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

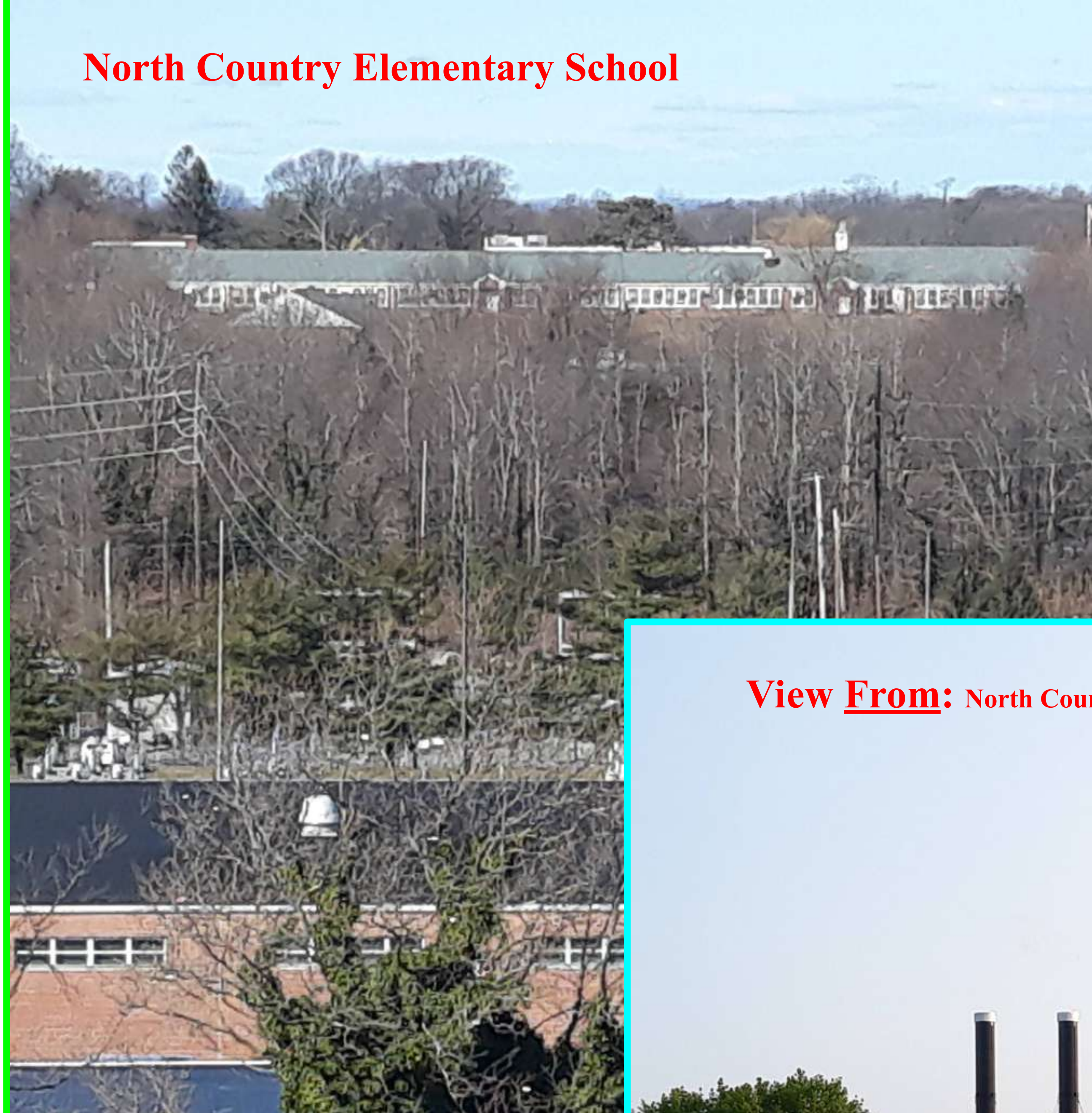
xFitter

SURGE COLLABORATION

CTEQ

CFNS
Stony Brook U
21 September 2023


STONY BROOK, L. I. DEPOT
STONY BROOK


North Country Elementary School


View From: North Country Elementary School

Objects in mirror are closer than they appear

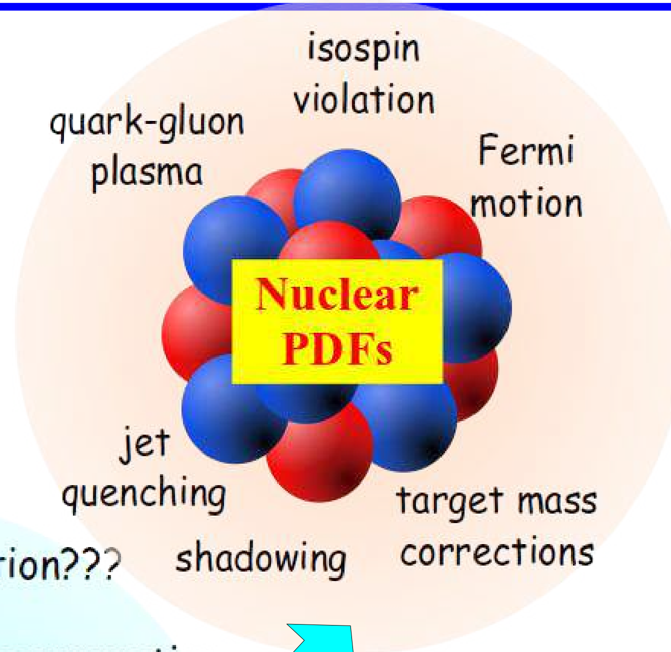
A Deeper Understanding of the strong nuclear force

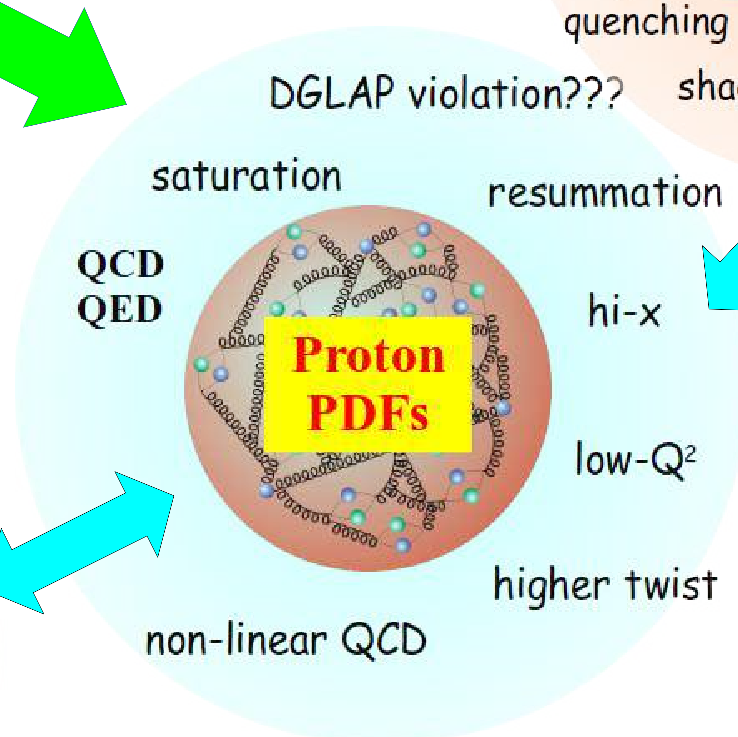
Quantum ChromoDynamics

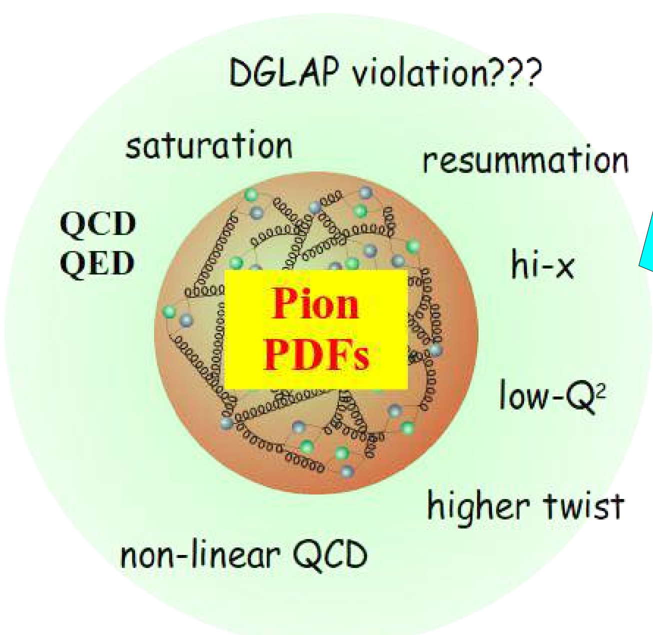
QCD

Lagrangian

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

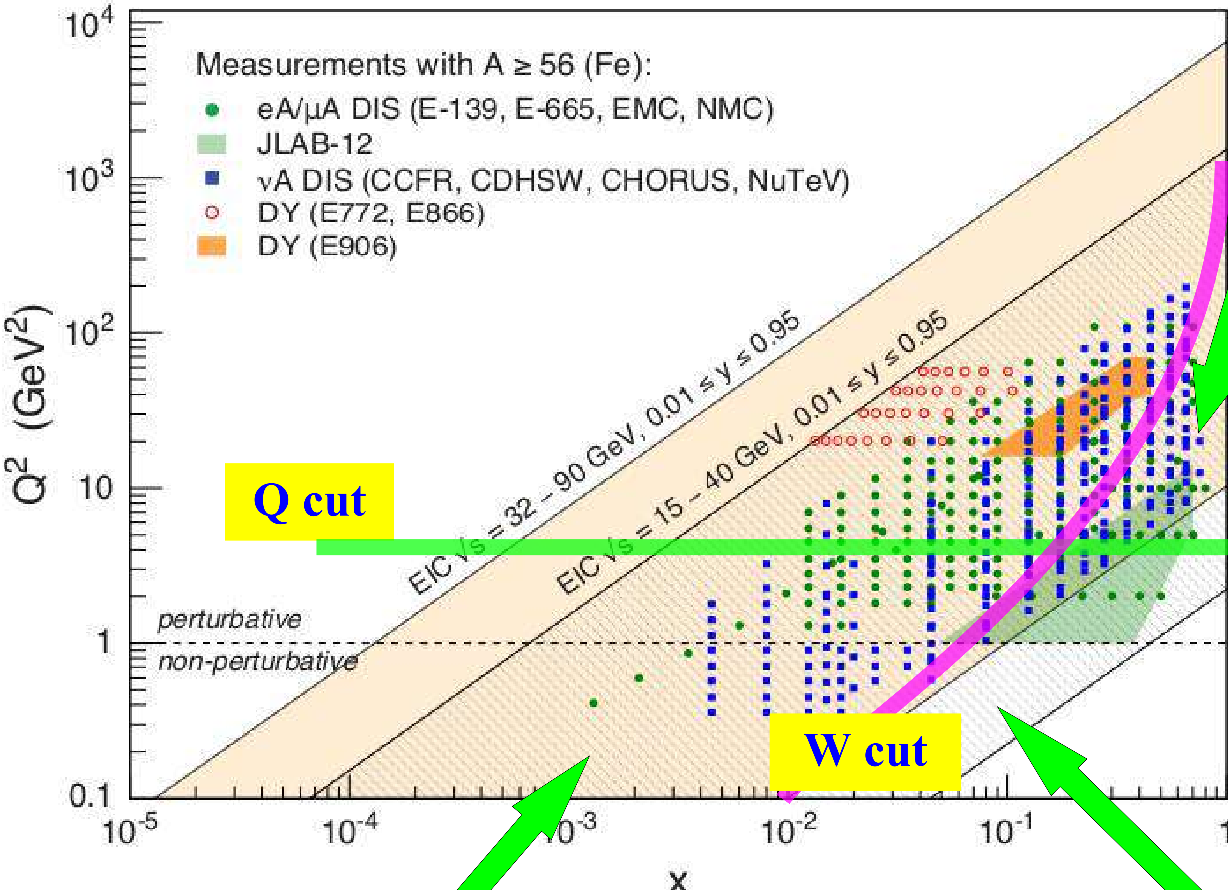






Conjecture: A theory can't be fundamental unless it fits on a coffee mug.

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

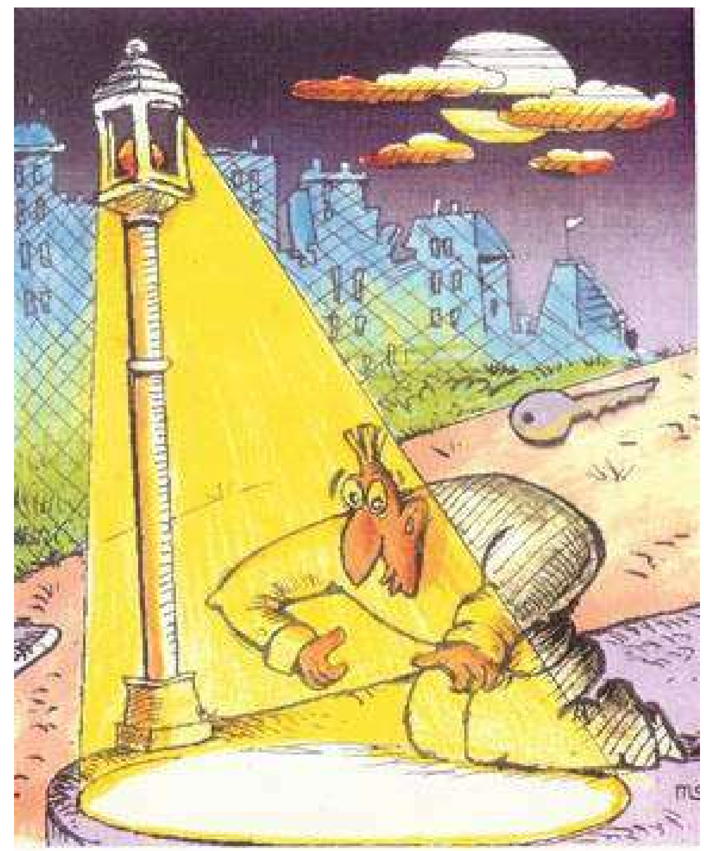
Low-x:

Shadowing
Recombination
Resummation
BFKL
Saturation

Low-Q²:

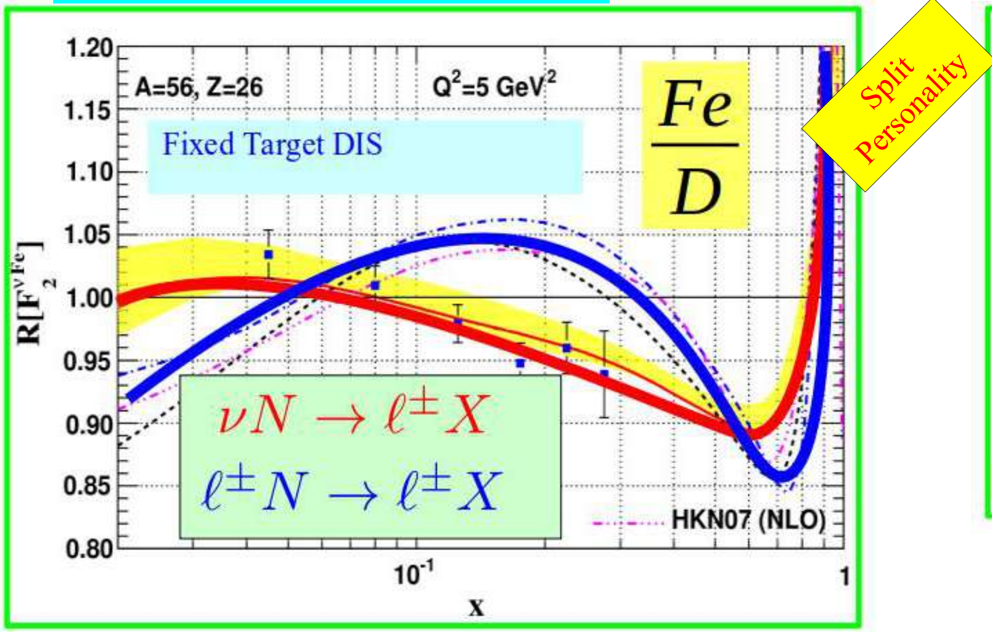
Non-Perturbative inteface
collective effects
Target Mass Corrections
pick up M^2/Q^2 higher twist
F_L at low Q^2 access to g(x)

Are we just looking under the lamppost



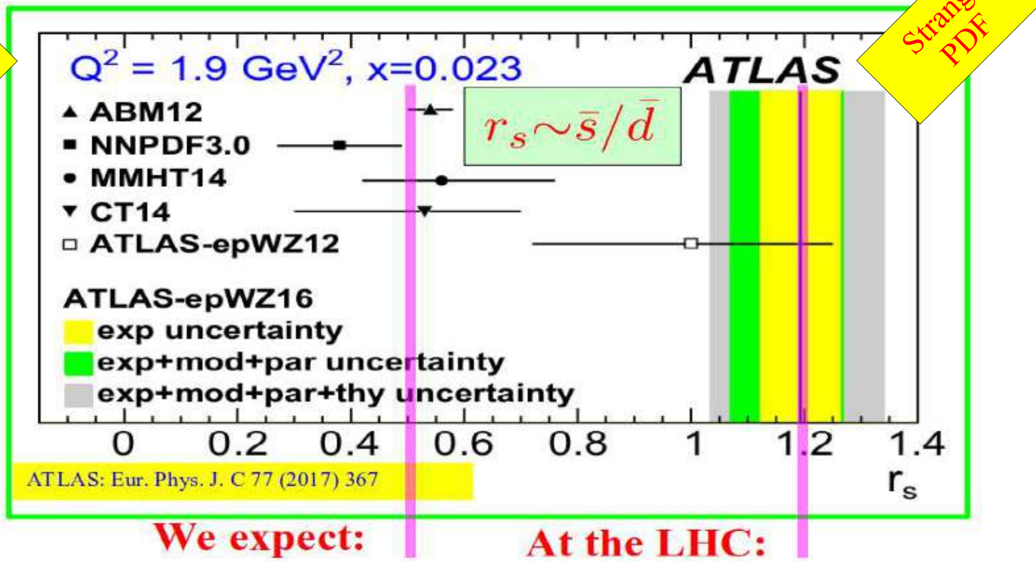
Need theoretical guidance in these regions

