The Polarized EMC Effect: Planned Experiments

Will Brooks

25TH INTERNATIONAL SPIN PHYSICS SYMPOSIUM

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The EMC Effect in Spin Structure Functions

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

S. Kuhn, W. Brooks

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 spin structure functions***.

We will perform this study with 11 GeV beam.

We could repeat this study at 22 GeV. What would be new? Cleanly in the **antishadowing region** with **higher Q^2**!

The experiment was reviewed in 2020
Its scientific rating was upgraded to A-

Read this document to understand theory ingredients:

https://www.dropbox.com/s/dnwp7weufiskrc0/10pageWriteup.pdf?dl=0

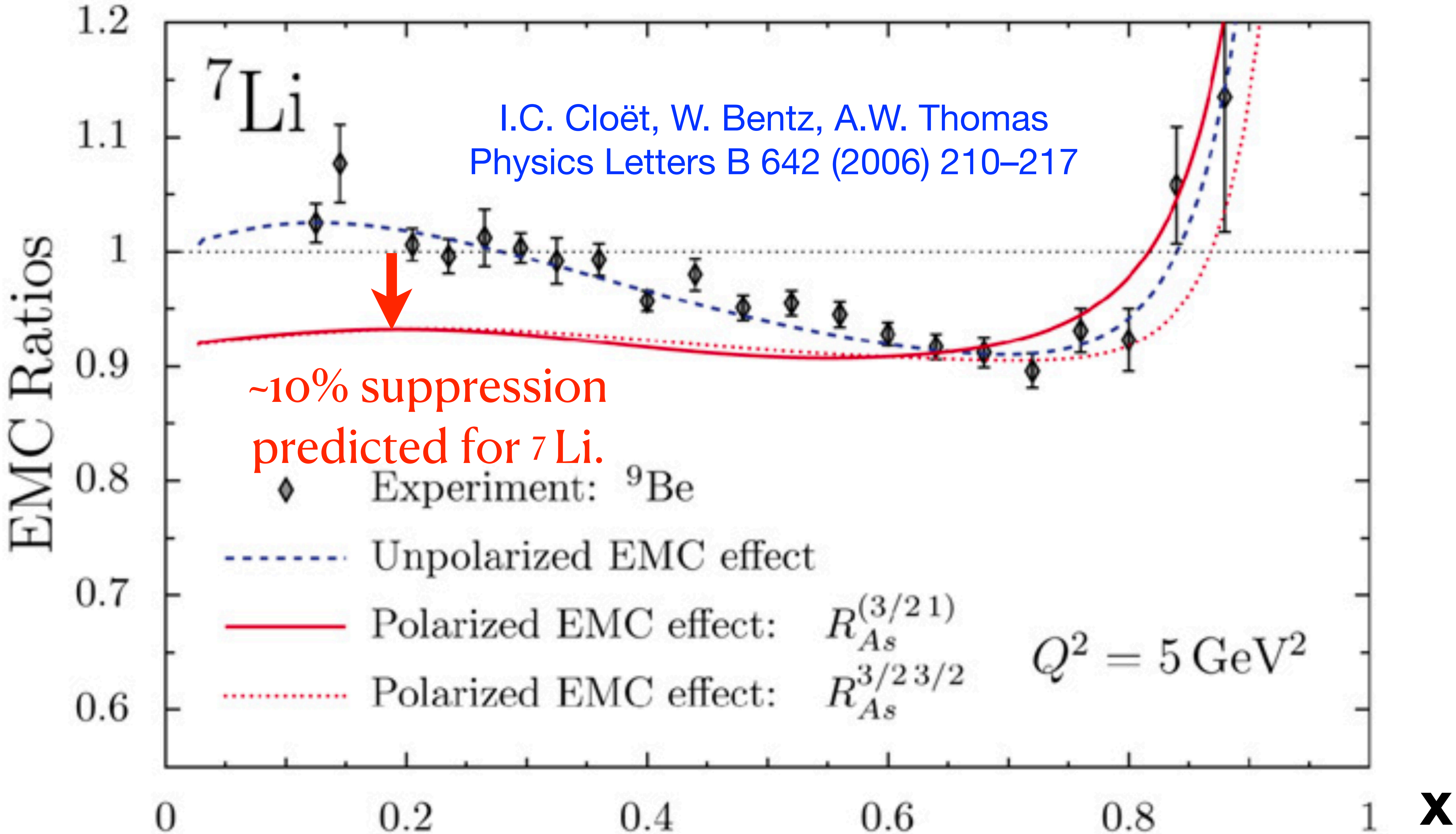
CLAS12 Run Group G Jeopardy Update Document

W.K. Brooks [a], H. Hakobyan, B. Kopeliovich, D. Aliaga,[1] K. Adhikari, S. Bültmann, S.E. Kuhn [b], V. Lagerquist, P. Pandey,[2] C.D. Keith, J.D. Maxwell,[3] K. Griffioen,[4] Raphaël Dupré,[5] N. Kalantarians,[6] D. Keller,[7] E. Long, K. Slifer, M. McClelland, L. Kurbany, T. Anderson, E. Mustafa, D. Ruth, N. Santiesteban,[8] C. Djalai,[9] A.W. Thomas,[10] E. Pace,[11] C. Ciofi, M. Rinaldi, S. Scopetta,[12] V. Guzey,[13] M. Strikman,[14] I. Cloët,[15] and W. Bentz[16]

[1] *Universidad Técnica Federico Santa María, Valparaíso, Chile*
[2] *Old Dominion University, Norfolk, VA 23529*
[3] *Jefferson Lab, Newport News, VA 23606*
[4] *College of William and Mary, Williamsburg, VA*
[5] *Université Paris-Saclay, CNRS, 911405 Orsay, France*
[6] *Virginia Union University, Richmond, VA*
[7] *University of Virginia, Charlottesville, VA*
[8] *University of New Hampshire, Durham, NH*
[9] *Ohio University, Athens, OH*
[10] *University of Adelaide, Australia*
[11] *University of Rome Tor Vergata, Italy*
[12] *University of Perugia, Italy*
[13] *Petersburg Nuclear Physics Institute, Russia*
[14] *Pennsylvania State University, PA*
[15] *Argonne National Laboratory, IL*
[16] *Tokai University, Japan*

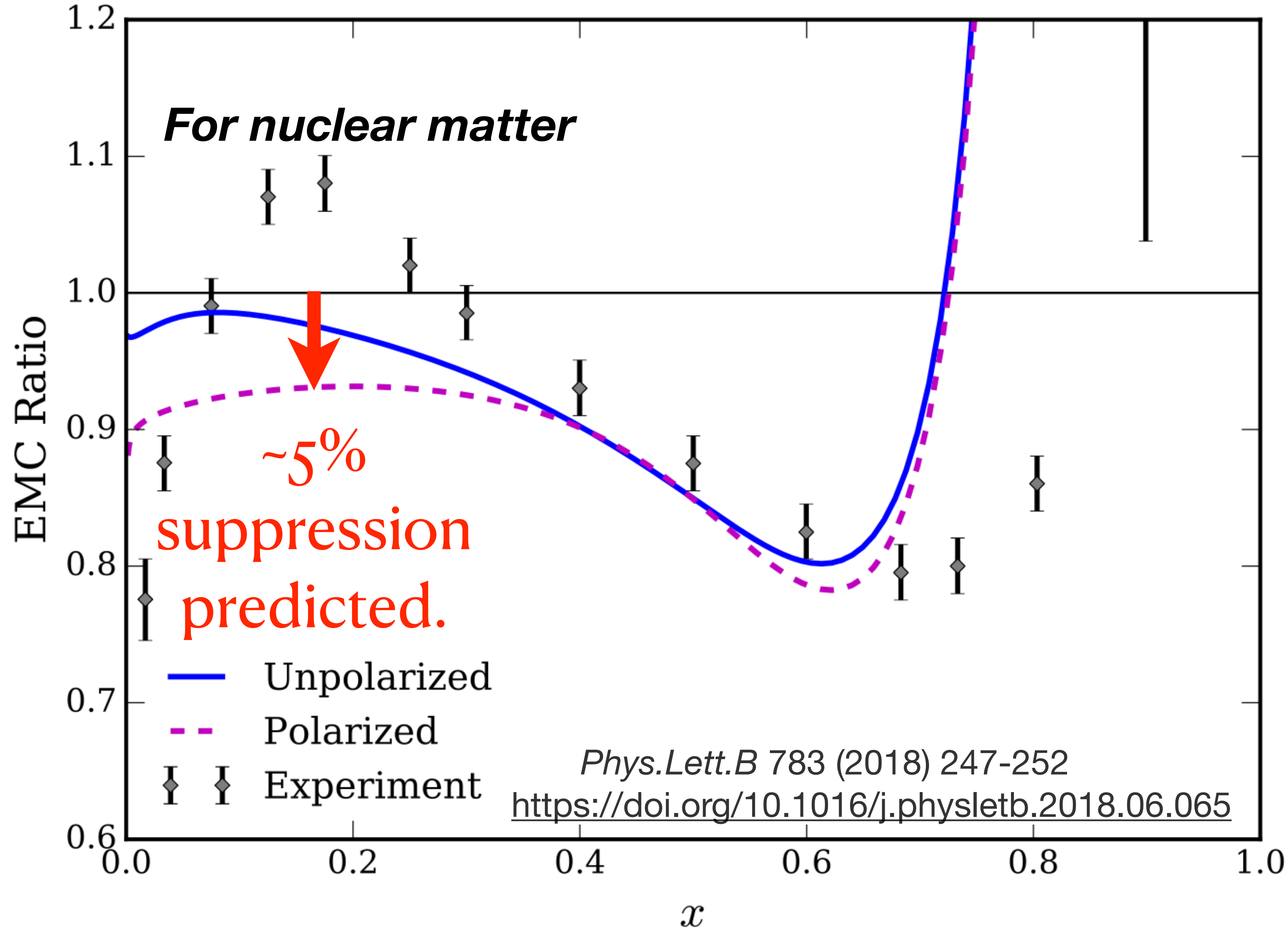
(Dated: June 20, 2020)

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

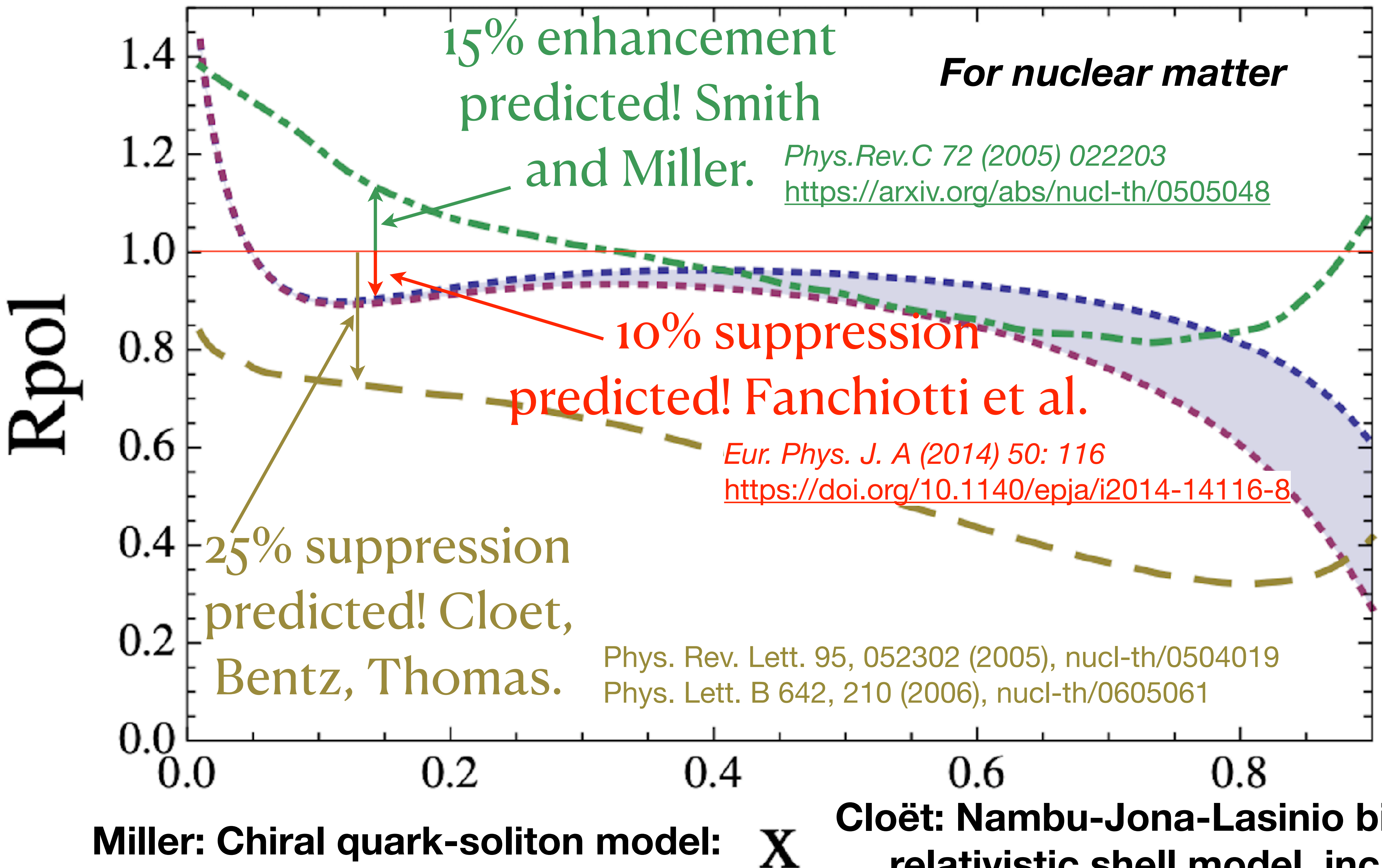


2018 paper

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



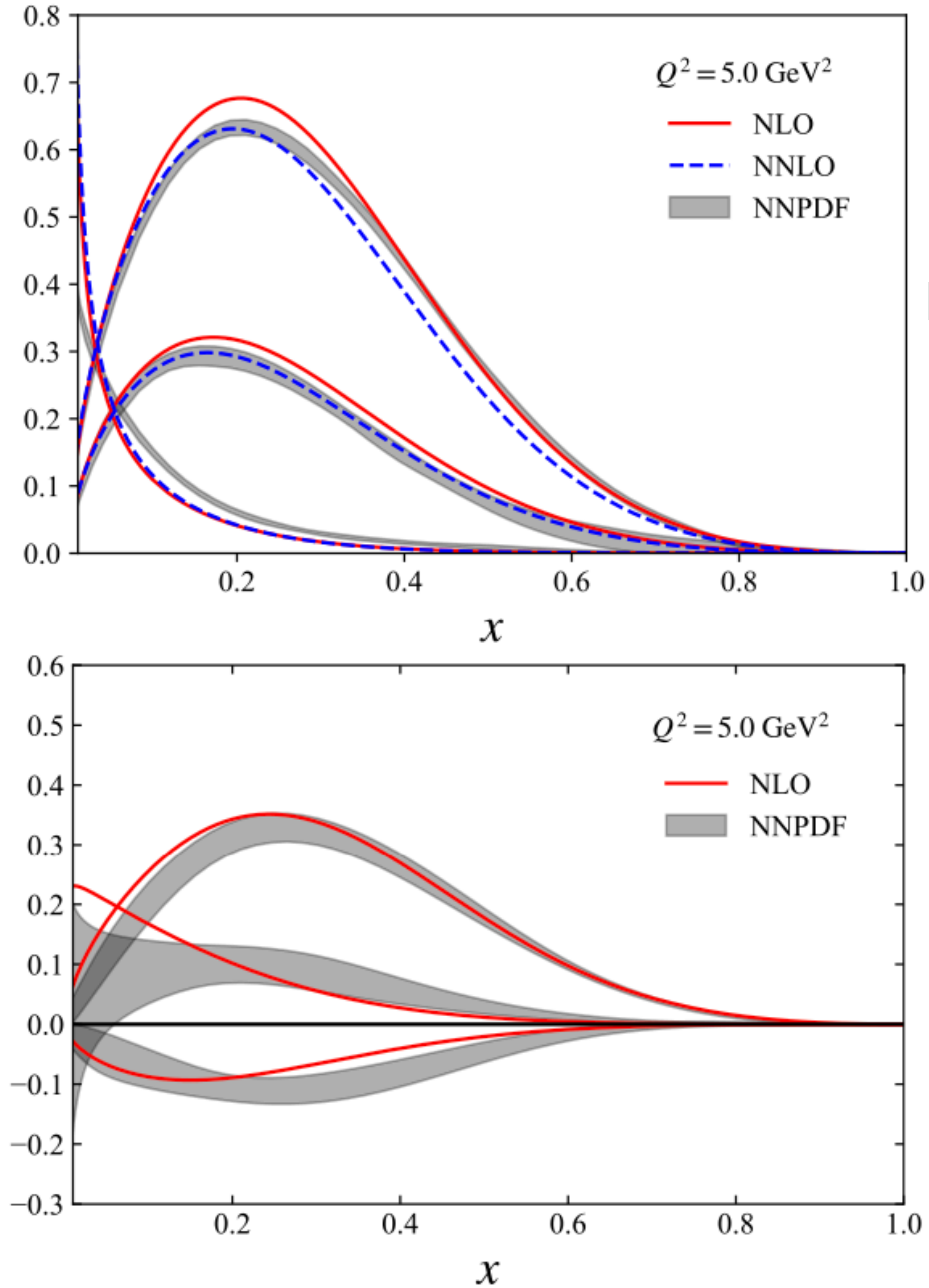
Fanchiotti: 1)x-rescaling 2)increase of sea quark components in the in medium nucleon, related to the low energy N-N interaction

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

New: 2022 paper Includes gluons!



