A Wish List: Nuclear PDFs at the EIC

…

From PDFs to the underlying QCD characteristics

Fred Olness
SMU

Thanks for substantial input
from my friends & colleagues

nCTEQ
nuclear parton distribution functions

xFitter

CTEQ

Theory for the EIC in the next decade
MIT
20 - 22 September 2022

QCD: From Parameterization to a Deeper Understanding

Proton PDF: $f_p(x,Q)$

generally NNLO; approaching ~1% precision; Boundary Conditions for nuclear PDF

Nuclear PDF: $f_A(x,Q)$

generally NLO; leverage proton PDF tools; recent progress encouraging *(e.g., PDG)*

with EIC, evolve from parameterizing to deeper understanding of QCD

Extend kinematic {x,Q} range: … probe extreme regions of QCD

Low Q: non-perturbative region; correlation effects …

Low x: resummation; saturation; BFKL; …

Low W: resonance region; duality; …

Need theoretical guidance in these regions

Extend Unpolarized Colinear to Spin, TMD & GPD

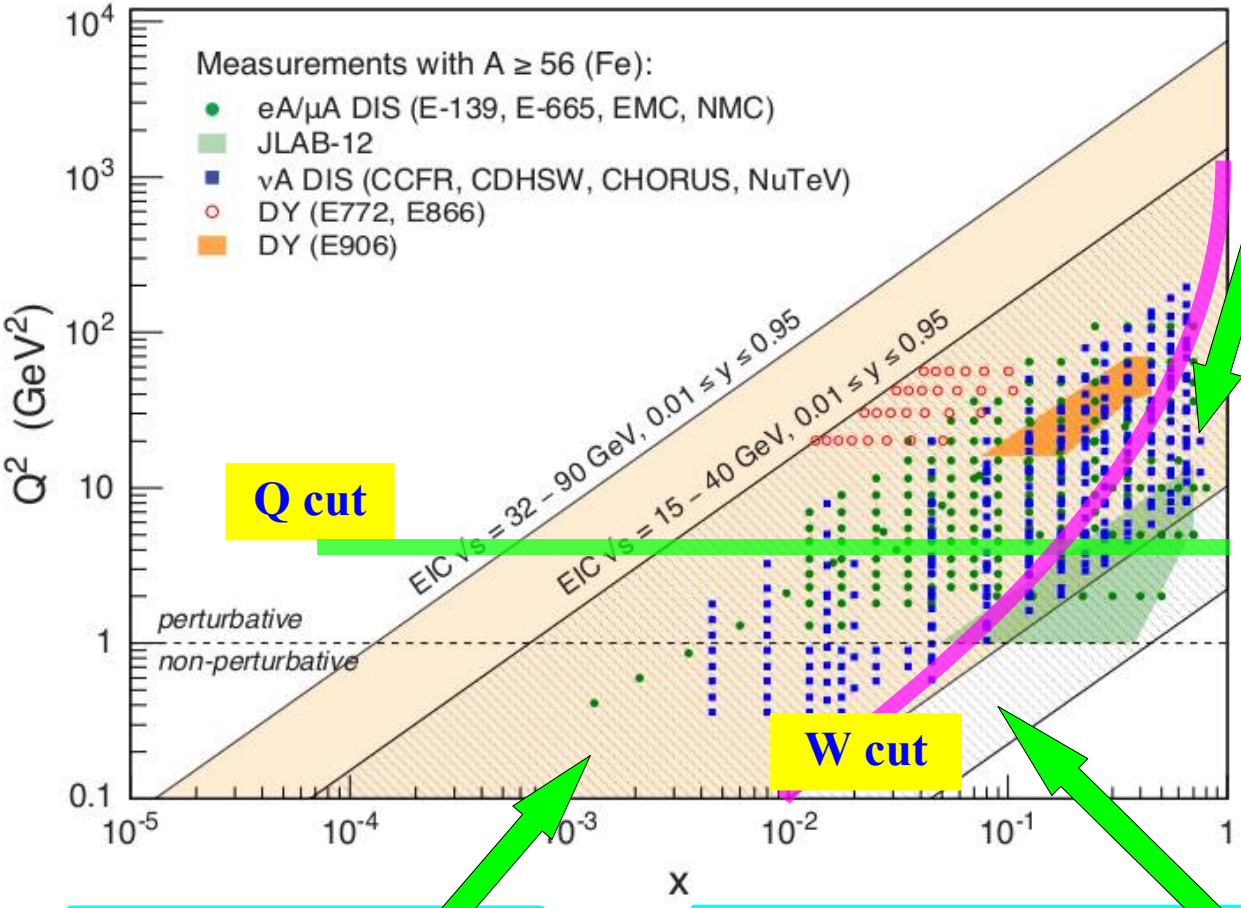
… explore full tomographic nuclear structure in **spin, k_T, b_T**

precision nPDFs $f_A(x,Q)$ can serve as Boundary Condition for $f_A(x,Q,k_T,b_T,\sigma)$

include Lattice QCD info on moments and quasi-PDFs

Need coordination/communication between efforts

Do we really understand QCD … push to extreme {x,Q}



High-x:

