ABMP16
Parton Distribution Functions

Sergey Alekhin, Sven Moch, Johannes Blümlein (DESY) and Ringailė Plačakytė

University of Hamburg

Parton Distribution Functions

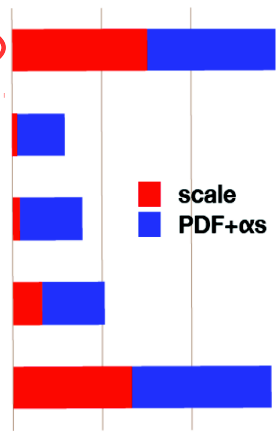
Parton Distribution Functions (PDFs) are of crucial for precision physics at hadron colliders because:

→ PDFs limit **the accuracy of the SM predictions** (including Higgs, W mass, etc.)

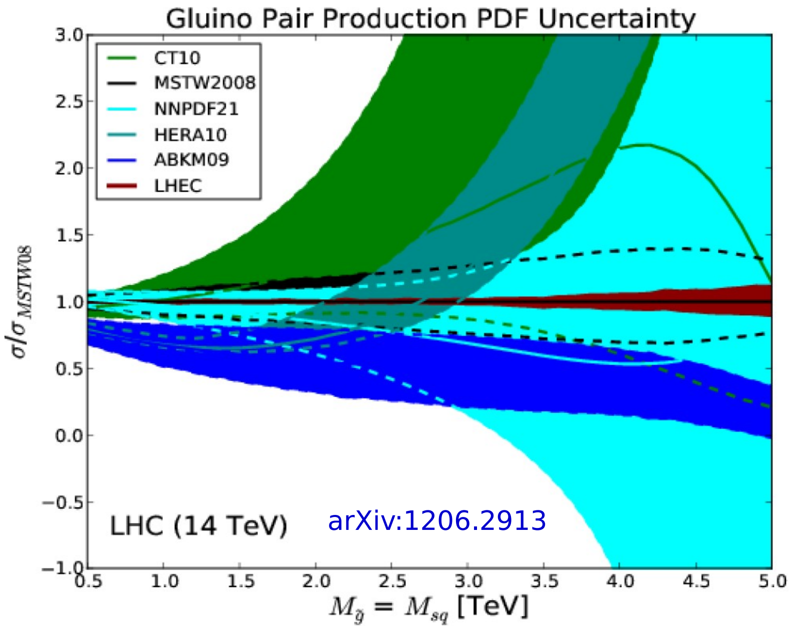
→ **reach of new physics** searches depends on PDF knowledge at high Bjorken-x

Higgs cross section is strongly gluon and α_s dependent

		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
NNLO QCD +NLO EW	VBF	1.56 pb	2.9%
	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



Production of SUSY particles are sensitive to gluon at high $x=2m_X/\sqrt{s} \sim 0.2$ -0.7



→ agreement with Standard Model depends on how well we know PDFs and α_s

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→ PDFs limit **the accuracy of the SM predictions** (including Higgs, W mass, etc.)

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QCD factorisation:

measured cross section = PDF hard-scattering ME

$$\sigma(\alpha_s,\mu_R^2,\mu_F^2)=\sum_{a,b}\int_{x_{min}}^{1} f_a(x_1,\mu_F^2) f_b(x_2,\mu_F^2)\,\hat{\sigma}(x_1,x_2;\alpha_s,\mu_R^2,\mu_F^2)+\ldots$$

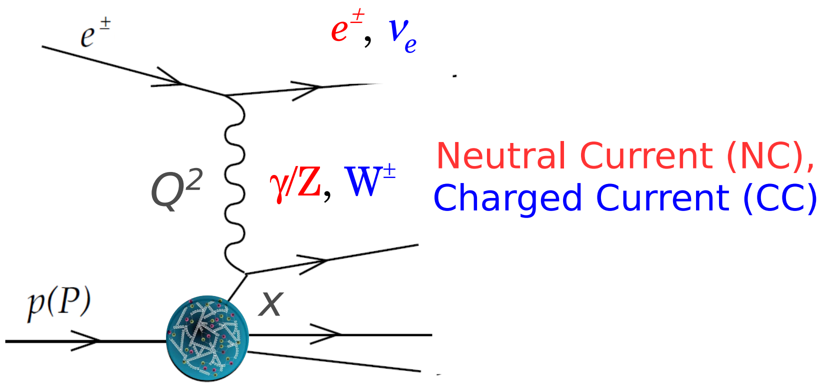
precision measurements of hadron collider data

PDF determination, heavy quark treatment, QCD analysis tools

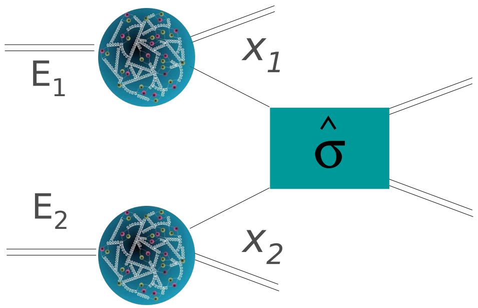
parton cross section (calculable in pQCD)

Experimental Data

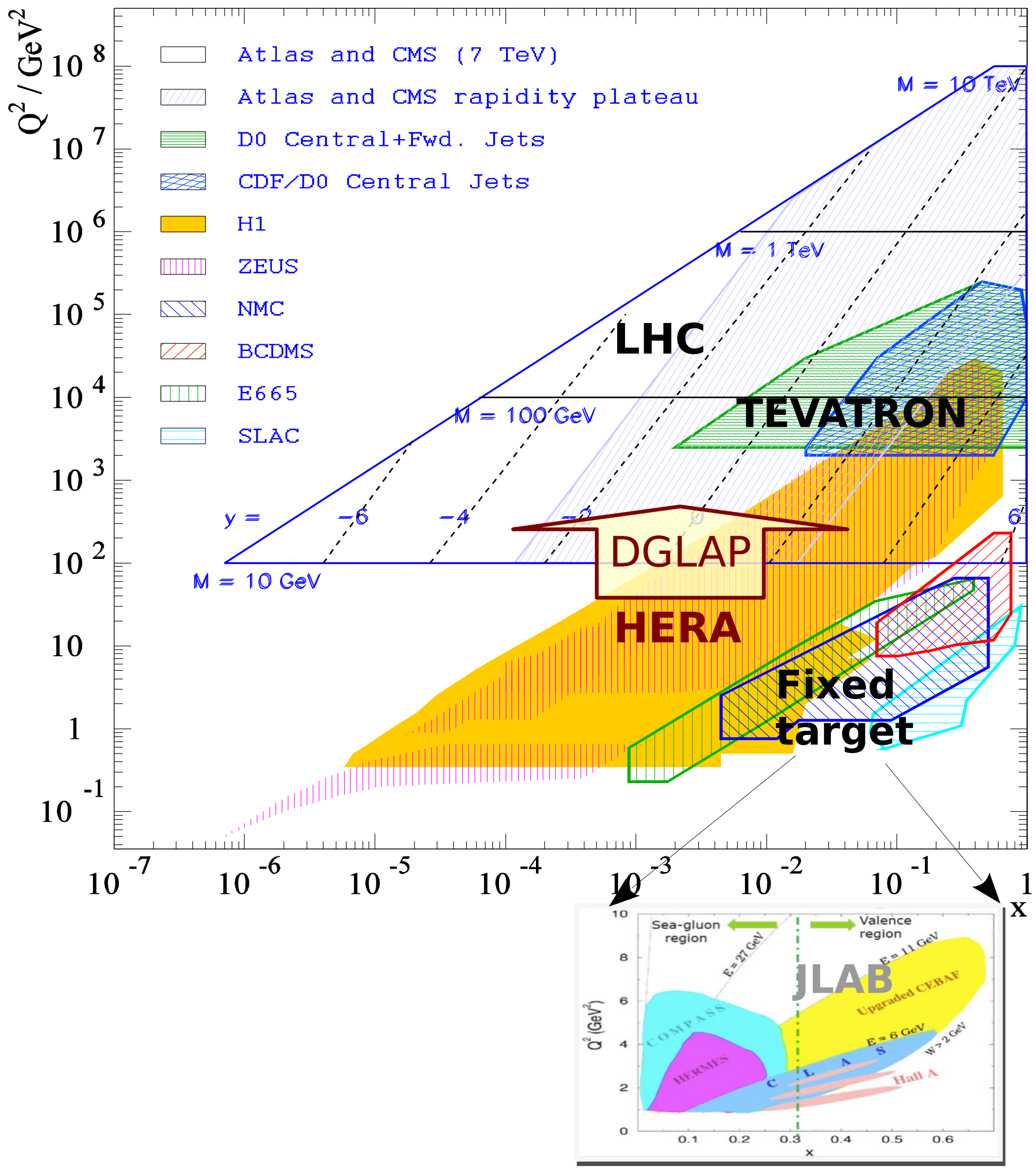
Deep Inelastic Scattering (**DIS**)
provides unique opportunity to study
the structure of the proton:



same PDFs can be used to predict *pp* collisions



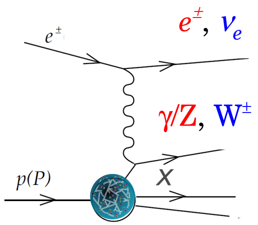
$\hat{\sigma}$ – perturbative QCD cross section



HERA data is basis for PDFs, other experimental data can improve PDFs further

Experimental Data

Deep Inelastic Scattering:



ep data: quarks and gluon at small x (F_L), flavour separation (CC)

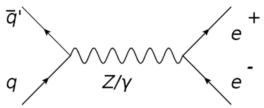
jets → gluons (moderate x) and α_s

heavy quarks → gluons, tests of heavy quark schemes, mass determination

fixed target data: higher x

neutrino DIS: flavour decomposition, x>0.01

Drell-Yan (DY) production:

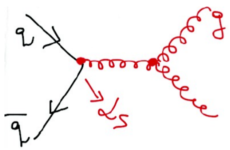


different PDF combinations (low/mid/high x), deuterium target – $\bar{u}/\bar{d}$ asymmetry

W/Z ratio, asymmetries → quark flavour separation

V+ heavy flavour → sensitivity to s quark

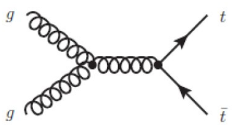
Photon, inclusive jets, dijets, trijets and ratios:



high x gluon, α_s

Isolated photon → gluon at medium and high x

ttbar, single top:



gluon at high x, u and d quarks, α_s

PDF Groups

ABM, CT/CTEQ, JR, NNPDFs, MMHT/MSTW, HERAPDFs

'global' PDFs (all but HERA) use data from different experiments

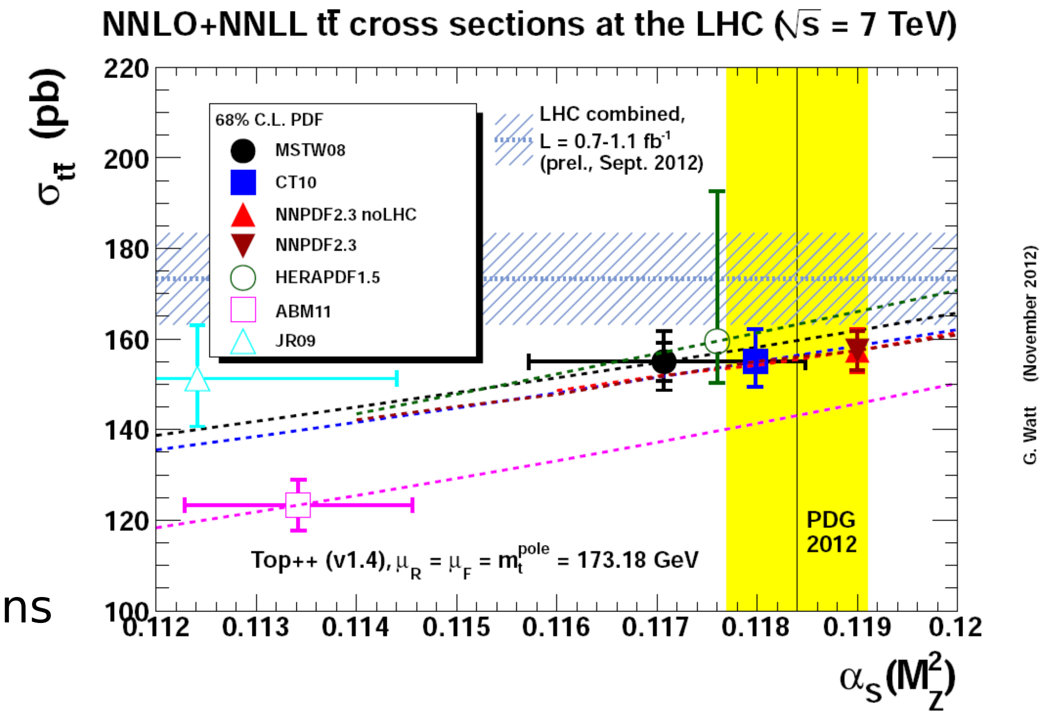
→ some data may not be fully consistent (may result in enhanced tolerance criteria in the fit)

