The EMC Effect in Spin Structure Functions

Jeopardy presentation for JLab Experiment E12-14-001

Will Brooks, for the Collaboration

Supporters of the Experiment

CLAS12 Run Group G Jeopardy Update Document

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[12] *University of Rome Tor Vergata, Italy*

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[14] *Pennsylvania State University, PA*

[15] *Argonne National Laboratory, IL*

[16] *Tokai University, Japan*

Conditional Schedule 2026-27

SAD or scheduled Run Group	Setup / Status	Target	Beam Energy	Start Date	End Date	Scheduled Calendar Days	Remaining PAC Days Before Run	Scheduled PAC Days	Actual PAC Days from ABUs	Remaining PAC Days After Run
Assuming ~ 100 PAC days in this period and successful Experiment Readiness Review in 2025										
RG-C		long. pol. NH3/ND3	11	2026-27		80	40	40		0
RG-G		long. pol. 7LiD	11	2026-27		110	55	55		0
SAD 2027	reconfigure	change					**sum:**	**95**		

- The centerpiece, the **longitudinal polarized target**, has been constructed and used
- **RG-C** will have **to return** for 40 days to complete its approved 120 PAC day program
- Consecutive execution of RG-C and RG-G would minimize substantial overhead
- RG-G no longer requests a double target but will alternate between NH_3 and ^{7}LiD, so **no modifications to the polarized target will be necessary**
- For producing paramagnetic radicals needed for DNP, **irradiation** using 8 MeV beam from injector and a variable temperature **cryostat**, commissioning expected 2024-25
- **Well aligned** with the **Spin-Polarized Fusion Project** (new engineer, technician, …)

The EMC Effect in Spin Structure Functions

https://www.jlab.org/exp_prog/proposals/14/PR12-14-001.pdf

It has been known for more than 35 years that the basic structure functions of protons and neutrons are modified inside nuclei. This has been observed in many measurements over the decades, including recent experiments at JLab. However, ***no experiment has ever searched for this effect in the spin structure functions***.

Polarization observables can provide new and important insights into longstanding problems!

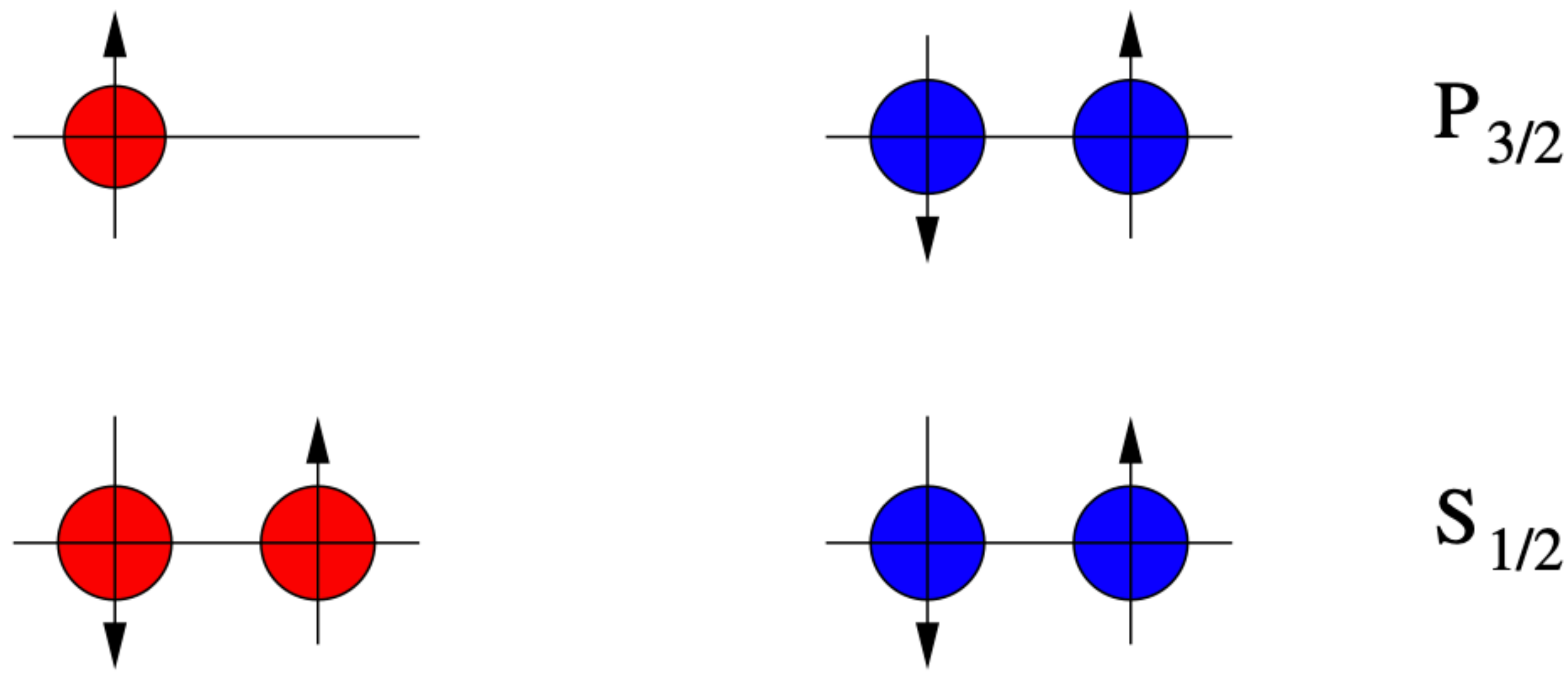
The strategy

We chose ^{7}Li because of its unique nuclear structure. In polarized ^{7}Li, **one proton** carries **nearly all of the polarization**. Thus it is a polarized proton embedded in a nuclear medium.

We take advantage of 100% of existing polarized target infrastructure for CLAS12. No modifications of the equipment are needed.

The beam time can be scheduled to immediately follow Run Group C which uses that target infrastructure, so only one major installation would be needed. This point was also reinforced in the TAC report.

Shell model picture of ^{7}Li



86.6% of the ^{7}Li nuclear polarization is carried by the unpaired proton.

This shell model result is confirmed by detailed Green Function Monte Carlo calculations.

New developments since 2014

In 2011 it was proposed that the EMC effect might be induced by short-range correlated nucleons (SRC; Weinstein, Piasetzky, et al.)

Since 2014 there have been both theoretical and experimental advances intensifying the debate over this assertion, underscoring the urgency of this experiment.

Mean-field based model calculations continue to consistently find modified spin structure functions.

Experiment-driven analyses found more evidence of the EMC⇔SRC hypothesis; however, disputed by some experts.

Technical readiness of the experiment

The only new items needed are the target samples of LiD and a way to irradiate and test them.

Source of LiD powder: multiple vendors identified. It will be natural ^{7}Li (95% isotopic purity) and ^{2}H (98-99$^+$%).

Press LiD powder into disks: Y12 facility (Oak Ridge) will do.

Target Group+Cryo+Accelerator are developing an irradiation facility in CEBAF injector. Eight MeV electrons. Ready ~5/25.

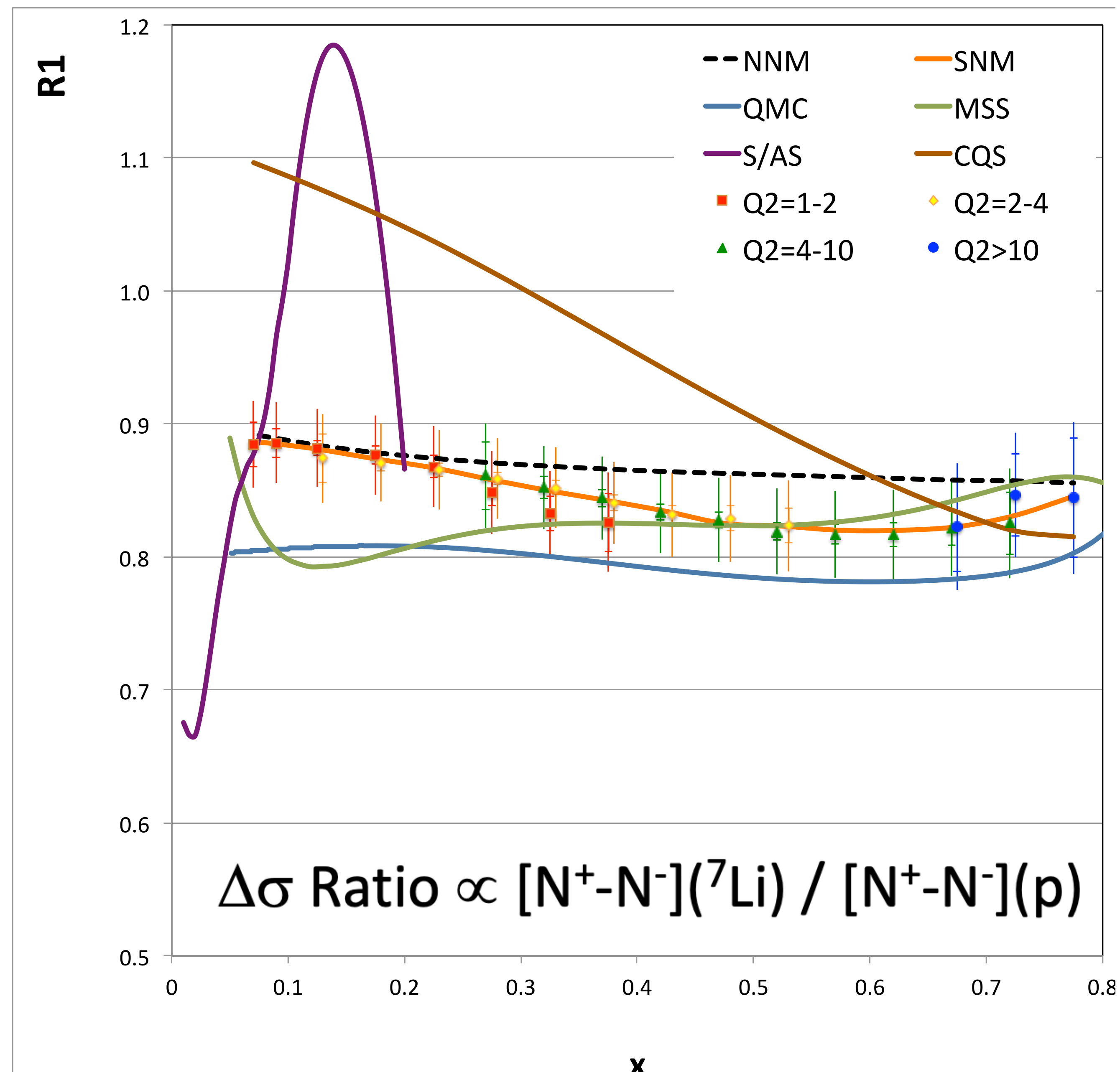
Measure polarization in new JLab Target Development Lab.

Well aligned with the new Spin-Polarized Fusion Project which is very interested in polarized LiD!

