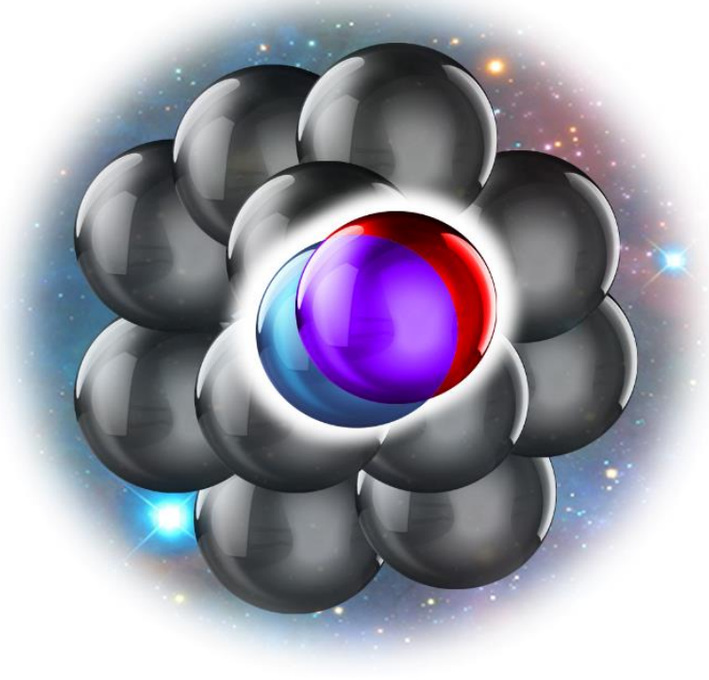
Short-Range Correlations and Backward Nucleon Tagging

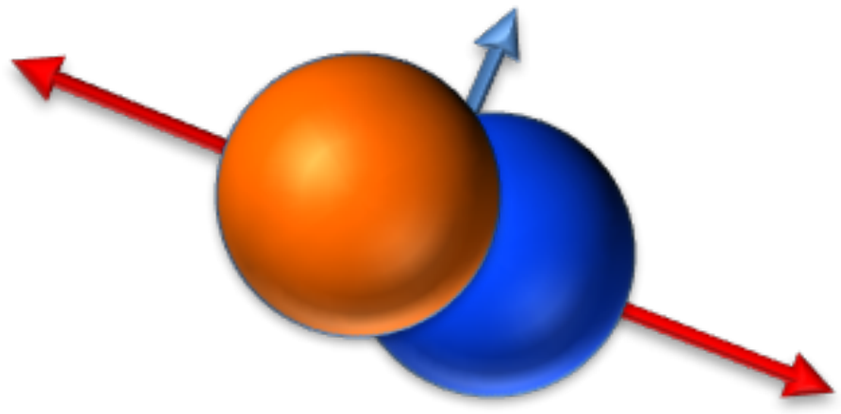
Florian Hauenstein
Backward Angle Workshop
09/22/20

Short Range Correlations

- Nucleon pairs that are close together in the nucleus
- *high relative* and *lower c.m.* momentum compared to the Fermi momentum $\mathbf{k_F}$

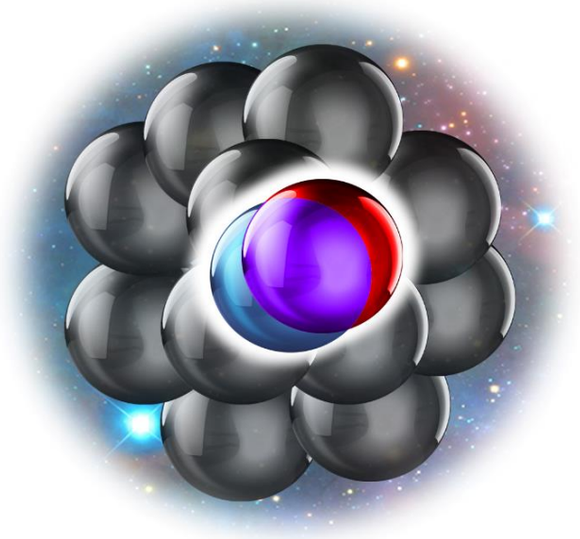


r-space



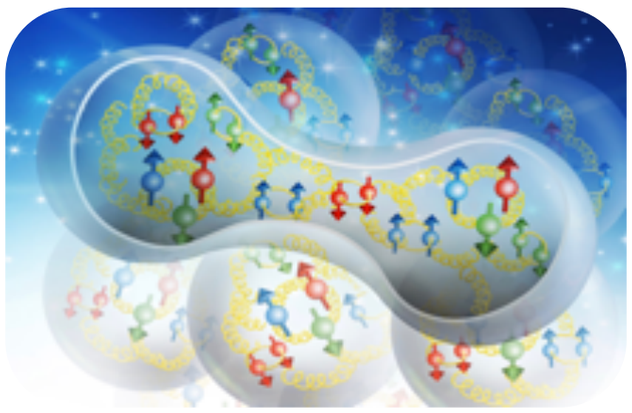
k-space

Why SRC?

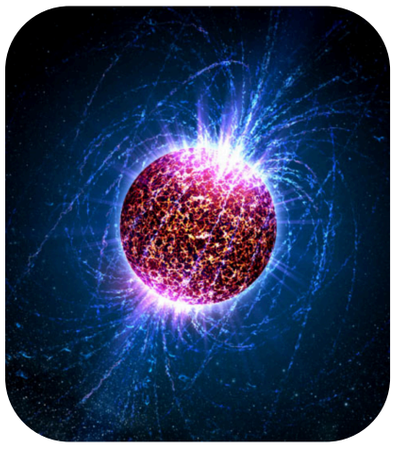


Necessary piece for a full description of nuclear systems and processes

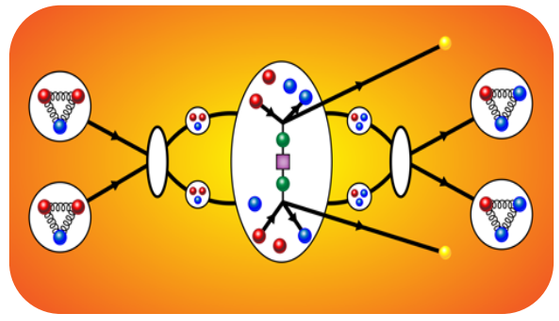
NN interactions & QCD in nuclei



High-density systems

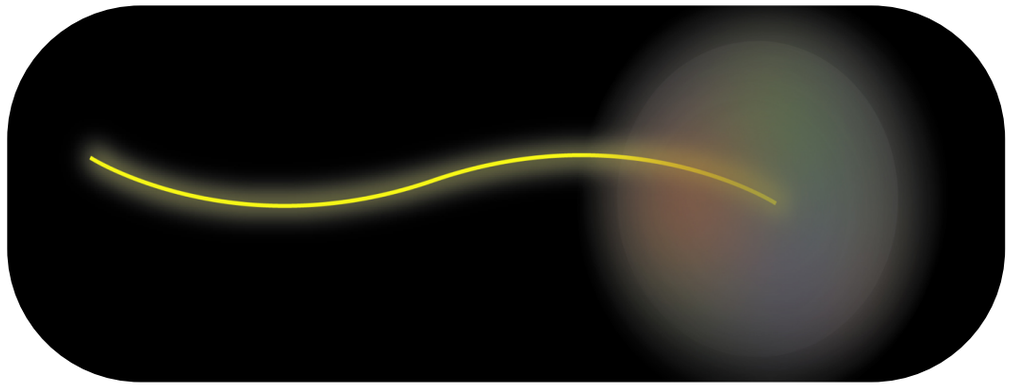


Nuclear processes (e.g. 0$\nu\beta\beta$ decay)

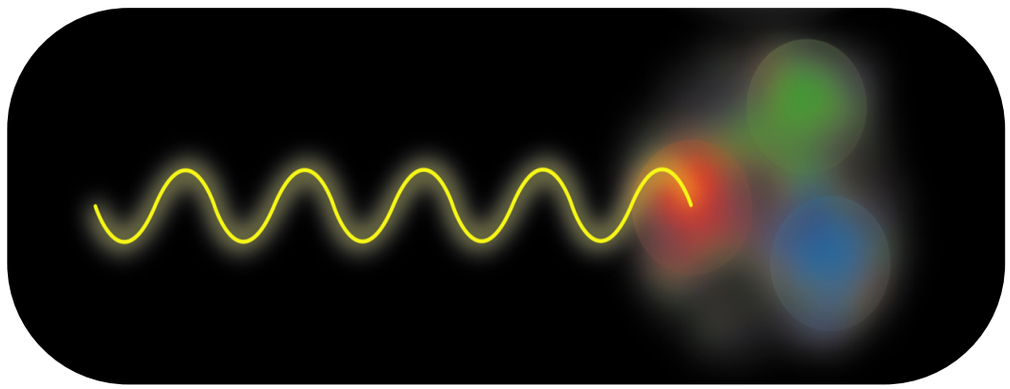


SRCs in Different Scales

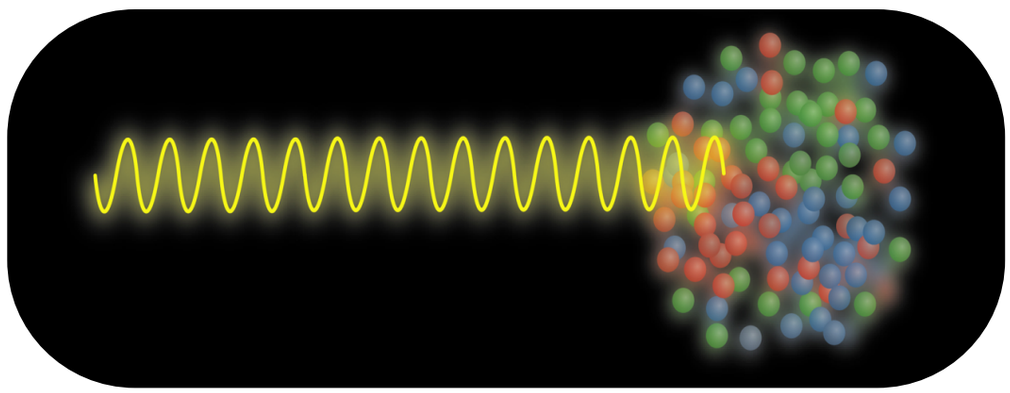
Many-Body Systems



Few-Body Systems &
NN interactions

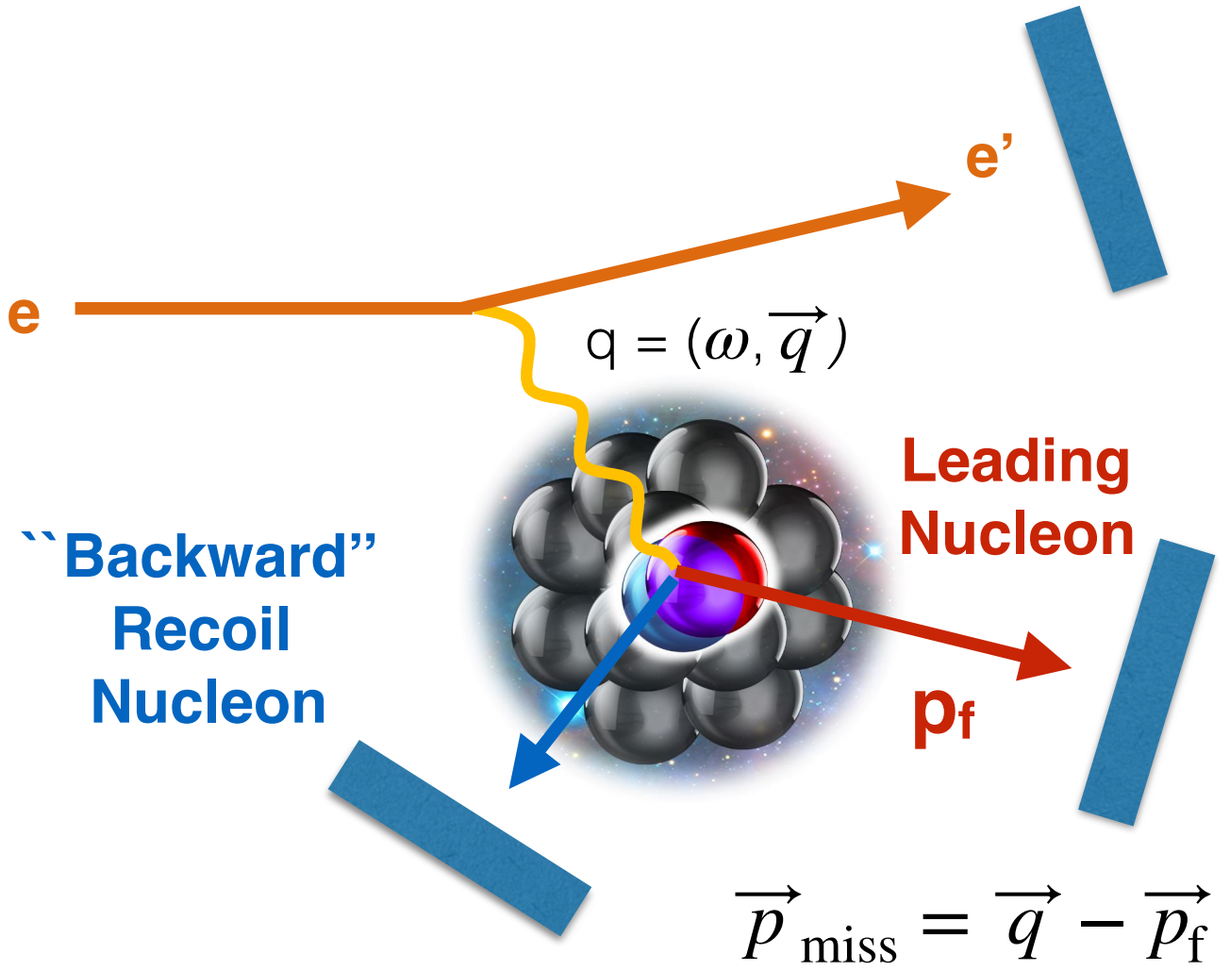


Nucleon Sub-Structure



Electron Scattering off SRC Pair

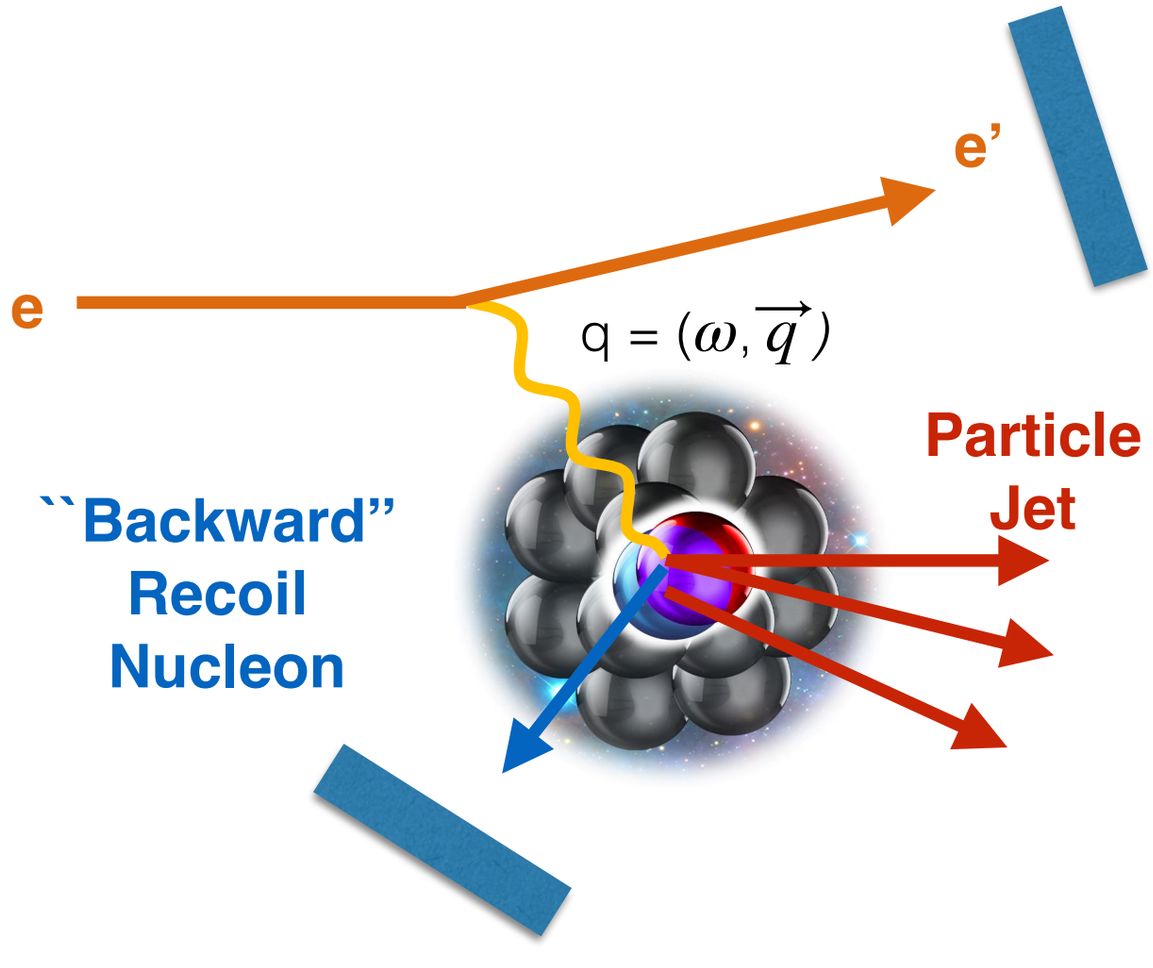
Quasi-Elastic



$$\vec{p}_{\text{miss}} = \vec{q} - \vec{p}_{\text{f}}$$

- Exclusive measurement

Deep Inelastic (DIS)



- Tagged DIS measurements

Electron Scattering off SRC Pair

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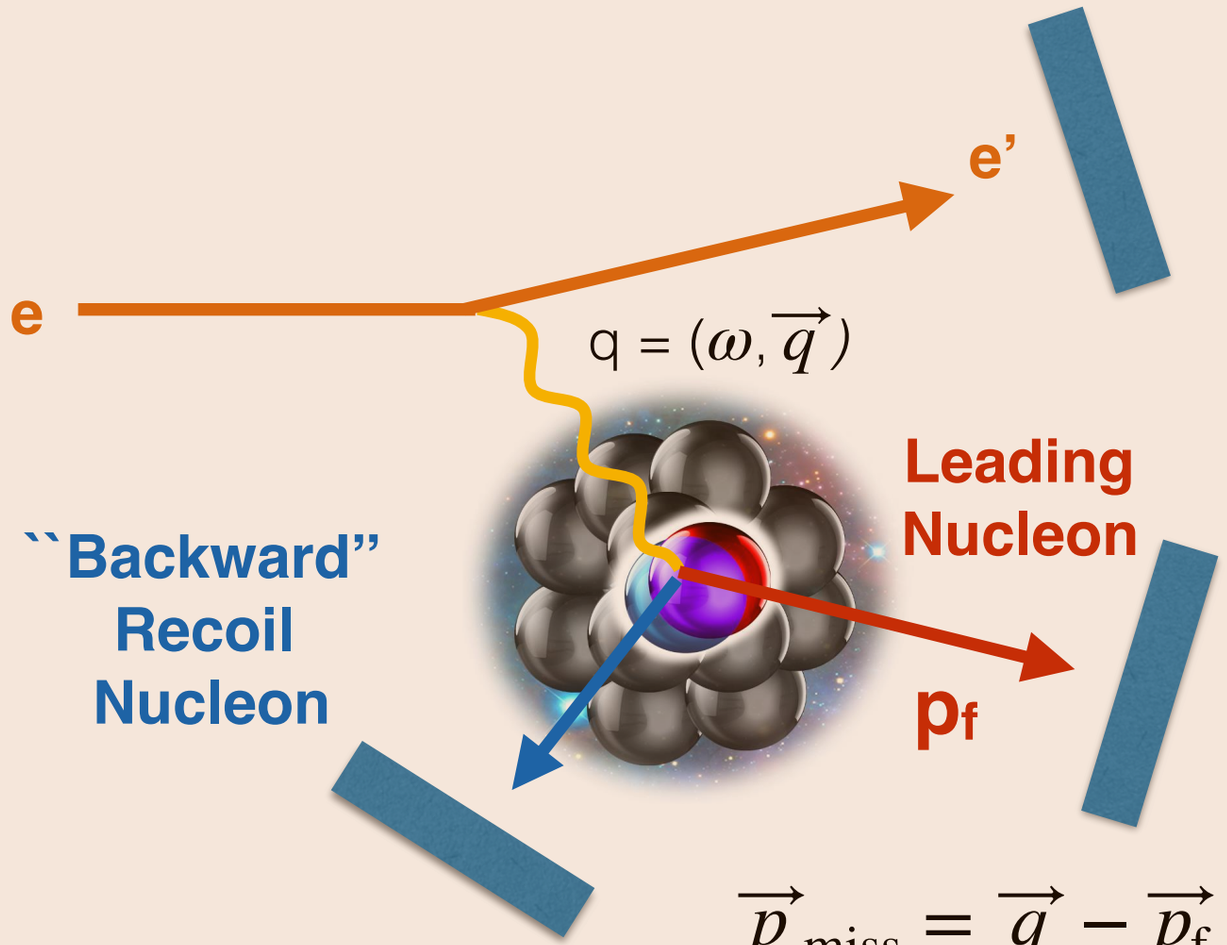

