Parton Distribution Functions in nuclei: status, recent work and future colliders

P. Zurita

Universität Regensburg

HRT

Outline

- PDFs
- PDFs in the nuclear medium
- Current sets of nPDFs
- Issues with nPDF extraction and improvement using existing data
- nPDFs @ future colliders
- Summary

PDFs

$$\sigma_r = F_2 - \frac{y^2}{1+(1-y)^2} F_L$$

$$F_2(x,Q^2) = \sum_{q,\bar{q}} q_i^2 f_i \otimes \left[C_{2,q}^{(0)} + \alpha_s C_{2,q}^{(1)} + \ldots \right] + \alpha_s g \otimes \left[C_{2,g}^{(1)} + \ldots \right]$$

$$F_L(x,Q^2) = \alpha_s \sum_{q,\bar{q}} q_i^2 f_i \otimes \left[C_{L,q}^{(1)} + \ldots \right] + \alpha_s g \otimes \left[C_{L,g}^{(1)} + \ldots \right]$$

- probability of looking at a proton with scale Q^2 and finding in it a parton *i* carrying a fraction *x* of its momentum
- can't be computed in pQCD
- they evolve by DGLAP evolution equations
- universal

PDFs in the nuclear medium

Phys. Rev. Lett. 51 (1983) 534

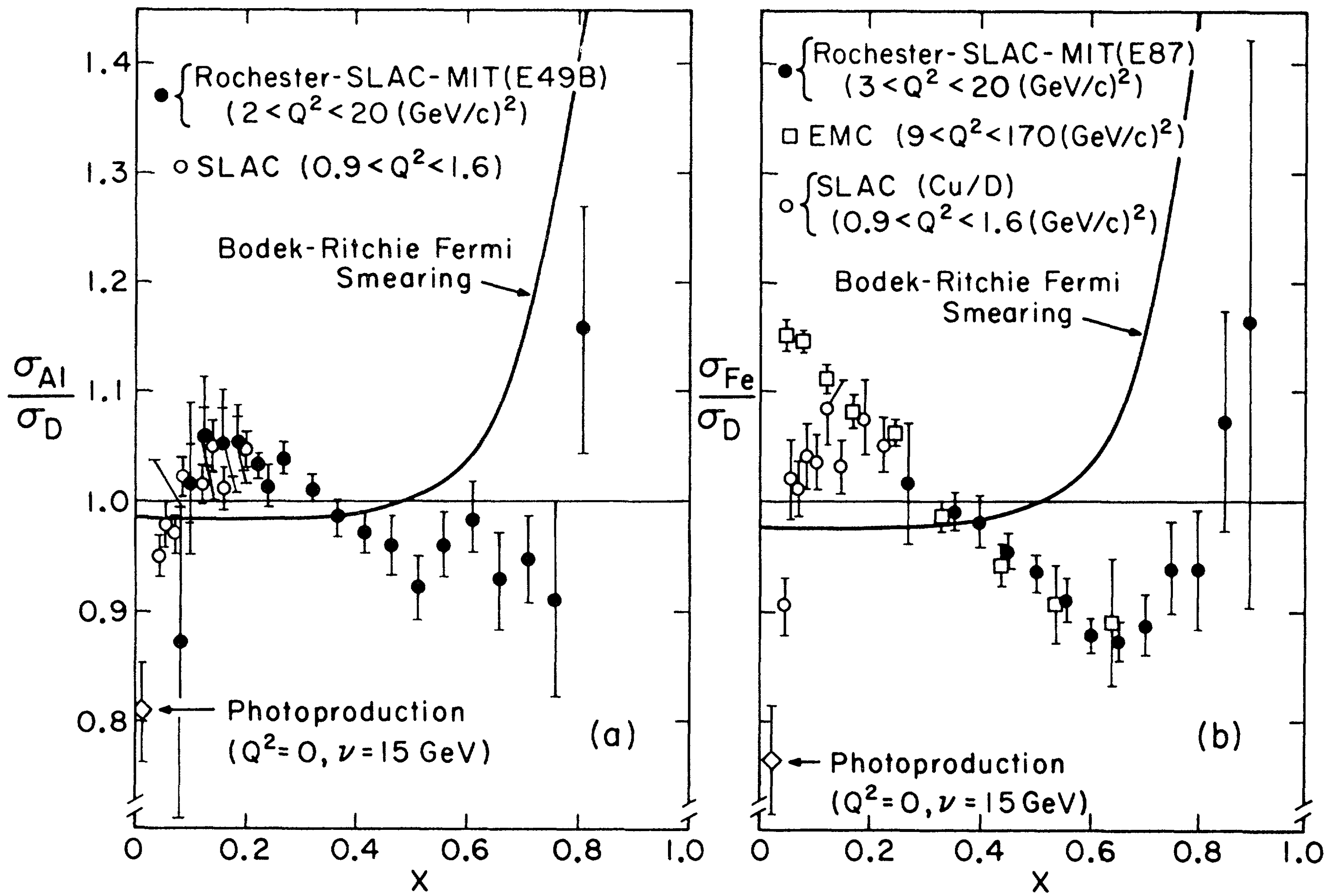

FIG. 1. (a) σ_{Al}/σ_D and (b) σ_{Fe}/σ_D vs x. Only random errors are shown. Point-to-point systematic errors have been added linearly (outer bars) where applicable. The normalization errors of $\pm 2.3\%$ and $\pm 1.1\%$ for σ_{Al}/σ_D (E49B) and σ_{Fe}/σ_D (E87), respectively, are not included. All data for $W \geq 1.8$ GeV are included. The data have been corrected for the small neutron excess and have *not* been corrected for Fermi-motion effects. The curve indicates the expected ratio if Fermi-motion effects were the only effects present (Ref. 11). High-Q^2 σ_{Fe}/σ_D data from EMC (Ref. 2), low-Q^2 σ_{Al}/σ_D and σ_{Cu}/σ_D data from Ref. 9, and photoproduction σ_{Al}/σ_D and σ_{Fe}/σ_D data from Ref. 13 are shown for comparison. The systematic error in the EMC data is $\pm 1.5\%$ at $x = 0.35$ and increases to $\pm 6\%$ for the points at $x = 0.05$ and $x = 0.65$.

- Despite the big uncertainties, it is clear from the data that something happens in the nuclear medium
- One can describe this in many different ways:

  theoretical models — S. A. Kulagin and R. Petti, Nucl. Phys. A 765 (2006), 126

  modify the evolution equations — H.T. Li, Z.L. Liu and I. Vitev, arXiv:2007.10994 [hep-ph]

  modify the PDFs

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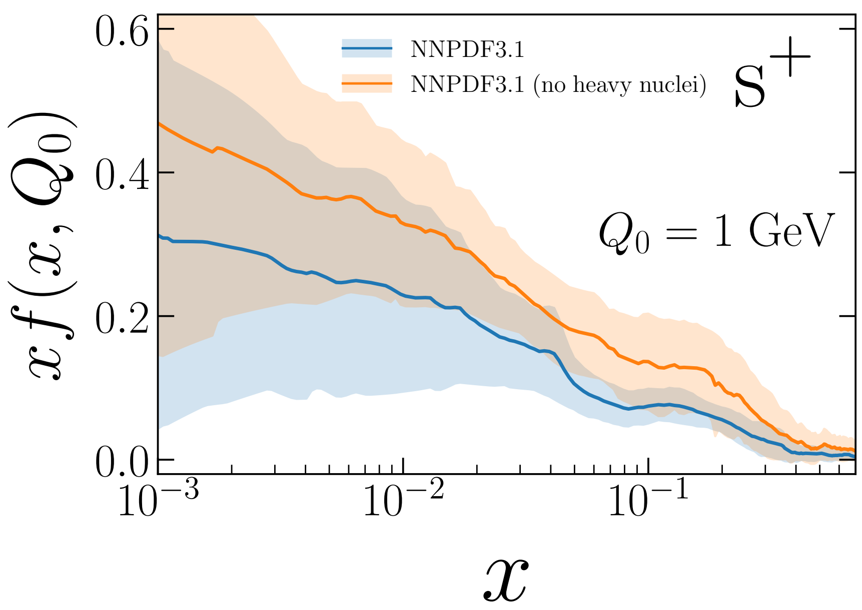
  - **modify the PDFs**

nPDFs: **one** way (among **many**) of describing how the partons behave in a nucleon bounded in a nucleus

Why do we need nPDFs?



- interesting on their own right
- for flavour separation of proton PDFs (until we get a neutron star)
- initial state of HI collisions, cold nuclear matter effects

How do we obtain them?

- through global fits to the world data
- assuming factorisation holds
- assuming DGLAP without any modification
- assuming isospin symmetry

Current sets of nPDFs

- LO, NLO, NNLO
- NC DIS + (if applies)
    - CC DIS
    - Drell-Yan
    - Electroweak bosons
    - Single Hadron production
    - Dijets
- ZM-VFNS, GM-VFNS
- Strategies:
    - Multiplicative factors
    - Convolutional factors
    - Extended parametrisation (from proton baseline)
    - Neural Networks
- ~ 20 parameters each fit (nNNPDF ~ 200 parameters)

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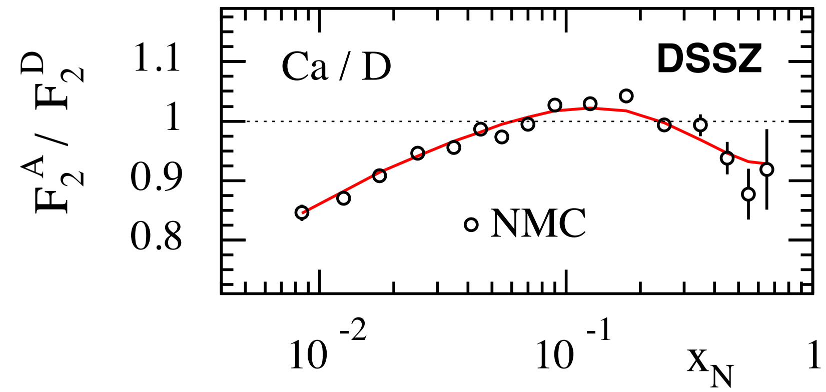

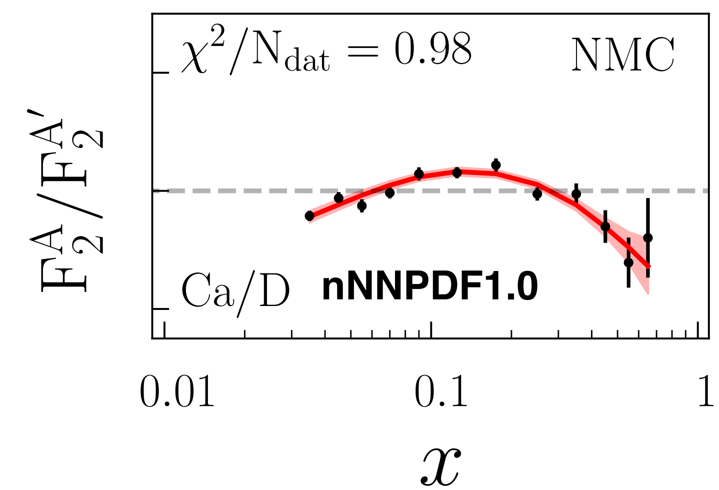

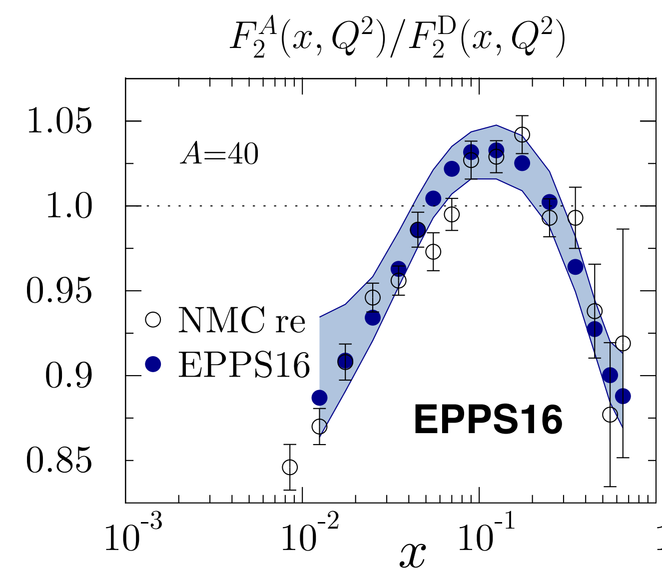

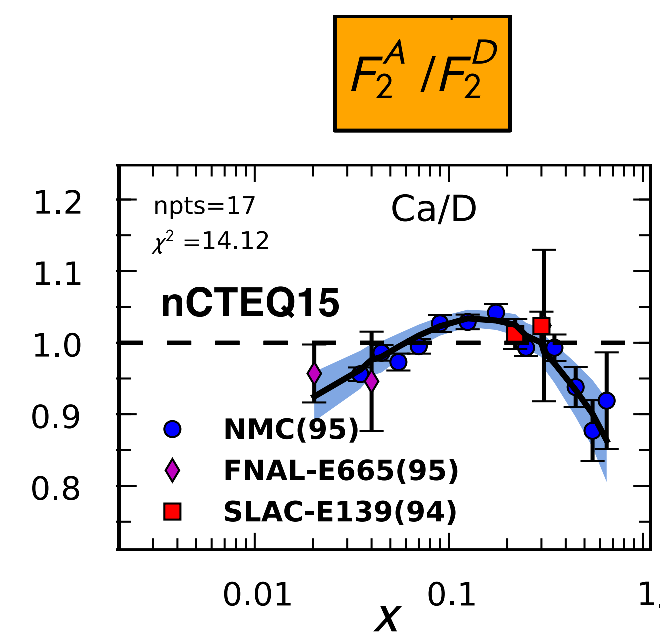

- **EKS:** K.J. Eskola, V.J. Kolhinen, C.A. Salgado, Eur. Phys. J. C9 (1999) 61. **FIRST EVER**
- **HKM:** M. Hirai, S. Kumano, M. Miyama, Phys. Rev. D64 (2001) 034003.
- **nDS:** D. de Florian, R. Sassot, Phys. Rev. D69 (2004) 074028. **FIRST NLO**
- **HKN07:** M. Hirai, S. Kumano, T.-H. Nagai, Phys. Rev. C76 (2007) 065207. **FIRST WITH THEORETICAL UNCERTAINTIES**
- **EPS09:** K.J. Eskola, H. Paukkunen, C.A. Salgado, JHEP 0904 (2009) 065.
- **DSSZ:** D. de Florian, R. Sassot, M. Stratmann, PZ, Phys. Rev. D85 (2012), 074028. **FIRST WITH CC AND nFFs**
- **nCTEQ15:** K. Kovarik, A. Kusina, T. Jezo, D. B. Clark, C. Keppel, F. Lyonnet, J. G. Morfin, F. I. Olness, J. F. Owens, I. Schienbein and J. Y. Yu, Phys. Rev. D93 (2016) no.8, 085037.
- **KA15:** H. Khanpour, S.A. Tehrani, Phys.Rev. D93 (2016) no.1, 014026. **FIRST NNLO**
- **EPPS16:** K. J. Eskola, P. Paakkinen, H. Paukkunen, C. A. Salgado, Eur. Phys. J. C77 (2017) no.3, 163. **FIRST WITH LHC DATA**
- **nNNPDF1.0:** R. A. Khalek, J. J. Ethier, J. Rojo, Eur. Phys. J. C79 (2019) no.6, 471. **FIRST WITH NEURAL NETWORKS**
- **nTuJu:** M. Walt, I. Helenius, W. Vogelsang, Phys. Rev. D100 (2019) no.9, 096015. **FIRST OPEN SOURCE**
- **nNNPDF2.0:** R. A. Khalek, J. J. Ethier, J. Rojo, G. van Weelden, arXiv: 2006.14629 [hep-ph].
- **nCTEQ15WZ:** A. Kusina, T. Ježo, D. B. Clark, P. Duwentäster, E. Godat, T. J. Hobbs, J. Kent, M. Klasen, K. Kovařík, F. Lyonnet, K. F. Muzakka, F. I. Olness, I. Schienbein and J. Y. Yu, arXiv:2007.09100 [hep-ph].

LO

$$F_2^A(x,Q^2) = \frac{Z}{A}\left[\frac{4}{9}(u+\bar{u}) + \frac{1}{9}(d+\bar{d}+s+\bar{s})\right] + \frac{(A-Z)}{A}\left[\frac{4}{9}(d+\bar{d}) + \frac{1}{9}(u+\bar{u}+s+\bar{s})\right]$$

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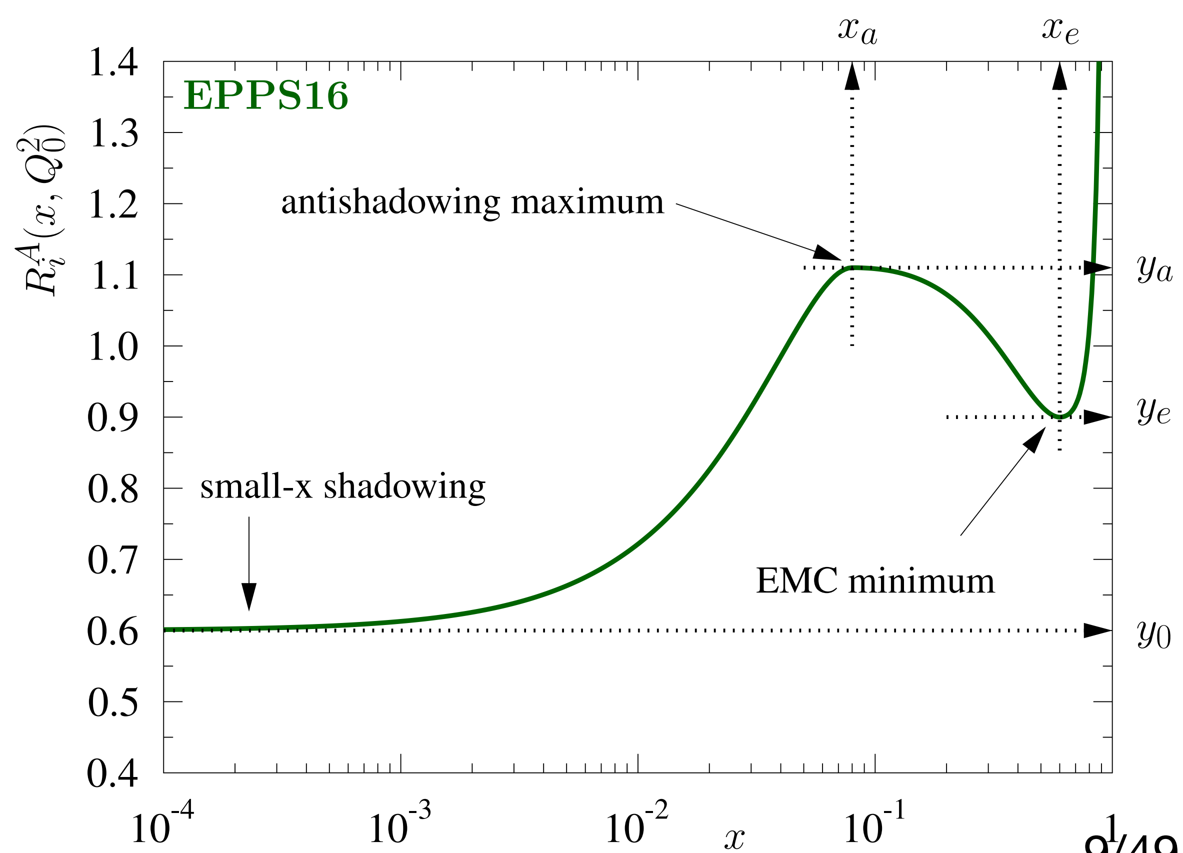
EKS98/EKS98r, EPS09

$$f_i^{p/A}(x,Q_0^2) = R_i(x,A) f_i^p(x,Q_0^2)$$

R_v, R_s, R_g

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

$$y_i(A) = y_i(A_{ref})\left(\frac{A}{A_{ref}}\right)^{\gamma_i[y_i(A_{ref})-1]}$$



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EKS98/EKS98r, EPS09: multiplicative factor

HKM, HKN07 $$w_i(x,A,Z) = 1 + \left(1 - \frac{1}{A^{1/3}}\right)\frac{a_i(A,Z) + b_i x + c_i x^2 + d_i x^3}{(1-x)^{\beta_i}}$$

relaxed in HKN

First attempt at flavour separation W_{uv}, W_{dv}, W_s, W_g

LO

$$F_2^A(x,Q^2) = \frac{Z}{A}\left[\frac{4}{9}(u+\bar{u}) + \frac{1}{9}(d+\bar{d}+s+\bar{s})\right] + \frac{(A-Z)}{A}\left[\frac{4}{9}(d+\bar{d}) + \frac{1}{9}(u+\bar{u}+s+\bar{s})\right]$$

EKS98/EKS98r, EPS09: multiplicative factor

HKM, HKN07: multiplicative factor

nDS

$$f_i^{p/A}(x_N, Q_0^2) = f_i^{p/A}(Ax_A, Q_0^2) = \int_{x_N}^{A} \frac{dy}{y} W_i(y,A,Z) f_i\left(\frac{x_N}{y}, Q_0^2\right)$$

$$W_v(y,A,Z) = A[a_v\delta(1-\epsilon_v - y) + (1-a_v)\delta(1-\epsilon_v^{'} - y)] + n_v\left(\frac{y}{A}\right)^{\alpha_v}\left(1-\frac{y}{A}\right)^{\beta_v} + n_s\left(\frac{y}{A}\right)^{\alpha_s}\left(1-\frac{y}{A}\right)^{\beta_s}$$

$$W_i(y,A,Z) = A\delta(1-y) + \frac{a_i}{N_i}\left(\frac{y}{A}\right)^{\alpha_i}\left(1-\frac{y}{A}\right)^{\beta_i}$$

i=sea, gluon

LO

SET		EKS/EKS98r	EPS09	HKM	HKN07	nDS
data type	NC DIS	🙂	🙂	🙂	🙂	🙂
	D-Y	🙂	🙂		🙂	🙂
	pions		🙂			
# data points		-	929	309	1241	420
χ^2		-	738.6	583.7, 546.6	1653.3	316.35
Q_0^2 (GeV^2)		2.25	1.69	1	1	0.4
deuteron				🙂		
flavour separation?				🙂 valence	🙂 valence	

It's important to notice that, as the initial scales are not the same, when comparing (n)PDFs, what is a "pure parametrisation" for one set is not necessarily for another one

The nPDFs can be given as

- ratio of flavour ***i*** in **proton** in nucleus ***A*** to a proton reference
- ratio of flavour ***i*** in nucleus ***A*** to a proton reference

- distribution of flavour ***i*** in **proton** in nucleus ***A***
- distribution of flavour ***i*** in nucleus ***A***

I'll do my best to be clear in the upcoming plots, but feel free to ask if in doubt

The nPDFs can be given as

- ratio of flavour *i* in **proton** in nucleus ***A*** to a proton reference
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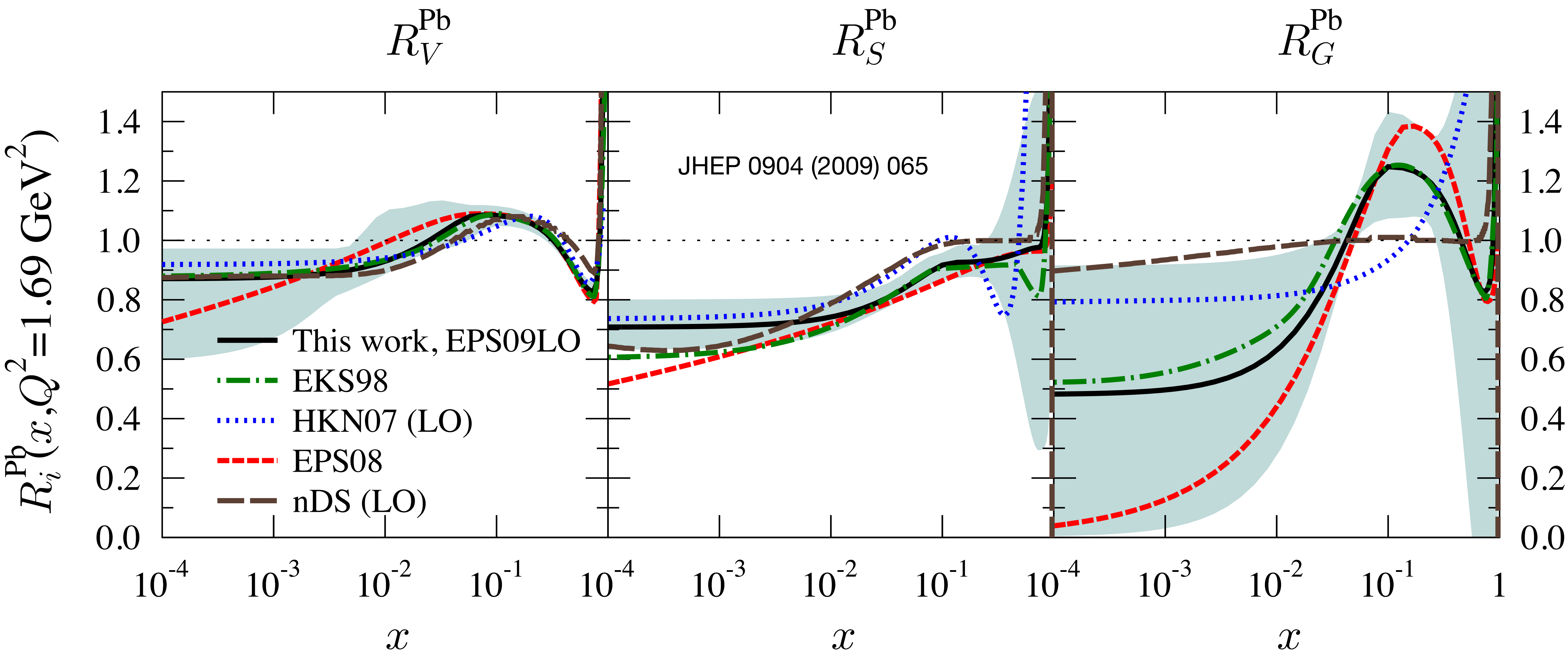

NLO

nDS, HKN07, EPS09: as for LO

EPPS16: like EPS09, with more freedom R_{uv}, R_{dv}, R_{ubar}, R_{dbar}, R_s, R_g

DSSZ: multiplicative factor, not piecewise R_v, R_s, R_g

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DSSZ: multiplicative factor, not piecewise R_v, R_s, R_g

nCTEQ15, nCTEQ15wz:

$$xf_{i/p}(x, Q_0^2) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4 x})^{c_5}$$

$$xf_{i/p} \to xf_{i/A} \quad \textbf{by} \quad c_k \to c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}})$$

$$i = g,\ u_v,\ d_v,\ \bar{u}+\bar{d},\ \bar{d}/\bar{u} \qquad s = \bar{s} = \frac{\kappa}{2}(\bar{u}+\bar{d})$$

relaxed in nCTEQ15wz

NLO

nDS, HKN07, EPS09: as for LO
EPPS16: like EPS09, with more freedom R_{uv}, R_{dv}, R_{ubar}, R_{dbar}, R_s, R_g
DSSZ: multiplicative factor, not piecewise R_v, R_s, R_g

nCTEQ15, nCTEQ15wz: extended parametrisation

nTuJu19: $xf_{i/p}(x, Q_0^2) = c_0 x^{c_1}(1-x)^{c_2}(1 + c_3 x + c_4 x^2)$ own proton reference using xFitter

$xf_{i/p} \to xf_{i/A}$ **by** $c_k \to c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}})$

$i = g,\ u_v,\ d_v,\ \bar{u},\ \bar{d},\ s = \bar{s}$

NLO

nDS, HKN07, EPS09: as for LO
EPPS16: like EPS09, with more freedom R_{uv}, R_{dv}, R_{ubar}, R_{dbar}, R_s, R_g
DSSZ: multiplicative factor, not piecewise R_v, R_s, R_g

nCTEQ15, nCTEQ15wz: extended parametrisation

nTuJu19: extended parametrisation

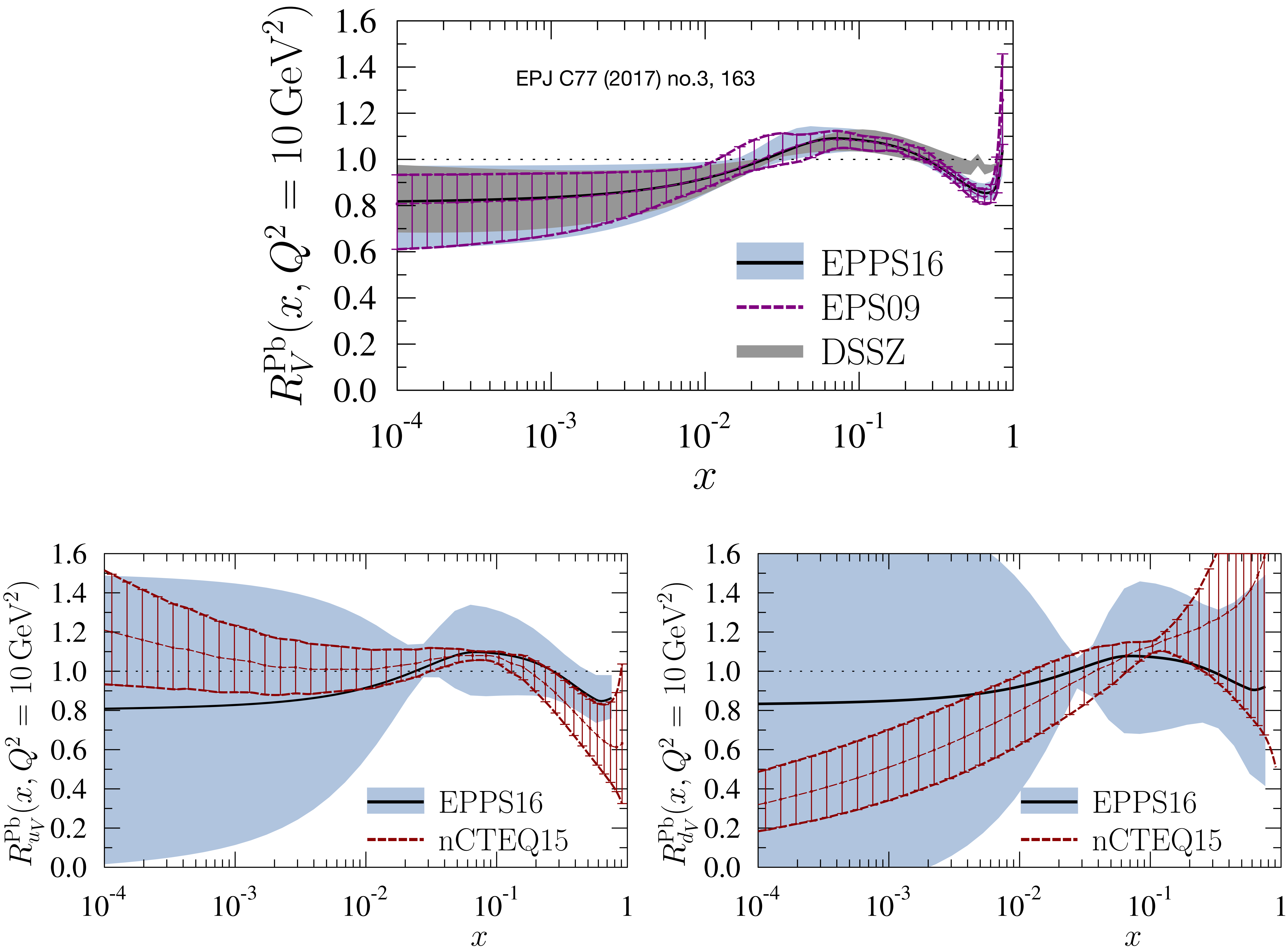
nNNPDF1.0, 2.0: neural networks

$$xf_{i/A}(x, Q_0^2) = N_i x^{\alpha_i}(1-x)^{\beta_i} NN_i \qquad q^{\pm} = q \pm \bar{q}$$

$$i = g,\ u^+ + d^+ + s^+,\ u^+ + d^+,\ u^+ + d^+ - 2s^+,\ u^- + d^-,\ u^- - d^-$$

NLO

SET		nDS	HKN07	EPS09	DSSZ	nCTEQ15	EPPS16	nNNPDF 1.0	nTuJu19	nNNPDF 2.0	nCTEQ 15wz
data type	NC DIS	🙂	🙂	🙂	🙂	🙂	🙂	🙂	🙂	🙂	🙂
	D-Y	🙂	🙂	🙂	🙂	🙂	🙂				🙂
	π			🙂	🙂	🙂	🙂				🙂
	CC DIS				🙂		🙂		🙂	🙂	
	EW						🙂			🙂	🙂
	jets						🙂				
# points		420	1241	929	1579	740	1811	451	2336	1467	860
χ^2/N		0.714	1.197	0.787	0.978	0.793	0.988	0.681	0.887	0.976	0.887
$Q_0^2(\mathrm{GeV}^2)$		0.4	1	1.69	1	1.69	1.69	1	1.69	1	1.69
deuteron			🙂			?			🙂	🙂	?
flavour separation?						🙂 valence	🙂		🙂 valence	🙂	🙂


EPJ C77 (2017) no.3, 163
$R_V^{\mathrm{Pb}}(x, Q^2 = 10\,\mathrm{GeV}^2)$
EPPS16
EPS09
DSSZ
x
$R_{u_V}^{\mathrm{Pb}}(x, Q^2 = 10\,\mathrm{GeV}^2)$
EPPS16
nCTEQ15
$R_{d_V}^{\mathrm{Pb}}(x, Q^2 = 10\,\mathrm{GeV}^2)$
EPPS16
nCTEQ15

