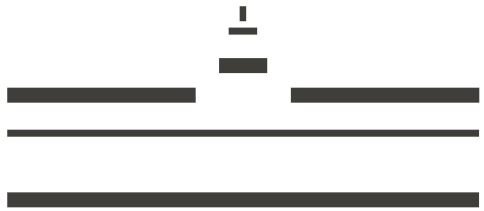
Recent developments in nuclear parton distribution functions

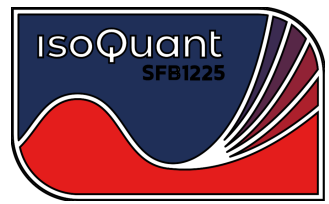
Pit Duwentäster

September 2, 2022



Westfälische
Wilhelms-Universität
Münster

nCTEQ
nuclear parton distribution functions



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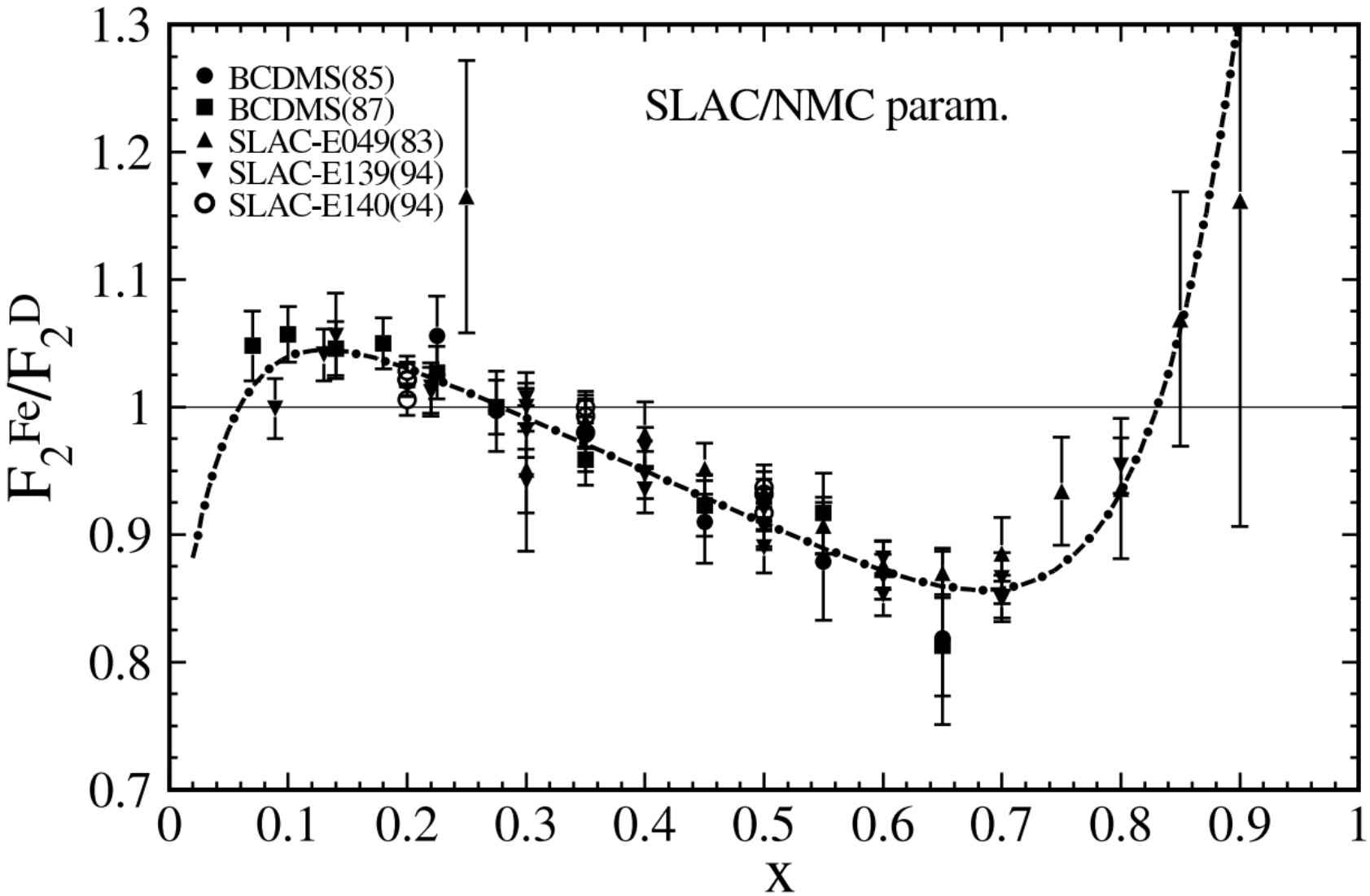
Introduction - nuclear PDFs

Nuclear PDFs are more than the sum of their parts, i.e. not just the sum of Z proton PDFs and $(A - Z)$ neutron PDFs.



nCTEQ15

[Kovarik et al., 1509.00792]

Data: DIS, DY, π^0 production
DIS cuts: $Q^2 > 4\,\text{GeV}^2$, $W^2 > 12.25\ \text{GeV}^2$ π_0 cut: $p_T > 1.7\,\text{GeV}$

- 740 Data points total

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Parameterization: CTEQ6 Proton parameterization

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

with A-dependent parameters:

$$c_k(A) = c_{k,0} + c_{k,a}(1 - A^{-c_{k,b}})$$

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Hessian uncertainties: Tolerance $T = 35$

EPPS16

[Eskola et al., 1612.05741]

Data: (ν)DIS, DY, π^0 production, W/Z boson production, dijet production
DIS cuts: $Q^2 > m_c^2$, νDIS cuts: $Q^2 > 4\,\text{GeV}^2$, $W^2 > 12.25\ \text{GeV}^2$

- 1811 Data points total

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Parameterization: R_pA based on CT14NLO Proton PDFs

$$R_i^A(x, Q_0^2) = \begin{cases} a_0 + a_1(x - x_a)^2 & x < x_a \\ b_0 + b_1 x^\alpha + b_2 x^{2\alpha} + b_3 x^{3\alpha} & x_a < x < x_b \\ c_0 + (c_1 - c_2 x)(1 - x)^{-\beta} & x > x_b \end{cases}$$

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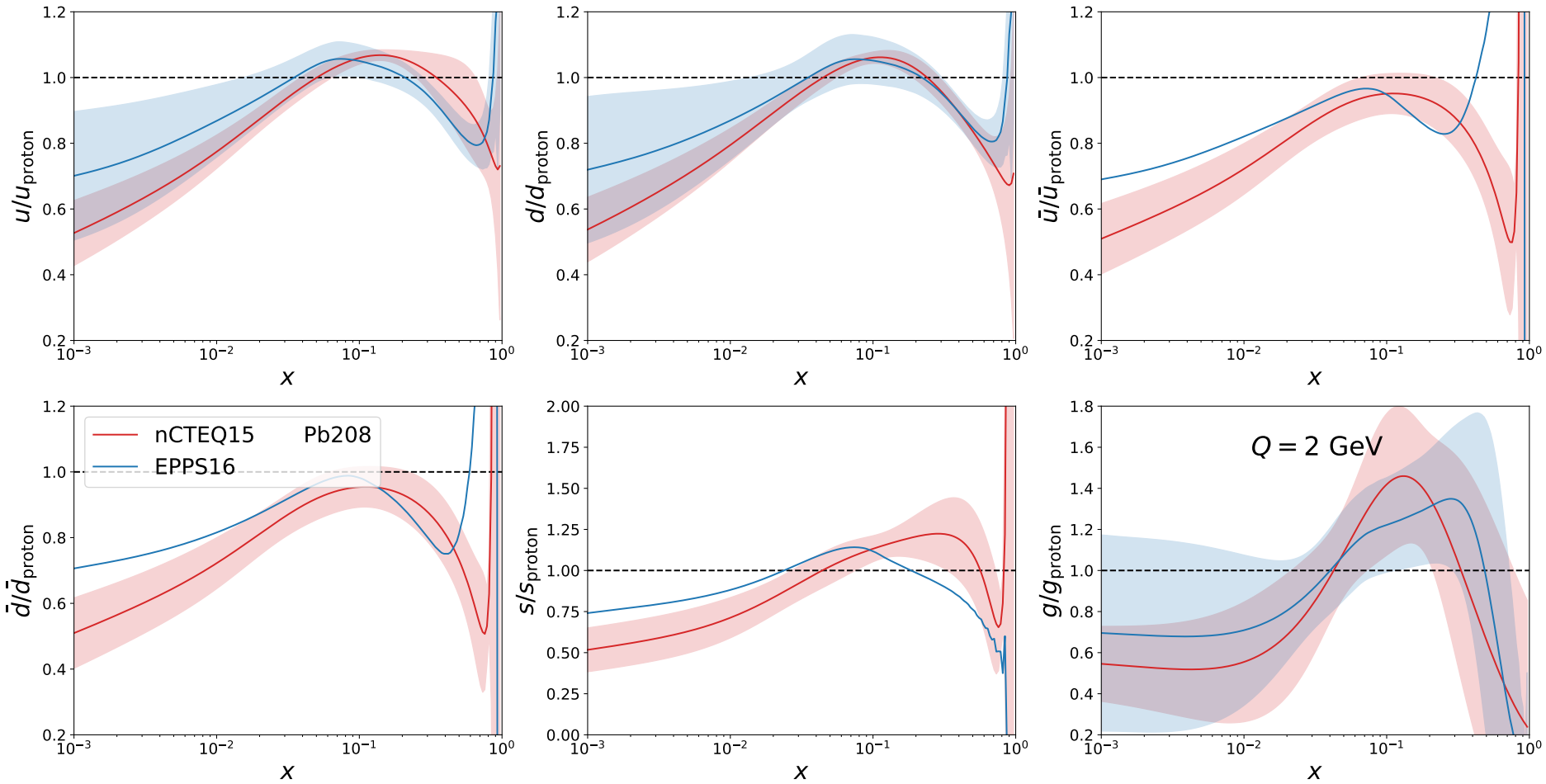
Hessian uncertainties: Tolerance $T = 52$