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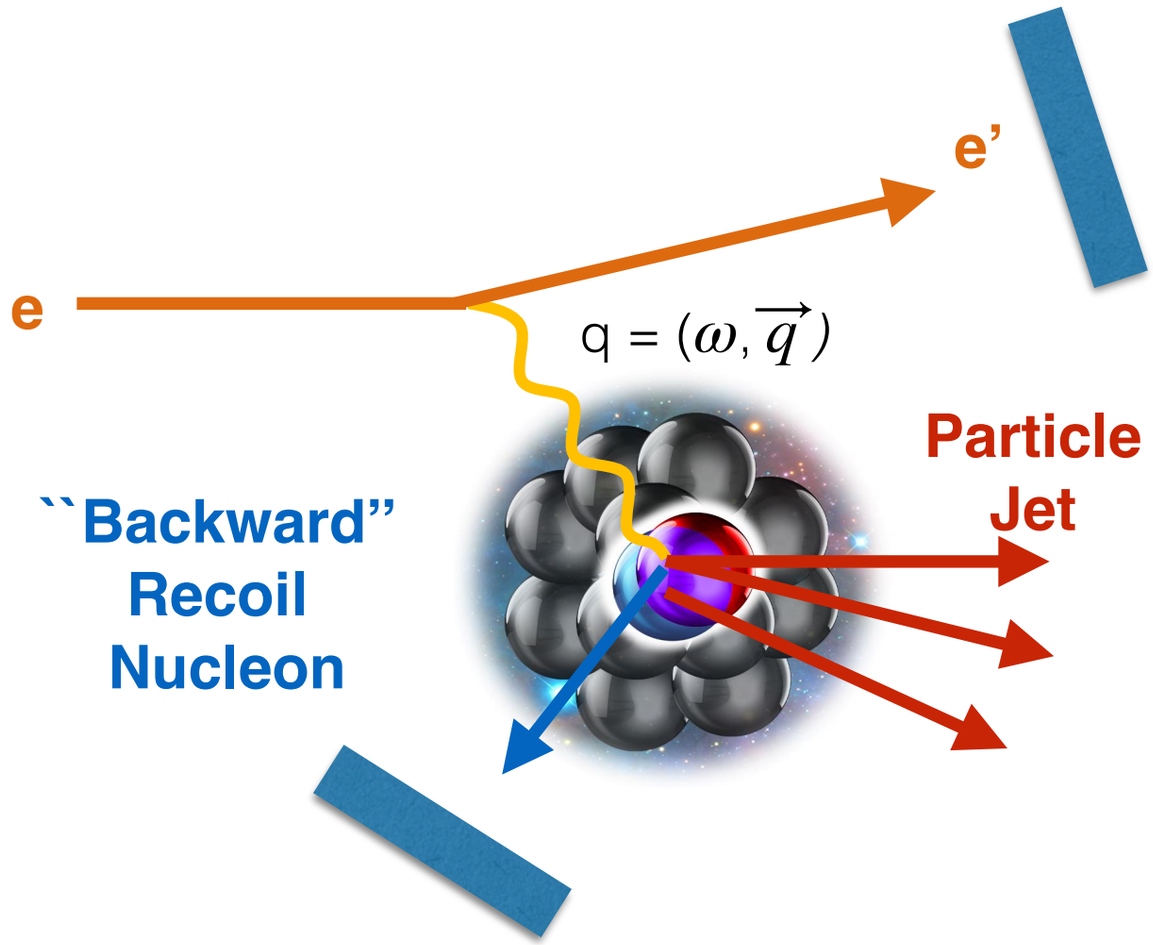
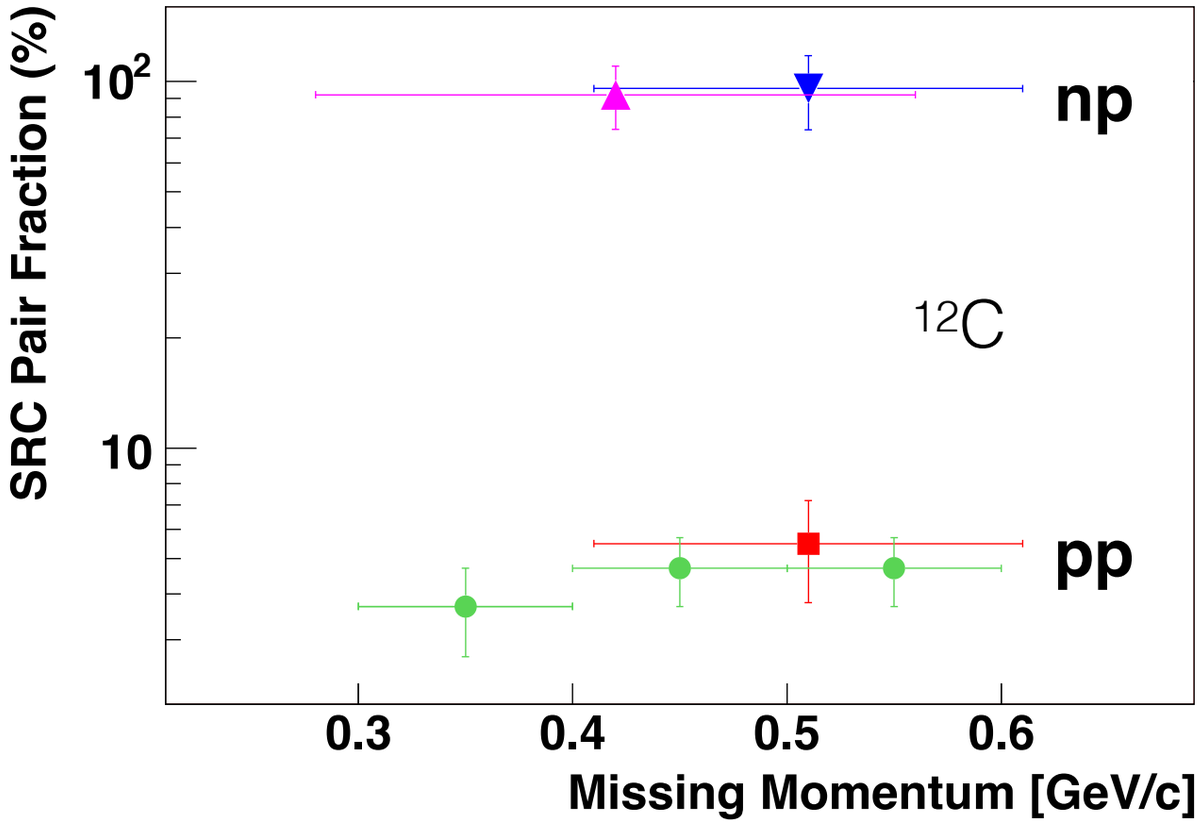
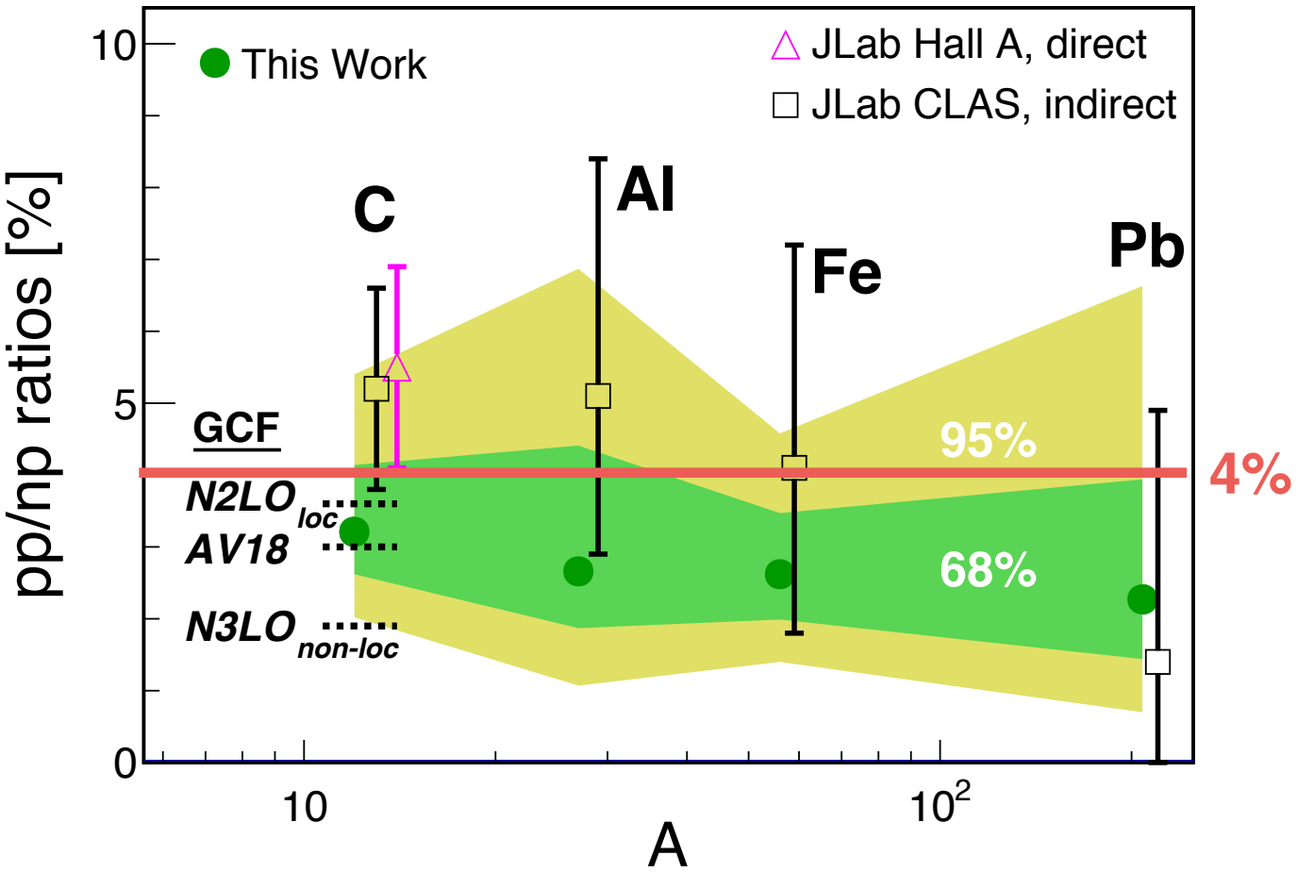


- Tagged DIS measurements

(e'Np) Measurements

Piasetzky, PRL (2006), Shneor, PRL (2007), Subedi, Science (2008), Korover, PRL (2014), Hen , Science (2014), Duer, Nature (2018), Duer, PRL (2019), Schmidt, Nature (2020), Korover (2020) Review: Hen, RMP (2017)

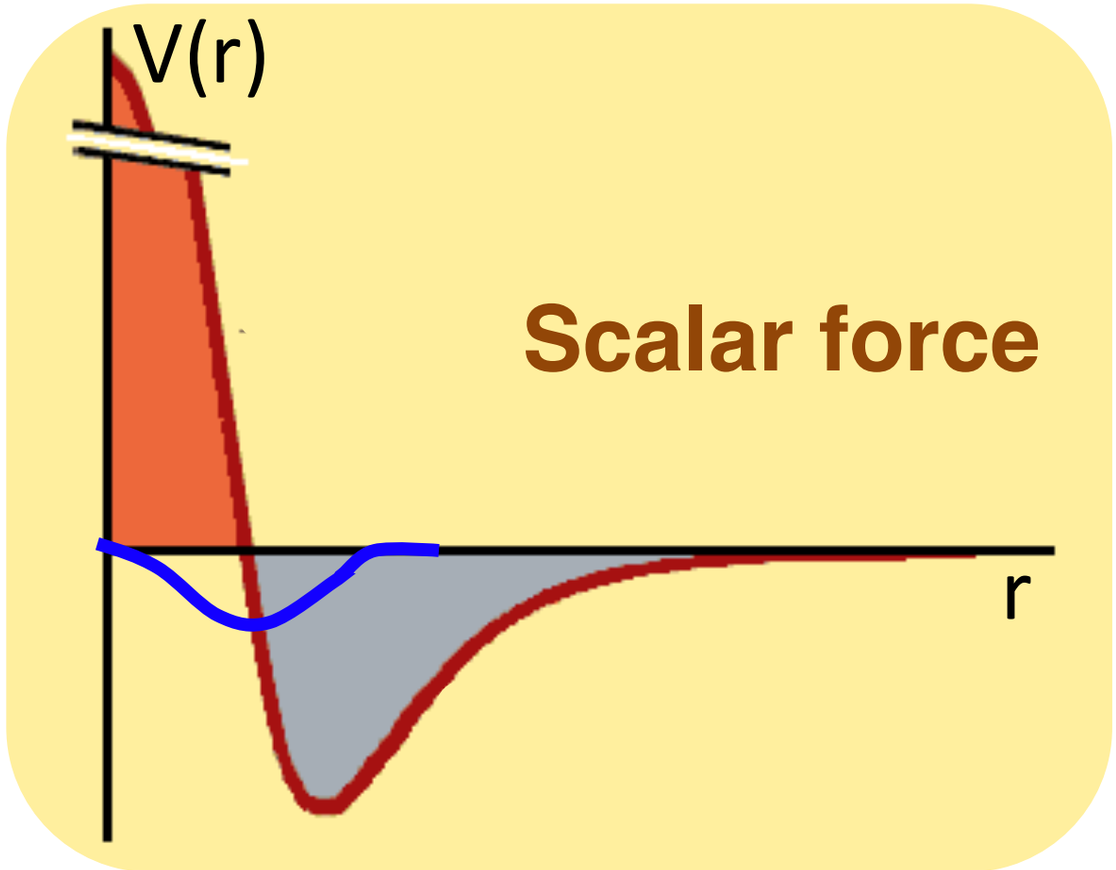




- Far more np pairs than pp pairs
- Similar in all nuclei

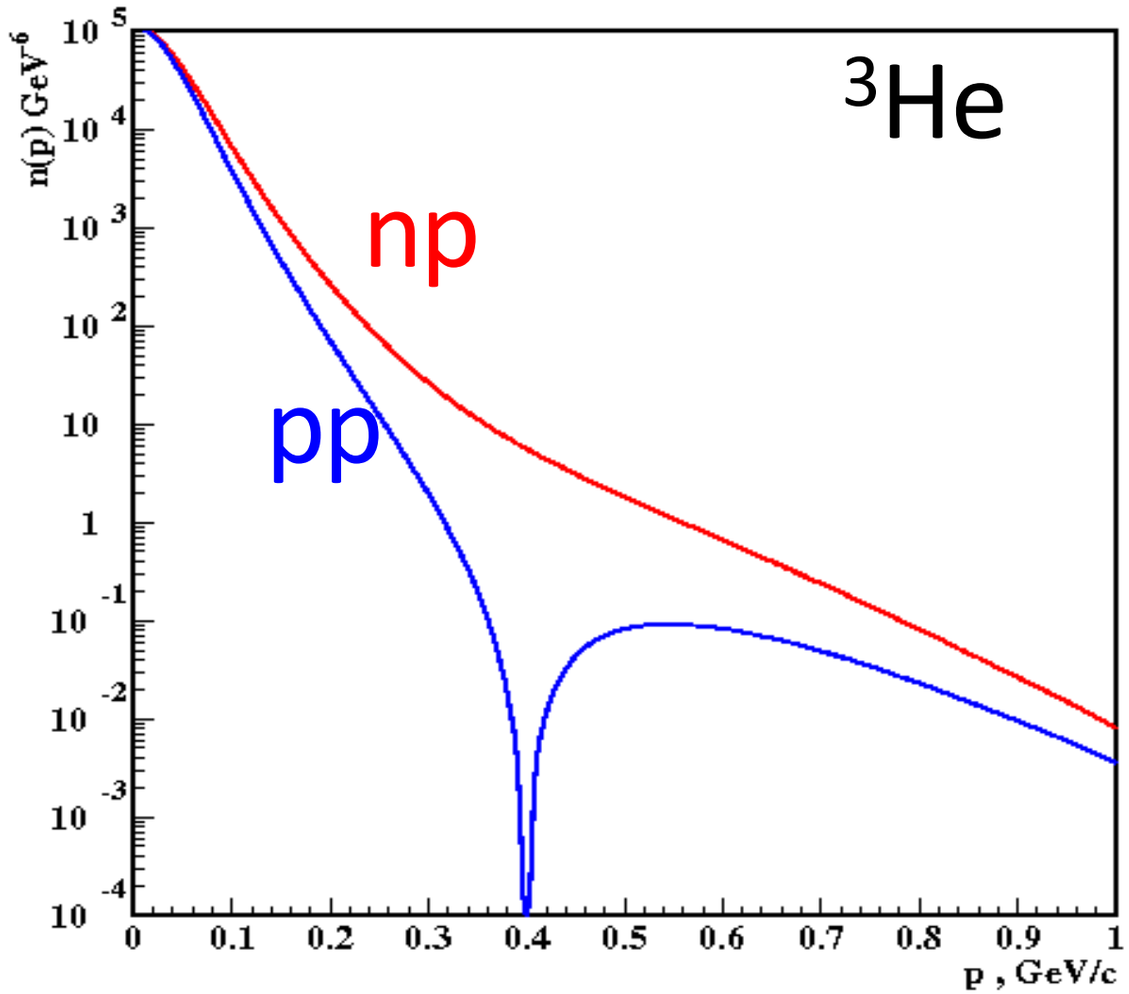
—> np-dominance

np-Dominance from Tensor Force



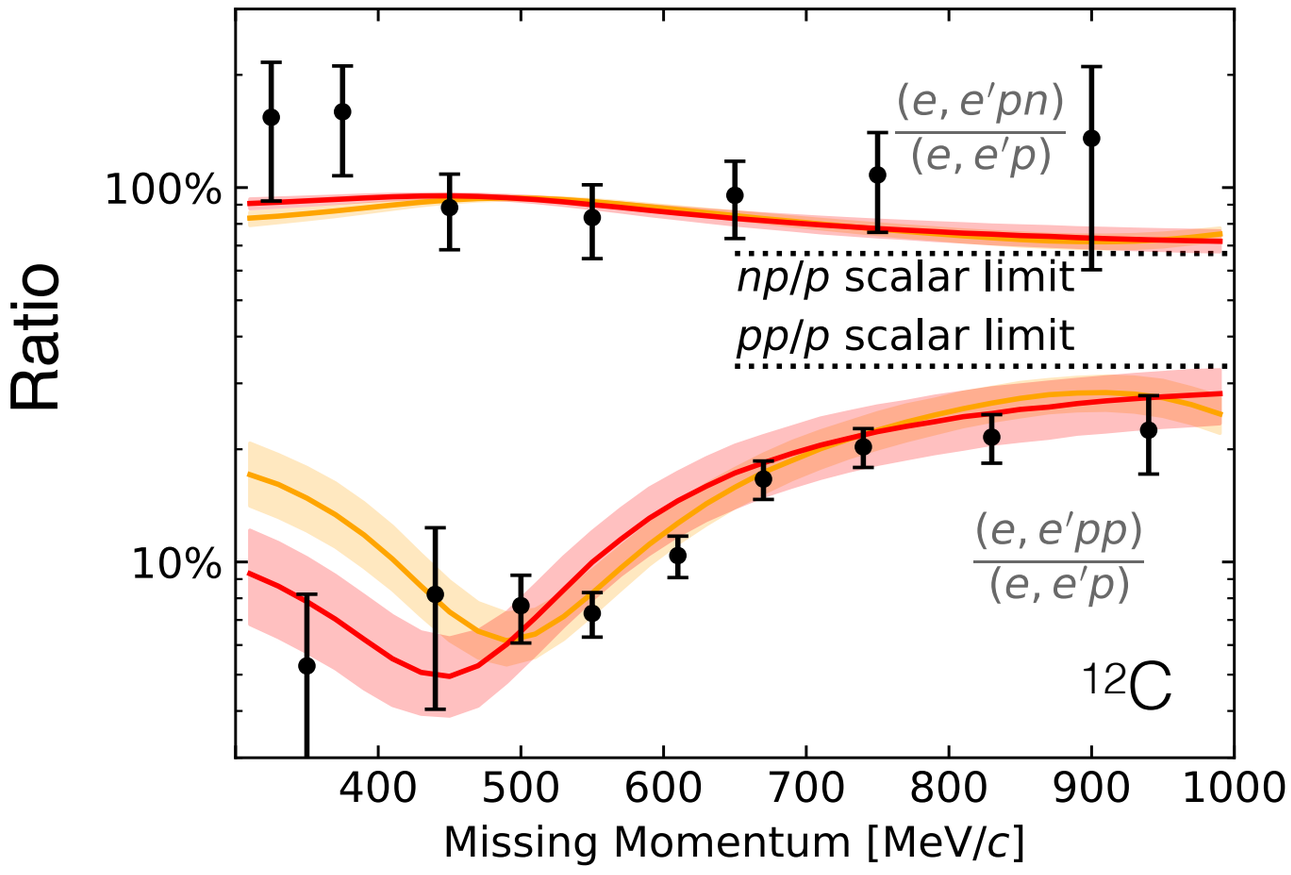
Tensor force
Short-Range attraction

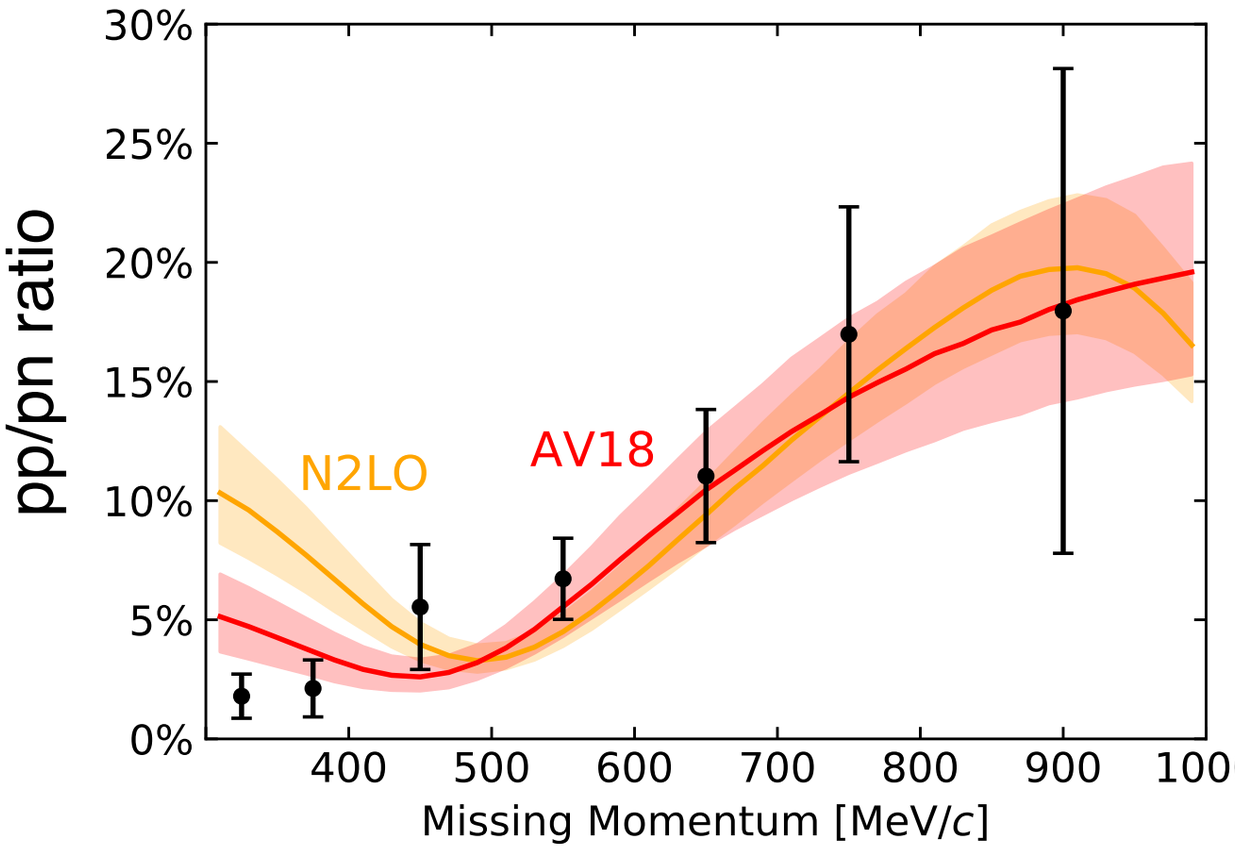
Sargsian et al., PRC (2005)



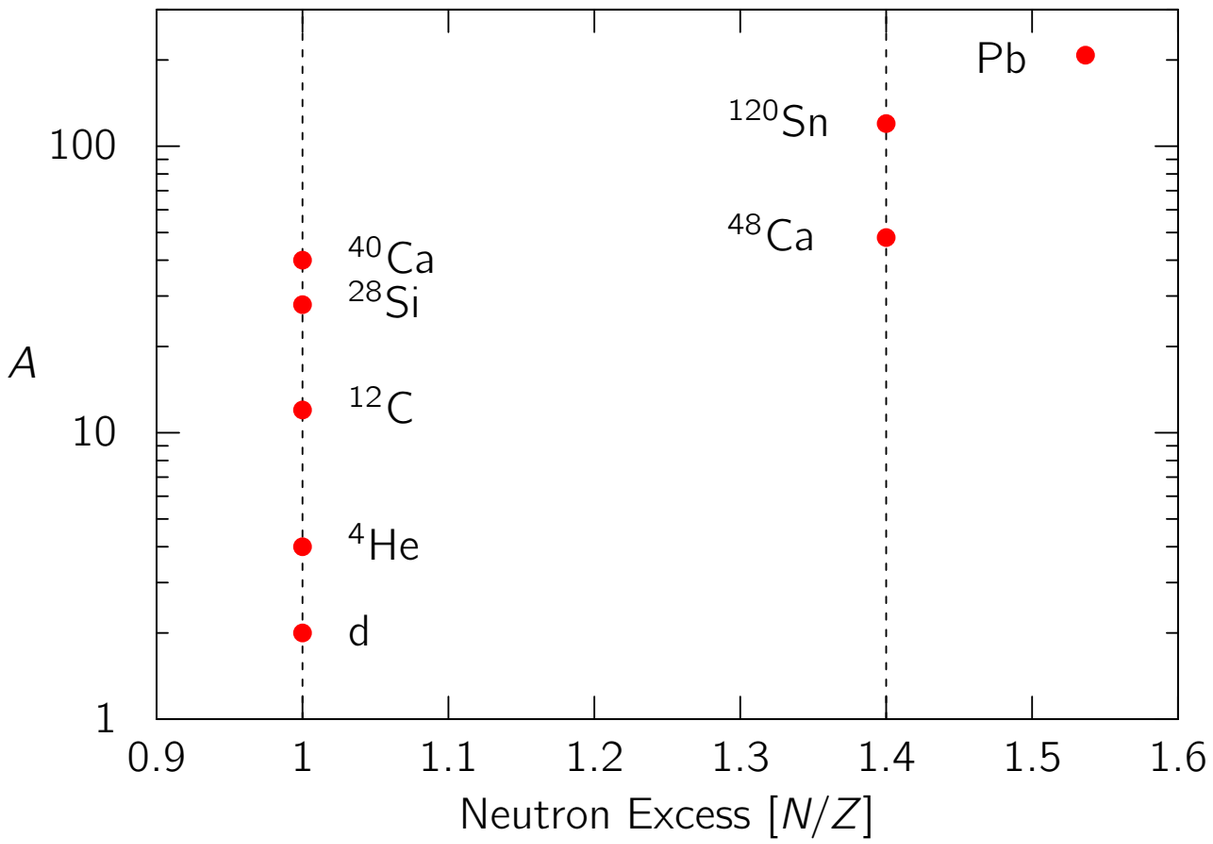
Mapping out NN interaction

Schmidt et al., Nature 578, 540544 (2020), Korover et al., arXiv 2004.07304





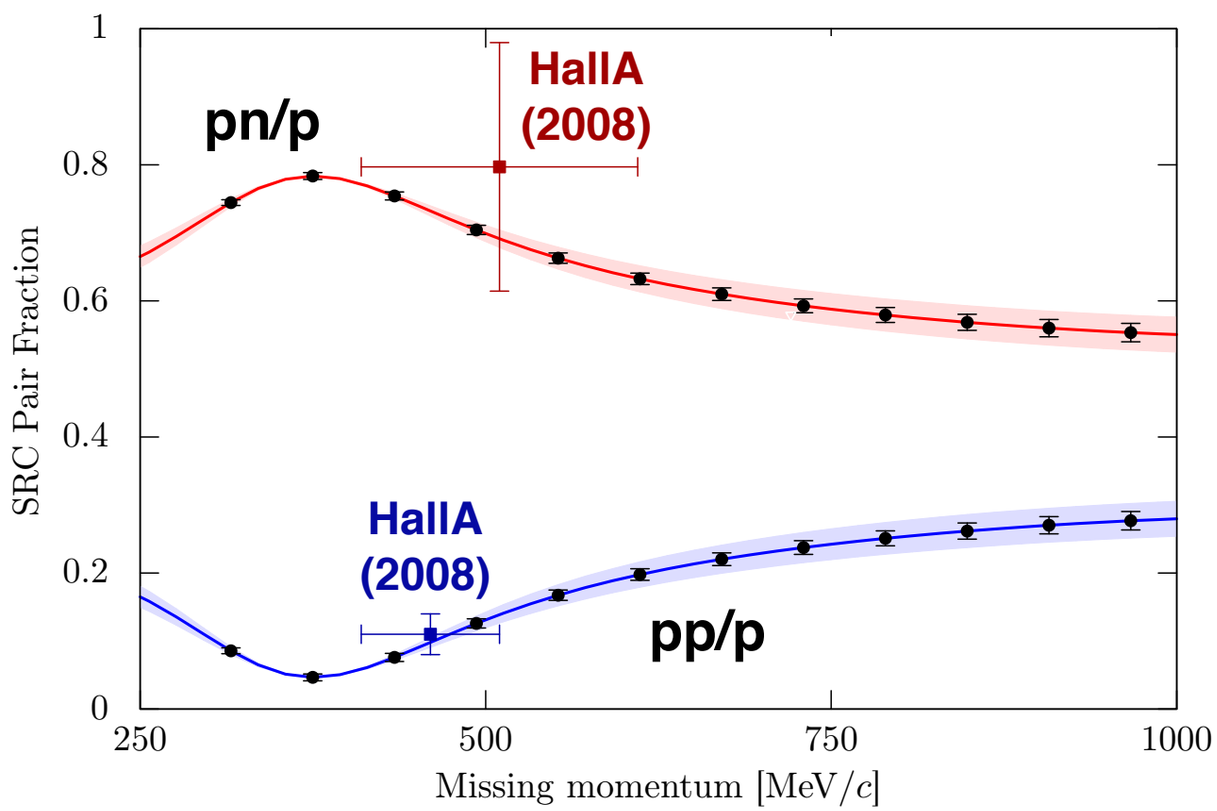
CLAS12 Run Group M in Hall B



- 2.2, 4.4 and 6.6 beam energy
- Several targets
- Various reaction channels
- Scheduled for 2021

