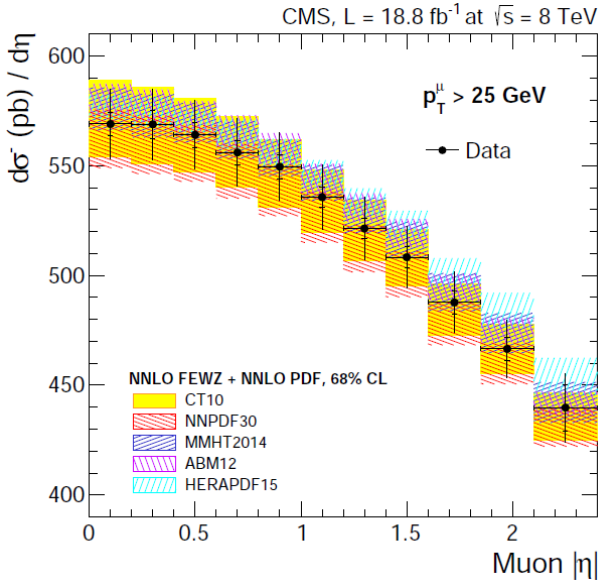
→ compared with theory predictions (FEWZ) at NNLO using different PDFs

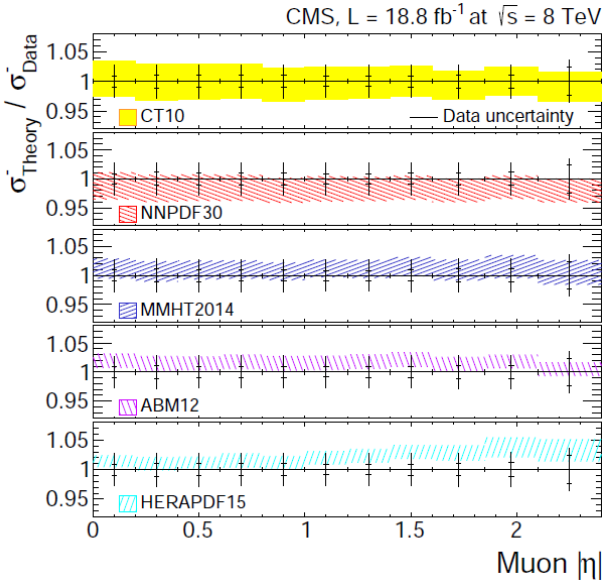
→ good agreement predictions obtained with all PDFs

(systematic correlations provided in the paper)







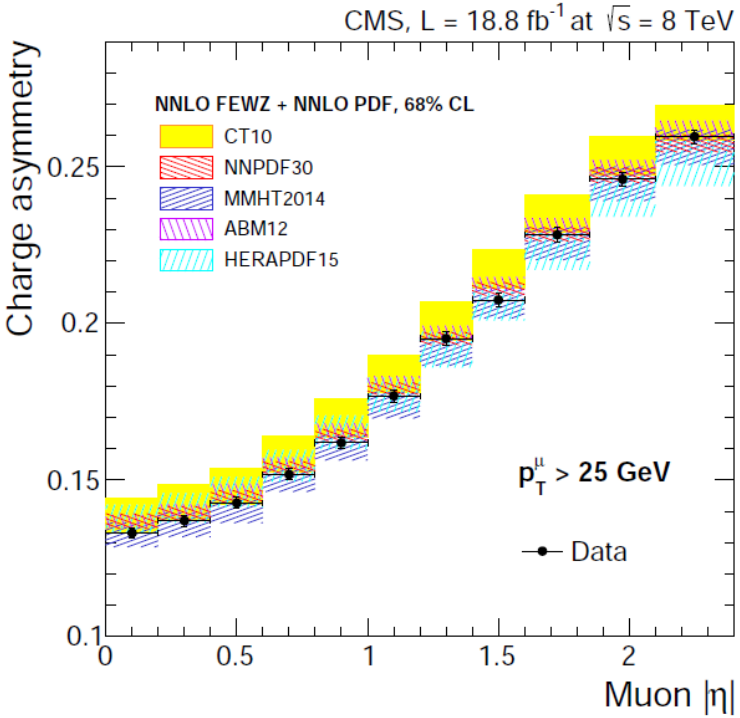


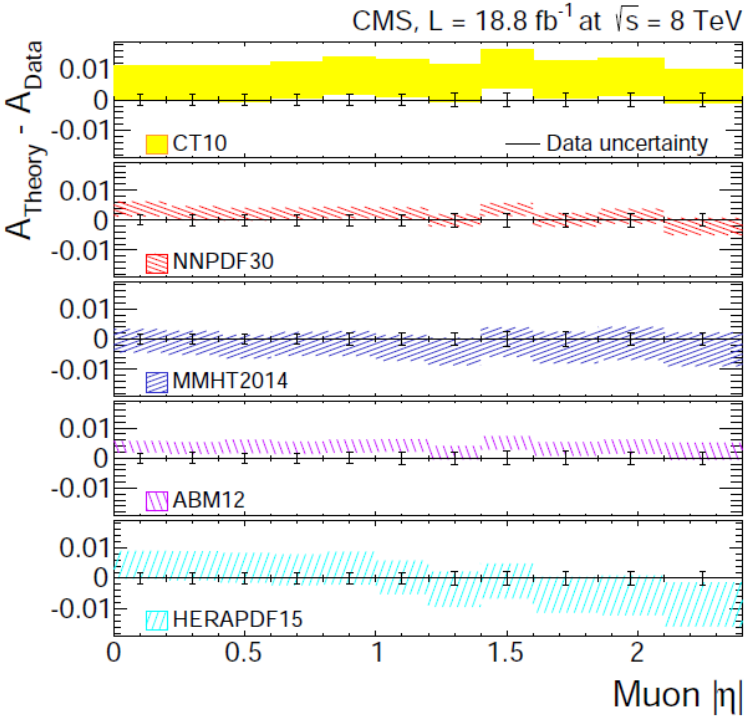
CMS W muon charge asymmetry at 8 TeV

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 settings

arXiv:1603.01803

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^2_0= 1.9 GeV^2

m_c = 1.43 GeV, m_b = 4.5 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*

QCD analysis settings

arXiv:1603.01803

PDF parametrisation at the starting scale (Q^2_0=1.9 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:

$$
\begin{aligned}
xg(x) &= A_g x^{B_g} (1-x)^{C_g} (1+D_g x), \\
xu_v(x) &= A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1+E_{u_v} x^2), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}}, \\
x\overline{U}(x) &= A_{\overline{U}} x^{B_{\overline{U}}} (1-x)^{C_{\overline{U}}} (1+E_{\overline{U}} x^2), \\
x\overline{D}(x) &= A_{\overline{D}} x^{B_{\overline{D}}} (1-x)^{C_{\overline{D}}},
\end{aligned}
$$

