The case for ions: the physics of nuclear PDFs and hadronization studies

Lecture 1

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Comunidad de Madrid

IPARCOS

Outline

- Why use a nucleus as a target/beam?
- How to deal with nuclei.
- Data used in nPDF fits.
- Sets (until 2015) and comparison.
- 2015-present: improving.
- Issues in nPDF extractions.
- What can the EIC do for nPDFs?
- Summary.

Why use a nucleus a a target/beam?

Let's think about NC DIS with protons. In the cross-section we have three partonic contributions:

$$\frac{d^2\sigma}{dxdQ^2} \propto F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x,Q^2)$$

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$$f_{proton}^S(x,Q^2) = \sum_{i=1}^{N_f} f_i(x,Q^2) \qquad f_{proton}^{NS}(x,Q^2) = \sum_{i=1}^{N_f} e_i^2 f_i(x,Q^2)$$

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We have a minimum of seven PDFs to determine: (anti-)up, (anti-)down, (anti-)strange, and gluon.

We can have l.i. combinations of PDFs if we use a neutron instead. Assuming isospin symmetry (i.e. $u_{proton} = d_{neutron}$) is valid

$$f^{S}_{proton}(x, Q^2) = f^{S}_{neutron}(x, Q^2)$$

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But we could use **deuterium**. A (very light) nucleus.

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In that case we have one more structure function, xF_3, which enters the cross-section with different signs (depending on the sign of the W boson).

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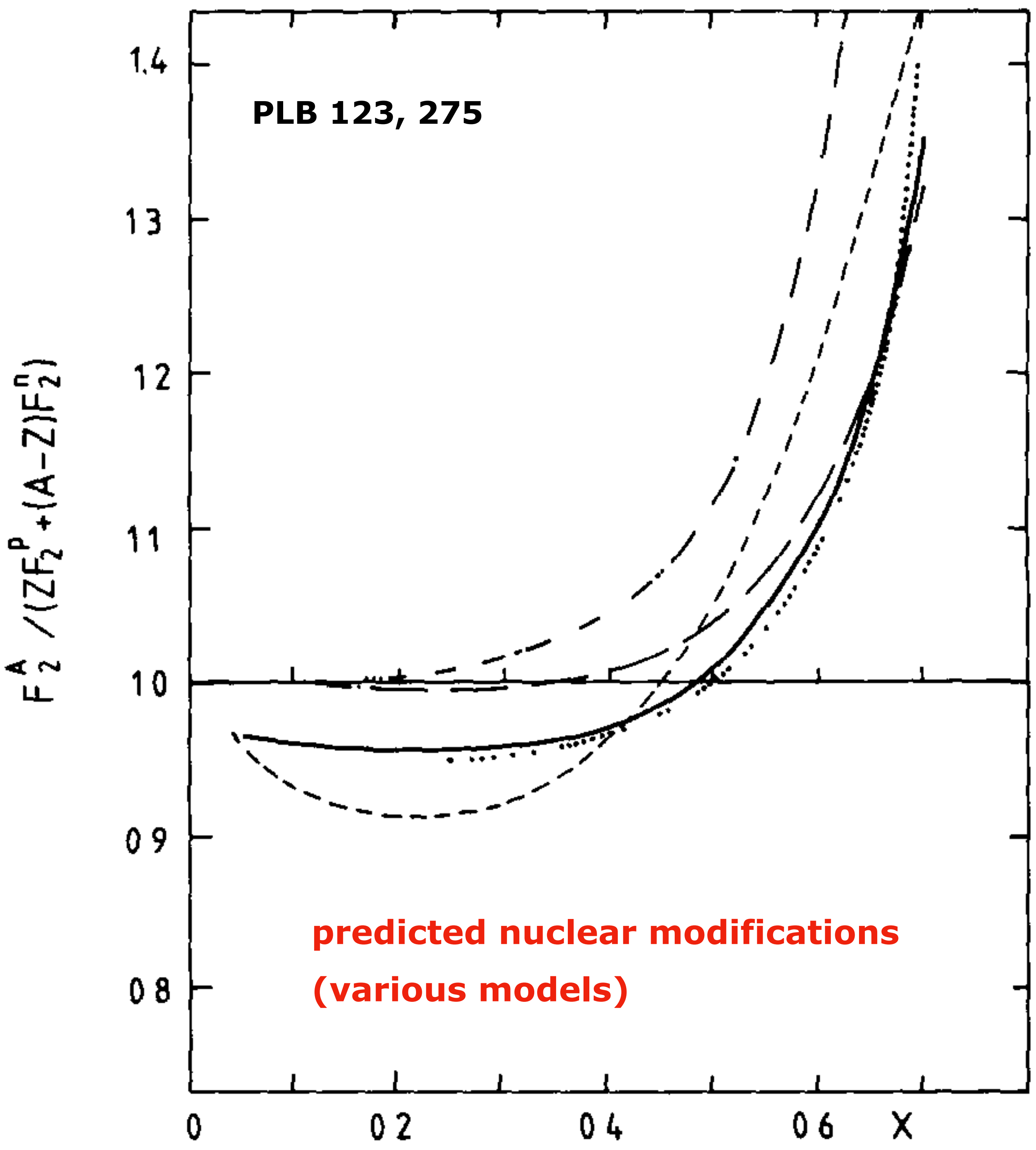
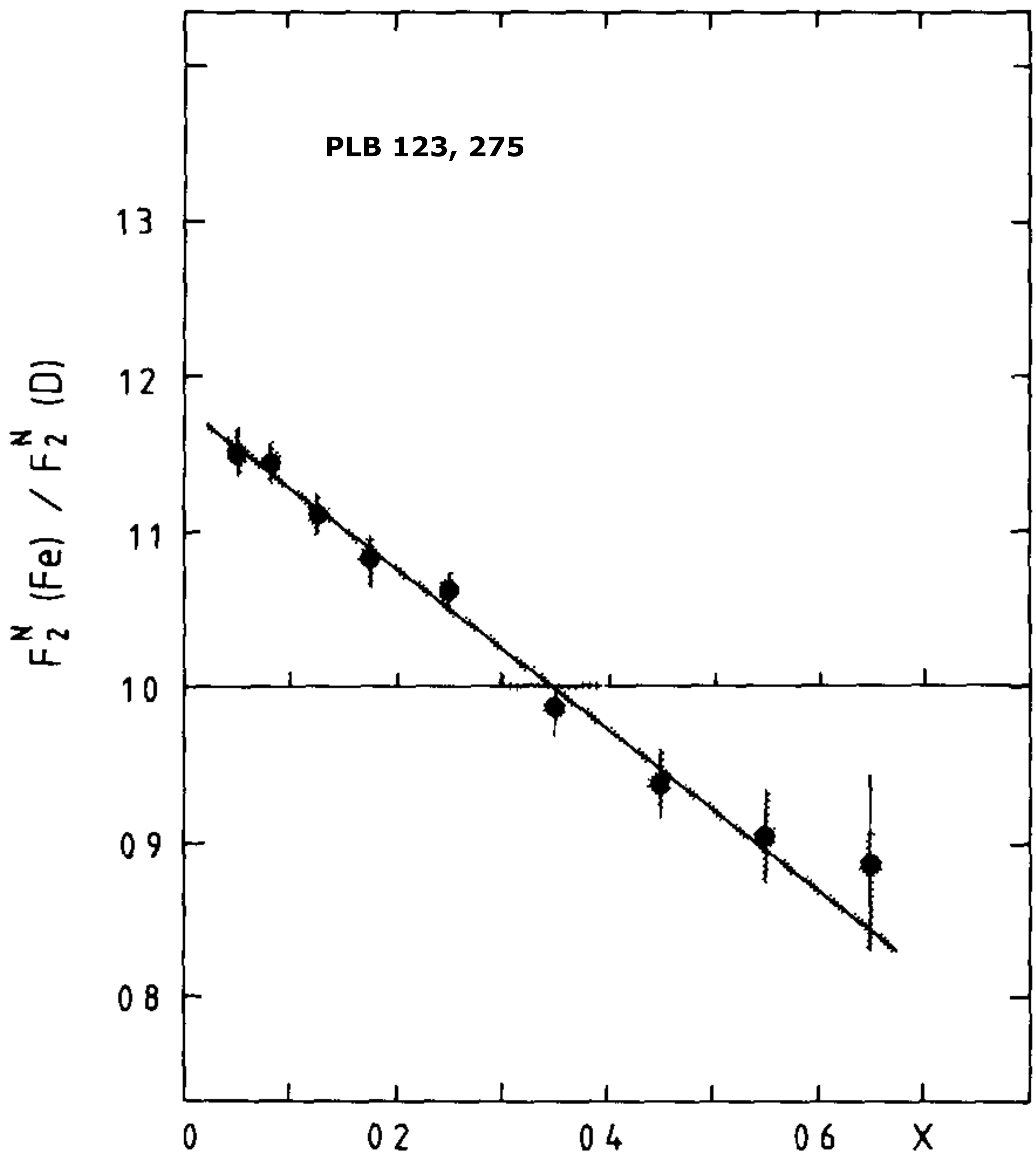
- if it is an outgoing neutrino, reconstructing the kinematics is non-trivial.
- if it is an incoming neutrino, it won't interact much with matter.

But we could use **larger nuclei** as targets.

- The expectation was that using a nucleus would be similar to using a proton.

- At most one would need to account for the non-isoscalar nuclei and the internal motion of nucleons in the nucleus (Fermi motion).





actual nuclear modification

(only statistical uncertainty shown)

"The result is **in complete disagreement with the calculations** illustrated in Fig. 1."

PLB 123, 275

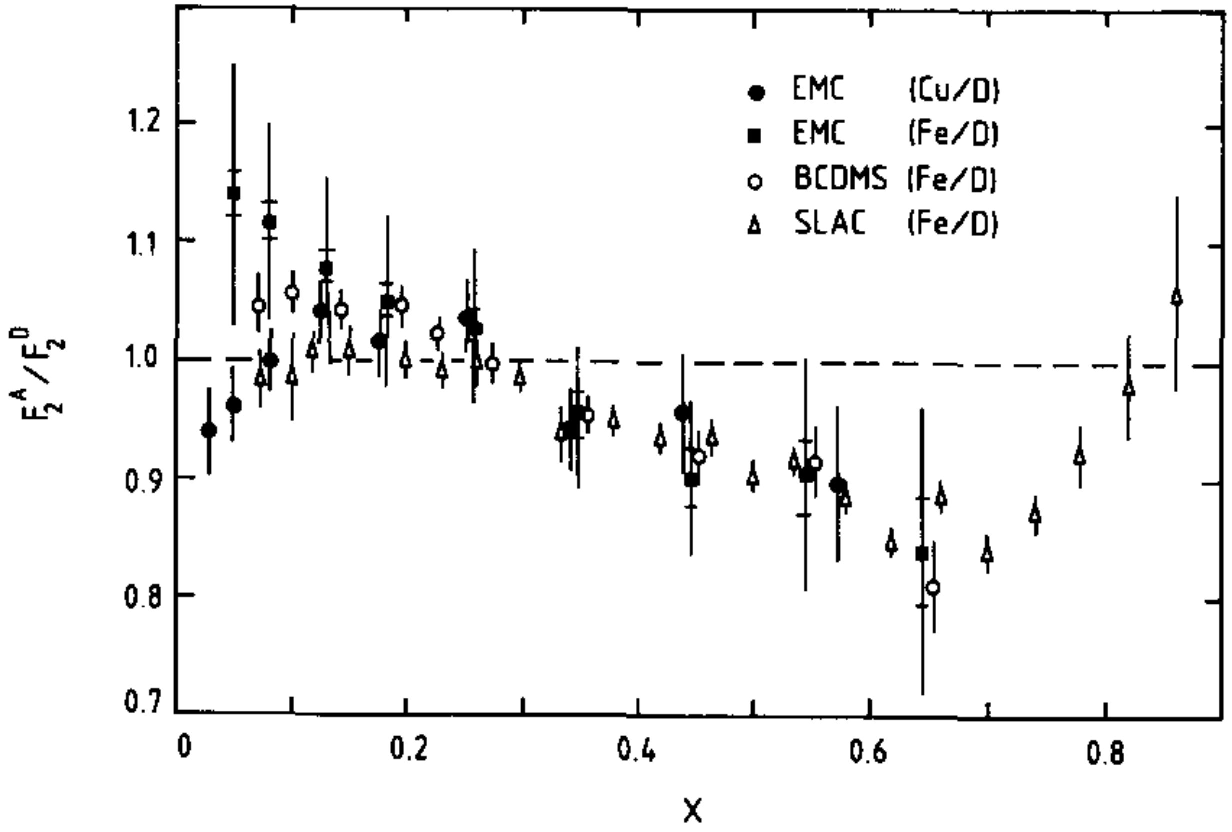
“The result is **in complete disagreement with the calculations** illustrated in Fig. 1.”

“**We are not aware of any published detailed prediction presently available which can explain the behaviour of these data**. However, there are **several effects** known and discussed which **can change the quarks distributions in a high A nucleus** compared to the free nucleon case and can contribute to the observed effect.”

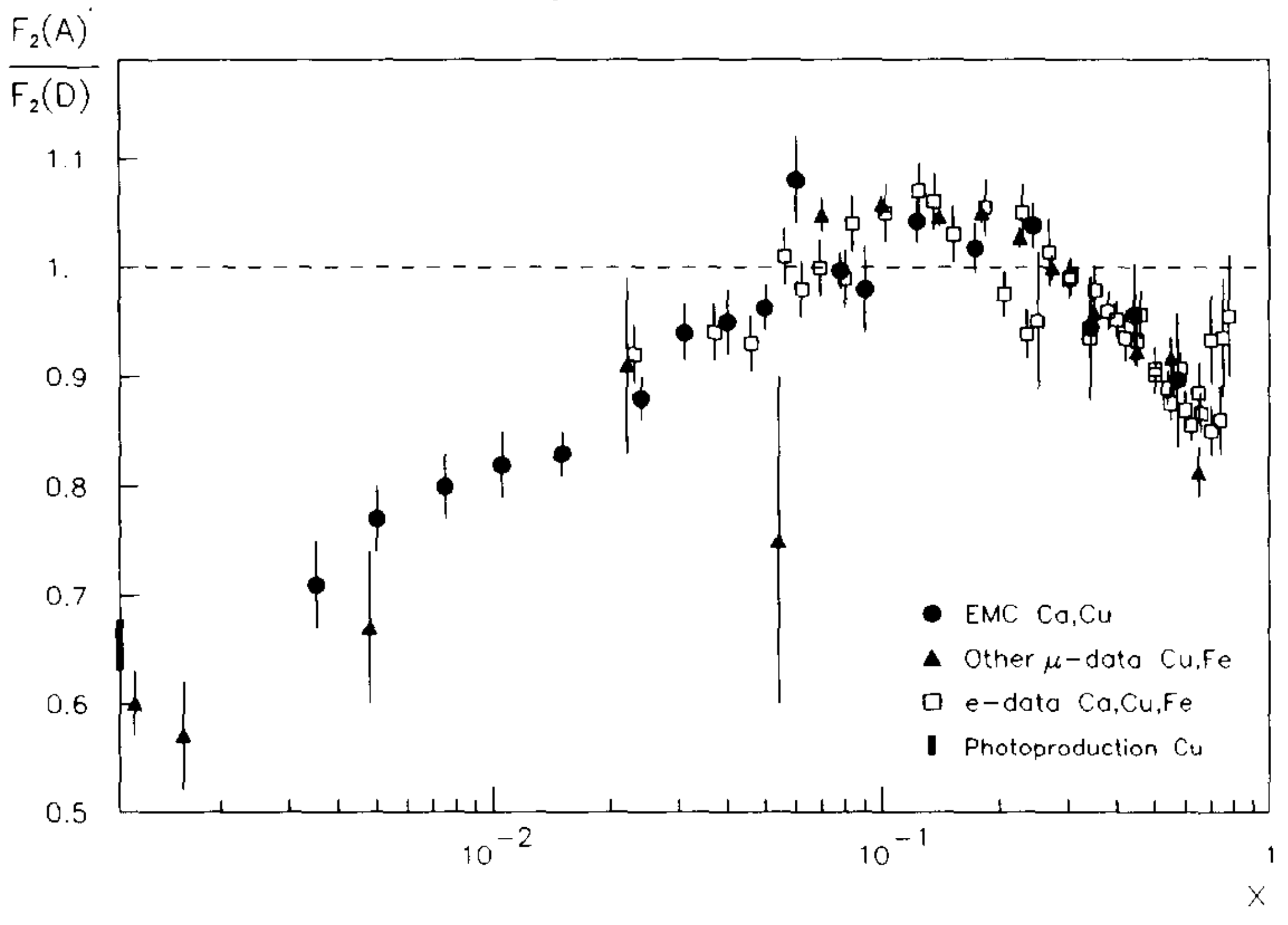
PLB 123, 275

The effects follow a very particular pattern:

PLB 202, 603



NPB 333, 1



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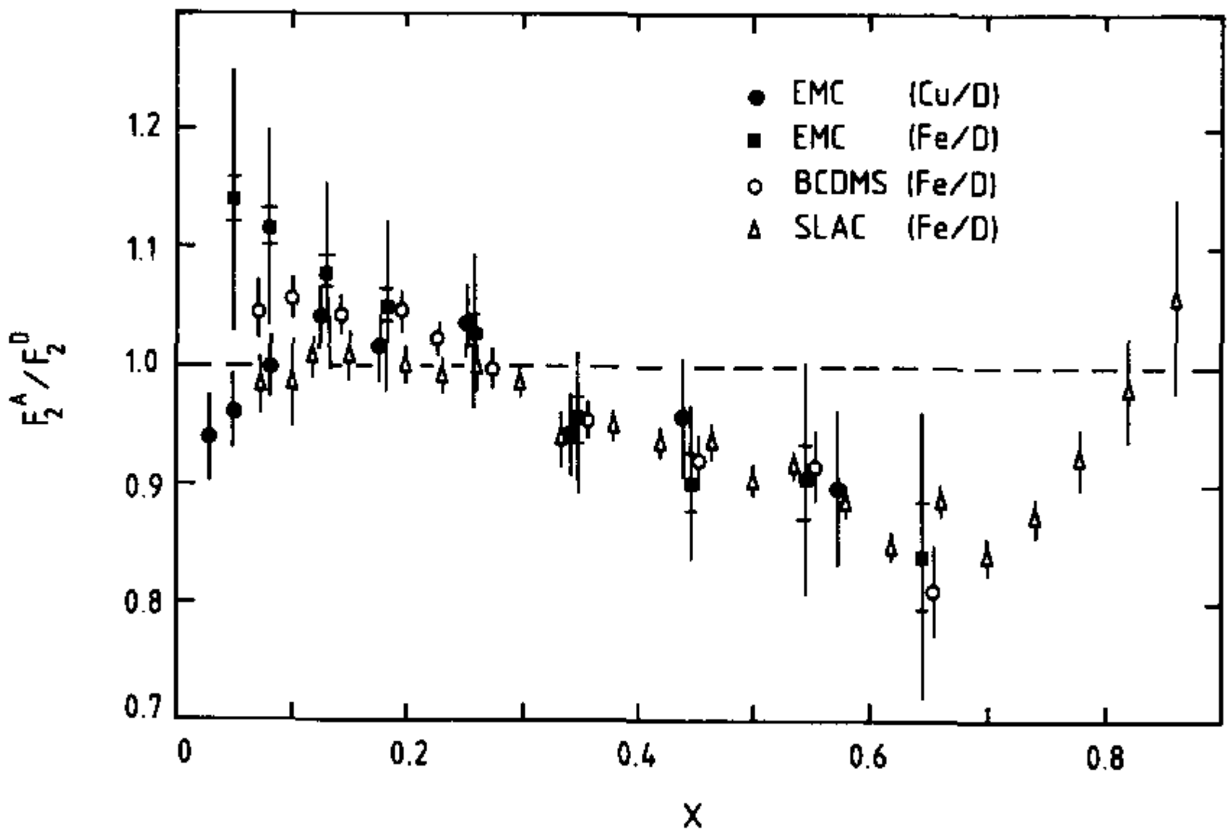

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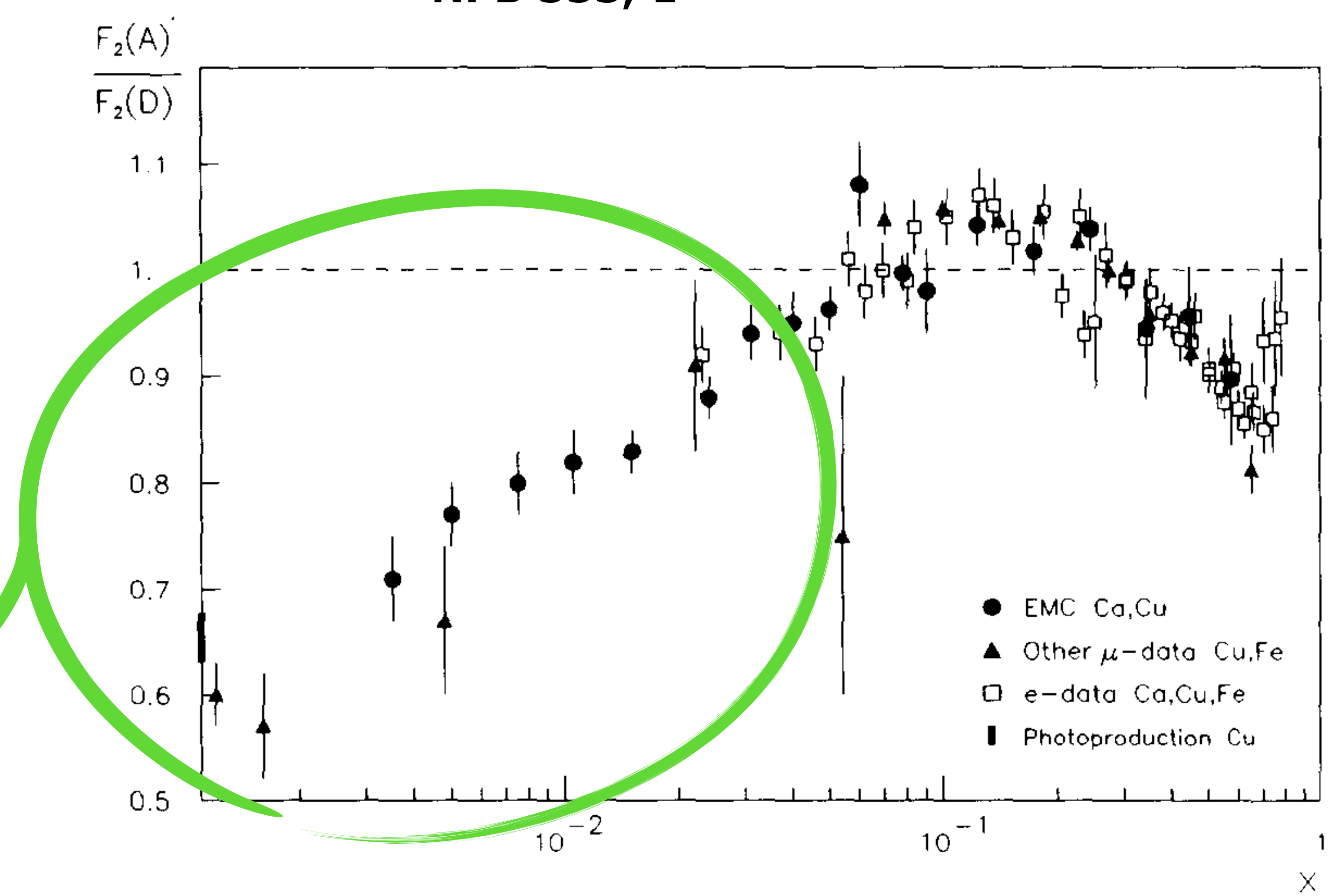

shadowing

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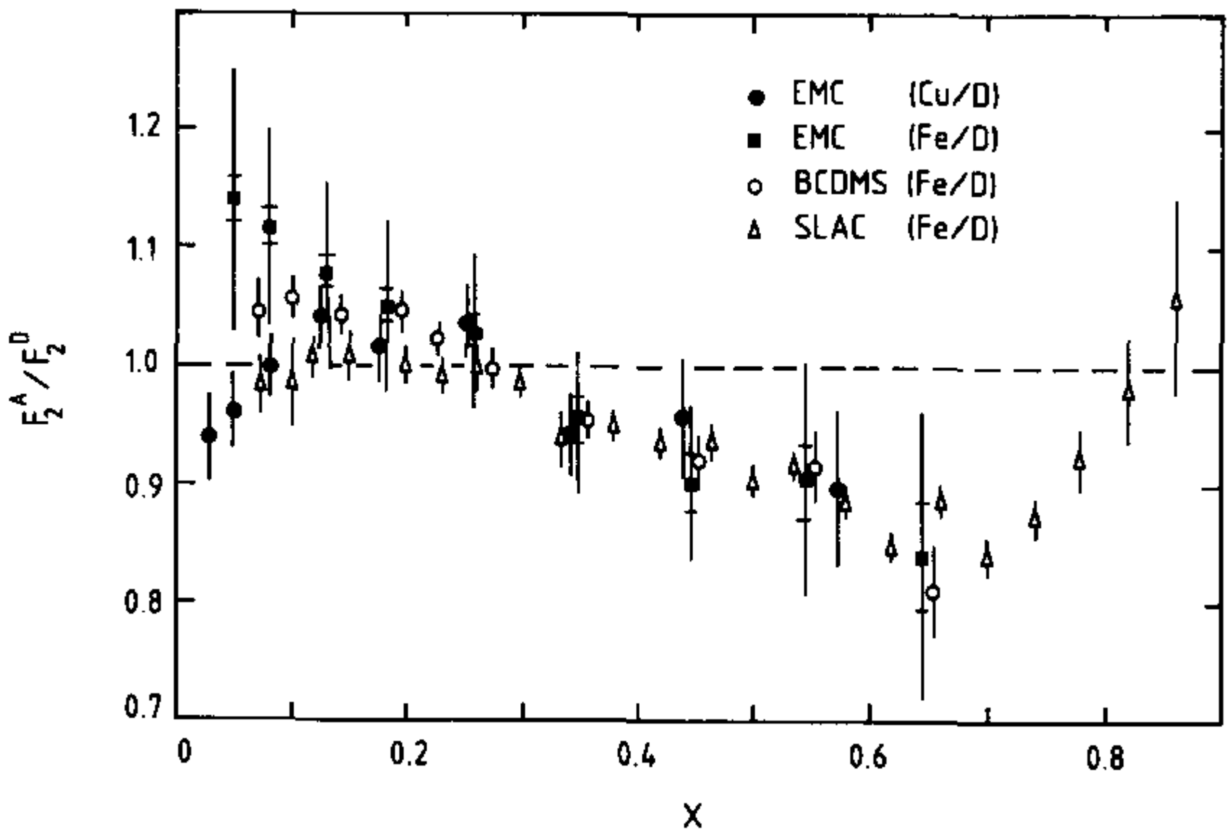
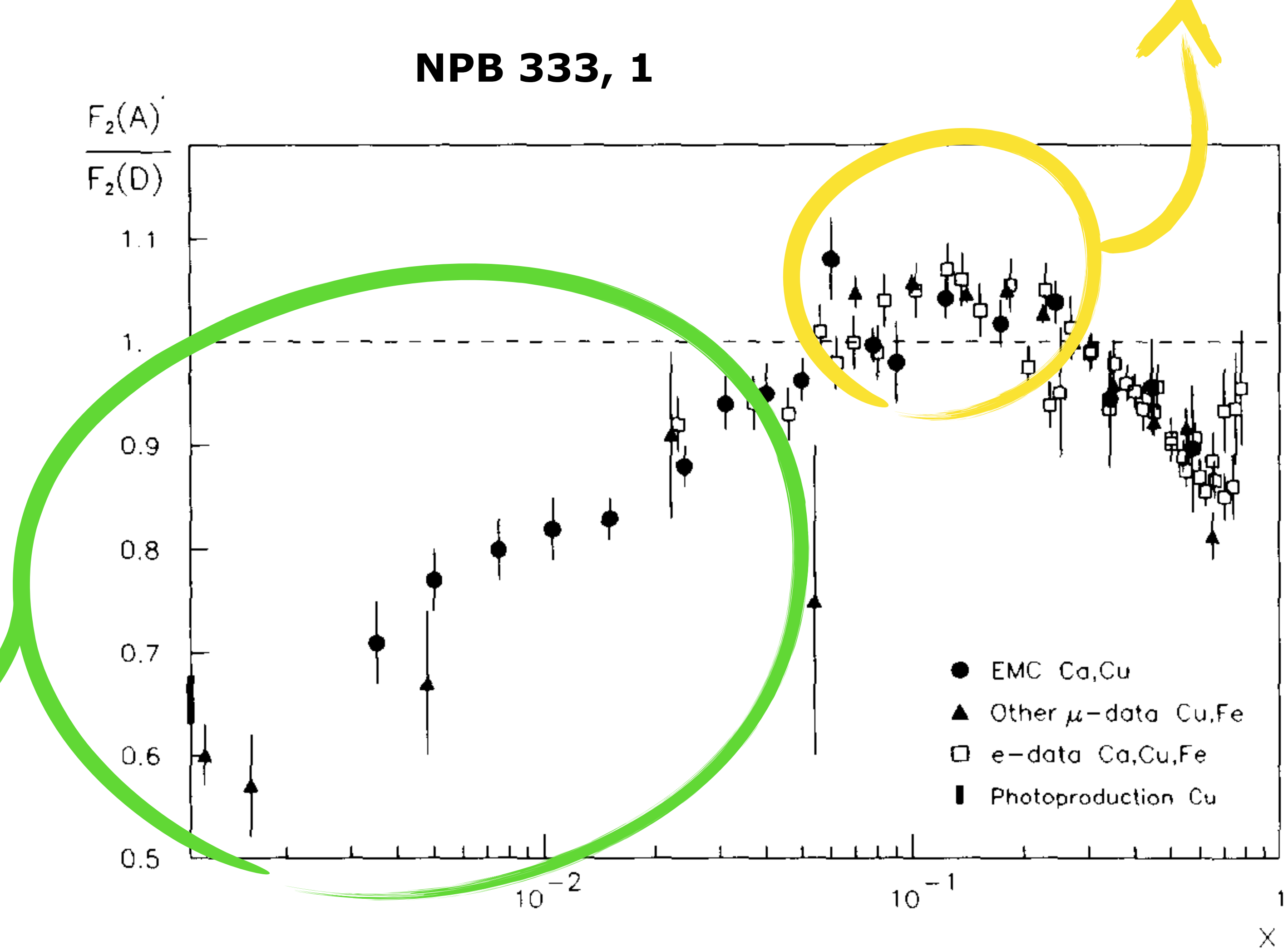


anti-shadowing

NPB 333, 1



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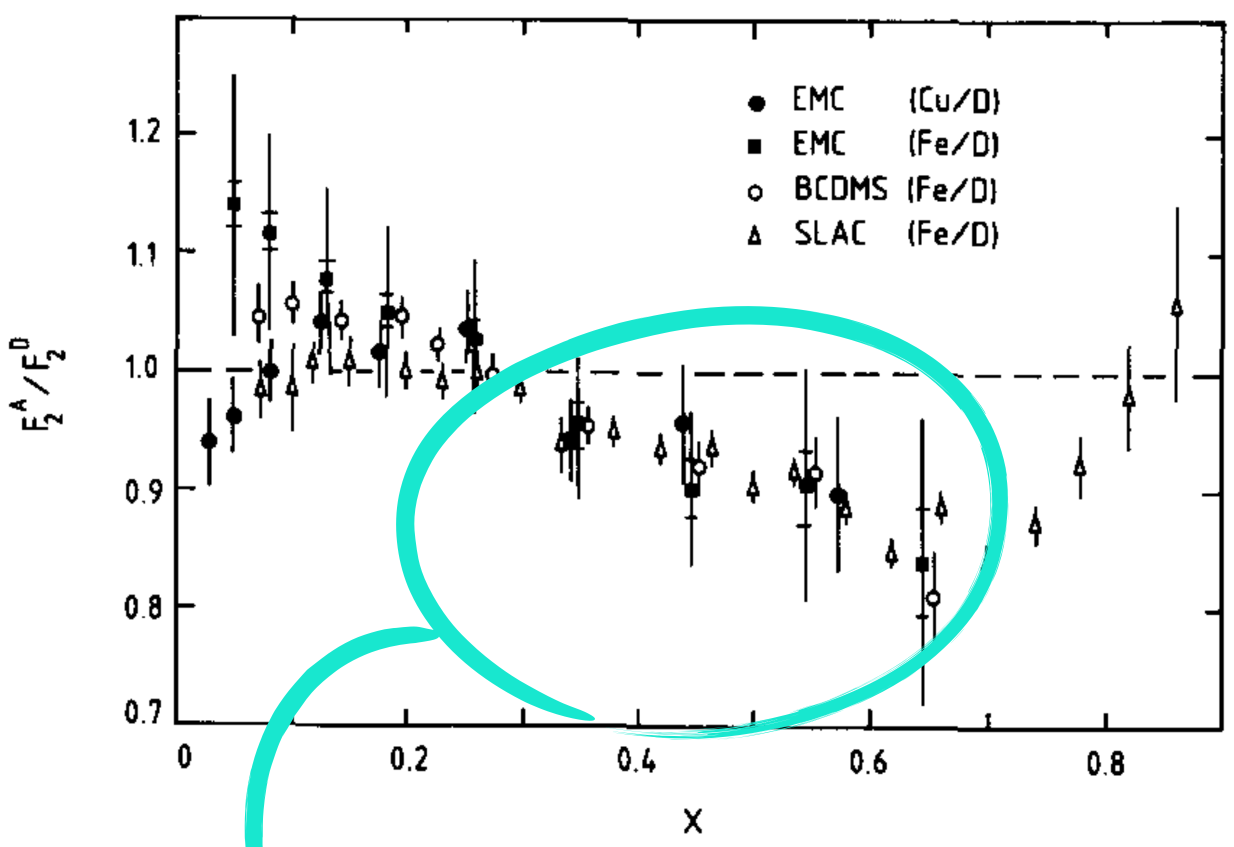
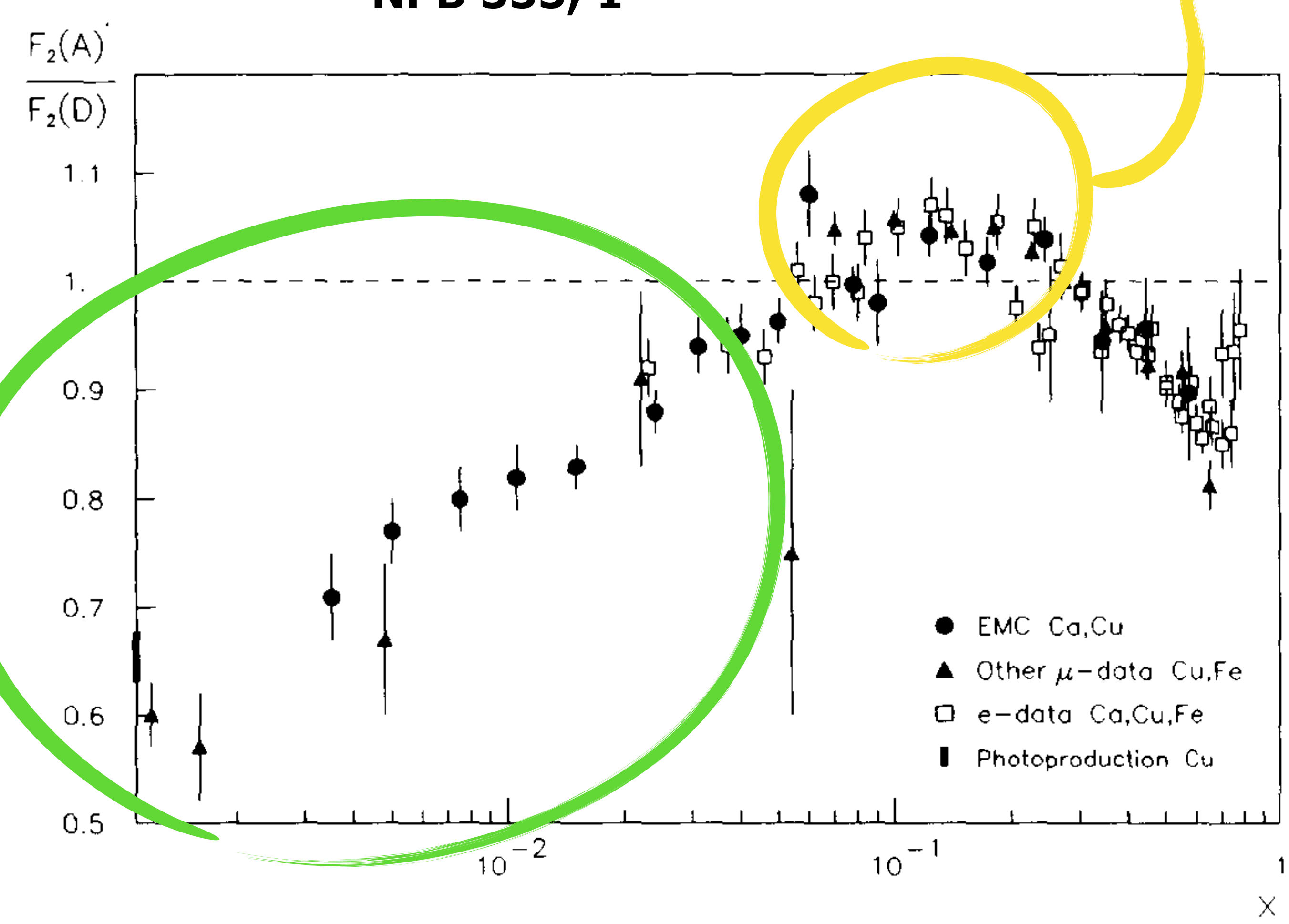