→ fixed target data need nuclear corrections

Differences between PDFs

- inclusion of different data
- methods of determining 'best fit'
- uncertainty treatment/sources
- assumptions in procedure (parametrisation)
- heavy flavour treatment
- PDF and α_s correlation

… causes differences in the predicted cross sections



→ it is essential to have consistent treatment of experimental data and theory in PDF fits and understand the differences between PDFs

ABMP16 PDFs

ABMP16 PDFs is an update of **ABM12** with intermediate studies on:

- s-quark suppression — PRD 91, no 9 (2015) 094002, arXiv:1404.6469
- iso-spin asymmetry — arXiv:1508.07923
- inclusion of top quark data — arXiv:1608.05212 — arXiv:1609.03327
- and corresponding updates in theory predictions for heavy quarks

Summary of what's new:

→ **Data**:

HERA I+II inclusive data: $\alpha_s(M_Z)$, m_c, and m_b

charm di-muon data (NOMAD, CHORUS): s-quark sea

LHC W,Z: iso-spin asymmetry and d/u at large x (including Tevatron data)

t-quark: m_t and gluon → *see S. Alekhin's talk*

→ **Theory**:

heavy quarks in DIS

single-top (HATHOR, CPC 182, 1034 (2011), CPC 191, 74 (2015))

ABMP16 PDFs: Main Fit Ingredients

DATA:

DIS NC/CC inclusive (HERA I+II added, no deuteron data included)
DIS NC charm production (HERA)
DIS CC charm production (HERA, NOMAD, CHORUS, NuTeV/CCFR)
fixed-target DY
LHC DY distributions (ATLAS, CMS, LHCb)
t-quark data from the LHC and Tevatron

QCD:

NNLO evolution
NNLO massless DIS and DY coefficient functions
NLO+ massive DIS coefficient functions (**FFN scheme**)
– NLO + NNLO threshold corrections for NC
– NNLO CC at $Q \gg m_c$
– running mass definition
NNLO exclusive DY (FEWZ 3.1) via fast grid technique
NNLO inclusive ttbar production

Power corrections in DIS:
target mass effects
dynamical twist-4 terms

PARAMETRISATION:

follows earlier prescription but with relaxed form of (dbar-ubar) at small x

Inclusive HERA I+II data

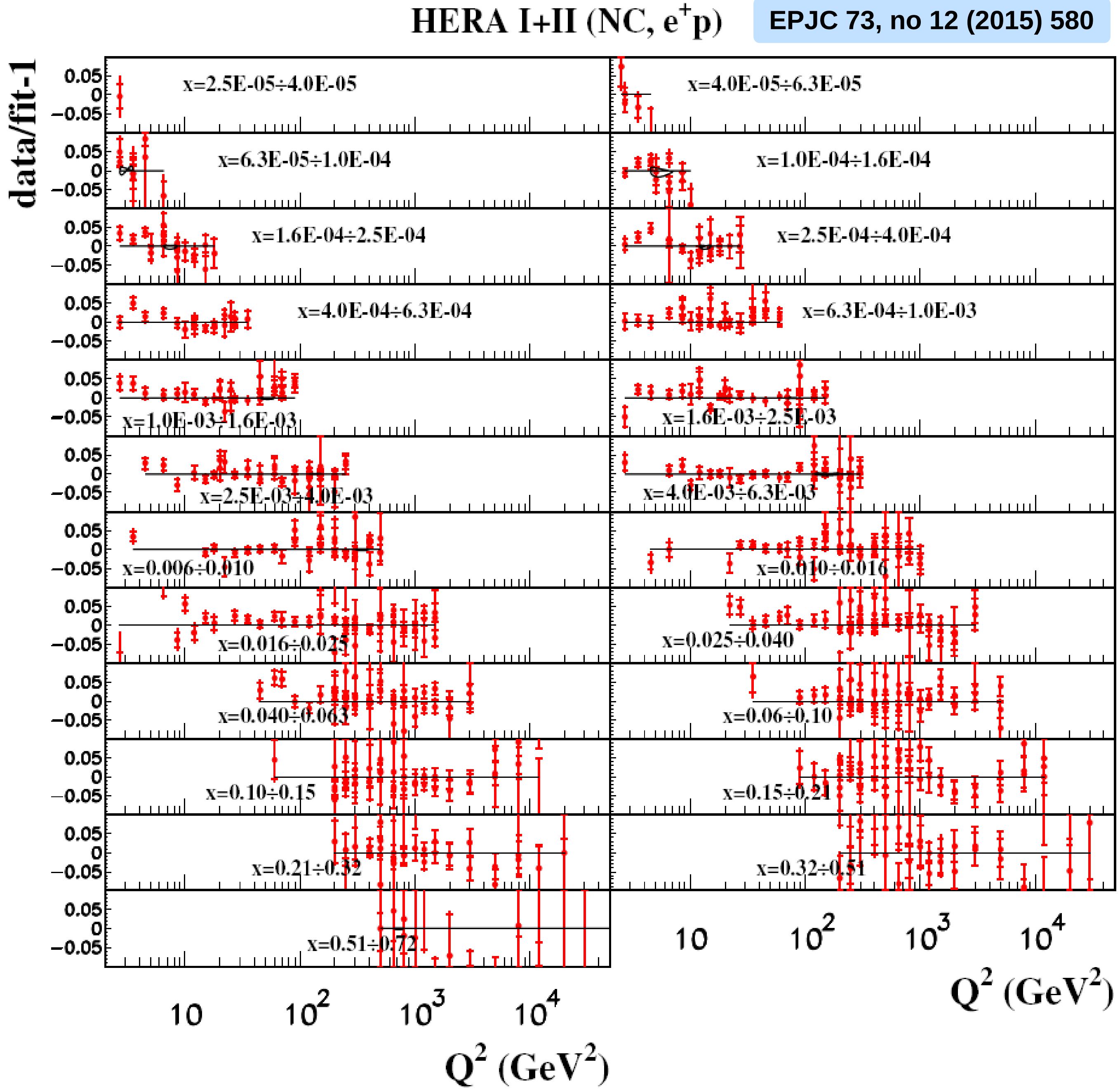
The final HERA I+II combination of inclusive data

→ increased data accuracy, especially in high Q^2 region

→ similar dependence on Q^2_{min} observed:

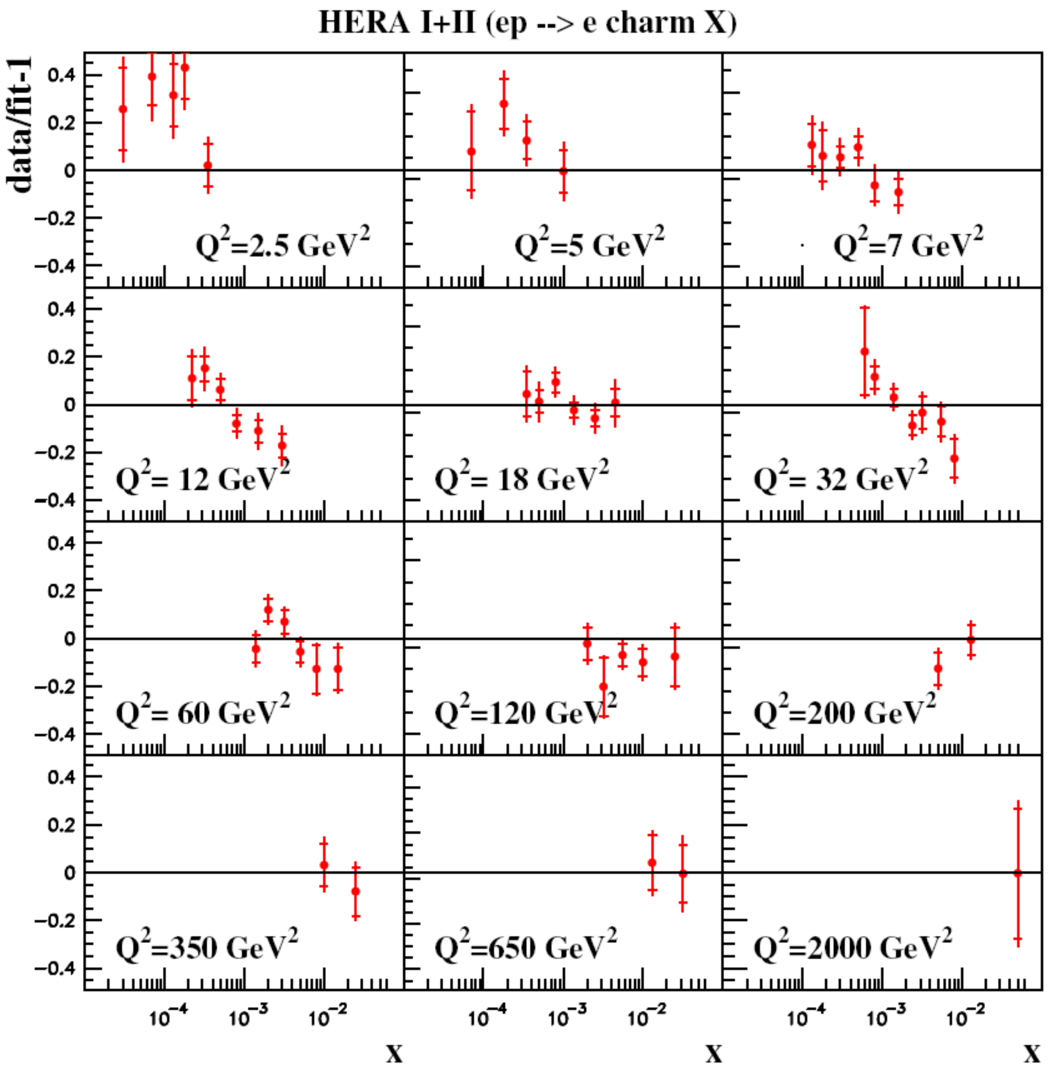
Q^2(HERA)	χ^2/NDP(HERA)
>2.5 GeV²	1509/1168=1.29
>5 GeV²	1354/1092=1.24
>10 GeV²	1228/1007=1.22

EPJC 73, no 12 (2015) 580



HERA Combined Charm Data

EPJC 73, 2311 (2013)



- **ABMP16** includes approximate NNLO massive Wilson coefficients (combination of the threshold corrections, high-energy limit and the NNLO massive OMEs)

Kawamura, Lo Presti, Moch, Vogt NPB 864, 399 (2012)

Update with the pure singlet massive OMEs

Ablinger et al. NPB 890. 48 (2014)