Nuclear PDFs: x>1 allowed;
impacts F_2^{Nuc}/F_2^{Iso} in Fermi region

Target Mass Corrections
pick up M^2/Q^2 higher twist

Deuteron Corrections
impacts $F_2^{Nuc}/F_2^{Deuteron}$ ratio

Low-x:

Shadowing
Recombination
Resummation
BFKL
Saturation

Low-Q^2:

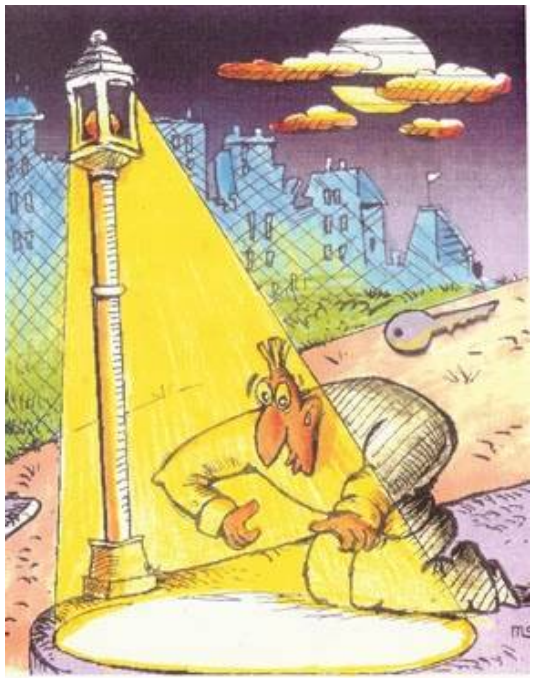
Non-Perturbative inteface
collective effects

Target Mass Corrections
pick up M^2/Q^2 higher twist

F_L at low Q^2 access to g(x)

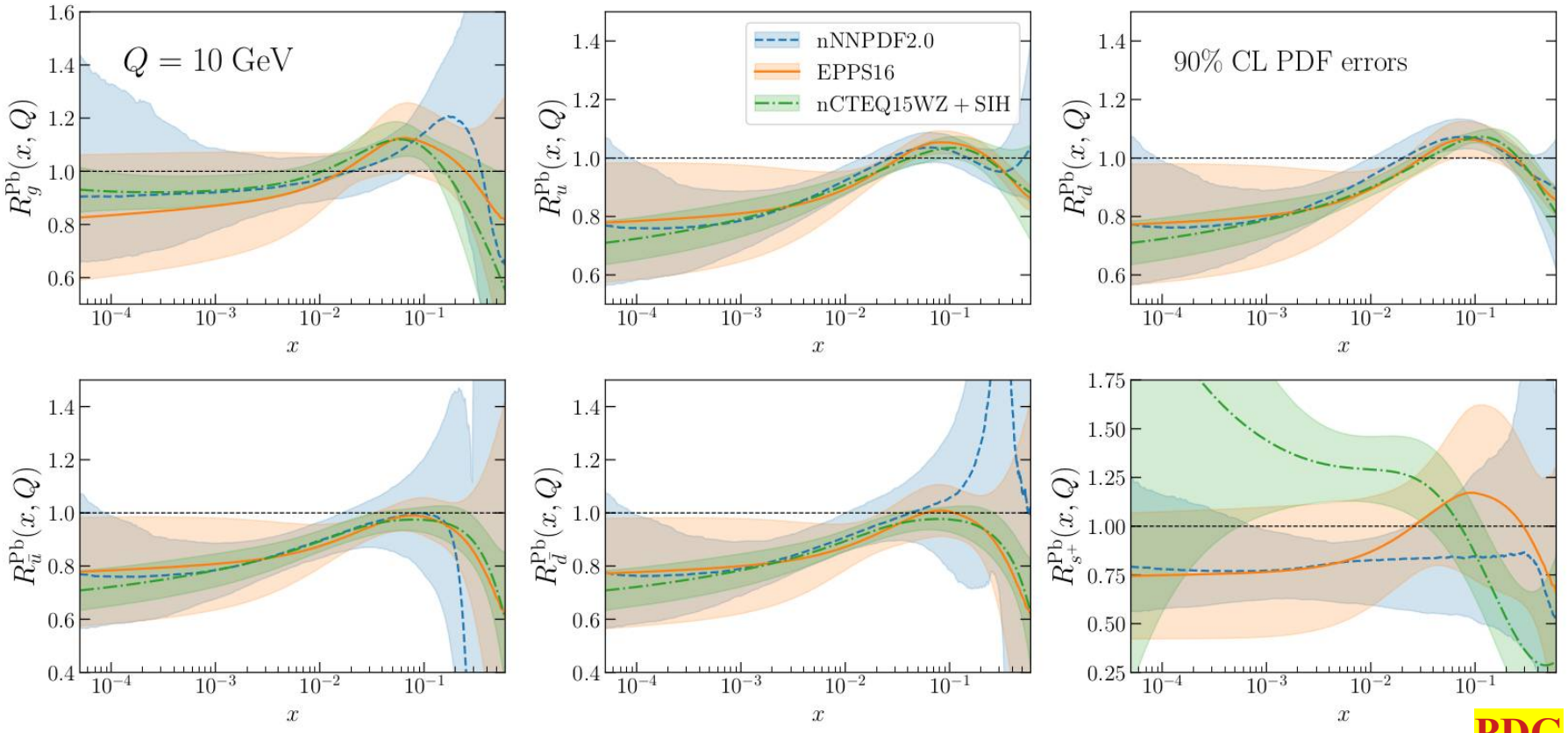
Need theoretical guidance in these regions

