Anti-Shadowing and Nuclear PDF Challenges

...

opportunities from a upgraded facility

Fred Olness
SMU

*Thanks for substantial input
from my friends & colleagues*

nCTEQ
nuclear parton distribution functions

xFitter

C T E Q

JLab High Energy Workshop Series
22-23 July 2022

Kinematics:

- Extend to lower x:
  - explore anti-shadowing region
- Extend to higher Q:
  - extended span in Q; can we extrapolate into non-pert region
  - larger Q: increased J/Psi $\rightarrow$ gluon PDF

Nuclear Corrections: Split Personality

- Explore EMC effect in mid-x range:
- CC vs NC; (limited CC data; separate nuc and flavor effects (e.g., strange)
- flavor decomposition and nuclear corrections: MARATHON

Gluon PDF

- J/Psi: charm production:
- threshold prod of charm
- mass effects: explore full range of m/Q

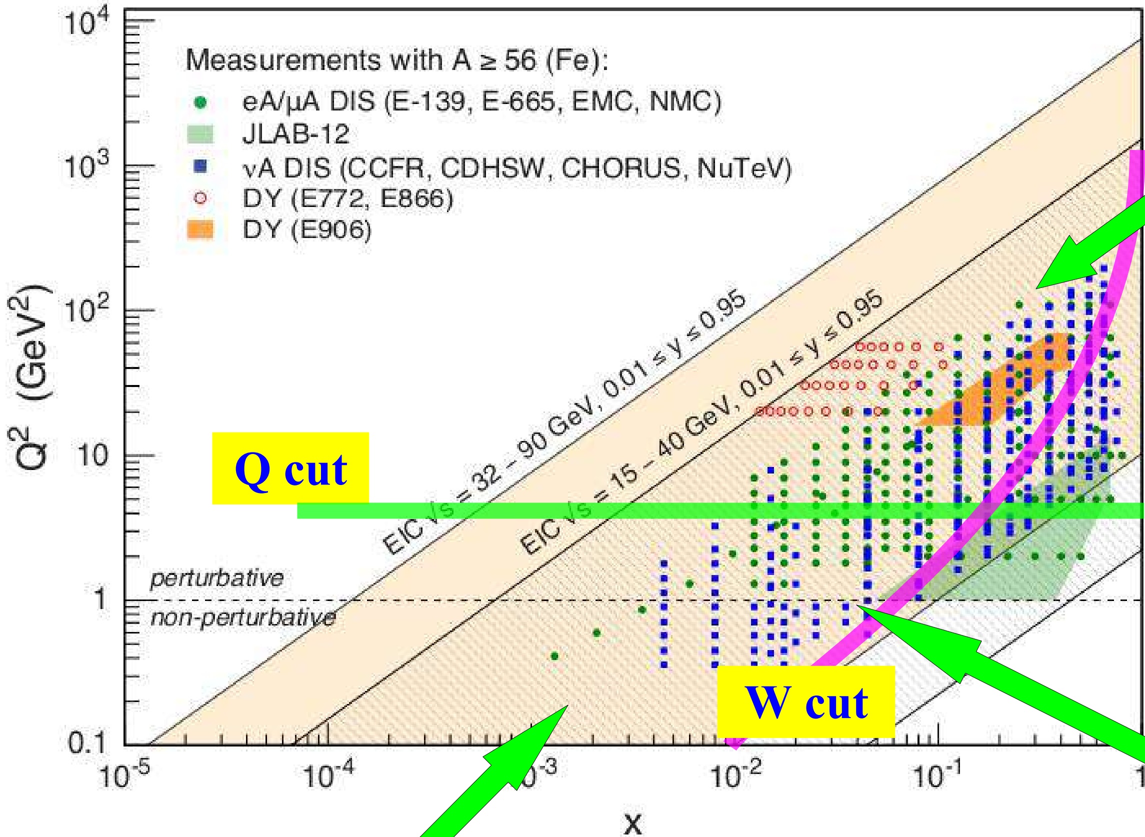
borrowing ideas from recent nCTEQ projects that can be extended to mid-x region

Broader Goals:

- Nuclear/Particle interface:
- increase precision at larger Q
  - press to lower Q
  - leverage Lattice QCD & TMDs/GPDs

KINEMATICS

Kinematic Plane in {x,Q^2}



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-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)

Run at multiple energies

JLab-12 in Green

Mid-x:

Nuclear PDFs: anti-shadowing

$F_2^{Nuc}/F_2^{Iso} > 1$

Collective effects

Good Stats:

… can this help us bridge

perturbative / non-pert interface

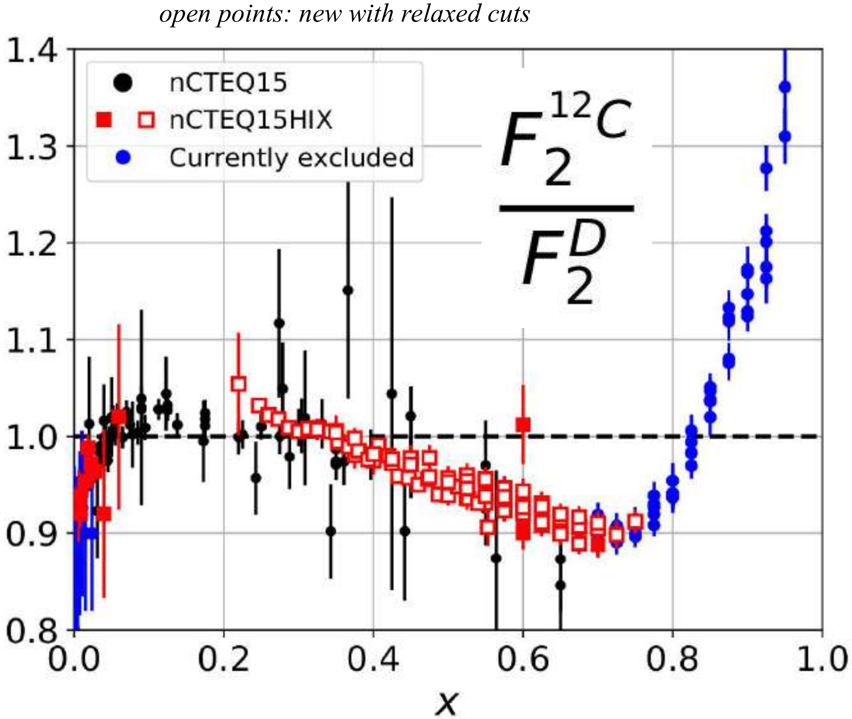
SHADOWING
&
ANTI-SHADOWING

An exercise at large x & low Q

...

extensible to mid-x region

Challenges at Large x & Low Q^2: JLab data ⇒ EIC



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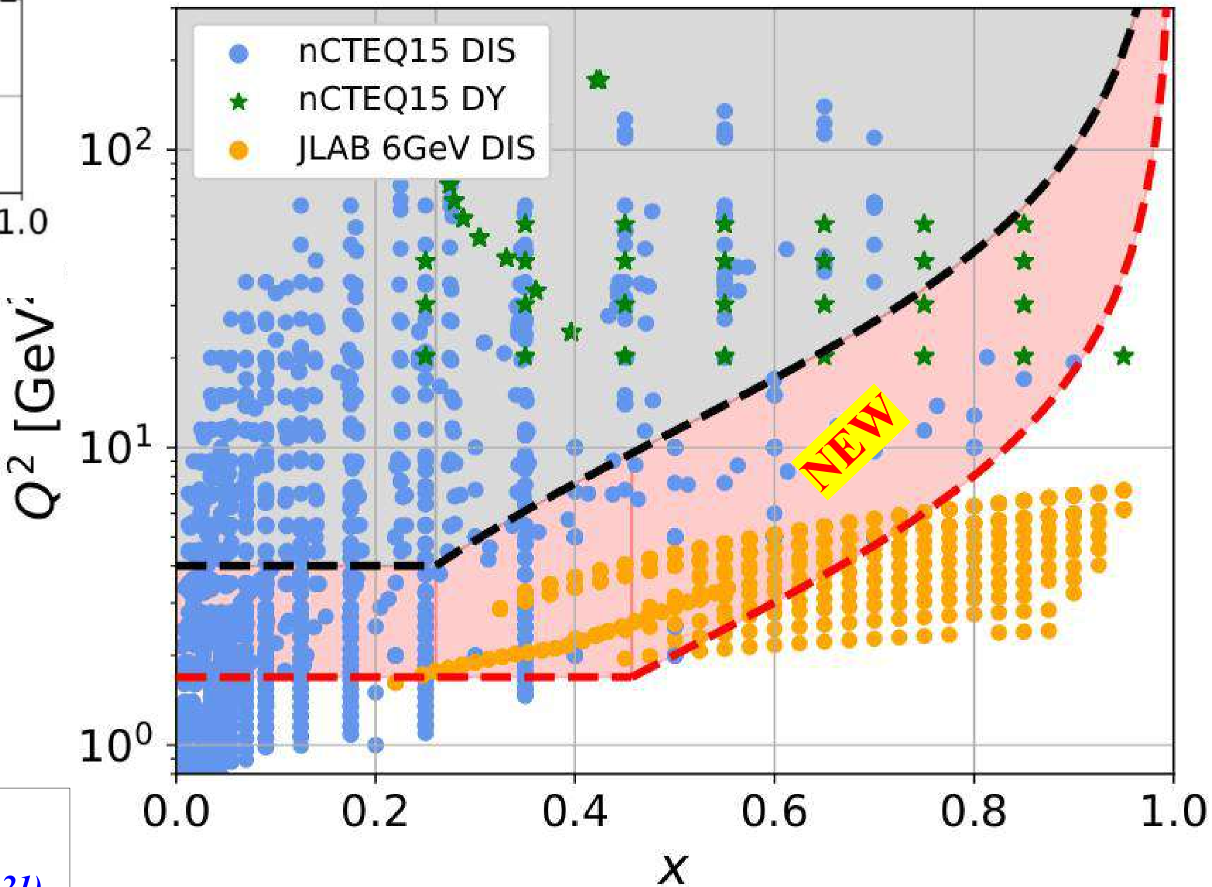