→ improved theoretical uncertainties

Running-mass definition of m_c

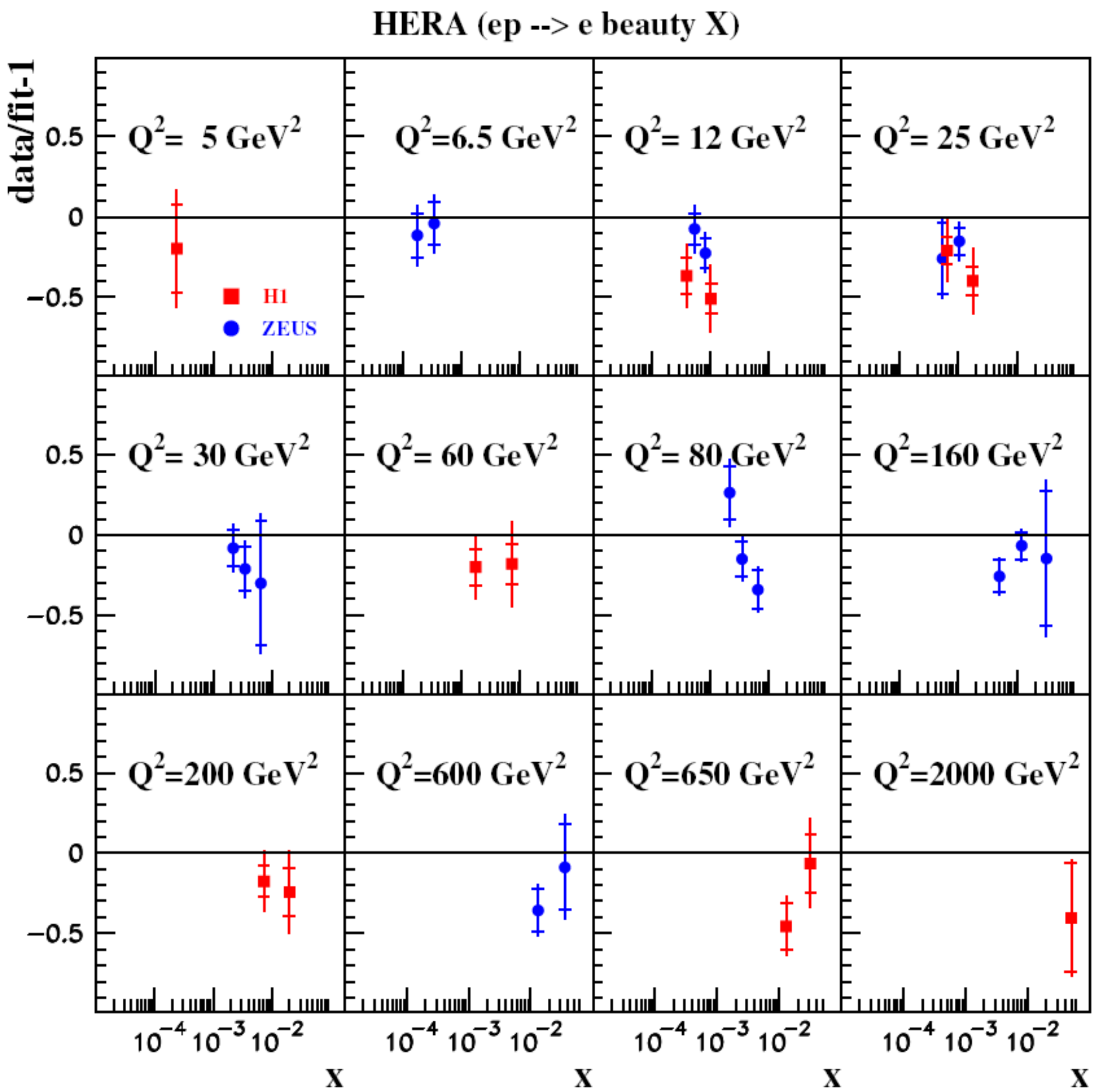
χ^2/NDP=66/52

$m_c(m_c)$=1.252±0.018(exp.)±0.012(th.) GeV ABMP16

$m_c(m_c)$=1.24±0.03(exp.) GeV ABM12

PDG: $m_c(m_c)$=1.275±0.025 GeV

HERA Beauty Data



Similarly to charm, the running-mass definition of m_b used:

H1 **EPJC 65, 89 (2010)**

χ^2/NDP=5/12

ZEUS **JHEP 09, 127 (2014)**

χ^2/NDP=16/17

$m_b(m_b)$=3.83±0.12(exp.)±0.12(th.) GeV

Charm Di-muon Production: NOMAD

In addition to NuTeV and CCFR, a new **NOMAD** (NPB 876, 339 (2013)) data added

→ $\mathcal{R}_{\mu\mu} \equiv \sigma_{\mu\mu}/\sigma_{CC}$ measurement (cancellation of systematics, nuclear corrections)

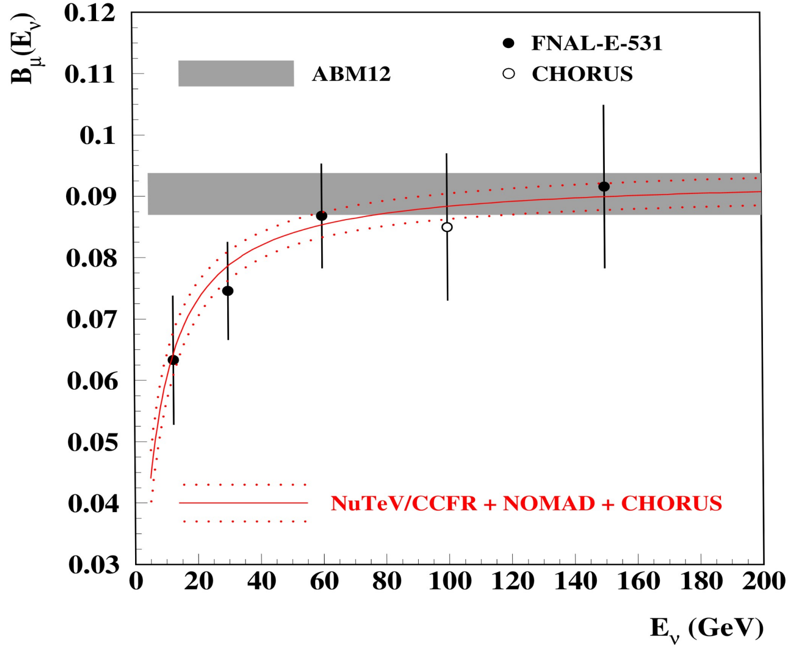
→ extended phase in E_ν = 6 GeV, better sensitivity to charm mass

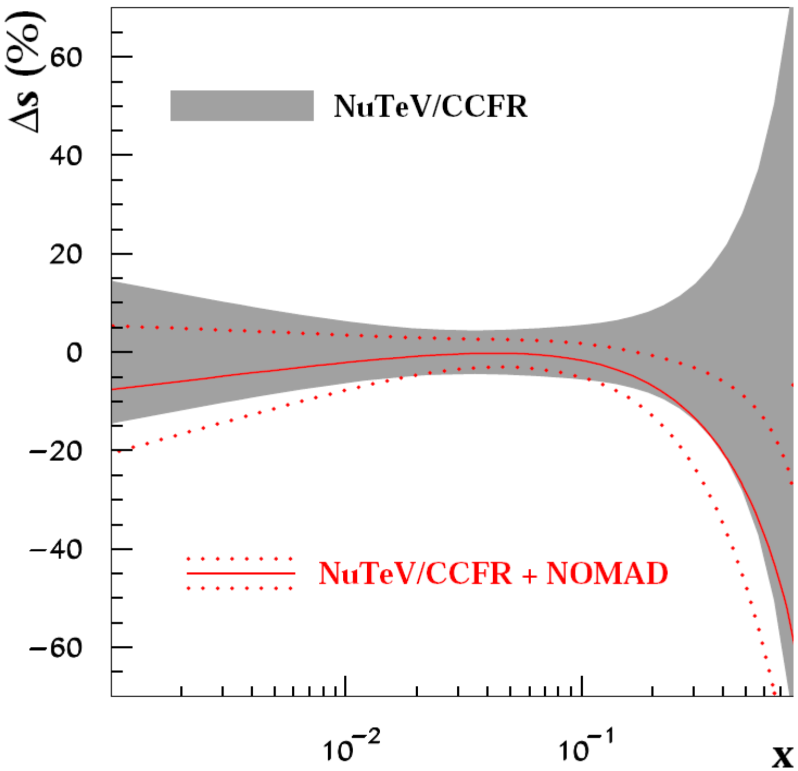
→ dependence on the semi-leptonic branching ratio B_ν:

$$B_\mu(E_\nu)=\sum_h r^h(E_\nu)B_\mu^h = a/(1+b/E_\nu)$$

→ fitted simultaneously with the PDFs, etc. using the constraint from the emulsion data

PRD 91, no 9 (2015) 094002, arXiv:1404.6469





→ prefers smaller s quark at x>0.1, sizable uncertainty reduction

→ $m_c(m_c)$=1.23±0.03(exp.) GeV is comparable to the previous determination in ABM12

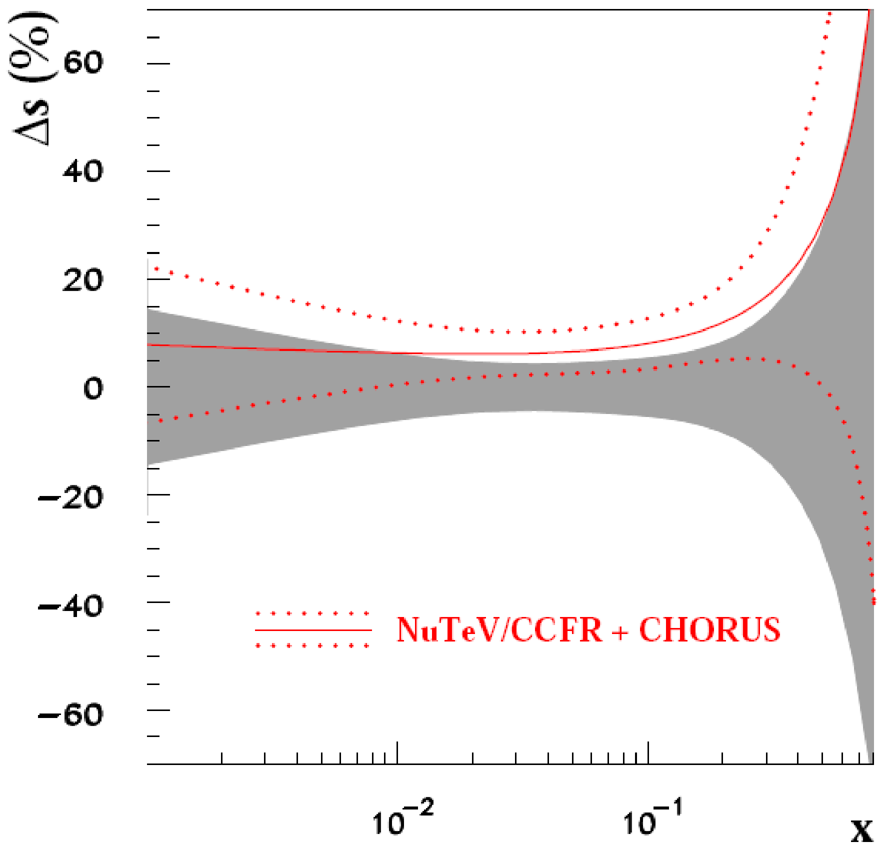
Charm Di-muon Production: CHORUS

Recent **CHORUS** (NJP 13, 093002 (2011)) measurement of $\mathcal{R}_{\mu\mu} \equiv \sigma_{\mu\mu}/\sigma_{CC}$

→ uses nuclear emulsion targets: independence on B_ν

→ lower energy resolution, less statistics

PRD 91, no 9 (2015) 094002, arXiv:1404.6469



→ in contrast to NOMAD, CHORUS prefers enhanced s quark (both measurements are consistent within uncertainties)

