

New Phenomena at the EIC:

Exploring the limits of the strong interaction force

with nPDFs

Fred Olness
SMU

*Thanks for substantial input
from my friends & colleagues*

nCTEQ
nuclear parton distribution functions



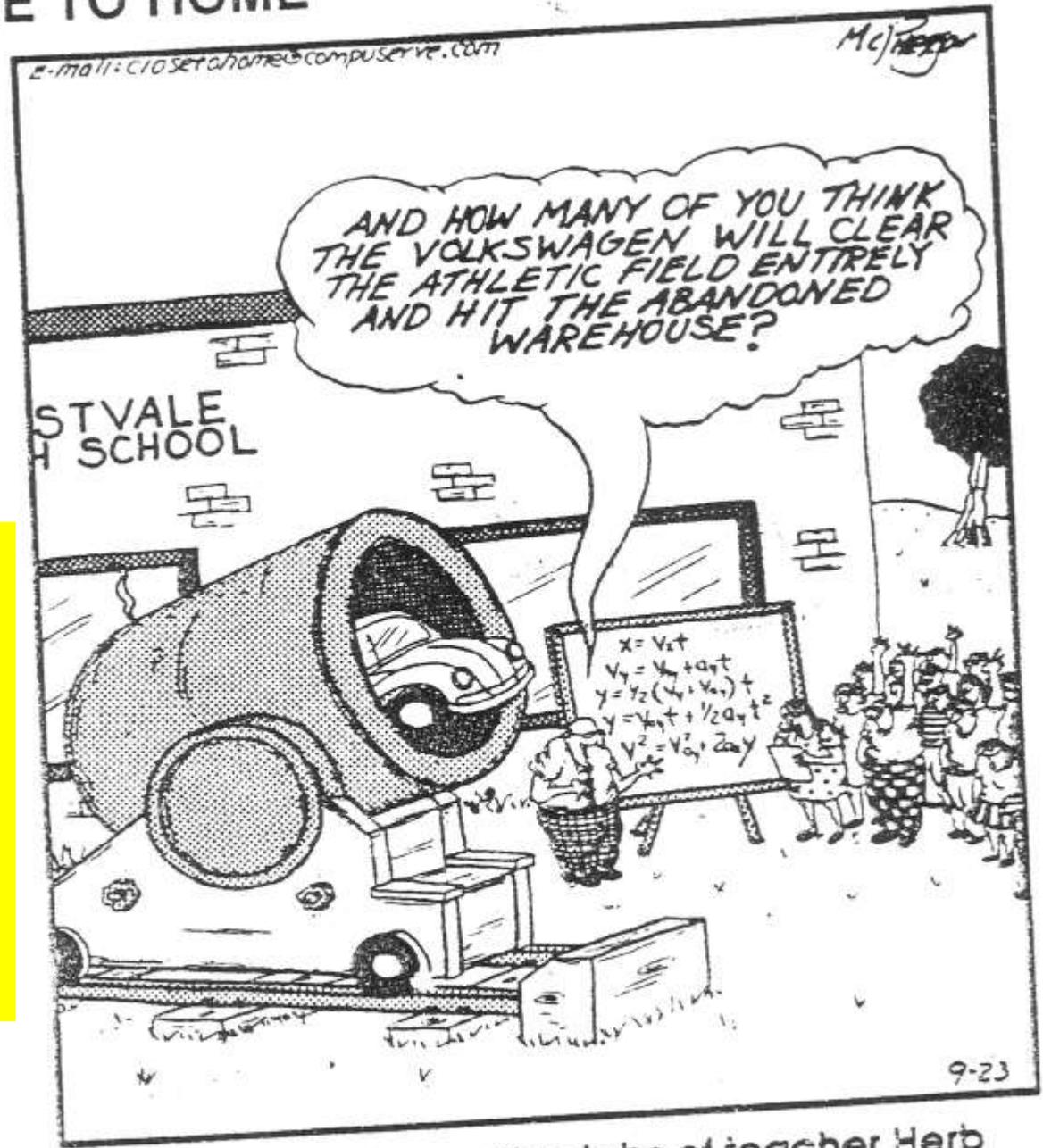
IITB-CFNS-CTEQ School
Indian Institute of Technology-Bombay
8-15 February 2026

The most exciting phrase to hear in science,
the one that heralds new discoveries, is not “Eureka!” (*I found it!*)
but “That’s funny ...”
— Isaac Asimov

Serendipitous scientific discoveries that are noteworthy

- **Penicillin:** Alexander Fleming's noticed a mold inhibiting bacterial growth in a neglected petri dish.
- **X-rays:** Wilhelm Roentgen observed a mysterious glow passing through objects and casting shadows.
- **Microwave Oven:** Percy Spencer, a Raytheon engineer, noticed a candy bar in his pocket melted while working with a magnetron.
- **Vulcanized Rubber:** Charles Goodyear accidentally spilled a rubber and sulfur mixture on a hot stove.
- **Post-it Notes:** Spencer Silver's attempt to create a super-strong adhesive at 3M.
- **Cosmic Microwave Background Radiation:** Arno Penzias and Robert Wilson were perplexed by persistent radio noise in their antenna.

Scientific progress isn't always a direct path ... often, it's about recognizing unexpected patterns found at the fringes of our expectations ...



Ours is an
experimental
science

Thanks to the innovative labs of teacher Herb Krenley, physics quickly became Westvale High's most popular course.



The FermiNews logo, consisting of the word "FERMI" in large, bold, black letters with small subscripts "N", "E", "W", and "S" below the "E", "R", and "M" respectively. The "F" is on a dark orange background, and the "E" is on a light orange background.

Volume 26 | Friday, January 17, 2003 | Number 1

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Data Make You Smarter

by **Dan Amidei, University of Michigan**
and **Chip Brock, Michigan State University**

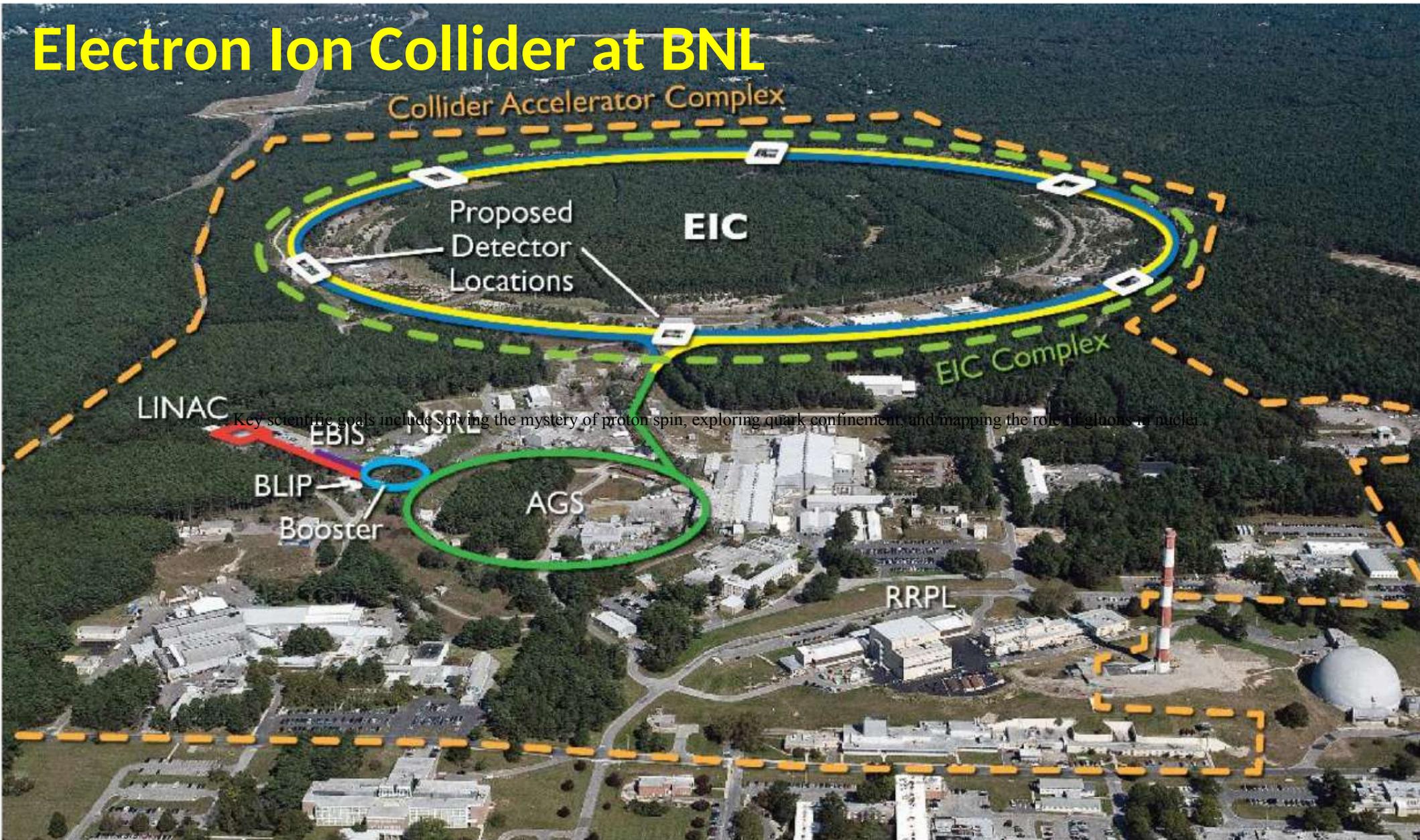
As Collider Run II gets under way with fits and starts it's become a question of its goals. But it would be wrong to pre-judge this program why.

The aggressive plan for Run II began in 1995-96 when a rag-tag group pulled together the tev_2000 workshop which studied the physics running of the Tevatron. Previously, SSC preparation had overshadowed the potential of a Fermilab program. With the cancellation of the SSC and the top quark discovery imminent, Tevatron began to present a certain attractiveness ...



Where does the data come from???

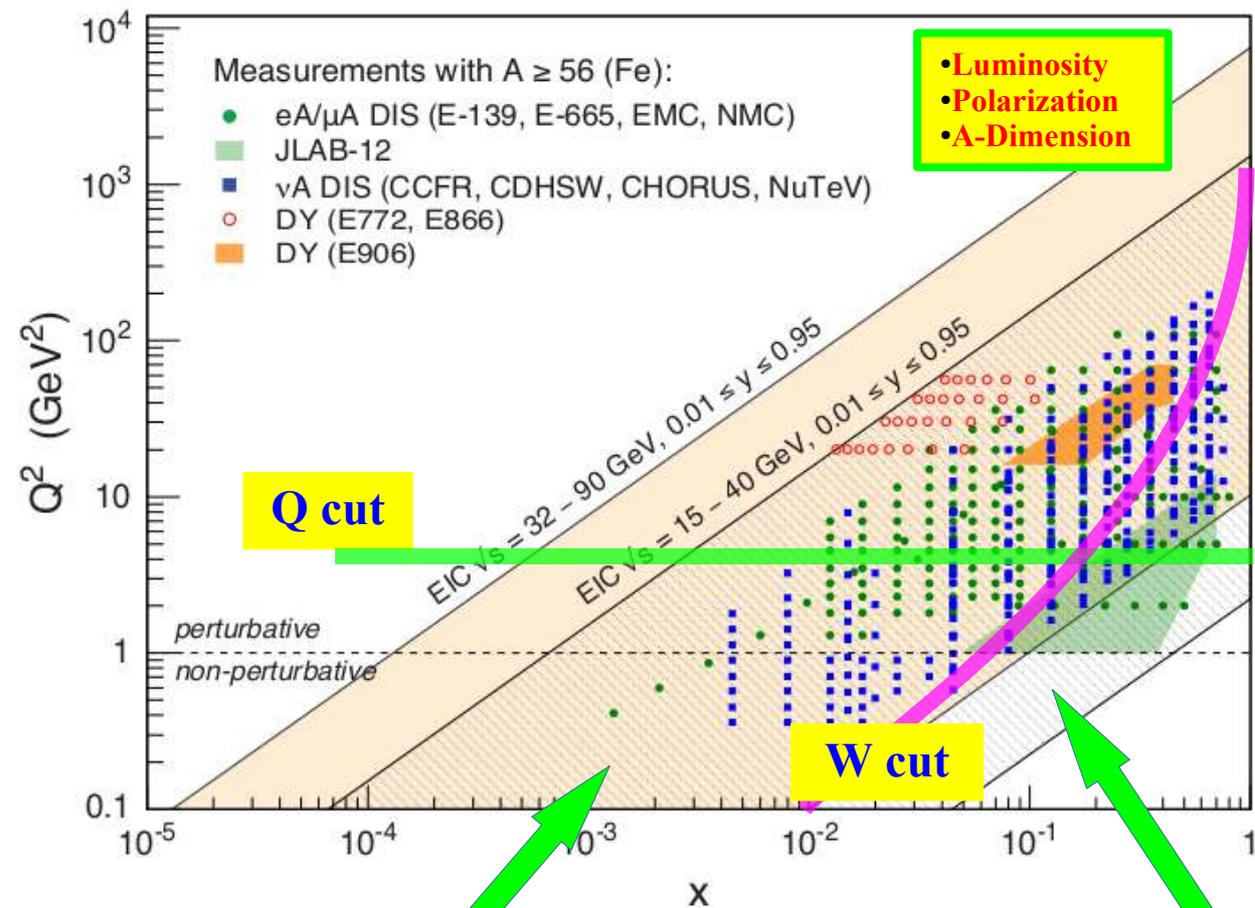
Electron Ion Collider at BNL



Key scientific goals include solving the mystery of proton spin, exploring quark confinement, and mapping the role of gluons in nuclei.

Solving the mystery of proton spin, exploring quark confinement, and mapping the role of gluons in nuclei.

We're going to study the gluon ... and at small-x, it's gluons all the way down



High-x:

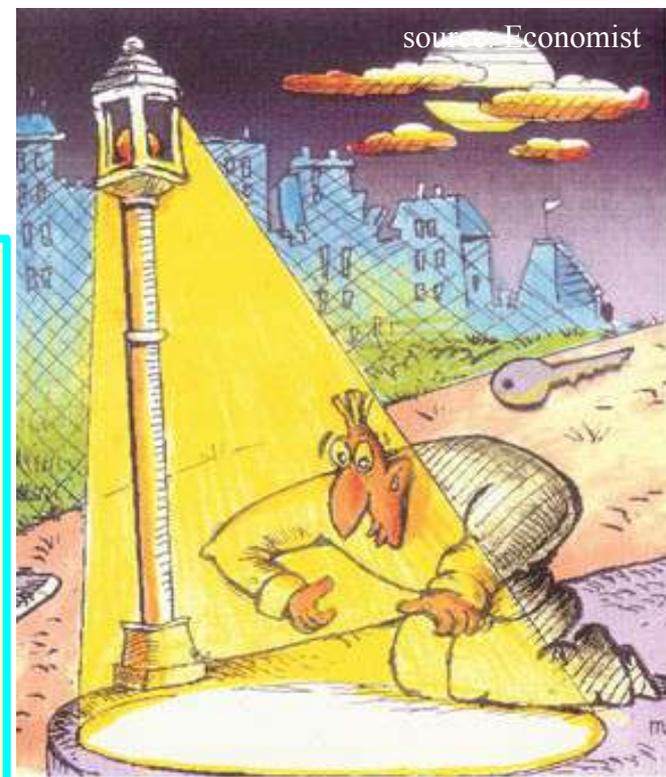
Nuclear PDFs: $x > 1$ allowed;
 impacts $F_2^{\text{Nuc}}/F_2^{\text{Iso}}$ in Fermi region
 Target Mass Corrections
 pick up M^2/Q^2 higher twist
 Deuteron Corrections
 impacts $F_2^{\text{Nuc}}/F_2^{\text{Deuteron}}$ ratio

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



nCTEQ

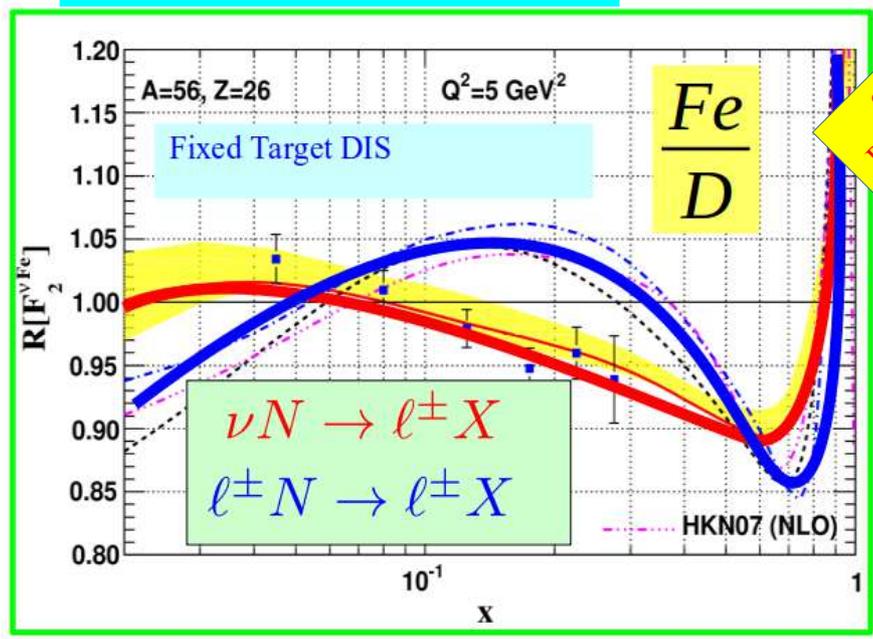
nuclear parton distribution functions

nCTEQ project is an extension of the CTEQ collaborative effort to determine nuclear parton distribution functions (nPDFs).

Grenoble, April 2024

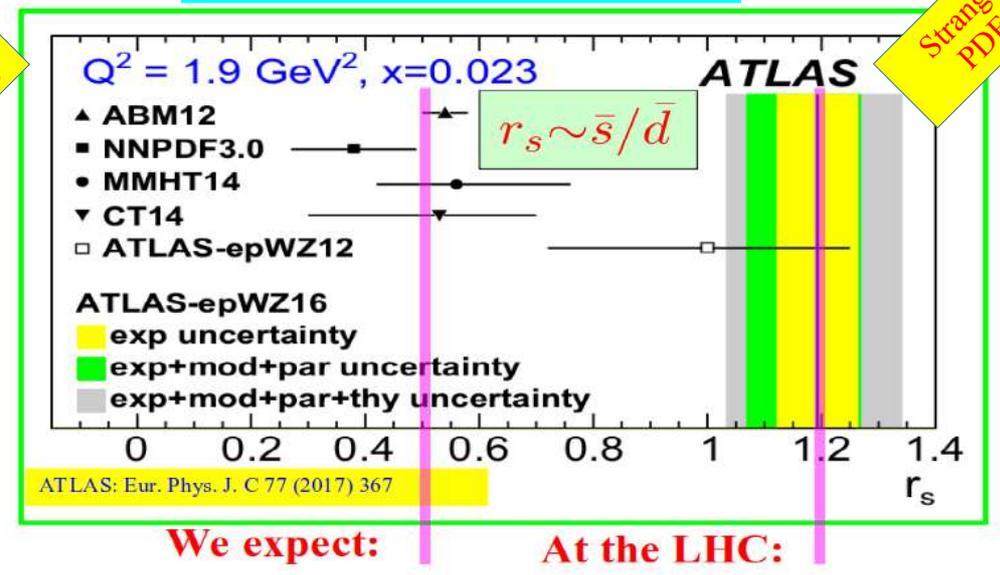


nCTEQ15 ν



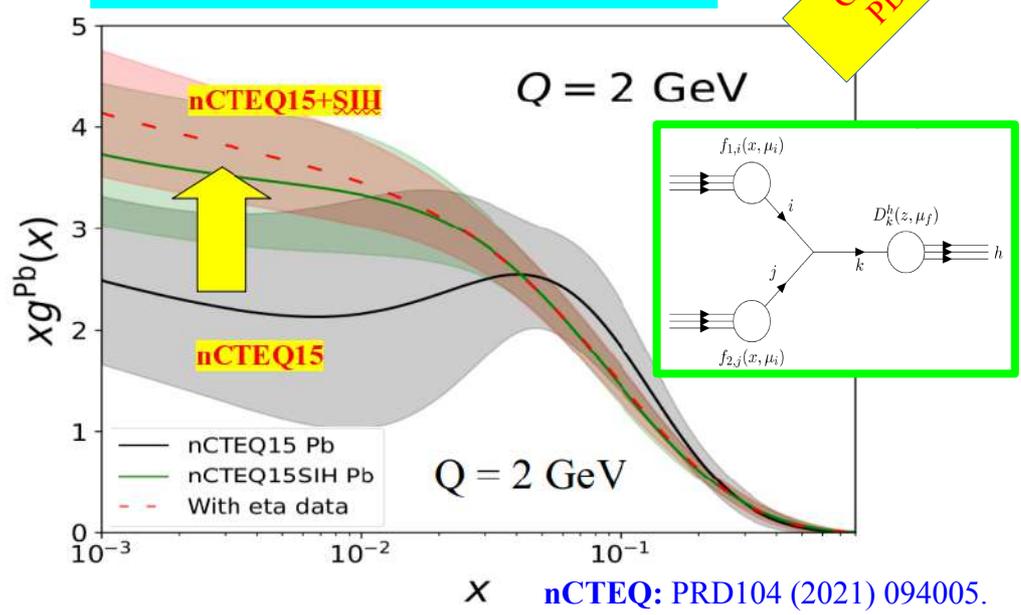
nCTEQ: arXiv: 2204.13157

nCTEQ15WZ



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

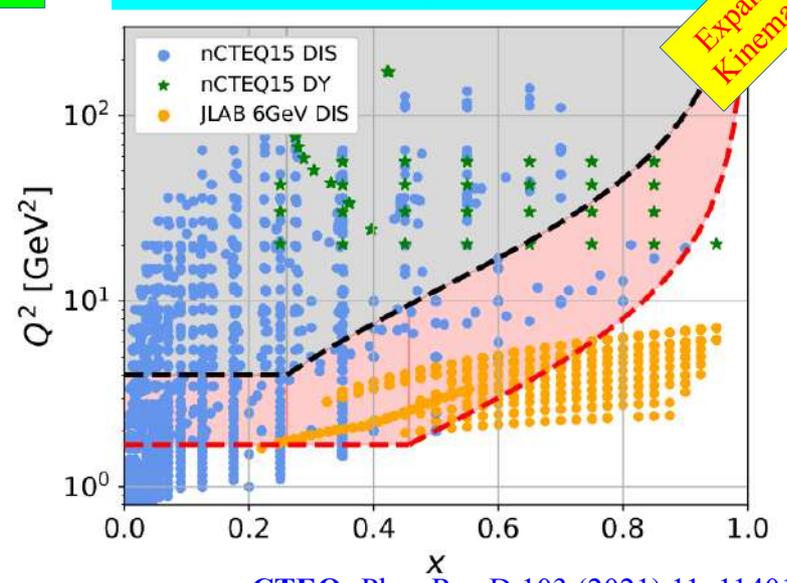
nCTEQ15WZ+SIH



nCTEQ: PRD104 (2021) 094005.