Are we just looking under the lamppost



nPDFs: Recent progress is impressive ...

nNNPDF, EPPS, nCTEQ, TUJU, ...



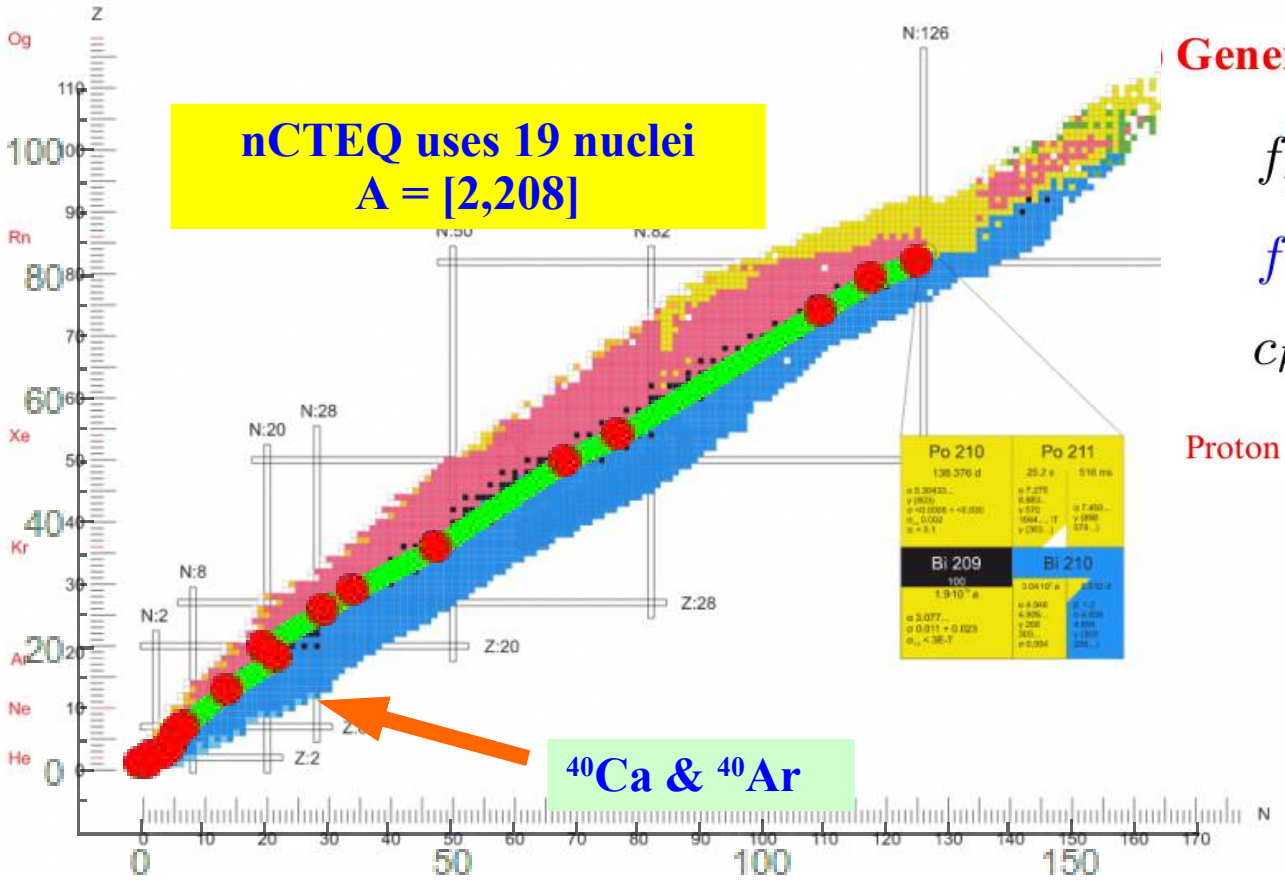
PDG

Figure 18.5: Comparison of the nNNPDF2.0, CTEQ15WZ+SIH and EPPS16 nuclear PDFs. The curves shown are ratios to the result in the limit of no nuclear corrections. Plot from NNPDF collaboration (Juan Rojo – private communication).