→ statistical significance of the effect is small

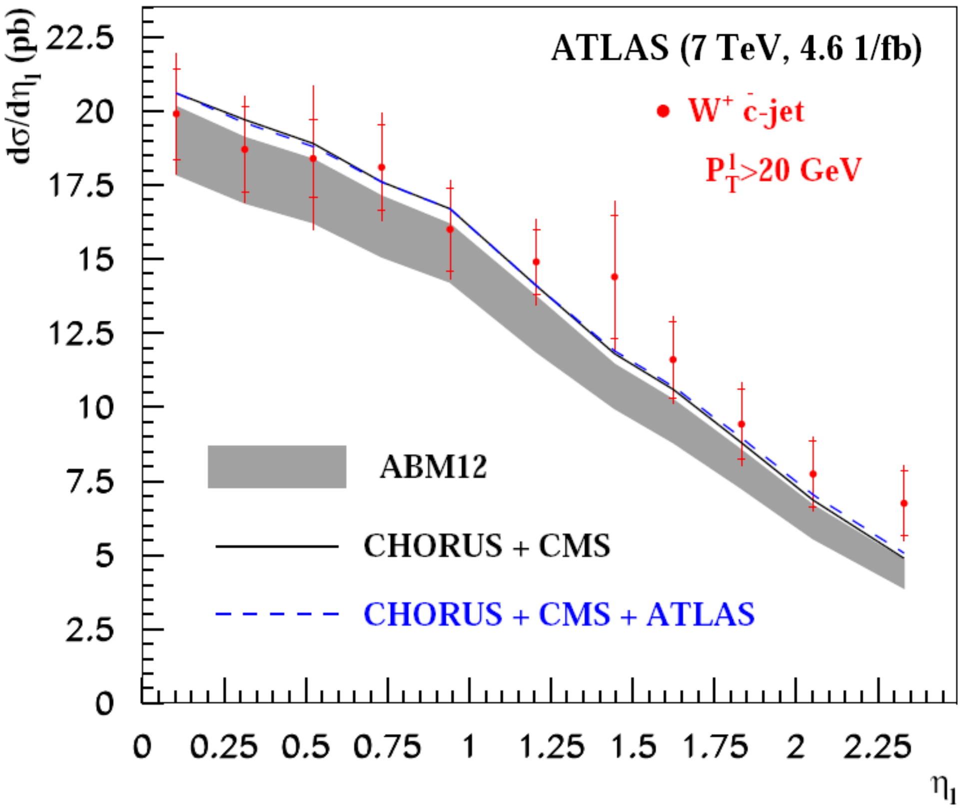
W+charm Data from LHC

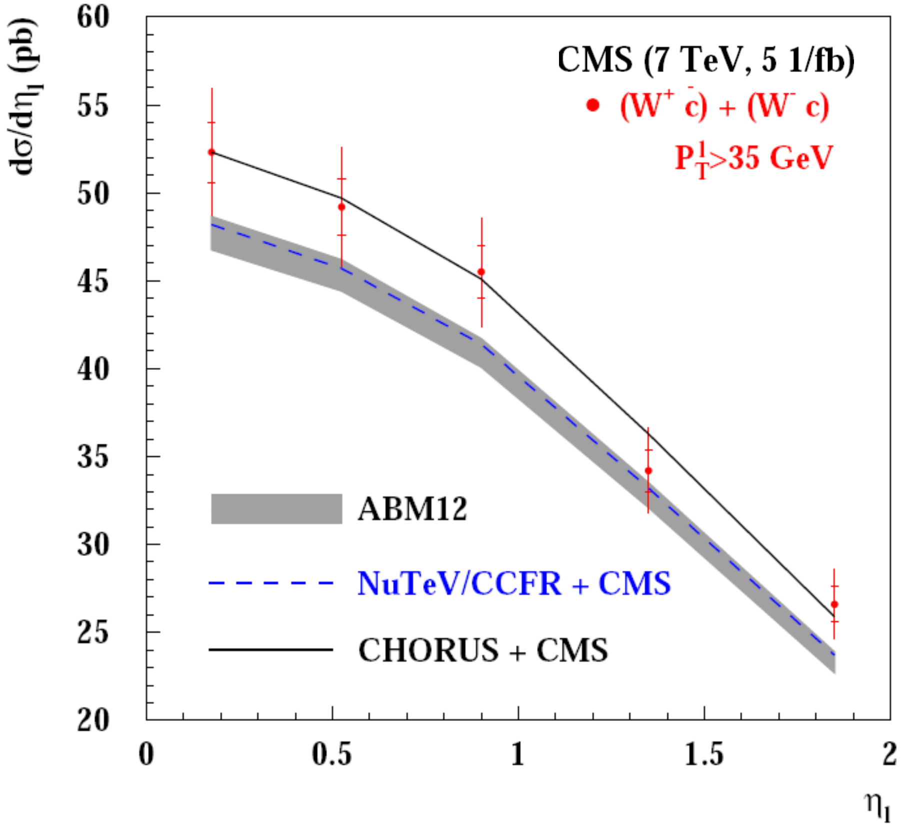
PRD 91, no 9 (2015) 094002, arXiv:1404.6469

W+charm production at LHC → direct sensitivity to strange quark

→ corresponding measurements at 7 TeV published by ATLAS and CMS collaborations

JHEP 05 (2014) 068 JHEP 02, 013 (2014)





→ enhances strange sea from ATLAS determination: correlated with d-quark sea suppression

→ CMS data in good agreement with CHORUS data, overall little impact on strange sea

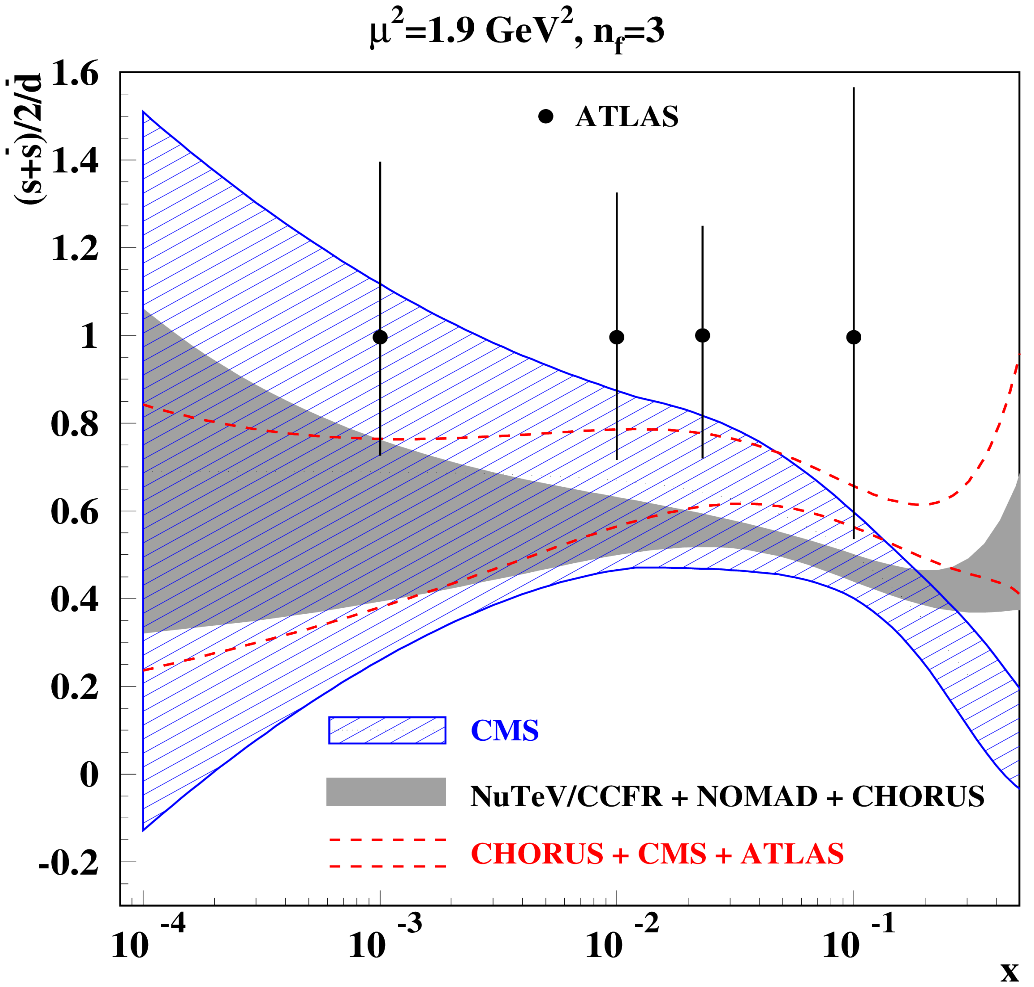
→ due to little impact, both measurements are **not** included in ABMP16 fit

Strange Sea in ABMP16

PRD 91, no 9 (2015) 094002, arXiv:1404.6469

Strange quark is the least known from the light quarks

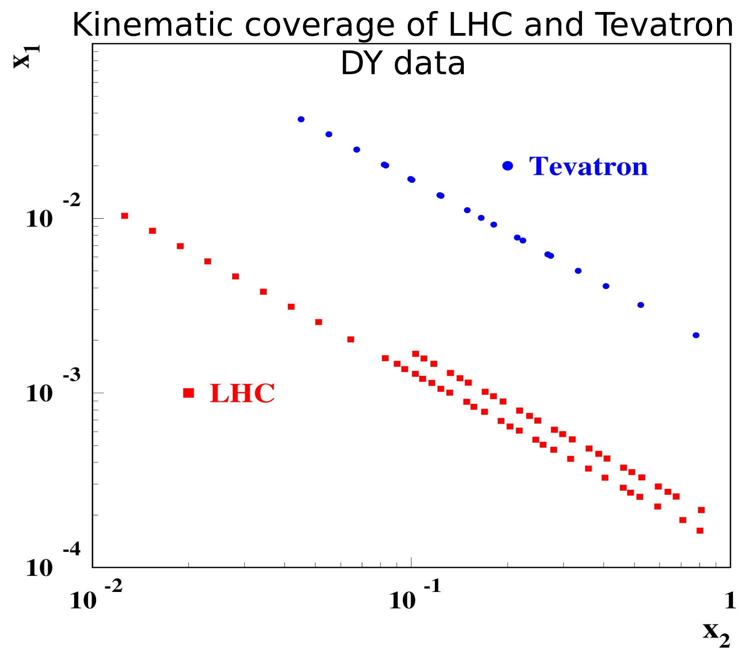
Update of **ABMP** PDFs with latest fixed target data (NOMAD+CHORUS) with smaller uncertainties on s-quark PDF



Drell-Yan (DY) Production in Hadron Colliders

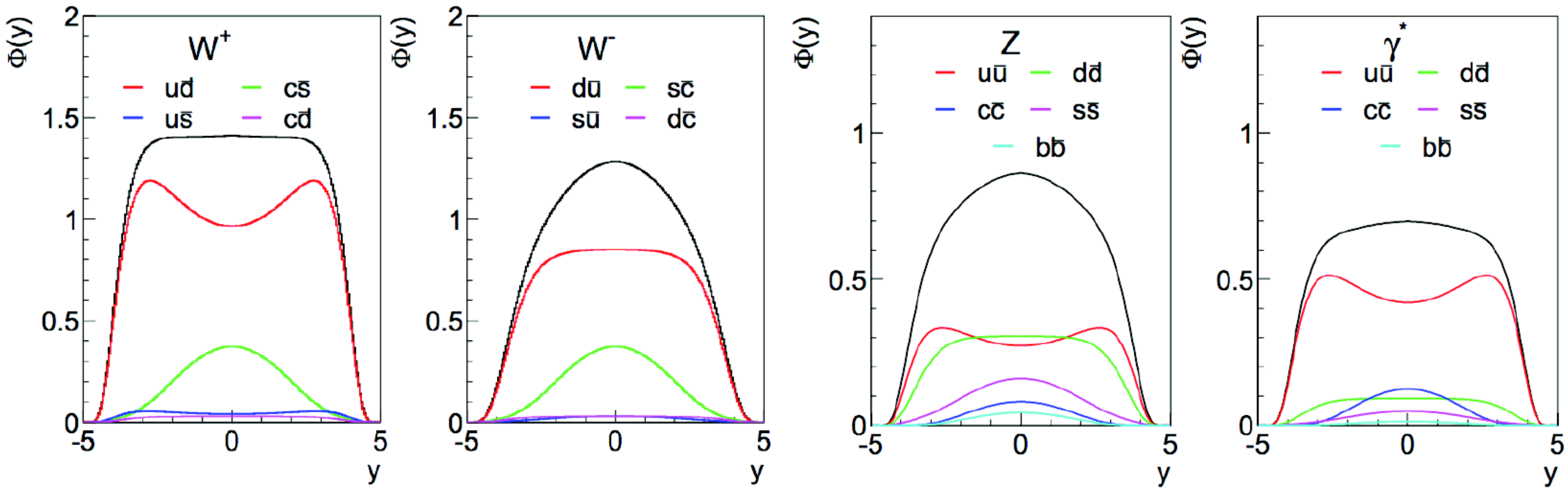
Z and W production at LHC and Tevatron

- → probe different flavour combinations
- → potential to improve quark PDFs
- → forward W,Z production probes small/large x
  - → complementary to the DIS, constraint on the quark iso-spin asymmetry



$$W^+ \approx 0.95(u\bar{d} + c\bar{s}) + 0.05(u\bar{s} + c\bar{d})$$
$$W^- \approx 0.95(d\bar{u} + s\bar{c}) + 0.05(d\bar{c} + s\bar{u})$$

$$Z \approx 0.29(u\bar{u} + c\bar{c}) + 0.37(d\bar{d} + s\bar{s} + b\bar{b})$$
$$\gamma^* \approx 0.44(u\bar{u} + c\bar{c}) + 0.11(d\bar{d} + s\bar{s} + b\bar{b})$$



(A.Glazov/V.Radescu)

