# Recent theoretical progress in nuclear structure (nuclear PDFs)

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**LHCP2021, June 7-12, 2021**


# Outline

- A quick reminder of nPDFs
- Latest results
- The future
- Summary

# What are the nPDFs?

We know that the PDF $f_a(x,Q^2)$

* is the probability of finding (in a hadron) a parton *a* carrying a fraction *x* of its momentum.
* can't be computed in pQCD but are universal.
* evolve in $Q^2$ with DGLAP evolution equations.
* obtained from global fits to the world data (DIS, DY, jets, EW boson, top, etc).

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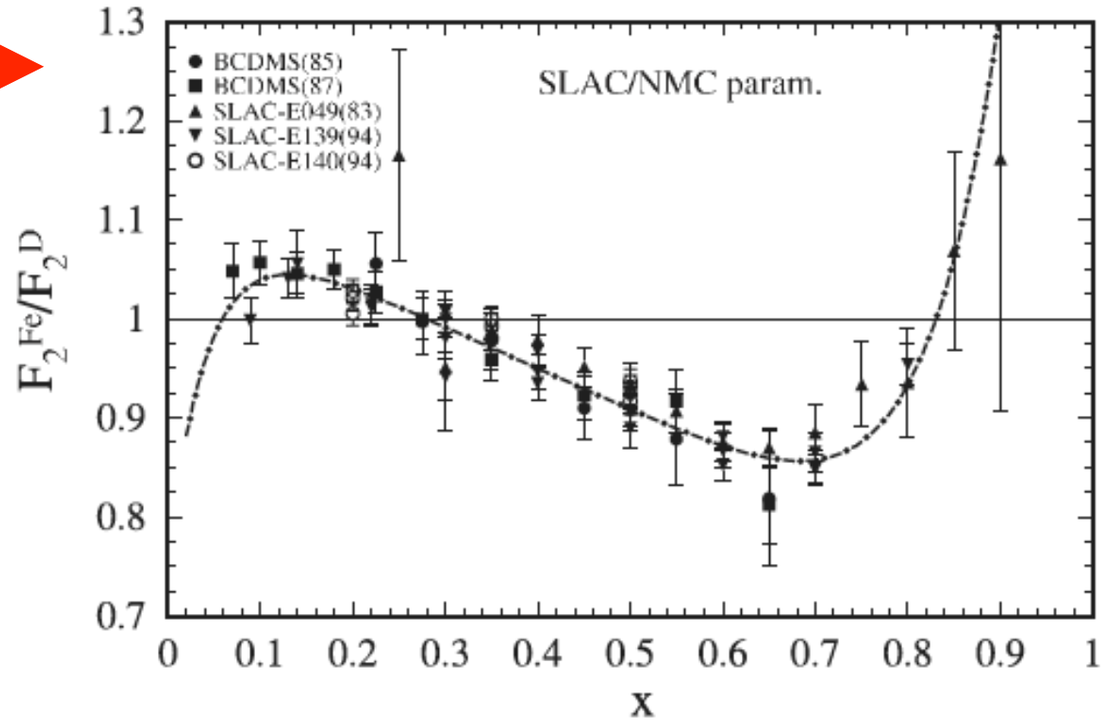
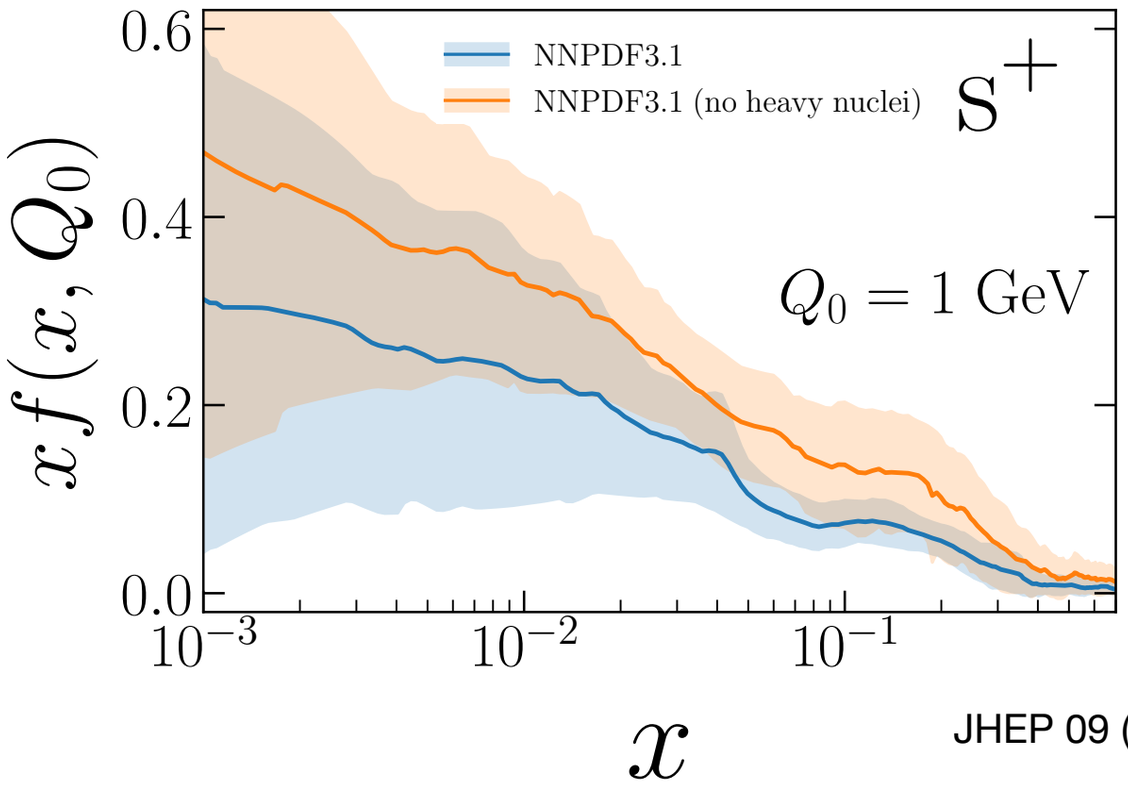
For the nuclear case we introduce $f_a^{p/A}(x,Q^2)$

# Why do we need them?

- to understand data like




- they are the initial state for HIC.
- they might be relevant to understand the composition of cosmic rays.




- nuclear data are used to separate flavours in proton PDF fits.

JHEP 09 (2020), 183

# How to extract nPDFs?

just like proton PDFs: take the data and do a fit

* a proton PDF is taken as baseline and a smooth dependence in A is assumed

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

- $f_i^p(x, Q_0^2) R_i(x, A)$
- $f_i^p(x, Q_0^2) \otimes R_i(x, A)$
- $f_i^{p/A}(x, Q_0^2, A)$
- **neural network**

* isospin symmetry is assumed to be valid

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

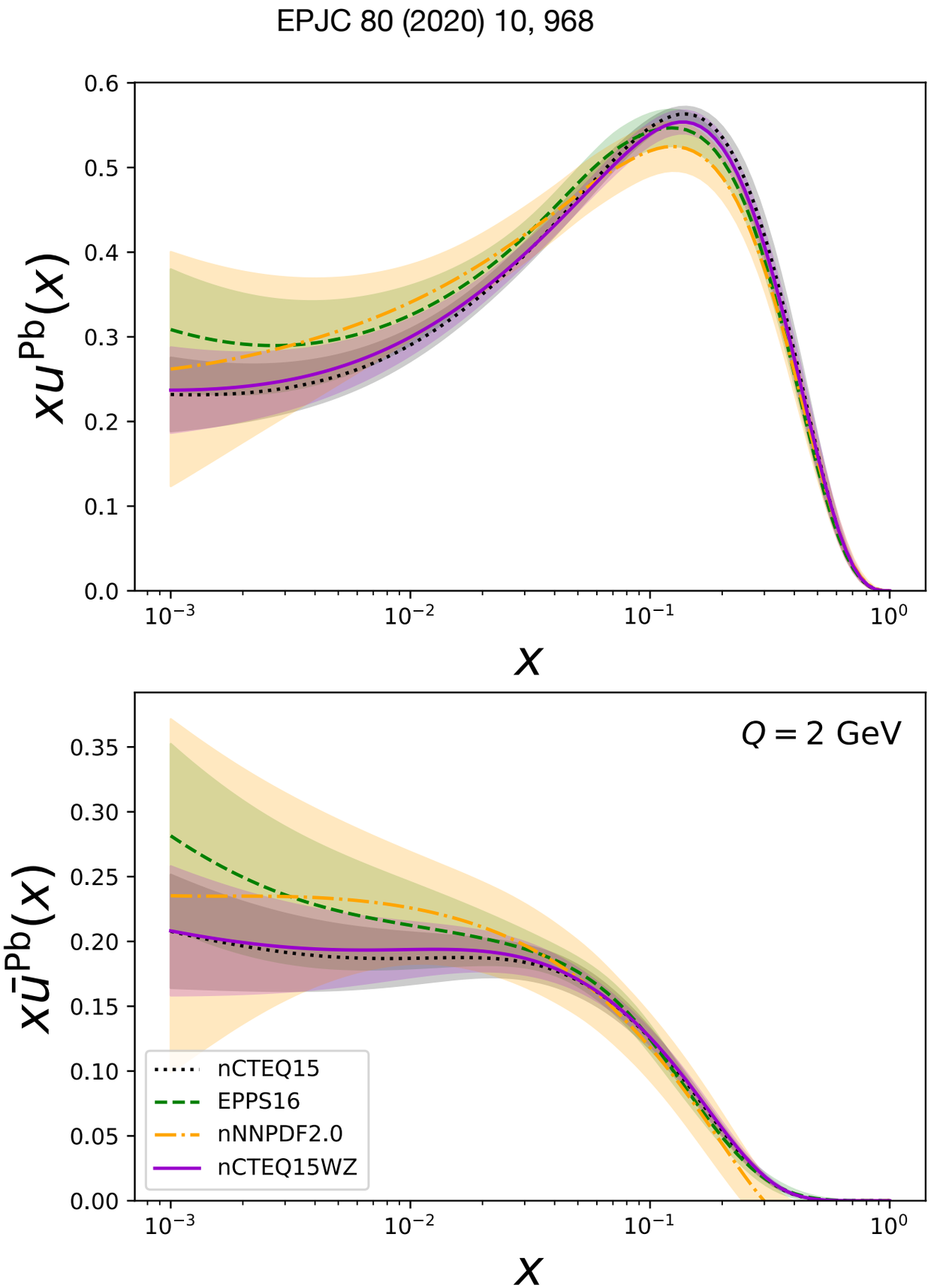
# In the fitting procedure every step implies a choice and each choice has an impact on the final result

