Nuclear PDFs

Ingo Schienbein
Université Grenoble Alpes/LPSC Grenoble

Laboratoire de Physique Subatomique et de Cosmologie

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Outline

- Introduction
- Brief review of available nuclear PDFs
- Vector boson production and the strange PDF
- Wishlist and Conclusions

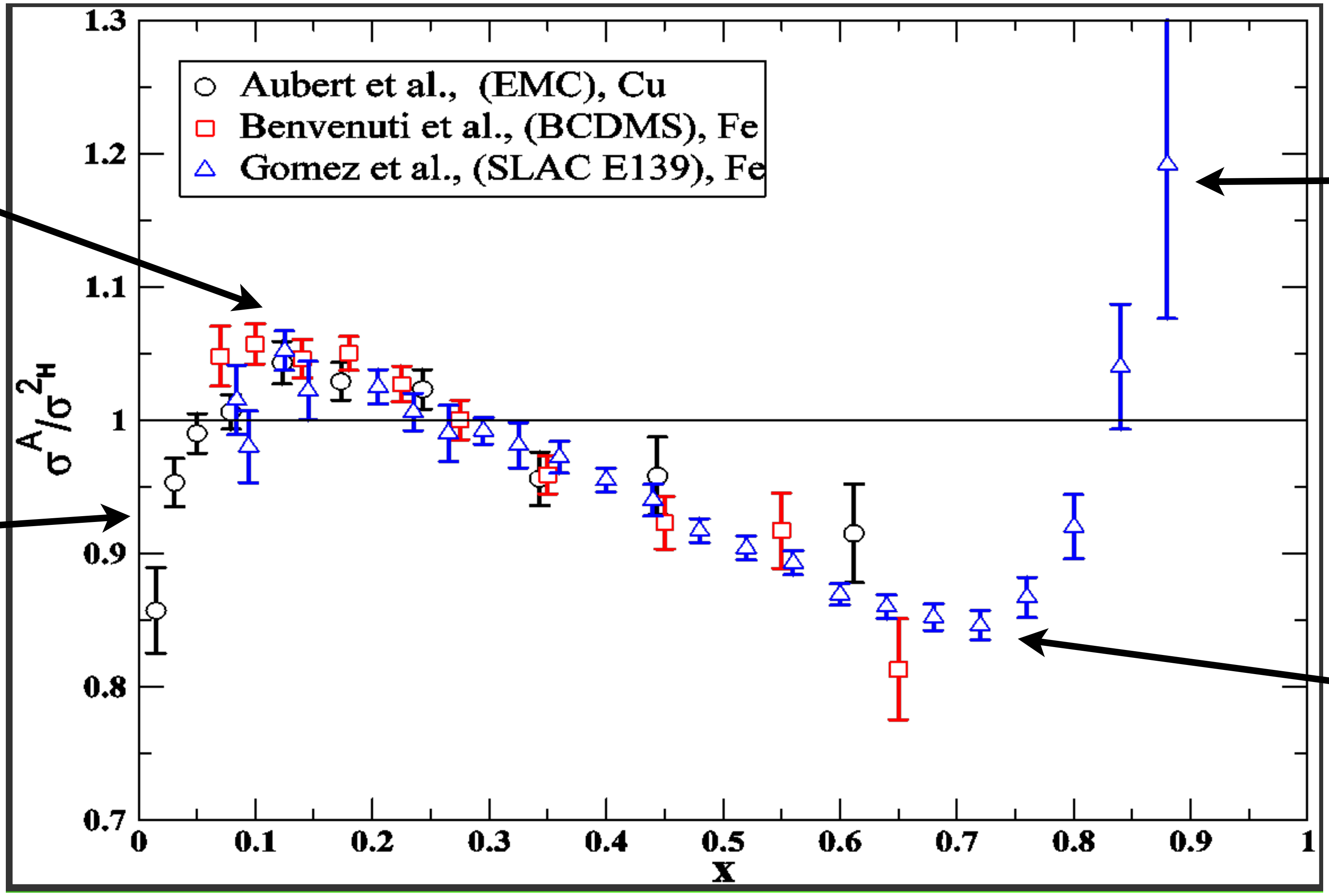
Introduction

Nuclear modifications of DIS structure functions

$$F_2^A(x) \neq ZF_2^p(x) + NF_2^n(x)$$

Anti-shadowing enhancement

Shadowing suppression at small x



Rise due to Fermi motion

EMC effect

Can we translate these modifications into universal nuclear PDFs?

Nuclear PDFs

- There are at least two motivations for NPDFs:

  1. They encode **information on the partonic structure** of nuclei

  2. They are **crucial tools** for the description of pA and AA collisions at RHIC/LHC and lepton-A DIS

- Predictions for observables have to include **reliable estimates of the uncertainties** due to the NPDFs

- So far NPDFs are determined by performing **global analyses of data** similar to global analyses of proton PDFs

Theoretical Framework

- Factorization theorems
  - provide (field theoretical) definitions of universal PDFs
  - make the formalism predictive
  - make a statement about the error

- PDFs and predicitions for observables+uncertainities **refer to this standard pQCD framework**

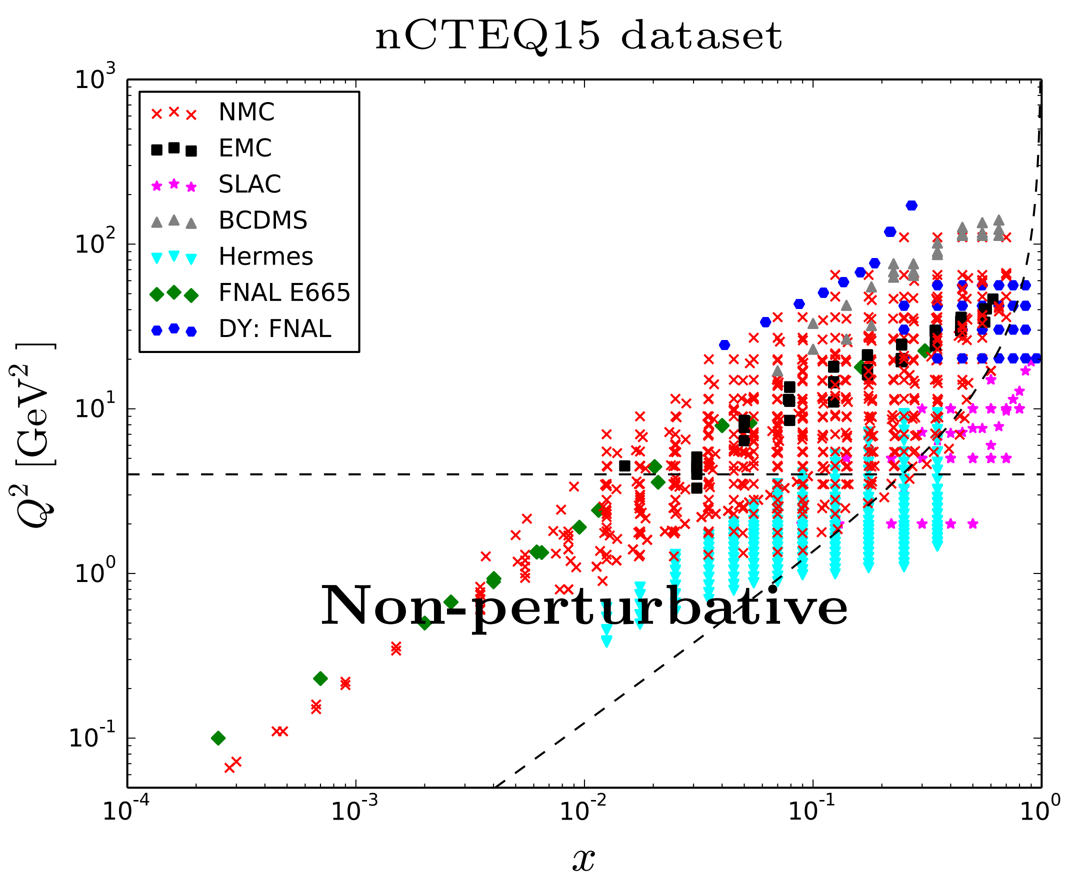
- There might be breaking of QCD factorization, deviations from DGLAP evolution — in particular in a nuclear environment

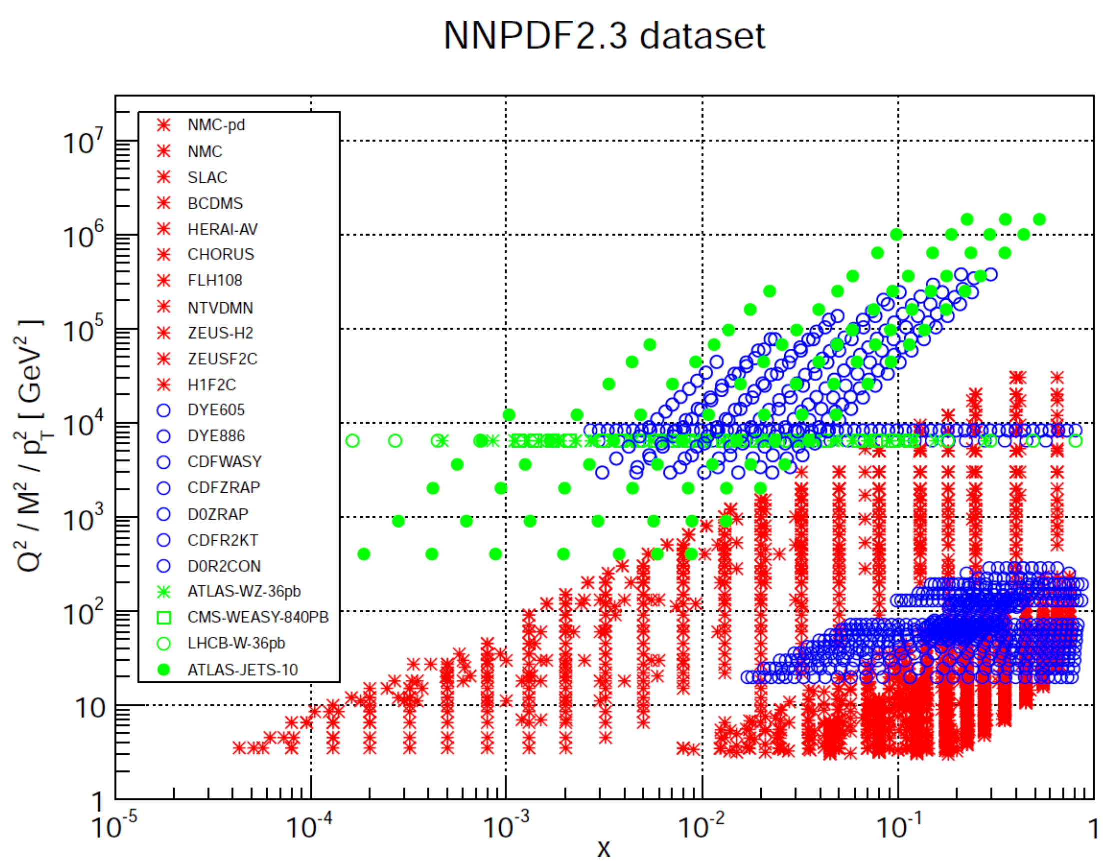
  Still need solid understanding of standard framework to establish deviations!

In the nuclear case, consider factorization as a working assumption to be tested phenomenologically

Main differences with free-proton PDFs

- Theoretical status of factorization
- Parametrization: more parameters to model A-dependence
- Less data constraints, much(!) smaller kinematic coverage





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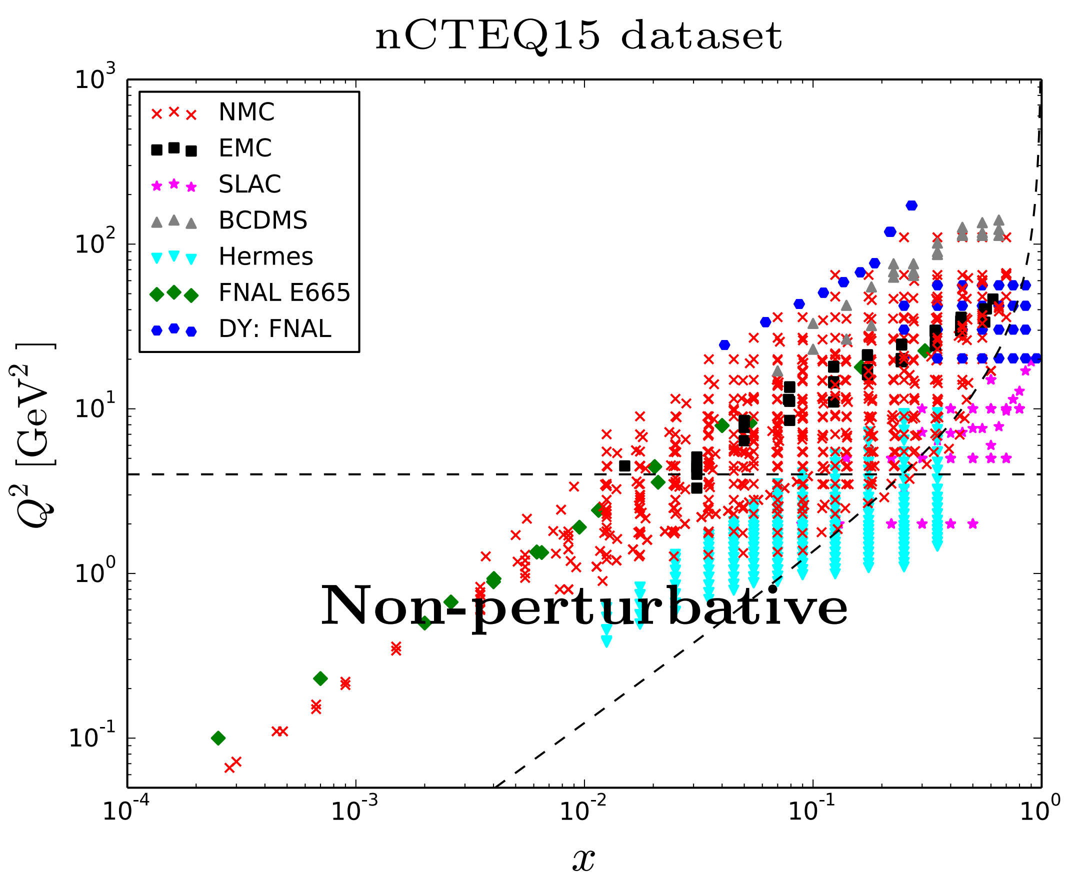

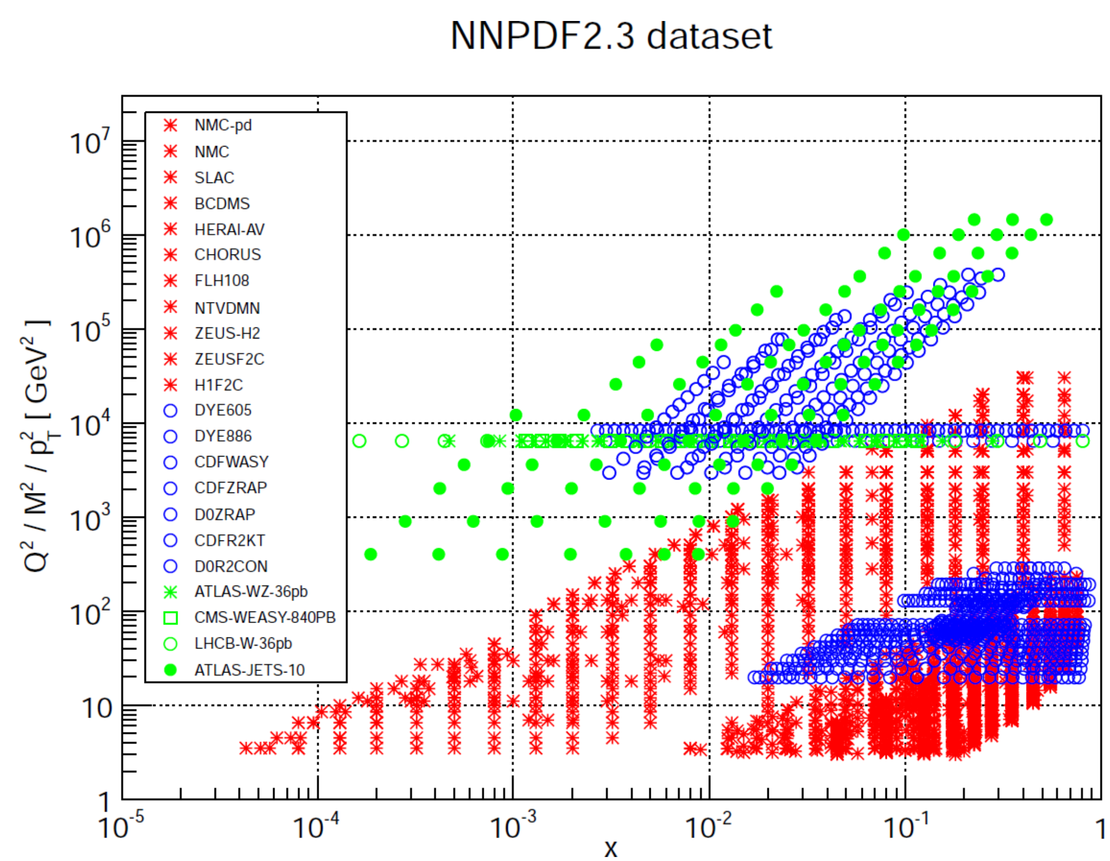

- Less data constraints → more **assumptions** about input PDFs
- Assumptions “hide” uncertainties!