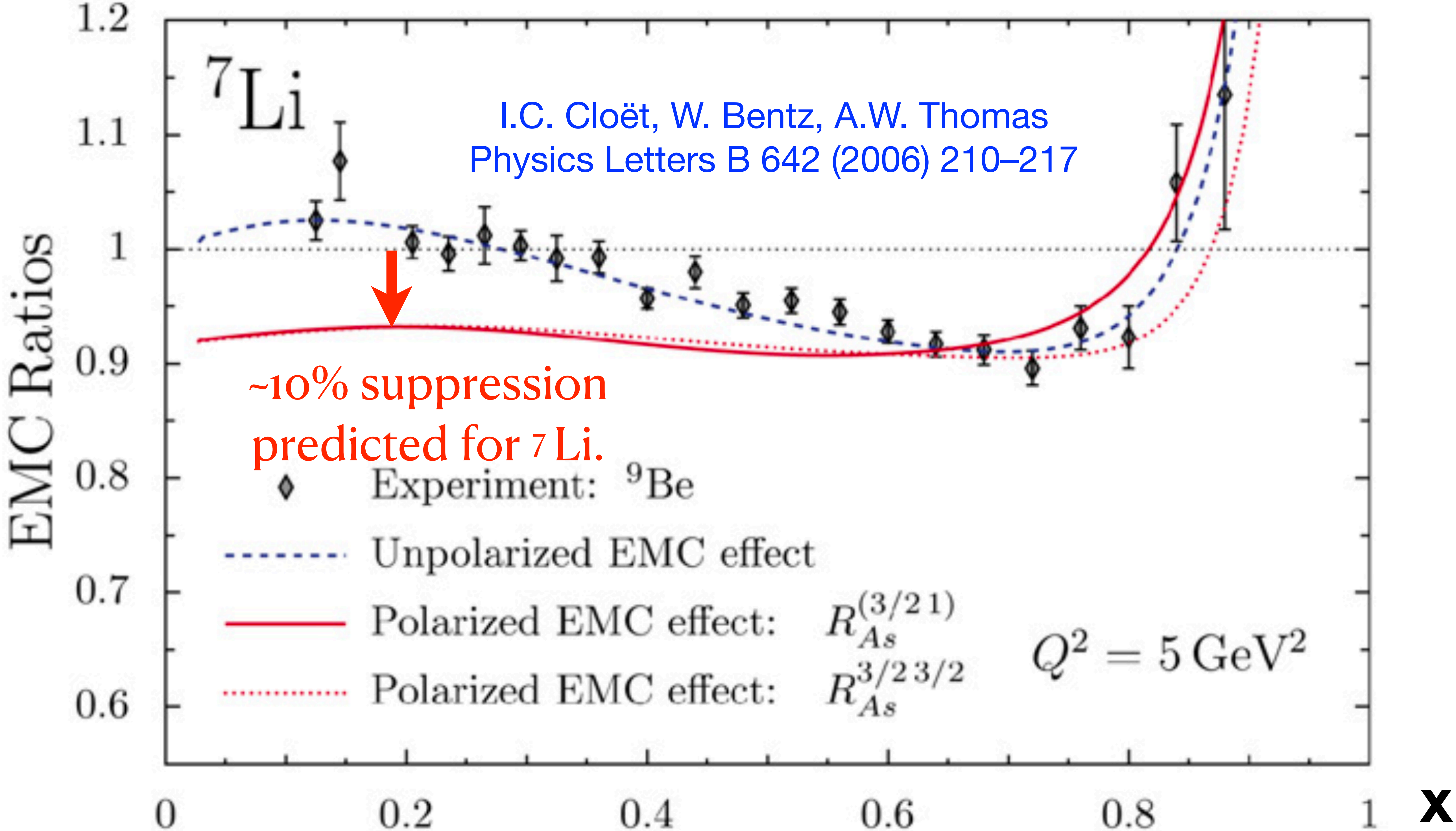
Theory TAC Report comments

"New theoretical work and new QCD global analyses of nuclear Parton Distribution Functions published after the re-approval of this proposal in PAC 48 have only **increased** the **interest** and **importance** of this experiment."

"….the results of this run group proposal can be expected to provide **important clues** into an effect that has **puzzled** the nuclear physics community for **nearly 40 years**, and that are not available only considering unpolarized targets."

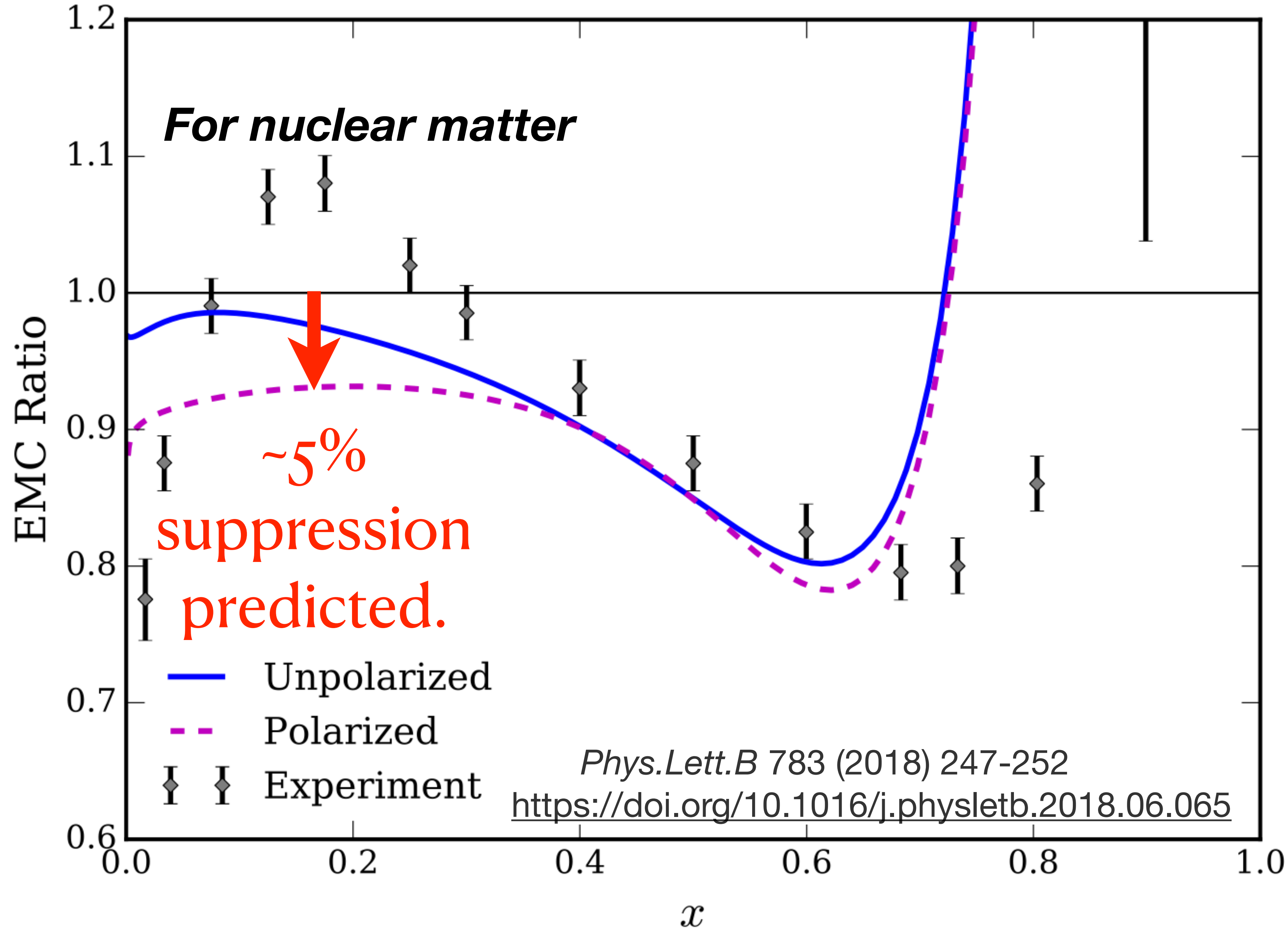


Theory results in EMC and antishadowing regions



Quark Meson Coupling (QMC) model, which explicitly allows the quark degrees of freedom to respond self-consistently to the nuclear mean fields and leads naturally to changes in the internal structure of the bound nucleons. Free nucleon given by the covariant quark–diquark equations in a confining Nambu–Jona-Lasinio model.

Theory results in EMC and antishadowing regions

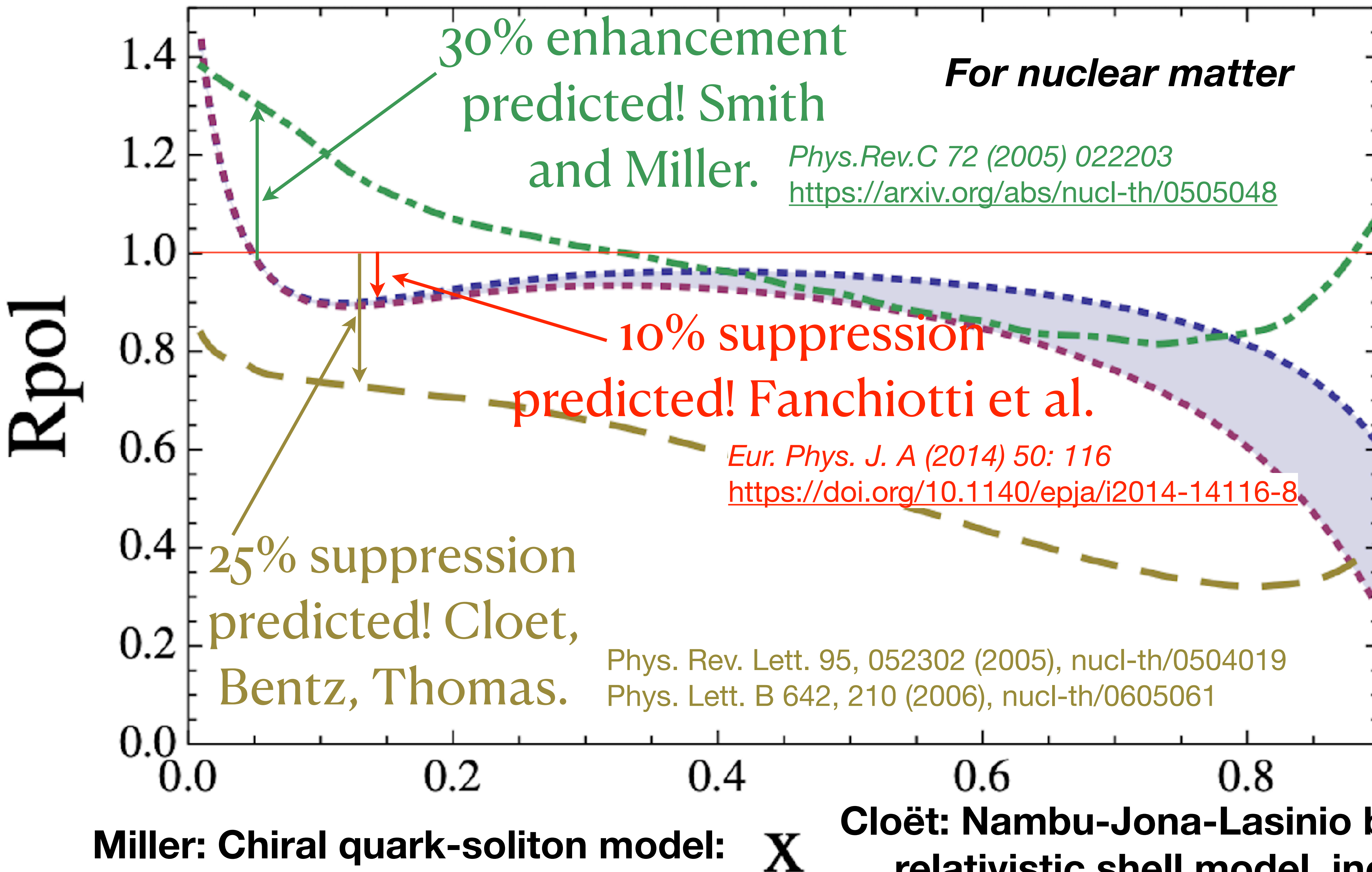


2018 paper

Unpolarized (blue solid line) and polarized (purple dashed line) EMC effect in the QMC model normalized to MIT bag model. The results are evolved to Q^2 = 10 GeV^2.

Stephen Tronchin, Hrayr H. Matevosyan, Anthony W. Thomas

Theory results in EMC and antishadowing regions



Fanchiotti: 1)x-rescaling 2)increase of sea quark components in the in medium nucleon, related to the low energy N-N interaction

Miller: Chiral quark-soliton model: relativistic mean field approximation to baryons, includes antiquarks.

