Revealing the fundamental character of the strong force

From PDFs to the underlying QCD

Fred Olness
SMU

Thanks for substantial input
from my friends & colleagues

nCTEQ
nuclear parton distribution functions

C T E Q

xFitter

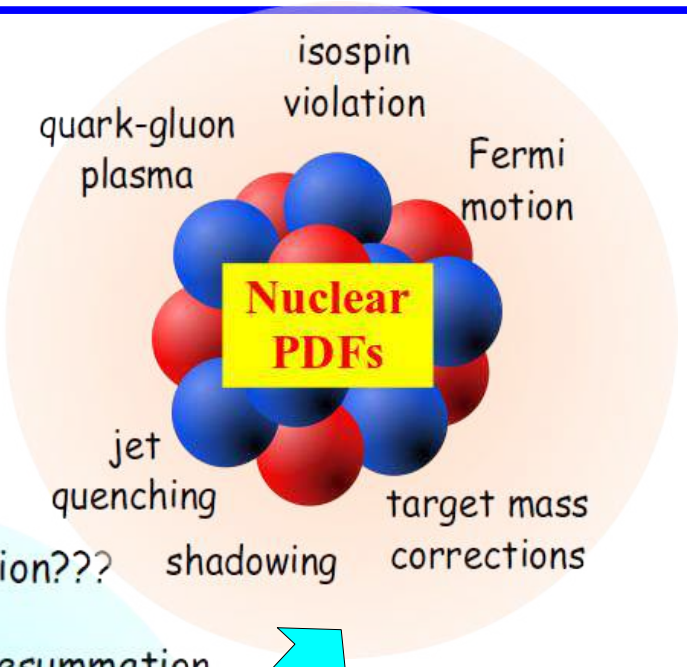
SURGE COLLABORATION

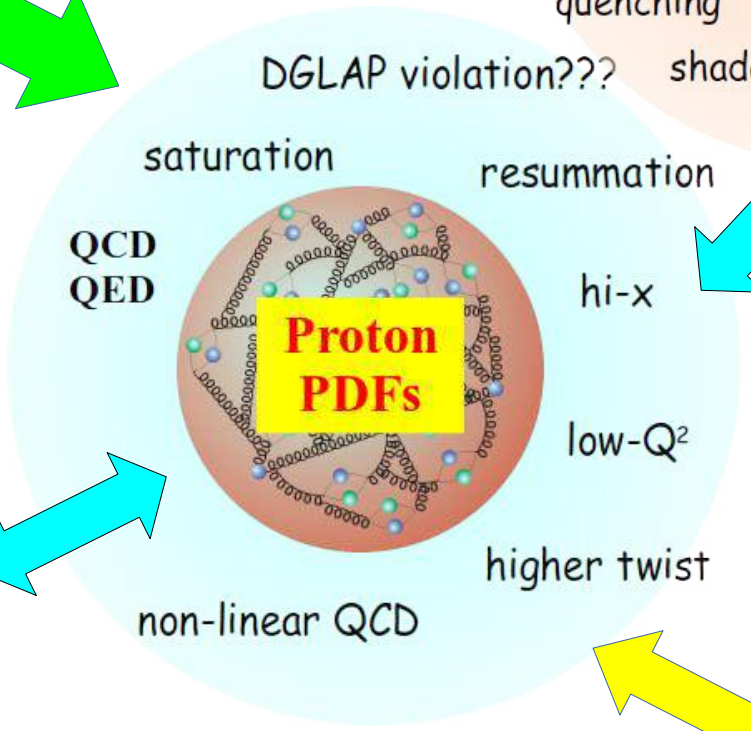
JLab
Nucleon & nuclei structure
20 June 2023

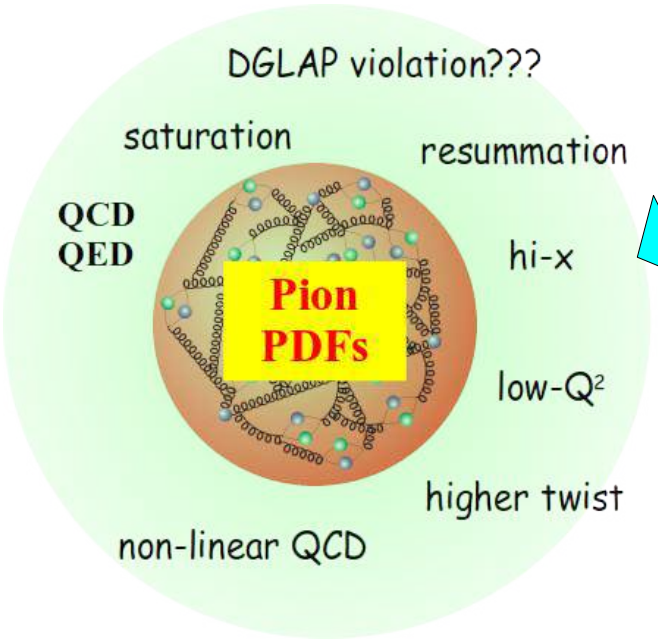
QCD: From PDFs to the underlying QCD

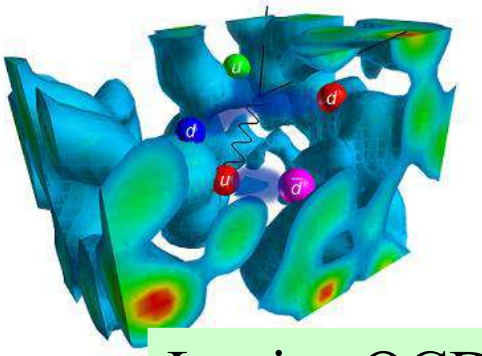
QCD
Lagrangian

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









Lattice QCD

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

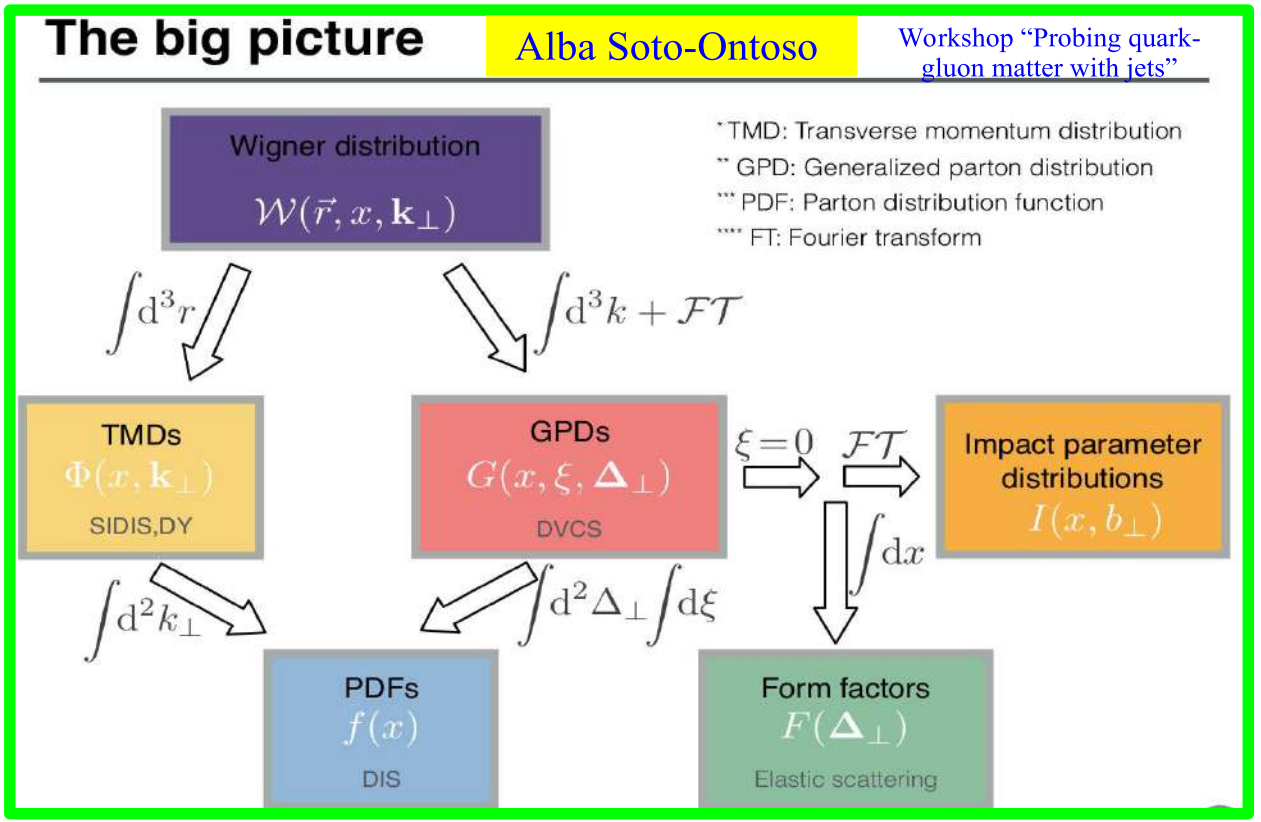
Apologies

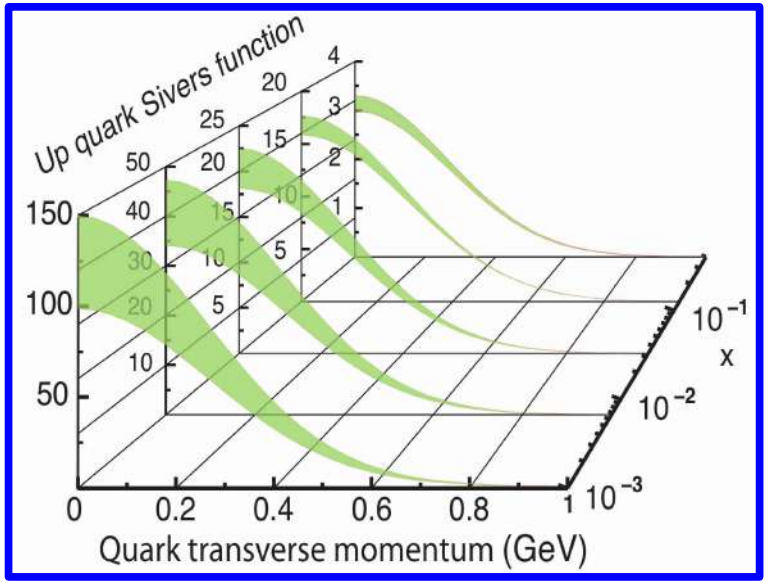
...

no time for

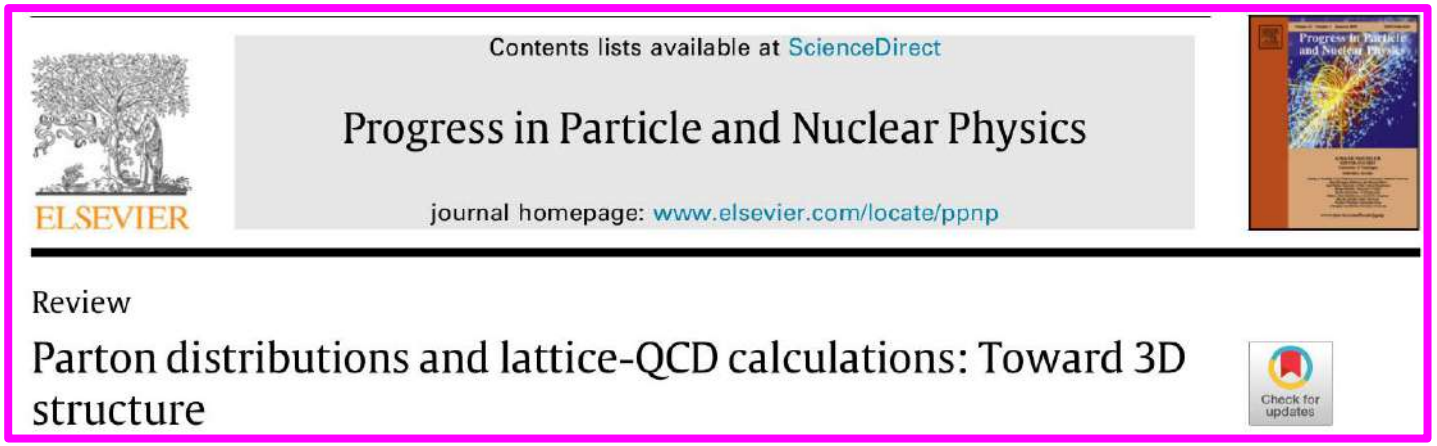
No time for … Lattice Calculations, TMDs, Generalized PDFs