Key for EIC

nCTEQ15HIX



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

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

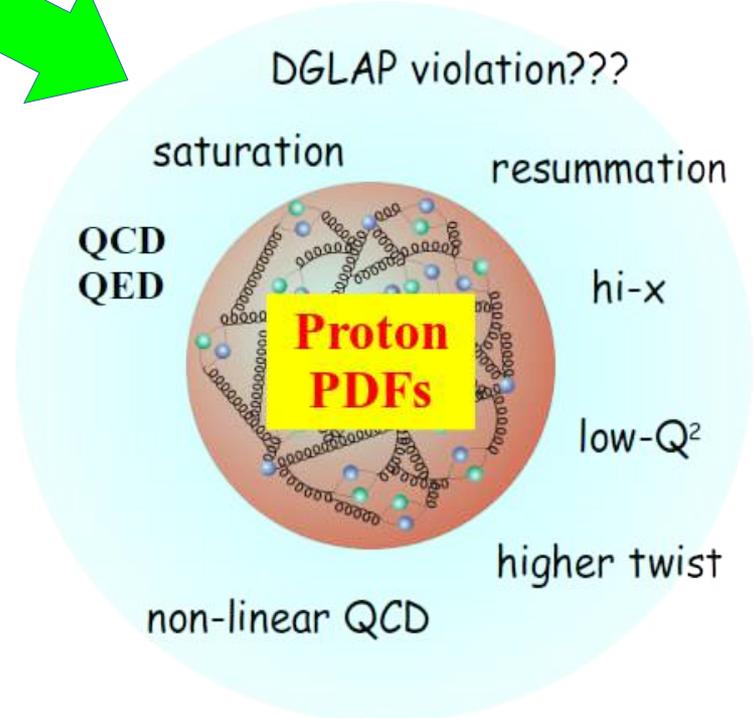
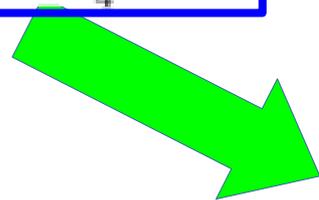
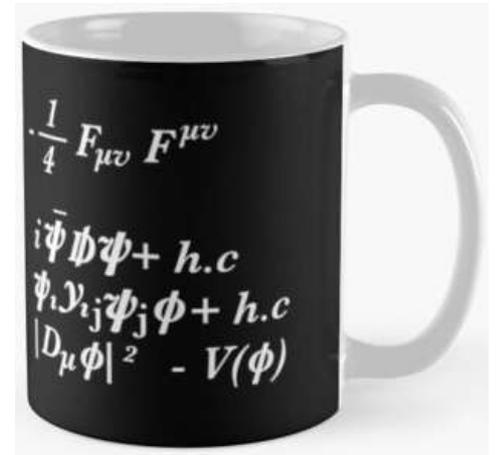
Quantum ChromoDynamics

QCD

Lagrangian

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

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



... we can go further

QCD
Lagrangian

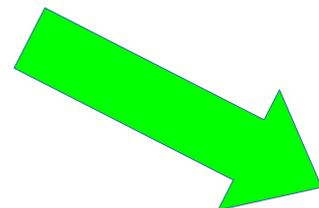
$$\mathcal{L}_{QCD} = \bar{\psi}_q (i\gamma_\mu D^\mu - m_q) \psi_q - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}$$



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

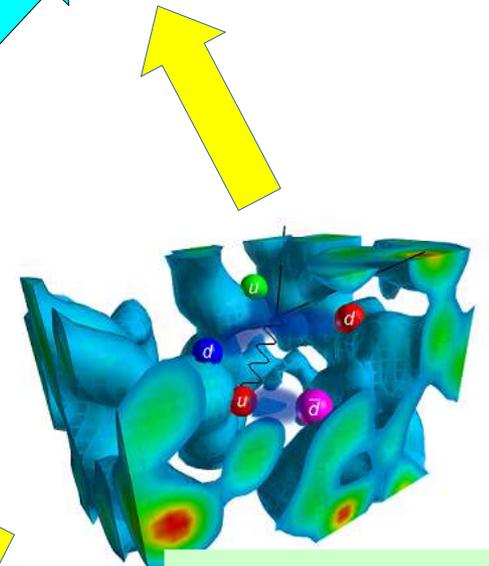


DGLAP violation???

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

Pion PDFs

QCD
QED



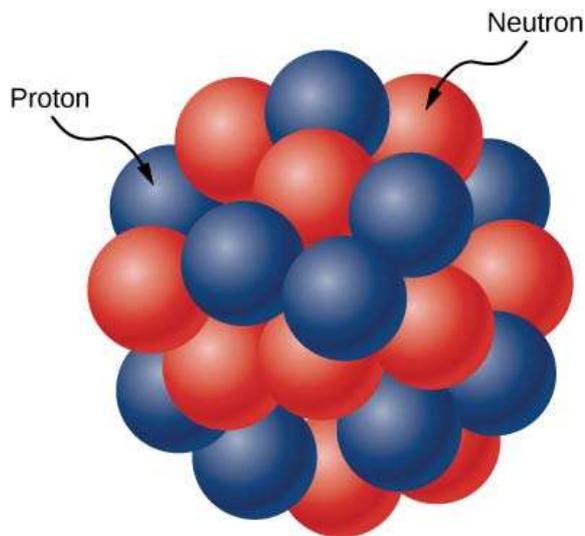
- **Spin**
- **TMDs**
- **GPDs**

Lattice QCD

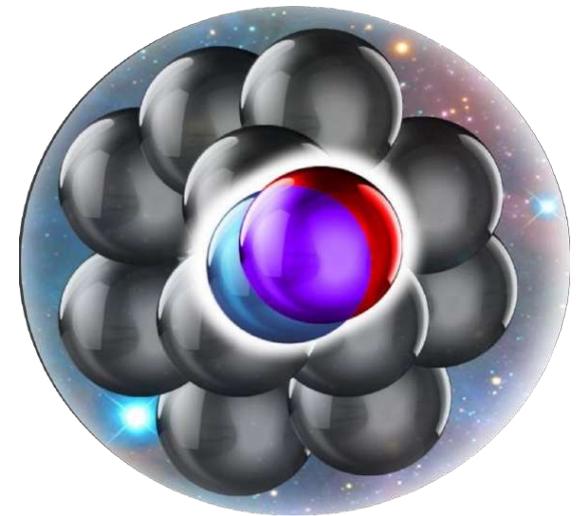
precision $f_A(x, Q)$ can serve as Boundary Condition for $f_A(x, Q, k_T, b_T, \sigma)$

Nuclear PDFs

Parton Distribution Functions



...



is it just a bag of
protons & neutrons ???

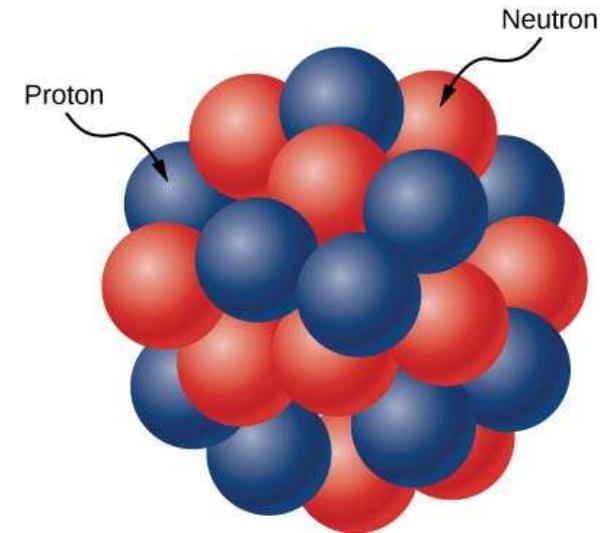
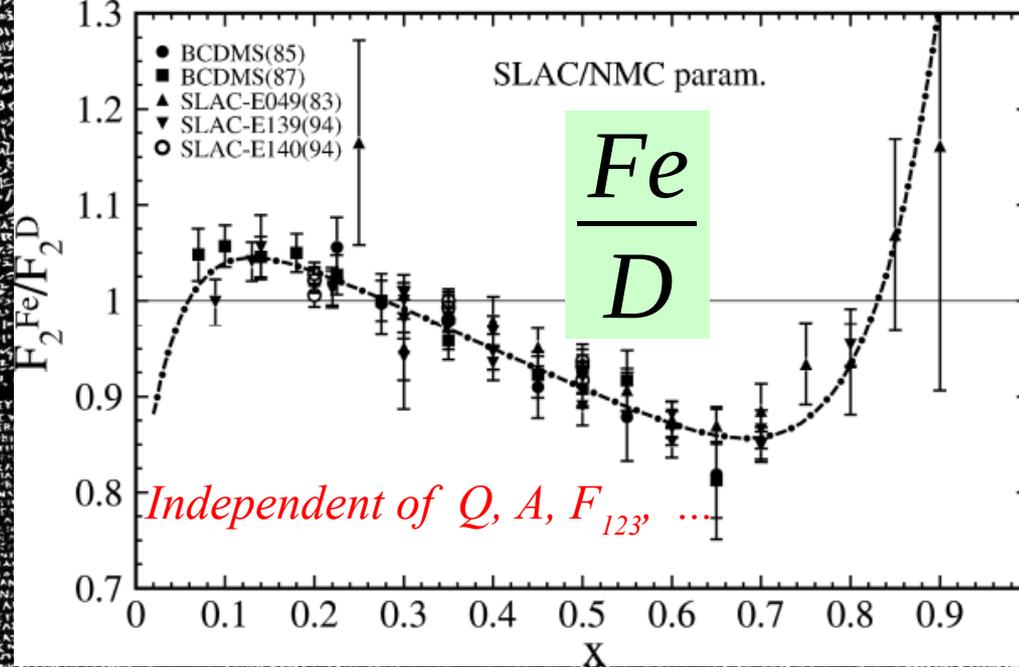
you'd be
~90% correct

The ratio of iron (Fe)
to Deuterium (D)

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

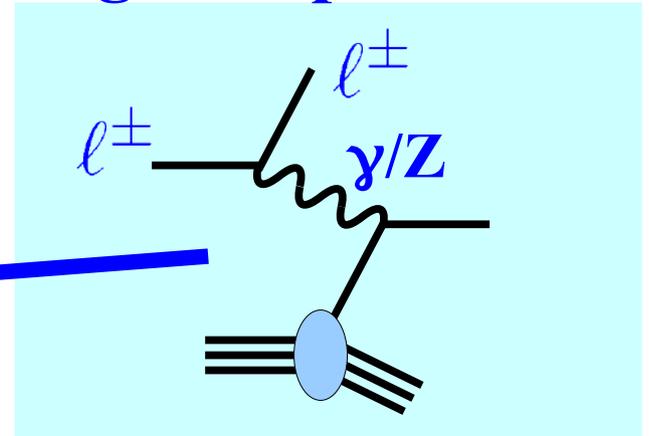
Iron

(proton + neutron)



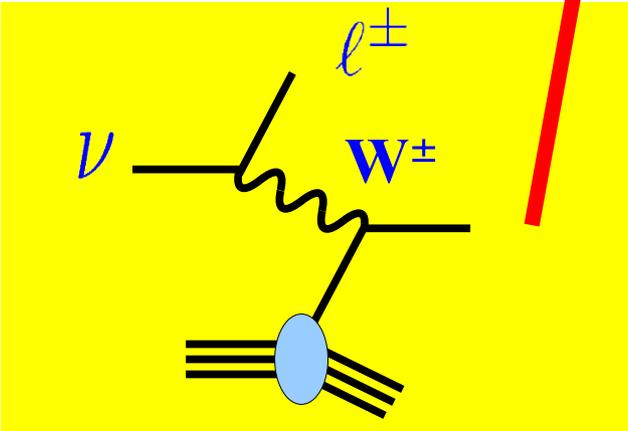
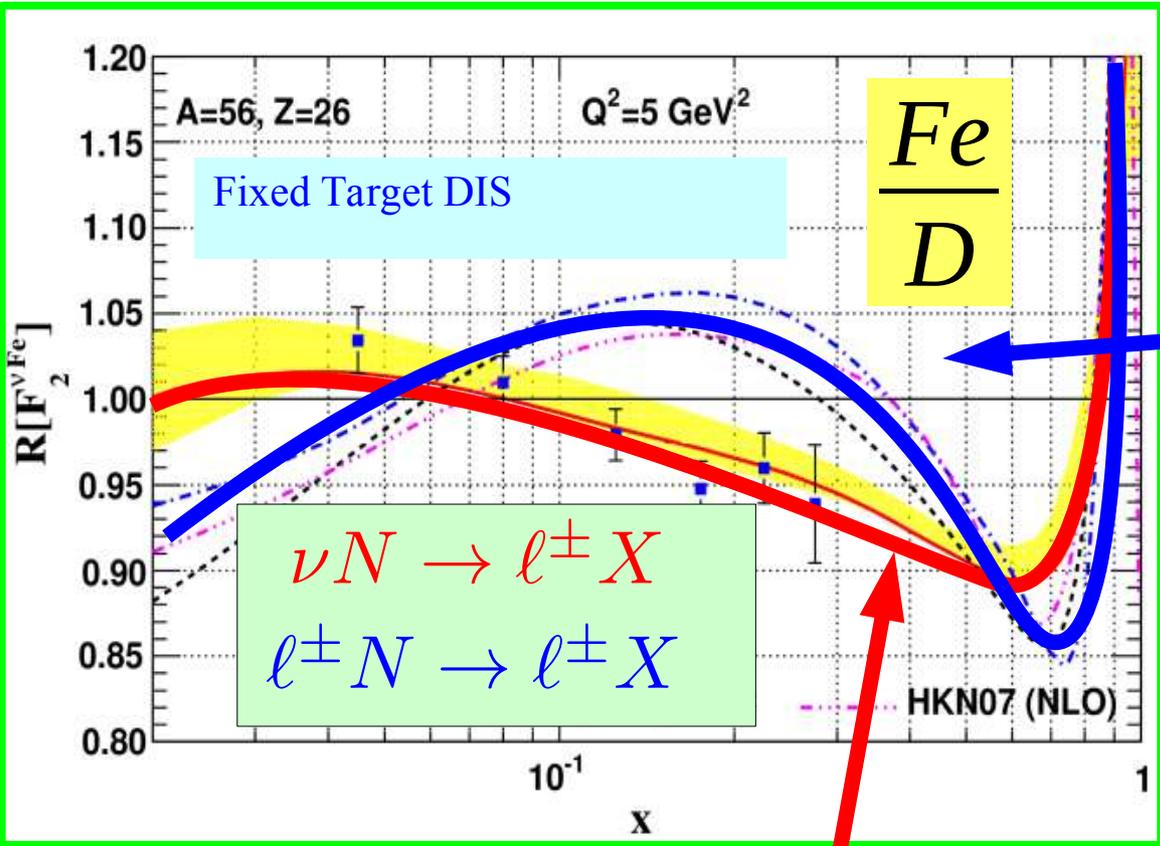
But ...

Charged Lepton DIS



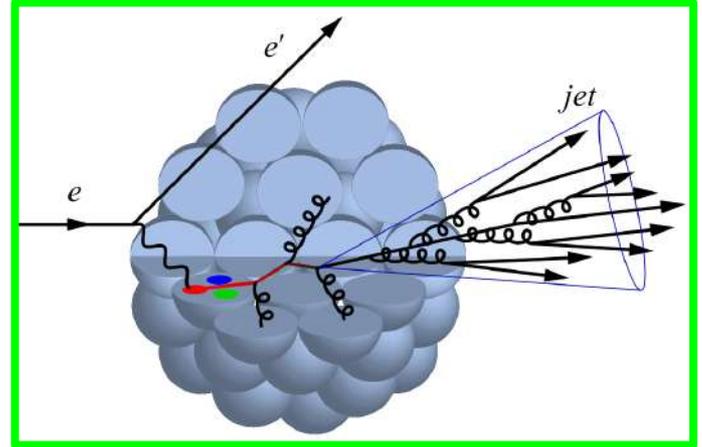
*some caveats
... correlated errors*

Ingo Schienbein, ... (2007)
Karol Kovarik, ... (2010)



Neutrino DIS

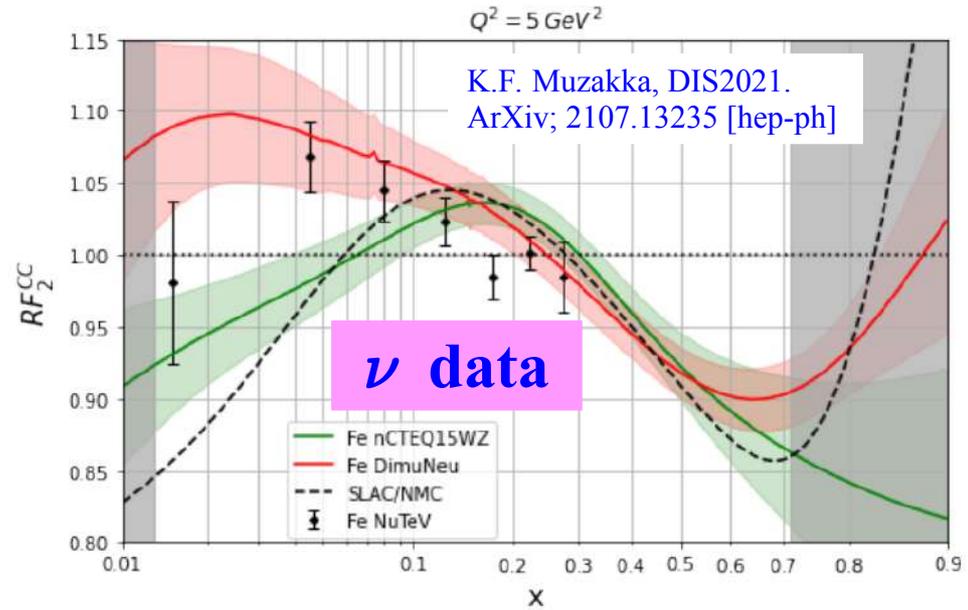
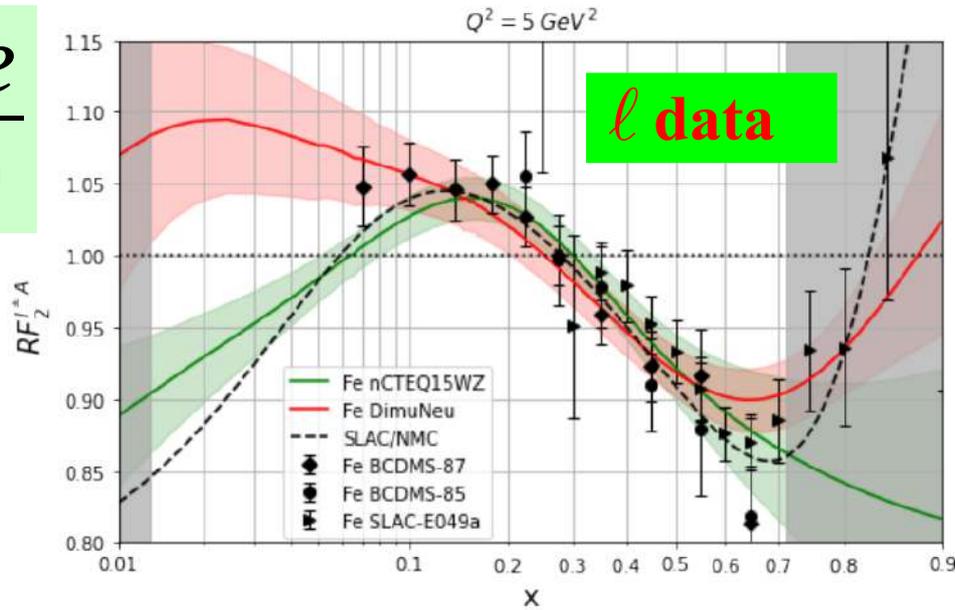
Depends on nuclear corrections



Propagation of γ/W thru nuclei

Faiq Muzakka, Karol Kovarik, ...