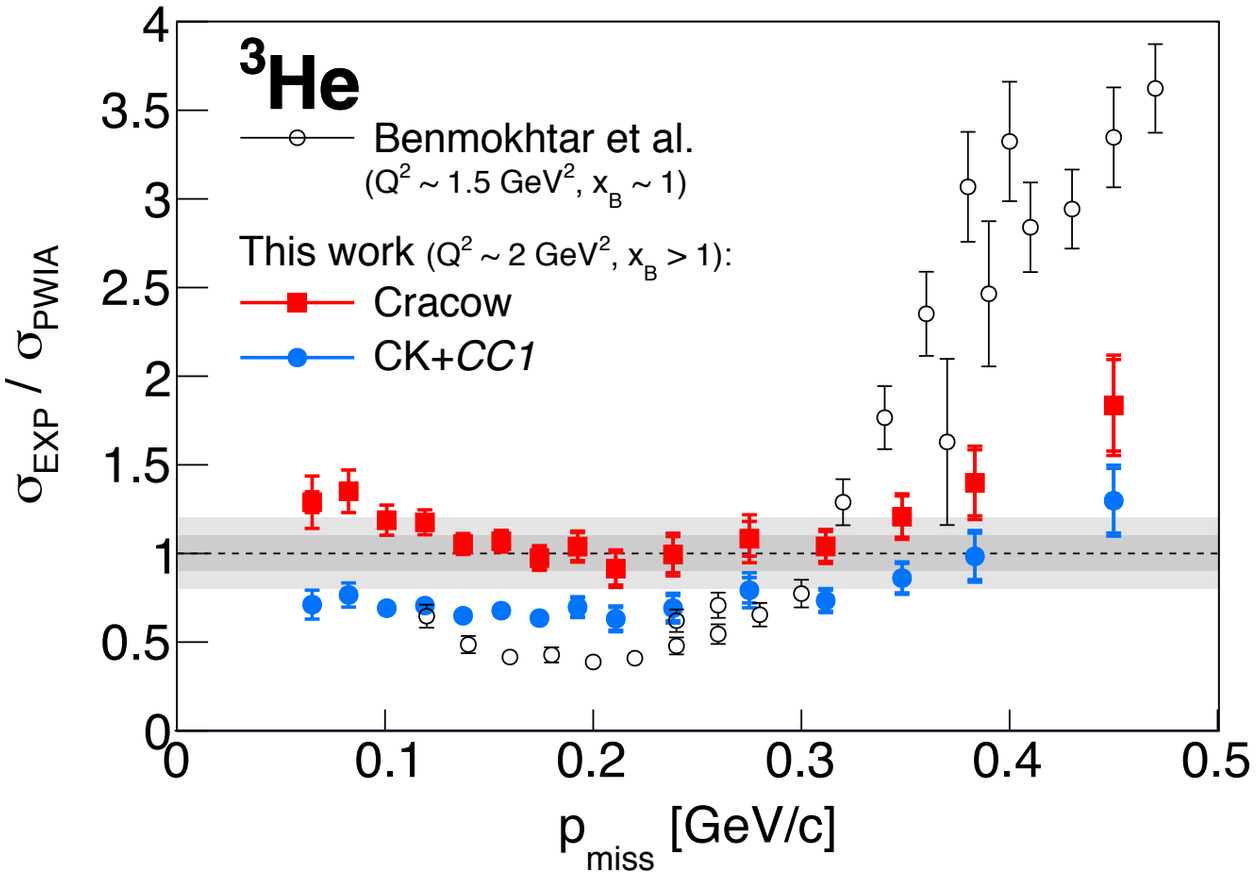
Achievable Statistics:

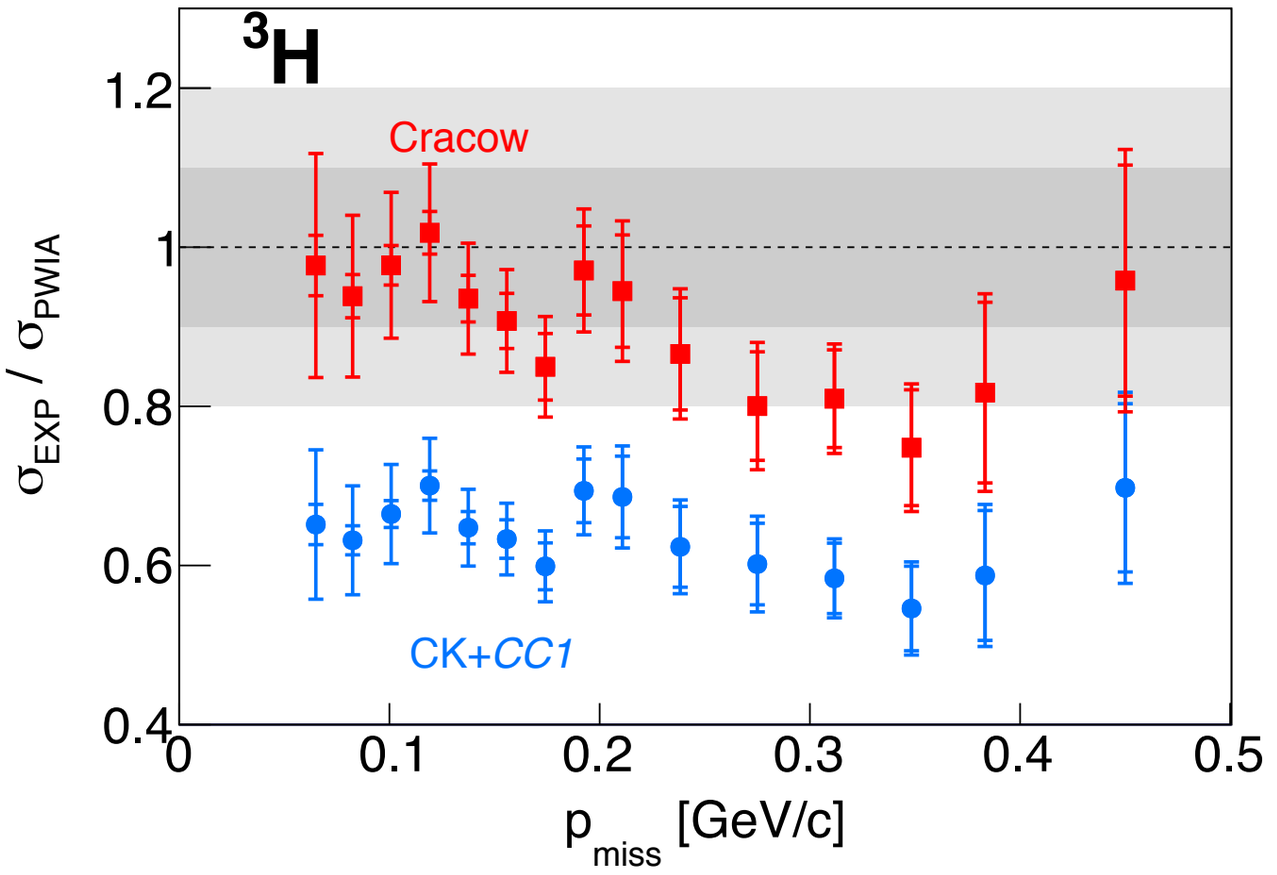
Reaction	*pp*	*pn*	*np*	*nn*
Counts per target	13,000	13,000	8,500	250



(e,e'p) with A = 3 Nuclei

Cruz-Torres, et al, PRL124, 212501 (2020), Cruz-Torres, et al, PLB 797, 134890 (2019)



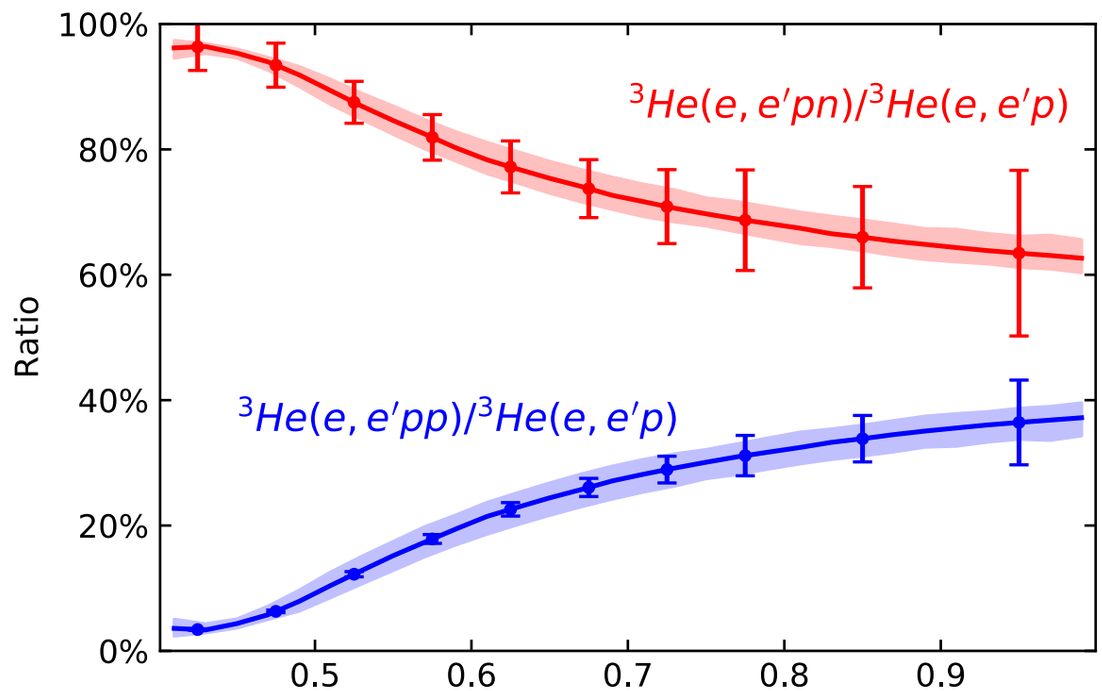


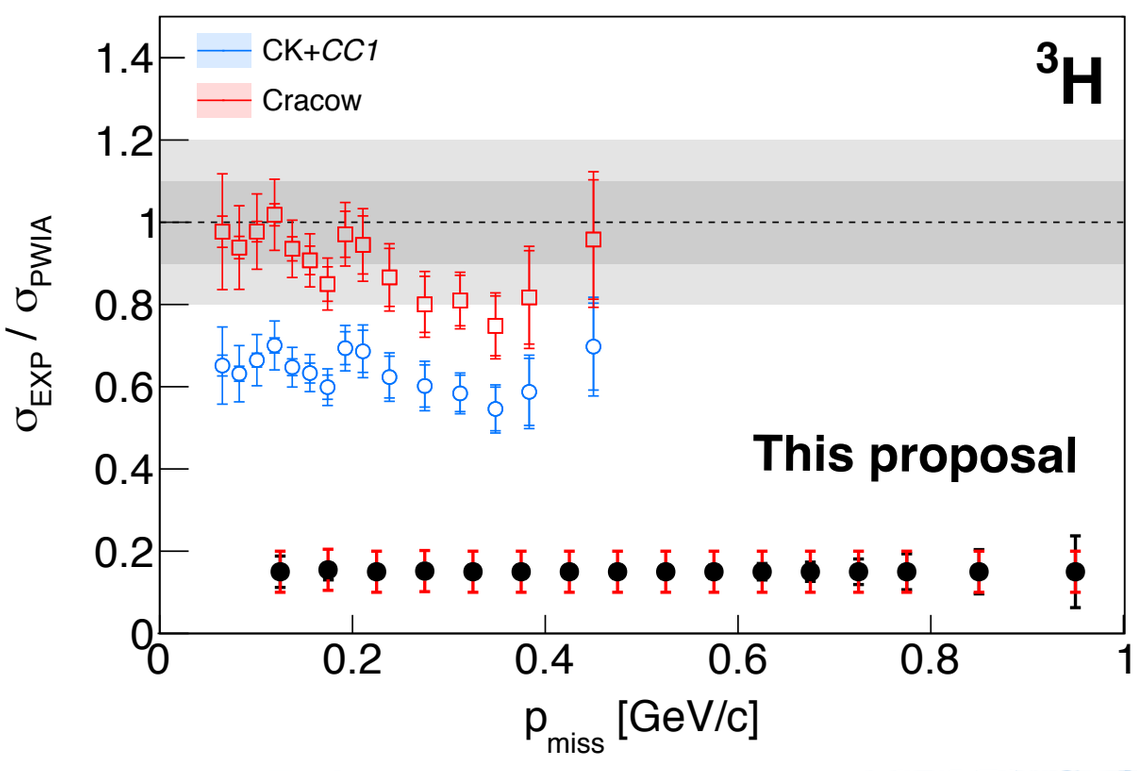
- Excellent test of state-of-art calculations of A = 3 system
- First results from the Hall A Tritium program
- How to do better?

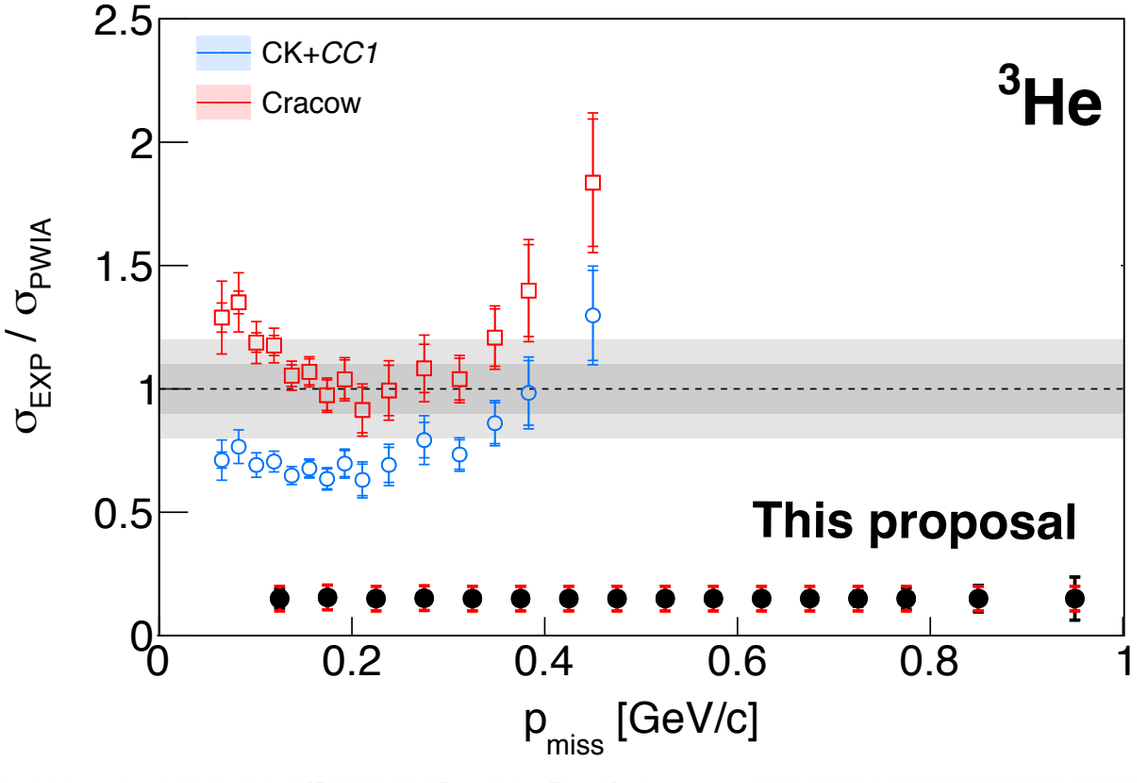
A = 3 Program in Hall B

Hen et al, arXiv:2009.03413

- 6.6 GeV beam
- ^{2}H, ^{3}H and ^{3}He targets
- Approved this PAC

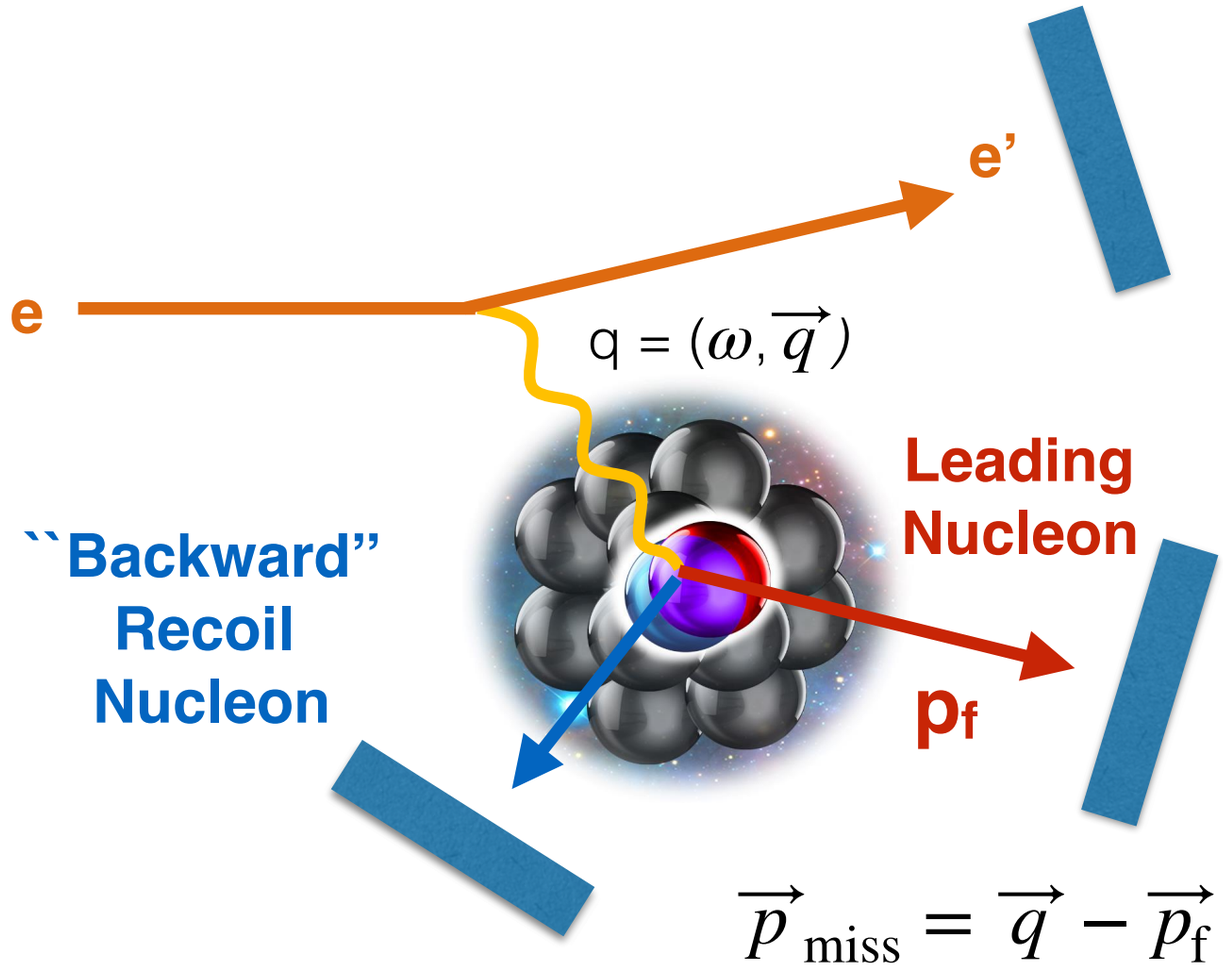






Electron Scattering off SRC Pair

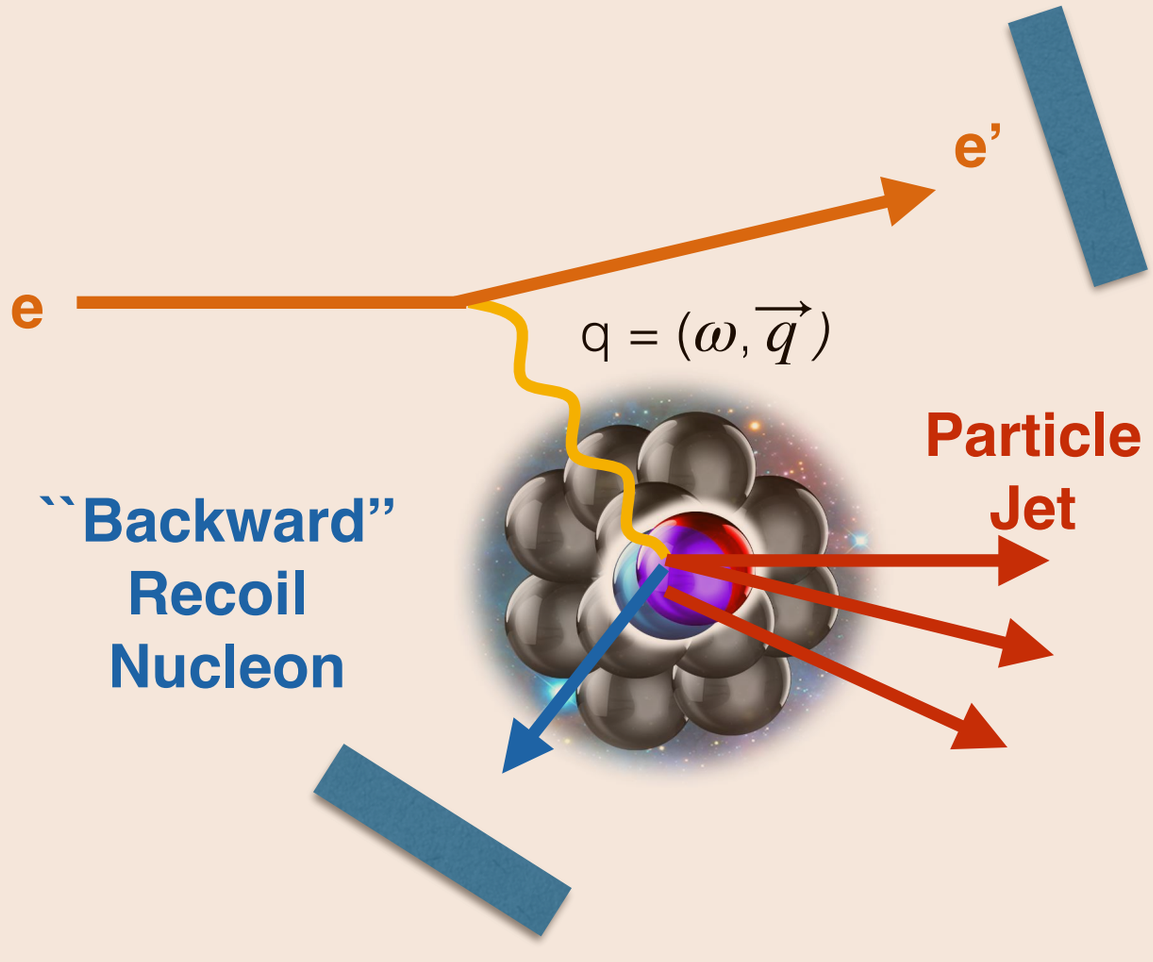
Quasi-Elastic



$$\vec{p}_{\text{miss}} = \vec{q} - \vec{p}_{\text{f}}$$

- Exclusive measurement

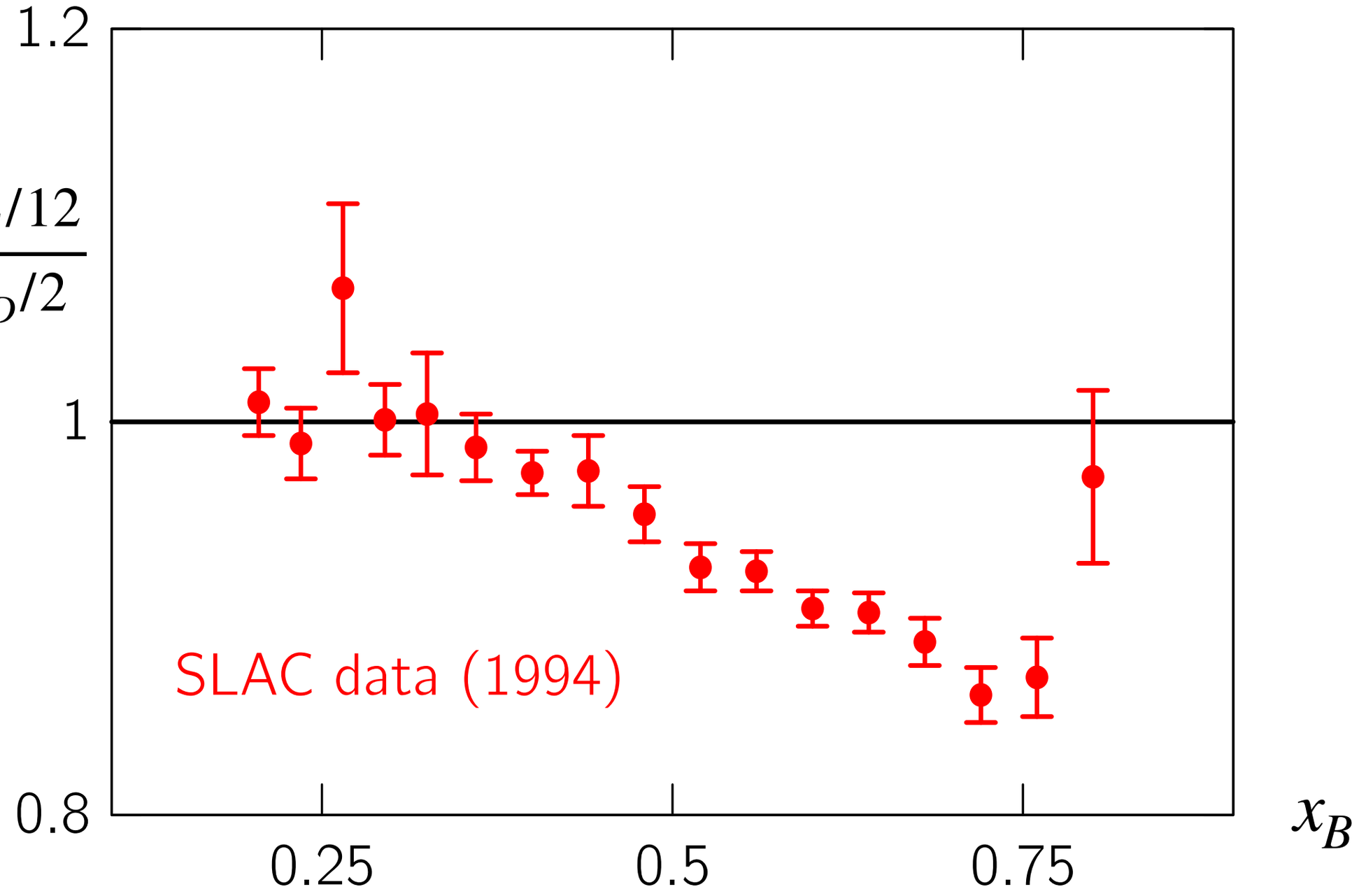
Deep Inelastic (DIS)