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

different data selection, error treatment, proton baseline, $Q_0$,

heavy flavour scheme, perturbative order, …

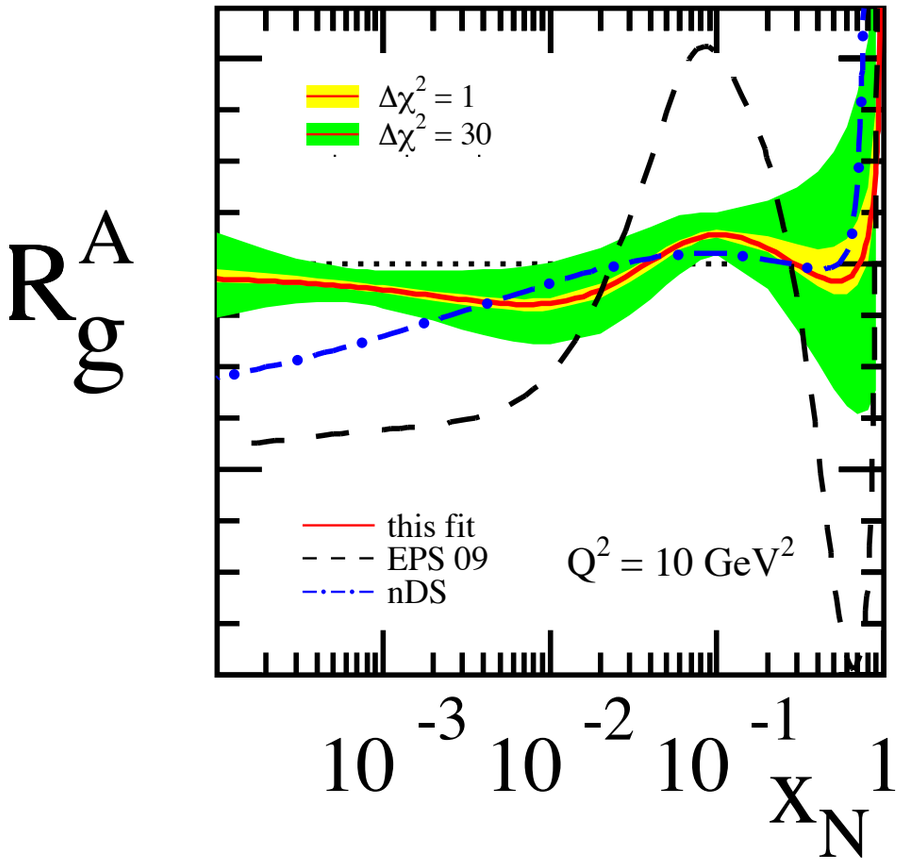
A quick reminder

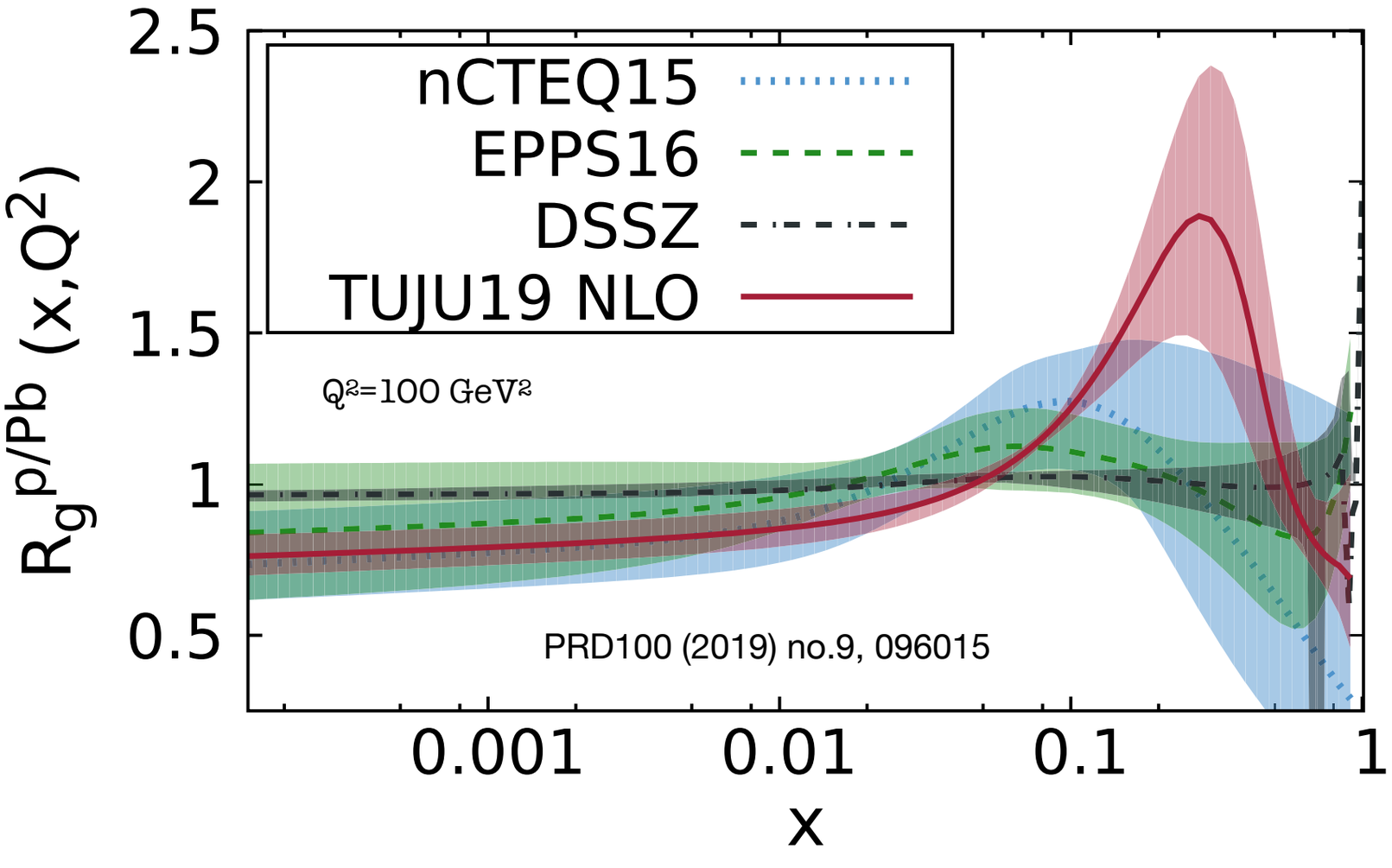



- most of the data used in the fits sit at $x > 0.01$.
- the modification of the valence up is the best constrained.
- separation of up and down mostly through NC and CC DIS.
- the sea distributions are not well constrained.
- flavour separation in the sea sector is not yet fully achieved.

PRD85 (2012), 074028

* gluon-sensitive data: single hadron production at RHIC




* TuJu19 has no data that can constrain the gluon.

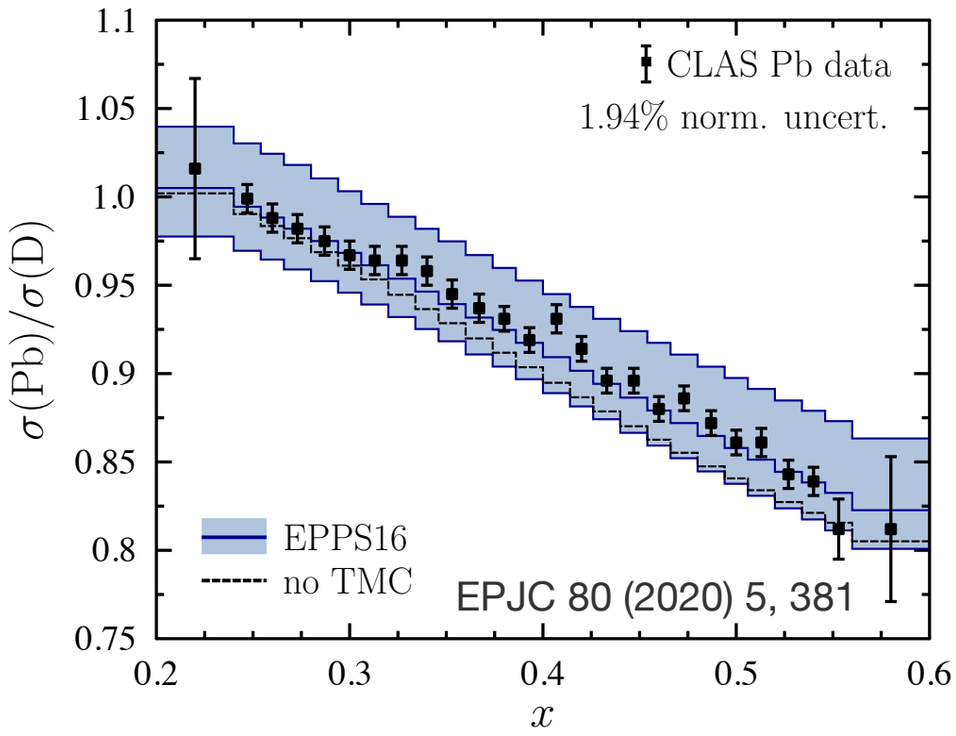
# Latest results on nPDFs

- many groups are currently updating their nPDFs using “new” and new data:

