

Revealing the fundamental character of the strong force

From PDFs to the underlying QCD

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SMU

*Thanks for substantial input
from my friends & colleagues*

nCTEQ
nuclear parton distribution functions



C T E Q

Pheno/DPF 2024
PITT PACC
14 May 2024

QCD
Lagrangian

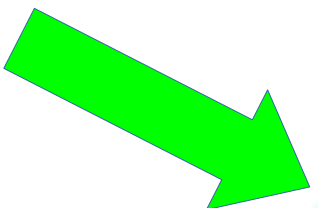
$$\mathcal{L}_{QCD} = \bar{\psi}_q (i\gamma_\mu D^\mu - m_q) \psi_q - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}$$



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

Nuclear PDFs

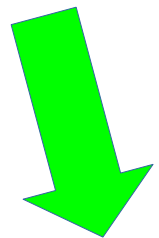
Nuclear targets key for flavor differentiation



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

Proton PDFs

QCD
QED

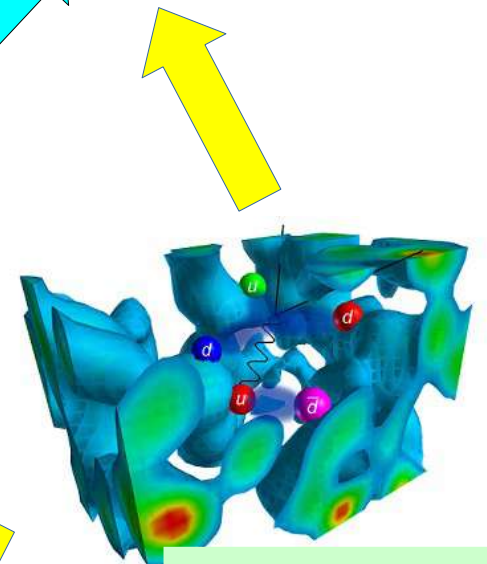


DGLAP violation???

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

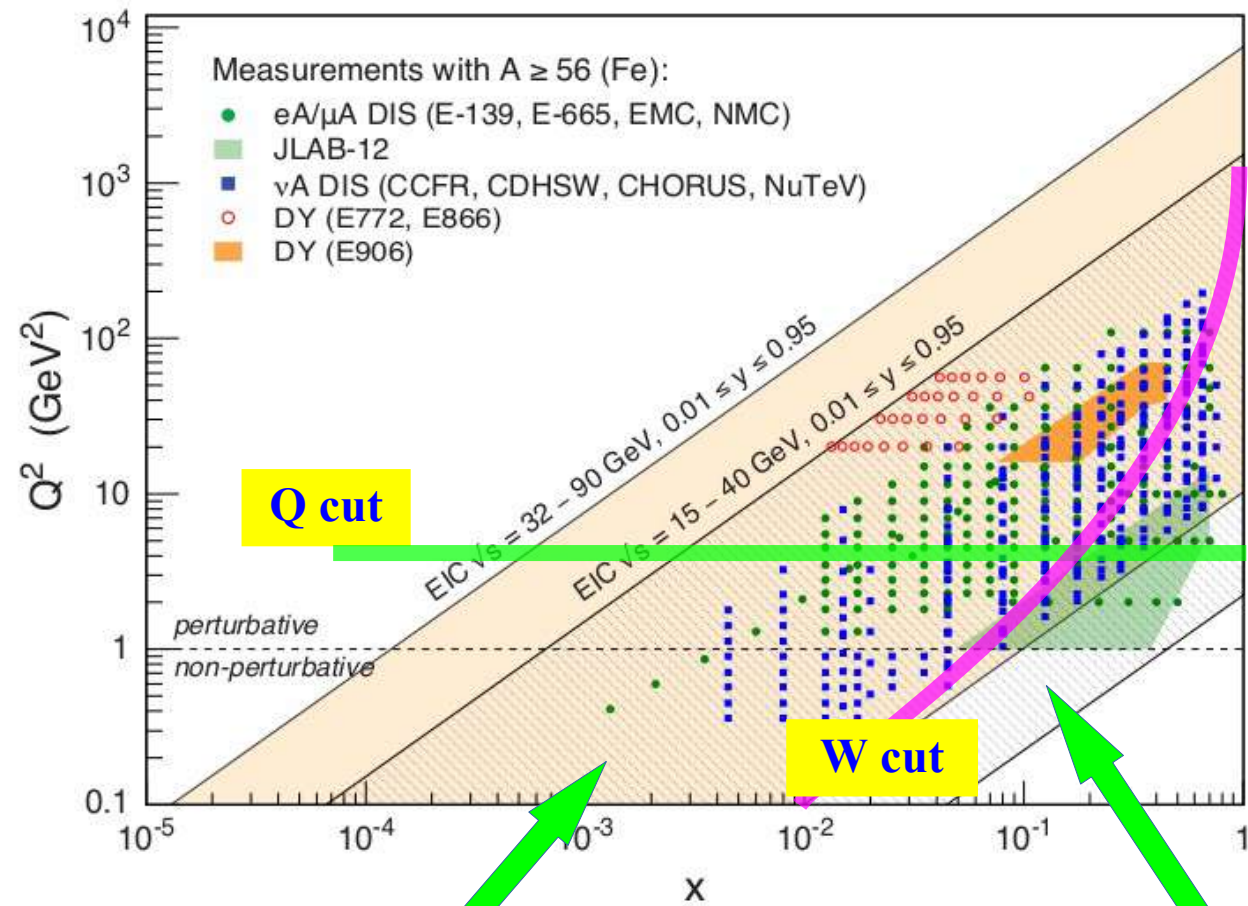
Pion PDFs

QCD
QED



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

Lattice QCD



High-x:

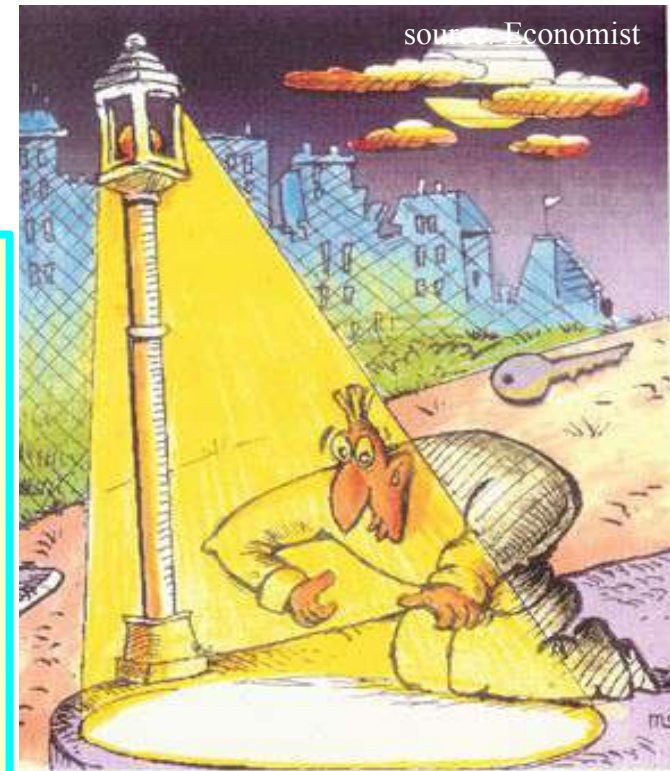
Nuclear PDFs: $x > 1$ allowed;
 impacts $F_2^{\text{Nuc}}/F_2^{\text{Iso}}$ in Fermi region
 Target Mass Corrections
 pick up M^2/Q^2 higher twist
 Deuteron Corrections
 impacts $F_2^{\text{Nuc}}/F_2^{\text{Deuteron}}$ ratio