nCTEQ15ν



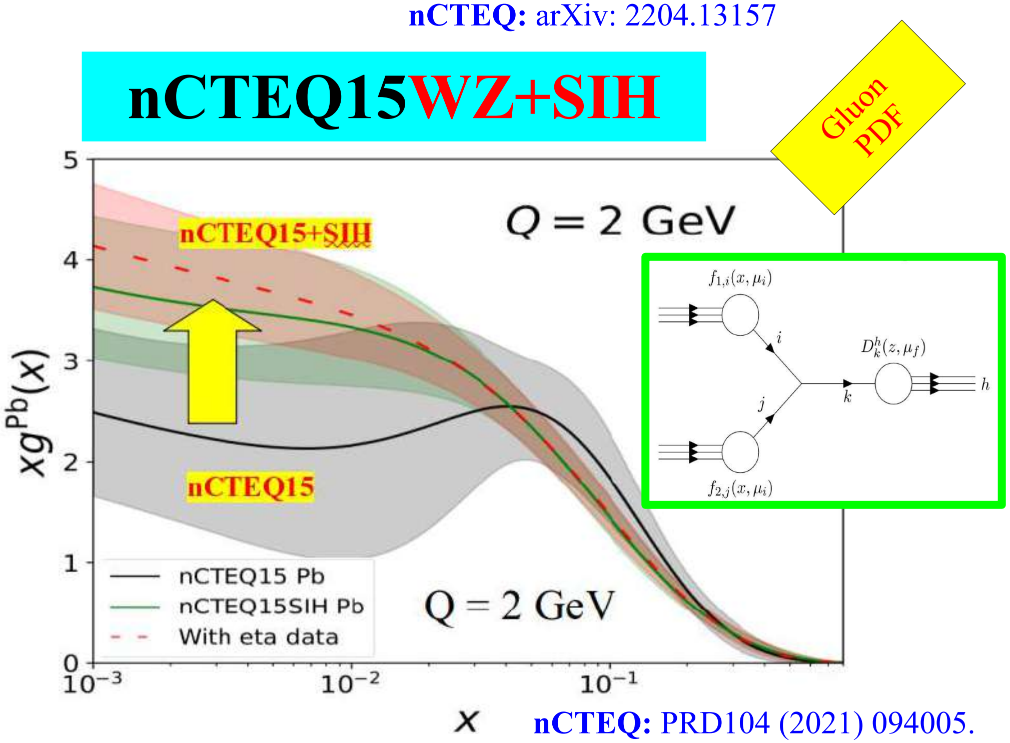
nCTEQ: arXiv: 2204.13157

nCTEQ15WZ



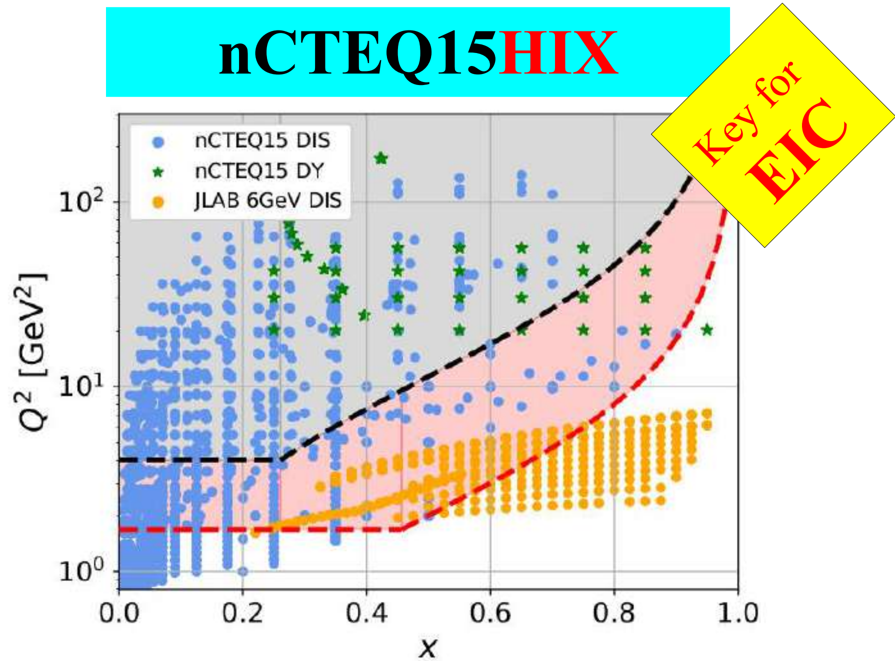
nCTEQ: Phys.Rev.D 104 (2021) 094005

nCTEQ15WZ+SIH



nCTEQ: PRD104 (2021) 094005.

nCTEQ15HIX



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

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

Strange PDF

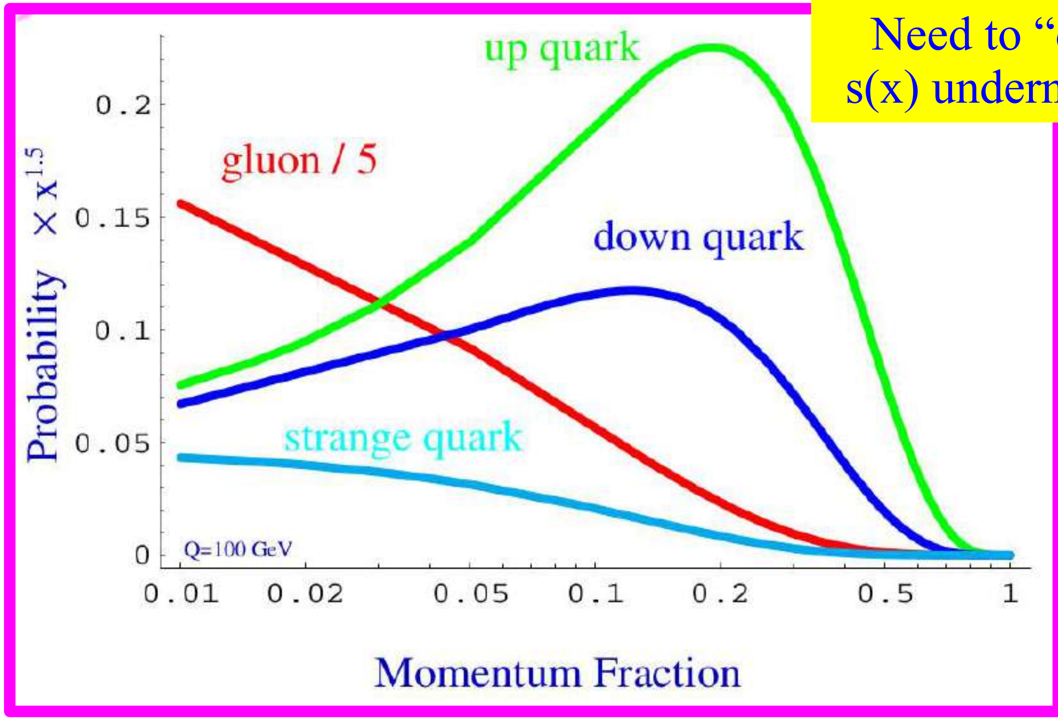
Parton Distribution Functions

nCTEQ

nuclear parton distribution functions

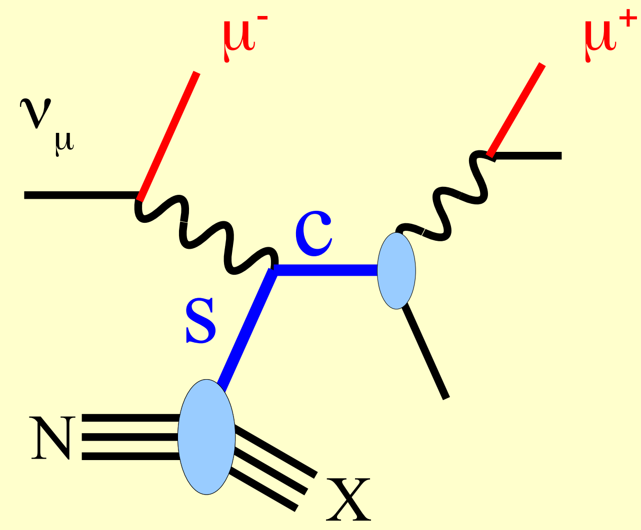
νDIS … has a significant impact on the strange quark PDF

Strange PDF: ν Nucleon di-muon Production

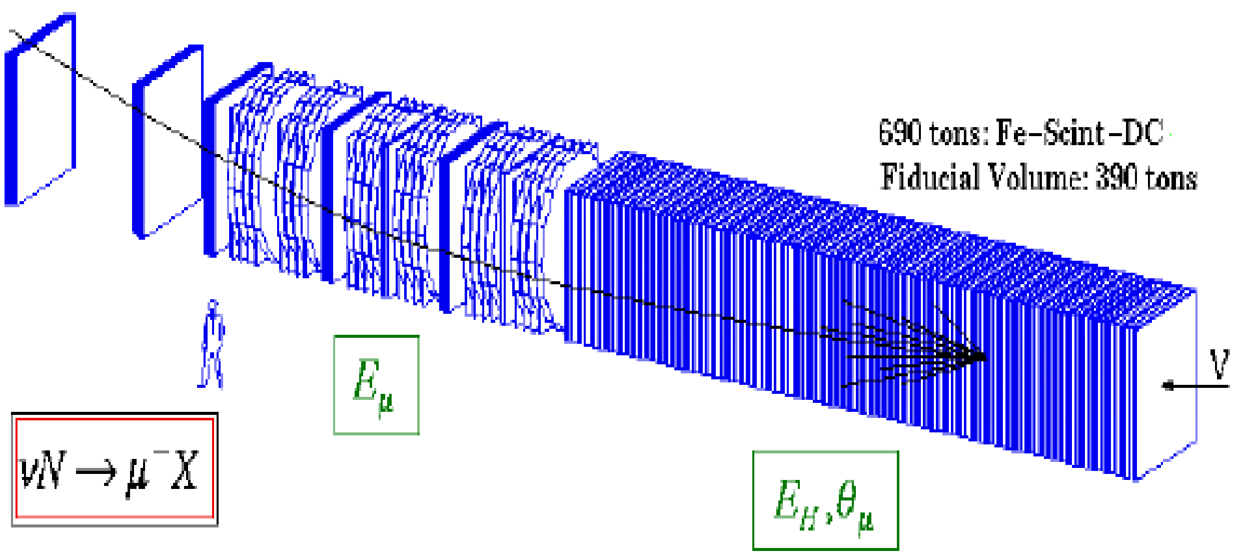


Need to "dig out" s(x) underneath d(x)

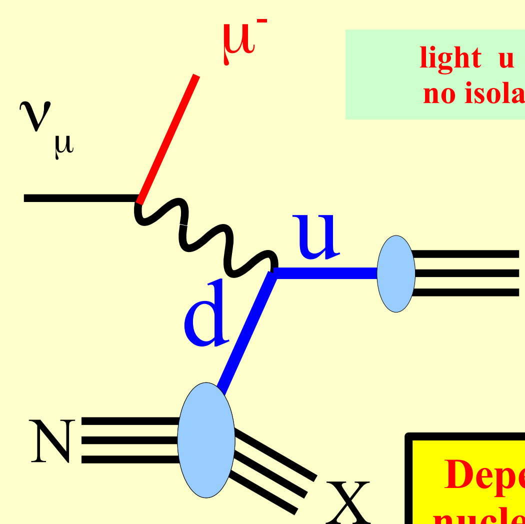
Strange Quark



LAB-E Detector - Fermilab E815 (NuTeV)



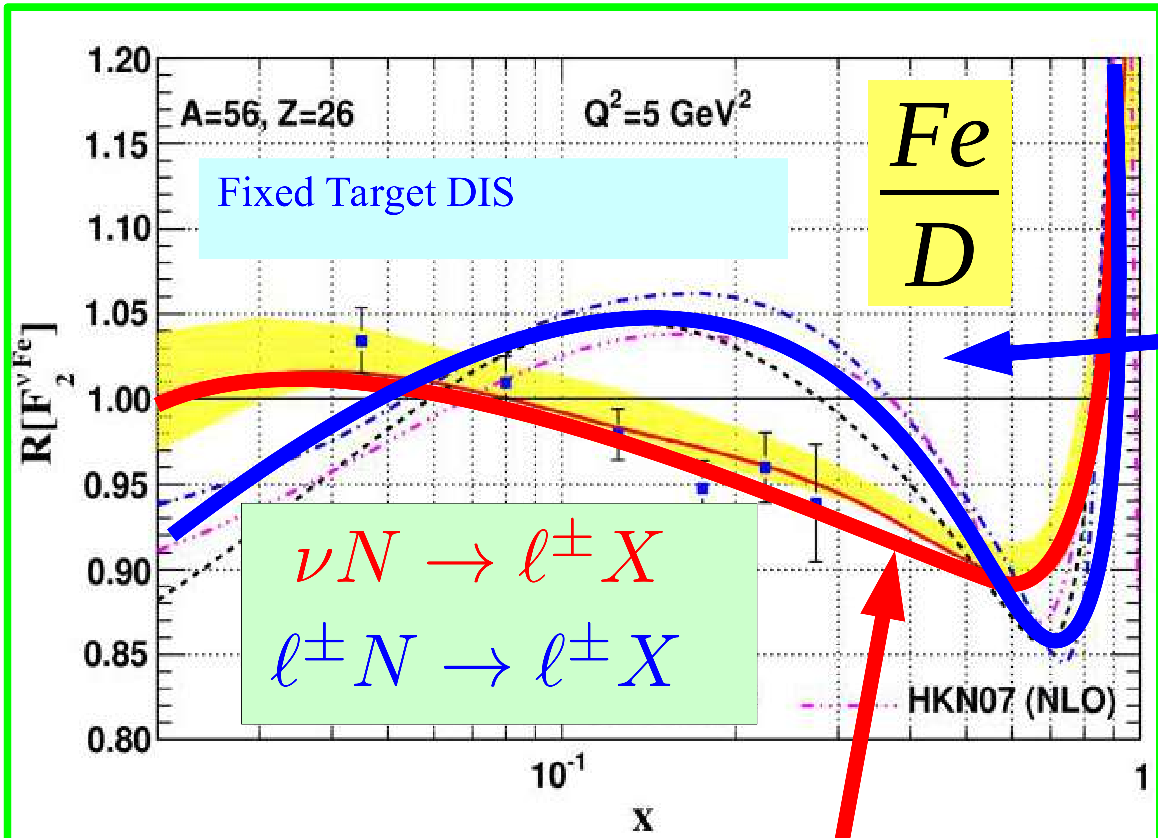
Down Quark



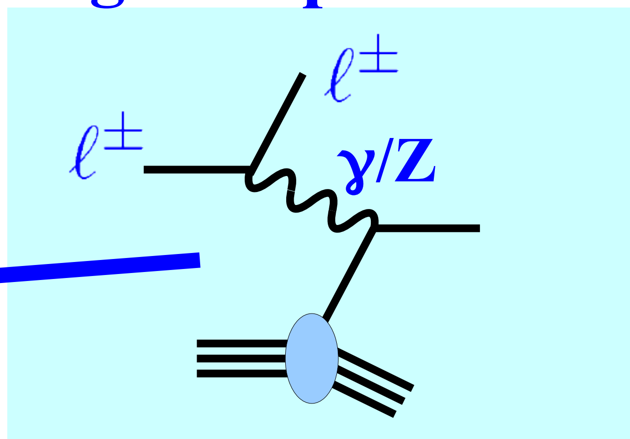
light u mass
no isolated μ

Depends on nuclear PDFs

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



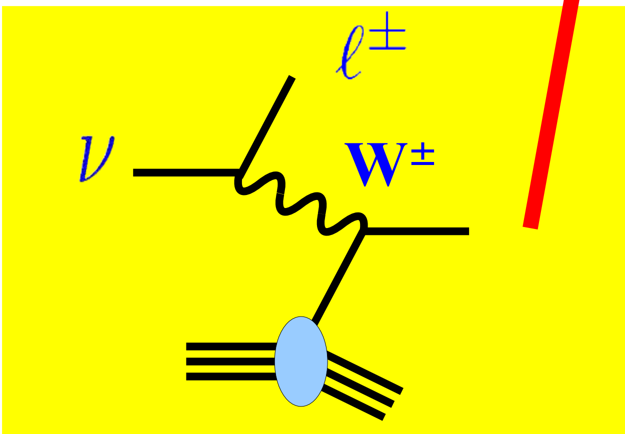
Charged Lepton DIS



some caveats
… correlated errors

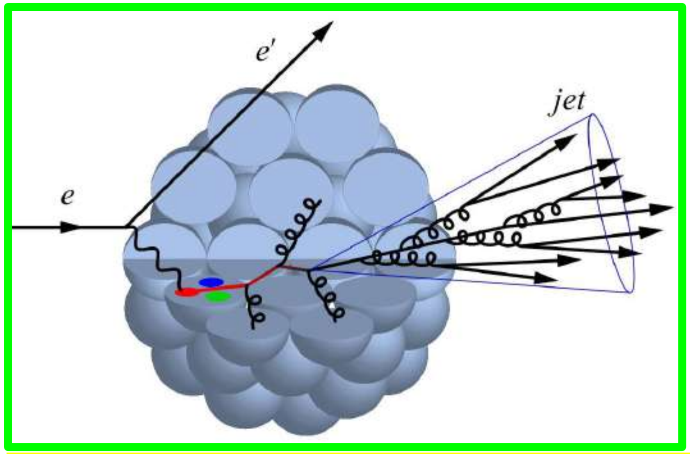
Ingo Schienbein, … (2007)

Karol Kovarik, … (2010)



Neutrino DIS

Depends on nuclear corrections

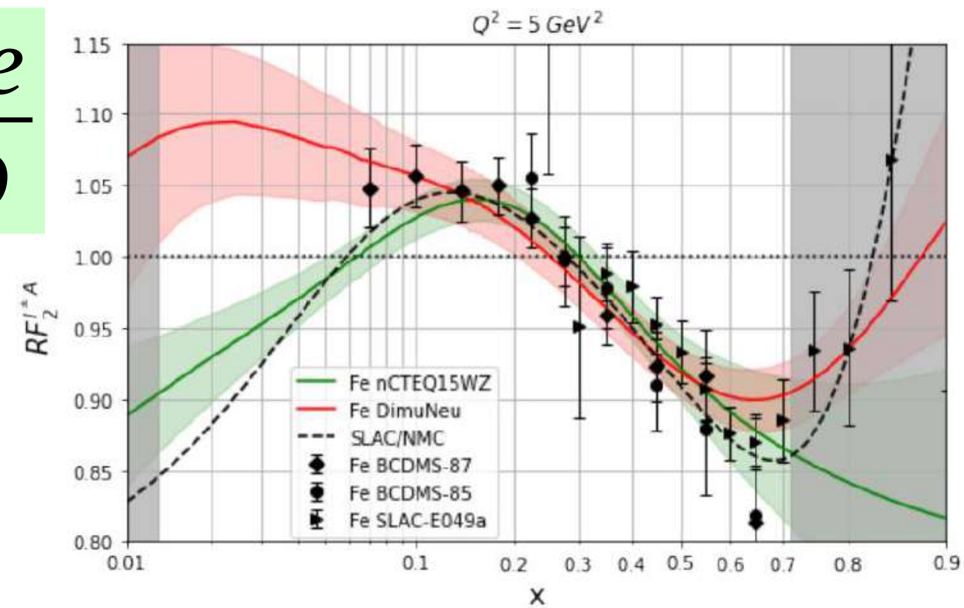


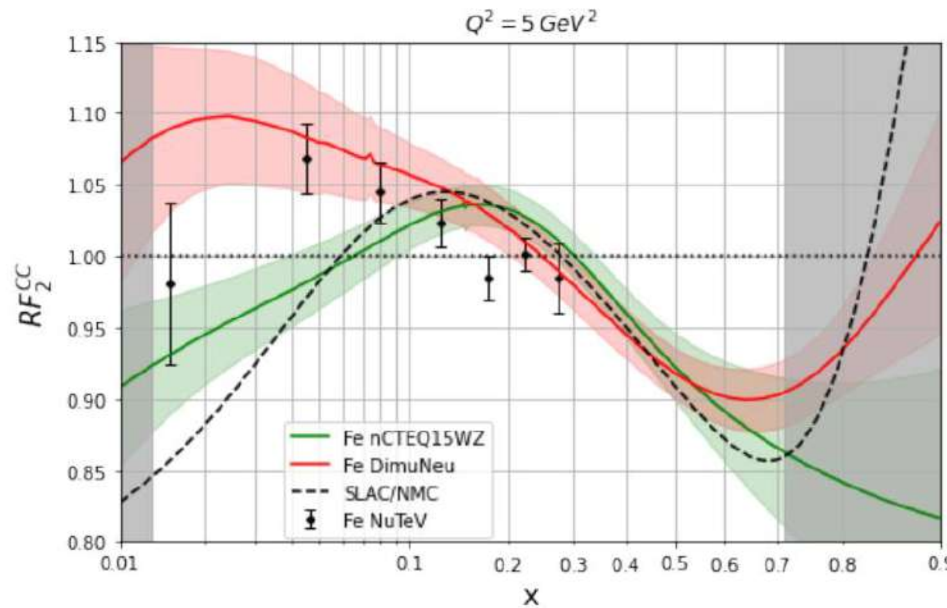
Propagation of γ/W thru nuclei

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

nCTEQ: Faiq Muzakka, Karol Kovarik, ...

