PDFs for Heavy Ions

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Outline

- PDFs: Theoretical Framework [Flash]
- From nucleons to nuclei [Skip]
- Current status of nuclear PDFs [Discuss]
- nCTEQ'15 NPDFs [Flash]
- EPPS'16 NPDFs [Flash]
- EPPS'16 vs nCTEQ'15 [Flash]
- Perspectives with lighter ions [Flash]
- Vector boson production and the strange PDF [Discuss]
- Heavy quark(onium) production and gluon shadowing [Discuss]
- Conclusions [Skip]

PDFs: Theoretical Framework

Parton Distribution Functions (PDFs)

- There are at least **two** motivations for PDFs:

  1. They encode **information on the structure** of nucleons seen **at high energies**

  2. They are **crucial tools** for the description of pp, pA and AA collisions at RHIC/LHC and ep and eA DIS at a future EIC

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

- So far PDFs are determined by performing **global analyses of data** for a large variety of hard processes

Theoretical Framework (pQCD formalism)

Factorization Theorems:

- Provide (field theoretical) **definitions** of the **universal** PDFs
- Make the formalism **predictive**!
- Make a statement about the **error** of the factorization formula

PDFs and predictions for **observables+uncertainties** **refer to this standard pQCD framework**

Need a solid understanding of the standard framework!

- For pp and ep collisions there a **rigorous factorization proofs**
- For pA and AA factorization is a **working assumption** to be tested phenomenologically

  There might be breaking of QCD factorization, deviations from DGLAP evolution, other nuclear matter effects to be included

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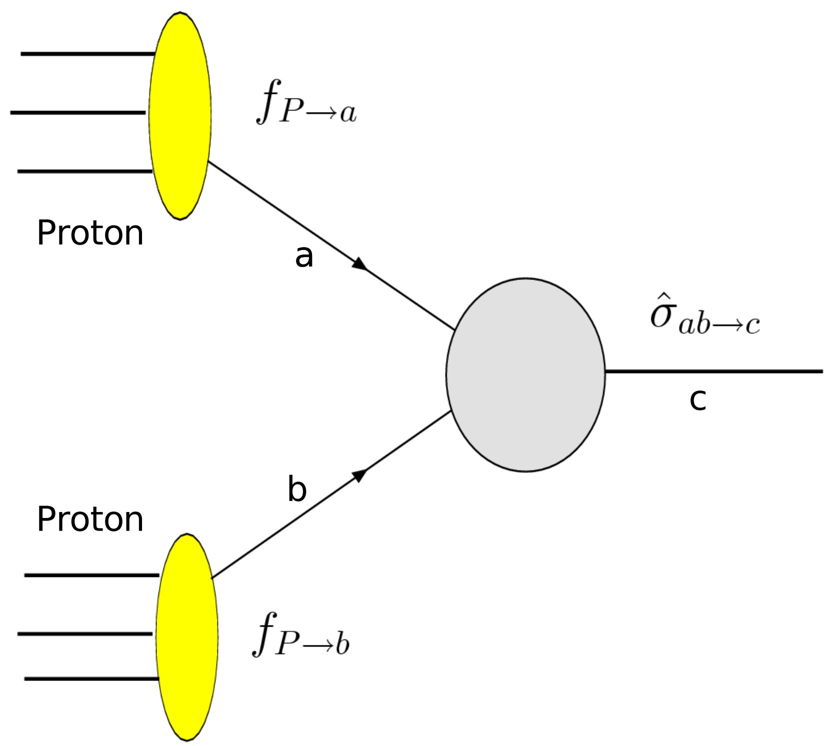
Factorization for pp collisions



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

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

Predictive Power

Universality: same PDFs/FFs enter different processes:

- DIS: $$F_2^A(x,Q^2) = \sum_i \left[f_i^A \otimes C_{2,i}\right](x,Q^2)$$
- DY: $$\sigma_{A+B\to\ell^+ +\ell^- +X} = \sum_{i,j} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j\to\ell^+ +\ell^- +X}$$
- A+B -> H + X: $$\sigma_{A+B\to H+X} = \sum_{i,j,k} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j\to k+X} \otimes D_k^H$$

- Predictions for unexplored kinematic regions and for your favorite new physics process

Scale dependence predicted by QCD

- x-**dependence** of PDFs is NOT calculable in pQCD
- μ^2-**dependence** is calculable in pQCD – given by **DGLAP** (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) evolution equations

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DGLAP evolution equations

$$\frac{df_q(x,\mu^2)}{d\log\mu^2} = \frac{\alpha_S(\mu^2)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{qq}\left(\frac{x}{y}\right)f_q(y,\mu^2) + P_{qg}\left(\frac{x}{y}\right)f_g(y,\mu^2)\right]$$

$$\frac{df_g(x,\mu^2)}{d\log\mu^2} = \frac{\alpha_S(\mu^2)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{gg}\left(\frac{x}{y}\right)f_g(y,\mu^2) + P_{gq}\left(\frac{x}{y}\right)f_q(y,\mu^2)\right]$$

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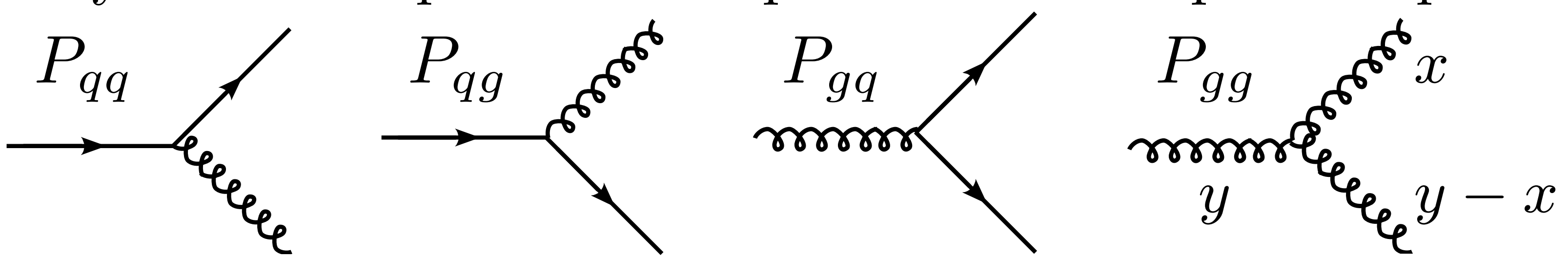
- Different PDFs mix – set of $(2n_f + 1)$ coupled integro-differential equations.
- Initial conditions obtained from fitting experimental data.
- Splitting functions are calculable in pQCD
  $P_{ij}(z) = P_{ij}^{(0)}(z) + \frac{\alpha_S}{2\pi}P_{ij}^{(1)}(z) + \cdots$
  they have interpretation as probabilities of parton splittings:



Boundary conditions

- Scale dependence **predicted** by QCD

  Test DGLAP, find deviations from DGLAP (non-linear effects, saturation, …)

- Need boundary conditions $f_i(x,Q_0)$ at some perturbative initial scale $Q_0 \gtrsim 1$ GeV

- The x-dependence is not calculable in pQCD, perform **global** analysis of experimental data

- Progress on the lattice: see arXiv:1711.07916, but not yet competitive in nucleon case

- Even efforts to compute nuclear PDFs on the lattice!

  See talk by Phiala Shanahan at workshop "Exposing novel Quark and Gluon effects in nuclei", Trento, Apr 16-20, 2018

Sum rules provide constraints

- **Number sum rules** – connect partons to quarks from SU(3) flavour symmetry of hadrons; proton (uud), neutron (udd). For protons:

For all scales:

$$\int_0^1 dx \underbrace{[f_u(x) - f_{\bar{u}}(x)]}_{u-\text{valence distr.}} = 2 \qquad \int_0^1 dx \underbrace{[f_d(x) - f_{\bar{d}}(x)]}_{d-\text{valence distr.}} = 1$$

$$\int_0^1 dx [f_s(x) - f_{\bar{s}}(x)] = \int_0^1 dx [f_c(x) - f_{\bar{c}}(x)] = 0$$

- **Momentum sum rule** – momentum conservation connecting all flavours

For all scales:

$$\sum_{i=q,\bar{q},g} \int_0^1 dx\, x f_i(x) = 1$$

Momentum carried by up and down quarks is only around half of the total proton momentum the rest of the momentum is carried by gluons and small amount by sea quarks. In case of CT14NLO PDFs ($\mu = 1.3$ GeV):

At 1.3 GeV:

$$\int_0^1 dx\, x[f_u(x) + f_d(x)] \simeq 0.51$$

$$\int_0^1 dx\, x f_g(x) \simeq 0.40$$

Global analysis of PDFs

1. Boundary conditions:
   Parameterize x-dependence of PDFs at initial scale Q_0

$$f(x,Q_0)=A_0 x^{A_1}(1-x)^{A_2} P(x;A_3,\ldots);\ f=u_v, d_v, g, \bar{u}, \bar{d}, s, \bar{s}$$

2. Evolve from Q_0 to Q solving the DGLAP evolution equations: $f(x,Q)$

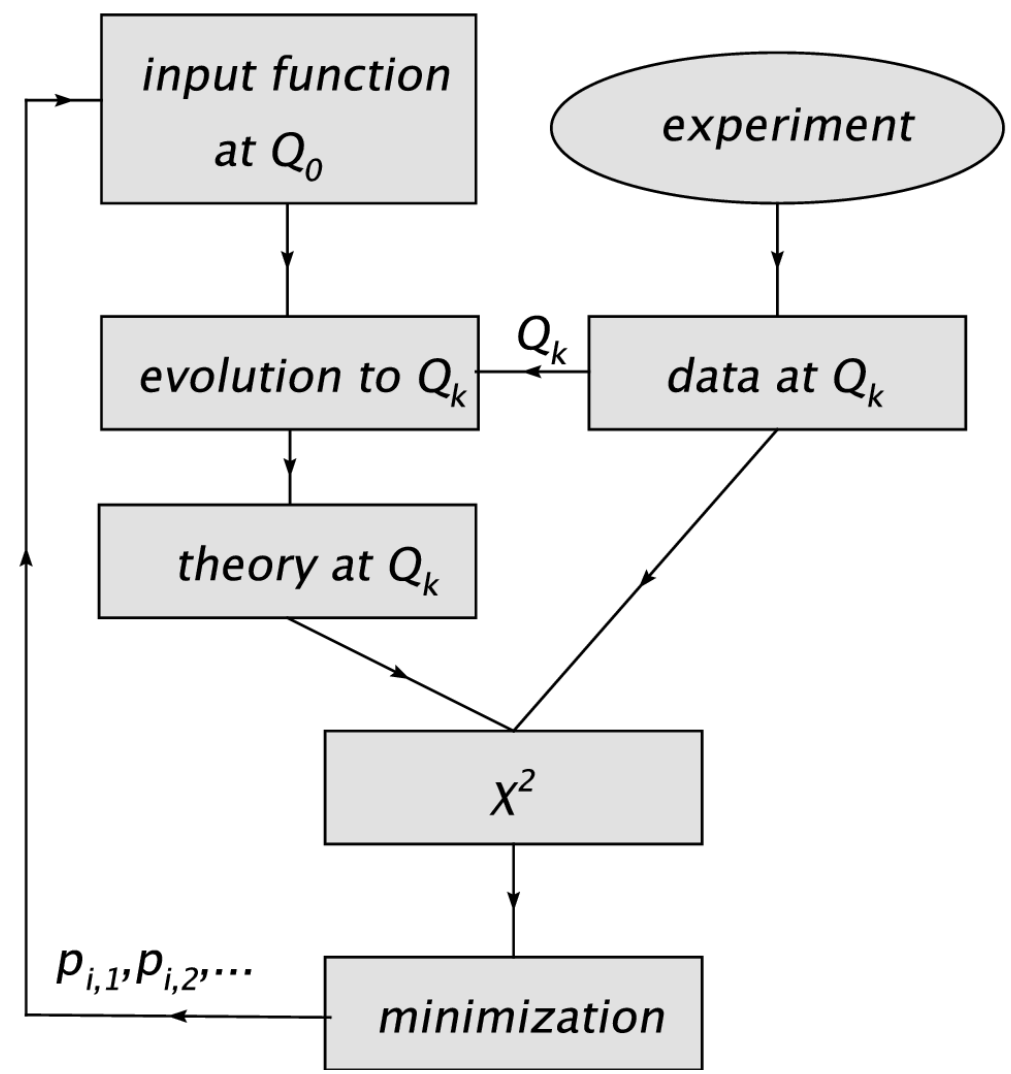
3. Define suitable χ^2 function and minimize w.r.t. fit parameters

$$\chi^2_{global}[A_i]=\sum_n w_n \chi^2_n;\ \chi^2_n=\sum_I \left(\frac{D_{nI}-T_{nI}}{\sigma_{nI}}\right)^2$$

Sum over experiments

Sum over data points

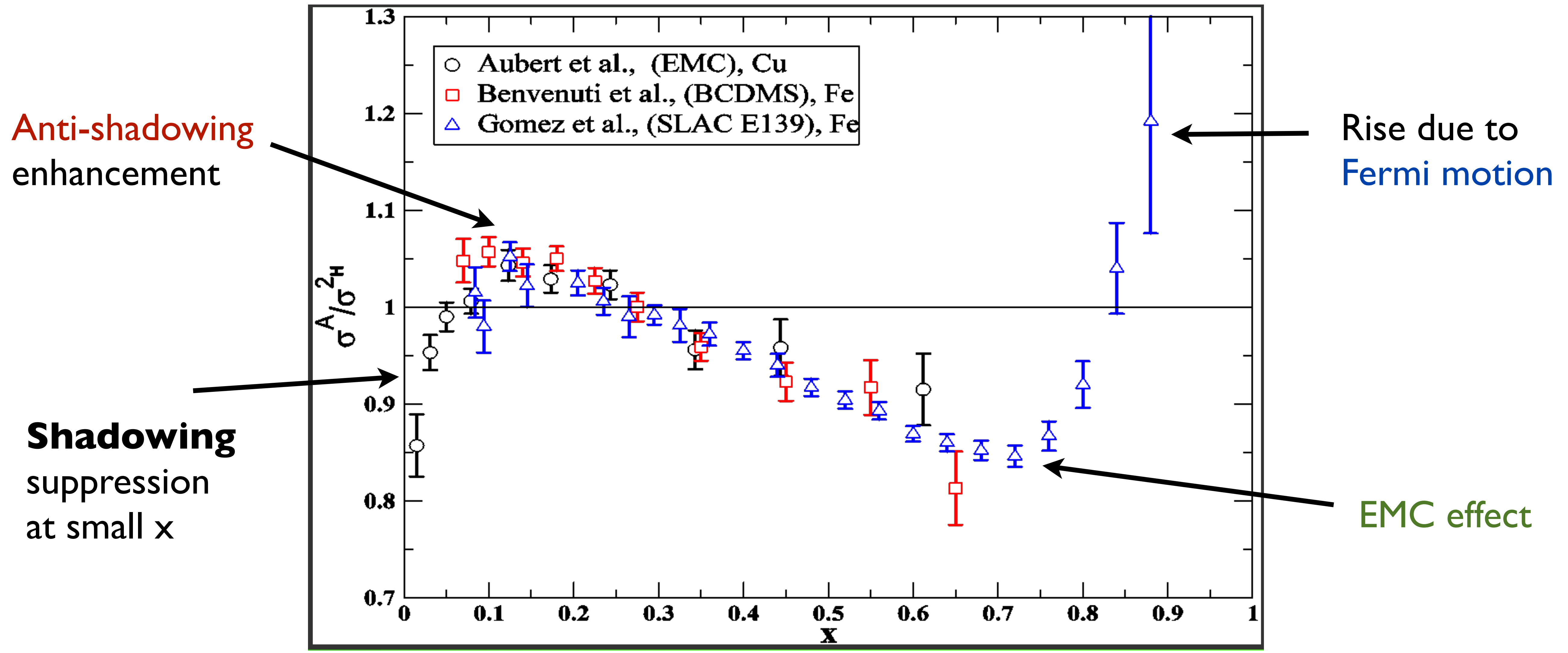
weights: default=1, allows to emphasize certain data sets



From nucleons to nuclei

Nuclear modifications of DIS structure functions

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



Can we translate these modifications into universal nuclear PDFs?

From Protons to Nuclei

- Starting point: global analysis framework for free nucleons
- Make sure it can be applied to the case of nuclear targets (A,Z)
  - Variable $0 < x_N < A$
  - Evolution equations
  - Sum rules
  - Observables
- Apart from validity of factorisation which is a working assumption and to be verified phenomenologically

DIS on nuclear targets

Consider deep inelastic lepton–nucleon collisions: $l(k) + A(p_A) \to l'(k') + X$

Introduce the usual DIS variables: $q \equiv k - k'$, $\quad Q^2 \equiv -q^2$, $\quad x_A \equiv \frac{Q^2}{2p_A \cdot q}$

Hadronic tensor: $W^A_{\mu\nu} \propto \langle A(p_A)|\, J_\mu J^\dagger_\nu \,|A(p_A)\rangle = \sum_i a^{(i)}_{\mu\nu}\, \tilde{F}^A_i(x_A, Q^2)$,
where $a^{(i)}_{\mu\nu}$ are Lorentz-tensors composed out of the 4-vectors q and p_A and the metric $g_{\mu\nu}$

Express structure functions in the QCD improved parton model in terms of NPDFs

$$\tilde{\mathcal{F}}^A_k(x_A, Q^2) = \int_{x_A}^1 \frac{\mathrm{d}y_A}{y_A}\, \tilde{f}^A_i(y_A, Q^2) C_{k,i}(x_A/y_A) + \tilde{\mathcal{F}}^{A,\tau\geq 4}_k(x_A, Q^2)$$

NPDFs: Fourier transforms of matrix elements of twist-two operators composed out of the quark and gluon fields:

$$\tilde{f}^A_i(x_A, Q^2) \propto \langle A(p_A)|\, O_i \,|A(p_A)\rangle$$

Definitions of $\tilde{F}^A_i(x_A, Q^2)$, $\tilde{f}^A_i(x_A, Q^2)$, and the varibale $0 < x_A < 1$ carry over one-to-one from the well-known free nucleon case

Evolution Equations and Sum Rules

DGLAP as usual:

$$\frac{\mathrm{d}\tilde{f}_i^A(x_A,Q^2)}{\mathrm{d}\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_{x_A}^1 \frac{\mathrm{d}y_A}{y_A}\, P_{ij}(y_A)\, \tilde{f}_j^A(x_A/y_A,Q^2)\ ,$$

$$= \frac{\alpha_s(Q^2)}{2\pi}\int_{x_A}^1 \frac{\mathrm{d}y_A}{y_A}\, P_{ij}(x_A/y_A)\, \tilde{f}_j^A(y_A,Q^2)\ ,$$

Sum rules:

$$\int_0^1 \mathrm{d}x_A\, \tilde{u}_v^A(x_A,Q^2) = 2Z+N\ ,$$

$$\int_0^1 \mathrm{d}x_A\, \tilde{d}_v^A(x_A,Q^2) = Z+2N\ ,$$

and the momentum sum rule

$$\int_0^1 \mathrm{d}x_A\, x_A \left[\tilde{\Sigma}^A(x_A,Q^2)+\tilde{g}^A(x_A,Q^2)\right] = 1\ ,$$

where $N = A - Z$ and $\tilde{\Sigma}^A(x_A) = \sum_i(\tilde{q}_i^A(x_A)+\tilde{\bar{q}}_i^A(x_A))$ is the quark singlet combination

Rescaled definitions!

Problem: average momentum fraction carried by a parton $\propto A^{-1}$
since there are 'A-times more partons' which have to share the momentum

- Different nuclei (A, Z) not directly comparable
- Functional form for x-shape would change drastically with A
- Need to rescale!

PDFs are number densities: $\tilde{f}_i^A(x_A)\,\mathrm{d}x_A$ is the number of partons carrying a momentum fraction in the interval $[x_A, x_A + \mathrm{d}x_A]$

Defi ne rescaled NPDFs $f_i^A(x_N)$ with $0 < x_N := Ax_A < A$:

$$\boxed{f_i^A(x_N)\,\mathrm{d}x_N := \tilde{f}_i^A(x_A)\,\mathrm{d}x_A}$$

The variable x_N can be interpreted as parton momentum fraction w.r.t. the **average** nucleon momentum $\bar{p}_N := p_A/A$

Rescaled evolution equations and sum rules

Evolution:

$$\frac{\mathrm{d}f_i^A(x_N,Q^2)}{\mathrm{d}\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_{x_N/A}^{1}\frac{\mathrm{d}y_A}{y_A}\,P(y_A)\,f_i^A(x_N/y_A,Q^2)\,,$$
$$= \frac{\alpha_s(Q^2)}{2\pi}\int_{x_N}^{A}\frac{\mathrm{d}y_N}{y_N}\,P(x_N/y_N)\,f_i^A(y_N,Q^2)\,.$$

Assume that $f_i^A(x_N)=0$ for $x_N>1$, then **original, symmetrical** form recovered:

$$\frac{\mathrm{d}f_i^A(x_N,Q^2)}{\mathrm{d}\ln Q^2} = \begin{cases}\frac{\alpha_s(Q^2)}{2\pi}\int_{x_N}^{1}\frac{\mathrm{d}y_N}{y_N}\,P(y_N)\,f_i^A(x_N/y_N,Q^2) & : 0<x_N\leq 1\\ 0 & : 1<x_N<A,\end{cases}$$

Sum rules for the rescaled PDFs:

$$\int_0^A \mathrm{d}x_N\,u_v^A(x_N) = 2Z+N\,,$$
$$\int_0^A \mathrm{d}x_N\,d_v^A(x_N) = Z+2N\,,$$

and

$$\int_0^A \mathrm{d}x_N\,x_N\left[\Sigma^A(x_N)+g^A(x_N)\right]=A\,,$$

Rescaled structure functions

The rescaled structure functions can be defi ned as

$$x_N \mathcal{F}_i^A(x_N) := x_A \tilde{\mathcal{F}}_i^A(x_A) \ ,$$

with $\mathcal{F}_{1,2,3}(x) = \{F_1(x), F_2(x)/x, F_3(x)\}$.

More explicitly:

$$\begin{aligned} F_2^A(x_N) &:= \tilde{F}_2^A(x_A) \ , \\ x_N F_1^A(x_N) &:= x_A \tilde{F}_1^A(x_A) \ , \\ x_N F_3^A(x_N) &:= x_A \tilde{F}_3^A(x_A) \ . \end{aligned}$$

This leads to consistent results in the parton model using the rescaled PDFs.

Effective PDFs of bound nucleons

Further decompose the NPDFs $f_i^A(x_N)$ in terms of effective parton densities for **bound** protons, $f_i^{p/A}(x_N)$, and neutrons, $f_i^{n/A}(x_N)$, inside a nucleus A:

$$f_i^A(x_N, Q^2) = Z\, f_i^{p/A}(x_N, Q^2) + N\, f_i^{n/A}(x_N, Q^2)$$

- 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 $x_N > 1$
- Neglecting the region $x_N > 1$, is consistent with the DGLAP evolution
- The region $x_N > 1$ is expected to have a minor influence on the sum rules of less than one or two percent (see also [PRC73(2006)045206])
- Isospin symmetry: $u^{n/A}(x_N) = d^{p/A}(x_N)$, $d^{n/A}(x_N) = u^{p/A}(x_N)$

An observable $\mathcal{O}^A$ is then given by:

$$\mathcal{O}^A = Z\, \mathcal{O}^{p/A} + N\, \mathcal{O}^{n/A}$$

In conclusion: the free proton framework can be used to analyse nuclear data

Current status of nuclear PDFs

Available sets of nuclear PDFs

- 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

Less global analyses

- Progress on Neural Network nuclear PDFs
  Abdul Khalek, Ethier, Rojo, arXiv:1811.05858

- AT'12
  Atashbar Tehrani, PRC86(2012)064301

- KA'15 (NNLO)
  Khanpour, Atashbar Tehrani, PRD93(2016)014026, arXiv:1601.009

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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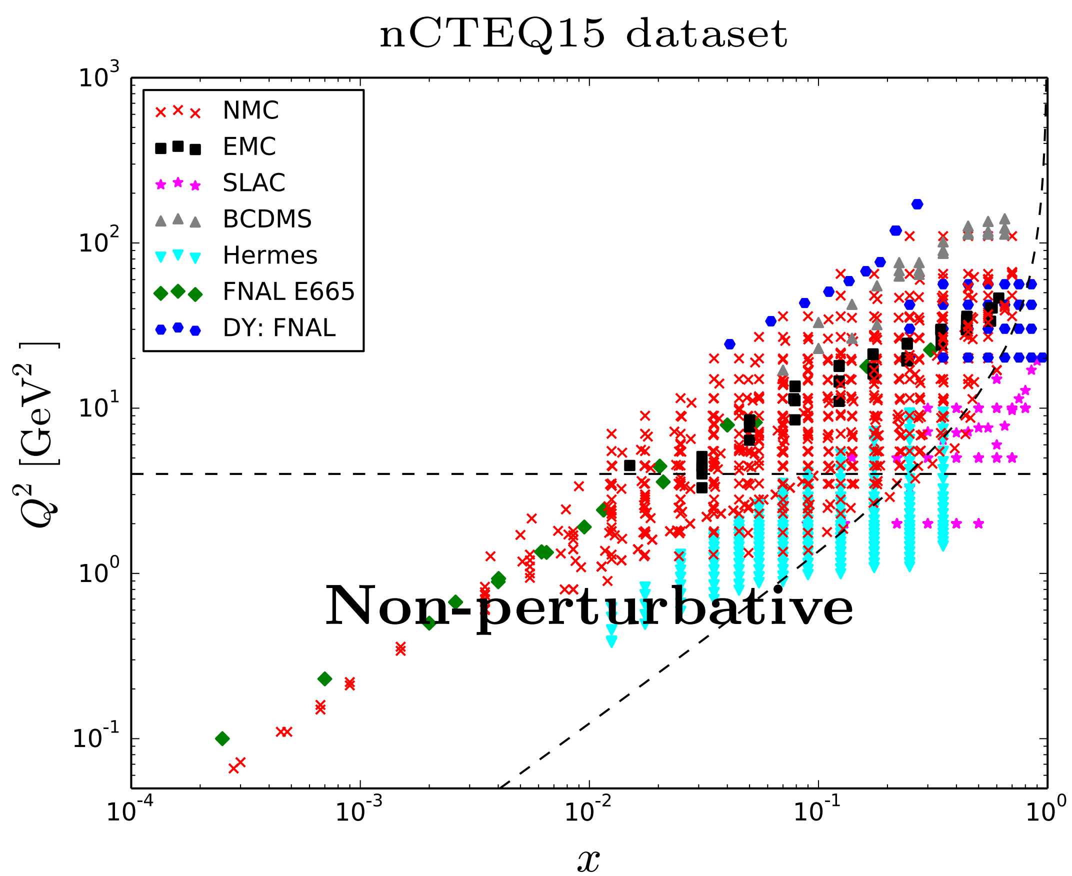
- **Parametrization**

