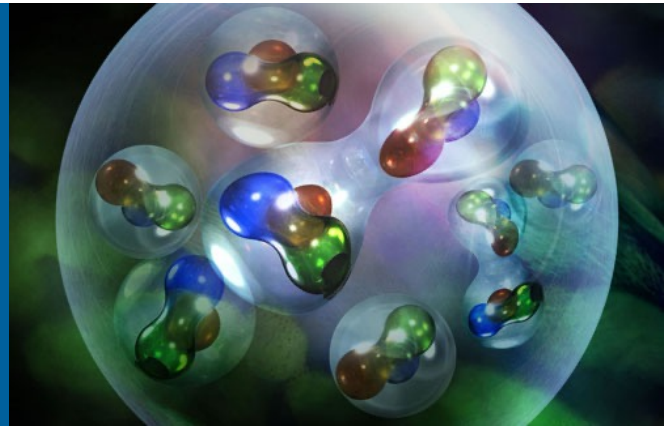
iNPC2022
Cape Town, South Africa

Argonne NATIONAL LABORATORY

EXPERIMENTS PROBING QUARKS IN NUCLEI



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Argonne National Laboratory

Cape Town, South Africa, 09/2022

EXPERIMENTS PROBING QUARKS IN NUCLEI

Outline

- Quasi elastic scattering and the Coulomb Sum
- Deep Inelastic scattering and the EMC effect
- Partonic structure of nuclei
- Conclusions

Related talks, Shor-range correlations: Marina Petri (Monday)
Julian Deniston (Monday)
Julian Kahlbow (next session)

ARE NUCLEONS MODIFIED IN THE NUCLEAR MEDIUM?

Is it mean field effect, short-range correlations effects or both?

- **A nucleonic picture**
  - Quasi-elastic scattering
    - Proton charge form factor in a nucleus vs a free proton.
- Key experiments:
  - Coulomb sum rule experiments Early eighties
  - MIT-Bates, Saclay, Nikhef, Mainz
  - JLab

- **A partonic picture**
  - Deep Inelastic scattering
    - Compare parton distribution in a nucleus vs in deuterium
- Key experiments:
  - European Muon Collaboration Experiments Early eighties
  - CERN, SLAC (NP program)
  - HERMES, JLab

INCLUSIVE QUASI-ELASTIC SCATTERING

- History in a nutshell

Disclaimer: can't be complete in a 25 minutes talk

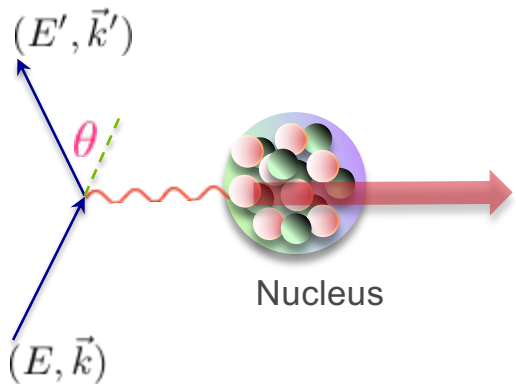
- A path to access pp correlations in the nucleus through the Coulomb sum rule (CSR) — McVoy and Van Hove (1962)
- First experiment at Bates sees quenching of R_L — Altemus et al. (1980)
- Swollen nucleon ideas emerge — Noble (1981)
- Relativistic vs non-relativistic CSR. — Walecka, Matsui, de Forest (1980-1983)
- Experiment at Saclay (1984) confirms quenching — Meziani et al.
- EMC results inspire models of nucleon modification in nuclear medium for both EMC and quasi-elastic. — Miller (1984-present), Thomas (1984-present), Guichon(1984-5), Shakin, et al. (1984-5)…
- Using Saclay and SLAC data with Coulomb corrections from DWBA shows no quenching. — Jourdan (1995, 1996), Wright (1994)
- Using Saclay alone or combining SLAC+Saclay+Bates using the effective momentum approximation; quenching persists. — Morgenstern and Meziani (2001)
- New experiment performed at Jefferson Lab: JLab E05-110 experiment — Chen, Choi and Meziani *et al.*

QUASI-ELASTIC RESPONSE FUNCTIONS

- In the Born approximation:

$$\frac{d^2\sigma}{d\Omega d\omega} = \sigma_{Mott}\left[\frac{Q^4}{q^4}R_L(q,\omega)\frac{Q^2}{2q^2}\frac{1}{\epsilon}R_T(q,\omega)\right]$$

$$\epsilon = \left[1 + \frac{2q^2}{Q^2}\tan^2\theta\right]^{-1}$$



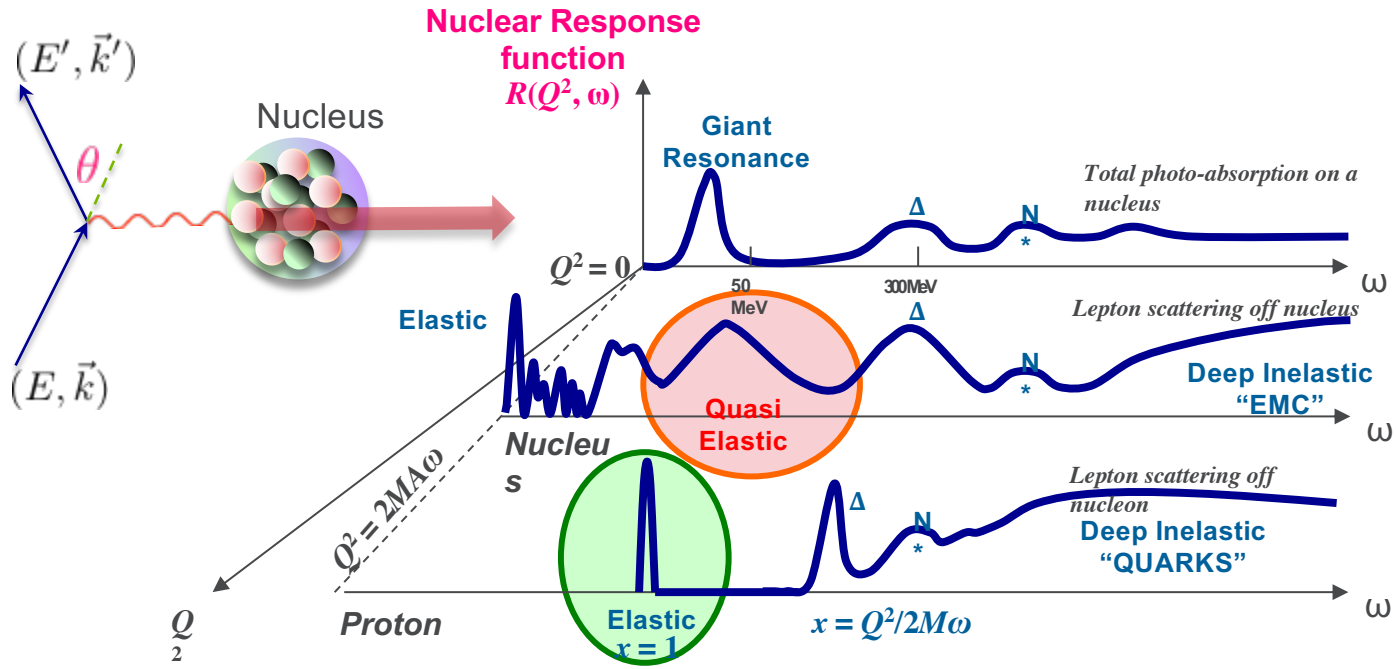
- Elastic scattering off bound nucleons
- Charge information in
  $R_L(q,\omega) \propto Z[G_E^p]^2 + N[G_E^n]^2$
- Magnetization and convection currents information in $R_T(q,\omega)$

$q = |\vec{k} - \vec{k}'|$ ➠ Three-momentum transfer

$\omega = E - E'$ ➠ Energy Transfer

$Q^2 = \omega^2 - q^2$ ➠ Four-momentum transfer

INCLUSIVE ELECTRON SCATTERING



- Elastic scattering on moving bound nucleons in the nucleus
- A special region of excitation energy where we can study nucleon-nucleon correlations and nucleon properties in the nuclear medium.