Brief review of available nuclear PDFs

Available nuclear PDFs (NLO)

NEW

- EPPS'16 (supersedes EPS'09)
  Eskola, Paakkinen, Paukkunen, Salgado, arXiv:1612.0574
- nCTEQ'15
  nCTEQ collaboration, PRD93(2016)085037, arXiv:1509.00792
- DSSZ'11
  de Florian, Sassot, Stratmann, Zurita, PRD85(2012)074028, arXiv:1509.00792
- HKN'07
  Hirai, Kumano, Nagai, PRC76(2007)065207, arXiv:0709.3038
- AT'12
  Atashbar Tehrani, PRC86(2012)064301

Available nuclear PDFs (NNLO)

- KA'15

  Khanpour, Atashbar Tehrani, PRD93(2016)014026, arXiv:1601.00939

Main differences

- **Used data sets**

  - **charged lepton-nucleus DIS, pA DY**: All groups (but **different cuts!**)
    (EPPS'16 uses also π-A DY data)

  - **RHIC single pion production**: EPPS'16, nCTEQ'15, DSSZ'11
    (EPPS now with weigth = 1; DSSZ includes nuclear corrections to FFs)

  - **neutrino-Pb DIS** (CHORUS): EPPS'16

  - **LHC data** (dijet production, W/Z production): EPPS'16

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- **Parametrization**

  - Multiplicative nuclear correction factors: EPPS'16, DSSZ'11, HKN'07, AT'12, KA'15
    (requires proton baseline, parametrization can be quite complicated)

  - Native nuclear PDFs (same treatment as proton PDFs): nCTEQ'16

Parametrization

- **Multiplicative nuclear correction factors**

$$f_i^{p/A}(x_N, \mu_0) = R_i(x_N, \mu_0, A)\ f_i^{free\ proton}(x_N, \mu_0)$$

  - **HKN**: Hirai, Kumano, Nagai
    [PRC 76, 065207 (2007), arXiv:0709.3038]
  - **EPS**: Eskola, Paukkunen, Salgado
    [JHEP 04 (2009) 065, arXiv:0902.4154]
  - **DSSZ**: de Florian, Sassot, Stratmann, Zurita
    [PRD 85, 074028 (2012), arXiv:1112.6324]

- **Native nuclear PDFs**
  - nCTEQ [PRD 93, 085037 (2016), arXiv:1509.00792]

$$f_i^{p/A}(x_N, \mu_0) = f_i(x_N, A, \mu_0)$$

$$f_i(x_N, A = 1, \mu_0) \equiv f_i^{free\ proton}(x_N, \mu_0)$$

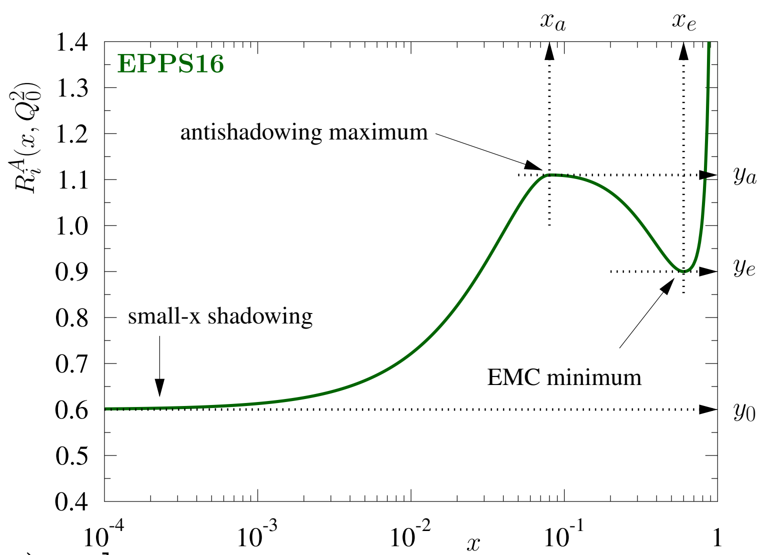
EPPS'16 framework

- NLO PDFs with errors (Hessian method, $\Delta\chi^2 = 52$)

- Parametrization (x_N<1, Q_0=1.3 GeV, i=u_v,d_v,ubar,dbar,s,g)

$$f_i^{p/A}(x_N, \mu_0) = R_i(x_N, \mu_0, A, Z)\, f_i(x_N, \mu_0),$$

$$R_i(x, A, Z) = \begin{cases} a_0 + (a_1 + a_2 x)(e^{-x} - e^{-x_a}) & x \le x_a \\ b_0 + b_1 x + b_2 x^2 + b_3 x^3 & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \le x \le 1 \end{cases}$$



A-dependence of fit parameters: $y_i(A) = y_i(A_{\rm ref}) \left(\frac{A}{A_{\rm ref}}\right)^{\gamma_i [y_i(A_{\rm ref}) - 1]}$

- CT14NLO free proton baseline, D (A=2) taken as free

- Data: lA DIS, DY, nu-A DIS, π^0@RHIC, LHC:dijets, W/Z

EPPS'16 framework: Data

- DIS cut: Q > 1.3 GeV
- No cut on W
- Underlying assumption: structure function ratios less sensitive to higher twist and TMC

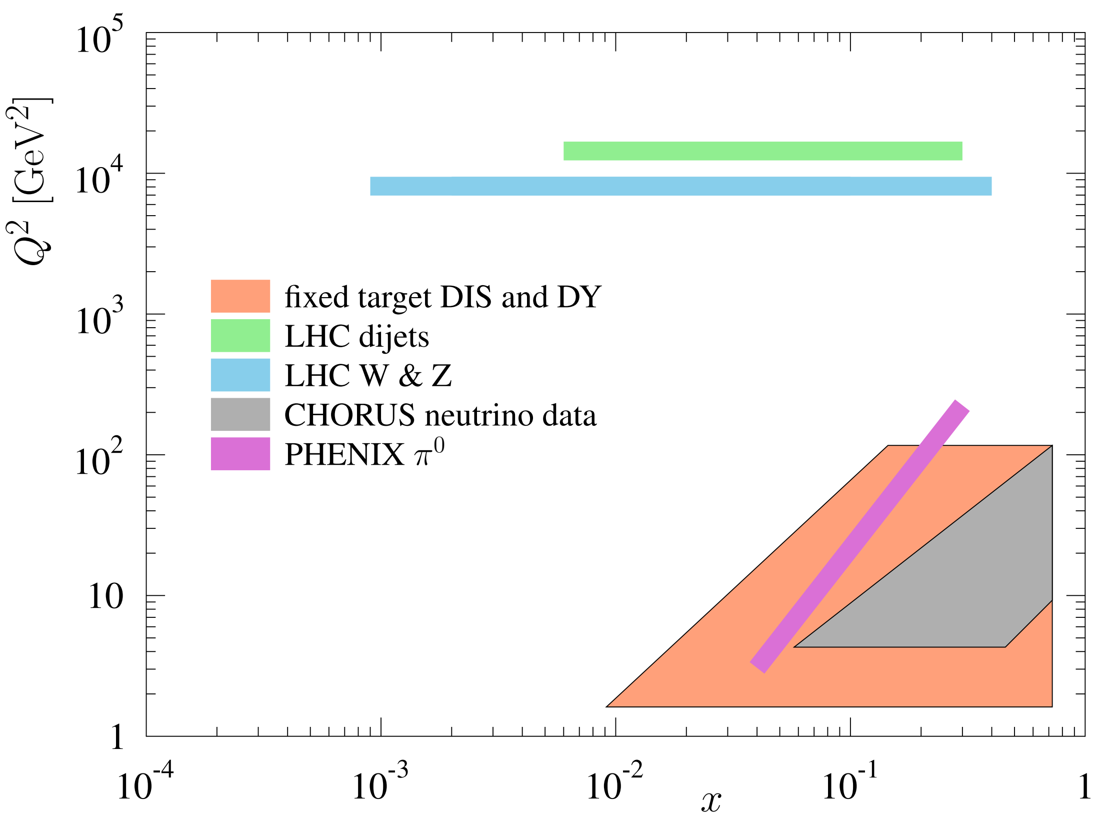


Fig. 2 The approximate regions in the (x, Q^2) plane at which different data in the EPPS16 fit probe the nuclear PDFs.

Experiment	Observable	Collisions	Data points	χ^2
SLAC E139	DIS	e^-He(4), e^-D	21	12.2
CERN NMC 95, re.	DIS	μ^-He(4), μ^-D	16	18.0
CERN NMC 95	DIS	μ^-Li(6), μ^-D	15	18.4
CERN NMC 95, Q^2 dep.	DIS	μ^-Li(6), μ^-D	153	161.2
SLAC E139	DIS	e^-Be(9), e^-D	20	12.9
CERN NMC 96	DIS	μ^-Be(9), μ^-C	15	4.4
SLAC E139	DIS	e^-C(12), e^-D	7	6.4
CERN NMC 95	DIS	μ^-C(12), μ^-D	15	9.0
CERN NMC 95, Q^2 dep.	DIS	μ^-C(12), μ^-D	165	133.6
CERN NMC 95, re.	DIS	μ^-C(12), μ^-D	16	16.7
CERN NMC 95, re.	DIS	μ^-C(12), μ^-Li(6)	20	27.9
FNAL E772	DY	pC(12), pD	9	11.3
SLAC E139	DIS	e^-Al(27), e^-D	20	13.7
CERN NMC 96	DIS	μ^-Al(27), μ^-C(12)	15	5.6
SLAC E139	DIS	e^-Ca(40), e^-D	7	4.8
FNAL E772	DY	pCa(40), pD	9	3.33
CERN NMC 95, re.	DIS	μ^-Ca(40), μ^-D	15	27.6
CERN NMC 95, re.	DIS	μ^-Ca(40), μ^-Li(6)	20	19.5
CERN NMC 96	DIS	μ^-Ca(40), μ^-C(12)	15	6.4
SLAC E139	DIS	e^-Fe(56), e^-D	26	22.6
FNAL E772	DY	e^-Fe(56), e^-D	9	3.0
CERN NMC 96	DIS	μ^-Fe(56), μ^-C(12)	15	10.8
FNAL E866	DY	pFe(56), pBe(9)	28	20.1
CERN EMC	DIS	μ^-Cu(64), μ^-D	19	15.4
SLAC E139	DIS	e^-Ag(108), e^-D	7	8.0
CERN NMC 96	DIS	μ^-Sn(117), μ^-C(12)	15	12.5
CERN NMC 96, Q^2 dep.	DIS	μ^-Sn(117), μ^-C(12)	144	87.6
FNAL E772	DY	pW(184), pD	9	7.2
FNAL E866	DY	pW(184), pBe(9)	28	26.1
CERN NA10★	DY	π^-W(184), π^-D	10	11.6
FNAL E615★	DY	π^+W(184), π^-W(184)	11	10.2
CERN NA3★	DY	π^-Pt(195), π^-H	7	4.6
SLAC E139	DIS	e^-Au(197), e^-D	21	8.4
RHIC PHENIX	π^0	dAu(197), pp	20	6.9
CERN NMC 96	DIS	μ^-Pb(207), μ^-C(12)	15	4.1
CERN CMS★	$W^\pm$	pPb(208)	10	8.8
CERN CMS★	Z	pPb(208)	6	5.8
CERN ATLAS★	Z	pPb(208)	7	9.6
CERN CMS★	dijet	pPb(208)	7	5.5
CERN CHORUS★	DIS	νPb(208), $\bar{\nu}$Pb(208)	824	998.6
Total			1811	1789

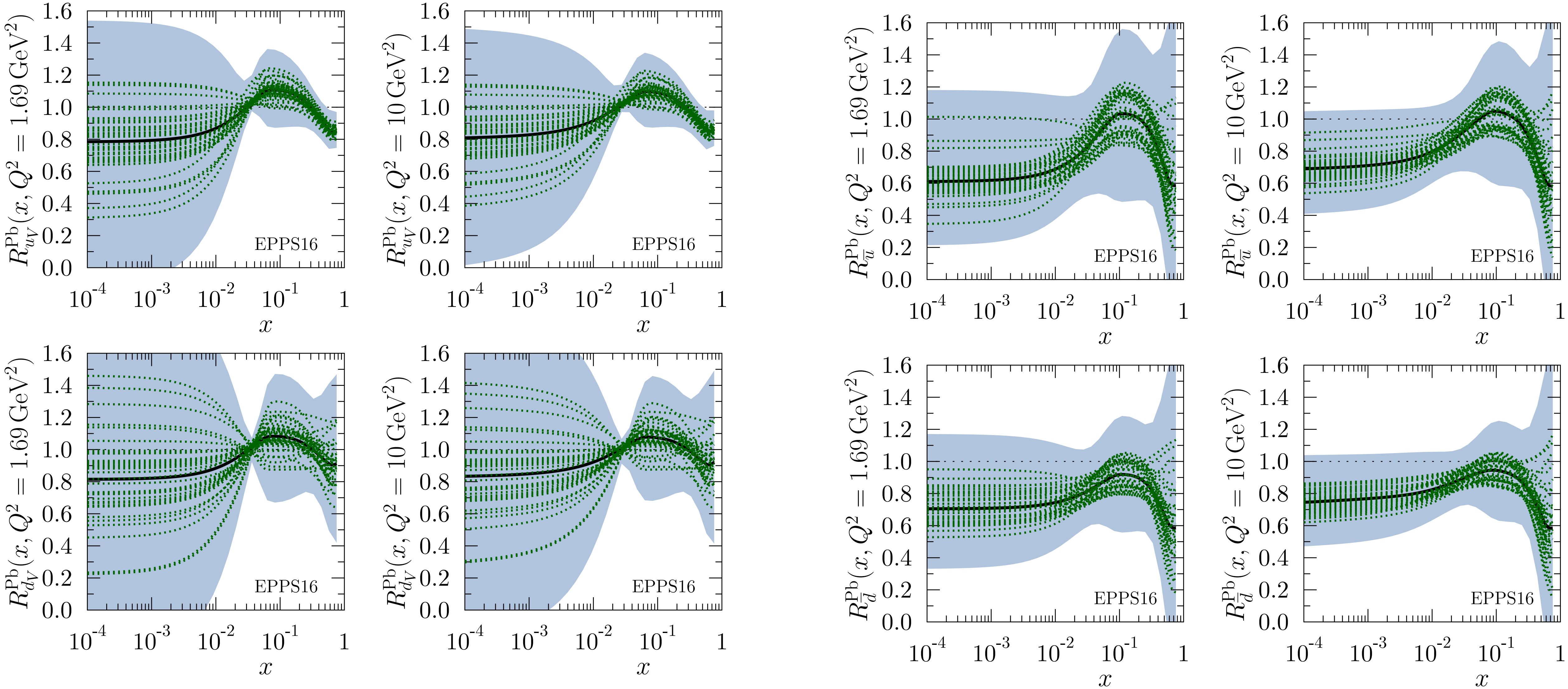
EPPS'16 framework: Results

Table 3 List of parameters defining the central set of EPPS16 at the initial scale $Q_0^2 = 1.69\,\mathrm{GeV}^2$. The numbers in bold indicate the 20 parameters that were free in the fit.

Parameter	u_V	d_V	$\overline{u}$
$y_0(A_{\mathrm{ref}})$	sum rule	sum rule	**0.844**
γ_{y_0}	sum rule	sum rule	**0.731**
x_a	**0.0717**	as u_V	**0.104**
x_e	**0.693**	as u_V	as u_V
$y_a(A_{\mathrm{ref}})$	**1.06**	**1.05**	**1.03**
γ_{y_a}	**0.278**	as u_V	0, fixed
$y_e(A_{\mathrm{ref}})$	**0.908**	**0.943**	**0.725**
γ_{y_e}	**0.288**	as u_V	as u_V
β	1.3, fixed	1.3, fixed	1.3, fixed

Parameter	$\overline{d}$	s	g
$y_0(A_{\mathrm{ref}})$	**0.889**	**0.723**	sum rule
γ_{y_0}	as $\overline{u}$	as $\overline{u}$	sum rule
x_a	as $\overline{u}$	as $\overline{u}$	**0.0820**
x_e	as u_V	as u_V	as u_V
$y_a(A_{\mathrm{ref}})$	**0.919**	**1.24**	**1.12**
γ_{y_a}	0, fixed	0, fixed	as u_V
$y_e(A_{\mathrm{ref}})$	as $\overline{u}$	as $\overline{u}$	**0.874**
γ_{y_e}	as u_V	as u_V	as u_V
β	1.3, fixed	1.3, fixed	1.3, fixed

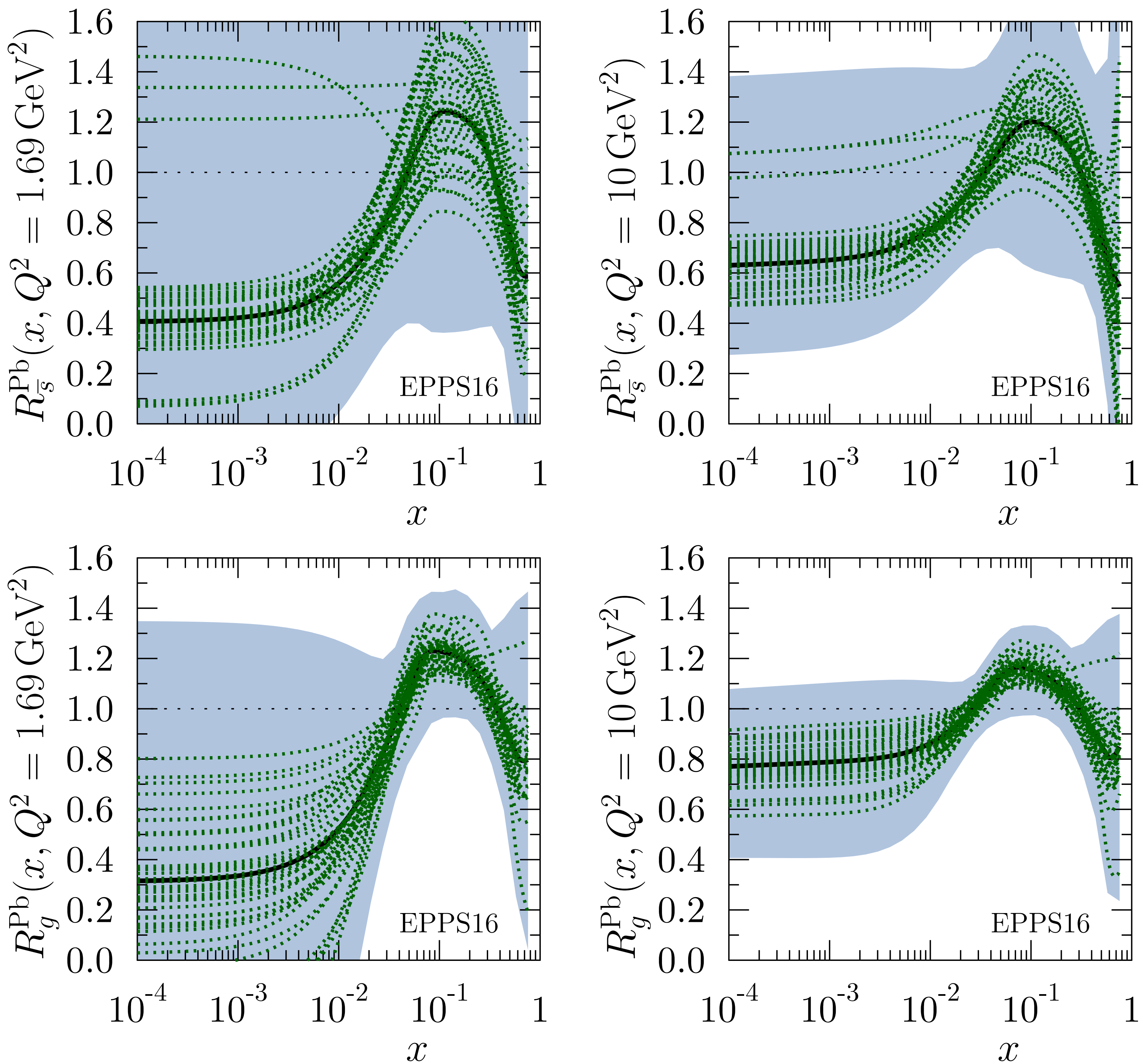
EPPS'16 framework: Results



- Considerably larger uncertainties than EPS'09 despite more data (more flexible param., larger tolerance). Main impact from CHORUS and CMS dijet data.
- No notable tensions with previous data sets. **Supports validity of theoretical framework!**
- Still some parametrization bias (shape of PDFs), still quite a number of assumptions on parametrization
- Some aggressive choices (low DIS cuts, π-A DY data, RHIC π^0 data)

EPPS'16 framework: Results

- Large uncertainties for nuclear gluon distribution
- Nuclear strange PDF poorly constrained
- Clearly more LHC pPb data required
  - from LHC5
  - from LHC8 (much higher statistics)



nCTEQ'15 framework

PRD93(2016)085037

- Functional form of the bound proton PDF same as for the free proton (`CTEQ6M`, x restricted to $0 < x < 1$)

$$x f_i^{p/A}(x, Q_0) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4} x)^{c_5}, \qquad i = u_v, d_v, g, \ldots$$
$$\bar{d}(x, Q_0)/\bar{u}(x, Q_0) = c_0 x^{c_1}(1-x)^{c_2} + (1+c_3 x)(1-x)^{c_4}$$

- A-dependent fit parameters (reduces to free proton for $A = 1$)

$$c_k \to c_k(A) \equiv c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right), \quad k = \{1, \ldots, 5\}$$

- PDFs for nucleus (A, Z)