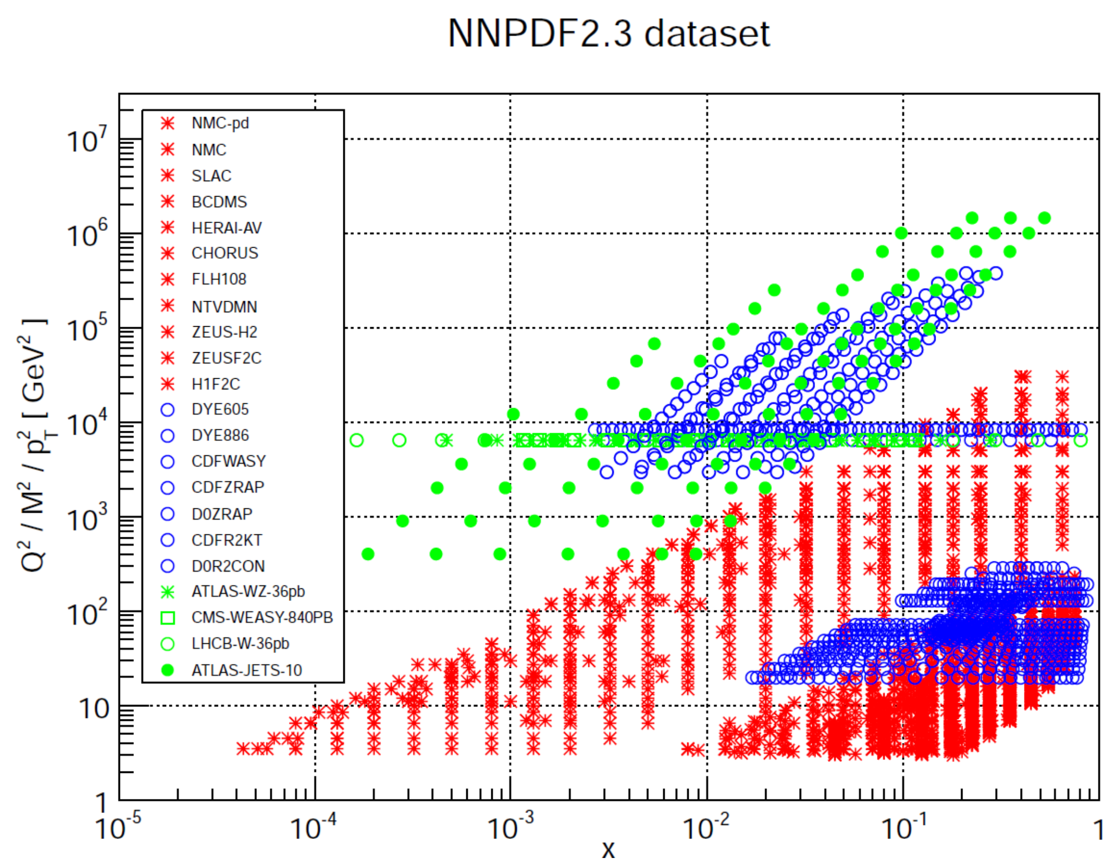
  - Multiplicative nuclear correction factors: EPPS'16, DSSZ'11, HKN'07, AT'12, KA'15
    (requires proton baseline, parametrization can be quite complicated)

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

Main differences between proton and nuclear PDFs

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





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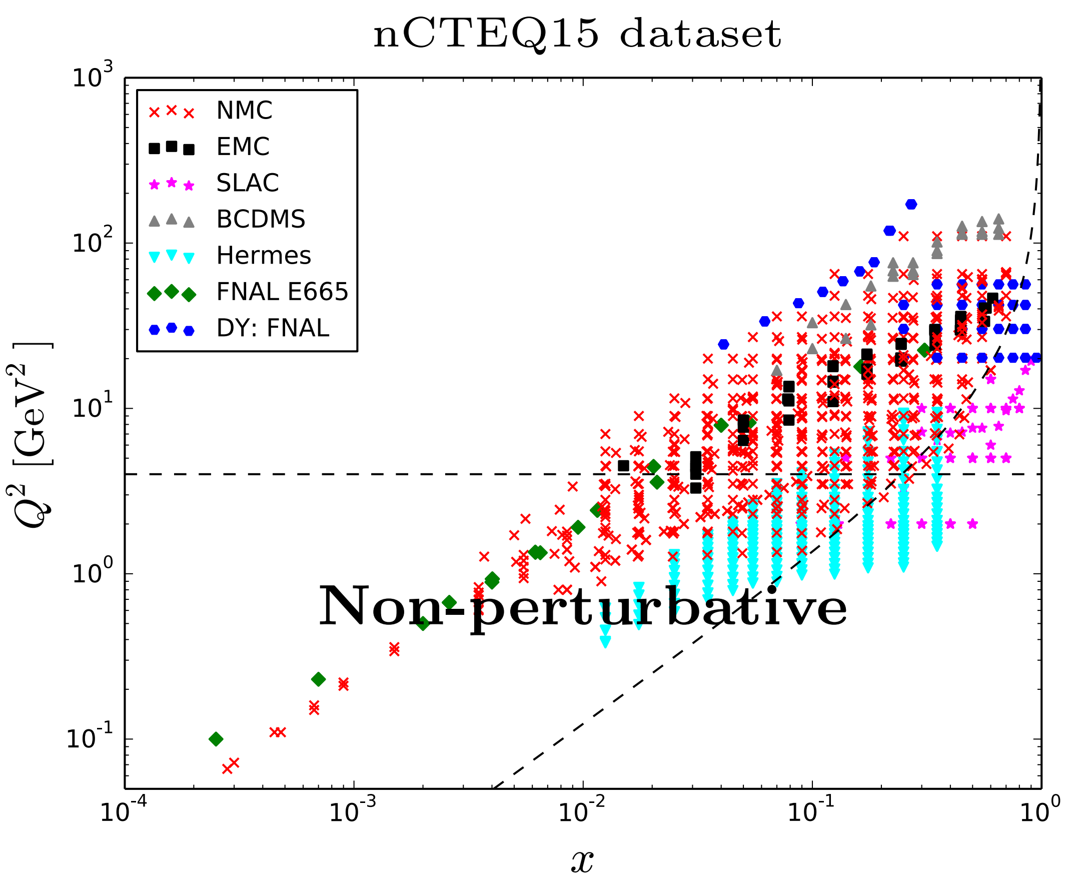
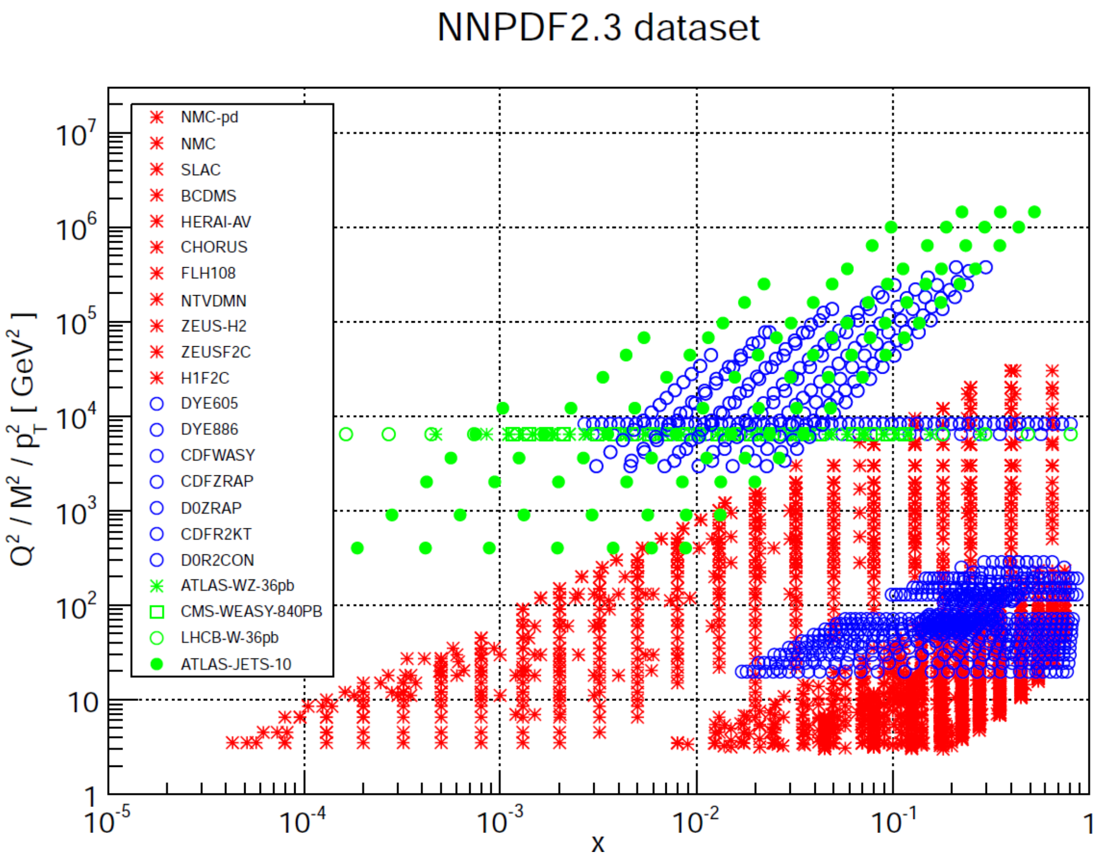




- Less data constraints → more **assumptions** about input PDFs
- Assumptions "hide" uncertainties!

Need to include collider data

- Inclusive W/Z production
- Low mass Drell-Yan data
- Heavy quark(-onium) production
- Inclusive prompt photon production
- Inclusive prompt diphoton production
- Heavy quark associated production: γ/Z/W+Q
- Top production
- Di-jet production

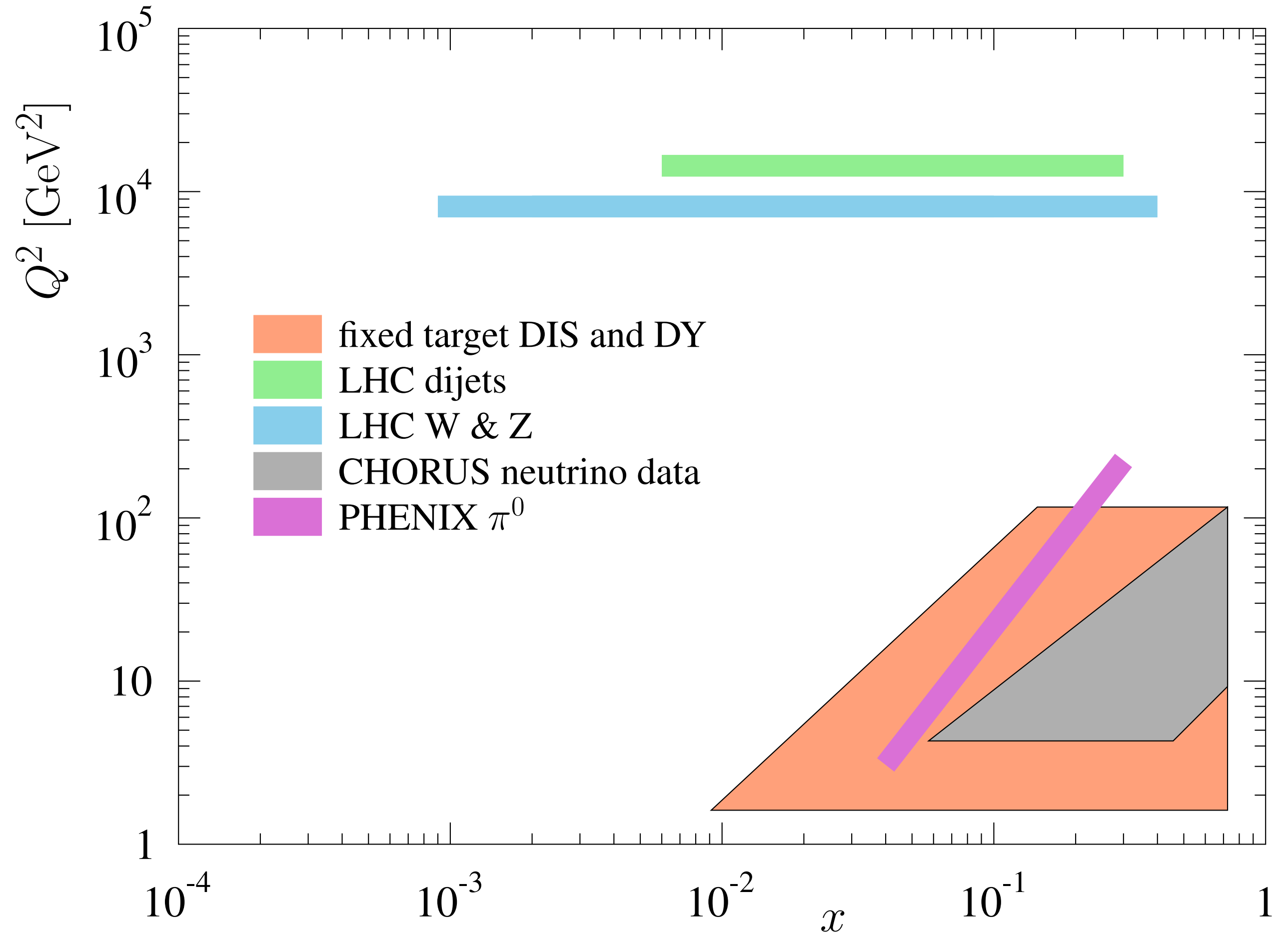


Fig. 2 The approximate regions in the (x, Q^2) plane at which different data in the EPPS16 fit probe the nuclear PDFs.

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]

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

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

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)

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

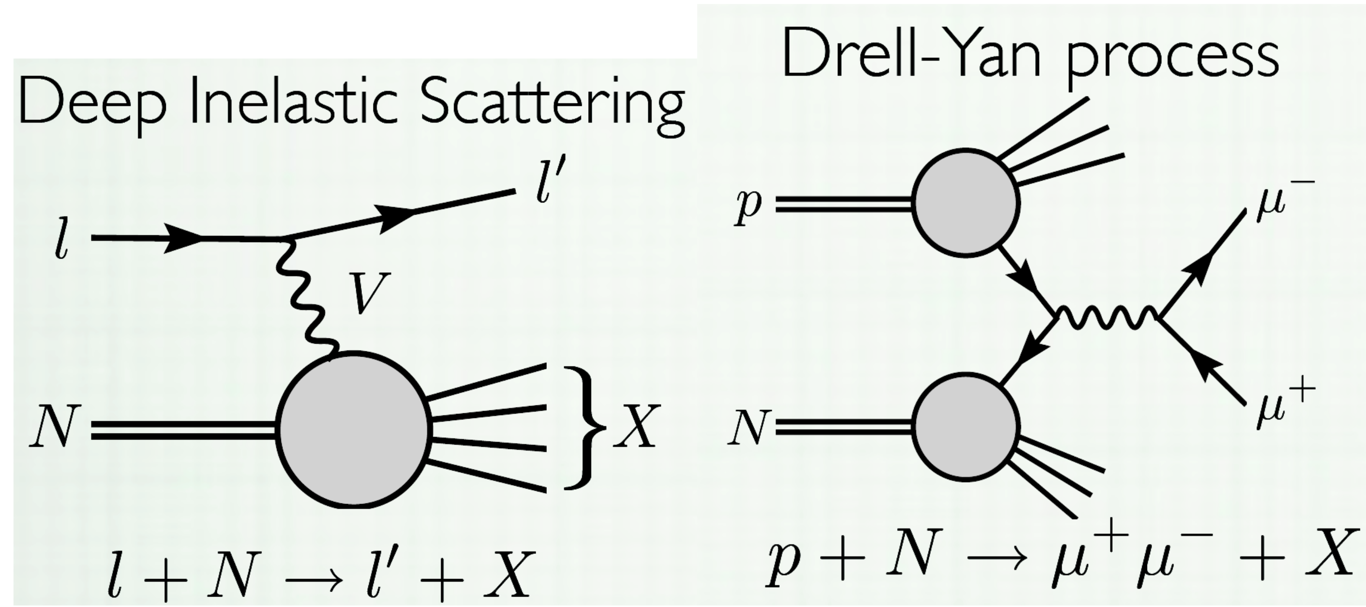
(bound neutron PDF $f_i^{n/A}$ by isospin symmetry)

nCTEQ'15 NPDFs

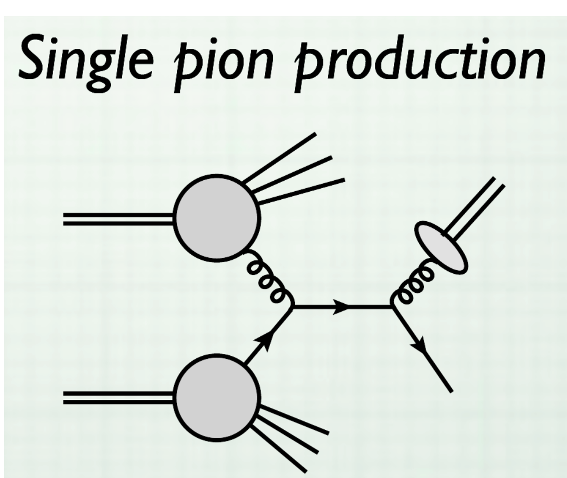
nCTEQ'15 framework: Data sets

- 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)



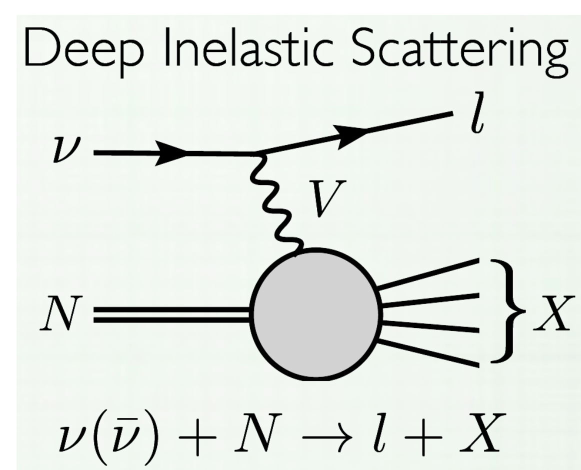
- Single pion production (new)



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 $\rightarrow$ 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 ... $\Delta\chi^2 = 35$ (every
  $= 740$ ... arget within 90% C.L.)
- 16+2 ... es span 10 orders of
  le $\rightarrow$ require numerical
  reducing derivatives
- $\chi^2 =$

Kinematic cuts

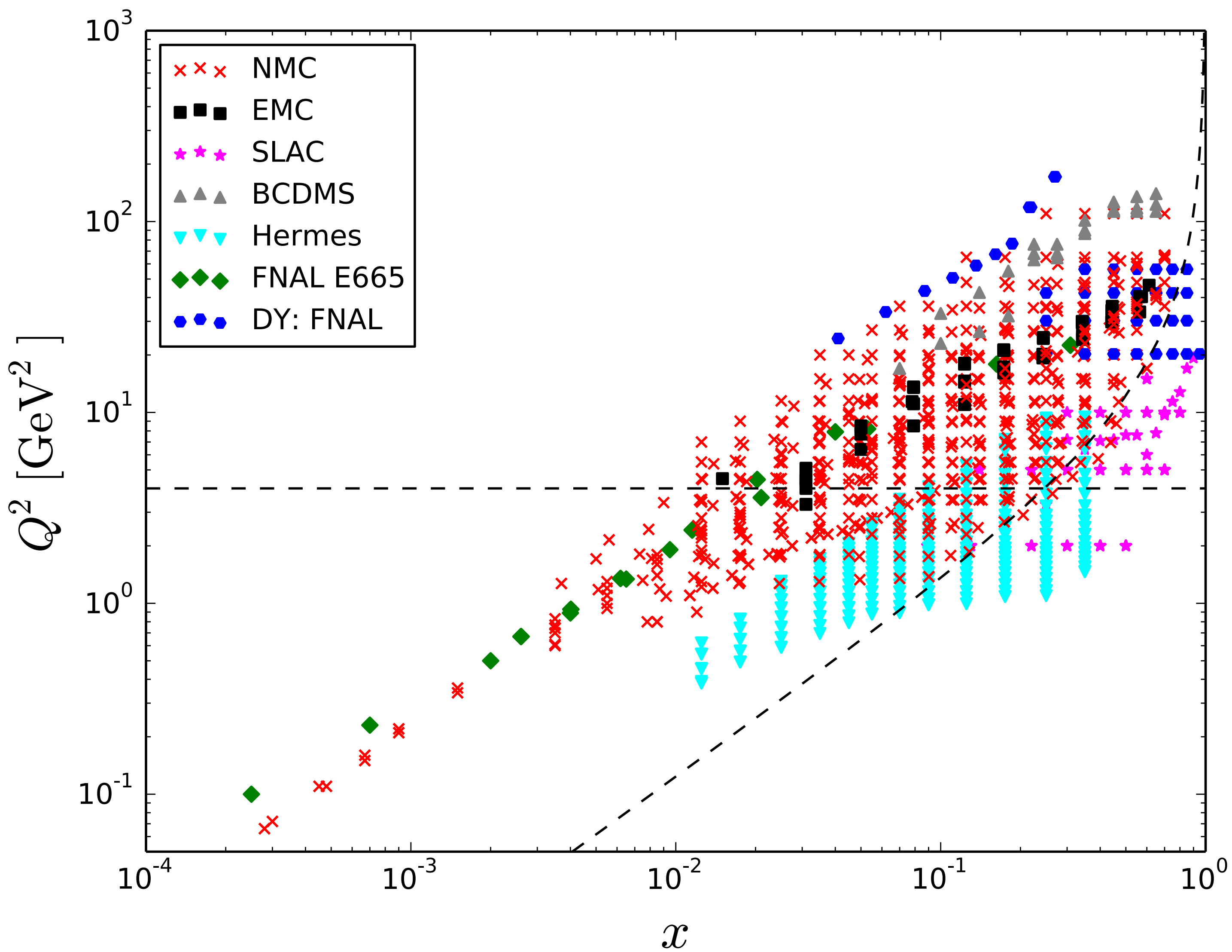
<u>nCTEQ:</u>

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

<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:

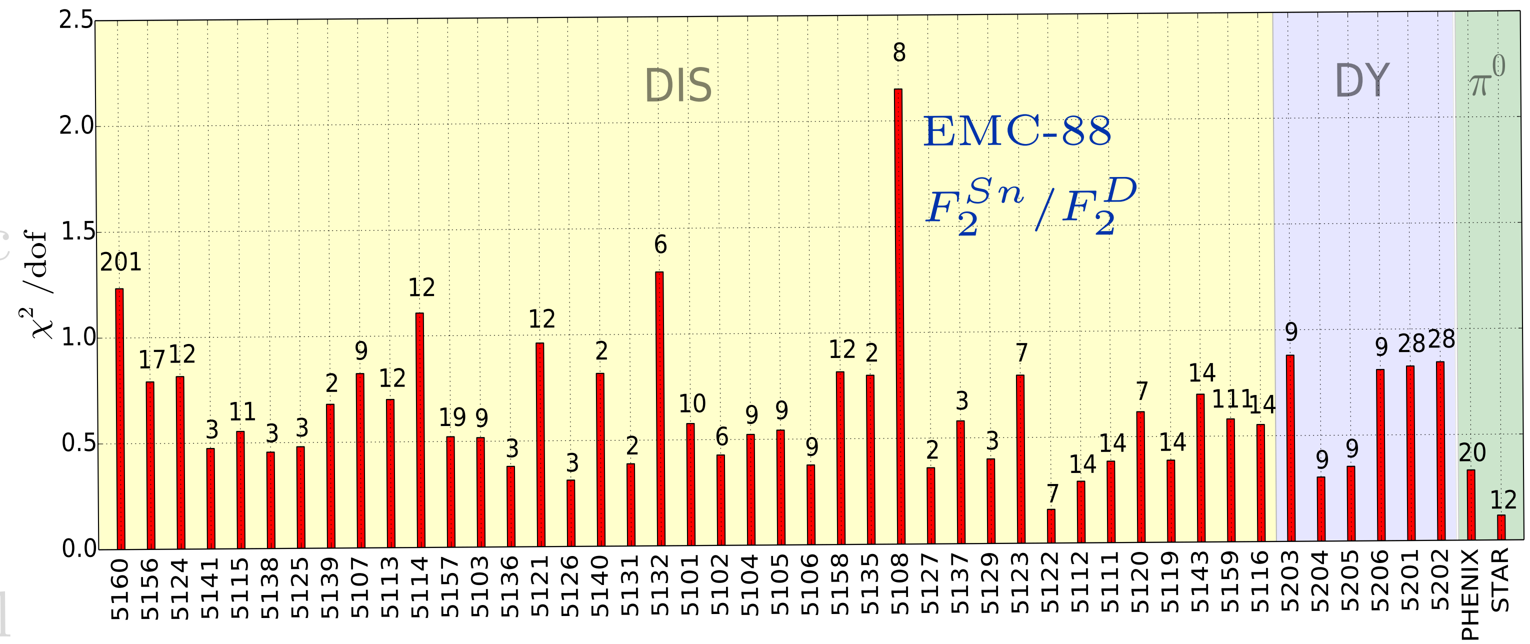
- fit @NLO
- $Q > 2\text{GeV},\ W > 3.5\text{GeV}$
  $p_T > 1.7$ GeV
- 708 (DIS & DY) + 32 (singl
  = 740 data points after cuts
- 16+2 free parameters
  - 7 gluon
  - 7 valence
  - 2 sea
  - 2 pion data normalizations
- $\chi^2 = 587$, giving $\chi^2/\text{dof} = 0.81$

