

Precision QCD: Preparing for the EIC

From PDFs to the underlying QCD

Fred Olness
SMU

*Thanks for substantial input
from my friends & colleagues*

nCTEQ
nuclear parton distribution functions



CTEQ

CTEQ Fall Meeting

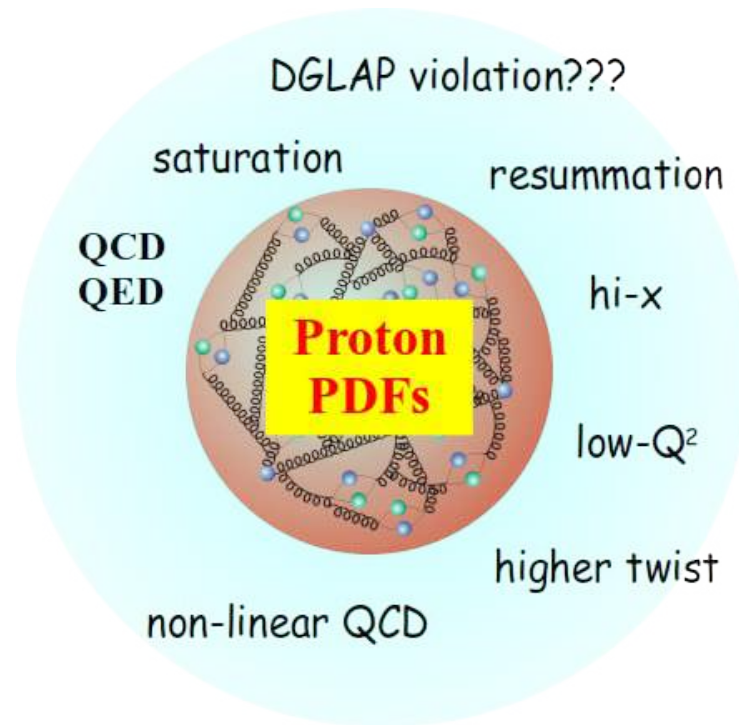
Christopher Newport University
21-22 November 2024

A few years ago ...



Busch
GARDENS.
WILLIAMSBURG, VA





QCD
Lagrangian

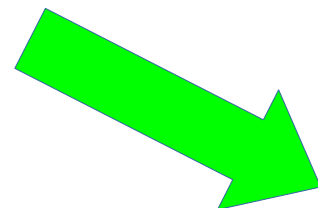
$$\mathcal{L}_{QCD} = \bar{\psi}_q (i\gamma_\mu D^\mu - m_q) \psi_q - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}$$



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

Nuclear PDFs

Nuclear targets key for flavor differentiation



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

Proton PDFs

QCD
QED

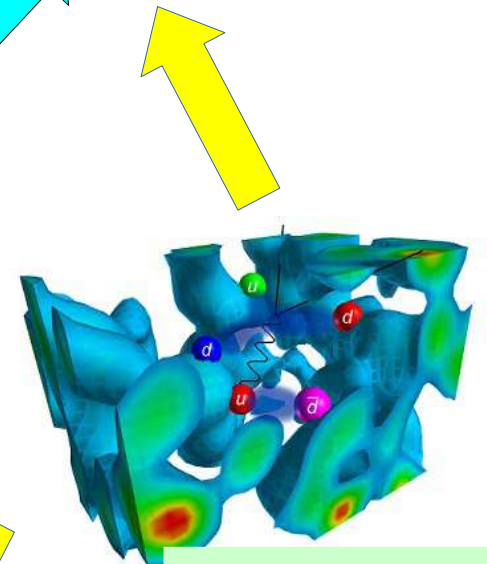


DGLAP violation???

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

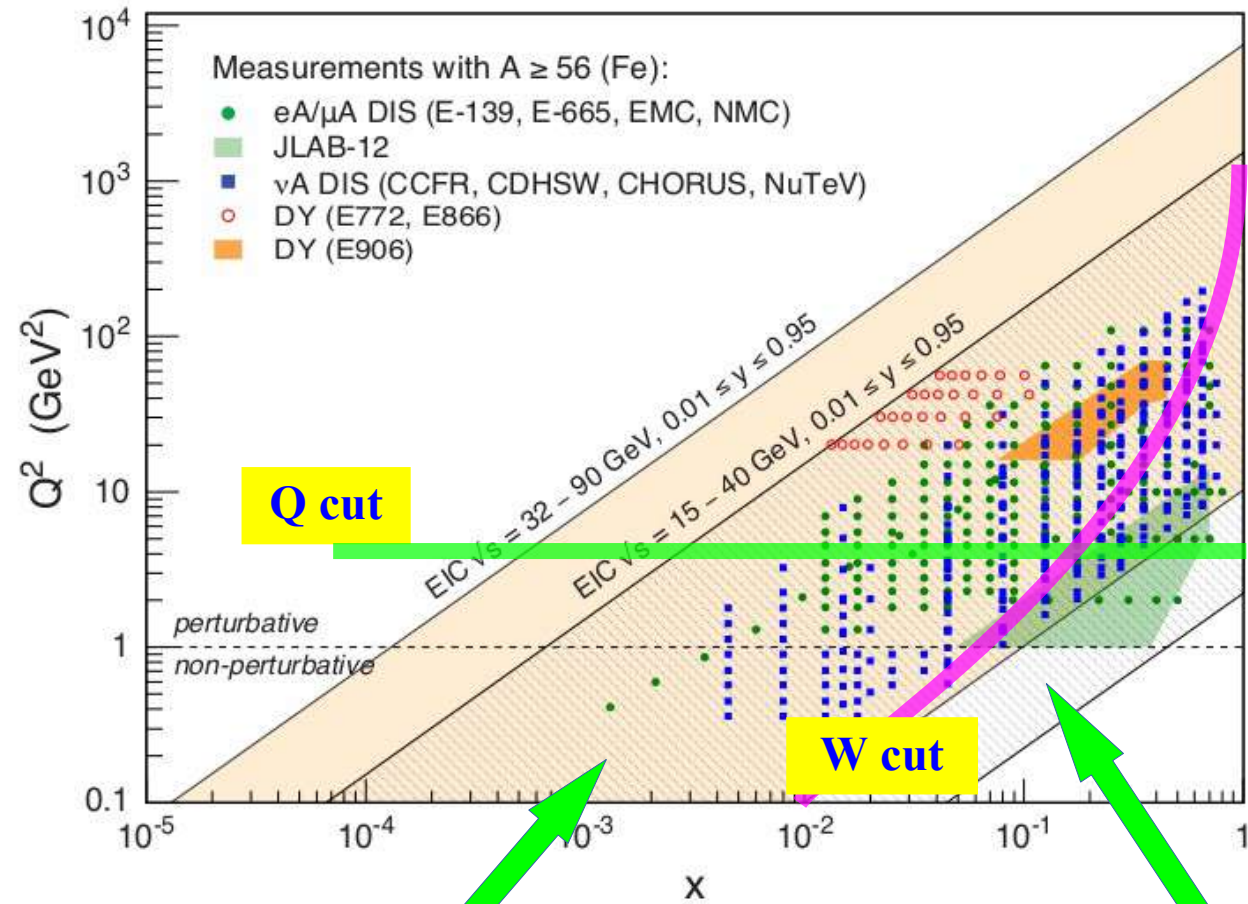
Pion PDFs

QCD
QED



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

Lattice QCD



High- x :

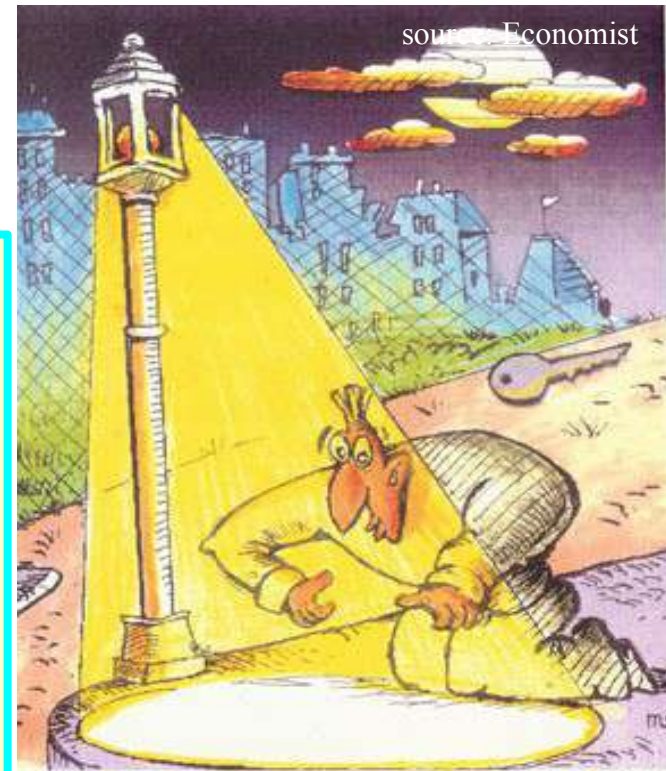
Nuclear PDFs: $x > 1$ allowed;
 impacts $F_2^{\text{Nuc}}/F_2^{\text{Iso}}$ in Fermi region
 Target Mass Corrections
 pick up M^2/Q^2 higher twist
 Deuteron Corrections
 impacts $F_2^{\text{Nuc}}/F_2^{\text{Deuteron}}$ ratio

Low- x :

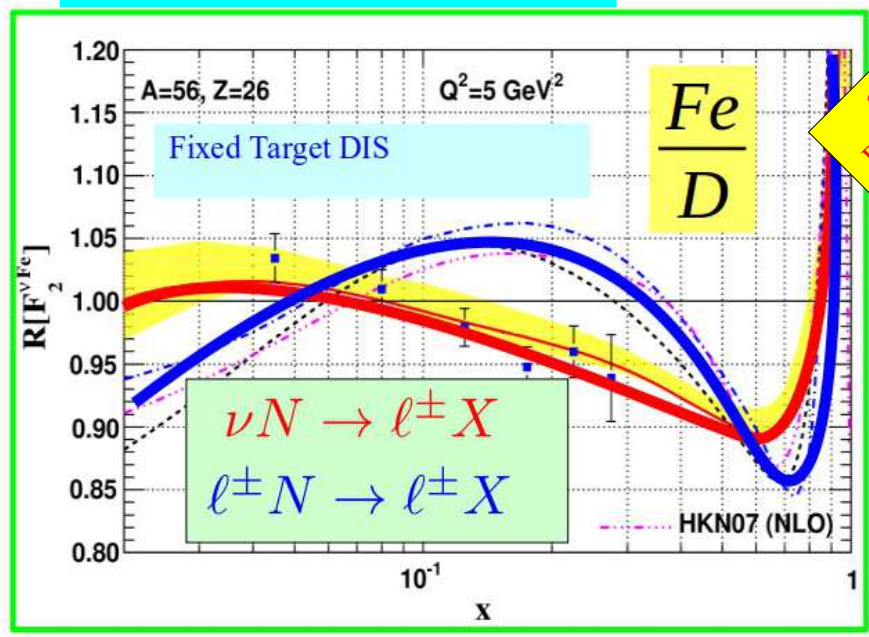
Shadowing
 Recombination
 Resummation
 BFKL
 Saturation

