Overview of nuclear PDFs

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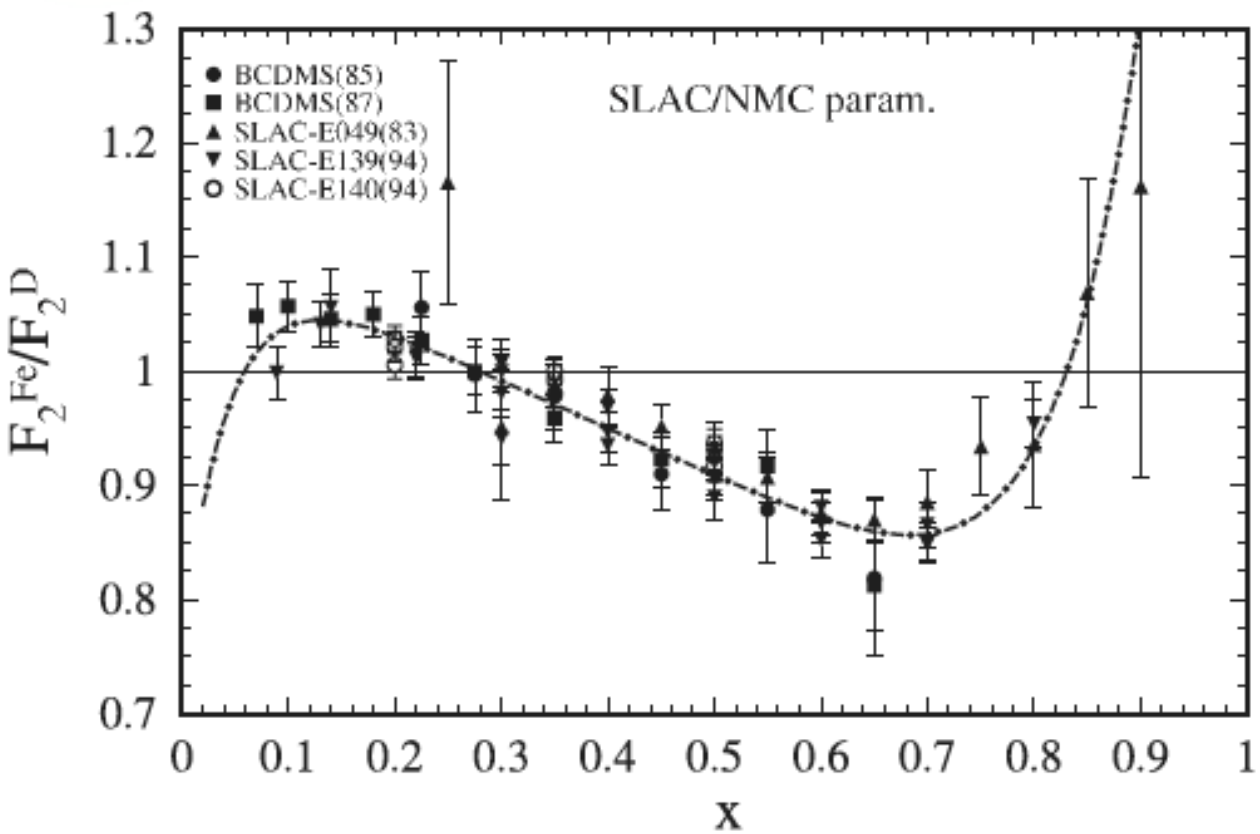
HRT

Outline

- What are the nPDFs? I'm not into nuclei, why should I care? How do we get them?
- Current sets of nPDFs. Latest results.
- Issues with the extraction of nPDFs.
- The future EIC.
- Summary.

What are the nPDFs?

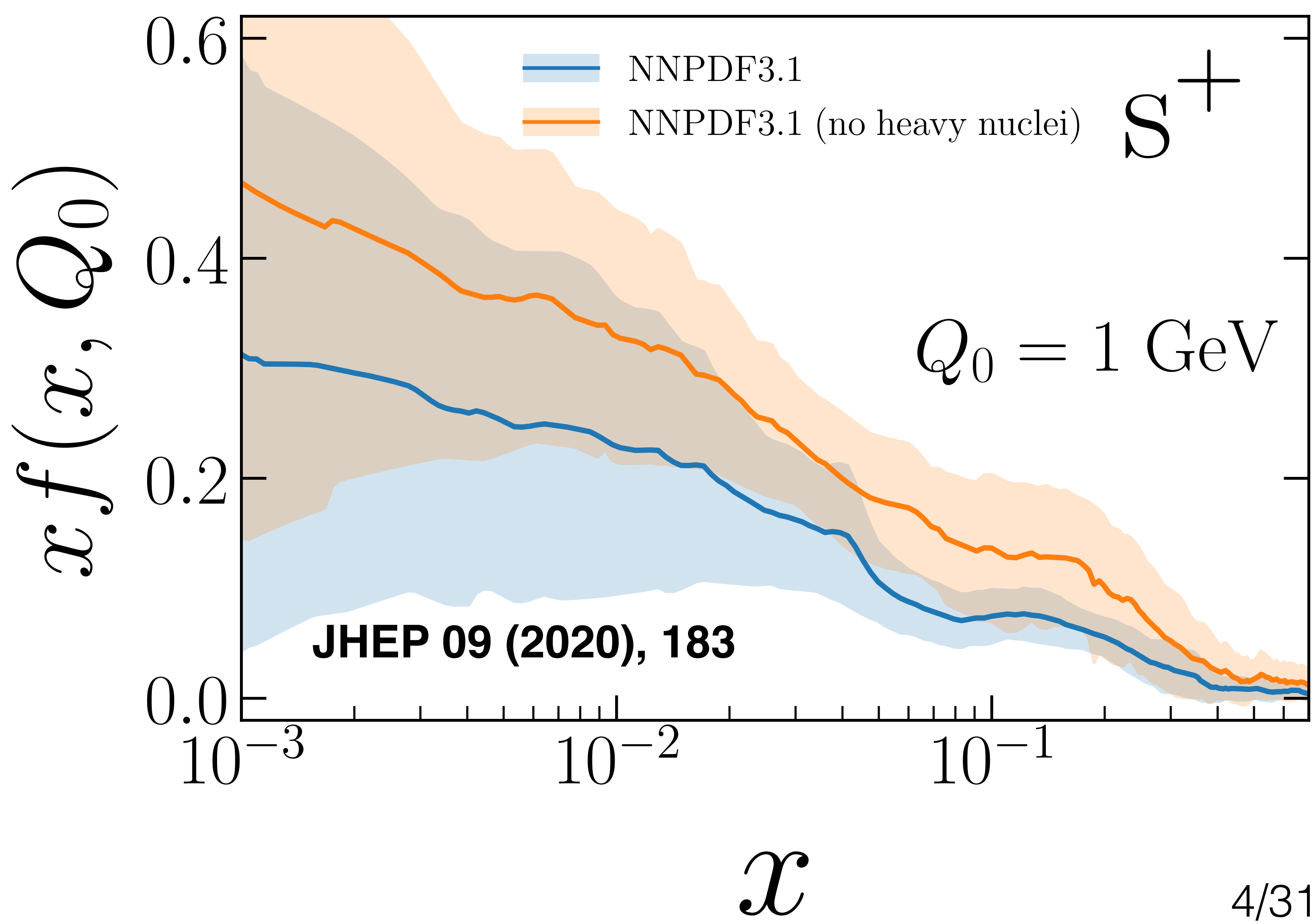


- In the early '80s people measured the cross-section for NC DIS off nuclei.
- The effect is non-negligible and differs from what one expects for free nucleons.

- Construct a theoretical model that could explain the observed data.
- Introduce new non-perturbative but universal objects, described by parameters that encode the nuclear behaviour: the nuclear PDFs.

Why even bother?

- If you work with cold nuclear matter effects, they are in your way.
- If you work on heavy-ions, they describe the initial state.
- But even if you only deal with protons, nuclear targets are used to separate the quark flavours!



To get nPDFs:

Just like the usual collinear proton PDFs, do a fit to data.

a) At some initial scale (Q_0), write the (n)PDFs in terms of free parameters.

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

→ $f_i^p(x, Q_0^2) R_i(x, A)$

→ $f_i^p(x, Q_0^2) \otimes R_i(x, A)$

→ $f_i^{p/A}(x, Q_0^2, A)$

→ **neural network**

b) Use isospin symmetry to construct the nPDFs (not proven to be valid!).

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

c) Follow a fitting procedure.

Current sets of nPDFs

- **EKS**: EPJC 9 (1999) 61. **FIRST EVER**
- **EPS09**: JHEP 0904 (2009) 065.
- **EPPS16**: EPJC 77 (2017) no.3, 163. **FIRST WITH LHC DATA**
- **HKM**: PRD 64 (2001) 034003.
- **HKN07**: PRC 76 (2007) 065207. **FIRST WITH THEORETICAL UNCERTAINTIES**
- **KA15**: PRD 93 (2016) no.1, 014026. **FIRST NNLO**
- **KSASG20**: arXiv:2010.00555 [hep-ph].
- **nDS**: PRD 69 (2004) 074028. **FIRST NLO**
- **DSSZ**: PRD 85 (2012), 074028. **FIRST WITH CC AND nFFs**
- **nCTEQ15**: PRD 93 (2016) no.8, 085037.
- **nCTEQ15WZ**: EPJC 80 (2020) 10, 968.
- **nTuJu**: PRD 100 (2019) no.9, 096015. **FIRST OPEN SOURCE**
- **nNNPDF1.0**: EPJC 79 (2019) no.6, 471. **FIRST WITH NEURAL NETWORKS**
- **nNNPDF2.0**: JHEP 09 (2020), 183.

Current sets

Focus on:

cyan: χ^2/N_{dat}

green: number of points

magenta: starting scale

the amount of smileys

SET		nDS	HKN07	EPS09	DSSZ	nCTEQ15	EPPS16	nNNPDF1.0	nTuJu19	nNNPDF2.0	nCTEQ15wz
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
$Q_0^2(GeV^2)$		0.4	1	1.69	1	1.69	1.69	1	1.69	1	1.69
deuteron			🙂			?			🙂	🙂	?
flavour separation ?						🙂 valence	🙂		🙂 valence	🙂	🙂

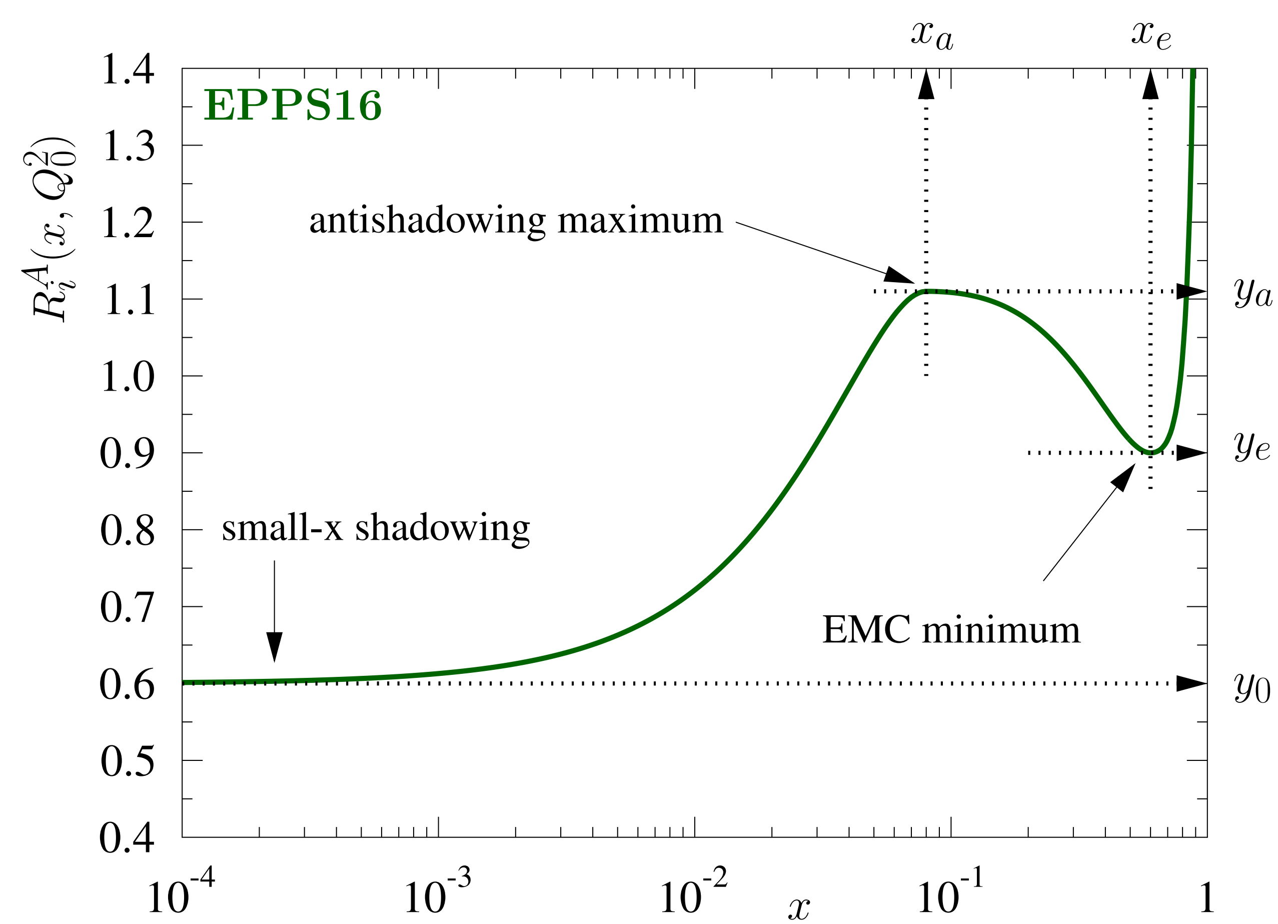
The nPDFs can be given as

- distribution of flavour ***i*** in **proton** in nucleus ***A*** $f_i^{p/A}(x,Q^2)$
- distribution of flavour ***i*** in nucleus ***A*** $f_i^{A}(x,Q^2)$
- ratios to the corresponding flavour in proton $R_i^A = f_i^{p/A}(x,Q^2)/f_i^p(x,Q^2)$

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

Why ratios?

(most of) the data used in fits are given as ratios and have this type of shape.



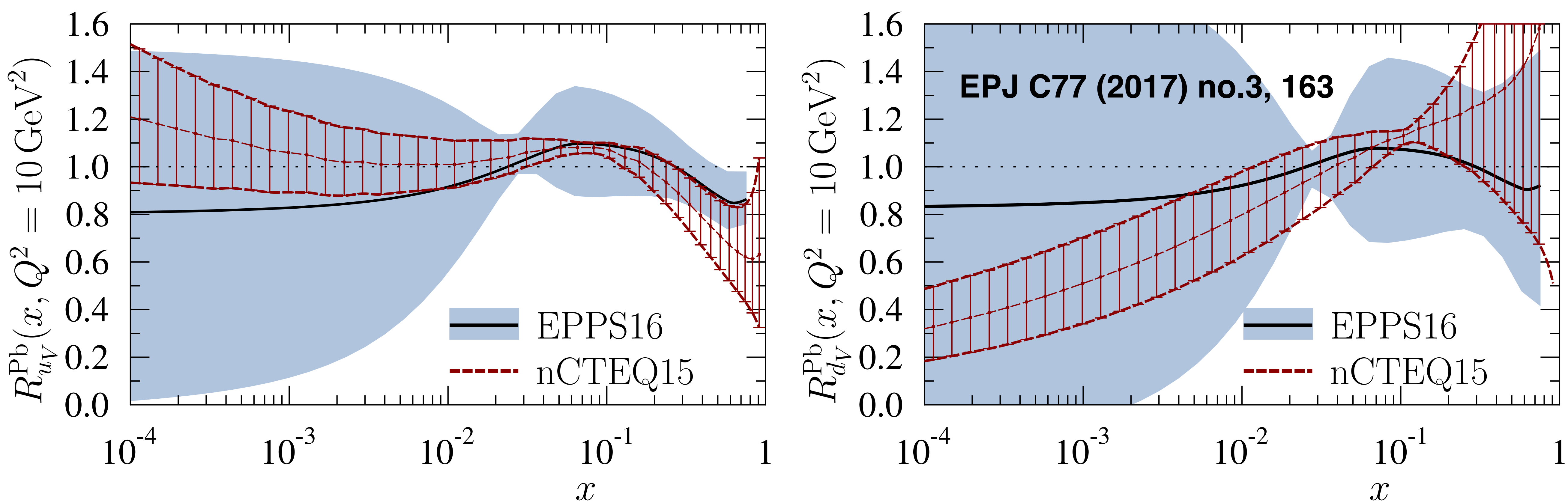
It is "natural" to expect that the individual modification of each parton will be similar.