  “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…

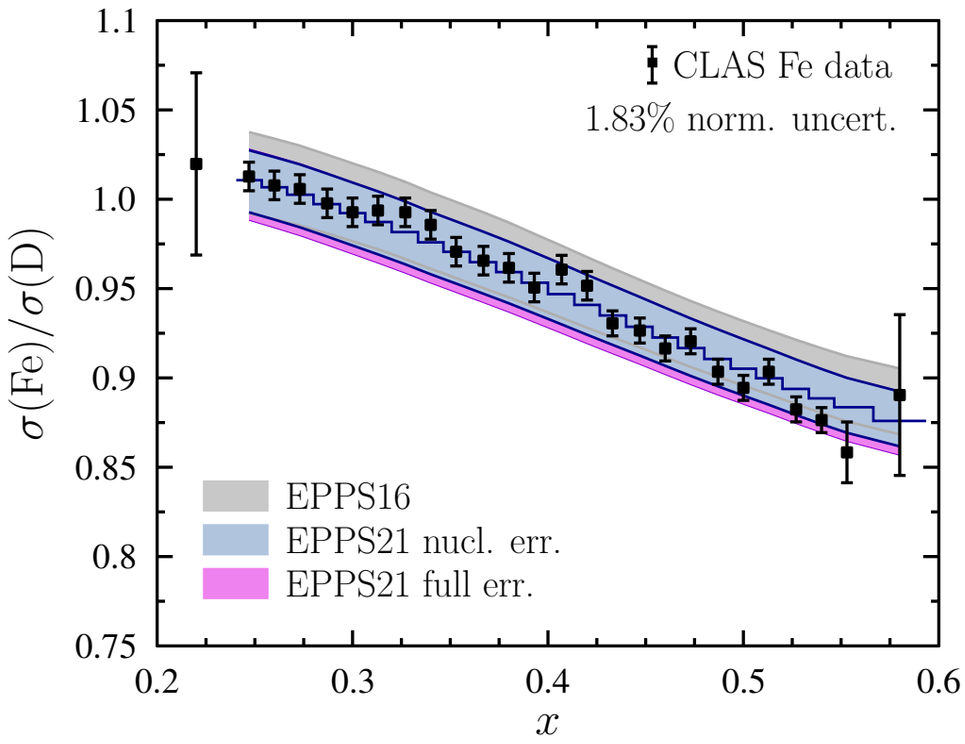


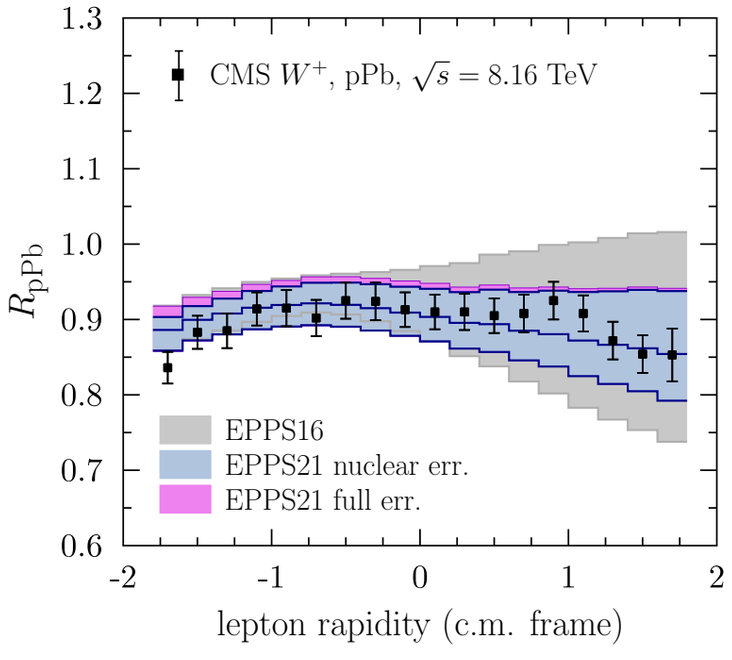

* see Cynthia Keppel’s talk tomorrow

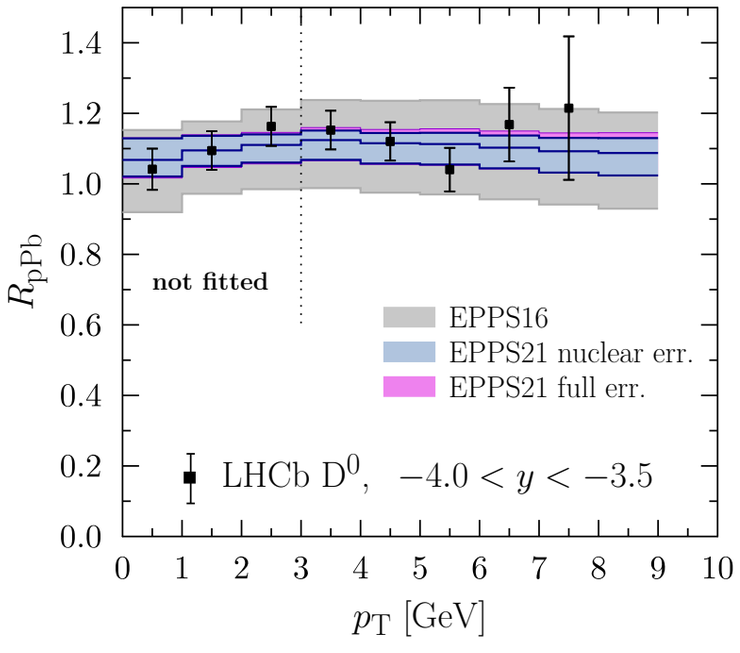
** see Vadim Guzey’s talk tomorrow

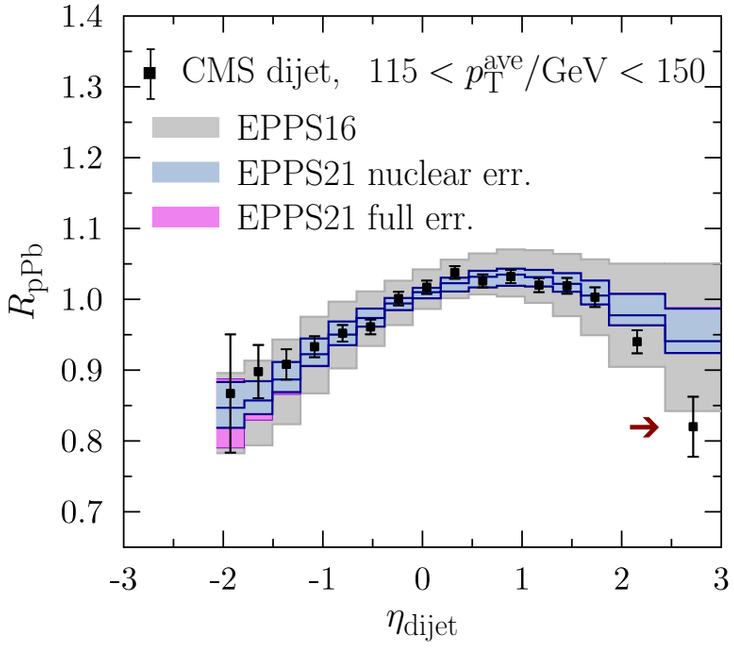
# (preliminary) results from EPPS*

- JLAB and LHC data
- leading TMC included
- proton uncertainties considered
- ratios used whenever possible