Drell-Yan (DY) Production in Hadron Colliders

Latest Z and W production data from LHC and Tevatron used in the **ABMP16** fit

Experiment		ATLAS		CMS		DØ		LHCb		
$\sqrt{s}$ (TeV)		7	13	7	8	1.96		7	8	
Final states		$W^+ \to l^+ \nu$ $W^- \to l^- \nu$ $Z \to l^+ l^-$	$W^+ \to l^+ \nu$ $W^- \to l^- \nu$ $Z \to l^+ l^-$	$W^+ \to \mu^+ \nu$ $W^- \to \mu^- \nu$ (asym)	$W^+ \to \mu^+ \nu$ $W^- \to \mu^- \nu$	$W^+ \to \mu^+ \nu$ $W^- \to \mu^- \nu$ (asym)	$W^+ \to e^+ \nu$ $W^- \to e^- \nu$ (asym)	$W^+ \to \mu^+ \nu$ $W^- \to \mu^- \nu$ $Z \to \mu^+ \mu^-$	$Z \to e^+ e^-$	$W^+ \to \mu^+ \nu$ $W^- \to \mu^- \nu$ $Z \to \mu^+ \mu^-$
Cut on the lepton P_T		$P_T^l > 20$ GeV	$P_T^e > 25$ GeV	$P_T^\mu > 25$ GeV	$P_T^\mu > 25$ GeV	$P_T^\mu > 25$ GeV	$P_T^e > 25$ GeV	$P_T^\mu > 20$ GeV	$P_T^e > 20$ GeV	$P_T^\mu > 20$ GeV
Luminosity (1/fb)		0.035	81	4.7	18.8	7.3	9.7	1	2	2.9
Reference		[63]	[21]	[17]	[18]	[16]	[15]	[19]	[20]	[14]
NDP		30	6	11	22	10	13	31	17	34
χ^2	present analysis [a]	31.0	9.2	22.4	16.5	17.6	19.0	45.1	21.7	40.0
	CJ15 [6]	–	–	–	–	20	29	–	–	–
	CT14 [7]	42	–	– [b]	–	–	34.7	–	–	–
	JR14 [8]	–	–	–	–	–	–	–	–	–
	HERAFitter [66]	–	–	–	–	13	19	–	–	–
	MMHT14 [9]	39	17	–	–	21	–	–	–	–
	NNPDF3.0 [10]	35.4	7.3[c]	18.9	–	–	–	–	–	–

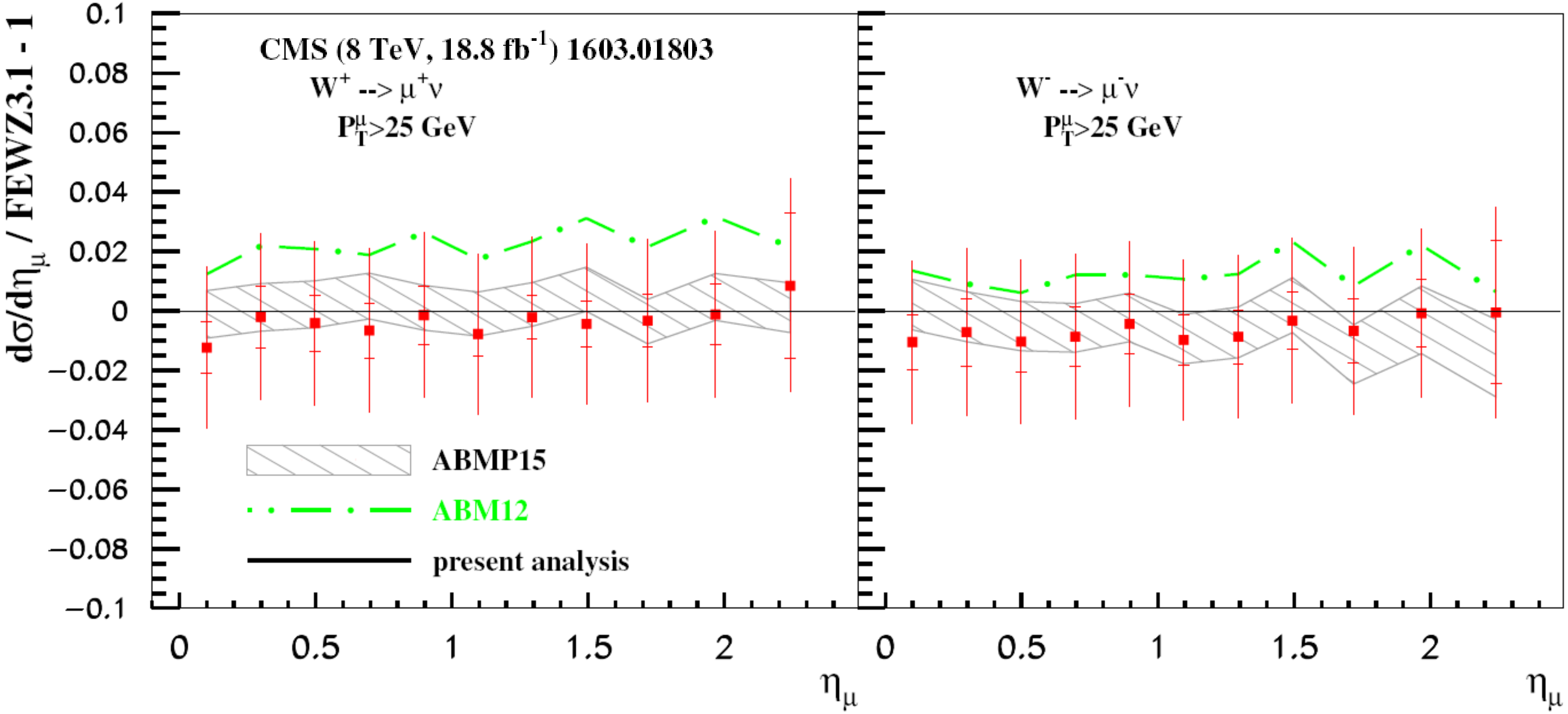
→ good description of all DY data (details in following slides)

CMS W^+, W^- Production Data

CMS measurement of the differential W cross section and charge asymmetry at 8 TeV

→ very good description of data, χ^2 = 16.5/22 NDP

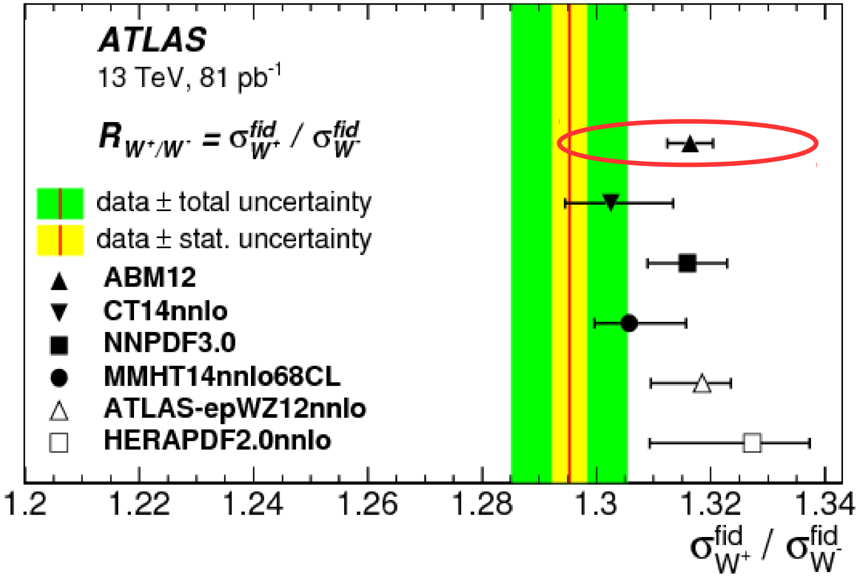
arXiv:1603.01803

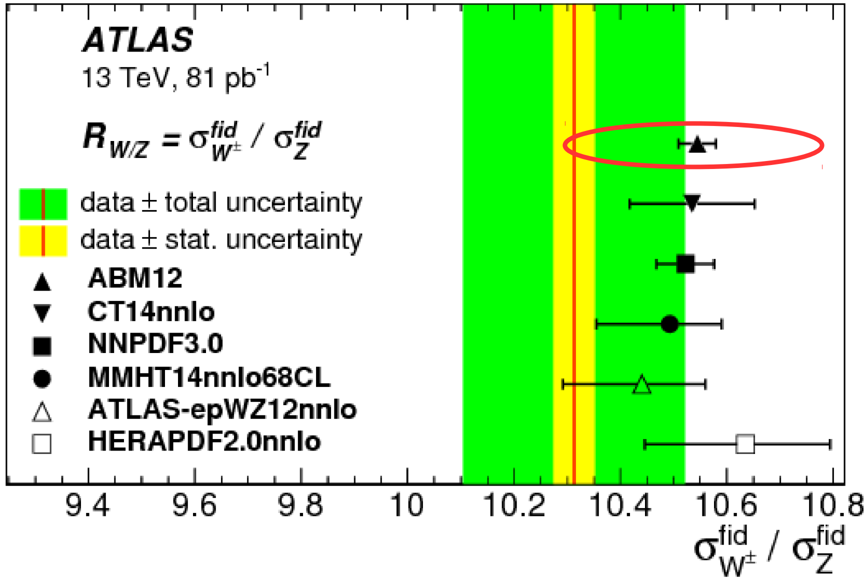


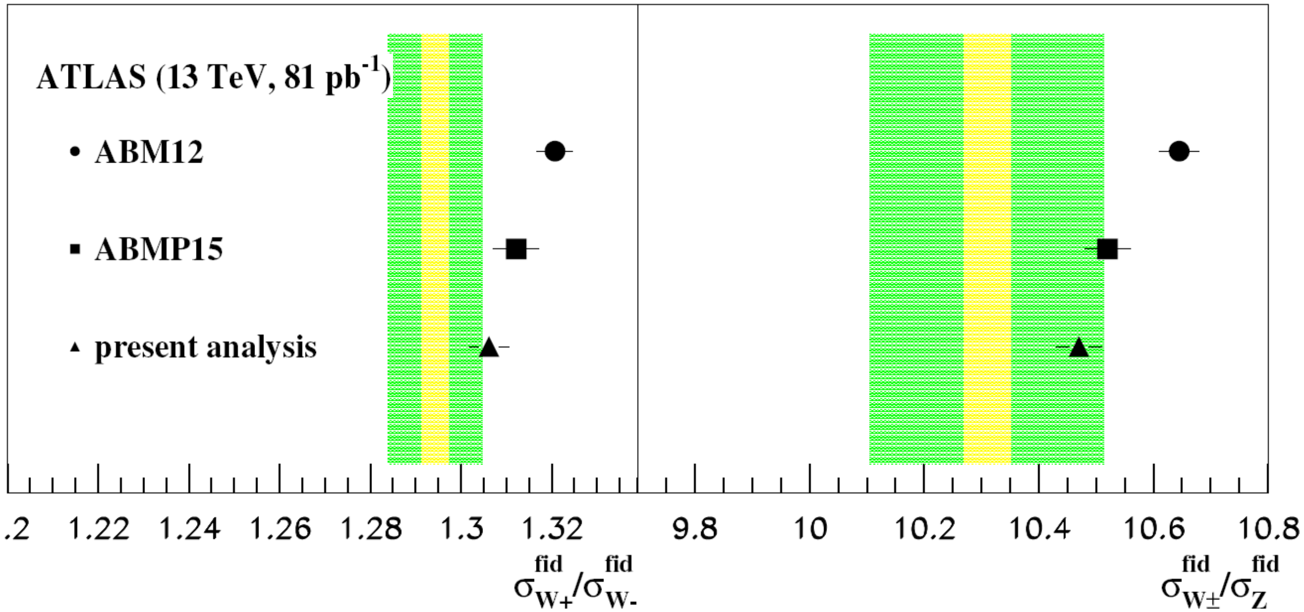
Earlier study and description of CMS W asymmetry data at 7 TeV available in arXiv:1508.07923