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





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

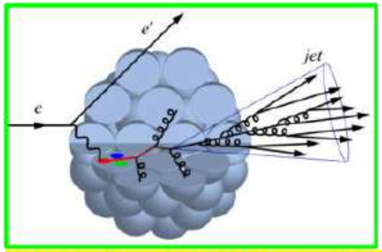
What is the correct nuclear correction ???

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

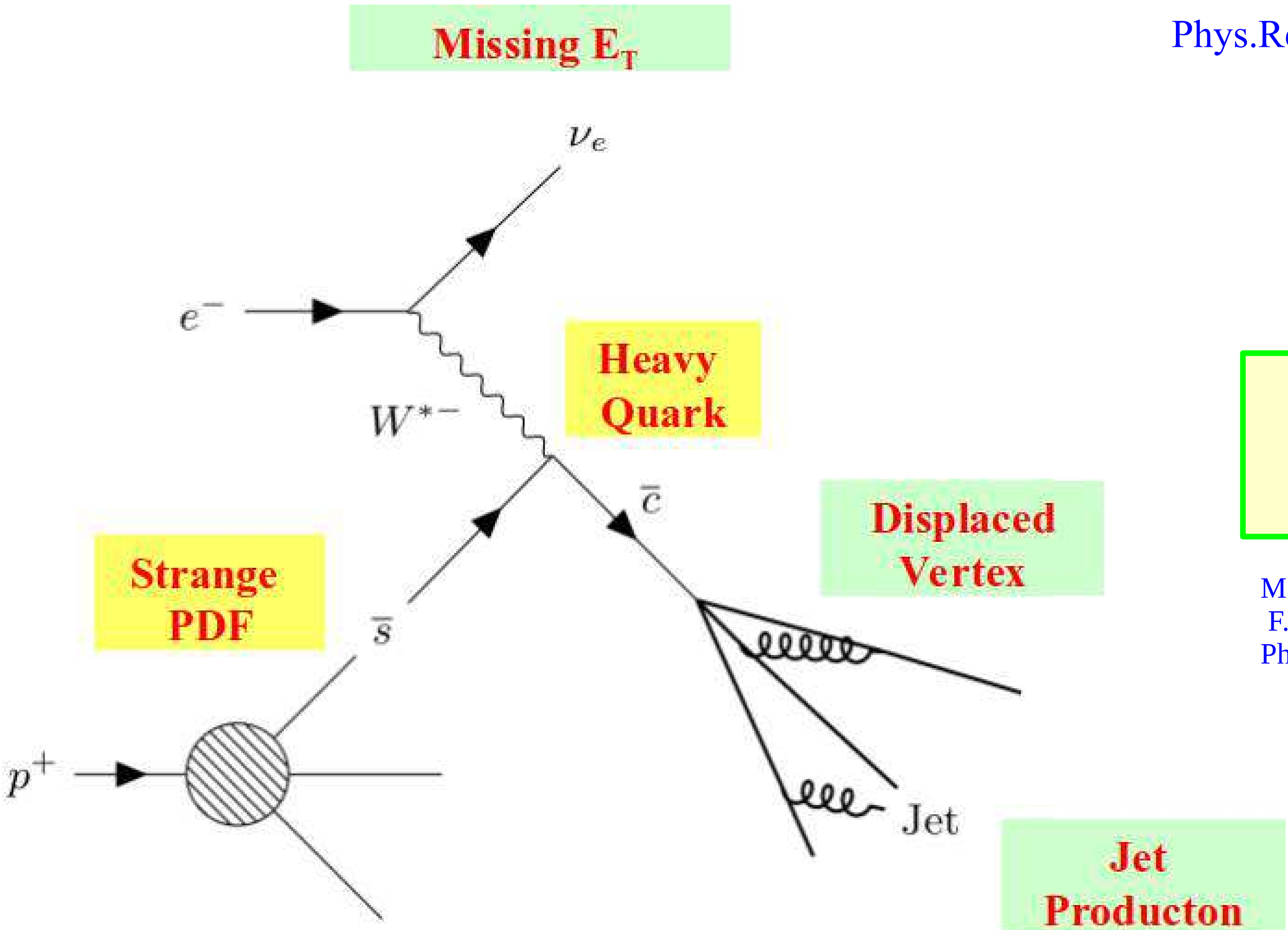
Charm Jets at the EIC

JLAB-PHY-20-3205, SMU-HEP-20-05

Charm jets as a probe for strangeness at the future Electron-Ion Collider

Miguel Arratia,[1,2] Yulia Furletova,[2] T. J. Hobbs,[3,4] Fredrick Olness,[3] and Stephen J. Sekula[3,*]

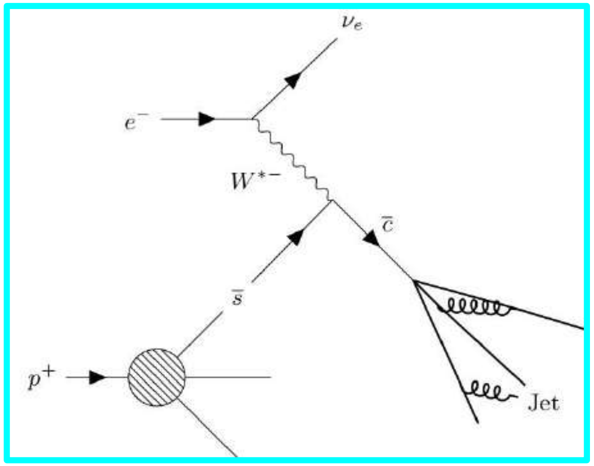
Phys.Rev.D 103 (2021) 7, 074023

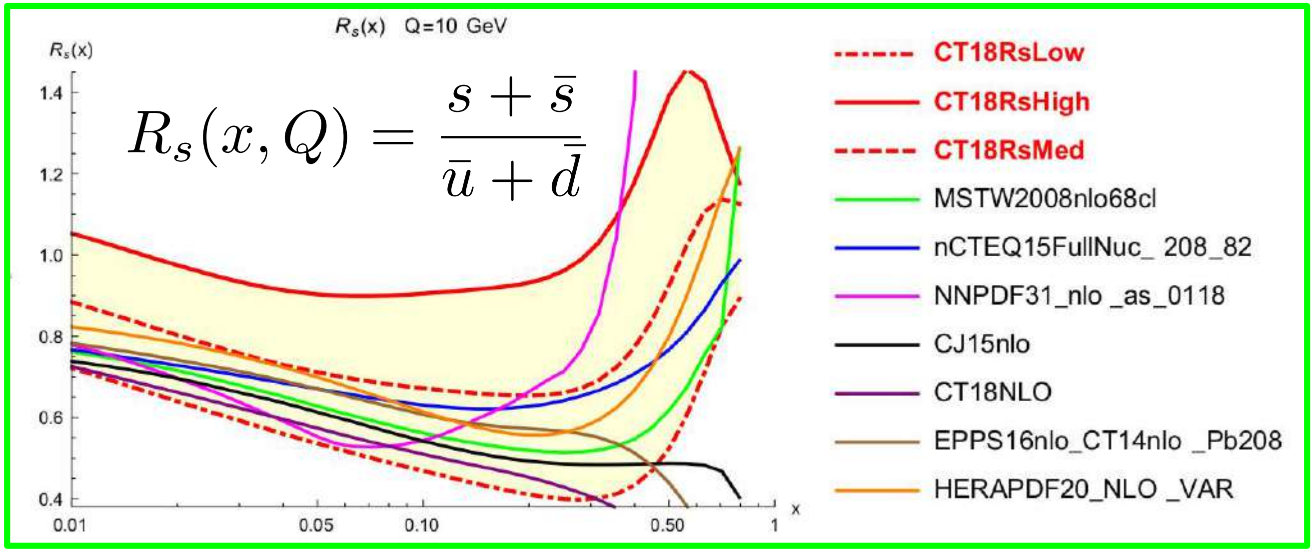


Clear measure of Strange PDF beyond uncertainties

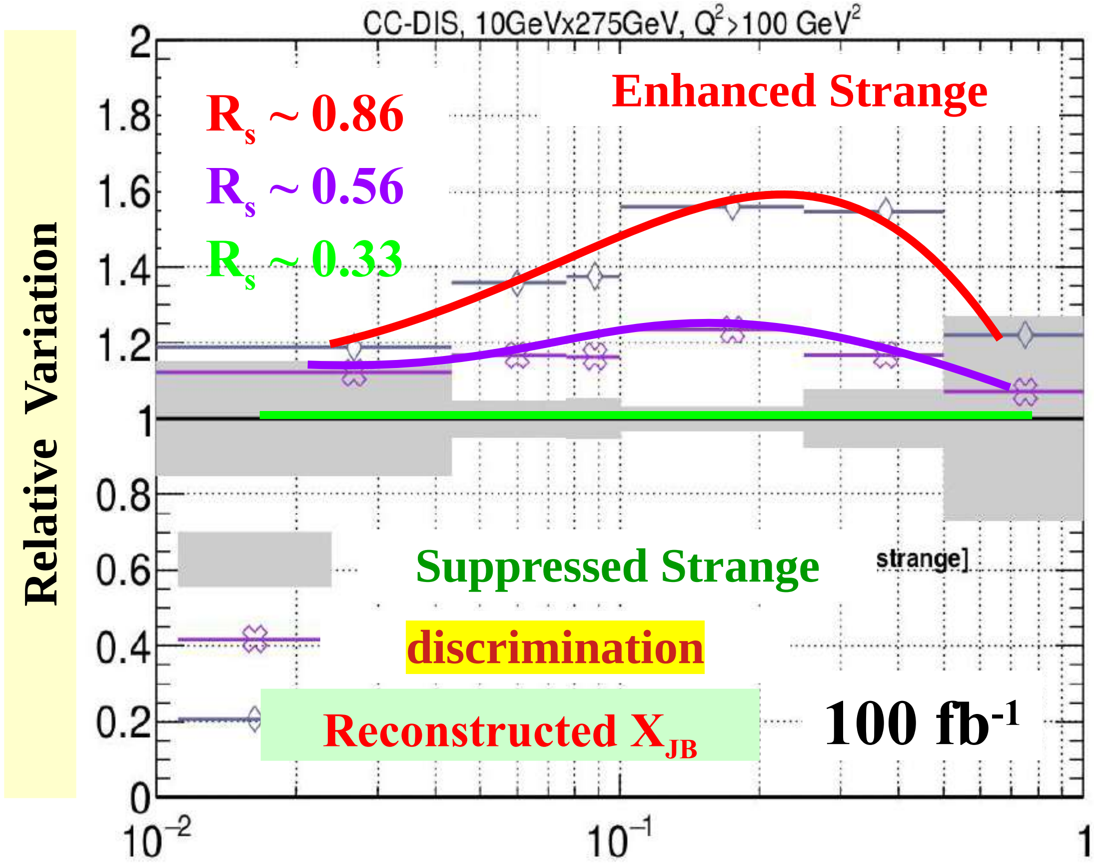
M. Arratia, Y. Furletova, T.J. Hobbs, F. Olness, S.J. Sekula, Phys.Rev.D 103 (2021) 7, 074023

Charm Jets at the EIC ⇒ The Strange PDF





W+s → c_{jet}

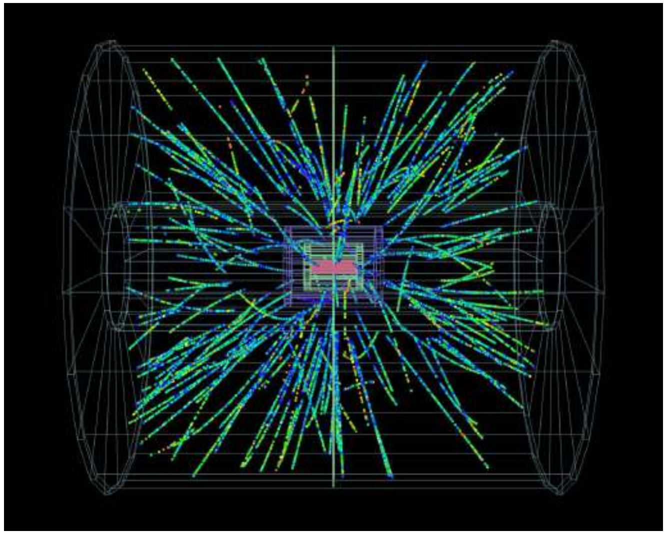


Clear measure of Strange PDF beyond uncertainties

M. Arratia, Y. Furletova, T.J. Hobbs, F. Olness, S.J. Sekula, Phys.Rev.D 103 (2021) 7, 074023

W and Z Boson Production at the Large Hadron Collider (LHC)

nCTEQ: Tomas Jezo, Aleksander Kusina, Fred Olness, ...



$$p\ p \to W, Z$$
$$p\,Pb \to W, Z$$

LHC Heavy Ion

… there's another way to measure the strange quark

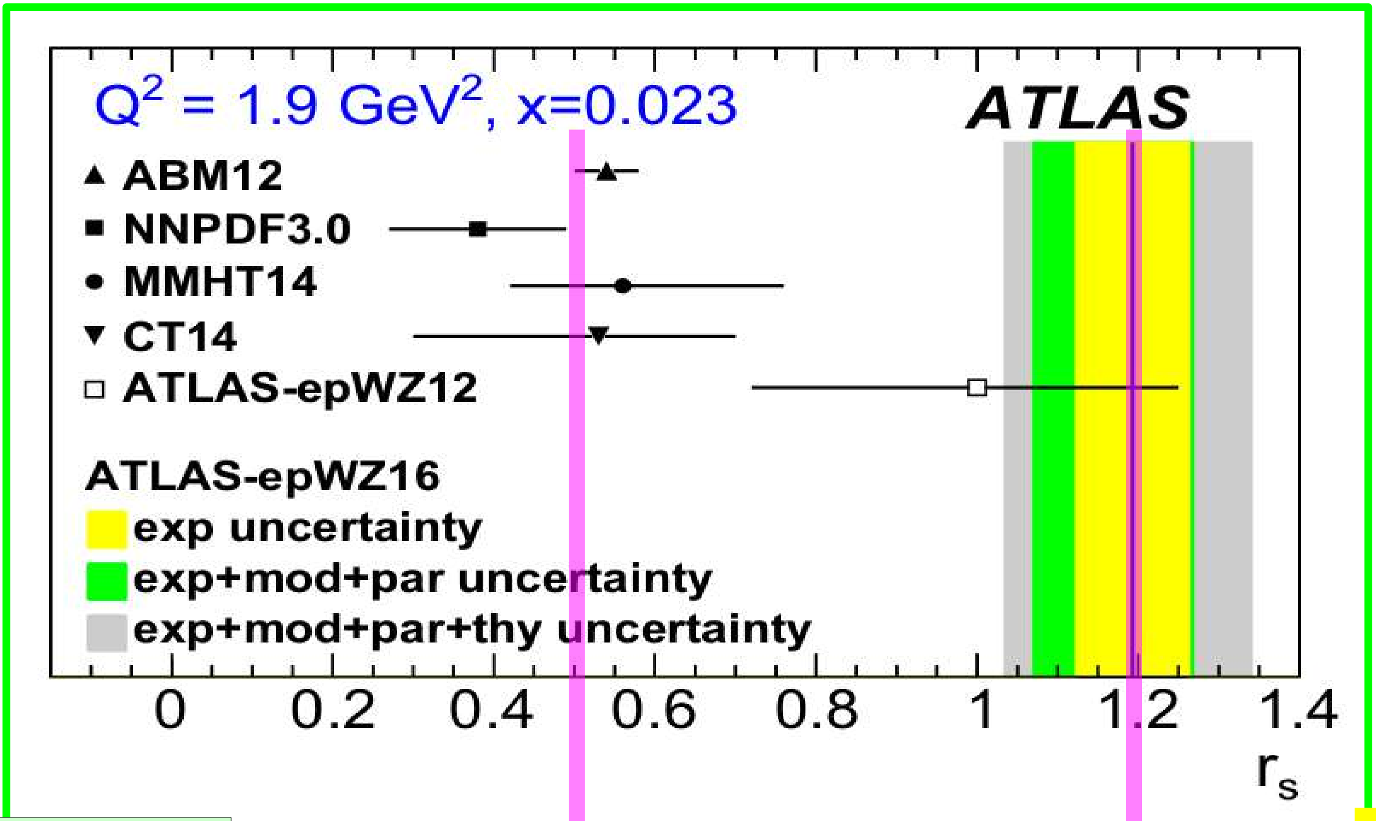
Surprise: … LHC sees more strange than expected

$$u\bar{d} + u\bar{s} + c\bar{d} + c\bar{s} \rightarrow W^+$$
$$\bar{u}d + \bar{u}s + \bar{c}d + \bar{c}s \rightarrow W^-$$
$$u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c} \rightarrow Z$$

Surprise:

We expected $r_s = 1/2$

LHC finds $r_s > 1$



Proton case

$$r_s \sim \bar{s}/\bar{d}$$

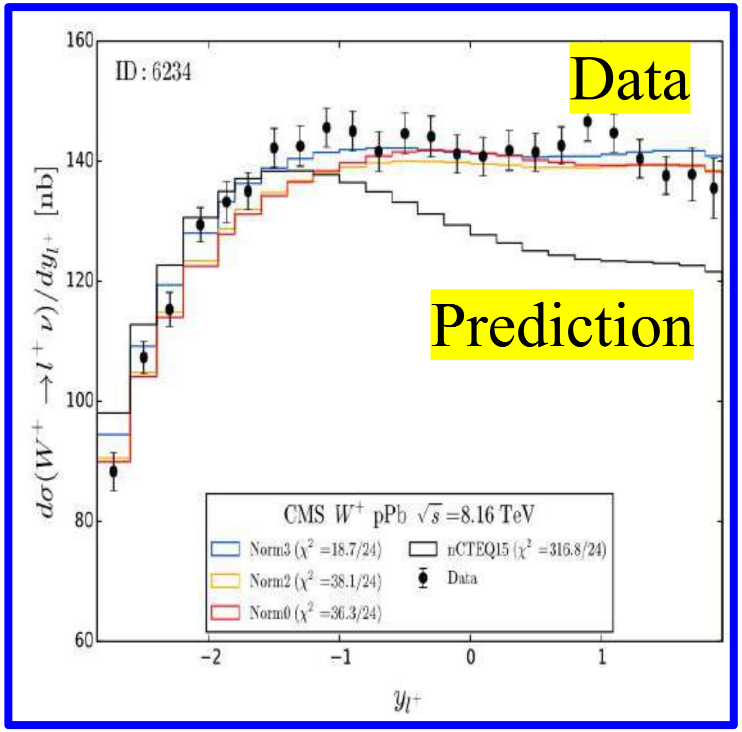
We expect:

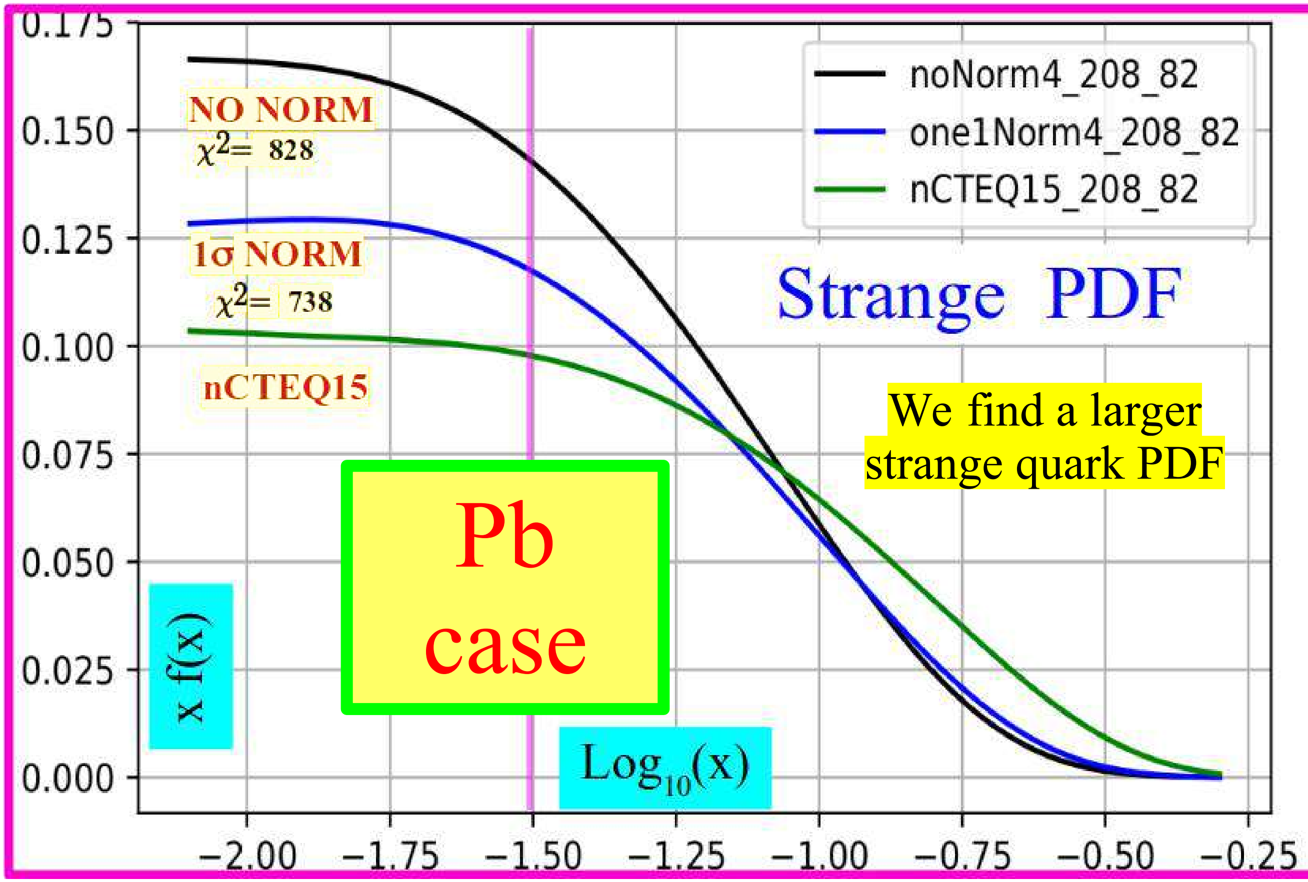
At the LHC:

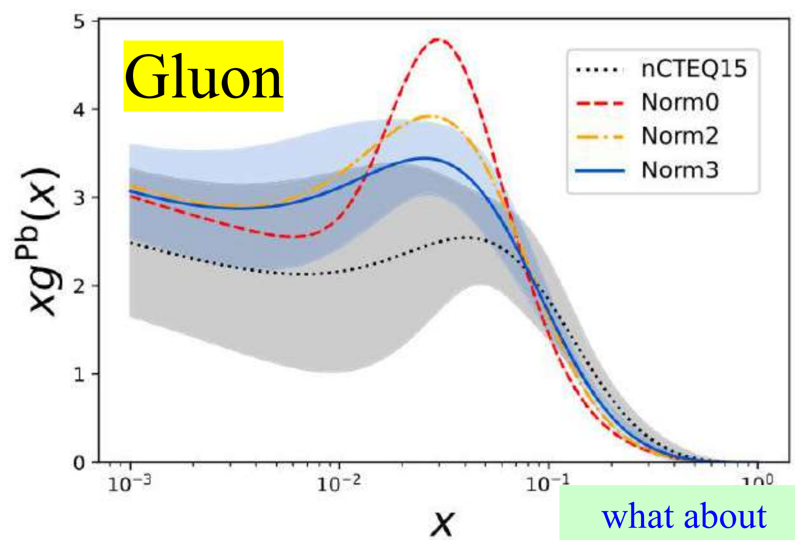
$$r_s = \frac{\bar{s} + s}{2\bar{d}}$$

ATLAS: Eur. Phys. J. C 77 (2017) 367

pPb Heavy Ion Case: … LHC STILL sees more strange than expected







Is the strange PDF driving the data ...

Or is the data driving the strange ???

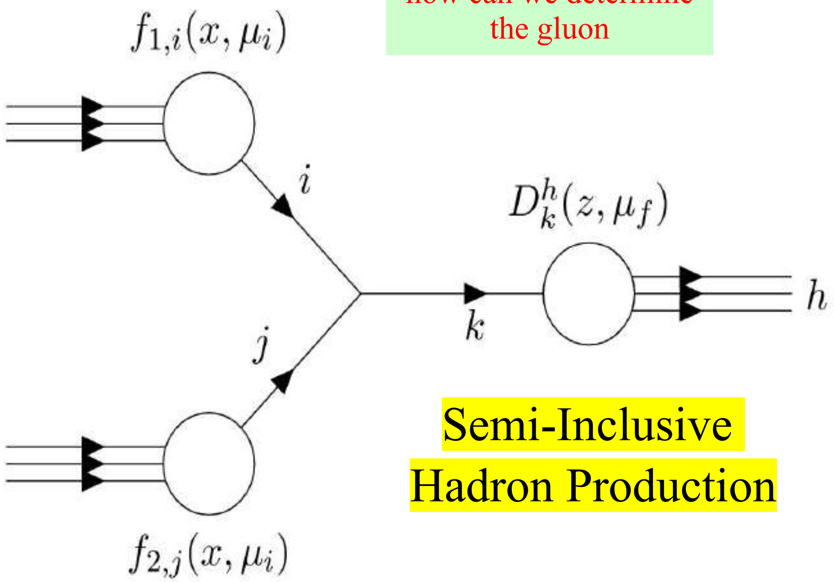
nCTEQ: Tomas Jezo, Aleksander Kusina, Fred Olness ...
Eur.Phys.J.C 80 (2020) 10, 968

what about the gluon???

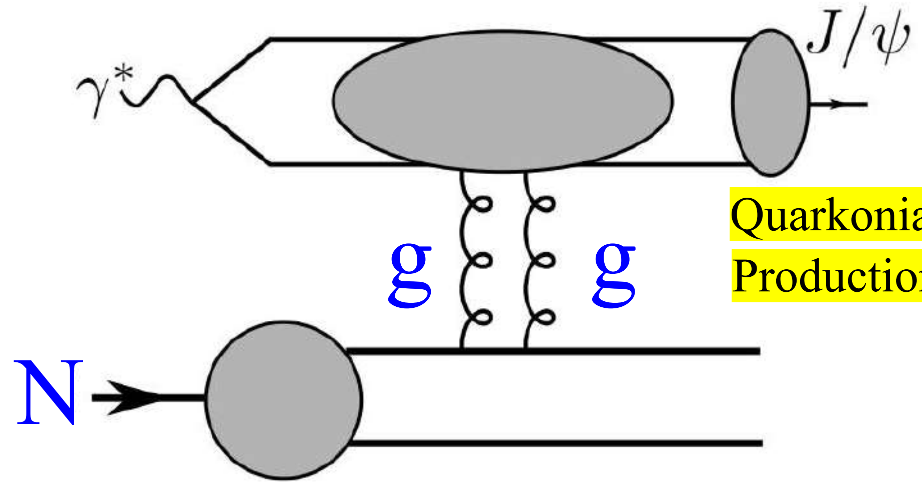
Measuring the nuclear Gluon PDF

Parton Distribution Functions

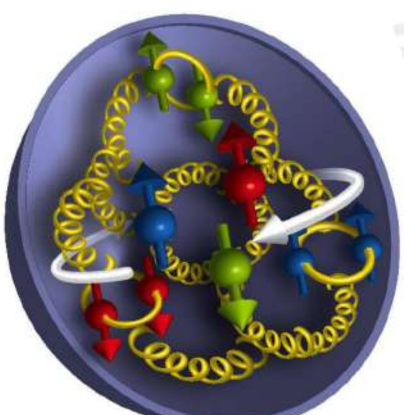
how can we determine the gluon

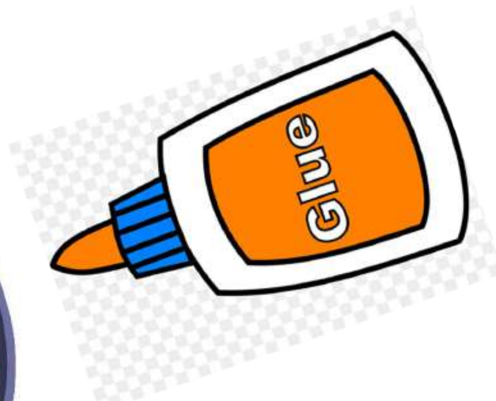


Semi-Inclusive Hadron Production

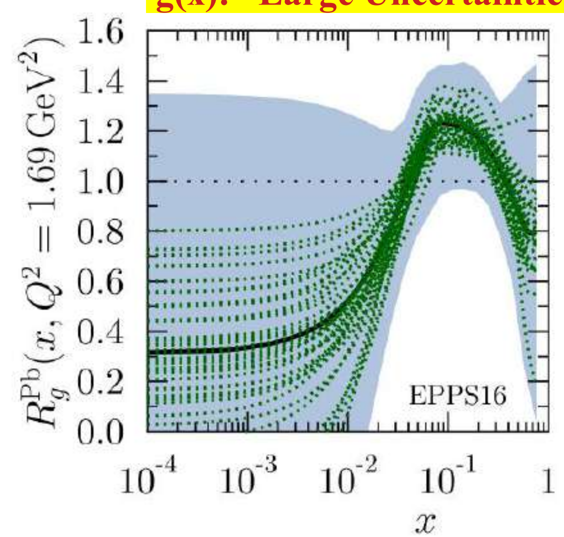


Quarkonia Production

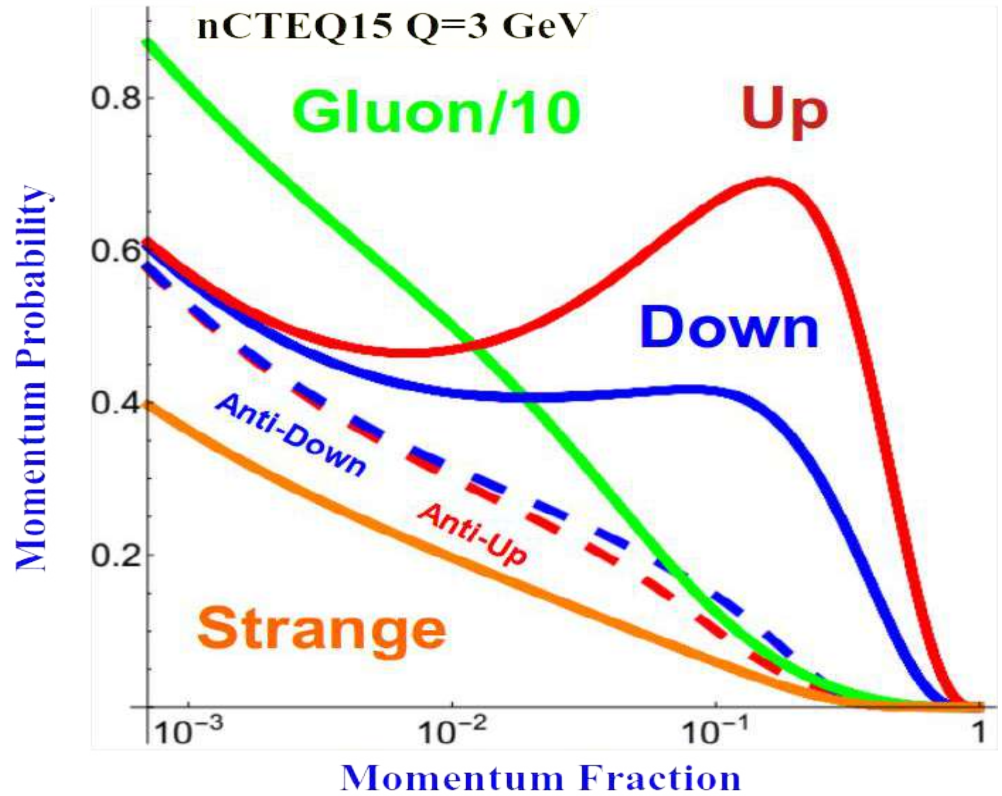


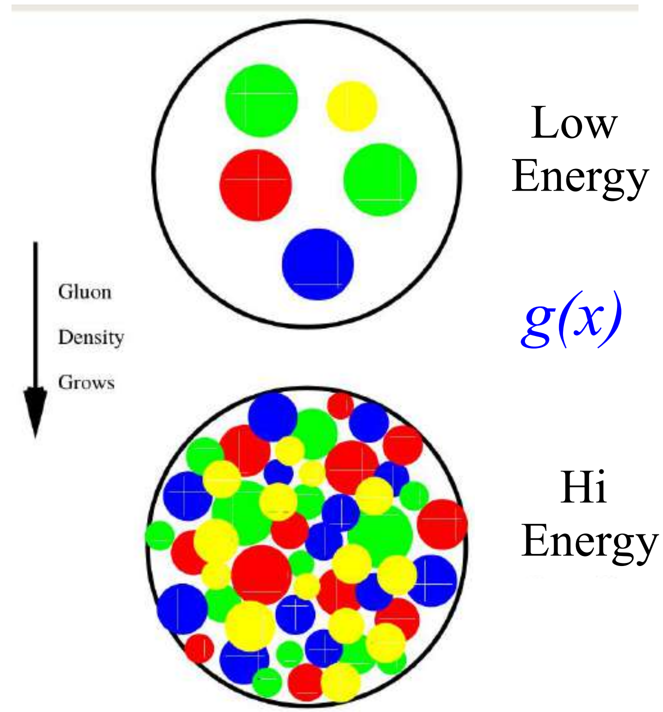


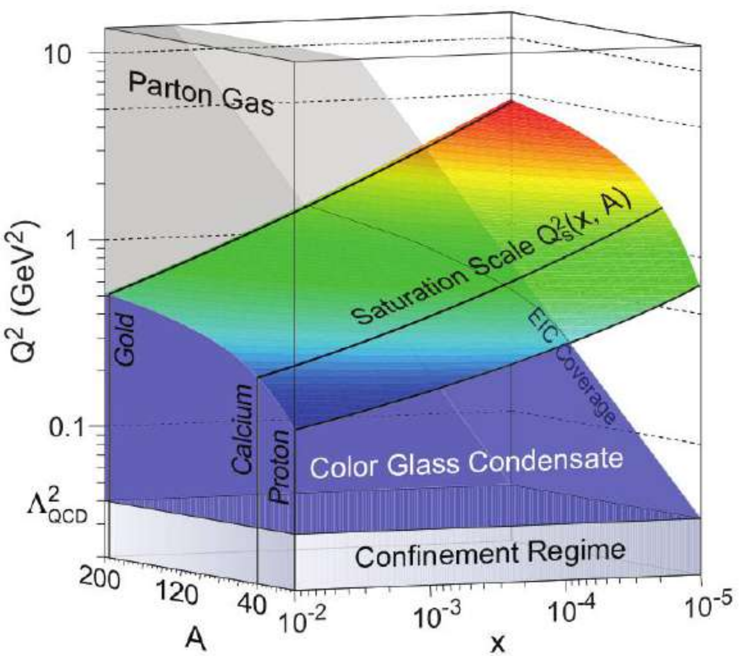
g(x): Large Uncertainties



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



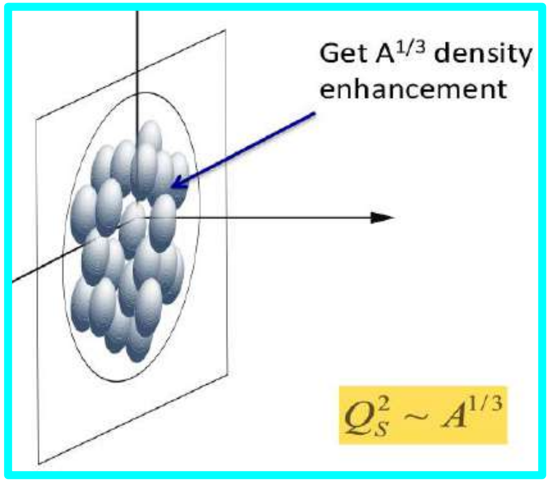




Nuclear medium effects:

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

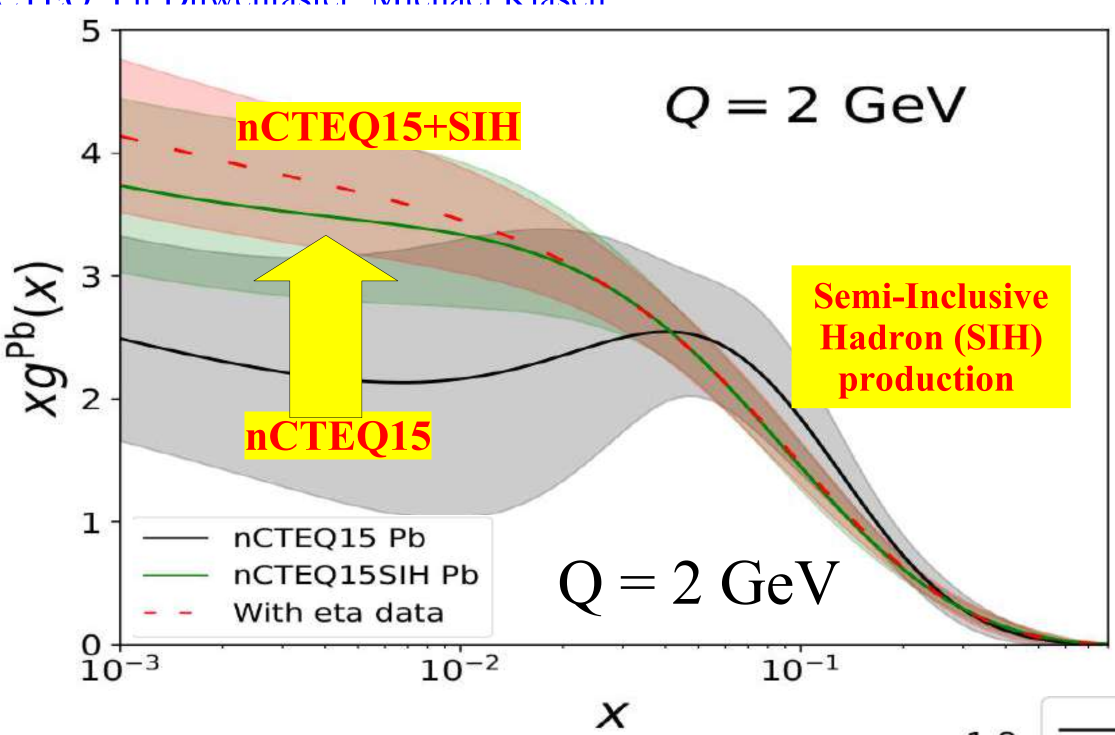
We gain a geometric factor of $A^{1/3}$



Review: Edmond Iancu & Raju Venugopalan: arXiv:0303204

Precision Gluon can help study nuclear medium effects

nCTEQ: Pit Duwentaster, Michael Klasen

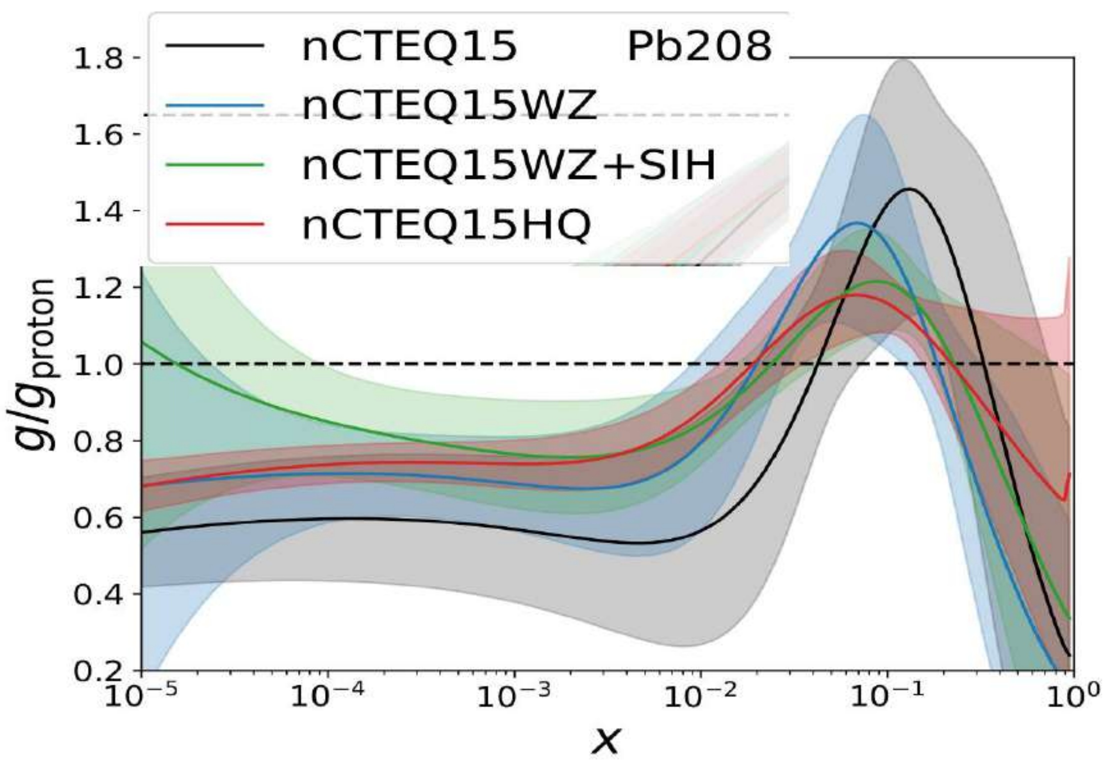


Data set	$\sqrt{s_{NN}}$ [GeV]	Observ.	No. points
PHENIX π^0	200	R_{dAu}	21
PHENIX η	200	R_{dAu}	12
PHENIX $\pi^\pm$	200	R_{dAu}	20
PHENIX $K^\pm$	200	R_{dAu}	15
STARπ^0	200	R_{dAu}	13
STAR η	200	R_{dAu}	7
STAR $\pi^\pm$	200	R_{dAu}	23
ALICE 5 TeV π^0	5020	R_{pPb}	31
ALICE 5 TeV η	5020	R_{pPb}	16
ALICE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

… UPDATE …

add HQ data

Determines gluon in small x region



Impact of heavy quark and quarkonium data on nuclear gluon PDFs
nCTEQ: Phys.Rev.D 105 (2022) 11, 114043

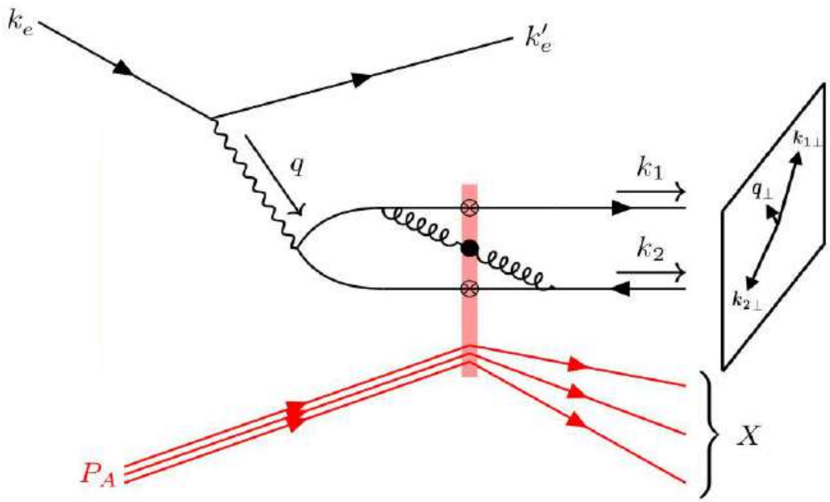
Impact of inclusive hadron production data on nuclear gluon PDFs
nCTEQ: P. Duwentäster, et al., PRD104 (2021) 094005.

Brookhaven National Laboratory

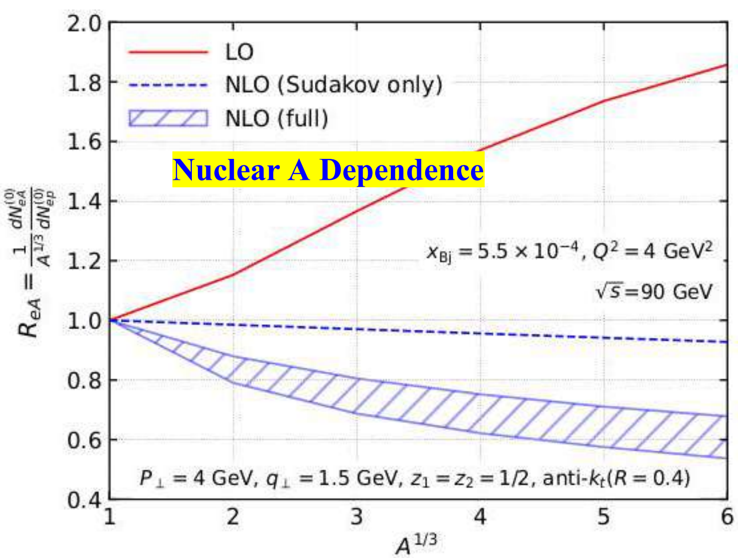
SURGE Collaboration

investigating gluon structure in extreme kinematic regions

SURGE COLLABORATION



Color Glass Condensate effective field theory



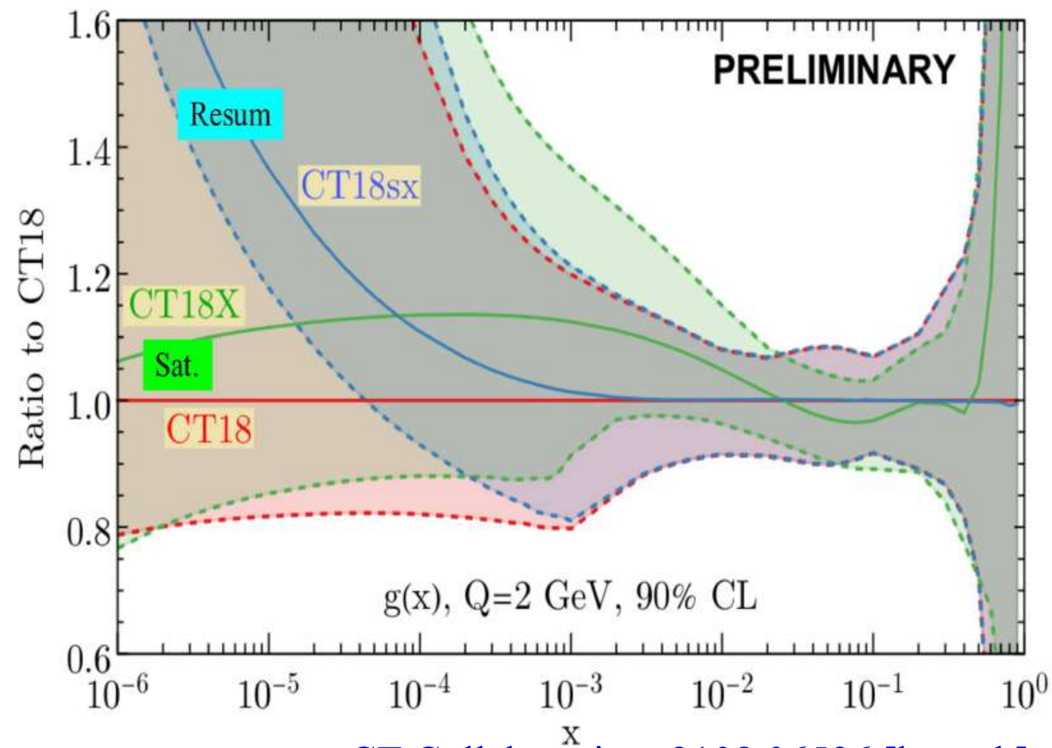
arXiv:2308.00022

Back-to-back inclusive dijets in DIS at small x: Complete NLO results and predictions

Paul Caucal, Farid Salazar, Björn Schenke, Tomasz Stebel, Raju Venugopalan

CT18x: Saturation inspired μ modification

CT18sx: w/ HELL small-x resummation code

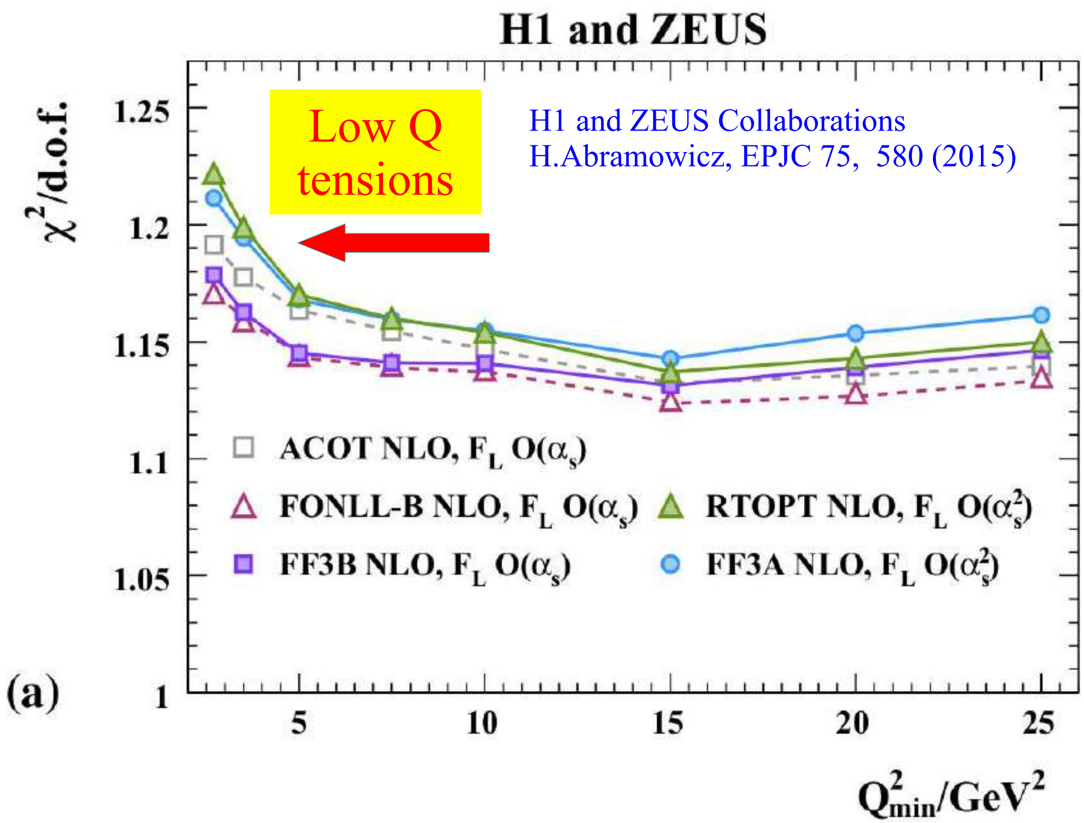


CT Collaboration: 2108.06596 [hep-ph]

XFITTER

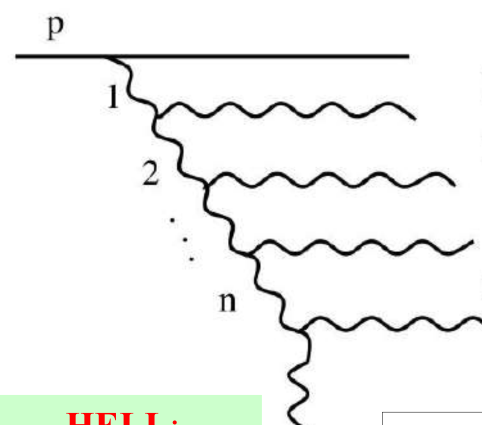
Motivation for Improved Treatment

Small x *(Low Q)*: need to improve fits
NNLO: "fits at NNLO do not improve agreement"



HERAPDF2.0 shows tensions between data and fit, independent of the heavy-flavour scheme used, at low Q^2, i.e. below $Q^2 = 15\,\mathrm{GeV}^2$, and at high Q^2, i.e. above $Q^2 = 150\,\mathrm{GeV}^2$. Comparisons between the behaviour of the fits with different Q^2_{min} values indicate that the NLO theory evolves faster than the data towards lower Q^2 and x. Fits at NNLO do not improve the agreement. HERAPDF2.0 NNLO and NLO have a similar fit quality.

NNLO vs. NLO



resum logs

$$\alpha_S^n \frac{\ln^k(x)}{x}$$

HELL:
High Energy
Leading Logs

Small-x resummation from HELL
Marco Bonvini, et al.,
Eur.Phys.J.C 76 (2016) 11, 597

Eur. Phys. J. C (2018) 78:621
https://doi.org/10.1140/epjc/s10052-018-6090-8

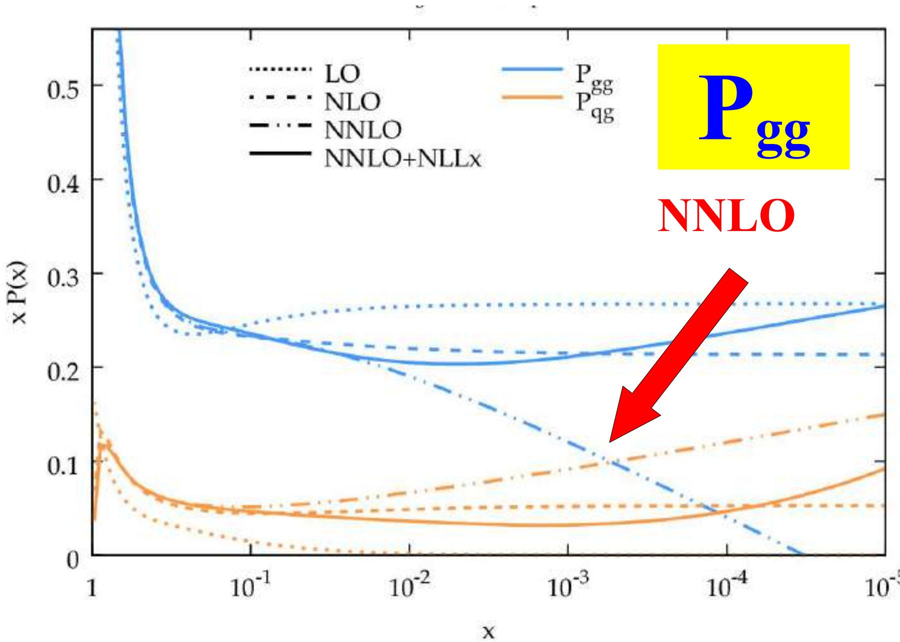
THE EUROPEAN PHYSICAL JOURNAL C

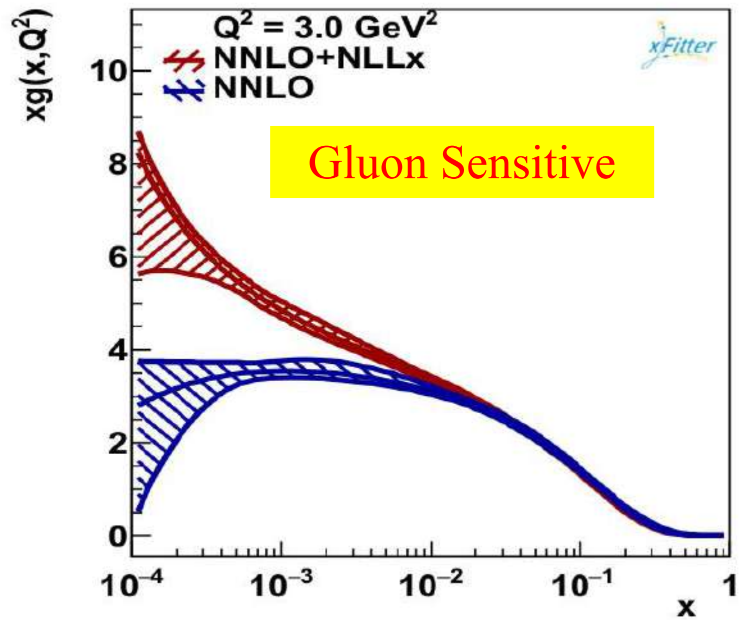
Regular Article - Theoretical Physics

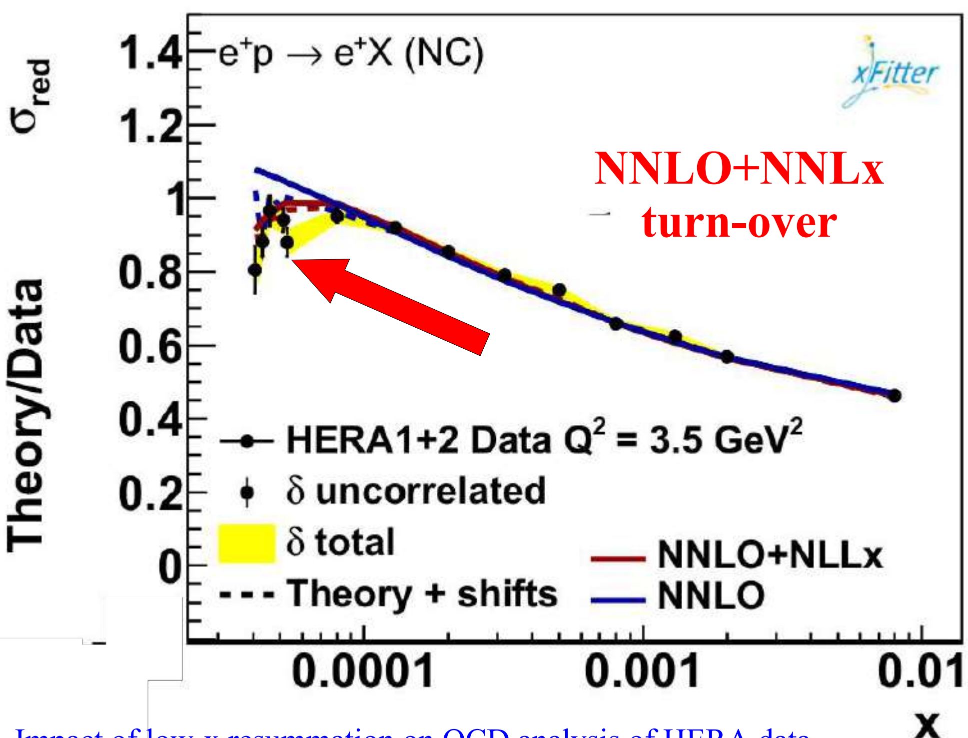
Impact of low-x resummation on QCD analysis of HERA data