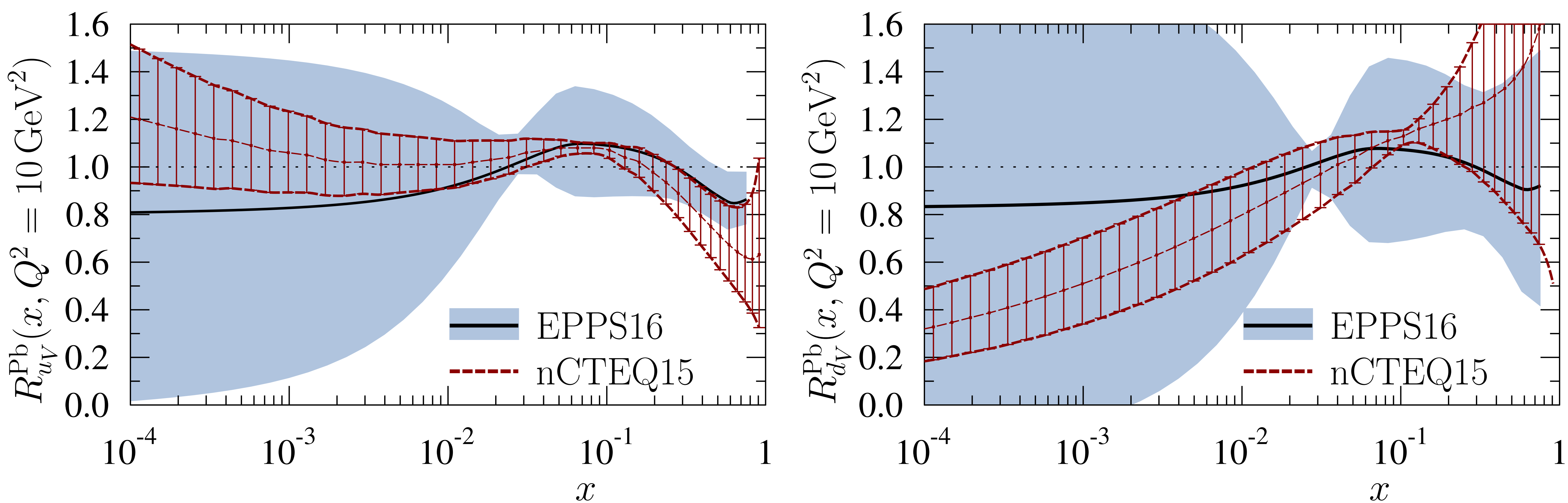
proton

nucleus

$$\frac{4}{9}u + \frac{1}{9}d \longrightarrow \left(\frac{A+3Z}{9A}\right)u + \left(\frac{4A-3Z}{9A}\right)d$$

Isoscalar or near isoscalar nuclei can't separate flavours

EPJ C77 (2017) no.3, 163

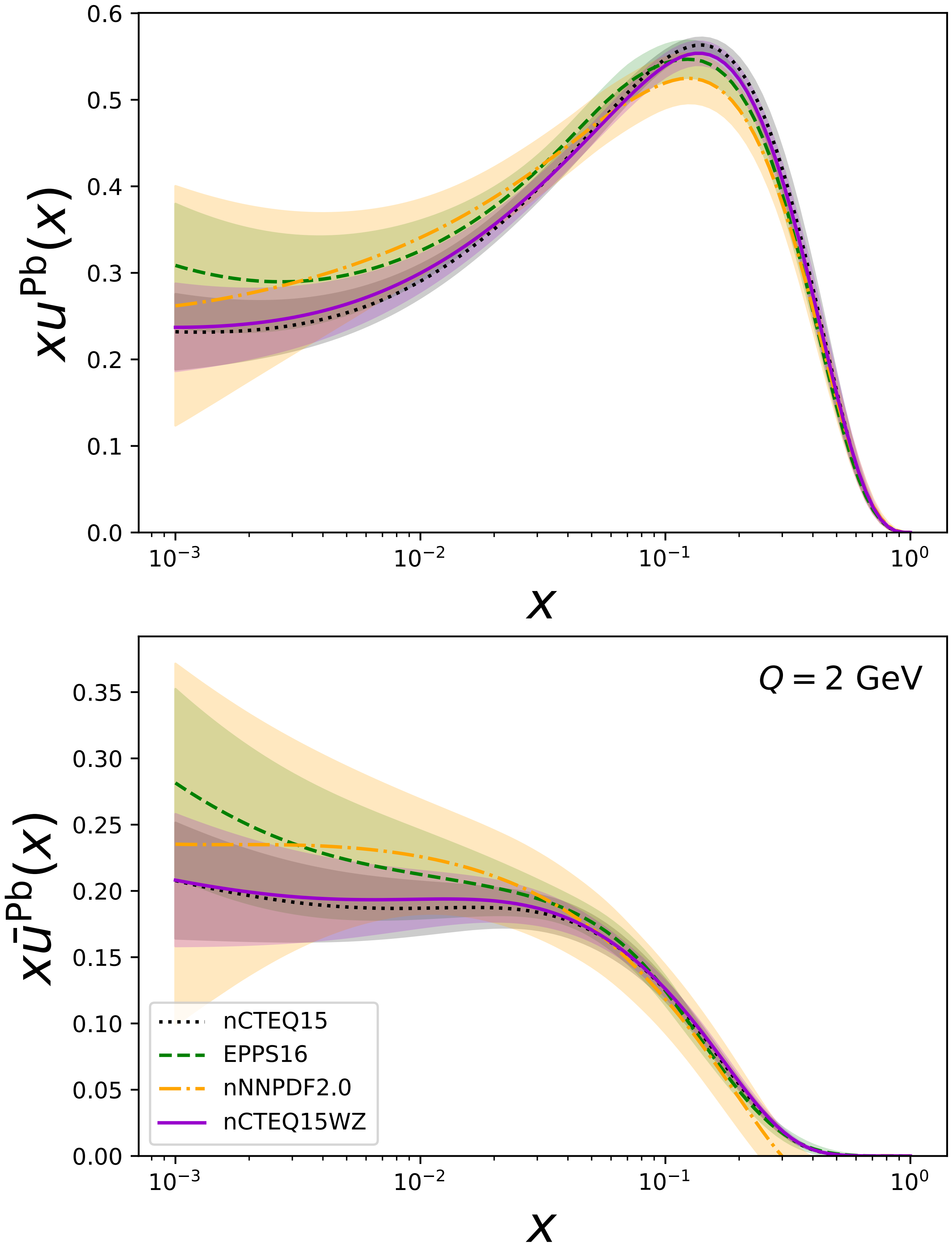


arXiv:2007.09100 [hep-ph]

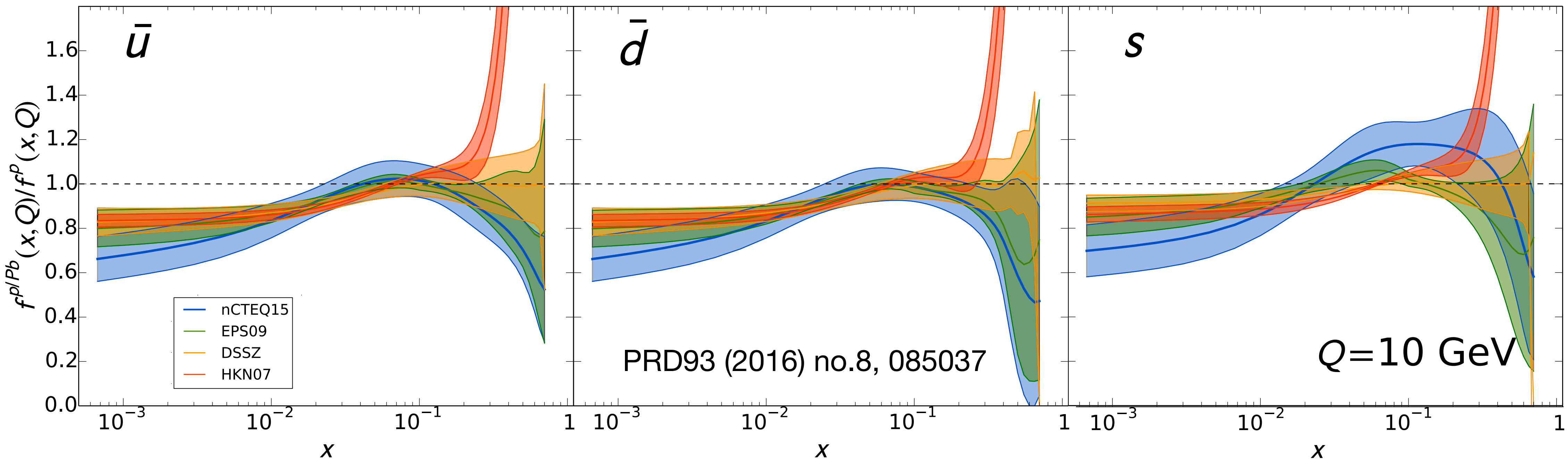
- If one takes the appropriate combinations, the nPDFs of the valence quarks in a nucleus are very similar

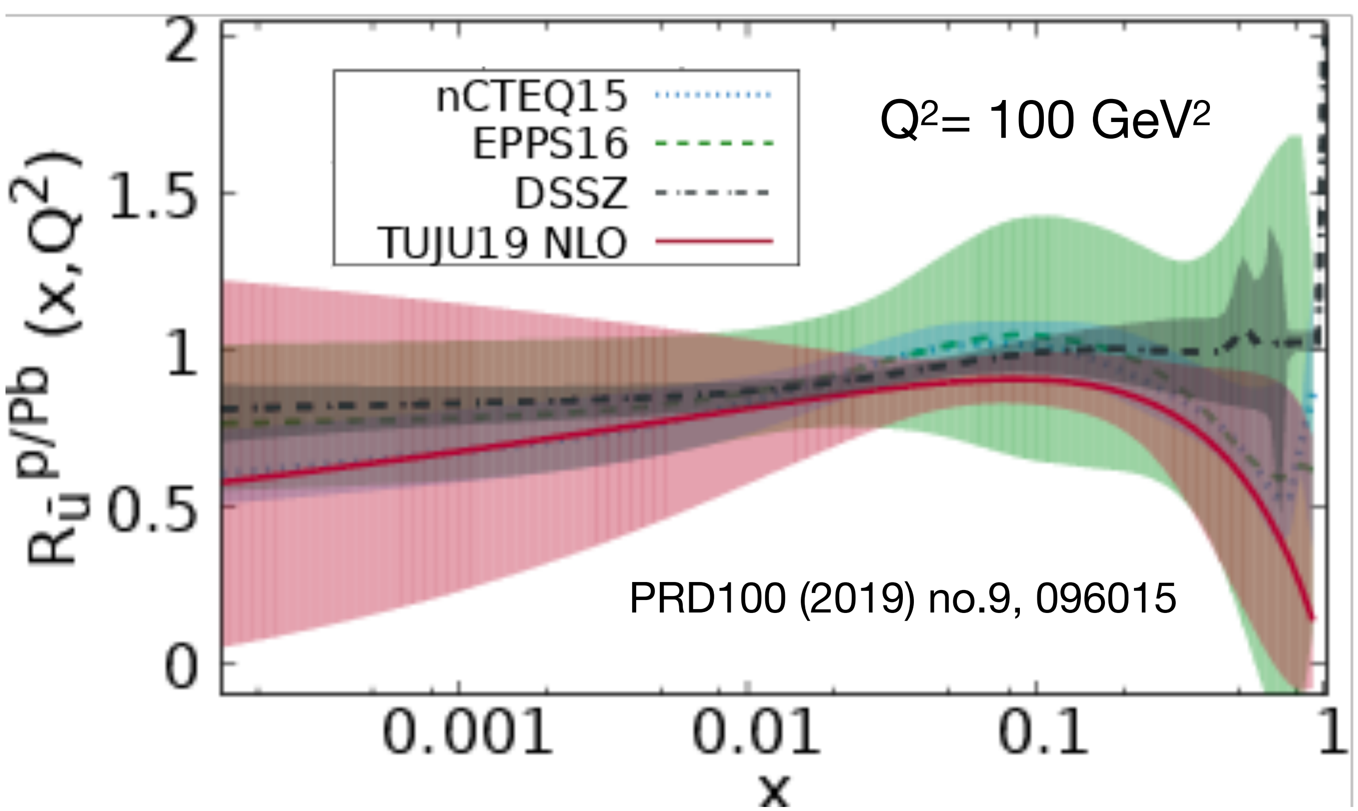
- This is due to the fact that most of the data fitted lies in the valence dominated region

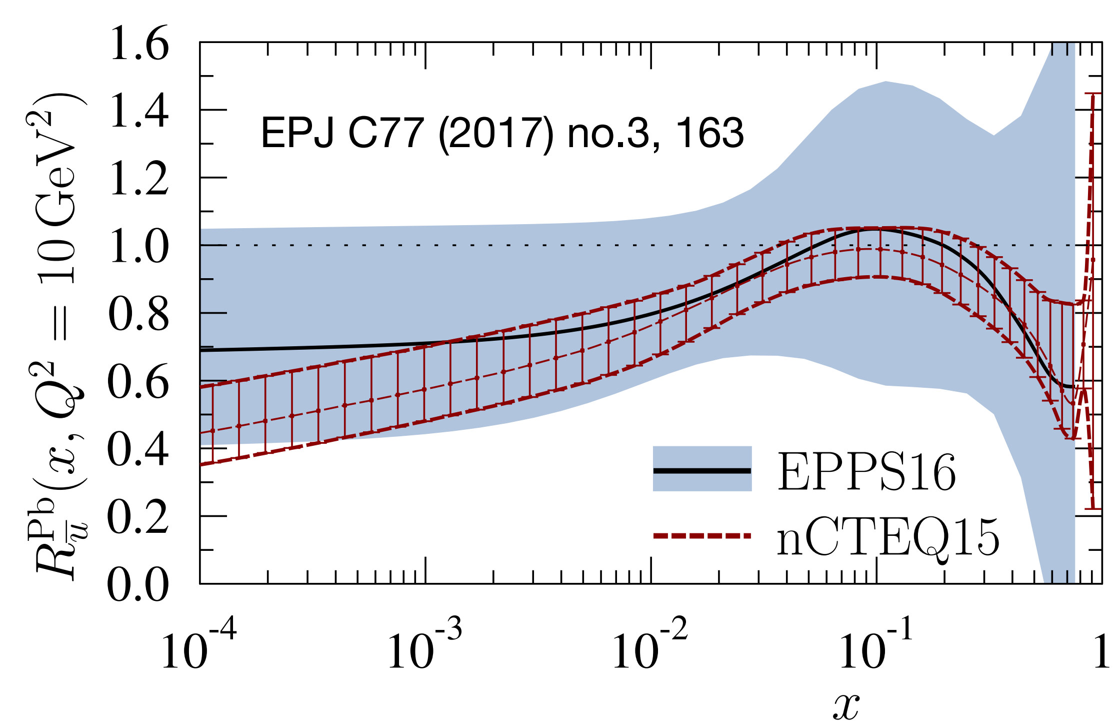
- The sea/antiquark region is quite unconstrained



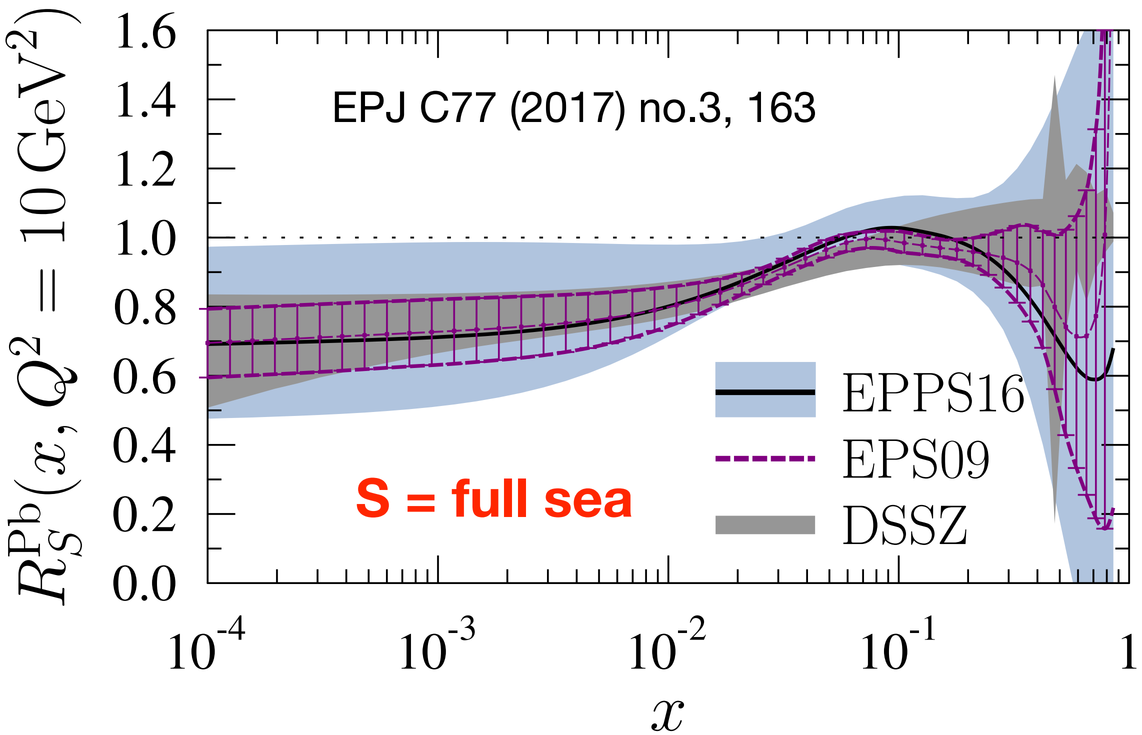
- Due to the lack of data in the low x region the sea is usually parametrised together

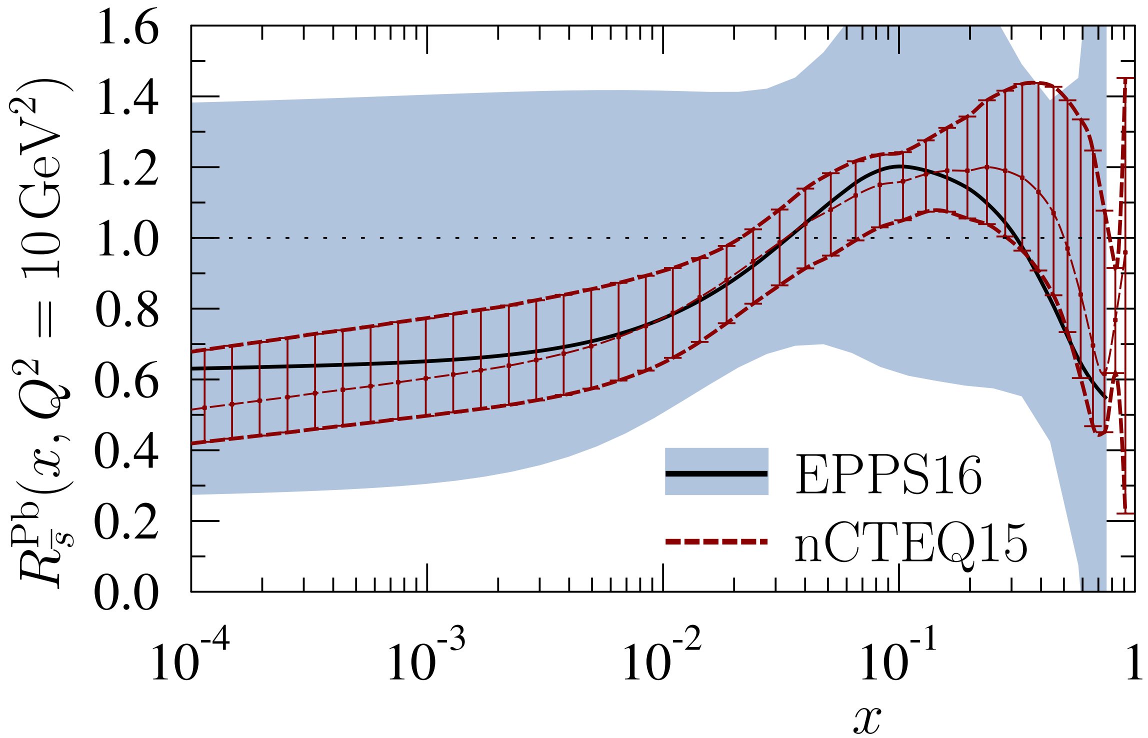


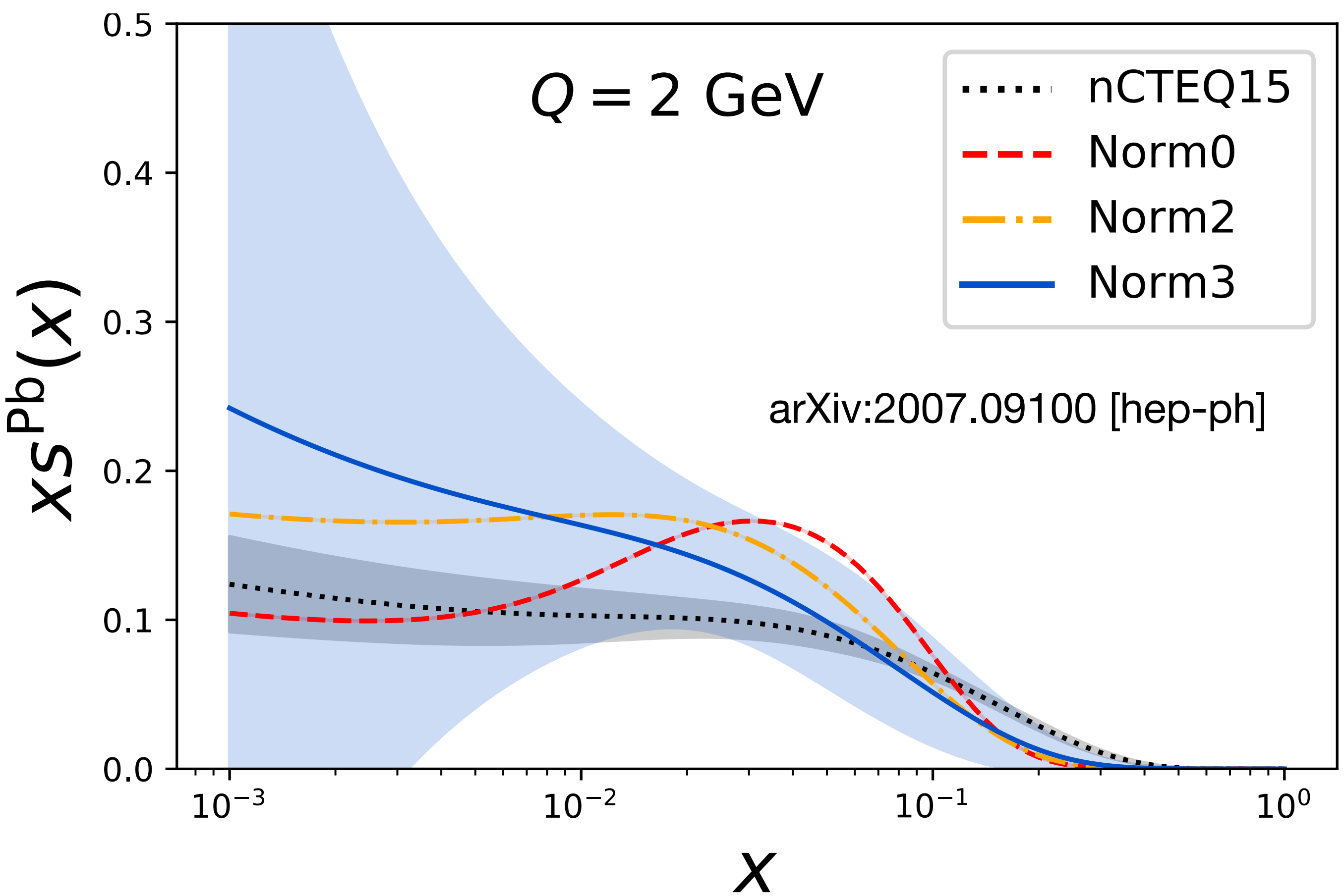




The nuclear strange modification is usually tied to the rest of the sea



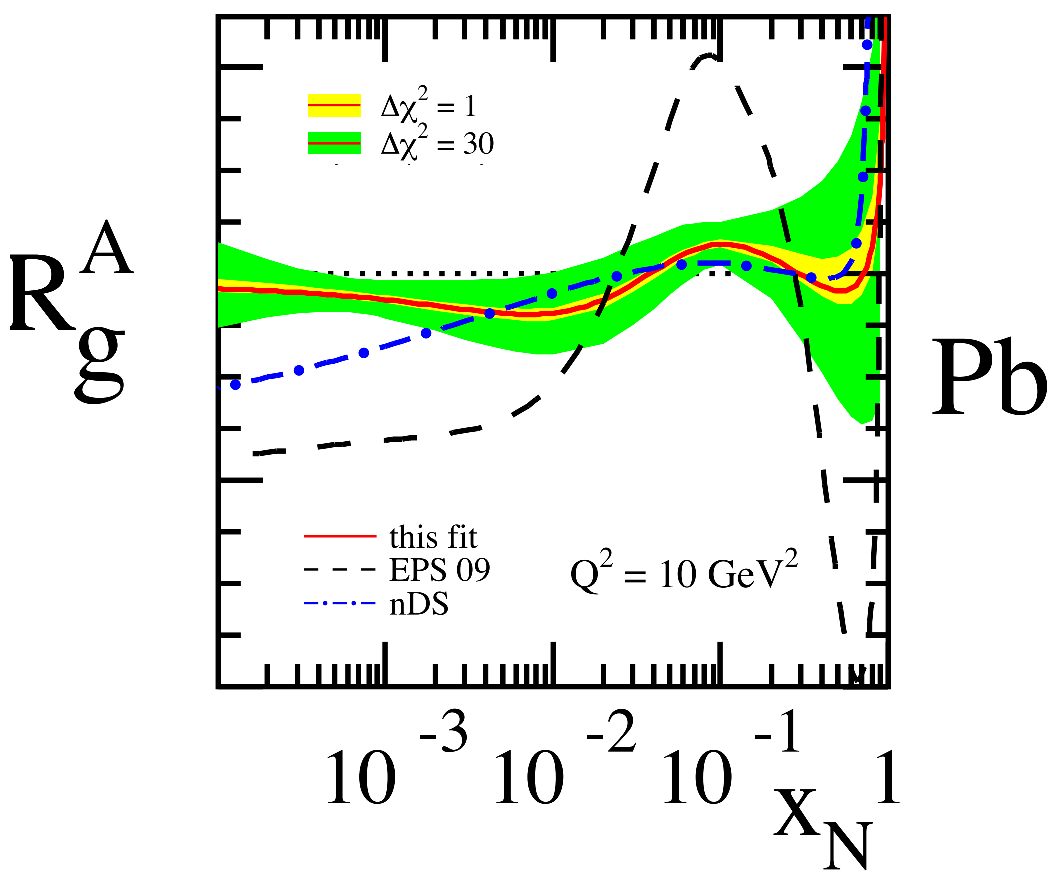


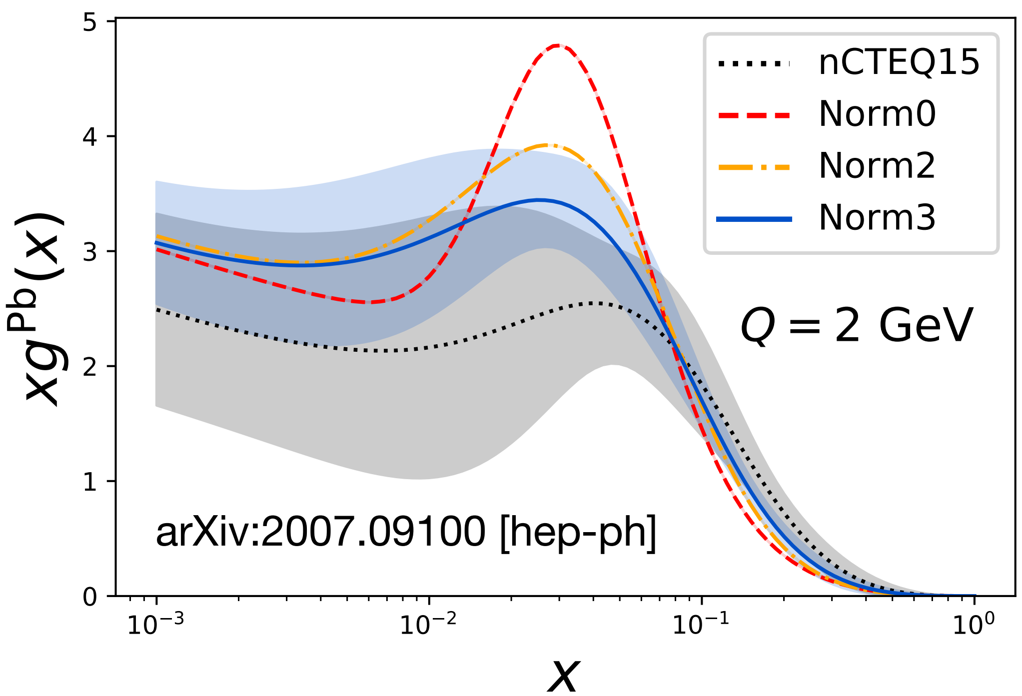


Norm_i: i free normalisation parameters for LHC data

And then there is the gluon:

PRD85 (2012), 074028

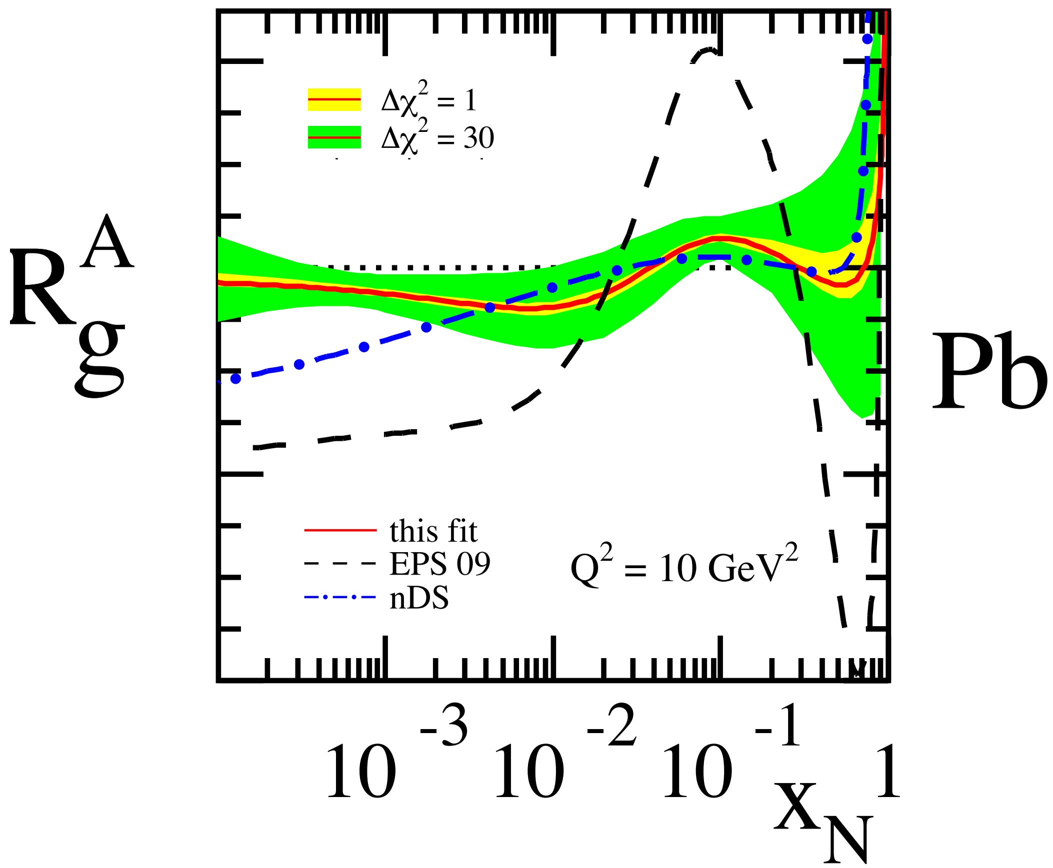


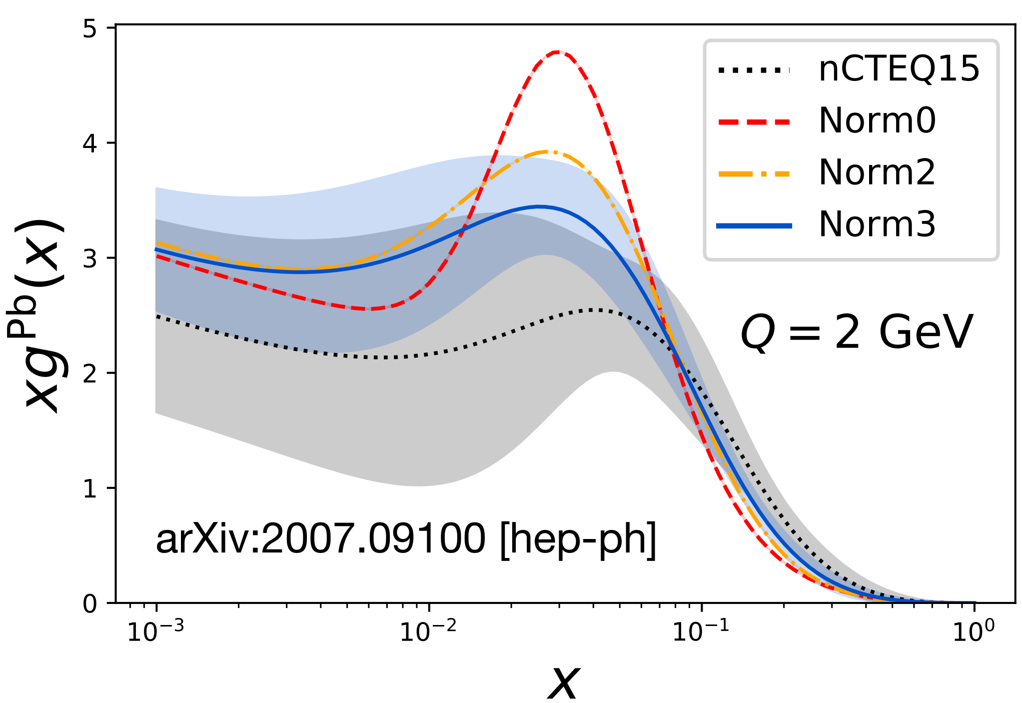


- π production at RHIC (~ 60 points) is the only observable in most fits directly sensitive to the gluon. Anything else is fantasy.