Comparison between nCTEQ15 and EPPS16



- Very close central values
- Strange quark uncertainty underestimated by nCTEQ15

New methodologies

nNNPDF

nNNPDF1.0 [Abdul Khalek et al., 1904.00018] - DIS only
nNNPDF2.0 [Abdul Khalek et al., 2006.14629] - (ν)DIS and W/Z production
nNNPDF3.0 [Abdul Khalek et al., 2201.12363] - to be discussed later

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- Reduced parameterization bias
- NNPDF3.1 proton as boundary condition

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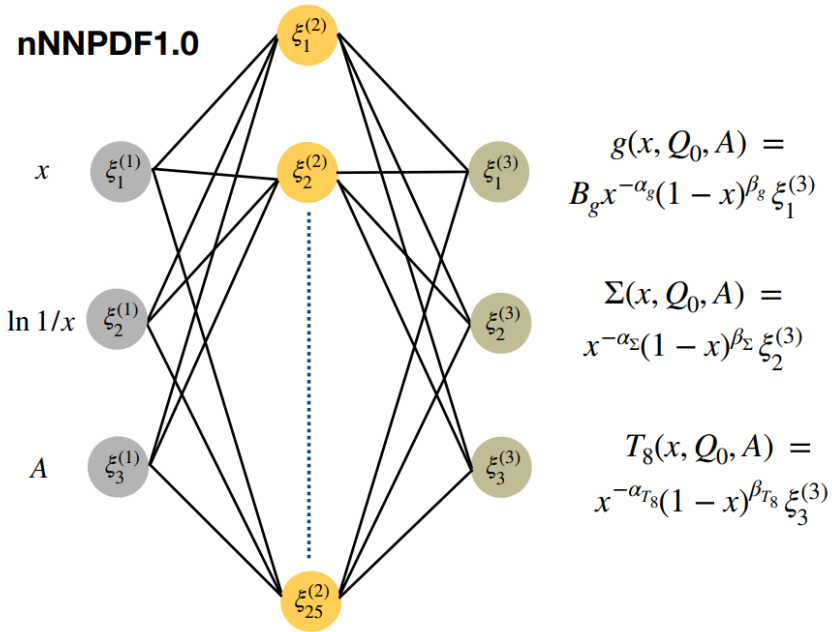

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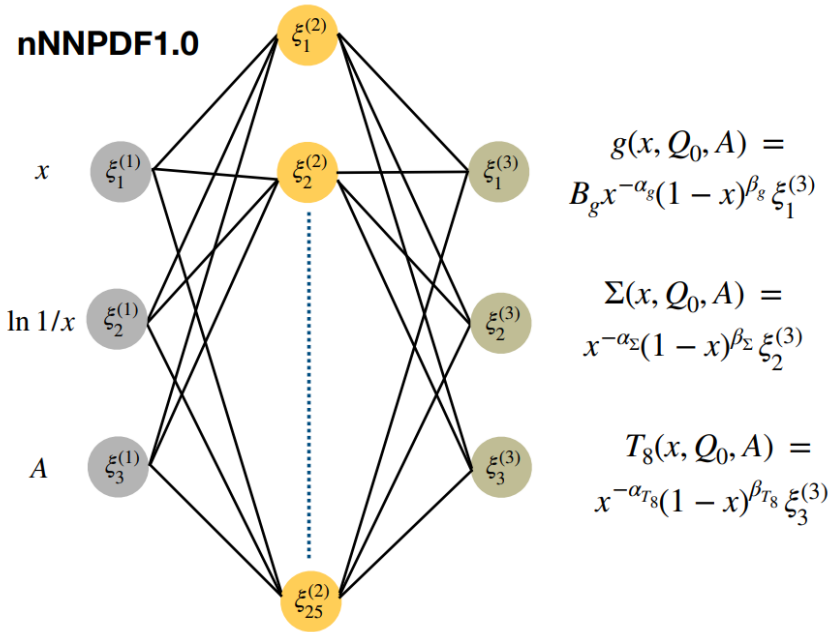

Uncertainties:
250 Monte-Carlo replicas

SRC parameterization

[Kusina et al., Presented at DIS2022]

Parameterization inspired by nuclear physics:

$$f_i^A(x,Q_0) = Z/A\left[(1-z_A)f_{i/p}(x,Q_0) + z_A f_{i/p}^{SRC}(x,Q_0)\right] + N/A\left[(1-n_A)f_{i/n}(x,Q_0) + n_A f_{i/n}^{SRC}(x,Q_0)\right]$$

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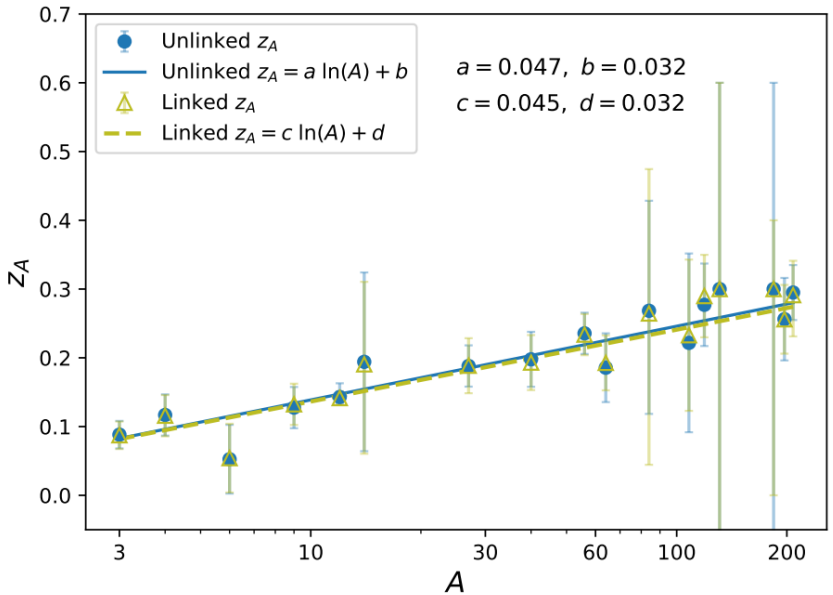
Fitted n_A and z_A values suggest that equal numbers of protons and neutrons participate in SRC pairs