JLab Data @ Hi-X Low-Q^2

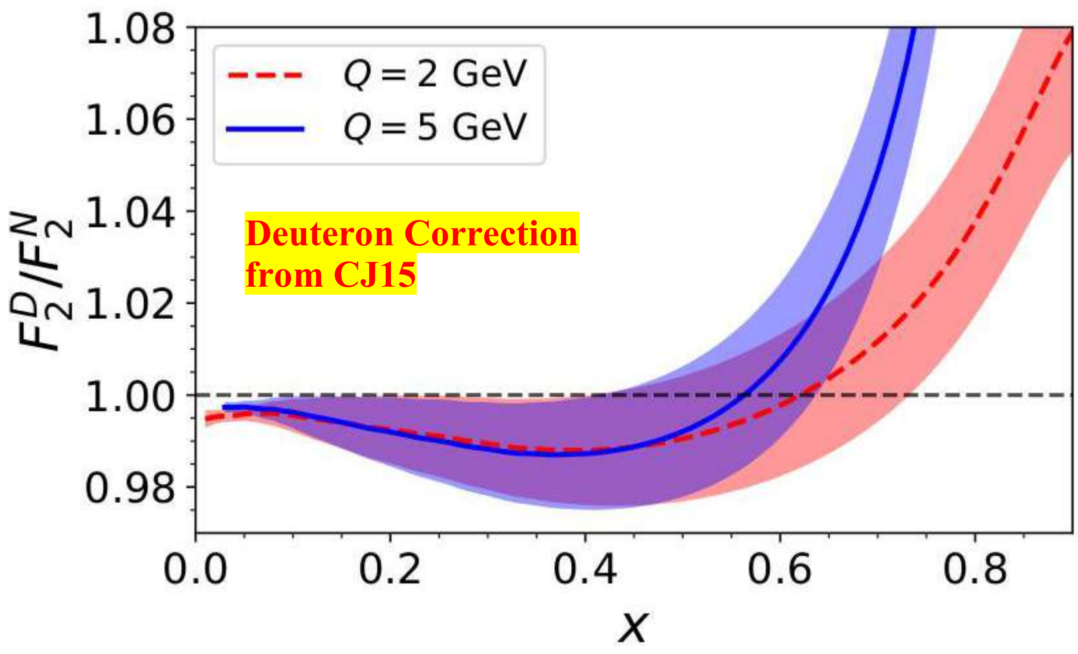
extend nCTEQ framework

to accommodate this region

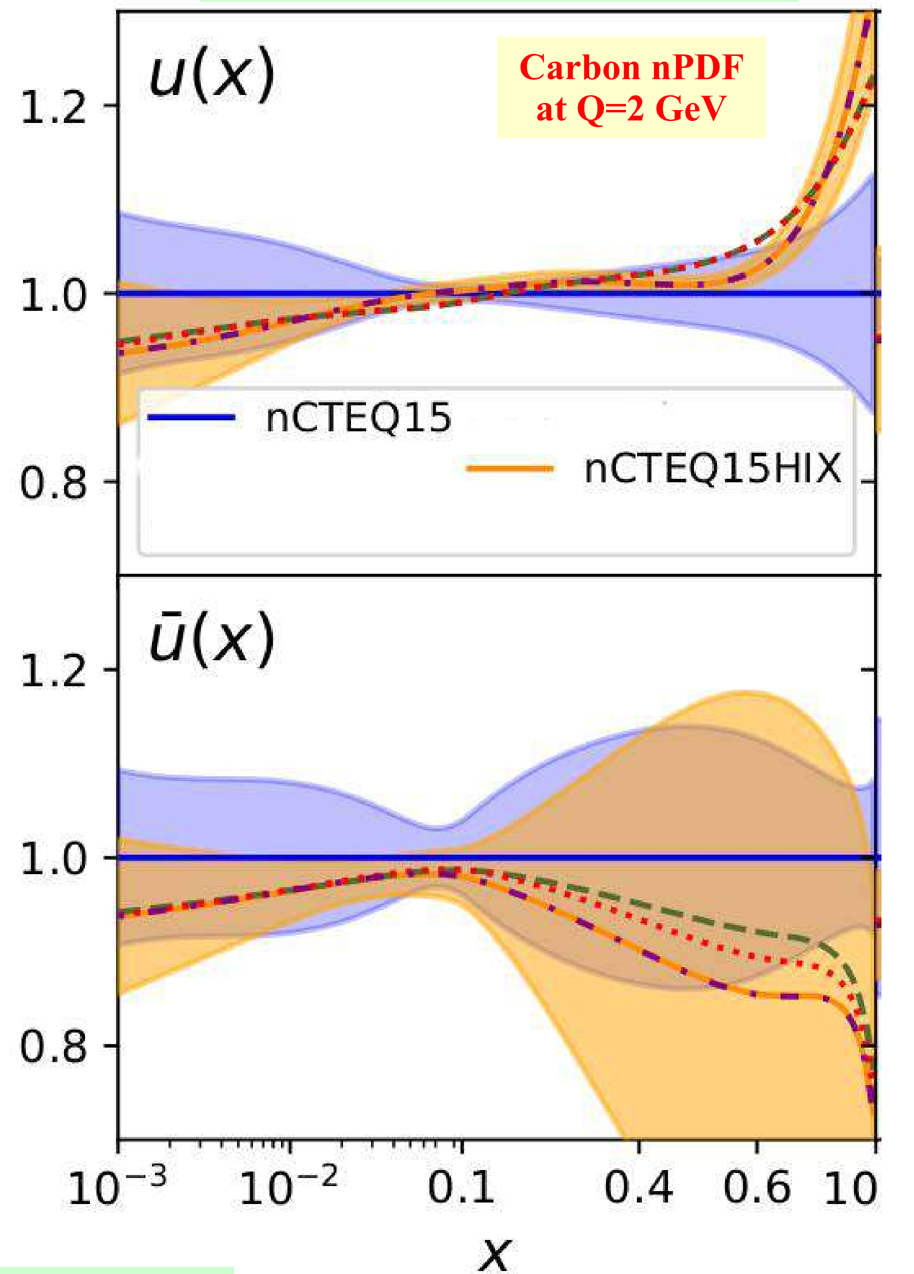
& prepare for EIC

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

nCTEQ15HIX include large x JLab data



JLab data: Shifts valence PDFs from low to hi-x



Deuteron Corrections Important!!!