Cloët: Nambu-Jona-Lasinio binding in relativistic shell model, including mean scalar and vector fields that couple to the quarks in the nucleon

Huner Fanchiotti, Carlos A. García Canal, Tatiana Tarutina, and Vicente Vento

Conclusions

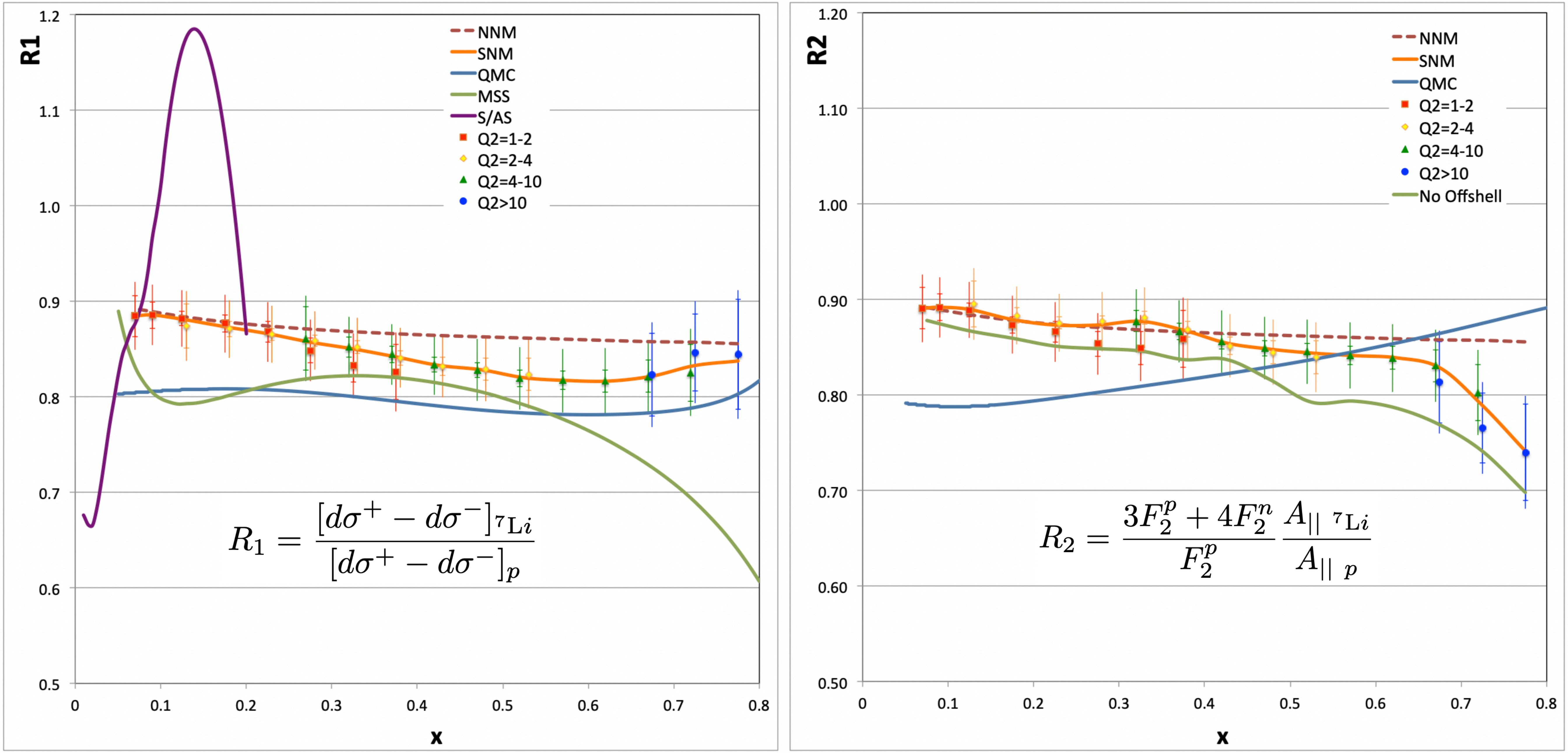
Many new developments since the experiment was approved in 2014. Clearly a vigorous community of scientists worldwide who are very interested.

Is the EMC effect a mean-field phenomenon, or a short-range correlation effect, or both, or neither? A polarization-based measurement will provide completely new information that will help to clarify this puzzle.

In the foreseeable future, JLab is the only lab in the world where this experiment can be done. All conditions are now fulfilled to run this experiment within the next 3-4 years.

We request the PAC to reaffirm the full 55 approved PAC days for RG-G.

Anticipated Uncertainties, 11 GeV experiment



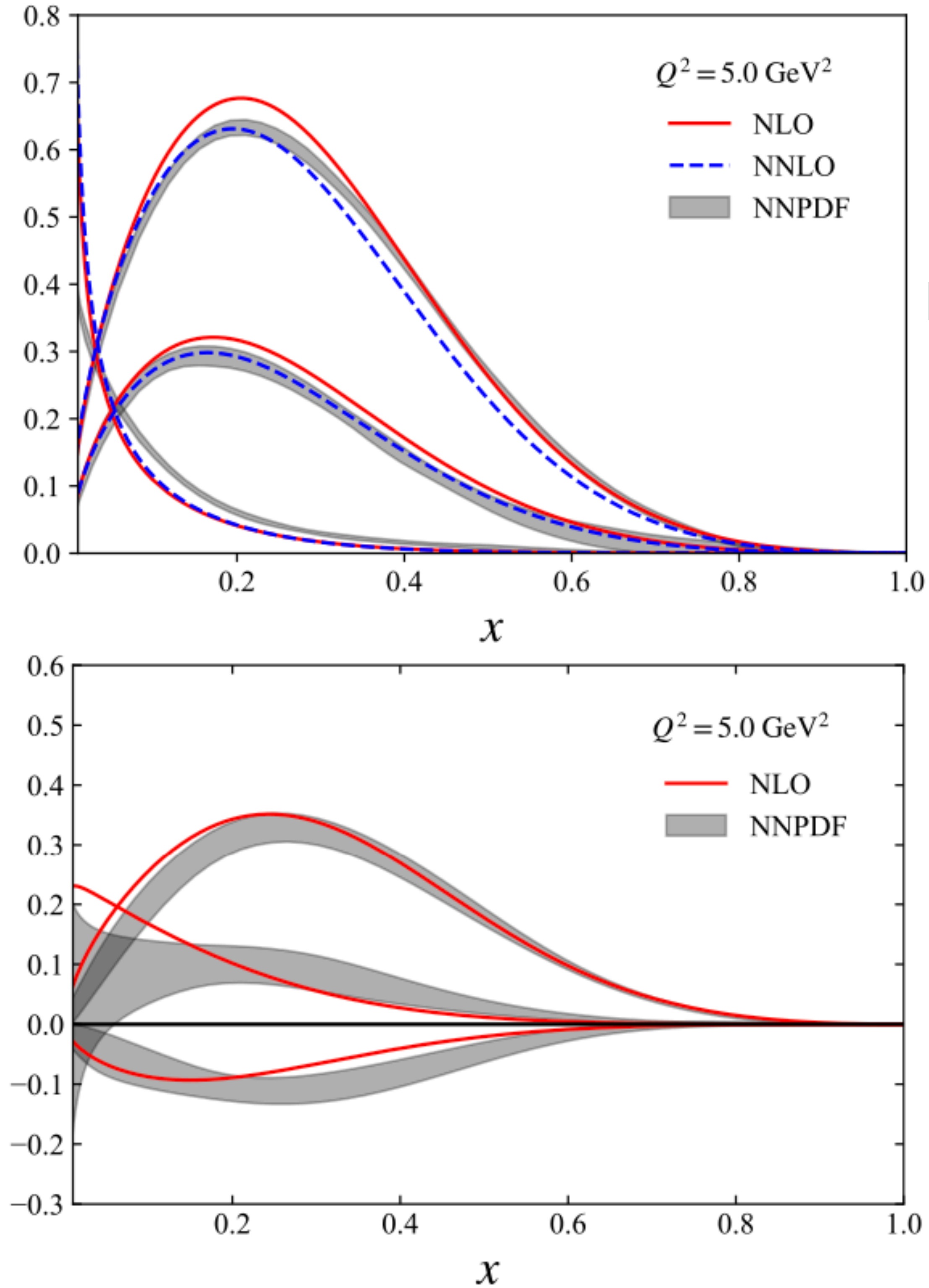
Ratio R_1 of cross section differences for double polarized ^{7}Li(e,e') over p(e,e') for several different models. Ratio R_2 of the parallel double spin asymmetry $A_{||}$ for ^{7}Li(e,e') over p(e,e), normalized by "naïve " unpolarized structure function ratio for ^{7}Li over hydrogen.

(NNM = naïve nuclear model, SNM = standard nuclear model, QMC = Quark-meson coupling model, MSS = modified sea scheme, S/AS = shadowing/antishadowing model).

Point-to-point systematic uncertainties added in quadrature to the statistical ones (with horizontal bars). An overall scale uncertainty of about 4% is not shown.

New since 2020: 2022 paper includes gluons!

(This is useful because they will obviously also be included in our measurement!)



Free nucleon, unpolarized PDF

Free nucleon, polarized PDF

Gluon EMC Effects in Nuclear Matter
X G Wang, W Bentz, I C Cloët, A W Thomas

https://arxiv.org/abs/2109.03591

J. Phys. G: Nucl. Part. Phys. 49 (2022) 03LT01

Figure 1. (Colour online) Results for the spin-independent (*upper*) and spin-dependent (*lower*) parton distributions of a free nucleon obtained by QCD evolution at both NLO and NNLO to the scale $Q^2 = 5\,\text{GeV}^2$. From top to bottom, the groups of lines represent xu_v, xd_v, $xg/10$ in unpolarized case, and $x\Delta u_v$, $x\Delta g$, $x\Delta d_v$ in polarized case. The phenomenological results of unpolarized and polarized PDFs are taken from NNPDF3.0 [51] and NNPDFpol1.1 [52], respectively.

Definitions: unpolarized and polarized gluonic modifications

$$R_G = \frac{g_A(x)}{Z/A\, g_p(x) + N/A\, g_n(x)} \longrightarrow \frac{g_A(x)}{g_p(x)},$$

$$\Delta R_G = \frac{\Delta g_A(x)}{P_p\, \Delta g_p(x) + P_n\, \Delta g_n(x)} \longrightarrow \frac{\Delta g_A(x)}{\Delta g_p(x)},$$

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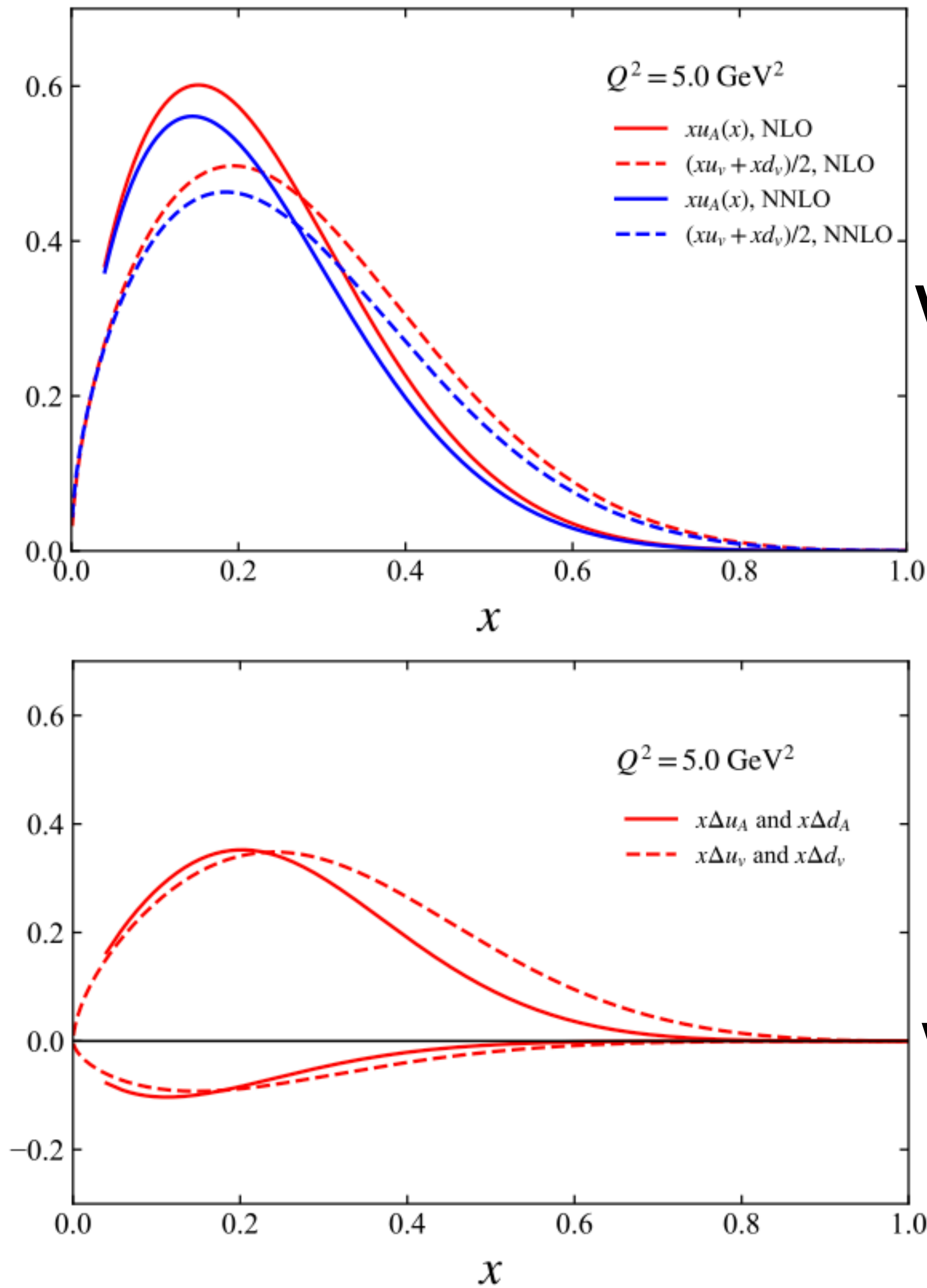
New since 2020: ISOSPIN SYMMETRIC NUCLEAR MATTER 2022 paper



Valence quark unpolarized PDF

Valence quark polarized PDF

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J. Phys. G: Nucl. Part. Phys. 49 (2022) 03LT01

Figure 2. The solid lines represent the (per-nucleon) spin-independent valence quark PDF in isospin symmetric nuclear matter (*top*) and the spin-dependent valence u and d PDF of a single polarized proton embedded in isospin symmetric nuclear matter (*bottom*). These results are at the scale $Q^2 = 5\,\mathrm{GeV}^2$ and are compared with the free nucleon PDFs (dashed lines) at the same scale.