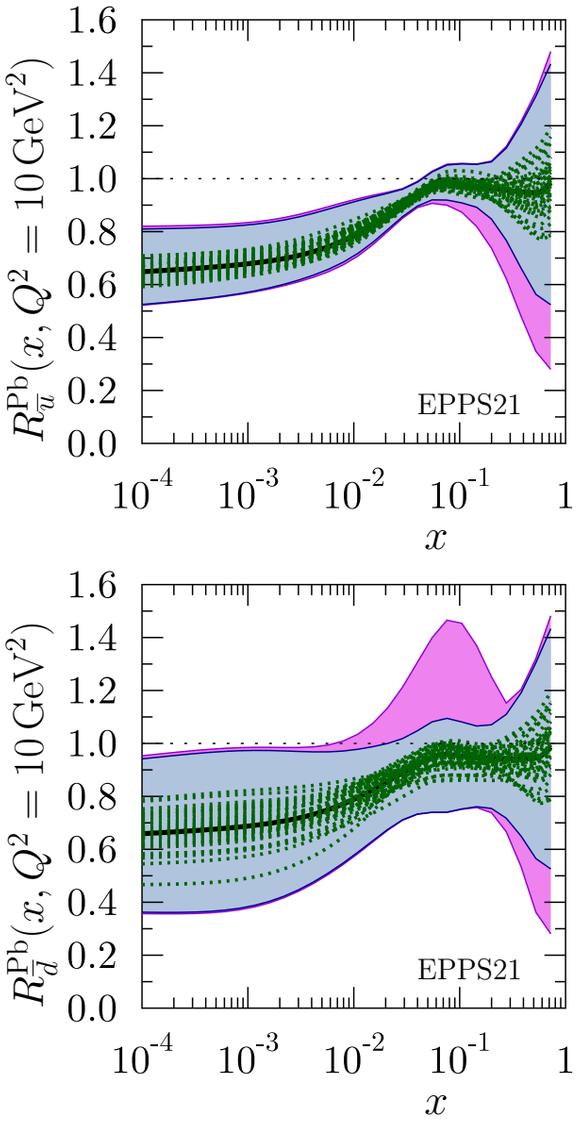




* from Petja Paakkinen's talk at DIS2021

# Latest results

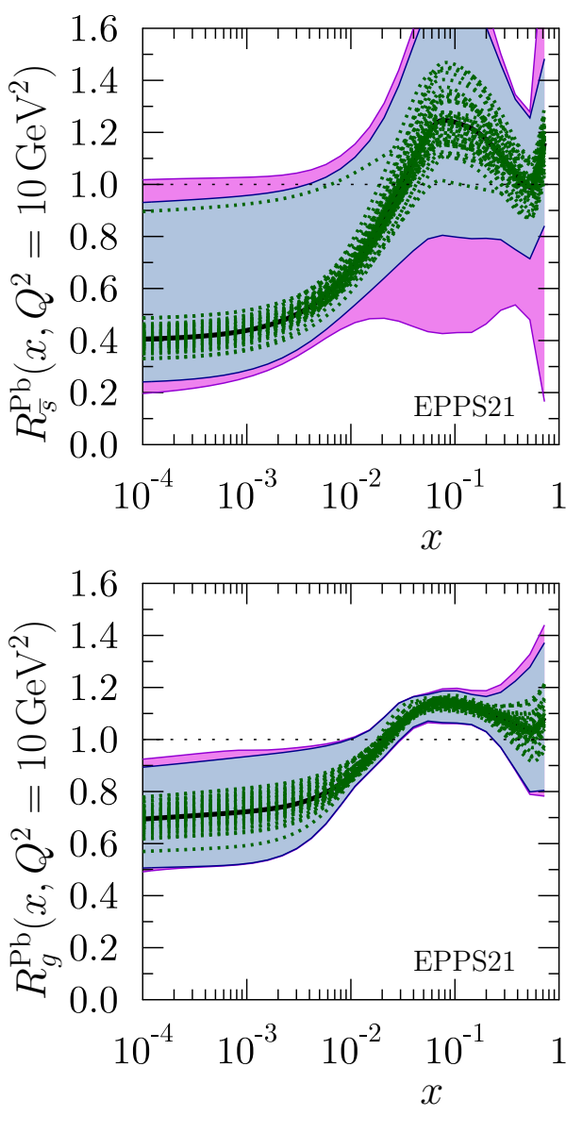
Lead







Lead

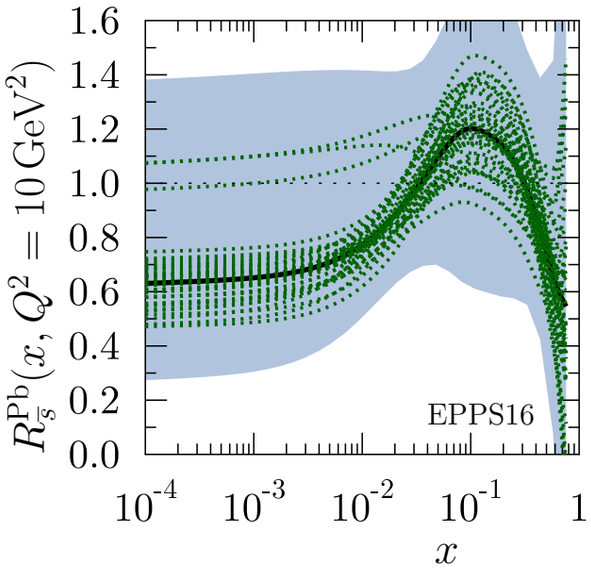






## Lead

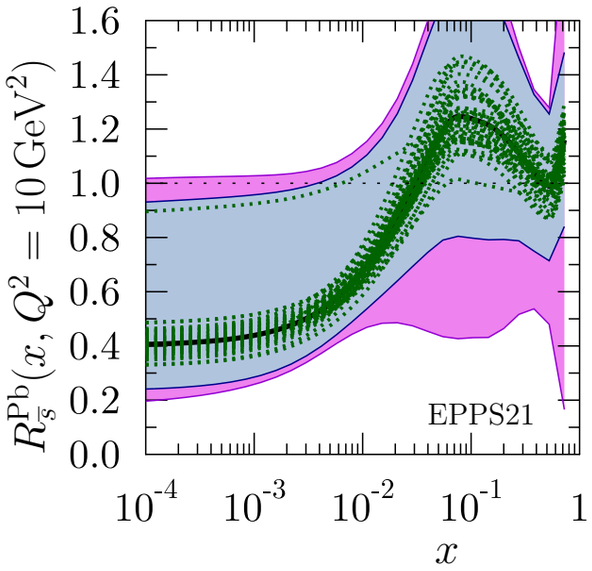
EPPS16







EPPS21 *prelim.*



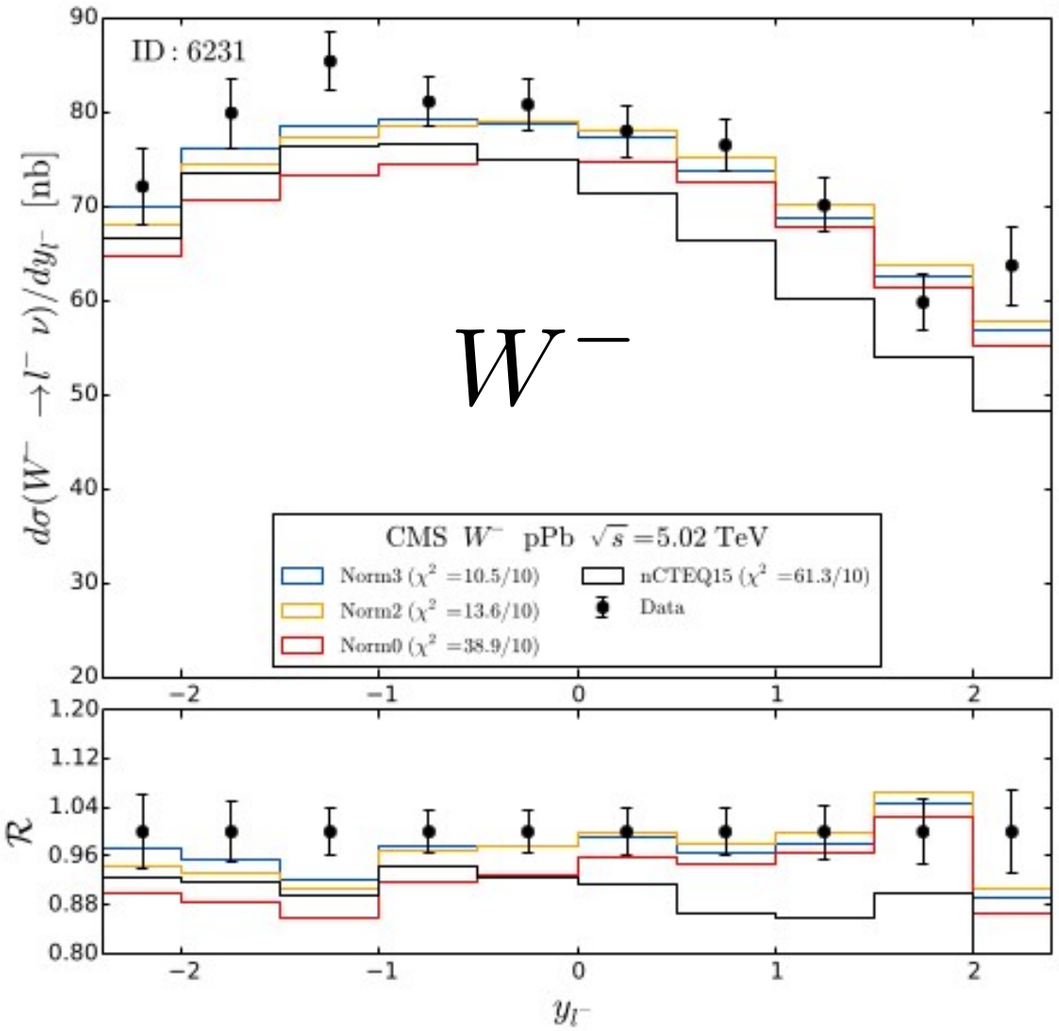


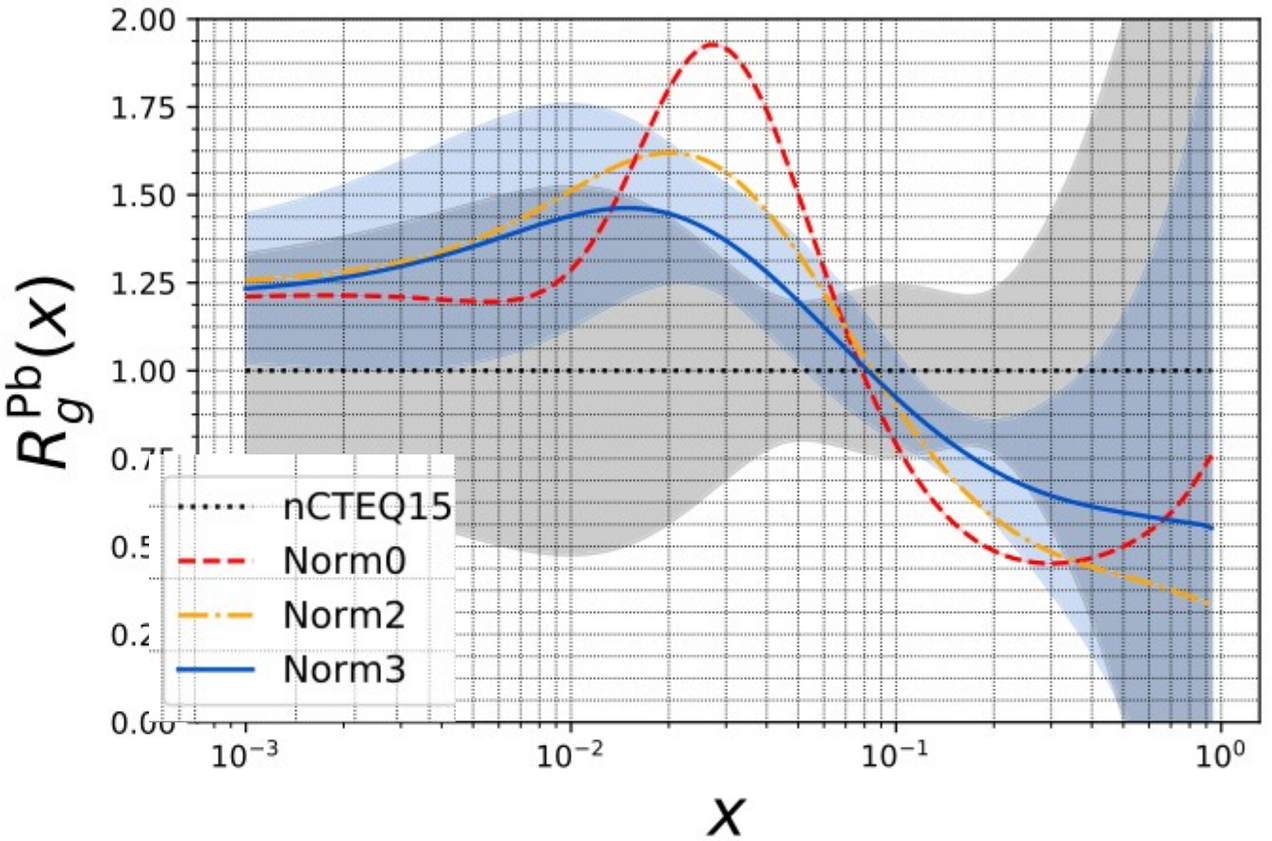


- Better constrained gluon anti-shadowing
- Flavour separation not (much) improved