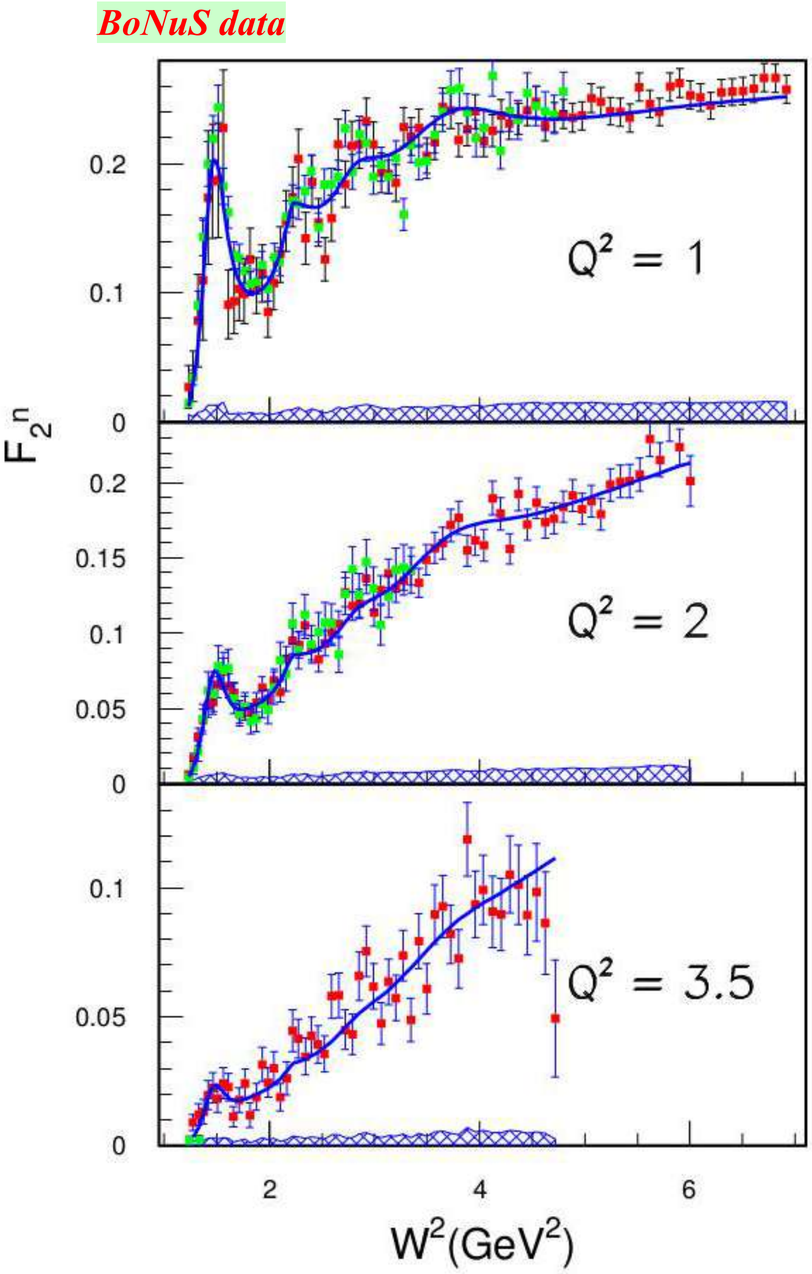
Overall χ^2/N_{dof} ~0.83

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

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

what about mid x region

How Low in W^2 and Q^2 can we go???



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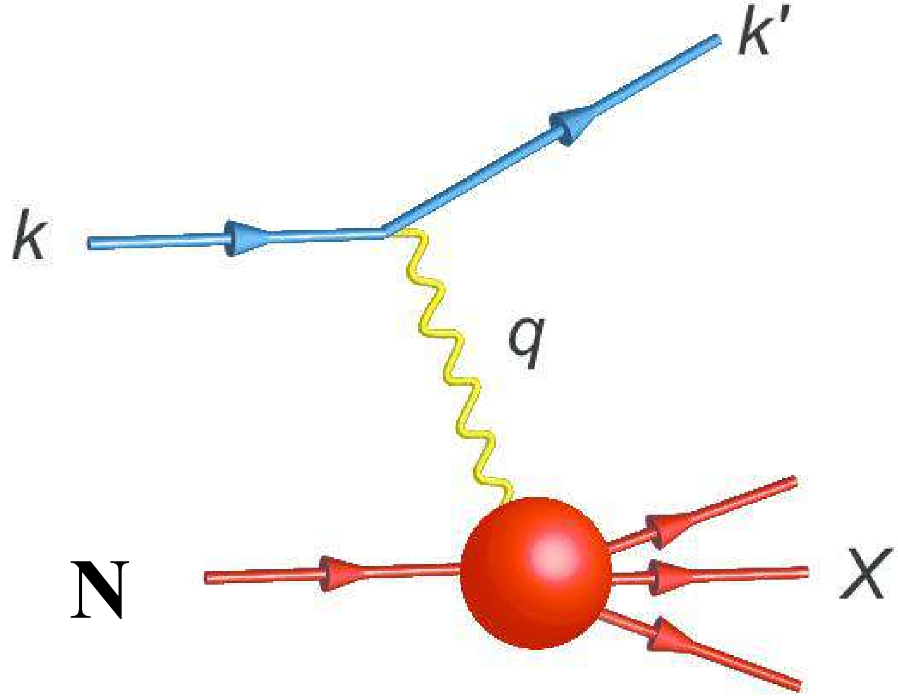
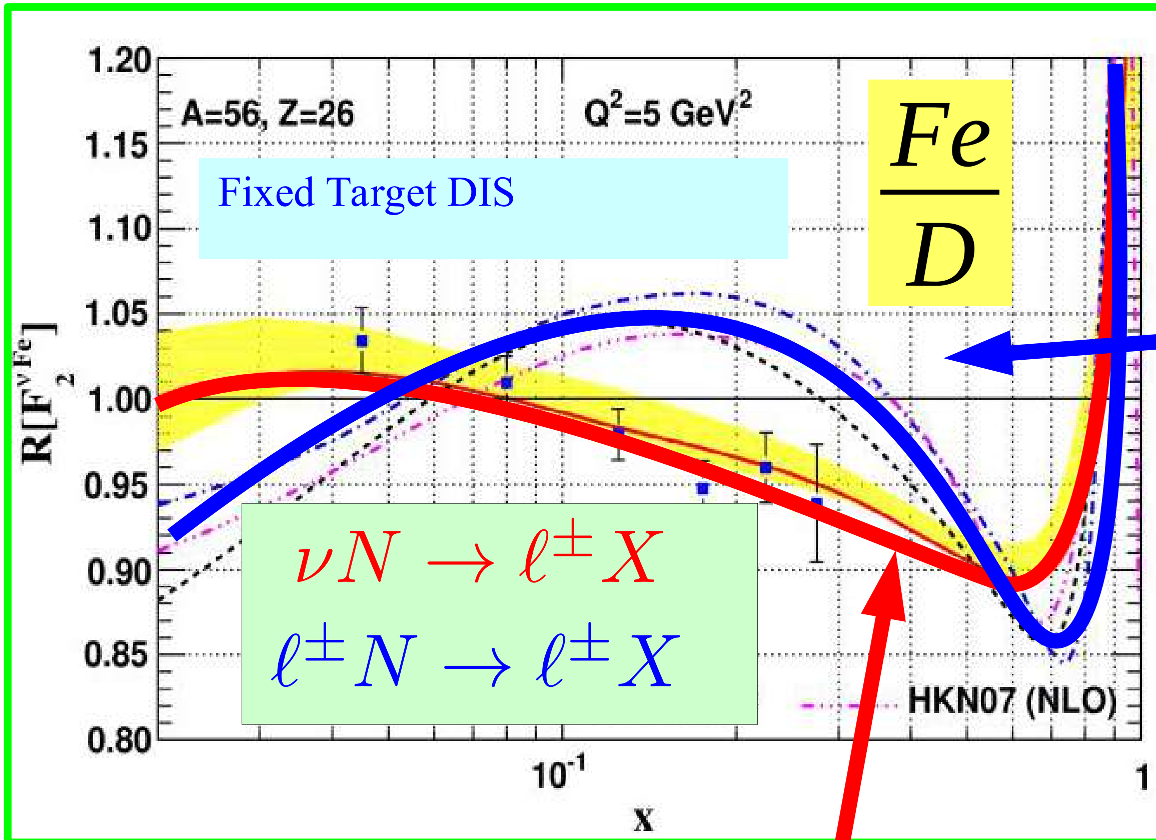
Can we push into the resonance region?