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 $Q^2 = 5\,\mathrm{GeV}^2$. 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

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

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

Gluon EMC Effects in Nuclear Matter
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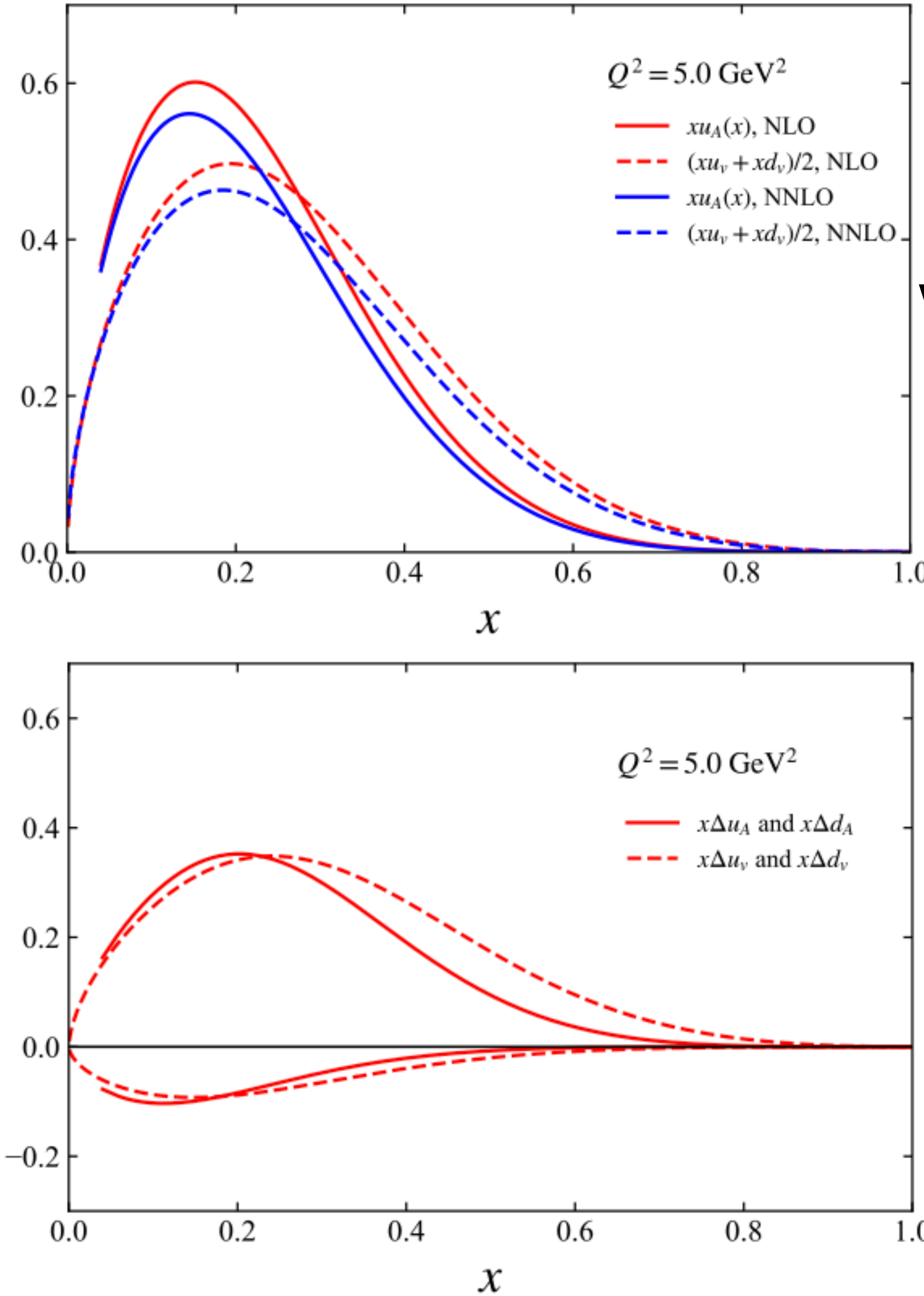
ISOSPIN SYMMETRIC NUCLEAR MATTER



Valence quark unpolarized PDF

Valence quark 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 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

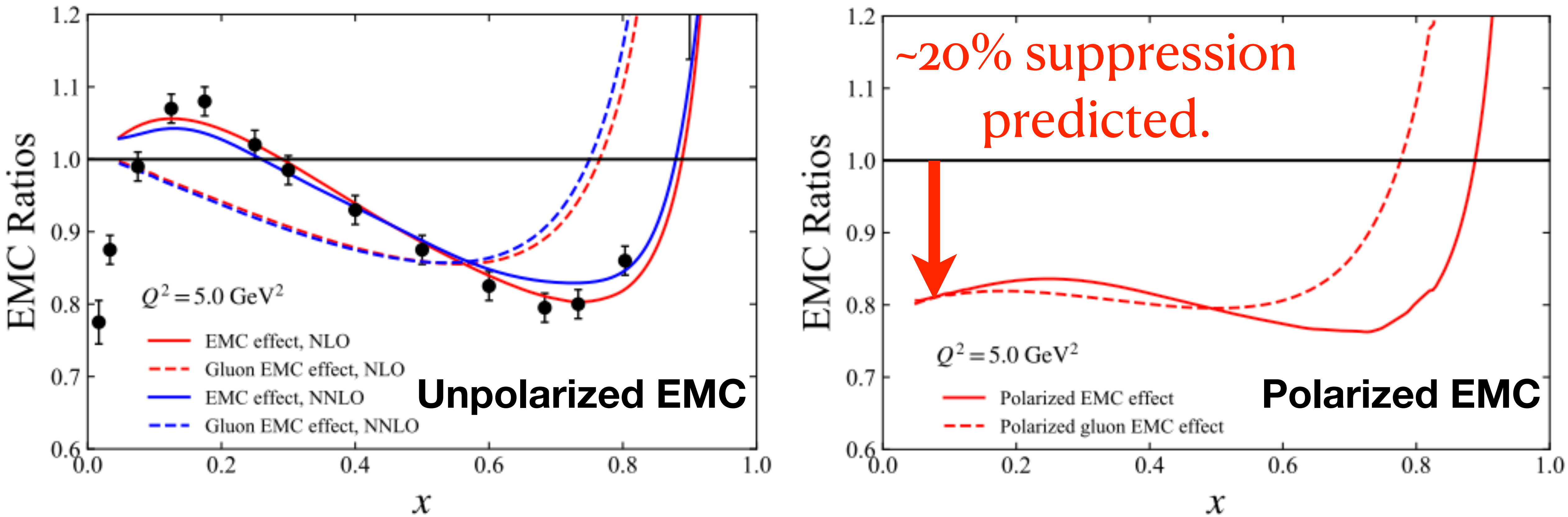


Figure 3. (Colour online) (*Left panel*) Unpolarized EMC ratios for the structure functions $F_{2A}(x)/F_{2N}(x)$ (solid) and the unpolarized gluon distributions $g_A(x)/g_p(x)$ (dashed). (*Right panel*) Polarized EMC ratios for the structure functions $g_{1A}(x)/g_{1p}(x)$ (solid) and polarized gluon 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].

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. (Some theorists also include Odderons and Reggions, see reference below.)
- **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) $$\frac{1}{2Mx_{Bj}} = \frac{\nu}{Q^2} = l_c$$

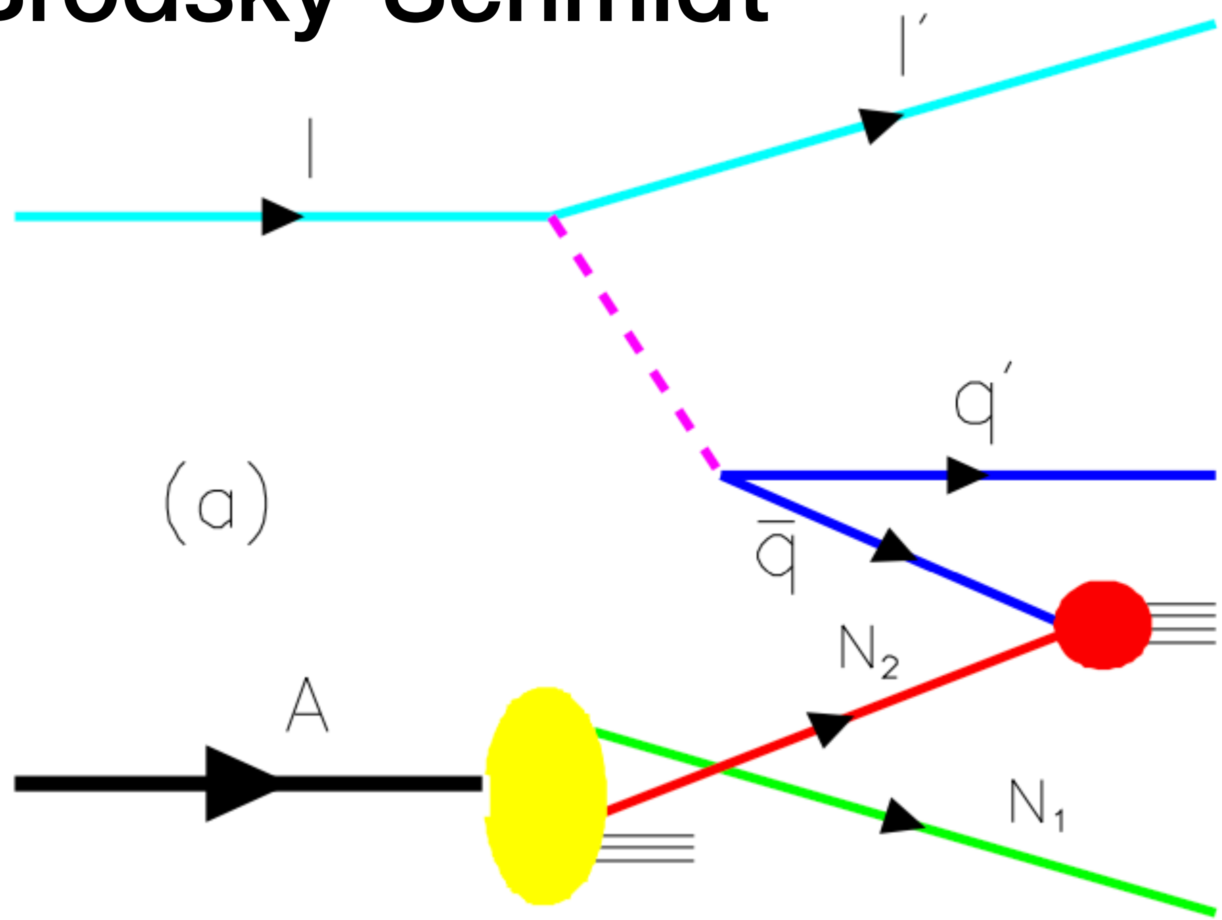
(x_{Bj}=0.1 means l_c = 1.1 fm)

This is ~internucleon distance in a nucleus.

So coherent processes **can/will** happen below x=0.1-0.2

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

Brodsky-Schmidt

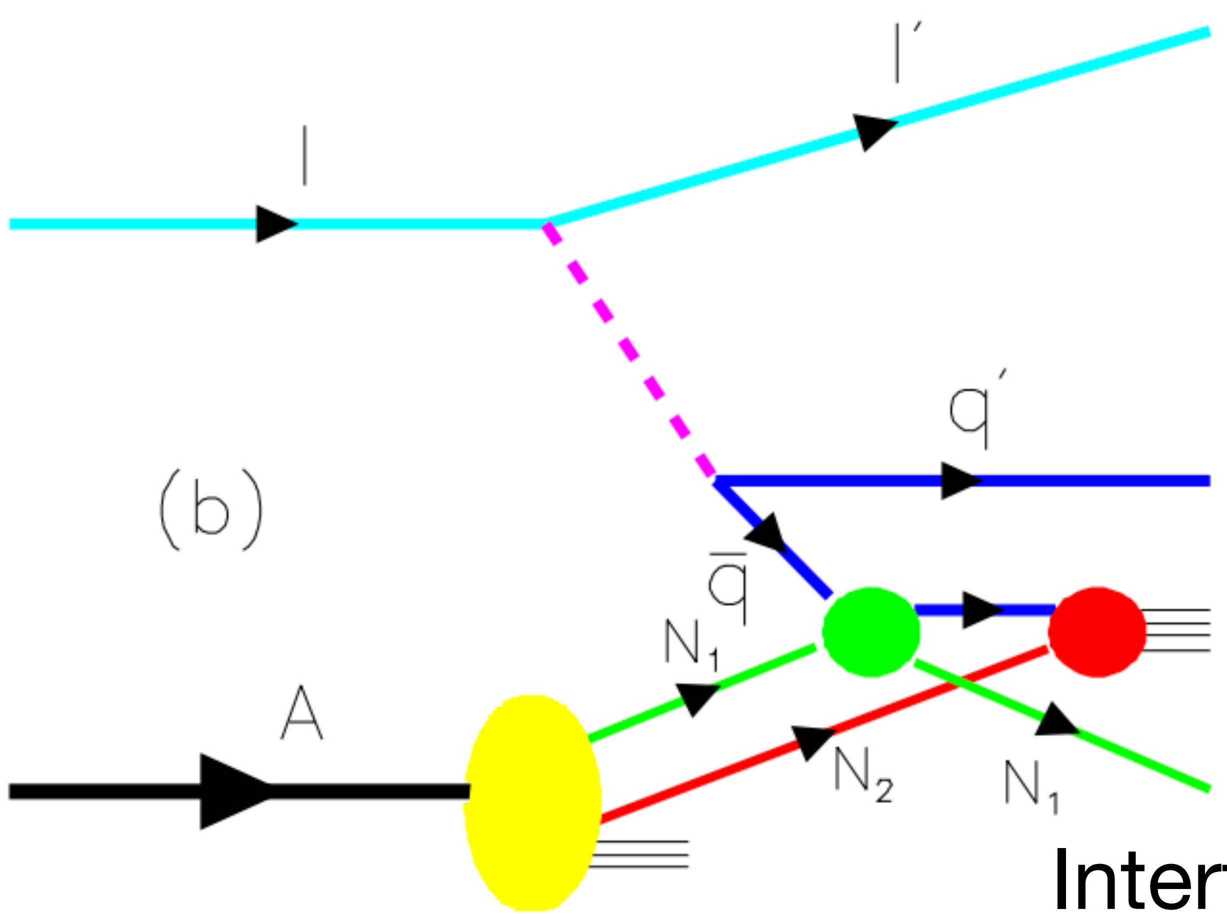


Single-step process

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

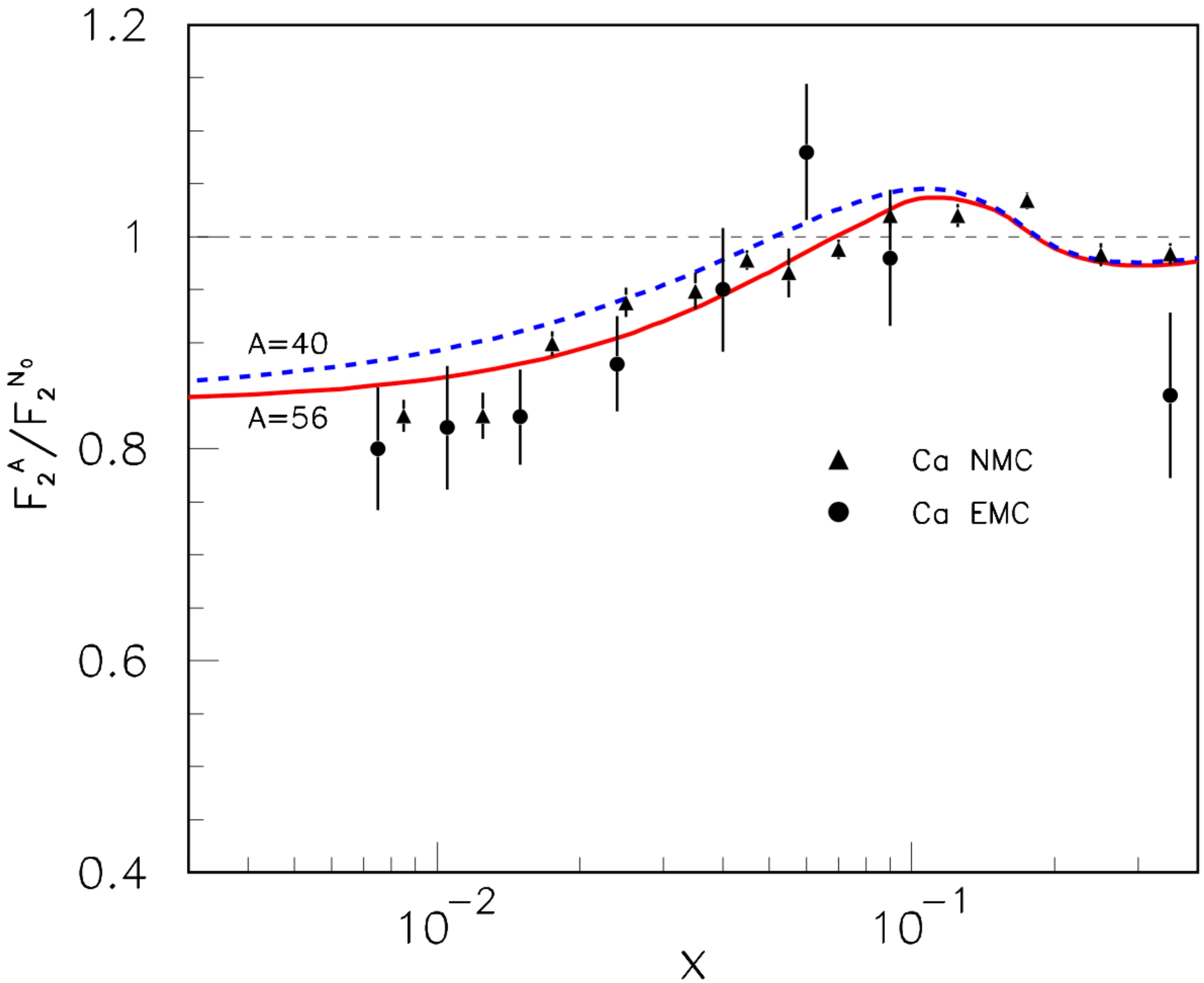
Exchange boson fluctuates into $q\bar{q}$ pair