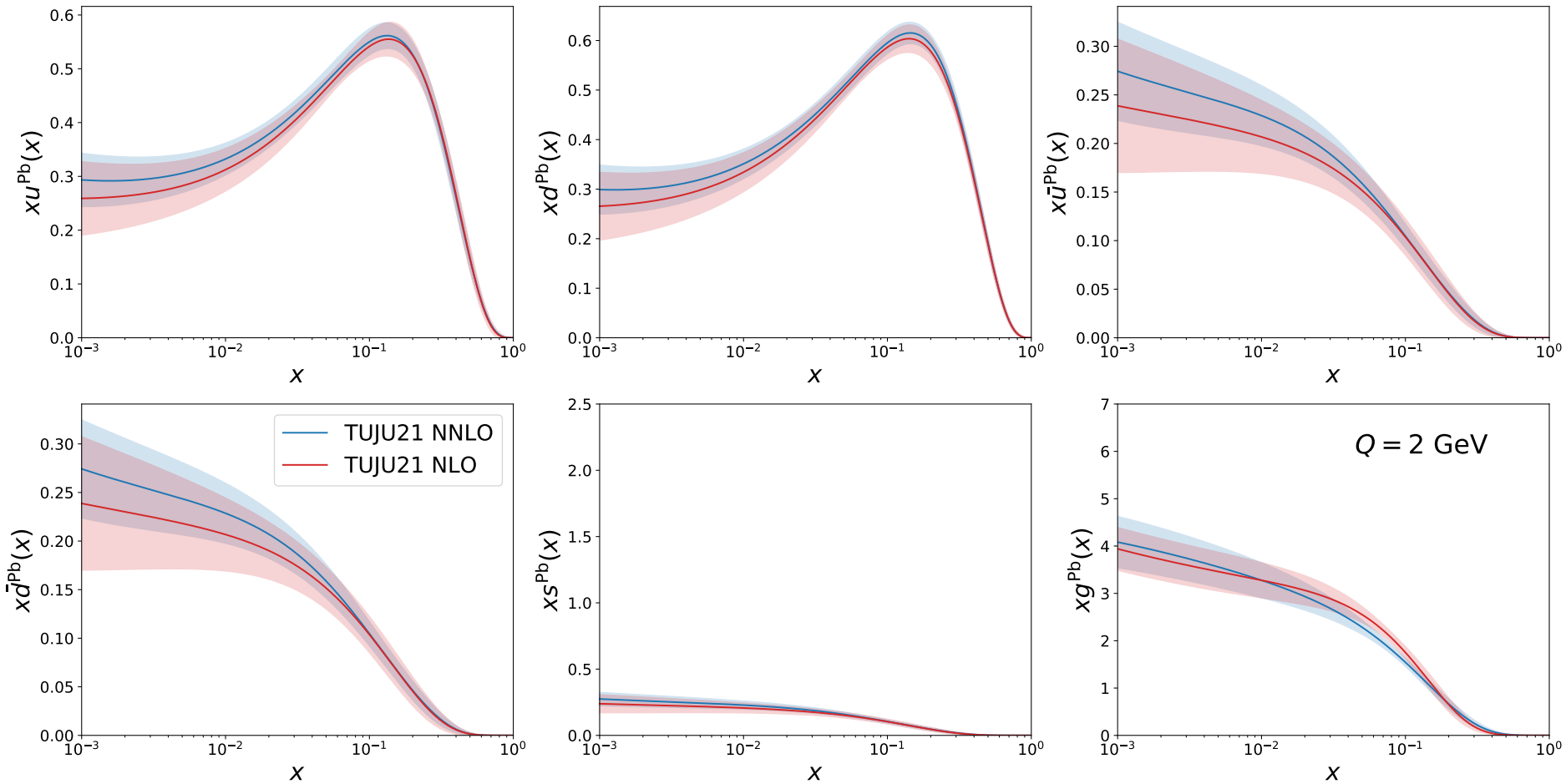
- Known from nuclear physics: pn pairs dominant SRC contribution



NNLO theory calculations

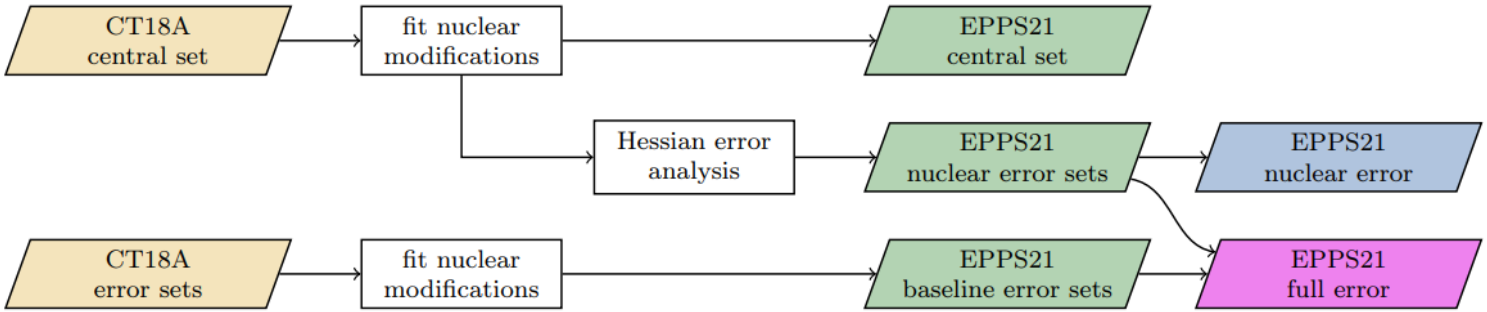
nNNPDF1.0 and TUJU19 [Walt et al., 1908.03355], TUJU21 [Helenius et al., 2112.11904]

Current status: NNLO improvemes fits, but excludes too many valuable datasets where NNLO theory is not available



Proton PDF dependence

EPPS21 [Eskola et al., 2112.12462]:



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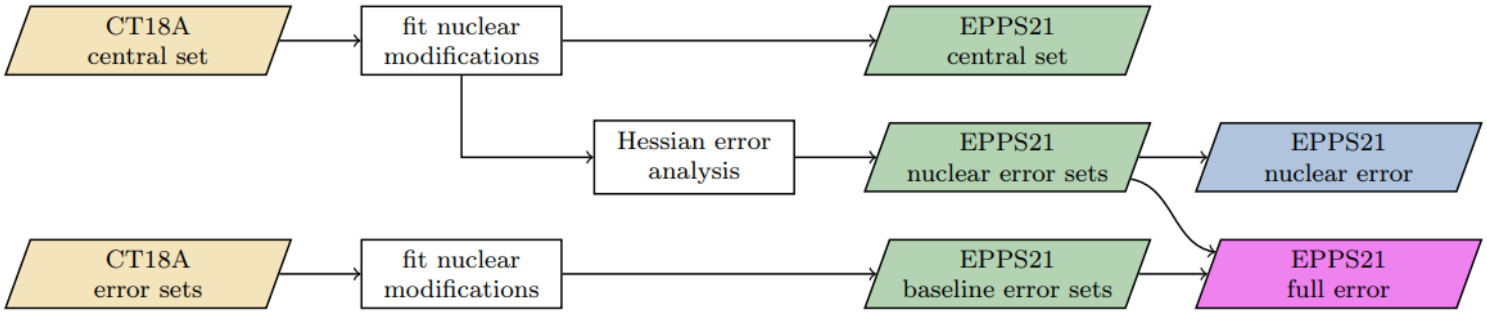

