Revealing the fundamental character of the strong force

From PDFs to the underlying QCD

Fred Olness
SMU

Thanks for substantial input
from my friends & colleagues

nCTEQ
nuclear parton distribution functions

xFitter

SURGE COLLABORATION

CTEQ

Mitchell Conference
TAMU
24 May 2024

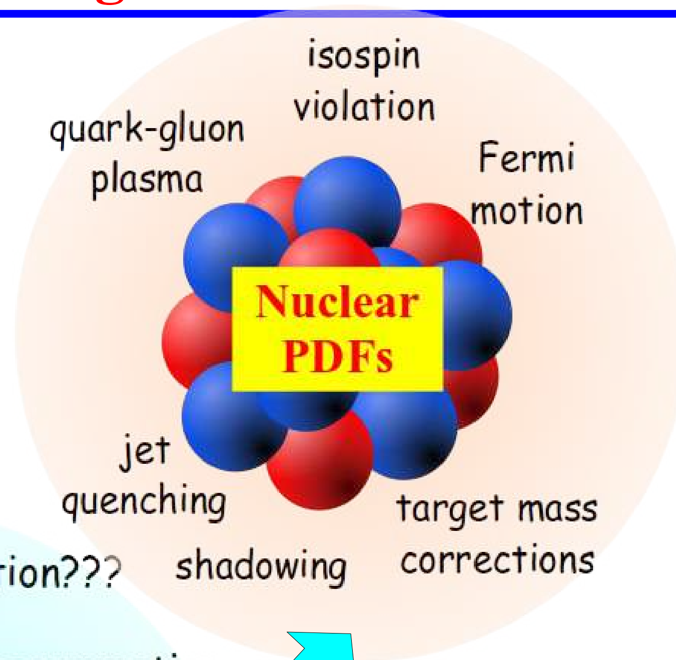
A Deeper Understanding of the strong nuclear force

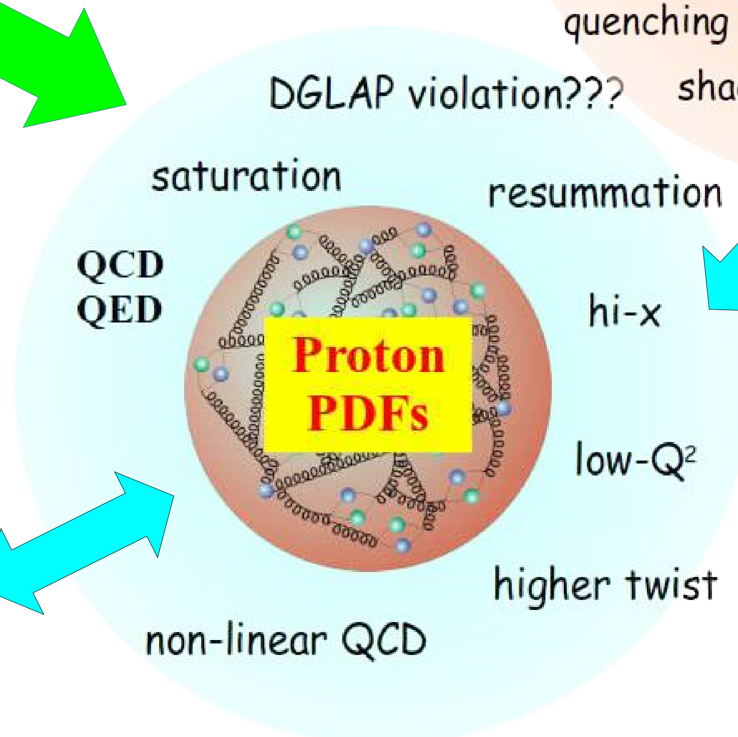
Quantum ChromoDynamics

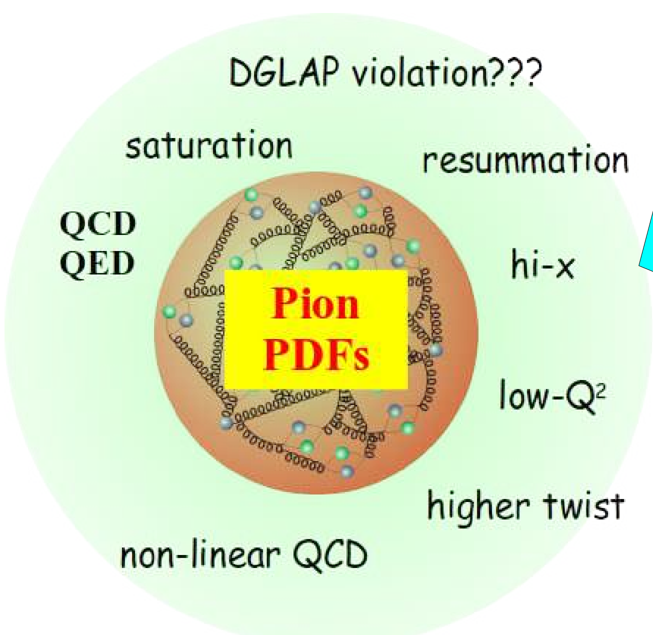
QCD

Lagrangian

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



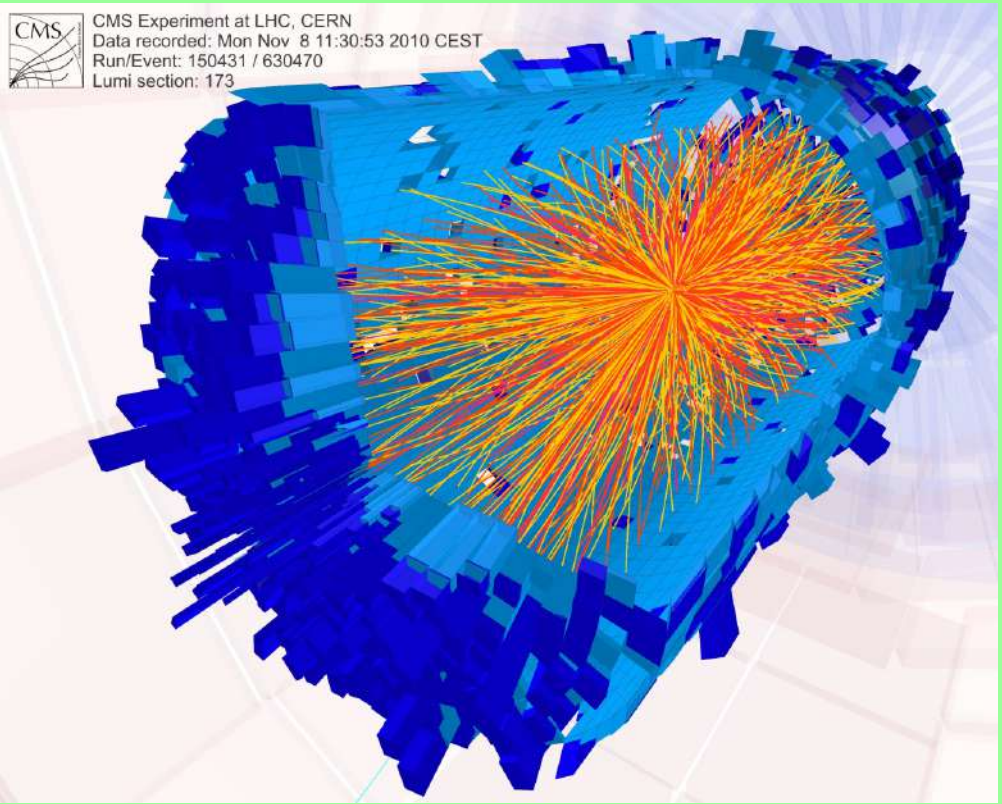




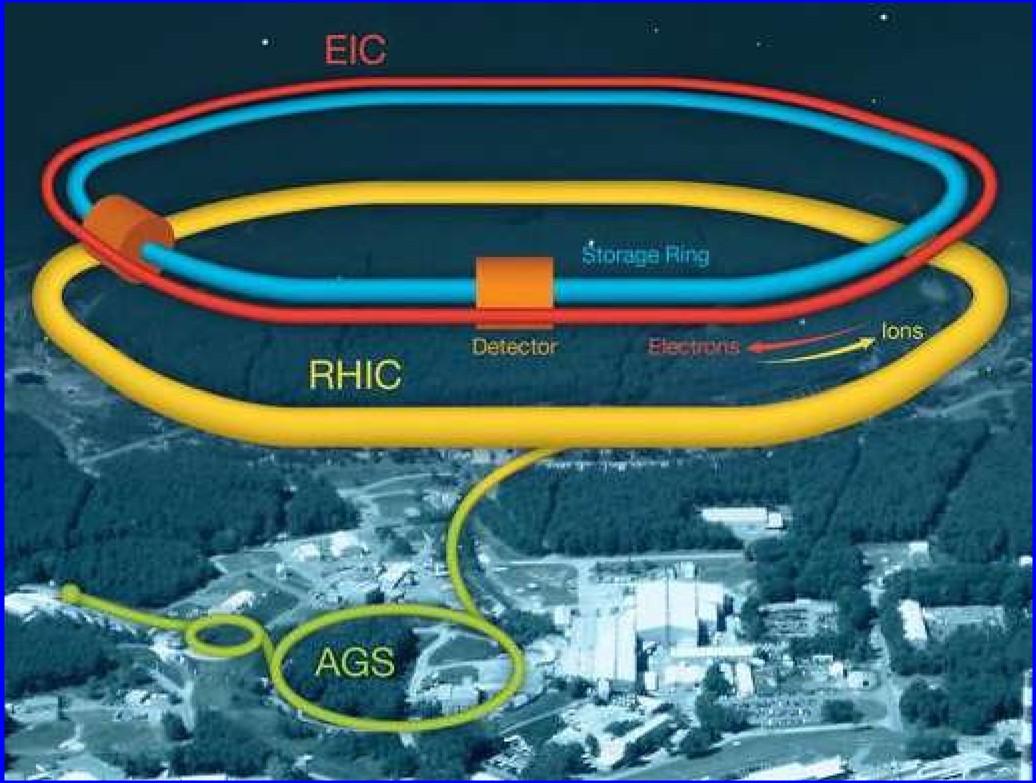
Olness Conjecture: A theory can't be fundamental unless it fits on a coffee mug.

HiLumi
HL-LHC PROJECT

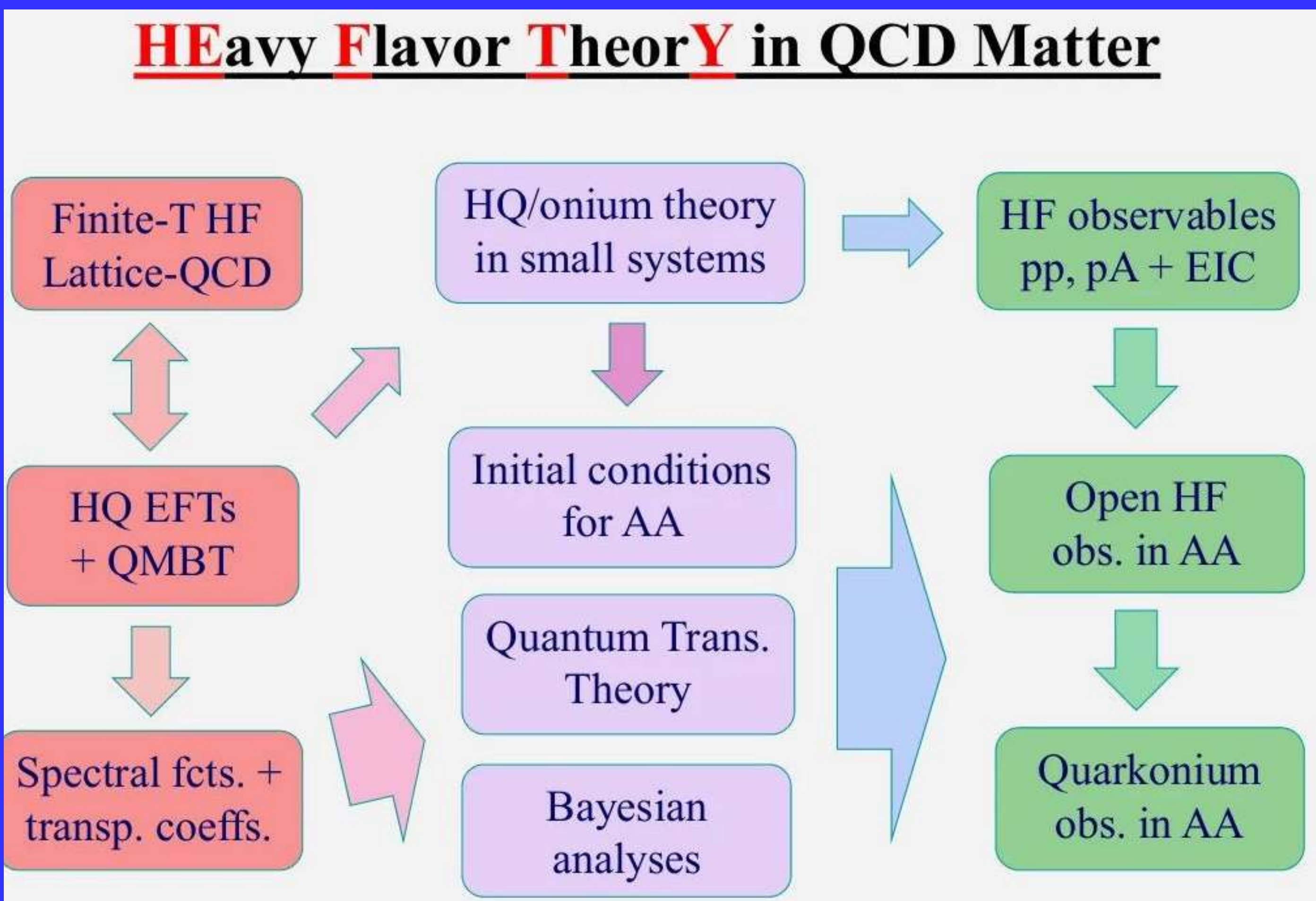
CMS Lead ion collisions



Electron-Ion Collider



Heavy-Flavor TheorY (HEFTY) for QCD Matter



Collaboration Membership

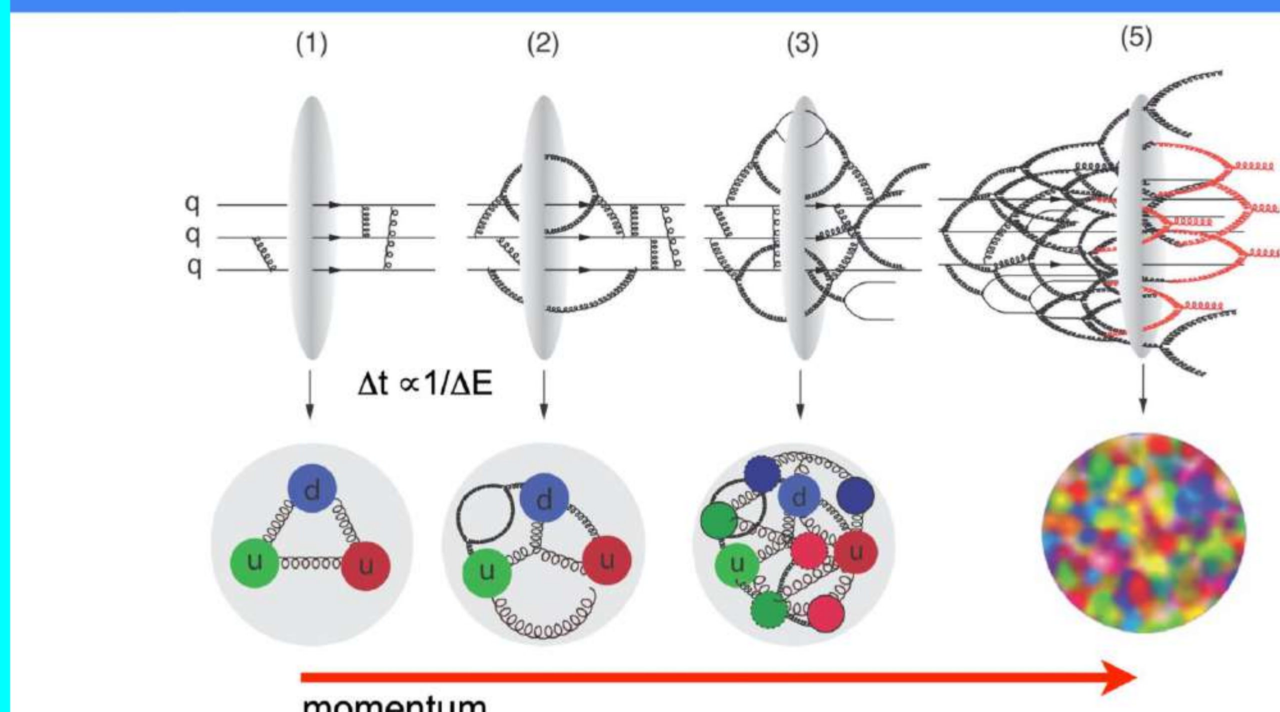
Ralf Rapp, Texas A&M University (PI)
Steffen Bass and Thomas Mehen, Duke U.
Swagato Mukherjee & Peter Petreczky, BNL
Jianwei Qiu, Jefferson Lab
Michael Strickland, Kent State University
Ivan Vitev, Los Alamos National Lab
Ramona Vogt, LLNL & UC Davis
Yen-Jie Lee, MIT
Xin Dong, Lawrence Berkeley Laboratory
Anthony Frawley, Florida State University

https://hefty.tamu.edu/

The Saturated Glue (SURGE) Collaboration

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).