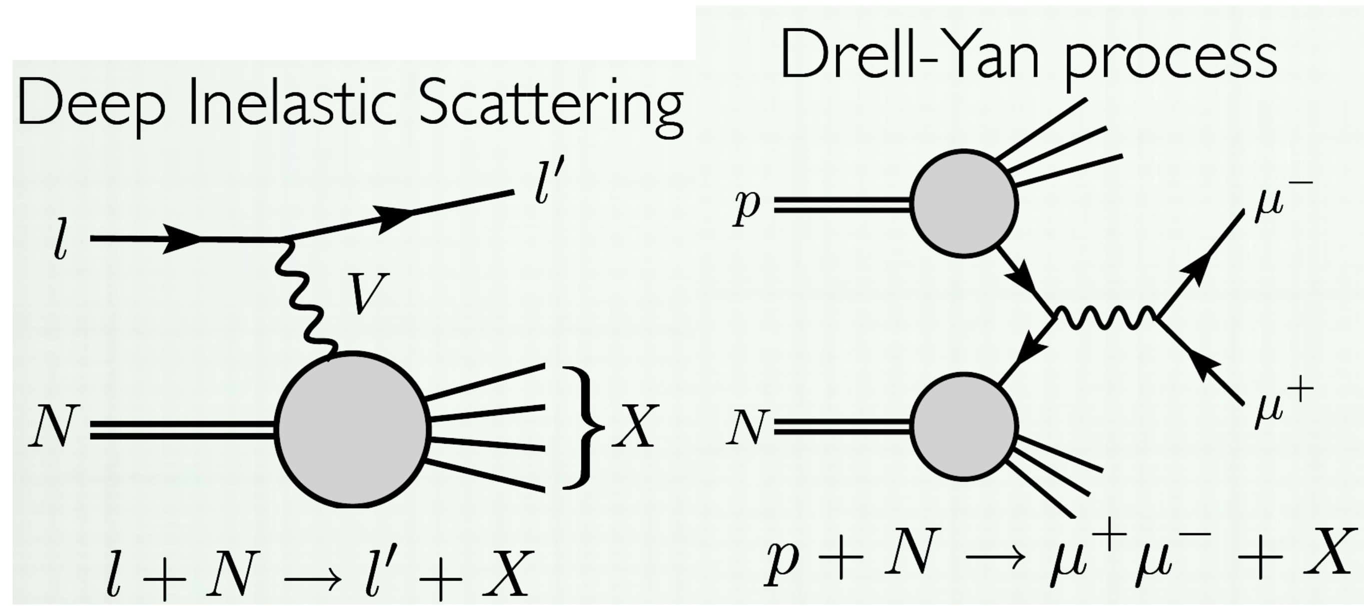
$$f_i^{(A,Z)}(x, Q) = \frac{Z}{A} f_i^{p/A}(x, Q) + \frac{A-Z}{A} f_i^{n/A}(x, Q)$$

(bound neutron PDF $f_i^{n/A}$ by isospin symmetry)

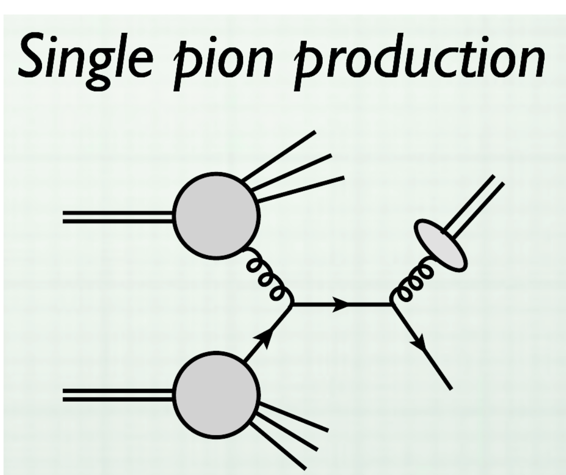
nCTEQ'15 framework: Data sets

- NC DIS & DY

CERN BCDMS & EMC & NMC
N = (D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W)
FNAL E-665
N = (D, C, Ca, Pb, Xe)
DESY Hermes
N = (D, He, N, Kr)
SLAC E-139 & E-049
N = (D, Ag, Al, Au, Be,C, Ca, Fe, He)
FNAL E-772 & E-886
N = (D, C, Ca, Fe,W)



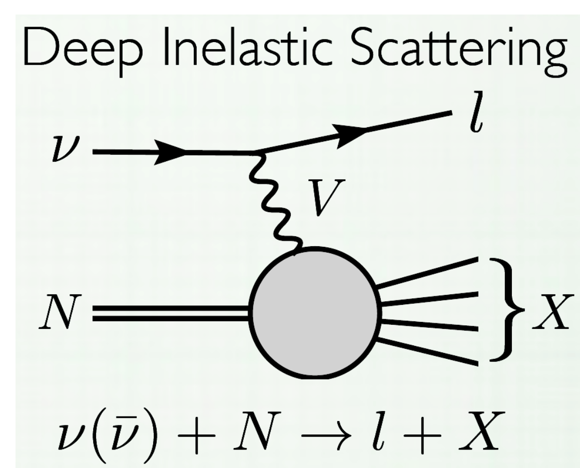
- Single pion production (new)



RHIC - PHENIX & STAR

N = Au

- Neutrino (to be included later)



CHORUS CCFR & NuTeV

N = Pb N = Fe

Fit details

PRD93(2016)085037

Fit properties:

- fit @NLO
- $Q_0 = 1.3\text{GeV}$
- using ACOT heavy quark scheme
- kinematic cuts:
  $Q > 2\text{GeV}$, $W > 3.5\text{GeV}$
  $p_T > 1.7$ GeV
- 708 (DIS & DY) + 32 (single π^0) = 740 data points after cuts
- 16+2 free parameters
  - 7 gluon
  - 7 valence
  - 2 sea
  - 2 pion data normalizations
- $\chi^2 = 587$, giving $\chi^2/\text{dof} = 0.81$

Error analysis:

- use Hessian method

$$\chi^2 = \chi_0^2 + \frac{1}{2} H_{ij}(a_i - a_i^0)(a_j - a_j^0)$$

$$H_{ij} = \frac{\partial^2 \chi^2}{\partial a_i \partial a_j}$$

- tolerance $\Delta\chi^2 = 35$ (every nuclear target within 90% C.L.)
- eigenvalues span 10 orders of magnitude → require numerical precision
- use noise reducing derivatives

Fit details

PRD93(2016)085037

Fit propert

- fit @N … d
- $Q_0 =$ … $a_i - a_i^0)(a_j - a_j^0)$
- using
- kinem … $Q > 2$ … $p_T >$
- 708 (l … $= 740$ … $\Delta\chi^2 = 35$ (every … arget within 90% C.L.)
- 16+2 … es span 10 orders of … le → require numerical … reducing derivatives
- $\chi^2 =$

Kinematic cuts

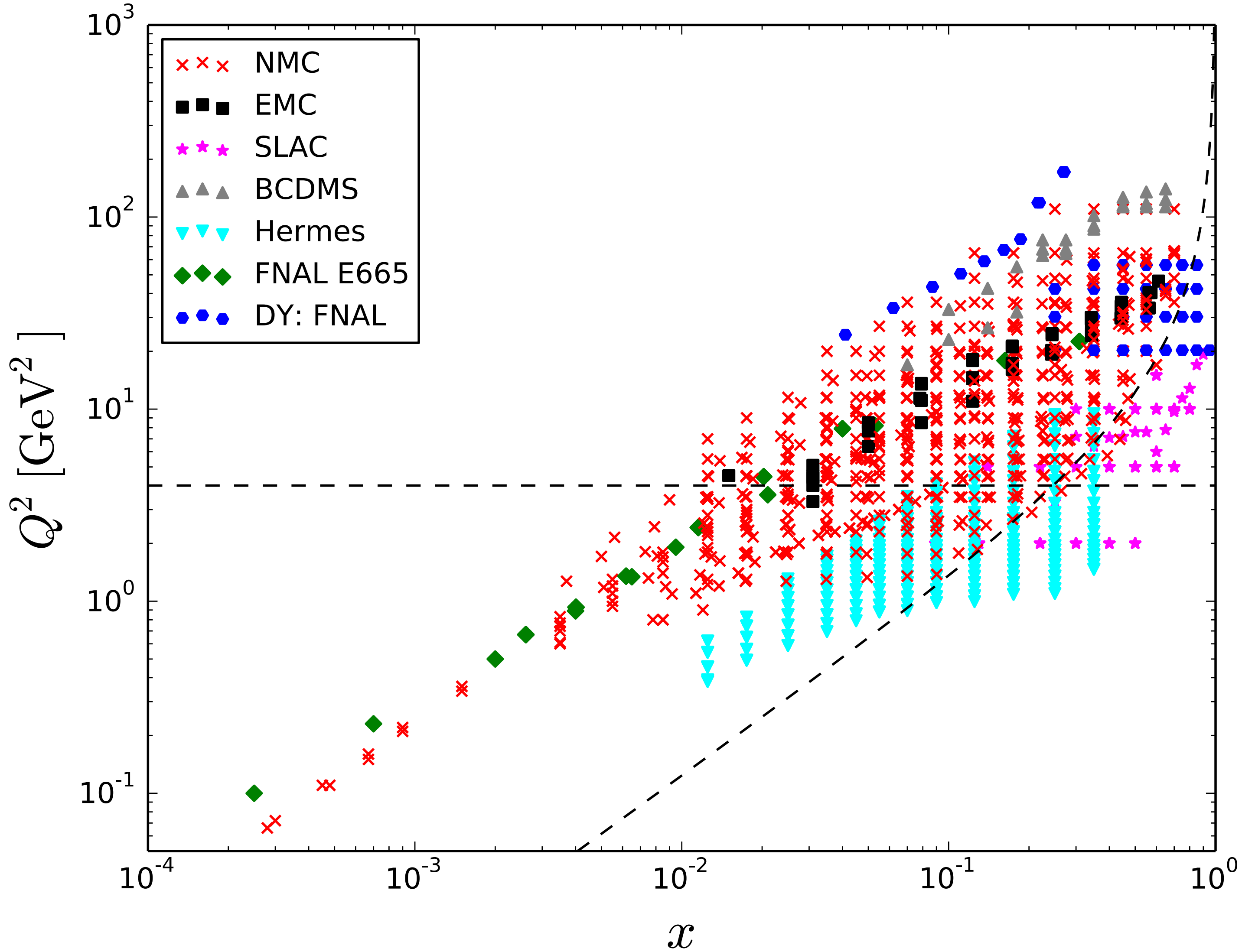
<u>nCTEQ:</u>

$$\begin{cases} Q > 2 \text{ GeV} \\ W > 3.5 \text{ GeV} \end{cases}$$

<u>EPS:</u> $Q > 1.3$ GeV

<u>HKN:</u> $Q > 1$ GeV

<u>DSSZ:</u> $Q > 1$ GeV



nCTEQ: 740 data points

EPS09: 929 data points

Fit details

PRD93(2016)085037

Fit properties:

- fit @NLO

Fit quality

- $\chi^2/dof = 0.81$

sc

$Q > 2\text{GeV},\ W > 3.5\text{GeV}$
$p_T > 1.7$ GeV

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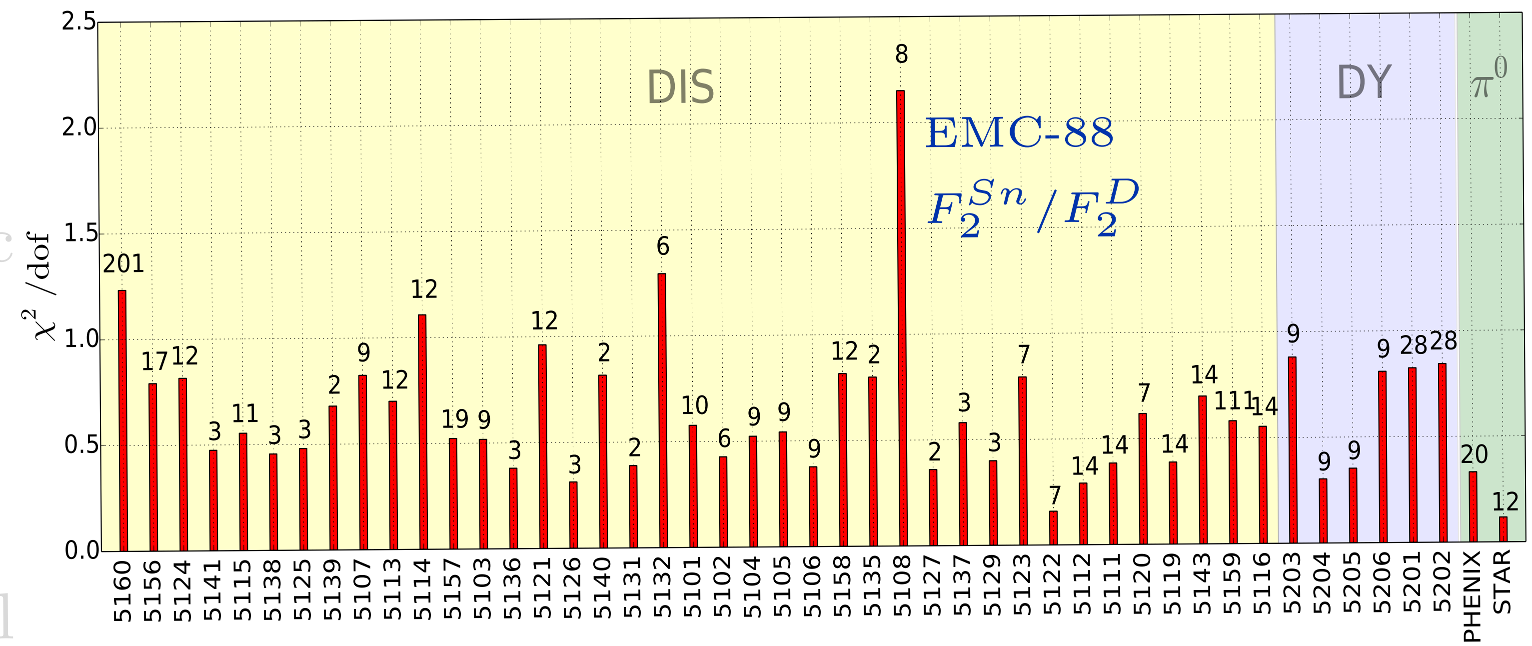
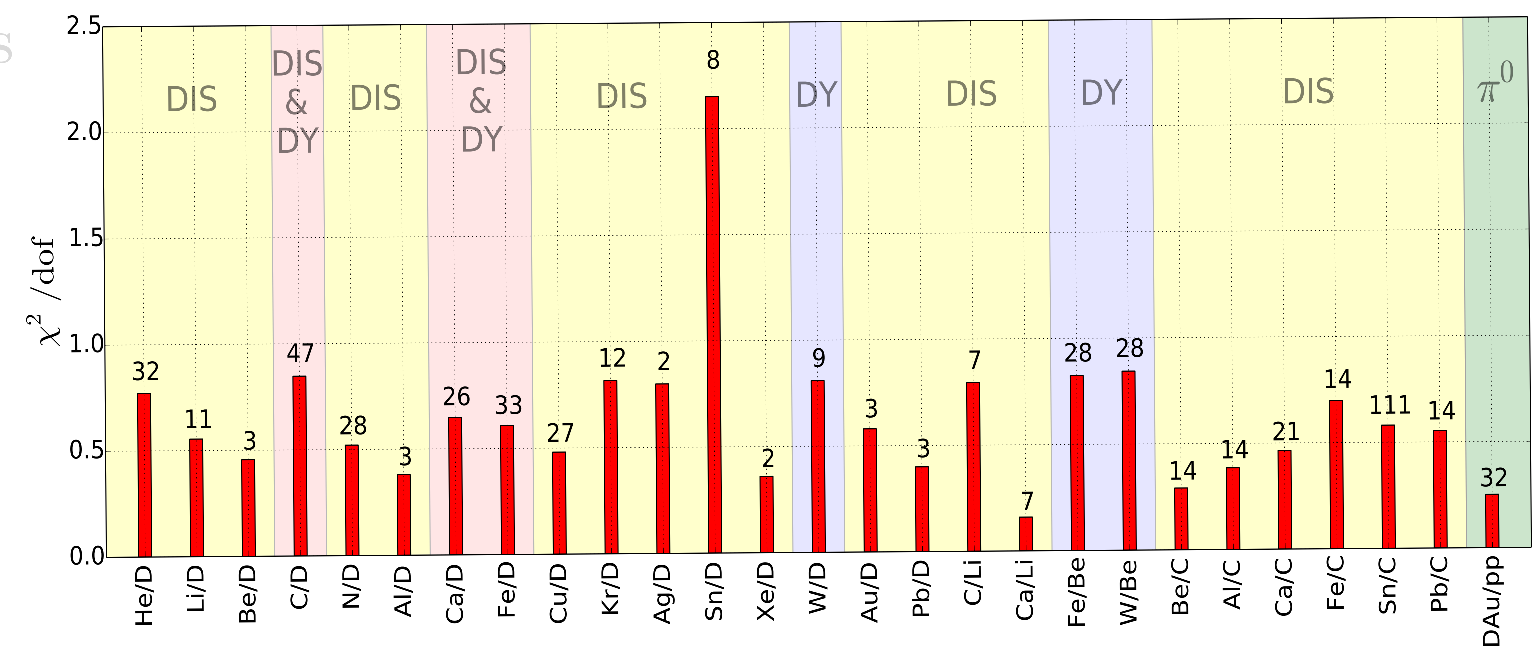
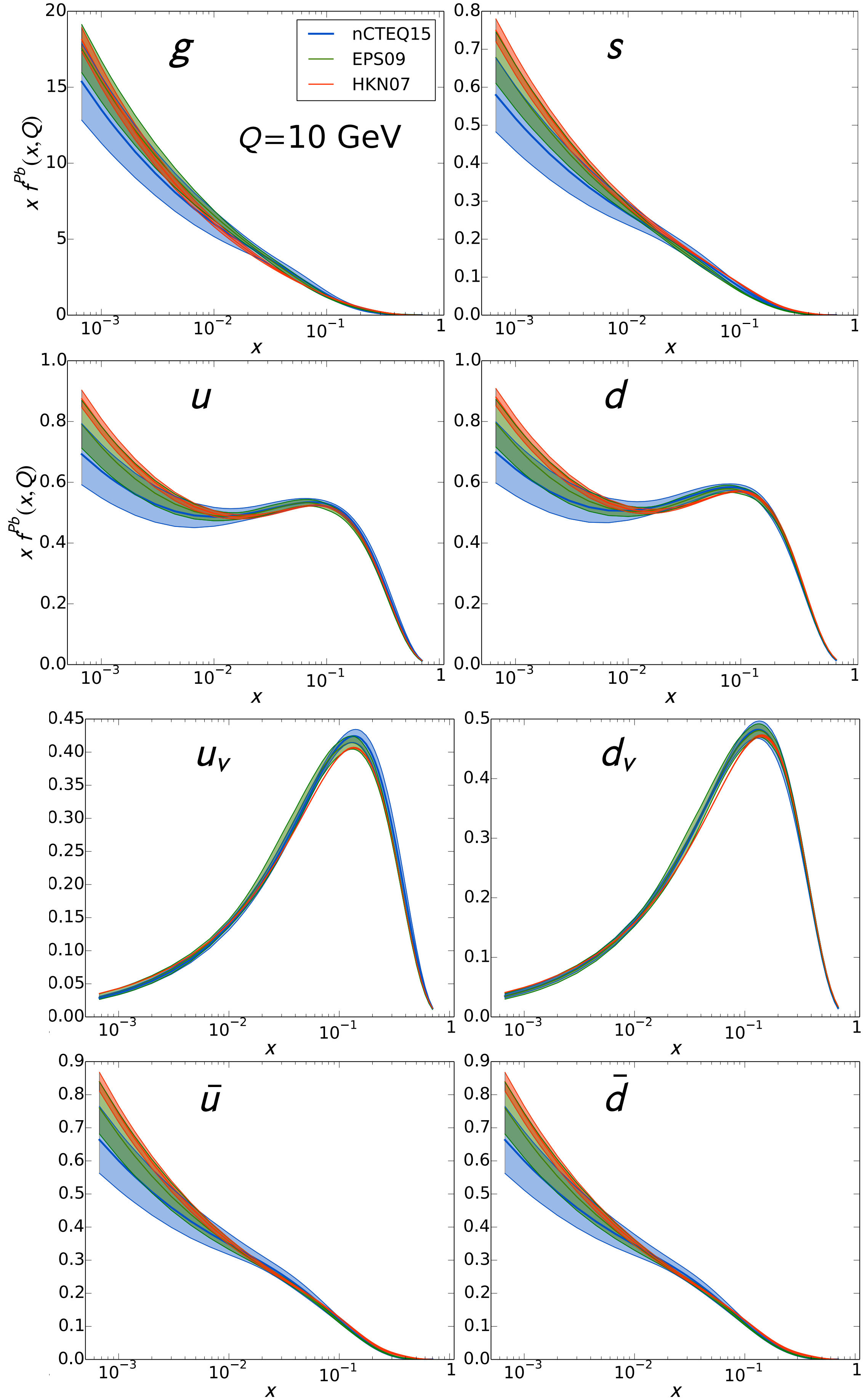