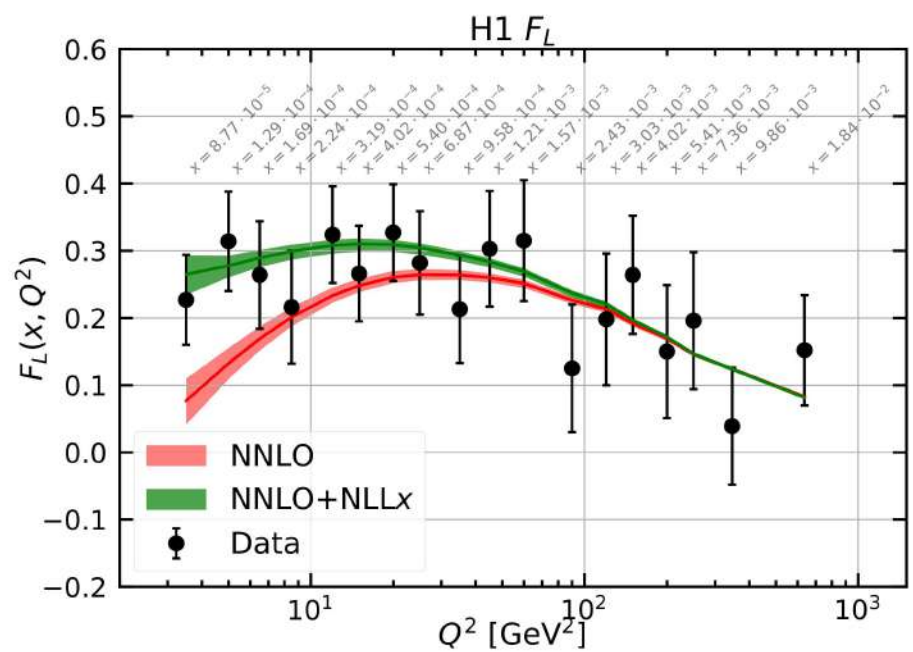
xFitter Developers' team, Hamed Abdolmaleki[1], Valerio Bertone[2,3,a], Daniel Britzger[4], Stefano

xFitter Resummation Study









Impact of low-x resummation on QCD analysis of HERA data

xFitter Developers' Team: Eur.Phys.J.C 78 (2018) 8, 621

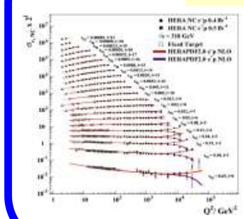
xFitter

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



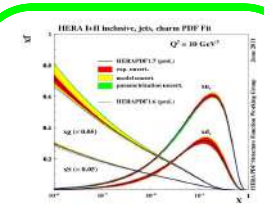
Data: HERA, Tevatron, LHC, fixed target experiments

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)

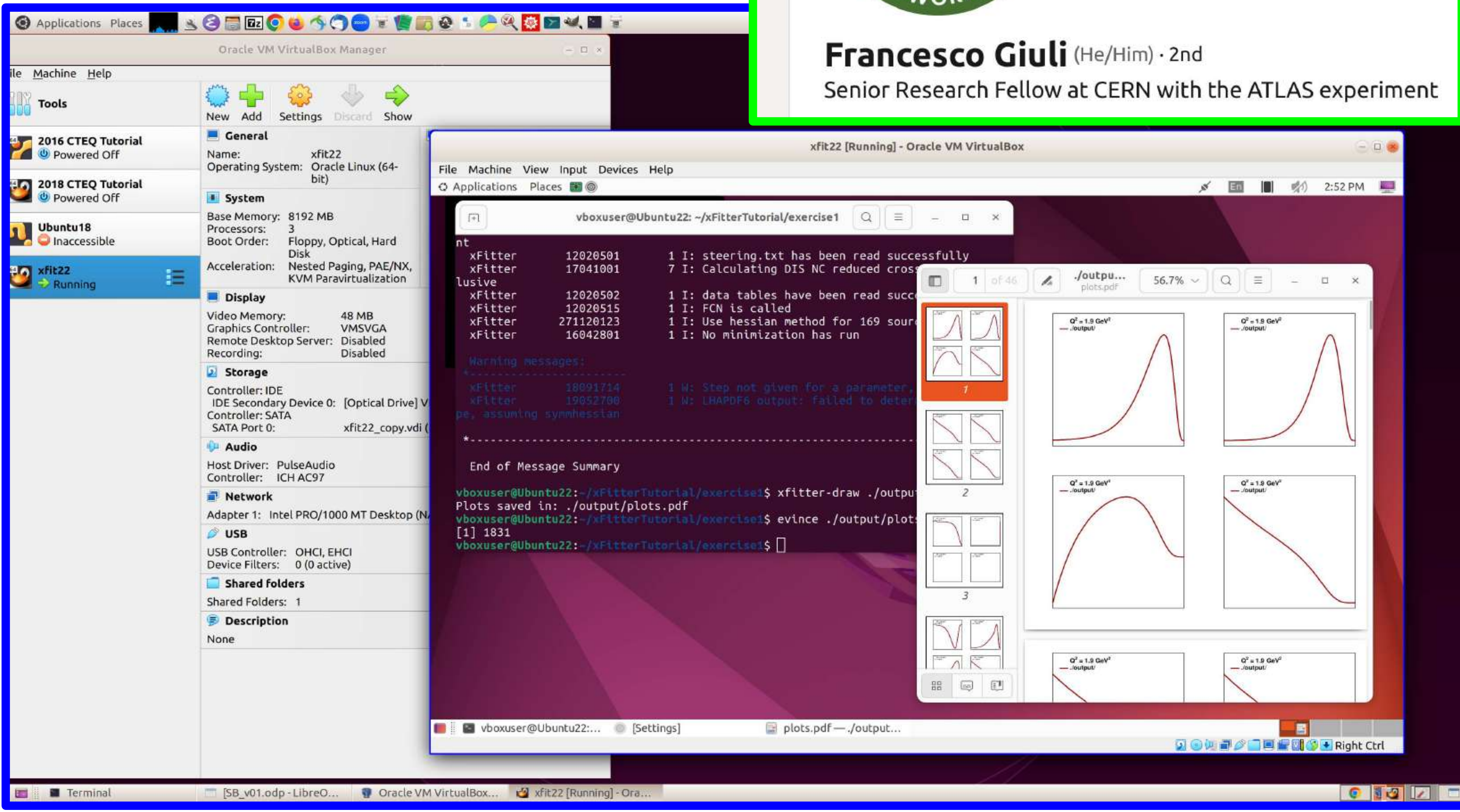
extensions include nuclear PDFs

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

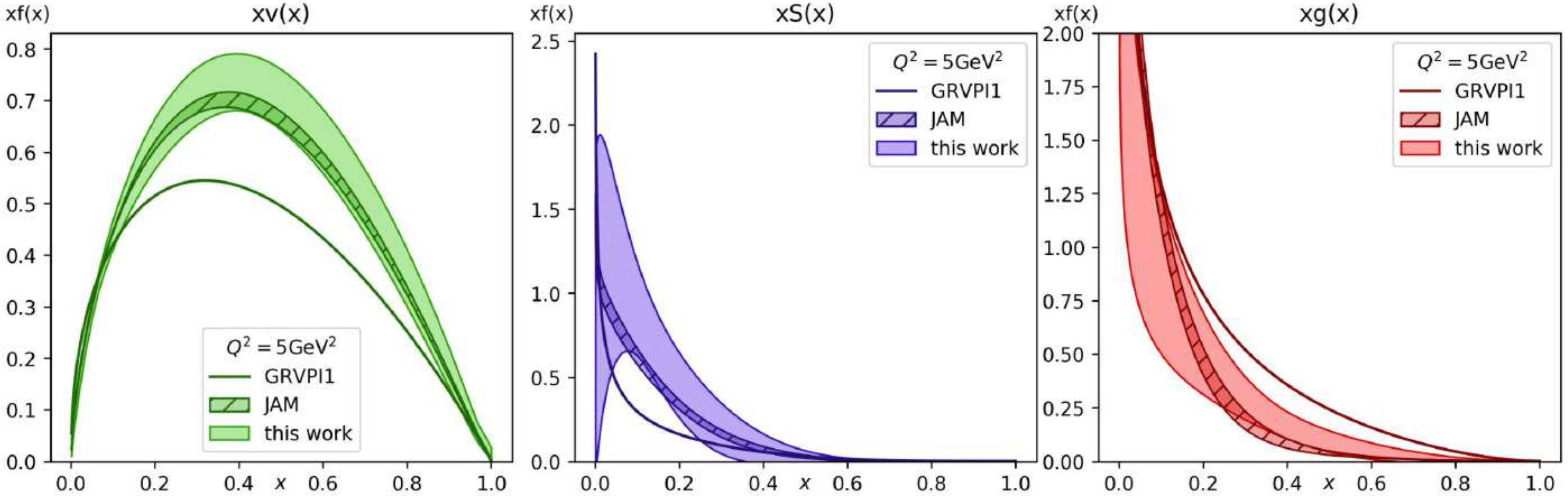
xFitter

VirtualBox



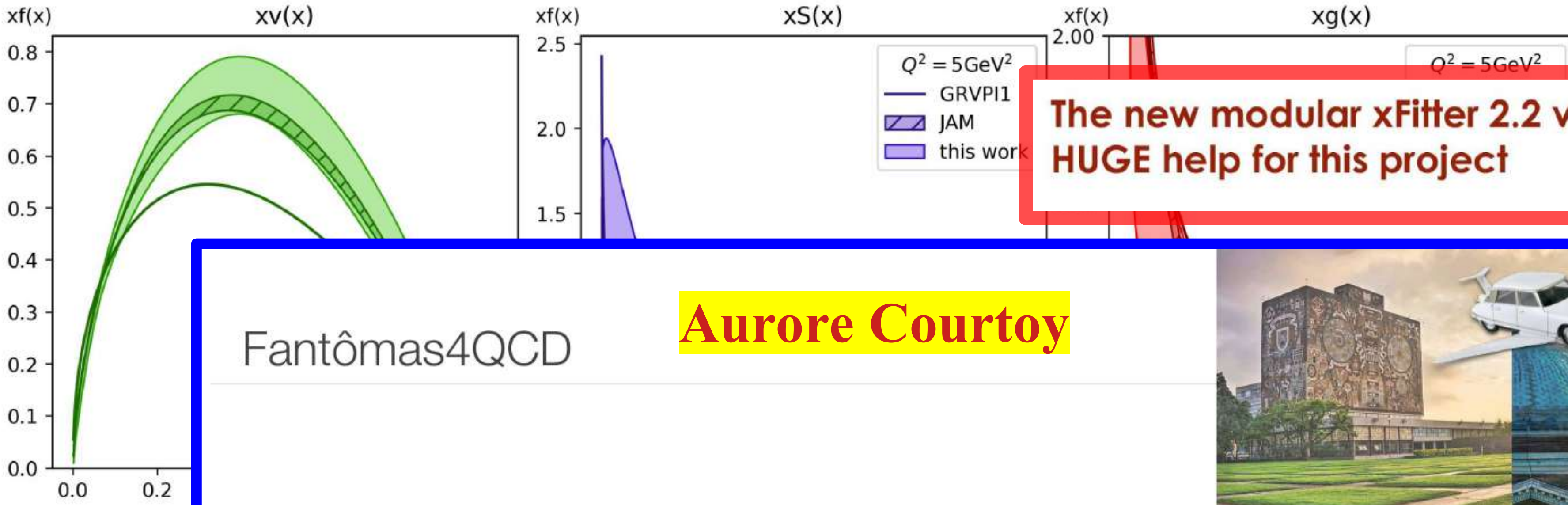
https://smu.box.com/s/78k1jr8l1ahrtd1h1t3khz05l1amh2g7

Charged Pion PDF



- Comparison with recent pion PDF determinations:
  - JAM collaboration
  - GRVPI1 pion PDF set
- Valence distribution in good agreement with JAM and both disagree with the early GRV analysis
- The relatively hard-to-determine sea and gluon distributions are different in all the three PDF sets

Charged Pion PDF



- Compo
  - JAI
  - GR
- Valenc early G
- The rel the thre

The new modular xFitter 2.2 version was a HUGE help for this project

Fantômas4QCD

Aurore Courtoy

Main idea: to quantify the rôle of parametrization form in global analyses.

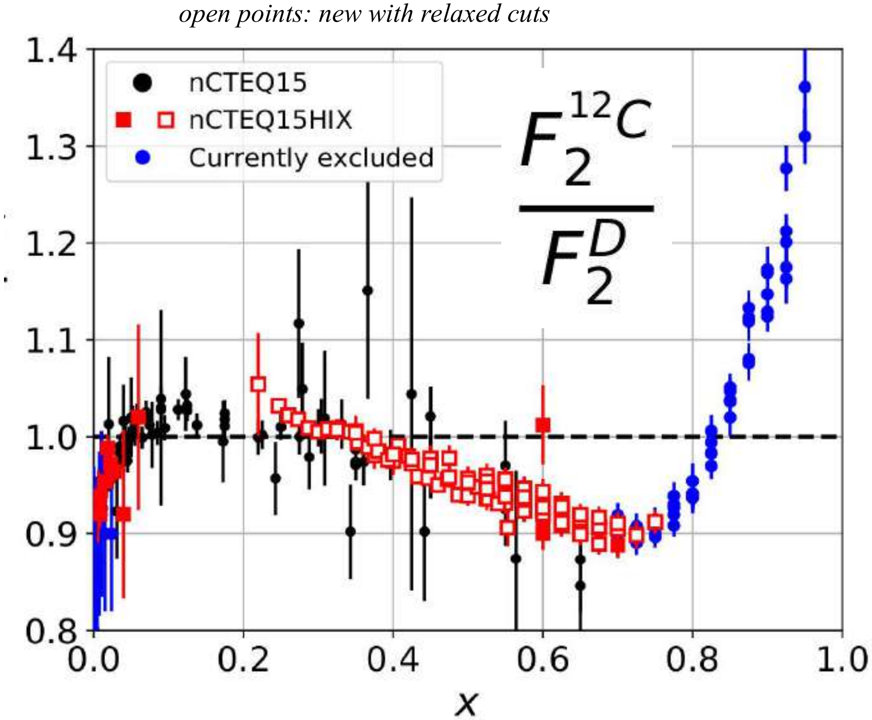
Fantômas4QCD: Our new c++ code, Fantômas, automates series of fits using multiple functional forms.

Just like neural networks, these polynomial functional forms can approximate any arbitrary PDF shape.

This code facilitates unbiased estimates of parametrization dependence.

