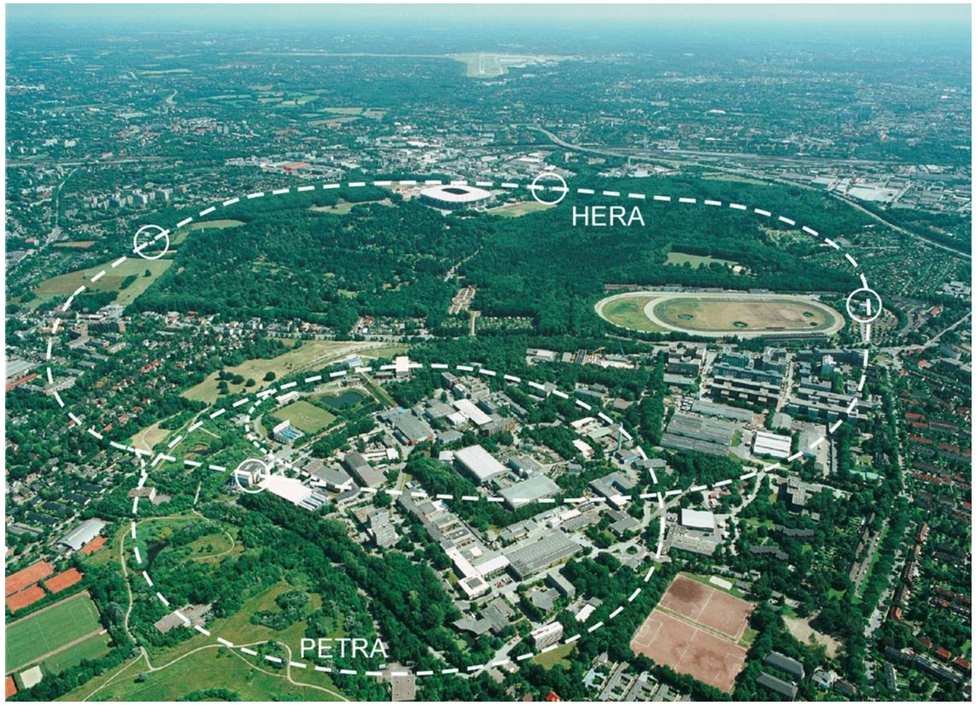
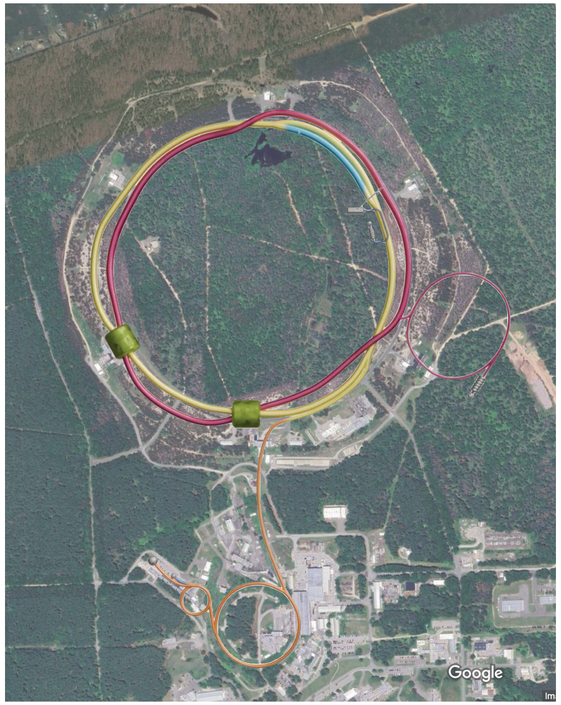
Nucleon and nuclear PDFs, from HERA to EIC

Tyler Kutz
JGU Mainz

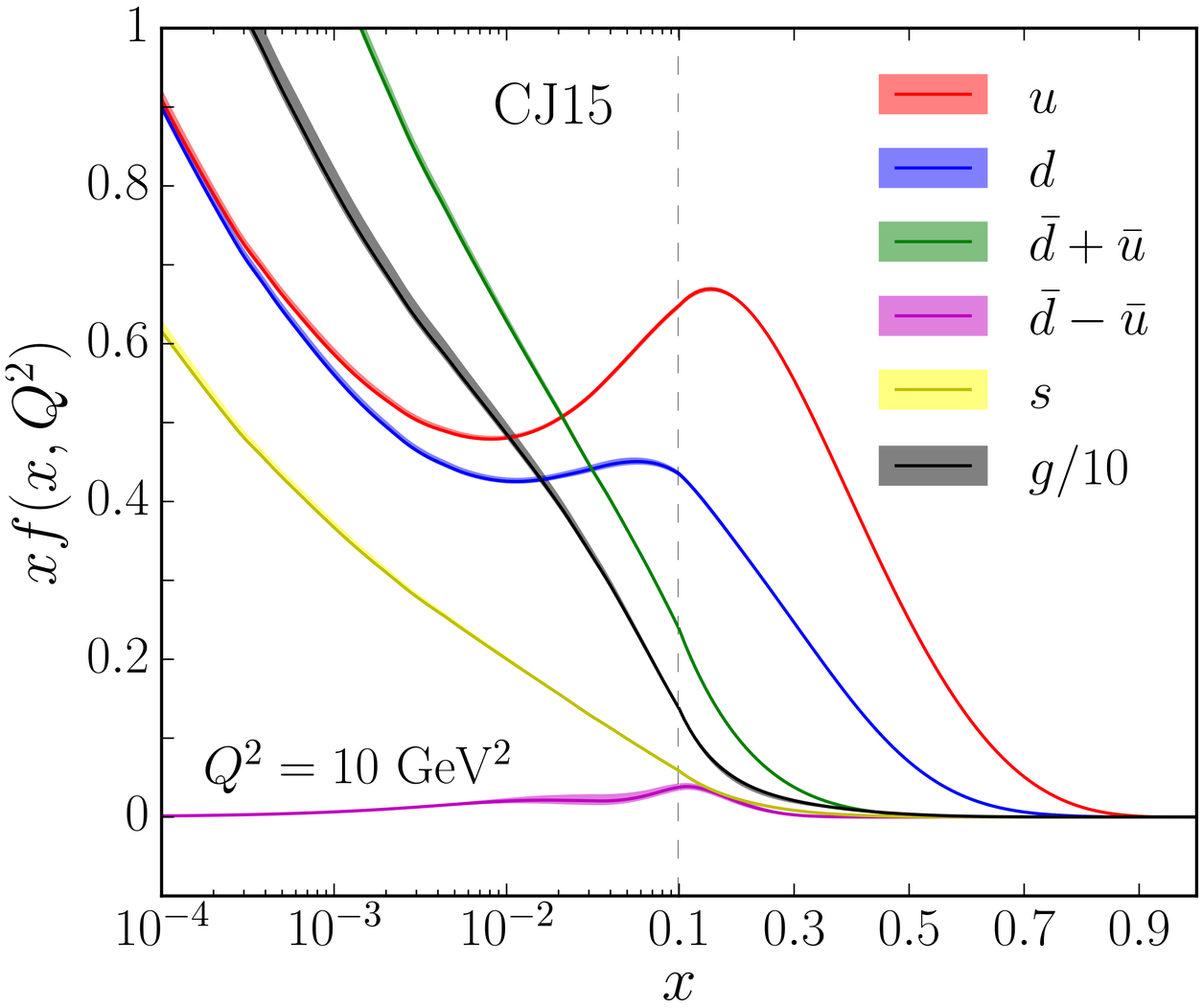




62nd International Winter Meeting on Nuclear Physics
January 19-23, 2026
Bormio, Italy

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

What are parton distribution functions (PDFs)?



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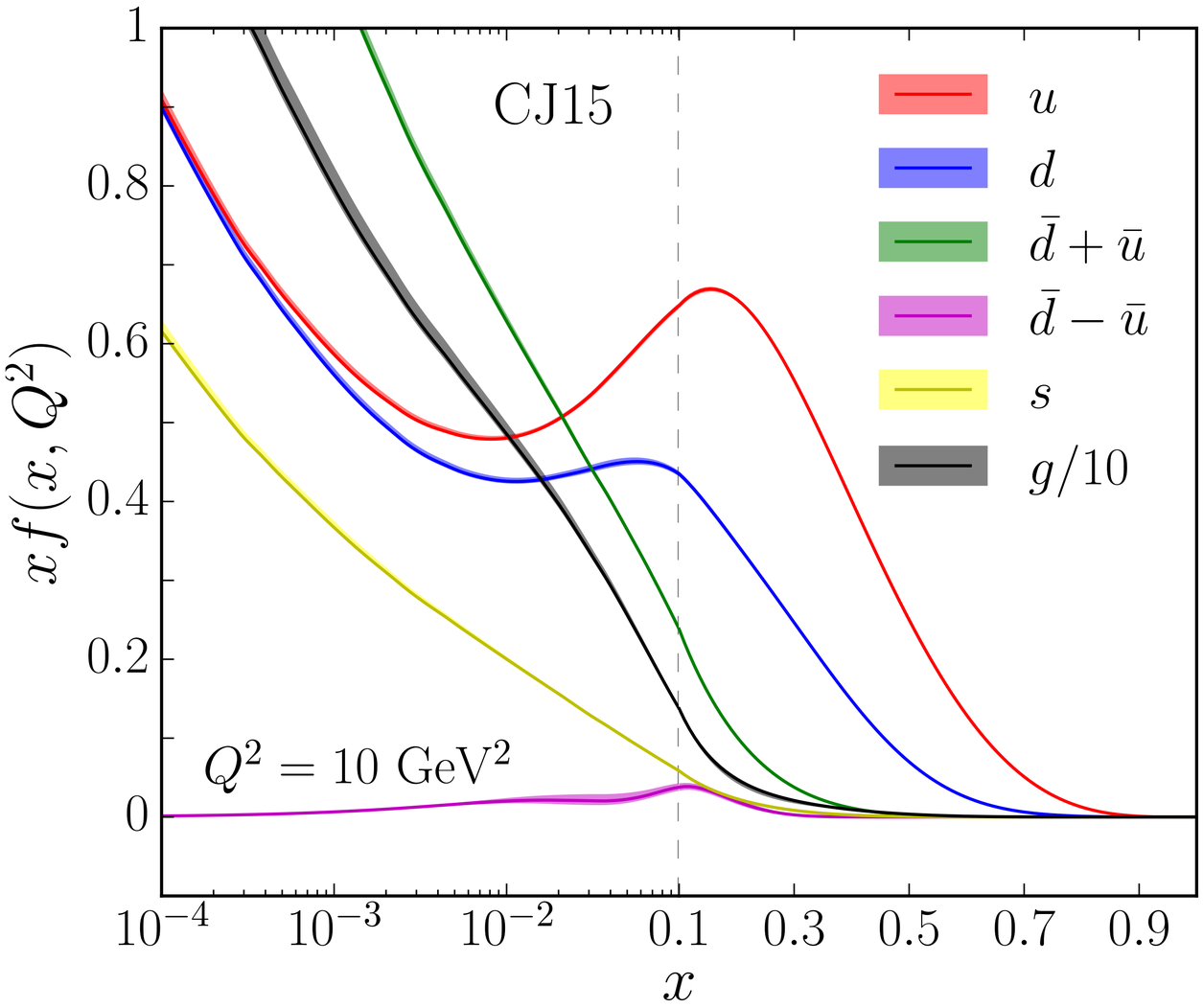

- Distribution of *longitudinal* momentum fraction

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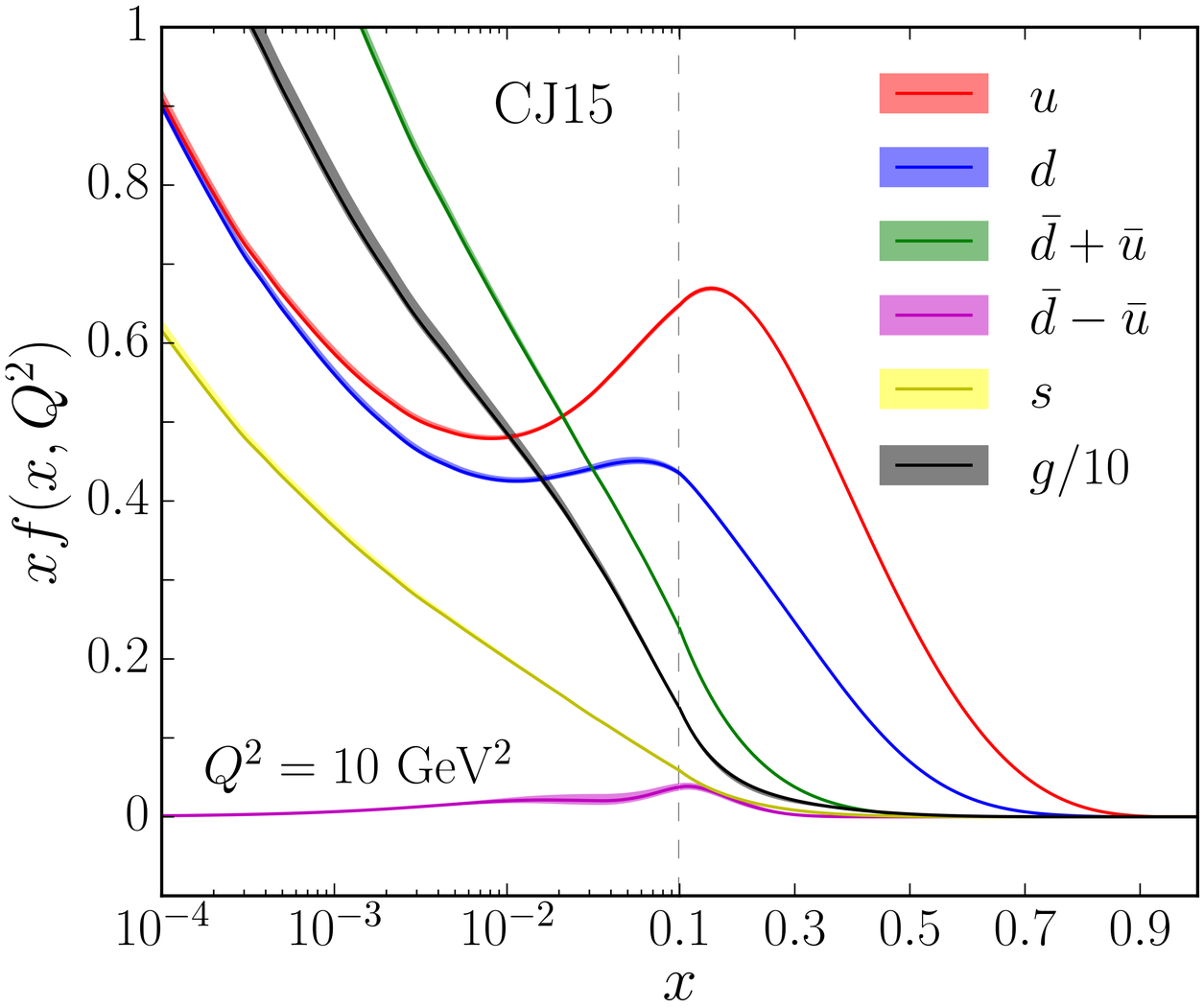

- Distribution of *longitudinal* momentum fraction
- Quark parton model:
  → Depend only on x (scaling)

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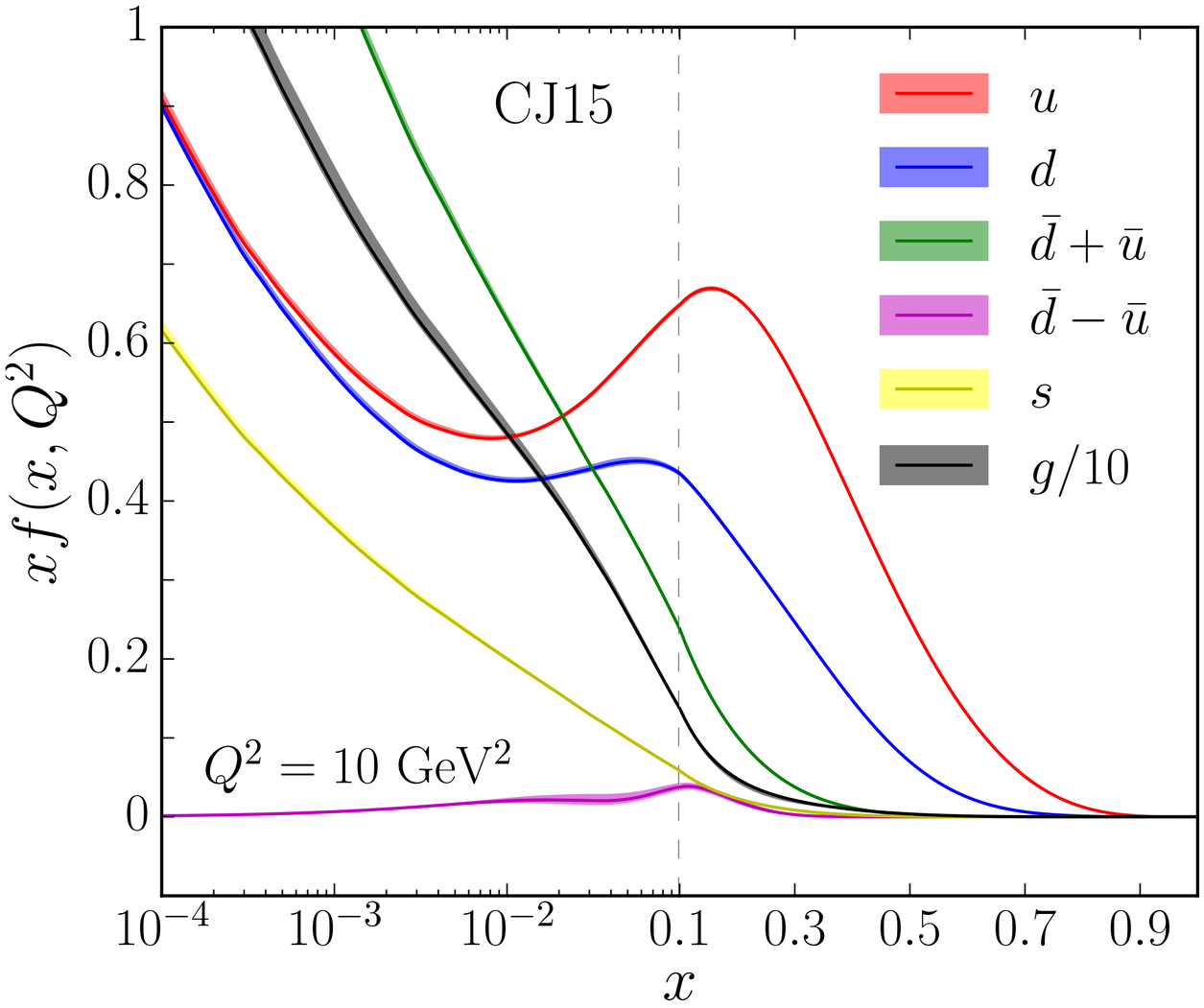

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  → Q^2 dependence (scaling violation)

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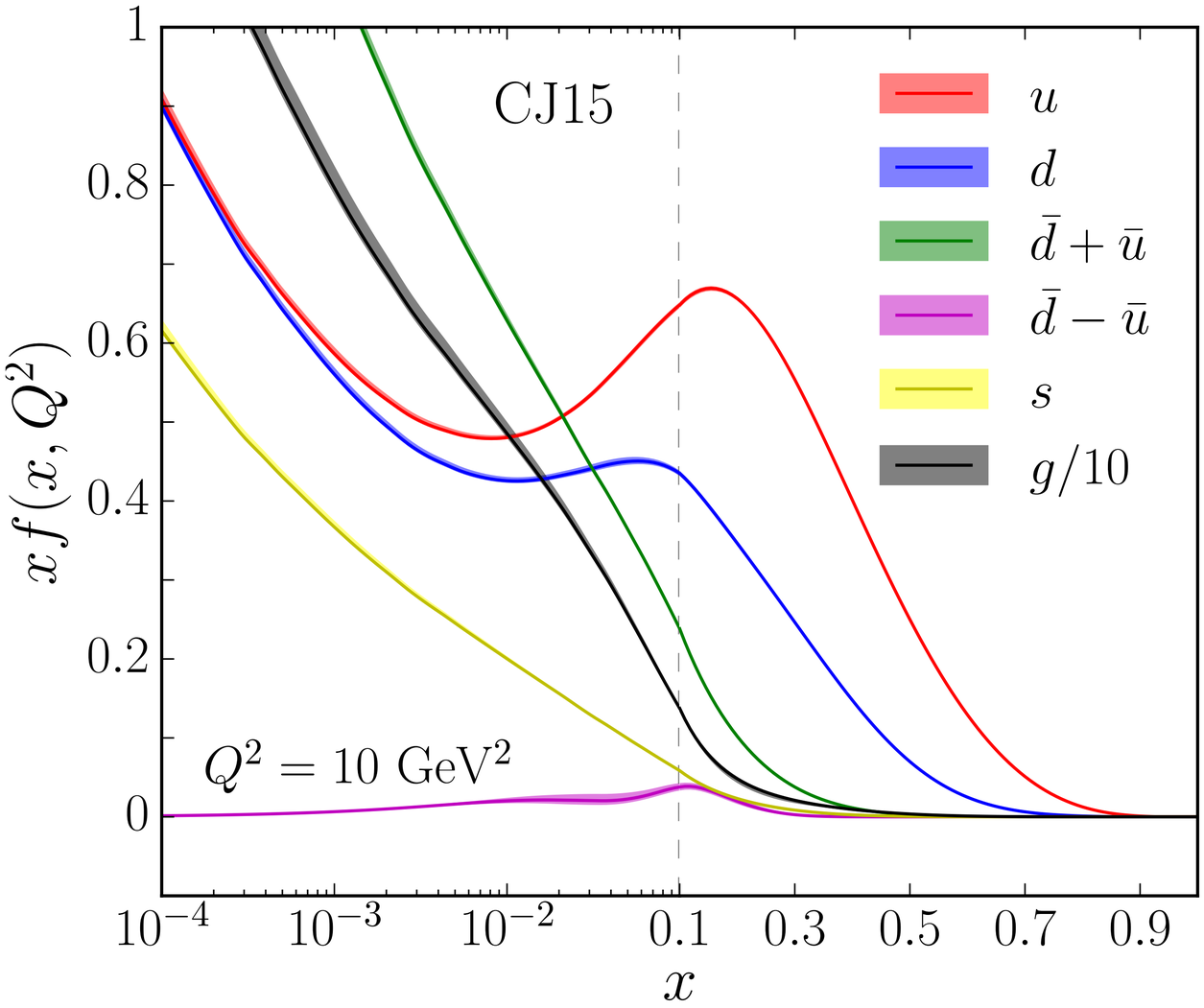
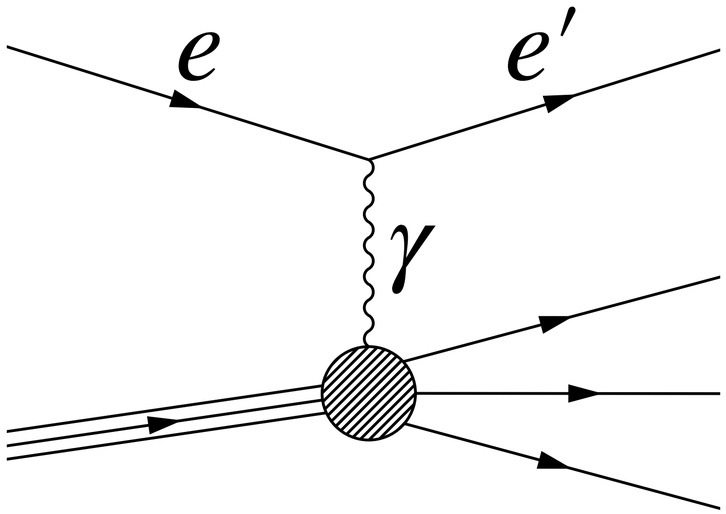


- Distribution of *longitudinal* momentum fraction
- Quark parton model:
  → Depend only on x (scaling)
- Quantum chromodynamics:
  → Q^2 dependence (scaling violation)
- *Most accessible* way to describe parton structure of hadrons

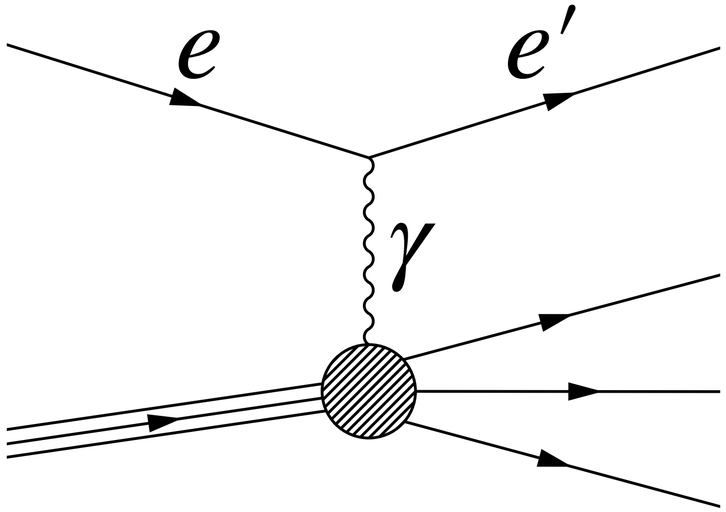
Inclusive deep inelastic scattering probes sum of PDFs



- High energy lepton incident on hadron target
- Reconstruct x and Q^2 from scattered lepton

$$\sigma_{DIS} \propto F_2\left(x, Q^2\right) = x \sum_i e_i^2 \left[q_i\left(x, Q^2\right) + \overline{q}_i\left(x, Q^2\right)\right]$$

Inclusive deep inelastic scattering probes sum of PDFs



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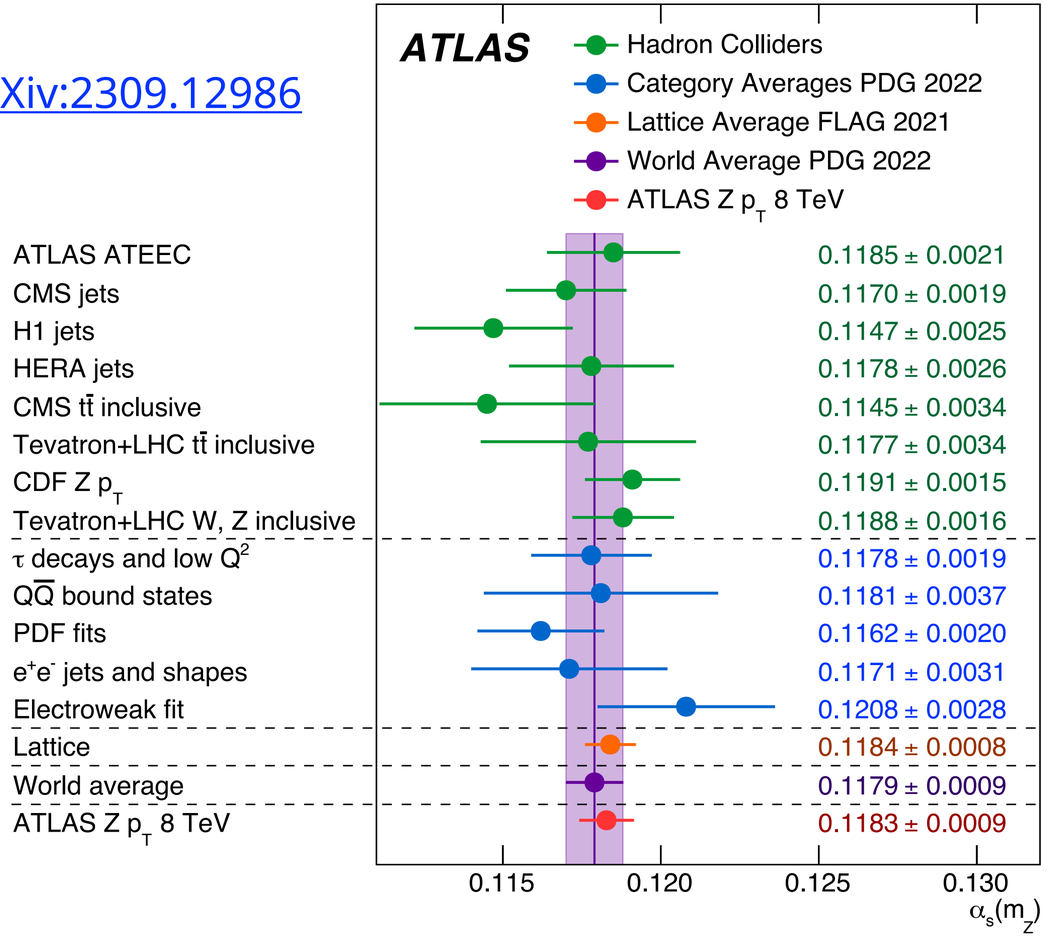
PDFs are *fundamental* to describing the emergence of nuclear properties from QCD…

…and are *limiting factors* to precision LHC measurements

arXiv:2309.12986



δ_{tot} = 0.0009

δ_{PDF} = 0.0005

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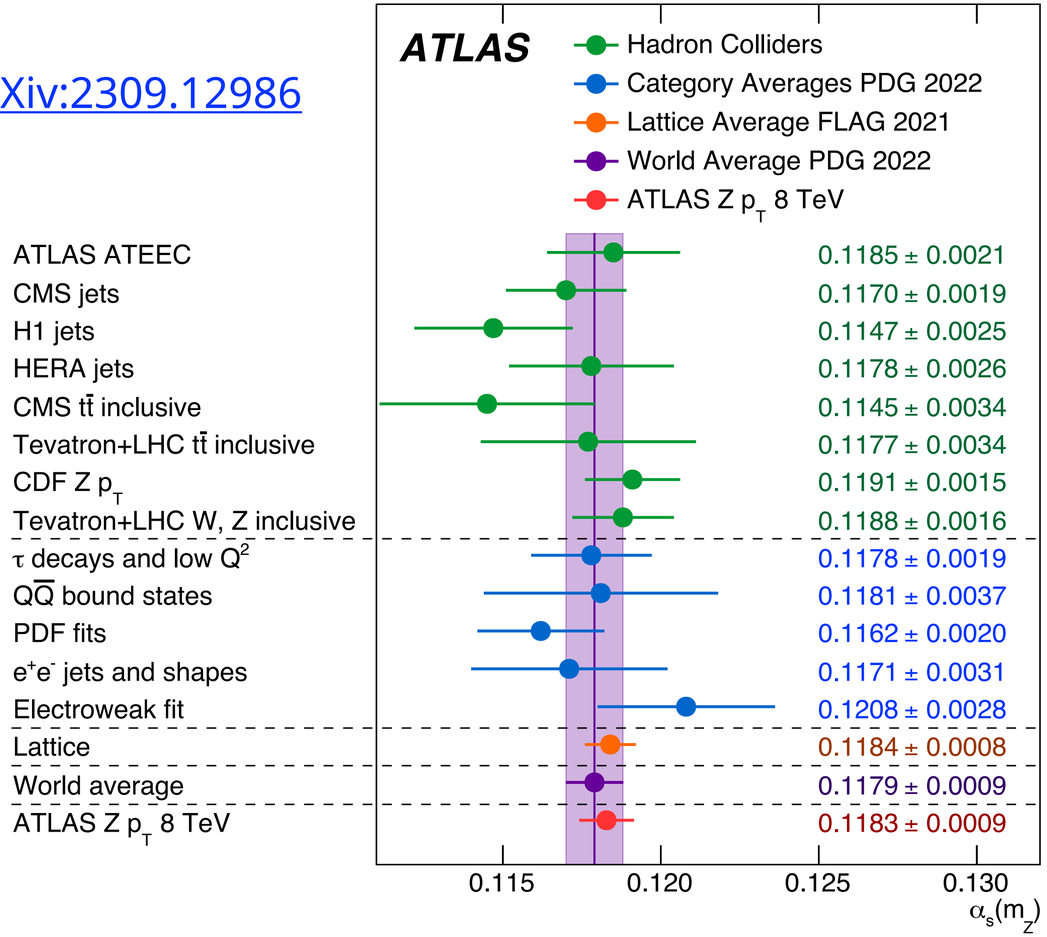
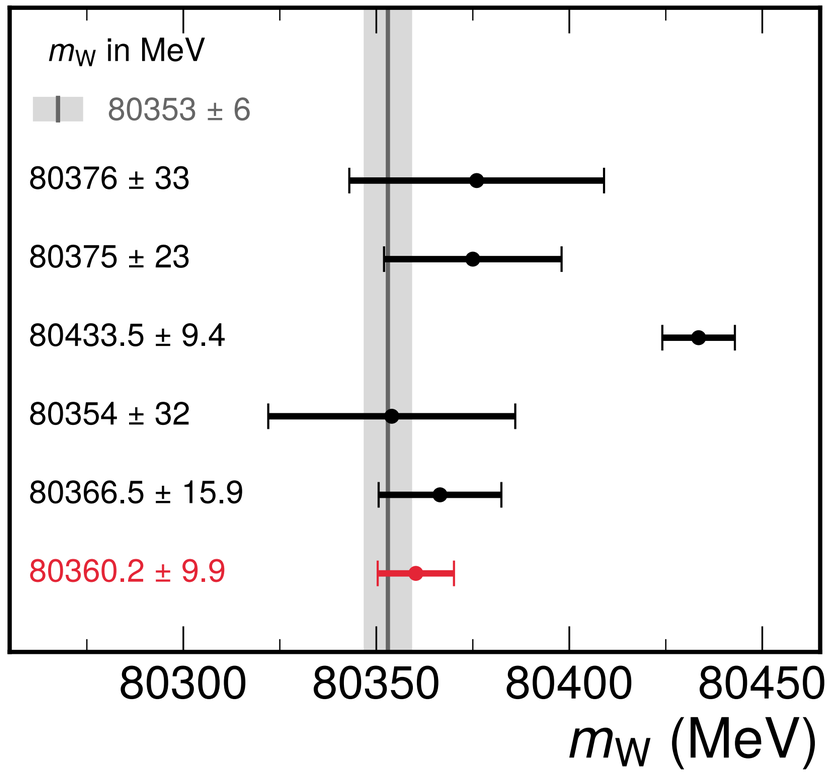


δ_{tot} = 0.0009

δ_{PDF} = 0.0005

Electroweak fit
PRD 110 (2024) 030001
LEP combination
Phys. Rep. 532 (2013) 119
D0
PRL 108 (2012) 151804
CDF
Science 376 (2022) 6589
LHCb
JHEP 01 (2022) 036
ATLAS
arXiv:2403.15085
CMS
This work

arXiv.2412.13872



δ_{tot} = 9.9 MeV

δ_{PDF} = 4.4 MeV

Recipe for PDFs

Recipe for PDFs

Experimental data

Ever-growing set of constraints on PDF fits

Recipe for PDFs

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Theory

N^{n}LO, heavy quarks, EW/QED corrections, initial photon…

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N^nLO, heavy quarks, EW/QED corrections, initial photon…

Methodology

Parameterization, uncertainty propagation, minimization procedure…

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N^nLO, heavy quarks, EW/QED corrections, initial photon…

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Parameterization, uncertainty propagation, minimization procedure…

Accurate, precise PDFs with robust uncertainties

End result limited by the quality of ingredients

- DIS data is the backbone of all modern PDF determinations

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- Hadron collisions provide *important constraints* on PDFs but cannot *precisely determine* them

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Today I will focus on DIS constraints on PDFs, with an emphasis on the legacy of HERA and expected impact of the EIC

The pre-HERA DIS landscape

Probes

- Electrons (SLAC)
- Muons (BCDMS, BFP, EMC)
- Neutrinos (BEBC, CDHSW, CCFRR, CHARM)

Targets

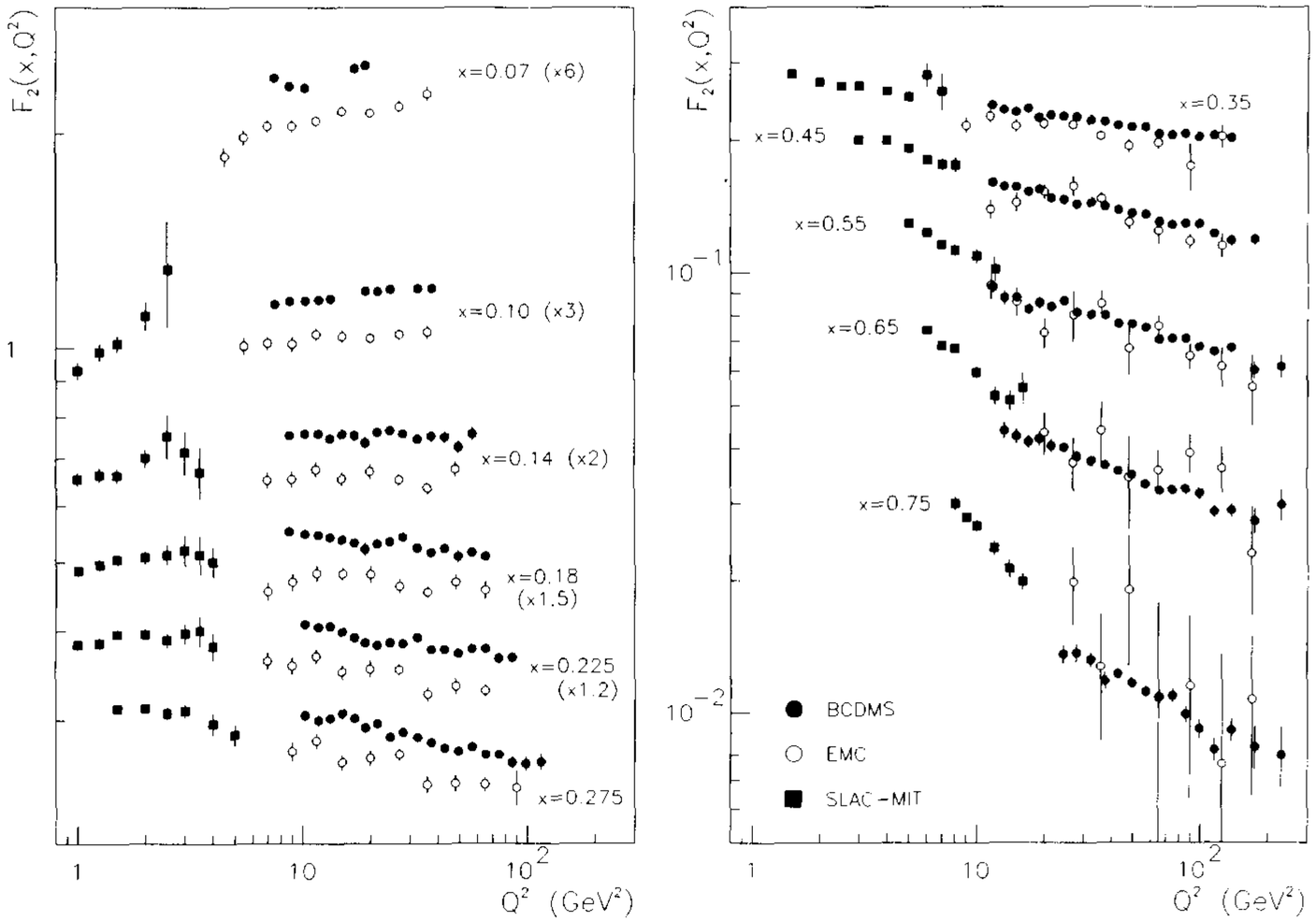
- Leptons: proton, nuclear targets
- Neutrinos: heavy nuclear targets