nCTEQ results

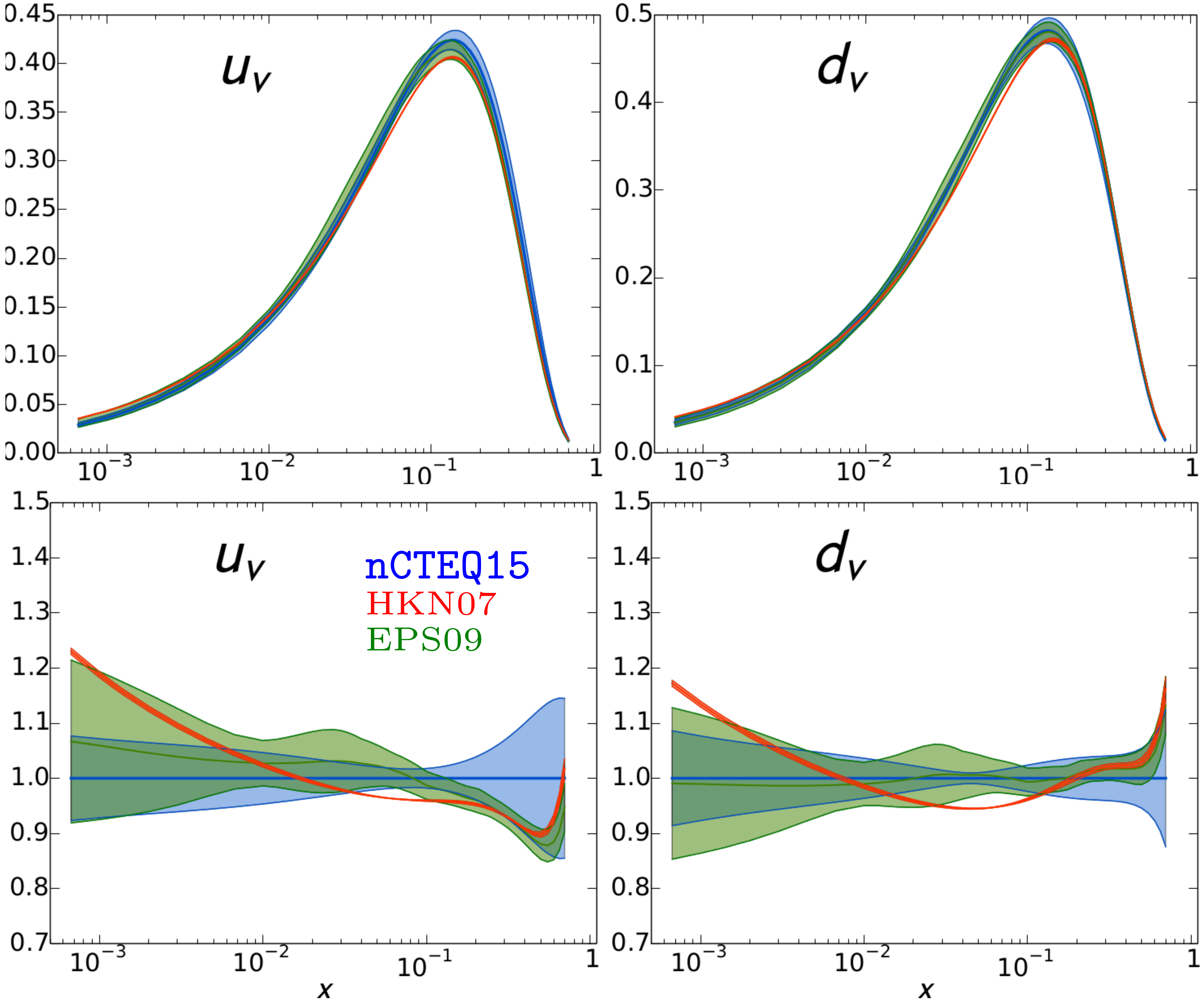
- First global analysis with Hessian error PDFs: [PRD93(2016]085037]
- Figure: PDFs inside lead at Q=10 GeV vs x
- nCTEQ features larger uncertainties than previous nPDFs
- better agreement between different groups



Valence distributions

Full lead nucleus distribution:

$$f^{Pb} = \frac{82}{208} f^{p/Pb} + \frac{208-82}{208} f^{n/Pb}$$



DSSZ'11 framework

- NLO PDFs with errors
- Error PDFs produced with *Hessian method*
- Parametrization (Q_0=1GeV)

$$f_i^{p/A}(x_N, Q_0) = R_i^A(x_N, Q_0)\, f_i^p(x_N, Q_0), \qquad i = \text{valence, sea}, g$$

$$R_v^A(x, Q_0) = \epsilon_1 x^{\alpha_1}(1-x)^{\beta_1}\left[1+\epsilon_2(1-x)^{\beta_2}\right]\left[1+a_v(1-x)^{\beta_3}\right]$$

$$R_s^A(x, Q_0) = R_v^A(x, Q_0)\frac{\epsilon_s}{\epsilon_1}\frac{1+a_s x^{\alpha_s}}{1+a_s}$$

$$R_g^A(x, Q_0) = R_v^A(x, Q_0)\frac{\epsilon_g}{\epsilon_1}\frac{1+a_g x^{\alpha_g}}{1+a_g}$$

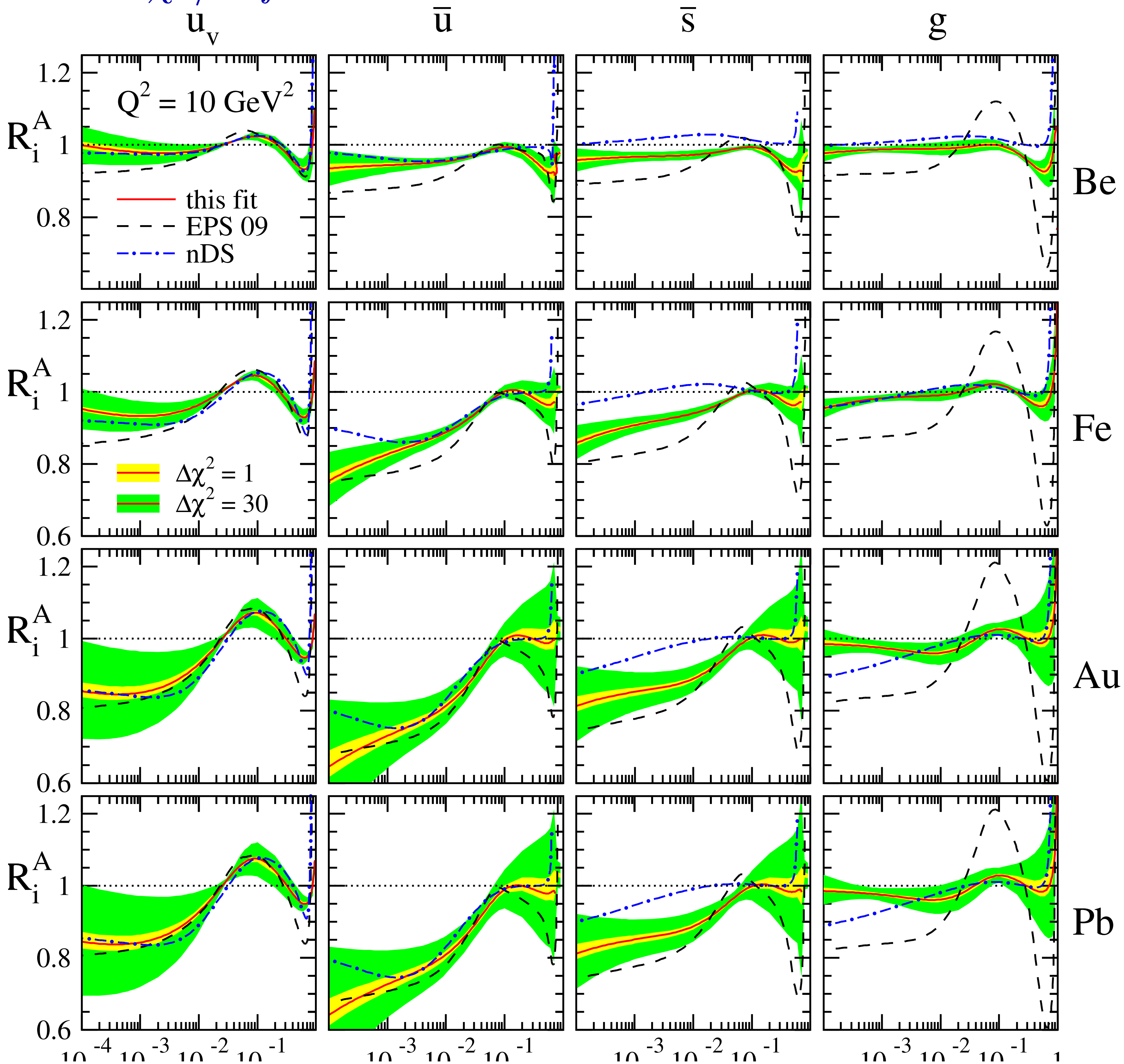
A-dependence of fitting parameters ($\xi = \alpha_v, \alpha_s, \ldots$)

$$\xi = \gamma_\xi + \lambda_\xi A^{\delta_\xi}$$

- MSTW 2008 free proton baseline
- Neglects $x_N > 1$
- Data: DIS, DY, $\pi^{0\pm}$ @ RHIC, Neutrino DIS

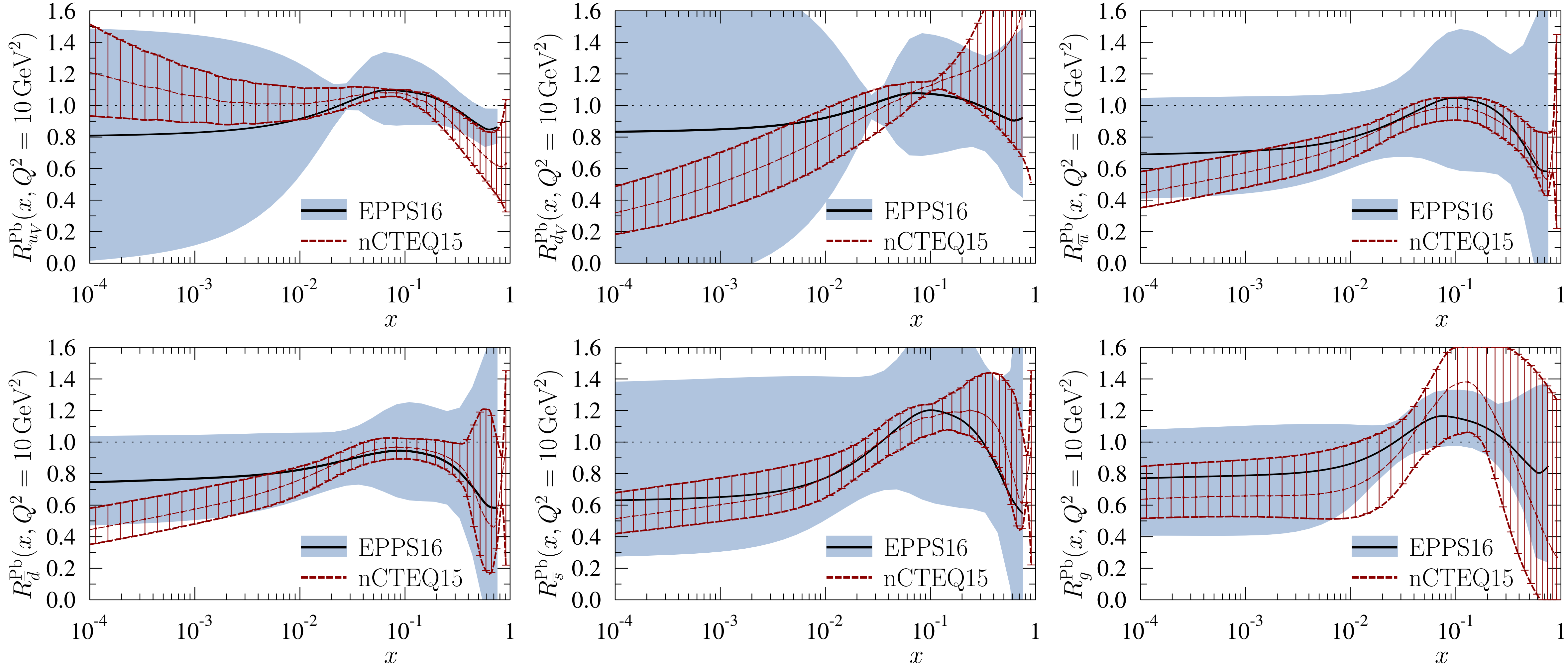
DSSZ'11 framework

- NLO fit: $\chi^2/dof = 0.99$



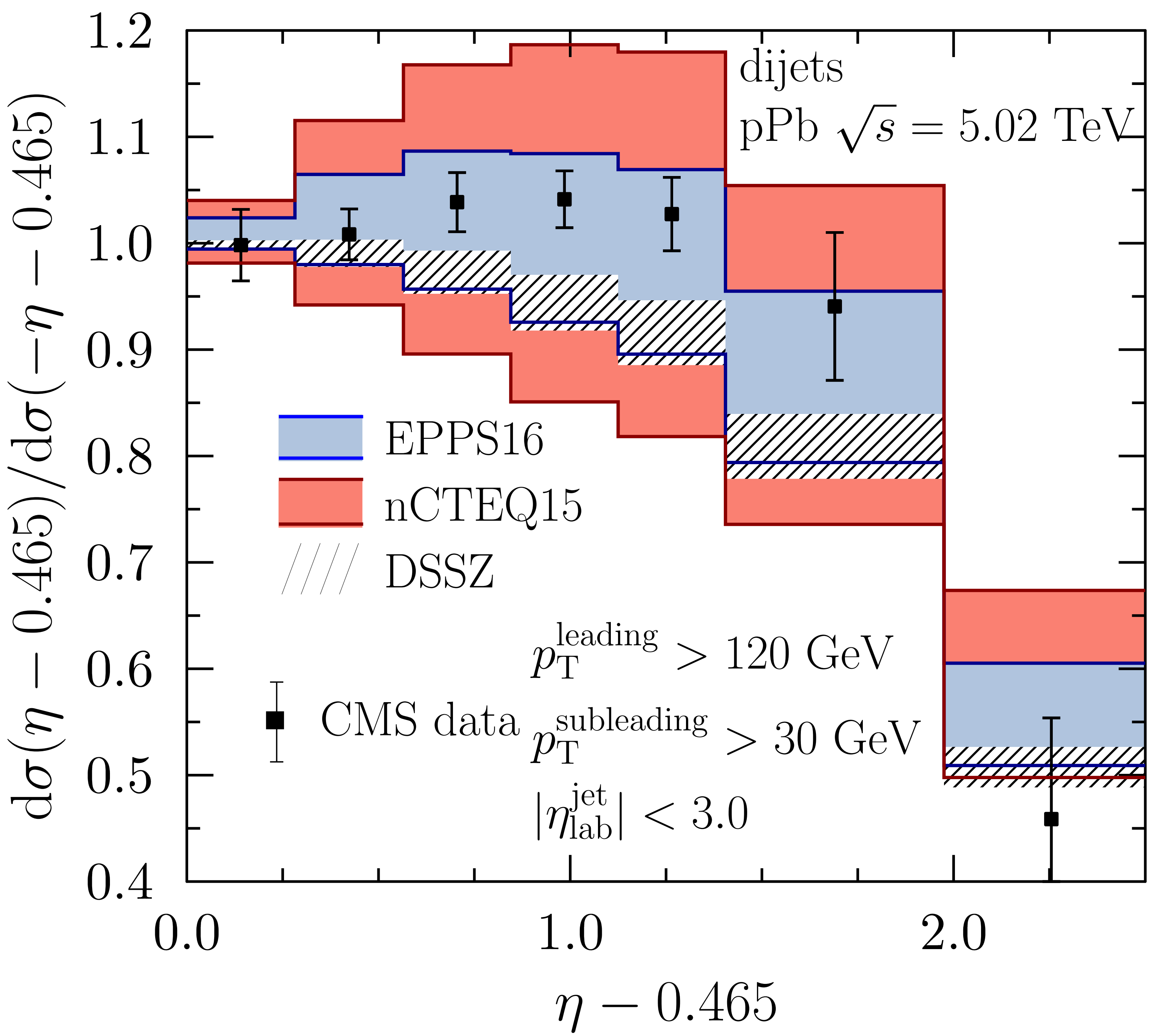
Some comparisons
(taken from EPPS'16 paper)

EPPS'16 vs nCTEQ'15 @Q^2=10 GeV^2



- Generally good agreement for x>0.01 (nCTEQ has no data constraints for x<0.01) $\Delta\chi^2$ = 35 (nCTEQ'15), $\Delta\chi^2$ = 52 (EPPS'16)
- Valence bands at large-x partly differ (valence at small-x <10^{-2} irrelevant); influence from CHORUS data?
- EPPS'16 bands for light sea more realistic; nCTEQ'15 has fewer fit parameters for sea
- Still quite some parametrization bias even for EPPS'16

Comparison with dijet data



- nCTEQ'15 in agreement with CMS data; including CMS dijet data in global analysis will help

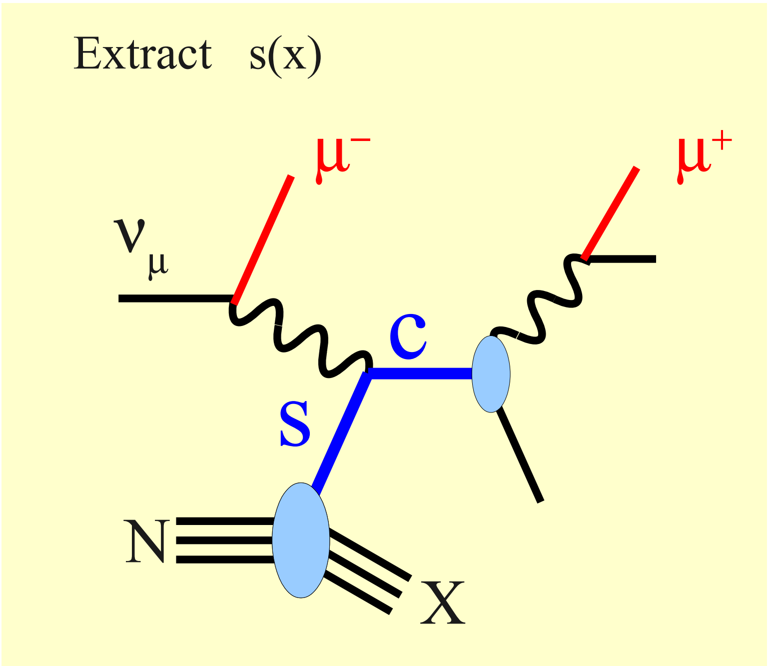
- DSSZ gluon needs to be revised since not enough shadowed **OR** energy loss effects need to be included?