Saturation



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

The Saturated Glue (SURGE) Collaboration

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

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

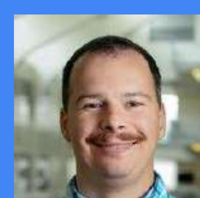
Final states WG
Construct a framework for hadronization in a saturated environment, including development of MC generator based on CGC calculations

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

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

- 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)**



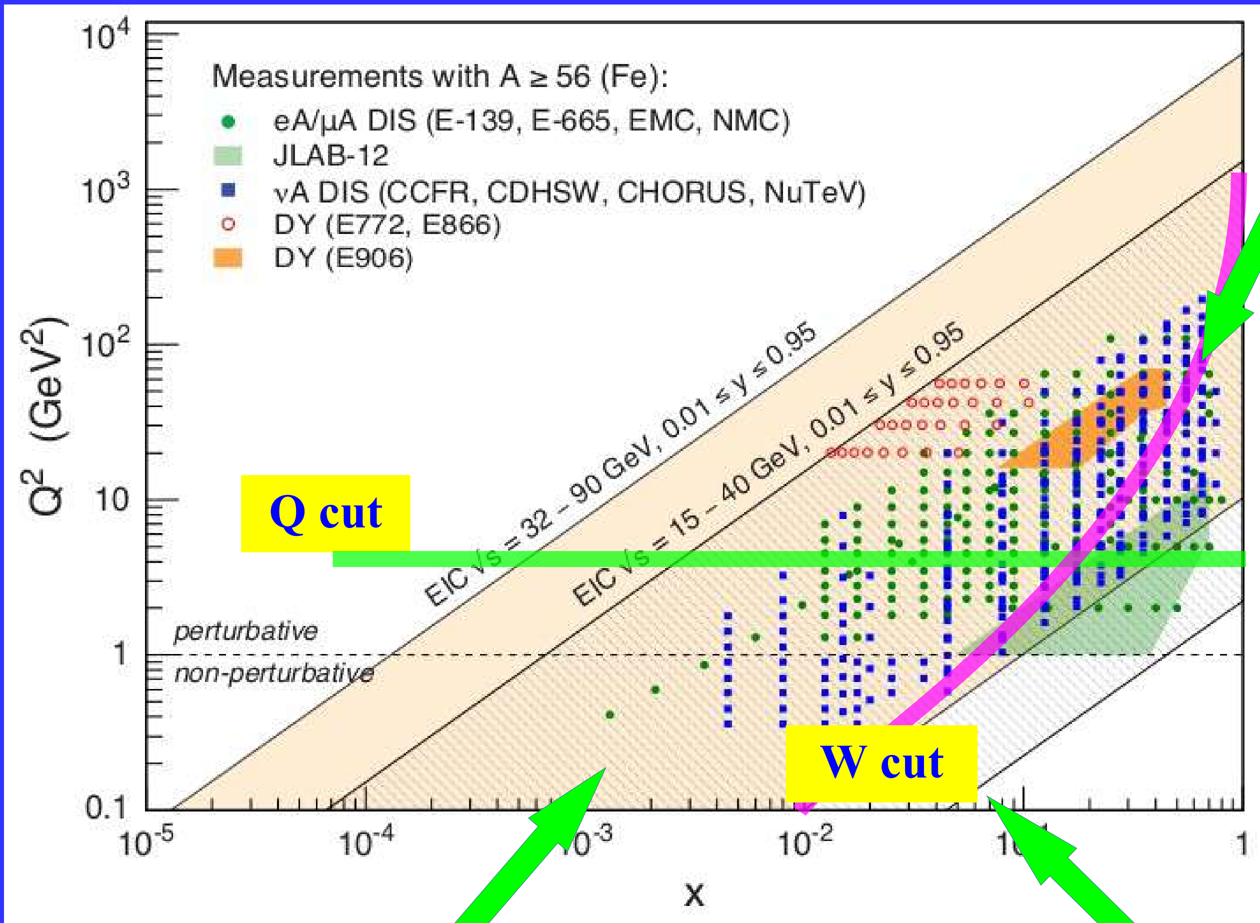



Bjoern Schenke
Project Director & Co-spokesperson
(631) 344-5805, bschenke@bnl.gov


Anna Stasto
Co-spokesperson
Penn State
(814) 865-7976, ams52@psu.edu

To boldy go where no analysis has gone before

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



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

Are we just looking under the lamppost

Low-x:
Shadowing
Recombination
Resummation
BFKL
Saturation

Low-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)

Need theoretical guidance in these regions

What's ν with ν

… an old problem

neutrino DIS

some new results

S-ACOT χ CC @ N2LO

Thanks to Peter Risse & Valerio Bertone

QCD for Precision Neutrino Physics

Un-ki Yang
Seoul National University

XXXI International Workshop on Deep Inelastic Scattering

8-12 April 2024, Grenoble, France

Precision, Precision… but systematic effect: theory and experiment

- Discrepancy between CCFR (ν) and NMC(μ) data at low x region (0.01<x<0.1)
  - Resolved by the proper handling of massive charm treatment (VFS, FFS): Model Ind. CCFR F2, xF3, δxF, *Phys.Rev.Lett.* 86 (2001) 2742
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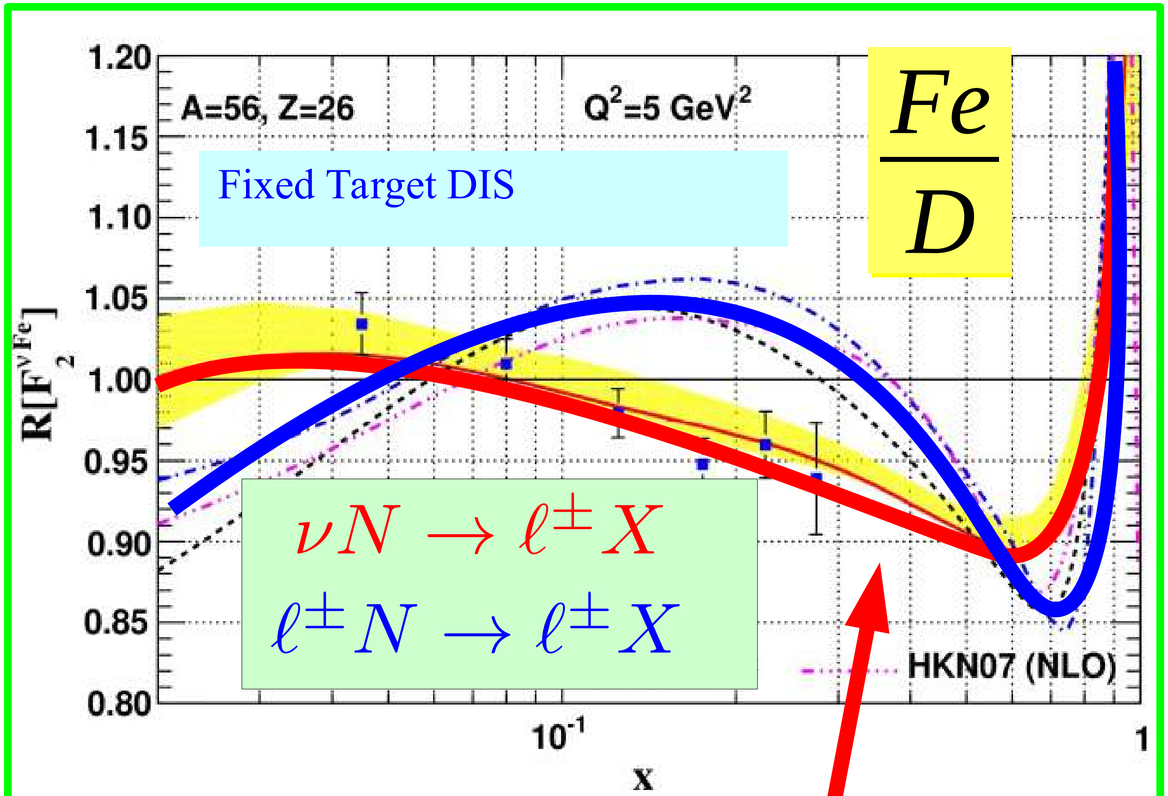
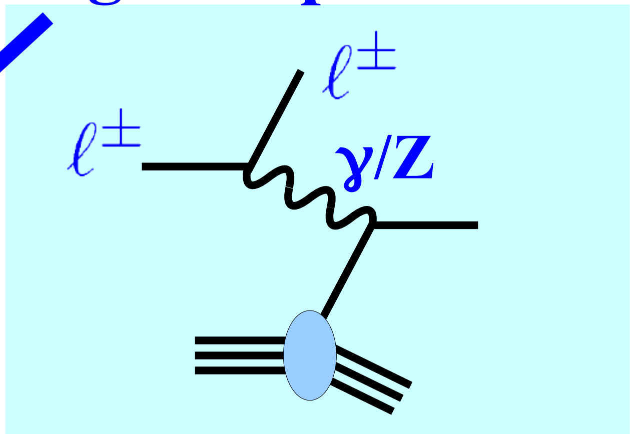
  - Problem appeared in the toroidal magnet calibration of the CCFR detector: *Phys.Rev.D* 74 (2006) 012008
- Different neutrino effect in neutrino: MINERvA saw a different nuclear effect?
- d/u at high x and asymmetry in strange sea
  - Updated d/u→0.2 or 0 at x=1
  - Asymmetry measurement in strange sea: correlated with d/u issue

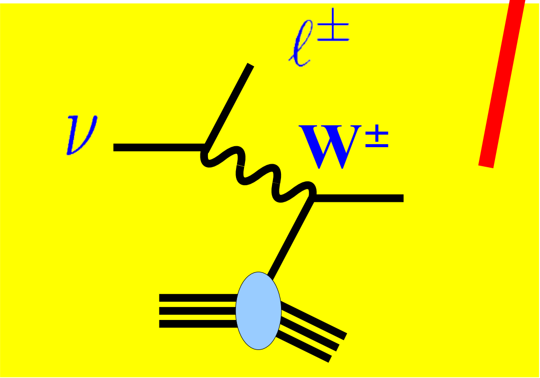
Puzzle: Split Personality … *What is the correct Nuclear ratio*