Kinematics

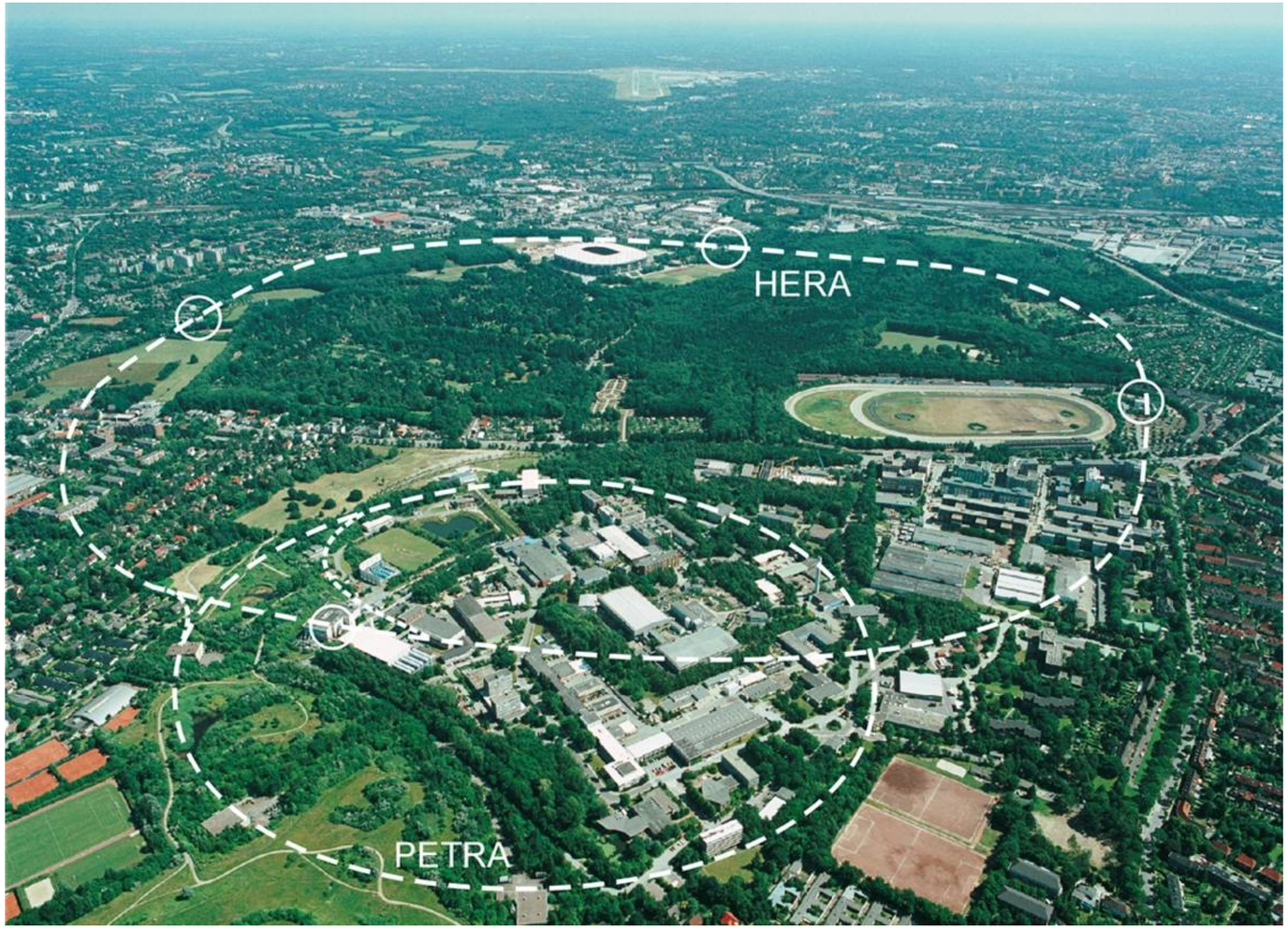
- Fixed target
- Q^2 up to ~200 GeV^2
- x in valence region

BCDMS

PLB 223, 485 (1989)



HERA at DESY (Hamburg, Germany)

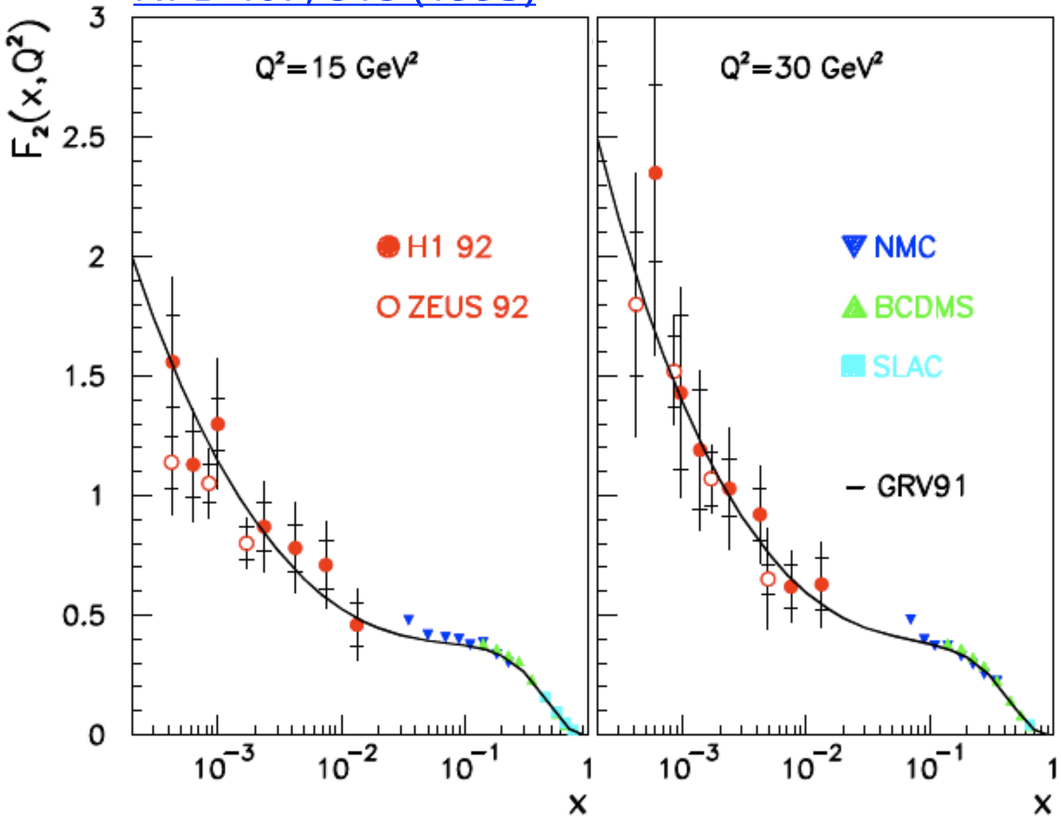


- First (and to-date, only) $e^{\pm}p$ collider
- First collisions in 1991, first physics data in 1992, operated until 2007
- Polarized leptons
- $\sqrt{s}$ up to 320 GeV → fixed-target equivalent of *tens of TeV* electron beam
- Two complementary detectors (H1 and ZEUS)
- HERA I+II combined results includes total luminosity of 200 pb^{-1} ($e^{+}p$), 30 pb^{-1} ($e^{-}p$)

HERA's impactful early discoveries

PLB 316, 412 (1993)

NPB 407, 515 (1993)



Steep rise in F_2 at low x

- Not unexpected, but onset scale was unknown
- Confirmed role of gluons at low x

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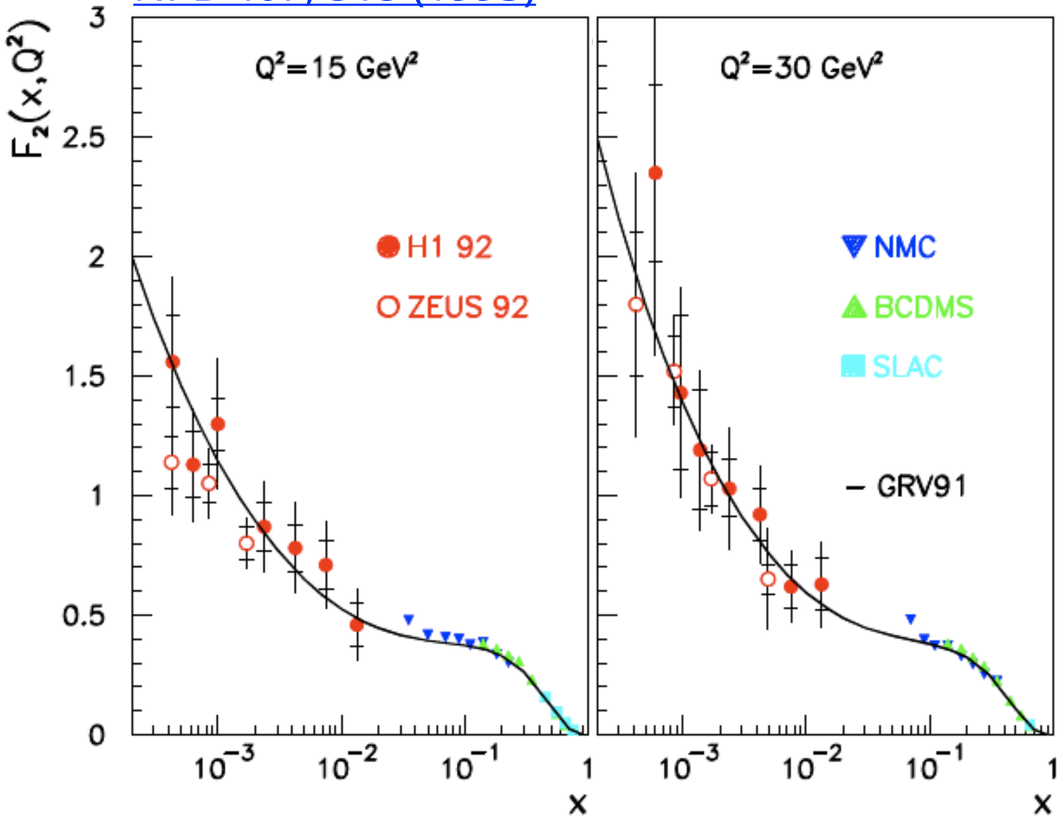

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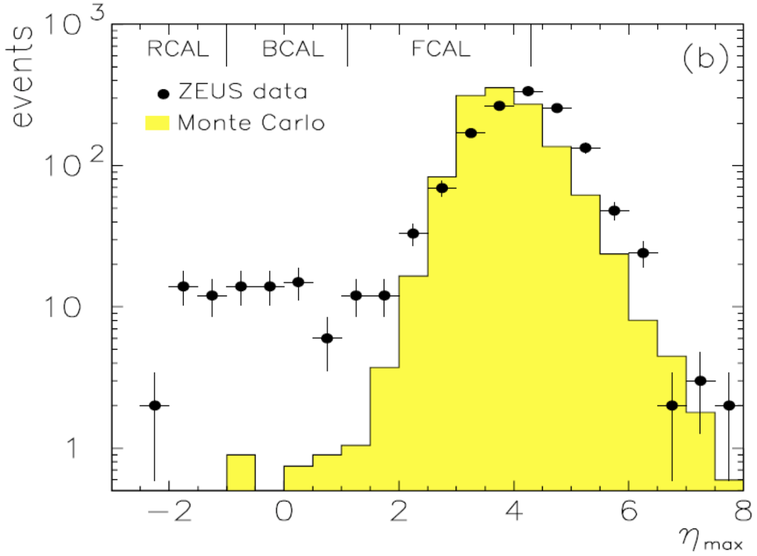
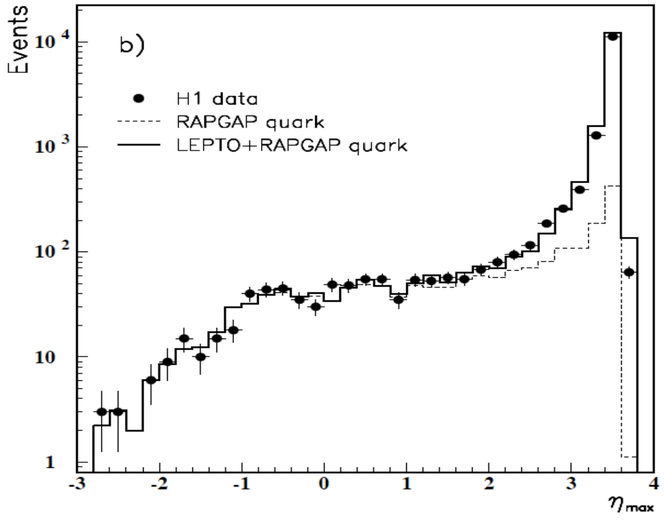
DESY 93-093

DESY 94-133





Diffractive DIS

- ~10% of events with intact proton
- Important to account for in PDF analyses

HERA I+II (H1 and ZEUS) data set

Eur. Phys. J. C (2015) 75:580
DOI 10.1140/epjc/s10052-015-3710-4

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

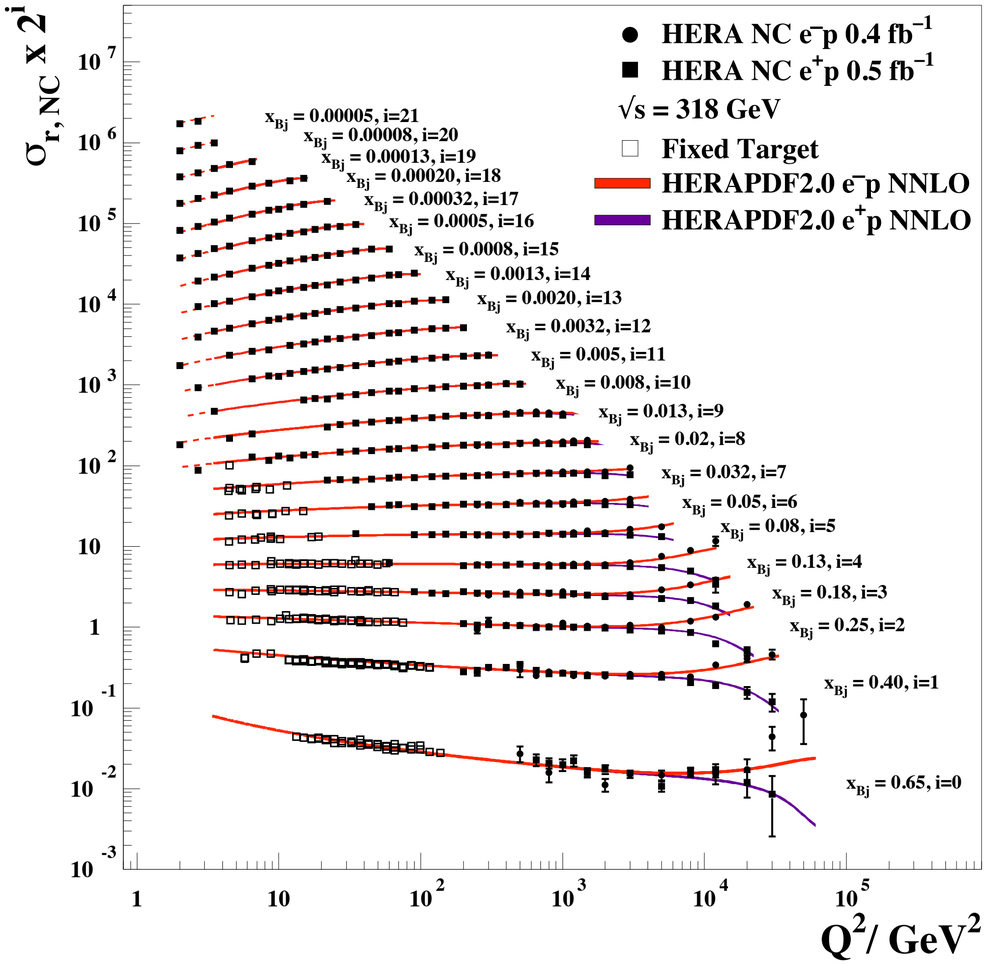
Combination of measurements of inclusive deep inelastic $e^{\pm}p$ scattering cross sections and QCD analysis of HERA data

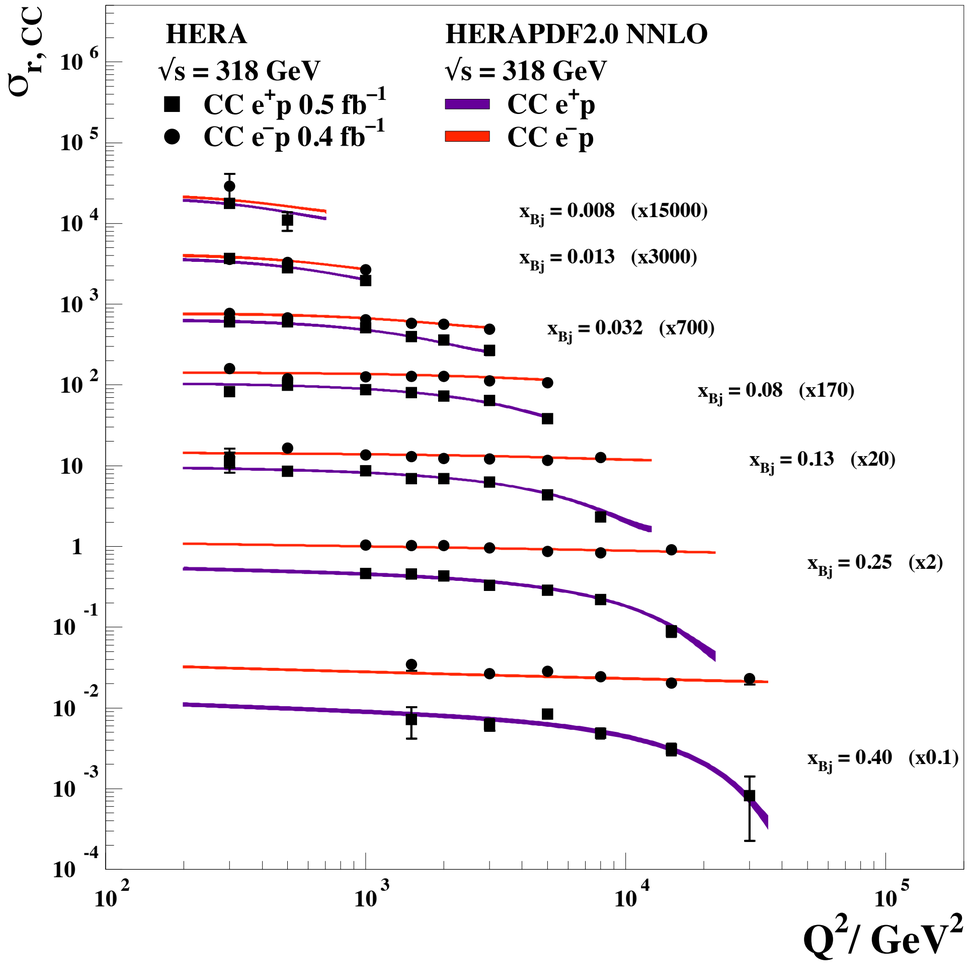
This paper is dedicated to the memory of Professor Guido Altarelli who sadly passed away as it went to press. The results which it presents are founded on the principles and the formalism which he developed in his pioneering theoretical work on Quantum Chromodynamics in deep-inelastic lepton-nucleon scattering nearly four decades ago

H1 and ZEUS Collaborations

- Combined analysis of approximately 230 pb^{-1} of $e^{\pm}p$ collisions
- Independence and complementary of H1 & ZEUS make combination more powerful than simply averaging results

Neutral- and charged-current $e^{\pm}p$ cross sections



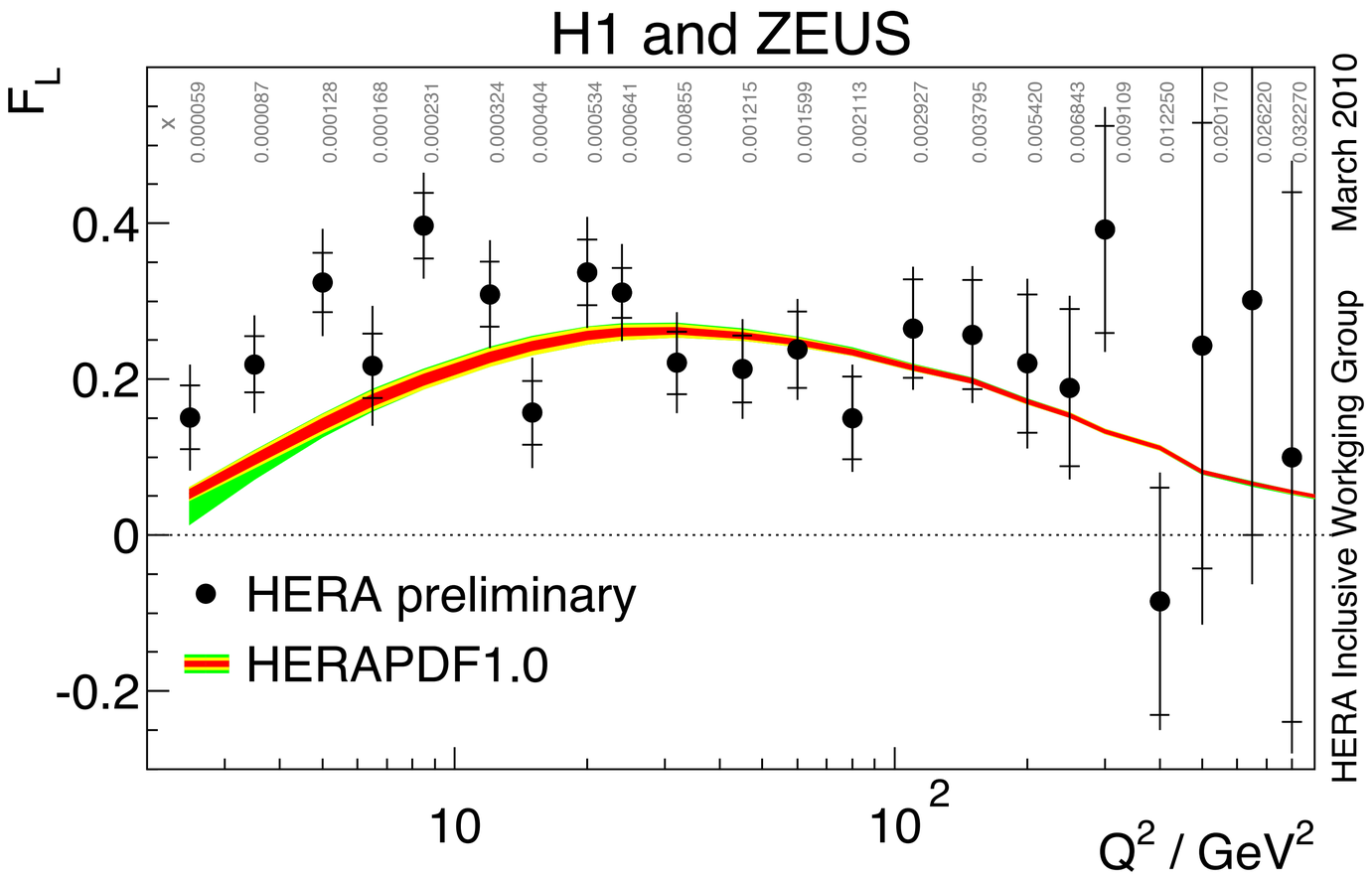


- High precision, systematic study of proton structure
- Enhanced flavor separation with $e^{\pm}$, CC DIS

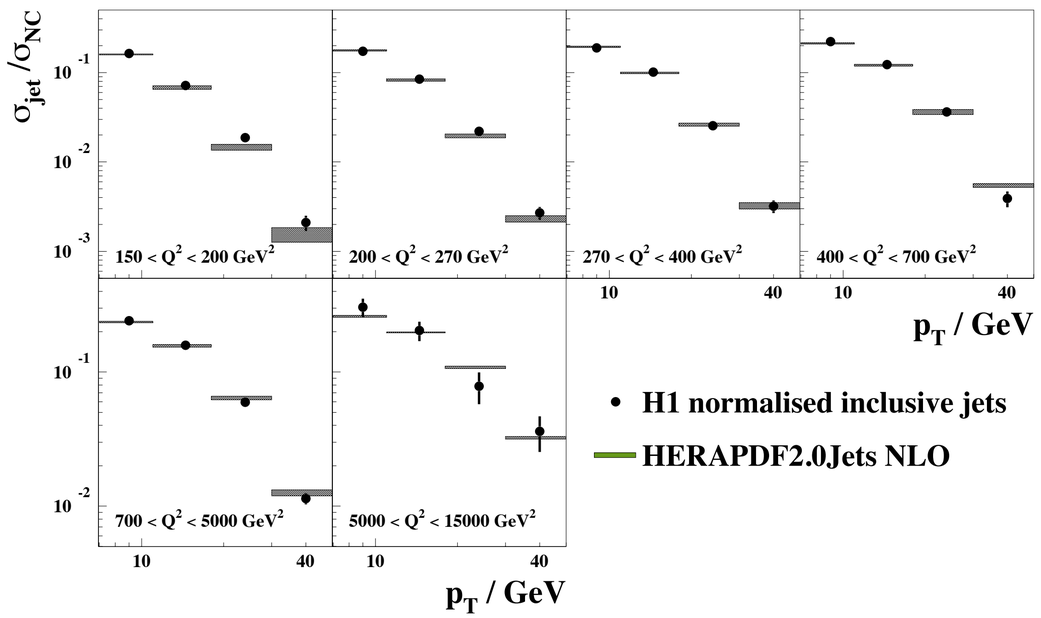
Extraction of longitudinal structure function

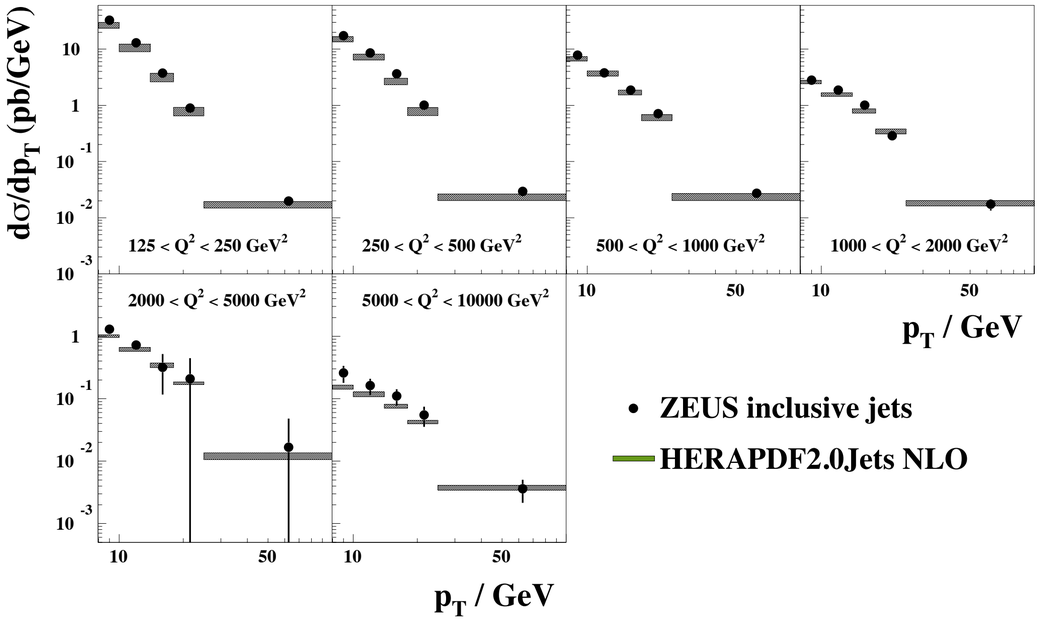
arXiv.1010.1023

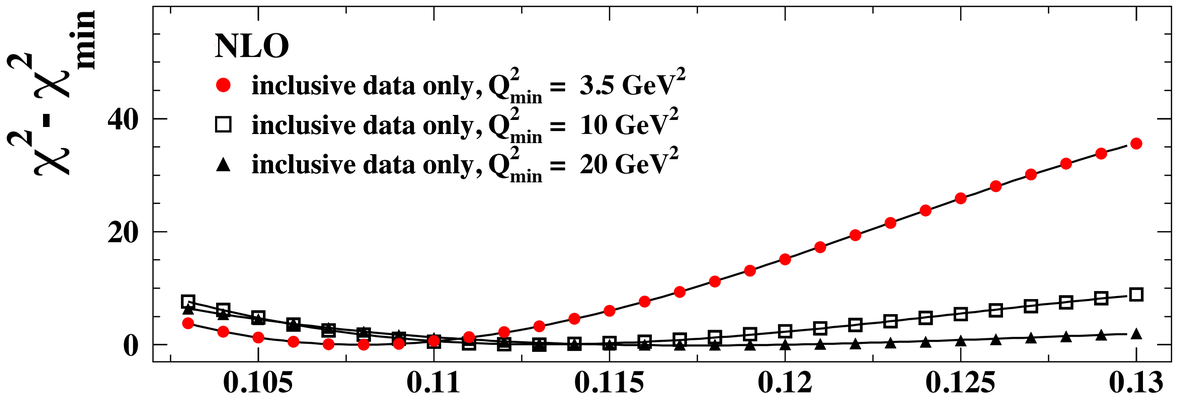
- Technically challenging analysis: requires precise cross sections with fixed (x, Q^2) at multiple y
- Strongly related to gluon PDF: F_L = 0 in QPM
- Test of pQCD: nonzero F_L at low x

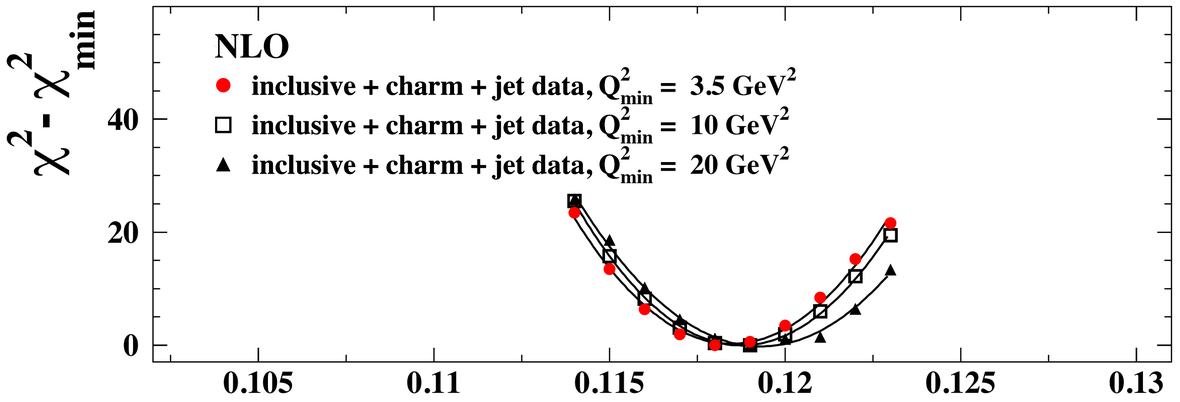


Jet production and α_S



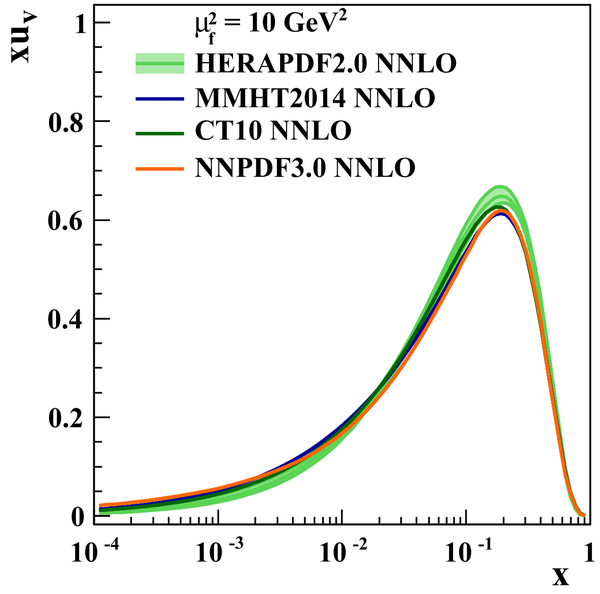


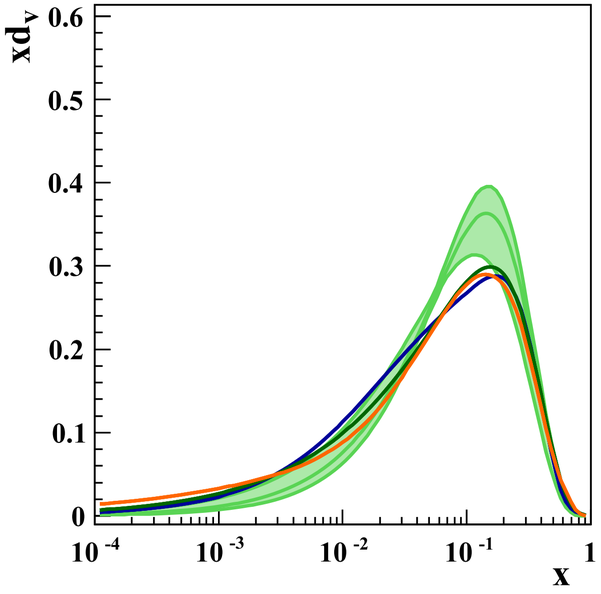


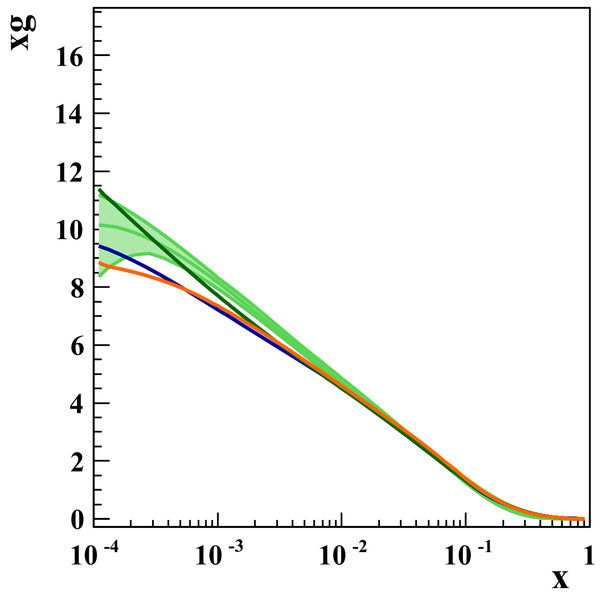


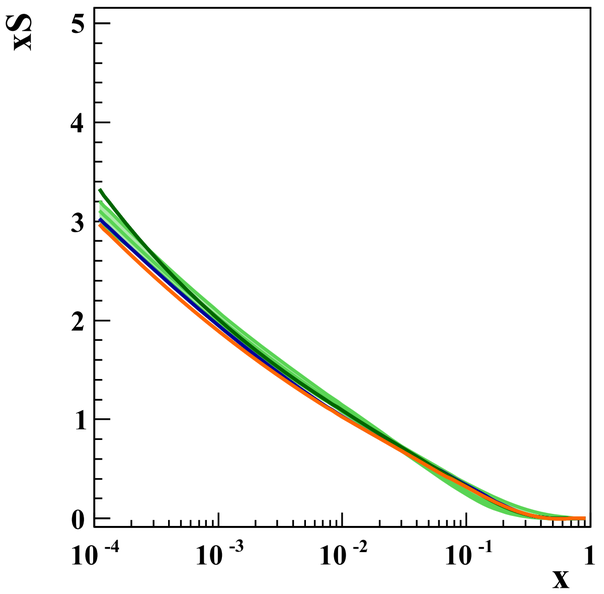
- Inclusive DIS data has limited ability to determine α_S due to correlation with g (DGLAP)
- Jet data has different dependence on α_S, g → helps break correlation

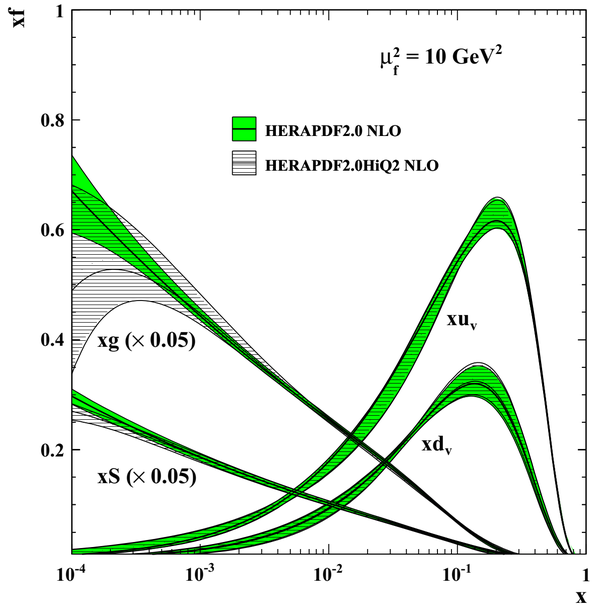
HERAPDF: PDF fit based *entirely on HERA data*