Hadron structure is much richer than f(x) conveys



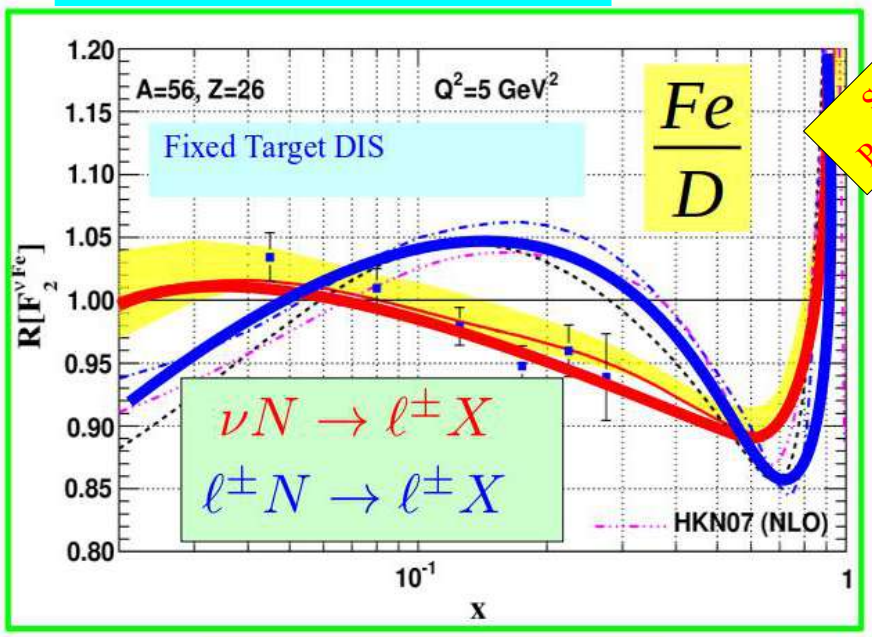


Conventional PDFs f(x) are the Boundary Conditions



Progress in Particle and Nuclear Physics 121 (2021) 103908

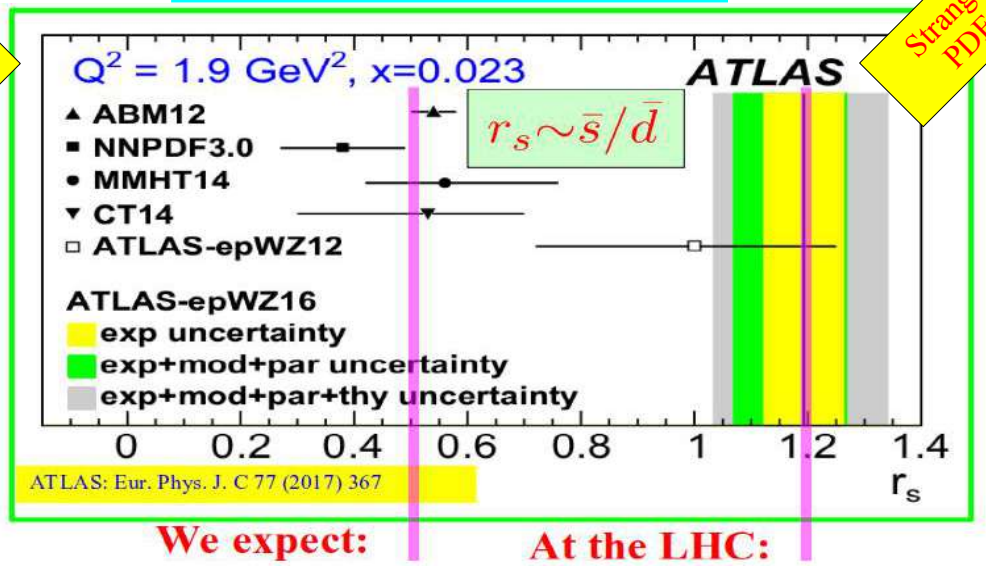
nCTEQ15ν



Split Personality

nCTEQ: arXiv: 2204.13157

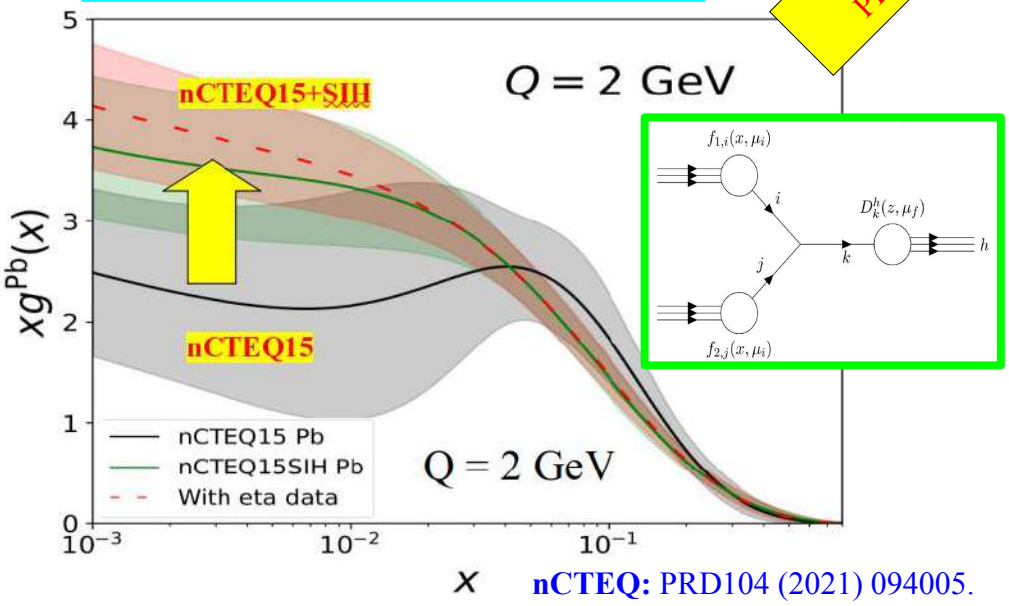
nCTEQ15WZ



Strange PDF

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

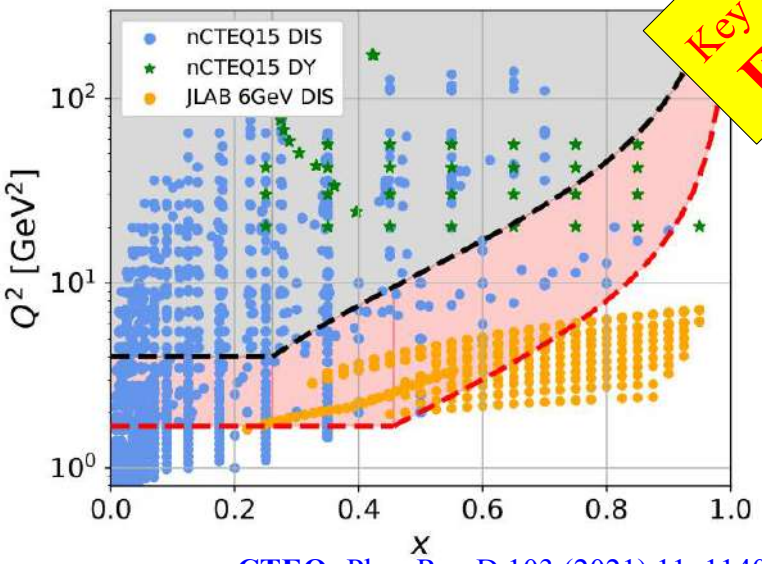
nCTEQ15WZ+SIH



Gluon PDF

nCTEQ: PRD104 (2021) 094005.

nCTEQ15HIX



Key for EIC

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

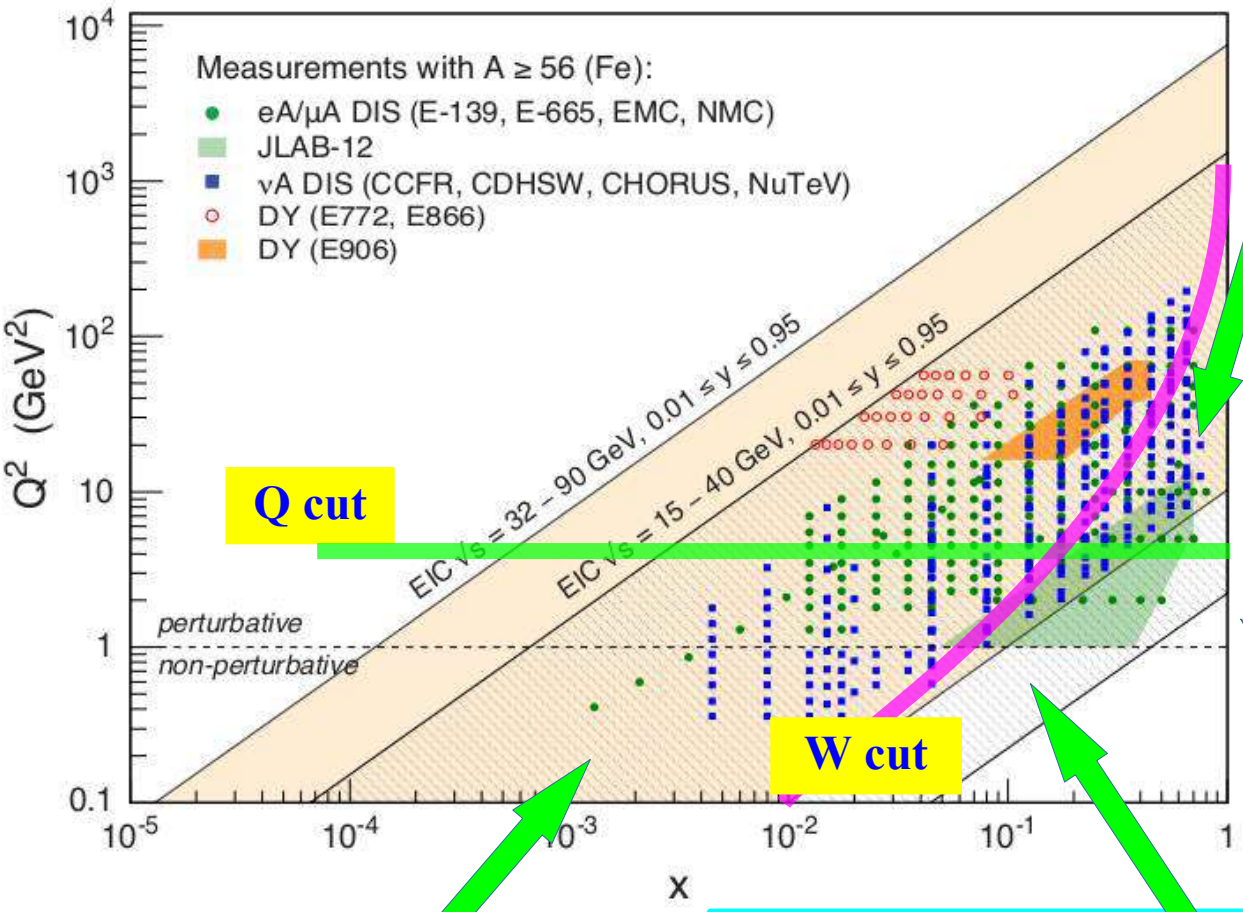
precision $f_A(x,Q)$ can serve as Boundary Condition for $f_A(x,Q,k_T,b_T,\sigma)$

nPDFs:

Extend Precision &

Kinematic Reach in $\{x,Q^2\}$

nPDFs: Extend Precision & Kinematic Reach in {x,Q²}



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

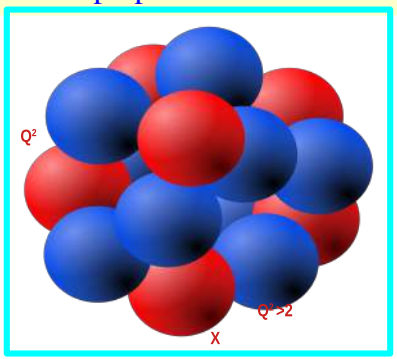
Low-Q²:

Non-Perturbative inteface
collective effects

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

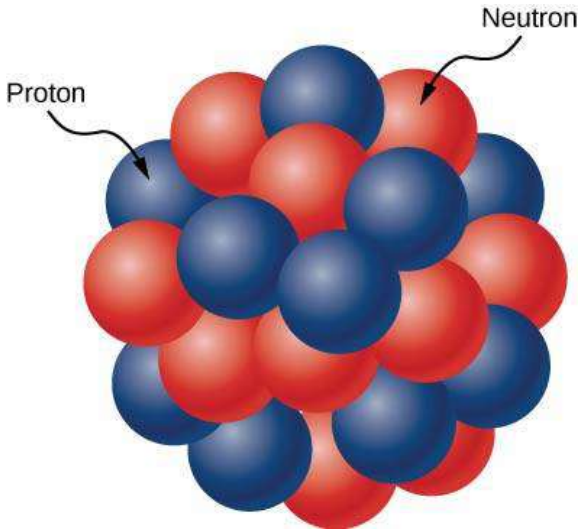
F_L at low Q^2 access to g(x)
Run at multiple energies

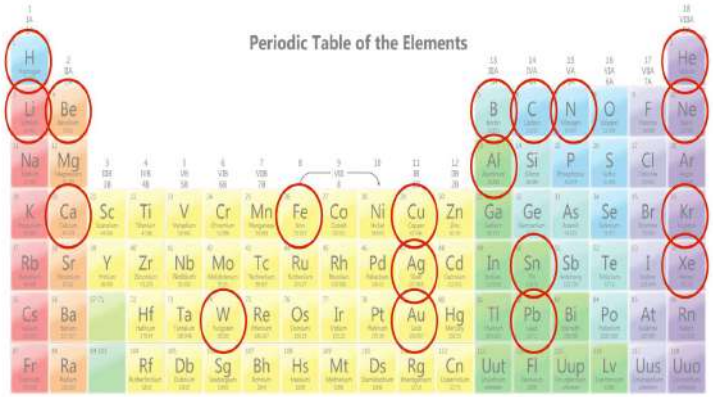
JLab Data @ Hi-X Low-Q²
extend nCTEQ framework for this region
& prepare for EIC

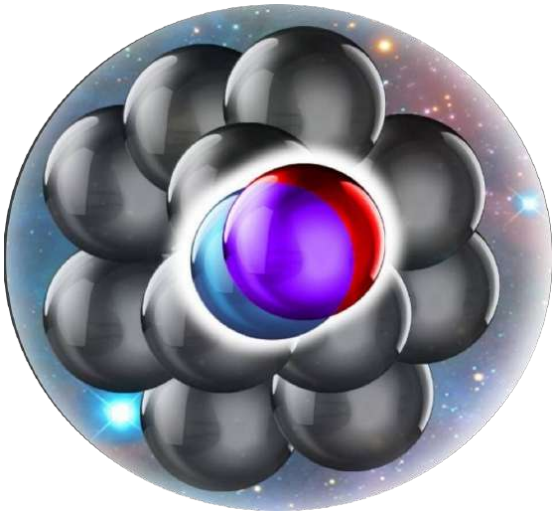


Nuclear PDFs

Parton Distribution Functions

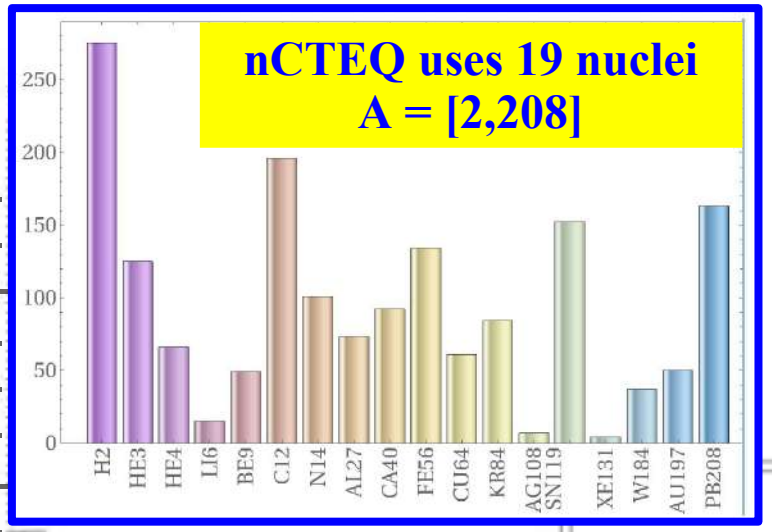






nCTEQ nuclear PDF parameterization

… Limitations, Assumptions ...


nCTEQ uses 19 nuclei
A = [2,208]
H2
HE3
HE4
LI6
BE9
C12
N14
AL27
CA40
FE56
CU64
KR84
AG108
SN119
XE131
W184
AU197
PB208

Og
Rn
Xe
Kr
Ar
Ne
He
N:126
N:82
N:28
N:20
N:8
N:2
Z:82
Z:28
Z:20
Z:8
Z:2
N
0
50
100
150

d
A=2
A=207
$x f^{p/A}$
x
A=2
A=4
A=9
A=12
A=27
A=40
A=56
A=84
A=119
A=131
A=197
A=207

2) Generalized A-parameterization (nCTEQ)

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

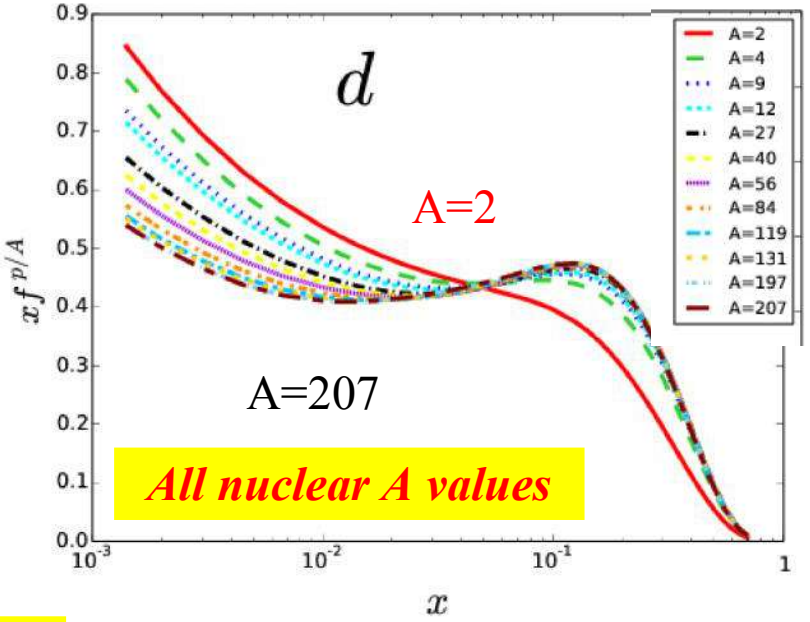
$$f \sim ...x^{c_1(A)}(1-x)^{c_2(A)}...$$