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

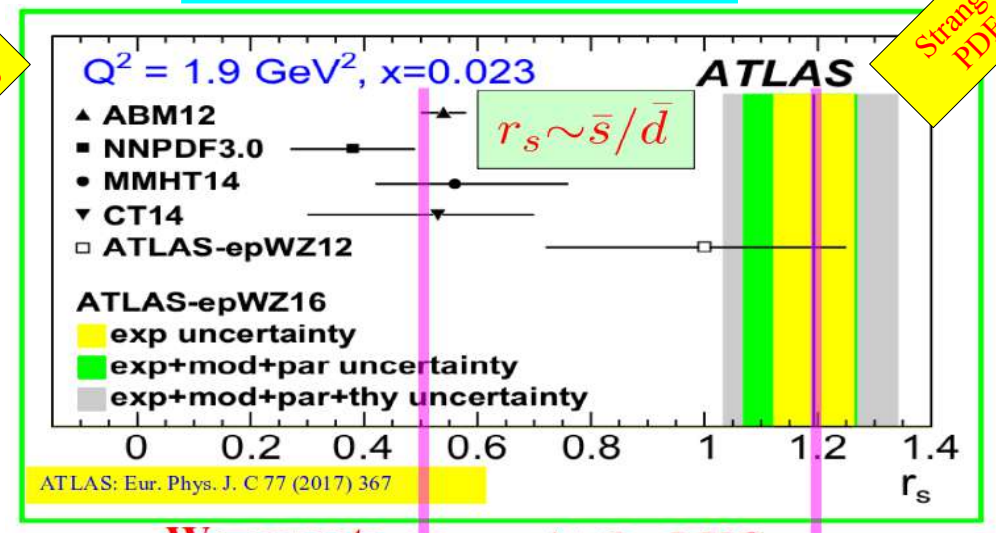


nCTEQ15 ν



nCTEQ: arXiv: 2204.13157

nCTEQ15WZ

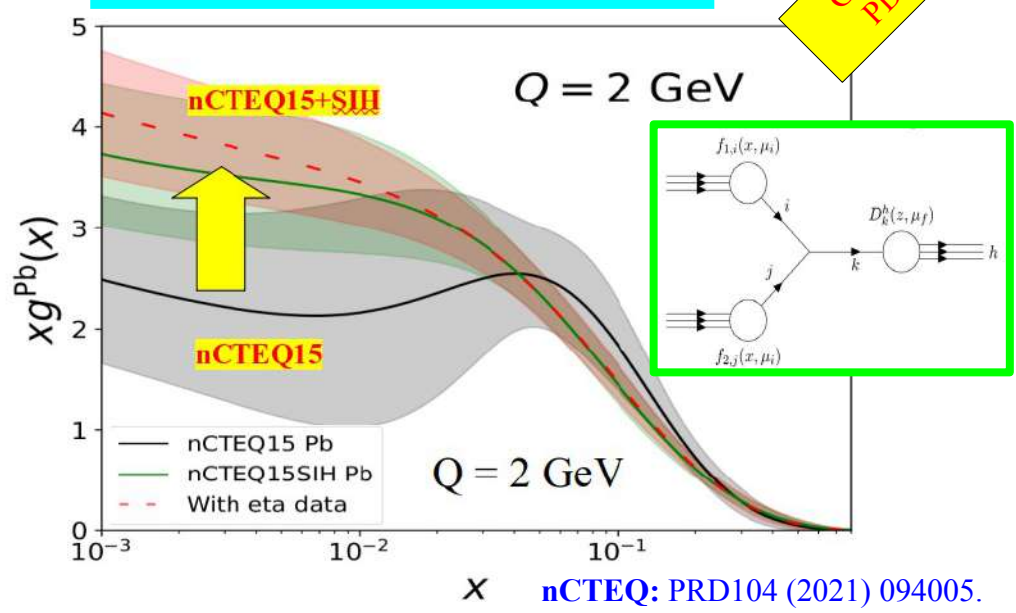


We expect:

At the LHC:

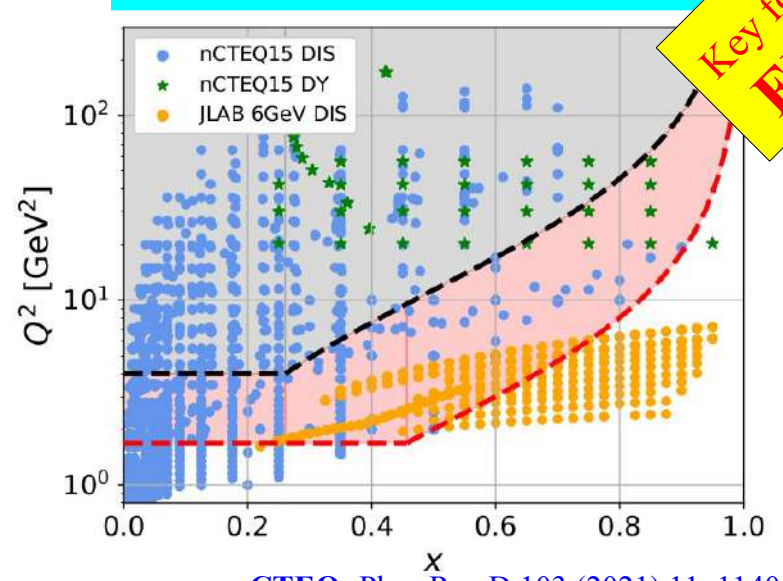
nCTEQ: Phys.Rev.D 104 (2021) 094005

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

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

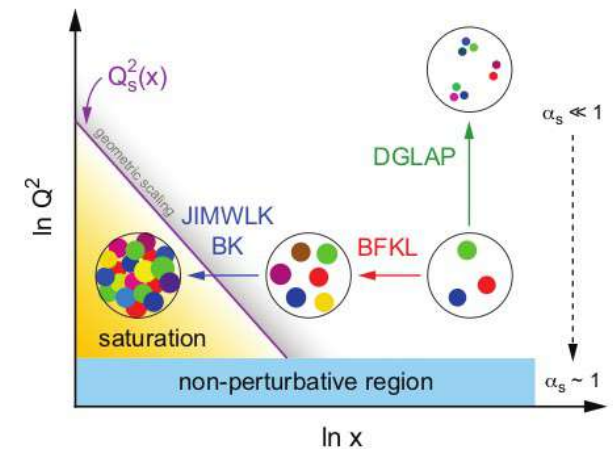
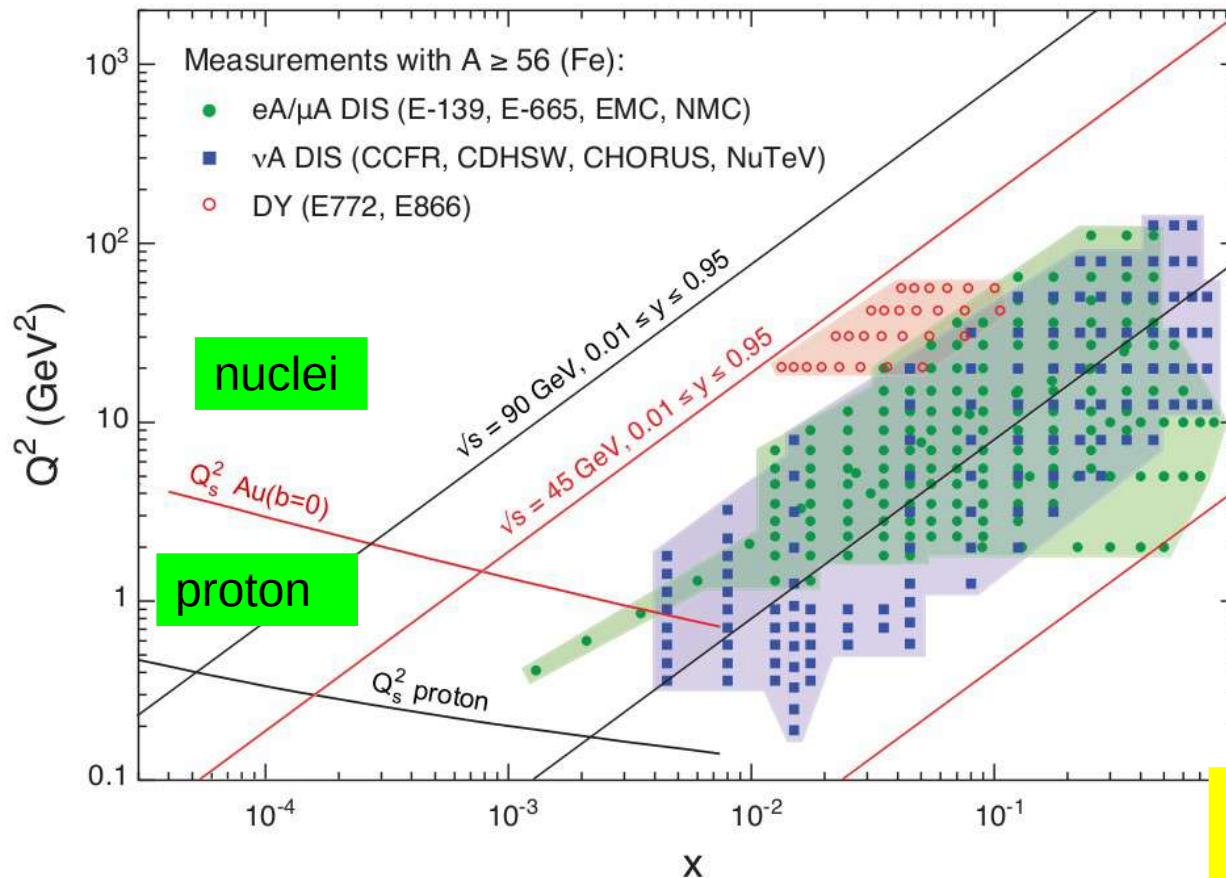
Need coordination/communication between efforts

TO DO LIST

Saturation, BFKL, recombination, ...