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

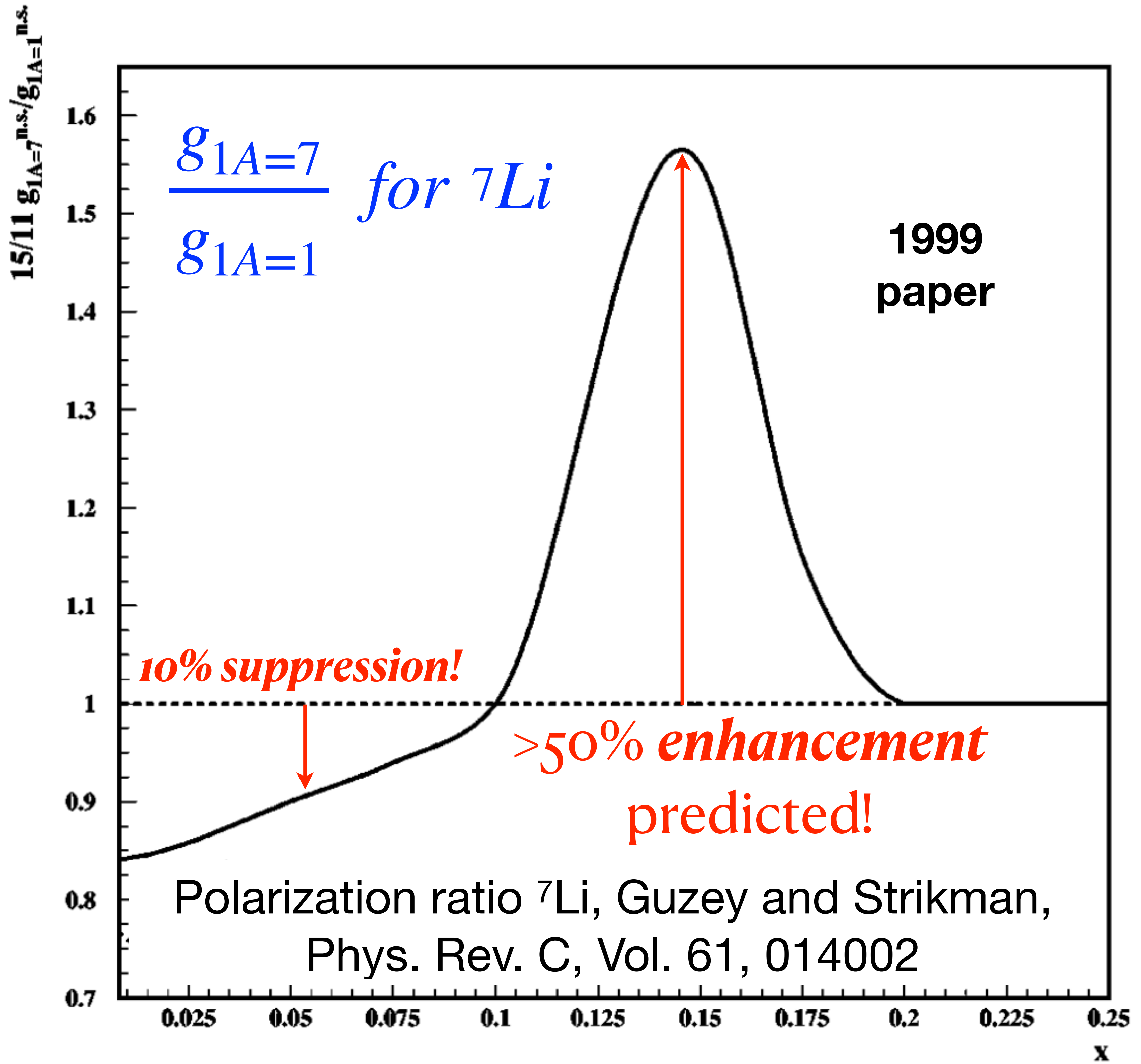


- Introducing the Reggion and the Odderon creates the possibility of having **constructive** interference, producing **anti-shadowing**.

- No polarization prediction yet in this approach

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

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.

Experimental measurements

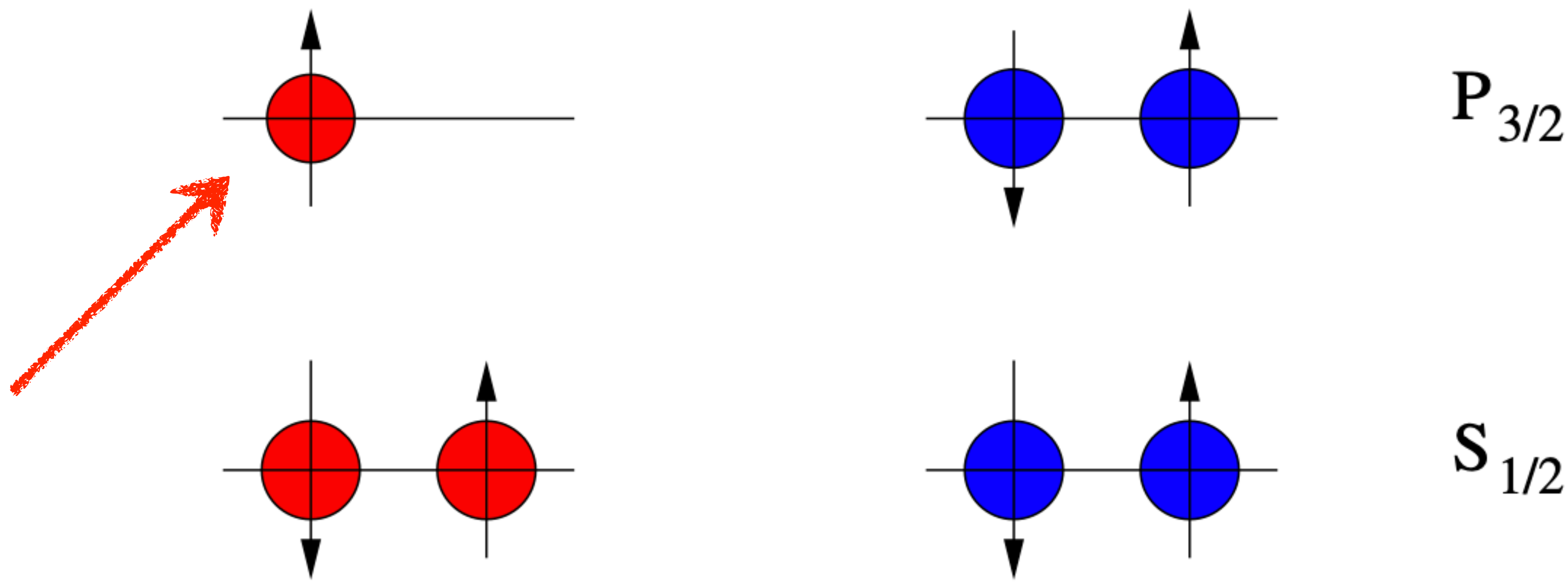
The strategy

We chose the nucleus ^{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 chose to have **two target cells**, in order to gain best control of systematic uncertainties by having polarized ^{7}Li and polarized H simultaneously.

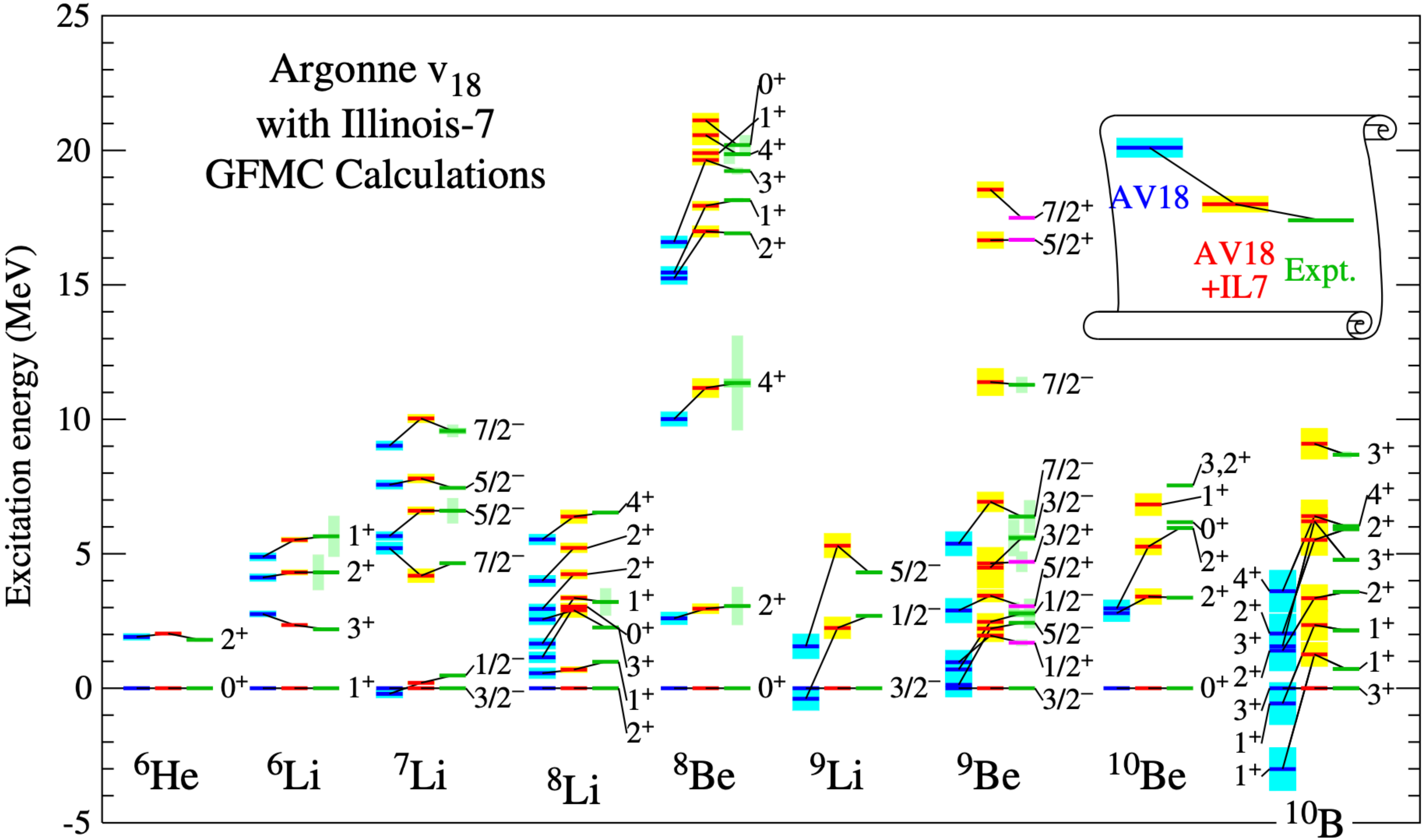
We take advantage of 99% of existing polarized target infrastructure for CLAS12.

Shell model picture of ^{7}Li



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

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



GFMC excitation energies of light nuclei for the AV18 and AV18 + IL7 Hamiltonians compared to experiment.

[REVIEWS OF MODERN PHYSICS, VOLUME 87, JULY–SEPTEMBER 2015, p. 1067]

Target sample (compacted powder) considerations

To reduce systematic uncertainties, we measure polarized ^{6}LiH and ^{7}LiD simultaneously in two separate locations along the beamline, with trim coils to adjust NMR frequency.

Max Thickness: 2% of X_0: 0.02*97 cm = 2 cm = **1.6 g/cm^2**

(Compare ammonia: 5 cm*0.82 g/cm^3 = 4 g/cm^2, packing fraction ~0.6). 2 cm = E.g. two ~1 cm disks, spaced 3 cm.

Radiation resistance of ^{7}Li not well known, but ^{6}Li is is 2-5 times more radiation resistant than NH_3.

Power deposit in a LiH target of 1.6 g/cm^2 would be **~2.4 W** at a luminosity of 10^{37} /cm^2/s. Requires refrigerator upgrade? also replacement/ annealing every few hours at best. Too risky?

The effects due to beam current: heating by power deposition, radiation damage, and depolarization need to be optimized, but it seems likely a favorable combination could be found.

E.g., a good compromise: **1 + 1 cm, 10^{36} /cm^2/s, 270 nA**

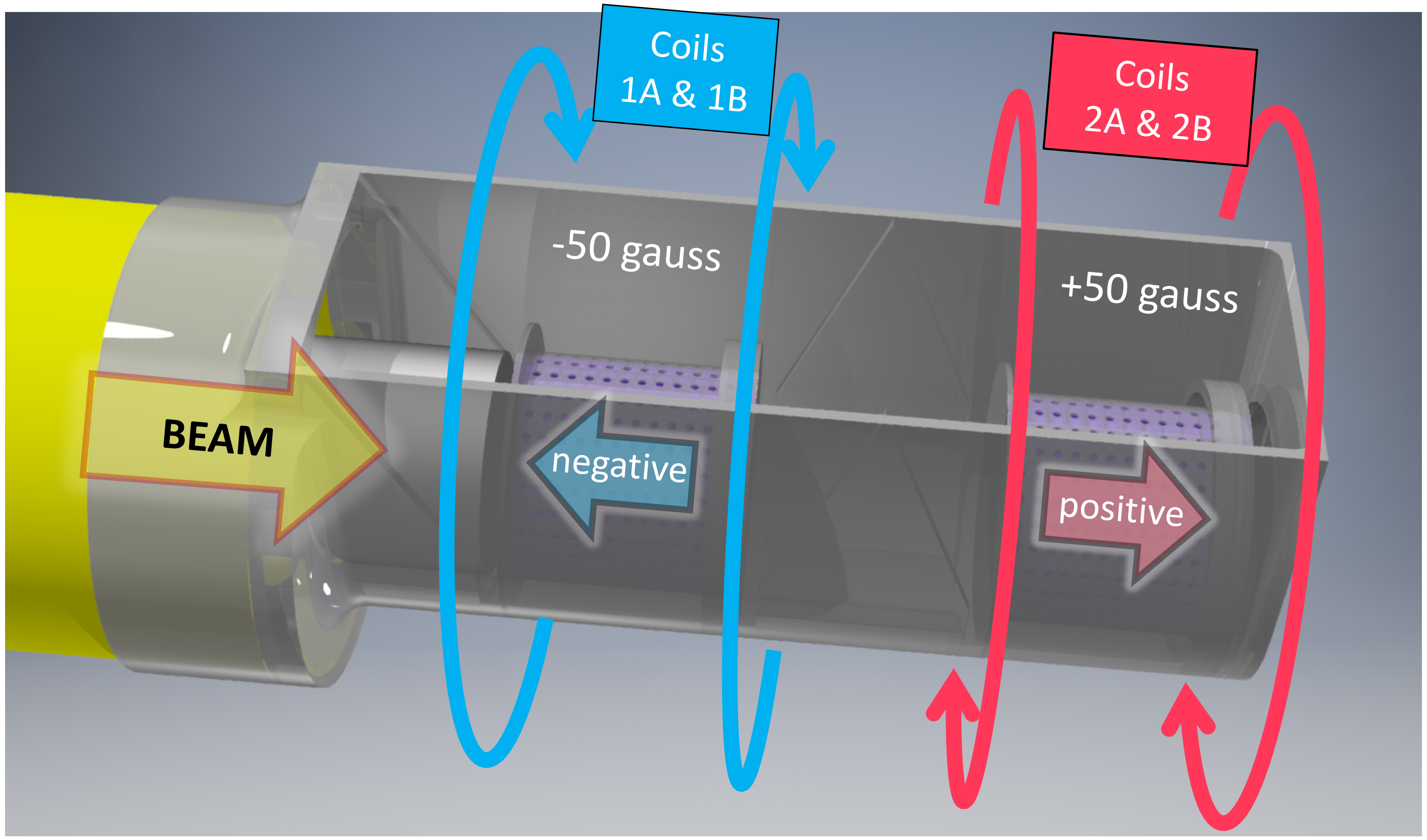
Double-cell Polarization

Can we polarize two samples at once, in opposite directions?
Small coils inside target cryostat shift the 5 T polarizing field:

- Upstream sample -50 gauss
- Downstream sample +50 gauss

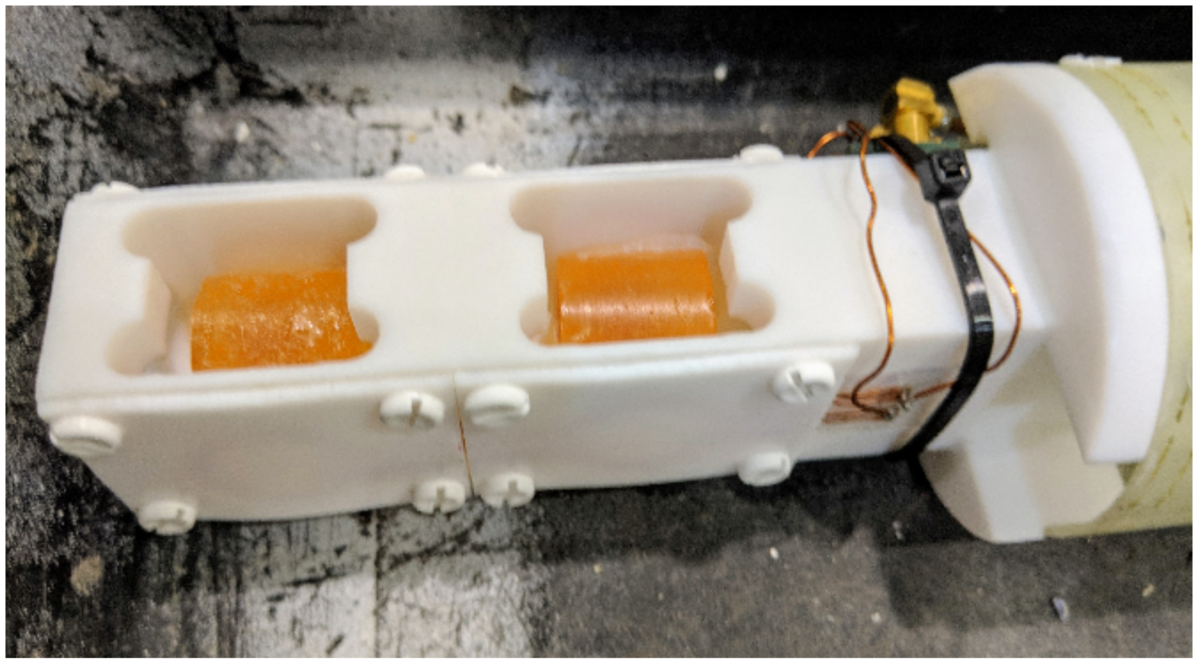
Microwave frequency halfway between the normal (+) and (-) polarization frequencies:

- high field sample will polarize (+)
- low field sample will polarize (-)

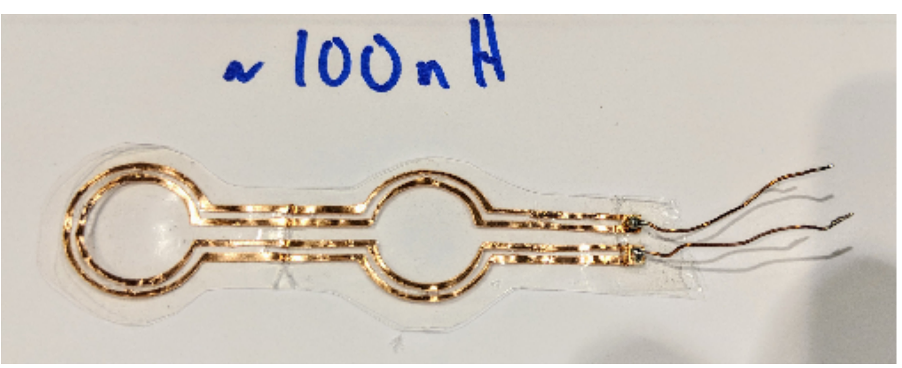


Double-cell Polarization

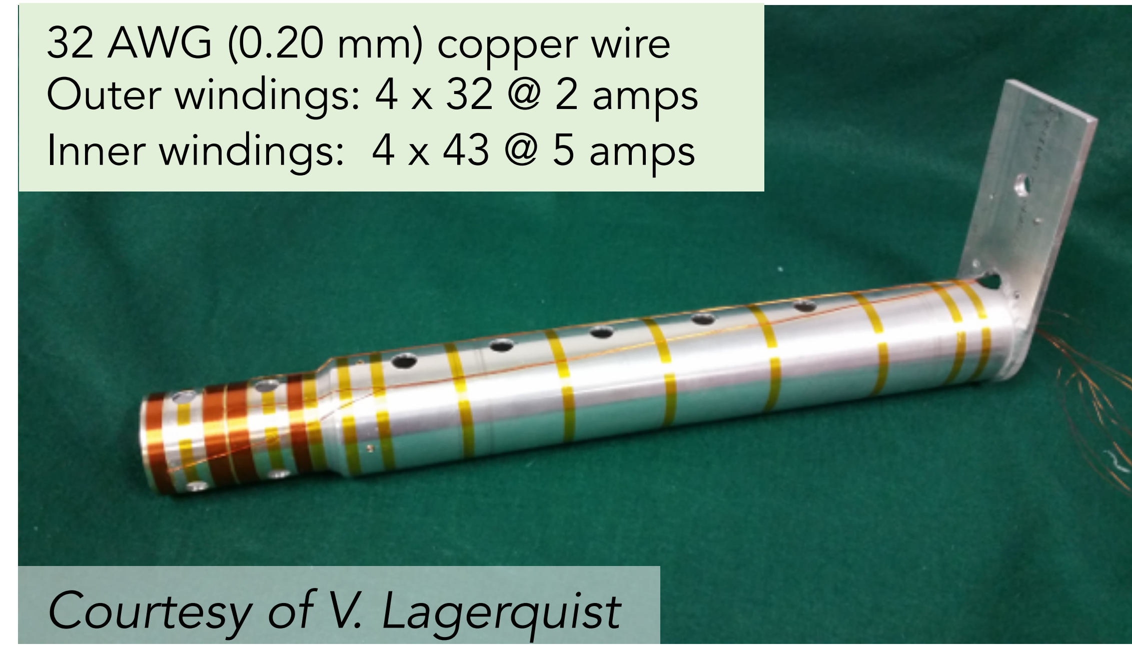
Proof-of-principle tests performed at 77 K and 5 T using TEMPO-doped polymer



Courtesy of J. Maxwell



- Two samples
- One NMR coil

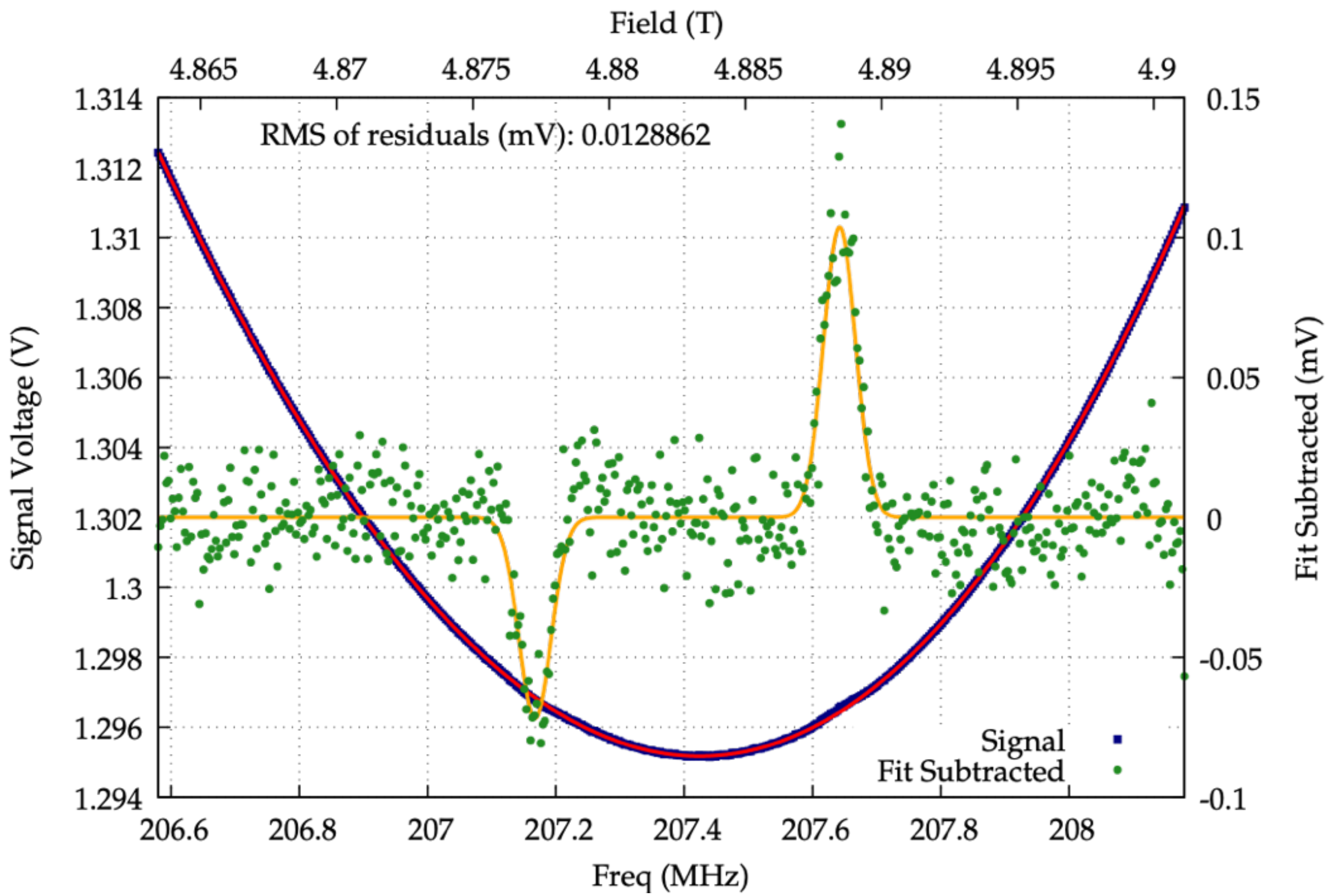


5 T solenoid used for FROST

Double-cell Polarization

Proof-of-principle tests performed at 77 K and 5 T using TEMPO-doped polymer

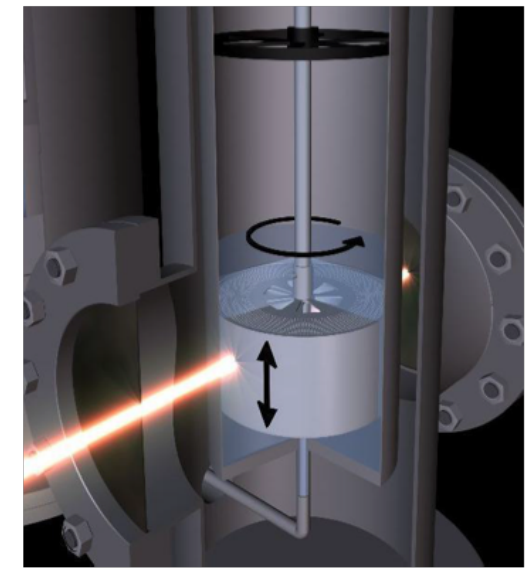
Success!

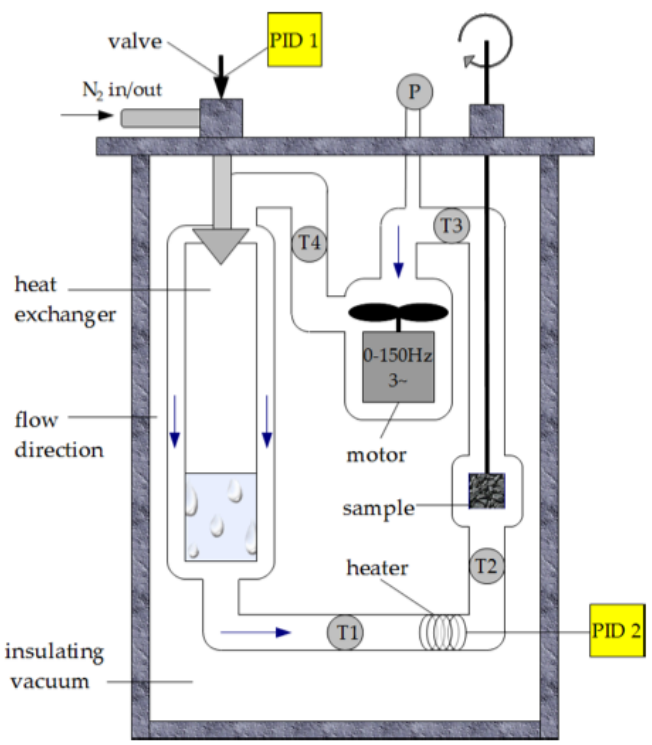


DNP of Lithium Hydride

Under 1K/5T conditions, 7Li has been polarized to about 80% and 6Li to 30%.

Optimal polarization requires pre-irradiating the samples in a narrow temperature band around 185 K.





This can be performed at the UITF, using a custom-built, variable-temperature irradiation cryostat.

Photos and drawings: Scott Reeve, U. Bonn.

Upgrade Injector Test Facility: UITF at JLab

See X. Li et al., NIM A Volume 1039, 11 September 2022, 167093.

LOW ENERGY RECIRCULATOR FACILITY (LERF)

Inspecting an injector assembly at Jefferson Lab's LERF.

ADDITIONAL LINKS

LERF Contact

Jefferson Lab's Low Energy Recirculator Facility, formerly known as the Free-Electron Laser, was developed using the lab's expertise in superconducting radiofrequency (SRF) accelerators. As an FEL, the facility was the world's highest-power tunable infrared laser and also provided ultraviolet laser light, including vacuum ultraviolet light, and Terahertz light. Currently, the lab is using the term Low Energy Recirculator Facility, or LERF, to refer to this facility, as future missions with potentially broader scope are under development.

The uniqueness of Jefferson Lab's LERF stems from what it does with the electrons. It generates the electrons' energy and then recovers it using a superconducting energy-recovering linac, or ERL. In the ERL, the electron beam is re-cycled back through the accelerator out of phase with the accelerating field, so that the beam energy generated in its first trip through the accelerator is returned to the SRF cavities. This power, which would normally be dumped, can represent 90 percent of the beam power in a high-power linear accelerator. While the Jefferson Lab facility remains the highest-power ERL system in existence, a number of other laboratories are adopting this technology.

Many of the future uses envisioned for the LERF use its underlying ERL. The present range of discussion includes future nuclear physics experiments, characterization of materials using low-energy positrons, and R&D on production of medical isotopes. There is also substantial potential for facilitation of commercial development of free-electron laser technology, and Jefferson Lab is pursuing this option, as well. The lab is developing a plan for future utilization of this facility in a manner that is of maximum benefit to the mission of the laboratory and of the nation.

