Nuclear PDFs:
Questions for WG A

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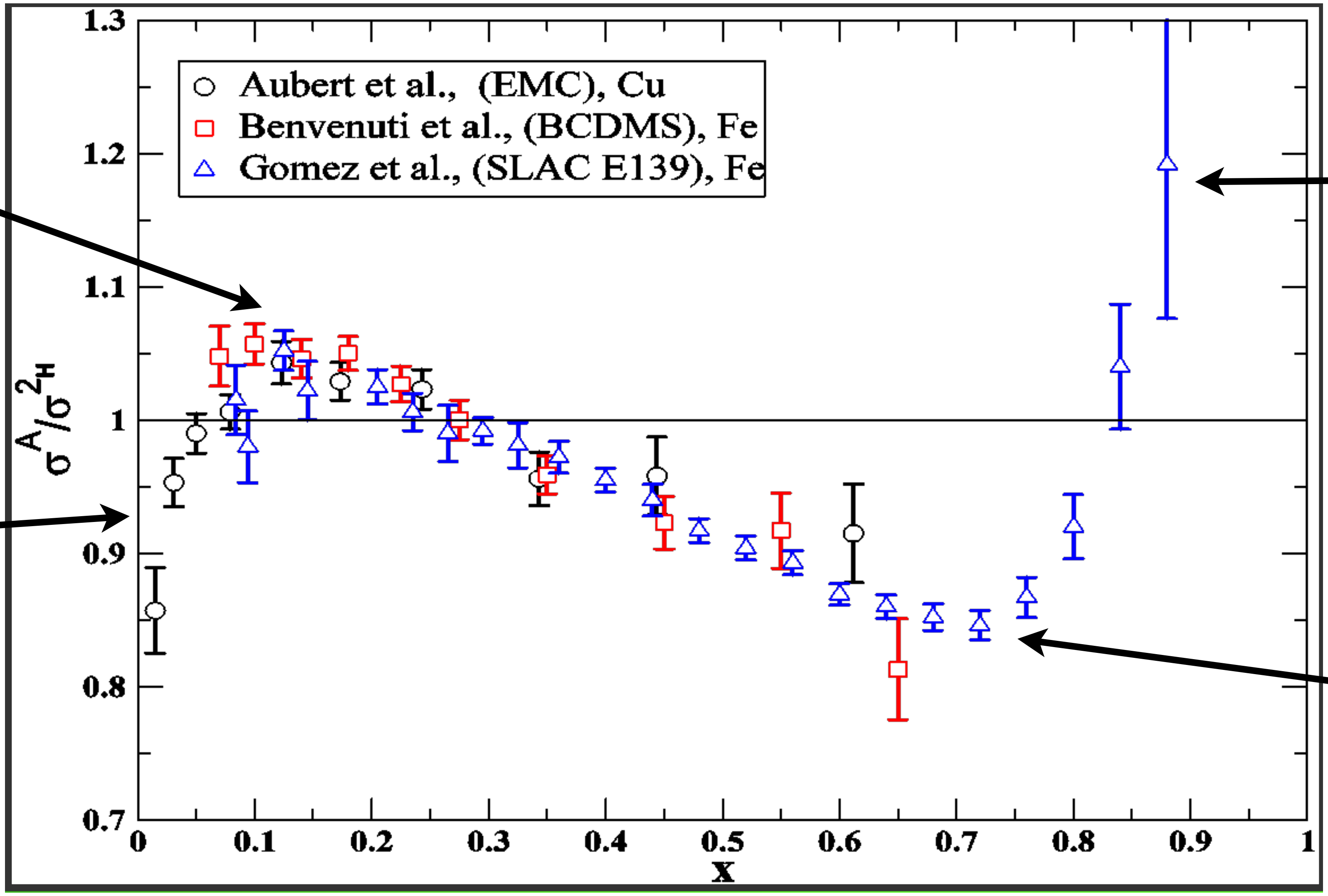
Cross sections in nuclear collisions are modified

Nuclear modifications

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



Anti-shadowing enhancement

Shadowing suppression at small x

Rise due to Fermi motion

EMC effect

Nuclear modifications

- As discovered more than 30 years ago by the European Muon Collaboration, nucleon structure functions are modified by the nuclear medium (EMC effect)
- Studies of nucleon structure: need to correct for nuclear effects
- Nuclear effects interesting in its own right!
    - Many models exist
    - However, charged lepton nuclear effects still not fully explained, in particular the EMC effect ($0.3 < x < 0.7$)

νA DIS vs lA DIS

- Not much information on nuclear ratios in νA DIS
- Often use information from lA DIS to correct for nuclear effects
- Sometimes the same nuclear correction factor is applied independent of the neutrino observable, Q^2, or the nuclear A
- **Big question**:

  Are nuclear effects in νA DIS the same as in lA DIS?

  Can we translate these modifications into universal quantities like nuclear PDFs?

Nuclear corrections: Parton model perspective

- Be O an observable calculable in the parton model
- Define **nuclear correction** factor in the following way:

$$R[O] = O[Z f^{p/A} + N f^{n/A}]/O[Z f^{p} + N f^{n}]$$

- **Advantages**:
  - very flexible: any $Q^2 > 1$ GeV^2, different nuclear A
  - different observables: $F_{1,2,3}^{W+}$, $F_{1,2,3}^{W-}$, $F_{1,2}^{\gamma}$, DY, $d\sigma/dxdy$
  - calculation of uncertainties possible
- Of course, no explanation of nuclear effects

Nuclear corrections: Parton model perspective

Even with same nuclear modification of the different parton flavors:

$$R[F_2^{\nu A}](x) \neq R[F_2^{lA}](x) \qquad R[F_3^{\nu A}](x) \neq R[F_2^{\nu A}](x)$$

simply because different observables depend differently on the partons.

measured needed correction factor

Often similar but **not** the same: $F_2^A/F_2^D \neq R[F_2^A]$

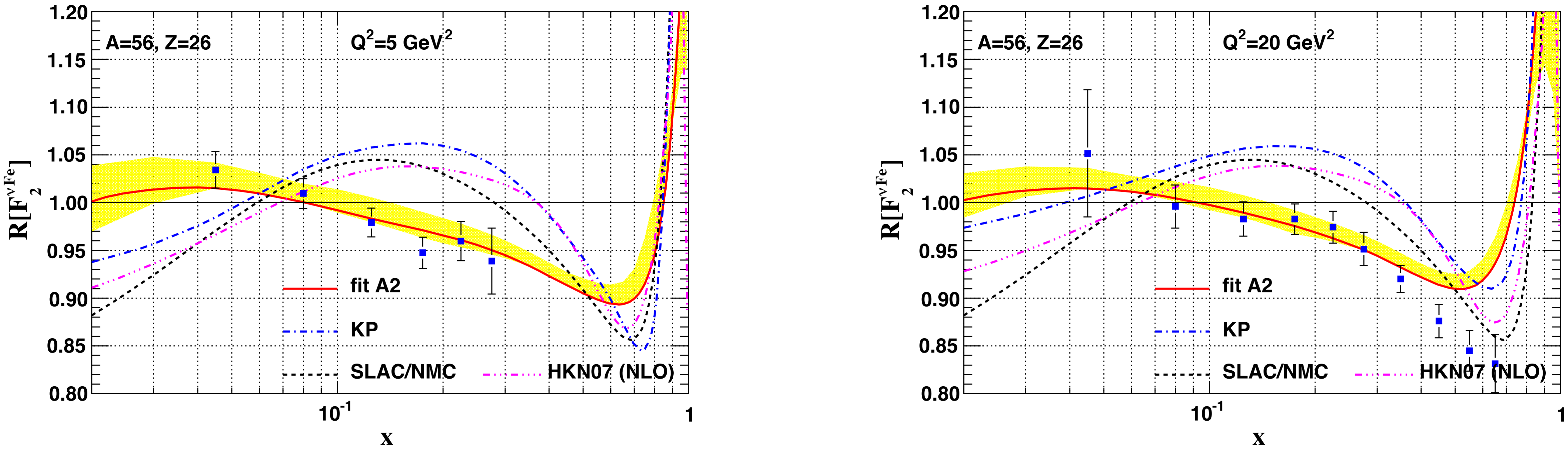
Non-isoscalarity effects; Deuteron has its own nuclear corrections.

In summary:

Nuclear correction factors will be (more or less) different even if the same nuclear mechanisms are at work/even if there are universal NPDFs

Big question: can νA+lA data be described by a universal set of NPDFs?

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



- Are nuclear corrections in charged-lepton and neutrino DIS different?
- Obviously the PDFs from fits 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.

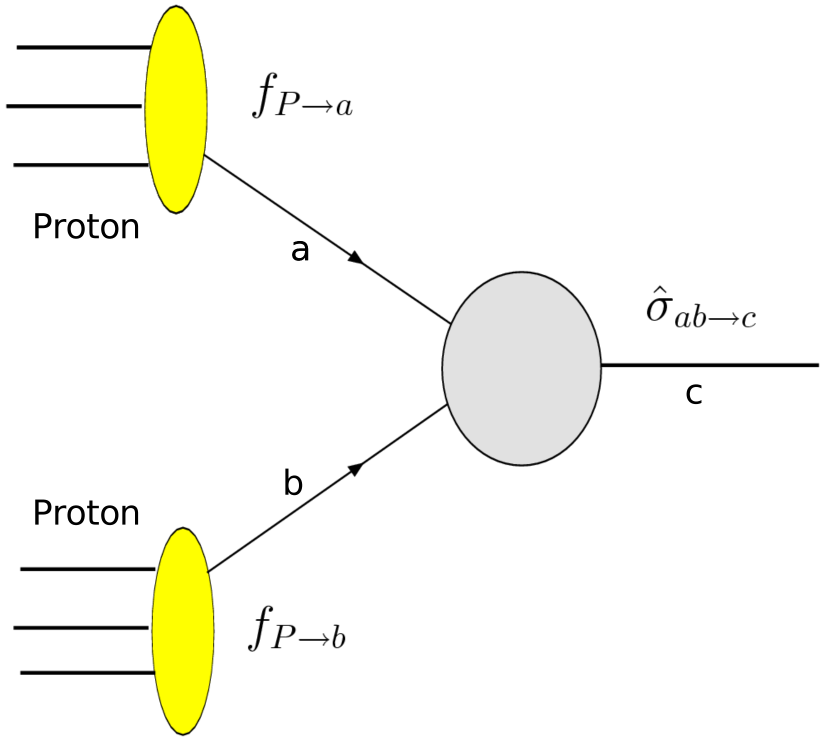
Note: $x_{\min} = 0.02$ in these figures.

Possible ToDo-List

- Dedicated pedagogic talks on
  - Models for EMC effect, anti-shadowing, shadowing, binding energy
  - Neutrino-Nucleus DIS
    - good understanding needed for LBL neutrino experiments
    - testing models for nuclear effects
- Work on nuclear corrections factors needed to use data taken on nuclear targets in proton PDF analyses

Theoretical Framework

Factorisation



$$\sigma = f_{P\to a} \otimes f_{P\to b} \otimes \hat{\sigma}_{ab\to c}$$

From experiment

Calculable from theoretical model

Parton Distribution Functions (PDFs)

$f_{P\to a,b}(x,\mu^2)$

- Universal
- Describe the structure of hadrons
- Obey DGLAP evolution equations

The hard part $\hat{\sigma}_{ab\to c}(\mu^2)$

- Free of short distance scales
- Calculable in perturbation theory
- Depends on the process

Error of the twist-2 factorization approximation suppressed by hard scale: $O((\Lambda/\mu)^P)$

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

Questions

- PDFs are twist-2 objects **defined** in the context of factorization theorems

- How good does twist-2 factorization hold in pA collisions?

- There is some work by J.-W. Qiu finding that twist-2 factorization holds but that higher twist terms may be nuclear enhanced

- How do we detect factorization breaking effects?

- What about AA collisions? Is there an alternative to nPDFs? Do we loose predictivity if we have to include other effects?

Possible ToDo-List

- Carefully revisit literature on factorization in pA and AA collisions
- Any factorization breaking effects or enhanced higher twist effects have to be embedded in the pQCD framework!