Charged Lepton DIS

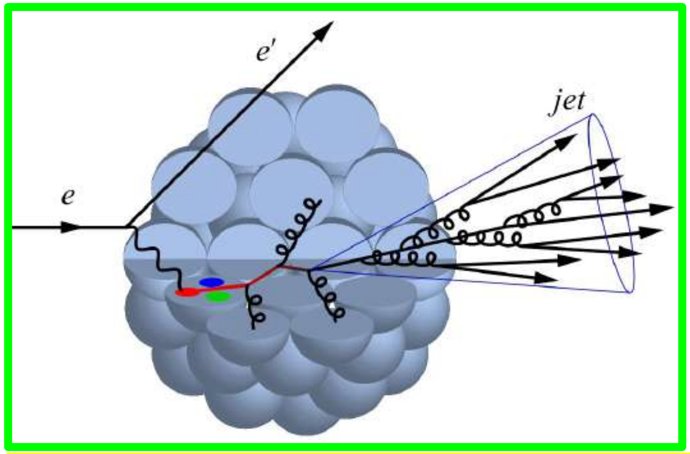


some caveats
… correlated errors



Neutrino DIS

Depends on nuclear corrections



Propagation of γ/W thru nuclei

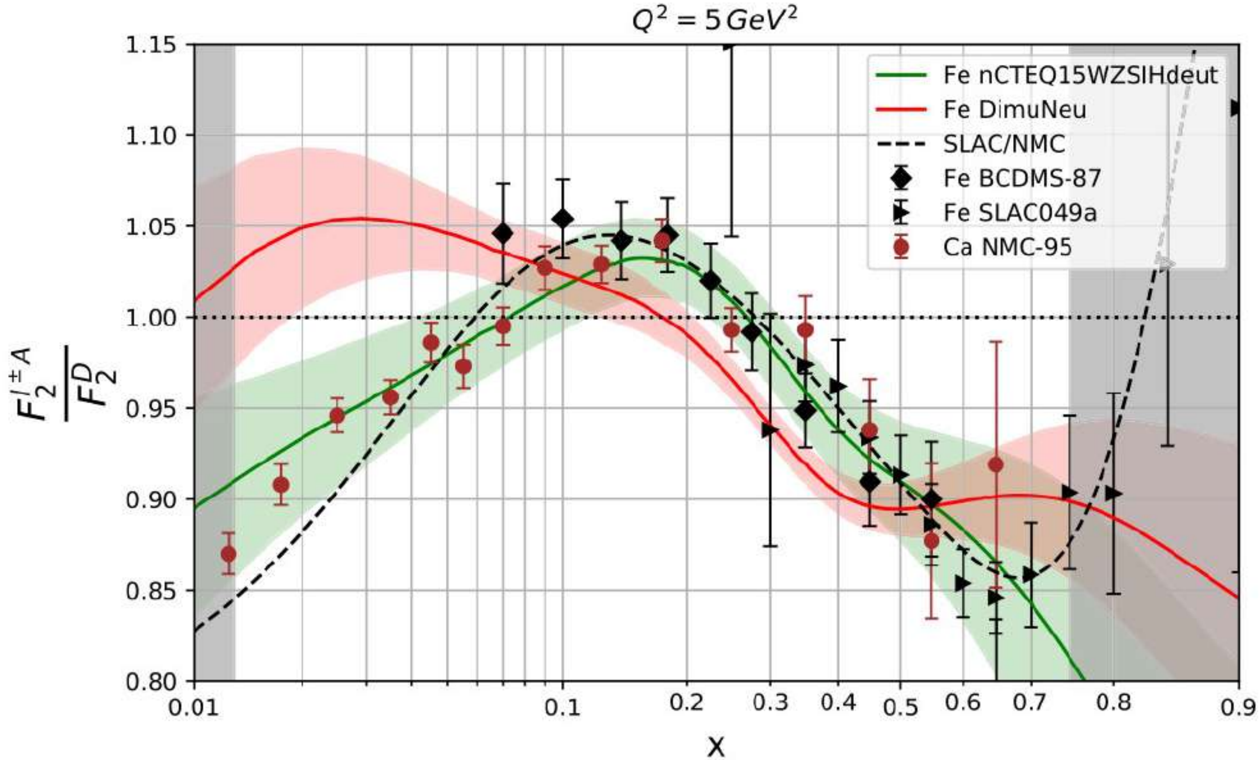
nCTEQ

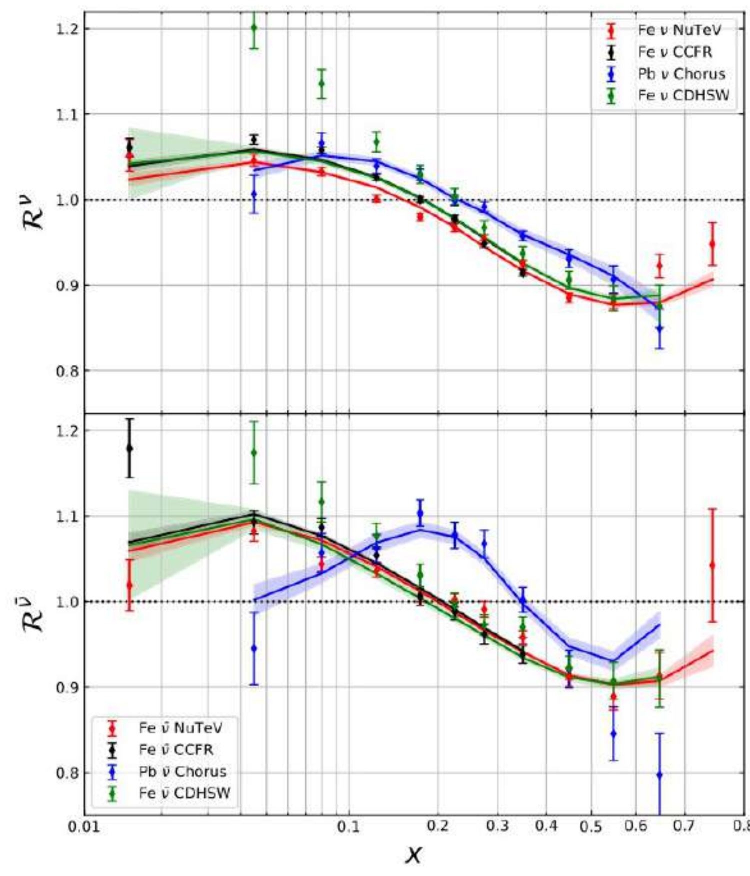
nuclear parton distribution functions

PHYSICAL REVIEW D **106**, 074004 (2022)

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] T. Ježo,[1] M. Klasen,[1] K. Kovařík,[1,†] A. Kusina,[4] J. G. Morfín,[2] F. I. Olness,[5] R. Ruiz,[4] I. Schienbein,[6] and J. Y. Yu[5]





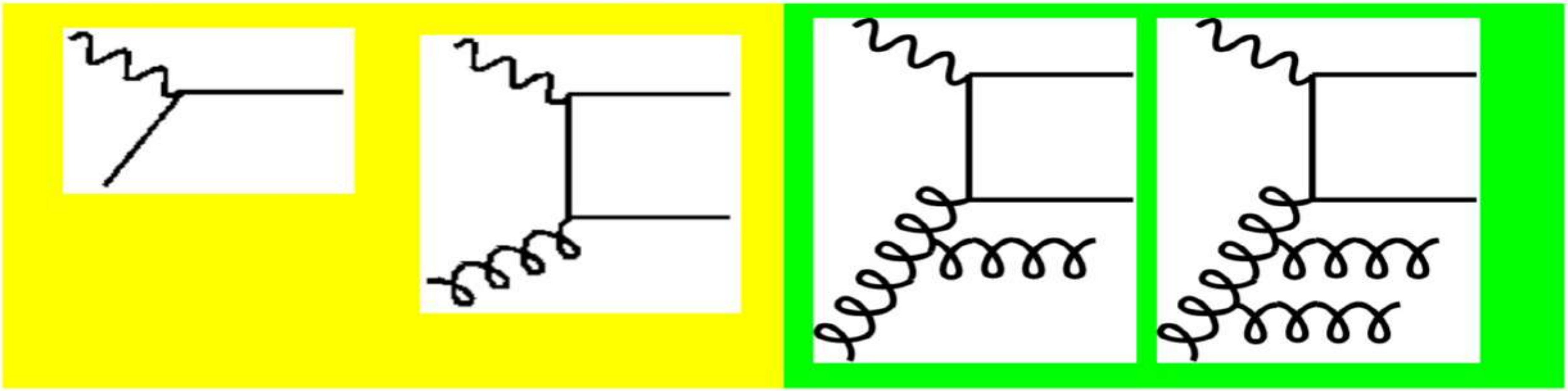
To Do List:

… more data

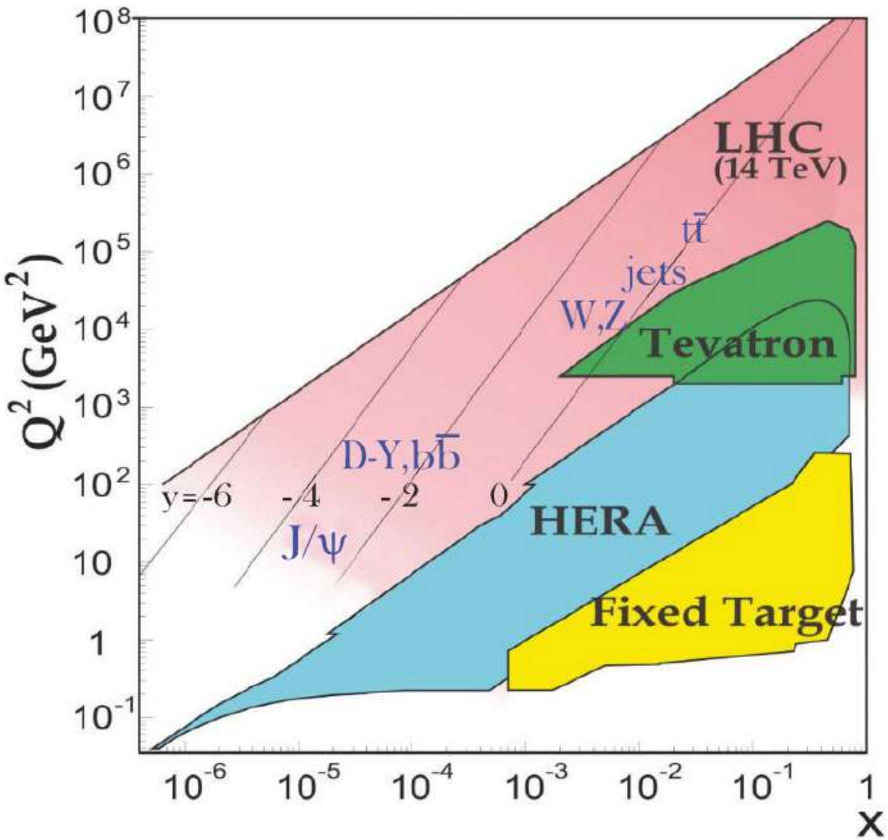
… improved predictions

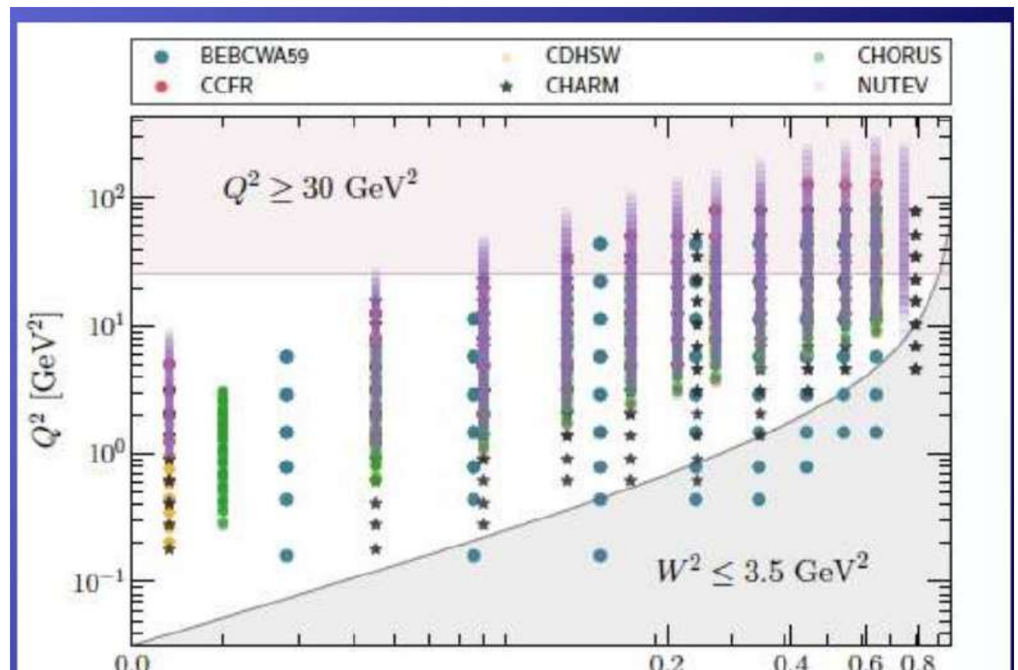
Higher Order Calculations: *... crossing mass thresholds*

LO **NLO** **N2LO** **N3LO**



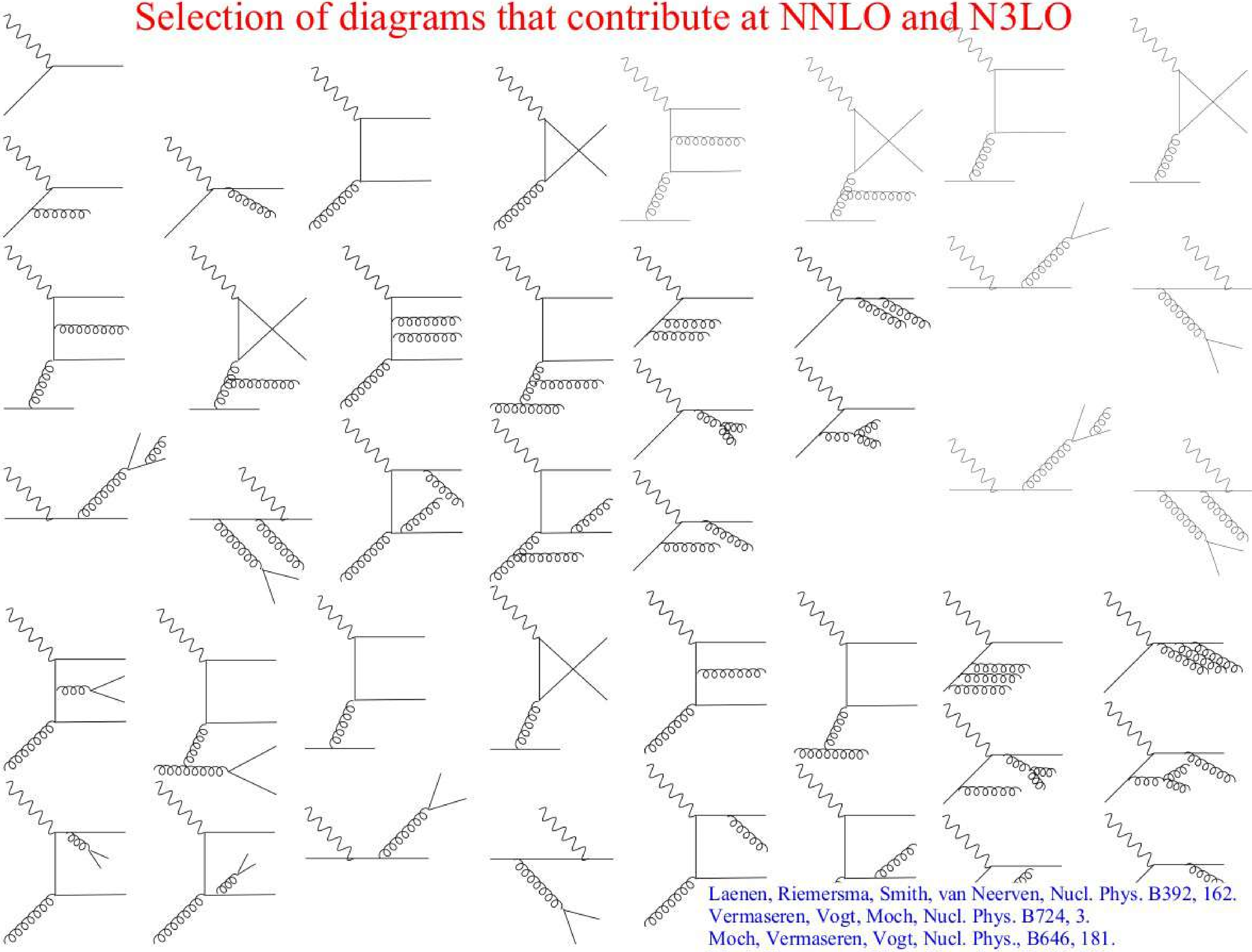
Full ACOT *Extensible to any order*





Neutrino Data (U,K. Yang)

Selection of diagrams that contribute at NNLO and N3LO



Laenen, Riemersma, Smith, van Neerven, Nucl. Phys. B392, 162.
Vermaseren, Vogt, Moch, Nucl. Phys. B724, 3.
Moch, Vermaseren, Vogt, Nucl. Phys., B646, 181.
Moch, Vermaseren, Vogt, Phys. Lett., B606, 123.
Blumlein, Hasselhuhn, Kovacikova, Moch, Phys.Lett. B700, (2011) 294.

Example #2: Multi-Scale Problems are Challenging

Two-Loop Total Cross Section: One Scale

$$\sigma(Q^2)=\sigma_0\left\{1+\frac{\alpha_s(Q^2)}{4\pi}(3C_F)+\left[\frac{\alpha_s(Q^2)}{4\pi}\right]^2\left[-C_F^2\left[\frac{3}{2}\right]+C_FC_A\left[\frac{123}{2}-44\zeta(3)\right]+C_FTn_f(-22+16\zeta(3))\right]\right.$$

Two-Loop Drell-Yan Cross Section: Two Scales

$$\begin{aligned}
H_{q\bar{q}}^{(2),S+V}(z)=\left[\frac{\alpha_s}{4\pi}\right]^2\delta(1-z)\Big\{&C_AC_F\left[\left[\tfrac{193}{3}-24\zeta(3)\right]\ln\left[\frac{Q^2}{M^2}\right]-11\ln^2\left[\frac{Q^2}{M^2}\right]-\tfrac{12}{5}\zeta(2)^2+\tfrac{592}{9}\zeta(2)+28\zeta(3)-\tfrac{1535}{12}\right]\\
&+C_F^2\left[[18-32\zeta(2)]\ln^2\left[\frac{Q^2}{M^2}\right]+[24\zeta(2)+176\zeta(3)-93]\ln\left[\frac{Q^2}{M^2}\right]\right.\\
&\left.+\tfrac{8}{5}\zeta(2)^2-70\zeta(2)-60\zeta(3)+\tfrac{511}{4}\right]\\
&+n_fC_F\left[2\ln^2\left[\frac{Q^2}{M^2}\right]-\tfrac{34}{3}\ln\left[\frac{Q^2}{M^2}\right]+8\zeta(3)-\tfrac{112}{9}\zeta(2)+\tfrac{127}{6}\right]\Big\}\\
+C_AC_F\Big[&-\tfrac{44}{3}\mathcal{D}_0(z)\ln^2\left[\frac{Q^2}{M^2}\right]+\{[\tfrac{536}{9}-16\zeta(2)]\mathcal{D}_0(z)-\tfrac{176}{3}\mathcal{D}_1(z)\}\ln\left[\frac{Q^2}{M^2}\right]\\
&-\tfrac{176}{3}\mathcal{D}_2(z)+[\tfrac{1072}{9}-32\zeta(2)]\mathcal{D}_1(z)+[56\zeta(3)+\tfrac{176}{3}\zeta(2)-\tfrac{1616}{27}]\mathcal{D}_0(z)\Big]\\
+C_F^2\Big[&[64\mathcal{D}_1(z)+48\mathcal{D}_0(z)]\ln^2\left[\frac{Q^2}{M^2}\right]+\{192\mathcal{D}_2(z)+96\mathcal{D}_1(z)-[128+64\zeta(2)]\mathcal{D}_0(z)\}\ln\left[\frac{Q^2}{M^2}\right]\\
&+128\mathcal{D}_3(z)-(128\zeta(2)+256)\mathcal{D}_1(z)+256\zeta(3)\mathcal{D}_0(z)\Big]\\
+n_fC_F\Big[&\tfrac{8}{3}\mathcal{D}_0(z)\ln^2\left[\frac{Q^2}{M^2}\right]+[\tfrac{32}{3}\mathcal{D}_1(z)-\tfrac{80}{9}\mathcal{D}_0(z)]\ln\left[\frac{Q^2}{M^2}\right]+\tfrac{32}{3}\mathcal{D}_2(z)-\tfrac{160}{9}\mathcal{D}_1(z)+[\tfrac{224}{27}-\tfrac{32}{3}\zeta(2)]\mathcal{D}_0(z)\Big].
\end{aligned}$$

Ref: CTEQ Handbook

Implementation

Neutral Current S-ACOT χ implemented at N2LO and N3LO

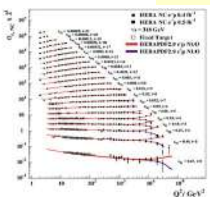
xFitter

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



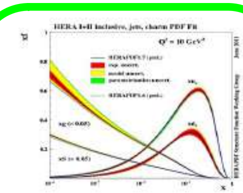
Data: HERA, Tevatron, LHC, fixed target experiments

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 ...