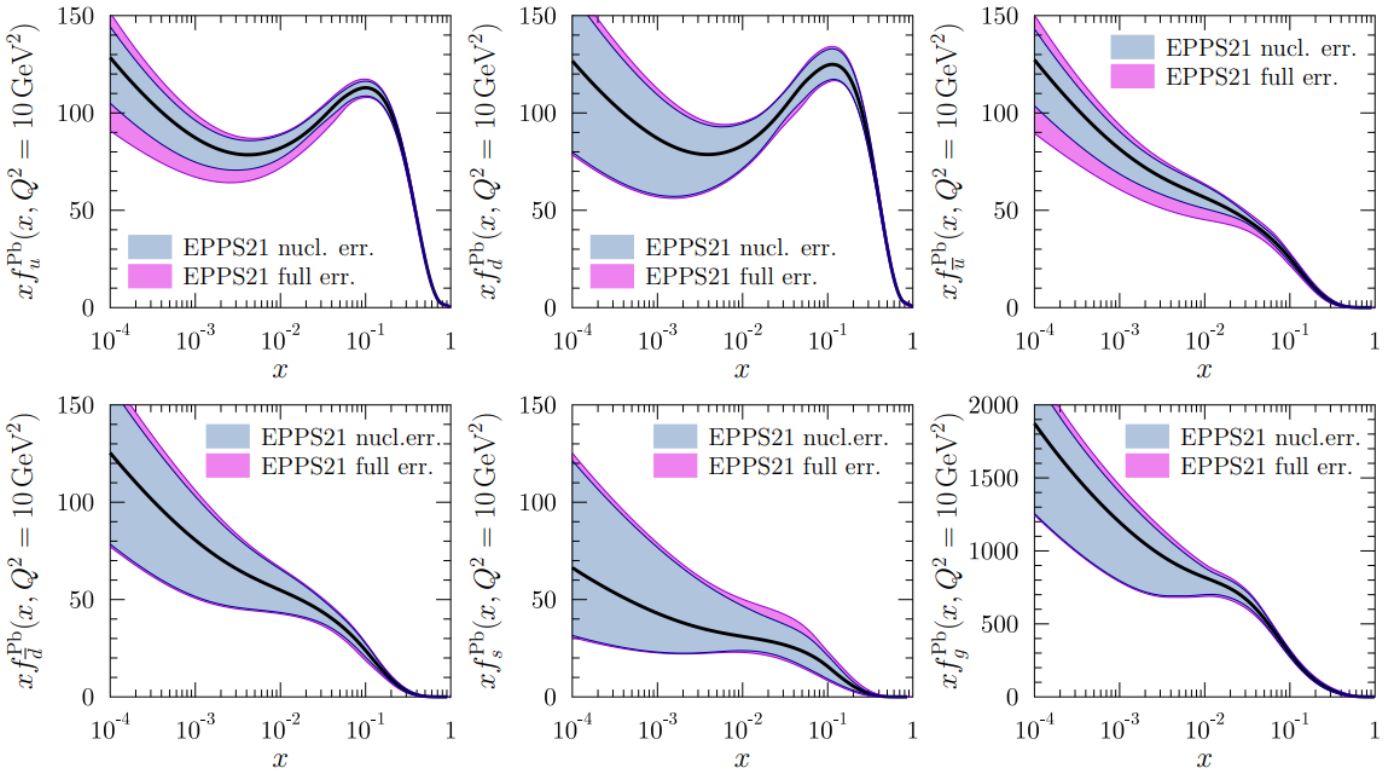

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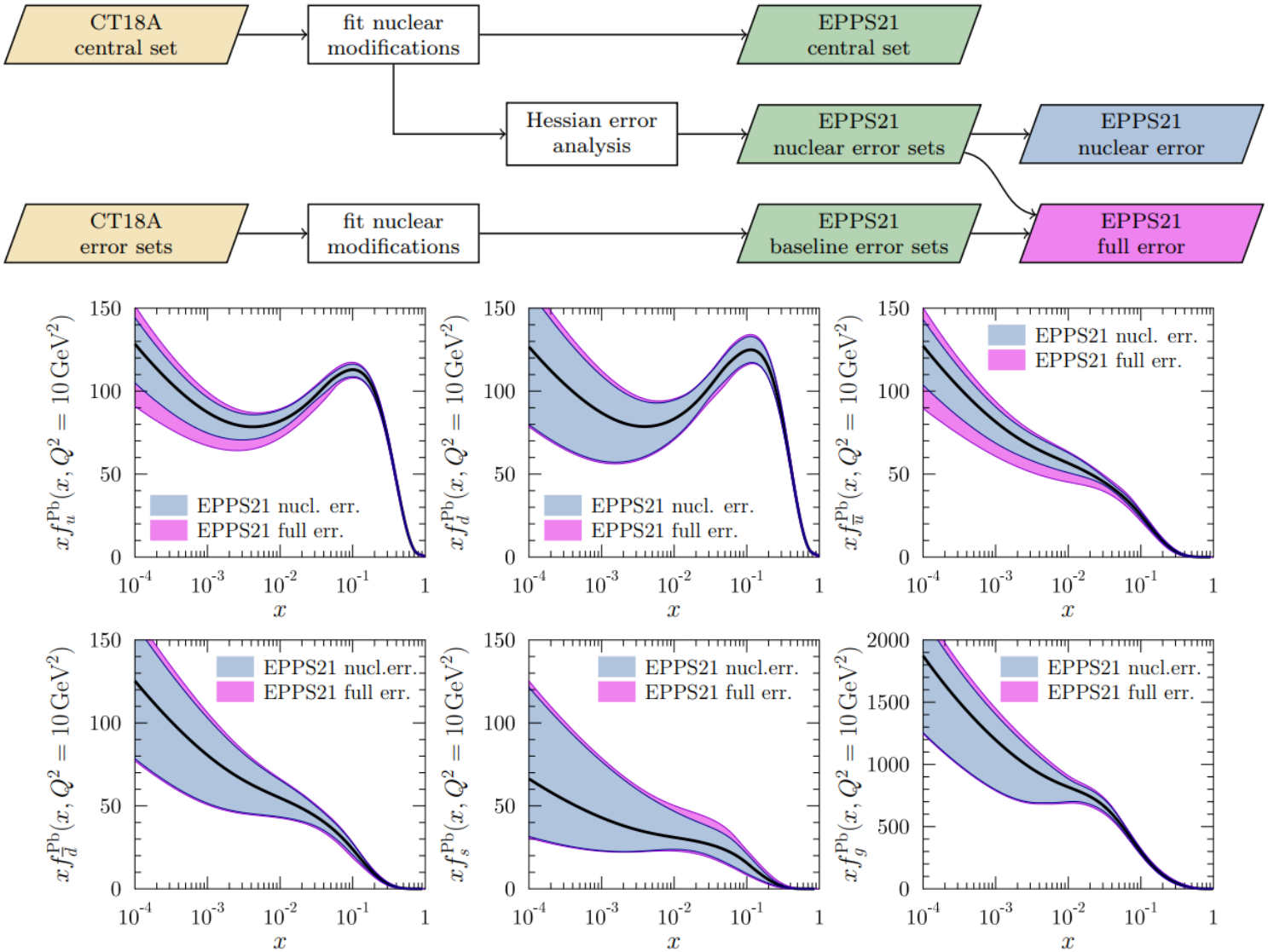

- Proton PDF uncertainties are still small, but increasingly relevant

New data

W and Z boson production

nCTEQ15WZ [Kusina et al., 2007.09100], EPPS21, nNNPDF2.0 [Abdul Khalek et al., 2006.14629]

- Sensitivity to strange quark PDFs and gluon PDFs

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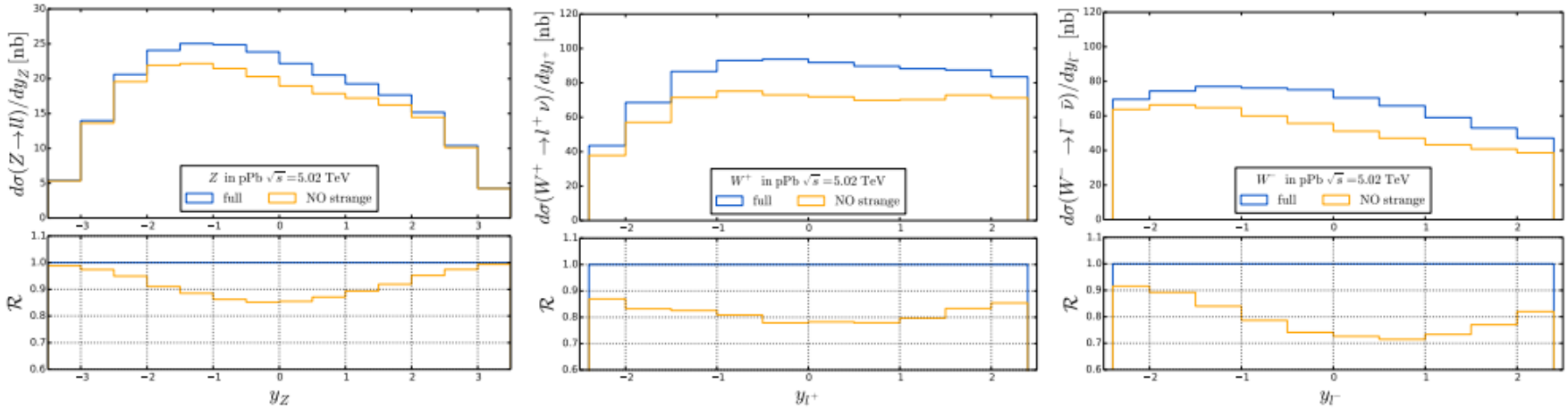
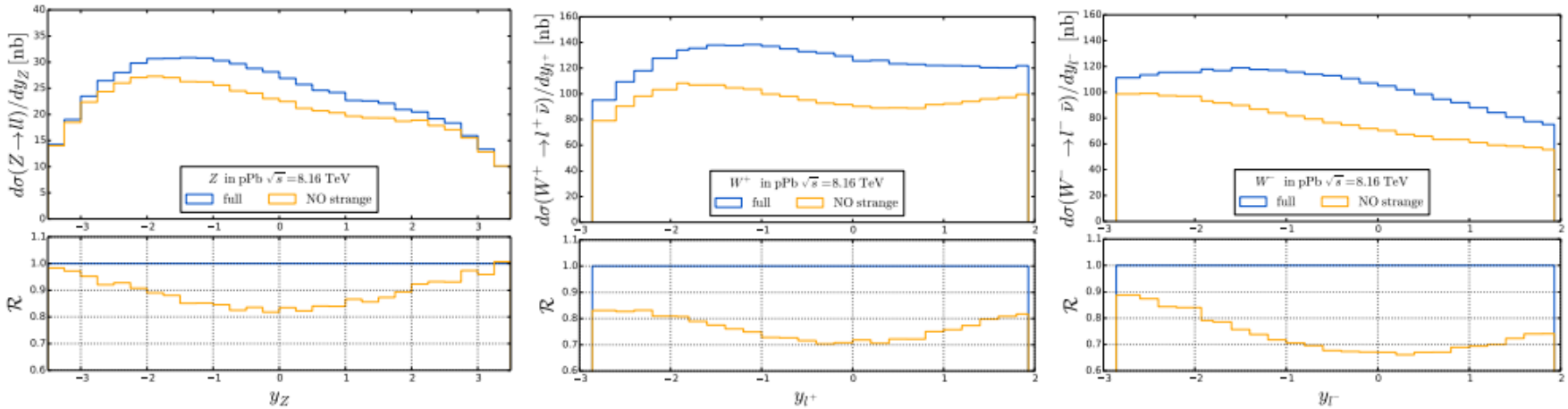