HI X JLAB

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

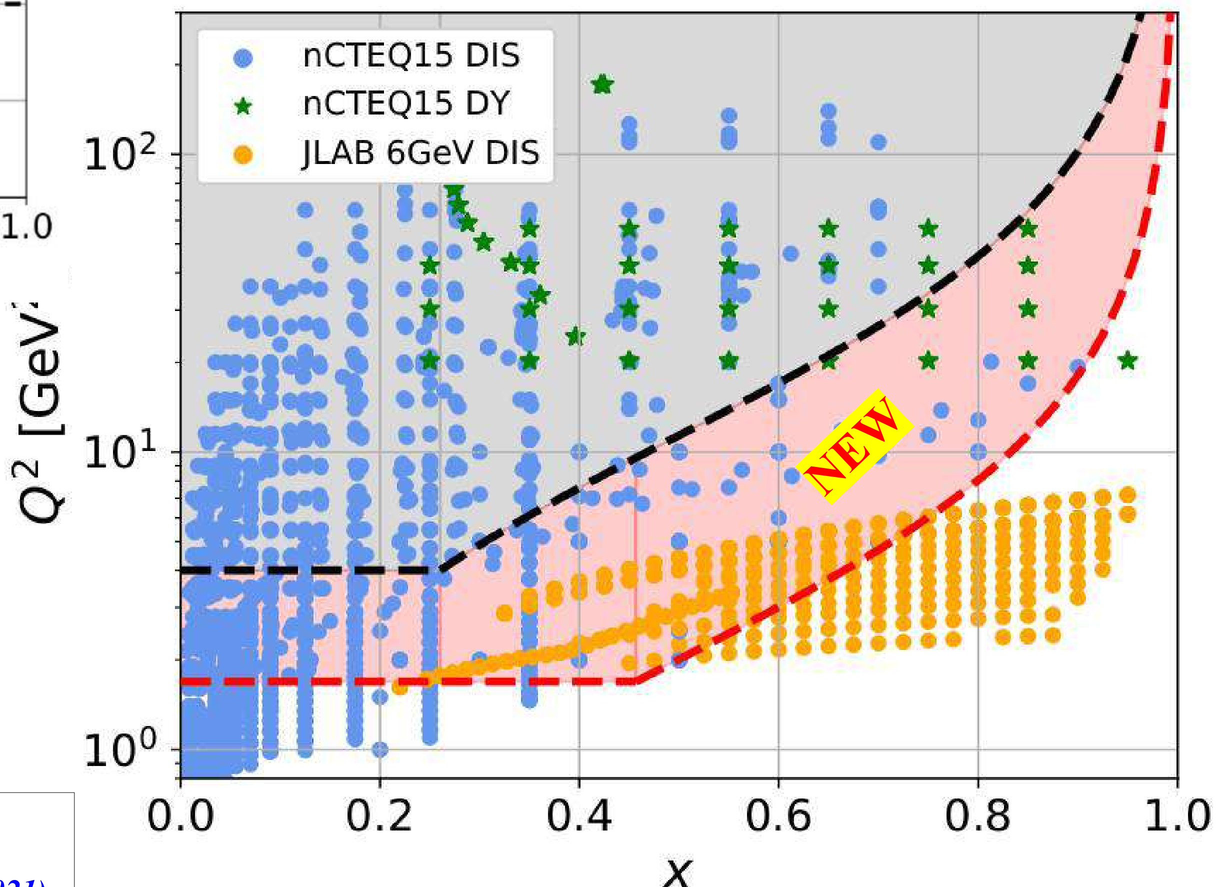


Nuclear PDFs: x>1 allowed;
impacts F_2^{Nuc}/F_2^{Iso} in Fermi region

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

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

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



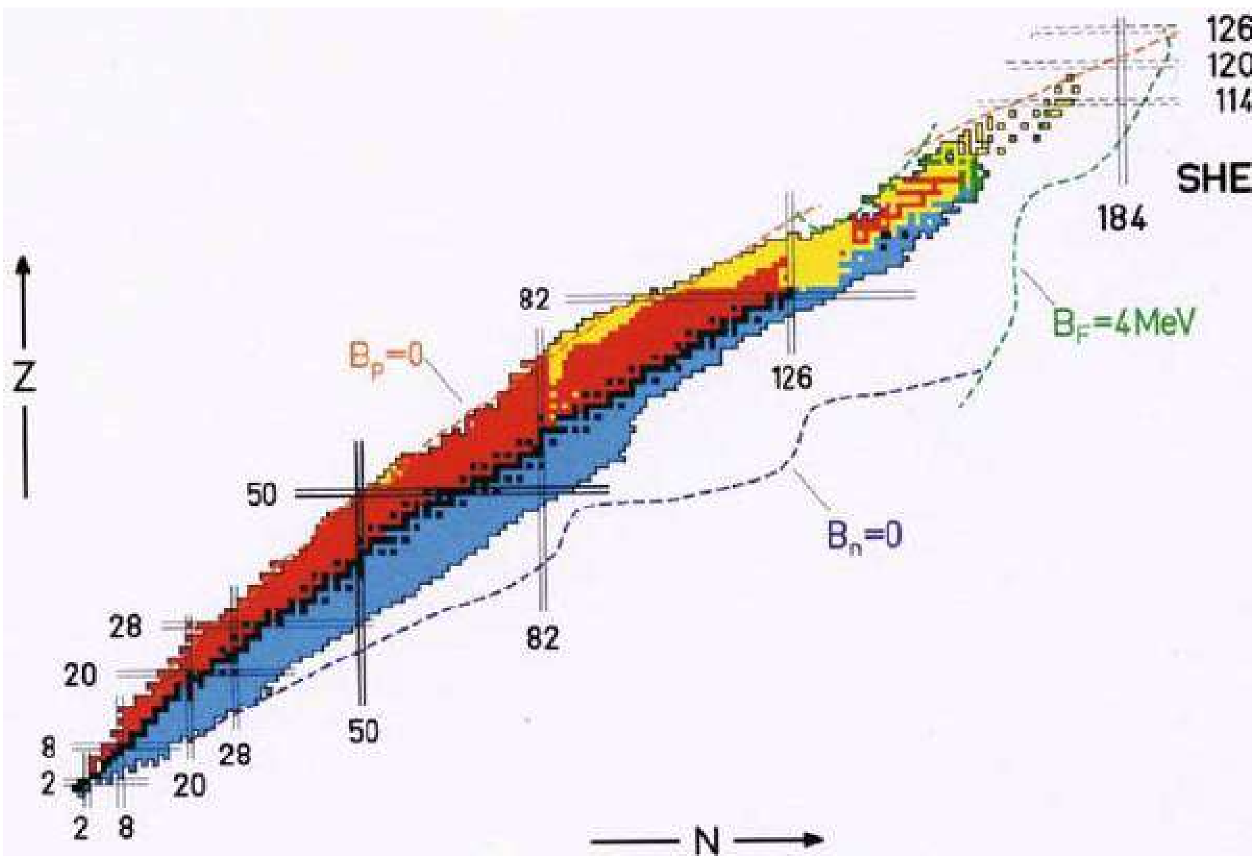
nCTEQ15HIX -- Extending nPDF Analyses into the High-x, Low Q2 Region
E.P. Segarra, T. Ježo, et al., ***PRD 103, 114015 (2021)***

Target Mass Corrections (TMC)

The challenge of a multi-scale problem

...

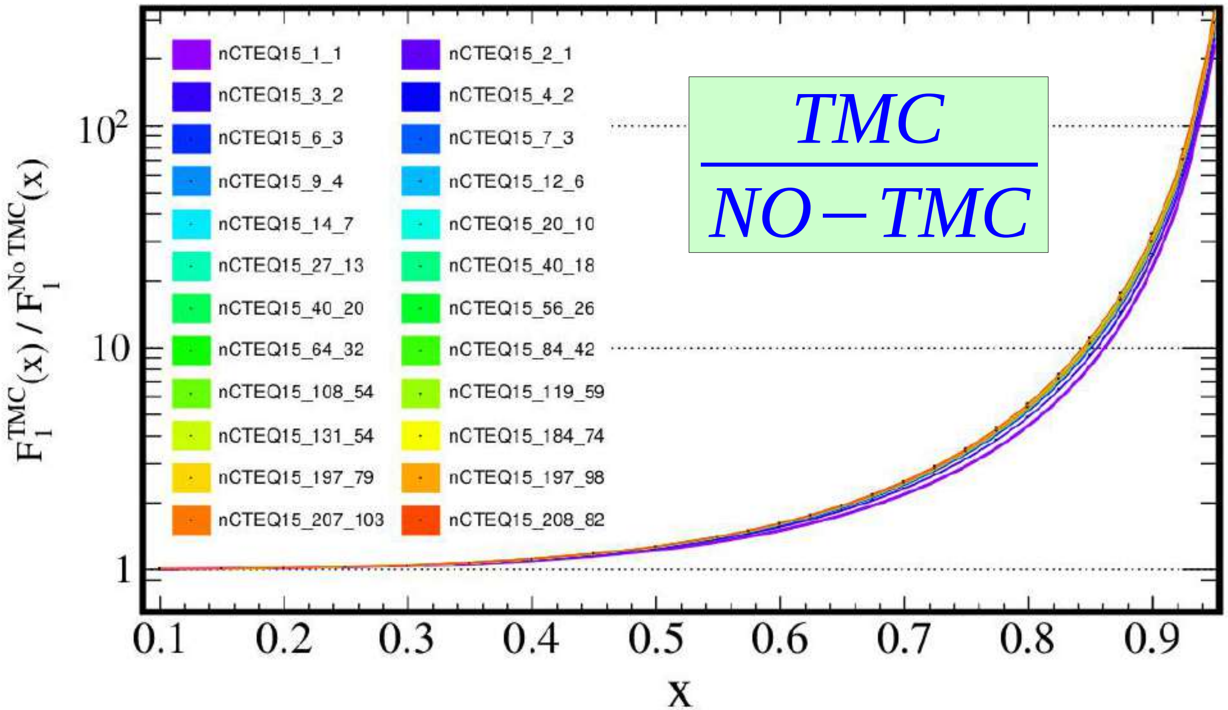
Ingo Schienbein, Chloe Leger, Richard Ruiz ...



Extend to nuclear case

arXiv:2301.07715
Target mass corrections in lepton-nucleus DIS: theory and applications to nuclear PDFs
nCTEQ: R. Ruiz, et al.,

Target Mass Corrections (TMC) for nuclear processes



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

TMCs can be large

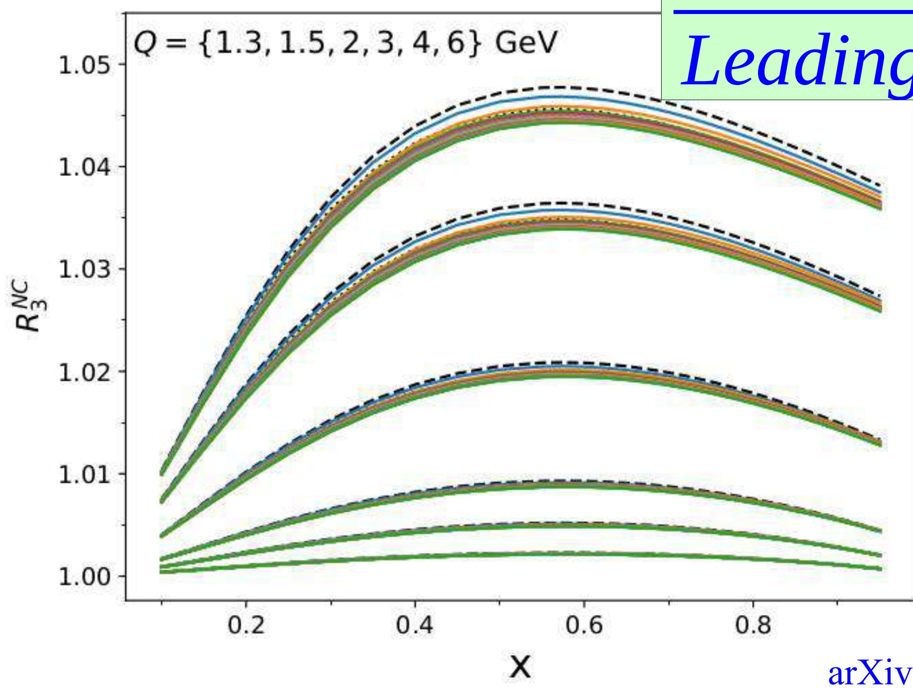
Corrections: M_P or M_A? $\left(\frac{M^2}{Q^2}\right)$

Answer: M is proton mass

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

Corrections are nearly universal

Important Calculational Advantage



Q=1.3

Q=1.5

Q=2

Q=3,4,6

Ingo Schienbein, Chloe Leger, Richard Ruiz ...

arXiv:2301.07715

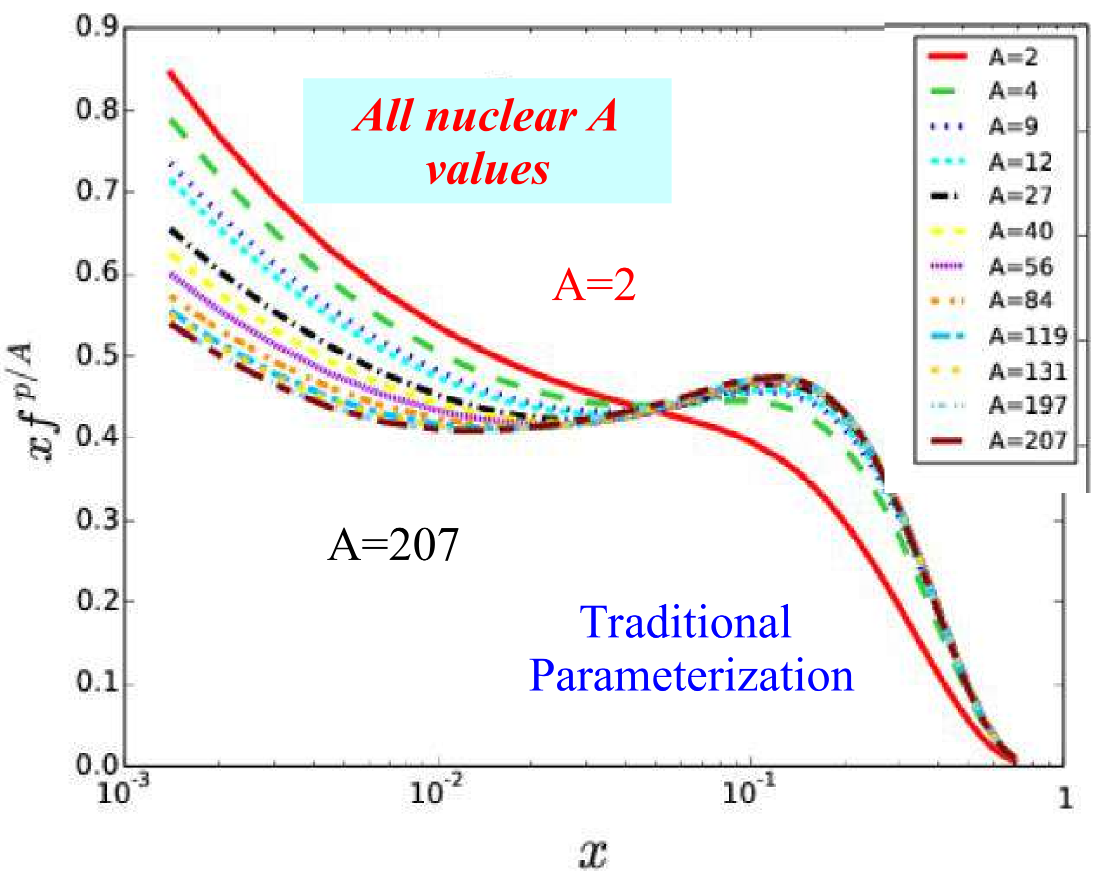
Short Range Correlations (SRC)

nCTEQ with

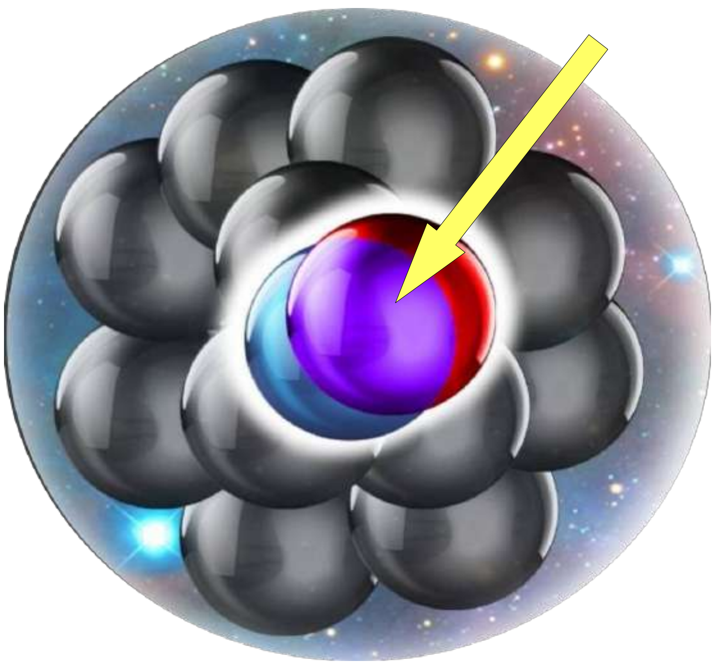
Andrew Denniston & Or Hen

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

nuclear PDF — normal proton PDF — SRC modified PDF

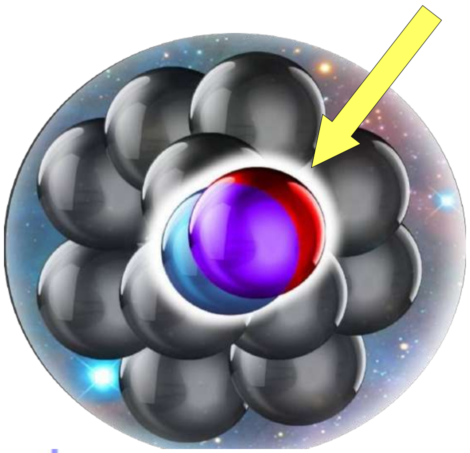


Short Range Correlations (SRC)



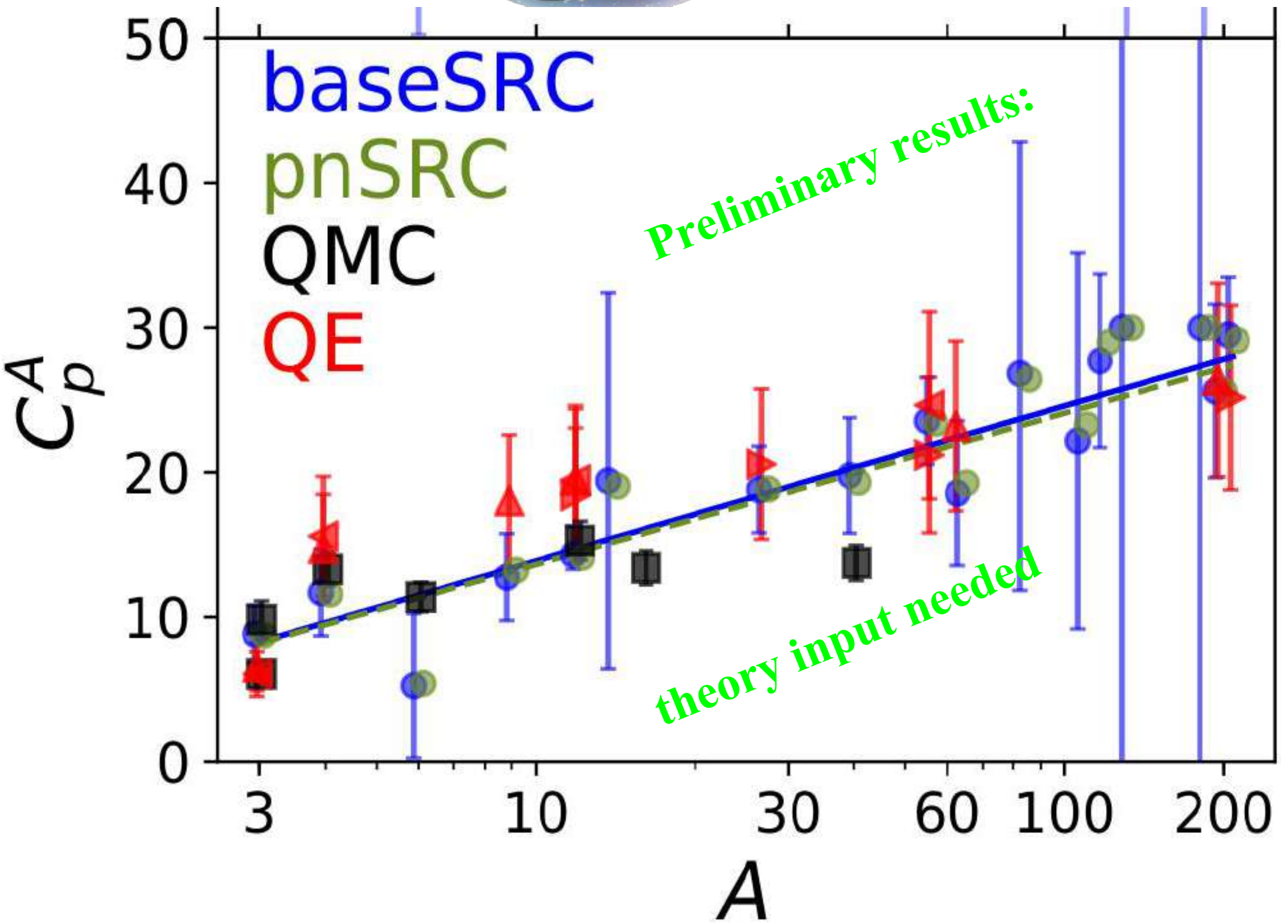
Short Range Correlations (SRC)

Short Range Correlations (SRC)