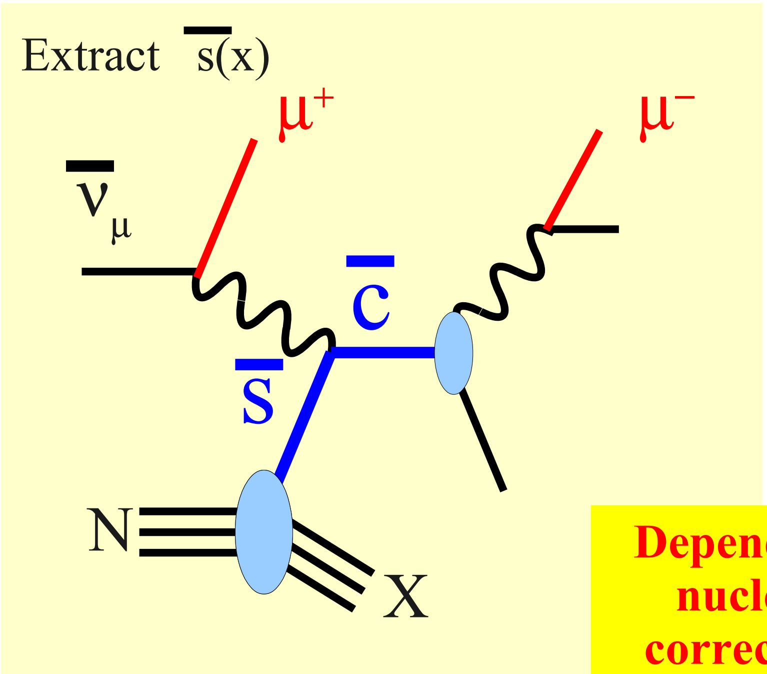
Vector boson production and the strange PDF

see arXiv:1203.1290 for a discussion of experimental constraints on the strange PDF

Strange PDF: experimental constraints

Opposite sign dimuon production in neutrino DIS: $\nu N \rightarrow \mu^+ \mu^- X$



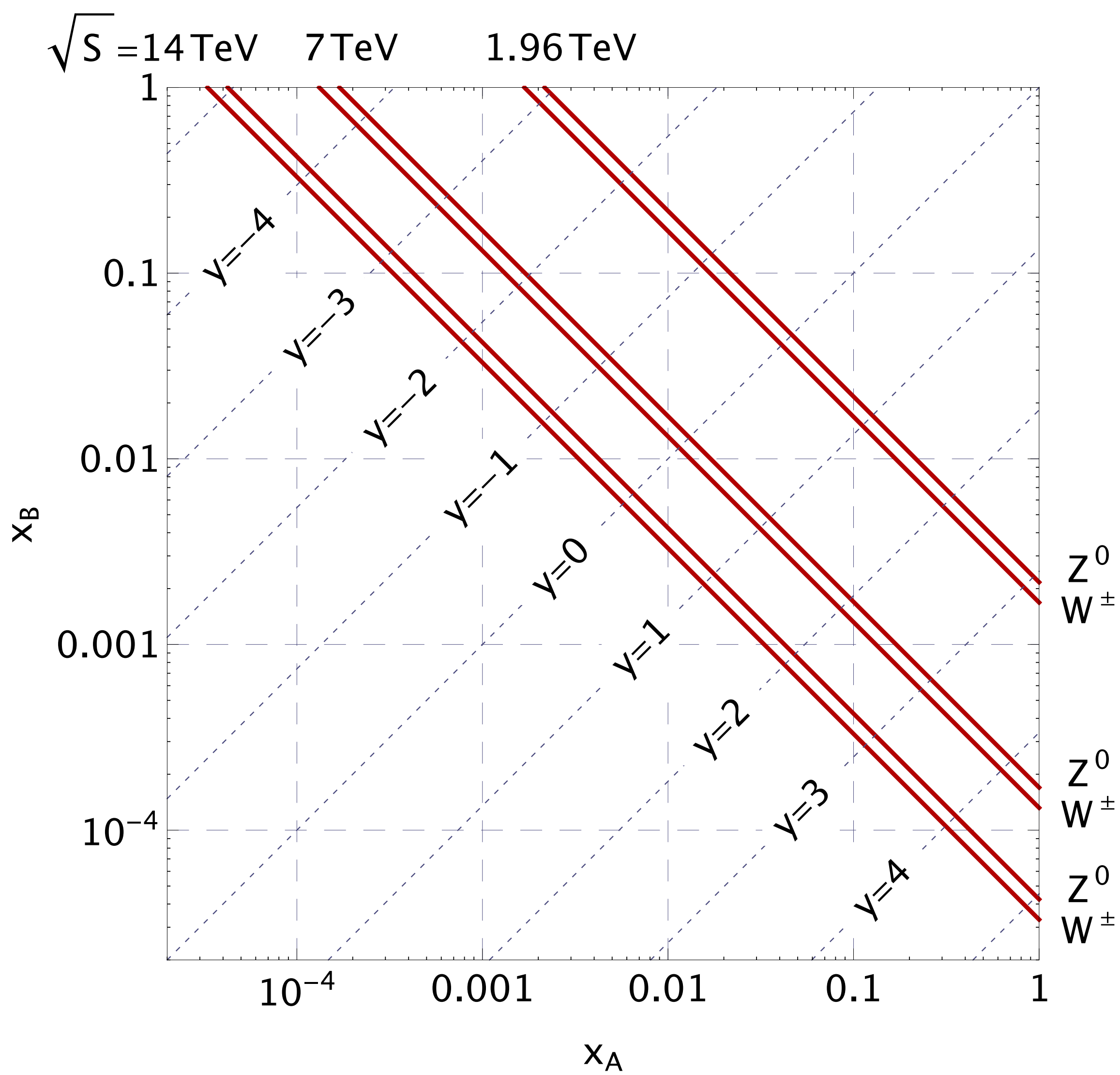


Depends on nuclear corrections

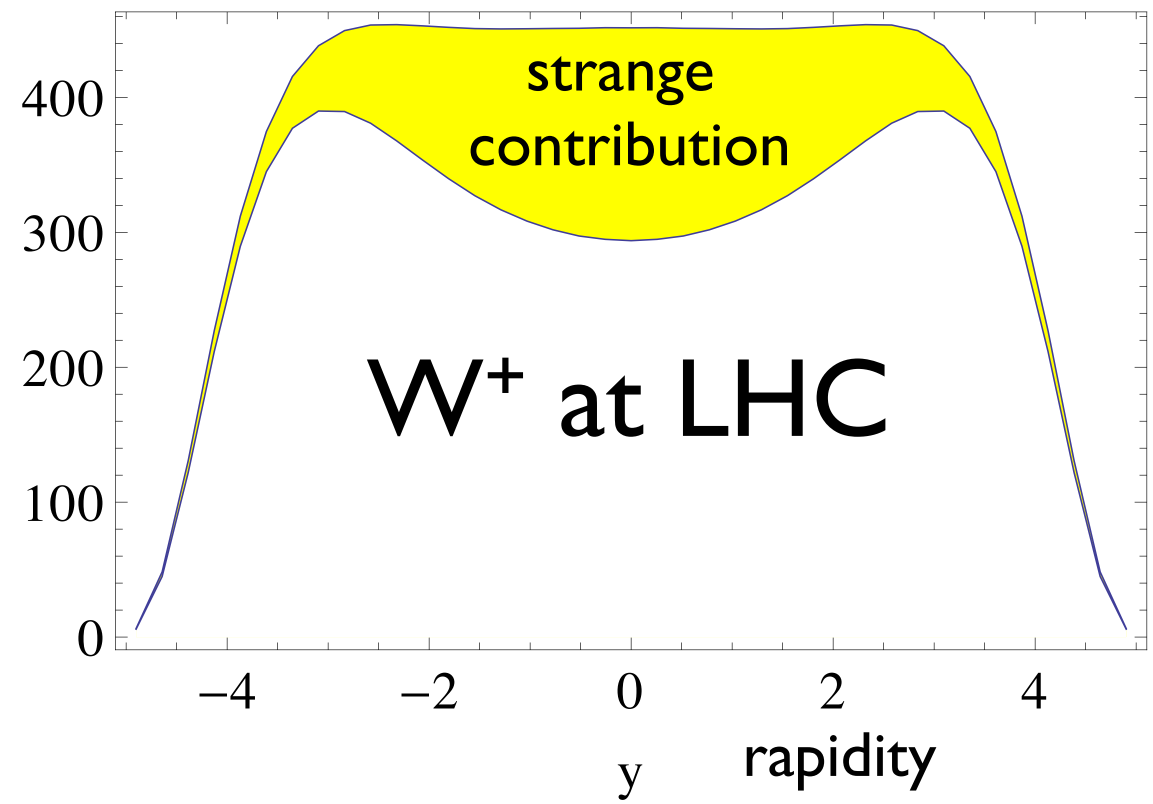
- High-statistics data from CCFR and NuTeV: **Main source** of information!
- x~[0.01,0.4]
- νFe DIS: need nuclear corrections! Problem: Final State Interactions (FSI)
- CHORUS (νPb): compatible with NuTeV, could be included
- NOMAD (νFe): data not yet published, in principle very interesting

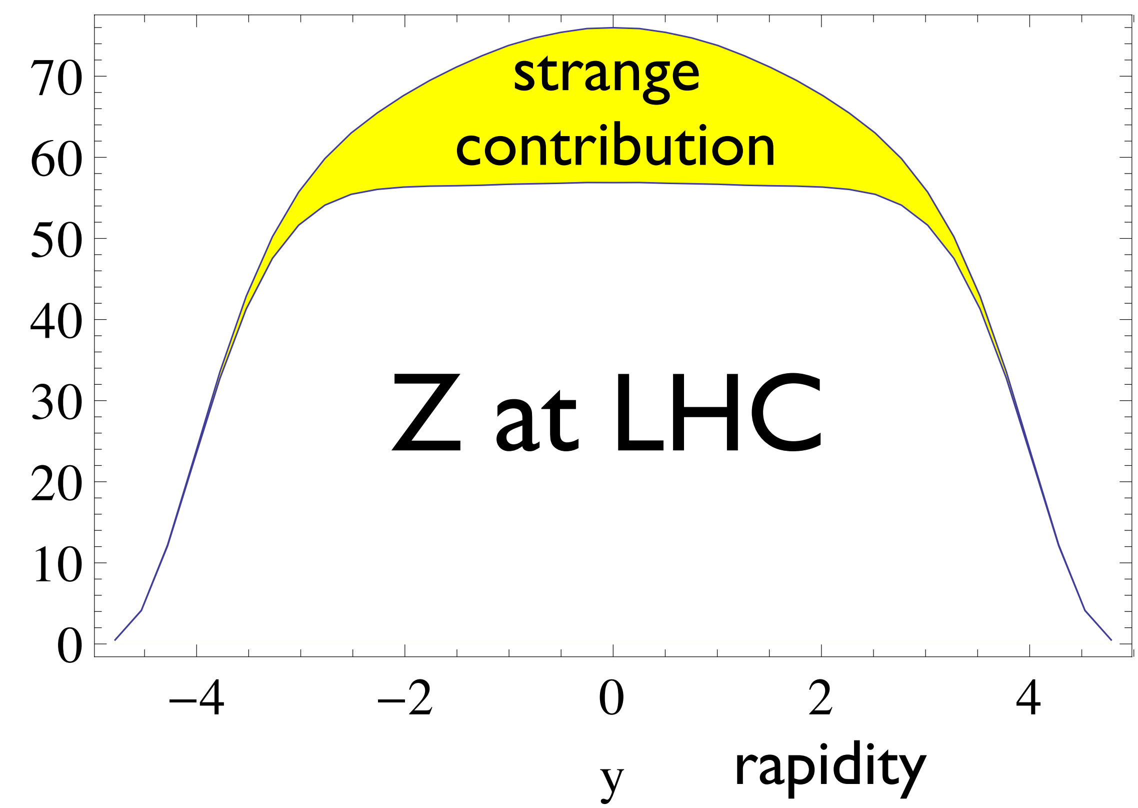
Drell-Yan production of W/Z at the LHC

Kinematic plane



$d^2\sigma/dM/dy$ [pb/GeV]





Uncertainty of strange-PDF will feed into benchmark process

VRAP code: Anastasiou, Dixon, Melnikov, Petriello, PRD69(2004)094008

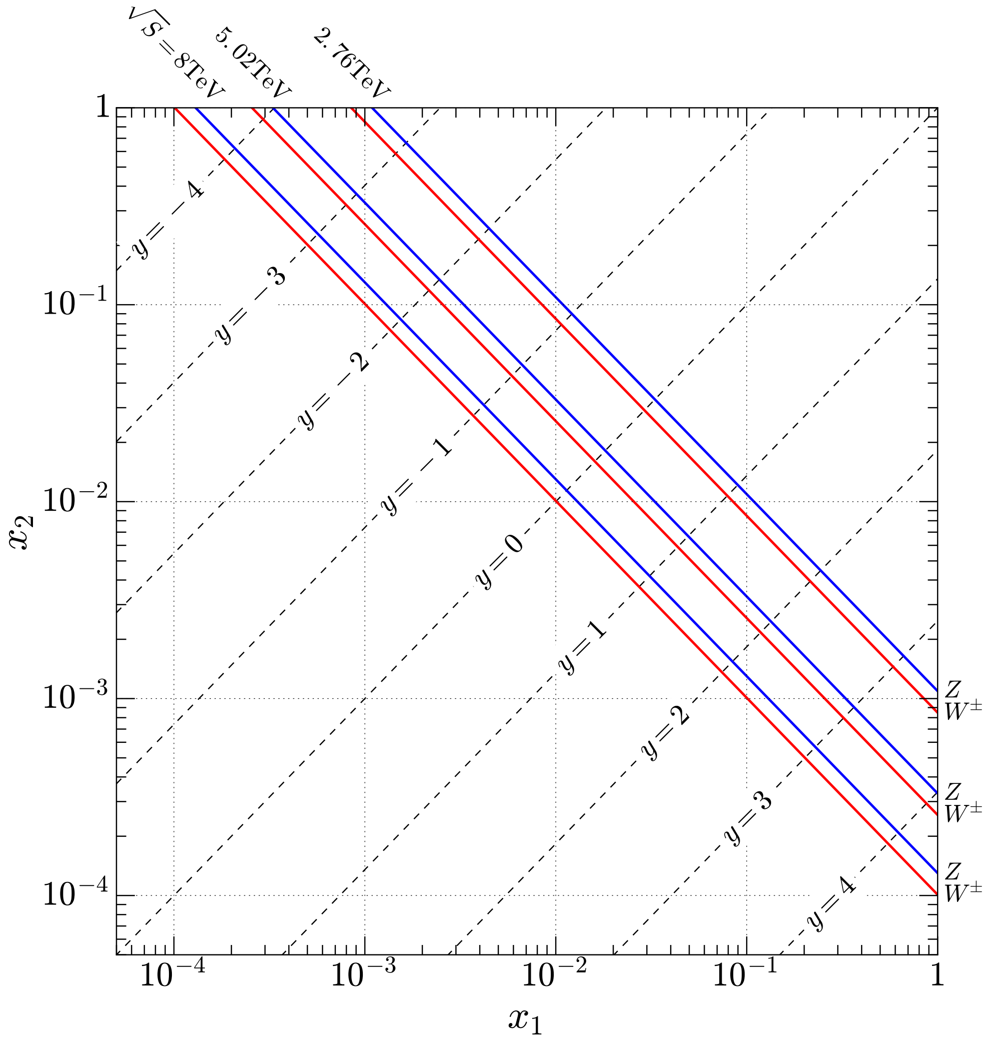
nCTEQ study of W,Z production at LHC

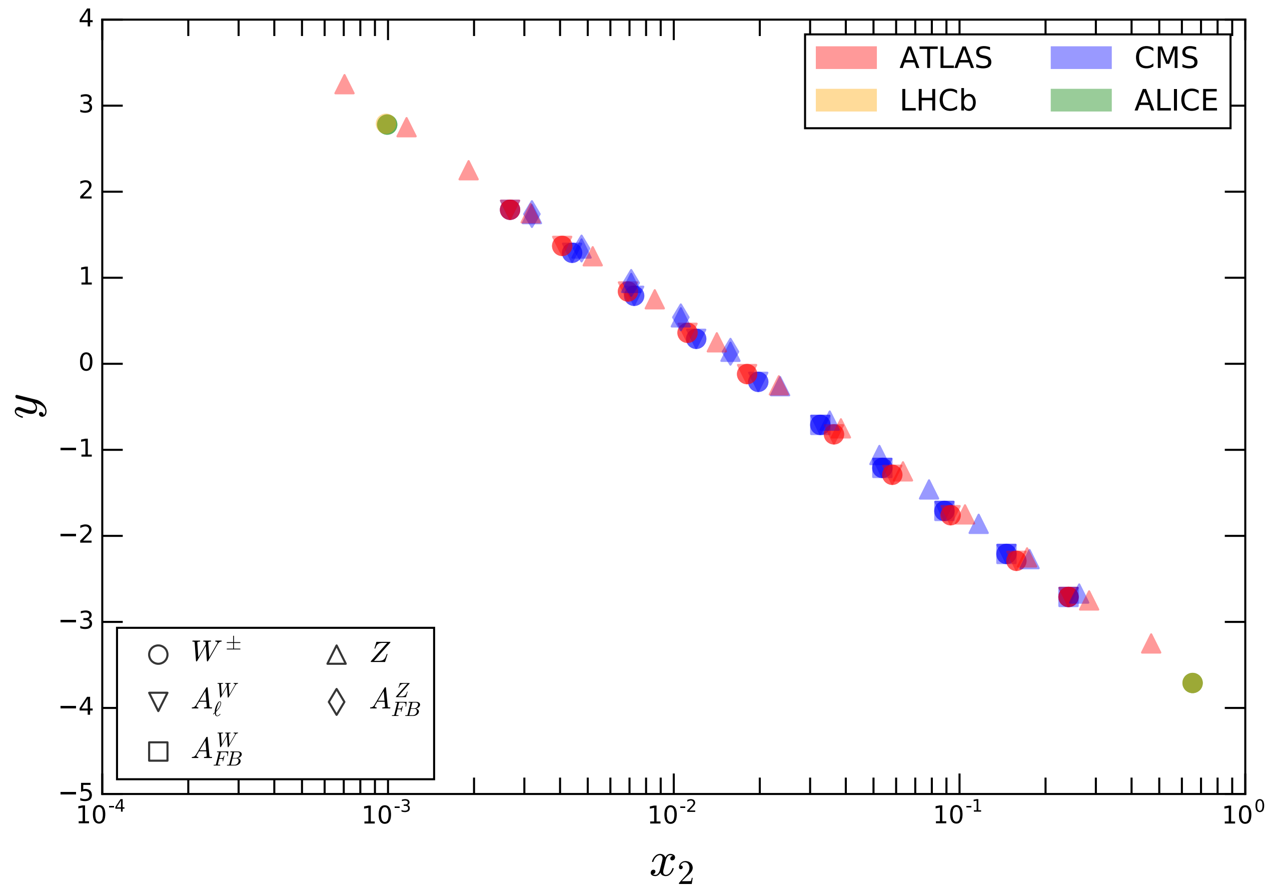
arXiv:1610.02925

		Observable	Cuts (GeV)	Figure
pPb	ATLAS	$d\sigma(Z \to \ell^+\ell^-)/dy_Z$ [2]	$\lvert y_Z^{CM}\rvert < 3.5$; $60 < m_{\ell^+\ell^-} < 120$	Fig. 3
		$d\sigma(W^+ \to \ell^+\nu)/dy_{\ell^+}$ [6]	$p_T^{\ell^\pm} > 25$; $m_T^{\ell^\pm} > 40$; $\lvert\eta_{lab}^{\ell^\pm}\rvert < 2.4$	Fig. 7a
		$d\sigma(W^- \to \ell^-\bar{\nu})/dy_{\ell^-}$ [6]	$p_T^{\ell^\pm} > 25$; $m_T^{\ell^\pm} > 40$; $\lvert\eta_{lab}^{\ell^\pm}\rvert < 2.4$	Fig. 7b
	CMS	$d\sigma(Z \to \ell^+\ell^-)/dy_Z$ [3]	$\lvert\eta_{lab}^{\ell^\pm}\rvert < 2.4$; $60 < m_{\ell^+\ell^-} < 120$; $p_T^{\ell^+(\ell^-)} > 20$	Fig. 4
		$d\sigma(W^+ \to \ell^+\nu)/dy_{\ell^+}$ [5]	$p_T^{\ell^\pm} > 25$; $\lvert\eta_{lab}^{\pm}\rvert < 2.4$	Fig. 6a
		$d\sigma(W^- \to \ell^-\bar{\nu})/dy_{\ell^-}$ [5]	$p_T^{\ell^\pm} > 25$; $\lvert\eta_{lab}^{\pm}\rvert < 2.4$	Fig. 6b
	LHCb	$\sigma(Z \to \ell^+\ell^-)$ [4]	$60 < m_{\ell^+\ell^-} < 120$; $p_T^{\ell^+(\ell^-)} > 20$; $2.0 < \eta^{\ell^\pm} < 4.5$; $-4.5 < \eta_{\ell^\pm} < -2.0$	Fig. 5
	ALICE	$\sigma(W^+ \to \ell^+\nu)$ [7]	$p_T^{\ell^\pm} > 10$; $2.03 < \eta_{lab}^{\ell^\pm} < 3.53$; $-4.46 < \eta_{lab}^{\ell^\pm} < -2.96$	Fig. 8a
		$\sigma(W^- \to \ell^-\bar{\nu})$ [7]	$p_T^{\ell^\pm} > 10$; $2.03 < \eta_{lab}^{\ell^\pm} < 3.53$; $-4.46 < \eta_{lab}^{\ell^\pm} < -2.96$	Fig. 8b
PbPb	ATLAS	$1/\sigma_{tot} d\sigma/dy_Z$ [8]	$66 < m_{\ell^+\ell^-} < 116$; $\lvert y_Z\rvert < 2.5$	Fig. 9a
		A_ℓ [10]	$p_T^\ell < 25$; $\lvert\eta_{lab}^\ell\rvert < 2.5$; $m_T > 40$; $p_T^{miss} < 25$	Fig. 10a
	CMS	$1/\sigma_{tot} d\sigma/dy_Z$ [9]	$60 < m_{\ell^+\ell^-} < 120$; $\lvert y_Z\rvert < 2.0$	Fig. 9b
		A_ℓ [11]	$p_T^\ell < 25$; $\lvert\eta_{lab}^\ell\rvert < 2.1$; $m_T > 40$	Fig. 10b

