

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



JLab
Nucleon & nuclei structure
20 June 2023

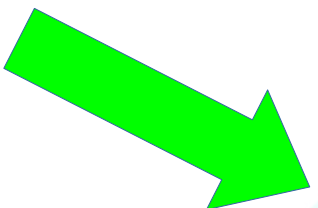
QCD
Lagrangian

$$\mathcal{L}_{QCD} = \bar{\psi}_q (i\gamma_\mu D^\mu - m_q) \psi_q - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}$$



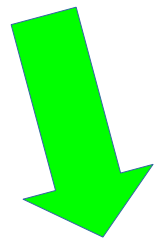
isospin violation
quark-gluon plasma
Fermi motion
jet quenching
target mass corrections
shadowing
DGLAP violation???

Nuclear PDFs



saturation
resummation
hi-x
low-Q²
higher twist
non-linear QCD
QCD
QED

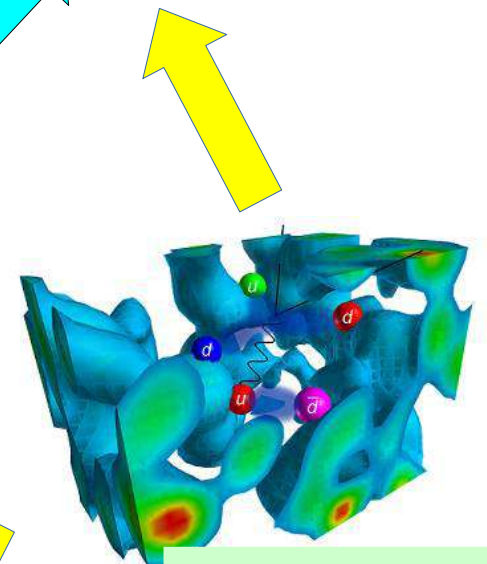
Proton PDFs



DGLAP violation???

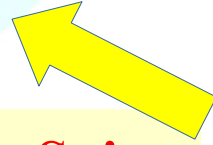
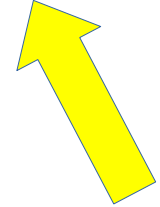
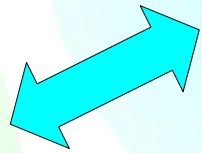
saturation
resummation
hi-x
low-Q²
higher twist
non-linear QCD
QCD
QED

Pion PDFs



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

Lattice QCD

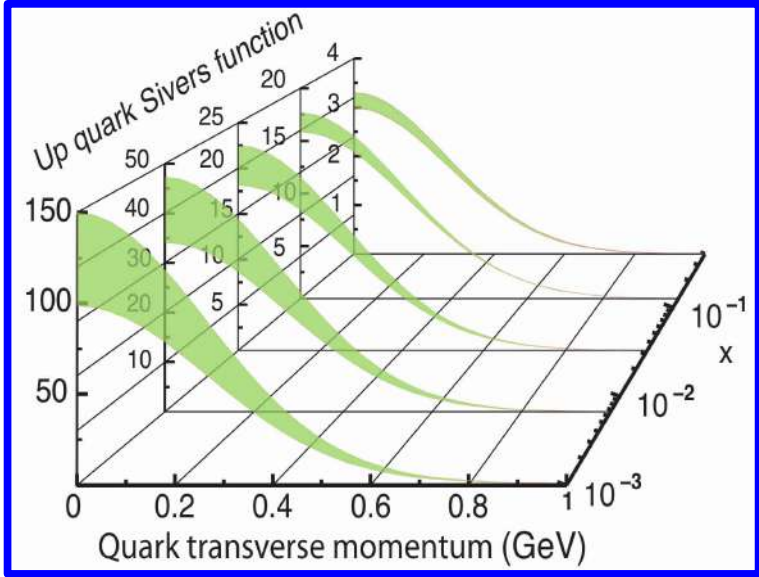
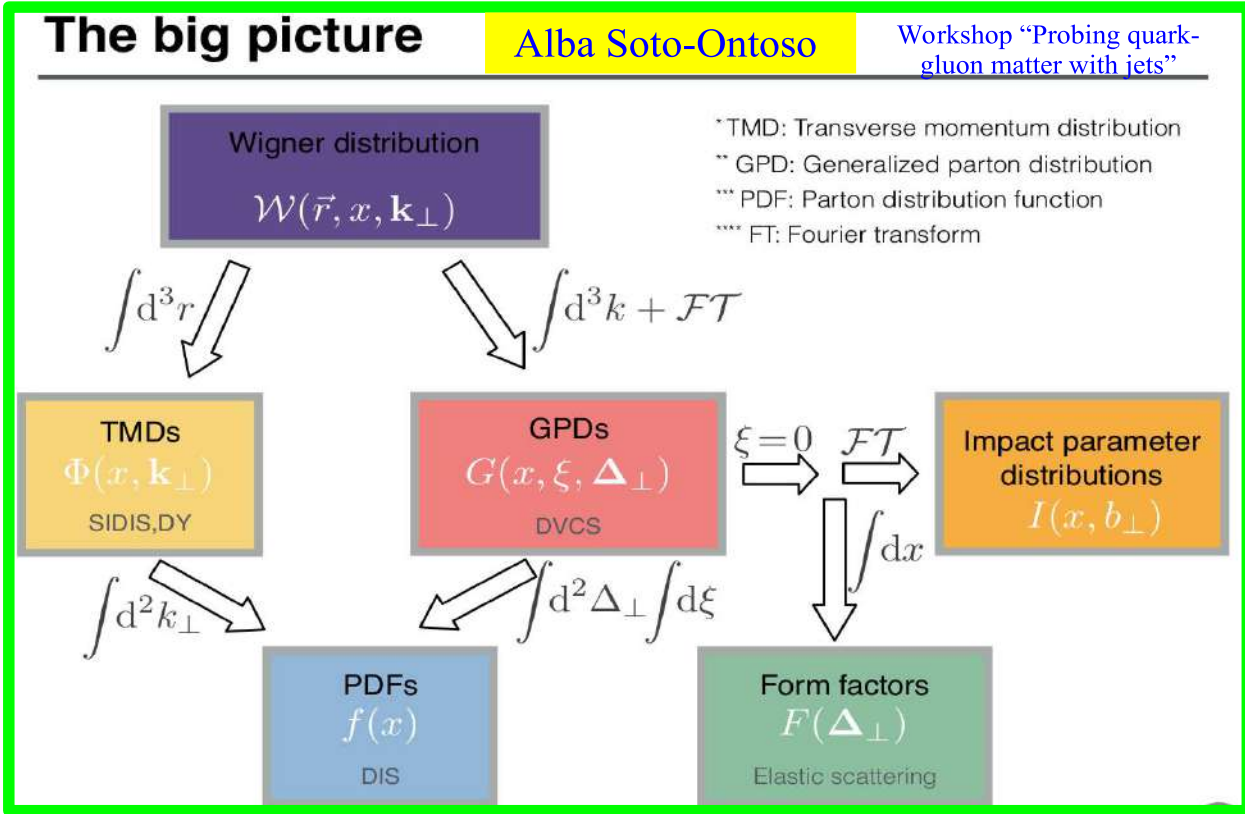


Apologies

...