EMC effect

NPB 333, 1



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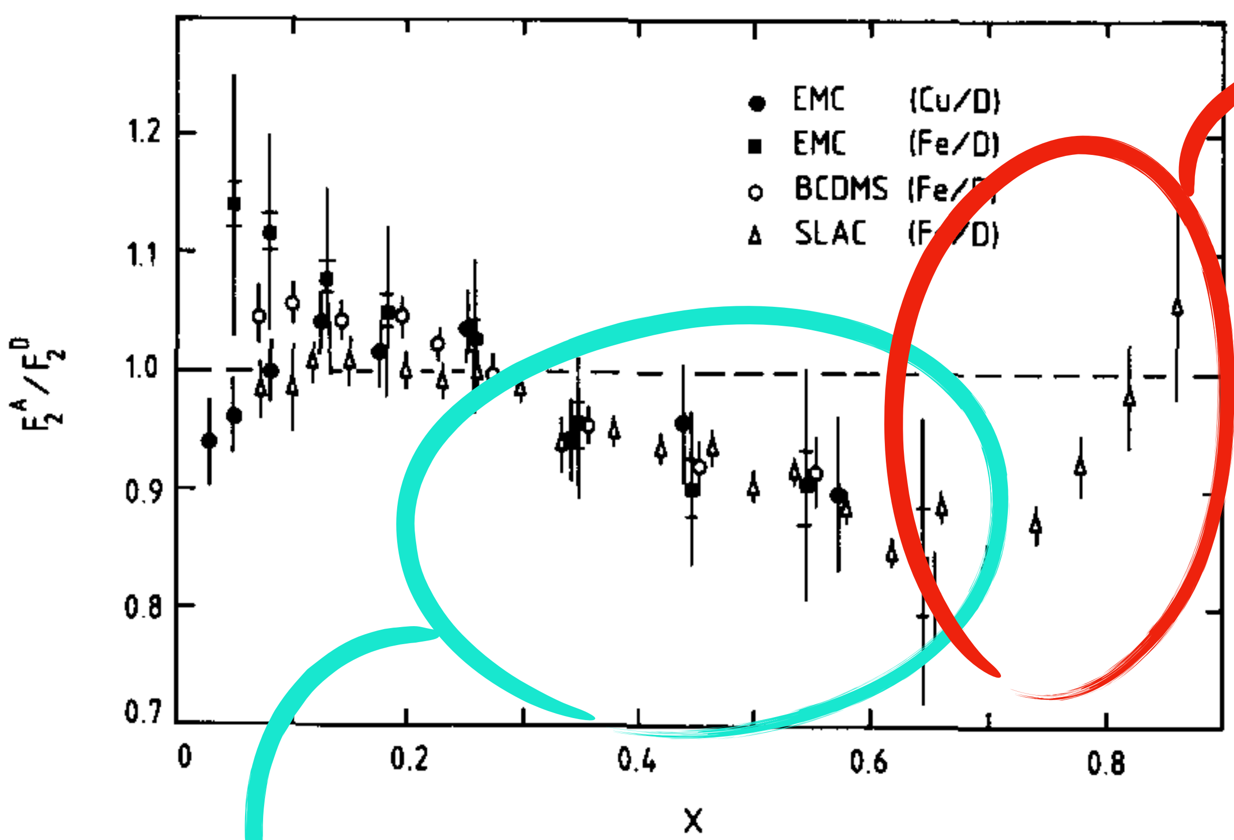
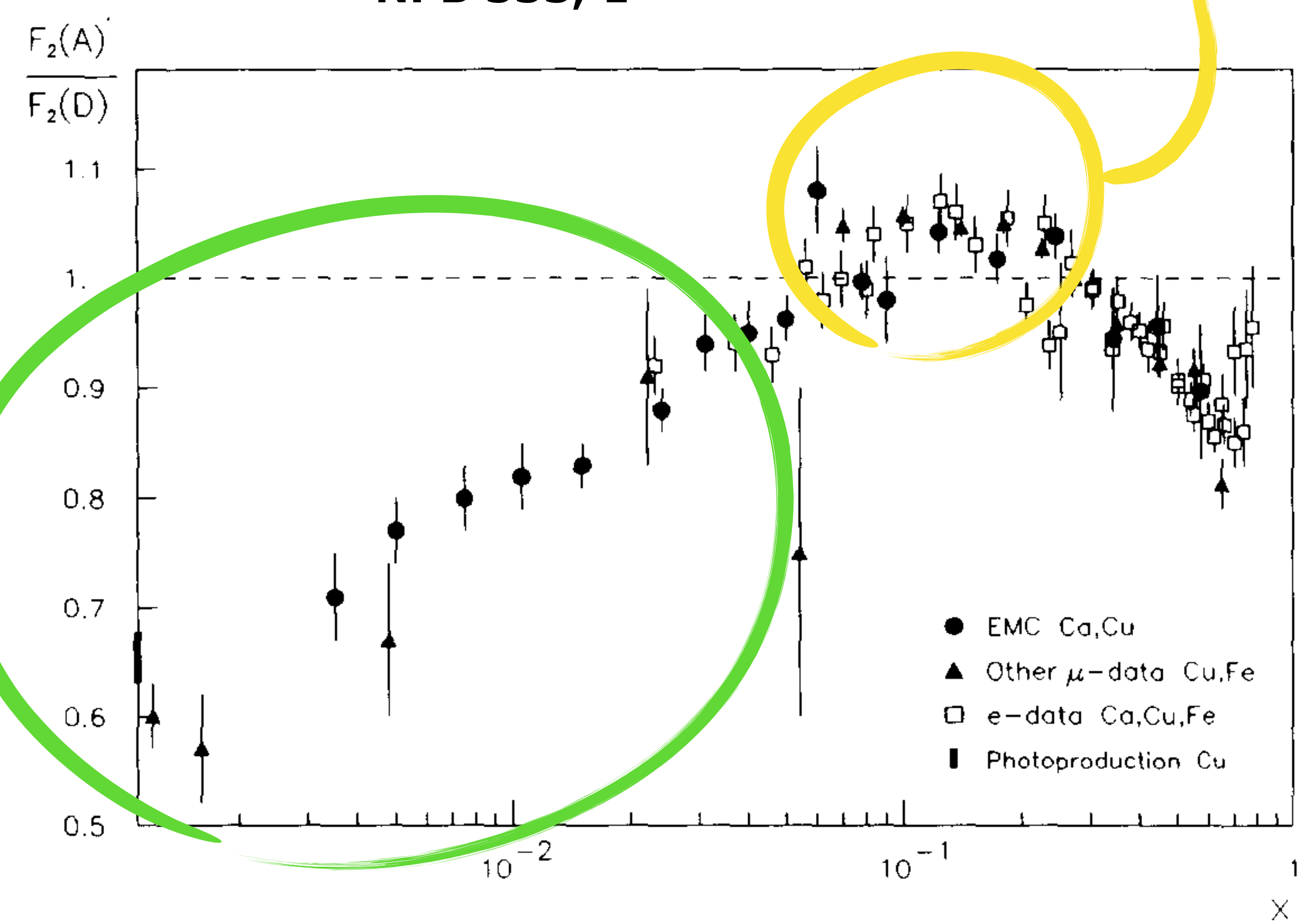


Fermi-motion

anti-shadowing

NPB 333, 1



EMC effect

shadowing

Moreover, we want to study nuclei also because:

- It **is interesting** and **we want to know how** and **why** this occurs.
- Tightly linked to neutrino physics.
- HI and the QGP benchmarking.
- Saturation studies (e.g. CGC).
- ...

ACE
AMANDA
ANTARES
ArgoNeuT
ATLAS
Bevatron
Borexino
Bubble Chamber
CDHS
CLAS detector
CMS
COMPASS (NA58)
Cowan–Reines experiment
CUORE
DAPHNE
DONUT
Enriched Xenon Observatory
EMC
FASER
Fermilab E-906/SeaQuest
Gargamelle
Germanium Detector Array
HARP
HERA-B
HERMES
IceCube
Irvine–Michigan–Brookhaven
Kamioka Liquid Scintillator Antineutrino Detector
Kamioka Observatory
KM3NeT
Large Volume Detector
LAND
LHCb
MINOS
Modular Neutron Array
Monopole, Astrophysics and Cosmic Ray Observatory
Mu to E Gamma
Mu2e
Mu3e
NA32
NA35
NA49
NA60
NA61
NA63
NESTOR Project
NEVOD
Kolar Gold Fields
PHENIX
PUMA
Rutherford gold foil experiment
SAGE
SciBooNE
SNO+
Soudan 1
Soudan 2
STAR
Sudbury Neutrino Observatory
Super-Kamiokande
...

How to deal with nuclei

- Do nothing.

- ~~Do nothing.~~

- Build theoretical models:
    - shadowing ~ 400
    - anti-shadowing ~ 40
    - EMC effect ~ 370
    - Fermi motion ~ 90

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- A purely phenomenological approach, assuming all we do for the proton will remain valid: **nuclear PDFs**.

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- A purely phenomenological approach, assuming all we do for the proton will remain valid: **nuclear PDFs**.

- We must test this idea.

Just like proton PDFs, these nPDFs should:

- be **universal**.
- **evolve** with the scale with DGLAP.
- be **non-perturbative** (we need **data** to determine them).
- contain all the information about the behaviour of partons in a nucleus.

Remember that we're talking about the collinear framework.

We can always study more involved observables in the nuclear environment.

Can we describe the behaviour with the average of protons and neutrons?

$$f_{i/A}(x, Q^2) = \frac{Z}{A} f_{i/p}(x, Q^2) + \frac{(A - Z)}{A} f_{i/n}(x, Q^2)$$

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The answer is ***NO***

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We see is a **genuine modification of the initial state** due to the medium.The naive attempt fails. **Miserably**.

We really have to do something else.

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Options used so far:

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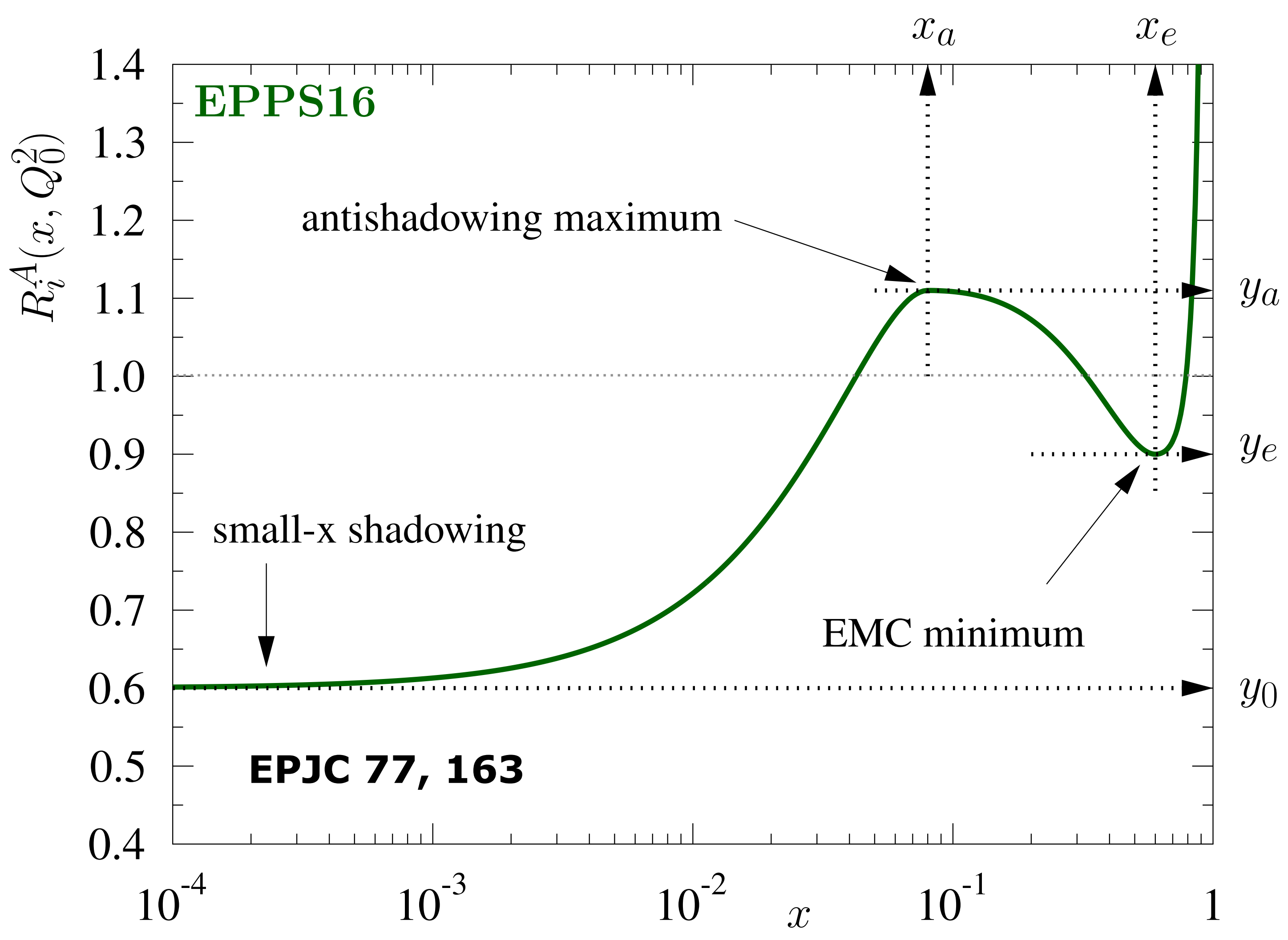

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$$xf_{i/p}(x, Q_0^2) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4 x})^{c_5}$$

$$c_k \to c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}})$$

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- $f_{i/p/A}(x, Q_0^2, A) \propto x^{\alpha}(1-x)^{\beta} NN$

to control the edges of the kin. space

very flexible, no need to assume the A dependence

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Now, do a ***global*** fit.

Data used in nPDF fits

- NC DIS: since ever.
- Drell-Yan with fixed target: since ever.
- Single inclusive hadron production: since 2009.
- CC DIS: since 2012.
- W and Z production at the LHC: since 2016.
- di-jets at the LHC: since 2016.
- D meson production at the LHC: since 2021.
- Prompt photon production at the LHC: since 2021.

Sets (until 2015)

and comparison

$\neq$ choices

When doing a fit one has to make choices, and these impact the outcome:

- initial scale for the evolution
- order of the perturbation theory
- heavy-flavour scheme
- data fitted
- parametrisation
- proton baseline
- ...

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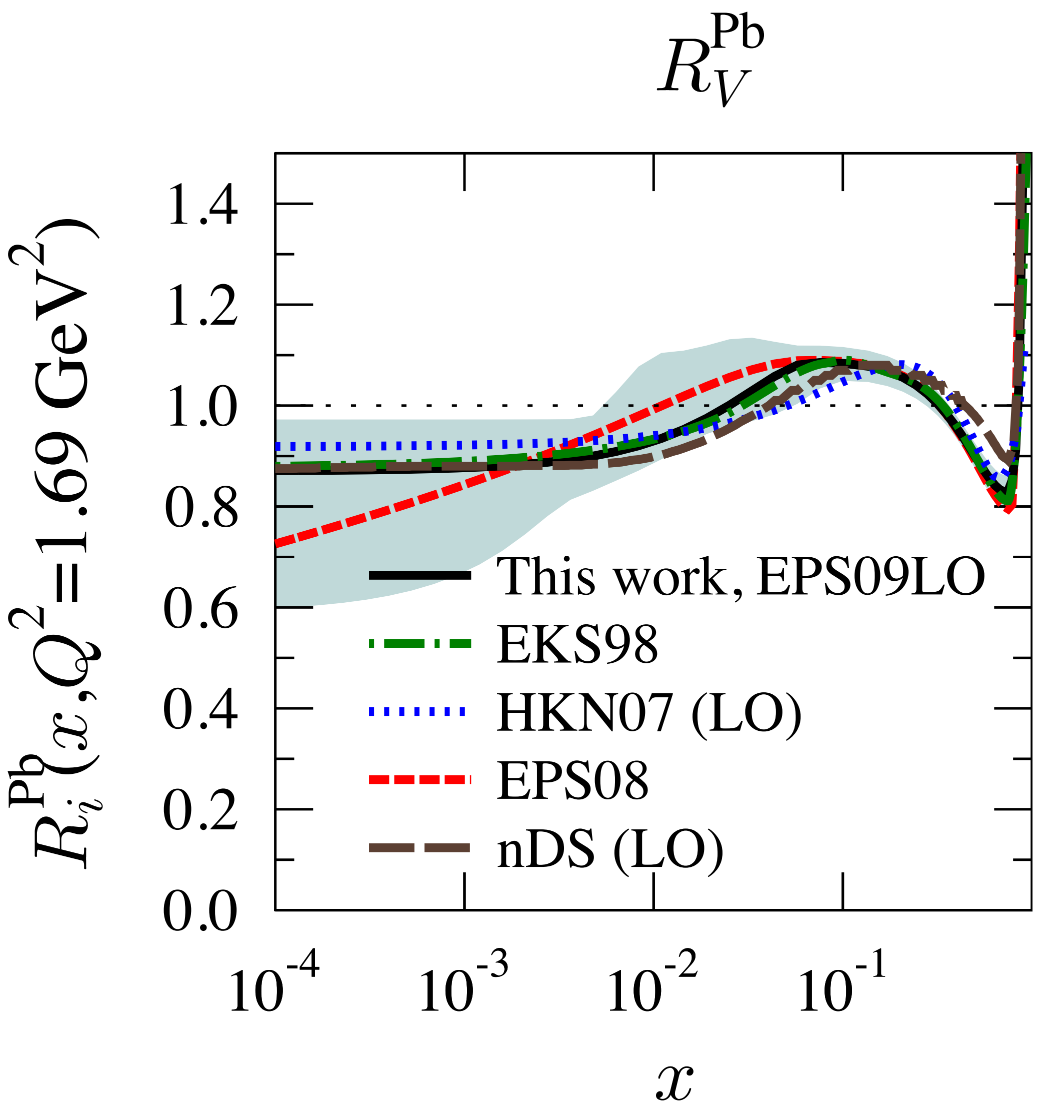
It is customary to show the nPDFs as ratios. We distinguish valence ($f_{i,\text{valence}} = f_i - f_{\bar{i}}$), sea and gluon modifications.

The old days: LO

- nDS used a convolutional approach, the rest a multiplicative factor.
- No flavour separation: only valence, sea and gluon.



JHEP 0904 (2009) 065

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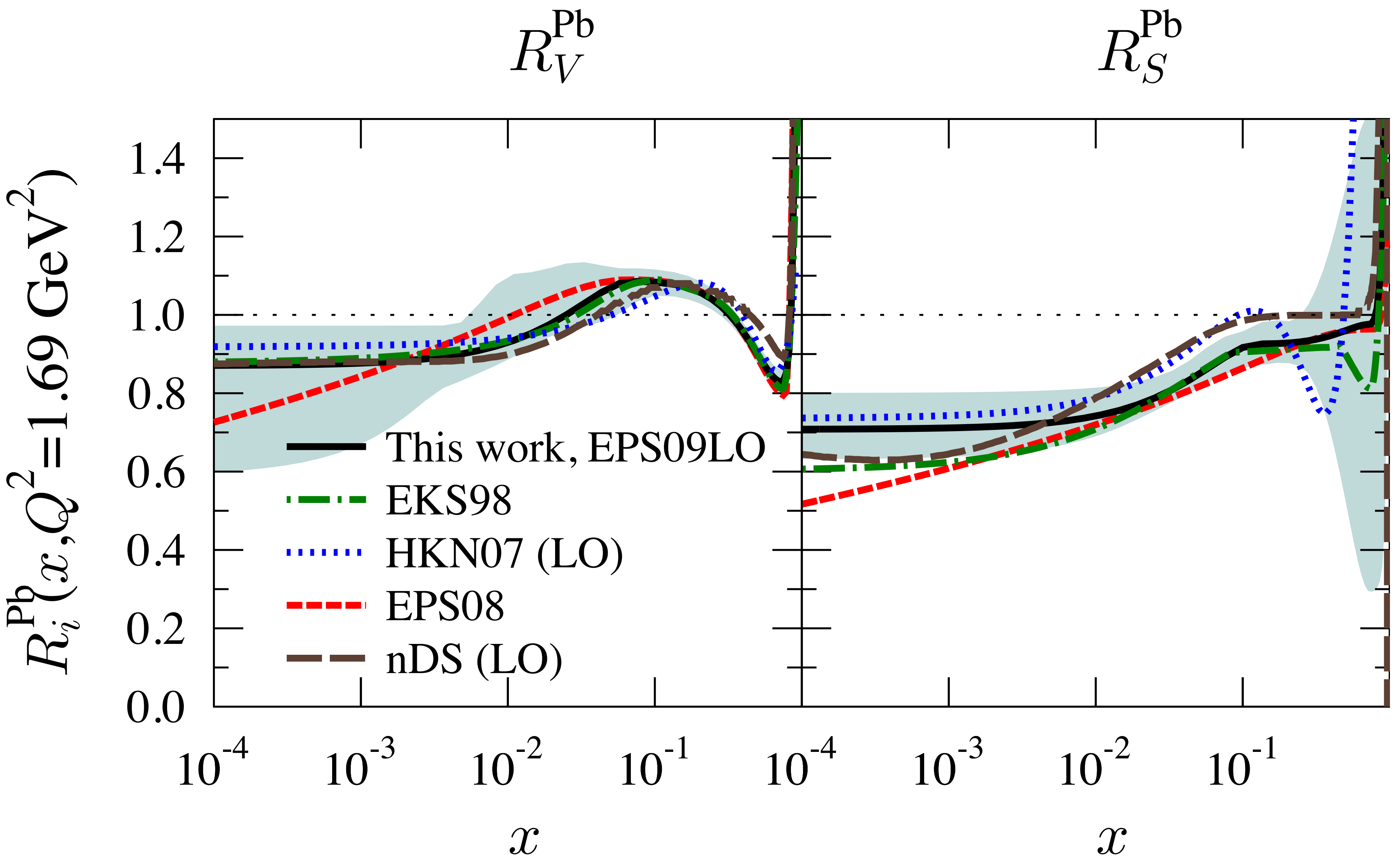

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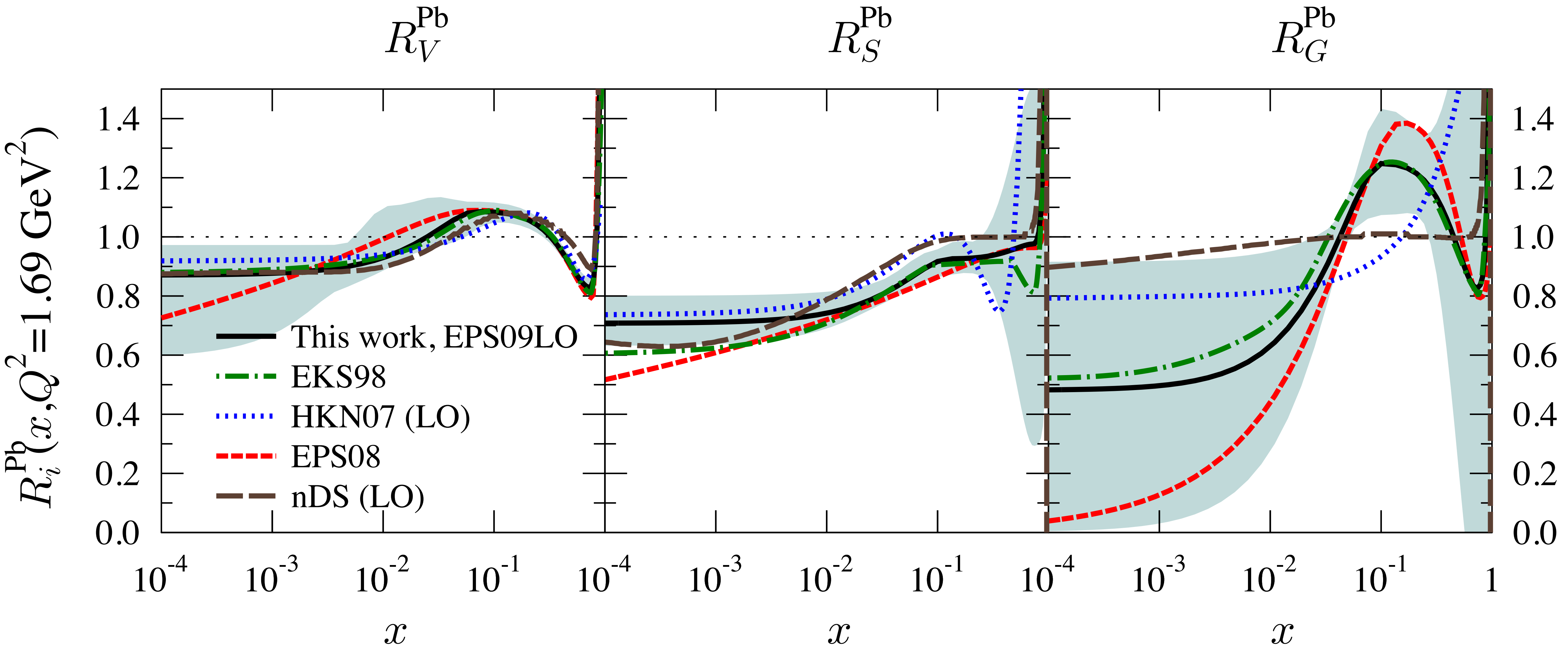