Theory results in EMC and antishadowing regions, including *gluon* degrees of freedom

ISOSPIN SYMMETRIC NUCLEAR MATTER

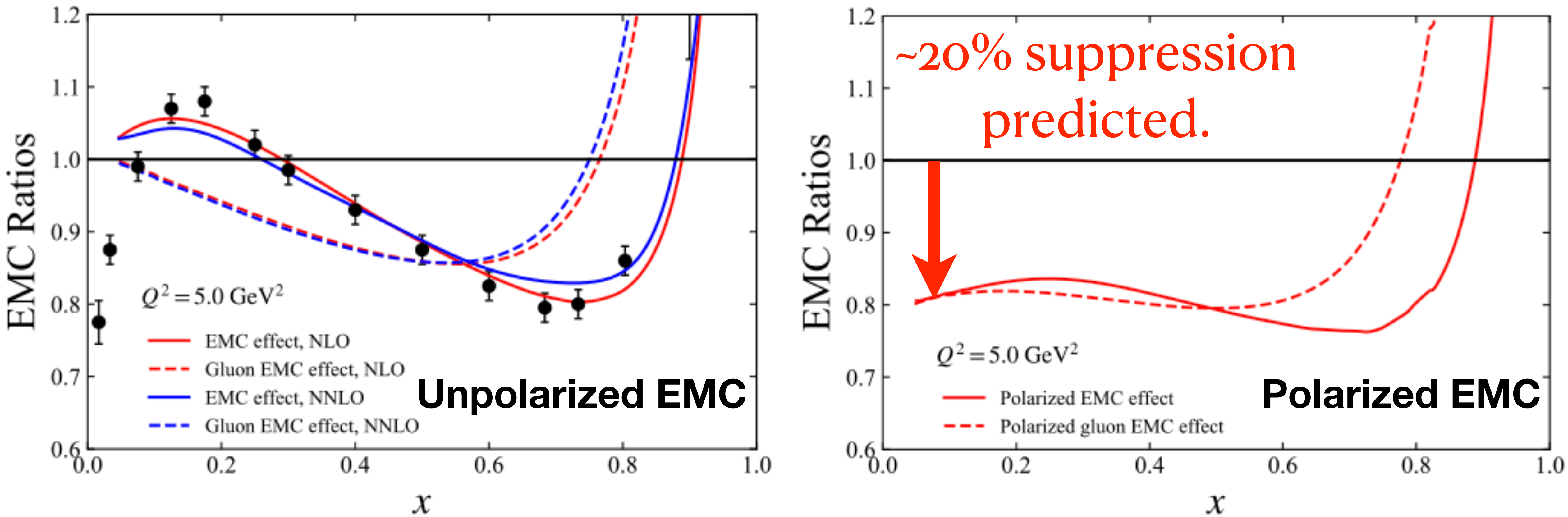
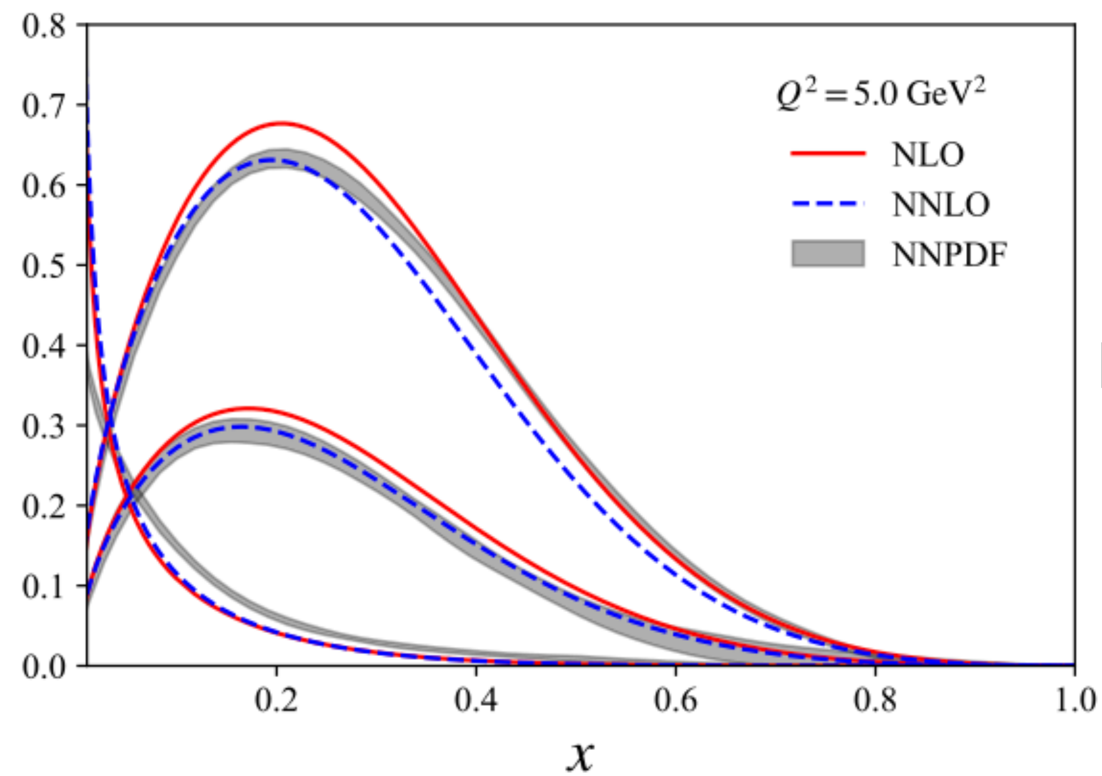


Figure 3. (Colour online) (*Left panel*) Unpolarized EMC ratios for the structure functions $F_{2A}(x)/F_{2N}(x)$ (solid) and the unpolarized gluon distributions $g_A(x)/g_p(x)$ (dashed). (*Right panel*) Polarized EMC ratios for the structure functions $g_{1A}(x)/g_{1p}(x)$ (solid) and polarized gluon distributions $\Delta g_A(x)/\Delta g_p(x)$ (dashed). The empirical data points are the unpolarized nuclear matter results for the EMC ratio from Ref. [53].



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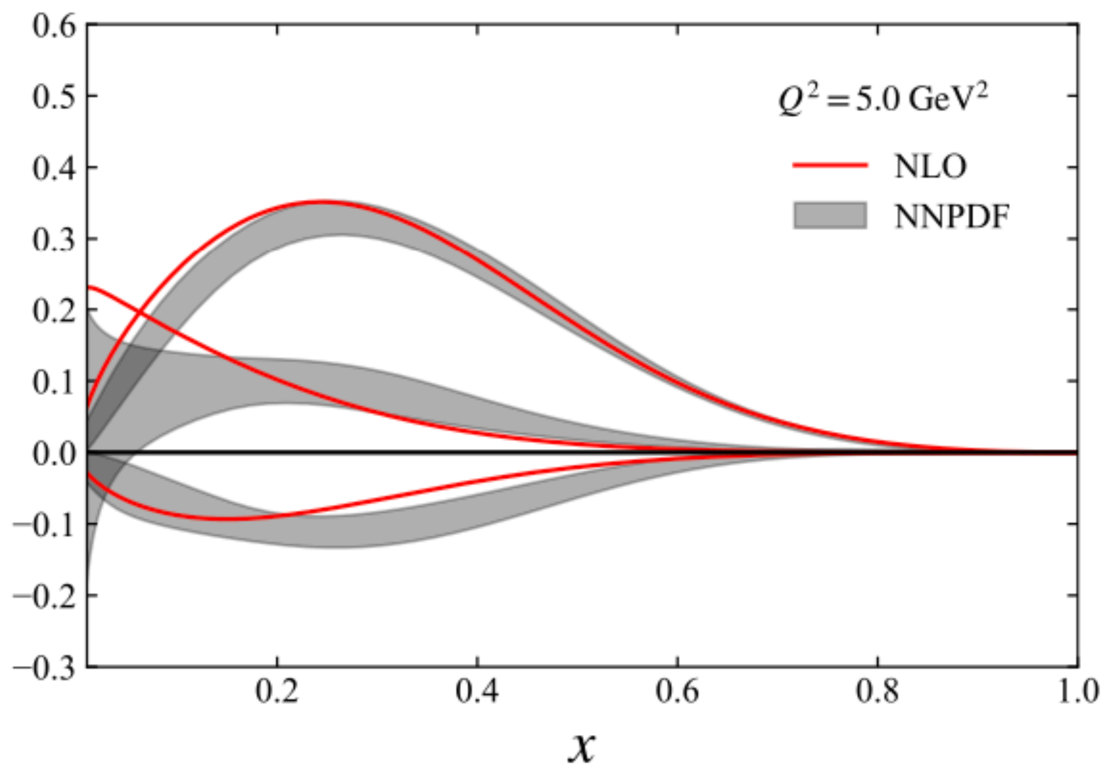

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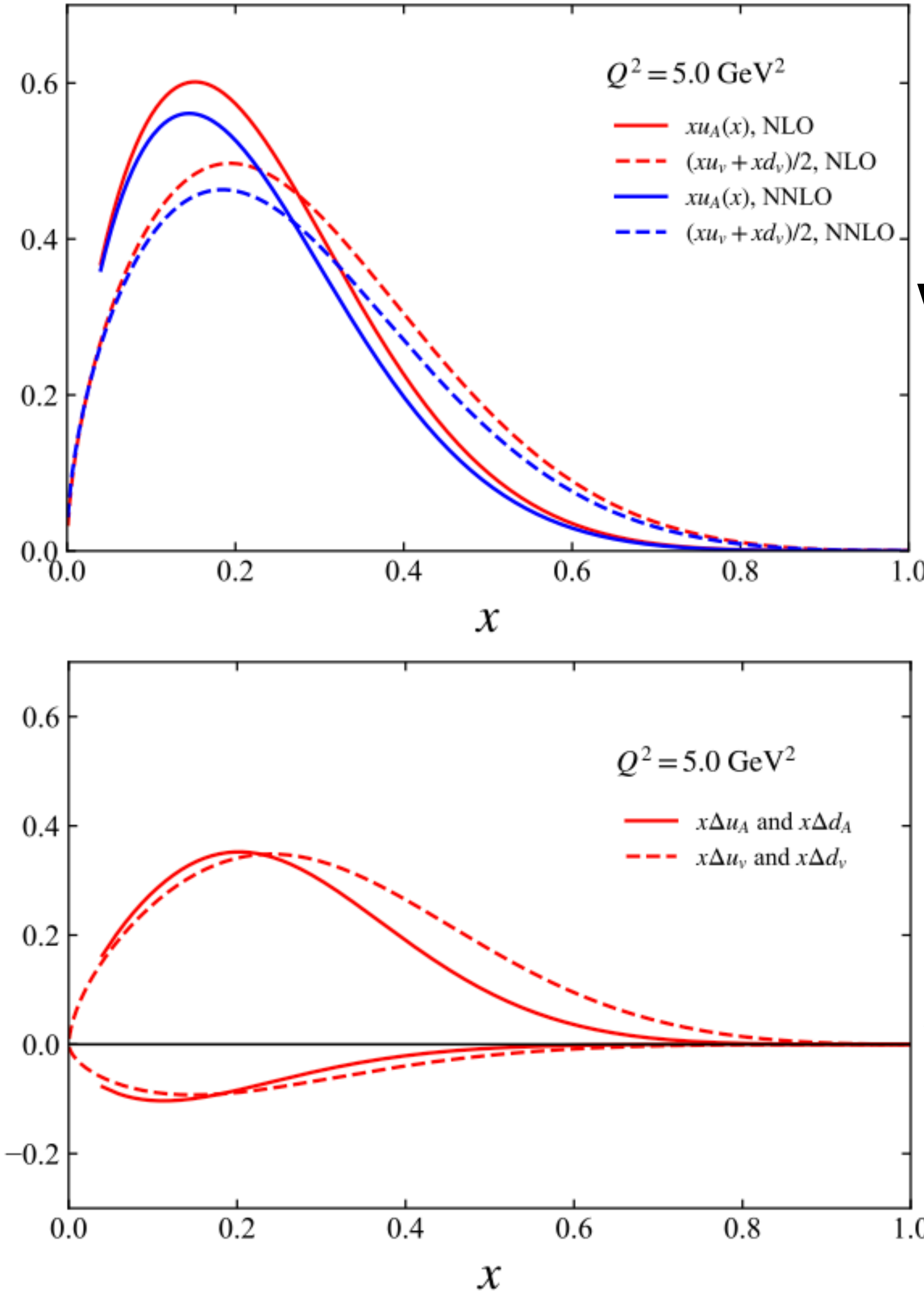