precision $f_A(x,Q)$ can serve as Boundary Condition for $f_A(x,Q,k_T,b_T,\sigma)$

TUJU at NLO and NNLO

Nuclear A-Dependence: *need input from theory and experiment*



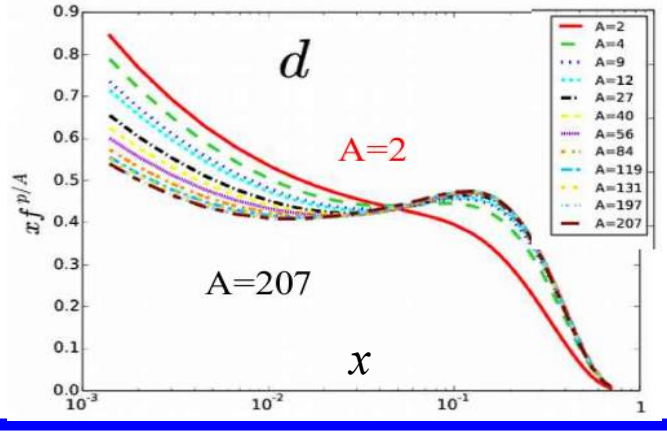
Generalized A-parameterization (nCTEQ)

$$f_i^{p/A}(x_N,\mu_0) = f_i(x_N, A, \mu_0)$$

$$f \sim ...x^{c_1(A)}(1-x)^{c_2(A)}...$$

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

Proton — Nuclear

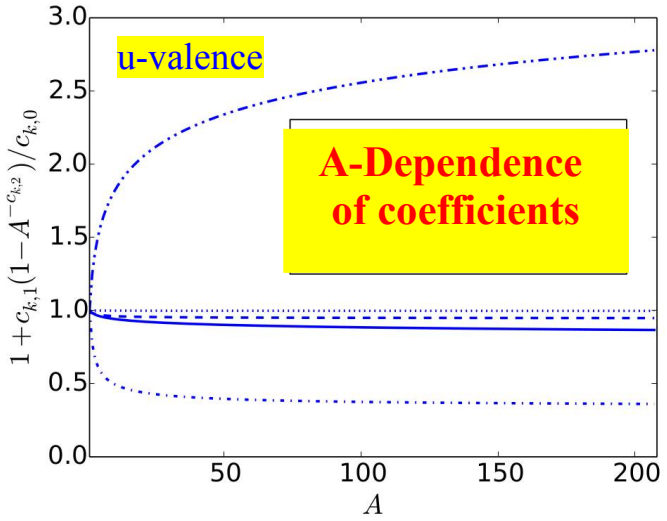


[[2, 275],
[3, 125],
[4, 66],
[6, 15],
[9, 49],
[12, 196],
[14, 101],
[27, 73],
[40, 92],
[56, 134],
[64, 61],
[84, 84],
[108, 7],
[119, 152],
[131, 4],
[184, 37],
[197, 50],
[208, 163]]

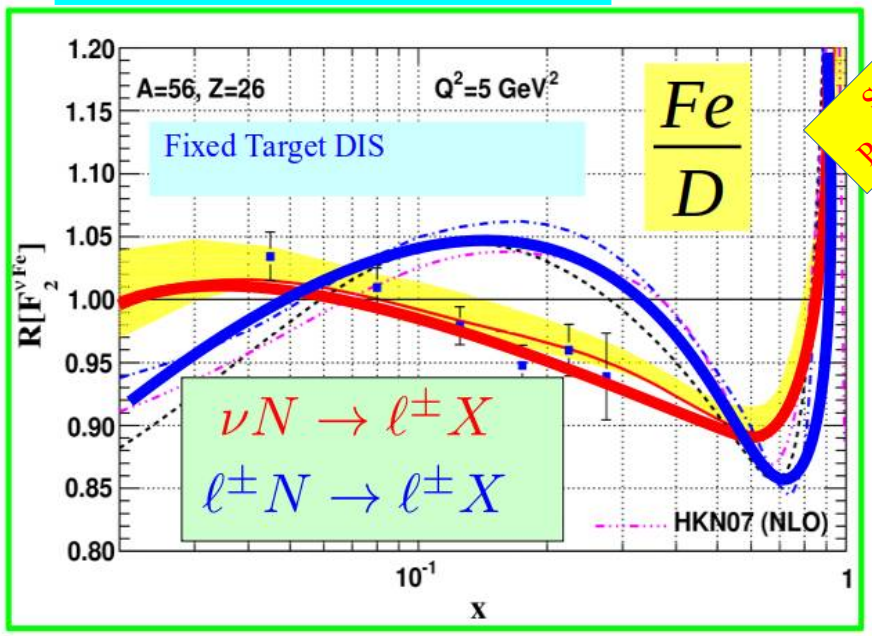
[A,#]