Low-x:

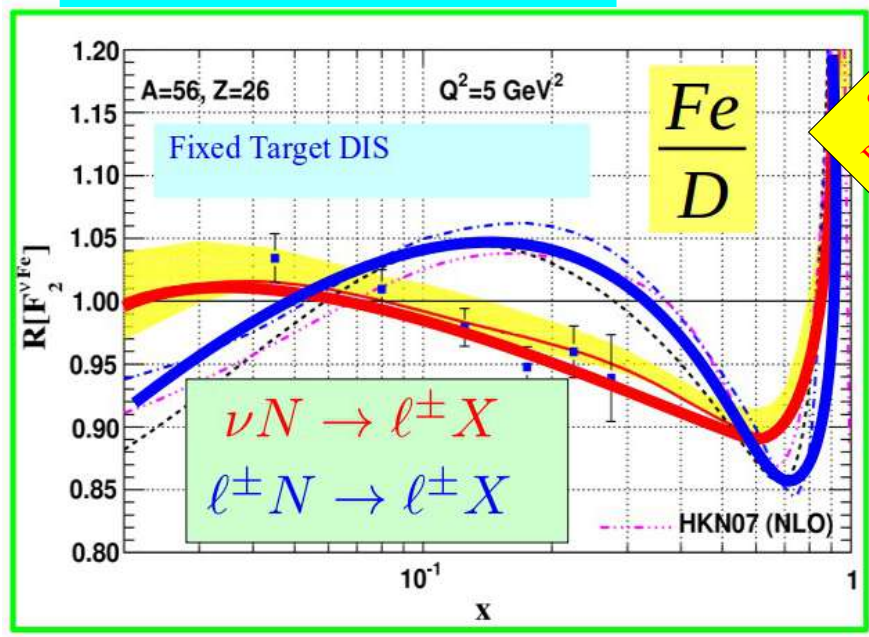
Shadowing
 Recombination
 Resummation
 BFKL
 Saturation

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

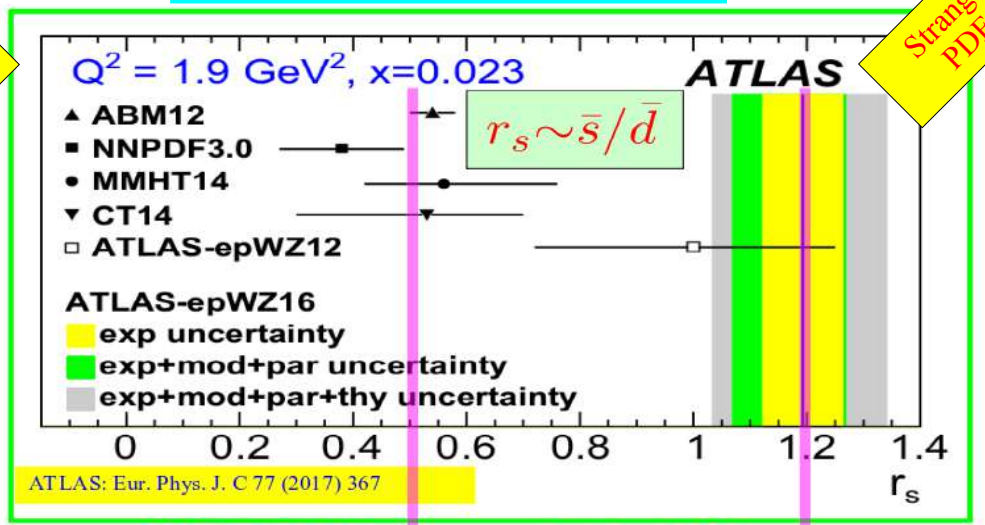


nCTEQ15 ν



nCTEQ: arXiv: 2204.13157

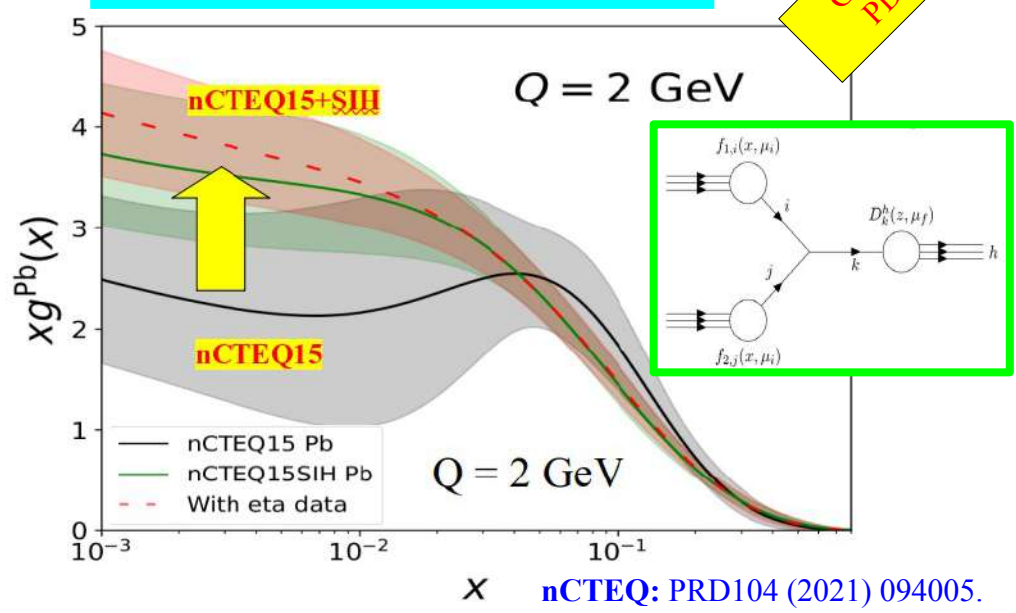
nCTEQ15WZ



We expect: At the LHC:

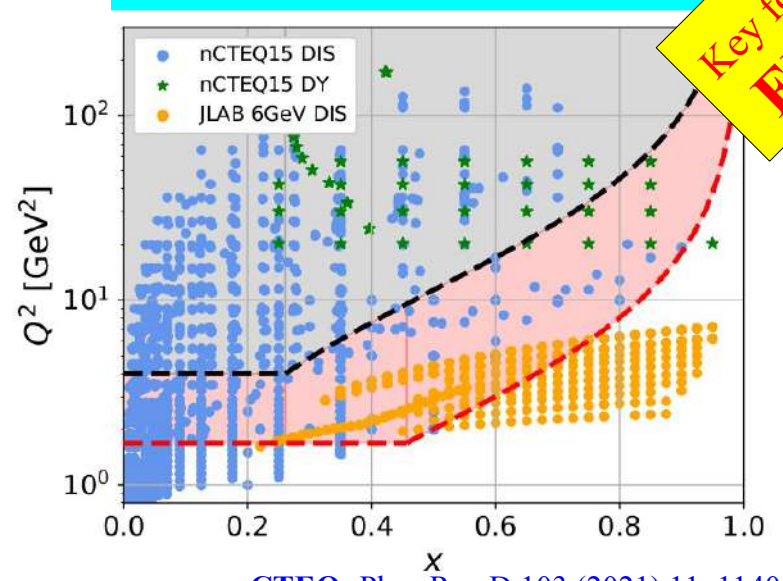
nCTEQ: Phys.Rev.D 104 (2021) 094005

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; ...