COULOMB SUM RULE (CSR)

- Coulomb sum
  - Integral of R_L to be used for the CSR

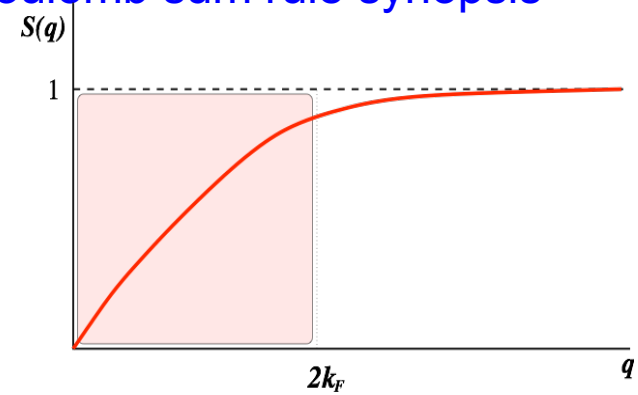
$$S_L(q) = \int_{\omega+} d\omega \frac{R_L(q,\omega)}{Z\tilde{G}_E^2(Q^2)}$$

  - Denominator includes protons and neutrons free electric form factors and a relativistic correction

$$Z\tilde{G}_E^2(Q^2) = \left(\left[G_E^p(Q^2)\right]^2 + (N/Z)\left[G_E^n(Q^2)\right]^2 \right) \times \frac{1+Q^2/4M^2}{1+Q^2/2M^2}$$

De Forest (1984)

- Coulomb sum rule synopsis

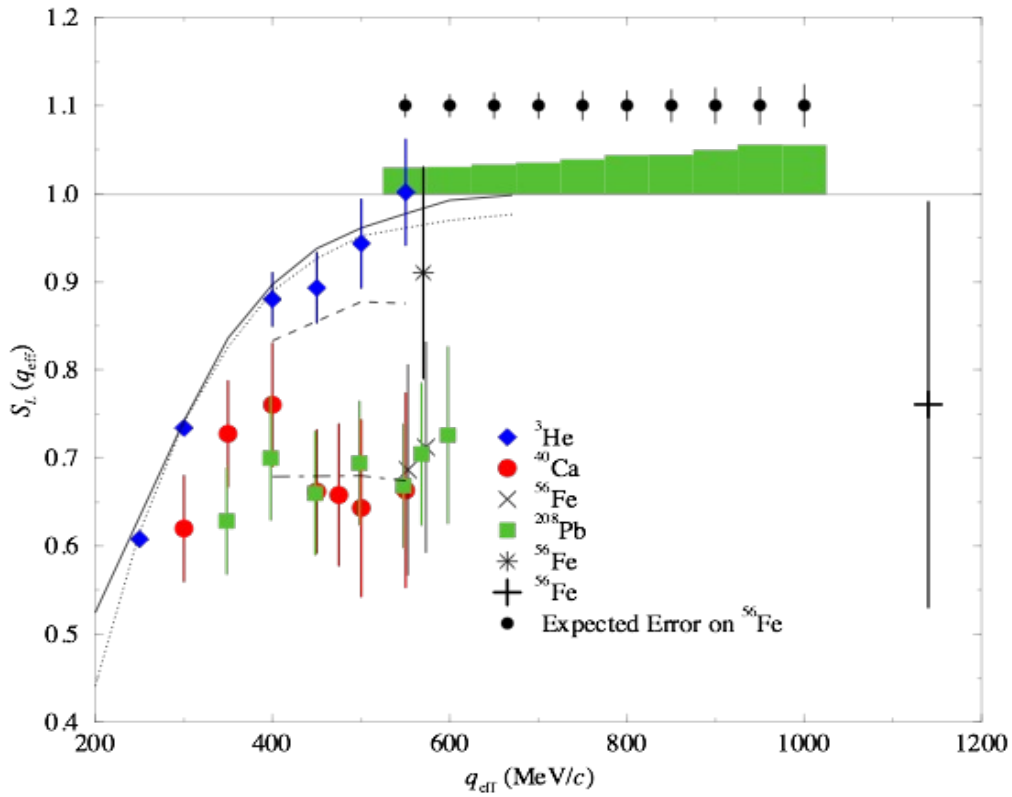


  - At large enough *q*, greater than twice the Fermi momentum k_F $S_L(q) \longrightarrow 1$

- Deviations from unity at low *q*
  - Pauli Blocking
  - NN long-range correlations

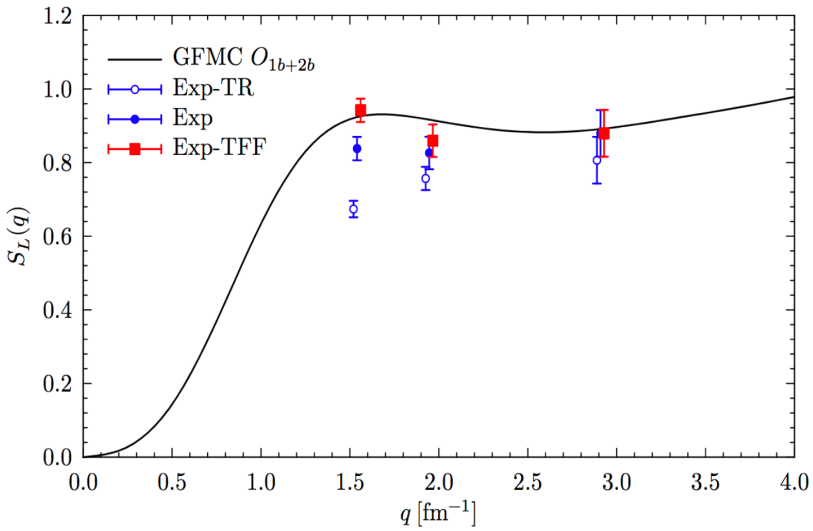
- Deviations at large *q* (>>$2k_F$)
  - Short-range NN correlations (<10%)
  - Nucleon properties in the nuclear medium

EXPECTED ERRORS ON ^{56} FE COULOMB SUM



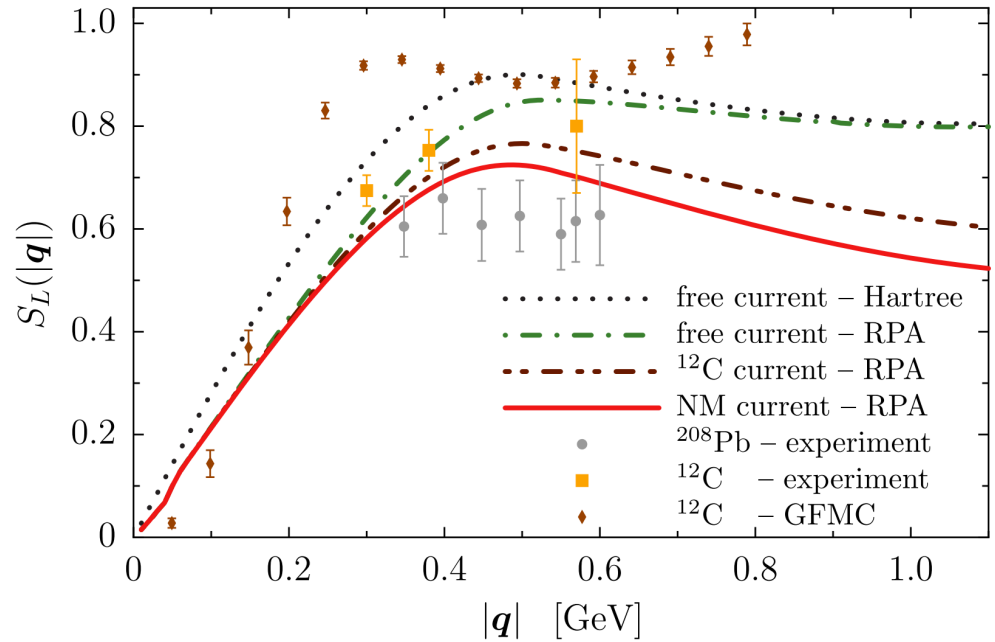
THEORETICAL INTERPRETATIONS

- The larger q region is essential to differentiating theoretical models



A. Lovato, S. Gandolfi, J. Carlson, Steven C. Pieper, R. Schiavilla, Phys. Rev. Lett. 117, 082501 (2016)

Ian C. Cloët, Wolfgang Bentz, Anthony W. Thomas , Phys. Phys. Rev. Lett. 116, 032701 (2016)

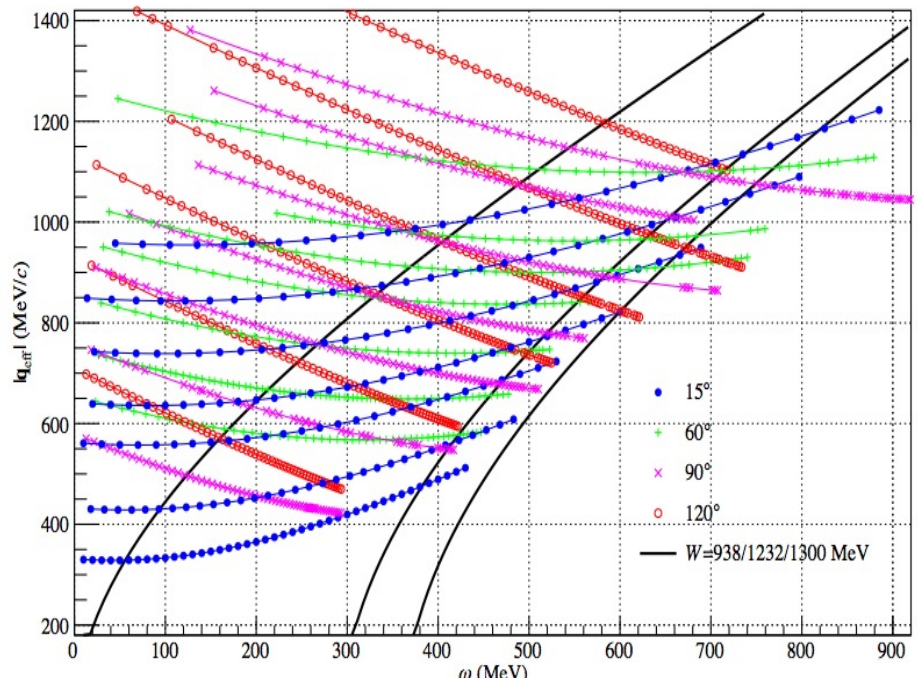


- Alternate calculations that do include medium modification show the largest divergences from free-current calculations at larger |q|