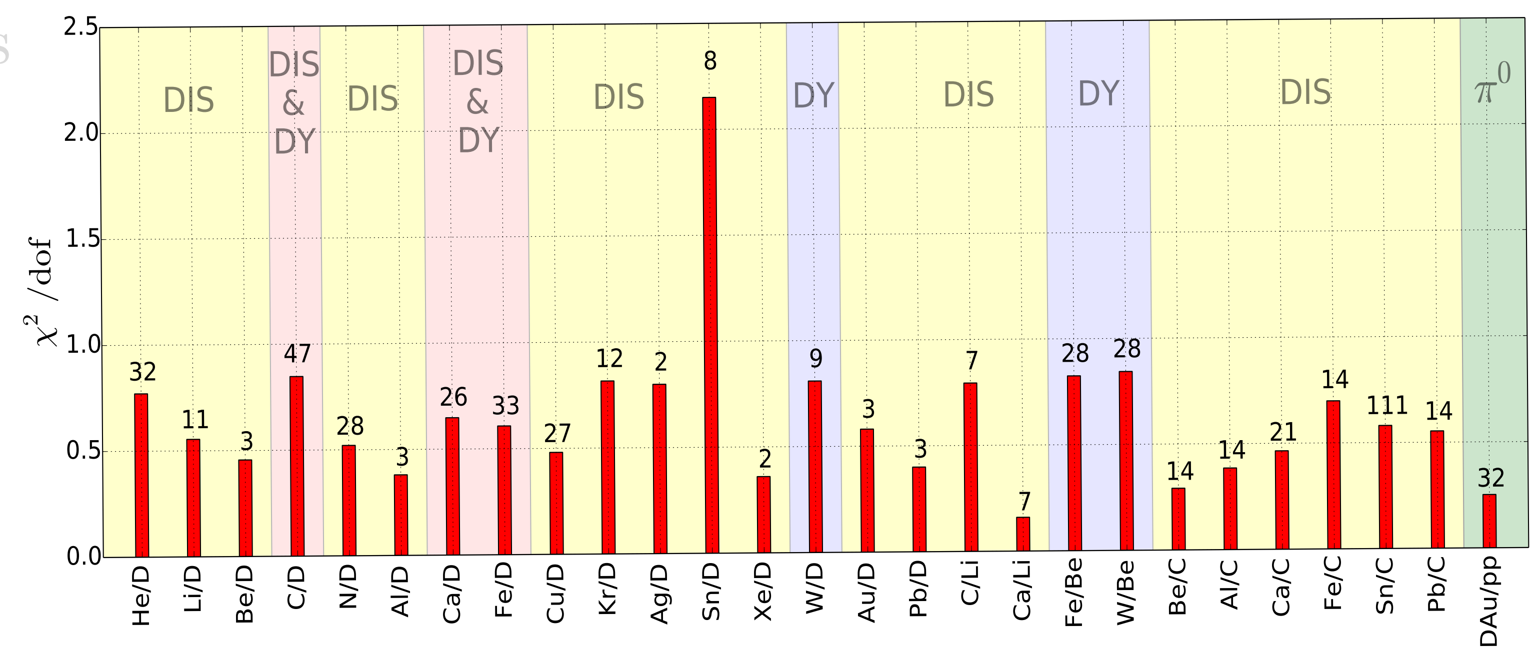
Fit quality

- $\chi^2/dof = 0.81$

Error analysis:

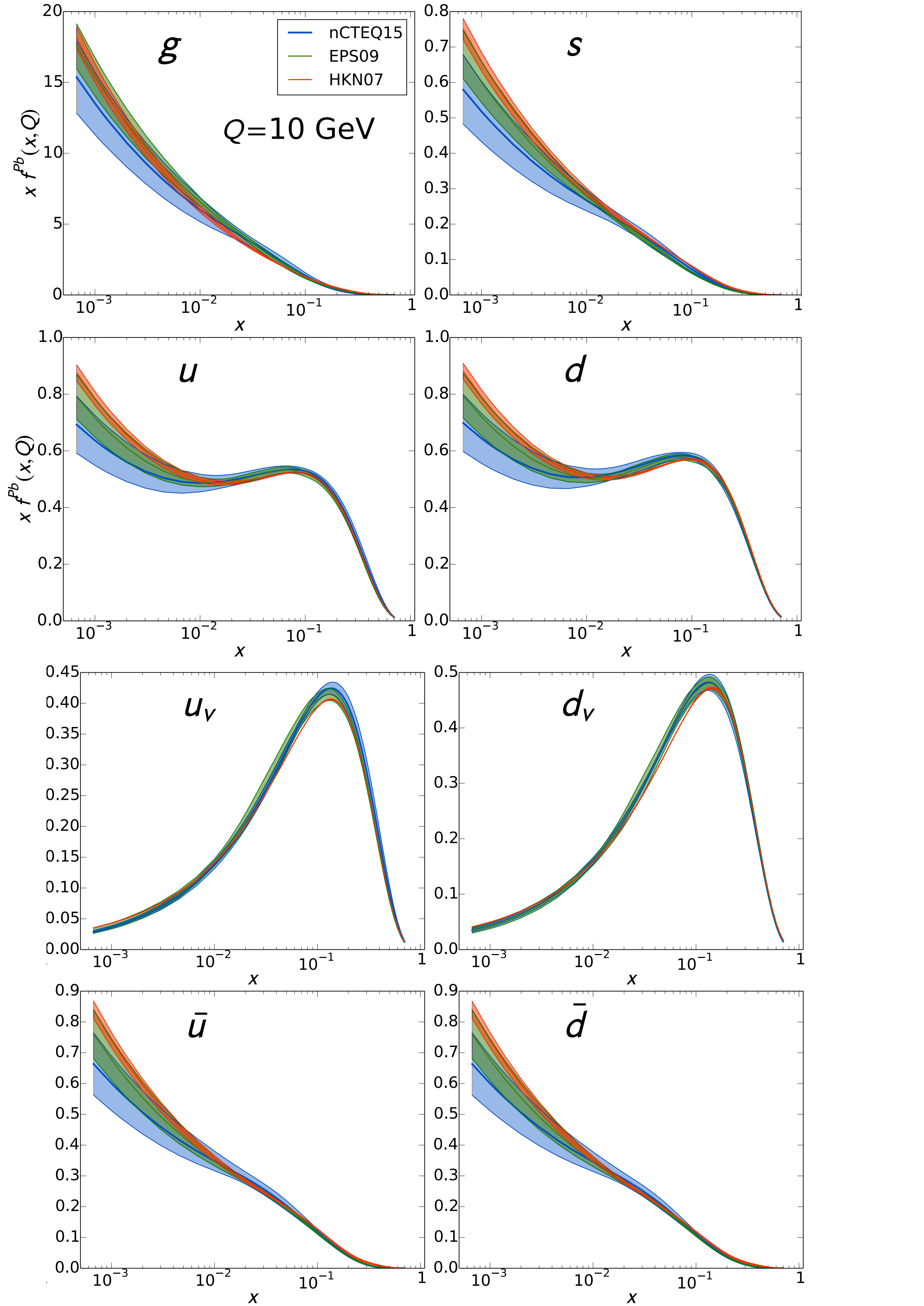
sc





nCTEQ results

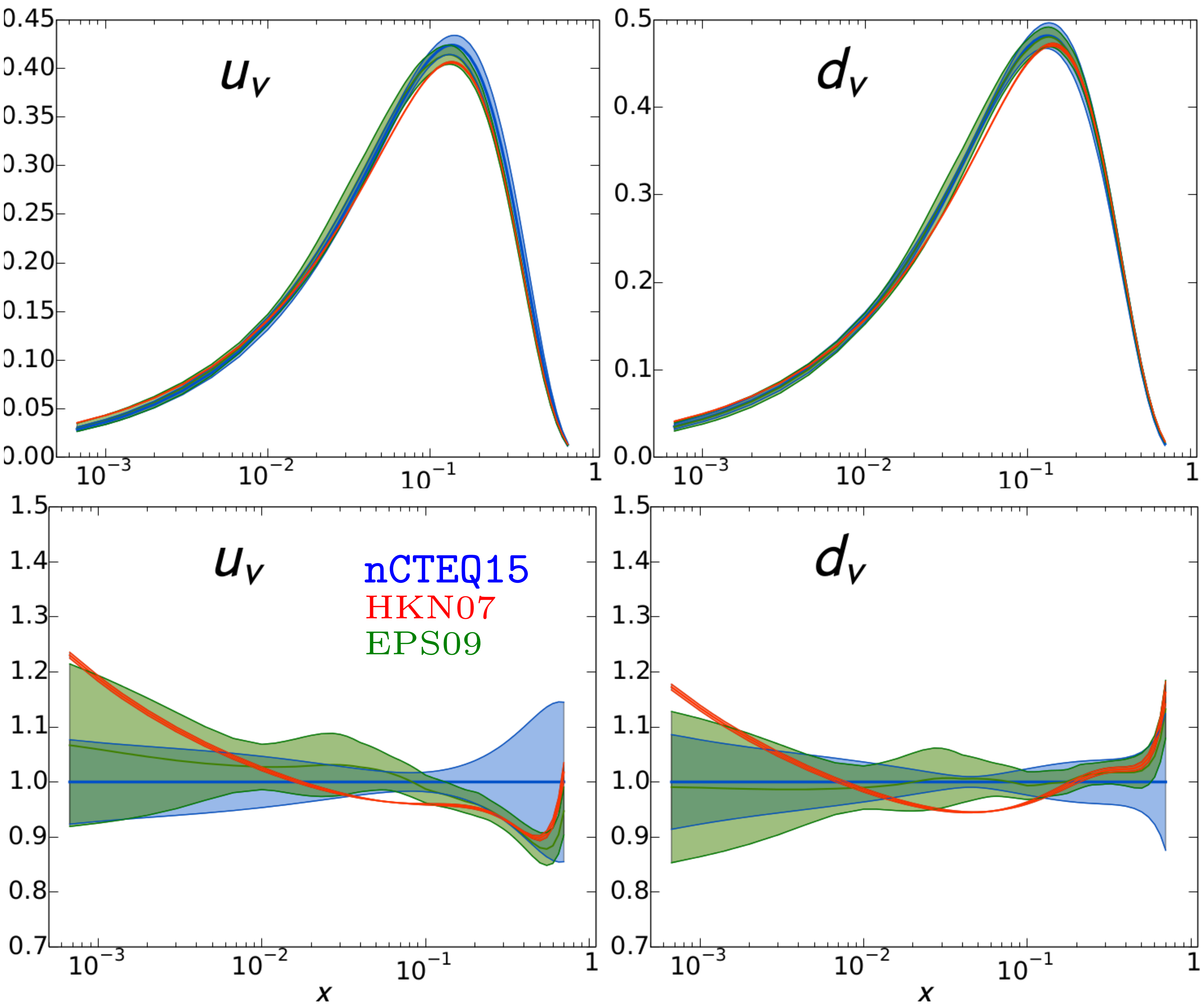
- First global analysis with Hessian error PDFs: [PRD93(2016]085037]
- Figure: PDFs inside lead at Q=10 GeV vs x
- nCTEQ features larger uncertainties than previous nPDFs
- better agreement between different groups



Valence distributions

Full lead nucleus distribution:

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



EPPS'16 NPDFs

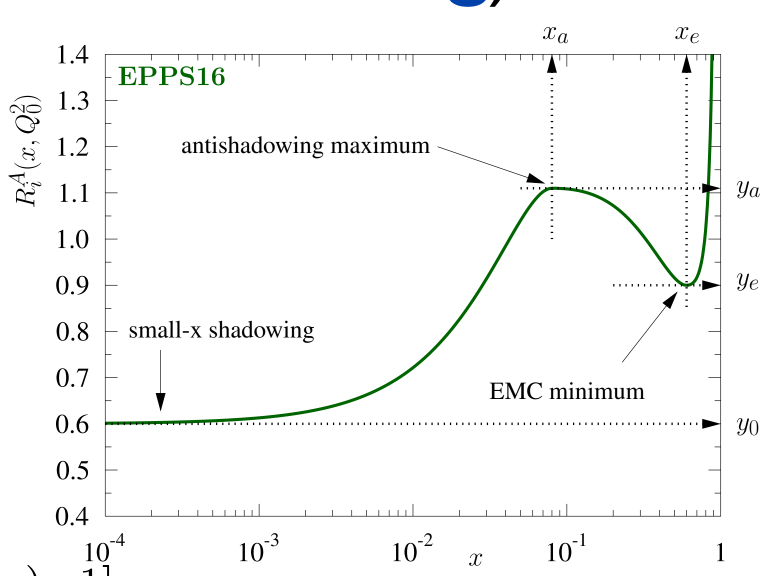
EPPS'16 framework

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

- Parametrization ($x_N<1$, $Q_0=1.3$ GeV, $i=u_v,d_v,\bar{u},\bar{d},s,g$)

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

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



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

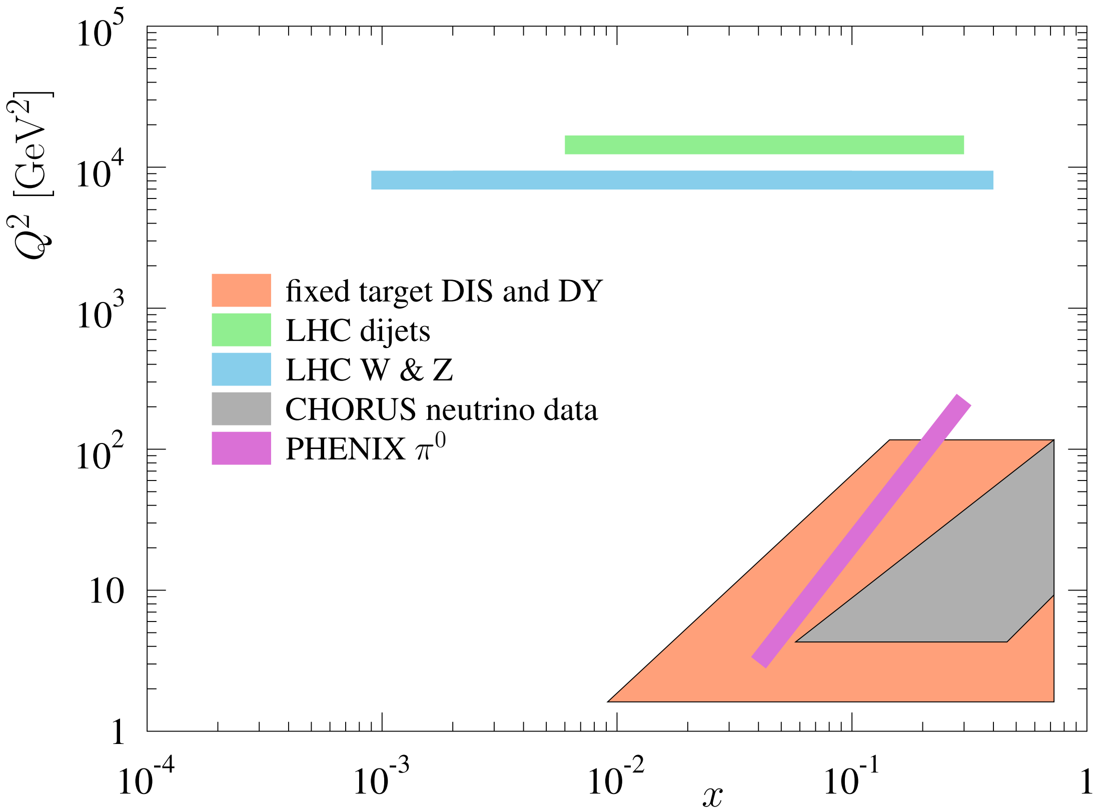


Fig. 2 The approximate regions in the (x, Q^2) plane at which different data in the EPPS16 fit probe the nuclear PDFs.

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

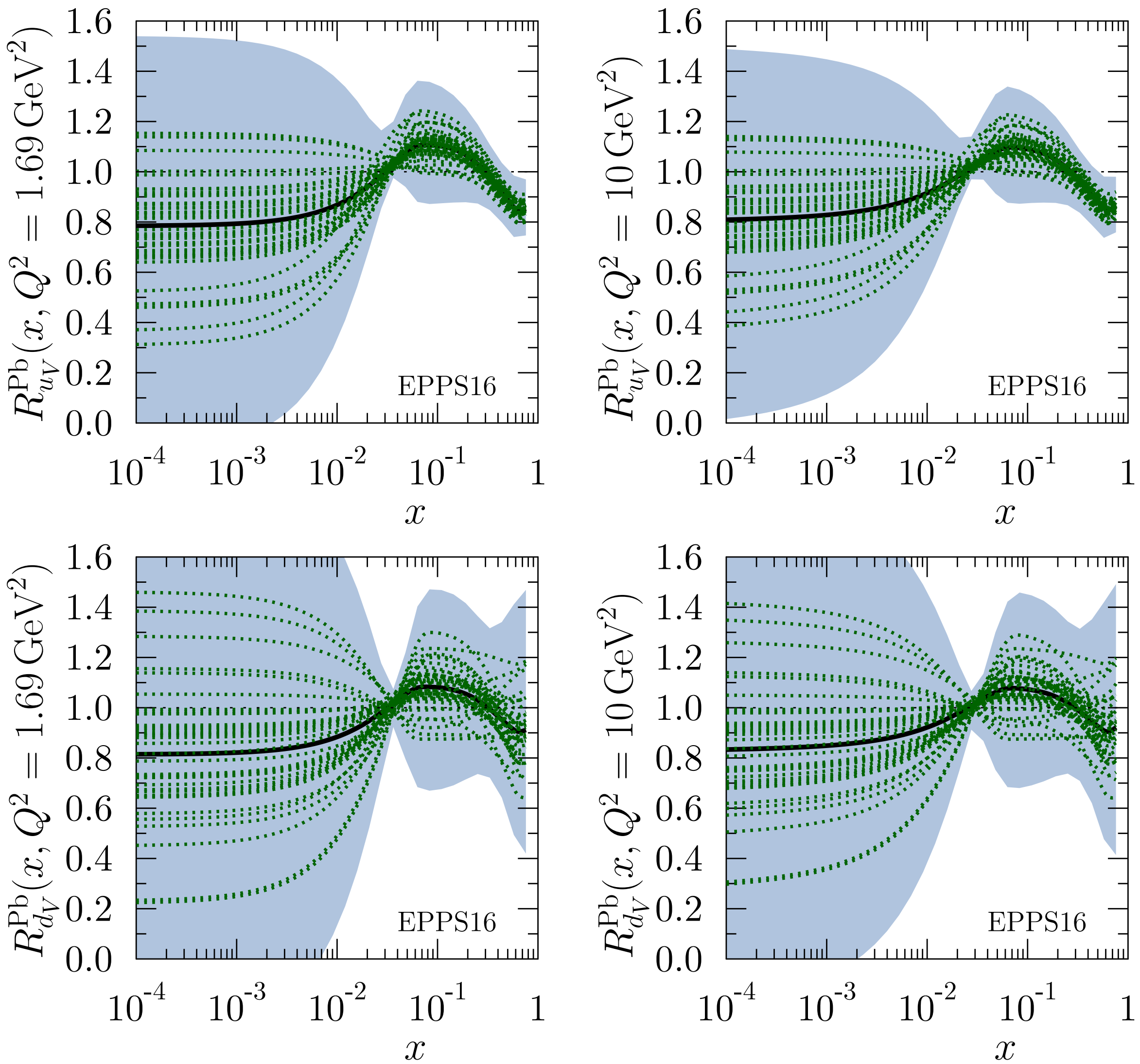
EPPS'16 framework: Results

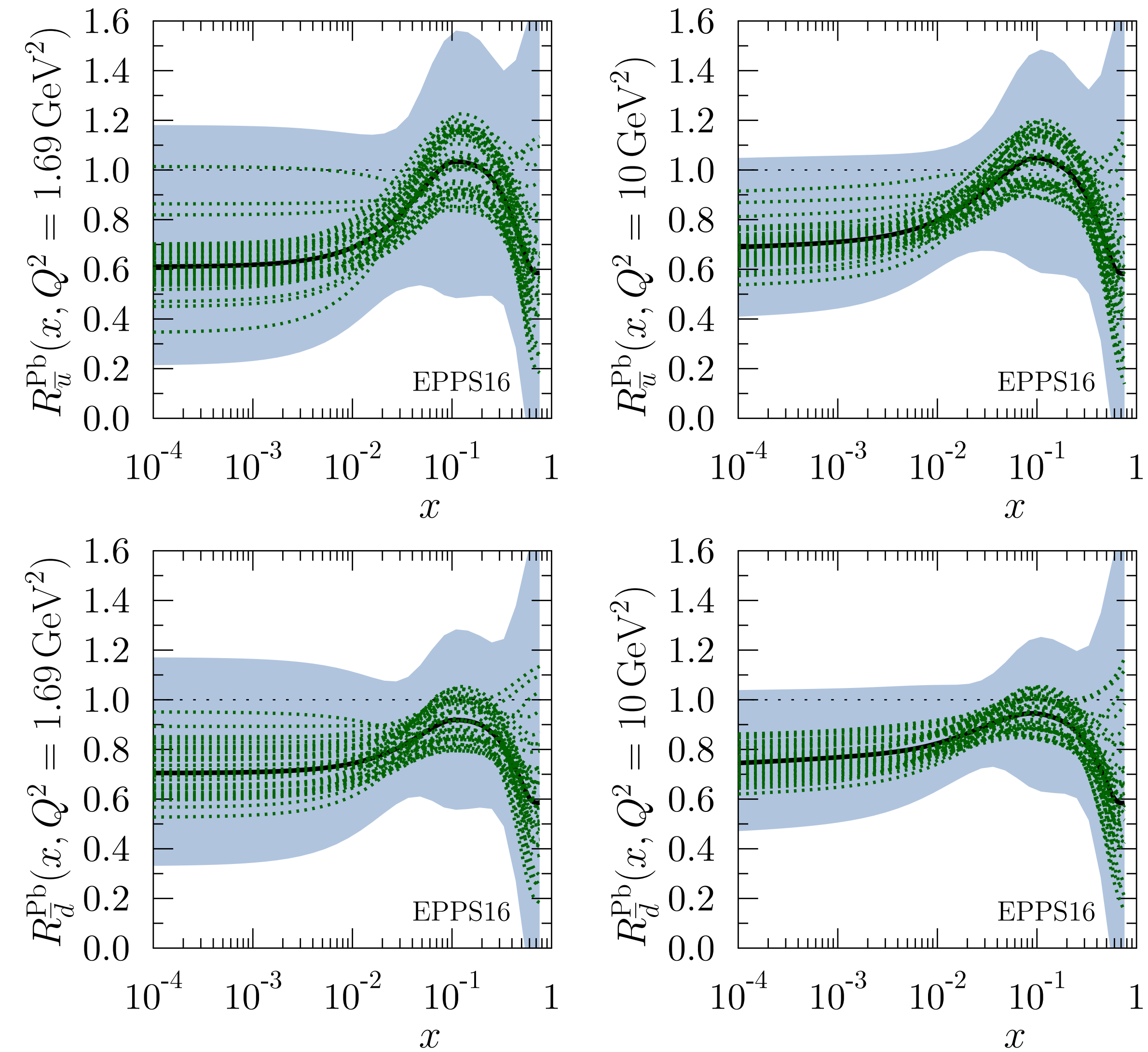
Table 3 List of parameters defining the central set of EPPS16 at the initial scale $Q_0^2 = 1.69\,\mathrm{GeV}^2$. The numbers in bold indicate the 20 parameters that were free in the fit.

