HIC initial state and (nuclear) Parton Distribution Functions

Lecture 2

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Summer school "Heavy-ion collisions in the QCD phase diagram"
08/07/2022, Subatech, Nantes, France

Universität Regensburg

Outline

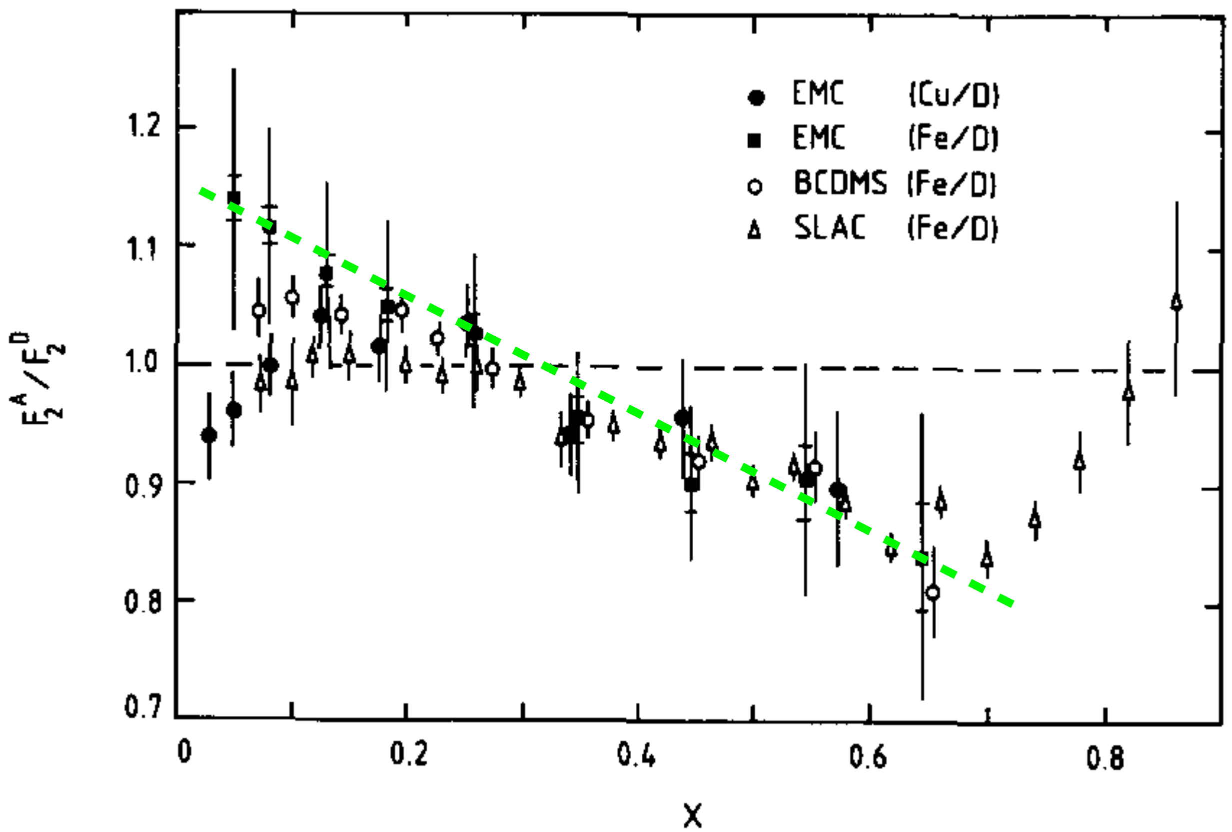
- Recap of PDFs.
- How to deal with nuclei.
- Data in nPDF fits
- Sets and comparison.
- Issues in nPDF extractions (compared with proton PDFs).
- Nuclear PDFs and heavy-ion collisions.
- Summary.

PDFs:

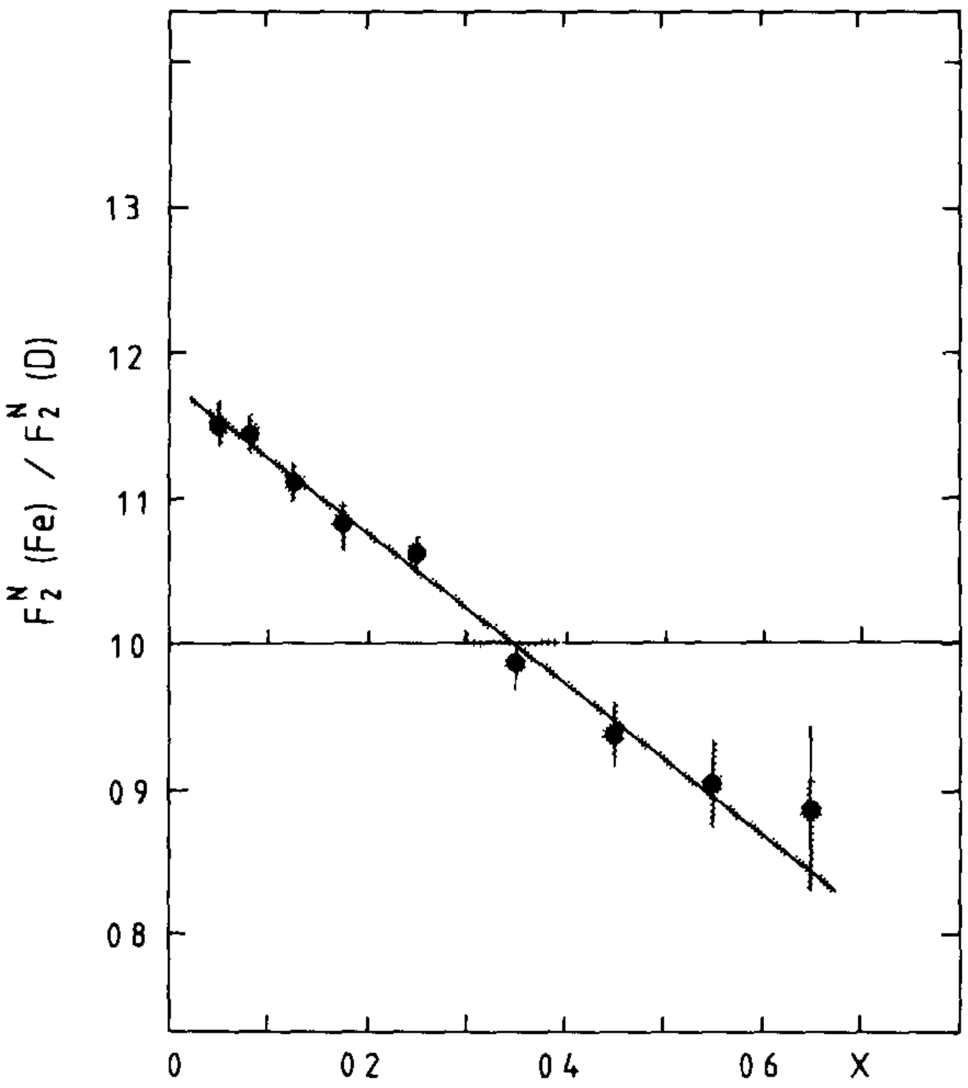
- are a **must** if we want to do anything beyond QED.
- are **universal**.
- contain all the information about the internal structure of the hadron. There are many PDF “families”.
- **evolve** with the scale (and this can be computed).
- can’t be computed from first principles. We need **data** to determine them.

The effects follow a very particular pattern:

Phys.Lett.B 202 (1988) 603.



Phys.Lett.B 123 (1983) 275.



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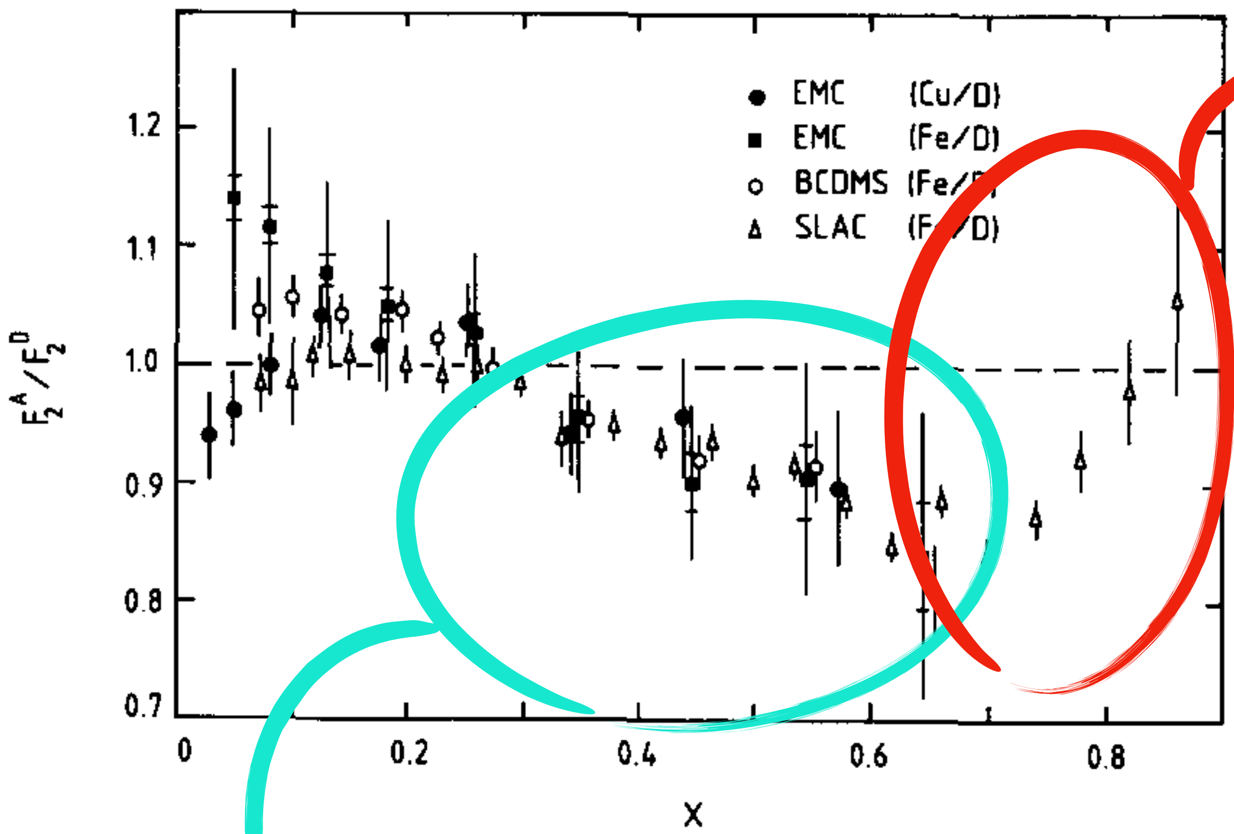
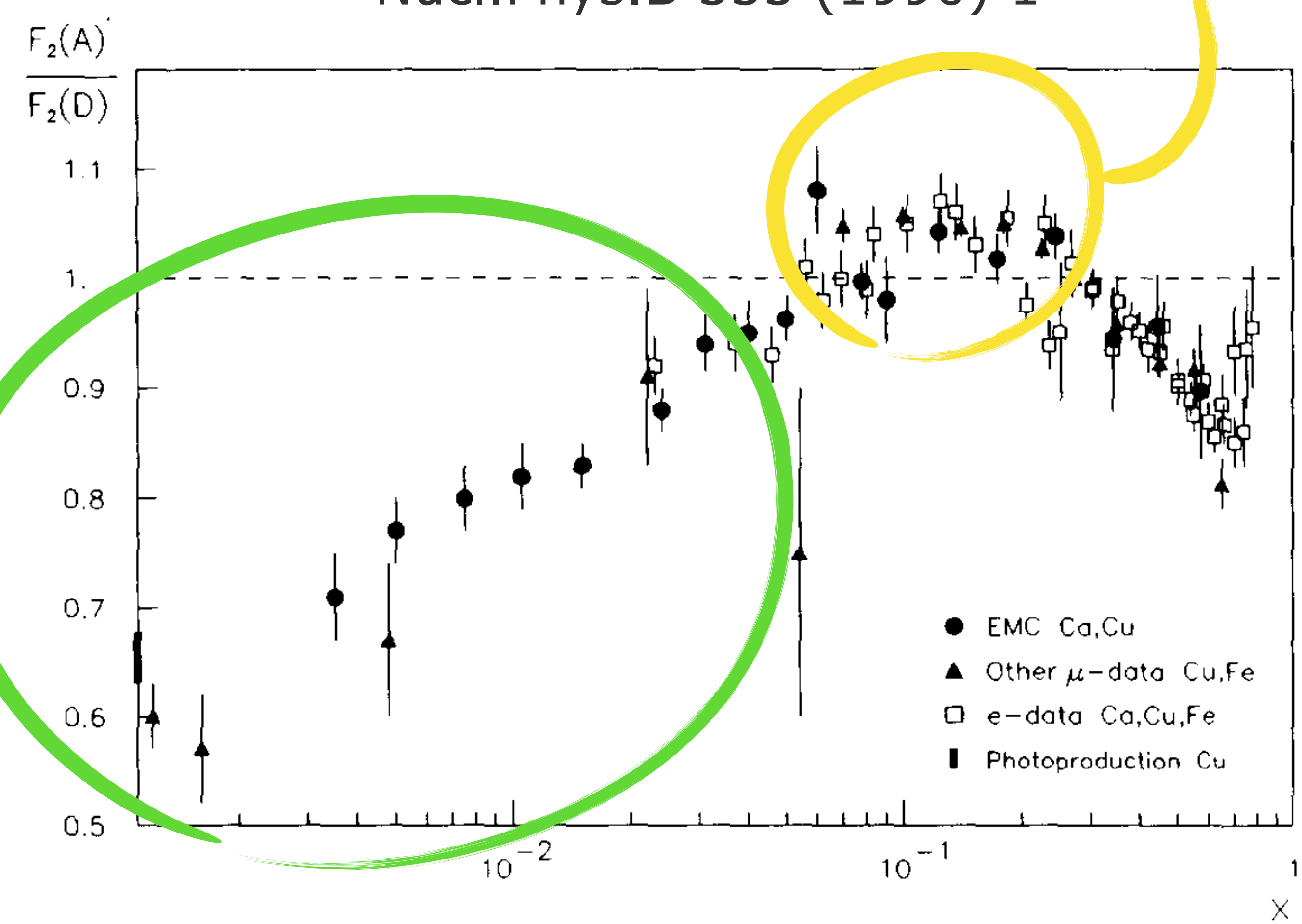


Fermi-motion

anti-shadowing

Nucl.Phys.B 333 (1990) 1



EMC effect

shadowing

How to deal with the nuclei?

- Do nothing. Not a real option:

  - We want to know how things work.
  - Useful for flavour separation of proton PDFs.
  - HI and the QGP benchmarking.
  - Neutrino physics.
  - ...

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 the nuclei?

- Do nothing.
- Build theoretical models:
  - shadowing ~ 400 (1973-2022)
  - anti-shadowing ~ 40 (1978-2020)
  - EMC effect ~ 370 (1983-2021)
  - Fermi motion ~ 90 (1966-2022)
- A purely phenomenological approach, assuming all we do for the proton will remain valid: **nuclear PDFs**.

- Can we describe the behaviour with the average of proton and neutrons?

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

NO

- For an isoscalar nucleus ($A = 2Z$) we would get $F_2^A / F_2^d = 1$.
- In those articles the data are corrected for the non-isoscalarity of the nuclei ($A \neq 2Z$).

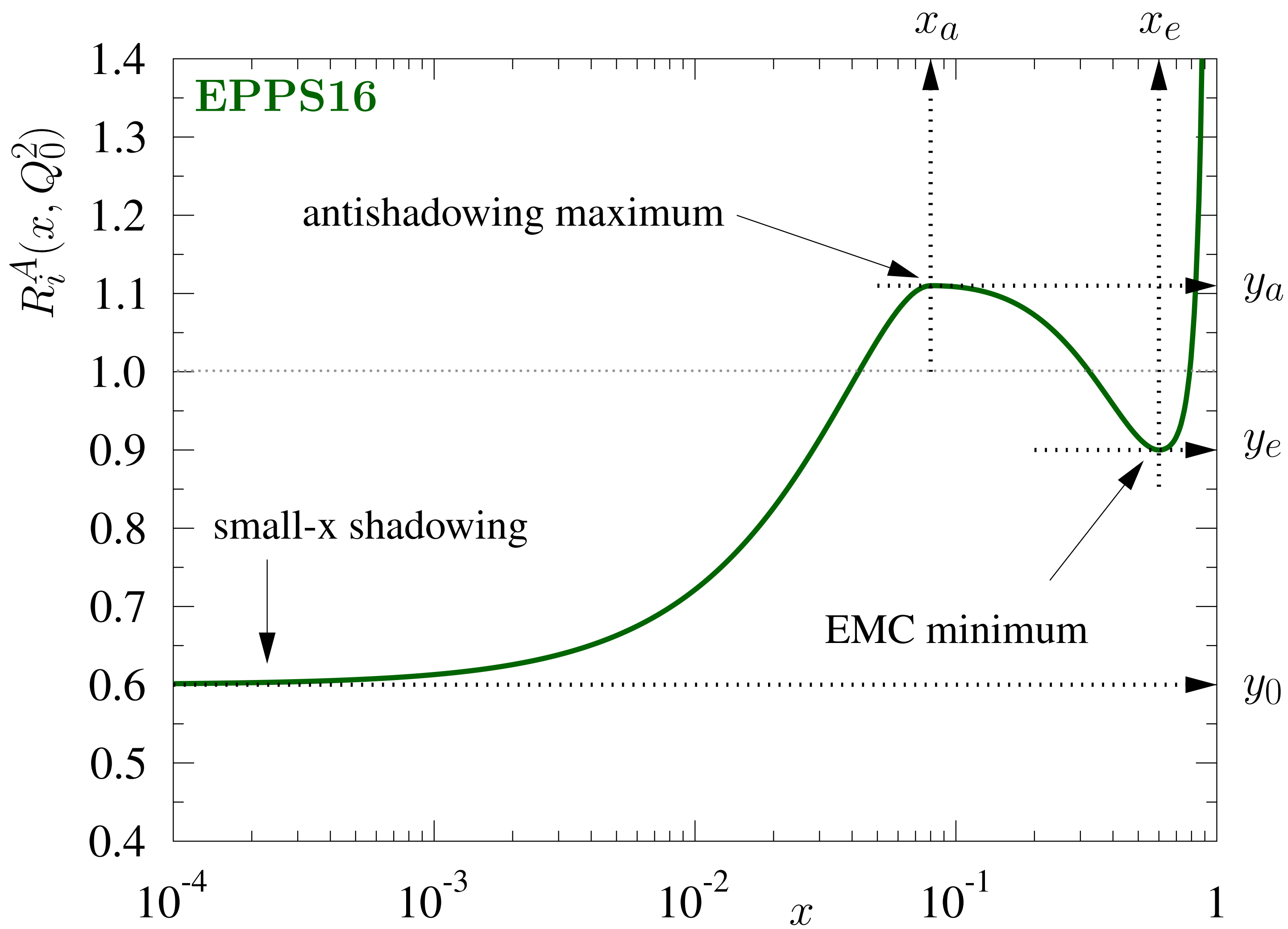
- What we see is a **genuine modification of the initial state** due to the medium.

The naive attempt fails. **Miserably**. 😓

- Alright, then we really have to get something else. Ideally, we would like to have an expression that is valid for all A.

- Options used so far:

  - $f_{i/p/A}(x, Q_0^2, A) = f_{i/p}(x, Q_0^2) R_i(x, A)$



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    - $f_{i/p/A}(x, Q_0^2, A) = f_{i/p}(x, Q_0^2, A)$

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

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

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  - $f_{i/p/A}(x, Q_0^2, A) = f_{i/p}(x, Q_0^2) R_i(x, A)$
  - $f_{i/p/A}(x, Q_0^2, A) = f_{i/p}(x, Q_0^2, A)$

can't account for the parton in the bound nucleon having more momentum than in the free one

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- Options used so far:

  - $f_{i/p/A}(x, Q_0^2, A) = f_{i/p}(x, Q_0^2) R_i(x, A)$
  - $f_{i/p/A}(x, Q_0^2, A) = f_{i/p}(x, Q_0^2, A)$
  - $f_{i/p/A}(x, Q_0^2, A) = f_{i/p}(x, Q_0^2) \otimes R_i(x, A)$
  - $f_{i/p/A}(x, Q_0^2, A) = NN$

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

- Now, do a global fit.

Data used in nPDF fits

- DIS: **NC** (always) and CC (not in all fits, since 2012).

  Mostly sensitive to the valence quarks.
  Mostly given as ratios to deuterium.

- Drell-Yan with fixed target: almost always).

- Single inclusive hadron production at RHIC: very sensitive to the gluon density, since 2009.

- W and Z production, and di-jets at the LHC: since 2016.

- D meson production at the LHC: twice, since 2021.

- Prompt photon at the LHC: once, since 2021.

Available sets

- 🇺🇸 and 🇺🇸-🇩🇪: **nCTEQ15**: PRD 93, 085037. **nCTEQ15WZ**: EPJC 80, 968. **nCTEQ15HiX**: PRD 103, 114015.
- 🇦🇷 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.

$\neq$ choices

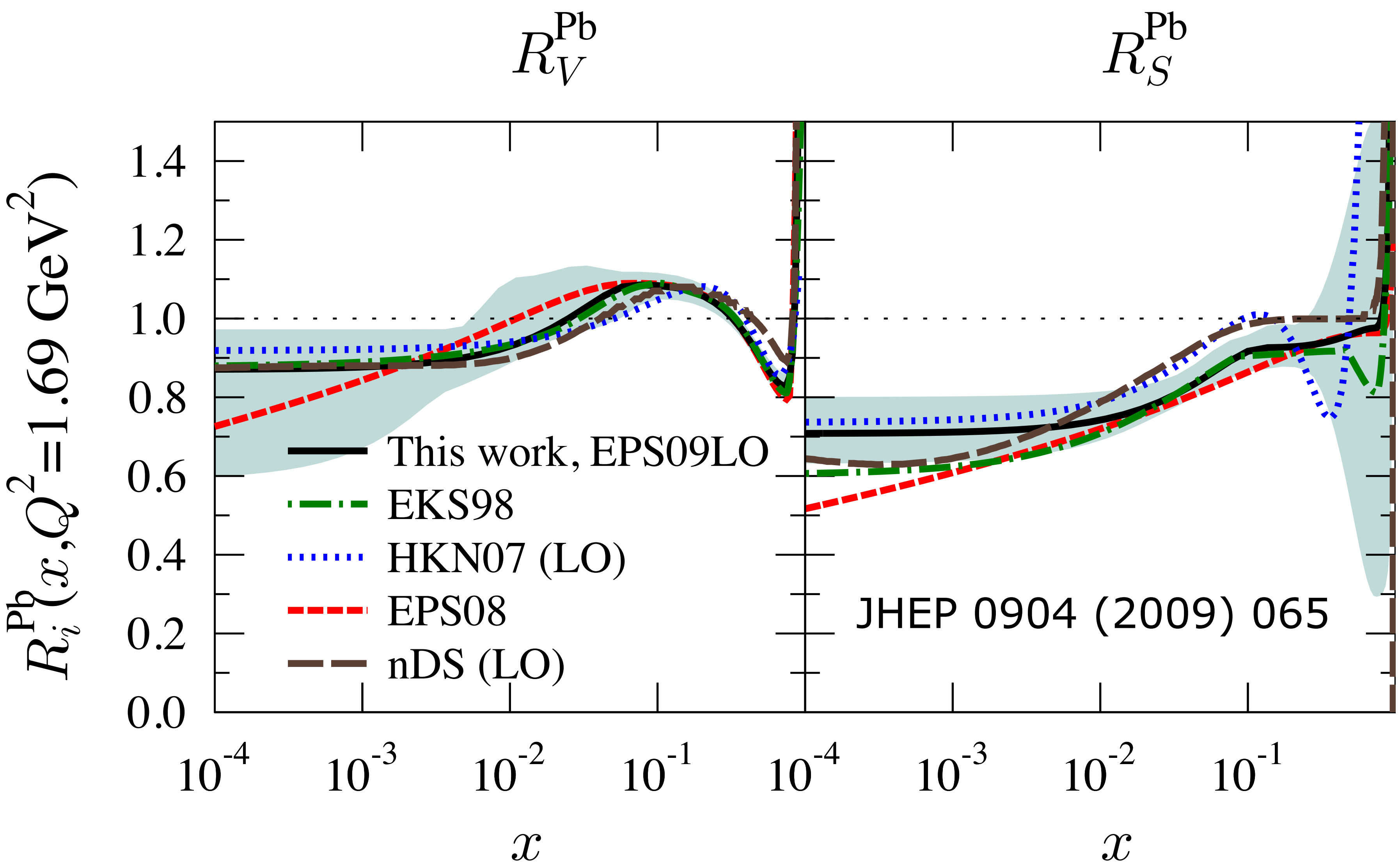
- Initial scale: 0.26 GeV^2 to 2.0 GeV^2.
- Order in of the perturbation: LO to NNLO.
- HF scheme: FFNS, ZM-FNS, GM-VFNS (several implementations).
- Number of points fitted: 309 to 4353.
- χ^2/N_{data}: 0.68 to 1.89.
- Number of parameters required (not NN): 7 to 25.

