Precision QCD: Preparing for the EIC

From PDFs to the underlying QCD

Fred Olness
SMU

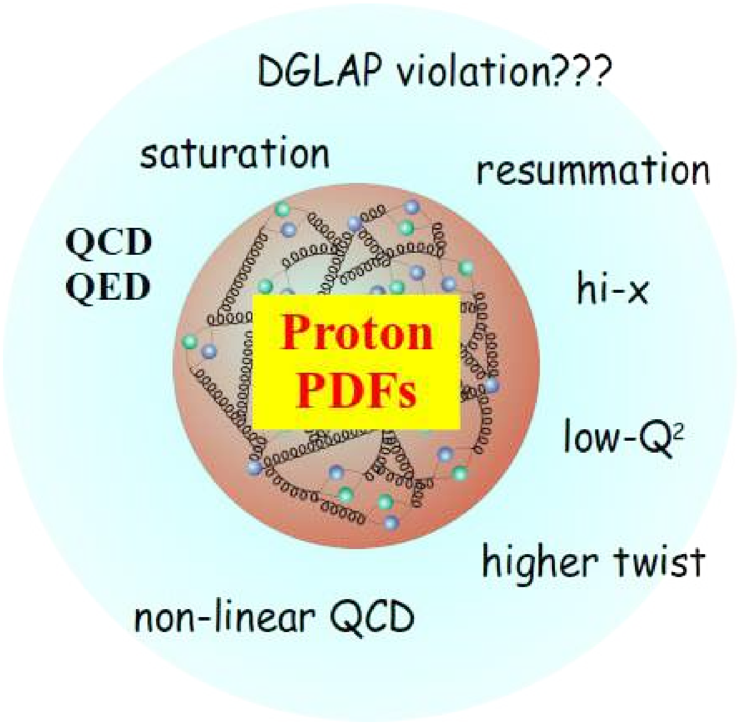
Thanks for substantial input
from my friends & colleagues

CTEQ Fall Meeting

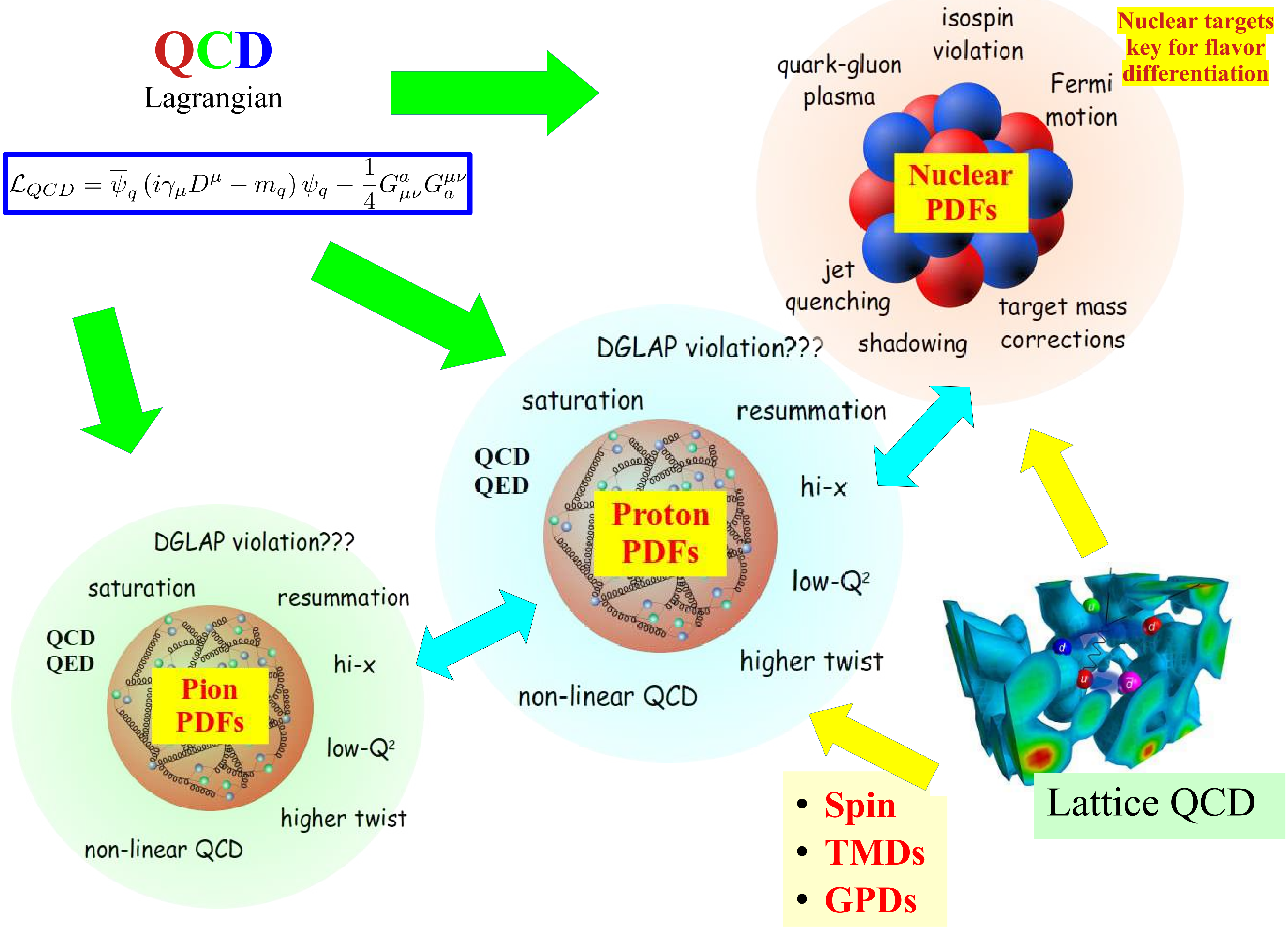
Christopher Newport University
21-22 November 2024

Busch
GARDENS.
WILLIAMSBURG, VA

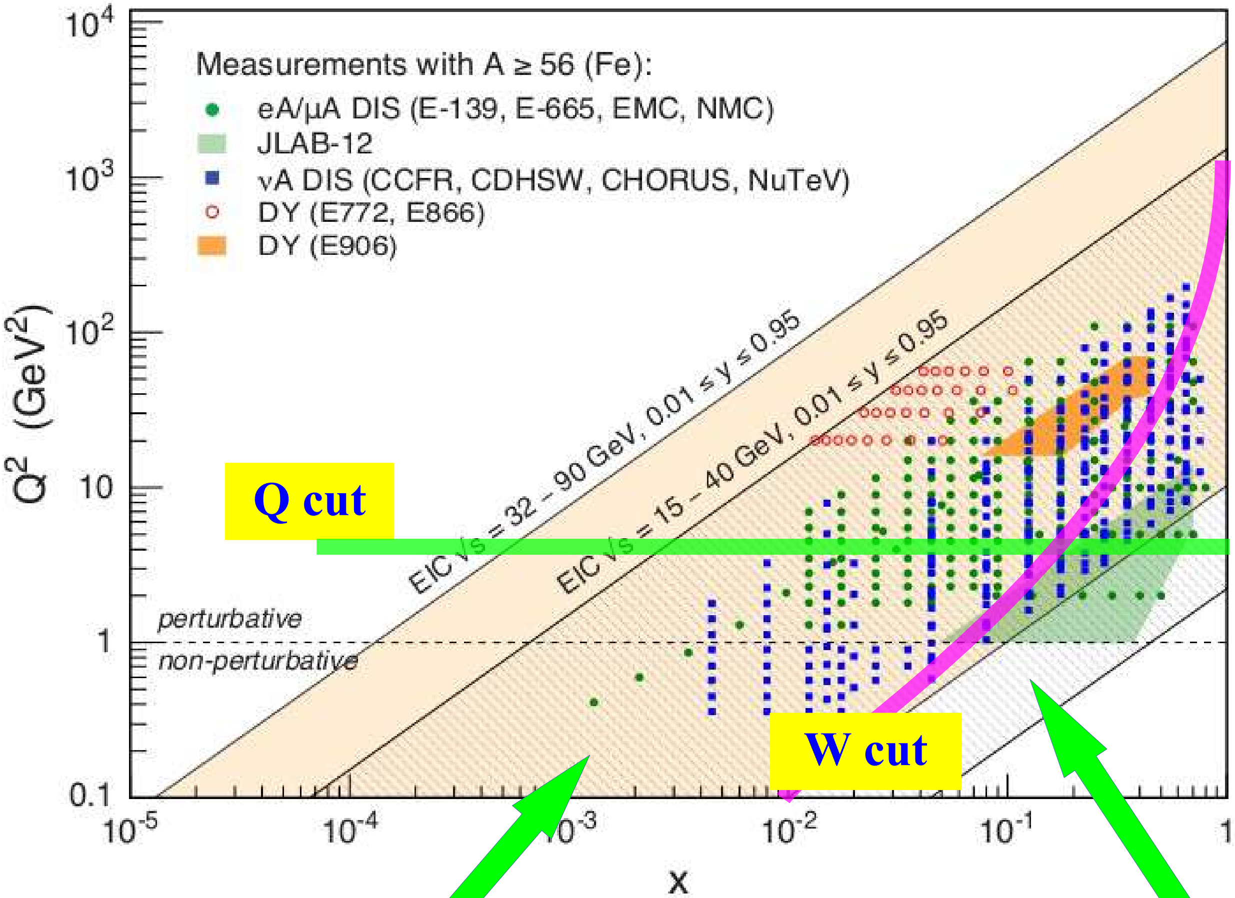
QCD: From PDFs to the underlying QCD



QCD: From PDFs to the underlying QCD



nPDFs: Extend Precision & Kinematic Reach in {x,Q^2}



High-x:

Nuclear PDFs: x>1 allowed;

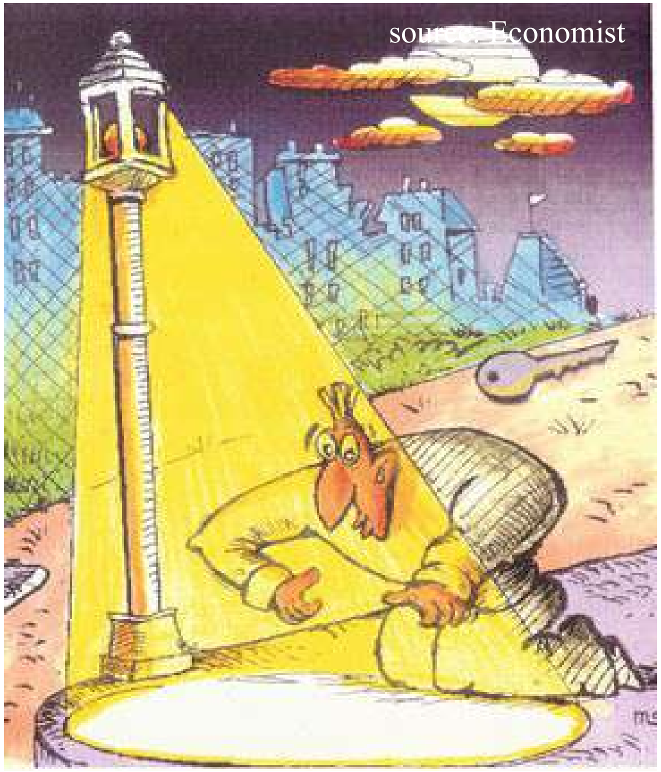
impacts F_2^{Nuc}/F_2^{Iso} in Fermi region

Target Mass Corrections

pick up M^2/Q^2 higher twist

Deuteron Corrections

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



Low-x:

Shadowing
Recombination
Resummation
BFKL
Saturation

Low-Q^2:

Non-Perturbative inteface

collective effects

Target Mass Corrections

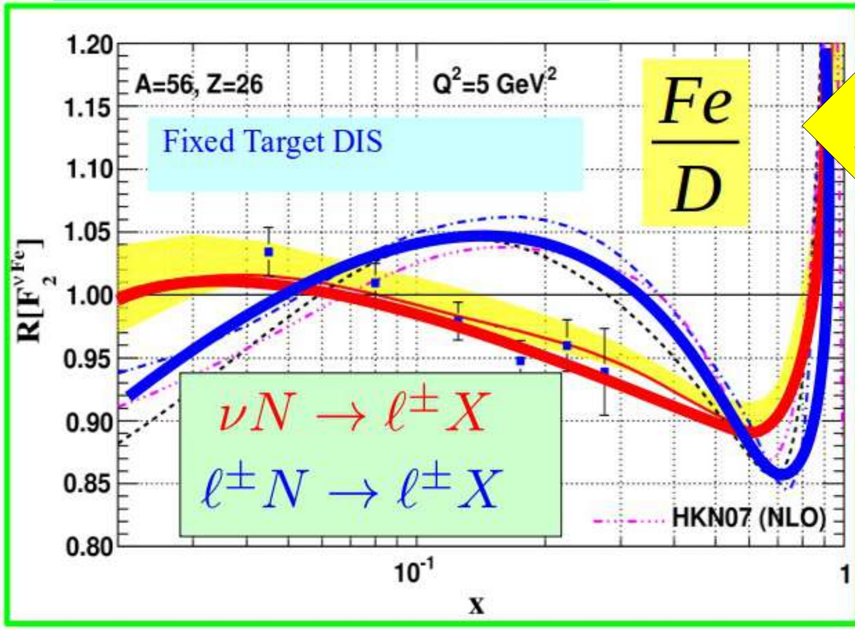
pick up M^2/Q^2 higher twist

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

Run at multiple energies

nCTEQ15ν

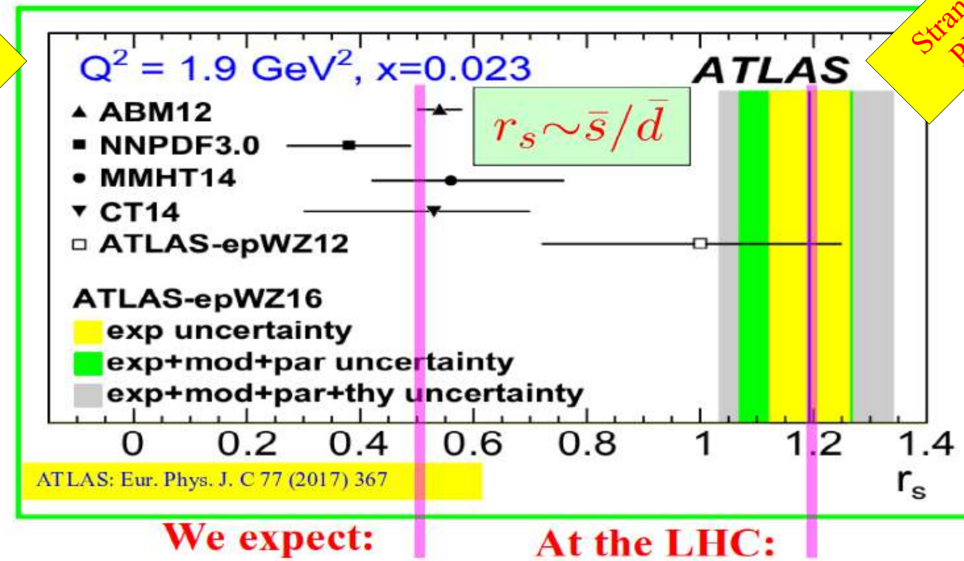
Split Personality



nCTEQ: arXiv: 2204.13157

nCTEQ15WZ

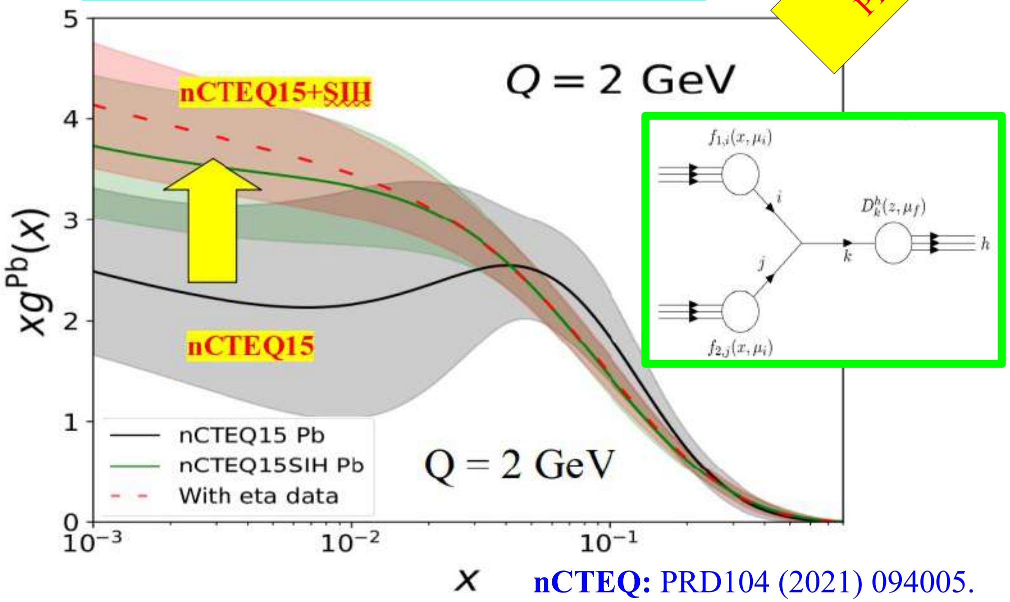
Strange PDF



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

nCTEQ15WZ+SIH

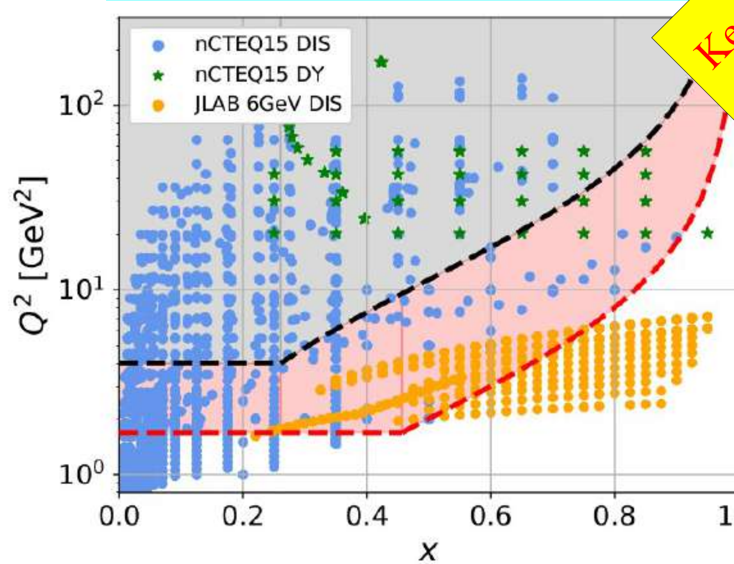
Gluon PDF



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 $f_A(x,Q,k_T,b_T,\sigma)$

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; …

TO DO LIST

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 $f_A(x,Q,k_T,b_T,\sigma)$

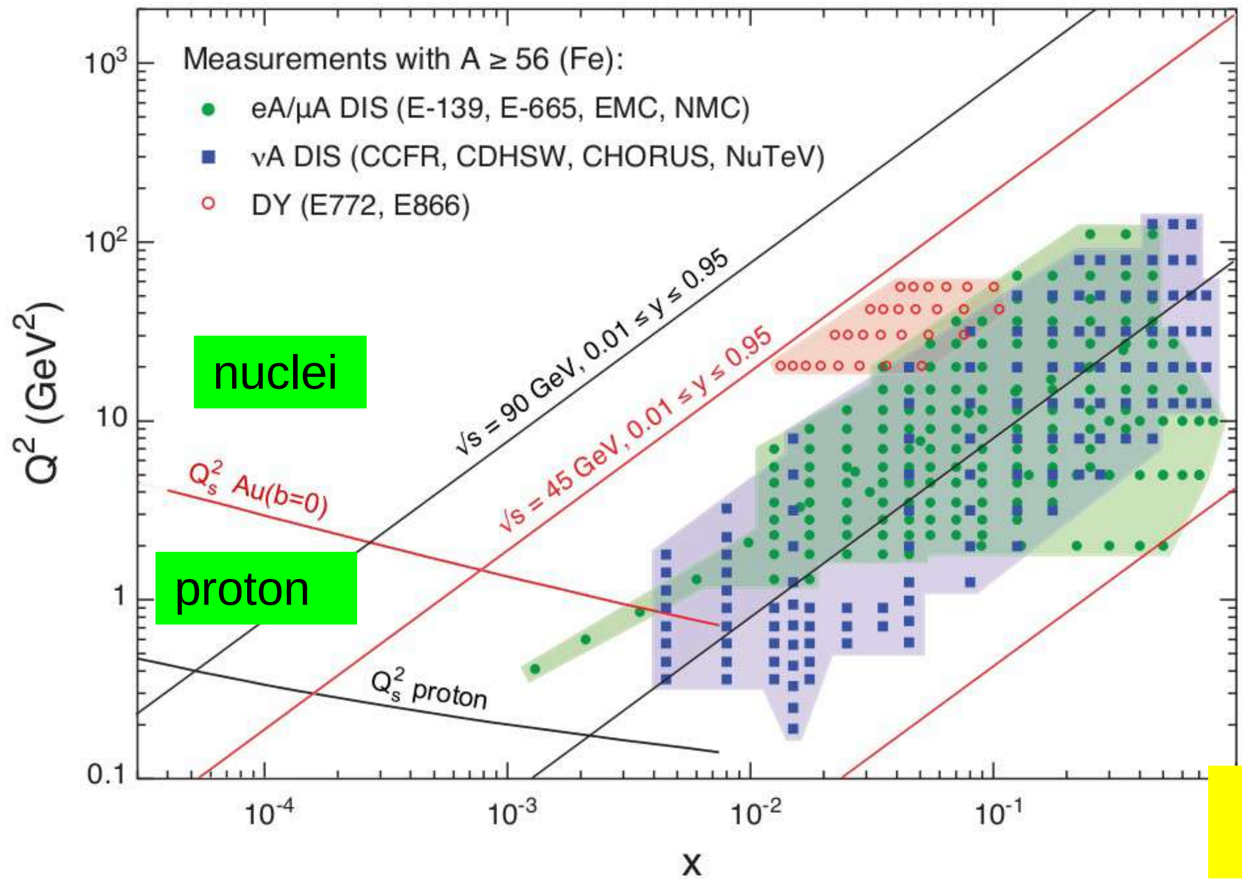
include Lattice QCD info on moments and quasi-PDFs

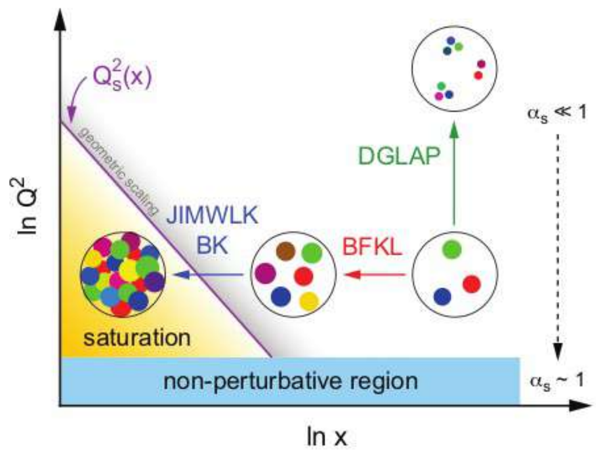
Need coordination/communication between efforts

Saturation, BFKL, recombination, ...

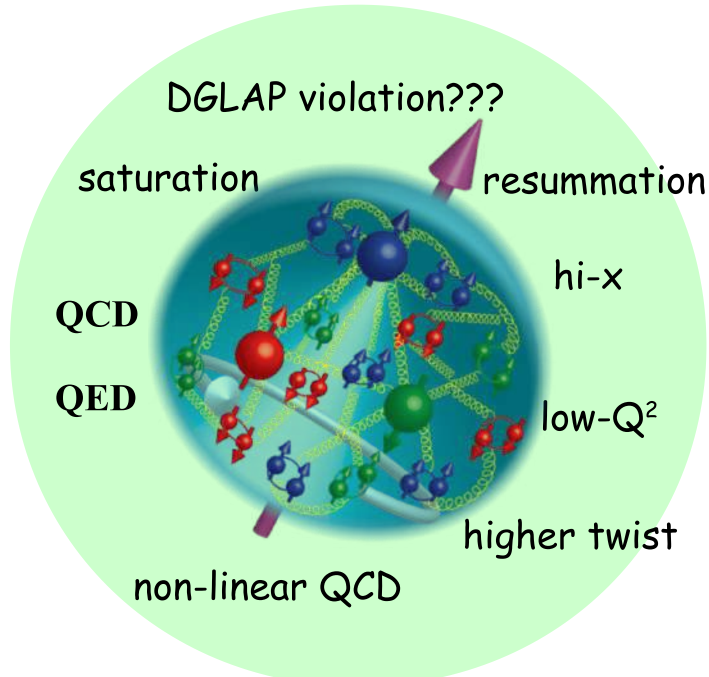
Can Saturation be Discovered at EIC?