ATLAS DY Production Data at 13 TeV

PLB 759 (2016) 601



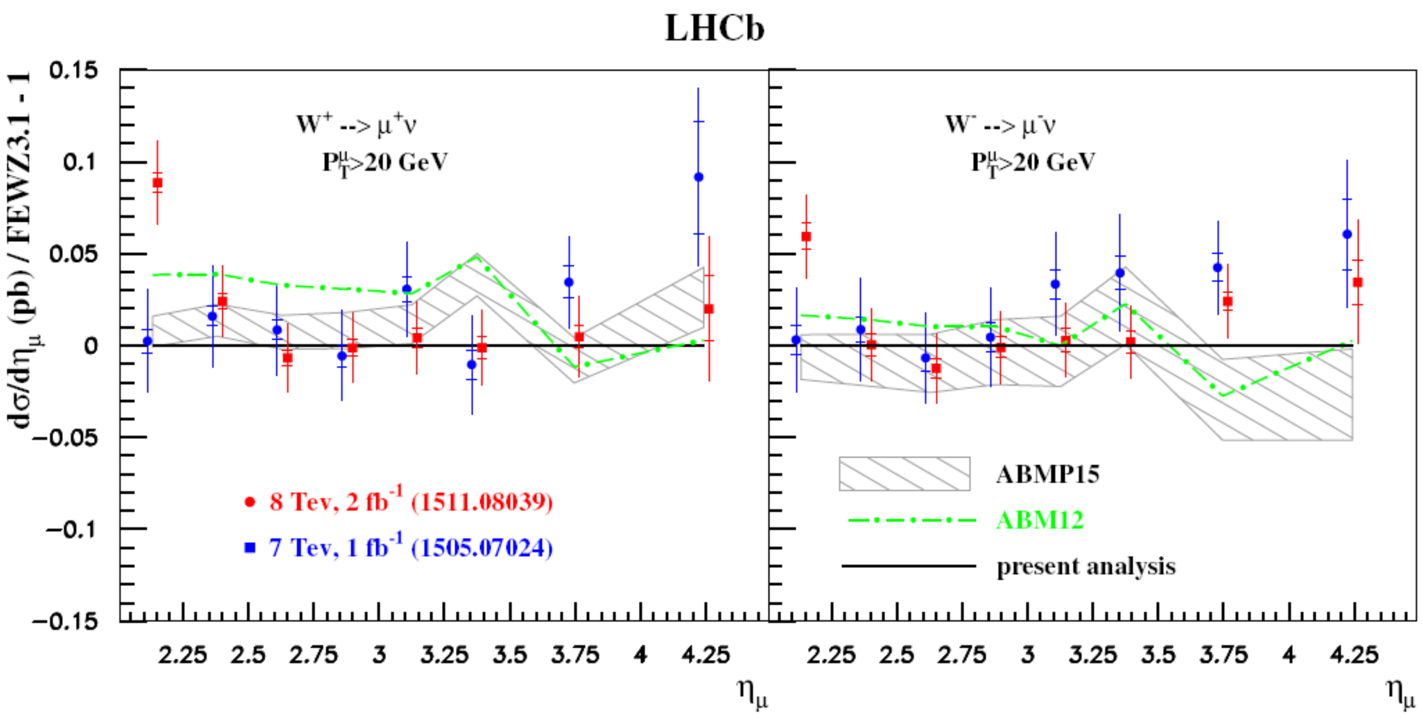


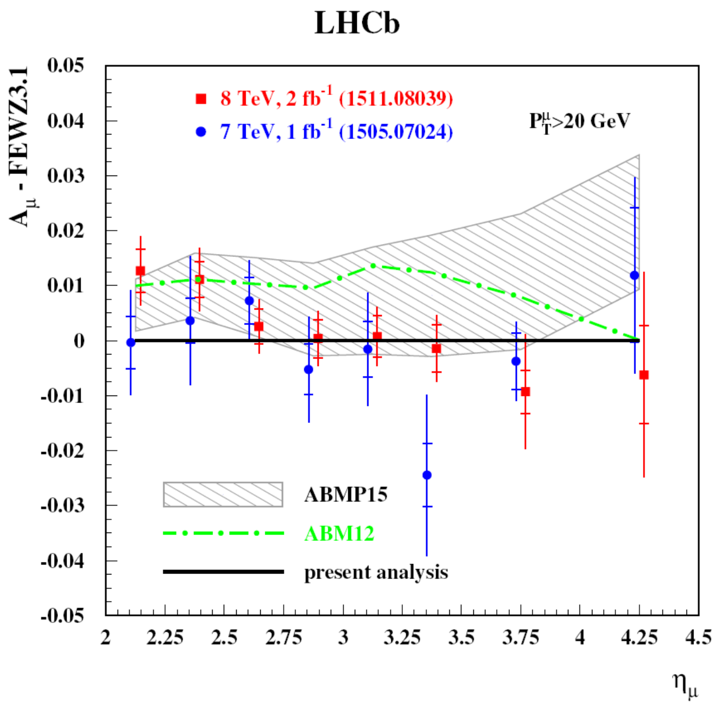


→ ATLAS W,Z inclusive data well accommodated into the fit, χ^2 = 9.2/6 NDP

LHCb W^+, W^- and Asymmetry Data

LHCb W-boson production and asymmetry data: constraints of PDFs in the low-x region





Some fluctuations observed in the data:

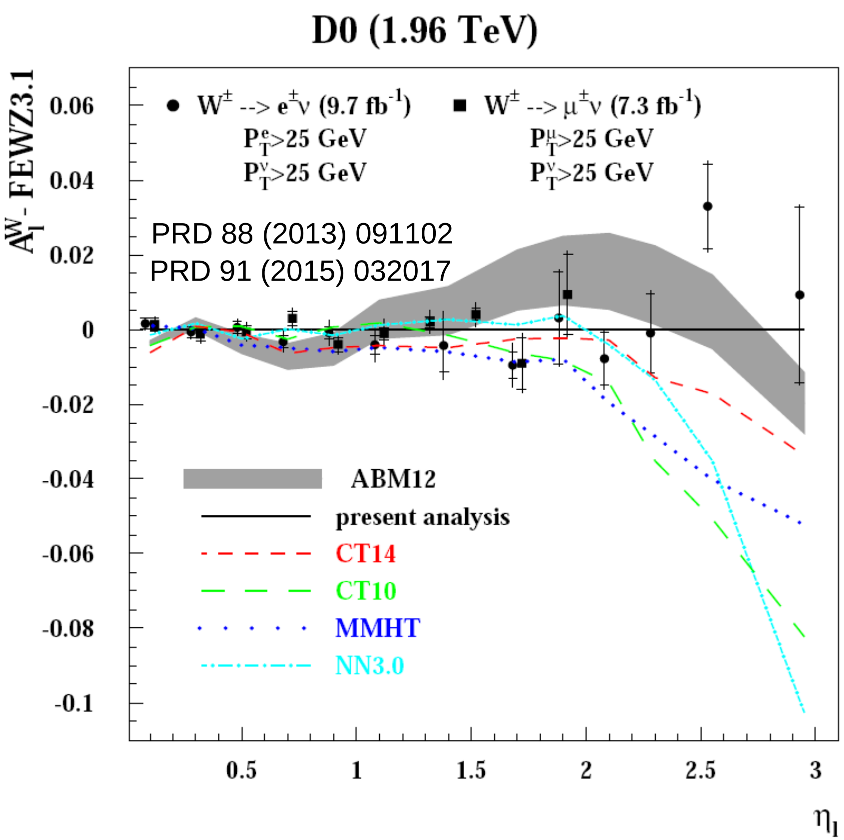
→ LHCb W asymmetry data at 7 TeV: η_μ = 3.275 bin excluded from the fit

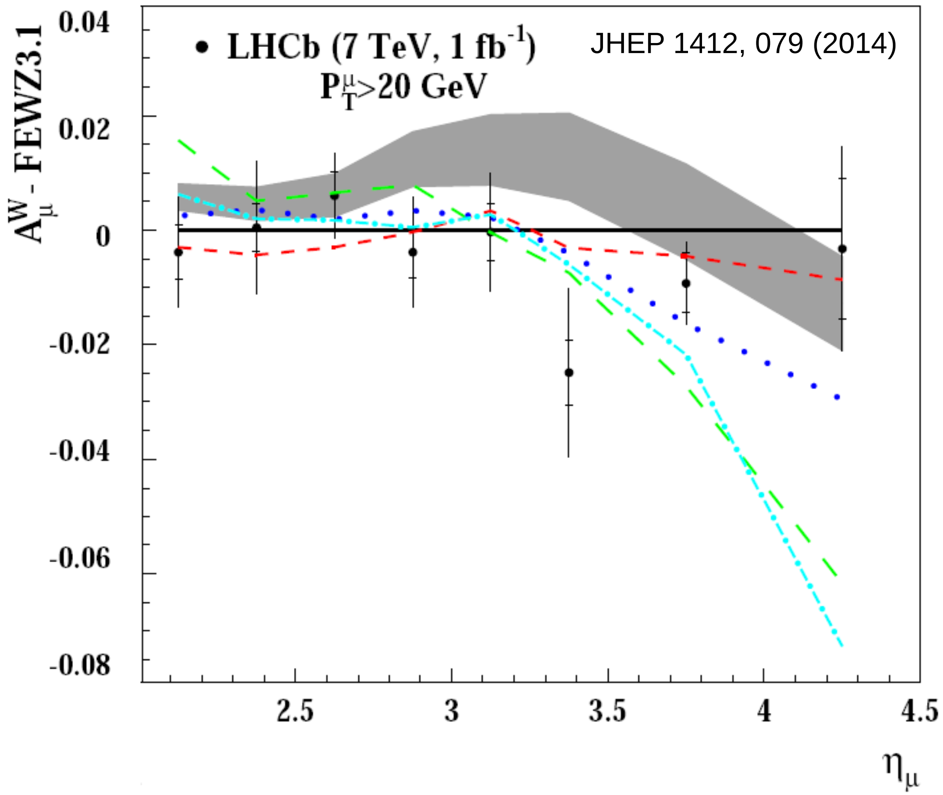
→ for W production data in muon channel point at small η_μ (8 TeV) excluded

→ LHCb Z electron data at 7 TeV show different trend as compared to the muon ones
→ excluded from the fit until these issues are resolved

→ 13 TeV data are also not yet included (currently larger uncertainties than in earlier sets)

DY Data and Theory Predictions





DY data compared with theory predictions calculated with FEWZ (PRD 094034 (2012), CPC 184, 208 (2013))

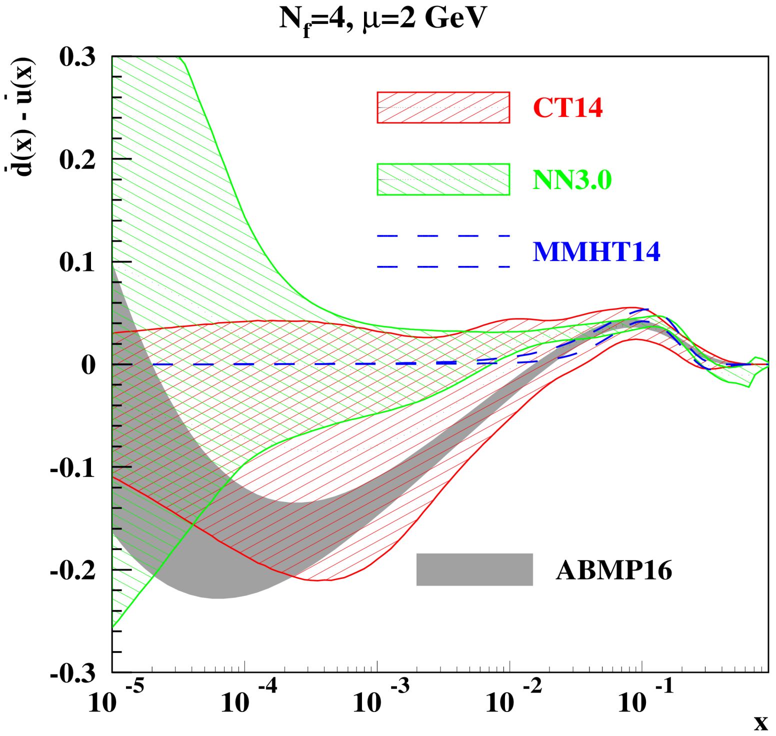
→ using interpolation of accurate NNLO grids (similar to FastNLO and Applgrid)