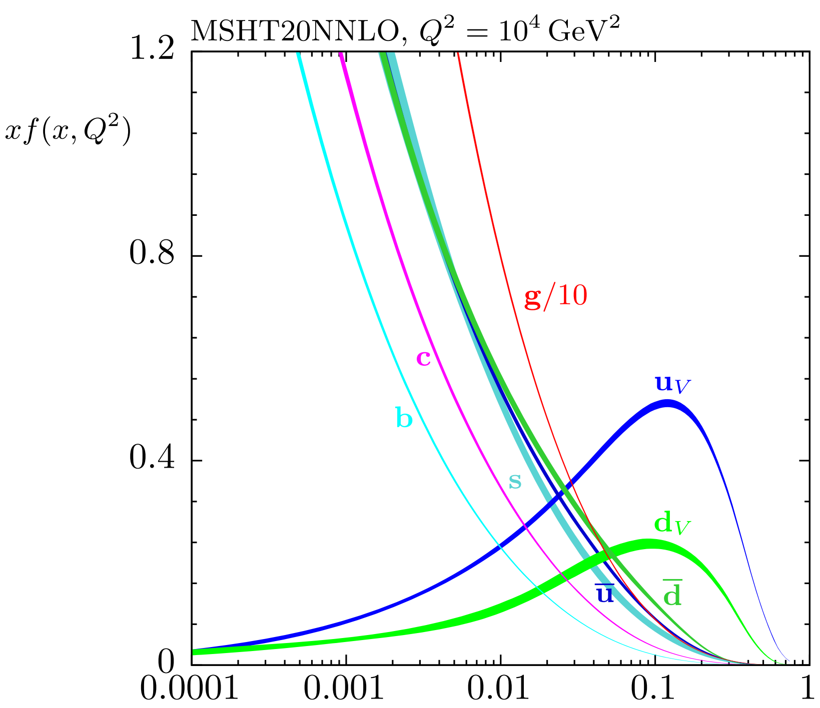
- ratio of flavour ***i*** in **proton** in nucleus ***A*** to a proton reference

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

LO

- nDS has a convolutional approach.
- The others have a multiplicative factor.
- No flavour separation.





LO

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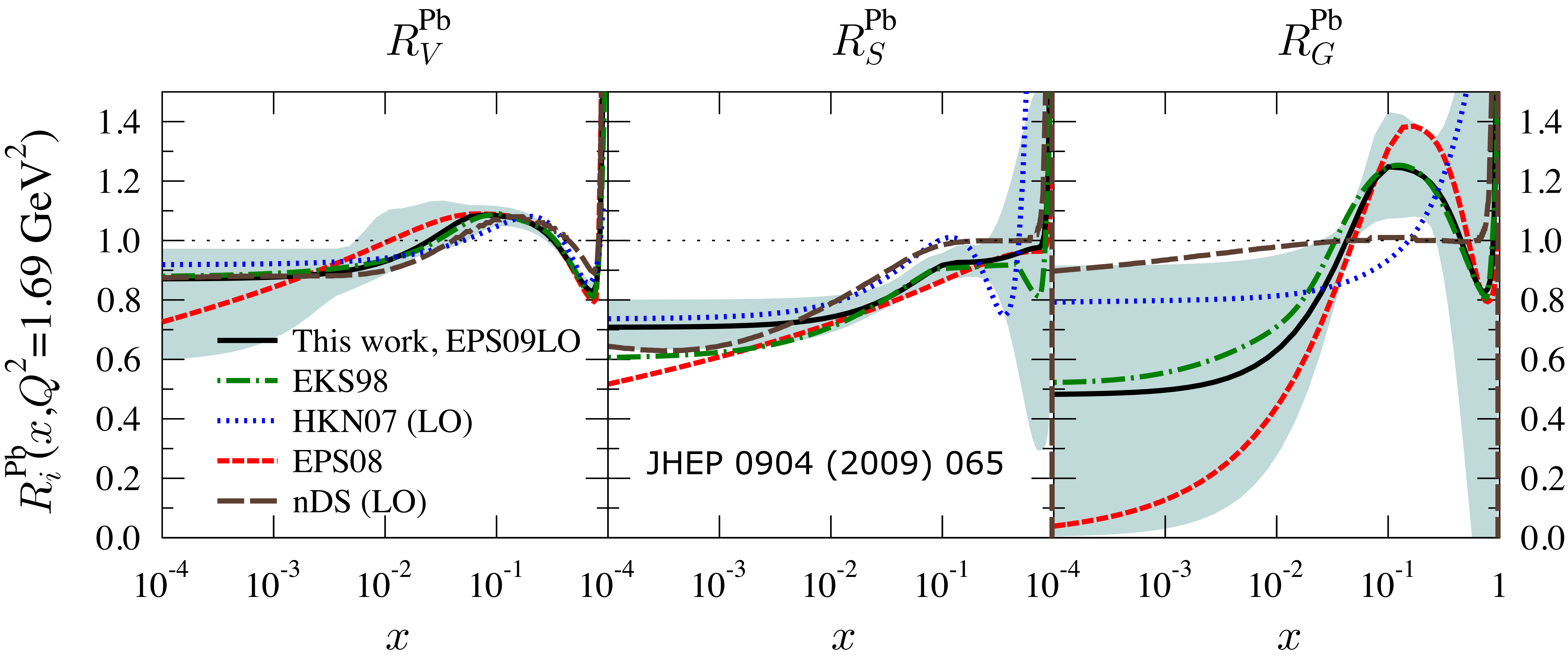
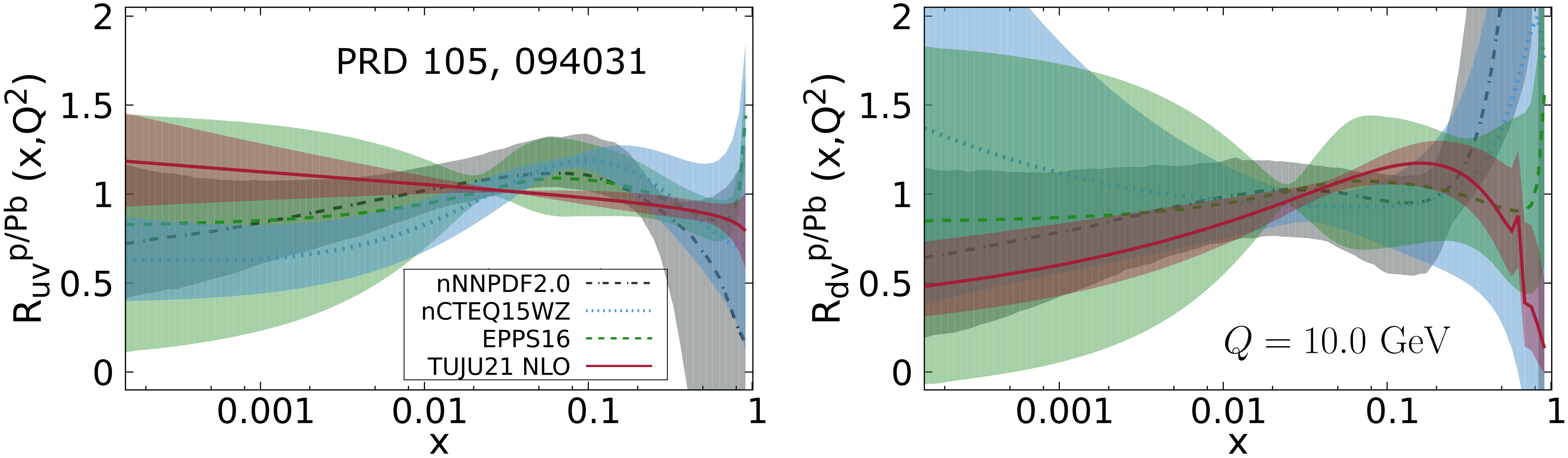
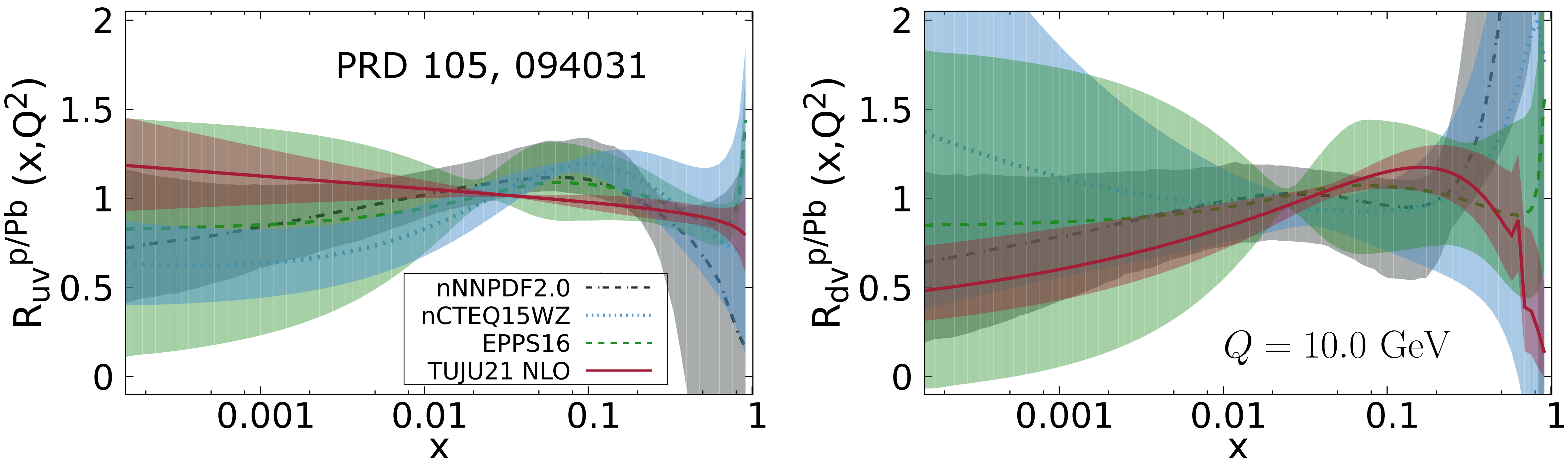


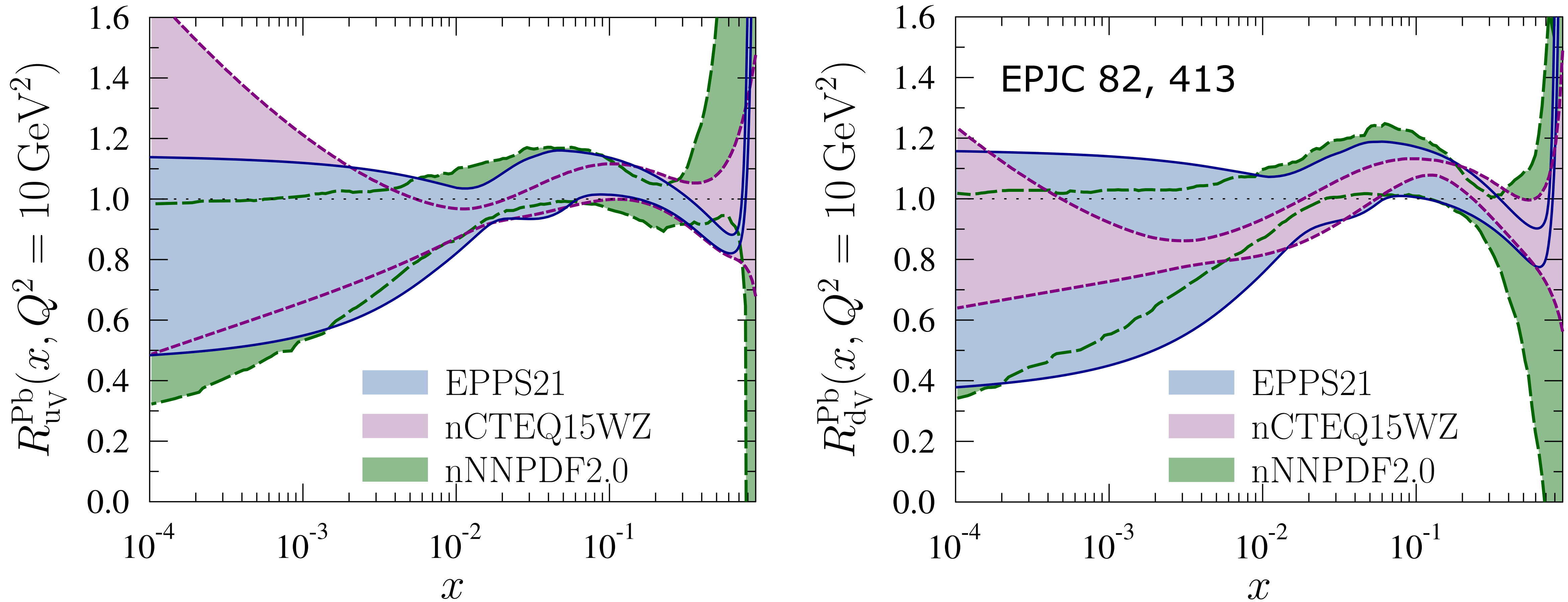
NLO: valence



- Extra parameters added to separate (at least) up and down quarks.
- CC DIS needed.

NLO: valence

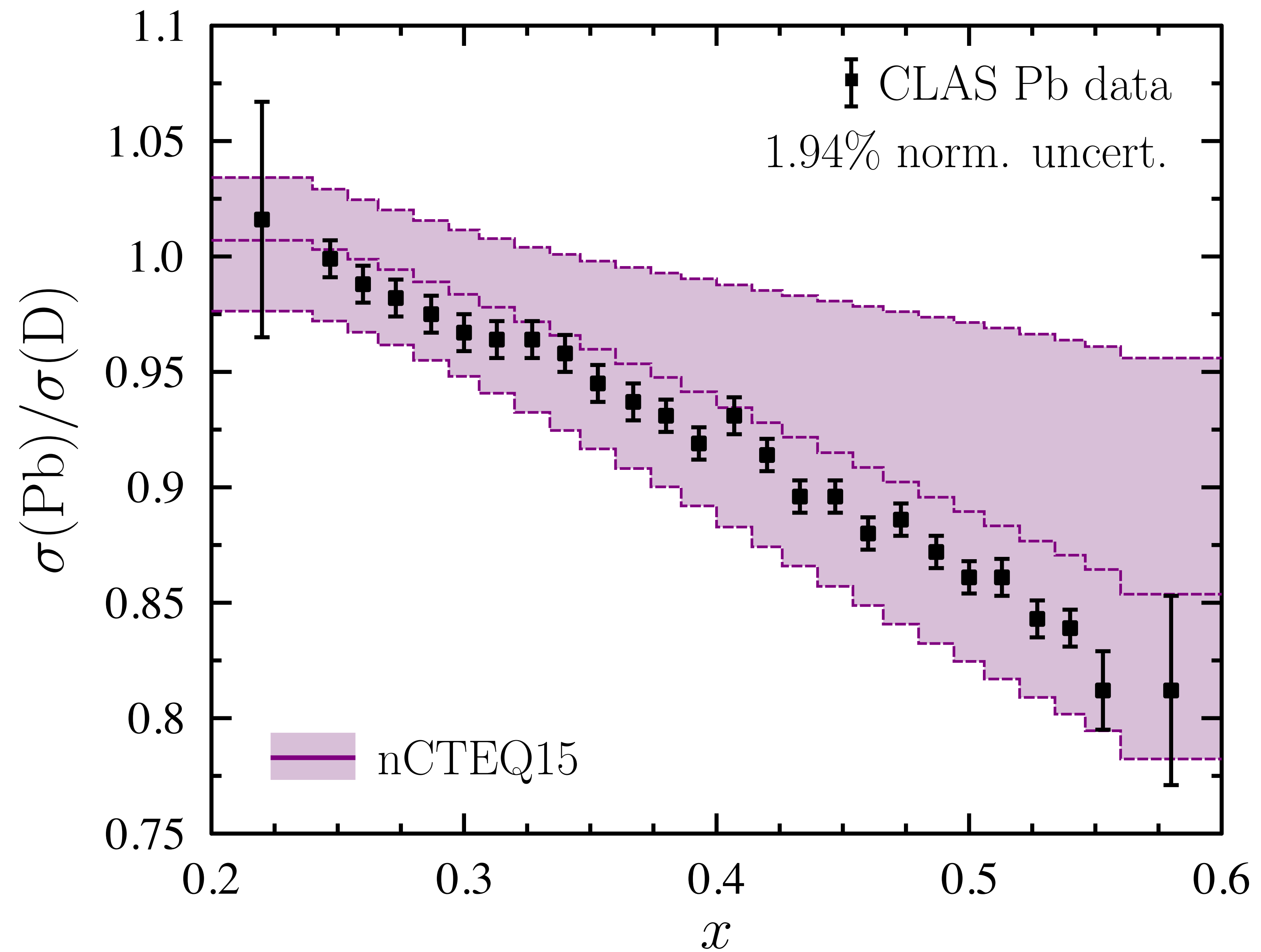

PRD 105, 094031
$R_{uv}^{p/Pb}$ (x,Q^2)
$R_{dv}^{p/Pb}$ (x,Q^2)
nNNPDF2.0
nCTEQ15WZ
EPPS16
TUJU21 NLO
$Q = 10.0$ GeV
x
0.001
0.01
0.1
1


EPJC 82, 413
$R_{u_V}^{Pb}(x, Q^2 = 10\,\mathrm{GeV}^2)$
$R_{d_V}^{Pb}(x, Q^2 = 10\,\mathrm{GeV}^2)$
EPPS21
nCTEQ15WZ
nNNPDF2.0
x

NLO: valence

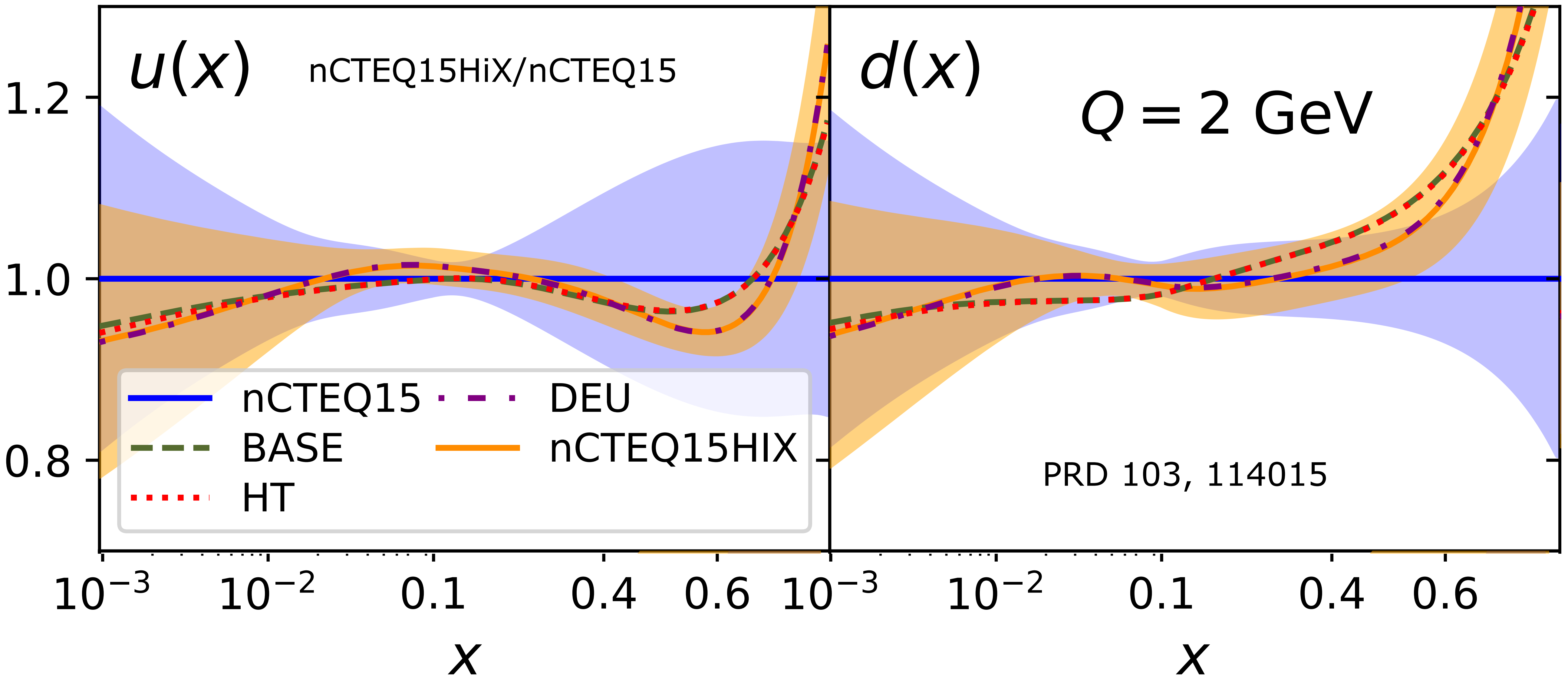
- More relaxed cut on W^2 to allow for the high precision JLAB data.

EPJC 80 (2020) 5, 381.