no time for

Hadron structure is much richer than $f(x)$ conveys



Conventional PDFs $f(x)$ are the Boundary Conditions

Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

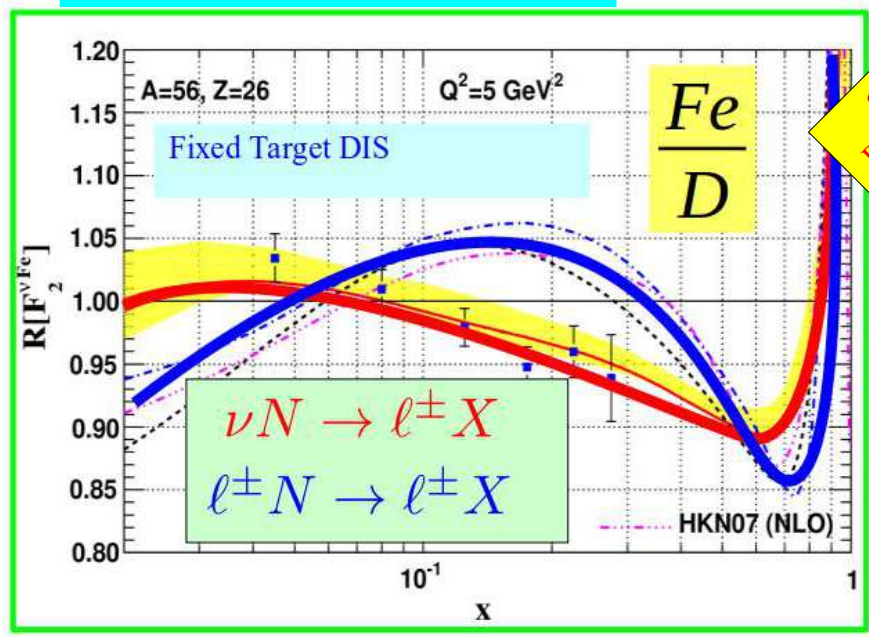
ELSEVIER

Review

Parton distributions and lattice-QCD calculations: Toward 3D structure

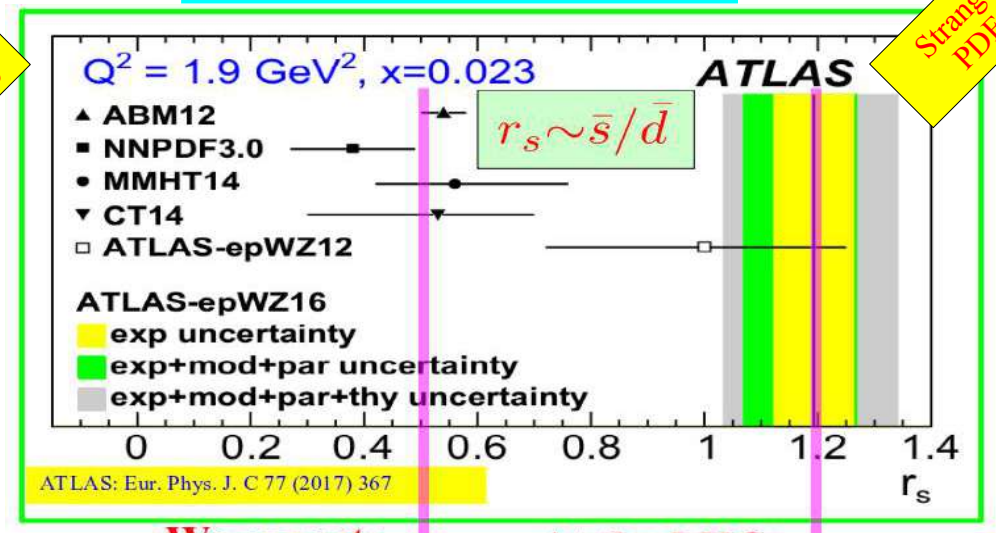
Check for updates

nCTEQ15 ν



Split Personality

nCTEQ15WZ

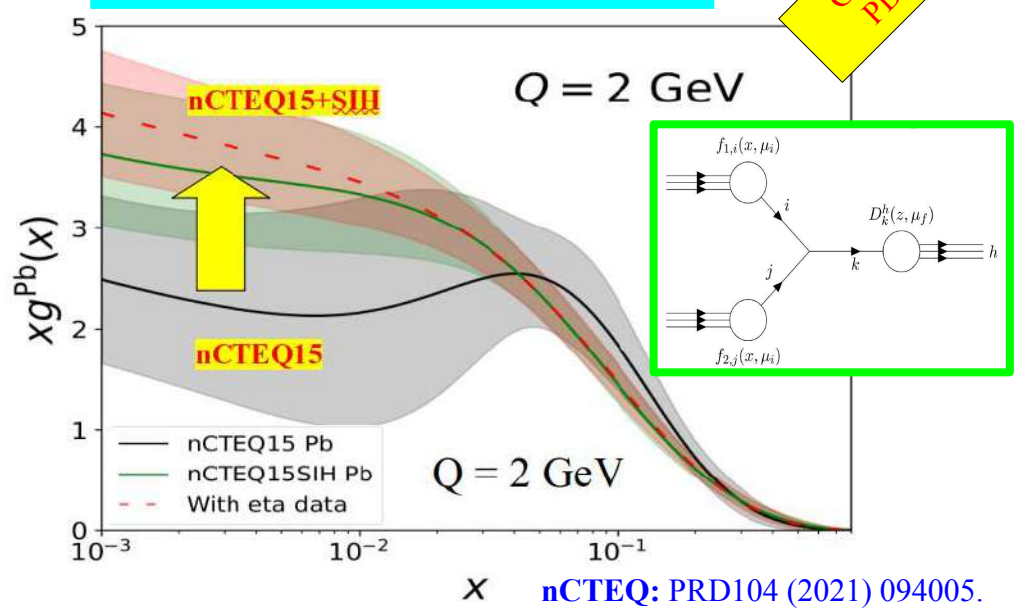


Strange PDF

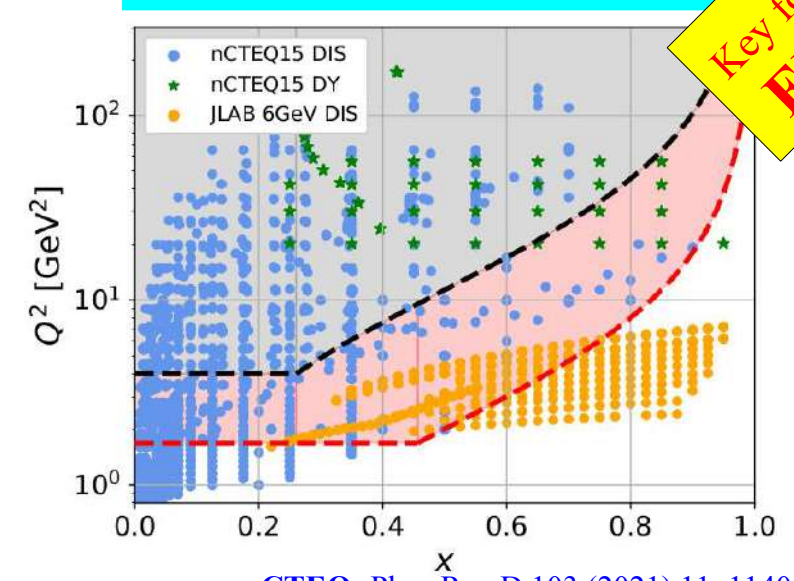
nCTEQ: Phys.Rev.D 104 (2021) 094005

nCTEQ: arXiv: 2204.13157

nCTEQ15WZ+SIH



nCTEQ15HIX

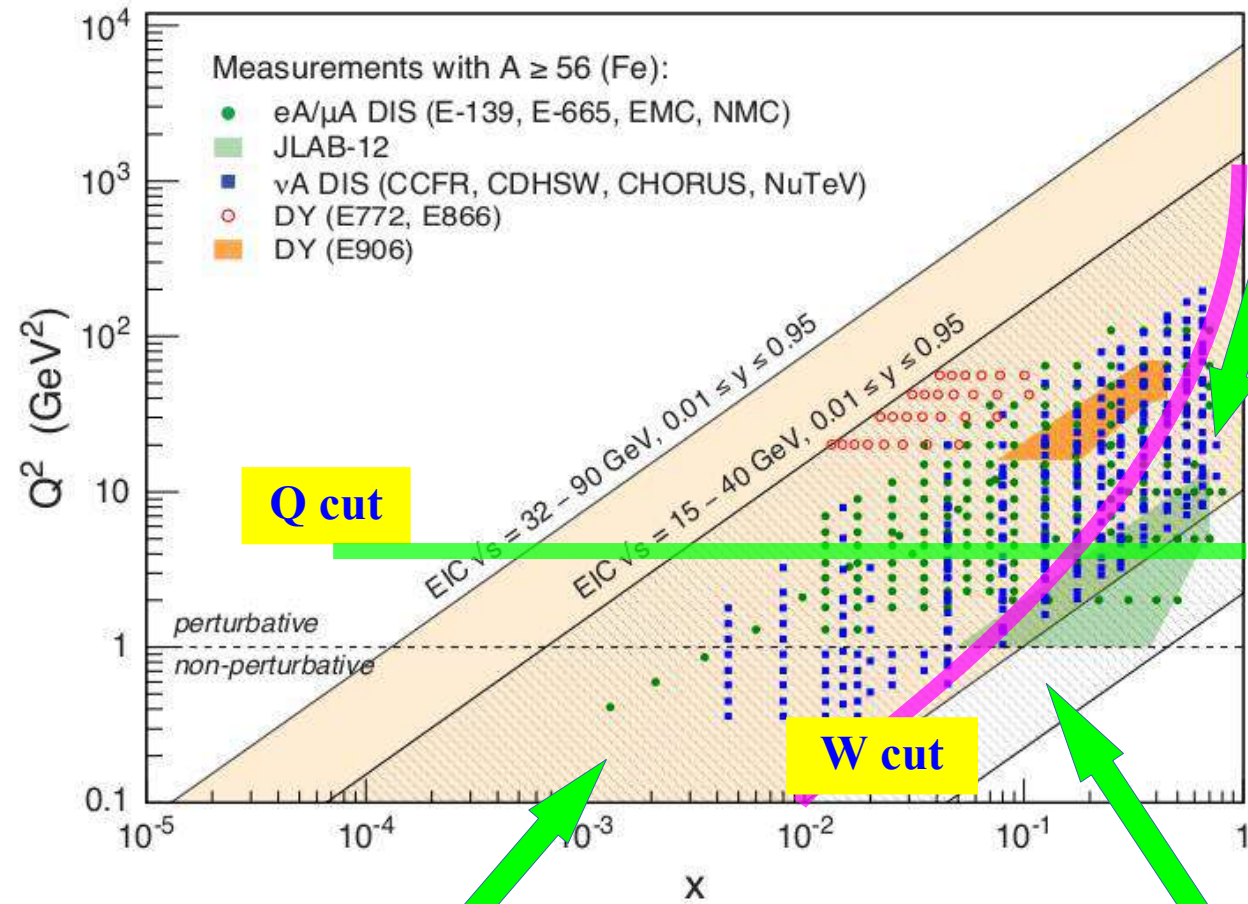


nCTEQ: Phys.Rev.D 103 (2021) 11, 114015

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 $\{x, Q^2\}$



High-x:

Nuclear PDFs: $x > 1$ allowed;
 impacts $F_2^{\text{Nuc}}/F_2^{\text{Iso}}$ in Fermi region
 Target Mass Corrections
 pick up M^2/Q^2 higher twist
 Deuteron Corrections
 impacts $F_2^{\text{Nuc}}/F_2^{\text{Deuteron}}$ ratio

Low-x:

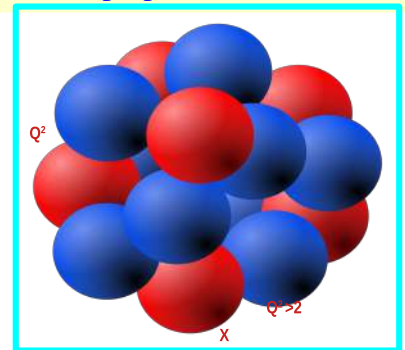
Shadowing
 Recombination
 Resummation
 BFKL
 Saturation

Low- Q^2 :

Non-Perturbative interface
 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

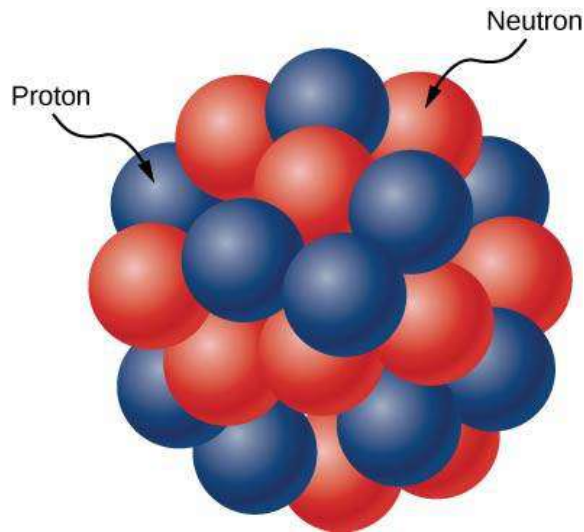
JLab Data @ Hi-X Low- Q^2

extend nCTEQ framework for this region
 & prepare for EIC



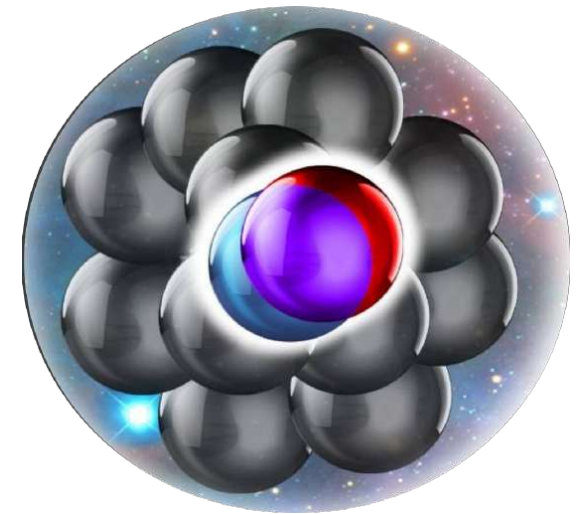
Nuclear PDFs

Parton Distribution Functions



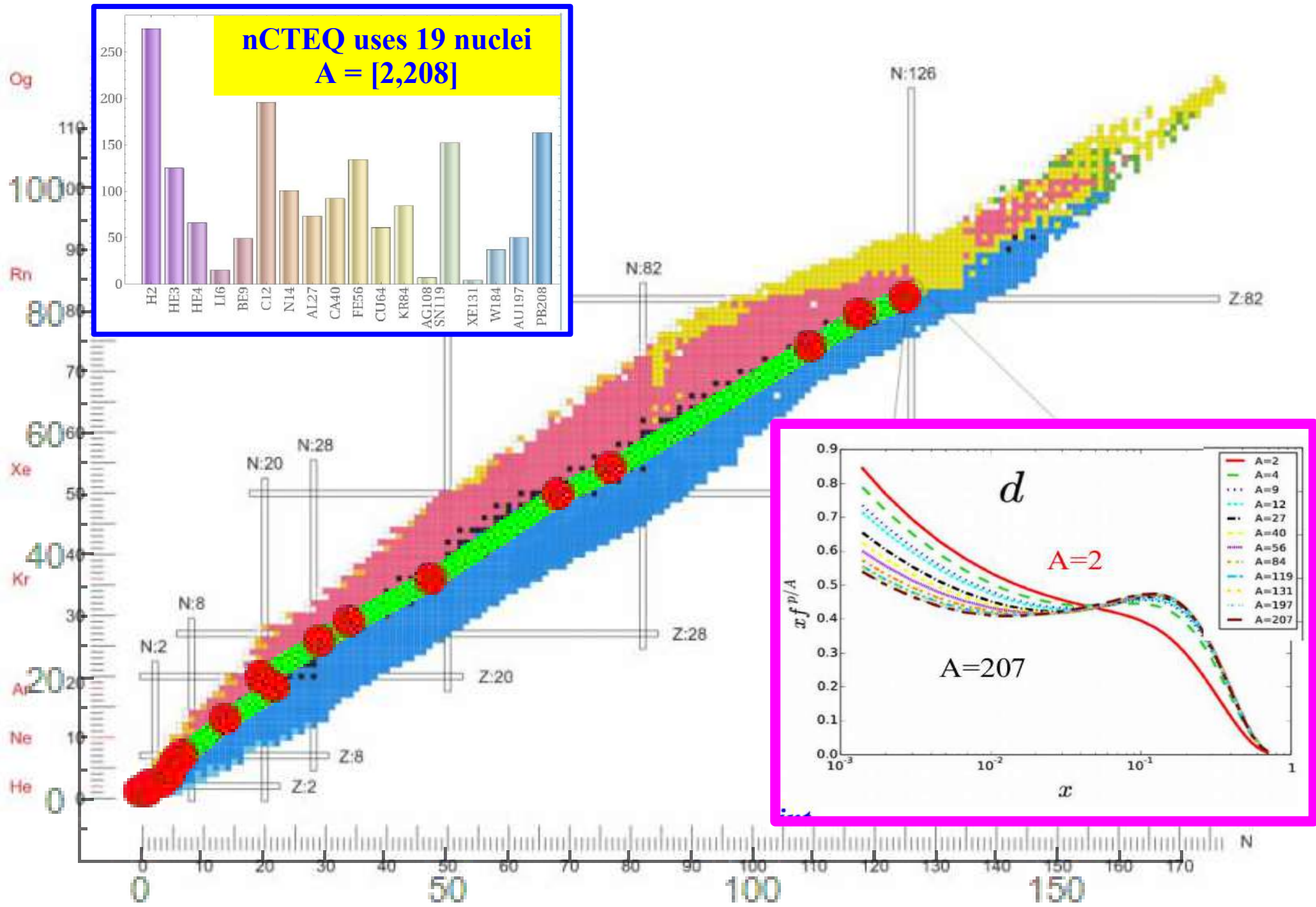
Periodic Table of the Elements

1	2																	18						
1	2																	18						
3	4																	18						
11	12	13	14	15	16	17	18																	18
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999	1000	1001	1002	1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013	1014	1015	1016	1017	1018					



nCTEQ nuclear PDF parameterization

... Limitations, Assumptions ...



2) Generalized A-parameterization (nCTEQ)

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

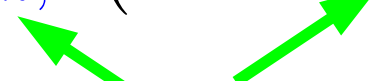
$$f \sim \dots x^{c_1(A)} (1-x)^{c_2(A)} \dots$$

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

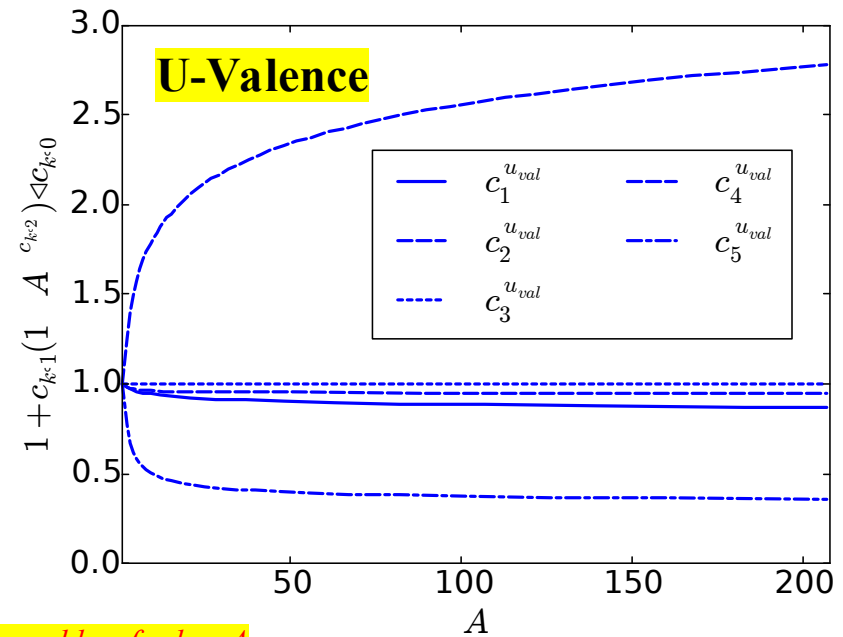
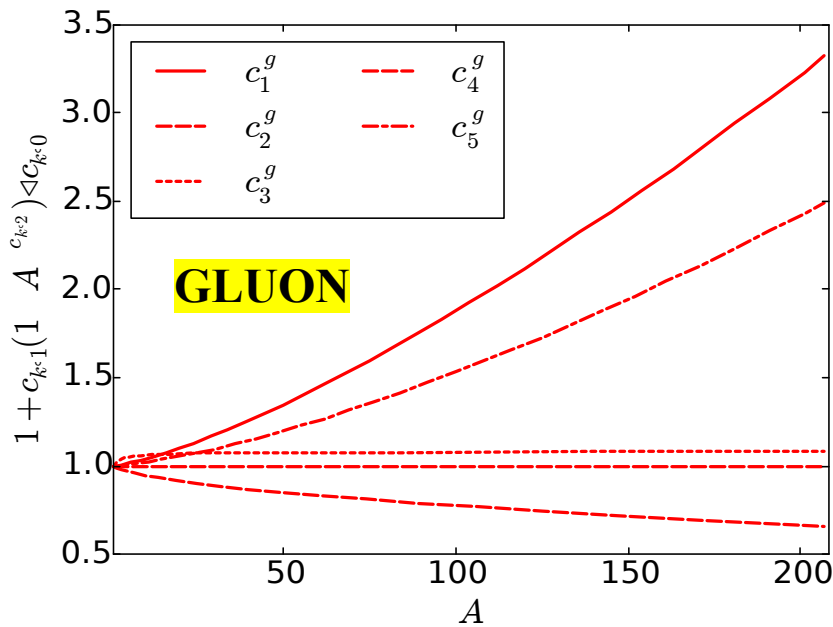
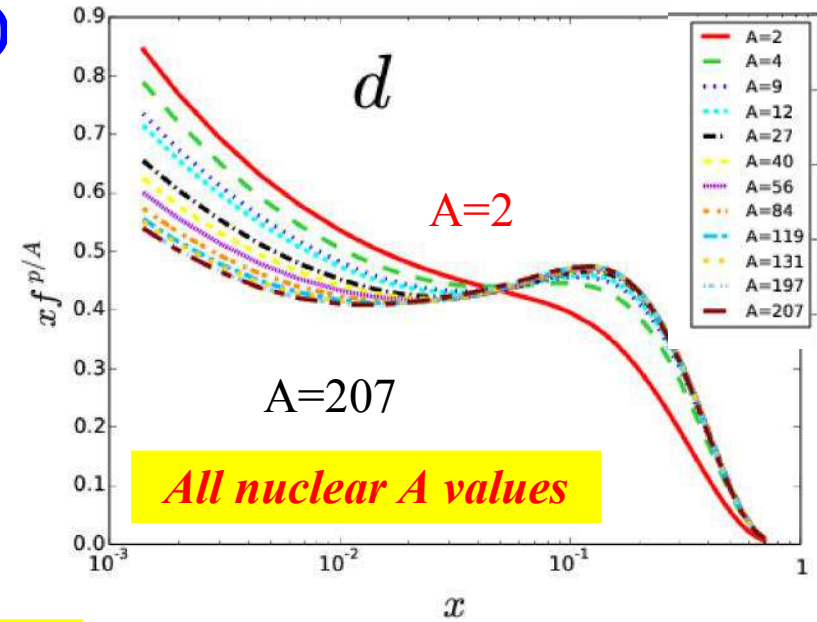
Proton