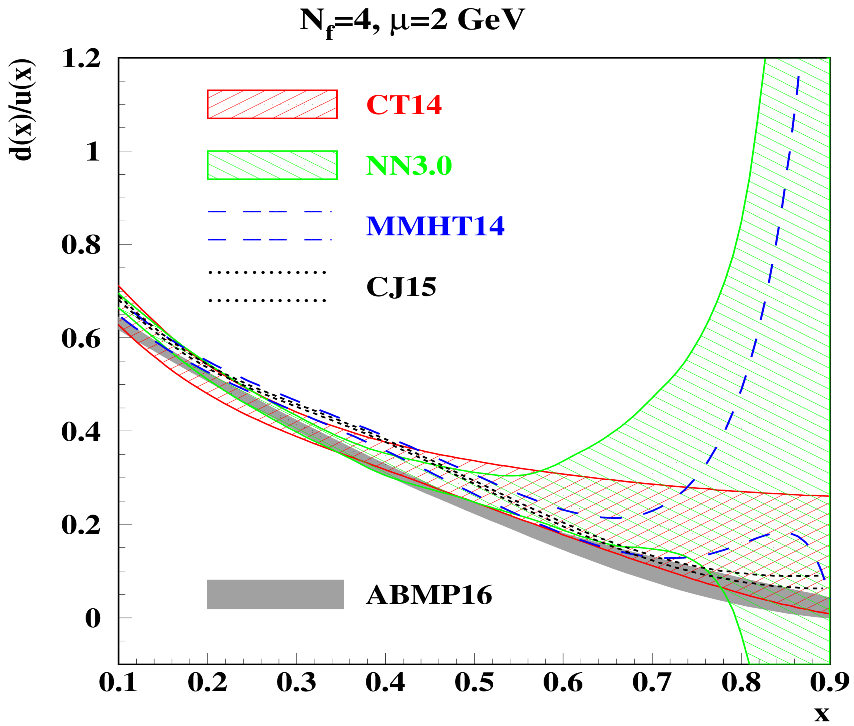
→ other PDF groups often use NLO+NNLO k-factor technique, may cause additional differences

Full study available in **arXiv:1508.07923**

Impact of the Forward DY Data

Precise forward DY data allow to relax parametrisation of the sea iso-spin asymmetry at small x



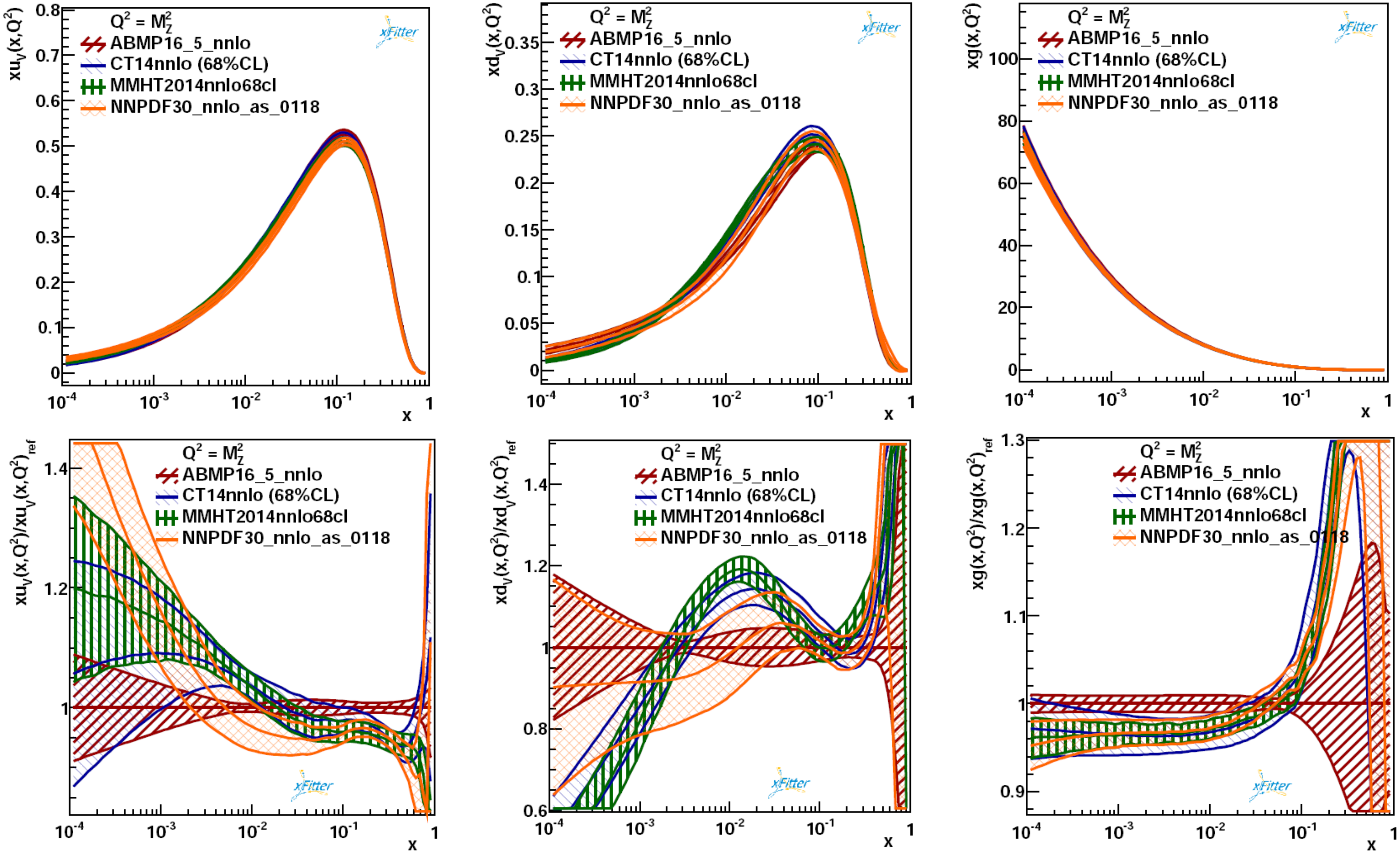


→ Regge-like behaviour is recovered only at $x \sim 10^{-6}$**,** at large x it is still defined by the phase-space constraint

→ constraint on the d/u ratio without deuteron data
→ independent extraction of the deuteron corrections (**PRD 93, 114017 (2016)** and **arXiv:1609.08463**)

→ large spread between different PDF sets (large x)

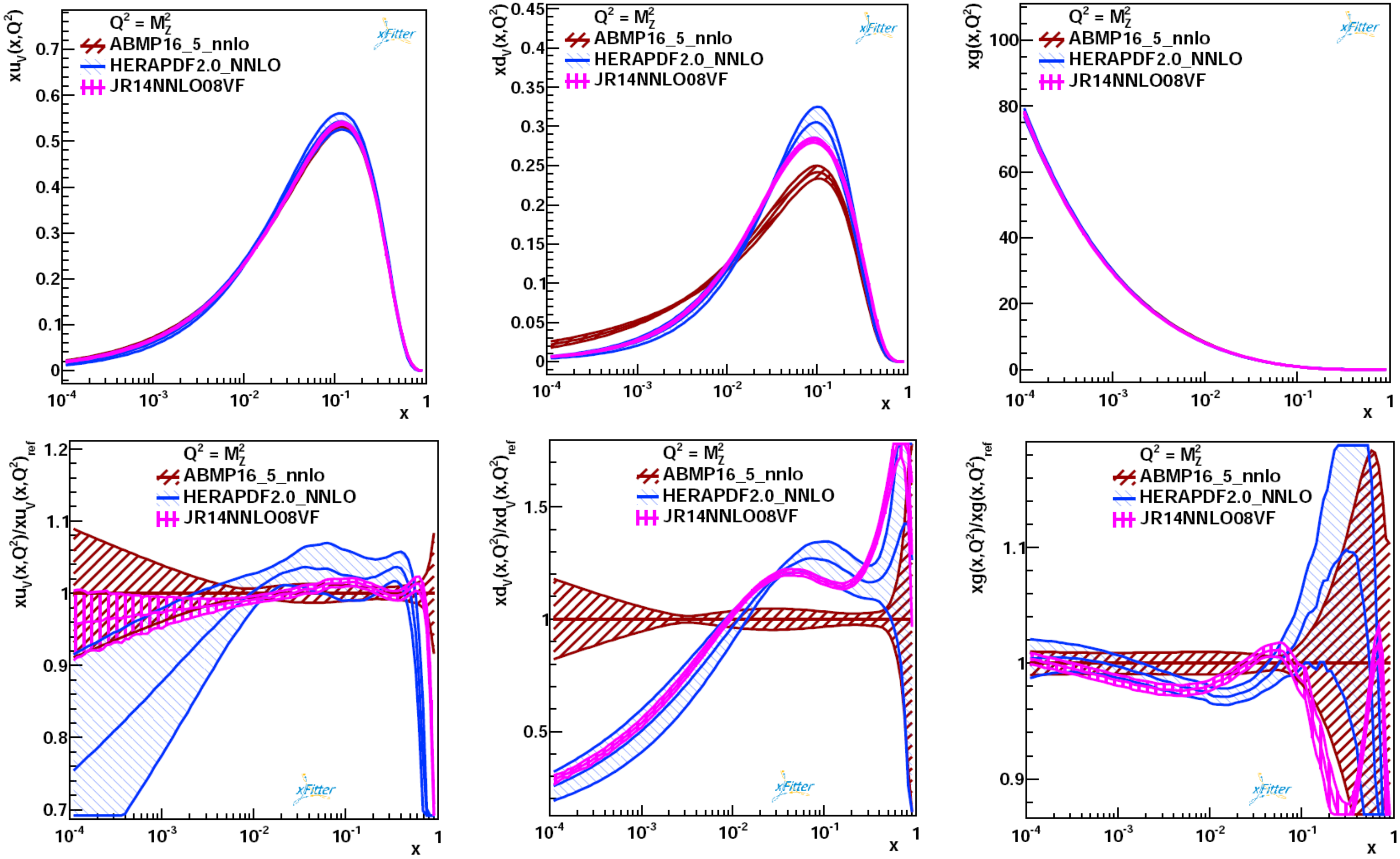
Comparison with other PDFs



Overall good agreement, smaller uncertainties due to latest data added in ABMP16 fit

→ smaller gluon at low x (compared to other global PDFs)

Comparison with other PDFs



Overall good agreement, smaller uncertainties due to latest data added in ABMP16 fit

→ different d_v quark shape compared to HERAPDF2.0

Summary

New **ABMP16** Parton Distribution Functions:

- deuteron data are replaced by the LHC and Tevatron Drell-Yan data
  → reduced theoretical uncertainties in PDFs, in particular in d/u at large x
- the small-x iso-spin sea asymmetry is relaxed and turns negative at $x \sim 10^{-3}$;
  an onset of the Regge asymptotics still may occur at $x < 10^{-5}$
- improved strange sea determination, particularly at large x
- impact of the ttbar data and $\alpha_s(M_Z)$ extraction *→ see S. Alekhin's talk*
- final HERA inclusive I+II data and t-quark data from LHC and Tevatron included
  → improved determination of heavy quark masses:

$$m_c(m_c) = 1.252 \pm 0.018 \text{ GeV}$$
$$m_b(m_b) = 3.83 \pm 0.12 \text{ GeV}$$
$$m_t(m_t) = 160.9 \pm 1.1 \text{ GeV}$$

- New ABMP16 grids (in LHAPDFv6 format) available upon request (soon in LHAPDF hepforge page)