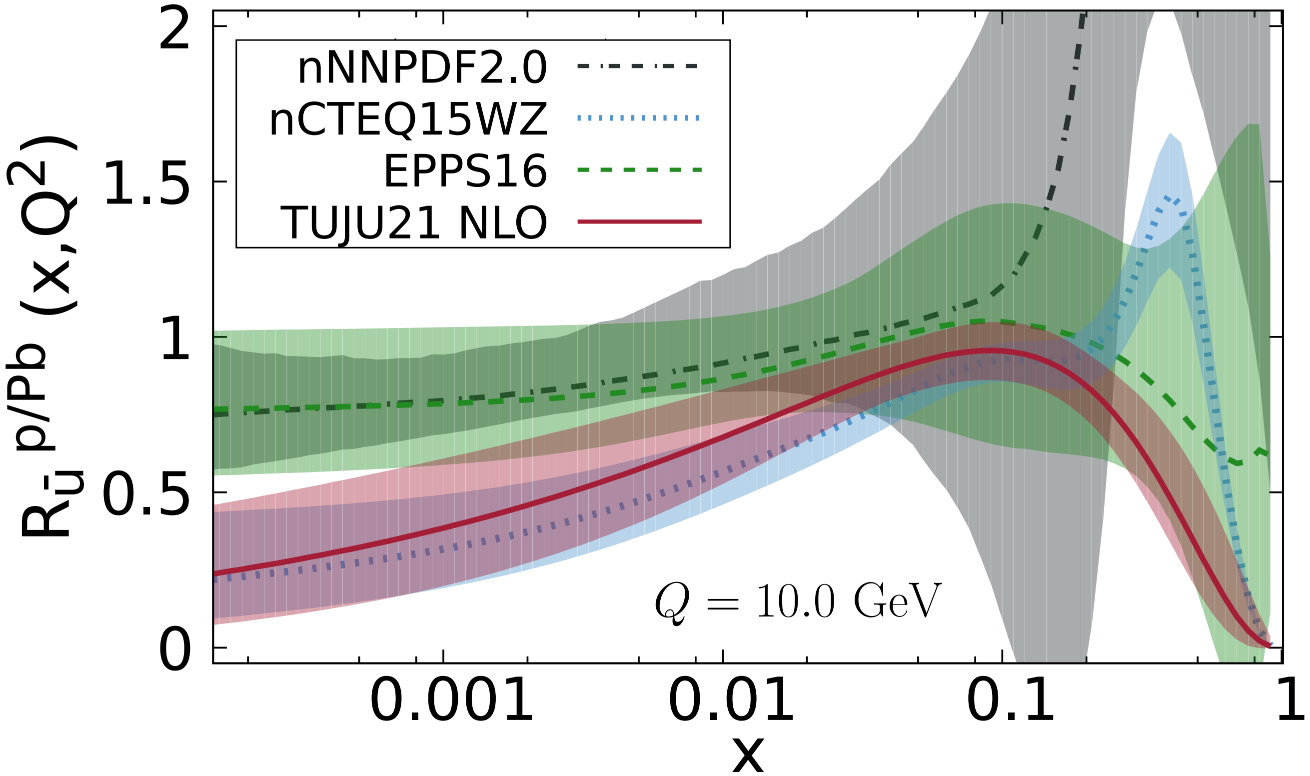


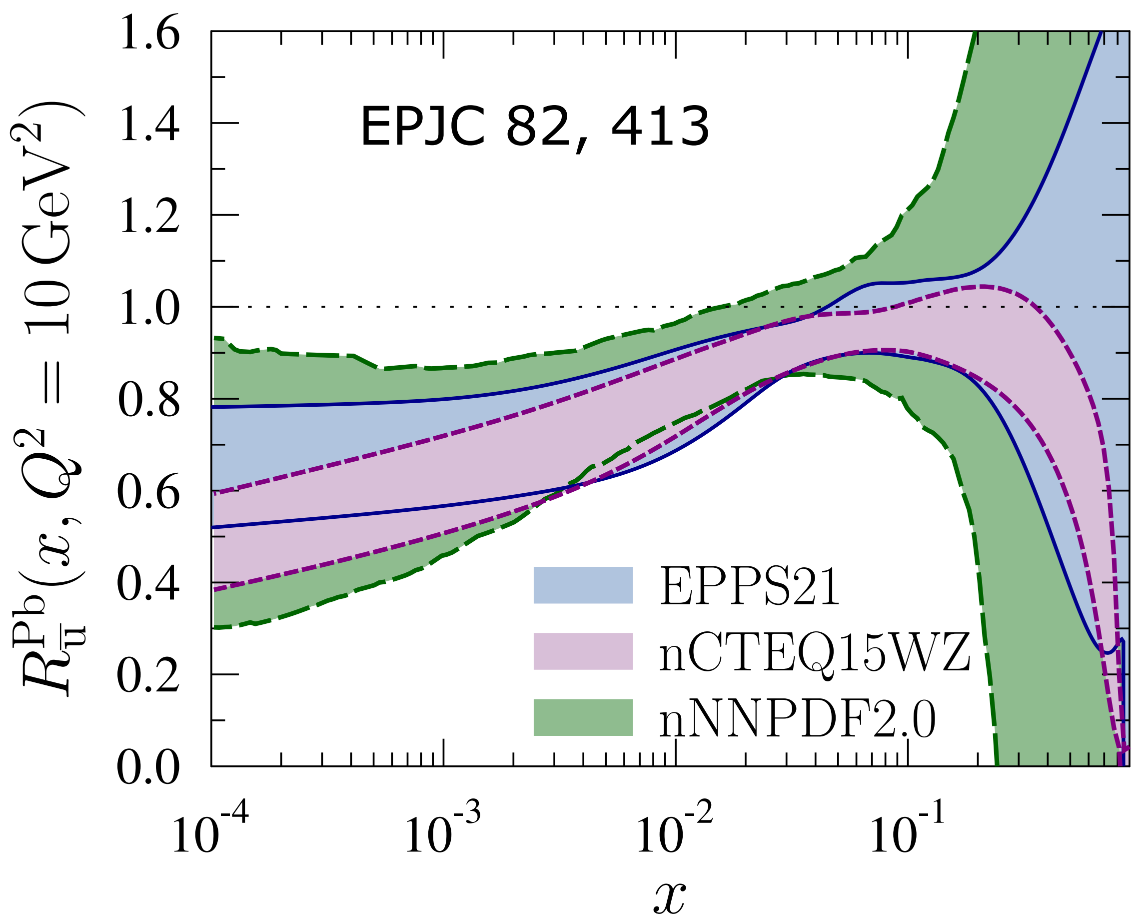
NLO: valence

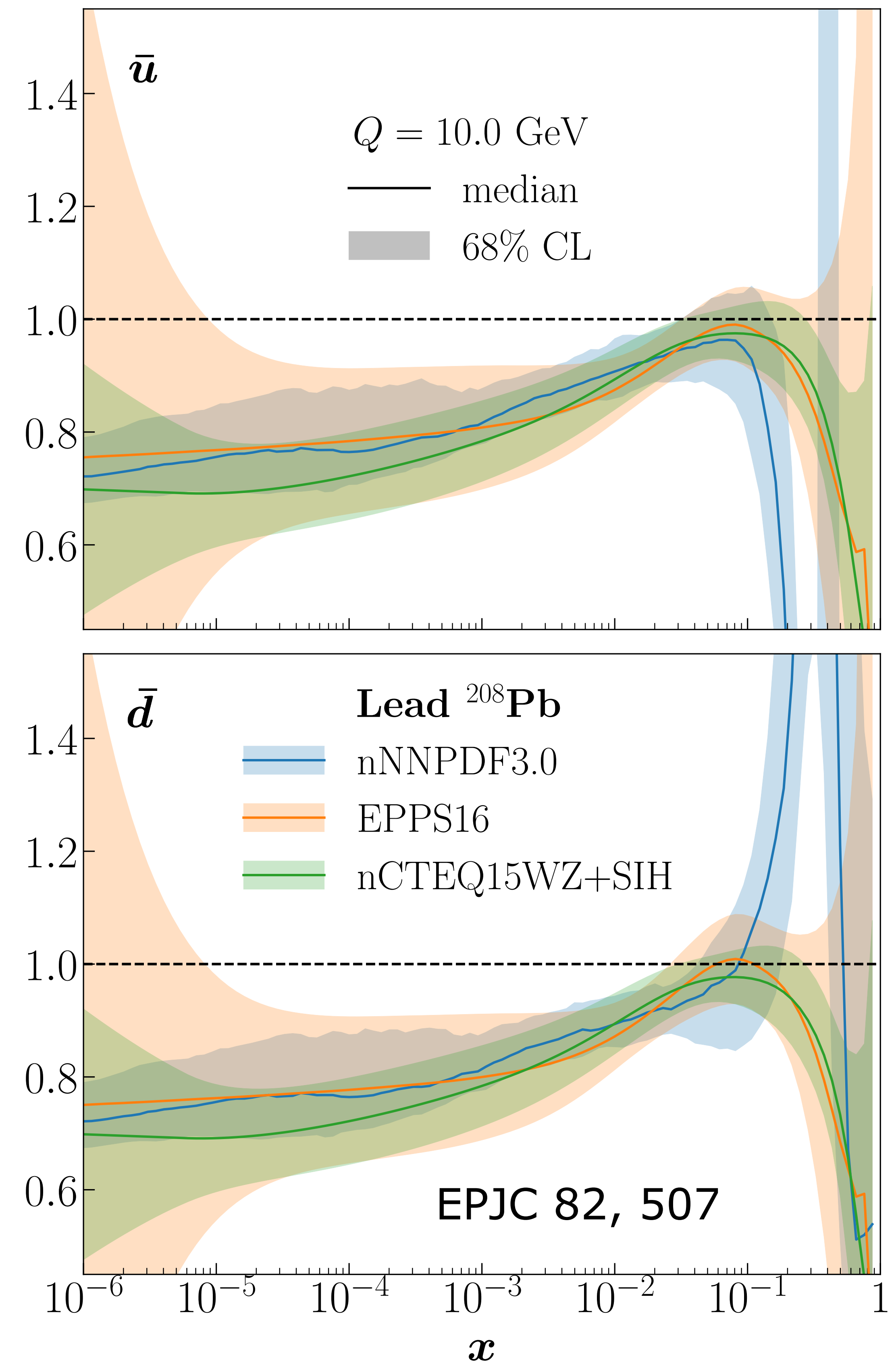
- More relaxed cut on W^2 to allow for the high precision JLAB data.



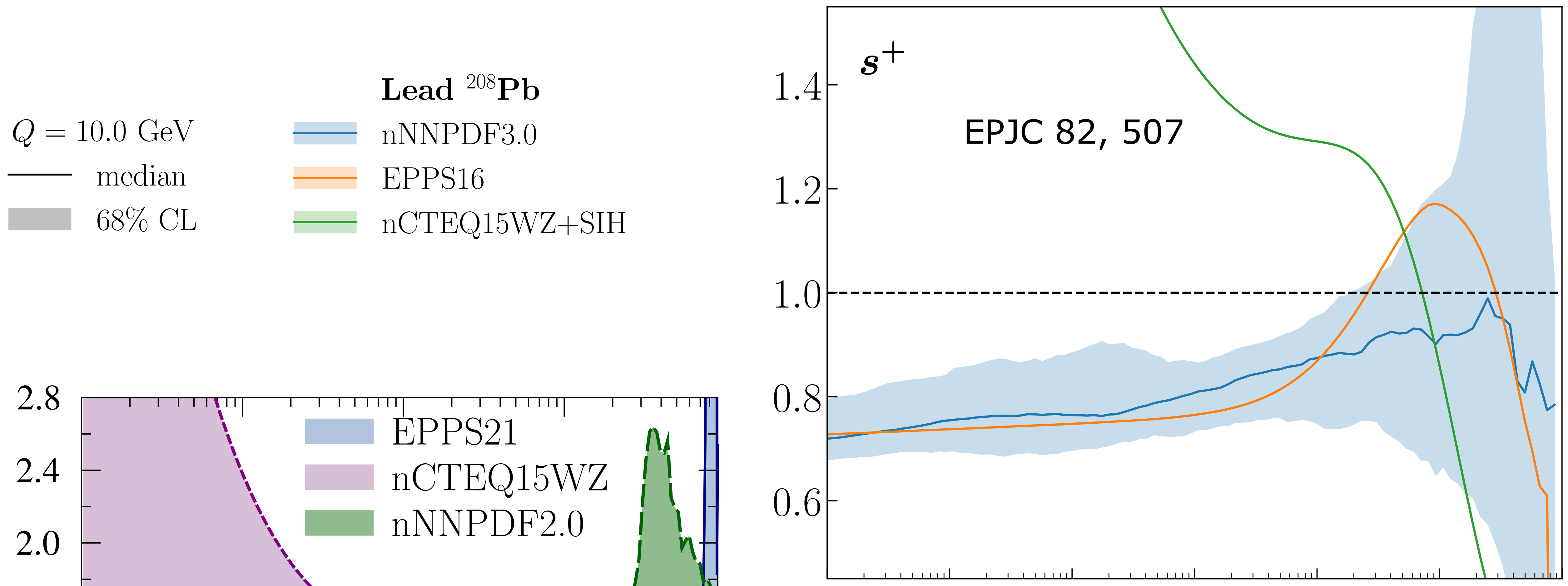
NLO: sea

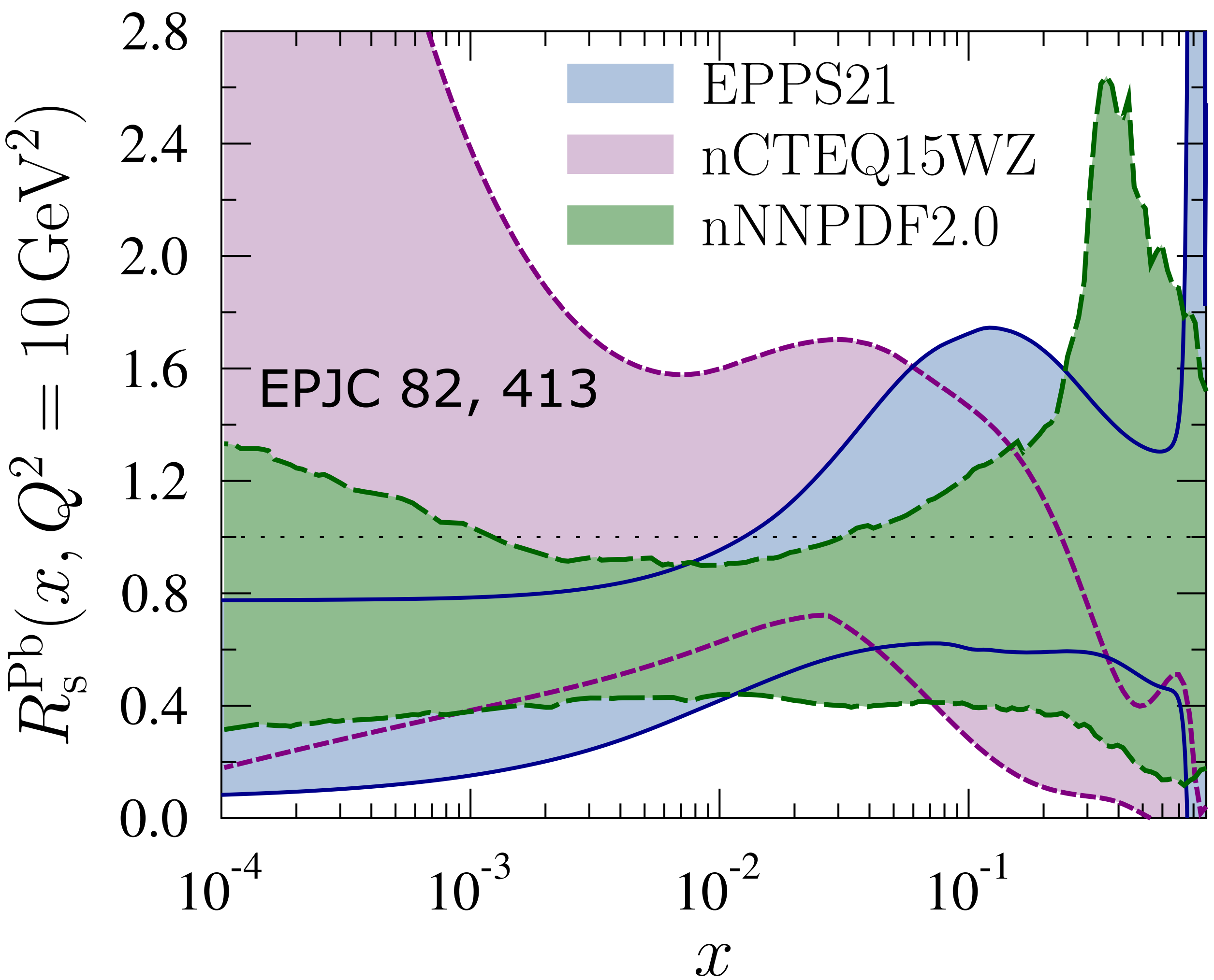

nNNPDF2.0
nCTEQ15WZ
EPPS16
TUJU21 NLO
Q = 10.0 GeV
$R_{\bar{u}}^{p/Pb}(x,Q^2)$
x
0.001
0.01
0.1
1


EPJC 82, 413
EPPS21
nCTEQ15WZ
nNNPDF2.0
$R_{\bar{u}}^{Pb}(x, Q^2 = 10\,GeV^2)$
x


$\bar{u}$
Q = 10.0 GeV
median
68% CL
$\bar{d}$
Lead ^{208}Pb
nNNPDF3.0
EPPS16
nCTEQ15WZ+SIH
EPJC 82, 507
x

NLO: strange

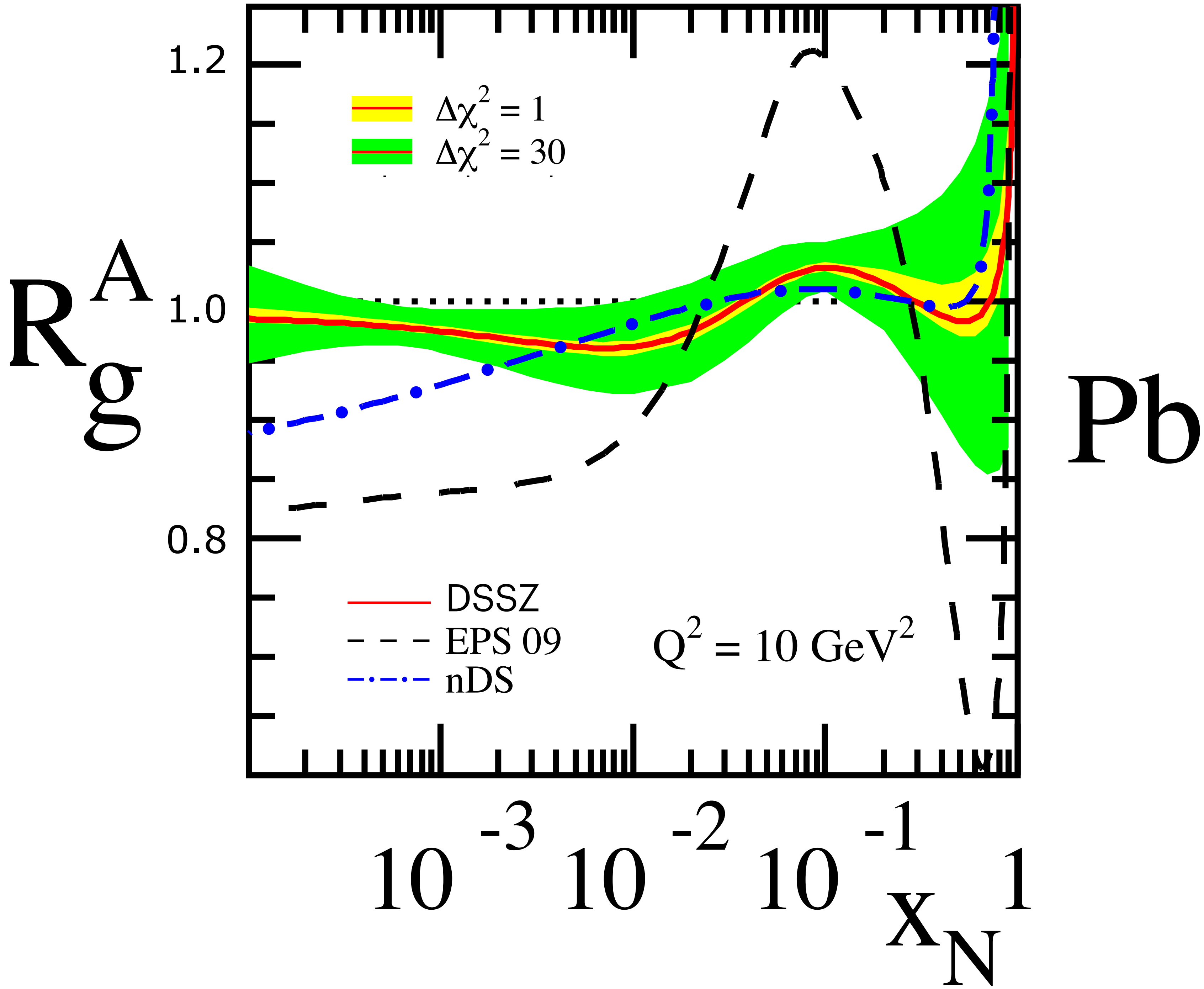

Lead ^{208}Pb
$Q = 10.0$ GeV
median
68% CL
nNNPDF3.0
EPPS16
nCTEQ15WZ+SIH
s^+
EPJC 82, 507
1.4
1.2
1.0
0.8
0.6


EPPS21
nCTEQ15WZ
nNNPDF2.0
EPJC 82, 413
$R_s^{Pb}(x, Q^2 = 10\,GeV^2)$
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x


strange quark
antistrange quark

NLO: gluon

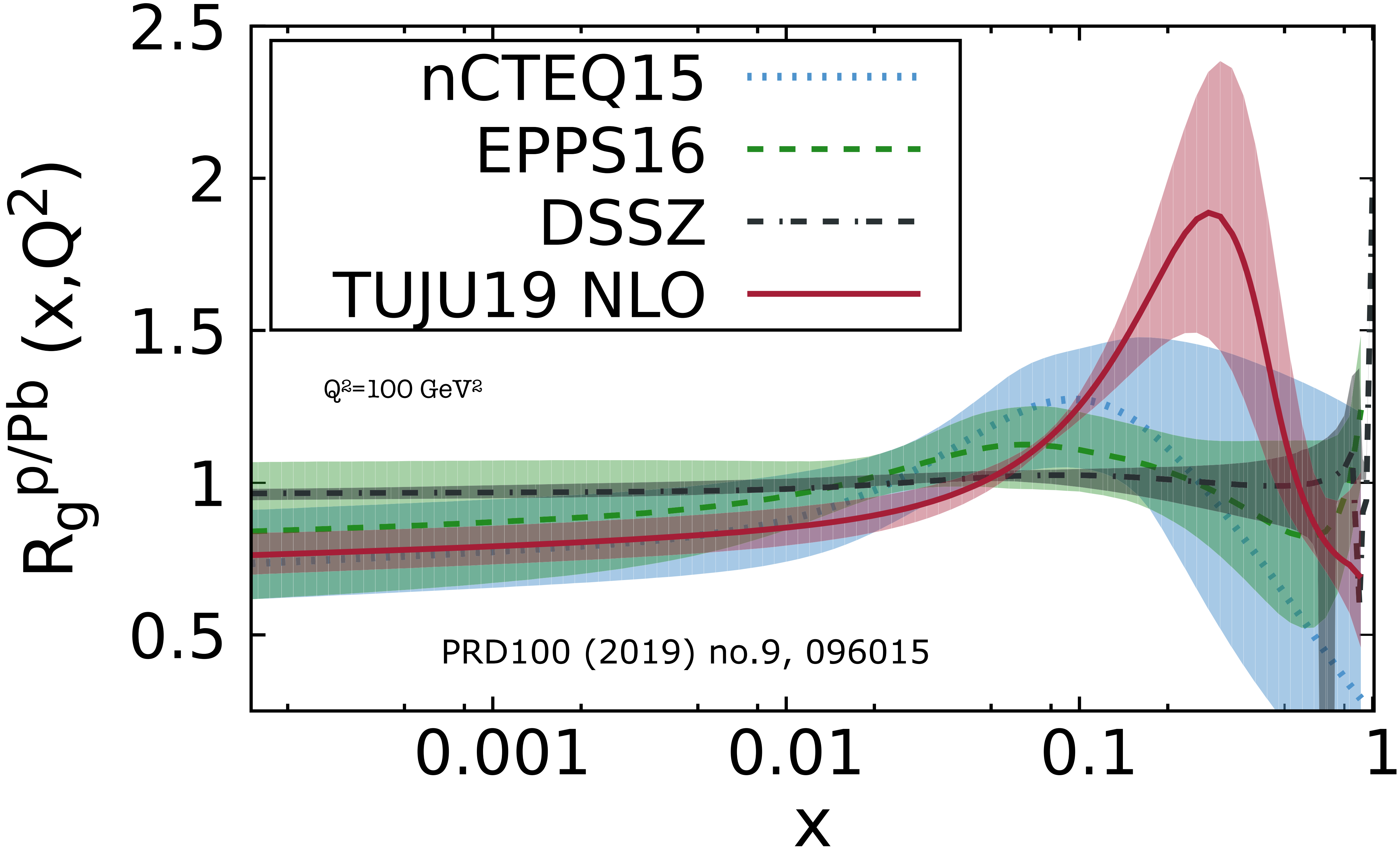
PRD85 (2012), 074028



how?