And then there is the gluon:

PRD85 (2012), 074028





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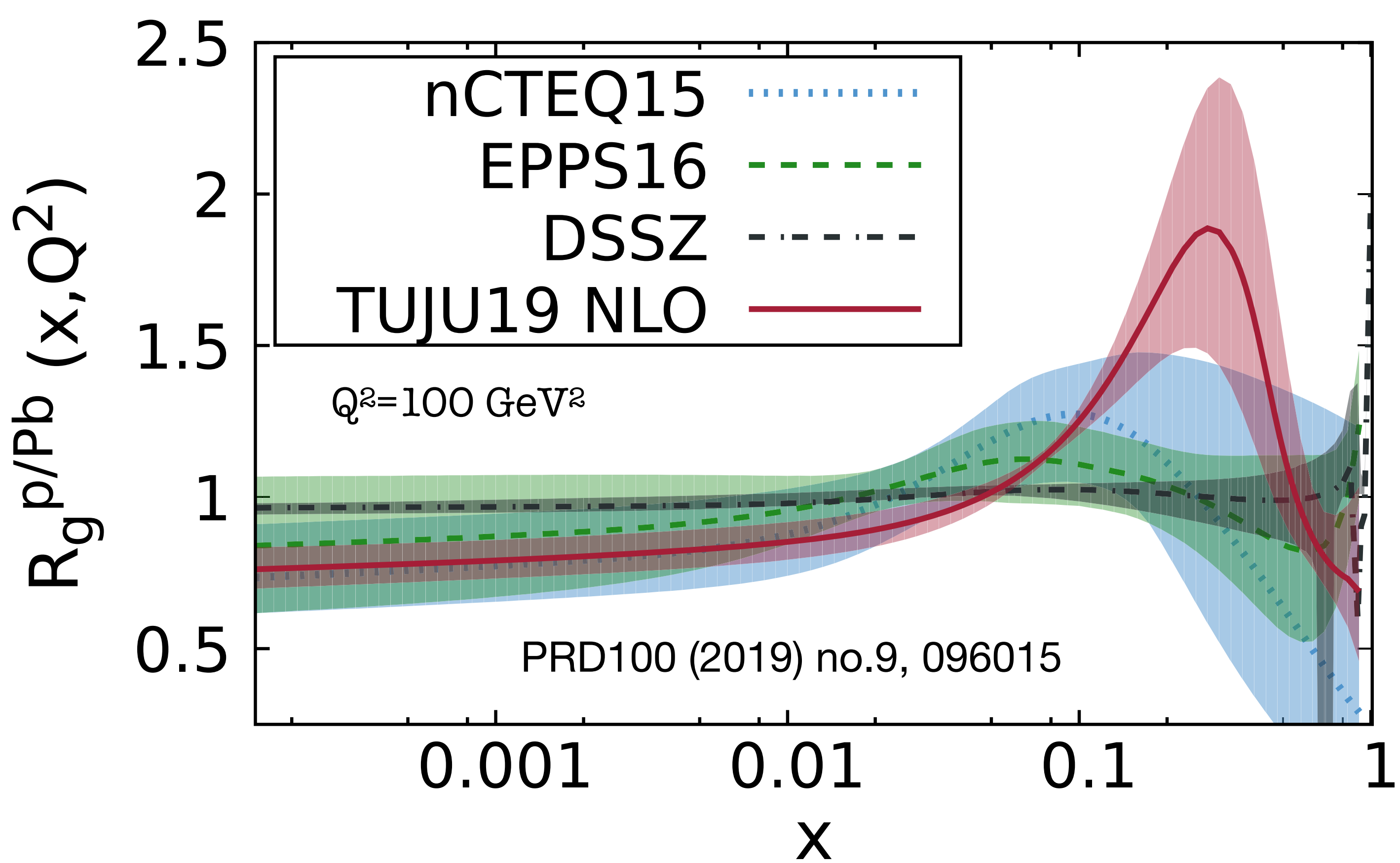
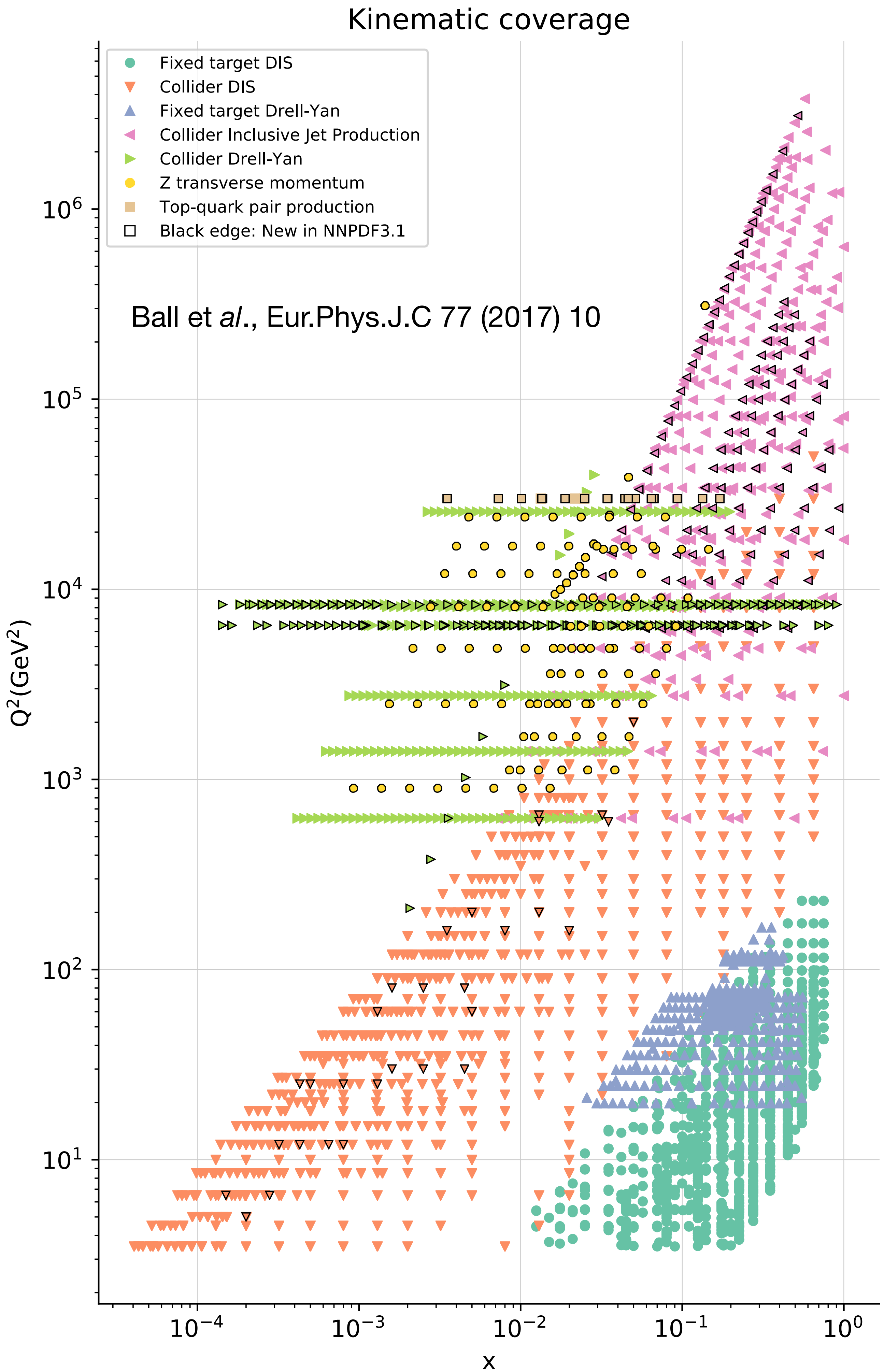


Issues with

nPDF extraction

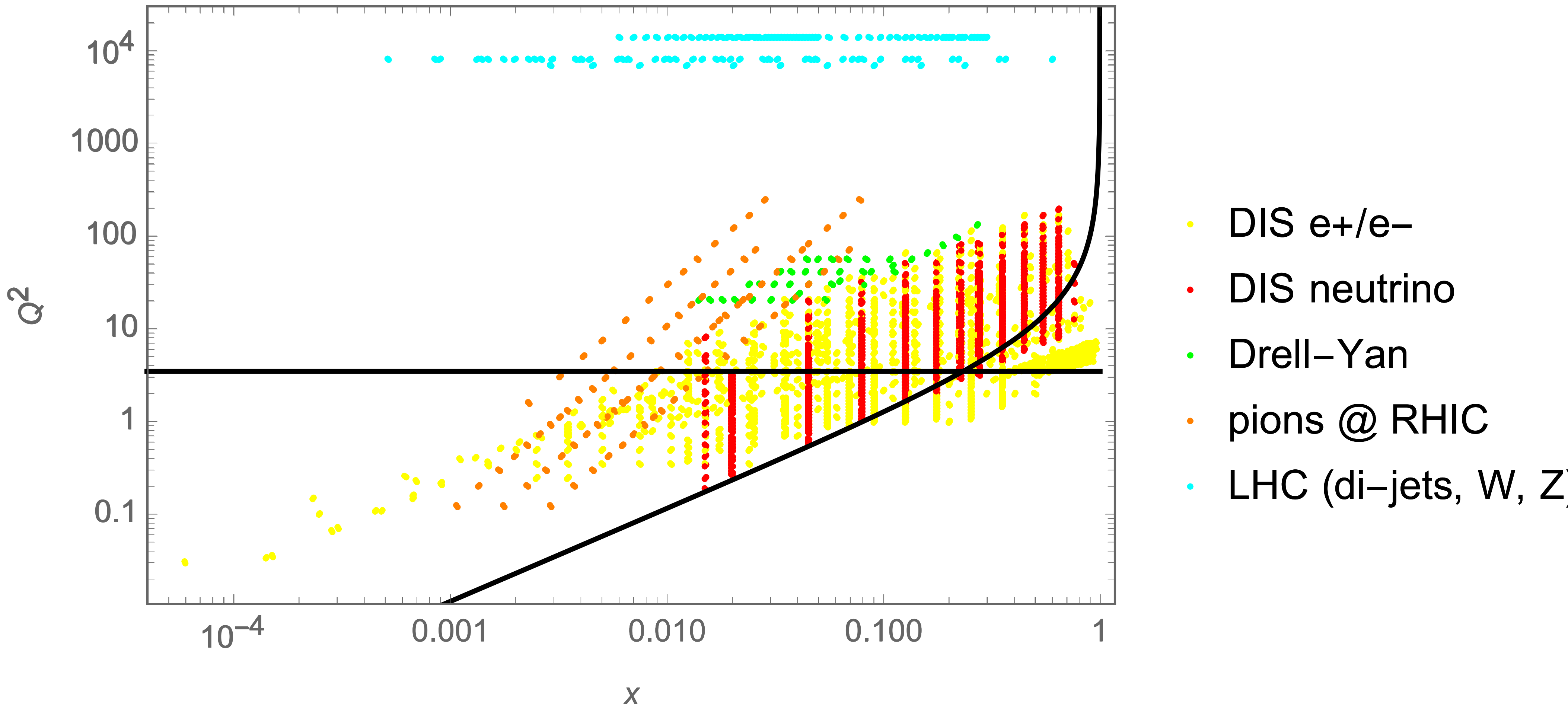
why is it so hard to extract accurate nPDFs when proton PDFs are SO much better?



1) THE DATA:

- quantity
- quality
- kinematic range
- presentation

- For proton PDFs 1/3 of the data (~ 1300) comes from HERA
- All for proton
- Large kinematic coverage
- One can obtain a set of PDFs just from HERA data



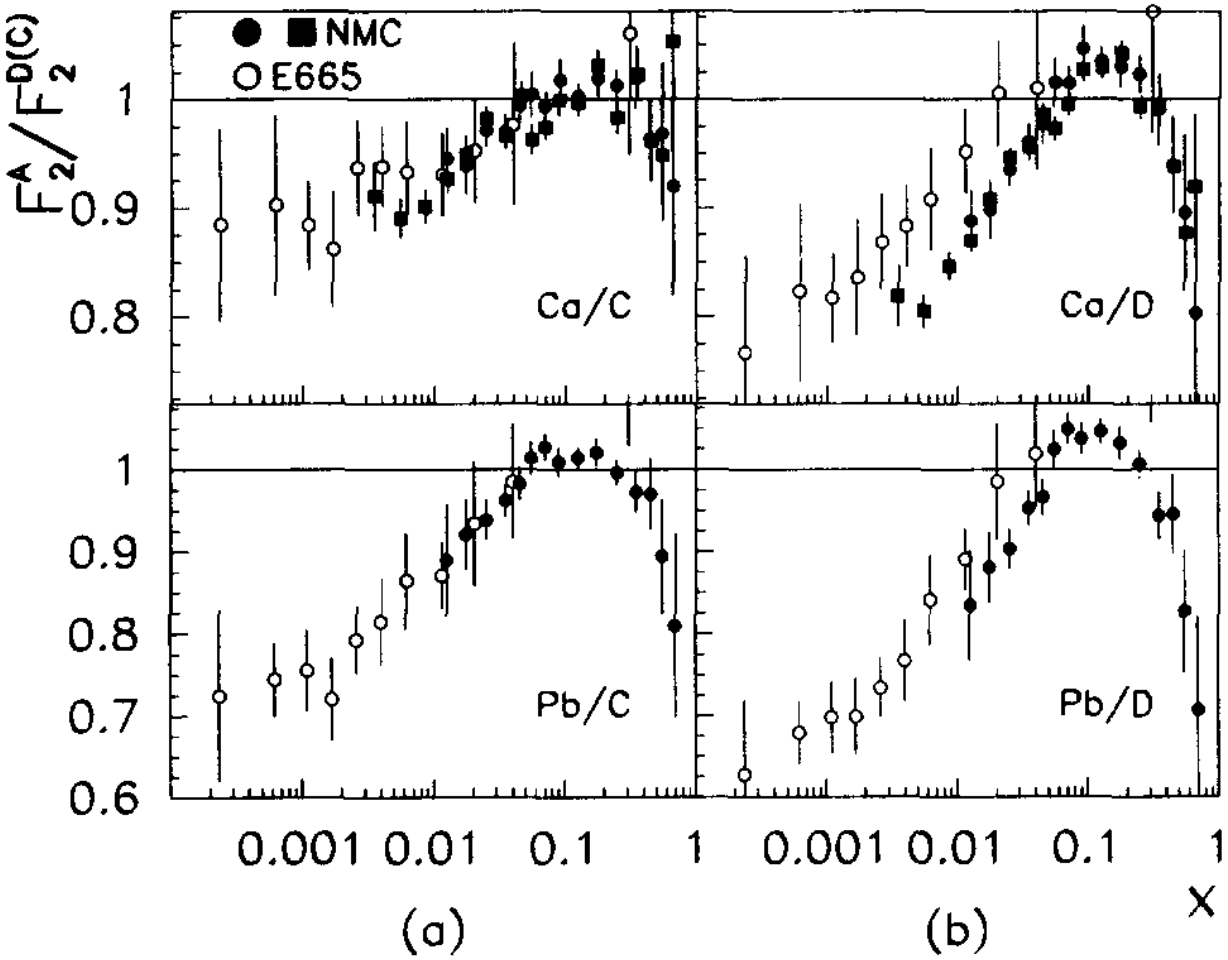
- In the nuclear case (NC DIS + CC DIS + Drell-Yan)

A	D	He	Li	Be	C	N	Al	Ca	Fe	Cu	Kr	Ag	Sn	Xe	W	Pt	Au	Pb
# points	615	60	146	17	422	51	20	123	873	29	34	1	174	3	37	7	2	603

232 from NC DIS

19 from NC DIS

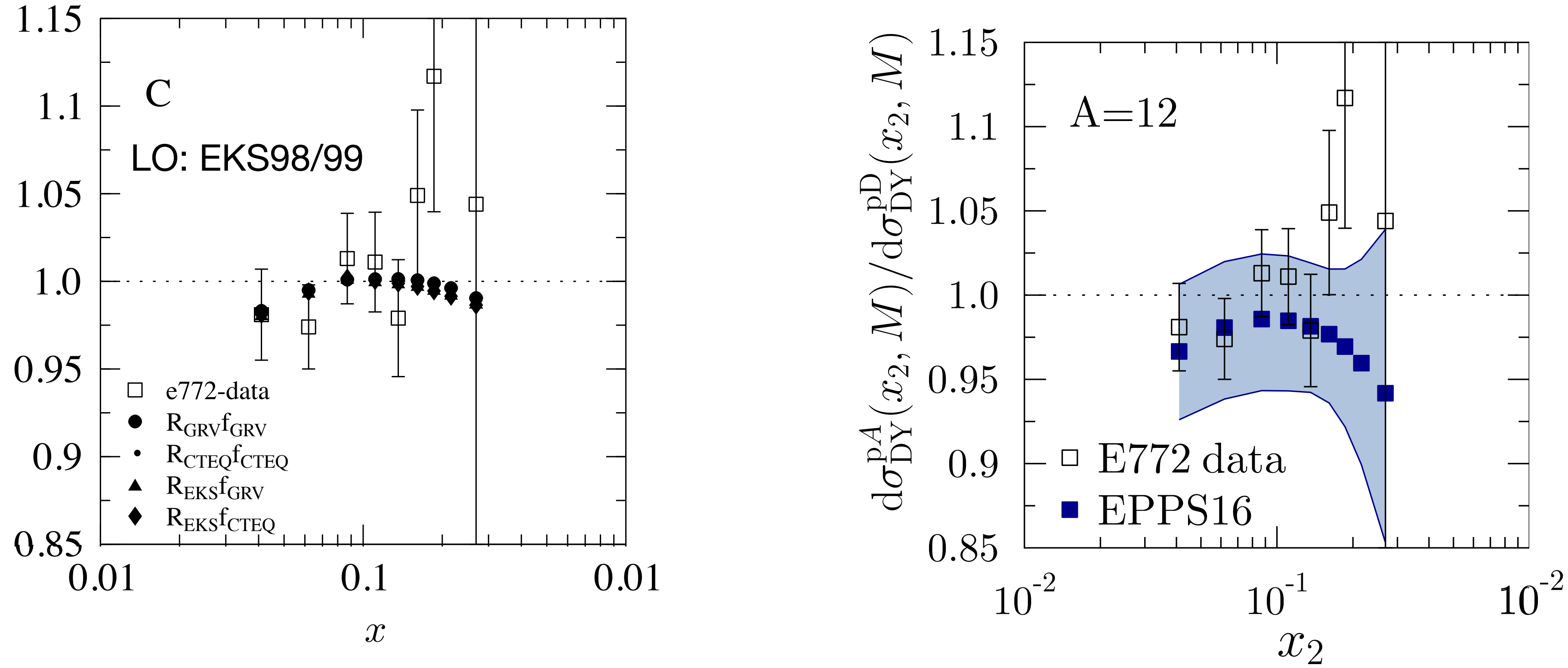
New Muon Collaboration, Nucl.Phys. B481 (1996) 3



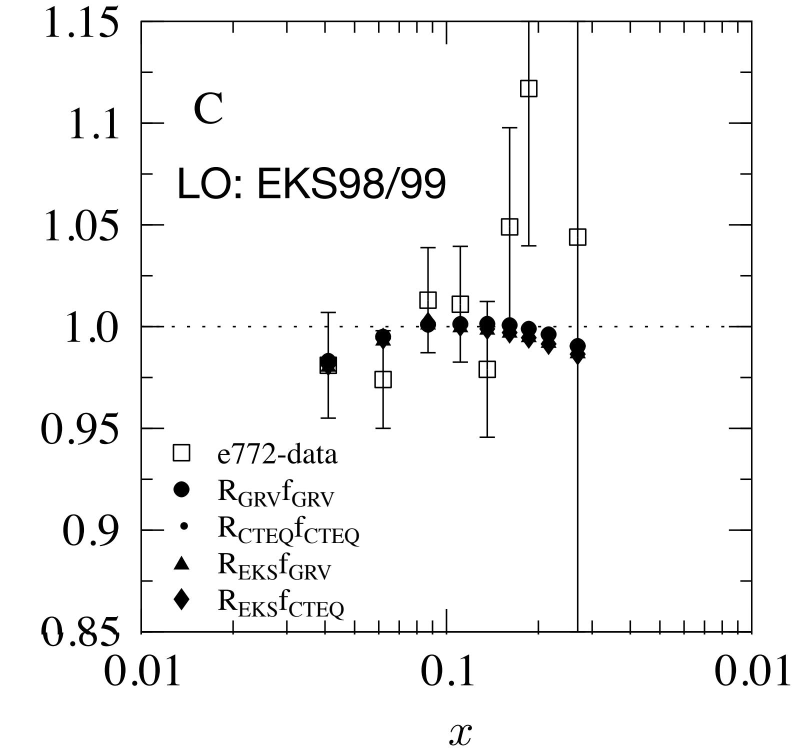
$$\sigma_{red} = F_2 - \frac{y^2}{1+(1-y)^2} F_L$$

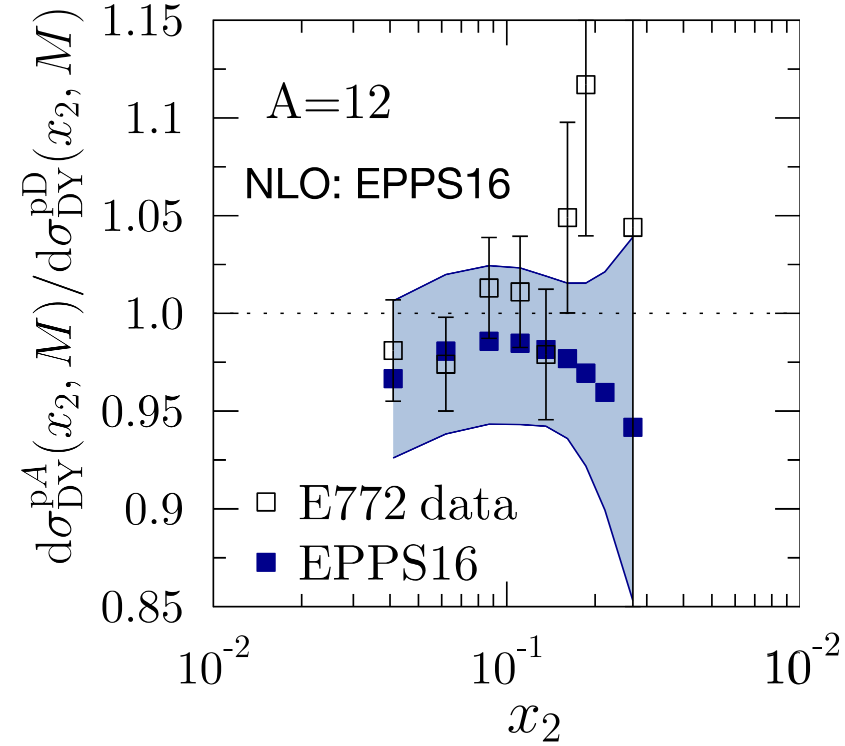
$$\sigma^A_{red}/\sigma^D_{red},\ F^A_2/F^D_2,\ f(F^A_L/F^A_2)$$

- For proton the reduced cross-section is (mostly) used
- For DIS with nuclei, most of the data (1108/1930) is given as ratios, some information is lost
- F_2 and F_L determination based on parameterizations of their ratio
- non-isoscalarity corrections included (not needed)



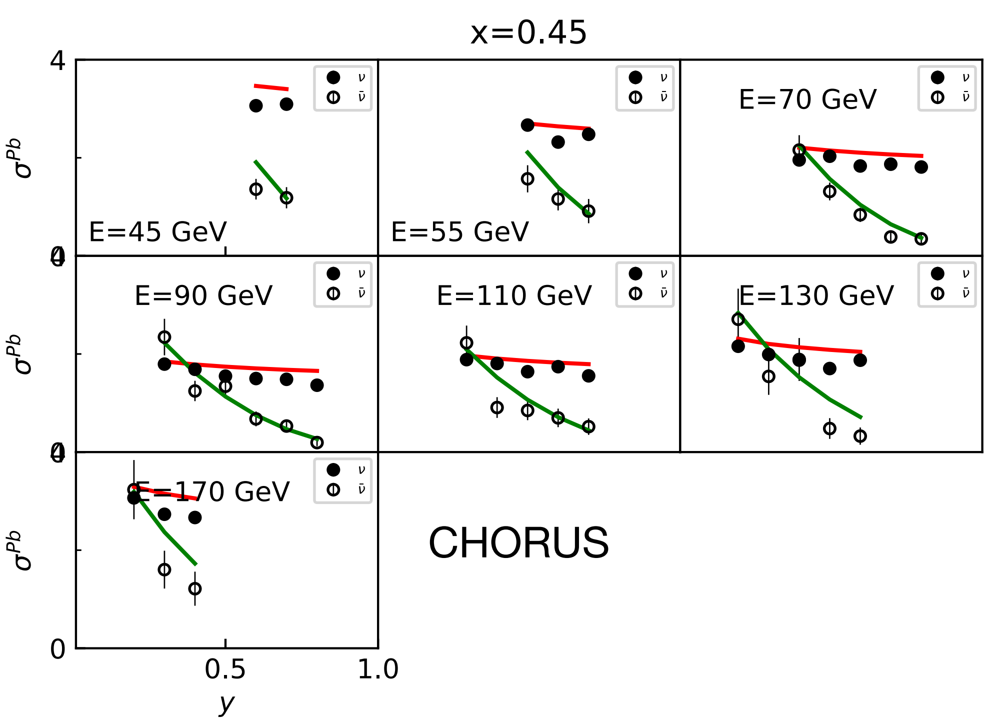
- using Drell-Yan does not improve much

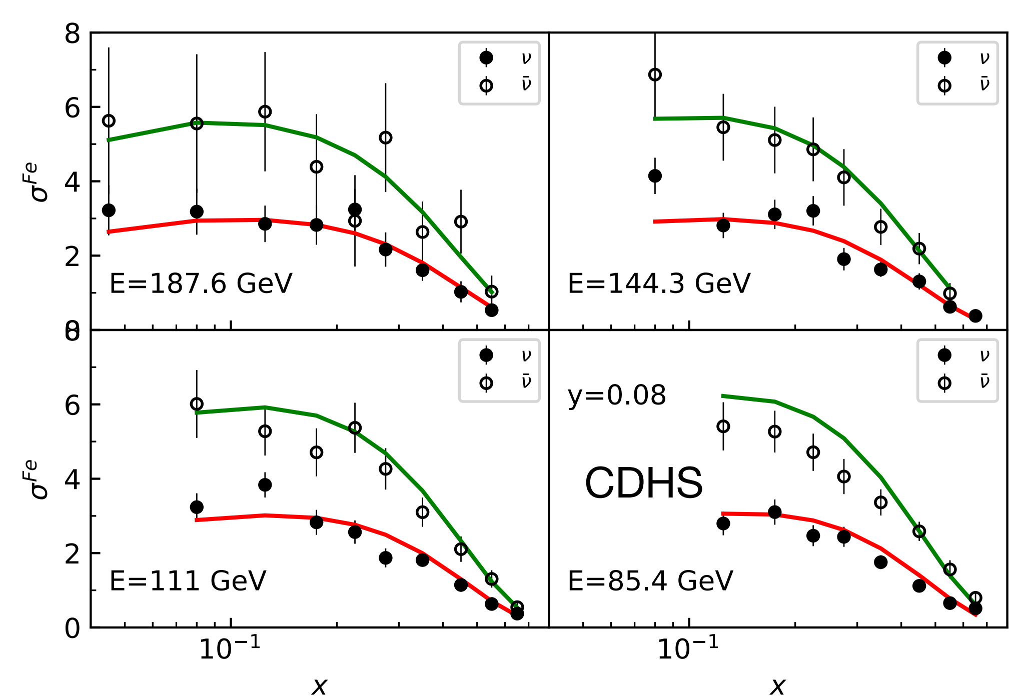




- using Drell-Yan does not improve much

- CC DIS might have some issues (NuTeV has tensions with other experiments)
- and they are not very sensitive to the nuclear effects





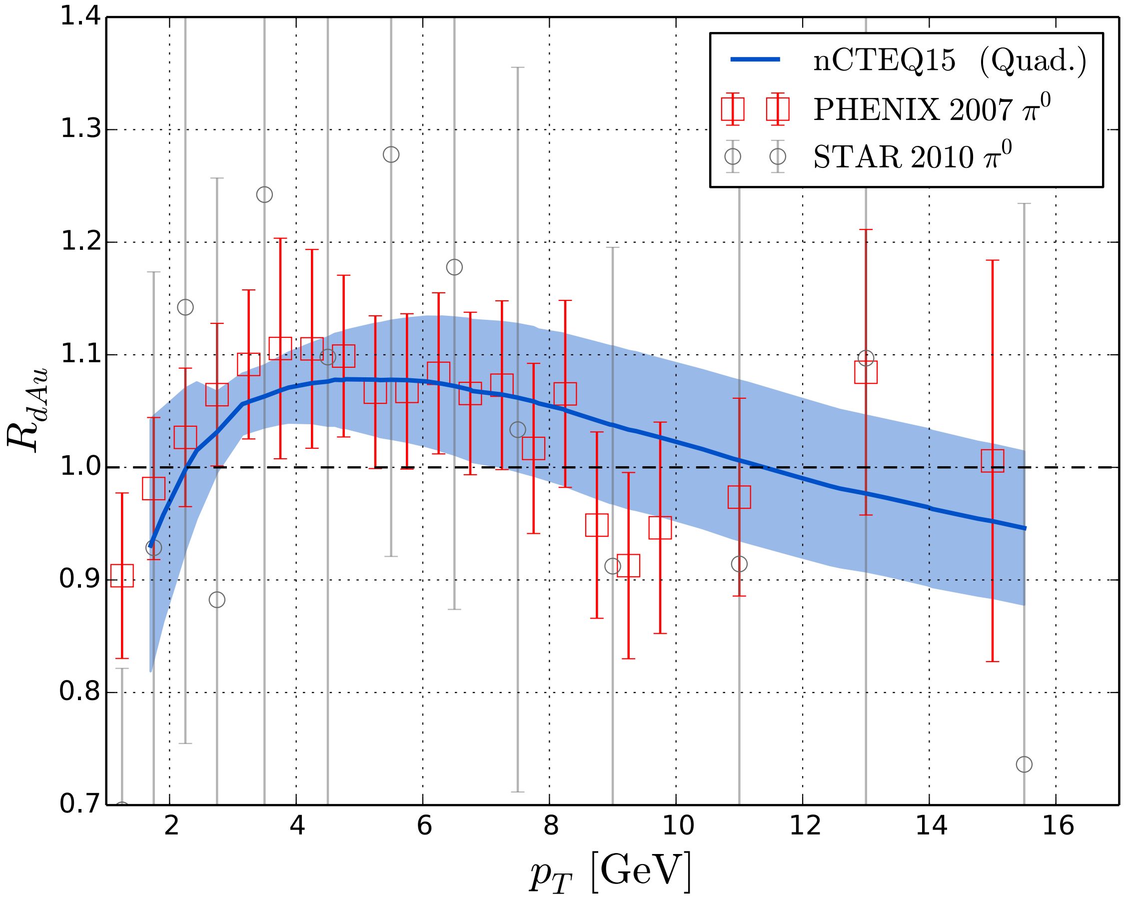
comparison (not a fit!) with proton PDFs

$$\chi^2_{CDHS}/N_{points} \approx 1.28$$

$$\chi^2_{CHORUS}/N_{points} \approx 1.72$$

pion product at RHIC

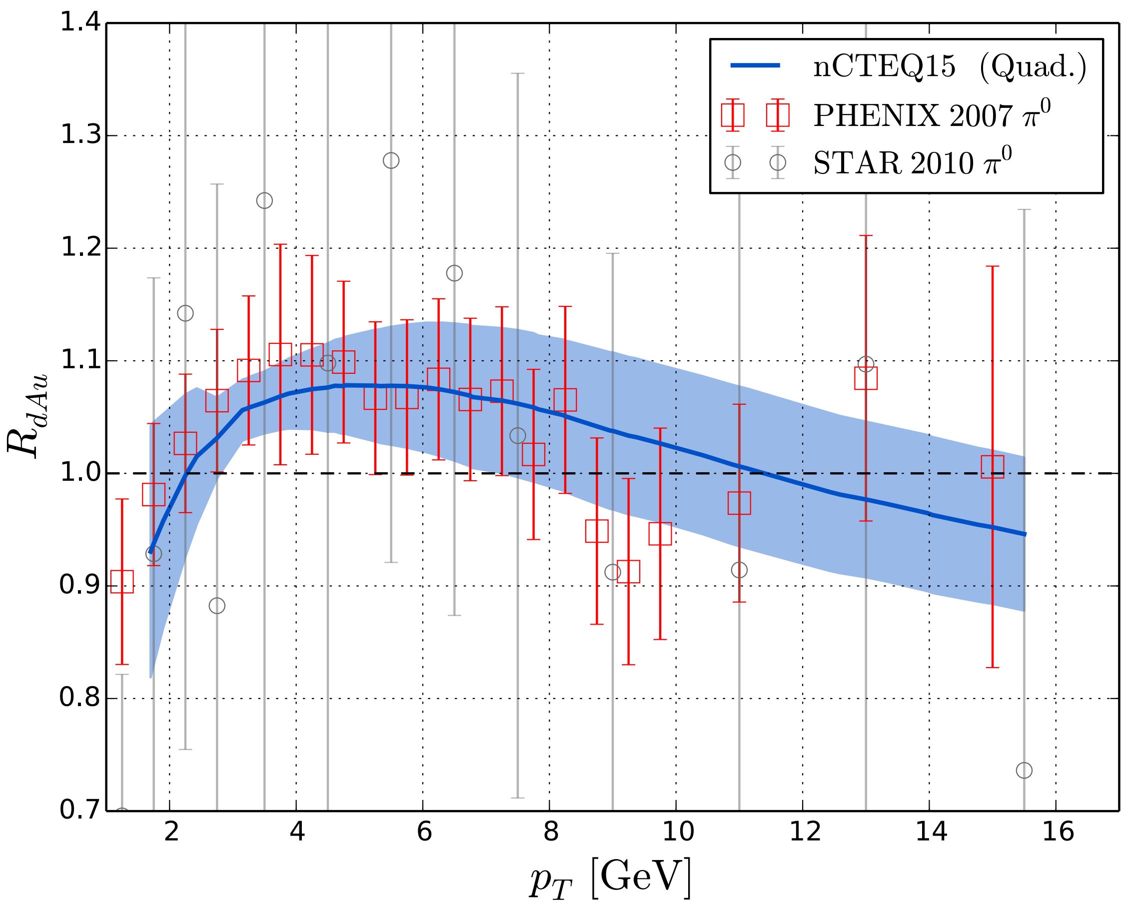
PRD93 (2016) no.8, 085037

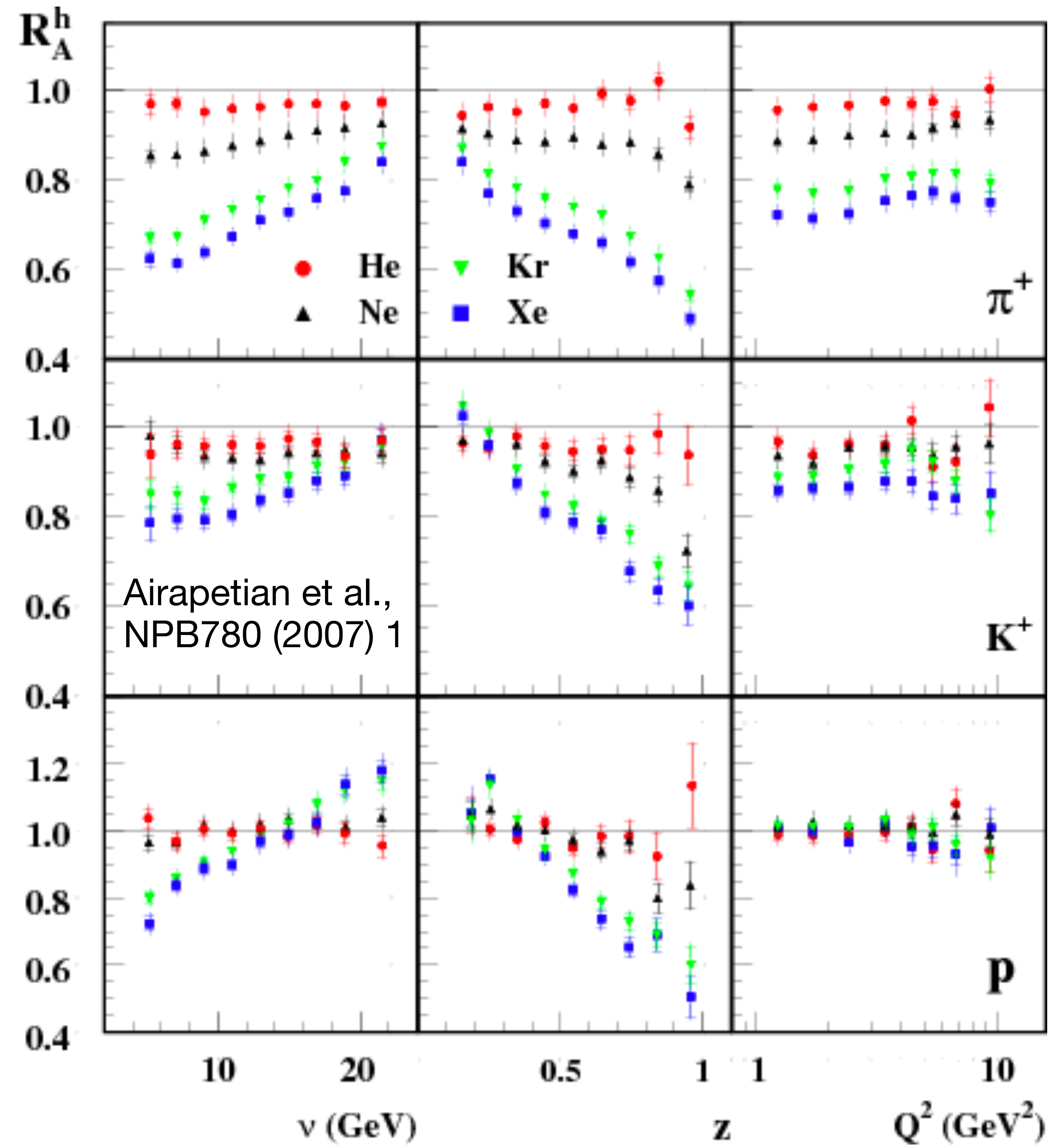


- Large uncertainties
- Depends on fragmentation functions
- Nuclear effects in the FFs?