Nuclear



use proton as a Boundary Condition

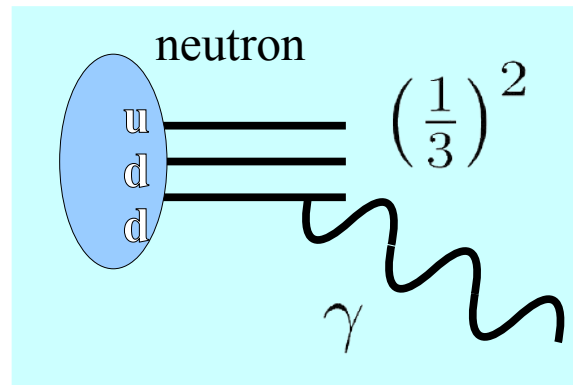
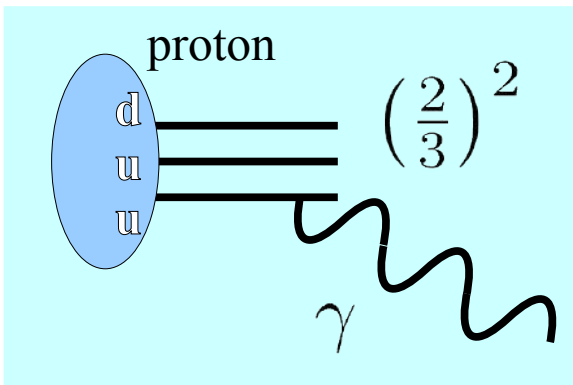
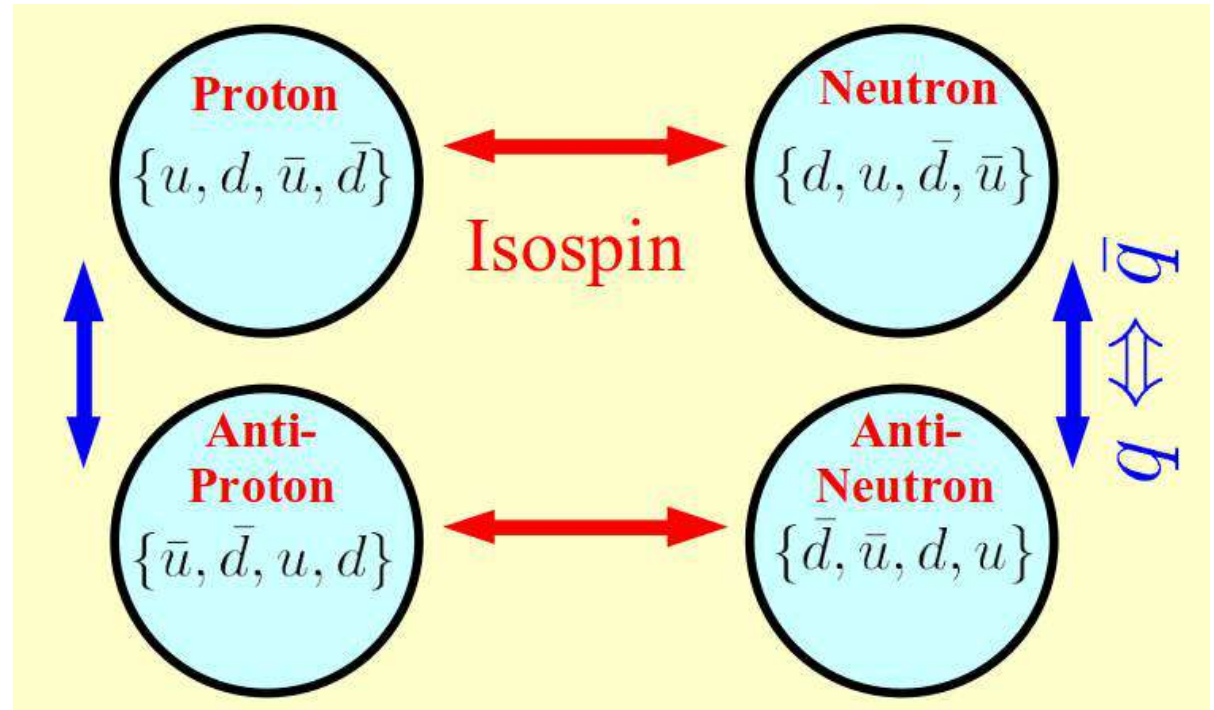


... a problem for low A

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

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

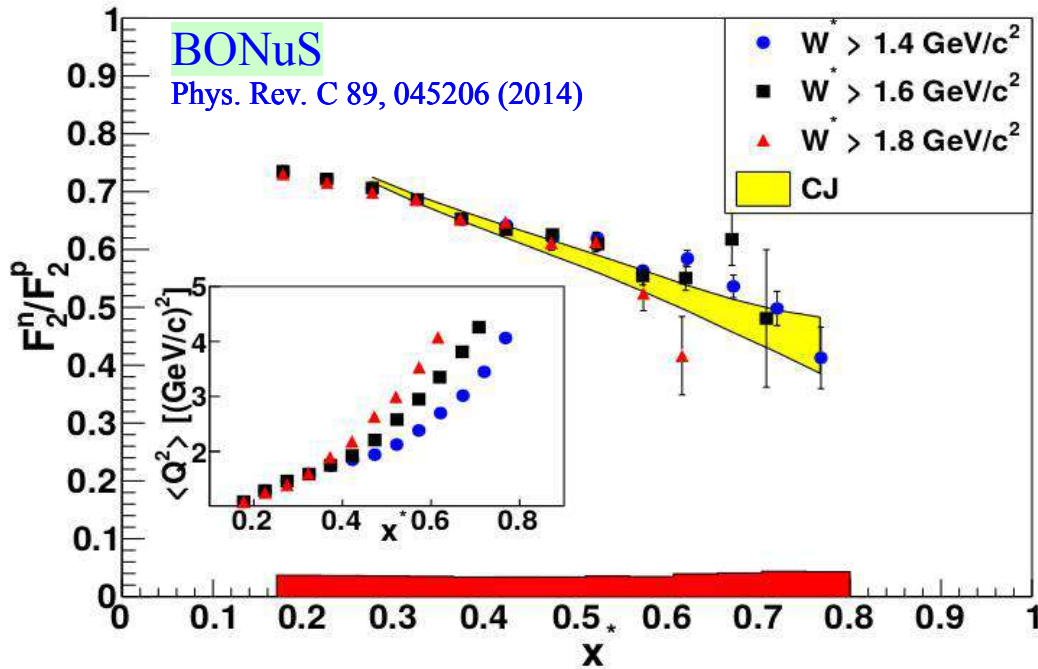
**“New”
Photon
PDFs**



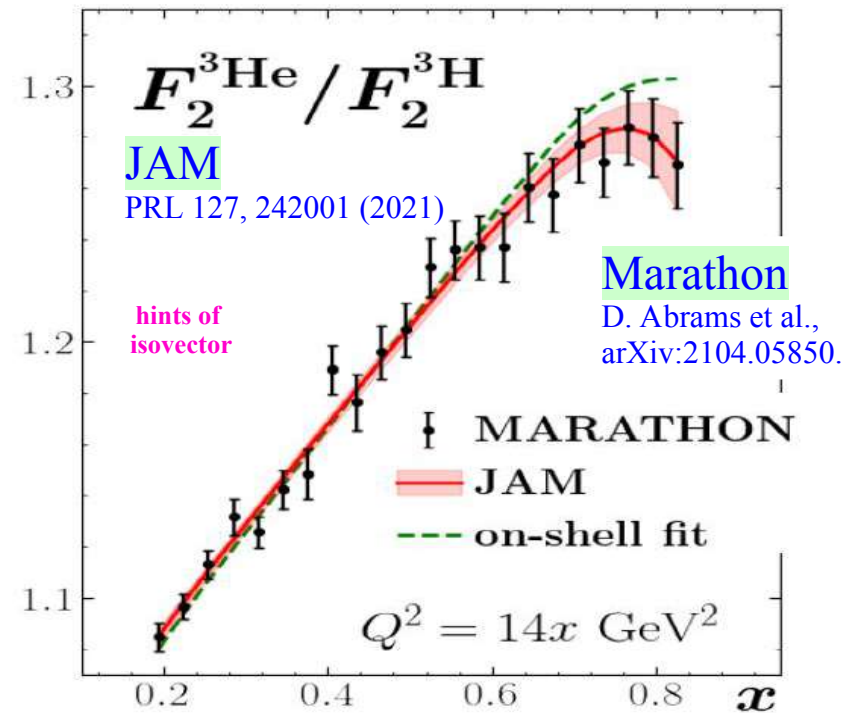
**Isospin terms are comparable
to NNLO QCD**

**QCD & EW Corrections
do NOT factorize**

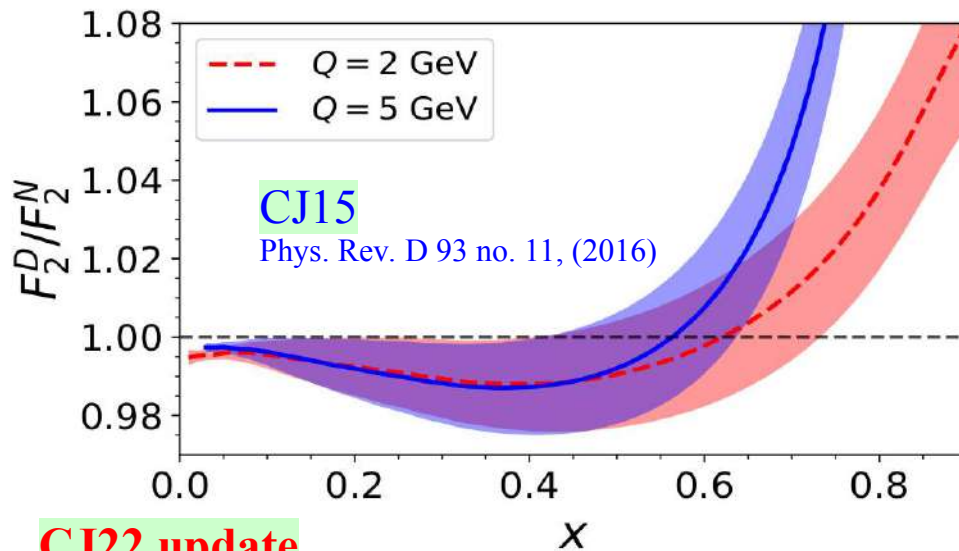
Measurements on "neutron" beam



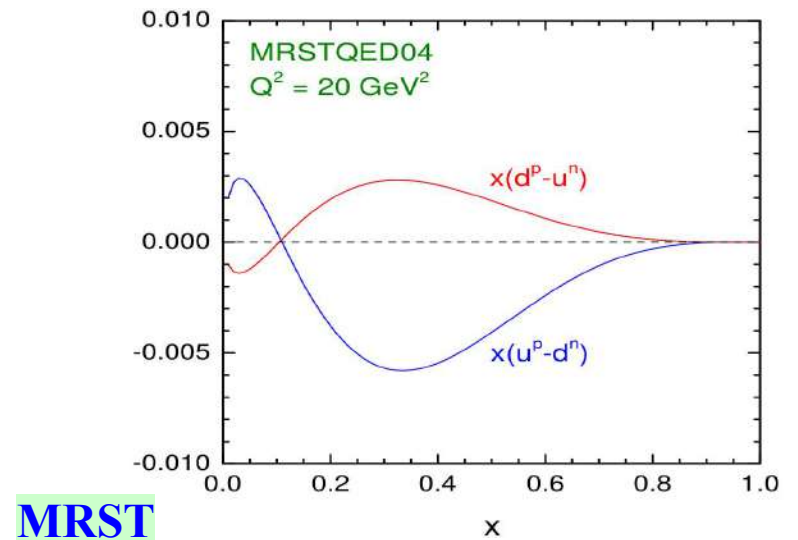
Measurements on Tritium



Deuteron Correction



Impact of QED Corrections



CJ22 update

MRST

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

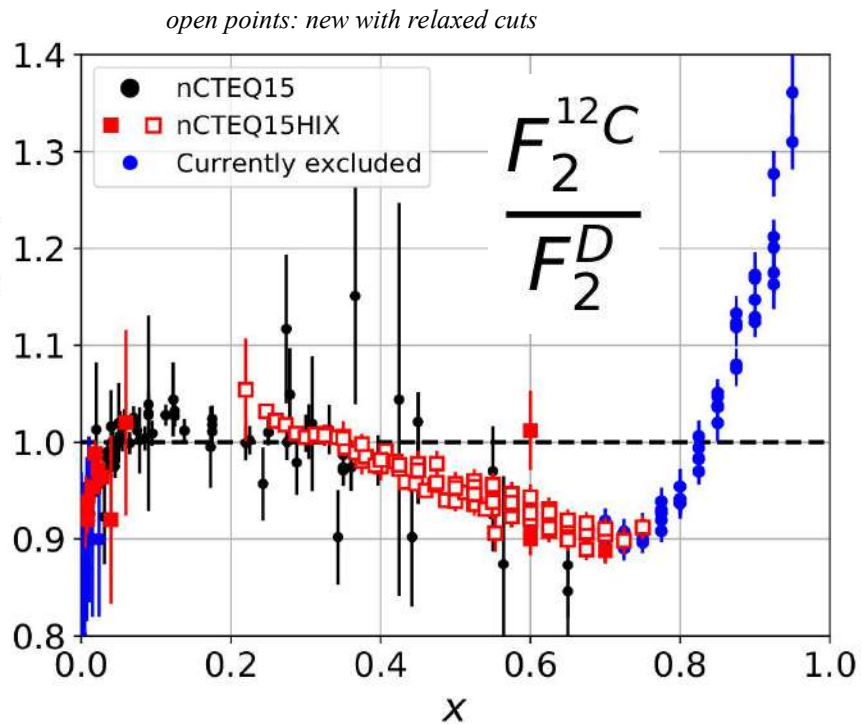
Extended Kinematics

Higher twist
mass effects
limit $x \rightarrow 1$

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. Duwentäster⁵, O. Hen¹, T. J. Hobbs^{6,4,7}, C. Keppel⁴, M. Klasen⁵,
K. Kovařík⁵, A. Kusina⁸, J. G. Morfin⁹, K. F. Muzakka⁵, F. I. Olness^{6,‡}, I. Schienbein¹⁰ and J. Y. Yu.¹⁰