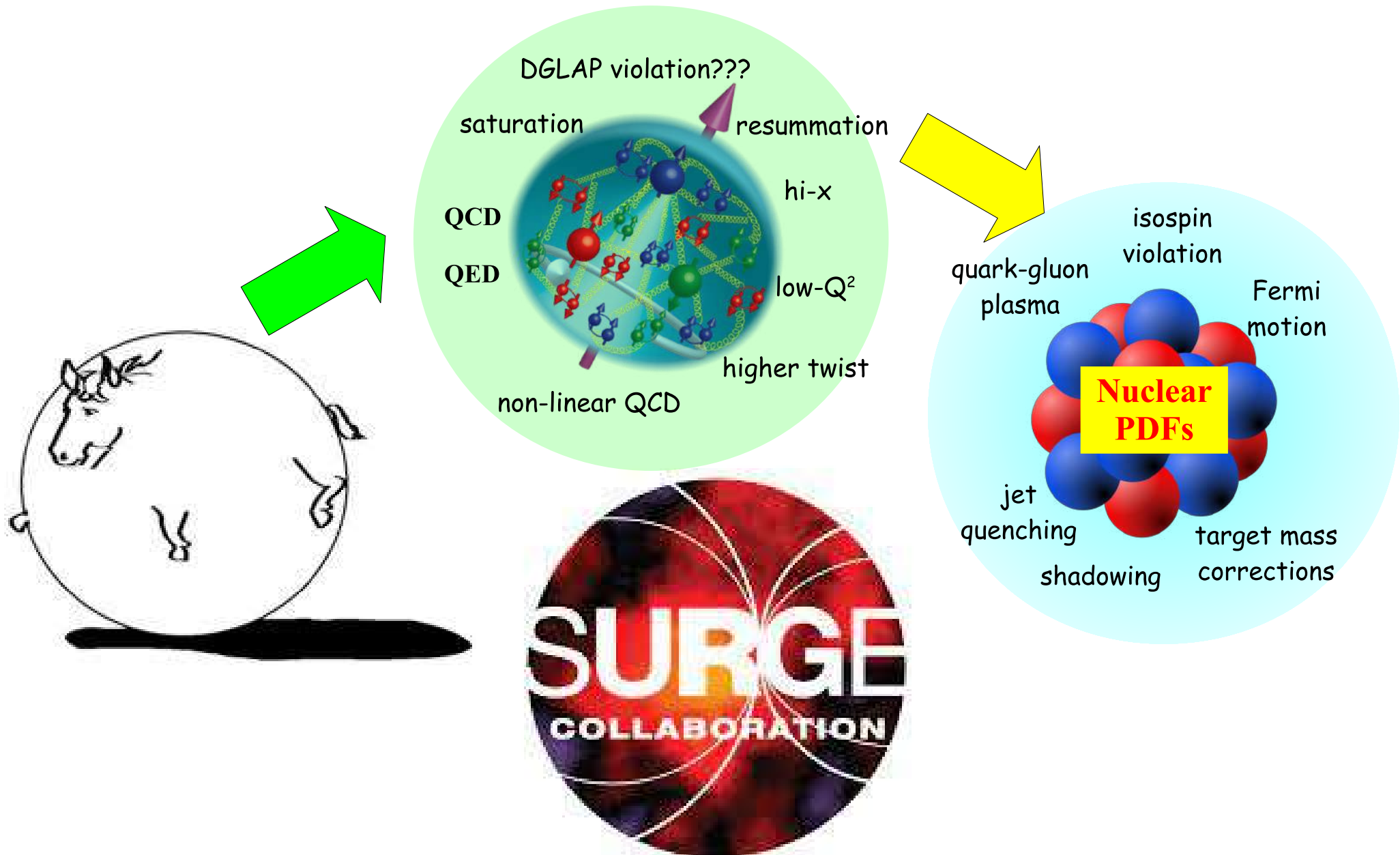
Can Saturation be Discovered at EIC?

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:



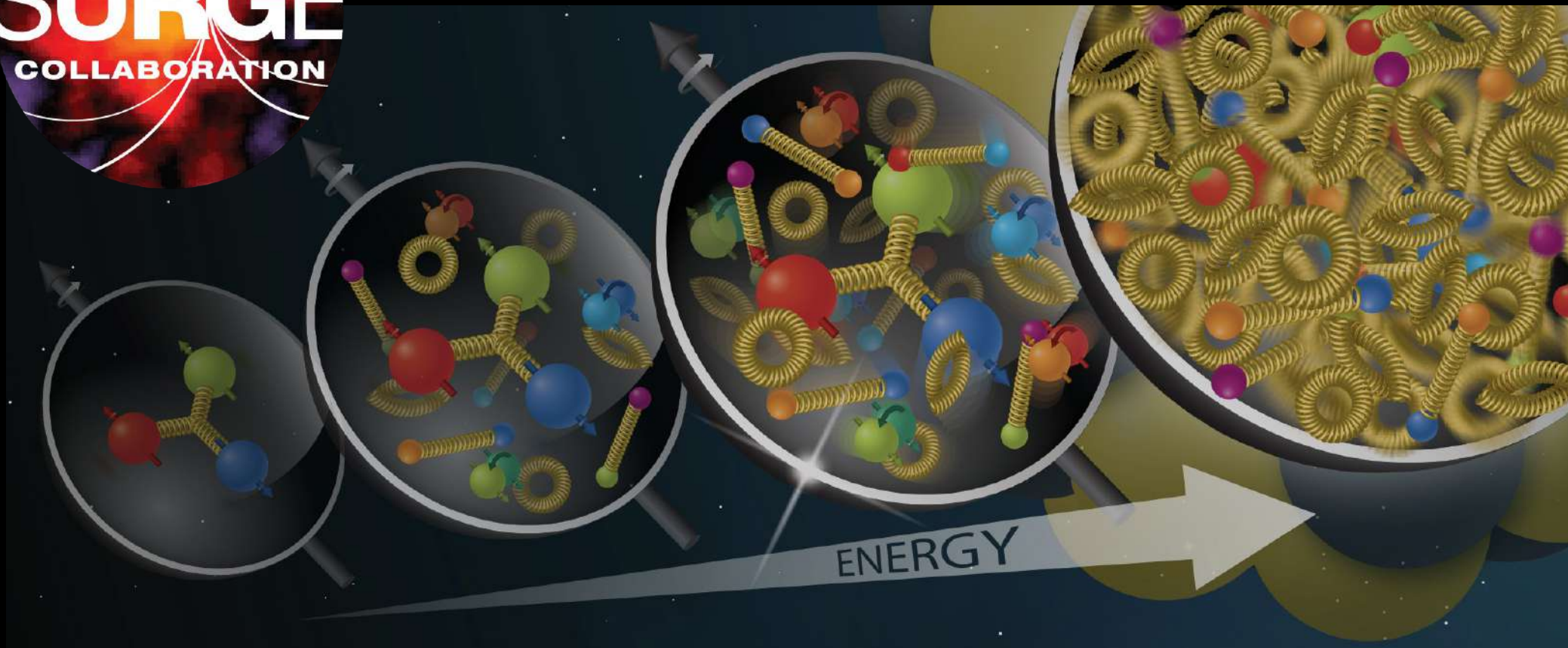
Yuri Kovchegov (OSU)
 MC4EIC: Monte Carlo event simulation for the EIC

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).

<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

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Old Dominion University / Thomas Jefferson Laboratory I.

Balitsky

McGill University

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The Ohio State University

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University of Connecticut

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University of Illinois at Urbana Champaign

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Penn State University

A. Stasto

University of California Berkeley / Lawrence

Berkeley National Laboratory

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Steering Committee



Björn Schenke



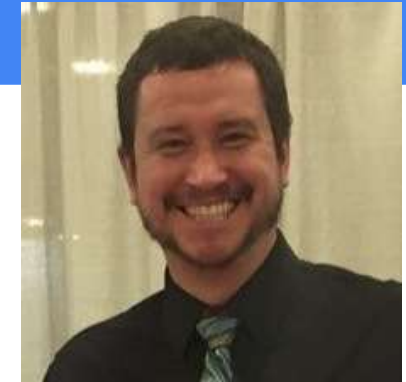
Anna Stasto



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.

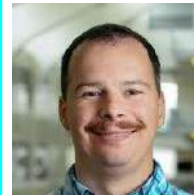
Final states WG

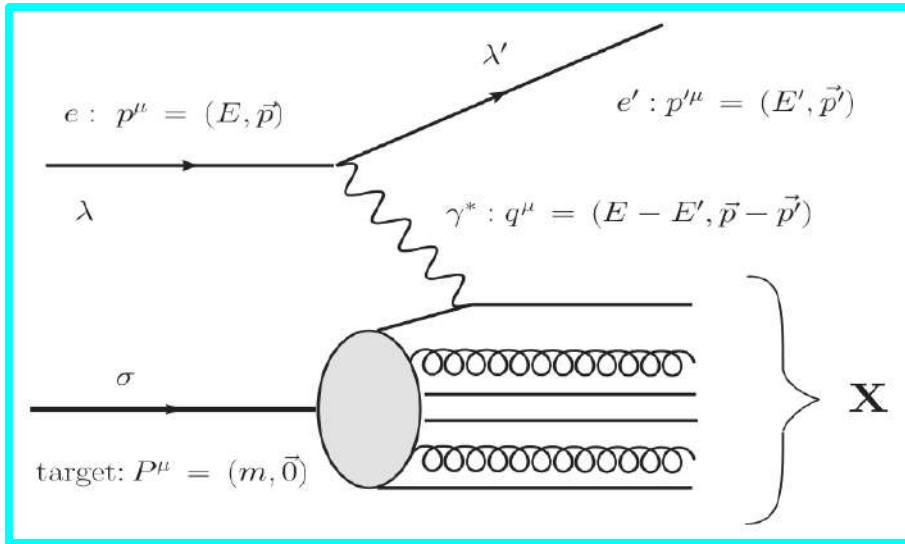
Construct a framework for hadronization in a saturated environment, including development of MC generator based on CGC calculations

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**)





Parton Model

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

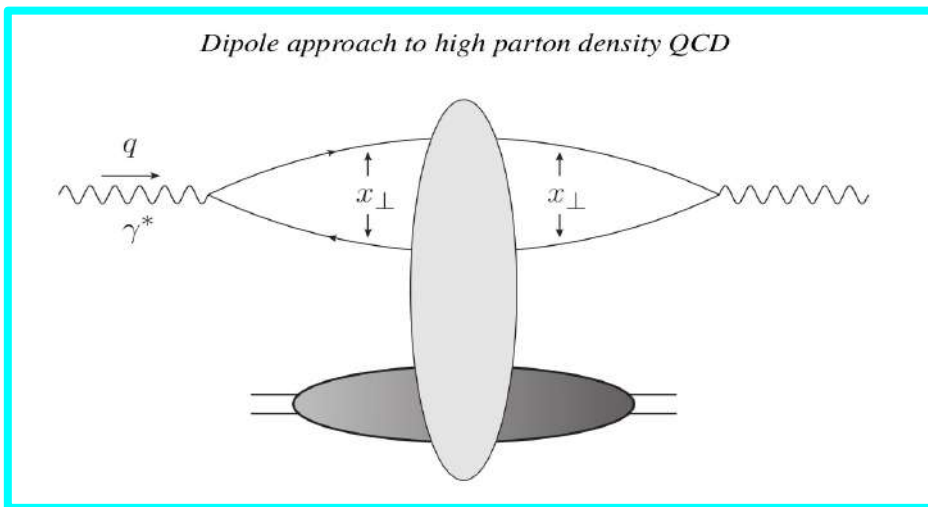
Implemented in **xFitter**
uses several numerical “tricks”
for efficient computation

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*)