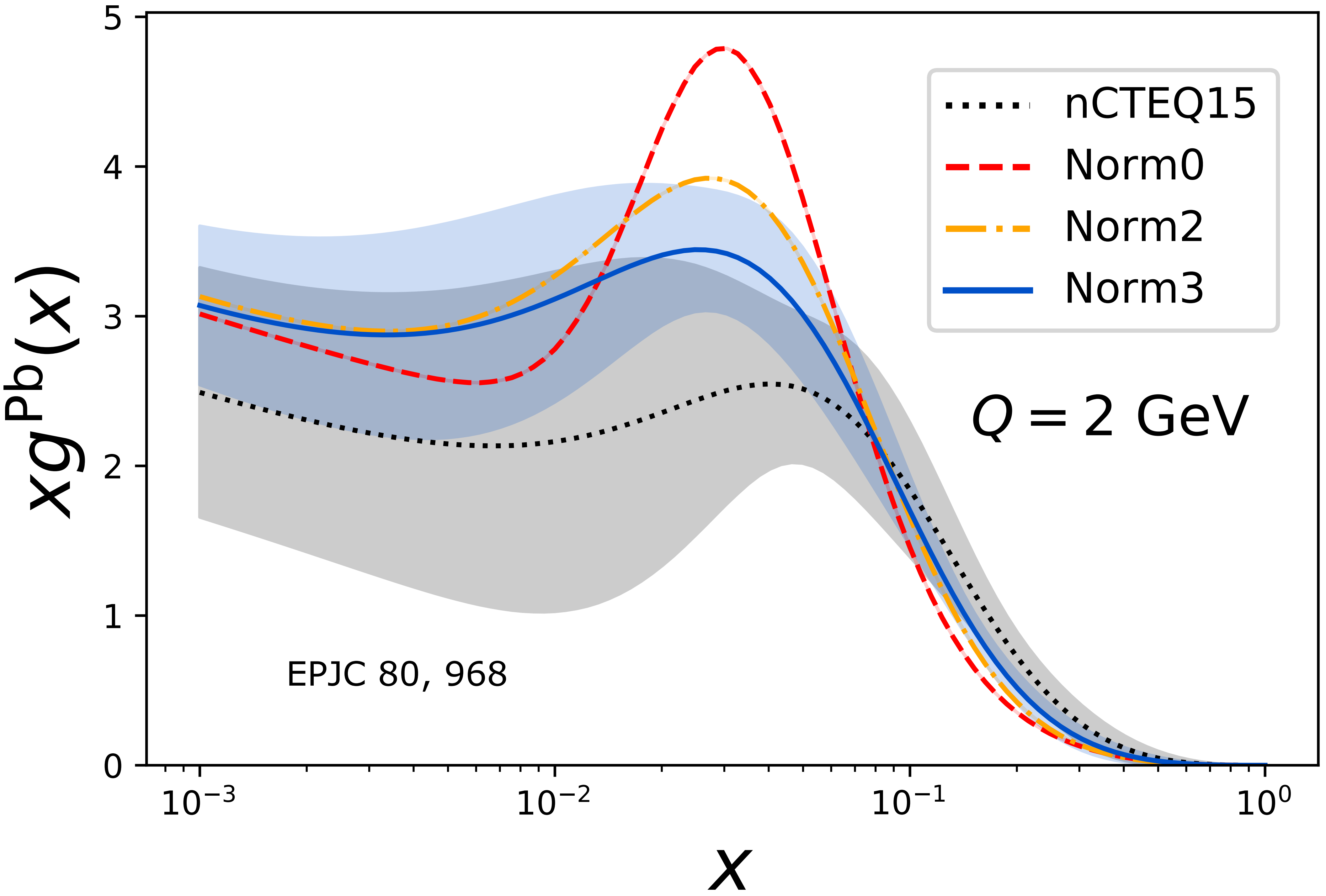
why?

NLO: gluon

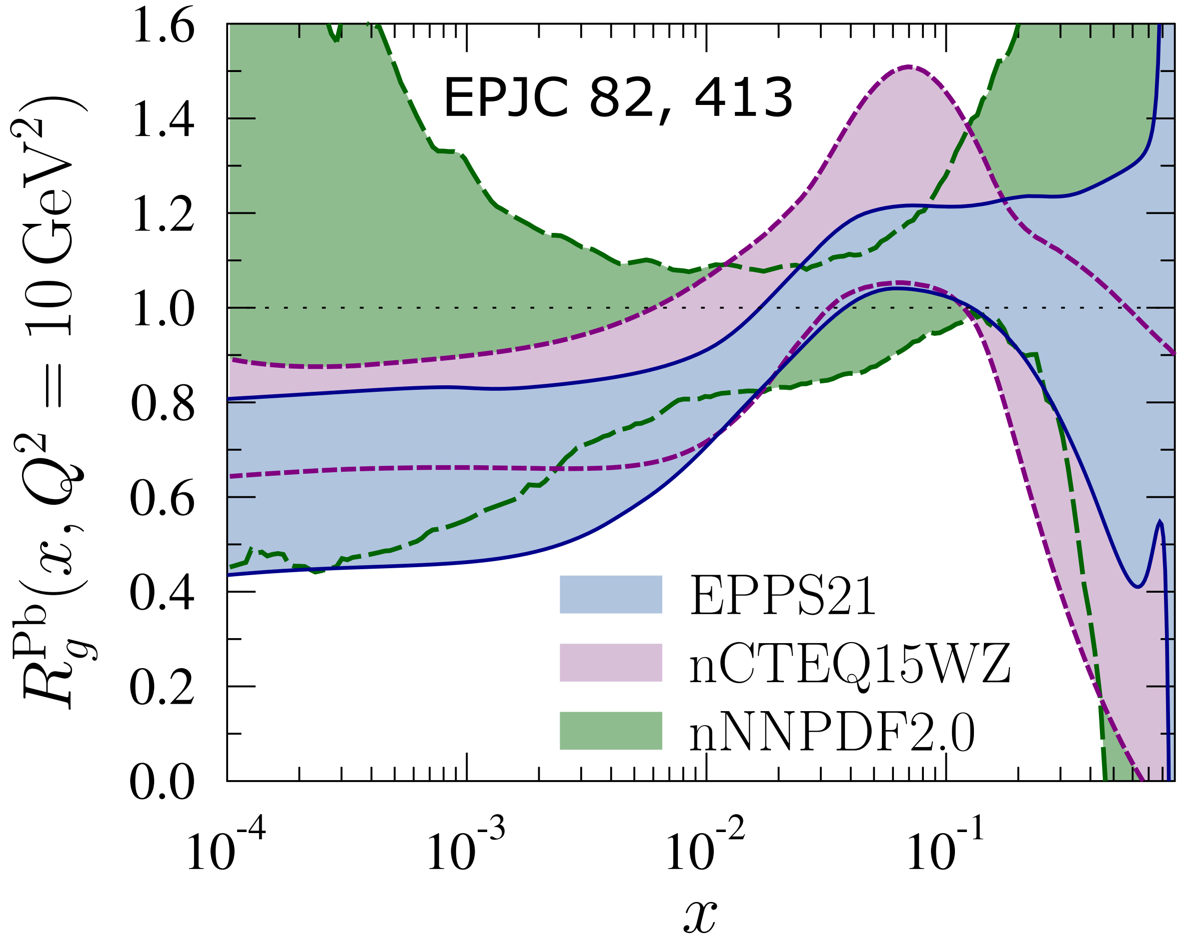


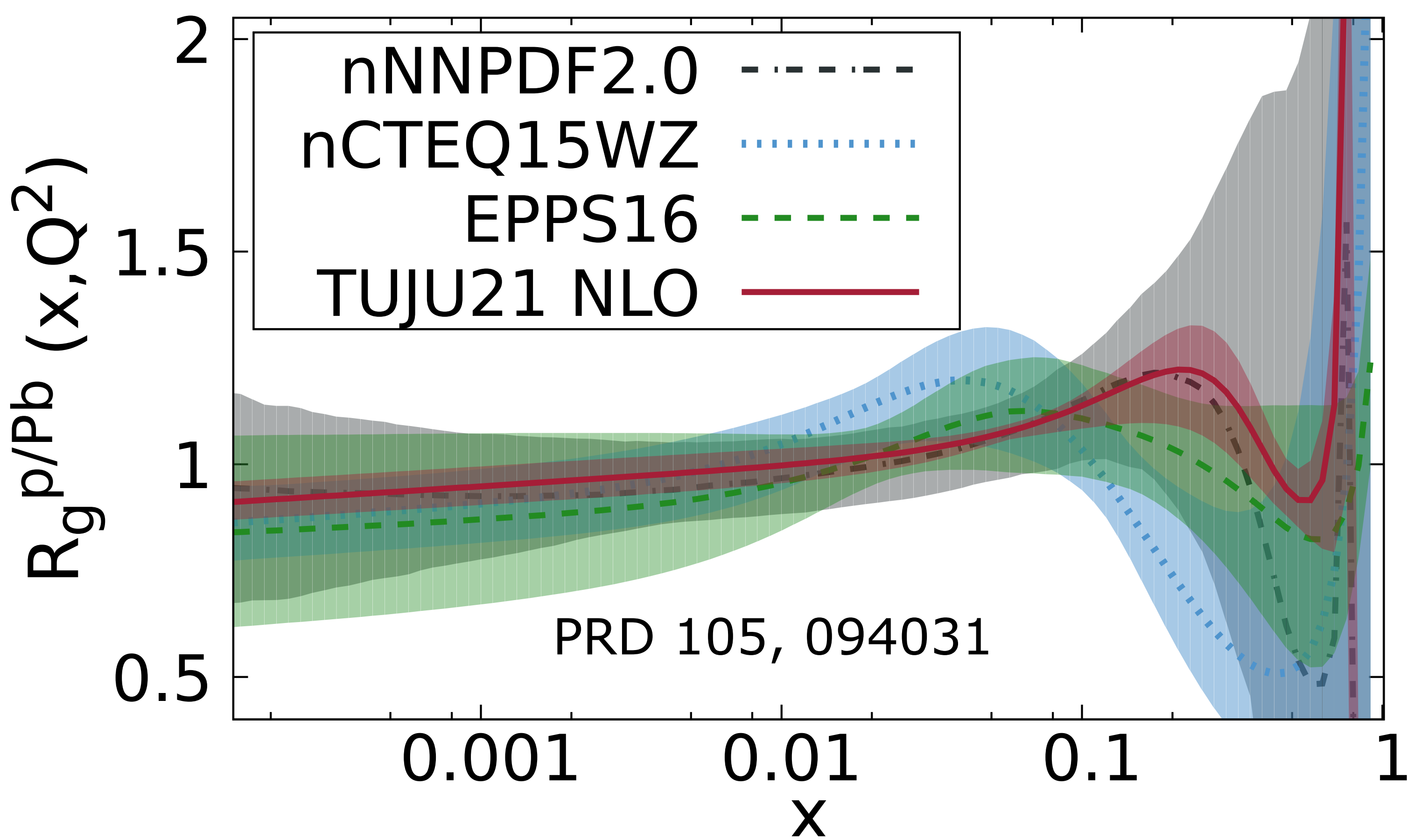
2.5
2
1.5
1
0.5
$R_g^{p/Pb}(x,Q^2)$
nCTEQ15
EPPS16
DSSZ
TUJU19 NLO
Q²=100 GeV²
PRD100 (2019) no.9, 096015
0.001
0.01
0.1
1
x

NLO: gluon

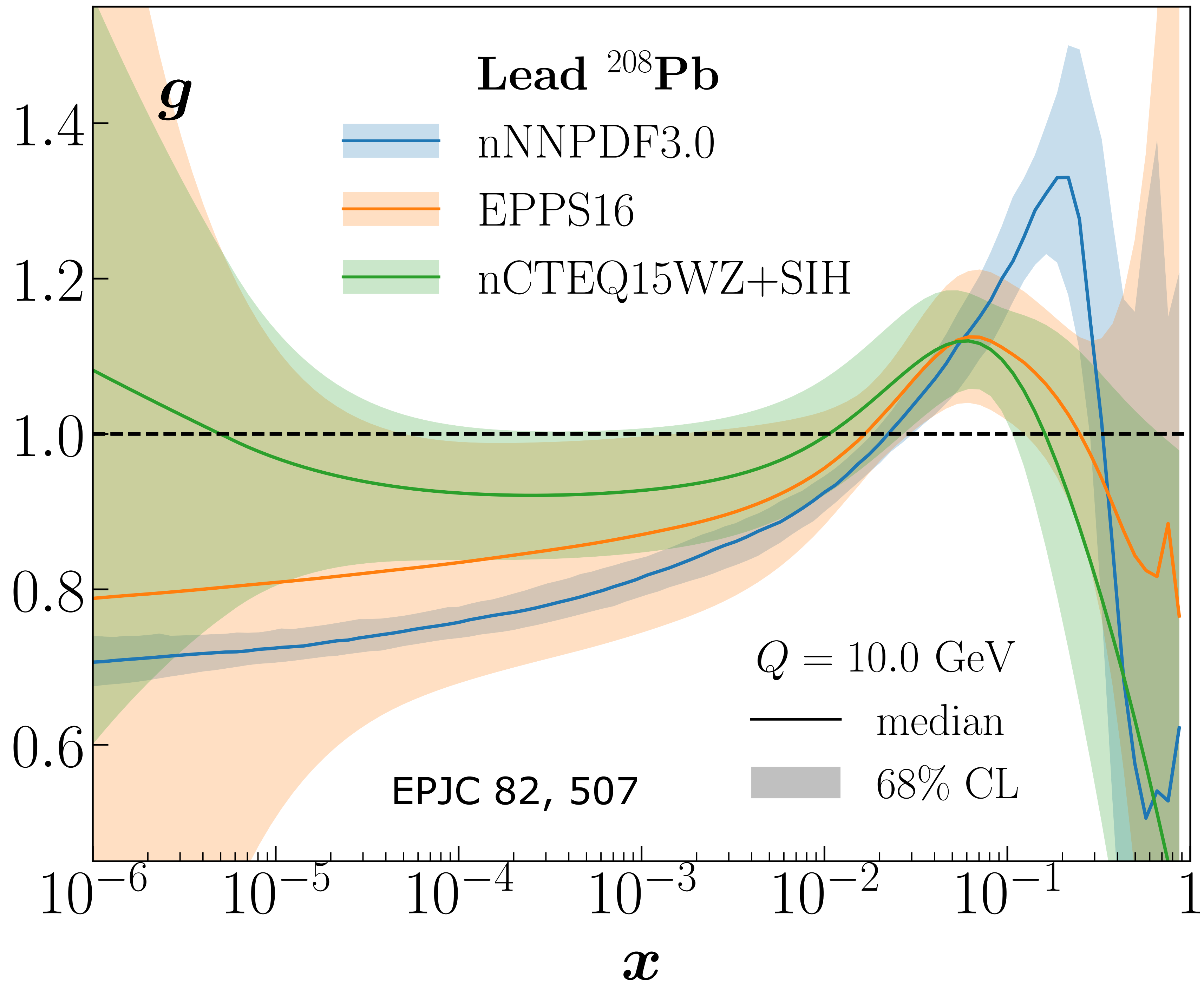

5
4
3
2
1
0
$xg^{\mathrm{Pb}}(x)$
10^{-3}
10^{-2}
10^{-1}
10^{0}
x
nCTEQ15
Norm0
Norm2
Norm3
$Q = 2$ GeV
EPJC 80, 968

NLO: gluon


1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$R_g^{Pb}(x, Q^2 = 10\,\mathrm{GeV}^2)$
EPJC 82, 413
EPPS21
nCTEQ15WZ
nNNPDF2.0
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x


2
1.5
1
0.5
$R_g^{p/Pb}(x,Q^2)$
nNNPDF2.0
nCTEQ15WZ
EPPS16
TUJU21 NLO
PRD 105, 094031
0.001
0.01
0.1
1
x

NLO: gluon


g
Lead ^{208}Pb
nNNPDF3.0
EPPS16
nCTEQ15WZ+SIH
Q = 10.0 GeV
median
68% CL
EPJC 82, 507
1.4
1.2
1.0
0.8
0.6
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x

- NNLO is pretty similar to NLO in terms of comparisons.

In general:

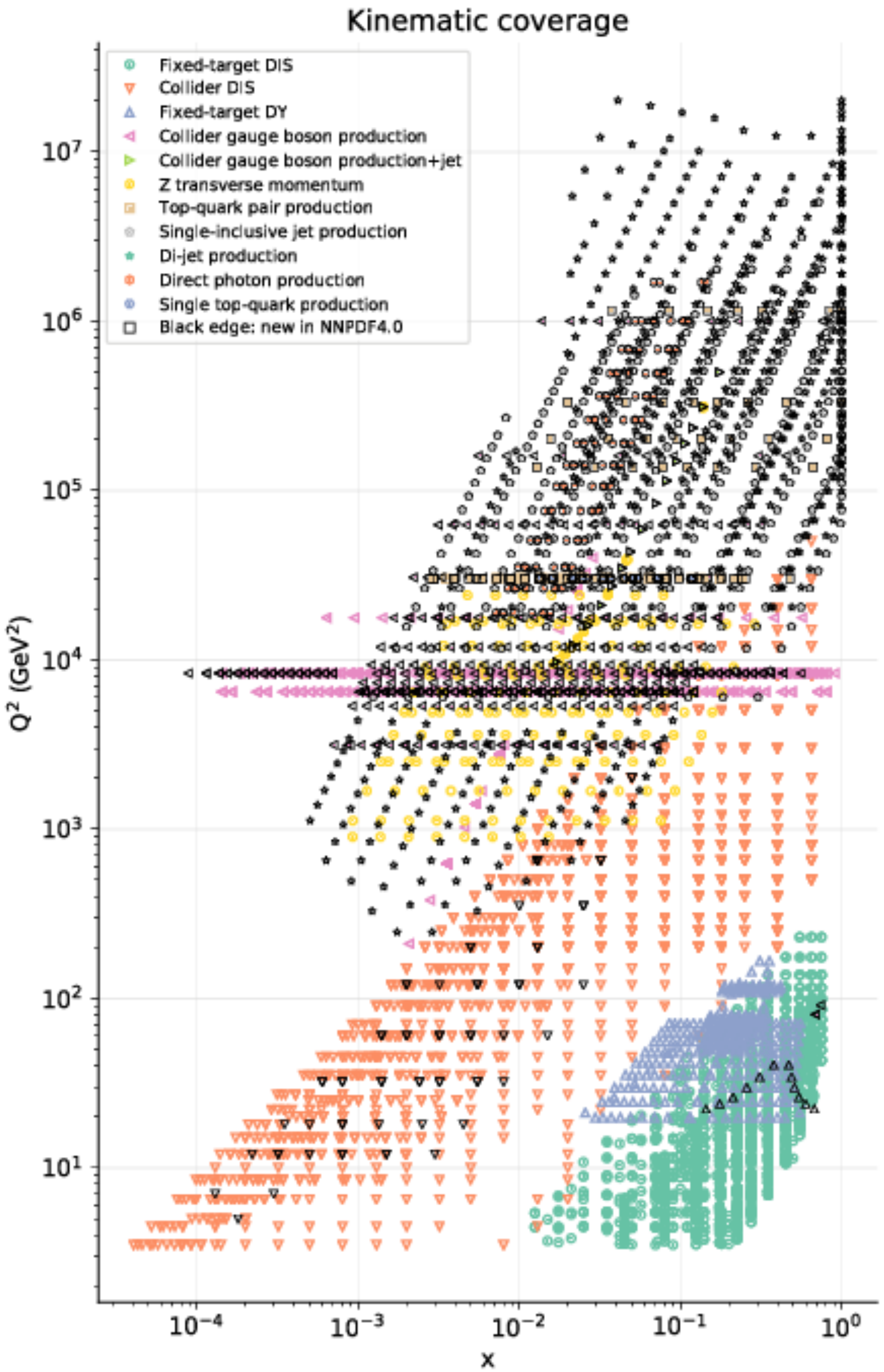
- The valence distributions are “well” constrained in the region where we have data.
- The non-strange sea densities are more of a challenge, but altogether they don’t look *that* bad.
- The strange quark lives up to its name.
- The gluon density is not in general well constrained. Except for the nNNPDF3.0 analysis.

Issues in nPDF extractions

- Things that could have been/can be done better with the data.
- Things that can be done better with the fit.