Nuclear Correction

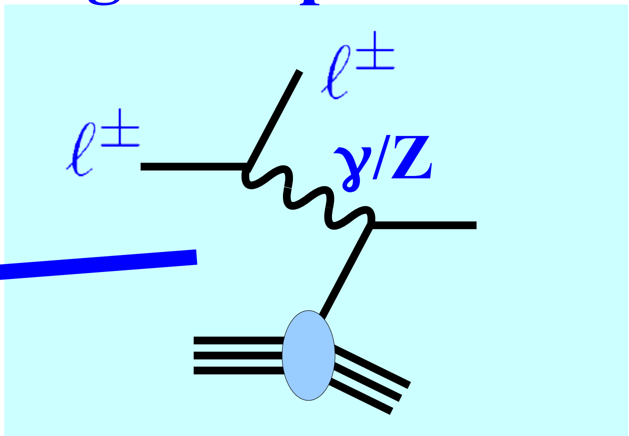
$$F^{A}/F^{iso}$$



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



Charged Lepton DIS

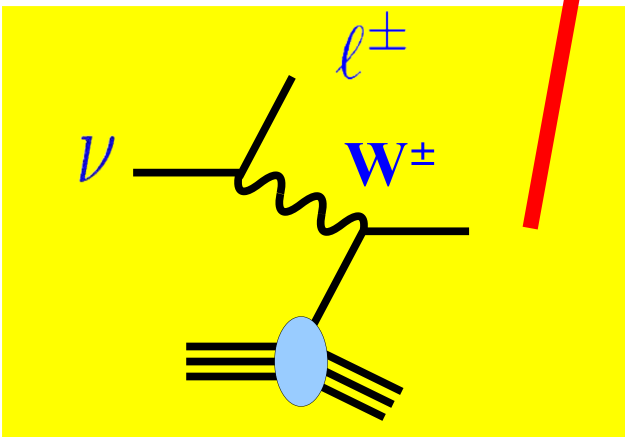


some caveats

… correlated errors

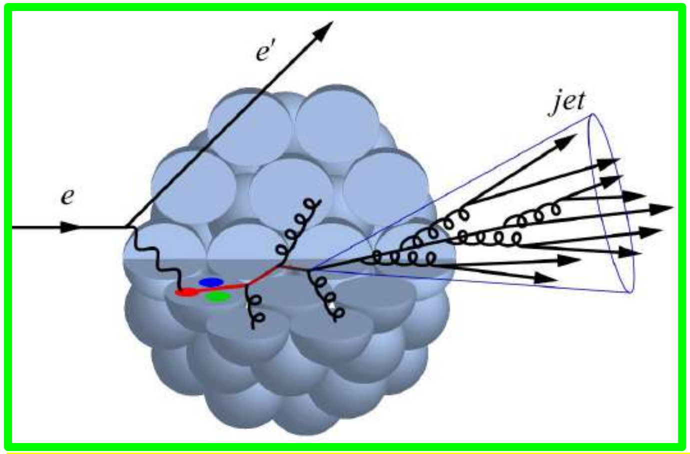
Ingo Schienbein, … (2007)

Karol Kovarik, … (2010)



Neutrino DIS

Depends on nuclear corrections

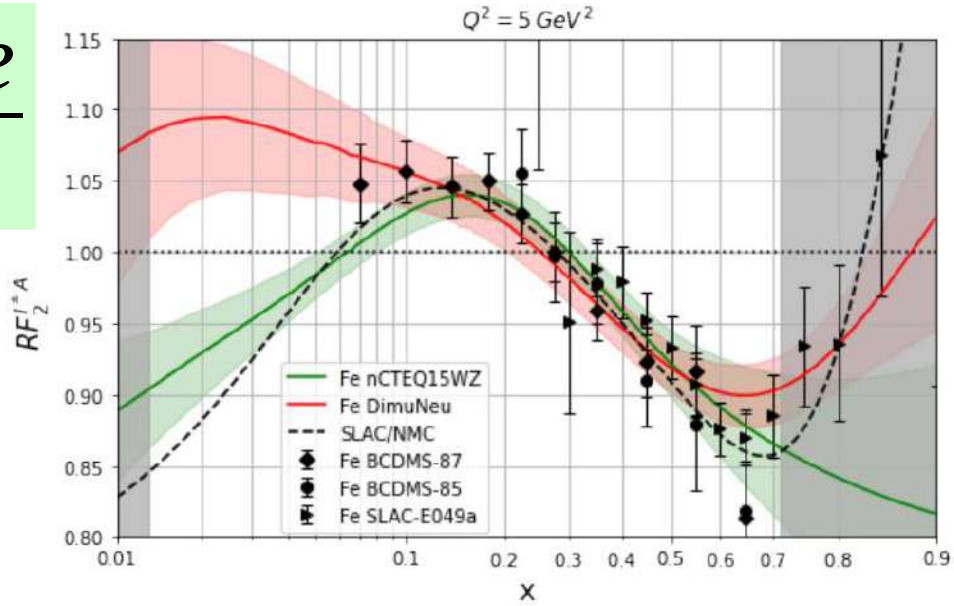


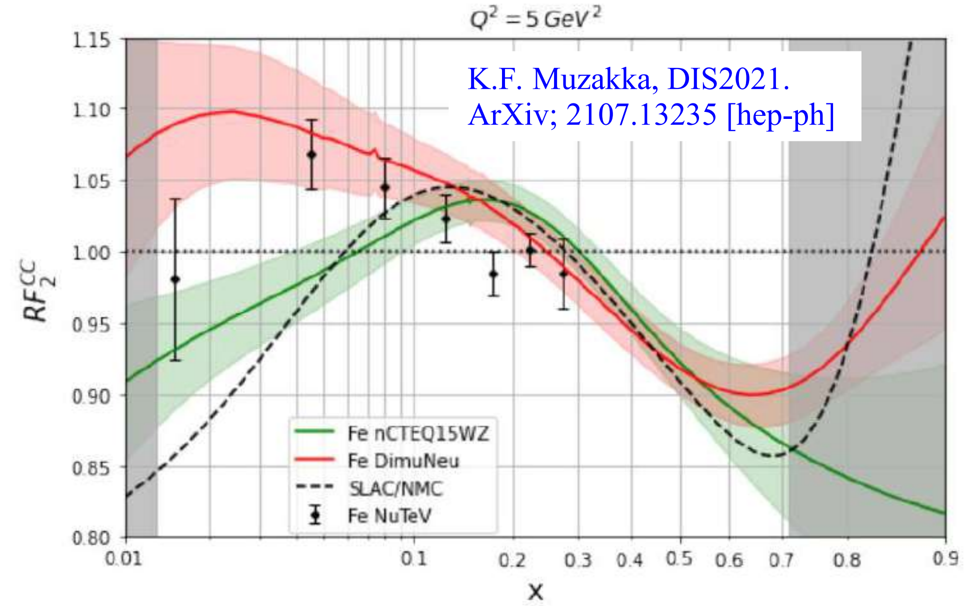
Propagation of γ/W thru nuclei

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

Faiq Muzakka, Karol Kovarik, ...

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





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

What is the correct nuclear correction ???

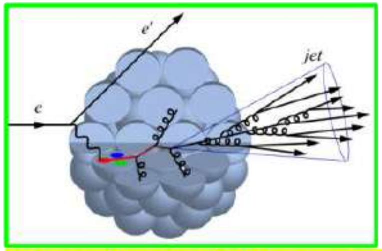
Are these data sets compatible???

e-Print: 2204.13157 [hep-ph]

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

JLAB-THY-21-3352, ADP-21-5/T1152

Isovector EMC effect from global QCD analysis with MARATHON data

C. Cocuzza,[1] C. E. Keppel,[2] H. Liu,[3] W. Melnitchouk,[2] A. Metz,[1] N. Sato,[2] and A. W. Thomas[4]

GLUON

An exercise at small x

...

extensible to mid-x region

Measuring the nuclear Gluon PDF

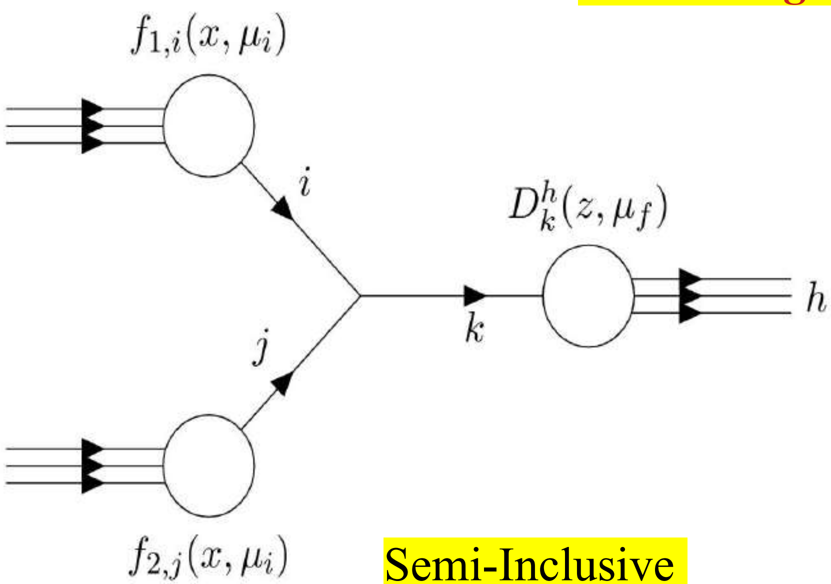
Parton Distribution Functions

Pit Duwentaster, Michael Klasen, ...