Number of data per A

Deuteron important
Lattice QCD nuclear
SRC inspired parm.
NEED INPUT



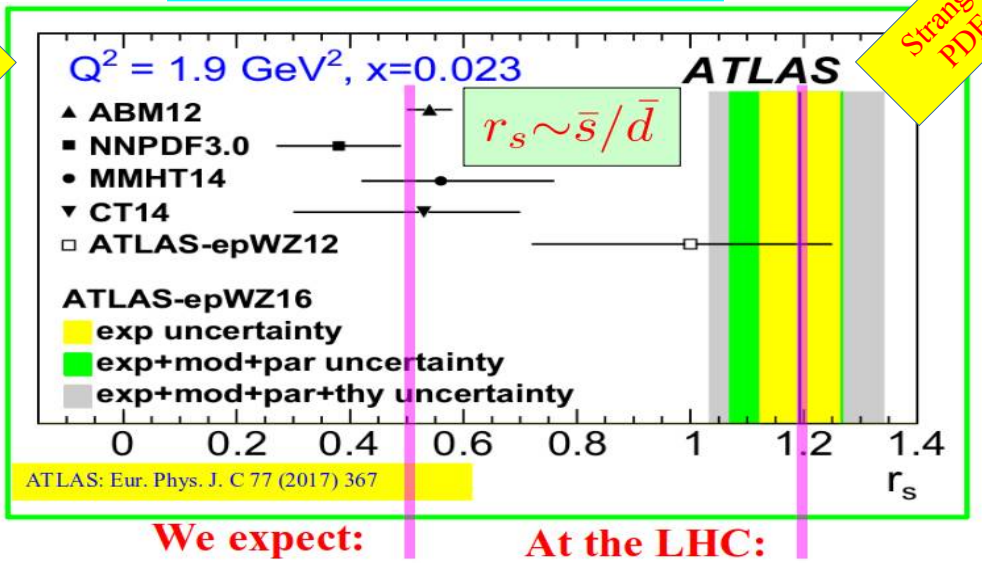
nCTEQ15ν



Split Personality

nCTEQ: arXiv: 2204.13157

nCTEQ15WZ

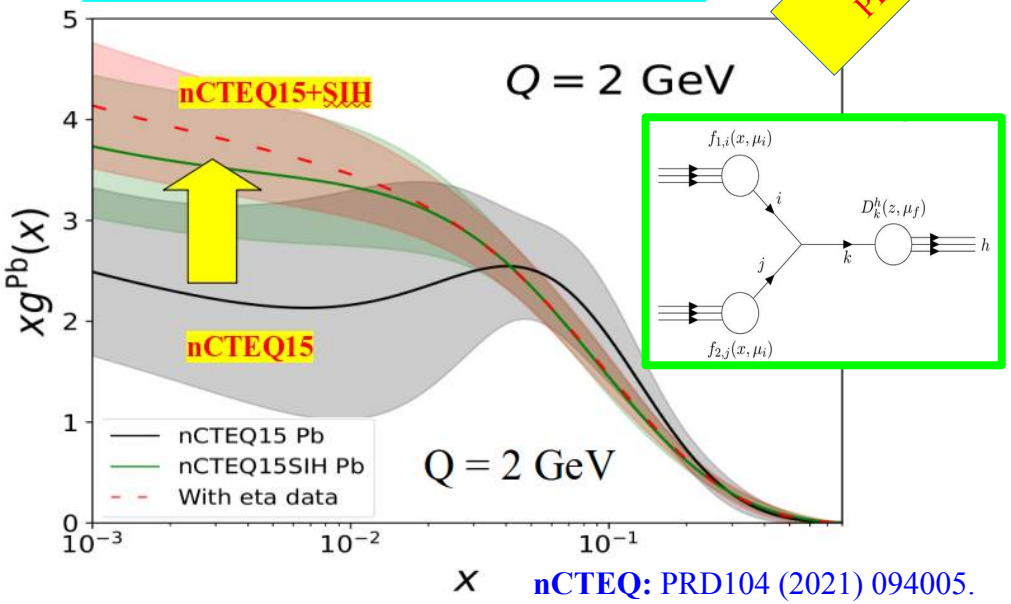


Strange PDF

We expect: At the LHC:

nCTEQ: Phys.Rev.D 104 (2021) 094005

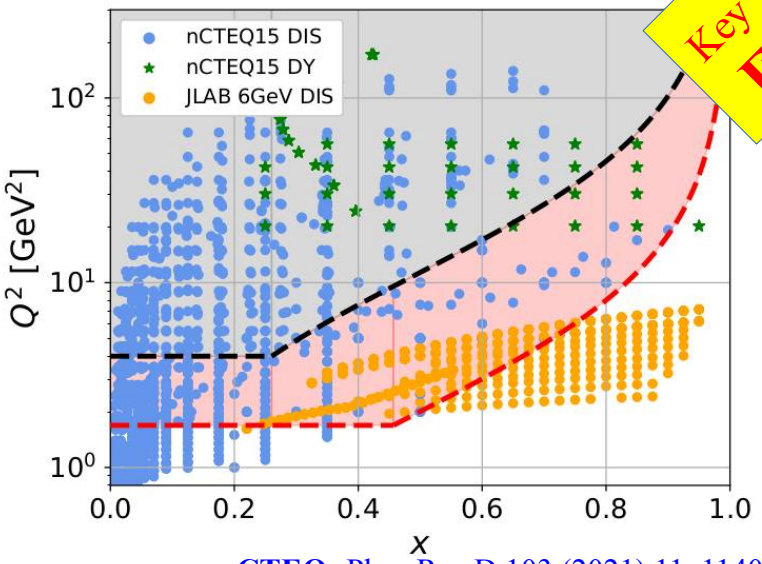
nCTEQ15WZ+SIH



Gluon PDF

nCTEQ: PRD104 (2021) 094005.

nCTEQ15HIX



Key for EIC

nCTEQ: Phys.Rev.D 103 (2021) 11, 114015

precision $f_A(x,Q)$ can serve as Boundary Condition for $f_A(x,Q,k_T,b_T,\sigma)$

Need coordination/communication between efforts

Open-source PDF framework suitable for comparing, experimenting, and PDF generation

New: modular C++ interface

xFitter

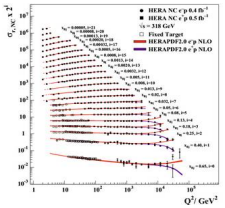
PROTON NUCLEON MESON

www.xFitter.org

Sample data files:

LHC: ATLAS, CMS, LHCb
Tevatron: CDF, D0
HERA: H1, ZEUS, Combined
Fixed Target: …
User Supplied: ...

Experimental Data



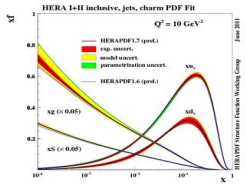
Data: HERA, Tevatron, LHC, fixed target experiments

Processes:
Inclusive DIS, Jets, Drell-Yan, Diffraction, Top production
W and Z production

Theory Calculations

HQ Schemes:	MSTW, NNPDF, ABM, ACOT
Jets, W, Z:	FastNLO, ApplGrid
Top:	Hathor
Evolution:	QCDNUM, APFEL, k_T
Other:	NNPDF reweighting TMDs, Dipole Model, ...

xFitter



Parton Distribution Functions:
PDF, Updf, TMD

$\alpha_S(M_Z)$, m_c,m_b,m_t ...

Theoretical Cross Sections

Comparisons to other PDFs (LHAPDF)

extensions include nuclear PDFs

Features & Recent Updates:

NNLO DGLAP
Photon PDF & **QED**
Pole & MS-bar masses
Profiling and Re-Weighting
BFKL interface

Heavy Quark Variable Treshold
Improvements in χ^2 and correlations
TMD PDFs (uPDFs)
... and many other