- pion product at RHIC

PRD93 (2016) no.8, 085037



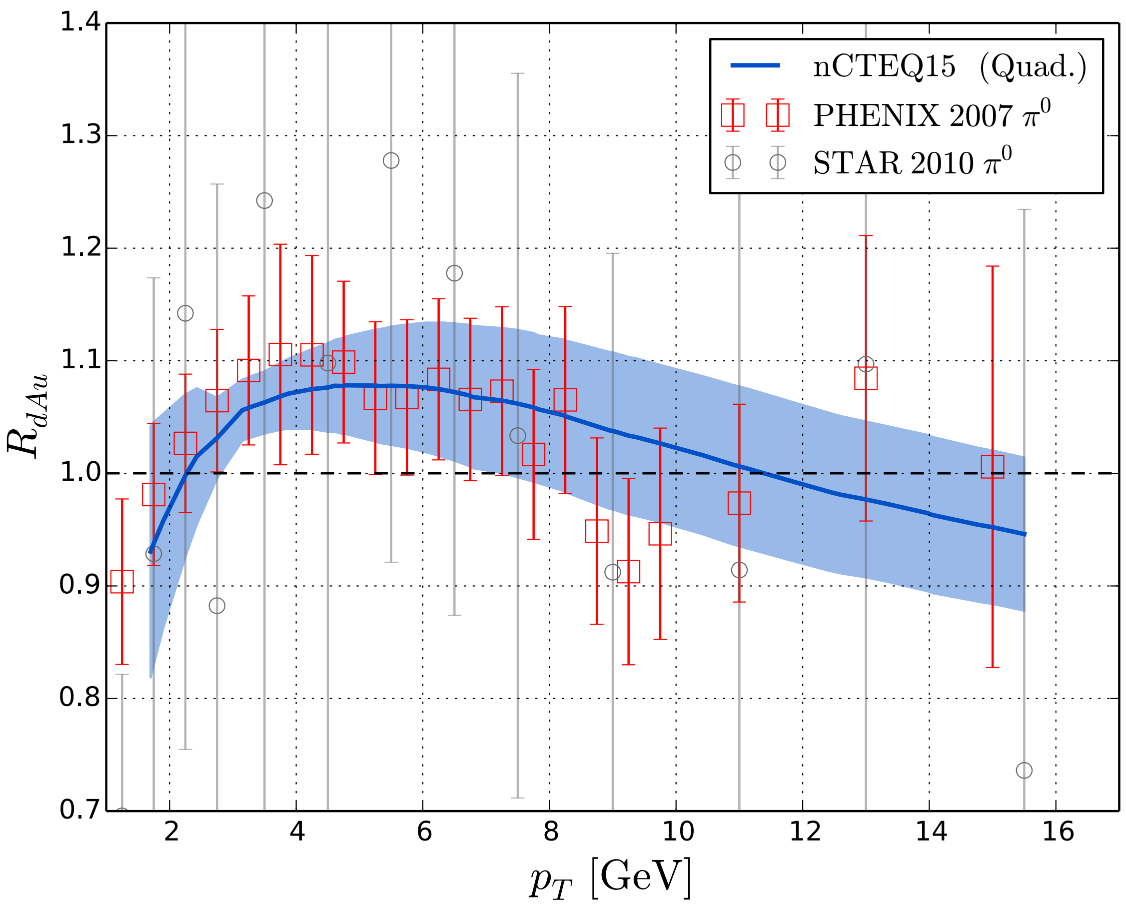


- Large uncertainties
- Depends on fragmentation functions
- Nuclear effects in the FFs?

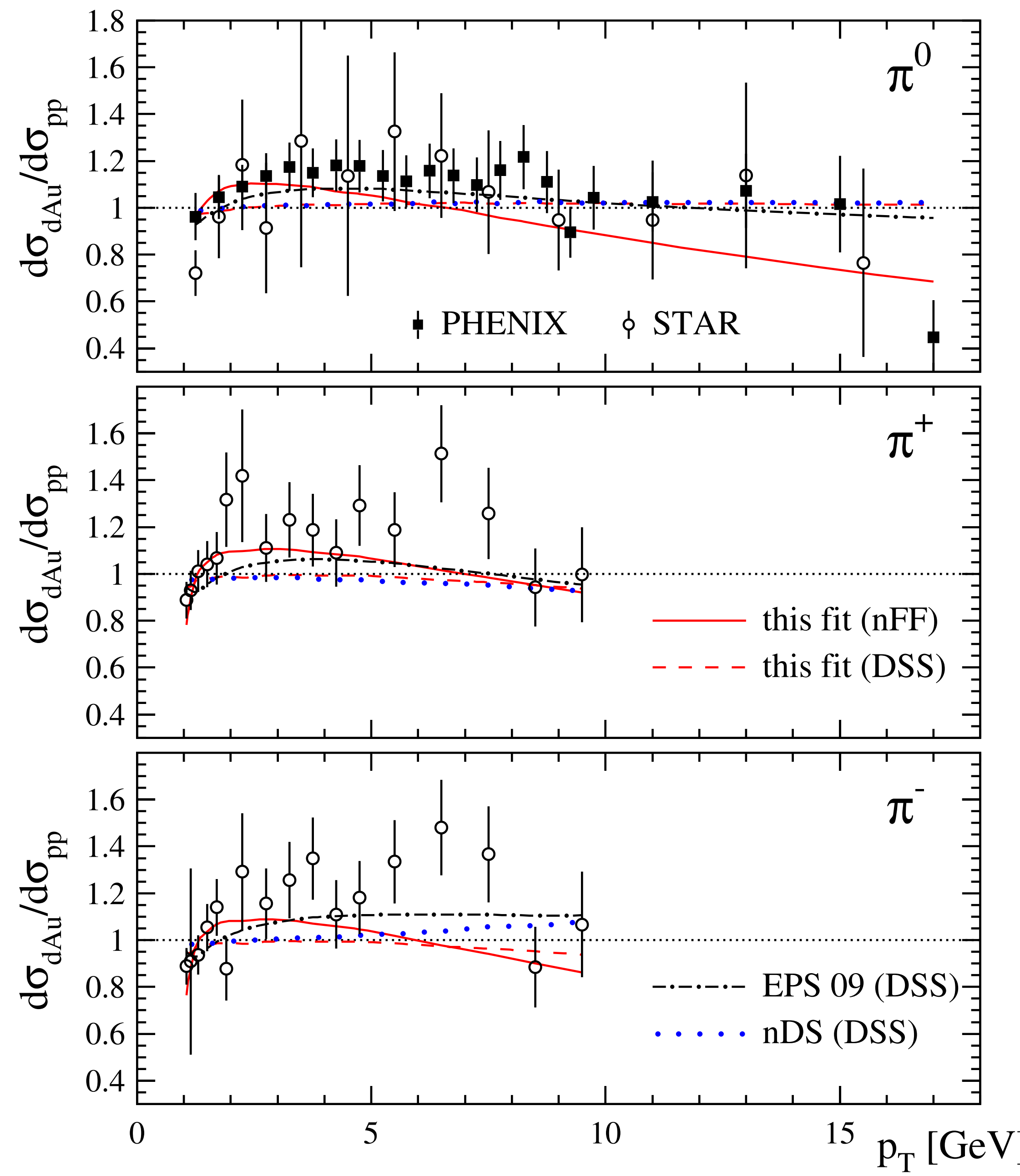
$$R^h_A(\nu, Q^2, z, p_T^2) = \frac{\left(\frac{N^h(\nu, Q^2, z, p_T^2)}{N^e(\nu, Q^2)}\right)_A}{\left(\frac{N^h(\nu, Q^2, z, p_T^2)}{N^e(\nu, Q^2)}\right)_D}$$

pion product at RHIC

PRD93 (2016) no.8, 085037



PRD85 (2012) 074028



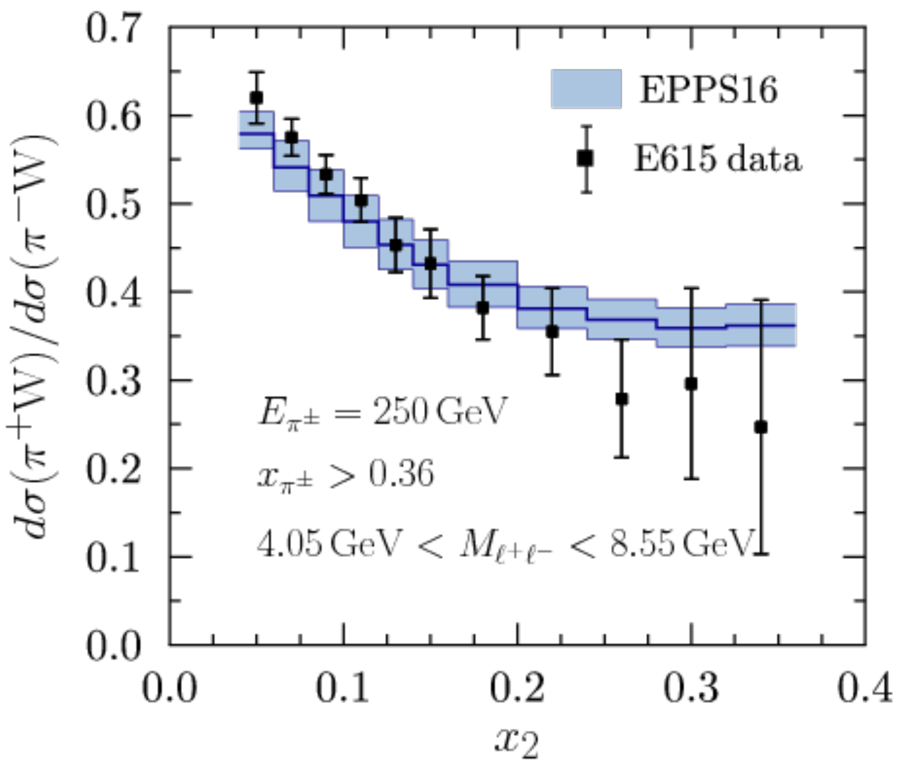
- Large uncertainties
- Depends on fragmentation functions
- Nuclear effects in the FFs?

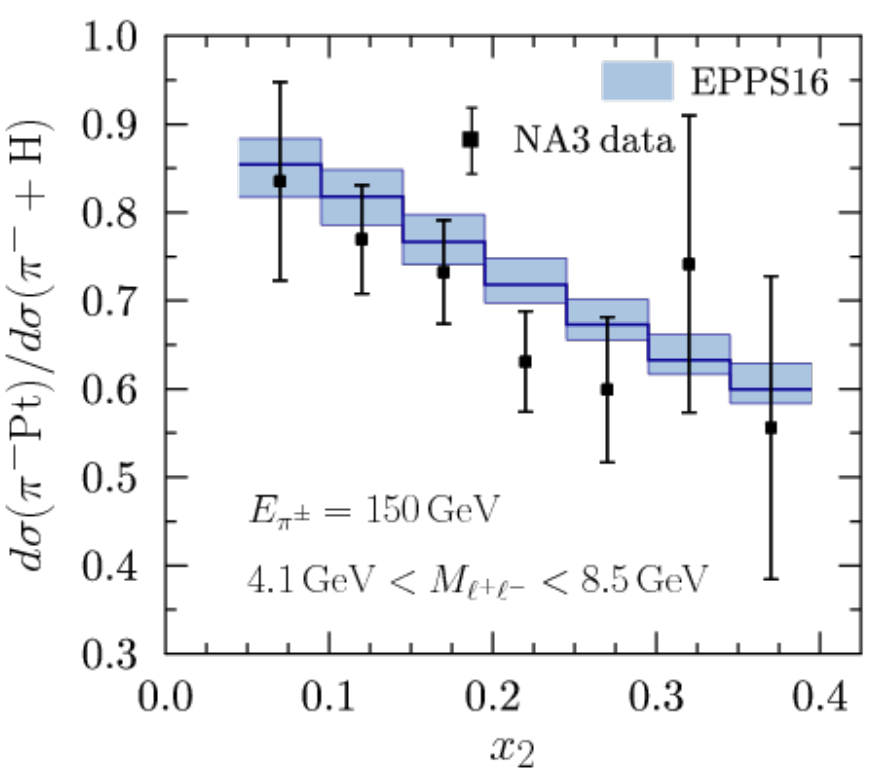
- only in DSSZ
- < 2% variation on the fit χ^2
- 25% variation in RHIC χ^2

Solution to the data problem? Add "new"/new data!

- "new" Drell-Yan data with pion beams (28 points), requires pion PDFs

EPJ C77 (2017) no.3, 163





- Badier, J. *et al.*, Phys.Lett. 104B (**1981**) 335.
- Bordalo, P. *et al.,* Phys.Lett. B193 (**1987**) 368.
- Heinrich, J.G. *et al.,* Phys.Rev.Lett. 63 (**1989**) 356.

DIS data from CLAS

H. Paukkunen and PZ, Eur.Phys.J.C 80 (2020) 5, 381

- Purely phenomenological analysis à la nPDF
- $0.2 < x < 0.6$
- $1.62\ \mathrm{GeV}^2 < Q^2 < 3.02\ \mathrm{GeV}^2$ (out of most kinematic cuts)
- Higher twist correction included: TMC

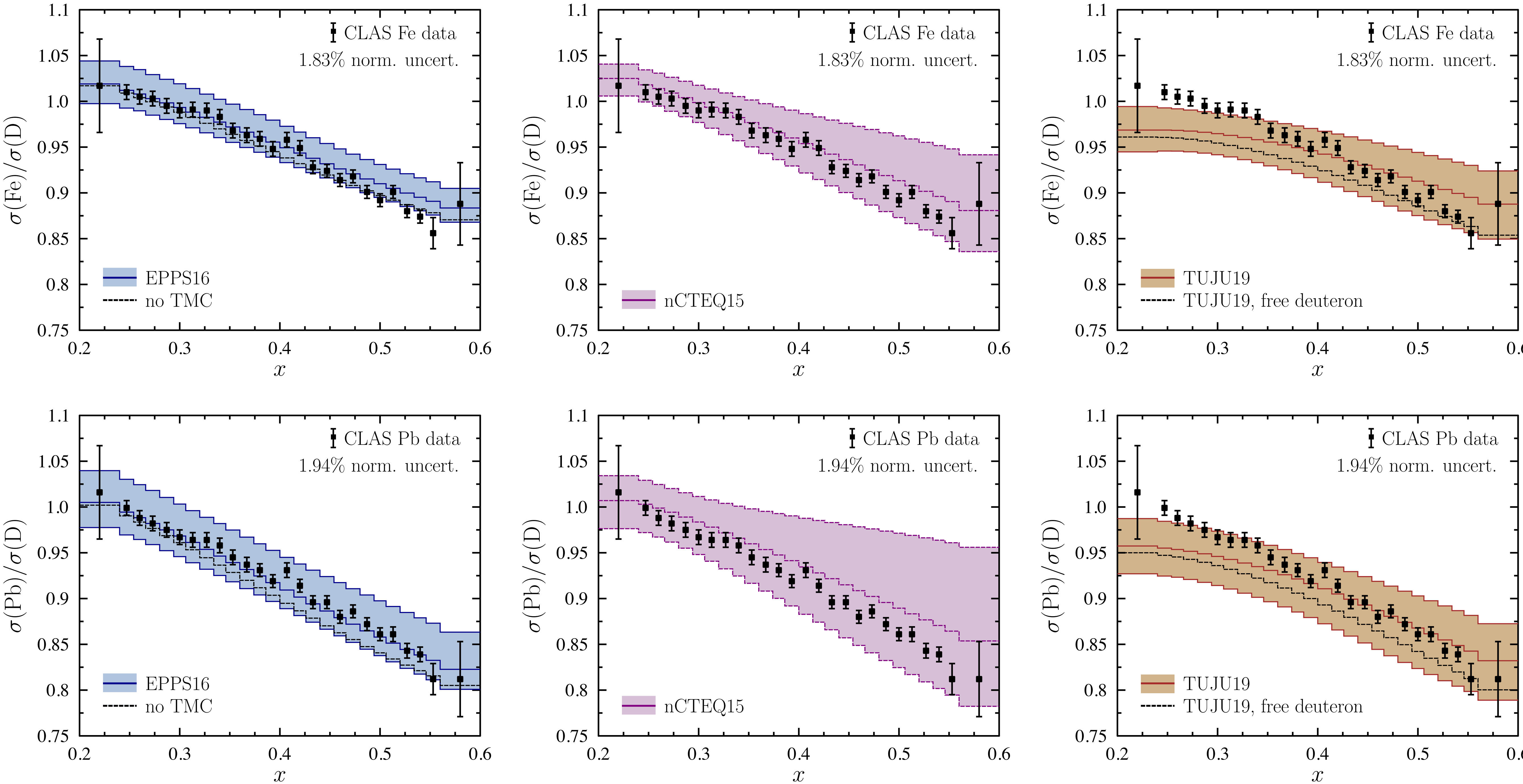
$$x \to \xi = \frac{2x}{1 + \sqrt{1 + 4x^2M^2/Q^2}}$$

$$F_2^{LT}(x, Q^2) \to F_2^{TMC}(x, Q^2) = \frac{x^2}{\xi^2(1 + 4x^2M^2/Q^2)^{3/2}} F_2^{LT}(\xi, Q^2)$$

$$F_L^{LT}(x, Q^2) \to F_L^{TMC}(x, Q^2) = \frac{x^2}{\xi^2(1 + 4x^2M^2/Q^2)^{1/2}} F_L^{LT}(\xi, Q^2)$$

DIS data from CLAS

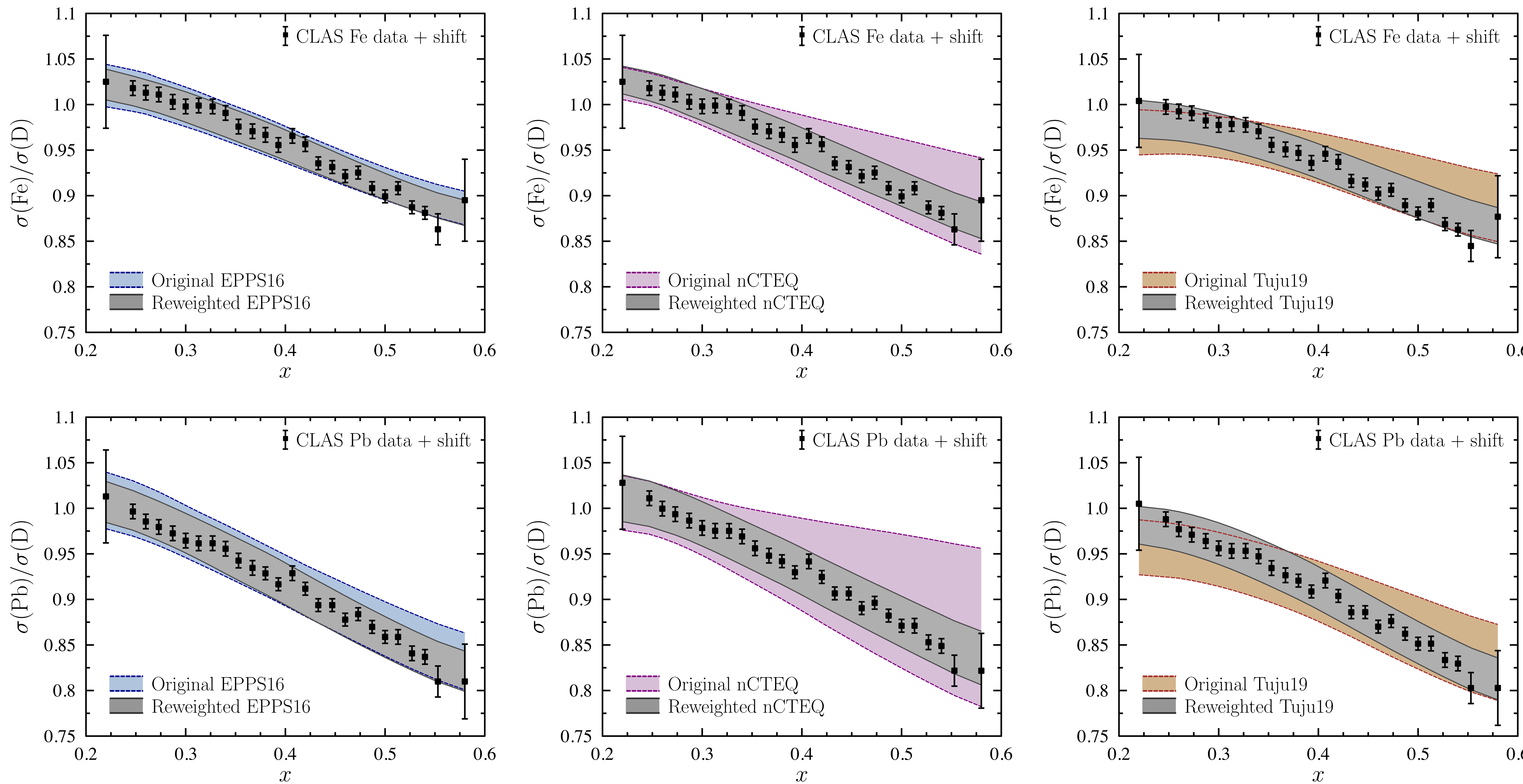
H. Paukkunen and PZ, Eur.Phys.J.C 80 (2020) 5, 381



- TMCs clearly improve the description of the data

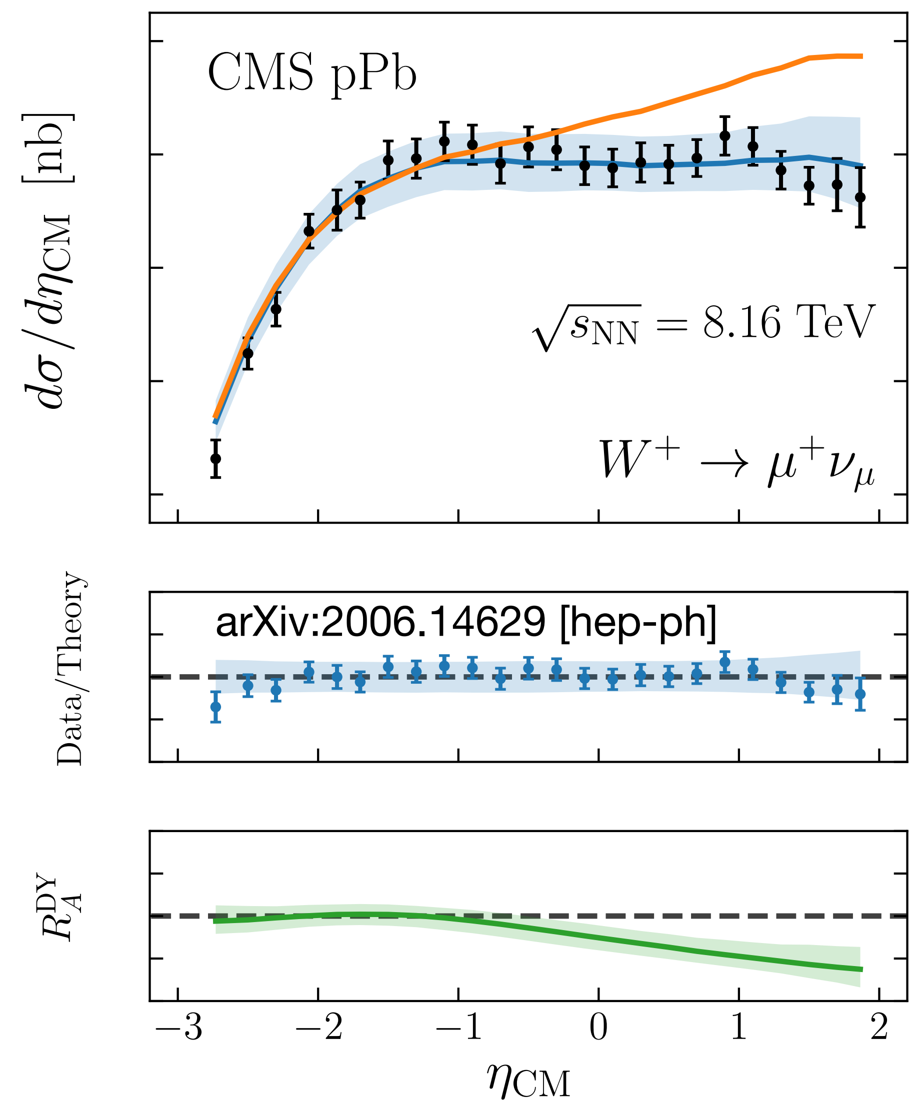
DIS data from CLAS

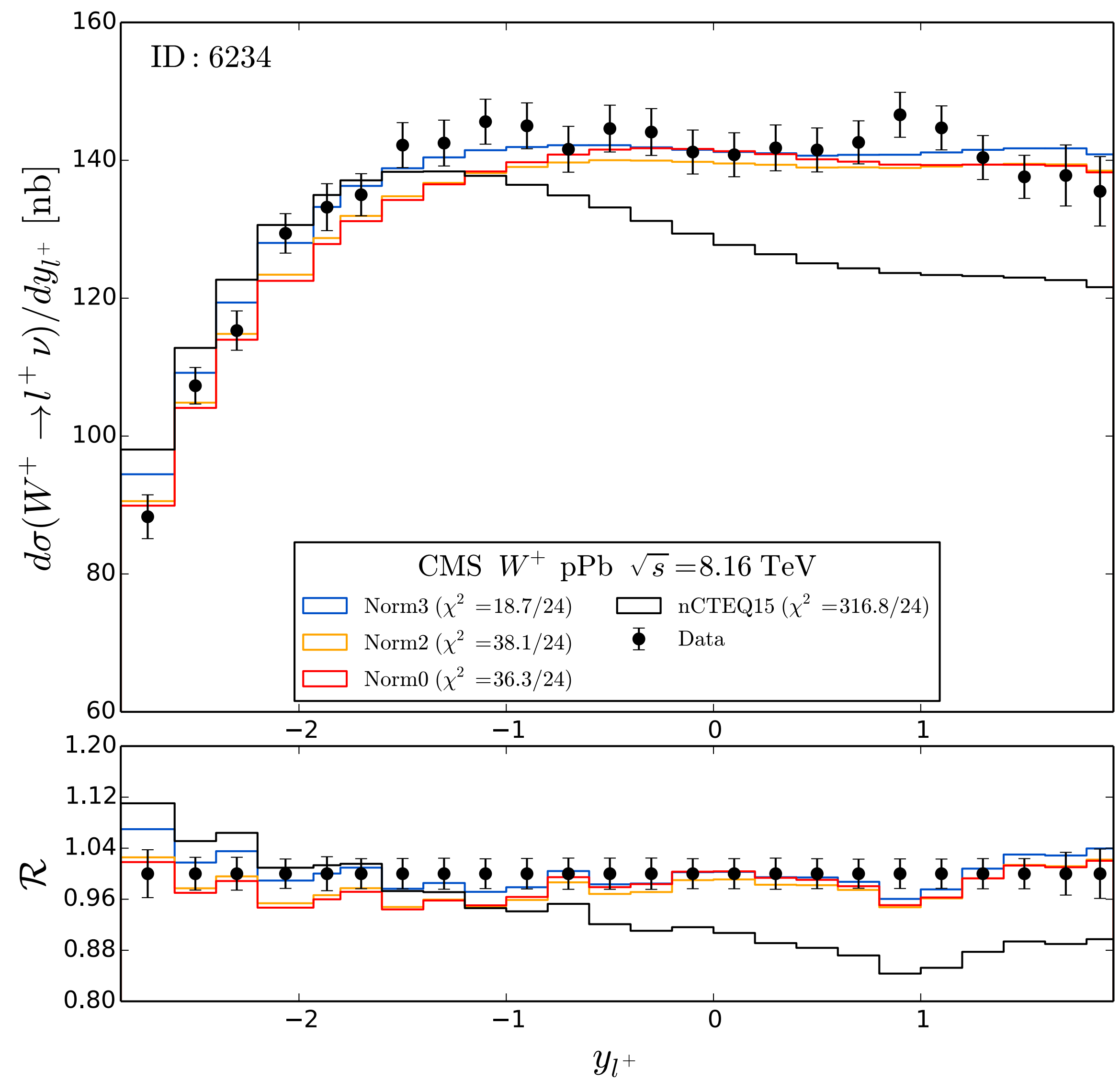
H. Paukkunen and PZ, Eur.Phys.J.C 80 (2020) 5, 381