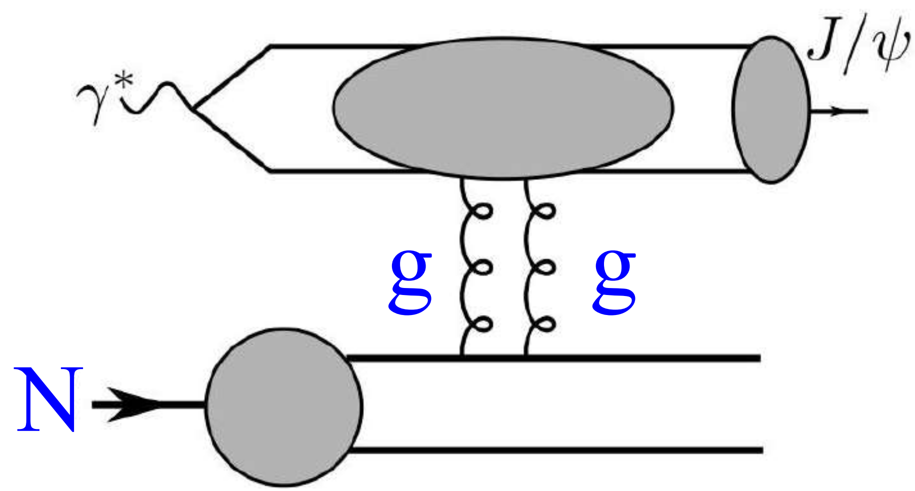
how can we determine the gluon

Multi-Scale Problem

… ideal region for JLab



Semi-Inclusive Hadron Production



Quarkonia Production

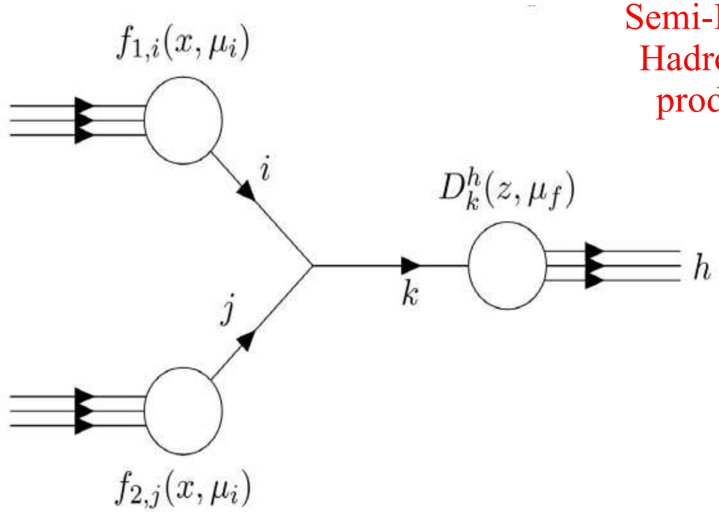
Impact of heavy quark and quarkonium data on nuclear gluon PDFs

P. Duwentäster[1,*] T. Ježo[1,†] M. Klasen[1] K. Kovařík[1] A. Kusina[2] K. F. Muzakka[1] F. I. Olness[3] R. Ruiz[2] I. Schienbein[4] and J. Y. Yu[4]

Phys.Rev.D 105 (2022) 11, 114043 • e-Print: 2204.09982 [hep-ph]

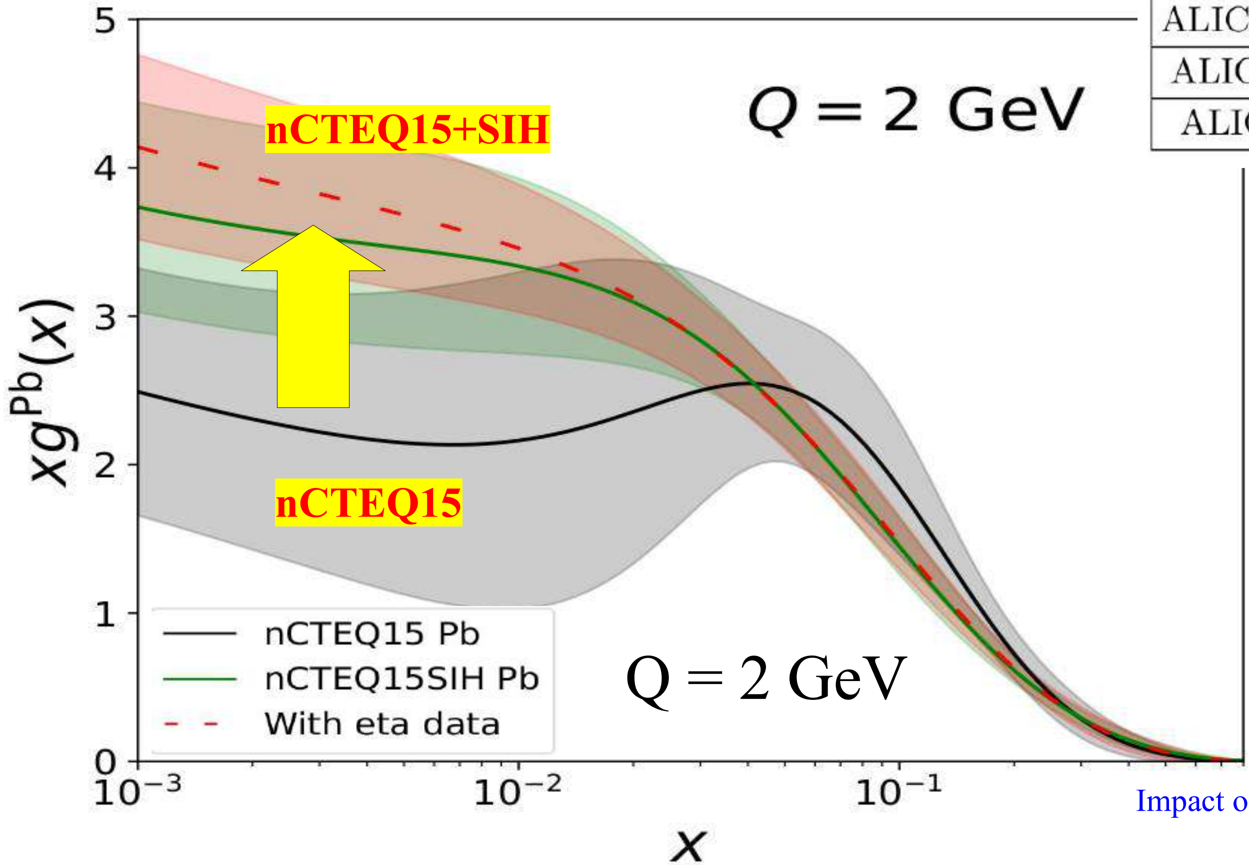
Precision Gluon can help study nuclear medium effects

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

Room for improvement in mid-x region

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

CONCLUSIONS

nCTEQ Wish List

nCTEQ
nuclear parton distribution functions

www.ncteq.org

PDF General Issues:

- Proton PDF; nuclear corrections for interpreting heavy target DIS (Ar, Fe, Pb).