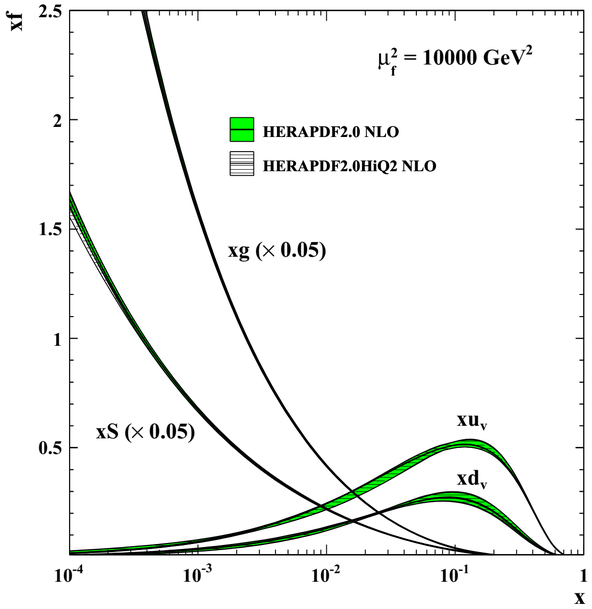












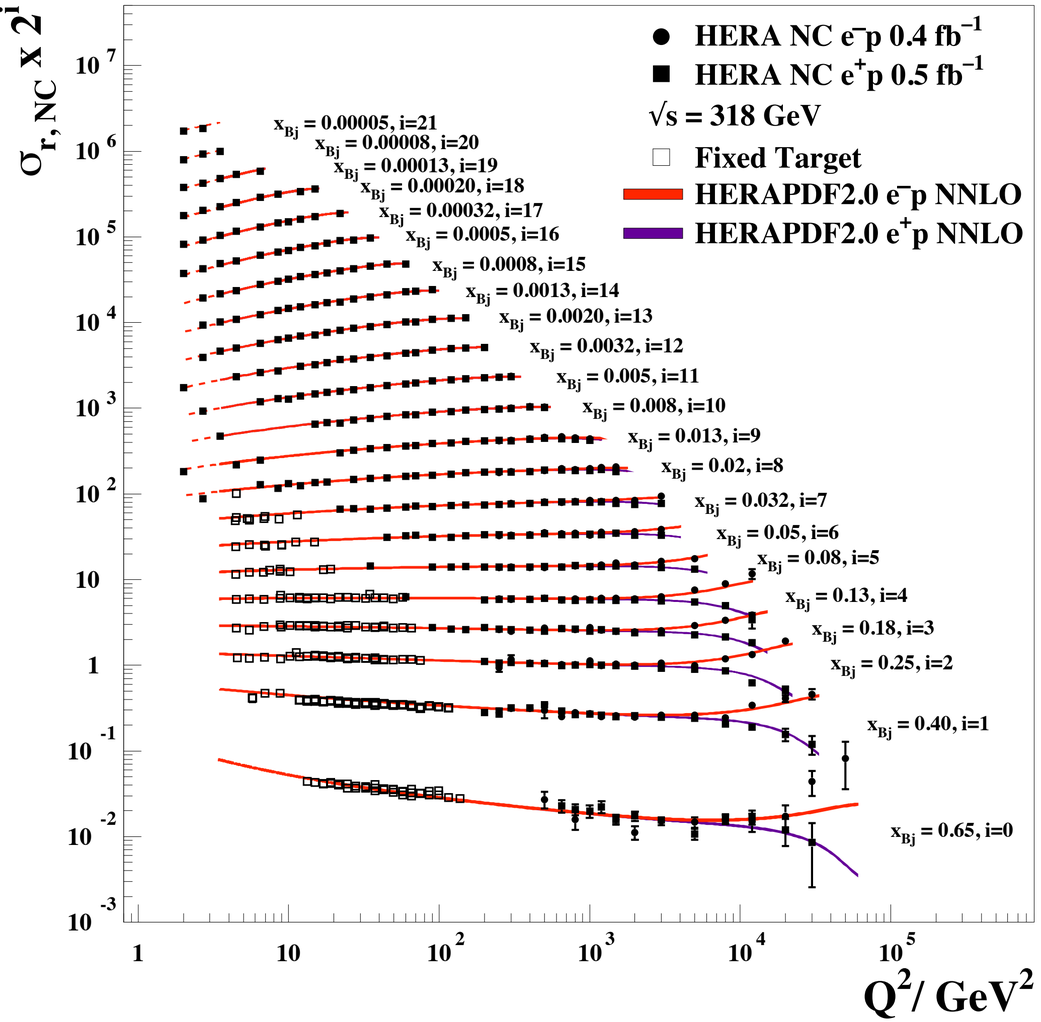
- Not the most precise, but demonstrates power of HERA dataset

HERA's lasting legacy

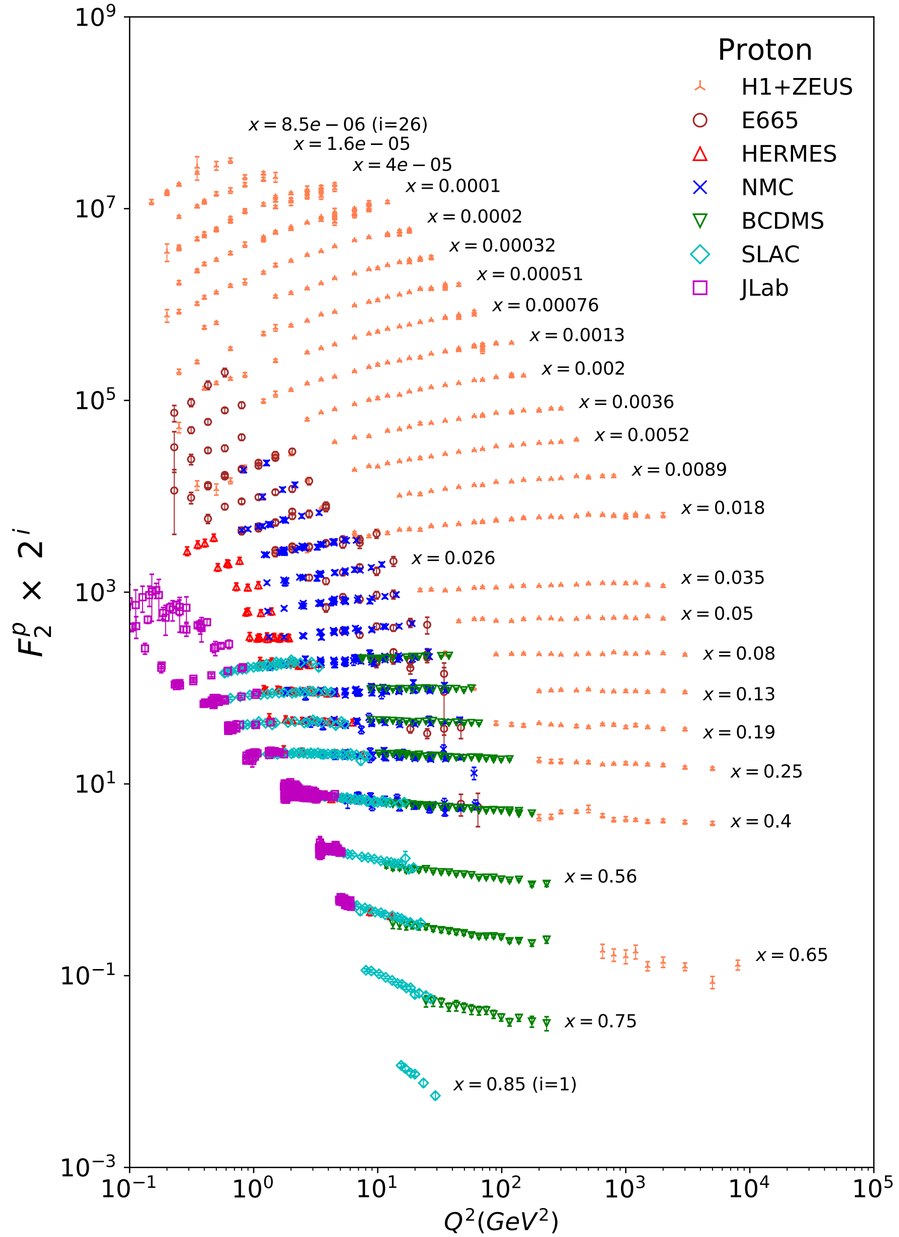
- HERA data remains the most important input to modern proton PDFs
  - Fixed-target proton data typically *completely excluded* from global analyses due to kinematics

- HERA also made important observations related to:
  - Electroweak physics
  - Limits on BSM physics, quark substructure

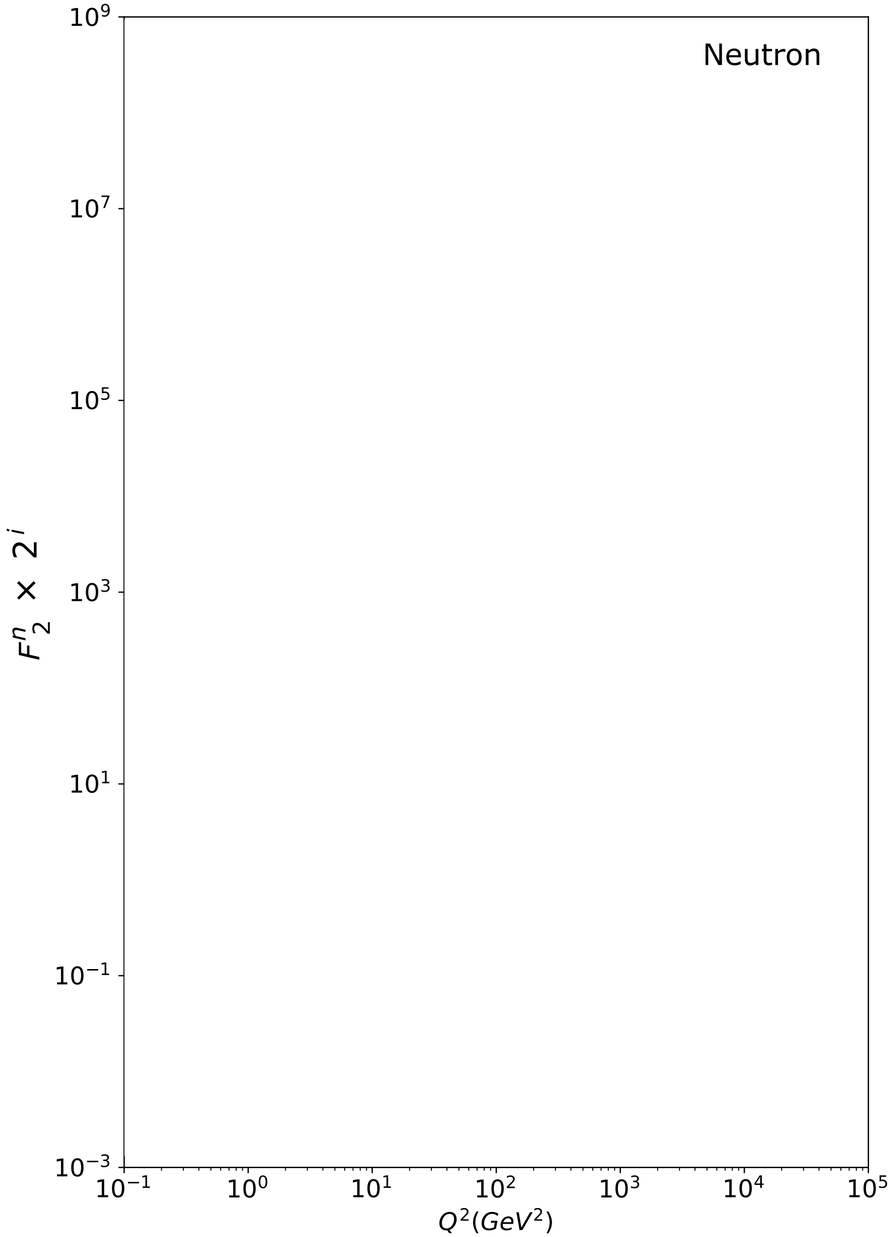
- However, HERA did have limitations:
  - No polarized protons (polarized proton PDFs)
  - No eA collisions (neutron structure, nuclear PDFs)



What about the neutron?



PRD 110, 030001 (2024)



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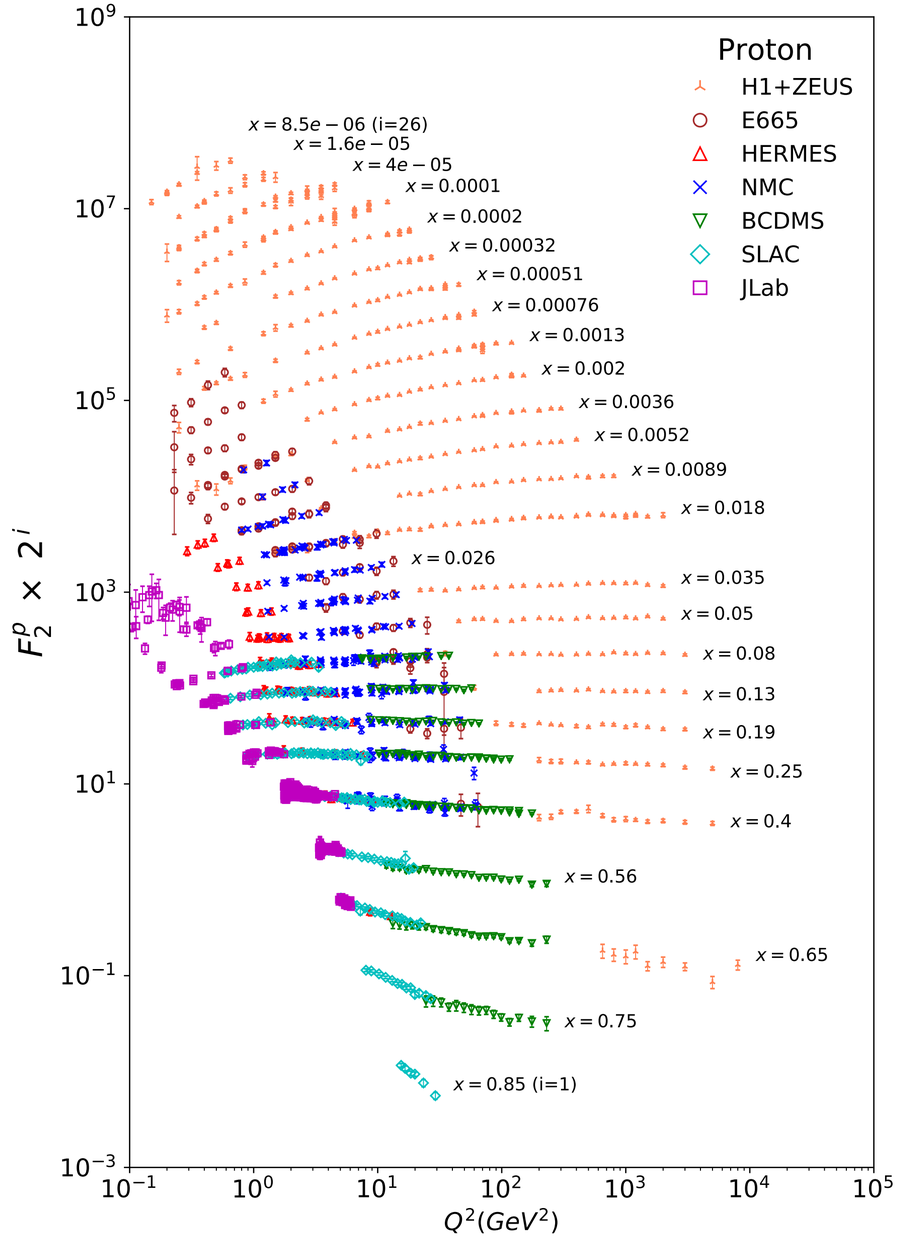

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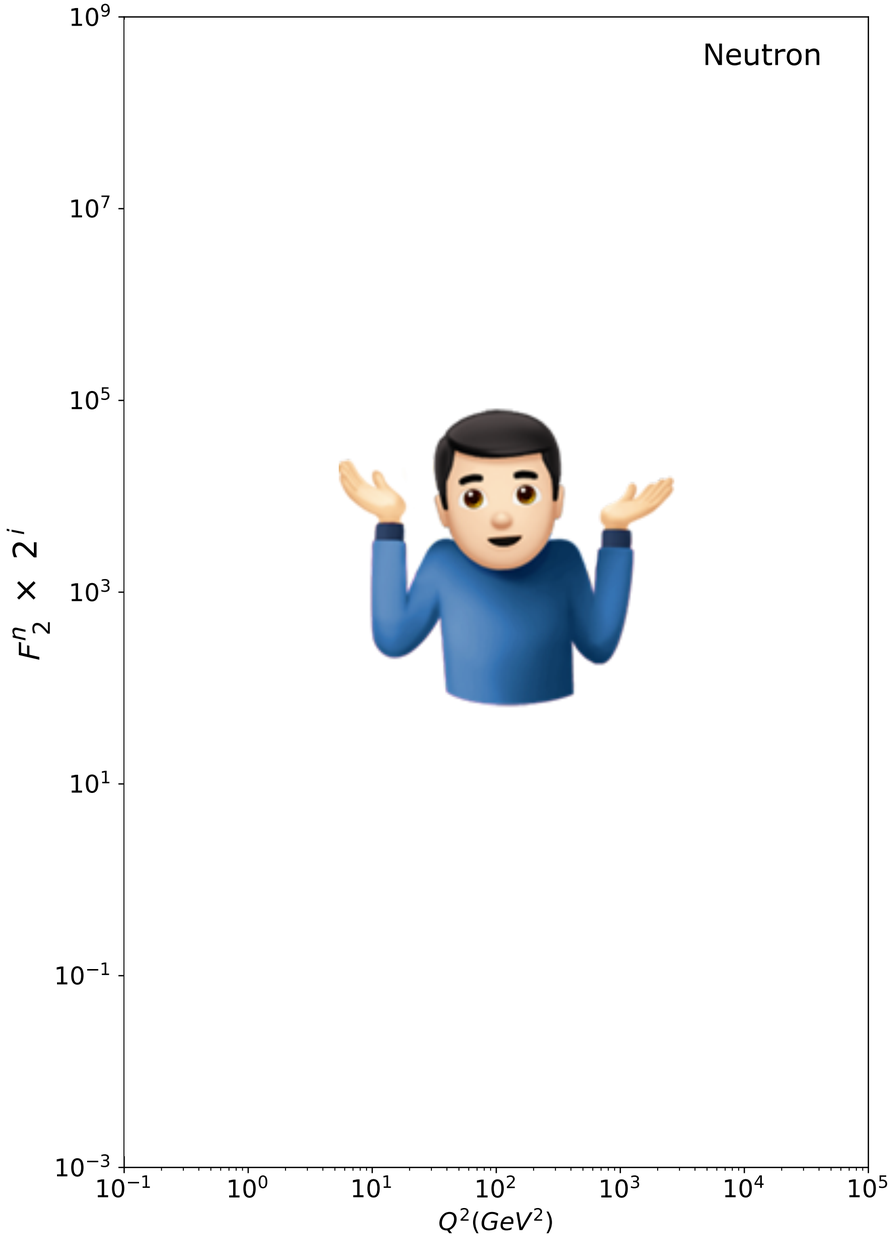

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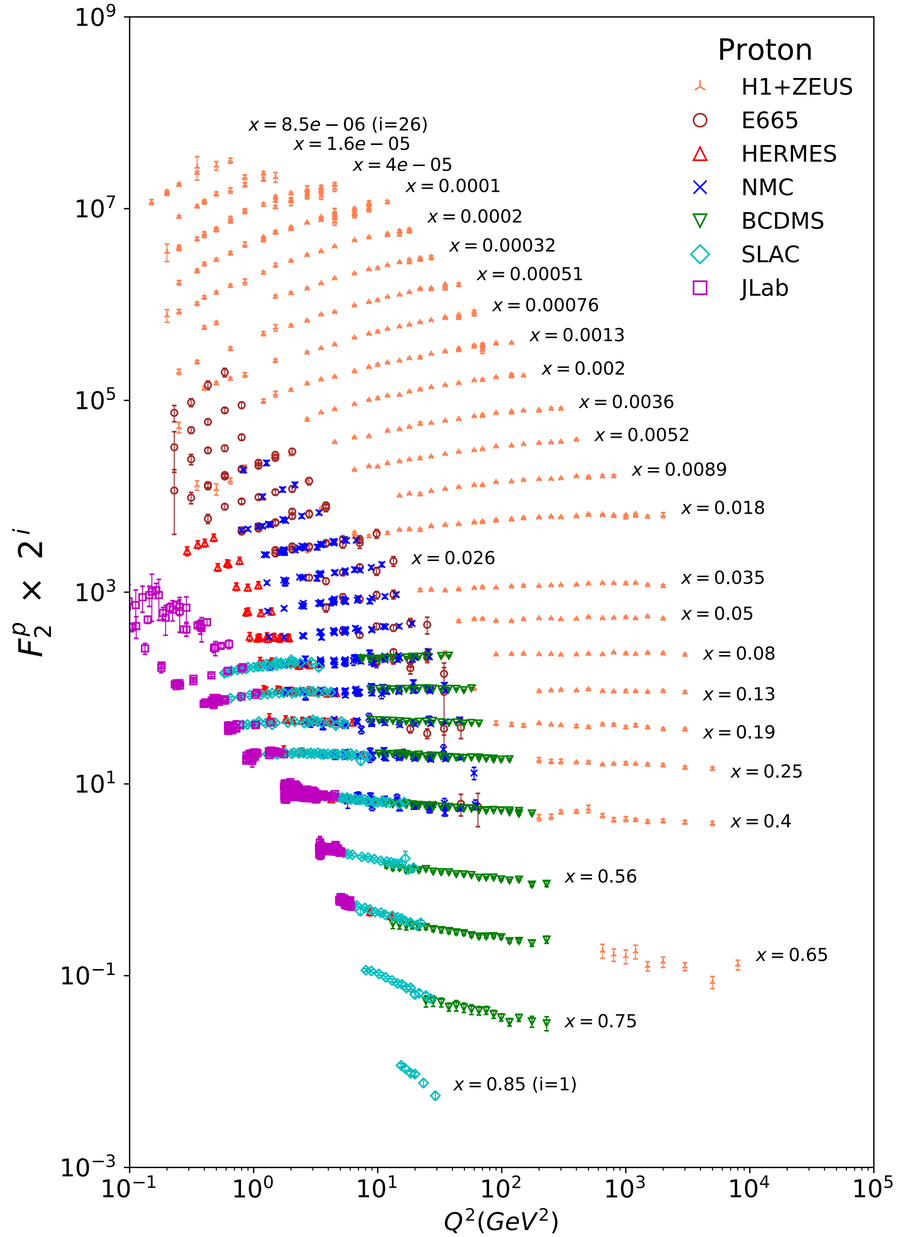

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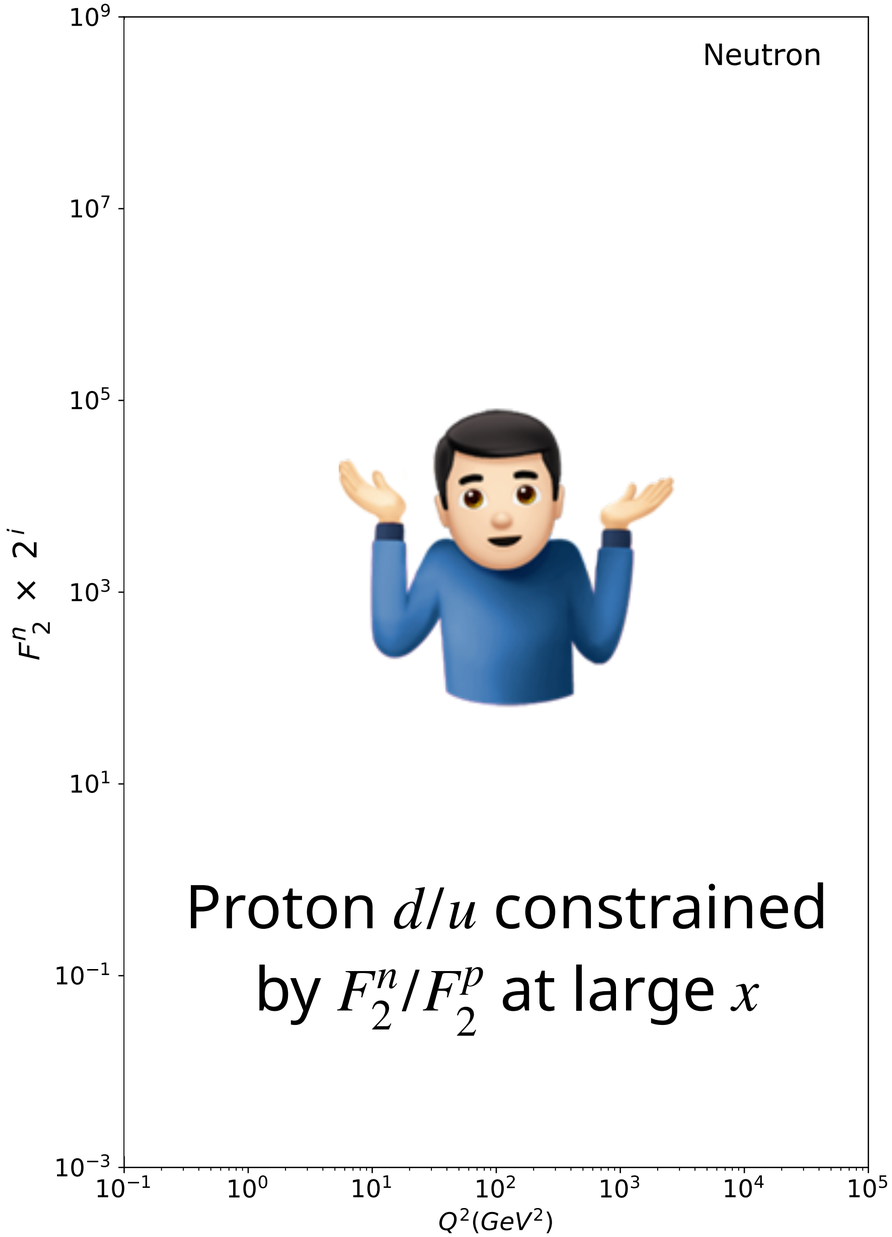
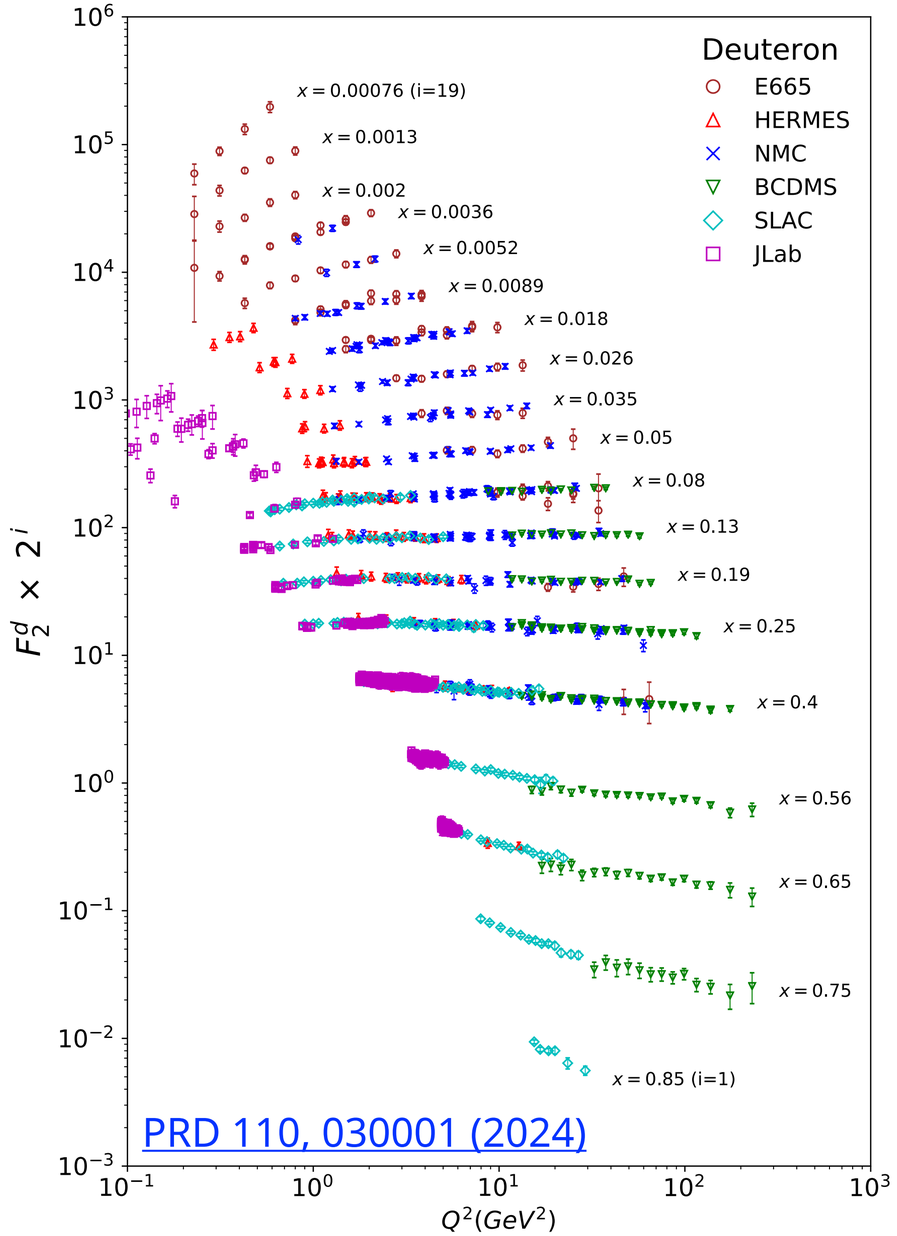


Proton d/u constrained by F_2^n/F_2^p at large x

Deuterium as $n + p$ proxy



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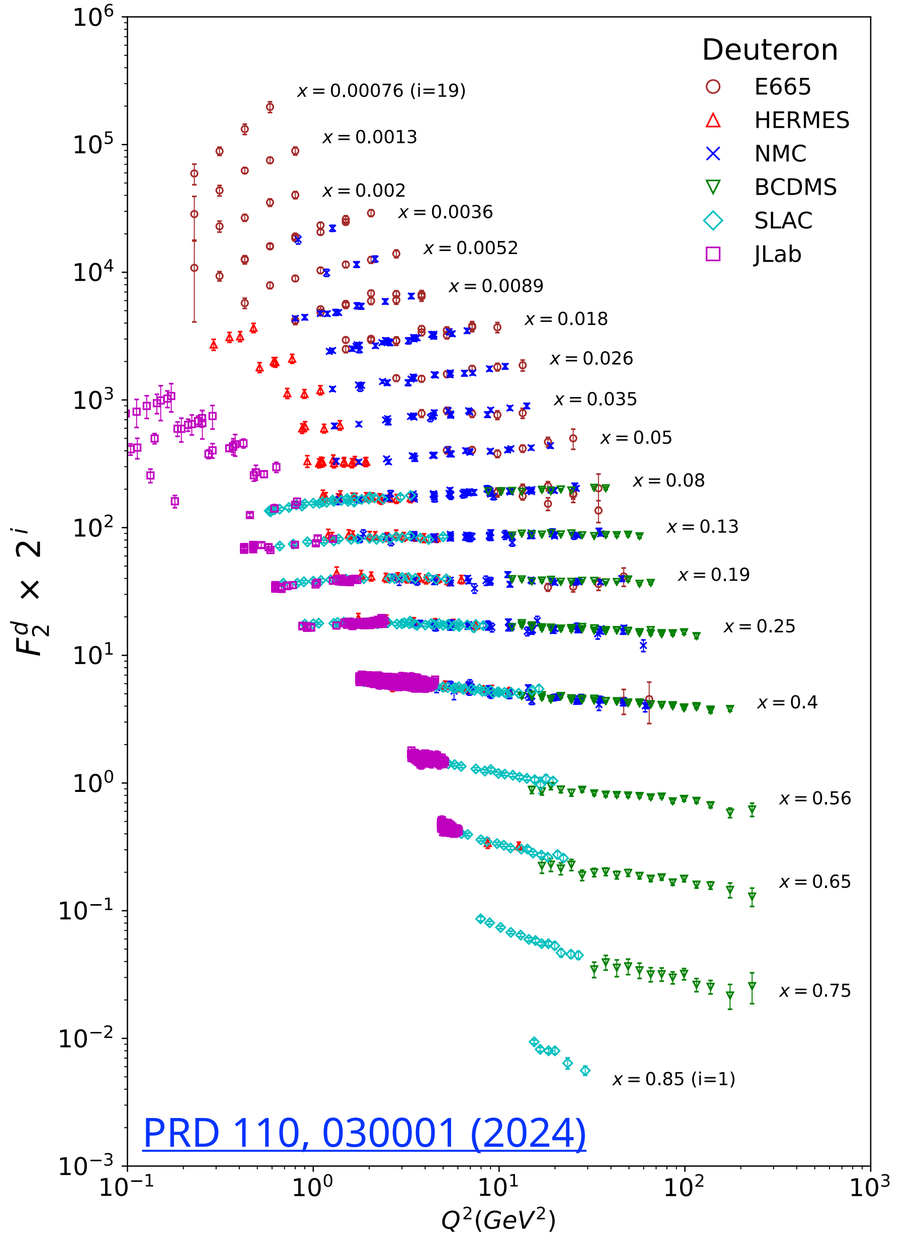


PRD 110, 030001 (2024)

But $F_2^A \neq ZF_2^p + (A - Z)F_2^n$

TOTAL NEUTRON CROSS SECTIONS MAY NOT BE WHAT THEY SEEM TO BE

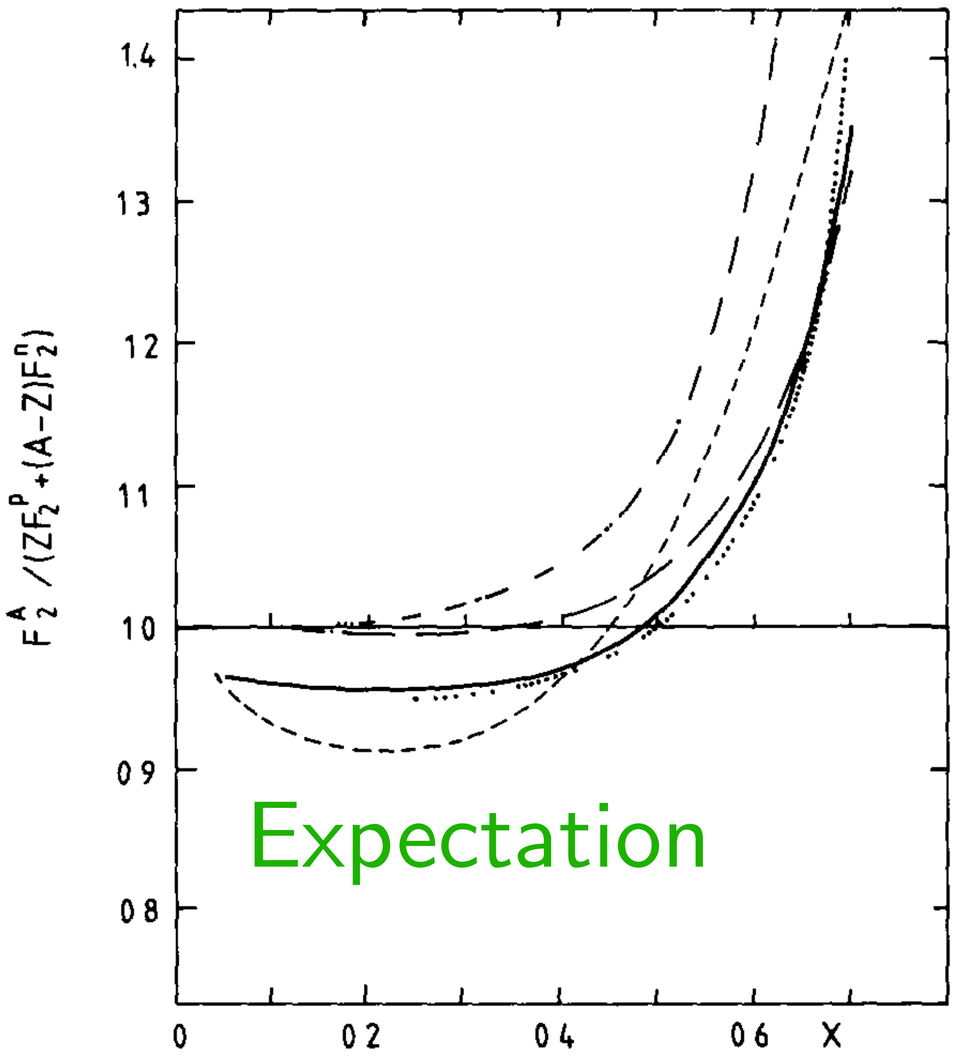
G. B. WEST
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, Calif. 94305, *USA*

Received 27 September 1971

rections, etc.) but, here, we would like to focus on a subtlety in what is perhaps the simplest correction, namely, that due to Fermi motion

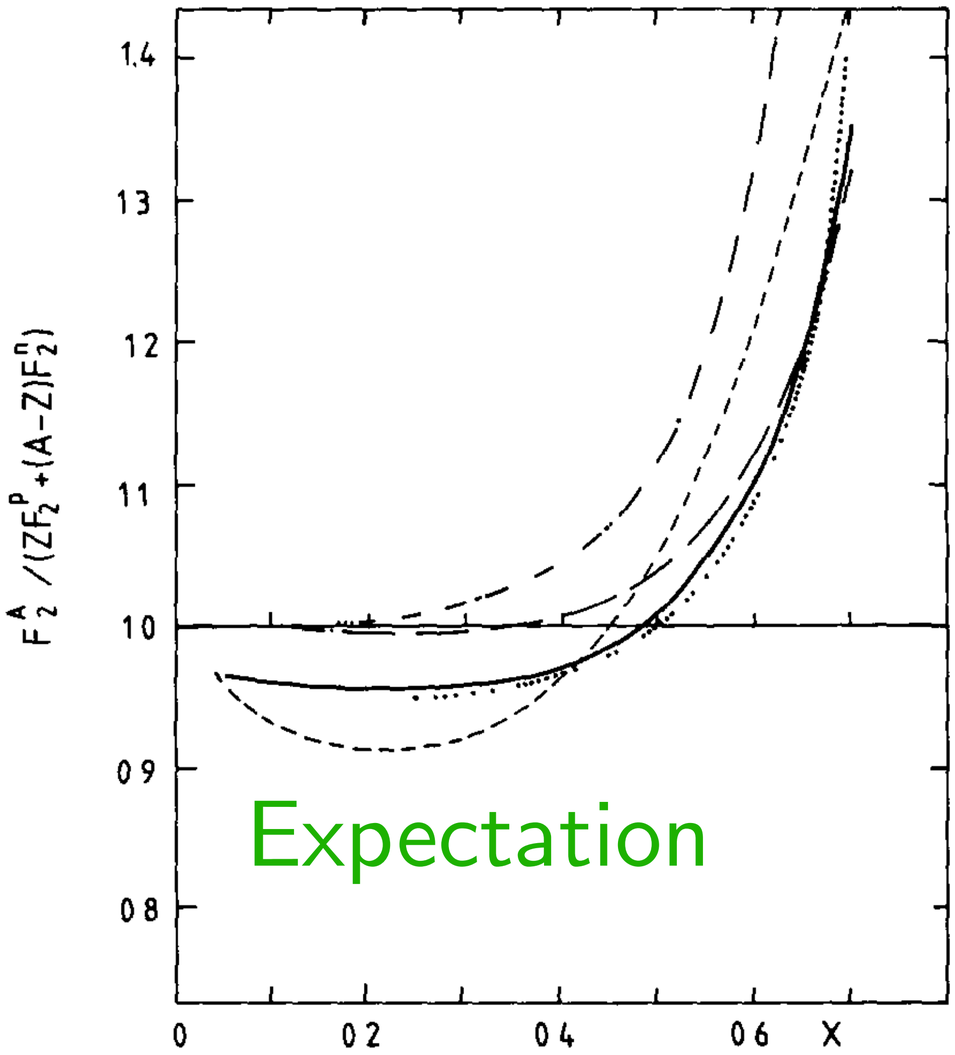
PLB 37, 509 (1971)