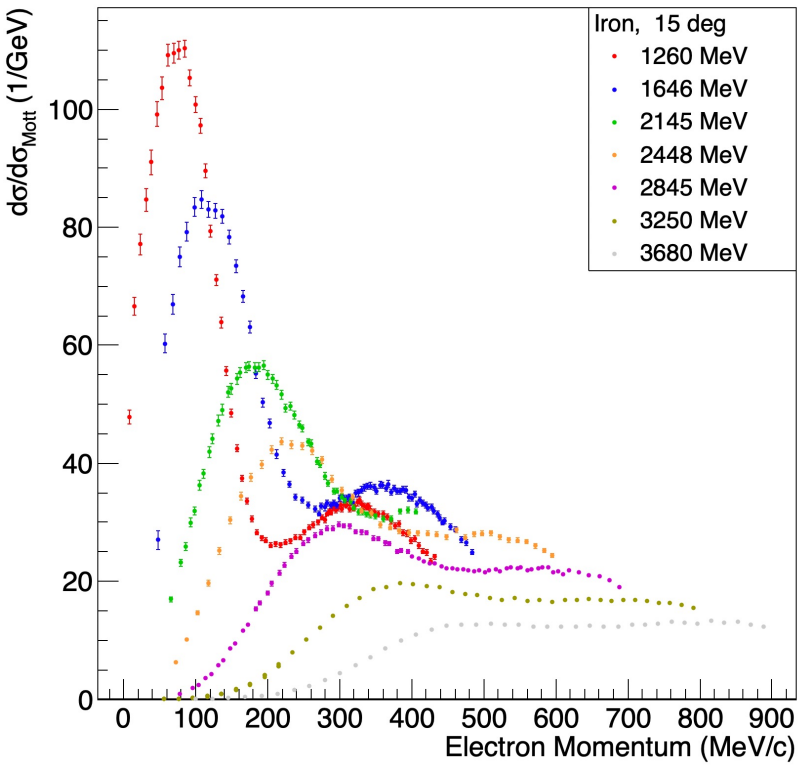
E05-110 EXPERIMENT AT JLAB

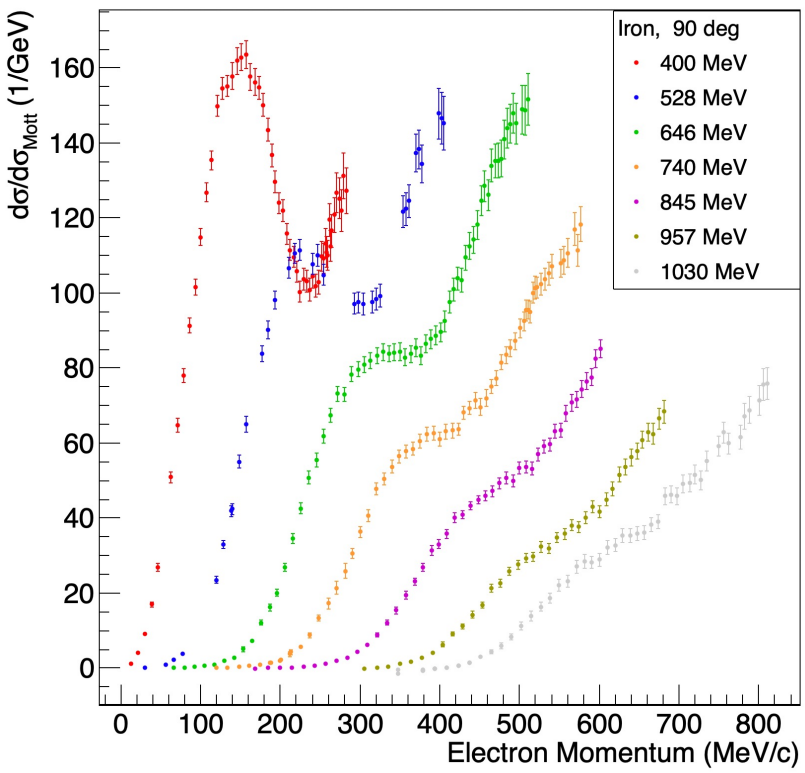
- Beam: 16 energies from 0.4 to 4.0 GeV
- Scattering angles: 15°, 60°, 90°, 120°
- Targets: ^{4}He, ^{12}C, ^{56}Fe, ^{208}Pb
- Spectrometer momenta range from 4 GeV down to 100 MeV
- Covers *q* from 550 to 1000 MeV/c
- Previously unexplored region
- High enough values of q compared to the Fe momentum
- Comprehensive single experiment
  - Largest lever arm
- Better control of background and systematics with well studied HRS detectors and with an additional NaI detector as calorimeter

Kinematic coverage of E05-110

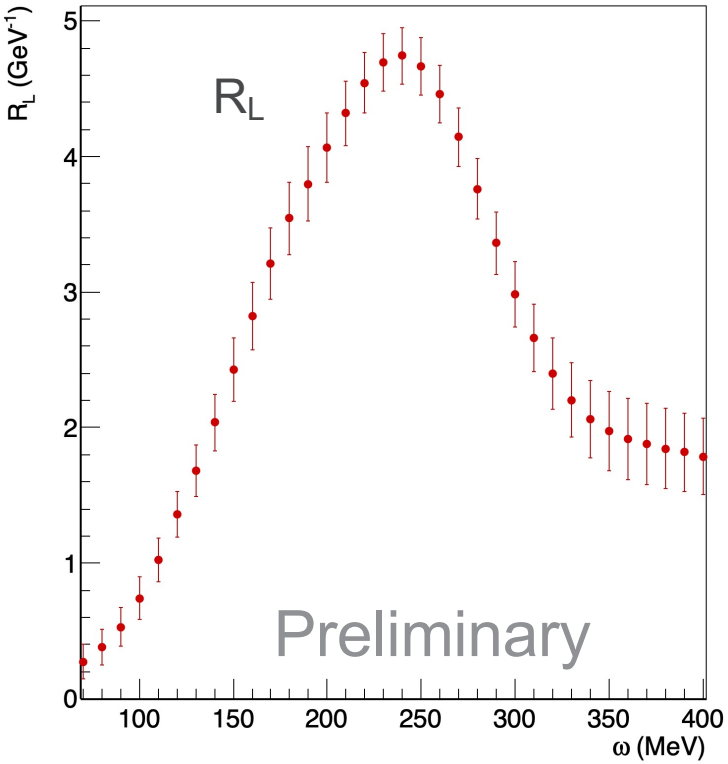


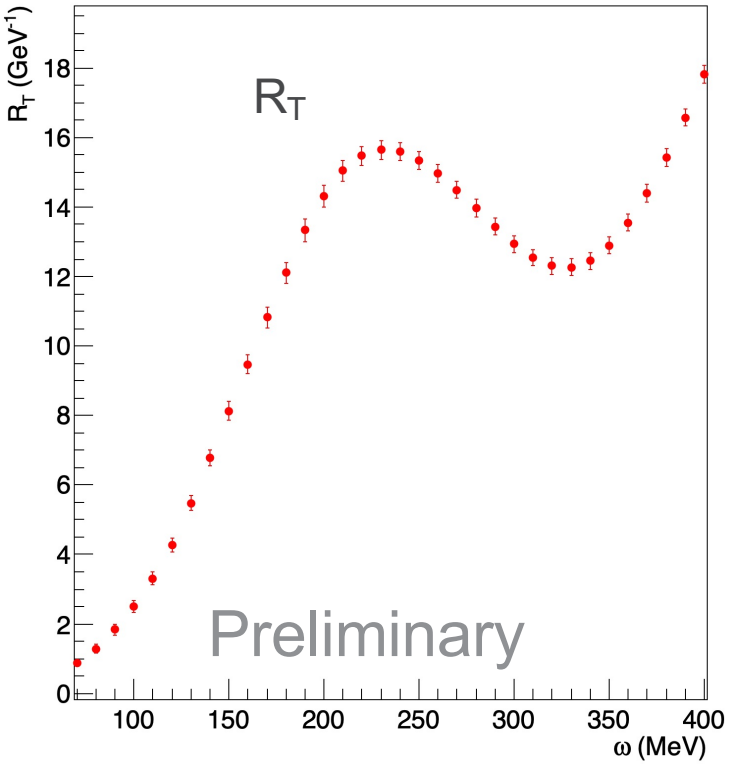
^{56}FE INCLUSIVE SPECTRA AT 15^0 AND 90^0