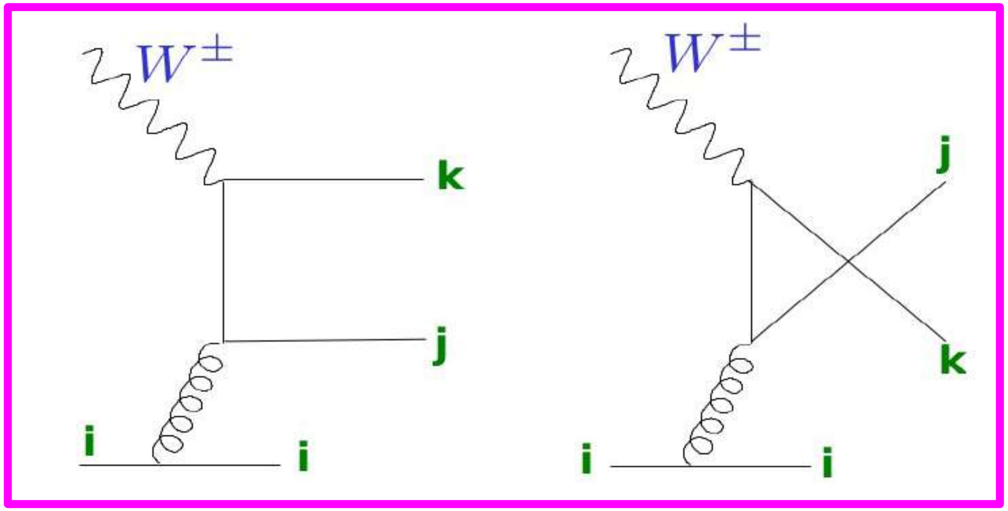
Theoretical Cross Sections

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 Tresho…
- Improvements in χ^2 and correlations
- **TMD** PDFs (uPDFs)
- *... and many other*

xFitter 2.2.0 Future Freeze

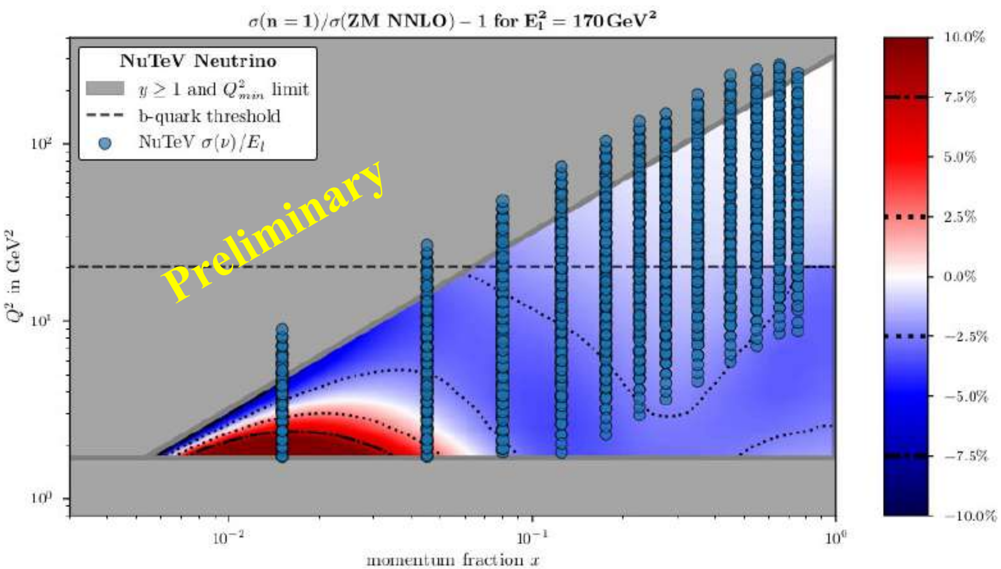


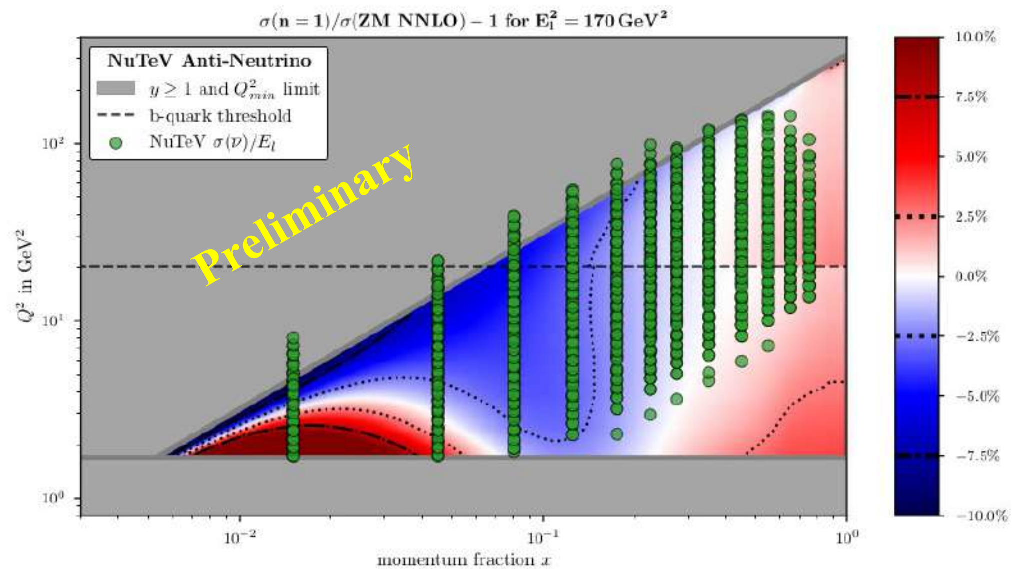
Fast evaluation of heavy-quark contributions to DIS in APFEL++

P. Risse[a,†], V. Bertone[b], T. Ježo[a], M. Klasen[a], K. Kovařík[a], F.I. Olness[c], I. Schienbein[d]

Peter Risse (Muenster)

arXiv:2307.08269v1





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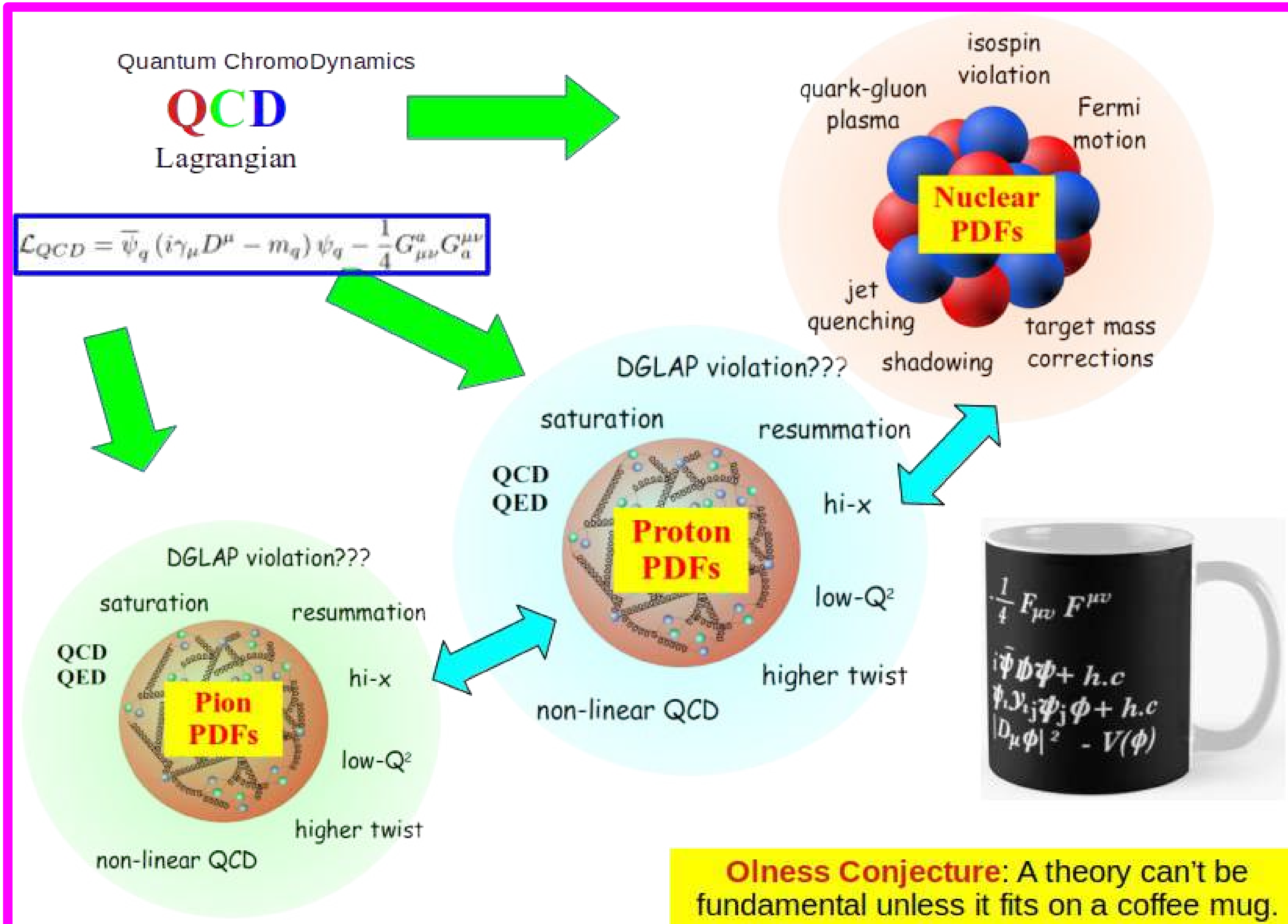
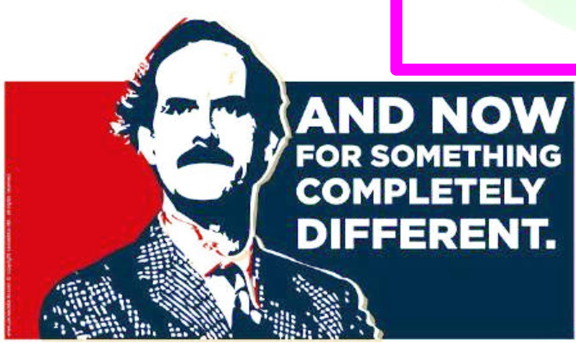
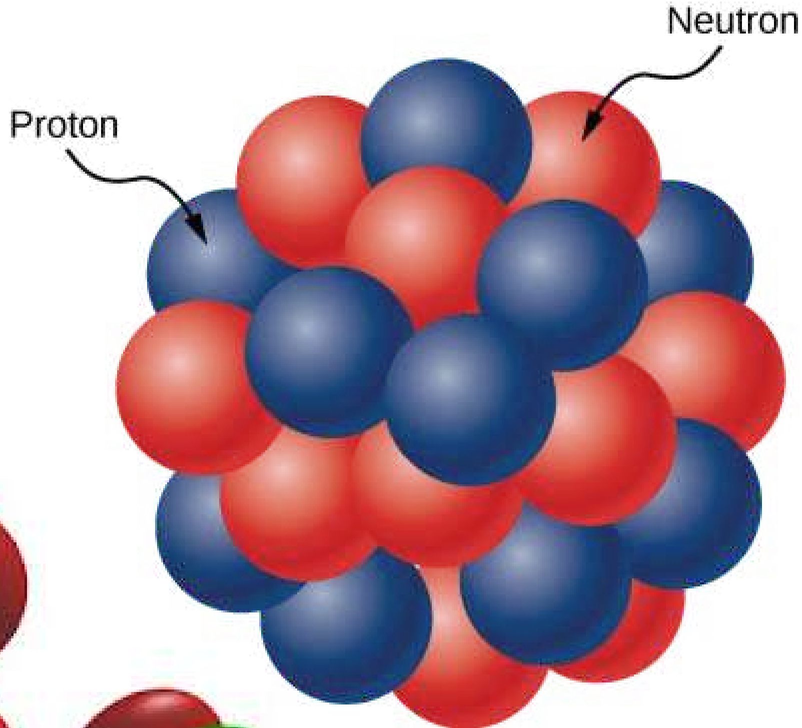
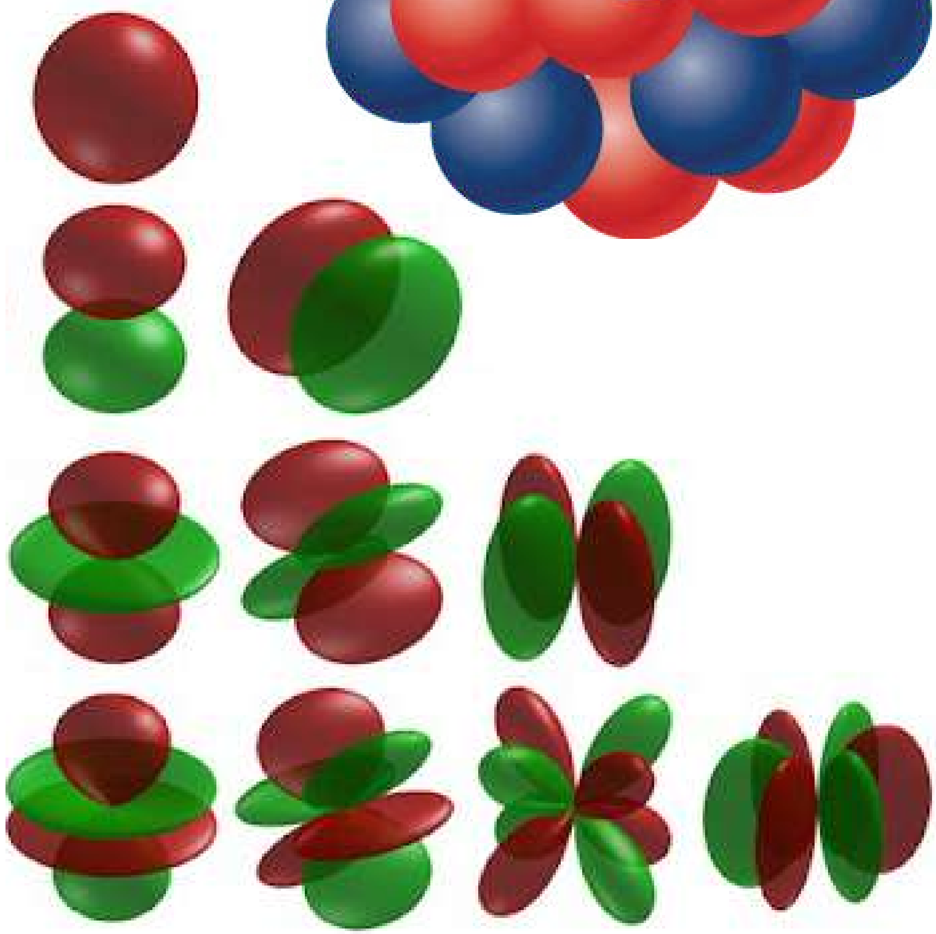
Beyond the proton …