$\frac{Fe}{D}$



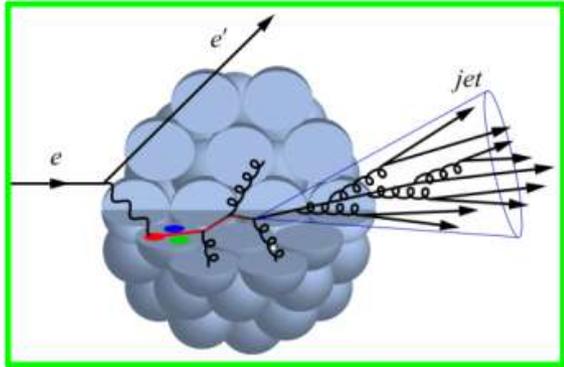
Iron
(proton + neutron)

What is the correct nuclear correction ???
Are these data sets compatible???

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. Kovarik ^{1,¶},
A. Kusina ^{1,6,**}, J.G. Morfin ^{7,††}, F. I. Olness ^{2,‡‡}, R. Ruiz ^{1,6}, I. Schienbein ^{1,8,§§}

¹Institut für Theoretische Physik, Westfälische Wilhelms-Universität Münster.



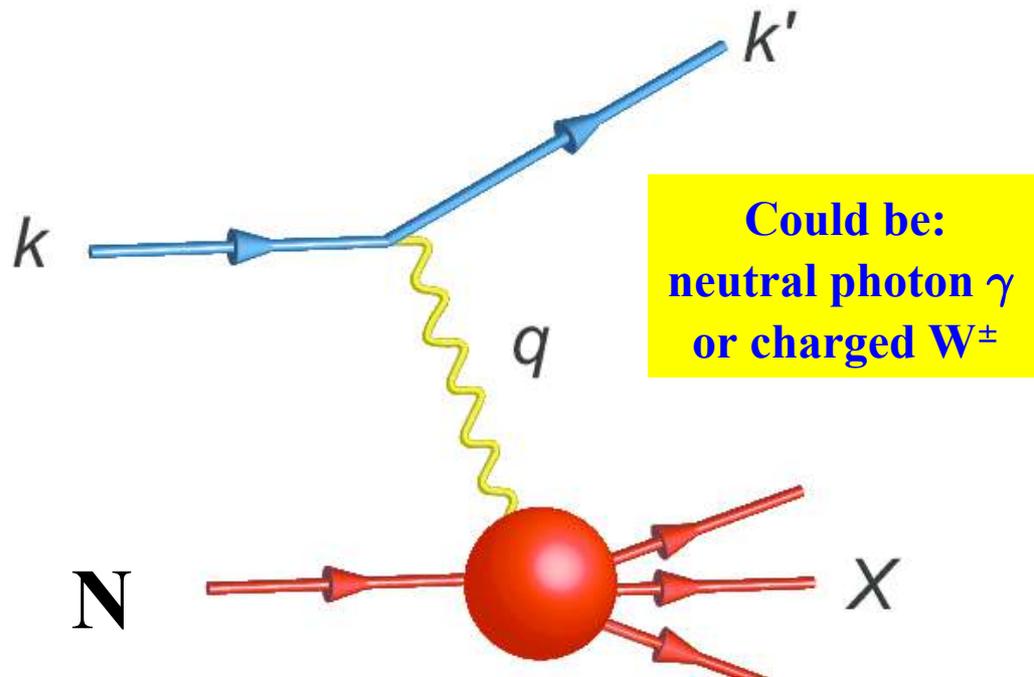
Propagation of γ/W thru nuclei

Neutrino Deep Inelastic Scattering (DIS)

(nCTEQ) Faiq Muzakka, Karol Kovarik, ...

Phys.Rev.D 106 (2022) 7, 074004 • e-Print: 2204.13157 [hep-ph]

Nuclear Targets Important



Neutrino DIS

$$F_2^\nu \sim [d + s + \bar{u} + \bar{c}]$$

$$F_2^{\bar{\nu}} \sim [\bar{d} + \bar{s} + u + c]$$

$$F_3^\nu \sim 2[d + s - \bar{u} - \bar{c}]$$

$$F_3^{\bar{\nu}} \sim 2[u + c - \bar{d} - \bar{s}]$$

Differentiate flavors of free-proton PDFs:

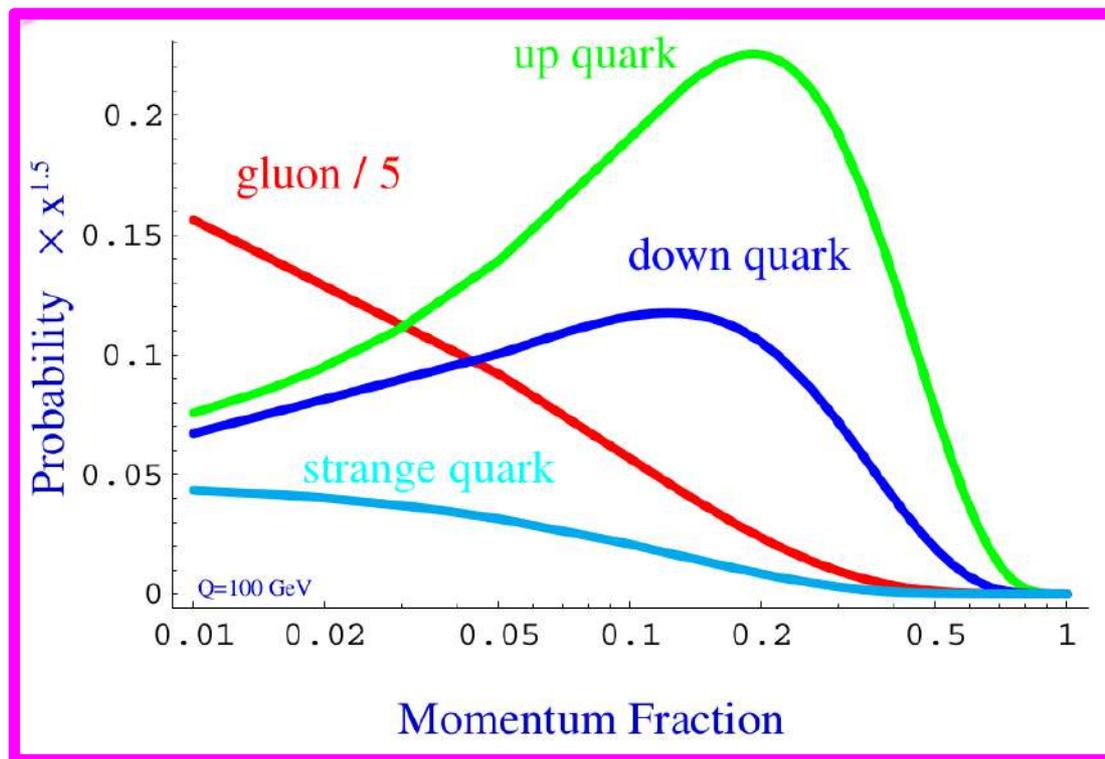
Strange PDF

Parton Distribution Functions



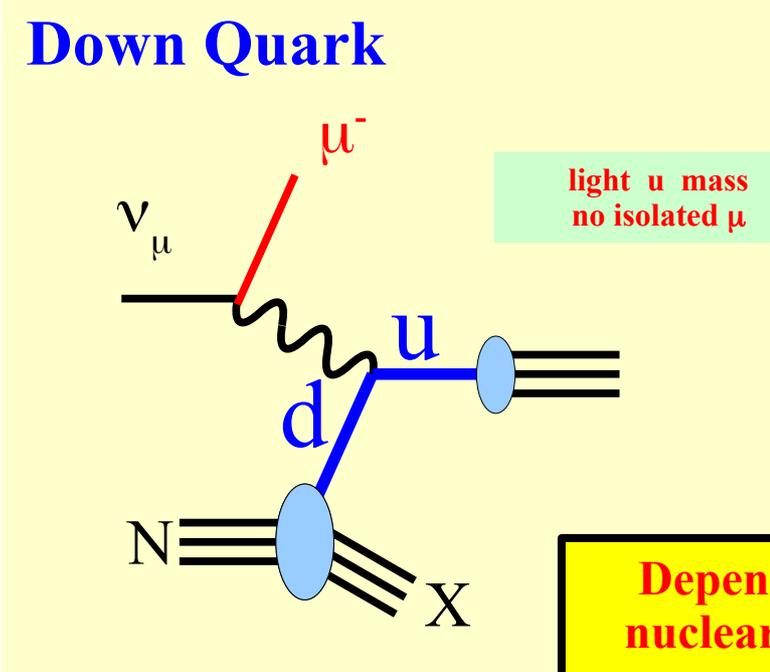
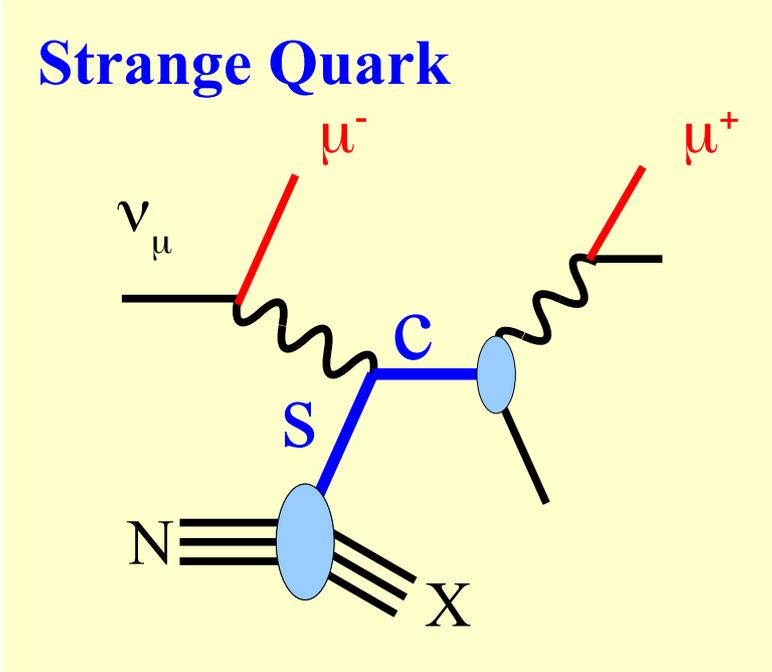
... this has a significant impact on the strange quark PDF

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



Result:

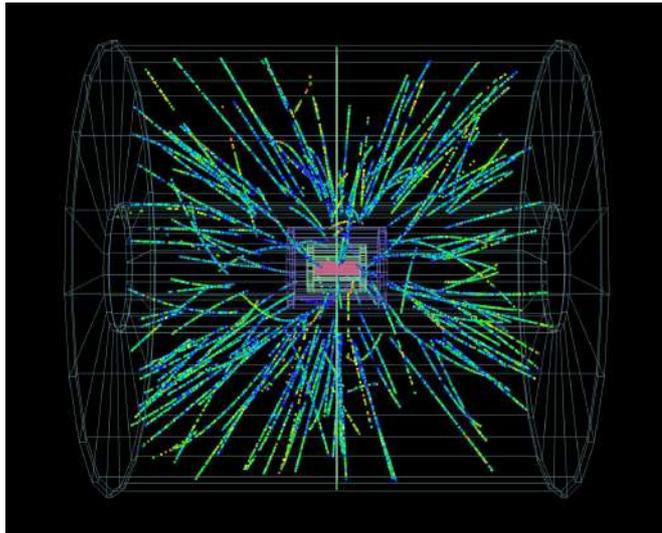
$$\bar{s}(x) \sim \frac{1}{2} \bar{d}(x)$$



Depends on nuclear PDFs

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

(nCTEQ) Tomas Jezo, Aleksander Kusina, Fred Olness, ...

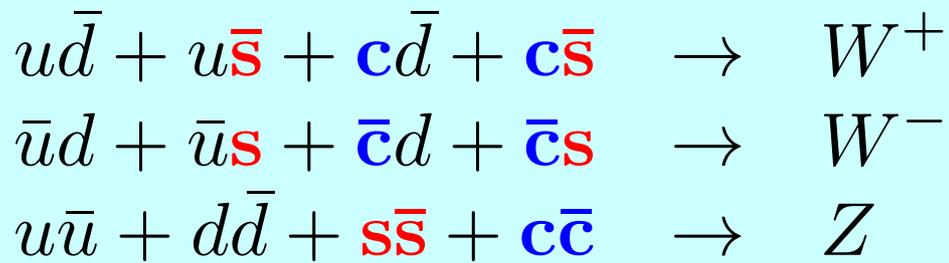


Independent of
Nuclear Corrections

$$\begin{aligned}
 p \ p &\rightarrow W, Z \\
 p \ Pb &\rightarrow W, Z
 \end{aligned}$$

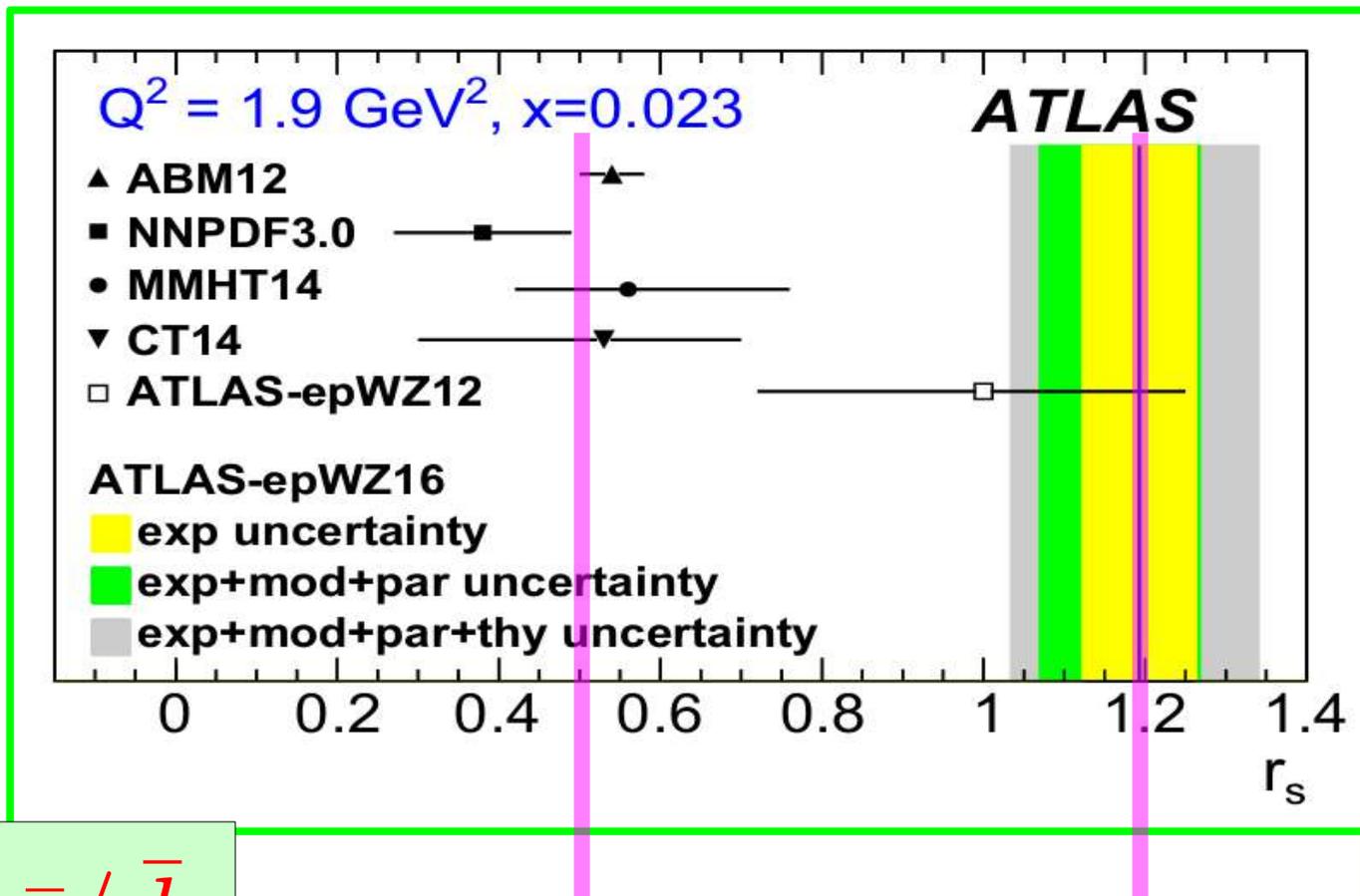
LHC Heavy Ion

... there's another
way to measure the
strange quark



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:

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

Current Tools

xFitter



xFitter Collaboration Meeting
February 2020, DESY



PROTON

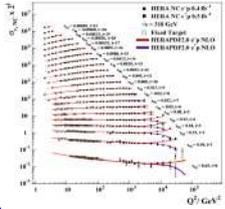
NUCLEON

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

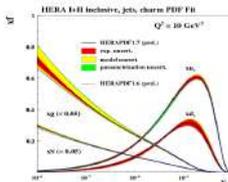
Processes:

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

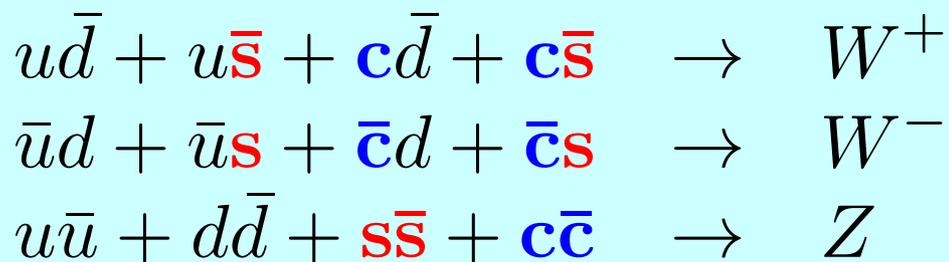
BFKL interface

Heavy Quark Variable Threshold Improvements in χ^2 and correlations

TMD PDFs (uPDFs)

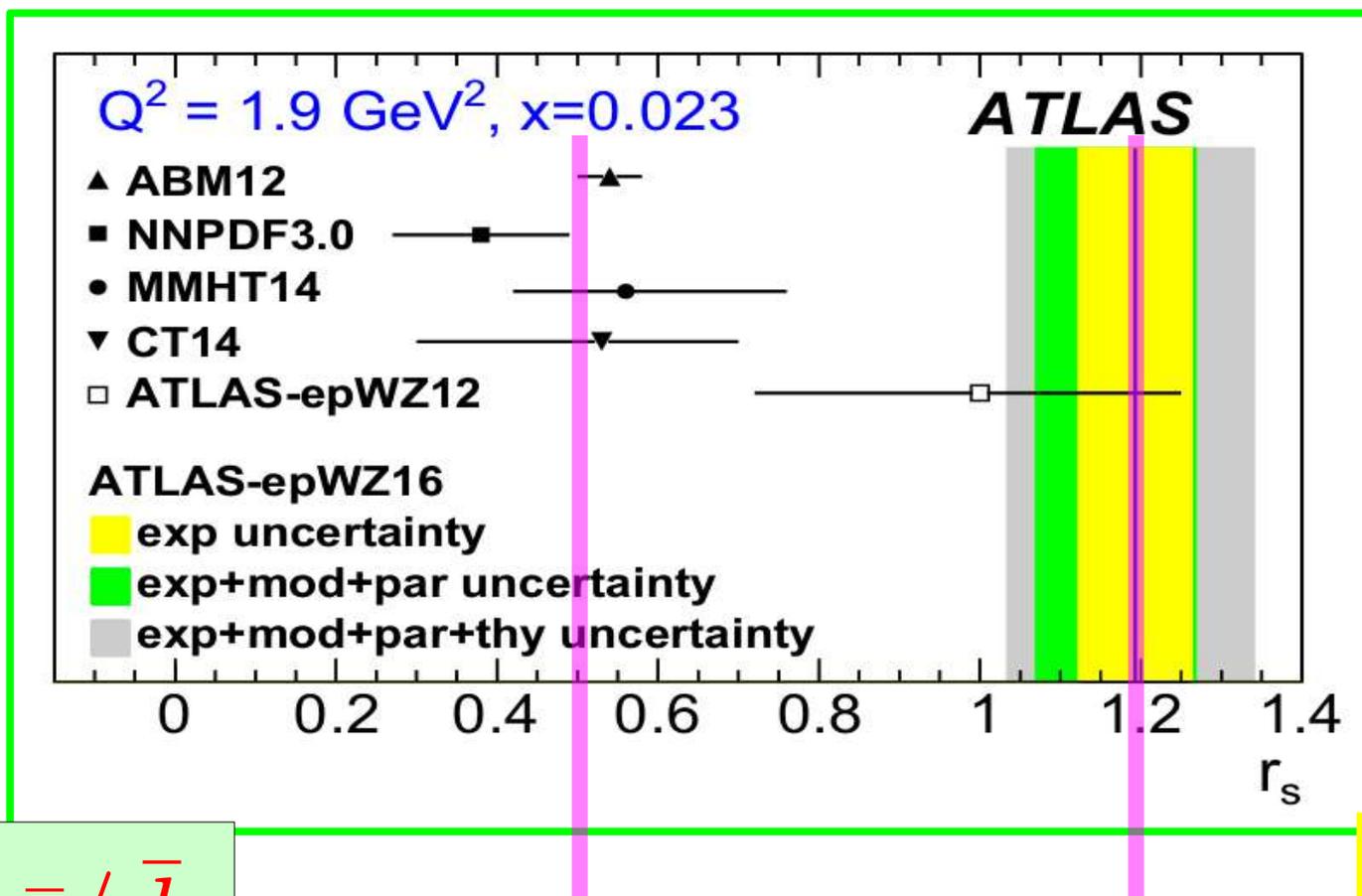
... and many other

xFitter 2.2.0
Future Freeze



Surprise:

We expected $r_s = 1/2$
LHC finds $r_s > 1$



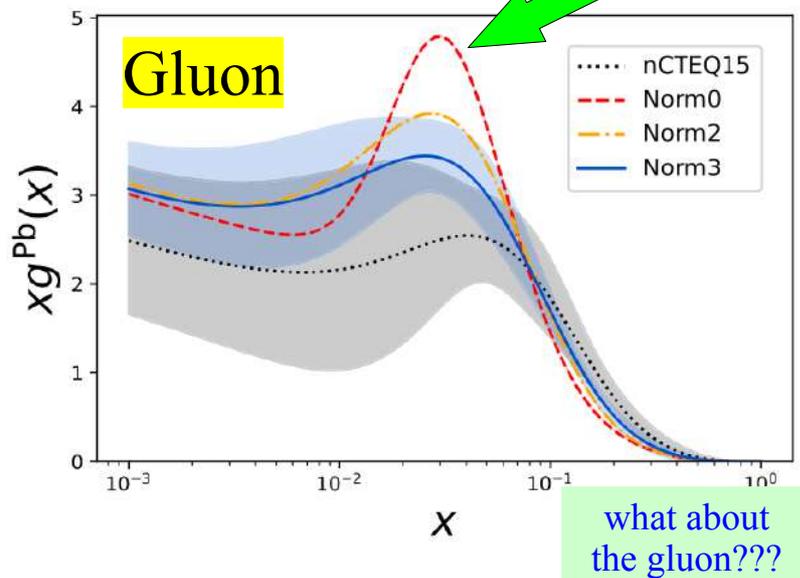
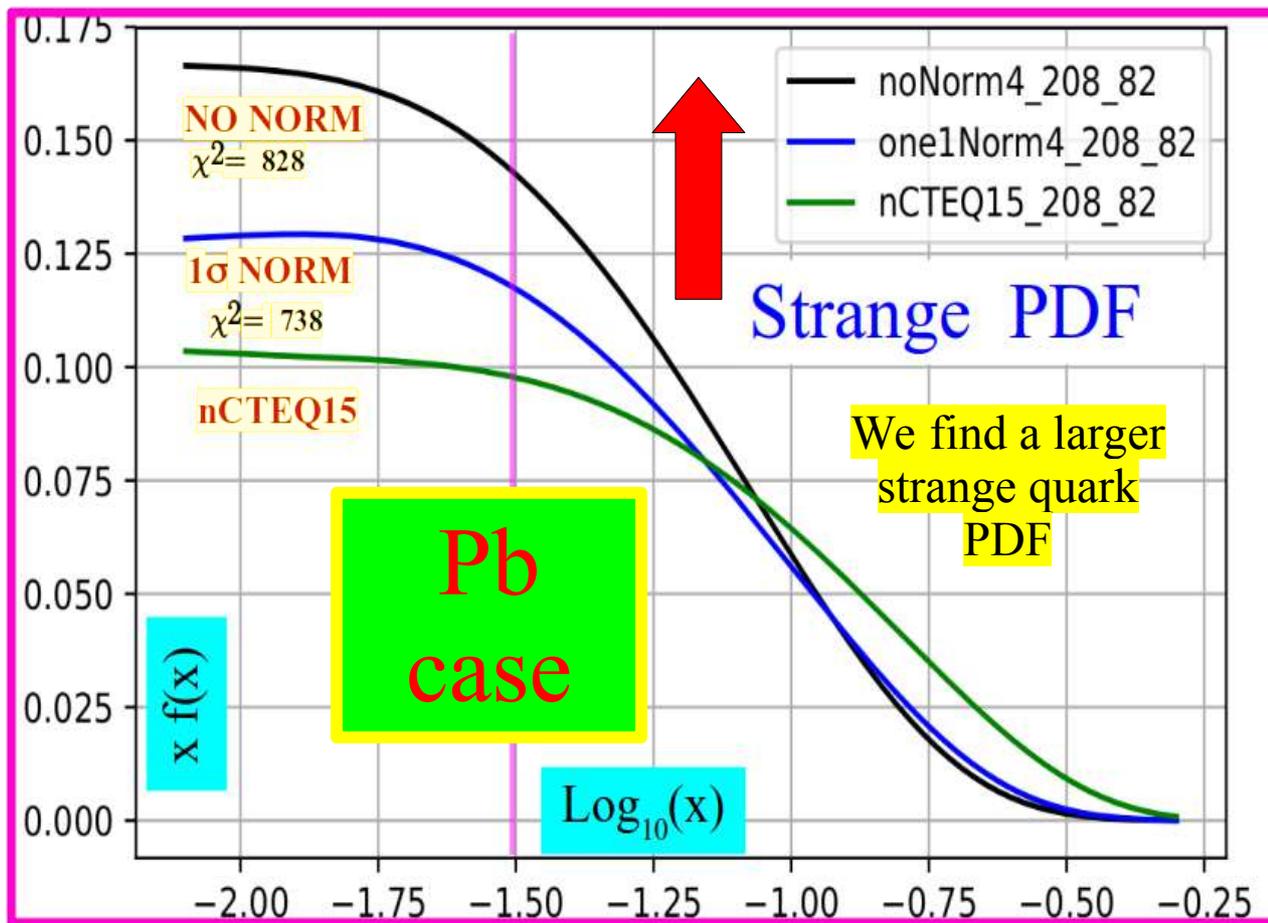
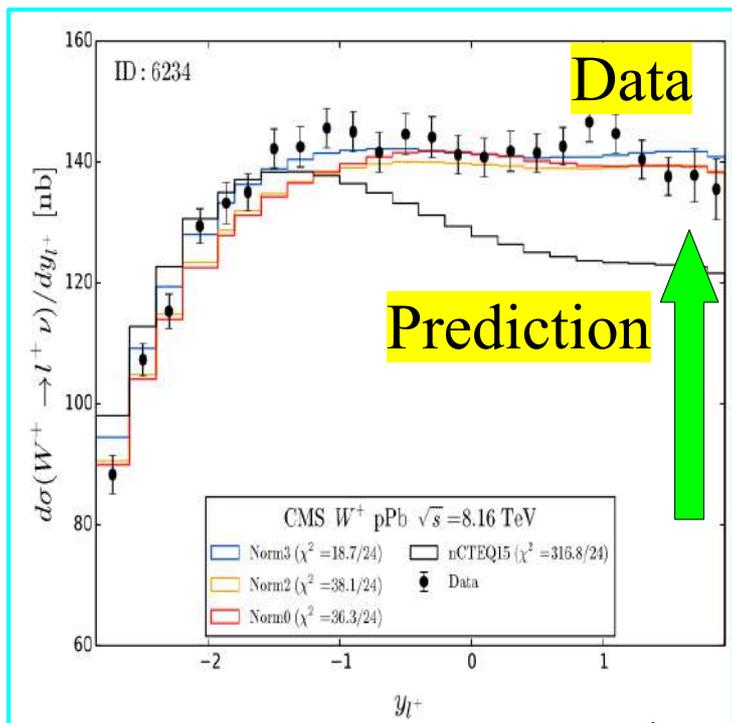
Proton case

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

We expect:

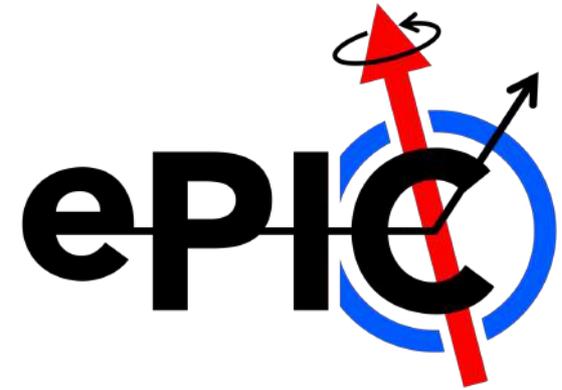
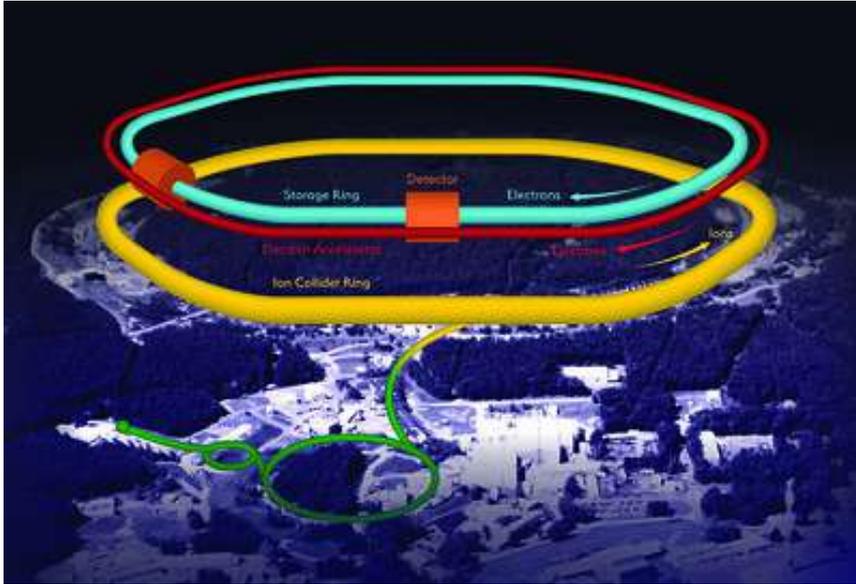
At the LHC:

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



Is the strange PDF driving the data ...
Or is the data driving the strange ???

If only we had more DIS data



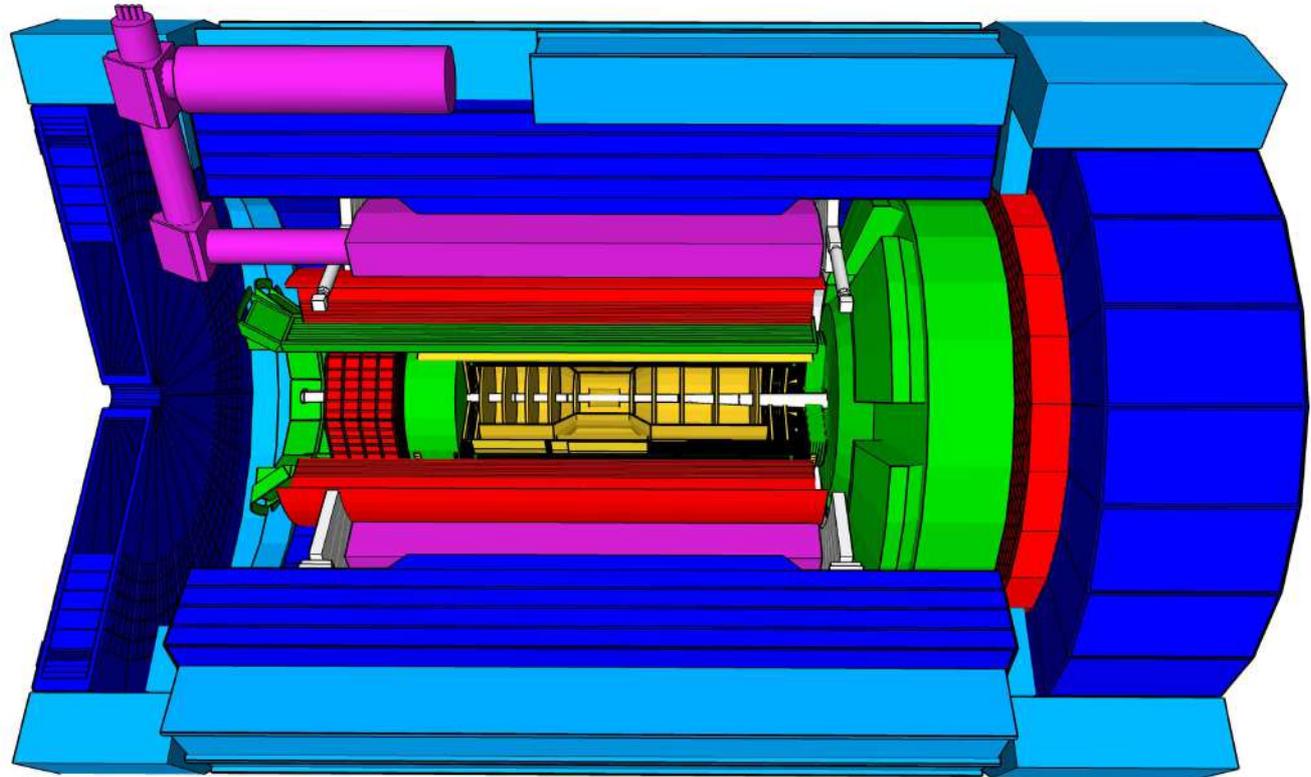
Hadronic
Calorimeters

Solenoid Magnet

Electromagnetic
Calorimeters

Particle
Identification

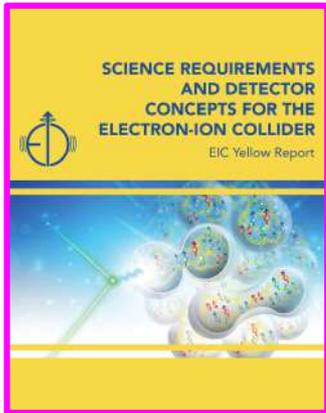
Tracking



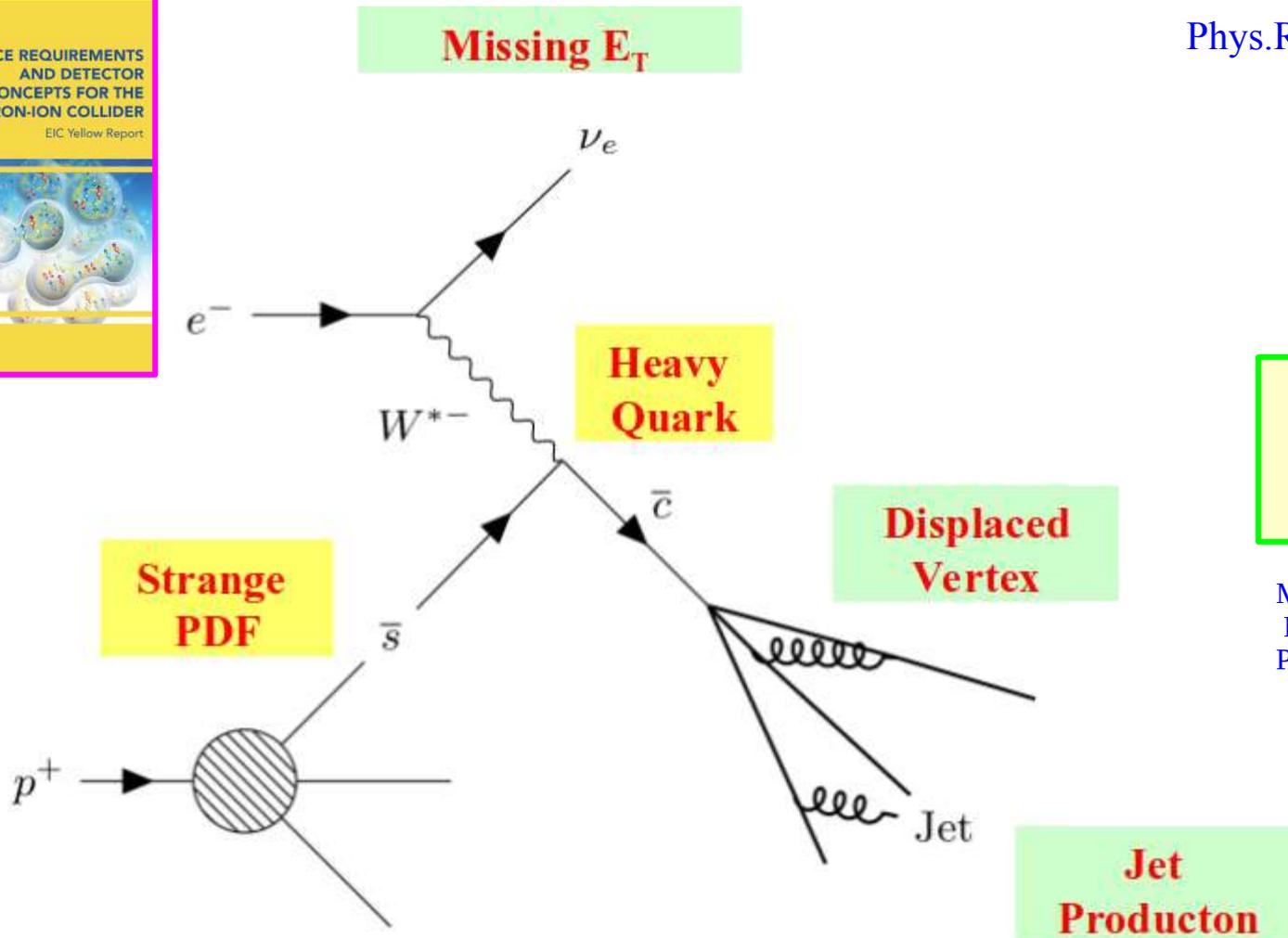
JLAB-PHY-20-3205, SMU-HEP-20-05

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,*}

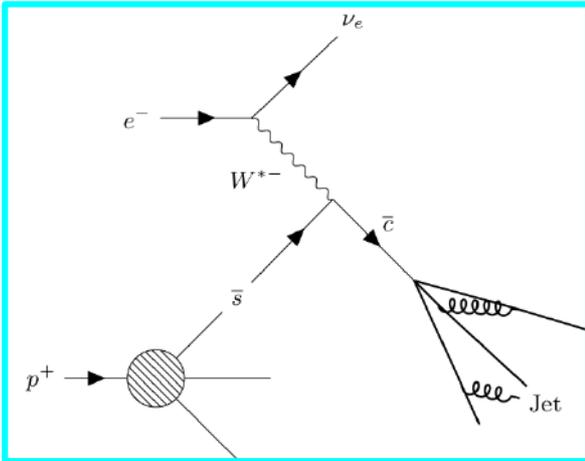


Phys.Rev.D 103 (2021) 7, 074023

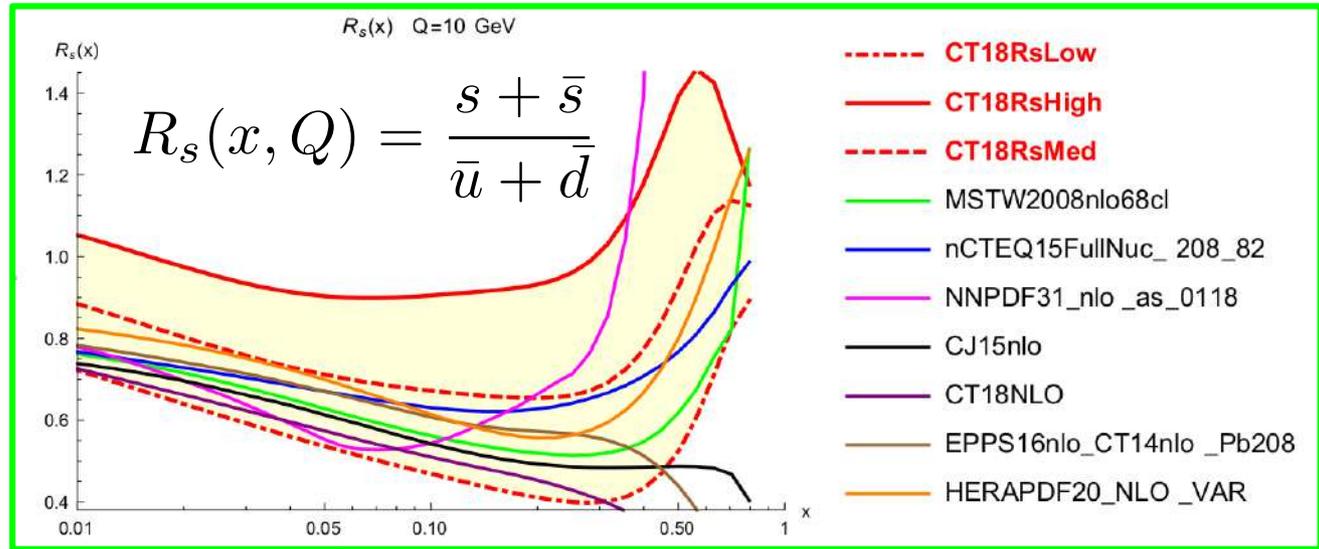


Clear measure of Strange PDF beyond uncertainties

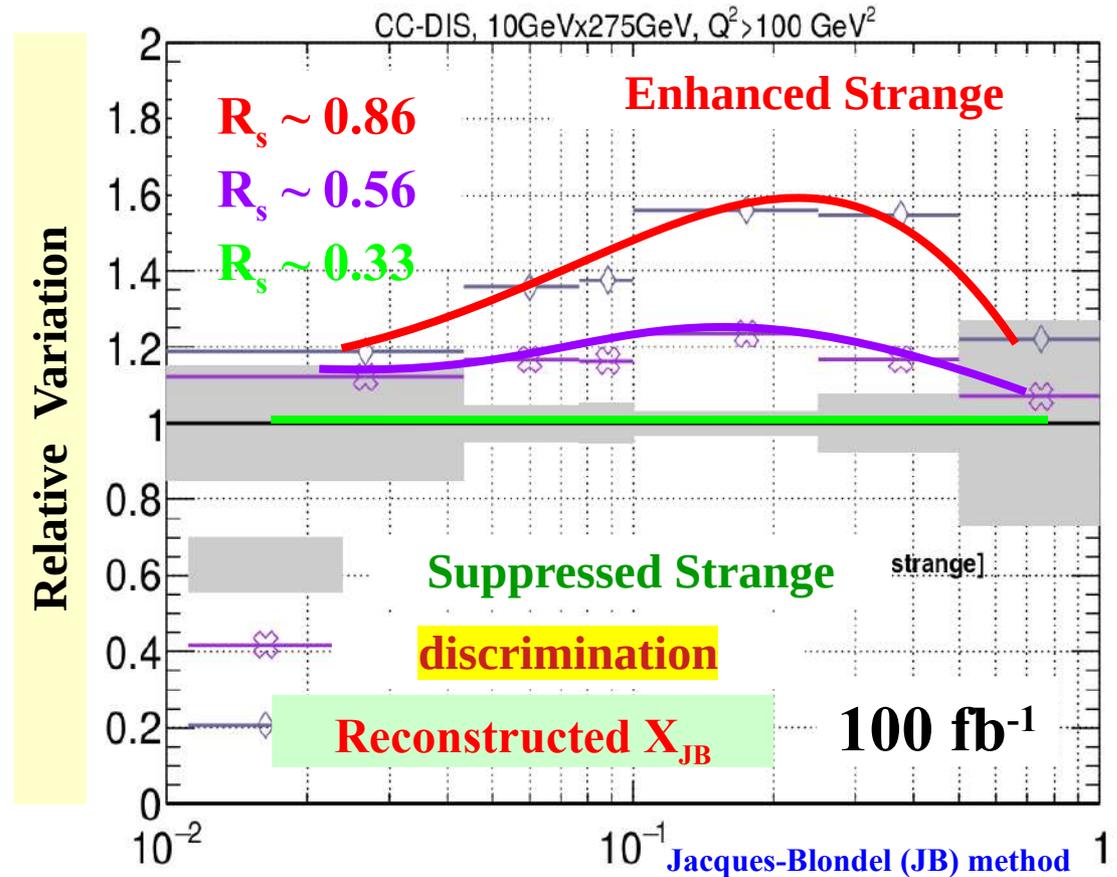
M. Arratia, Y. Furletova, T.J. Hobbs, F. Olness, S.J. Sekula, Phys.Rev.D 103 (2021) 7, 074023