Strange quark & Gluon PDF:

- Resolve tension between fixed-target (νN, ℓN) and collider expectations ($W^{\pm}$,Z)

Charm & Bottom: c(x) & b(x)

- Multi-scale & resummation issues: $\text{Log}(m_{c,b}/Q)$
- "Fitted" charm: $c(x)\neq 0$ at m_c
- Intrinsic heavy flavors: $c(x)\neq 0$ at $Q<m_c$

Neutrino cross sections on heavy targets (Ar, Fe, Pb)

- Universality of Neutral Current (γ) & Charged Current ($W^{\pm}$) processes

Expanded $\{x,Q^2\}$ Kinematic Regime

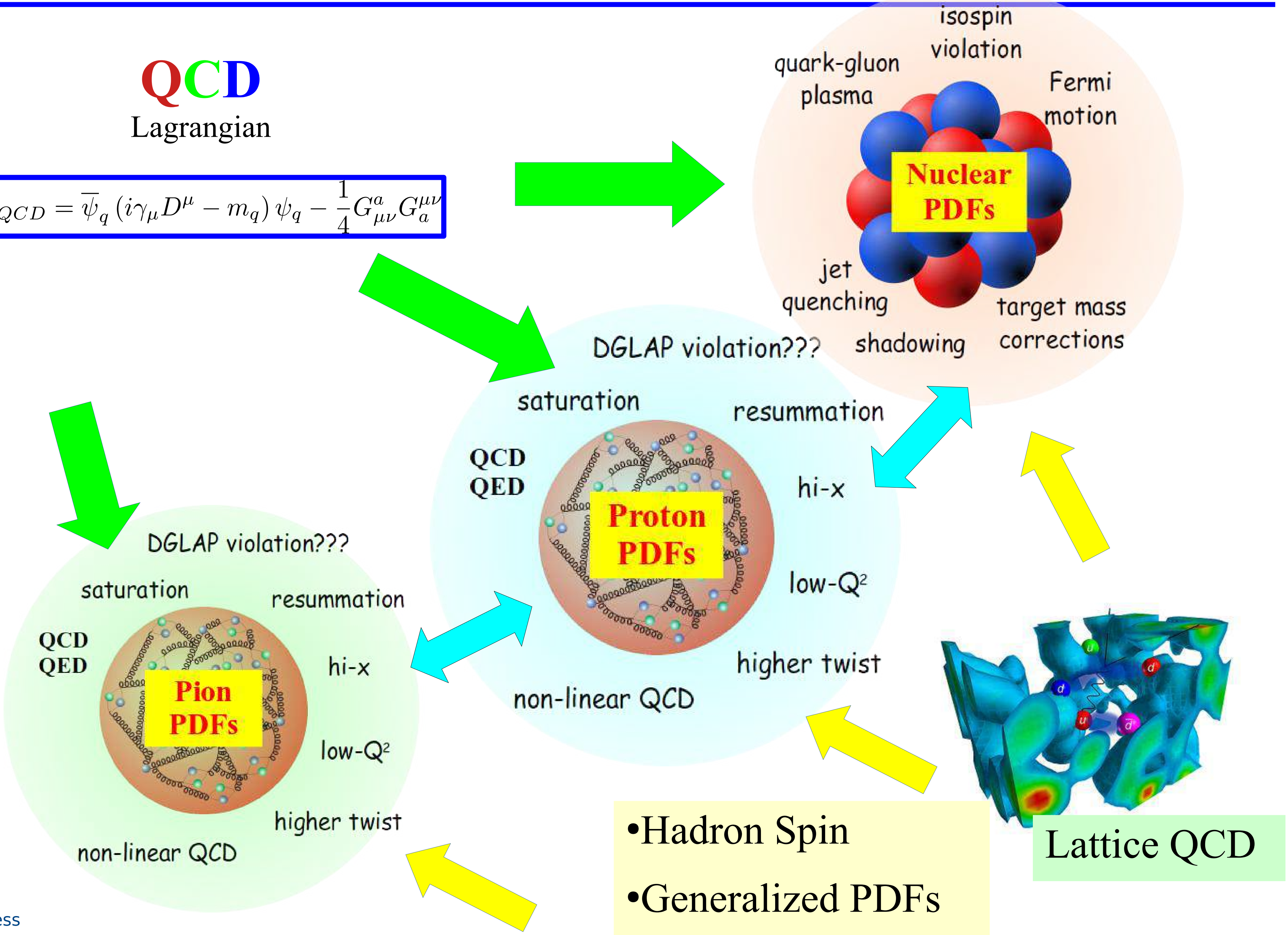
- Small-x saturation, resummation: Log[1/x]
- Large-x higher twist: (M^2/Q^2)
- Low Q^2 non-perturbative effects

F Compilation by Fred Olness with helpful feedback from: Alberto Accardi, Tim Hobbs, Tomas Jezo, Thia Keppel, Michael Klasen, Karol Kovarik, Aleksander Kusina, Jorge Morfin, Pavel Nadolsky, Jeff Owens, Ingo Schienbein, Efrain Segarra, Steve Sekula, Ji-Young Yu

“Solving” QCD: ... concerted interdisciplinary effort

QCD
Lagrangian

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



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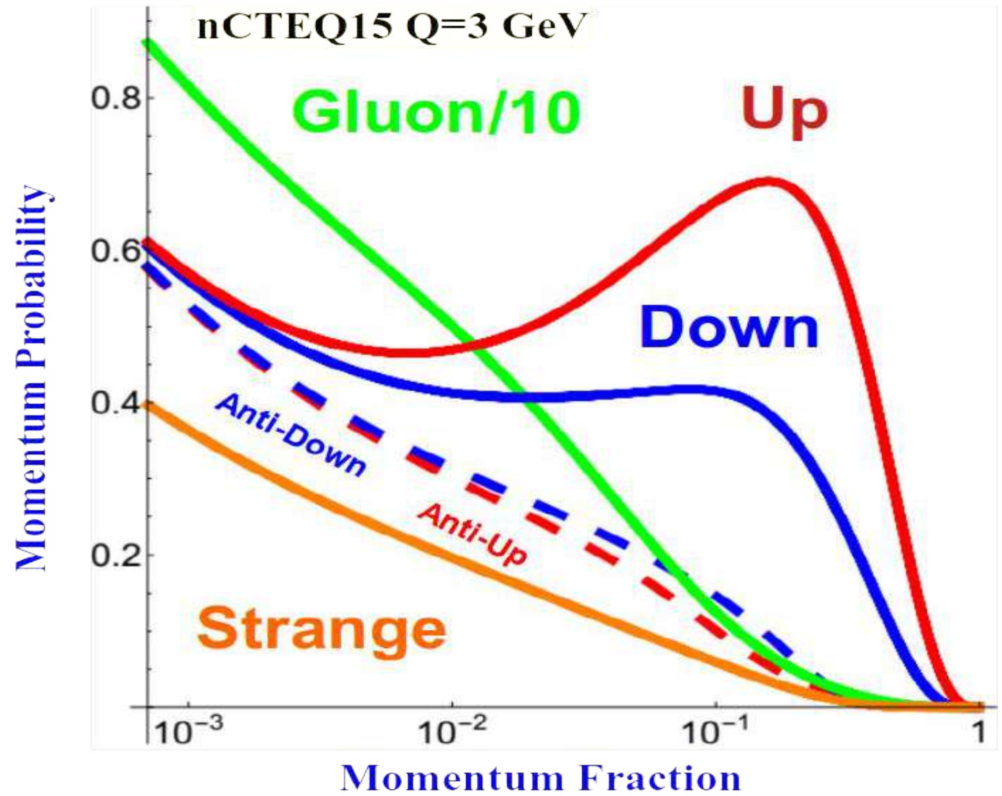
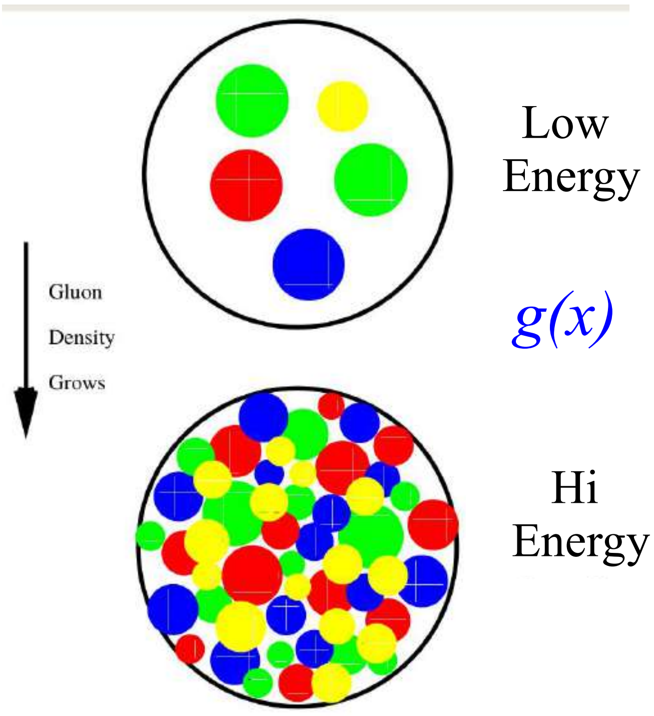
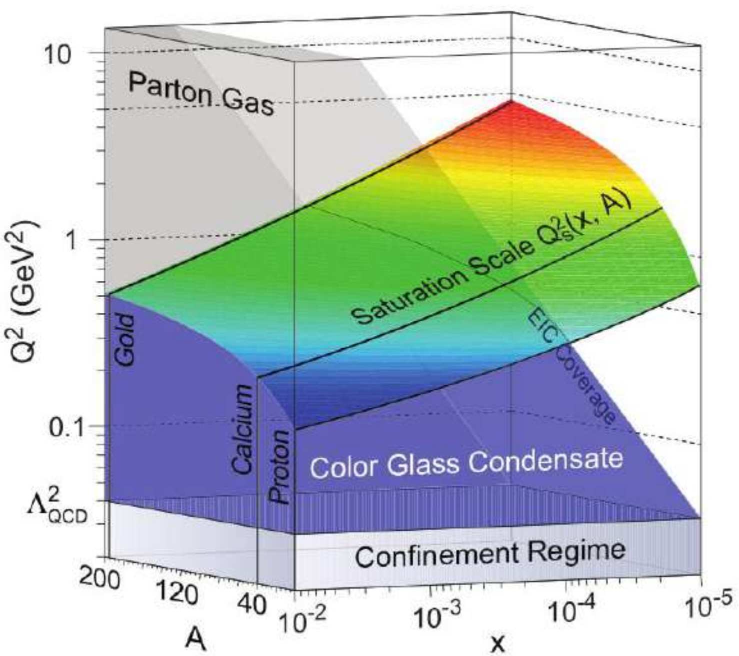
EXTRAS