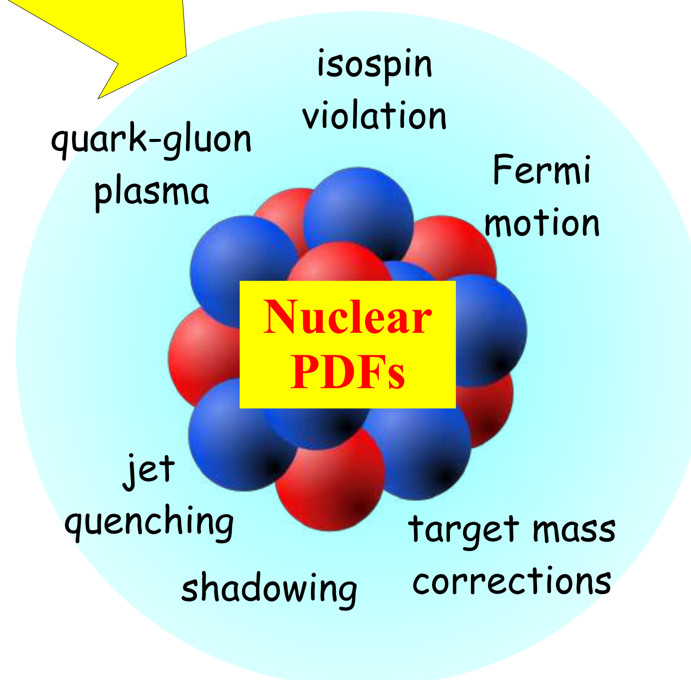
EIC has an unprecedented small-x reach for DIS on large nuclear targets, allowing to seal the discovery of saturation physics and study of its properties:

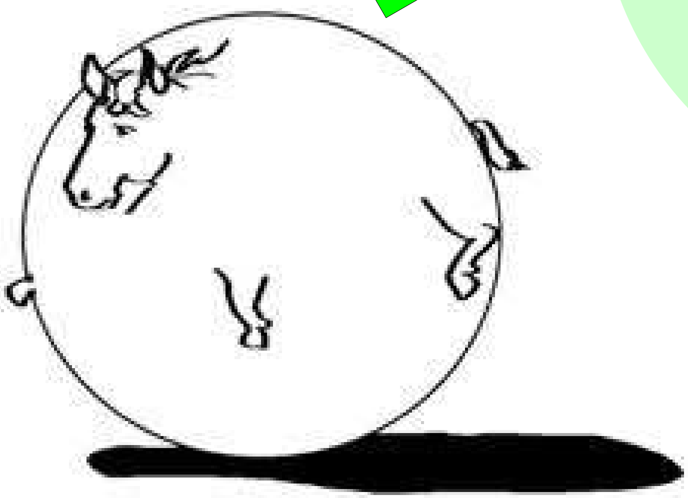




Need theoretical guidance



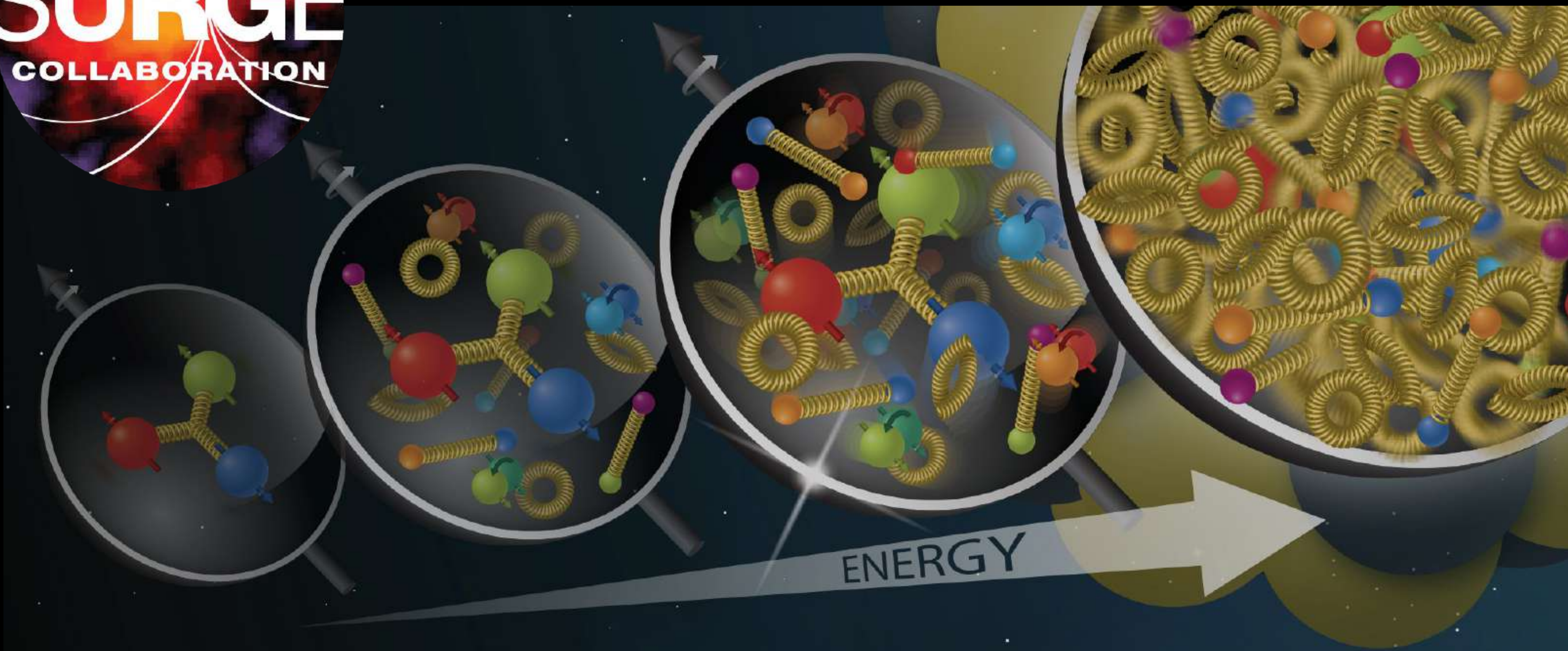




The Saturated Glue (SURGE) Collaboration is a Topical Collaboration in Nuclear Theory which aims at the discovery and exploration of the gluon saturation regime in quantum chromodynamics (QCD).

SURGE COLLABORATION

https://www.bnl.gov/physics/surge/



Mission statement: Discover and explore the gluon saturation regime of quantum chromodynamics by advancing calculations to high precision and developing a comprehensive framework to compute observables and compare to a wide range of experimental data, including predictions for the Electron Ion Collider (EIC).

Members

Brookhaven National Laboratory
Y. Hatta, D. Kharzeev, Y. Mehtar-Tani, S. Mukherjee, P. Petreczky, R. Venugopalan

Old Dominion University / Thomas Jefferson Laboratory I. Balitsky

McGill University
S. Caron-Huot

CUNY, Baruch College
A. Dumitru, J. Jalilian-Marian

University of California, Los Angeles
Z. Kang

The Ohio State University
Y. Kovchegov

University of Connecticut
A. Kovner

University of Illinois at Urbana Champaign
J. Noronha-Hostler

Southern Methodist University
F. Olness

Lebanon Valley College
D. Pitonyak

New Mexico State University
M. Sievert

North Carolina State University
V. Skokov

Penn State University
A. Stasto

University of California Berkeley / Lawrence Berkeley National Laboratory
X.-N. Wang

Steering Committee

Björn Schenke

Anna Stasto

Zhongbo Kang

Jaki Noronha-Hostler

Matt Sievert

Physics questions

Initial conditions: How to parametrize and/or compute initial conditions for the evolution ?

Small x evolution: LO evolution is not sufficient for accuracy. Need the NLO and beyond. How to consistently implement resummation in non-linear evolution and match small with large x, relevant for EIC kinematic regime ?

Impact factors: Need impact factors at NLO for accuracy. For many observables analytical and numerical implementations are missing.

Spin: How proton spin emerges from spins and angular orbital momenta of quarks and gluons? What is the contribution of the small x region to the proton spin ?

Hadronization: How hadronization is affected by the presence of saturated gluons ?

Global analysis: Much progress made in increasing accuracy of cross sections in the collinear approach. Need to increase accuracy of predictions based on high energy factorization.

Topics and working groups

Initial state WG
Improve the initial conditions for evolution for unpolarized and polarized observables.

Small x evolution + NLO calculations WG
Non-linear evolution at NLO and beyond, computation and implementation of impact factors

Spin WG
Analyze role saturation in the polarized observables. Elucidate the role of chiral anomaly in small x helicity evolution.

Final states WG
Construct a framework for hadronization in a saturated environment, including development of MC generator based on CGC calculations

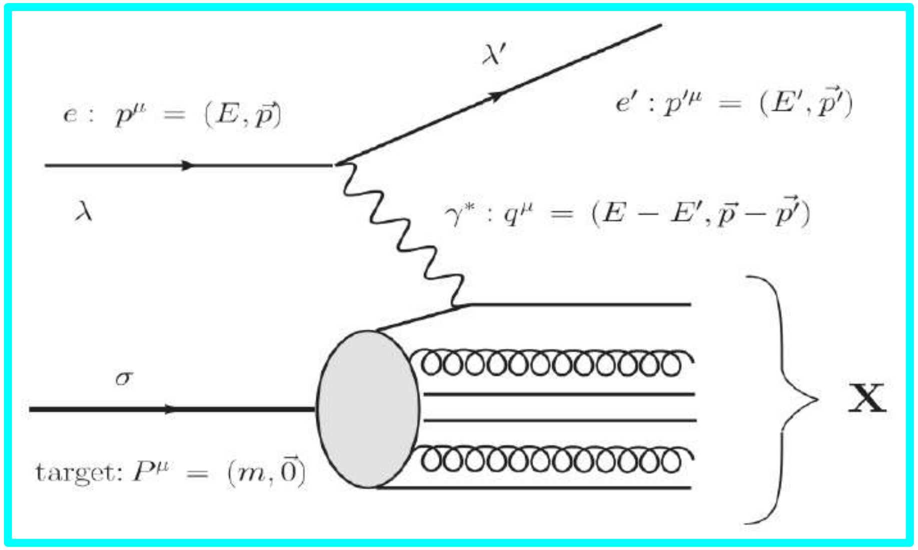
Global analysis WG
To establish saturation, perform comprehensive global analysis quantifying and minimizing uncertainties, extracting universal building blocks of high energy factorization.

- Initial state **(Vladi Skokov)**
- Small x evolution + NLO calculations **(Zhongbo Kang)**
- Spin **(Yuri Kovchegov)**
- Framework and global analysis **(Fred Olness)**
- Final state **(Xin-Nian Wang)**





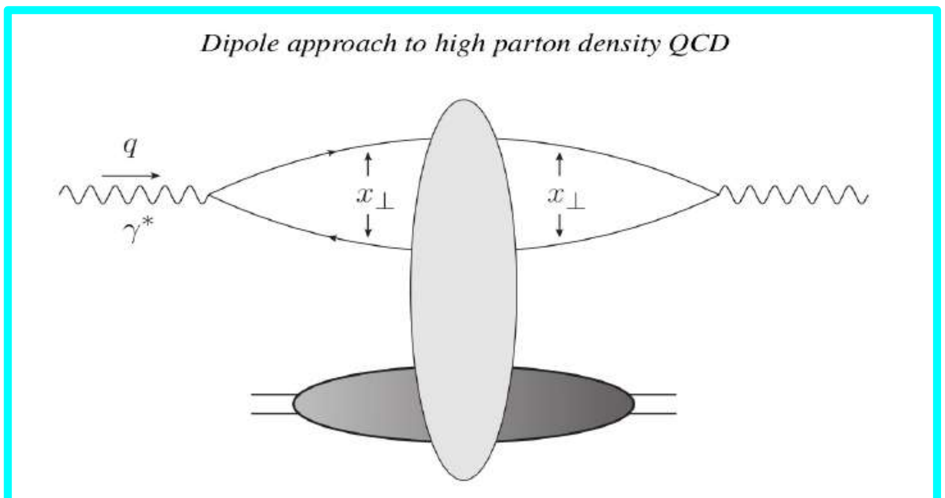
Paradigm Choice: Parton Model & Dipole Model



Parton Model

$$\sigma = f_{P\to a}(x, Q) \otimes \widehat{\sigma}_{a\gamma\to X}(x, \hat{s})$$

Implemented in **xFitter**
uses several numerical "tricks"
for efficient computation



Dipole Model

GOAL: Develop flexible framework to test initial/final-state, spin, NLO ...