A: normalisation
B: small x behavior
C: x→ 1 shape

Additional constraints applied:

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

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

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

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

$x\overline{s}=f_s x\overline{D}$ with

$f_s=x\overline{s}/(x\overline{d}+x\overline{s})=0.31+0.08$ (as determined in EPJC 63 (2009) 189)

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

Results of QCD analysis

arXiv:1603.01803

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

all correlated χ^2 part is from the HERA data

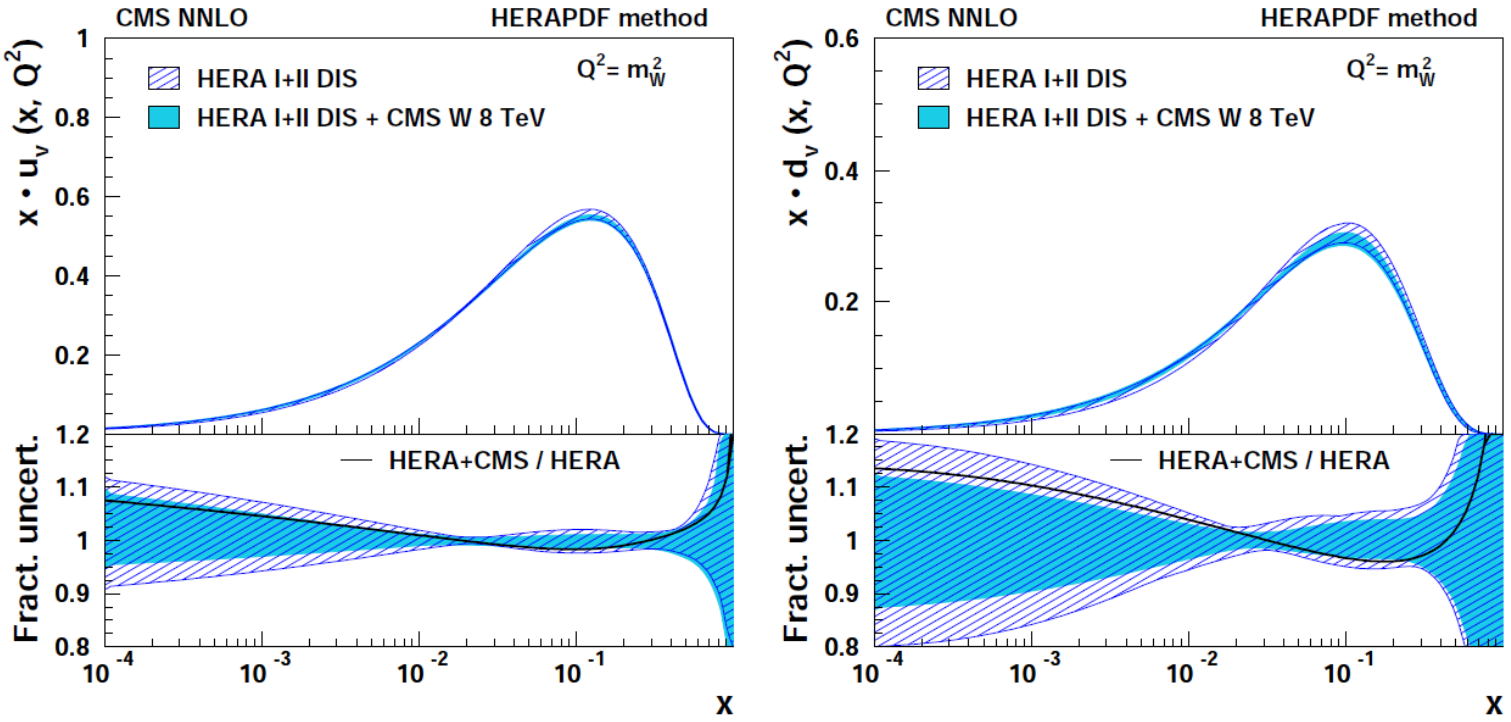
→ good χ^2 observed for CMS data, higher values for HERA data are consistent with the results obtained in HERAPDF2.0 analysis EPJC 75 (2015) 580

Results of QCD analysis

arXiv:1603.01803

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 $\int L = 19.7\ 0.5\ fb^{-1}$

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

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

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

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

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

(MADGRAPH5 AMC@NLO): $9.47 \pm 0.04\,(stat) \pm 0.15\,(PDF) \pm 0.50\,(scales)$

$$\sigma(pp \to Z + c + X)/\sigma(pp \to Z + b + X) = 2.0 \pm 0.2\,(stat.) \pm 0.2\,(syst.)$$