Nuclear Medium Effects at small momentum fraction (x)

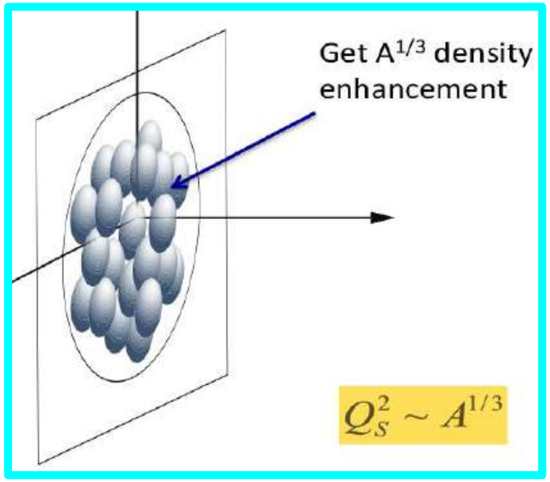




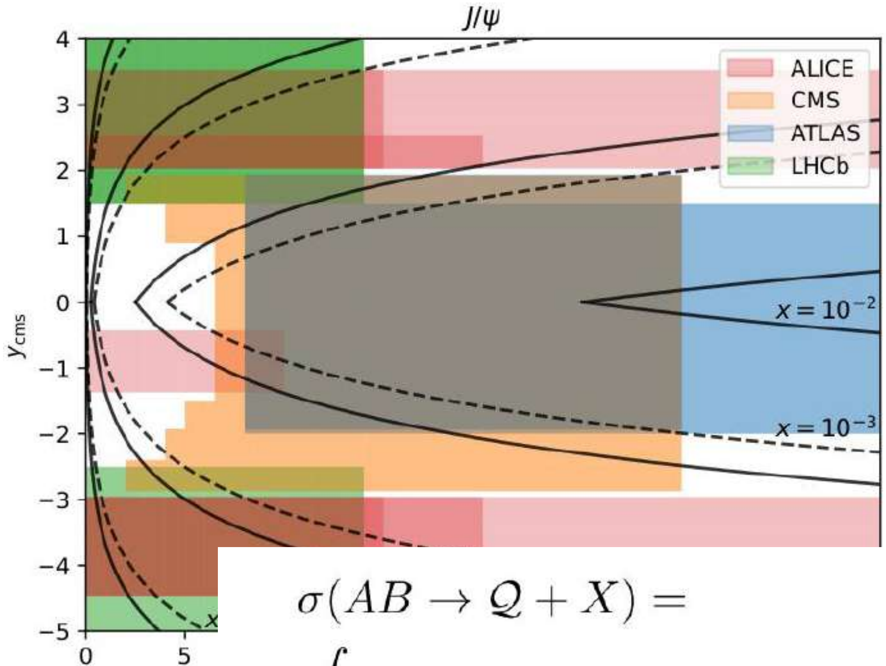


Nuclear medium effects:
- Quark Gluon Plasma
- Color Glass Condensate
- Recombination
- Saturation
- Resummation
- … *your theory here*

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



Review: Edmond Iancu & Raju Venugopalan: arXiv:0303204



$$\sigma(AB \to \mathcal{Q} + X) =$$
$$\int \mathrm{d}x_1 \ \mathrm{d}x_2 f_{1,g}(x_1, \mu) f_{2,g}(x_2, \mu) \frac{1}{2\hat{s}} \overline{|\mathcal{A}_{gg\to\mathcal{Q}+X}|^2} \mathrm{dPS}.$$

The effective scattering matrix element is parameterized with the Crystal Ball function

$$\overline{|\mathcal{A}_{gg\to\mathcal{Q}+X}|^2} = \frac{\lambda^2 \kappa \hat{s}}{M_{\mathcal{Q}}^2} e^{a|y|}$$
$$\times \begin{cases} e^{-\kappa \frac{p_T^2}{M_{\mathcal{Q}}^2}} & \text{if } p_T \leq \langle p_T \rangle \\ e^{-\kappa \frac{\langle p_T \rangle^2}{M_{\mathcal{Q}}^2}} \left(1 + \frac{\kappa}{n} \frac{p_T^2 - \langle p_T \rangle^2}{M_{\mathcal{Q}}^2}\right)^{-n} & \text{if } p_T > \langle p_T \rangle \end{cases}, \quad (4)$$