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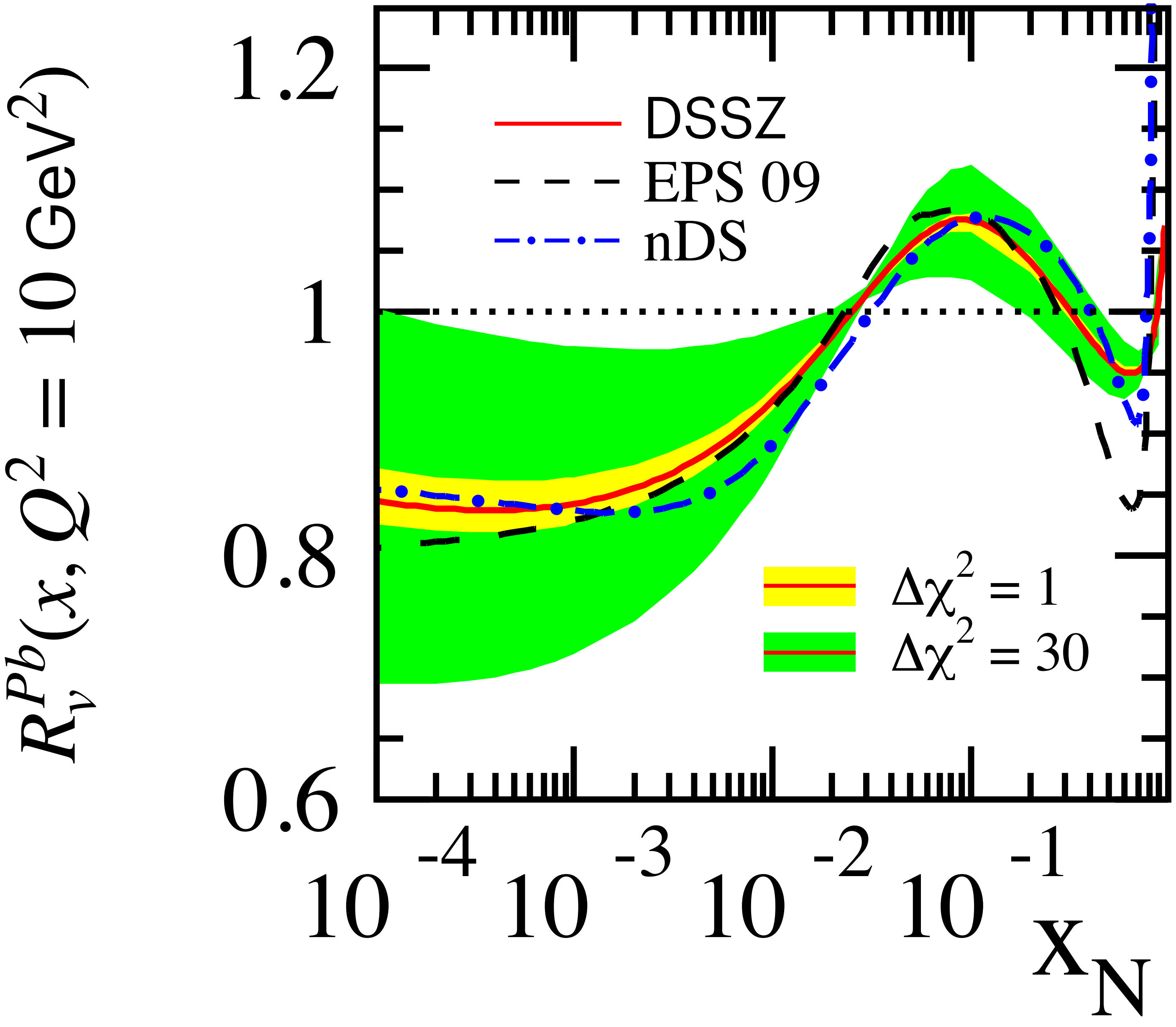
NLO: valence

$$R_{u_v} = R_{d_v}$$



PRD 85, 074028

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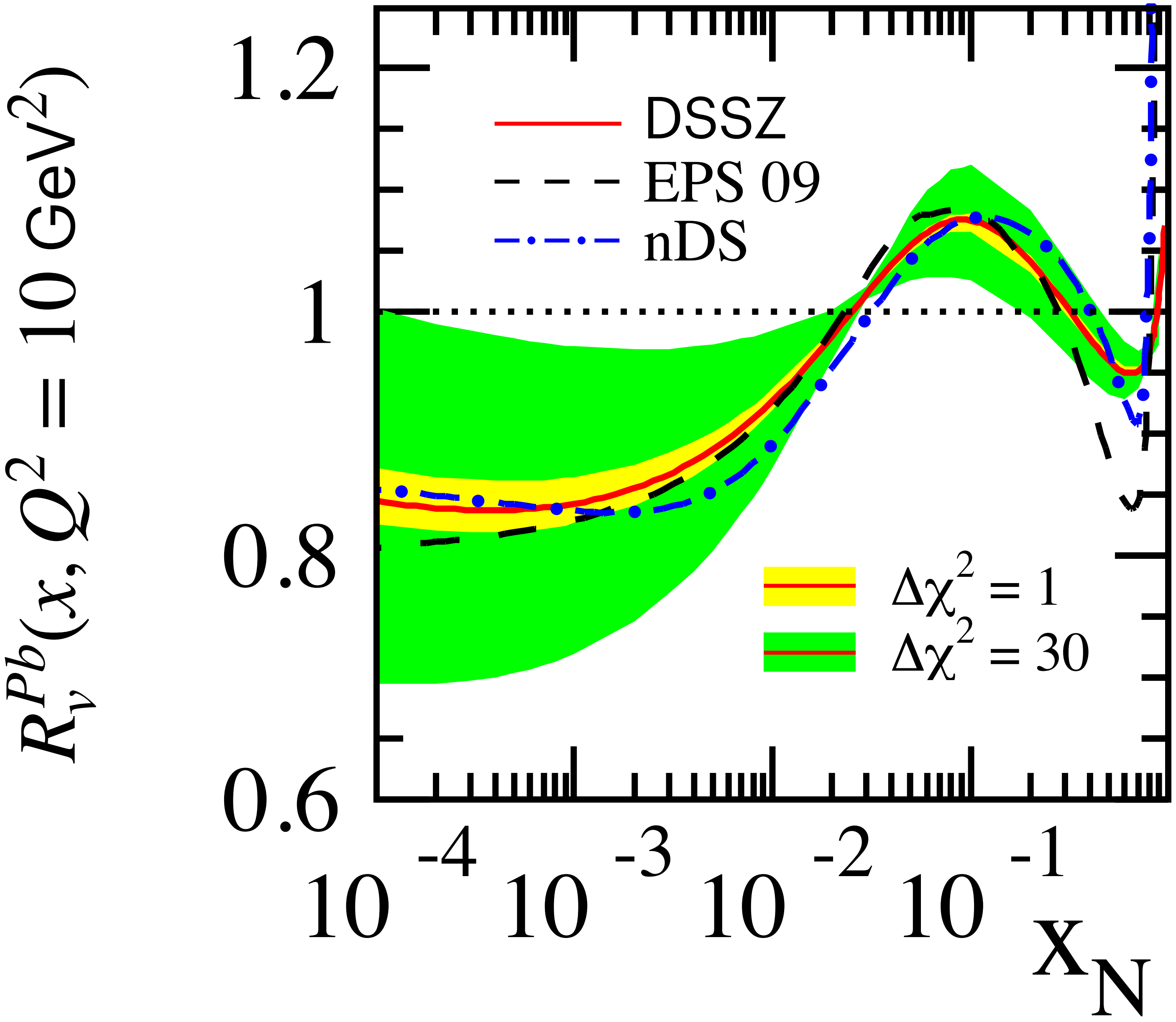


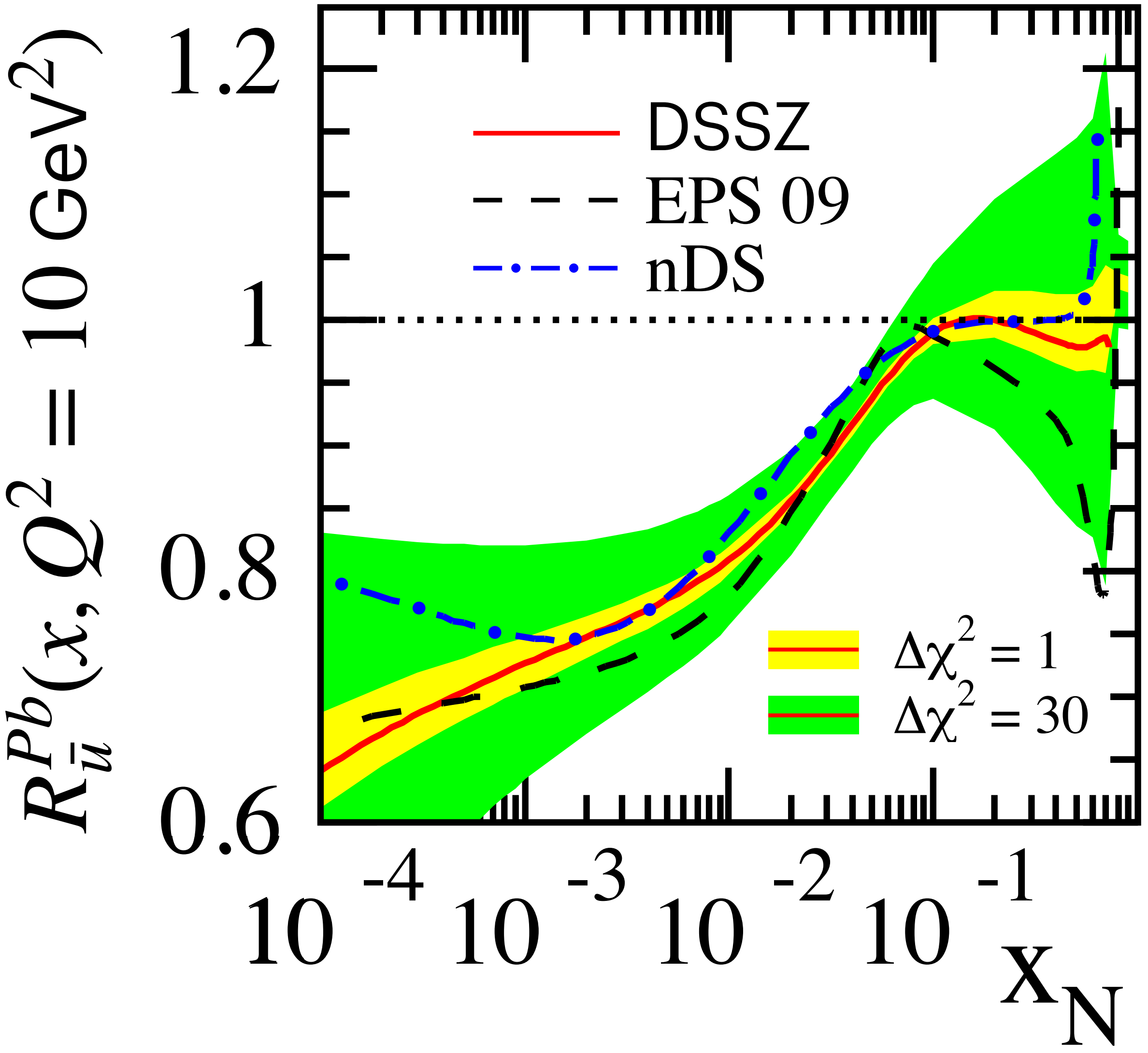
- almost no data below x=0.01
- DSSZ: no W^2 cut
- EPS09: W^2 cut

- overall overlap within uncertainties where we have data

PRD 85, 074028

NLO: sea

$$R_{\bar{u}} = R_{\bar{d}} = R_{\bar{s}} = R_s$$



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NLO: sea

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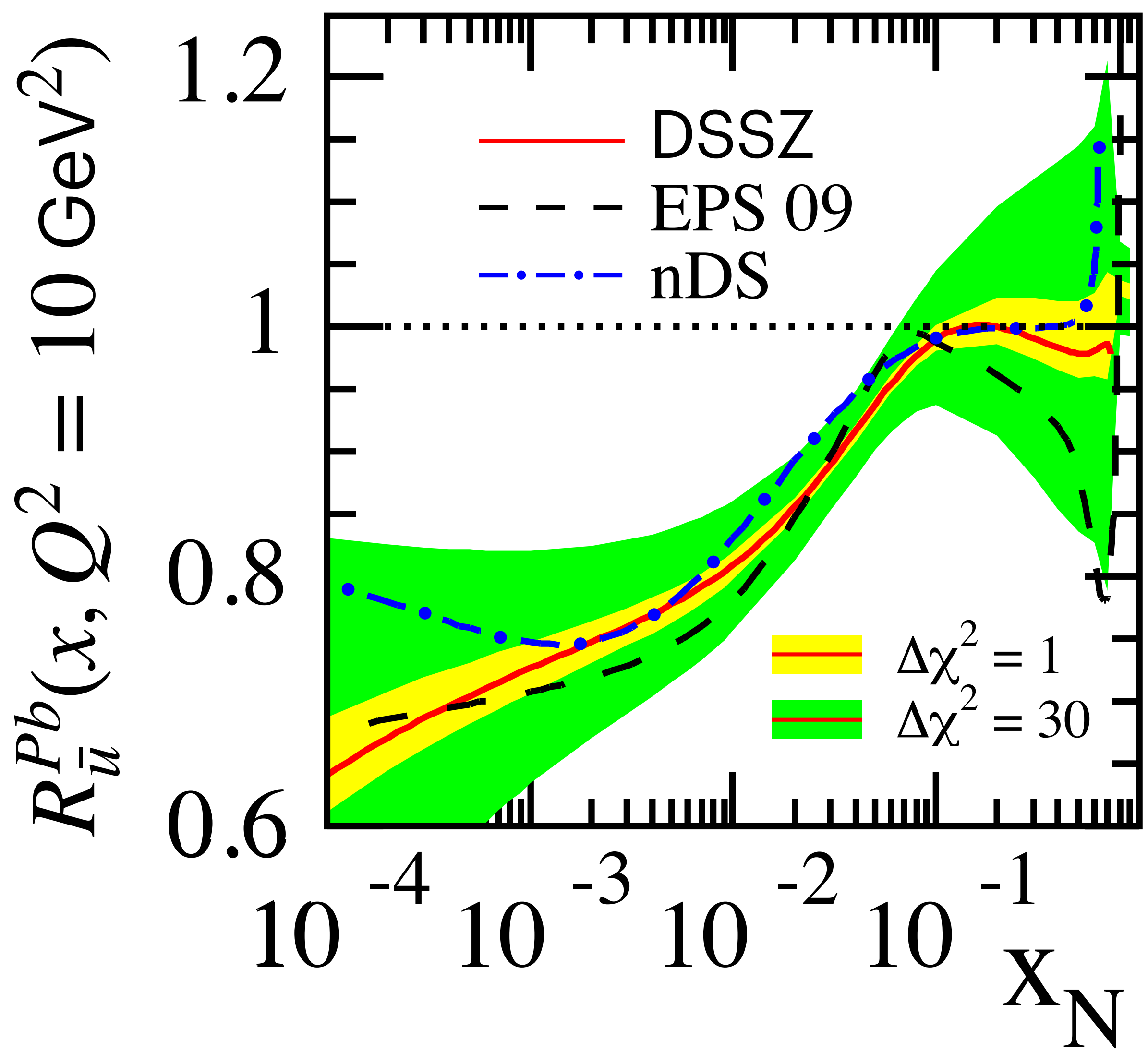

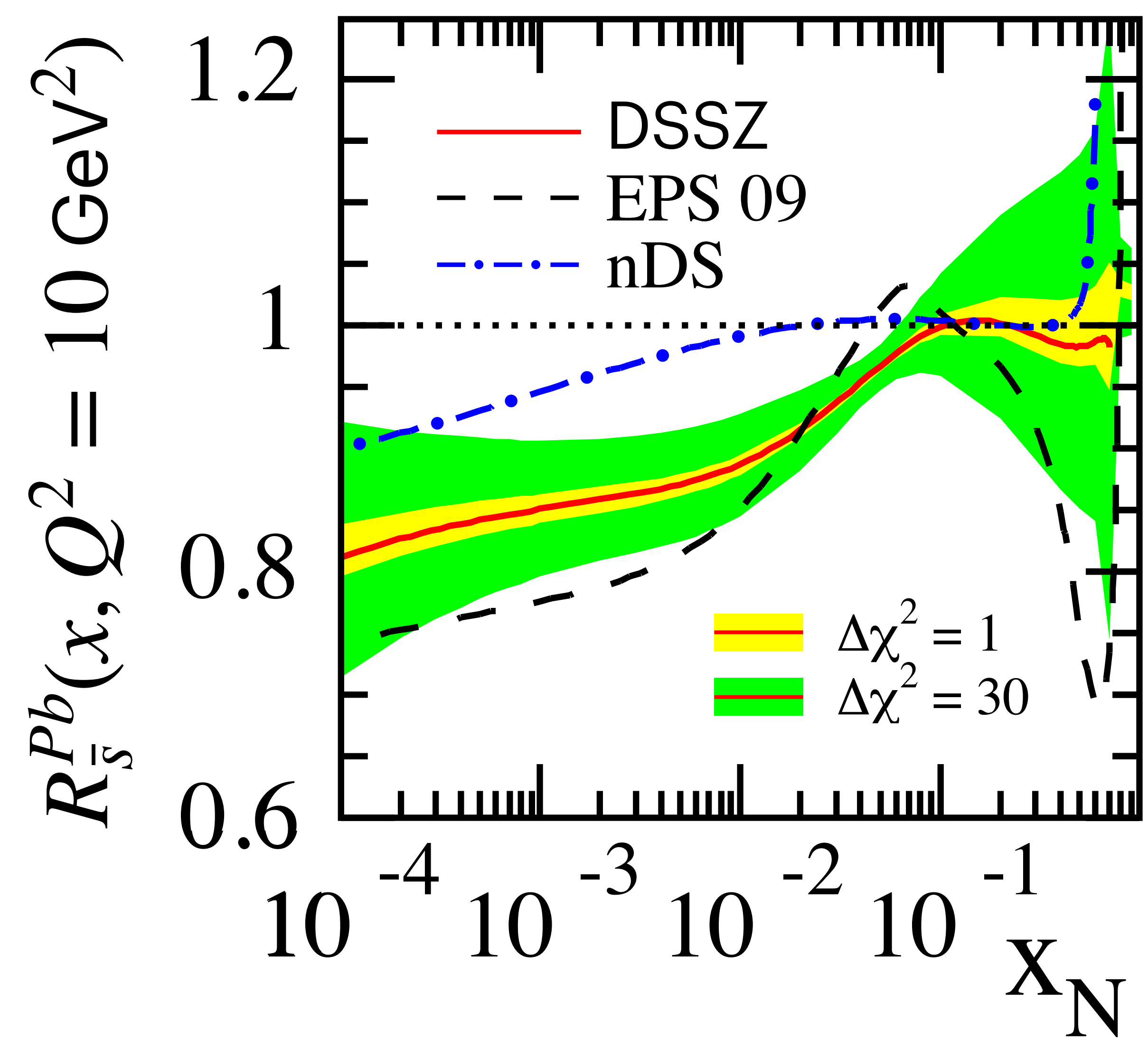

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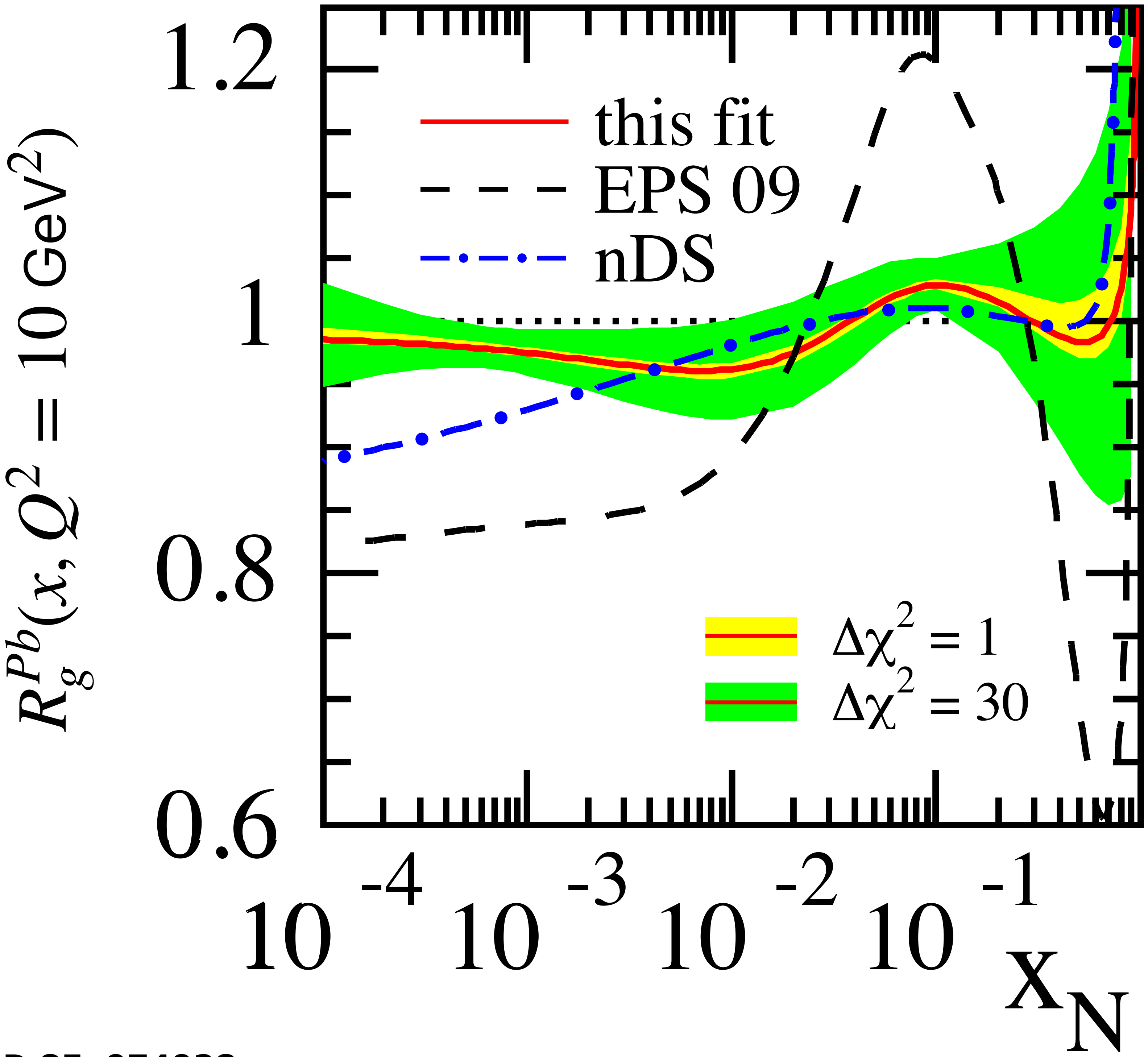
NLO: gluon



- nDS didn't use d+Au data
- EPS09 and DSSZ used d+Au data

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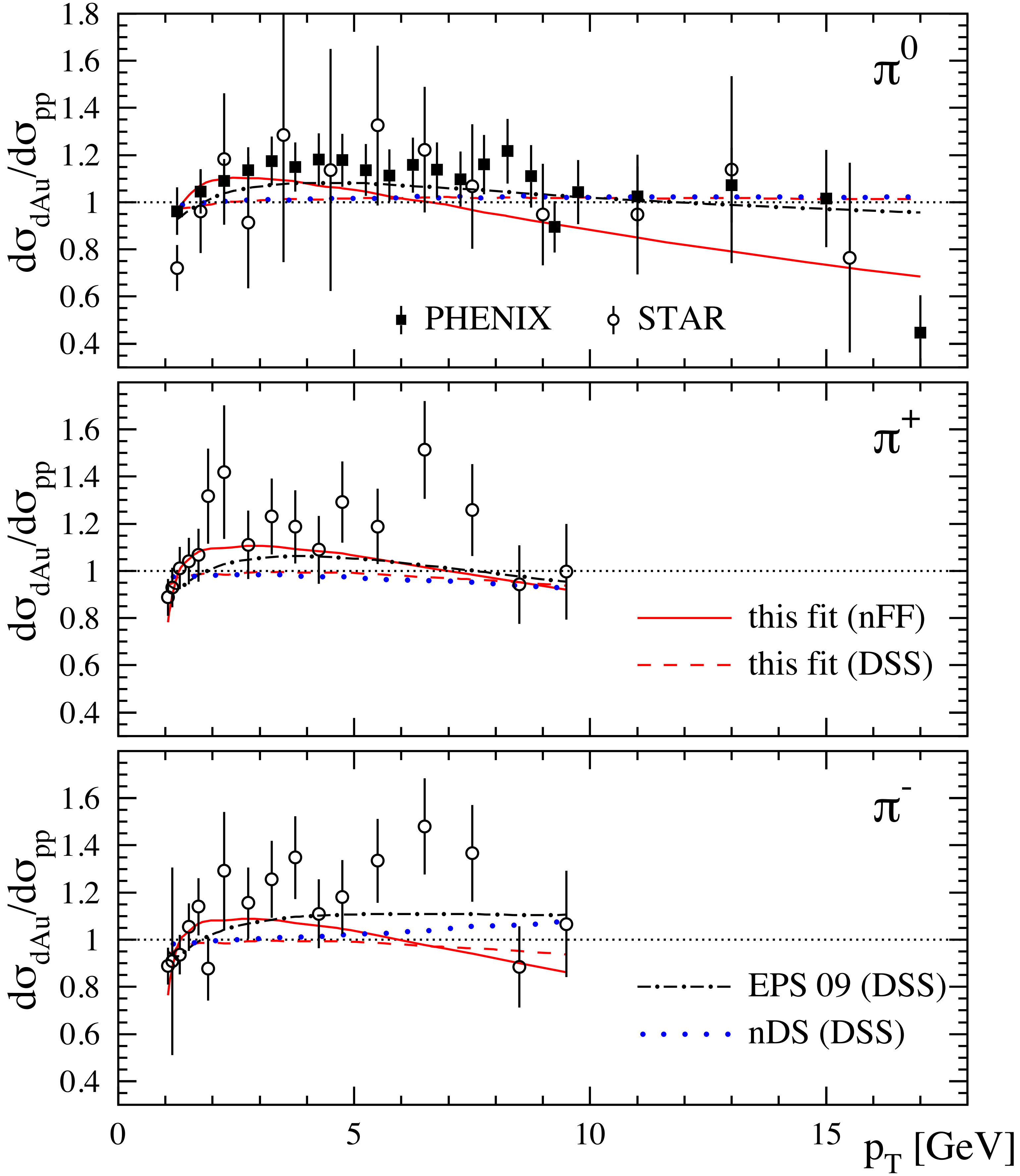


- This is a very involved observable (in terms of parton distributions).
- RHIC data are not very precise.
- EPS09 and DSSZ used a totally different treatment.

PRD 85, 074028

In general, up to 2012:

- The valence distributions are *well* constrained in the region where we have data.

- Idem for the non-strange sea densities, but with ad-hoc constraints. They don't look *that* bad.

- The strange quark lives up to its name.

- The gluon density is a **BLOODY MESS**.

2015-present: improving

To improve (n)PDFs we can:

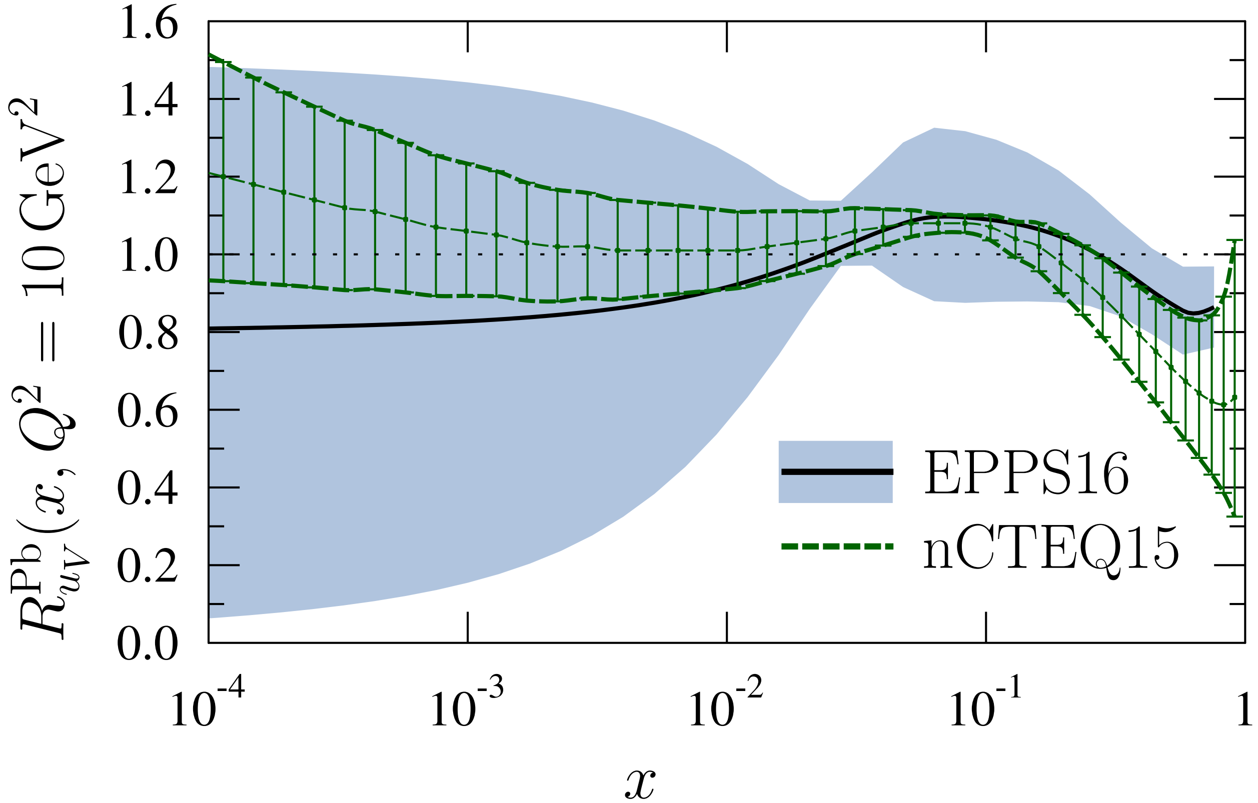
- use the same observables with higher precision and/or broader kinematic coverage: **NC DIS**, **Drell-Yan**, **single inclusive hadron production**.

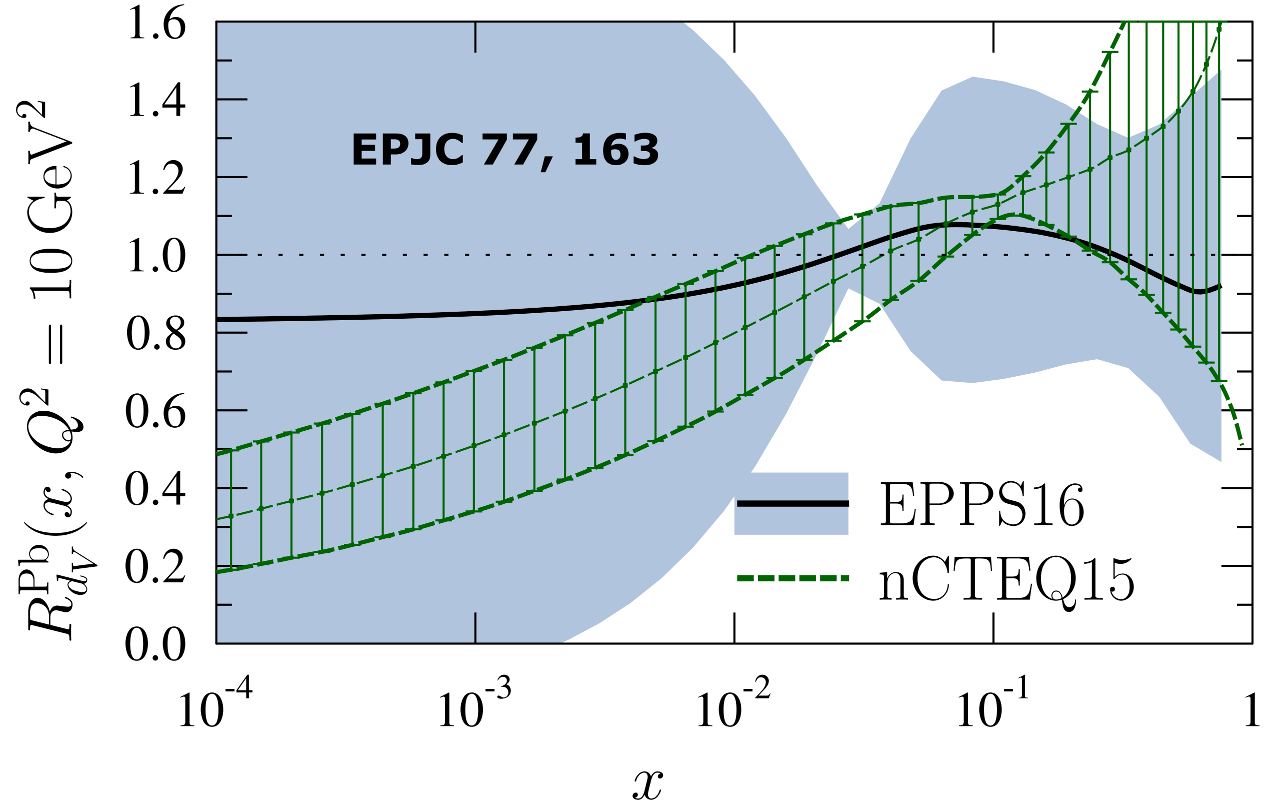
- use other observables: **CC DIS**, **W/Z production**, **di-jets**, **D meson production**.

- **improve the theoretical computation**.

CC DIS

- $R_{u_v} \neq R_{d_v}$ requieres data that can better distinguish up from down.





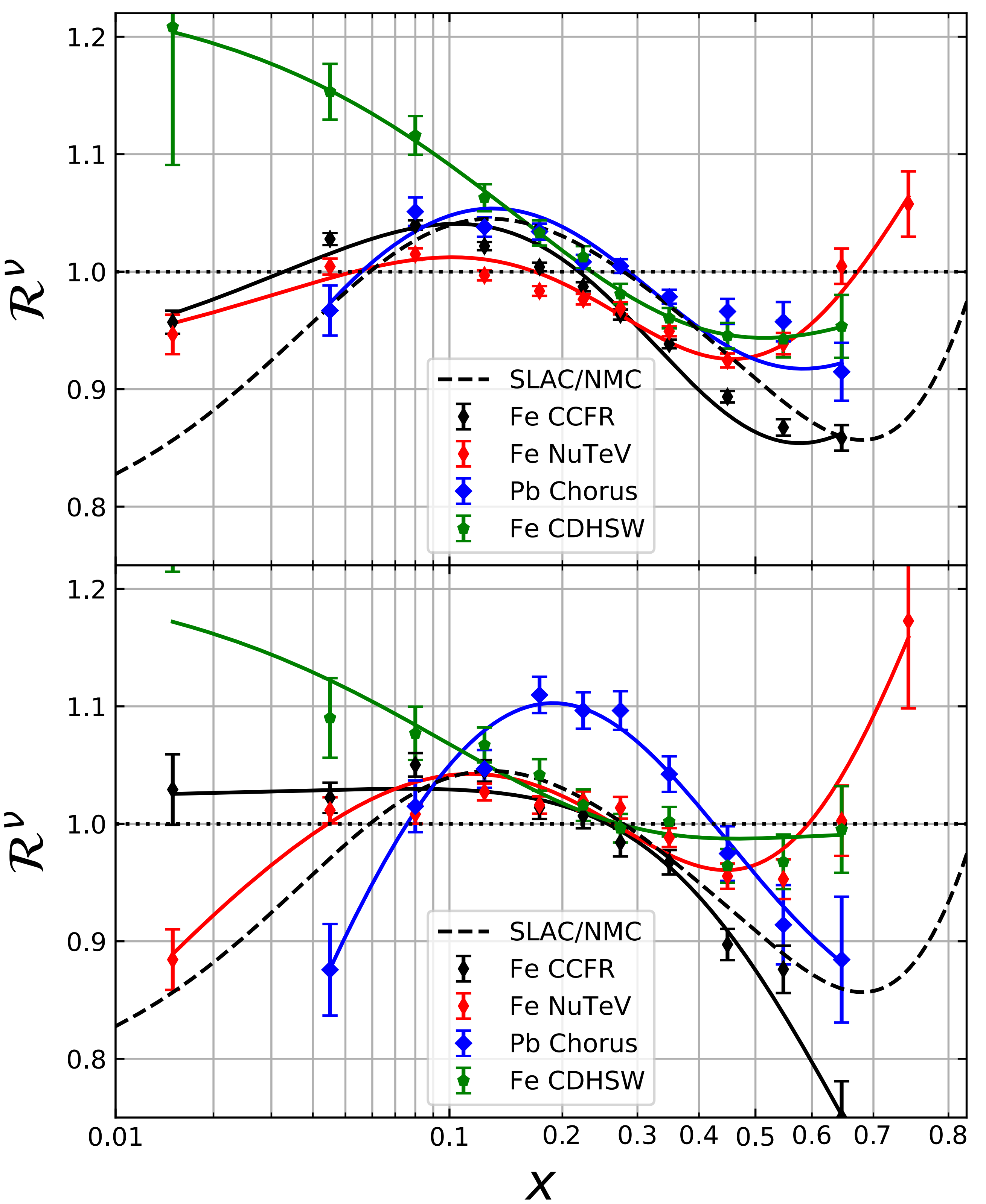
- Clearly the green band looks very different. They didn't use CC DIS data.