NPDF uncertainties

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

Available nuclear PDFs

- **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`]

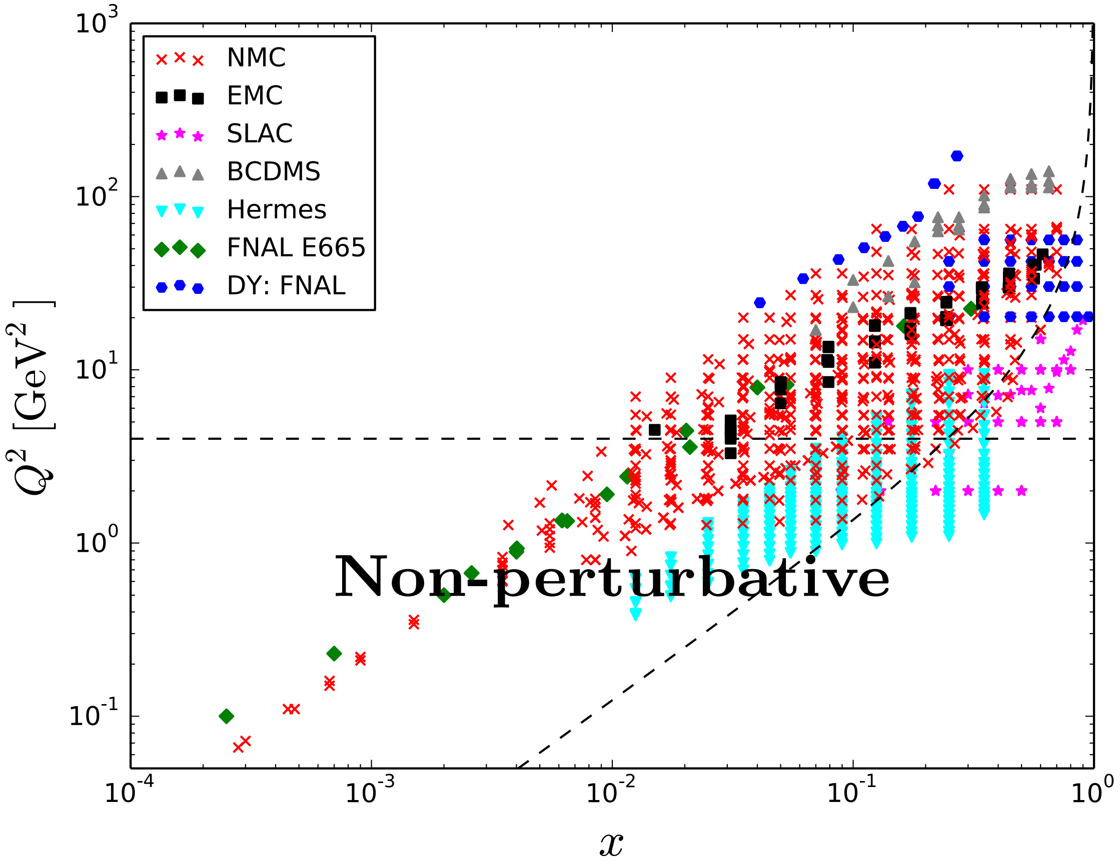
$$f_i^{p/A}(x_N,\mu_0) = f_i(x_N,A,\mu_0)$$

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

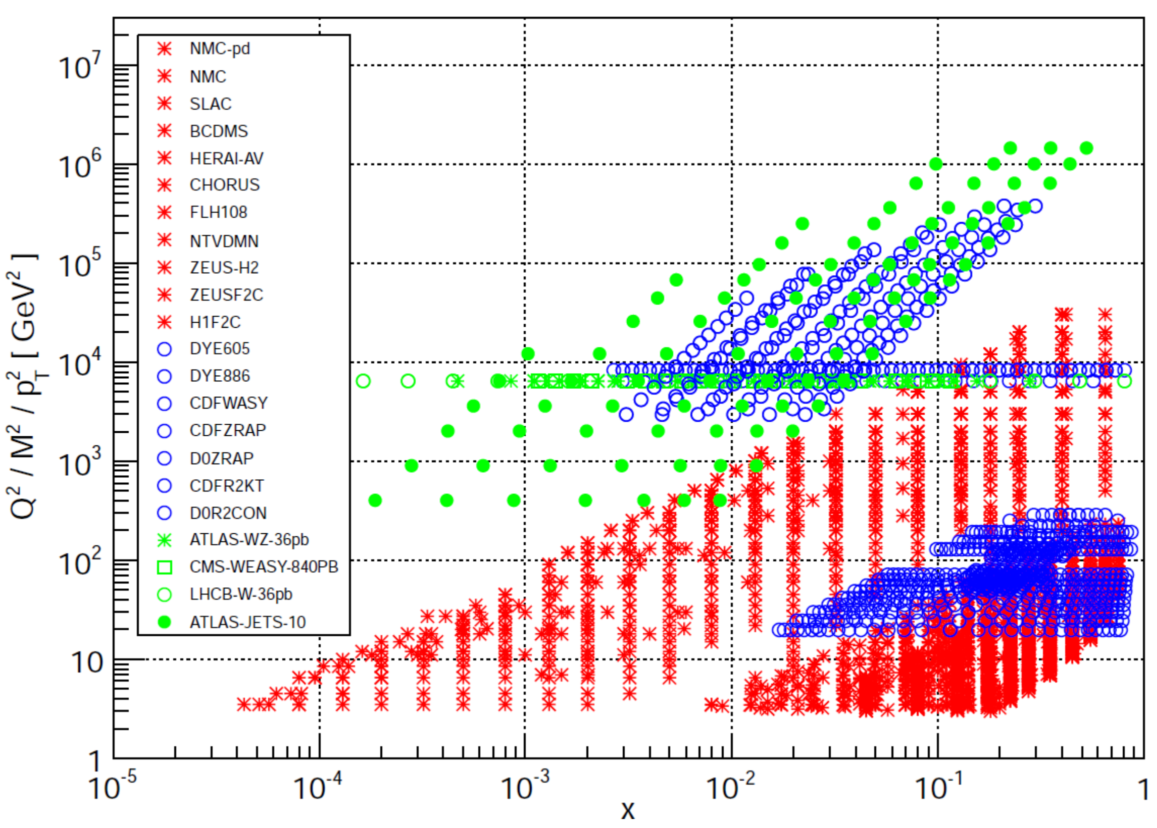
Differences with the proton case

- Theoretical status of Factorization
- Parametrization – more parameters to model A-dependence
- Different data sets – much less data:

nCTEQ15 dataset



NNPDF2.3 dataset



- Less data → less constraining power → **more assumptions** (fixing) about fitting parameters

Common assumptions

1. **Factorization** & DGLAP evolution
    - allow for definition of **universal PDFs**
    - make the formalism **predictive**
    - needed even if it is broken
2. Isospin symmetry $\begin{cases} u^{n/A}(x) = d^{p/A}(x) \\ d^{n/A}(x) = u^{p/A}(x) \end{cases}$
3. The *bound proton* PDFs have the *same evolution equations* and sum rules as the free proton PDFs *provided we neglect any contributions from the region* $x > 1$ (which is expected to have negligible contribution [PRC 73, 045206 (2006), `arXiv:hep-ph/0509241`])

Then observables $\mathcal{O}^A$ can be calculated as:

$$\mathcal{O}^A = Z\,\mathcal{O}^{p/A} + (A - Z)\,\mathcal{O}^{n/A}$$

With the above assumptions we can use the free proton framework to analyze nuclear data

Specific assumptions

- Choice and weight of data sets
- Cuts on (x,Q)-plane
- Parameterization of x-dependence of NPDFs:
  - fixed functional form
  - assumptions necessary to reduce number of free fit parameters (to make the fit converge)

    → Parametrization bias: underestimation of uncertainties!
- Parameterization of A-dependence
- Heavy flavour treatment

Questions

- How to get a more realistic estimate of the PDF uncertainties?
- Combine NPDFs from different groups?
- Do methods proposed for proton PDFs work for the NPDFs with suffer under much larger systematics?
- Need a reliable and practical solution. Quite important!
- New data from pA collisions at the LHC will help reduce the systematics
- In the future: EIC, AFTER, LHeC, ...

Possible ToDo-List

- Better understand NPDF uncertainties
- Work on recommendations for a practical approach to get a realistic estimate of the NPDF uncertainties

nCTEQ15

nCTEQ 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)

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

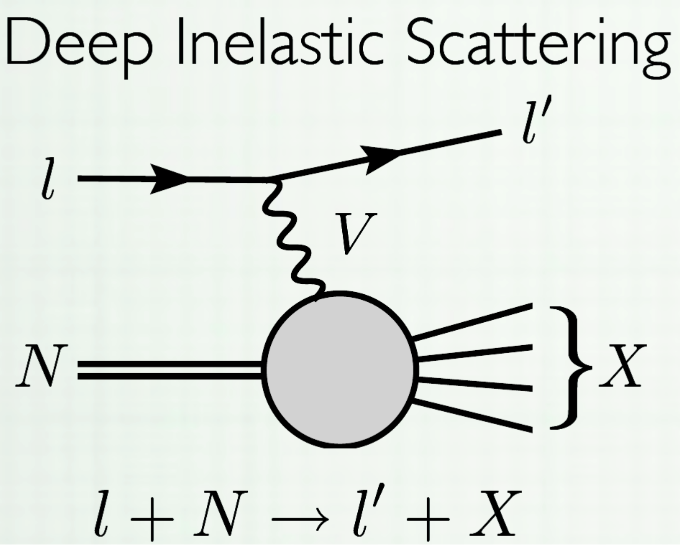
(bound neutron PDF $f_i^{n/A}$ by isospin symmetry)

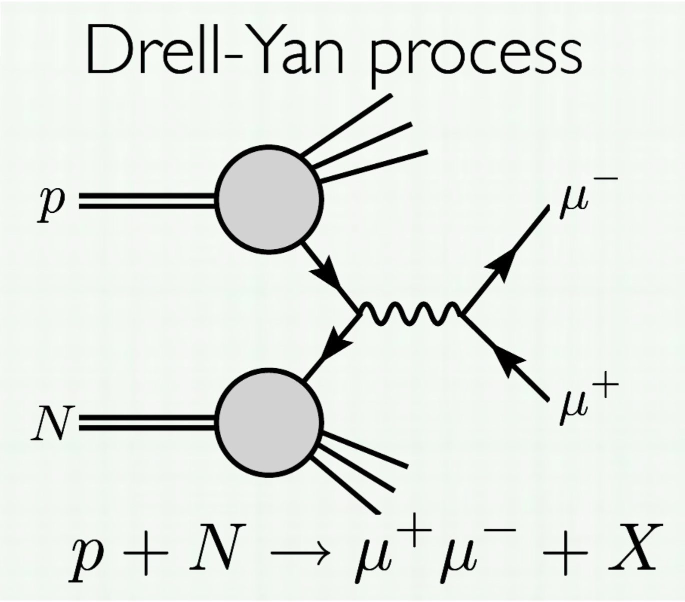
Data sets

PRD93(2016)085037

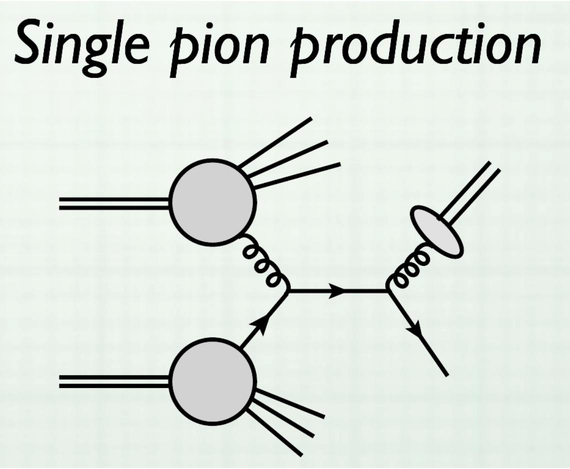
- NC DIS & DY

  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)





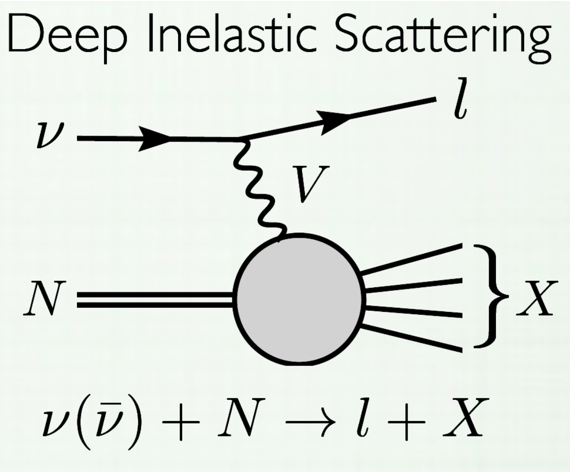
- Single pion production (new)



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 ... od
- $Q_0 =$ ... $a_i - a_i^0)(a_j - a_j^0)$
- using
- kinem
  $Q > 2$
  $p_T >$
- 708 (I
  $= 74($
- 16+2
- $\chi^2 =$