- Tagged DIS measurements

C/D DIS Cross Section Ratios

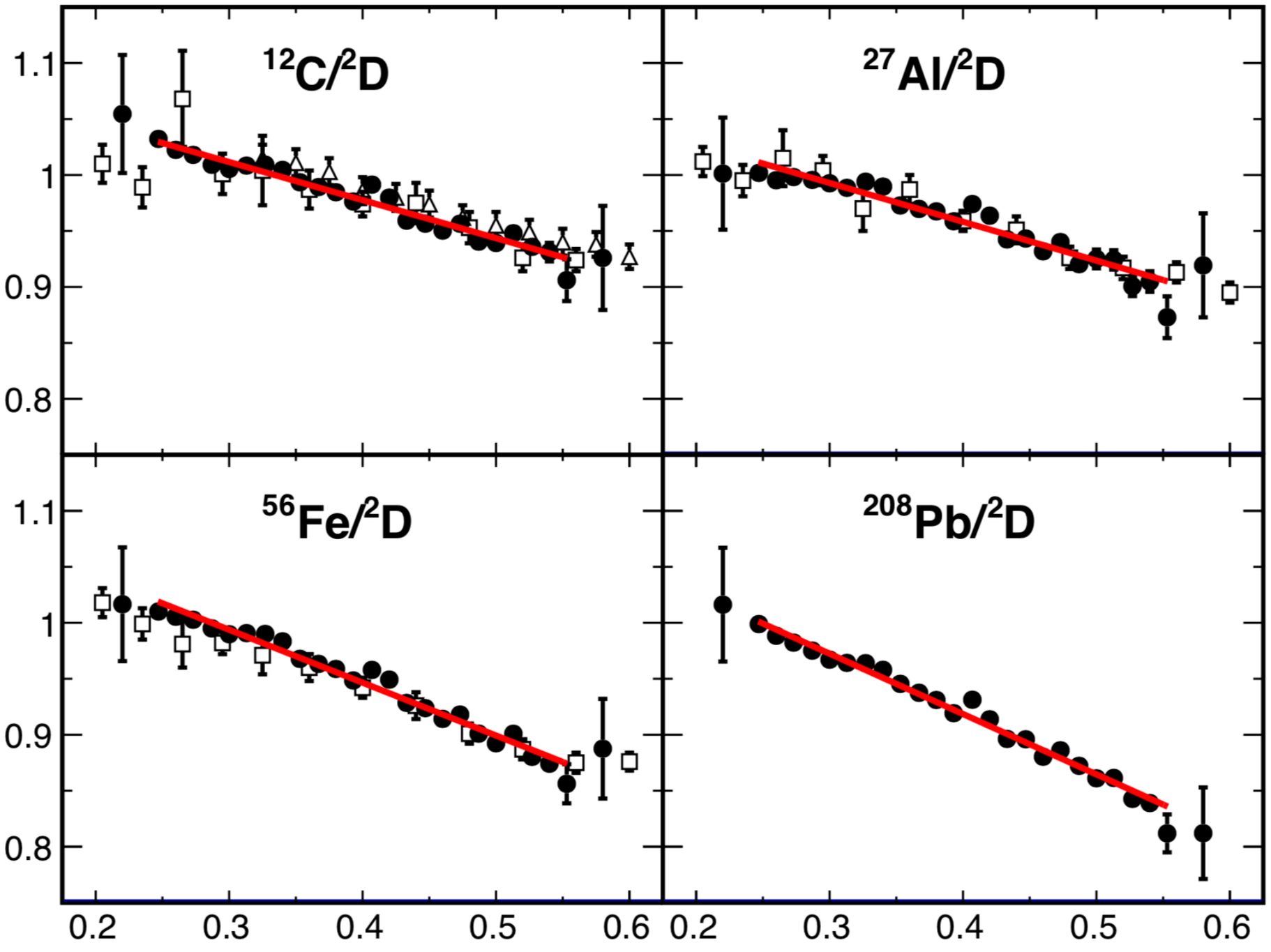
$$\frac{F_2(C)}{F_2(D)} = \frac{\sigma_C/12}{\sigma_D/2}$$



- No scaling with deuterium —> **EMC effect**
- F_2 is modified stronger in heavier nuclei

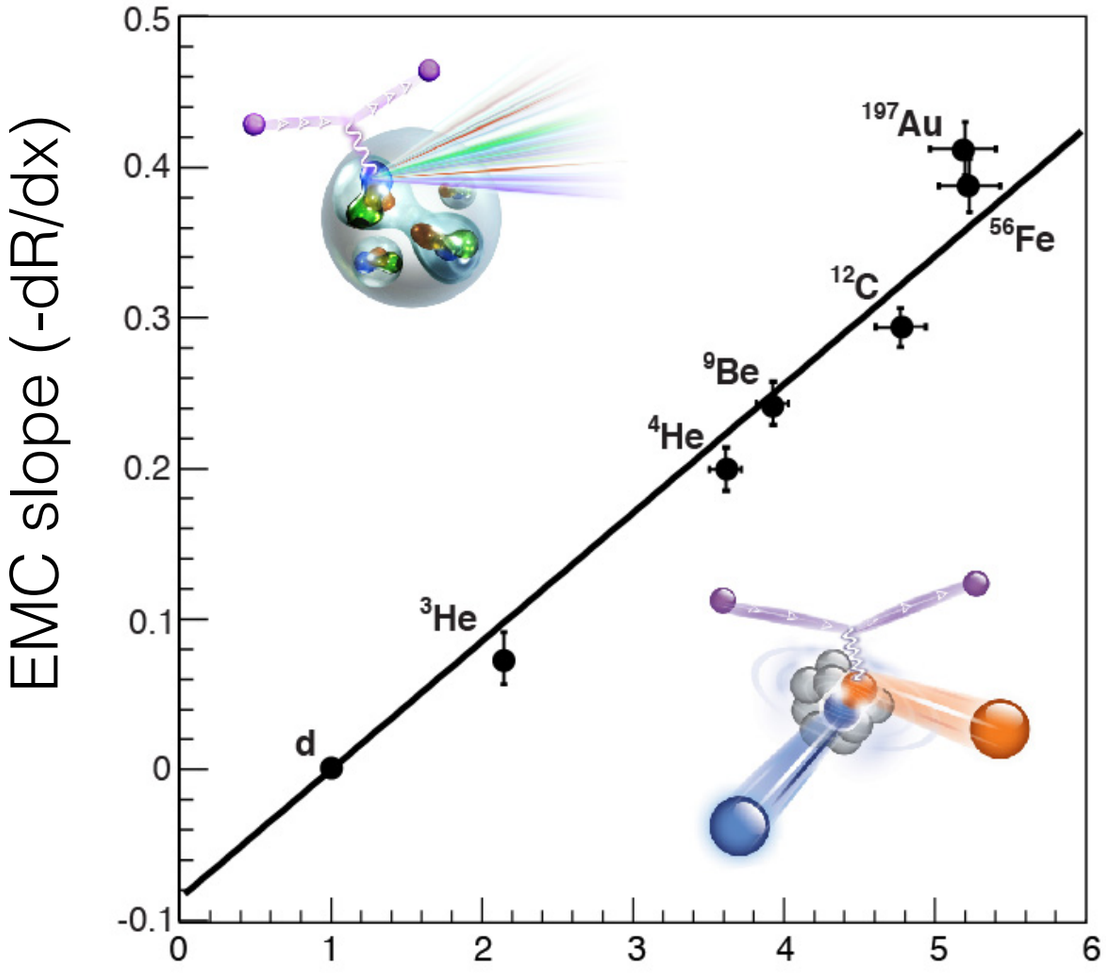
EMC Effect increases with Nuclear Size

B. Schmookler et al. (CLAS collaboration), Nature 566, 354 (2019)

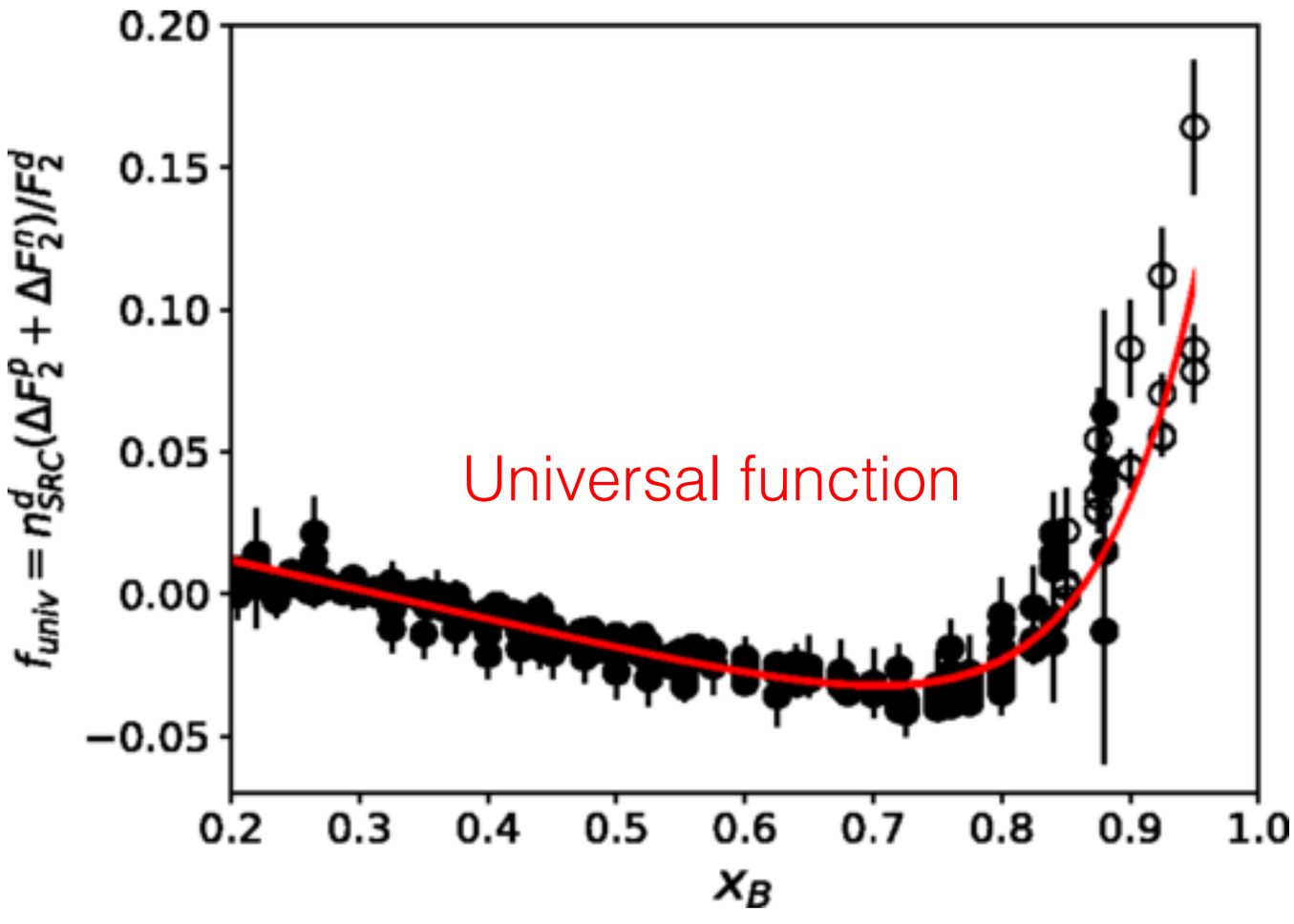


EMC and SRC Correlation

Weinstein et al., PRL 106, 052301 (2011),
Hen et al., Rev. Mod. Phys. 89, 045002 (2017)



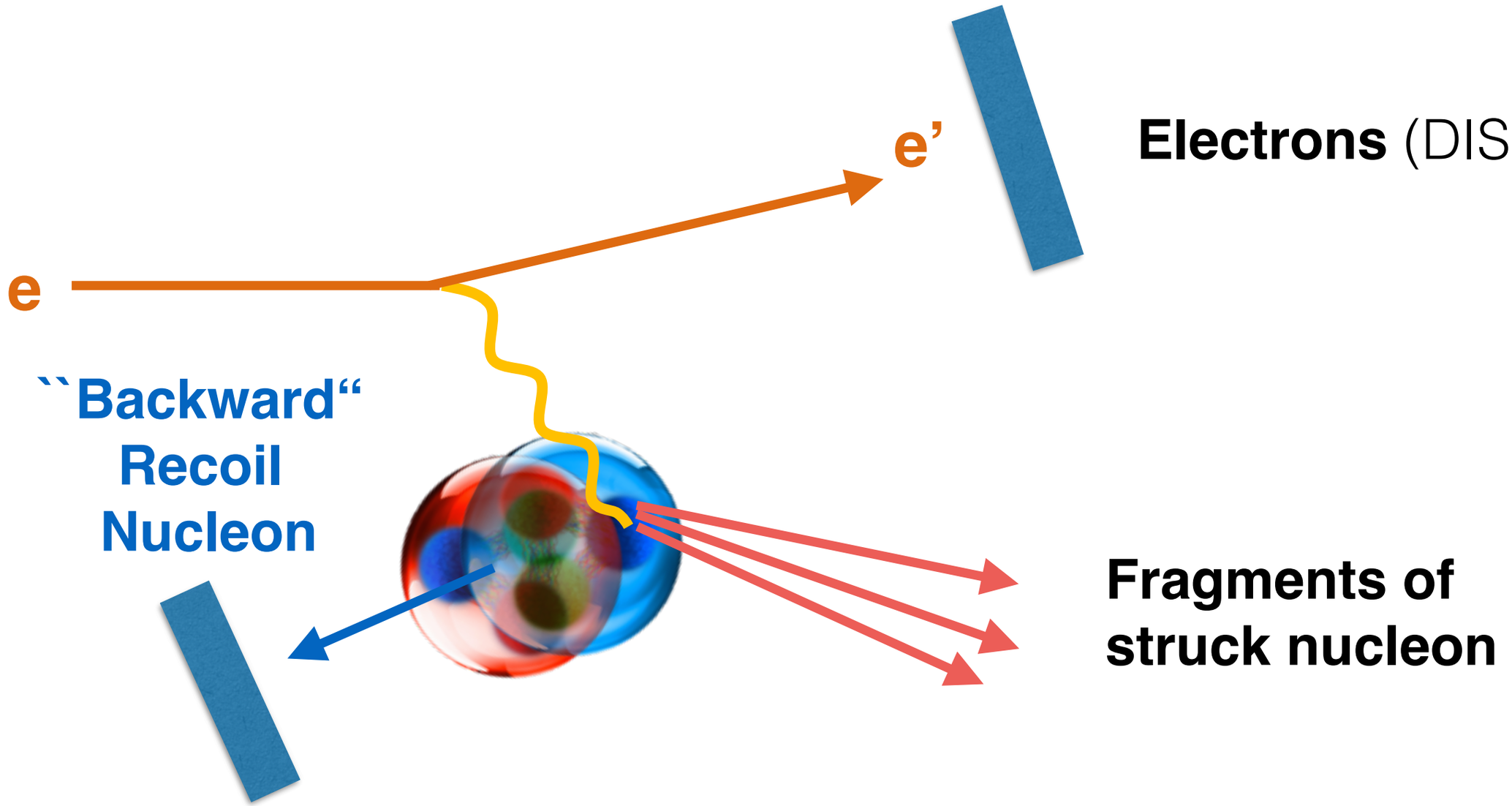
Schmookler et al., Nature 566, 354 (2019),
Segarra et al., PRL 124, 092002 (2020)



- Are high-momentum nucleons responsible for the EMC effect?

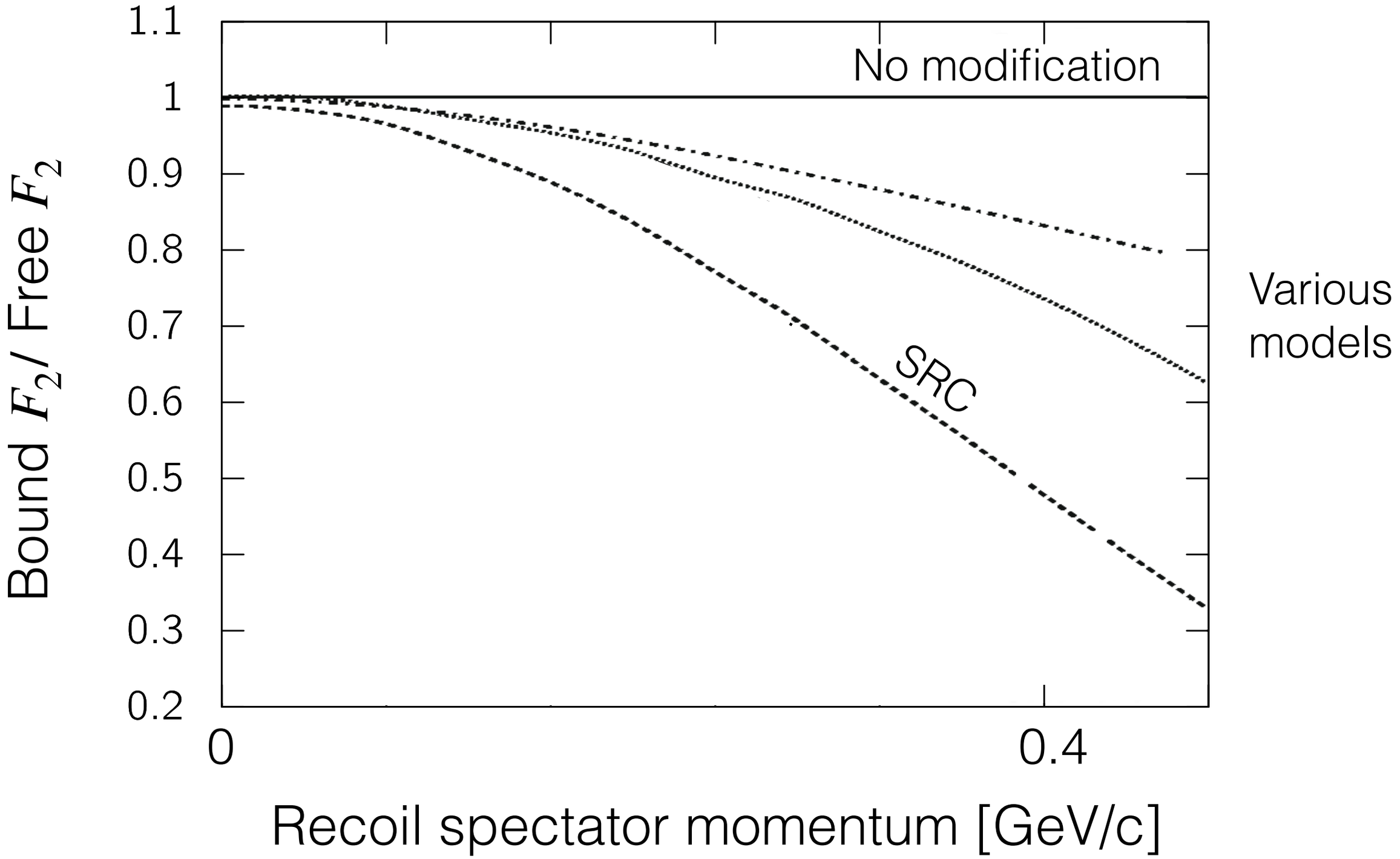
—> Tagged DIS measurements

Tagged DIS on Deuterium

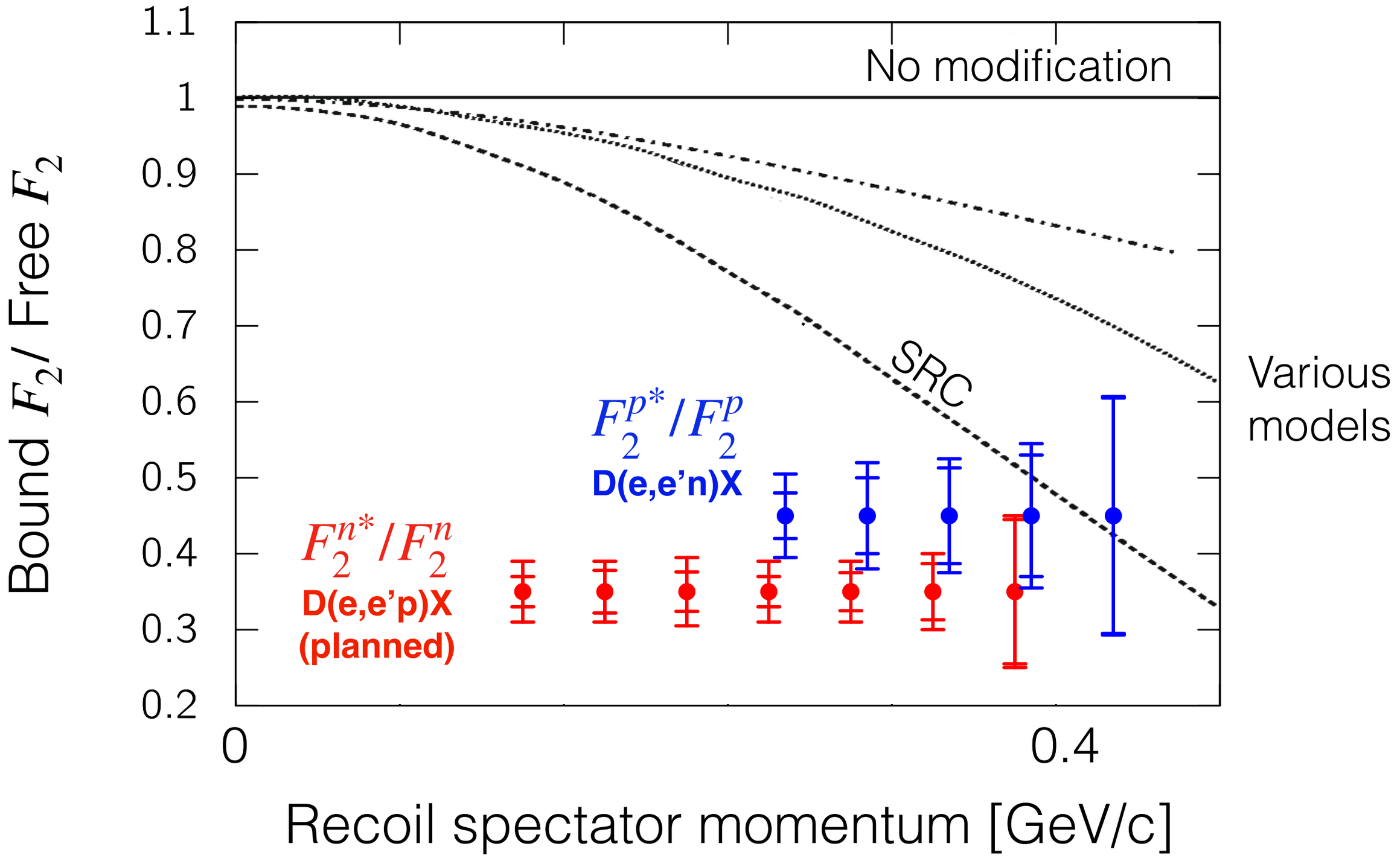


- “Tag“ interacting nucleon by measuring recoil spectator
- Measure dependence of bound nucleon structure function on nucleon momentum