# (preliminary) results from nCTEQ*

- incorporate W and Z boson production from LHC

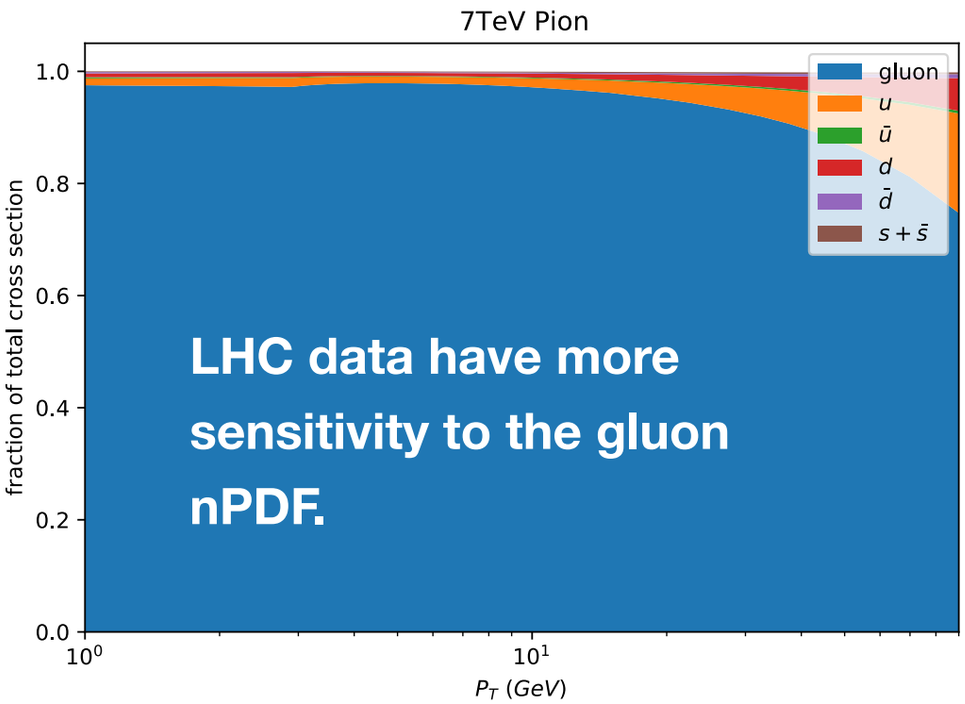



* from F. Muzakka, P. Duwentäster and E. Segarra's talks at DIS2021

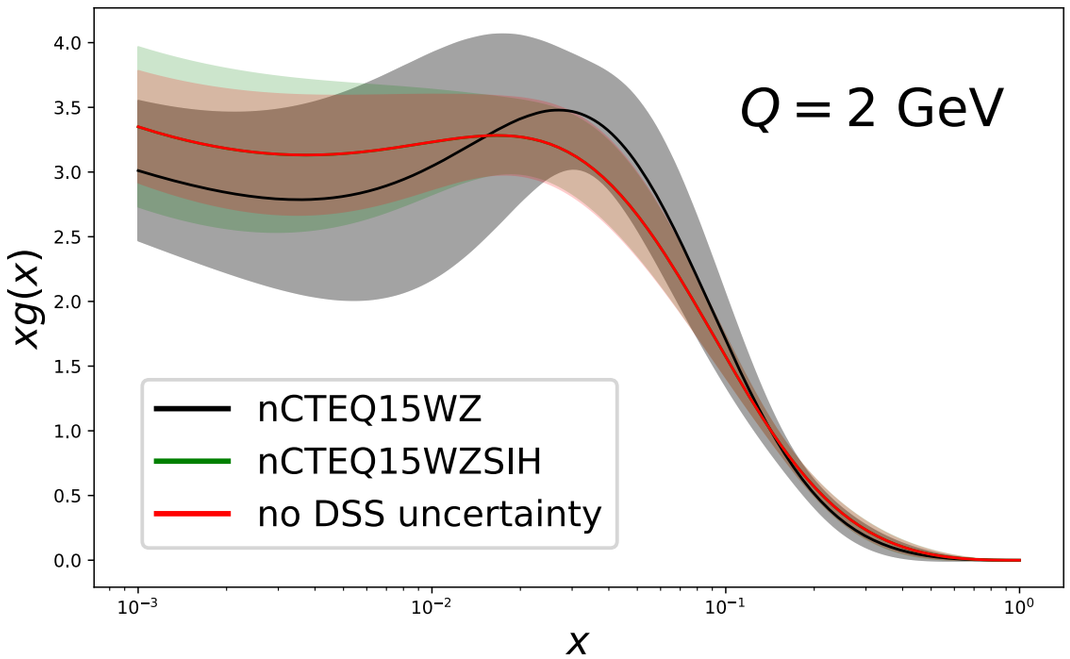
# incorporate single hadron production to access gluon PDFs









## CC DIS (a bit controversial)

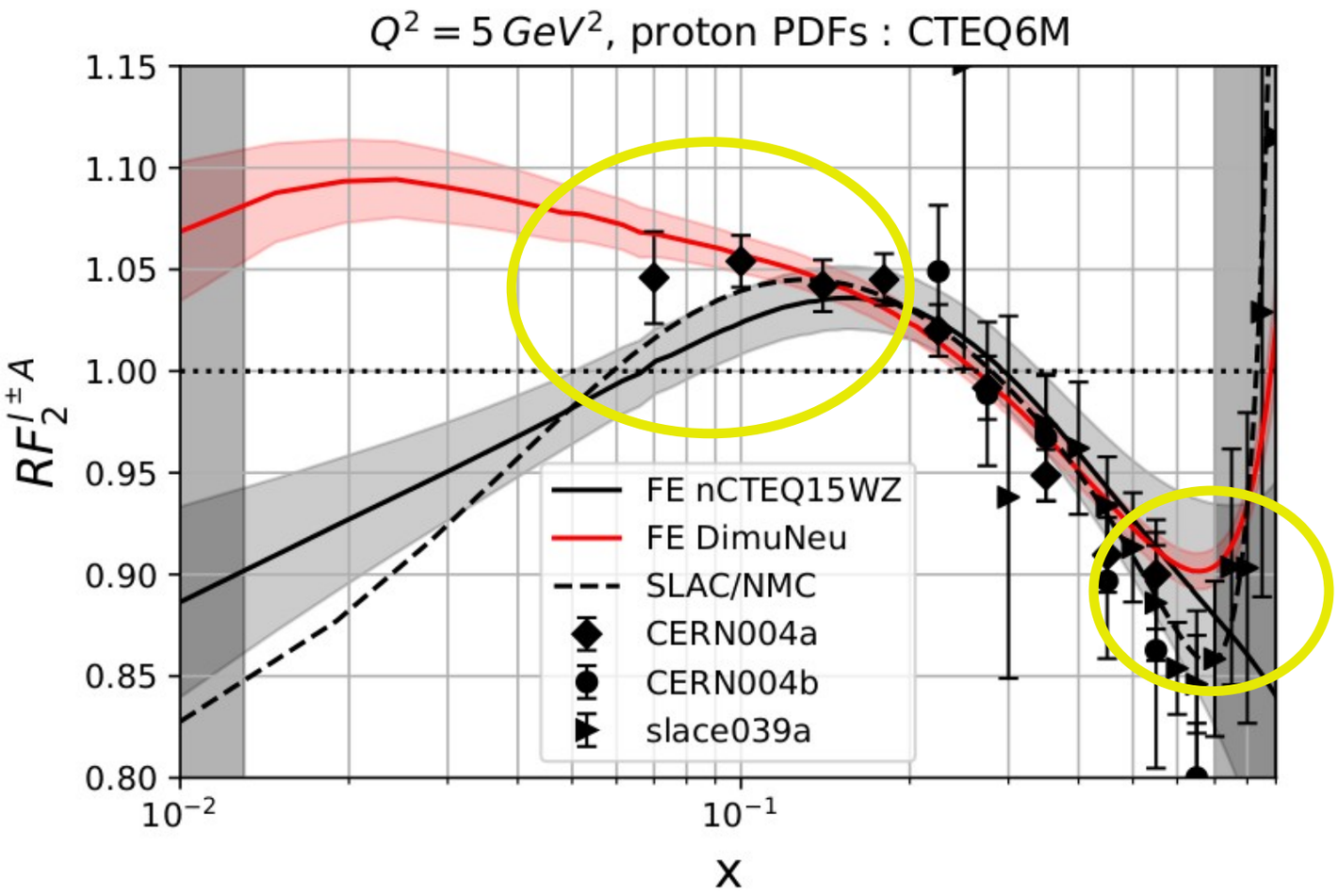
There is tension among the different neutrino experiments.

PRL 110 (2013) 212301

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

- **DimuNeu : Dimuon+ CDHSW+Chorus+NuTeV**
- **Total $\chi^2/pt$ :**
  - **Dimuon : 1.27**
  - **NuTeV neu, antineu : 1.50 , 1.23**
  - **Chorus neu, antineu : 1.27 , 1.09**
  - **CDHSW neu, antineu : 0.60 , 0.72**
  - **ALL : 1.17**
- **TENSION between neutrino data sets at low x!**

"low x" : x < 0.1

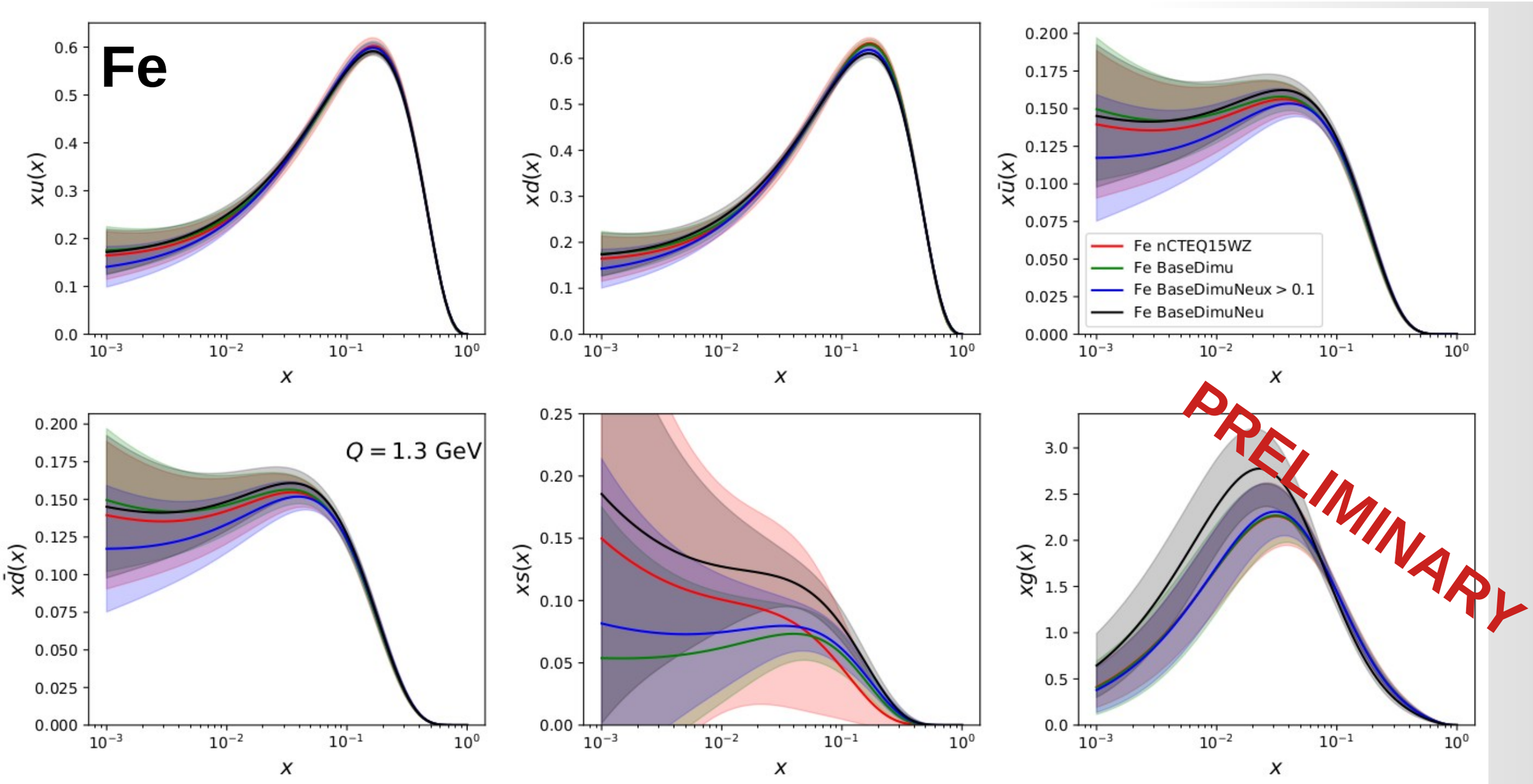



The tensions in the new fit only happen for NuTeV data.

They disappear if x < 0.1 from CC are removed.