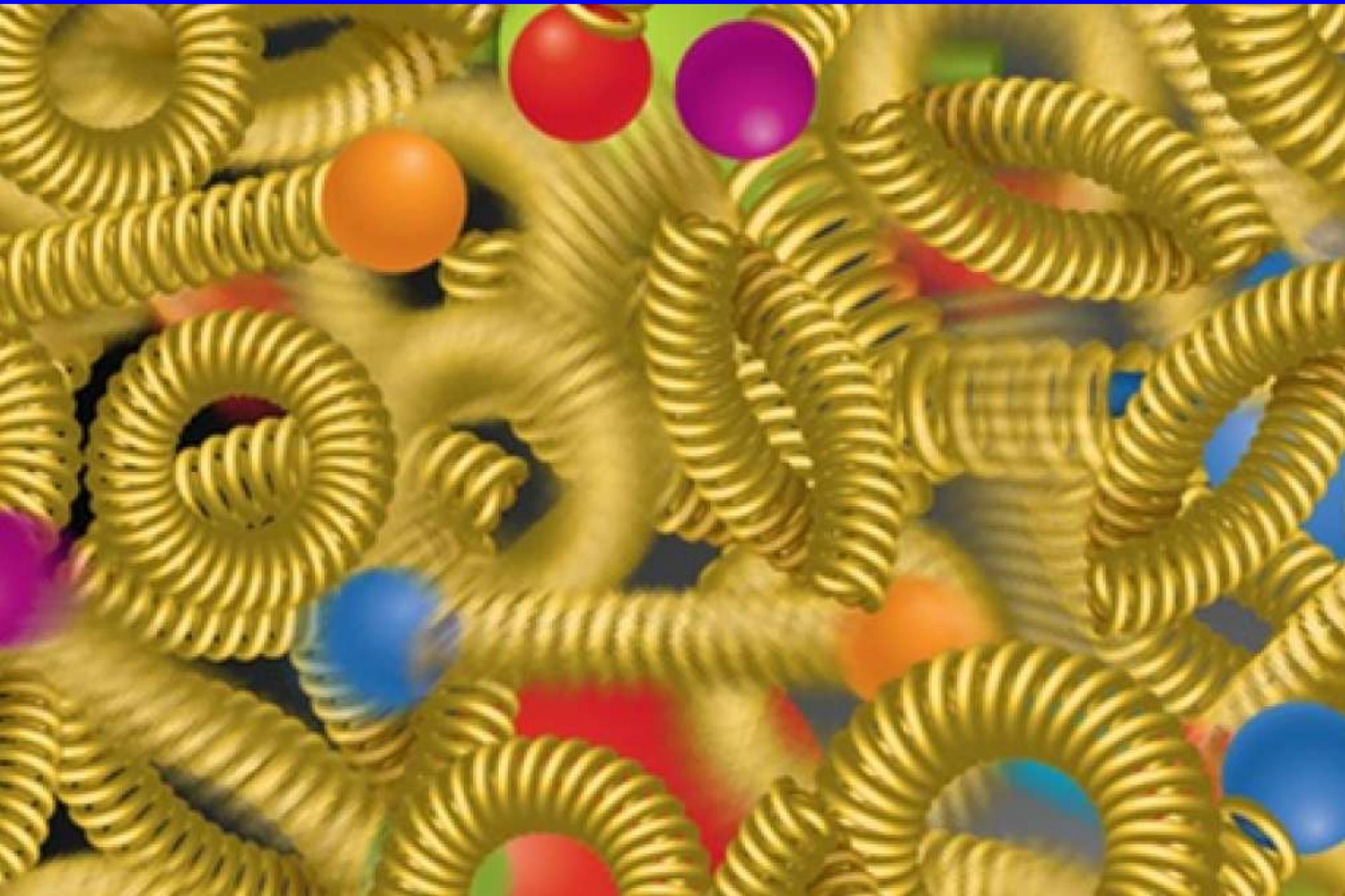
W+S → Cjet

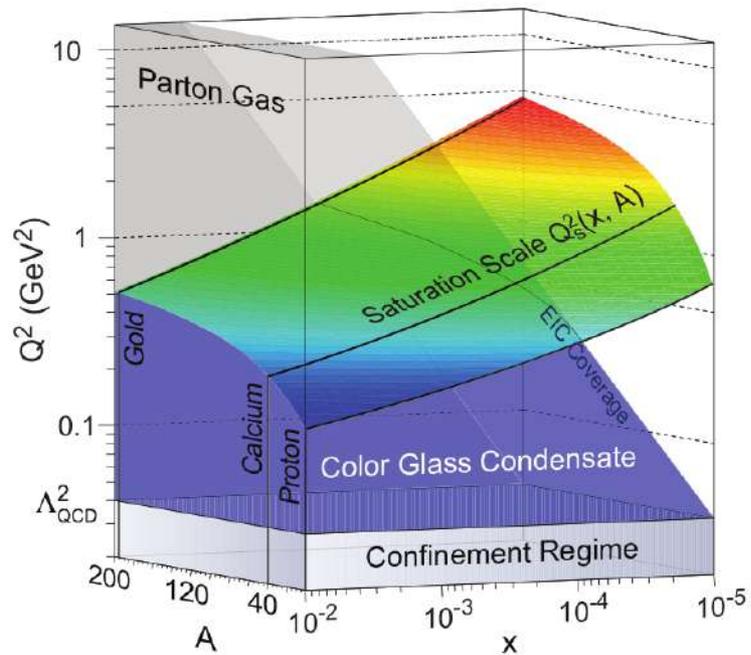
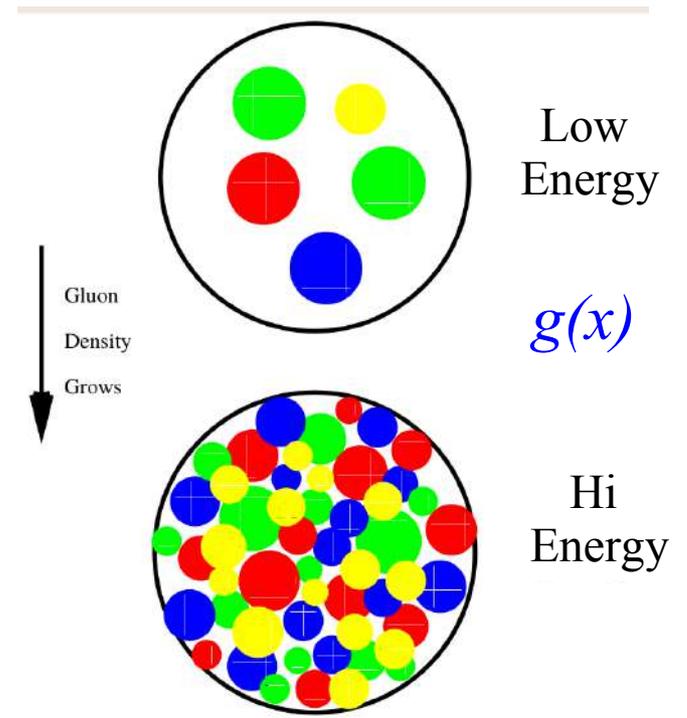
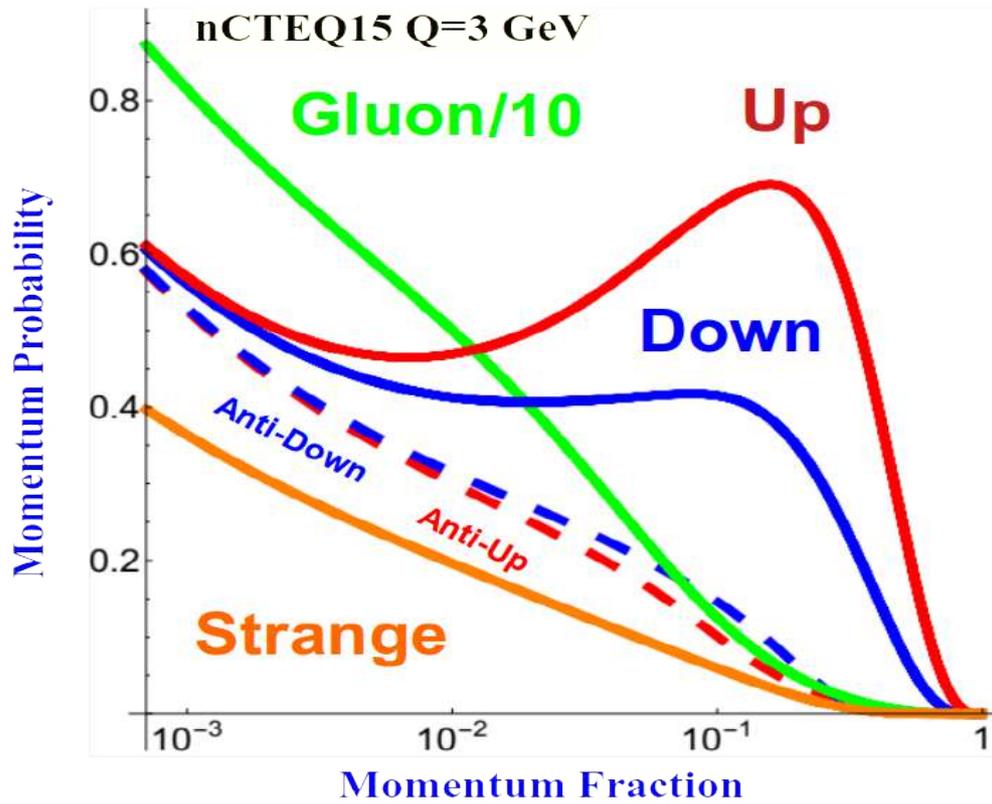


Clear measure of Strange PDF beyond uncertainties



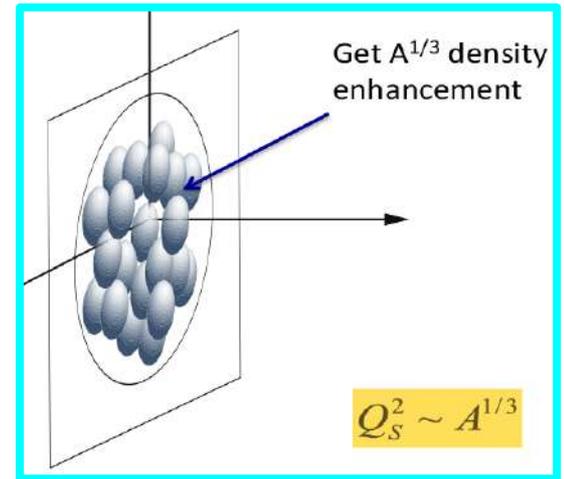
The Gluon

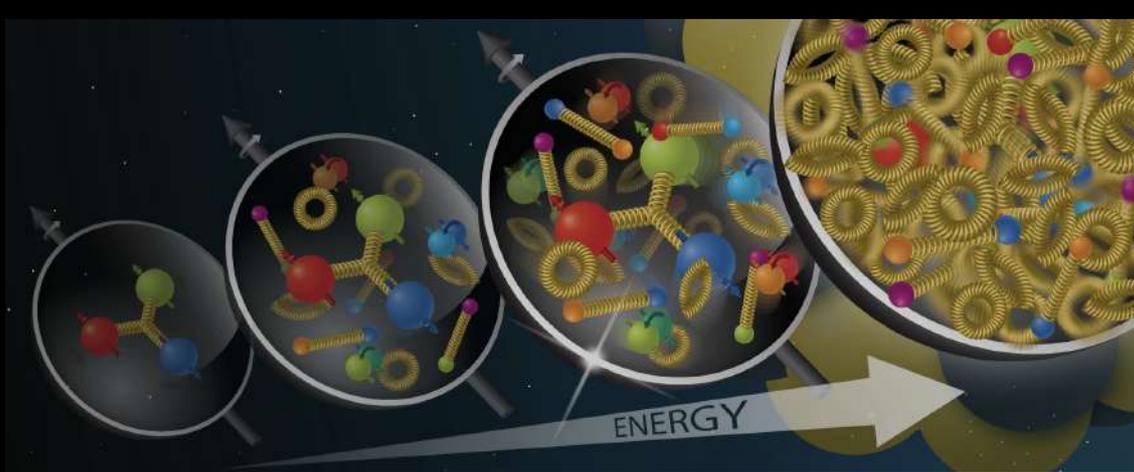




- Nuclear medium effects:**
- Quark Gluon Plasma
 - Color Glass Condensate
 - Recombination
 - Saturation
 - Resummation
 - ... *your theory here*

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





Discover and explore the gluon saturation regime of quantum chromodynamics

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

Members

Brookhaven National Laboratory

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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

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M. Sievert

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V. Skokov

Penn State University

A. Stasto

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Lawrence Berkeley National Laboratory

X.-N. Wang

Penn State U

UConn

CUNY Baruch College

BNL

Lebanon Valley College

OSU

Washington D C

DISTRICT OF COLUMBIA

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Old Dominion U

NC

NCSU

New Mexico State U

Southern Meth

Penn State University

A. Stasto

University of California Berkeley /

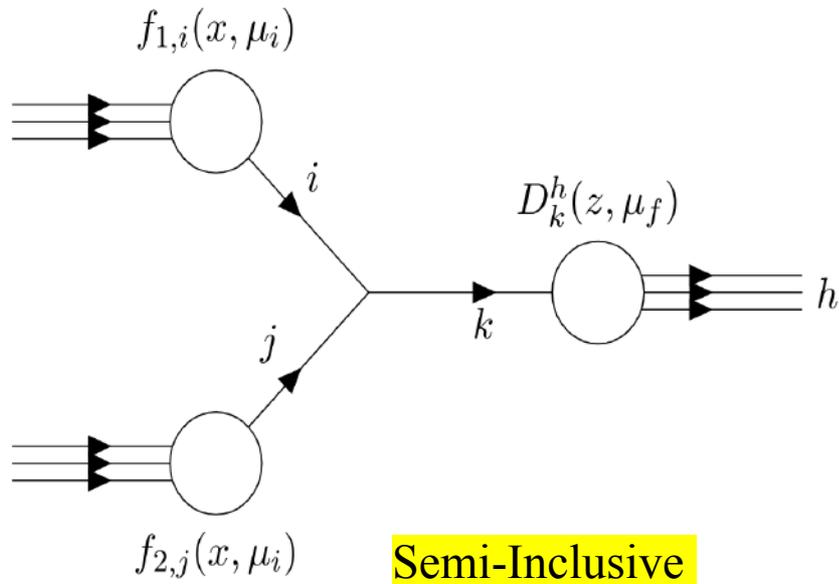
Lawrence Berkeley National Laboratory

X.-N. Wang

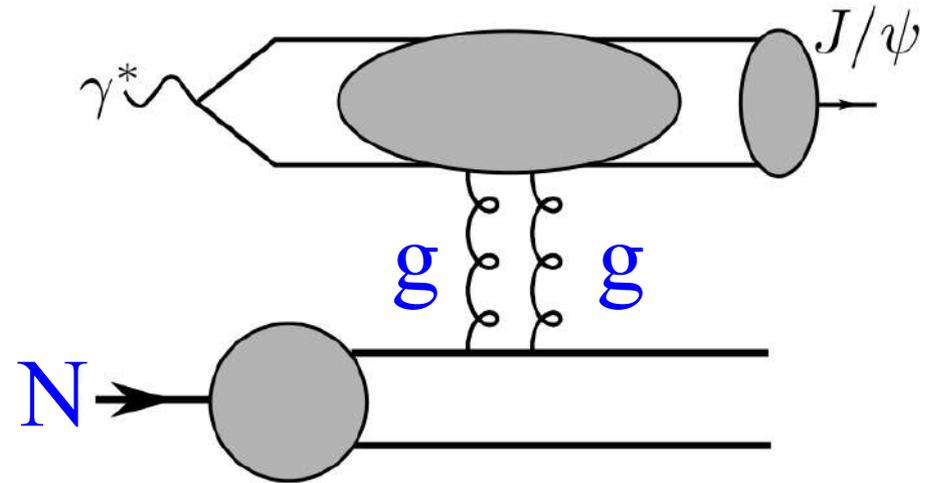
Measuring the nuclear Gluon PDF 30

Parton Distribution Functions

(nCTEQ) Pit Duwentaster, Michael Klasen, ...



Semi-Inclusive
Hadron Production

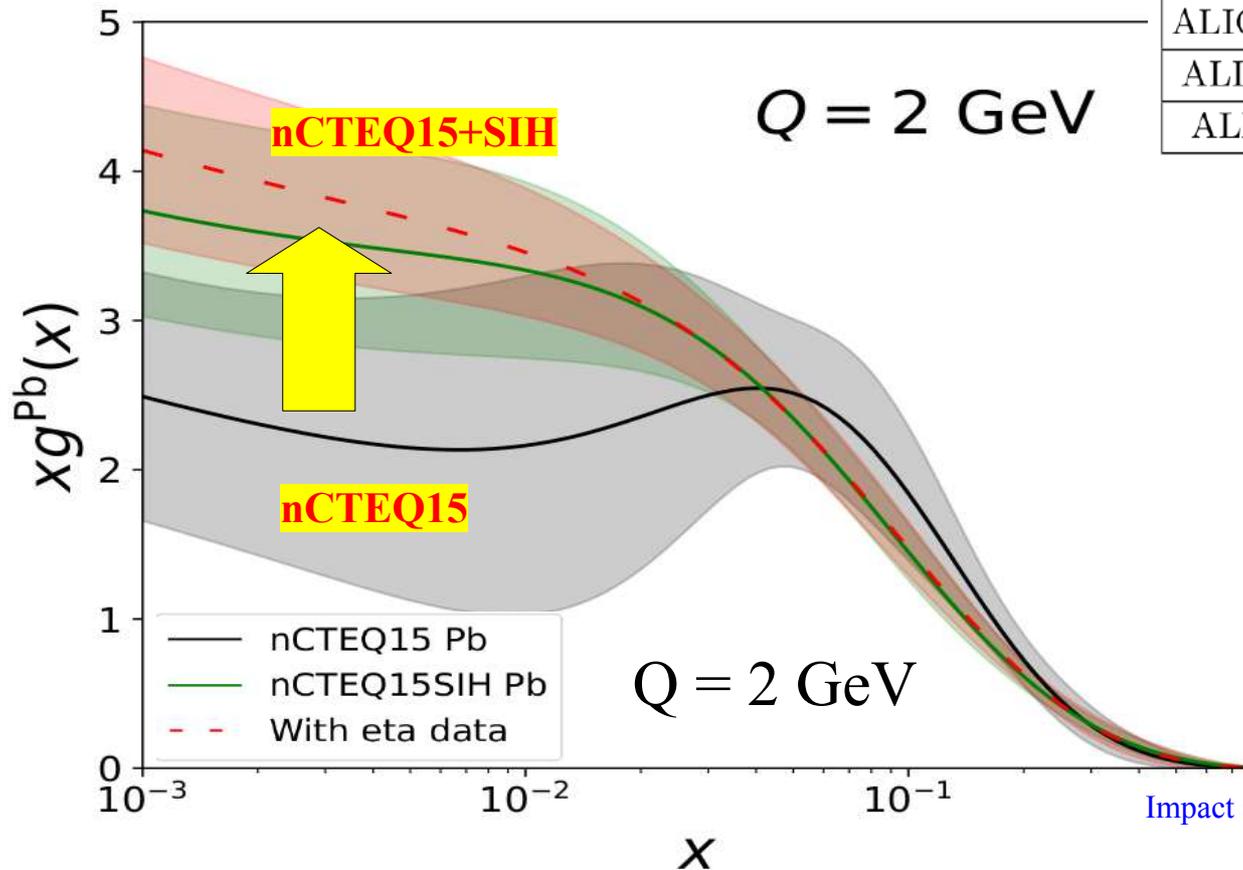
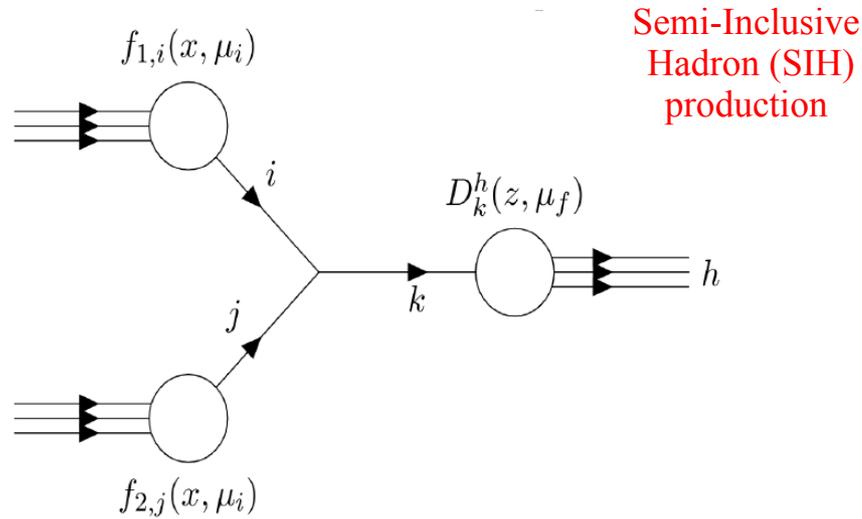


Quarkonia
Production



how can we determine
the gluon

Pit Duwentaster, Michael Klasen, ...