DIS Recoil Tagging d(e,e'N)X - Expected Results

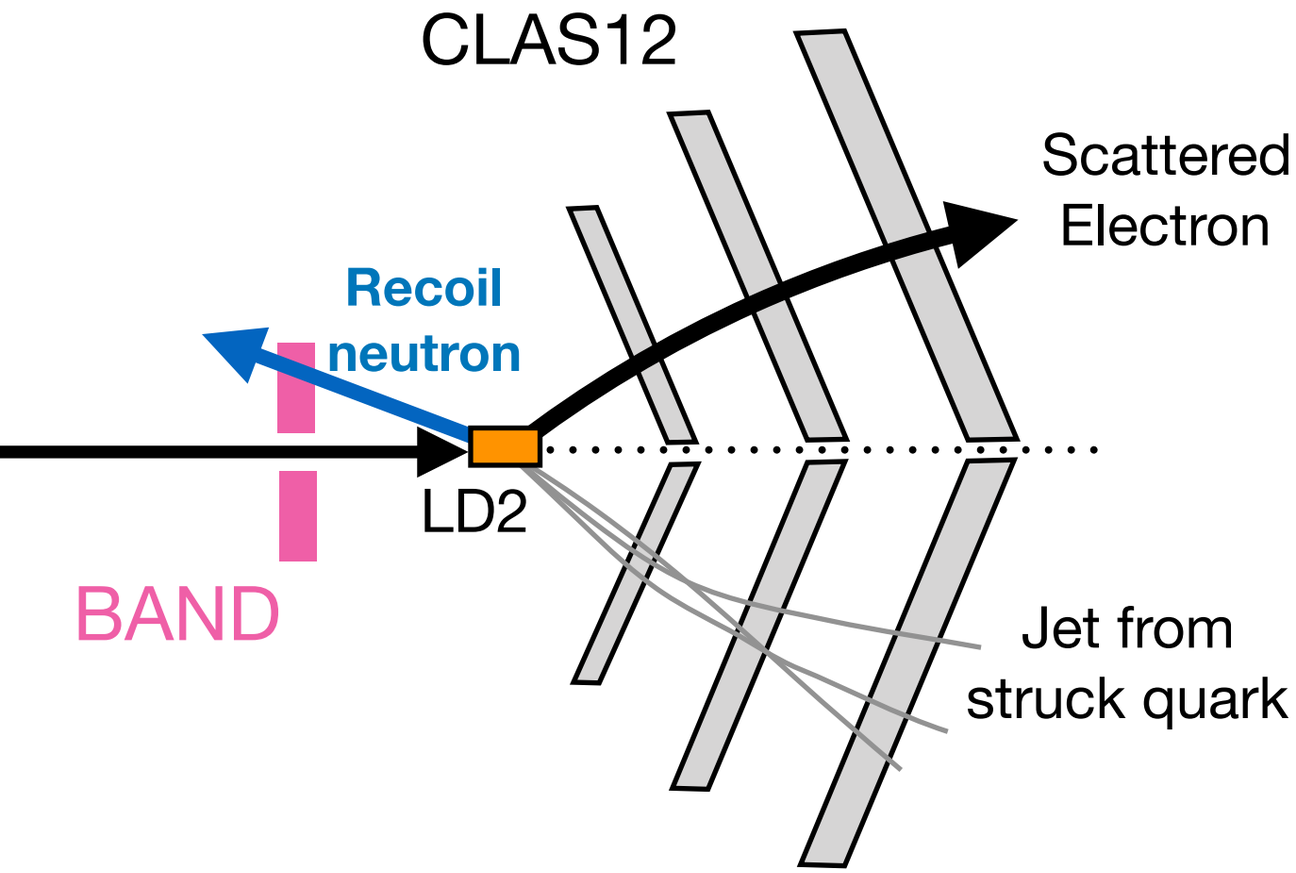


DIS Recoil Tagging D(e,e'N)X - Expected Results



Tagged DIS at Jefferson Lab

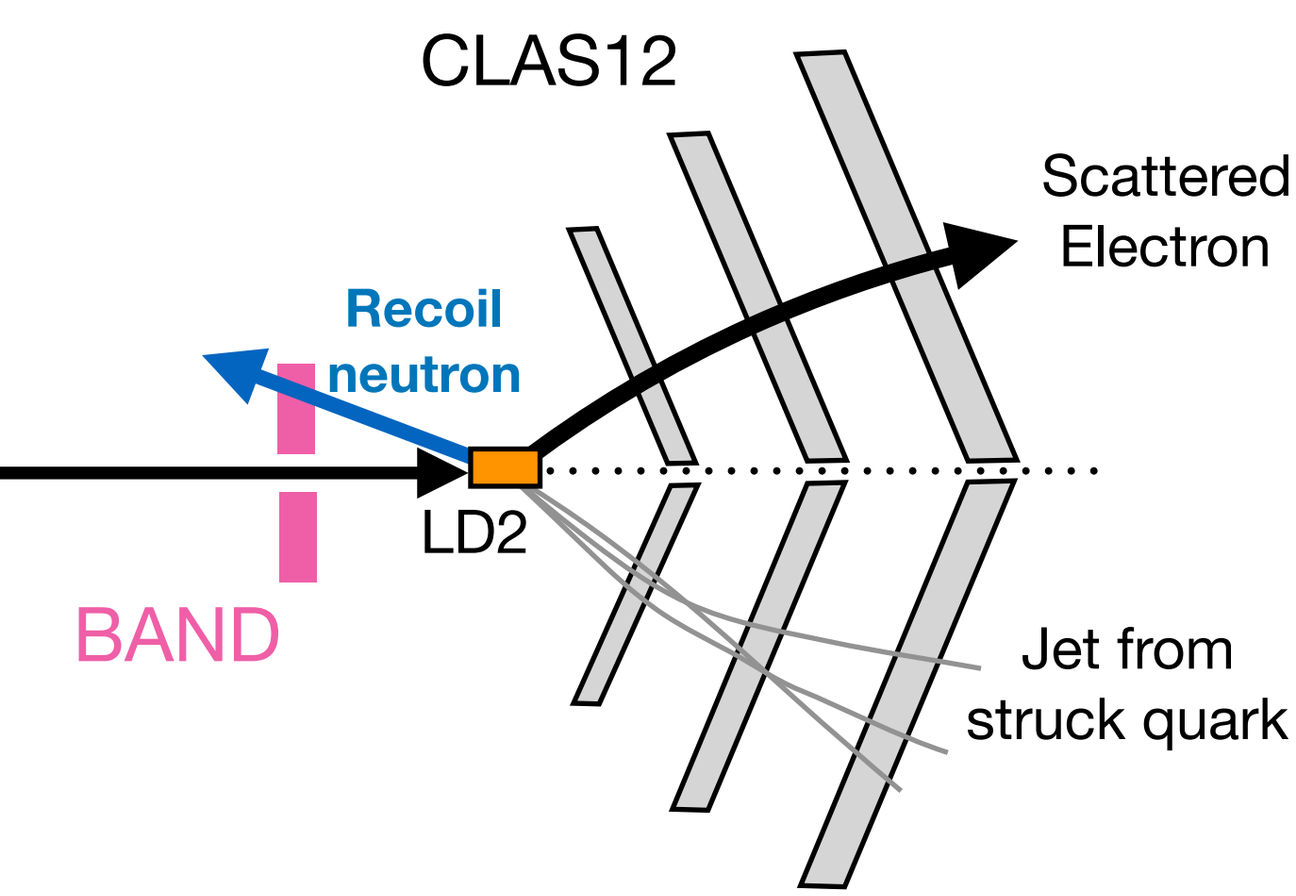
Hall B:
CLAS 12 + Backward Angle Neutron Detector (BAND)



- Took data in 2019/20
- Analysis in progress

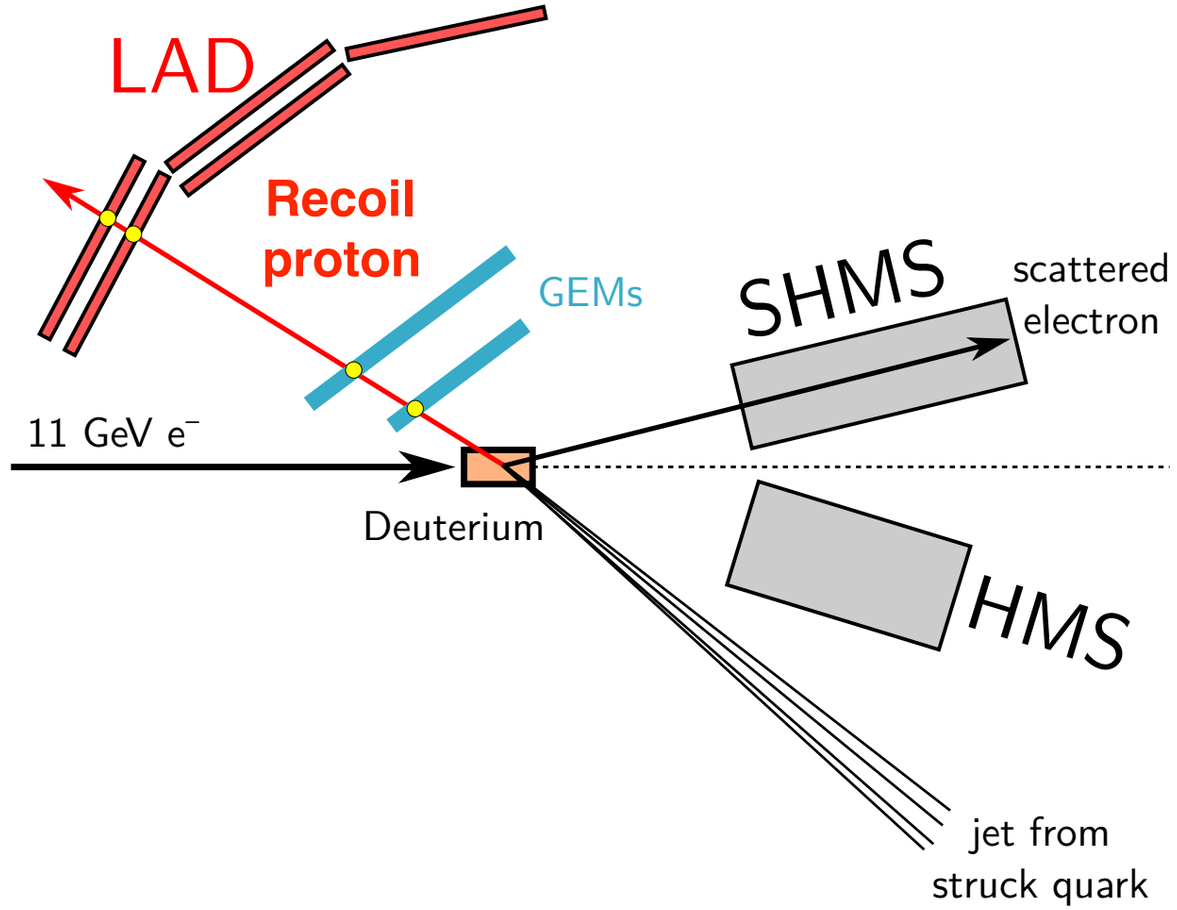
Tagged DIS at Jefferson Lab

Hall B:
CLAS 12 + Backward Angle Neutron Detector (BAND)



- Took data in 2019/20
- Analysis in progress

Hall C:
SHMS/HMS + Large Angle Detector (LAD)

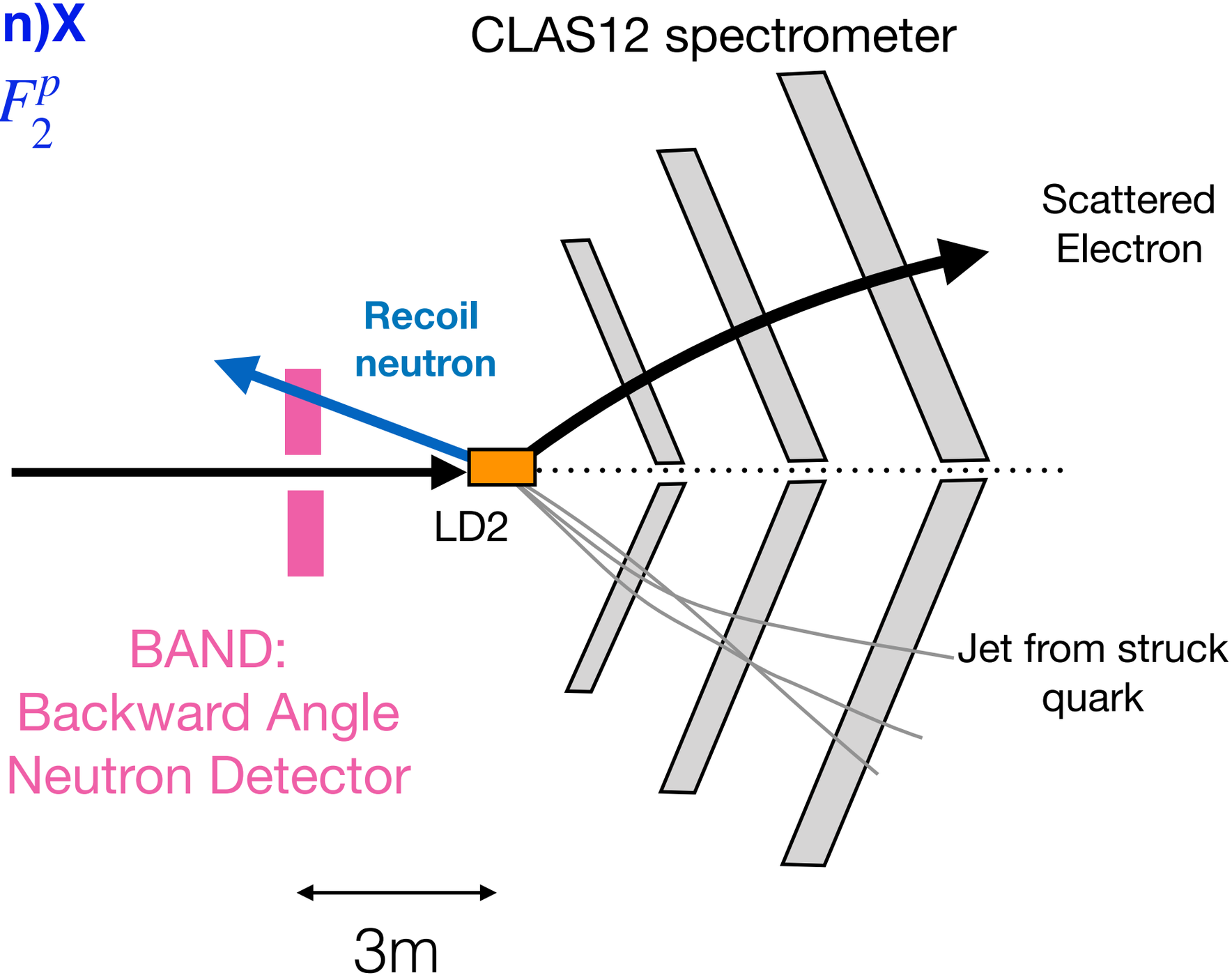


- Experiment ready
- Run in 2022?

Tagged DIS in HallB

D(e,e'n)X

F_2^{p*}/F_2^p



Overview of BAND

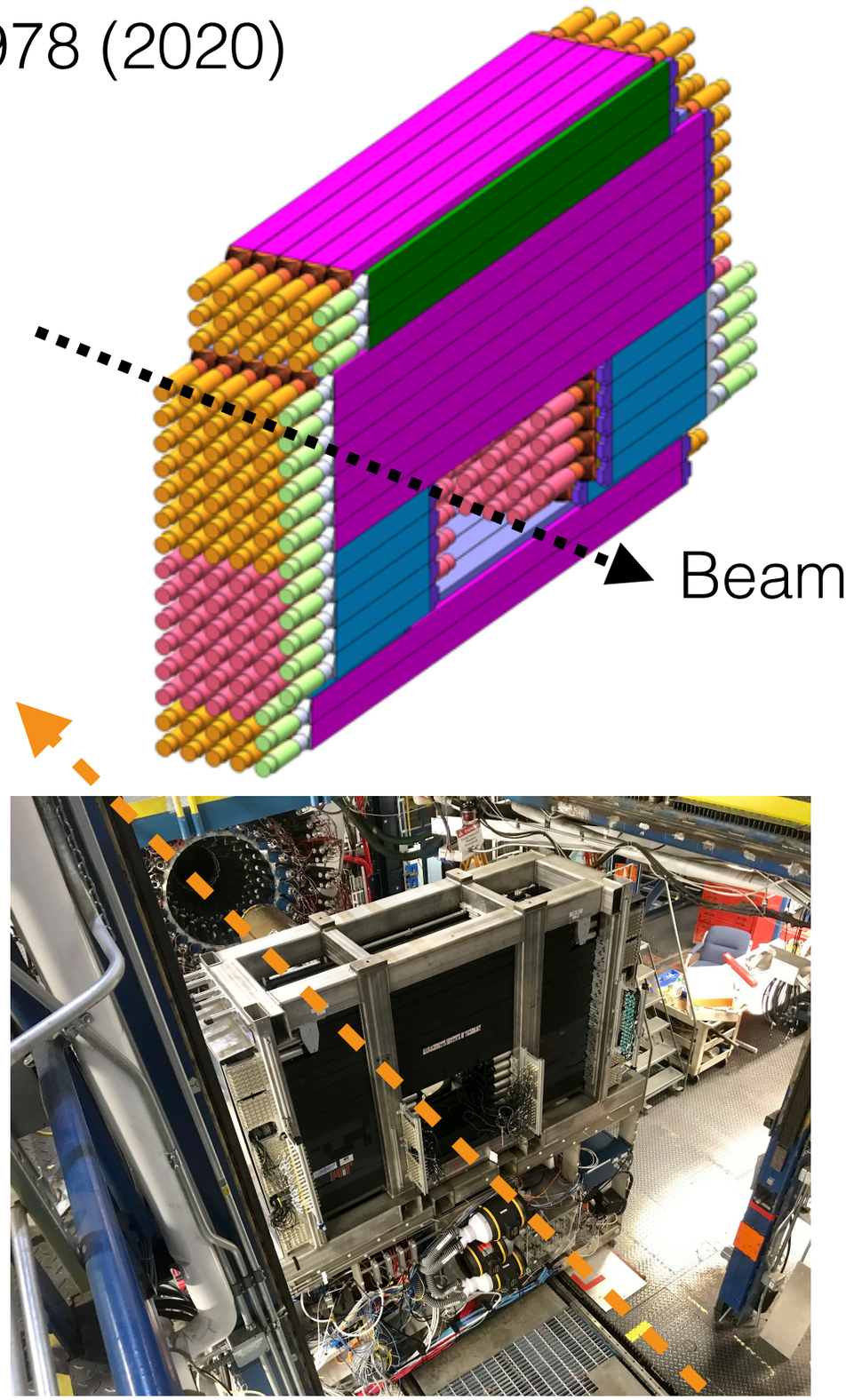
Segarra, Hauenstein et al., NIM A978 (2020)

- 140 scintillator bars
  - 5 layers (36cm total thickness)
  - veto layer (1cm thick)
  - time resolution < 250 ps

- 3 meters upstream of target, coverage in θ ~ 155-176°

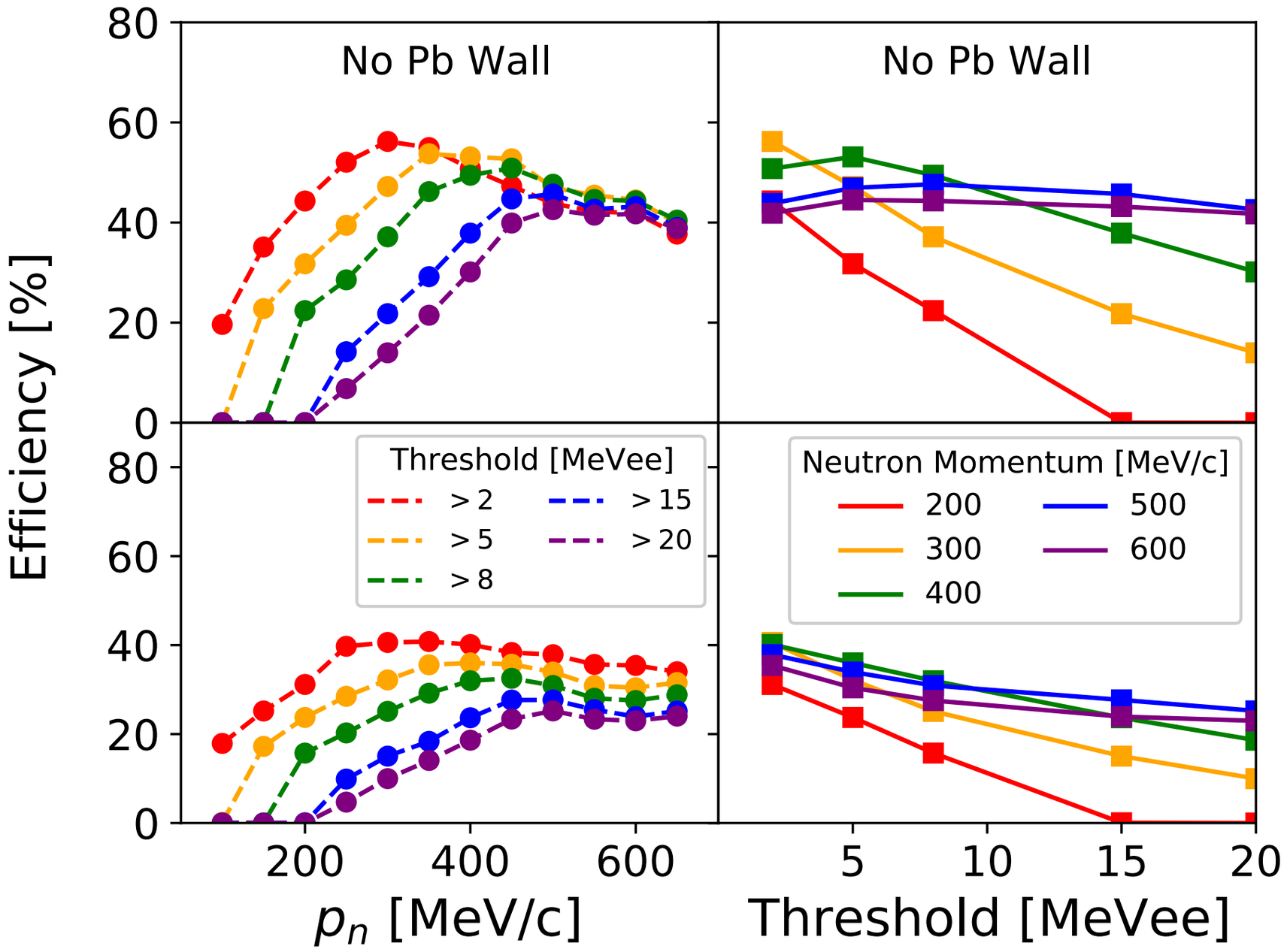
- Lead wall (downstream)

- Laser system for calibrations
  [Denniston et al., NIM A973 (2020)]



BAND Neutron Efficiency

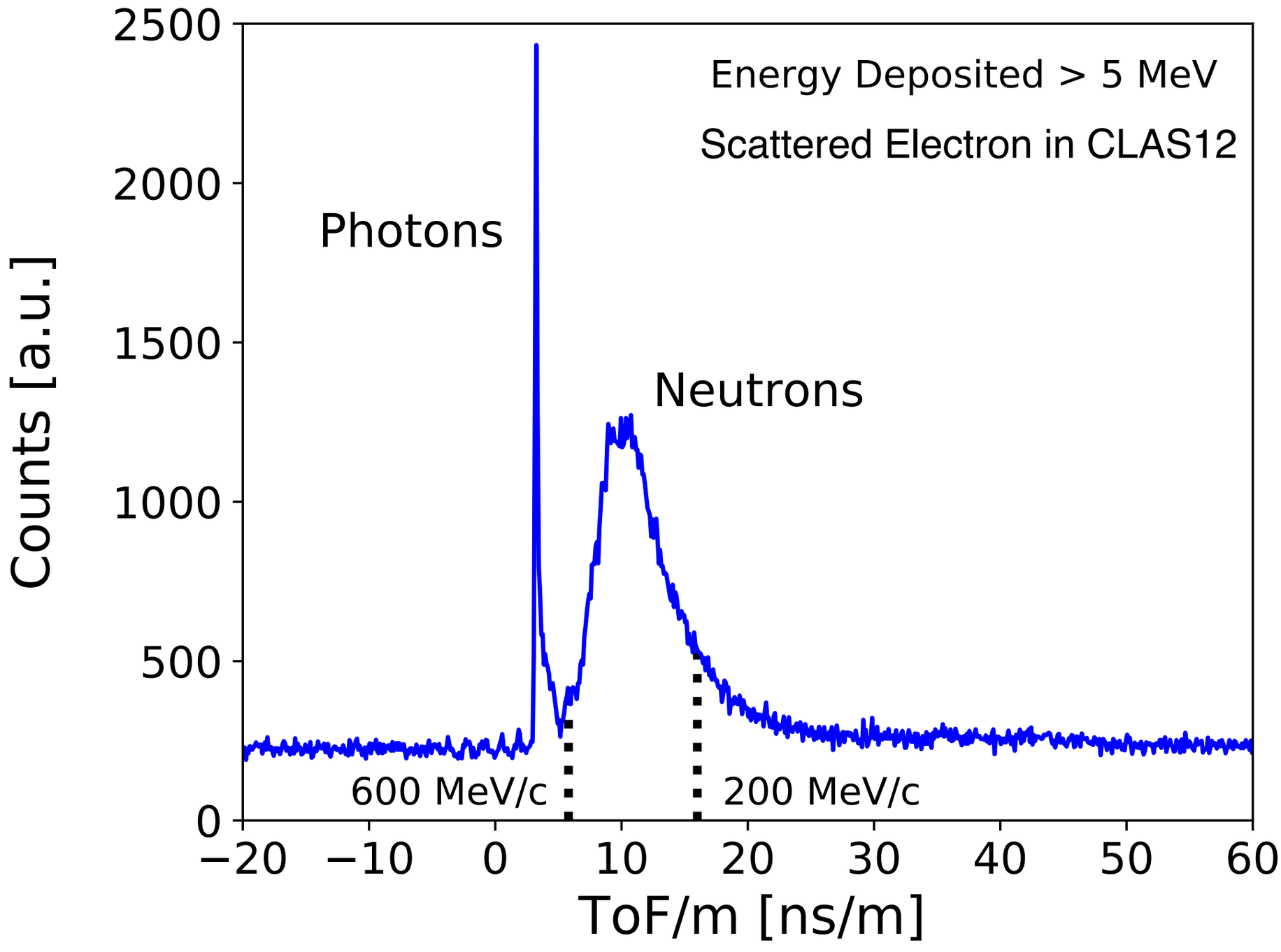
E. Segarra et al, NIM A978, 164356 (2020)