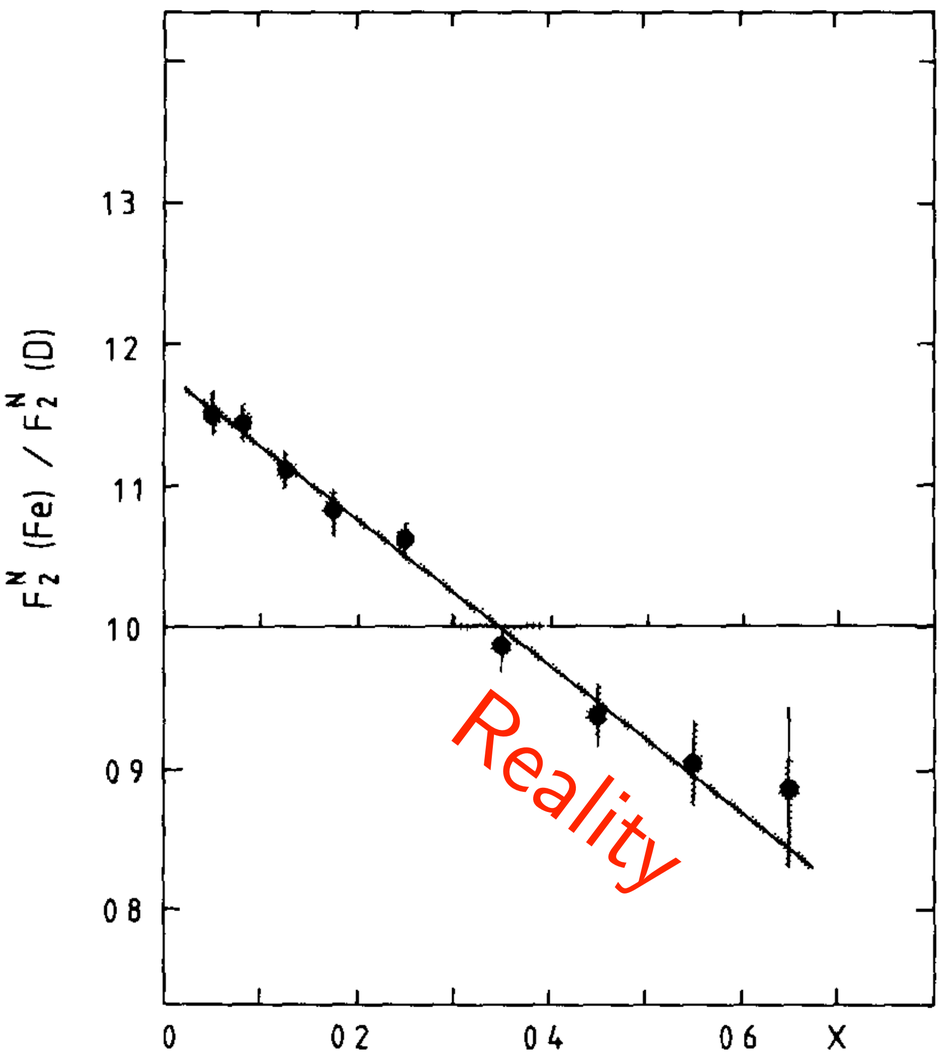
The EMC effect



PLB 123, 275 (1983)

The EMC effect

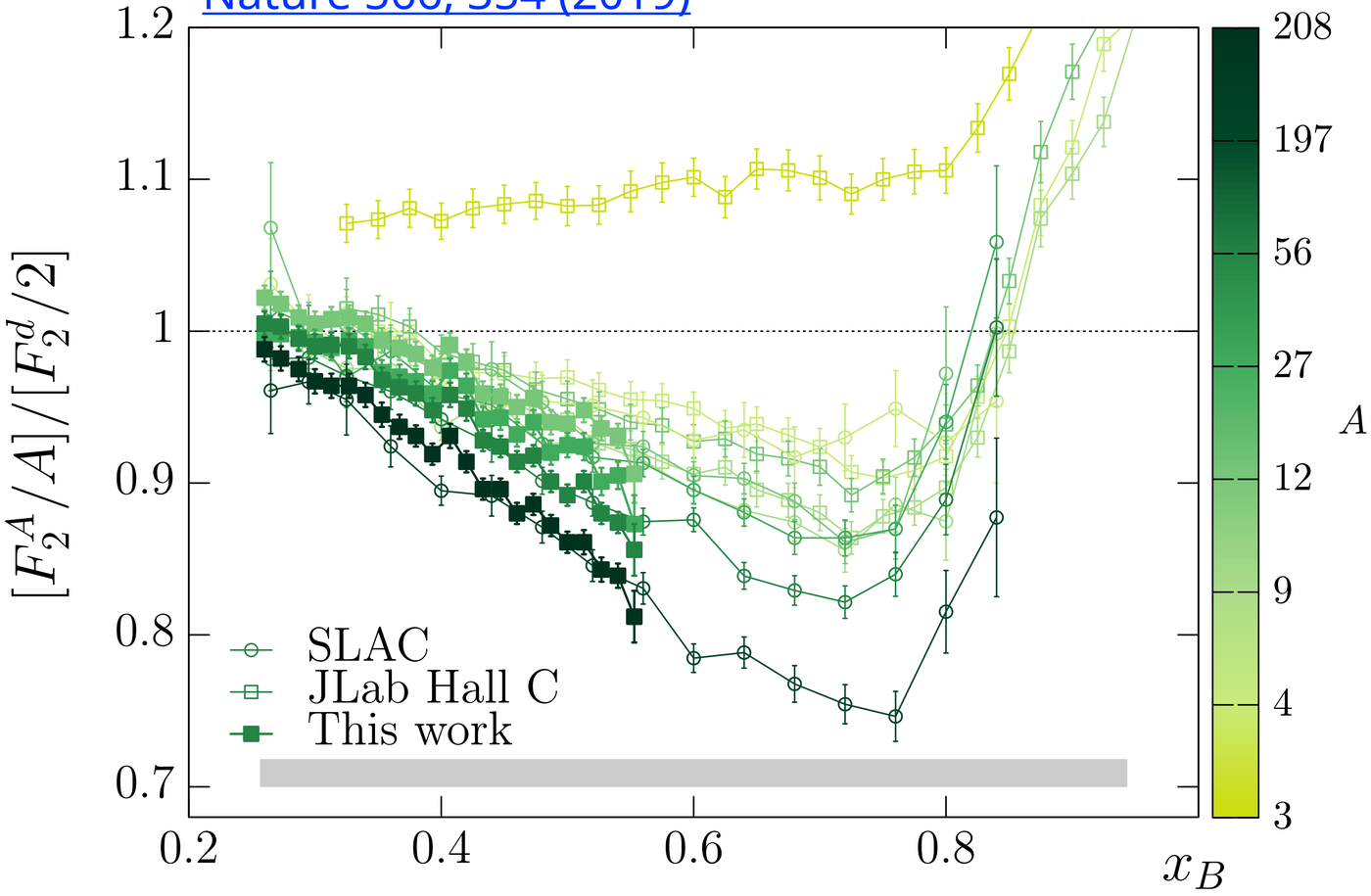




PLB 123, 275 (1983)

The EMC effect

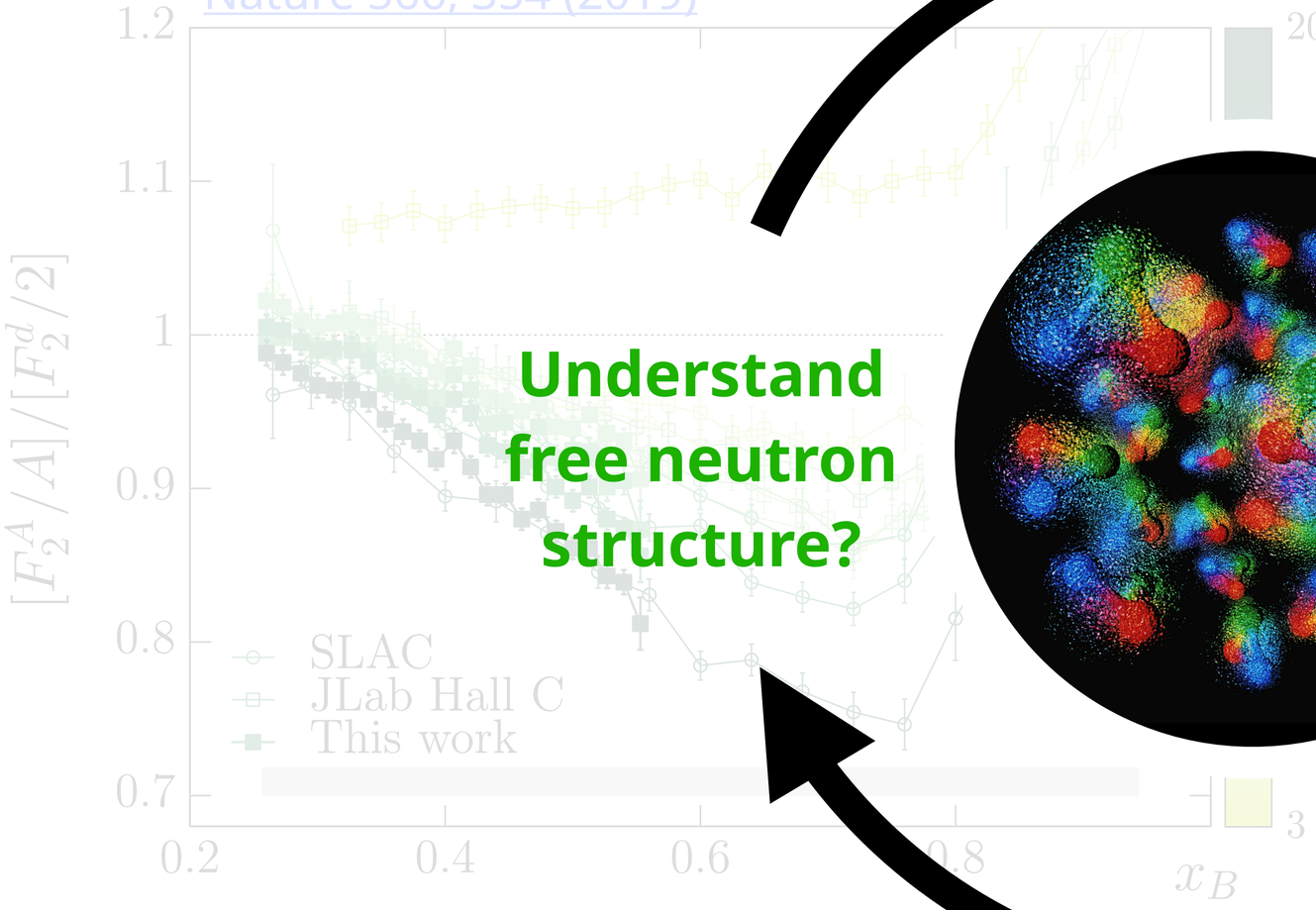
Nature 566, 354 (2019)



- Motivated large campaign of nuclear measurements at SLAC, JLab, CERN, DESY
- A-dependent effect observed in all nuclei
- Data described by wide array of models → “Everybody’s Model is Cool.” -G. Miller
- *No consensus* on physical origin of effect

The EMC effect

Nature 566, 354 (2019)



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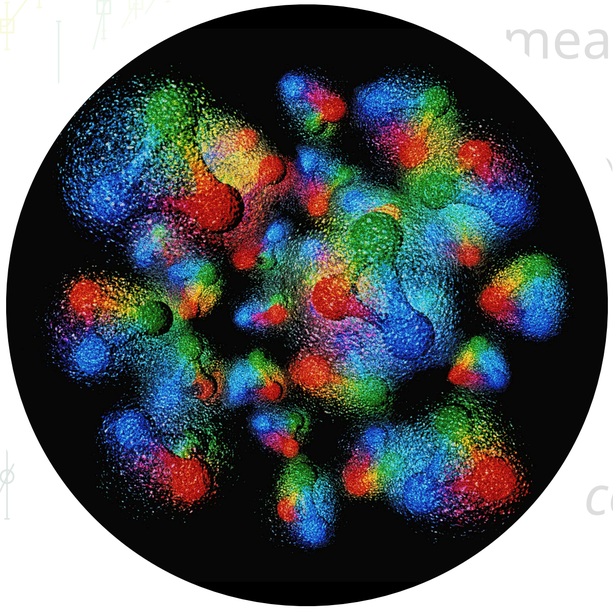
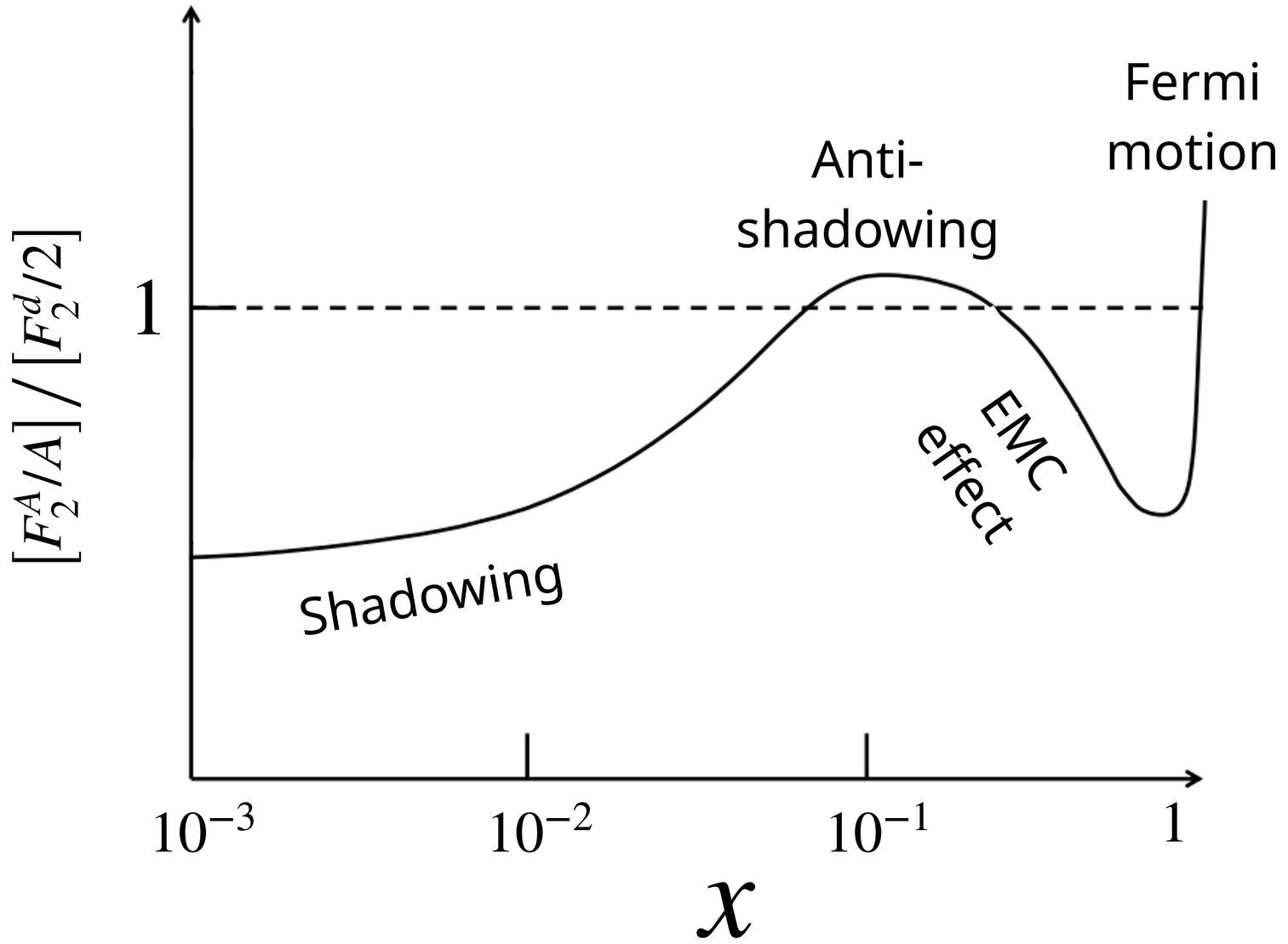
Understand free neutron structure?



Understand bound nucleon modification?

EMC effect only one element of nuclear modification



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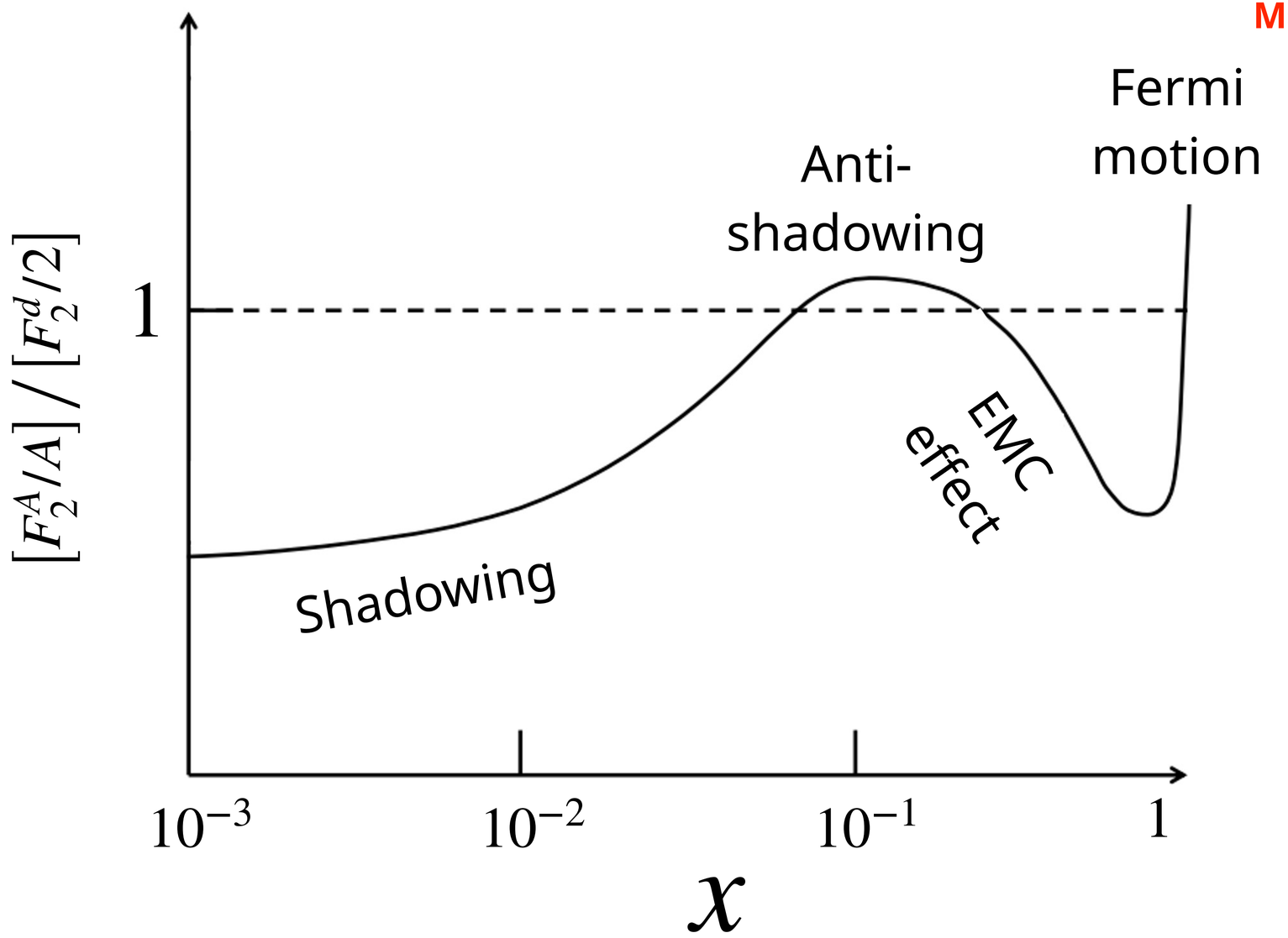
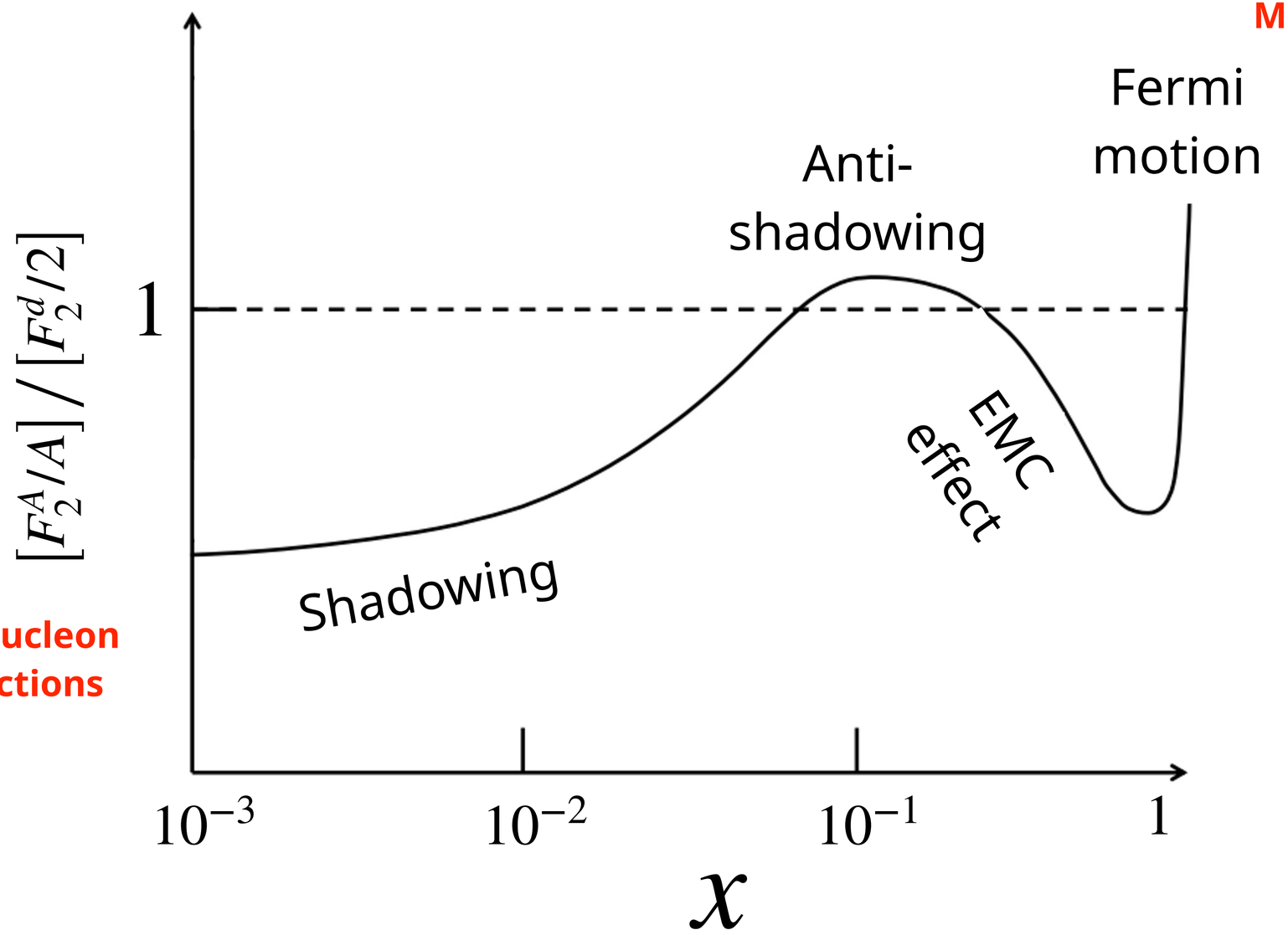


Motion of bound nucleons (smearing, offshell…)

EMC effect only one element of nuclear modification



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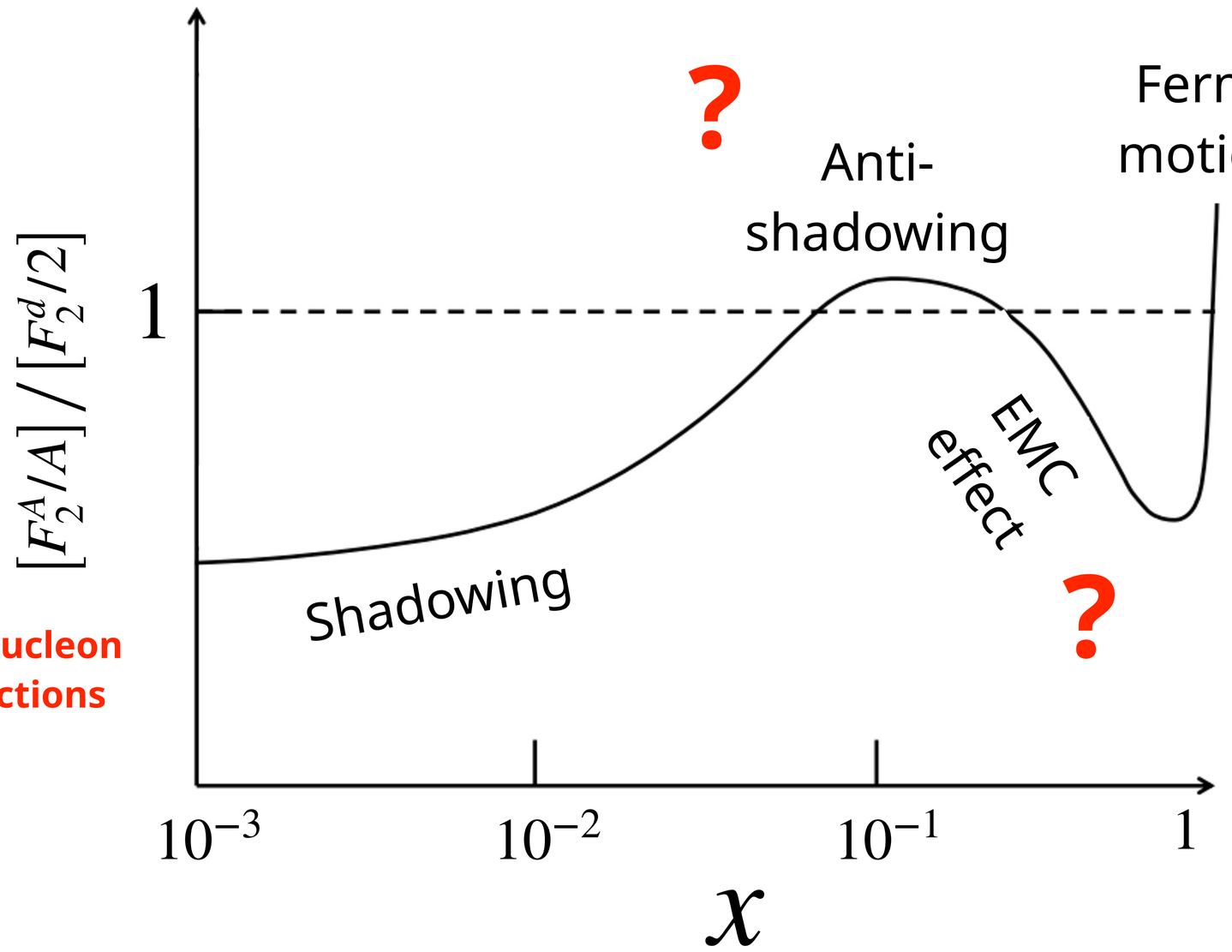

General approach to nuclear PDFs

$$f_i^{(A,Z)}\left(x,Q^2\right) = \frac{Z}{A} f_i^{p/A}\left(x,Q^2\right) + \frac{A-Z}{A} f_i^{n/A}\left(x,Q^2\right)$$

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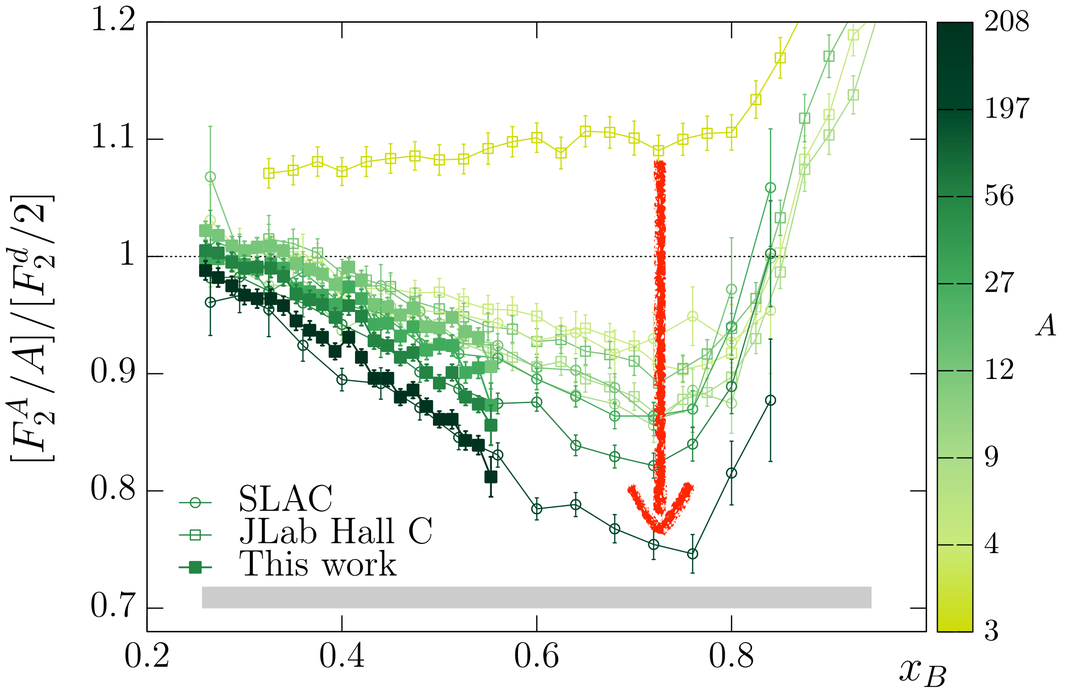

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- Coefficients depend (smoothly) on A

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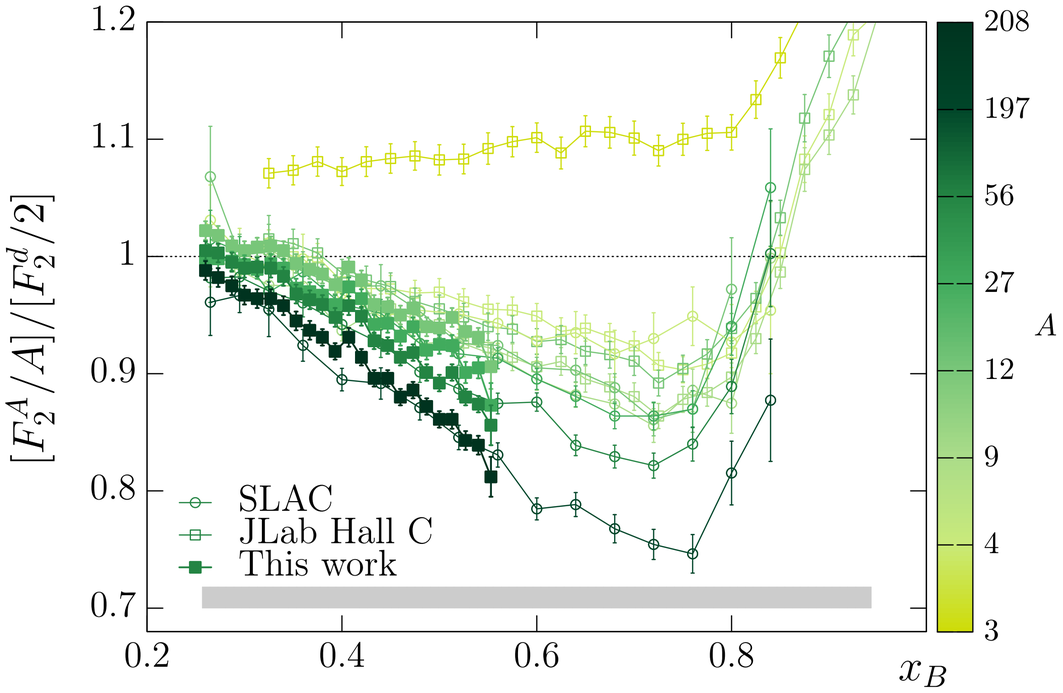

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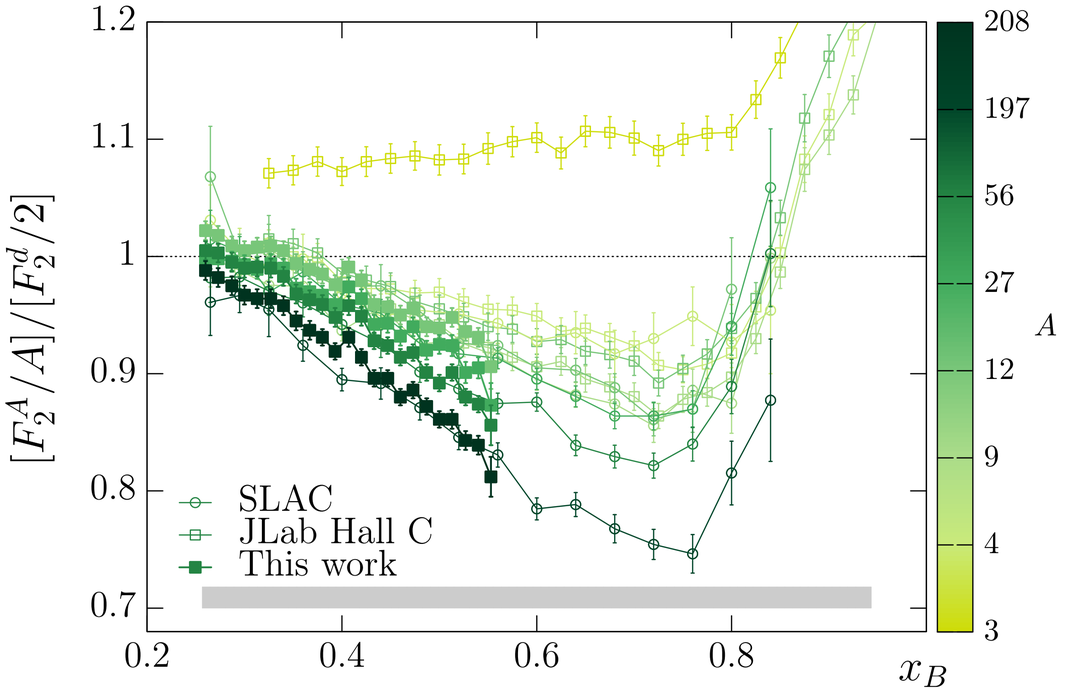

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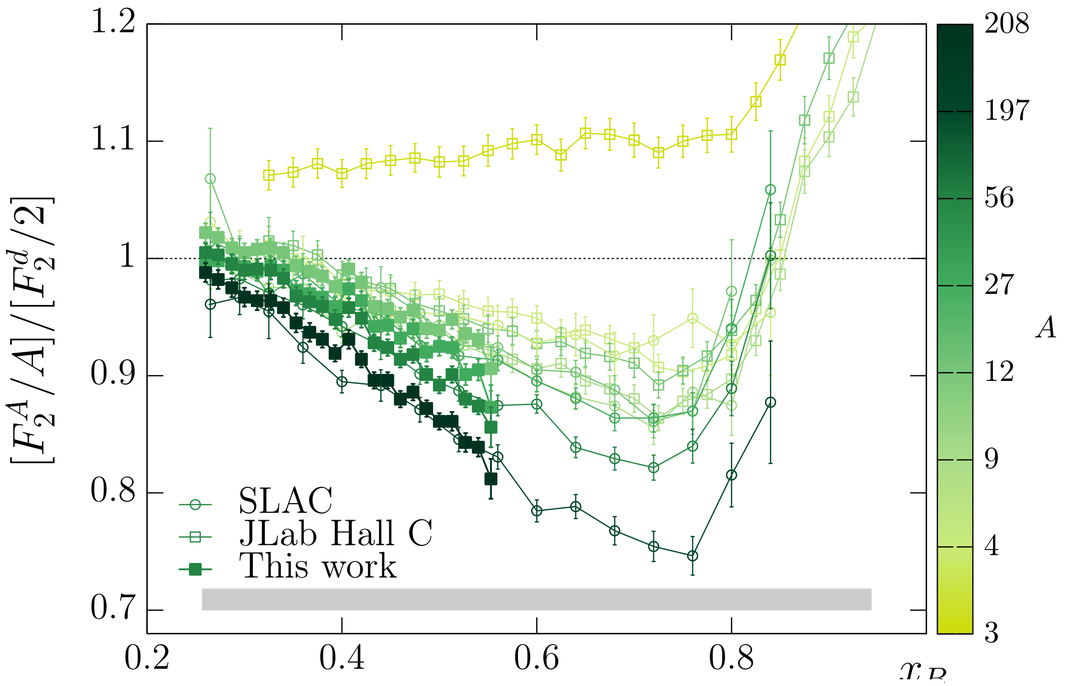

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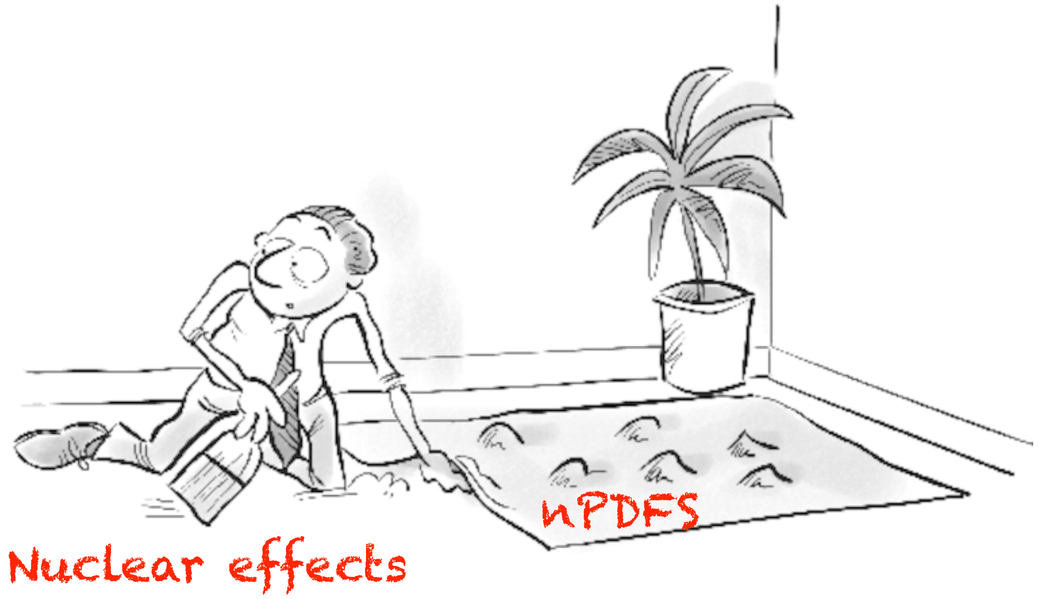