Table I: LHC data sets considered in this analysis.

nCTEQ study of W,Z production at LHC

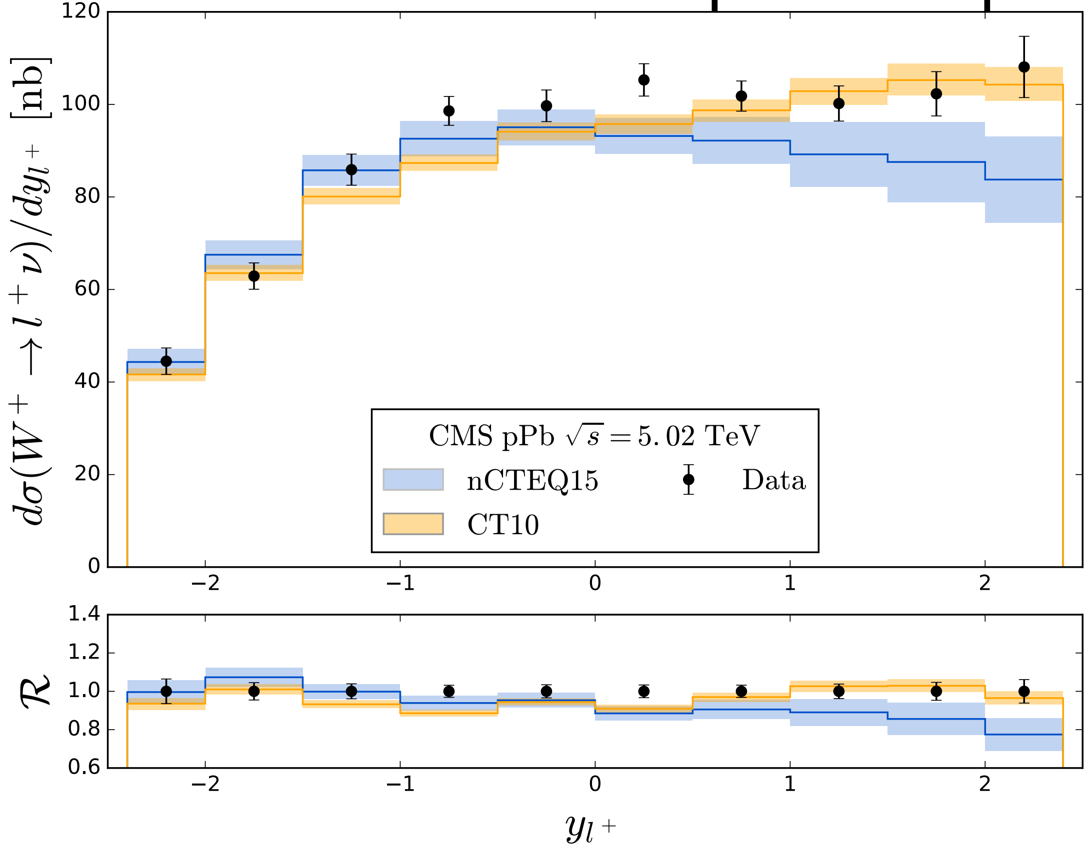




- y < -1: x > 5 x10^{-2} ... 0.3 (region where nPDFs are constrained by data in global analysis)
- |y| < 1: x ~ 10^{-2} (transition region from anti-shadowing to shadowing)
- y > 1: x < 5 x 10^{-3} (pure extrapolation!)

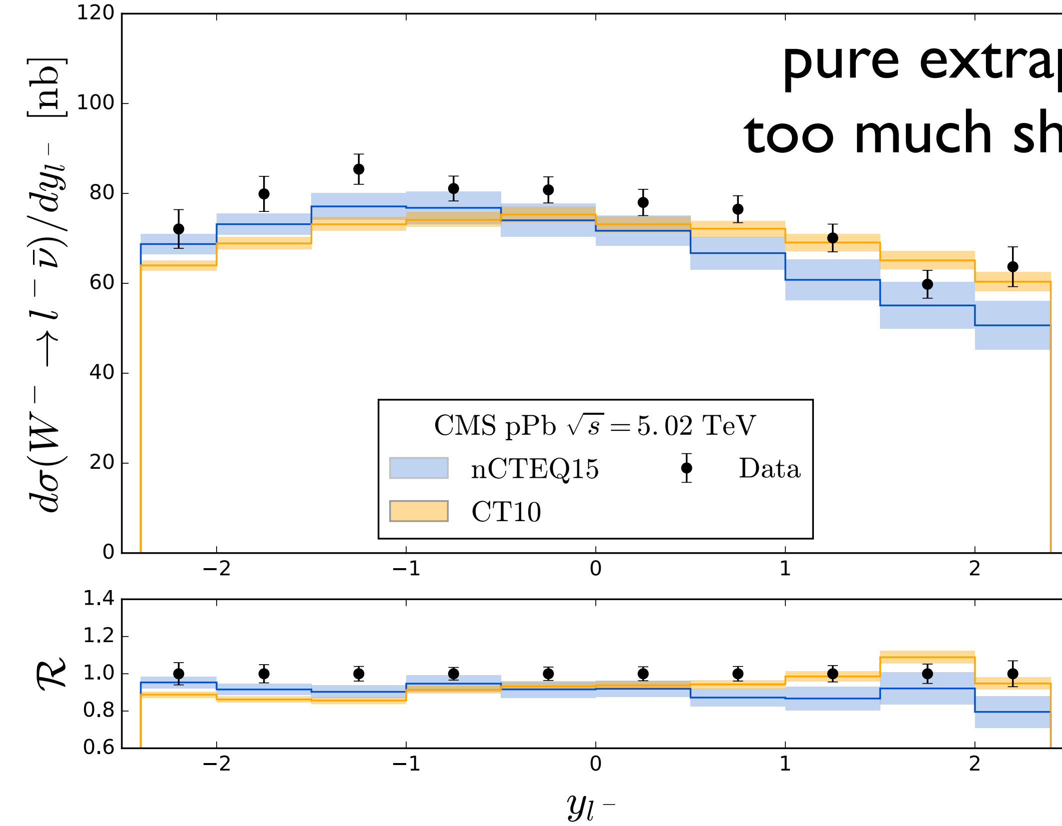
W-boson rapidity distributions

nPDFs better — pure extrapolation

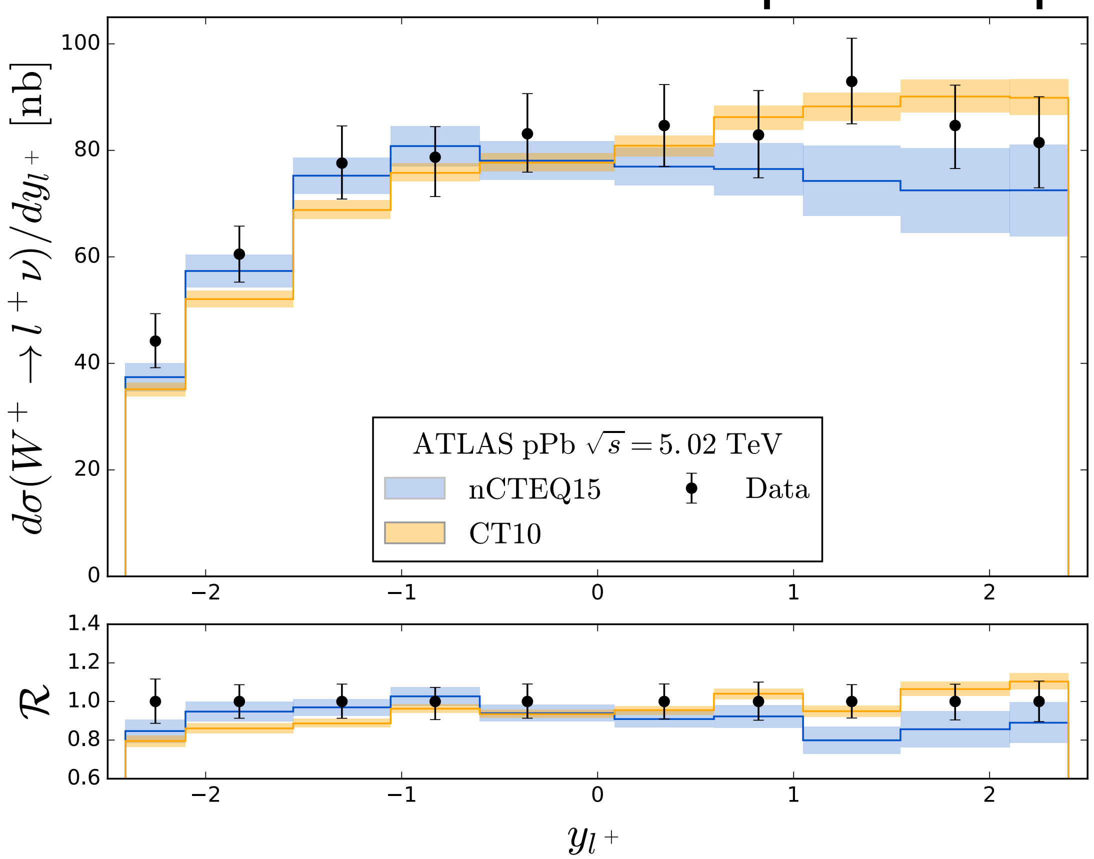


nPDFs better

pure extrapolation
too much shadowing?

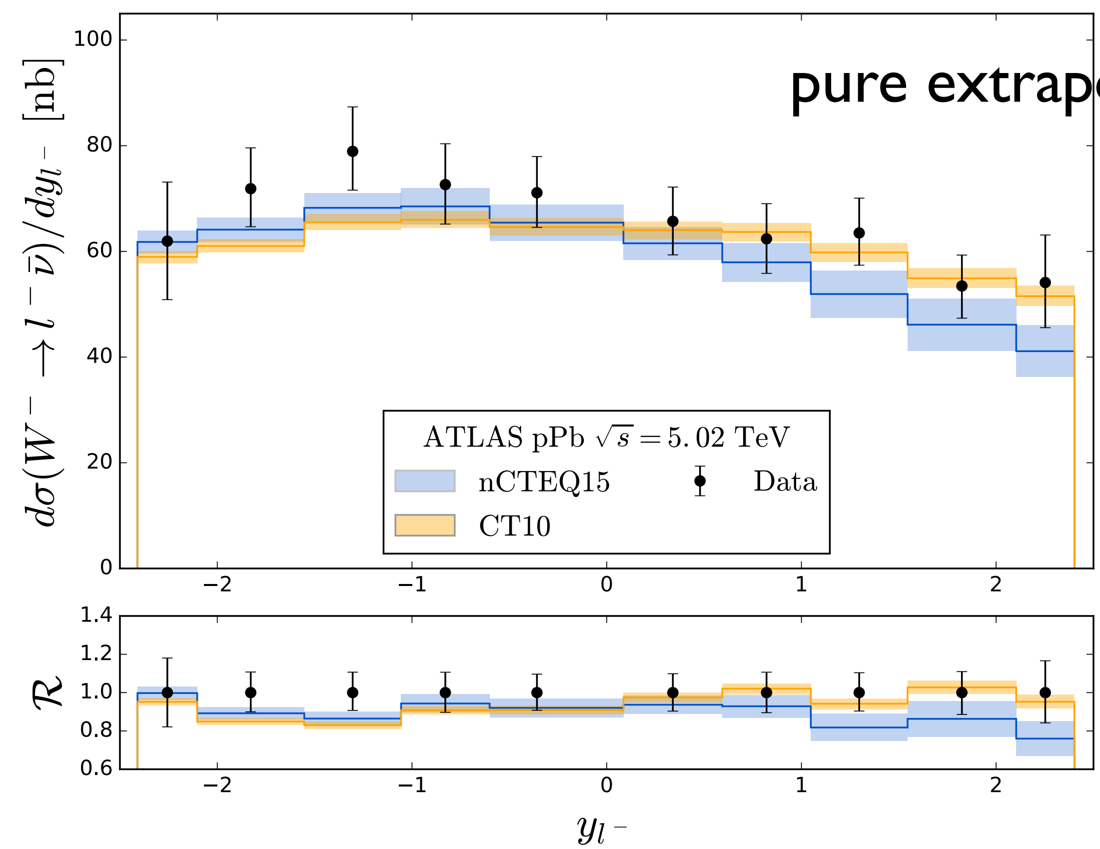


nPDFs better — pure extrapolation



nPDFs better

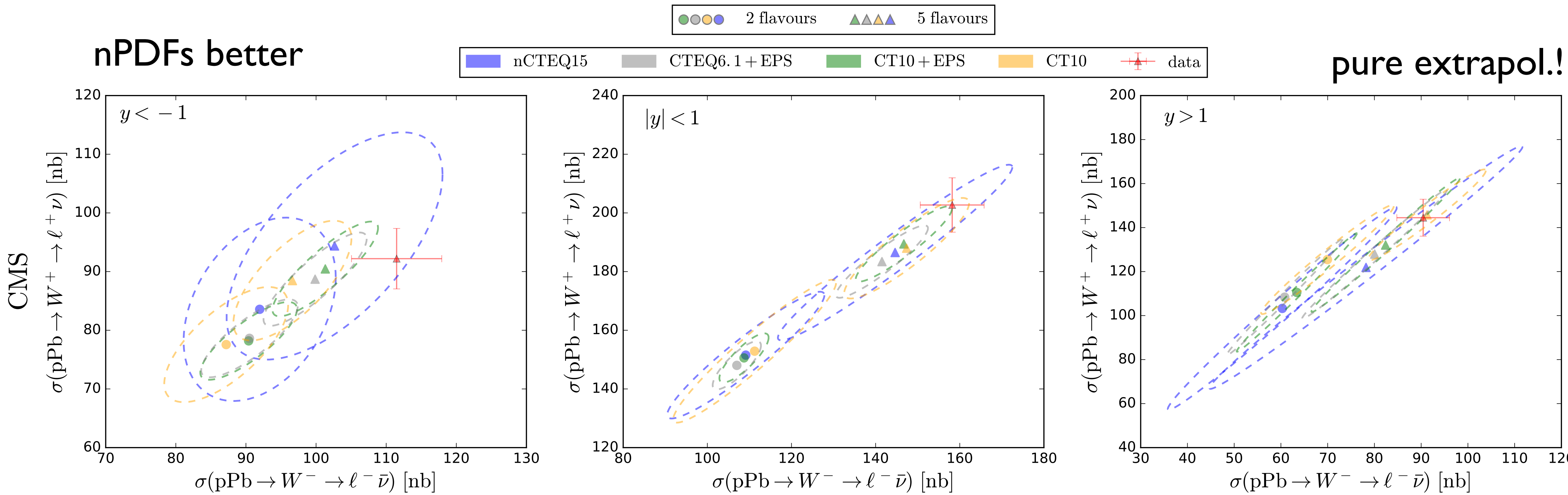
pure extrapolation



Importance of strange PDF

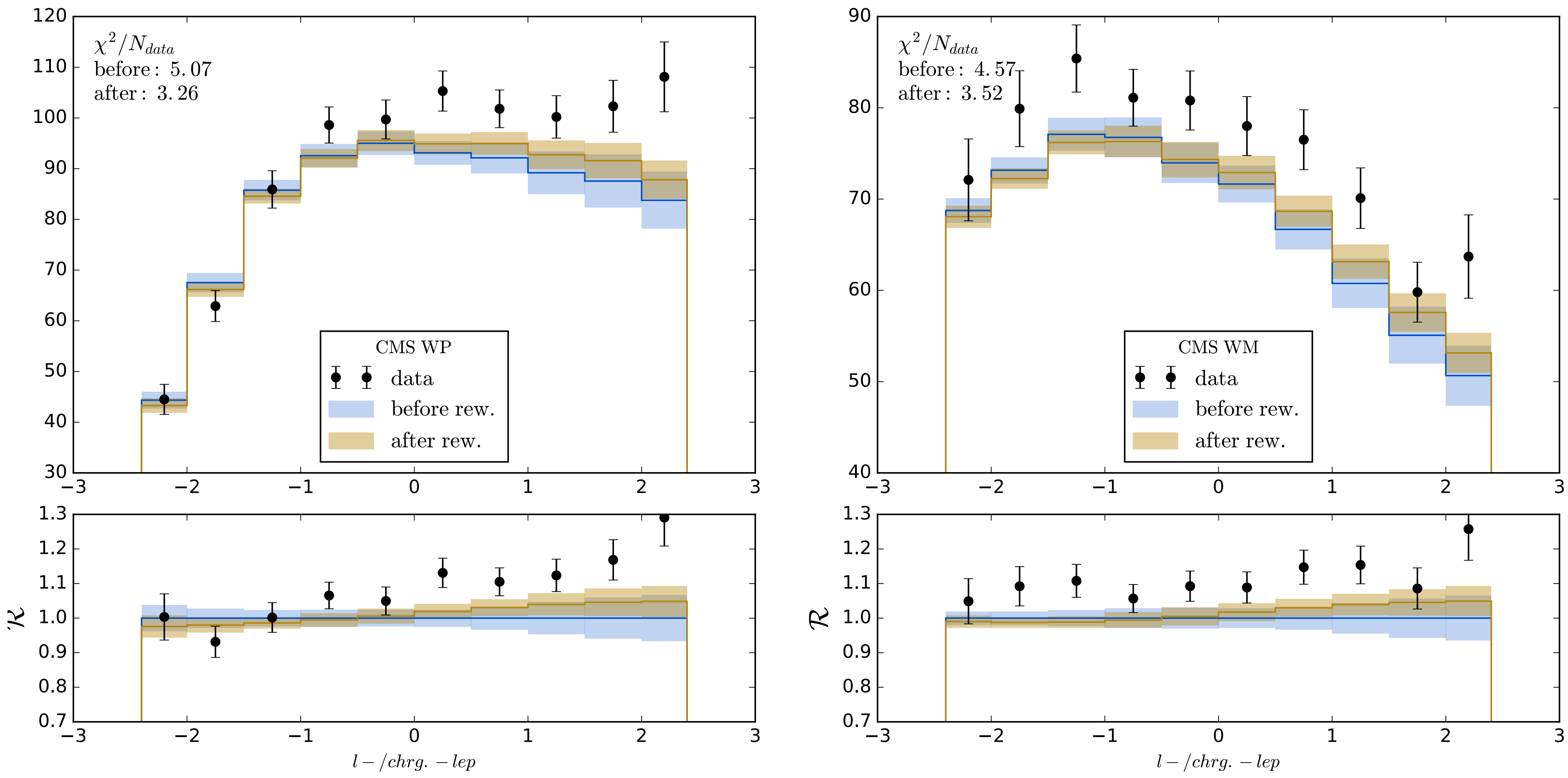
nPDFs better

pure extrapol.!