no Pb wall

with Pb wall

Neutron Identification - Time of Flight

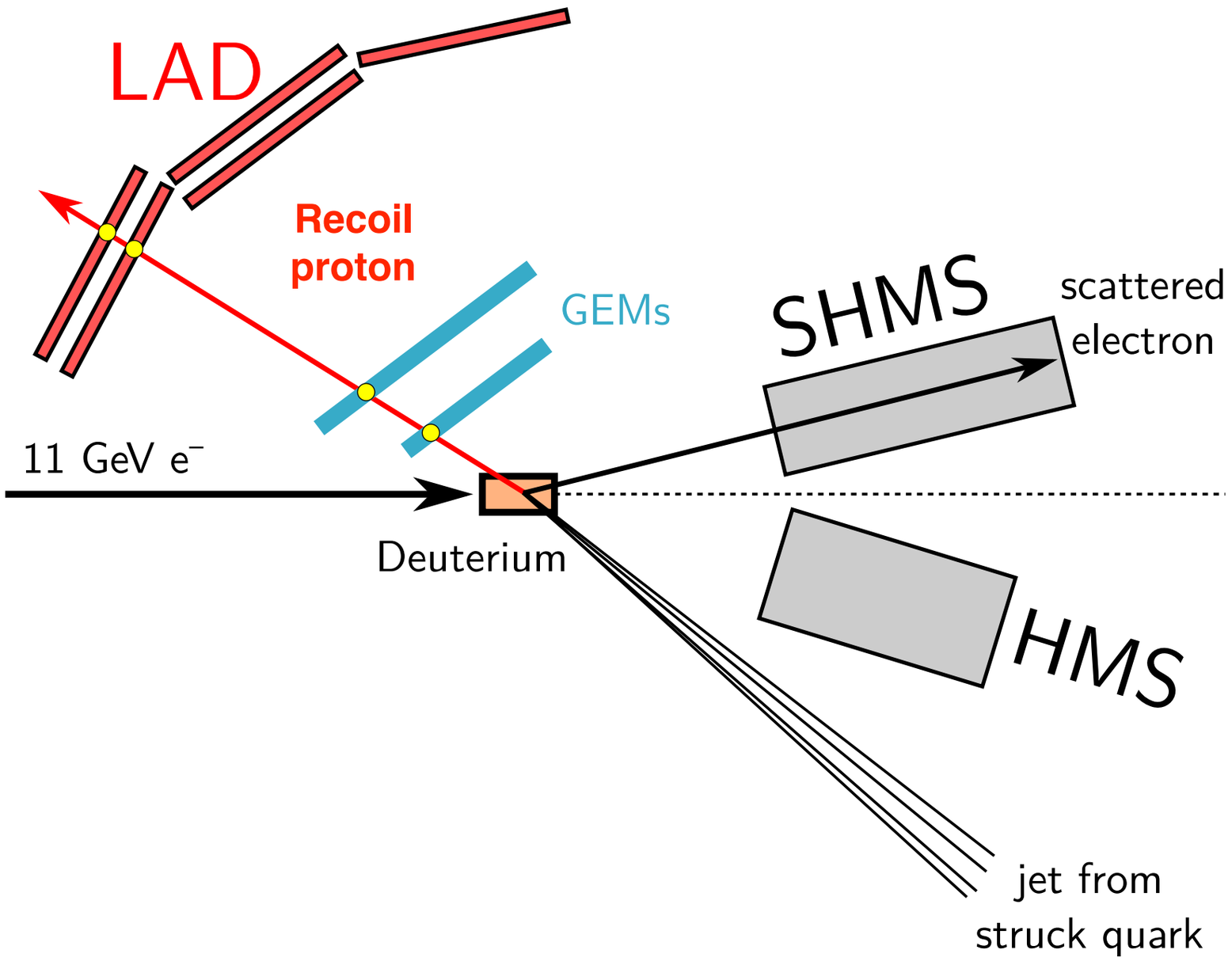


E. Segarra et al, NIM A978, 164356 (2020)

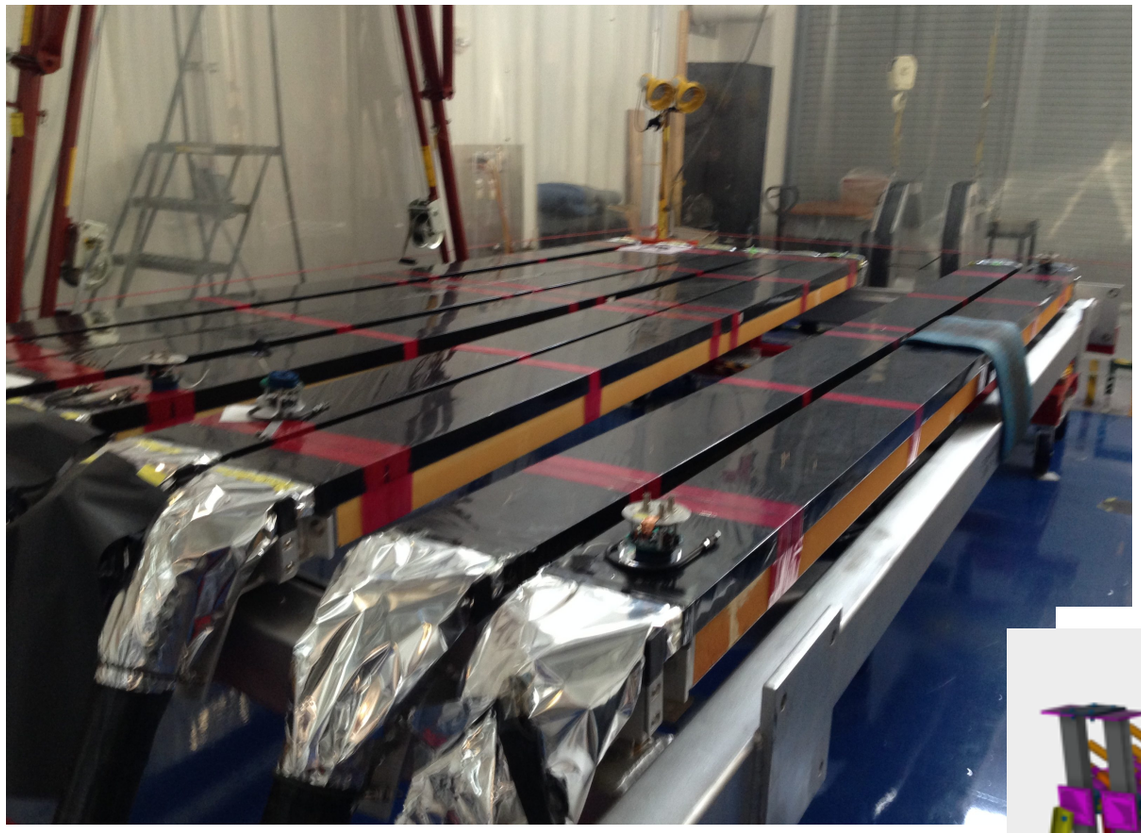
Tagged DIS in Hall C

D(e,e'p)X

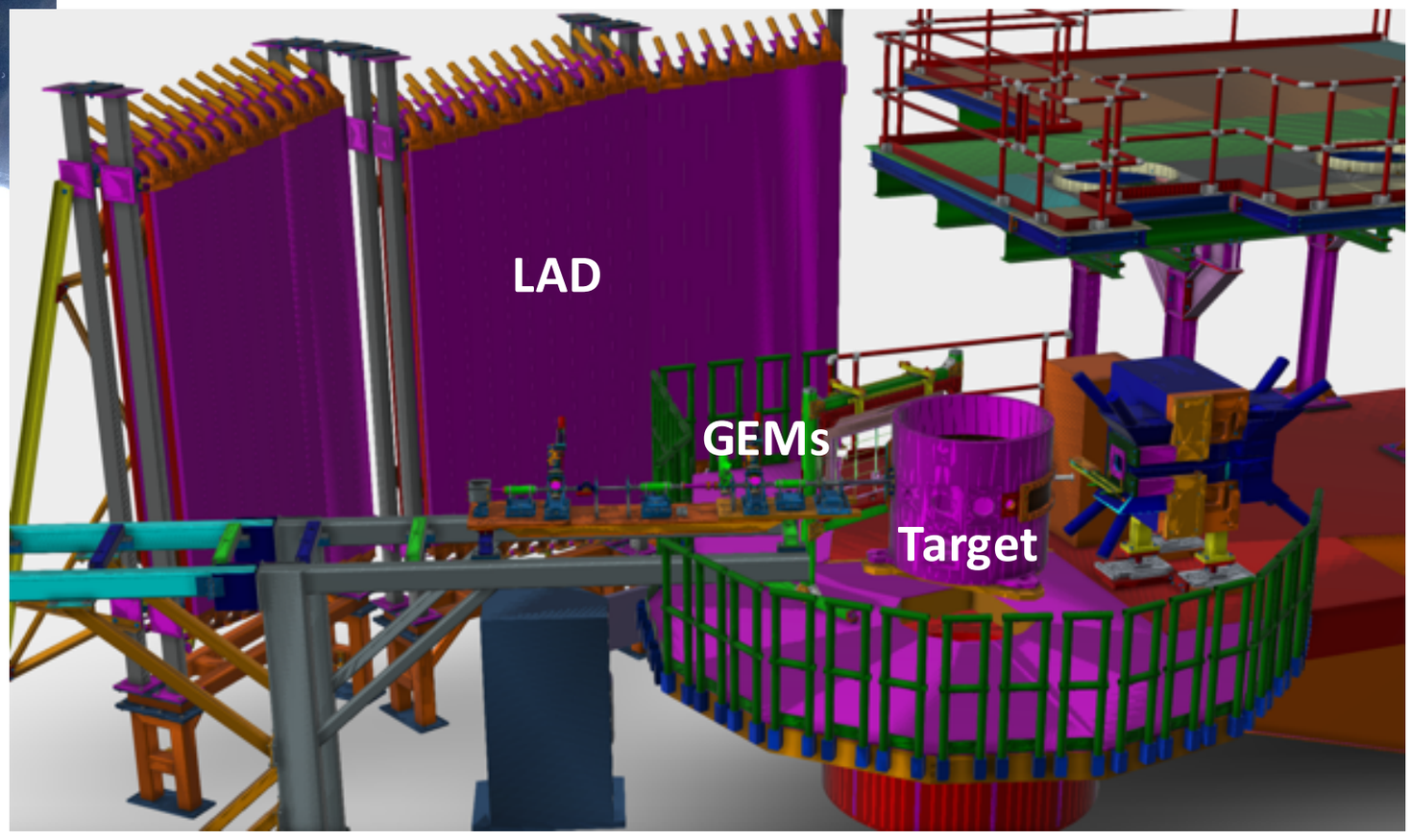
F_2^{n*}/F_2^n



LAD - Refurbished CLAS6 Scintillators



- 4m long, 5 panels, 55 bars
- 5-6m away from the target
- coverage 90 - 157 degree
- ~200ps time resolution



Tagged SRC at EIC (JLab LDRD19)

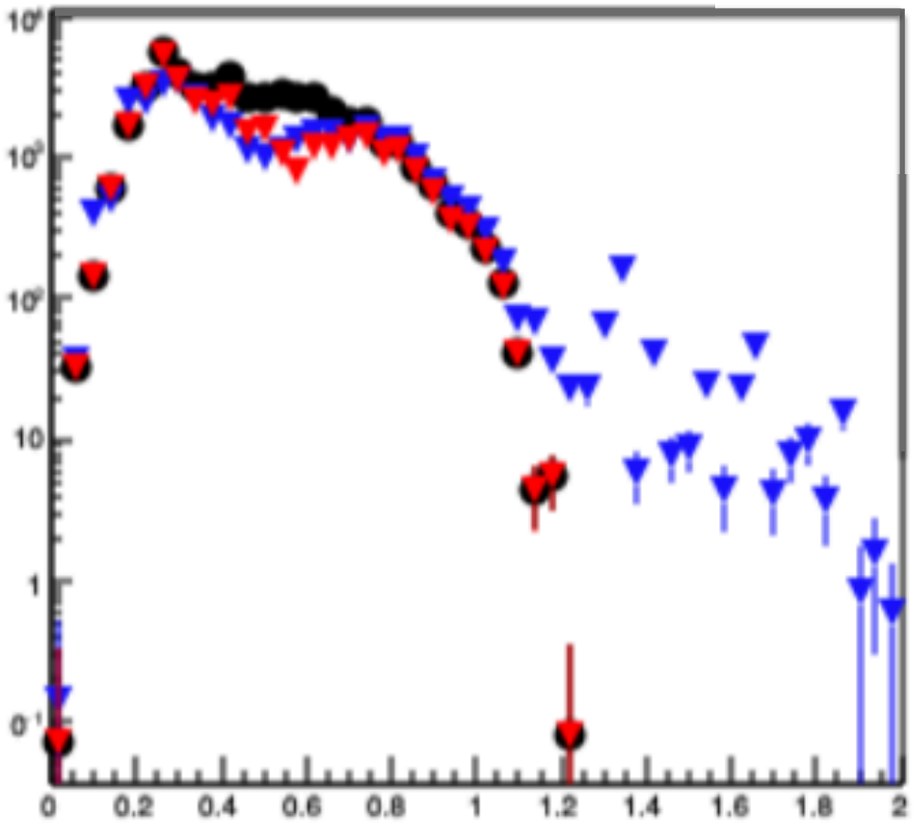
- Feasibility of tagged SRC in DIS
  - Rates
  - Detector requirements (focus on forward direction)
  - Optimal beam energies

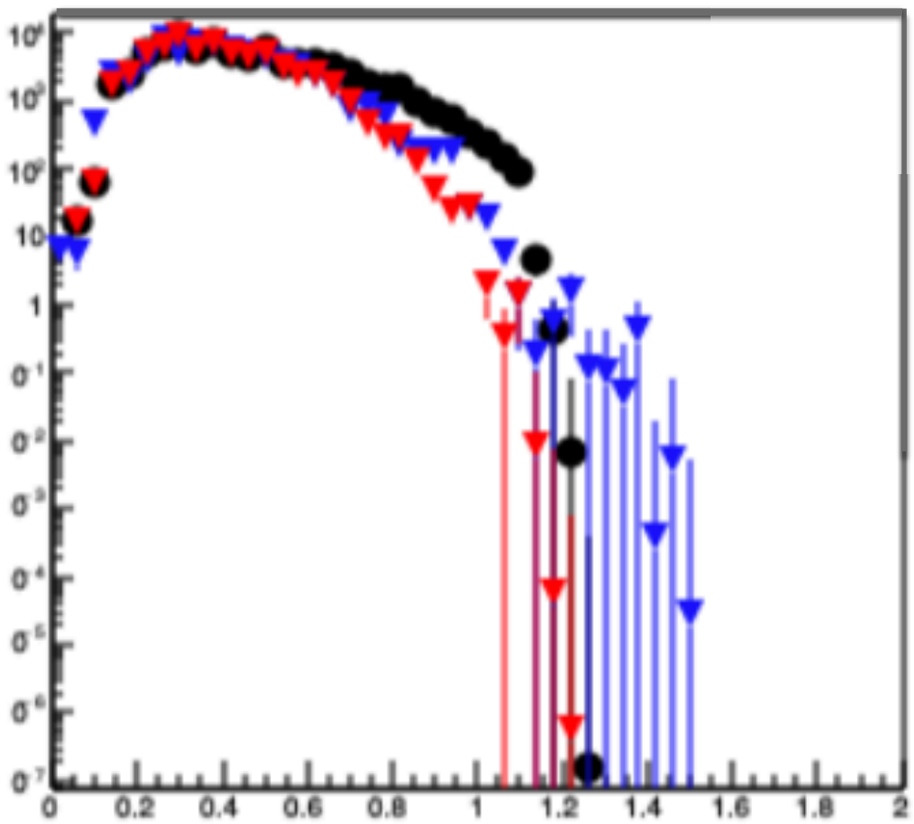
- Tools
  - BeAGLE - eA event generator
  - GCF - SRC event generator
  - g4e - Geant4 simulation for EIC

- First step achieved - Tagged Quasi-elastic SRC@EIC

(also incoherent diffractive J/ψ production on deuterium
[Tu et al., arXiv:2005:14706])

e+C: 10GeVx110GeV/A - recoil Nucleons





MC truth

Accepted

Accepted + Smeared

plots by A. Jentsch

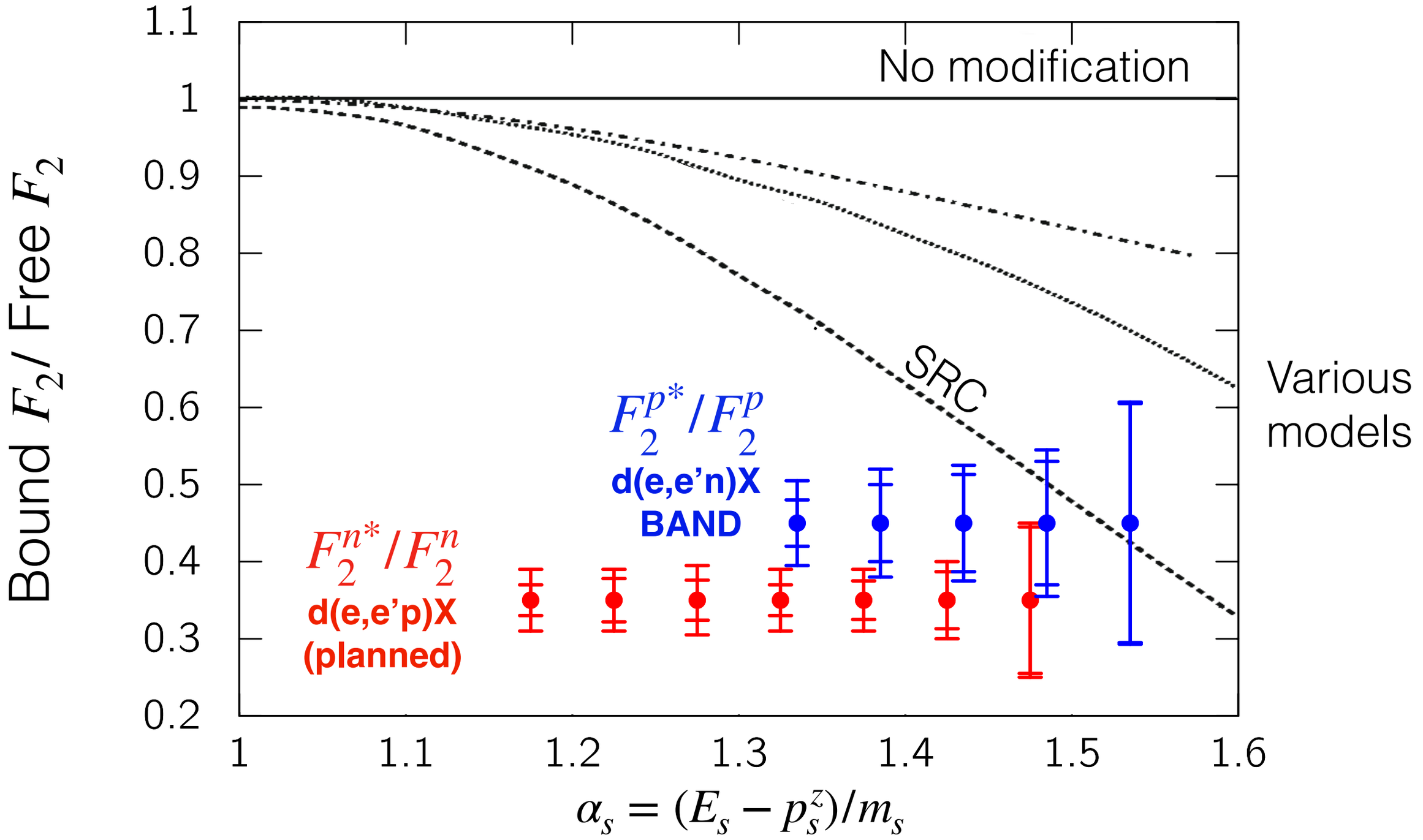
- Accepted in QE kinematics
  - 74% protons
  - 84% neutrons
- Similar values expected for DIS

Summary

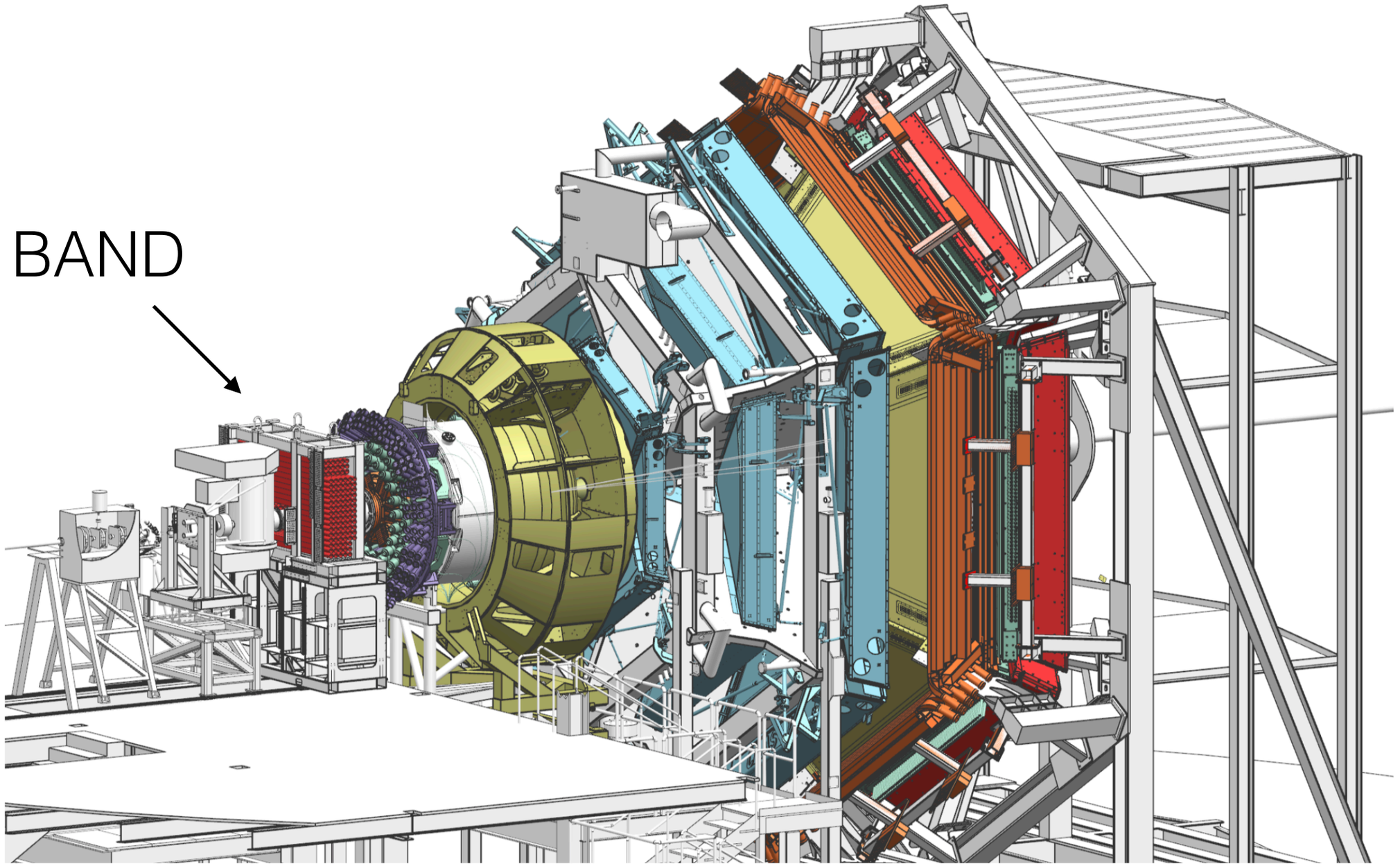
- Measurement of recoil nucleons (``backward'') crucial
- (e'Np) and (e'pN) experiments
  - direct observation of np-dominance
  - mapping out NN interaction
  - 3N-SRCs@RGM
- Tagged DIS measurements on deuterium
  - F_2^p with CLAS12+BAND
  - F_2^n in Hall C with LAD
- Recoil tagging of SRCs at EIC

Back up slides

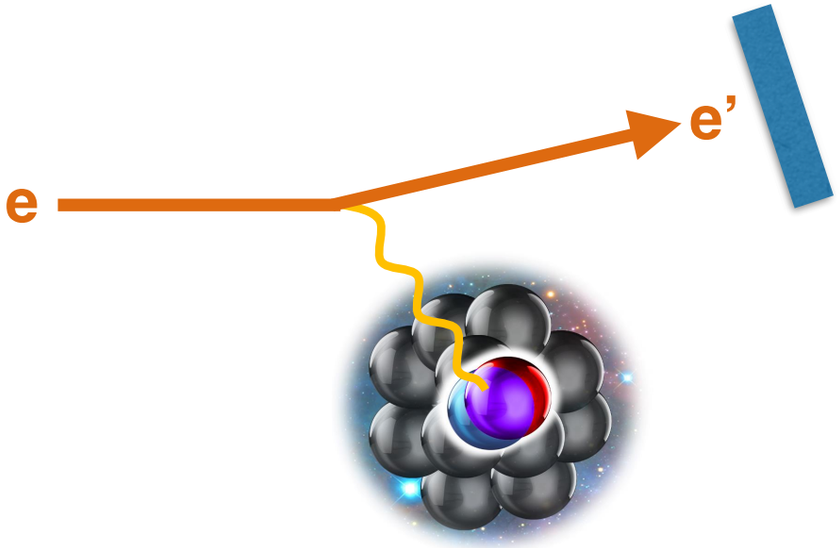
DIS Recoil Tagging d(e,e'N)X - Expected Results