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

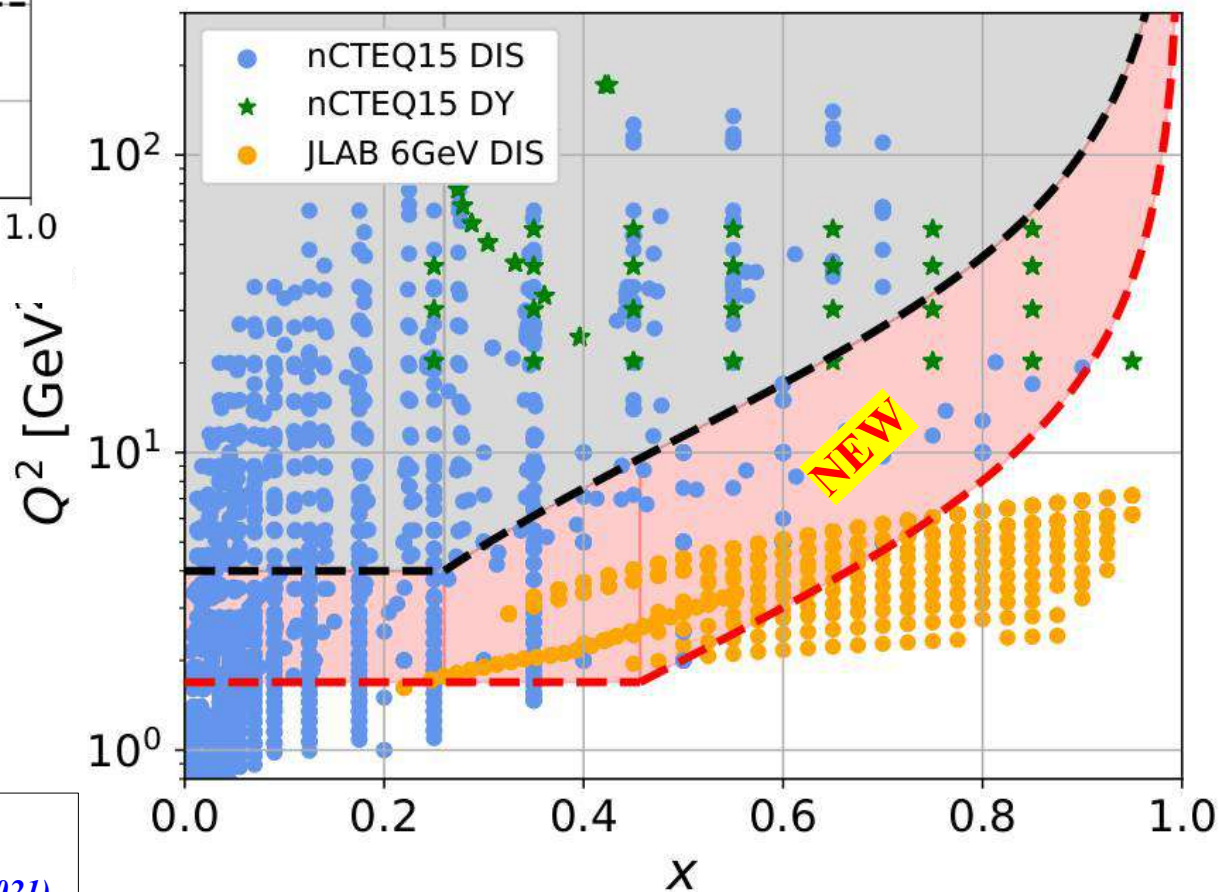
Target Mass Corrections

pick up M^2/Q^2 higher twist contributions

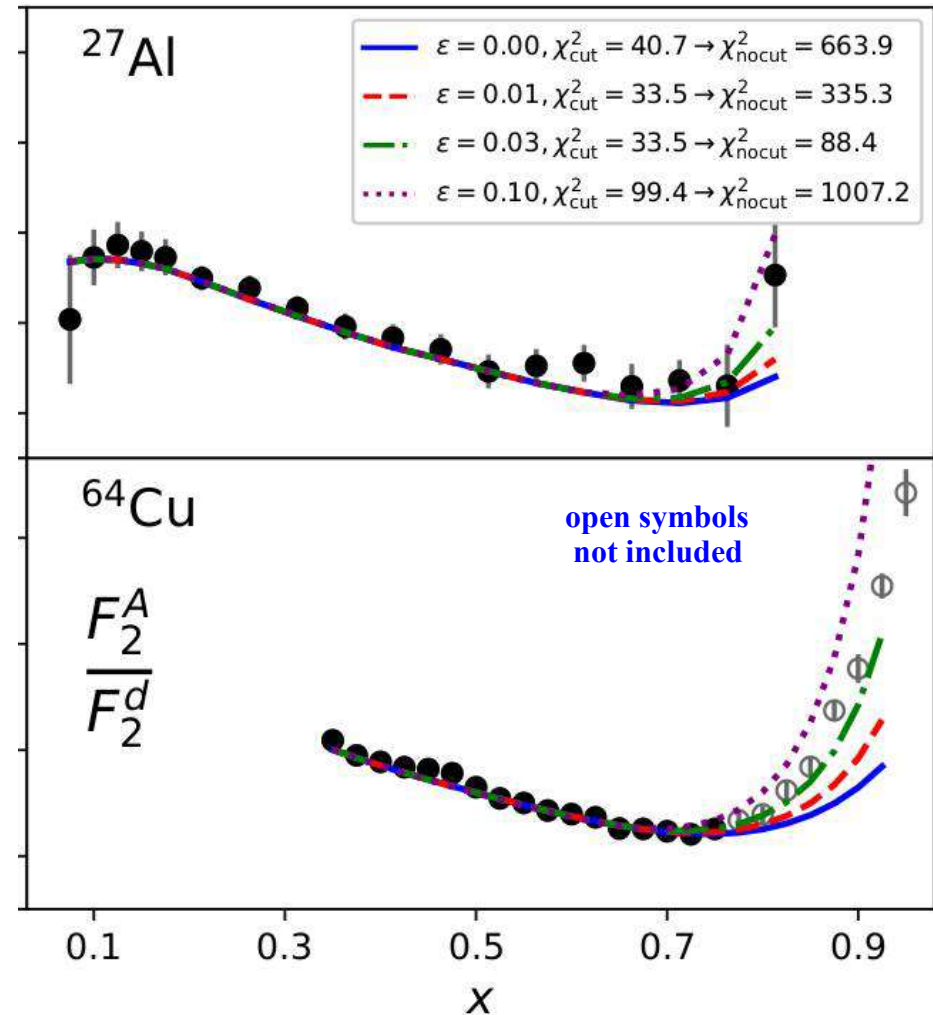
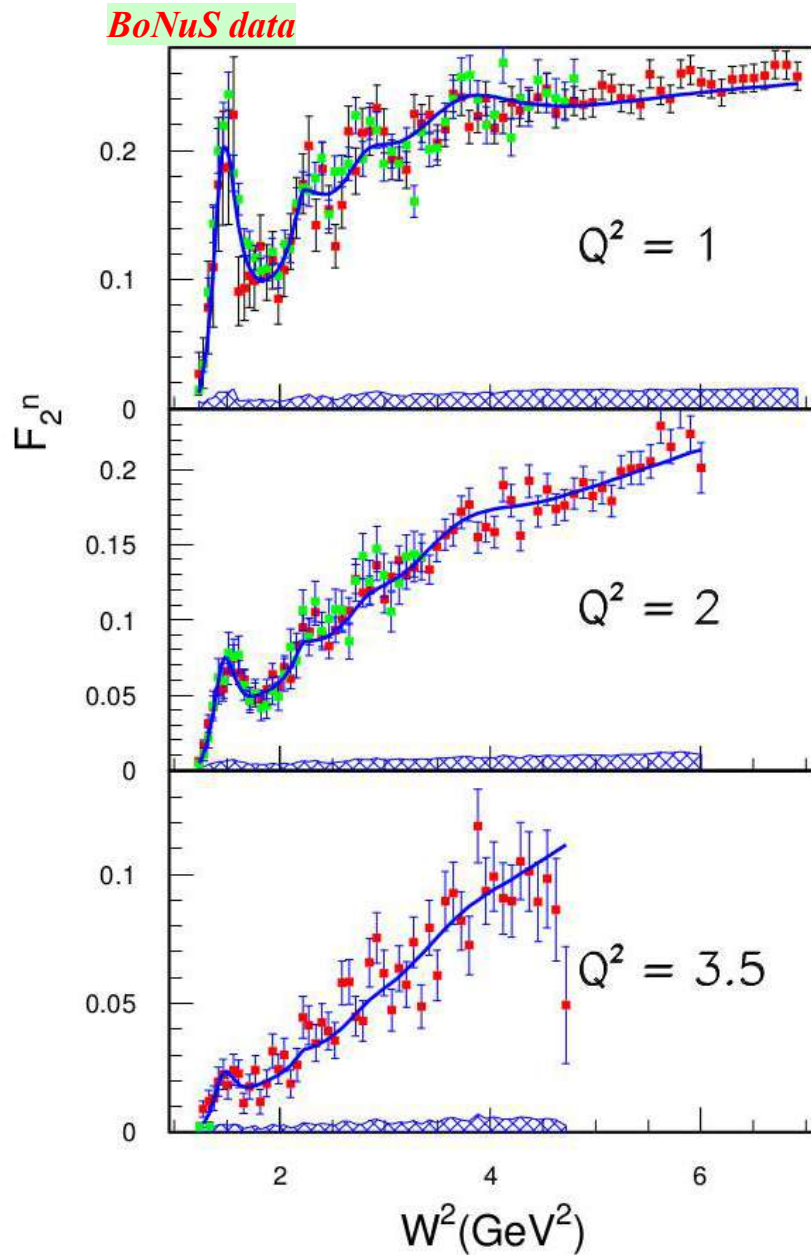
Deuteron Corrections

impacts $F_2^{\text{Nuc}}/F_2^{\text{Deuteron}}$ ratio

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



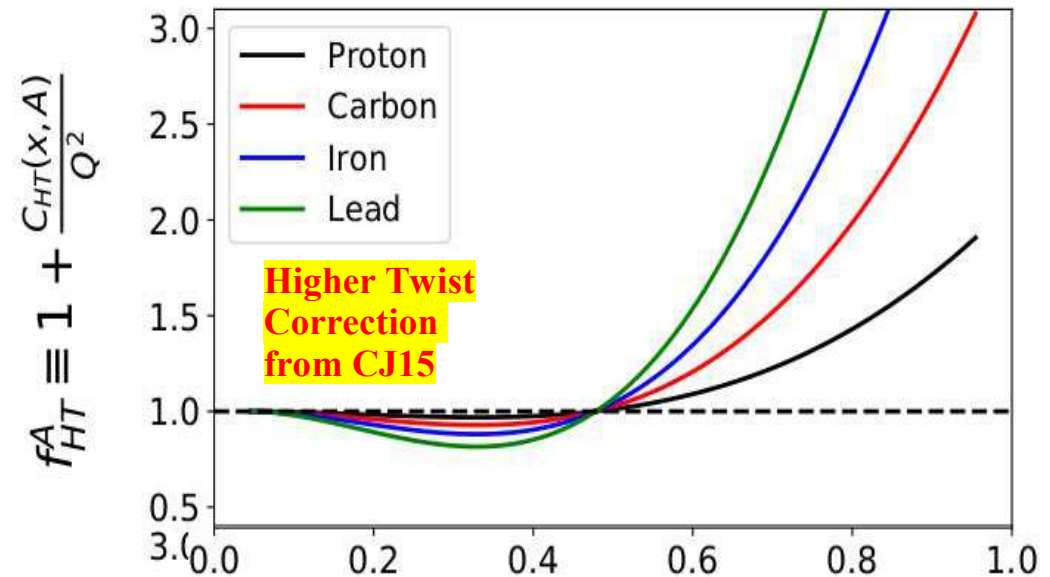
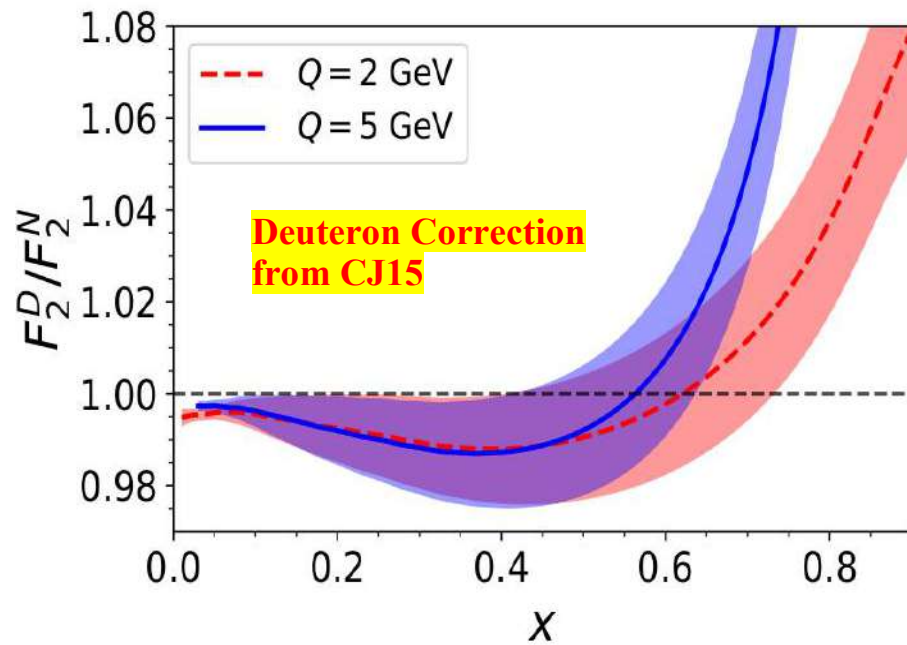
nCTEQ15HIX -- Extending nPDF Analyses
into the High- x , Low Q^2 Region
E.P. Segarra, T. Ježo, et al., PRD 103, 114015 (2021)



Reduces $\{Q, W\}$ cuts

Can we push into the resonance region?