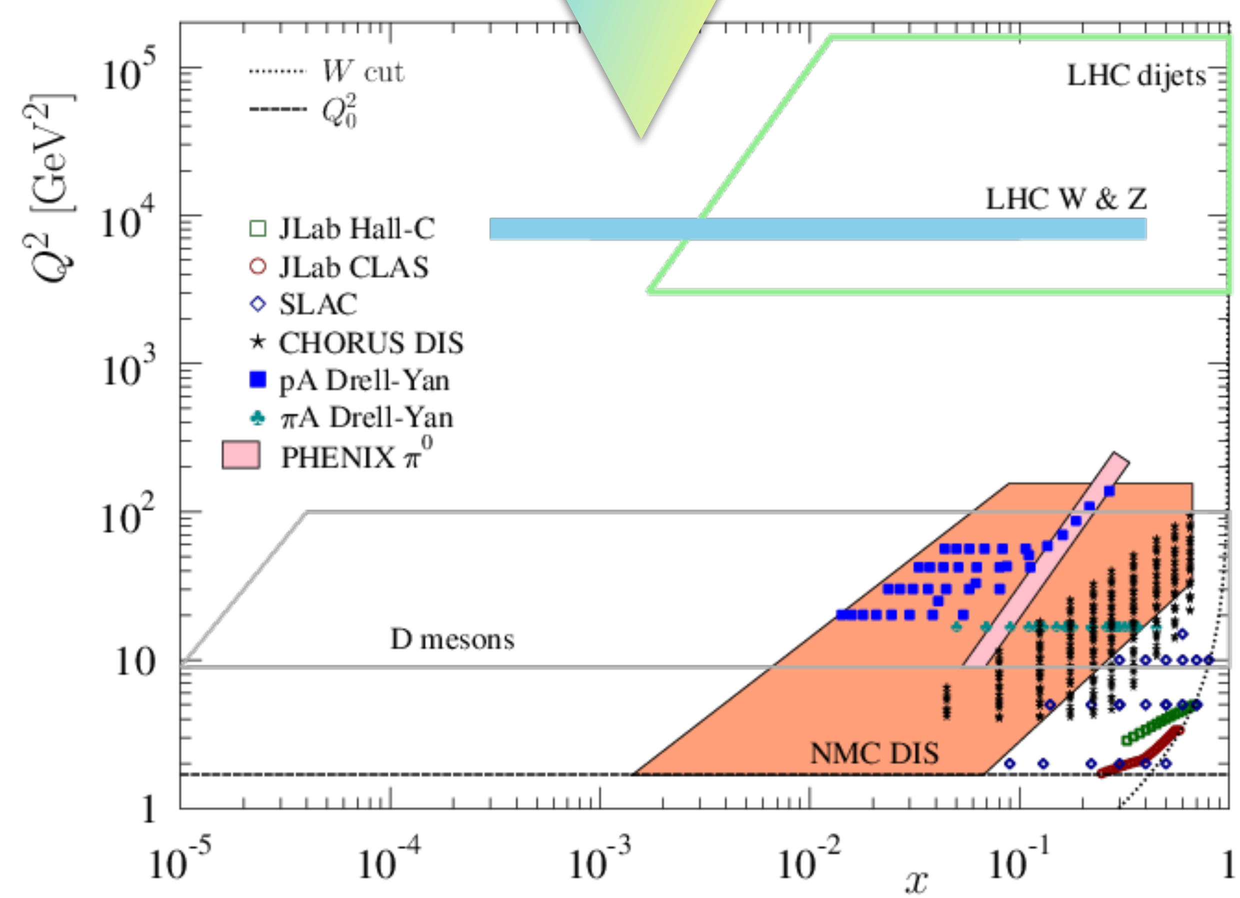
Issues in nPDF extractions

- 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 (2021) 4, 341	433	513	1264

one can basically 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 (2021) 4, 341	433	513	1264
nuclear case	2309	812	**0**

◉ How the data were/are published.

$$\frac{d^2\sigma}{dx dQ^2} \propto F_2 - \frac{y^2}{Y_+} F_L \equiv \sigma_{\text{reduced}}$$

computable/what the measurement can be turned into

- The quantity of data.

NC DIS data	Fixed target (FT)	FT deuterium	Collider
proton PDF fit e.g. EPJC 81 (2021) 4, 341	433	513	1264
nuclear case	2309	812	**0**

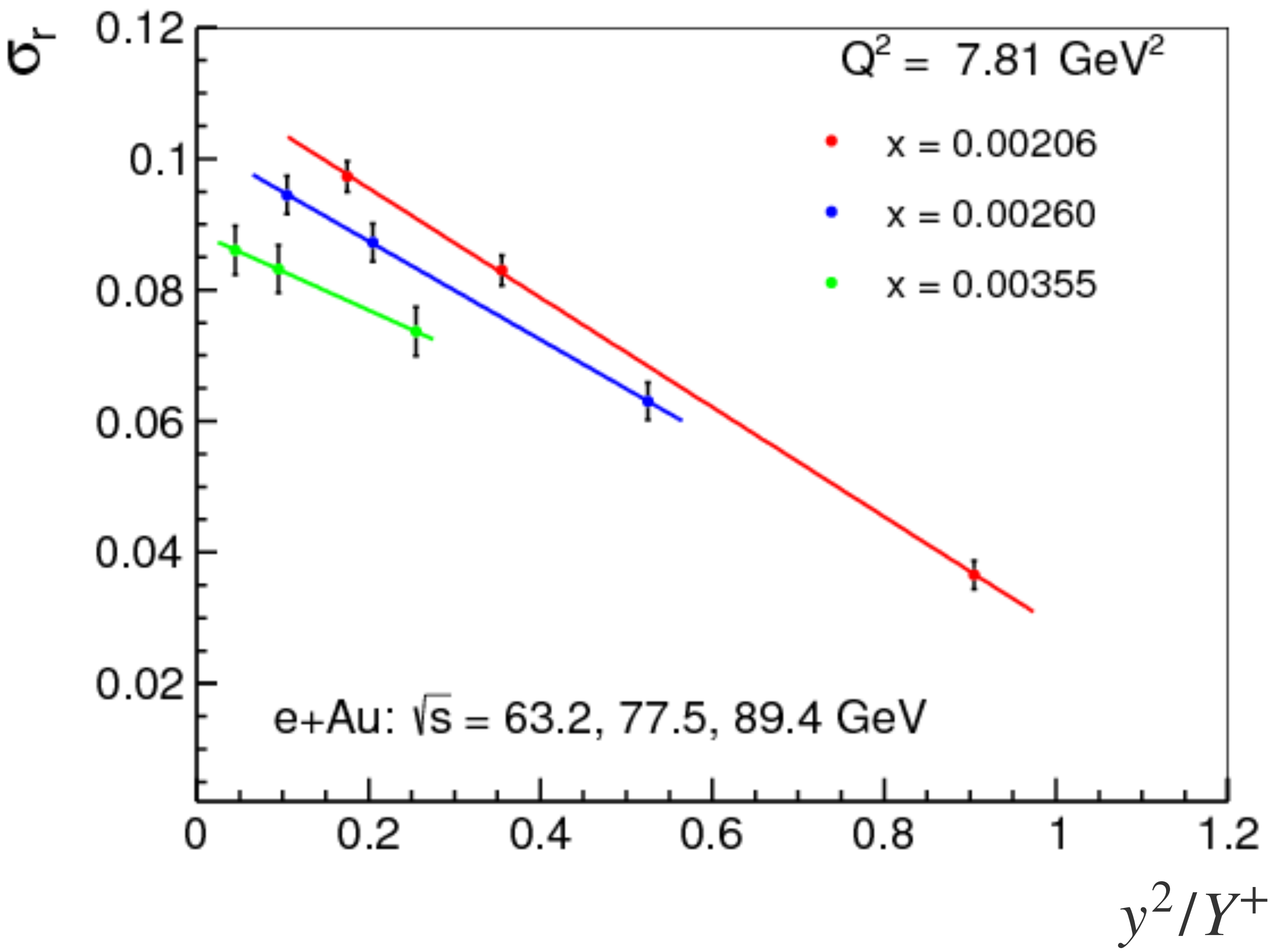
- How the data were/are published.

$$\frac{d^2\sigma}{dxdQ^2} \propto F_2 - \frac{y^2}{Y_+} F_L \equiv \sigma_{\text{reduced}}$$

computable/must be extracted
from the measurement

- To extract the structure functions one does a Rosenbluth separation: plot as a function of y^2/Y_+, the slope is $-F_L$.

Phys.Rev.D 96 (2017) 11, 114005

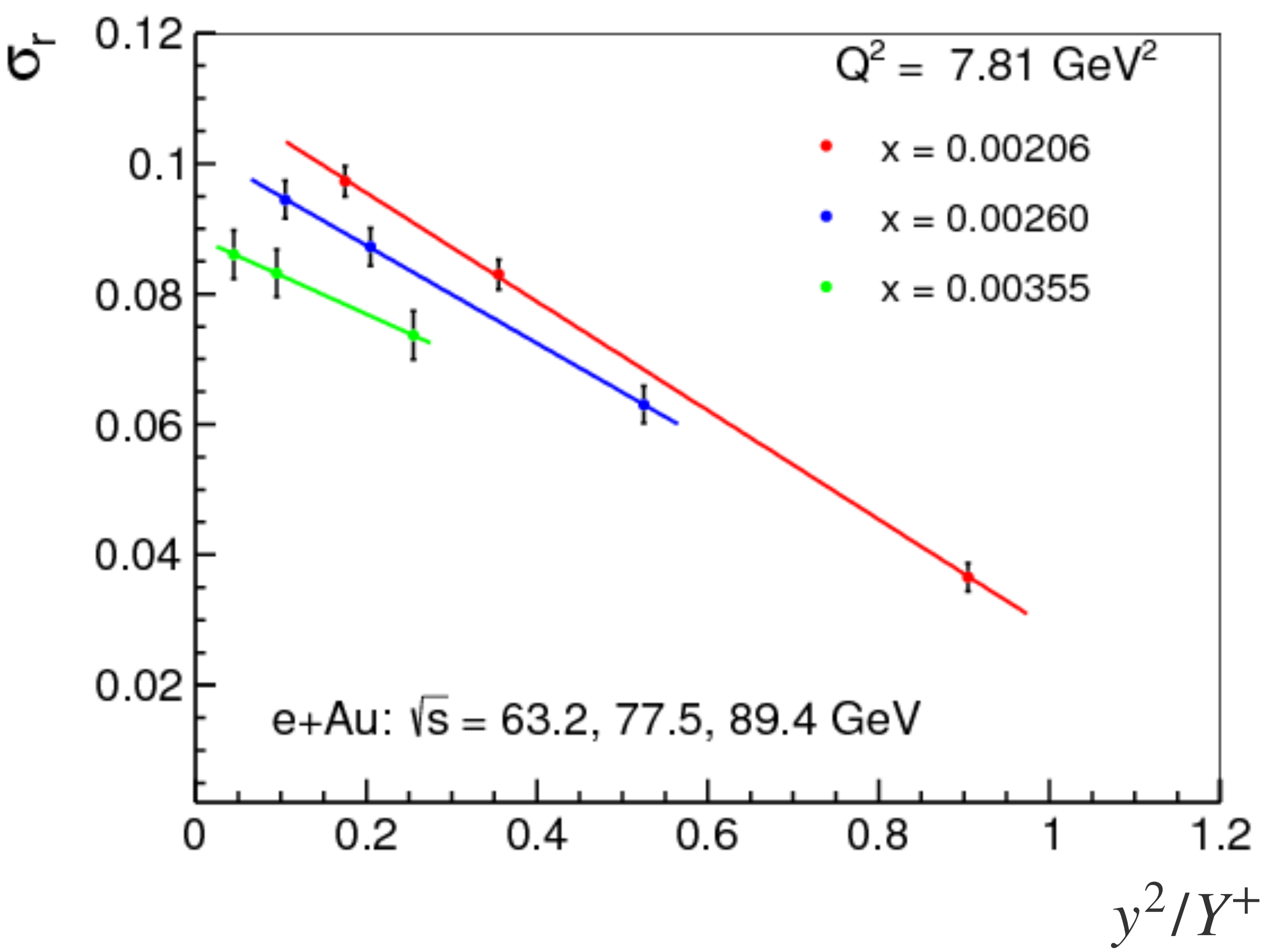


$$y \approx Q^2/sx$$

$$Y_+ = 1 + (1-y)^2$$

- To extract the structure functions one does a Rosenbluth separation: plot as a function of y^2/Y_+, the slope is $-F_L$.

Phys.Rev.D 96 (2017) 11, 114005



- To vary y^2, we must measure for different $\sqrt{s}$.

- In nuclei, F_2 was determined from a parametrisation of $R = F_L/F_2$. Or $R = 0$. Or $R = 0.2$. **Take your pick**.

- ~ 60% of the NC DIS data are F_2, F_L, R, so much information is lost.
- ~ 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.

◉ The type of data available: charged current DIS.

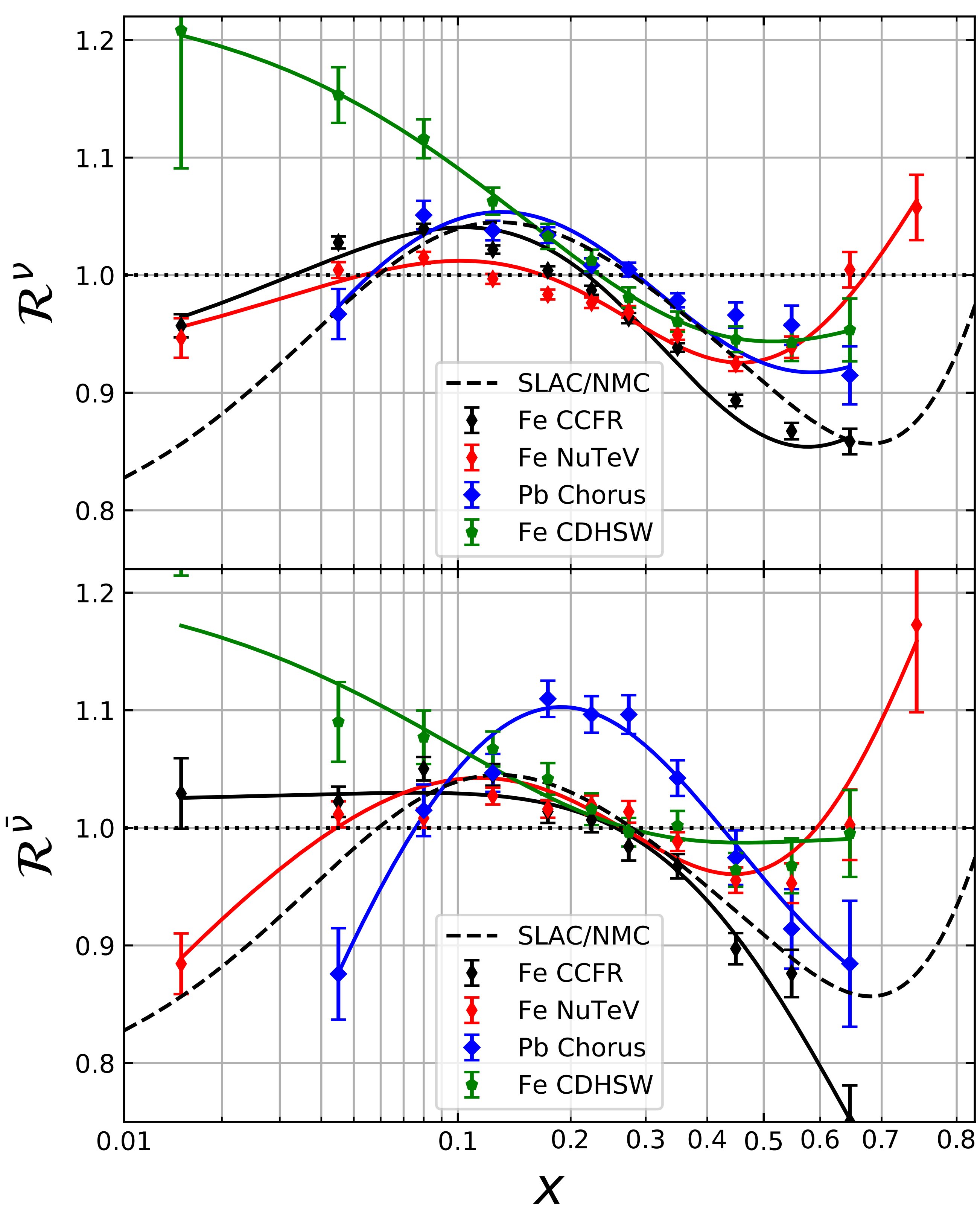
nCTEQ, arXiv:2204.13157

- ◉ Basically 4 experiments: CCFR, NuTeV, CDHSW, and Chorus.

- ◉ There are tensions among the different neutrino experiments if we try to fit the cross-sections.

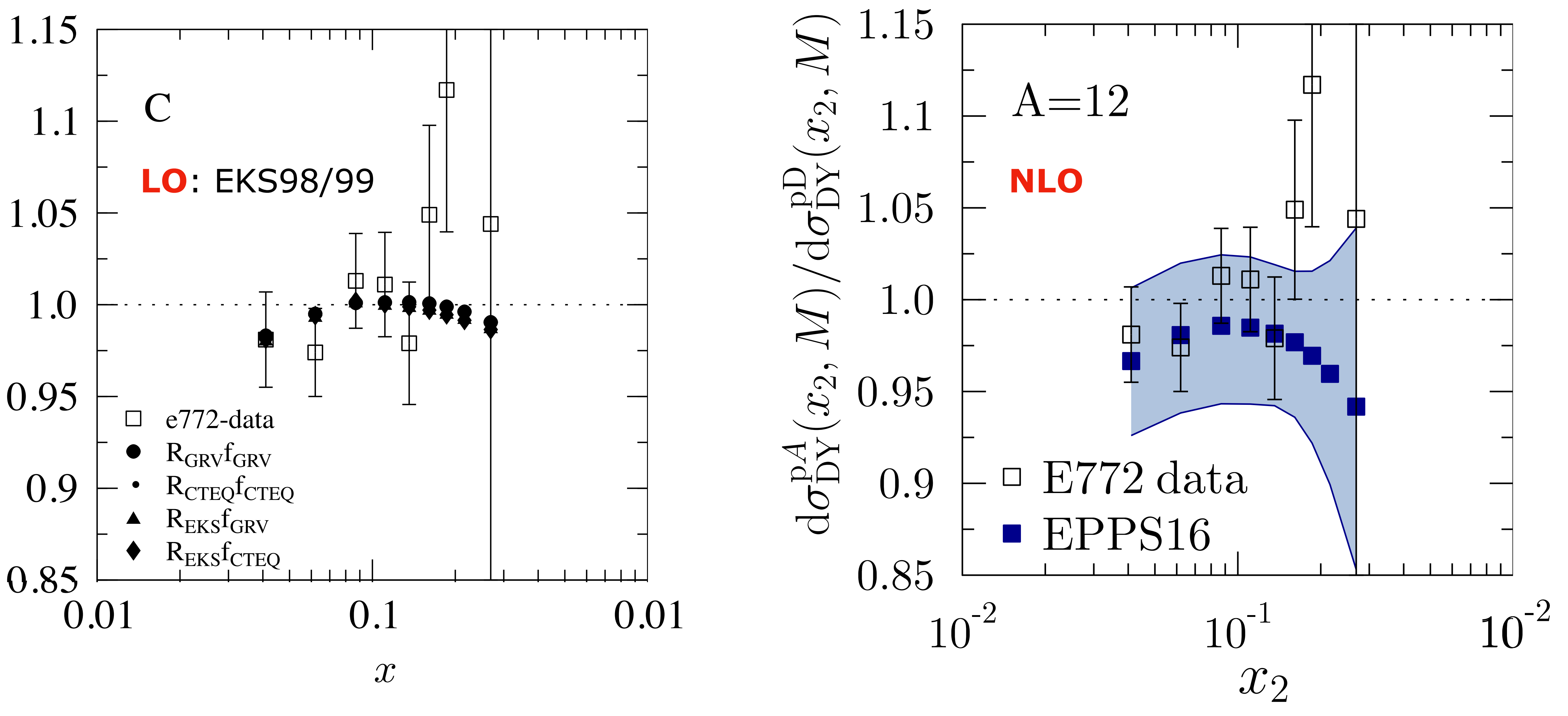
- ◉ No problem to accommodate the structure functions in a global fit, nor with Chorus cross-sections.

Could NOMAD solve this?



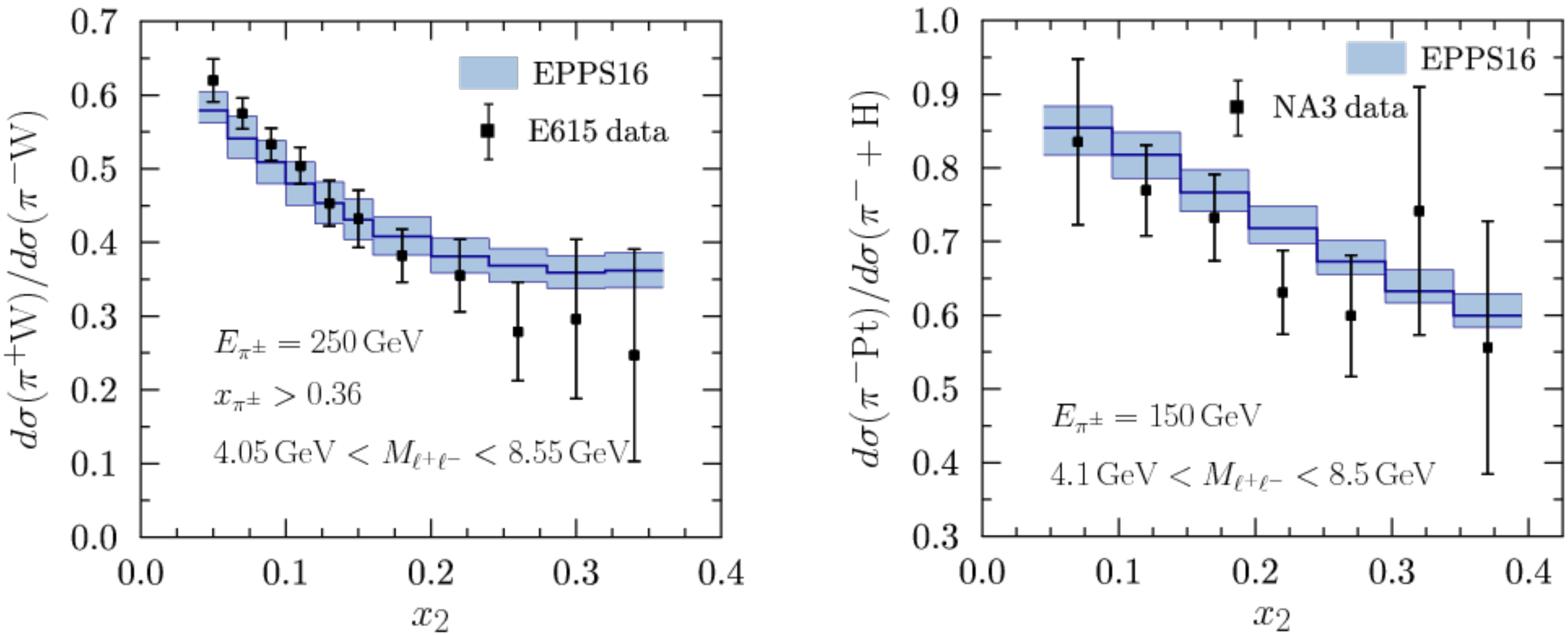
- The type of data available: Drell-Yan.

If we don't consider the deuterium DY data, older fits included only 92 points, given as ratios to $p+d$.