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

nuclear PDF — normal proton PDF — SRC modified PDF



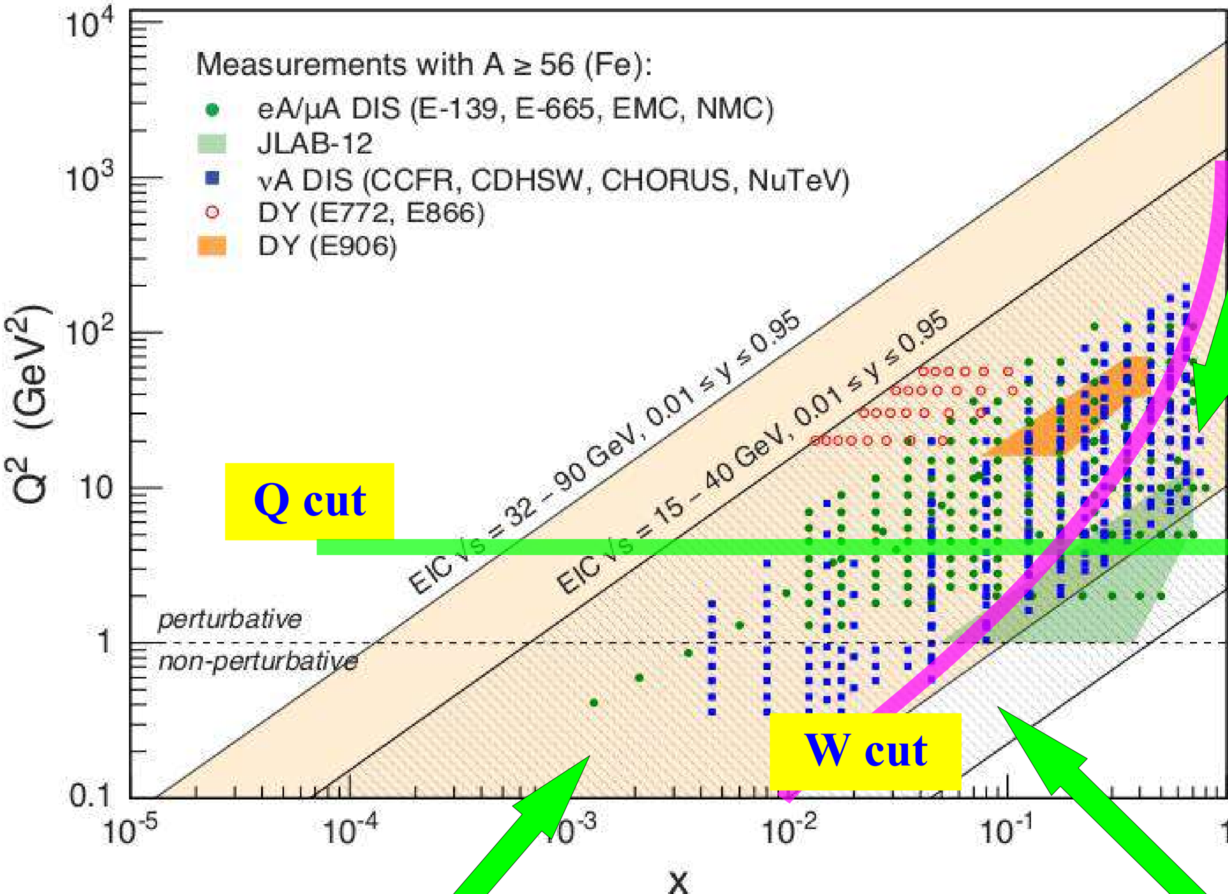
Use relaxed {Q,W} cuts

Preliminary results:

- Yields good fit: $\chi^2/N \sim 0.80$ vs. 0.85
- Compatible with (pn) SRC pairs

CONCLUSIONS

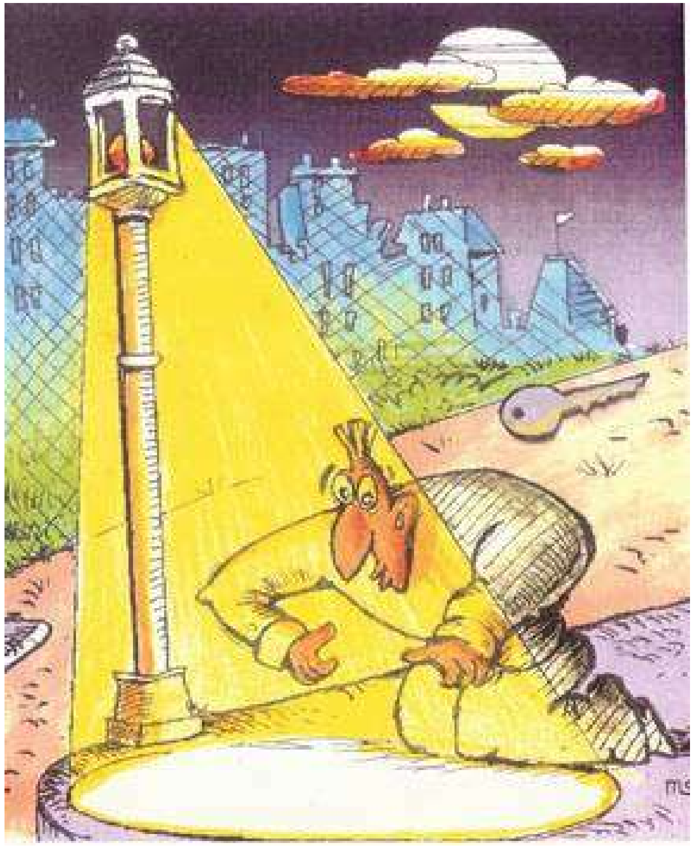
Do we really understand QCD … push to extreme {x,Q}



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

Are we just looking under the lamppost



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)

Need theoretical guidance in these regions

nPDF Wish List

nCTEQ
nuclear parton distribution functions

www.ncteq.org

nPDF 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: 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

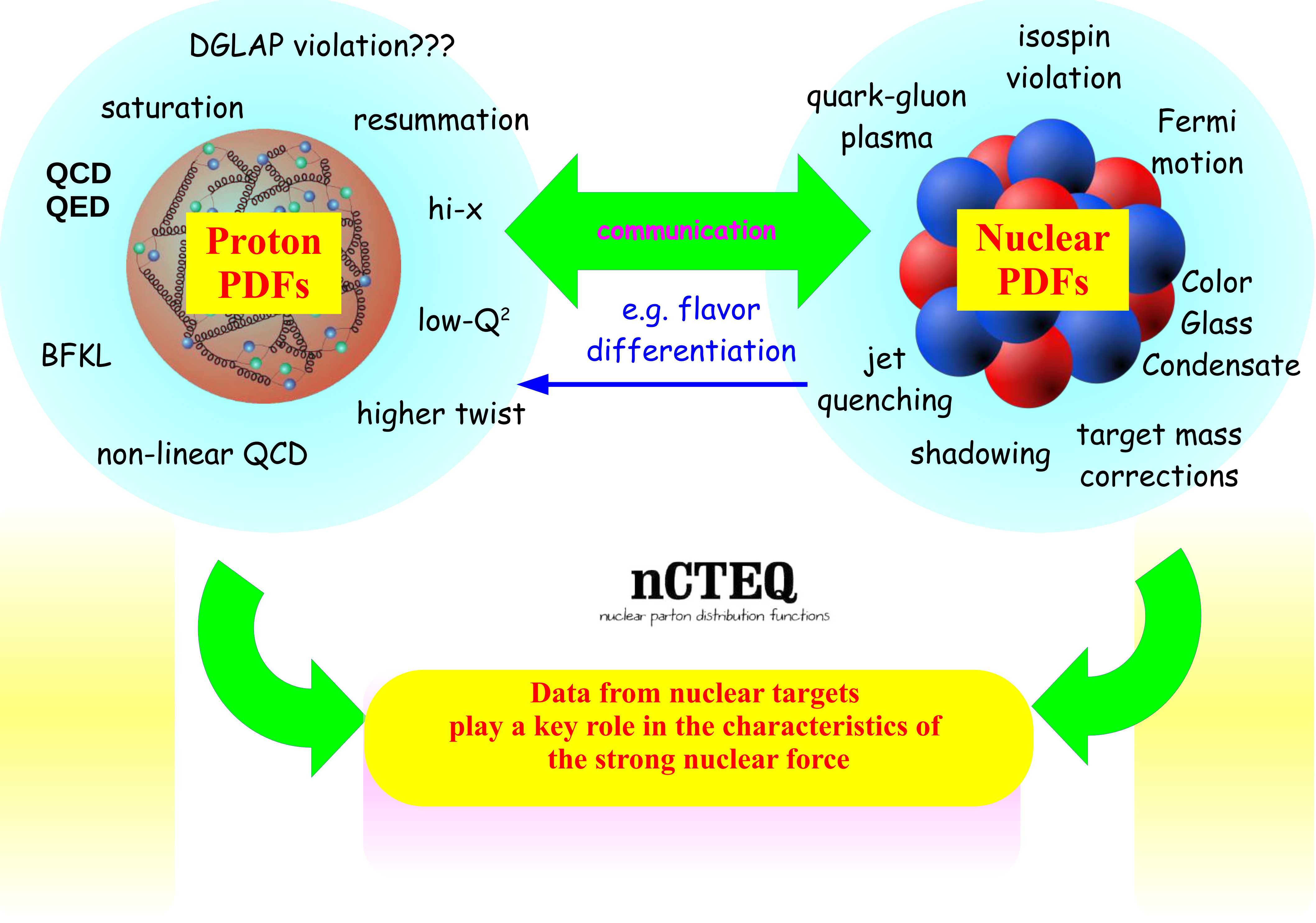
Expanded {x,Q^2} Kinematic Regime

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

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

EXTRAS

… the ultimate goal for nPDFs



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

include Lattice QCD info on moments and quasi-PDFs

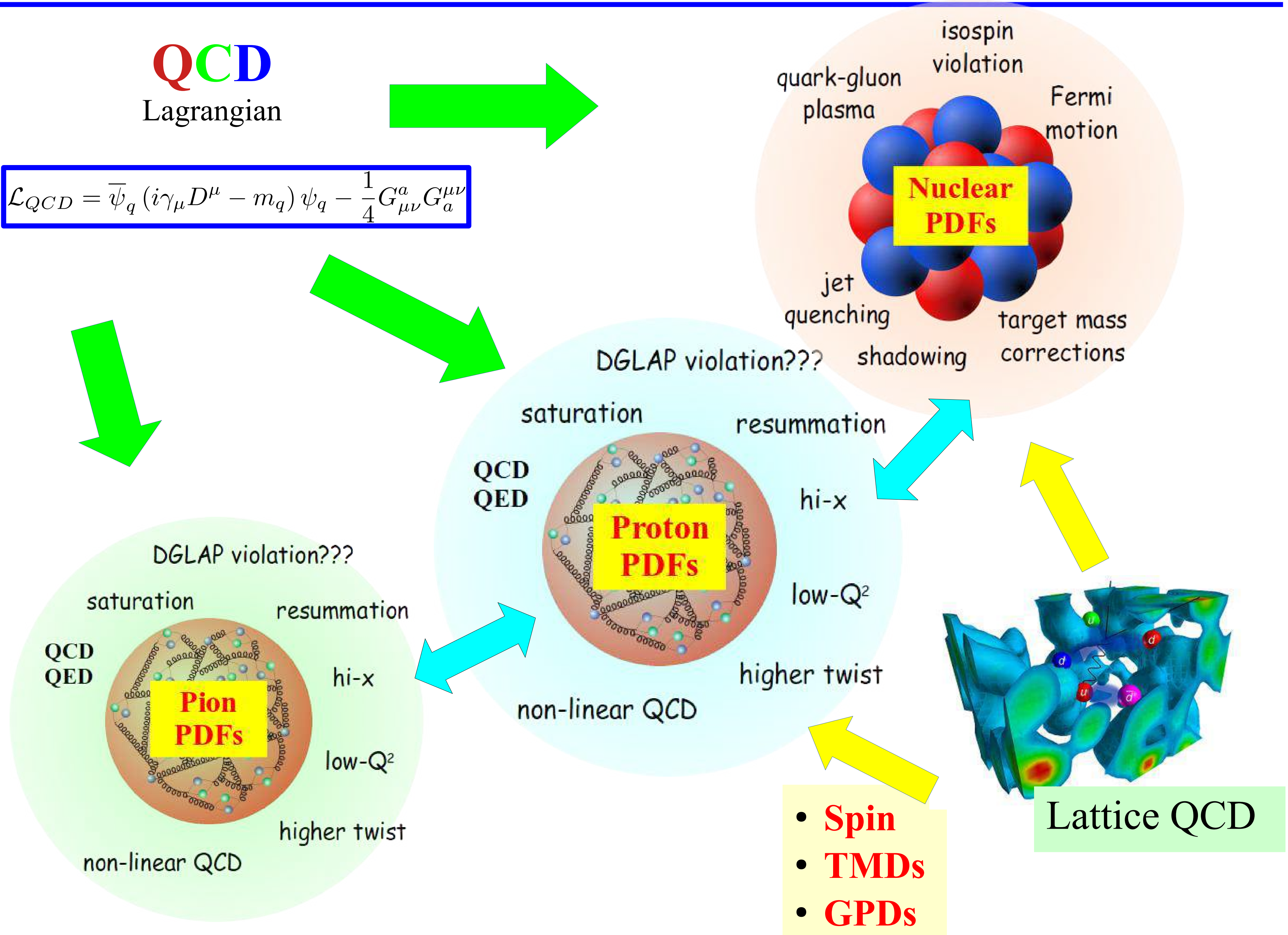
Need coordination/communication between efforts

QCD: From Parameterization to a Deeper Understanding

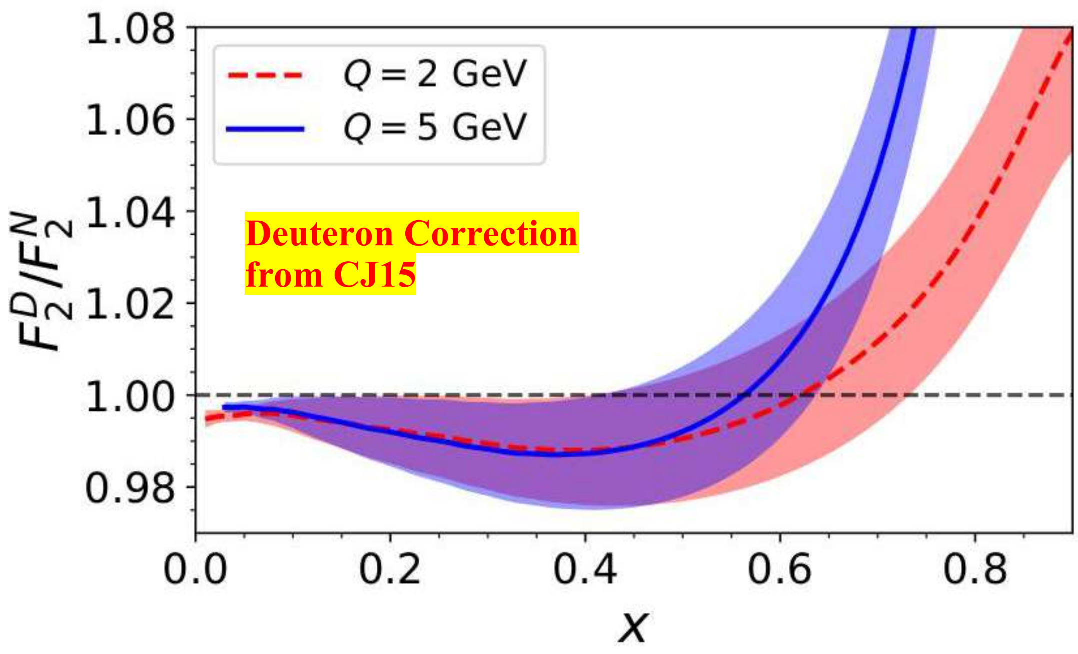
QCD

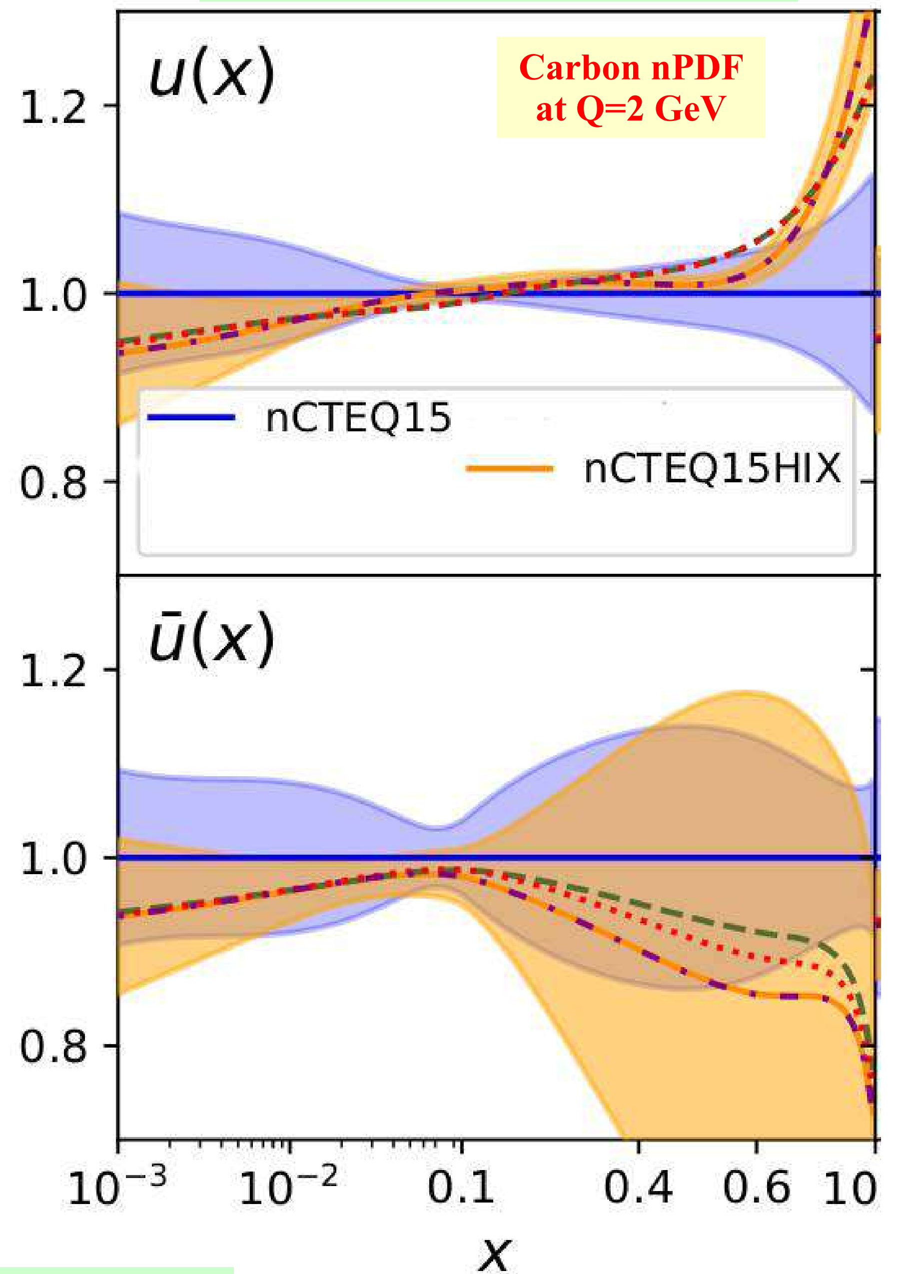
Lagrangian

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



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,Q²}

what about mid x region