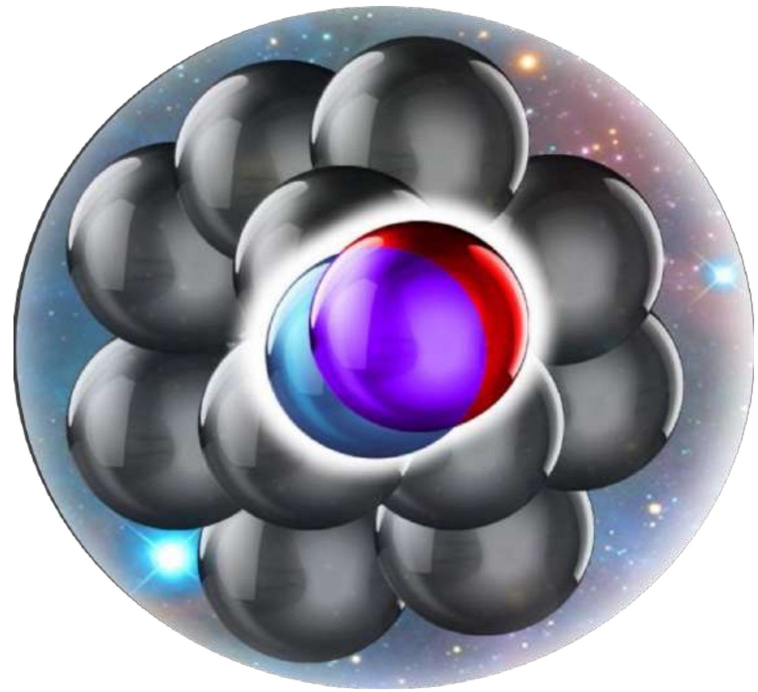


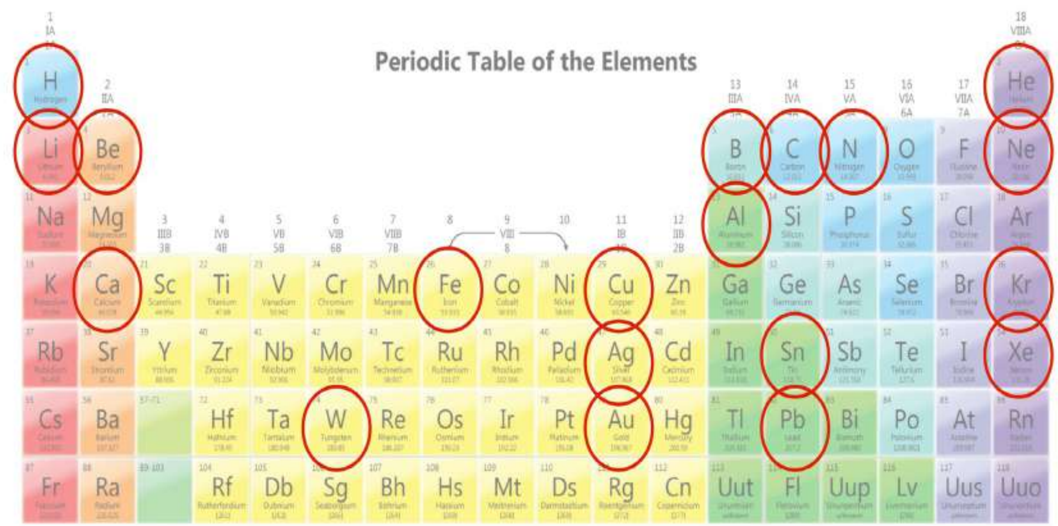
Olness Conjecture: A theory can't be fundamental unless it fits on a coffee mug.



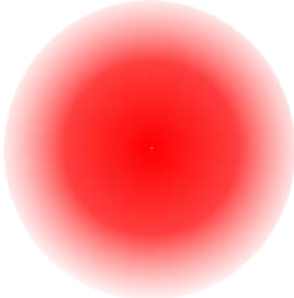

Neutron
Proton



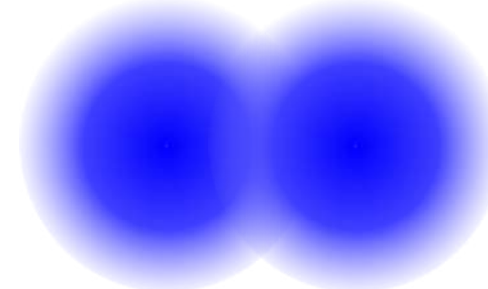


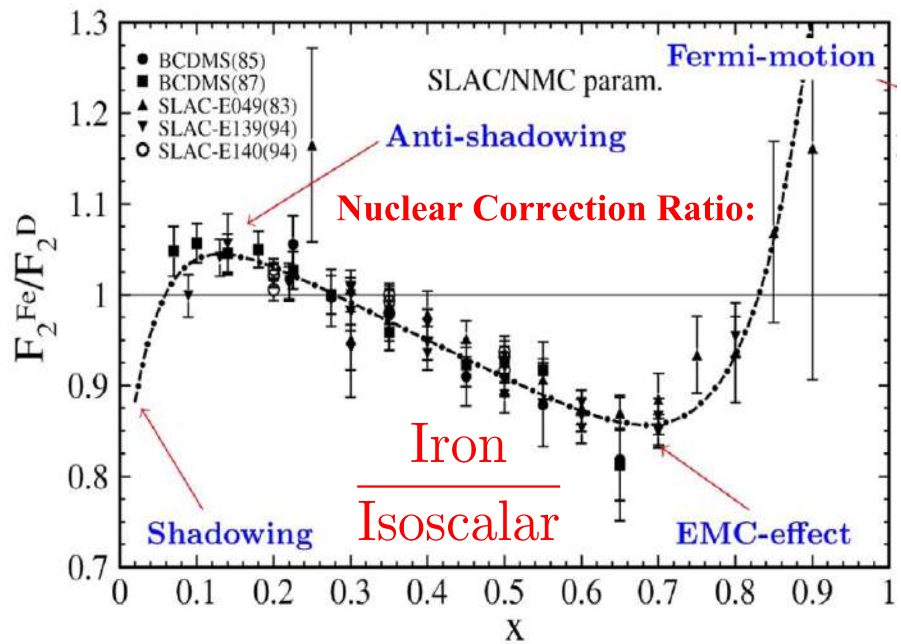

Periodic Table of the Elements
H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Rf Db Sg Bh Hs Mt Ds Rg Cn Uut Fl Uup Lv Uus Uuo

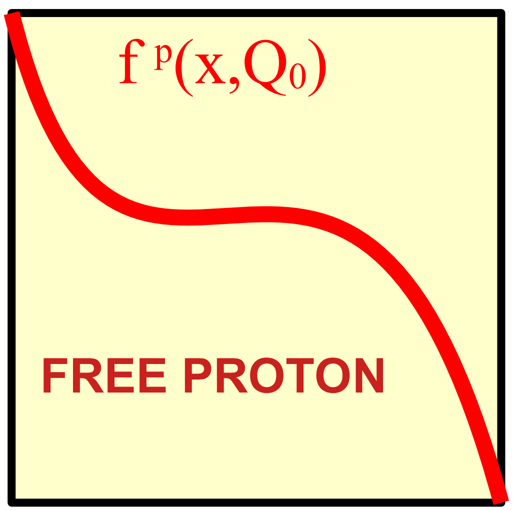
nucleon

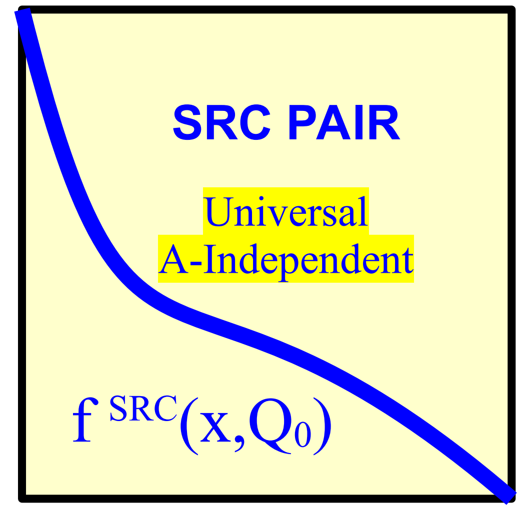


nucleon - nucleon









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

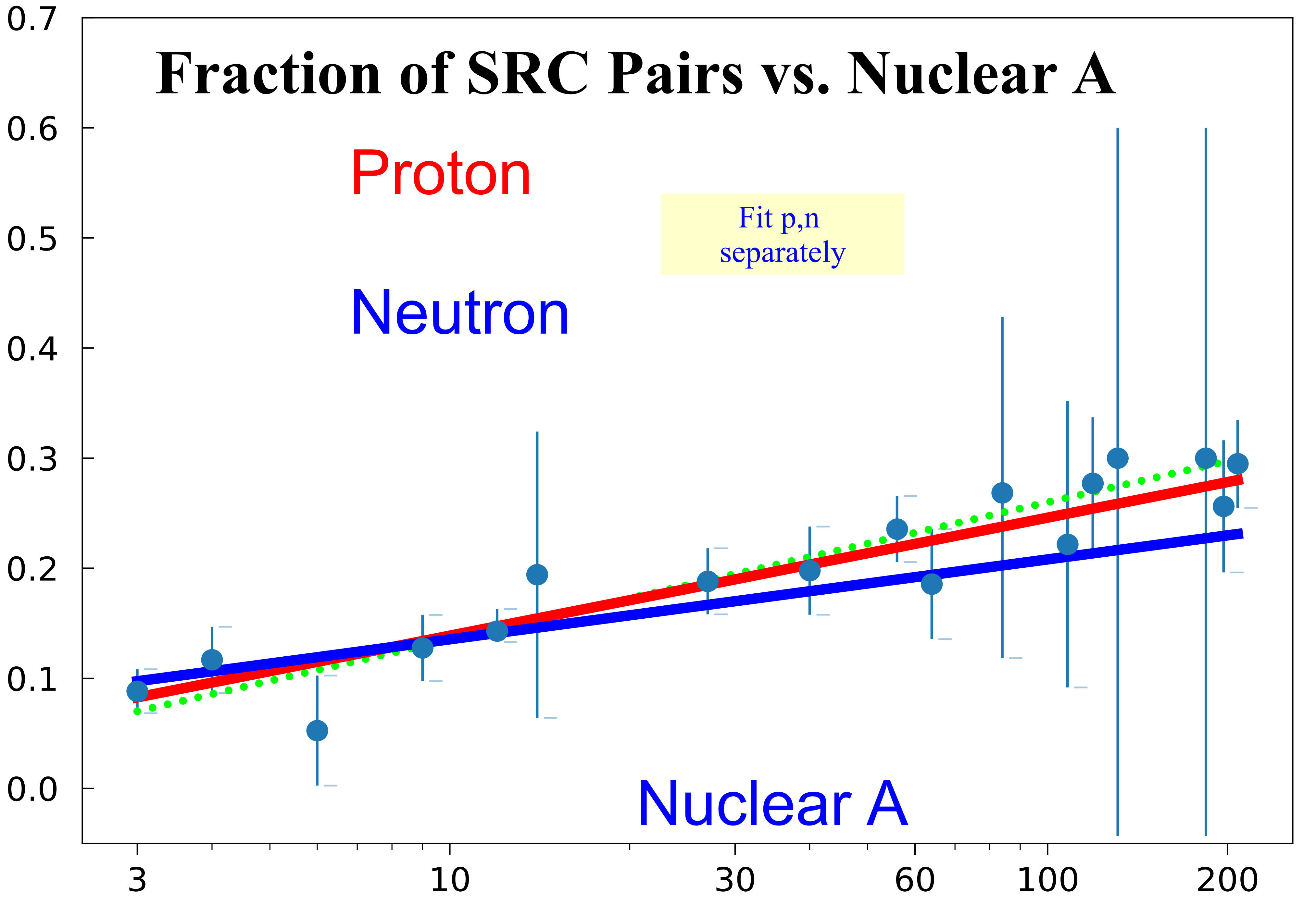
Evidence for Modified Quark-Gluon Distributions in Nuclei by Correlated Nucleon Pairs

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]