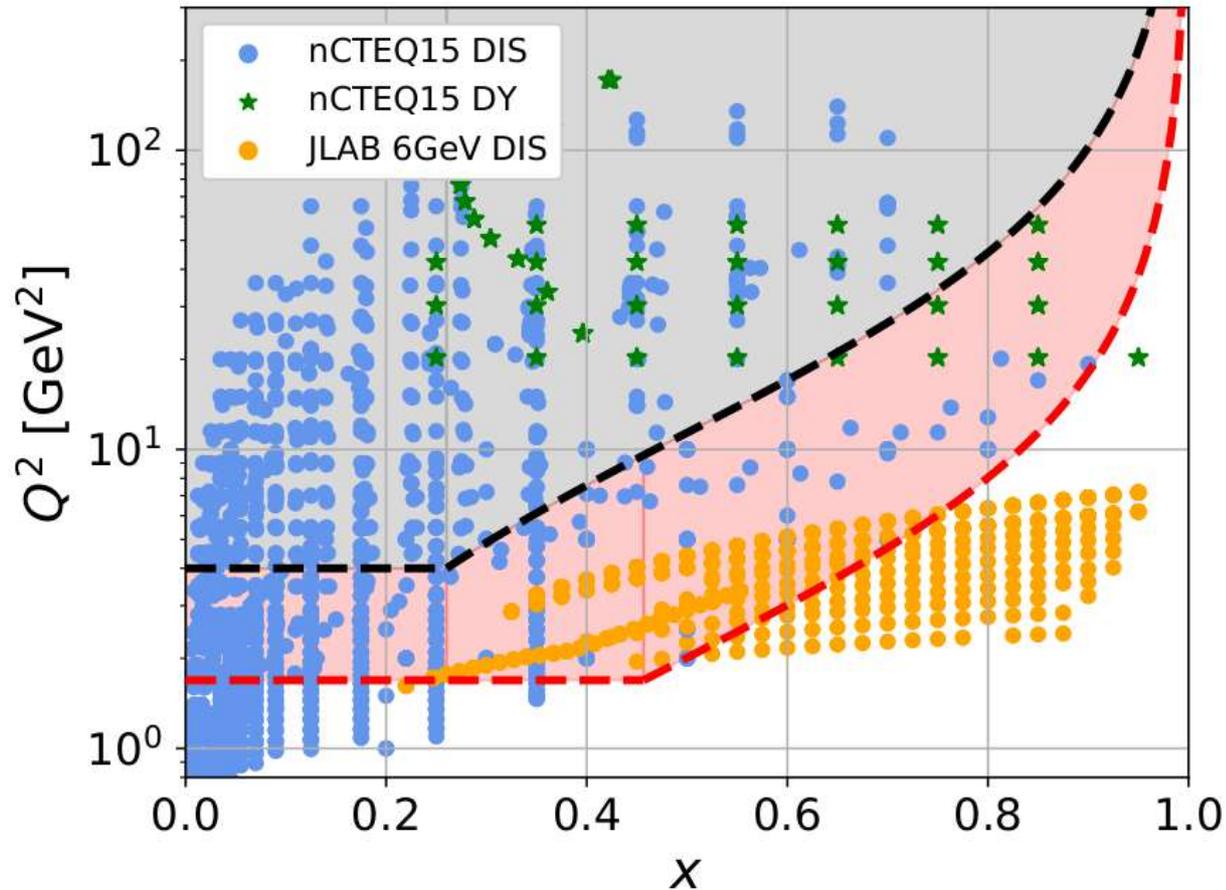


Data set	$\sqrt{s_{NN}}$ [GeV]	Observ.	No. points
PHENIX π^0	200	R_{dAu}	21
PHENIX η	200	R_{dAu}	12
PHENIX π^\pm	200	R_{dAu}	20
PHENIX K^\pm	200	R_{dAu}	15
STAR π^0	200	R_{dAu}	13
STAR η	200	R_{dAu}	7
STAR π^\pm	200	R_{dAu}	23
ALICE 5 TeV π^0	5020	R_{pPb}	31
ALICE 5 TeV η	5020	R_{pPb}	16
ALICE 5 TeV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

Extended $\{x, Q^2\}$ Kinematics



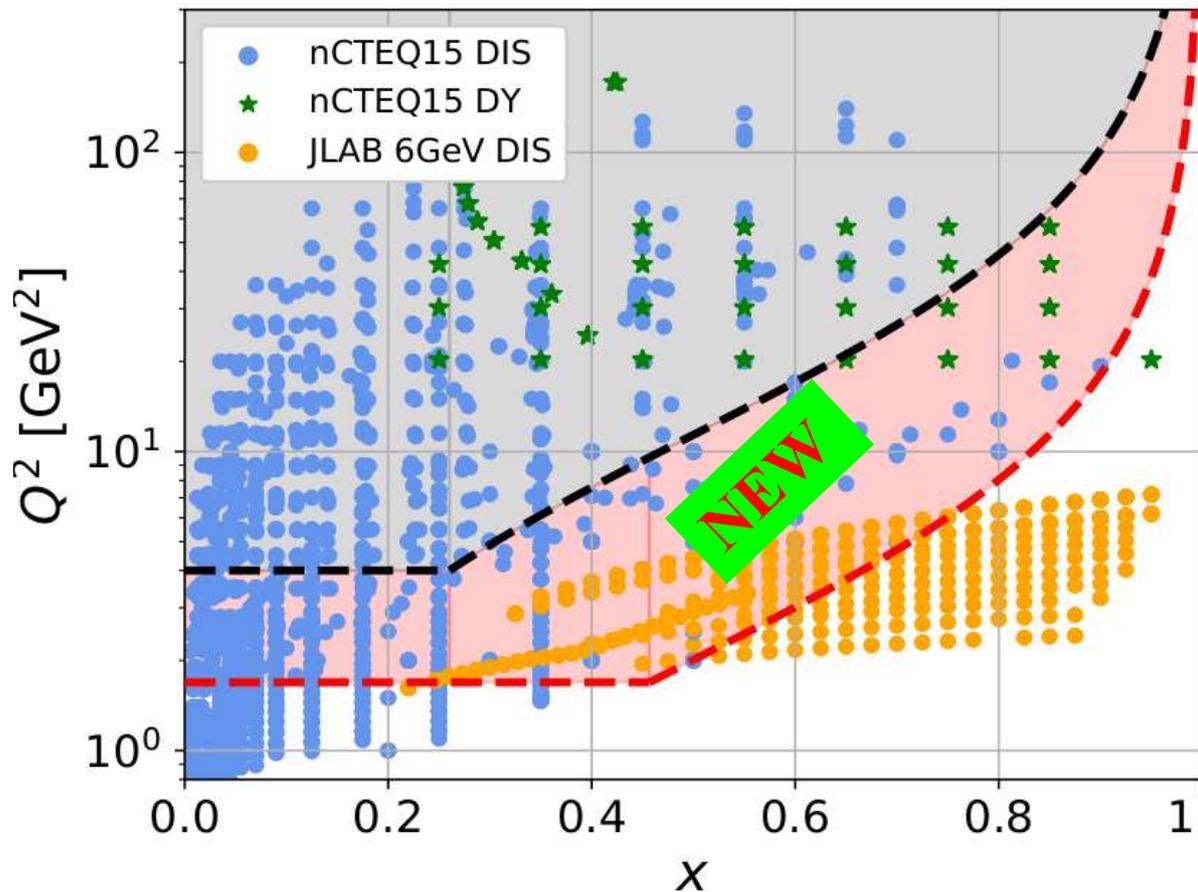
PHYSICAL REVIEW D **103**, 114015 (2021)

Extending nuclear PDF analyses into the high- x , low- Q^2 region

E. P. Segarra^{1,*}, T. Ježo^{2,†}, A. Accardi^{3,4}, P. Duwentäster⁵, O. Hen¹, T. J. Hobbs^{6,4,7}, C. Keppel⁴, M. Klasen⁵,
K. Kovarik⁵, A. Kusina⁸, J. G. Morfin⁹, K. F. Muzakka⁵, F. I. Olness^{6,‡}, I. Schienbein¹⁰, and J. Y. Yu¹⁰

Important effects:

- Deuteron Corrections
- Higher twist
- Target Mass Effects



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

Target Mass Corrections

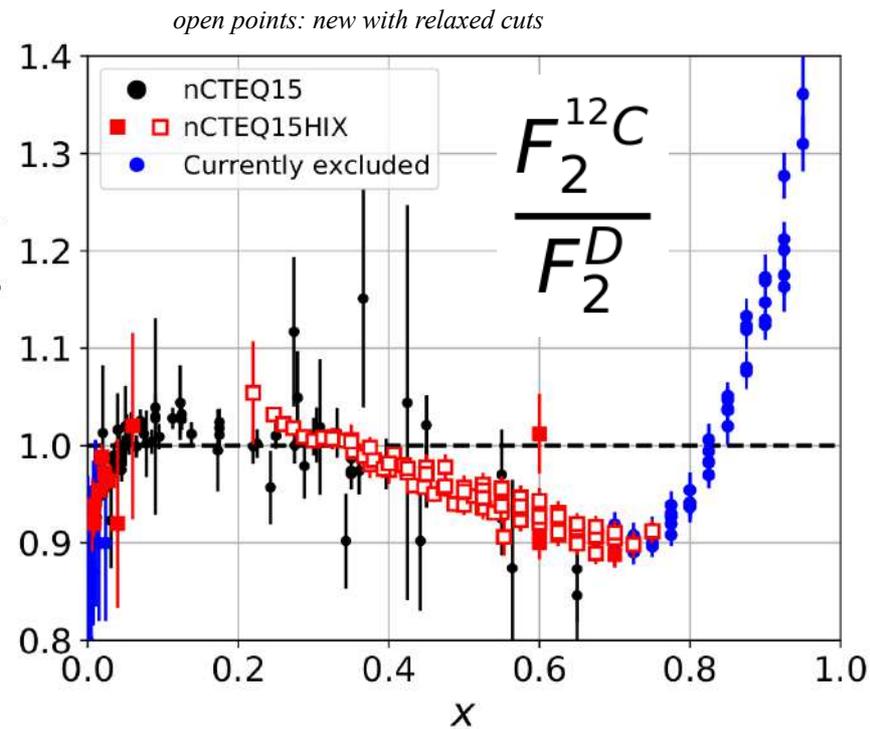
pick up M^2/Q^2 higher twist cont.

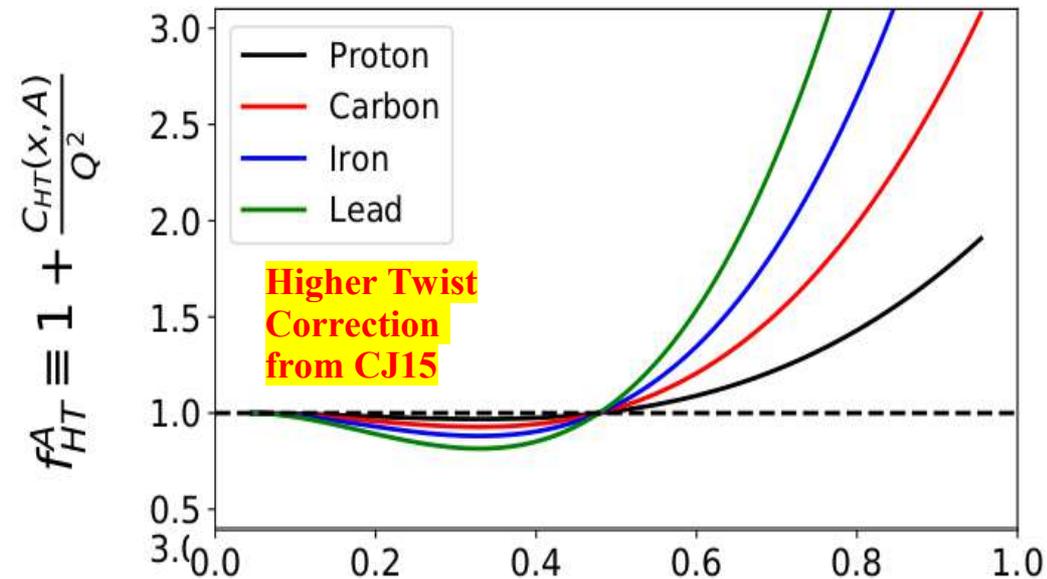
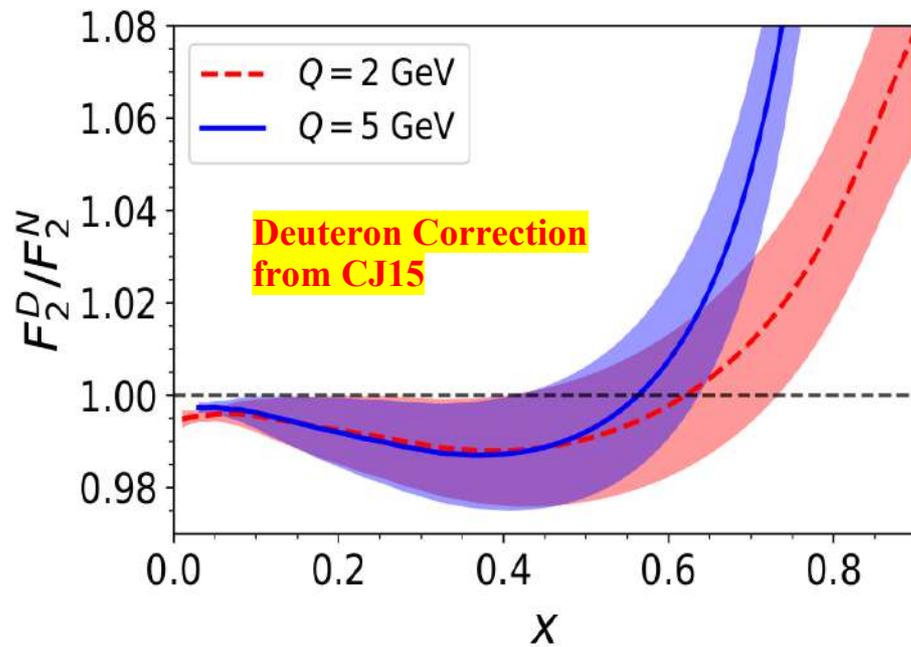
Deuteron Corrections

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

Extend nCTEQ framework
 to accommodate this region
 $\{Q, W\} = \{2, 3.5\} \Rightarrow \{1.3, 1.7\}$

nCTEQ15HIX -- Extending nPDF Analyses
 into the High- x , Low Q^2 Region
E.P. Segarra, T. Ježo, et al., PRD 103, 114015 (2021)





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
BASE	1525	1564	0.99		
HT	1482	1564	0.96		
DEUT	1331	1564	0.85		
nCTEQ15HIX	1291	1564	0.83		

Reference

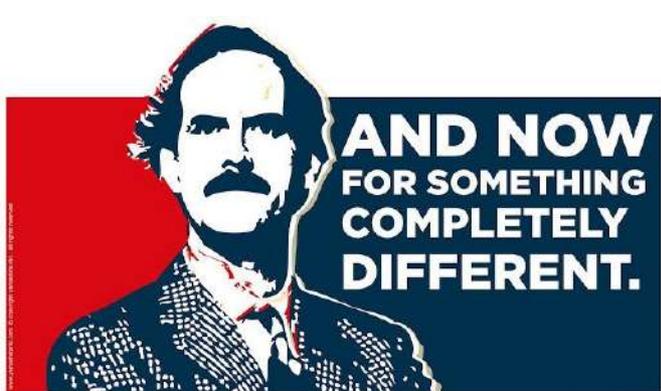
Higher Twist ~3%

Deuteron ~14%

Combined ~16%

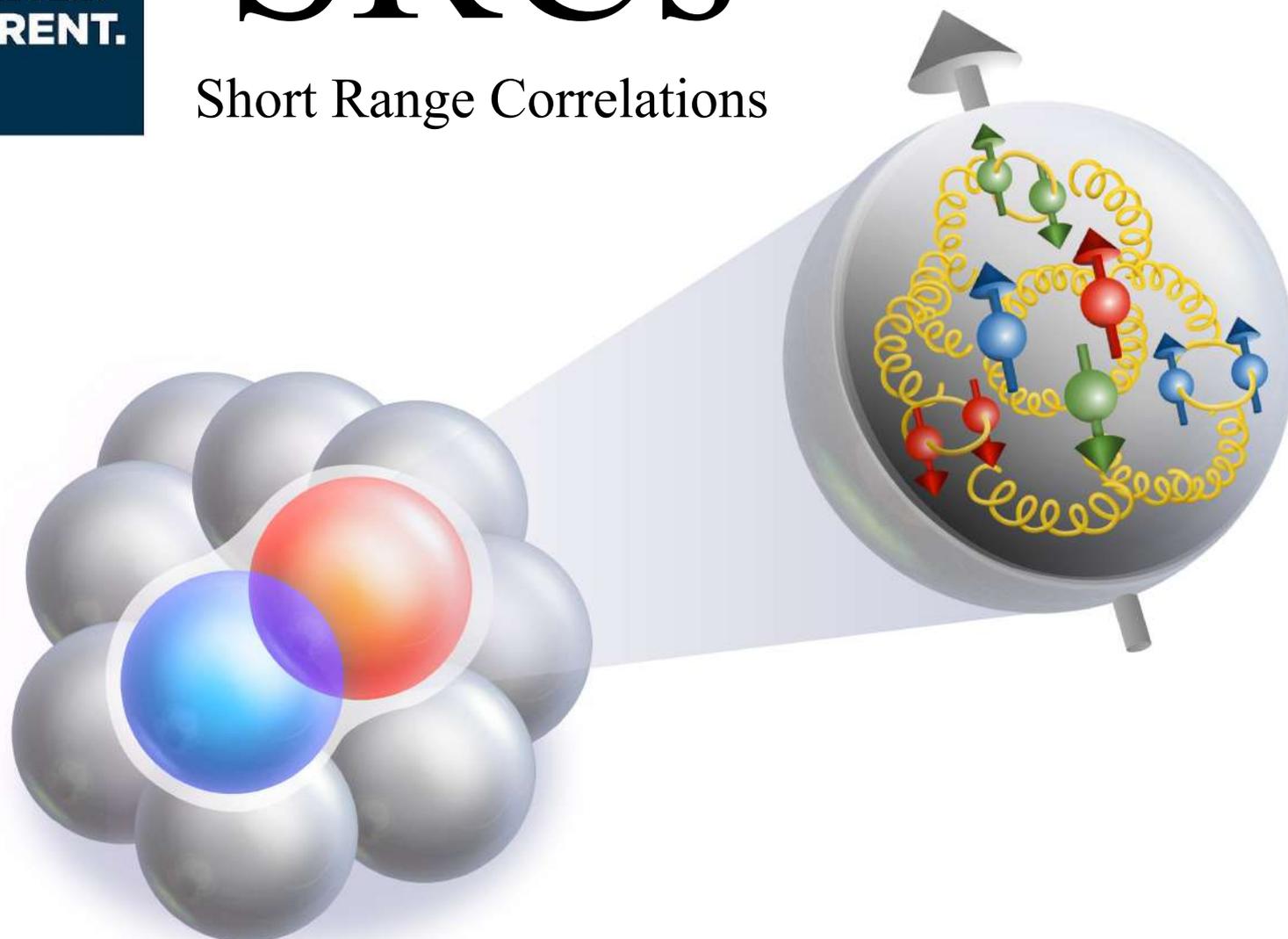
We can extend our kinematic reach in $\{x, Q^2\}$