Valence quark unpolarized PDF

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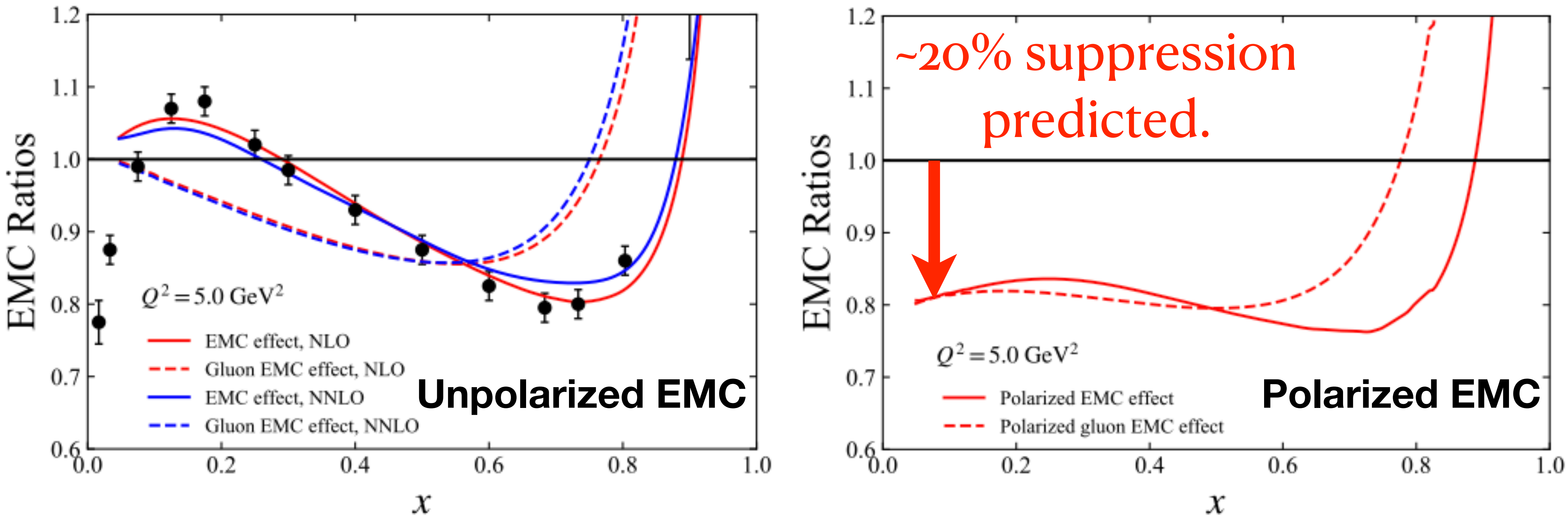

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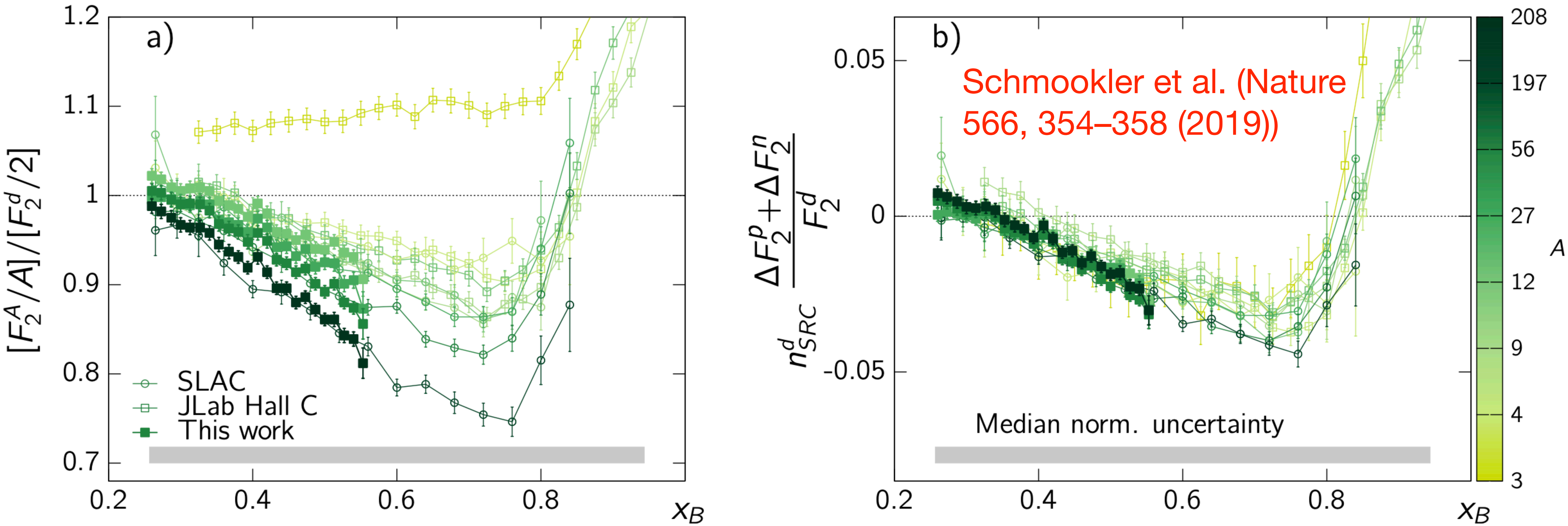
New developments since 2014



Schmookler et al.: if assume EMC is caused *entirely* by *np*-SRC, can derive a universal function that describes EMC well for **all** nuclei. (Assumes F_2^{*p} and F_2^{*n} are universal.)

$$F_2^A = (Z - n_{SRC}^A)F_2^p + (N - n_{SRC}^A)F_2^n + n_{SRC}^A(F_2^{p*} + F_2^{n*})$$

$$= ZF_2^p + NF_2^n + n_{SRC}^A(\Delta F_2^p + \Delta F_2^n)$$

$\Delta F_2^n \equiv F_2^{n*} - F_2^n$

$\Delta F_2^p \equiv F_2^{p*} - F_2^p$

Reflections on the origin of the EMC effect

1809.06622

Anthony W. Thomas

Asserts that SRC will significantly depolarize the participants.

Do short-range correlations cause the nuclear EMC effect in the deuteron?

X. G. Wang,[1] A. W. Thomas,[1] and W. Melnitchouk[2]

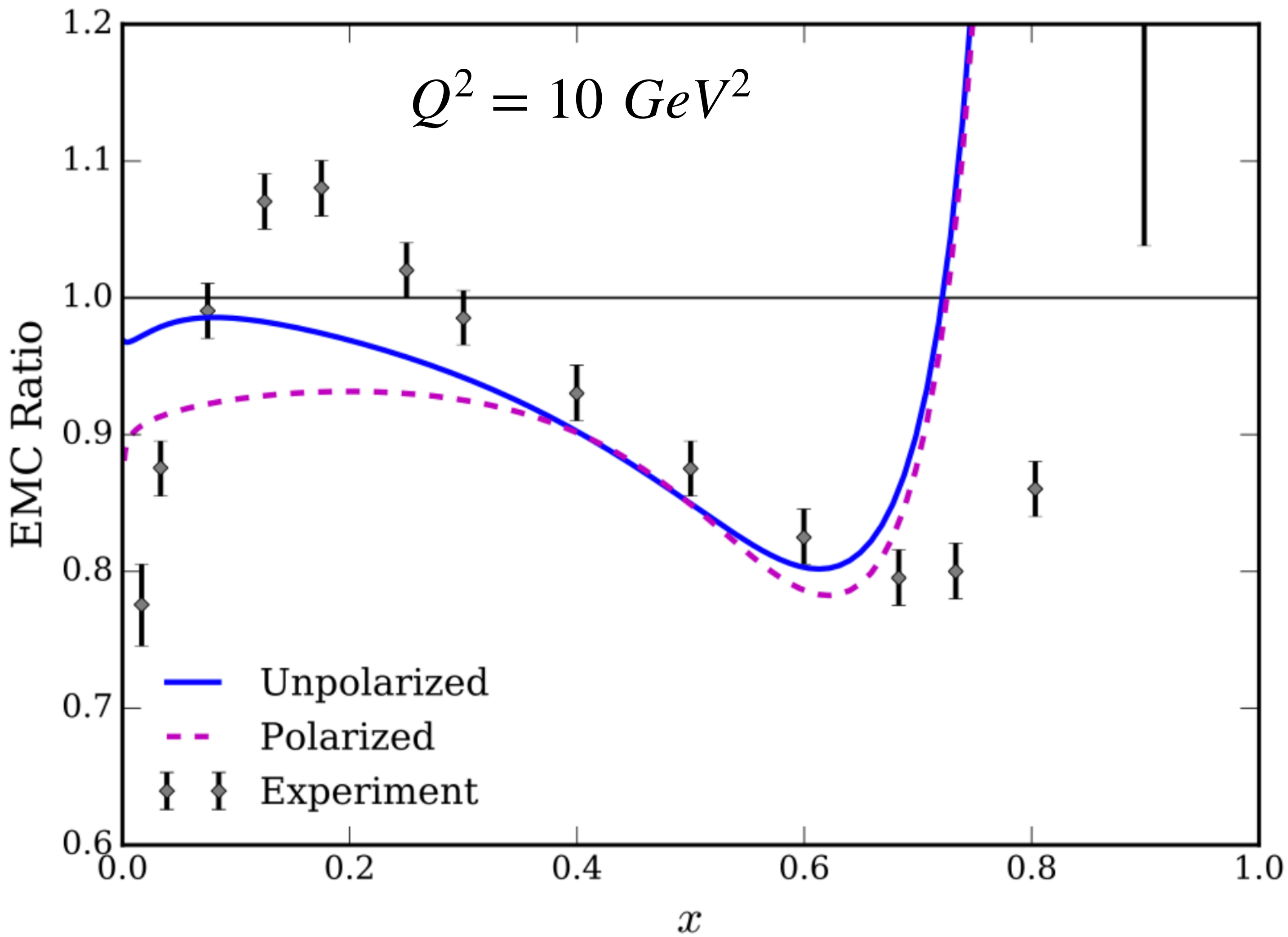
Test of three phenomenological models with nuclear binding, Fermi motion, and nucleon off-shell effects, can classify into low momentum and high momentum components. They found that high-momentum nucleons, such as those found in SRCs, were not the main source of the EMC effect in the models studied. 2004.03789

Short-Range Correlations and the Nuclear EMC Effect in Deuterium and Helium-3

E.P. Segarra,[1] J.R. Pybus,[1] F. Hauenstein,[1,2] D.W. Higinbotham,[3] G.A. Miller,[4]
E. Piasetzky,[5] A. Schmidt,[6] M. Strikman,[7] L.B. Weinstein,[2] and O. Hen[1,*]

June 2020 response in favor of EMC⇔SRC for A=2, 3 2006.10249

Other developments since 2014



1806.00481 (2018)

QMC model

S. Tronchin,

H. H. Matevosyan

A. W. Thomas

"Short-Range Correlations and the EMC Effect in Effective Field Theory," J.-W. Chen, W. Detmold, J. E. Lynn, and A. Schwenk, Phys. Rev. Lett. 119, 262502 (2017). 1607.03065 - correlation between EMC slope and SRC comes naturally from a scale separation in EFT. Focus is on light nuclei.