prediction (MadGraph): $1.805 \pm 0.006\,(stat) \pm 0.004\ (PDF)$

(MADGRAPH5 AMC@NLO): $1.87 \pm 0.07\,(stat) \pm 0.50\,(scales)$

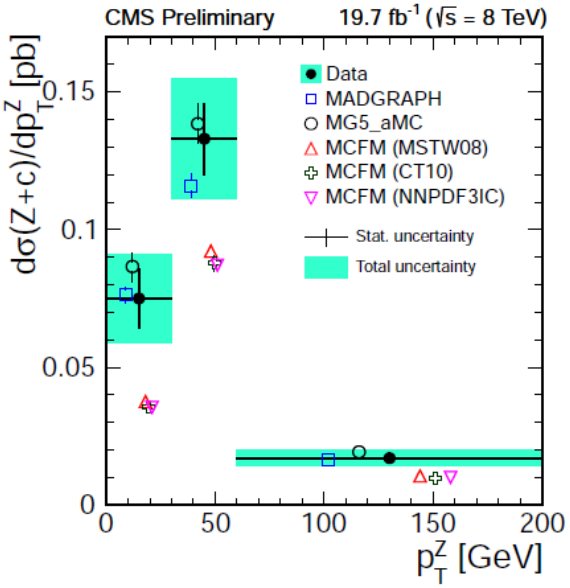
CMS Z+charm measurement at 8 TeV

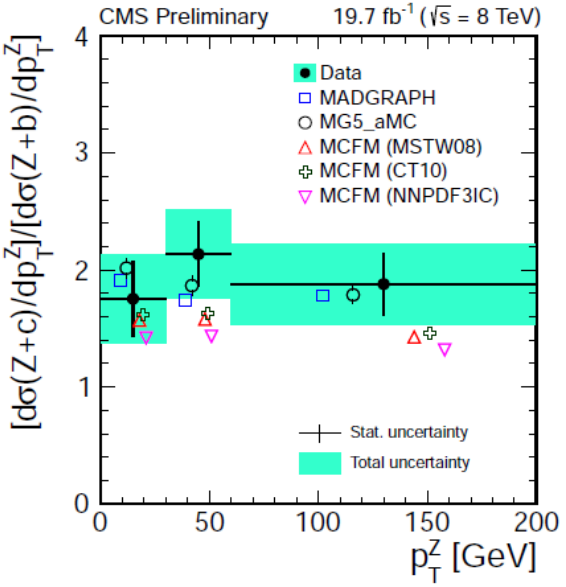
CMS PAS SMP-15-009

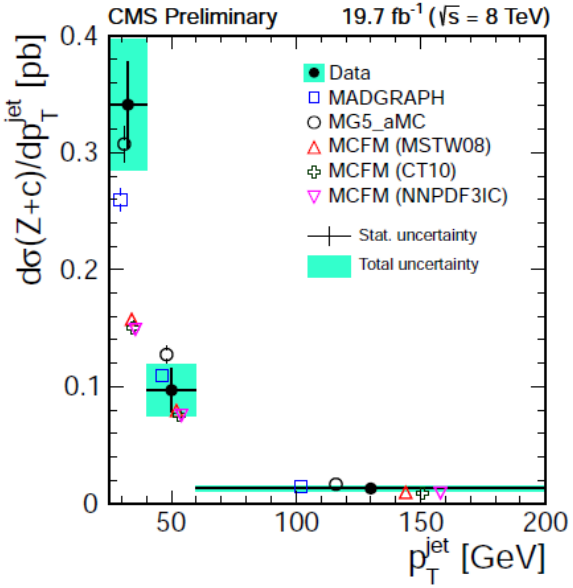
Theoretical predictions (NLO) obtained with the MCFM using the NLO PDF sets MSTW08, CT10, NNPDF3IC and NNPDF3nIC

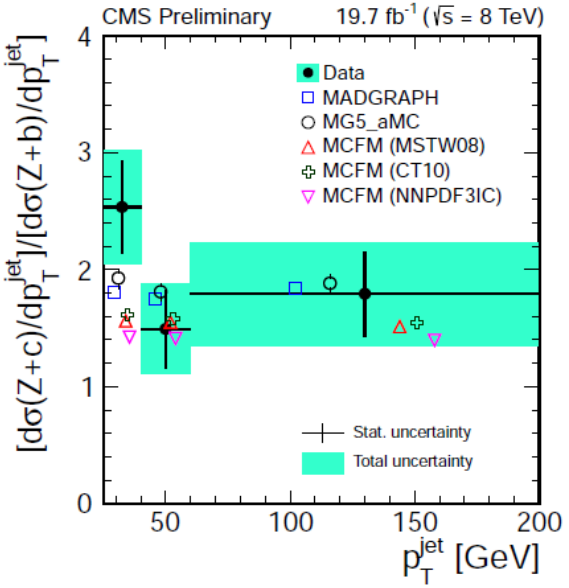
→ all predictions are smaller than measured cross sections

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









CMS W+$b\bar{b}$ measurement at 8 TeV

CMS PAS SMP-14-020

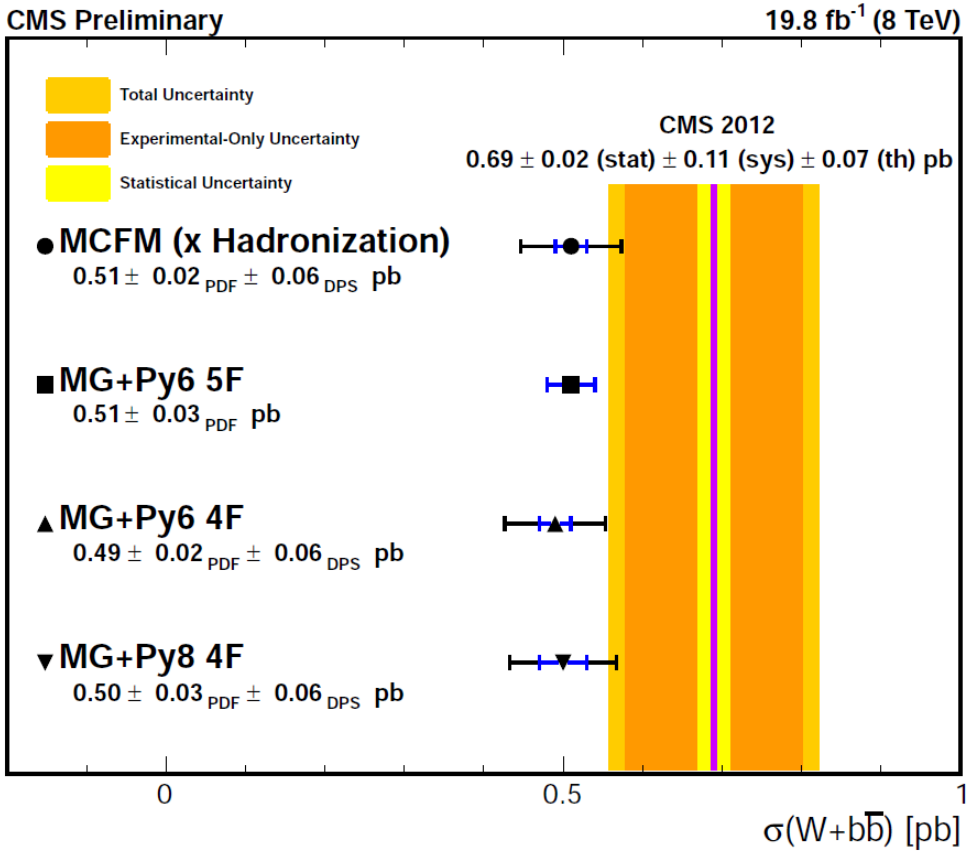
Extension of earlier W+$b\bar{b}$ measurement (with muons) with both, muon and electron, W decay channels and $\int L = 19.8\ fb^{-1}$

→ analysis with $p_T^l > 30$ GeV, $|\eta^l| < 2.1$ and b-tagged jets $p_T > 25$ GeV and $|\eta| < 2.4$

Comparison with predictions (hadron level) including the estimated hadronization and double parton scattering (DPS) corrections