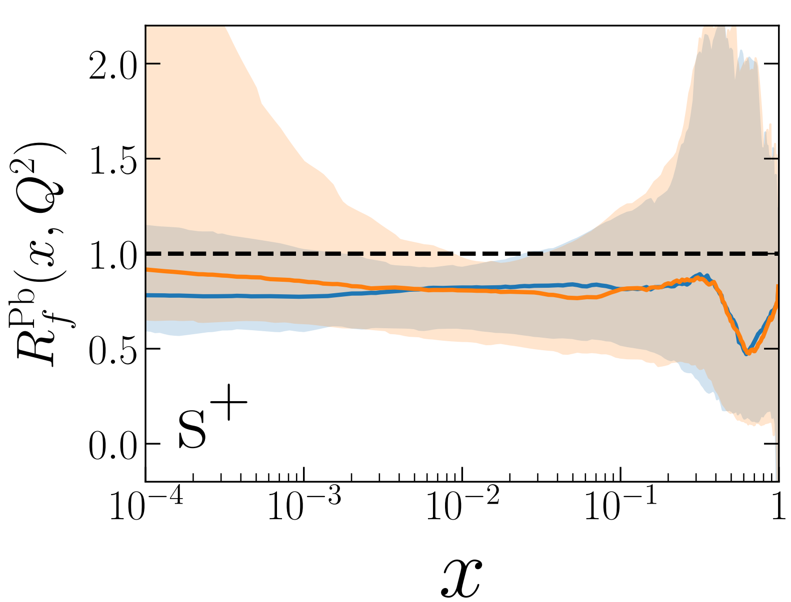


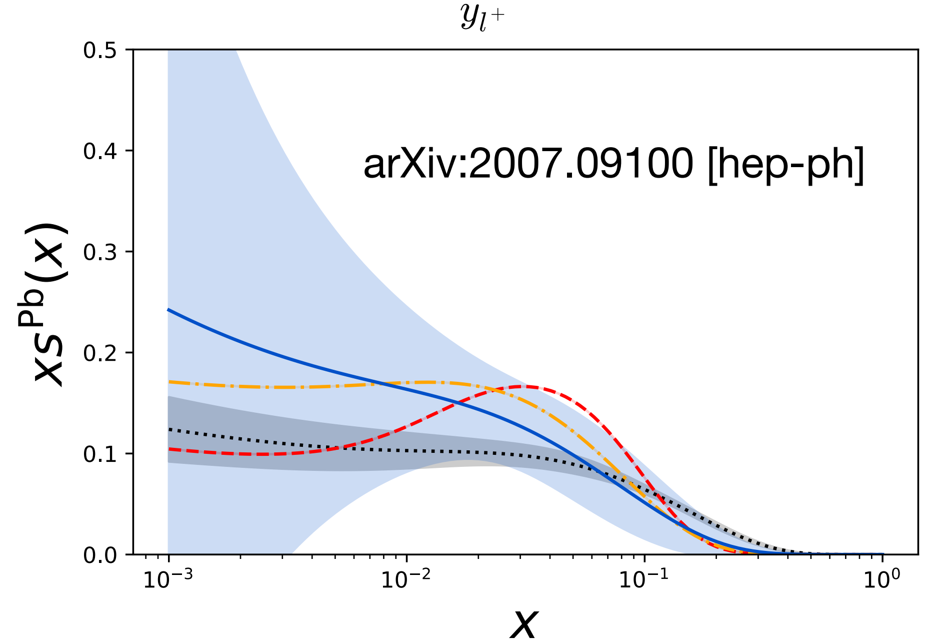
- significant reduction of uncertainties in nCTEQ15 (includes W^2 cut)
- significant reduction of uncertainties in nTuJu19 (includes W^2 cut) and change of "low" x slope

EW boson production at the LHC: EPPS16, nNNPDF2.0, nCTEQ15wz





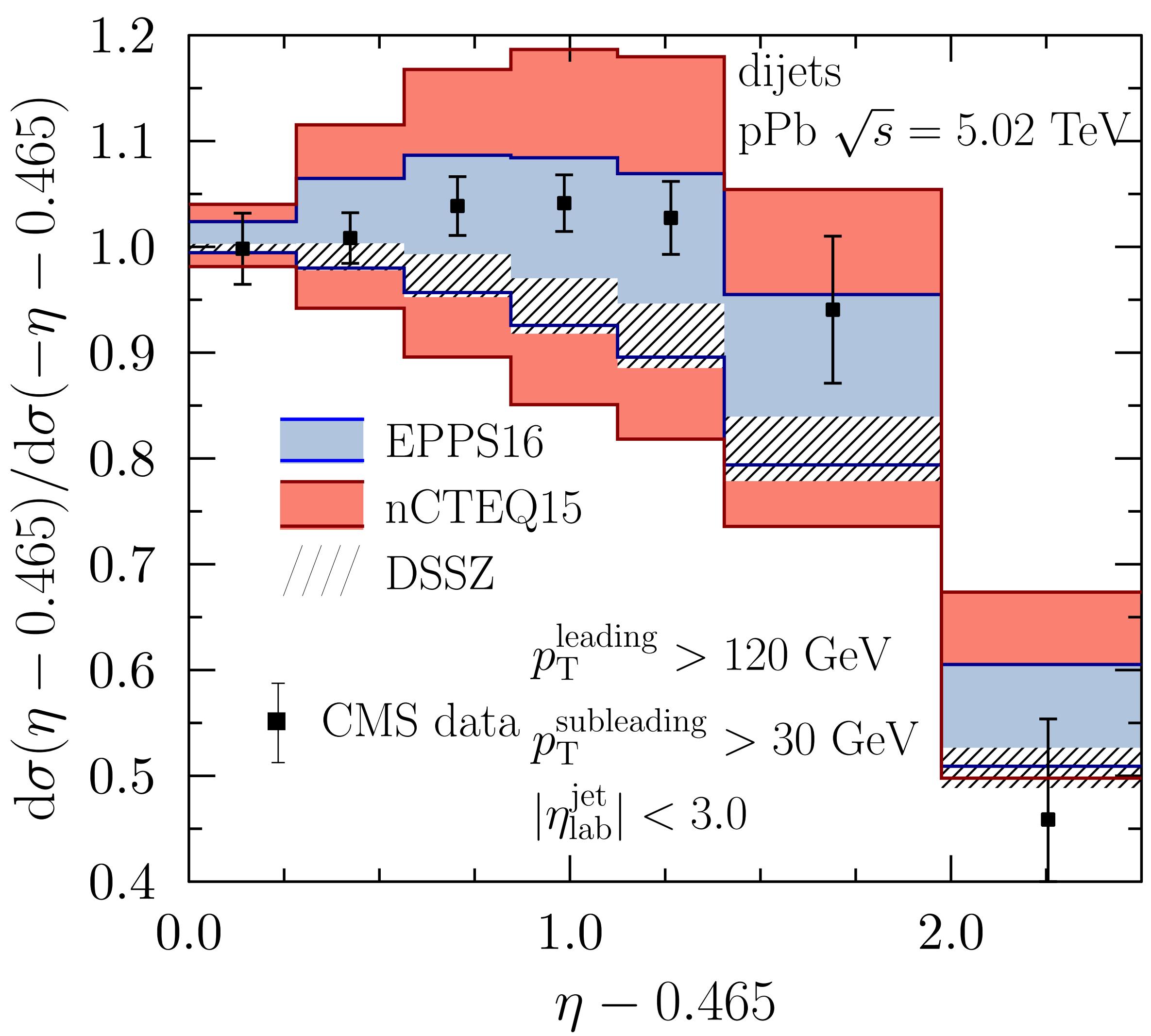




Dijets at CMS: in EPPS16

- decrease of the gluon uncertainties (w.r.t. EPS09) at large x
- excludes solutions with no anti-shadowing
- reduces the relevance of RHIC pion data

EPJ C77 (2017) no.3, 163



are there truly no final state effects in the jet production?

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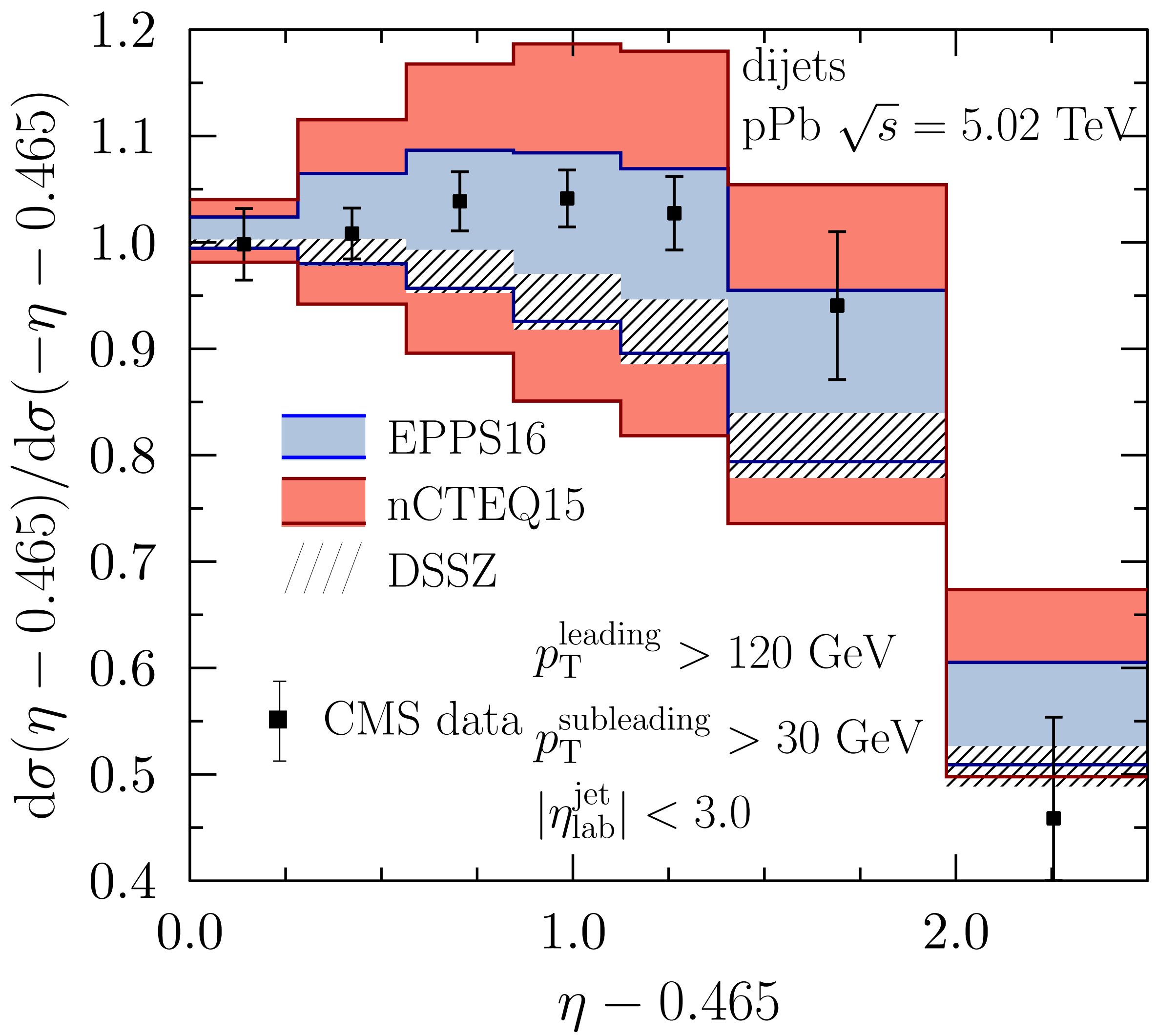
EPJ C77 (2017) no.3, 163



are there truly no final state effects in the jet production?

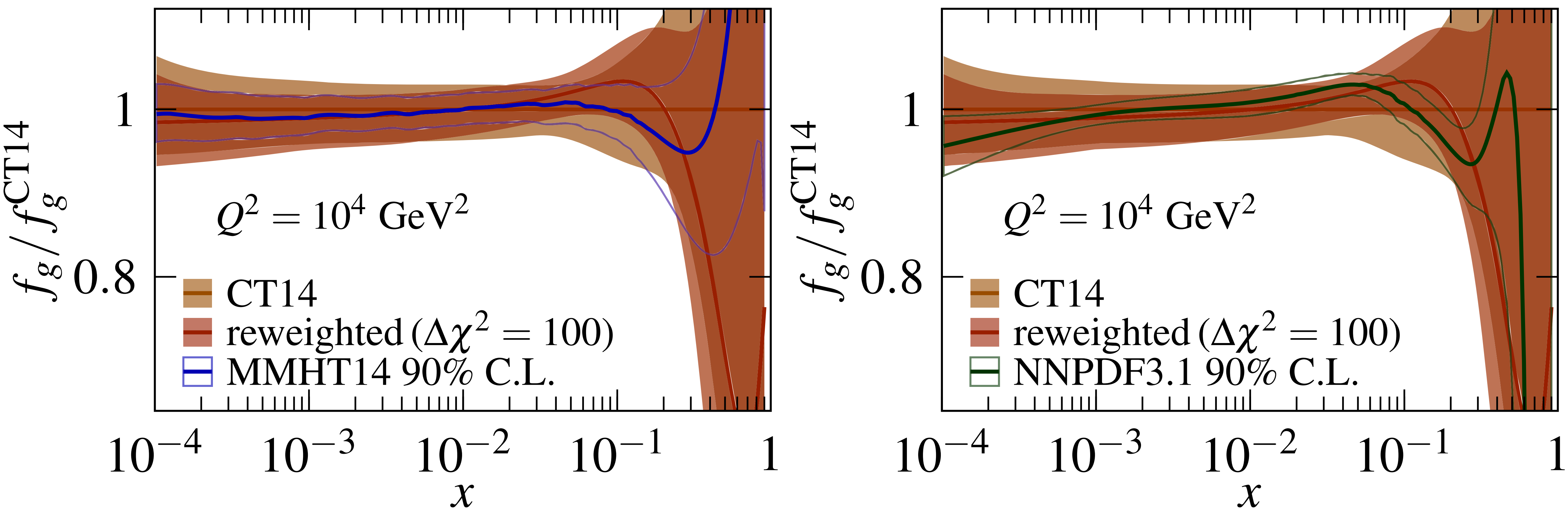
while including new/“new” data can help, it also can introduce additional sources of uncertainties

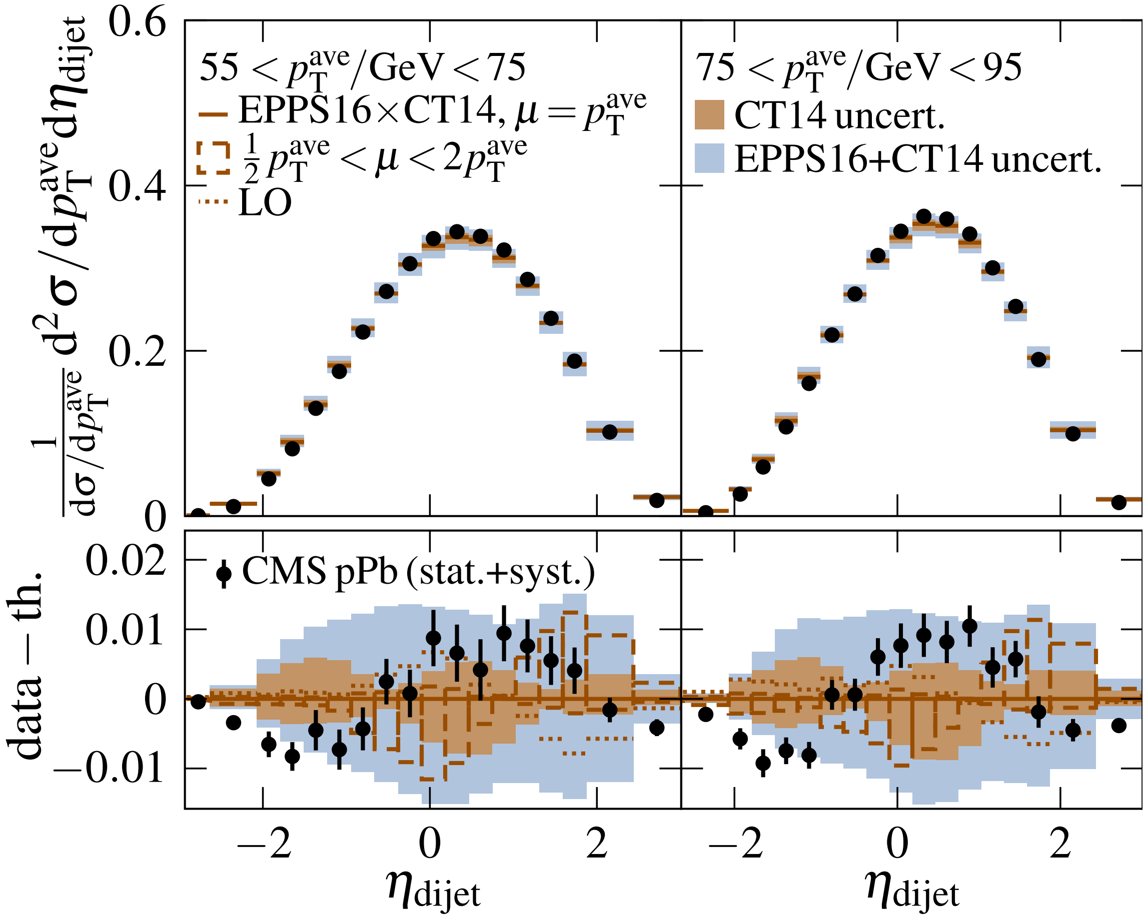
2) THE PROTON BASELINE

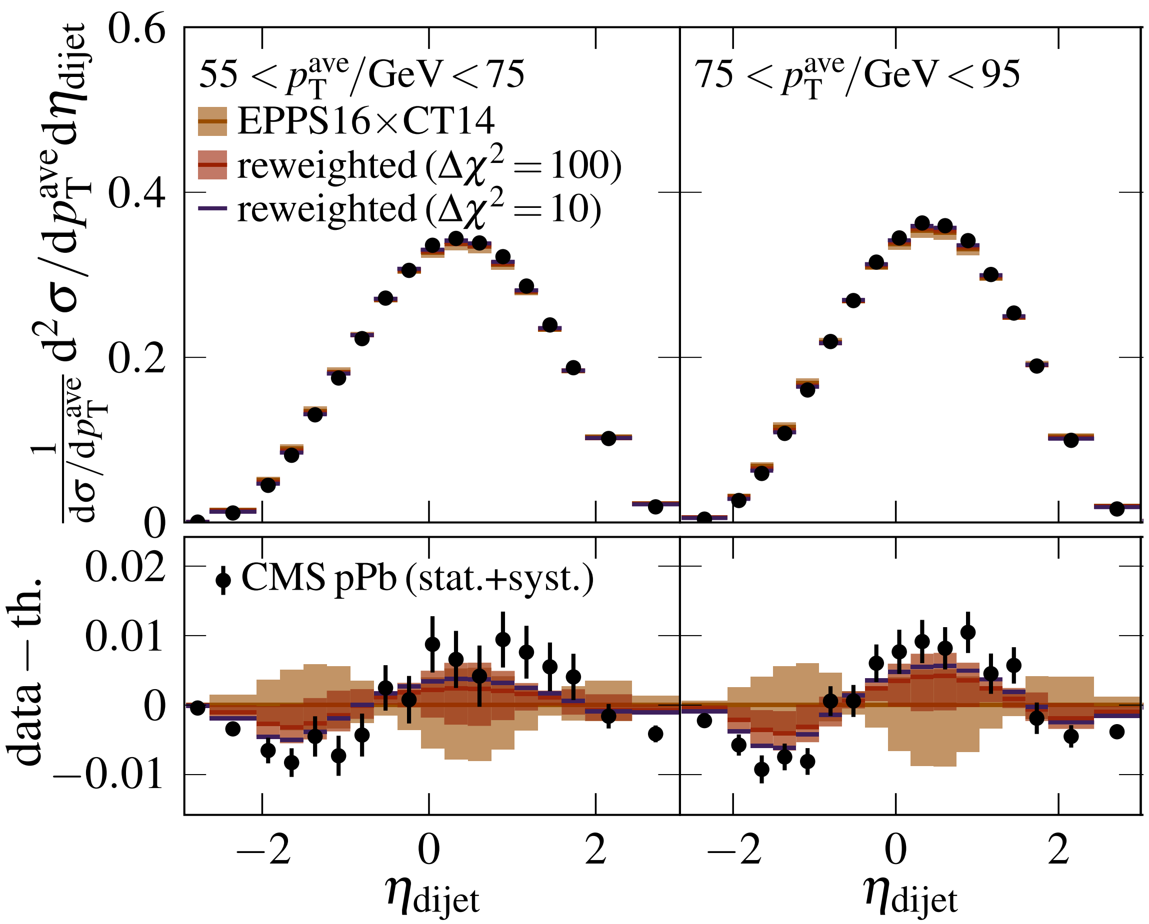
- study of R_{pPb} using Hessian re-weighting

EPJ C79 (2019) no.6, 511

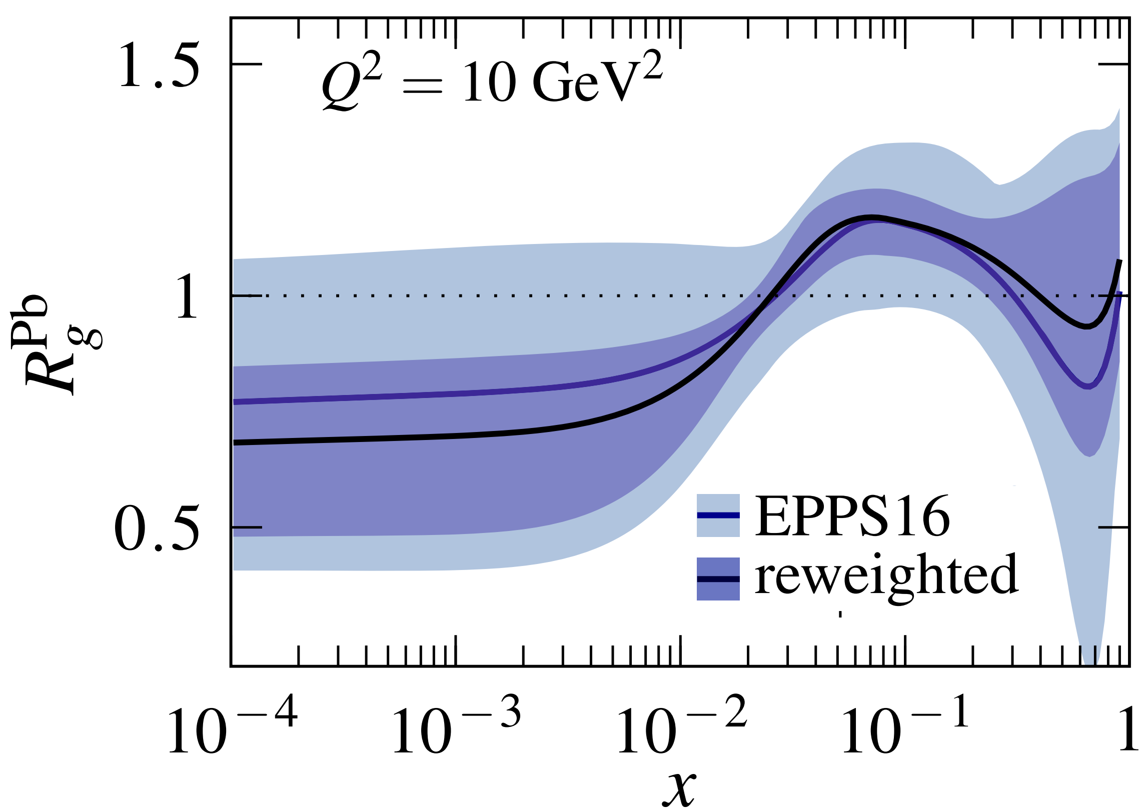
- "We show that the **strong disagreement** between the **pp measurement** and next-to-leading order (NLO) calculations using CT14 NLO PDFs [5] can be brought to a much better agreement upon reweighting the CT14 PDFs, but that **this requires rather strong modifications for high-x gluons**."







EPJ C79 (2019) no.6, 511



3) THE PARAMETRISATION

- initial scale
- how many flavours, how flexible
- recover the proton for A=1

4) THE THEORETICAL CALCULATION

- perturbative order: LO, NLO, etc, and meaning of it
- heavy flavour scheme (FFNS, ZM-VFNS, GM-VFNS)
- nuclear effects in the deuteron?
- final state effects for hadrons?

5) THE FITTING

- define the χ^2, error treatment
- weights for certain data sets
- finding the best tolerance

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5) THE FITTING

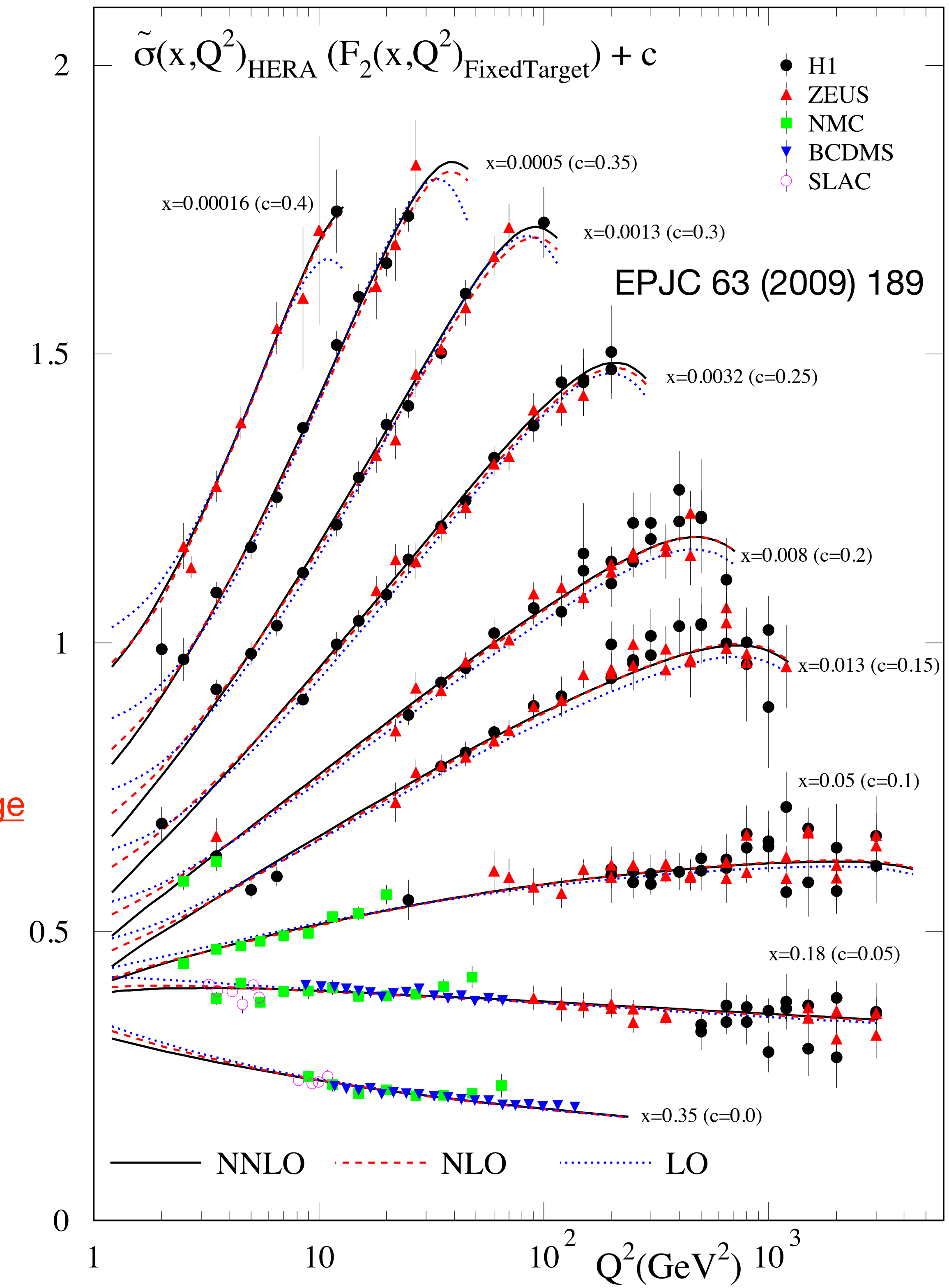
- define the χ^2, error treatment
- weights for certain data sets
- finding the best tolerance

Existing data can only go so far, so what do we need to have precise nPDFs?

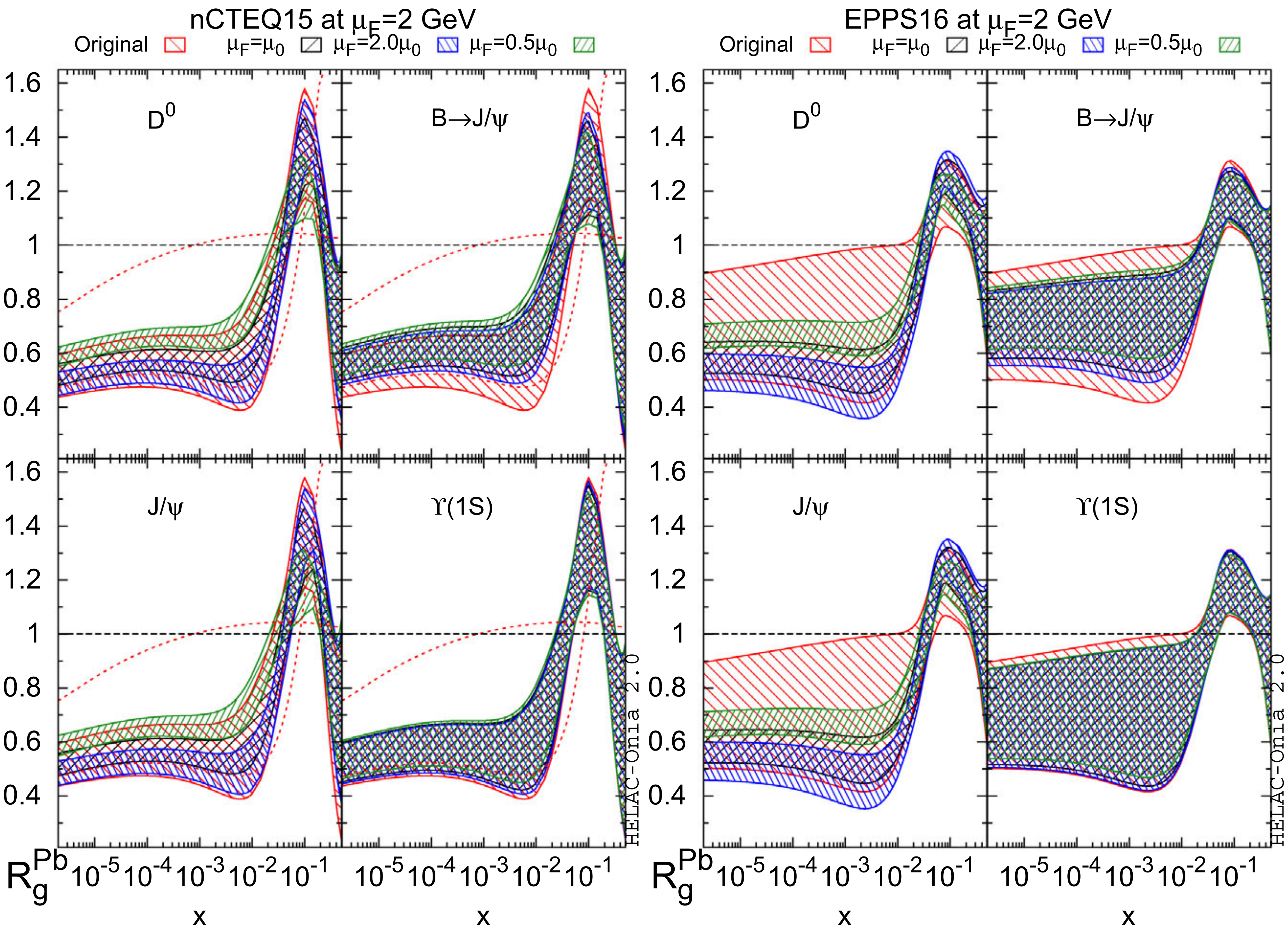
nPDFs @ future colliders

- ideally we should have a “nuclear HERA” and scan the whole kinematic range for many nuclei
- **other existing data**
- JLAB
- AFTER@LHC http://after.in2p3.fr/after/index.php/Main_Page
- but also **RHIC** (STAR forward upgrade + sPHENIX)
- hopefully **EIC** + **LHeC** + FCC-he

MSTW 2008



use of heavy-flavours (also proposed for AFTER)



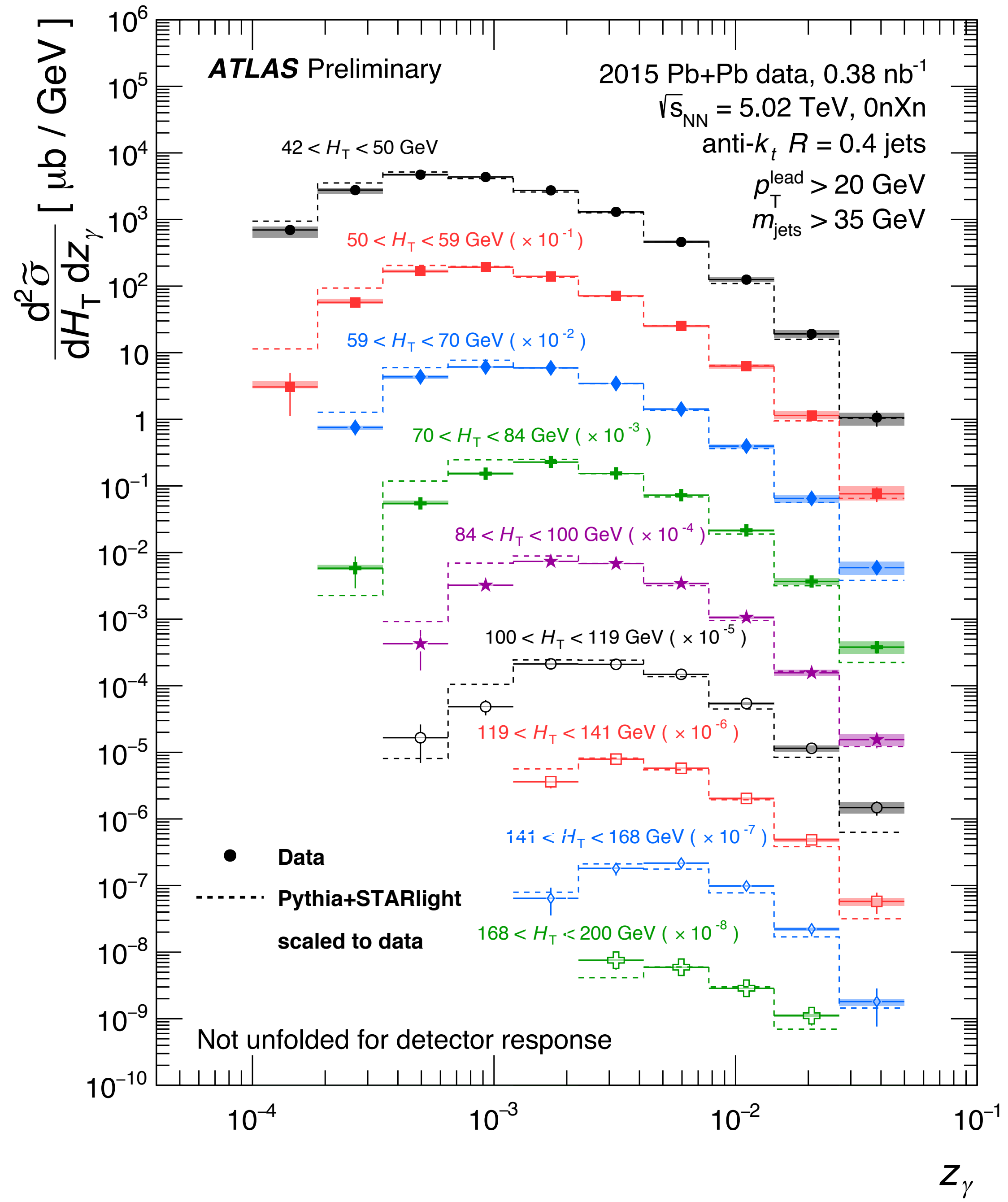
(e) nCTEQ15 nPDF

(f) EPPS16 nPDF

- relies on the assumption that the only nuclear modification appears on the PDFs
- heavy flavour meson production extracted from the p+p LHC data