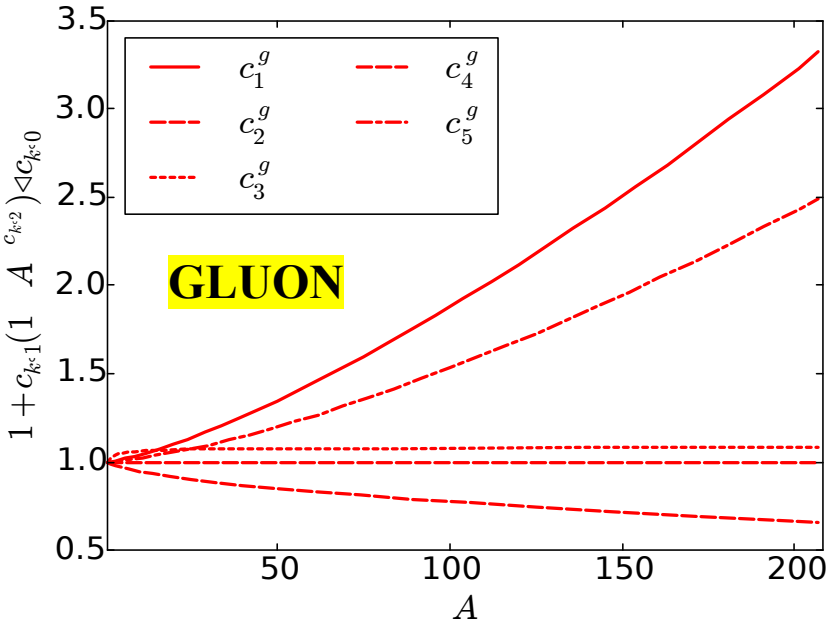
$$c_k \sim c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right)$$

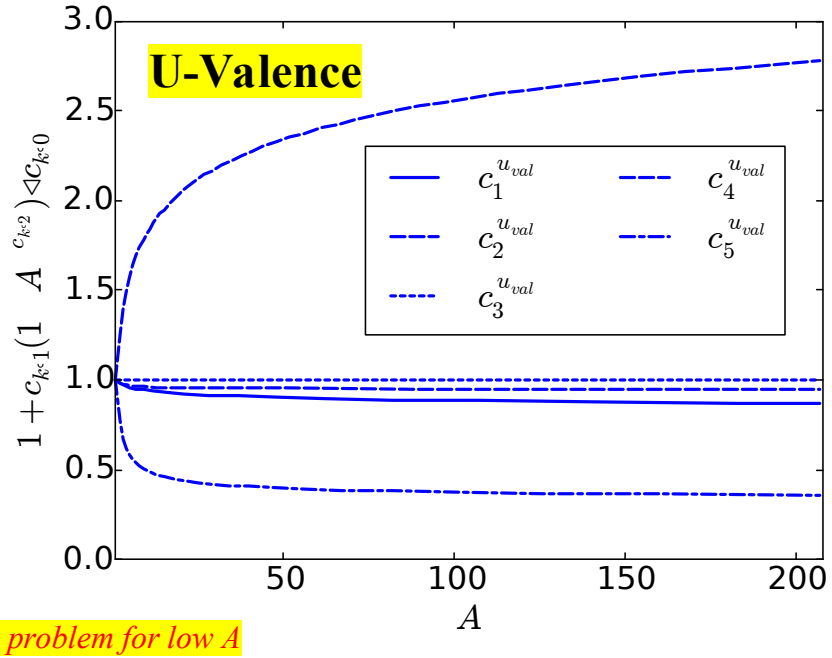
Proton

Nuclear

use proton as a Boundary Condition





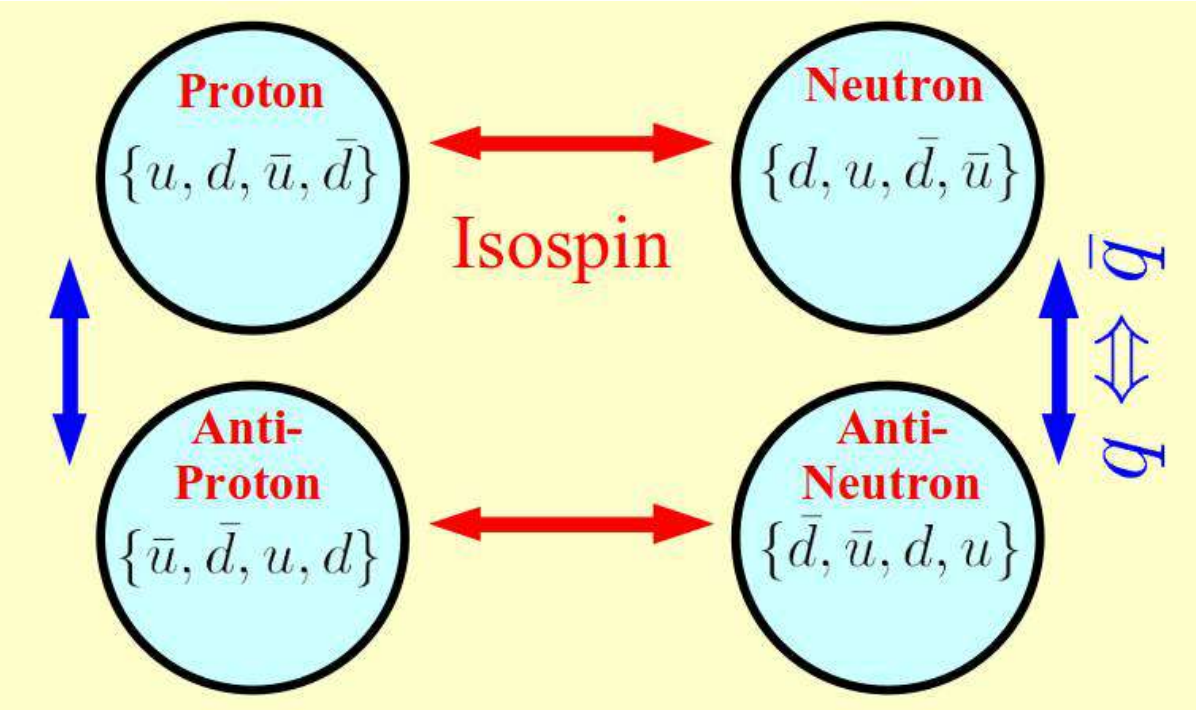


... a problem for low A

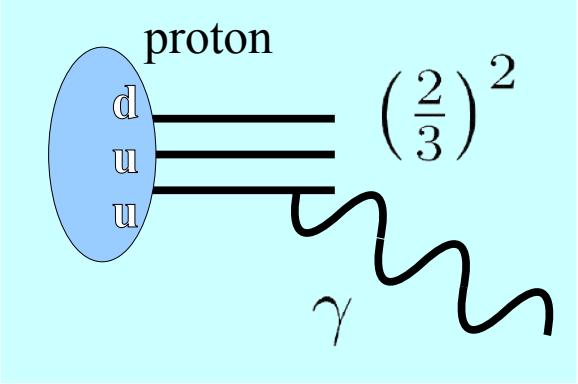
Isospin Symmetry used to generate nPDFs

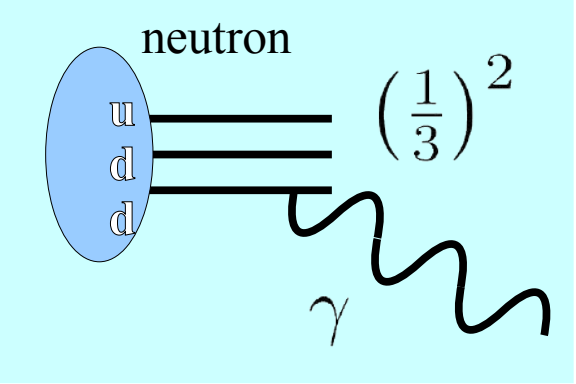
Parameterize $f^{p/A}(x,Q_0)$

$$\alpha_s^2 \sim \alpha$$



"New" Photon PDFs





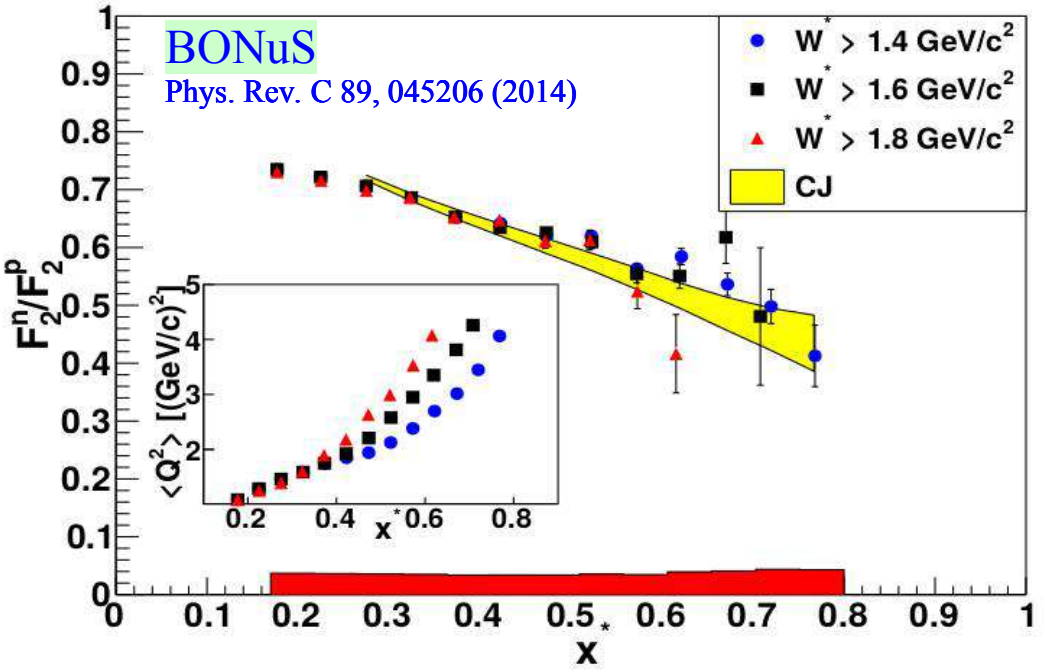
Isospin terms are comparable to NNLO QCD

QCD & EW Corrections do NOT factorize

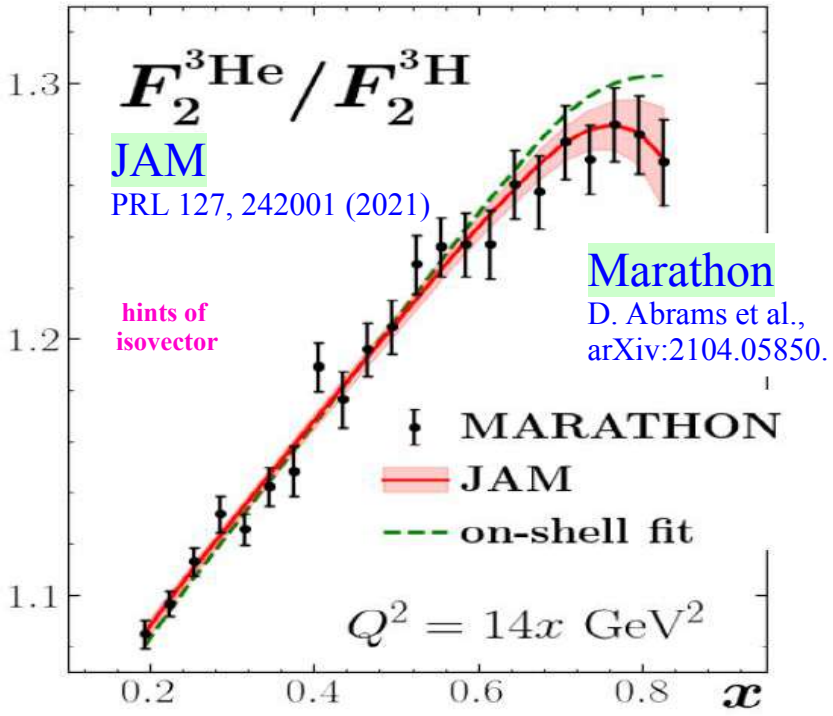
A Review of Target Mass Corrections.
Ingo Schienbein et al,
J.Phys.G35:053101,2008.

Combined Challenges for Precision nPDFs

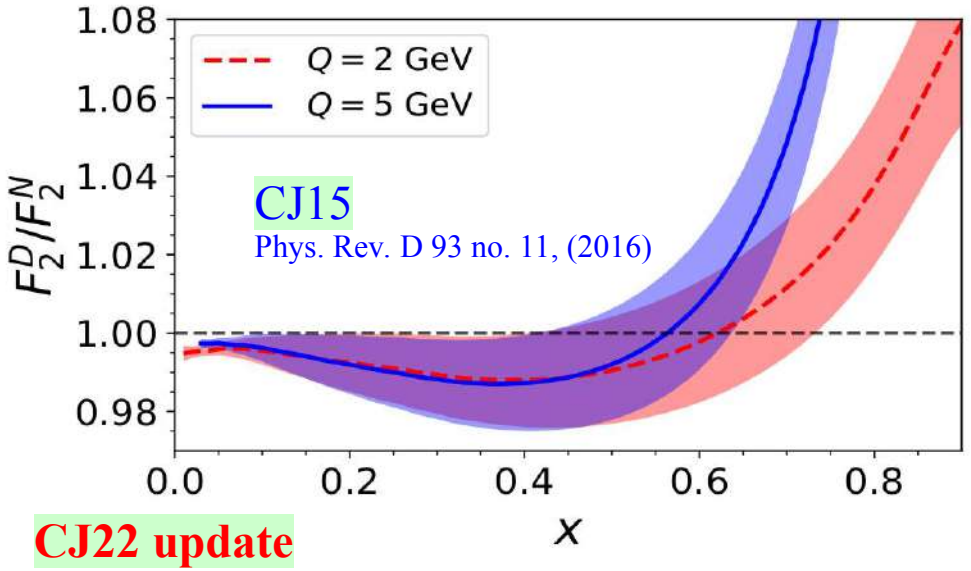
Measurements on "neutron" beam



Measurements on Tritium

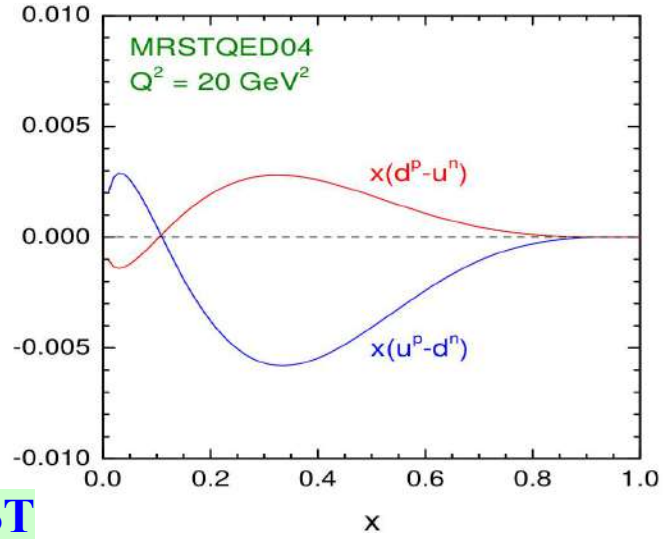


Deuteron Correction



CJ22 update

Impact of QED Corrections



MRST

Eur.Phys.J.C39:155-161,2005

Extended Kinematics

Higher twist
mass effects
limit $x \to 1$

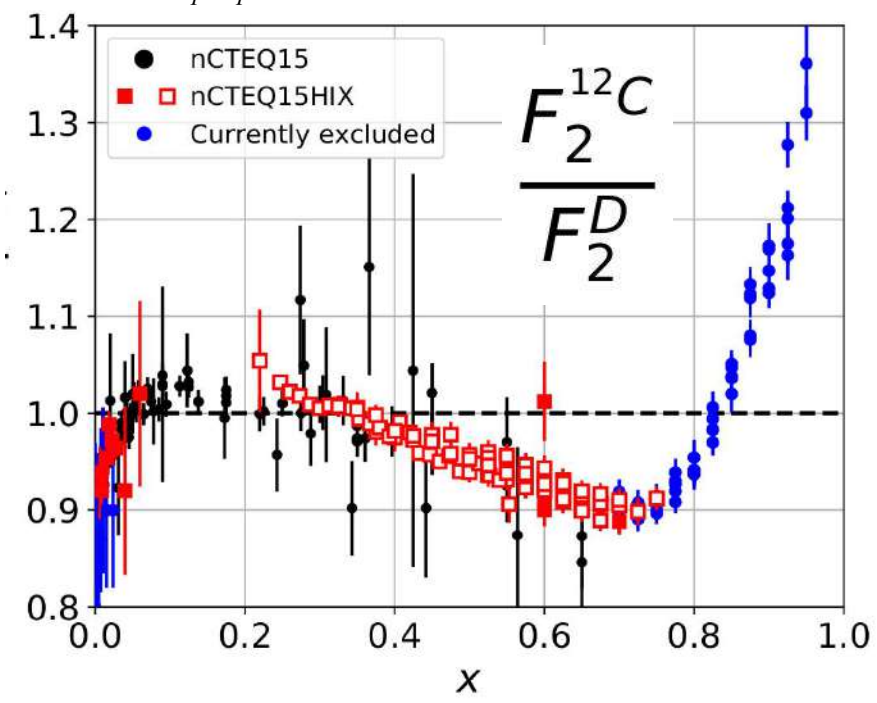
PHYSICAL REVIEW D **103,** 114015 (2021)