→ agree within 1 standard deviation

→ useful to test PDFs with different number of flavours



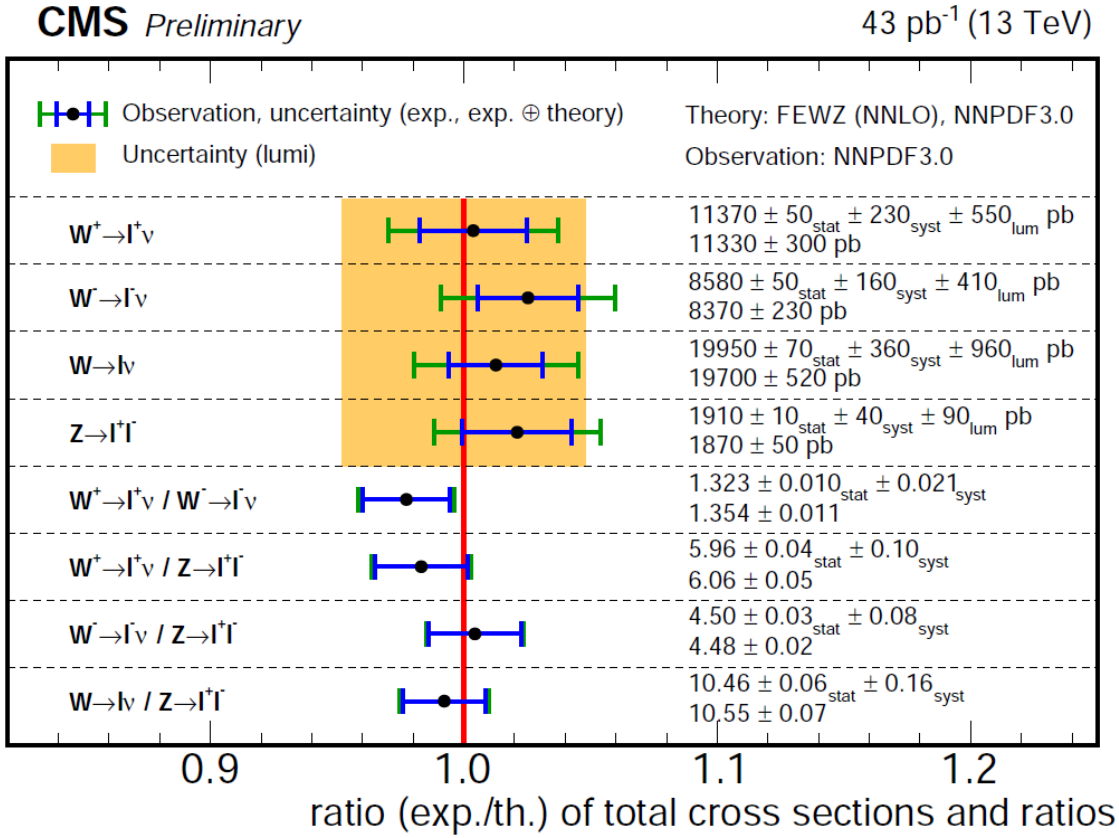
CMS inclusive W and Z production at 13 TeV

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

→ measurement performed in the electron and muon decay channels (dilepton mass range of 60 to 120 GeV)