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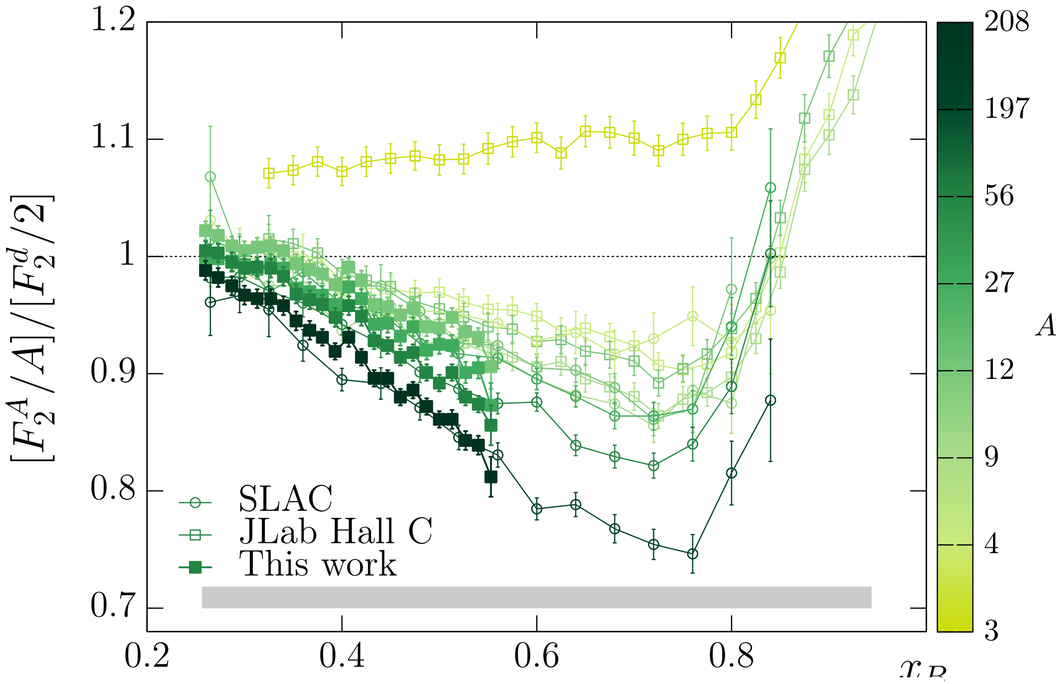

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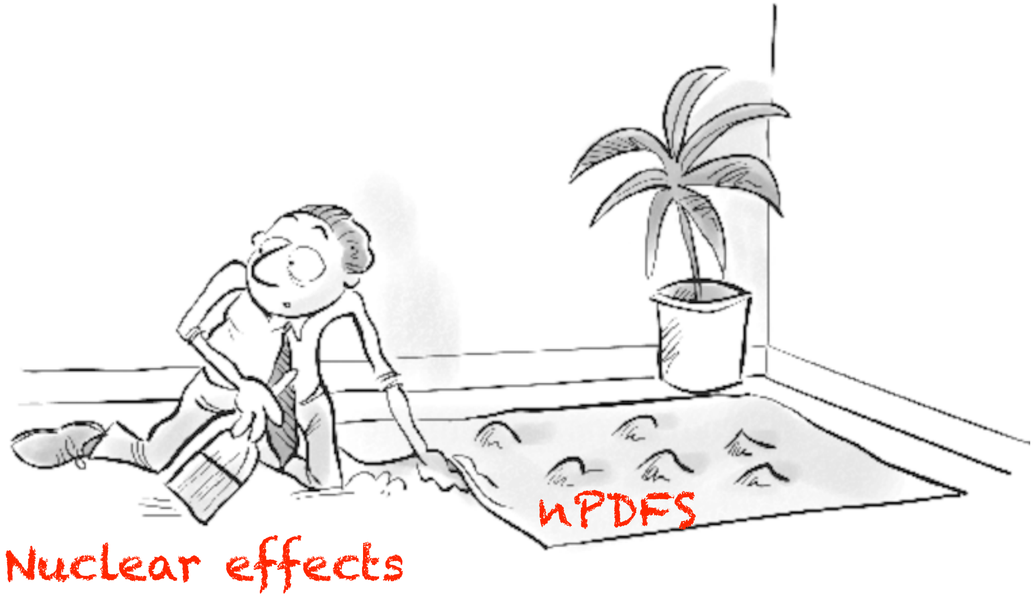
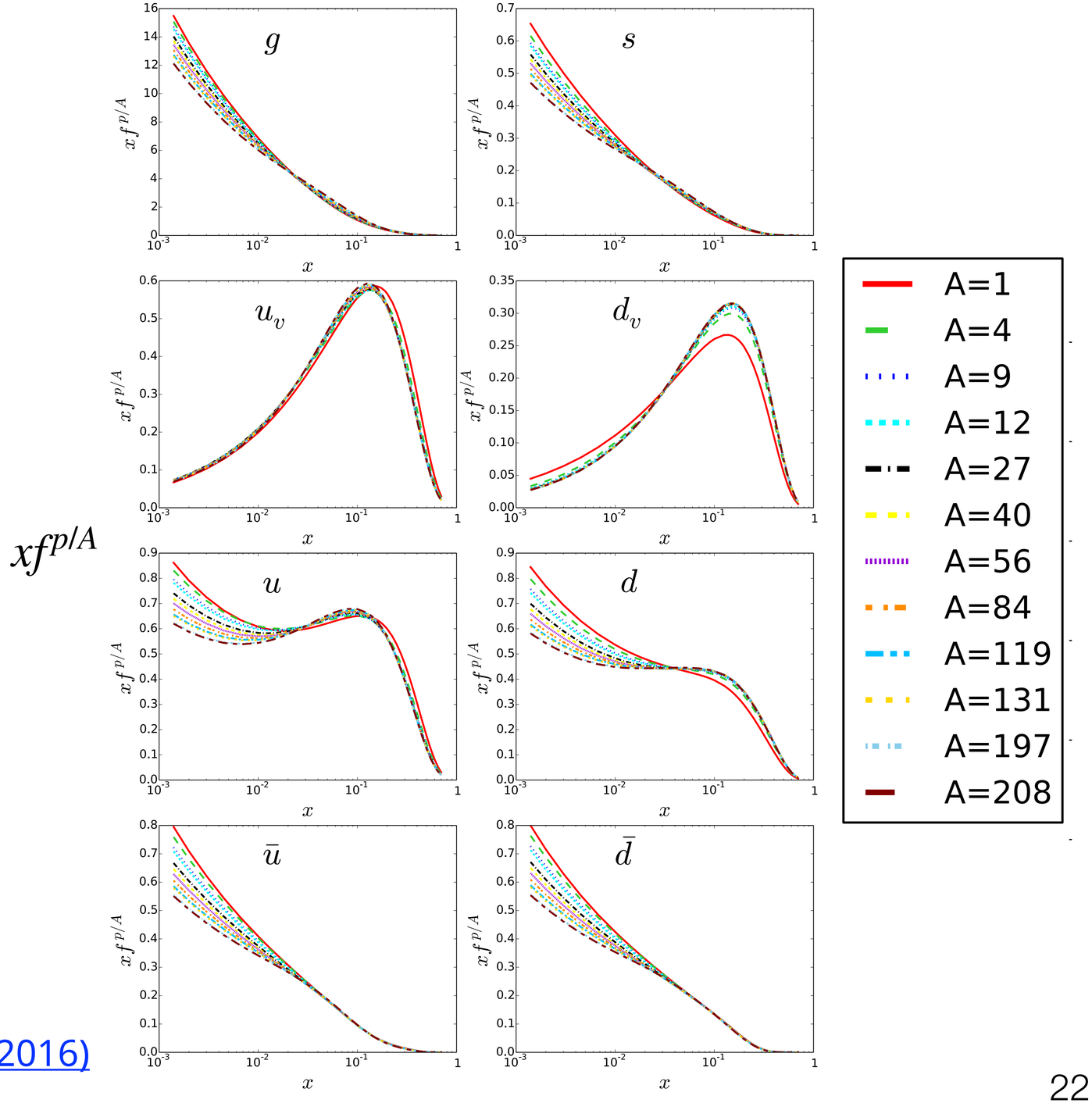
Currently, DIS constraints on nPDFs come entirely from fixed-target experiments!



A-dependence of nPDFs (from nCTEQ15)

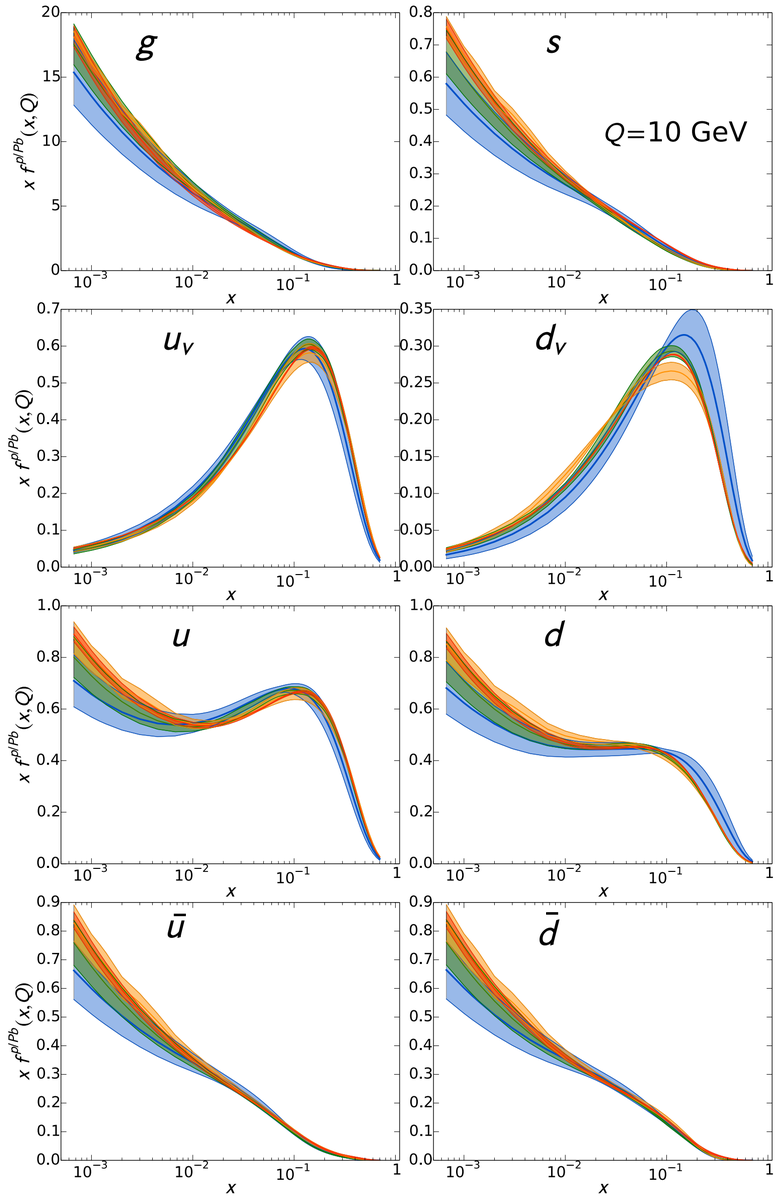
- At low x, gluon and sea distributions (including u and d) decrease with A
- Effect largely cancels in valence distributions, resulting in reduced A-dependence



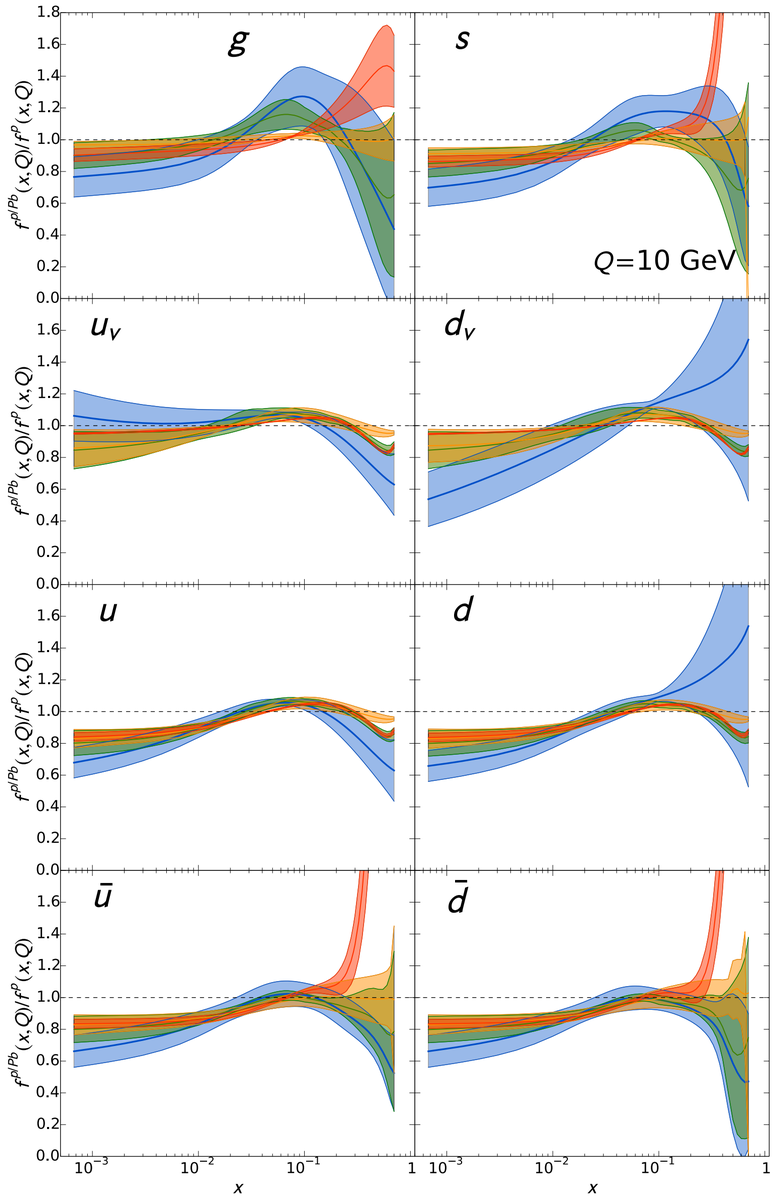
PRD 93, 085037 (2016)

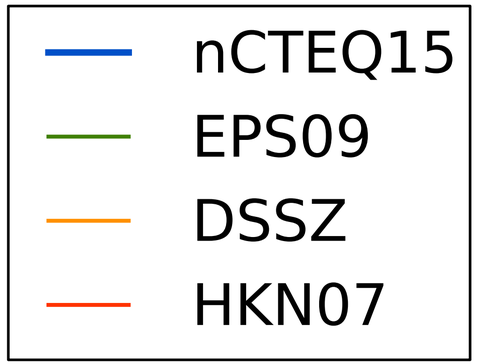
Comparison of different nPDF analyses

$xf^{p/Pb}$ vs. x



$f^{p/Pb}/f^{p}$ vs. x



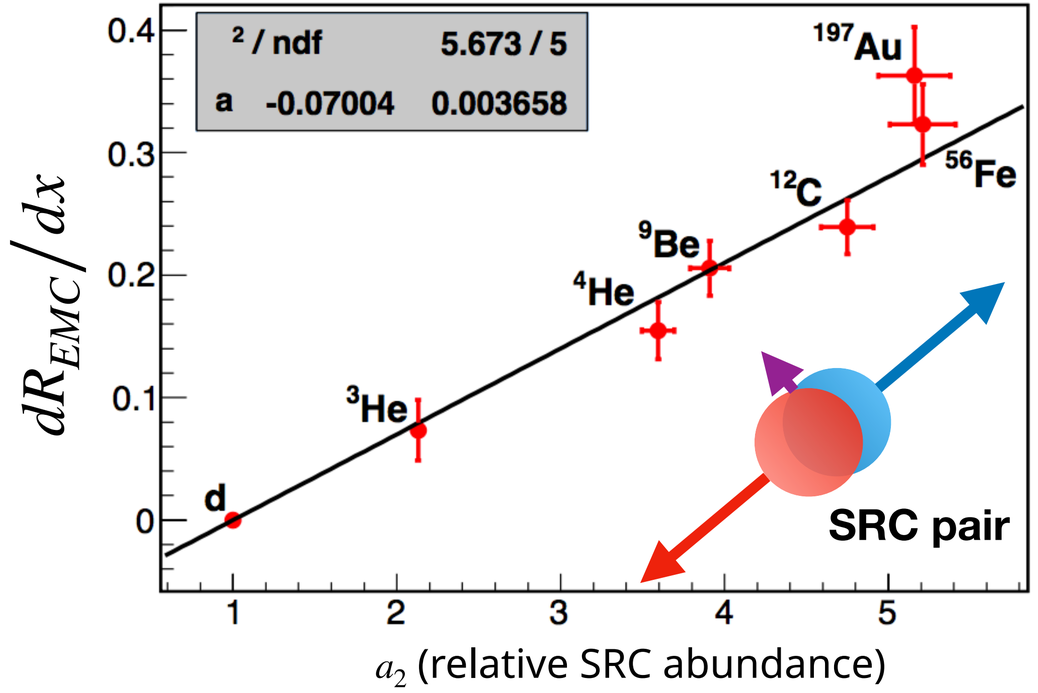


- (Mostly) qualitative agreement among different analyses
- nCTEQ15 does *not* enforce isospin symmetry of valence modification (flavor dependent EMC effect?)

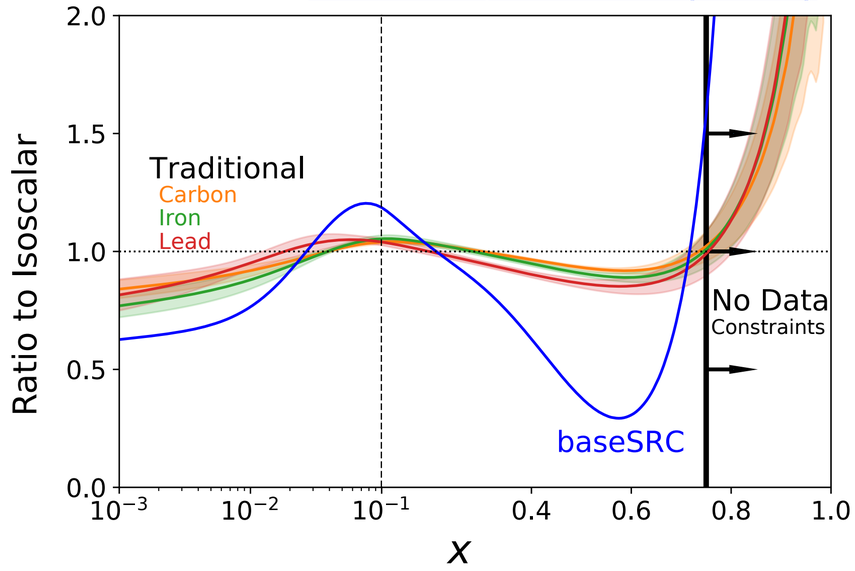
PRD 93, 085037 (2016)

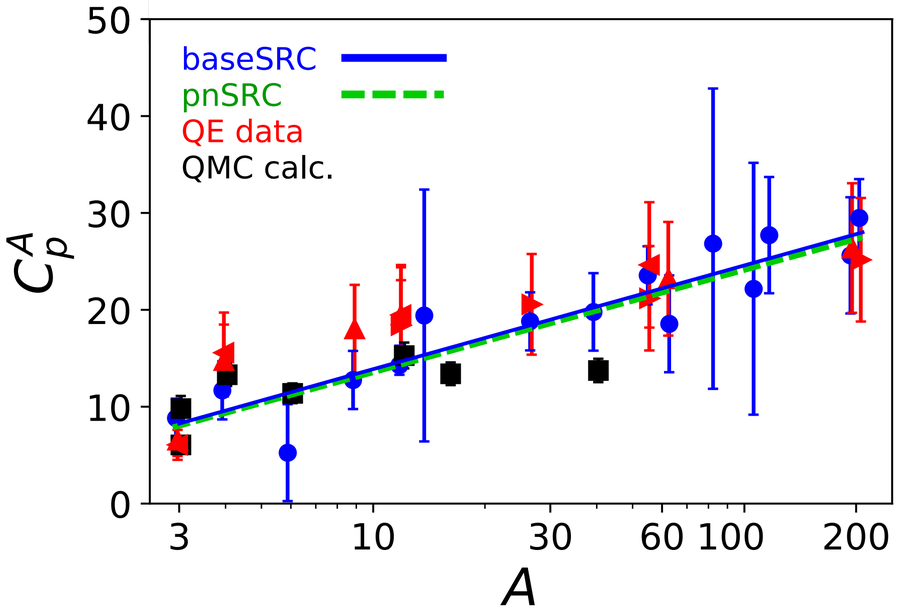
Short-range correlated nucleons: bridge between nuclear and parton structure?

Rev. Mod. Phys. 89, 045002 (2017)

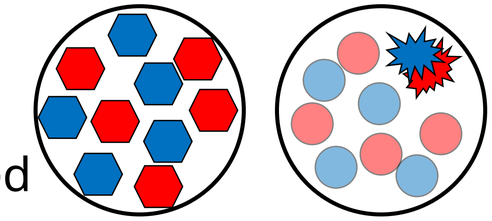


PRL 133, 152502 (2024)





Traditional: All nucleons slightly modified



SRC-EMC hypothesis: Few (SRC) nucleons highly modified

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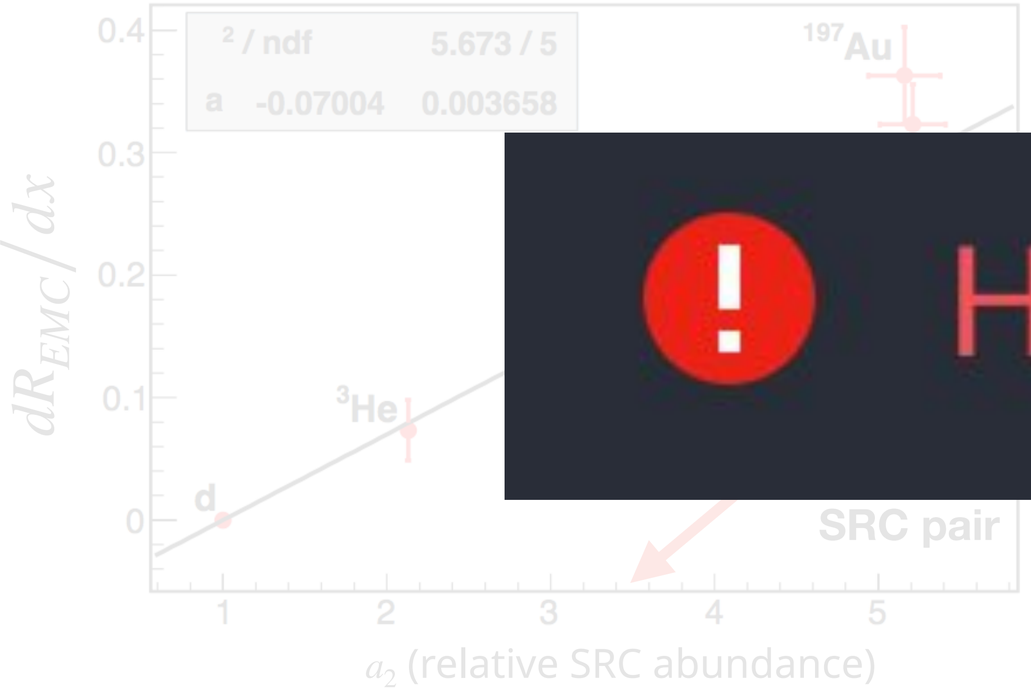
Rev. Mod. Phys. 89, 045002 (2017)



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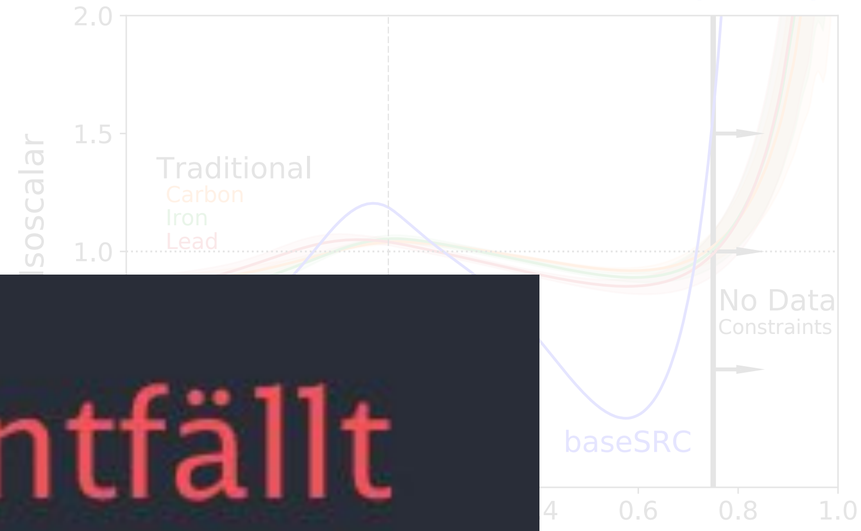

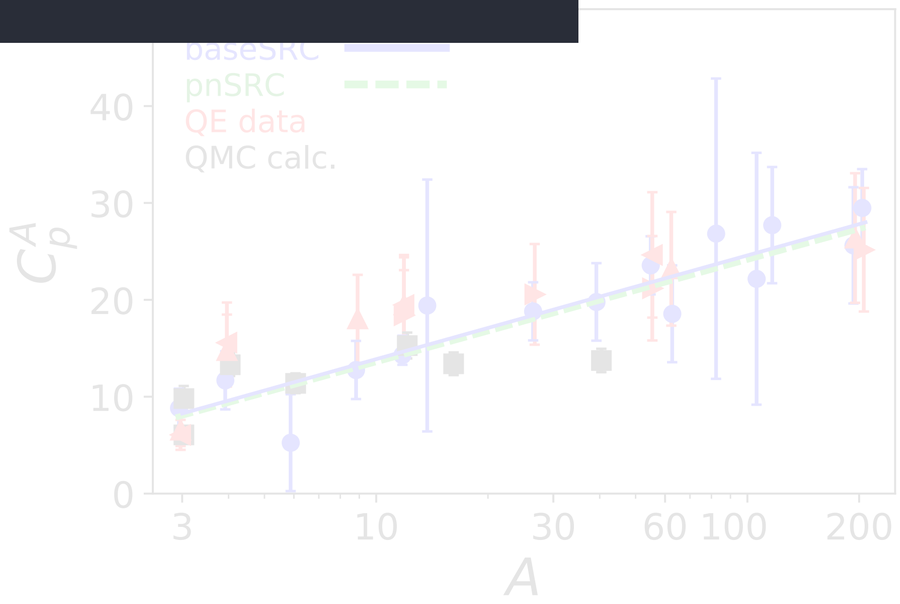

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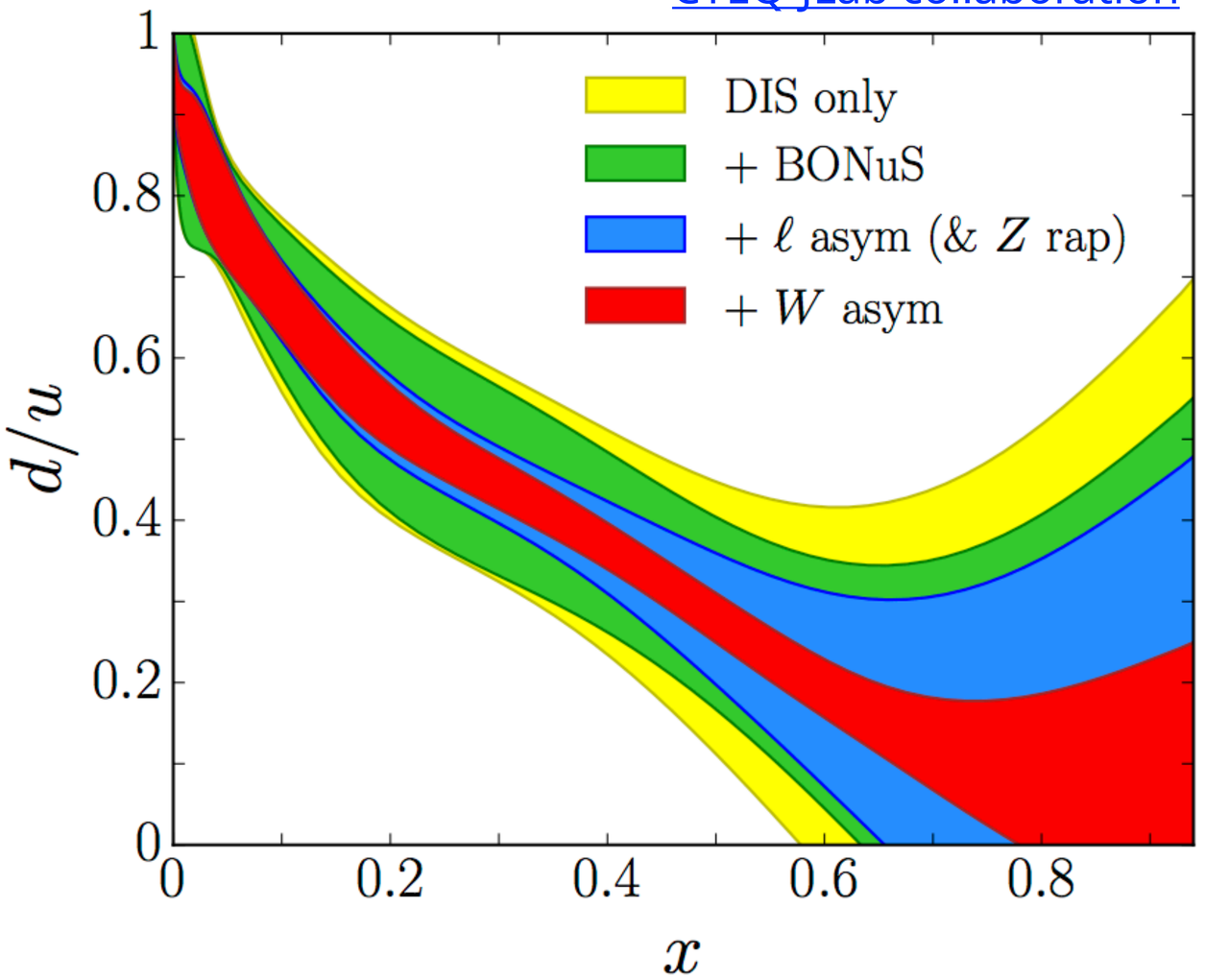
SRC-EMC hypothesis: Few (SRC) nucleons highly modified

Where do we stand?

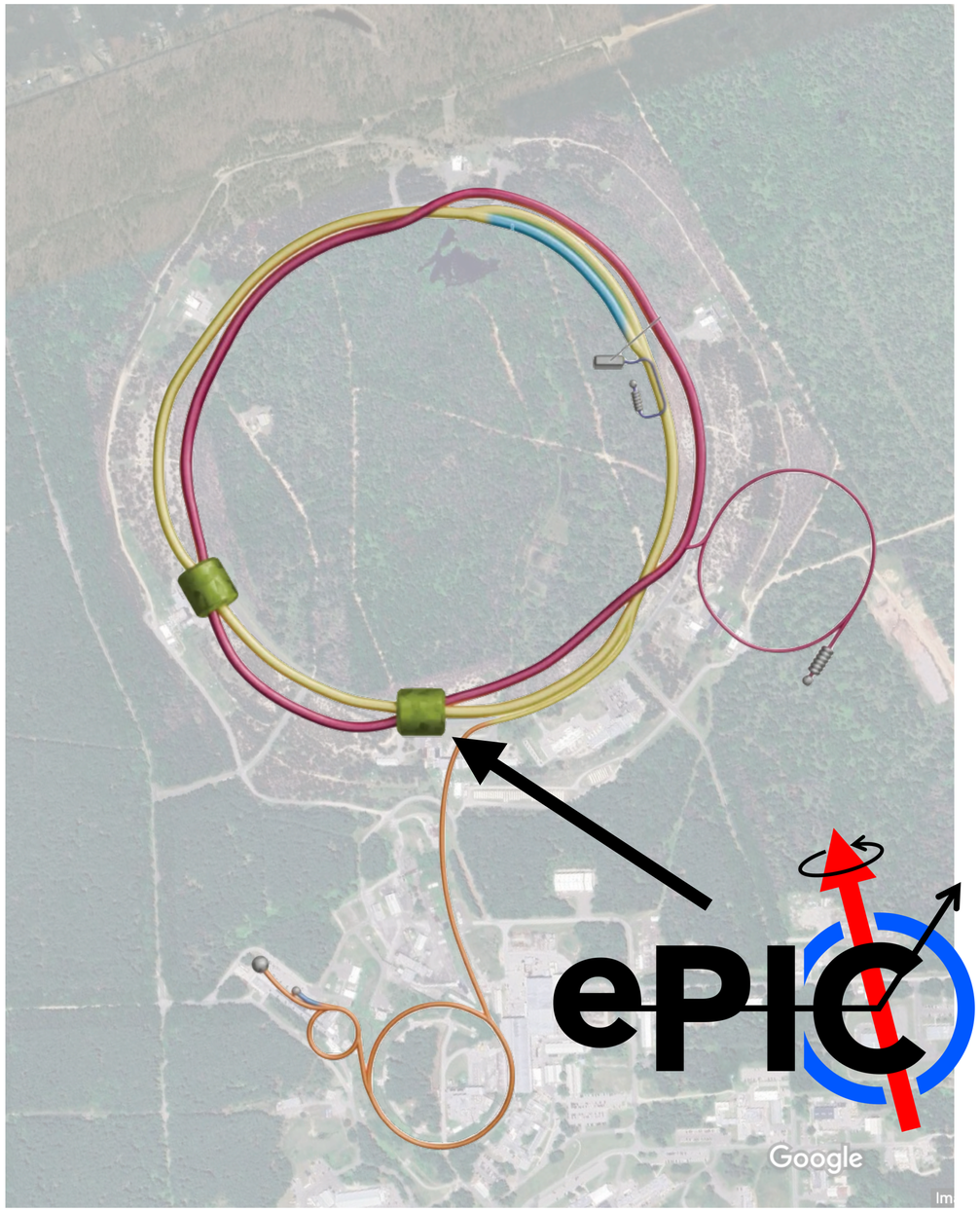
- Proton PDFs poorly constrained at high x
  - d/u at large x?
  - Strange quarks, gluons?
- Knowledge of neutron structure still poor and model-dependent
- Nuclear PDFs, modifications constrained only by fixed-target data

CTEQ-JLab collaboration

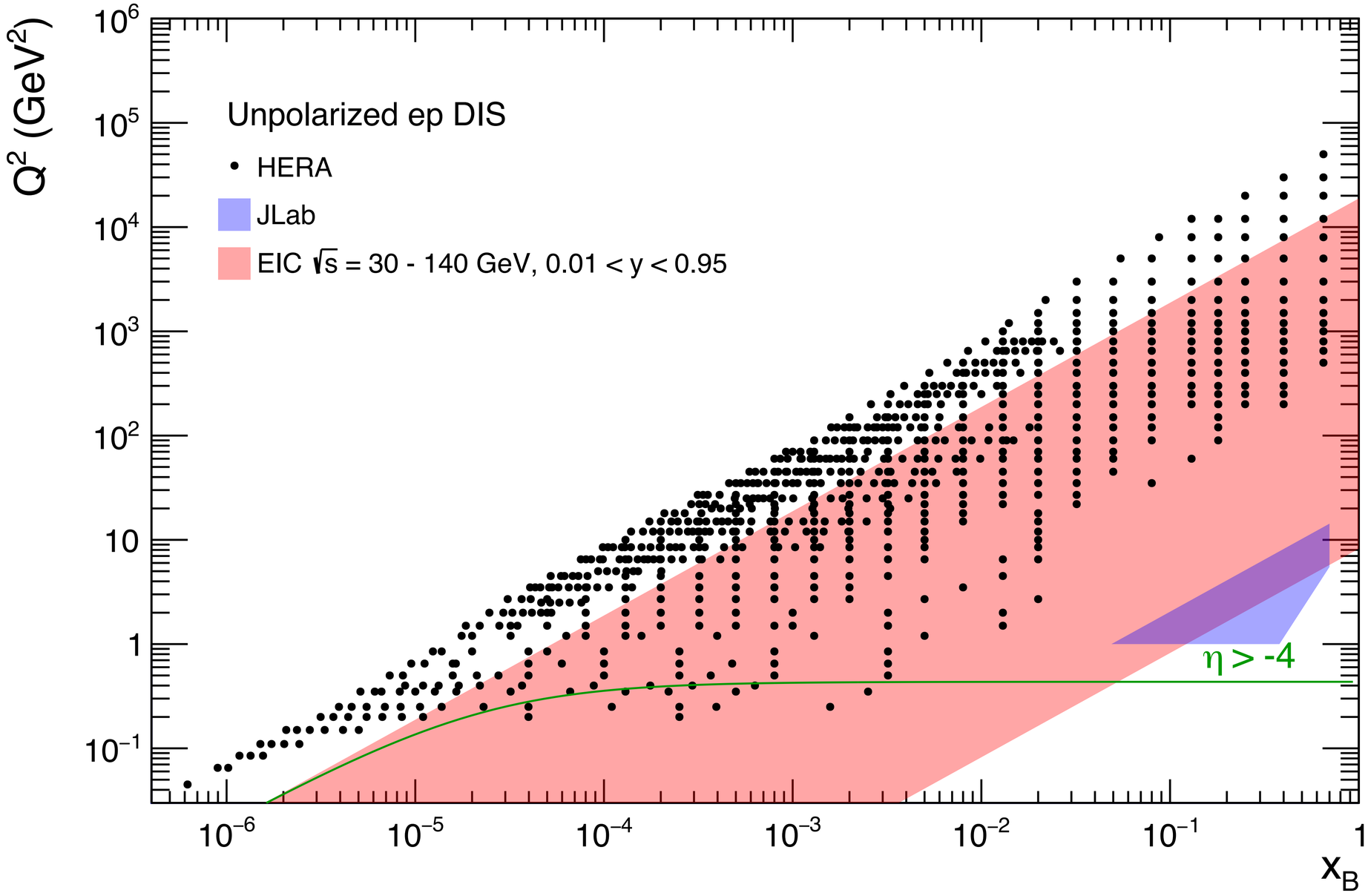


The electron-ion collider at BNL (Upton, New York)