APPROACH:

1) Prototype in Python
2) Use fast numerical approximations
3) Flexible framework
4) Interface to xFitter *(eventually)*

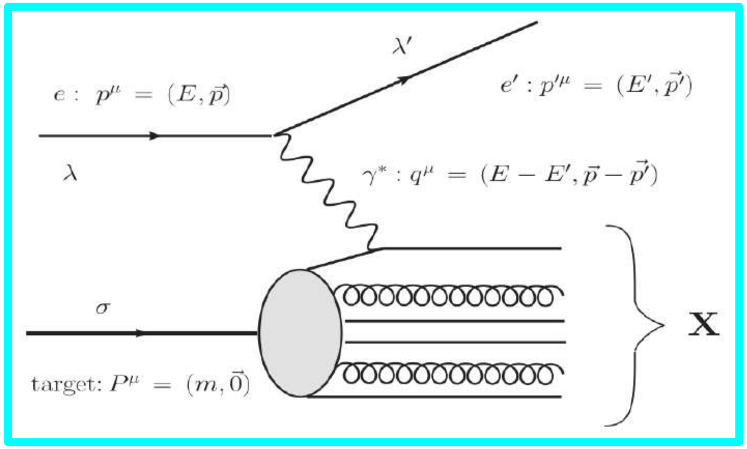
$$\sigma_{tot}^{\gamma^* A}(x, Q^2) \simeq \iint |\Psi^{\gamma^*\to q\bar{q}}(\vec{x_\perp}, z))|^2 \otimes \sigma_{tot}^{q\bar{q}A}(\vec{x_\perp}, Y)$$

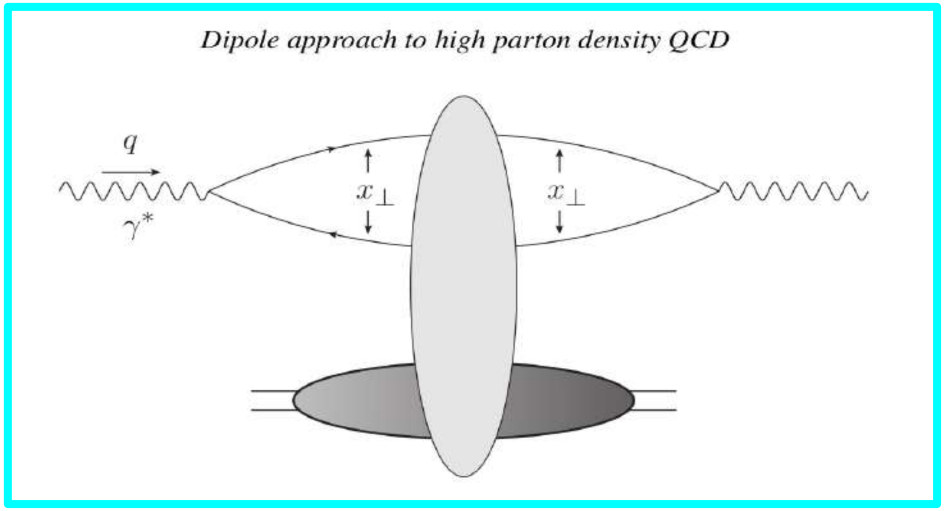
Parton Model & Dipole Model Comparison

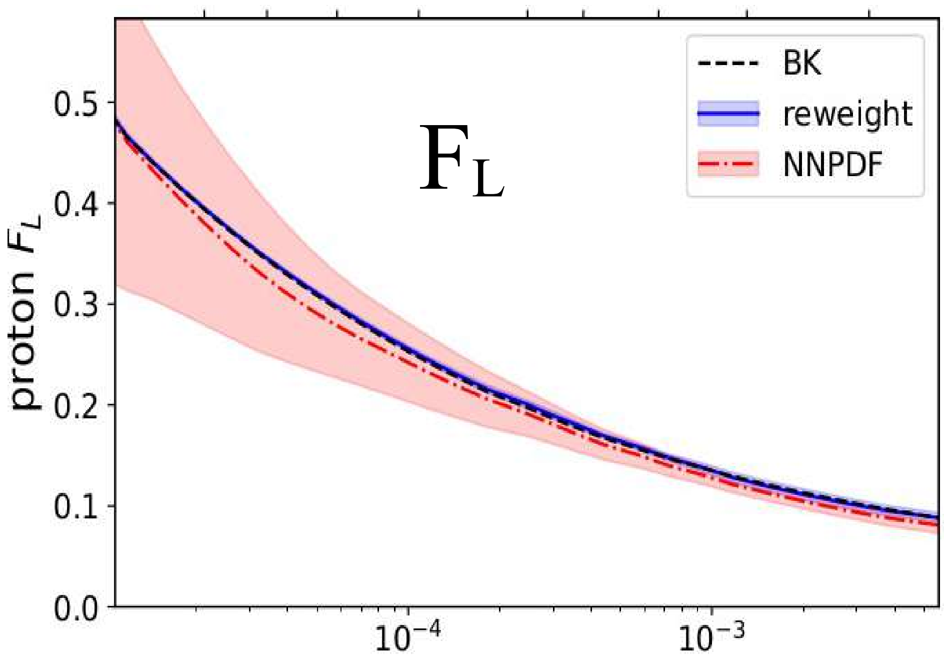
Signatures of gluon saturation from structure-function measurements

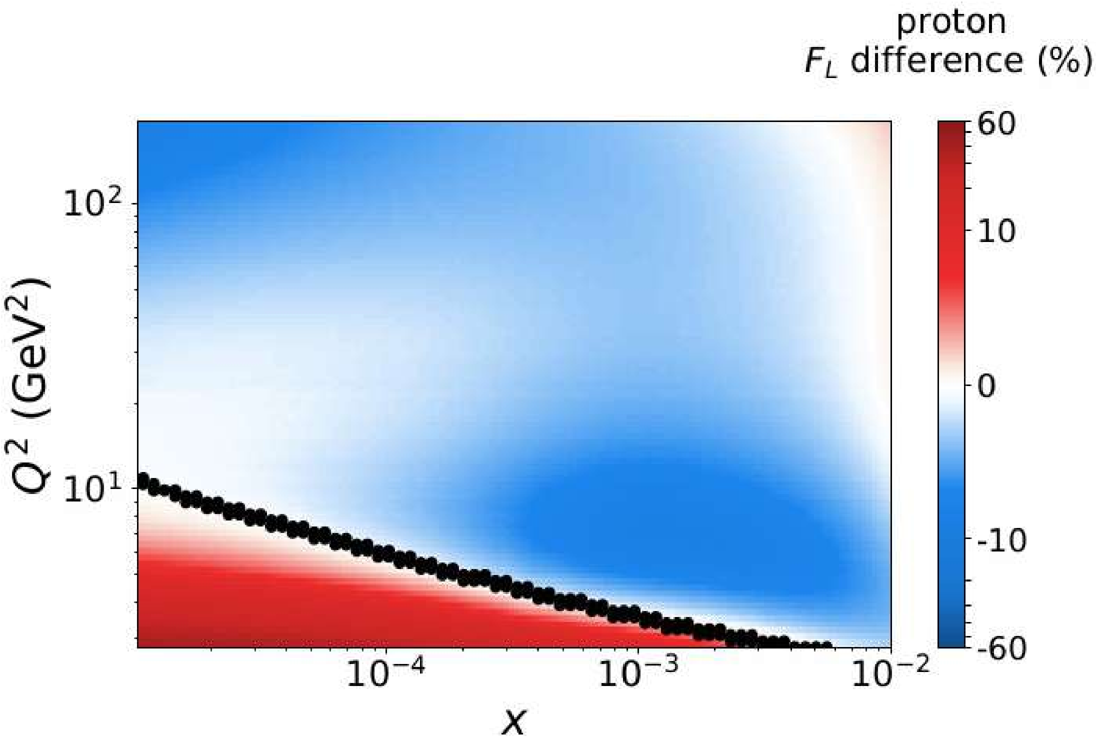
Nestor Armesto,[1,*] Tuomas Lappi,[2,3,†] Heikki Mäntysaari,[2,3,‡] Hannu Paukkunen,[2,3,§] and Mirja Tevio[2,3,¶]

Phys.Rev.D 105 (2022) 11, 114017 • e-Print: 2203.05846 [hep-ph]









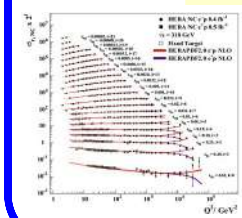
xFitter

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



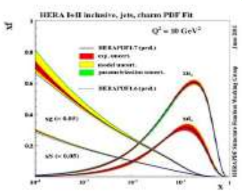
Data: HERA, Tevatron, LHC, fixed target experiments

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

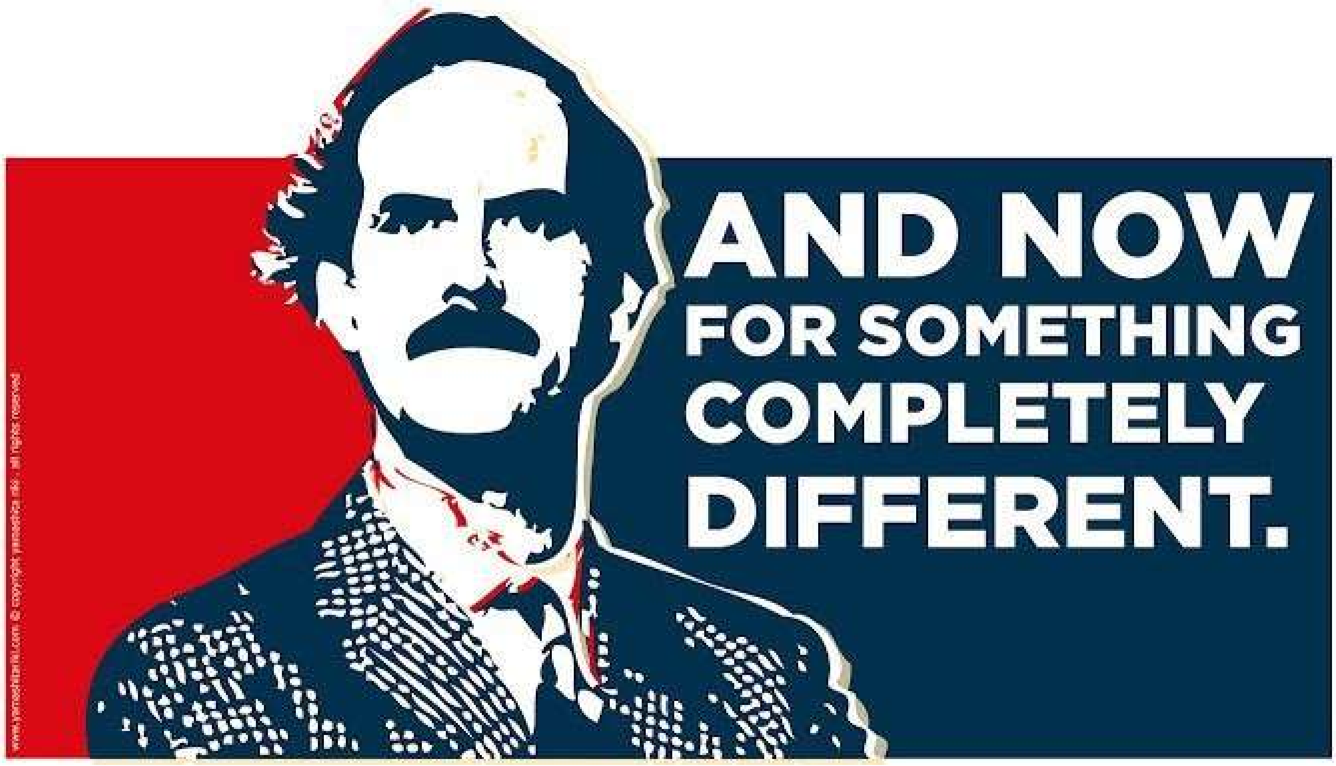
Features & Recent Updates:
- **NNLO DGLAP**
- Photon PDF & **QED**
- Pole & MS-bar masses
- Profiling and Re-Weighting
- **BFKL interface**
- Heavy Quark Variable Treshold
- Improvements in χ^2 and correlations
- **TMD** PDFs (uPDFs)
- *… and many other*