→ inclusive cross sections and ratios

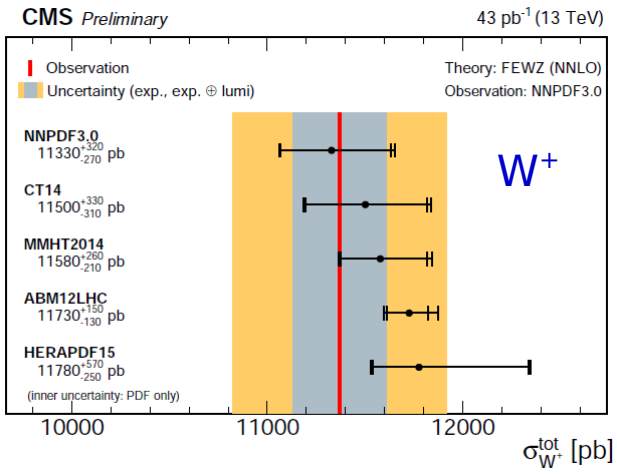
CMS PAS SMP-15-004

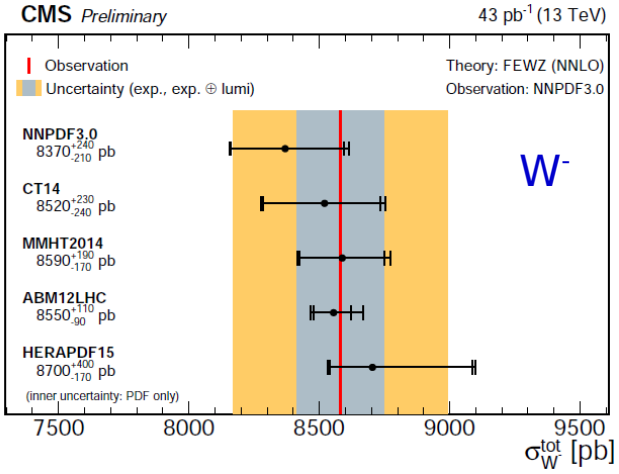


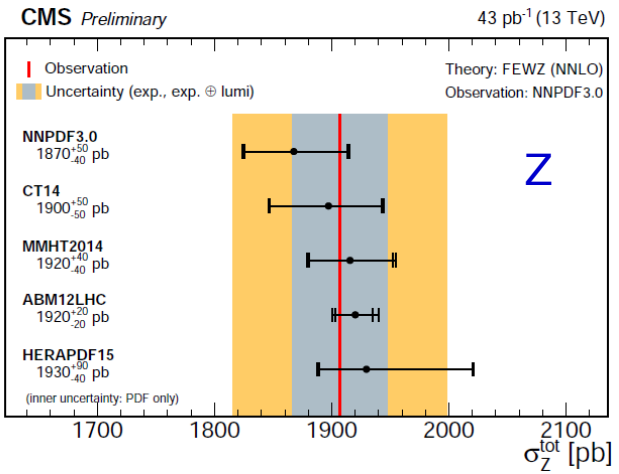
W and Z cross sections at 13 TeV

CMS PAS SMP-15-004

Dominant systematic uncertainty: luminosity





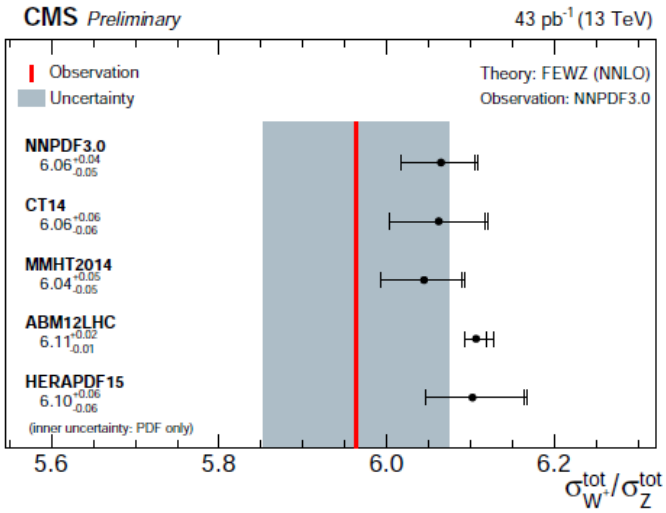


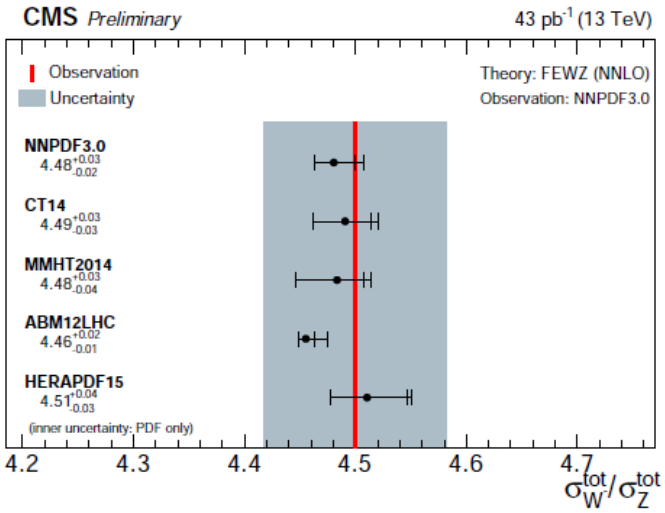
Compared with FEWZ (NNLO QCD and NLO order EW calculations) with various PDFs:

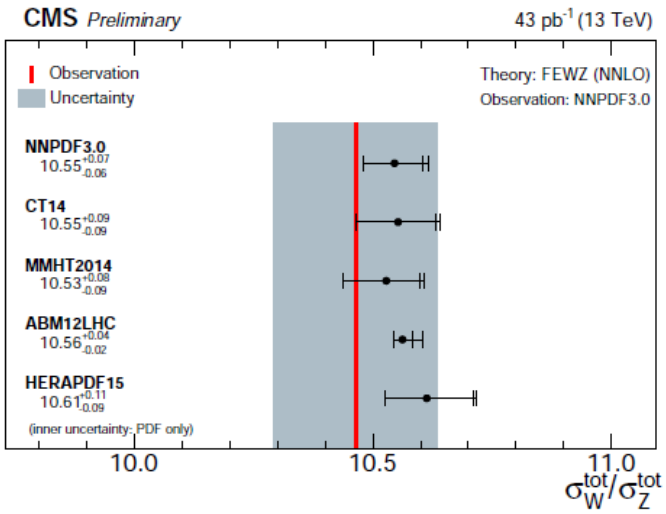
	NNPDF3.0	CT14	MMHT2014	ABM12LHC	HERAPDF15
σ^{tot}_{W+} [pb]	11330^{+320}_{-270}	11500^{+330}_{-310}	11580^{+260}_{-210}	11730^{+150}_{-130}	11780^{+570}_{-250}
σ^{tot}_{W-} [pb]	8370^{+240}_{-210}	8520^{+230}_{-240}	8590^{+190}_{-170}	8550^{+110}_{-90}	8700^{+400}_{-170}
σ^{tot}_{W} [pb]	19700^{+560}_{-470}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

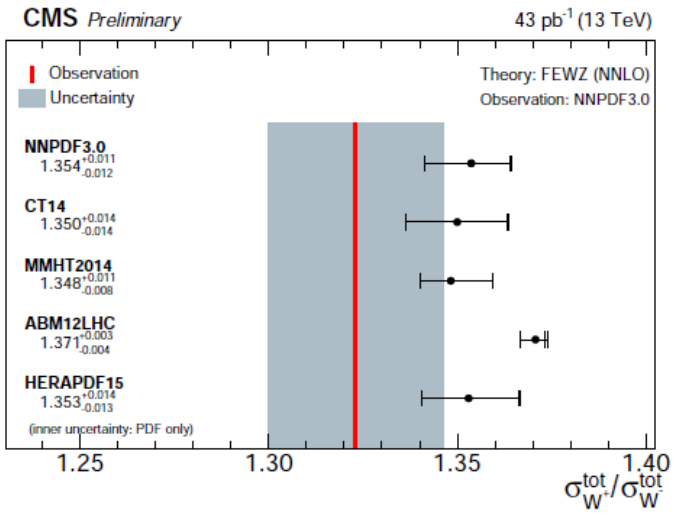
W and Z cross section ratios at 13 TeV

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 ∫L =2.3 fb^{-1}

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

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

	σ_Z^{tot} [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 ∫L =2.3 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

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

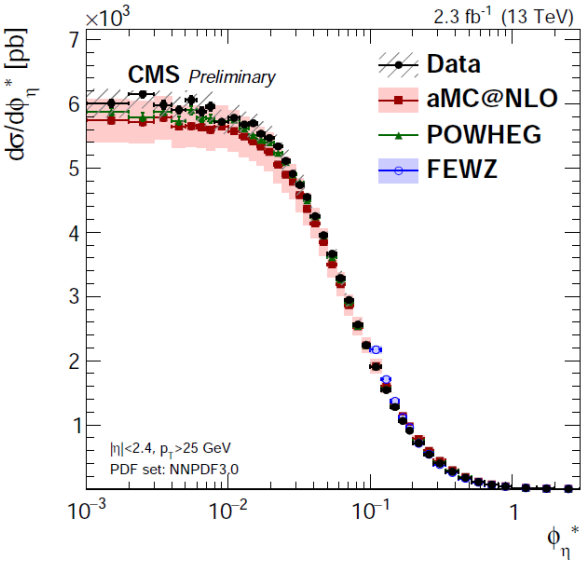
probes Z boson p_T but depends on direction of muon → smaller exp. uncertainty