ABMP16_3_NNLO
ABMP16_4_NNLO
ABMP16_5_NNLO

Back-up Slides

ABMP16 PDFs: Parametrisation

FIT PARAMETRISATION:

$$xq_v(x, Q_0^2) = \frac{2\delta_{qu} + \delta_{qd}}{N_q^v} x^{a_q} (1-x)^{b_q} x^{P_{qv}(x)}$$

$$P_{qv}(x) = \gamma_{1,q} x + \gamma_{2,q} x^2 + \gamma_{3,q} x^3$$

$$xg(x, Q_0^2) = A_g x^{a_g} (1-x)^{b_g} x^{a_g P_g(x)}$$

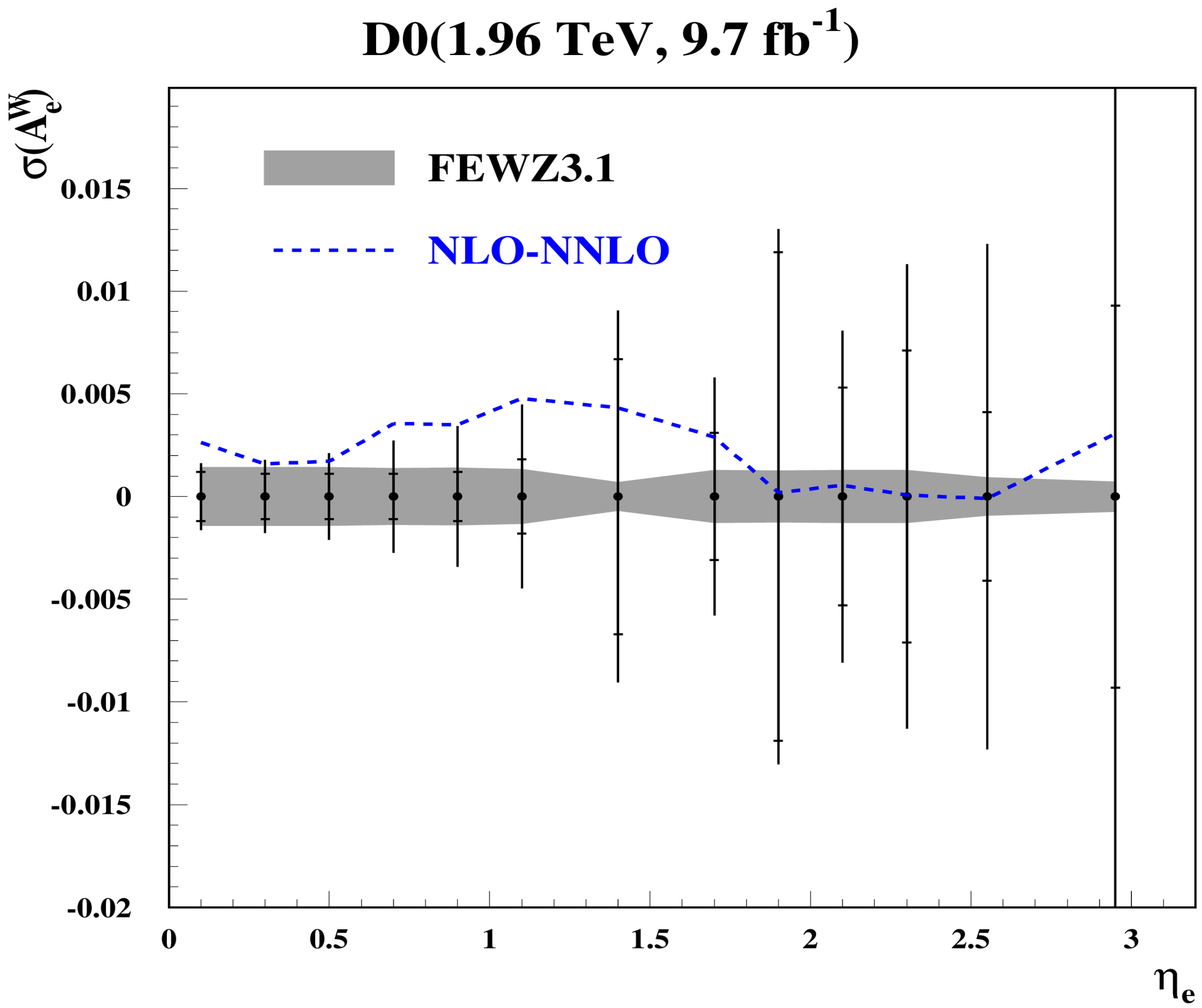
$$P_g(x) = \gamma_{1,g} x$$

$$xq_s(x, \mu_0^2) = \bar{q}_s(x, \mu_0^2) = A_{qs} (1-x)^{b_{qs}} x^{a_{qs} P_{qs}(x)}$$

$$q = u, d, s, \qquad P_{qs}(x) = (1 + \gamma_{-1,qs} \ln x)(1 + \gamma_{1,qs} x)$$

allows non-zero values of the sea isospin asymmetry: $I(x) = x[\bar{d}(x) - \bar{u}(x)]$

Computation Accuracy



- Accuracy of O(1 ppm) is required to meet uncertainties in the experimental data → O(10^4 h) of running FEWZ 3.1 in NNLO
- An interpolation grid a la FASTNLO is used

NNLO DY Corrections in the fit

The existing NNLO codes (DYNNLO, FEWZ) are quite time-consuming → fast tools are employed (FASTNLO, Applgrid,.....)

- the corrections for certain basis of PDFs are stored in the grid
- the fitted PDFs are expanded over the basis
- the NNLO c.s. in the PDF fit is calculated as a combination of expansion coefficients with the pre-prepared grids

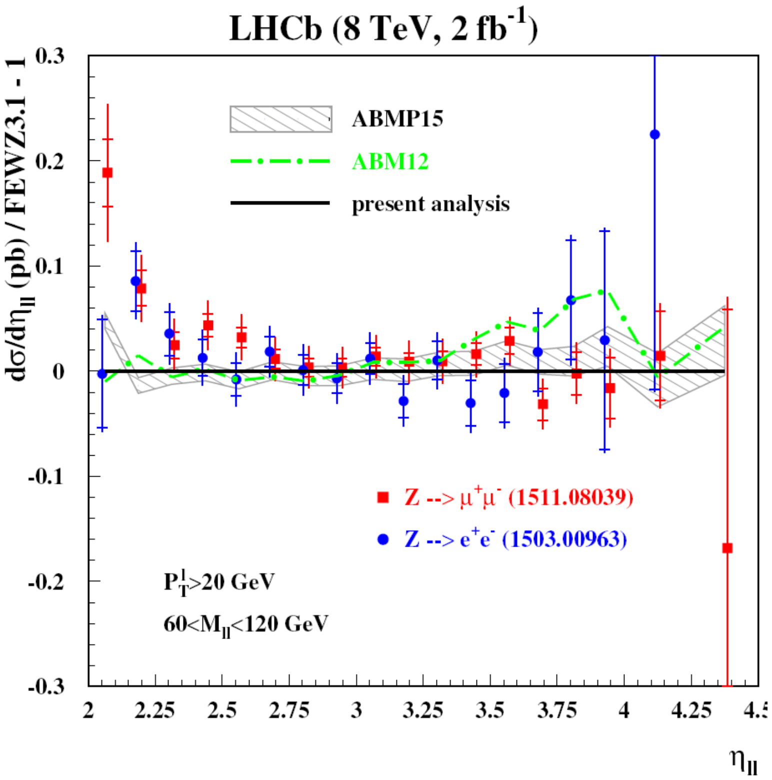
The general PDF basis is not necessary since the PDFs are already constrained by the data, which do not require involved computations → *use as a PDF basis the eigenvalue PDF sets obtained in the earlier version of the fit*

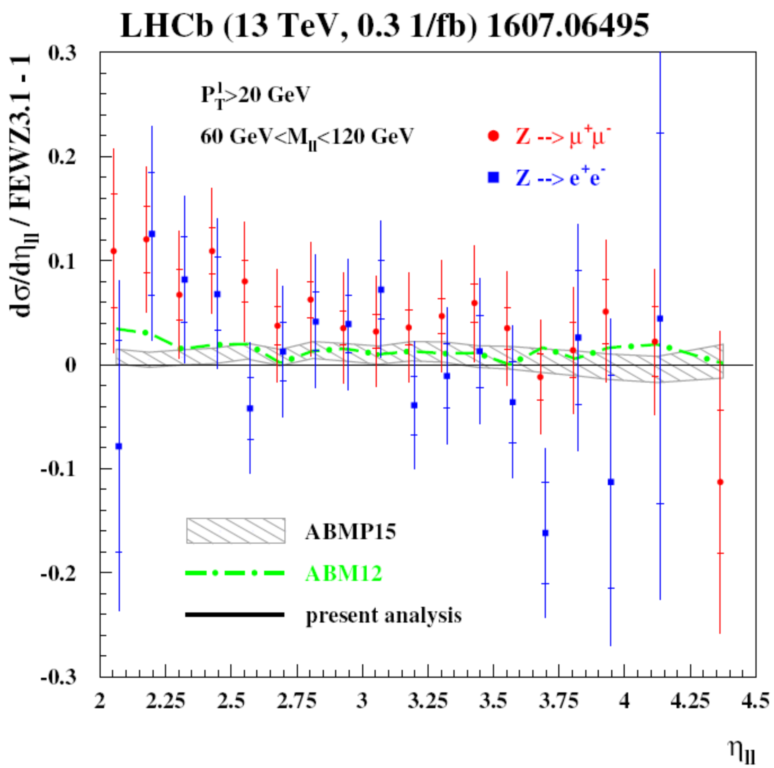
$\mathbf{P_0} \pm \Delta\mathbf{P}_0$ – vector of PDF parameters with errors obtained in the earlier fit
E – error matrix
P – current value of the PDF parameters in the fit

- store the DY NNLO c.s. for all PDF sets defined by the eigenvectors of **E**
- the variation of the fitted PDF parameters ($\mathbf{P} - \mathbf{P}_0$) is transformed into this eigenvector basis
- the NNLO c.s. in the PDF fit is calculated as a combination of transformed ($\mathbf{P} - \mathbf{P}_0$) with the stored eigenvector values

LHCb W^+, W^- Production Data

LHCb Z-boson production data: constraints of PDFs in the low-x region



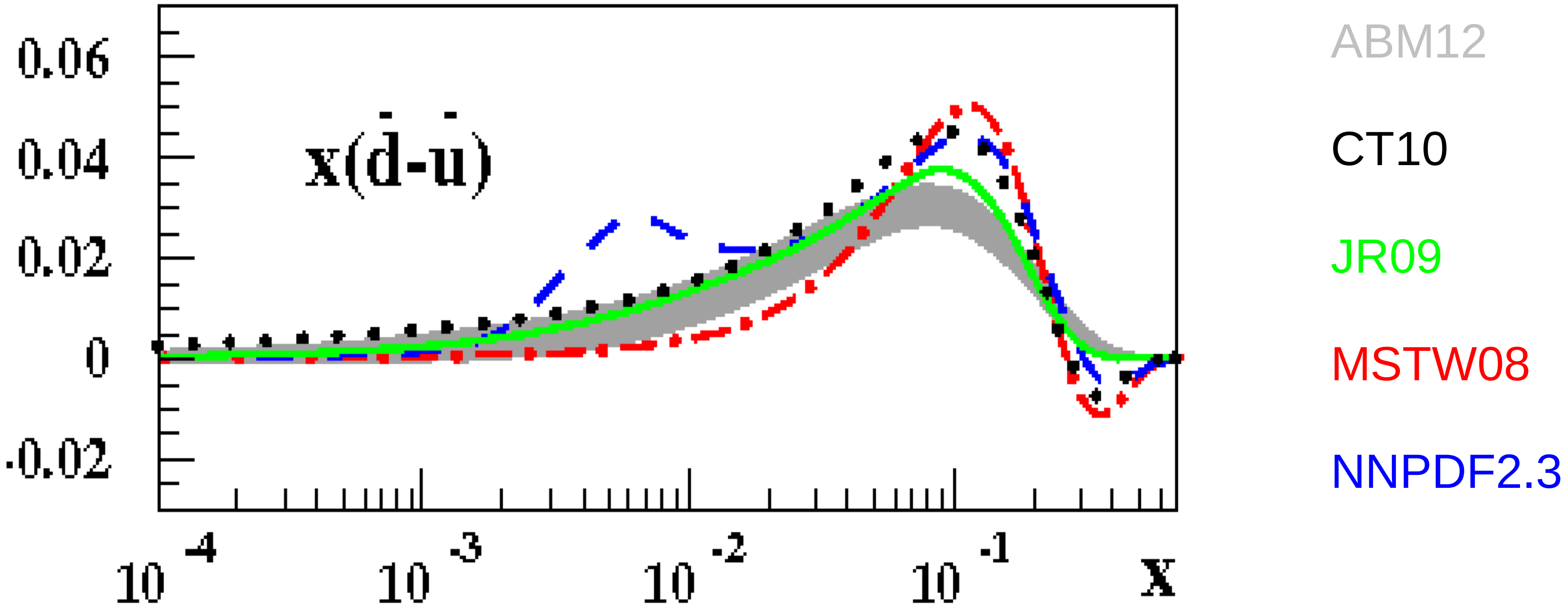


→ LHCb Z electron data at 7 TeV show different trend as compared to the muon ones

→ excluded from the fit until these issues are resolved

→ 13 TeV data are also not yet included (currently larger uncertainties than in earlier sets)

Sea Iso-Spin asymmetry



sa, Blümlein, Moch PRD 89, 054028 (2014)

- At x~0.1 the sea quark iso-spin asymmetry is controlled by the fixed-target DY data (E-866), weak constraint from the DIS (NMC)

- At x<0.01 Regge-like constraint like $x^{(a-1)}$, with a close to the meson trajectory intercept; the “unbiased” NNPDF fit follows the same trend

Onset of the Regge asymptotics is out of control

Comparison with other PDFs: d-u