Extending nuclear PDF analyses into the high-x, low-Q^2 region

E. P. Segarra,[1,*] T. Ježo,[2,†] A. Accardi,[3,4] P. Duwentäster,[5] O. Hen,[1] T. J. Hobbs,[6,4,7] C. Keppel,[4] M. Klasen,[5] K. Kovařík,[5] A. Kusina,[8] J. G. Morfín,[9] K. F. Muzakka,[5] F. I. Olness,[6,‡] I. Schienbein,[10] and J. Y. Yu.[10]

Challenges at Large x & Low Q^2 & Low W^2:

open points: new with relaxed cuts

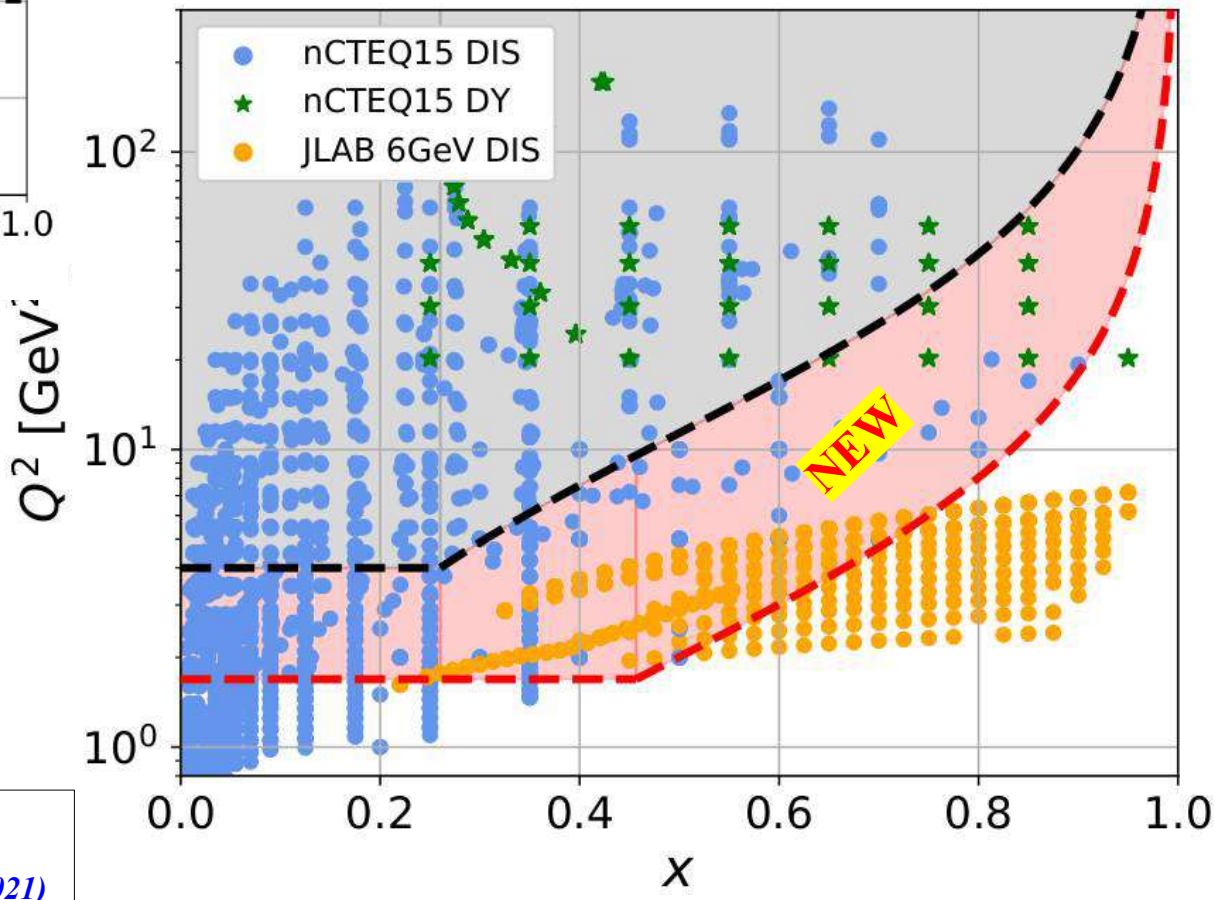


JLab Data @ Hi-X Low-Q^2
extend nCTEQ framework
to accommodate this region
& prepare for EIC

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 contributions

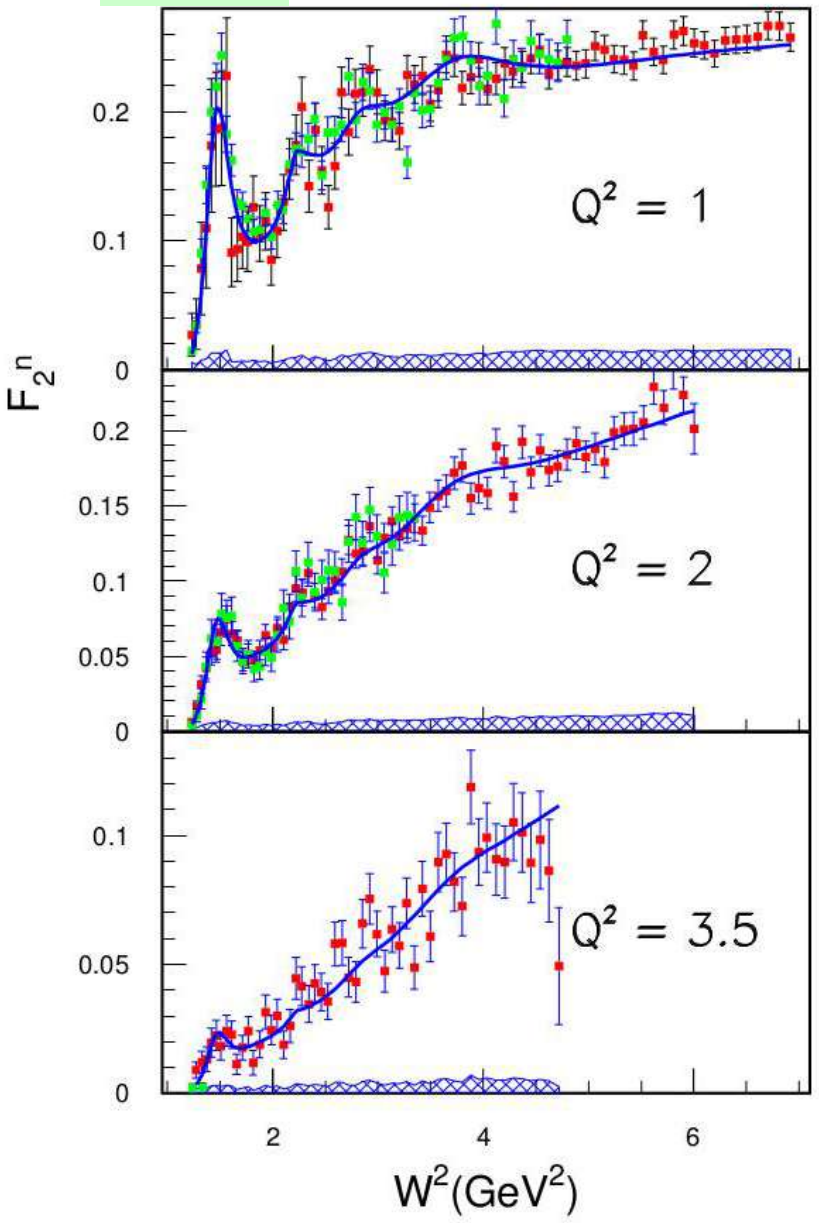
Deuteron Corrections
impacts $F_2^{Nuc}/F_2^{Deuteron}$ ratio



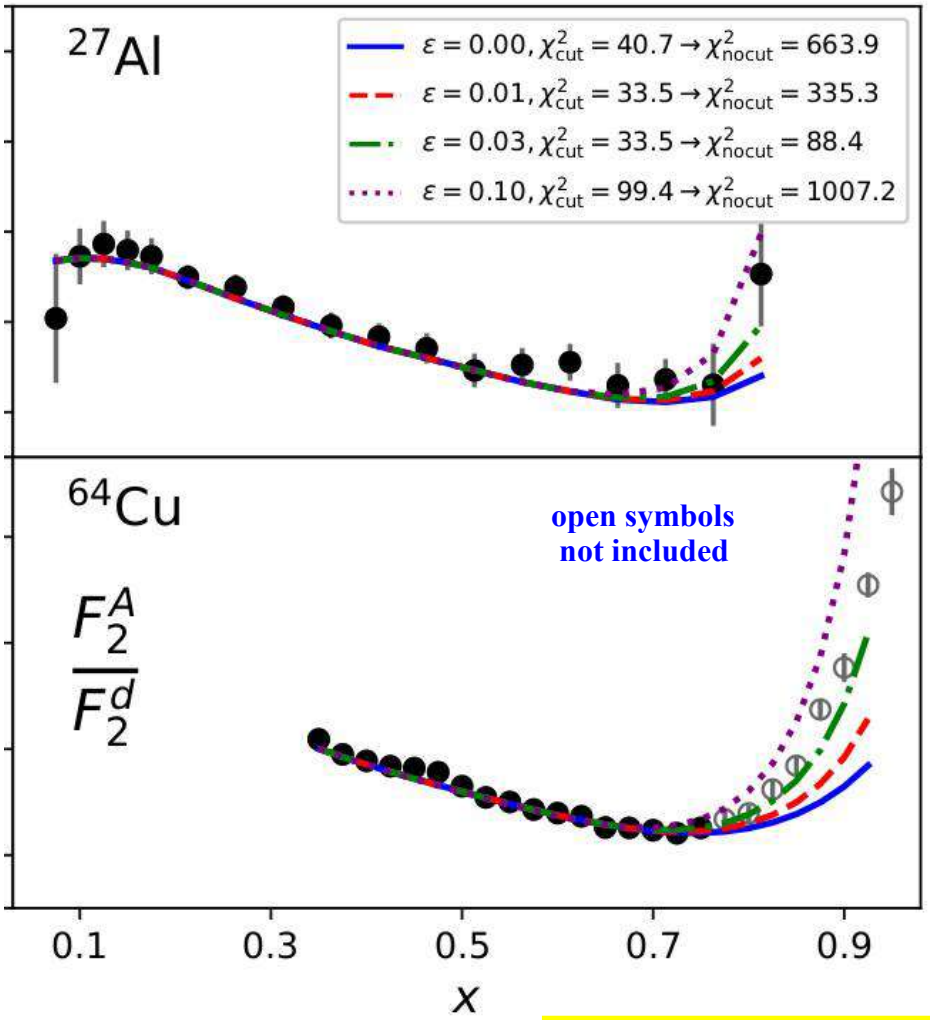
nCTEQ15HIX -- Extending nPDF Analyses into the High-x, Low Q2 Region
E.P. Segarra, T. Ježo, et al., ***PRD 103, 114015 (2021)***

Hadron / Parton Transition: How Low in W^2 and Q^2 can we go???

BoNuS data



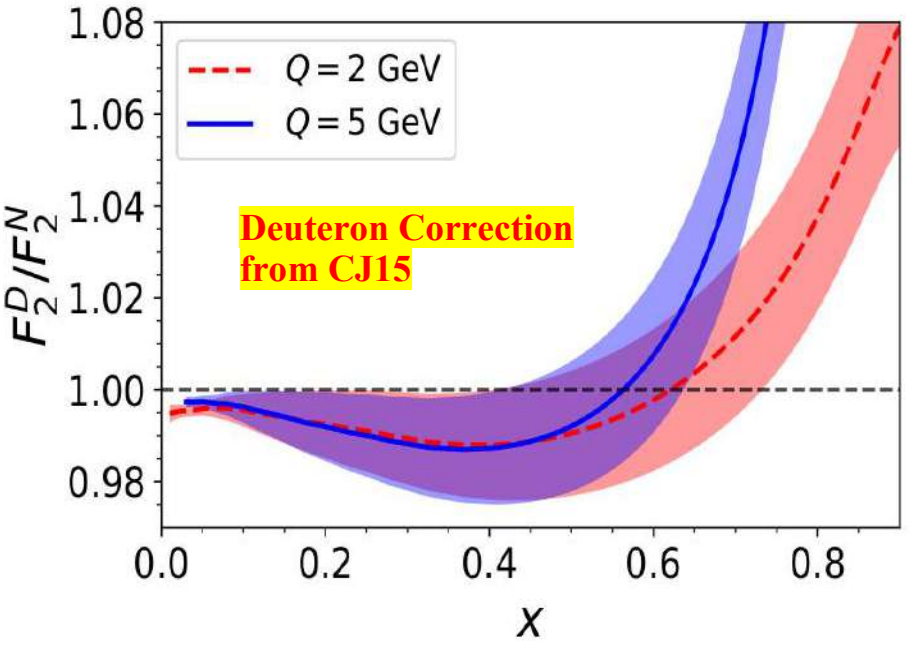
Can we push into the resonance region?