This is **~ true** for **valence quarks**, don't assume it will be for other partons.

proton | nucleus

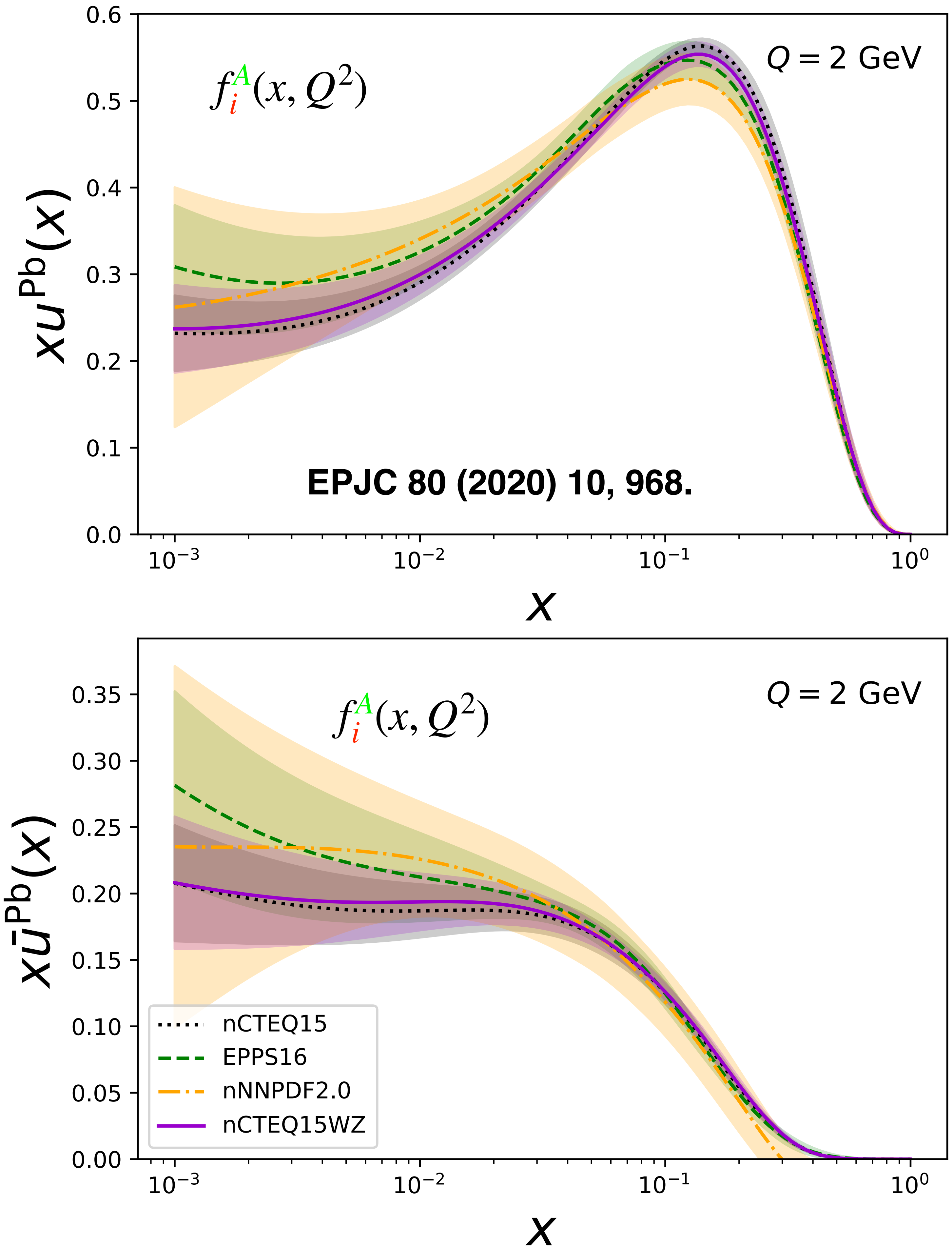
$$\frac{4}{9}u + \frac{1}{9}d \longrightarrow \left(\frac{A+3Z}{9A}\right)u + \left(\frac{4A-3Z}{9A}\right)d$$

Isoscalar or nearly isoscalar nuclei can't separate flavours.



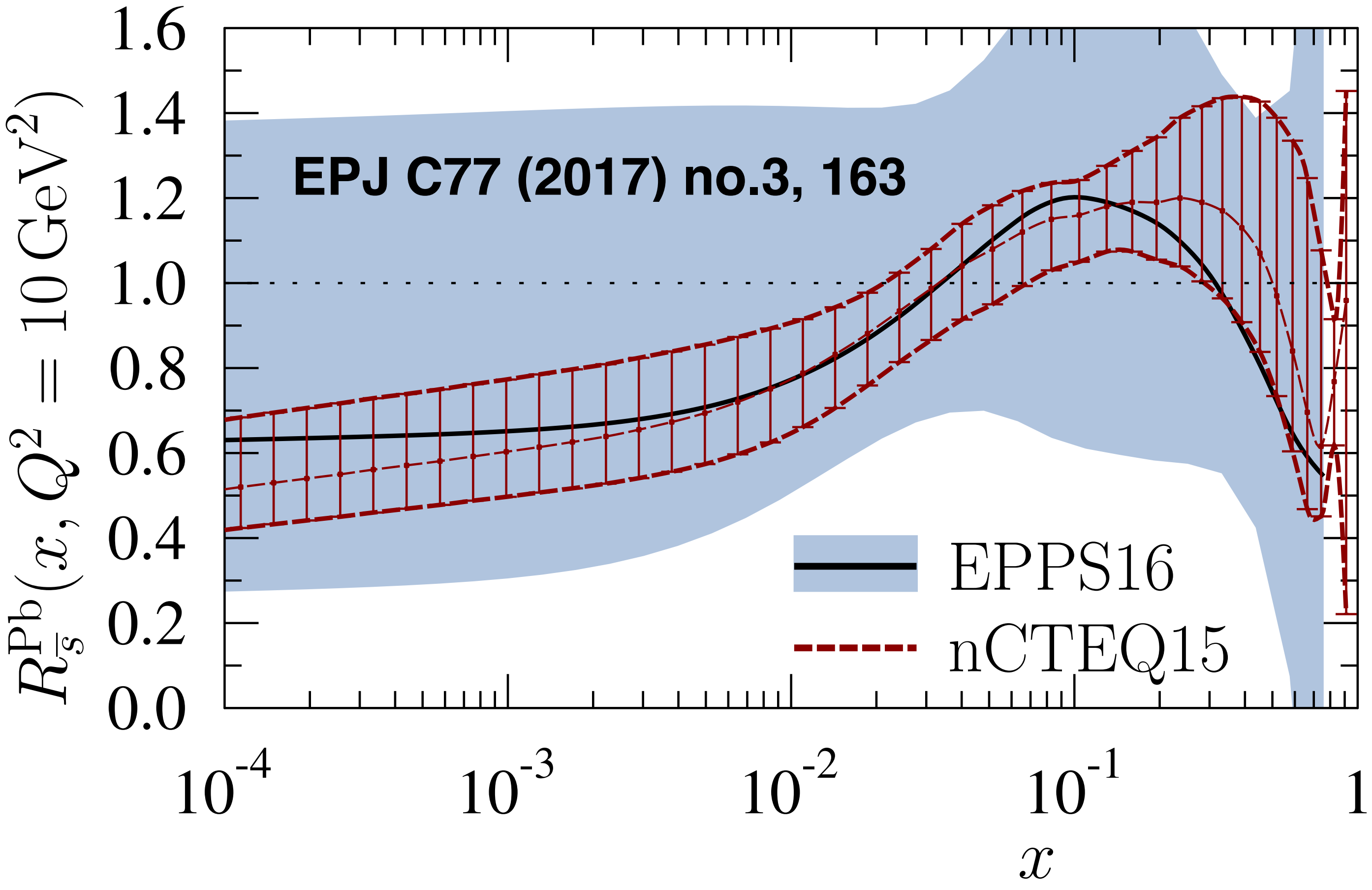
- Shapes for separate up/down don't usually match.
- (weighted) averages do overlap.

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

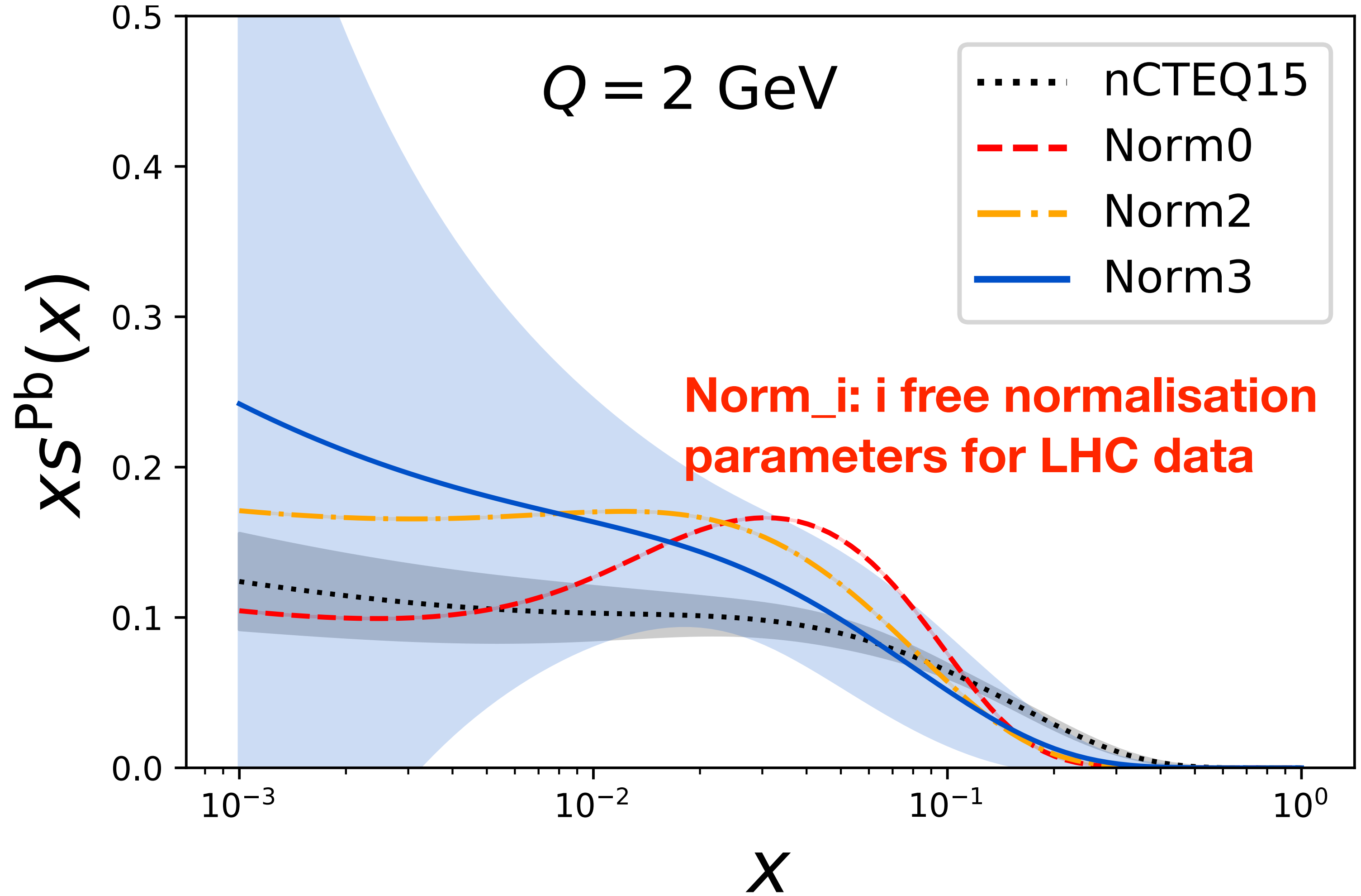


- The nPDFs of the valence up and down quarks in a nucleus are similar for all fits.
- This is not so for the sea quarks. Particularly for the strange/anti-strange quark.
- Usually the sea is given one common parametrisation.

- One can of course try to separate the nPDF of the strange, but little constraint is given by the data.



EPJC 80 (2020) 10, 968.

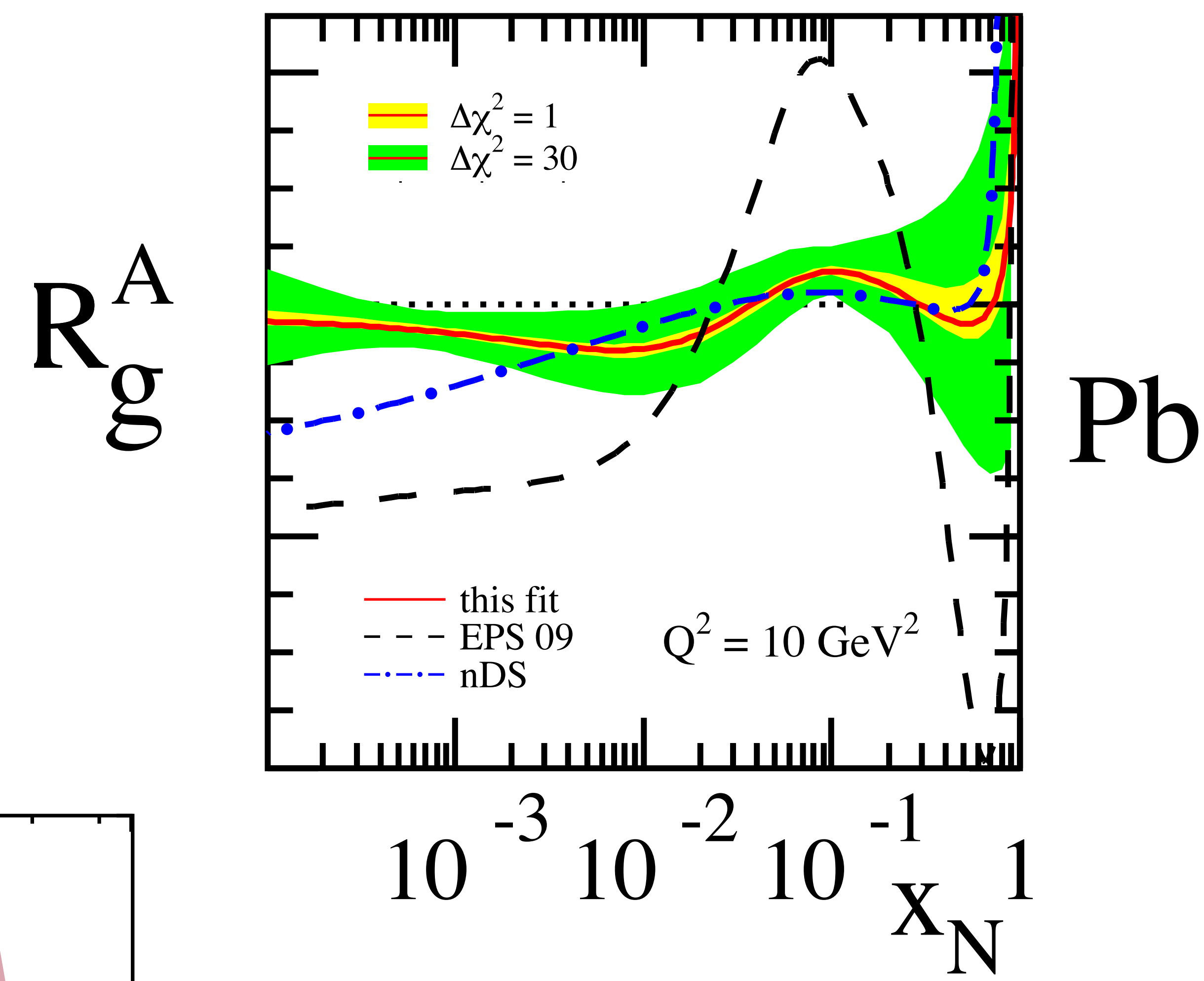


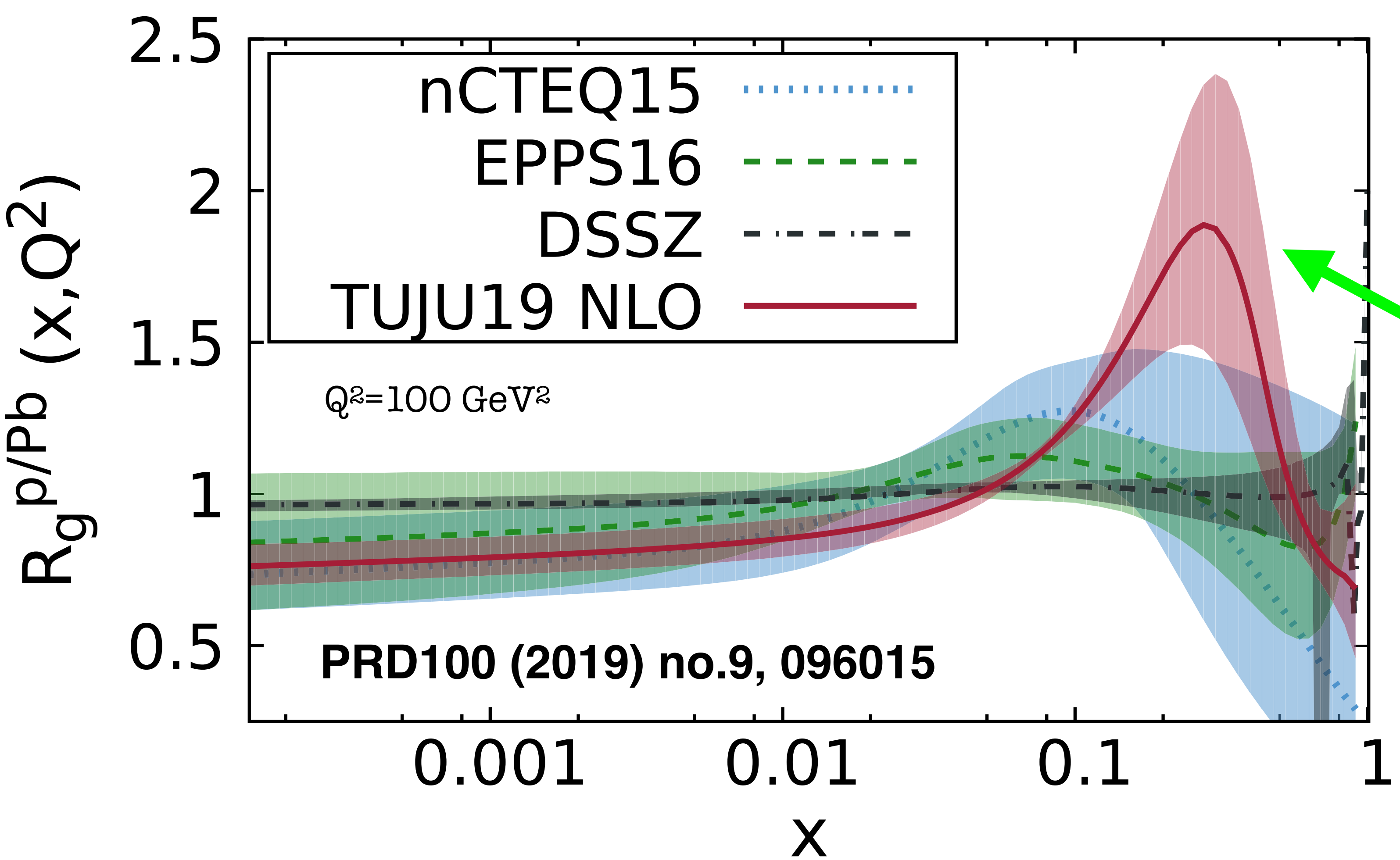
- W and Z bosons in p+Pb collisions at the LHC are not decisive either.