◉ CC DIS

- Basically 4 experiments: CCFR, NuTeV, CDHSW, and Chorus.
- There are tensions among the different neutrino experiments if we try to fit the cross-sections.
- No problem to accommodate the structure functions in a global fit, nor with Chorus cross-sections.

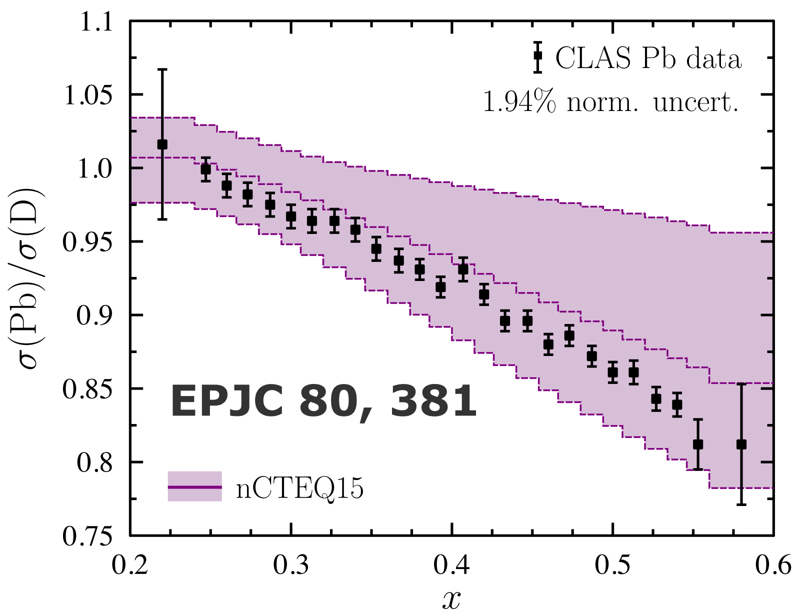
Could NOMAD solve this?

PRD 106, 074004



NC DIS at JLAB

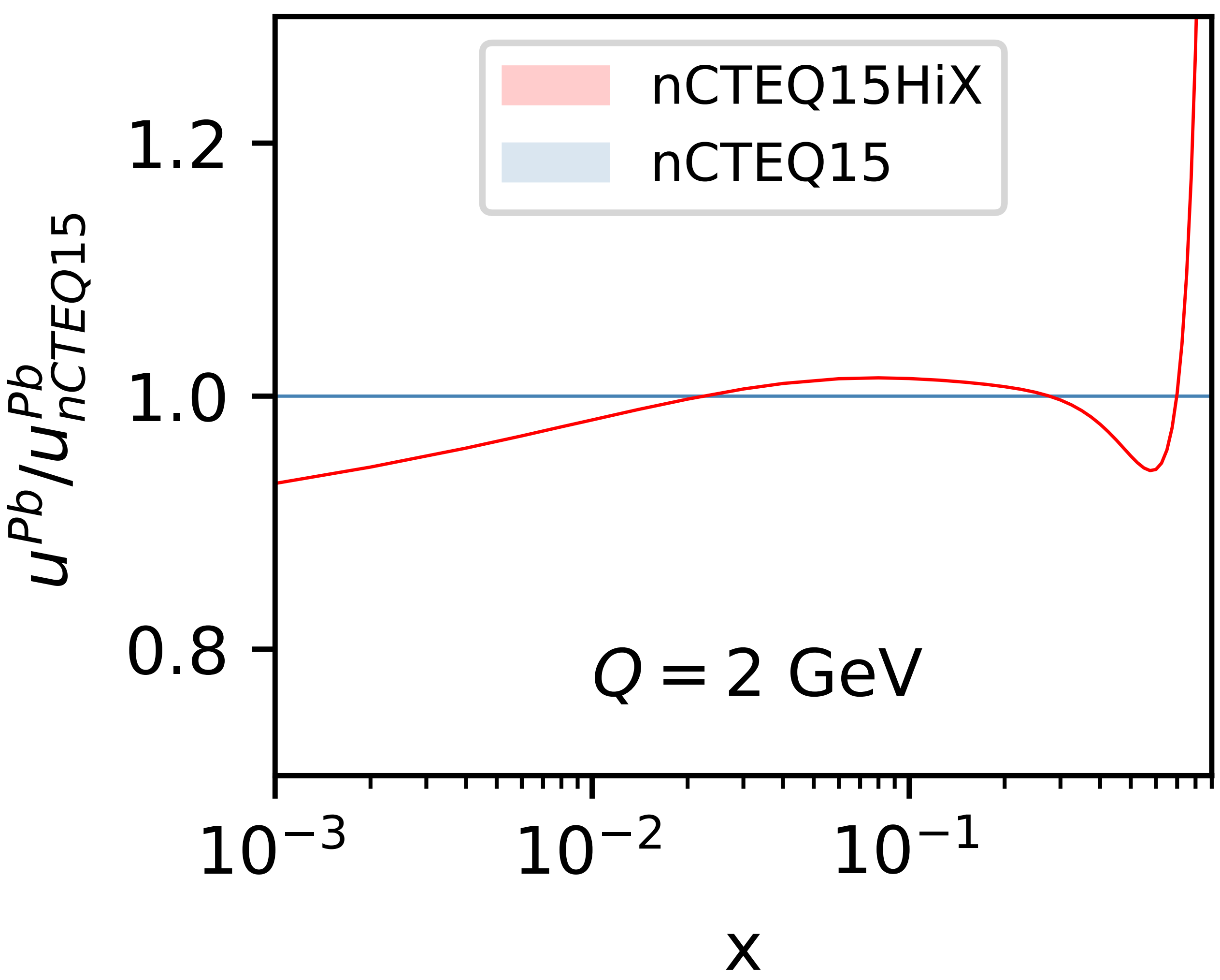
- Very precise data at high-x, but low W^2.

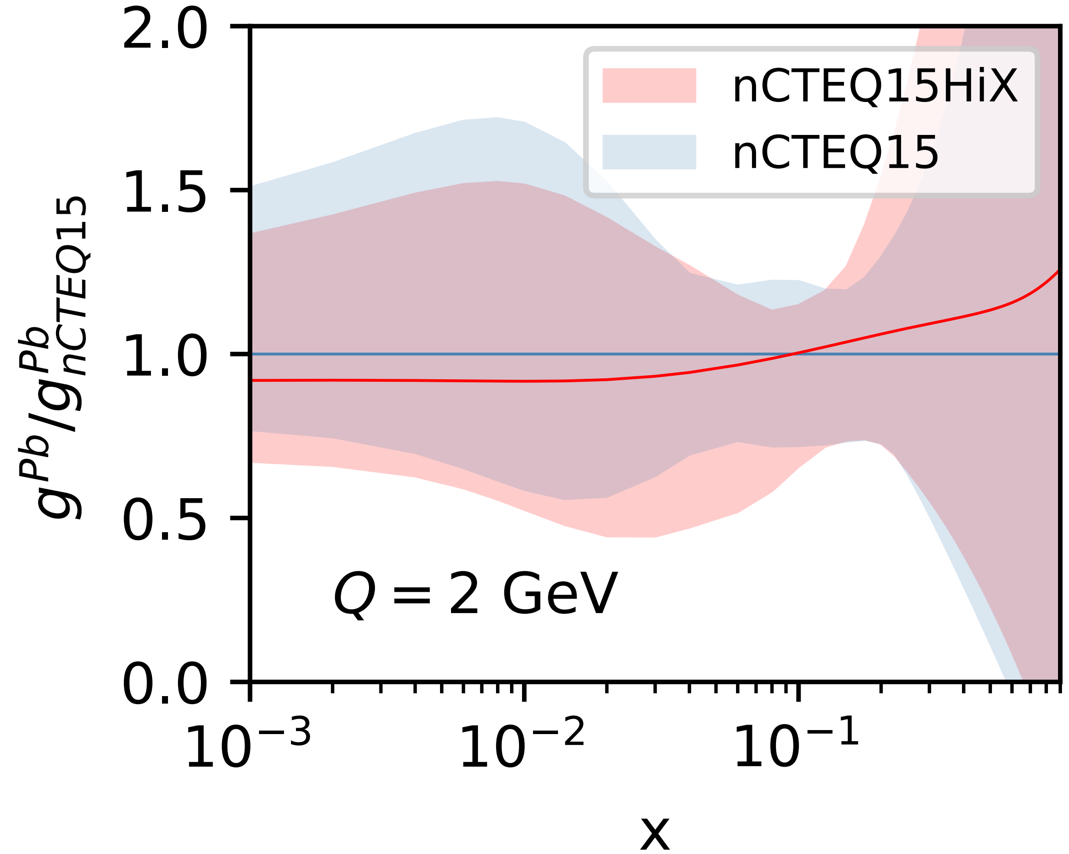


- Relaxing the cut on W^2 could be useful. This should also be explored for the baseline proton PDFs.

- Large impact on the valence nPDFs.

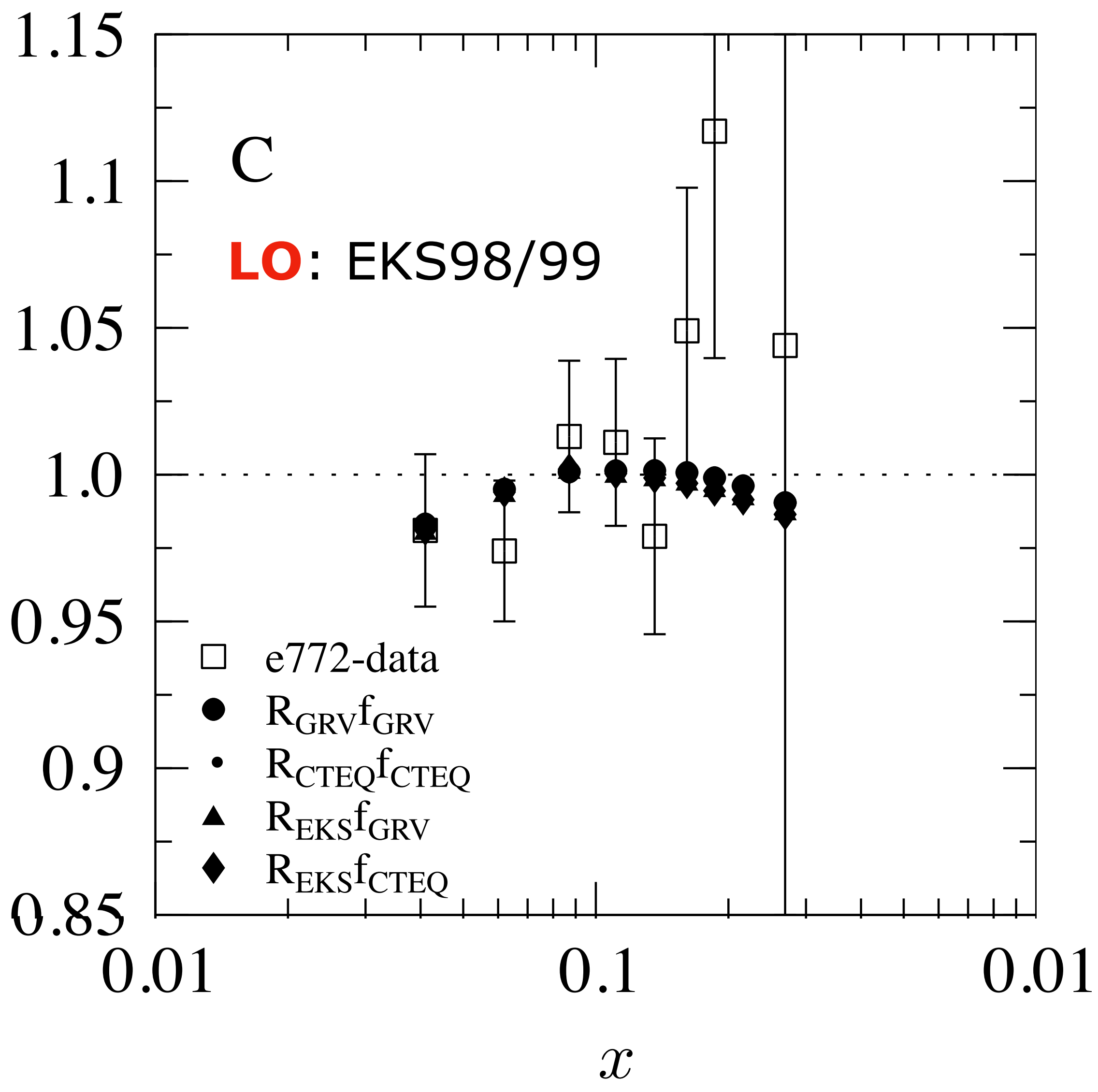
PRD 103, 114015





◉ Drell-Yan

Scarce amount of data in older fits: only 92 points, given as ratios to $p + d$ and $p + Be$.



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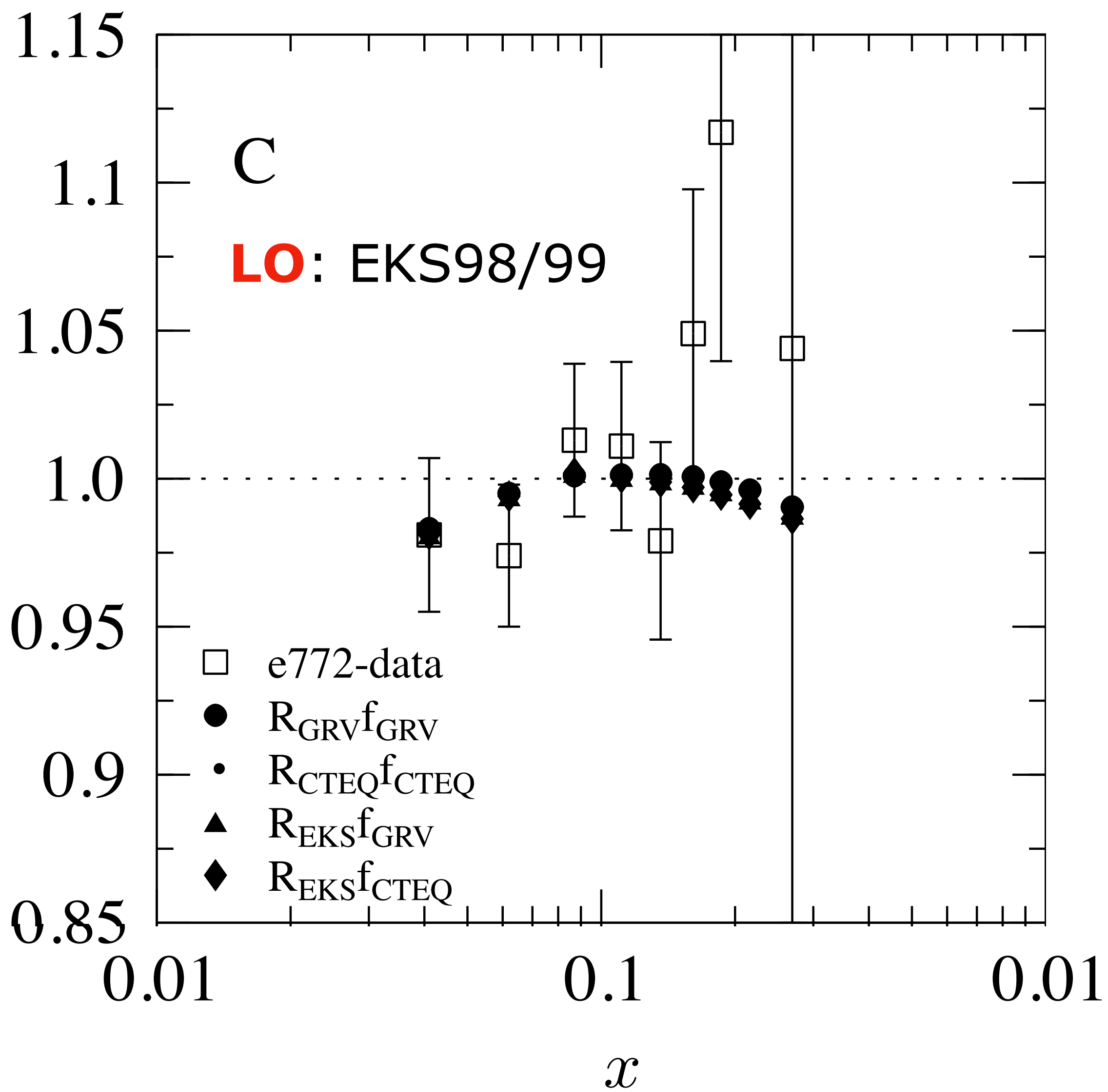
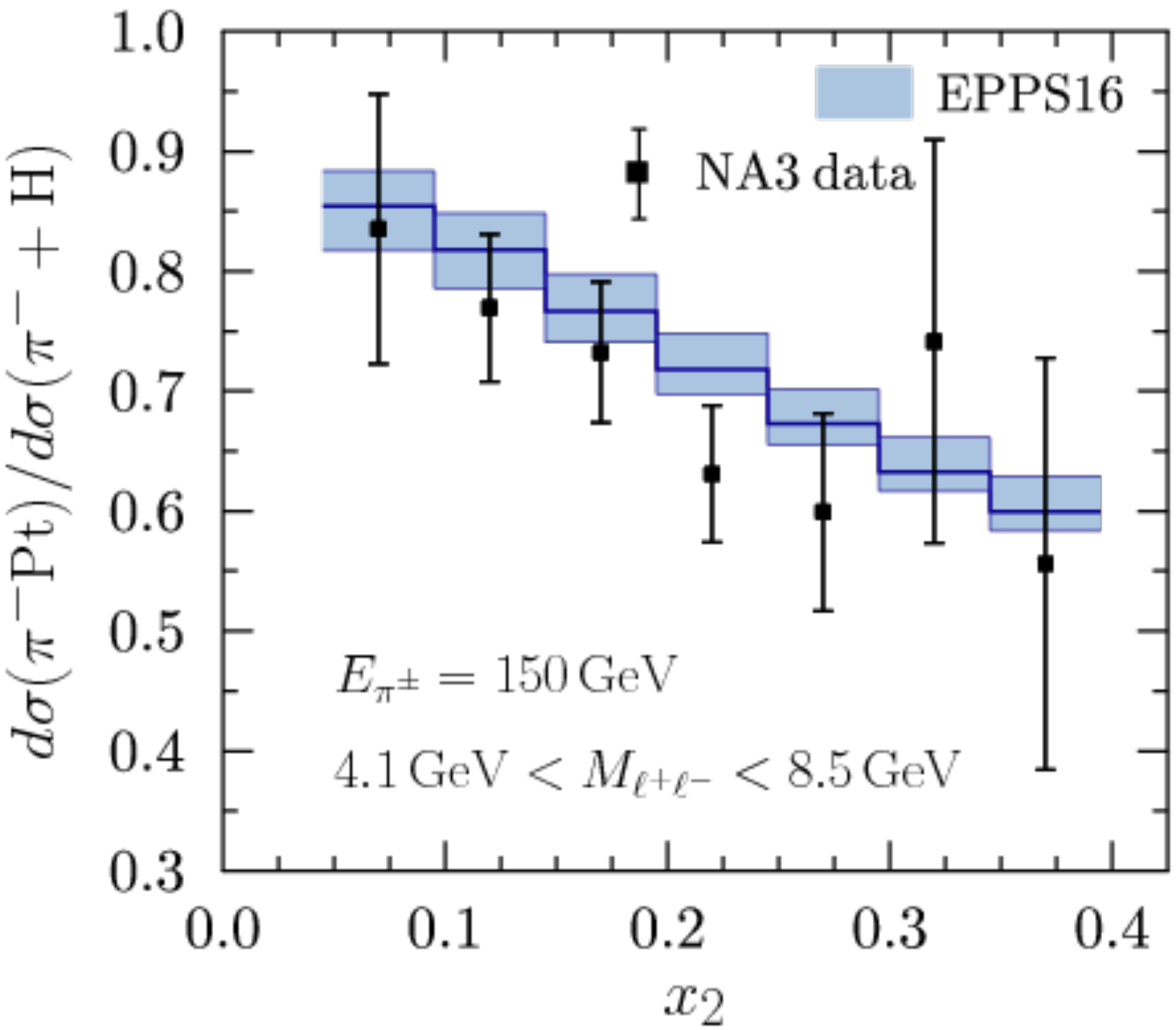


EPJC 77, 163



Since 2016, “new” Drell-Yan data (**1981**, **1987**, **1989**) has been to be considered.

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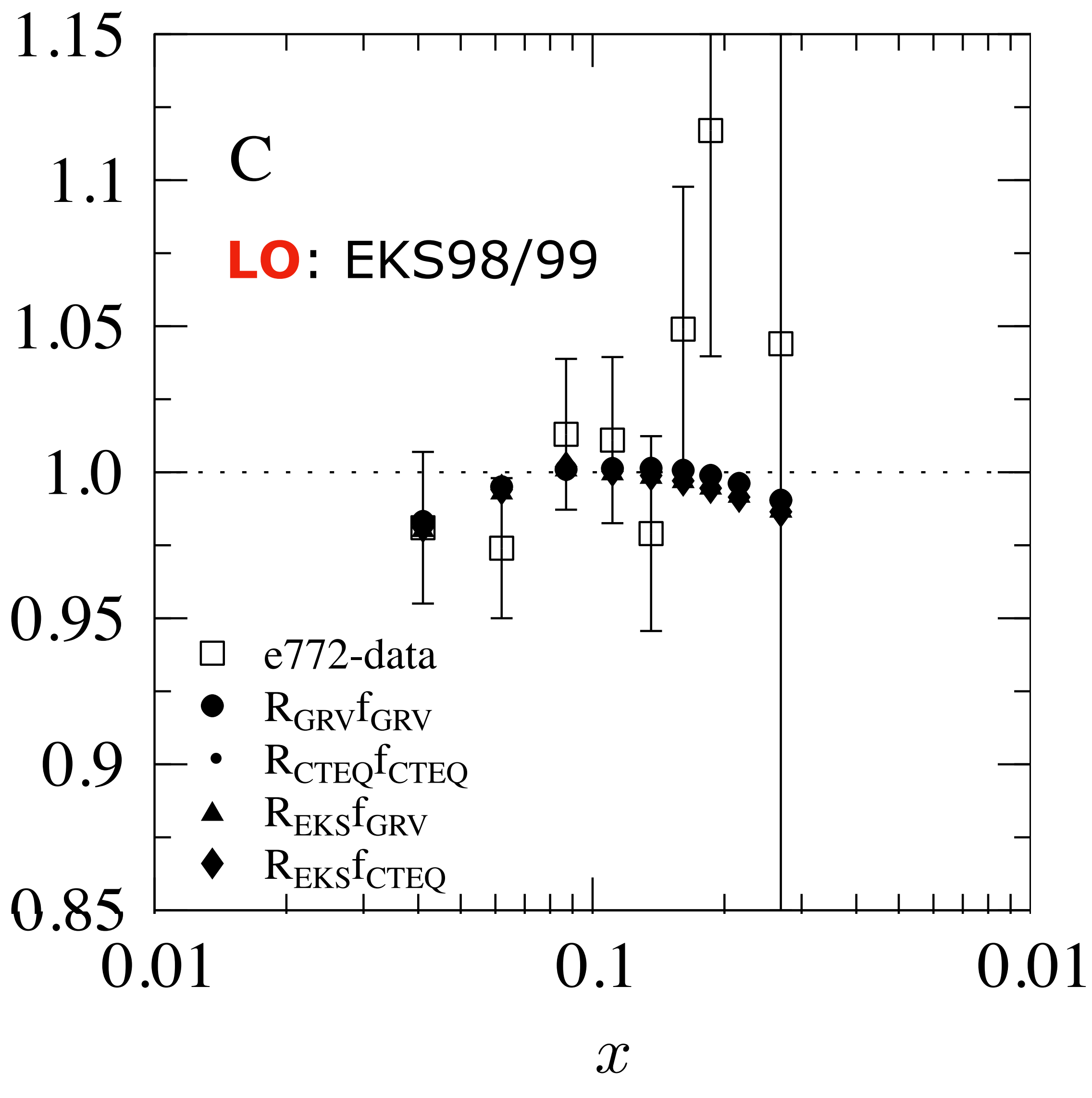
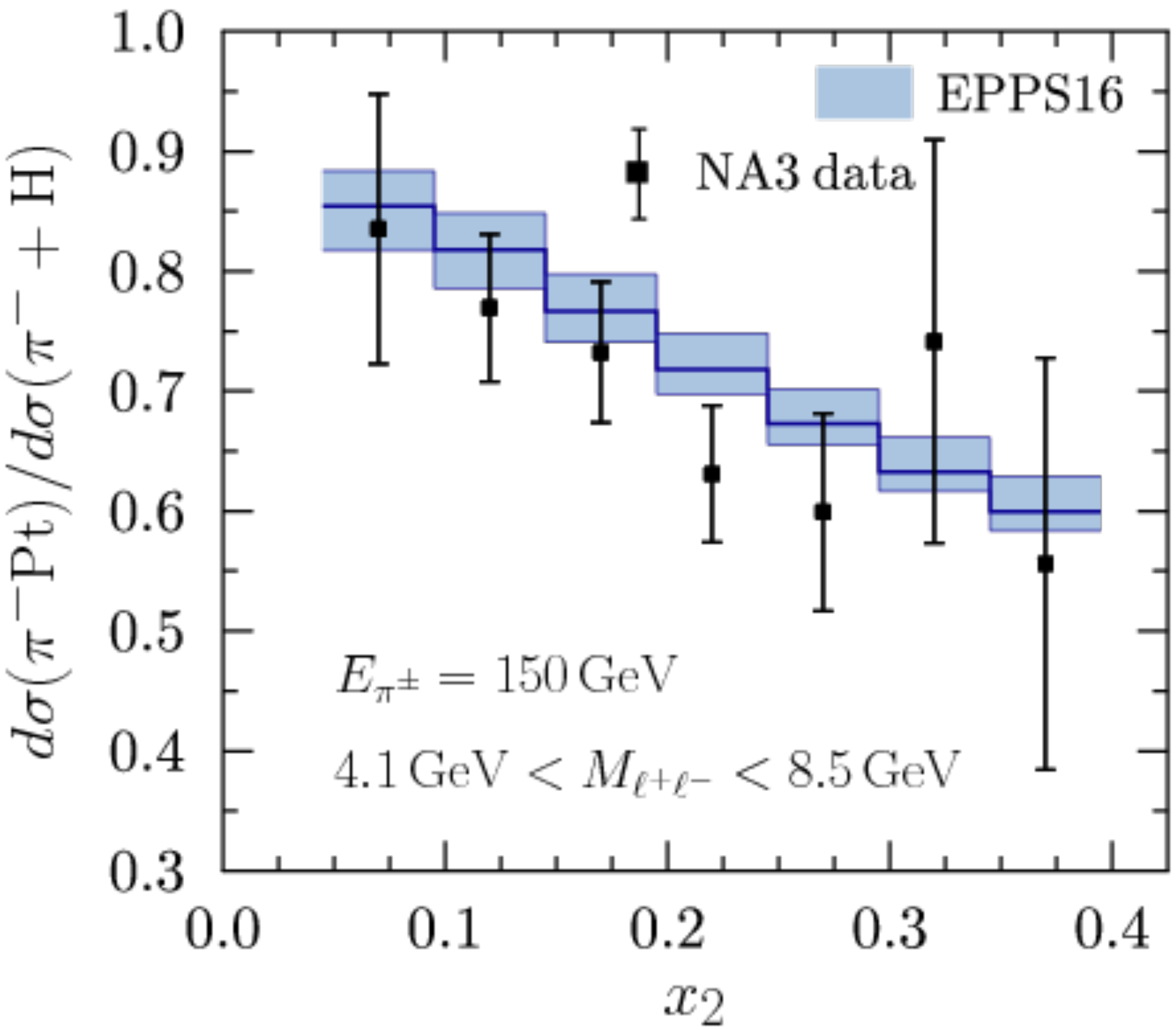


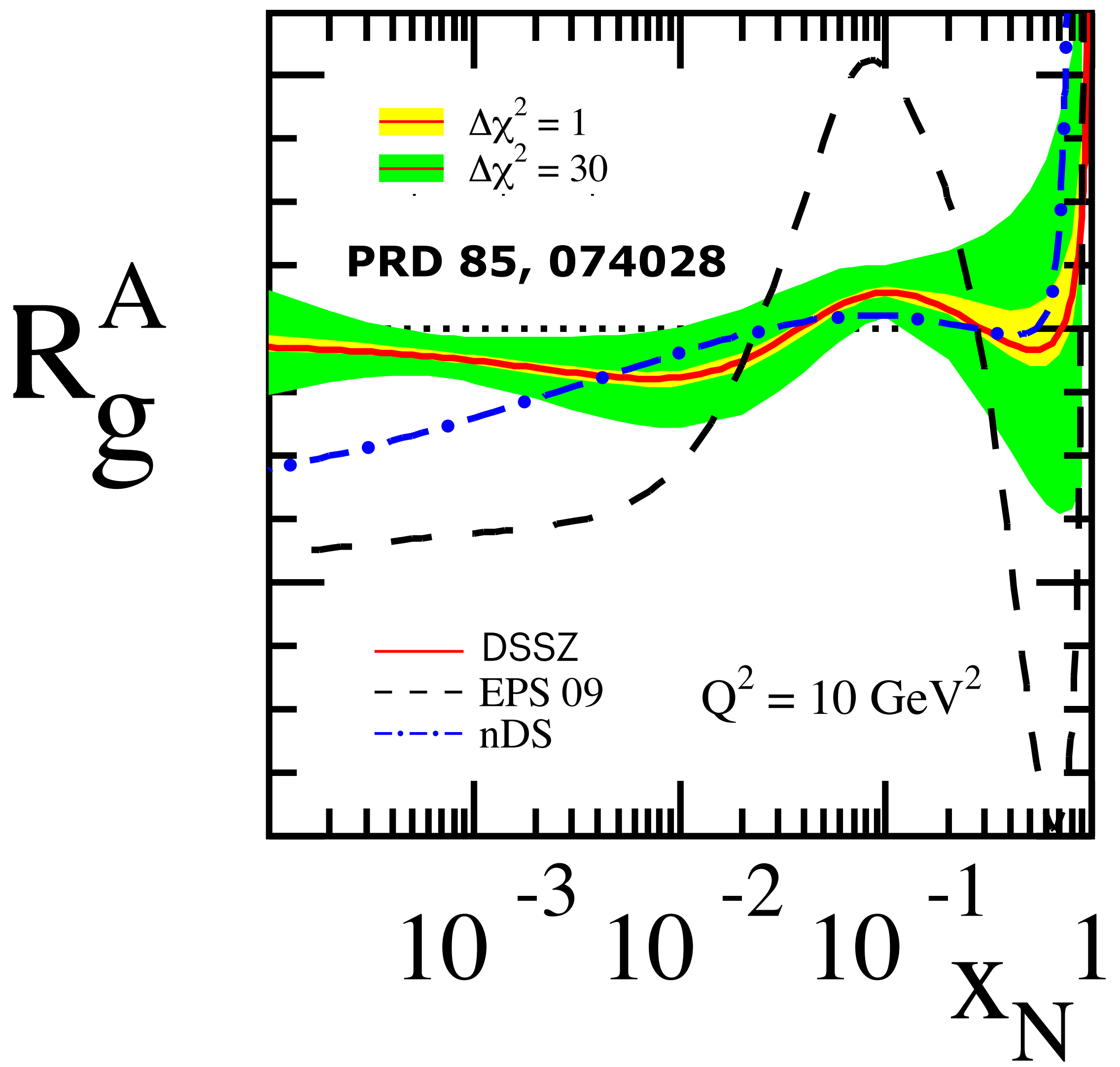
EPJC 77, 163



Since 2016, "new" Drell-Yan data (**1981**, **1987**, **1989**) has been to be considered. 28 points from $\pi^{\pm}+W$, and $\pi^{-}+Pt$. **Requires π PDFs**.