(a) $\sqrt{s} = 5.02$ TeV



(b) $\sqrt{s} = 8.16$ TeV

Single inclusive (light) hadron production

nCTEQ15WZ+SIH [Duwentäster et al., 2105.09873]

- RHIC neutral pions were already used in nCTEQ15 and EPPS16, but not LHC data, kaons and charged pions
- Investigation of FF dependence

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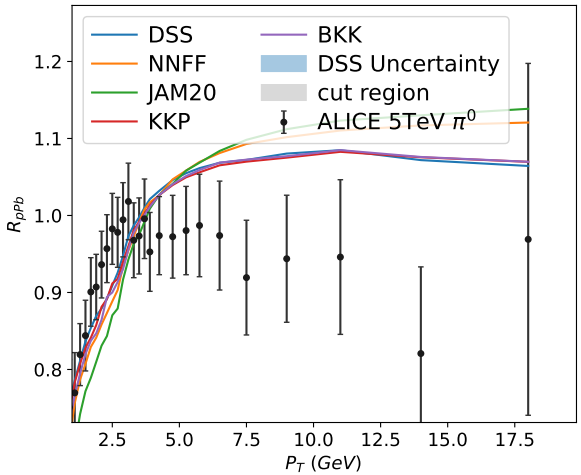
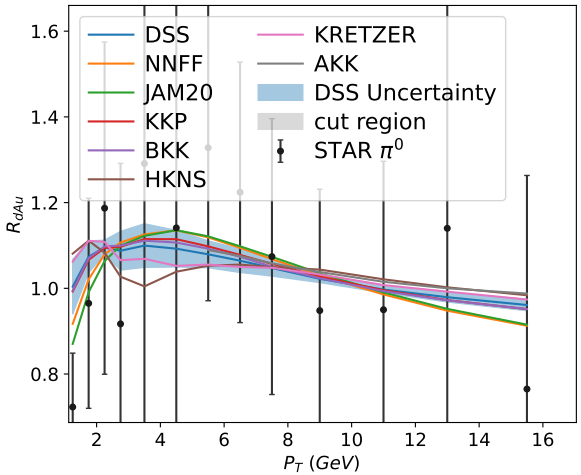
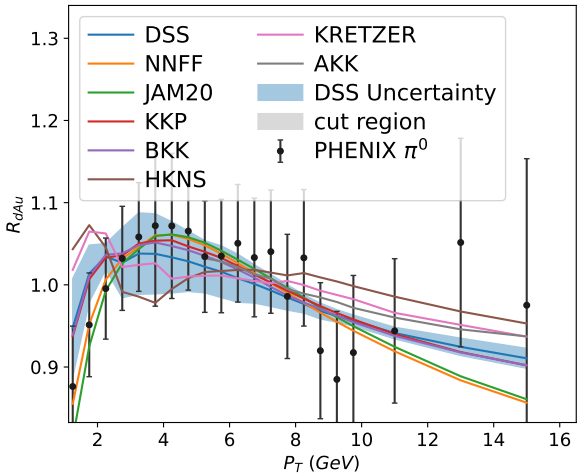




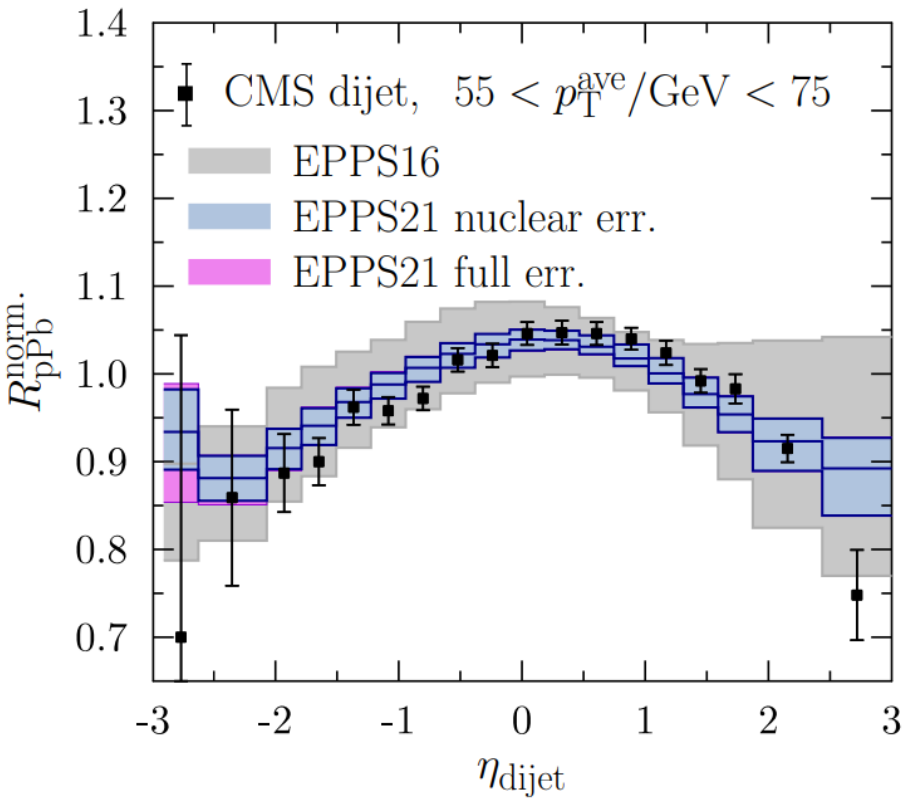


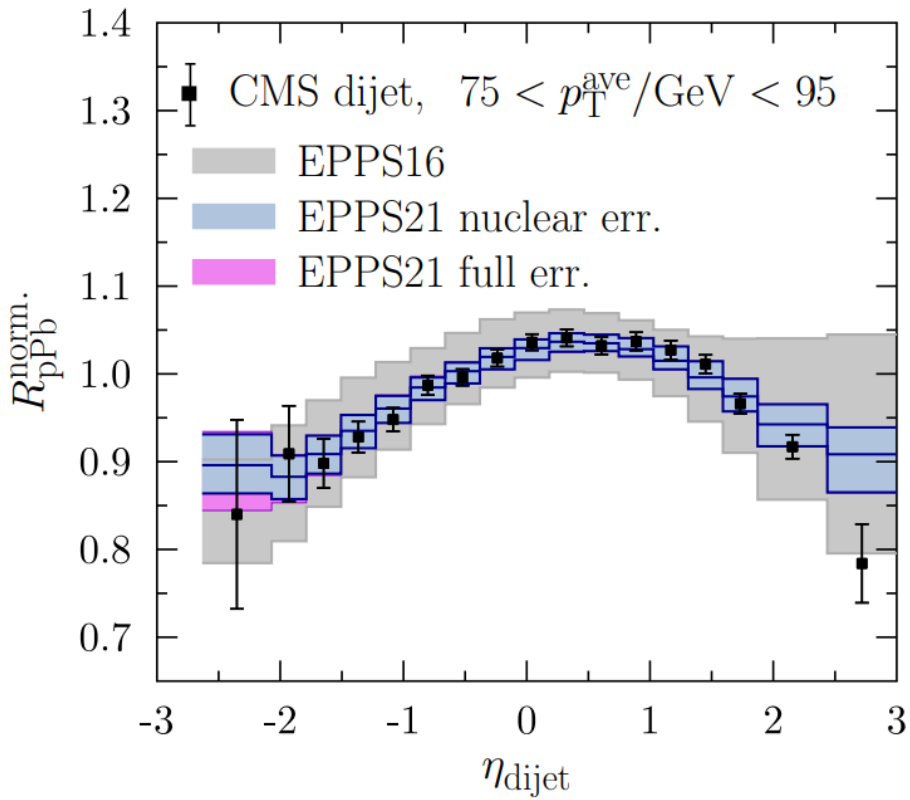
- See next talk for details

Dijets

EPPS21, nNNPDF3.0

- Sensitive to (valence)-quark and gluon PDFs between $10^{-3} < x < 0.4$ at high Q^2
- Prefers strong low-x shadowing