xFitter 2.2.0 Future Freeze

xFitter

xFitter Collaboration Meeting February 2020, DESY

www.xFitter.org



SRC

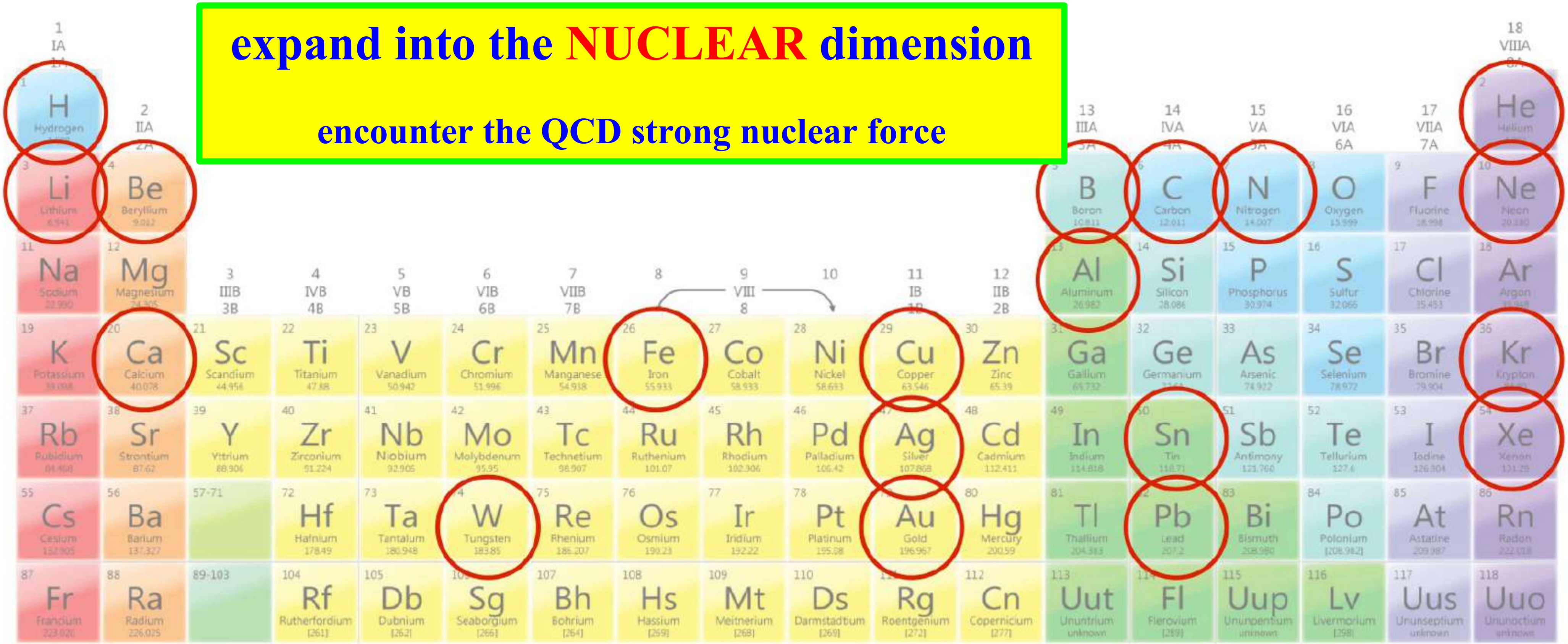
nCTEQ

nuclear parton distribution functions

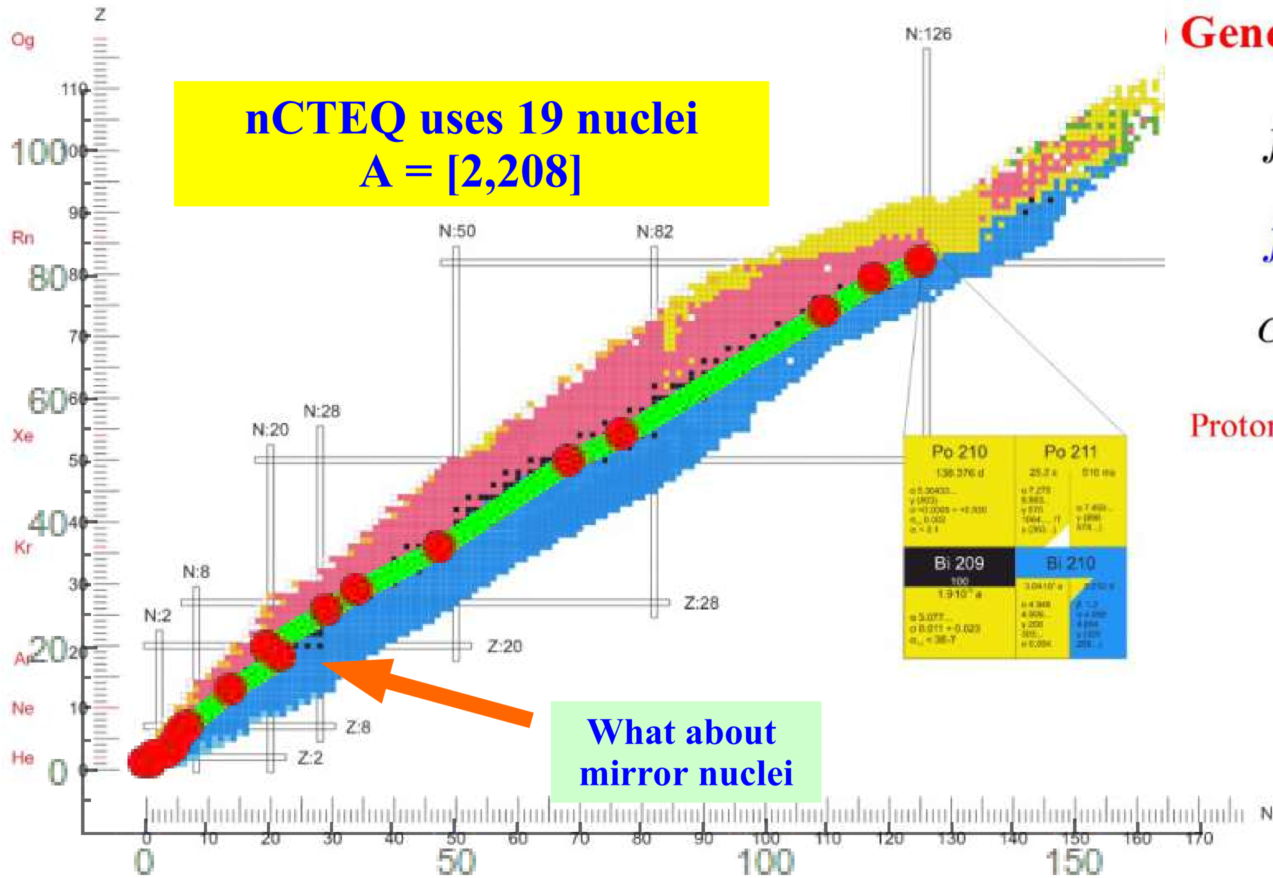
nuclear Coordinated Theoretical-Experimental Project on QCD

expand into the NUCLEAR dimension

encounter the QCD strong nuclear force



Nuclear A-Dependence



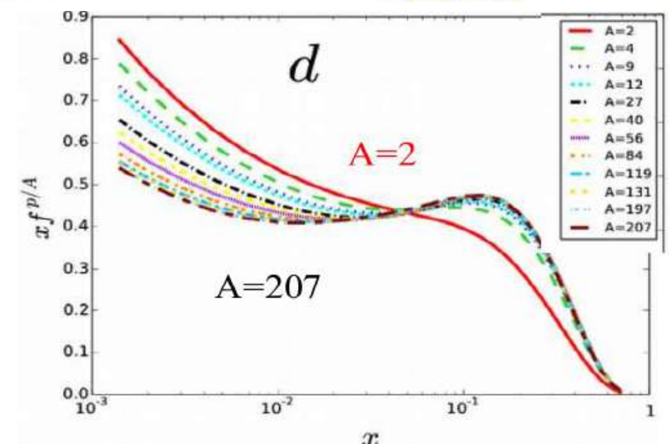
Generalized A-parameterization (nCTEQ)

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

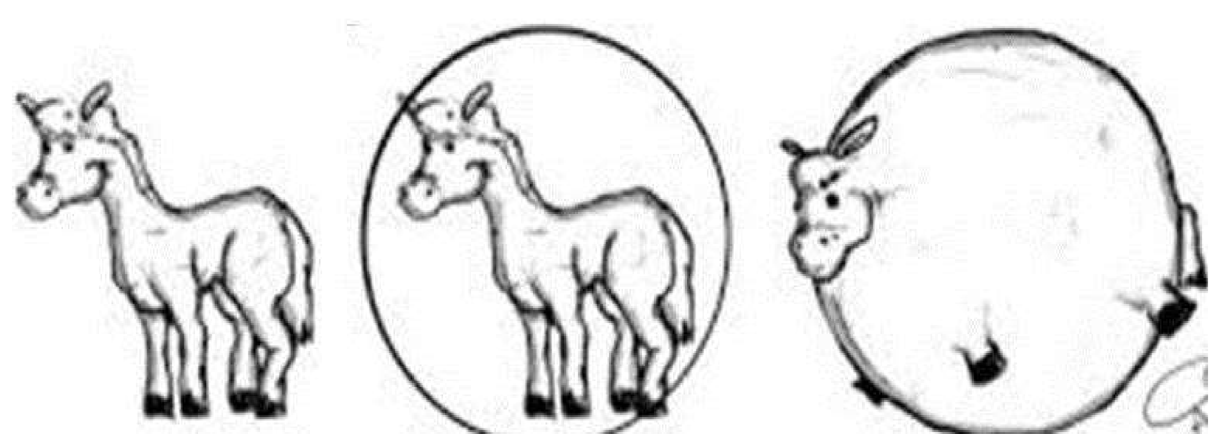
$$f \sim \ldots x^{c_1(A)}(1-x)^{c_2(A)}\ldots$$

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

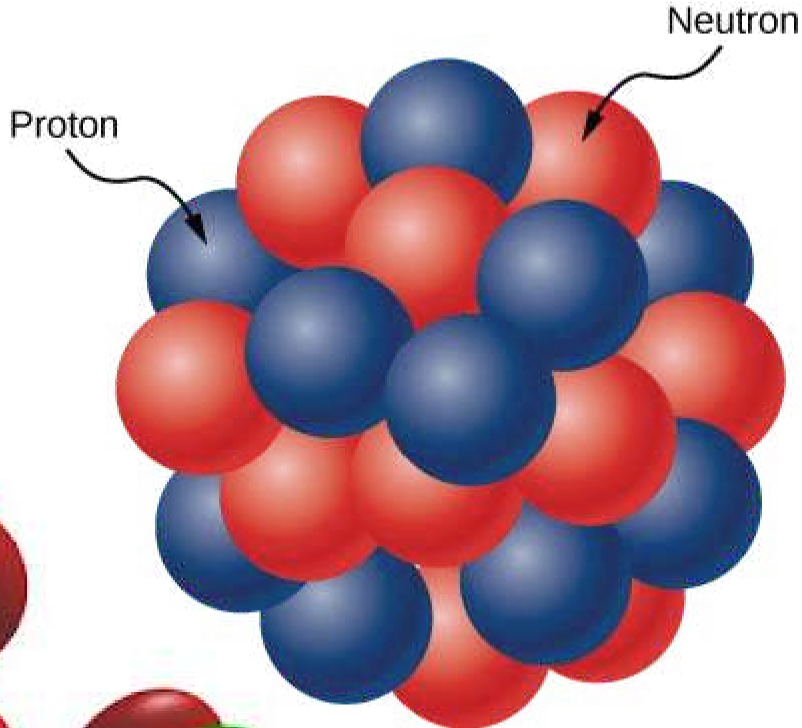
Proton → $c_{k,0}$; Nuclear → $c_{k,1}$, $c_{k,2}$