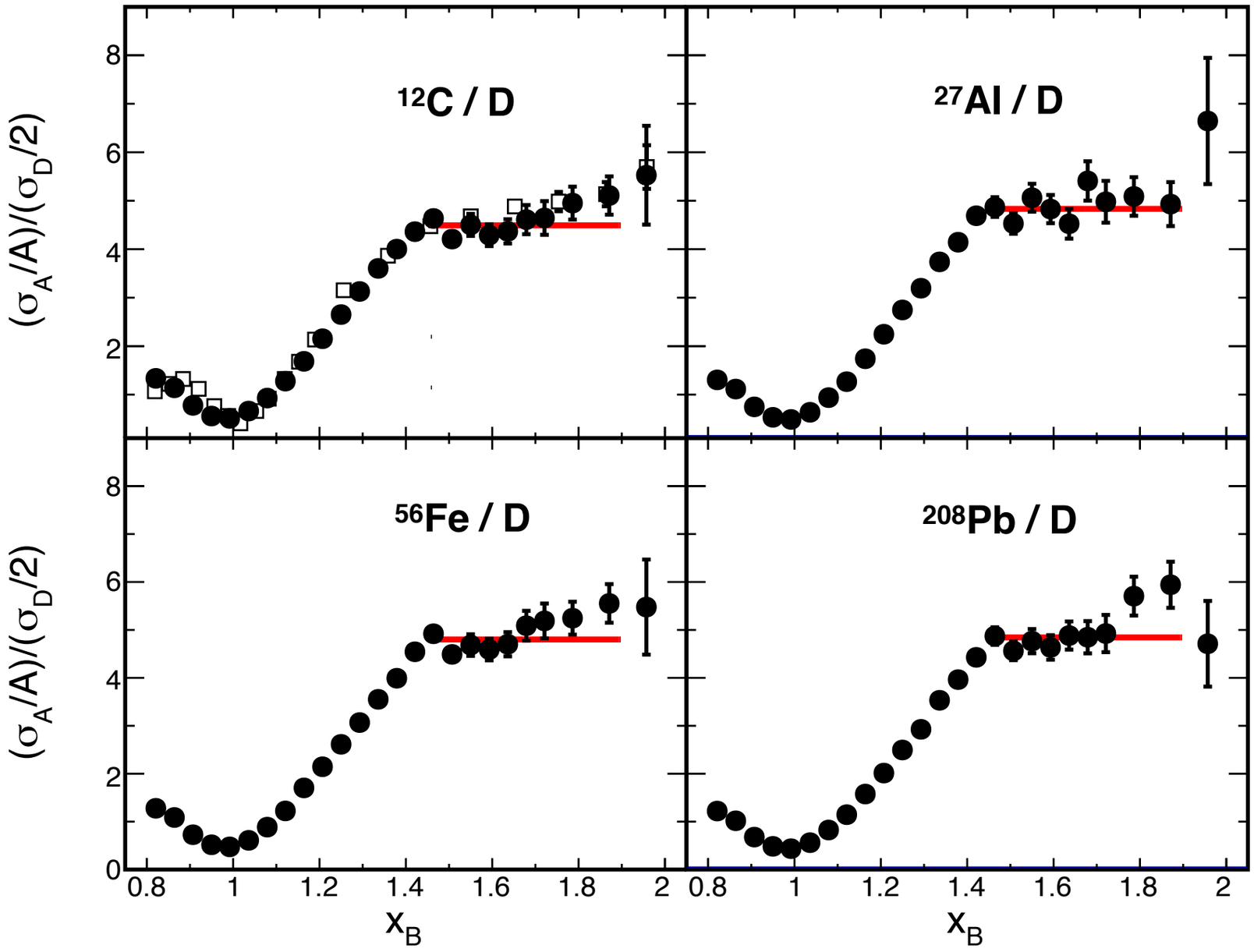
CLAS12 and BAND



SRCs in Inclusive QE Scattering



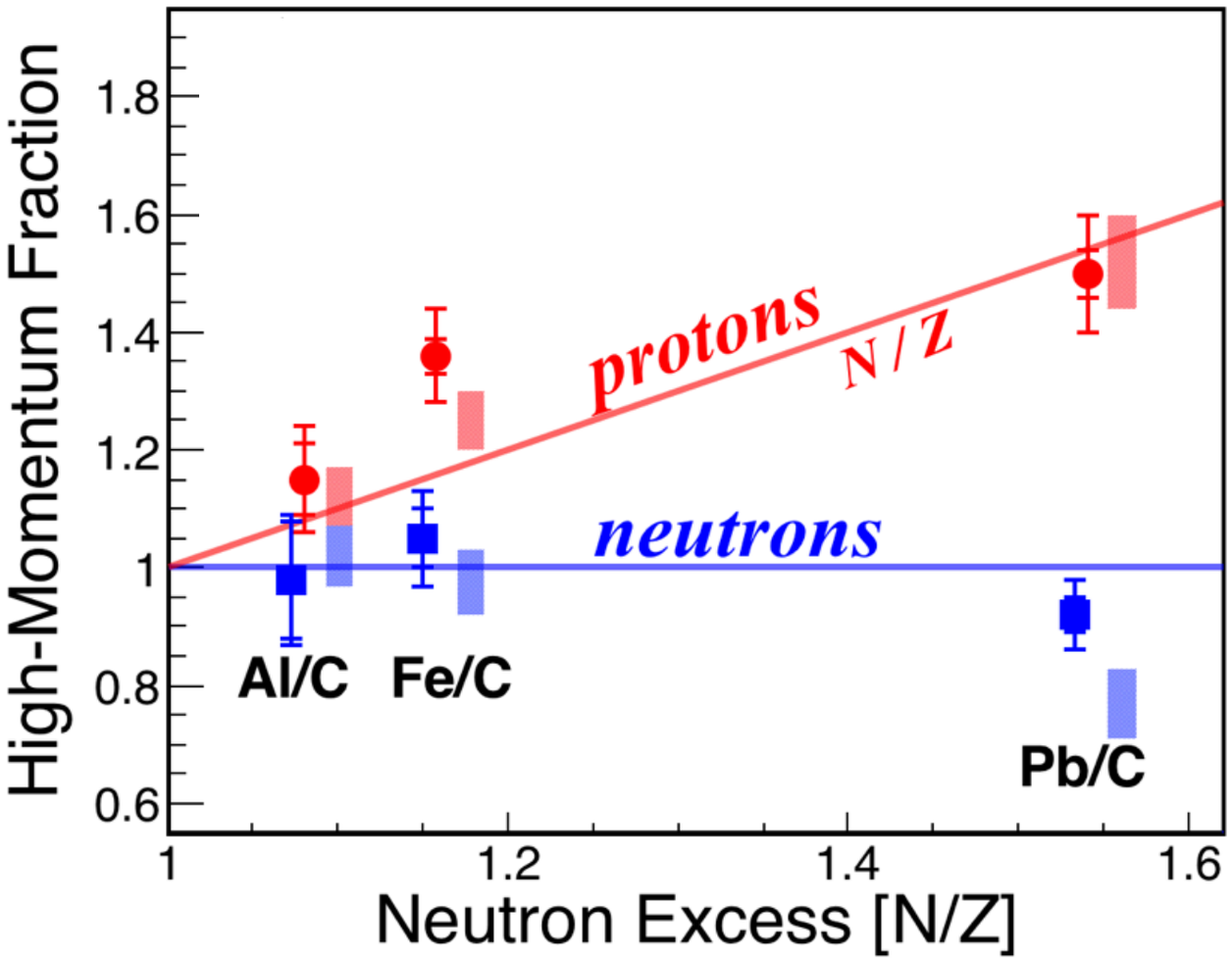
B. Schmookler et al. (CLAS collaboration), Nature 566, 354 (2019)

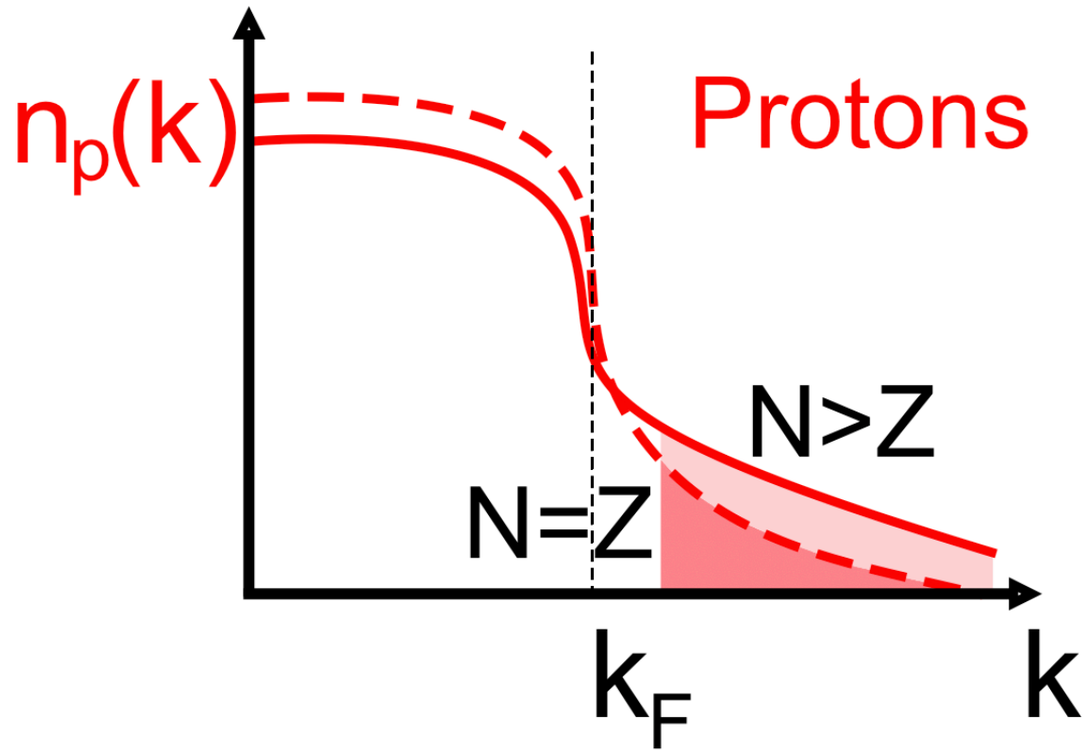


- Plateaus due to SRCs
- SRC probability about 20%

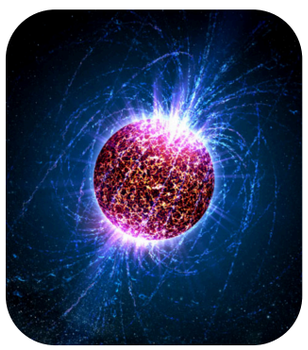
Protons `speed up' in Neutron-Rich Nuclei

Duer et al. (CLAS collaboration), Nature 560, 617 (2018)



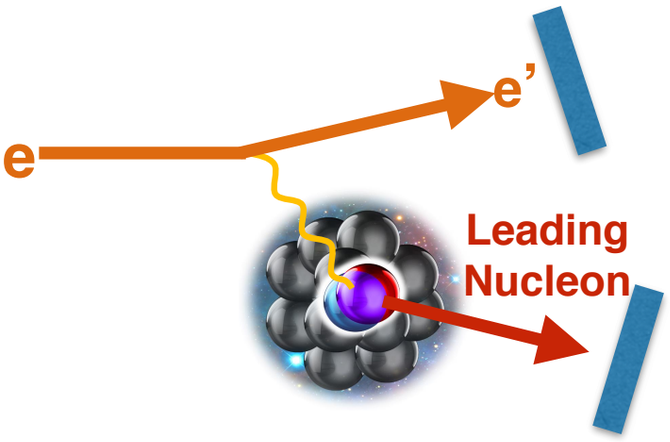


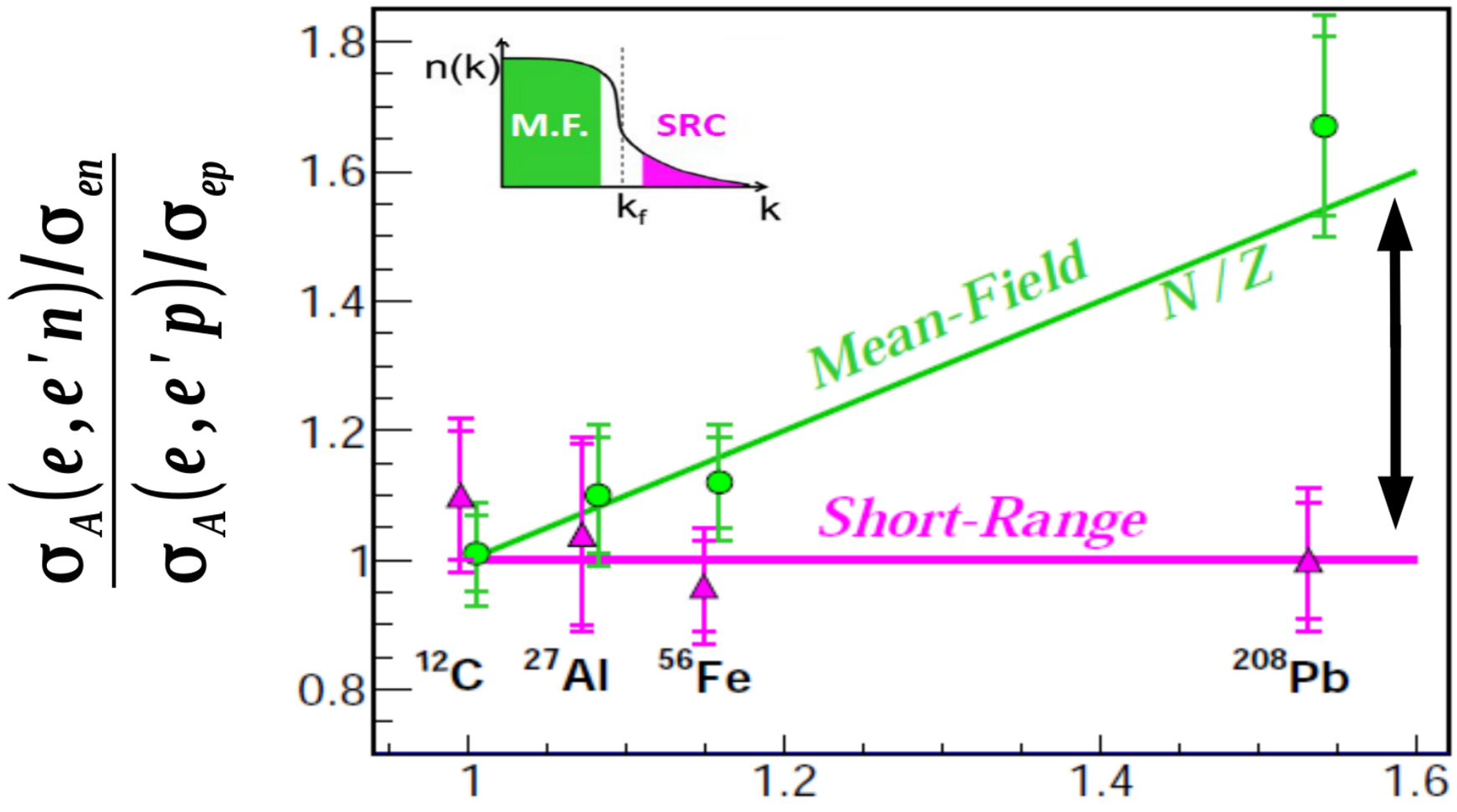
- Minority nucleons faster than majority
- Important for neutron stars



np-dominance in Single Nucleon Knockout

Duer et al. (CLAS collaboration), Nature 560, 617 (2018)





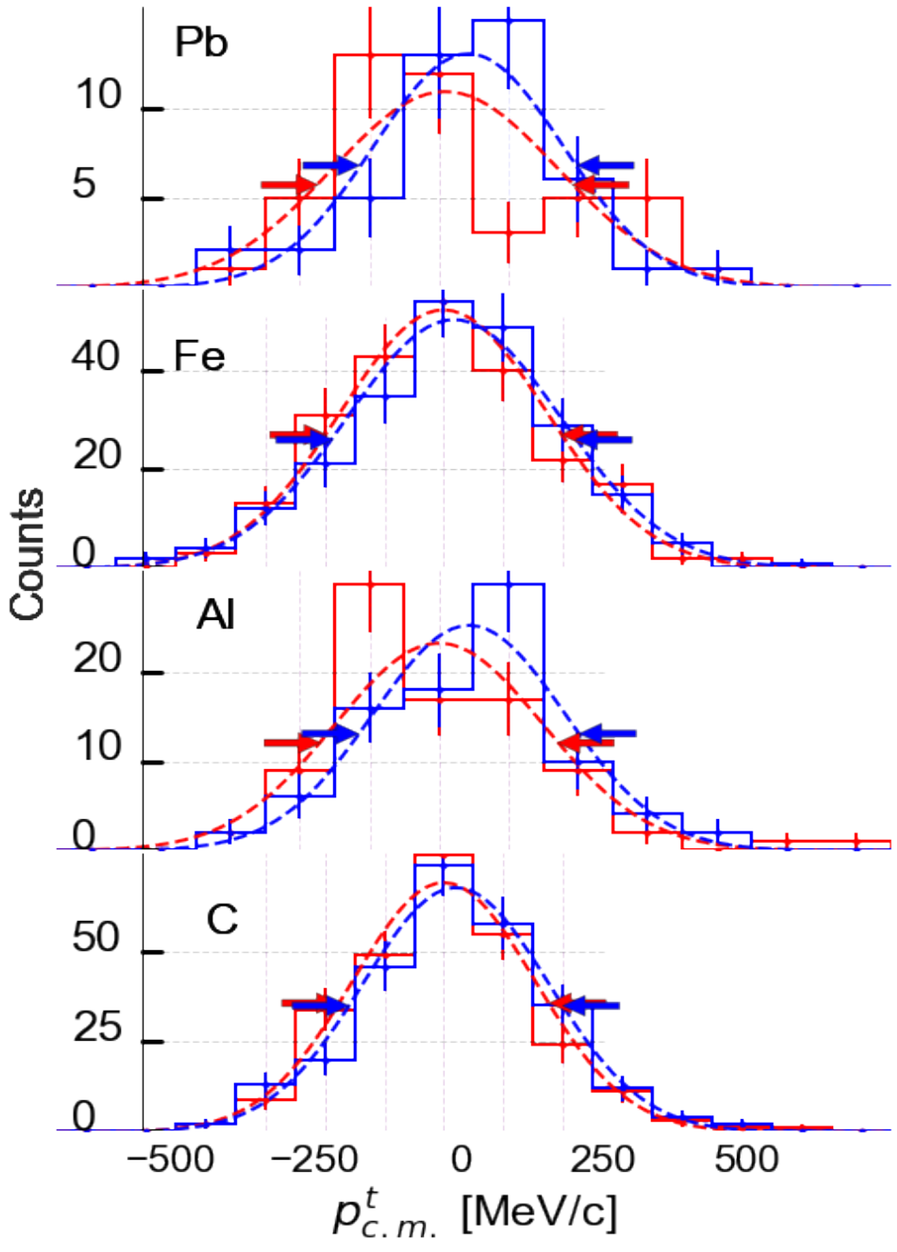
$$\frac{\sigma_A(e,e'n)/\sigma_{en}}{\sigma_A(e,e'p)/\sigma_{ep}} \approx \frac{N\sigma_{en}/\sigma_{en}}{Z\sigma_{en}/\sigma_{en}}$$

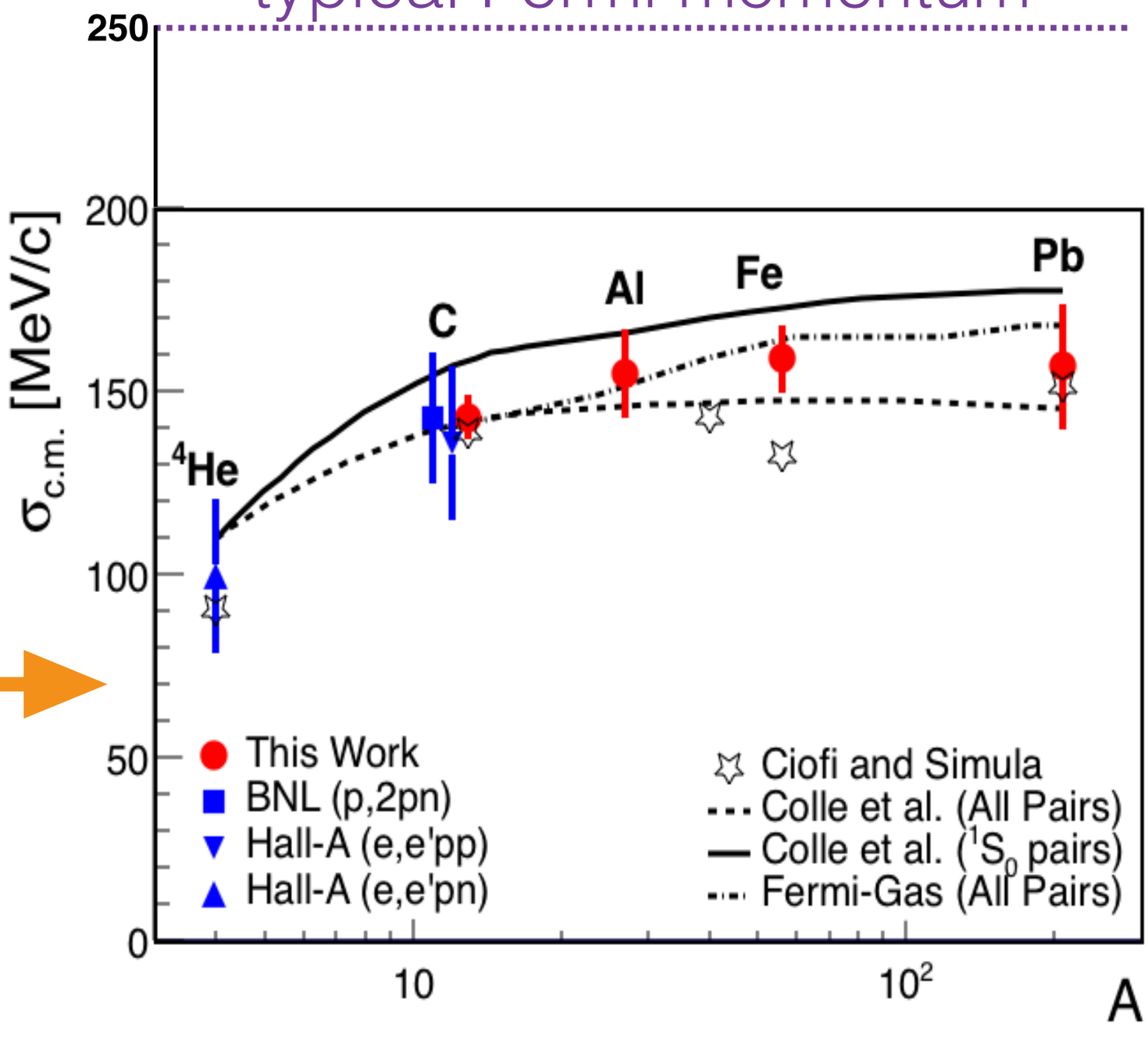
$$\frac{\sigma_A(e,e'n)/\sigma_{en}}{\sigma_A(e,e'p)/\sigma_{ep}} \approx \frac{N\sigma_{en}/\sigma_{en}}{N\sigma_{en}/\sigma_{en}}$$

SRC pair c.m. momentum

E. Cohen et al.(CLAS collaboration), PRL (2018)

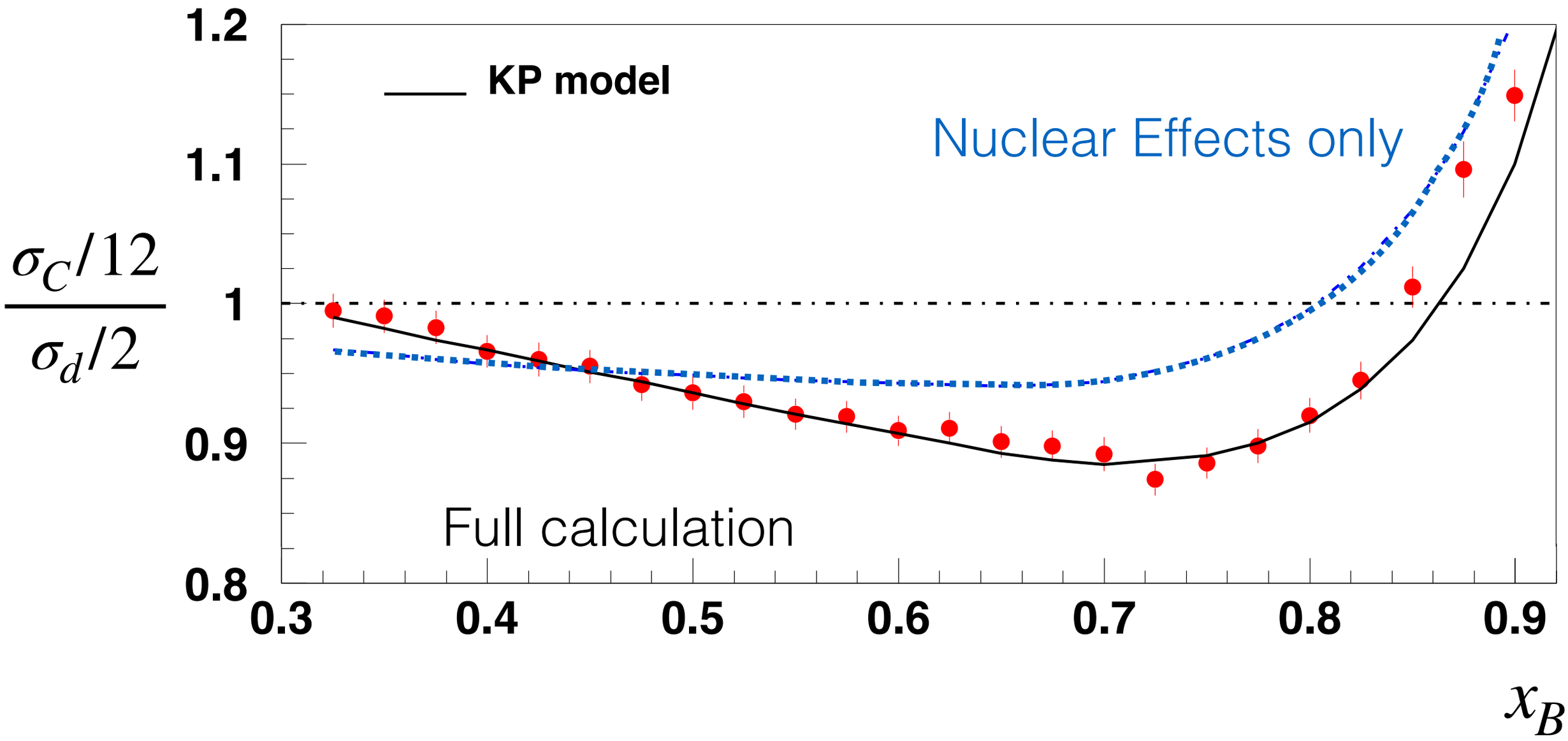
typical Fermi momentum





Nuclear Effects not sufficient

S. Kulagin and R. Petty, PRC 82, 054614 (2010)



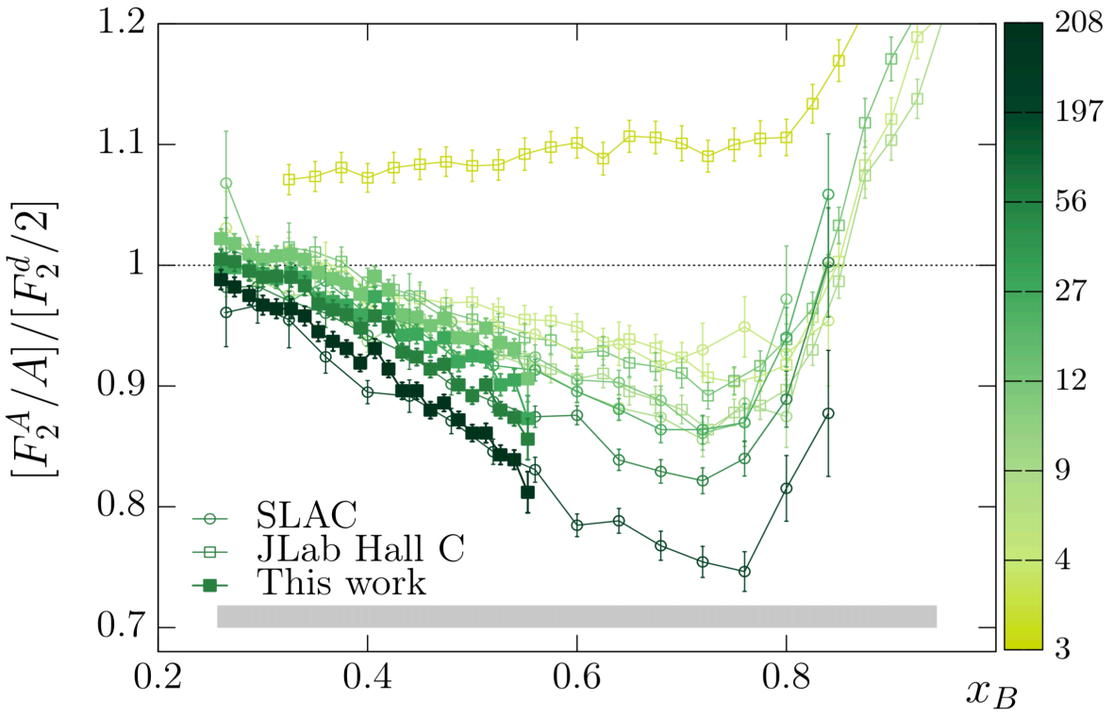
SRC-EMC Model and Universal function

B. Schmookler et al., Nature 566, 354 (2019)

- Data driven approach
- Modification of F_2 by np-SRC pairs (neglect nn and pp pairs)