And now, the gluon. Gluons are 😈

- Early fits only had data from RHIC (single hadron production, ~ 60 points) to constrain the gluon nPDF.

PRD85 (2012), 074028

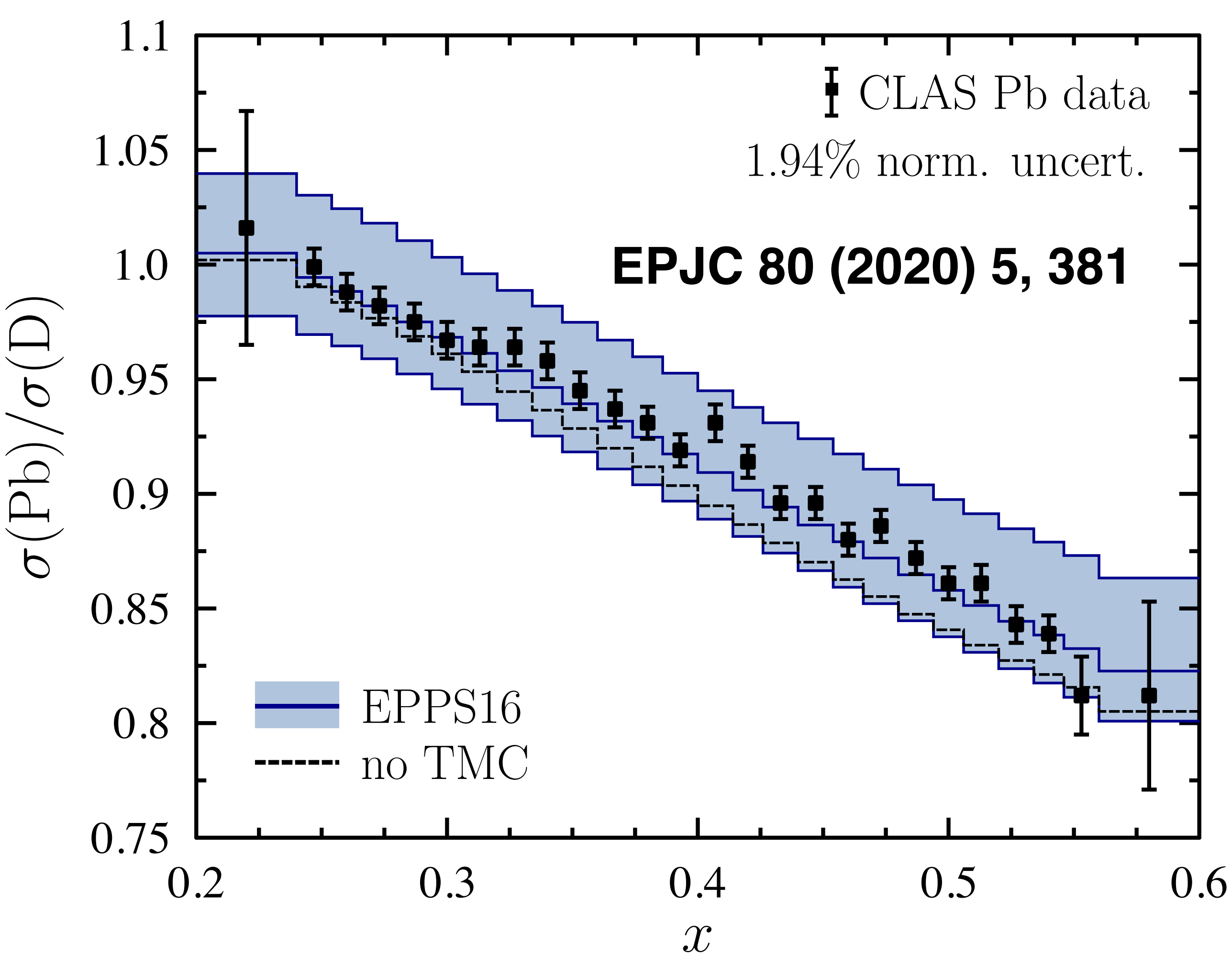




Not constrained by data!

Latest results

- We are all working to get new sets.
- Efforts focus on using "new" and new data, and exploring the region of validity of applied assumptions/approximations.

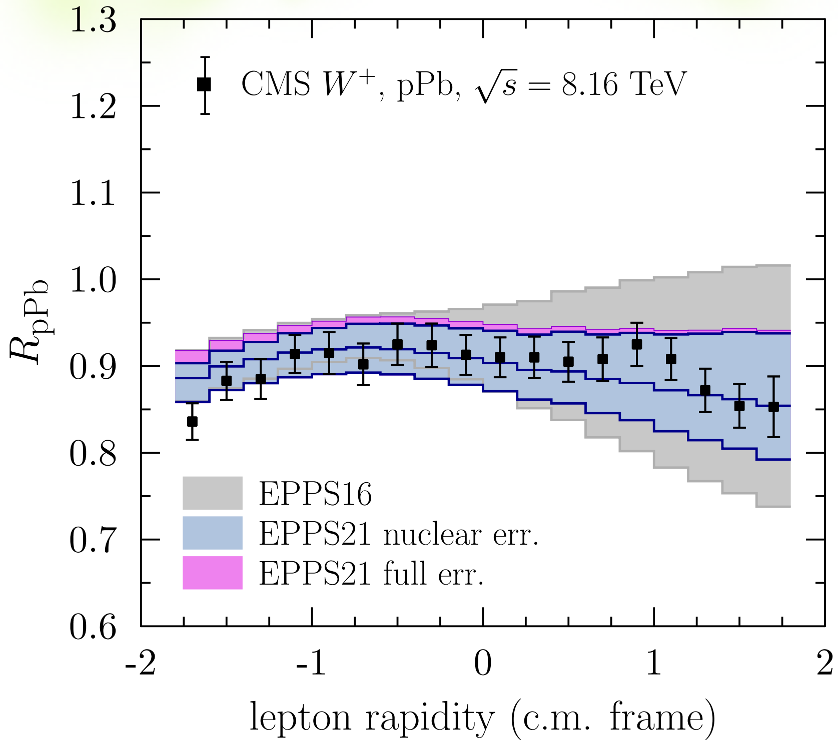


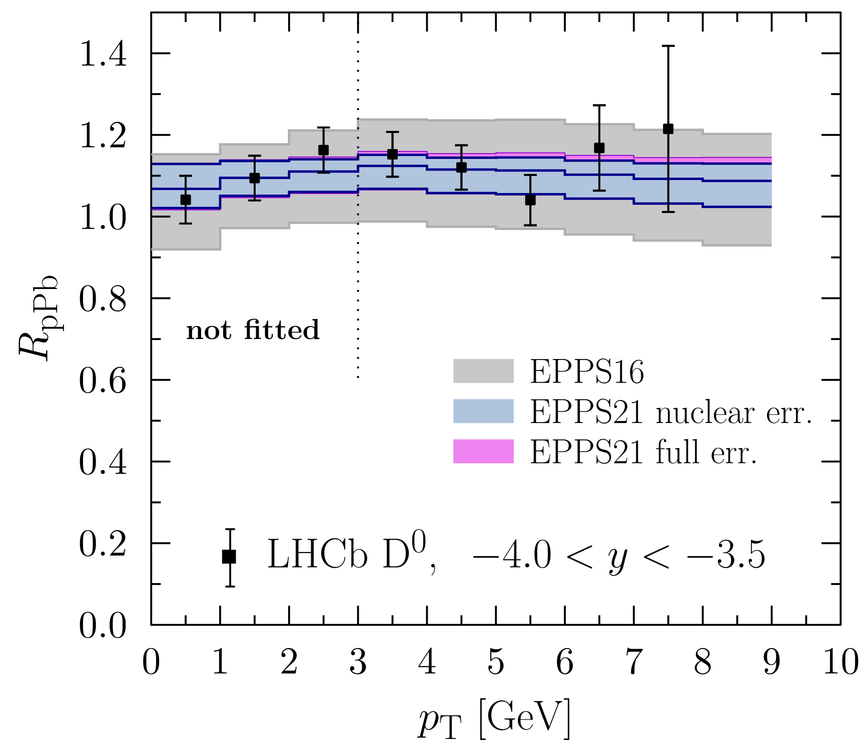
"new": e.g. pion+A Drell-Yan (**1981**, **1987**, **1989**), single hadron production at LHC.

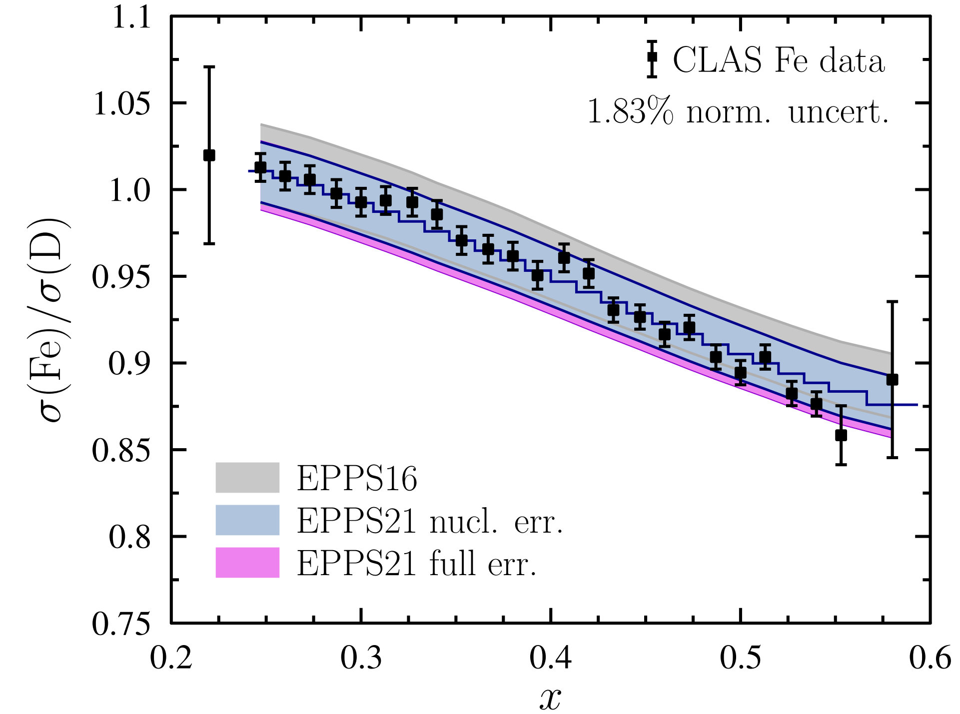
new: e.g. JLab NC DIS, LHC p+Pb (Z and W from Run 2, dijet R_{pPb}, D^0).

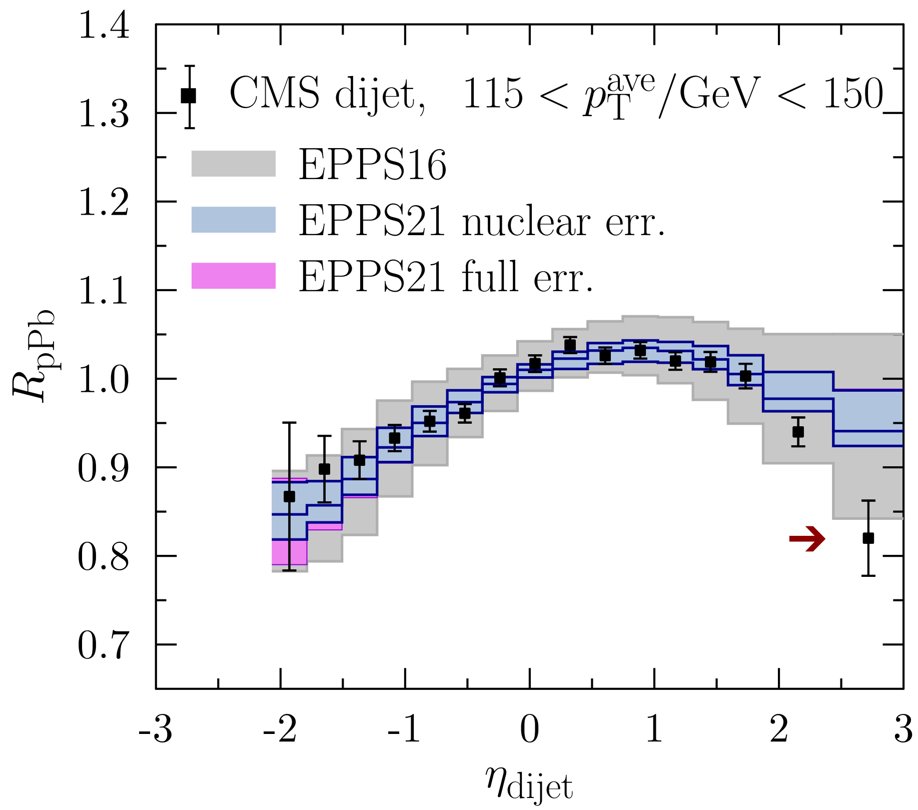
relaxing kinematic cuts, including TMC, etc…

EPPS21*









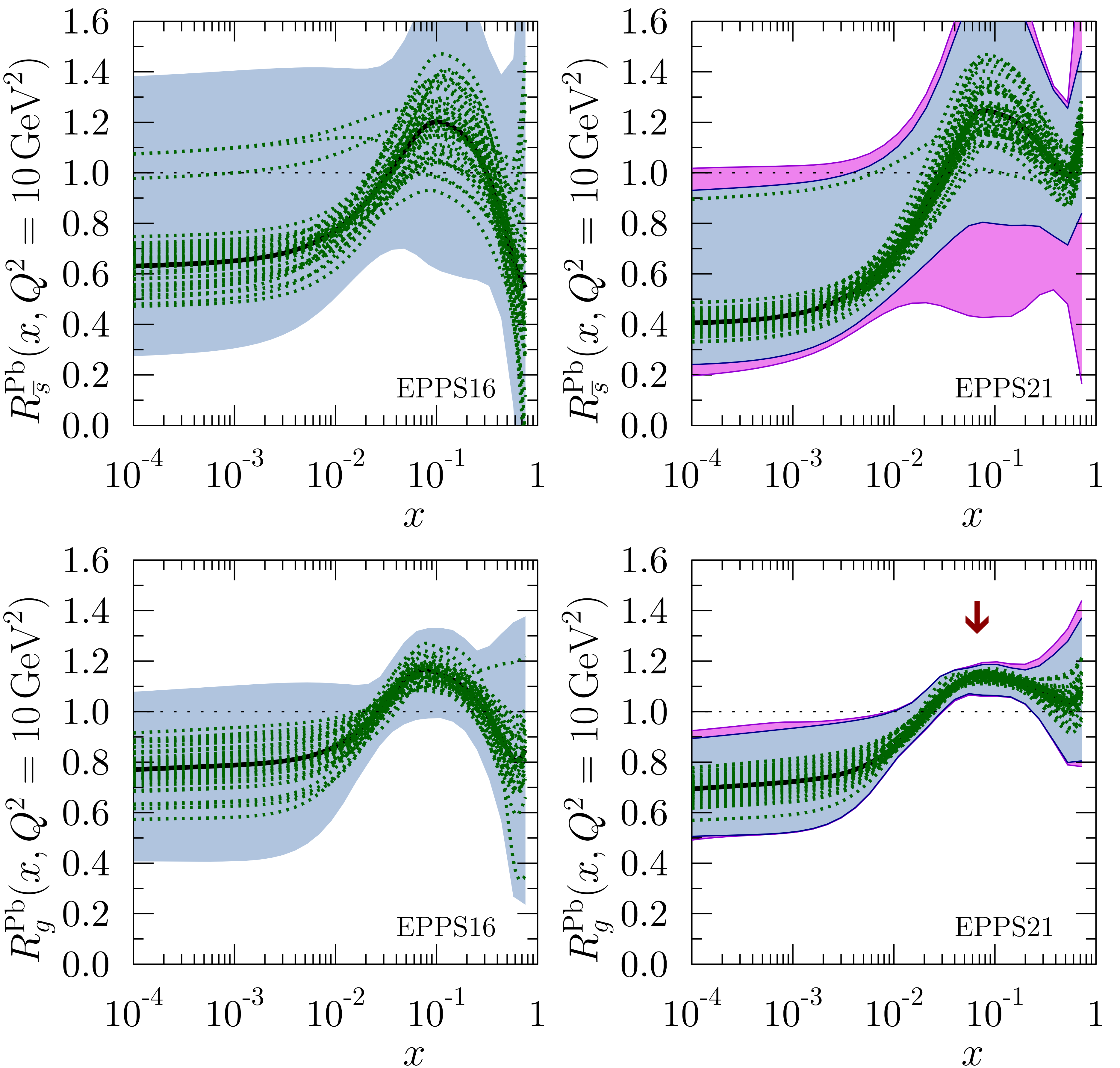
- JLAB and LHC data
- TMC included
- proton uncertainties considered
- ratios used when possible
- For CMS di-jets large rapidity bins can't be fitted (neither in p+p).