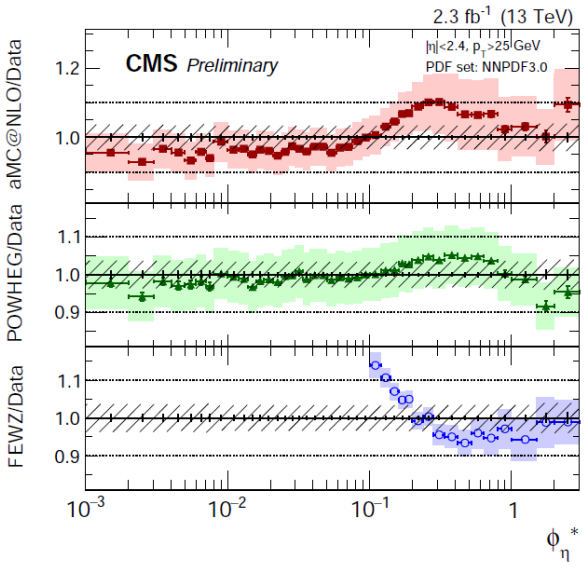
CMS differential Z measurement at 13 TeV

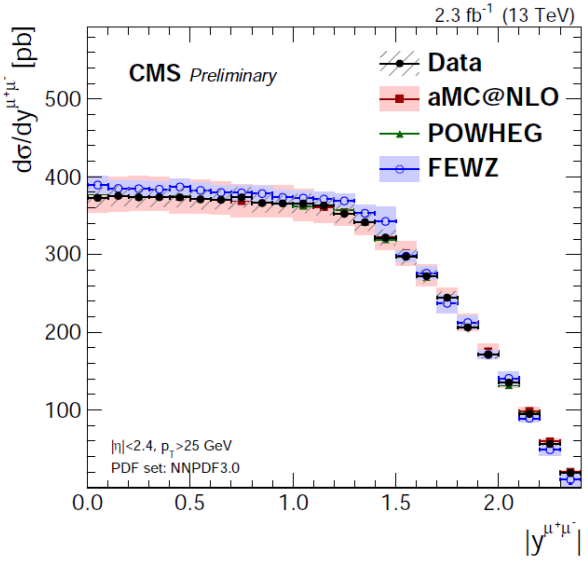
CMS PAS SMP-15-011

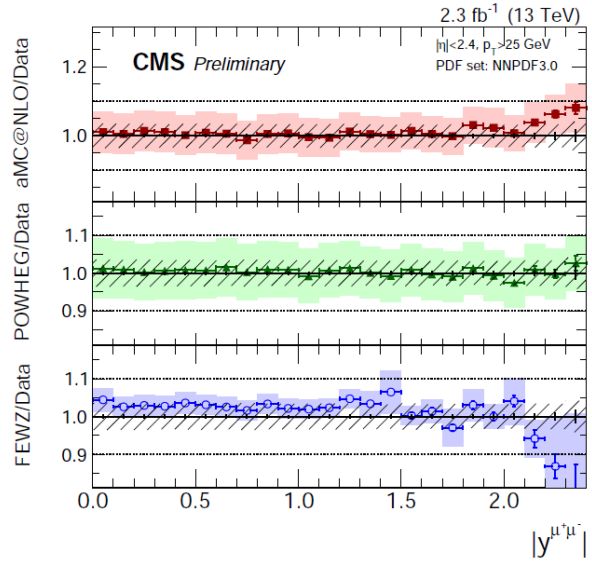
Data compared to MADGRAPH5_AMC@NLO, POWHEG and FEWZ

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









Summary

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

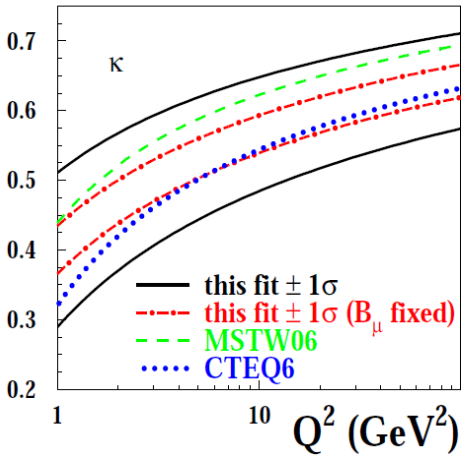
→ also can probe other QCD and EW aspects (e.g. boson polarisation, A_{FB} asymmetry, angular coefficients, MC tuning, ..)

Back-up slides

Strange quark density determination

Strange quark density in the proton is still poorly known

Phys. Lett. B 675, 433 (2009)



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

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NOMAD measurement

K_s (20 GeV^2)= 0.59 ± 0.019

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

→ 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

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

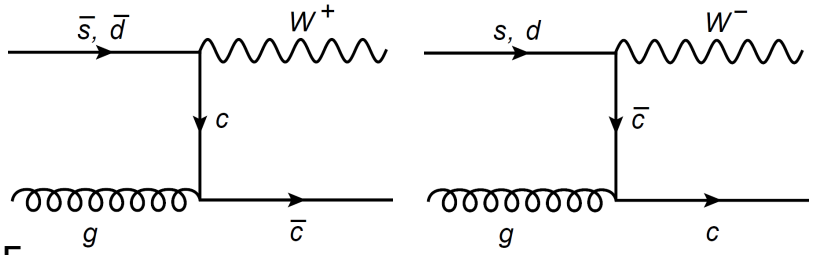
→ same results confirmed by the ATLAS W+charm data (obtained from the χ^2 minimisation procedure)

arXiv:1402:6263

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

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^T_{jet}>25GeV, $|\eta_{jet}|$<2.5

jets identified: secondary vertex $D^+ \to K^-\pi^+\pi^+$ ($D^- \to \bar{K}^+\pi^-\pi^-$)

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

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

arXiv:1310:1138

semileptonic decay with well identified muon

Background subtraction:

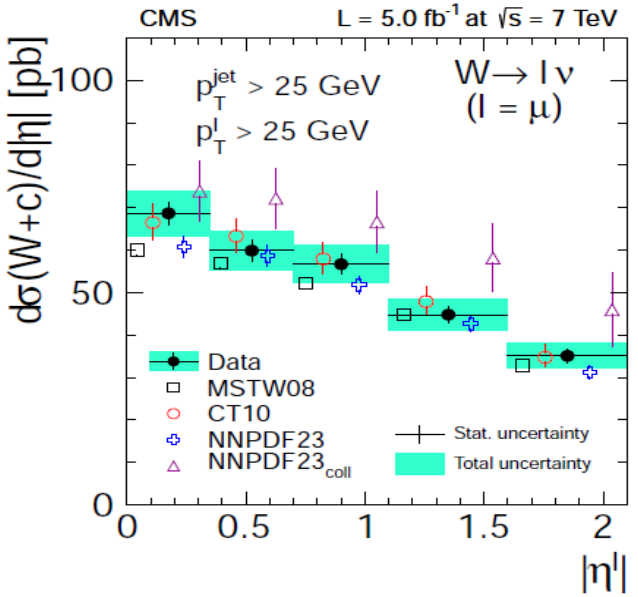
perform by subtracting the Same Sign (SS) from the Opposite Sign (OS) distributions