D^0 mesons

EPPS21, nNNPDF3.0, nCTEQ15HQ [Duwentäster et al., 2204.09982]

- Sensitive to the gluon PDFs at very low x
- 3 Different methods:
  - EPPS21: R_{pPb}; calculation in GMVFNS
  - nNNPDF3.0: R_{pPb}; POWHEG+PYTHIA8; Reweighting
  - nCTEQ15HQ: $\frac{d\sigma}{dp_T dy}$; Data-driven approach

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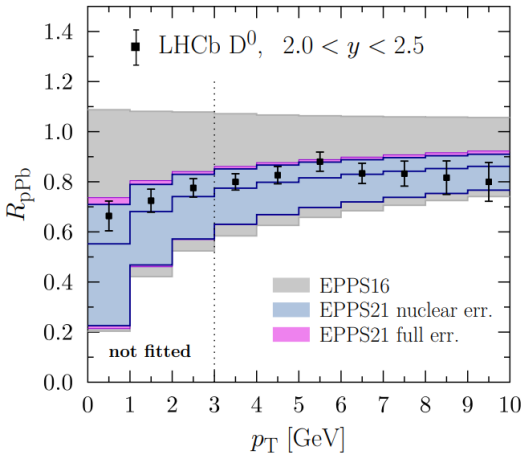

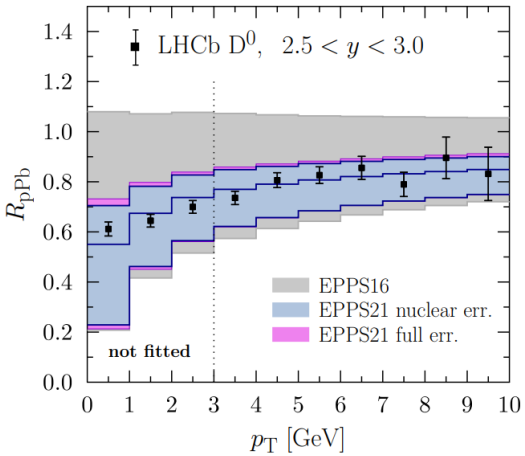

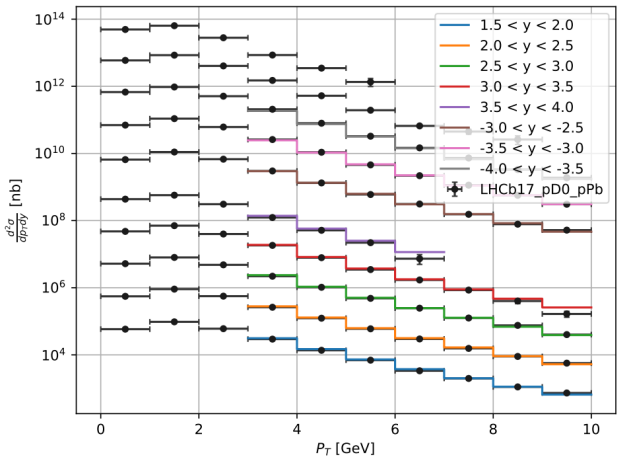

Quarkonia - J/ψ, $\psi(2S)$, $\Upsilon(1S)$

nCTEQ15HQ

- Similar kinematics as D meson production, but **significantly** more data
- No perturbative calculation publicly available, but data-driven method can be applied and matches NRQCD results

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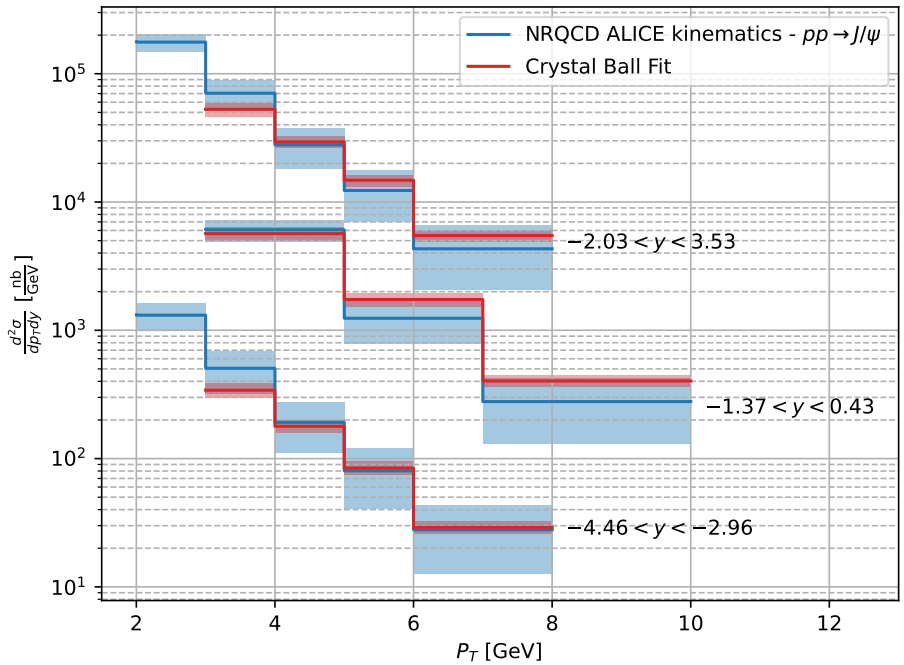

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Prompt photons

nNNPDF3.0, (nCTEQ15HQ)

- ATLAS provides forward, central and backwards rapidity data.
- Probes similar nPDF kinematics as previous two, but with color-neutral probe
- Important cross-check for higher-twist effects

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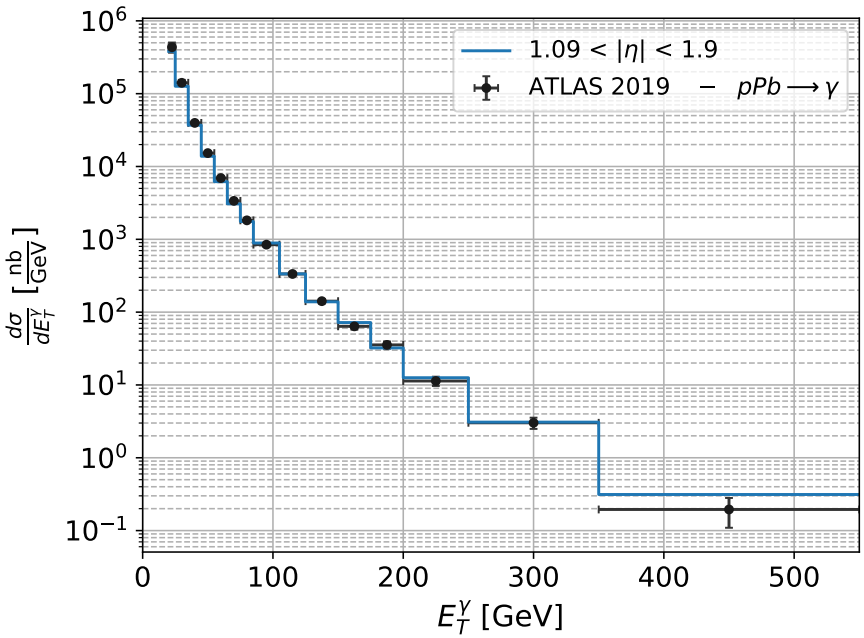