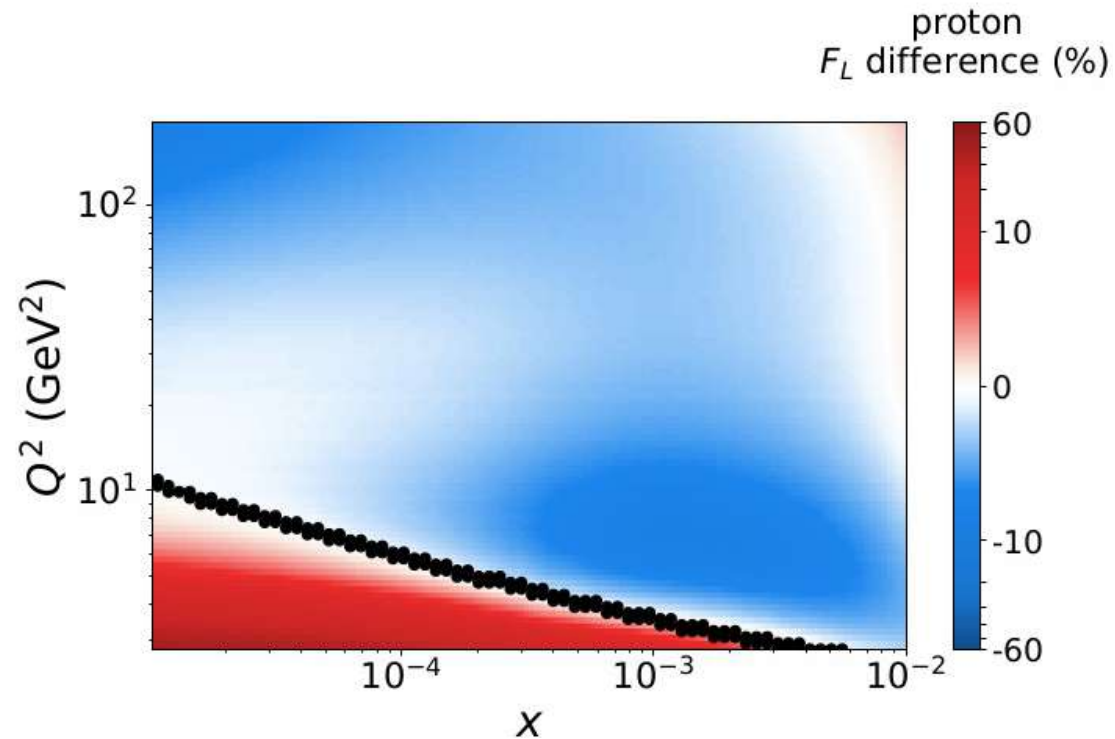
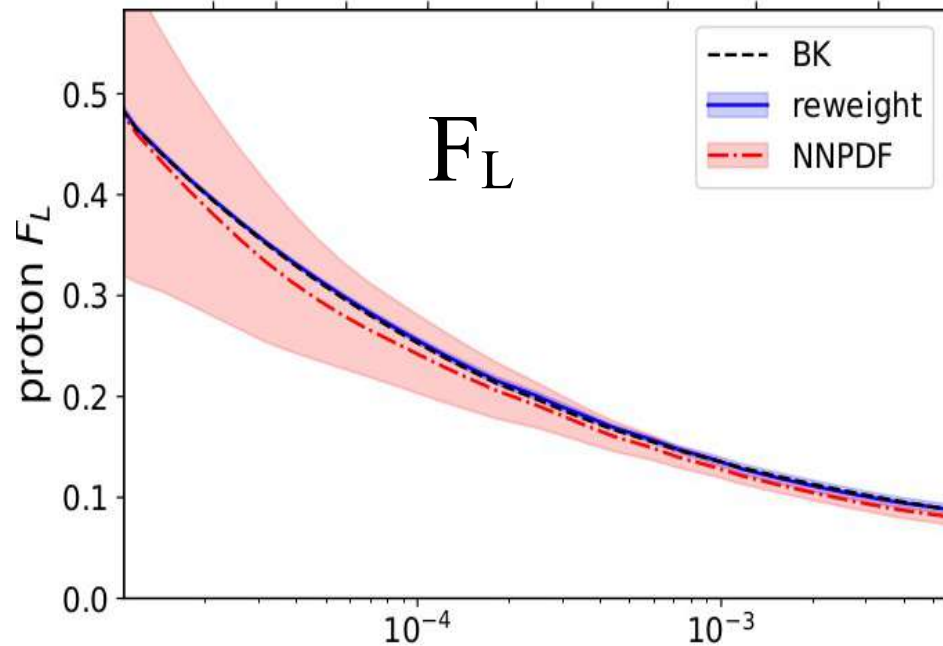
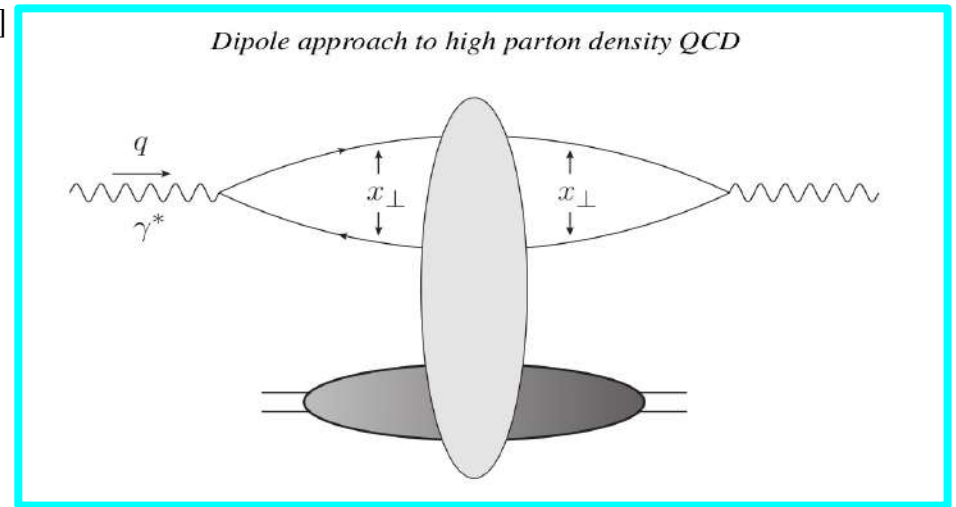
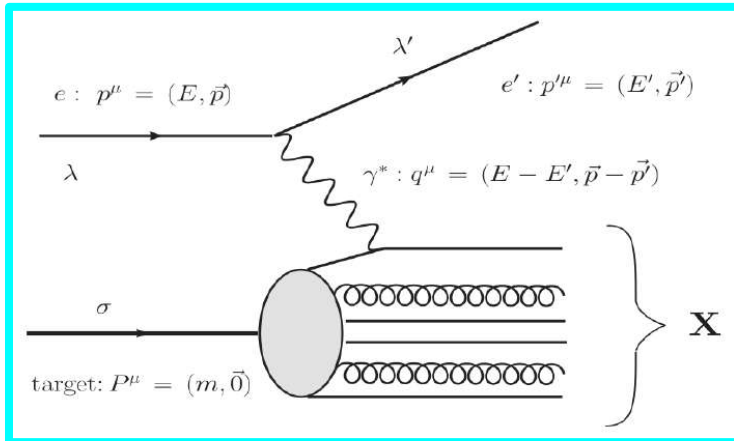


$$\sigma_{tot}^{\gamma^* A}(x, Q^2) \simeq \iint |\Psi^{\gamma^* \rightarrow q\bar{q}}(\vec{x}_\perp, z)|^2 \otimes \sigma_{tot}^{q\bar{q}A}(\vec{x}_\perp, Y)$$

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/xFitterT level... adPage

PROTON

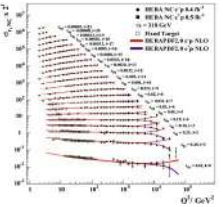
NUCLEON

MESON

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

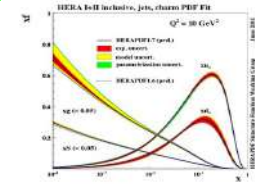
Jets, W, Z: FastNLO, ApplGrid

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 & \overline{MS} masses
- Profiling and Re-Weighting
- BFKL interface**

Heavy Quark Variable Treshold Improvements in χ^2 and correlations

TMD PDFs (uPDFs)