Total and differential cross sections

p_l^T > 25 GeV (W→μν)

p_l^T > 35 GeV (W→μν, W→eν)

Ratios (W^++cbar)/(W^-+c)



Parametrisation

PDF parametrisation at the starting scale (Q^2_0=1.9 GeV^2):

"13p":

$$
\begin{aligned}
xg(x) &= A_g x^{B_g} \cdot (1-x)^{C_g} - A'_g x^{B'_g} \cdot (1-x)^{C'_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}} \cdot (1-x)^{C_{u_v}} \cdot (1 + E_{u_v} x^2), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} \cdot (1-x)^{C_{d_v}}, \\
x\overline{U}(x) &= A_{\overline{U}} x^{B_{\overline{U}}} \cdot (1-x)^{C_{\overline{U}}}, \\
x\overline{D}(x) &= A_{\overline{D}} x^{B_{\overline{D}}} \cdot (1-x)^{C_{\overline{D}}}.
\end{aligned}
$$

A: normalisation
B: small x behavior
C: x→ 1 shape

$x\bar{U}=x\bar{u}(+x\bar{c})$
$x\bar{D}=x\bar{d}+x\bar{s}(+x\bar{b})$
$x\bar{s}=f_s x\bar{D}$ with
$f_s=x\bar{s}/(x\bar{d}+x\bar{s})=0.31$

"15p" or "free-s":

$$
\begin{aligned}
xg(x) &= A_g x^{B_g} \cdot (1-x)^{C_g} - A'_g x^{B'_g} \cdot (1-x)^{C'_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}} \cdot (1-x)^{C_{u_v}} \cdot (1 + E_{u_v} x^2), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} \cdot (1-x)^{C_{d_v}}, \\
x\overline{U}(x) &= A_{\overline{U}} x^{B_{\overline{U}}} \cdot (1-x)^{C_{\overline{U}}}, \\
\sout{x\overline{D}(x) = A_{\overline{D}} x^{B_{\overline{D}}} \cdot (1-x)^{C_{\overline{D}}}.}
\end{aligned}
$$

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

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

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

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

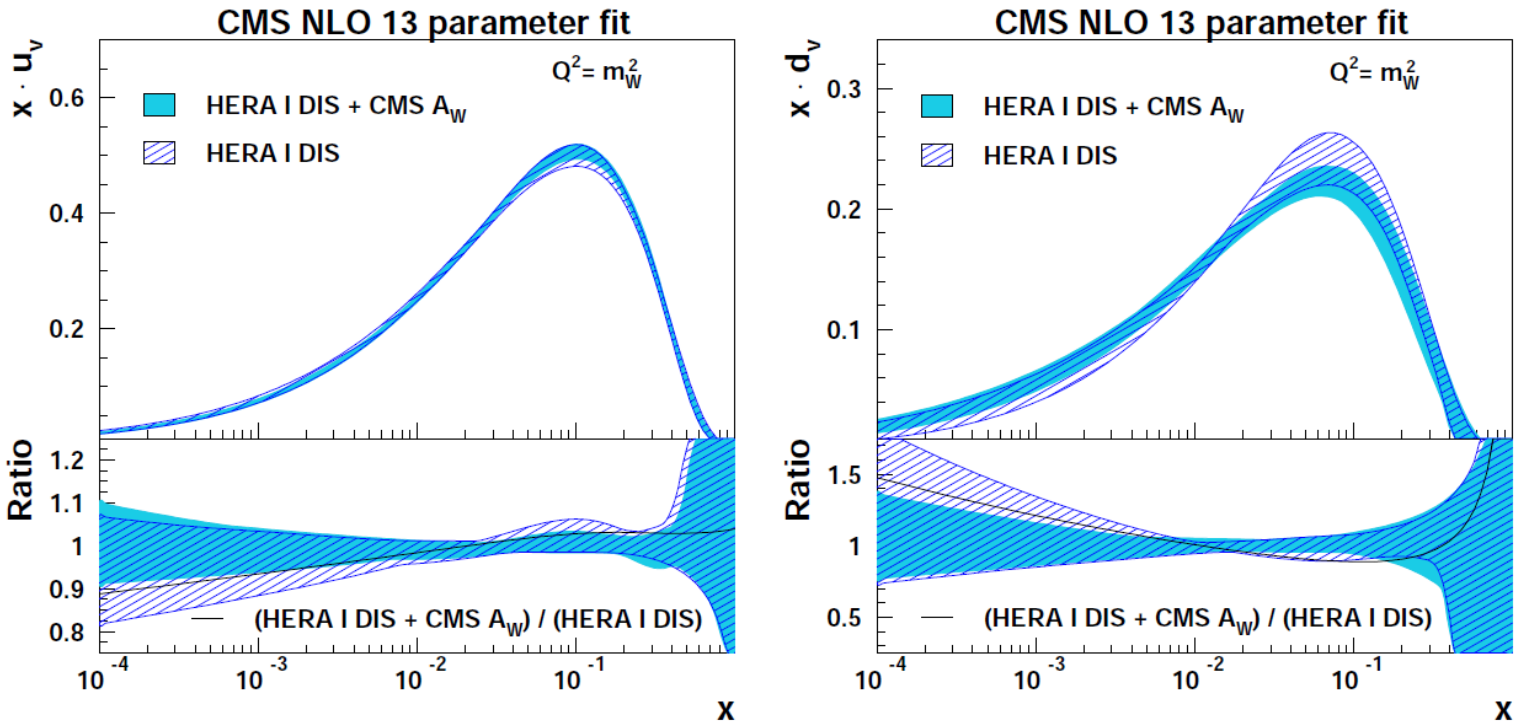
HERA data alone cannot be fitted with this parametrisation because has no sensitivity to s