* from Petja Paakkinen's talk at DIS2021

EPJ C79 (2019) no.6, 511

Latest results

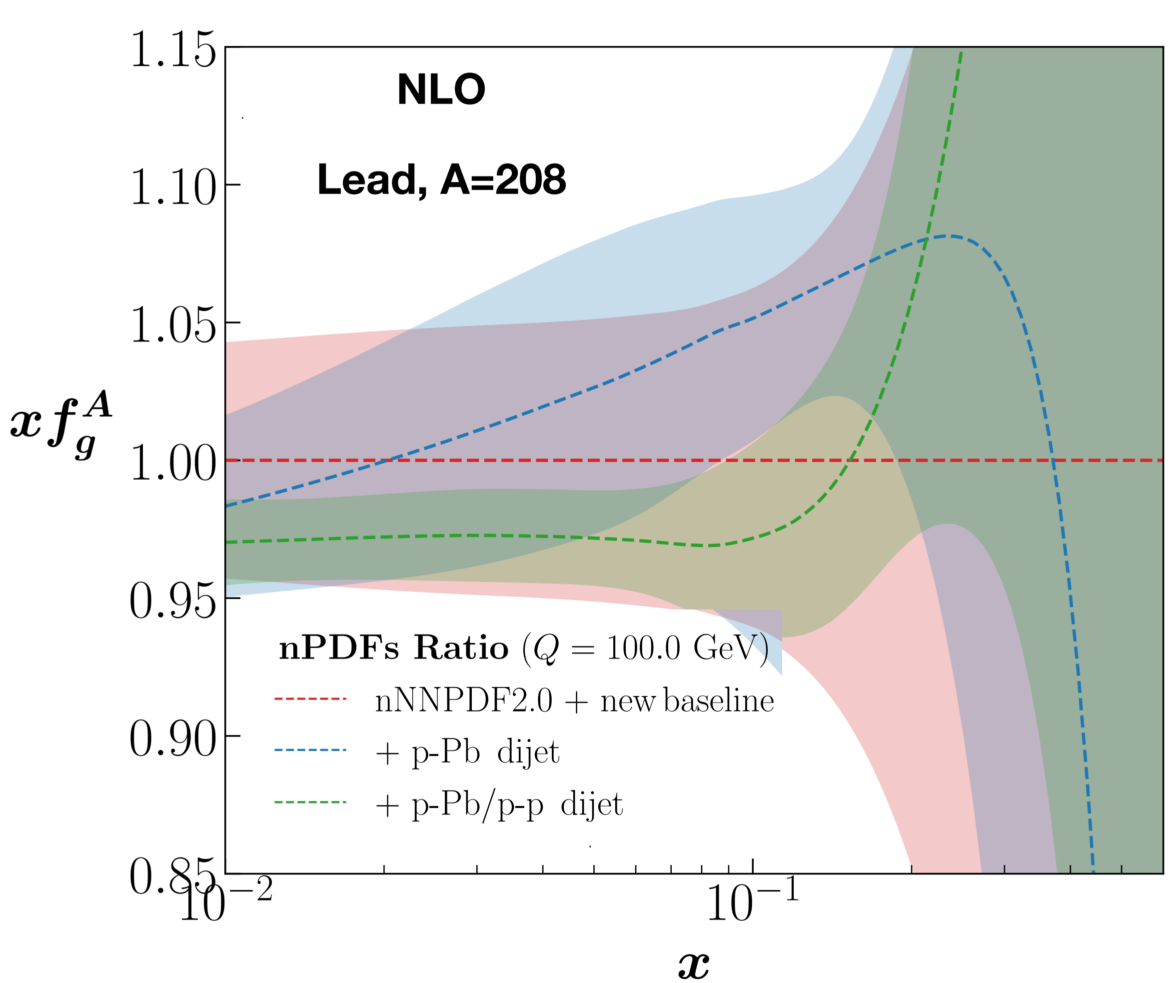
EPPS16 EPPS21 prelim.

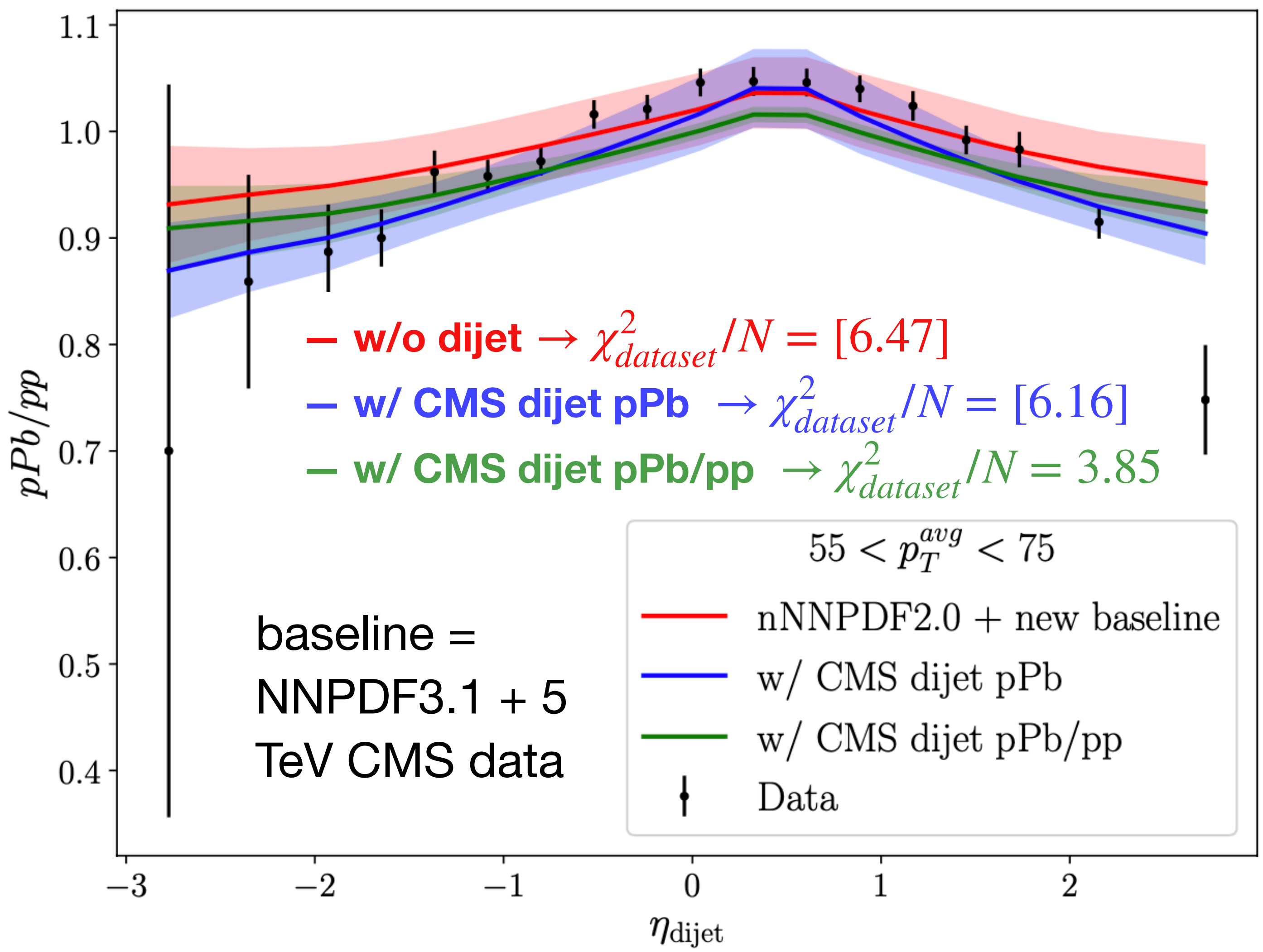


- Flavour separation not dramatically improved ☹️
- Gluon anti-shadowing better constrained 🙂

nNNPDF*

- NLO and NNLO
- Incorporates dijets and EW bosons in p+Pb
- Positivity constraint imposed



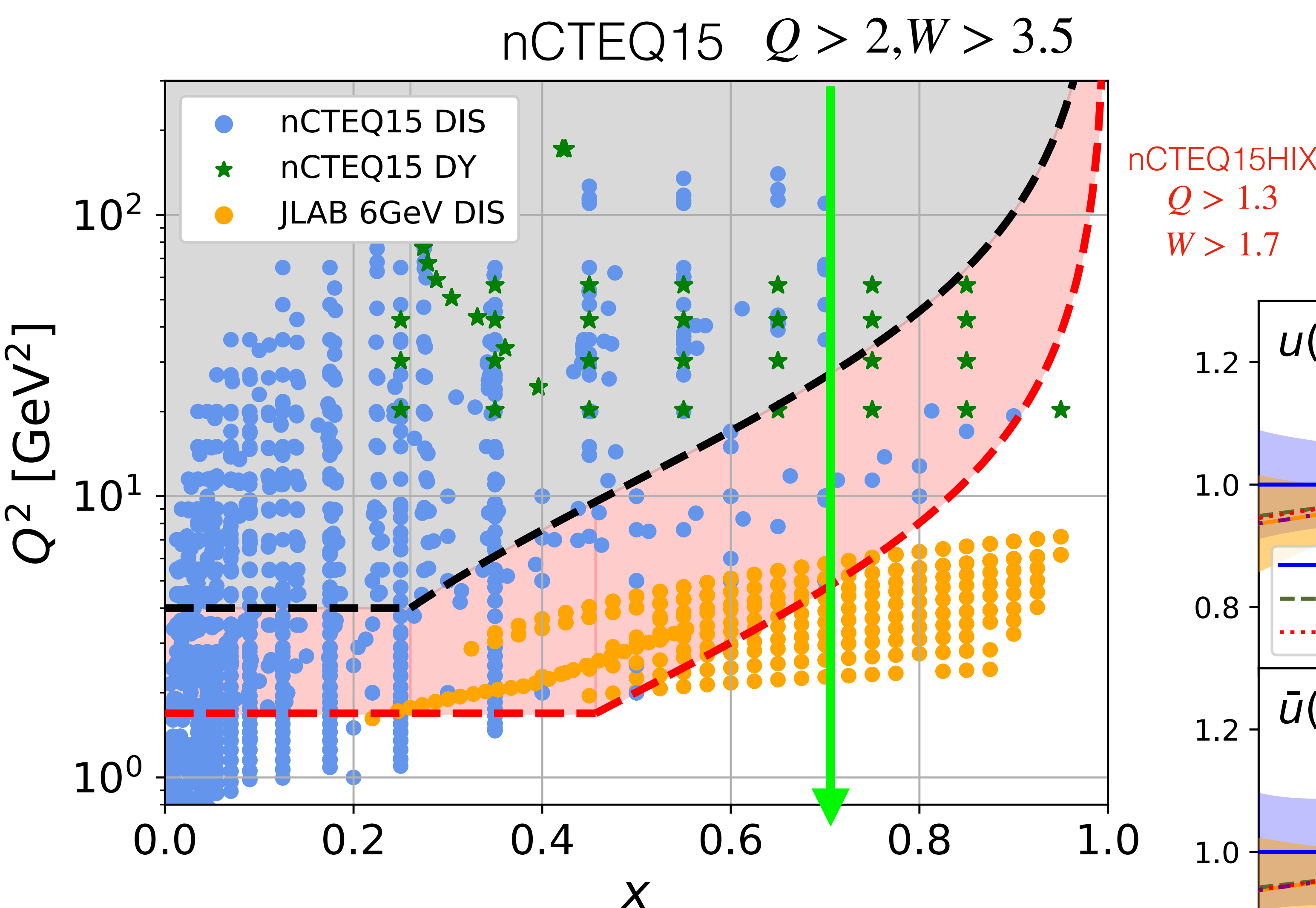


- Missing correlations.
- Inability to describe p+p dijet data with baseline affects the p+Pb description.
- Gluon shape still unconstrained.

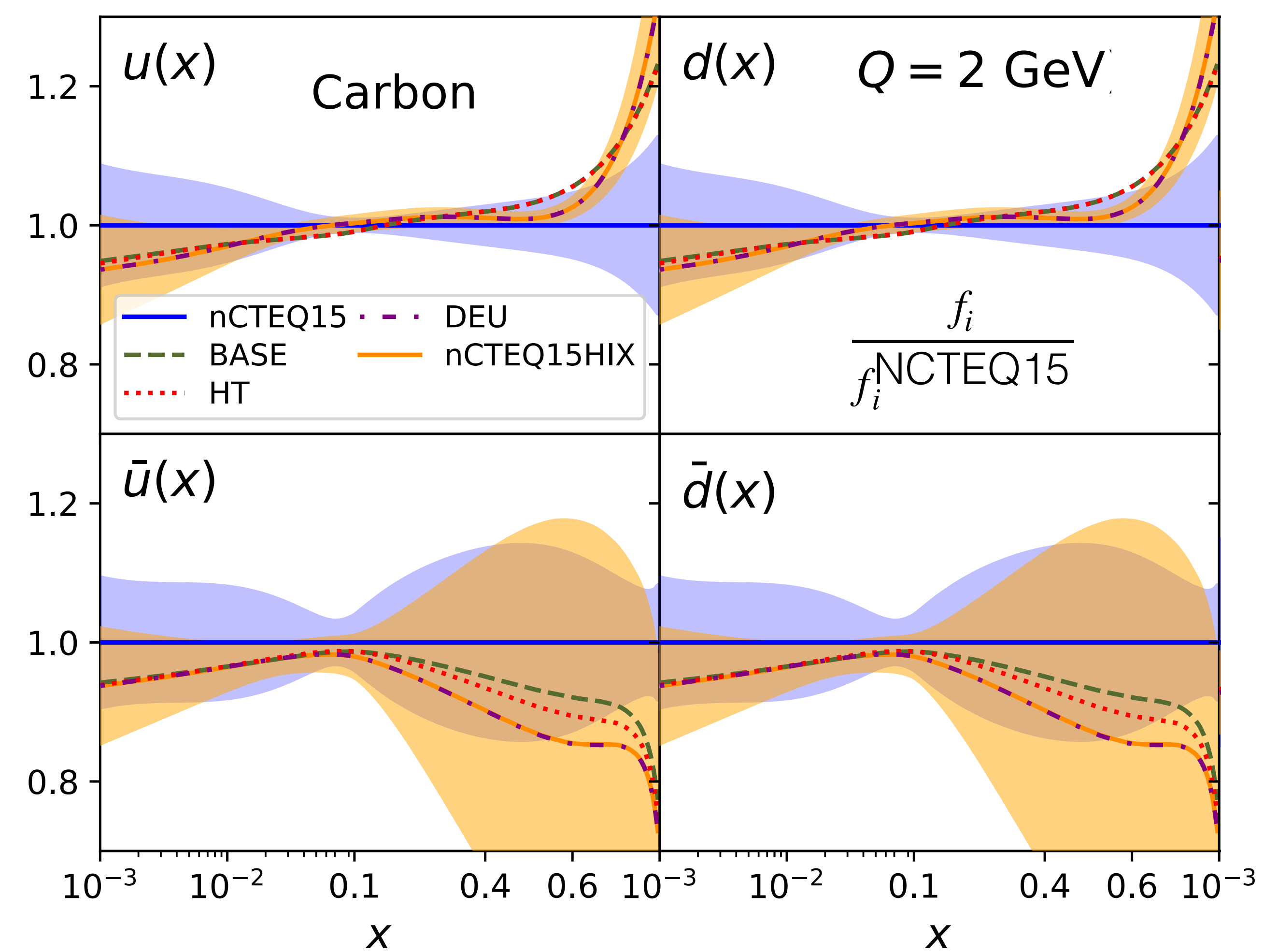
nCTEQ*

Unlike the EPPS and nNNPDF analyses, the following studies are being done independently

- Use the very precise JLAB 6 GeV data (high *x*).