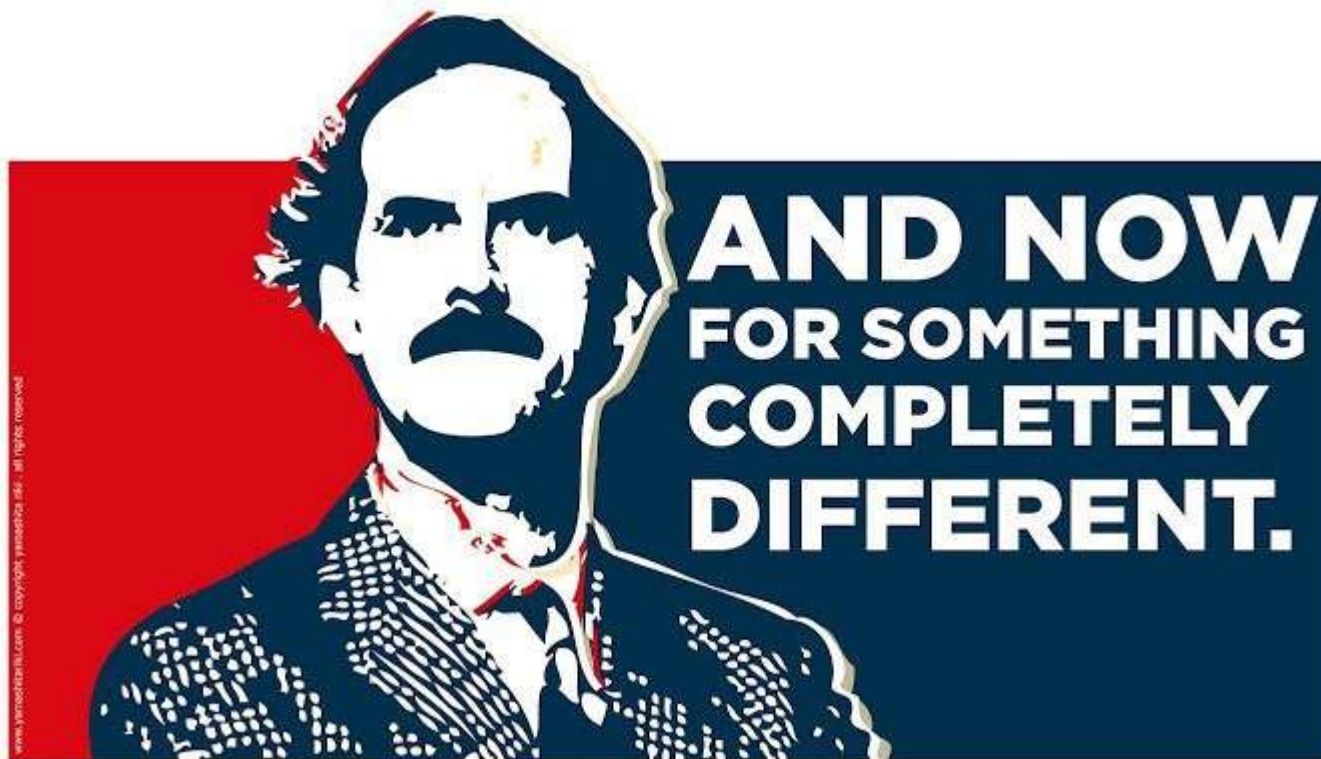
... and many other

xFitter 2.2.0
Future Freeze



xFitter Collaboration Meeting February 2020, DESY

www.xFitter.org



SRC

nCTEQ

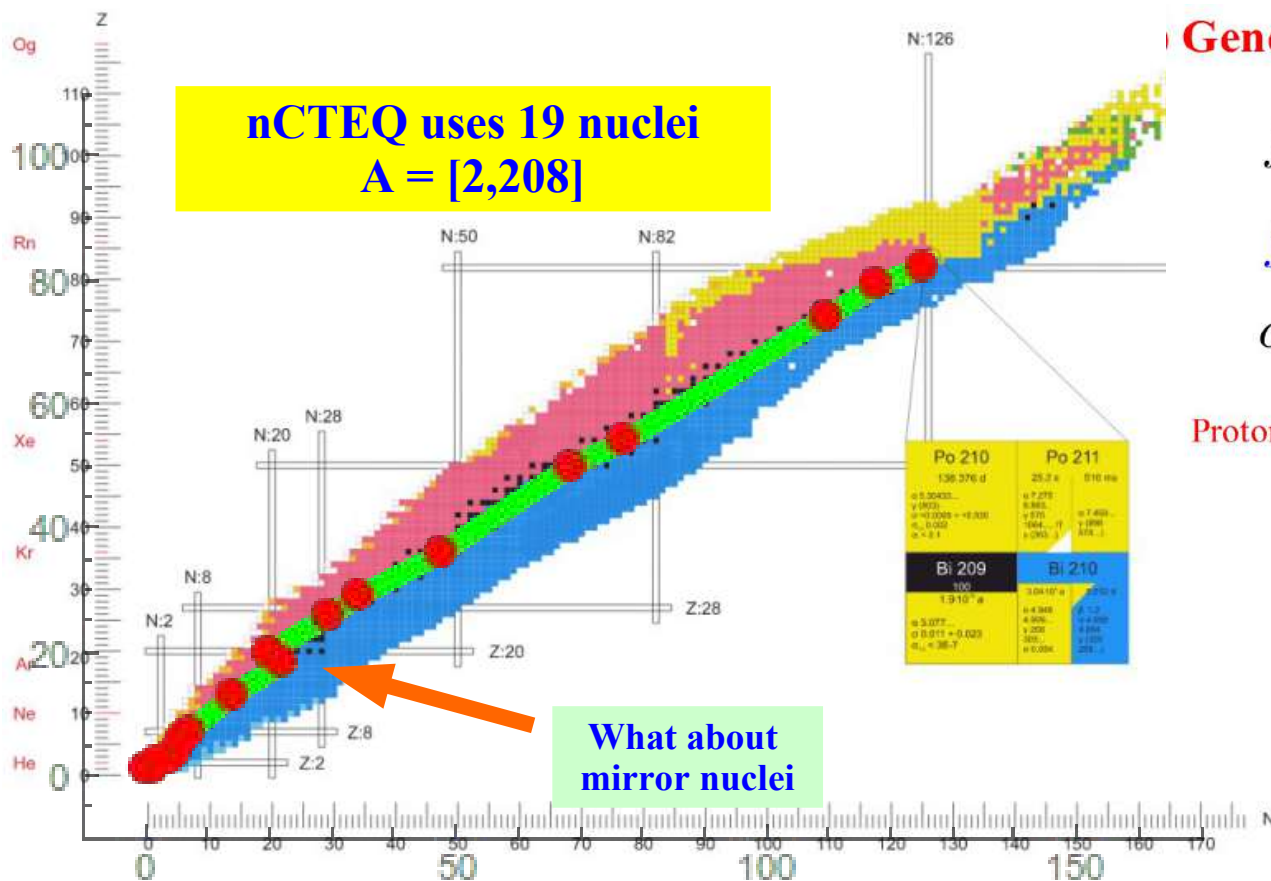
nuclear parton distribution functions

nuclear Coordinated Theoretical-Experimental Project on QCD

expand into the **NUCLEAR** dimension

encounter the QCD strong nuclear force

1 IA H Hydrogen 1.008	2 IIA Be Beryllium 9.012																18 VIIIA He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											13 IIIA B Boron 10.811	14 IVA C Carbon 12.011	15 VA N Nitrogen 14.007	16 VIA O Oxygen 15.999	17 VIIA F Fluorine 18.998	18 VIIIA Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305	3 IIIB Sc Scandium 44.956	4 IVB Ti Titanium 47.88	5 VB V Vanadium 50.942	6 VIB Cr Chromium 51.996	7 VIIB Mn Manganese 54.938	8 VIII Fe Iron 55.933	9 VIII Co Cobalt 58.933	10 VIII Ni Nickel 58.693	11 IB Cu Copper 63.546	12 IIB Zn Zinc 65.39	13 IIIA Al Aluminum 26.982	14 IVA Si Silicon 28.086	15 VA P Phosphorus 30.974	16 VIA S Sulfur 32.065	17 VIIA Cl Chlorine 35.453	18 VIIIA Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 83.8
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.905	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [209]	86 Rn Radon [222]
87 Fr Francium [223]	88 Ra Radium [226]	89-103 Actinides	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [293]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown



Generalized A-parameterization (nCTEQ)

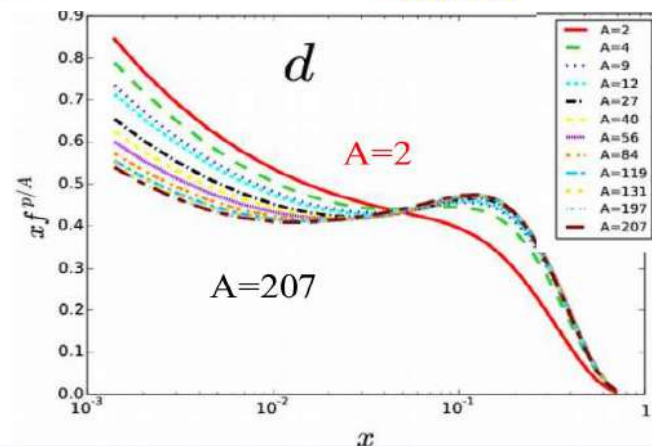
$$f_i^{p/A}(x_N, \mu_0) = f_i(x_N, A, \mu_0)$$

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

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

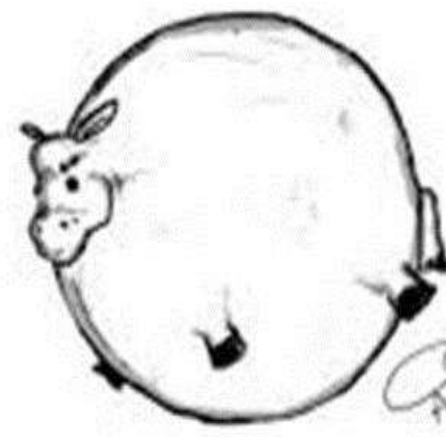
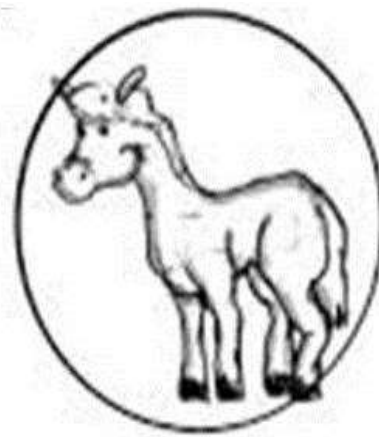
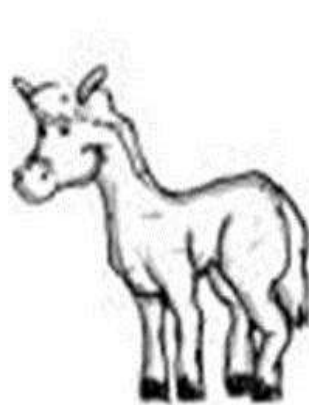
Proton

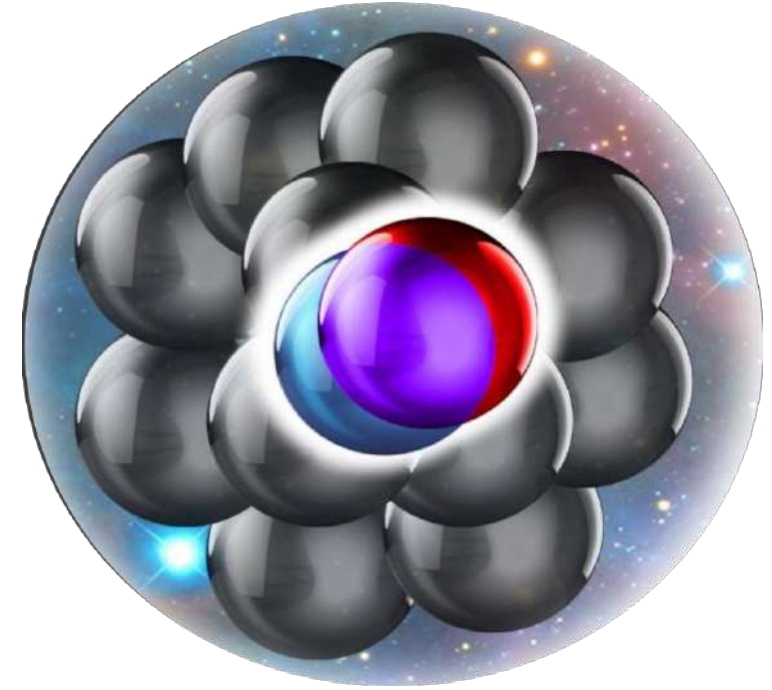
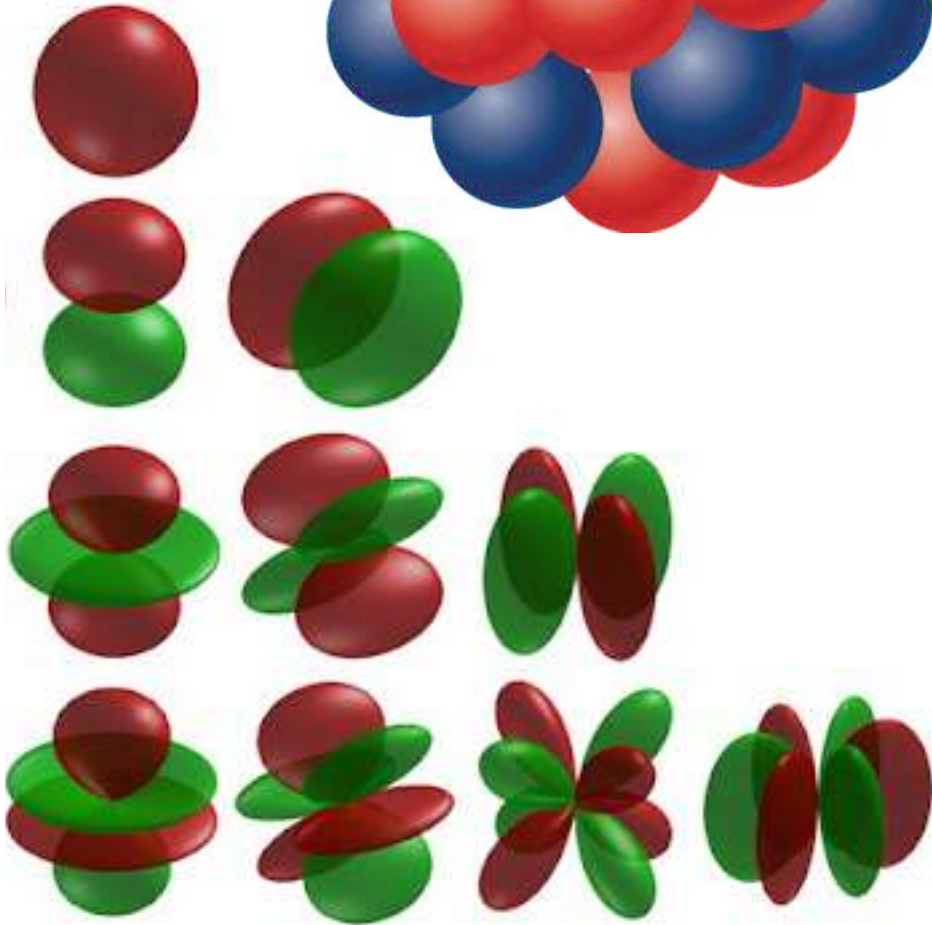
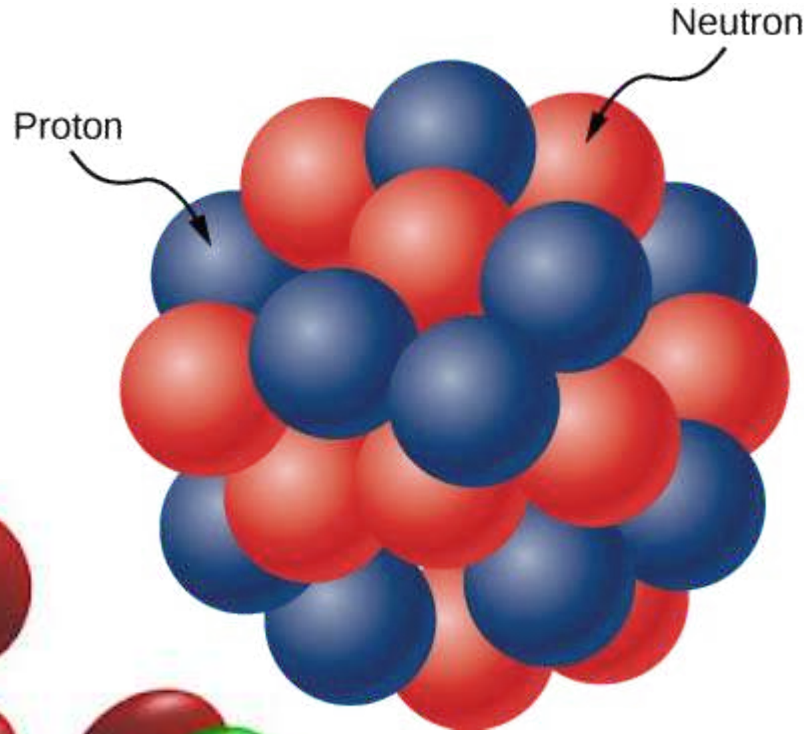
Nuclear