Baseline = nCTE15WZ

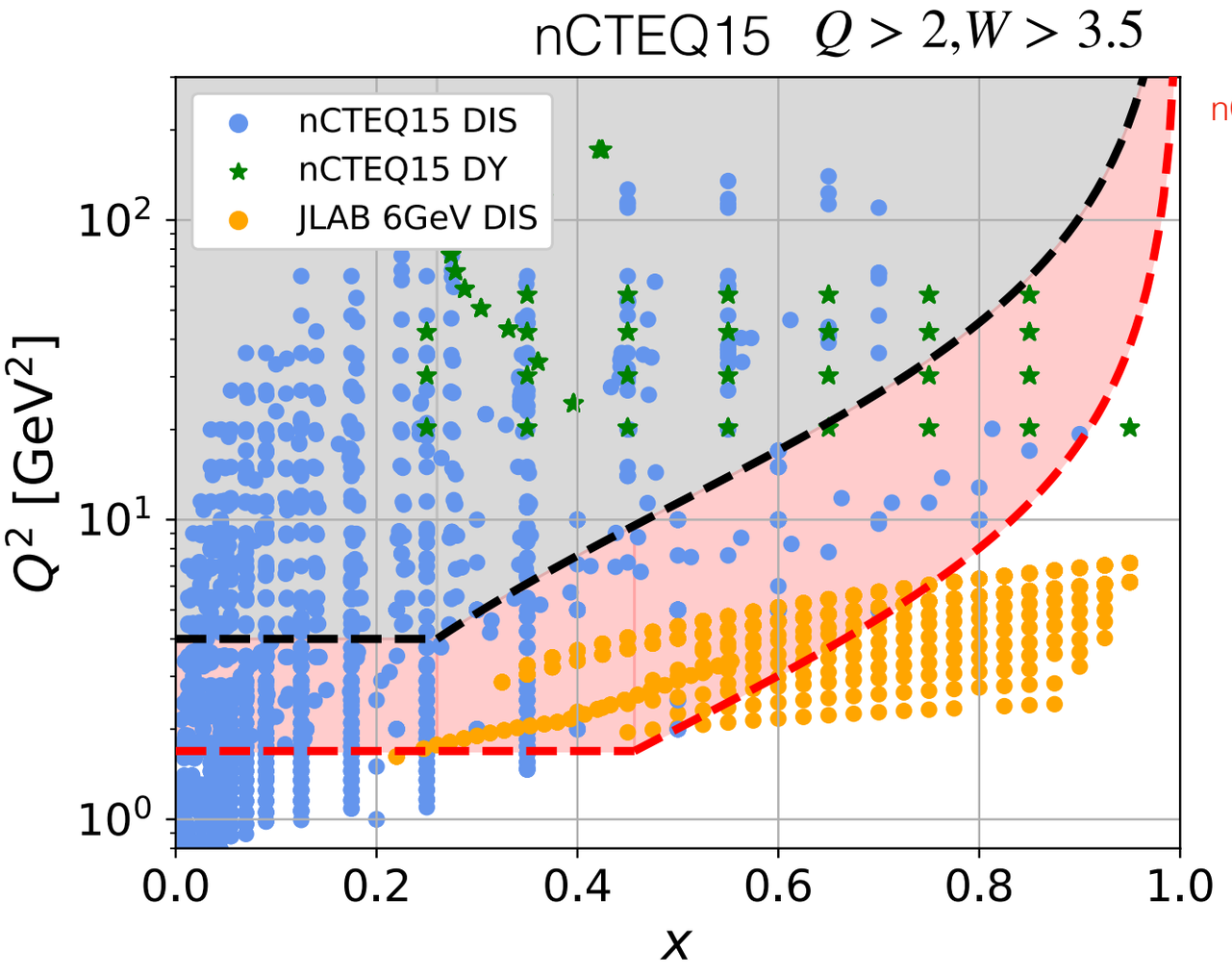
# Latest results



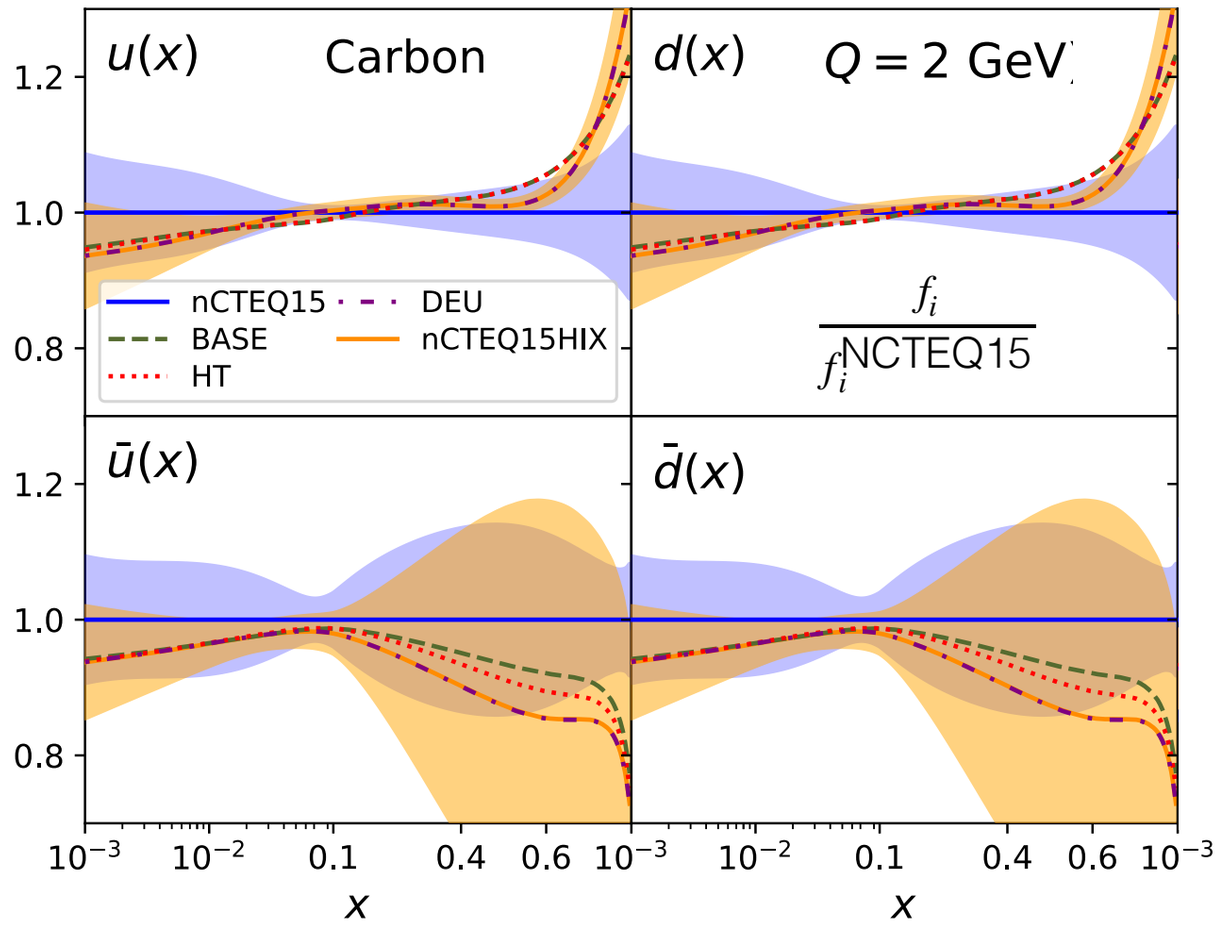

The CC DIS data seems to favour a lower strange at low x.

The single hadron production data seem to favour a higher strange at low x.

# High x data and TMC: using JLAB very precise data




only data up to x=0.7 (so far)