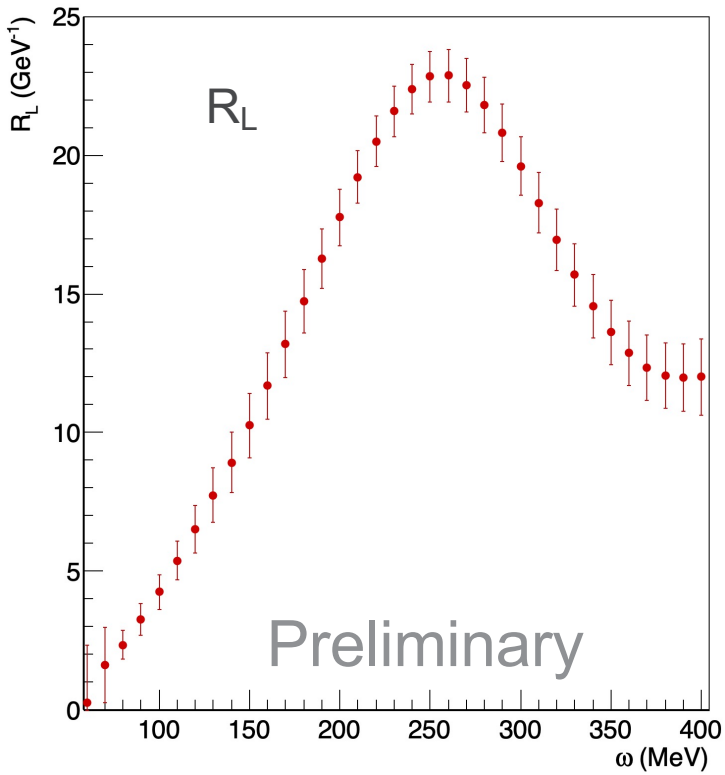


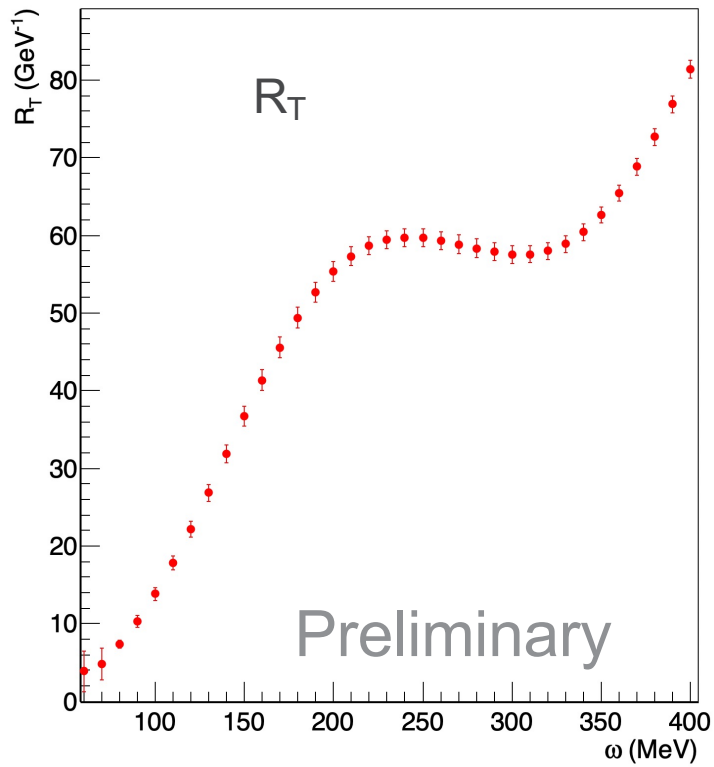
^{12}C, q_{eff} = 650 MeV/c (with Coulomb corrections)



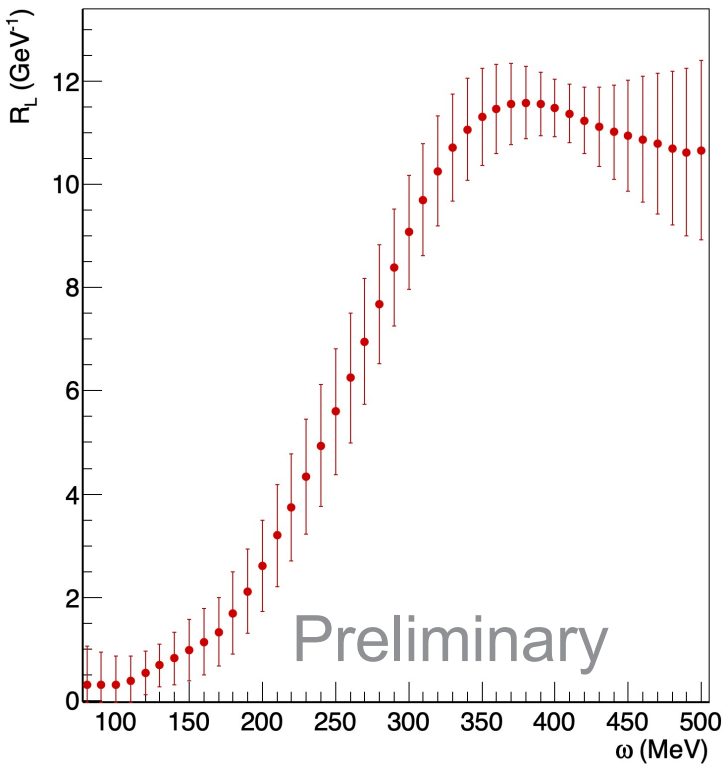


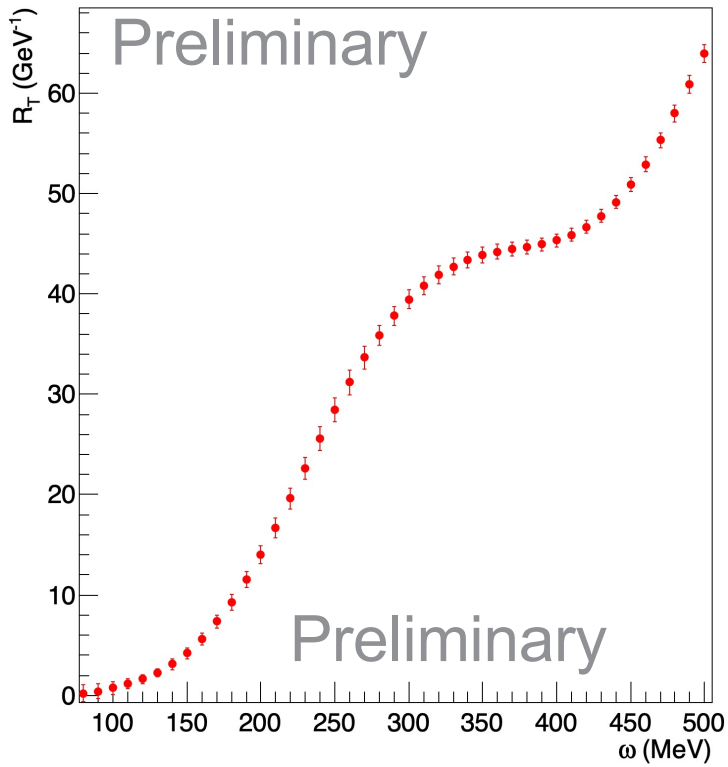
^{56}Fe, q_{eff} = 650 MeV/c (with Coulomb corrections)



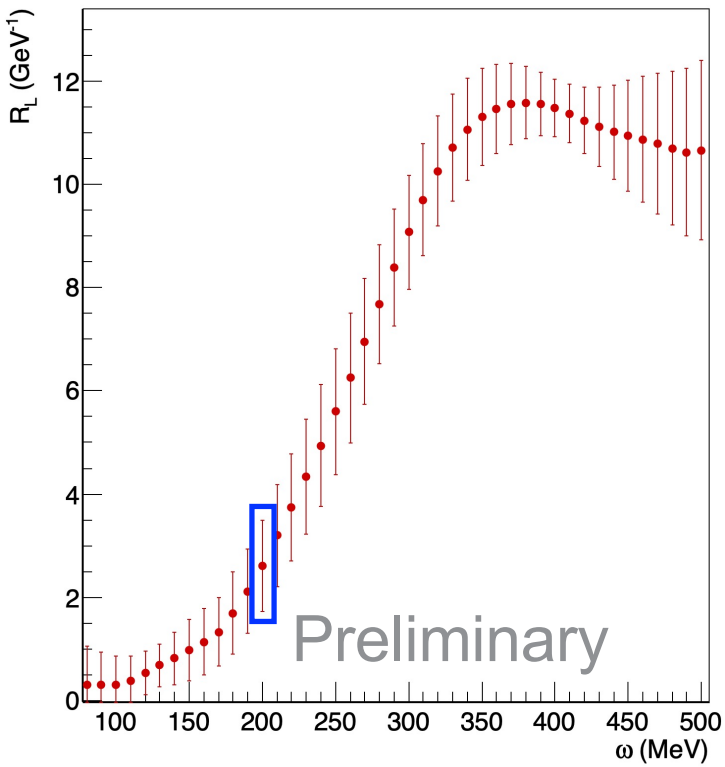


^{56}Fe, q_{eff} = 800 MeV/c (with Coulomb corrections)