- Under development at Brookhaven National Lab
- Fully polarized ep and eA collisions
- $20 < \sqrt{s} < 140$ GeV
- High luminosity
  → surpass total HERA dataset in first year of running
- ePIC detector under development
- Second interaction region for complementary detector

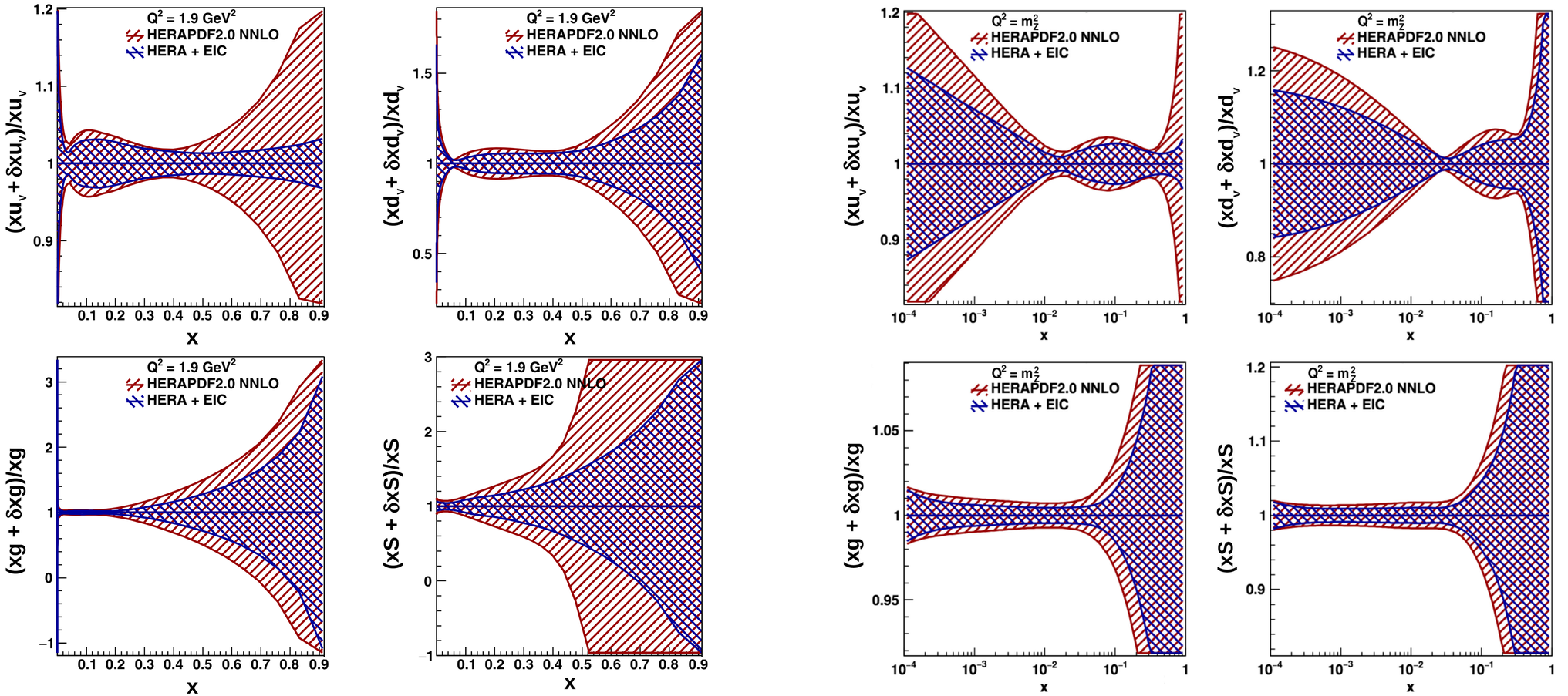


Unpolarized ep scattering



Projected impact on proton PDFs

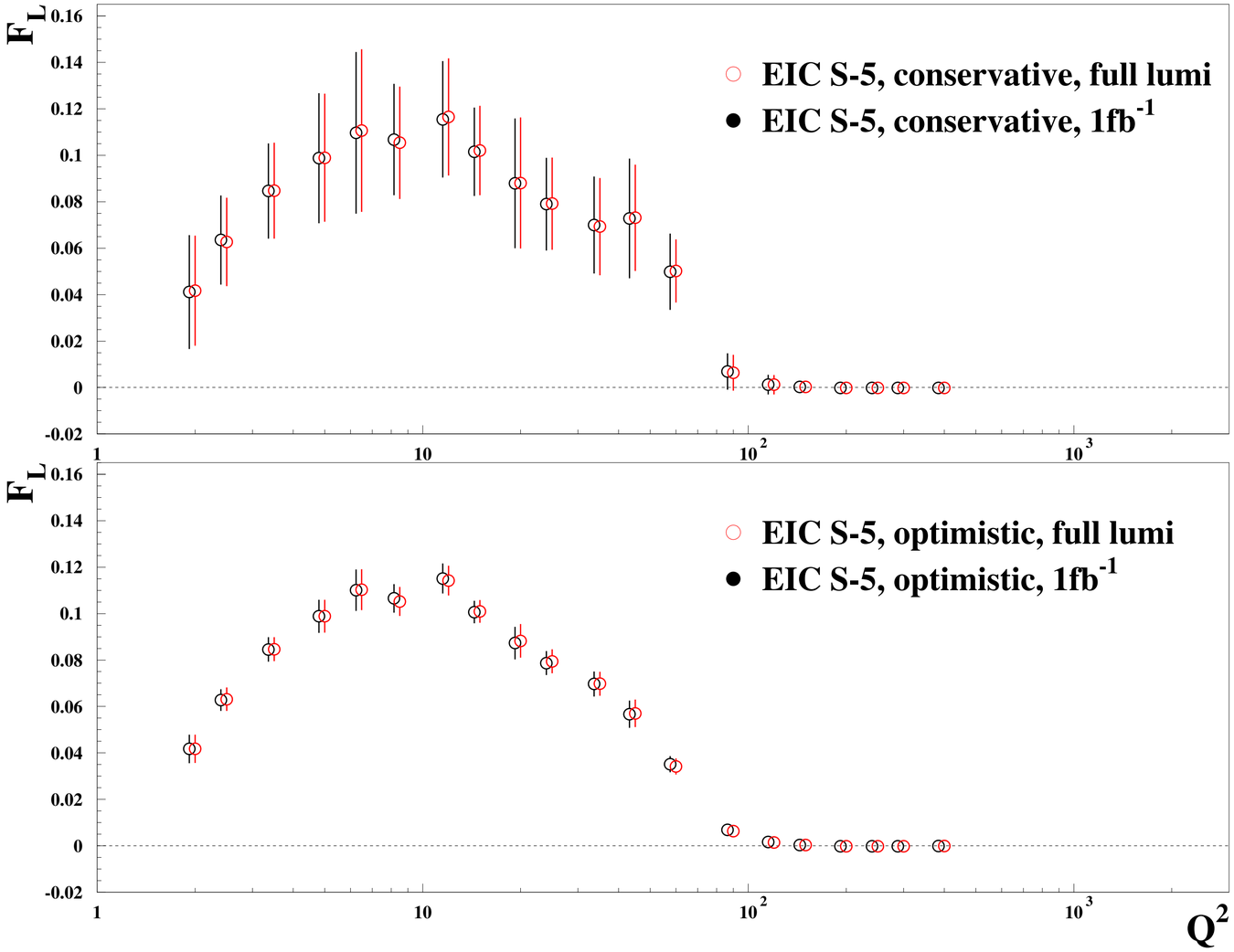
PRD 109, 054019 (2024)



- Assumes 1 year of running at 5 center of mass energies (at design luminosity)
- Conservative systematics based on HERA experience
- Biggest impact at large x

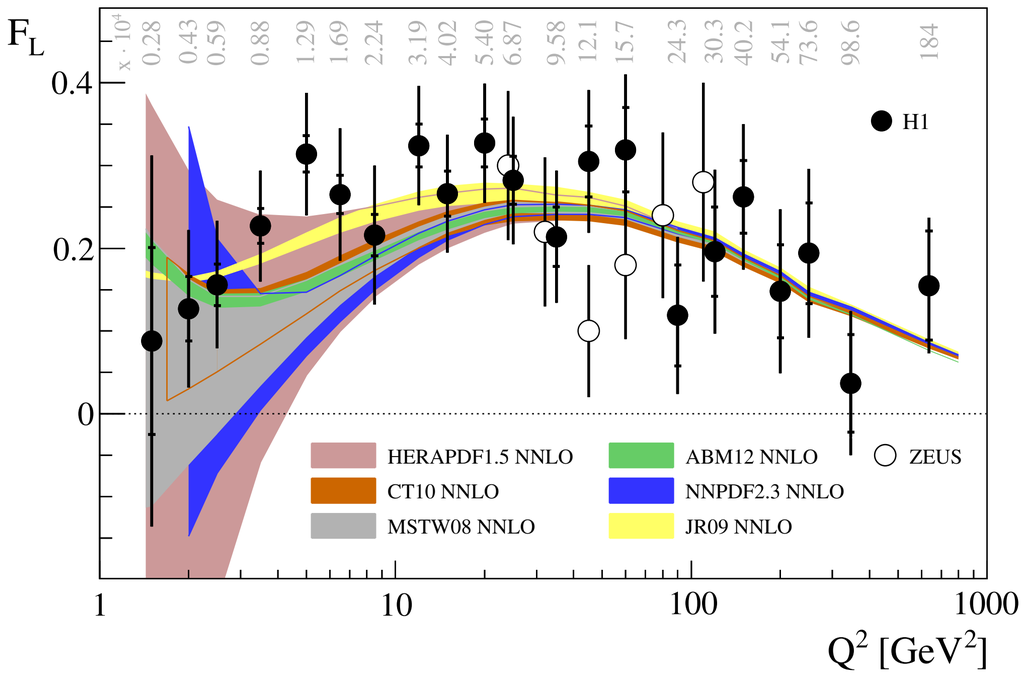
• Previous studies rely on fast MC and/or simple assumptions on systematics
• EIC is high luminosity → systematics limited
• Rigorous estimates of systematics from full ePIC simulation underway
• New impact studies planned, with focus on early science and long-term impact

Prospects for F_L extraction



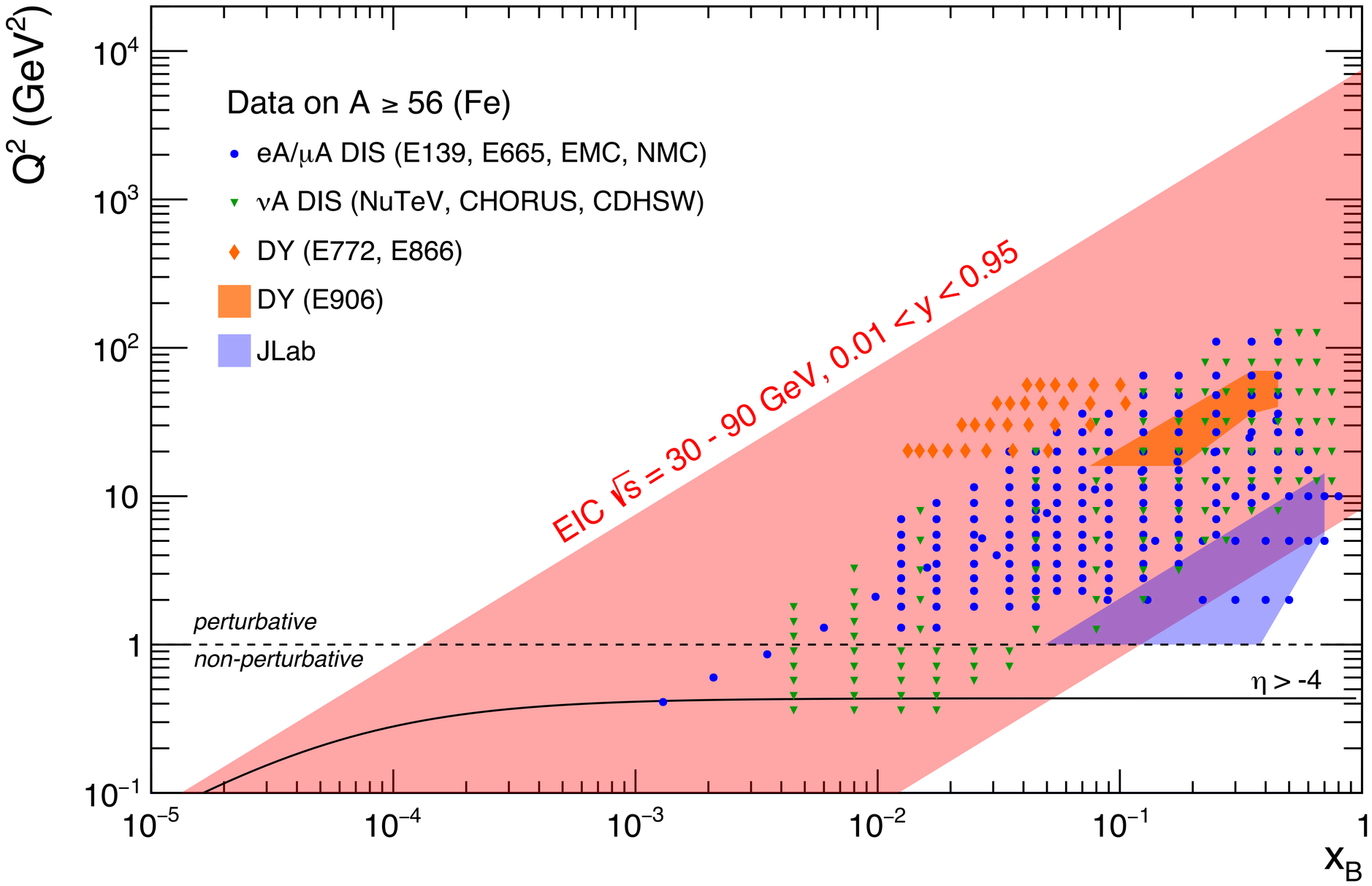
arXiv.2412.16123

EPJC 74, 2814 (2014)



- 1 fb^{-1} at five center of mass energies
- Optimistic vs. pessimistic systematics

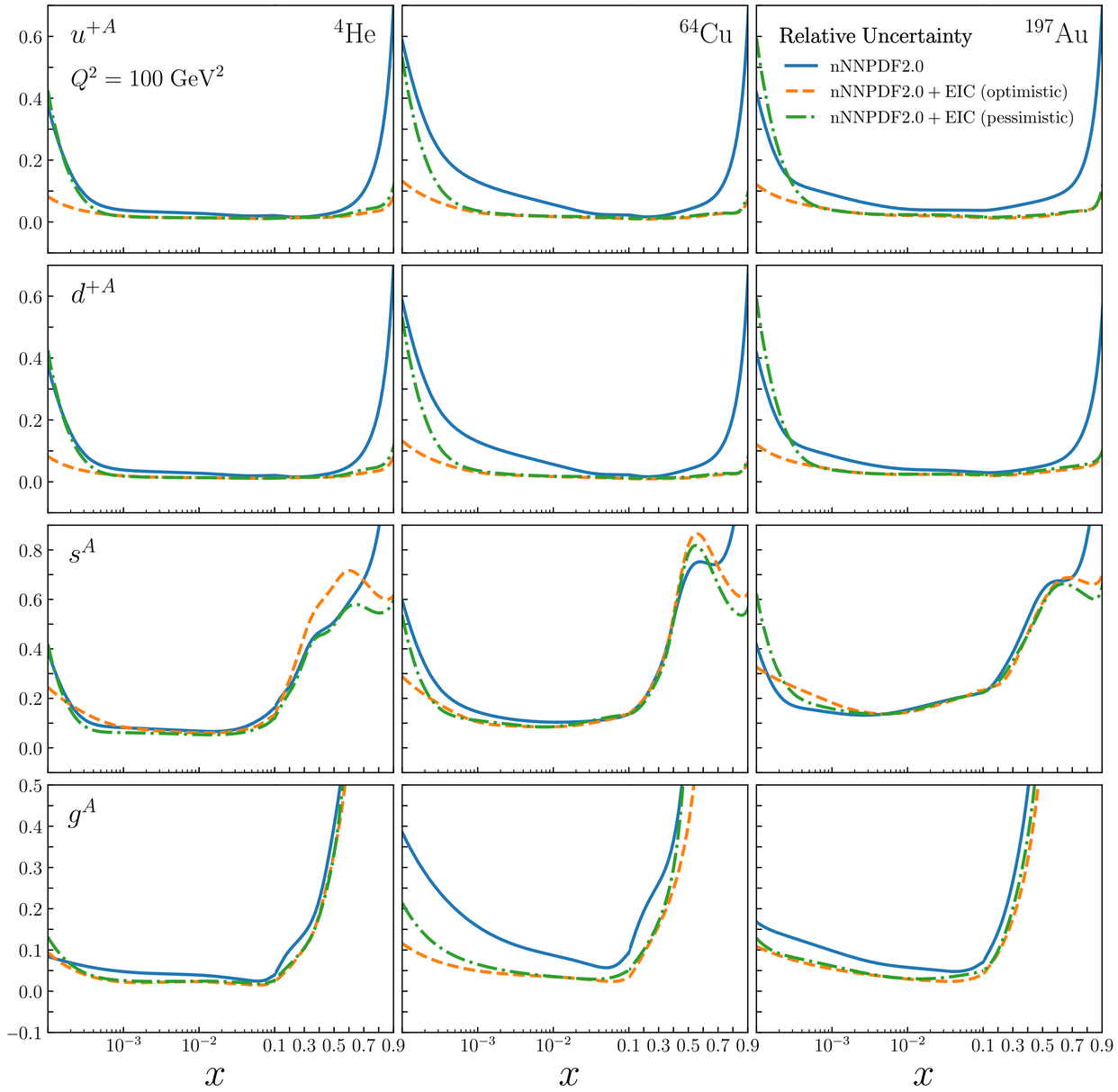
Unpolarized eA scattering



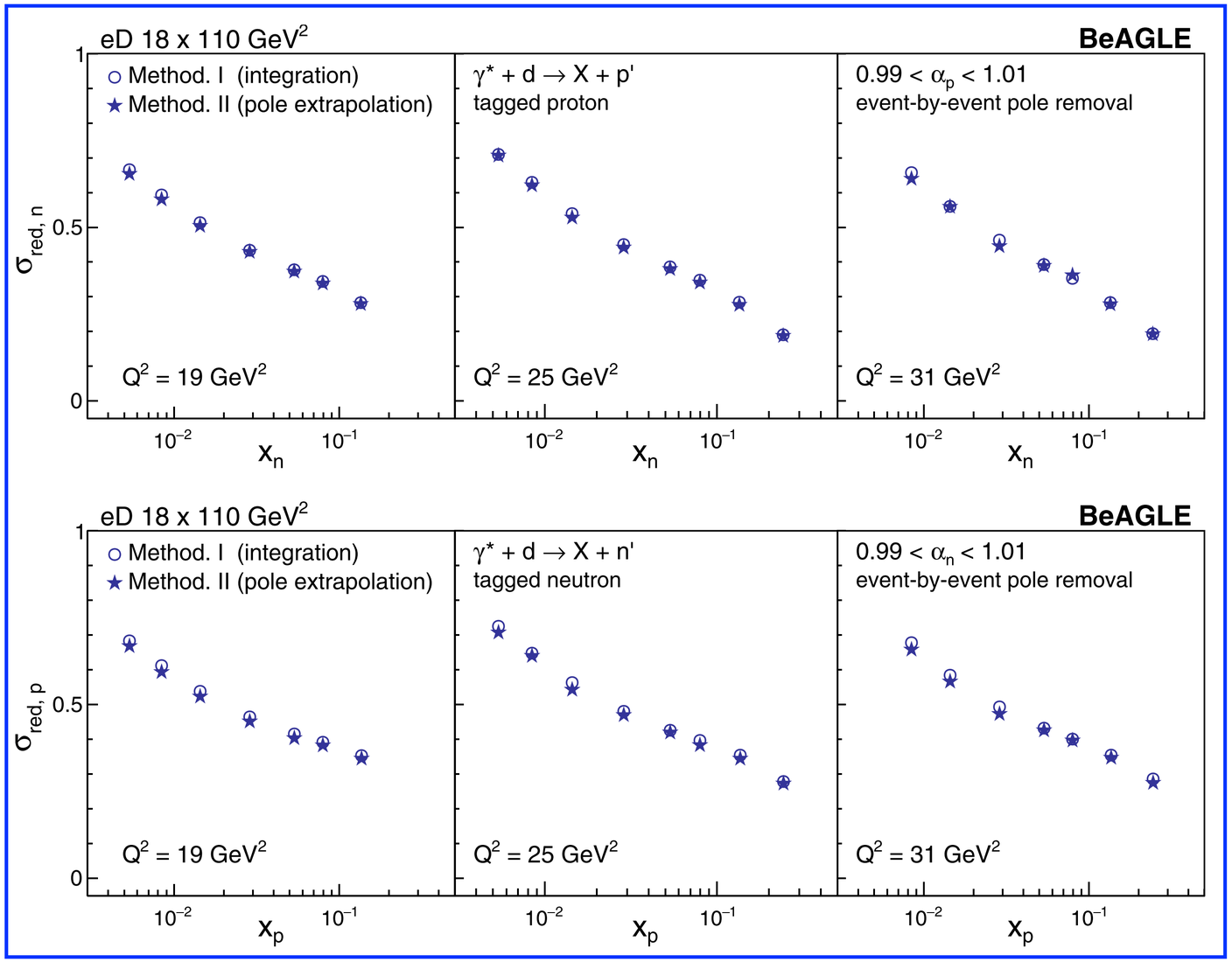
Projected impact on nPDFs

PRD 103, 096005 (2021)

- Assumes 10 fb^{-1} at three center of mass energies for each ion species
- Optimistic vs. pessimistic systematics
- Biggest impact at low, high x
- Larger reductions for heavier ions due to A-dependence of nPDFs
  → EIC data will largely equalize uncertainties among nuclei



Spectator-tagged DIS



[PRC 104, 065205 (2021)](#)

- Spectator-tagged DIS: $d(e, e'p_s)$
- Measure bound nucleon structure as a function of initial nuclear configuration
- Detect spectator in far-forward region
- Spectator nucleon highly boosted in lab frame → access to very low rest-frame spectator momentum
- Low p_s → extrapolate to free neutron structure
- Increasing p_s → measure bound nucleon modification as function of virtuality

Projected EIC impact: the fine print

- Previous studies rely on fast MC and/or simple assumptions on systematics
- EIC is high luminosity → systematics limited
- Rigorous estimates of systematics from full ePIC simulation underway
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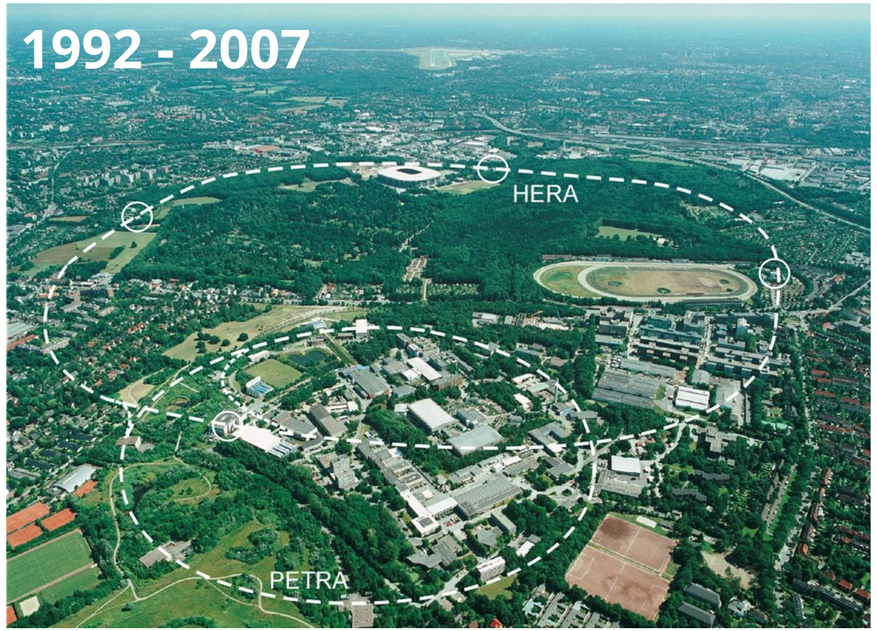
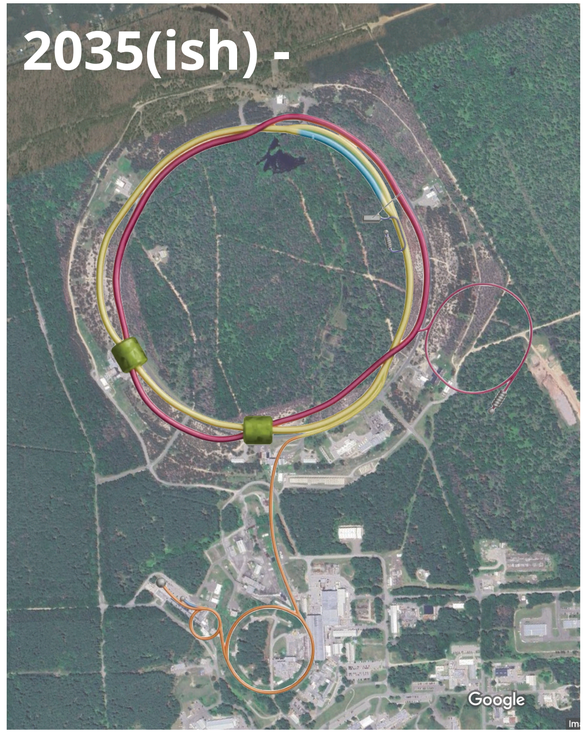
Summary

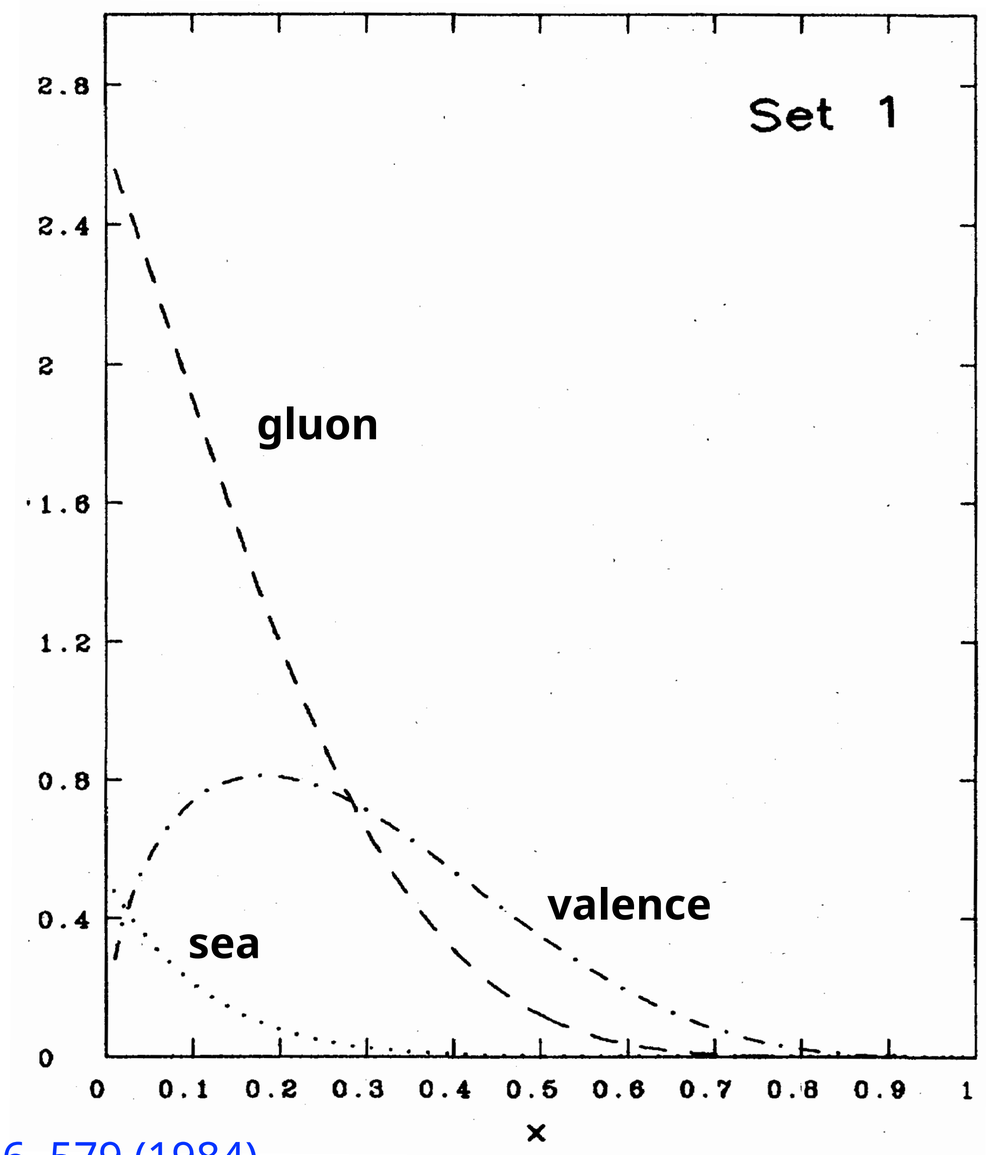
- DIS data is the *most important* constraint on modern PDFs
- Nearly 20 years after shutdown, HERA continues to be critical input to global QCD analyses
- The EIC will carry on HERA's legacy, making major contributions to:
  - Proton PDFs at large x
  - Nuclear PDFs at low x, high Q^2
  - Nuclear modification



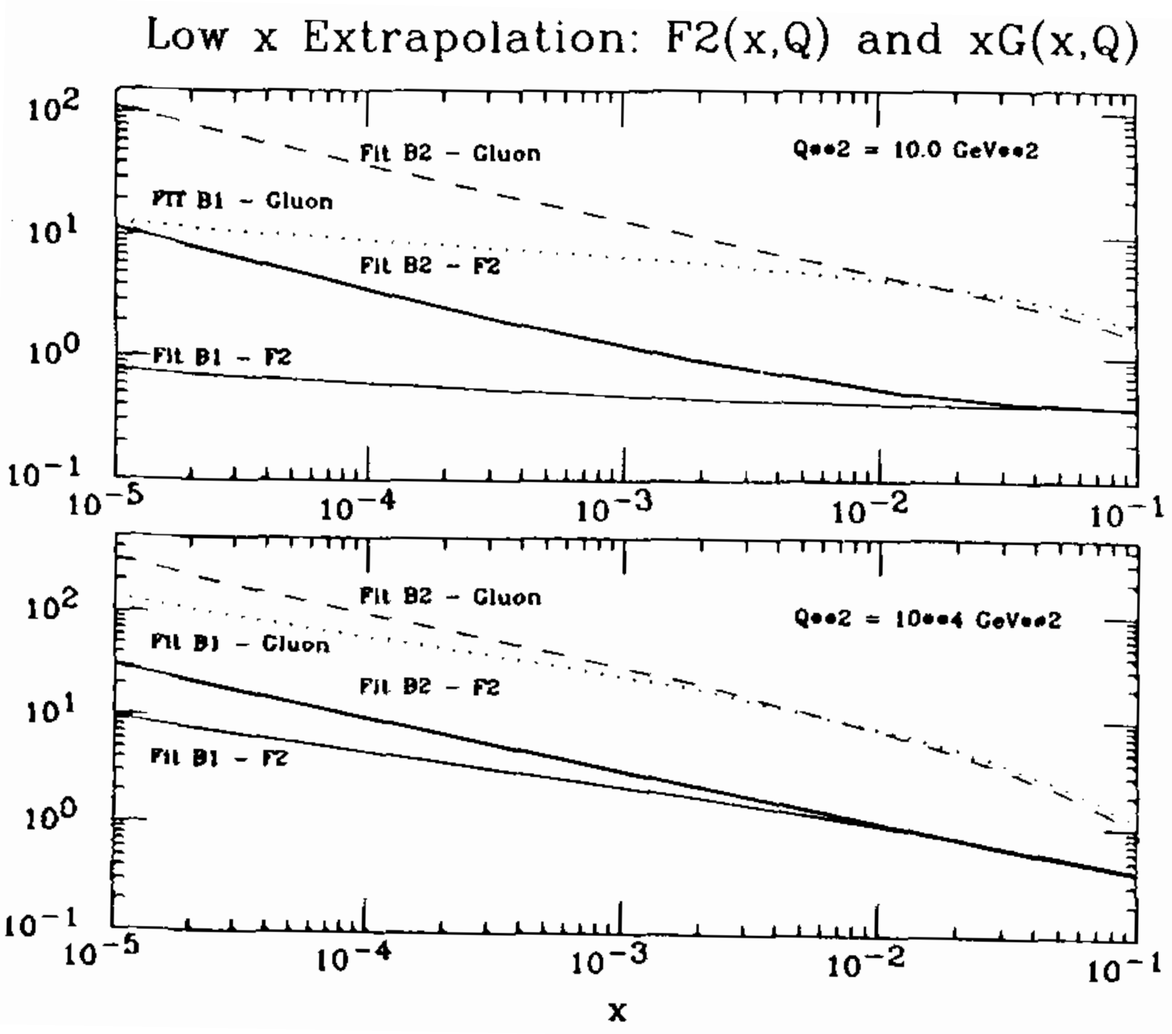


Backup

Expectation for structure function at low x?