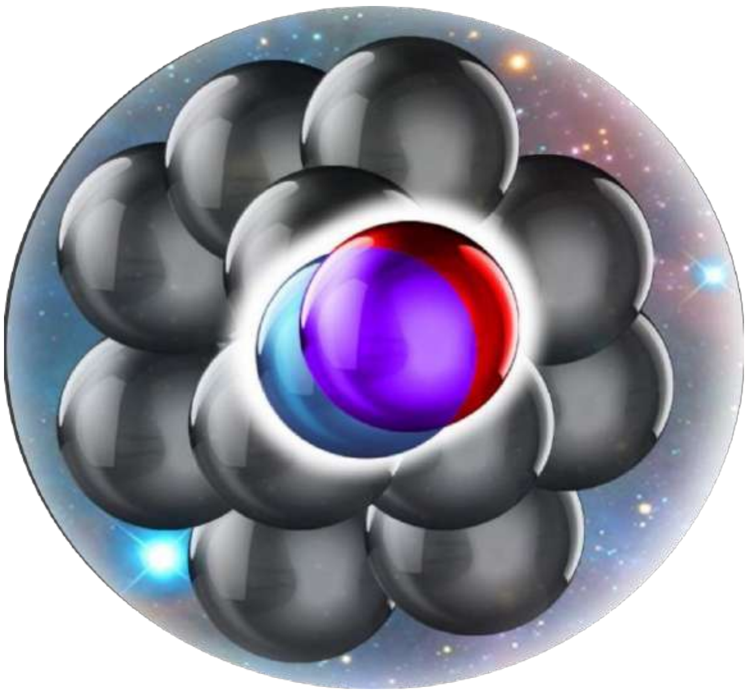


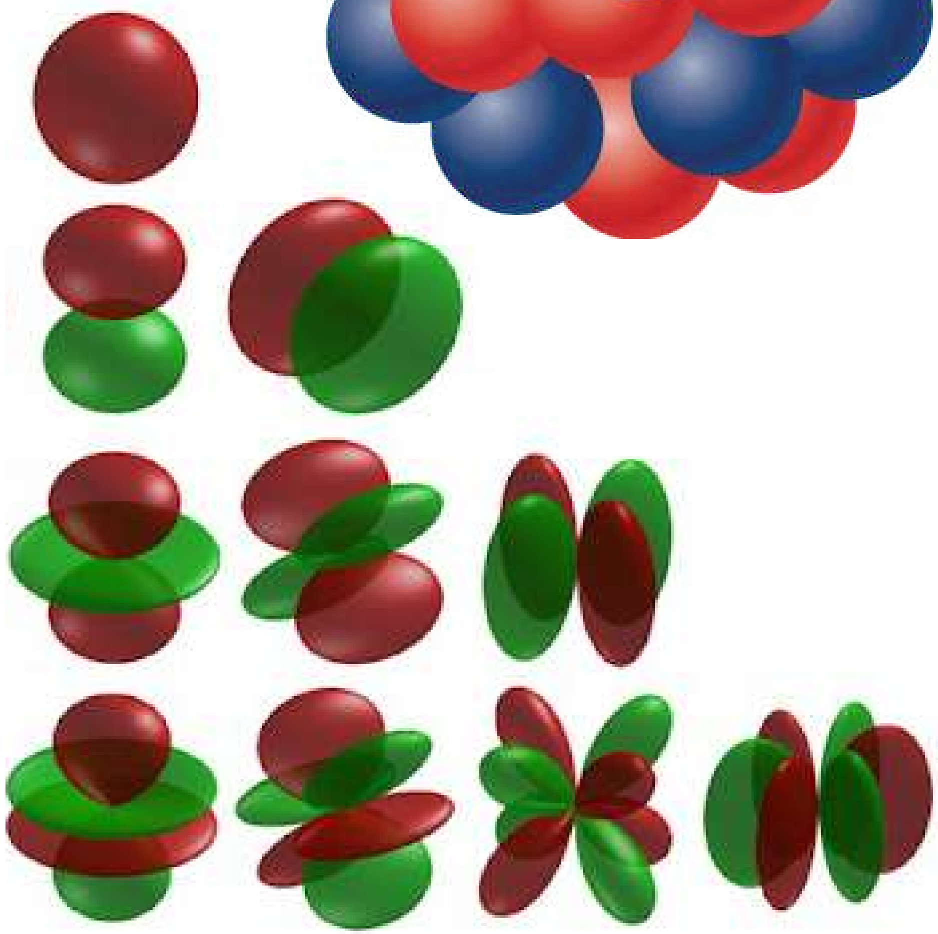
[[2, 275],	[56, 134],
[3, 125],	[64, 61],
[4, 66],	[84, 84],
[6, 15],	[108, 7],
[9, 49],	[119, 152],
[12, 196],	[131, 4],
[14, 101],	[184, 37],
[27, 73],	[197, 50],
[40, 92],	[208, 163]]

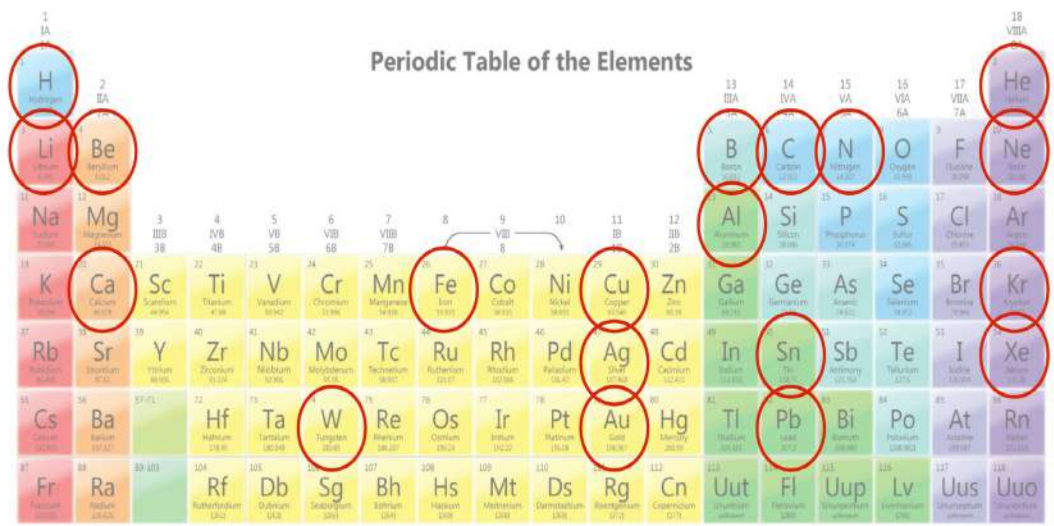


P, H2, HE3, HE4, LI6, LI7, BE9, C12, N14, AL27, CA40, FE56, CU64, KR84, AG108, SN119, XE131, W184, AU197, PB208


Neutron
Proton

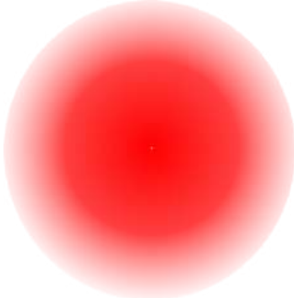




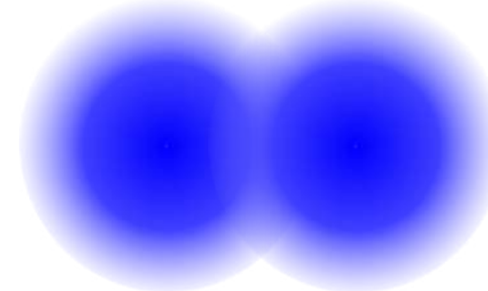

Periodic Table of the Elements
H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Rf Db Sg Bh Hs Mt Ds Rg Cn Uut Fl Uup Lv Uus Uuo

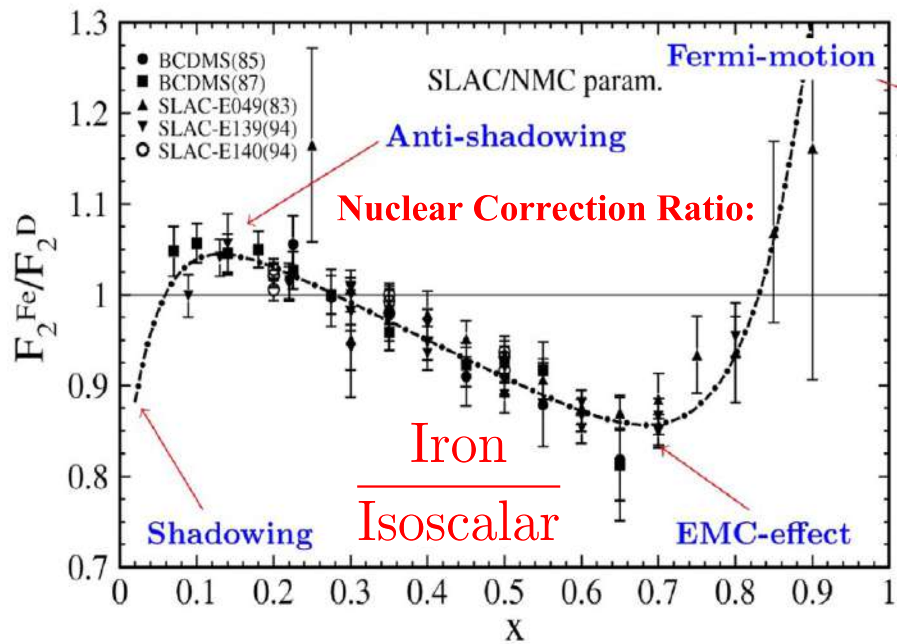
“Free nucleons” + “nucleon pairs”

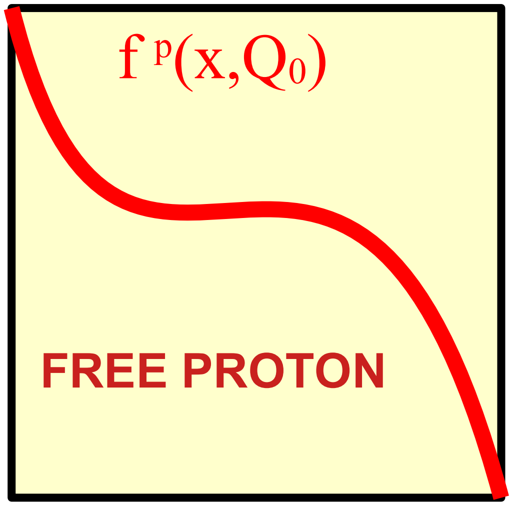
nucleon

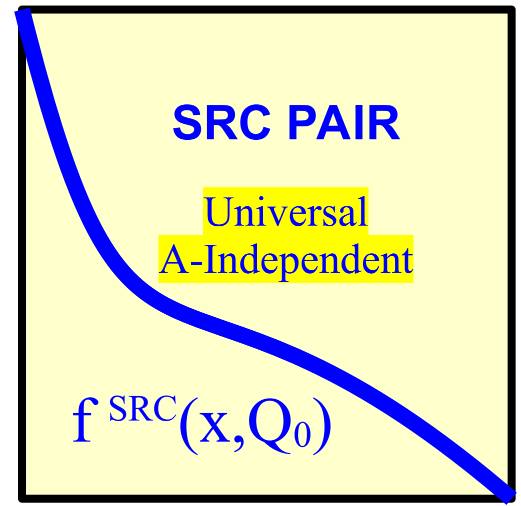


nucleon - nucleon









Linear Combination of 2 functions

$$f^{A}(x,Q_0) = (1-c_A)\, f^{p}(x,Q_0) + (c_A)\, f^{SRC}(x,Q_0)$$

Universal
A-Independent

Very different from standard parm. (e.g., nCTEQ)

Question: do C_A coefficients display any patterns???

Is the fit reasonable???

Improved fit compared to traditional approach

$\chi^2/N_{\rm data}$	DIS	DY	W/Z	JLab	$\chi^2_{\rm tot}$	$\frac{\chi^2_{\rm tot}}{N_{\rm DOF}}$
traditional	0.85	0.97	0.88	0.72	1408	0.85
baseSRC	0.84	0.75	1.11	0.41	1300	0.80
pnSRC	0.85	0.84	1.14	0.49	1350	0.82
$N_{\rm data}$	1136	92	120	336	1684	

Standard

Free p & n

Link p & n

Fully accounts for all DOF

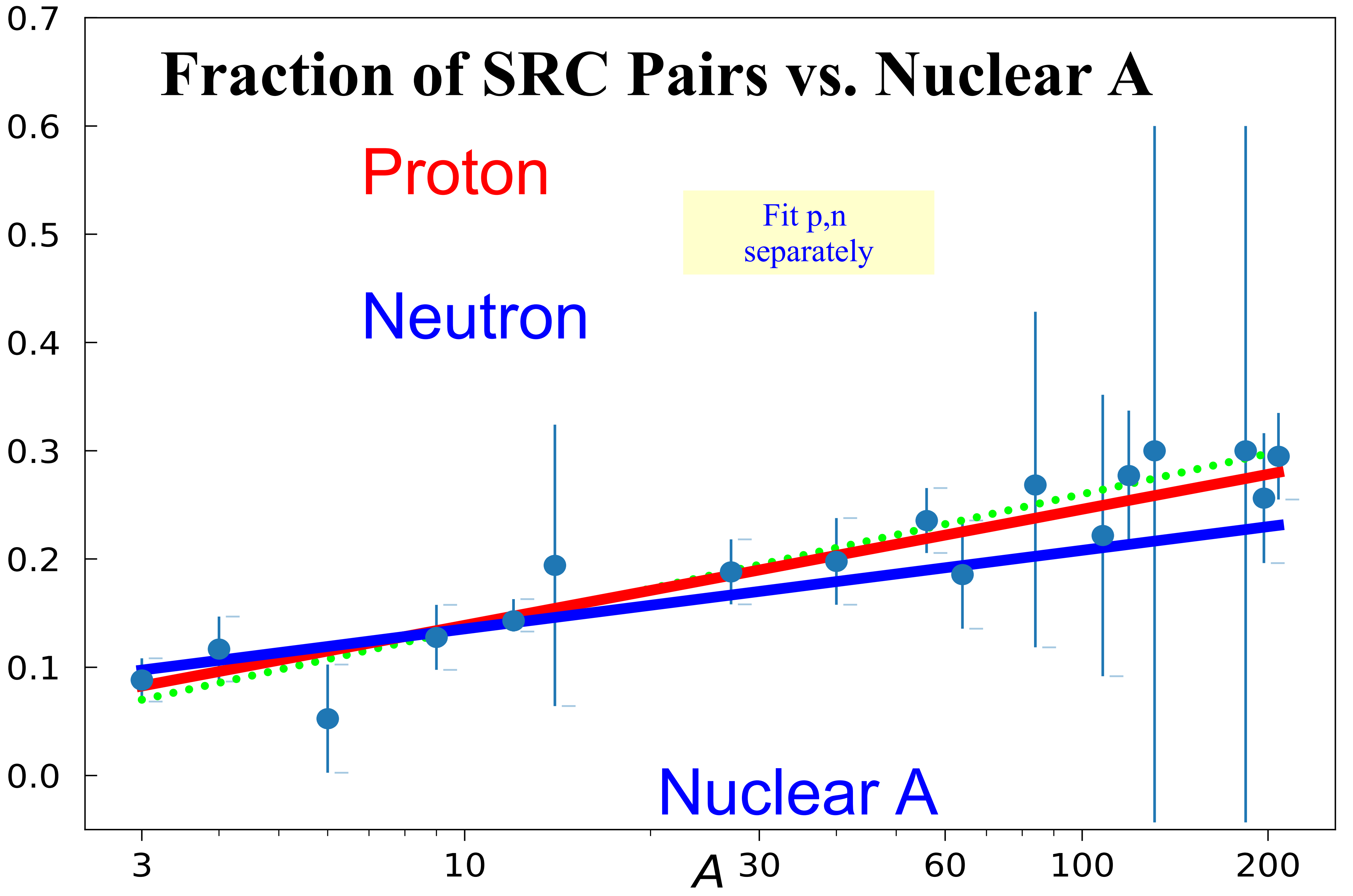
Evidence for Modified Quark-Gluon Distributions in Nuclei by Correlated Nucleon Pairs