Comments on Theory Predictions

- The predictions shown give quite varied results, from suppression to enhancement, from few percent to 25%
- The ingredients of the models vary rather widely too
- They typically start at high x and “work downwards”
- In the antishadowing region, **diffractive processes** will become important, and **interference effects** will arise
- These are not ingredients in the models just shown
- I will next show one that **does** have those ingredients. It starts at low x and “works upwards” to x=0.2

Glauber-Gribov Picture in DIS

- γ^*, W, Z produces a colored $q\bar{q}$ dipole pair
- Dipole can interact diffractively or inelastically on nucleons
- **Interference** of diffractive amplitudes from Pomeron exchange on upstream nucleons causes shadowing of γ^* interactions on the downstream nucleons.
- **Coherence length l_c** of the virtual photon allows interaction on **two nucleons** separated by a distance d - if l_c>d, constructive/destructive **interference is possible**

(Brodsky) $\frac{1}{Mx_{Bj}} = \frac{2\nu}{Q^2} = l_c$

(x_{Bj}=0.1 means l_c = 2.2 fm)

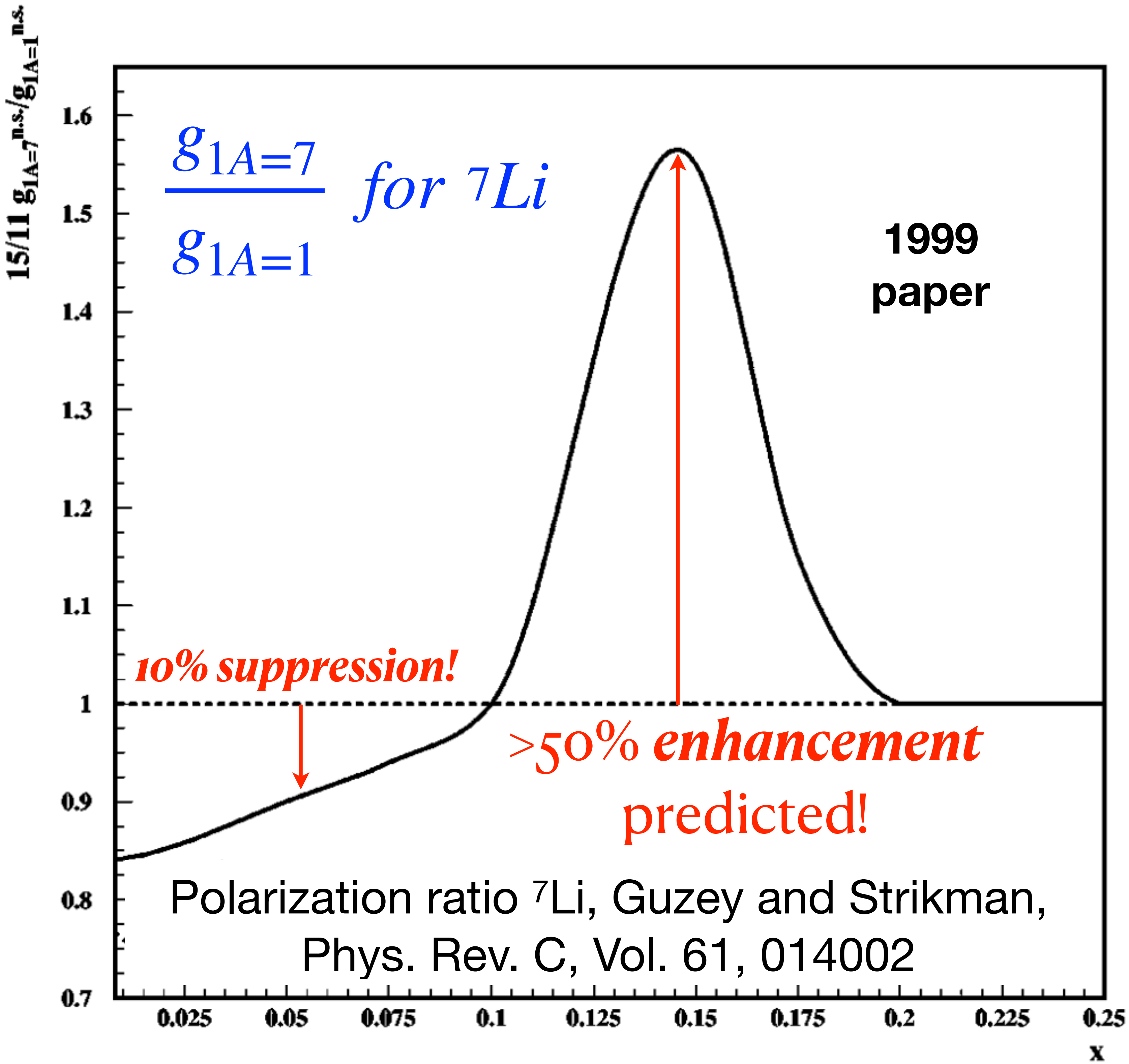
(Strikman) $\frac{1}{2Mx_{Bj}} = \frac{\nu}{Q^2} = l_c$

(x_{Bj}=0.1 means l_c = 1.1 fm)

This is ~internucleon distance in a nucleus.
So coherent processes **can** happen below x=0.1-0.2

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.70.116003

Theory results in the antishadowing region



This approach uses an extension of the Gribov theory of nuclear shadowing in DIS, while requiring the polarized Bjorken sum rule to remain satisfied.

Theory results in EMC and antishadowing regions

This work was performed in the chiral quark-soliton (CQS) model

Relativistic mean-field approach, therefore includes anti-quarks; reproduces EMC and satisfies bounds on unpolarized nuclear antiquark enhancement provided by Drell-Yan measurements

These authors argue that polarized Bjorken Sum Rule for nuclei will not be sufficiently the same for nucleons as assumed in previous calculation (Guzey and Strikman)

Does NOT include coherence length effects (per Jerry Miller)

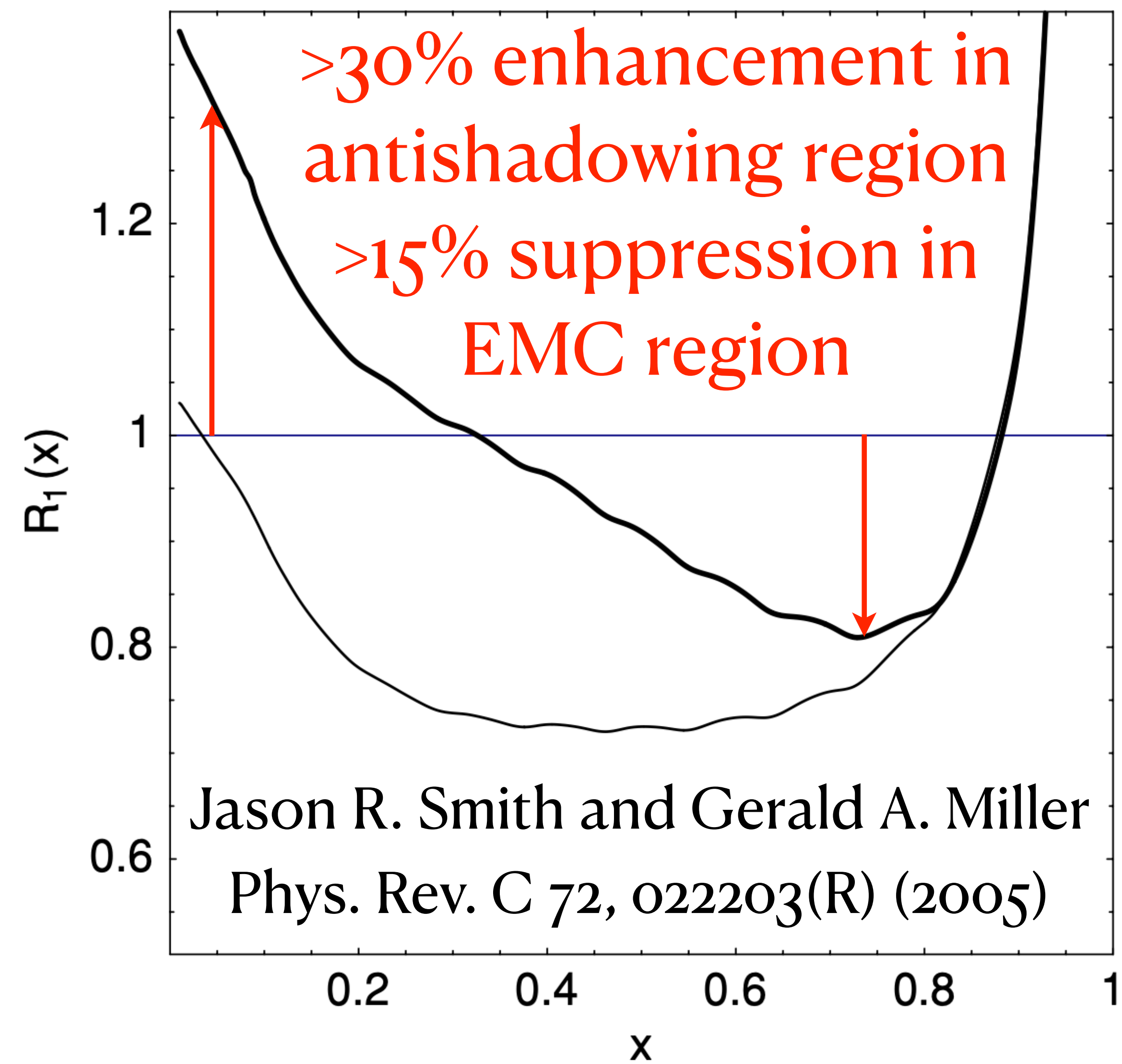
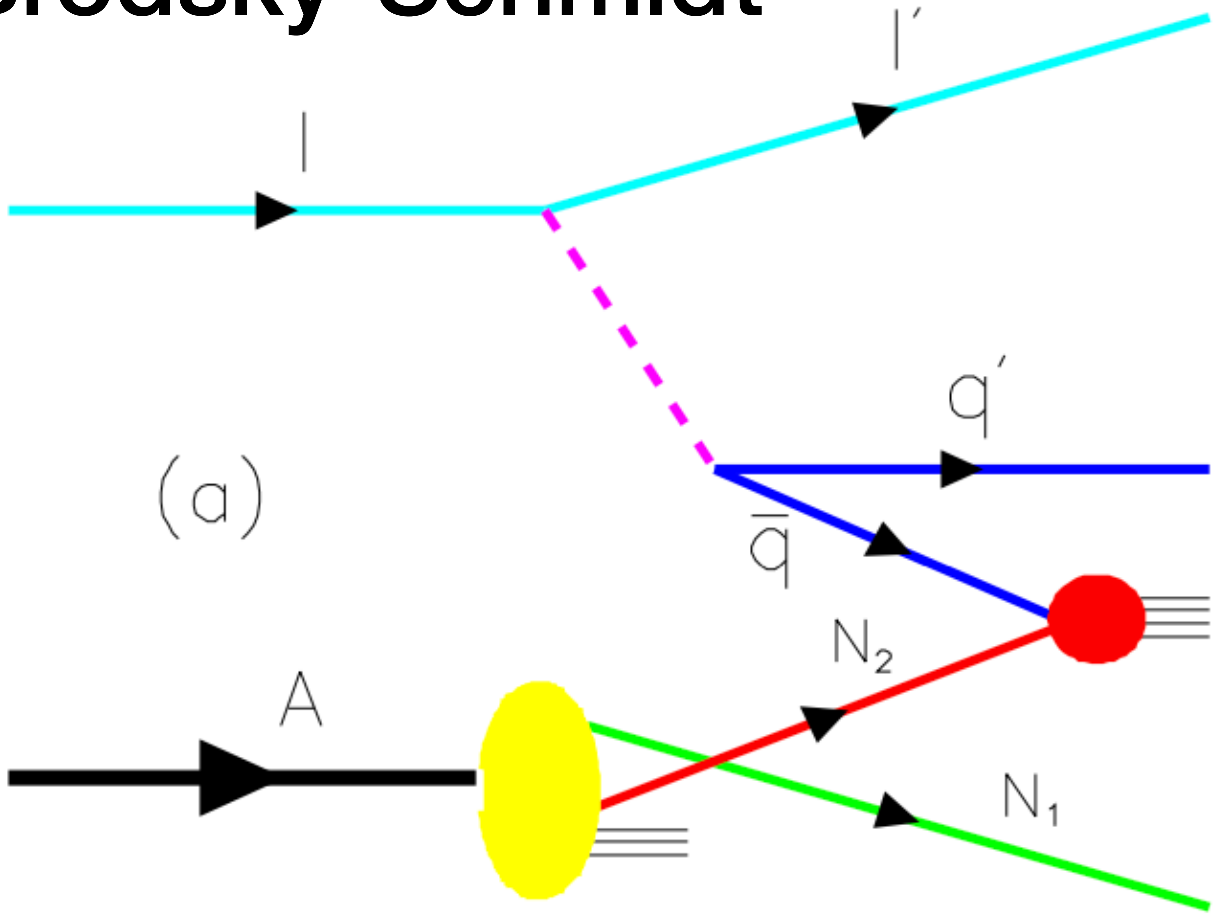


FIG. 1. Ratio of Eq. (13) at the scale $Q^2 = 10\ \mathrm{GeV}^2$ for nuclear matter. The heavy curve is the full calculation for nuclear matter. The thin curve is the effect calulated by using only medium modifications to the valence energy level as decribed in the text.

$$R_1(x, Q^2) = \frac{g_1^{(p|A)}(x, Q^2, k_F)}{A g_1^{(p)}(x, Q^2, k_F = 0)},$$
$$g_1^{(p|A)}(x, Q^2, k_F) = \int_x^A \frac{dy}{y} f(y) g_1^{(p)}(x/y, Q^2, k_F). \quad (13)$$