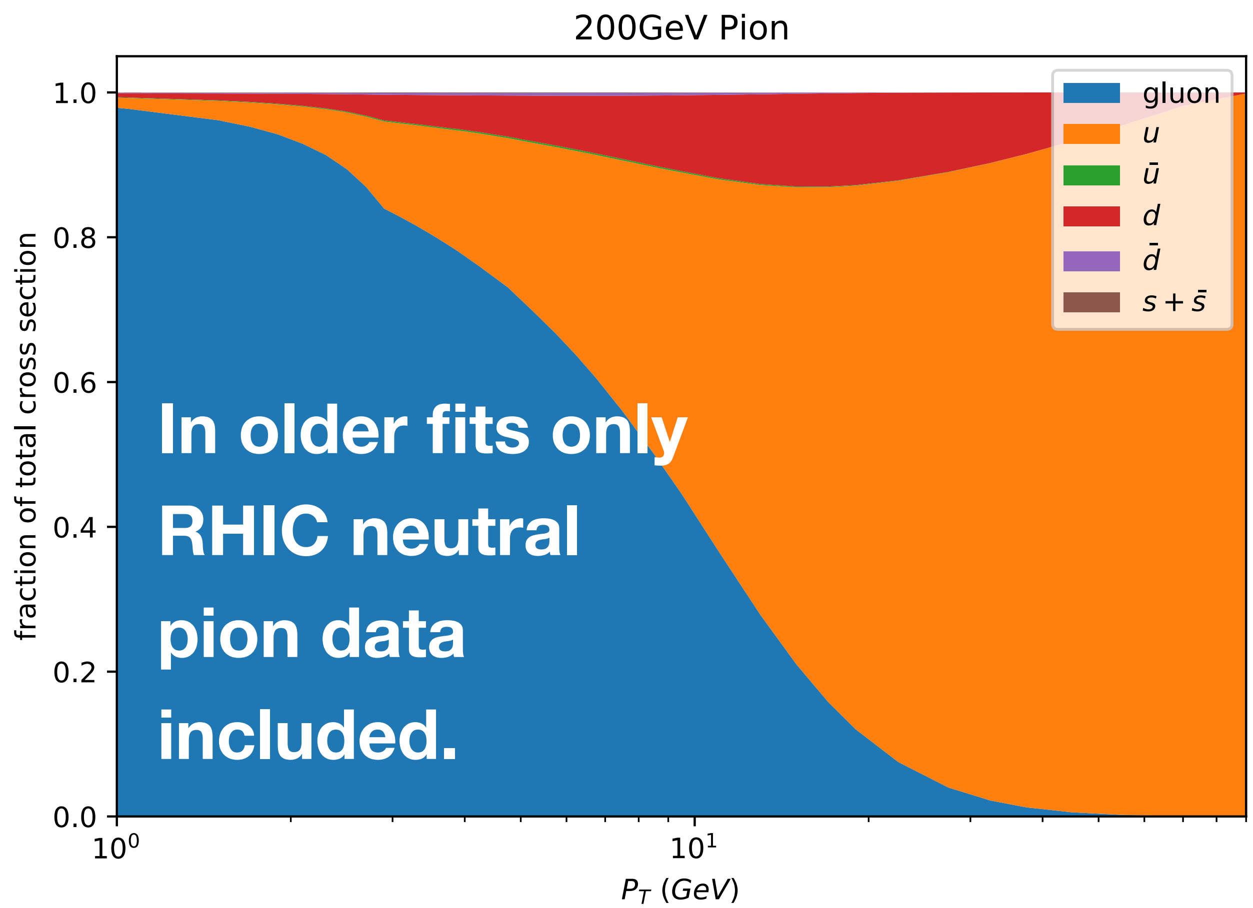


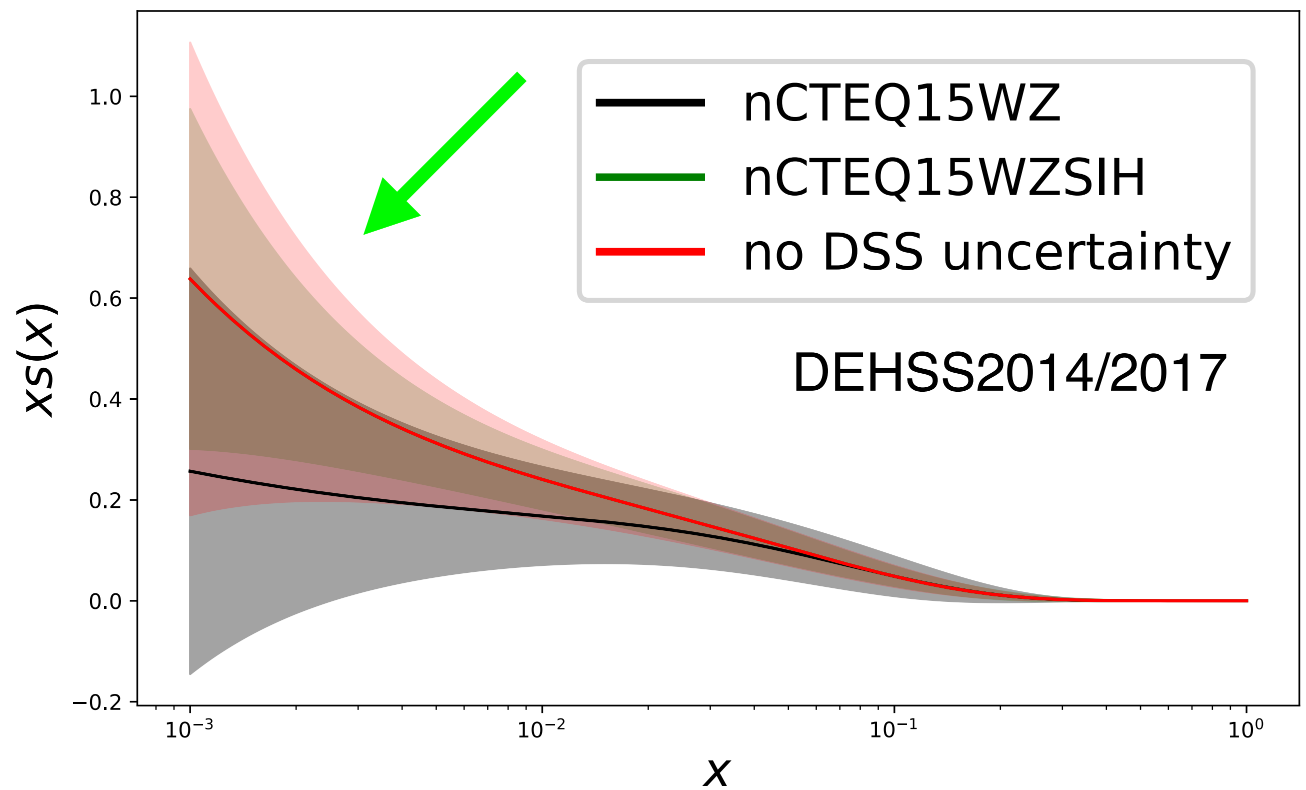
only data up to x=0.7

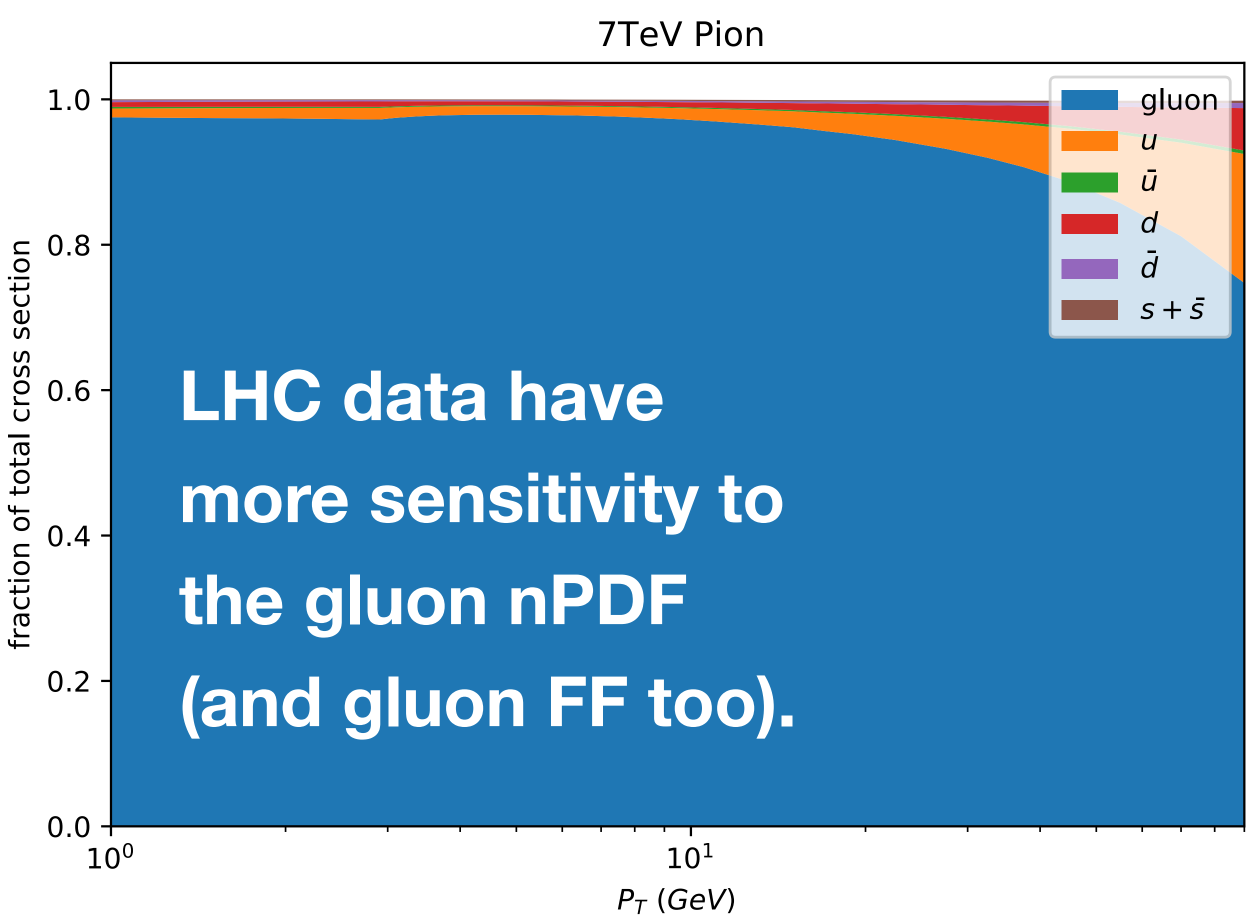


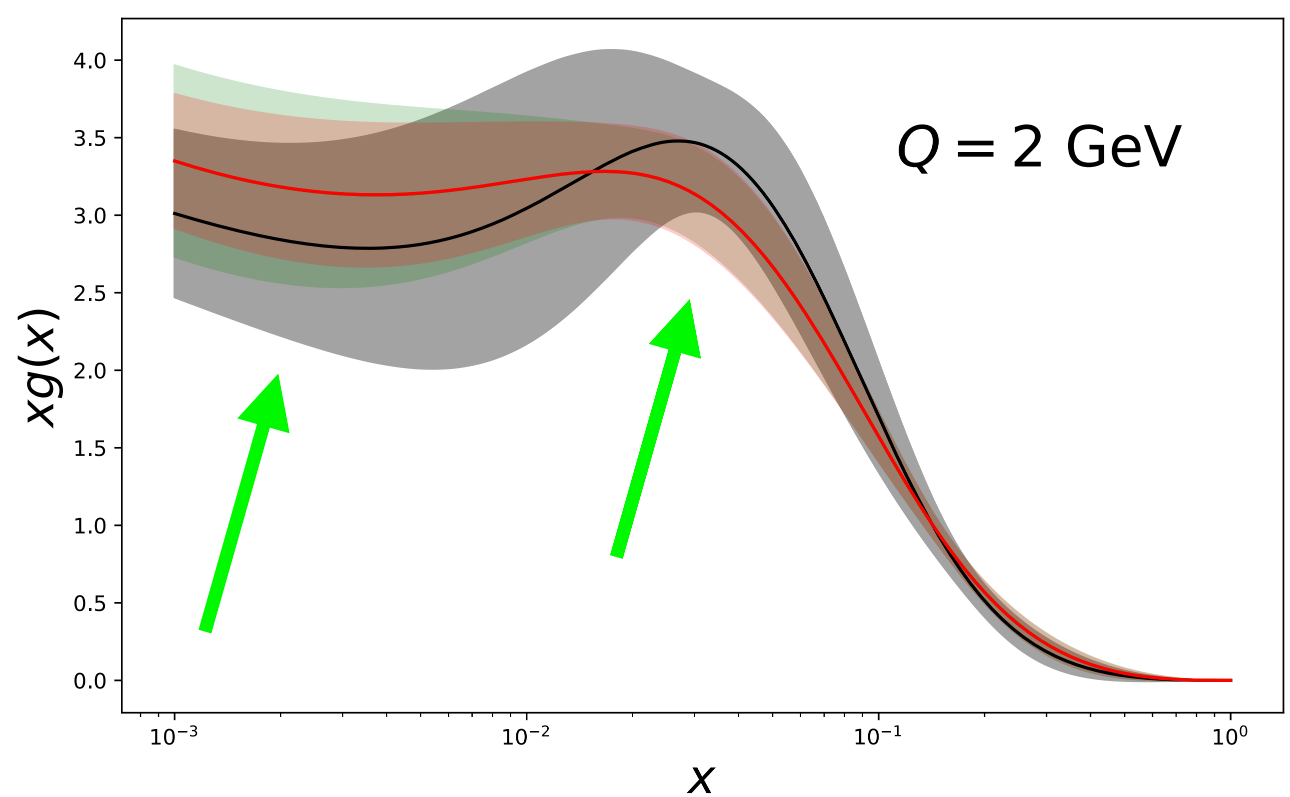
* from F. Muzakka, P. Duwentäster and E. Segarra's talks at DIS2021