TO DO LIST

Need theoretical guidance in these regions

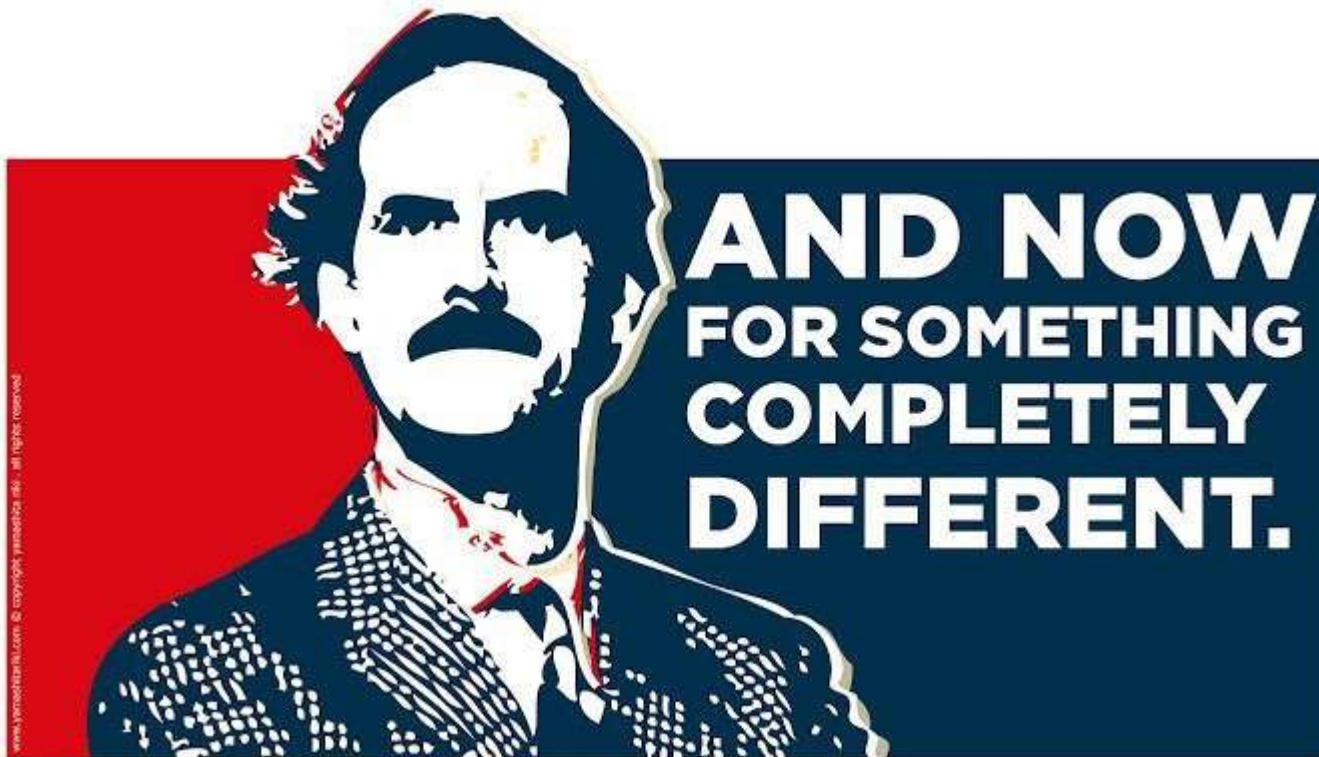
Extend Unpolarized Colinear to Spin, TMD & GPD

... explore full tomographic nuclear structure in spin, k_T , b_T

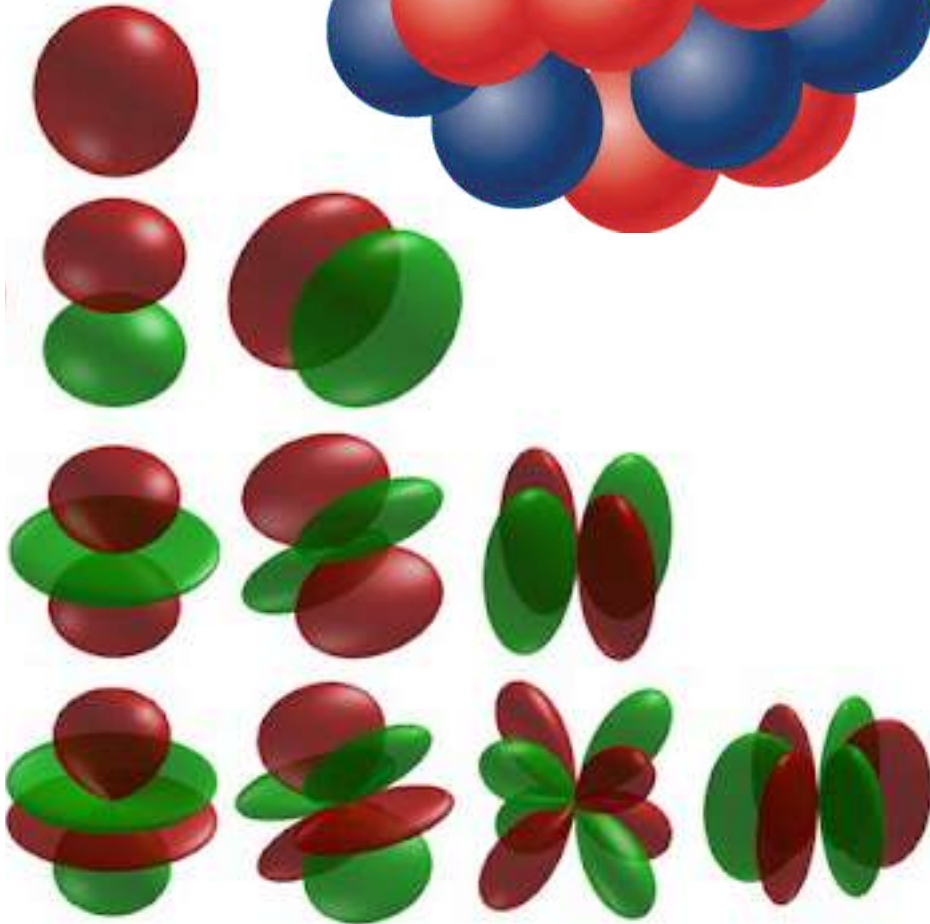
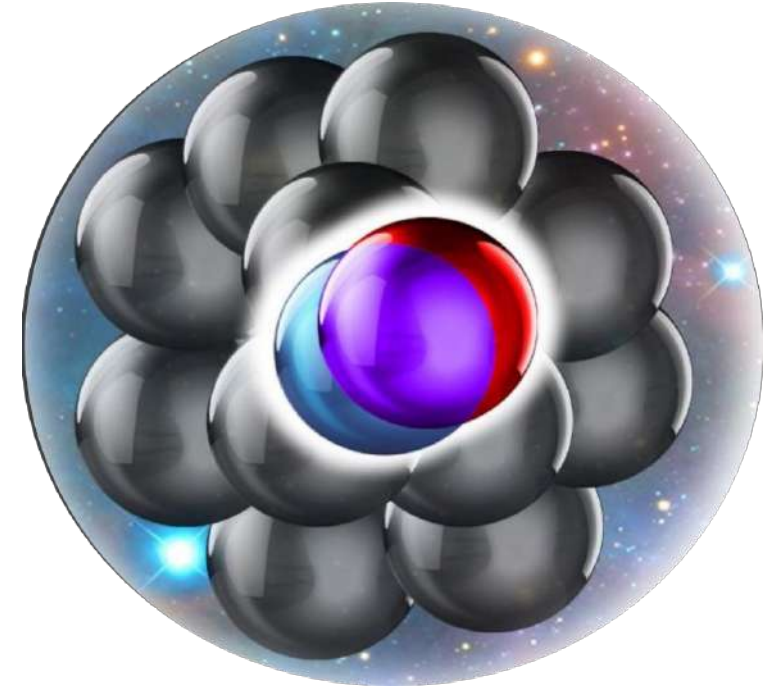
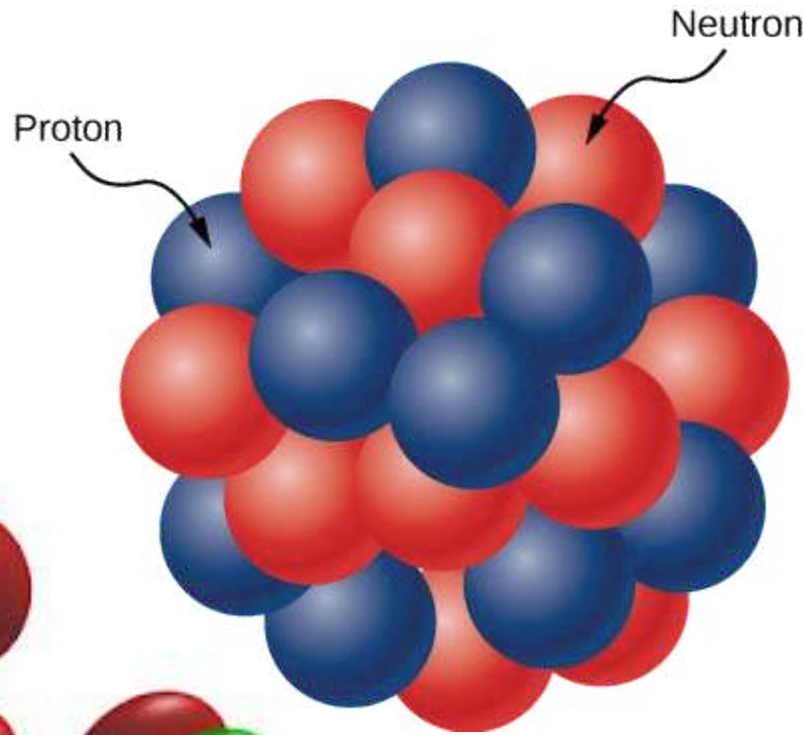
precision $f_A(x, Q)$ can serve as Boundary Condition for $f_A(x, Q, k_T, b_T, \sigma)$