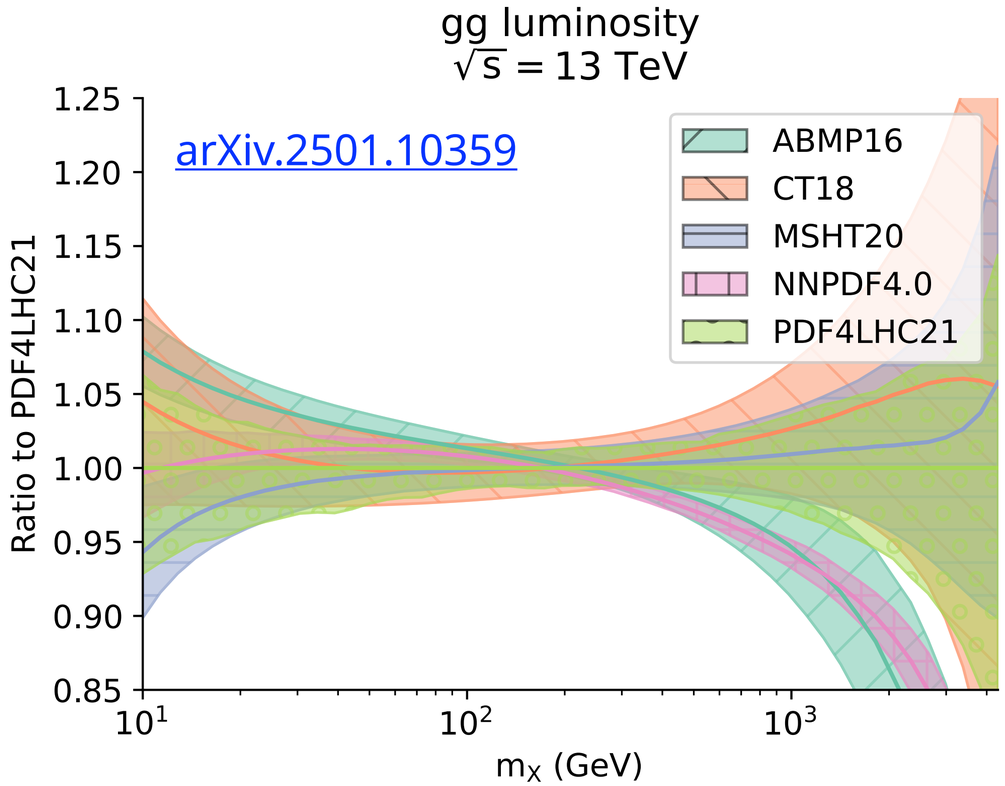


RMP 56, 579 (1984)



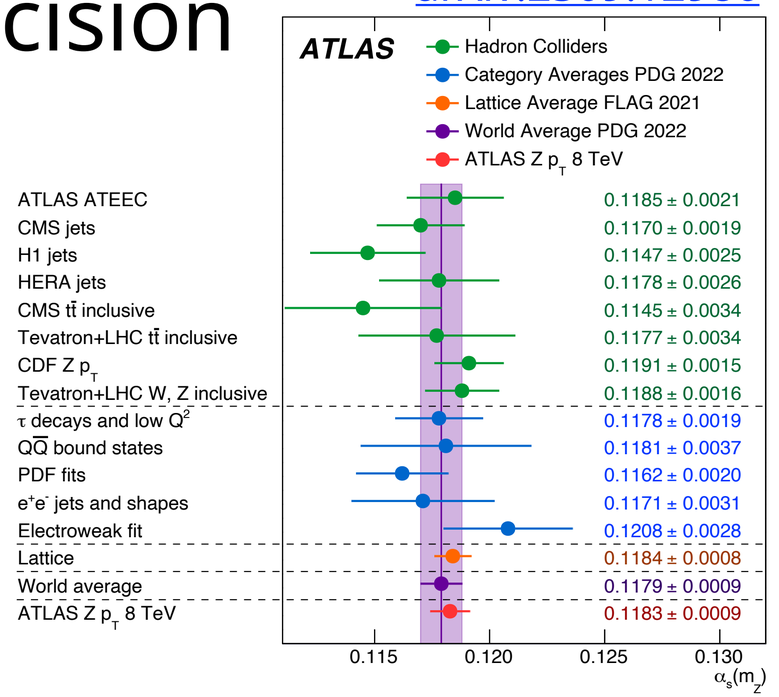
ZPC 52, 13 (1991)

...and are limiting factors to precision measurements at the LHC



Many interesting processes are gg initiated (t, H, LQ...)

arXiv:2309.12986

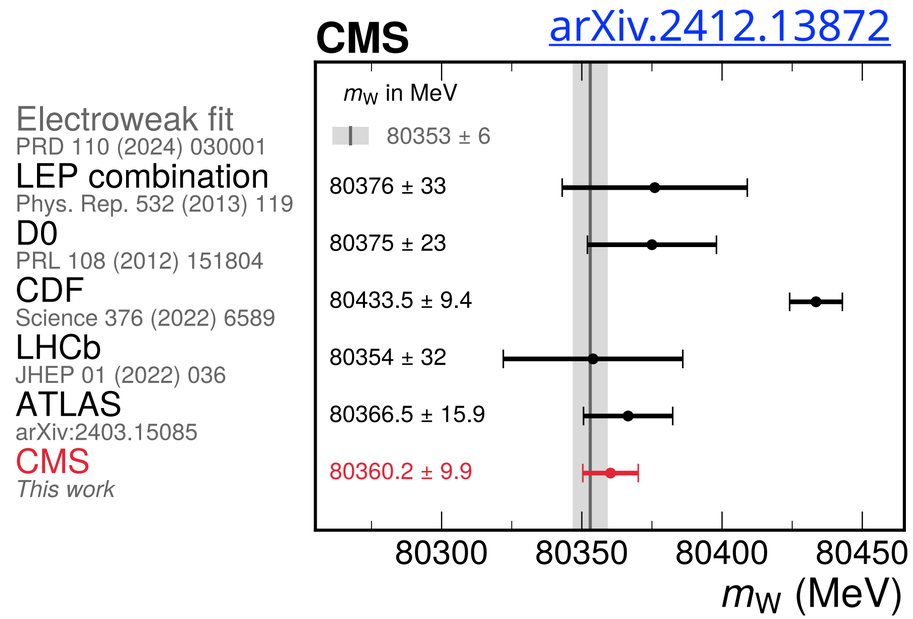


α_S from ATLAS

$\delta_{tot} = 0.0009$

$\delta_{PDF} = 0.0005$

arXiv.2412.13872

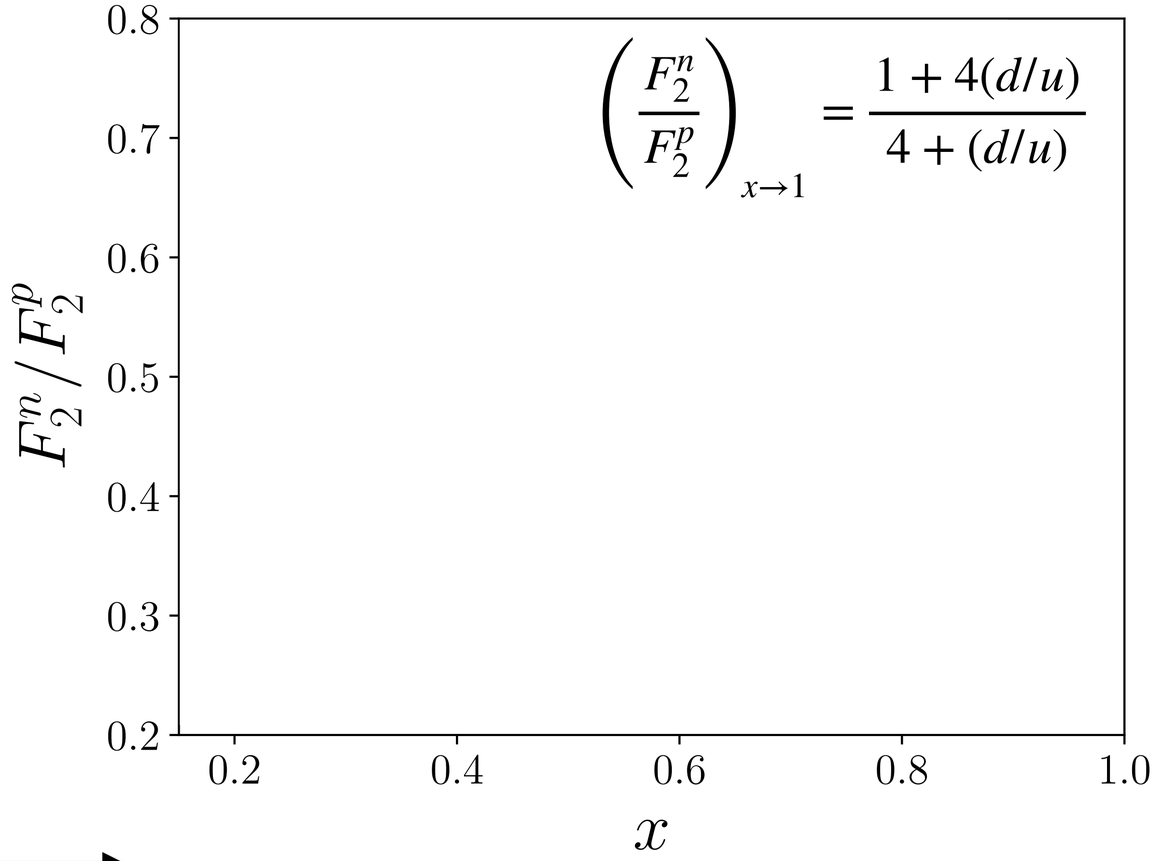


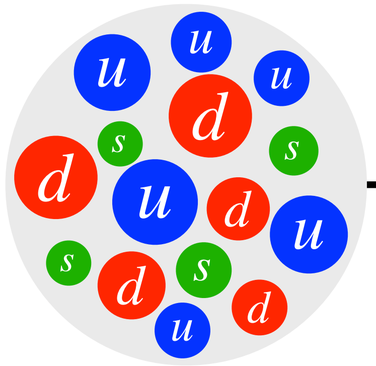
M_W from CMS

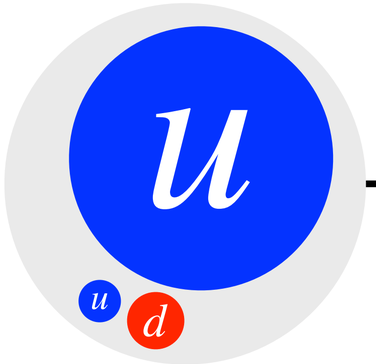
$\delta_{tot} = 9.9$ MeV

$\delta_{PDF} = 4.4$ MeV

F_2^n/F_2^p, d/u at high x sensitive to spin-flavor symmetry breaking







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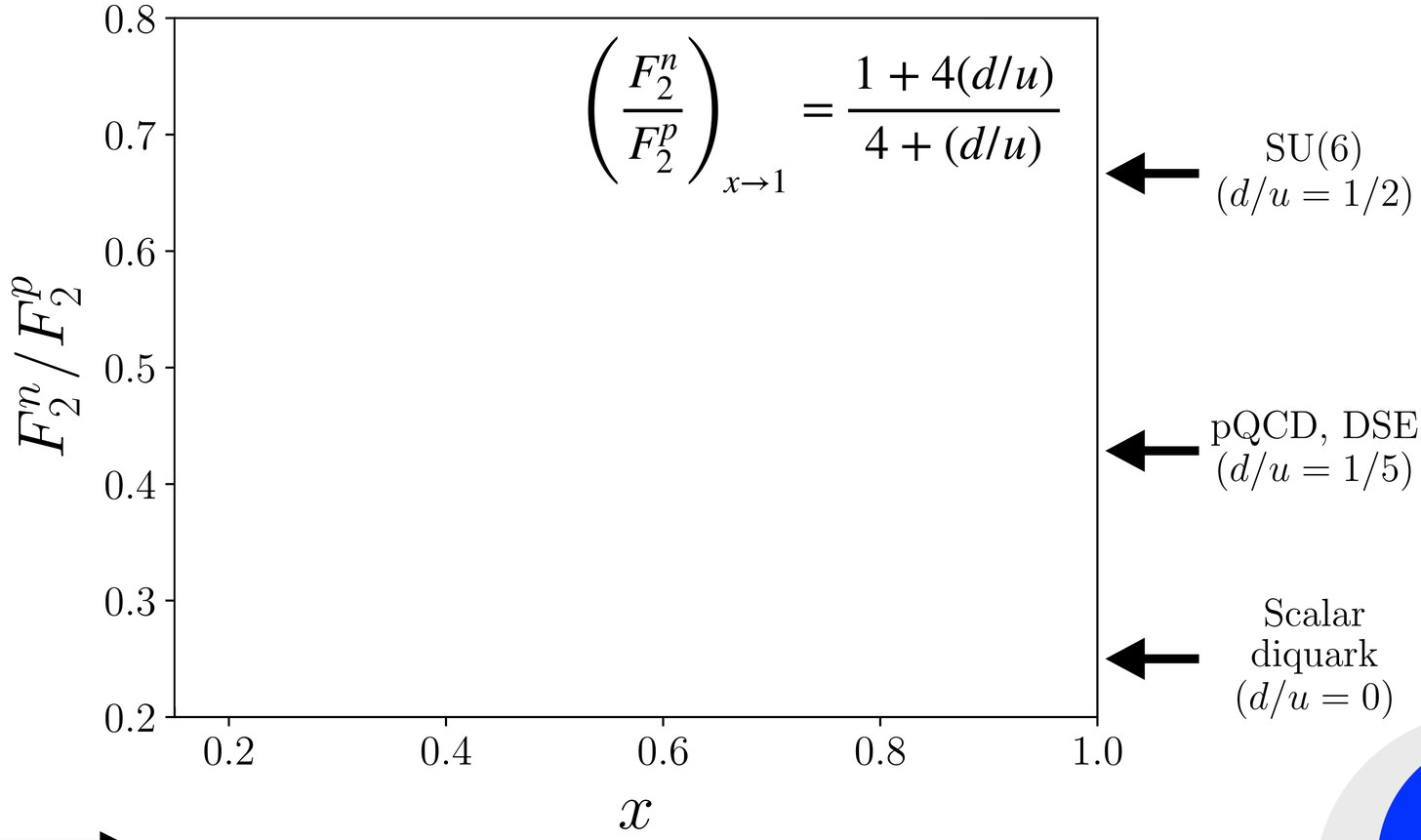
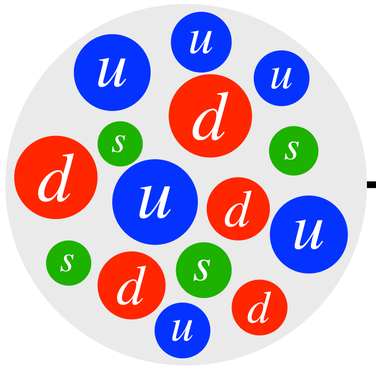
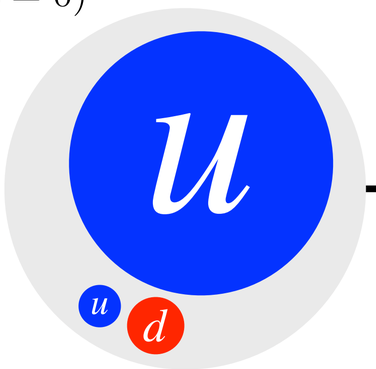
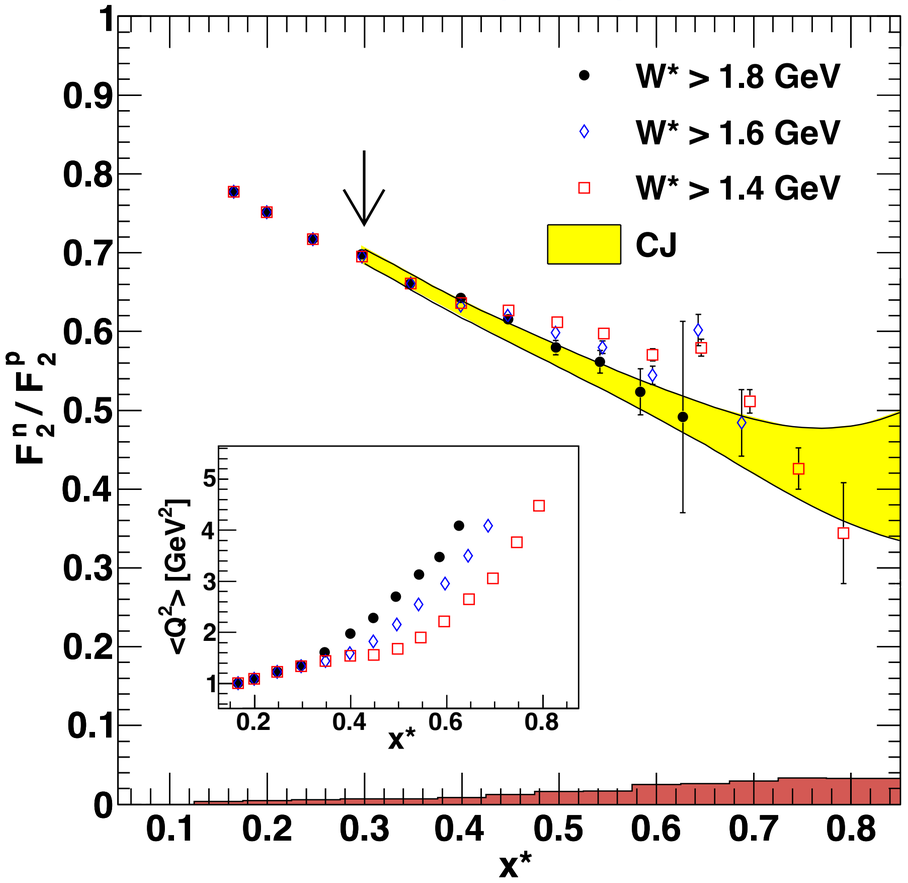






Alternative methods for constraining d/u...

PRL 108, 142001 (2012)



BoNuS/BoNuS12

- Spectator-tagged DIS: $d(e, e' p_s)$
- Extract nearly-free F_2^n

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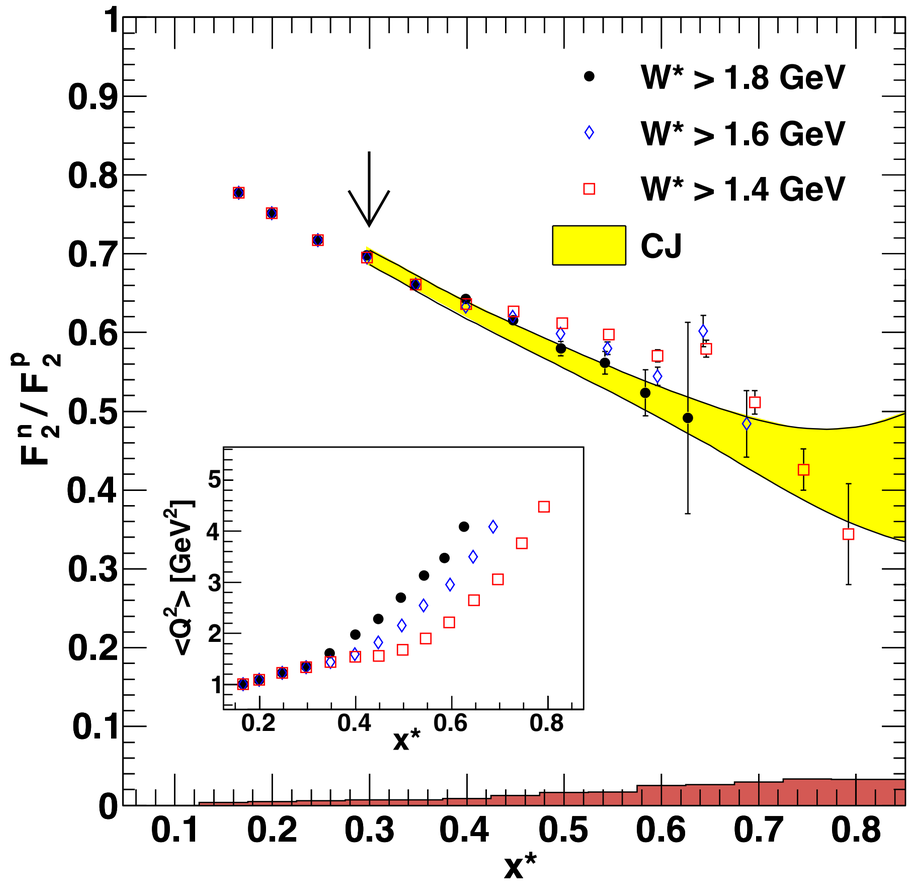

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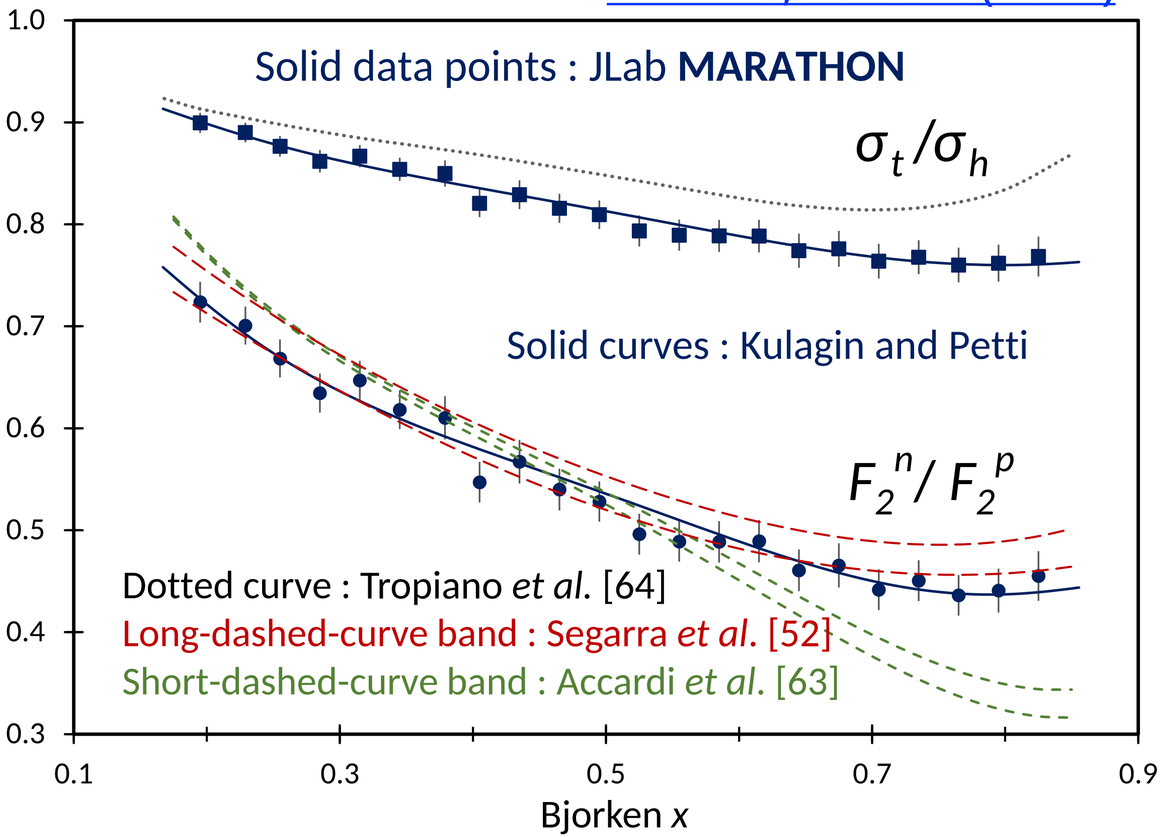
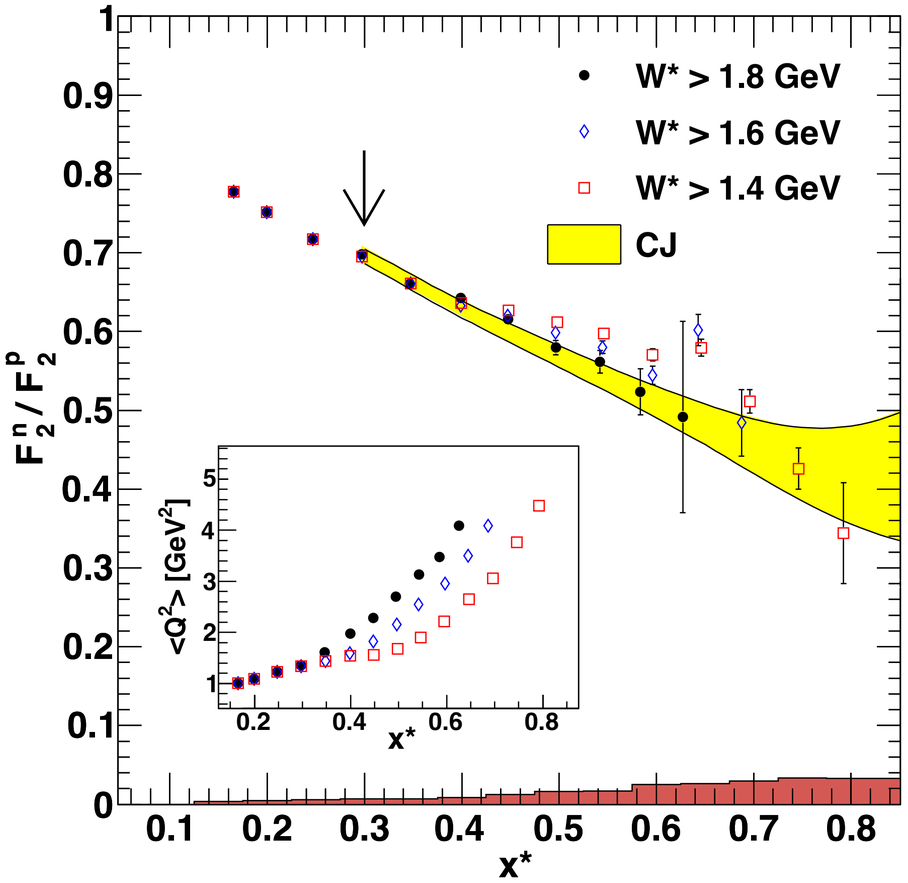
PRL 128, 132003 (2022)



MARATHON:

- Inclusive DIS ratio ^{3}He/^{3}H
- Extract F_2^n / F_2^p with minimal model corrections

Alternative methods for constraining d/u...



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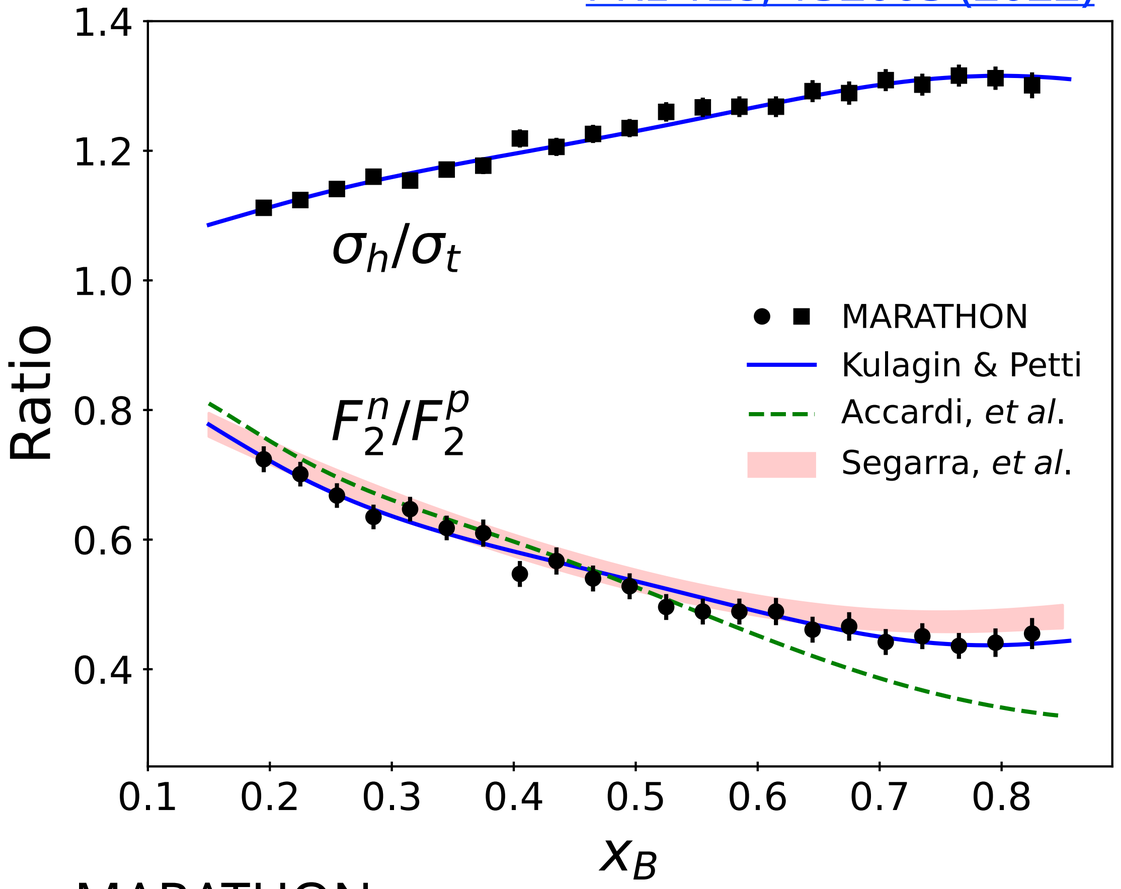
PRL 128, 132003 (2022)



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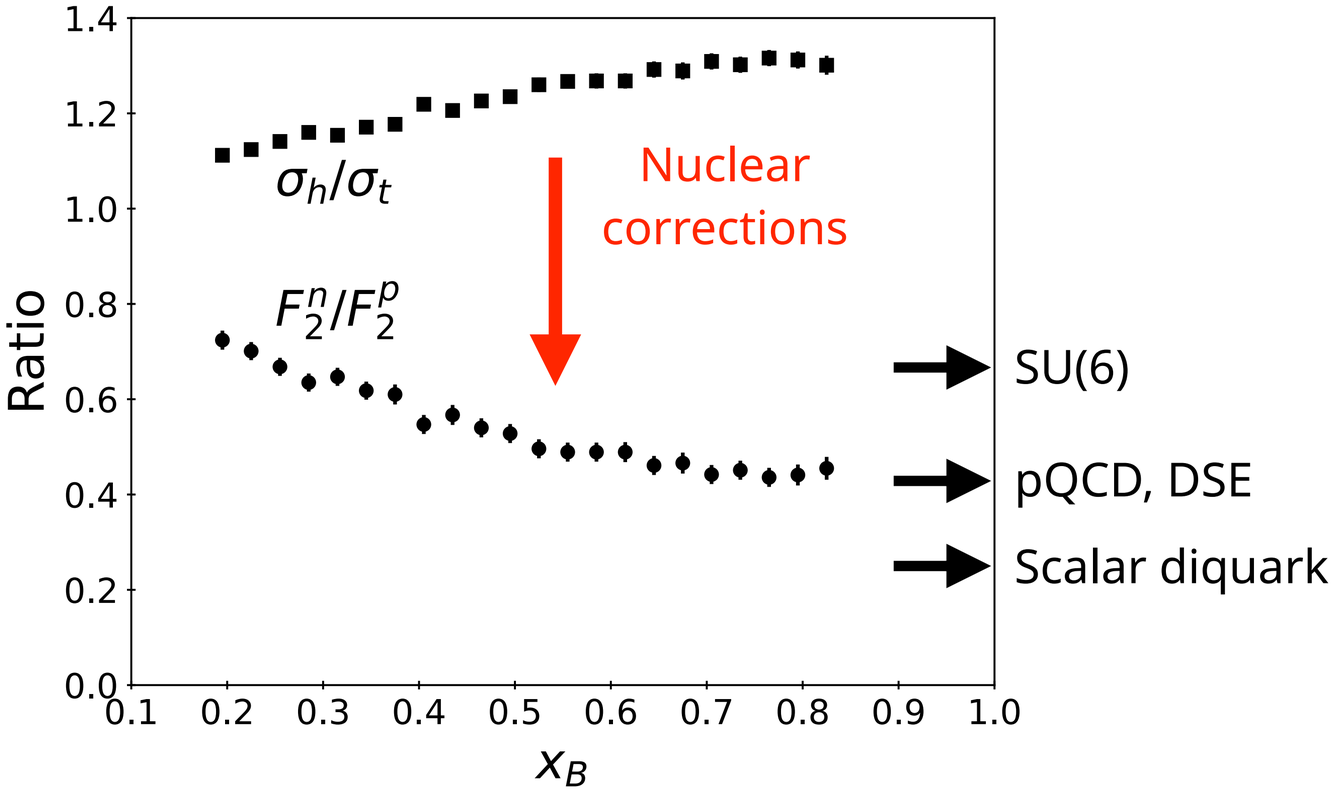
...are still inconclusive



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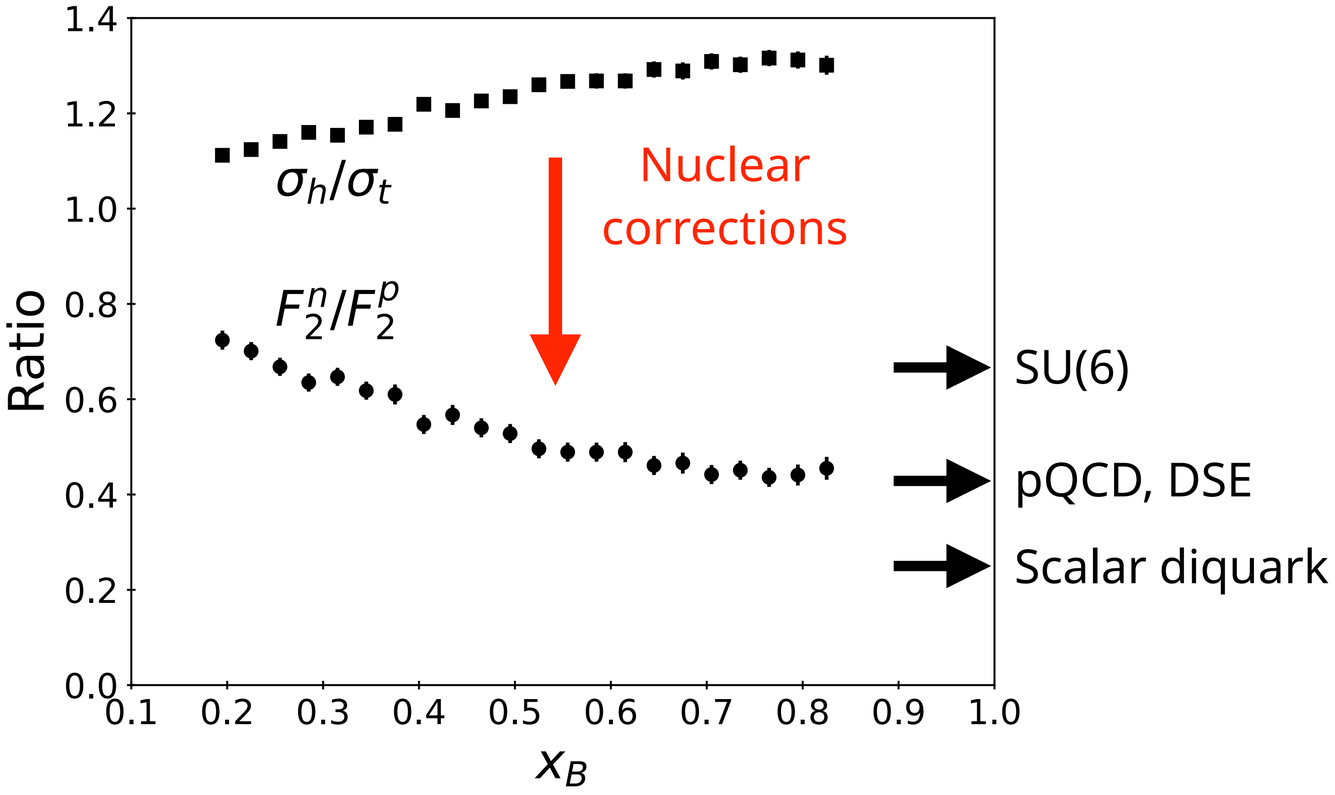

- Both BoNuS/BoNuS12 and MARATHON fixed-target with $Q^2 < 12$ GeV^2
- Non-negligible contribution from higher twist, target mass effects
- More *large, model-dependent, poorly-constrained* corrections

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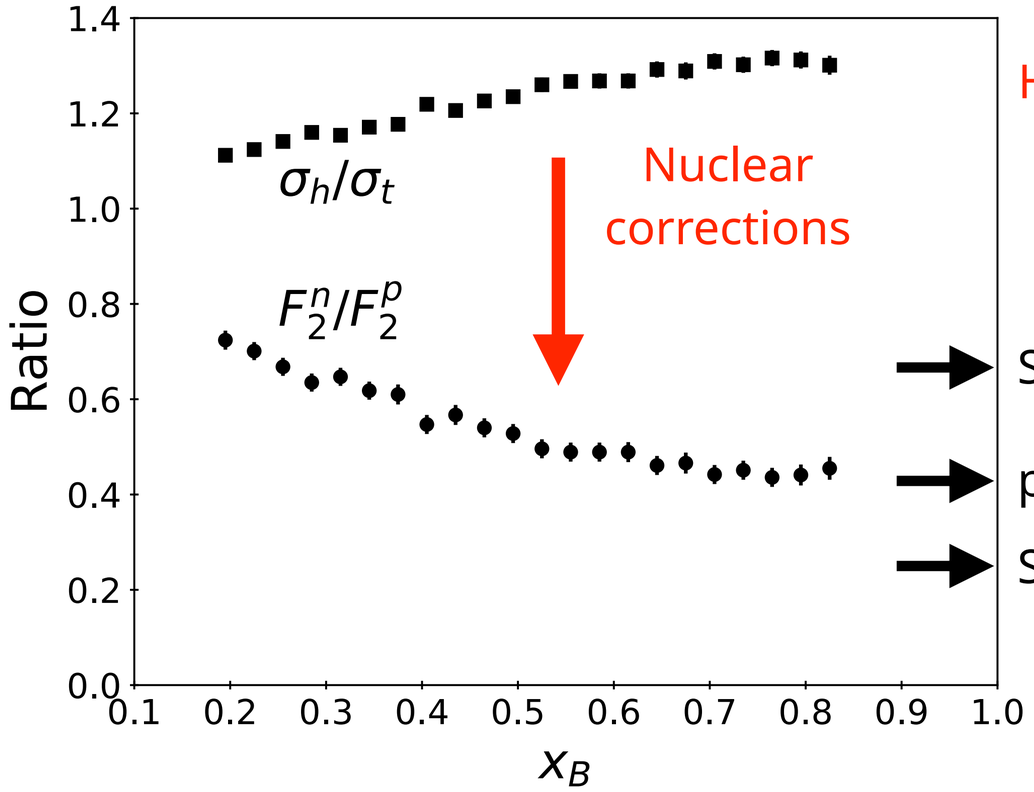
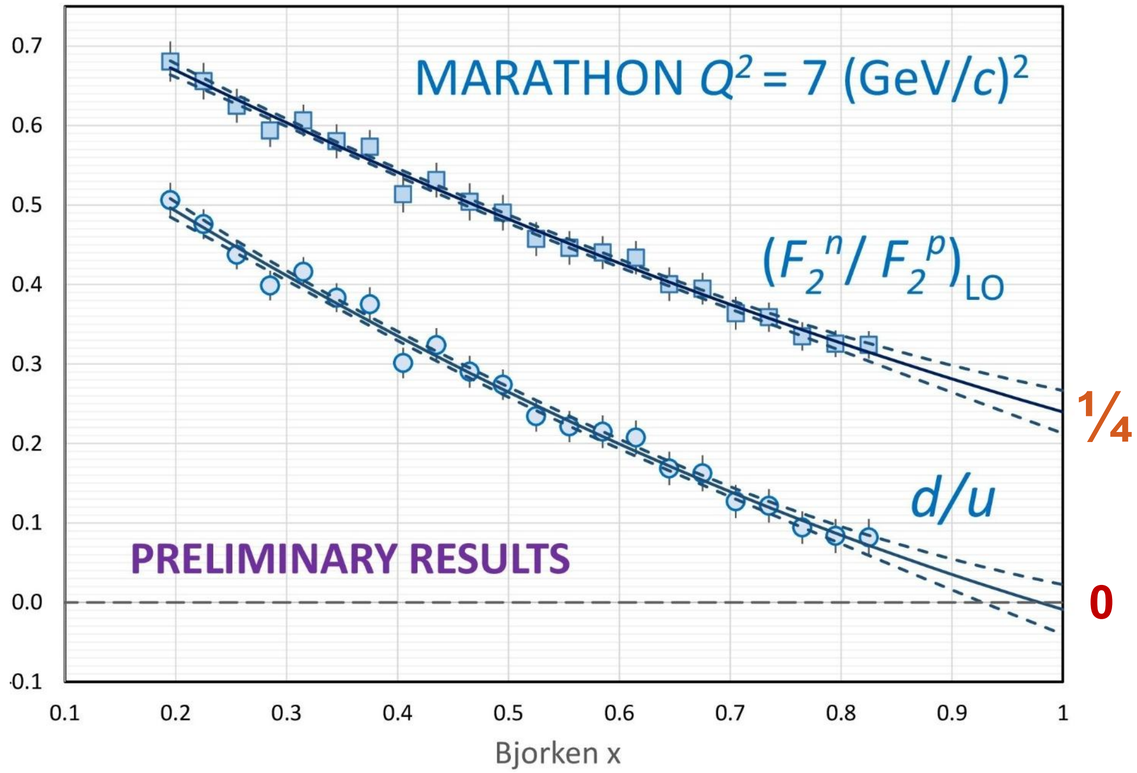
Preliminary analysis by G. Petratos, A. Katramatou, S. Alekhin, S. Kulagin, R. Petti
Presented at XIV International Conference on New Frontiers in Physics



HT, TM, s-quark corrections?