A.W. Denniston[1,*] T. Ježo[2,†] A. Kusina[3] N. Derakhshanian[3] P. Duwentäster[2,4,5] O. Hen[1] C. Keppel[6] M. Klasen[2,7] K. Kovařík[2] J.G. Morfín[8] K.F. Muzakka[2,9] F.I. Olness[10] E. Piasetzky[11] P. Risse[2] R. Ruiz[3] I. Schienbein[12] and J.Y. Yu.[12]

Hen Lab

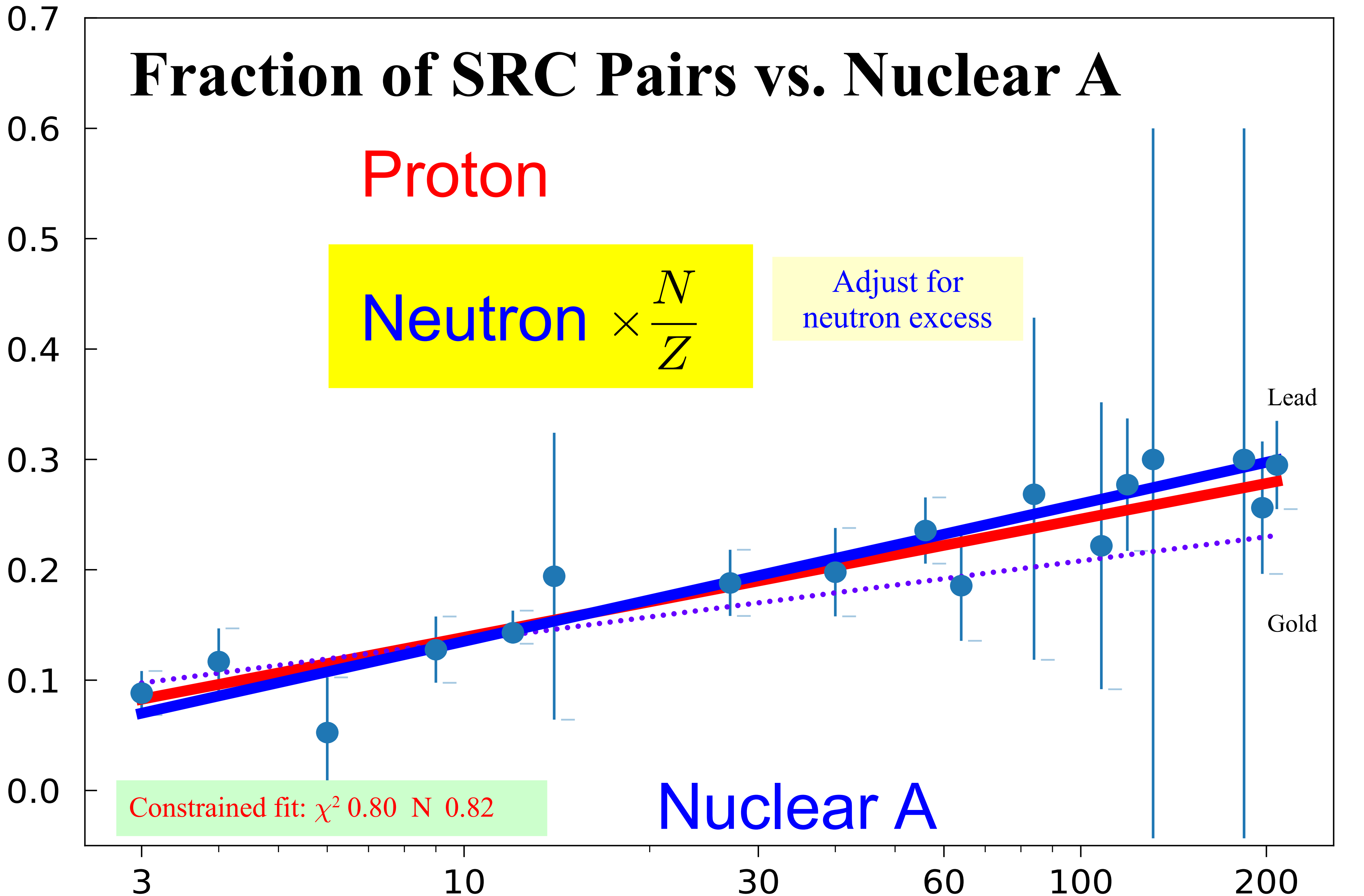
Laboratory for Nuclear Science @ MIT

ArXiV:2312.16293



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

P, H2, HE3, HE4, LI6, LI7, BE9, C12, N14, AL27, CA40, FE56, CU64, KR84, AG108, SN119, XE131, W184, AU197, PB208



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

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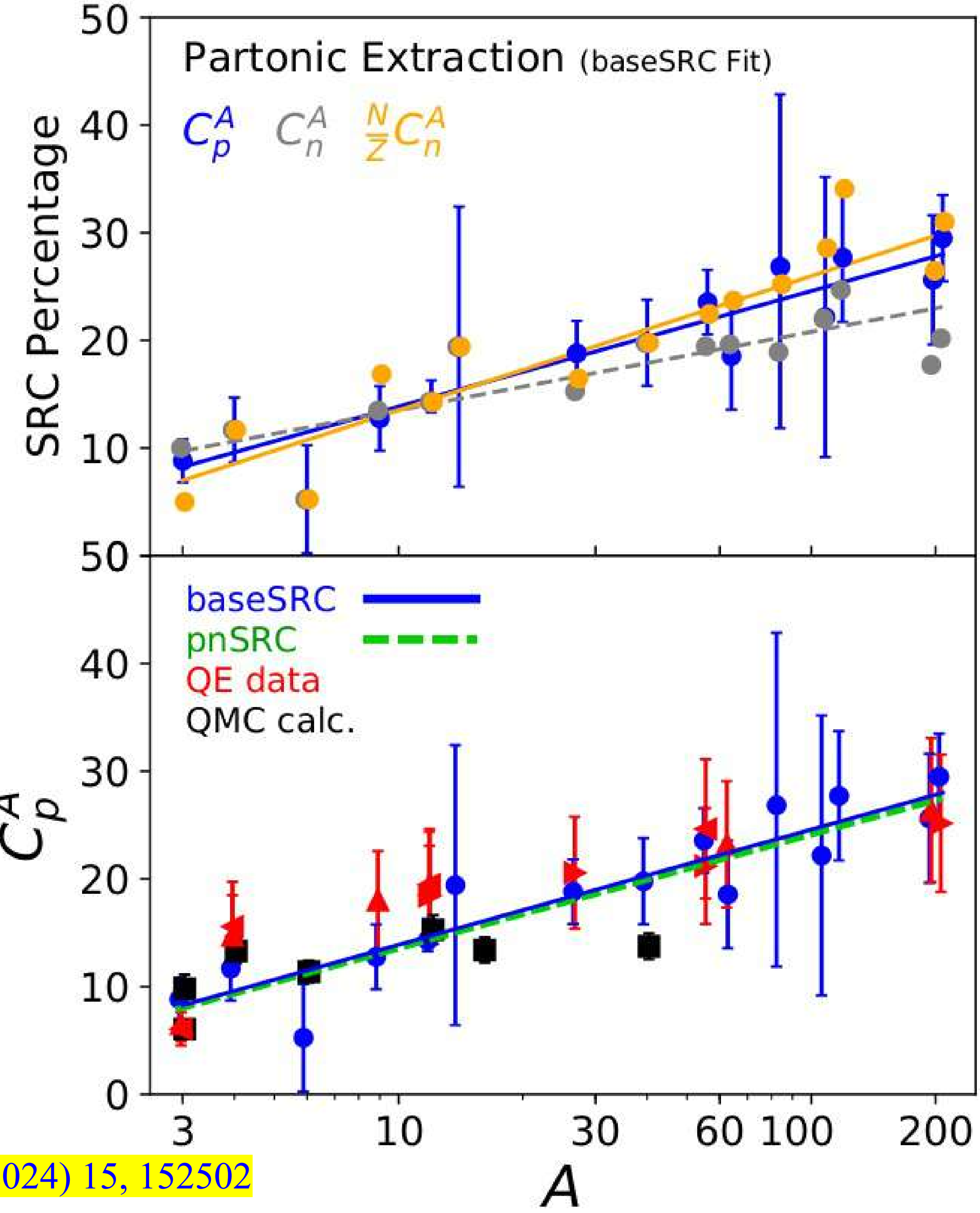
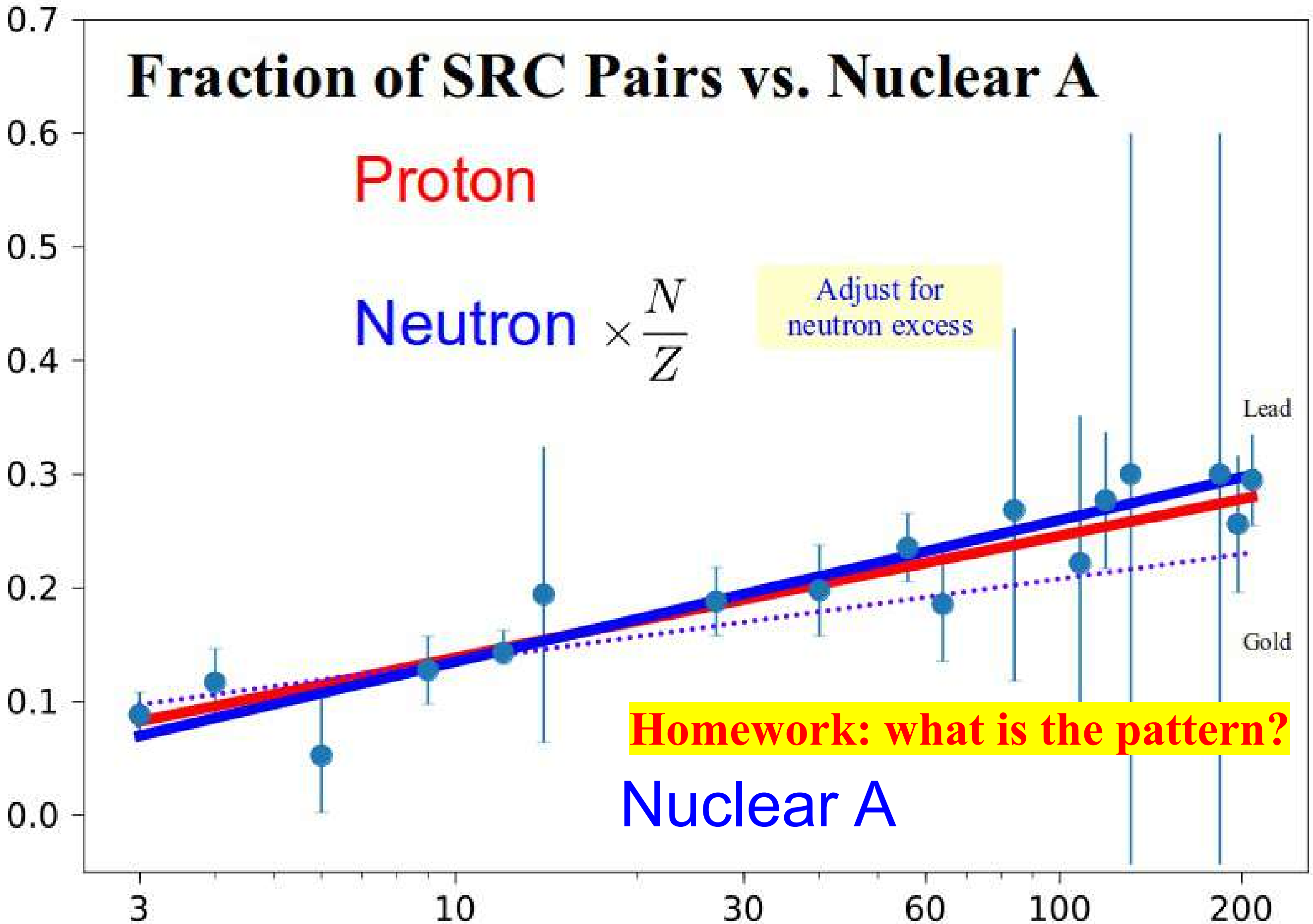