what about mid x region



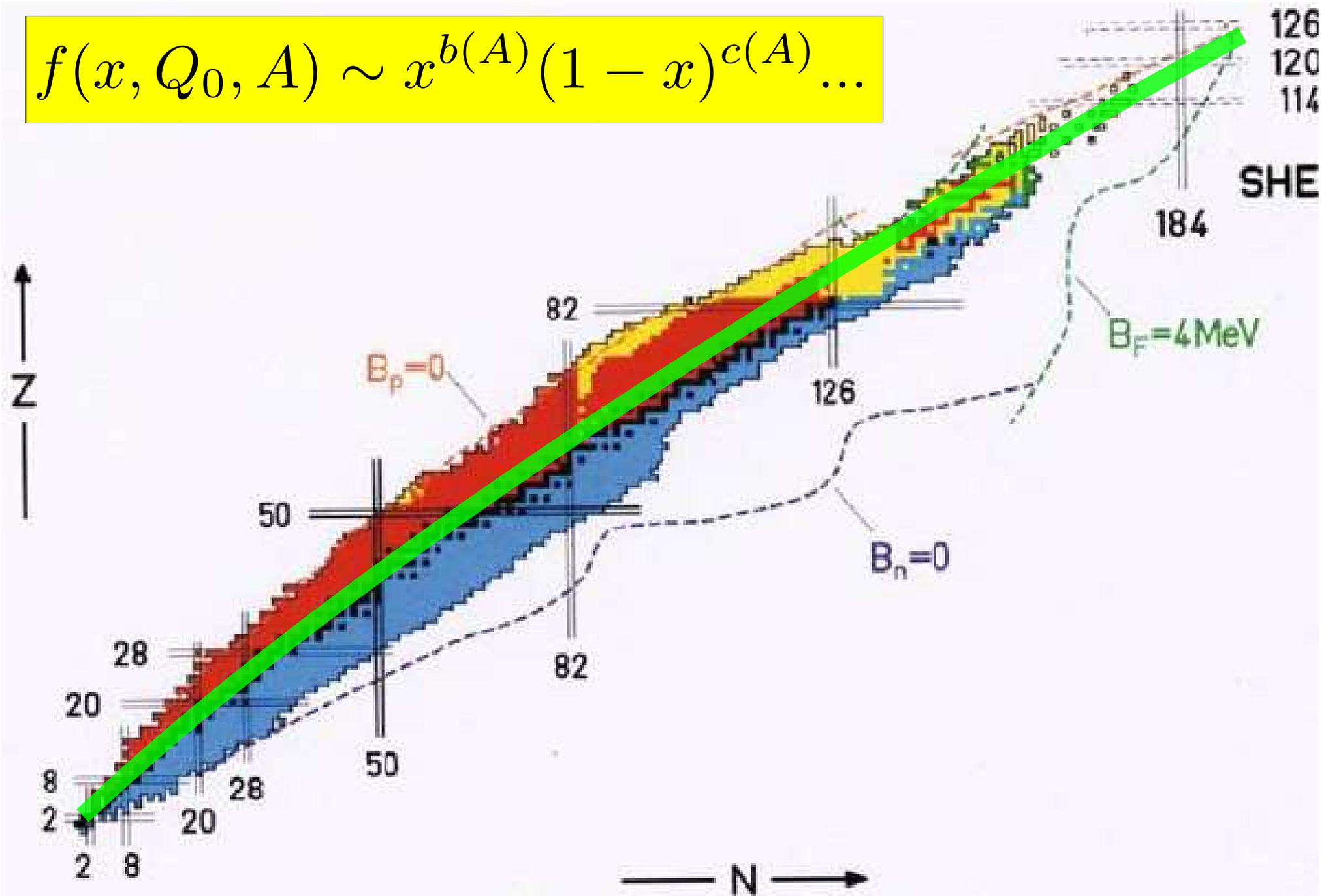
SRCs

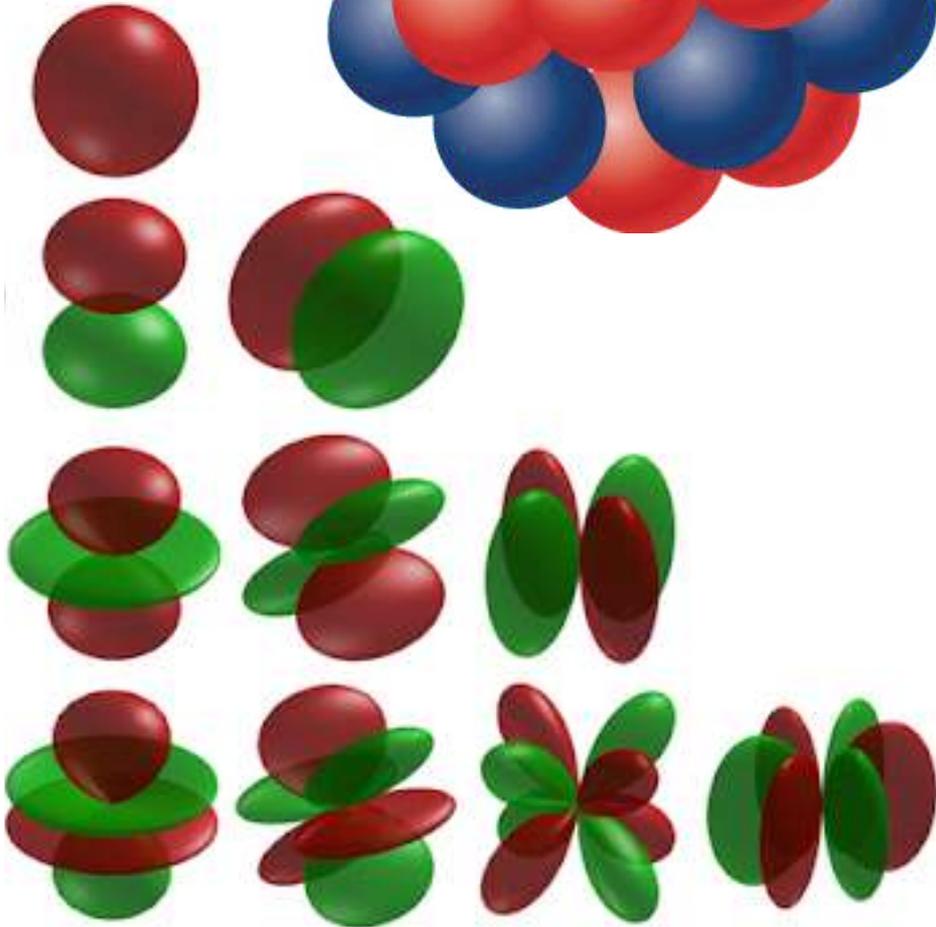
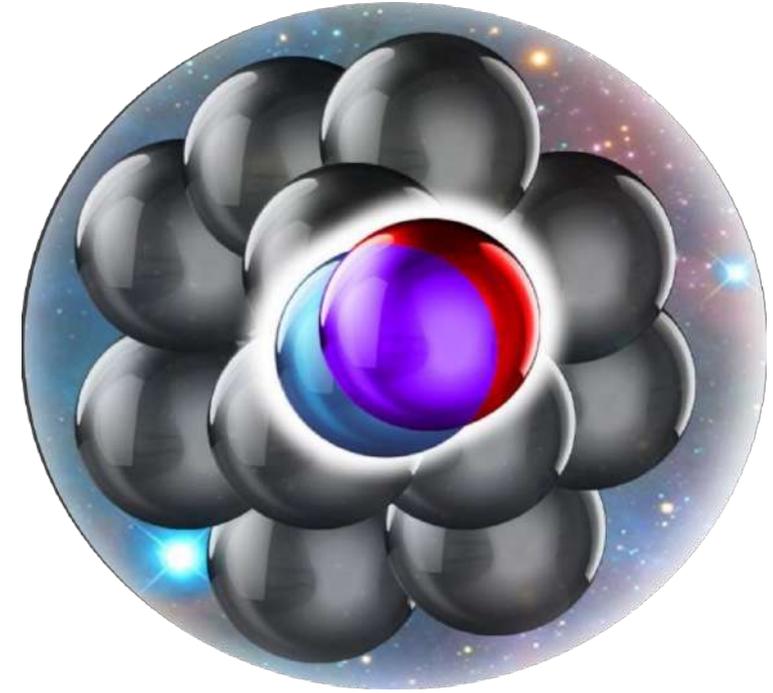
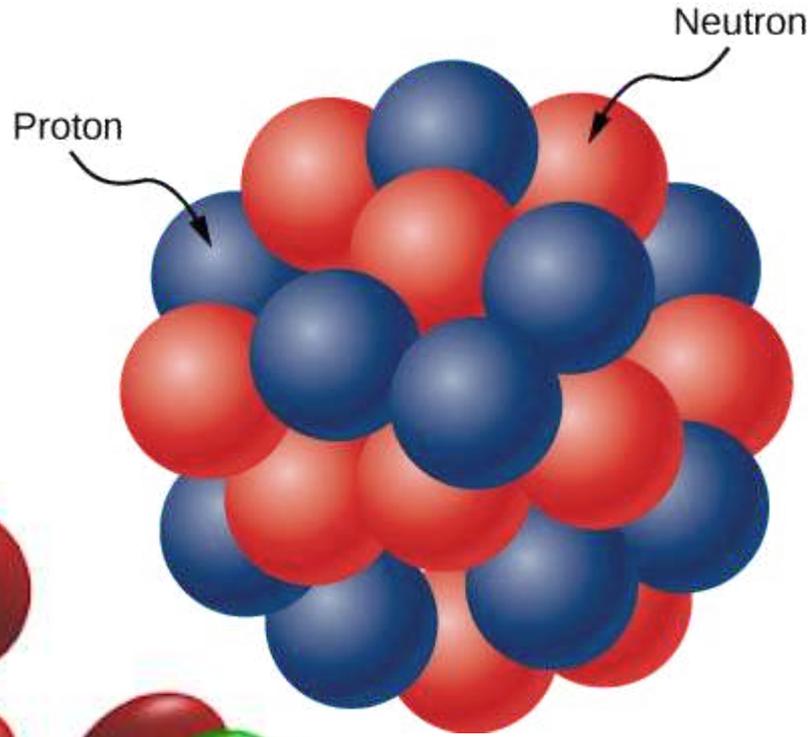
Short Range Correlations



Connecting nuclear and partonic properties

$$f(x, Q_0, A) \sim x^{b(A)} (1 - x)^{c(A)} \dots$$

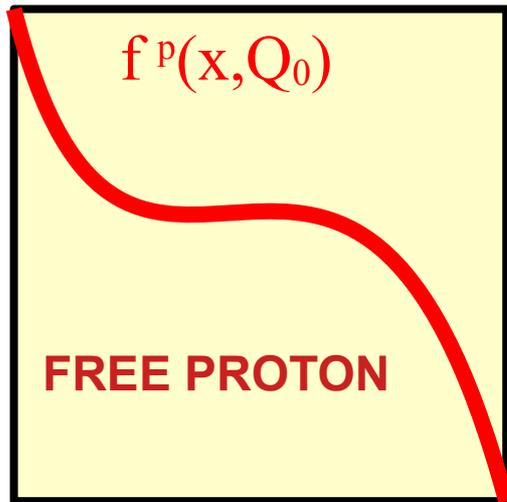
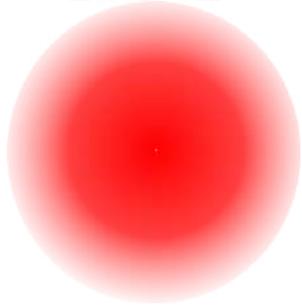




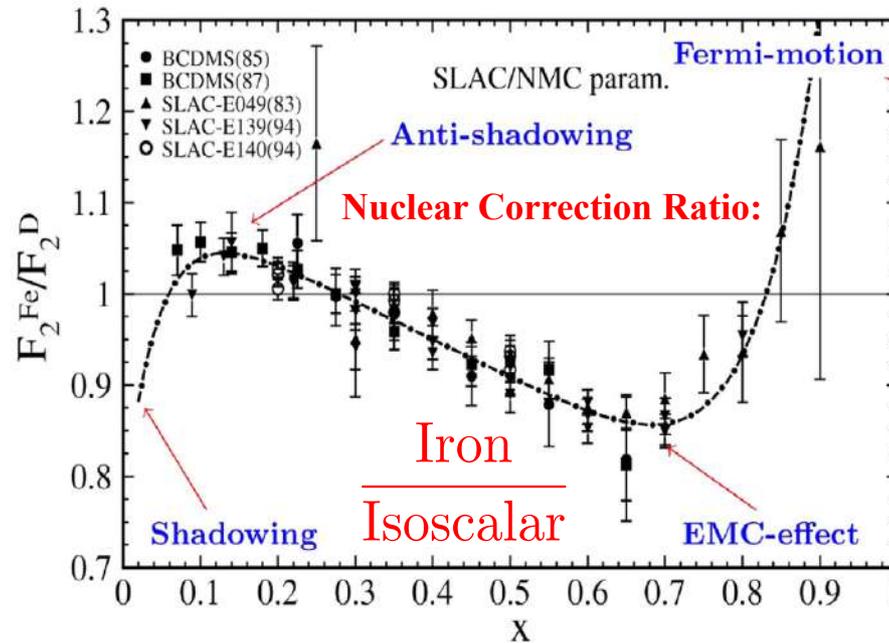
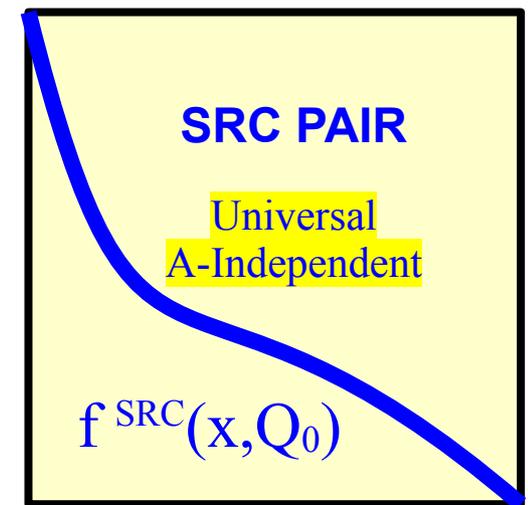
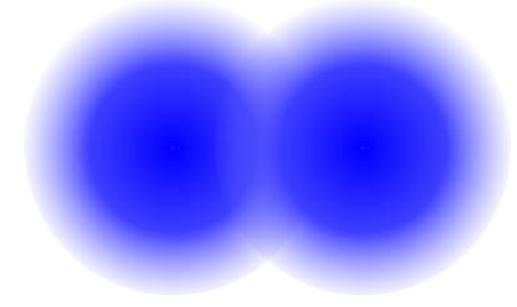
Periodic Table of the Elements

1 1A H Hydrogen	2 2A He Helium											13 3A B Boron	14 4A C Carbon	15 5A N Nitrogen	16 6A O Oxygen	17 7A F Fluorine	18 8A Ne Neon
3 3A Li Lithium	4 4A Be Beryllium											5 5A Al Aluminum	6 6A Si Silicon	7 7A P Phosphorus	8 8A S Sulfur	9 9A Cl Chlorine	10 10A Ar Argon
11 1A Na Sodium	12 2A Mg Magnesium	3 3B Sc Scandium	4 4B Ti Titanium	5 5B V Vanadium	6 6B Cr Chromium	7 7B Mn Manganese	8 8 Fe Iron	9 9 Co Cobalt	10 10 Ni Nickel	11 1B Cu Copper	12 2B Zn Zinc	13 3B Ga Gallium	14 4B Ge Germanium	15 5B As Arsenic	16 6B Se Selenium	17 7B Br Bromine	18 8B Kr Krypton
19 1A K Potassium	20 2A Ca Calcium	21 3B Sc Scandium	22 4B Ti Titanium	23 5B V Vanadium	24 6B Cr Chromium	25 7B Mn Manganese	26 8 Fe Iron	27 9 Co Cobalt	28 10 Ni Nickel	29 11 Cu Copper	30 12 Zn Zinc	31 13 Ga Gallium	32 14 Ge Germanium	33 15 As Arsenic	34 16 Se Selenium	35 17 Br Bromine	36 18 Kr Krypton
37 1A Rb Rubidium	38 2A Sr Strontium	39 3B Y Yttrium	40 4B Zr Zirconium	41 5B Nb Niobium	42 6B Mo Molybdenum	43 7B Tc Technetium	44 8 Ru Ruthenium	45 9 Rh Rhodium	46 10 Pd Palladium	47 11 Ag Silver	48 12 Cd Cadmium	49 13 In Indium	50 14 Sn Tin	51 15 Sb Antimony	52 16 Te Tellurium	53 17 I Iodine	54 18 Xe Xenon
55 1A Cs Cesium	56 2A Ba Barium	57-71 3B-10B Lanthanides and Actinides	72 4B Hf Hafnium	73 5B Ta Tantalum	74 6B W Tungsten	75 7B Re Rhenium	76 8 Os Osmium	77 9 Ir Iridium	78 10 Pt Platinum	79 11 Au Gold	80 12 Hg Mercury	81 13 Tl Thallium	82 14 Pb Lead	83 15 Bi Bismuth	84 16 Po Polonium	85 17 At Astatine	86 18 Rn Radon
87 1A Fr Francium	88 2A Ra Radium	89-103 3B-10B Lanthanides and Actinides	104 4B Rf Rutherfordium	105 5B Db Dubnium	106 6B Sg Seaborgium	107 7B Bh Bohrium	108 8 Hs Hassium	109 9 Mt Meitnerium	110 10 Ds Darmstadtium	111 11 Rg Roentgenium	112 12 Cn Copernicium	113 13 Uut Ununtrium	114 14 Fl Flerovium	115 15 Uup Ununpentium	116 16 Lv Livermorium	117 17 Uus Ununseptium	118 18 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

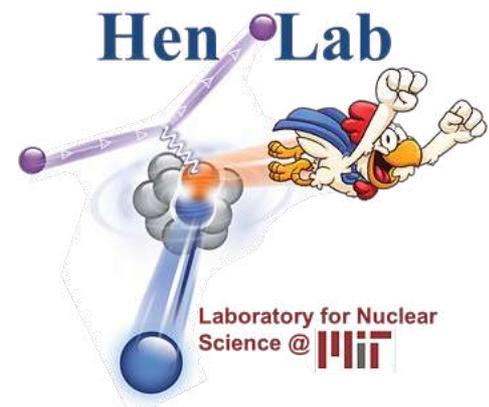
Is the fit reasonable???