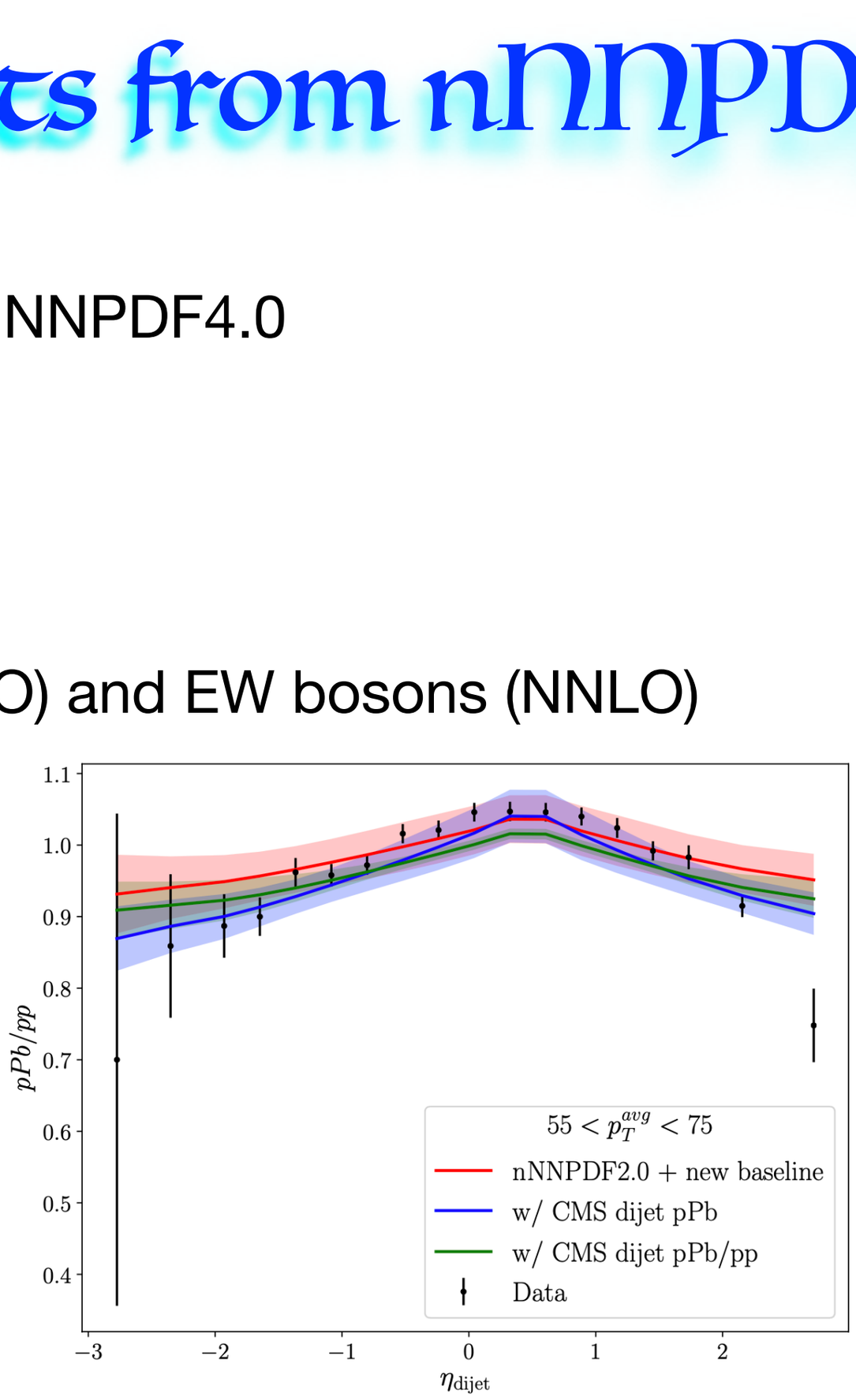


# (preliminary) results from nNNPDF*

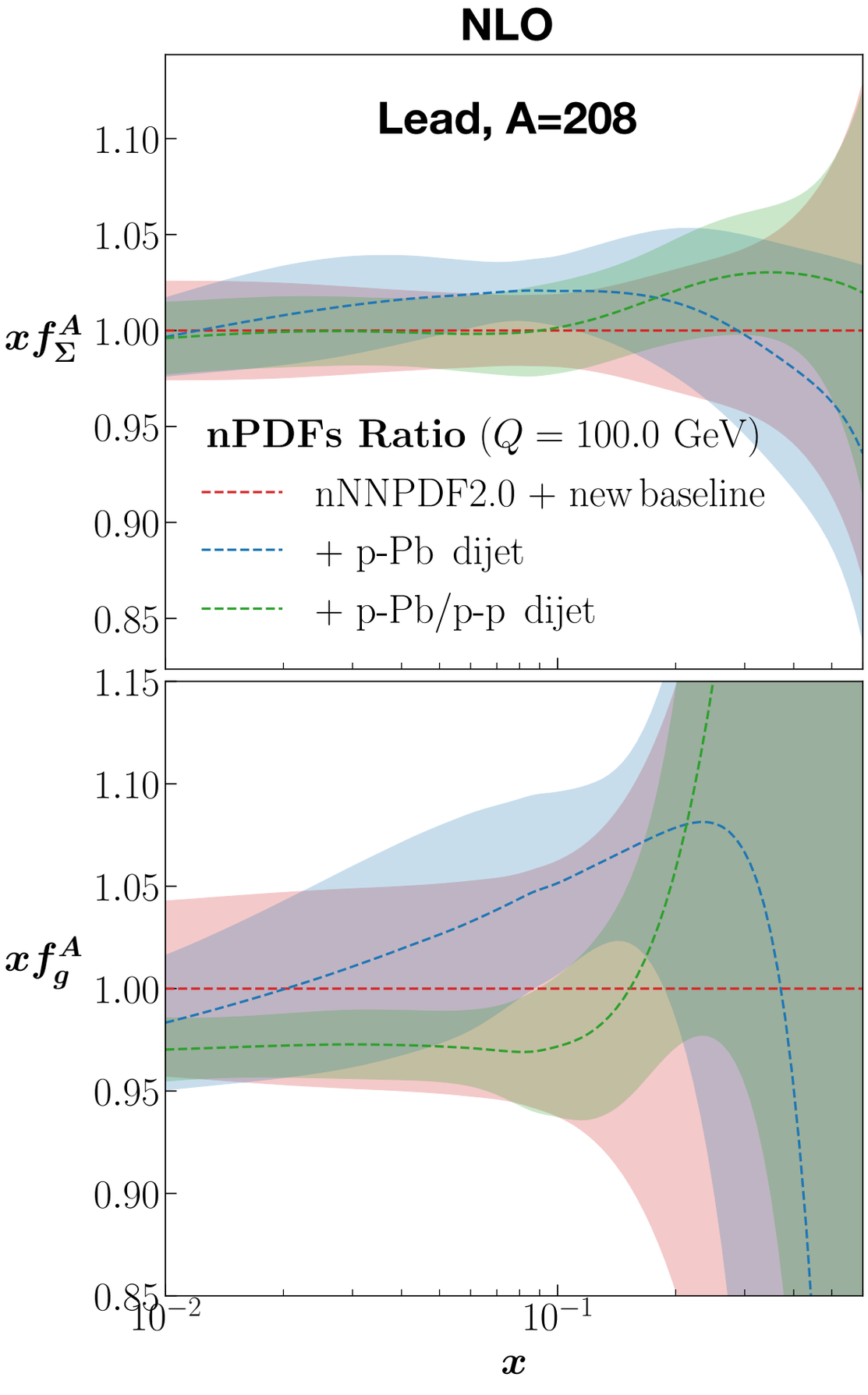
- new baseline for nNNPDF3.0: NNPDF4.0
- NLO and NNLO
- positivity constraint
- include dijet p+Pb (NLO, NNLO) and EW bosons (NNLO)

– **w/o dijet** $\rightarrow \chi^2_{dataset}/N = [6.47]$
– **w/ CMS dijet pPb** $\rightarrow \chi^2_{dataset}/N = [6.16]$
– **w/ CMS dijet pPb/pp** $\rightarrow \chi^2_{dataset}/N = 3.85$

baseline = NNPDF3.1 + 5 TeV CMS data




* from R. Abdul Khalek's talk at DIS2021




Missing correlations might be crucial to describe this data set.

Inability to describe p+p data with NNPDF3.1 severely affects the p+Pb description with nNNPDF2.0.

Largest rapidity bins should be removed (same tension as seen by EPPS21).

Gluon shape still unconstrained.

# The future

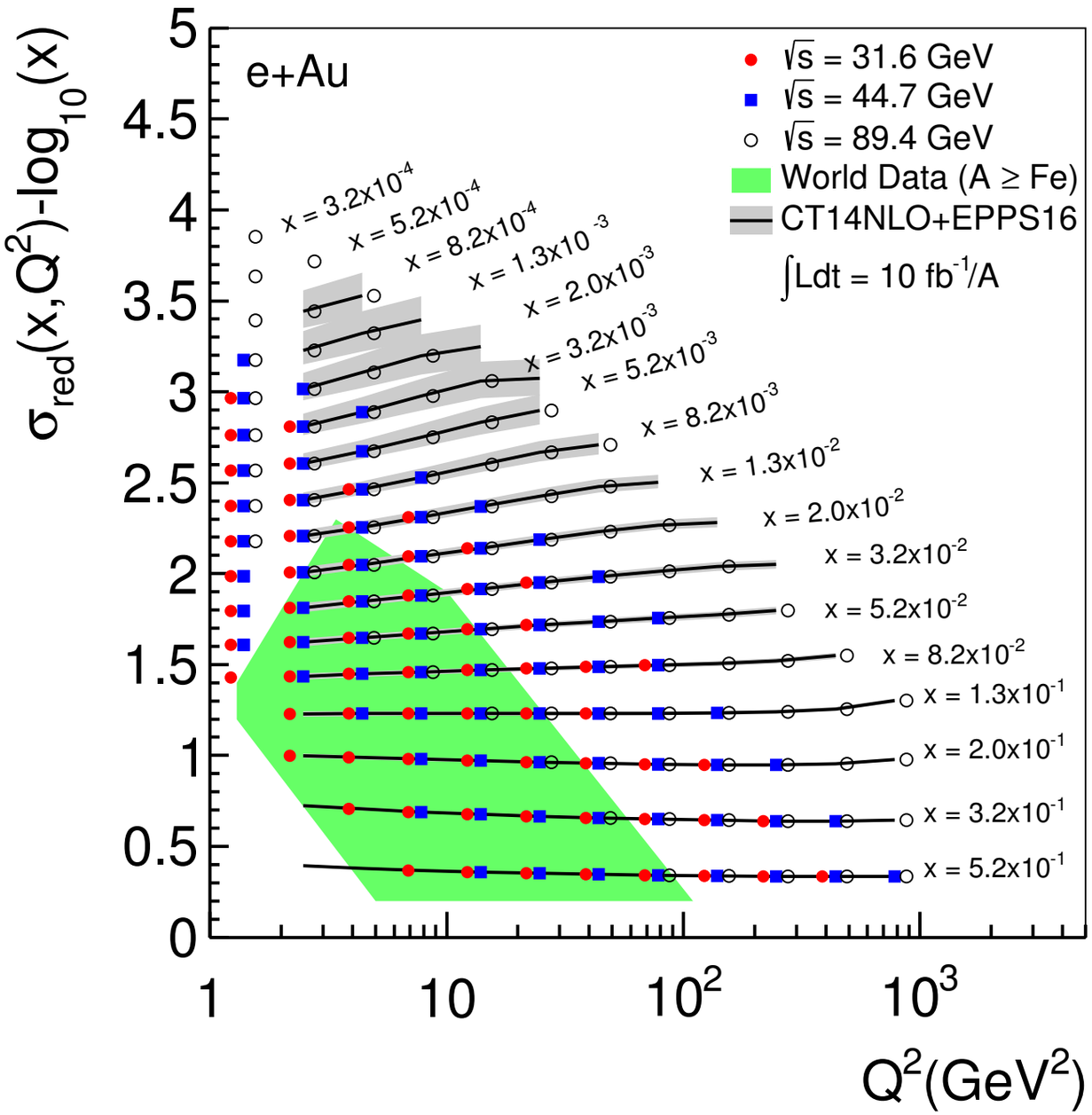
- LHC: gluon sensitivity through dijets/hadron production. Oxygen run?
- Inclusion of other observables (large amount of data available but not used in fits).
- LHeC? FCC-eh?
- STAR forward upgrade + sPHENIX
- JLAB12: explore the high *x* region and validity of kinematic cuts.
- EIC: down to $x \sim 10^{-4}$.

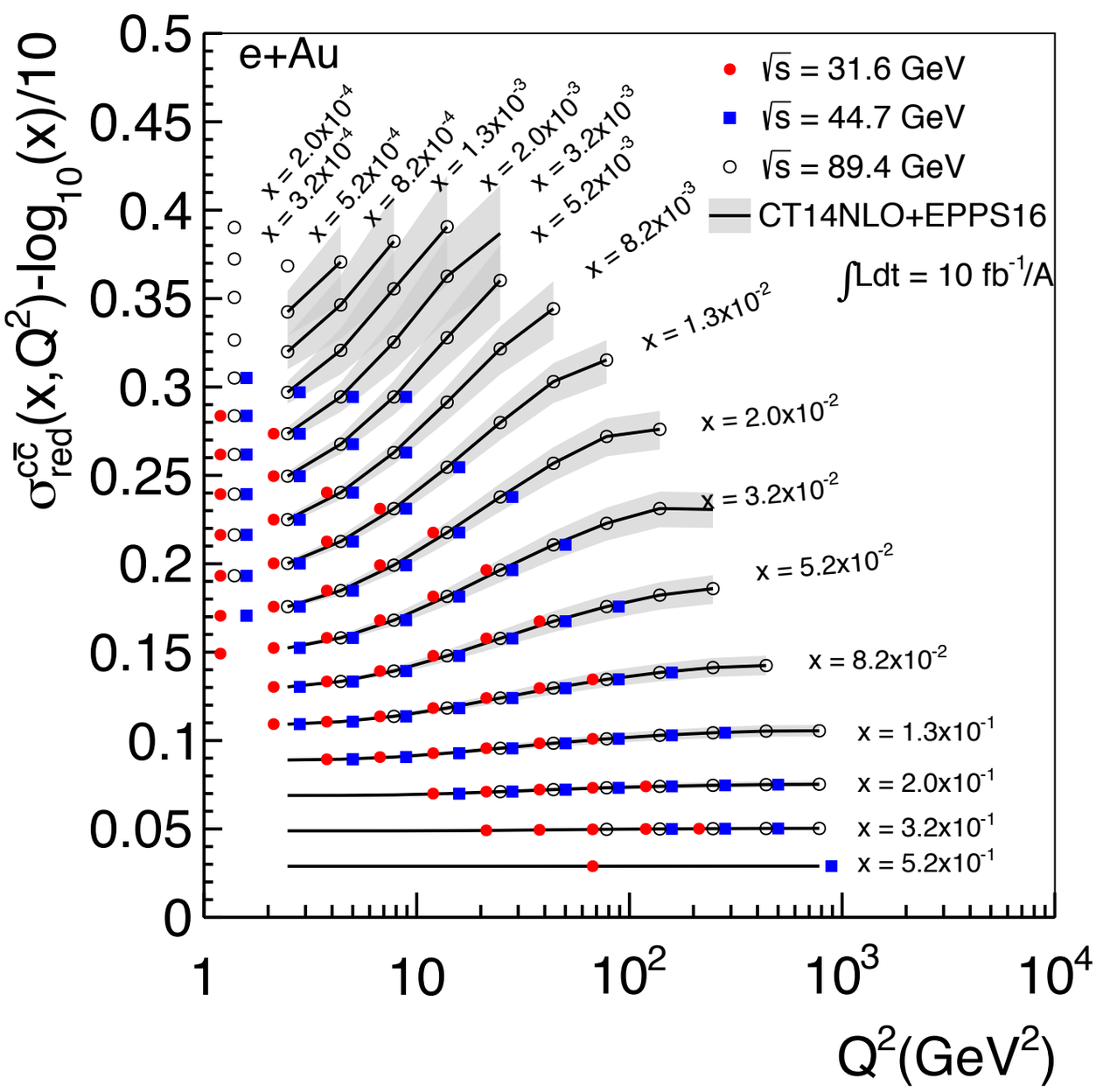
# The future

- DIS in collider mode is crucial.
- Current DIS data can be described quite nicely ($\chi^2$/d.o.f=1.02) with just 3 parameters (and exploiting the sum rules).