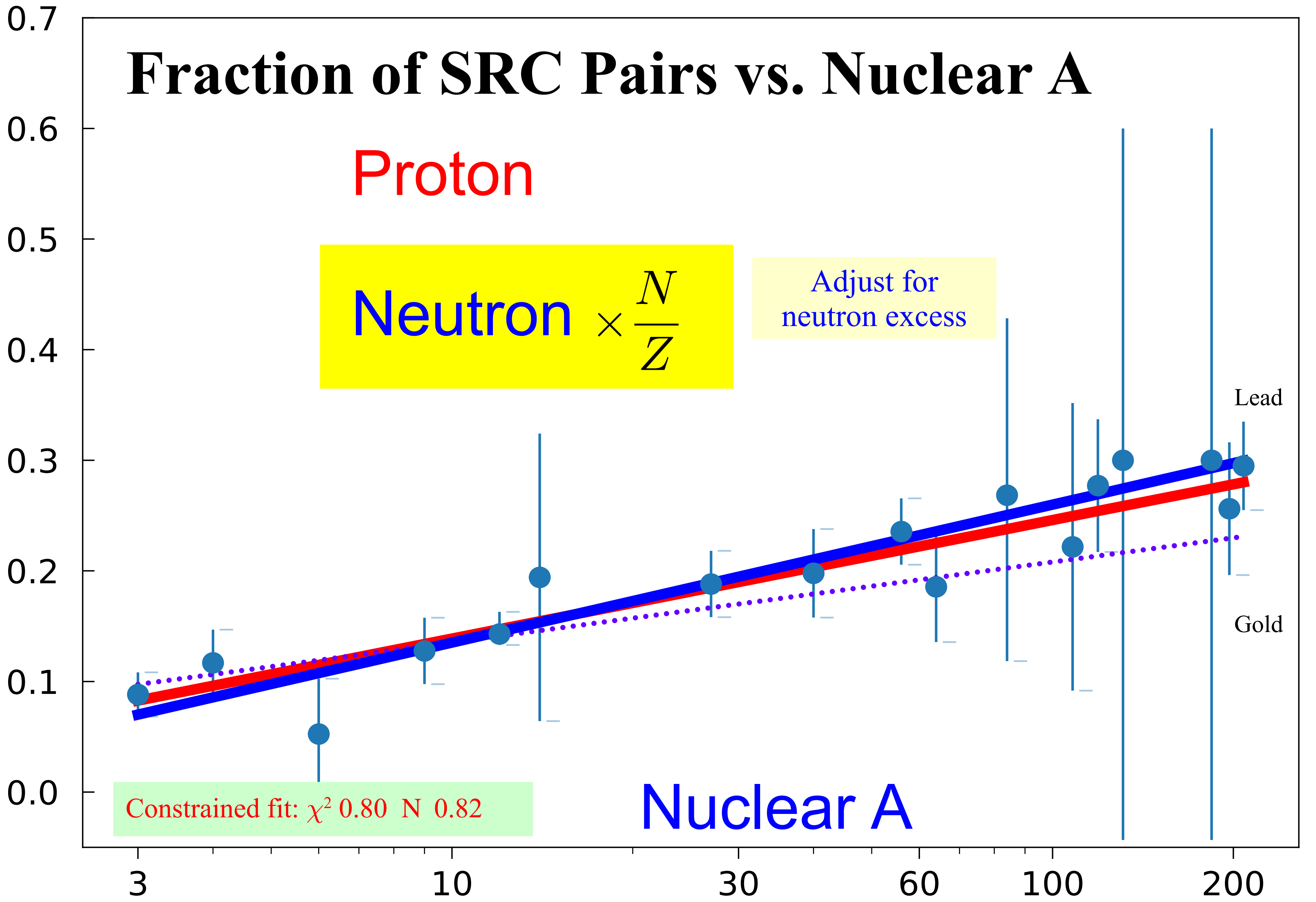
Hen Lab

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



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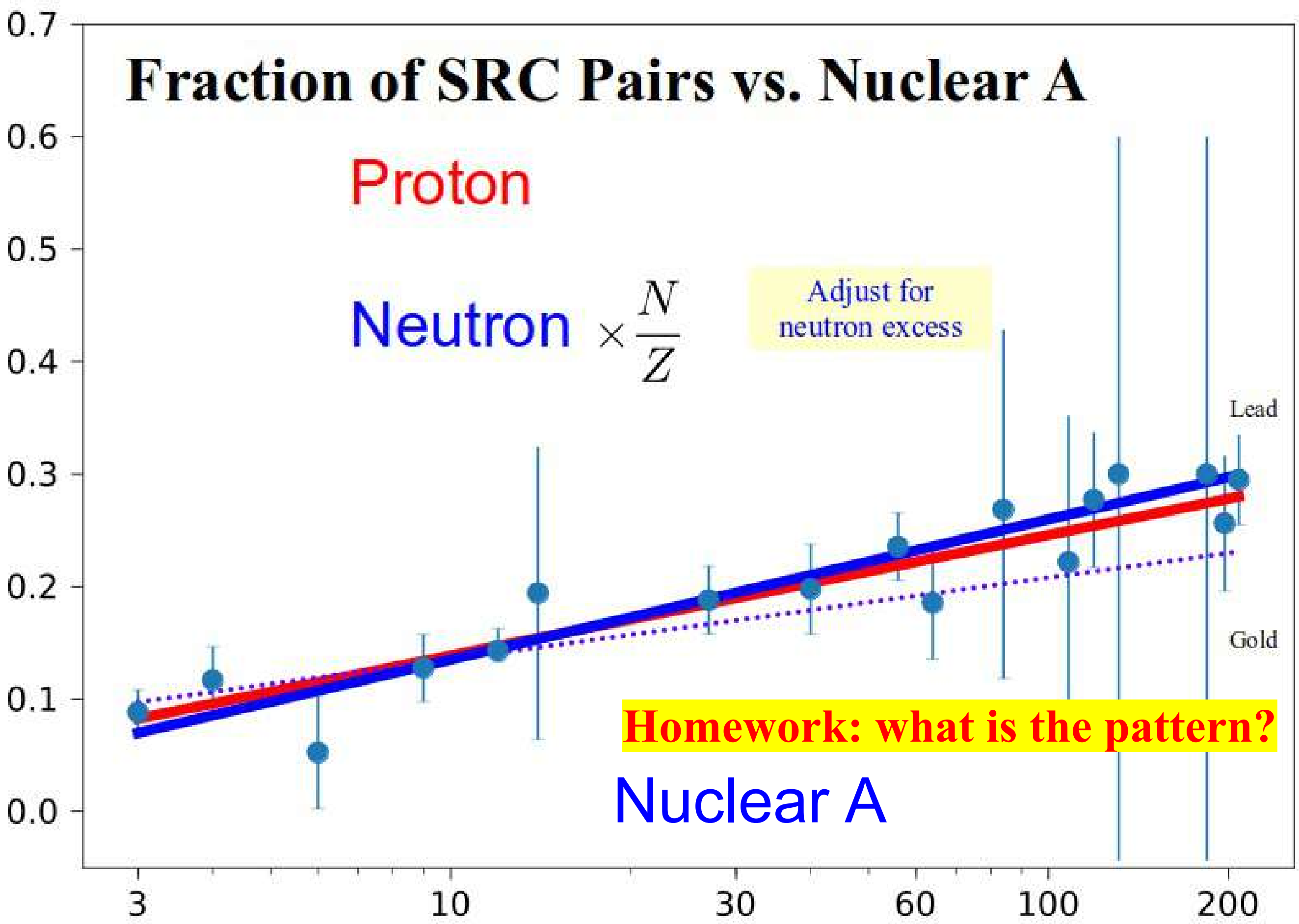


Gold $^{197}_{79}$Au

$C_p = 0.256$

$C_n = 0.177$

A = 197

Z = 79

N = 118

$C_p \times Z =$ **20.2**

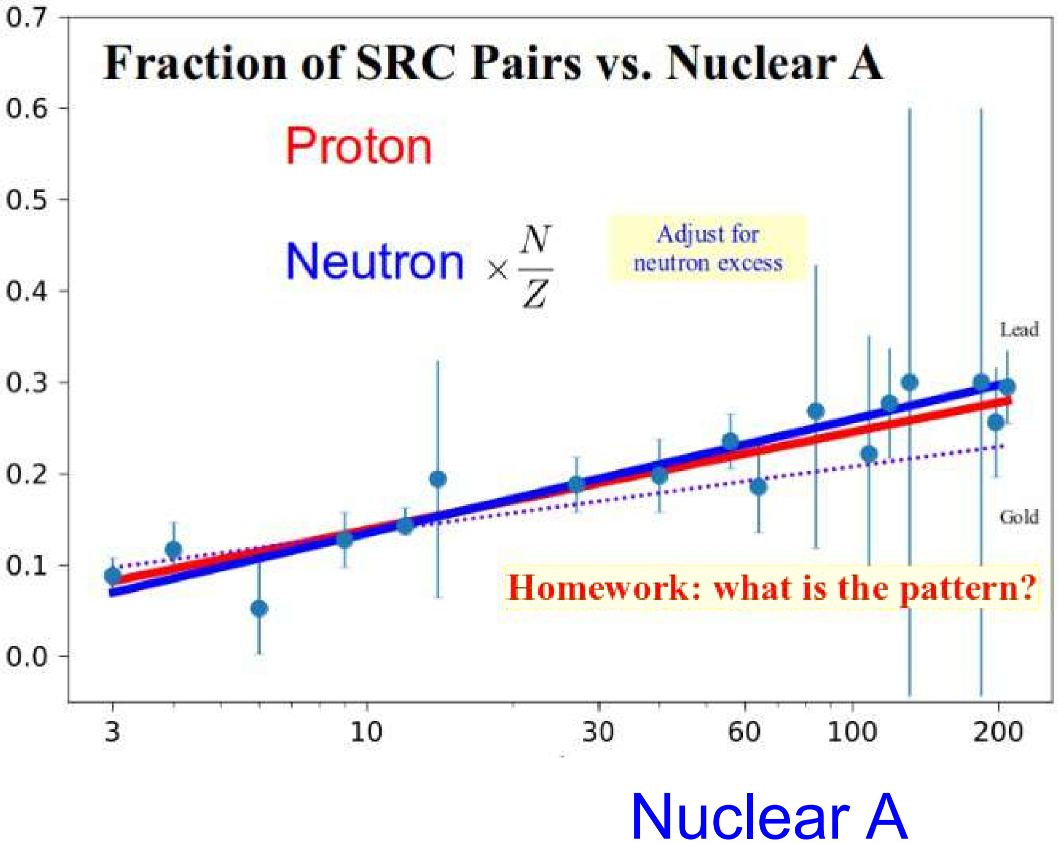
$C_n \times N =$ **20.9**

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

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

$\chi^2/N_{\rm data}$	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	

Nature is trying to tell us something

This parameter form connects to new concepts

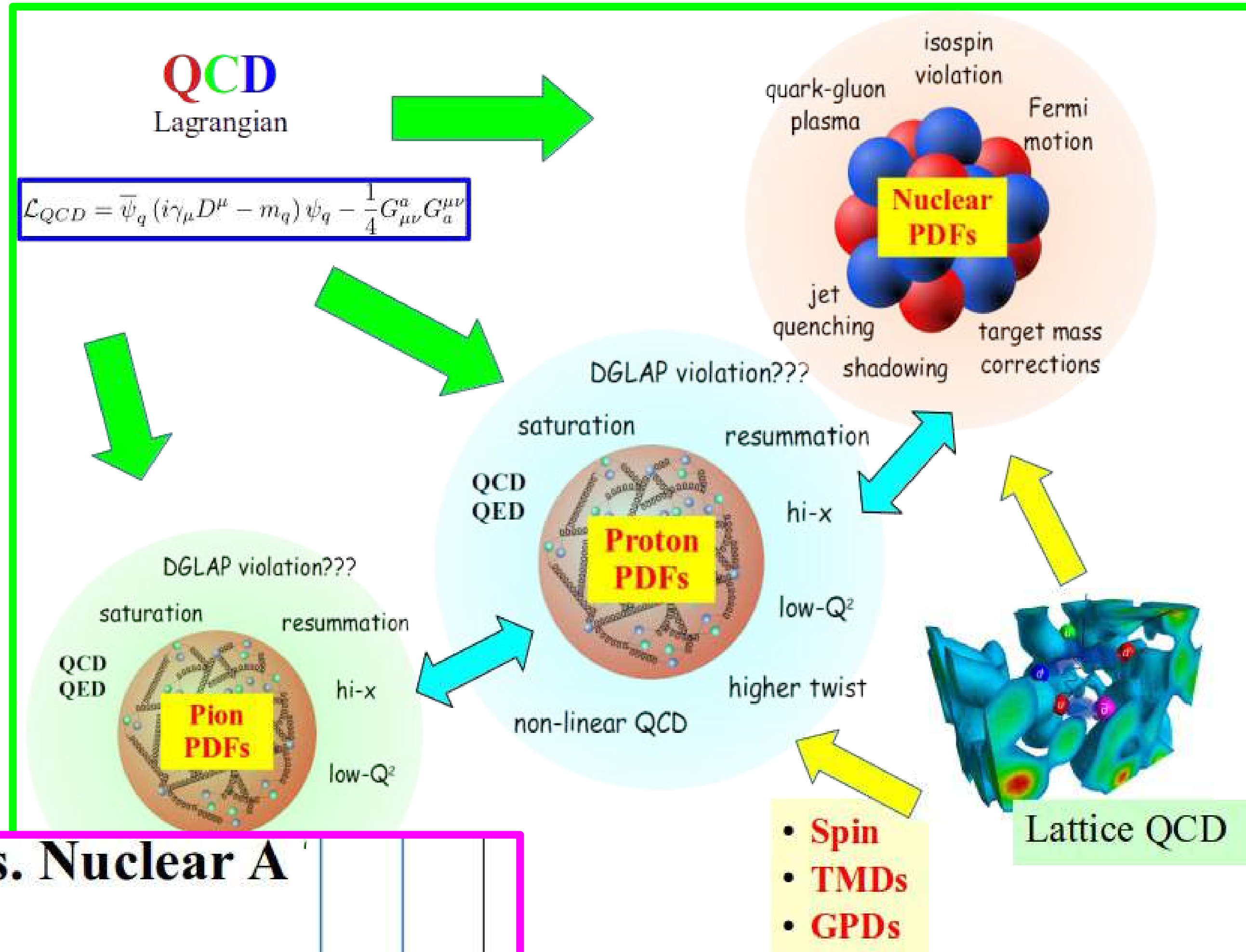
CONCLUSIONS:

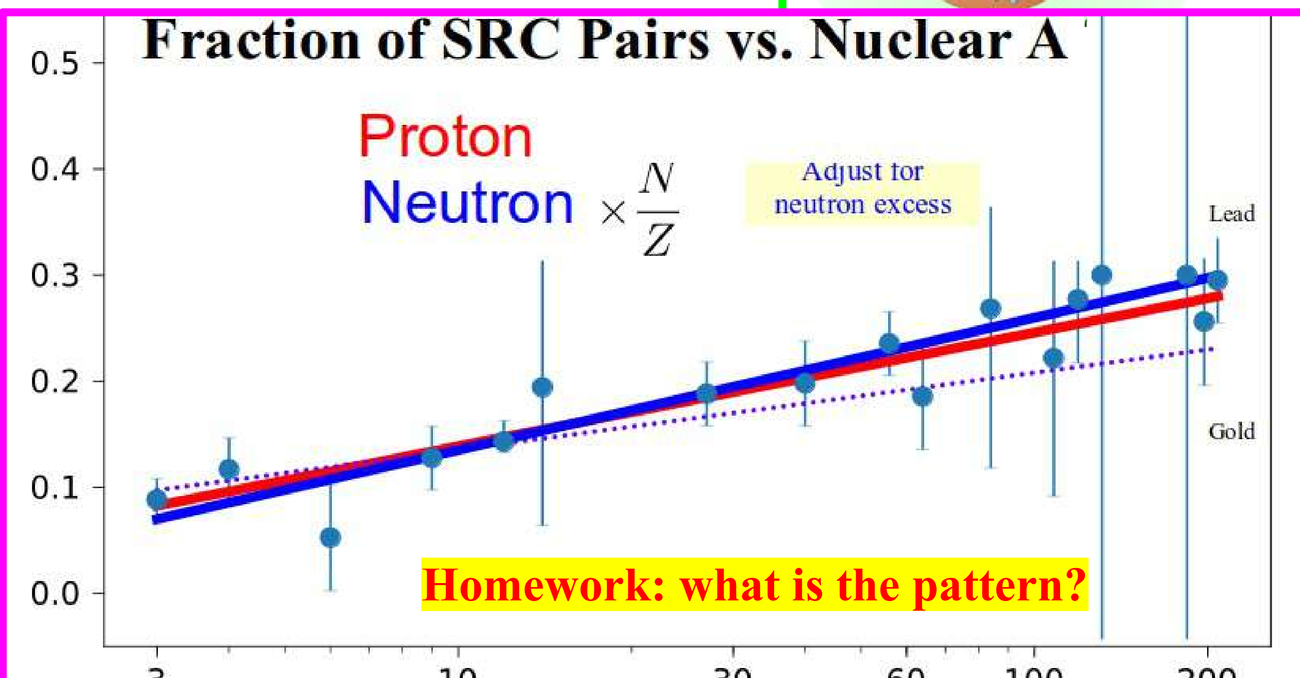
Assembling the puzzle pieces

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?