Include single hadron production to access the gluon nPDF









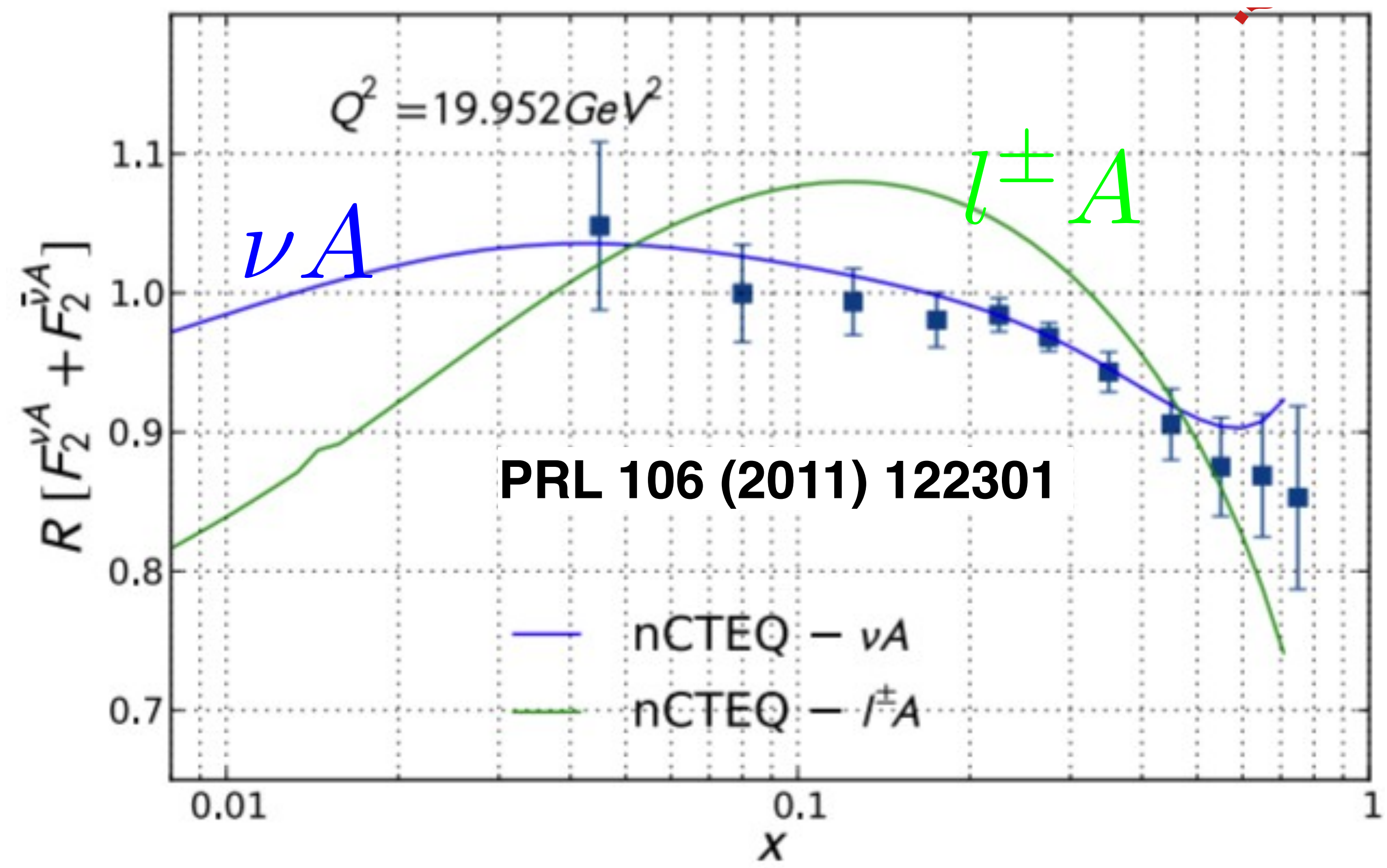
- Systematic study of CC DIS

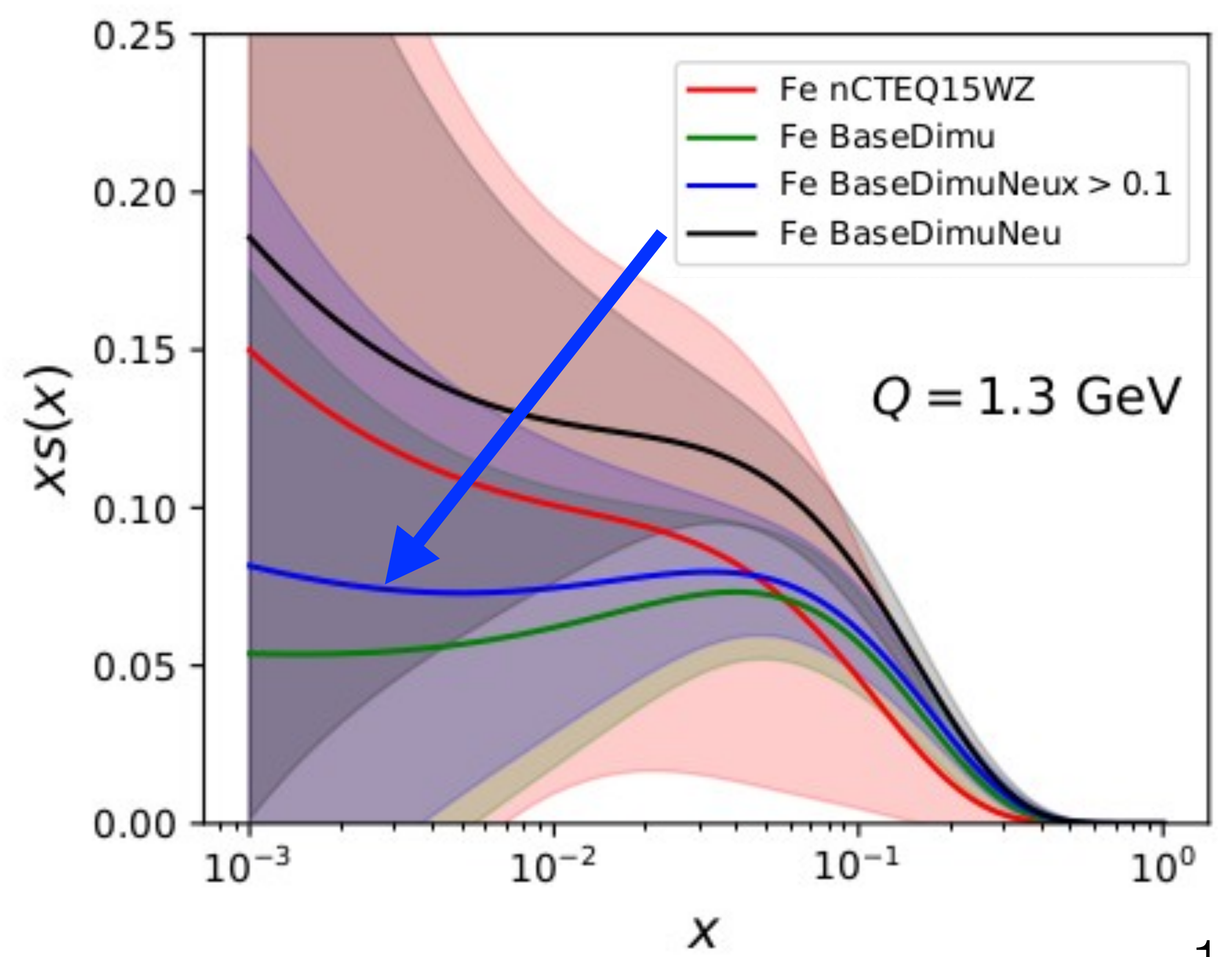
- There is tension among the different neutrino experiments.
  PRL 110 (2013) 212301

- The tensions in the new fit only happen for NuTeV data, and mostly disappear if $x < 0.1$ is removed.

- No problem if fitting structure functions*.
  PRD85, 074028 (2012)

*correlated uncertainties not used (no issue in EPPS16 with CHORUS data and correlated uncertainties)



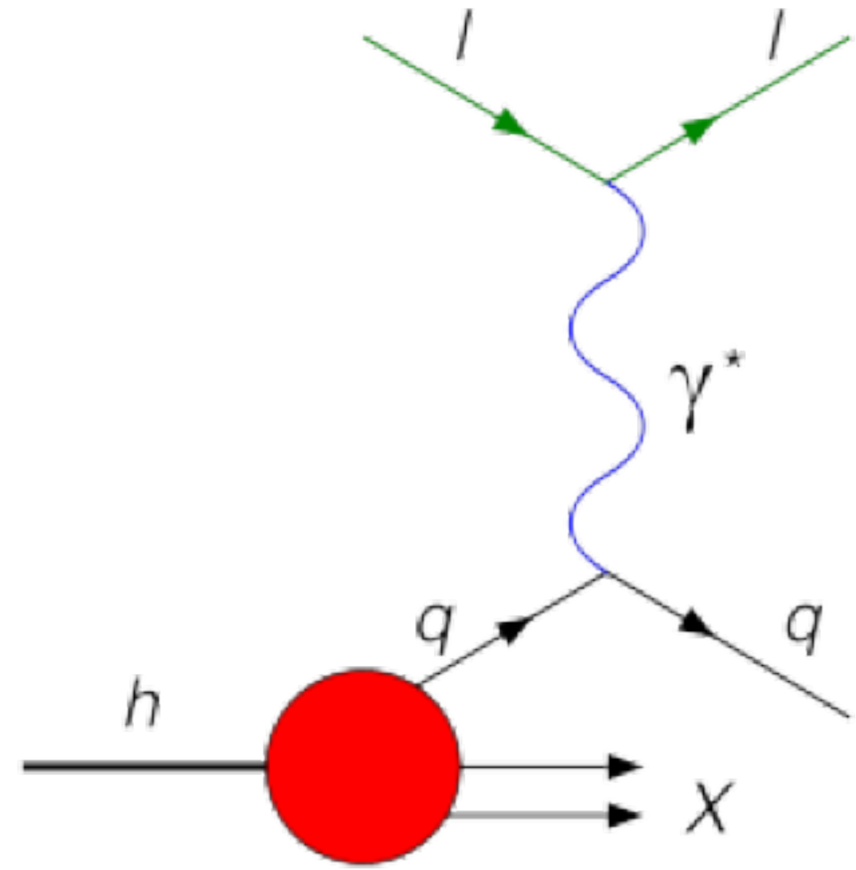


Issues with the extraction of nPDFs

- The amount of data:

NC DIS data	Collider (HERA)	Fixed target, proton/nucleus (16)	Fixed target deuterium
proton PDF fit MSHT EPJC 81 (2021) 4, 341	1264	433	513
nuclear case, same cuts	**0**	1314	615

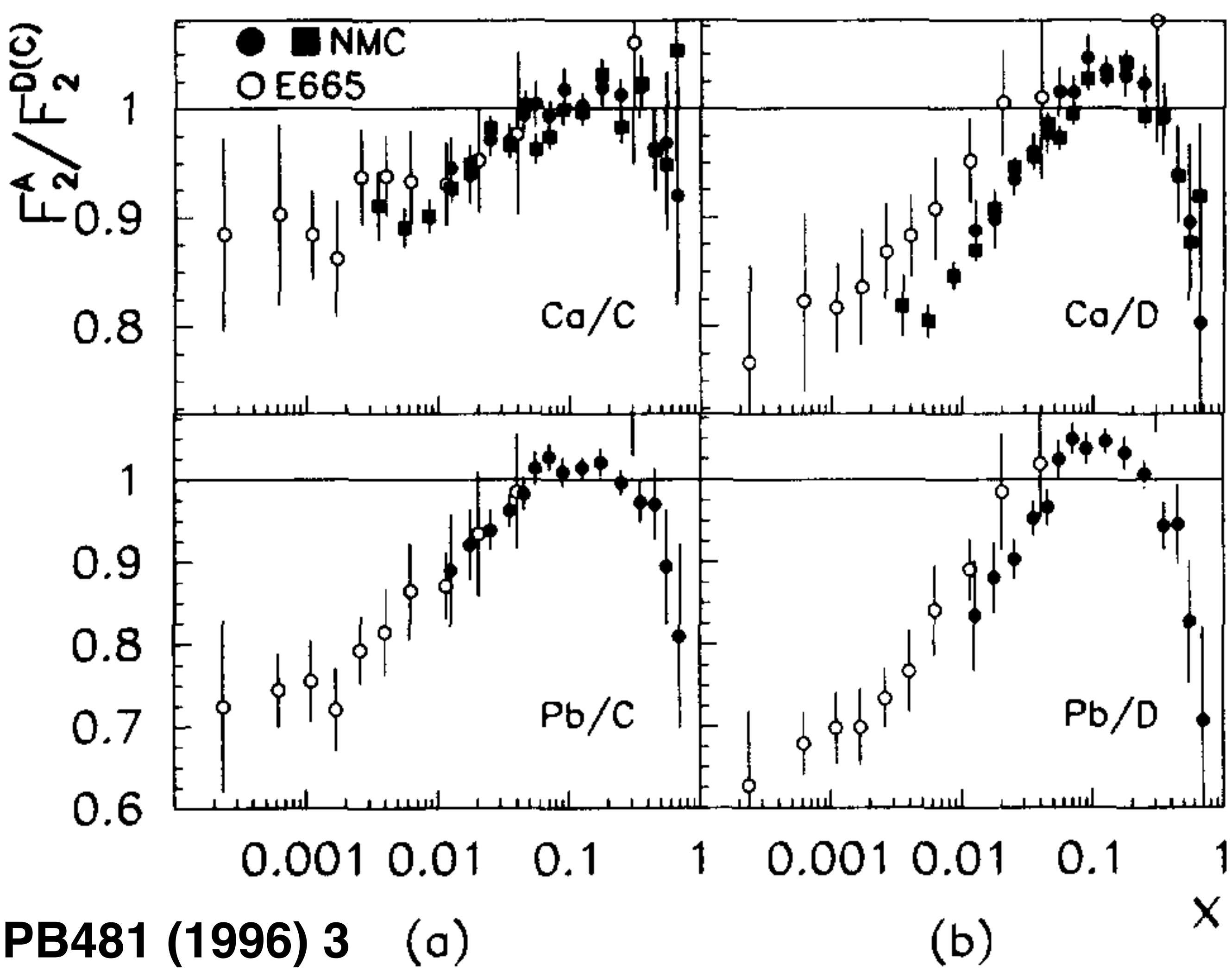
- Most data from fixed target DIS.
- ~57% given as ratios, the rest as F_2.
- Information on F_L lost.
- Drell-Yan does not make a difference.



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

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

~10% ~43% ~2.3%

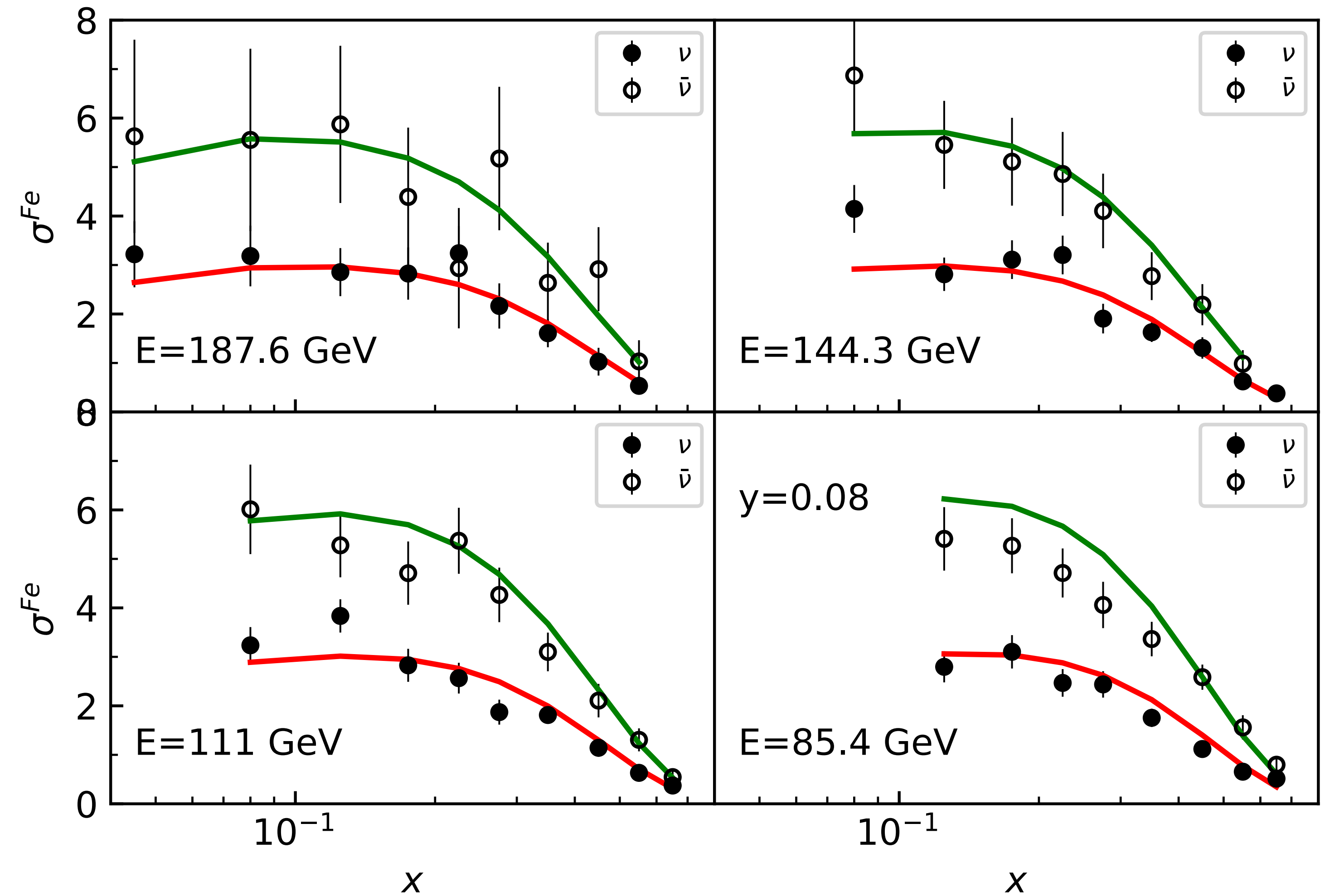


NPB481 (1996) 3

- NC DIS complemented with CC DIS: tensions between data sets, and not very sensitive to nuclear effects.

comparison (not a fit!) using proton PDFs

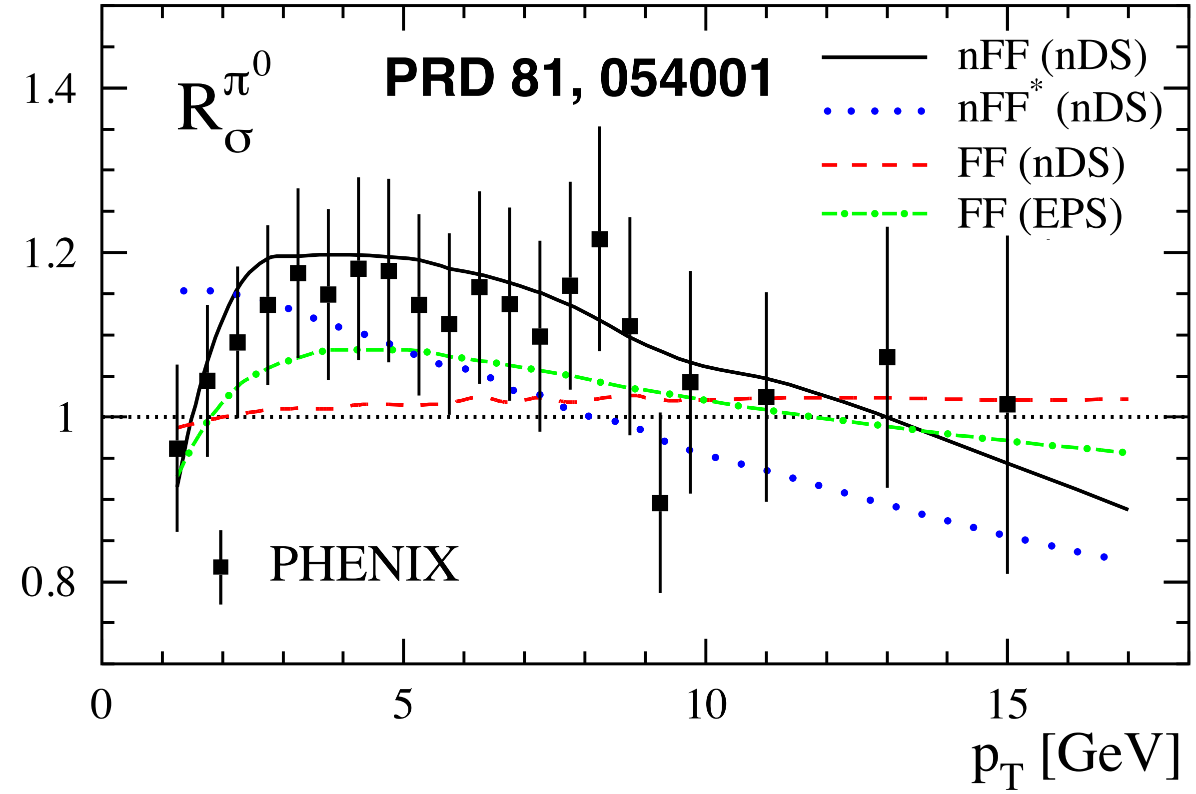
$\chi^2_{CDHS}/N_{points} \approx 1.28$



- The CC DIS data, just like NC DIS off deuterium, are used in almost all proton PDF fits.

we are all guilty of double counting!