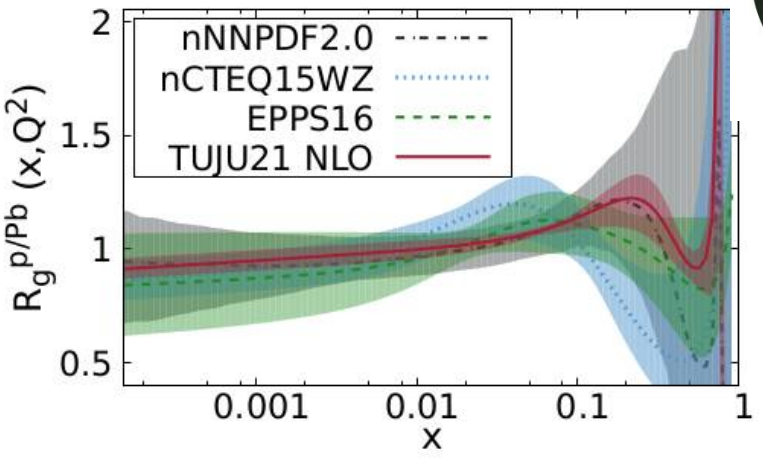
xFitter 2.2.0
Future Freeze

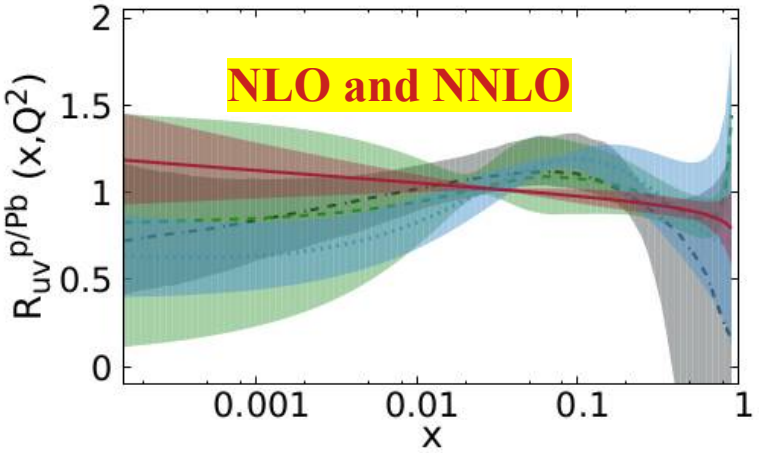
Nuclear xFitter: *(Daiquiri)*

PHYSICAL REVIEW D **100,** 096015 (2019)

Open-source QCD analysis of nuclear parton distribution functions at NLO and NNLO

Marina Walt,[1,*] Ilkka Helenius,[2,3,†] and Werner Vogelsang[1,‡]





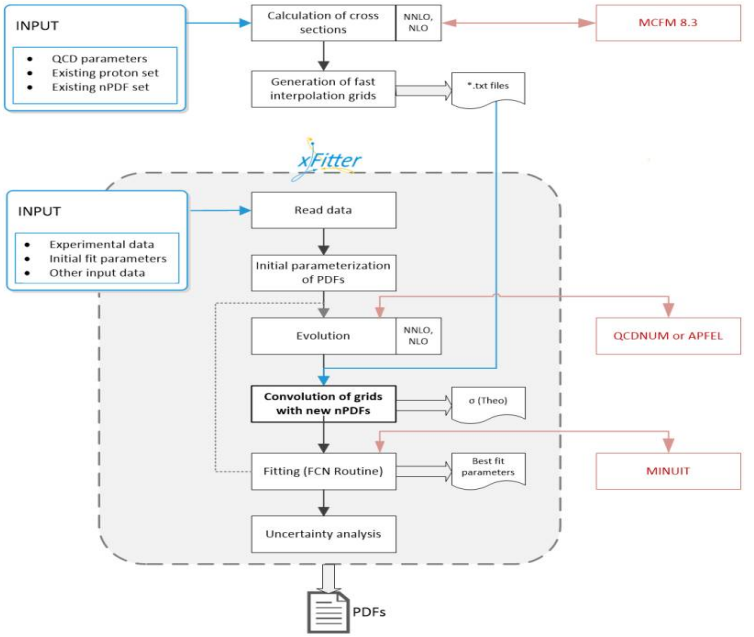


FIG. 1: Schematic view of the high-level xFitter functionalities as relevant for Drell-Yan and $W^{\pm}$, Z boson production processes, with the newly implemented convolution routine in xFitter as used for the nPDF fit TUJU21. xFitter logo credited from [60].

DESY. xFitter

Could be valuable EIC resource

Date	Version	Files	Remarks
 02/2020	**2.0.1N Nuclear Daiquiri**	xfitter-2.0.1N.tgz	Nuclear xFitter based on OldFashioned 2.0.1

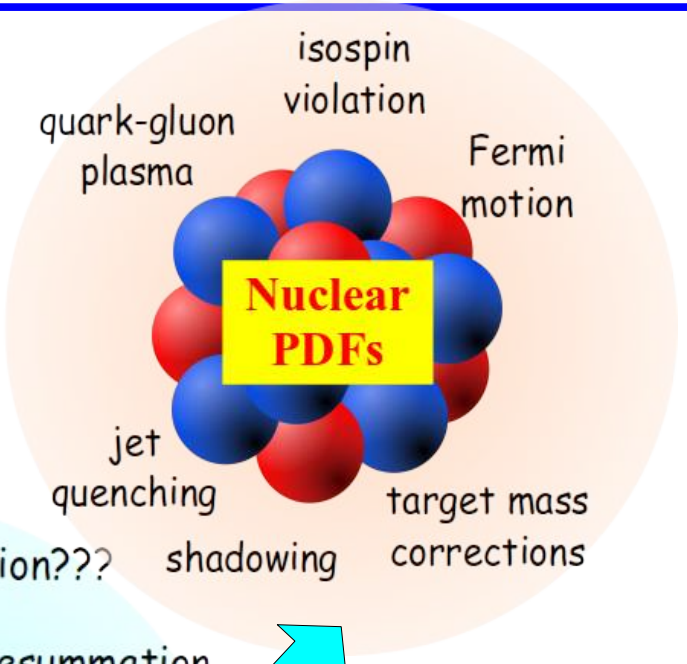
Open-source PDF framework suitable for comparing, experimenting, and PDF generation