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

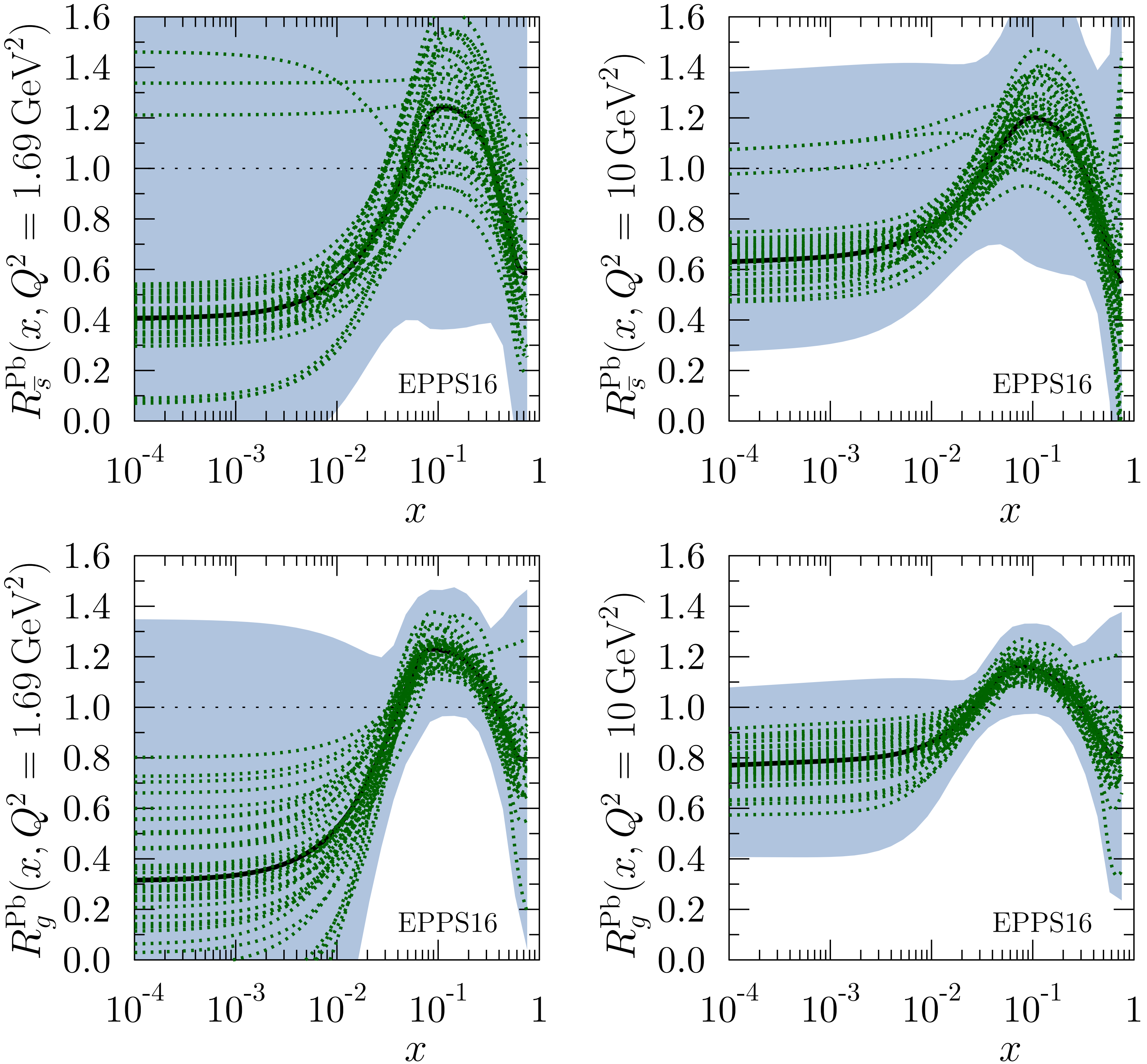




- Considerably larger uncertainties than EPS'09 despite more data (more flexible param., larger tolerance). Main impact from CHORUS and CMS dijet data.
- No notable tensions with previous data sets. **Supports validity of theoretical framework!**
- Still some parametrization bias (shape of PDFs), still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

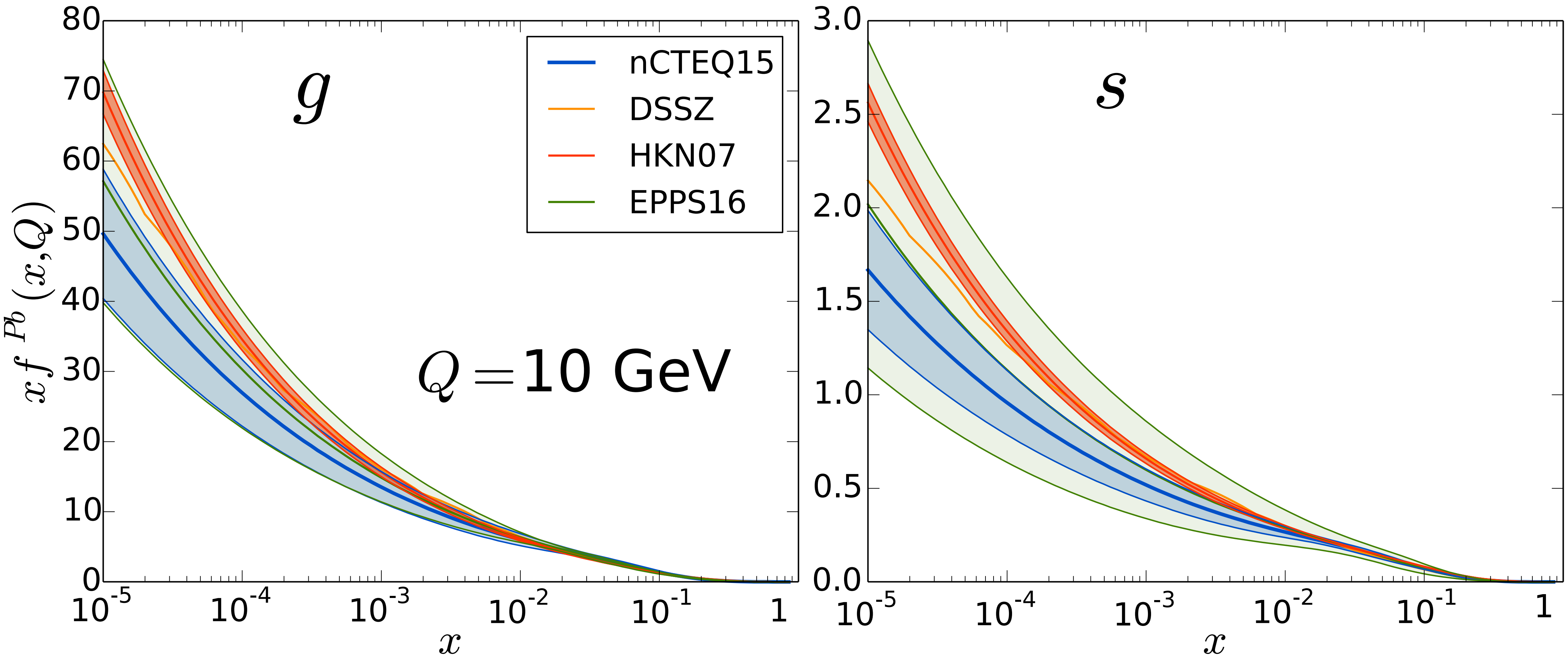
EPPS'16 framework: Results

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

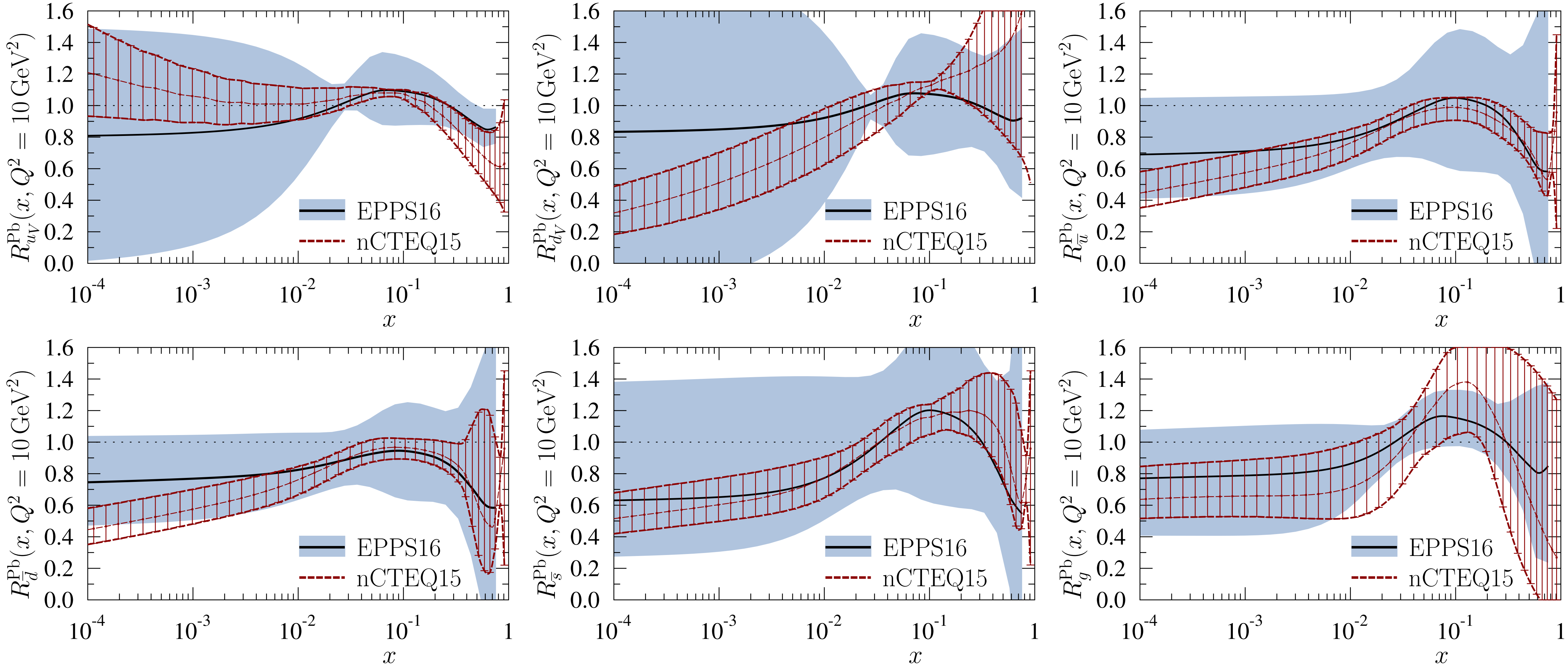


EPPS'16 vs nCTEQ'15

Gluon and Strange distributions

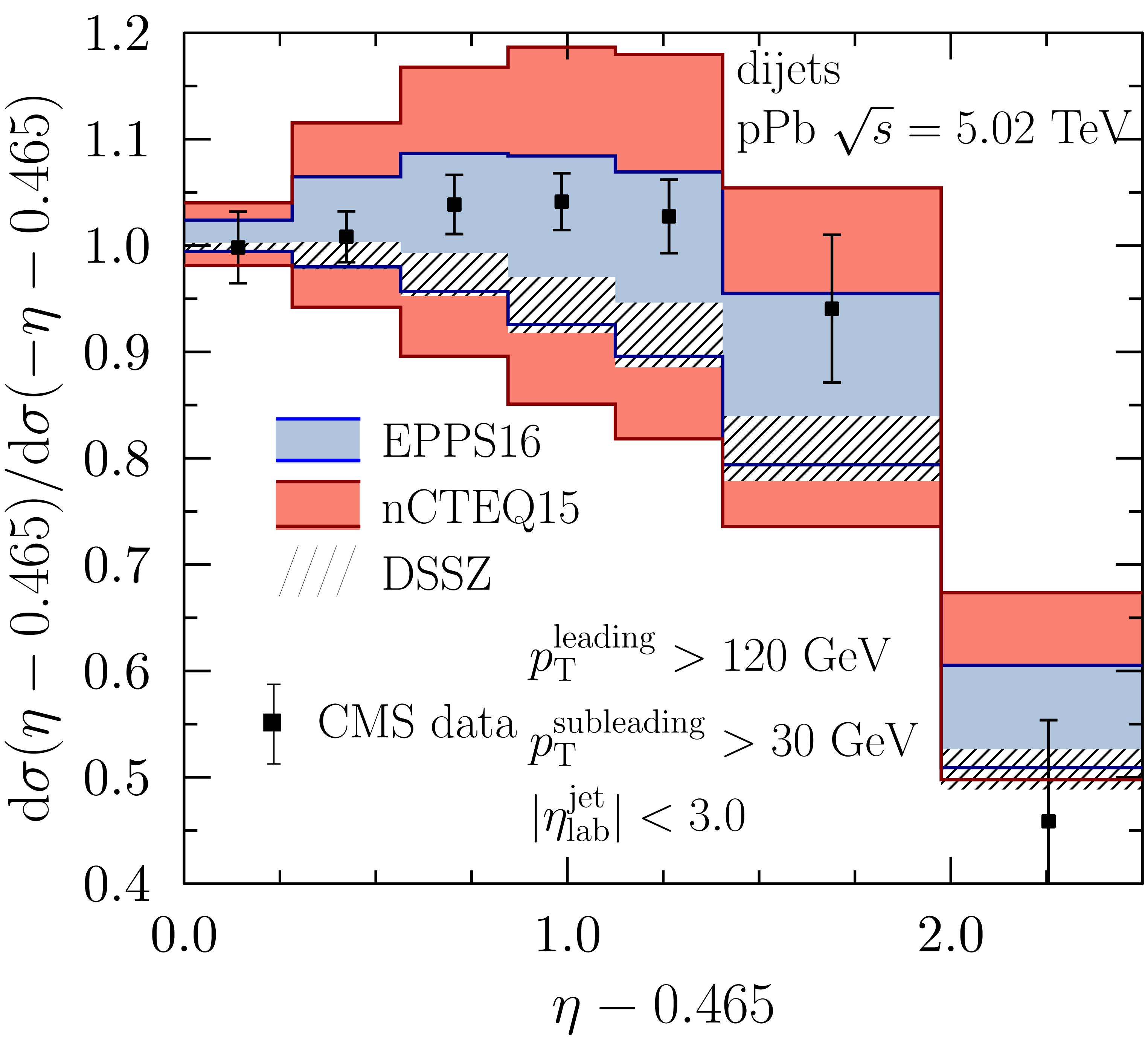


EPPS'16 vs nCTEQ'15 @Q^2=10 GeV^2



- 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

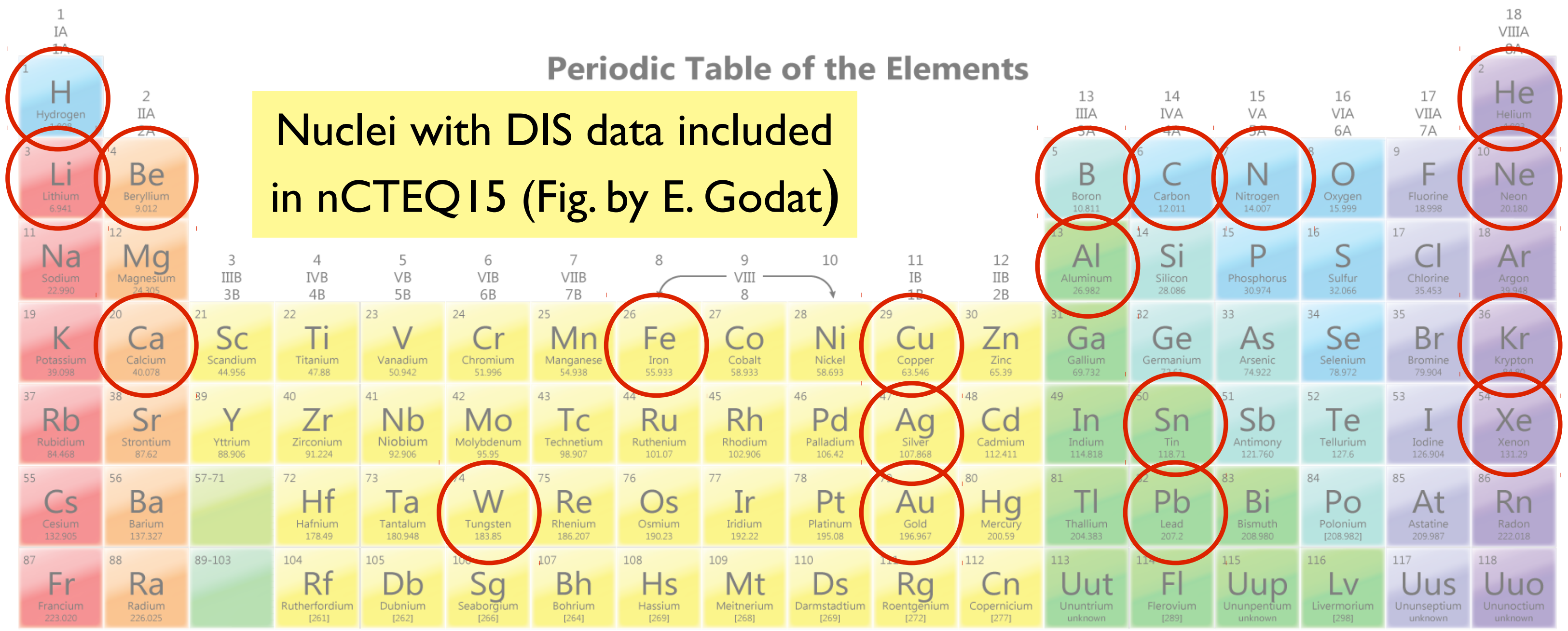
Comparison with dijet data



- 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?

Perspectives with lighter ions

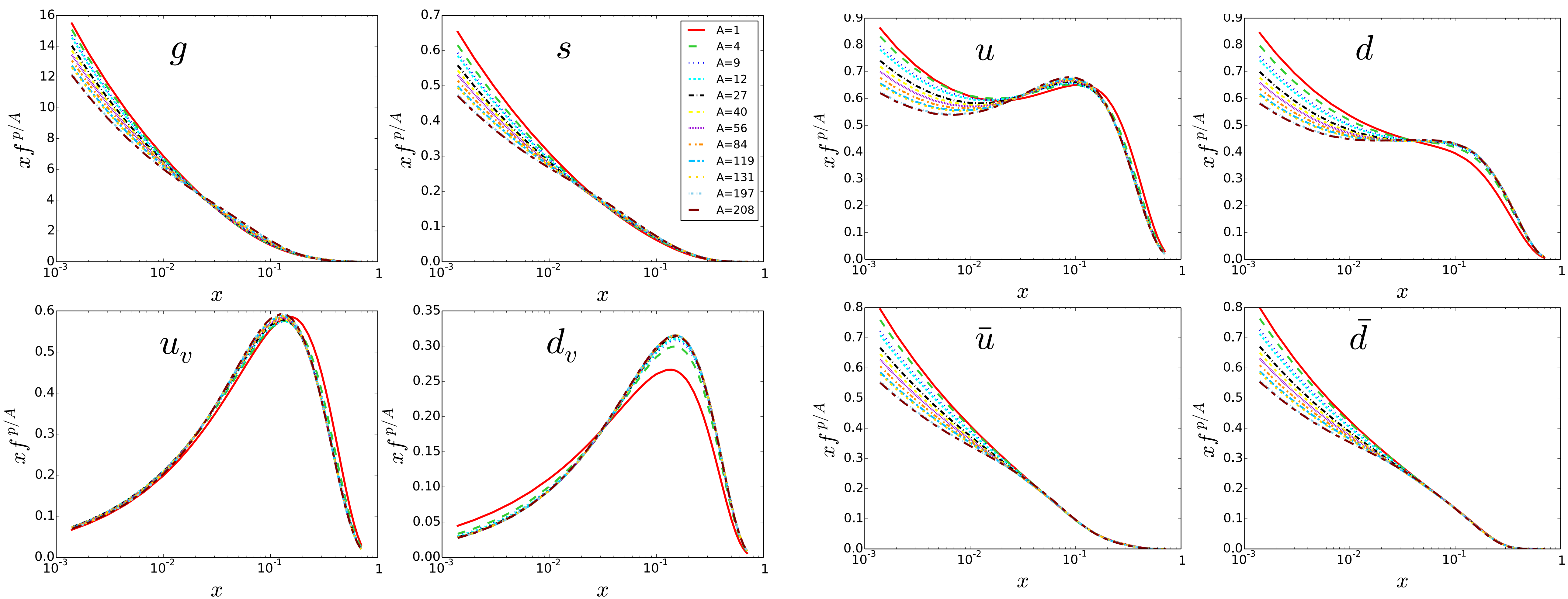
A-dependence of the partonic structure



- Fundamental quest
- New data from LHC, AFTER@LHC, EIC will allow a refined parametrization; zoom in on high-x region
- Ultimately, fits to lead only (or other targets); no need to combine different A in one analysis

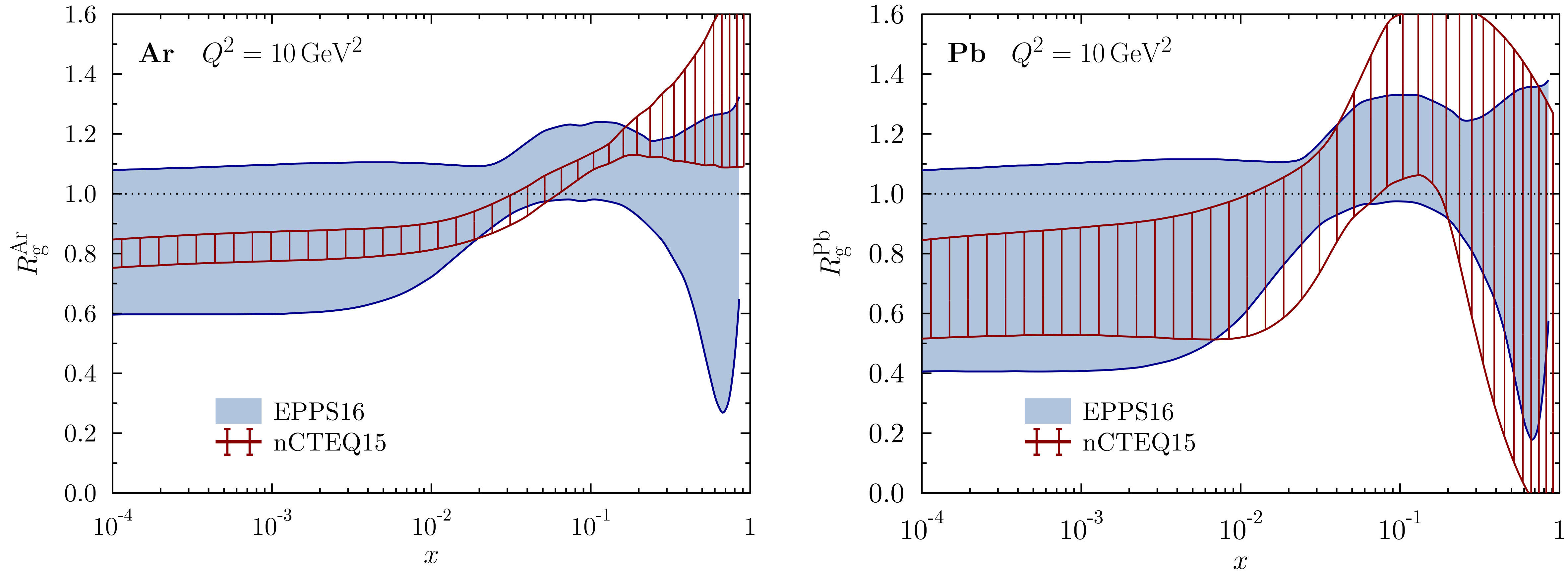
nCTEQ15, arXiv:1509.00792

$$x f_i^{p/A}(x, Q_0) = x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5} \qquad c_k(A) = c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right)$$



Gluon distribution for Argon and Lead

Figure form WG5 contribution to CERN Yellow Report on HL-LHC



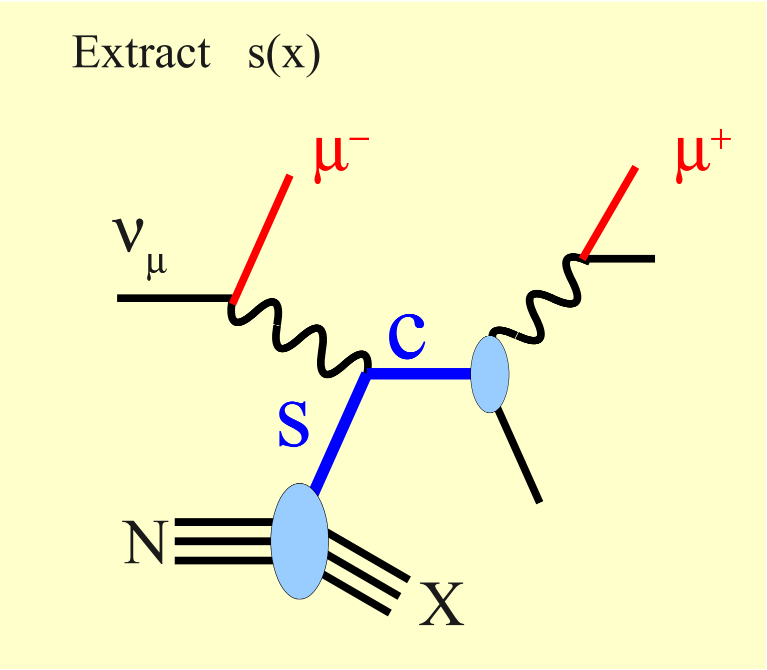
- Due to scarcity of nuclear data a PDF fit for a single nucleus not yet possible (except maybe lead)
- Important parametrization bias, in particular concerning the A-dependence
- Data on lighter nuclei may help to constrain such parametrisations

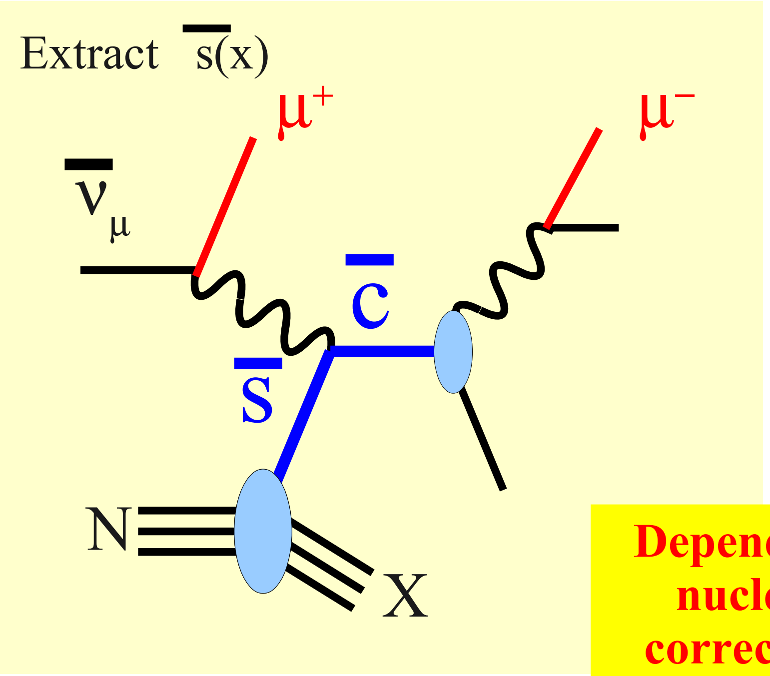
Vector boson production and the strange PDF

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: $\nu N \rightarrow \mu^+ \mu^- X$