- No much data sensitive to gluons: single hadron production at RHIC (now also at dijets at LHC).



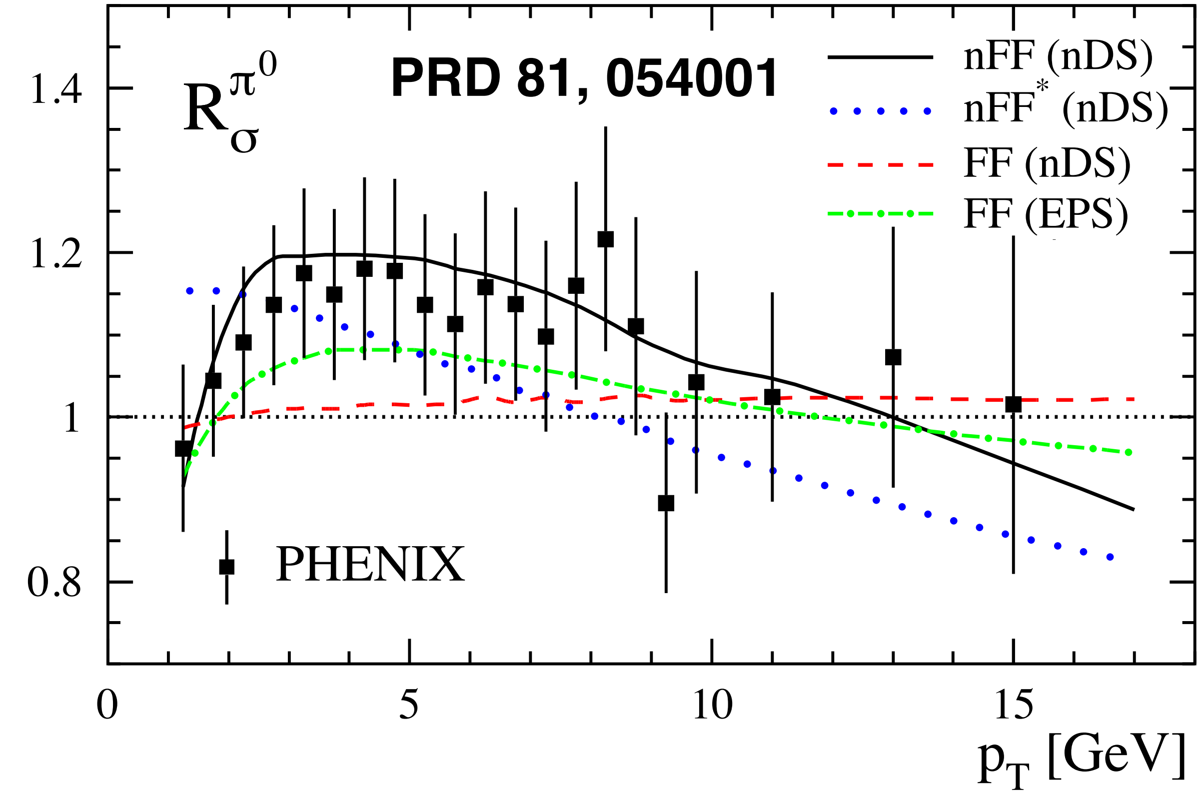
- Tiny problem with this:

We could also have final state effects in the fragmentation process!

- single hadron production data are used to constrain the **gluon FFs**.

- single hadron production data are used to constrain the **gluon nPDF**.

- No much data sensitive to gluons: single hadron production at RHIC (now also at dijets at LHC).



- Tiny problem with this:

We could also have final state effects in the fragmentation process!

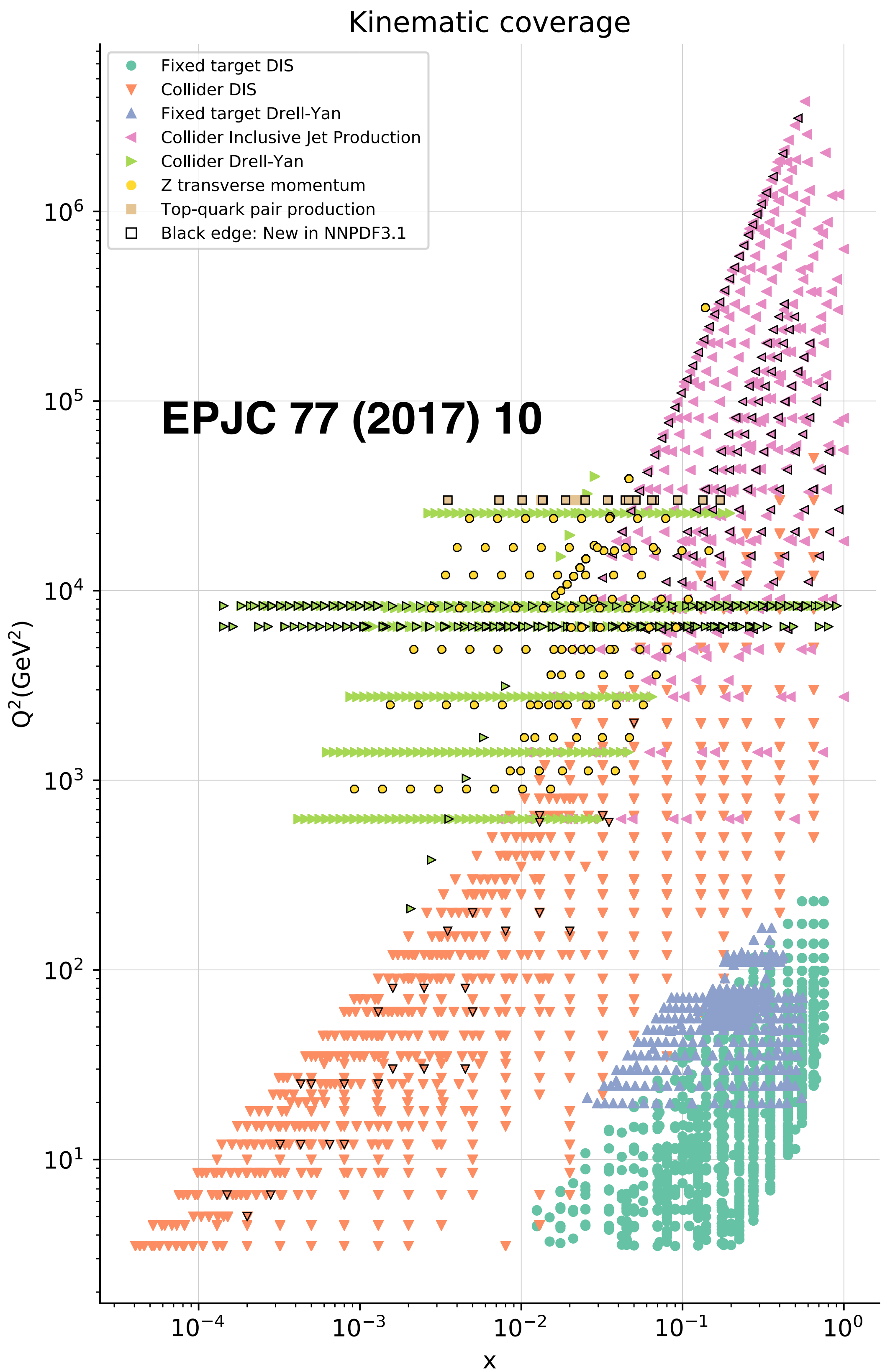
- single hadron production data are used to constrain the **gluon FFs**.

- single hadron production data are used to constrain the **gluon nPDF**.

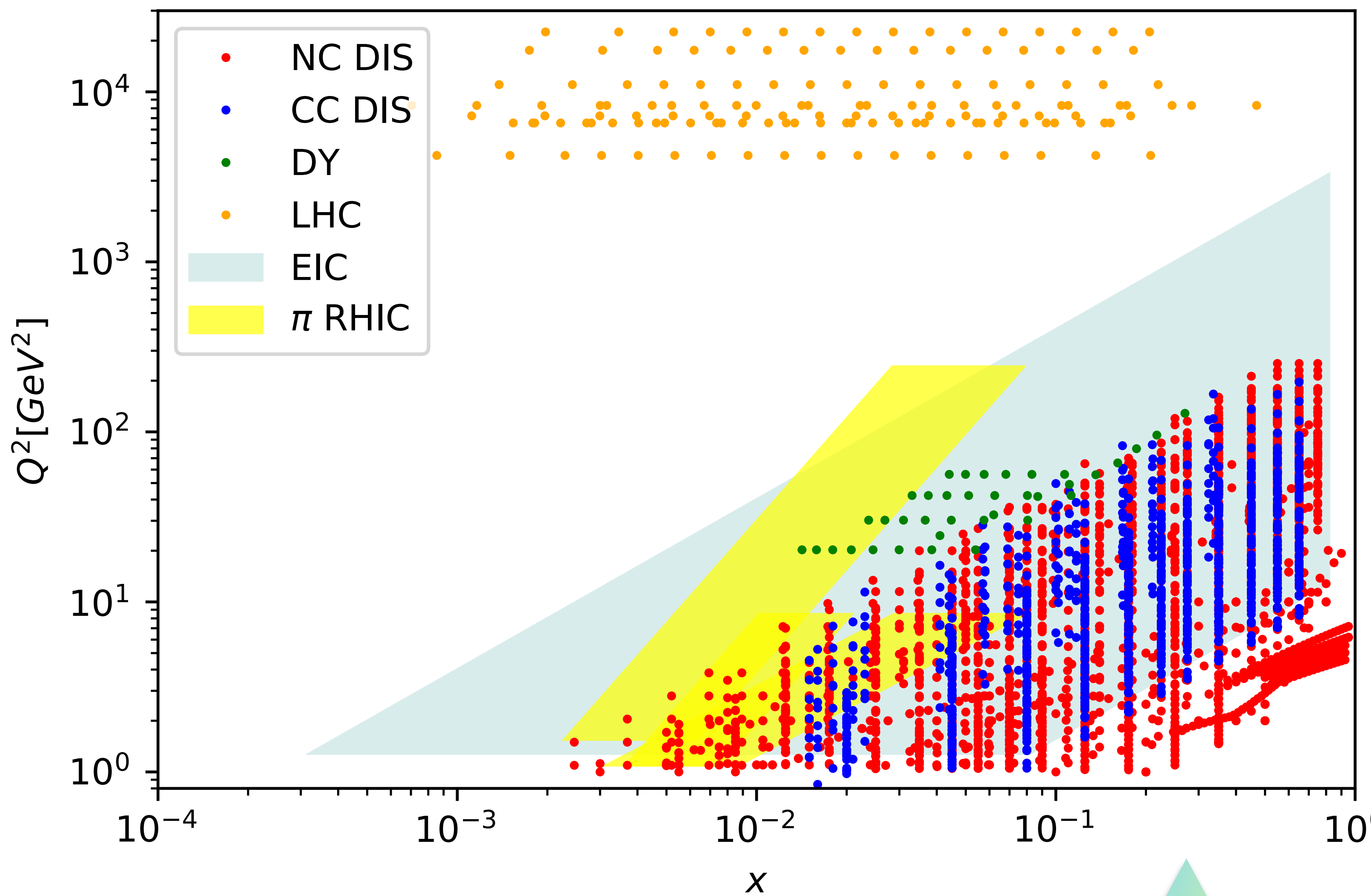
This is us*

*** Of course we are orders of magnitude less adorable.**

Possibly, the worse problem is the kinematic coverage of the data



EIC Yellow Report: arXiv:2103.05419



All fixed target DIS data (~3000 points) can be described with 3 parameters (χ^2/d.o.f ~ 1.02).

proton fit

nuclear fit

How do we solve this?

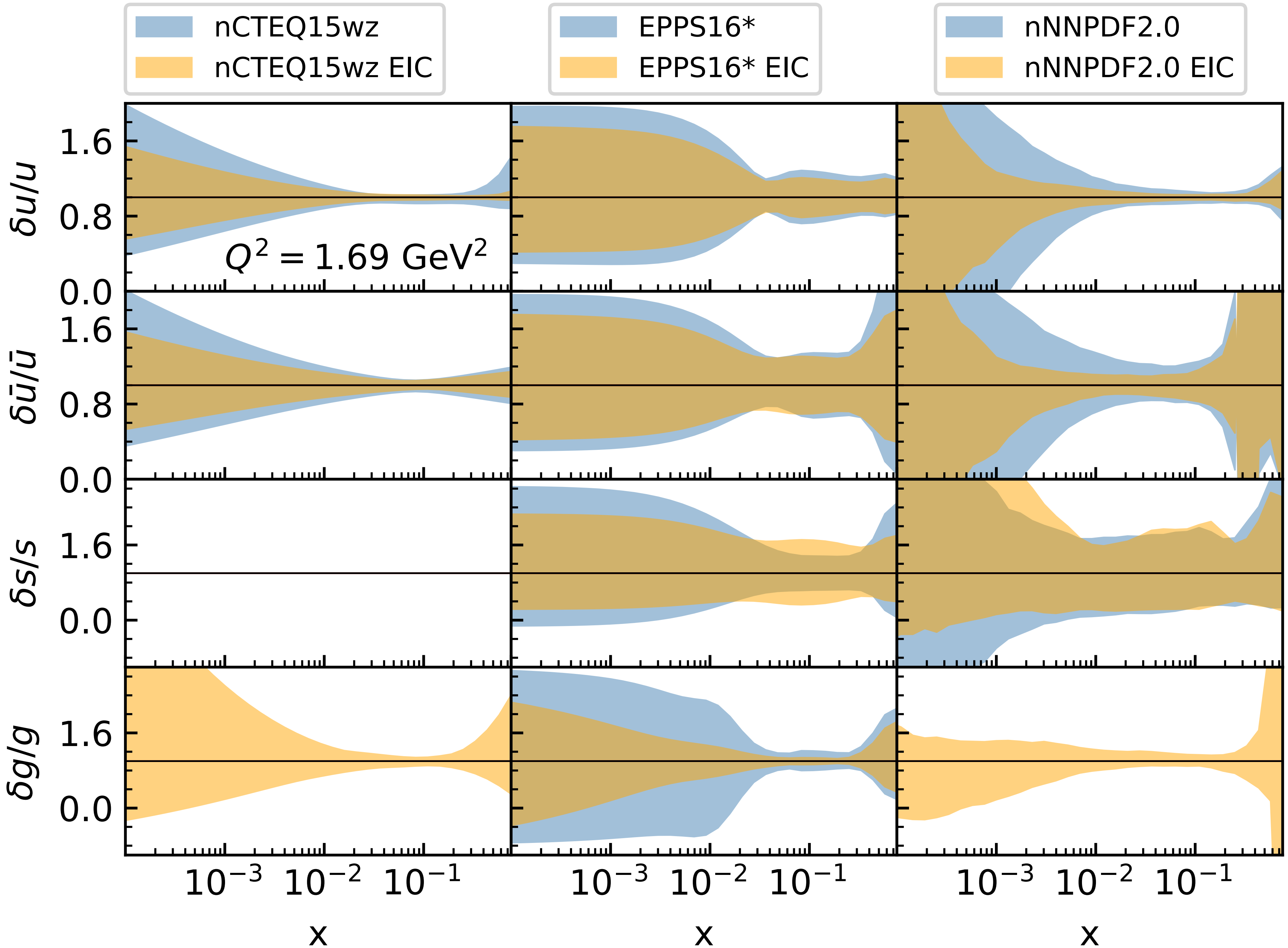
- get more data in the fit
  - new data from current experiments
  - "new" data from old experiments
- get more observables in the fit
  - e.g. heavy mesons
  - SIDIS?
  - impact parameter dependent data?
- just build a new experiment!
  - **EIC**
  - LHeC?
  - FCC-eh?