◉ Single inclusive hadron production

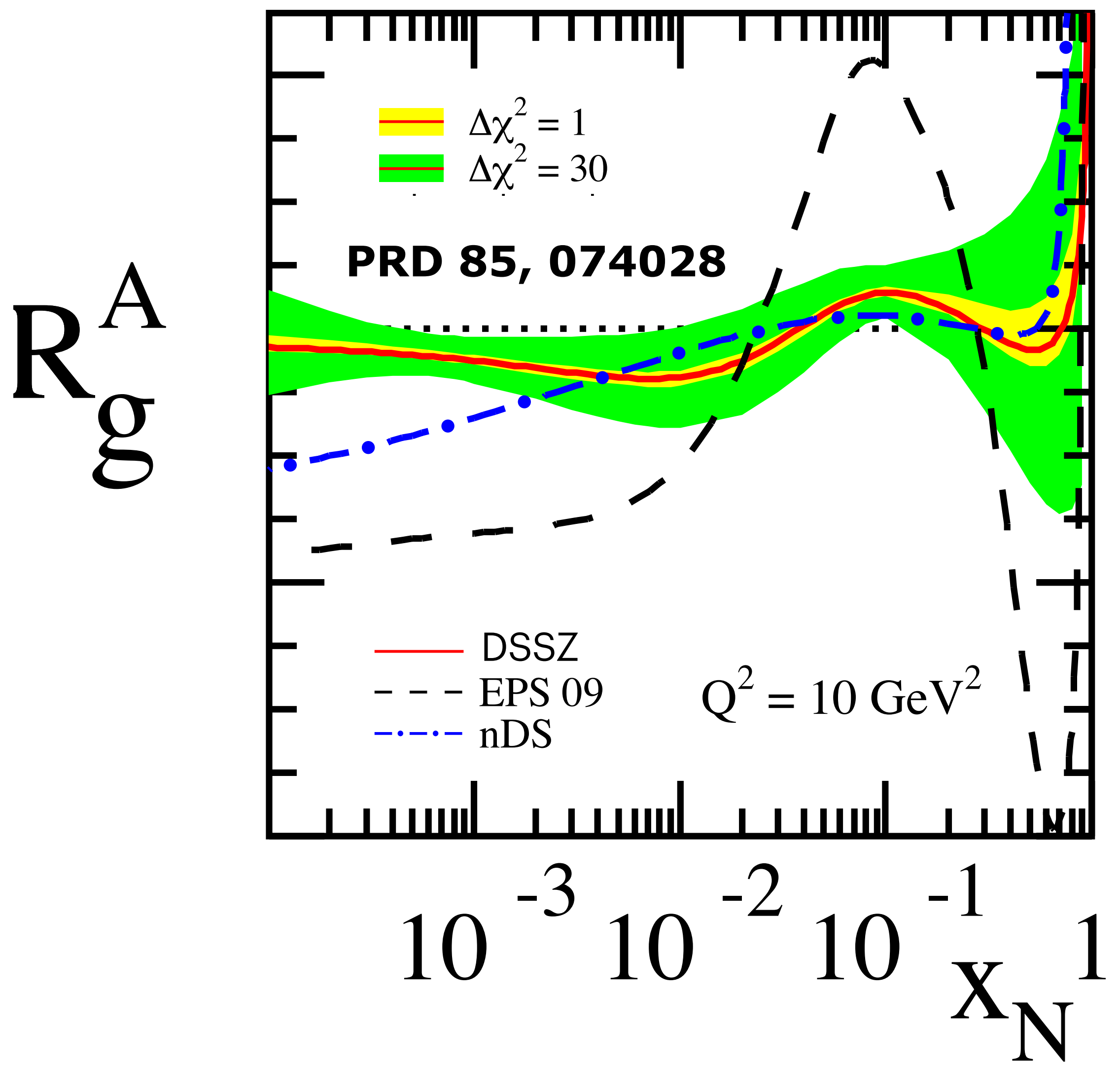
Remember this? How can this be?



◉ Single inclusive hadron production

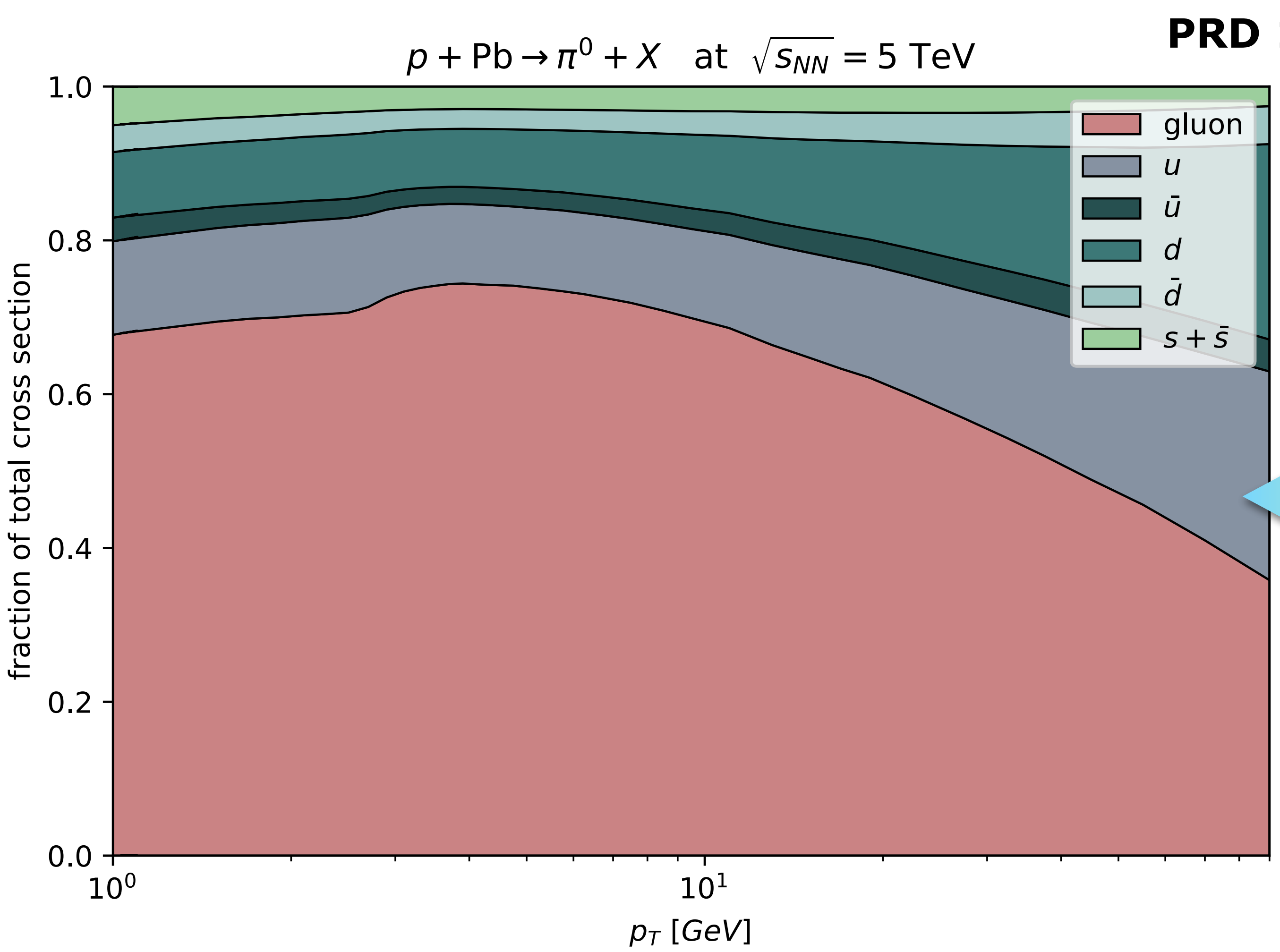
Remember this? How can this be?

$$d + Au \to h + X$$

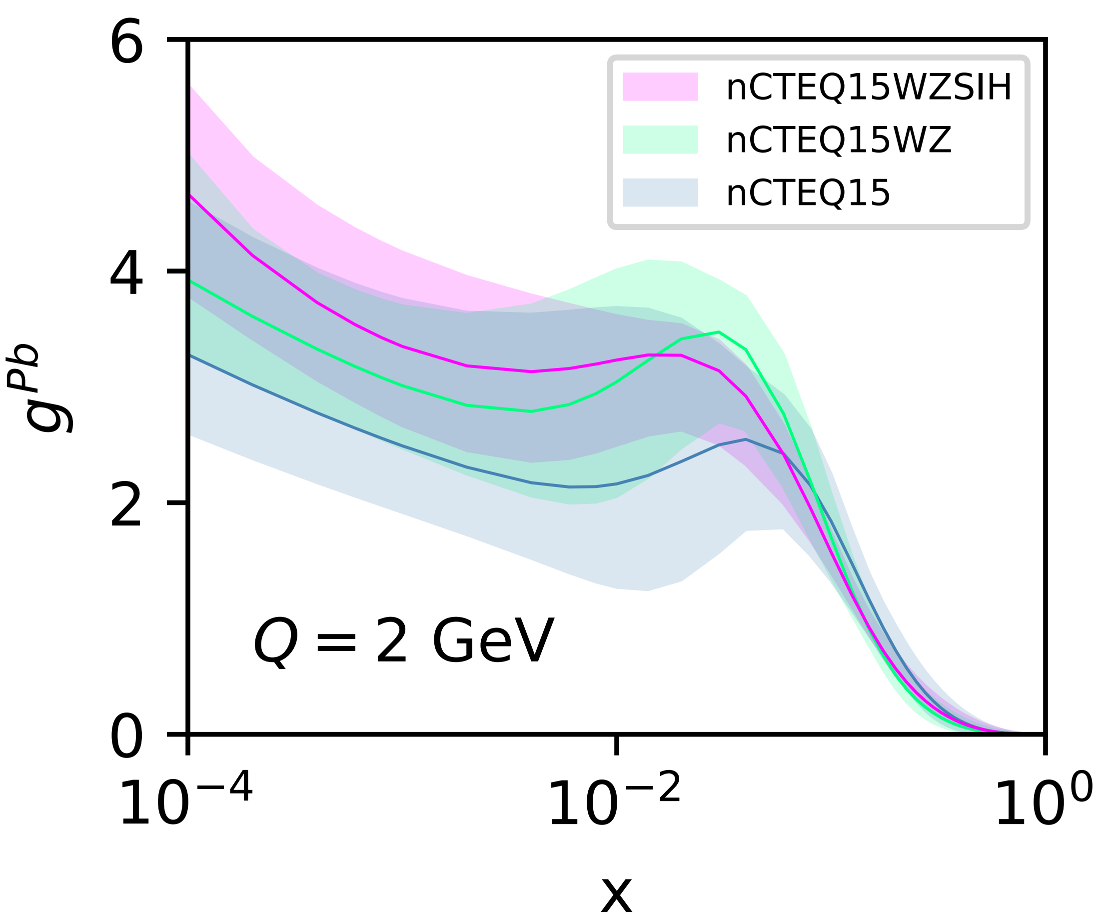


- ◉ SIH depends on the **fragmentation functions** (FFs).
- ◉ EPS09 enhanced the weight of the SIH data.
- ◉ DSSZ included final state effects in the FFs.

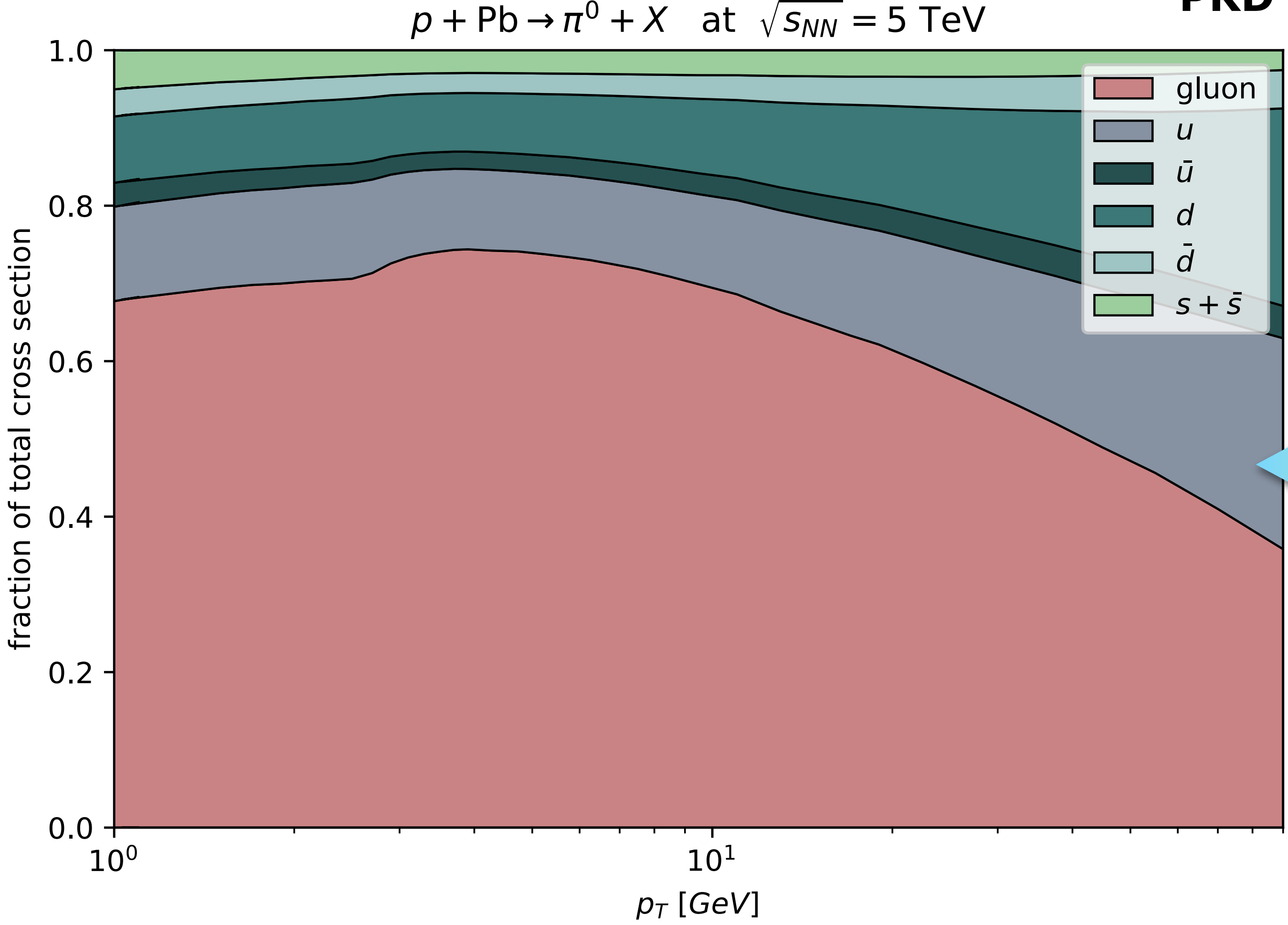
PRD 104, 094005



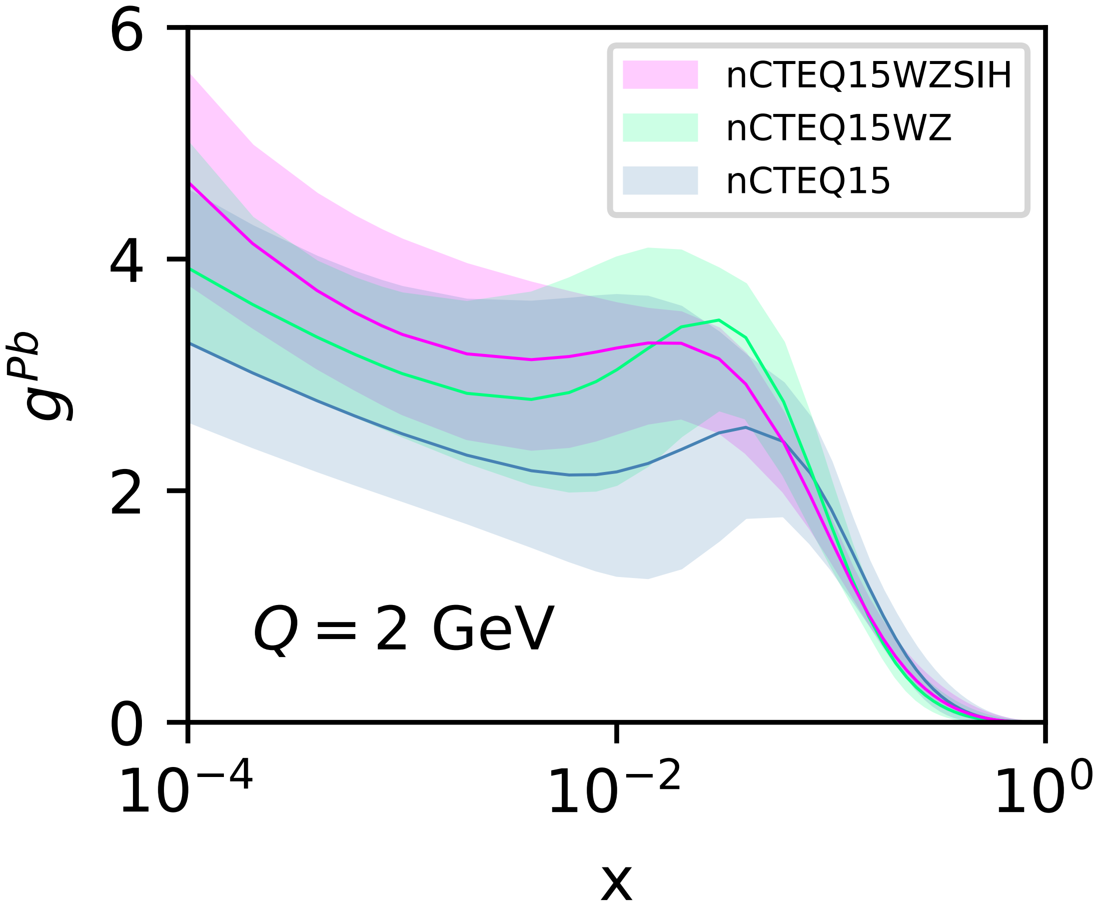
contribution of each initial state parton in p+Pb collisions at the LHC

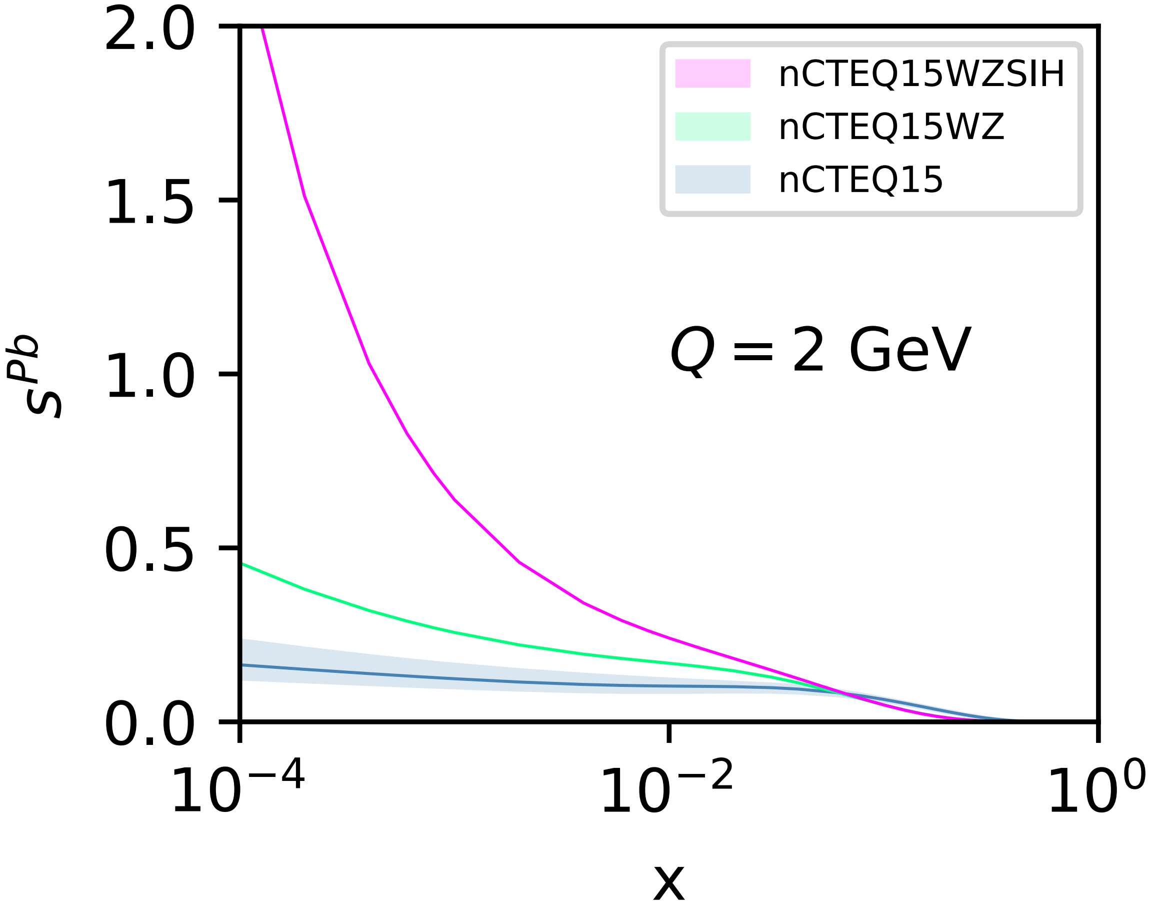


PRD 104, 094005



contribution of each initial state parton in p+Pb collisions at the LHC

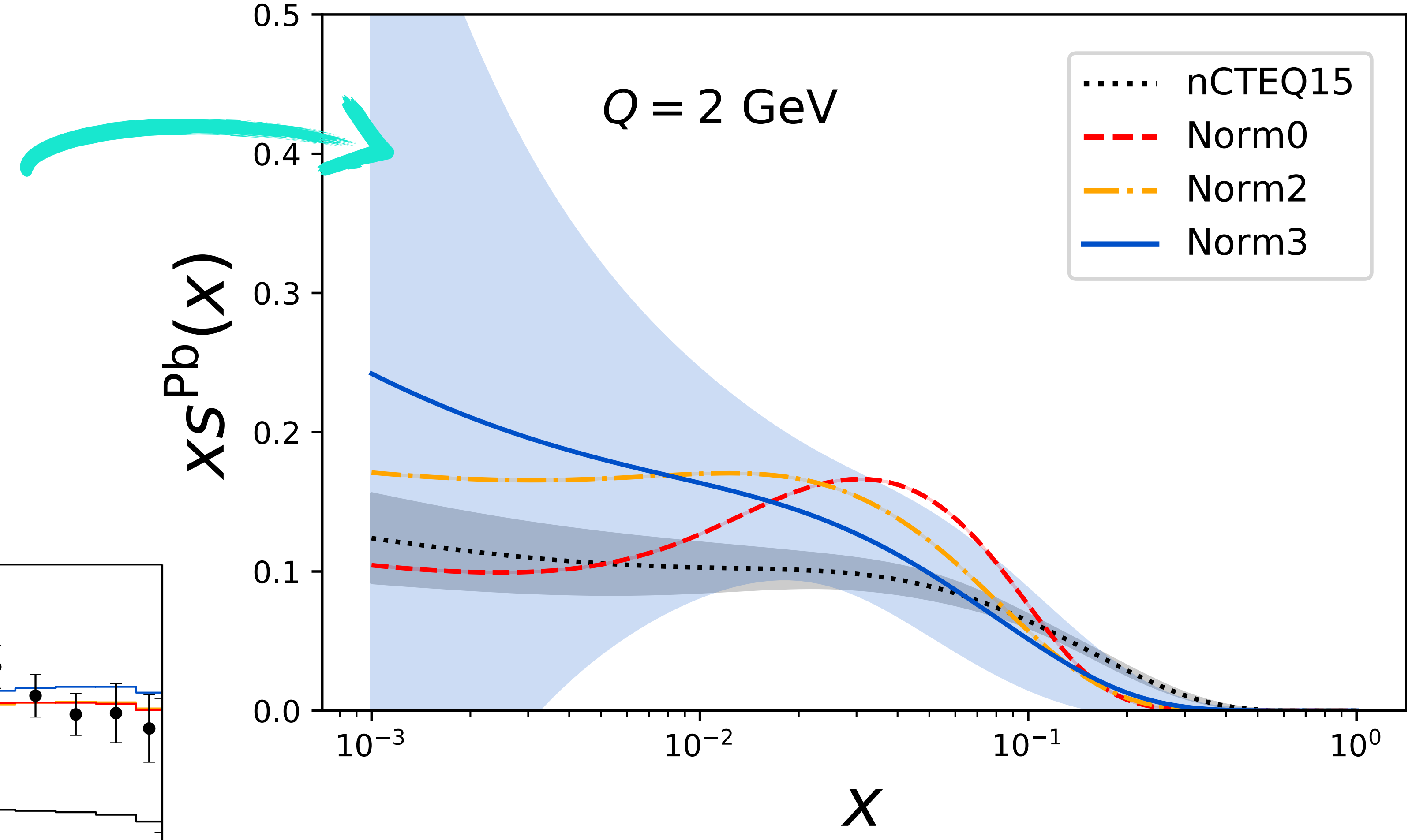


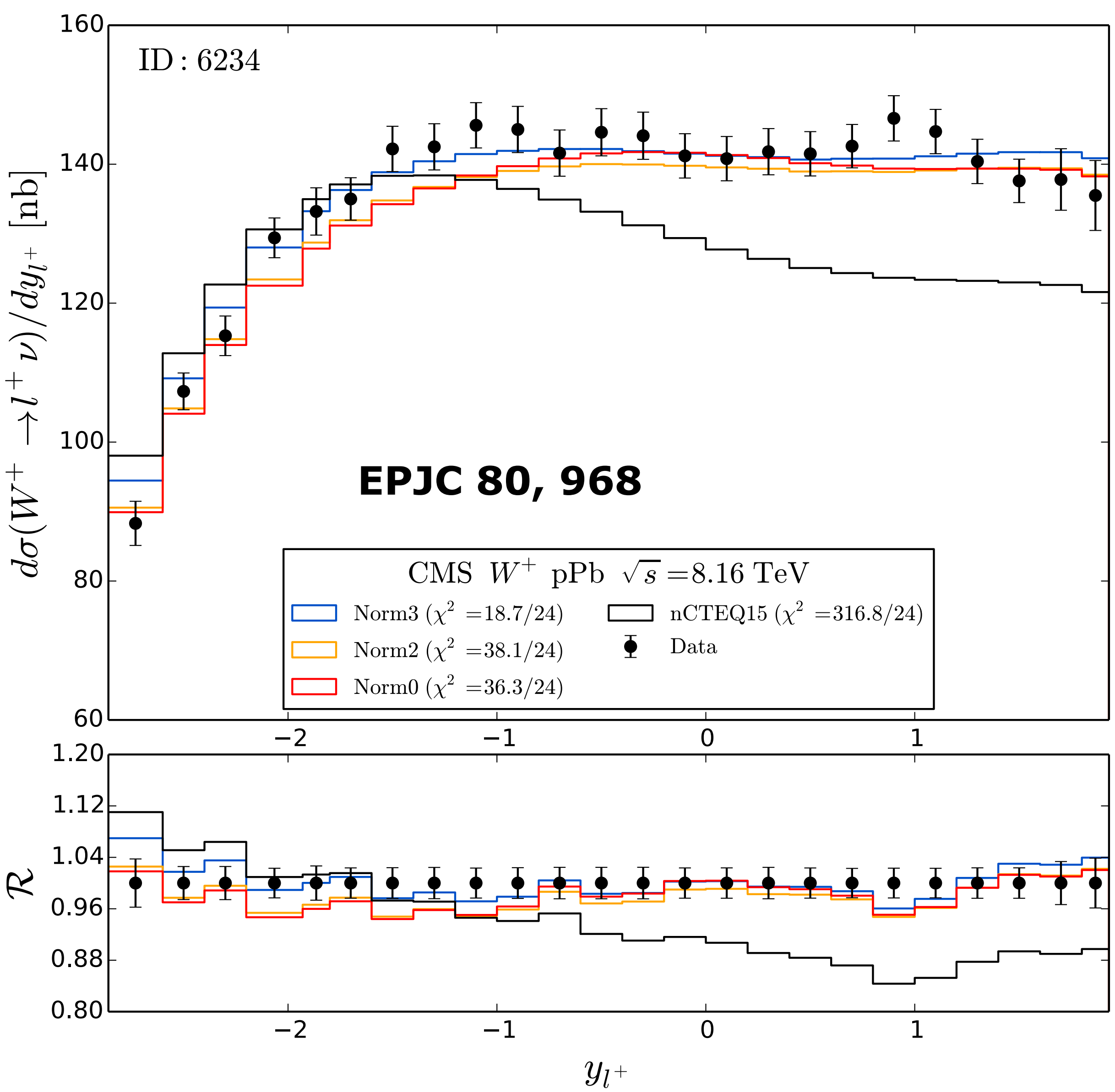


SIH can also constrain the strange nPDF

W and Z boson production

Is there a problem with the normalisation?





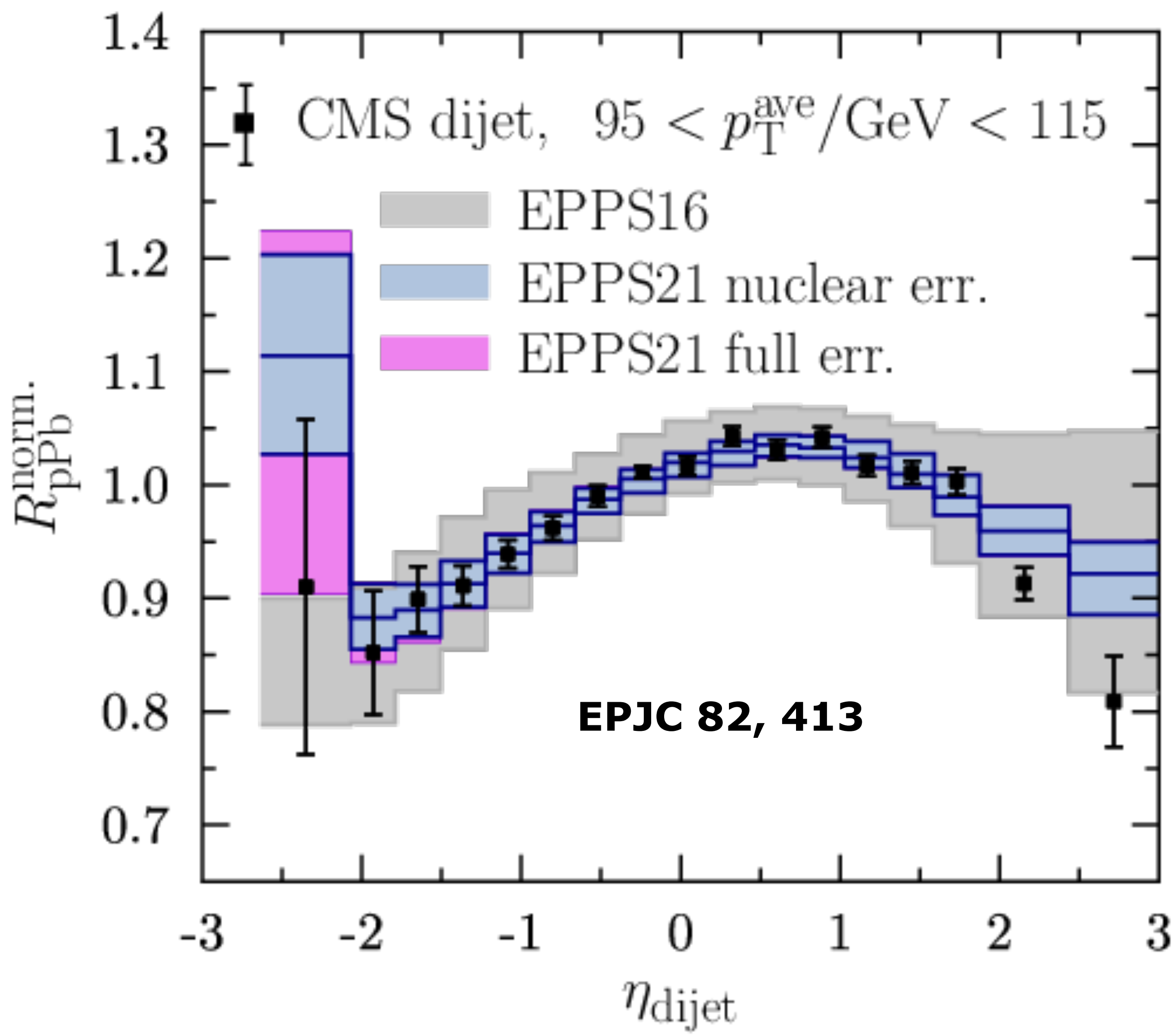
Norm 0: no normalisation parameter.