Kinematic cuts

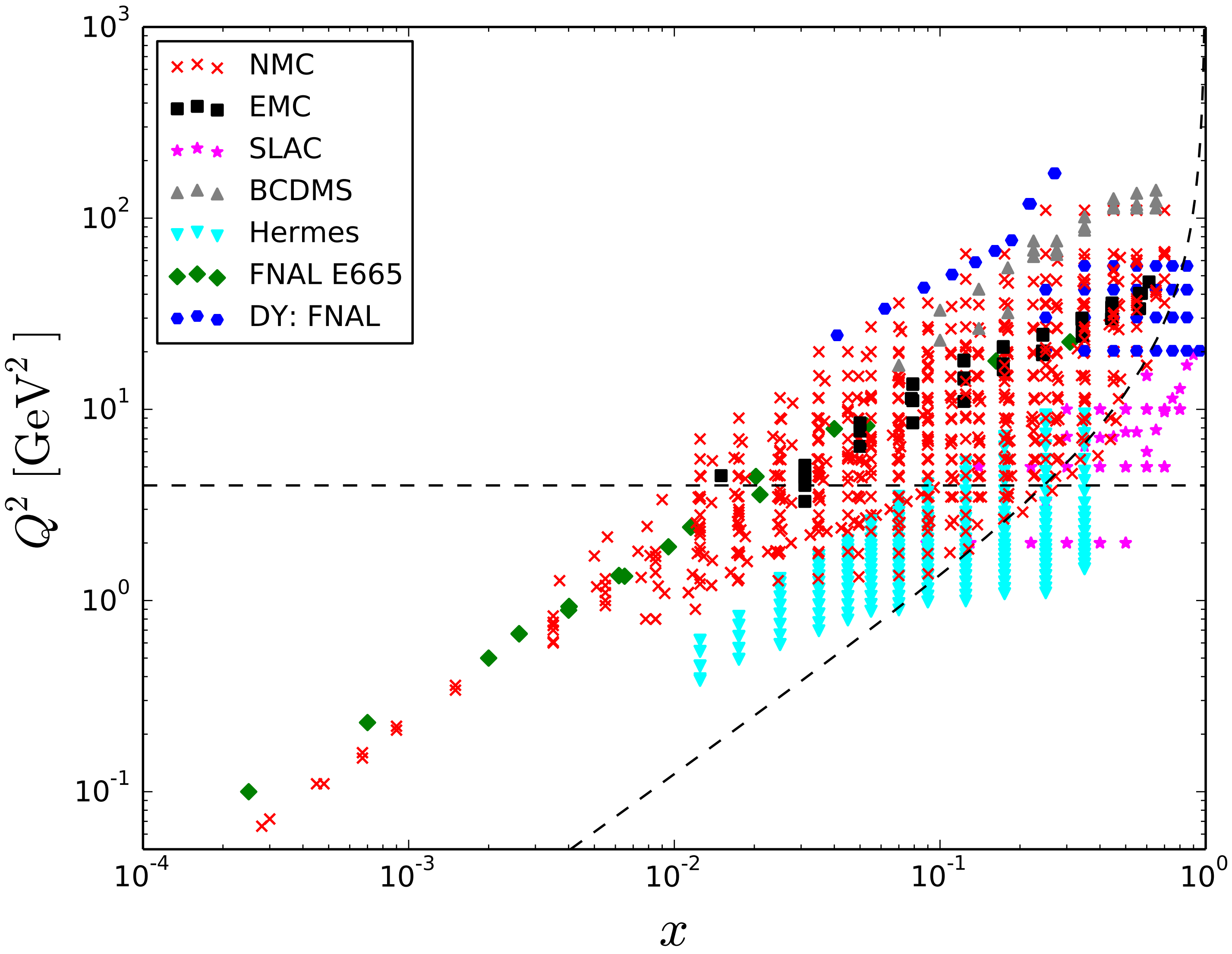
nCTEQ:

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

EPS: $Q > 1.3$ GeV

HKN: $Q > 1$ GeV

DSSZ: $Q > 1$ GeV



$\Delta\chi^2 = 35$ (every

arget within 90% C.L.)

es span 10 orders of

le → require numerical

nCTEQ: 740 data points

reducing derivatives

EPS09: 929 data points

Fit details

PRD93(2016)085037

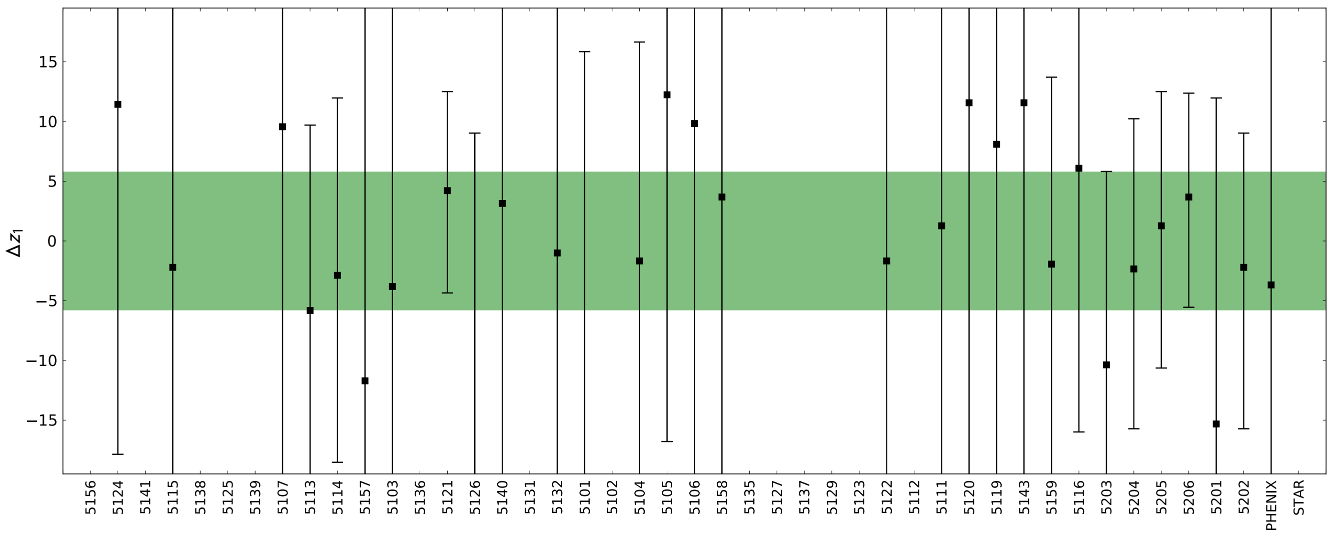
Fit properties:

- fit @NLO

Hessian method

- choice of tolerance: $T = 35$ [PRD65 (2001) 014012, `arXiv:hep-ph/0101051`]
- quadratic approximation

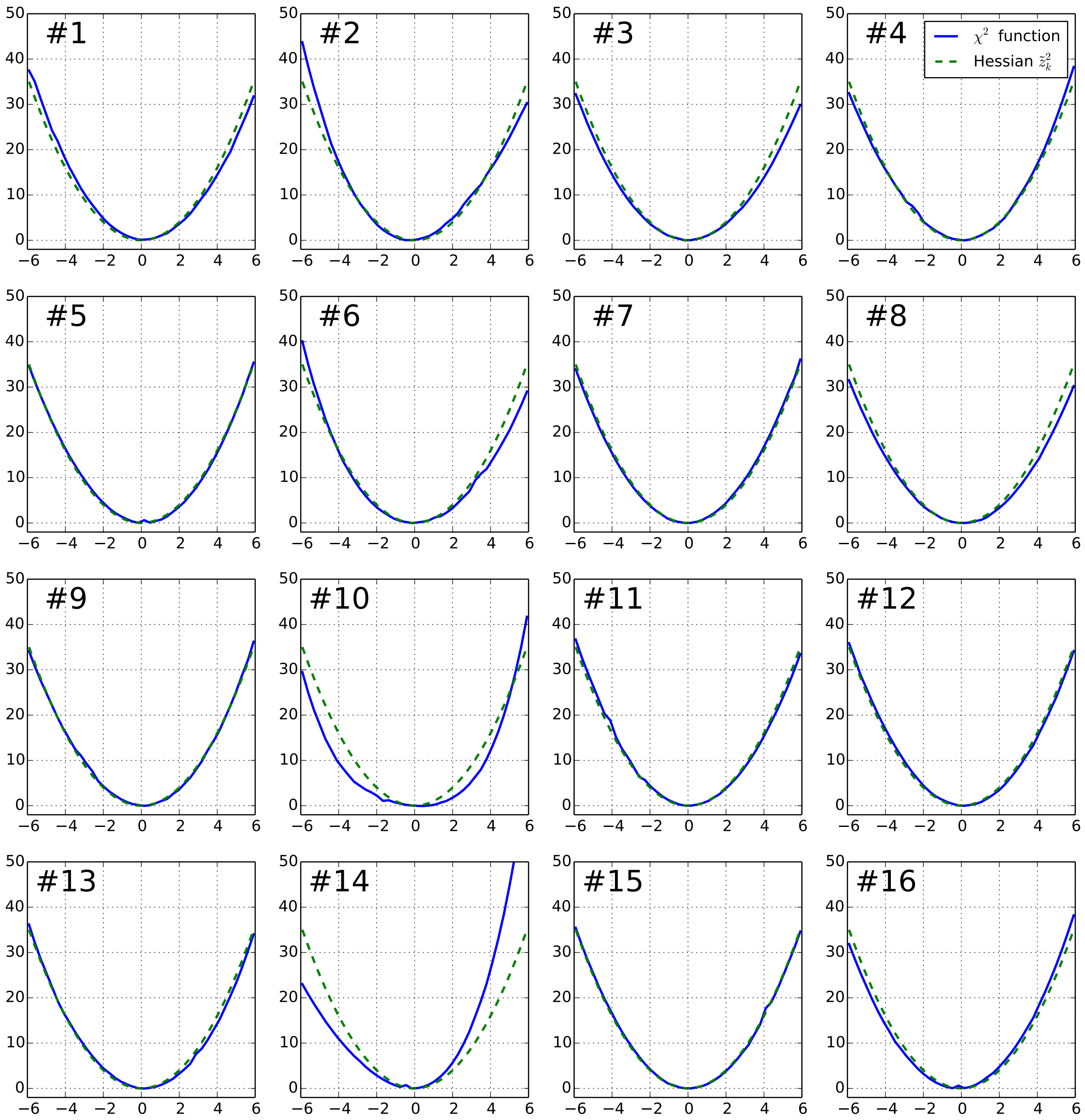
- 708 (DIS & DY) + 32 (single π^0) = 740 data points after cuts



normalizations

- $\chi^2 = 587$, giving $\chi^2/\mathrm{dof} = 0.81$

Error analysis:



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

- 708 (DIS & DY) + 32 (singl
  = 740 data points after cuts
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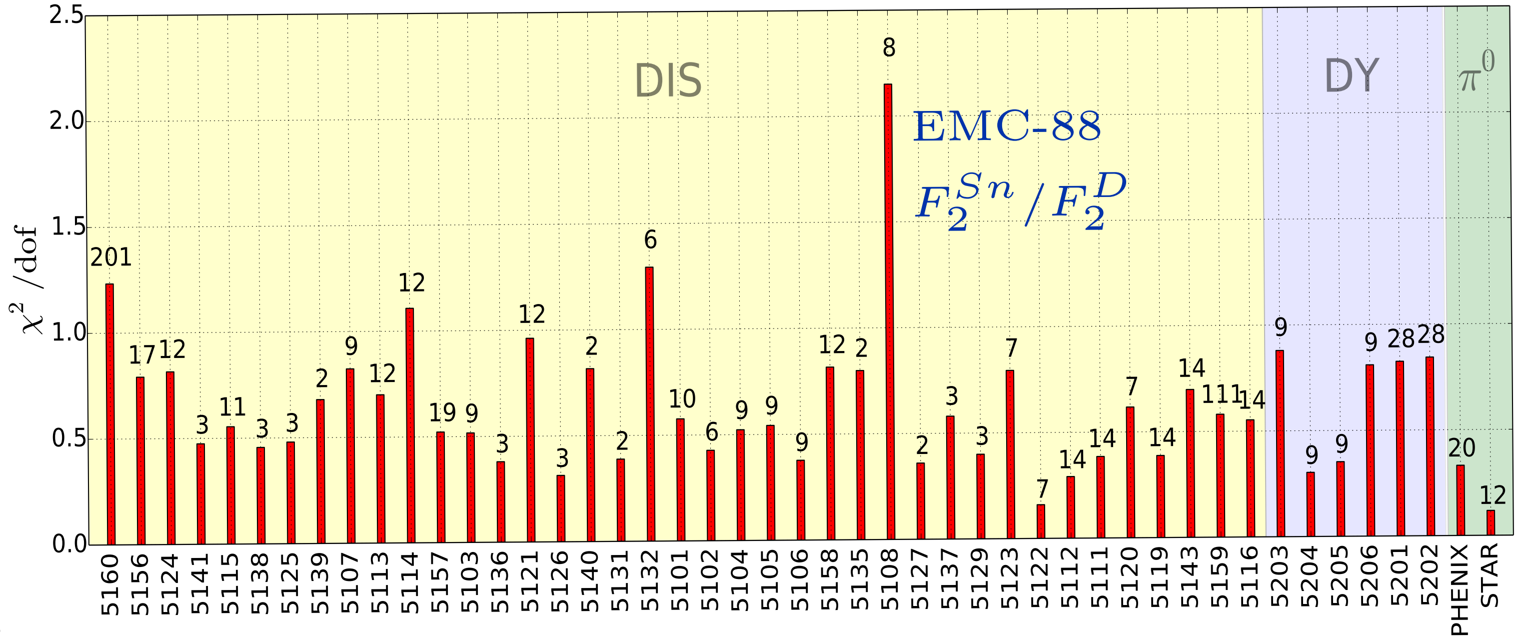
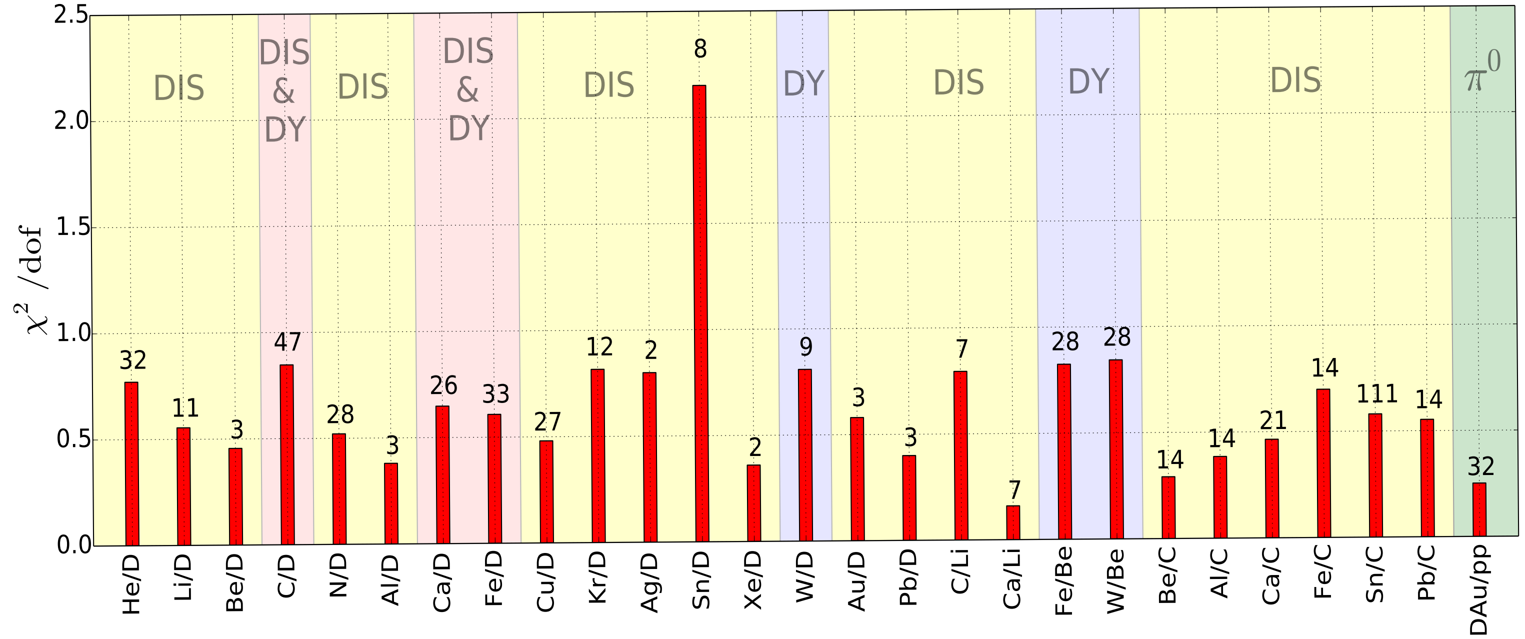
Error analysis:



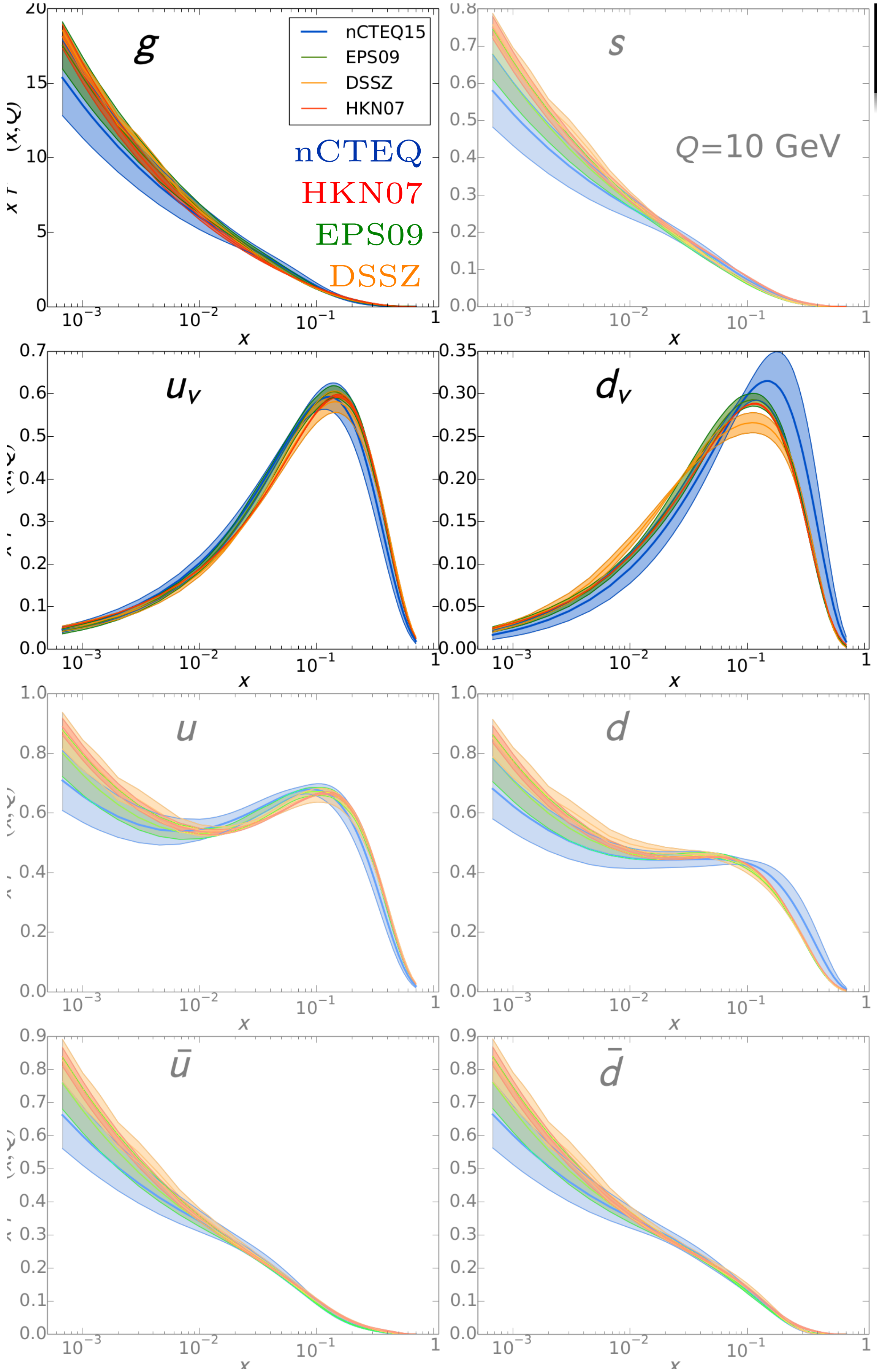


nCTEQ results

Bound proton PDFs
$(Q = 10\text{GeV})$

$$x\, f_i^{p/Pb}(x, Q)$$

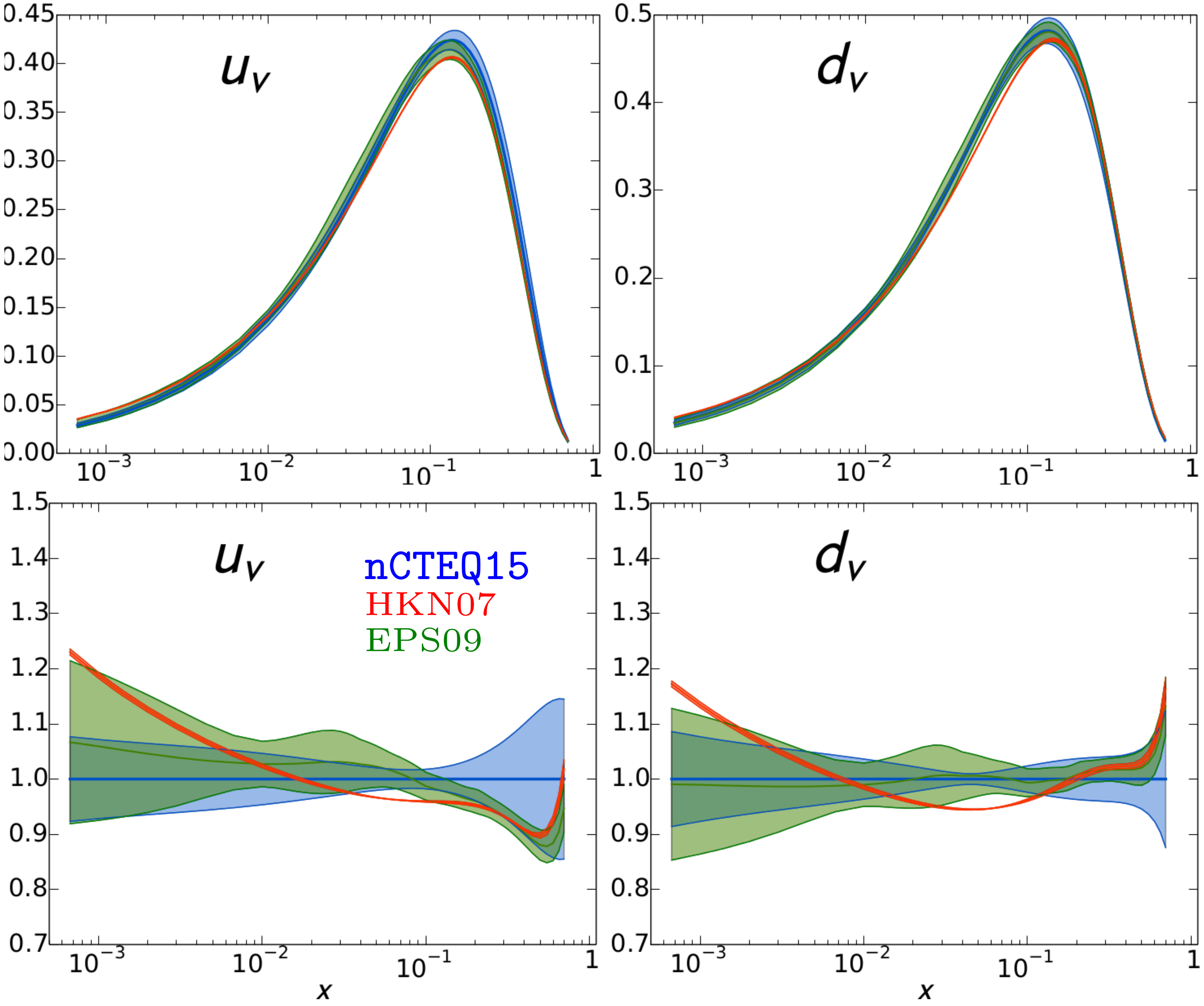
- nCTEQ features larger uncertainties than previous nPDFs
- better agreement between different groups (nPDFs don't depend on proton baseline)



Valence distributions

Full lead nucleus distribution:

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



Valence distributions

nCTEQ15

$$u_v^{p/A} \neq d_v^{p/A}$$

$$x u_v^{p/A}(Q_0) = x^{c_1^u}(1-x)^{c_2^u} e^{c_3^u x}(1+e^{c_4^u} x)^{c_5^u}$$

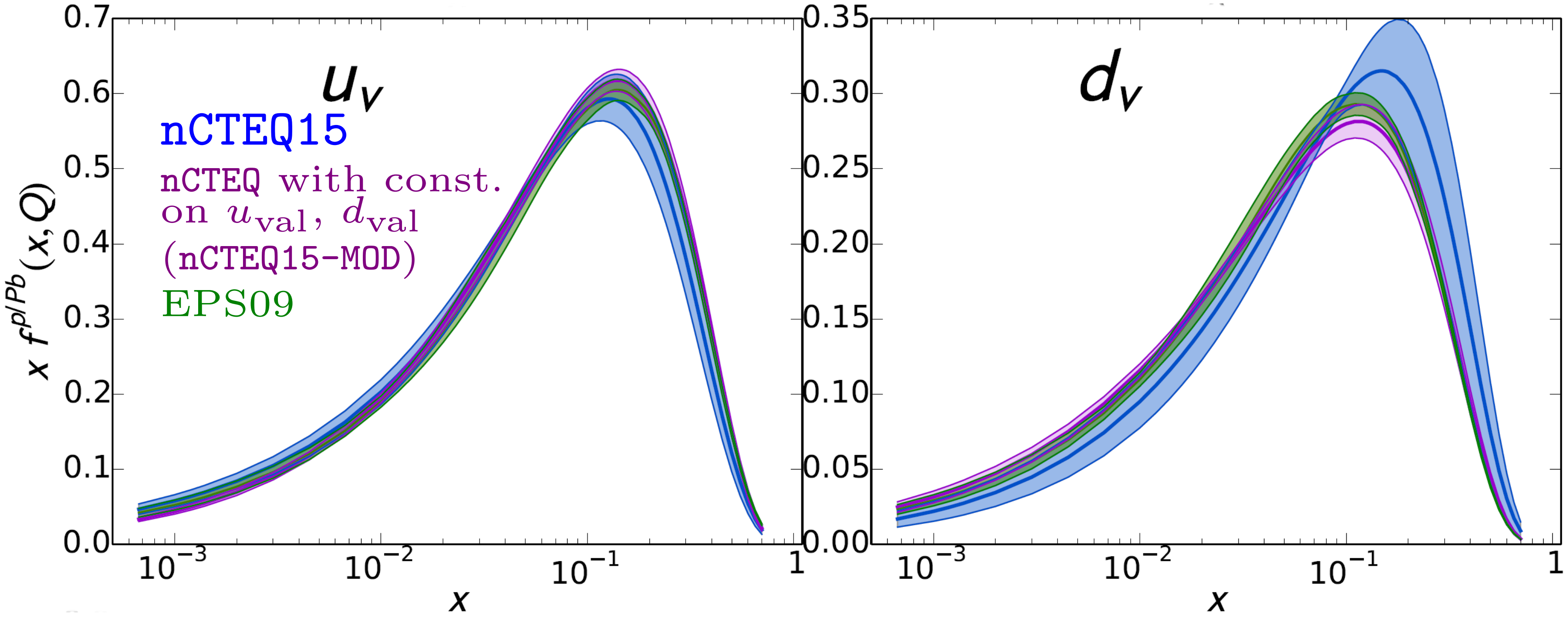
$$x d_v^{p/A}(Q_0) = x^{c_1^d}(1-x)^{c_2^d} e^{c_3^d x}(1+e^{c_4^d} x)^{c_5^d}$$

EPS09

$$R_v^u(x,A,Z) = R_v^d(x,A,Z)$$

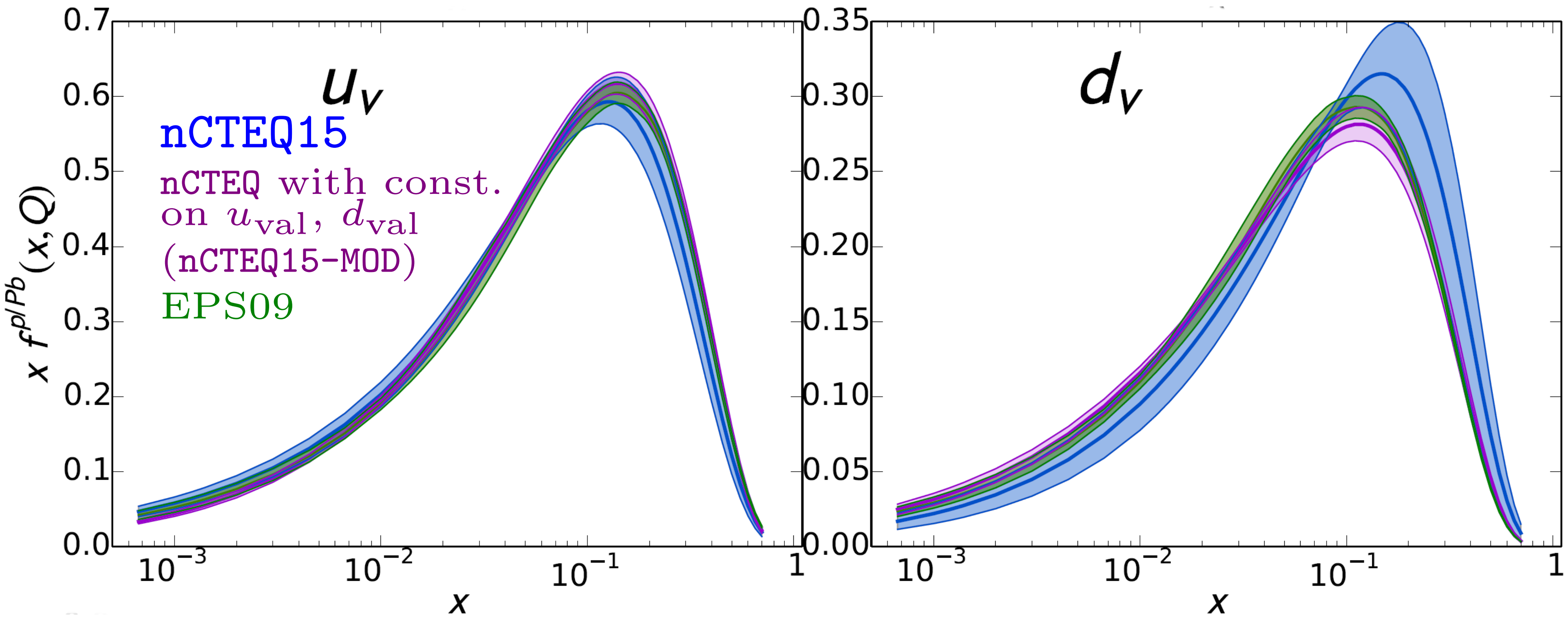
$$u_v^{p/A}(Q_0) = R_v(x,A,Z)\, u_v(x,Q_0)$$

$$d_v^{p/A}(Q_0) = R_v(x,A,Z)\, d_v(x,Q_0)$$



nCTEQ15-MOD: $u_v^{p/A} \simeq d_v^{p/A}$

nCTEQ15 vs nCTEQ-Mod



- χ^2 of both fits is very similar (~ 590) → there is not enough data to properly constrint u and d distributions.
- Differences between u and d distributions are washed out in the nuclei

$$f^{Pb} = \frac{Z}{A} f^{p/Pb} + \frac{A-Z}{A} f^{n/Pb}$$

because of the proton/neutron combination.

- Additionally most of DIS data is isoscalar corrected → insensitive to u/d differences.
- Differences between the two fits represents an unaccounted systematic uncertainty of the nPDFs.

Data from pA collisions at the LHC

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]

Questions

- We need to include more data in the global analyses.
  Data from pA collisions at the LHC!
  - Vector boson production, DY lepton pair production
  - Inclusive jet production, Dijet production
  - Prompt photons
  - Heavy quark production (inclusive D mesons)
  - **More processes?**
- Typically, **each new data set requires a dedicated study** before it can be used in a global analysis.
- Need fast routines for the hard processes at NLO