PRL 121 (2018) no.5, 052004 (based on the method of EPJ C77, 1 (2017)), see also JHEP 05 (2020) 037

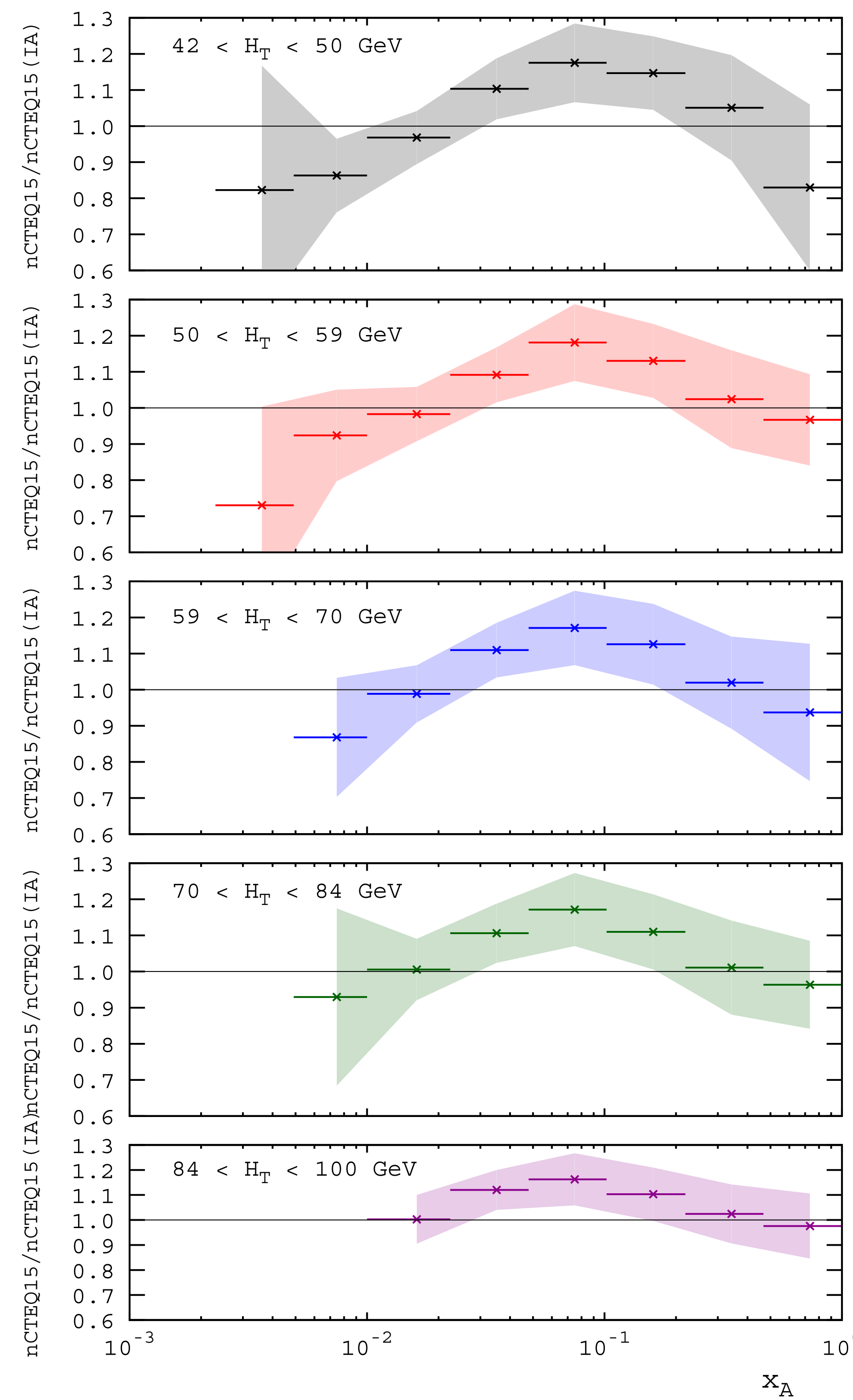
inclusive dijet photoproduction in UPCs in A+A at the LHC



$$H_T \equiv \sum_i p_{T\,i}\,, \quad m_{jets} \equiv \left[\left(\sum_i E_i\right)^2 - \left|\sum_i \vec{p}_i\right|^2\right]^{1/2}, \quad y_{jets} \equiv \frac{1}{2}\ln\left(\frac{\sum_i E_i + \sum_i p_{z\,i}}{\sum_i E_i - \sum_i p_{z\,i}}\right)$$

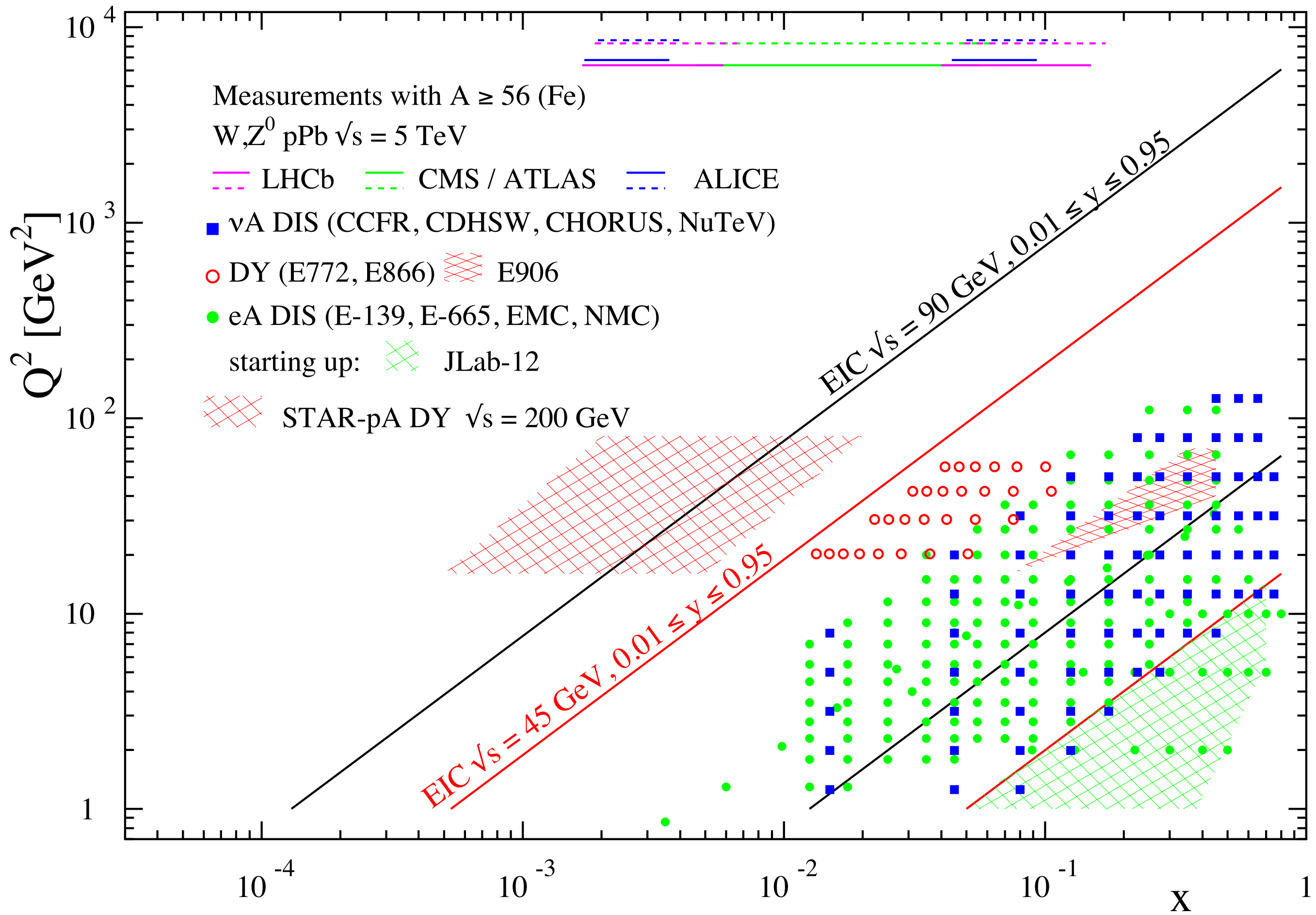
$$z_\gamma \equiv \frac{m_{jets}}{\sqrt{s}}e^{+y_{jets}}\,, \quad x_A \equiv \frac{m_{jets}}{\sqrt{s}}e^{-y_{jets}}$$

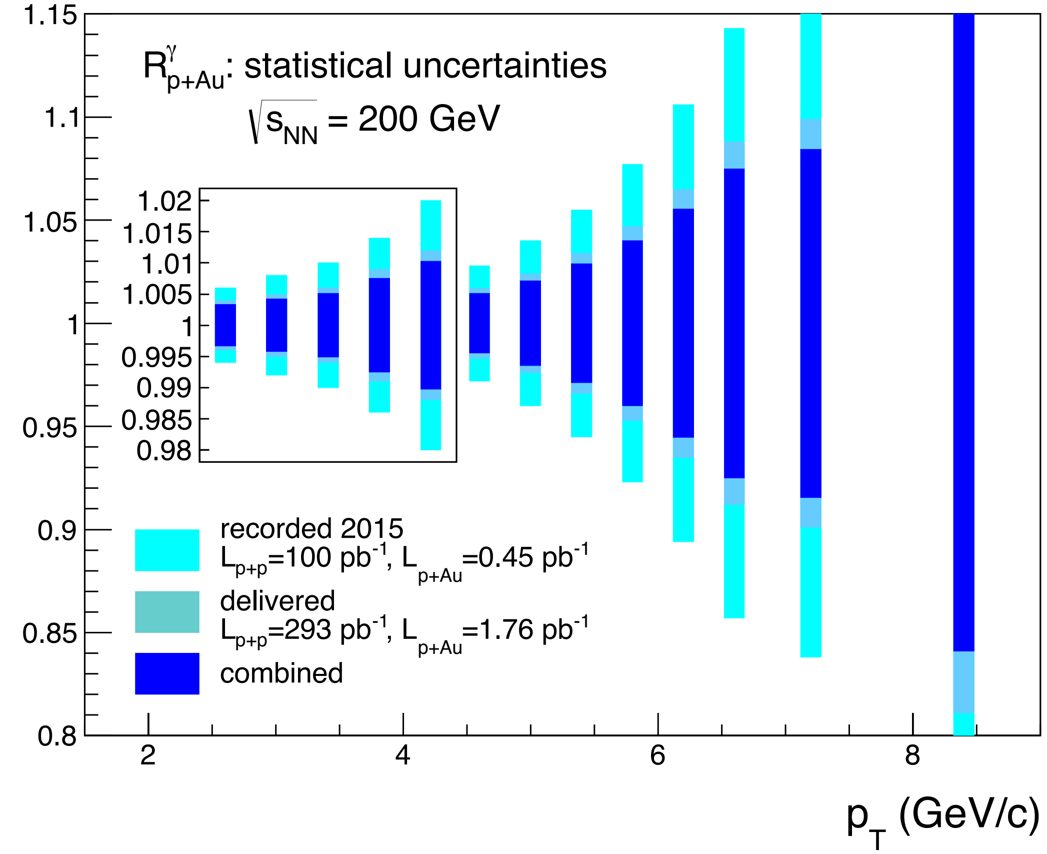
V. Guzey and M. Klasen, PRC99, 065202 (2019)



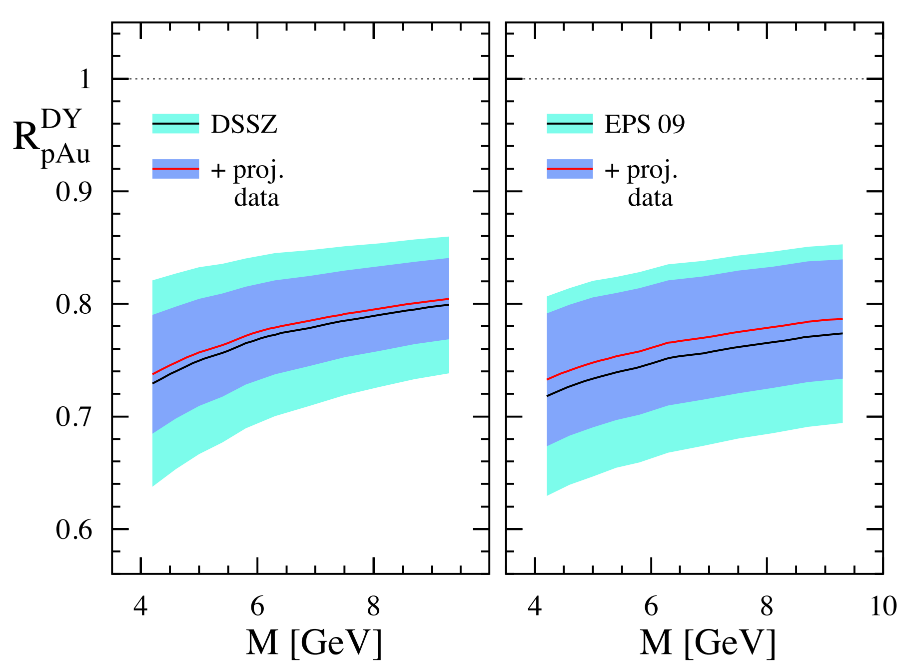
with pseudo data @ RHIC

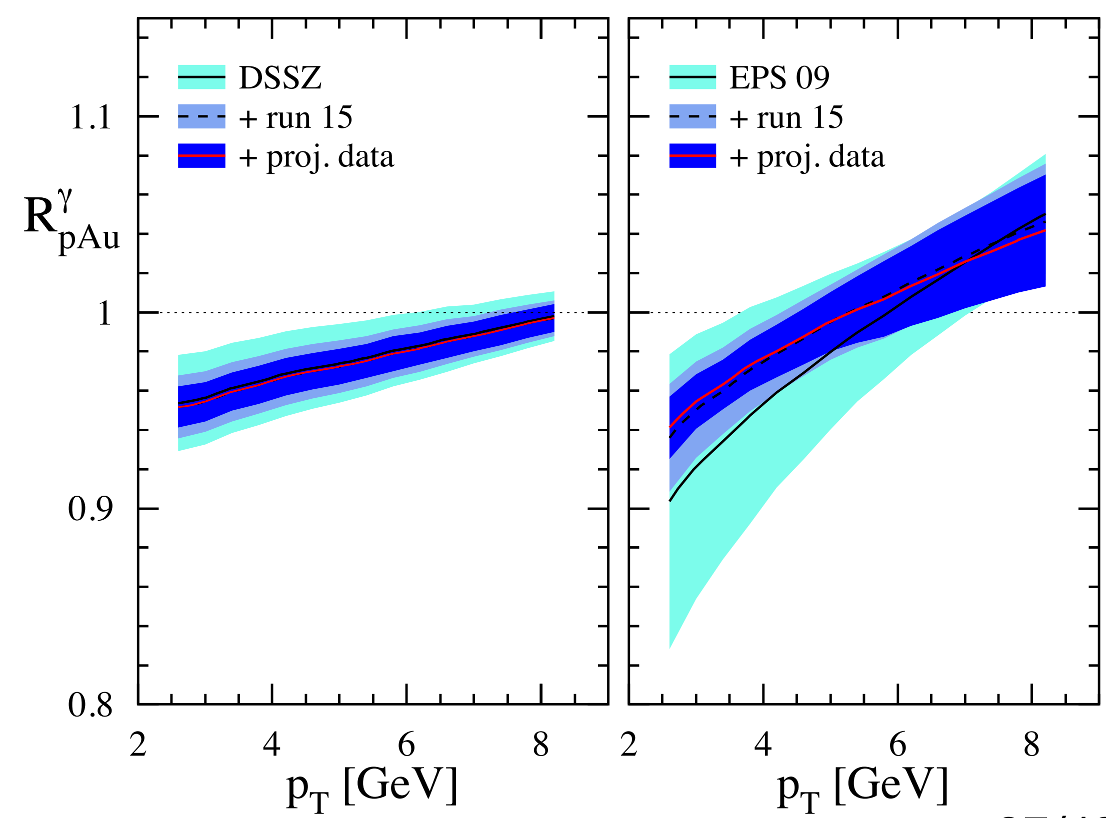
arXiv:1602.03922v1 [nucl-ex]





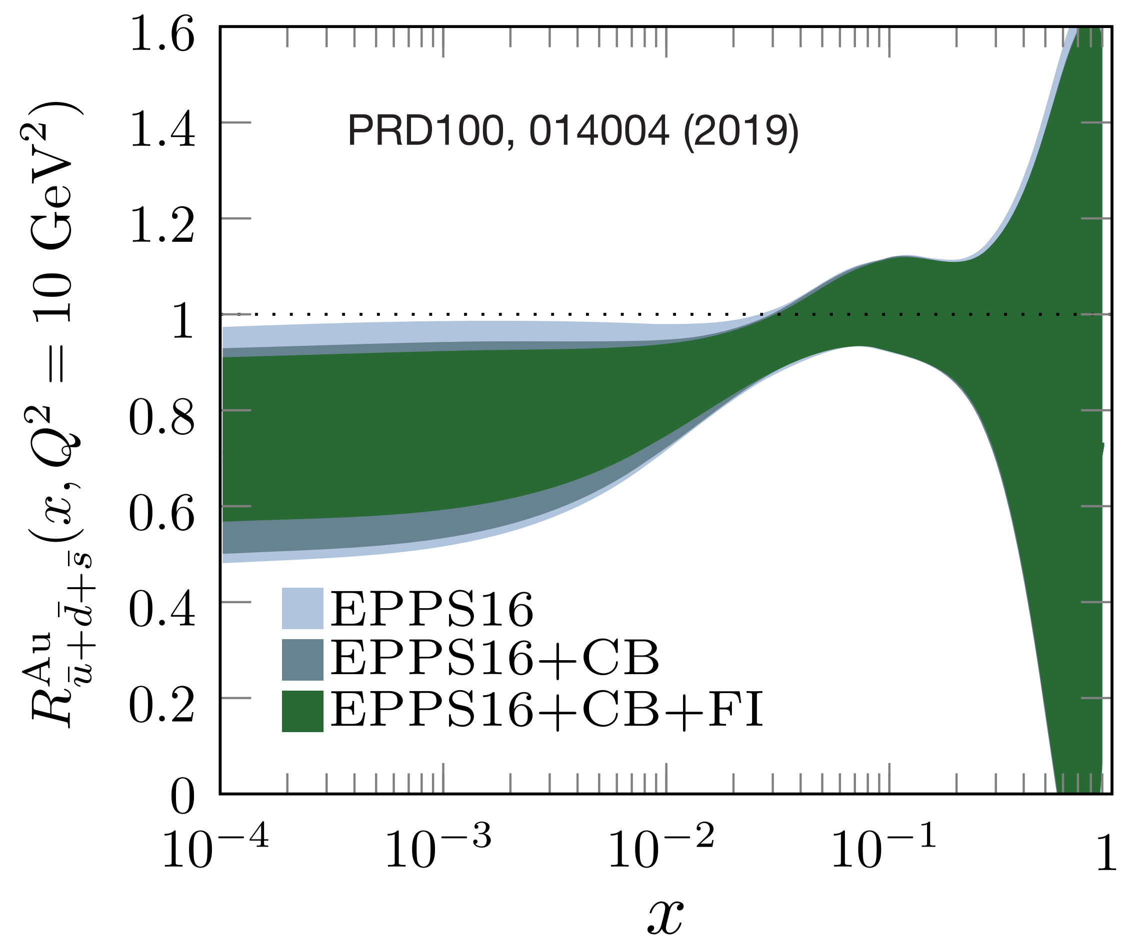
- c.m.s : 200 GeV
- p+Au
- Drell-Yan
- Prompt photon

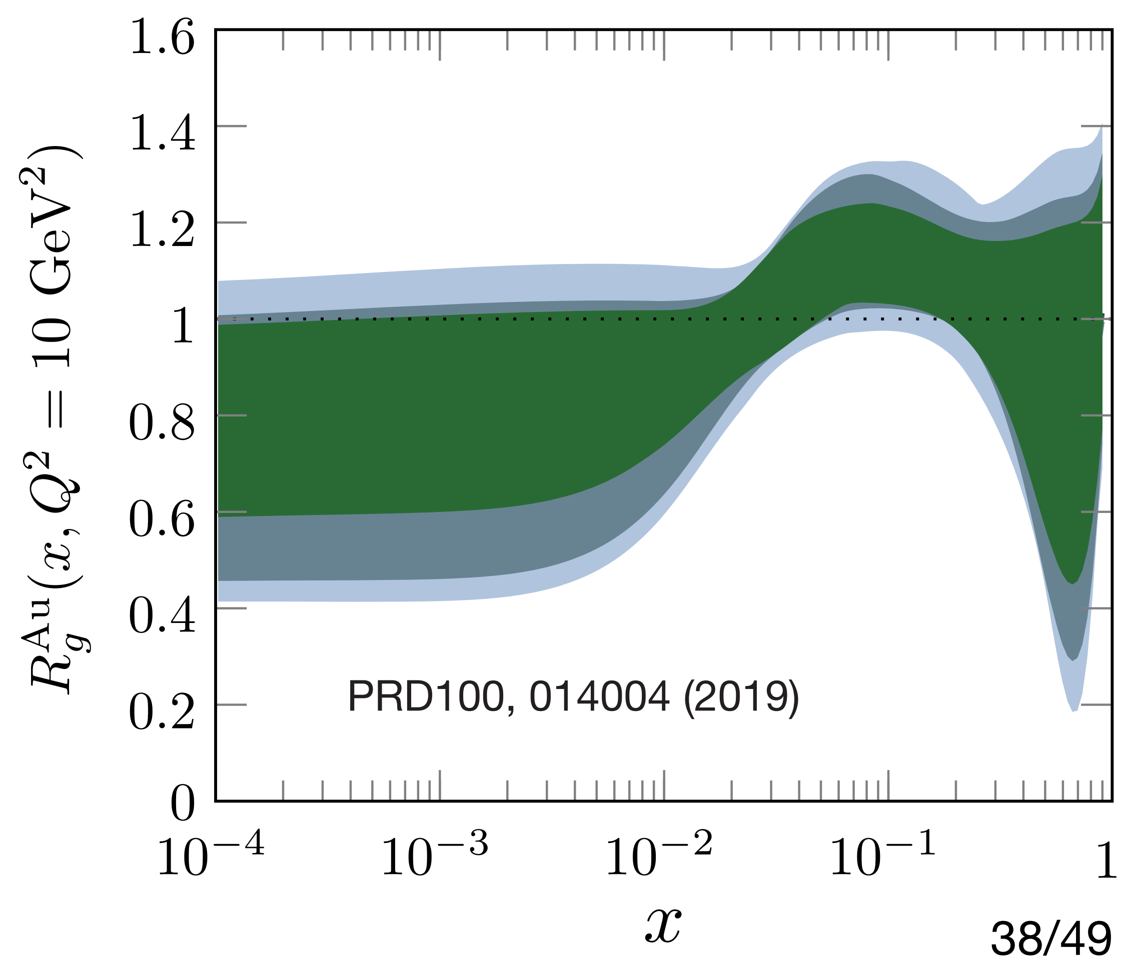




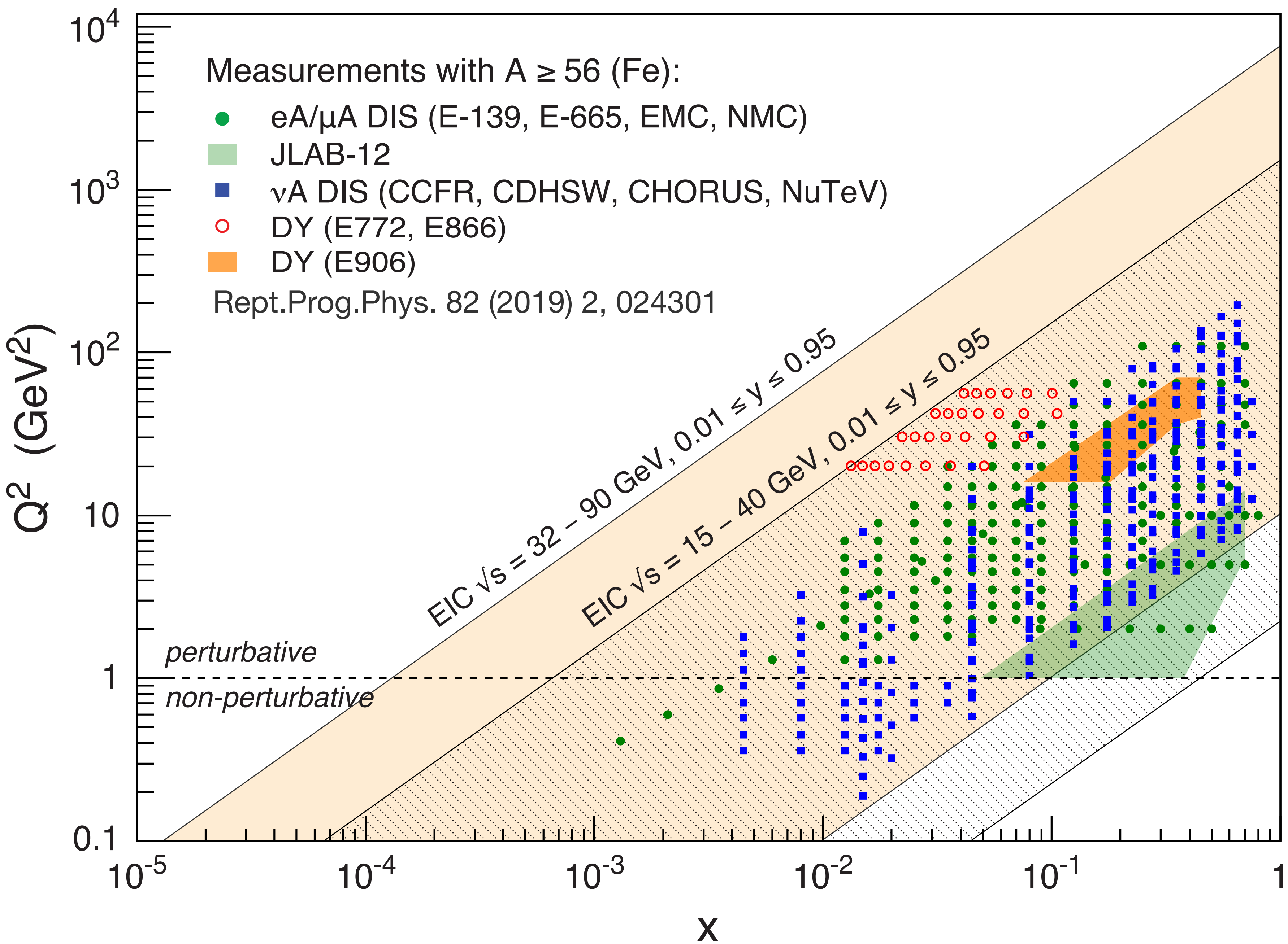
- Comprehensive study: Drell-Yan + dijets + photon jet
- CB : central barrel
- FI : forward instrumentation (STAR upgrade, sPHENIX)

- Joint impact studies (as it would be in a global fit) decrease the relevance of individual data sets
- Medium-modifications of the FFs can also be studied at RHIC



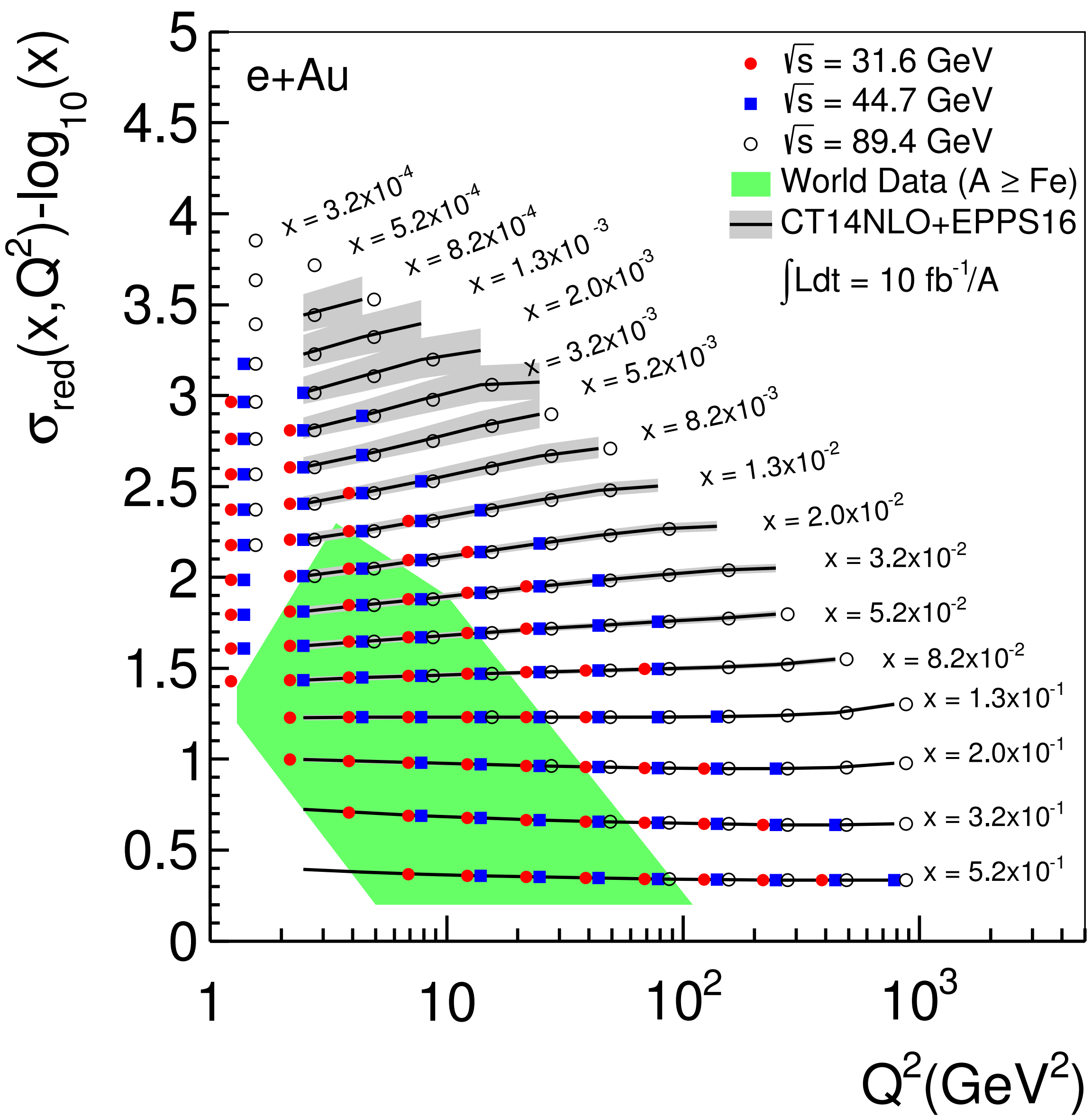


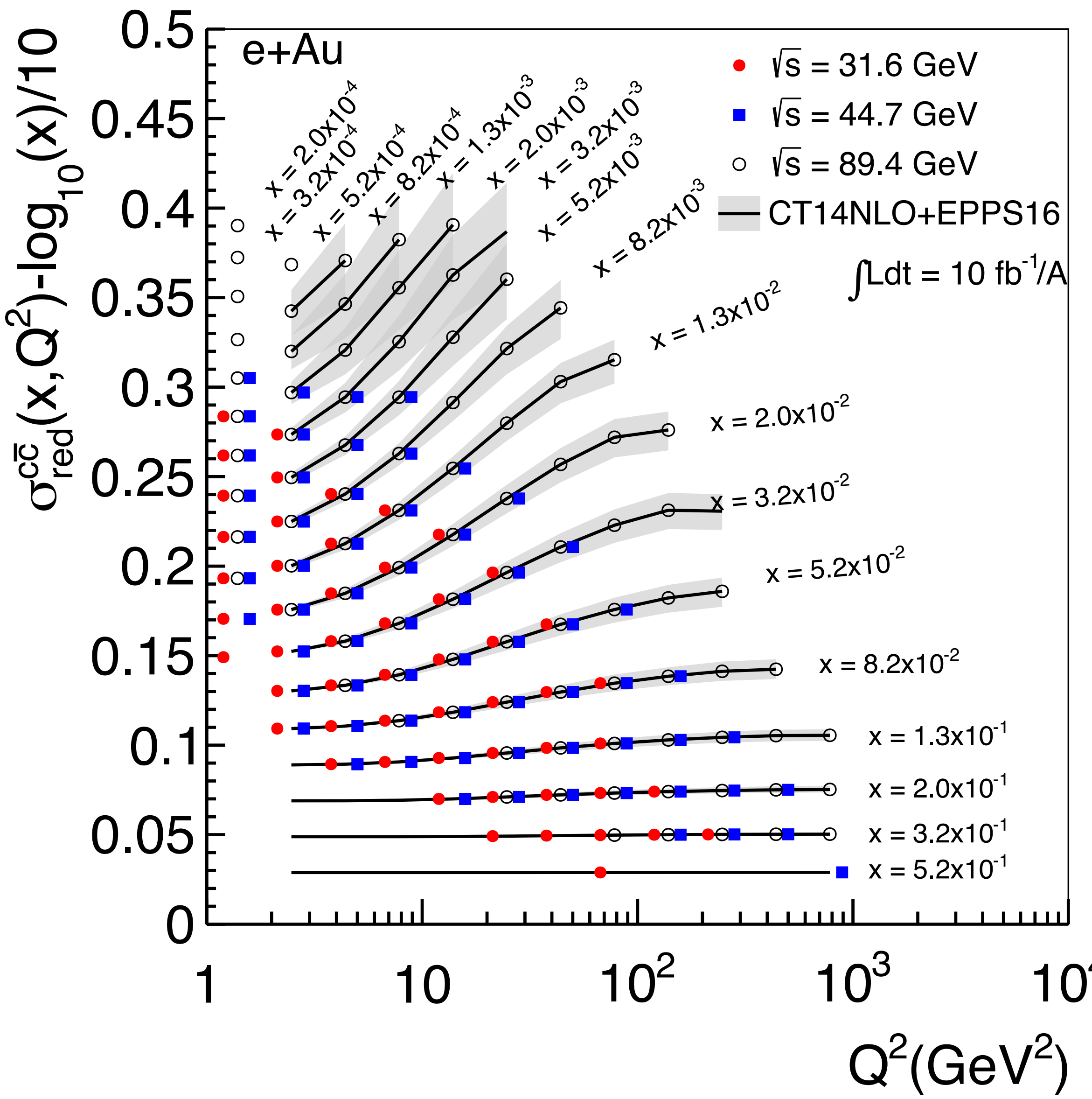
with pseudo data @ EIC



- DIS
- jets
- SIDIS?