include Lattice QCD info on moments and quasi-PDFs

Need coordination/communication between efforts



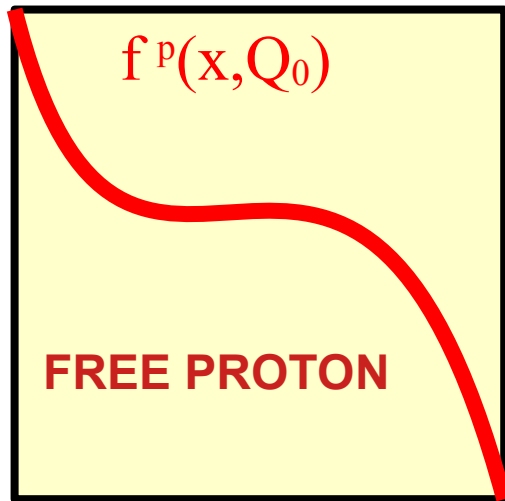
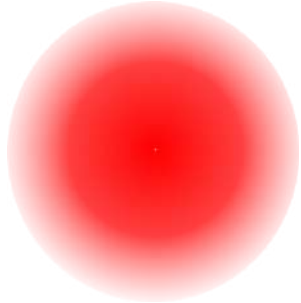
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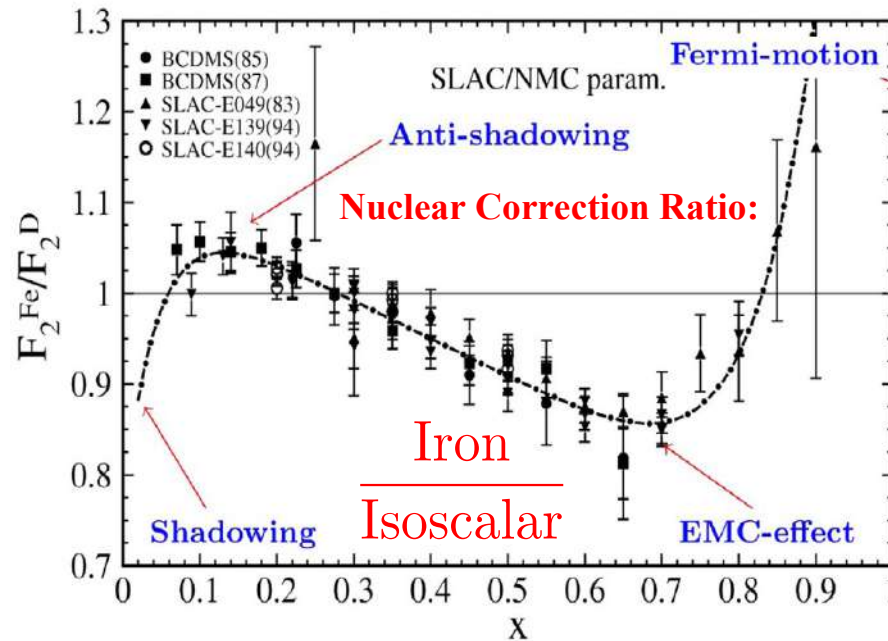
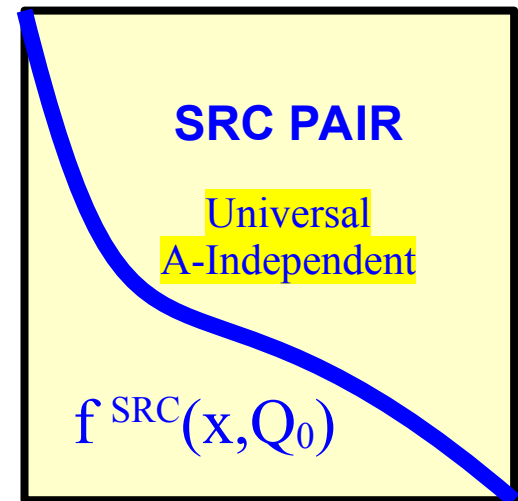
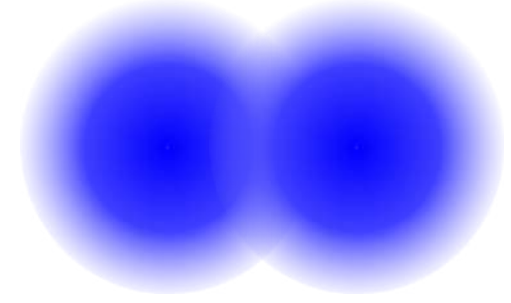
Periodic Table of the Elements

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 Fe Iron	9 VIII Co Cobalt	10 VIII Ni Nickel	11 IB Cu Copper	12 IIB Zn Zinc	13 IIIA Al Aluminum	14 IVA Si Silicon	15 VA P Phosphorus	16 VIA S Sulfur	17 VIIA Cl Chlorine	18 VIIIA Ar Argon		
19 IB K Potassium	20 IIB Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 IB Rb Rubidium	38 IIB Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 IB Cs Cesium	56 IIB Ba Barium	57-71 Lanthanides	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 IB Fr Francium	88 IIB Ra Radium	89-103 Actinides	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicium	113 Nh Nihonium	114 Fl Flerovium	115 Uu Ununpentium	116 Lv Livermorium	117 Uus Ununseptium	118 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???


