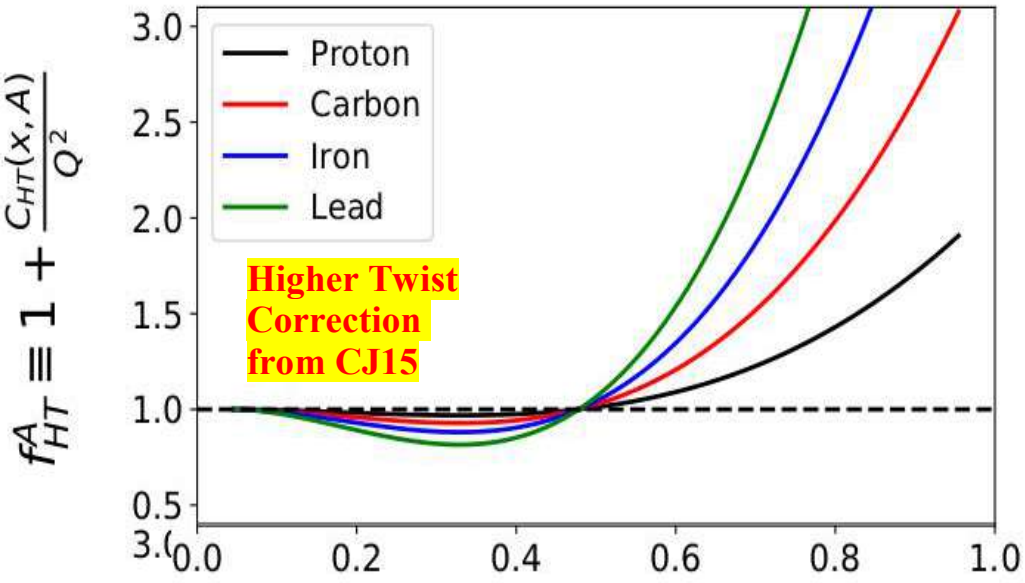


Reduces {Q,W} cuts

Fit	χ^2	N_{data}	χ^2/N_{dof}	Q_{cut}	W_{cut}
nCTEQ15	587	740	0.81	2.0	3.5
nCTEQ15*	2664	1564	1.70	1.3	1.7
nCTEQ15HIX	1291	1564	0.83	1.3	1.7

nCTEQ15HIX include large x JLab data





Fit	χ^2	N_{data}	χ^2/N_{dof}	Q_{cut}	W_{cut}
nCTEQ15	587	740	0.81	2.0	3.5
nCTEQ15*	2664	1564	1.70	1.3	1.7
BASE	1525	1564	0.99		
HT	1482	1564	0.96		
DEUT	1331	1564	0.85		
nCTEQ15HIX	1291	1564	0.83		

Reference

Higher Twist ~3%

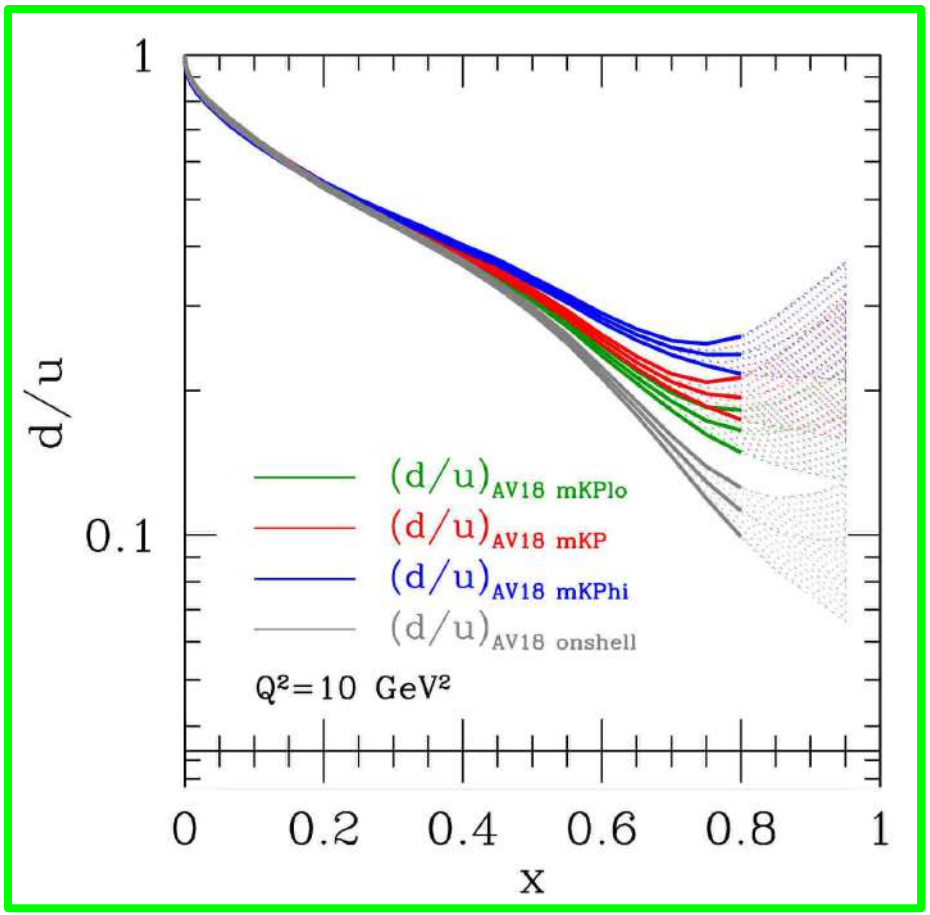
Deuteron ~14%

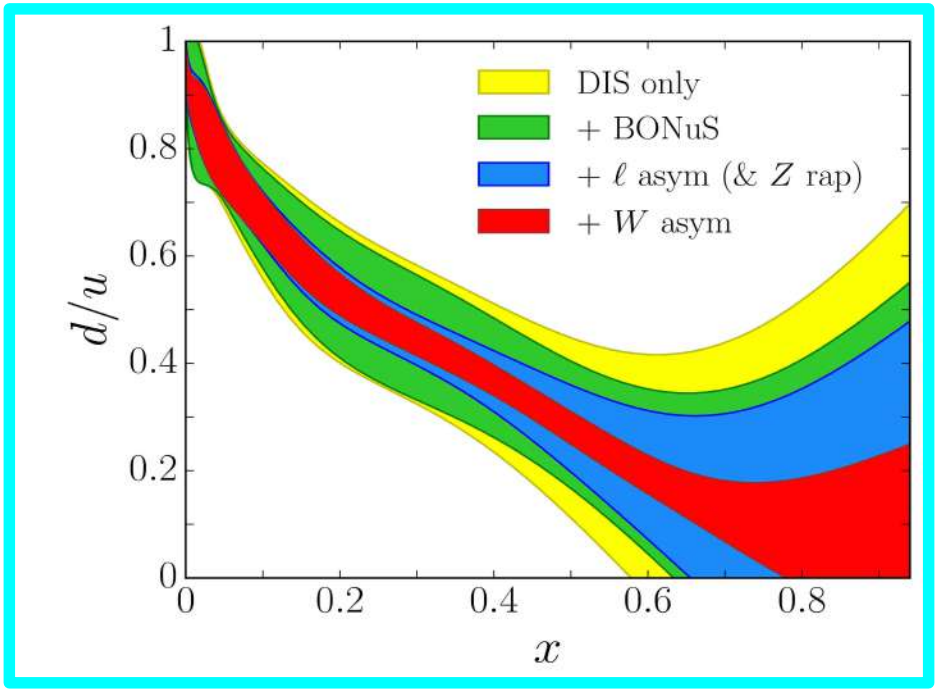
Combined ~16%

We can extend our kinematic reach in {x,Q²}

what about mid x region

Nuclear PDFs: In the limit x → 1





CJ-15

$$d_v \to a_0^{d_v}\left(\frac{d_v}{a_0^{d_v}} + b\,x^c\,u_v\right)$$

- d/u → 1/2 : SU(6) Spin-Flavor symmetry
- d/u → 0 : Scalar diquark dominance
- d/u → 1/5 : pQCD power counting
- Local quark hadron duality:

$$d/u \to \frac{4\mu_n^2/\mu_p^2 - 1}{4 - \mu_n^2/\mu_p^2} \simeq 0.42$$

- Better understanding important for BSM searches of new heavy states

Ingo Schienbein
2018 Trento Workshop

A.Accardi, W.Melnitchouk, J.F.Owens, M.E.Christy, C.E.Keppel, L.Zhu, J.G.Morfin
Phys.Rev.D84:014008,2011

A. Accardi, L.T. Brady, W. Melnitchouk, J.F. Owens, N. Sato,
Phys.Rev. D93 (2016) no.11, 114017

Target Mass Corrections

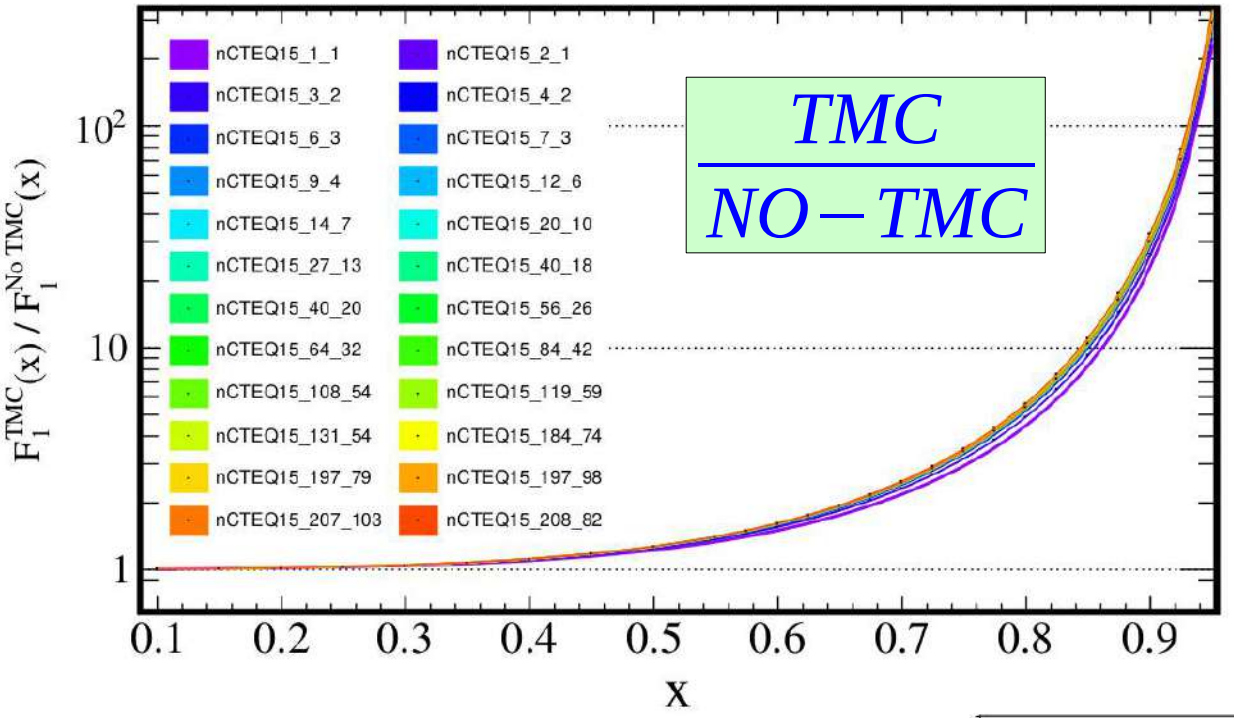
The challenge of a multi-scale problem

January 20, 2023

Target mass corrections in lepton-nucleus DIS:
theory and applications to nuclear PDFs

R. Ruiz [a], K.F. Muzakka [b,c], C. Leger, [d] P. Risse [b], A. Accardi [e,f], P. Duwentäster [b,g,h], T.J. Hobbs [i], T. Ježo [b], C. Keppel [e], M. Klasen [b,j], K. Kovařík [b], A. Kusina [a], J.G. Morfín [k], F.I. Olness [l], J.F. Owens, [m], I. Schienbein [d], J.Y. Yu. [d]

Target Mass Corrections (TMC) for nuclear processes



$$\frac{TMC}{NO-TMC}$$

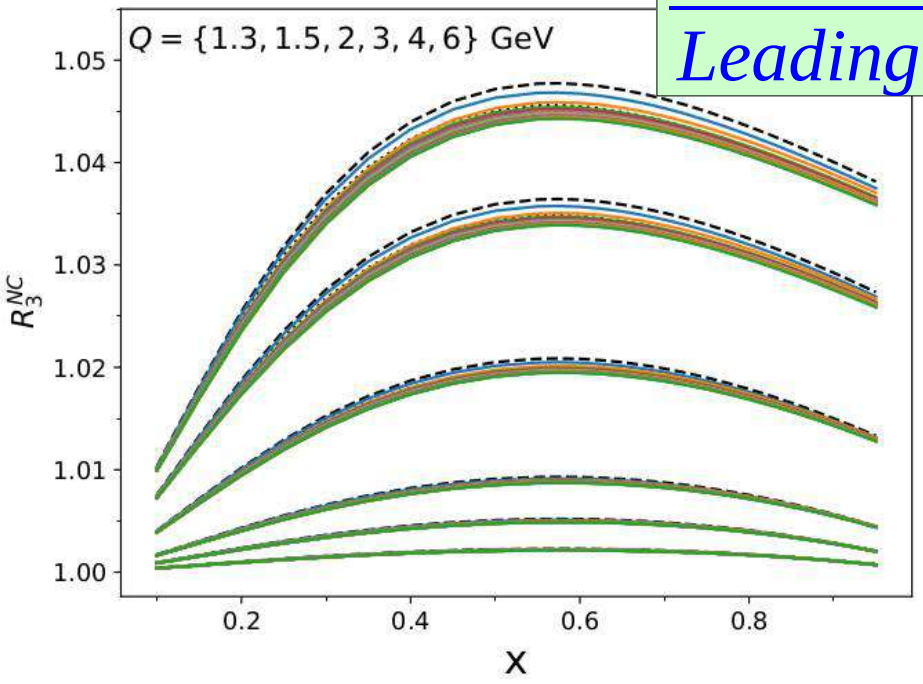
TMCs can be large

… but uniform, even for large A

$$\left(\frac{xM}{Q}\right)$$

$$\frac{FULL-TMC}{Leading-TMC}$$

Corrections are nearly universal



Q=1.3

Q=1.5

Q=2

Q=3,4,6

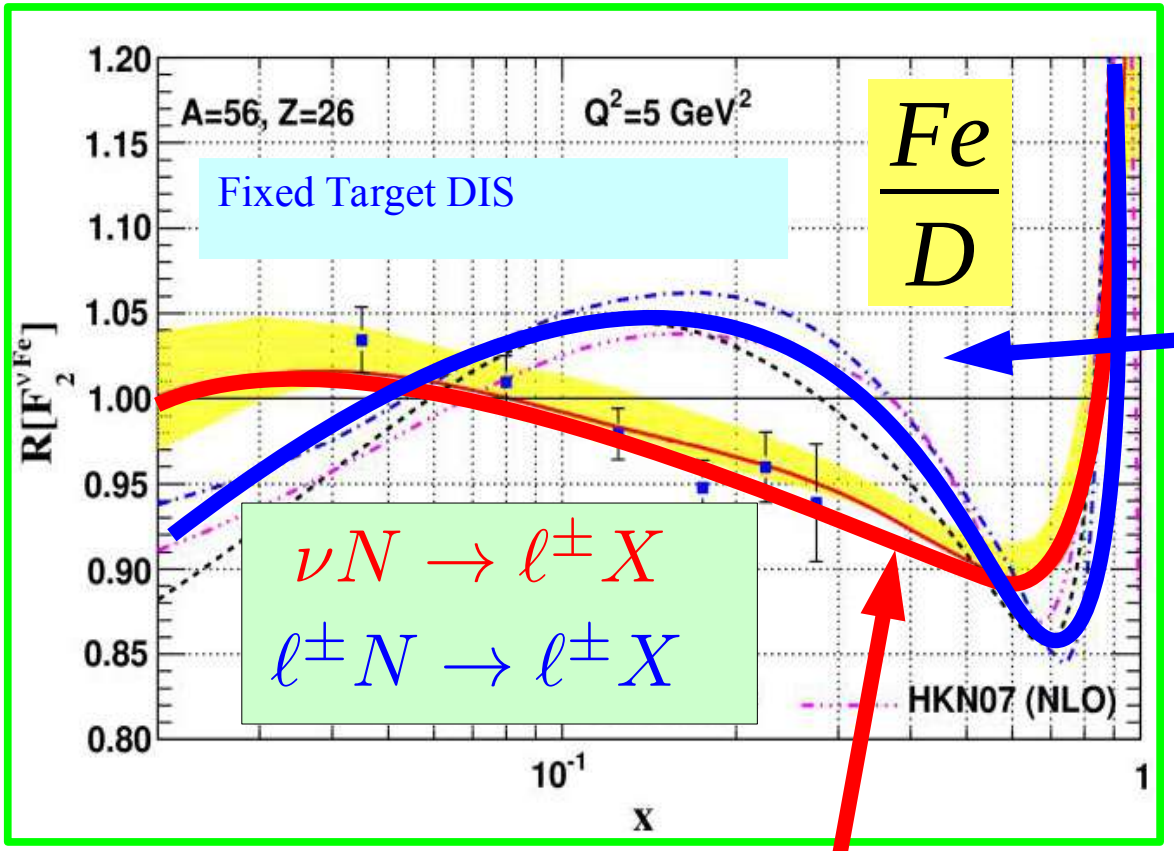
Target mass corrections in lepton-nucleus DIS
nCTEQ: R. Ruiz, et al., arXiv:2301.07715