The future

PRD96 (2017) no.11, 114005

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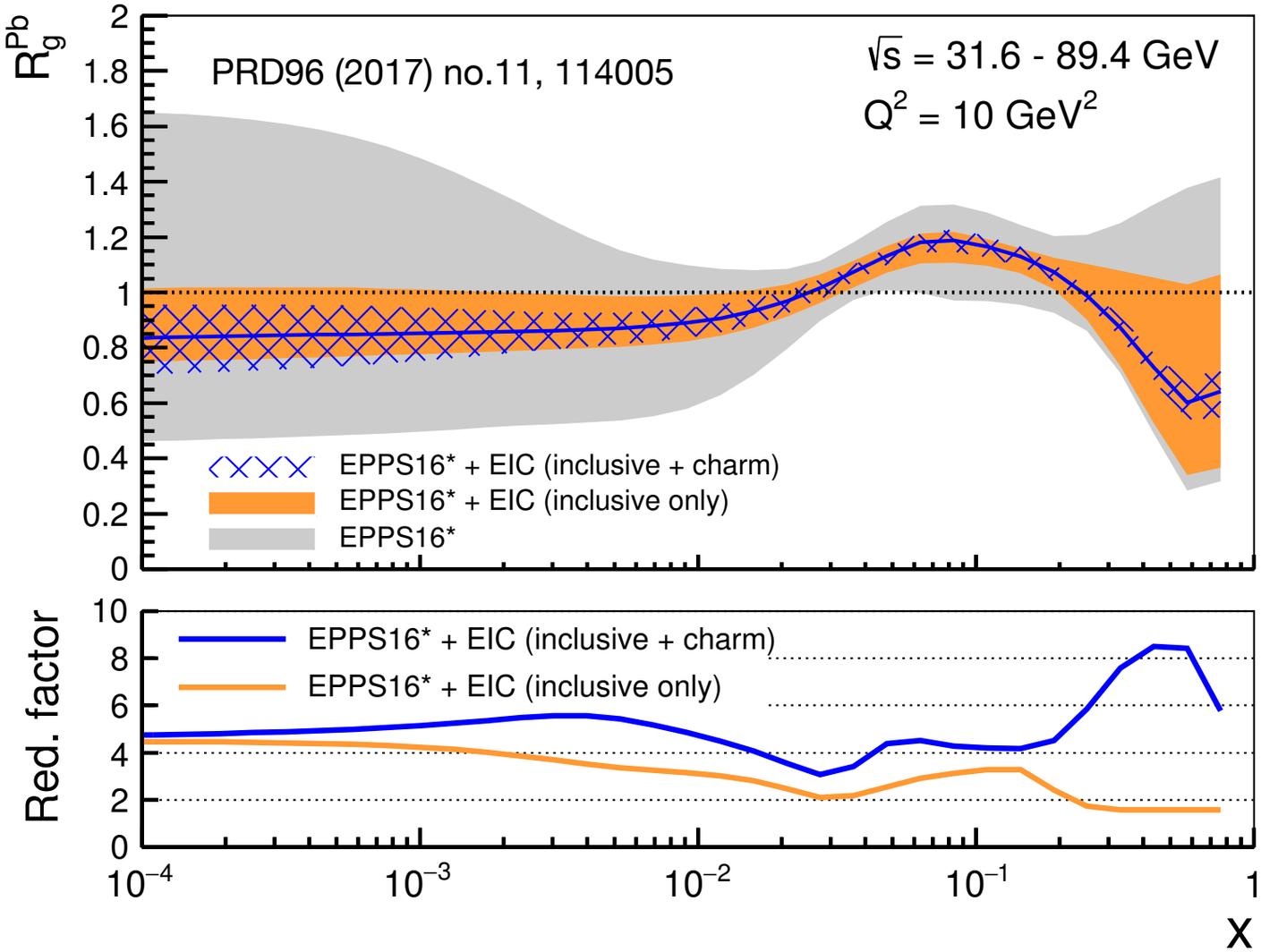


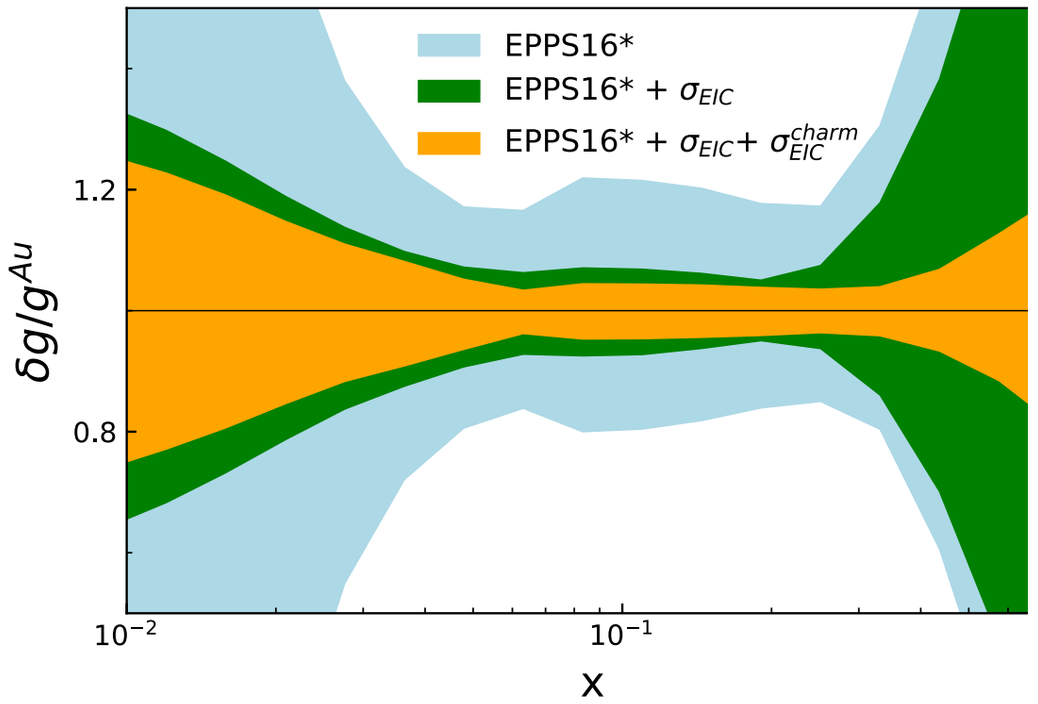


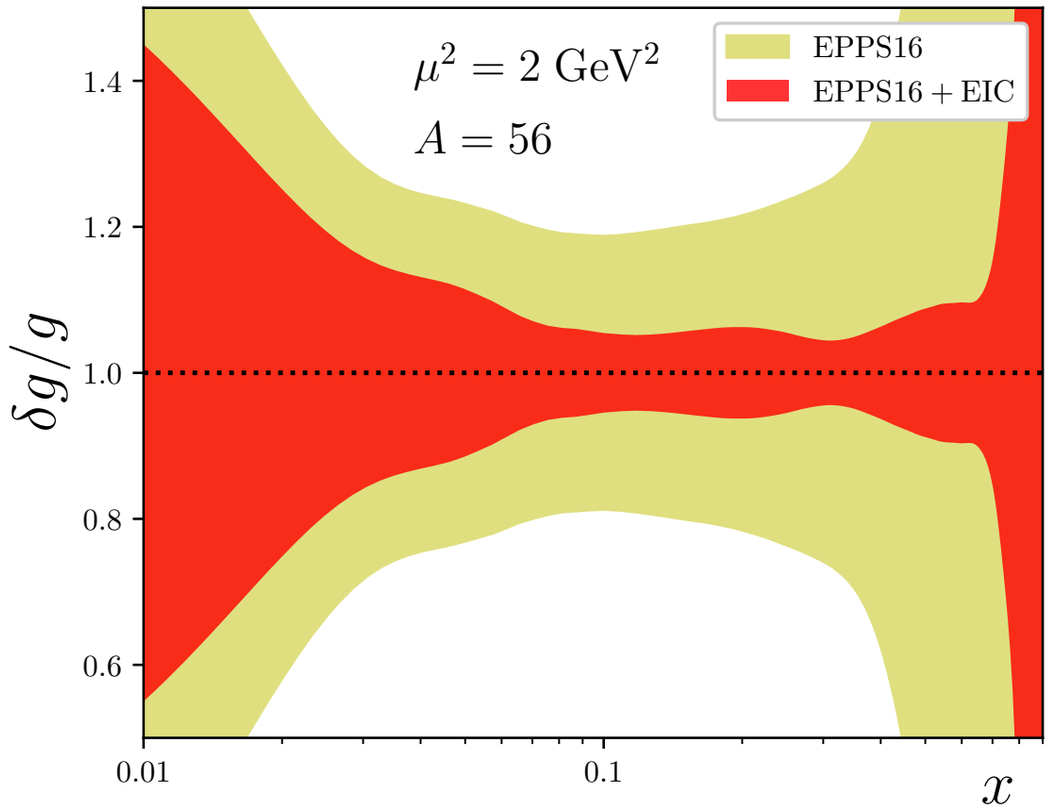


EIC Yellow Report: arXiv:2103.05419

# Summary

- Many nPDFs sets available, still far from the precision of proton PDFs. More data needed (quantity AND quality).

- PDF fitters are taking into account the nuclear effects in their fits.

- “New”/new data and treatments improve the description.

- New results support the existence of anti-shadowing for the gluon.

- Flavour decomposition still far from achieved despite precise data.

- Future experiments have a huge potential to improve nPDFs.