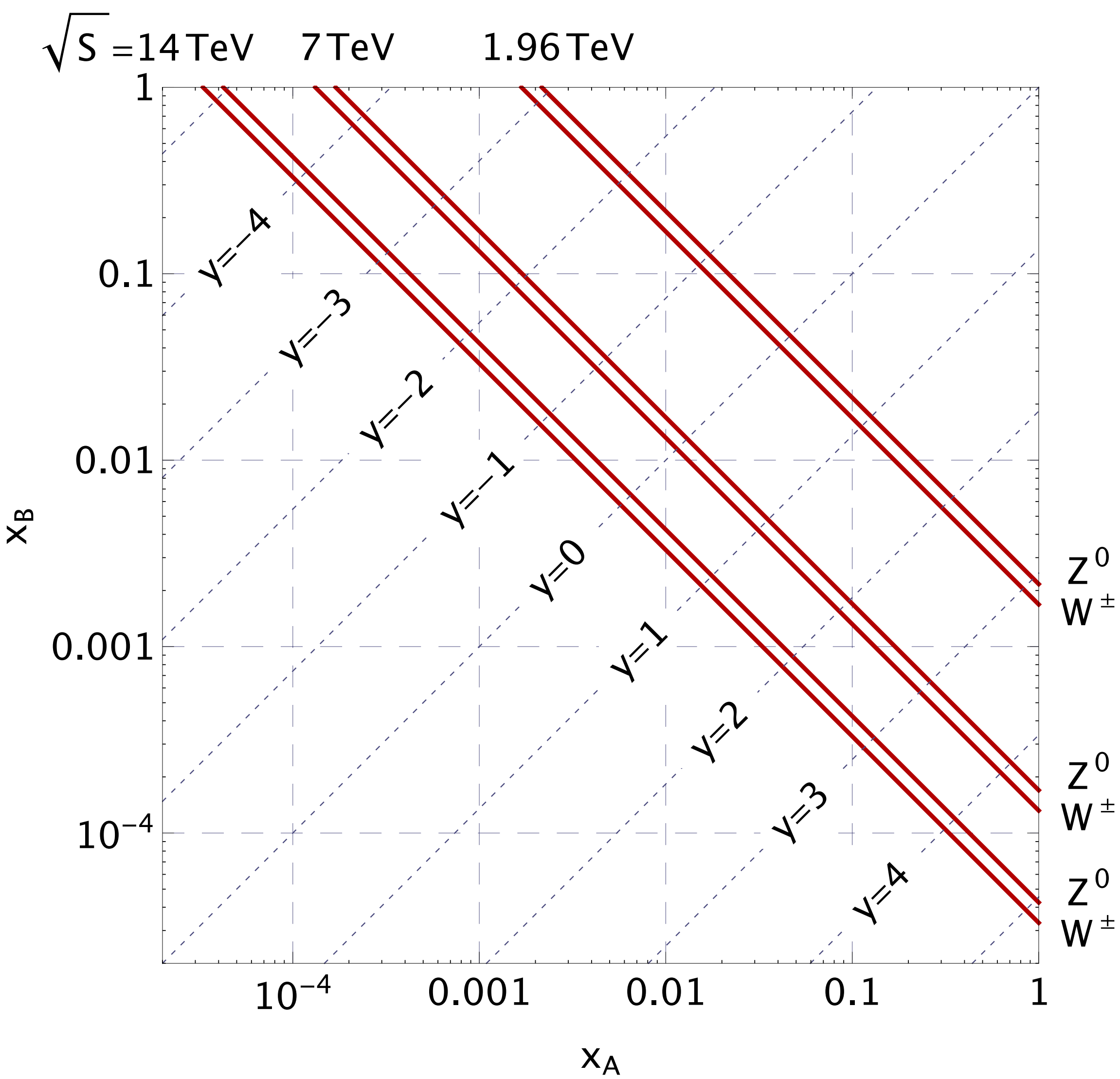


Depends on nuclear corrections

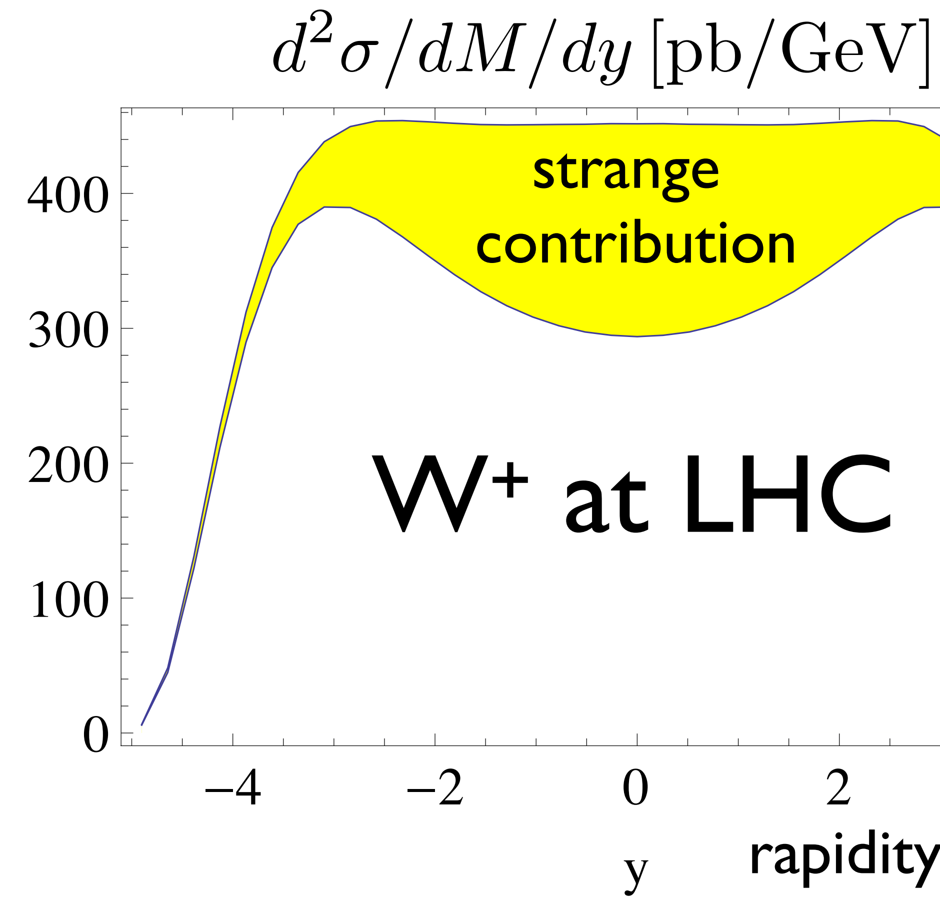
- High-statistics data from CCFR and NuTeV: **Main source** of information!
- x~[0.01,0.4]
- νFe DIS: need nuclear corrections! Problem: Final State Interactions (FSI)
- CHORUS (νPb): compatible with NuTeV, could be included
- NOMAD (νFe): data not yet published, in principle very interesting

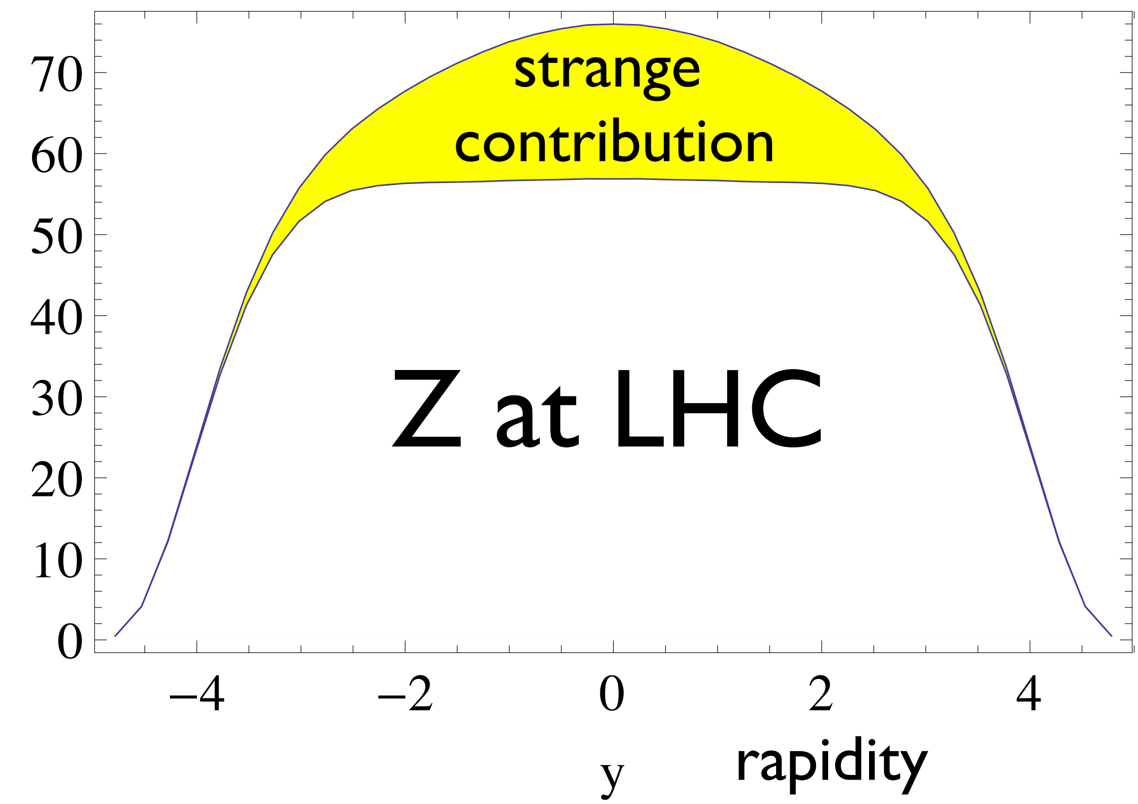
Drell-Yan production of W/Z at the LHC

Kinematic plane



Uncertainty of strange-PDF will feed into benchmark process





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

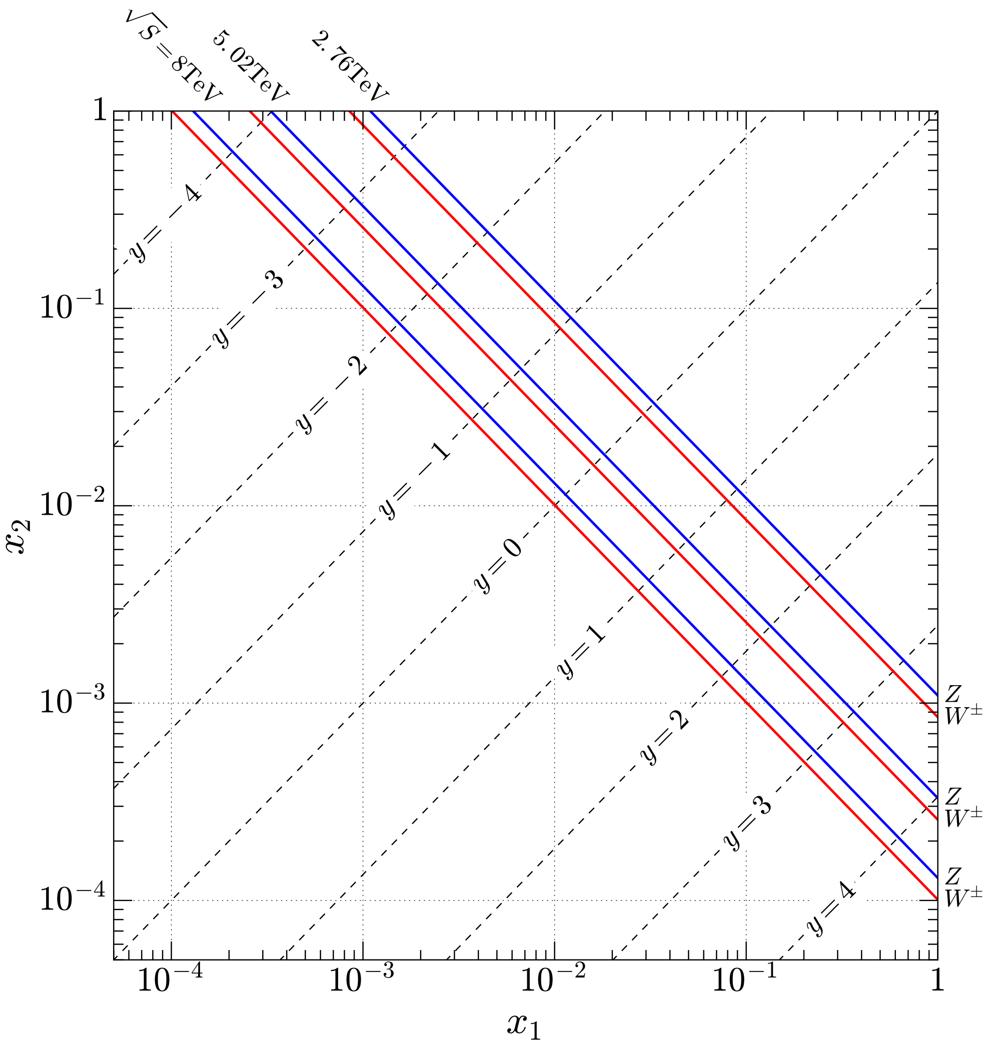
nCTEQ study of W,Z production at LHC

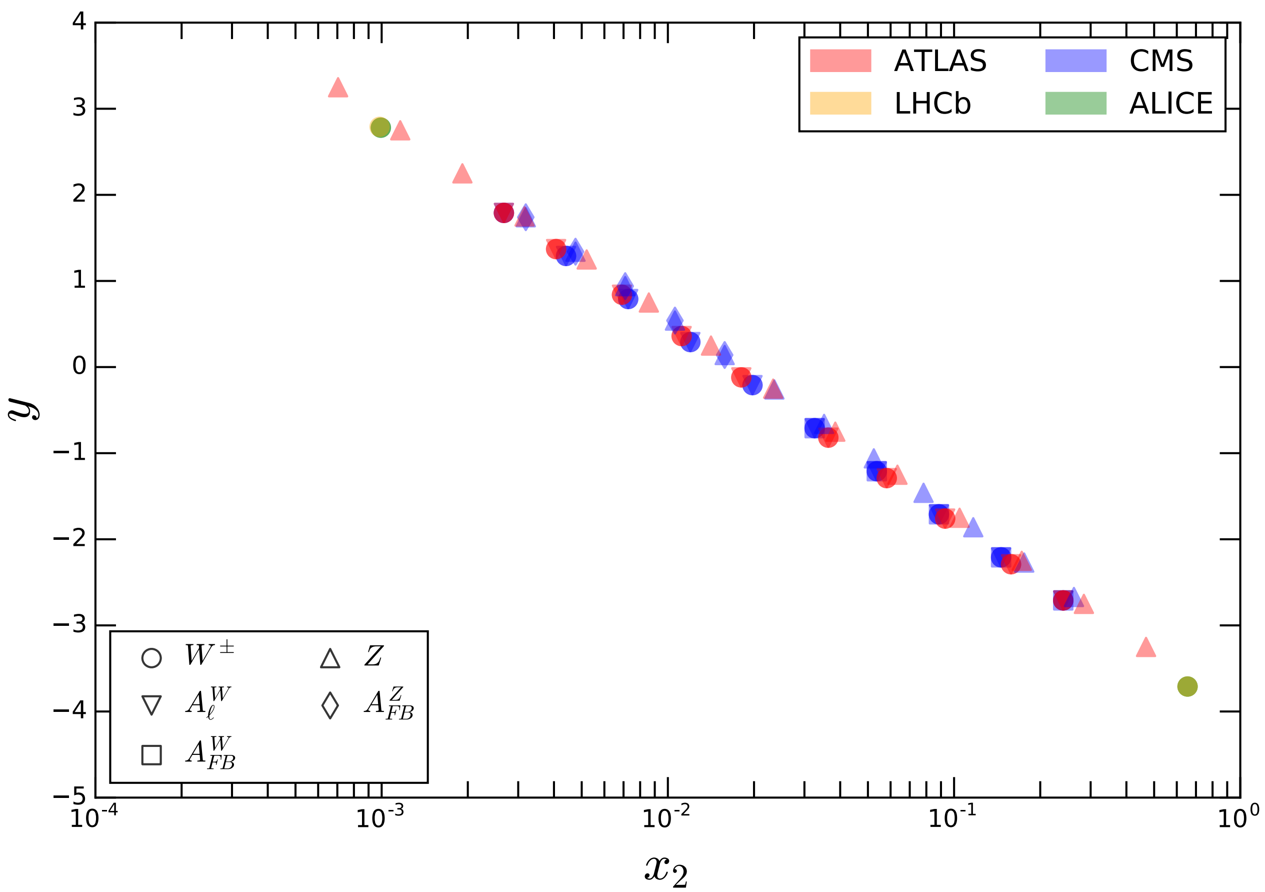
arXiv:1610.02925

		Observable	Cuts (GeV)	Figure
pPb	ATLAS	$d\sigma(Z \to \ell^+\ell^-)/dy_Z$ [2]	$\|y_Z^{CM}\| < 3.5$; $60 < m_{\ell^+\ell^-} < 120$	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 at LHC



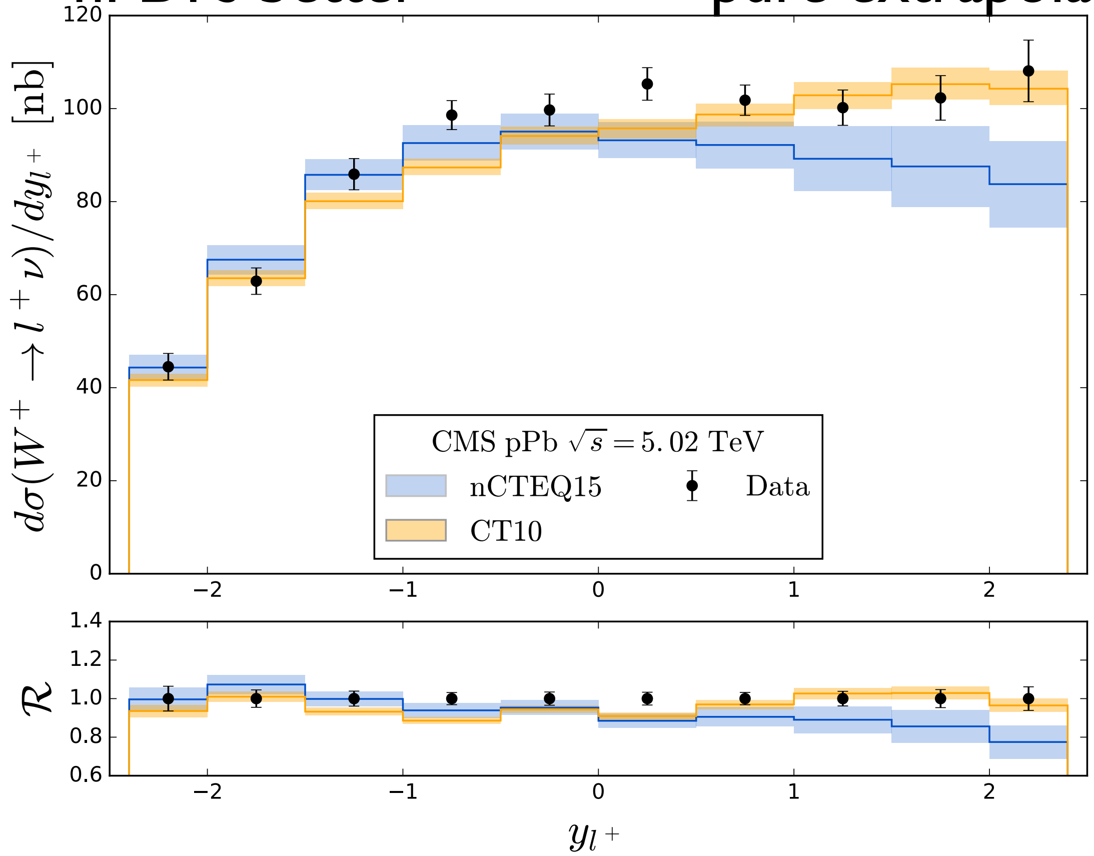


- y < -1: x > 5 x10^{-2} ... 0.3 (region where nPDFs are constrained by data in global analysis)
- |y| < 1: x ~ 10^{-2} (transition region from anti-shadowing to shadowing)
- y > 1: x < 5 x 10^{-3} (pure extrapolation!)

W-boson rapidity distributions

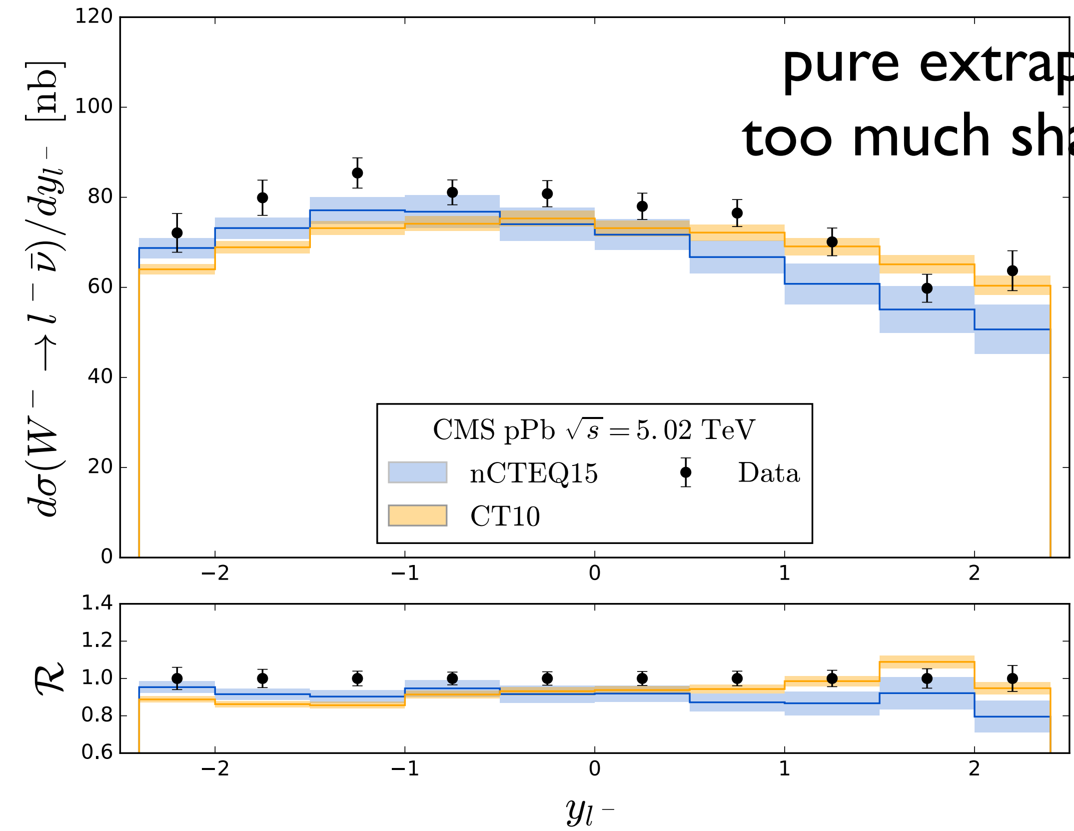
nCTEQ, EPJC77(2017)488

nPDFs better   pure extrapolation

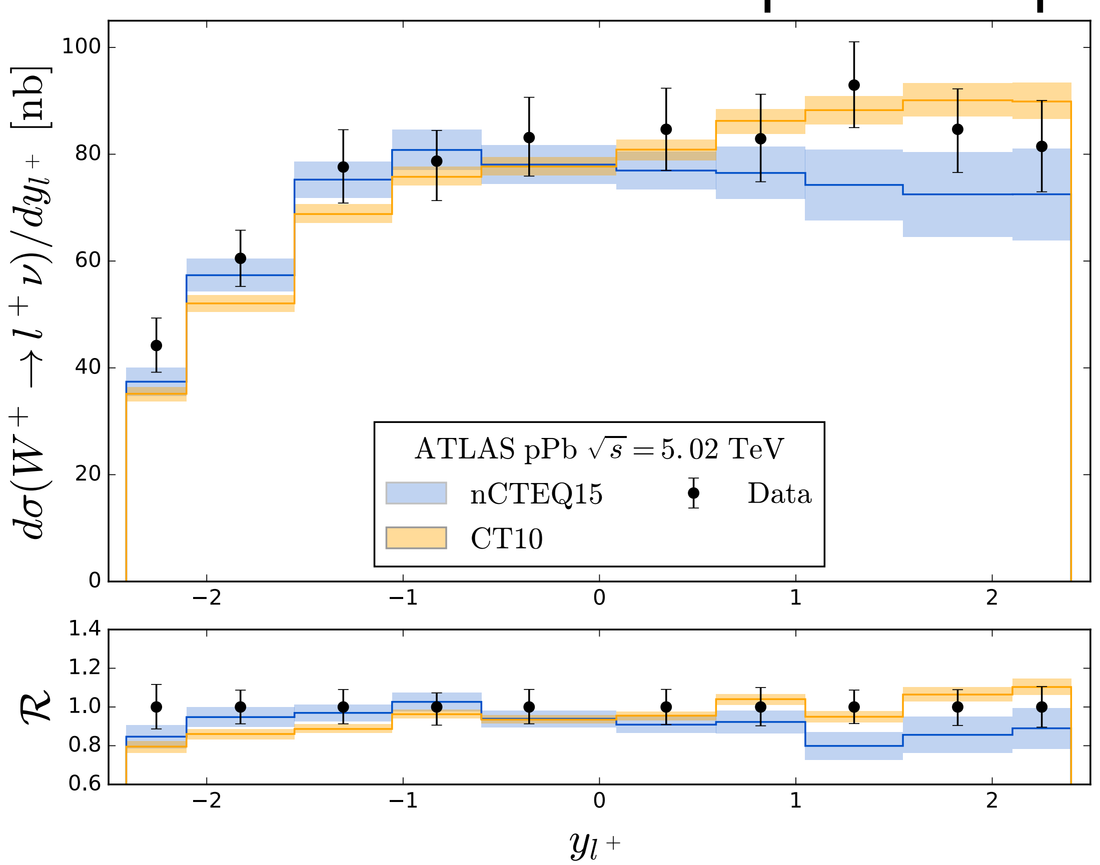


nPDFs better

pure extrapolation
too much shadowing?