χ^2/N_{data}	DIS	DY	W/Z	JLab	χ_{tot}^2	$\frac{\chi_{\text{tot}}^2}{N_{\text{DOF}}}$
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	

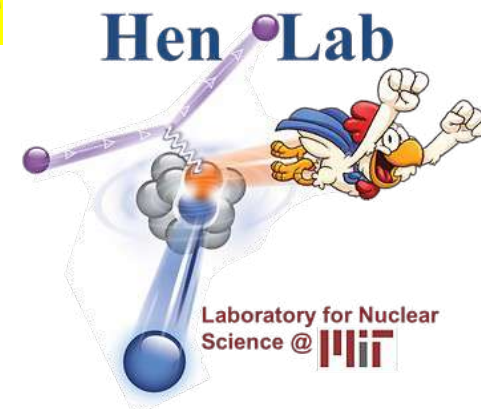
Improved fit compared to traditional approach

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. Piassetzky ¹¹ P. Risse ² R. Ruiz ³ I. Schienbein ¹² and J.Y. Yu. ¹²



ArXiv:2312.16293

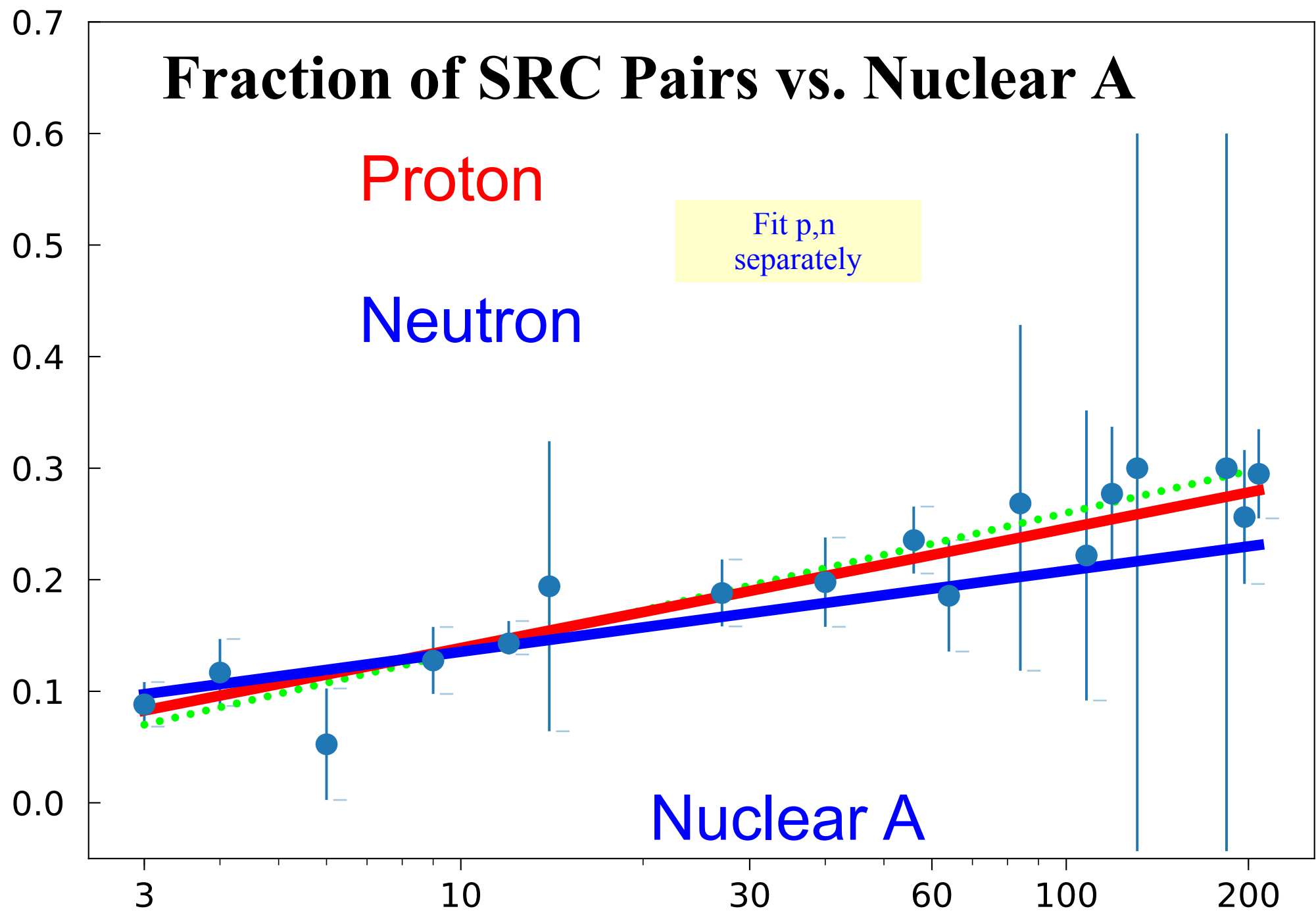
Fraction of SRC Pairs vs. Nuclear A

Proton

Neutron

Fit p,n
separately

Nuclear A



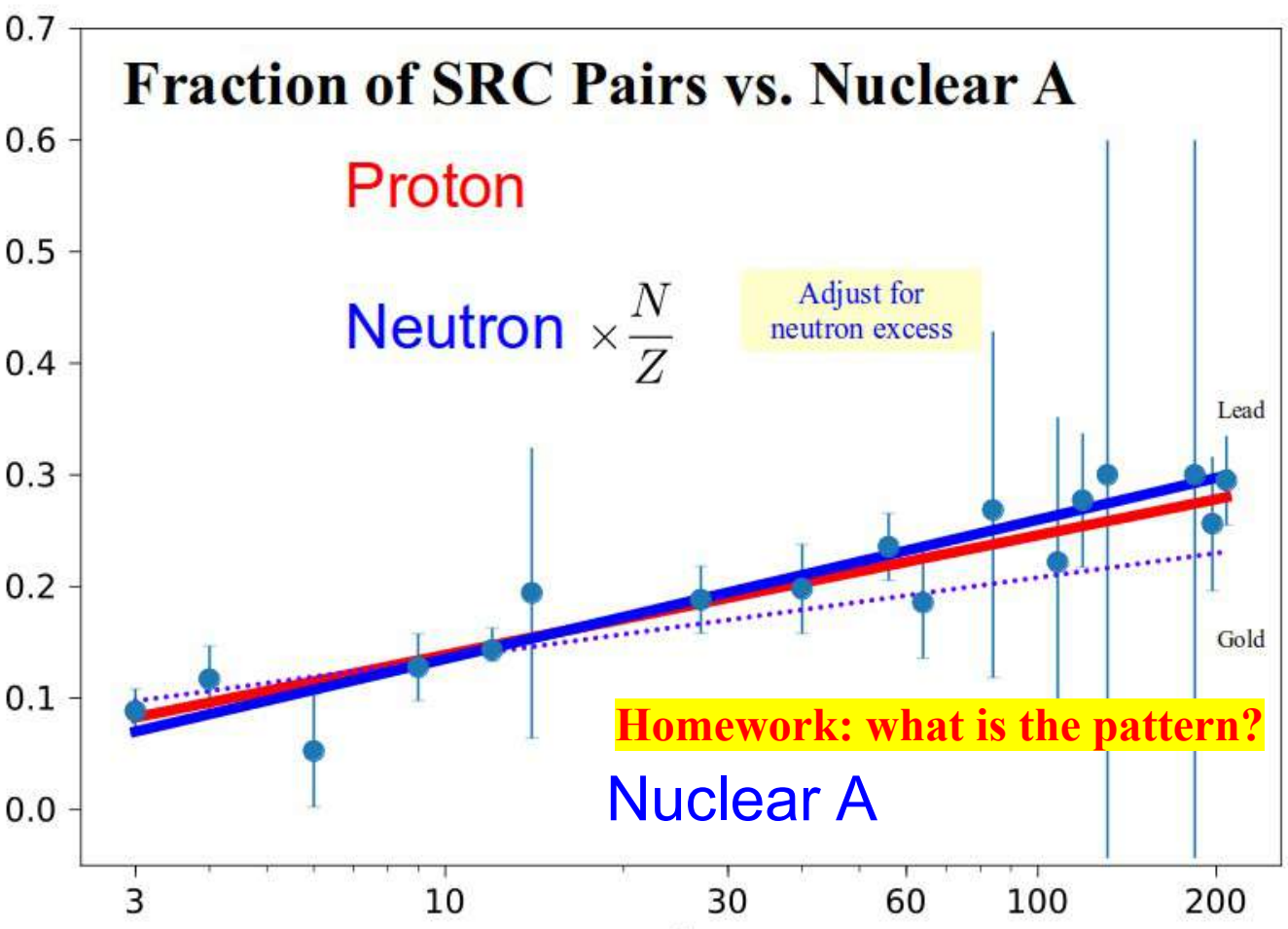