Brodsky-Schmidt

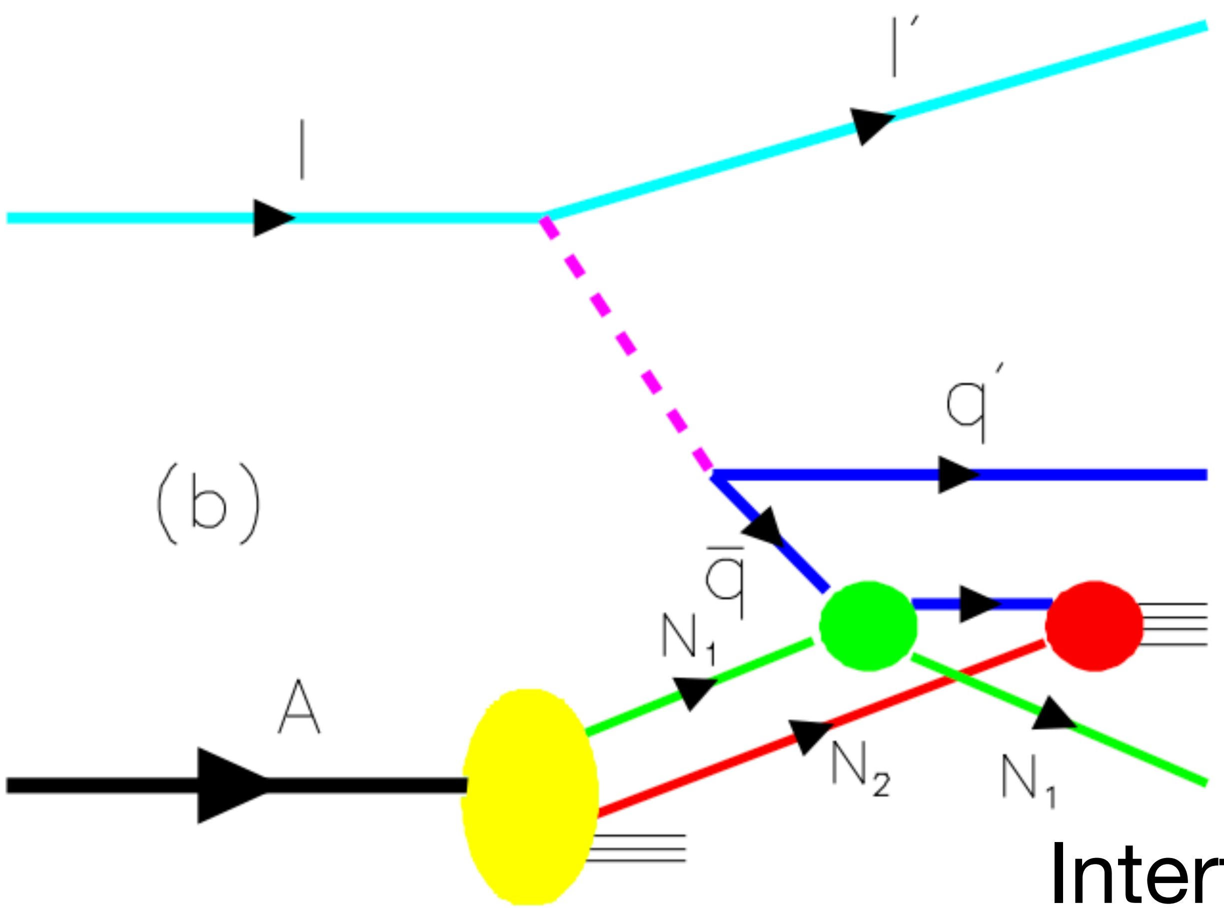


Single-step process

Exchange boson fluctuates into $q\bar{q}$ pair

The $\bar{q}$ interacts strongly with nucleon N_2 from the nucleus A

Nucleon N_1 is a spectator



Two-step process

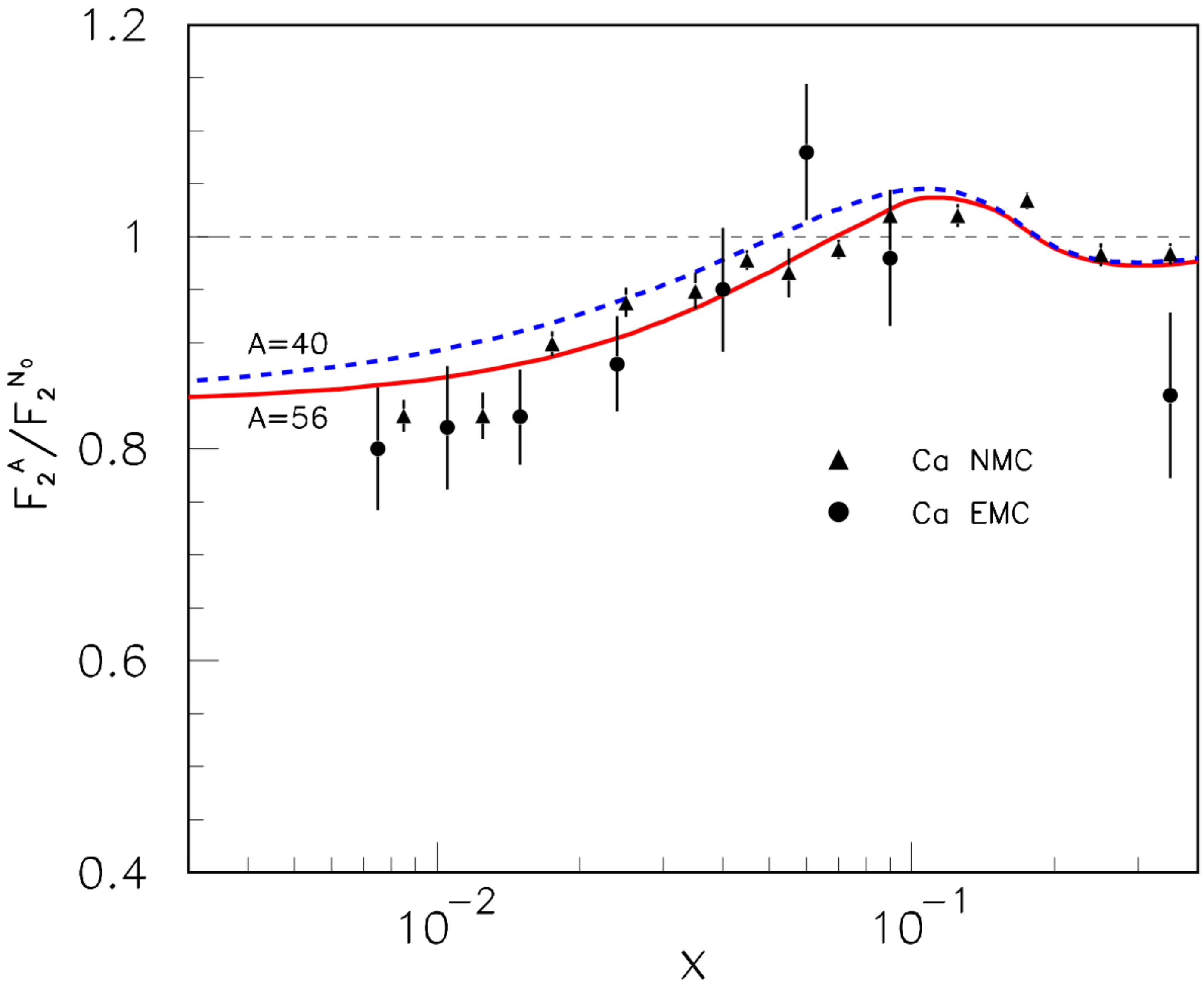
Exchange boson fluctuates into $q\bar{q}$ pair

The $\bar{q}$ interacts *softly* with nucleon N_1 by pomeron exchange, then goes on to interact strongly with N_2

Nucleon N_1 emerges intact

Interference between the two processes!

Brodsky-Schmidt: Pomeron, Reggion, Odderon



- Introducing the Reggion and the Odderon creates the possibility of having **constructive** interference, producing **anti-shadowing**.

- No polarization prediction yet in this approach

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.70.116003

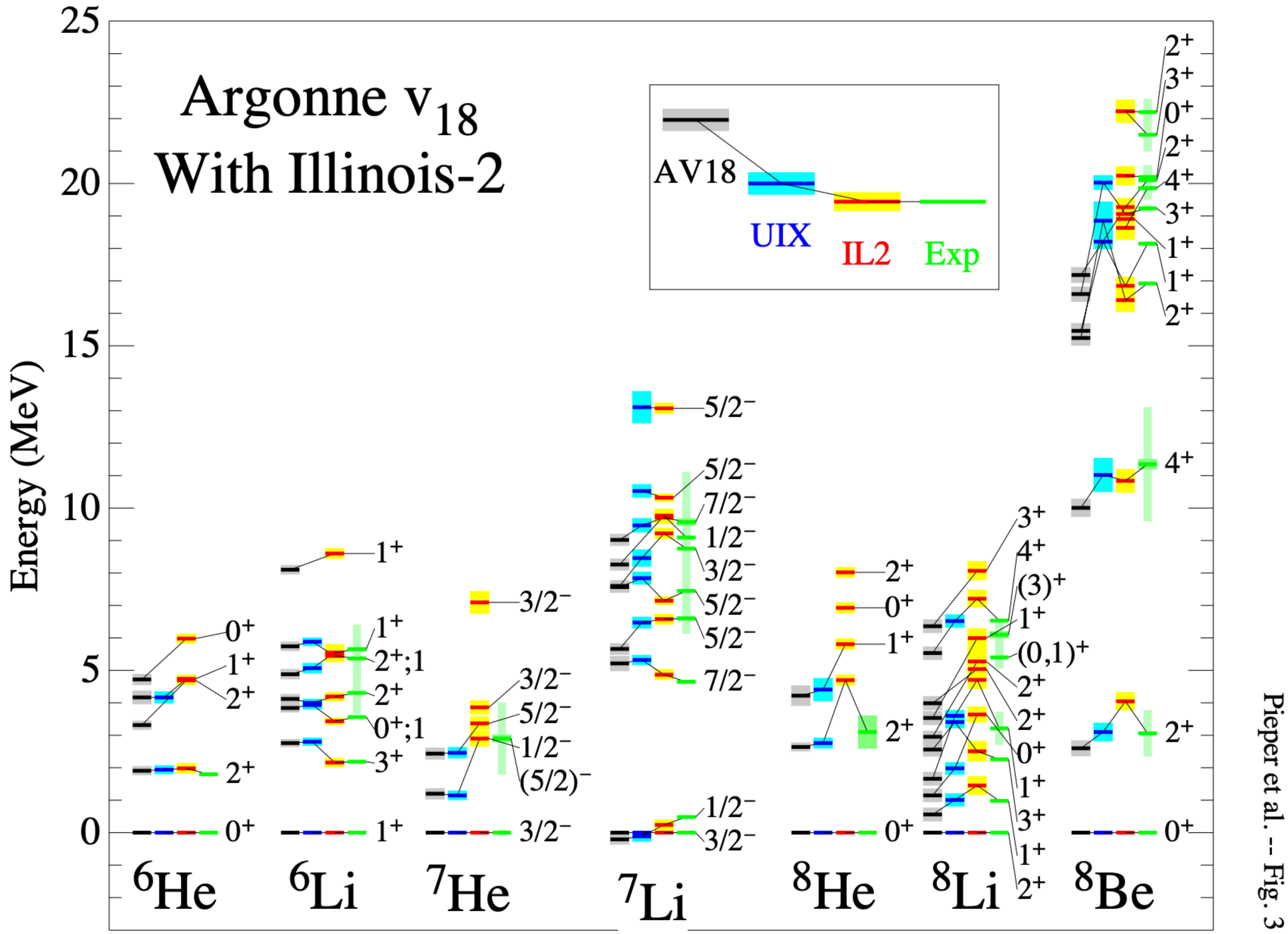


FIG. 3. Green's Function Monte Carlo (GFMC) calculations for ground states and excited states in the $A = 6 - 8$ region from [42]. This figure illustrates the precision achieved in modern few-body nuclear structure calculations. Typical deviation from experimental values (where available) are of order 100 keV or less.