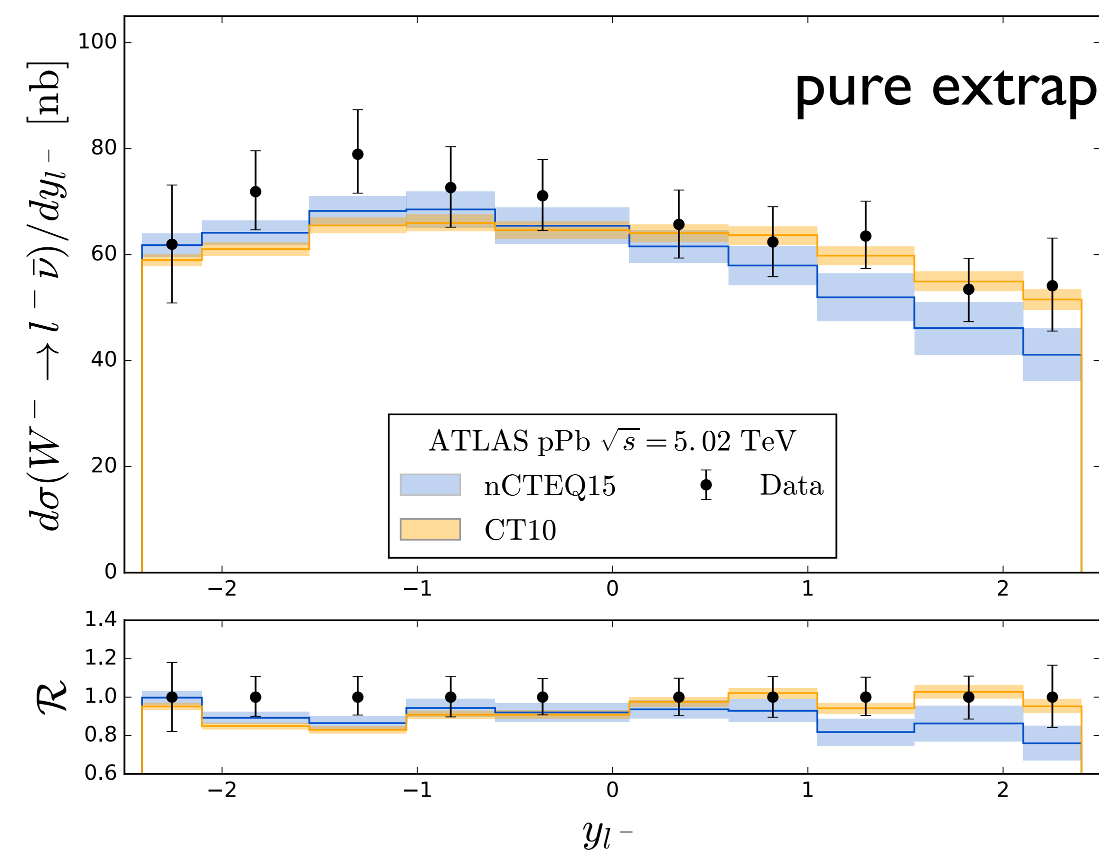


nPDFs better   pure extrapolation

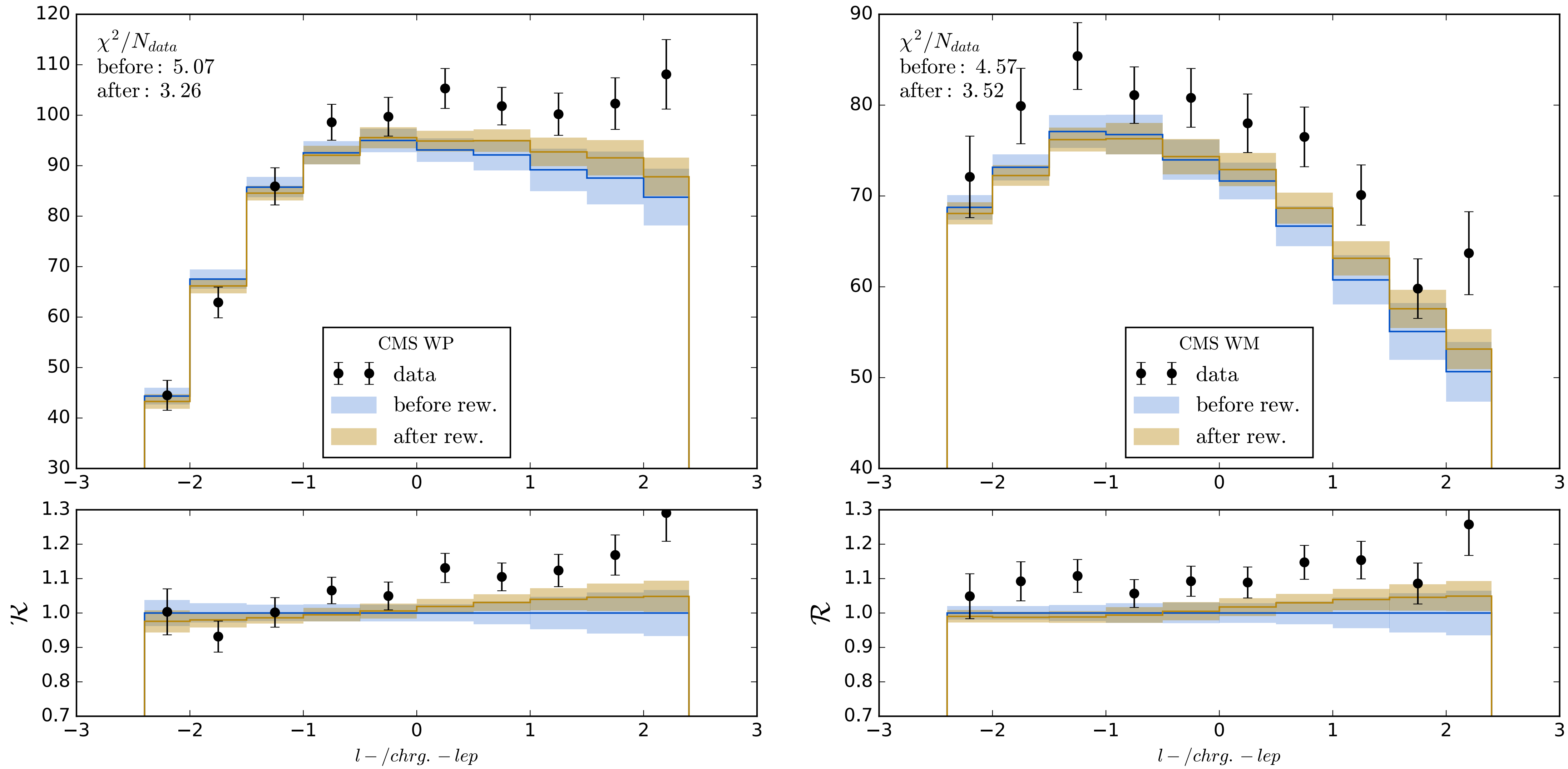


nPDFs better

pure extrapolation



Reweighting



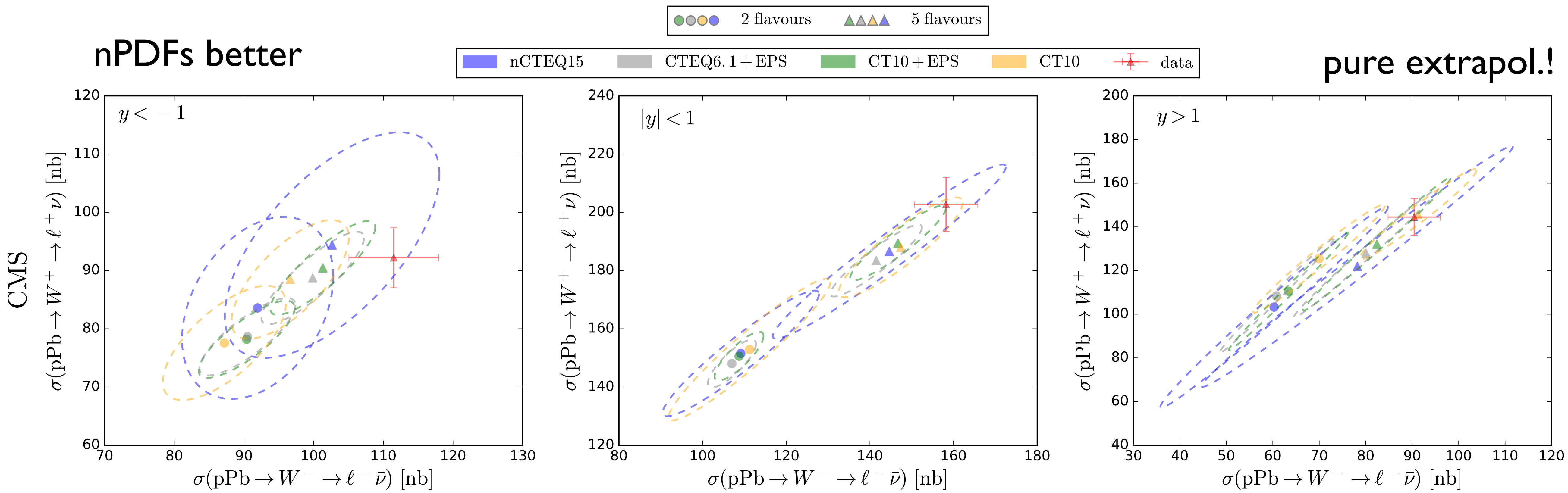
(a) W^+ (b) W^-

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

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?

Strange sea larger than expected?

Figure form WG5 contribution to CERN Yellow Report on HL-LHC

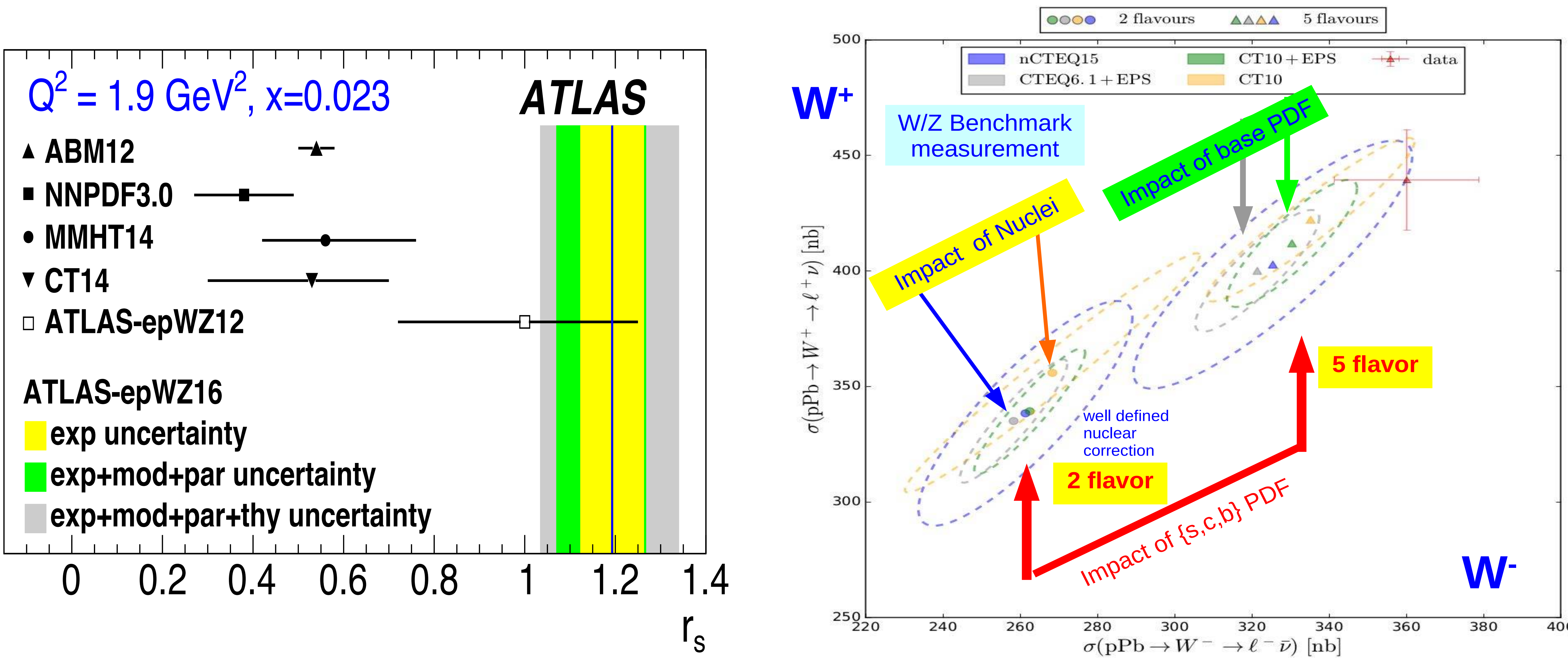
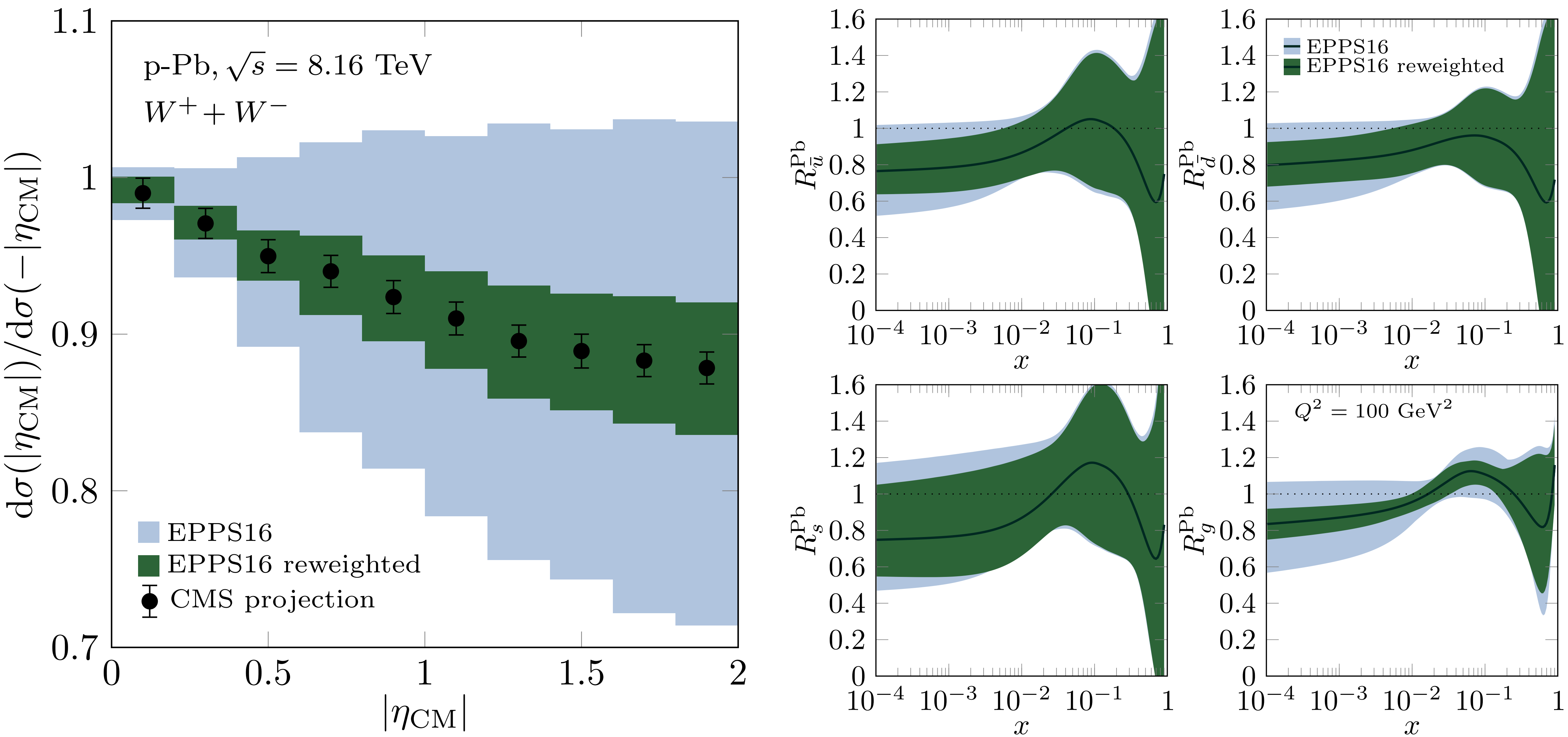


Fig. 12: Left: The relative strange-to-down sea quark fractions $r_s = 0.5(s+\bar{s})/\bar{d}$ as compared with predictions from different NNLO PDF sets; figure from Ref. [147]. Right: correlations between W^+ and W^- pPb cross sections calculated with different input PDFs and assumptions to illustrate the separate impact of the i) nuclear corrections, ii) heavy flavor components, and iii) base PDFs [148, 149].

Using the W-asymmetries

Figure form WG5 contribution to CERN Yellow Report on HL-LHC



- Reweighting shows that W-asymmetry projected data have a strong impact on the gluon

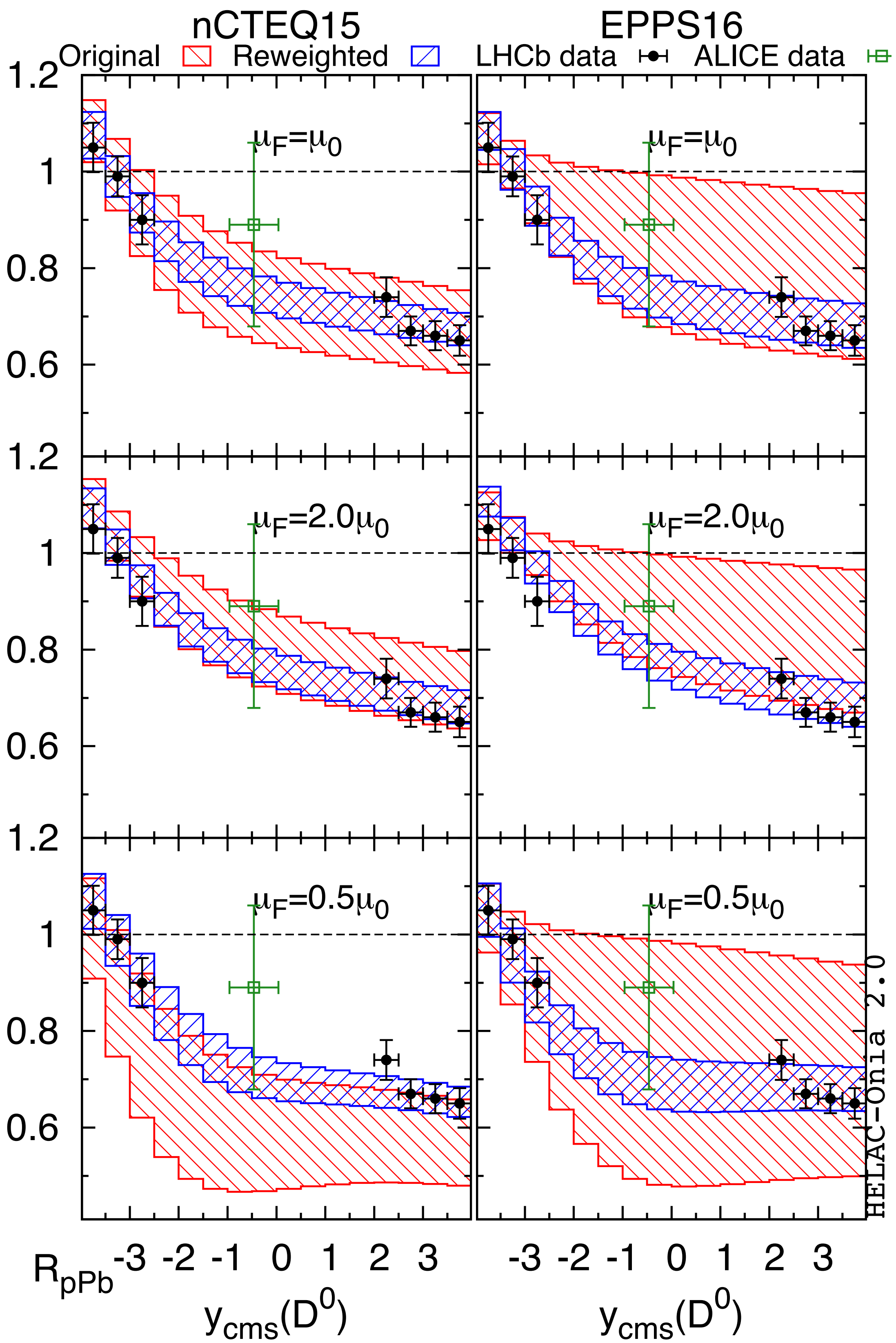
Heavy quark(onium) production and gluon shadowing

Impact of LHC heavy quark data on NPDFs

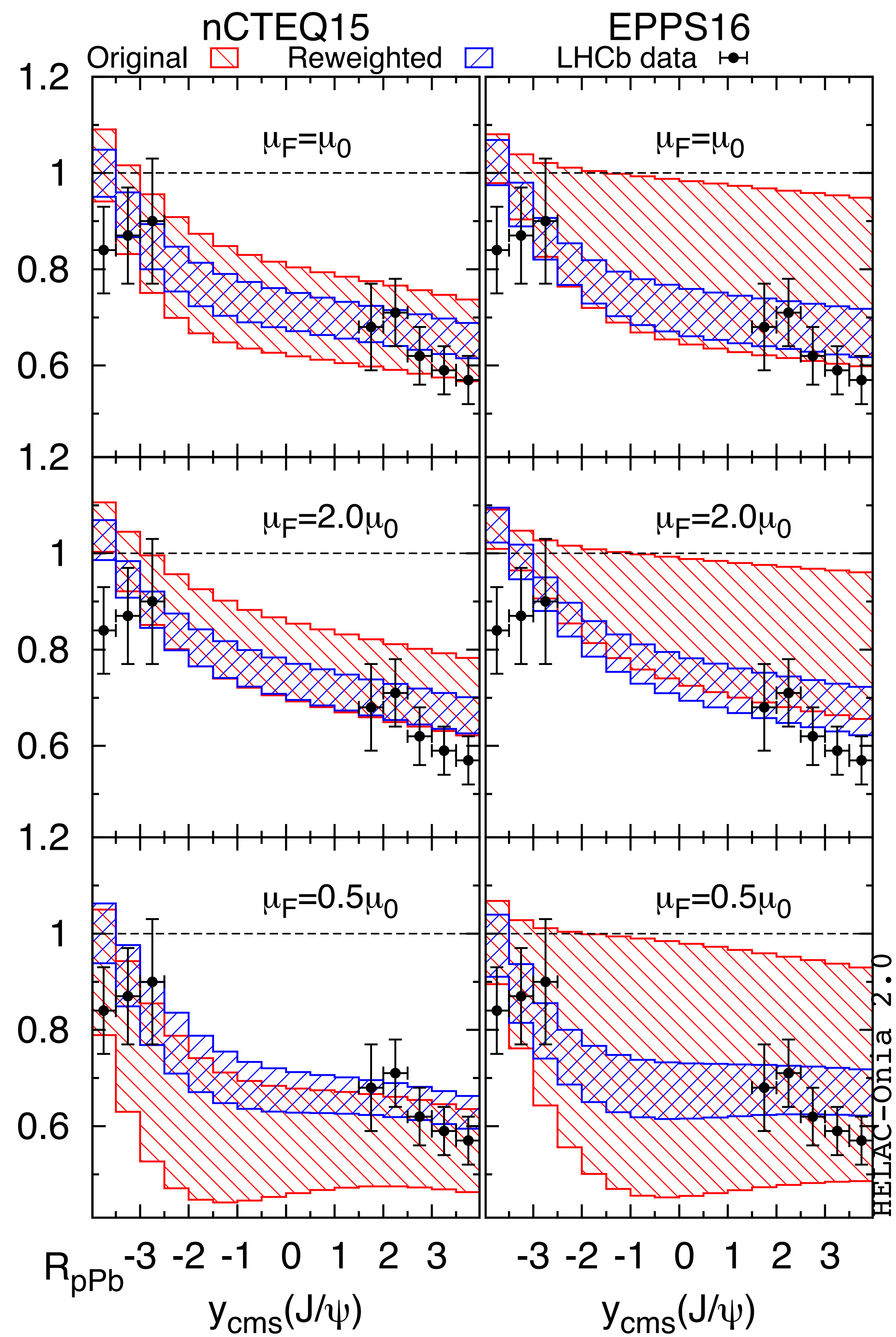
A. Kusina, J.P. Lansberg, IS, H.S. Shao, arXiv:1712.07024

- Use data for D^0, J/Ψ, $B \to J/\Psi$, $\Upsilon(1S)$ production in p-Pb collisions at LHC at 5.02 and 8.16 TeV
- Comparison with predictions from nCTEQ15 and EPPS16
- Perform reweighting analysis of nuclear effects
- Goal: constrain small-x gluon in lead (down to $x \sim 10^{-6}$)