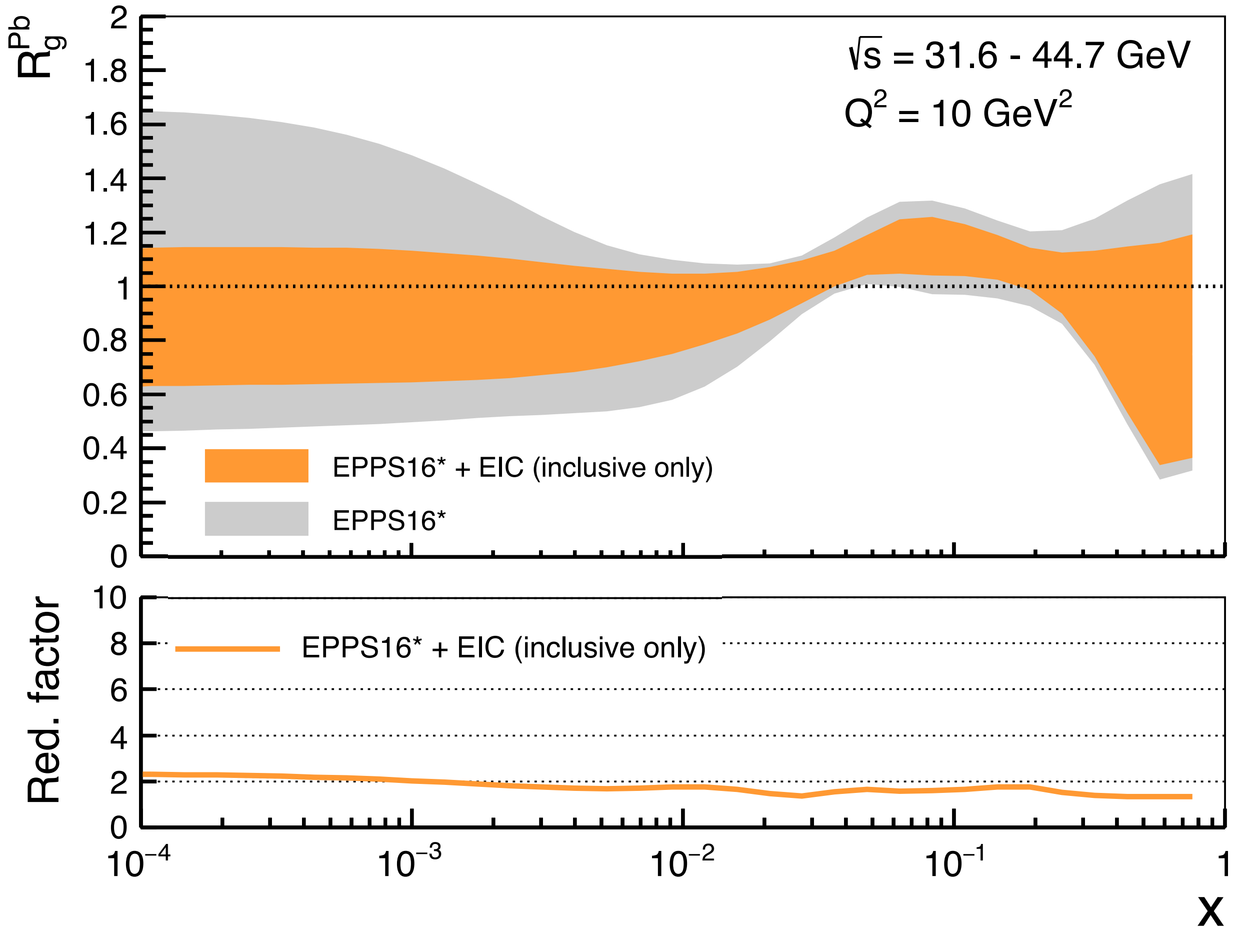
- DIS: reduced cross-section (inclusive and charm)
- pseudo-data using CT10 NLO proton PDFs + EPS09 nPDFs
- check impact on EPPS16*

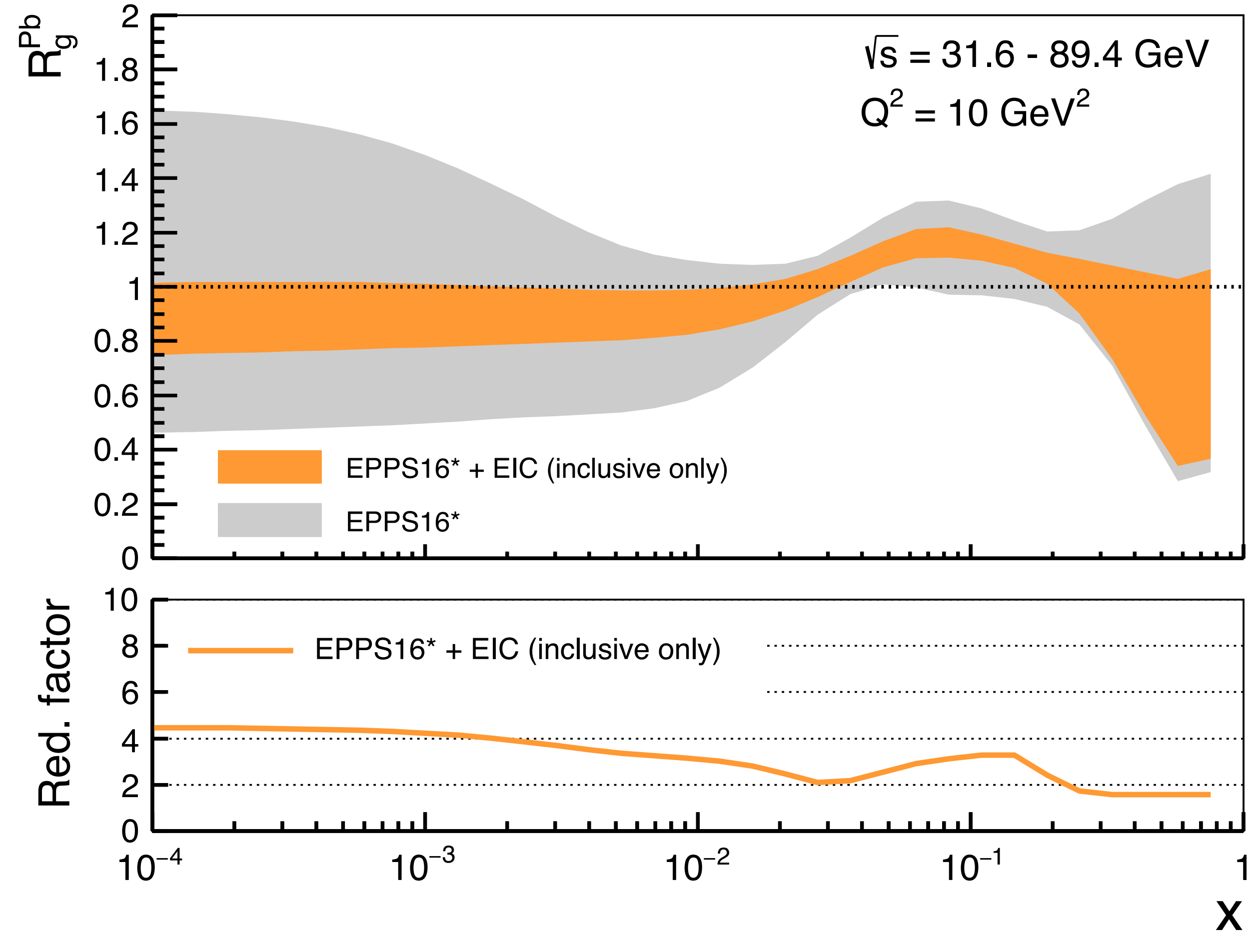




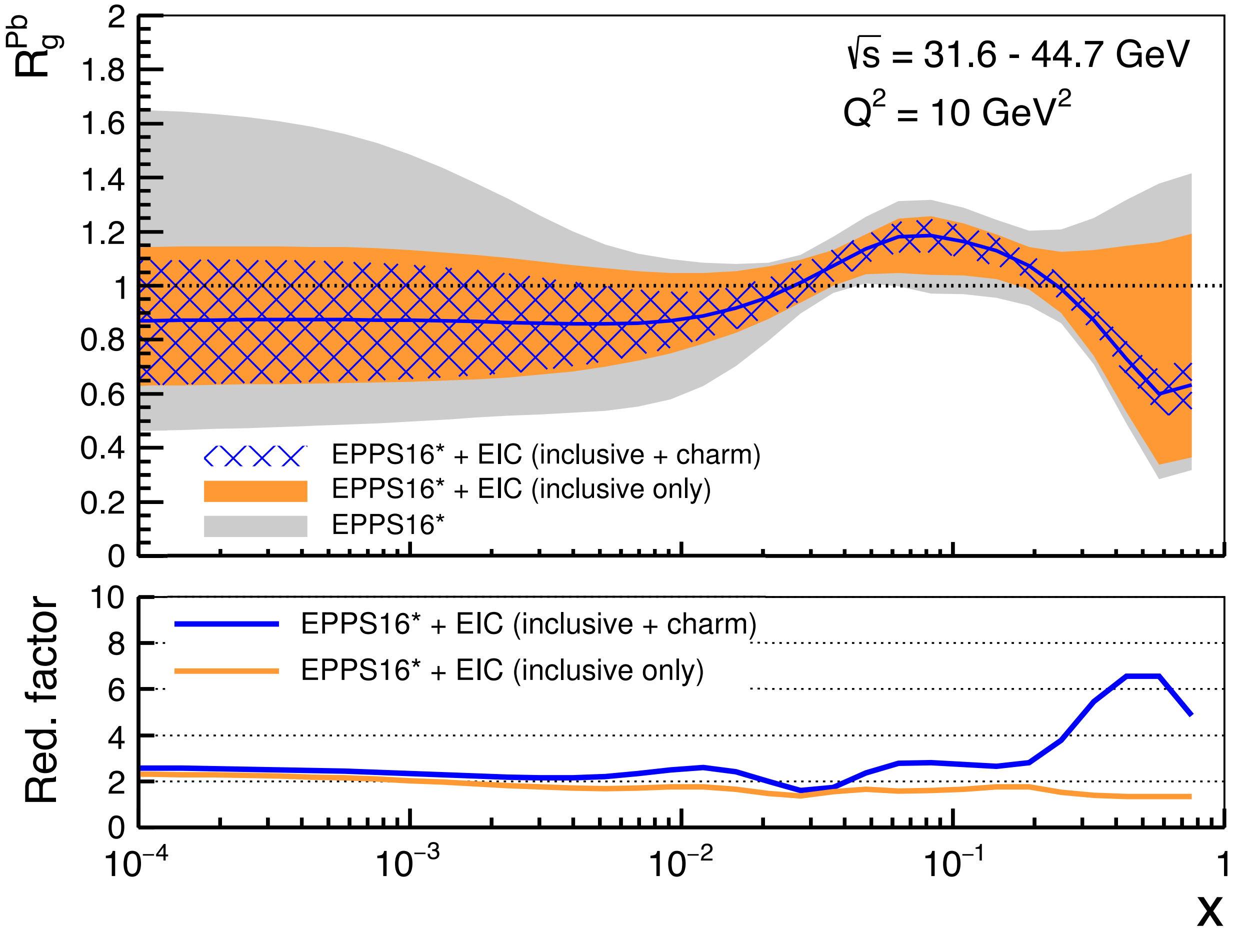
Aschenauer, Fazio, Lamont, Paukkunen, PZ, PRD96 (2017) no.11, 114005

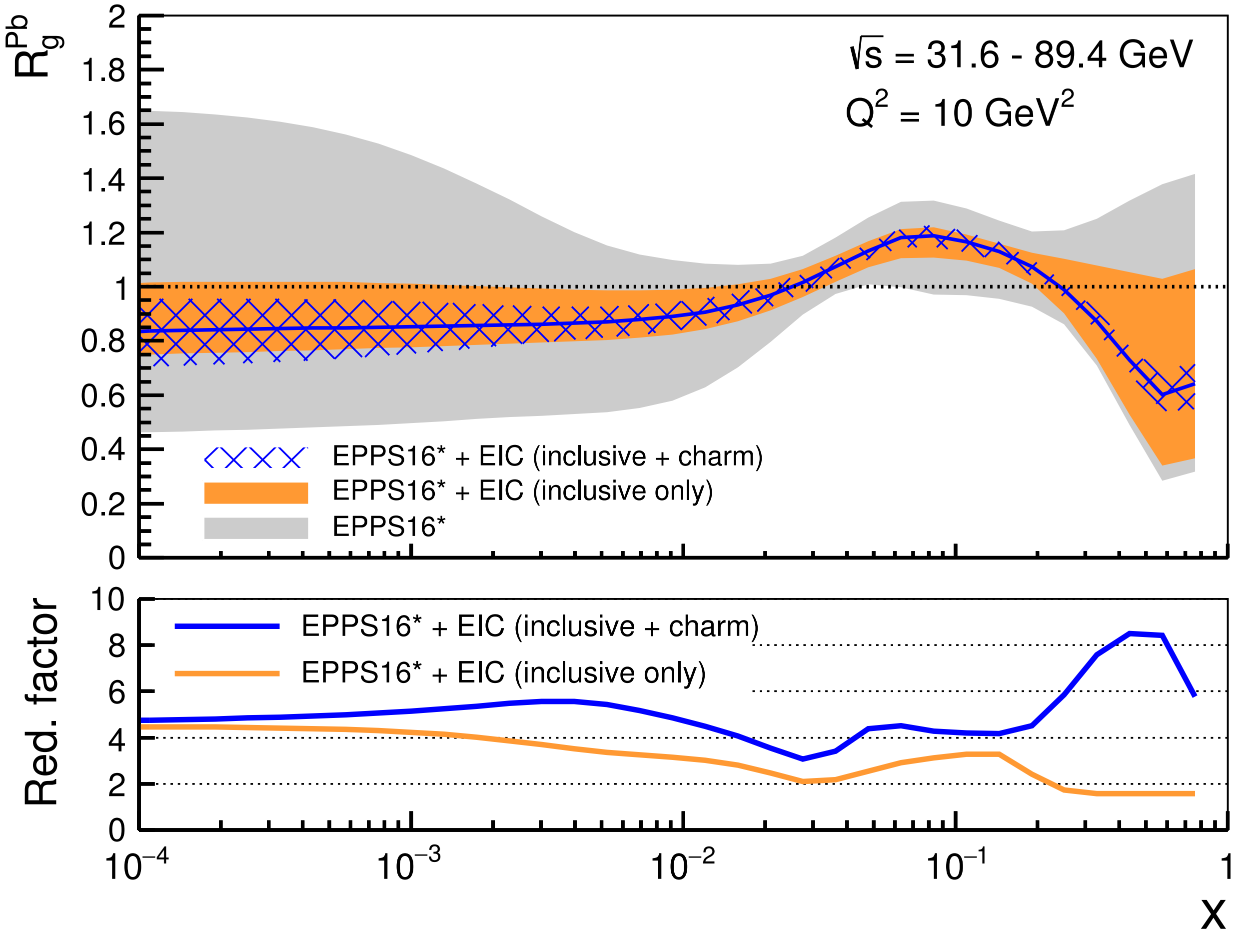
PRD96 (2017) no.11, 114005



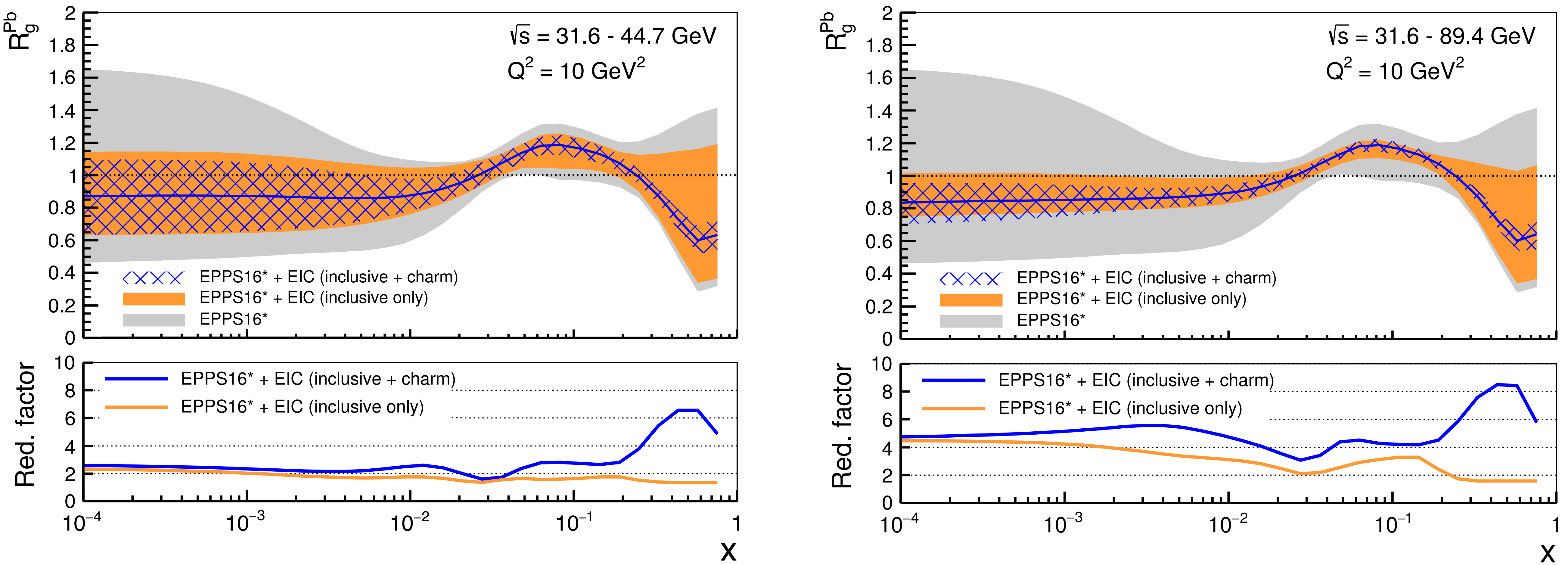


PRD96 (2017) no.11, 114005





PRD96 (2017) no.11, 114005

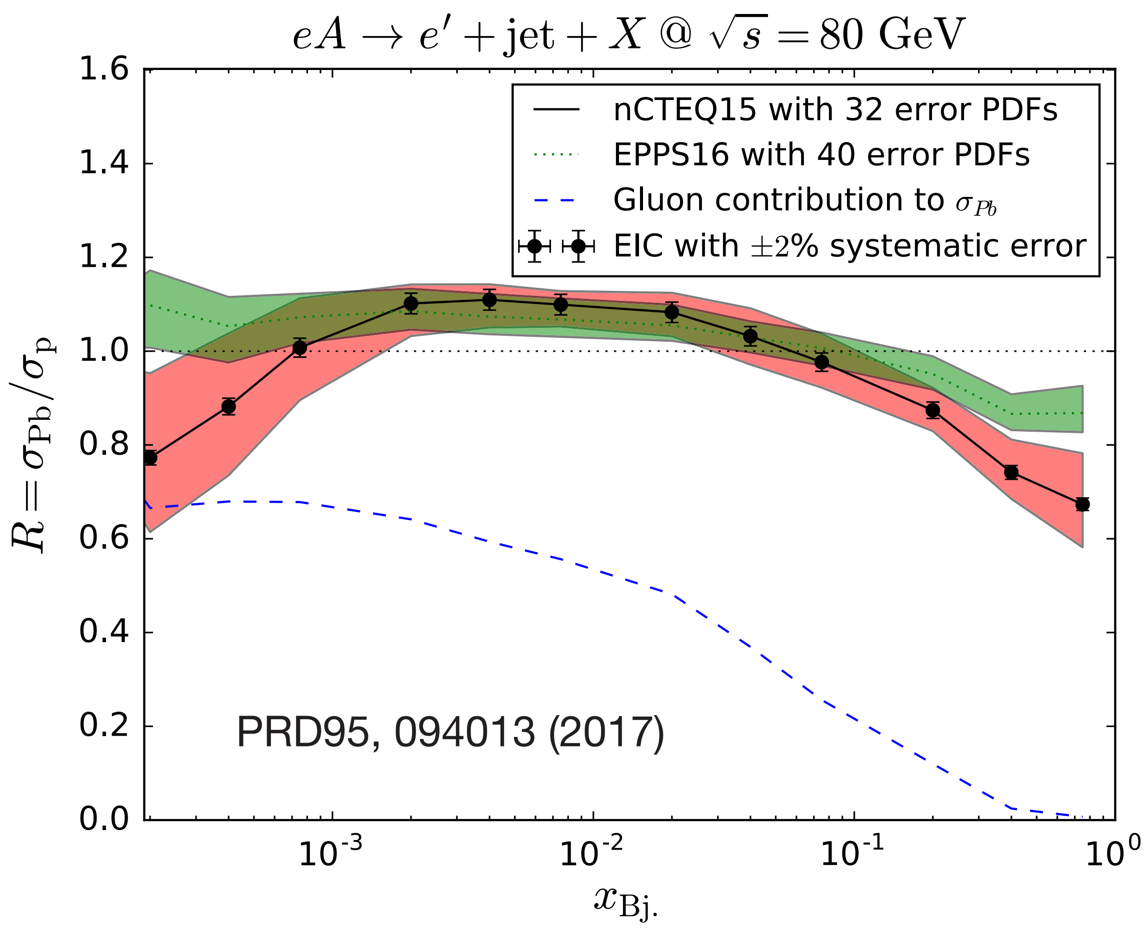


- we only checked the impact on the gluon (but also affects other partons)
- inclusive DIS constrains the gluon at low x, not at high x (unsurprisingly)
- charm cross-section has an enormous impact on the high x gluon

inclusive jet production in e+A

gluon initiated processes give

- ~ 60% of the cross-section at low scales
- ~ 60% of the cross-section for x < 0.01



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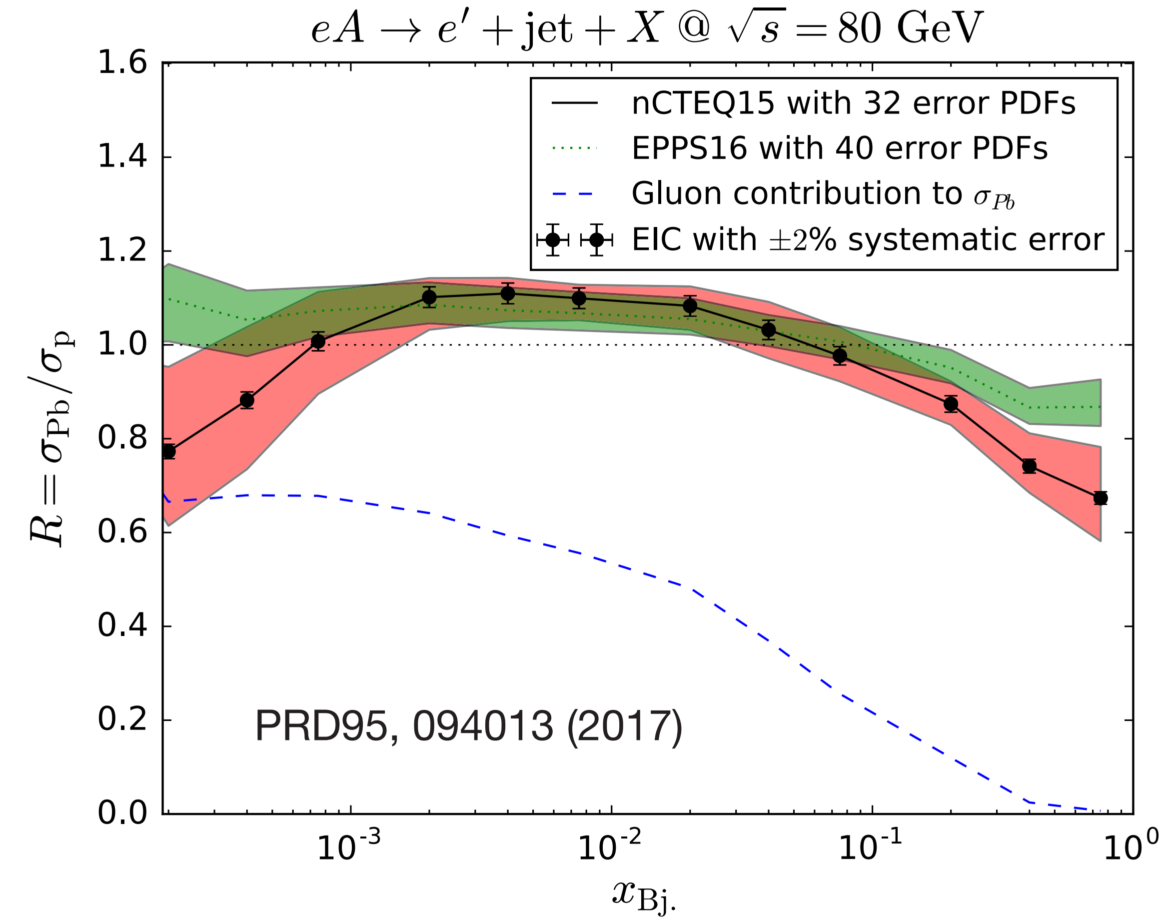
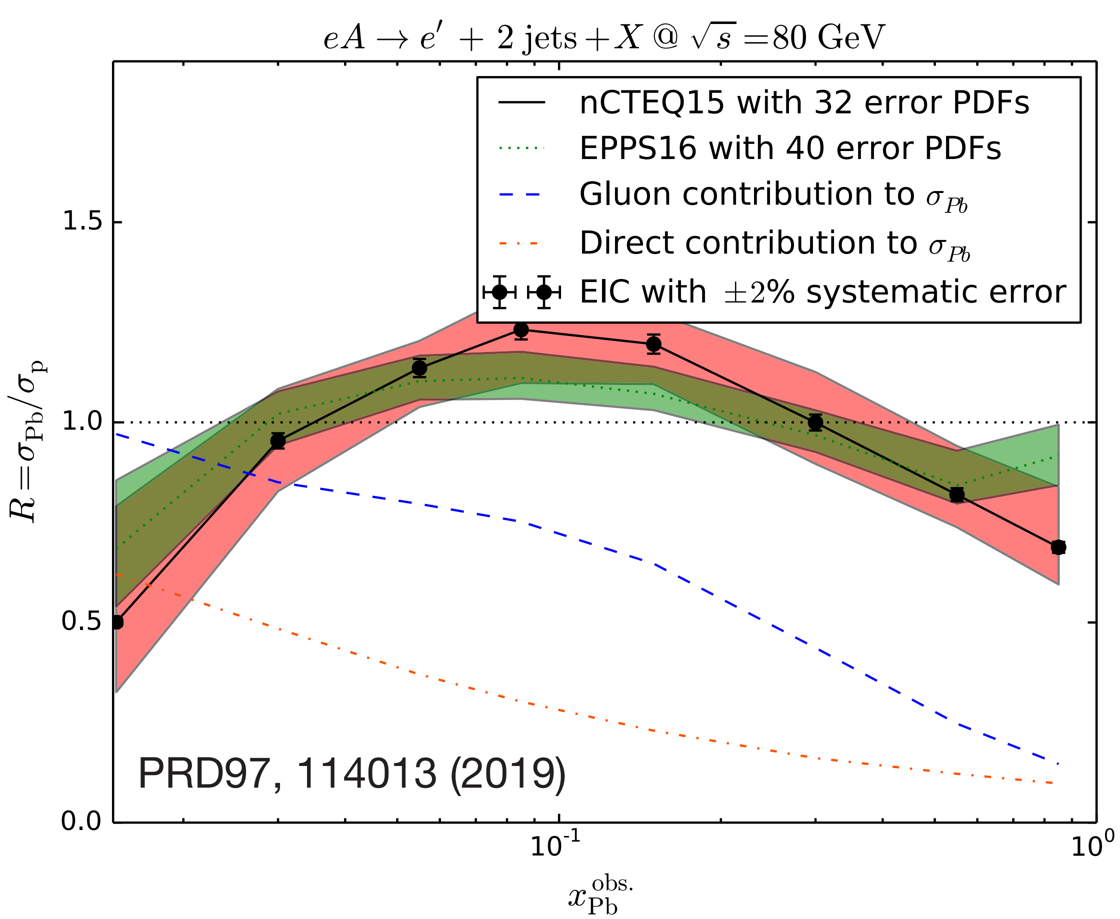


- dijet photoproduction in e+A



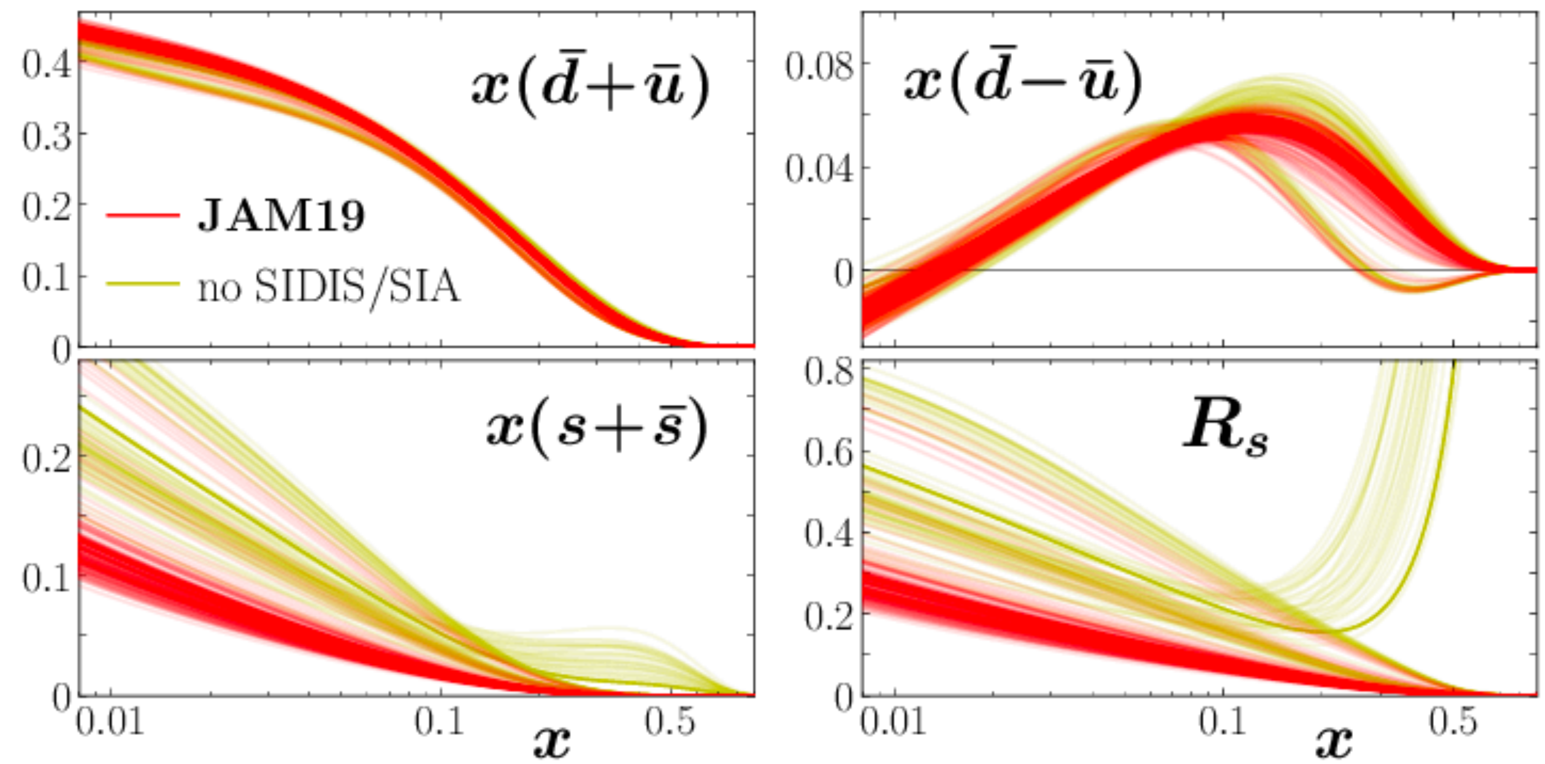
- gluon initiated processes give ~ 50% of the cross-section for 0.1 < x < 0.3 (the anti-shadowing region)

see also: arXiv:2003.09129 [hep-ph]

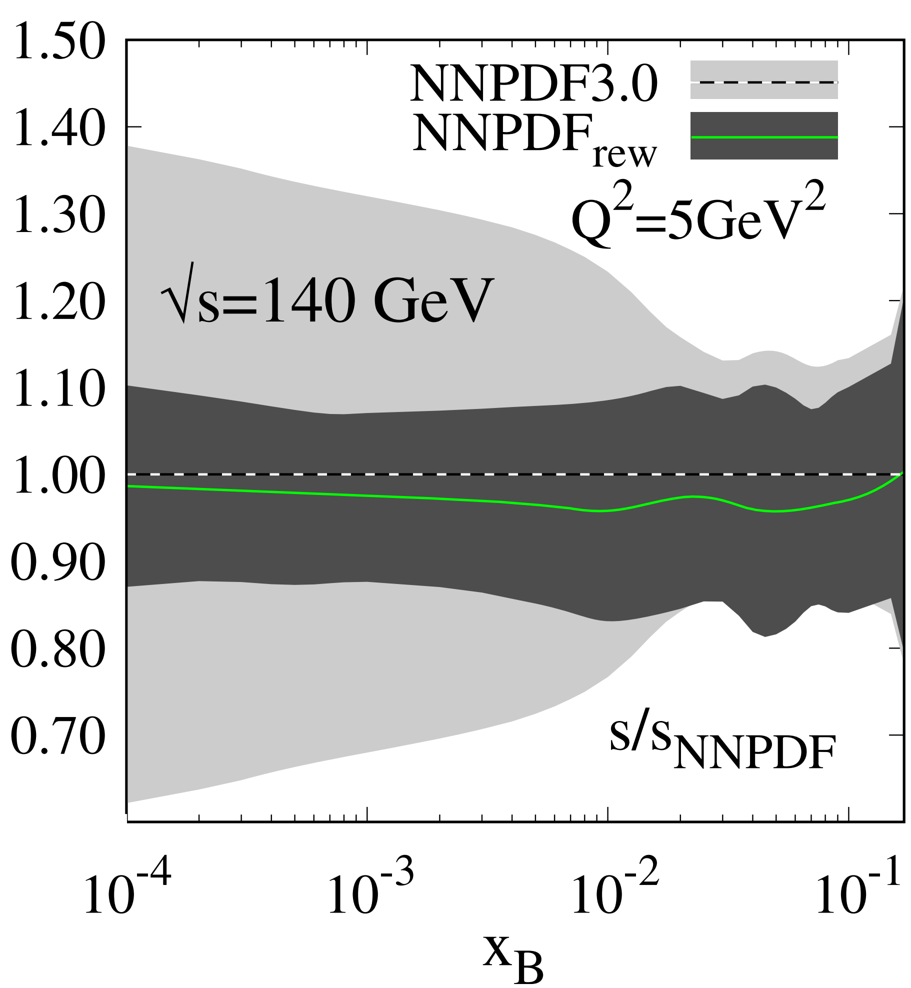
- study the impact of semi-inclusive data on the initial state densities?