→ *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

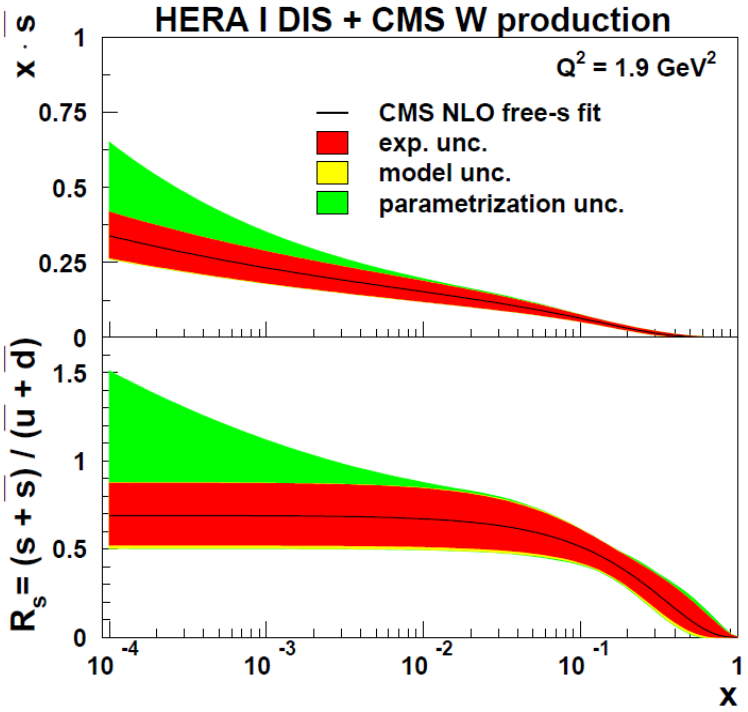


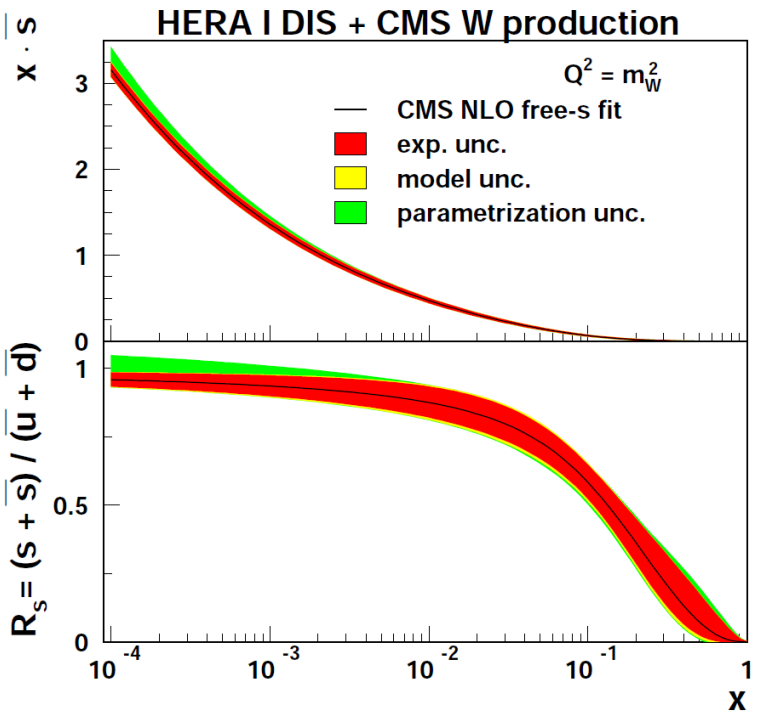
error bands represent total uncertainties, (experimental, model and parametrisation uncertainties)

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):

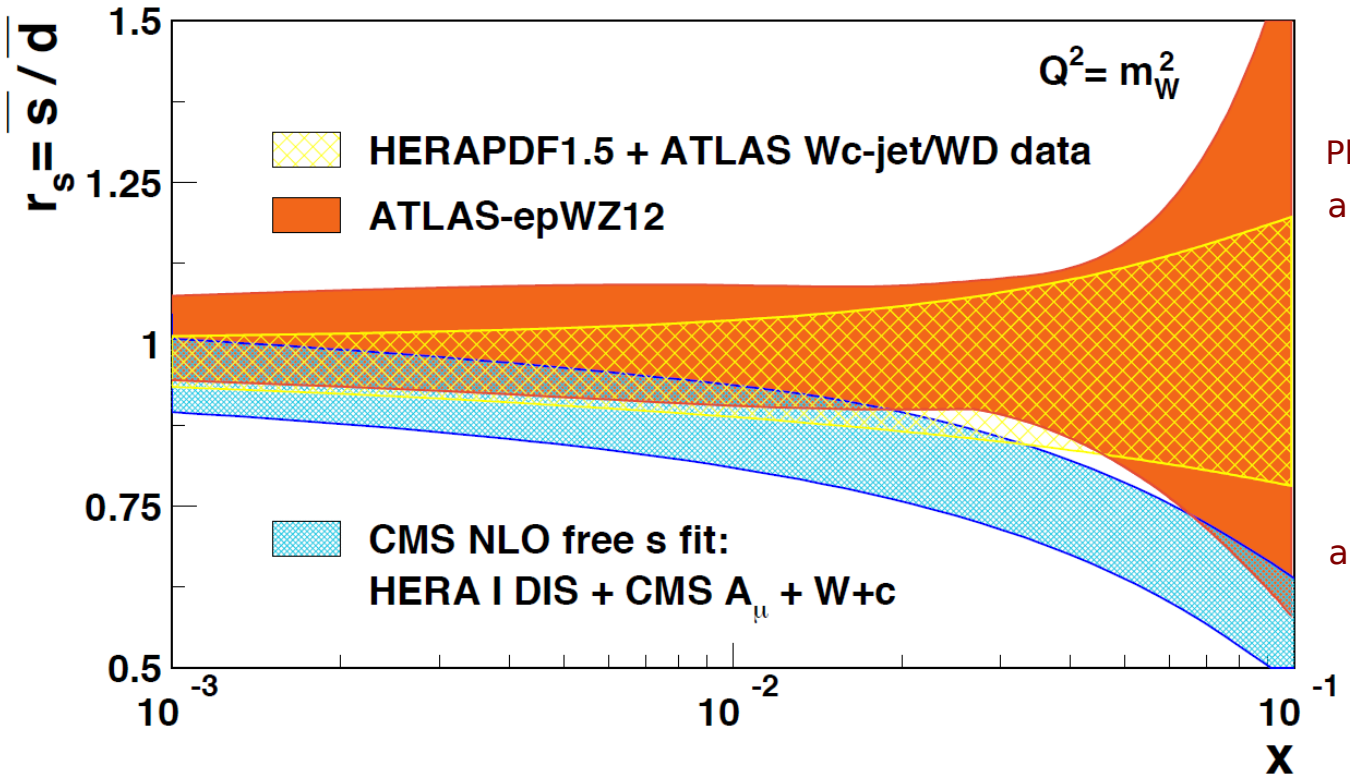
$$\kappa_s = 0.52^{+0.12}_{-0.10}\,(\text{exp.})^{+0.05}_{-0.06}\,(\text{model})^{+0.13}_{-0.10}\,(\text{parametrization})$$

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 sbar over dbar determined by ATLAS and CMS



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