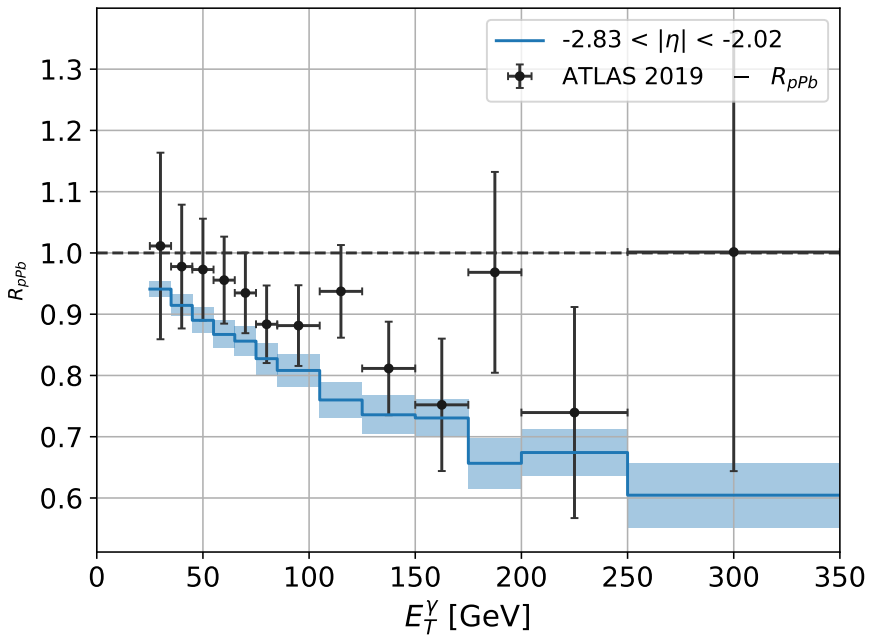

JLab DIS

EPPS21, nCTEQ15HIX [Segarra et al., 2012.11566]

- high x, low Q^2
- Different nuclei: ^{4}He, ^{9}Be, ^{12}C, ^{56}Fe, ^{64}Cu, ^{197}Au
- Potentially sensitive to higher-twist effects, target-mass corrections, and deuteron structure

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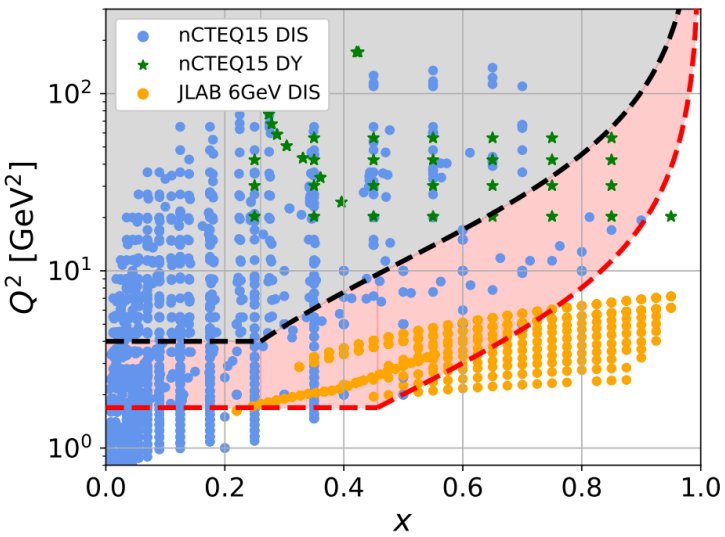
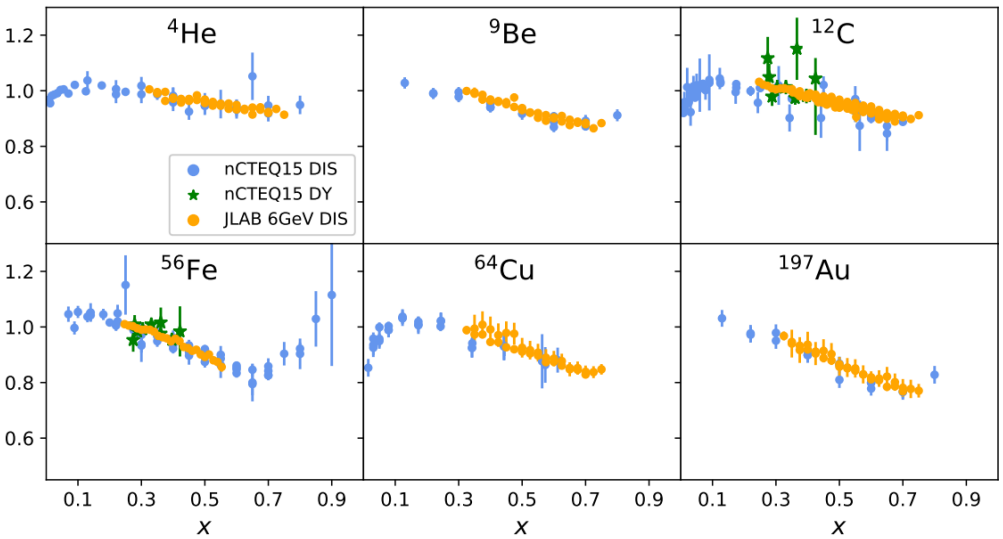


$\frac{F_2^A}{F_2^D}$



Neutrino DIS revisited

nCTEQ15ν [Muzakka et al., 2204.13157], (EPPS21), (nNNPDF3.0)
Long standing tensions between neutral current DIS and certain neutrino DIS data sets

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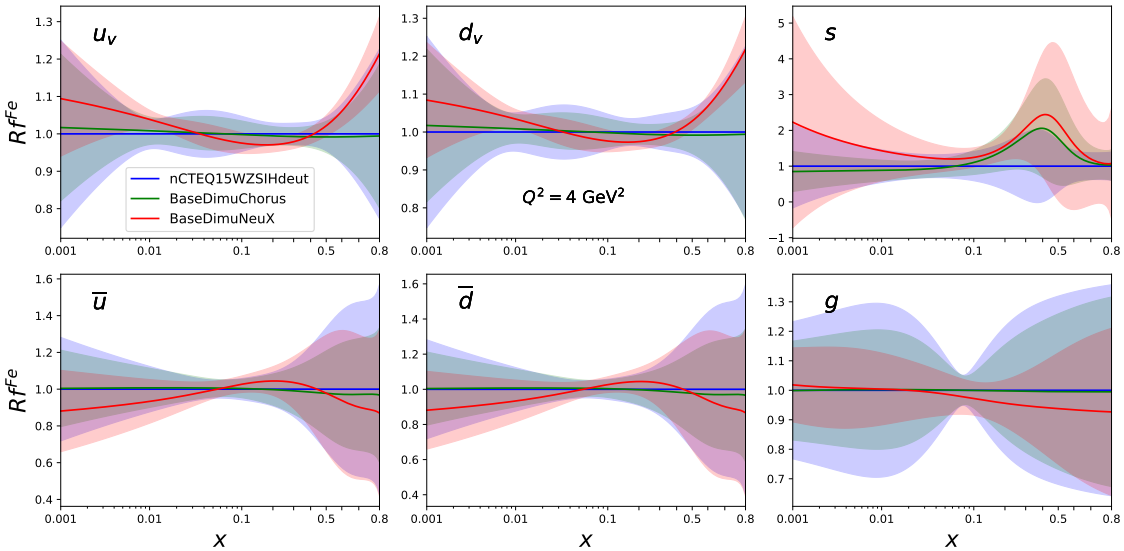
Long standing tensions between neutral current DIS and certain neutrino DIS data sets Results: Different ways to obtain compatibility:

- Cut $x < 0.1$ neutrino data
- (Uncorrelated NuTeV uncertainties)
- Use only CHORUS and semi-inclusive di-muon production data



Comparison of current nPDFs

	N_{data}	N_{params}	Observables
nCTEQ15HQ	1488	19	DIS, DY, SIH, WZ, D, Quarkonia
EPPS21	2077	24	(ν)DIS, DY, SIH, WZ, dijet, D
nNNPDF3.0	2151	256	(ν)DIS, DY, WZ, dijet, γ, D