Nuclear A	2	3	4	6	9	12	14	27	40	56	64	84	108	119	131	184	197	208
# data	275	125	66	15	49	196	101	73	92	134	61	84	7	152	4	37	50	163

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

$C_p = 0.256$
 $C_n = 0.177$

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

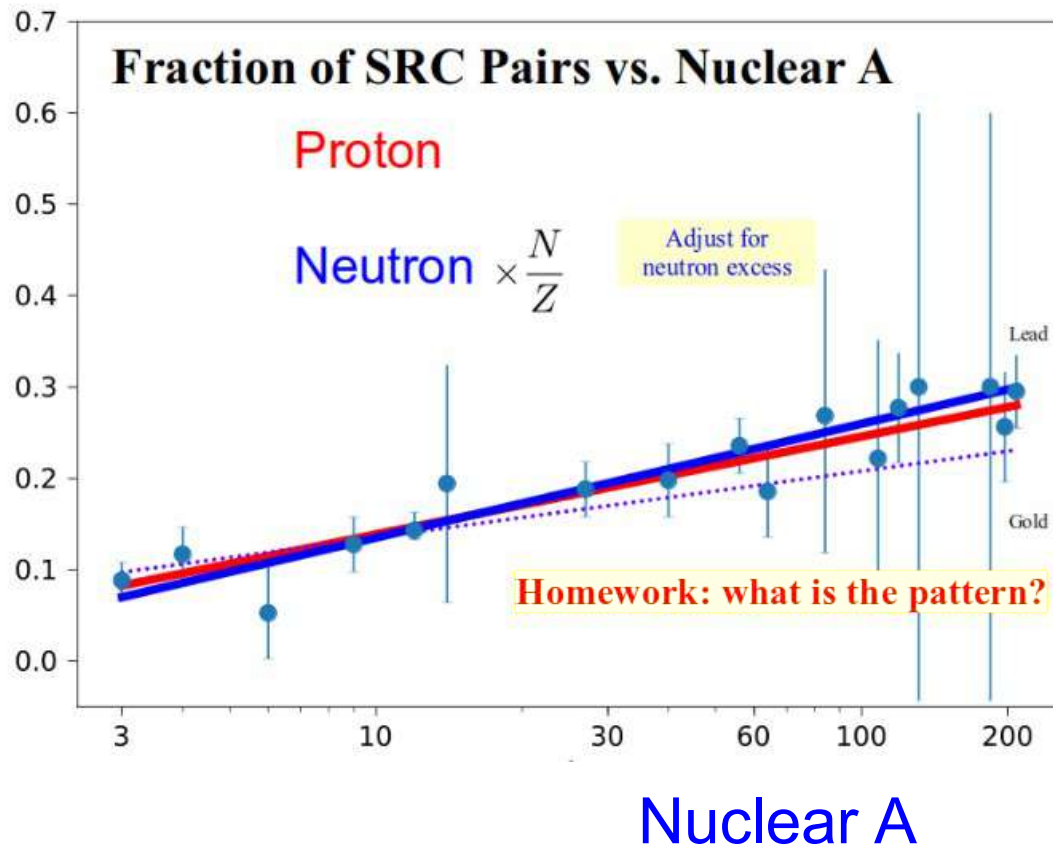
$C_p \times Z = 20.2$
 $C_n \times N = 20.9$



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
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Nature is trying to tell us something

CONCLUSIONS:

Assembling the puzzle pieces

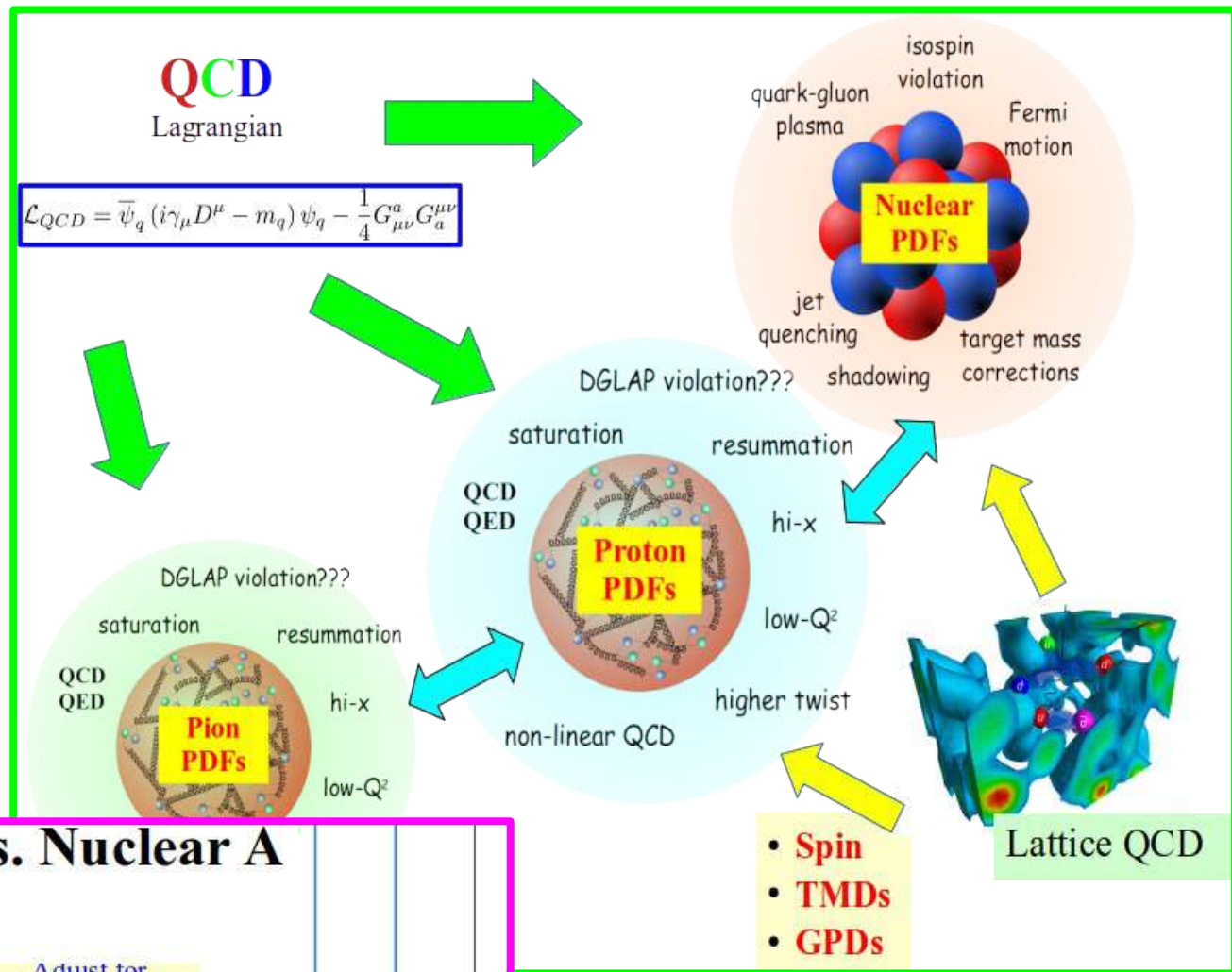
Interdisciplinary ...

Use tools from

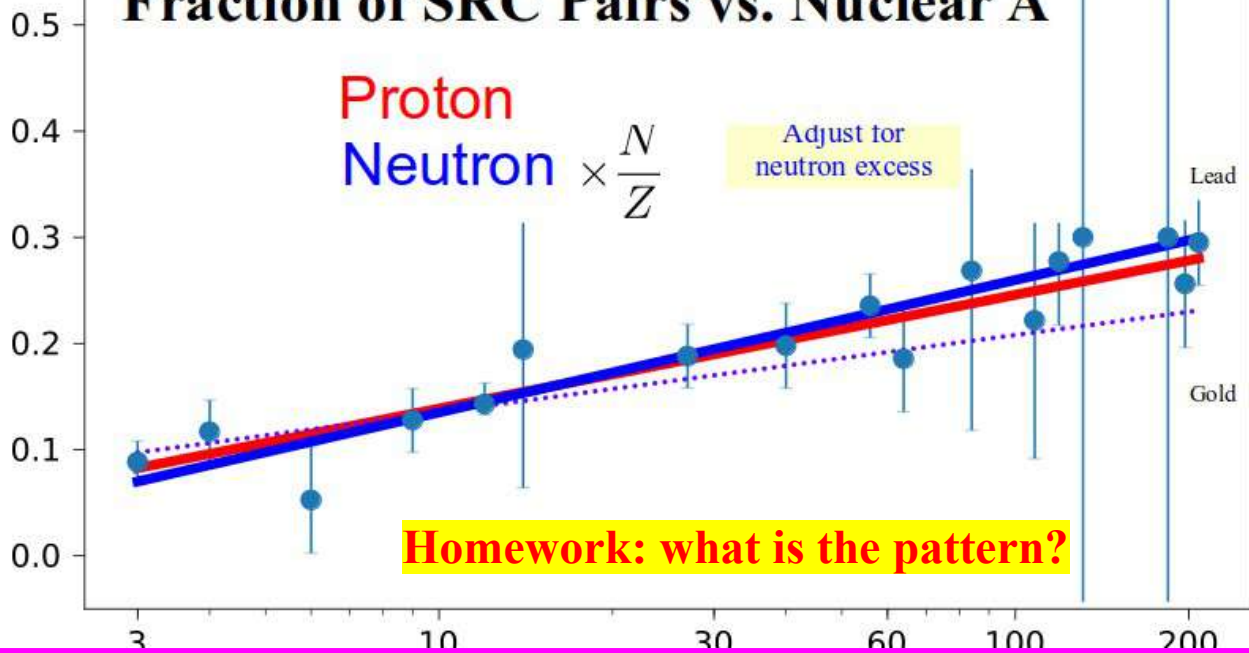
**HEP, Nuclear,
& Lattice QCD**

... to really understand the

strong force



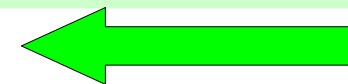
Fraction of SRC Pairs vs. Nuclear A

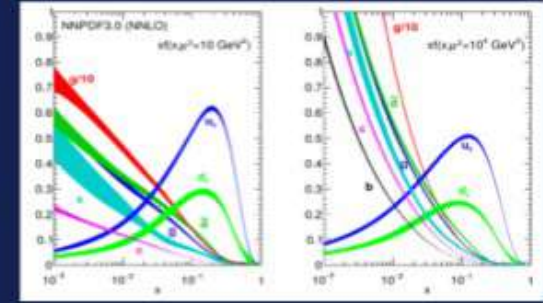
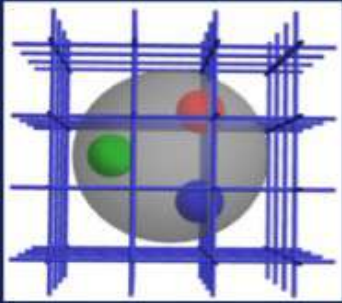


Nature is telling us ...

Why (pn) pairs?

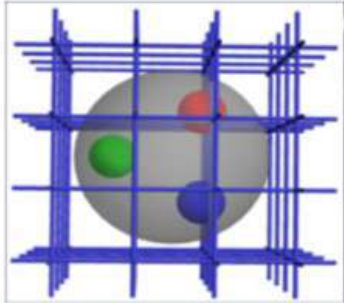
What drives this pattern?