What about mirror nuclei

- | | |
|------------|-------------|
| [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] |

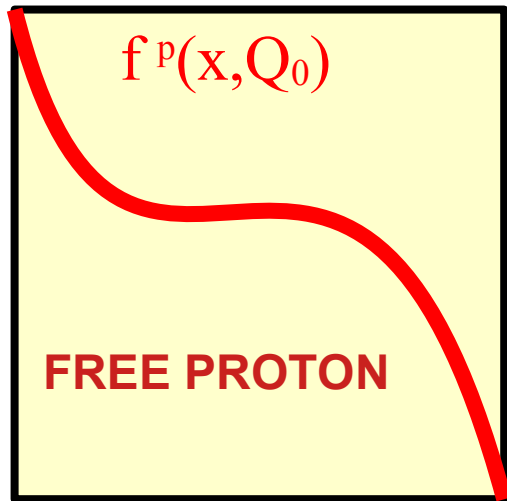
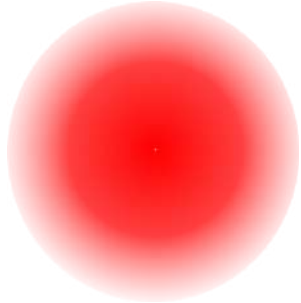




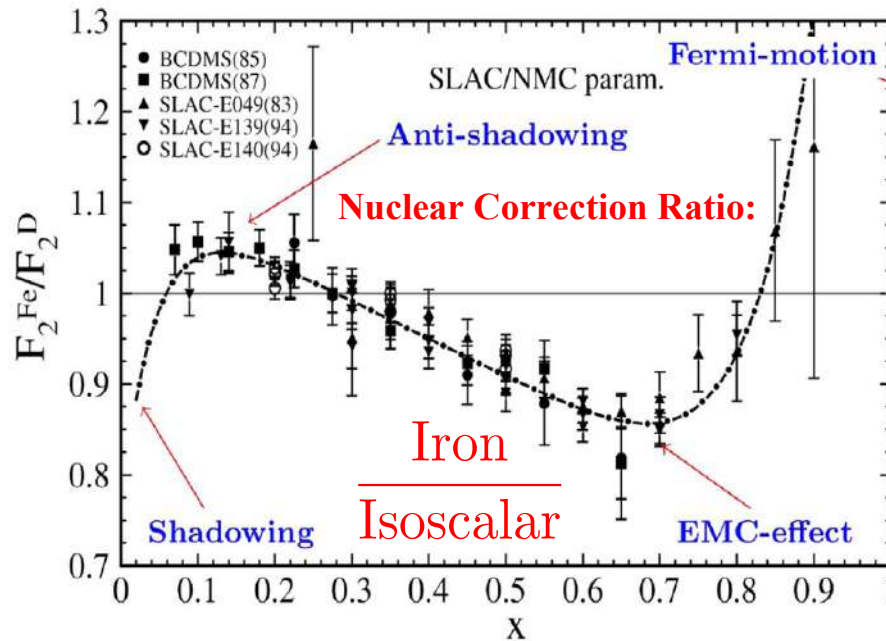
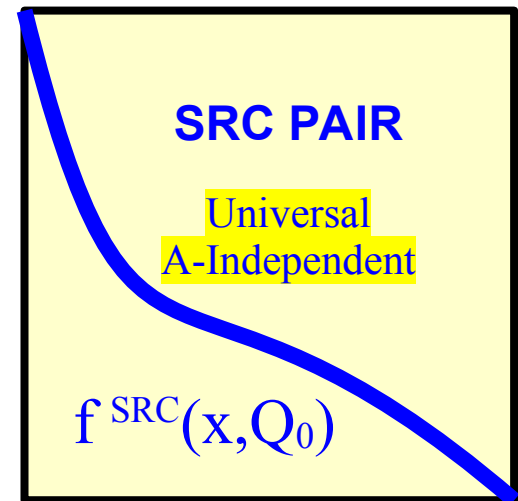
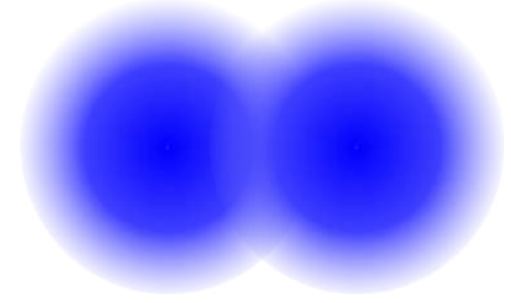
Periodic Table of the Elements

1 IA H Hydrogen	2 IIA He Helium											13 IIIA B Boron	14 IVA C Carbon	15 VA N Nitrogen	16 VIA O Oxygen	17 VIIA F Fluorine	18 VIIIA Ne Neon																										
3 IIIB La Lanthanum	4 IVB Ce Cerium	5 VB Pr Praseodymium	6 VIB Nd Neodymium	7 VIIB Pm Promethium	8 VIII Sm Samarium	9 VIII Eu Europium	10 VIII Gd Gadolinium	11 IB Tb Terbium	12 IIB Dy Dysprosium	13 IIIB Ho Holmium	14 IVB Er Erbium	15 VB Tm Thulium	16 VIB Yb Ytterbium	17 VIIB Lu Lutetium	18 VIIIA Hf Hafnium	19 IIIB Ta Tantalum	20 IVB W Tungsten	21 VB Re Rhenium	22 VIB Os Osmium	23 VIIB Ir Iridium	24 VIII Pt Platinum	25 VIII Au Gold	26 VIII Hg Mercury	27 IIIB Tl Thallium	28 IVB Pb Lead	29 VB Bi Bismuth	30 VIB Po Polonium	31 VIIB At Astatine	32 VIIIA Rn Radon														
33 IIIB Na Sodium	34 IVB Mg Magnesium	35 VB Al Aluminum	36 VIB Si Silicon	37 VIIB P Phosphorus	38 VIII S Sulfur	39 VIII Cl Chlorine	40 VIII Ar Argon	41 IB K Potassium	42 IIB Ca Calcium	43 IIIB Sc Scandium	44 IVB Ti Titanium	45 VB V Vanadium	46 VIB Cr Chromium	47 VIIB Mn Manganese	48 VIII Fe Iron	49 VIII Co Cobalt	50 VIII Ni Nickel	51 VIII Cu Copper	52 VIII Zn Zinc	53 IIIB Ga Gallium	54 IVB Ge Germanium	55 VB As Arsenic	56 VIB Se Selenium	57 VIIB Br Bromine	58 VIIIA Kr Krypton	59 IIIB Rb Rubidium	60 IIB Sr Strontium	61 IIIB Y Yttrium	62 IVB Zr Zirconium	63 VB Nb Niobium	64 VIB Mo Molybdenum	65 VIIB Tc Technetium	66 VIII Ru Ruthenium	67 VIII Rh Rhodium	68 VIII Pd Palladium	69 IB Ag Silver	70 IIB Cd Cadmium	71 IIIB In Indium	72 IVB Sn Tin	73 VB Sb Antimony	74 VIB Te Tellurium	75 VIIB I Iodine	76 VIIIA Xe Xenon
87 IIA Cs Cesium	88 IIA Ba Barium	89-103 Lanthanide Series	104 IVB Rf Rutherfordium	105 VB Db Dubnium	106 VIB Sg Seaborgium	107 VIIB Bh Bohrium	108 VIII Hs Hassium	109 VIII Mt Meitnerium	110 VIII Ds Darmstadtium	111 IB Rg Roentgenium	112 IIB Cn Copernicium	113 IIIB Nh Nihonium	114 IVB Fl Flerovium	115 VB Uup Ununpentium	116 VIB Lv Livermorium	117 VIIB Uus Ununseptium	118 VIIIA Uuo Ununoctium																										

nucleon



nucleon - nucleon



Linear Combination of 2 functions

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

Very different from standard parm. (e.g., nCTEQ)
 Question: do C_A coefficients display any patterns???

Universal
 A-Independent

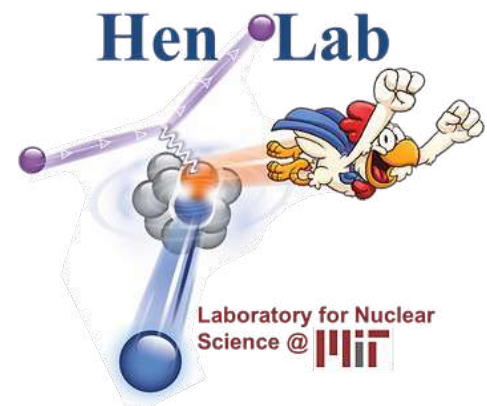
Is the fit reasonable???