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

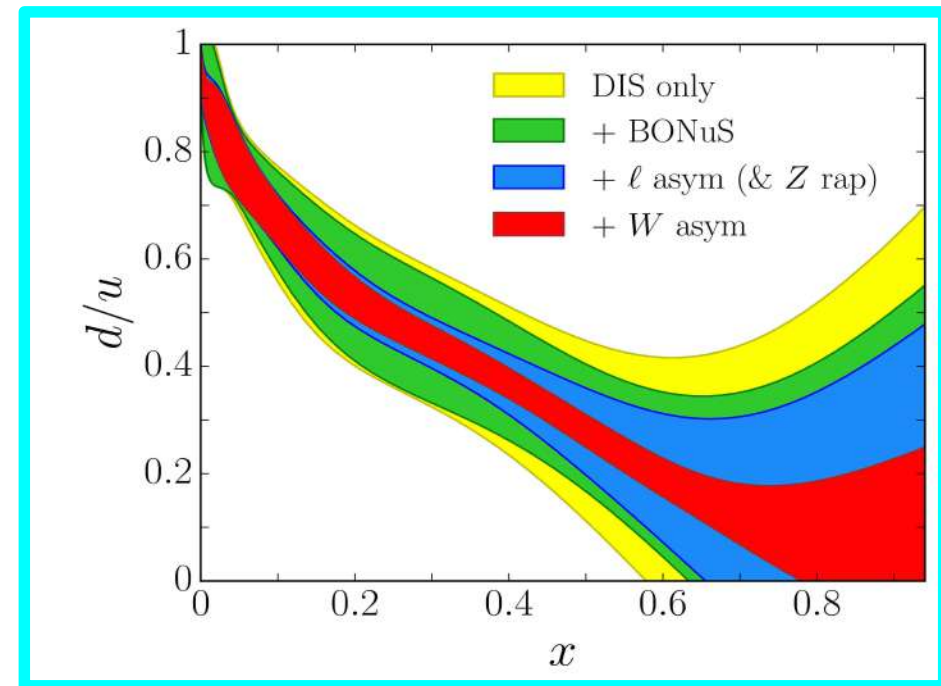
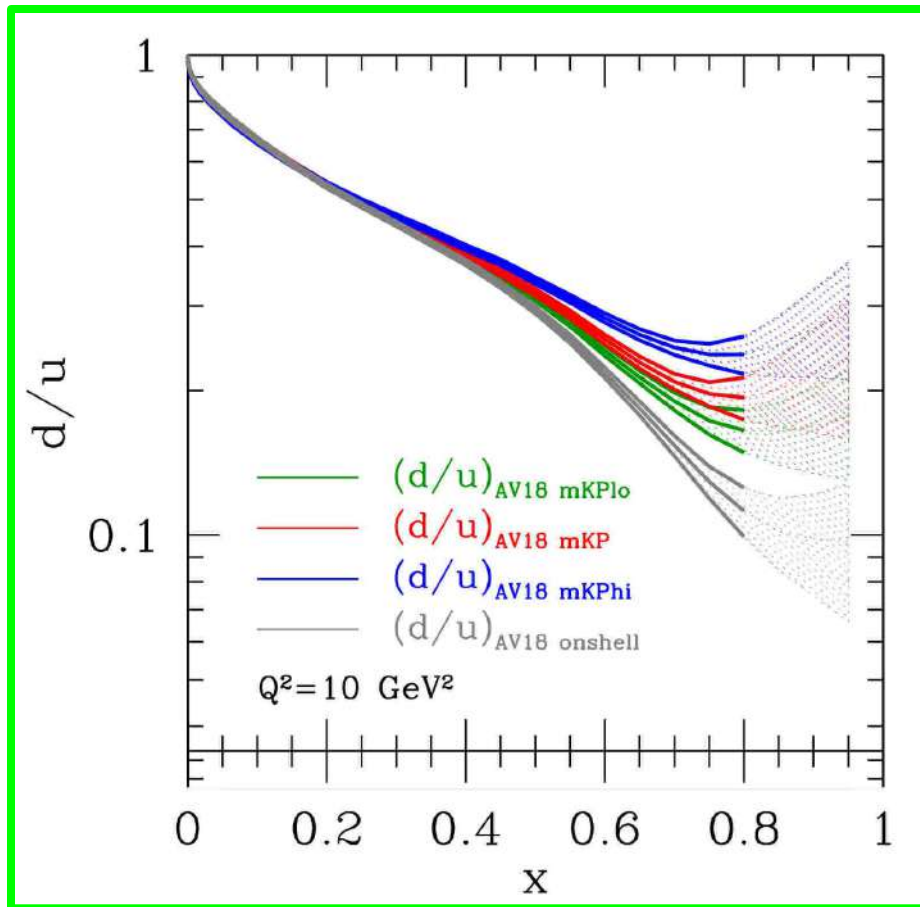


Fit	χ^2	N_{data}	χ^2/N_{dof}	Q_{cut}	W_{cut}
nCTEQ15	587	740	0.81	2.0	3.5
nCTEQ15*	2664	1564	1.70	1.3	1.7
BASE	1525	1564	0.99		
HT	1482	1564	0.96		
DEUT	1331	1564	0.85		
nCTEQ15HIX	1291	1564	0.83		

Reference
Higher Twist ~3%
Deuteron ~14%
Combined ~16%

We can extend our kinematic reach in $\{x, Q^2\}$

what about mid x region


CJ-15

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

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

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

- Better understanding important for BSM searches of new heavy states

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

Ingo Schienbein
 2018 Trento Workshop

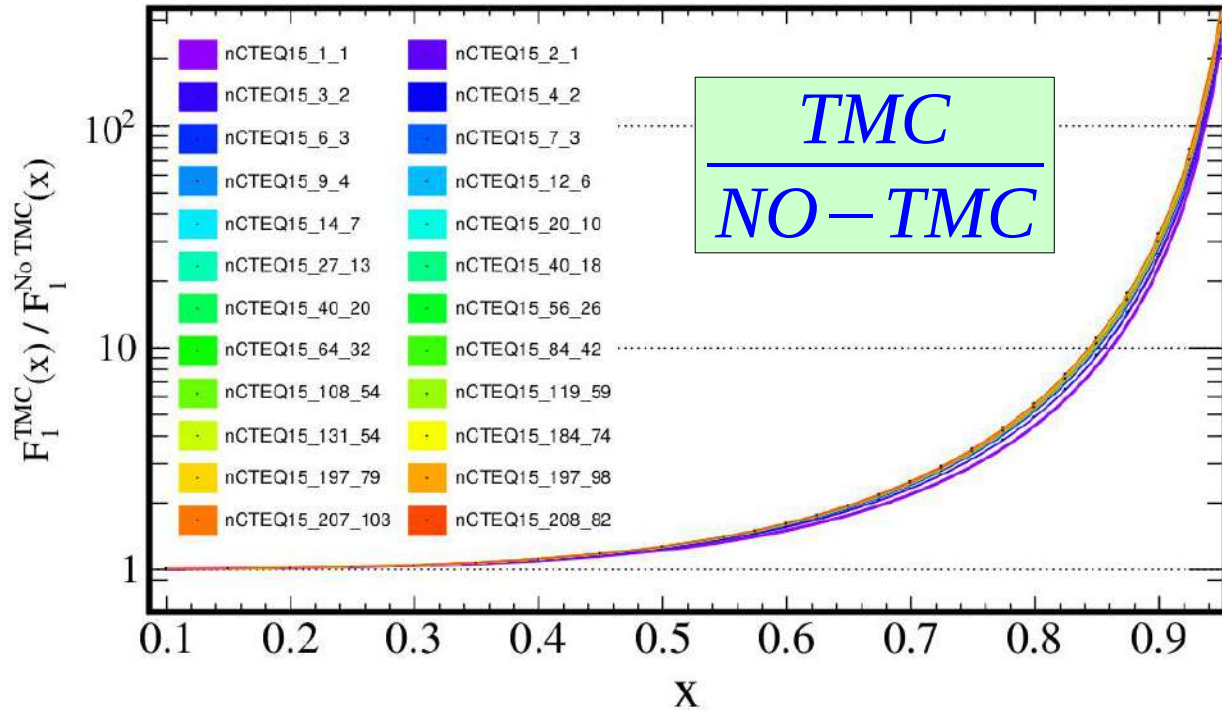
Target Mass Corrections

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. Duventäster ^{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