- SU(6)
- pQCD, DSE
- Scalar diquark



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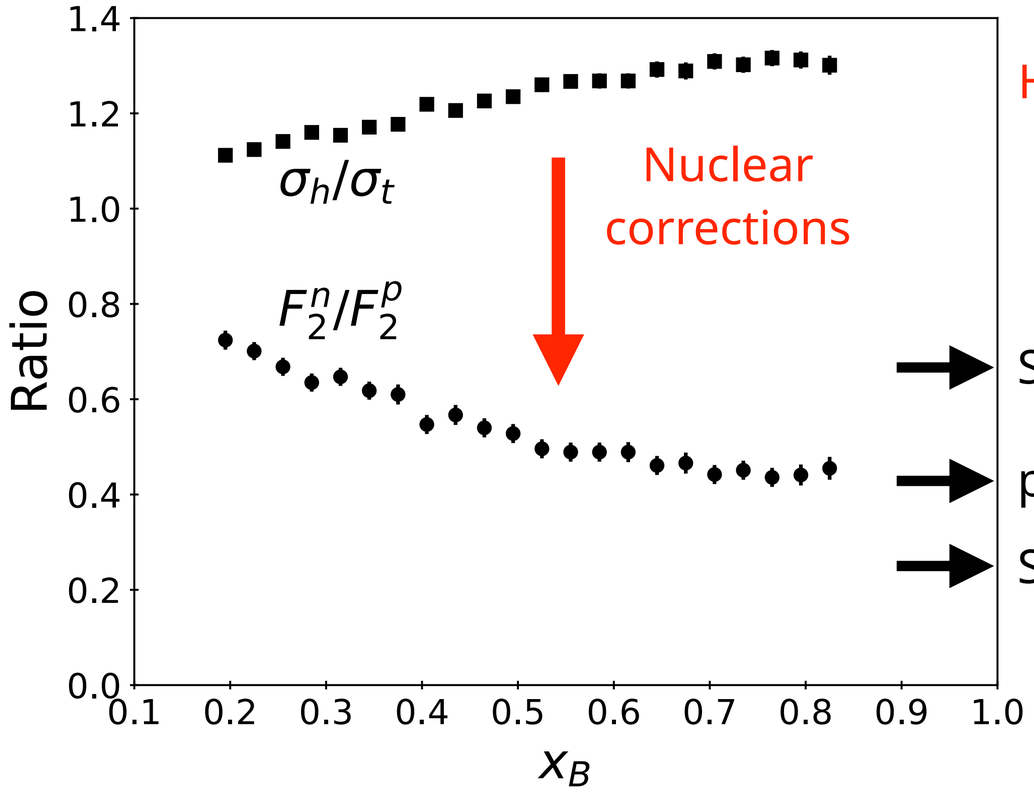

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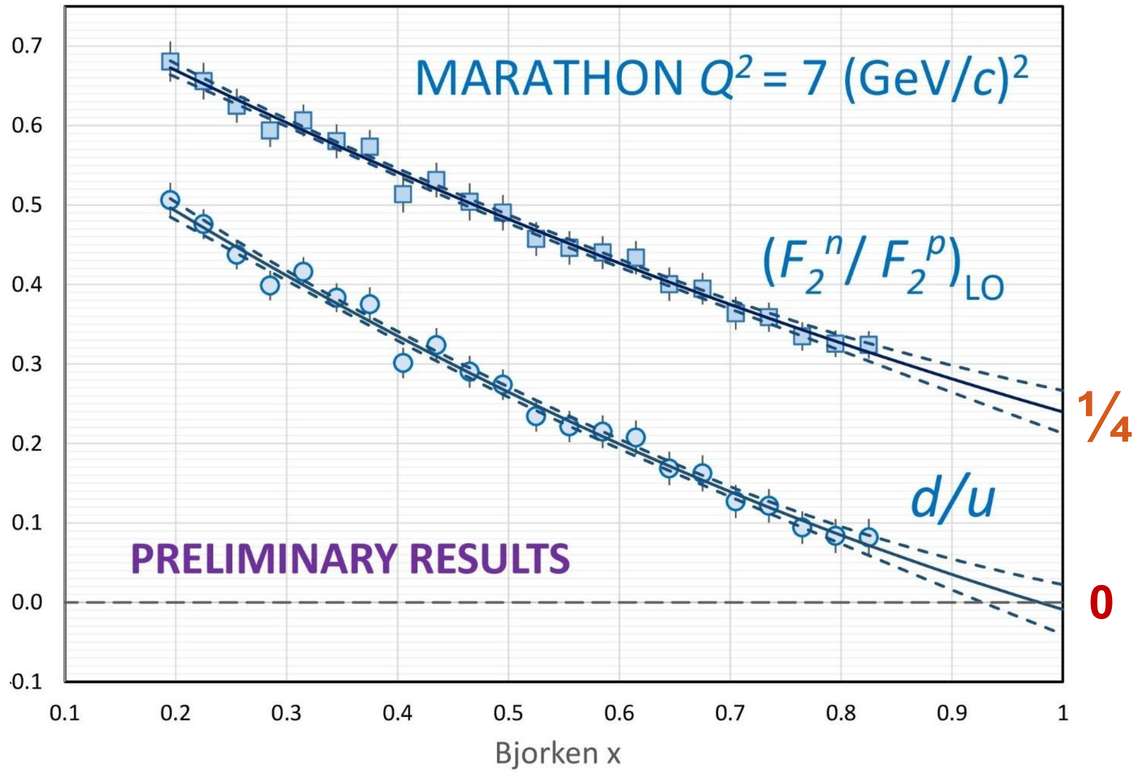

- Both BoNuS/BoNuS12 and MARATHON fixed-target with $Q^2 < 12$ GeV^2
- Non-negligible contribution from higher twist, target mass effects
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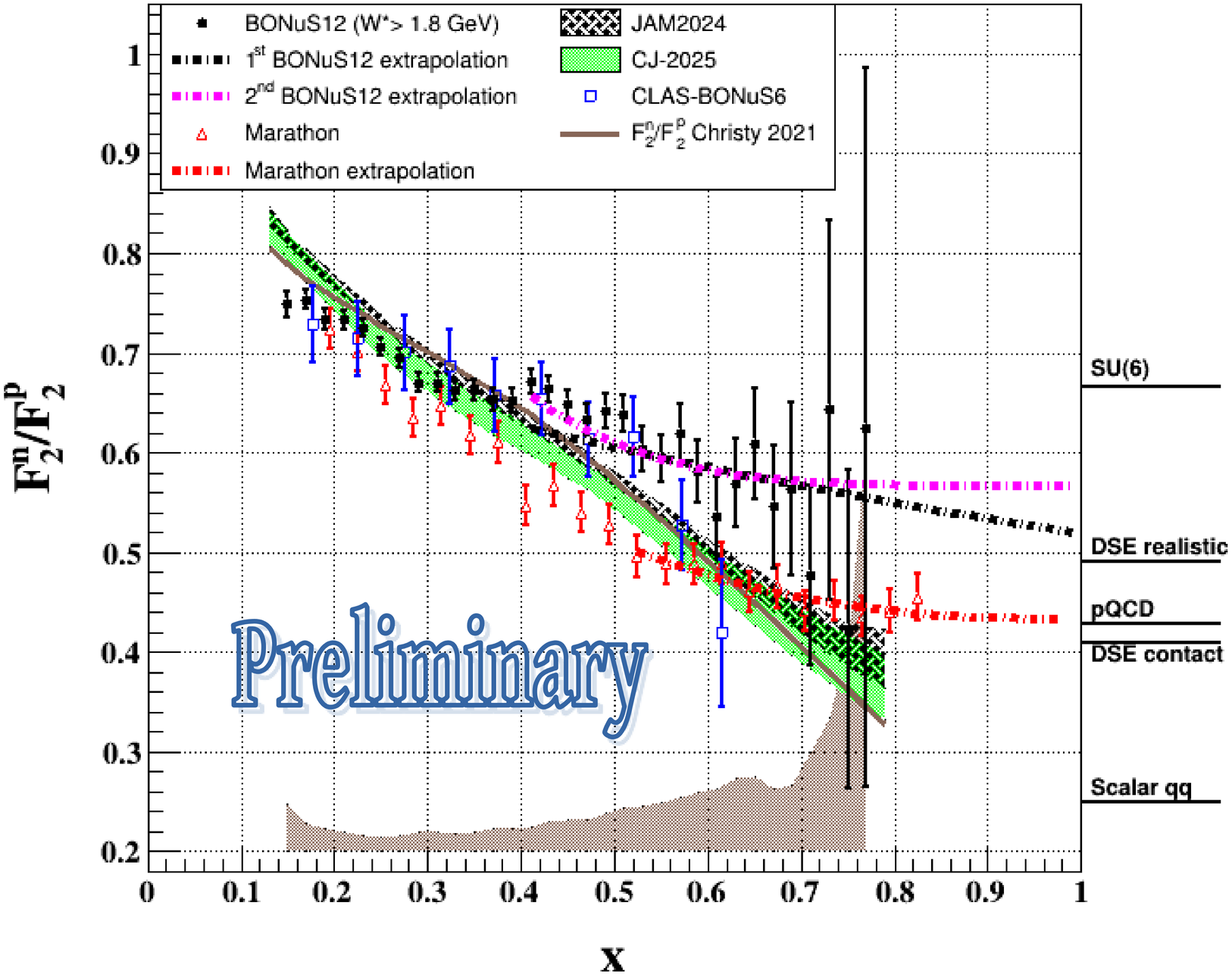
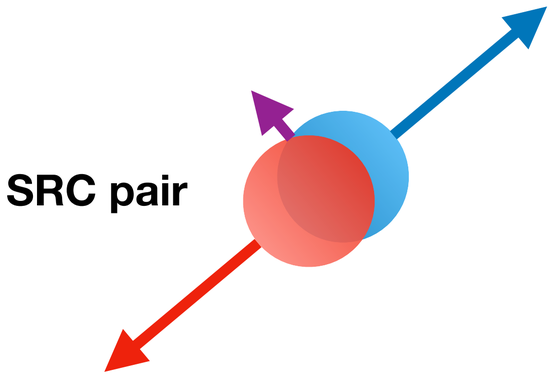
- ***No definitive DIS determination of*** d/u ***at large*** x

BoNuS12

BoNuS12


BONuS12 (W*> 1.8 GeV)
1st BONuS12 extrapolation
2nd BONuS12 extrapolation
Marathon
Marathon extrapolation
JAM2024
CJ-2025
CLAS-BONuS6
F2n/F2p Christy 2021
Preliminary
SU(6)
DSE realistic
pQCD
DSE contact
Scalar qq
F2n/F2p
x

Alternative approach…modification of short-range correlated (SRC) nucleons



- Small separation ($\lesssim$ radius)
- Large relative, small center of mass momentum (relative to k_F)
- Dominated by np pairs

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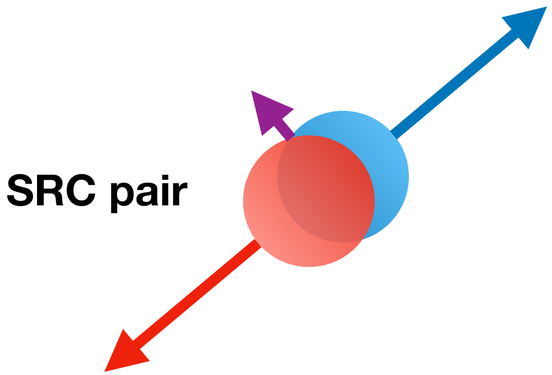

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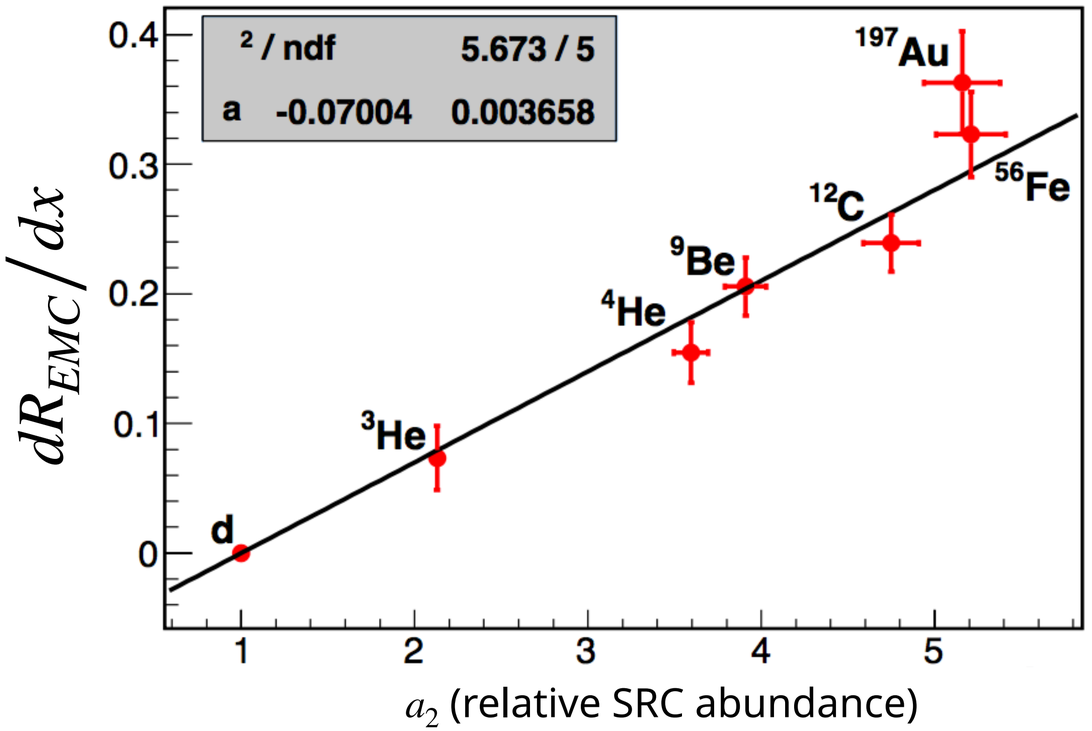
Rev. Mod. Phys. 89, 045002 (2017)



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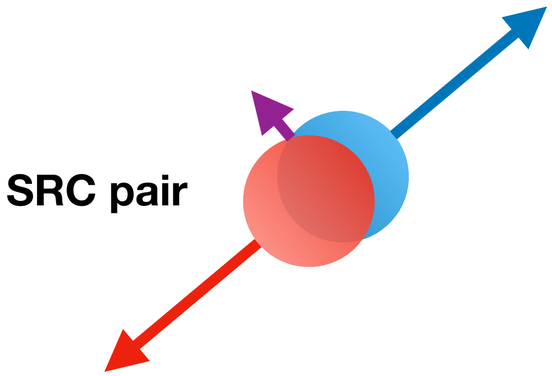

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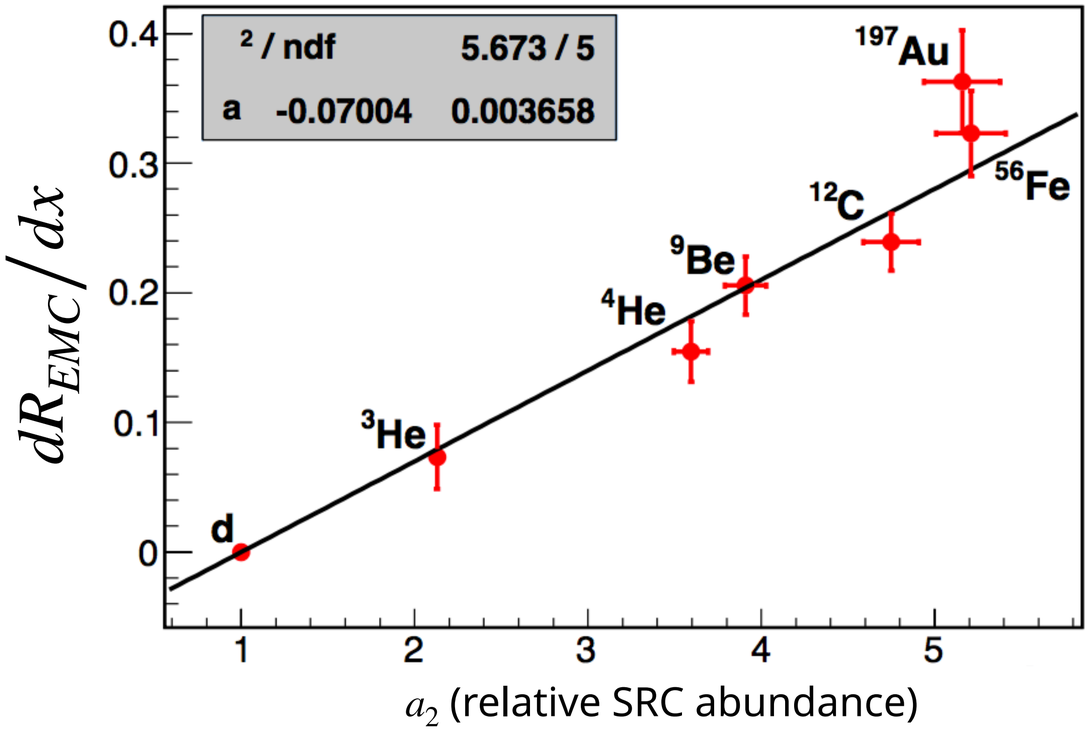
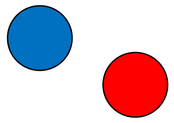
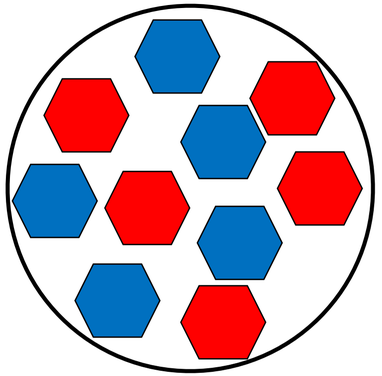
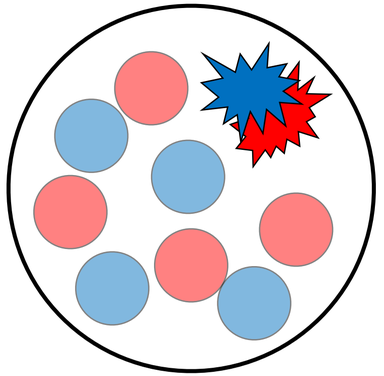




Free nucleons

Traditional:
All nucleons slightly modified





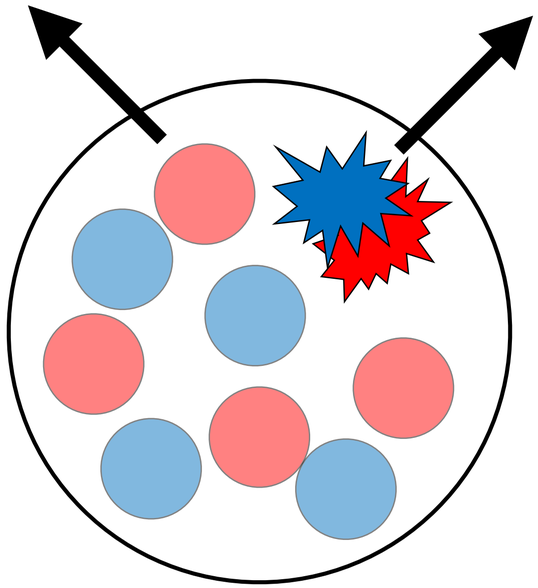
SRC-EMC hypothesis:
Few (SRC) nucleons highly modified

nCTEQ fit with only *some* nucleons modified

Abundance and structure of *free* nucleons

Abundance and structure of *modified* nucleons

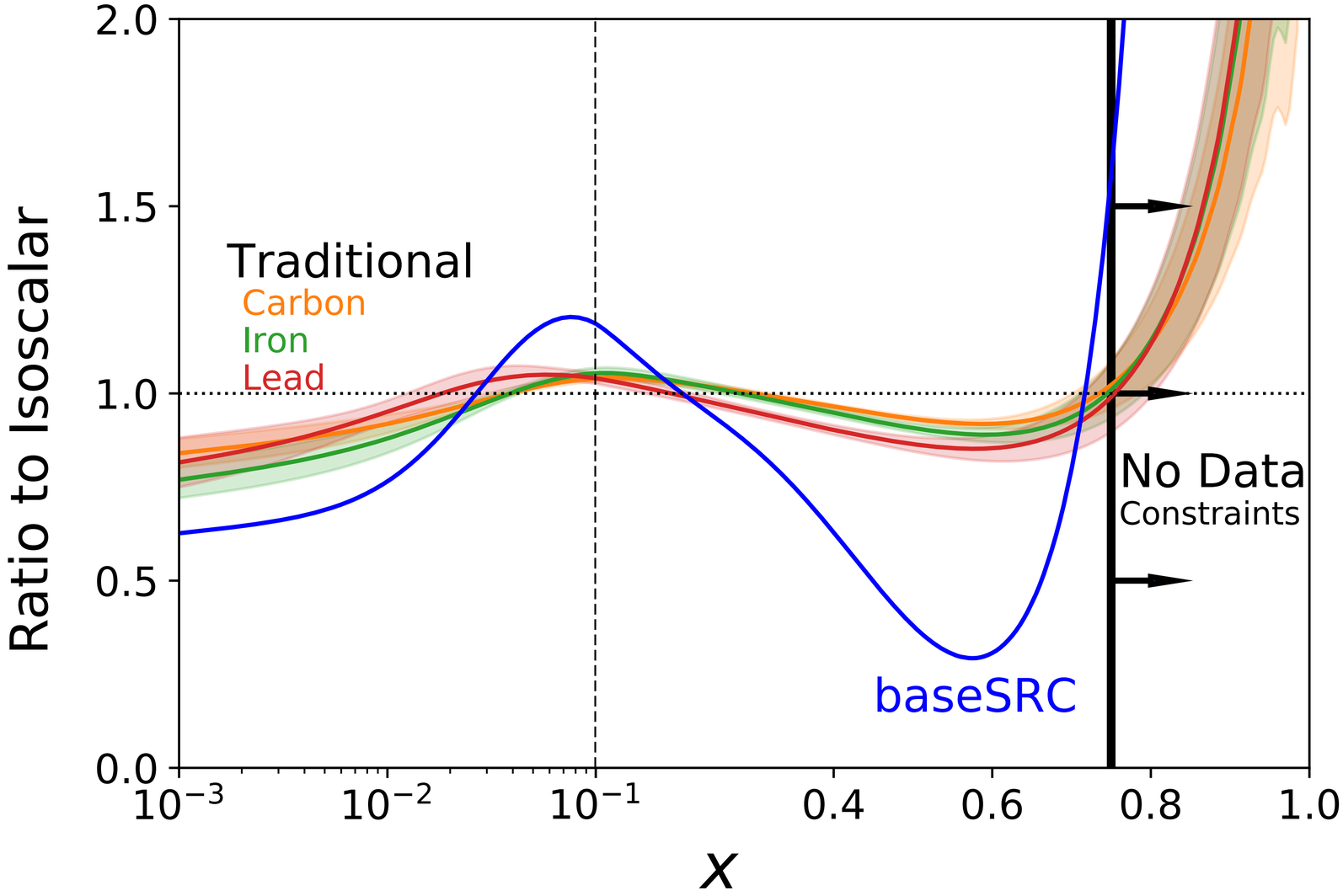
$$f_i^A\left(x,Q^2\right) = \frac{Z}{A}\left[(1-C_p^A)\times f_i^p\left(x,Q^2\right) + C_p^A \times f_i^{SRC\ p}\left(x,Q^2\right)\right]$$
$$+\frac{A-Z}{A}\left[(1-C_n^A)\times f_i^n\left(x,Q^2\right) + C_n^A \times f_i^{SRC\ n}\left(x,Q^2\right)\right]$$



PRL 133, 152502 (2024)

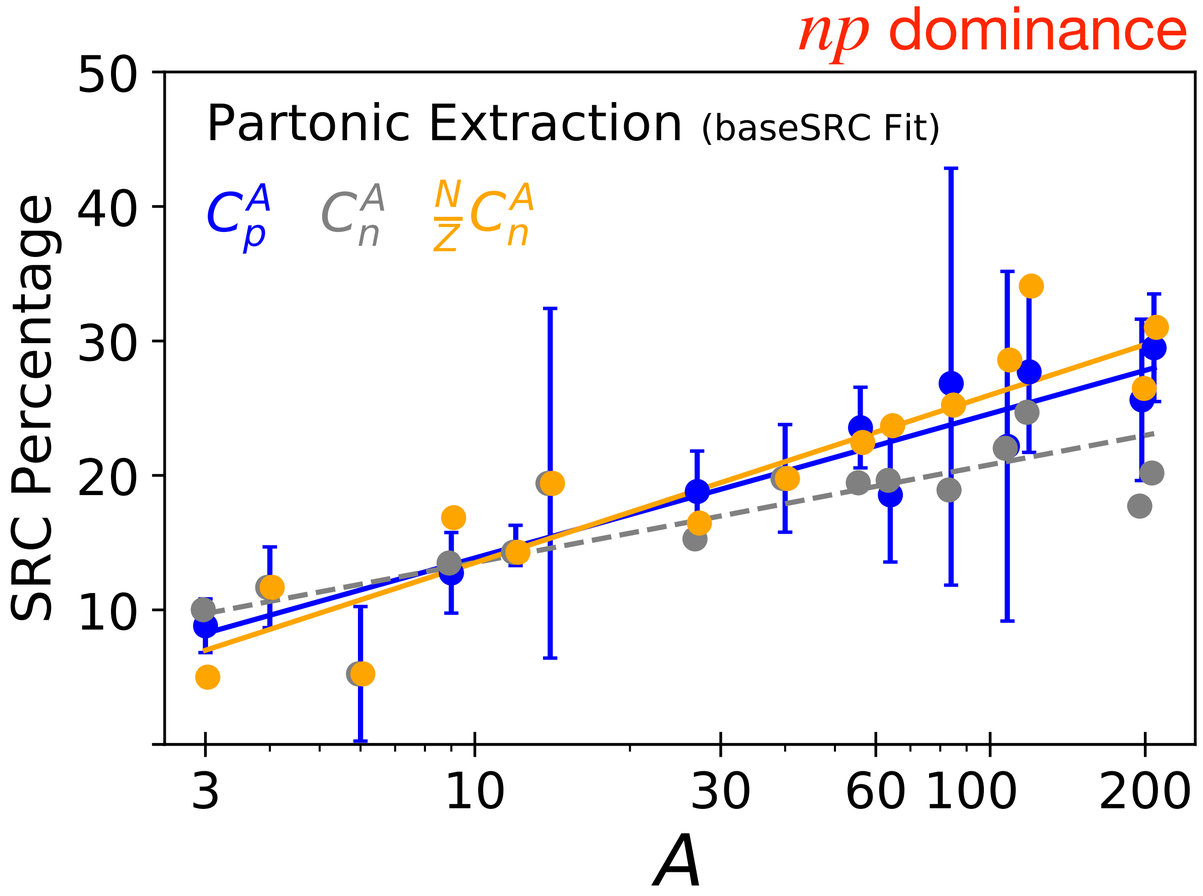
Results show large modification of SRC nucleons

	χ^2/N_{dof}
Traditional	0.85
baseSRC	0.82



PRL 133, 152502 (2024)

Coefficients consistent with nuclear structure measurements and calculations



PRL 133, 152502 (2024)

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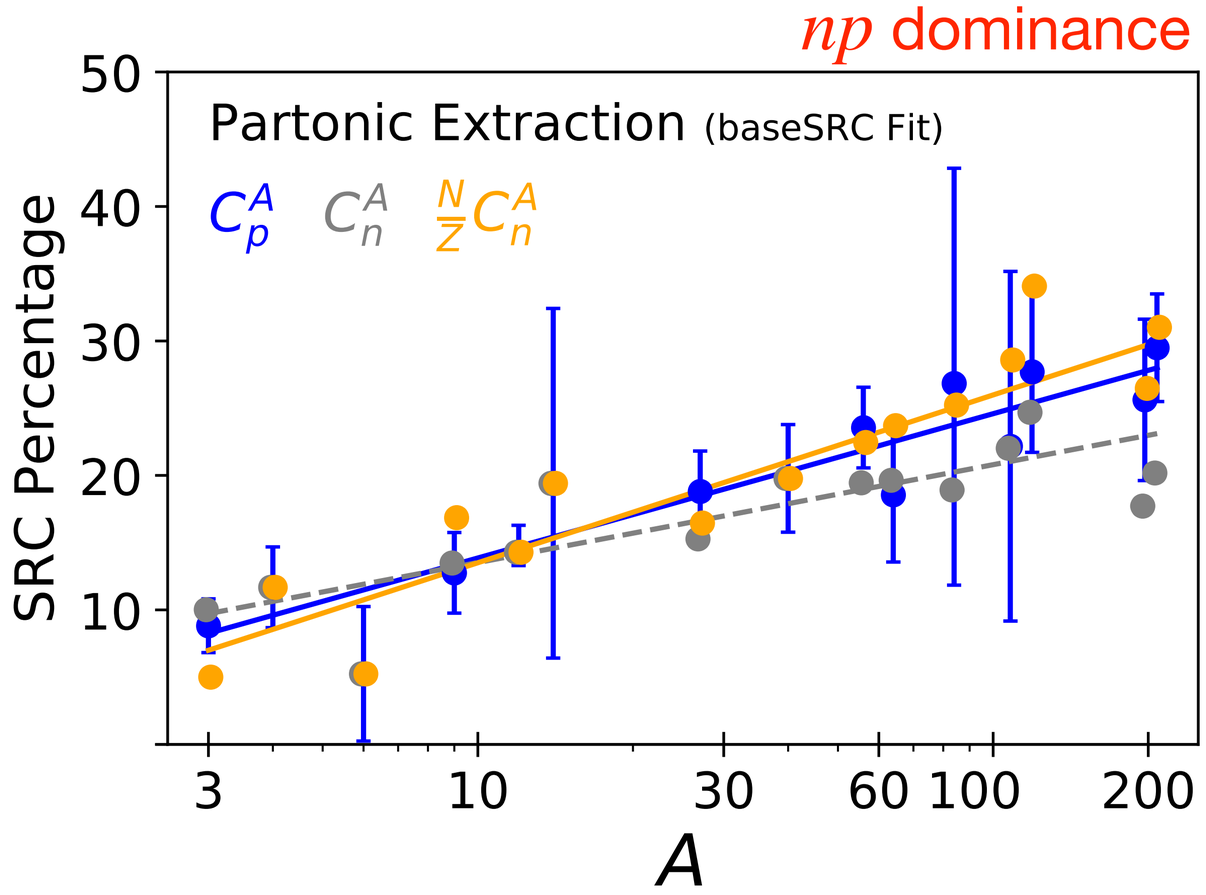

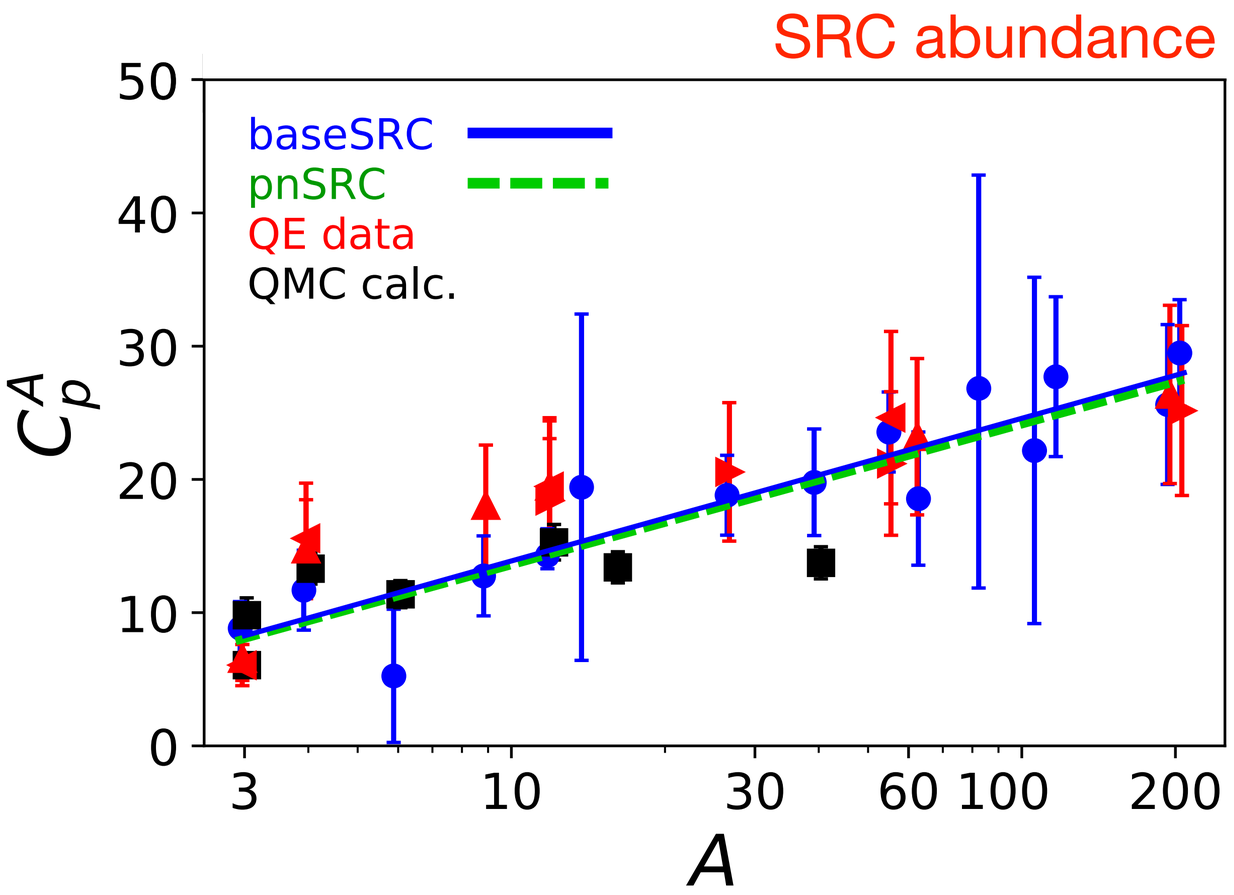

PRL 133, 152502 (2024)

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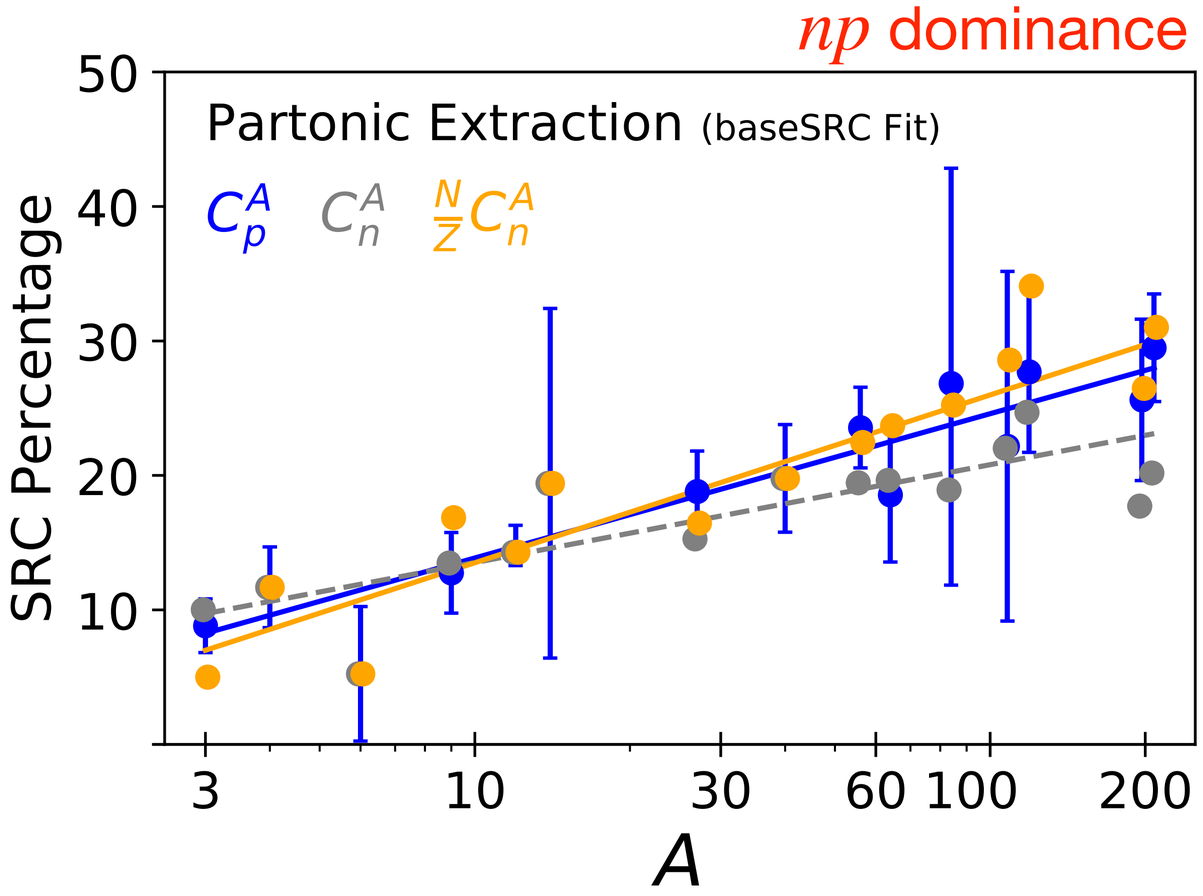

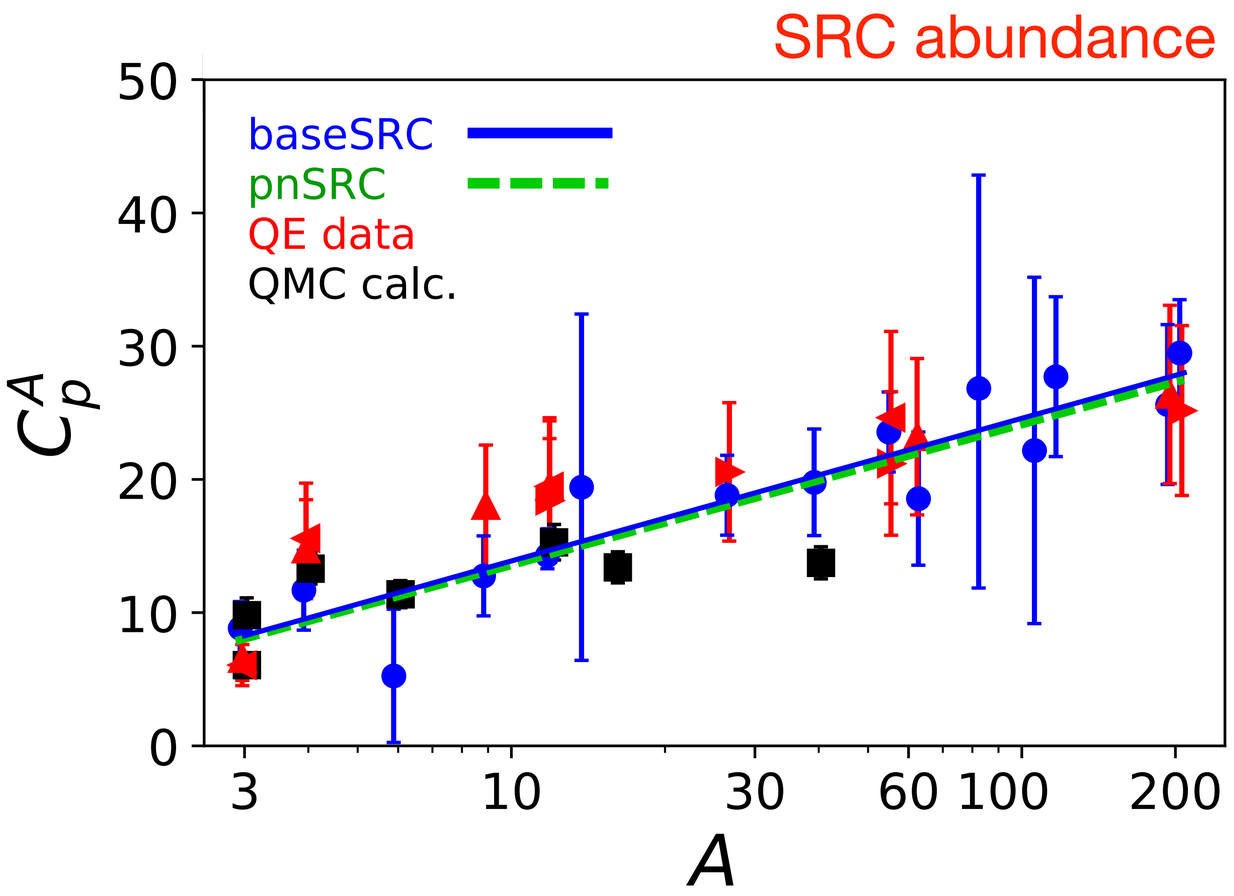

Low-energy nuclear structure emerging from *partonic fit*

PRL 133, 152502 (2024)