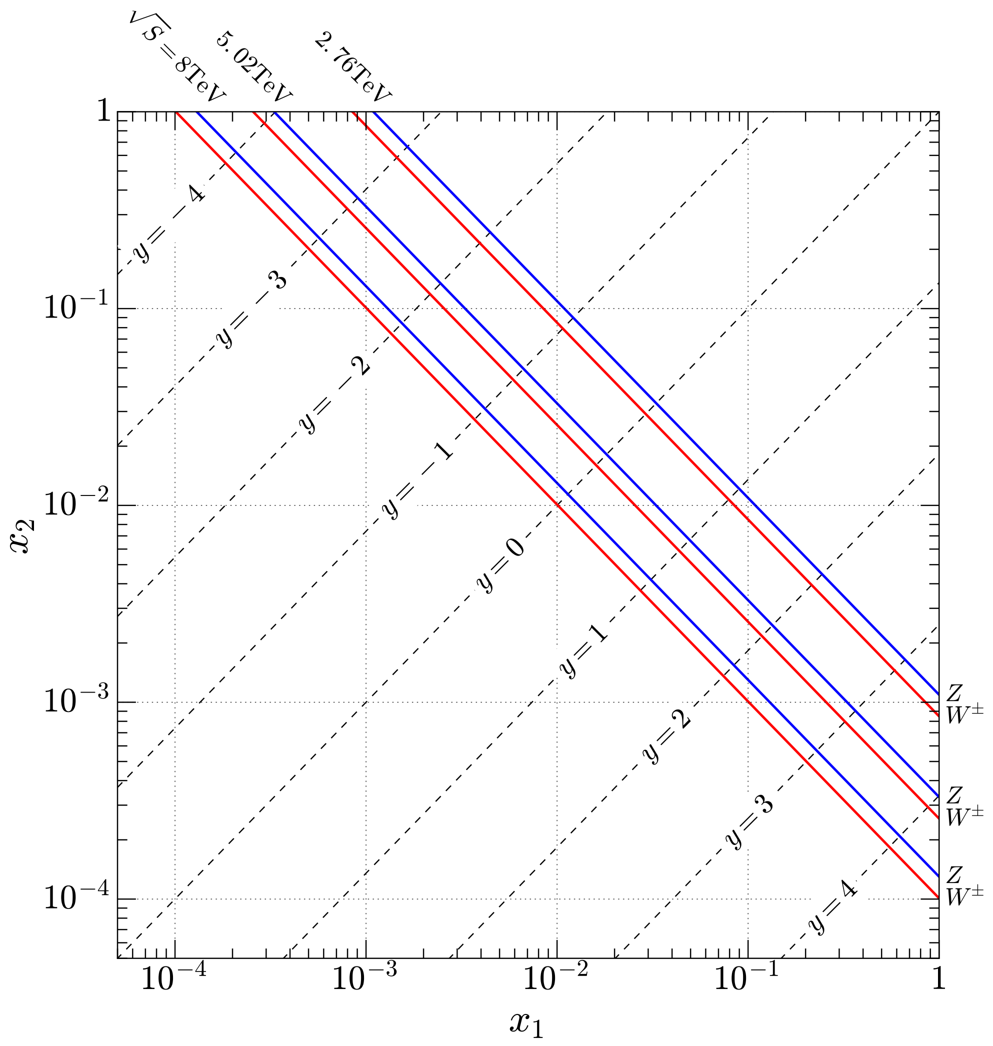
nCTEQ study of W,Z production

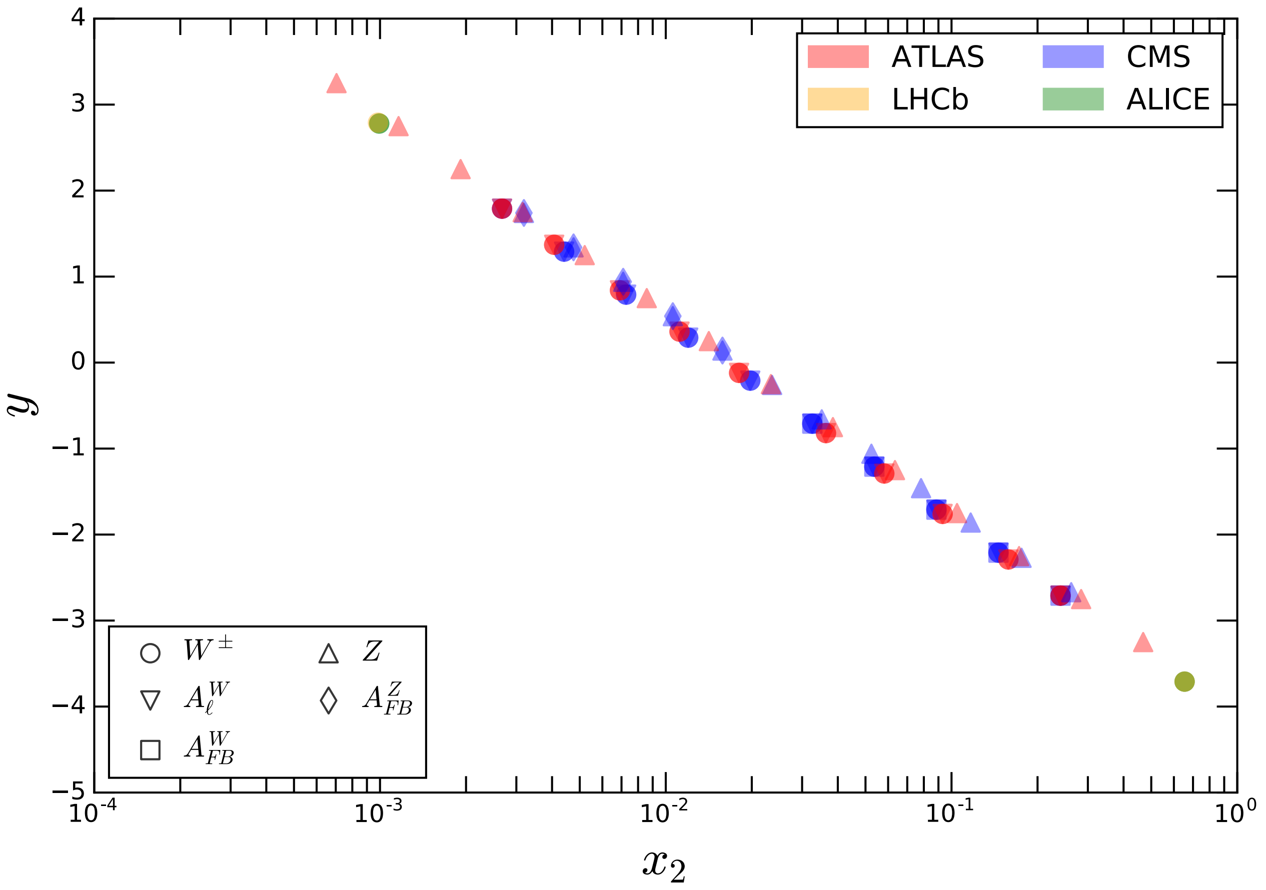
Paper will be out next few days

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

Table I: LHC data sets considered in this analysis.

nCTEQ study of W,Z production



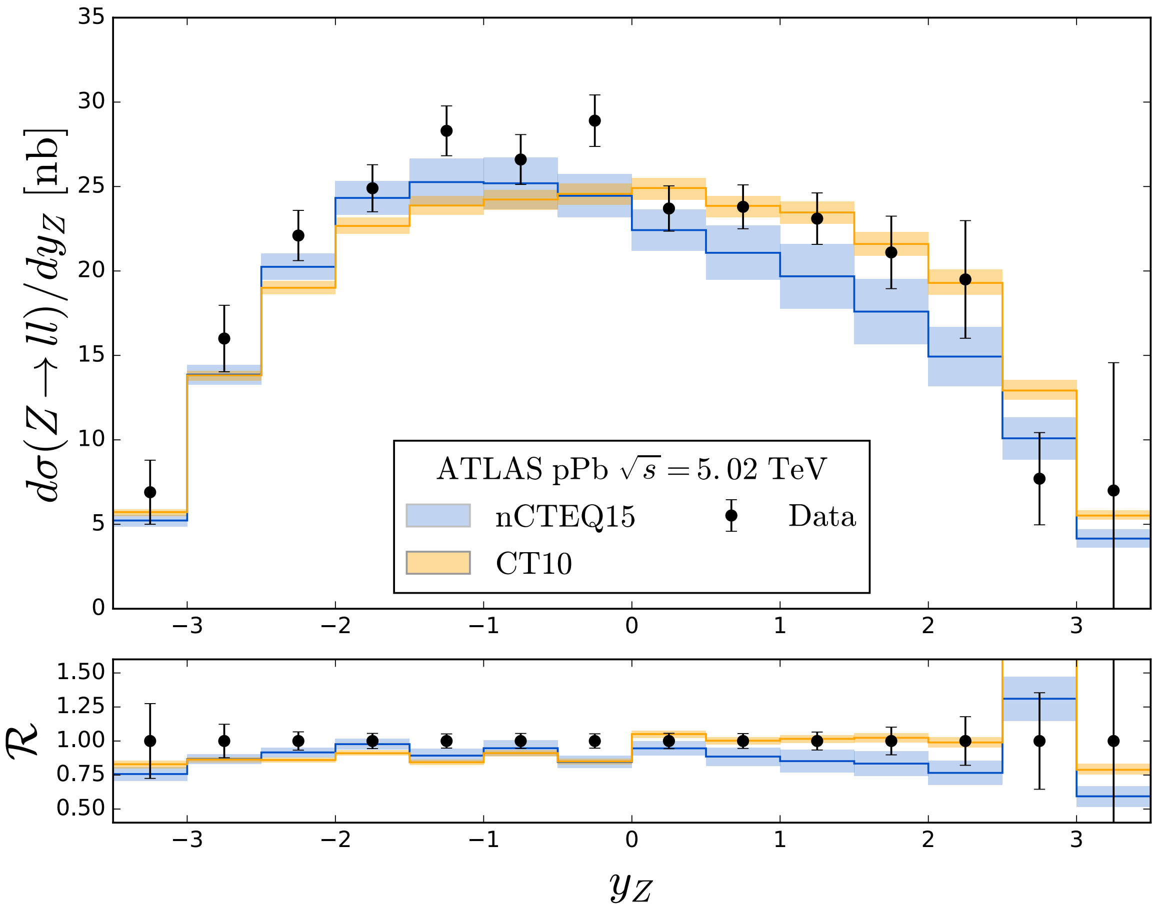


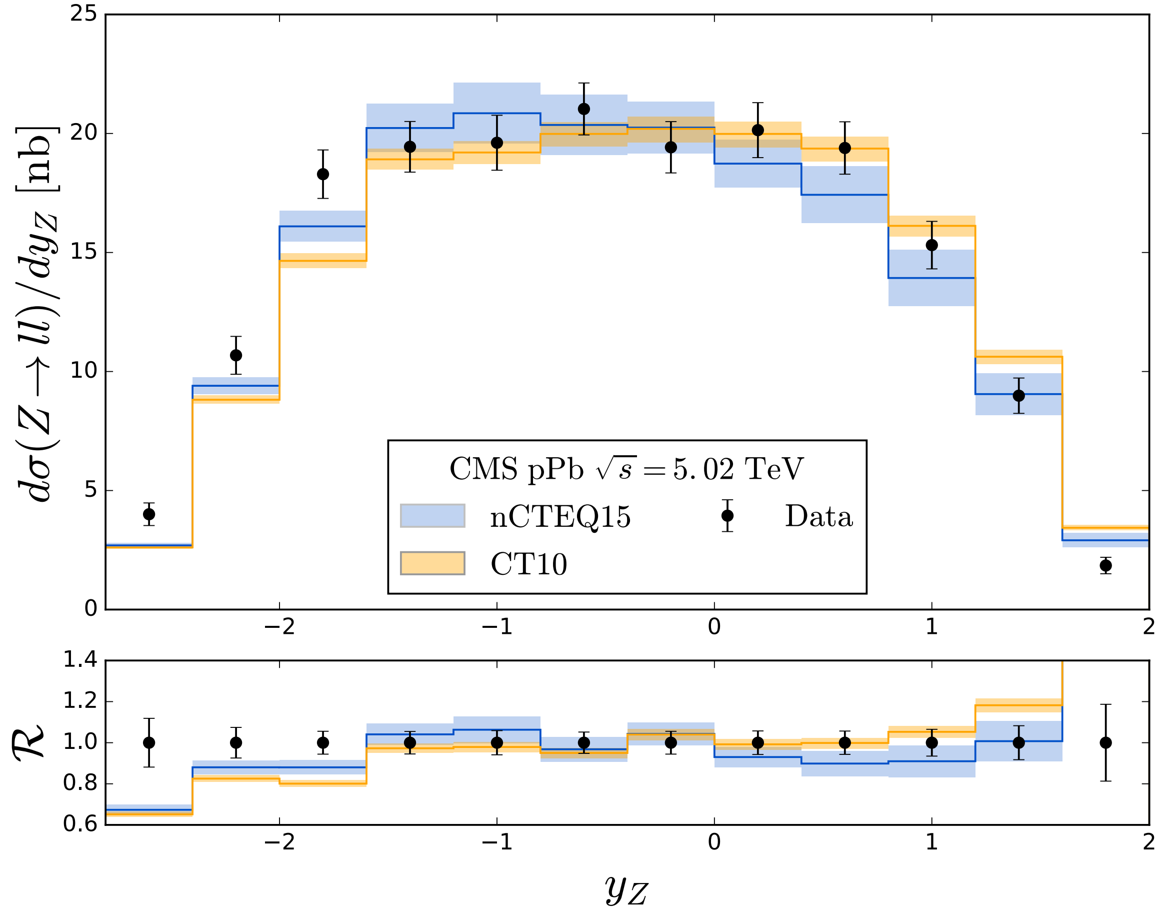
- y < -1: x > 5 x10^{-2} ... 0.3 (region where nPDFs are constrained by data in global analysis)

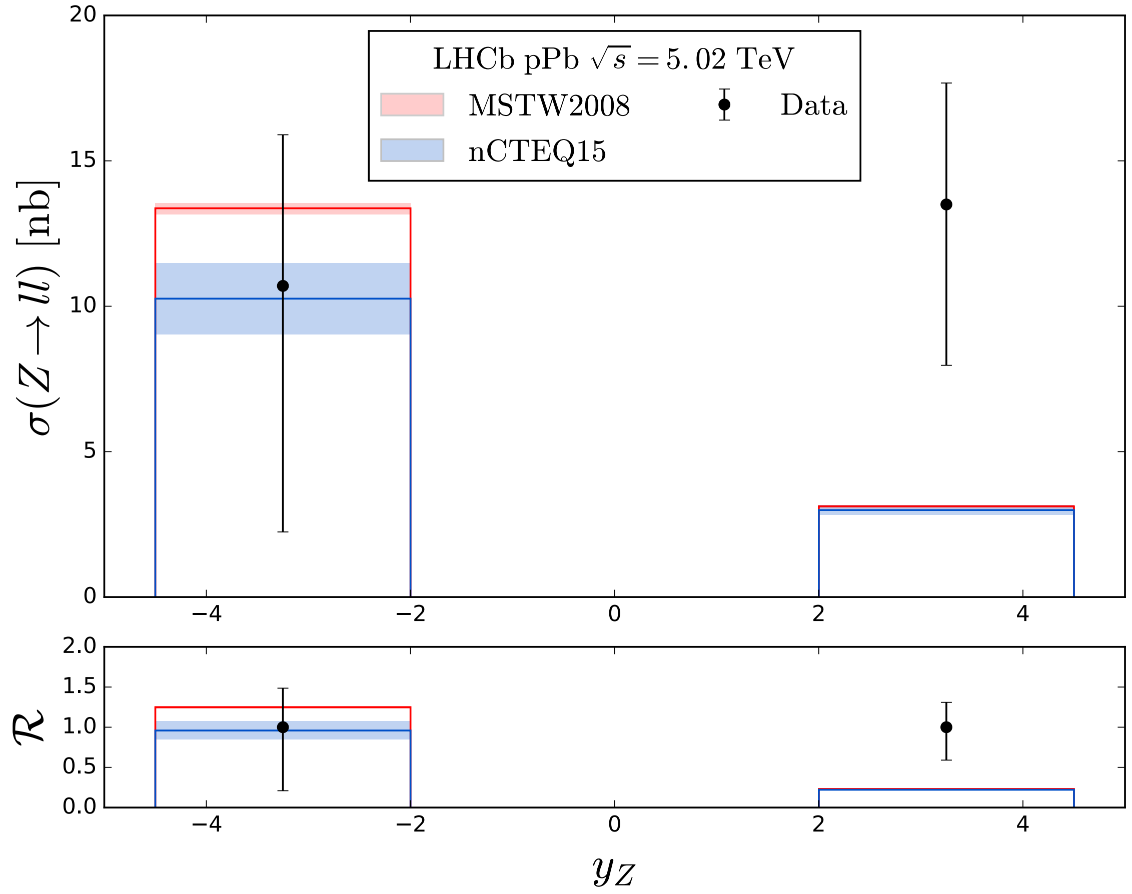
- |y| < 1: x ~ 10^{-2} (transition region from anti-shadowing to shadowing)

- y > 1: x < 5 x 10^{-3} (pure extrapolation!)