Strange PDF

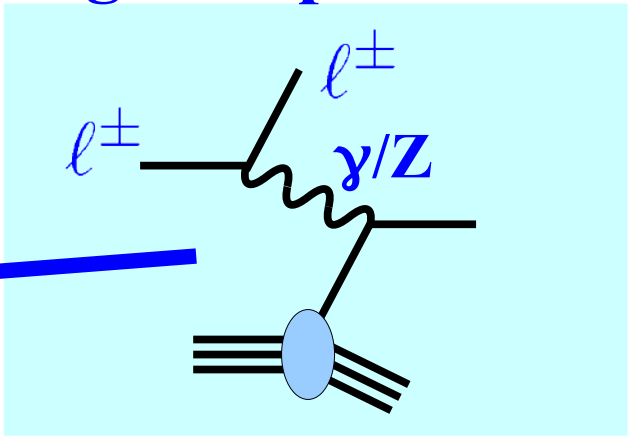
Parton Distribution Functions

vDIS ... has a significant impact on the strange quark PDF

Puzzle: Split Personality … *What is the correct Nuclear ratio*

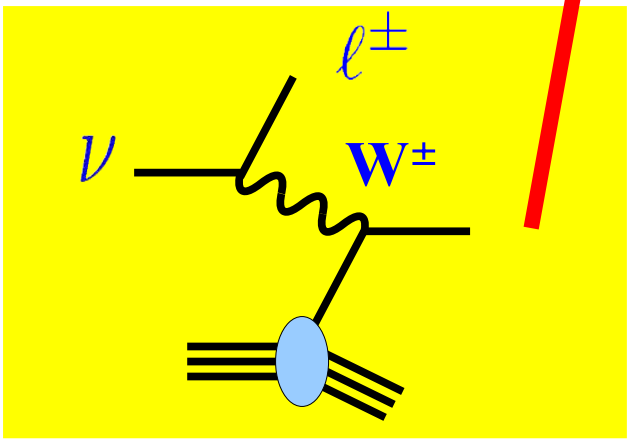


Charged Lepton DIS



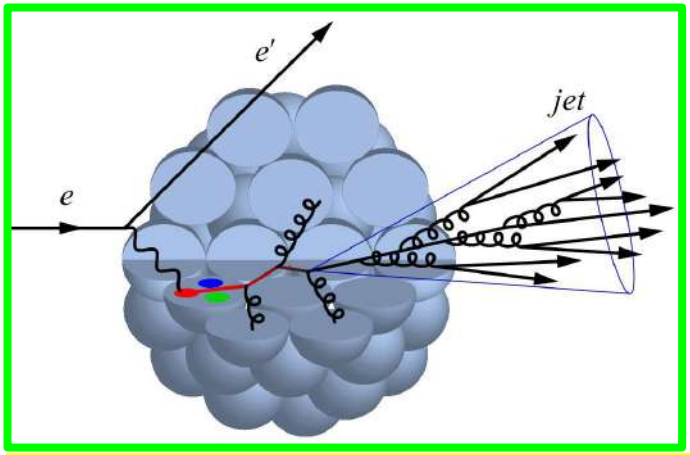
some caveats
… correlated errors

Ingo Schienbein, … (2007)
Karol Kovarik, … (2010)



Neutrino DIS

Depends on nuclear corrections

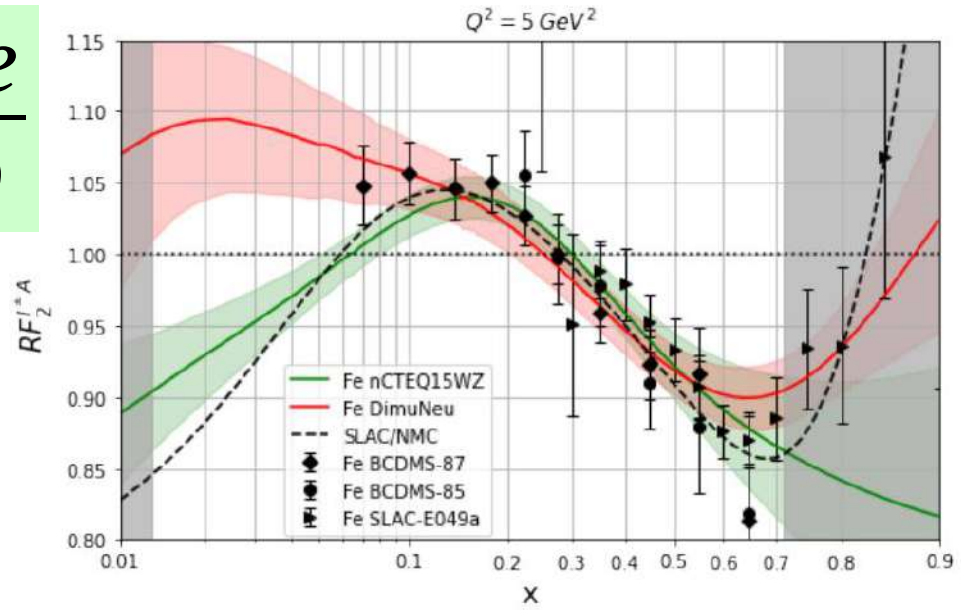


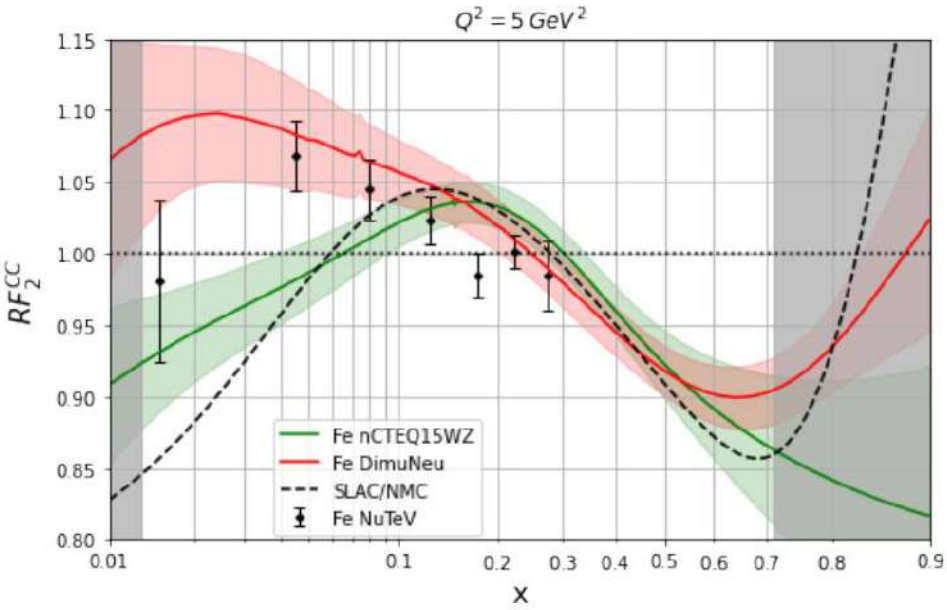
Propagation of γ/W thru nuclei

Puzzle: Split Personality … *What is the correct Nuclear ratio*

nCTEQ: Faiq Muzakka, Karol Kovarik, ...

$$\frac{Fe}{D}$$





$$\frac{Iron}{(proton + neutron)}$$

What is the correct nuclear correction ???

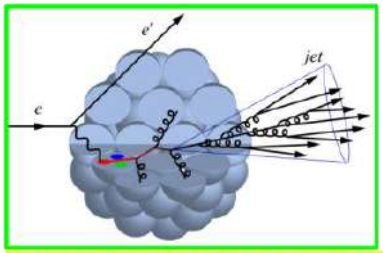
Are these data sets compatible???

nCTEQ: K.F. Muzakka, ...
Phys.Rev.D 106 (2022) 7, 074004

Compatibility of neutrino DIS data and its impact on nuclear parton distribution functions

K.F. Muzakka [1,*] P. Duwentäster [1,†] T.J. Hobbs [2,3,4] T. Ježo [5,‡] M. Klasen [1,§] K. Kovařík [1,¶]
A. Kusina [6,**] J.G. Morfín [7,††] F. I. Olness [2,‡‡] R. Ruiz [6] I. Schienbein [8,§§]

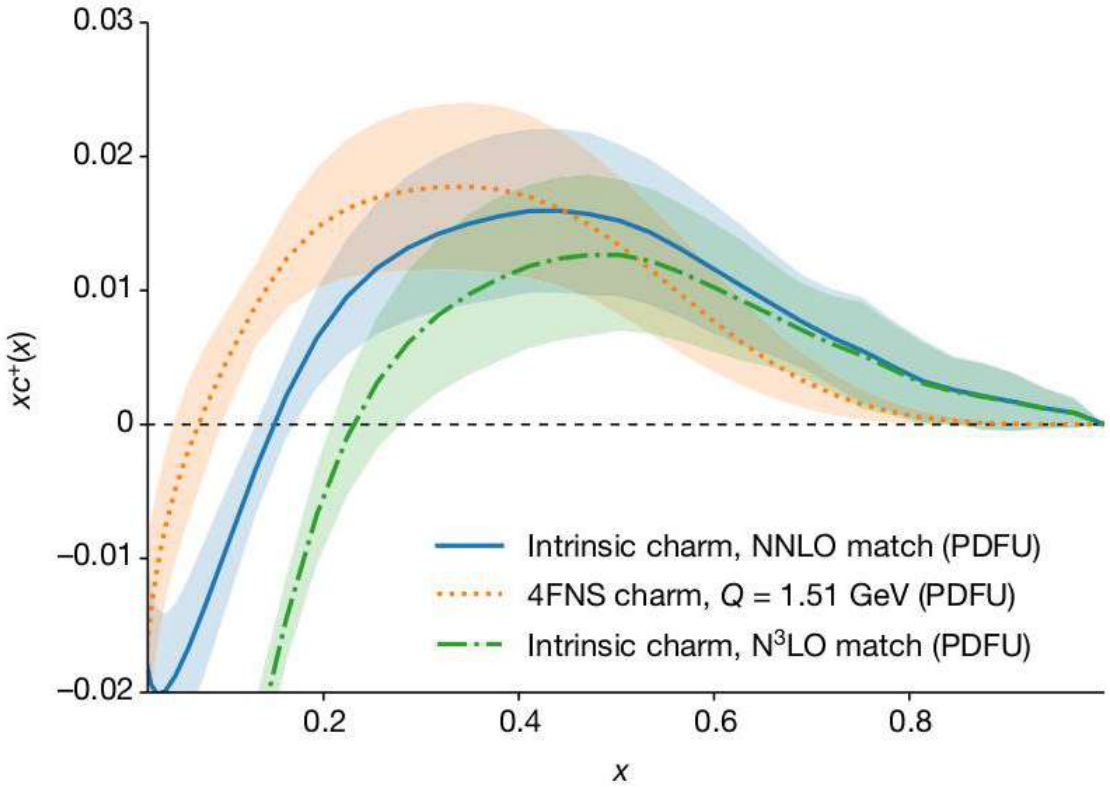
[1] *Institut für Theoretische Physik, Westfälische Wilhelms-Universität Münster,*



Propagation of γ/W thru nuclei

Charm PDF

Parton Distribution Functions



What is the status of Intrinsic Charm?