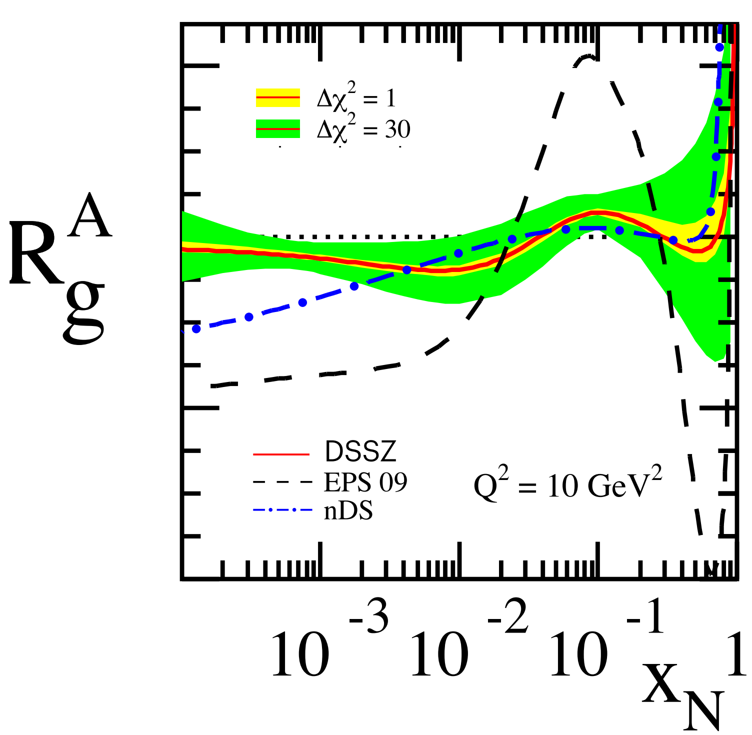
Norm 2: normalisation parameters for CMS and ATLAS Run I.

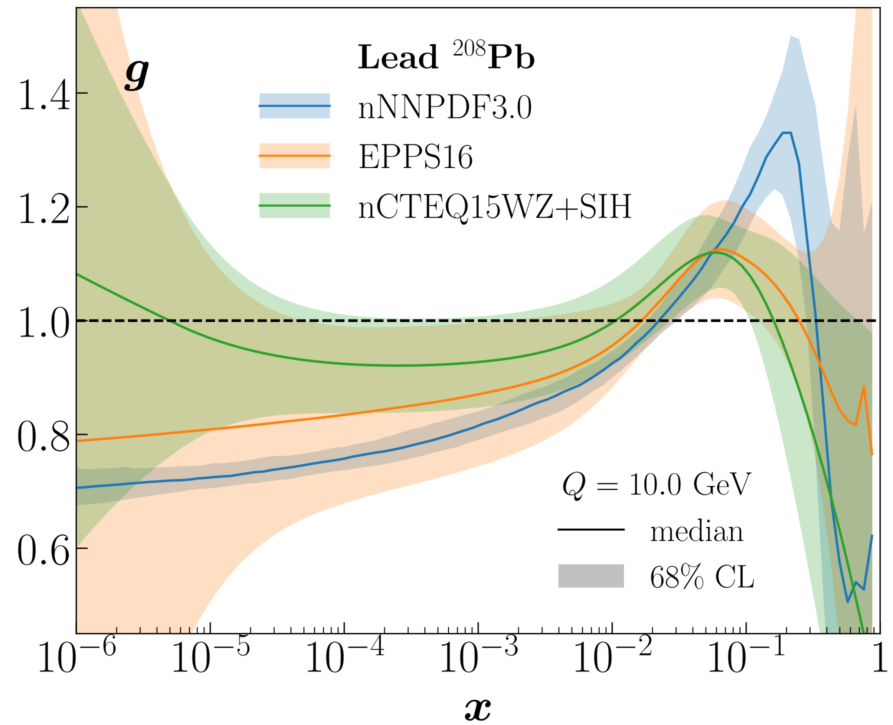
Norm 3: normalisation parameters for CMS and ATLAS Run I, and CMS Run II.

Di-jets at the LHC

- Constrains the gluon density without FFs.
- Excludes gluons with no anti-shadowing.

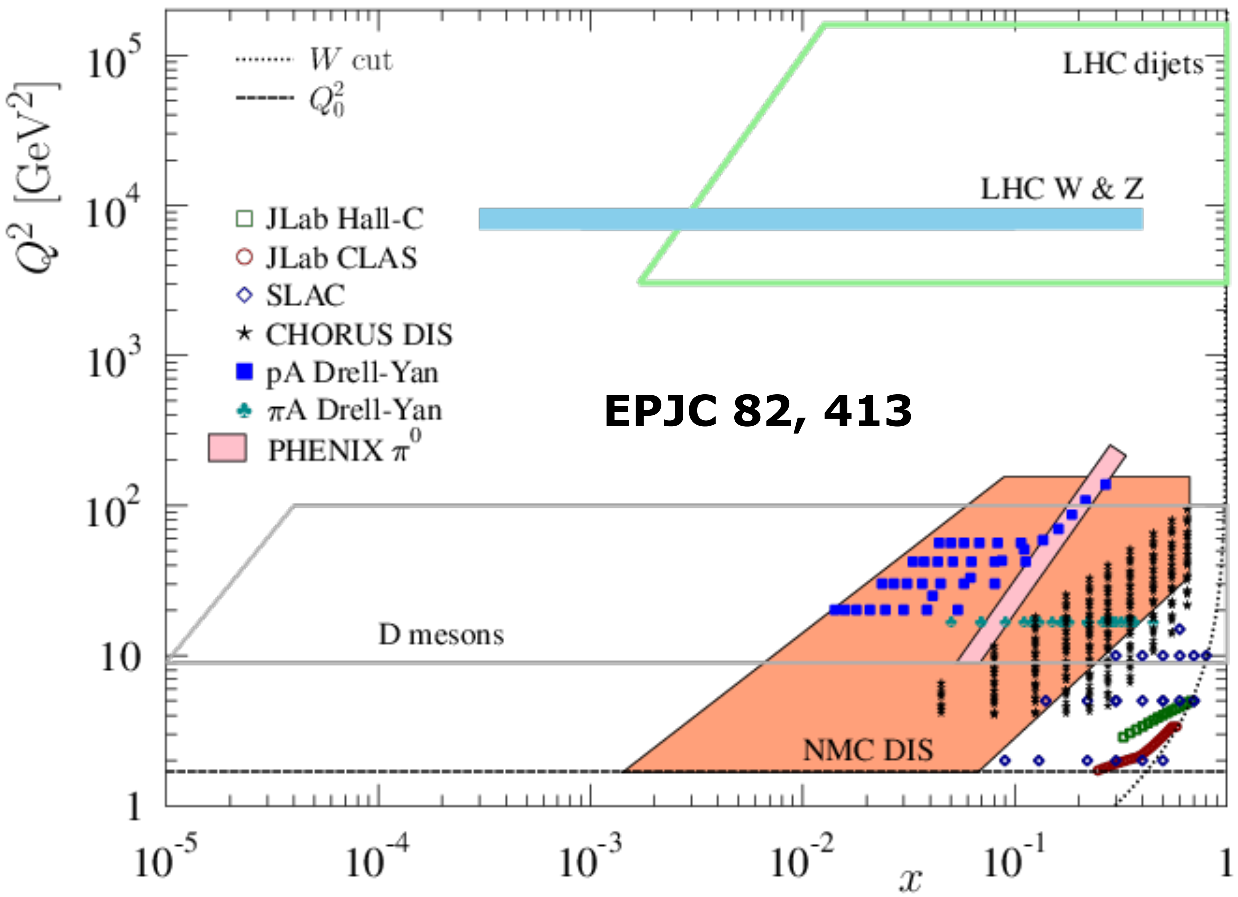


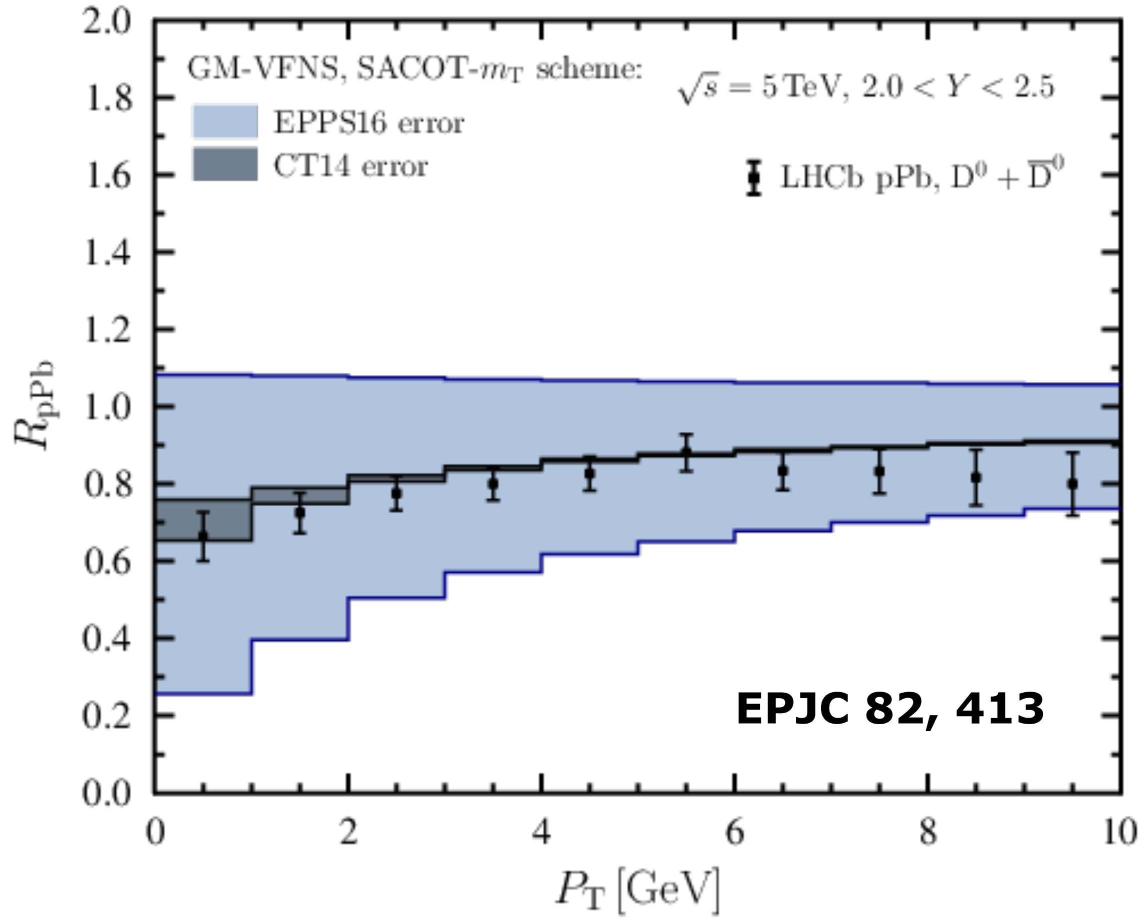




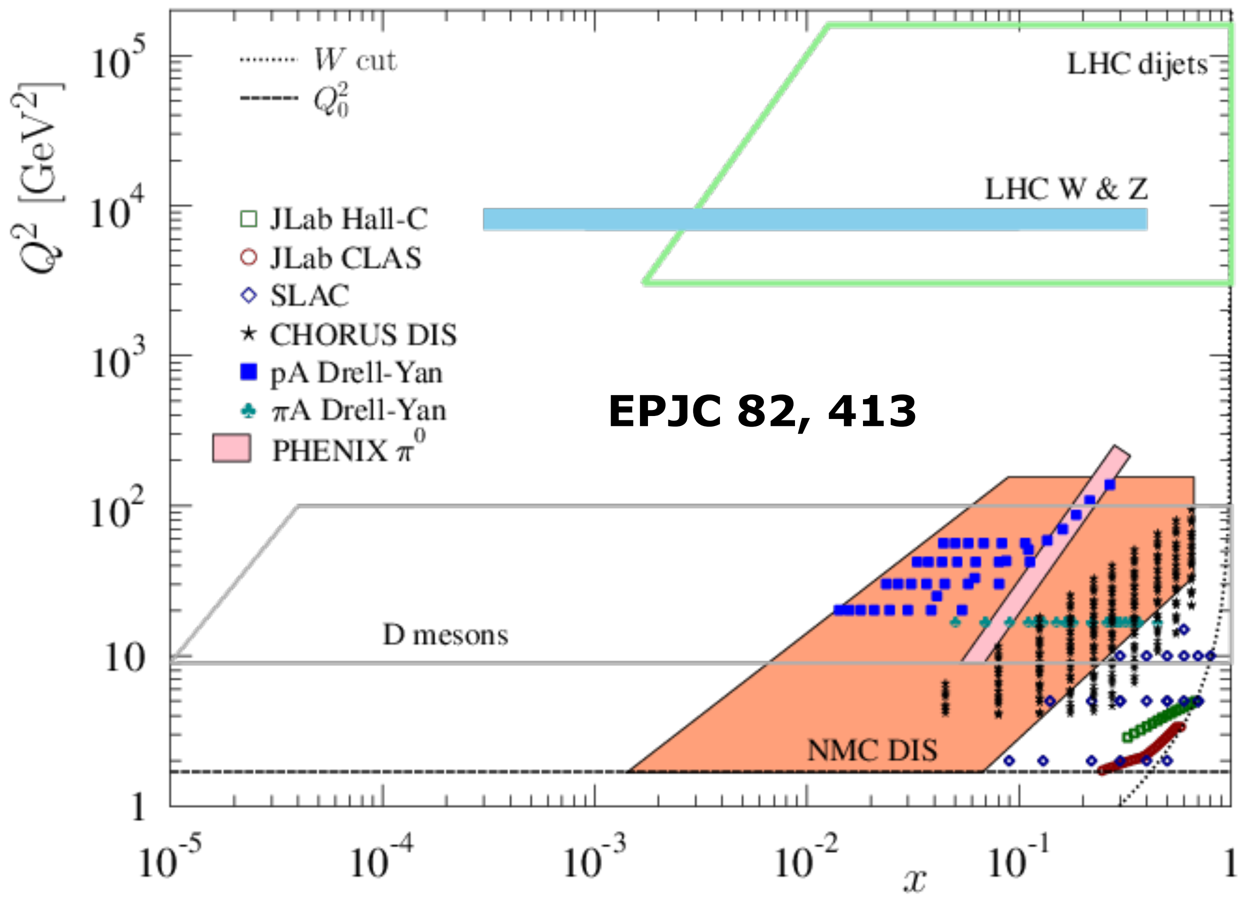
- Some bins are not well reproduced, even in $p + p$.

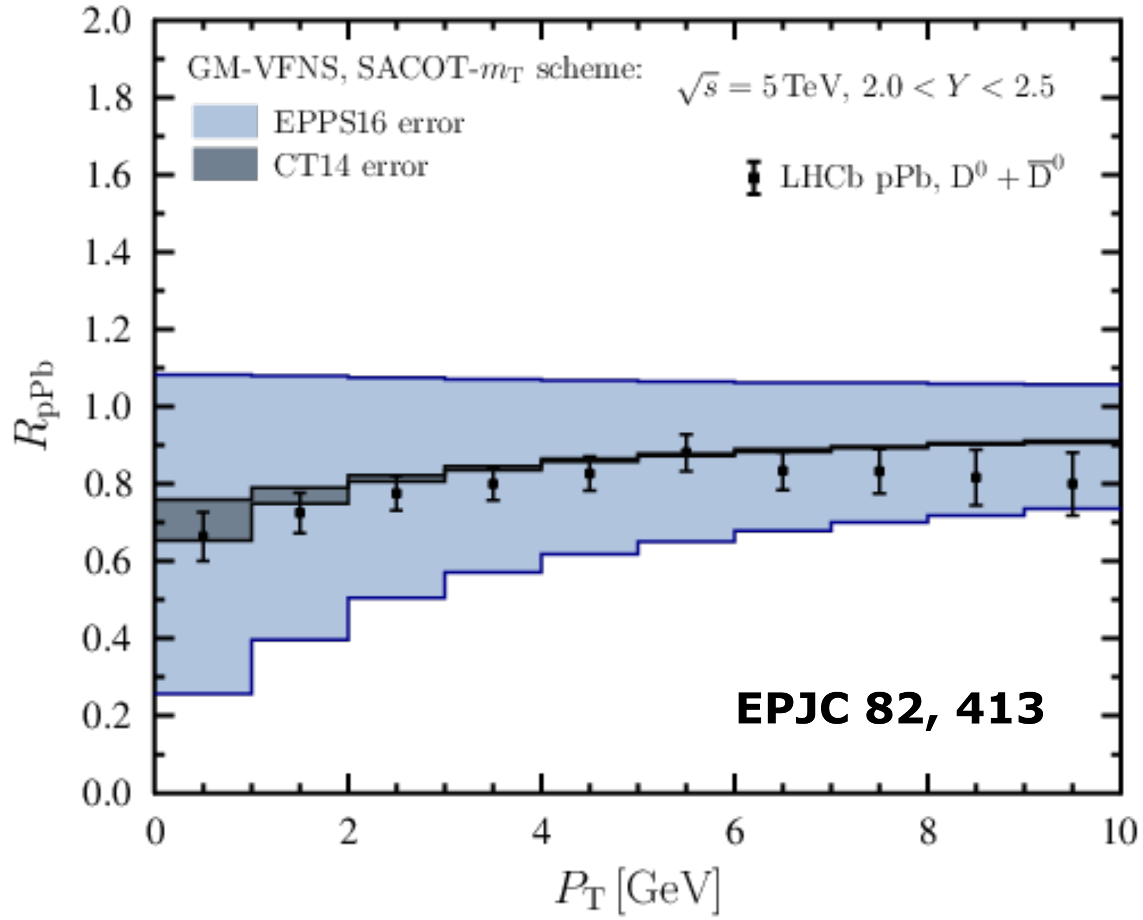
◉ D^0 production

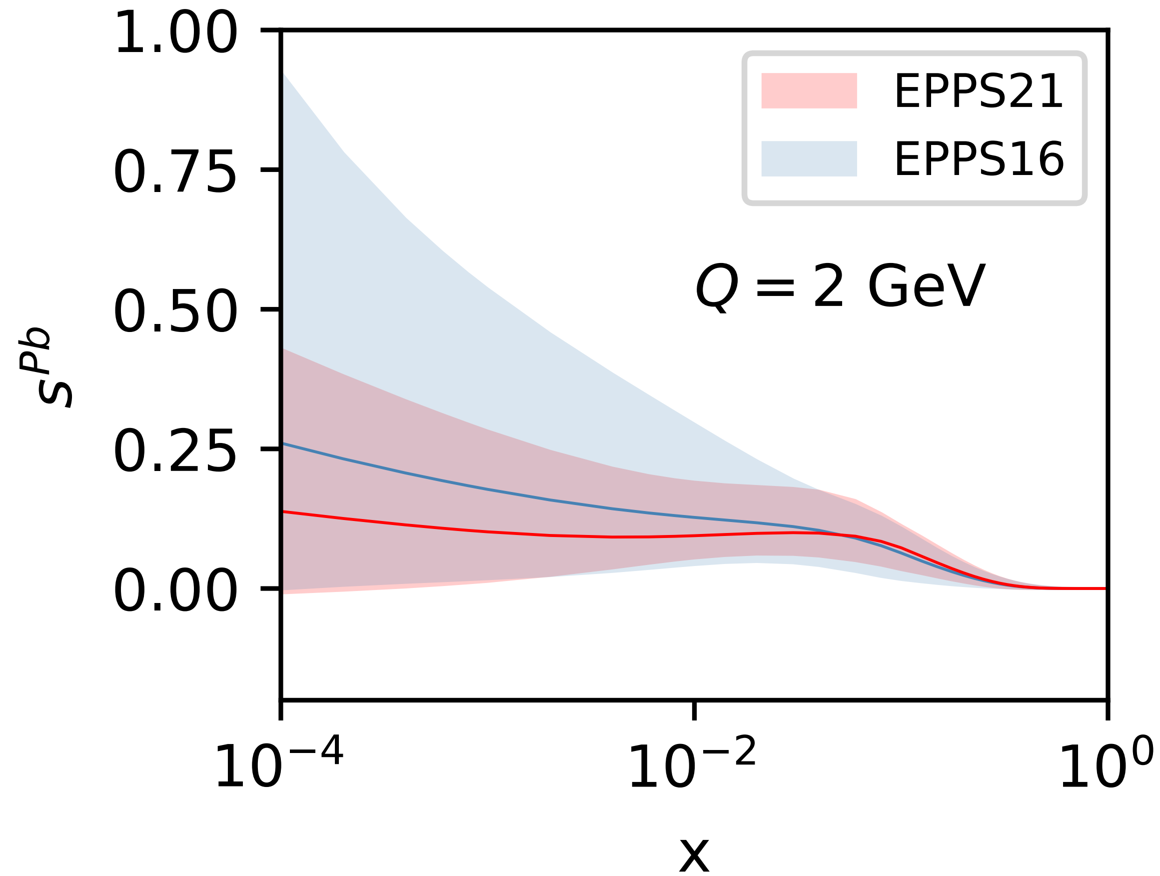




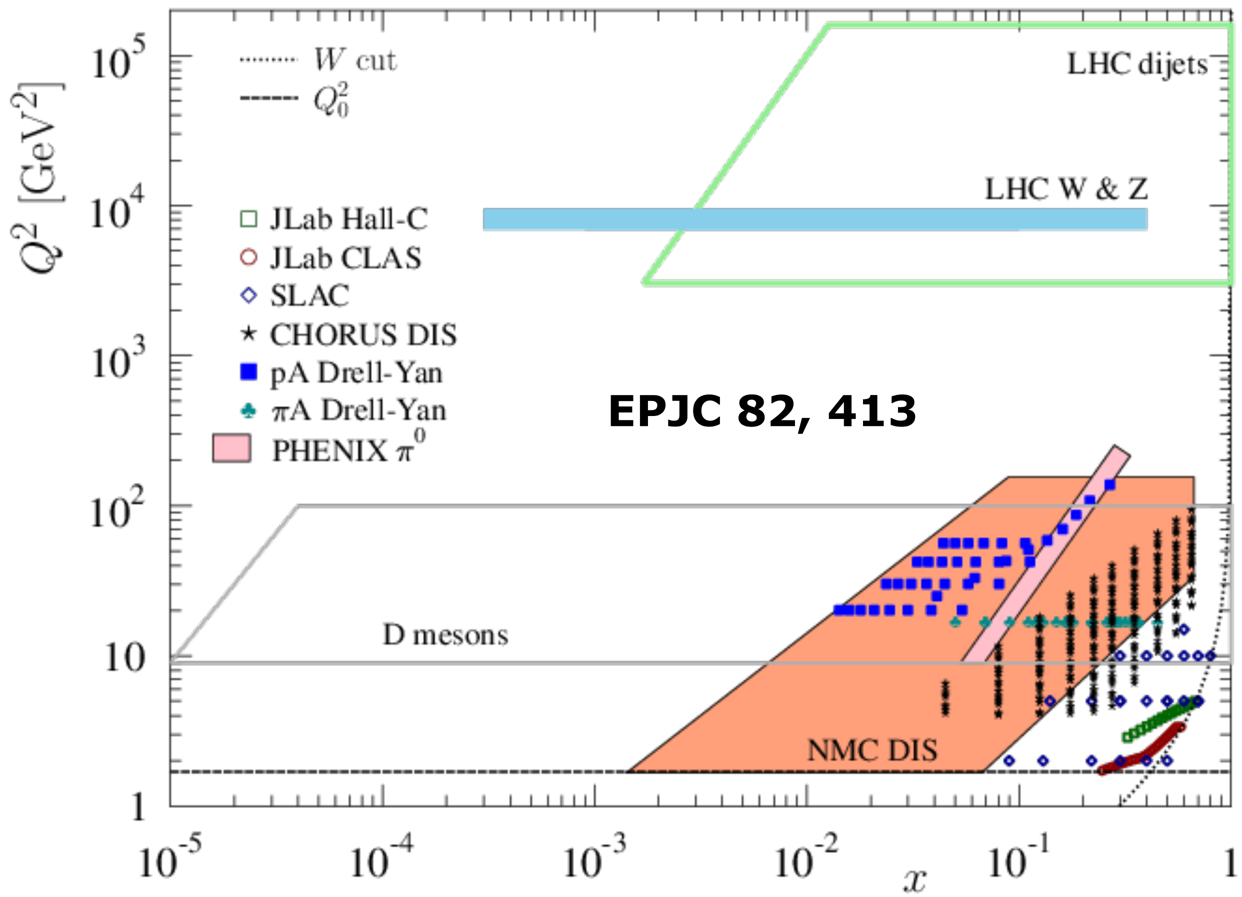
D^0 production

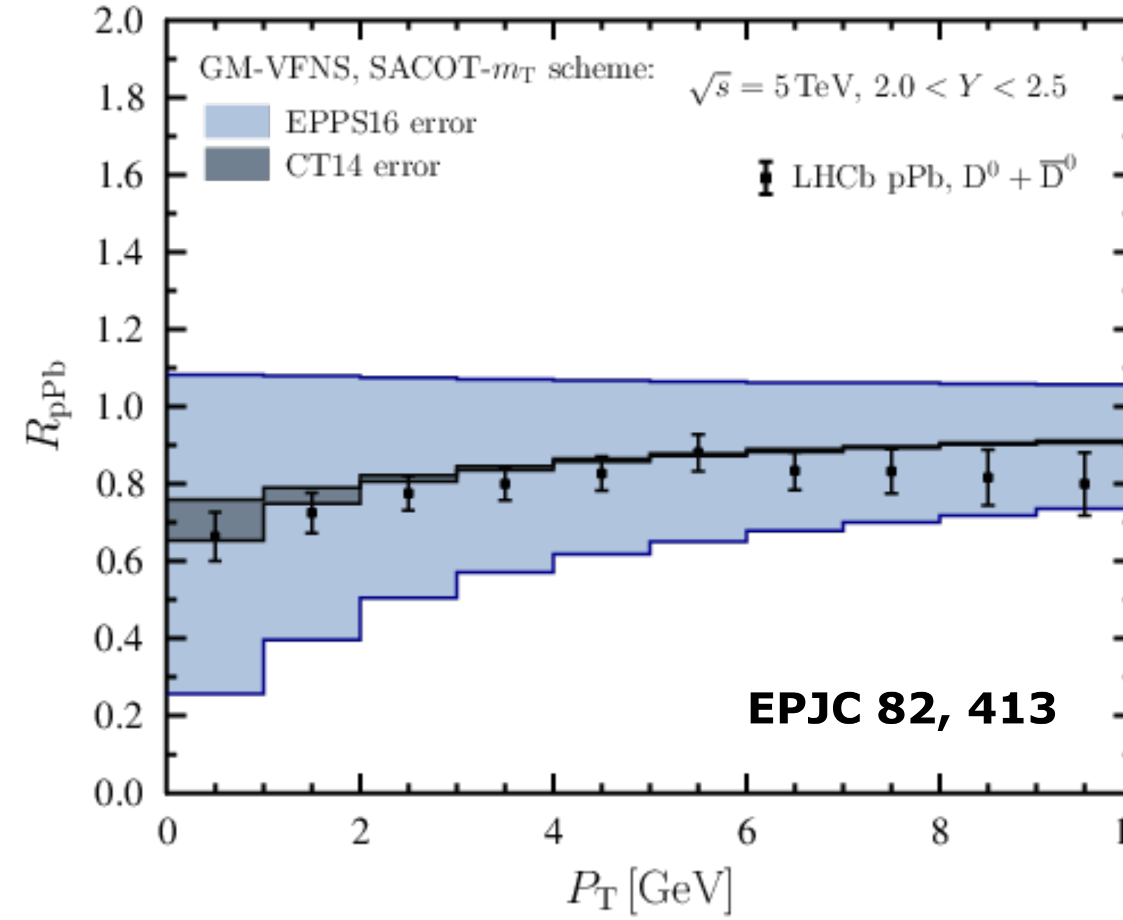


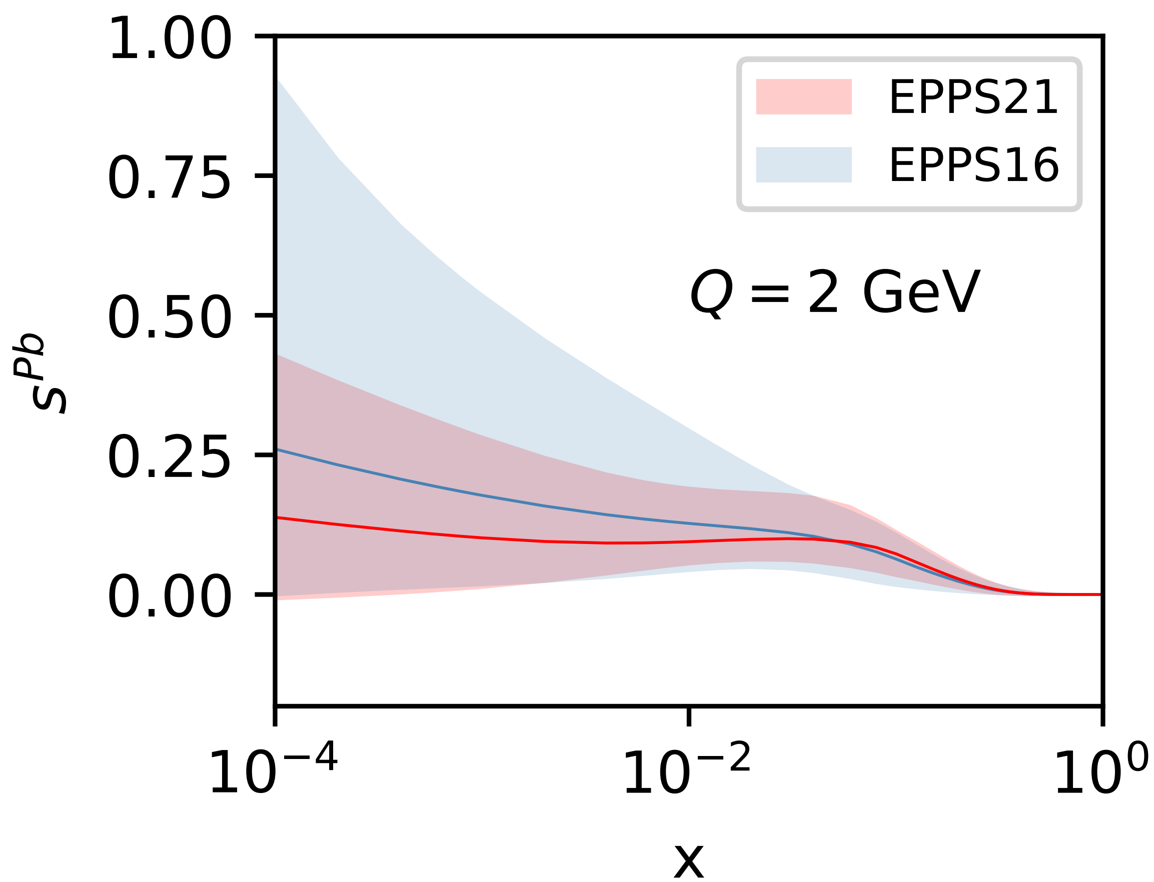


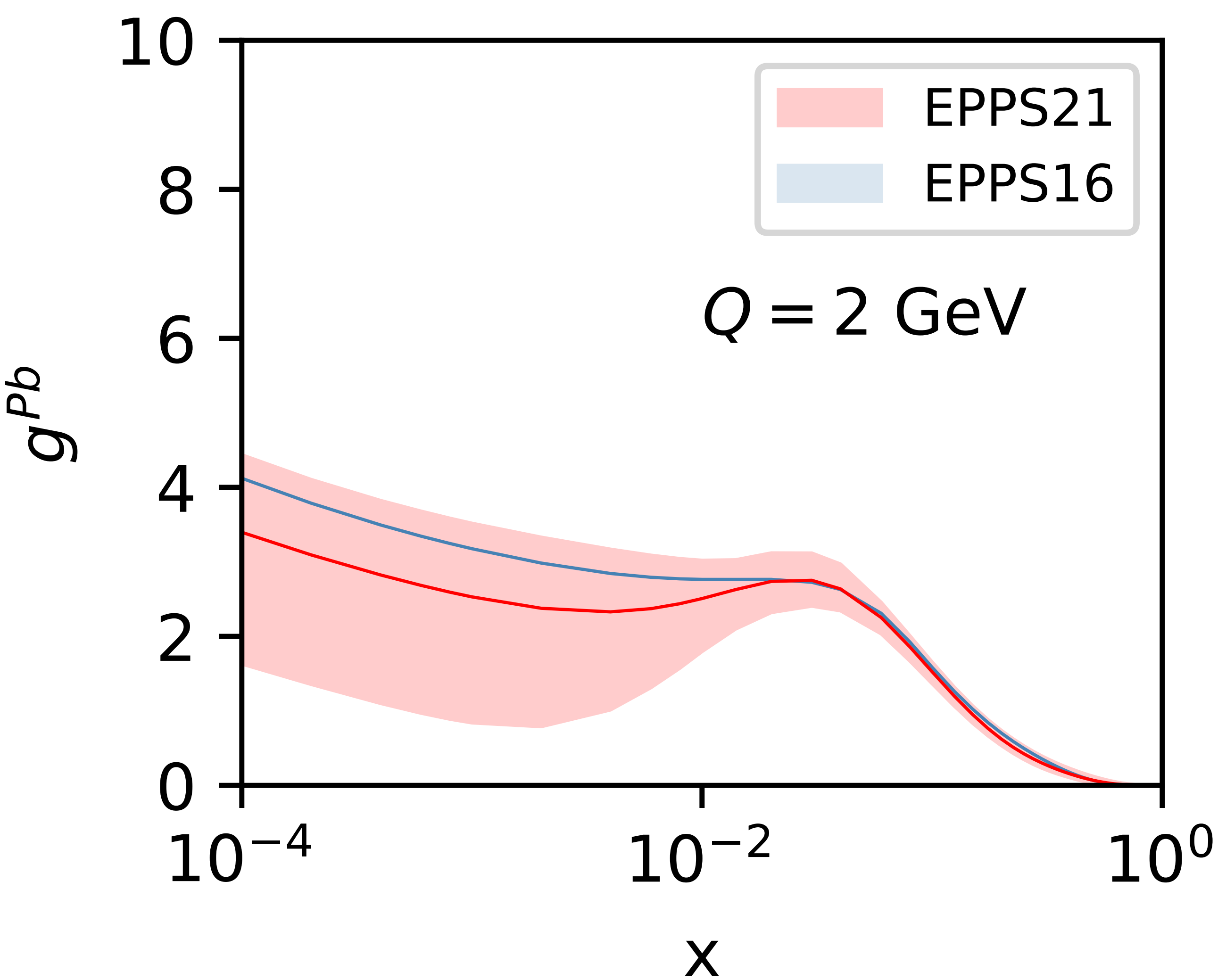


◉ D^0 production

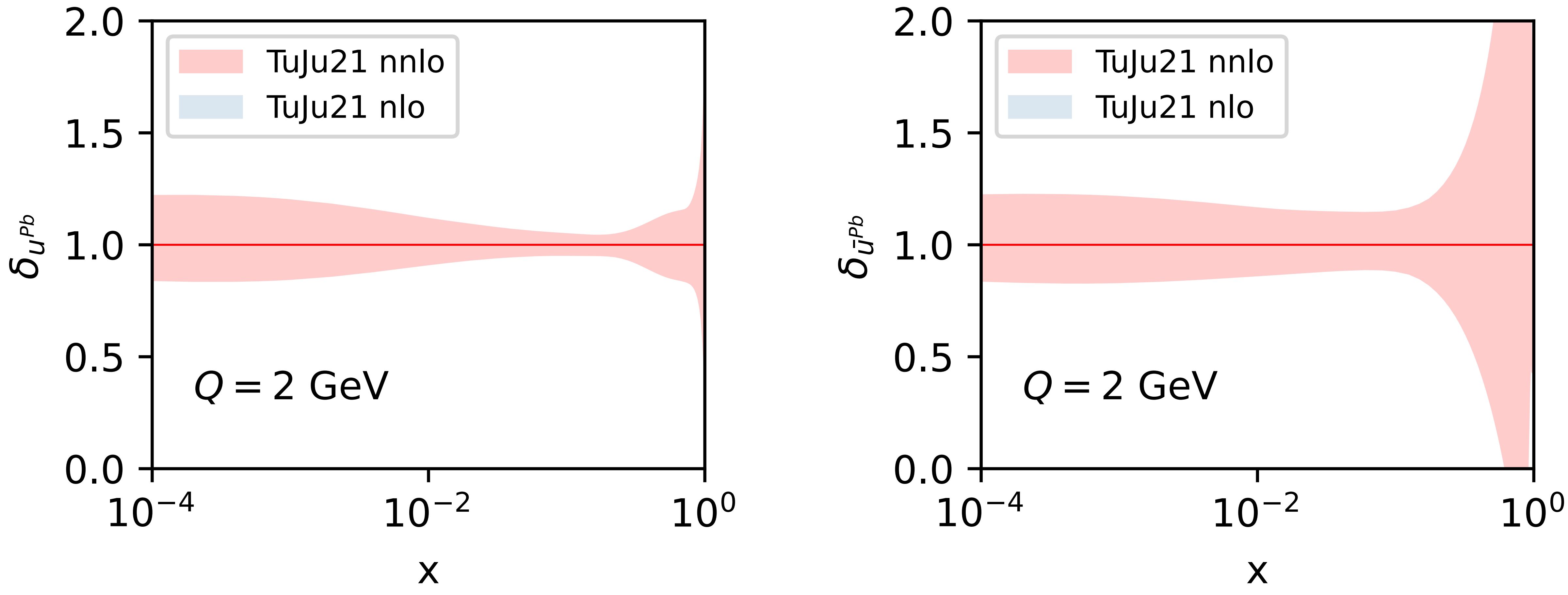








◉ better theoretical computation



- From NLO to NNLO (for some observables).
- Consistent treatment of heavy quarks, with correct mass schemes.
- Inclusion of nuclear effects in deuterium and other light nuclei.
- Deep learning to reduce the parametrisation bias.