Improved fit compared to traditional approach

Standard
Free p & n
Link p & n

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	

Fully accounts for all DOF



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

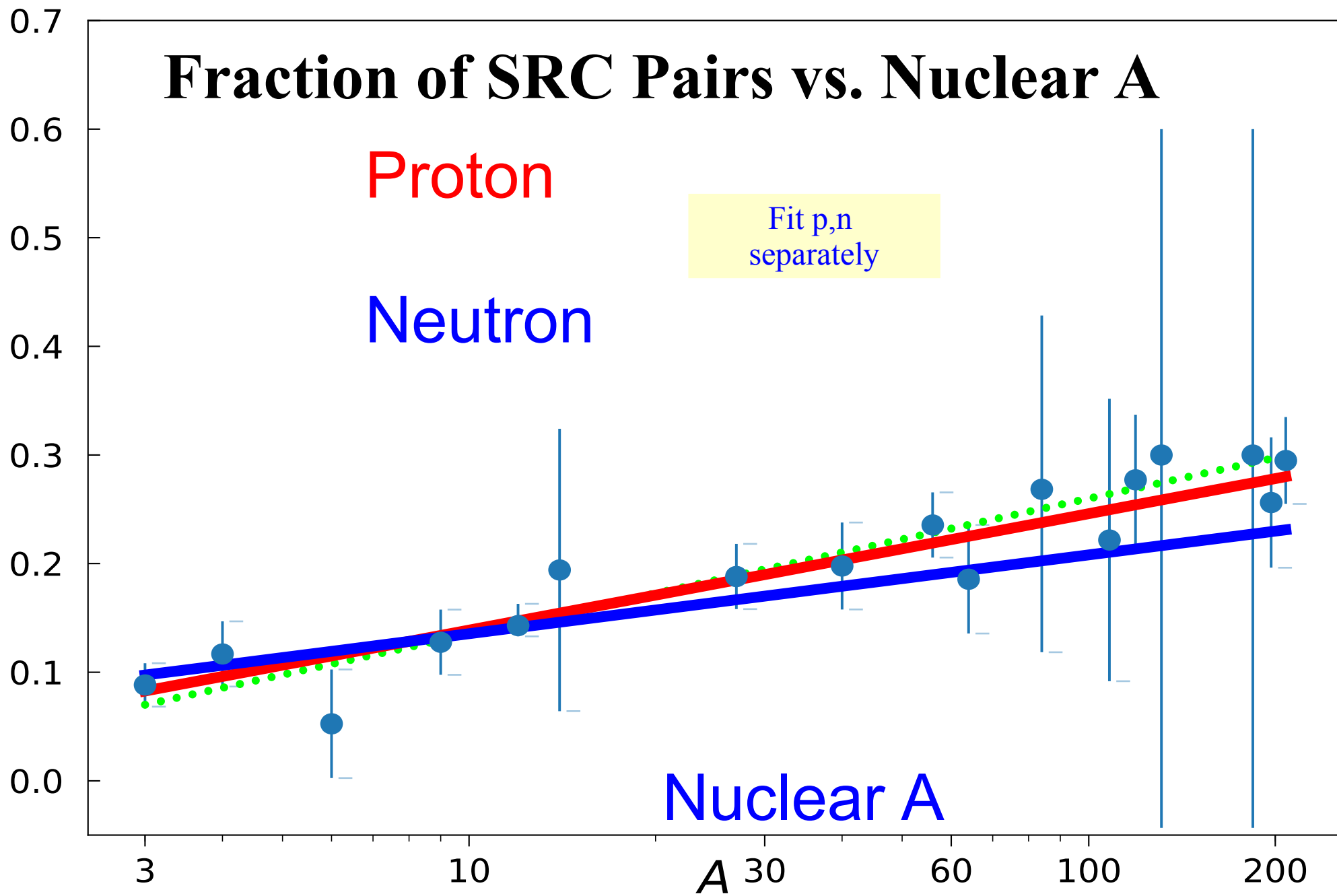
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 O. Hen ¹ C. Keppel ⁶ M. Klasen ^{2,7} K. Kovařík ² J.G. Morfín ⁸ K.F. Muzakka ^{2,9}
 F.I. Olness ¹⁰ E. Piassetzky ¹¹ P. Risse ² R. Ruiz ³ I. Schienbein ¹² and J.Y. Yu. ¹²

Fraction of SRC Pairs vs. Nuclear A

Proton

Neutron

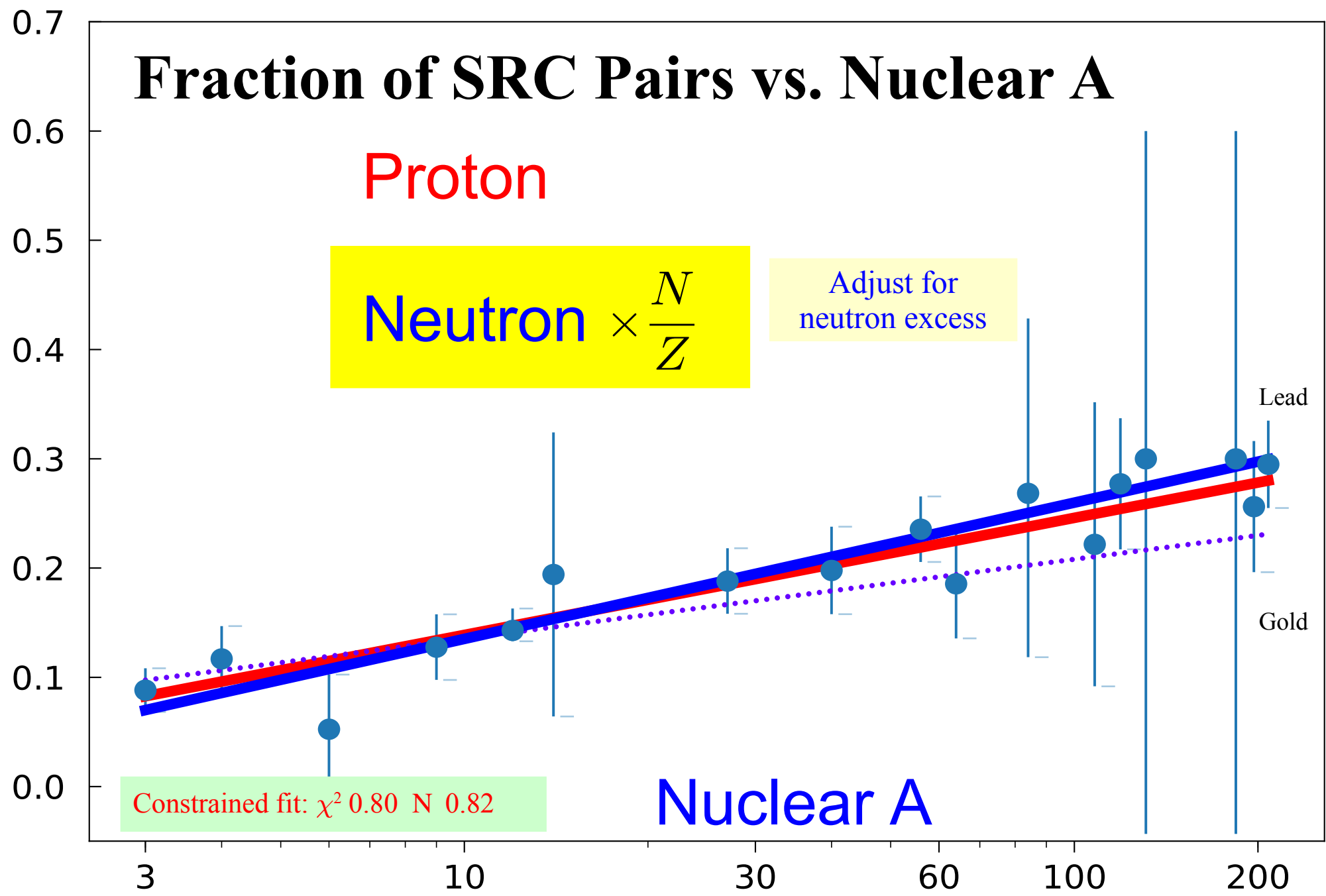
Fit p,n
separately



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

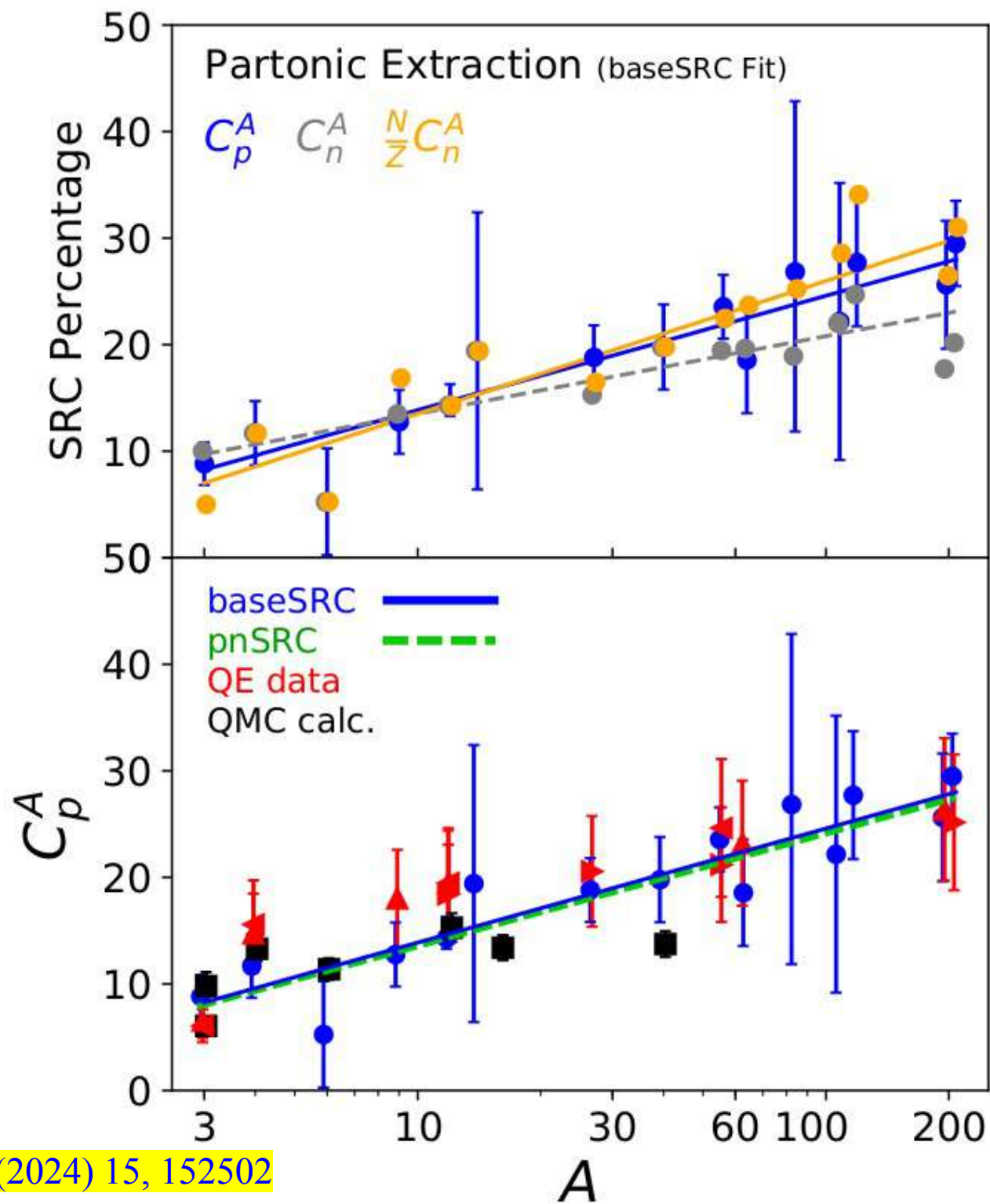
P, H2, HE3, HE4, LI6, LI7, BE9, C12, N14, AL27, CA40, FE56, CU64, KR84, AG108, SN119, XE131, W184, AU197, PB208