Recently, “new” Drell-Yan data has started to be considered. 28 points from $\pi^{\pm} + W$, and $\pi^{-} + Pt$

EPJ C77 (2017) no.3, 163

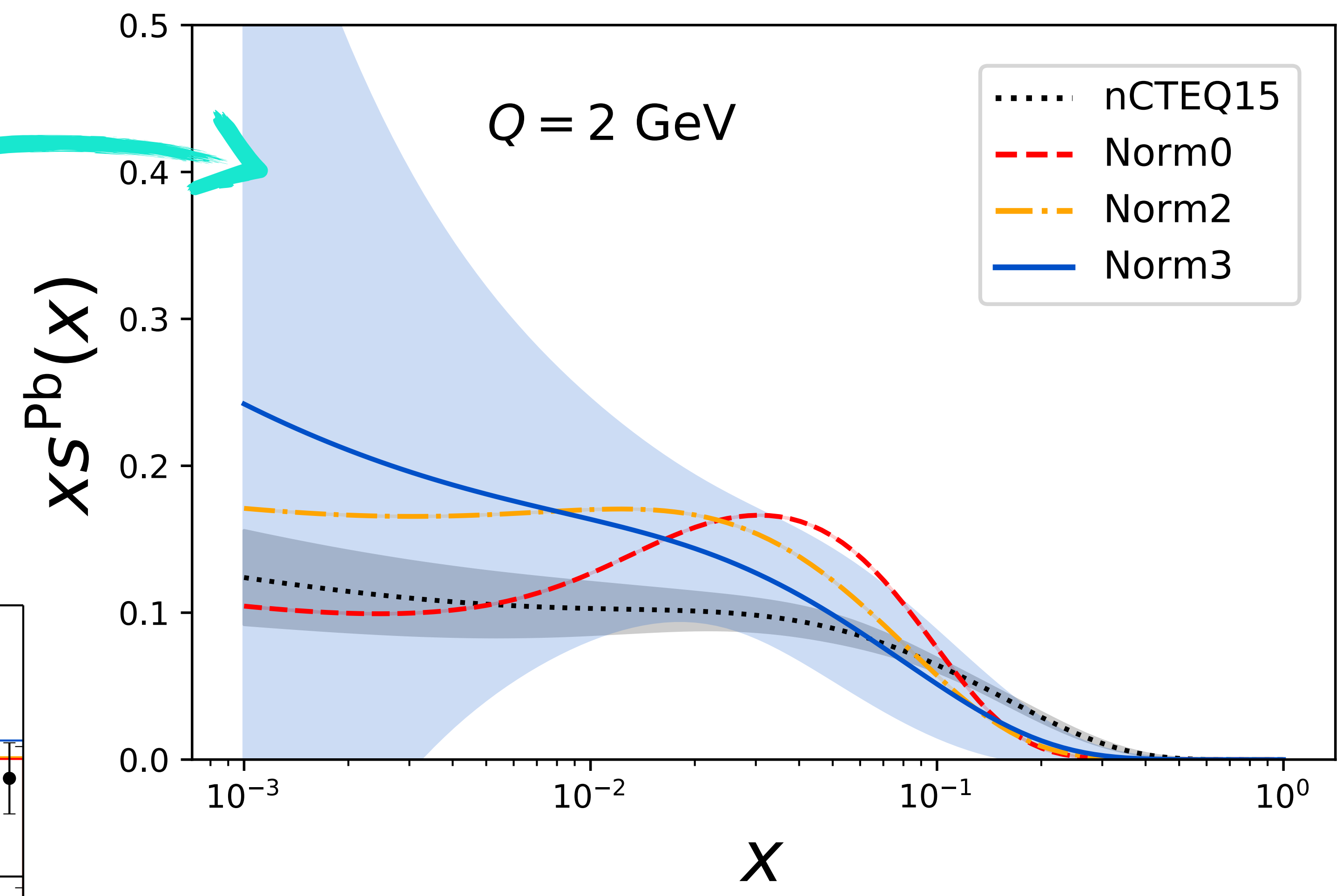


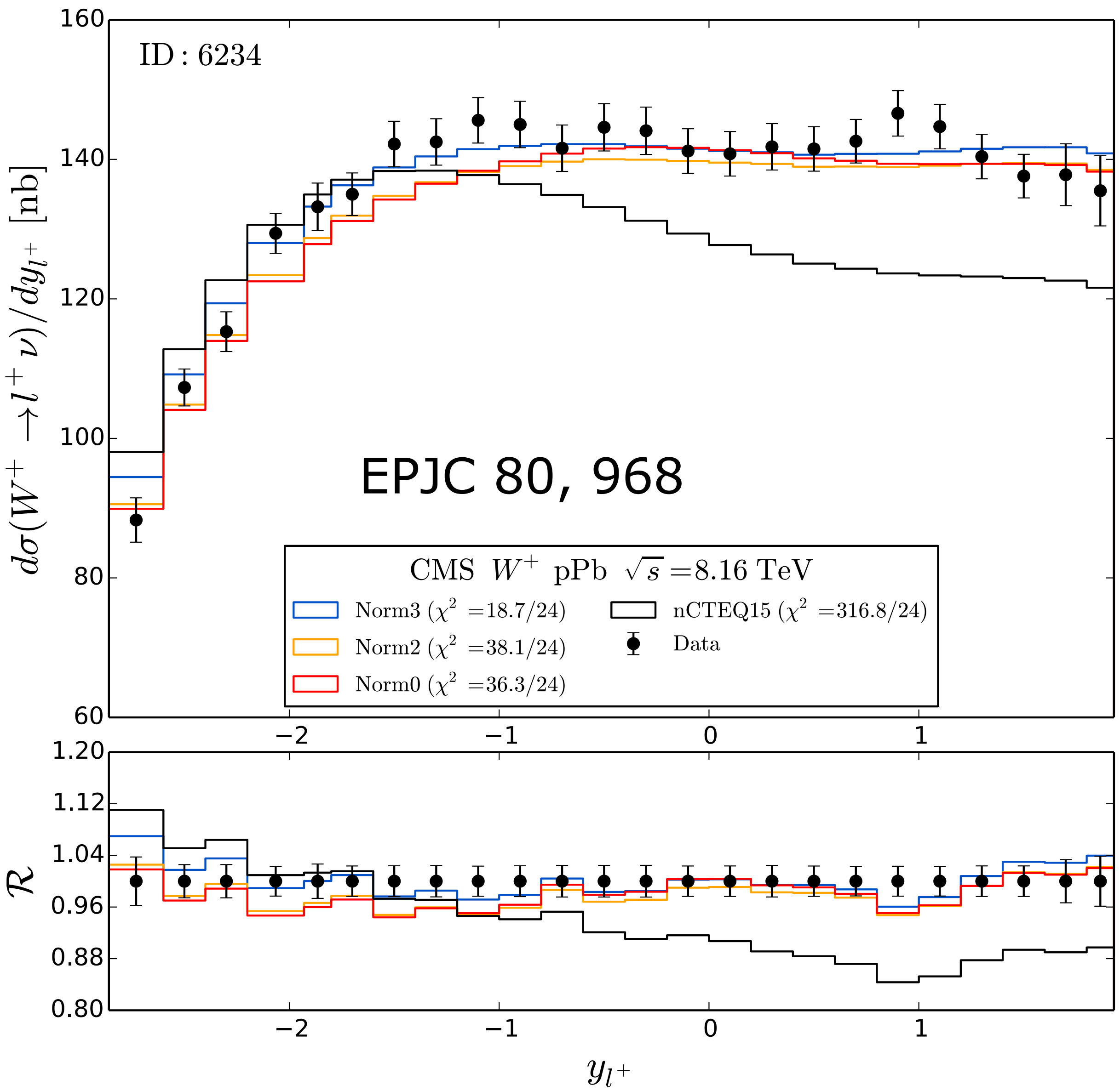
- Pt is a novel nucleus for nPDFs.

PL104B (**1981**) 335, PLB193 (**1987**) 368, PRL63 (**1989**) 356.

LHC W data are more useful:

Is there a problem with the normalisation?





Norm 0: no normalisation parameter.

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

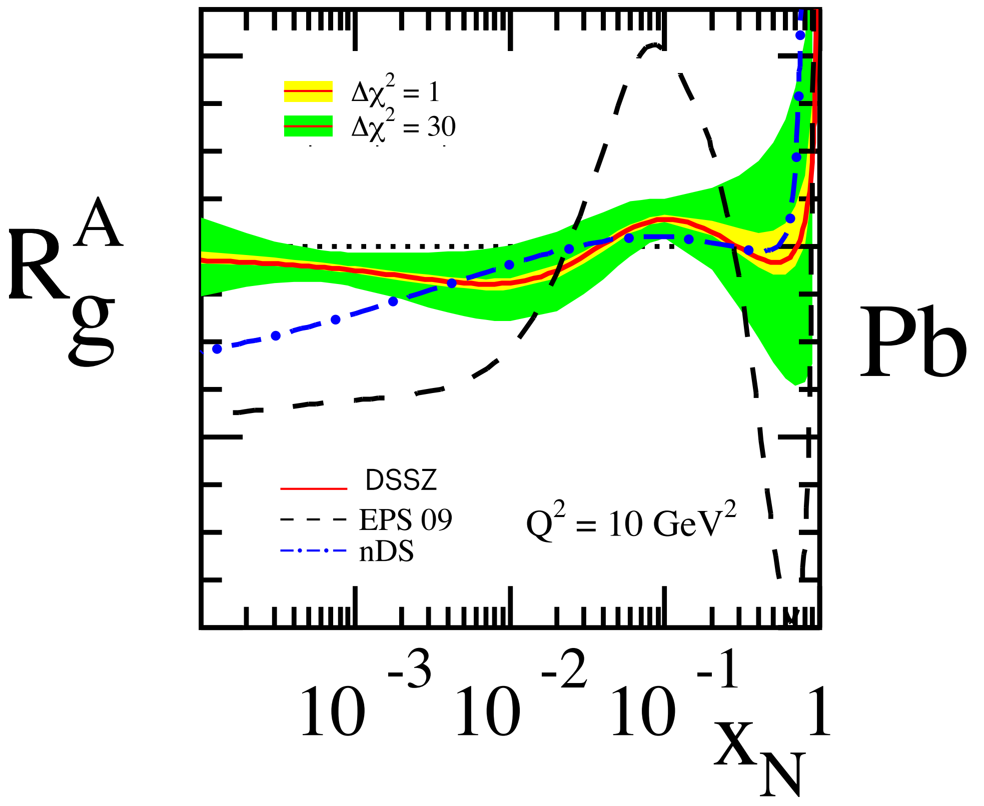
Norm 3: normalisation parameters for CMS and ATLAS Run I, and CMS Run II.

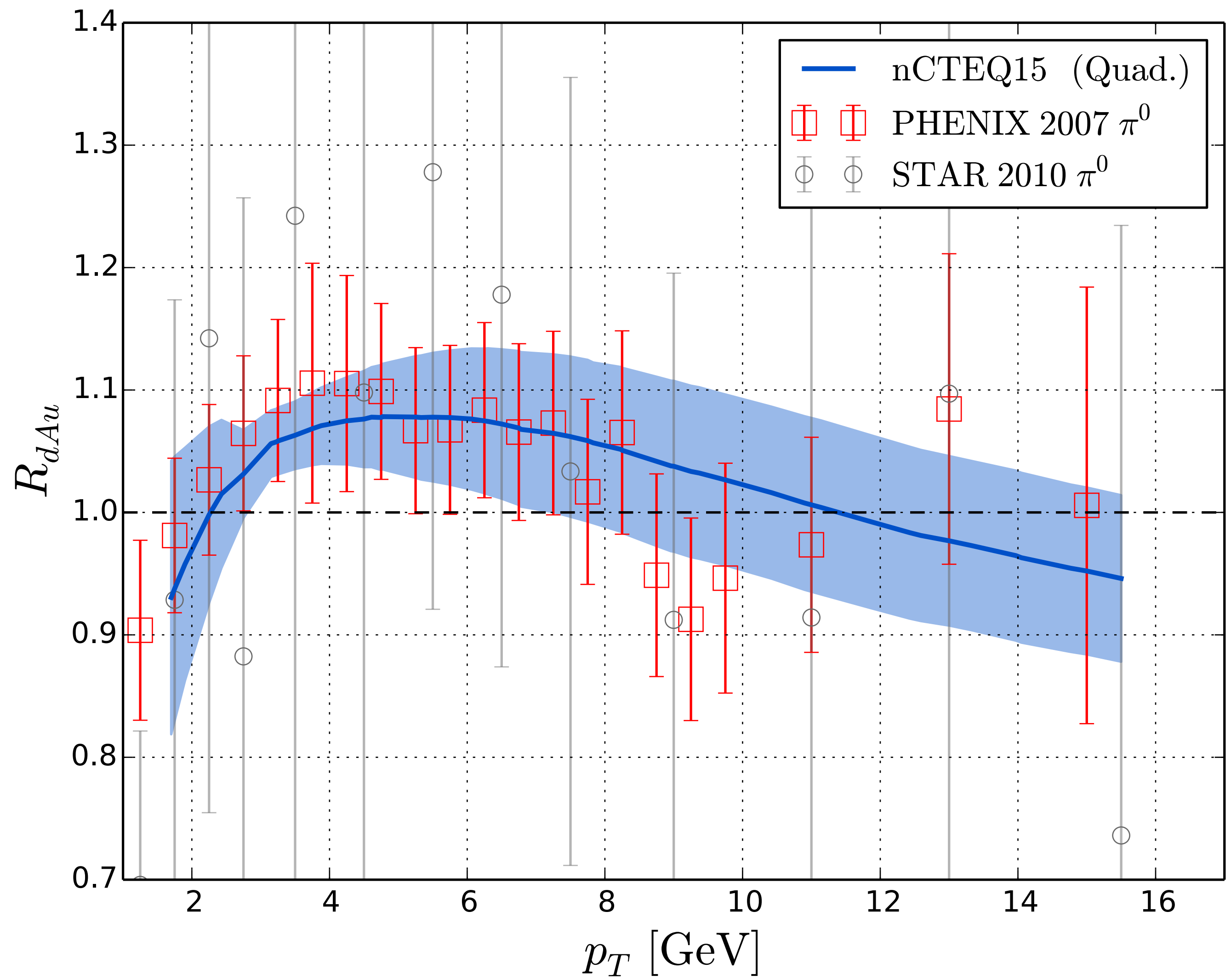
- The type of data available: single inclusive hadron (SIH) production.

PRD85 (2012), 074028

Remember this?

How can this be?





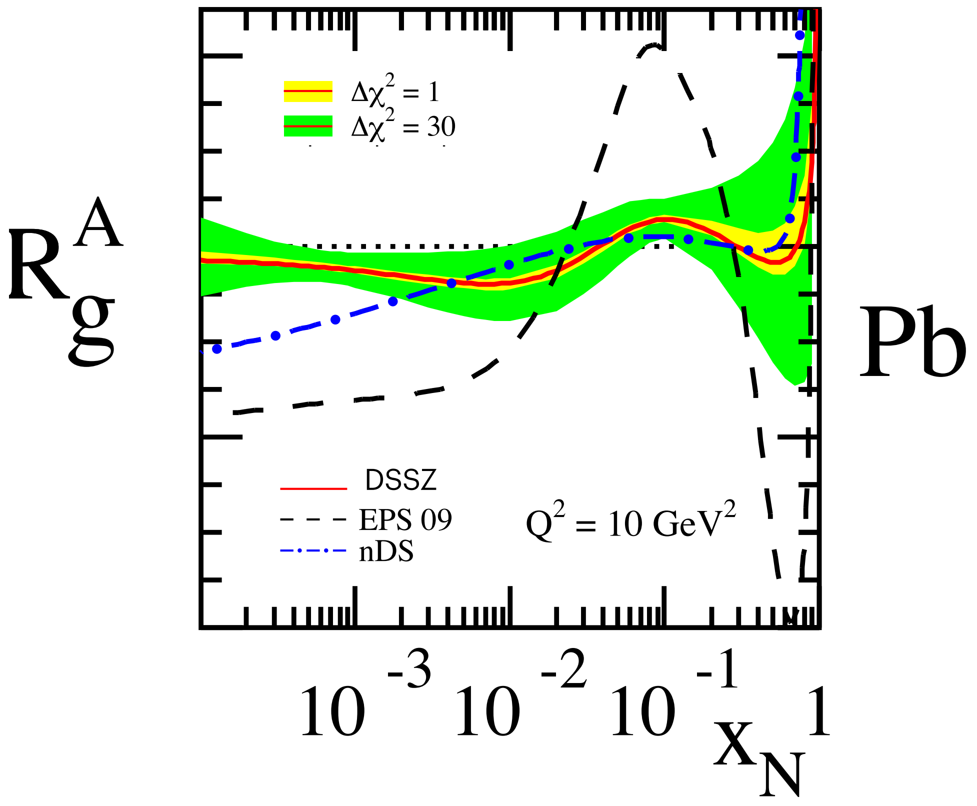
Not the most precise data I've ever seen (new data from PHENIX yet to be included).

PRD93 (2016) no.8, 085037

But it is also how we included the data in the fits.

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

PRD85 (2012), 074028



But it is also how we included the data in the fits.

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

- What about LHC data? Well, there is an extra price to pay:

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

published

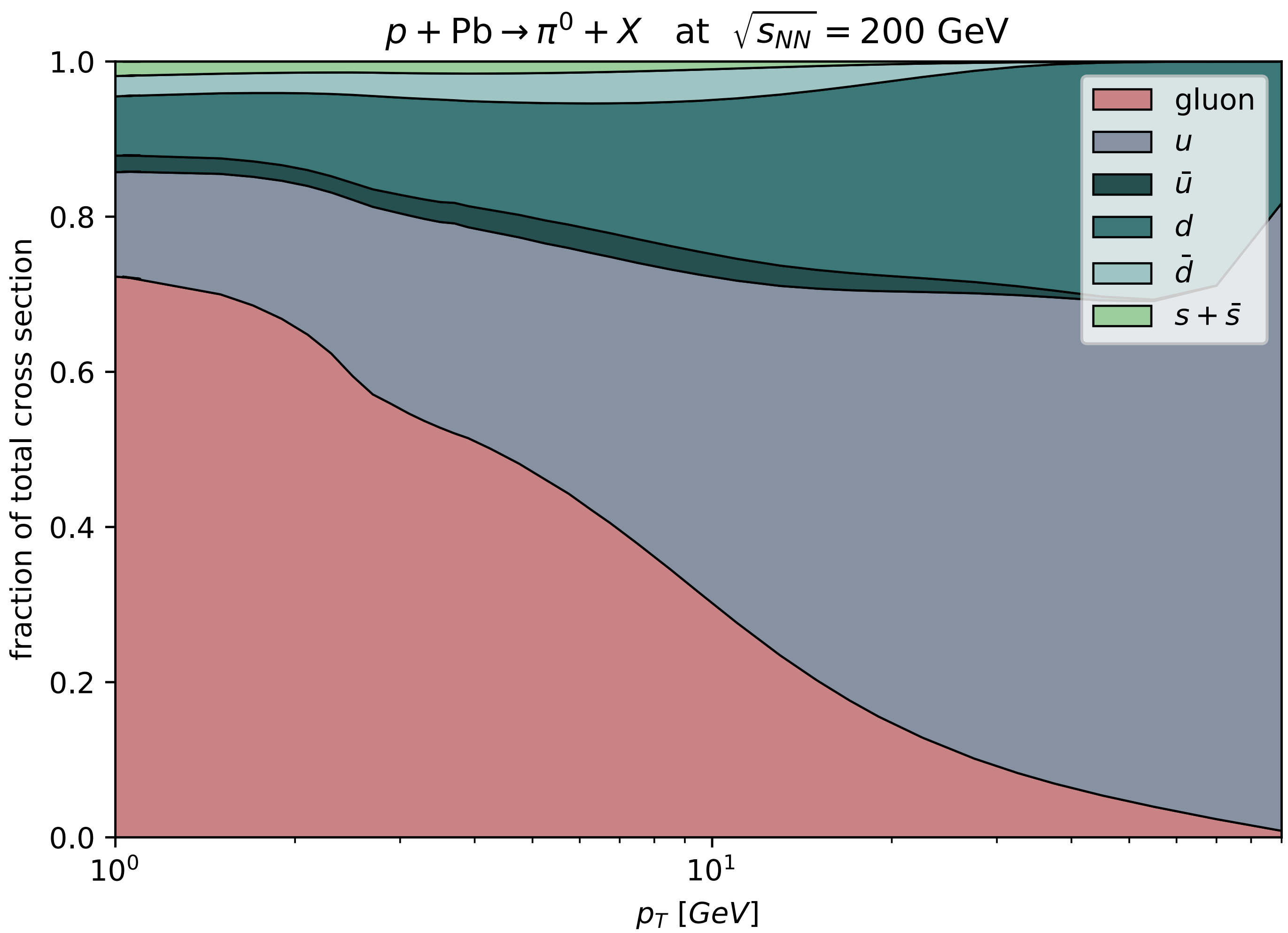
$$\frac{1}{N_{ev}}\frac{d^2N}{dydp_T} = \frac{1}{\sigma^{INEL}}\frac{d^2\sigma}{dydp_T}$$

missing part

can be calculated

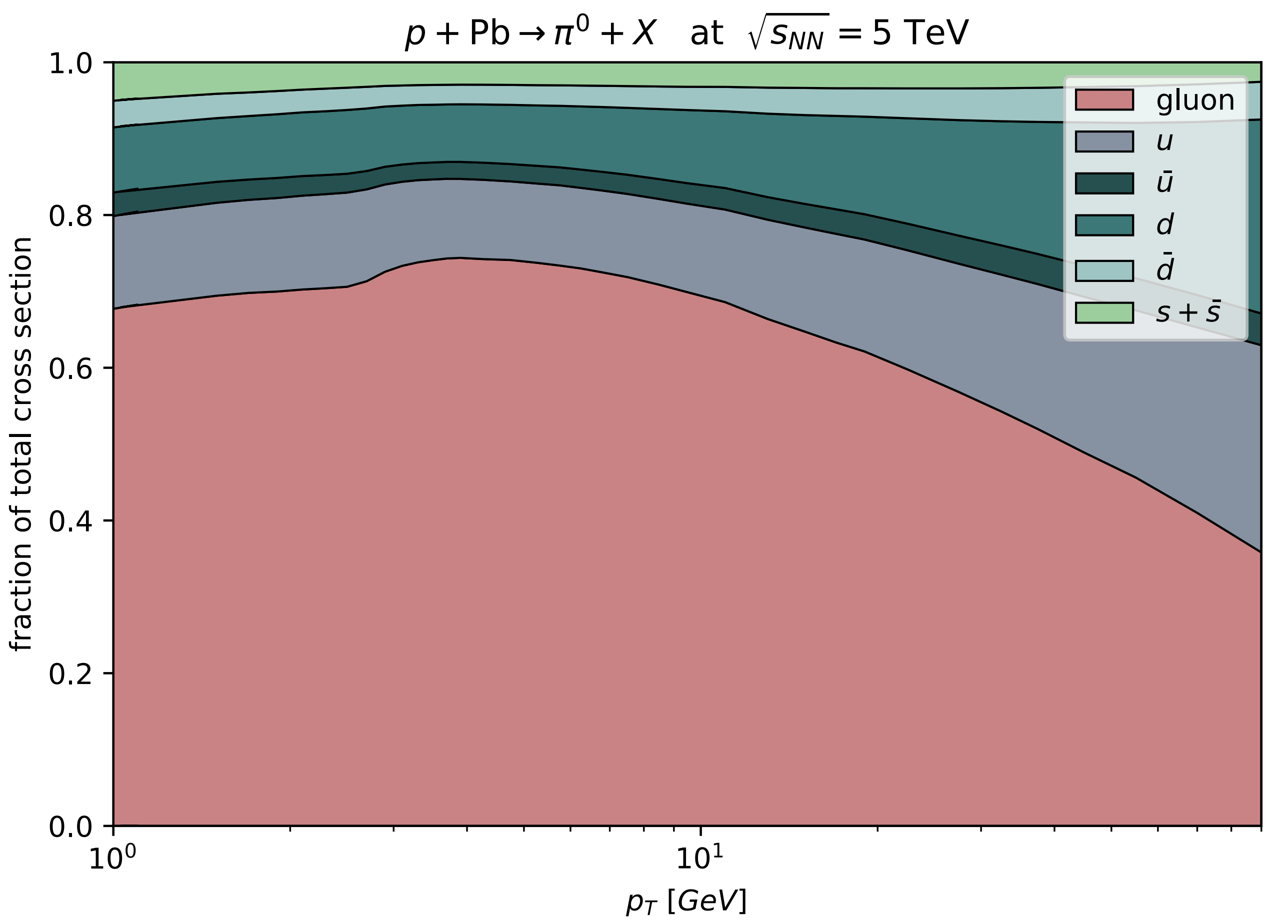
SIH can provide significant constraints over the gluon nPDF:

Phys.Rev.D 104 (2021) 094005

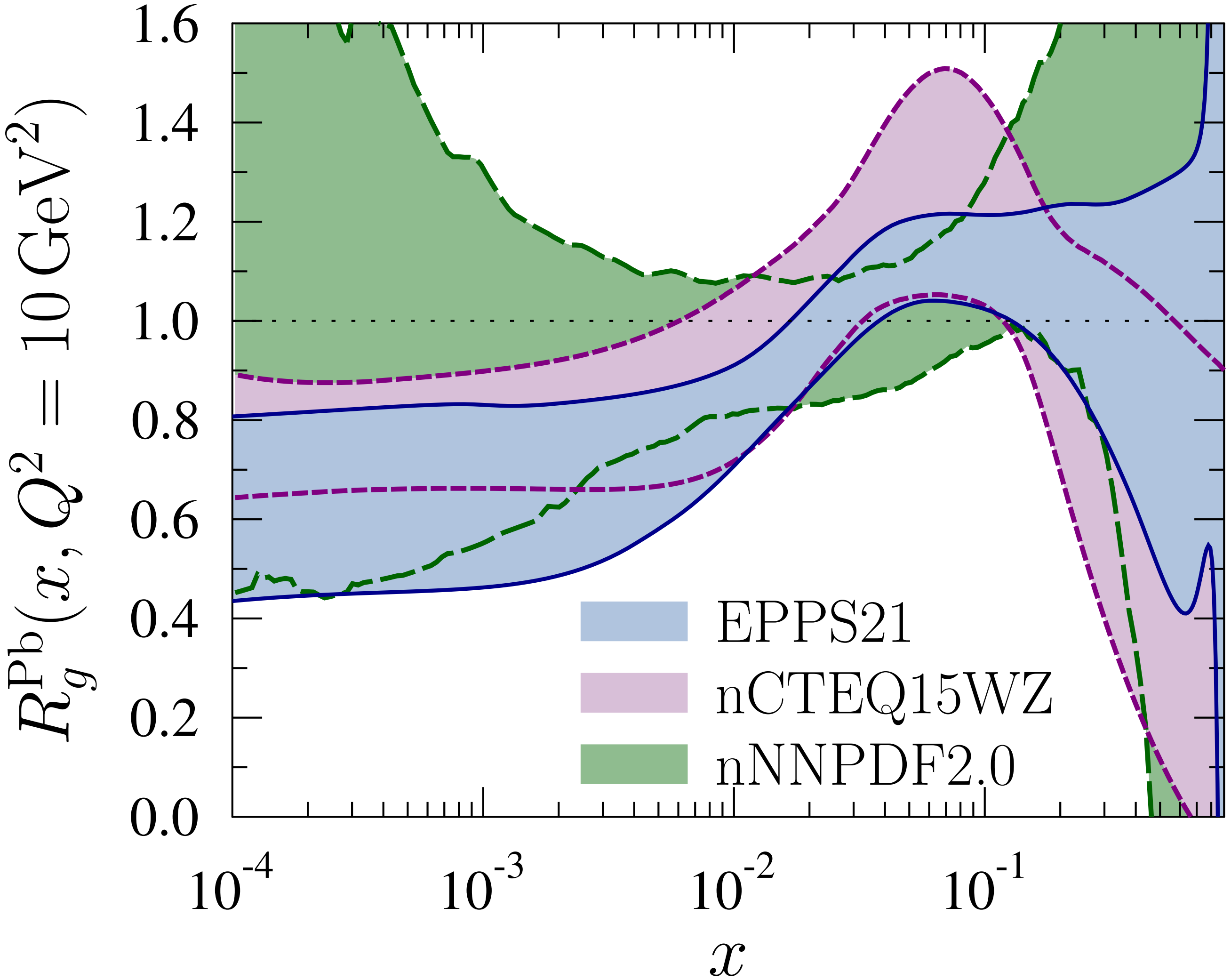


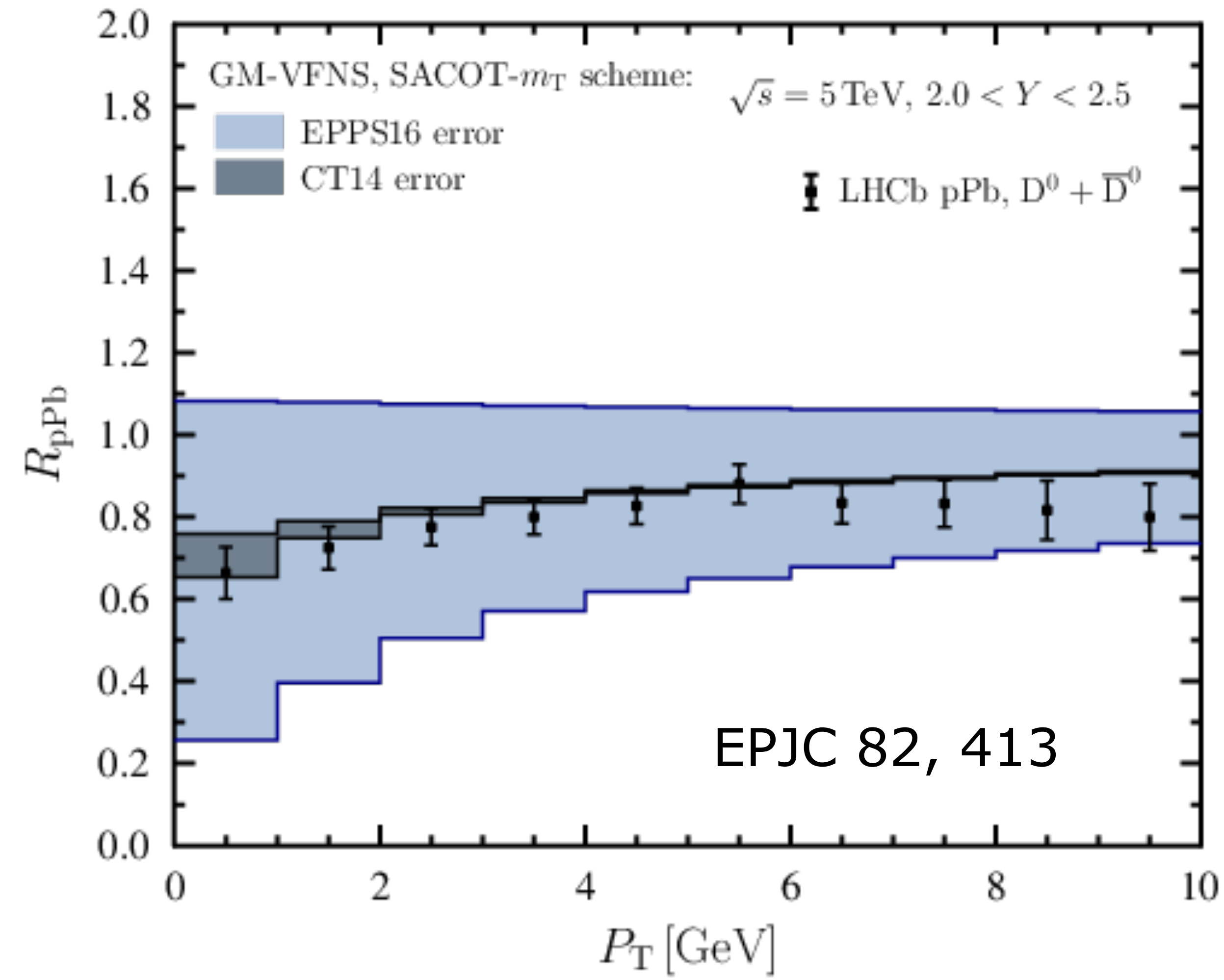
contribution of each initial state parton at RHIC

contribution of each initial state parton at the LHC



Another recently included data: D^0 production



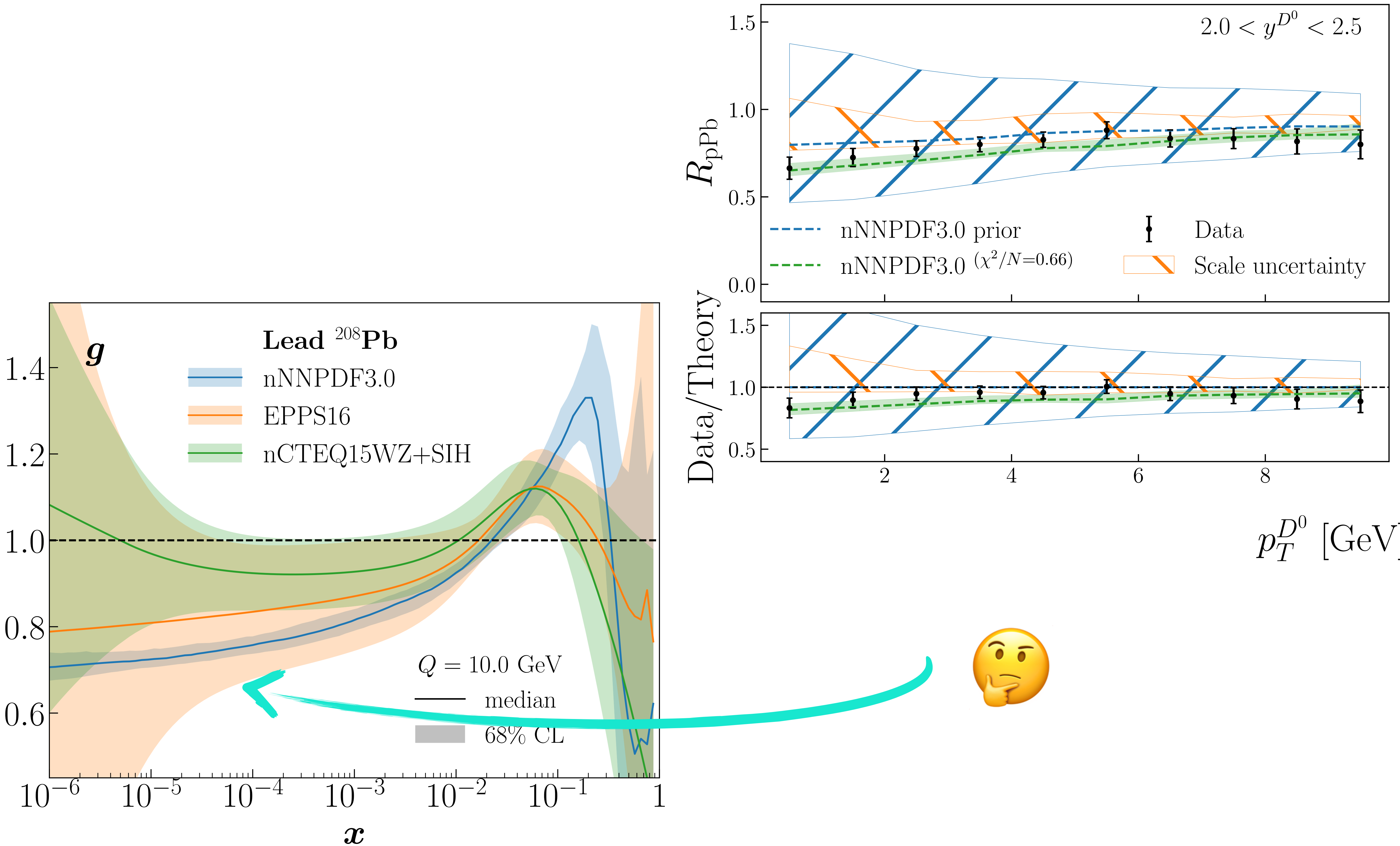


This depends on having the D^0 FF.

In this case, KKKS08, which comes from a limited amount of data.

Re-weighted in (not fitted).

Computation with Pythia8 (with tune).

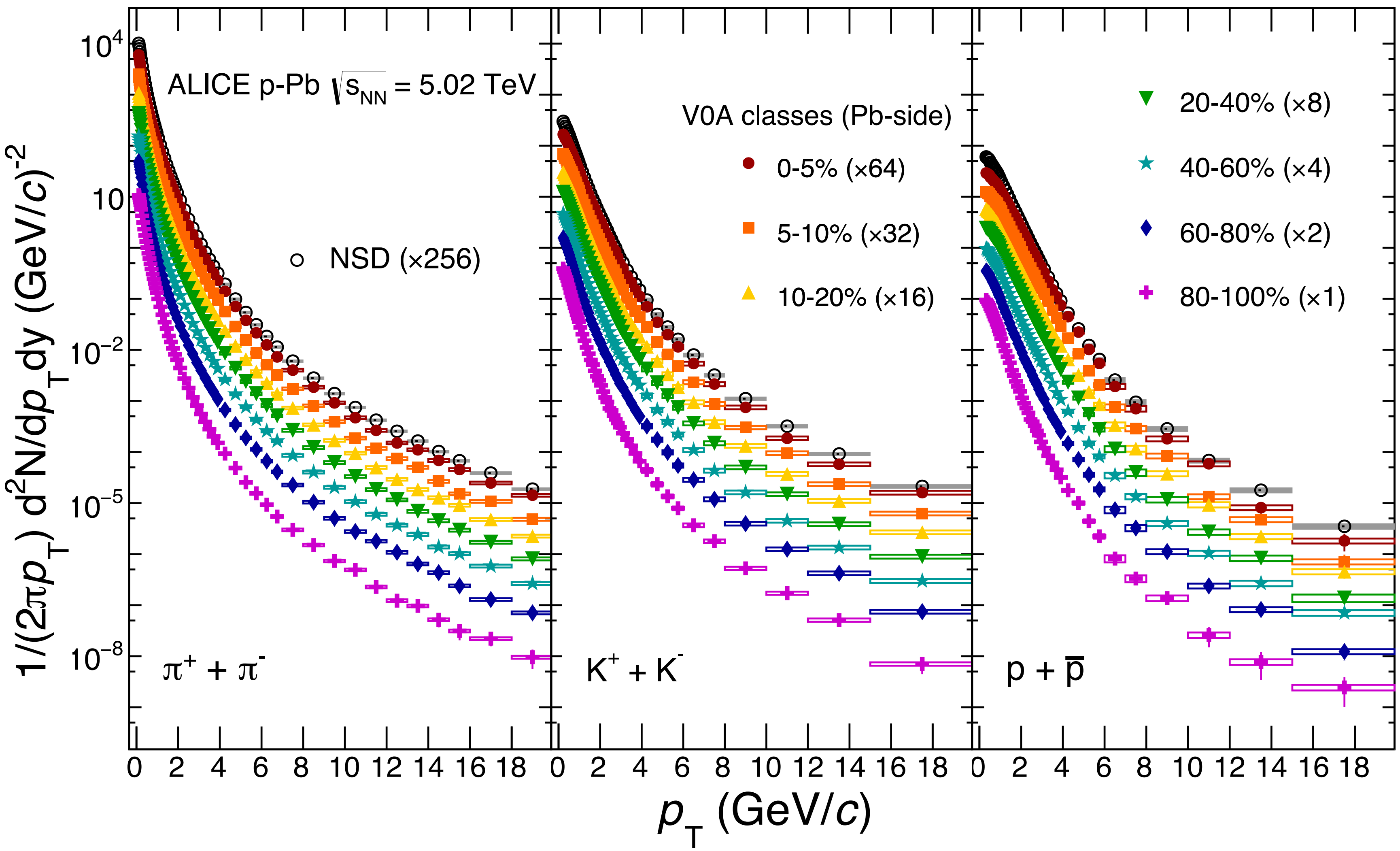


- The type of data: jets from ATLAS

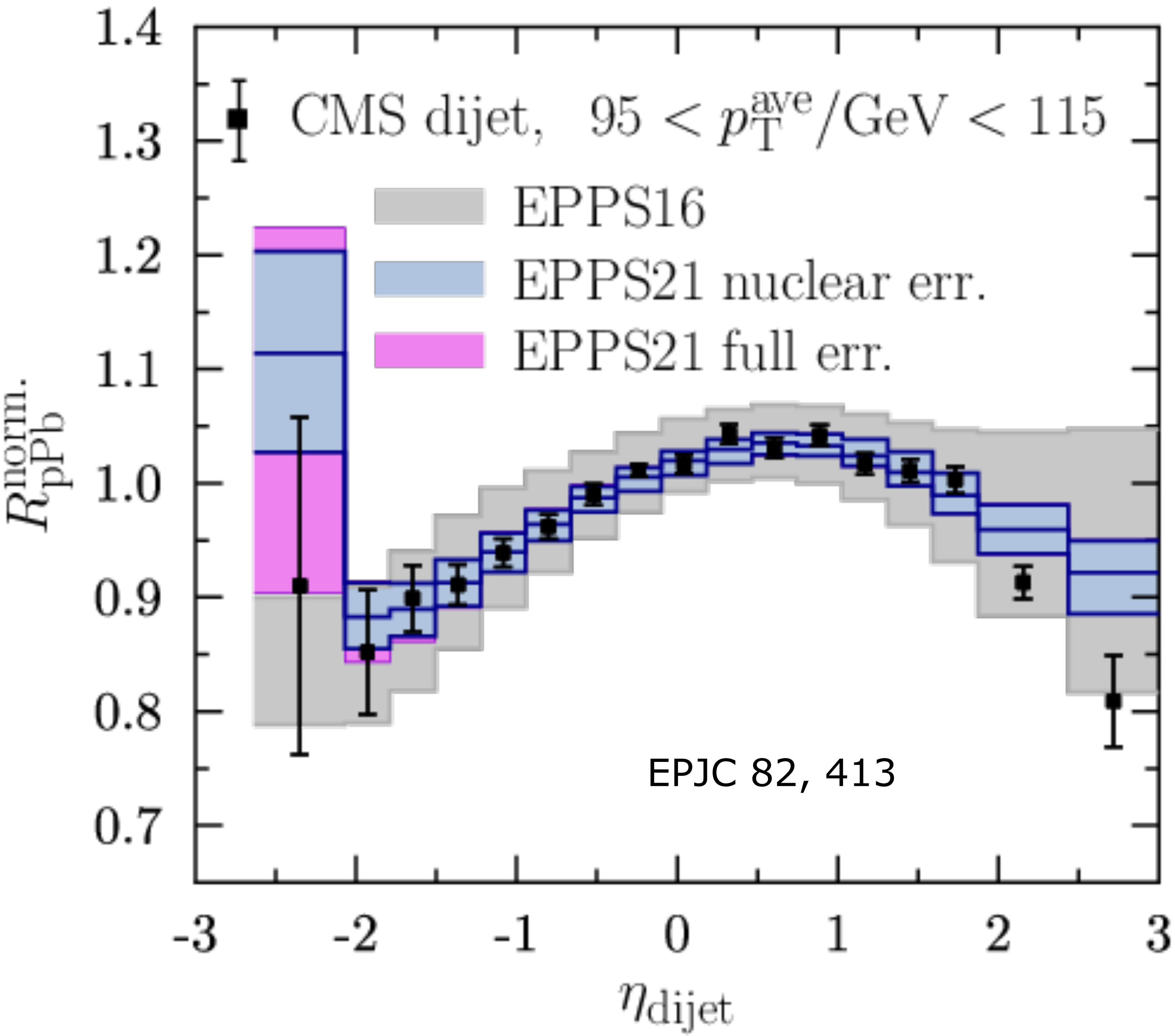
  - Compatible with no nuclear modification in most bins.

  - They are not min. bias. Remember, we can't compute centrality in pQCD!

  - The same goes for SIH.



- The type of data: di-jets

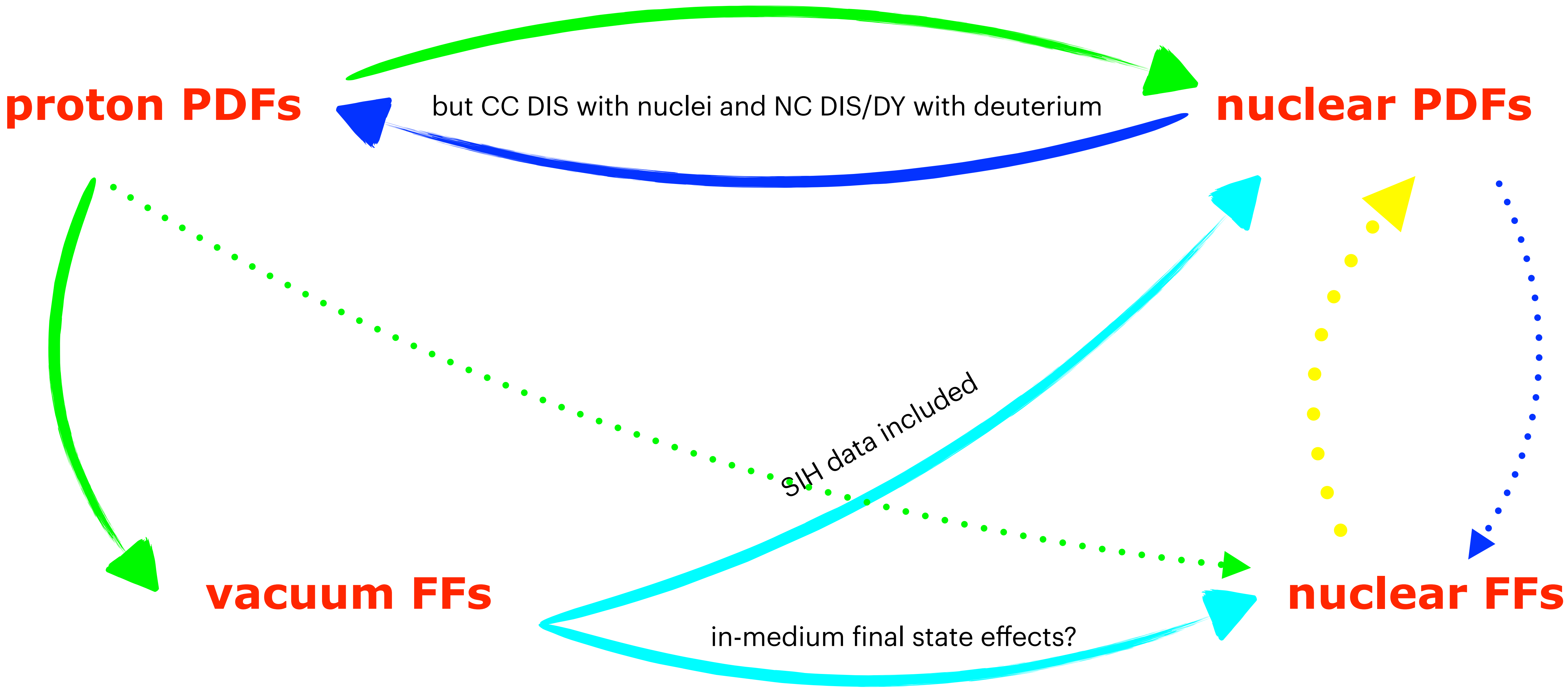


- Constrains the gluon density without FFs.
- Excludes gluons with no anti-shadowing.
- Some bins are not well reproduced, neither in $p + p$.

What about final state effects?