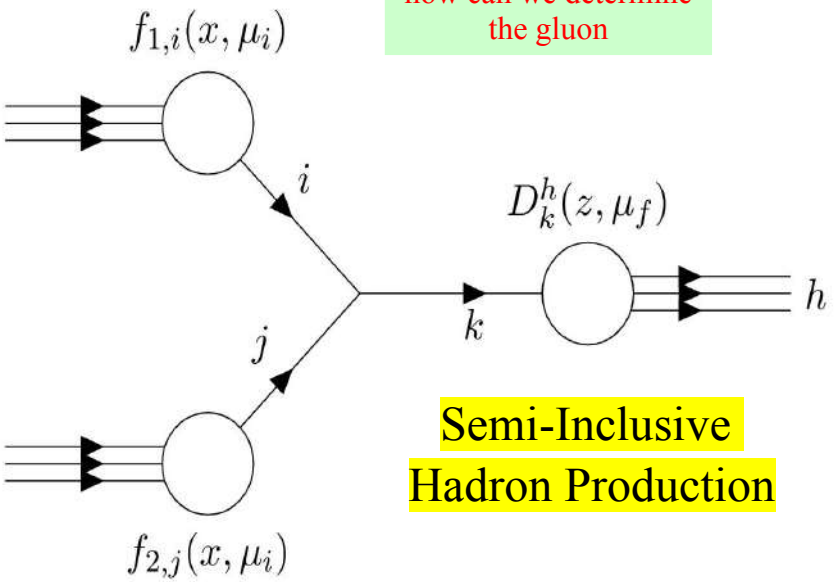
The NNPDF Collaboration

https://doi.org/10.1038/s41586-022-04998-2

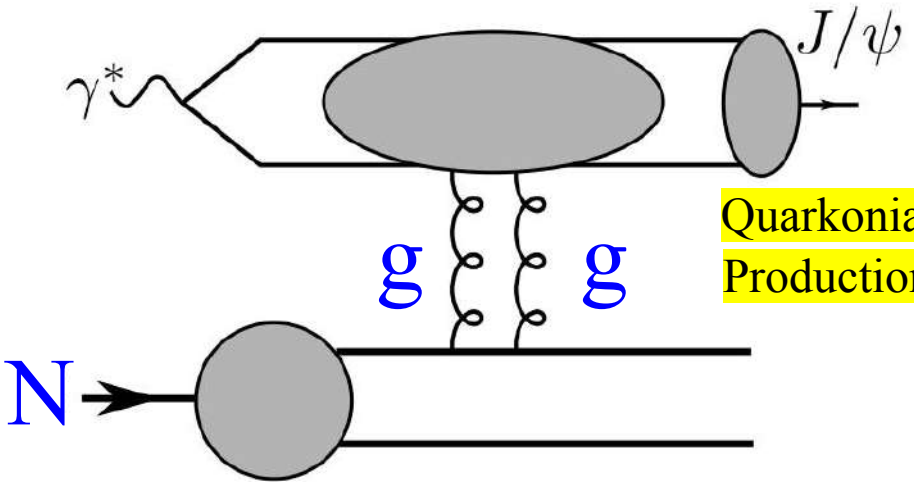
Measuring the nuclear Gluon PDF

Parton Distribution Functions

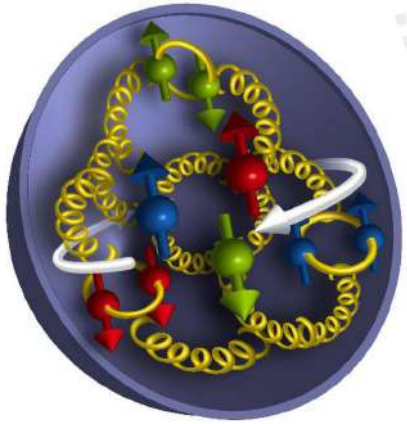
how can we determine the gluon



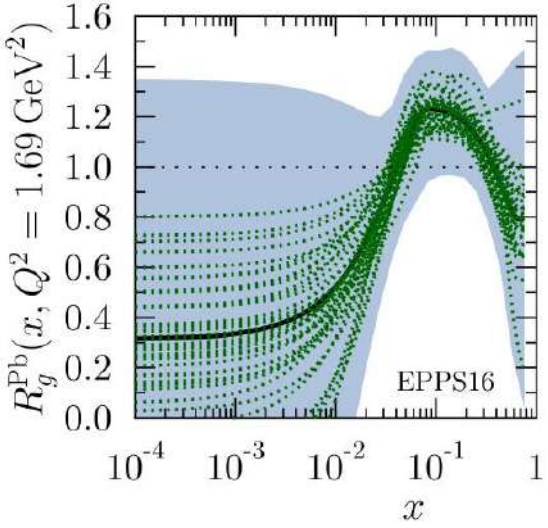
Semi-Inclusive Hadron Production



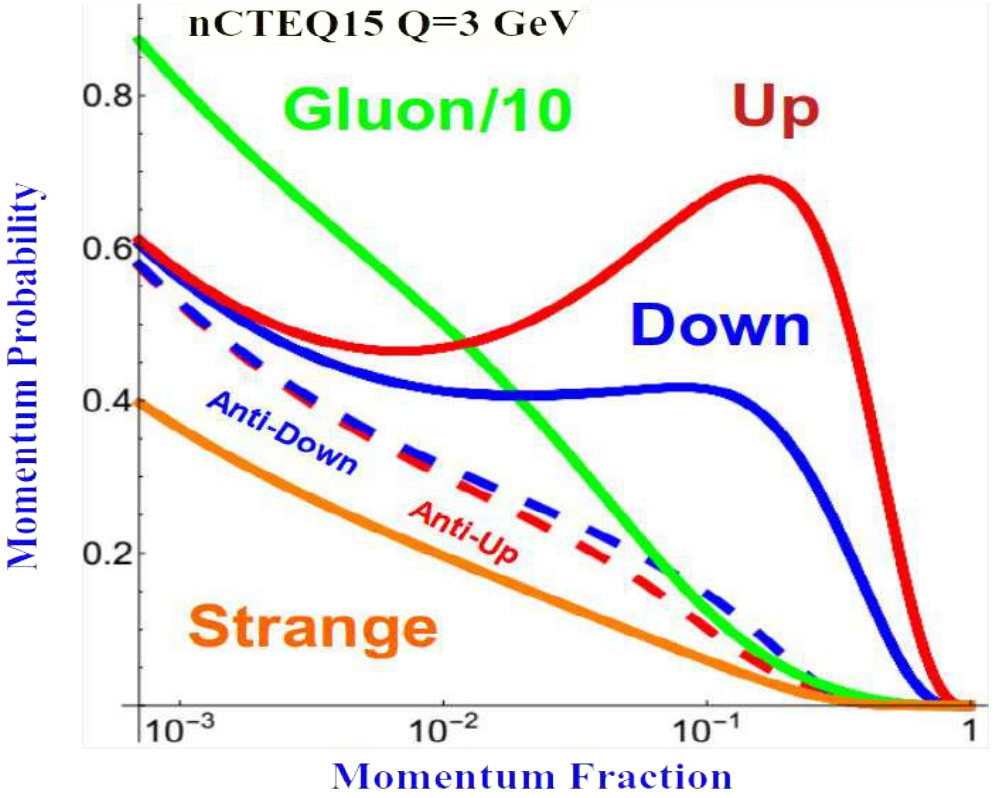
Quarkonia Production

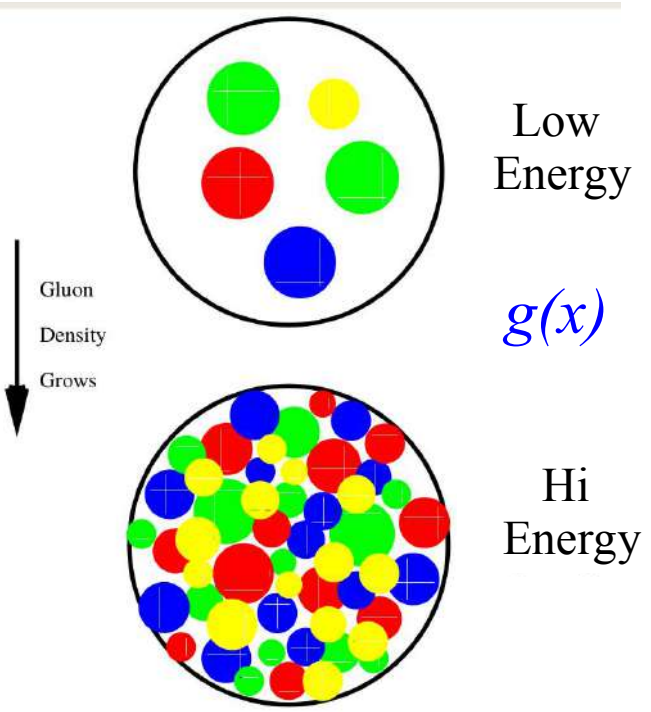


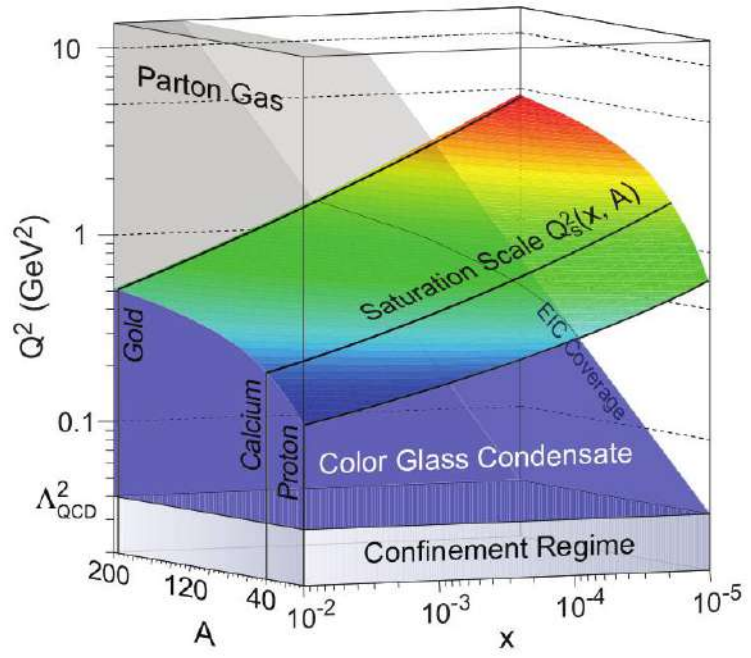
g(x): Large Uncertainties



Gluon: Nuclear Medium Effects at small momentum fraction (x)



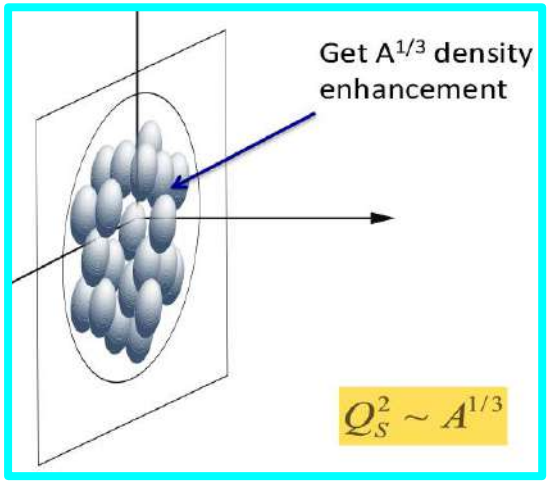




Nuclear medium effects:

- Quark Gluon Plasma
- Color Glass Condensate
- Recombination
- Saturation
- Resummation
- . . . *your theory here*

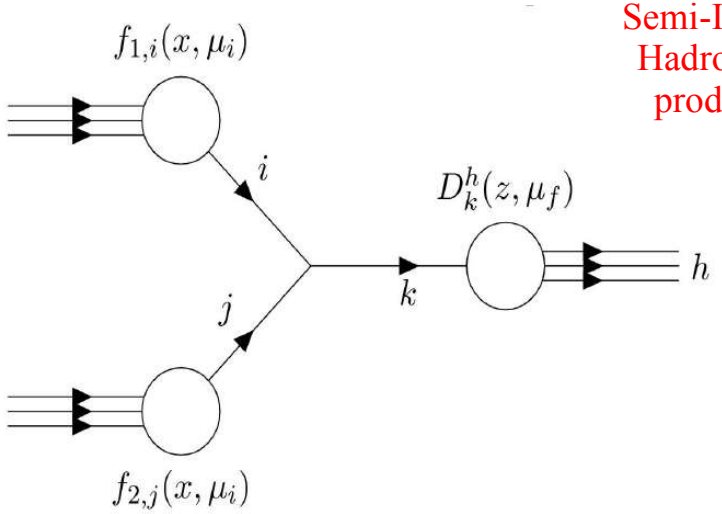
We gain a geometric factor of $A^{1/3}$



Review: Edmond Iancu & Raju Venugopalan: arXiv:0303204

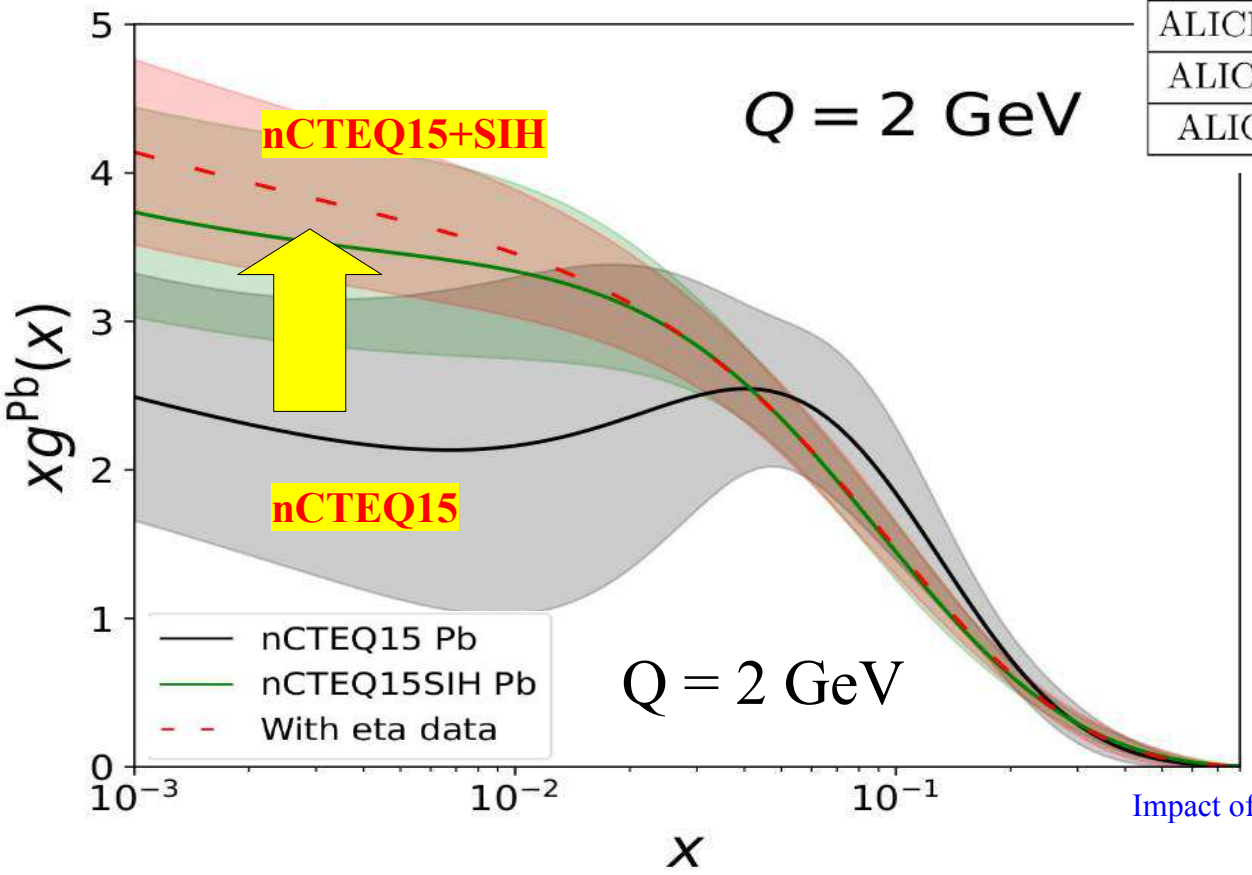
Precision Gluon can help study nuclear medium effects

nCTEQ: Pit Duwentaster, Michael Klasen, ...



Semi-Inclusive Hadron (SIH) production

Data set	$\sqrt{s_{NN}}$ [GeV]	Observ.	No. points
PHENIX π^0	200	R_{dAu}	21
PHENIX η	200	R_{dAu}	12
PHENIX $\pi^{\pm}$	200	R_{dAu}	20
PHENIX $K^{\pm}$	200	R_{dAu}	15
STARπ^0	200	R_{dAu}	13
STAR η	200	R_{dAu}	7
STAR $\pi^{\pm}$	200	R_{dAu}	23
ALICE 5 TeV π^0	5020	R_{pPb}	31
ALICE 5 TeV η	5020	R_{pPb}	16
ALICE 5 TeV $\pi^{\pm}$	5020	R_{pPb}	58
ALICE 5 TeV $K^{\pm}$	5020	R_{pPb}	58
ALICE 8 TeV π^0	8160	R_{pPb}	30
ALICE 8 TeV η	8160	R_{pPb}	14

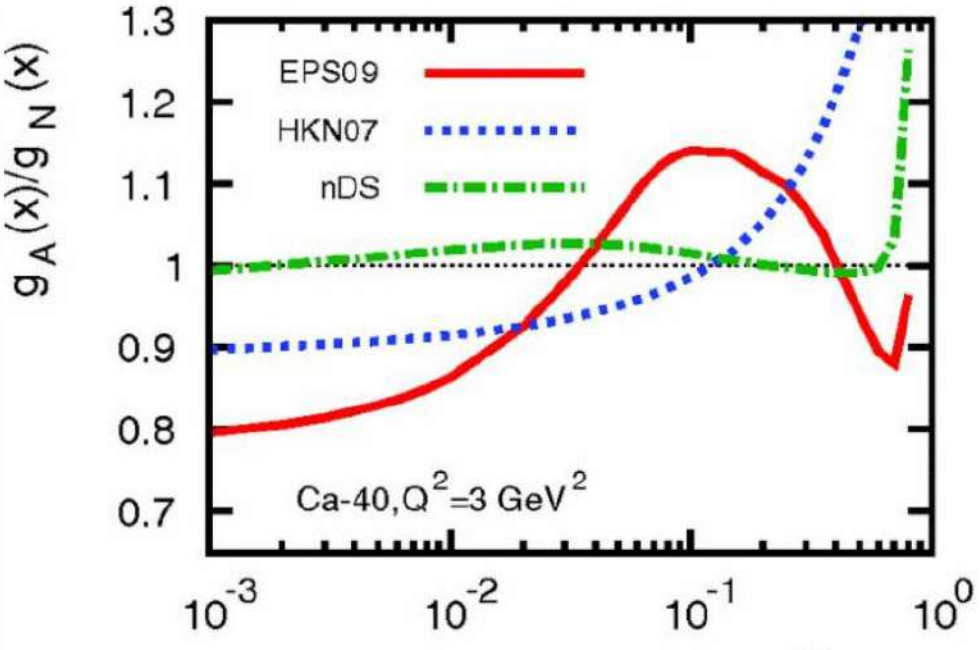


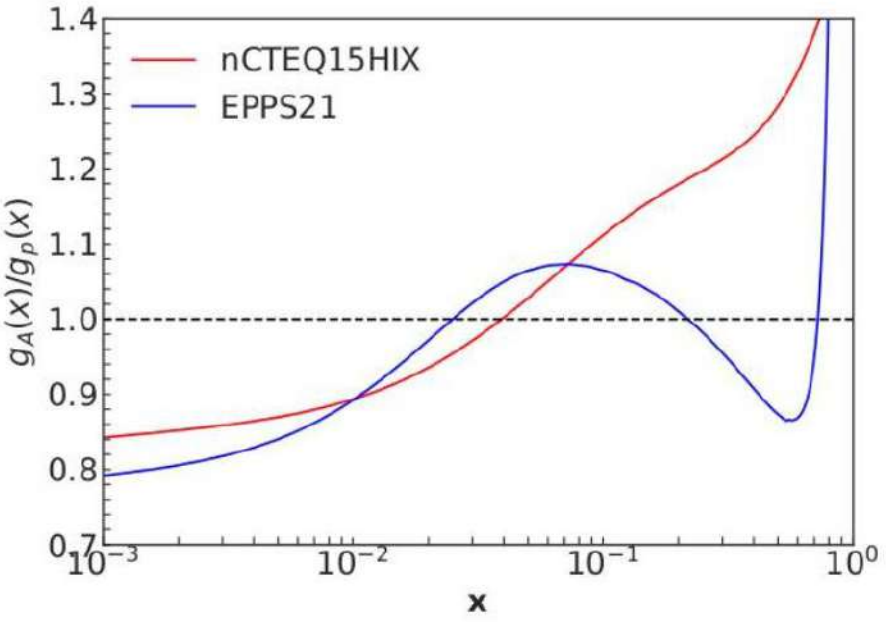
Semi-Inclusive Hadron (SIH) production

Determines gluon in small x region

Impact of inclusive hadron production data on nuclear gluon PDFs
nCTEQ: P. Duwentäster, et al., PRD104 (2021) 094005.