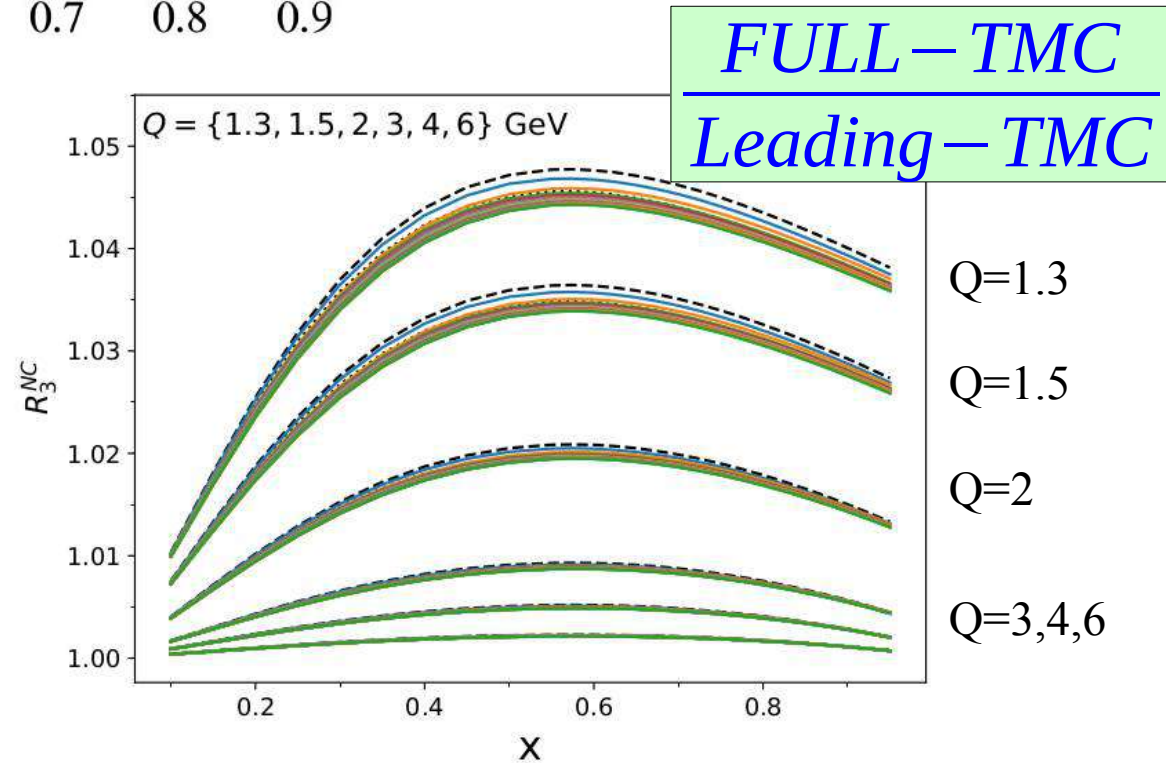


TMCs can be large

... but uniform, even for large A

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

Corrections are nearly universal



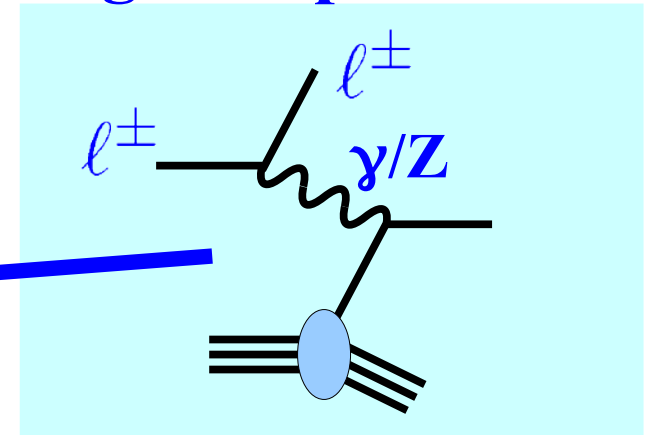
Strange PDF

Parton Distribution Functions



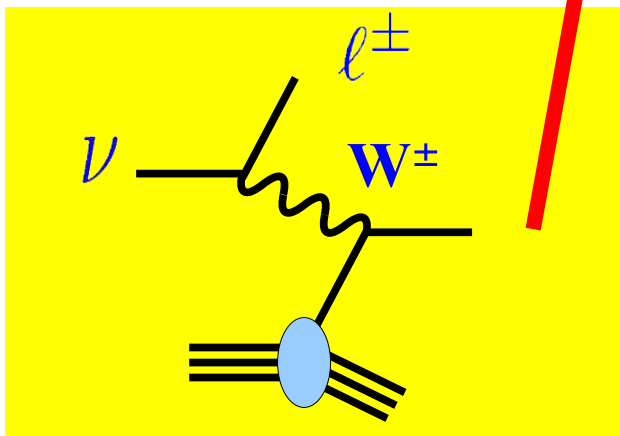
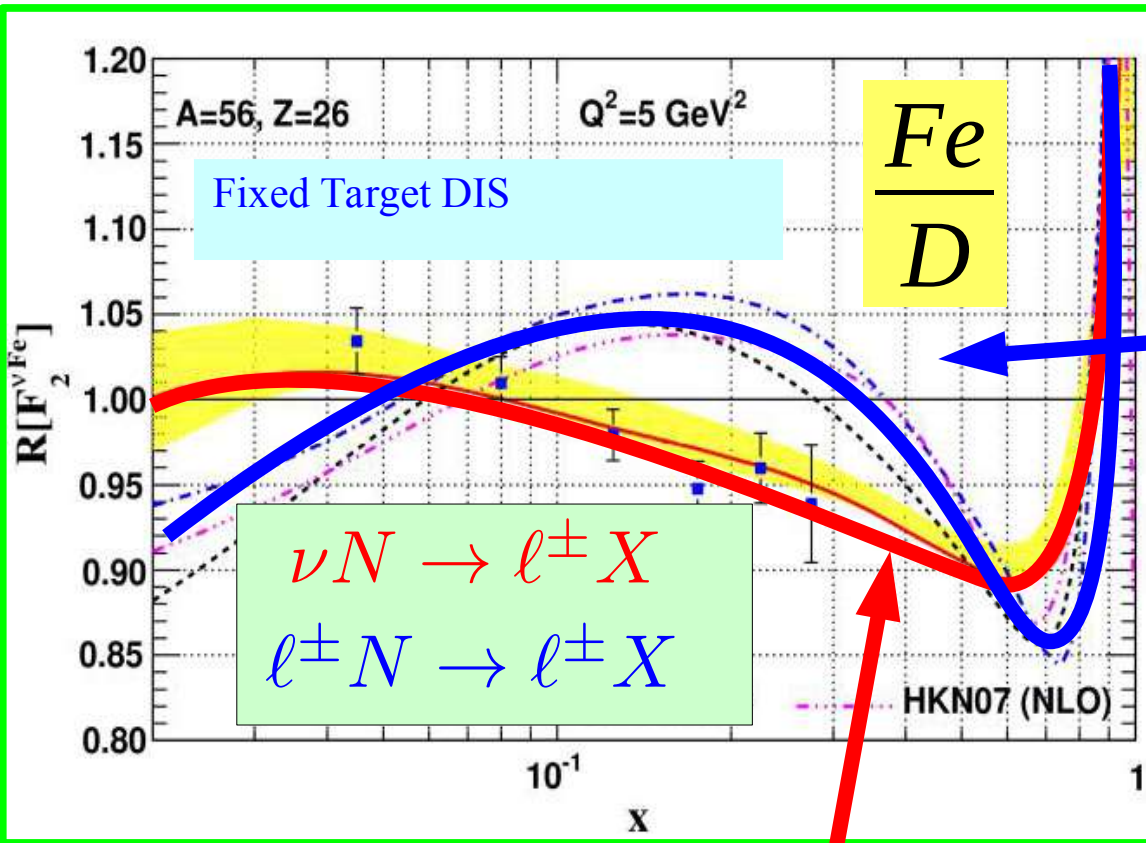
vDIS ... has a significant impact on the strange quark PDF

Charged Lepton DIS



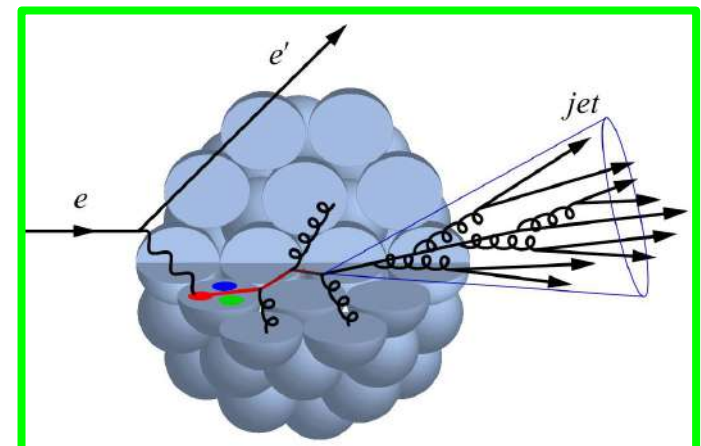
*some caveats
... correlated errors*

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



Neutrino DIS

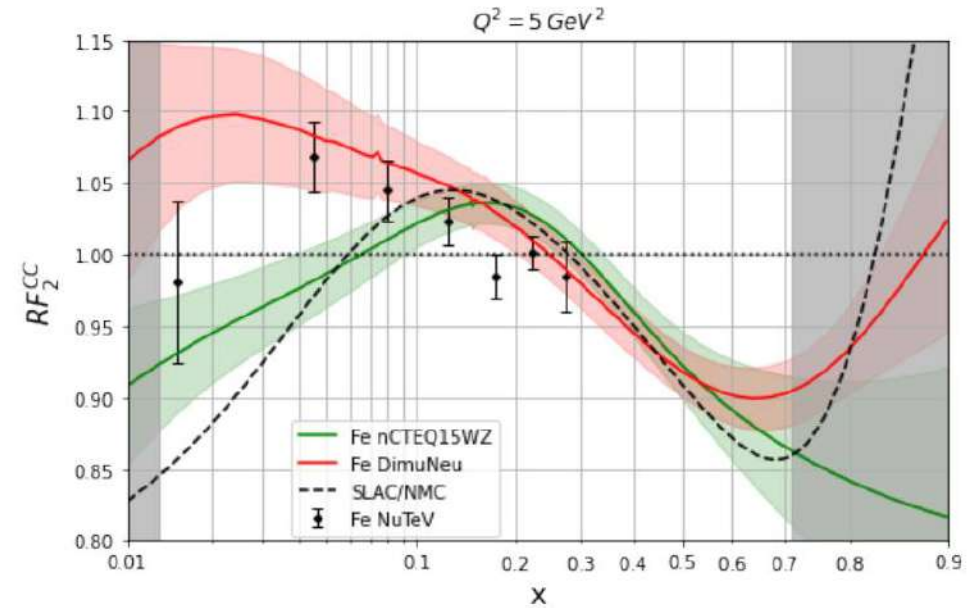
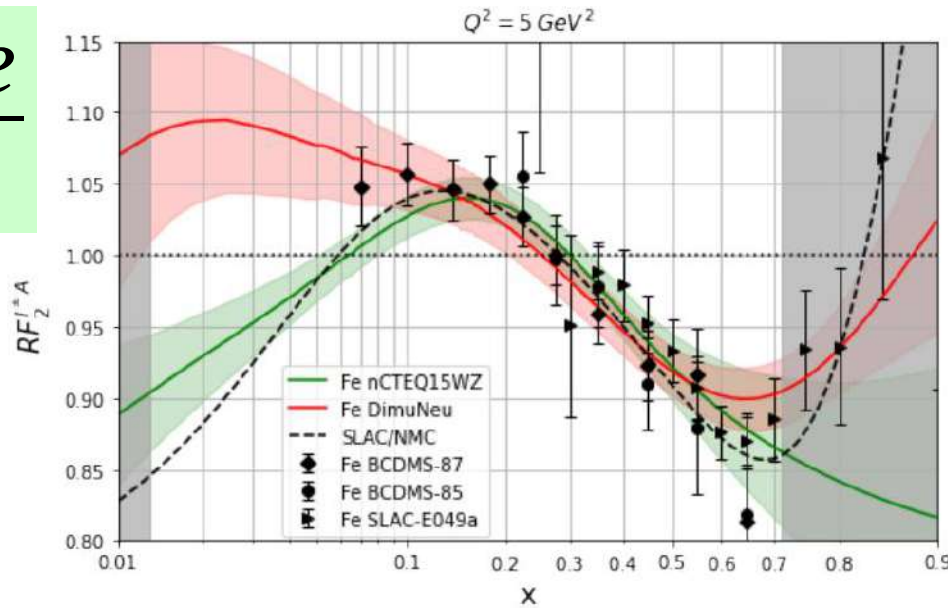
Depends on nuclear corrections



Propagation of γ/W thru nuclei

nCTEQ: Faiq Muzakka, Karol Kovarik, ...

$\frac{Fe}{D}$



Iron
 (proton + neutron)

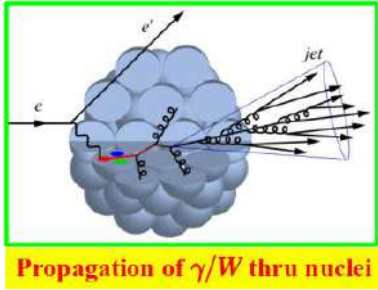
What is the correct nuclear correction ???
 Are these data sets compatible???

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

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

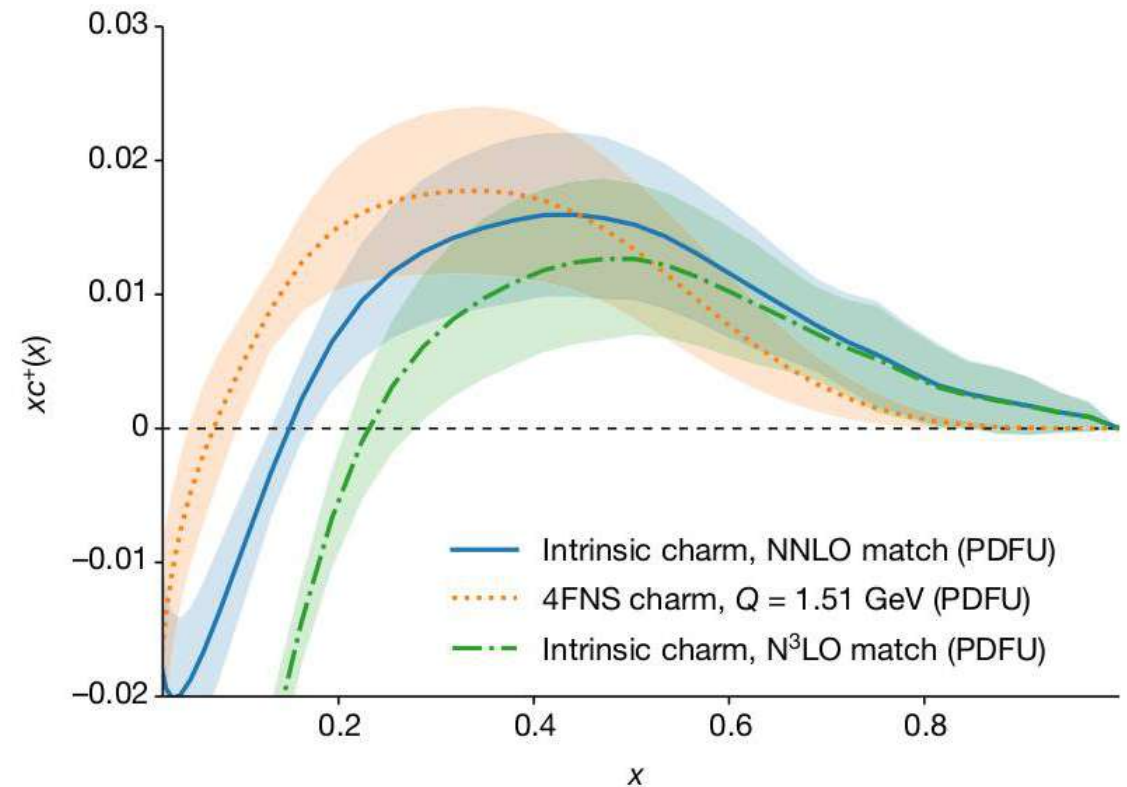
K.F. Muzakka ^{1,*}, P. Duwentäster ^{1,†}, T.J. Hobbs ^{2,3,4}, T. Ježo ^{5,‡}, M. Klasen ^{1,§}, K. Kovařík ^{1,¶},
 A. Kusina ^{6,**}, J.G. Morfin ^{7,††}, F. I. Olness ^{8,‡‡}, R. Ruiz ⁶, I. Schienbein ^{8,§§}

¹Institut für Theoretische Physik, Westfälische Wilhelms-Universität Münster.



Charm PDF

Parton Distribution Functions



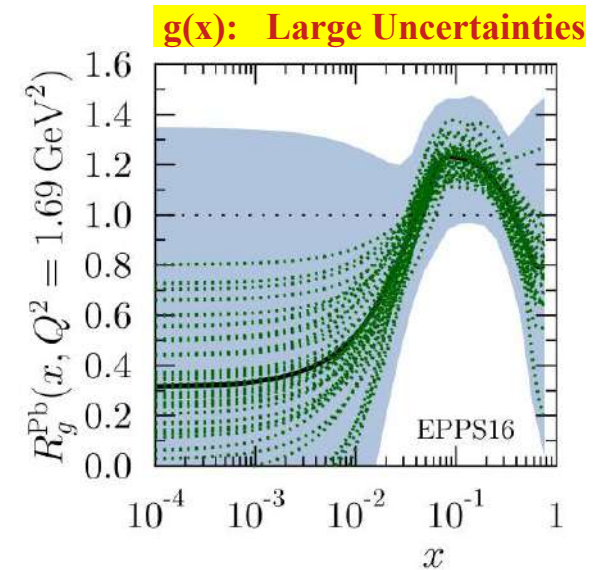
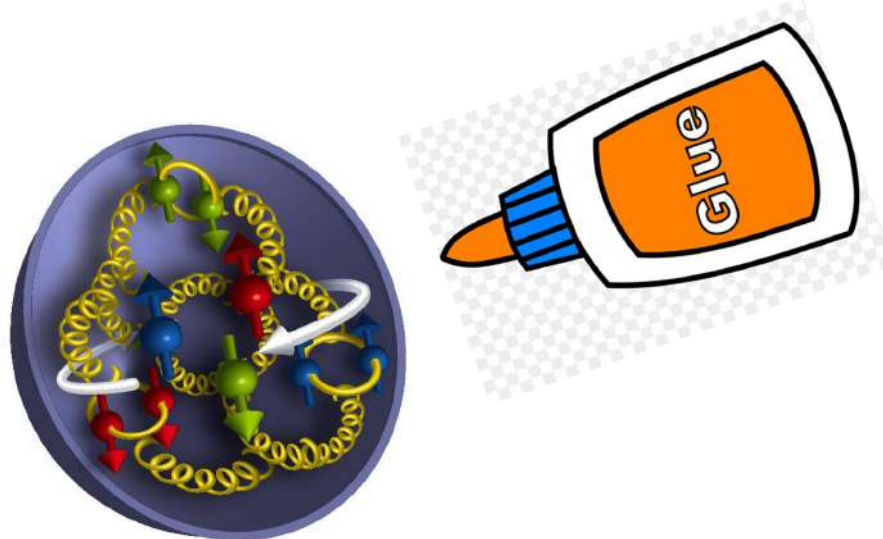
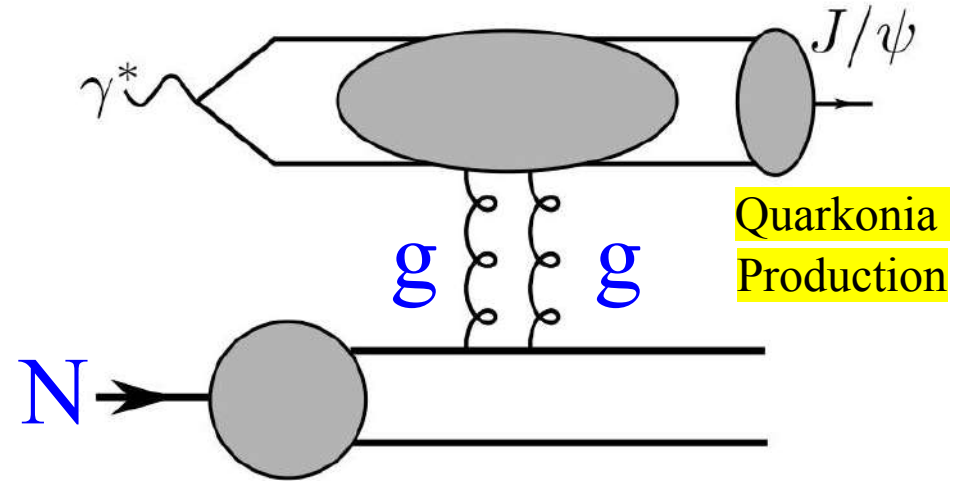
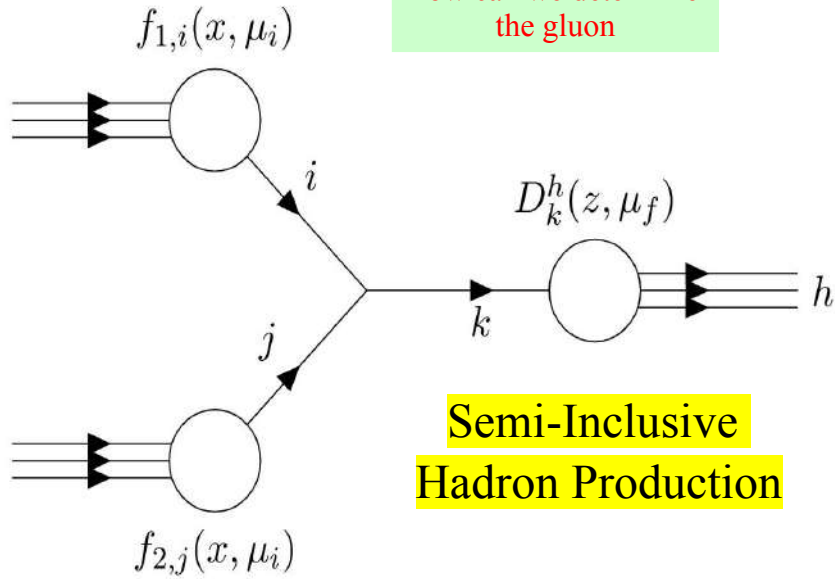
What is the status of Intrinsic Charm?