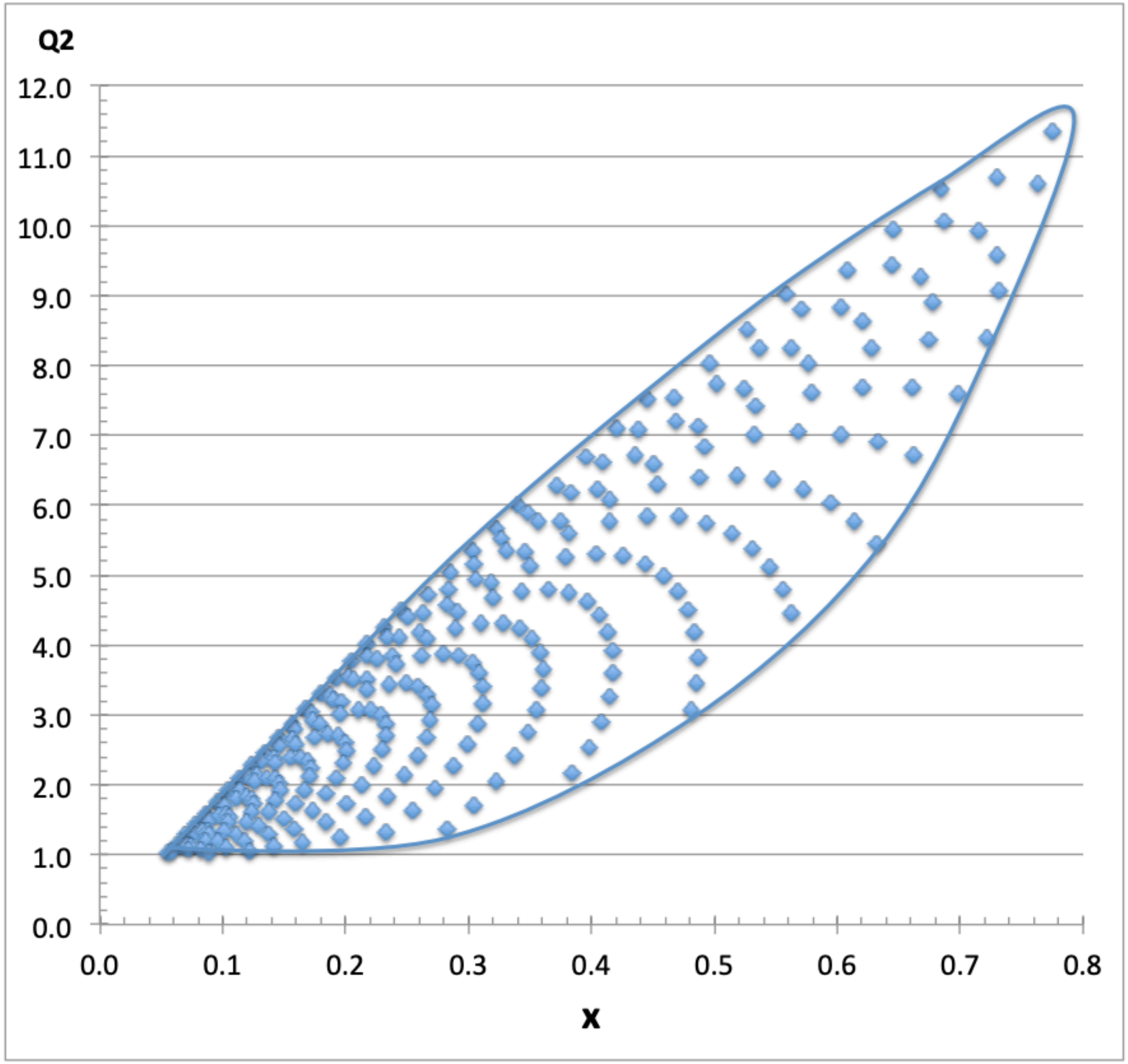


FIG. 10. Kinematic acceptance of the proposed experiment.

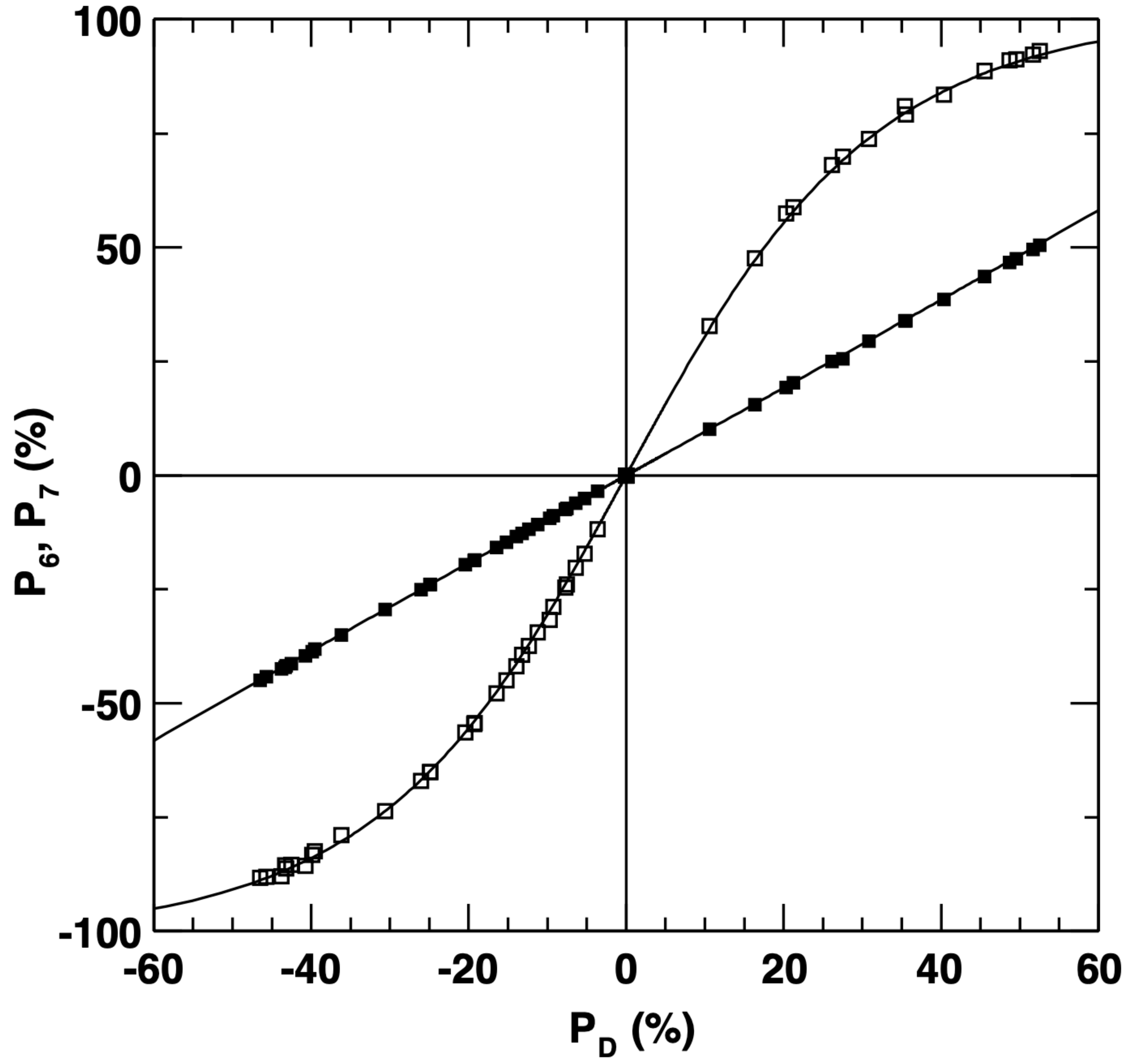


FIG. 13. Relationship between the measured polarizations of various target species (open symbols for ^{7}Li and black squares for ^{6}Li), as found by the COMPASS collaboration [53]. The prediction by the EST concept is shown by solid lines, which describe the data extremely well.

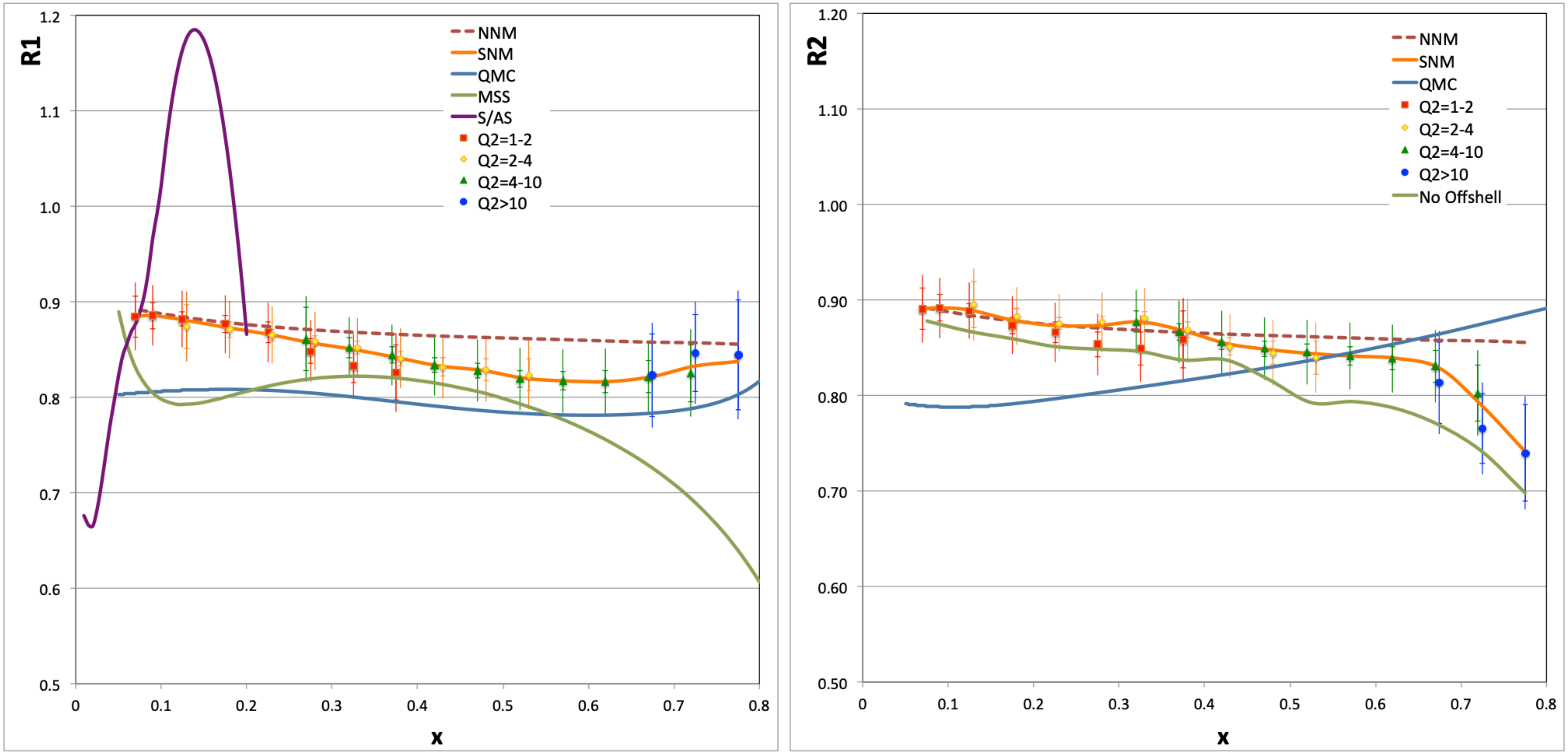


FIG. 22. Expected results for both ratios as in Figs. 20 and 21, with point-to-point systematic uncertainties added in quadrature (total length of error bars) to the statistical ones (horizontal bars). An overall scale uncertainty of about 4% is not shown

Reader Comments: Pasquale Di Nezza

Dear Will,

I read the PAC E12-14-001 and PR12-14-001 with interest.
I found them very clear and well-structured.
In general, I did not identify any weak points, and in my opinion, the rating and original approval can be proposed unchanged.

I have one question only. It appears you need to define a procedure to mitigate the radiation damage to the target and its polarization. Has this been discussed and formulated?

Best regards,
Pasquale

Dear Pasquale,

Thank you for your comments and question.

I have discussed your question with Sebastian Kuhn (a fellow spokesperson) and Chris Keith (JLab Target Group leader), both in cc. We think the basic procedure will use the same methods (restoring, annealing, replacing target material) as for the ammonia and deuterated ammonia. However, according to Chris, there may be a difference between the radiation resistance of LiD from the ammonias, and it is expected to go in a favorable direction. Chris said the following:

"The radiation behavior of LiD has not been studied as extensively as ND3. Based on the SLAC E155 results (Bueltmann et al., SLAC-PUB-7904), we expect LiD to have a radiation resistance about 5x better than ND3. During E155 the LiD sample was only annealed twice (185 K, 20 minutes) to repair the radiation damage, after 10^16 e-/cm2. The sample reattained its previous maximum polarization, but the decay of polarization with accumulated charge was higher than before the anneal. This behavior is also observed in ammonia."

This radiation resistance behavior, of course, must be reconfirmed during the experiment under realistic JLab conditions, however, from what we know now, we don't see any reason for concern.

Best regards,

 - Will