Fake it till we make it: impact studies

- make a fit using the data and the "data" → the "real" thing 🙂 takes a long time ☹️
- use a statistical method to add the "data" to a fit → depends a lot on the parametrisation ☹️ fast 🙂

JHEP 1412 (2014) 100

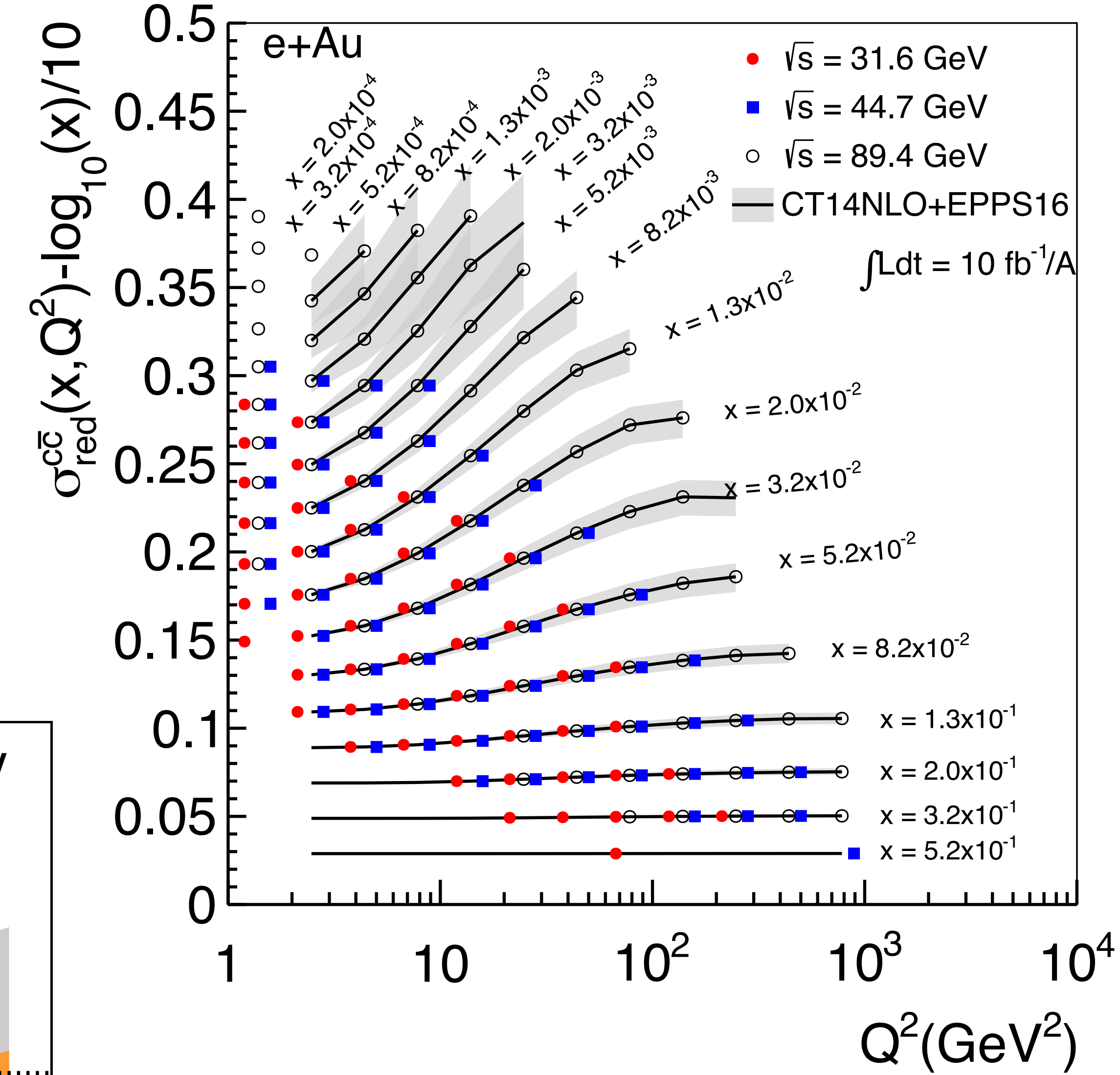
- Of course we want colliders like LHeC and FCC-eh.
- We have seen already impact studies for RHIC yesterday.

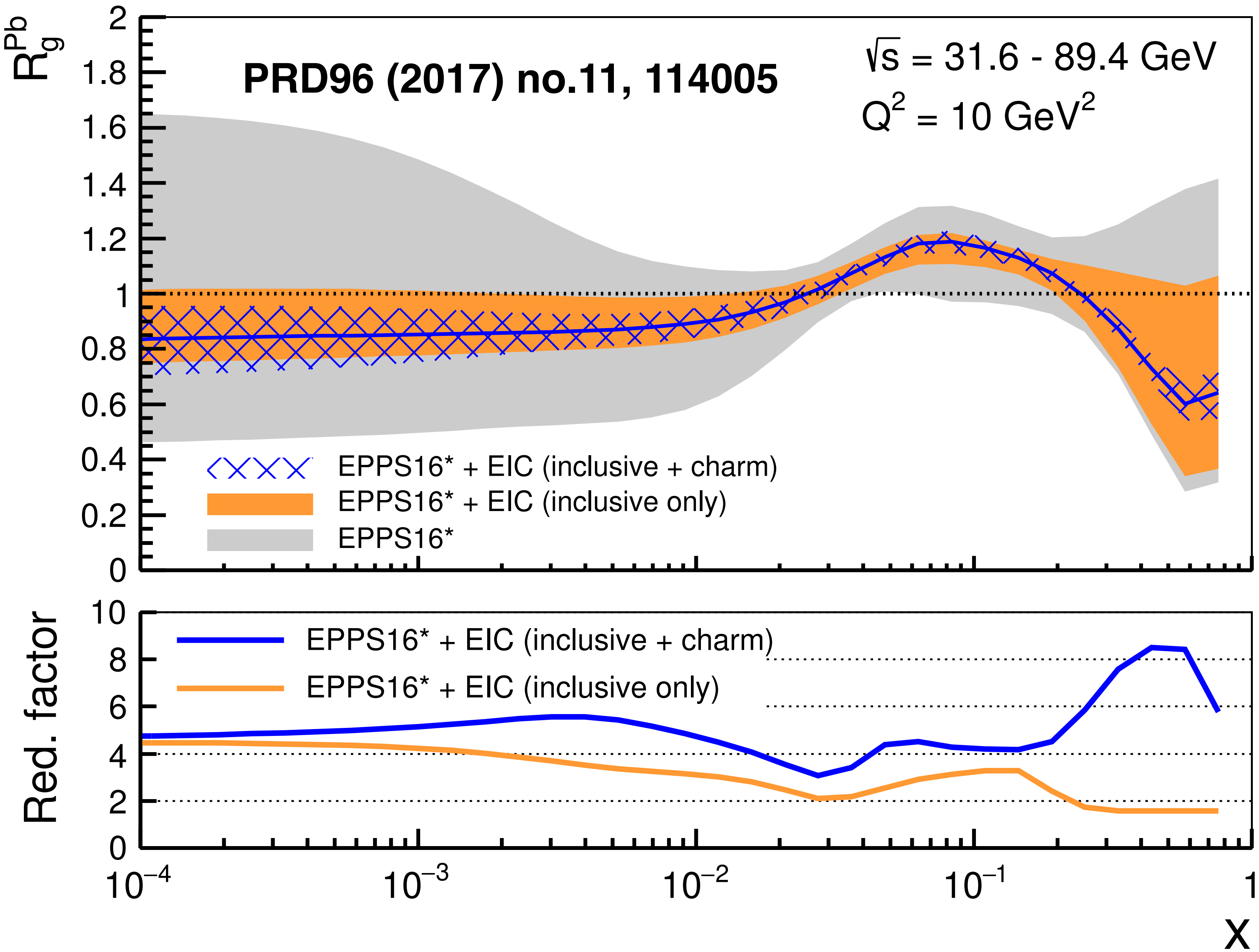


- change in the relative uncertainty after inclusion of EIC pseudo-data.
- the majority of the effect lies in the x < 10^{-2} region.

EIC Yellow Report: arXiv:2103.05419

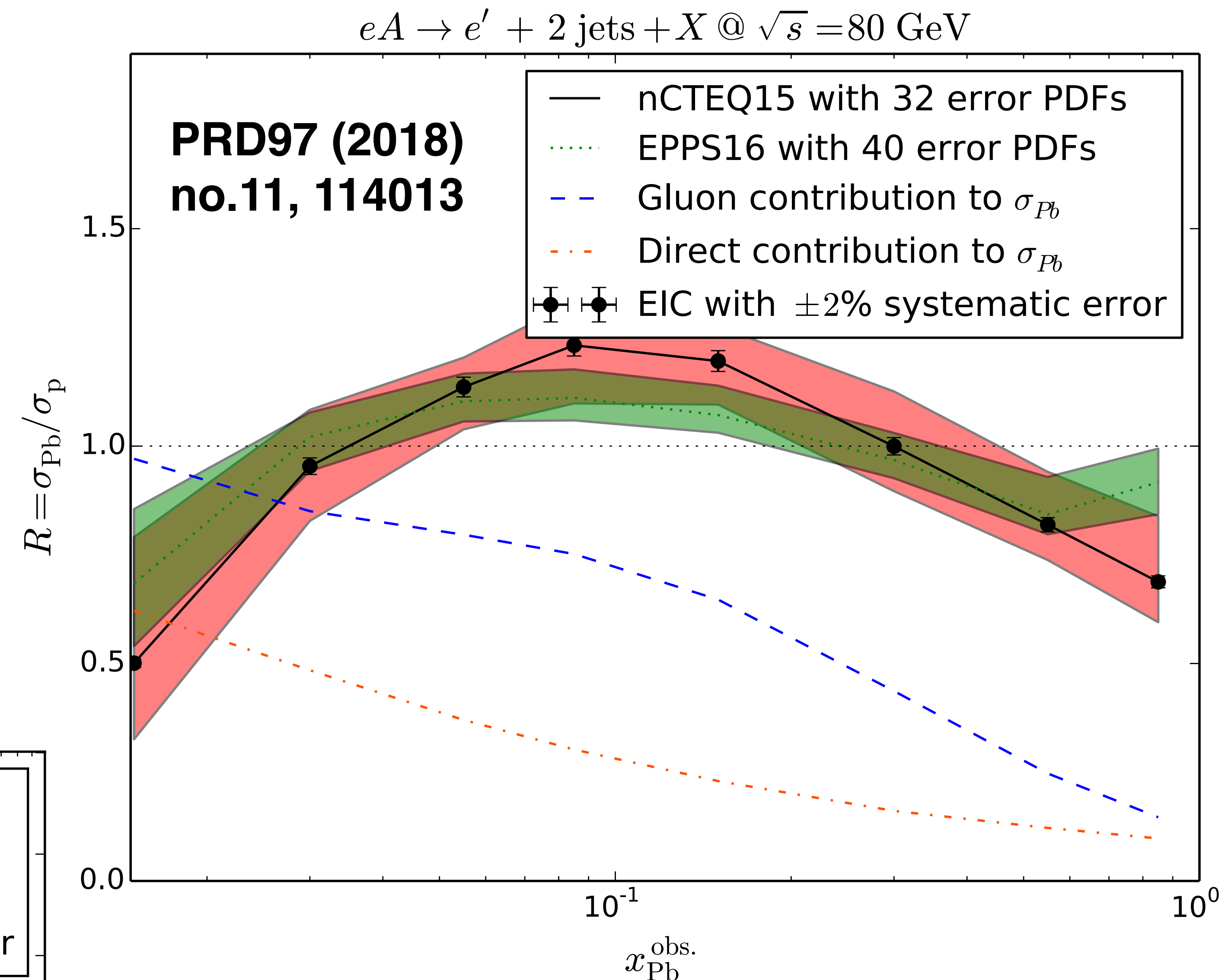
new! charm DIS

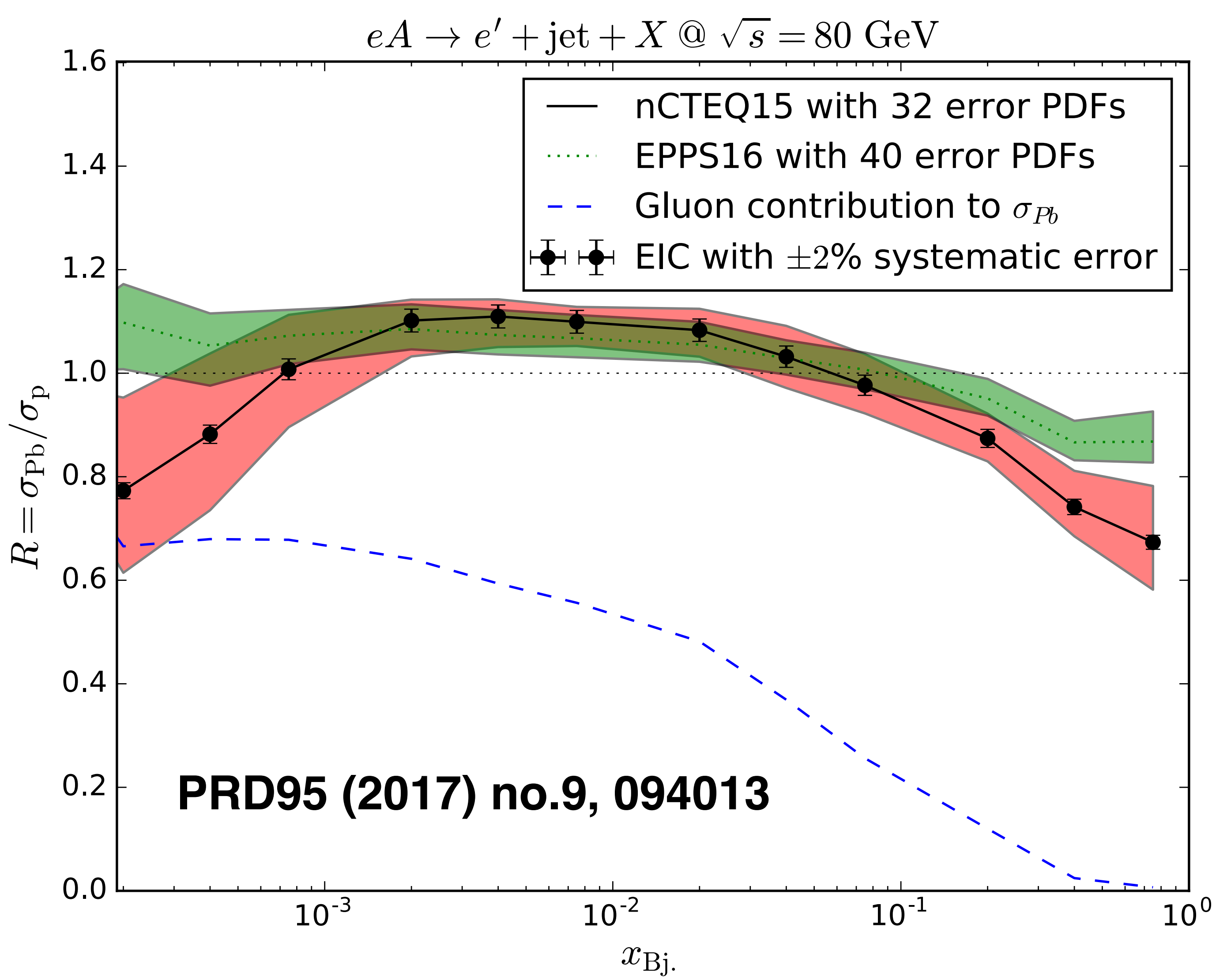




- Up to a factor 8 reduction of the nuclear gluon uncertainty at high x!

sensitivity to the gluon PDF
at low x





sensitivity to the gluon PDF
at low and high x

Summary

- There are many different sets of nPDFs available (all “good”).
- The limited kinematic coverage of the data (among other things) severely hampers the extraction of nPDFs.
- Within limitations, improvements are achieved. New ideas and data are coming into play.
- For some observables the inclusion in fits require extra considerations from the theory side.
- The issue of nuclear effects in proton PDFs is being seriously addressed.

"… 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