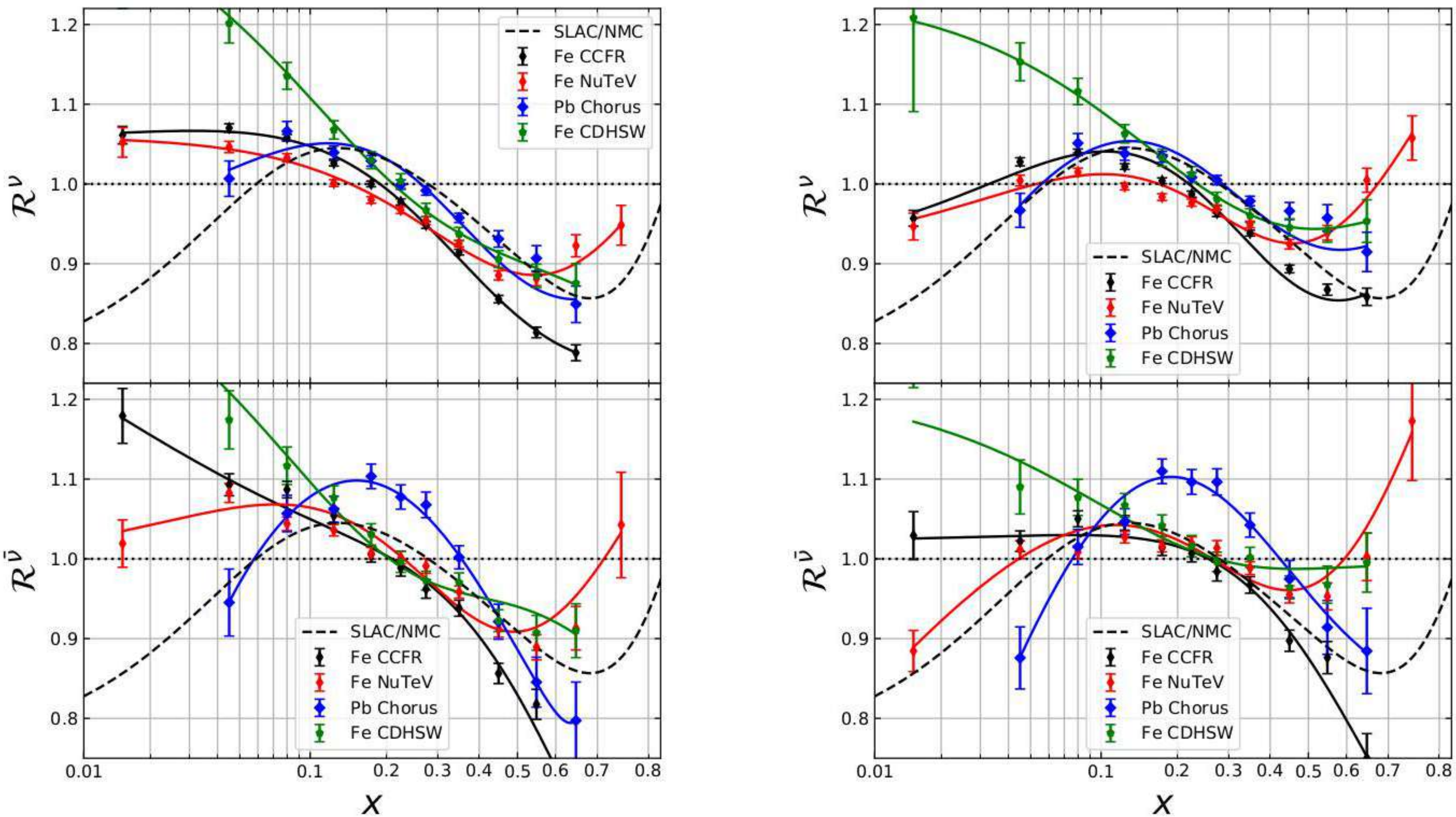


FIG. 4. The weighted average of the cross-section ratios for $Q^2 > 4$ GeV^2 and $W^2 > 12.25$ GeV^2 from CDHSW, CCFR, NuTeV, and Chorus data. The denominator (σ_{free}) is computed using nCTEQ15 proton baseline (left) and CT18 (no nu A) NLO proton PDFs without neutrino data of Ref. [61] (right).

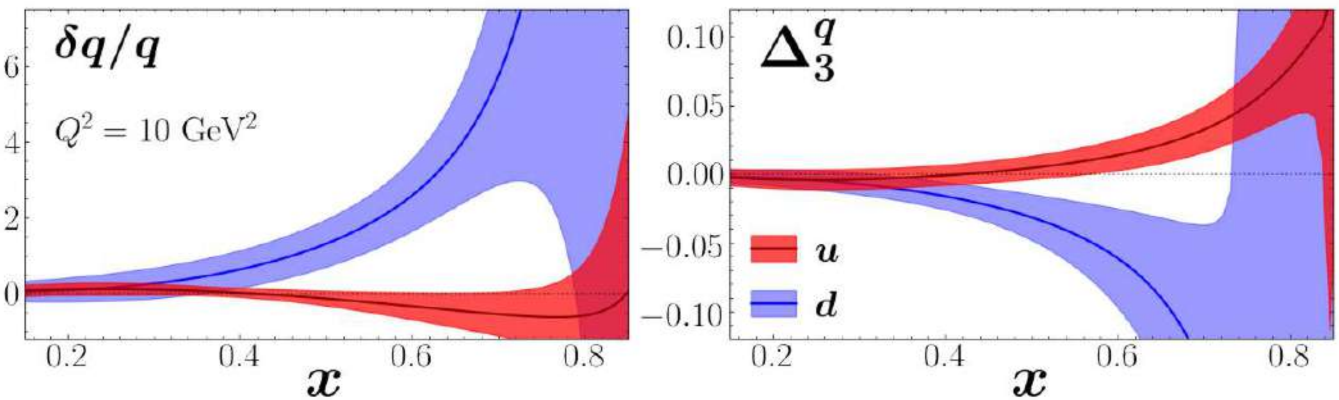


FIG. 3. Ratio of off-shell to on-shell PDFs $\delta q/q$ (left) and the difference between proton valence quarks in ^{3}He and ^{3}H normalized to the sum, Δ_3^q
and d (blue bands) quarks,

$$\Delta_3^q \equiv \frac{q_{p/^3\mathrm{H}} - q_{p/^3\mathrm{He}}}{q_{p/^3\mathrm{H}} + q_{p/^3\mathrm{He}}},$$

JLAB-THY-21-3352, ADP-21-5/T1152

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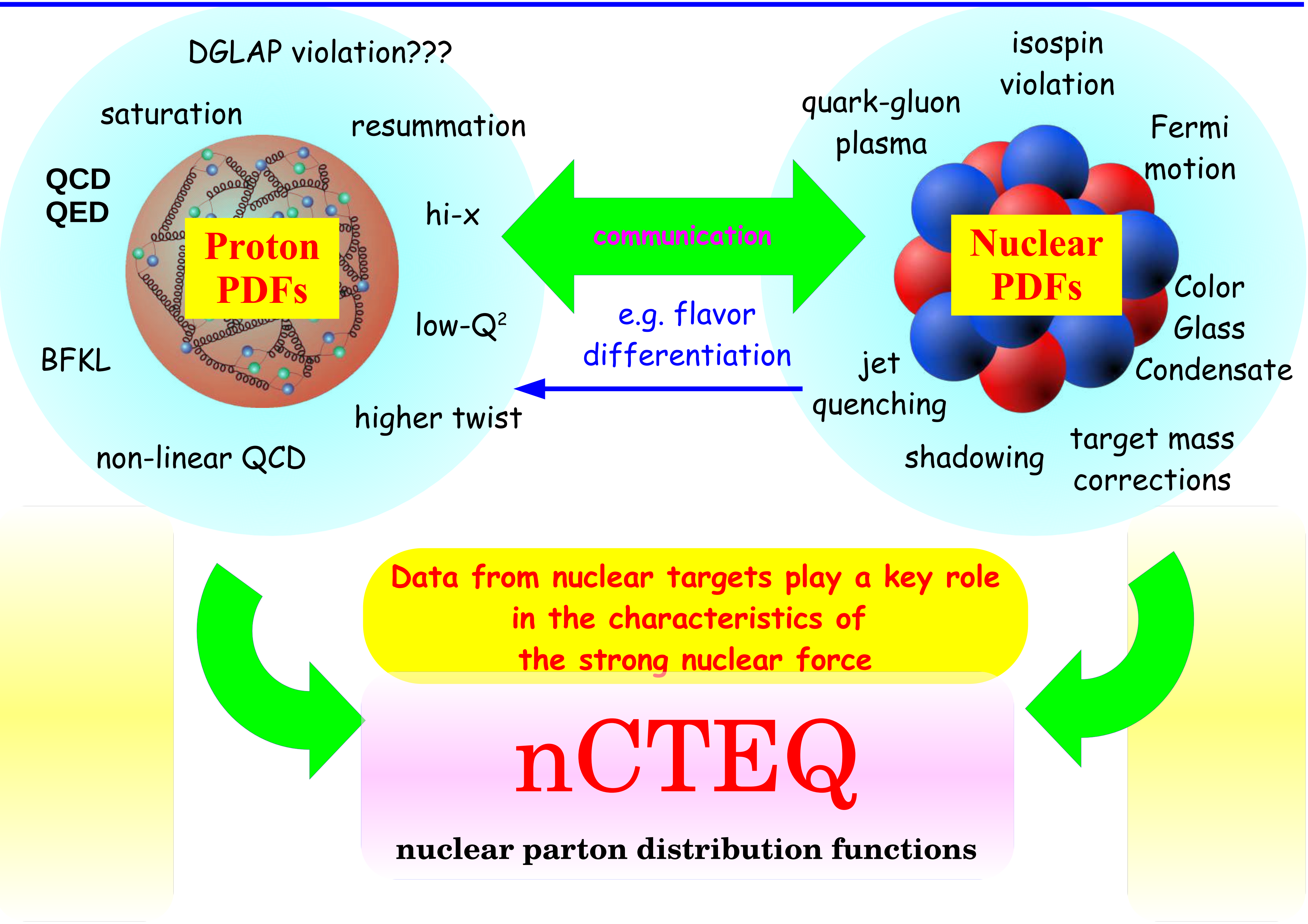
… the ultimate goal for nCTEQ



xFitter

PROTON NUCLEON MESON

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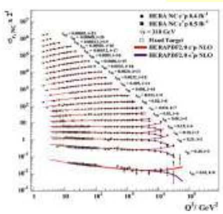
www.xFitter.org

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, ...

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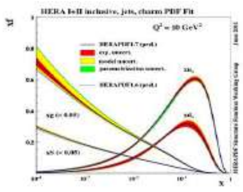

Parton Distribution Functions: PDF, Updf, TMD

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

Theoretical Cross Sections

Comparisons to other PDFs (LHAPDF)

extensions include nuclear PDFs

Features & Recent Updates:
- Photon PDF & QED
- Pole & MS-bar masses
- Profiling and Re-Weighting
- Heavy Quark Variable Treshold
- Improvements in χ^2 and correlations
- TMD PDFs (uPDFs)
- *... and many other*

xFitter 2.0.1 Old Fashioned