Available sets*

- 🇺🇸 and 🇺🇸-🇩🇪: **nCTEQ15**: PRD 93, 085037. **nCTEQ15WZ**: EPJC 80, 968. **nCTEQ15HiX**: PRD 103, 114015. **nCTEQ15WZ+SIH**: PRD 104, 094005.

- 🇦🇷 and 🇦🇷-🇩🇪: **nDS**: PRD 69, 074028. **DSSZ**: PRD 85, 074028.

- 🇫🇮-🇩🇪: **nTuJu19**: PRD 100, 096015. **nTuJu21**: PRD 105, 094031.

- 🇫🇮-🇪🇸: **EKS**: EPJC 9, 61. **EPS09**: JHEP 0904, 065. **EPPS16**: EPJC 77, 163. **EPPS21**: EPJC 82, 413.

- 🇯🇵: **HKM**: PRD 64, 034003. **HKN07**: PRC 76, 065207.

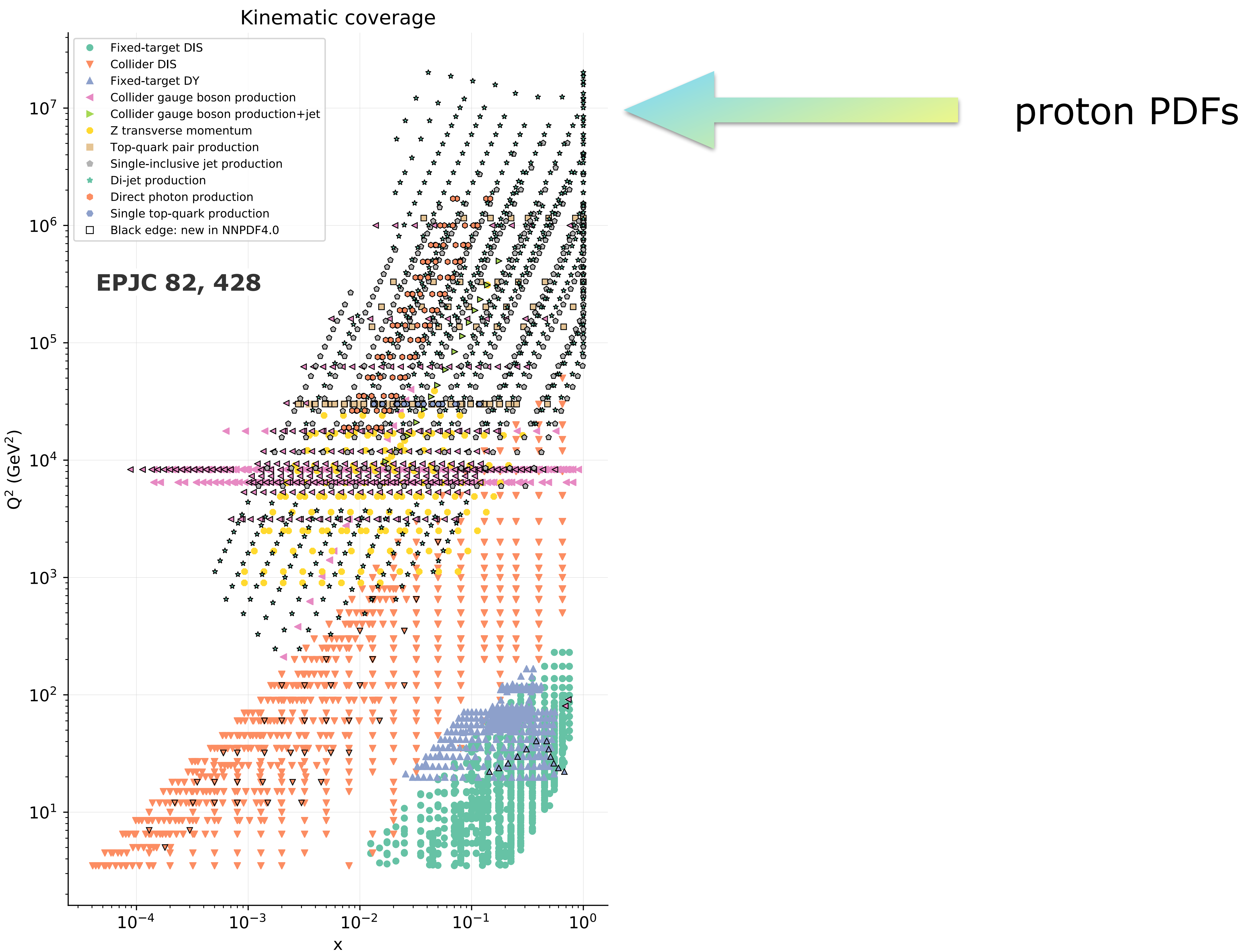
- 🇮🇷 and 🇮🇷-🇩🇪: **KA15**: PRD 93, 014026. **KSASG20**: PRD 104, 034010.

- **NN**: **nNNPDF1.0**: EPJC 79, 471. **nNNPDF2.0**: JHEP 09, 183. **nNNPDF3.0**: EPJC 82, 507.

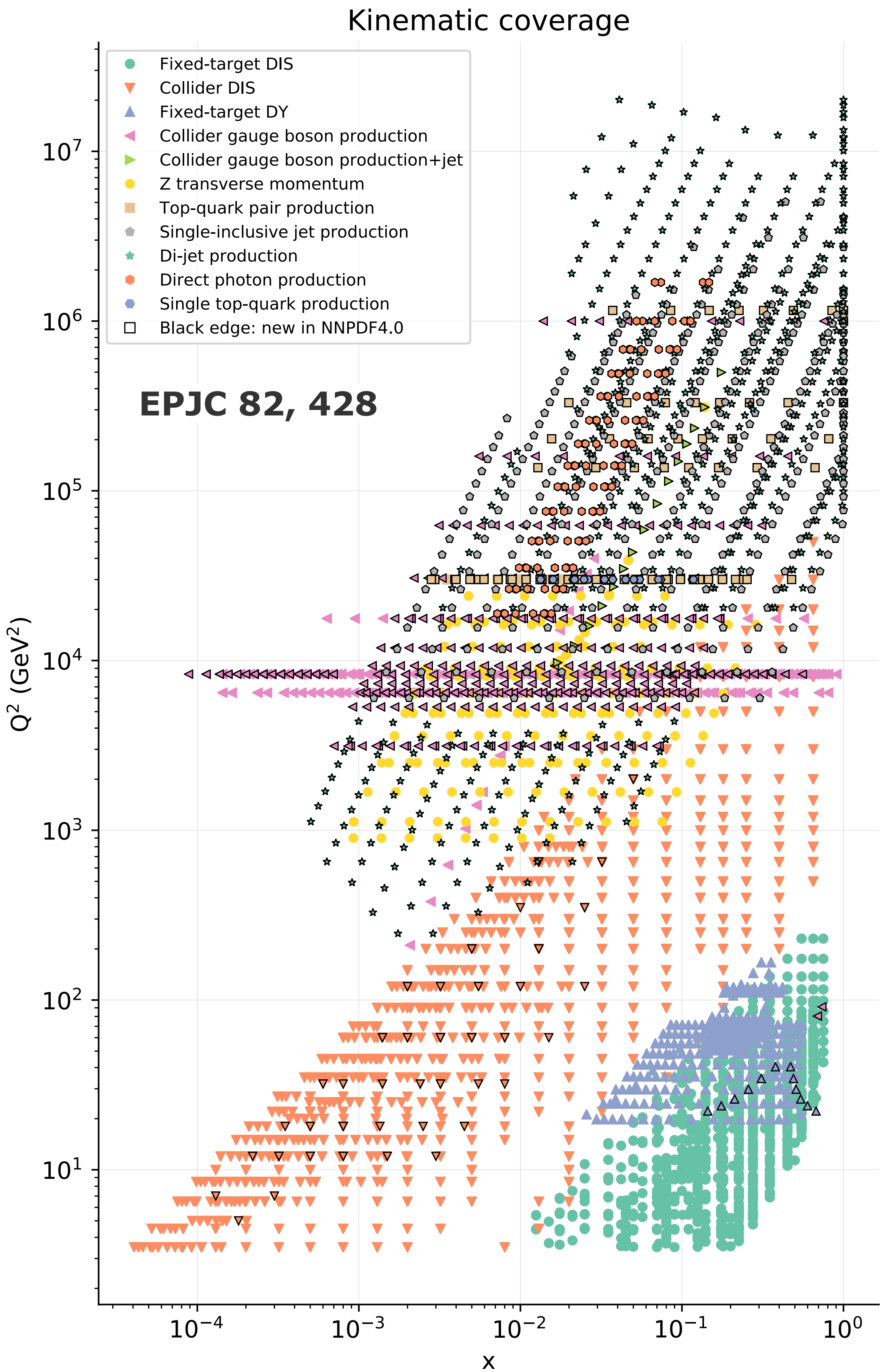
* not all

Issues in nPDF extractions

◉ The kinematic coverage of the data.

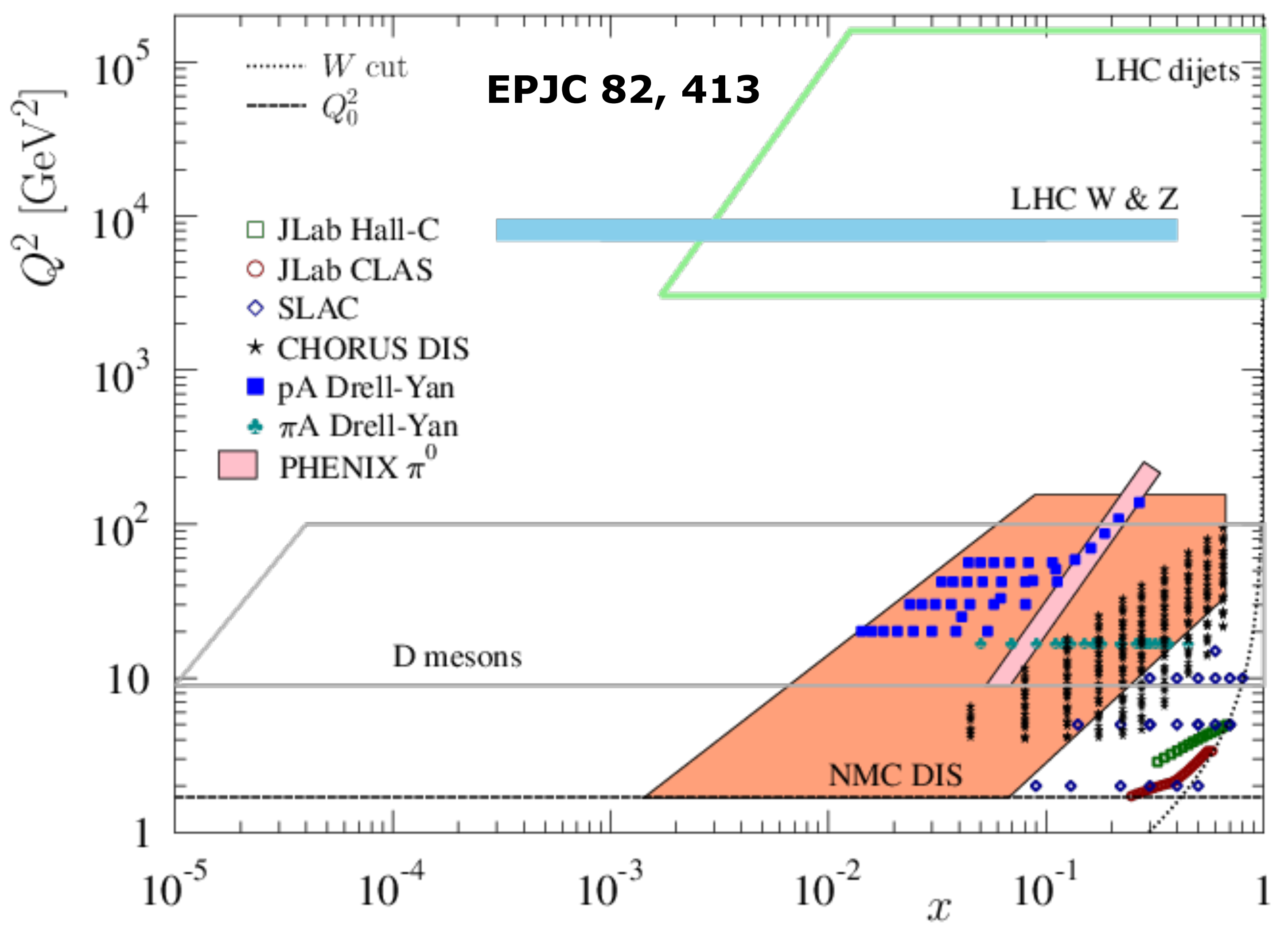


◉ The kinematic coverage of the data.



proton PDFs

nuclear PDFs



- The quantity of data.

NC DIS data	Fixed target (FT)	FT deuterium	Collider
proton PDF fit e.g. EPJC 81, 341	433	513	1264

one can use these to do a proton PDF fit: HERAPDF

◉ The quantity of data.

NC DIS data	Fixed target (FT)	FT deuterium	Collider
proton PDF fit e.g. EPJC 81, 341	433	513	1264
nuclear case	2309	812	**0**

- The quantity of data.

NC DIS data	Fixed target (FT)	FT deuterium	Collider
proton PDF fit e.g. EPJC 81, 341	433	513	1264
nuclear case	2309	812	**0**

- How the data were/are published

  - ~ 63% of the non-deuterium NC DIS data are ratios to deuterium.
  - ~ 15% of the non-deuterium NC DIS data are ratios to other nuclei.

This cancels out effects and makes fitting waaaaaaaaaay longer.

- ~ 60% of the NC DIS data are $F_2, F_L, R = F_L/F_2$:

$$\frac{d^2\sigma^{NC}}{dxdQ^2} \propto F_2 - \frac{y^2}{Y_+}F_L \equiv \sigma_r^{NC}$$

computable/what the measurement can be turned into

- ~ 60% of the NC DIS data are $F_2, F_L, R = F_L/F_2$:

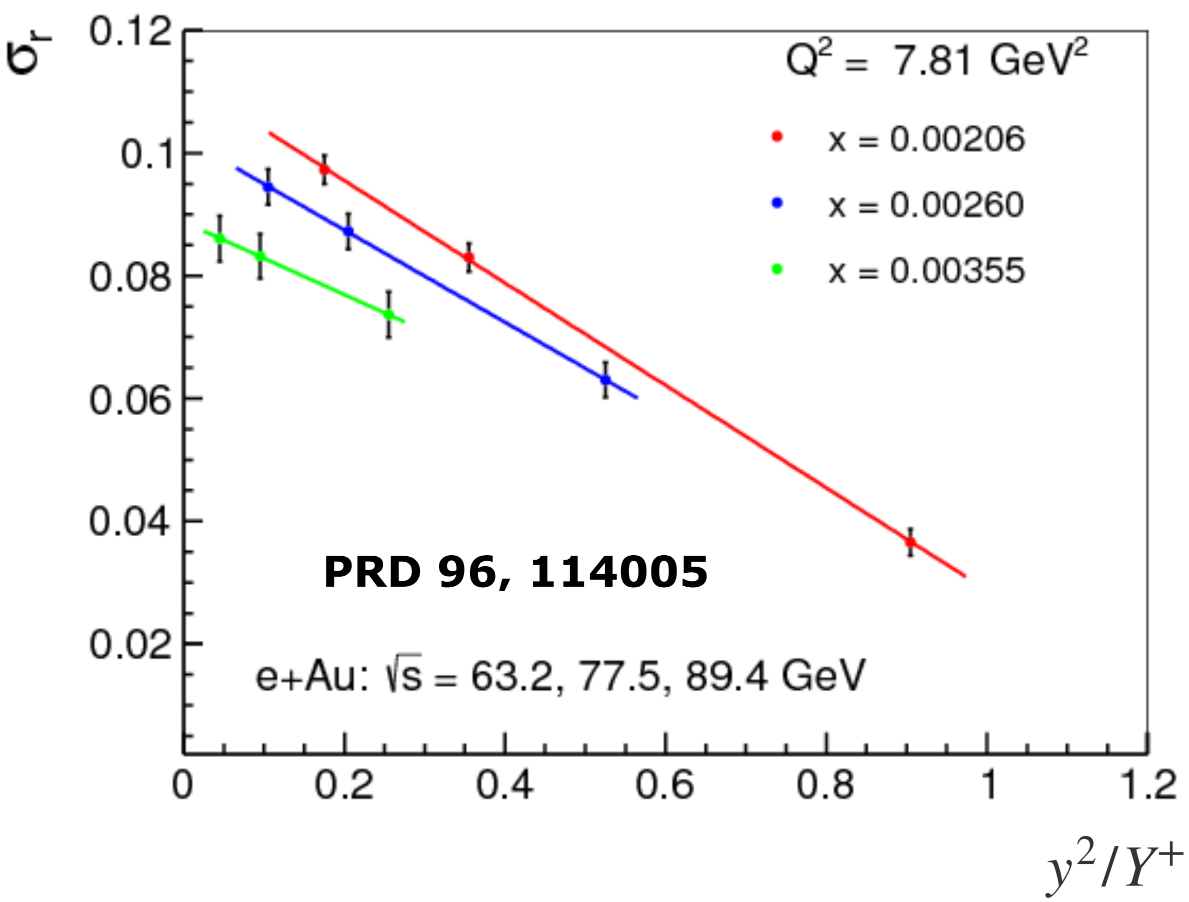
$$\frac{d^2\sigma^{NC}}{dxdQ^2} \propto F_2 - \frac{y^2}{Y_+} F_L \equiv \sigma_r^{NC}$$

computable/must be extracted from the measurement

- $\sim$ 60% of the NC DIS data are $F_2, F_L, R = F_L/F_2$:

$$\frac{d^2\sigma^{NC}}{dxdQ^2} \propto F_2 - \frac{y^2}{Y_+}F_L \equiv \sigma_{\rm r}^{NC}$$

- To extract the structure functions one plots σ_r as a function of y^2/Y_+, the slope is $-F_L$. To vary y^2, we measure for different $\sqrt{s}$.



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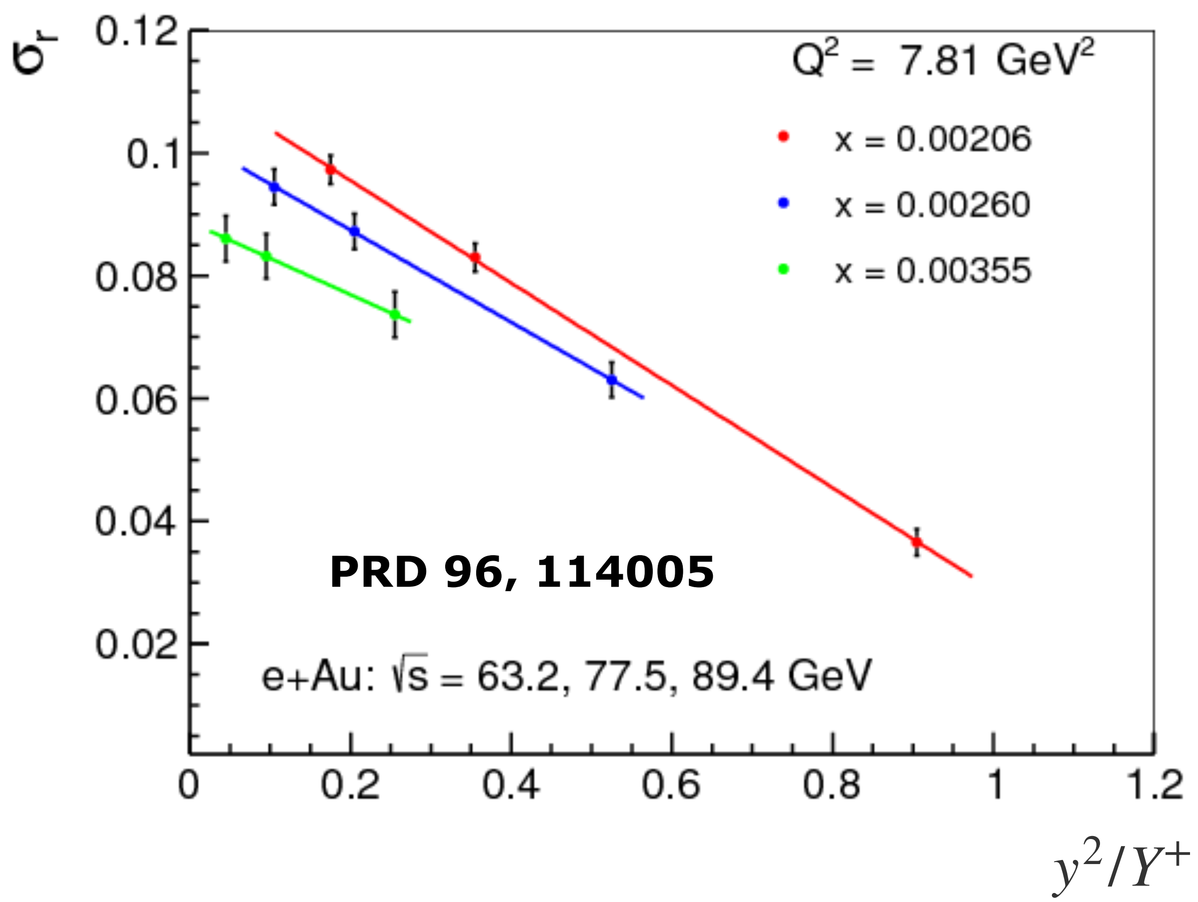

◉ If you go through the literature, you will find that F_2 has been determined from either a parametrisation of R, R=0 or R=0.2. **Take your pick**.

- Some of the new data available has been published in a way that can't be computed in pQCD for proper comparisons. We must rely on theoretical models or nag the experimentalists. E.g.

$$R_{pPb} = \frac{d^2N_{pPb}/dydp_T}{\langle T_{pPb}\rangle d^2\sigma_{pp}^{INEL}/dydp_T}$$

published

$$\frac{1}{N_{ev}}\frac{d^2N}{dydp_T} = \frac{1}{\sigma^{INEL}}\frac{d^2\sigma}{dydp_T}$$

missing part

can be calculated

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published

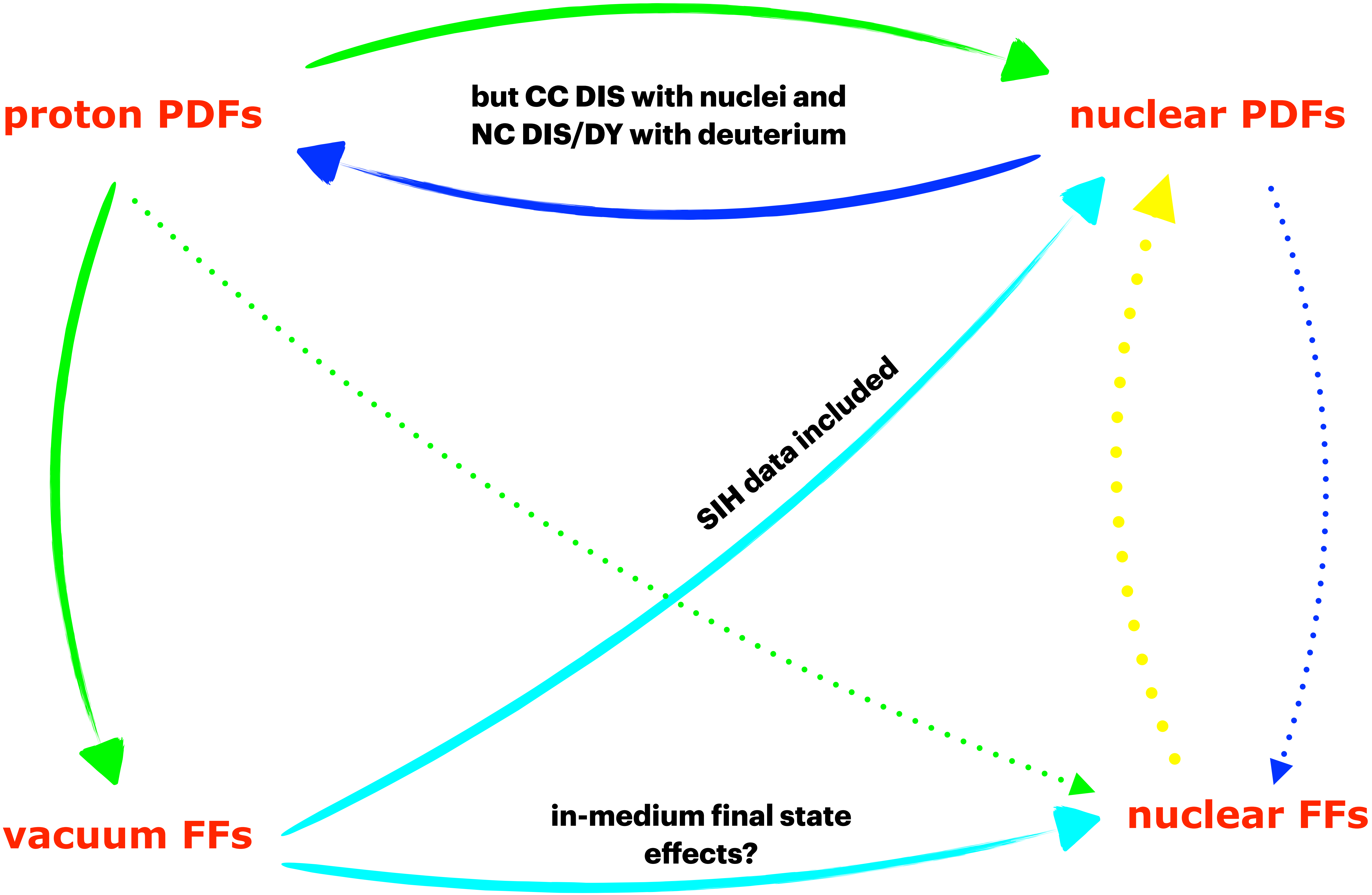
$$\frac{1}{N_{ev}}\frac{d^2N}{dydp_T} = \frac{1}{\sigma^{INEL}}\frac{d^2\sigma}{dydp_T}$$

missing part

can be calculated

- Some of the data that we're using **might suffer from a medium modification of the final state**: SIH, D0 production, di-jets in p+Pb collisions.

- From the phenomenological side we have "contamination":



- From the phenomenological side we have “contamination”:

We should be extremely careful not to double, triple, quadruple count effects.

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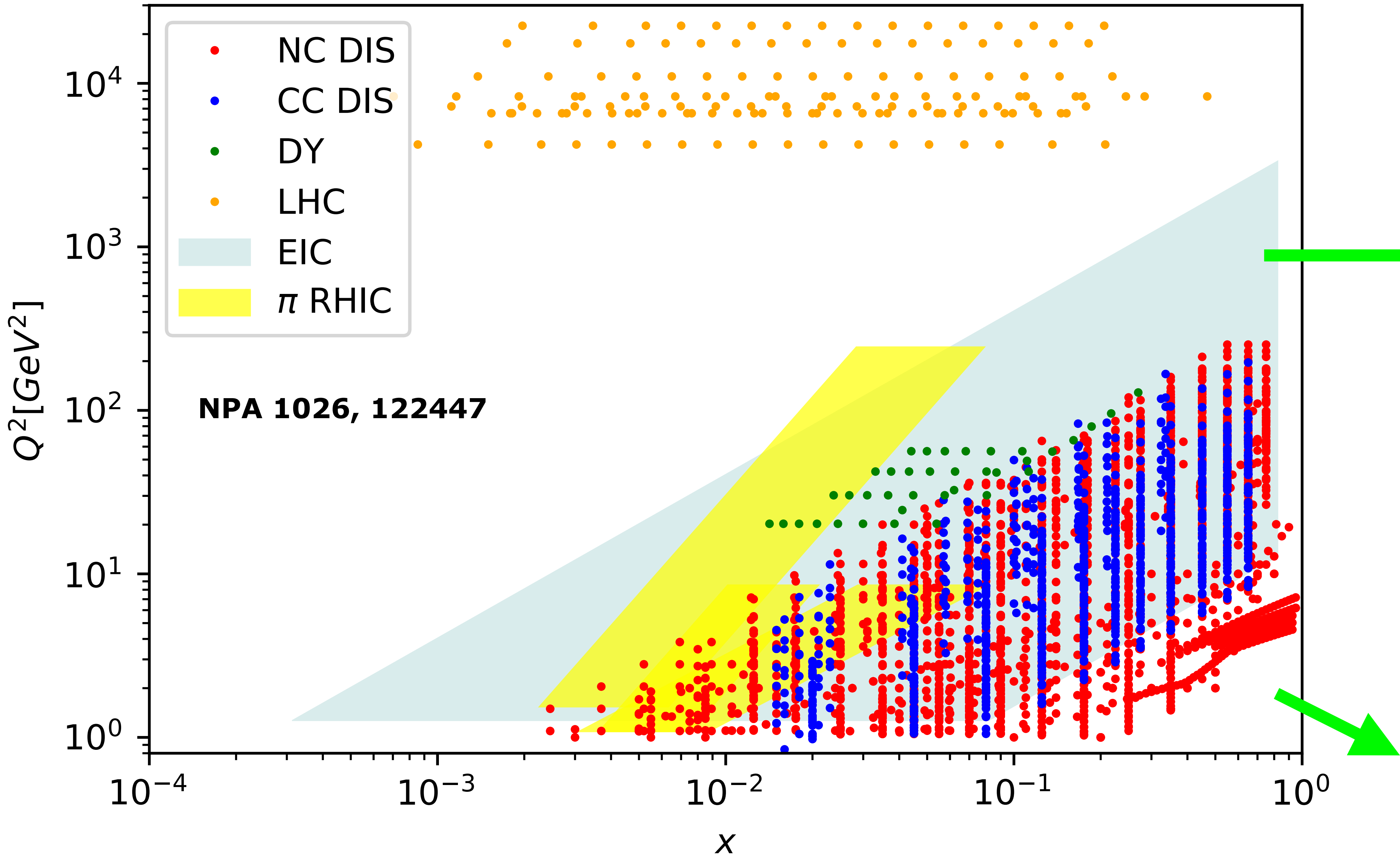
What can the EIC do for nPDFs?