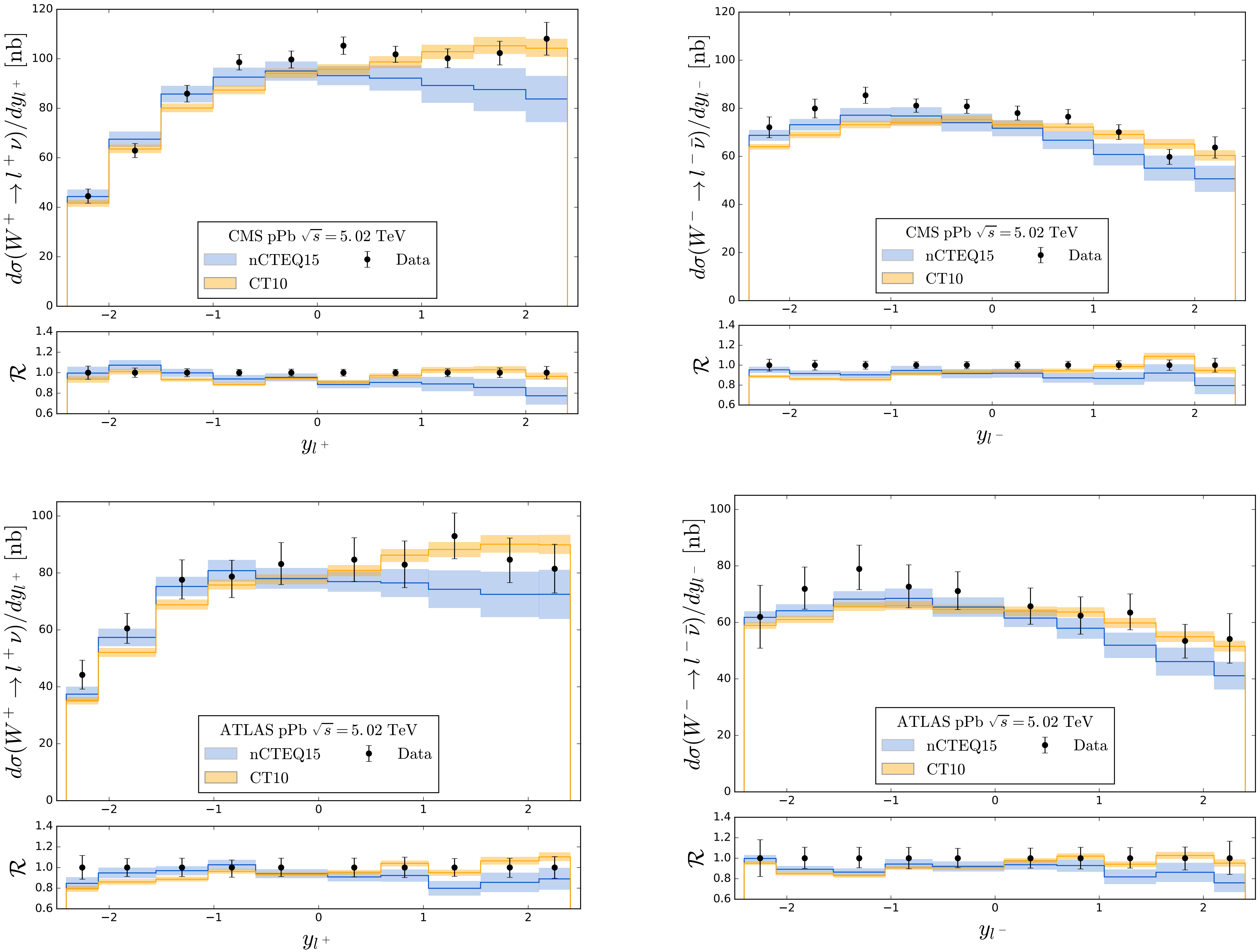
Z-boson rapidity distributions



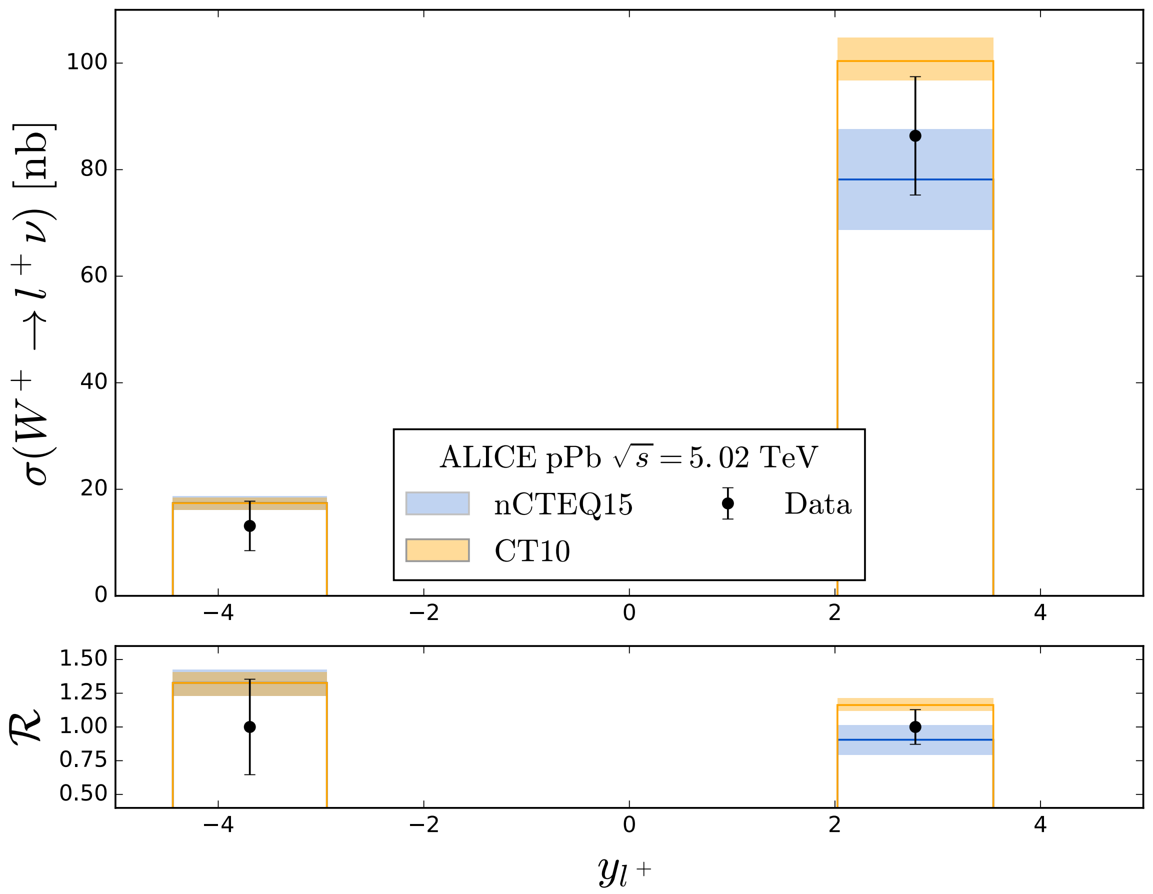


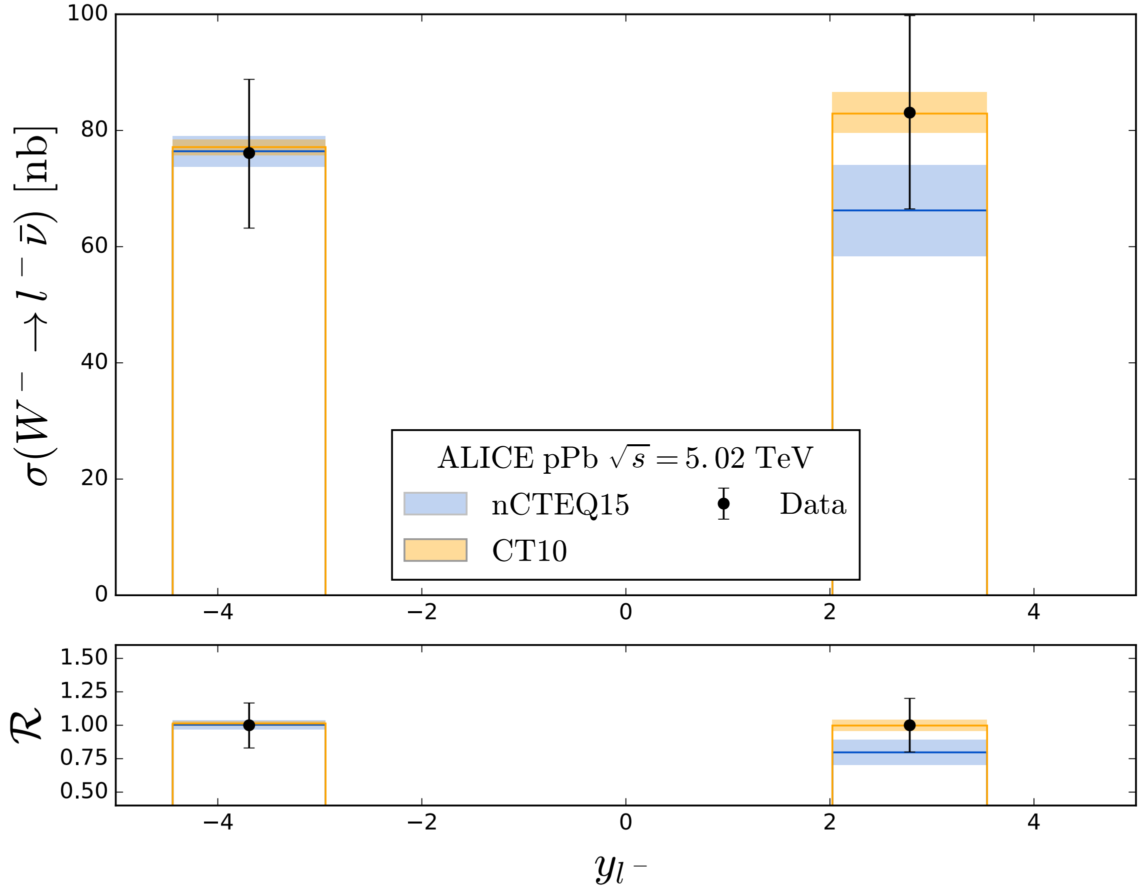


W-boson rapidity distributions

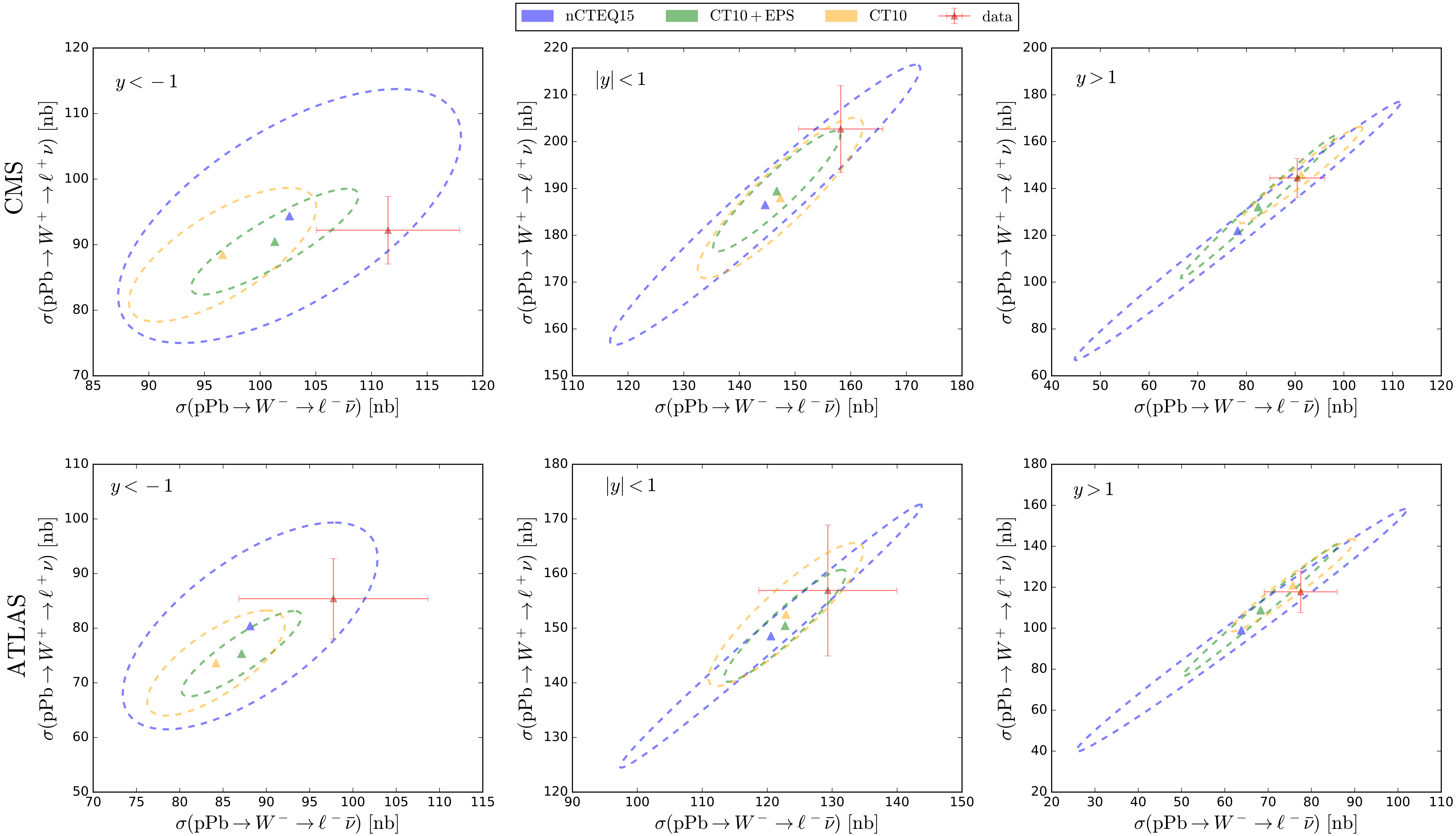


W-boson rapidity distributions

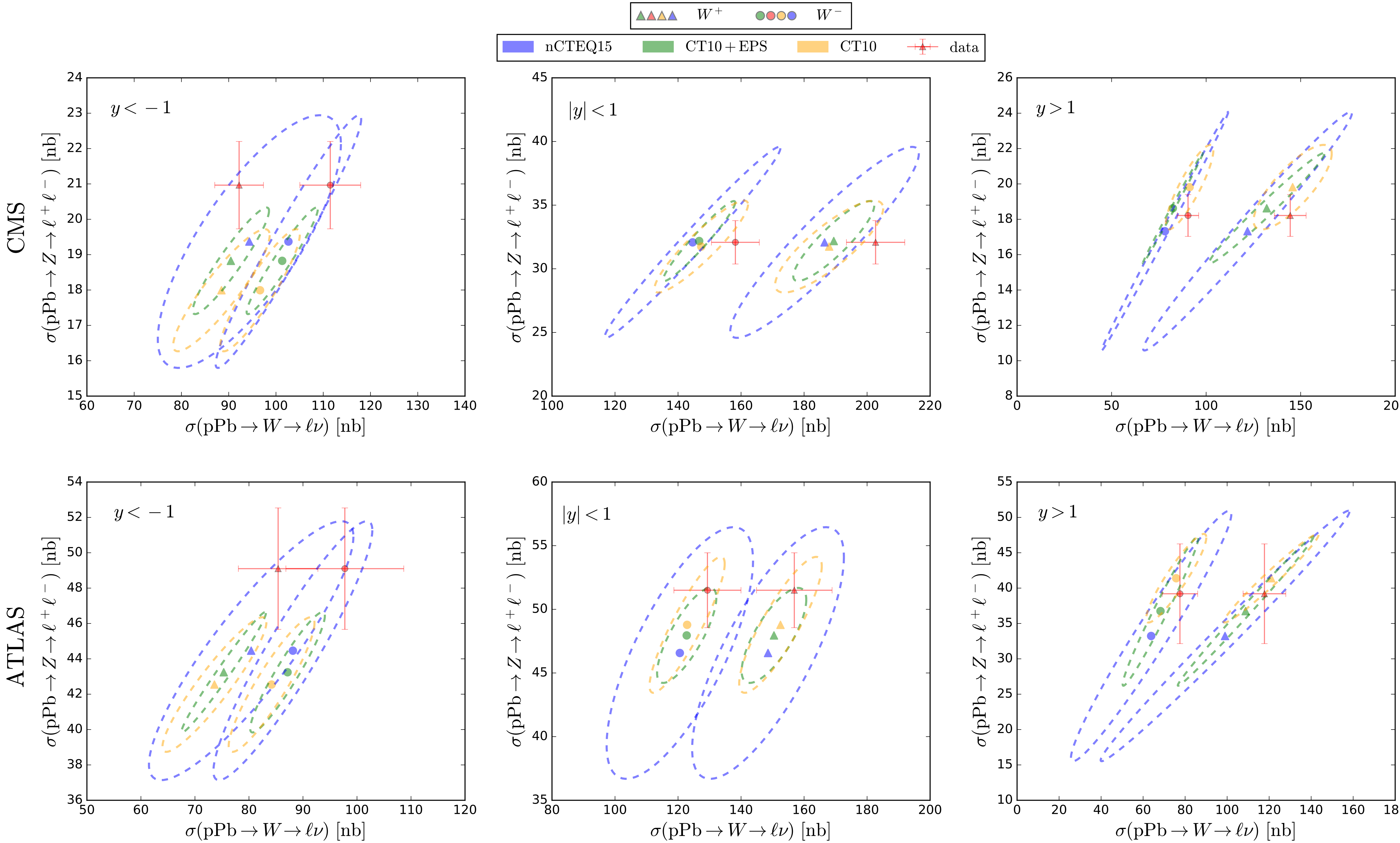




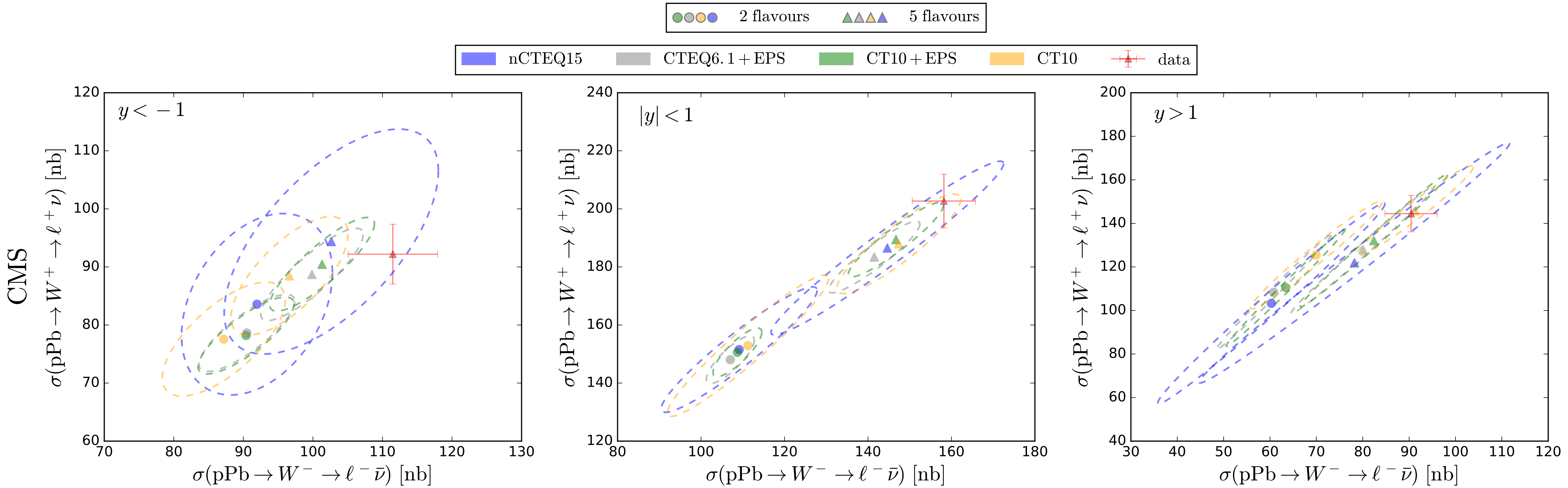
(W+,W-) Correlation



(Z,W) Correlation

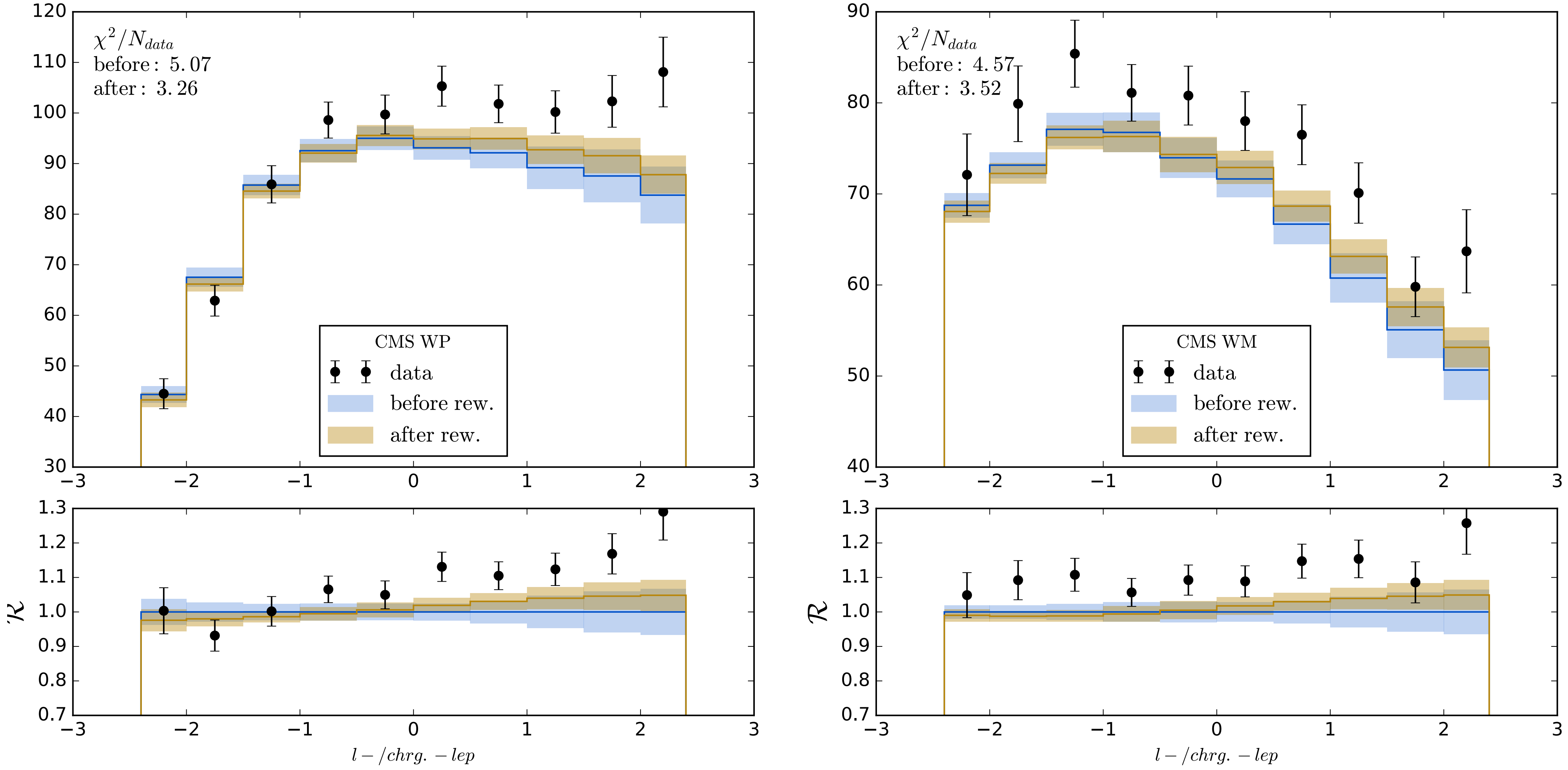


Importance of strange PDF



- 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

ToDo-List

- Discuss and understand p-Pb data from the LHC
- Include the data in the global analysis frameworks
- Possibly also consider future facilities (EIC, AFTER, LHeC)

Non-standard global analyses of nuclear PDFs

Testing a hypothesis

- A global analysis framework can be used/should be used to test a physics hypothesis.
- For example, let's assume that energy loss effects have been taken into account in pA collisions for processes with coloured final state.
- A given theoretical framework for energy loss should then be used to modify the hard process calculations.
- The corresponding "energy loss improved" global analysis can then be compared with the standard global analysis.

Questions

- Which “cold nuclear effects” might be interesting to test?
- How will the NPDFs change?
- Will the chi^2 improve?
- How do the predictions with these non-standard NPDFs for other observables look like?
- NPDFs might be flexible enough to absorb effects like saturation, non-linear evolution,...
  How do we test for deviations from the standard framework?

ToDo-List

- A lot can be done here...

More questions?

More Questions

- NPDFs vs Lattice calculations?
  - Invite talk on status of PDF calculations on lattice
  - Bring together lattice and PDF phenomenologists
  - Define tasks (first for proton PDFs though!)
- NPDFs vs nuclear GPDs?
- How to test for the heavy flavours?
- Small-x nuclear PDFs and saturation?
- ...?