APFEL++

APFEL++ – A PDF evolution library in c++

Valerio Bertone

Peter Risse

APFEL++

Bertone, arXiv:1708.00911

Available schemes in APFEL++

scheme	$\mathcal{O}(\alpha_s)$		NC: F_2	NC: F_3	NC: F_L		CC: F_2	CC: F_3	CC: F_L
ZM	N2LO		✓	✓	✓		✓	✓	✓
FONLL-C	N2LO		✓	✗	✓		✗	✗	✗
ACOT	NLO		✓	✓	✓		✗	✗	✗
sACOT-χ	NLO		✓	✓	✓		✓	✓	✓
approx. sACOT-χ	N2LO		✓	✓	✓		✓	✓	✓

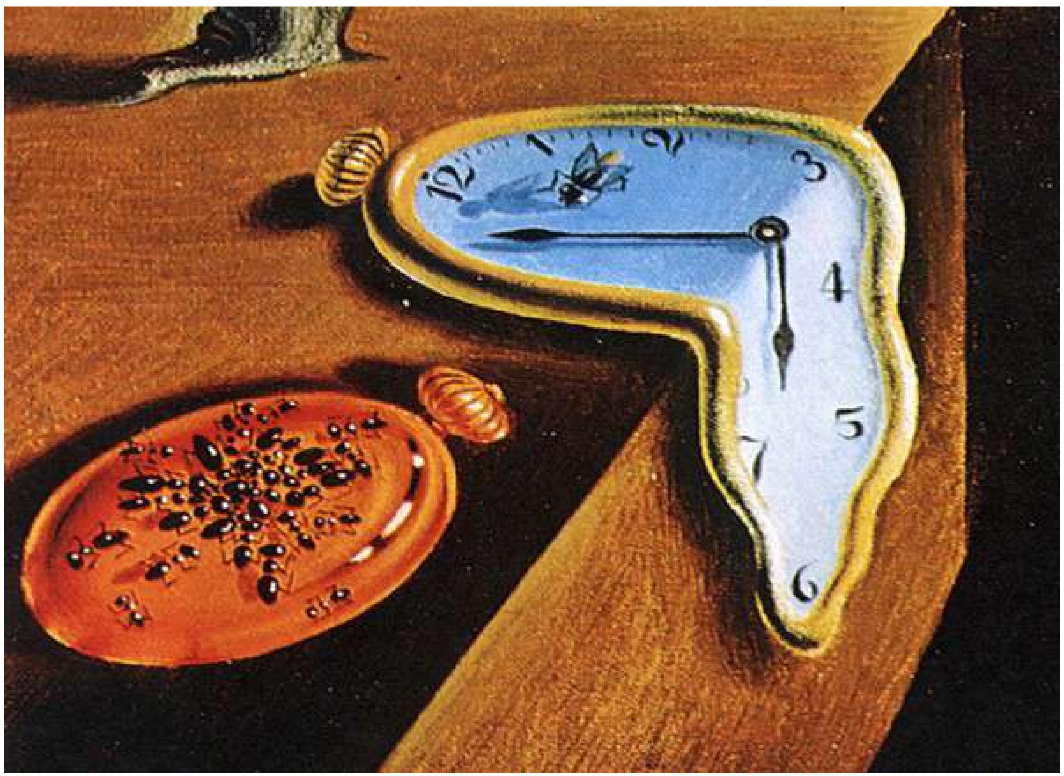
Code benchmark timings:

Original Fortran Code

contains multiple levels of integrals

New C++ Code

using modern grid techniques



Typical fits current run a few days to a week.
This will be reduced to a few hours.

High order DIS processes
(Peter Risse)

Conclusions

Multi-scale problems are hard: Thank you to those computing these results

Proper mass treatment: essential to fit PDFs over large Q scales

Many outstanding issues related to neutrino DIS analysis

Improved calculations can help

Approximate S-ACOT-χ:

leverages N2LO and N3LO results

Neutral Current:

N2LO and N3LO available in xFitter (no grids)

Preliminary

Results with APFEL++ Grids:

<u>BOTH</u> Charged Current & Neutral Current results

Speed increase of ~100×

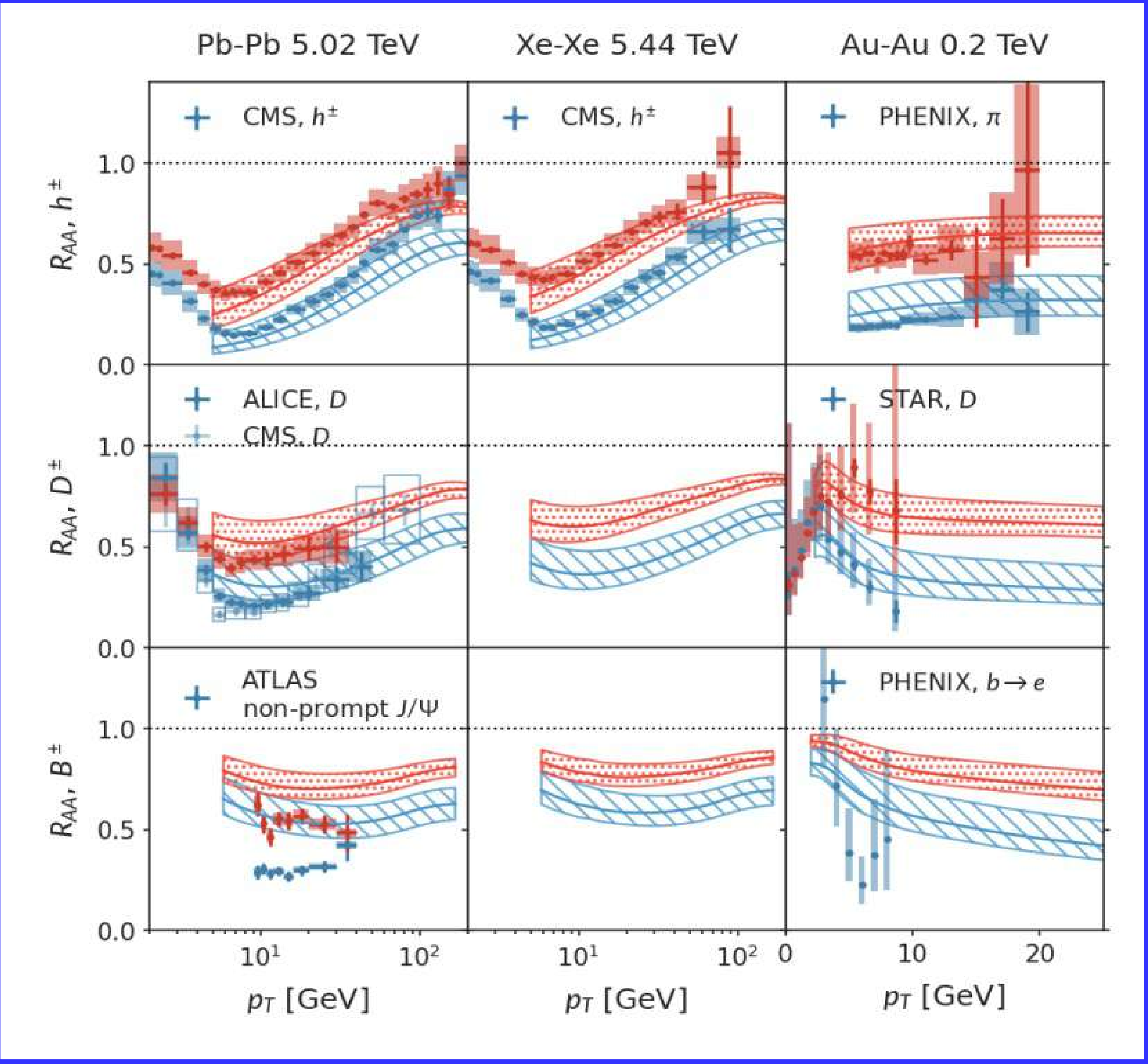
Peter Risse
Valerio Bertone

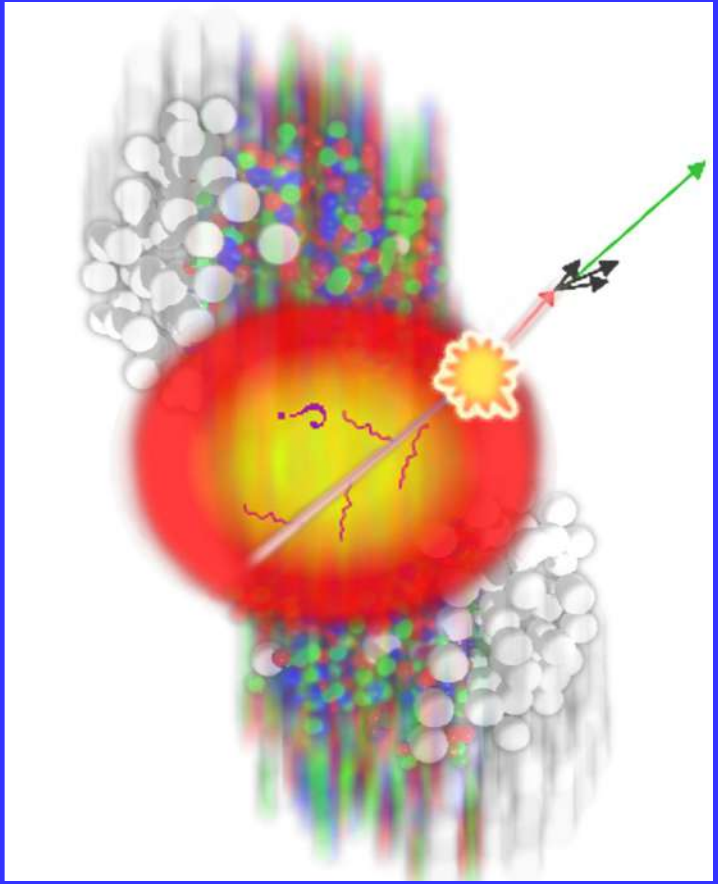
EXTRAS

HEFTY
Q COLLABORATION Q
Texas A&M University Physics and Astronomy

Heavy-Flavor TheorY (HEFTY) for QCD Matter

Jet nuclear modification factor



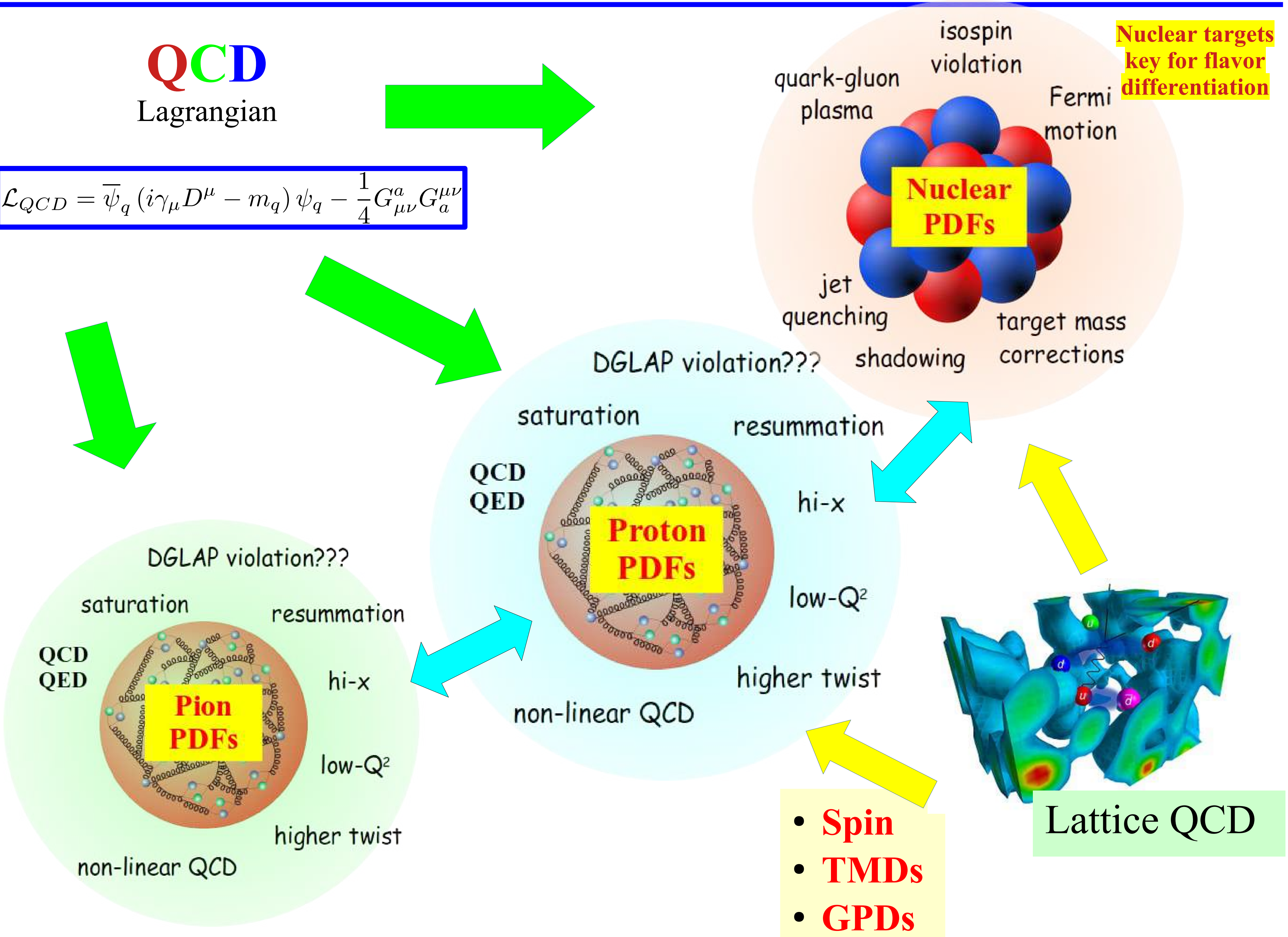


QCD: From PDFs to the underlying QCD

QCD

Lagrangian

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



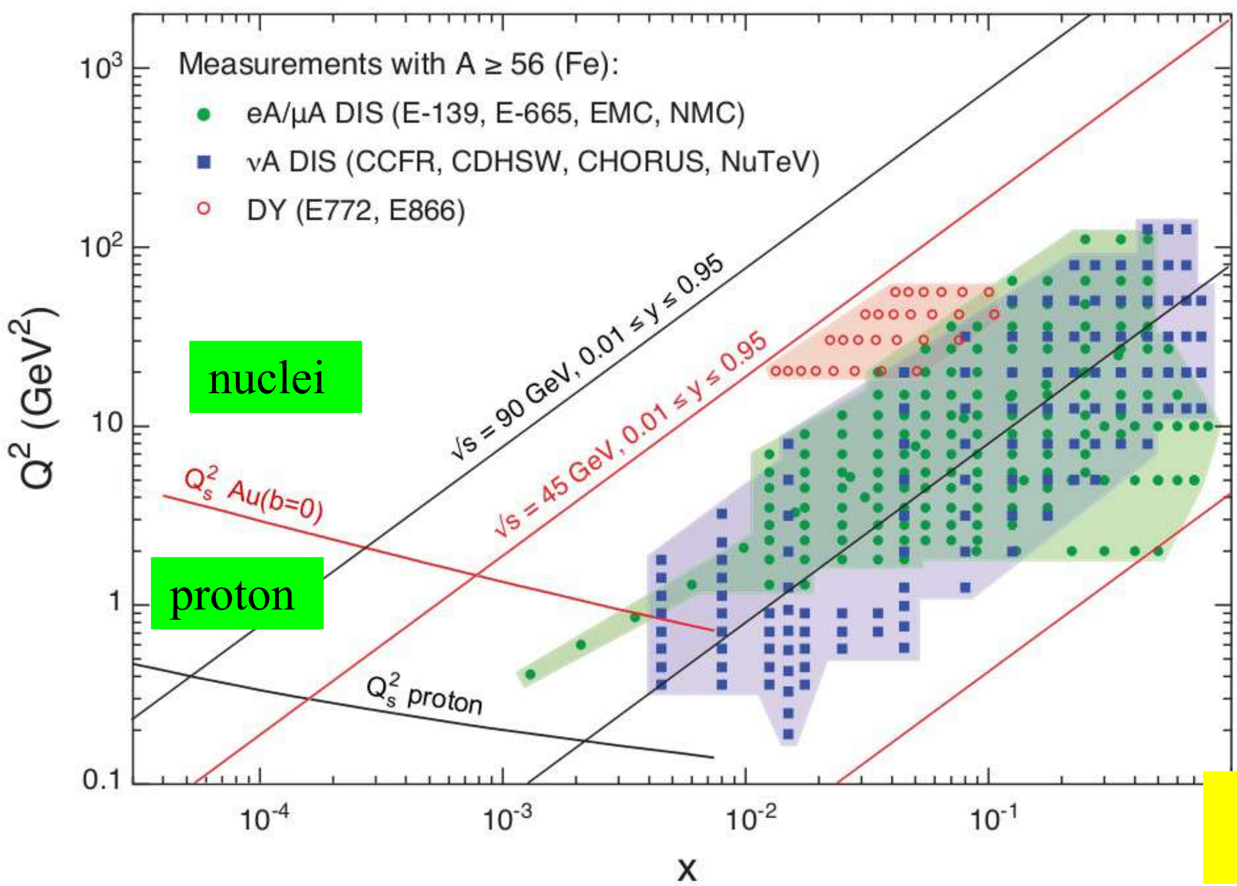
- **Spin**
- **TMDs**
- **GPDs**

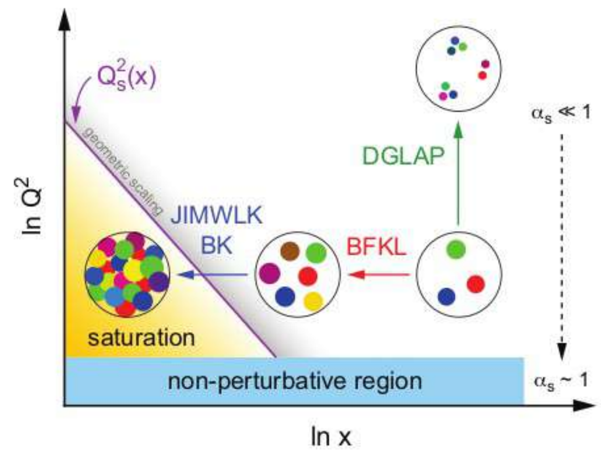
New Phenomena in Corners of Kinematic Plane