- **y<-1** (large x): s > sbar could help!
- **|y|<1**: delayed transition from anti-shadowing to shadowing could help **as seen in NuTeV neutrino data**
- **y>1**: Extrapolation, rather no shadowing at very small x?

Reweighting



(a) W^+ (b) W^-

- Improvements after reweighting
- However, strange PDF not fitted independently in nCTEQ15
- Need to include data in global analysis and open up strange PDF

Wishlist and Conclusions

Available pPb LHC data

- W/Z production
  - ATLAS [arXiv:1507.06232, ATLAS-CONF-2015-056]
  - CMS [arXiv:1512.06461, arXiv:1503.05825]
  - LHCb [arXiv:1406.2885]
  - ALICE [arXiv:1511.06398]
- Jets
  - ATLAS [arXiv:1412.4092]
  - CMS [arXiv:1401.4433, CMS-PAS-HIN-14-001]
- Charged particle production (FFs dependence)
  - CMS [CMS-PAS-HIN-12-017]
  - ALICE [arXiv:1405.2737, arXiv:1505.04717]
- Isolated photons (PbPb)
  - ATLAS [arXiv:1506.08552]
  - CMS [arXiv:1201.3093]
  - ALICE [arXiv:1509.07324]

Wishlist

- More precise data for W/Z production
  - Advantage: uncolored final state!
  - sensitive to strange PDF at $y<-1$ assuming light sea known;
    comparison with **dimuon data** from NuTeV
  - **small-x**: constraints on light sea (and strange sea but flavour separation difficult)
- Inclusive D-meson production
  - Very sensitive to gluon production at small-x!
    see PROSA study (for the gluon in the proton): EPJC75(2015)396, arXiv: 1503.04581
  - at large p_T and forward rapidites: probe of IC
- Inclusive photon+charm production
  - probe of intrinsic charm

Wishlist: Fixed target mode

- several different nuclei, constrain **large-x** nuclear PDFs
- Modern measurement of DY lepton pair production
- Inclusive D-meson production
  - probe nuclear gluon at large-x
  - constrain heavy quark (charm) distribution, test models of intrinsic charm
- Inclusive photon+charm production
  - ideal testing ground for intrinsic charm [recent review, arXiv:1504.06287]

Conclusions

- Much recent progress (EPPS'16, NCTEQ'15, W/Z analysis)
- nPDF uncertainties still substantial
- Need more precise LHC pA data (LHC5, LHC8) from as many hard processes as possible! Lead-only analysis possible!
- Coloured and un-coloured final states to test shadowing vs energy loss effects
- Bright future: future fixed target experiments, EIC, LHeC, π-A data from COMPASS
- A lot of room for theoretical progress

Backup

EPS'09 framework

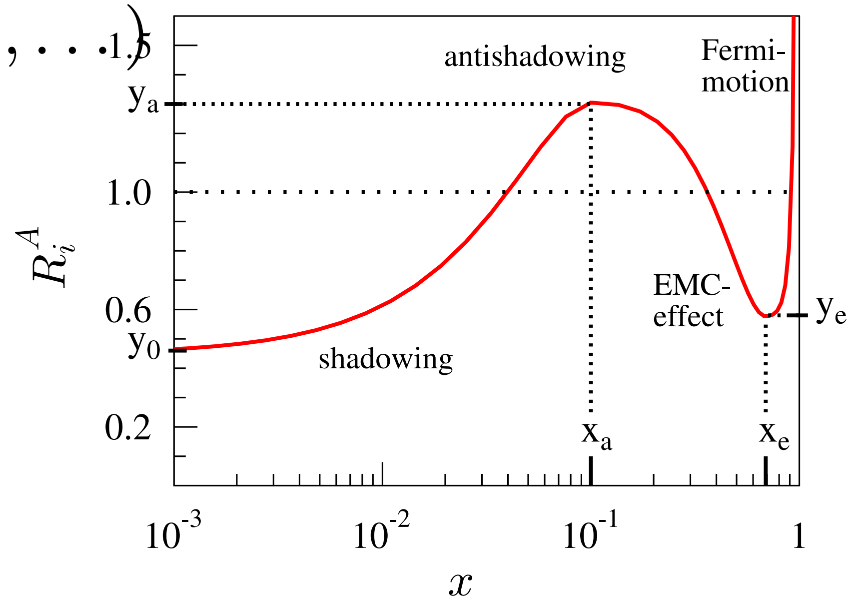
- LO & NLO PDFs with errors
- Error PDFs produced with *Hessian method*
- Parametrization (Q_0=1.3GeV)

$$f_i^{p/A}(x_N, \mu_0) = R_i(x_N, \mu_0, A, Z)\, f_i(x_N, \mu_0), \qquad i = \text{valence}, \text{sea}, g$$

$$R_i(x, A, Z) = \begin{cases} a_0 + (a_1 + a_2 x)(e^{-x} - e^{-x_a}) & x \le x_a \\ b_0 + b_1 x + b_2 x^2 + b_3 x^3 & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \le x \le 1 \end{cases}$$

A-dependence of fitting parameters ($d_i = a_i, b_i, \ldots$)

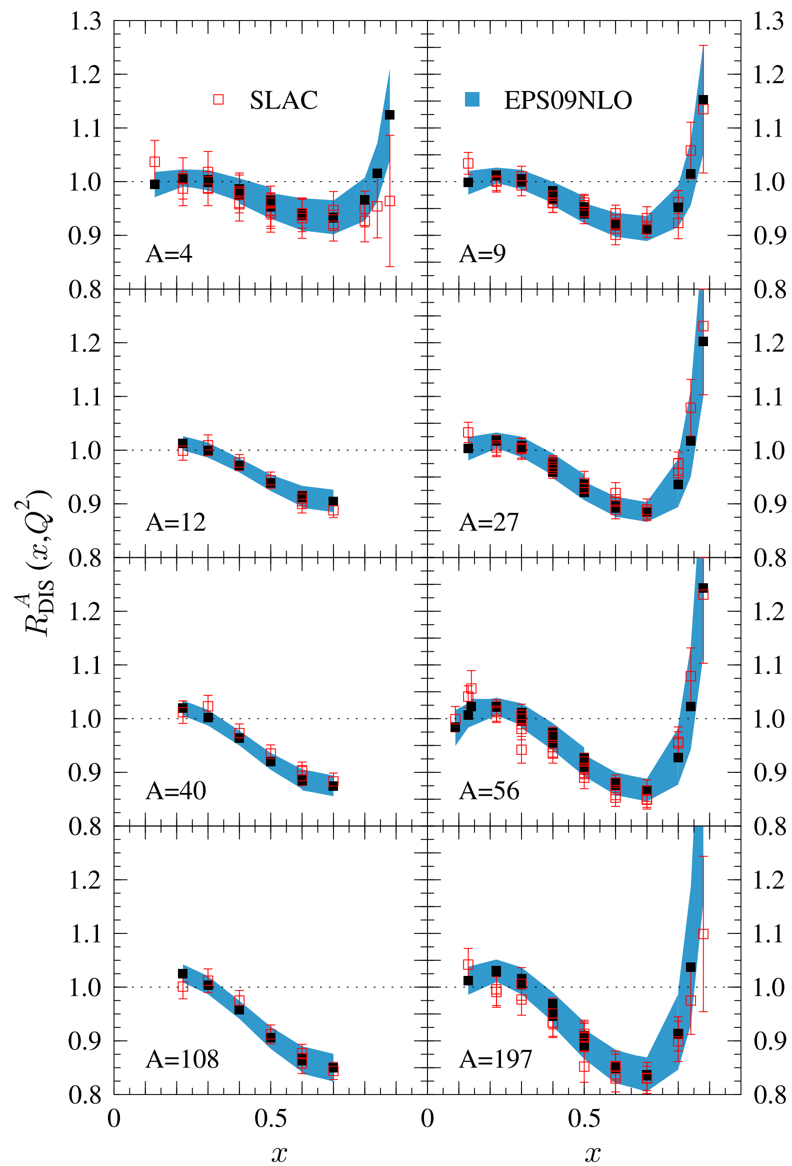
$$d_i^A = d_i^{A_{ref}} \left(\frac{A}{A_{ref}}\right)^{p_{d_i}}$$

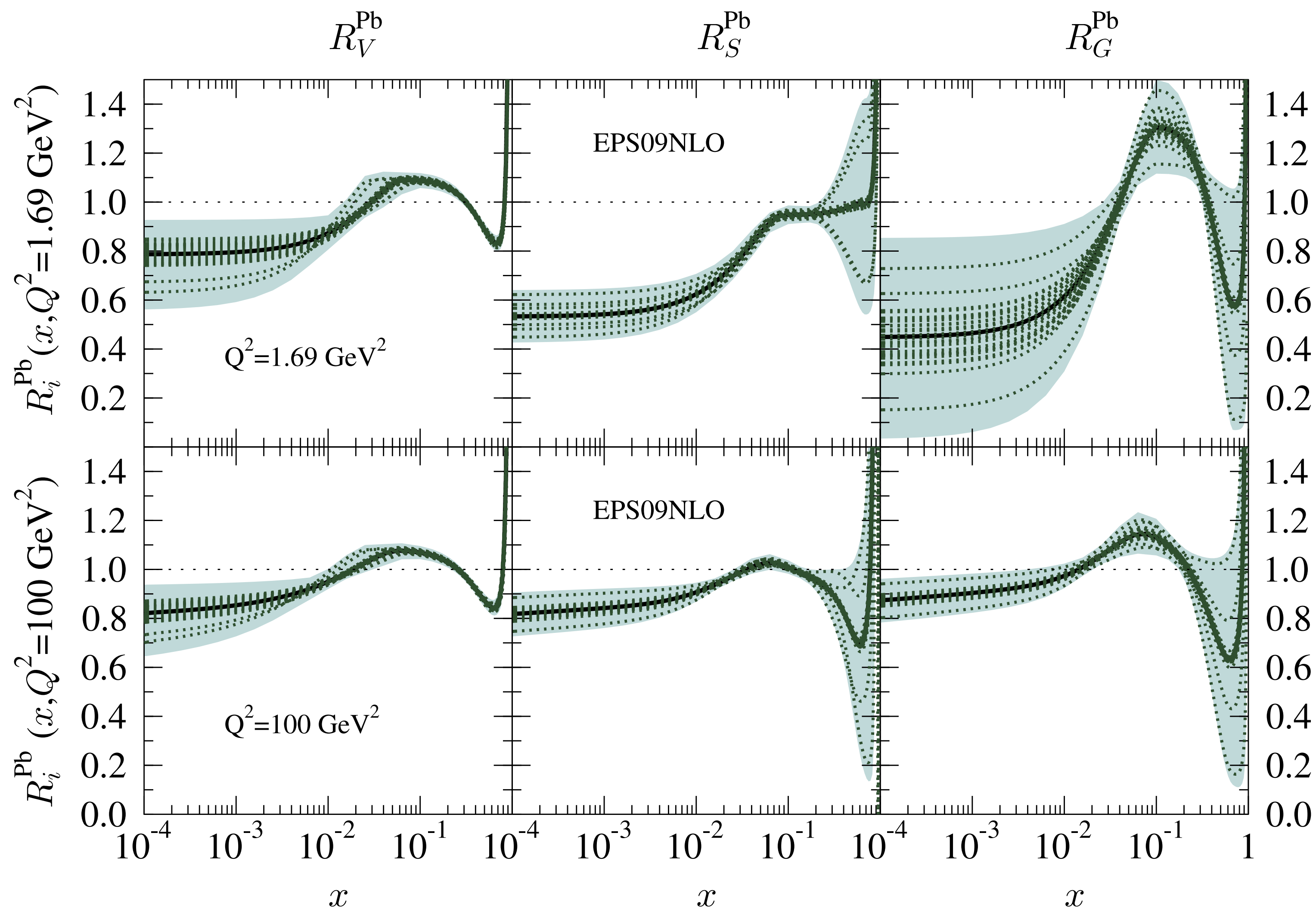


- CTEQ6.1M free proton baseline
- Neglects $x_N > 1$
- Data: DIS, DY, π^0 @ RHIC

EPS'09 framework

- NLO fit: $\chi^2/dof = 0.79$





HKN'07 framework

- LO & NLO PDFs with errors
- Error PDFs produced with *Hessian method*
- Parametrization (Q_0=1GeV)

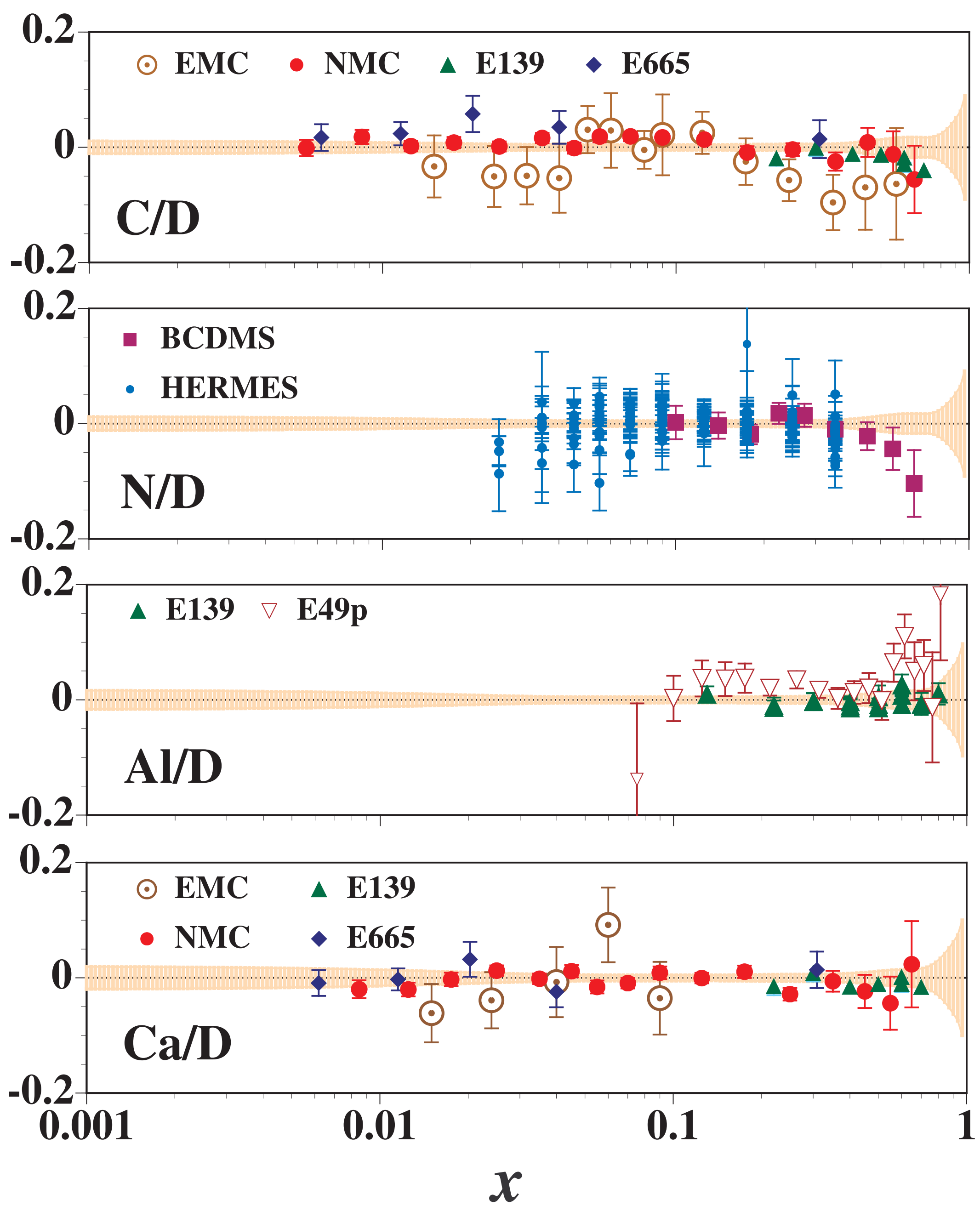
$$f_i^{p/A}(x_N, Q_0) = R_i^A(x_N, Q_0)\, f_i^p(x_N, Q_0), \qquad i = \text{valence, sea}, g$$

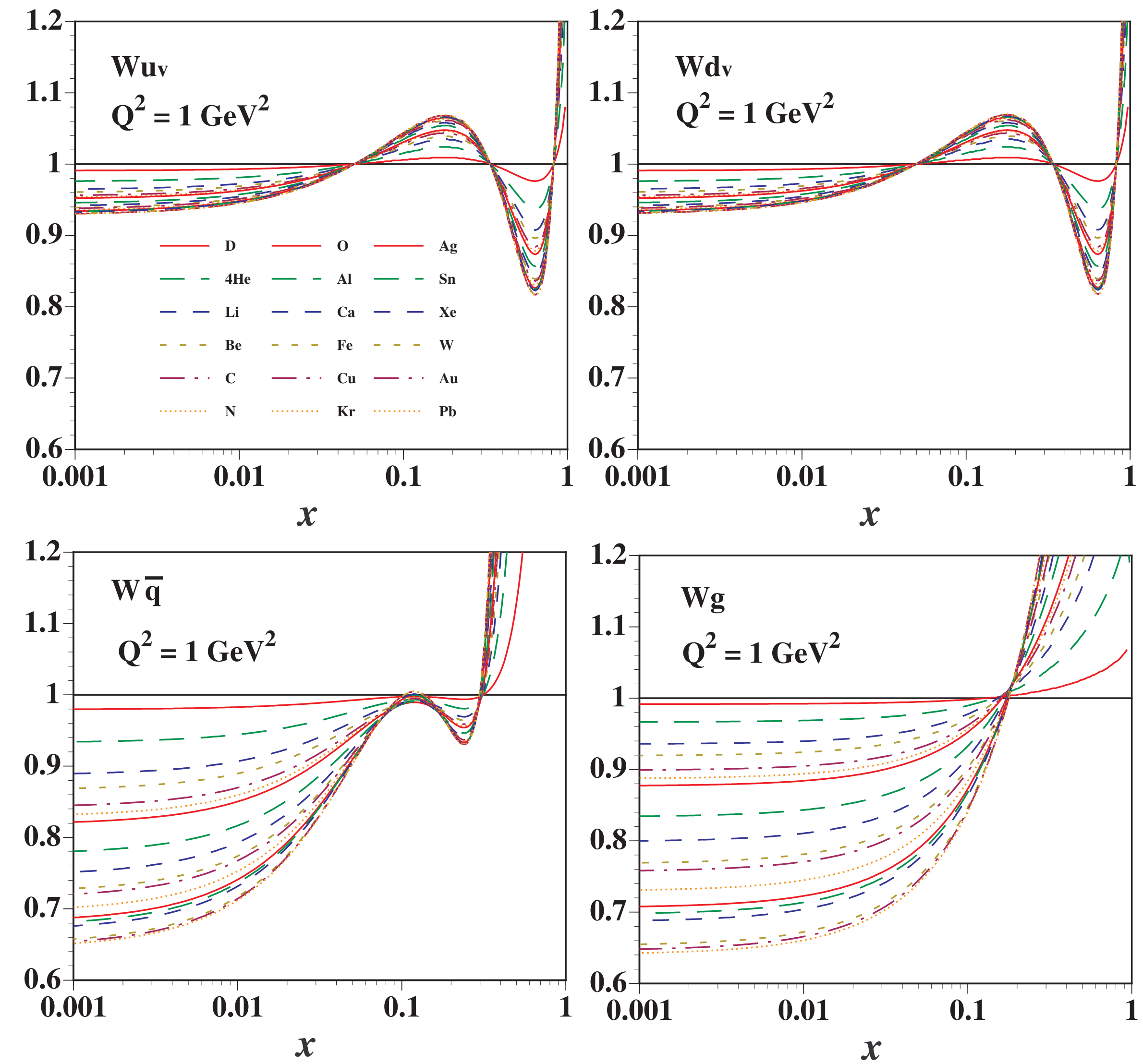
$$R_i(x, Q_0, A) = 1 + \left(1 - \tfrac{1}{A^\alpha}\right) \frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^{\beta_i}}$$