JAM Collaboration, PRD 101 (2020) 7, 074020

$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$

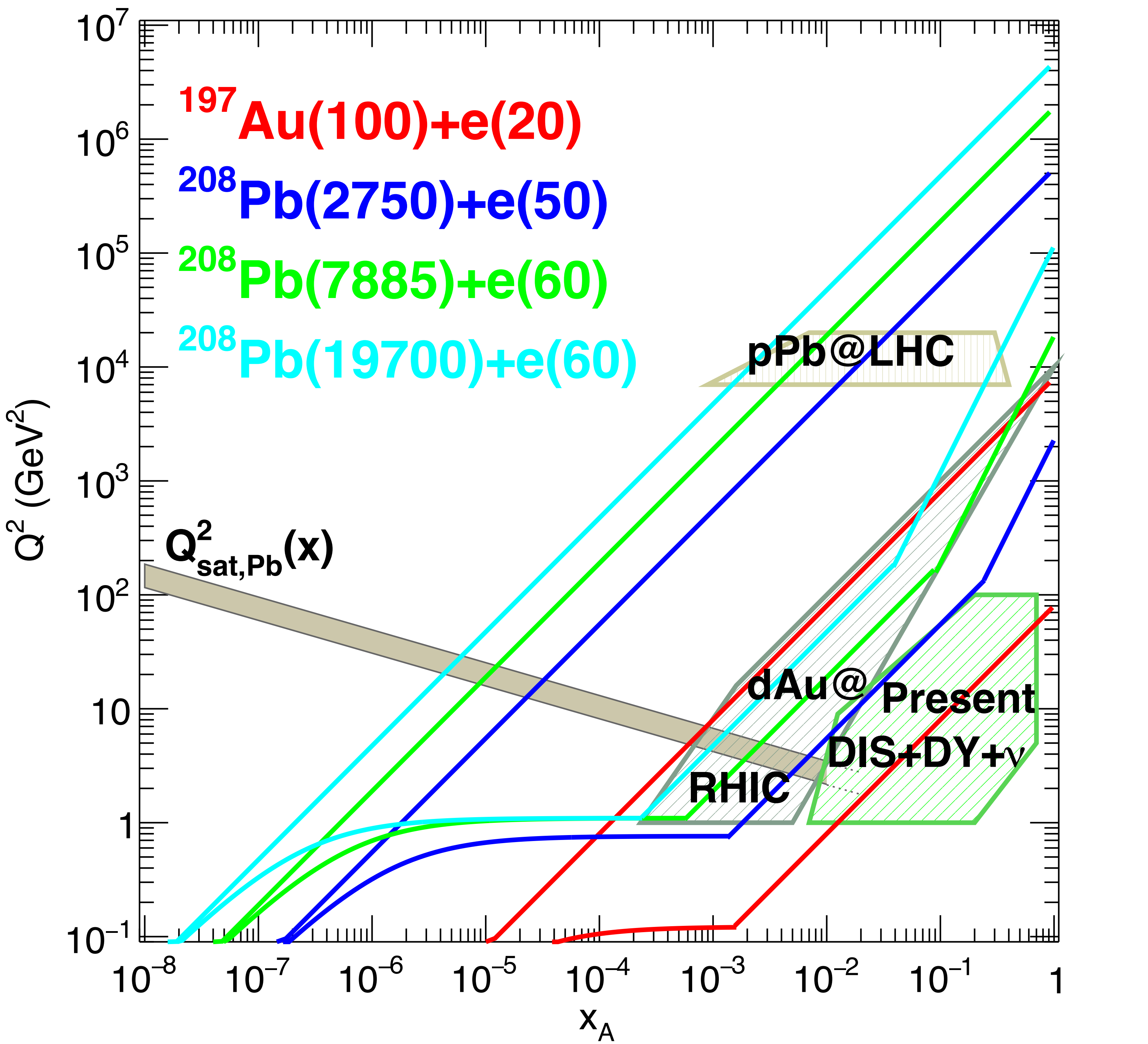


PRD99 (2019) no.9, 094004

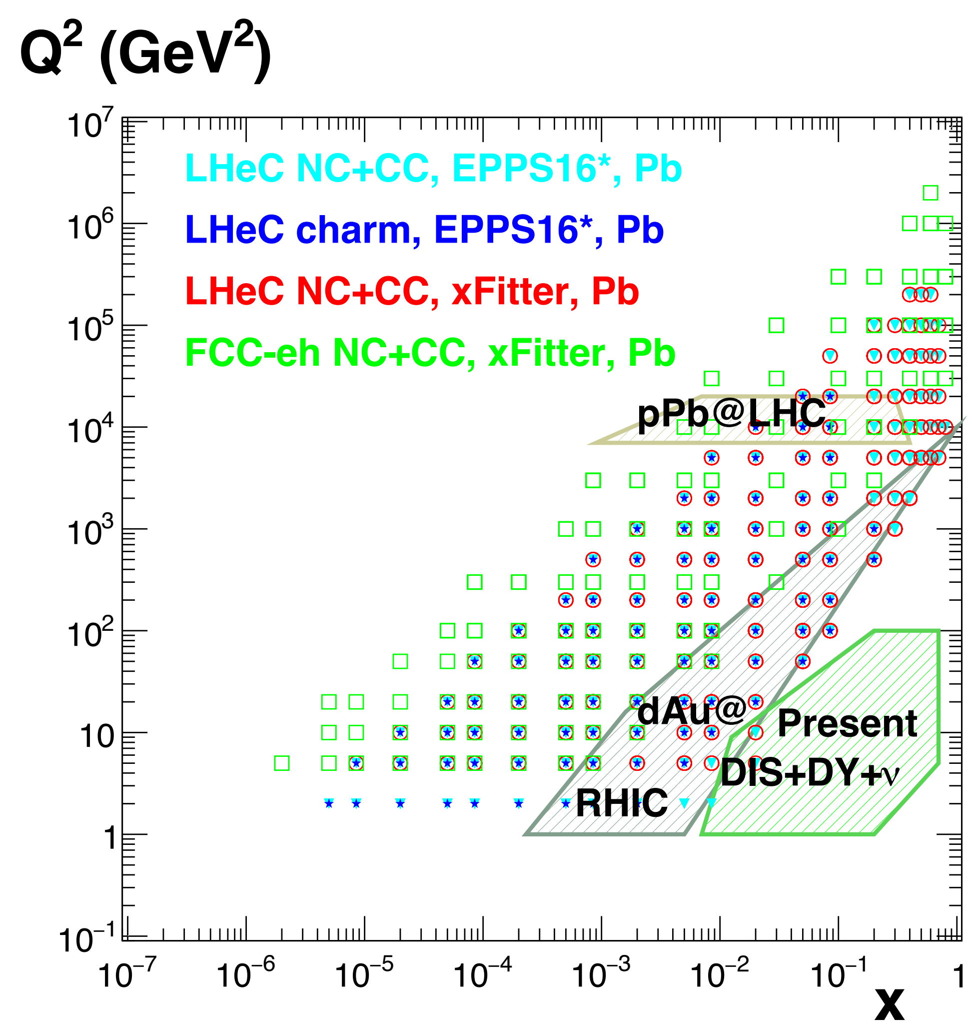


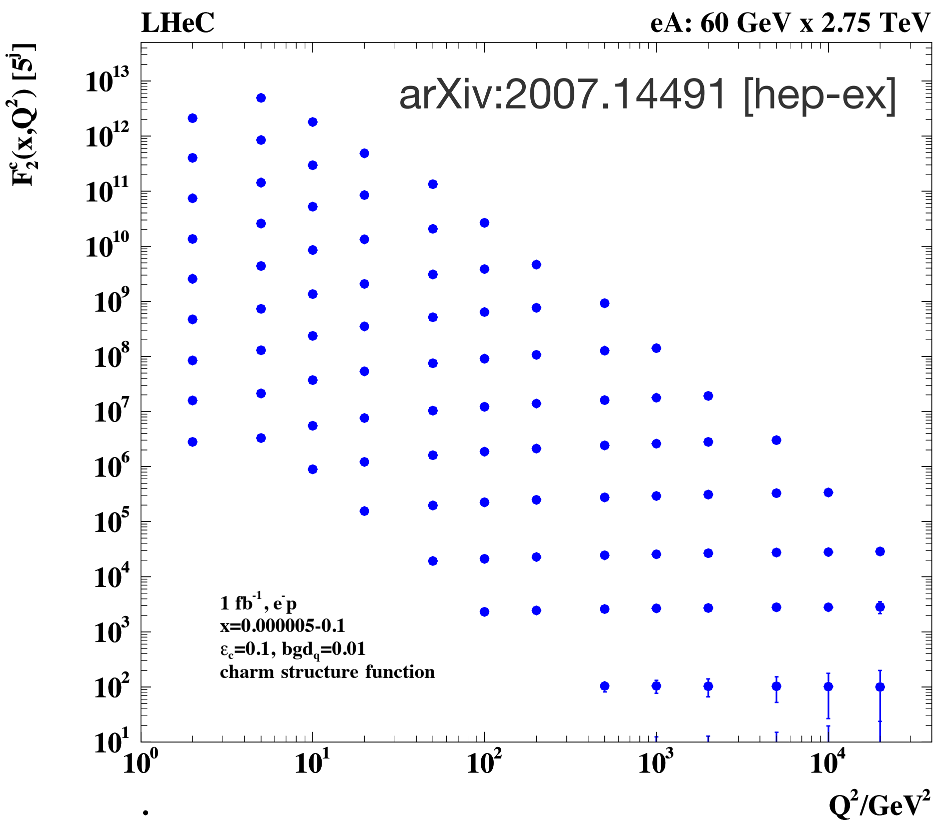
- currently updating the only set of medium modified FFs
- impact study for EIC to come
- maybe try a joint fit?

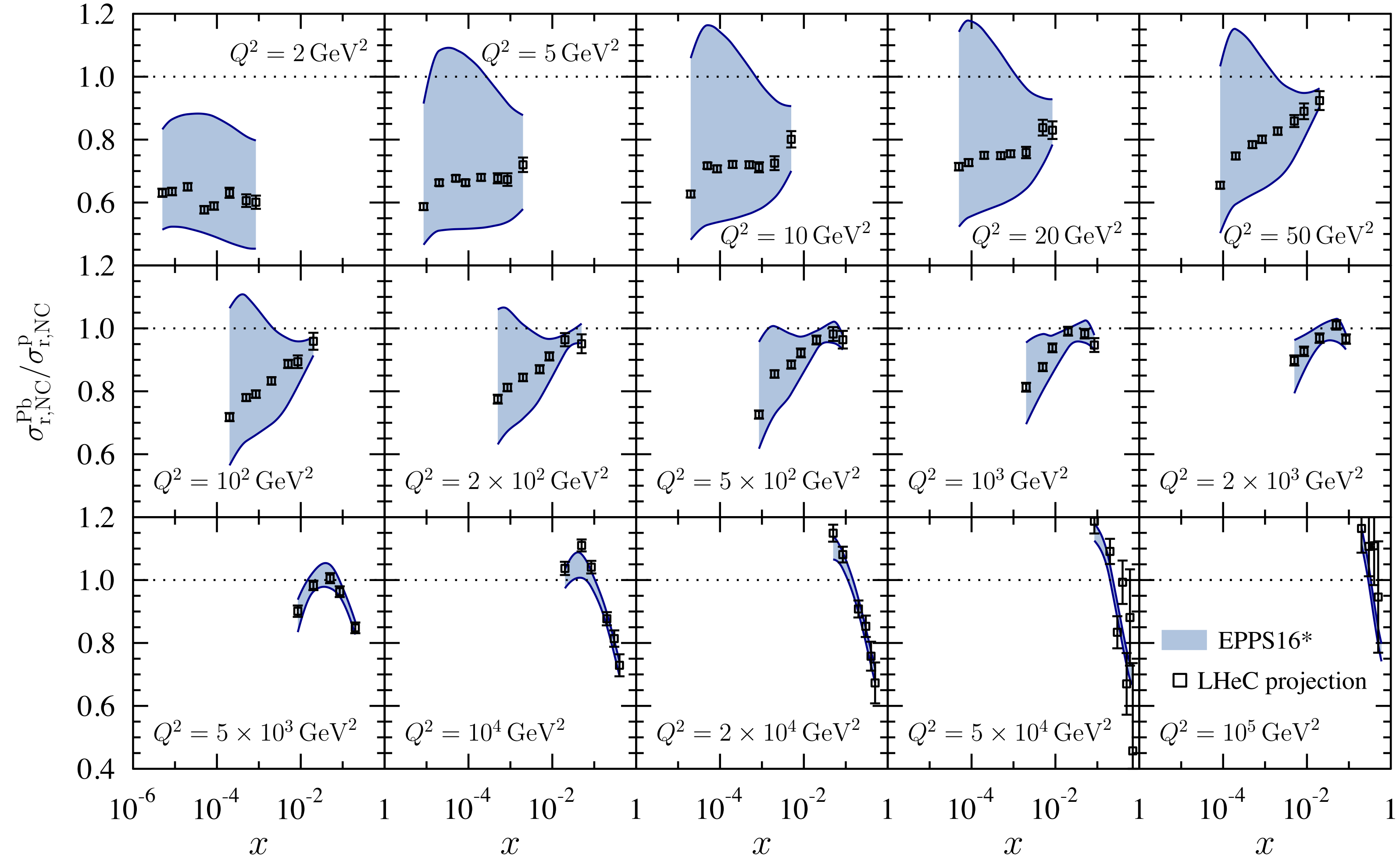
with pseudo data @ LHeC

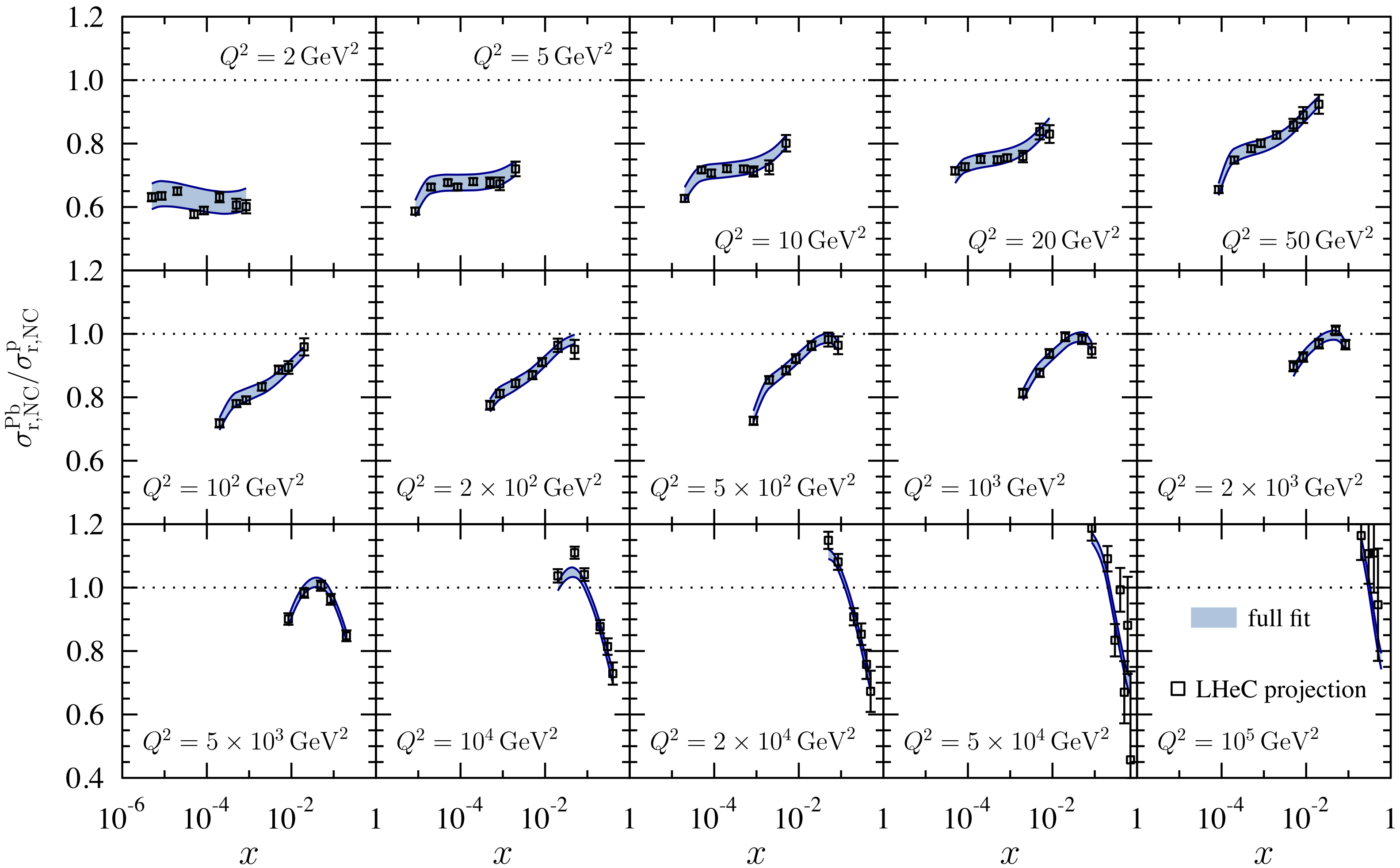


arXiv:2007.14491 [hep-ex]

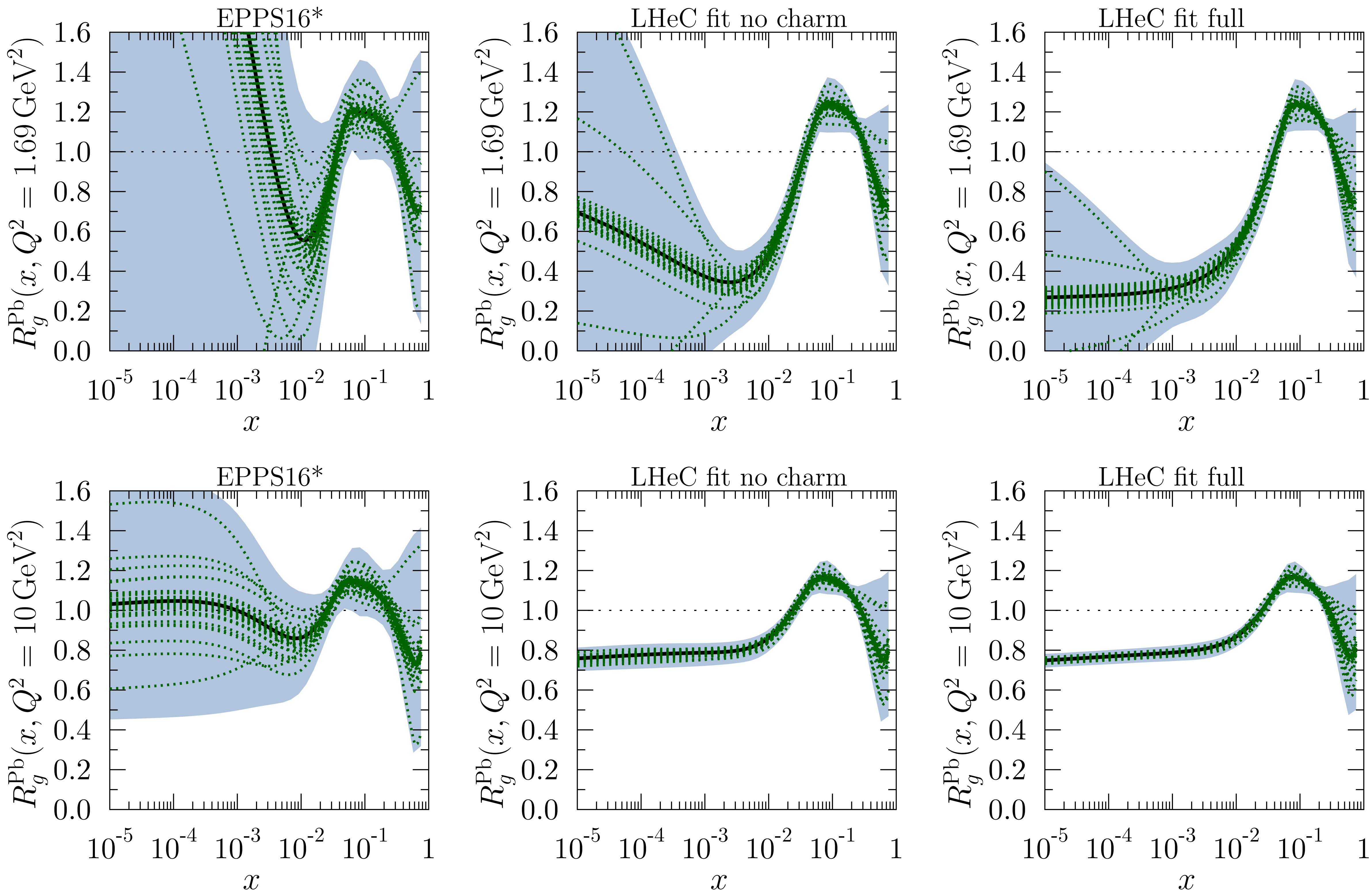








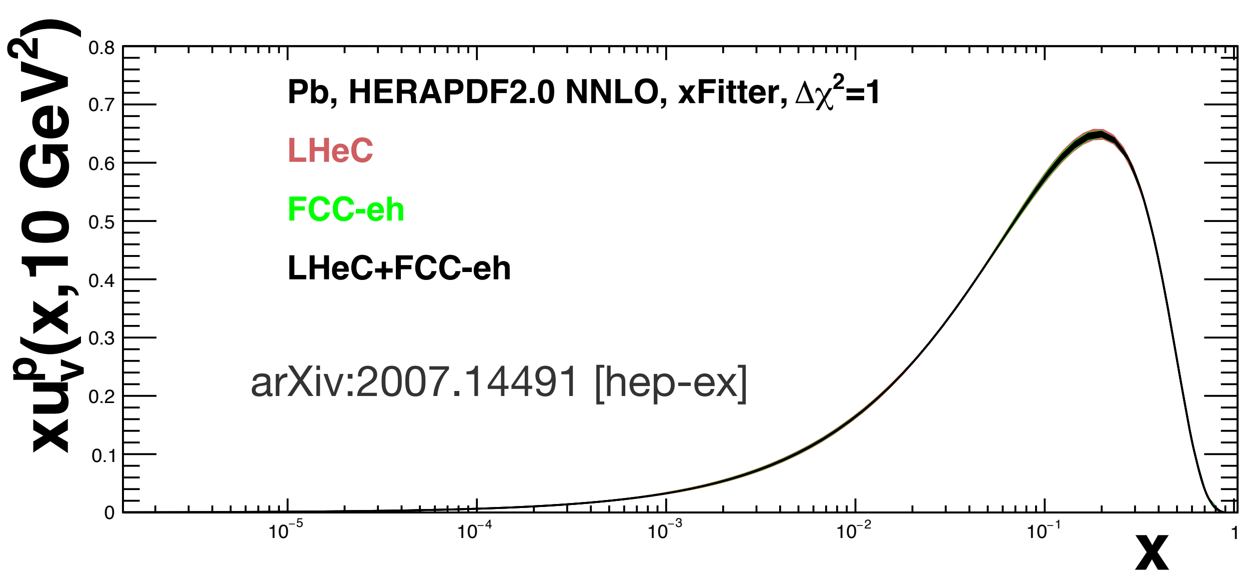
- simulated NC and CC for inclusive, charm and bottom
- impact of fitting LHeC pseudo data in EPPS16*

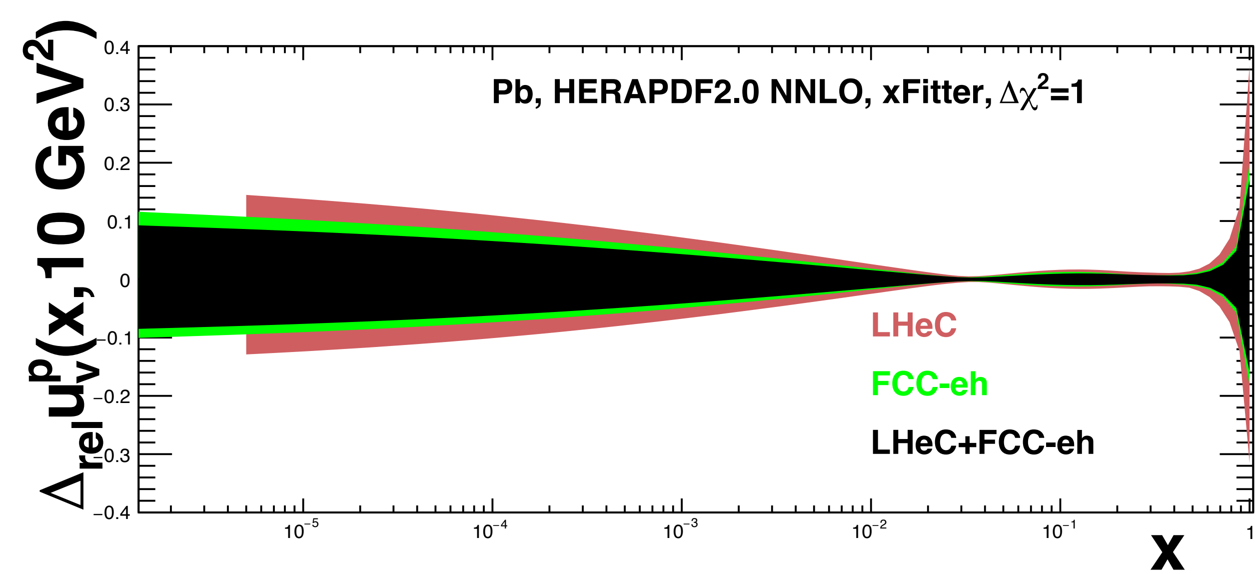


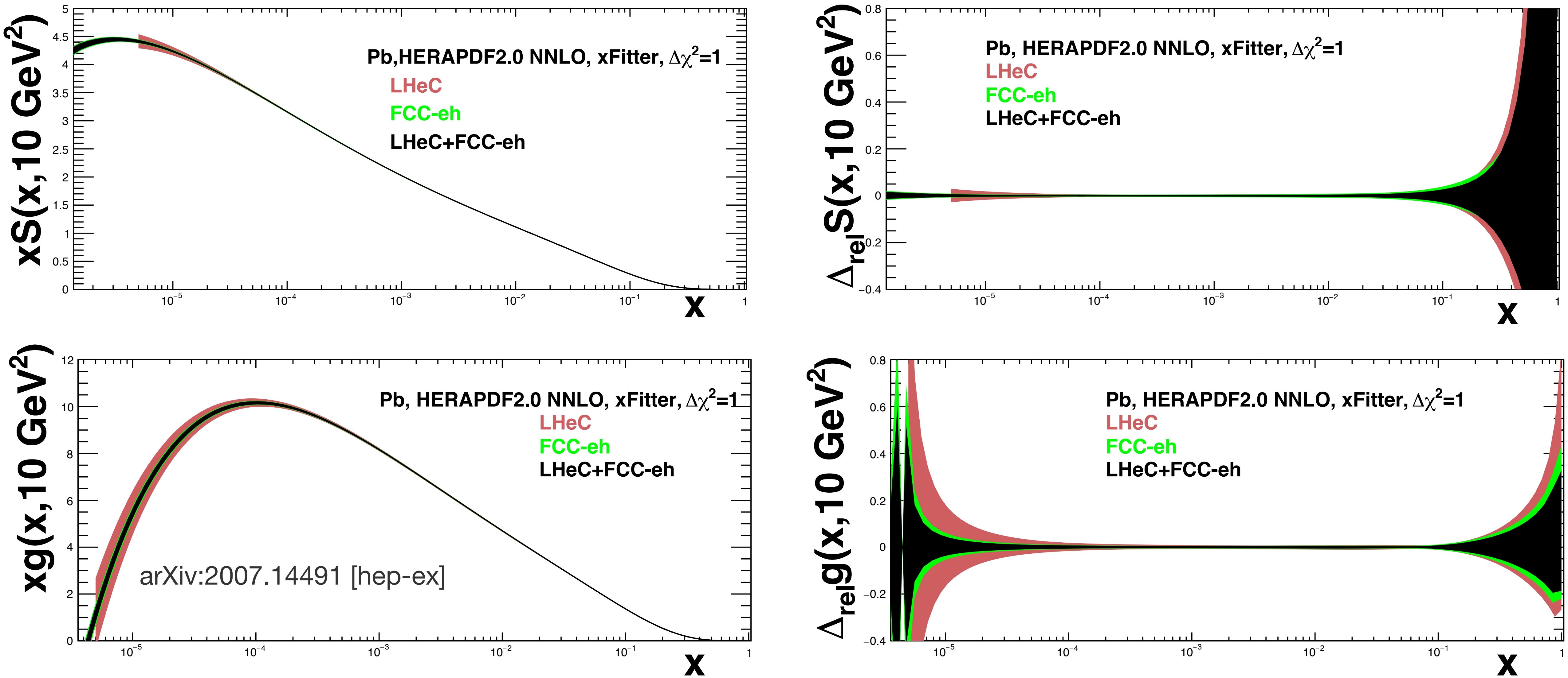
arXiv:2007.14491 [hep-ex]

- alternative: do a fit for each individual nucleus
- advantages:
    - no proton baseline needed
    - no A dependence in the parameters
    - all data from one experiment, $\Delta\chi^2 = 1$

- NNLO with RT improved GM-VFNS
- HERAPDF2.0-like parametrisation
- 484 (150) points from NC+CC at LHeC (FCC-he)
- $Q^2 > 3.5$ GeV^2







- Valence unconstrained at low x
- Sea unconstrained at high x
- At such low x already HERA data seems to need resummation (see talk by A. Cooper-Sarkar: https://indico.fnal.gov/event/44075/contributions/189702/attachments/132103/162127/snowmass21_lowx.pdf)
- Maybe new phenomena will appear

Summary

- There are any different sets of nPDFs available (all "good" fits).
- The limited kinematic coverage of the data severely hampers the extraction of nPDFs.
- New and "new" data are not as sensitive to the nPDFs as e+A, or lie outside the kinematic cuts.
- For some observables the inclusion in fits require extra considerations from the theory side.

"… the data have rather small Q^2 values in a restricted Q^2 range at small x. It suggests that **it is difficult to determine the nuclear gluon distributions from the scaling violation at small x**. In order to obtain the smaller x or larger Q^2 data than those in Fig. 2, **we should wait for a next generation project such as HERA-eA [26] or eRHIC [27]**."

HKM, PRD64 (2001) 034003

NNLO

SET		KA15	nNNPDF1.0	TuJu19
data type	NC DIS	🙂	🙂	🙂
	D-Y	🙂		
	pions			
	CC DIS			🙂
	EW			
	dijets			
# data points		1479	451	2336
χ^2/N		1.147	0.678	0.862
Q_0^2 (GeV^2)		2	1	1.69
Q^2_{min} (GeV^2)		1	3.5	3.5
W^2_{min} (GeV^2)		— — —	12.5	12
proton PDF		JR09	NNPDF3.1	own fit
deuteron		?	🙂	🙂
flavour separation?				🙂 valence