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:

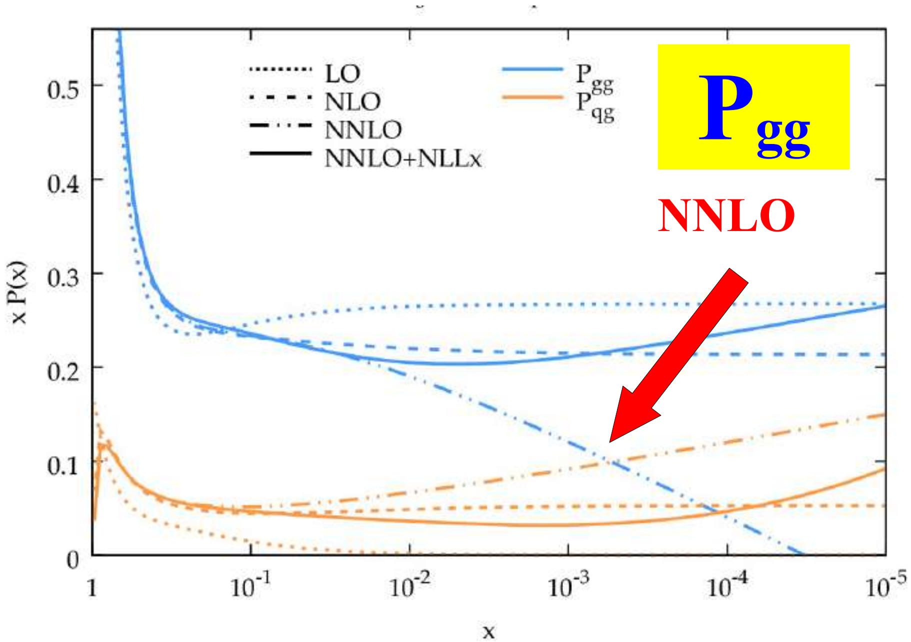


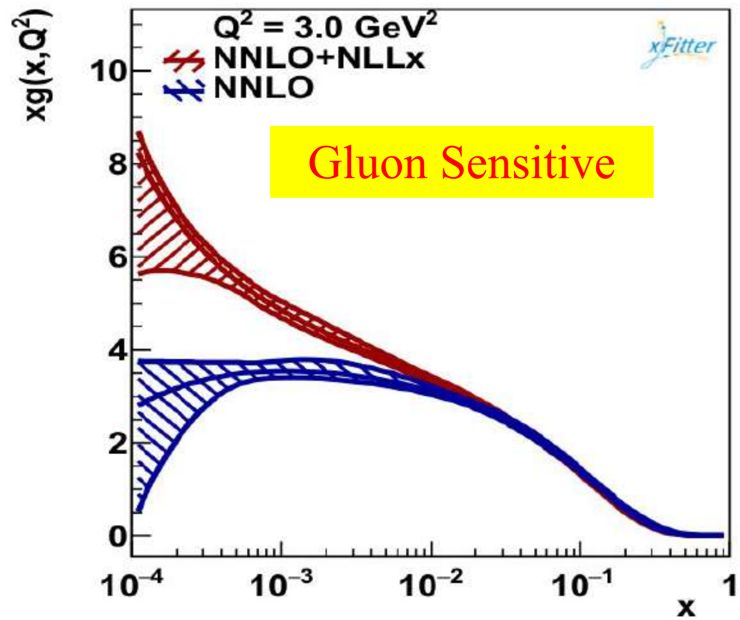


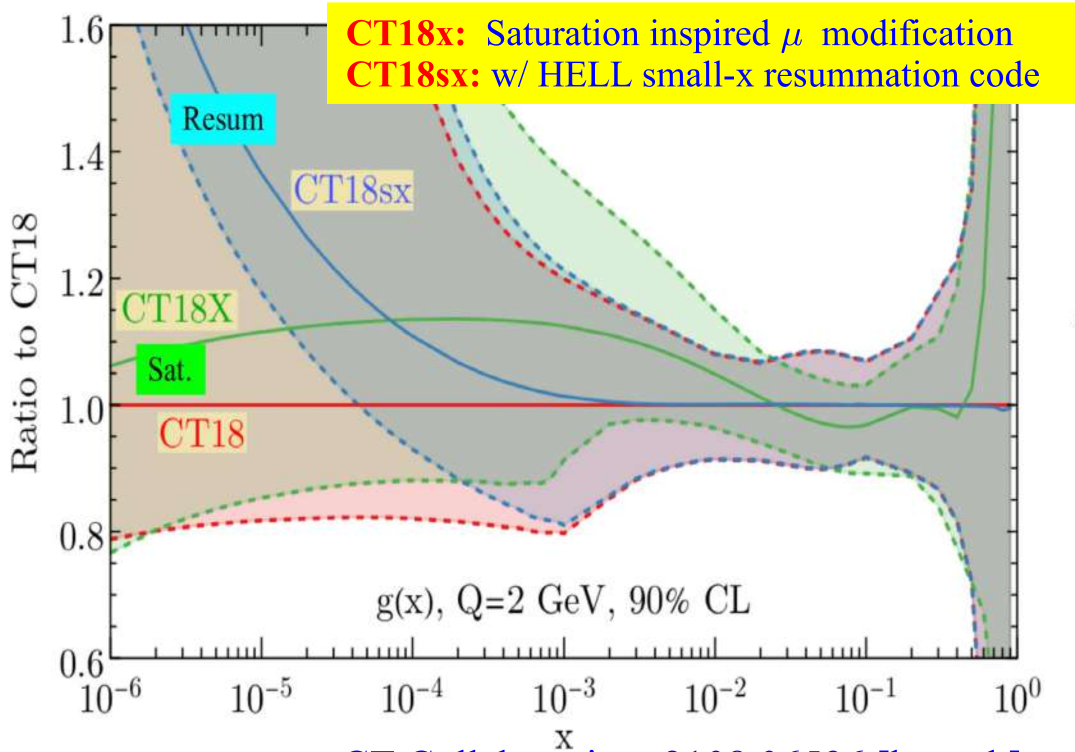
Yuri Kovchegov (OSU)

MC4EIC: Monte Carlo event simulation for the EIC

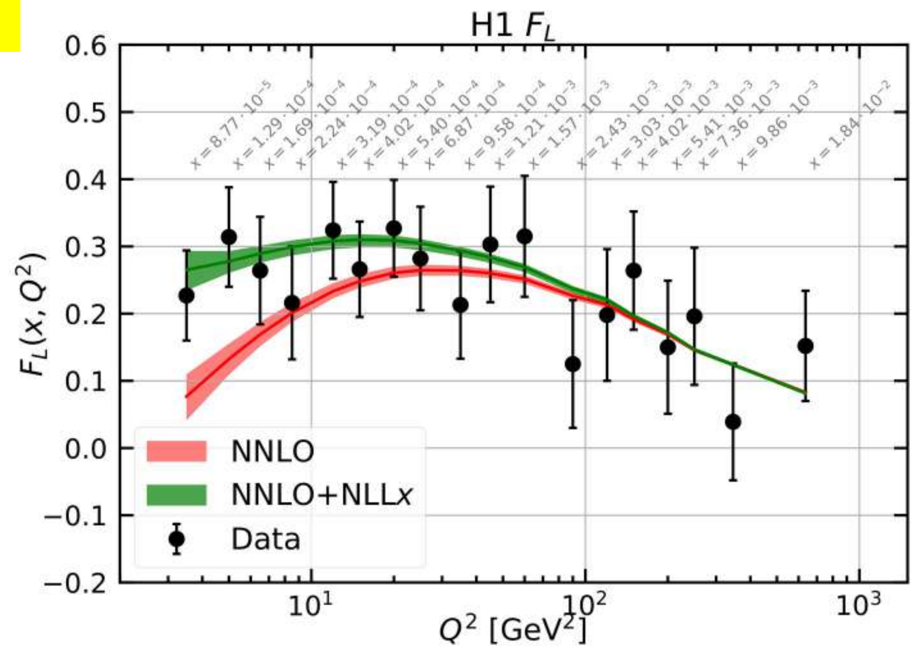
xFitter Resummation Study





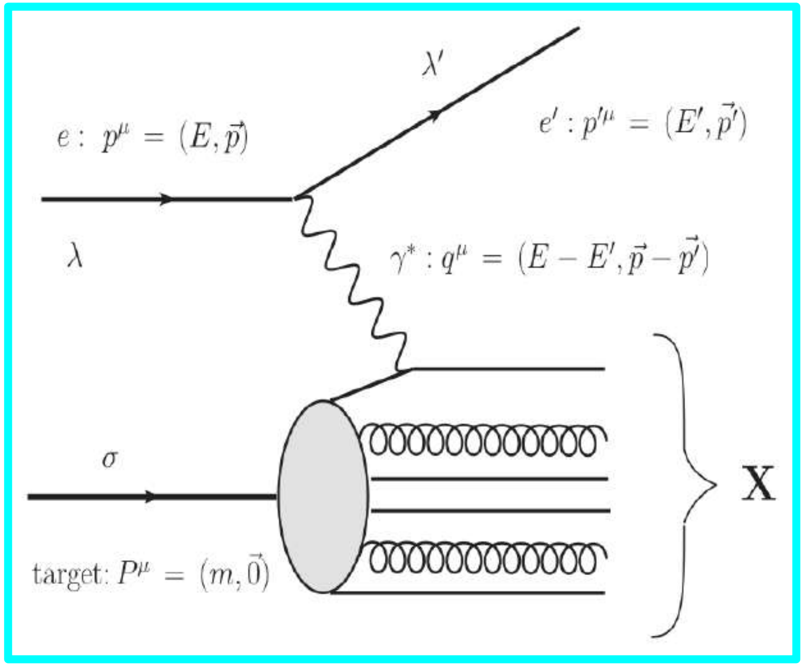


CT Collaboration: 2108.06596 [hep-ph]



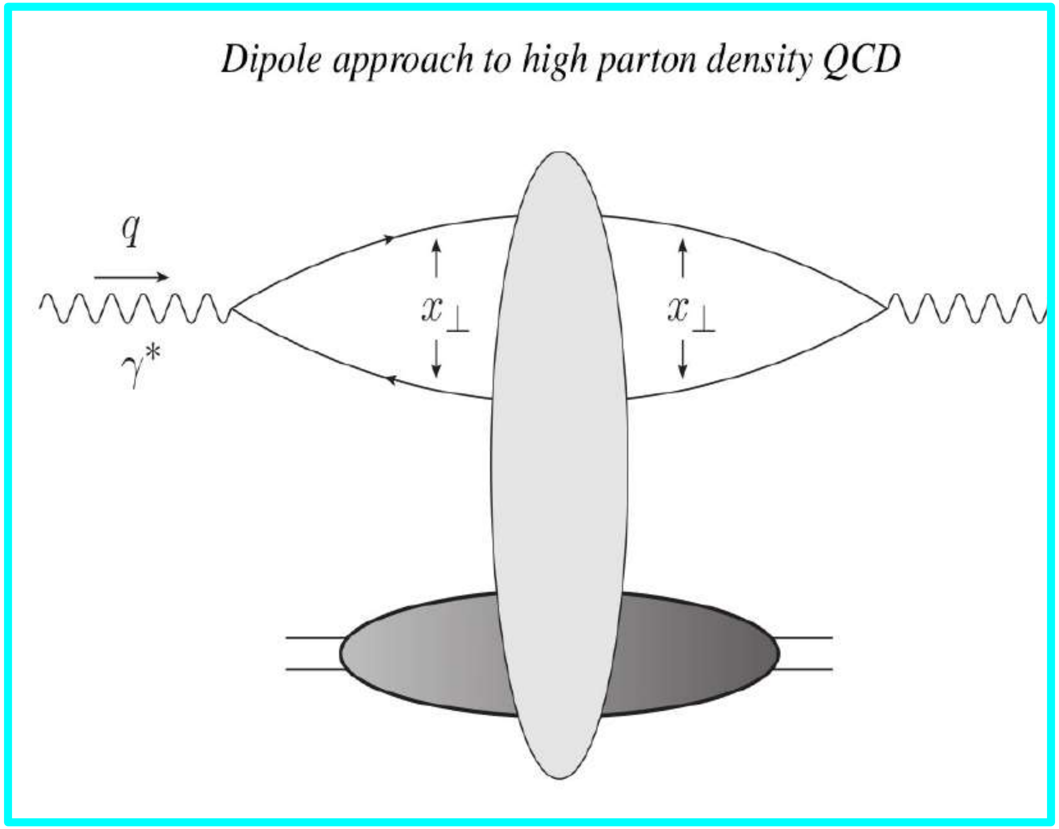
Two approaches to the calculation

Parton Model



$$\sigma = f(x, Q) \otimes \widehat{\sigma}$$

Dipole



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

nPDF Wish List

nCTEQ
nuclear parton distribution functions

www.ncteq.org

nPDF General Issues:

- Proton PDF; nuclear corrections for interpreting heavy target DIS (Ar, Fe, Pb).

Strange quark & Gluon PDF:

- Resolve tension between fixed-target (νN, ℓN) and collider expectations ($W^{\pm}$,Z)

Charm & Bottom: c(x) & b(x)

- Multi-scale & resummation issues: $\mathrm{Log}(m_{c,b}/Q)$
- "Fitted" charm: $c(x)\neq 0$ at m_c
- Intrinsic heavy flavors: $c(x)\neq 0$ at $Q<m_c$

Neutrino cross sections on heavy targets (Ar, Fe, Pb)

- Universality of Neutral Current (γ) & Charged Current ($W^{\pm}$) processes

Expanded $\{x,Q^2\}$ Kinematic Regime

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

Compilation by Fred Olness with helpful feedback from: Alberto Accardi, Tim Hobbs, Tomas Jezo, Thia Keppel, Michael Klasen, Karol Kovarik, Aleksander Kusina, Jorge Morfin, Pavel Nadolsky, Jeff Owens, Ingo Schienbein, Efrain Segarra, Steve Sekula, Ji-Young Yu

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