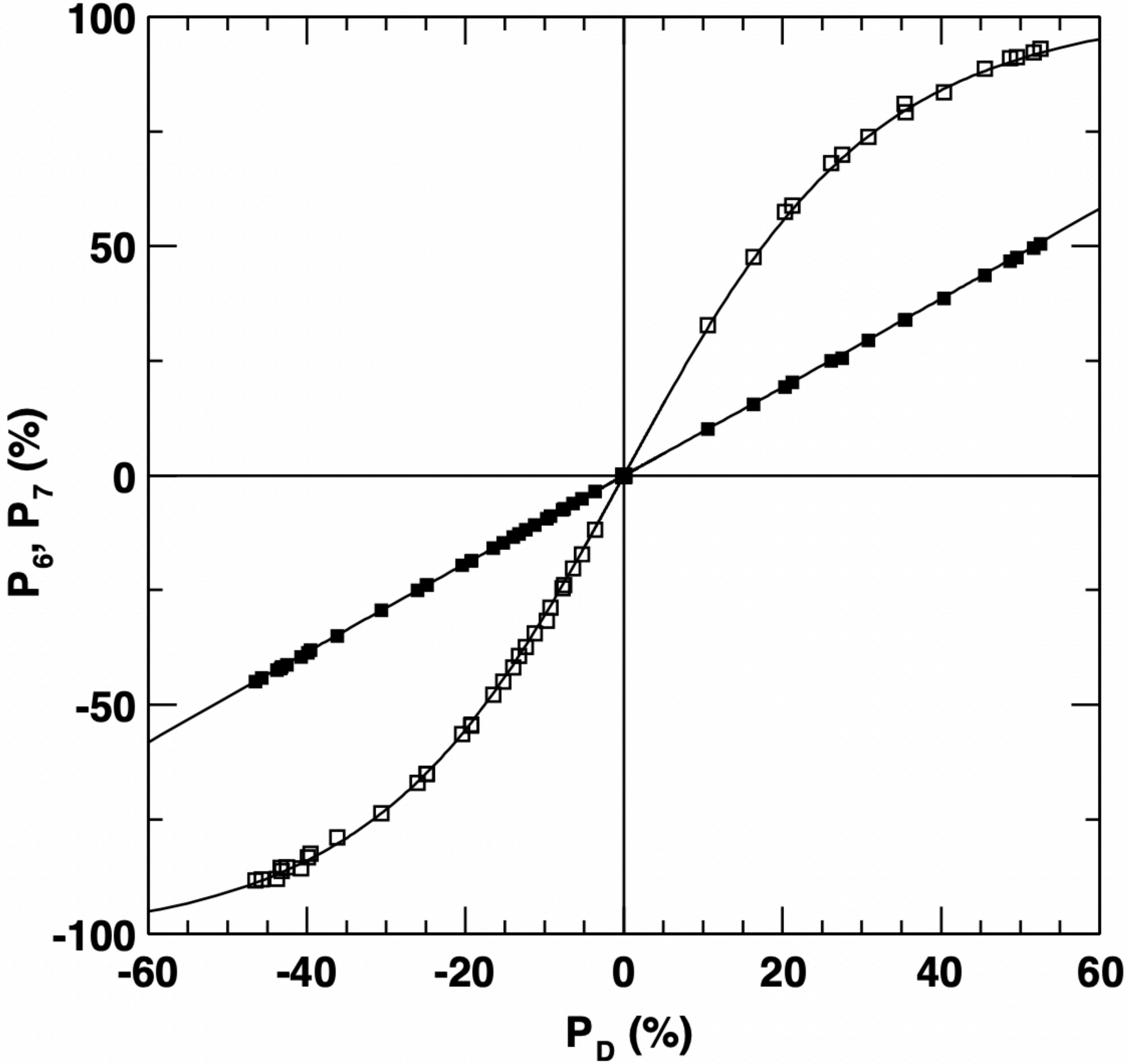
The Low Energy Recirculation Facility LERF currently appears to be the most likely place to irradiate LiH/LiD samples at JLab for this experiment.

https://www.jlab.org/low-energy-recirculator-facility

https://en.wikipedia.org/wiki/Dynamic_nuclear_polarization "DNP can also be induced using unpaired electrons produced by radiation damage in solids"

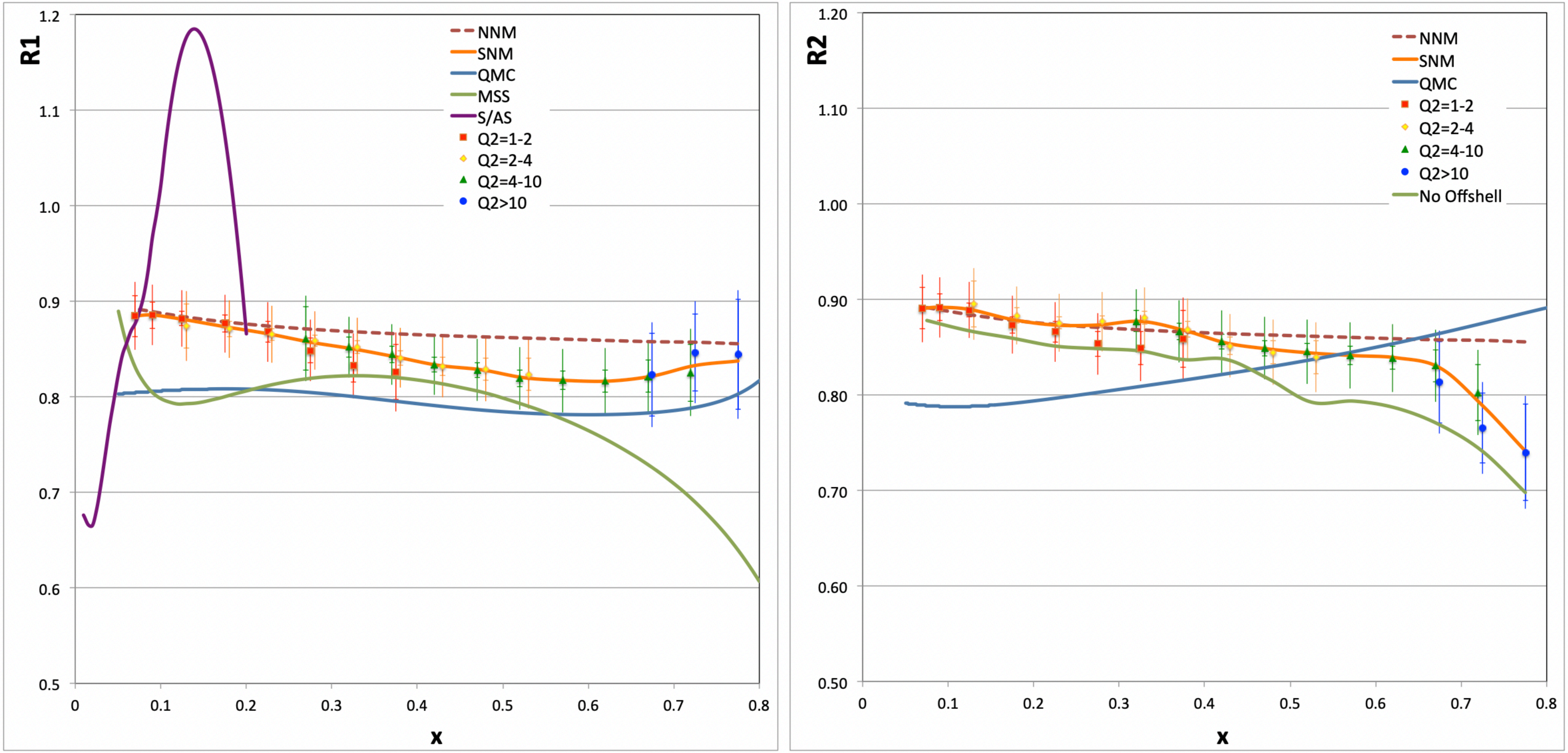
Progress Forward for Run Group G Readiness

- JLab target group is acquiring a tube furnace for synthesizing lithium hydrides or deuterides (^{6}Li, ^{7}Li)
- Will start with naturally occurring lithium and H_2
- Irradiation beam line still under discussion, favoring LERF



Relationship between the measured polarizations of ^{7}Li (open symbols) and ^{6}Li relative to deuterium as found by COMPASS Collaboration. Lines are Equal Spin Temperature calculations.

Anticipated Uncertainties, 11 GeV experiment

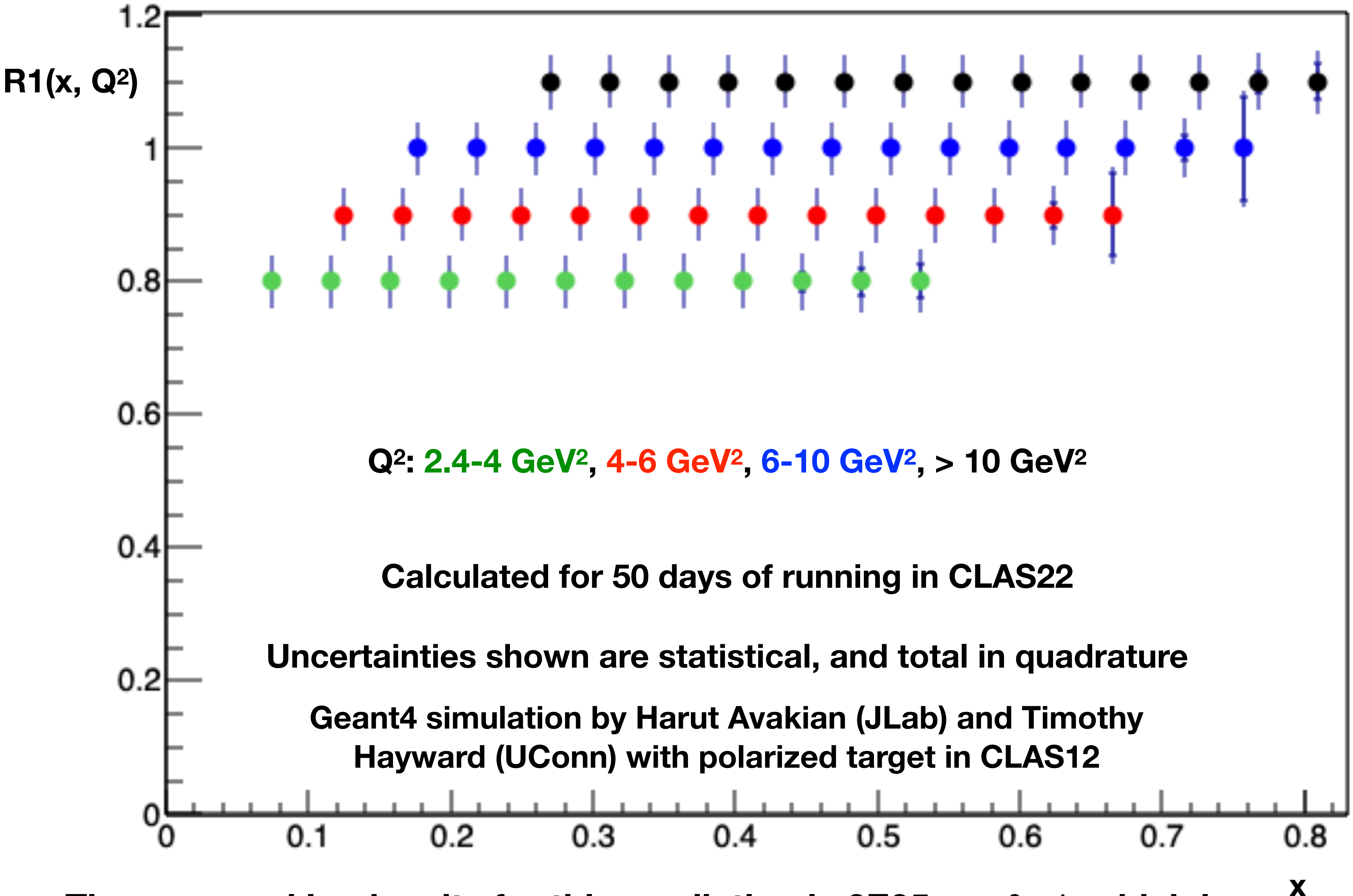


Ratio R_1 of cross section differences for double polarized ^{7}Li(e,e') over p(e,e') for several different models. Ratio R_2 of the parallel double spin asymmetry $A_{\|}$ for ^{7}Li(e,e') over p(e,e), normalized by "naïve " unpolarized structure function ratio for ^{7}Li over hydrogen.

(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.

Anticipated results at 22 GeV JLab



The assumed luminosity for this prediction is 2E35 $cm^{-2}s^{-1}$, which has already been demonstrated in present-day CLAS for light nuclear targets.

Conclusions

- A very interesting measurement of medium-modified structure functions is feasible in the EMC and anti-shadowing region.

- The theoretical predictions from various models range from 25% suppression to 50% enhancement.

- It can be argued that models which survive testing in the EMC region may still be eliminated in the anti-shadowing region, where new interference phenomena will emerge.

Backup slides

QMC model in a nutshell - see 2105.12327 by A.W. Thomas

The significance of the enhancement of the lower component of the Dirac wave-function of the confined valence quark should not be underestimated. For the nucleon as a whole, the effective nucleon-σ coupling constant, $g_{\sigma N}$, is proportional to the integral of the upper Dirac component of the quark wave-function squared minus the square of the lower component. Thus the change in the internal structure of the nucleon naturally leads to a reduction of $g_{\sigma N}$ with increasing density. The Lorentz-vector character of the repulsive ω-nucleon coupling means that it is density independent. This provides an interesting new, natural mechanism for the saturation of nuclear matter, with the vector repulsion growing linearly with density while the growth of the scalar attraction is suppressed by the change in internal structure. Indeed, this mechanism is sufficient to saturate nuclear matter even if we neglect the kinetic energy of the nucleons, unlike QHD where the relativistic correction to the nucleon kinetic energy provides the saturation mechanism.

Mathematically, the change of the σN coupling with increasing scalar-field strength re- quires a self-consistent solution of the field equations. The resulting effective mass of the nucleon may be written as

$M_N^* = M_N - g_{\sigma N}(\sigma)\sigma$ (1) where the nucleon-σ coupling may be expressed as

$g_{\sigma N}(\sigma) = g_{\sigma N}(0)[1 - \frac{d}{2}(g_{\sigma N}(0)\sigma)]$. (2) By analogy with electromagnetism, where the electric polarizability characterizes the ten-

dency of the electrons in an atom to rearrange to oppose an applied electric field, d is called 8

the scalar polarizability. In the bag-model, d is approximately 0.2 R, with R the bag radius. While the development of this approach, known as the ‘quark-meson coupling (QMC)’ model [58–62], was based upon the MIT bag-model for hadron structure, it should be clear that the general features are not model dependent. Indeed, a formulation based upon the model of Nambu and Jona-Lasinio (NJL) [63], which is covariant and respects chiral

symmetry, leads to the same mechanism for the saturation of nuclear matter [64].
As we discuss later, this approach to nuclear structure has been used to derive an energy density functional (EDF) [66], with a form a little more complicated than the usual Skyrme forces [65] but which has nevertheless been applied to nuclear structure with some success. In particular, the quality of the overall description of nuclear binding and sizes across the periodic table was found to be comparable with modern Skyrme forces [70] but

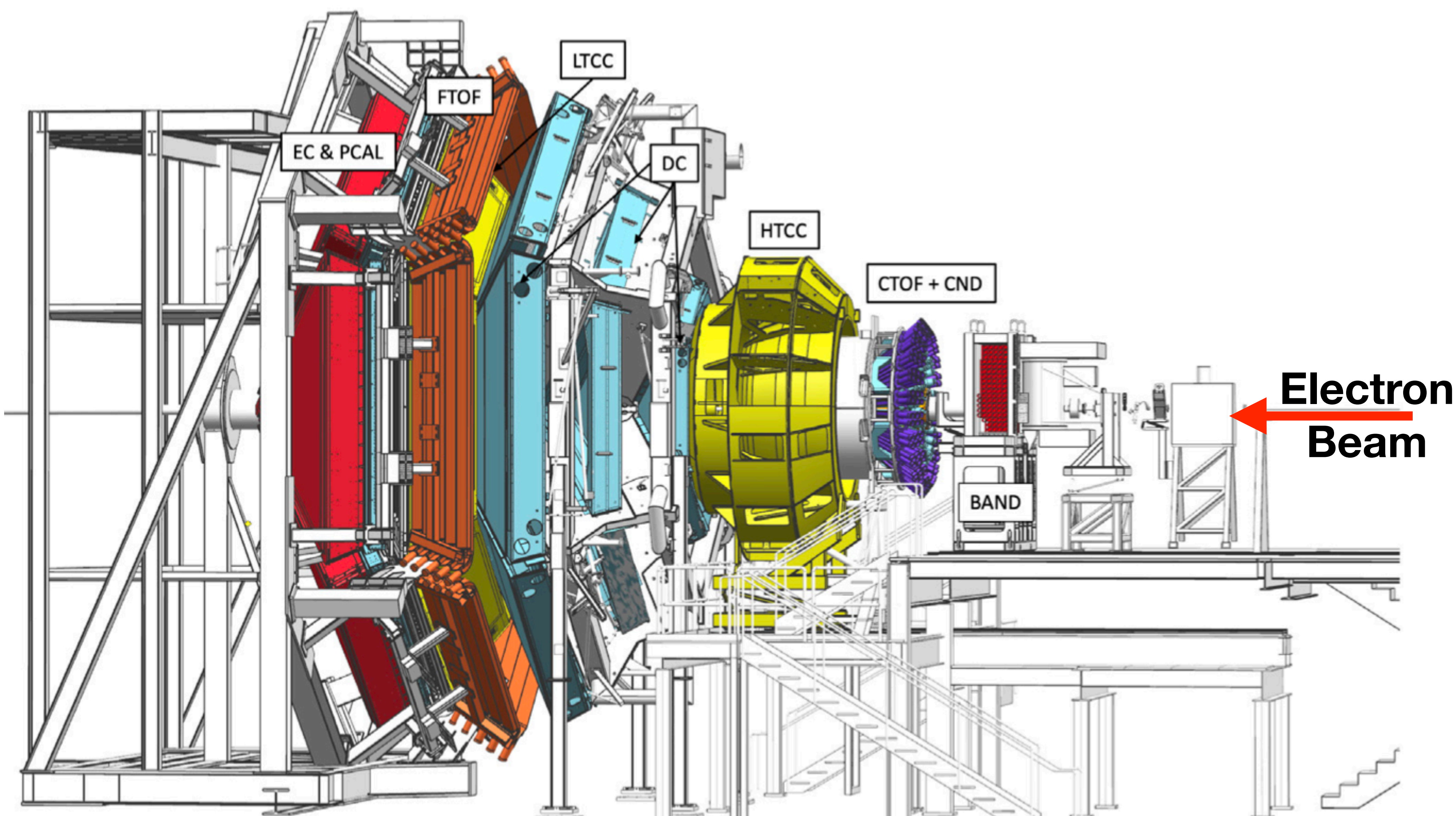
with considerably fewer parameters.