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

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

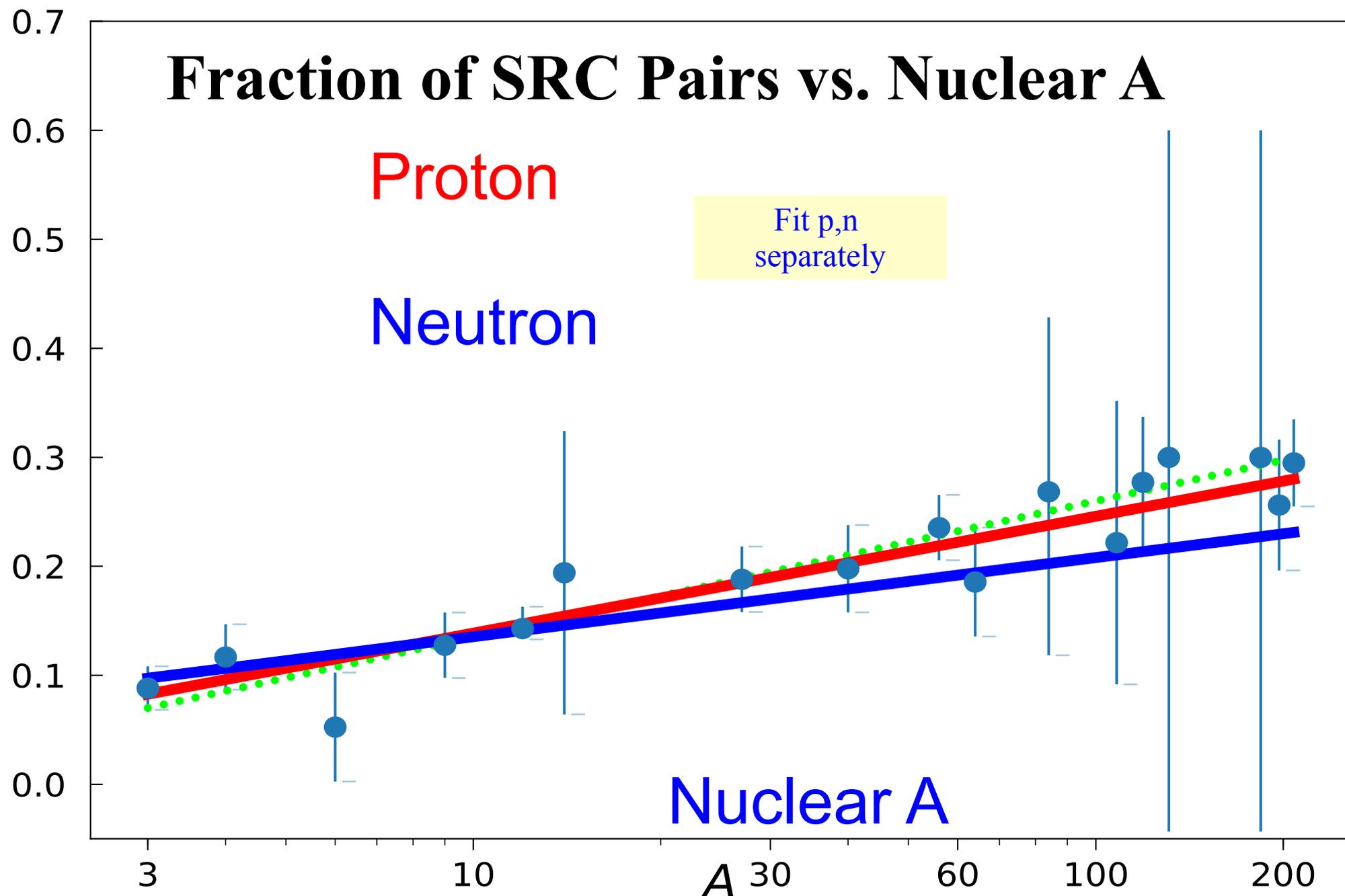
Fraction of SRC Pairs vs. Nuclear A

Proton

Neutron

Fit p,n
separately

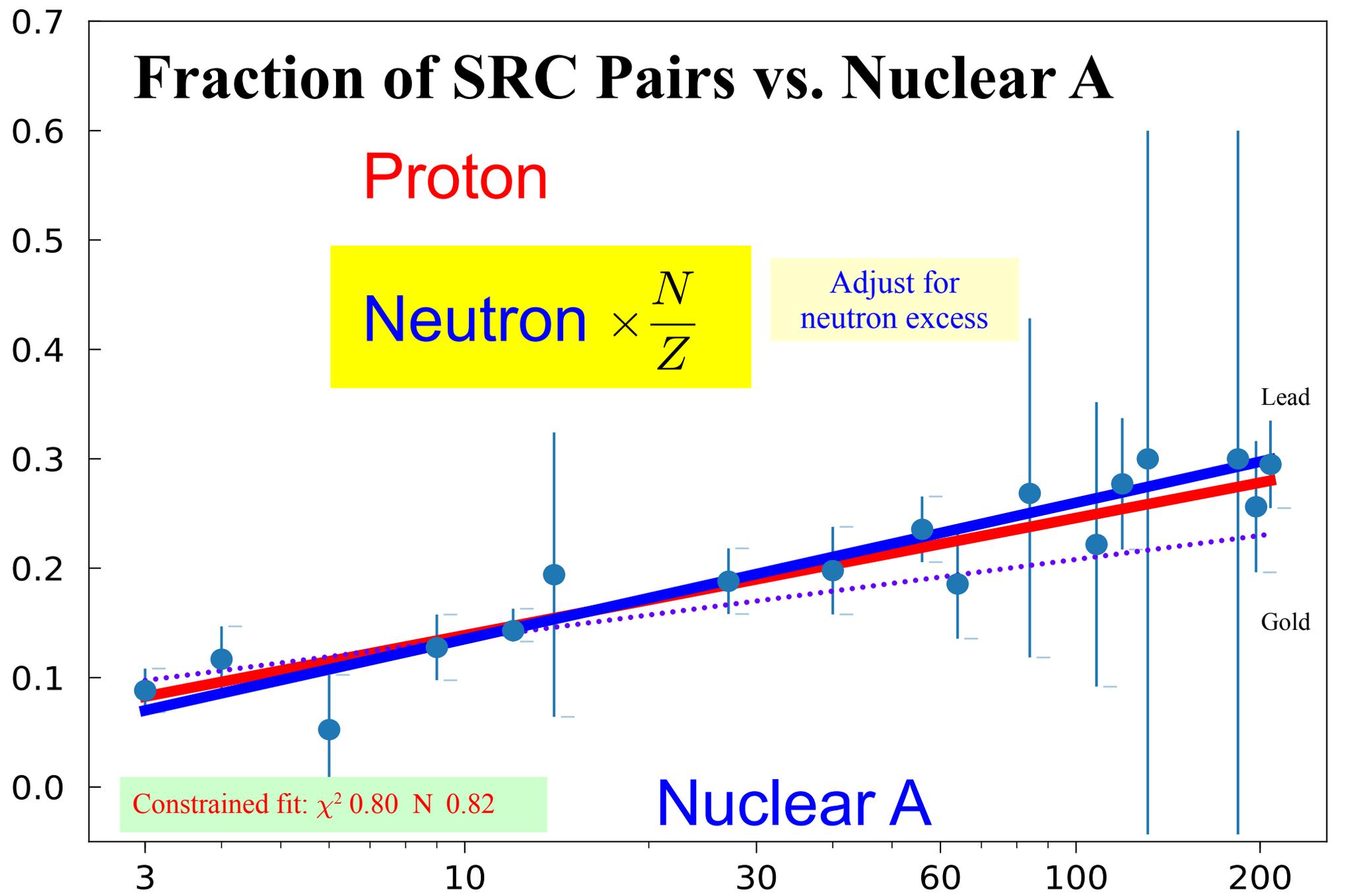
Nuclear A



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

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
# 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

Proton

Neutron $\times \frac{N}{Z}$

Adjust for neutron excess

Homework: what is the pattern?

Nuclear A

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

$C_p = 0.256$
 $C_n = 0.177$

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

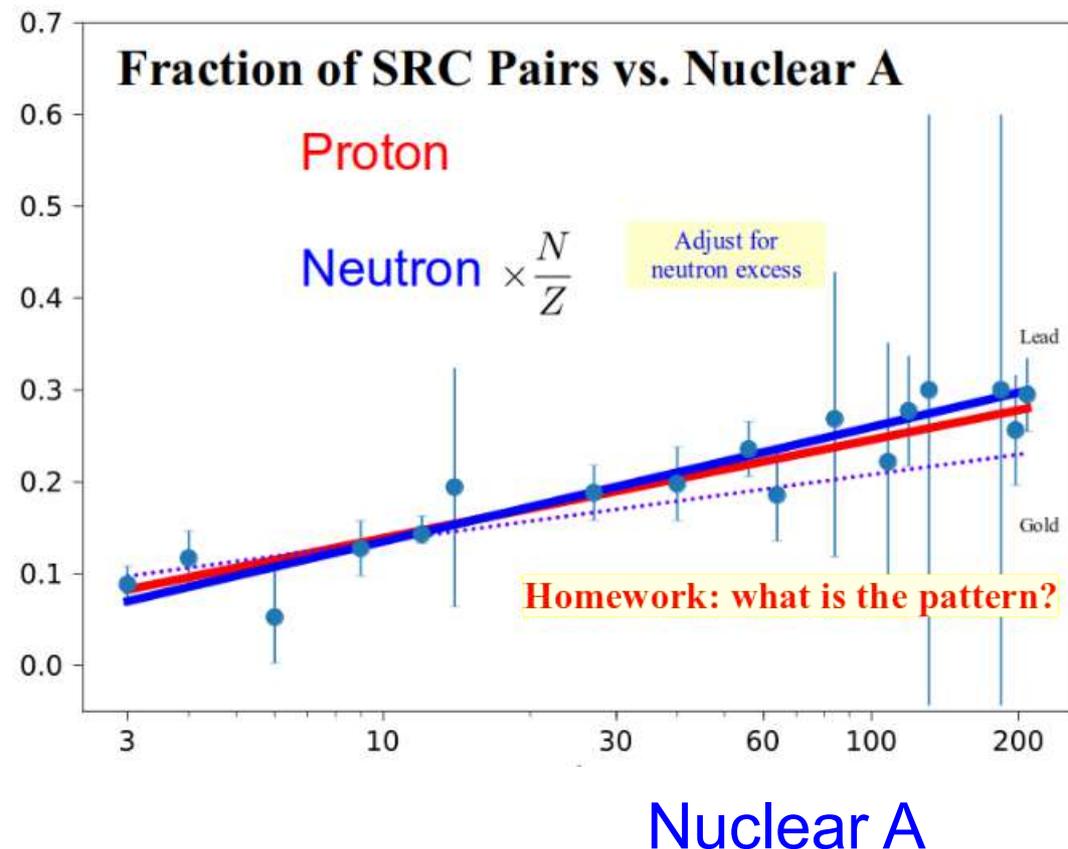
 $C_p \times Z = 20.2$
 $C_n \times N = 20.9$

The fit suggests equal # of protons & neutrons participate

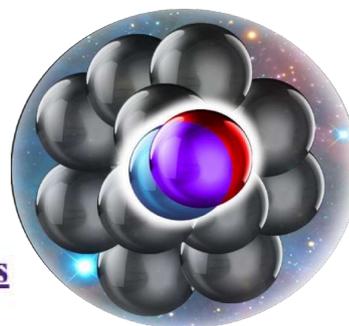
Consistent with hypothesis that SRCs are (pn) pairs

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

Nature is trying to tell us something



- 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



Relate nuclear to particle properties

Physics World 2024: Top 10 Breakthroughs of the Year in Physics

Press Release: "Two distinct descriptions of nuclei unified for the first time"

This nCTEQ project partnered SMU with JLab, MIT, and Muenster, to produce the new analysis published in *Physical Review Letters*.

This parameter form connects to new concepts

physics world
TOP 10
BREAKTHROUGH
2024



The Electron-Ion Collider

A machine that will unlock the secrets of the strongest force in Nature



nCTEQ

nuclear parton distribution functions

nuclear Coordinated Theoretical-Experimental Project on QCD

v DIS: Muzakka, Kovarik, Klasen, ...

W/Z: Jezo, Kusina, Olness, ...

Gluons: Duwentaster, Klasen, ...

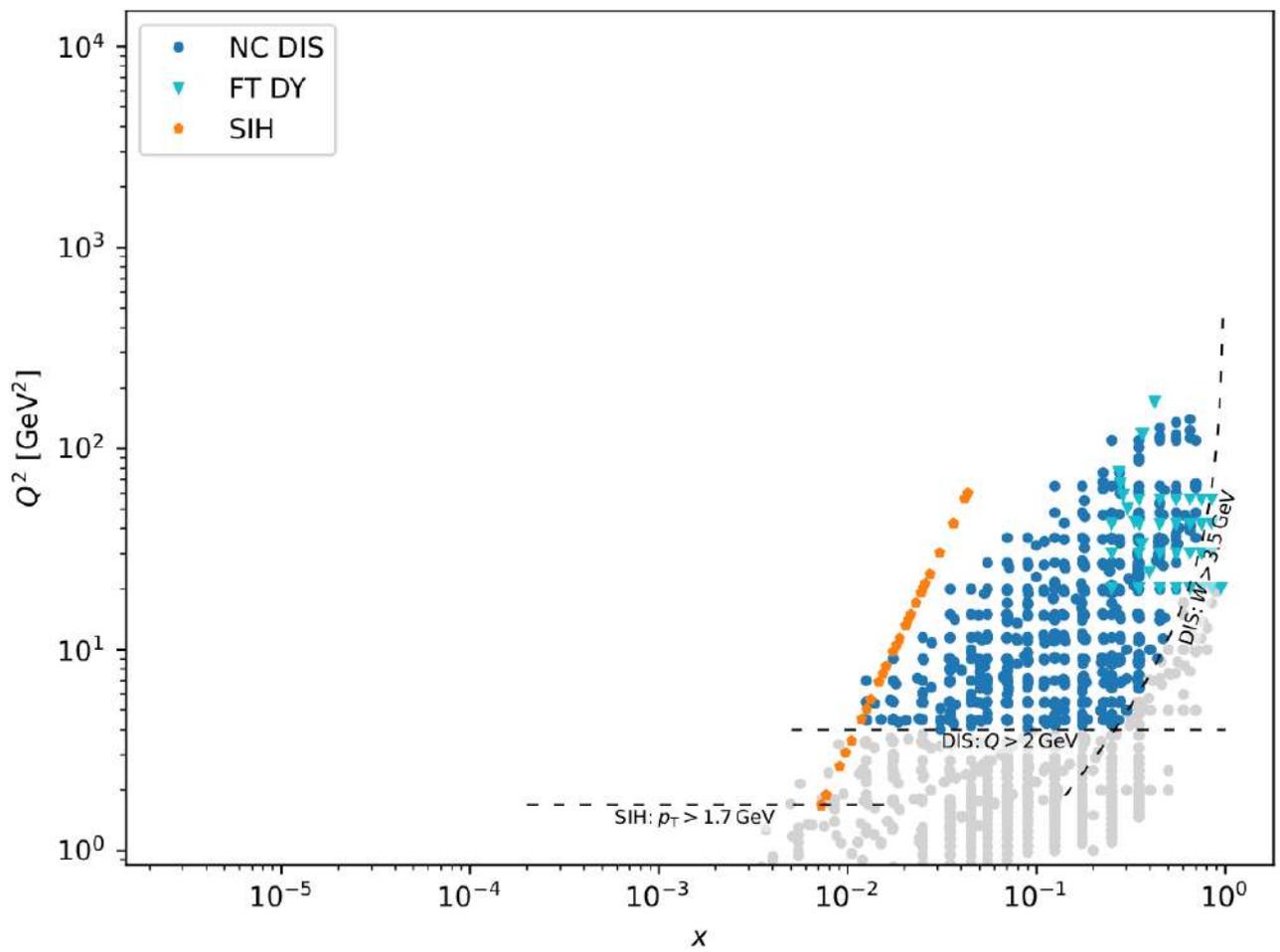
SRC: Jezo, Kusina, Olness, ...

Masses: Schienbein, Leger, Ruiz, ...

nCTEQ++: Jezo, Risse, Muzakka, Wissmann...

multifaceted
approach

Data Overview: nCTEQ15



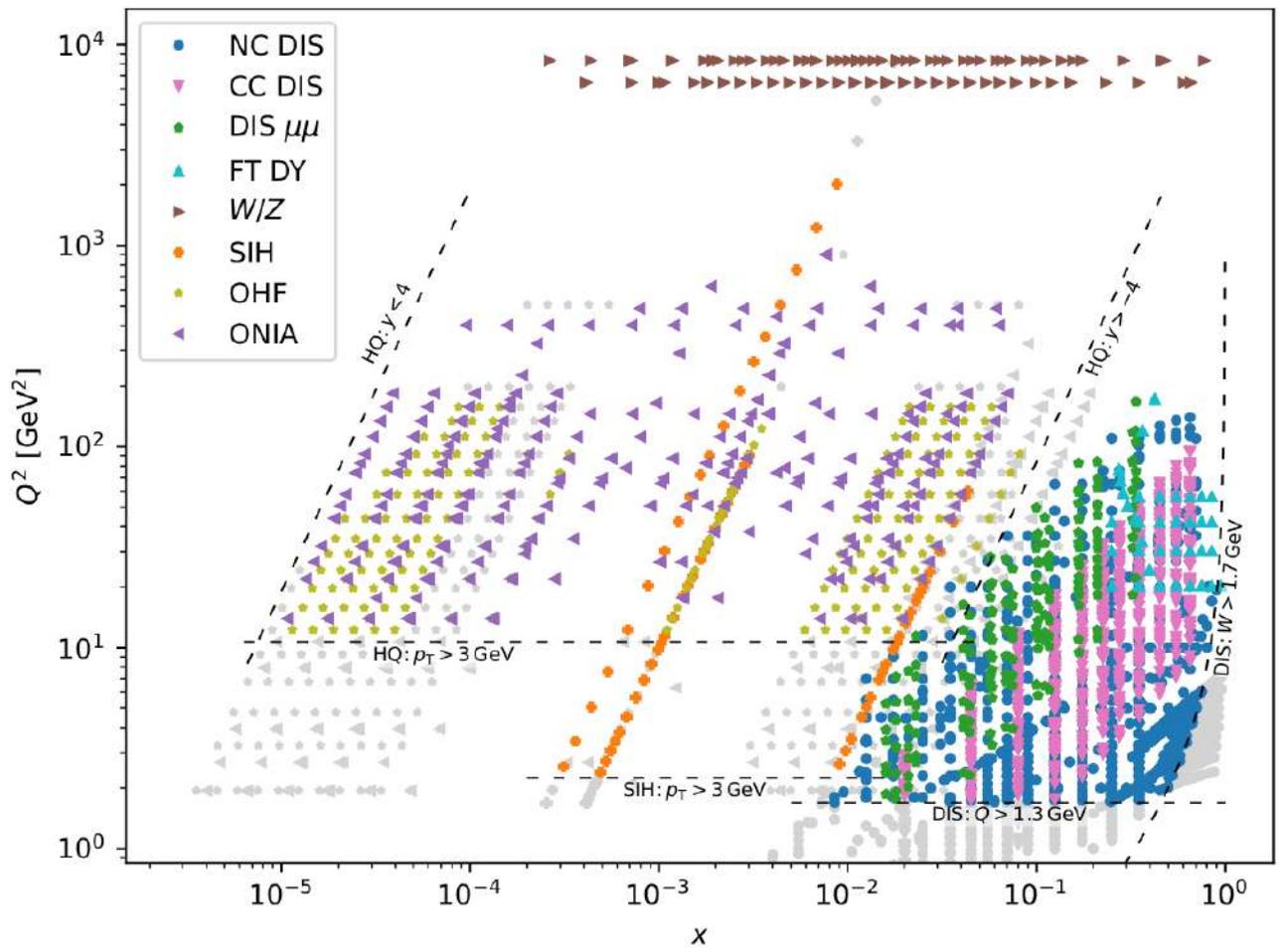
→ DIS, DY, SIH data
→ $N_{\text{data}} = 740$

Jan Wissmann (jan.wissmann@uni-muenster.de)

nCTEQ

nuclear parton distribution functions

Data Overview: nCTEQ25



PRELIMINARY

- new CC DIS, DIS $\mu\mu$, DY
W/Z, HQ data
- $N_{\text{data}} = 3518$
- looser cuts

Jan Wissmann (jan.wissmann@uni-muenster.de)

nCTEQ

nuclear parton distribution functions



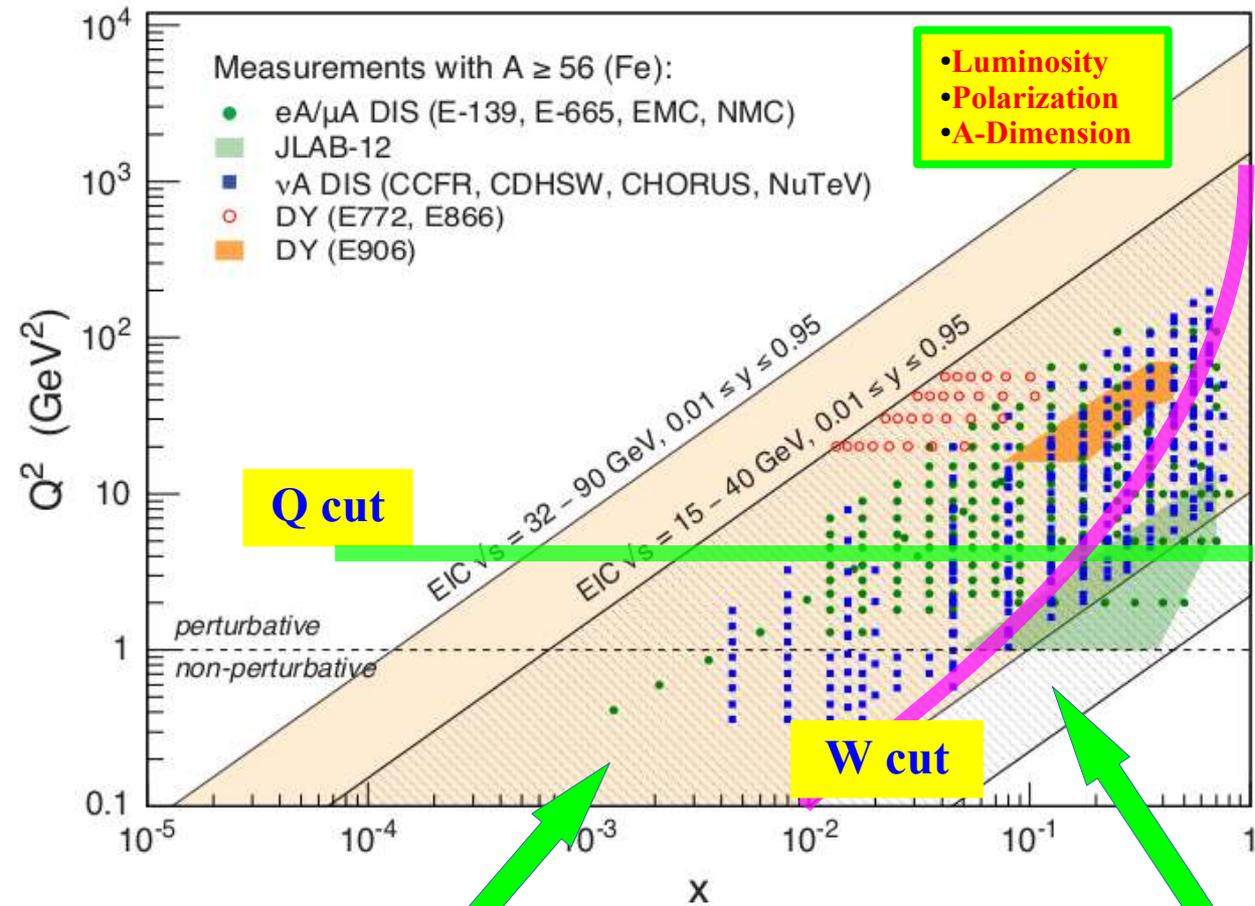
CONCLUSIONS

The most exciting phrase to hear in science,
the one that heralds new discoveries, is not “Eureka!” (*I found it!*)
but “That’s funny ...”

— Isaac Asimov

Chance favors the prepared mind

Louis Pasteur



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