Fraction of SRC Pairs vs. Nuclear A



Nuclear A	2	3	4	6	9	12	14	27	40	56	64	84	108	119	131	184	197	208
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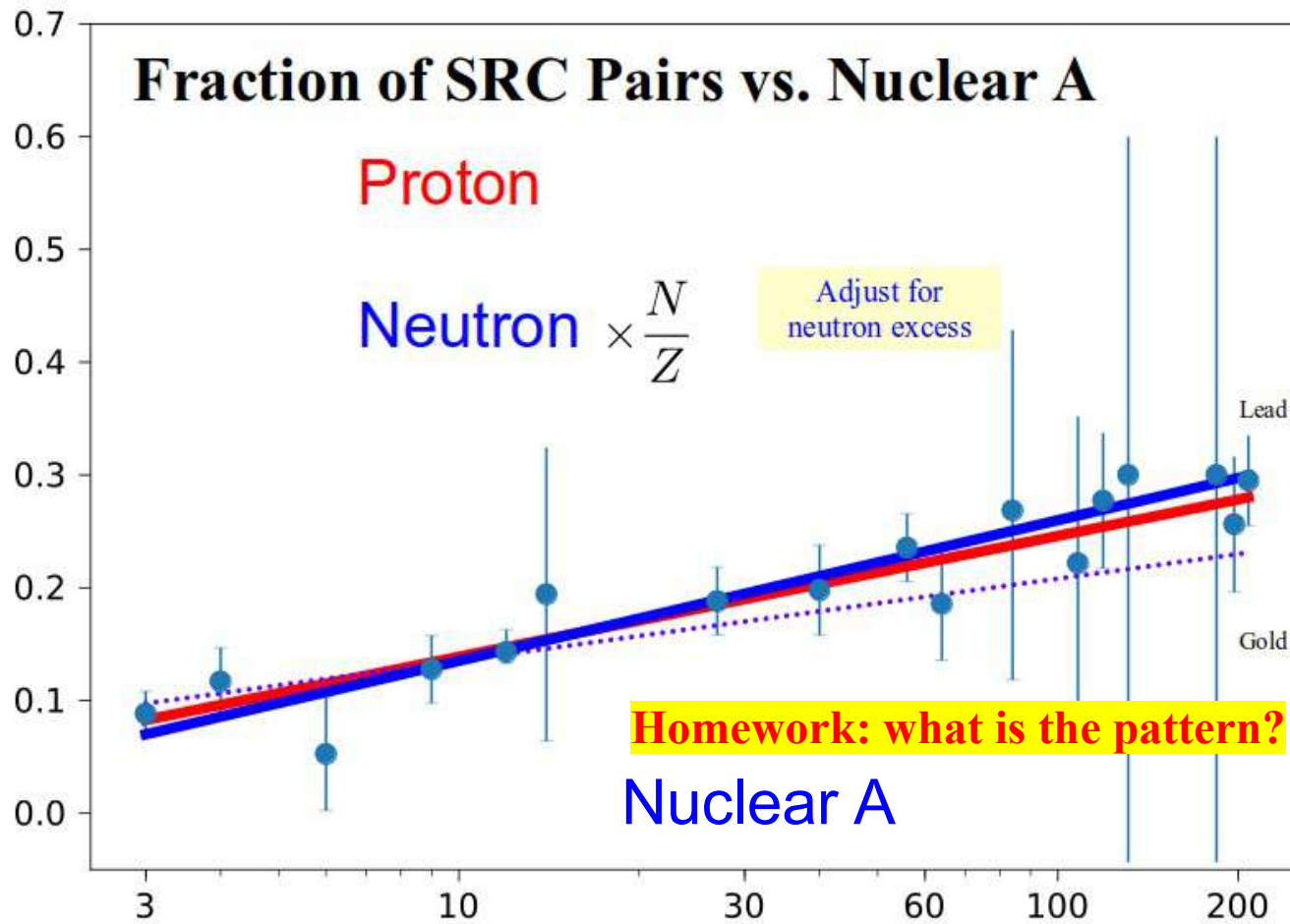


Gold $^{197}_{79}\text{Au}$

$C_p = 0.256$
 $C_n = 0.177$

$A = 197$
 $Z = 79$
 $N = 118$

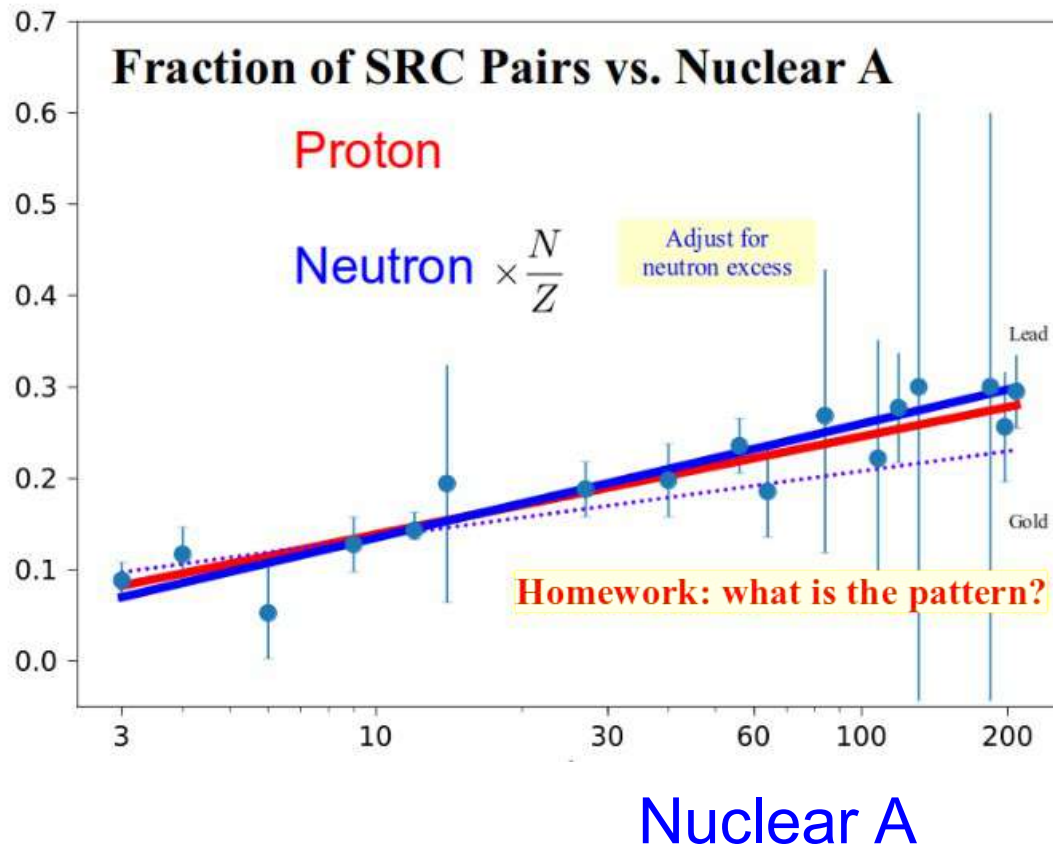
$C_p \times Z = 20.2$
 $C_n \times N = 20.9$



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



- \rightarrow Simple Nearest-Neighbor (SRC) inspired form yields remarkably good fit
- \rightarrow Comparable/better than traditional approach
- \rightarrow Coefficients scale with $\ln(A)$
- \rightarrow 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

CONCLUSIONS:

Assembling the puzzle pieces

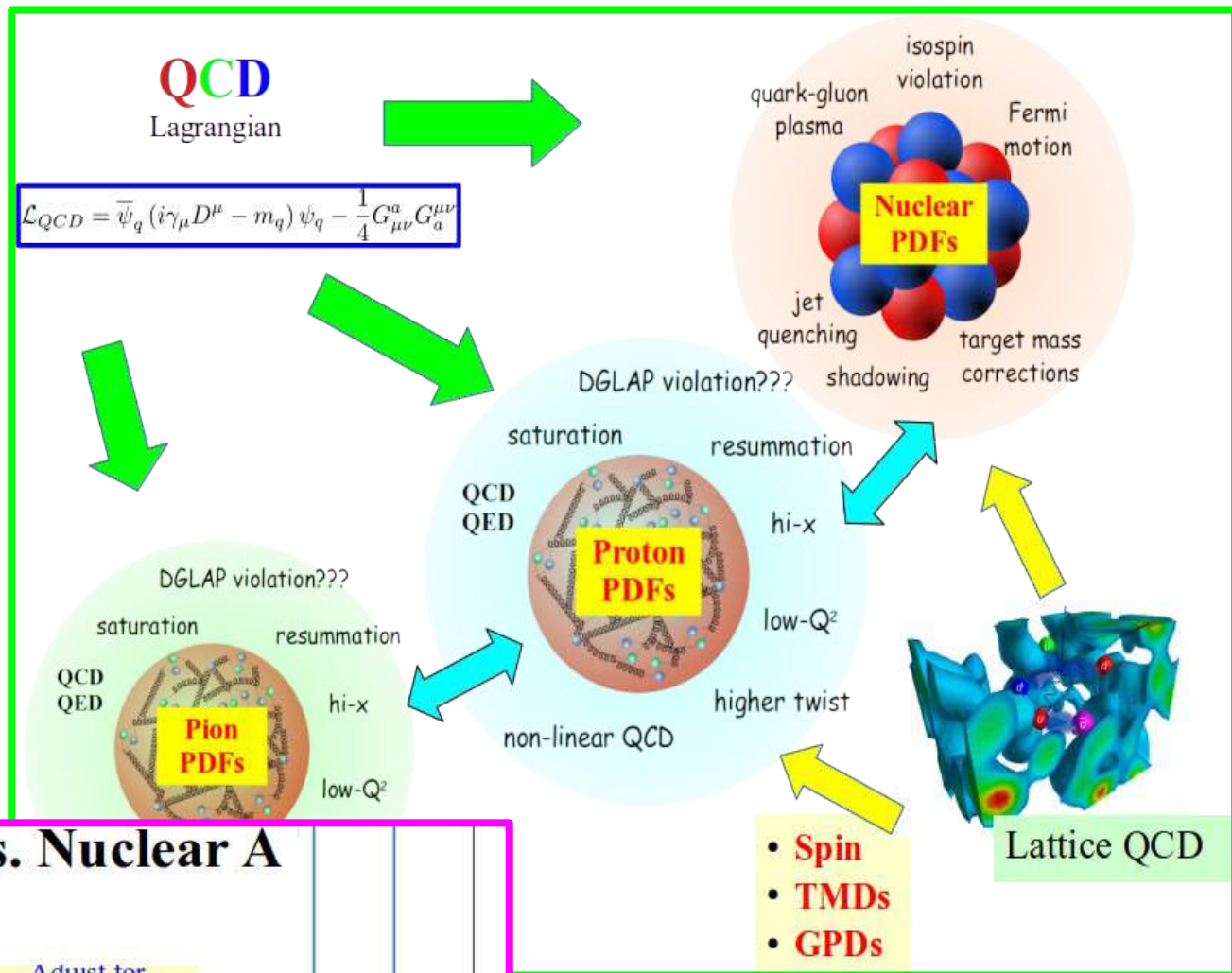
Interdisciplinary ...

Use tools from

**HEP, Nuclear,
& Lattice QCD**

... to really understand the

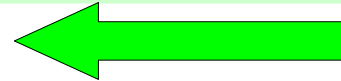
strong force



Nature is telling us ...

Why (pn) pairs?

What drives this pattern?



Fraction of SRC Pairs vs. Nuclear A