Without meaning to diminish the importance of the results for gross nuclear properties, we stress the change of paradigm that it represents. Rather than neutrons and protons occupying shell model orbits in a nucleus, those orbits are occupied by clusters of quarks with the quantum numbers of nucleons but whose internal structure has adjusted to the local scalar mean-field.

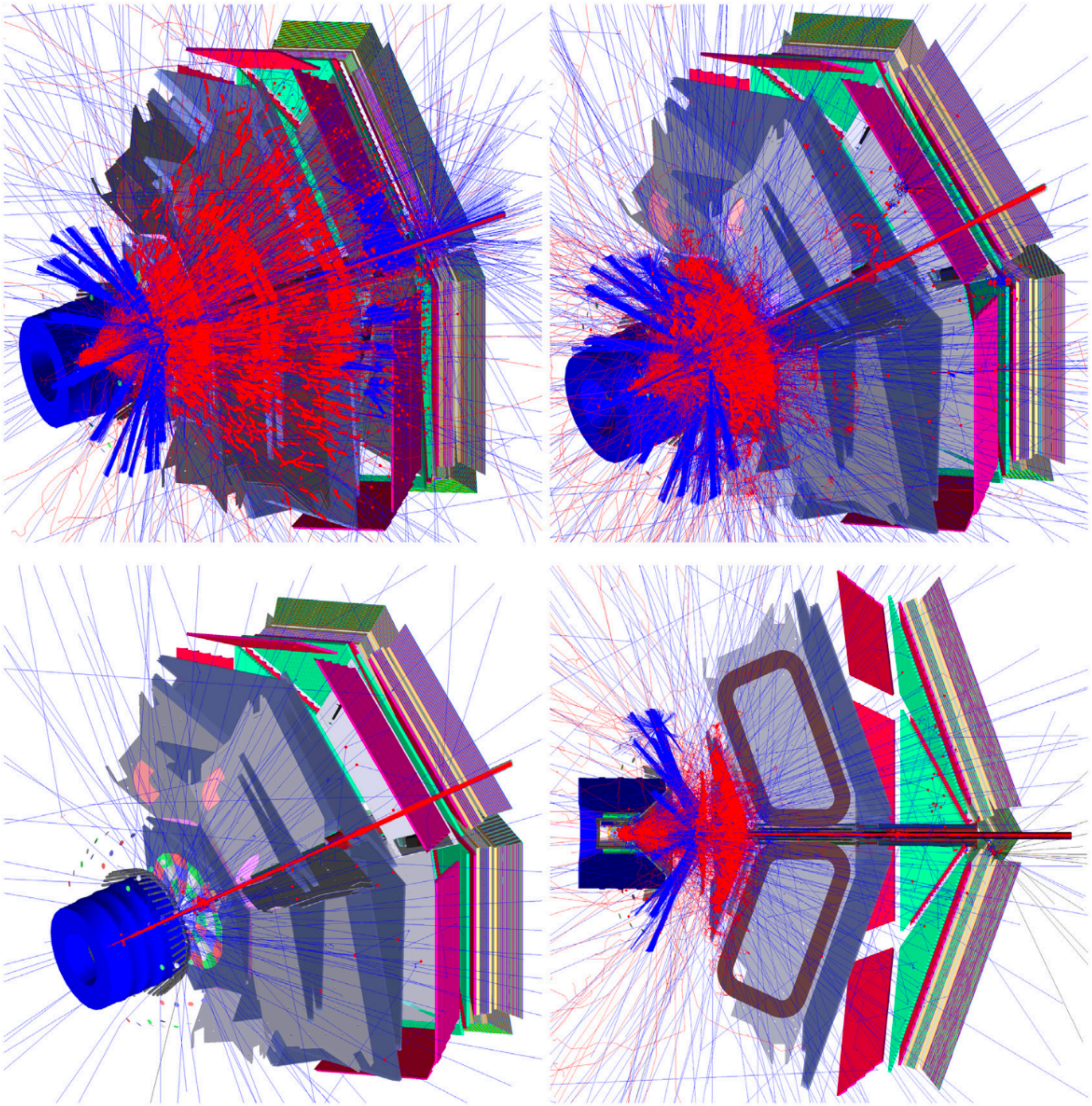
The CLAS12 Spectrometer

- **The 11 GeV measurements described will be carried out in the CLAS12 spectrometer.**

- **The 22 GeV measurements would use an upgraded CLAS12**

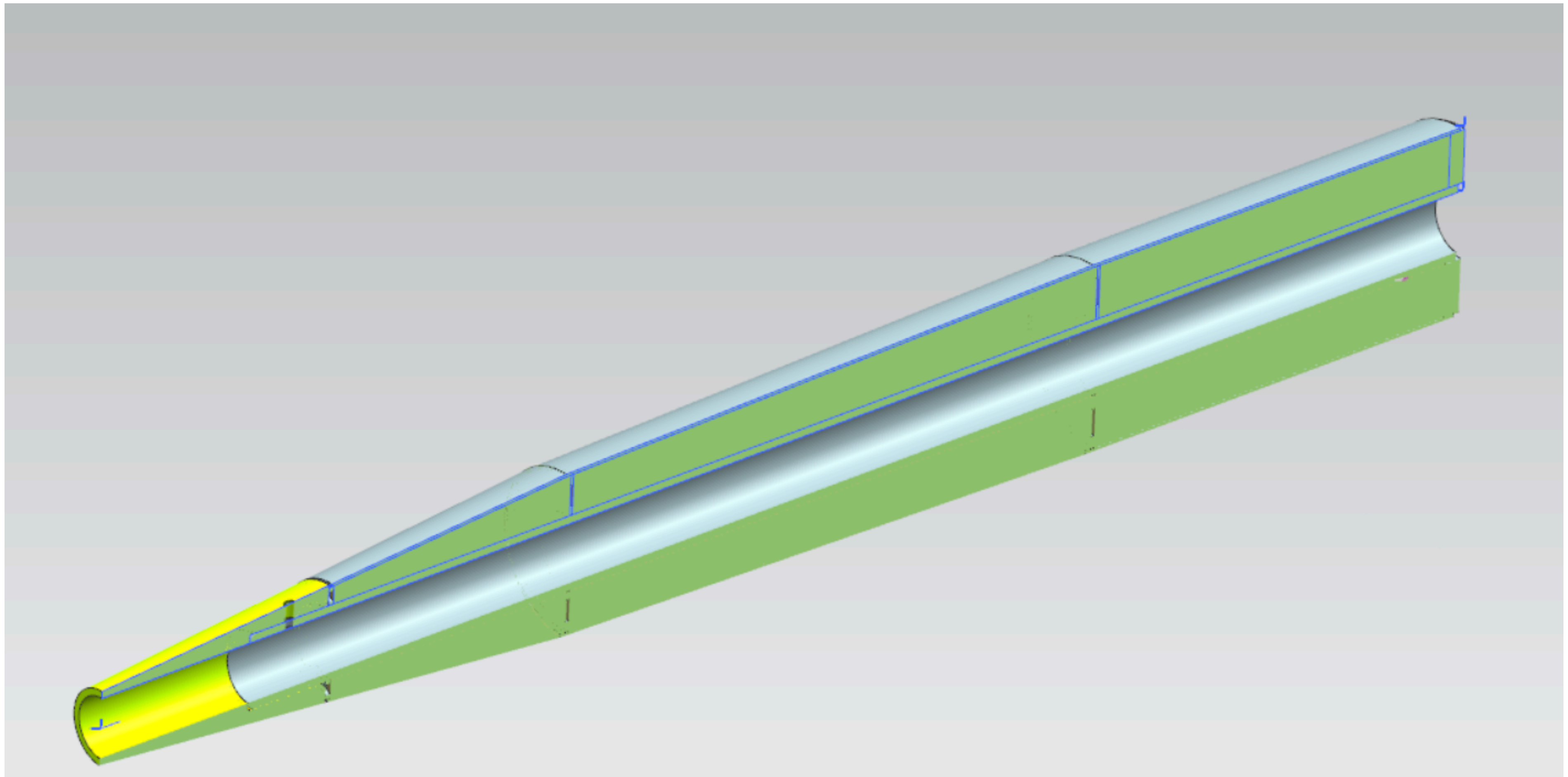


Why we talk about Møller electrons



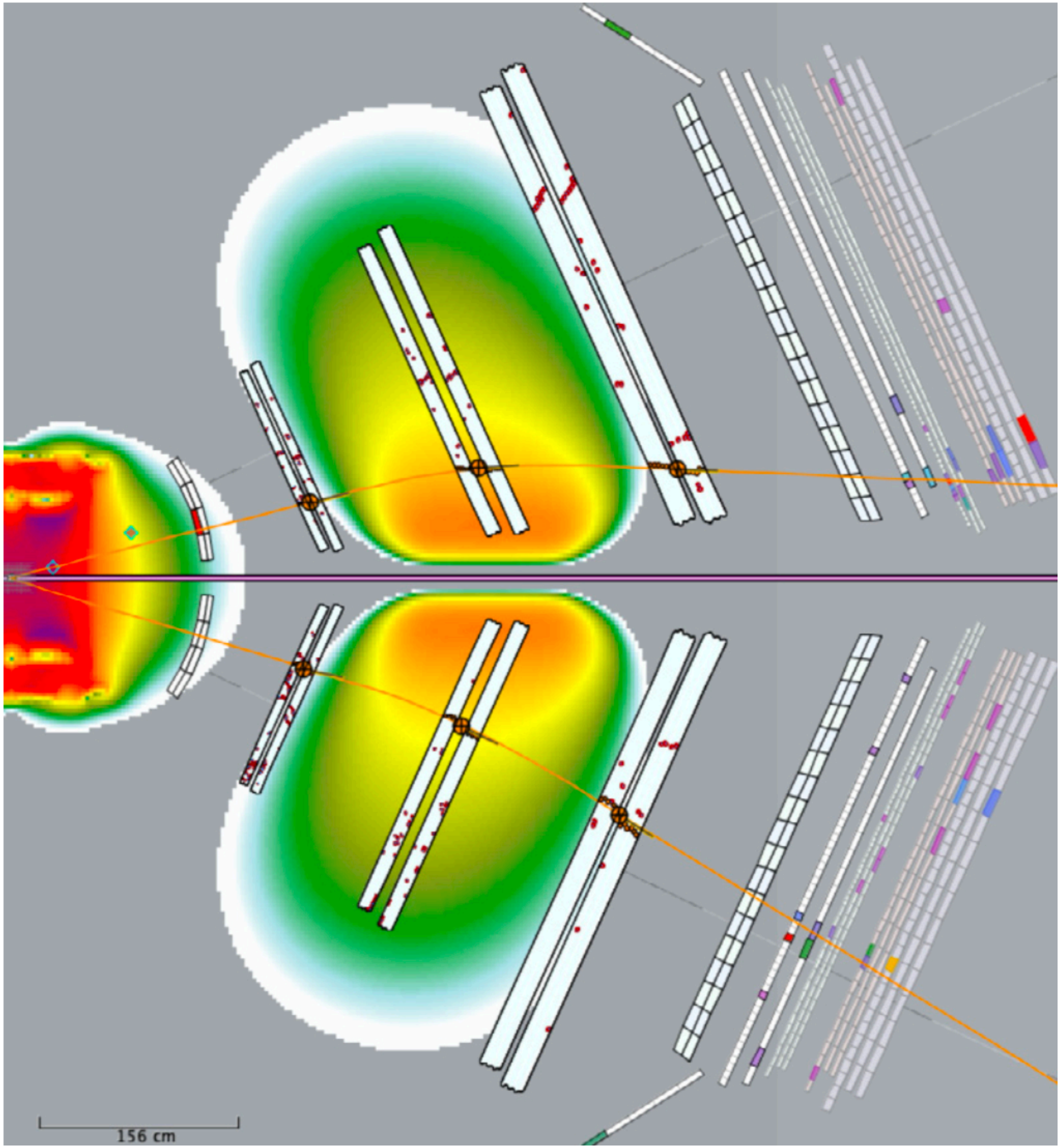
1) Fixed target experiment, where the target material is made of atoms (with electrons!)
2) Open detector design

Nuclear Inst. and Methods in Physics Research, A 959 (2020) 163419



- New tungsten Møller electron shield for use with rastered beam on a polarized target.
- Optimized to contain the electromagnetic background produced by the electron beam as far as 1 cm off the nominal beam axis, to accommodate rastering.
- RG-G will use a configuration with the Forward Tagger (FT) removed and this new Møller shield installed, to be able to run with the highest luminosity possible.

Present-Day CLAS12 Spectrometer



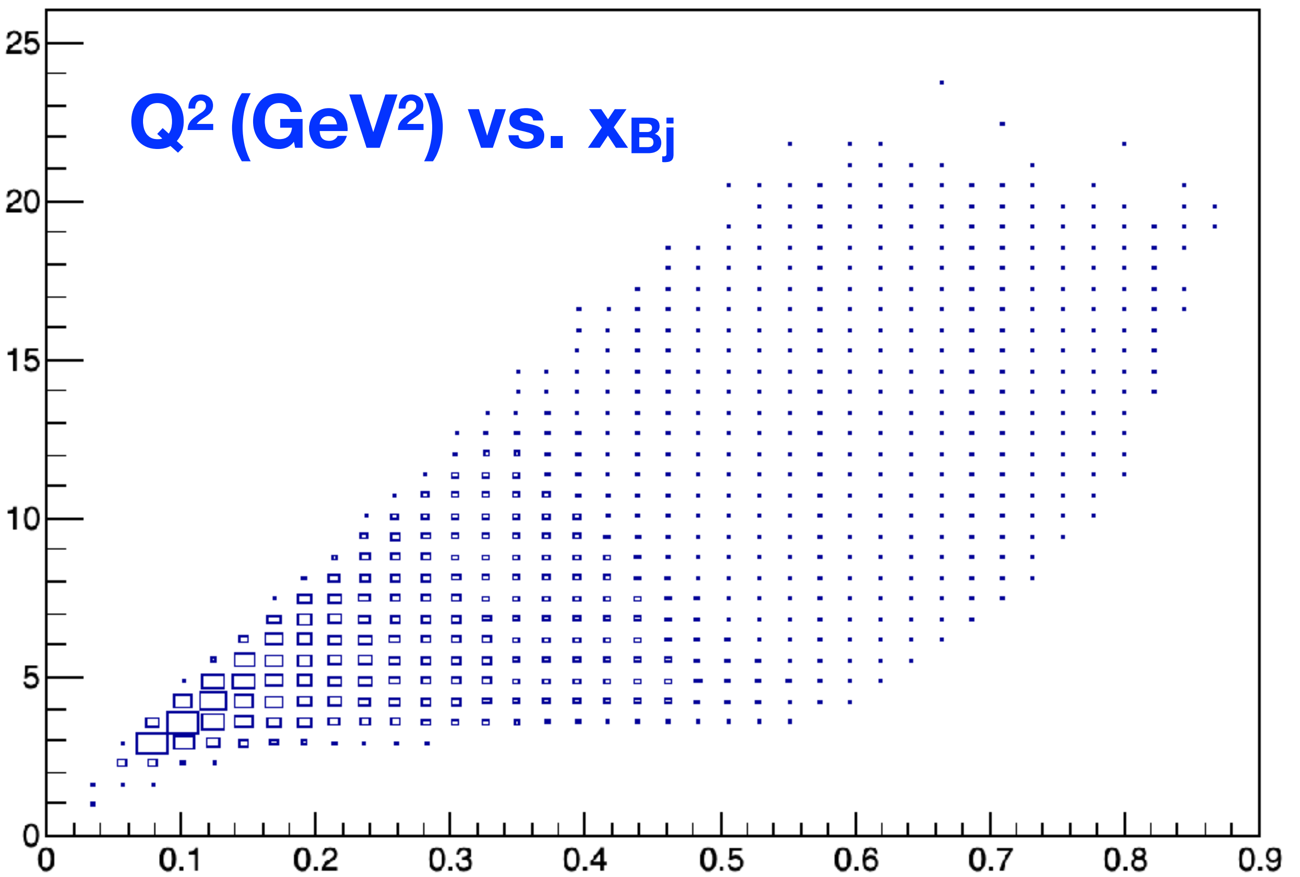
Scattered Electron
(“inbending”)