◉ Improve the kinematic coverage of NC DIS: *nuclear HERA*.

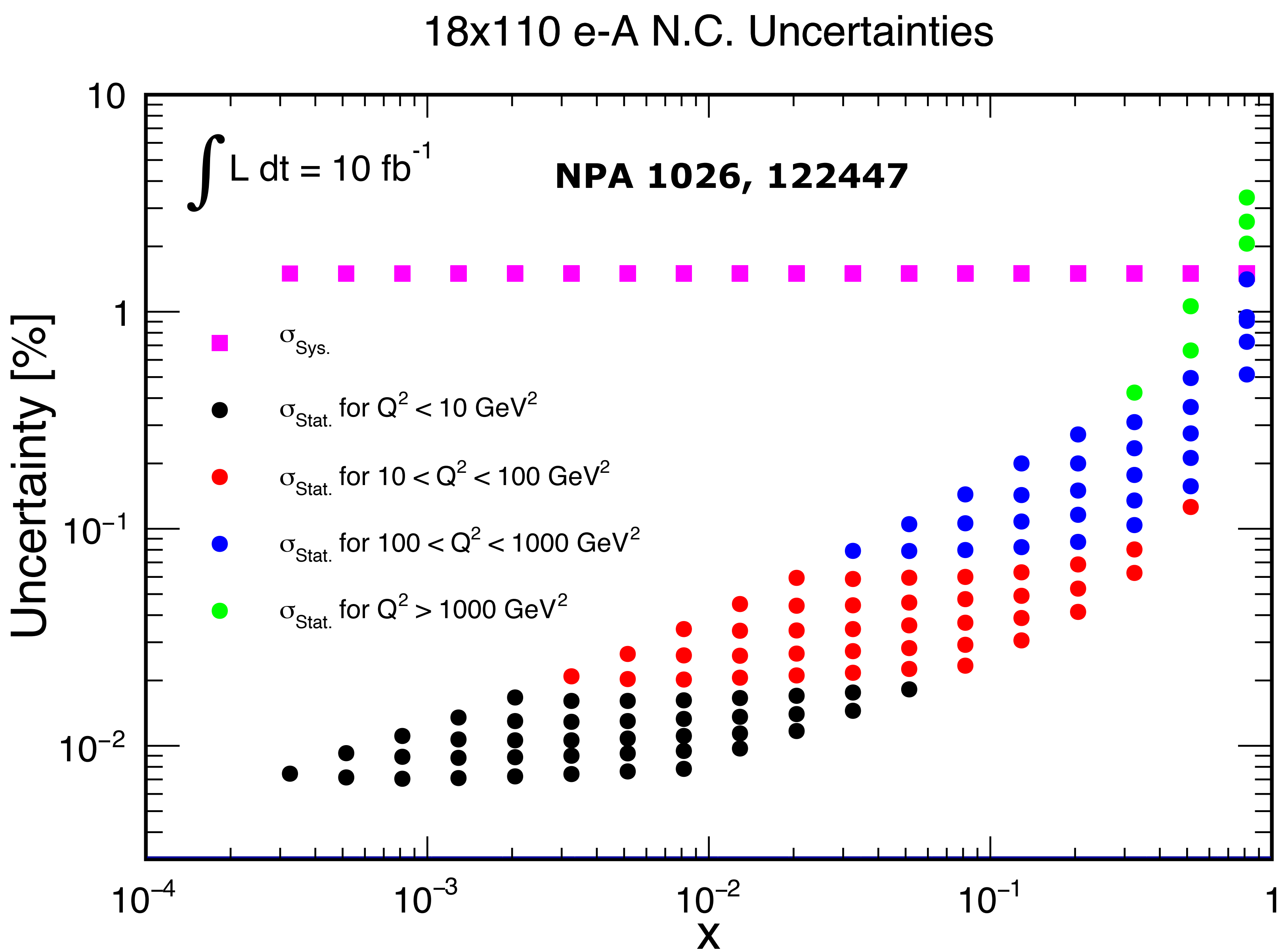


EIC

very precise mapping at JLAB12

"This broad kinematic coverage … will revolutionize our current understanding of partonic distributions in nuclei."

- Reduce the data uncertainty (at least according to simulations)

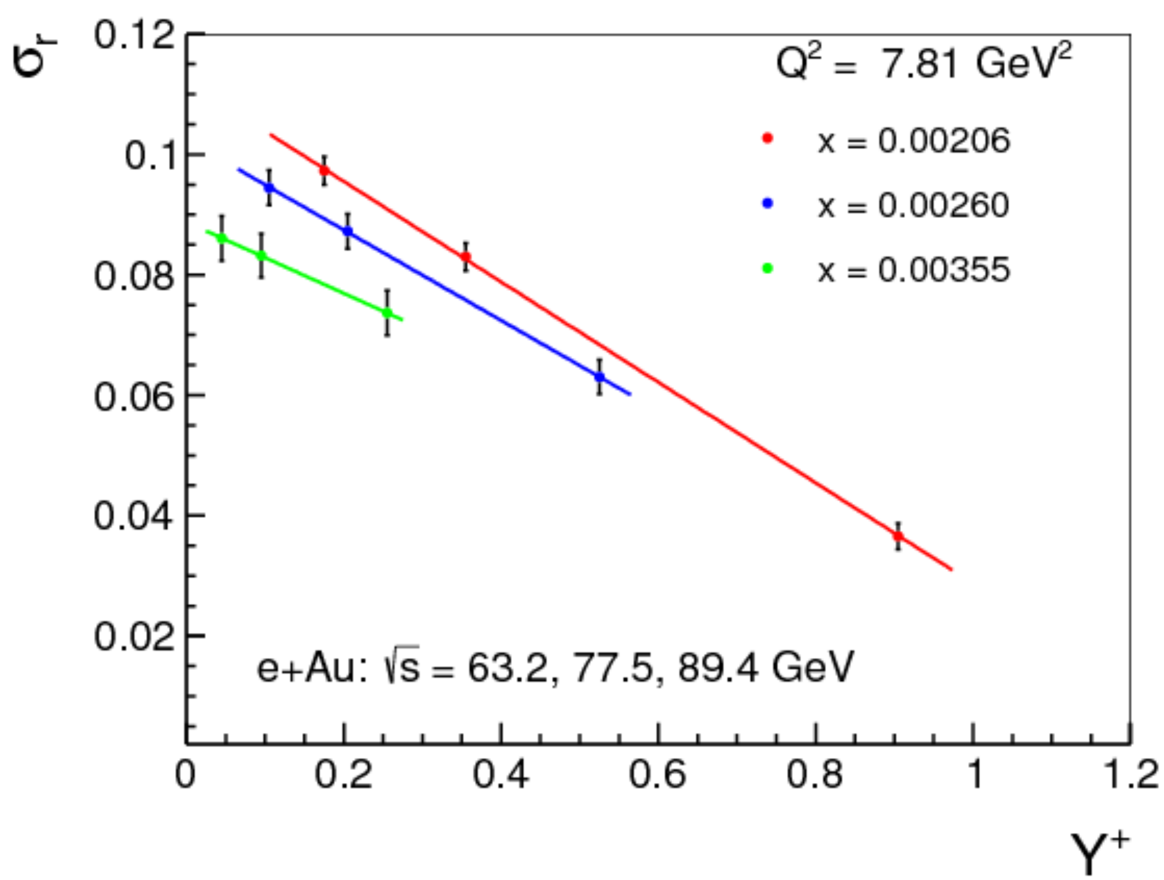


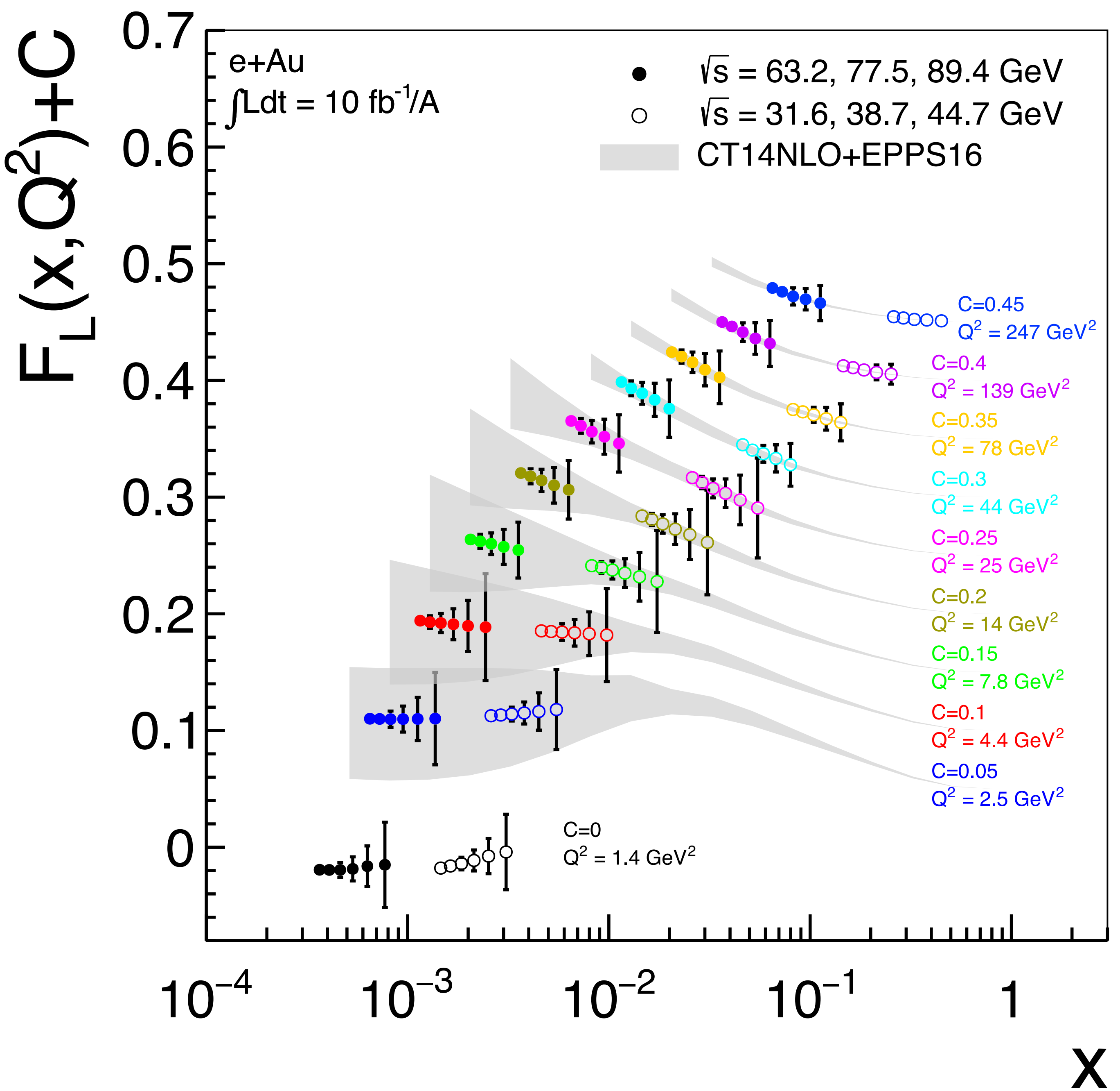
- Provide data for more nuclei: from deuterium to ^{238}U.

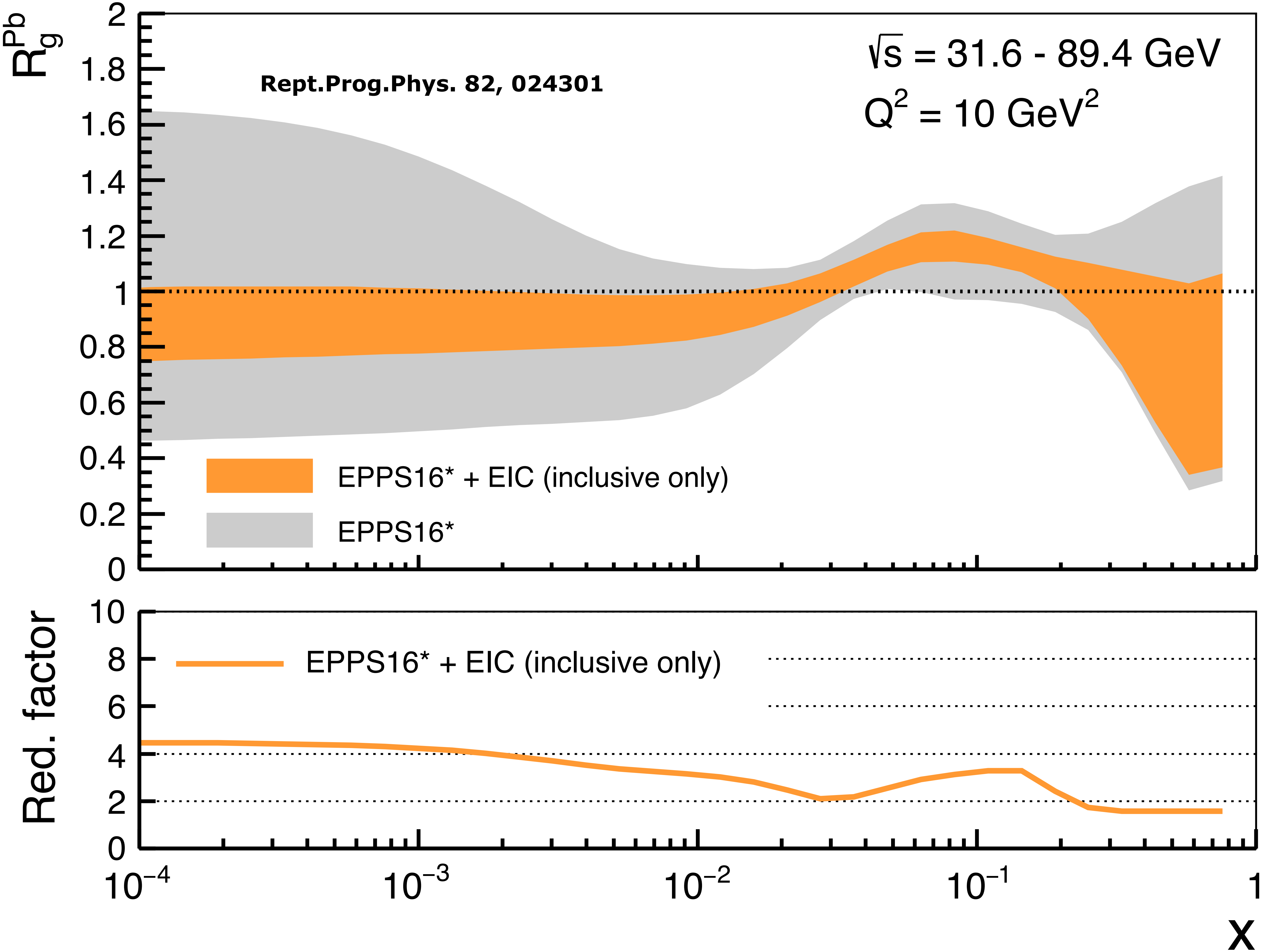
- We will be able to use the **EIC data as basis for nPDF fits**.

- We will also be able to properly separate the longitudinal structure function that is ***sensitive*** to the ***gluon*** density.

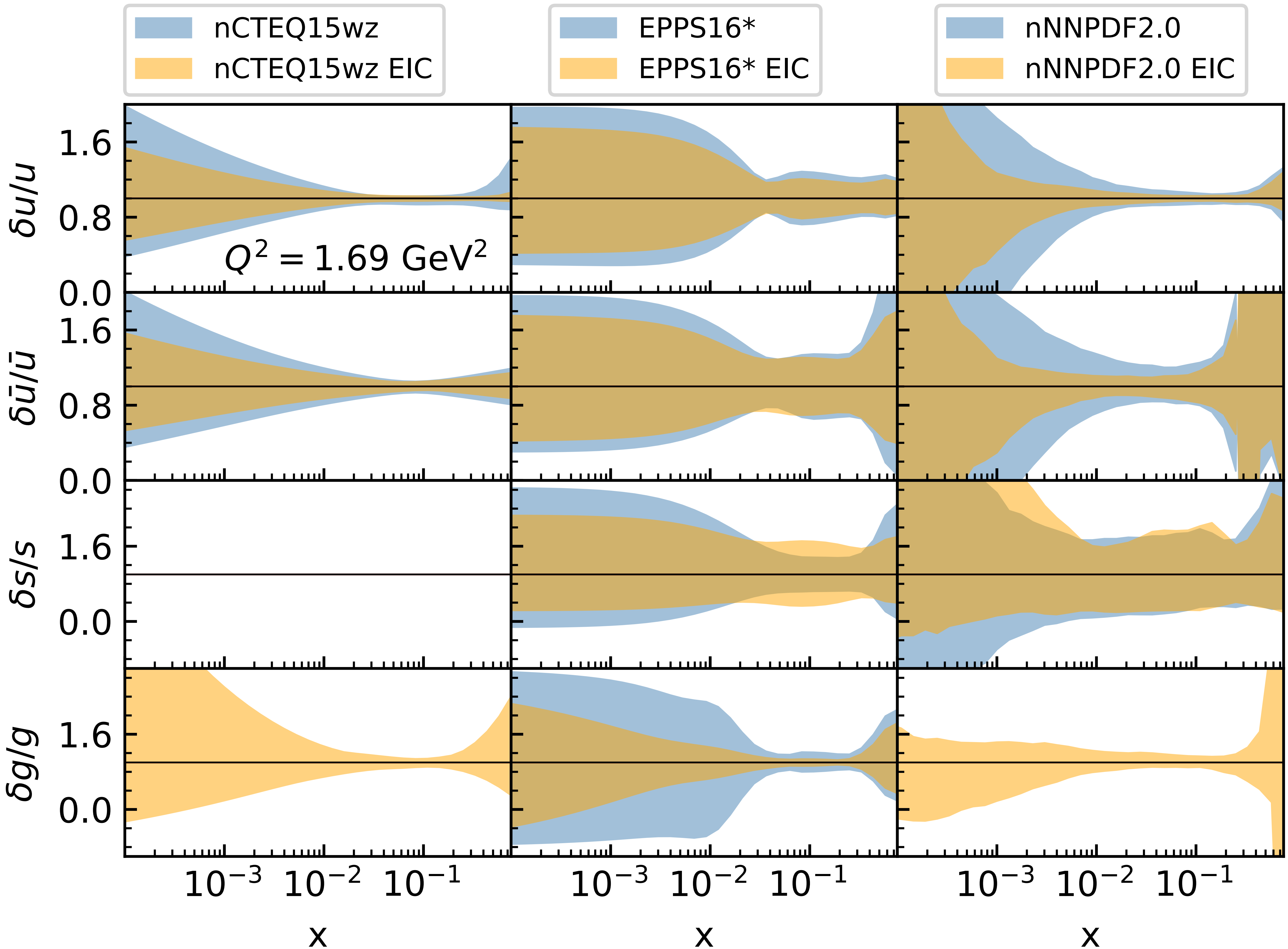
PRD 96, 114005





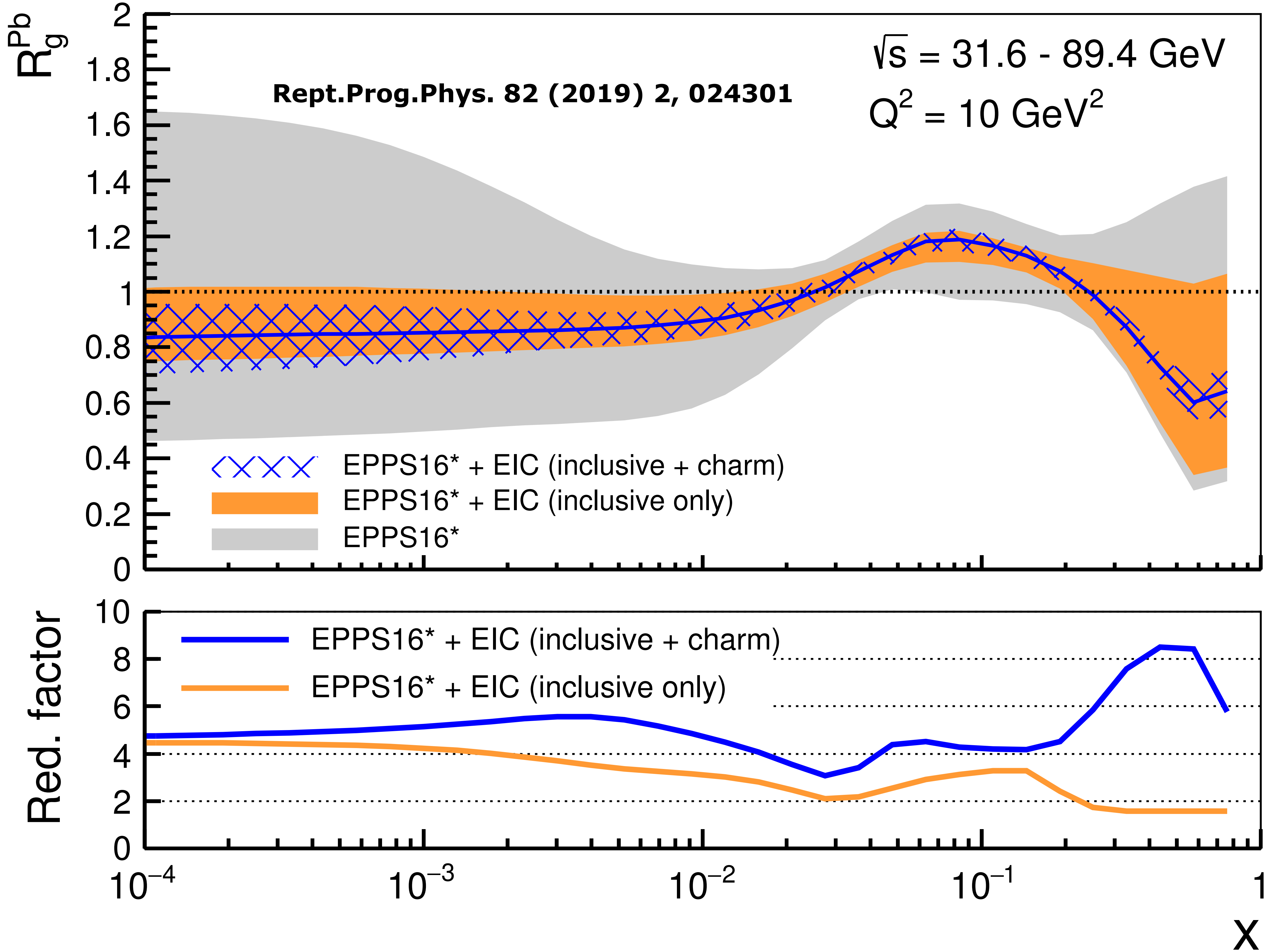


R_g^{Pb}
Rept.Prog.Phys. 82, 024301
$\sqrt{s}$ = 31.6 - 89.4 GeV
Q^2 = 10 GeV^2
EPPS16* + EIC (inclusive only)
EPPS16*
Red. factor
EPPS16* + EIC (inclusive only)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10
8
6
4
2
0
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x

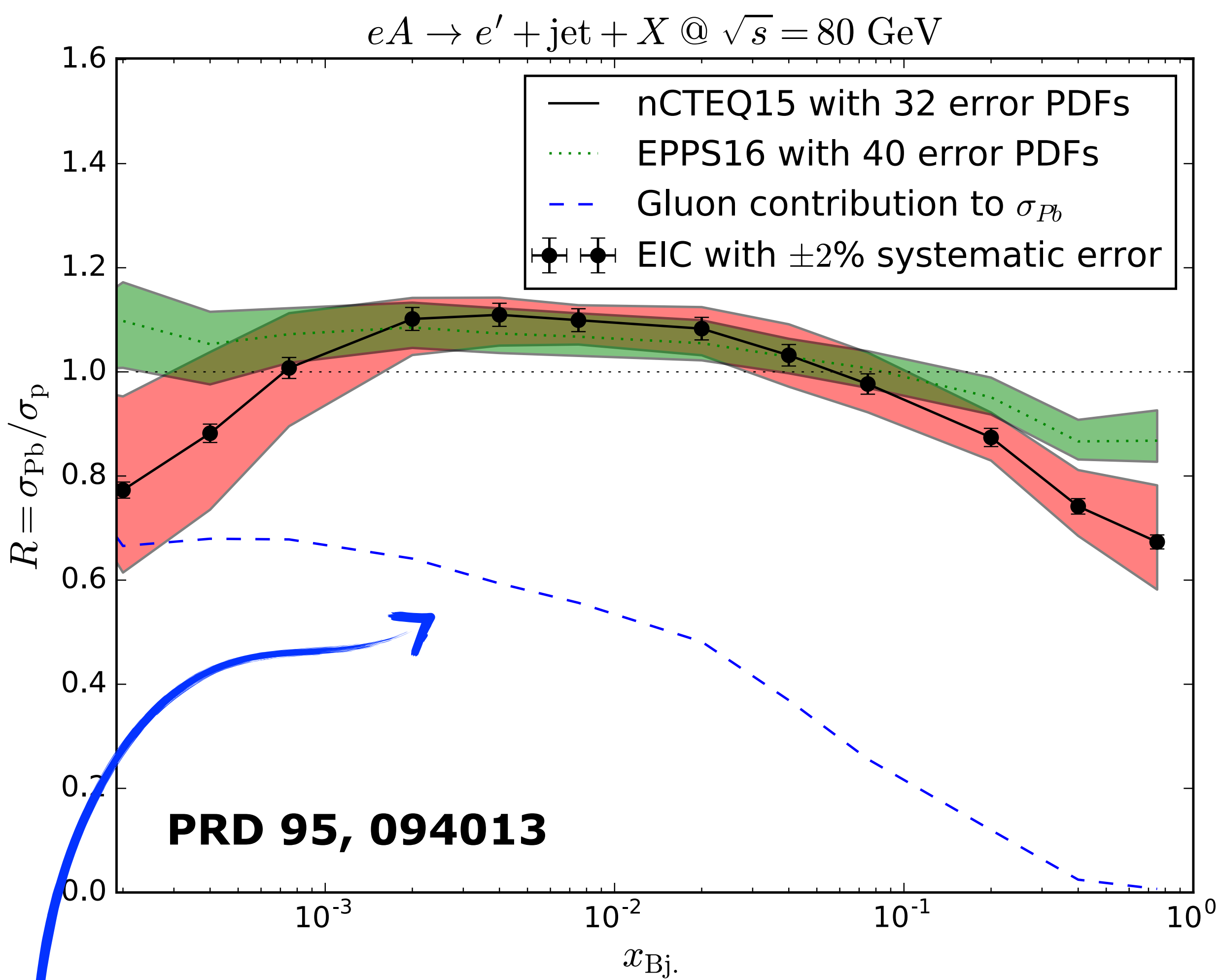


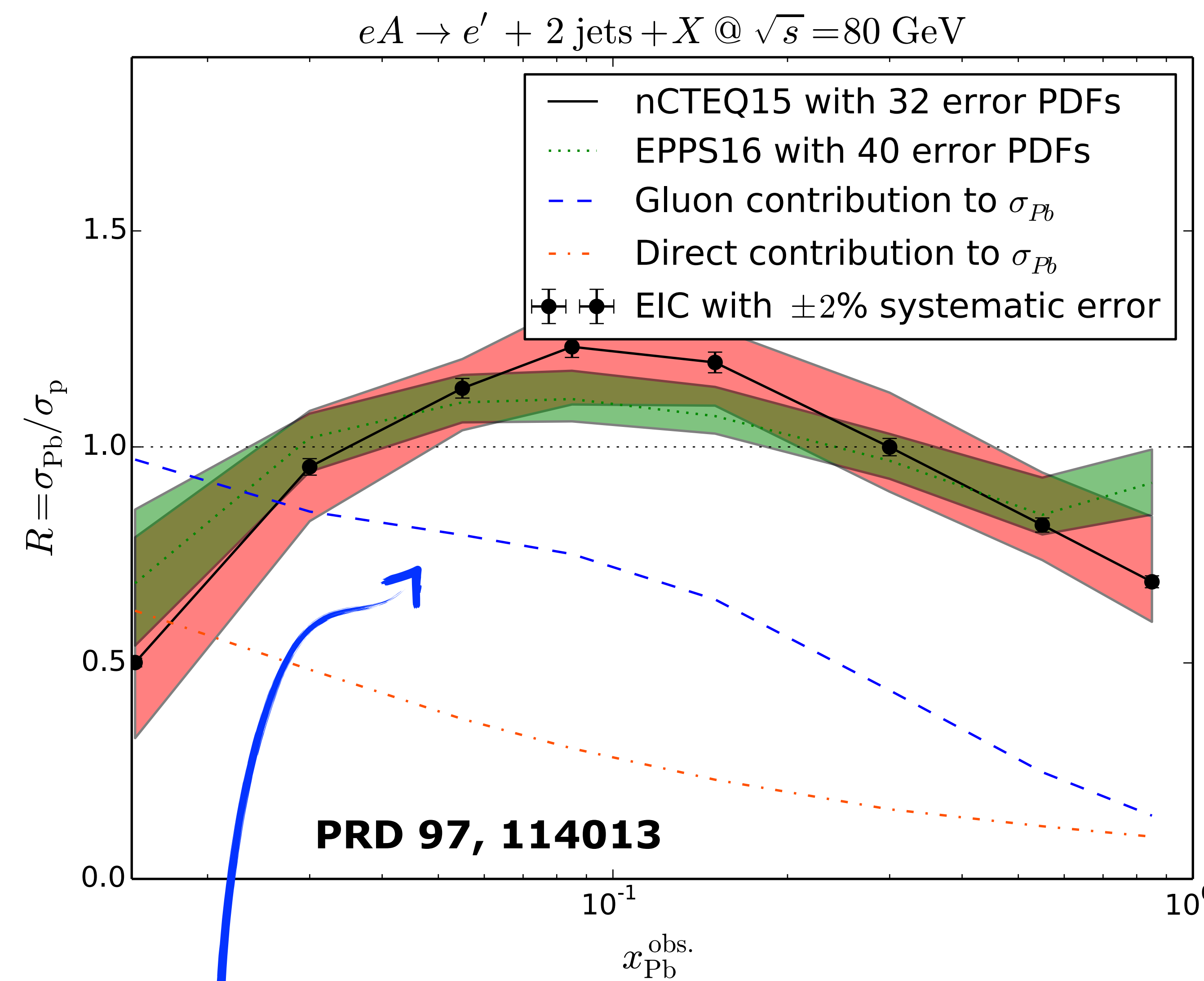
NPA 1026, 122447

- Using the PID needed for SIDIS, we can identify e.g. kaons coming from *c* quarks.



- For the first time we will have ***jets*** and ***di-jets in e+A***!





~ 50% of the cross-section for x < 0.01

more than 50% of the cross-section for 0.1 < x < 0.3 (the anti-shadowing region)

Jets as precision probes in e+A at the EIC:

Phys.Rev.C 101 (2020) 6, 065204

Summary

- The presence of a nuclear medium affects (non-trivially) the measured observables in high energy physics.

- The differences proton/nuclei can be explained by interacting mechanisms between the partons in bound nucleons, resulting in the need for medium-modified or nuclear PDFs.

- While one can propose theoretical models for the nPDFs, using the factorised framework of pQCD we can find *model independent* distributions, just as in the proton case.

- There are available several sets of nPDFs, and they all provide very good description of the data considered.

- Despite all the effort, nPDFs are very much behind proton PDFs. Mostly due to the amount and limited kinematic coverage of the data.

- While waiting for *clean* data, fitting groups have turned to more involved observables.

- These are sensitive to kinematic regions unreachable otherwise (for now) and/or to poorly constrained densities.


nPDF fitters waiting for the
EIC (LHeC? FCC-eh?) data