Results for R_{pA} vs rapidity

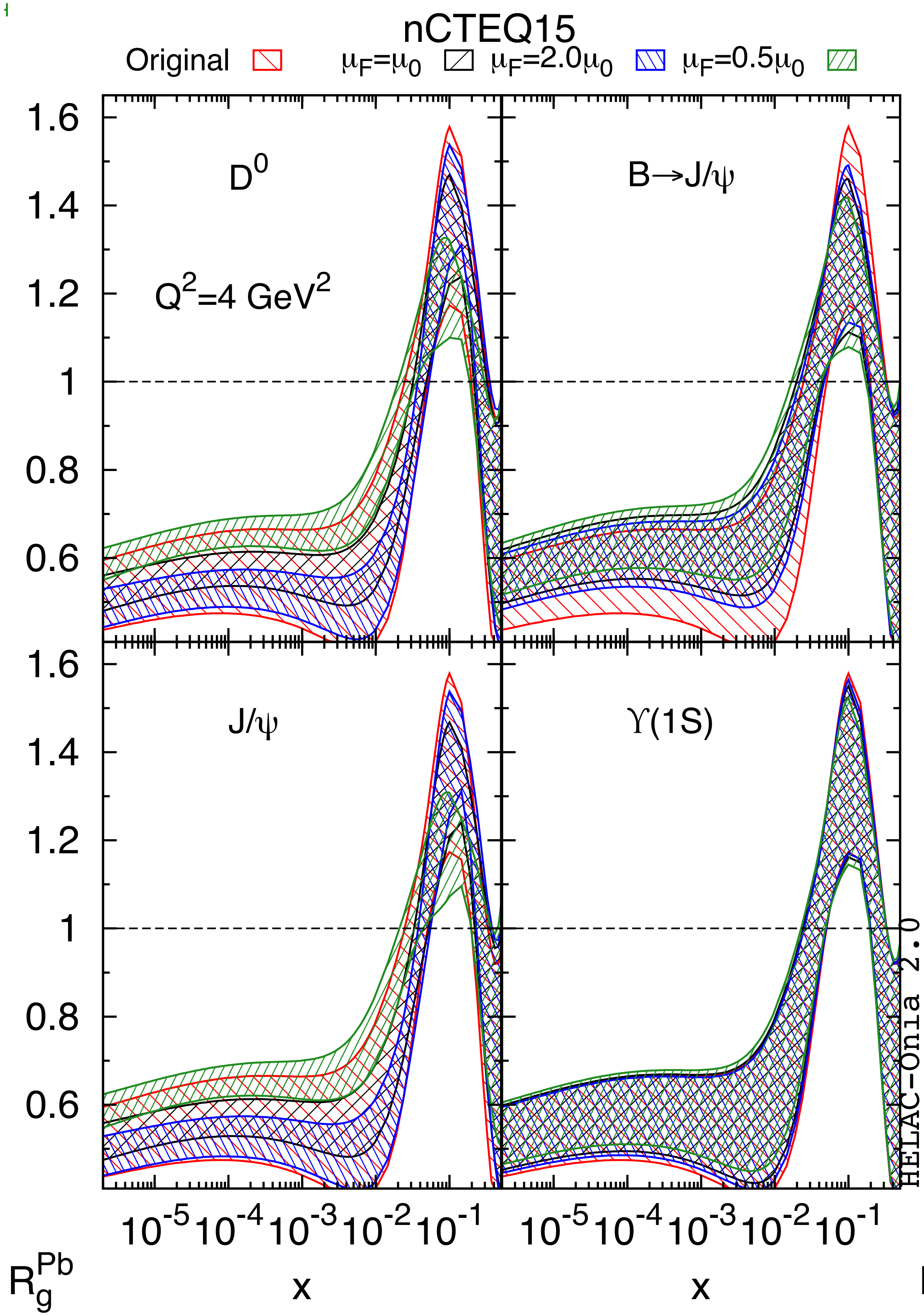


(a) Prompt D^0

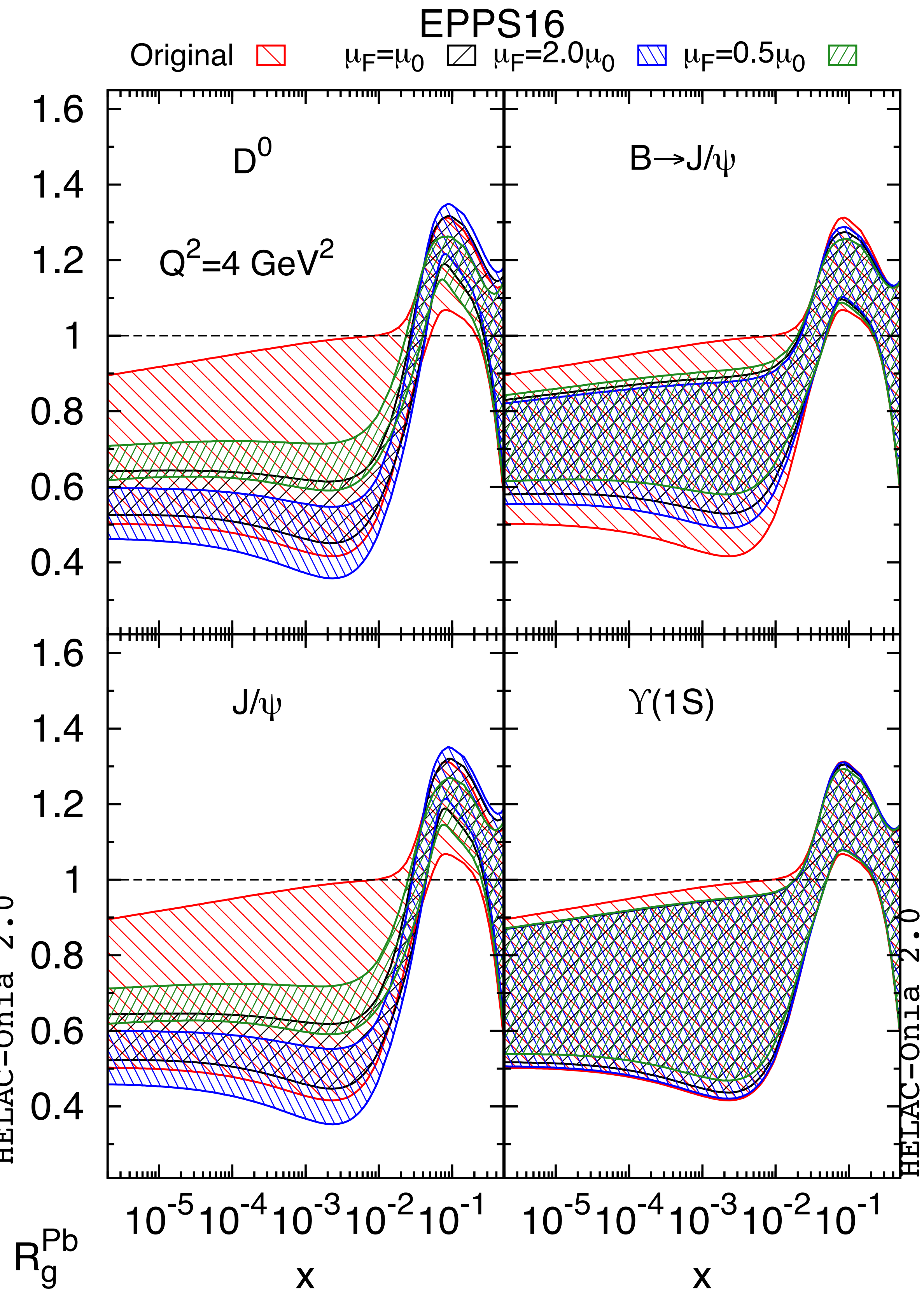


(b) Prompt J/ψ

R_g^{Pb} vs x



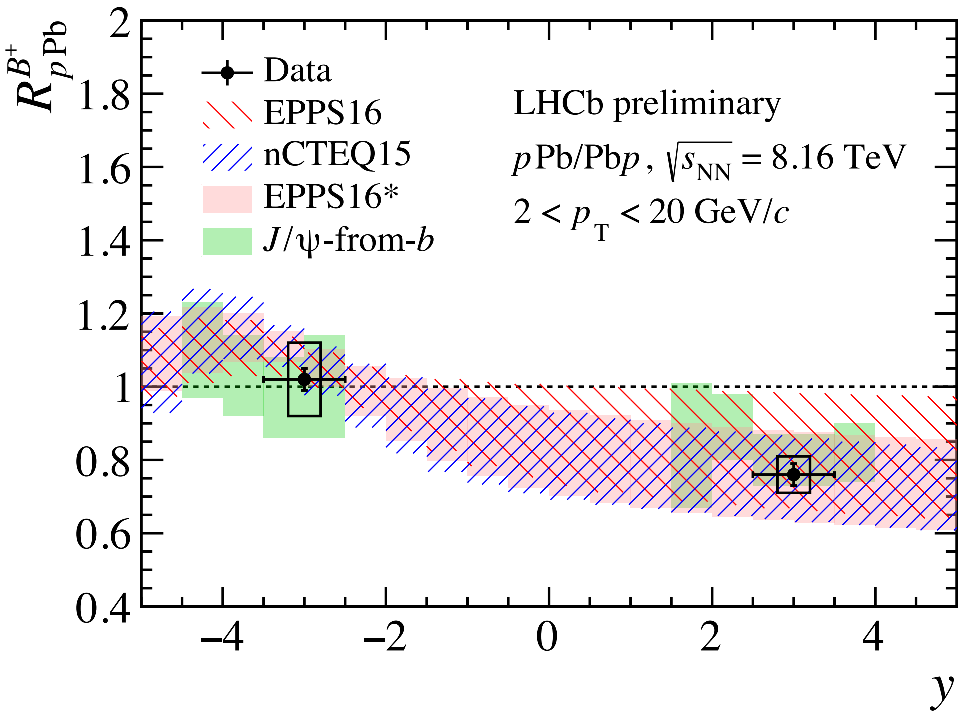
(e) nCTEQ15 nPDF

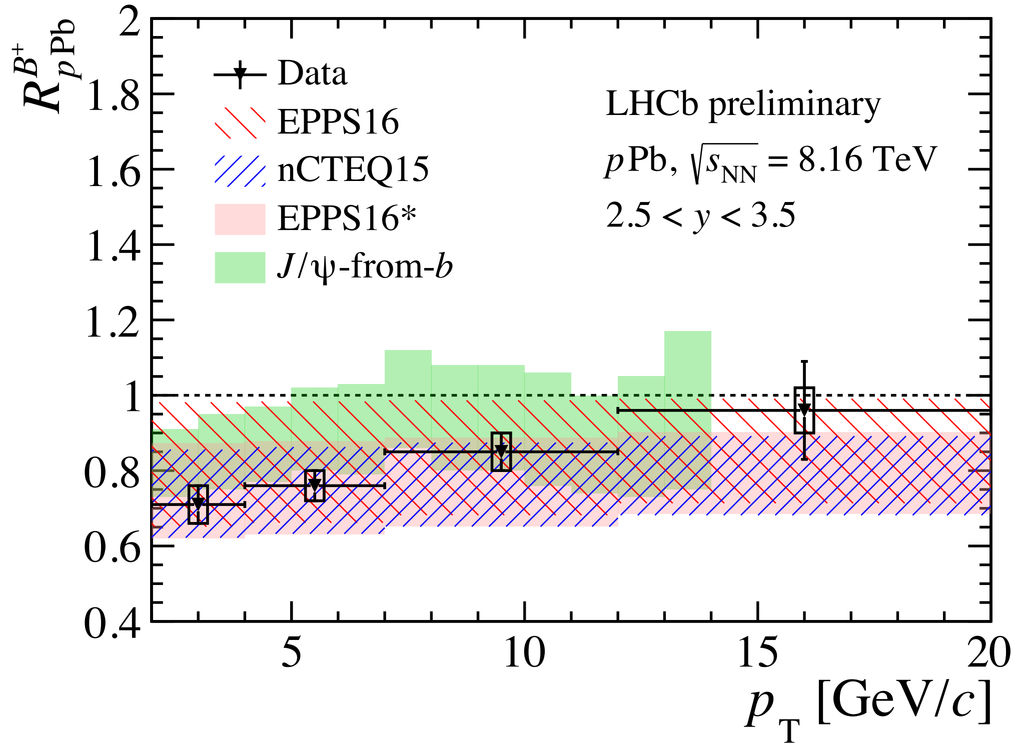


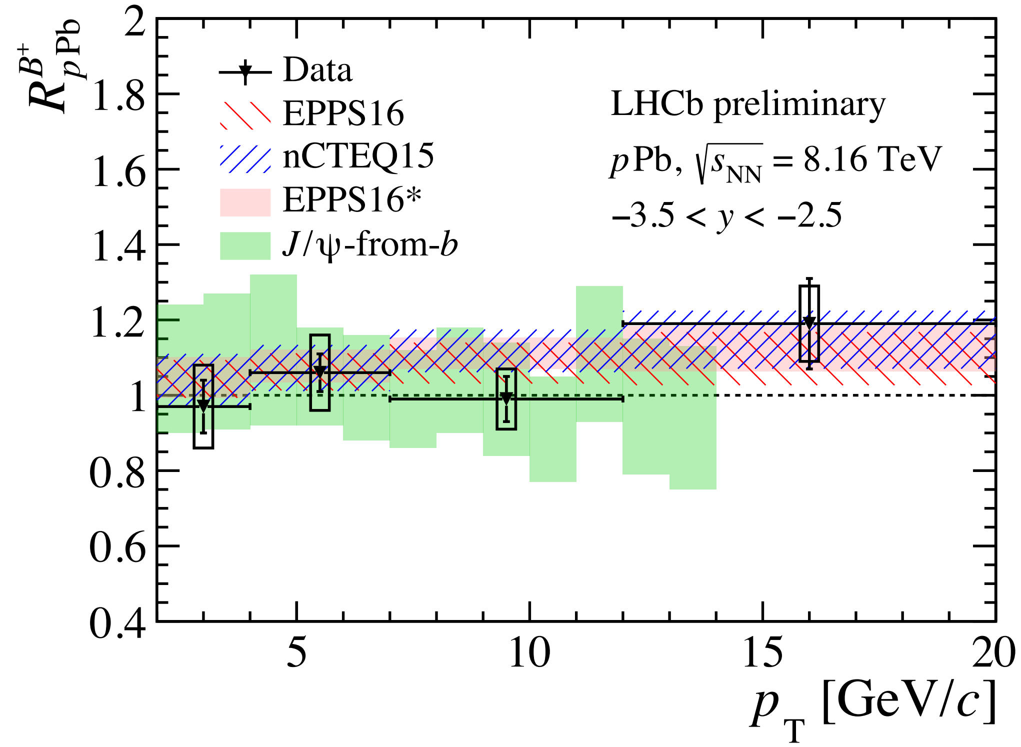
(f) EPPS16 nPDF

Agreement with new LHCb results

LHCb-CONF-2018-004







Conclusions

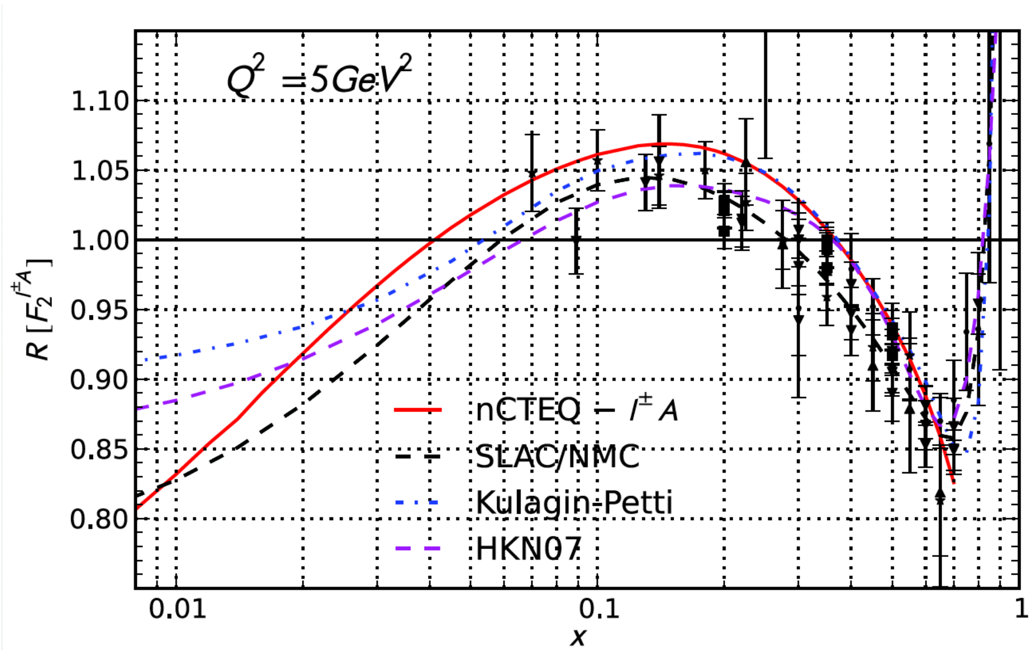
- Much recent progress (EPPS'16, NCTEQ'15, W/Z analysis)
- nPDF uncertainties still substantial
- Need more precise LHC pA data (LHC5, LHC8) from as many hard processes as possible! Lead-only analysis possible!
- Coloured and un-coloured final states to test shadowing vs energy loss effects
- Bright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

Backup slides

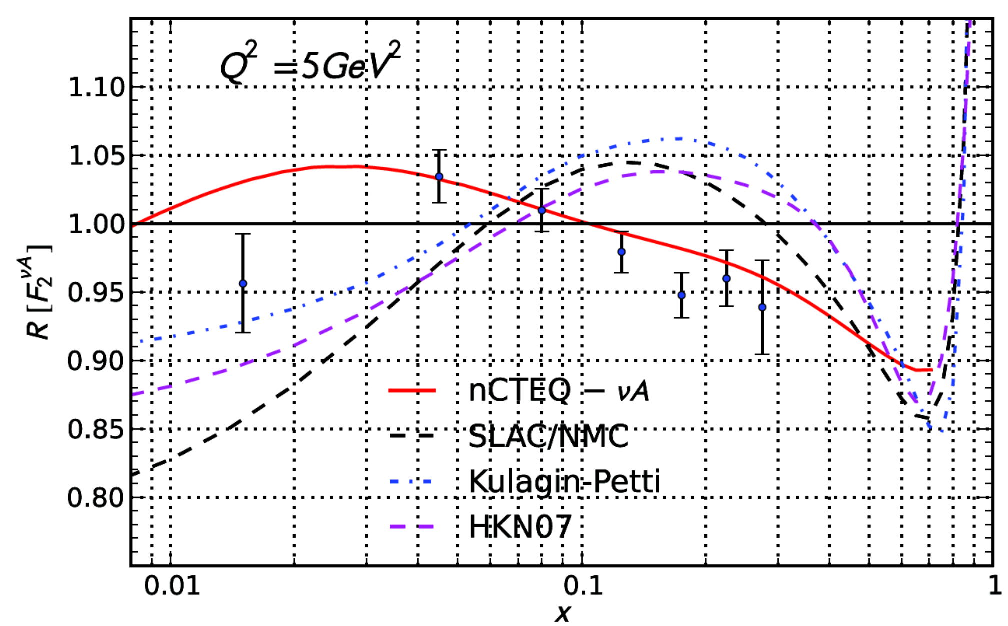
Nuclear modifications: l-A DIS vs nu-A DIS vs DY

nCTEQ, arXiv:1012.0285, arXiv:0907.2357

Fit to $l^{\pm}A$ DIS and DY data
$\chi^2/\text{dof} = 0.89$

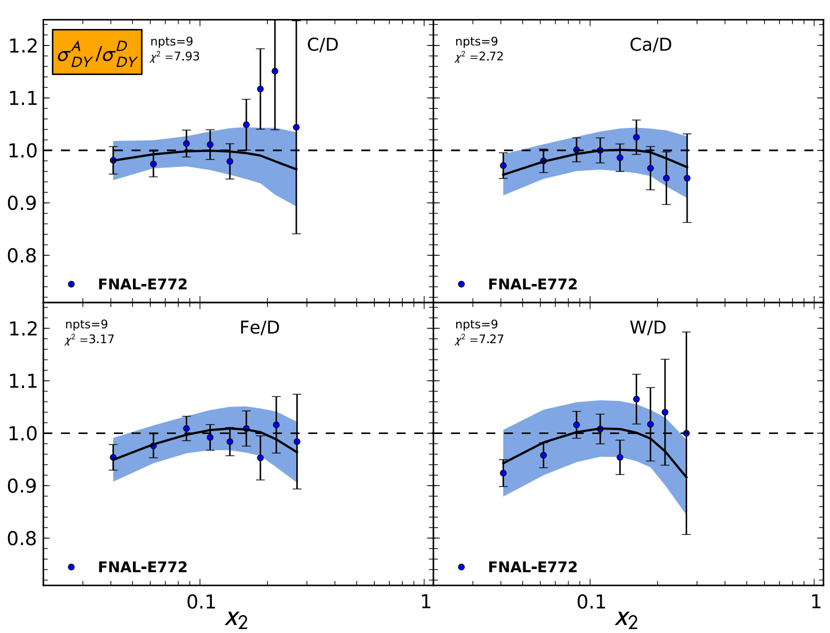


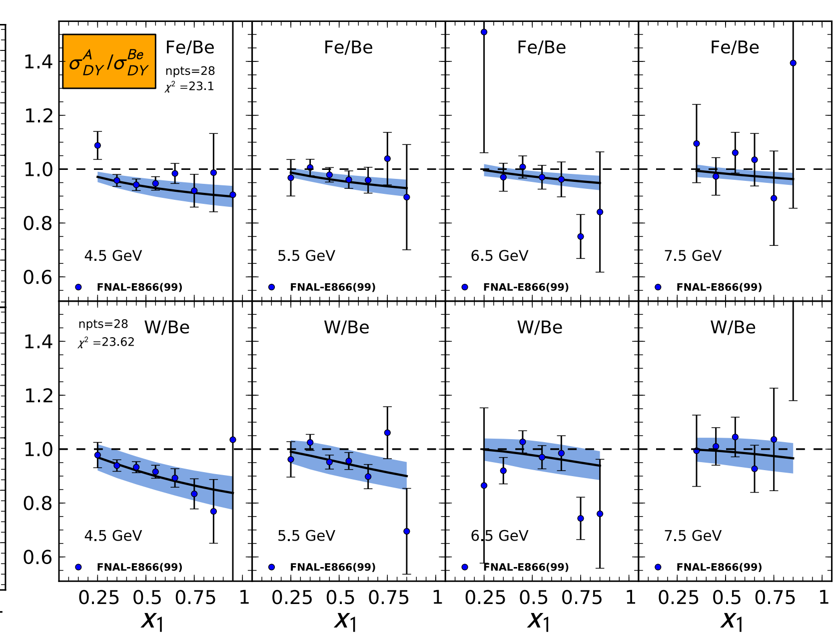
Fit to νA DIS data only
$\chi^2/\text{dof} = 1.33$



EMC effect in DY?
Less obvious

nCTEQ15, arXiv:1509.00792

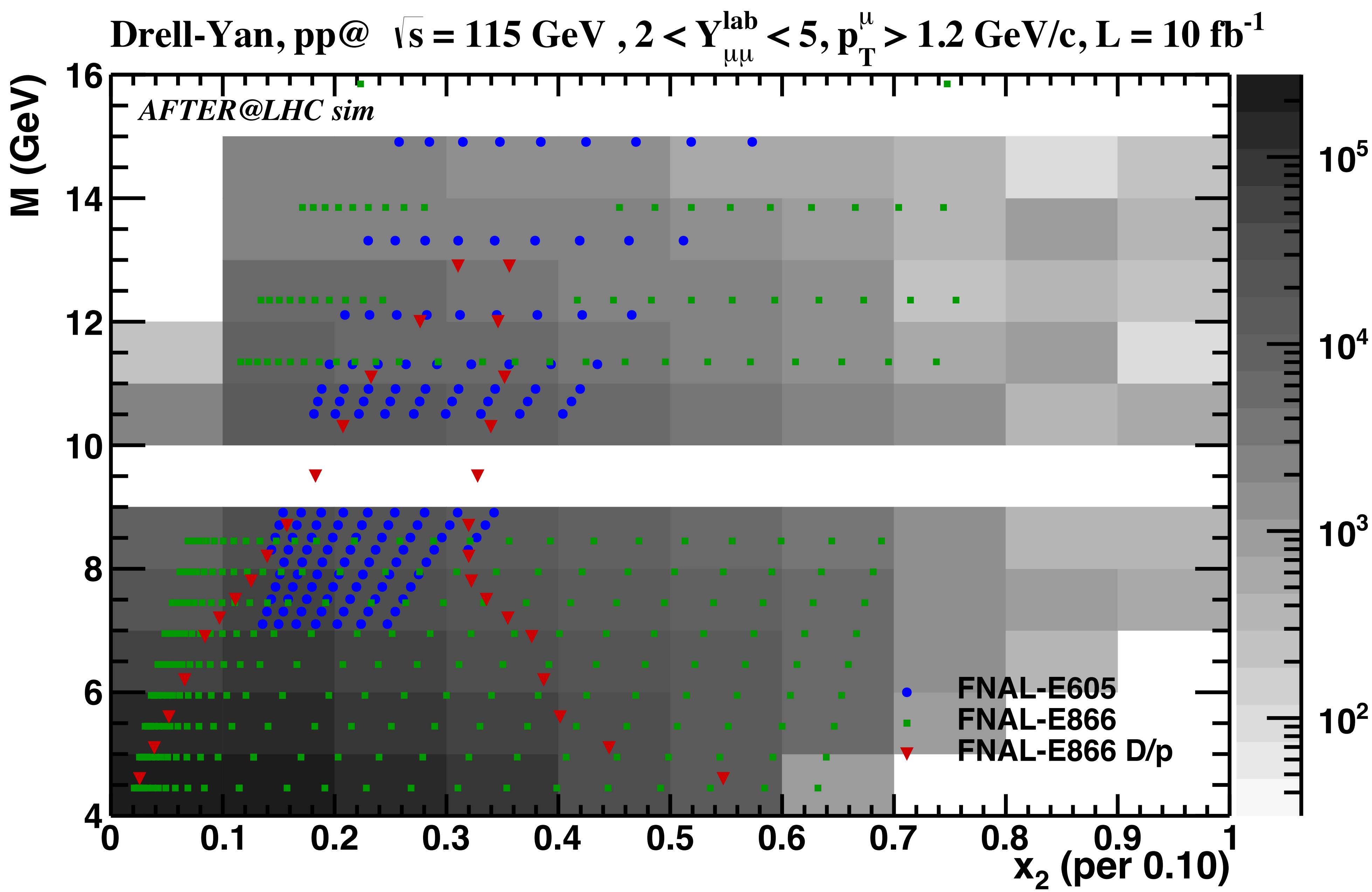




$\sigma^{pA}_{DY}/\sigma^{p}$… Observa…	χ^2
C/H2	7.92
Ca/H2	2.73
Fe/H2	3.17
W/H2	7.28
Fe/Be	23.09
W/Be	23.62
Total:	67.81

- Only 92 DY data points in global analysis
- Need more precise DY data at high-x. Important for flavor separation of EMC effect
- AFTER@LHC can greatly contribute with different targets

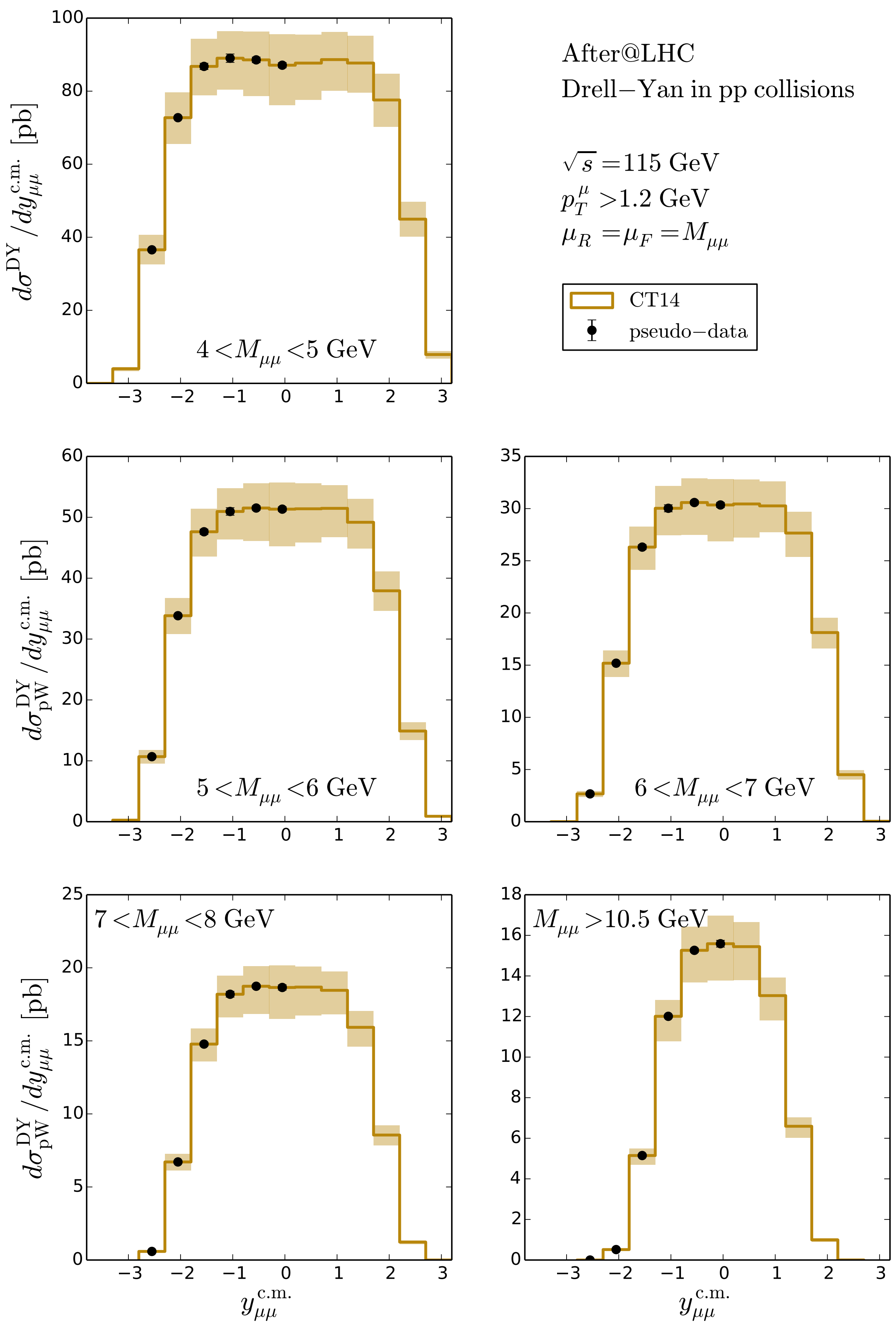
Kinematical plane of DY at AFTER



AFTER:

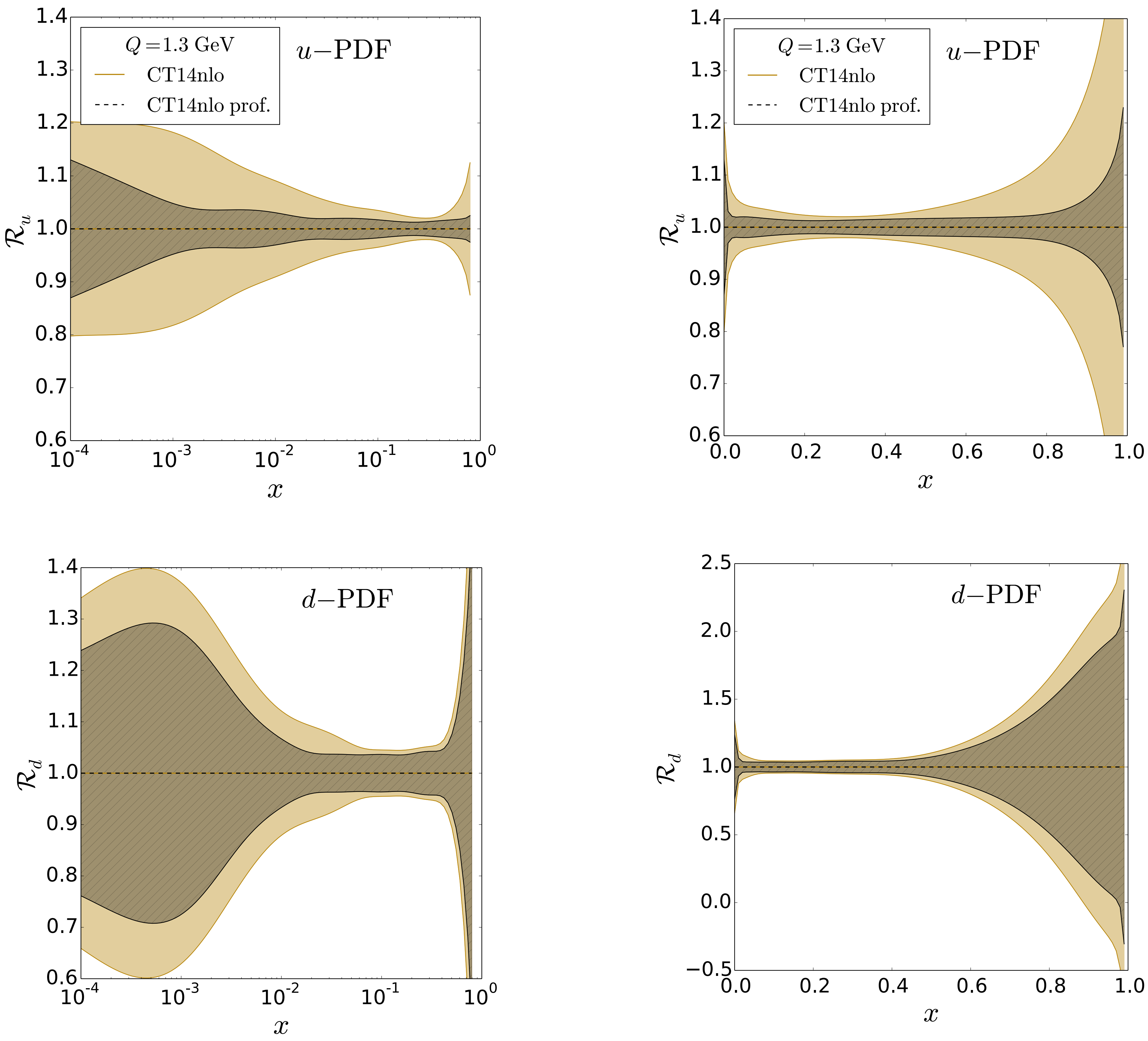
- Extend kinematic plane to very large x (and smaller x, M > 10 GeV)
- Much higher statistics in the region covered by NuSea (E866)
- Data points used in global analysis of NNPDF

DY pseudo data compared to NLO theory

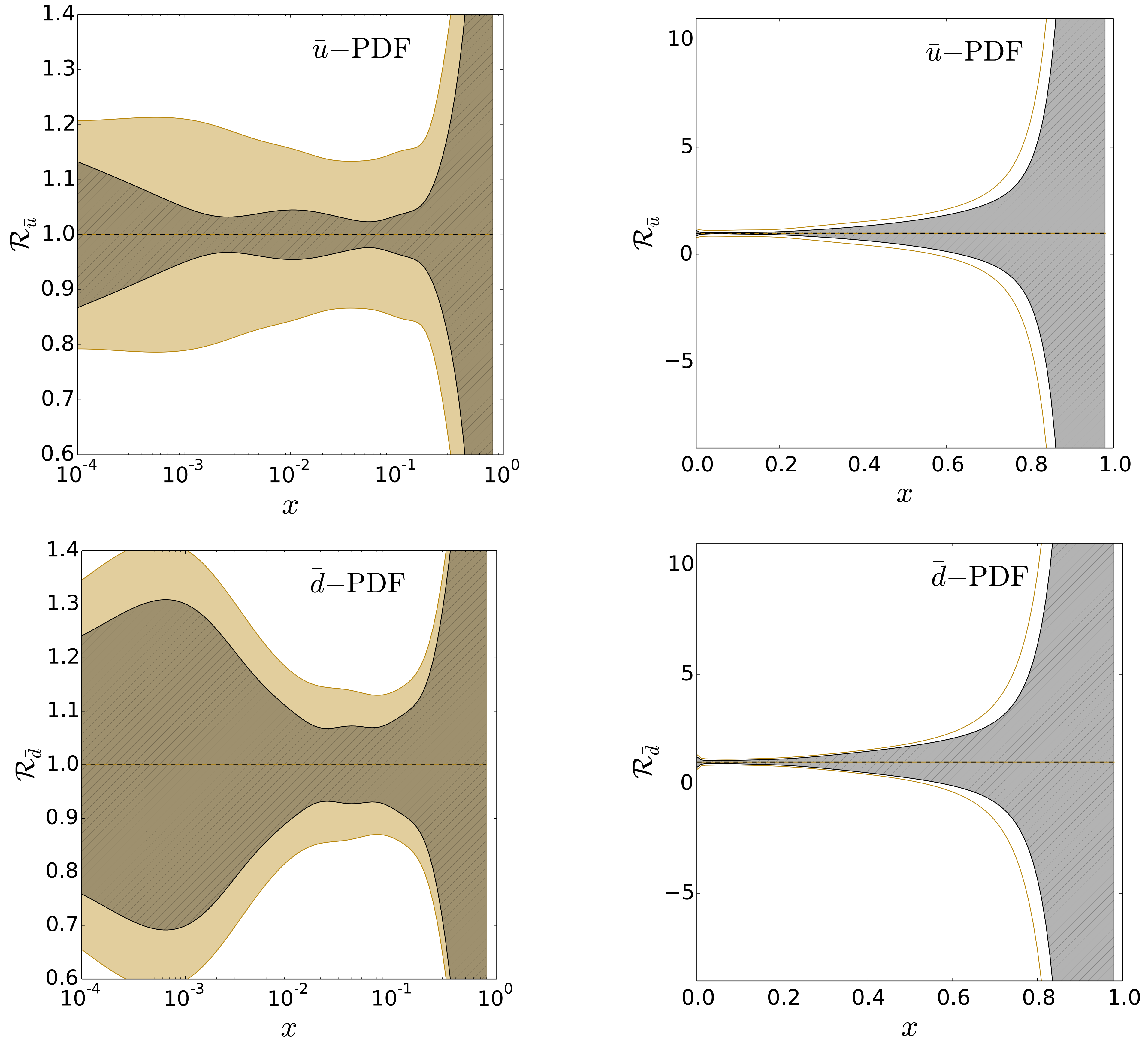


- Pseudo-data for the rapidity distributions using MCFM and projected experimental uncertainties
- Performed reweighting analysis using the XFitter package

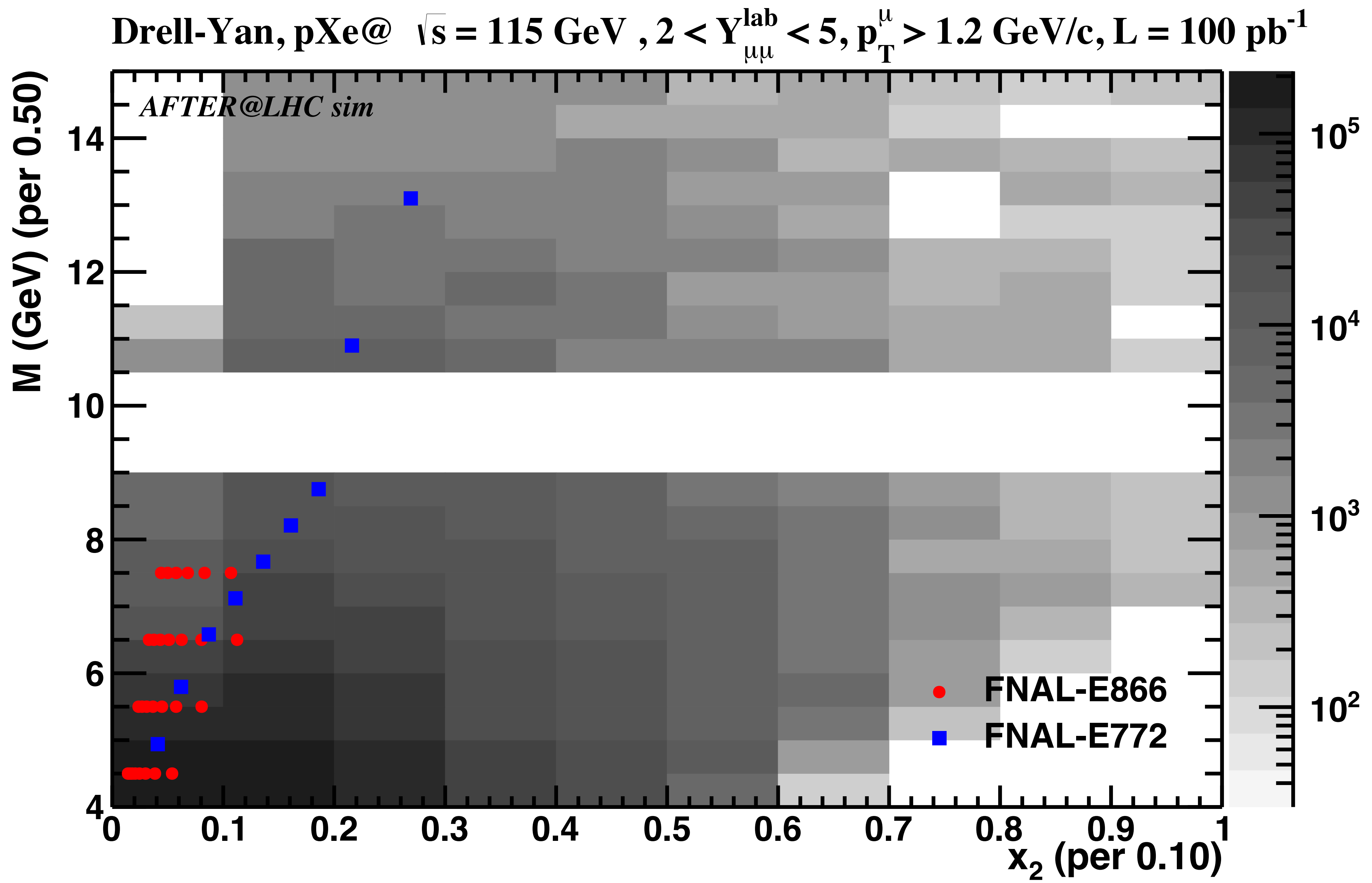
Impact of DY pseudo data on proton PDFs



Impact of DY pseudo data on proton PDFs



Kinematical plan of DY in p-Xe

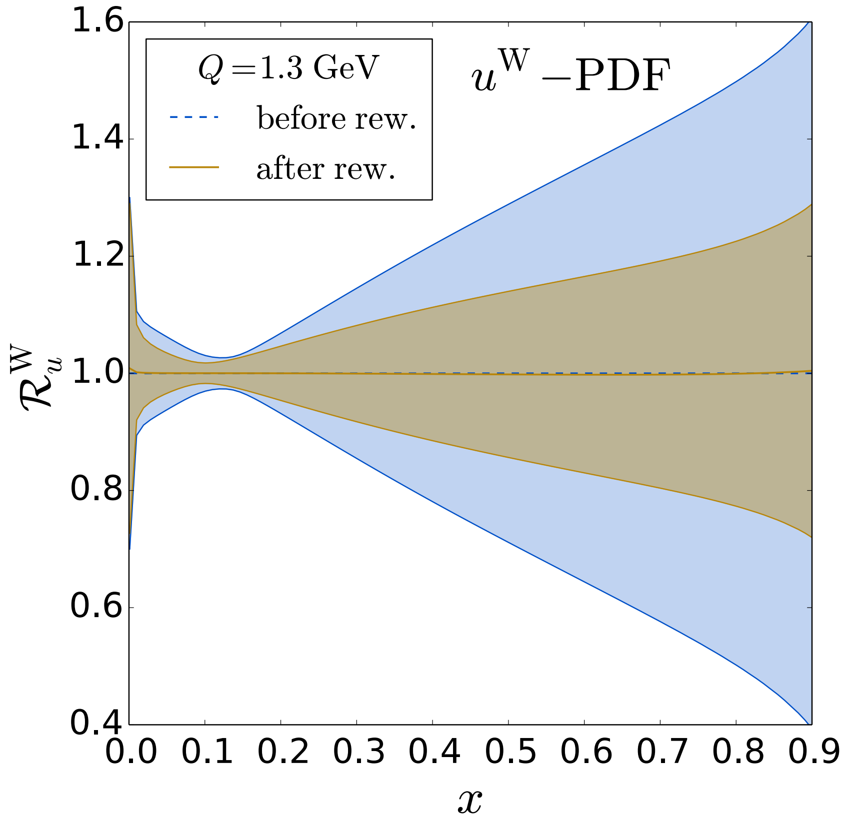


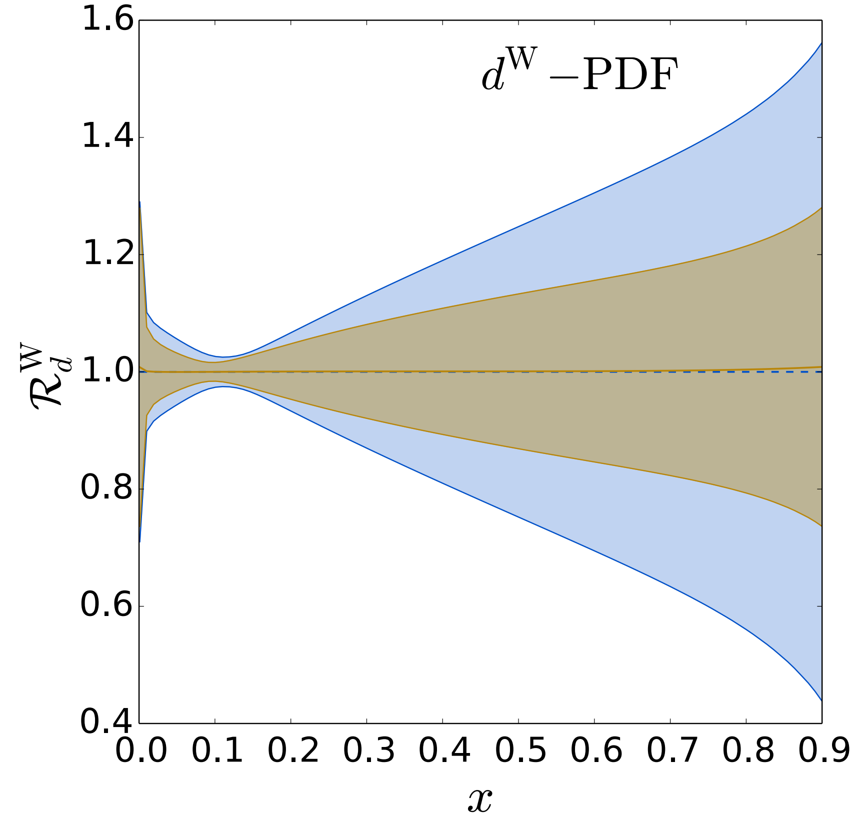
AFTER:

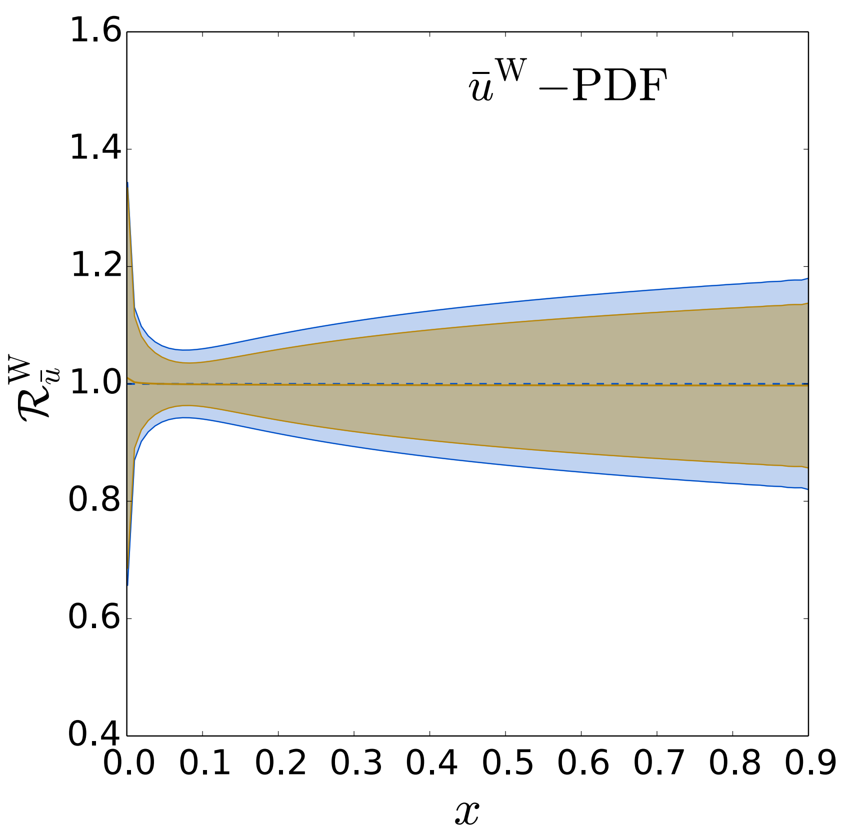
- Unique acceptance compared to existing DY pA data used in global analyses of nuclear PDFs (E866 & E772 @Fermilab)
- Extremly large yields up to $x_2 \rightarrow 1$ [plot made for p-Xe with a HERMES like target]

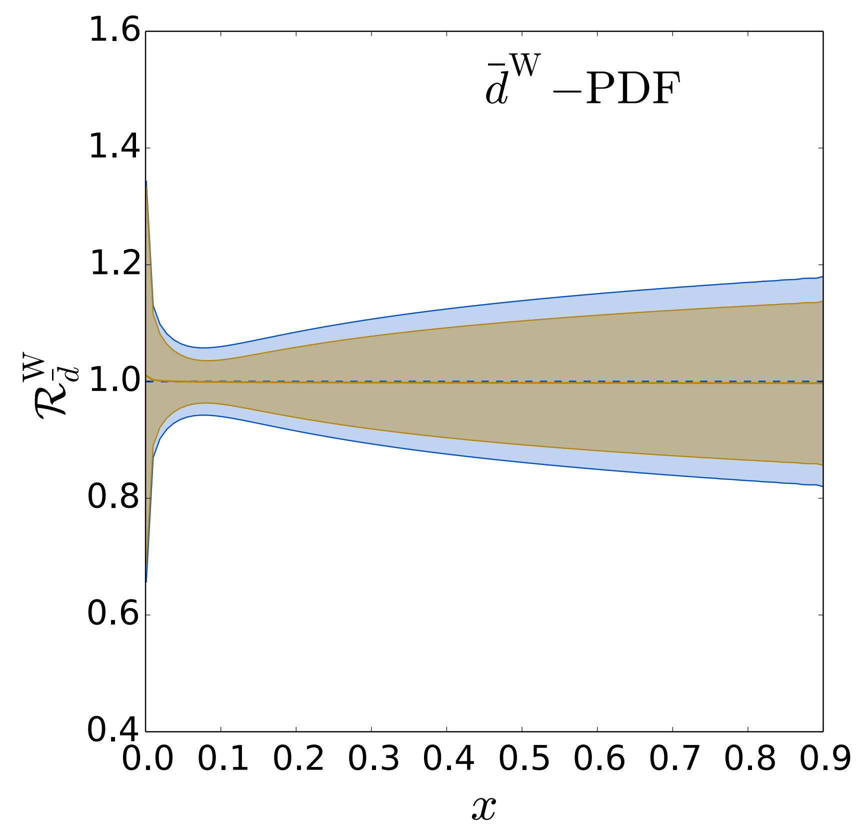
Impact of DY pA pseudo data on nCTEQ15 NPDFs

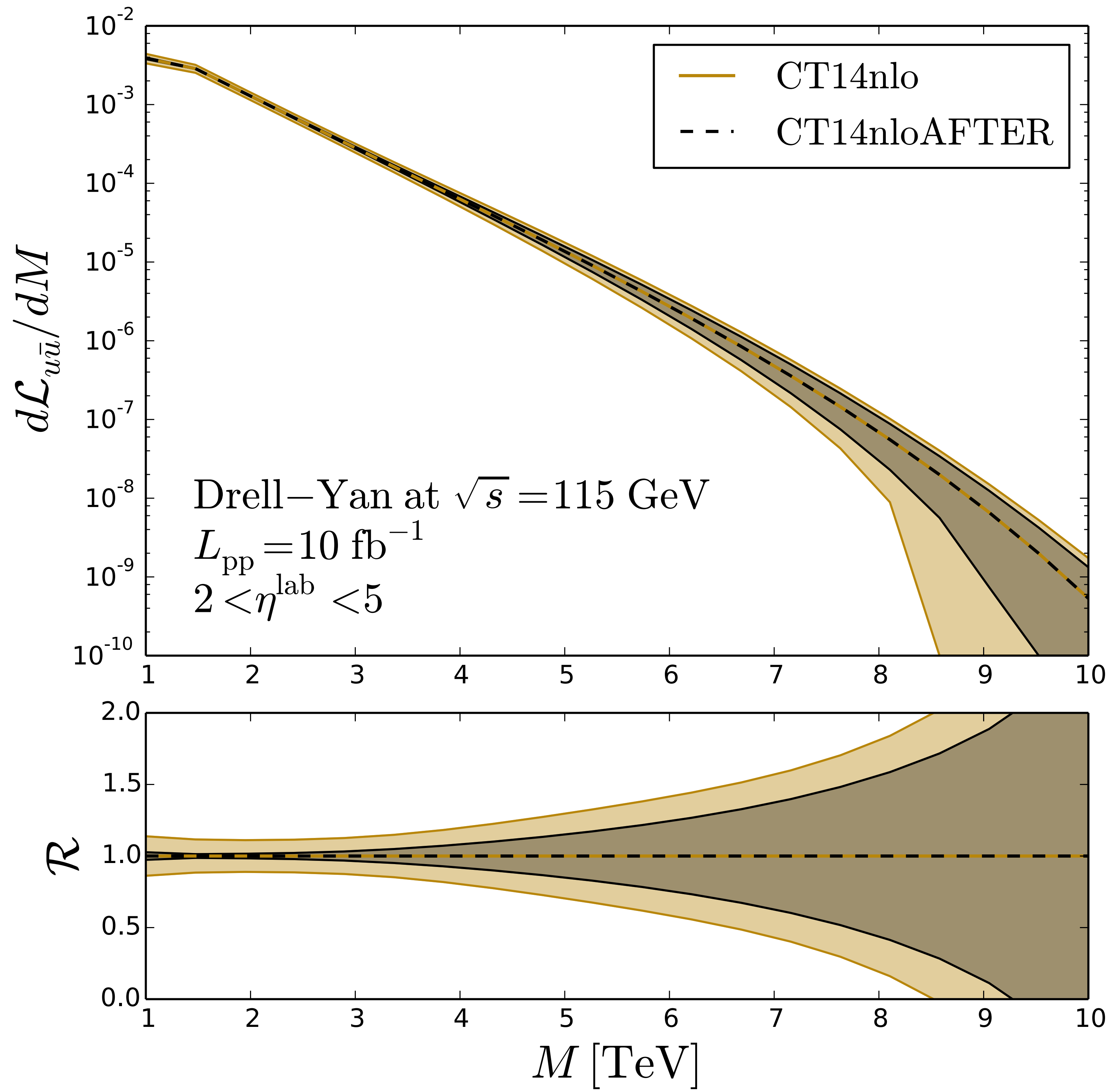
L=150/pb











CT14nlo
CT14nloAFTER
Drell−Yan at $\sqrt{s}$ =115 GeV
$L_{\rm pp}$ =10 fb^{-1}
2 < $\eta^{\rm lab}$ < 5
$d\mathcal{L}_{u\bar{u}}/dM$
$\mathcal{R}$
M [TeV]