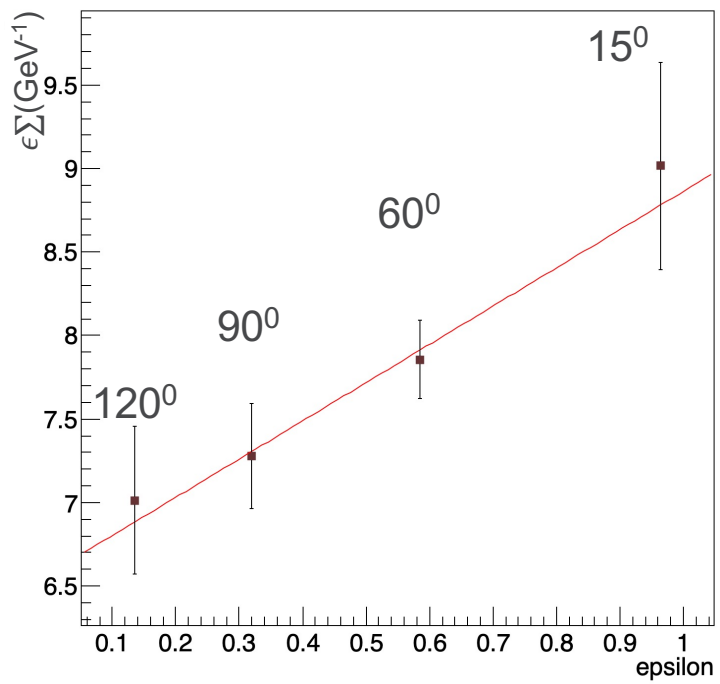




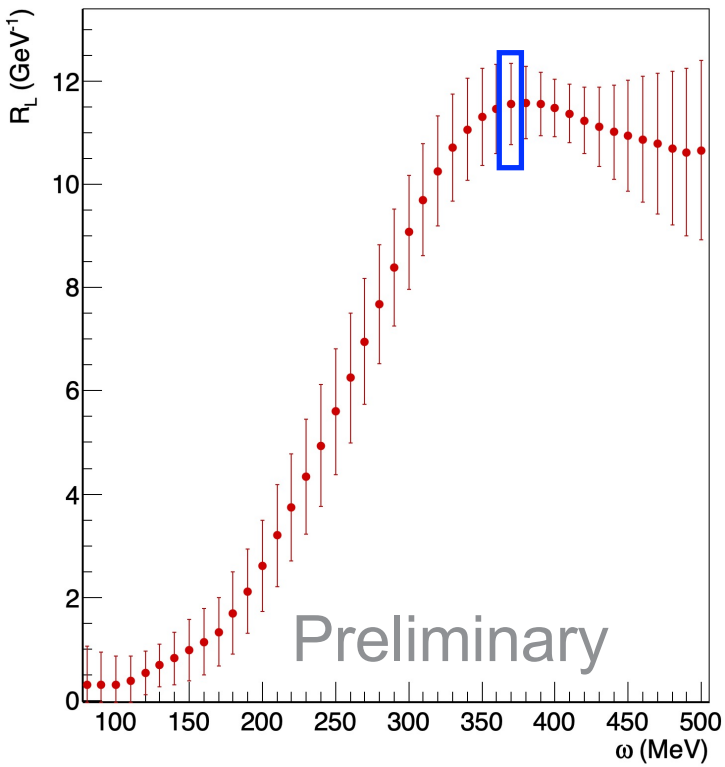
^{56}Fe, q_{eff} = 800 MeV/c (with Coulomb corrections)



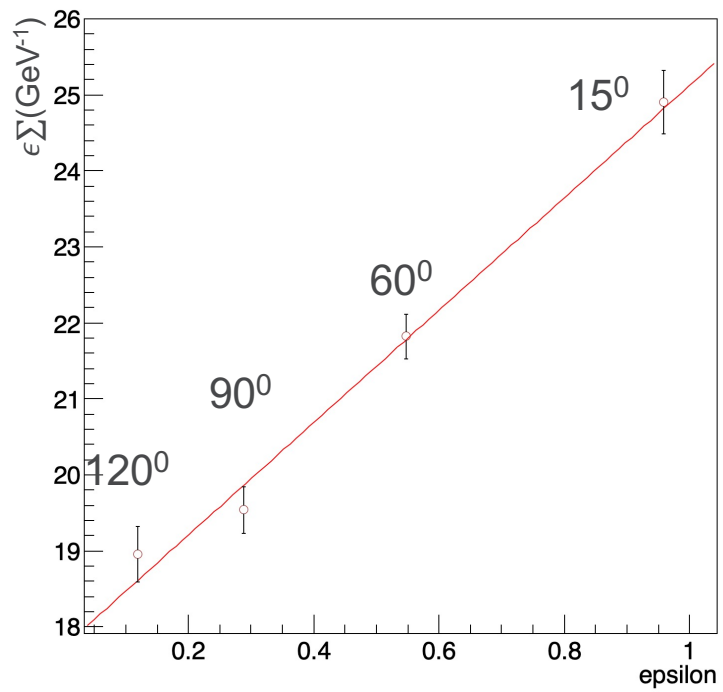
ω = 200 MeV



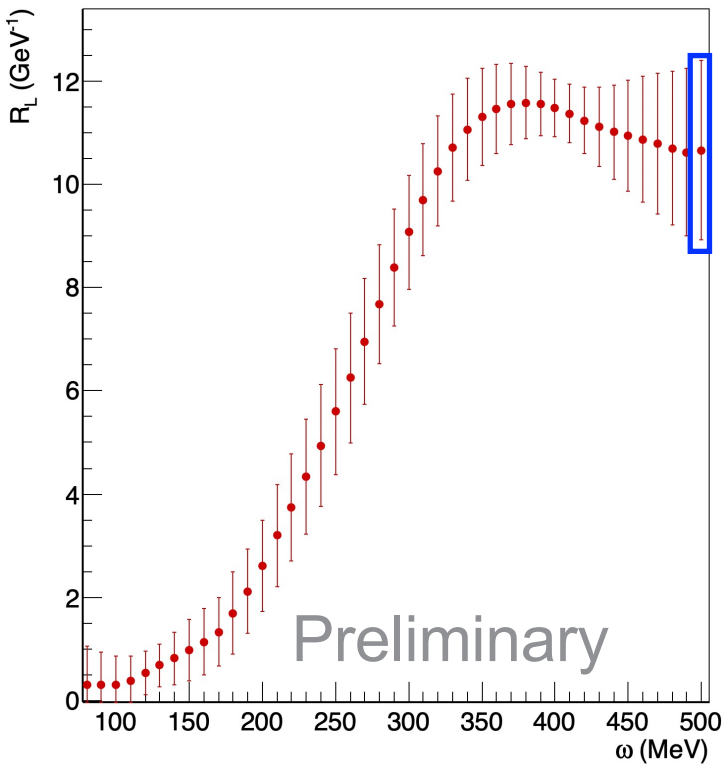
^{56}Fe, q_{eff} = 800 MeV/c (with Coulomb corrections)



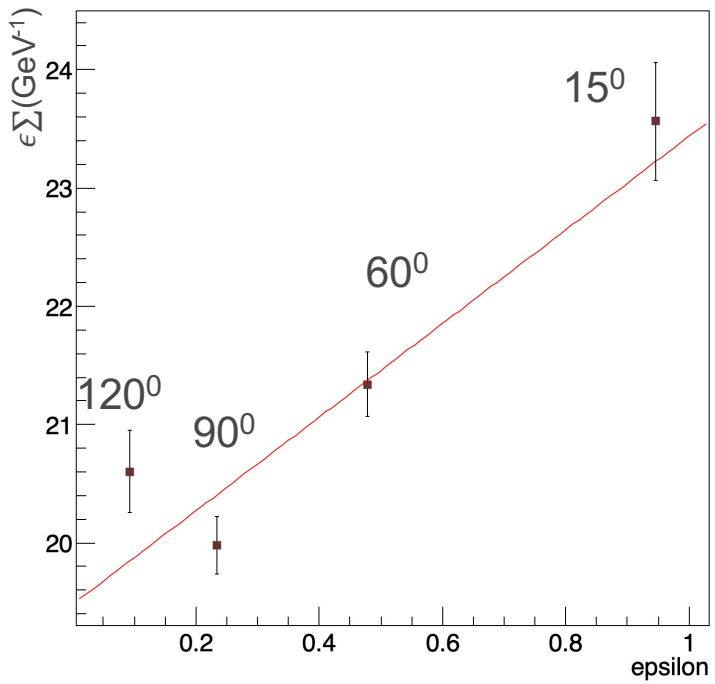
ω = 350 MeV



^{56}Fe, q_{eff} = 800 MeV/c (with Coulomb corrections)