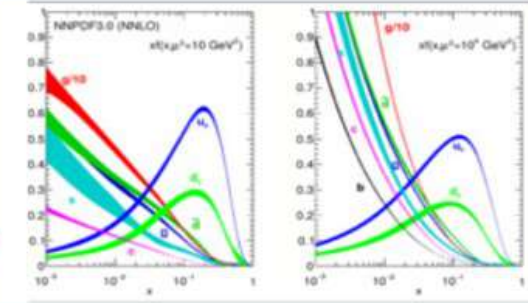


Parton Distributions and Lattice Calculations in the LHC era (PDFLattice 2017)

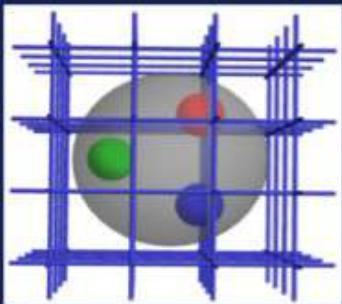
22-24 March 2017, Oxford, UK



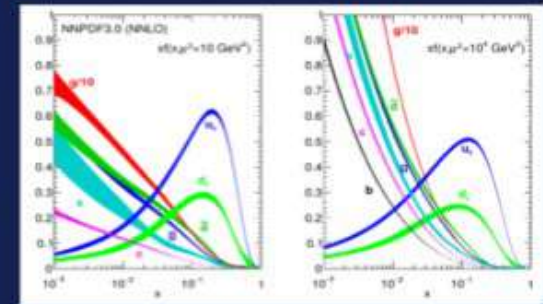
W. K. Kellogg
Biological Station
MICHIGAN STATE UNIVERSITY



Parton Distributions and Lattice Calculations (PDFLattice 2019)



Jefferson Lab



Parton Distributions and Lattice Calculations (PDF Lattice 2024)

18-20 November 2024

CONCLUSIONS:

Assembling the puzzle pieces

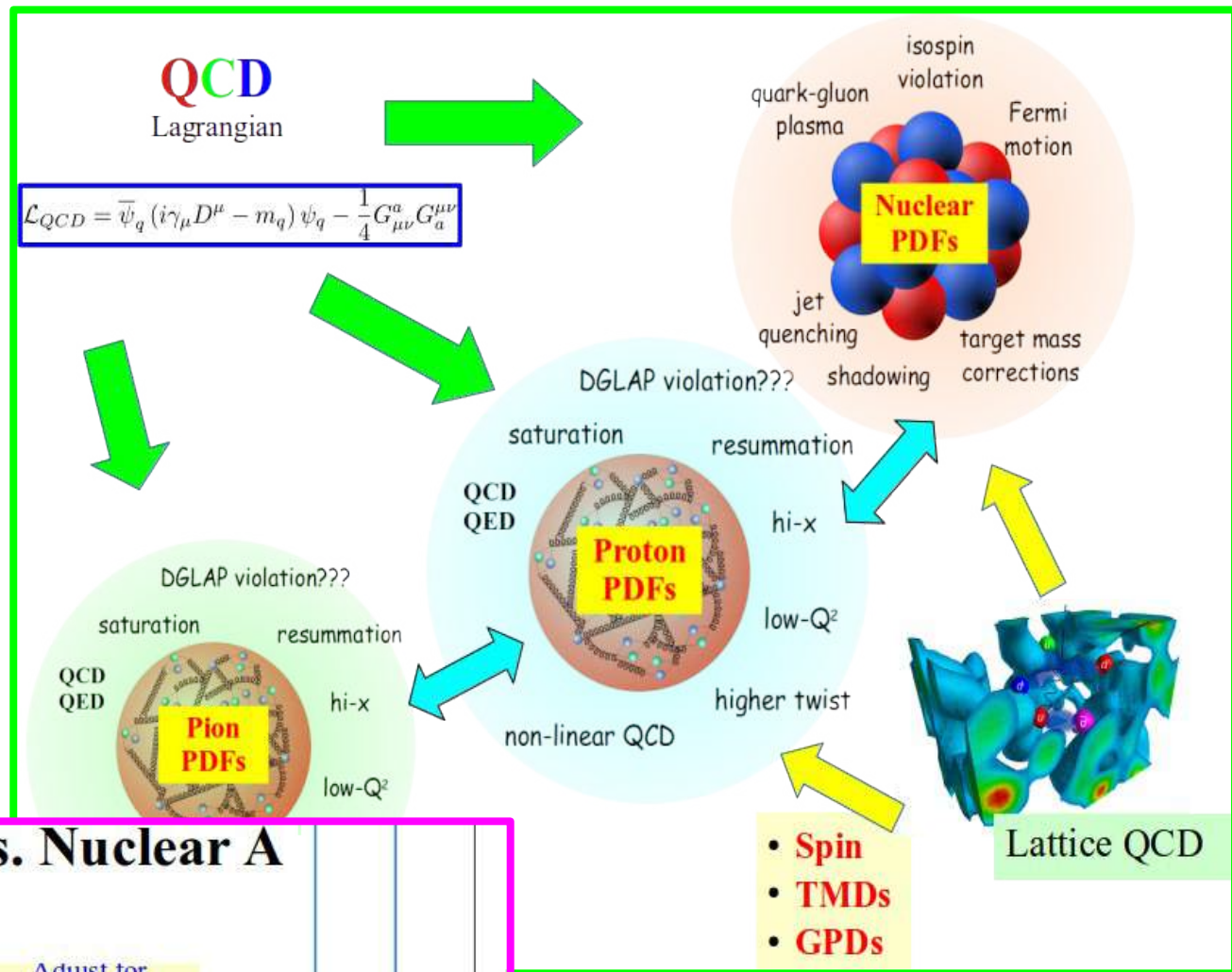
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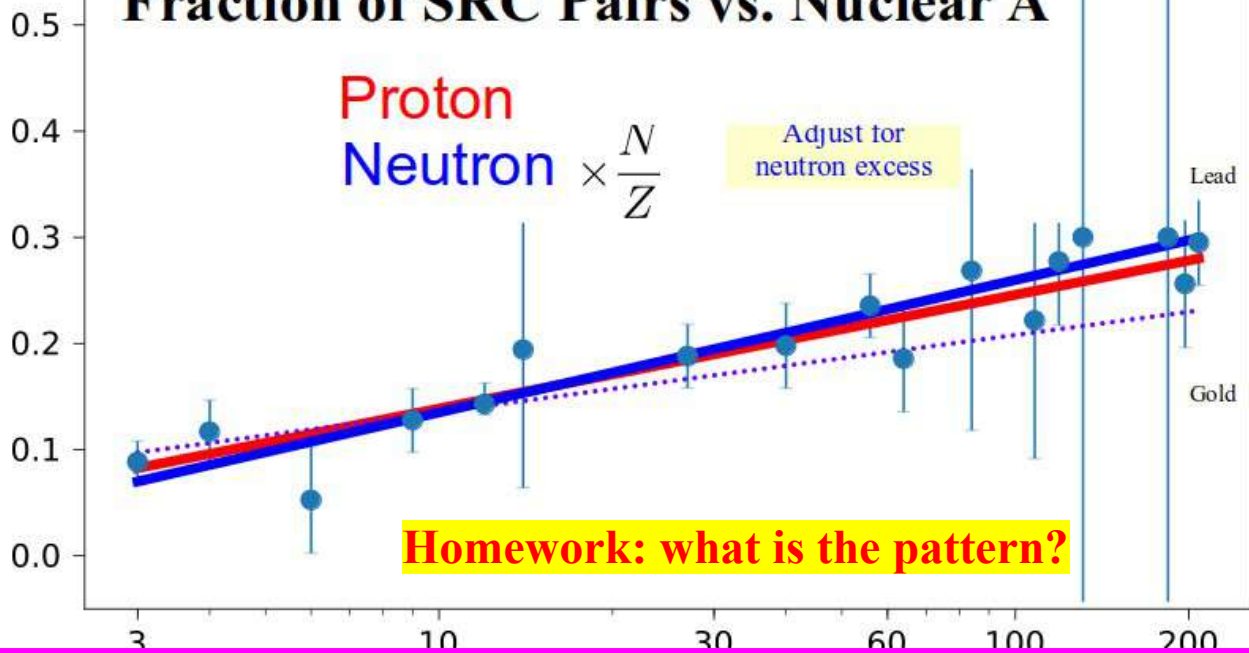
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Fraction of SRC Pairs vs. Nuclear A



Nature is telling us ...

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