- MRST 1998 free proton baseline
- Neglects $x_N > 1$
- Data: DIS & DY

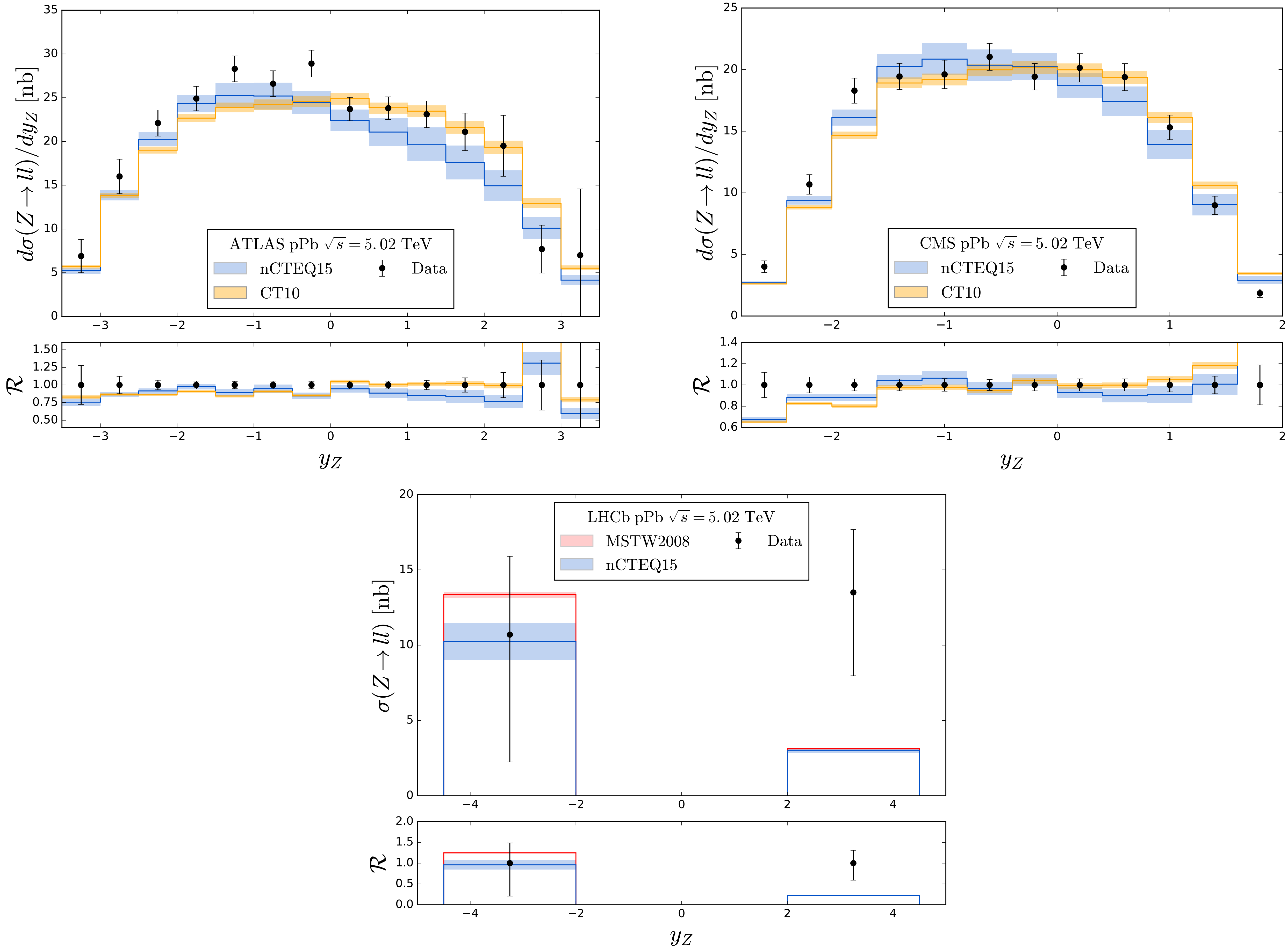
HKN'07 framework

- NLO fit: $\chi^2/dof = 1.21$

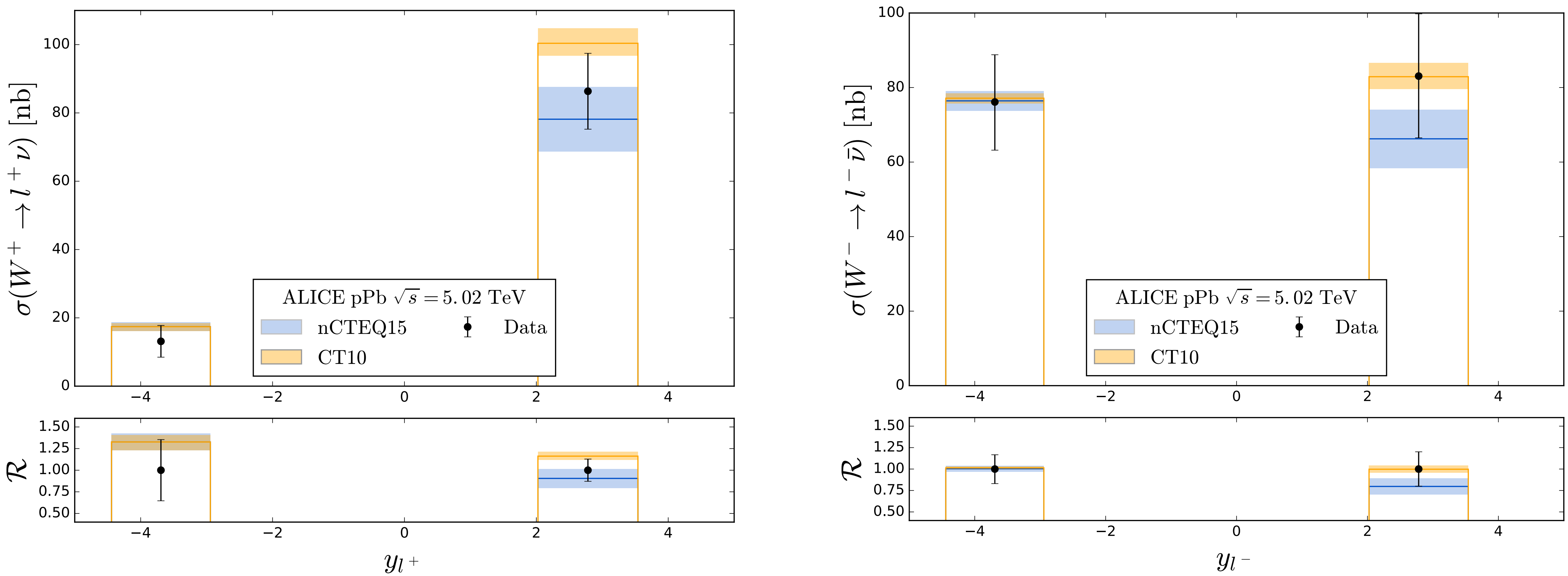




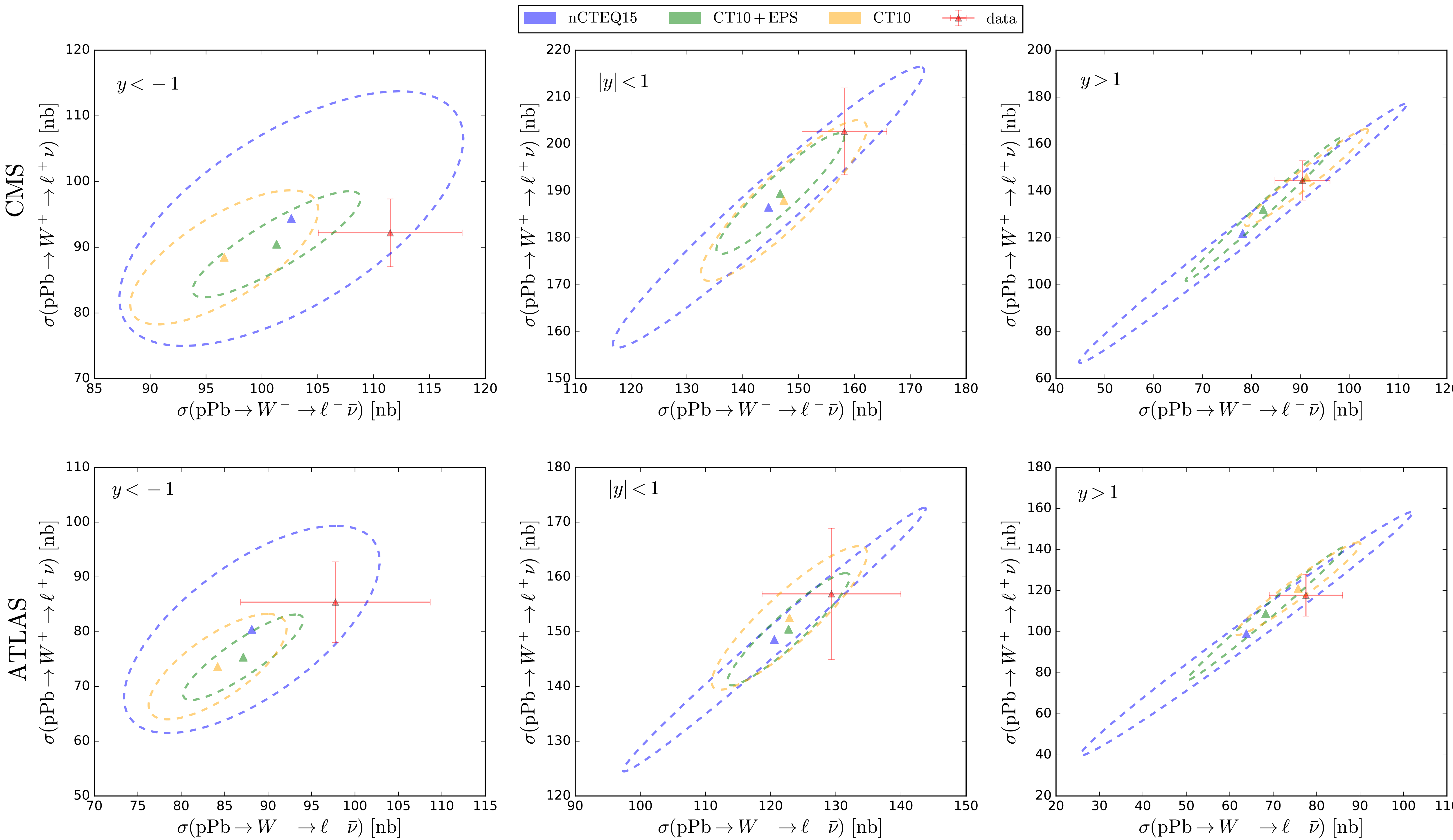
Z-boson rapidity distributions



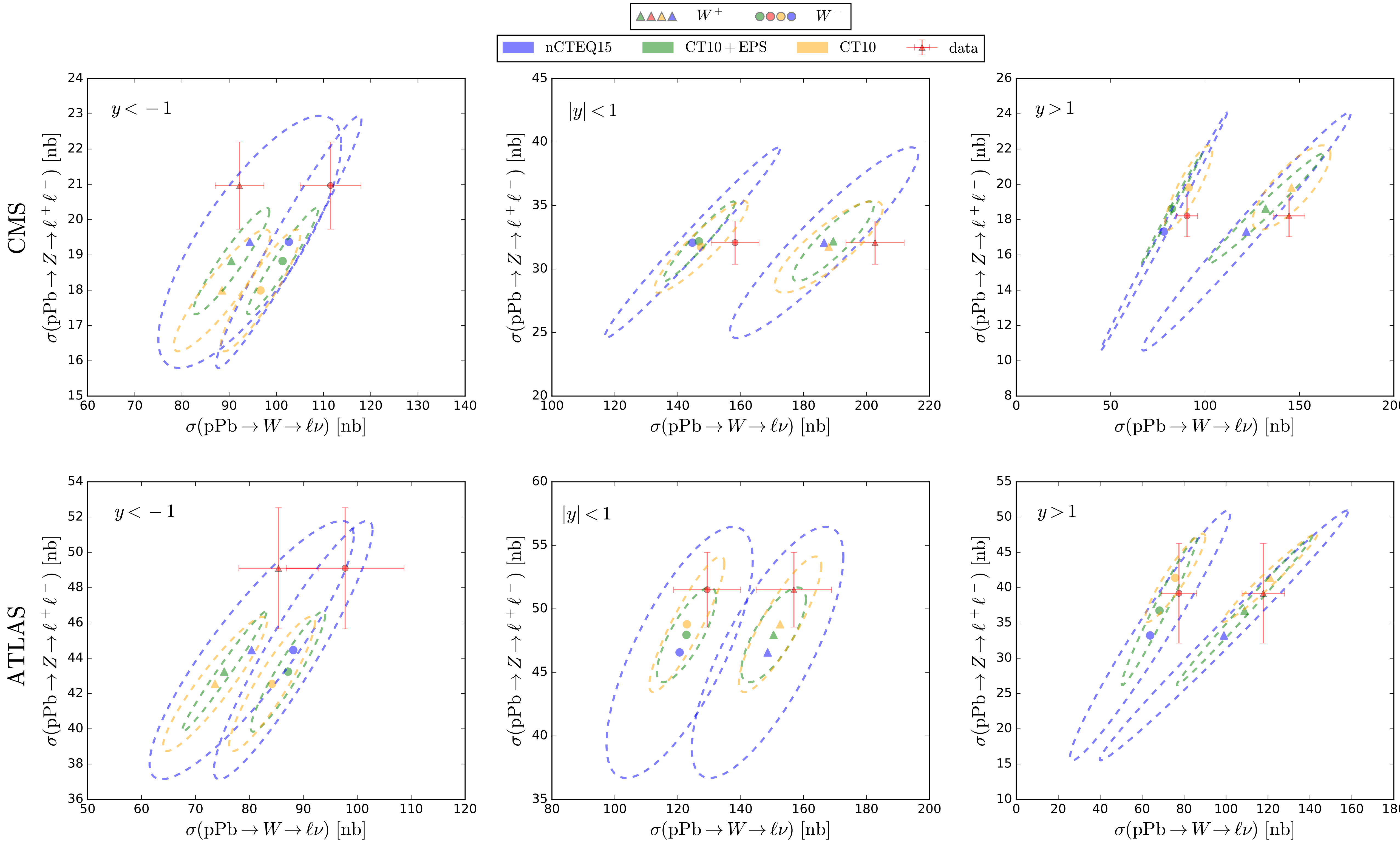
W-boson rapidity distributions



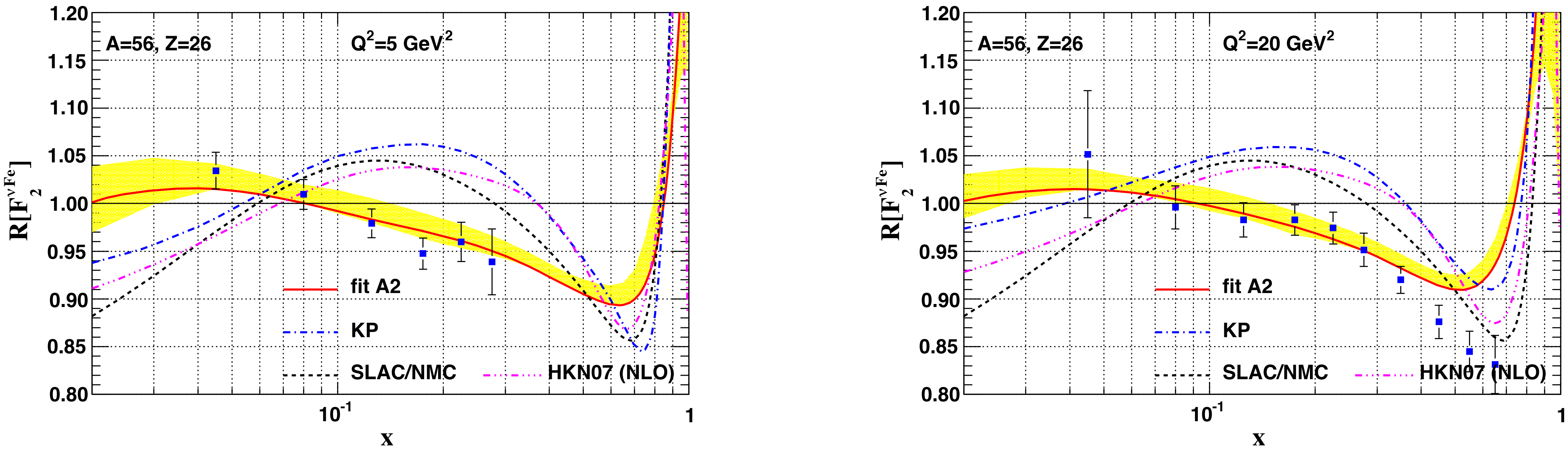
(W^+, W^-) Correlation



(Z,W) Correlation



NUCLEAR CORRECTION FACTOR $R[F_2^{\nu Fe}]$



- Are nuclear corrections in charged-lepton and neutrino DIS different?
- Obviously the PDFs from fi ts to ℓA + DY data do not describe the neutrino DIS data.
- However, a better flavor decomposition could be possible resulting from a global analysis of ℓA, DY and νA data.

Note: $x_{\min} = 0.02$ in these figures.

Tolerance criterion

Probability distribution for the χ^2 function

$$P_N(\chi^2) = \frac{(\chi^2)^{N/2-1} e^{-\chi^2/2}}{2^{N/2}\Gamma(N/2)}$$

Determine ξ_{50}^2 and ξ_{90}^2 (i.e. $p = 50$, $p = 90$):

$$\int_0^{\xi_p^2} d\chi^2 P_N(\chi^2) = p/100$$

Condition for compatibility of two fits:
The 2nd fit (χ_n^2) should be within the 90% C.L. region of the first fit ($\chi_{n,0}^2$)

$$\chi_n^2/\chi_{n,0}^2 < \xi_{90}^2/\xi_{50}^2 \quad \Leftrightarrow \quad C_{90} \equiv \frac{\Delta\chi^2}{\frac{\chi_{n,0}^2}{\xi_{50}^2}(\xi_{90}^2 - \xi_{50}^2)} < 1$$

see CTEQ'01, PRD65(2001)014012; MSTW'09, EPJC(2009)63,189-285