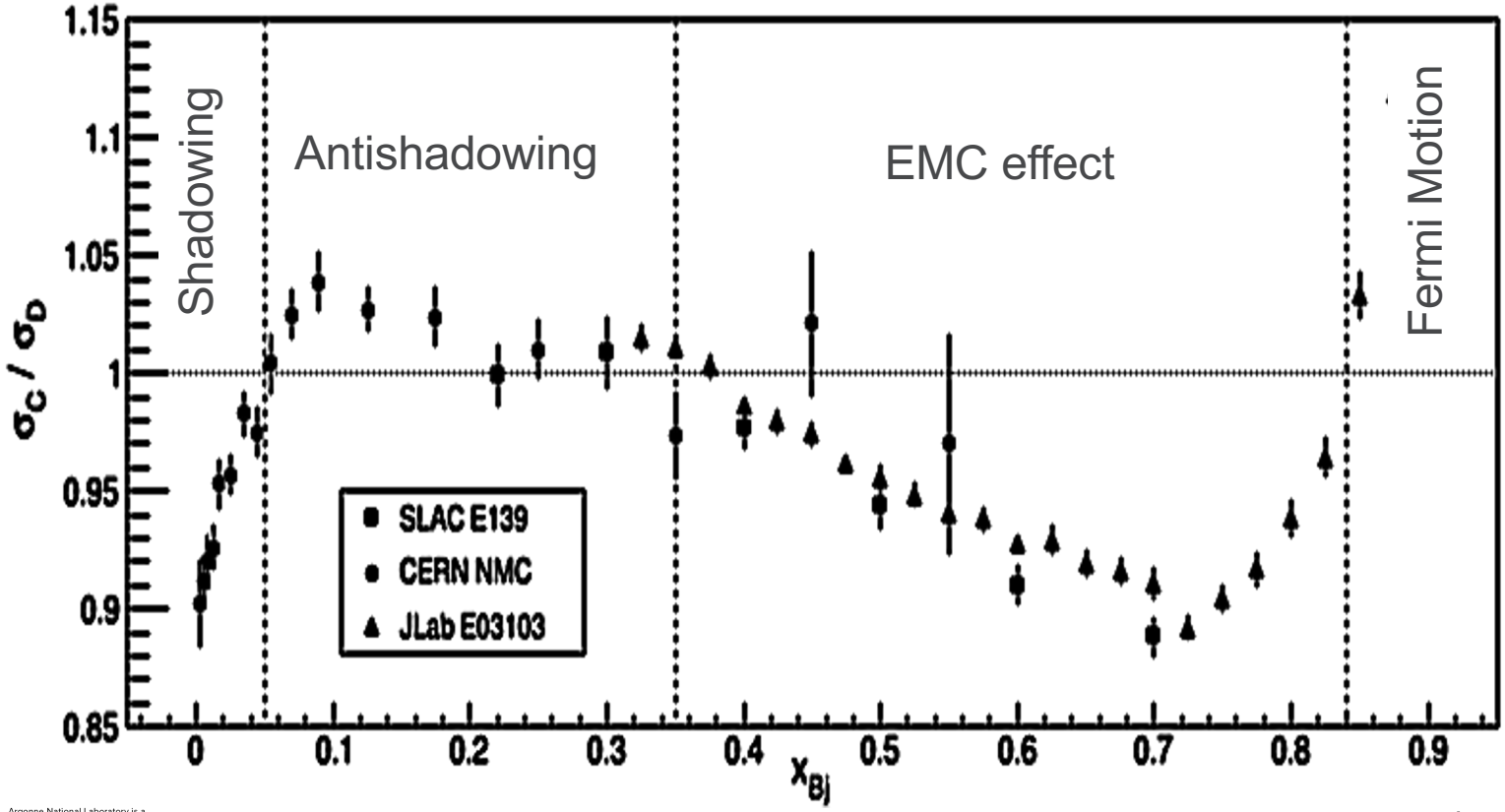
ω = 500 MeV



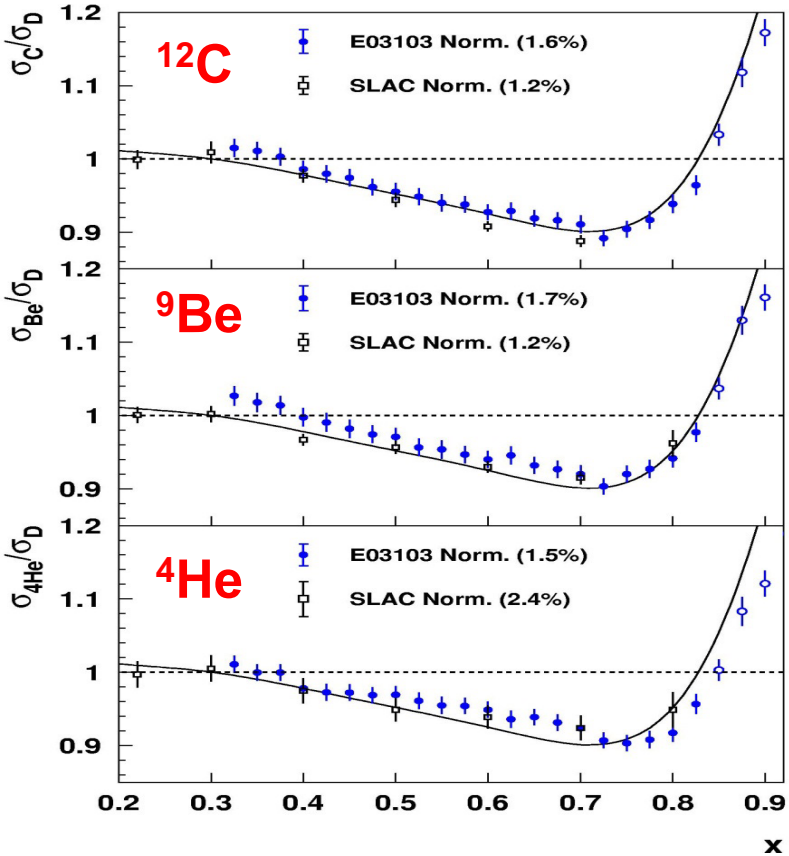
PARTONIC STRUCTURE OF NUCLEI

NUCLEAR EFFECTS ON QUARK DISTRIBUTIONS
EMC EFFECT

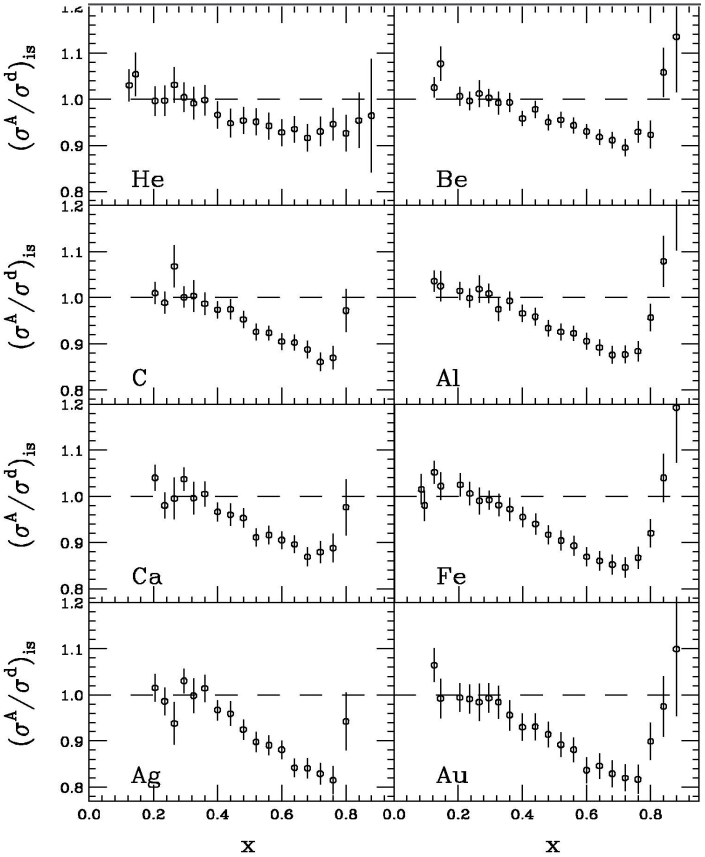
J. J. Aubert, et al., PLB 123, 275 (1983)



J.Seely, et al., PRL103, 202301 (2009)



J. Gomez, et al., PRD49, 4349 (1994)



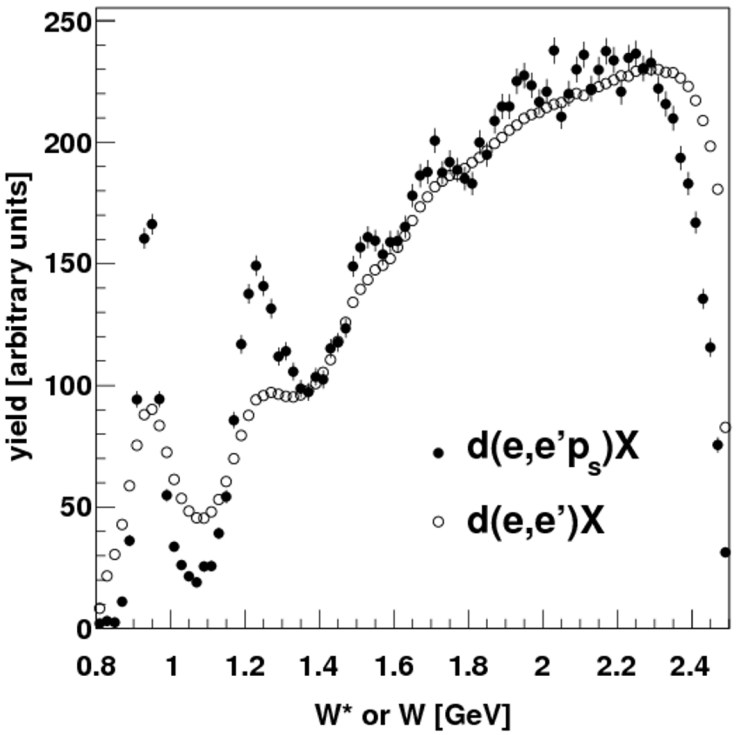
In order to make progress tagging becomes critical and understanding it starts with the deuteron.