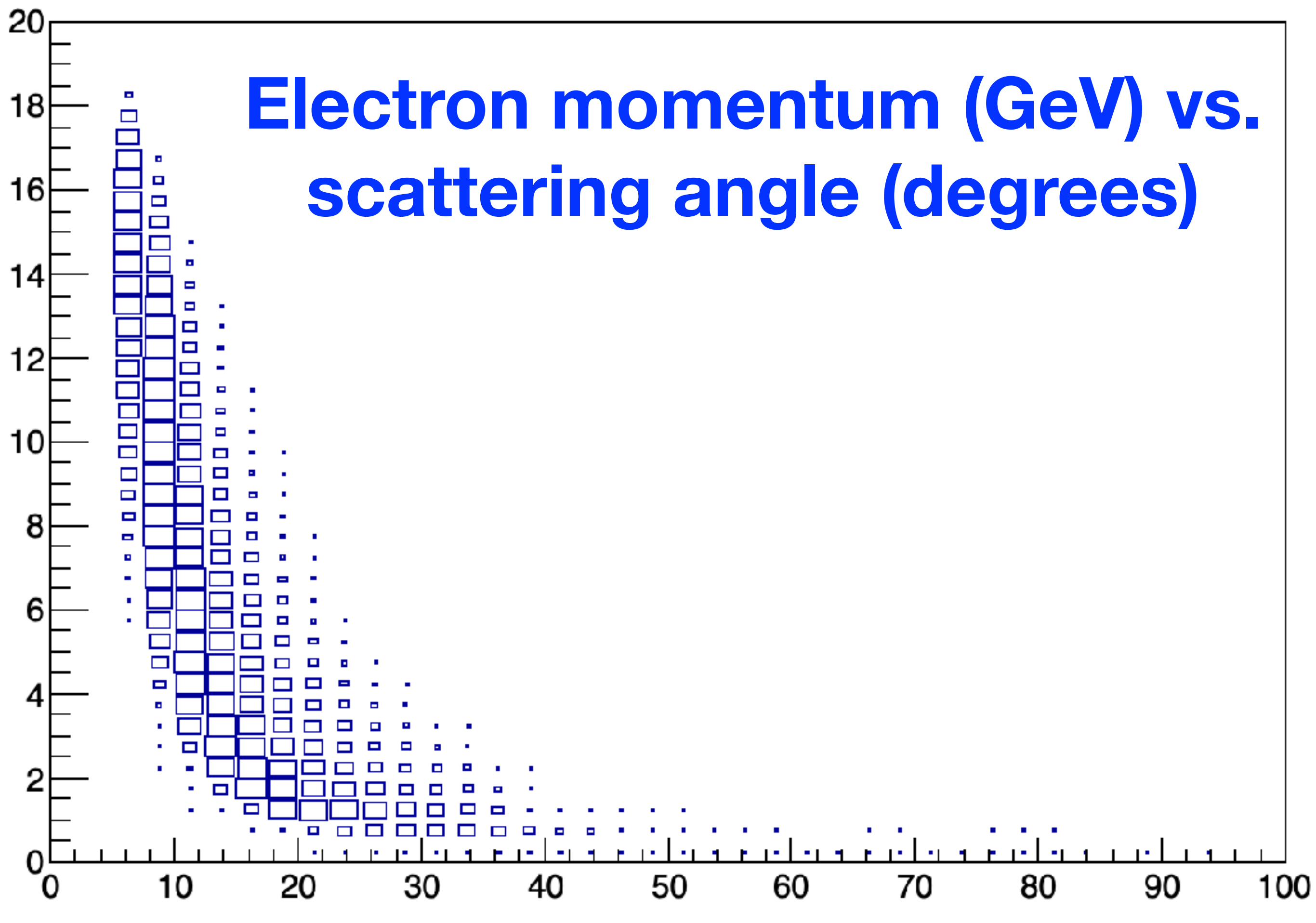
Positive Particle
(“outbending”)

22 GeV Simulations of CLAS12 with Polarized Target and Fiducial Cuts

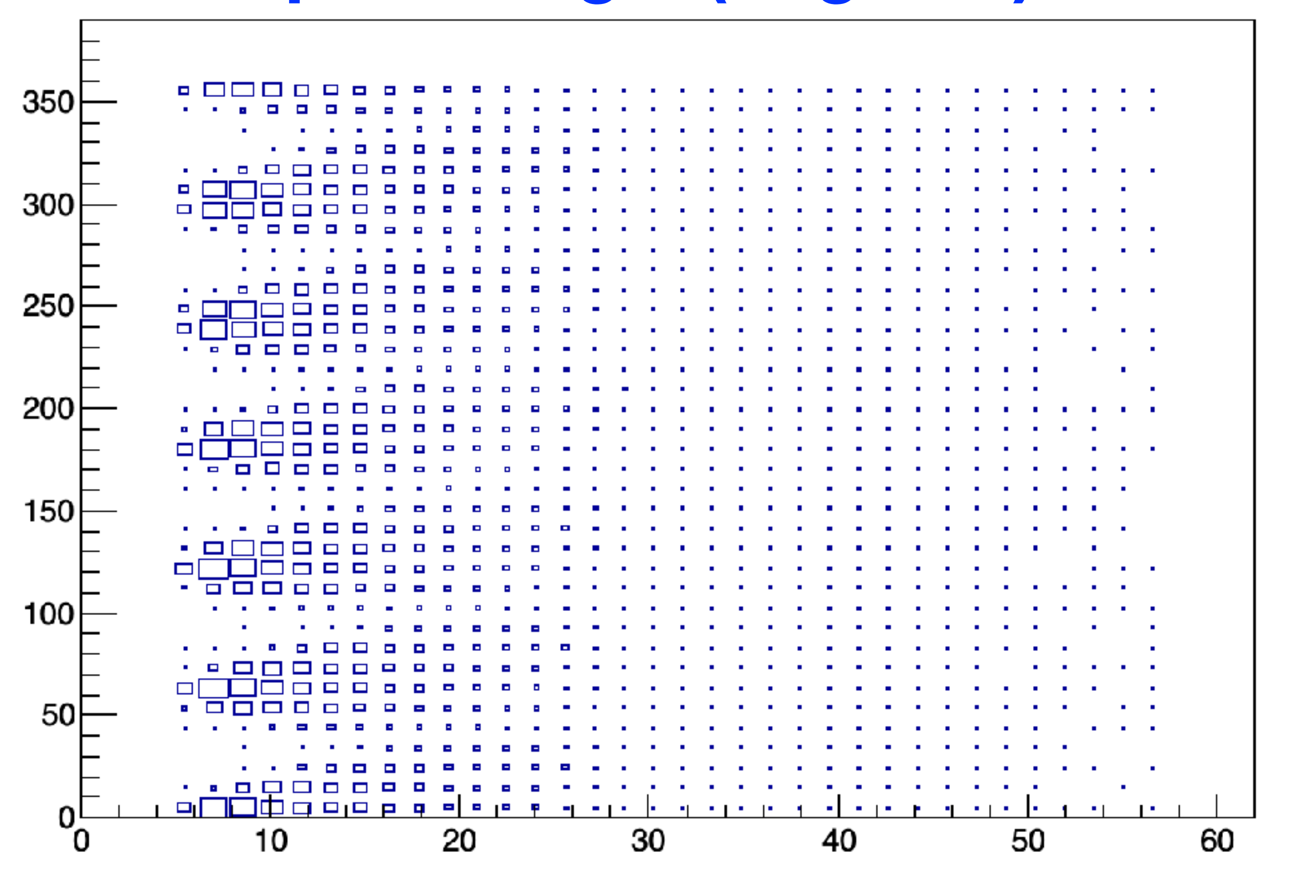
Inbending electrons

Simulation files from Harut Avakian (JLab) and Timothy Hayward (UConn)





Electron azimuthal angle vs. polar angle (degrees)



22 GeV Simulations of CLAS12 with **Polarized Target** and Fiducial Cuts

Inbending electrons

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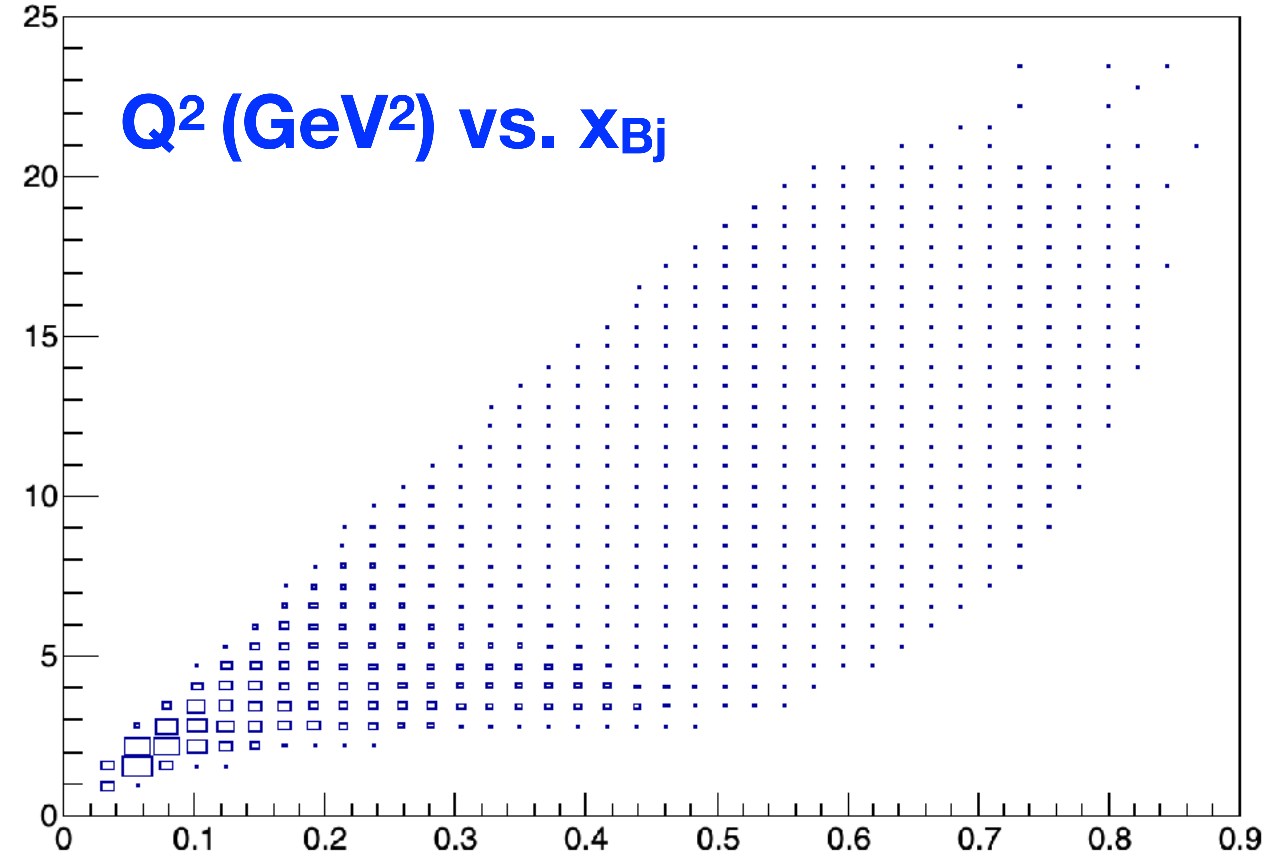
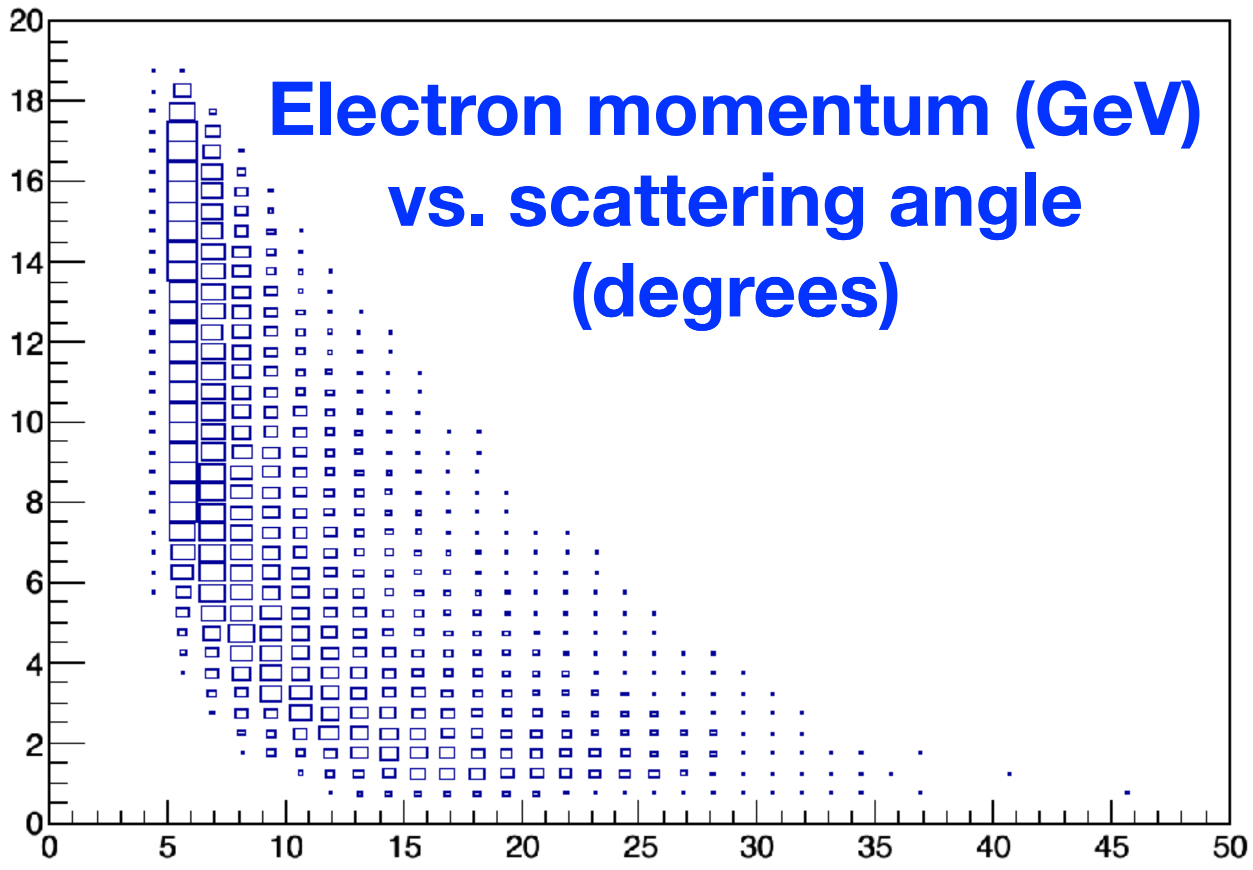
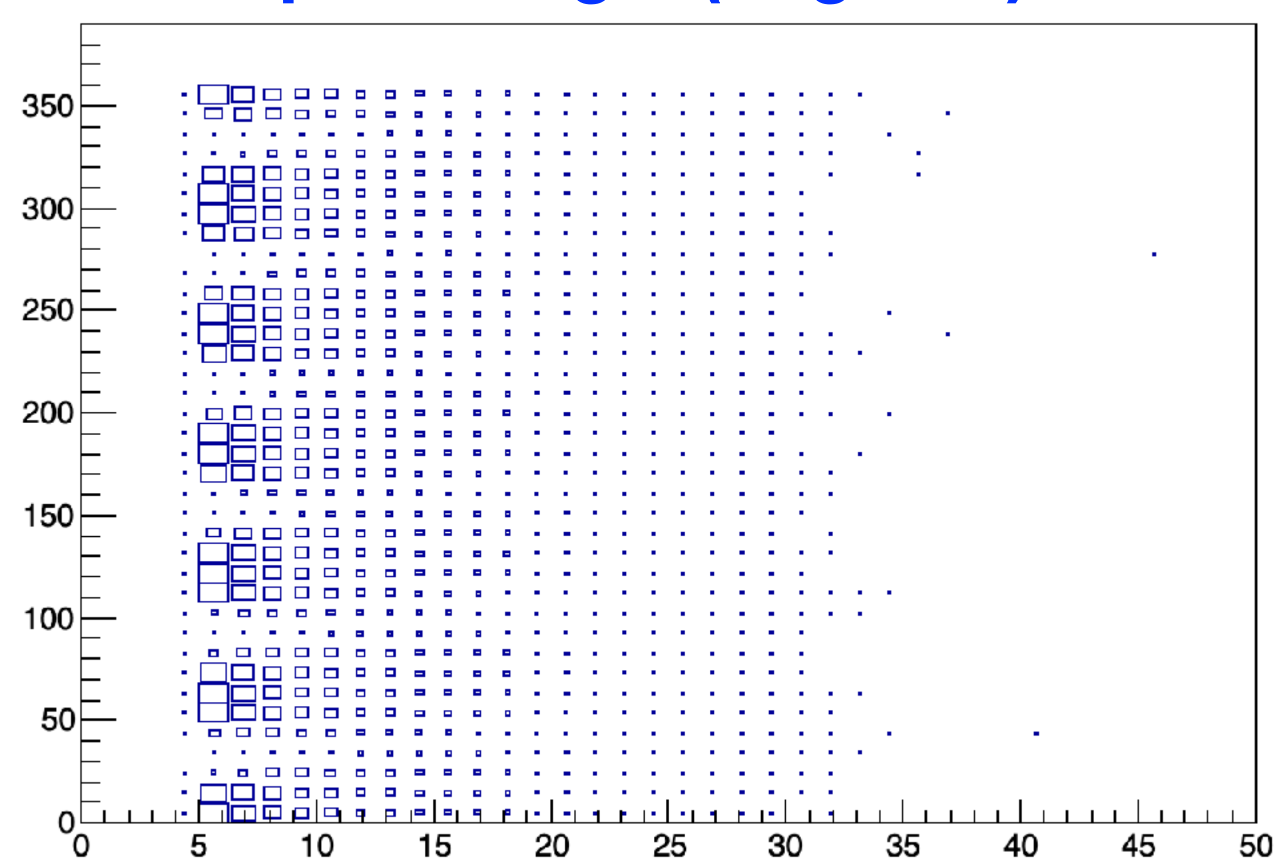
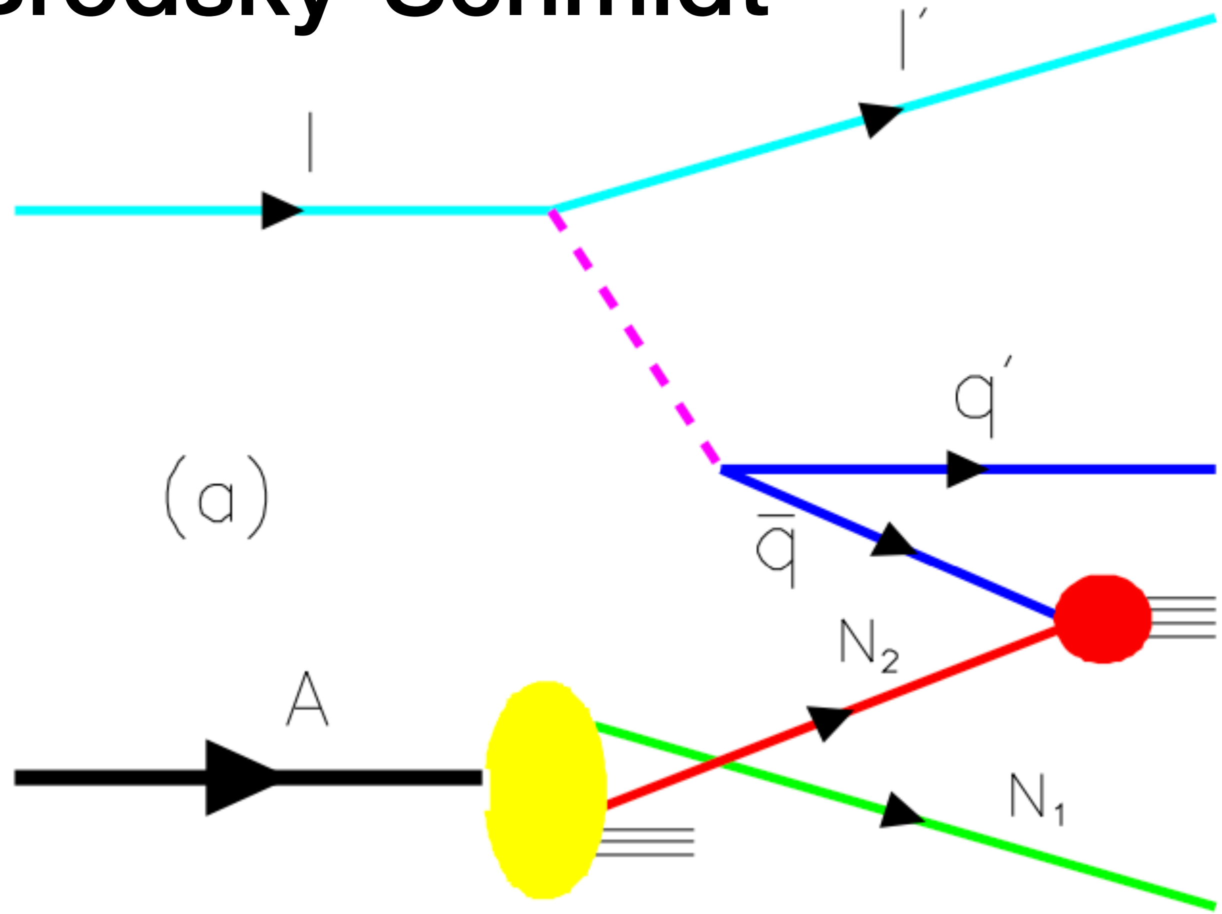