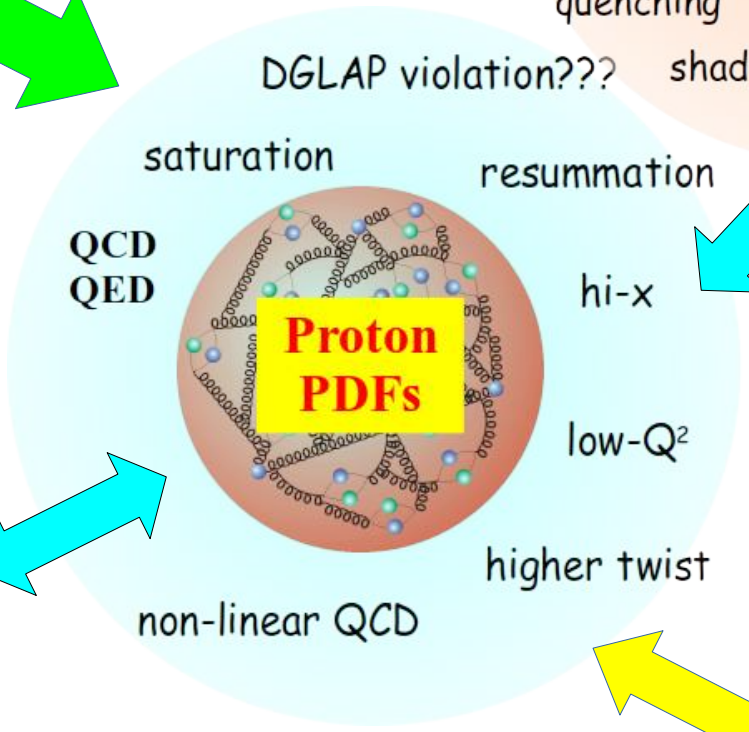
CONCLUSIONS

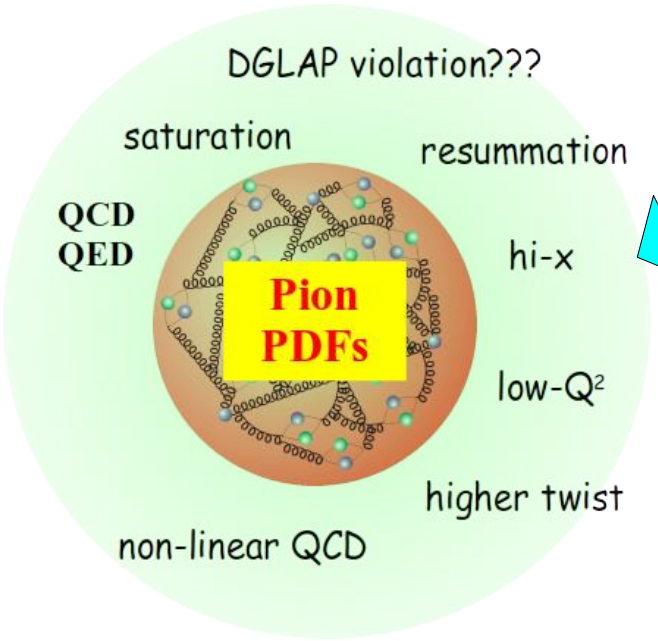
QCD: From Parameterization to a Deeper Understanding

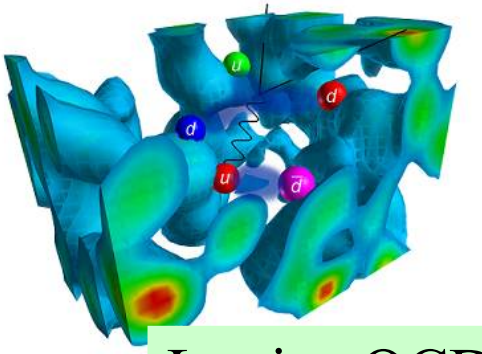
QCD
Lagrangian

$$\mathcal{L}_{QCD} = \overline{\psi}_q \left(i\gamma_\mu D^\mu - m_q \right) \psi_q - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$









Lattice QCD

- **Spin**
- **TMDs**
- **GPDs**

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… explore full tomographic nuclear structure in spin, k_T, b_T

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include Lattice QCD info on moments and quasi-PDFs

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