TAGGING IN NUCLEAR REACTIONS

Needed to:

- Control final state interaction
- Control the initial state by
  - Access to the nucleon's kinematics
  - Access to the nucleon's virtuality

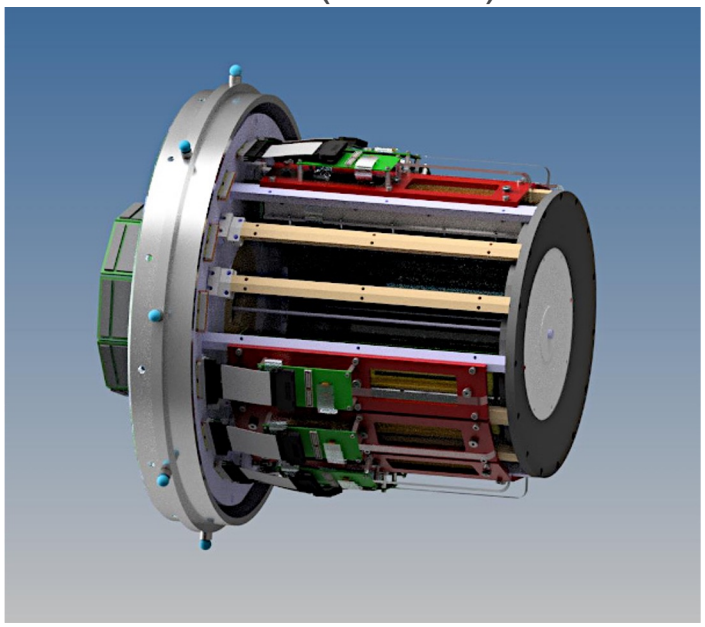
- Performed on deuterium at JLab 6 GeV
  - Bonus measurement from CLAS --->
- Need a recoil detector (fixed target)
- Or a forward detector (collider)



TAGGING AT JEFFERSON LAB

- Deuterium (polarized or not)
  - Study pion and kaon content (TDIS @ JLab)
  - Study the unpolarized neutron (Bonus @ JLab)
  - Study nuclear effects and SRC (BAND @ JLab)
- Helium-3 (polarized)
  - Effective polarized neutron
- Helium-4
  - Study bound nucleons (ALERT @ JLab)
  - Study of EMC and SRC (ALERT @ Jlab)

A Low Energy Recoil Tracker (ALERT)

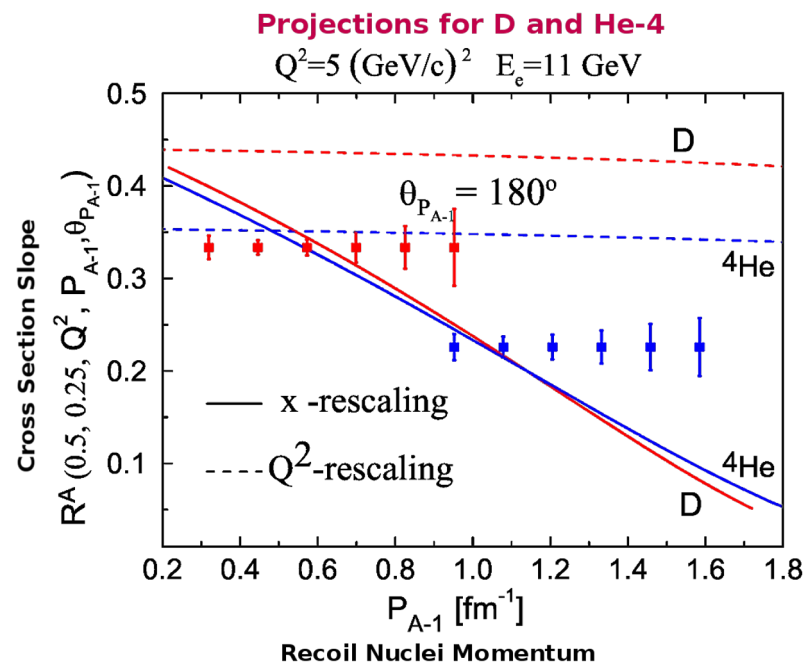


Placed in the center of CLAS12 (Hall-B)

TAGGING TO ACCESS OFFSHELLNESS

$$v(|\mathbf{p}|, E) = \left(M_A - \sqrt{(M_A - m_N + E)^2 + \mathbf{p}^2}\right)^2 - \mathbf{p}^2 - m_N^2$$

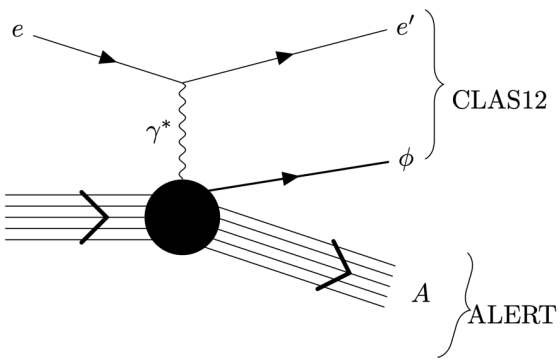
- Tagging links EMC to nucleon kinematics
  - Linked to virtuality thus differentiate mean field from SRC
- Test models and more
  - Comparison between deuterium and helium
  - It unequivocally resolve the link between EMC and nucleon momentum
- Different nuclei
  - Cover different momentum ranges
  - Mean field vs SRC



C. Ciofi degli Atti et al. Eur. Phys. J., vol. A5 (1999) 191
C. Ciofi degli Atti et al. Phys.Rev. C76 (2007) 055206

RG-L/ALERT SCIENCE PROGRAM AT CLAS12

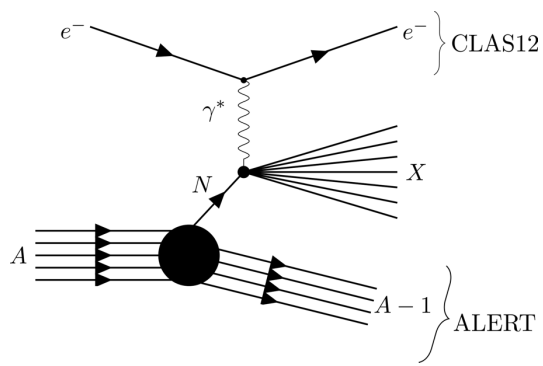
A comprehensive program to study nuclear matter at the partonic and nucleonic level



Coherent Processes on ^{4}He

- $^4\mathrm{He}(e, e'\gamma)^4\mathrm{He}$
- $^4\mathrm{He}(e, e'\phi)^4\mathrm{He}$

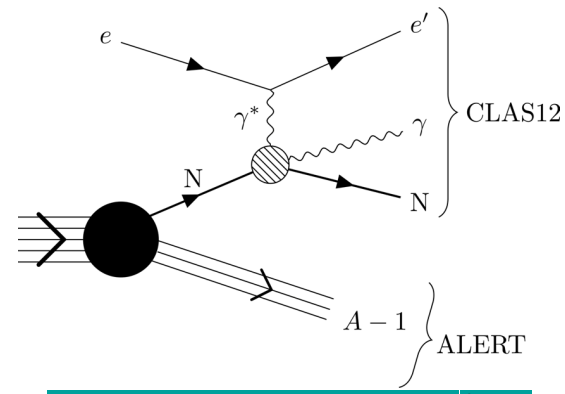
Explores the partonic structure of ^{4}He



DIS on ^{4}He and ^{2}H: Tagged EMC Effect

- $^4\mathrm{He}(e, e'\ ^3\mathrm{H})\mathrm{X}$
- $^4\mathrm{He}(e, e'\ ^3\mathrm{He})\mathrm{X}$
- $^2\mathrm{H}(e, e'\ p)\mathrm{X}$

Test initial vs final states models



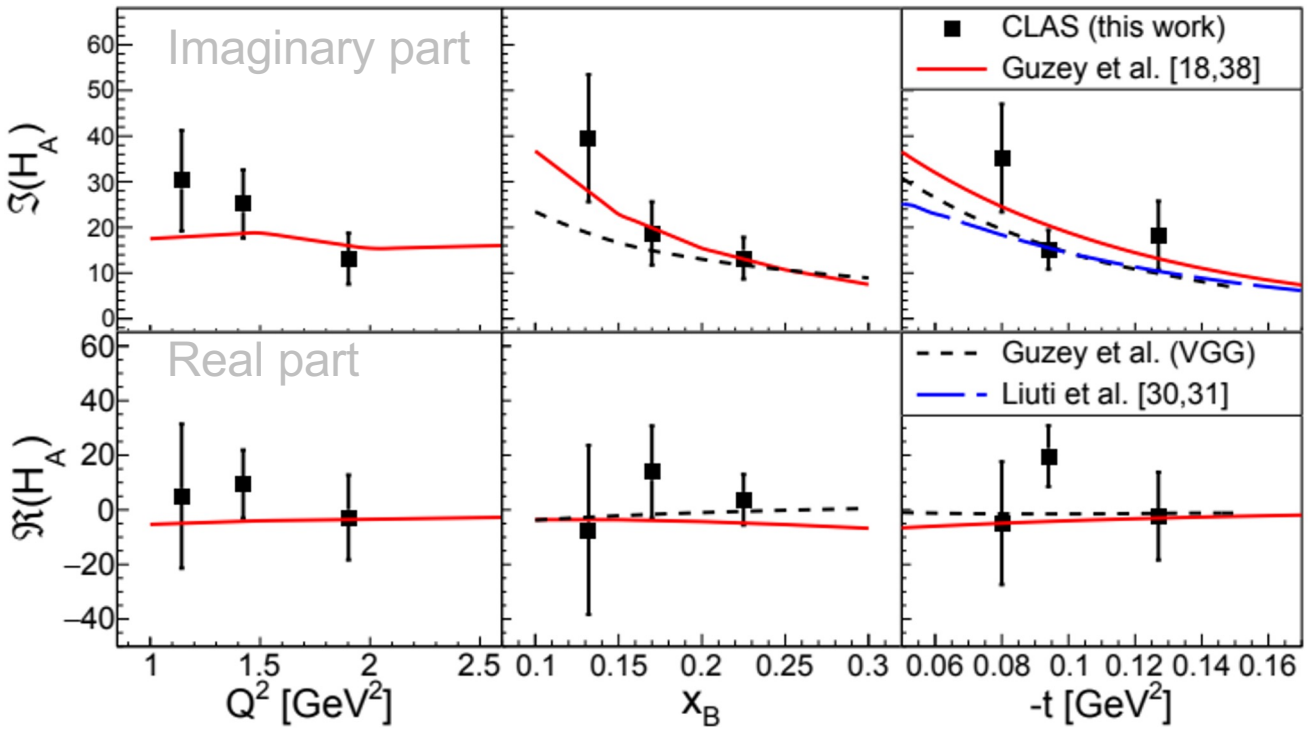
Incoherent processes on ^{4}He and ^{2}H