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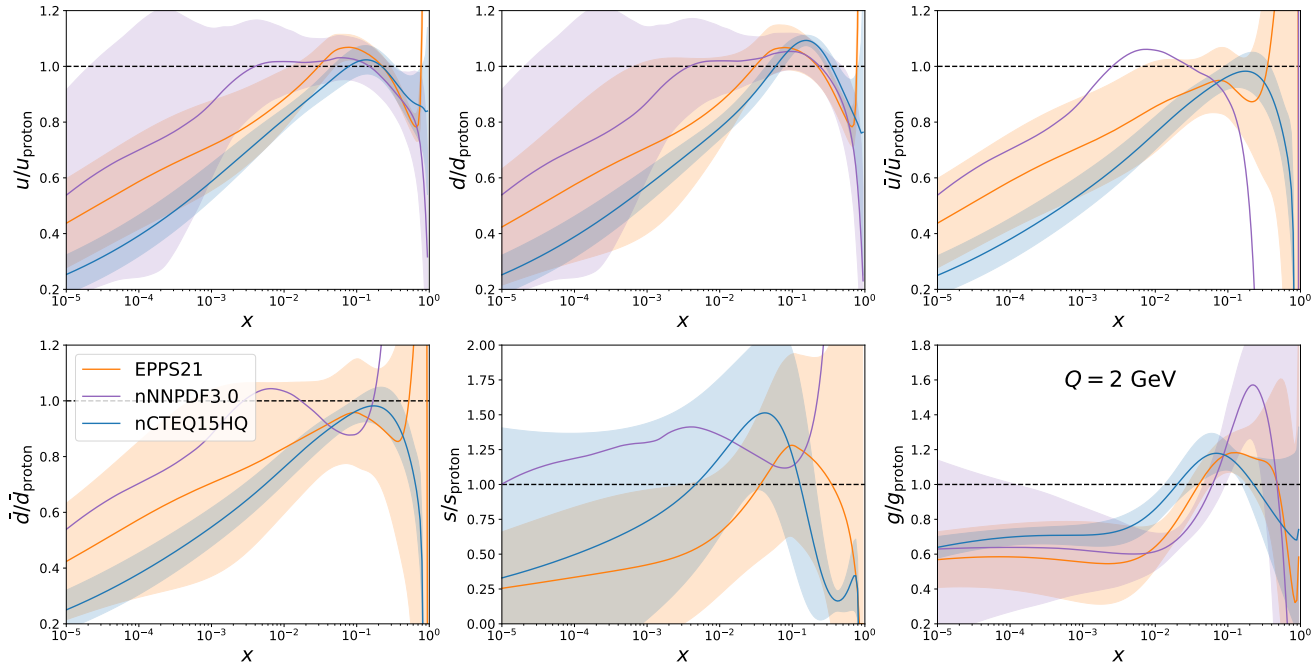

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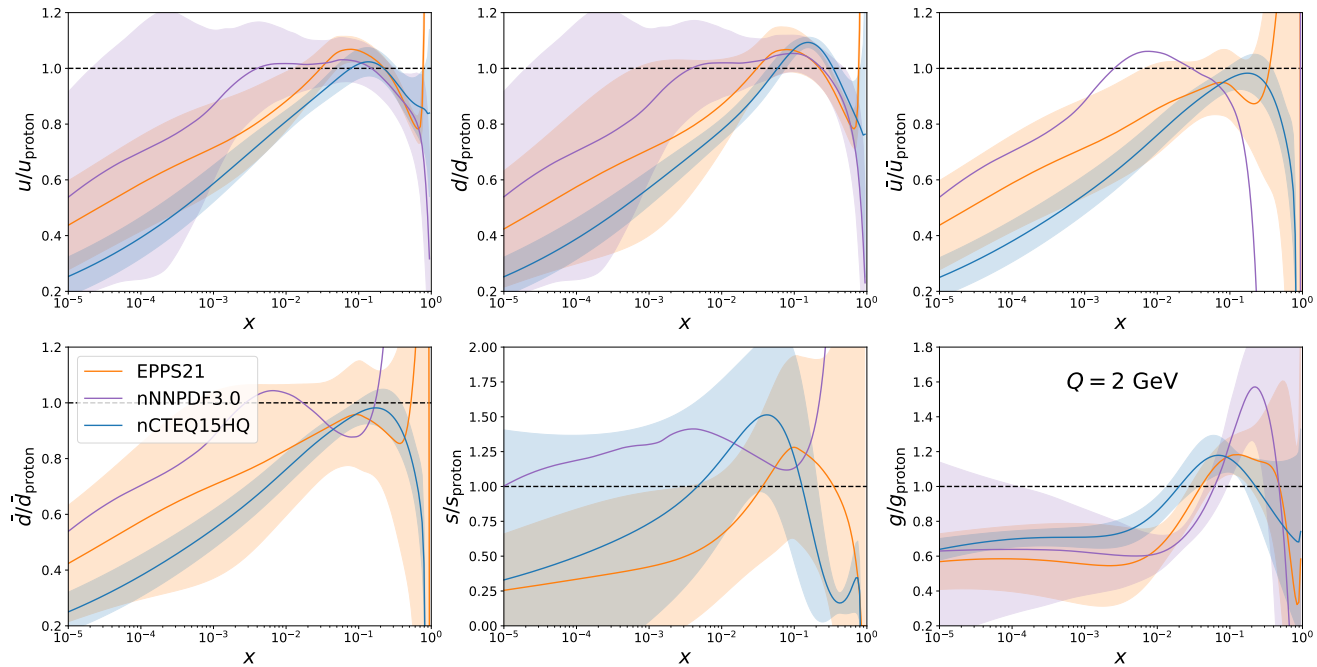


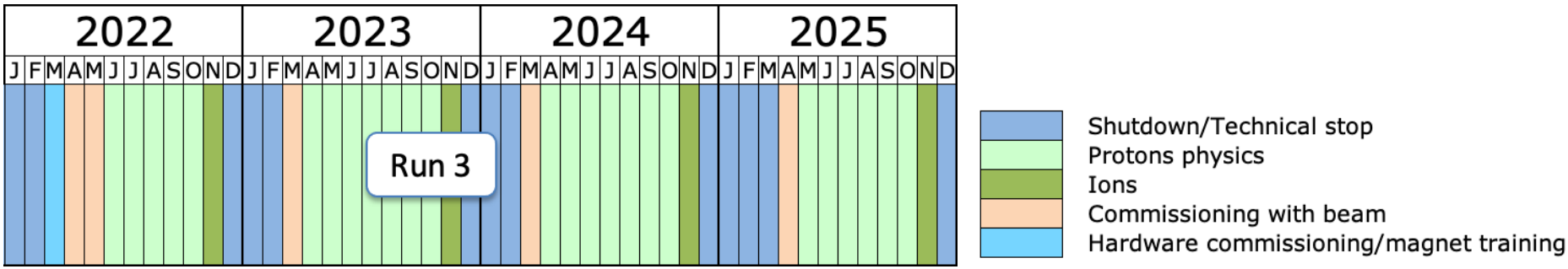
Many others exist: KSASG20, TUJU21, DSSZ,...

Goals and challenges for the future

- Include more available data sets
- Better treatment of theoretical uncertainties (MHOs, proton PDFs)
- Combined proton+nuclear PDF fit
- Systematically compare different nPDF fits (Similar to PDF4LHC in proton case)
- Develop stronger connections with nuclear physics community
- More differential quantities
  - Generalized parton distributions
  - Transverse momentum dependence
  - Parton polarizations
  - Multiparton interactions

Future of LHC data

- LHC Run 3 just started
  - update data of included observables with better statistics and improved detectors
  - proton-oxygen and oxygen-oxygen runs



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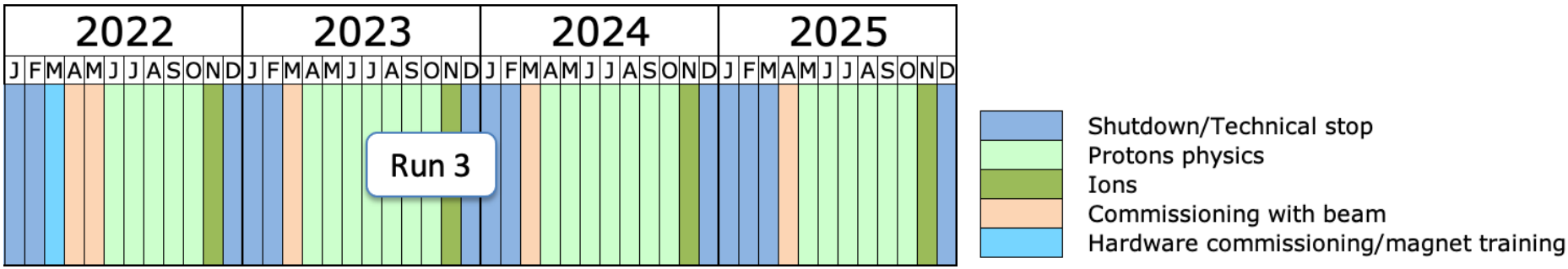
  - update data of included observables with better statistics and improved detectors
  - proton-oxygen and oxygen-oxygen runs



- EIC starts in 2031
  - DIS provieds a very clean probe into nuclear PDFs
  - Extended DIS kinematic range
  - Runs with many different nuclei
  - Transverse structure of nuclei