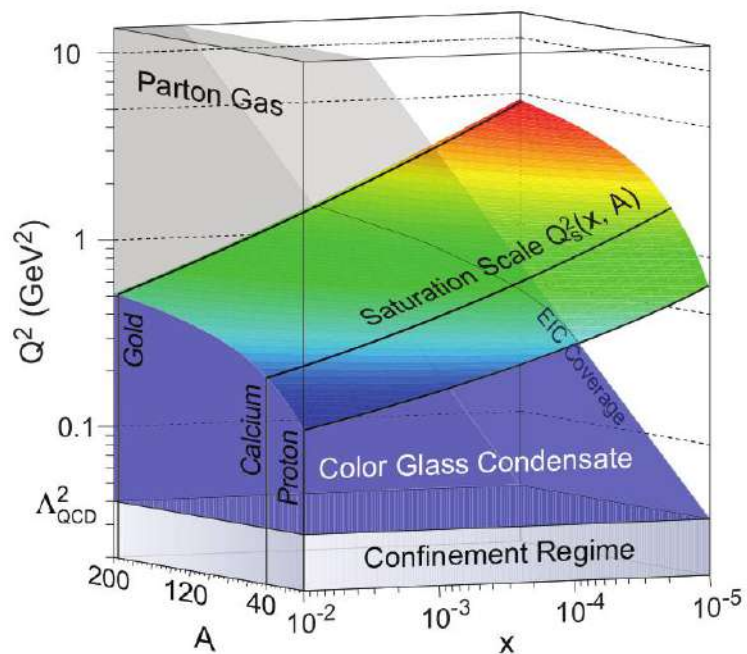
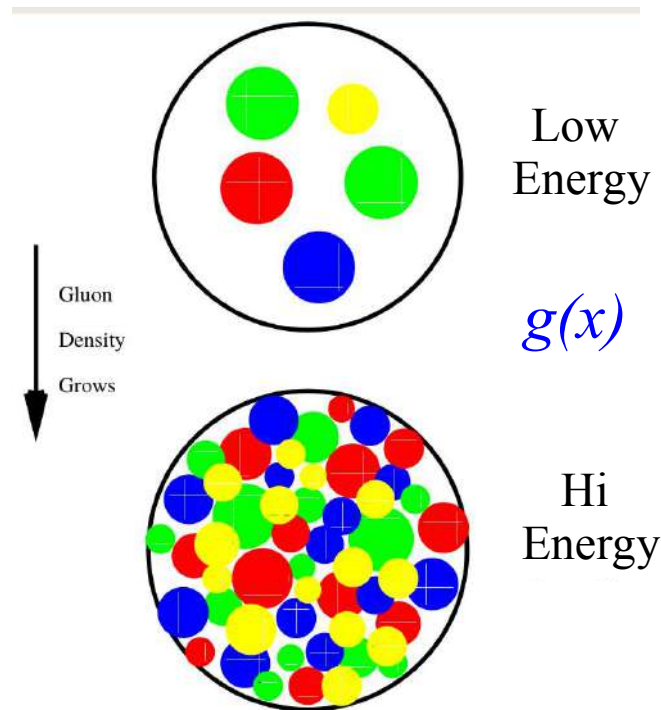
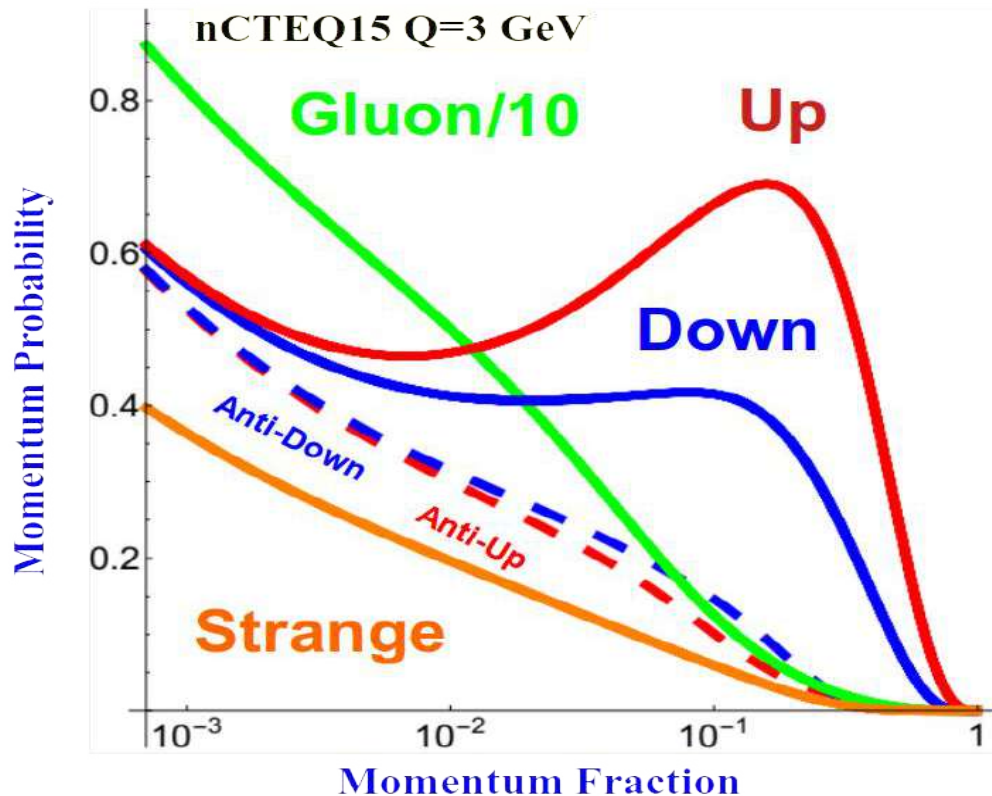
The NNPDF Collaboration
<https://doi.org/10.1038/s41586-022-04998-2>

Measuring the nuclear Gluon PDF 24

Parton Distribution Functions

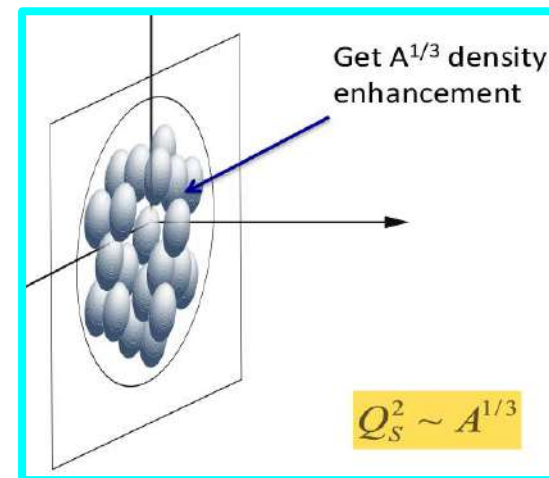
how can we determine the gluon



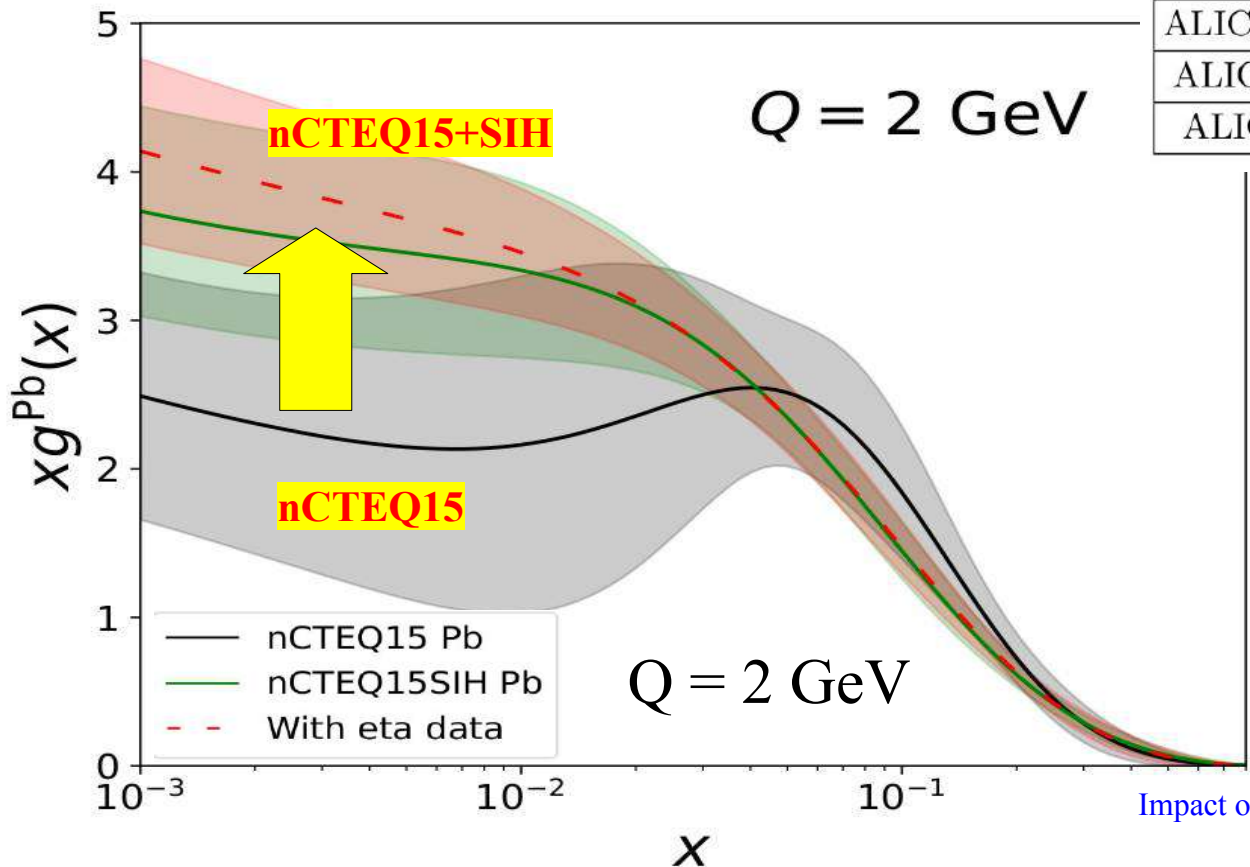
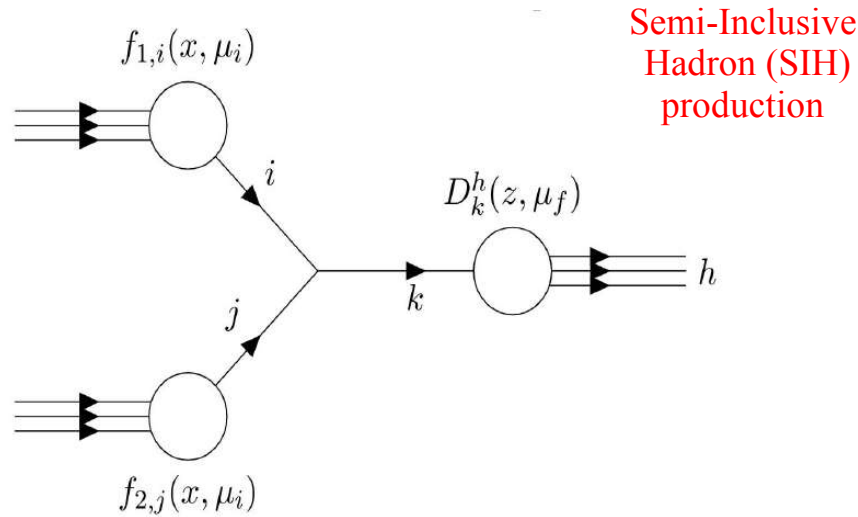


- Nuclear medium effects:**
- Quark Gluon Plasma
 - Color Glass Condensate
 - Recombination
 - Saturation
 - Resummation
 - ... *your theory here*

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



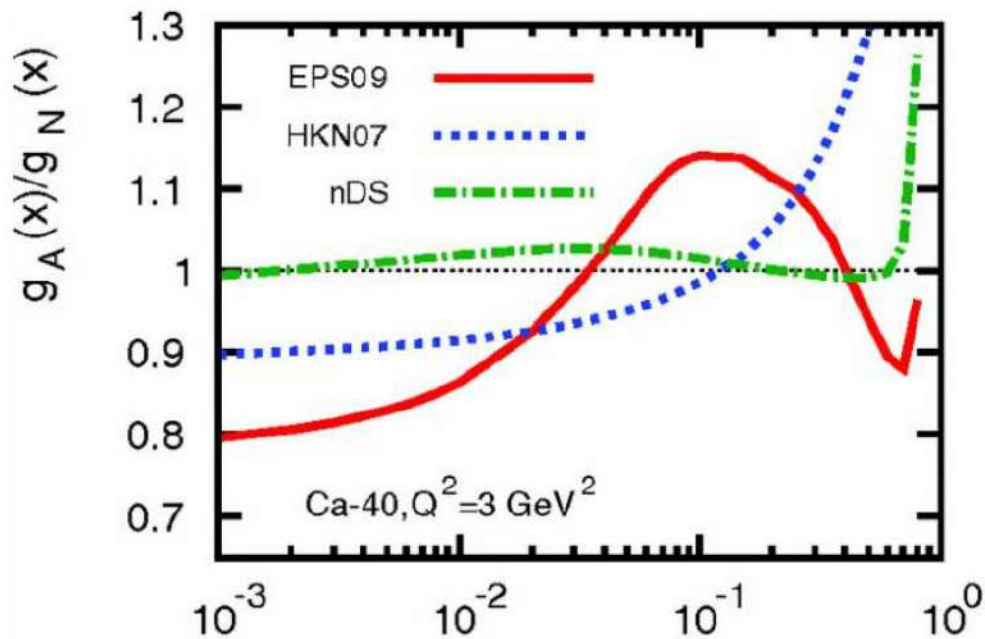
nCTEQ: Pit Duwentaster, Michael Klasen, ...