- $^4\mathrm{He}(e, e'\gamma\ p\ ^3\mathrm{H})$
- $^4\mathrm{He}(e, e'\ \gamma\ ^3\mathrm{He})\mathrm{n}$
- $^2\mathrm{H}(e, e'\ \gamma\ p)\mathrm{n}$

Test medium modification of nucleons

HELIUM-4 COMPTON FORM FACTOR FROM DVCS

M. Hattawy et al. (CLAS Coll.) Phys. Rev. Lett., 119(20):202004, 2017.



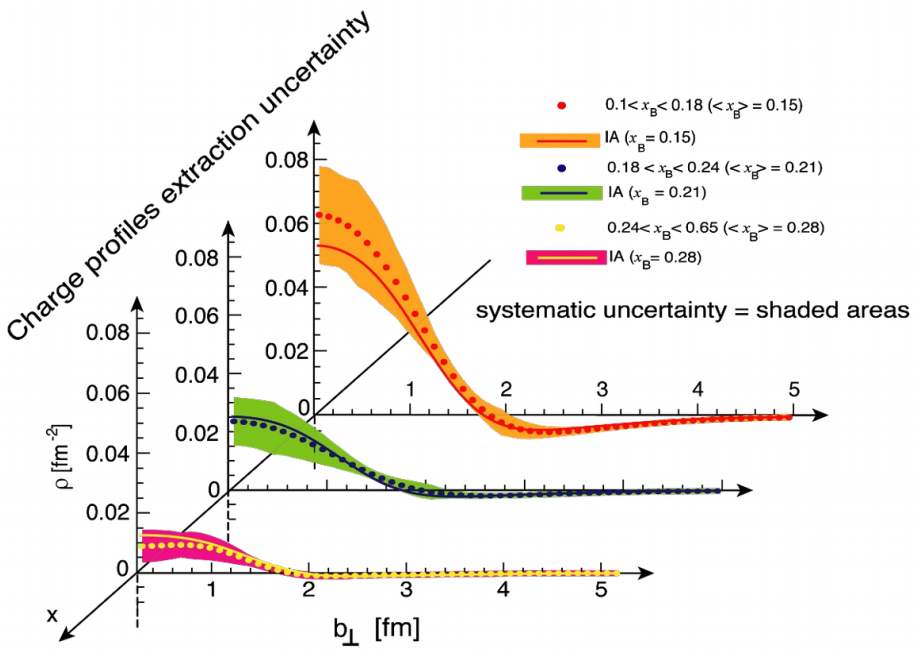
ALERT RUN GROUP-L PROGRAM IN CLAS12 AT JLAB

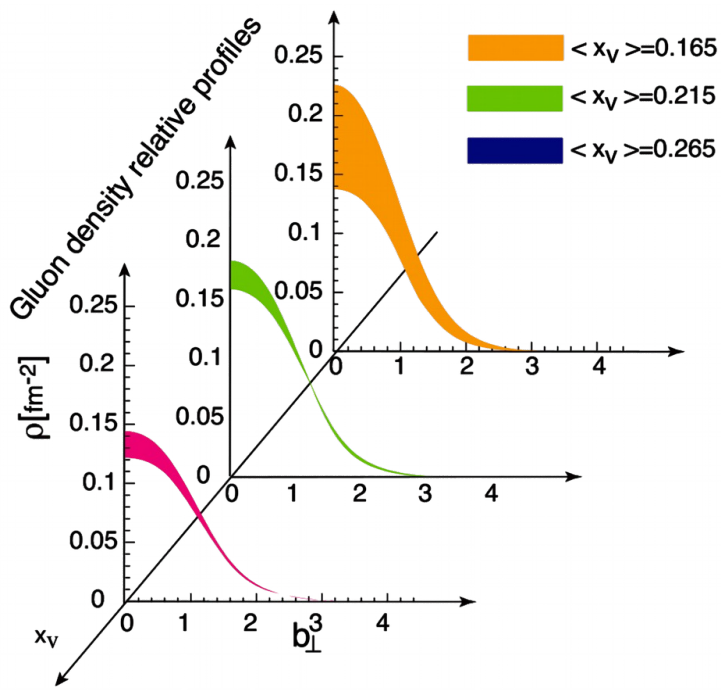
Novel program of QCD structure of nuclei

- 3D imaging of the partonic structure of a light but tightly bound nucleus using DVCS and DVMP
  - Quarks and gluon structure of ^{4}He at large x through *coherent* DVCS and DVMP (φ)
- Comprehensive study of a nucleon in a nucleus at the partonic level through *Tagged DIS* and *Tagged DVCS* and *Tagged DVMP*
  - A step closer to understanding the EMC effect through complementary approaches that explore both the initial and the final state.
- A natural extension to the EIC science program

3D PARTONIC PROFILES OF ^{4}HE

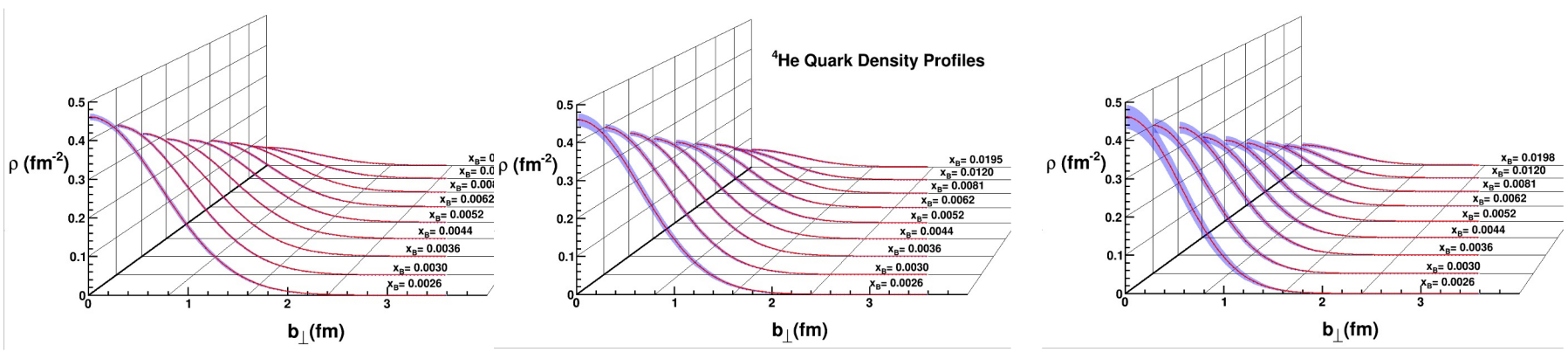
Unraveling the charge and the mechanical radii of ^{4}He





NUCLEAR DVCS (^{4}HE) AT THE EIC

- Detecting the nuclear recoil very close to the beam line using the Roman pot
- Below are profile extractions
  - For transverse momentum thresholds of 0.1 (left), 0.2 (center) and 0.3 GeV (right)



R.Abdul Khalek *et al.*, Electron-Ion Collider: EIC Yellow Report," Nucl. Phys. A **1026** (2022), 122447

CONCLUSIONS

- The longitudinal response has been extracted in ^{12}C and ^{56}Fe in a large range of momentum transfer. The physics of R_L at large excitation energies need to be understood before any conclusions are drawn on the modification of nucleonic properties in the mean field are drawn.
  - Understanding the inclusive cross sections in a wide angular range will have an impact on other fields; For example the DUNE experiment science program.

- The nucleon parton distributions are modified in nuclei but many competing interpretations require the need for tagging.

- The study of the partonic structure of nuclei is just beginning with modern tools and high luminosity machines. JLab CLAS12 is poised to make progress understanding the EMC effect and provide 3D partonic profiles in the valence region and the EIC in the see region

THANK YOU!