Precision Gluon can help study nuclear medium effects





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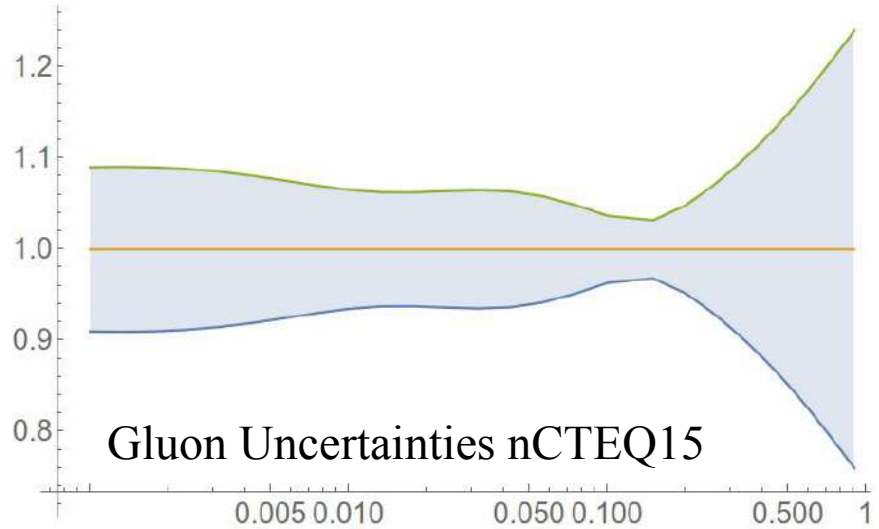
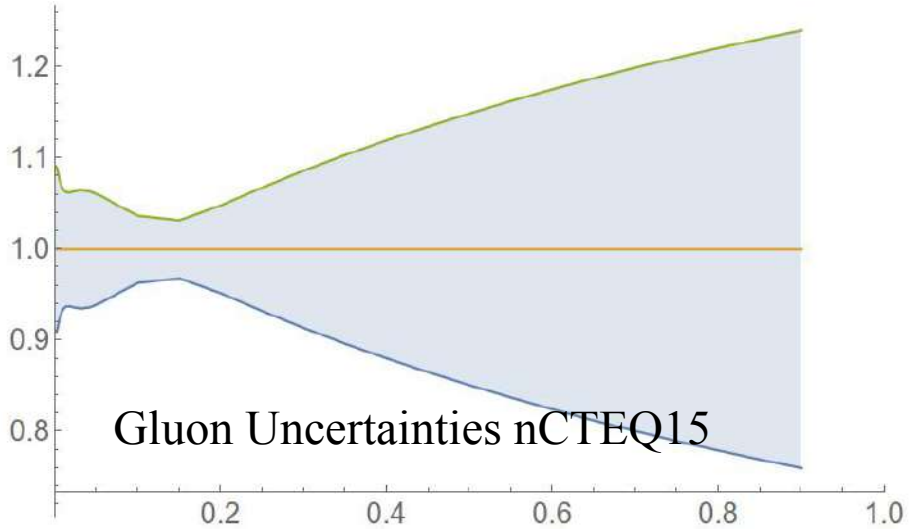
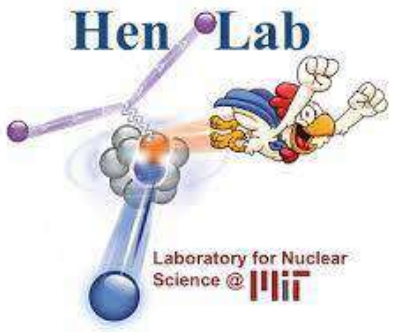




nPDFs:

Physics inspired parameterizations

Short Range Correlations (SRC)

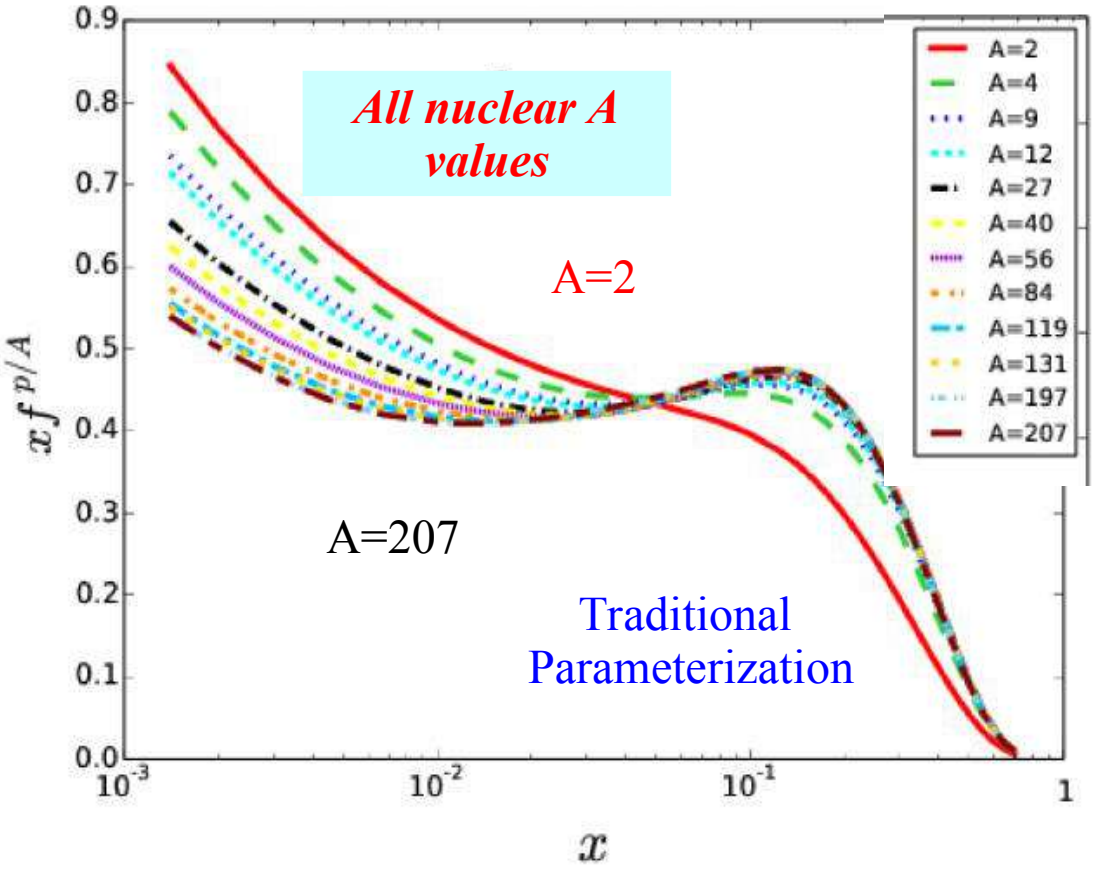


nCTEQ with

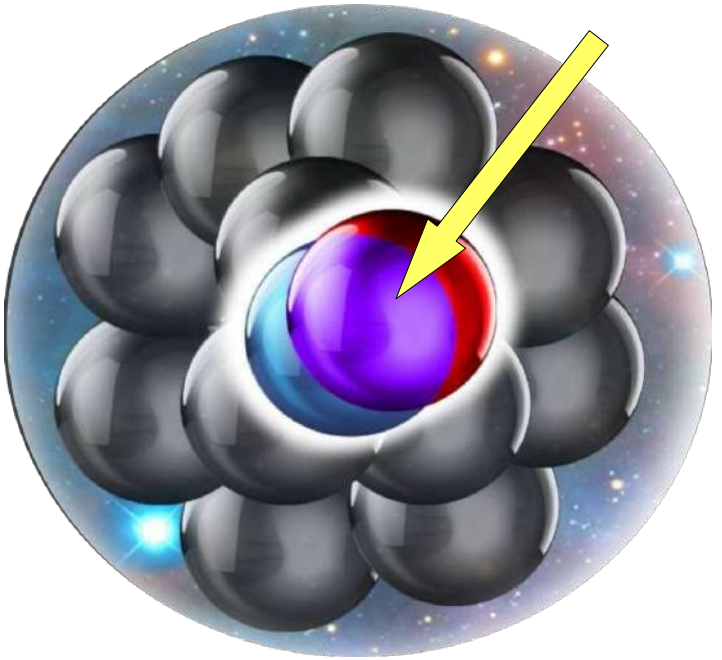
Andrew Denniston & Or Hen

$$f_A = (1\text{-}c)\, f_p + c\, f_{SRC}$$

nuclear PDF | normal proton PDF | SRC modified PDF



Short Range Correlations (SRC)



CONCLUSIONS

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)*

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

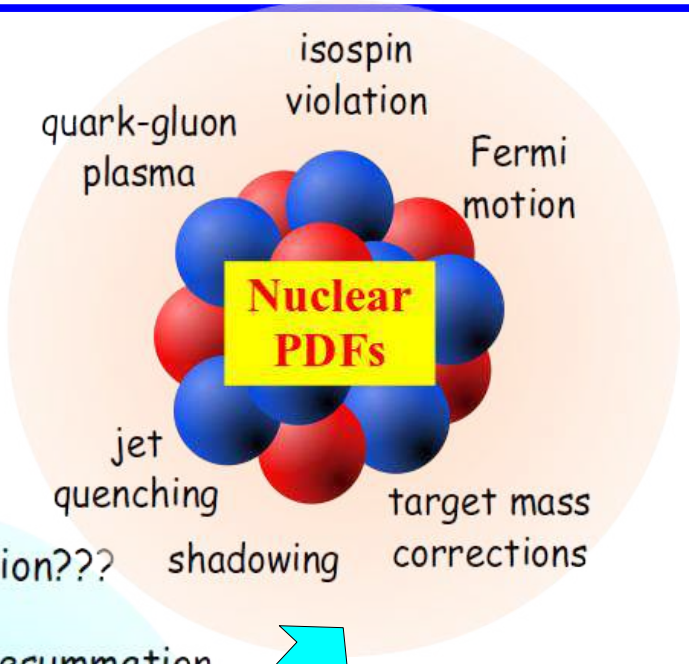
include Lattice QCD info on moments and quasi-PDFs

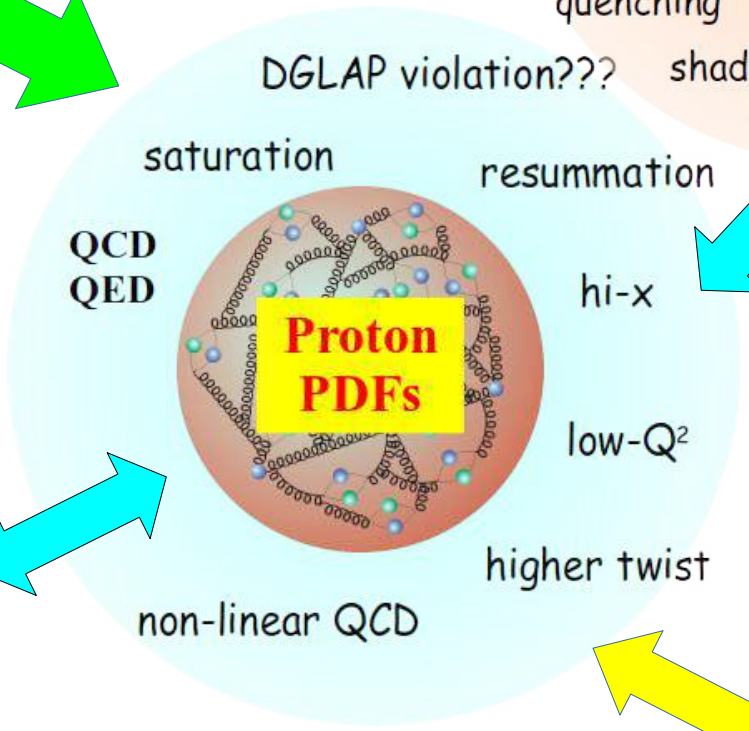
Need coordination/communication between efforts

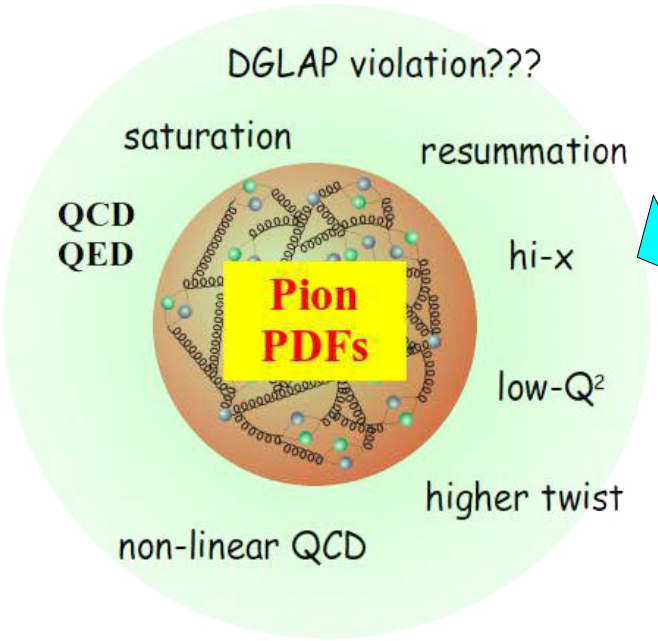
QCD: From Parameterization to a Deeper Understanding

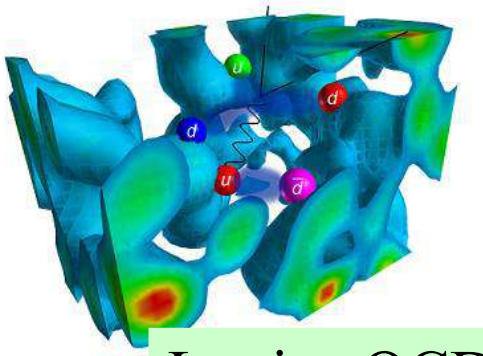
QCD
Lagrangian

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









Lattice QCD

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