Electron azimuthal angle vs. polar angle (degrees)



Brodsky-Schmidt

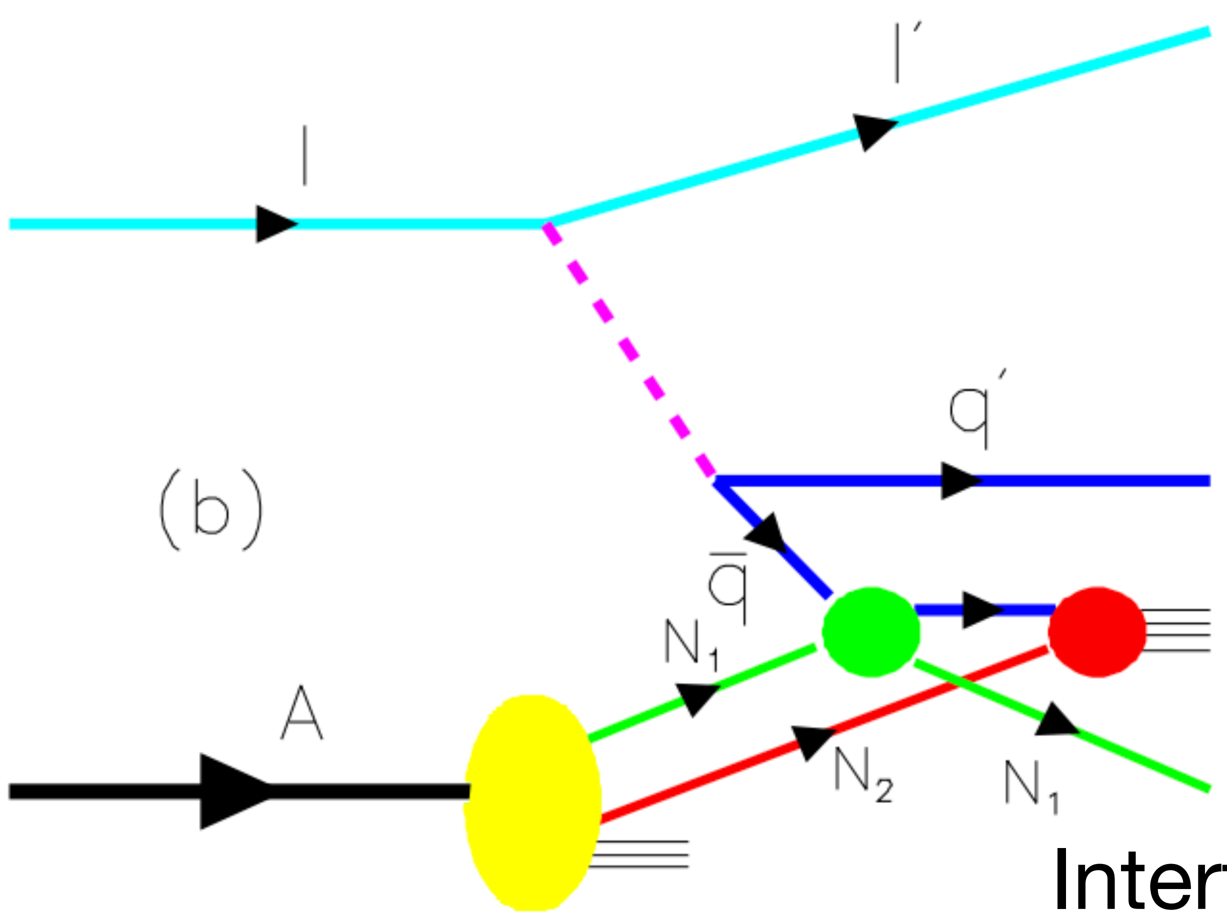


Single-step process

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

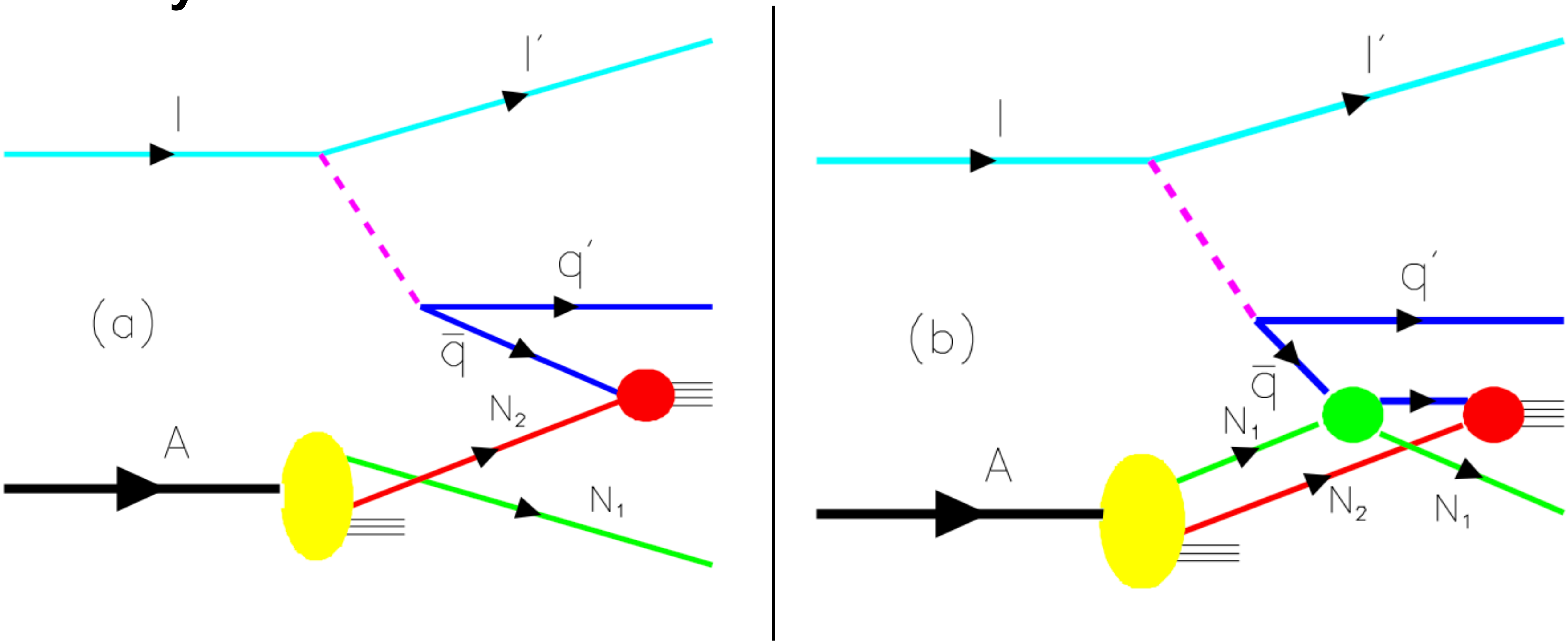
Exchange boson fluctuates into $q\bar{q}$ pair

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!

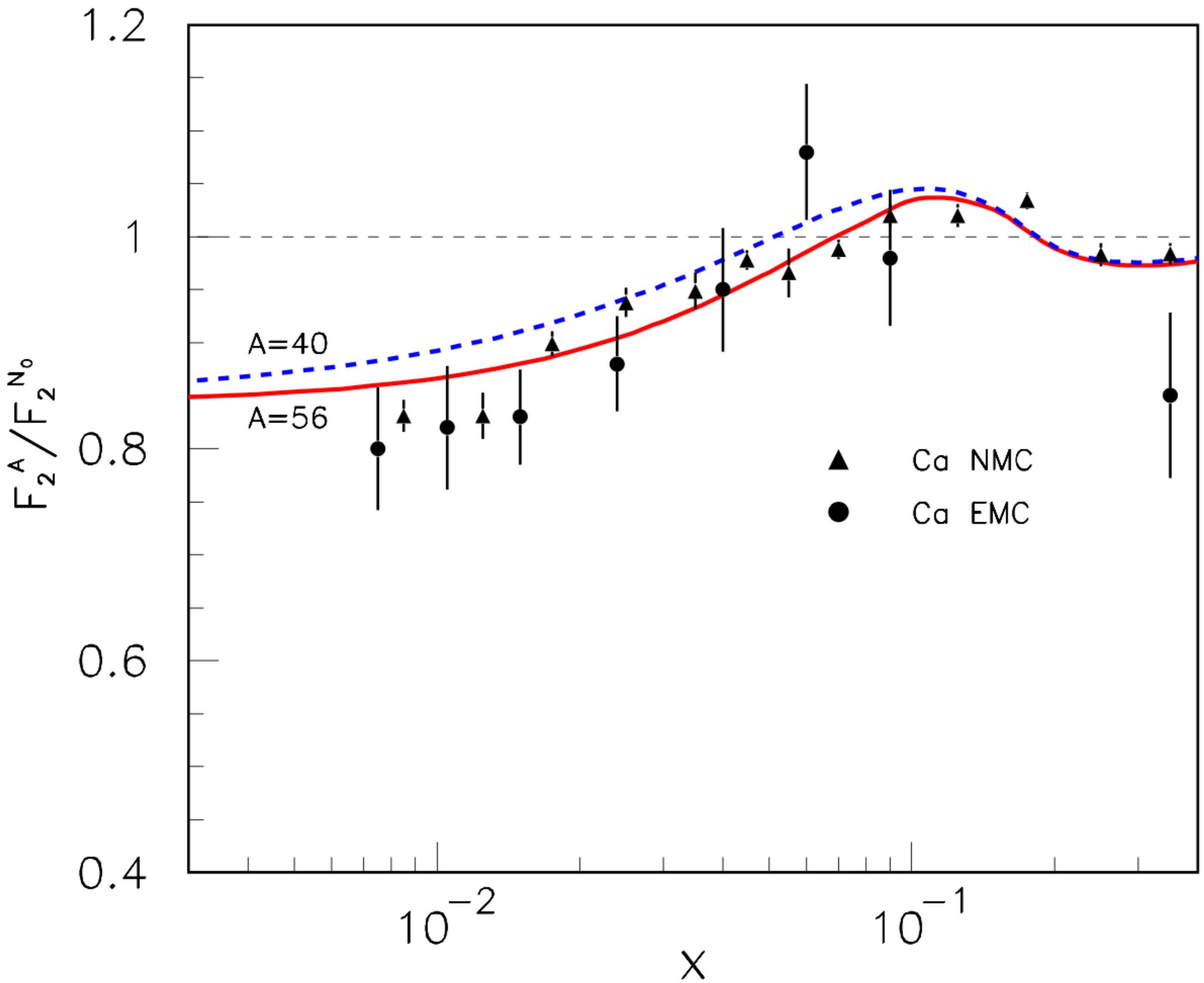
Brodsky-Schmidt



The one-step (a) and two-step (b) processes in DIS on a nucleus. If the scattering on nucleon N_1 is via Pomeron exchange, the one-step and two-step amplitudes are **opposite in phase**, thus diminishing the $\bar{q}$ flux reaching N_2. This causes **shadowing** of the charge and neutral current nuclear structure functions.

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

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

Glauber-Gribov Picture in DIS

- The Diffractive contribution to DIS (DDIS) where the nucleon absorbing a pomeron remains intact, is a constant fraction of the total DIS rate ➙ that process is *leading twist*.

- Bjorken scaling of DDIS was observed at HERA.

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