From the phenomenological side:

- The parametrisation bias (except for nNNPDF):
  - choice of parametrisation.
  - smooth A-dependence assumed, not ideal for light nuclei.
- The "contamination":



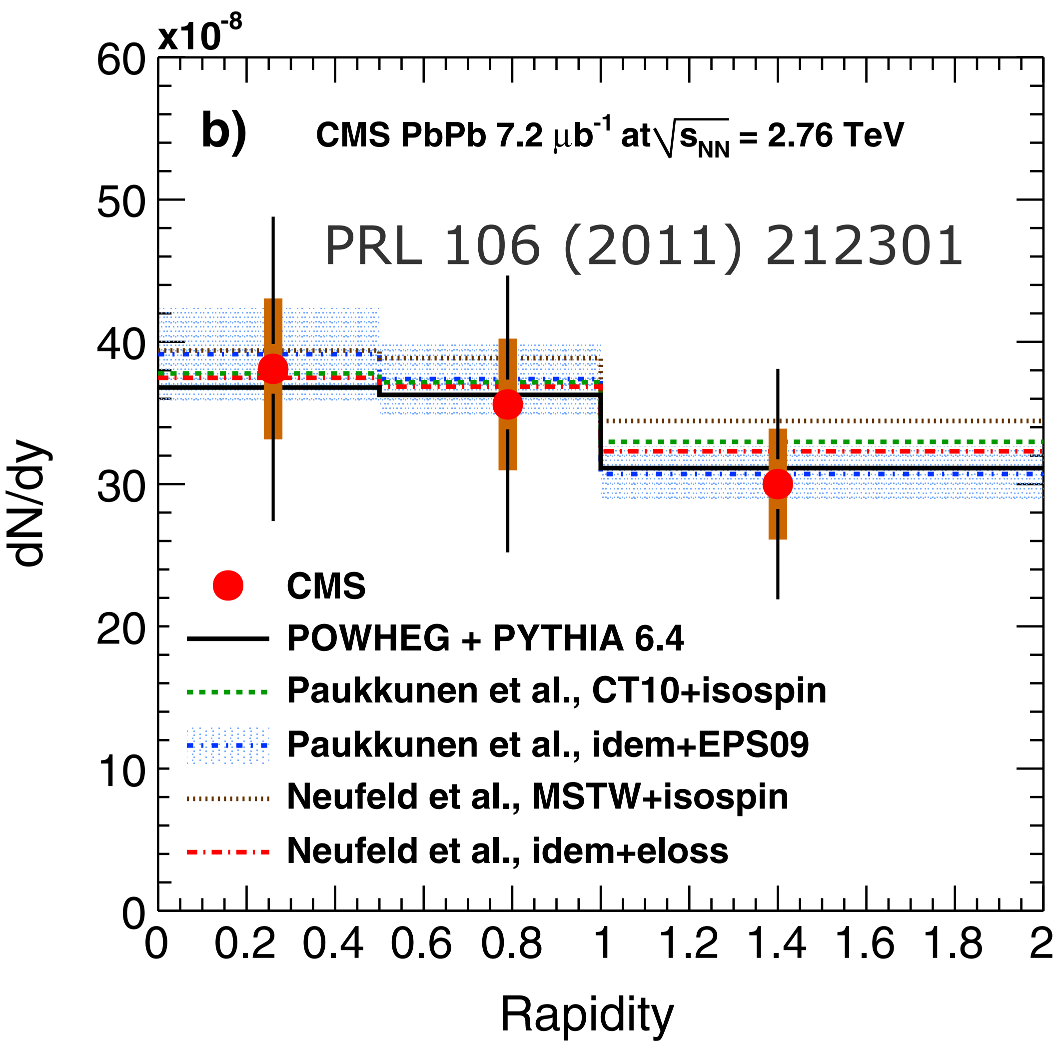
From the phenomenological side:

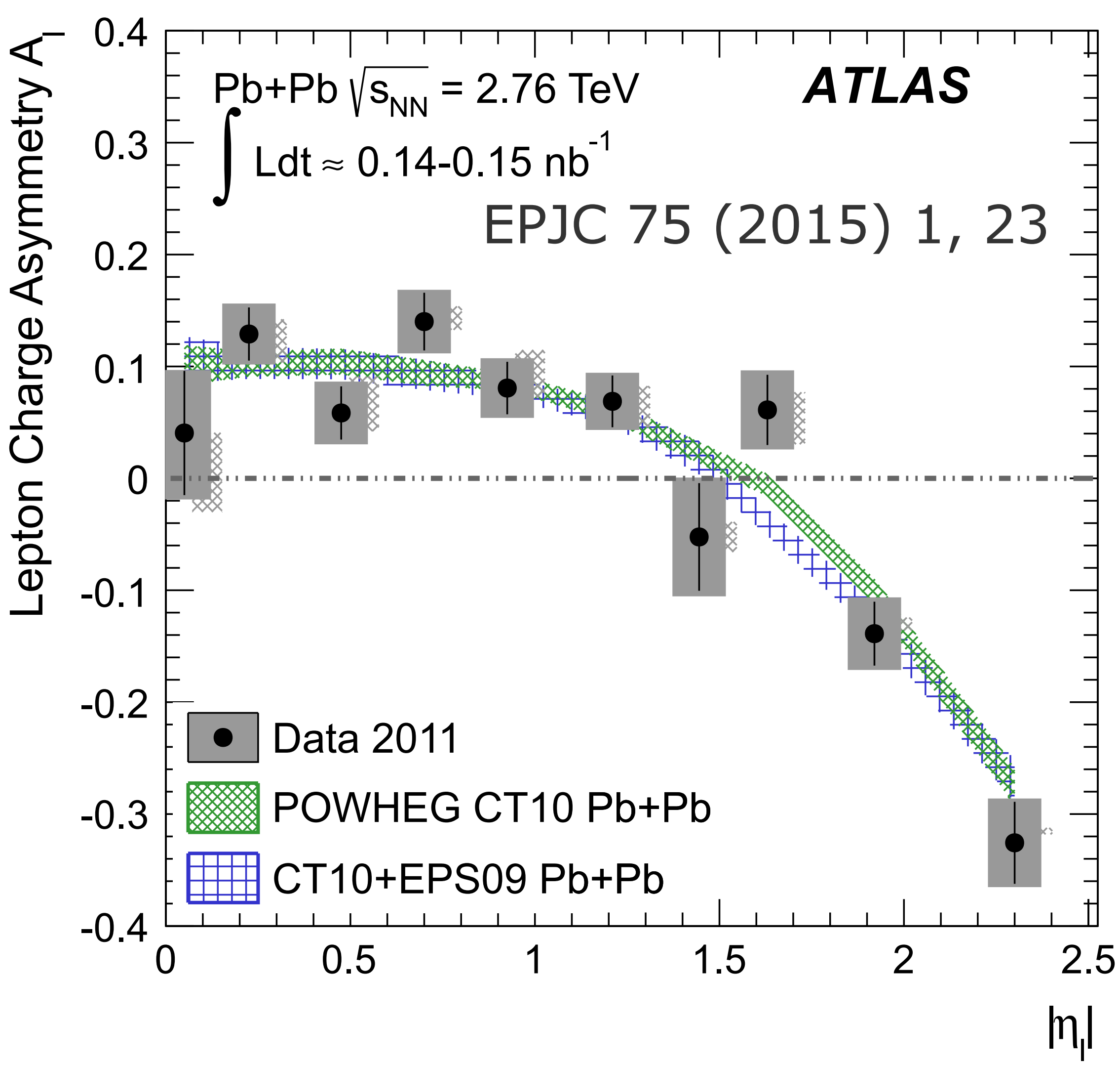
- The parametrisation bias (except for nNNPDF):
    - choice of parametrisation.
    - smooth A-dependence assumed, not ideal for light nuclei.
- The "contamination":

We should be extremely careful not to double, triple, quadruple, n-ple counting effects.

Nuclear PDFs and HI collisions

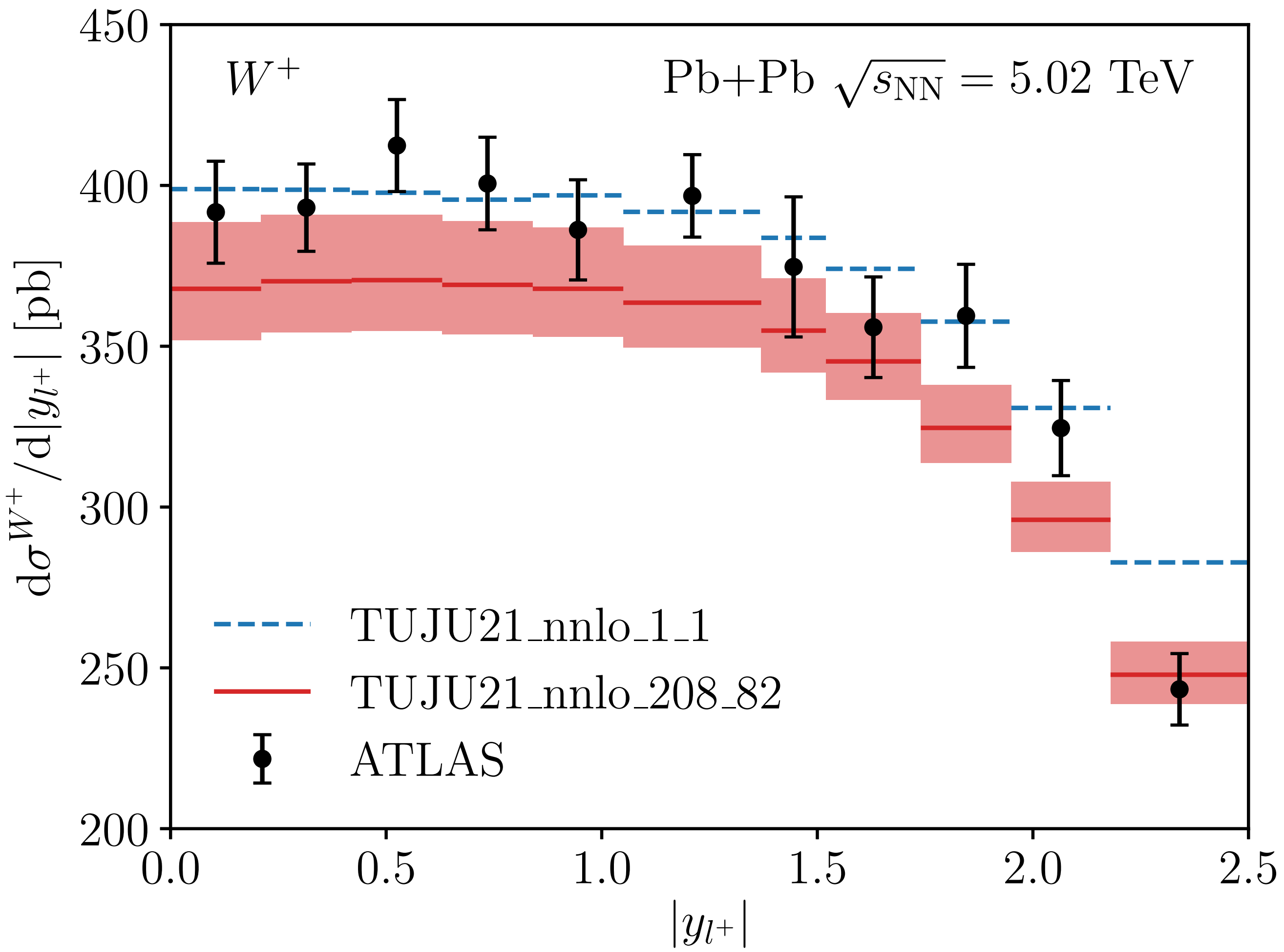
- Data from HI collisions are not used in the fits:
    - due to the possibility of QGP effects (for most data).
    - due to not finding a discrepancy in the 2.76 TeV data.

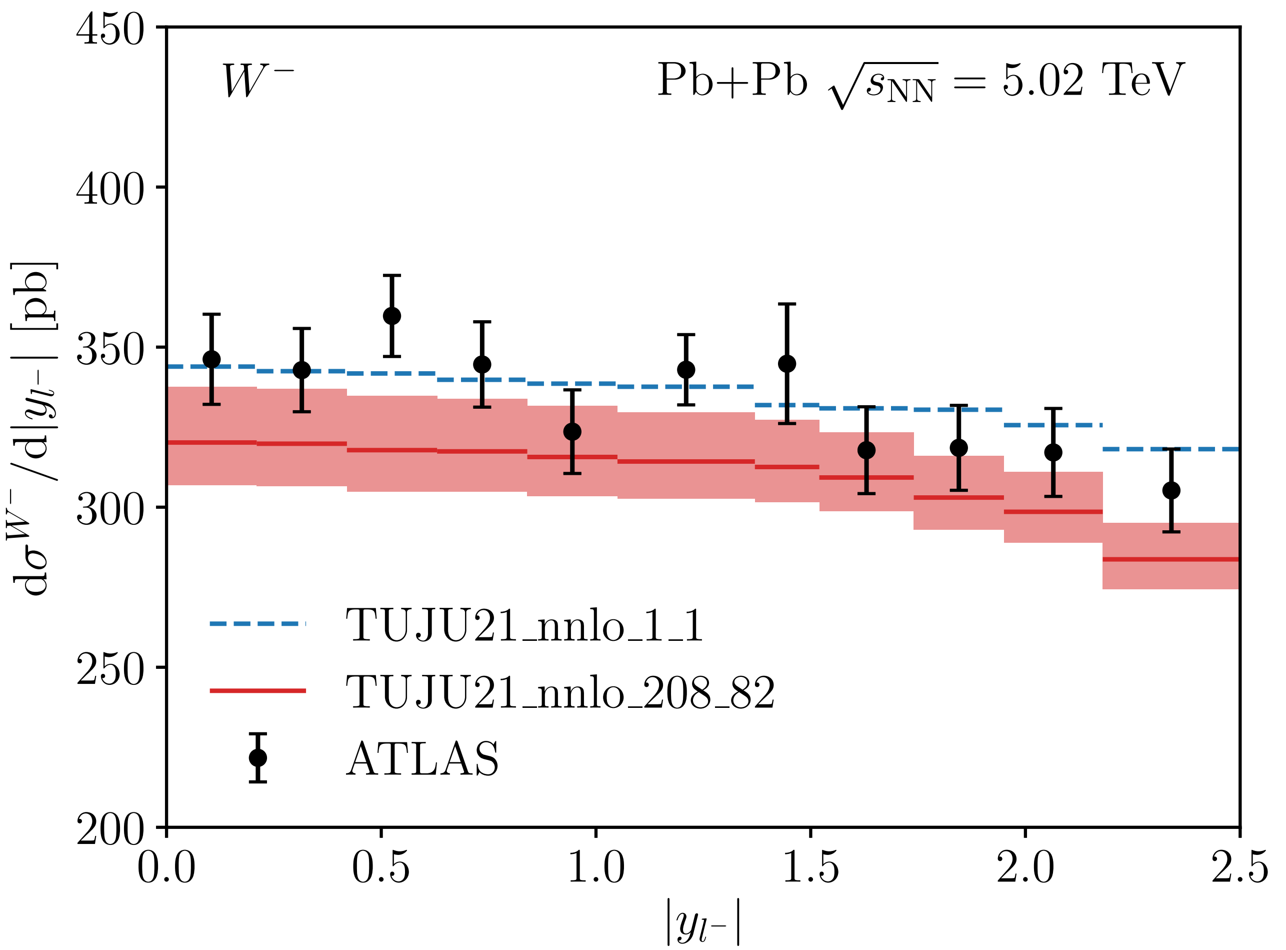




- Another reason is that it is computationally costly: one needs to create look up tables for both hadrons, only for a few points.

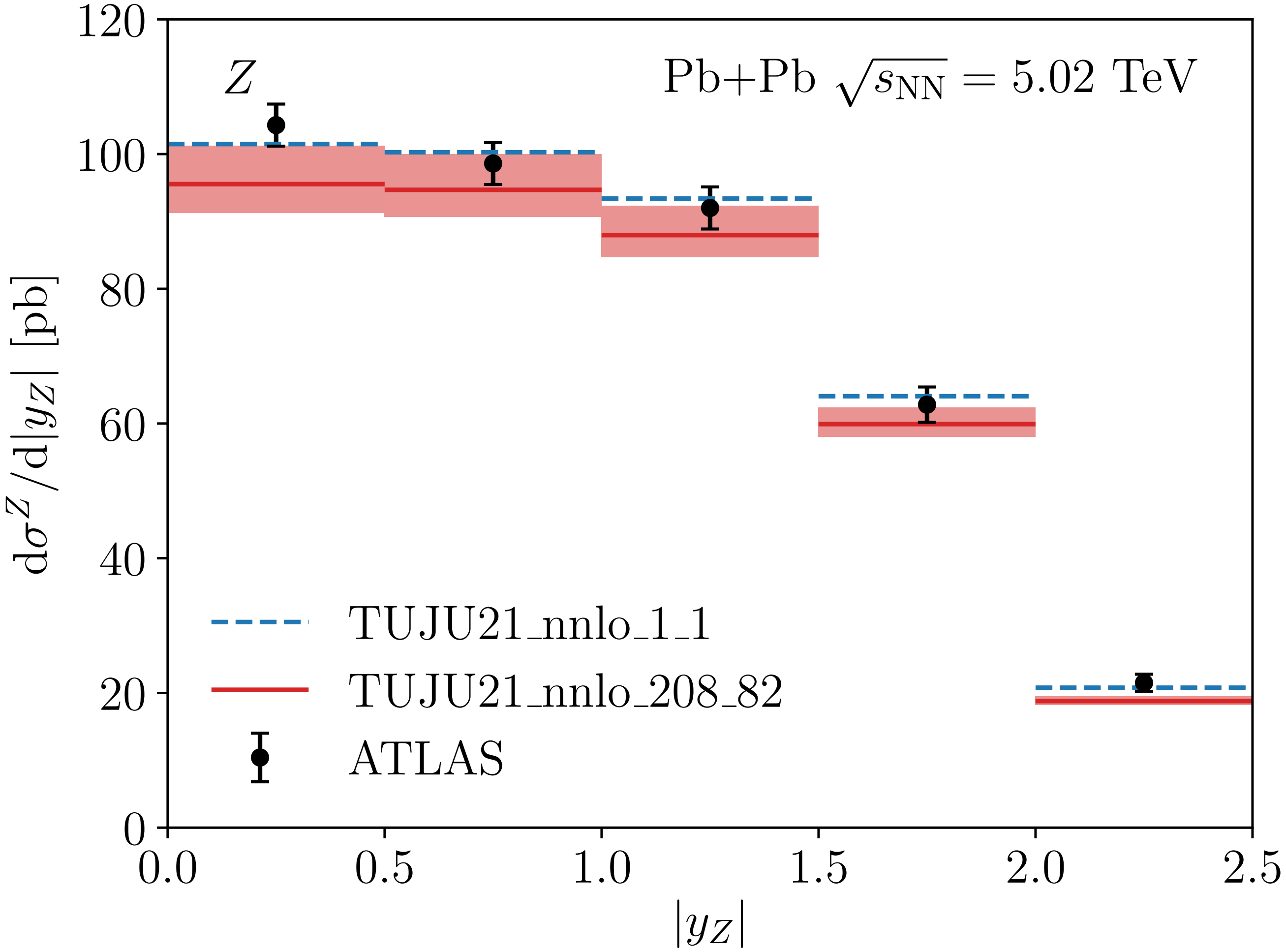
- In TuJu21: comparison with EW boson production at 5.02 TeV.

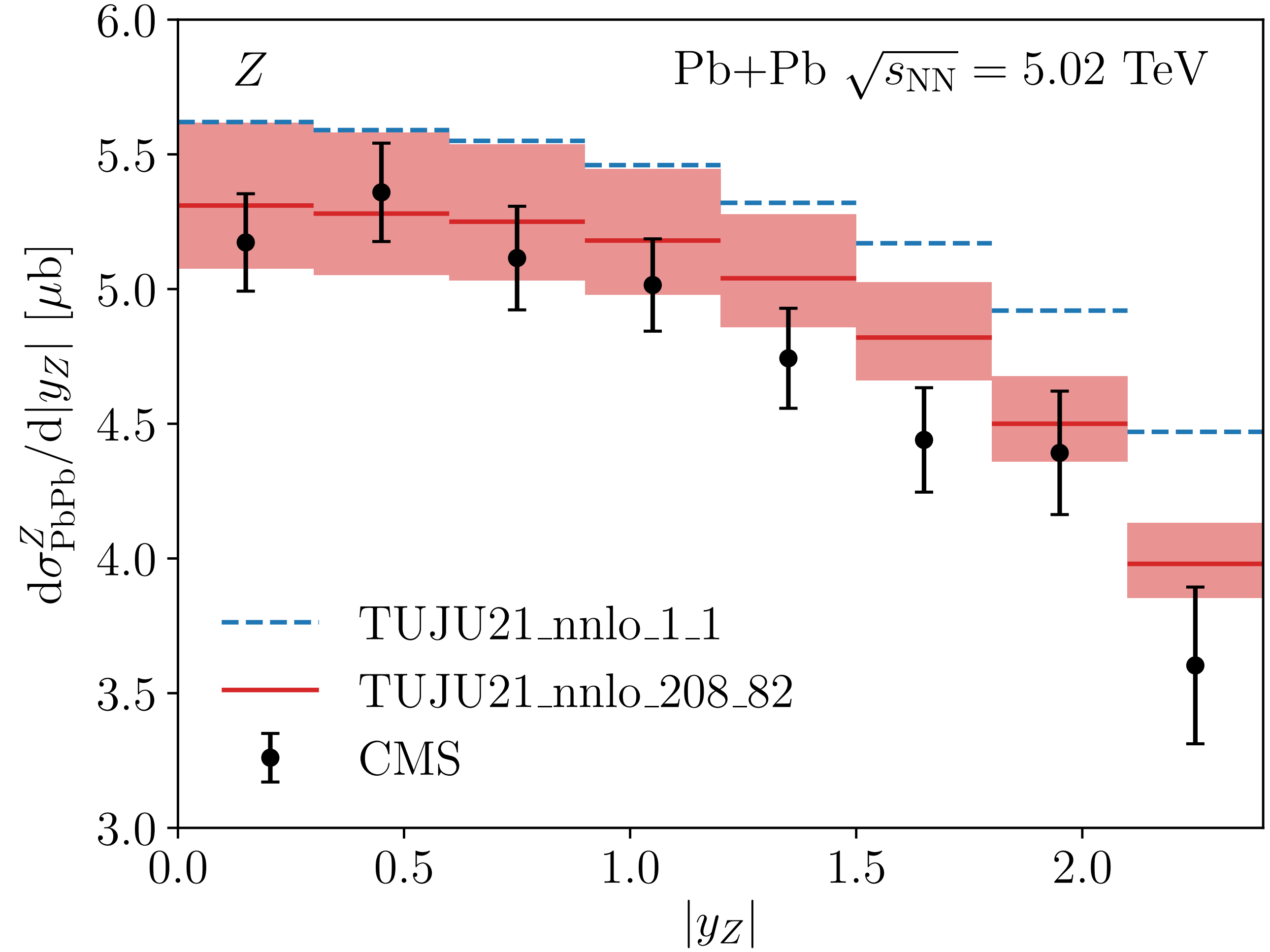




Phys.Rev.D 105 (2022) 9, 9

Phys.Rev.D 105 (2022) 9, 9





- ATLAS data are best described by proton PDFs.
- CMS data are best described by nuclear PDFs.

Is this due to the procedure used to obtain the cross-section?

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.

nPDF fitters waiting for the EIC data

- 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.

- But be careful! Sometimes there are issues that should be addressed first.

Beware!

To properly interpret calculations done with any set of (nuclear) parton distributions, you must know the details!