Phys.Rev.Lett. 133 (2024) 15, 152502



Gold $^{197}_{79}\mathrm{Au}$

Cp = 0.256
Cn = 0.177

A = 197
Z = 79
N = 118

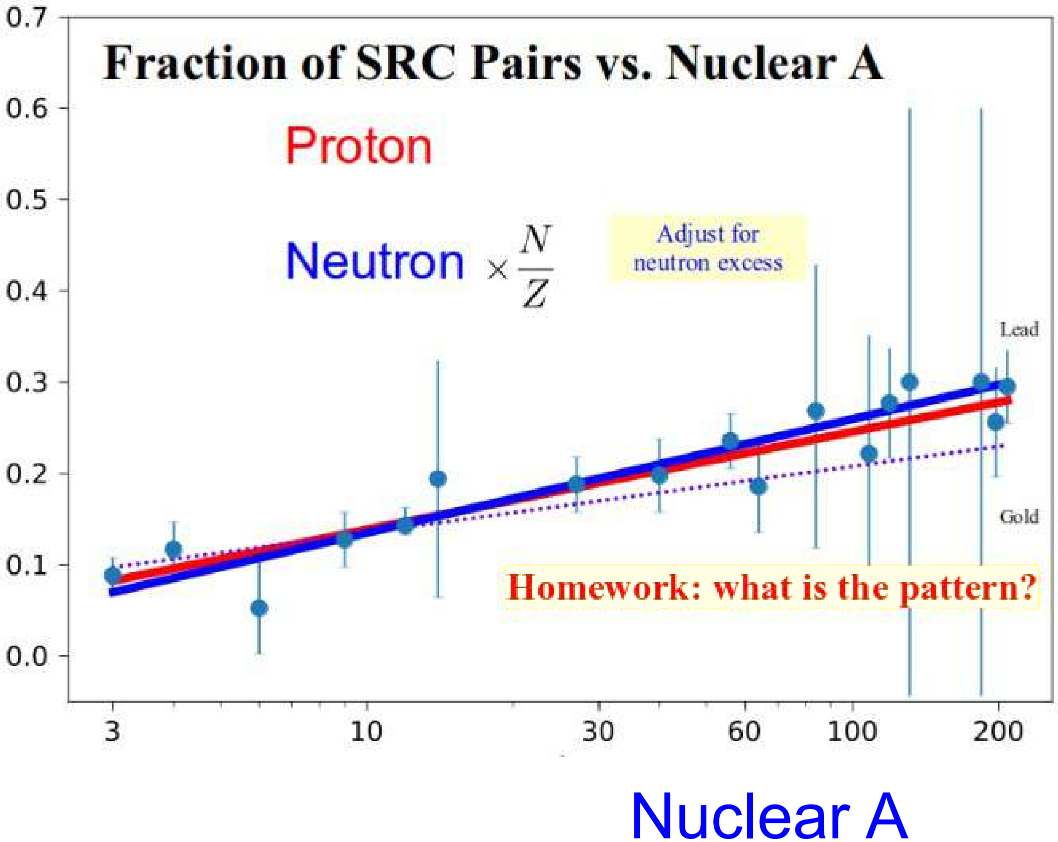
Cp × Z = **20.2**
Cn × N = **20.9**

The fit suggests equal # of protons & neutrons participate

Consistent with hypothesis that SRCs are (pn) pairs

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

Different Param. ⇒ i) NN / SRC and ii) nuclear character



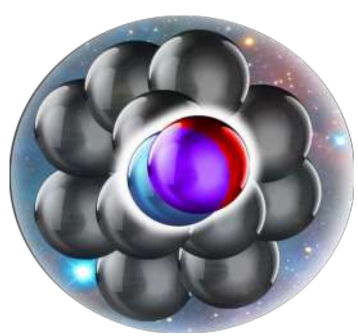
➔ Simple Nearest-Neighbor (SRC) inspired form yields remarkably good fit

➔ Comparable/better than traditional approach

➔ Coefficients scale with **ln(A)**

➔ Separate p,n fits are consistent with (pn) SRC pairs

χ^2/N_{data}	DIS	DY	W/Z	JLab	χ^2_{tot}	$\frac{\chi^2_{\text{tot}}}{N_{\text{DOF}}}$
traditional	0.85	0.97	0.88	0.72	1408	0.85
baseSRC	0.84	0.75	1.11	0.41	1300	0.80
pnSRC	0.85	0.84	1.14	0.49	1350	0.82
N_{data}	1136	92	120	336	1684	



Nature is trying to tell us something

This parameter form connects to new concepts

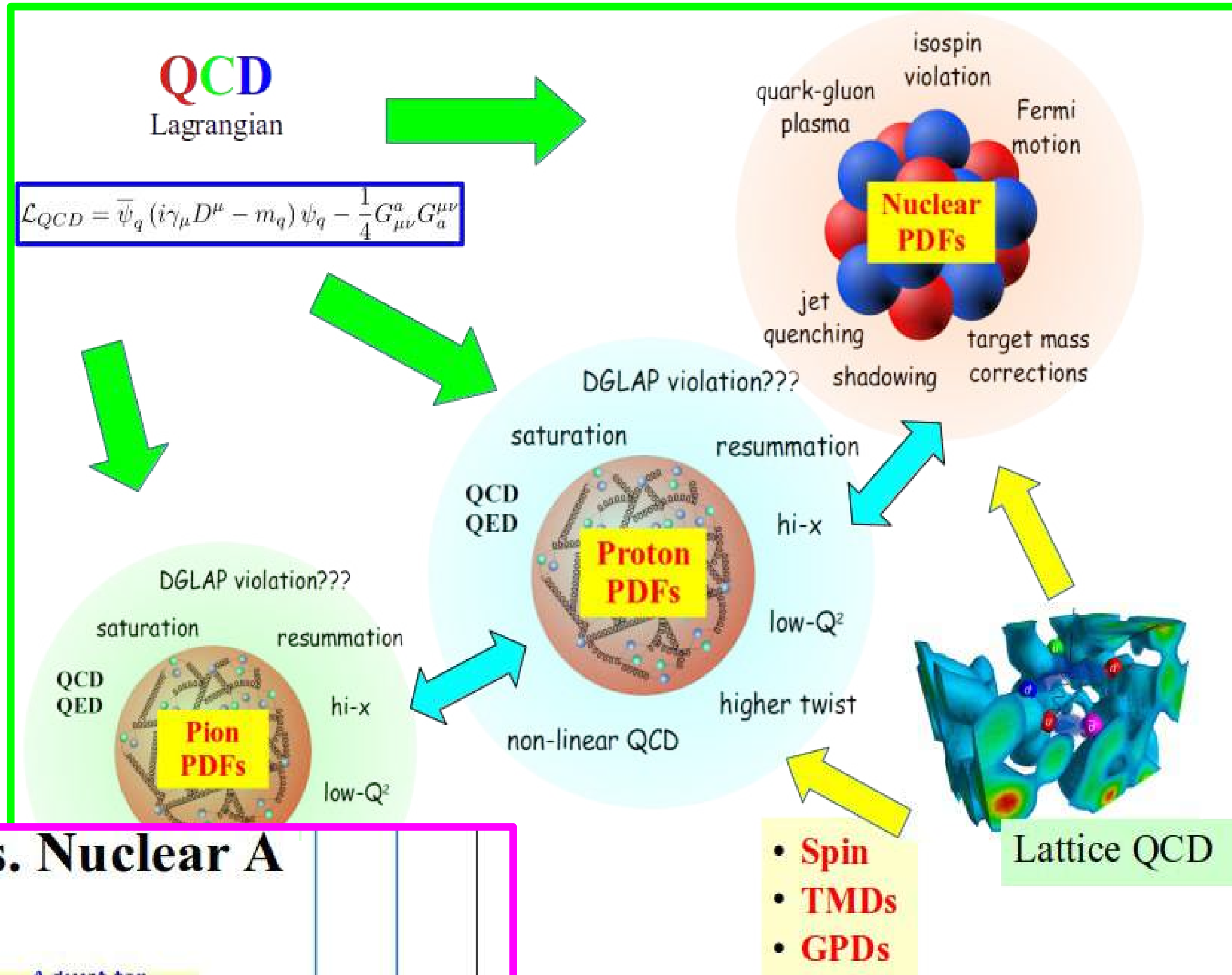
CONCLUSIONS:

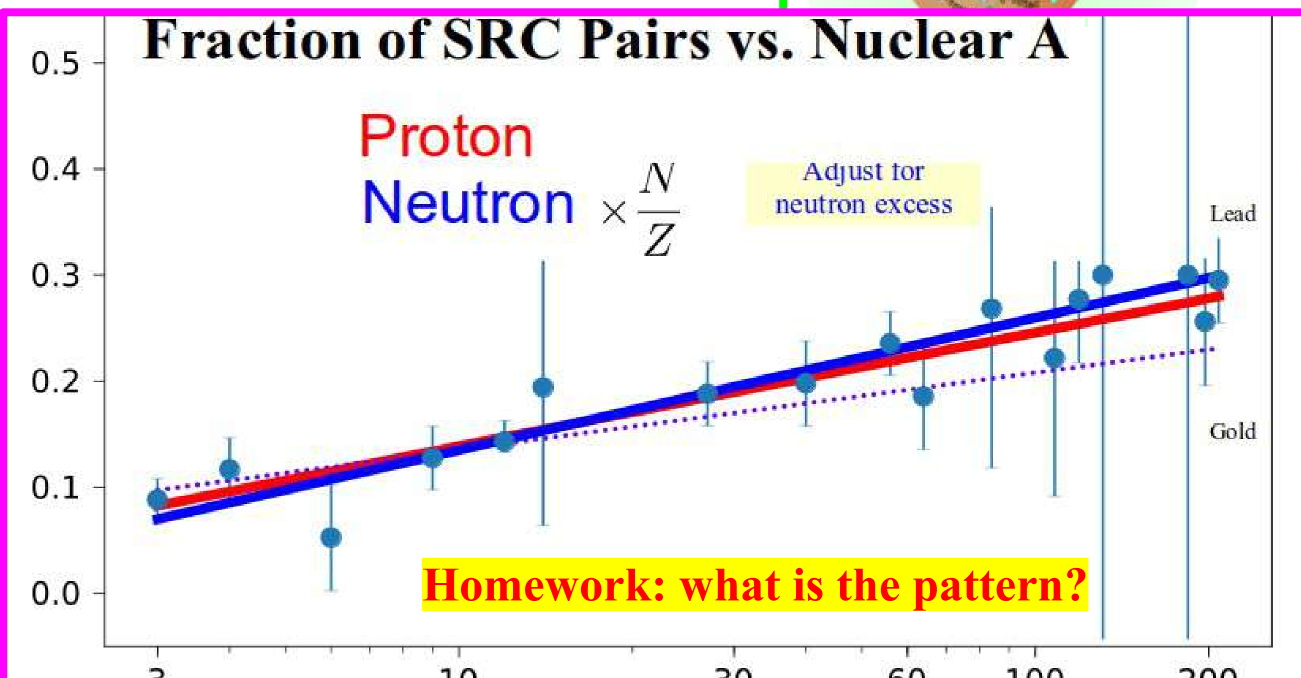
Assembling the puzzle pieces

Interdisciplinary …
Use tools from
HEP, Nuclear,
& Lattice QCD

… to really understand the

strong force





Nature is telling us ...

Why (pn) pairs?

What drives this pattern?