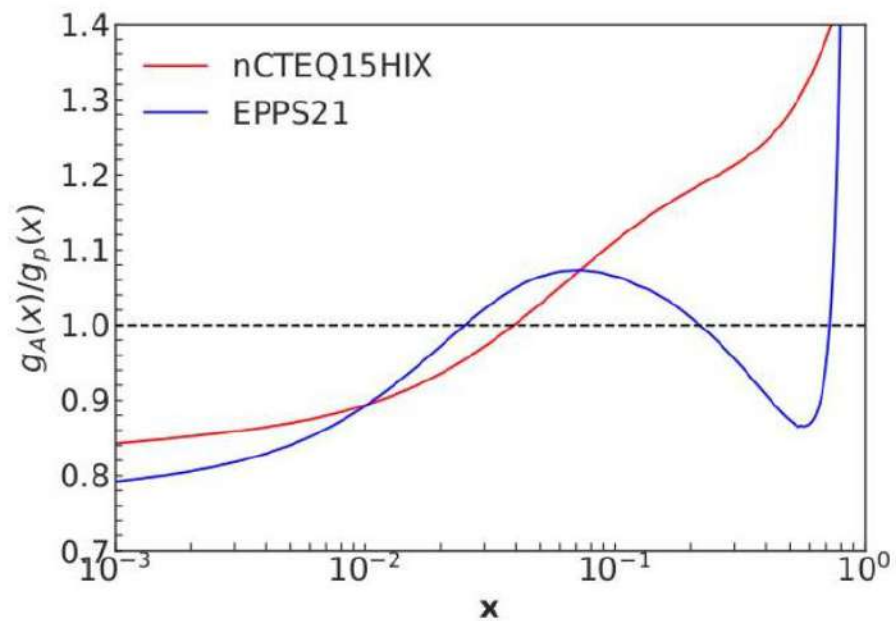
Data set	$\sqrt{s_{NN}}$ [GeV]	Observ.	No. points
PHENIX π^0	200	R_{dAu}	21
PHENIX η	200	R_{dAu}	12
PHENIX π^\pm	200	R_{dAu}	20
PHENIX K^\pm	200	R_{dAu}	15
STAR π^0	200	R_{dAu}	13
STAR η	200	R_{dAu}	7
STAR π^\pm	200	R_{dAu}	23
ALICE 5 TeV π^0	5020	R_{pPb}	31
ALICE 5 TeV η	5020	R_{pPb}	16
ALICE 5 TeV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

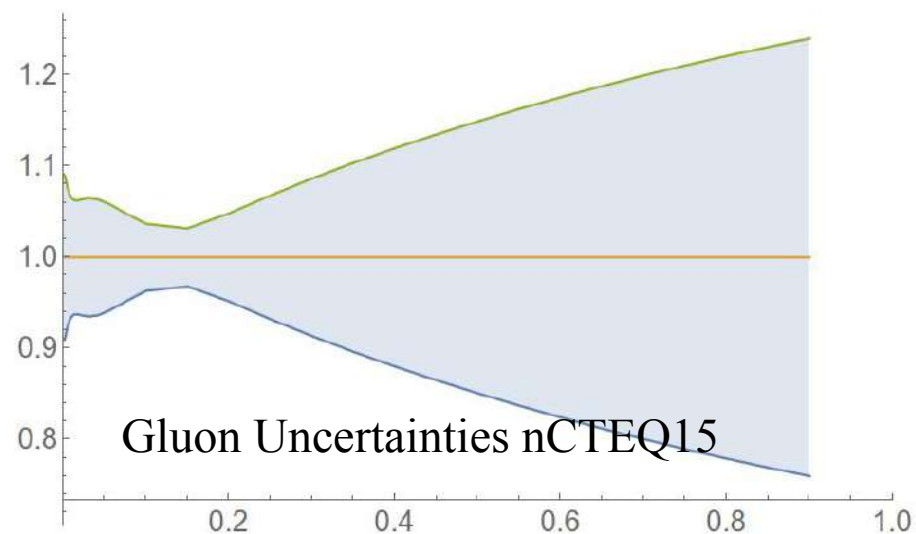
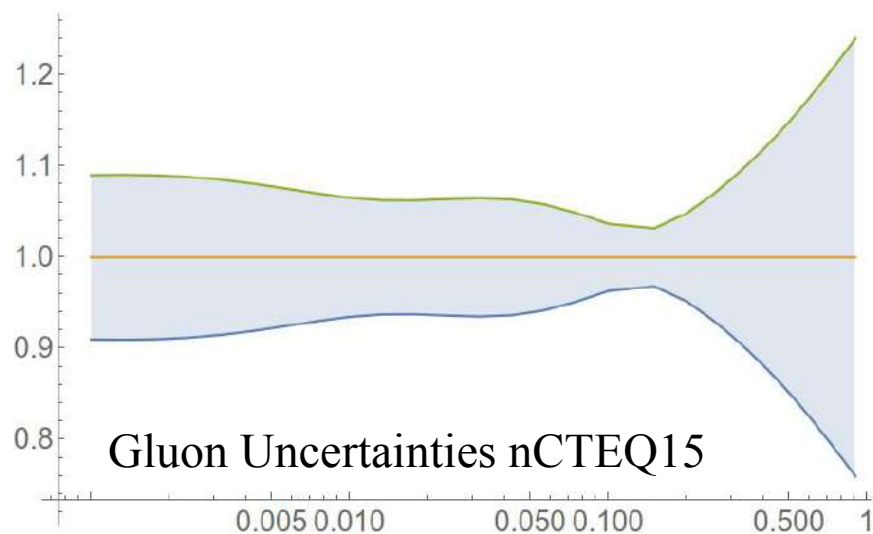
*Determines gluon
in small x region*



pdfnCTEQ154020



pdfnCTEQ154020

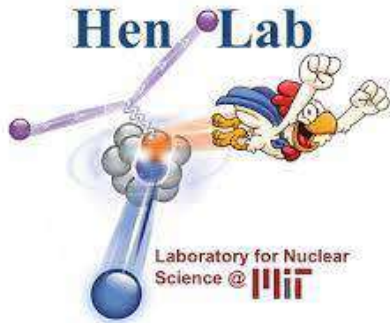


nPDFs:

Physics inspired parameterizations

Short Range Correlations (SRC)

nCTEQ with
 Andrew Denniston & Or Hen

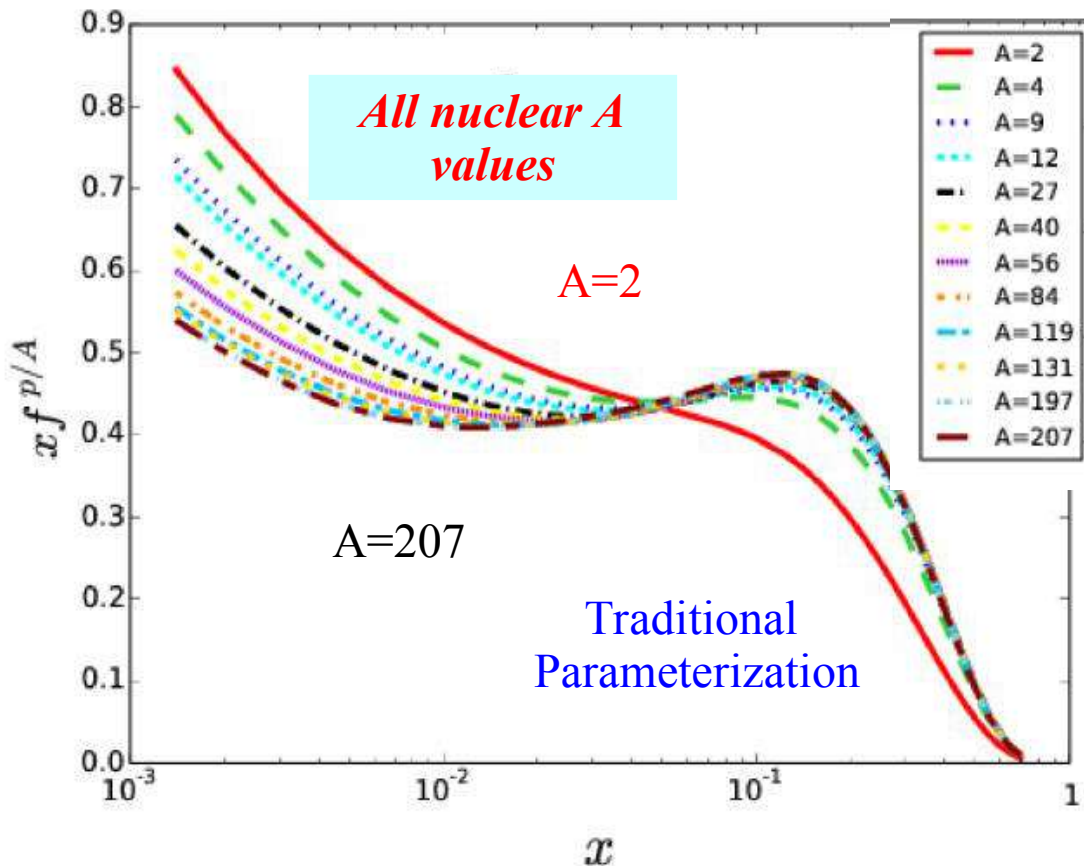


$$f_A = (1-c) f_p + c f_{\text{SRC}}$$

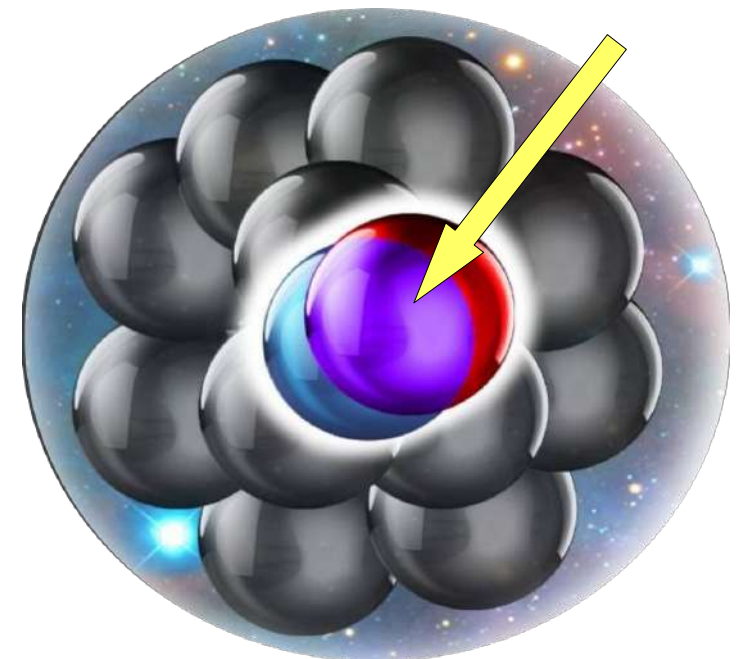
nuclear PDF

normal proton PDF

SRC modified PDF



Short Range Correlations (SRC)



CONCLUSIONS

Proton PDF: $f_p(x, Q)$

generally NNLO; approaching $\sim 1\%$ 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

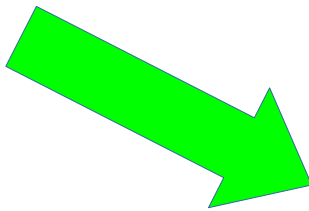
QCD
Lagrangian

$$\mathcal{L}_{QCD} = \bar{\psi}_q (i\gamma_\mu D^\mu - m_q) \psi_q - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}$$



isospin violation
quark-gluon plasma
Fermi motion
jet quenching
target mass corrections
shadowing
DGLAP violation???

Nuclear PDFs



saturation
resummation
hi-x
low-Q²
higher twist
non-linear QCD

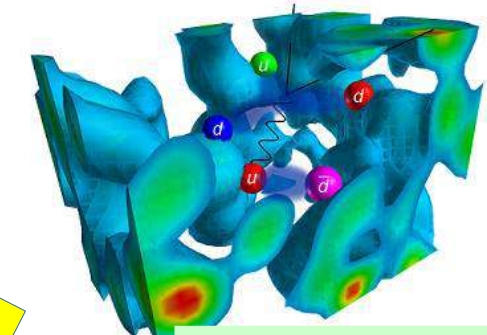
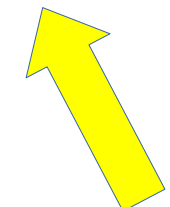
Proton PDFs



DGLAP violation???

saturation
resummation
hi-x
low-Q²
higher twist
non-linear QCD

Pion PDFs



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

Lattice QCD