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

Bound = ``Quasi-free“ + Modified SRC



SRC-EMC Model and Universal function (2)

B. Schmookler et al., Nature 566, 354 (2019)

- Data driven approach
- Modification of F_2 by np-SRC pairs (neglect nn and pp pairs)

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

Bound = ``Quasi-free“ + Modified SRC

F_2^n not well constrained but solve by

- $F_2^d = F_2^p + F_2^n + n_{SRC}^d(\Delta F_2^p + \Delta F_2^n)$
- $a_2 = \frac{2}{N} n_{SRC}^A / n_{SRC}^d$

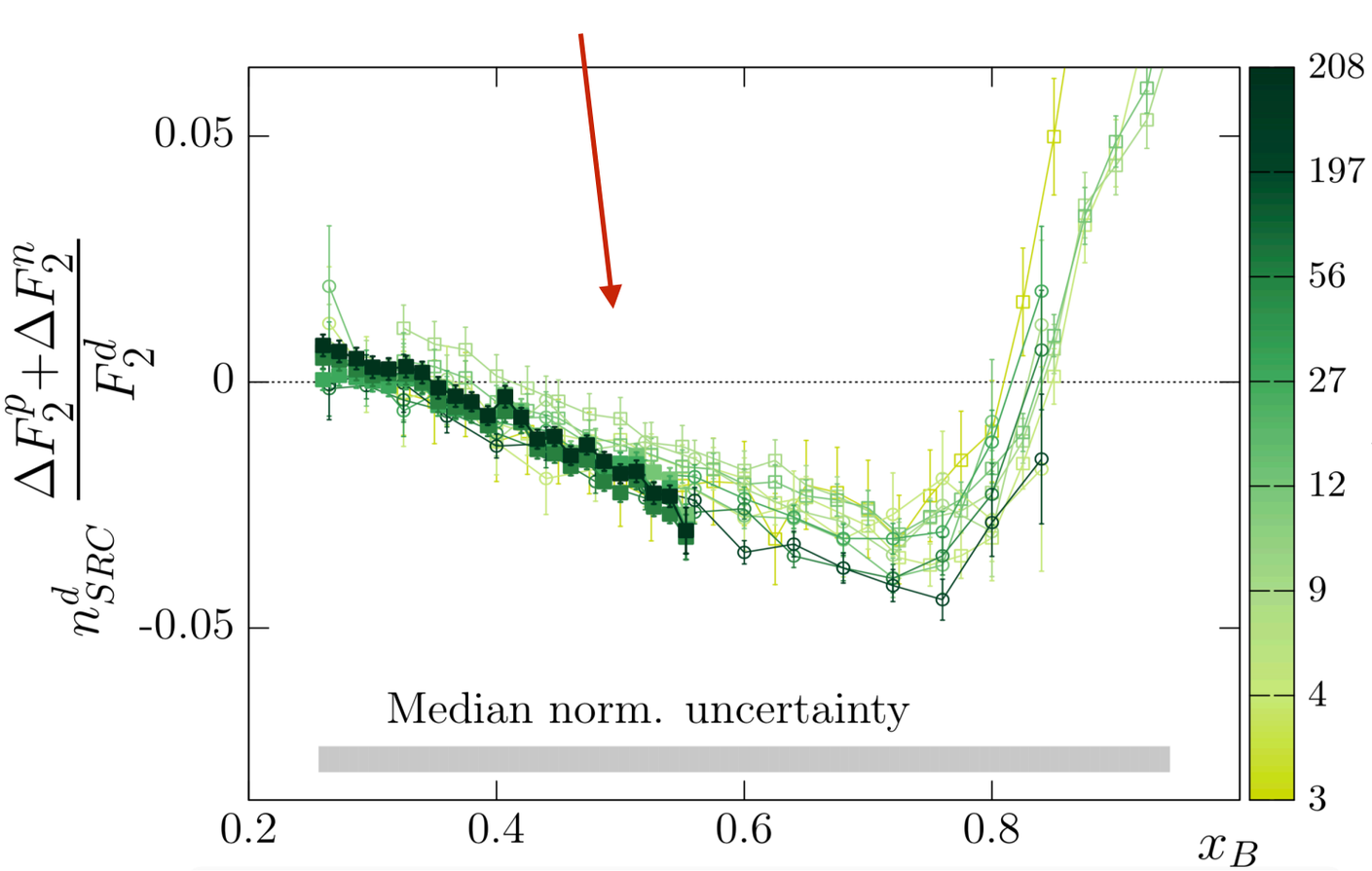
SRC-EMC Model and Universal function (3)

B. Schmookler et al., Nature 566, 354 (2019)

$$n_{SRC}^{d}\frac{\Delta F_2^p + \Delta F_2^n}{F_2^d} = \frac{\frac{F_2^A}{F_2^d} - (Z-N)\frac{F_2^p}{F_2^d} - N}{\frac{A}{2}a_2 - N}$$

Universal function

Nucleus Dependent



Tagged DIS: What will be measured

- Measuring cross section ratios to minimize uncertainties
- Choose kinematics with minimal FSI $\theta_{rq} > 107°$

$$\frac{\sigma_{DIS}(x'_{\text{high}}, Q_1^2, \alpha_s)}{\sigma_{DIS}(x'_{\text{low}}, Q_2^2, \alpha_s)} \cdot \frac{\sigma_{DIS}^{\text{free}}(x_{\text{low}}, Q_2^2)}{\sigma_{DIS}^{\text{free}}(x_{\text{high}}, Q_1^2)} \cdot R_{FSI} = \frac{F_2^{\text{bound}}(x'_{\text{high}}, Q_1^2, \alpha_s)}{F_2^{\text{free}}(x_{\text{high}}, Q_1^2)}$$

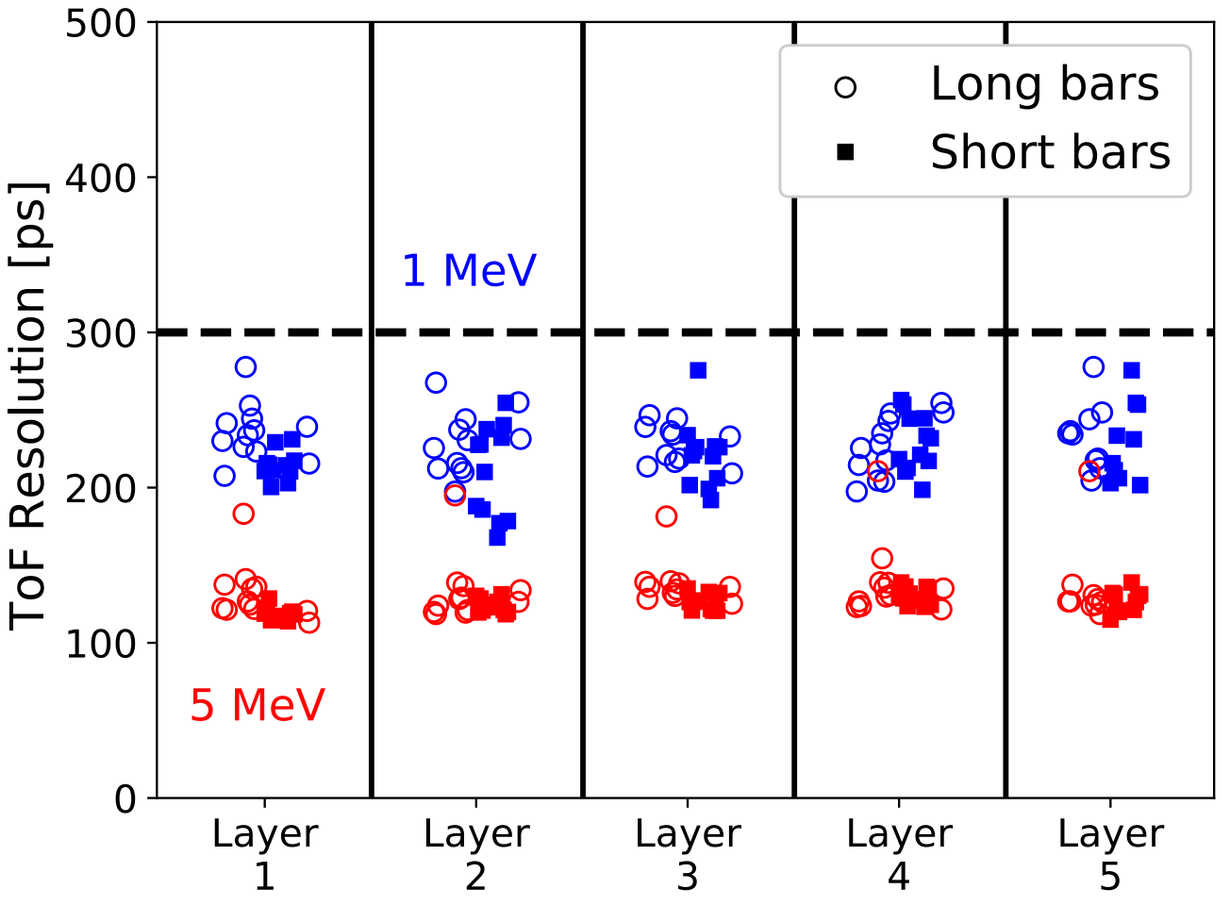
measurement theory

- $x' = x$ for moving nucleon $= Q^2/(2p \cdot q)$
- $x'_{\text{high}} > 0.45$
- no EMC effect at $0.25 \leq x'_{\text{low}} \leq 0.35$

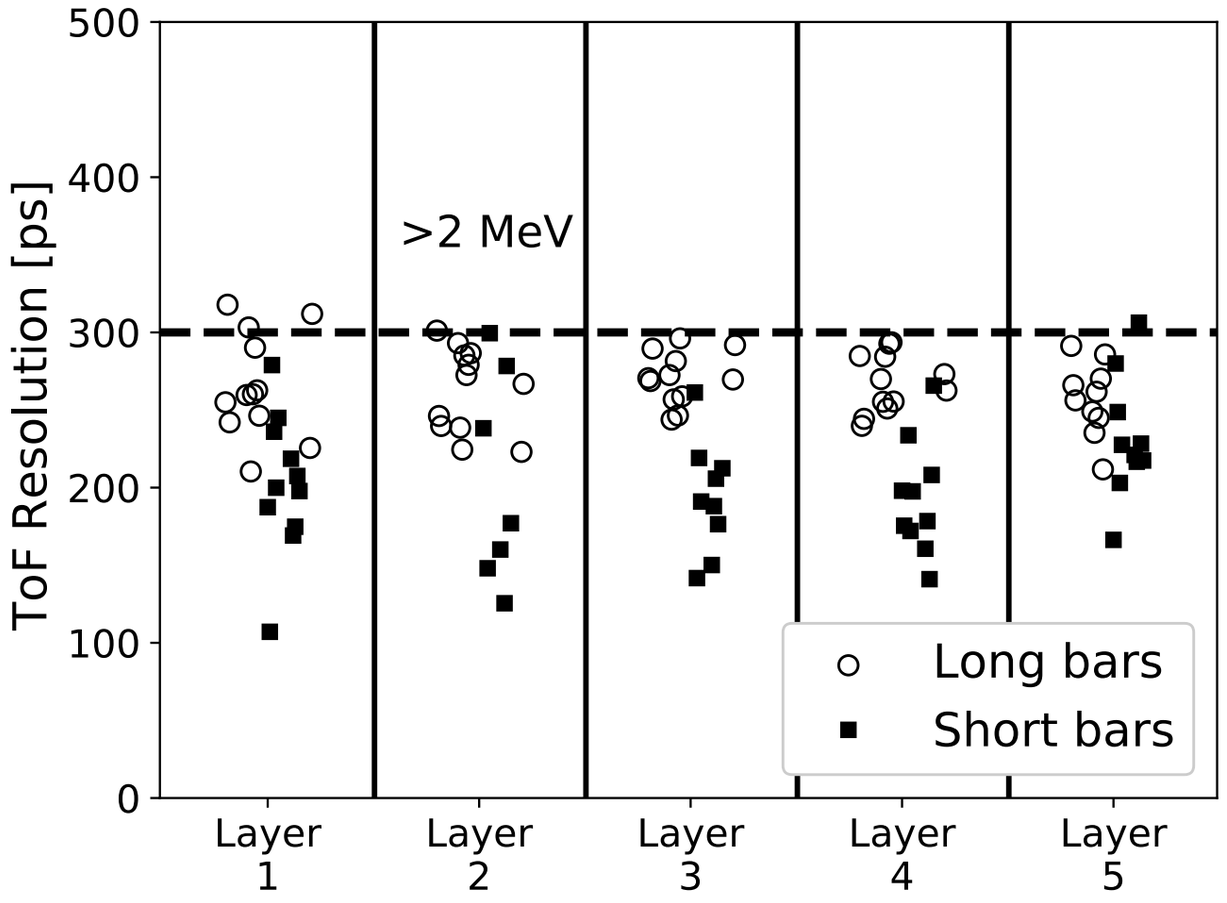
Resolutions of BAND Bars

E. Segarra, et al, NIM A978, 164356 (2020)

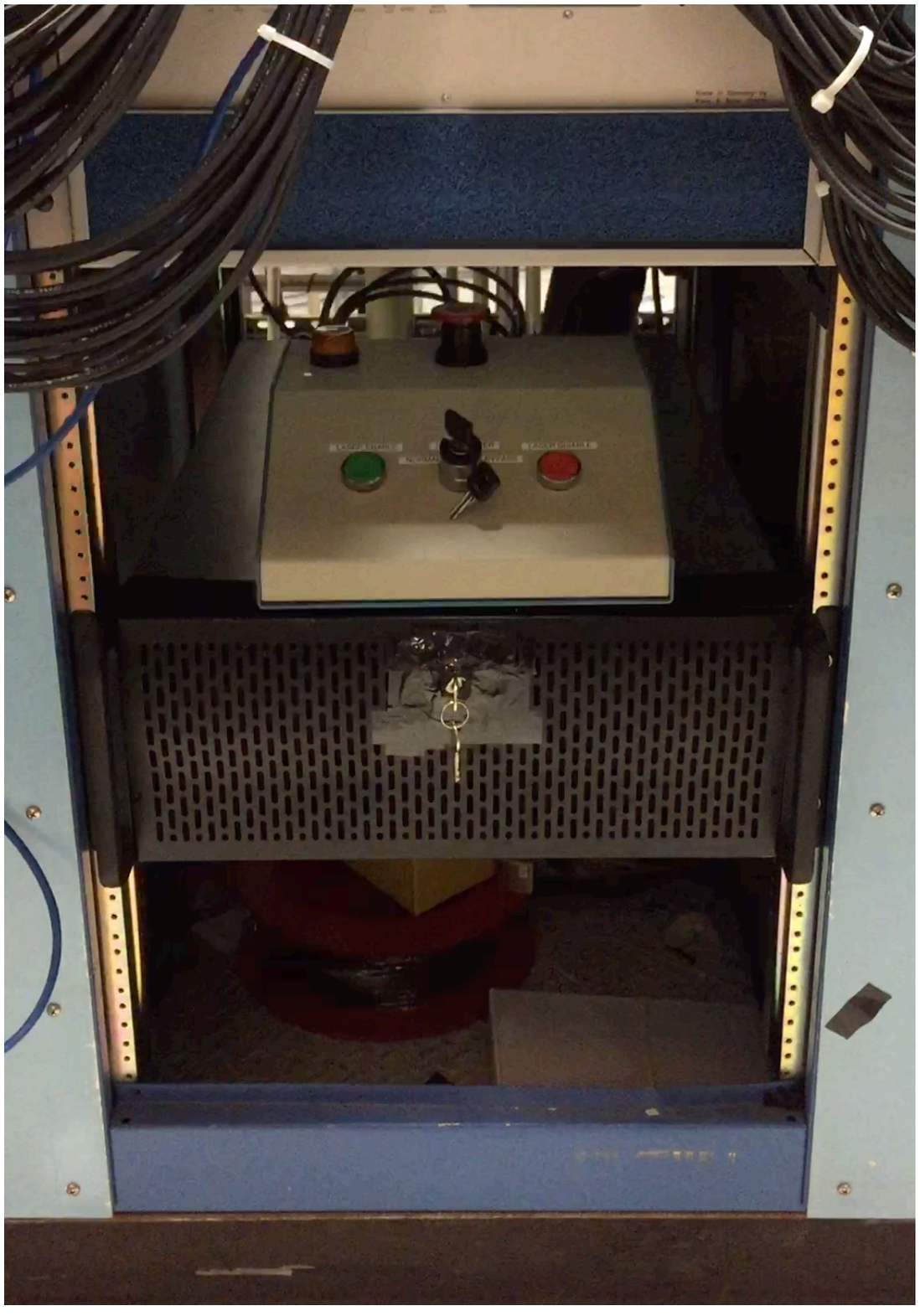
Laser

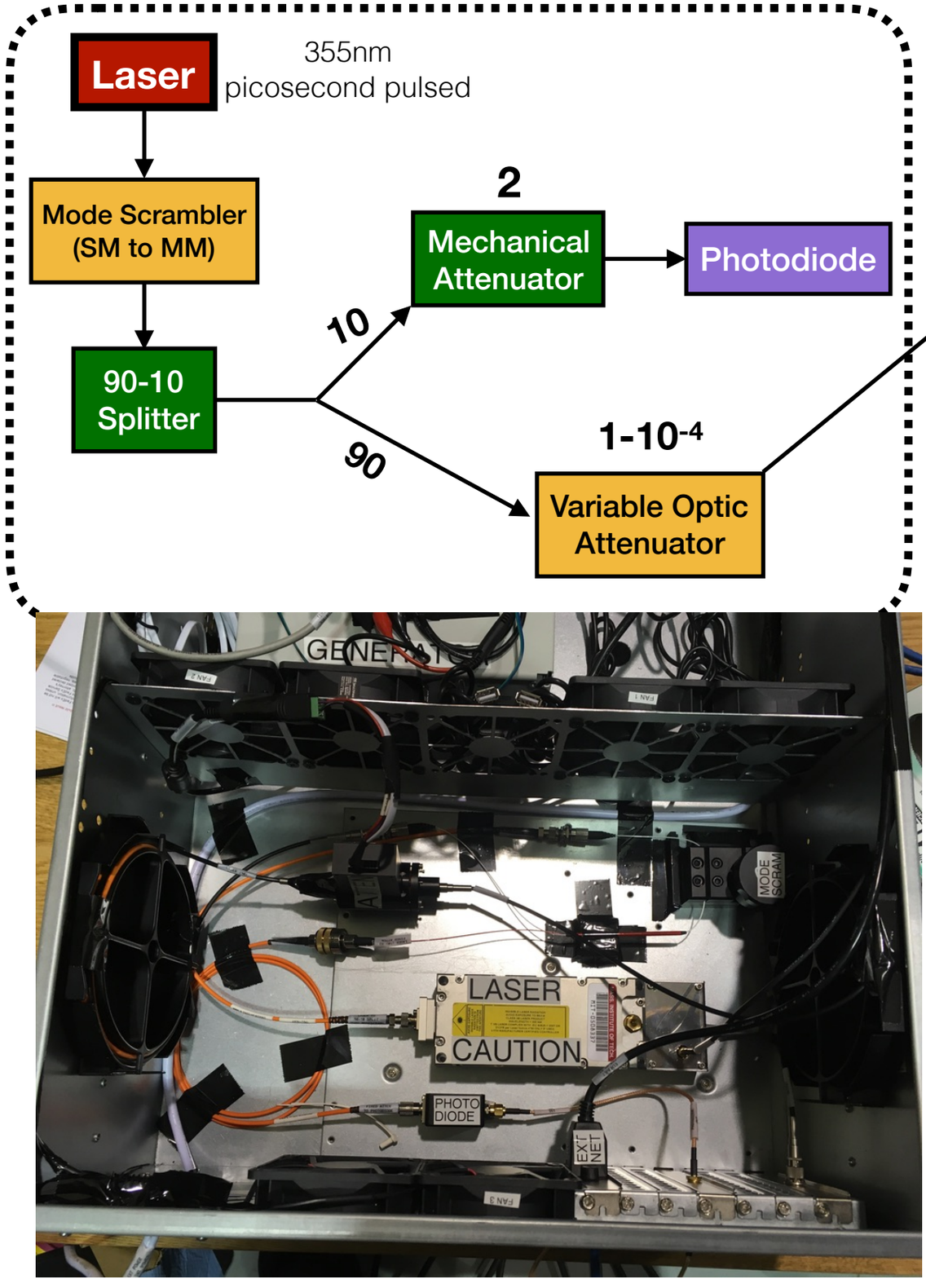


Photons



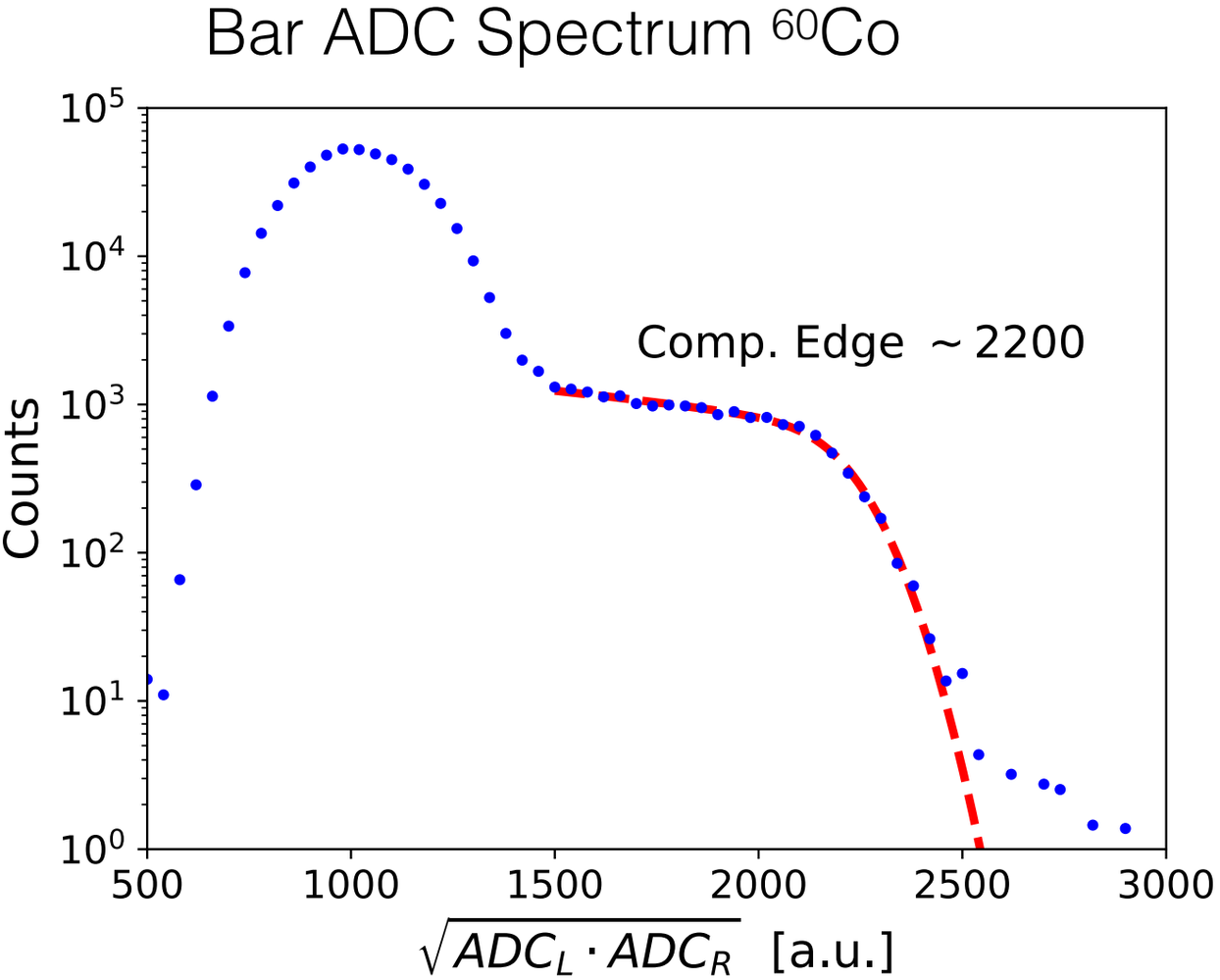
Laser System

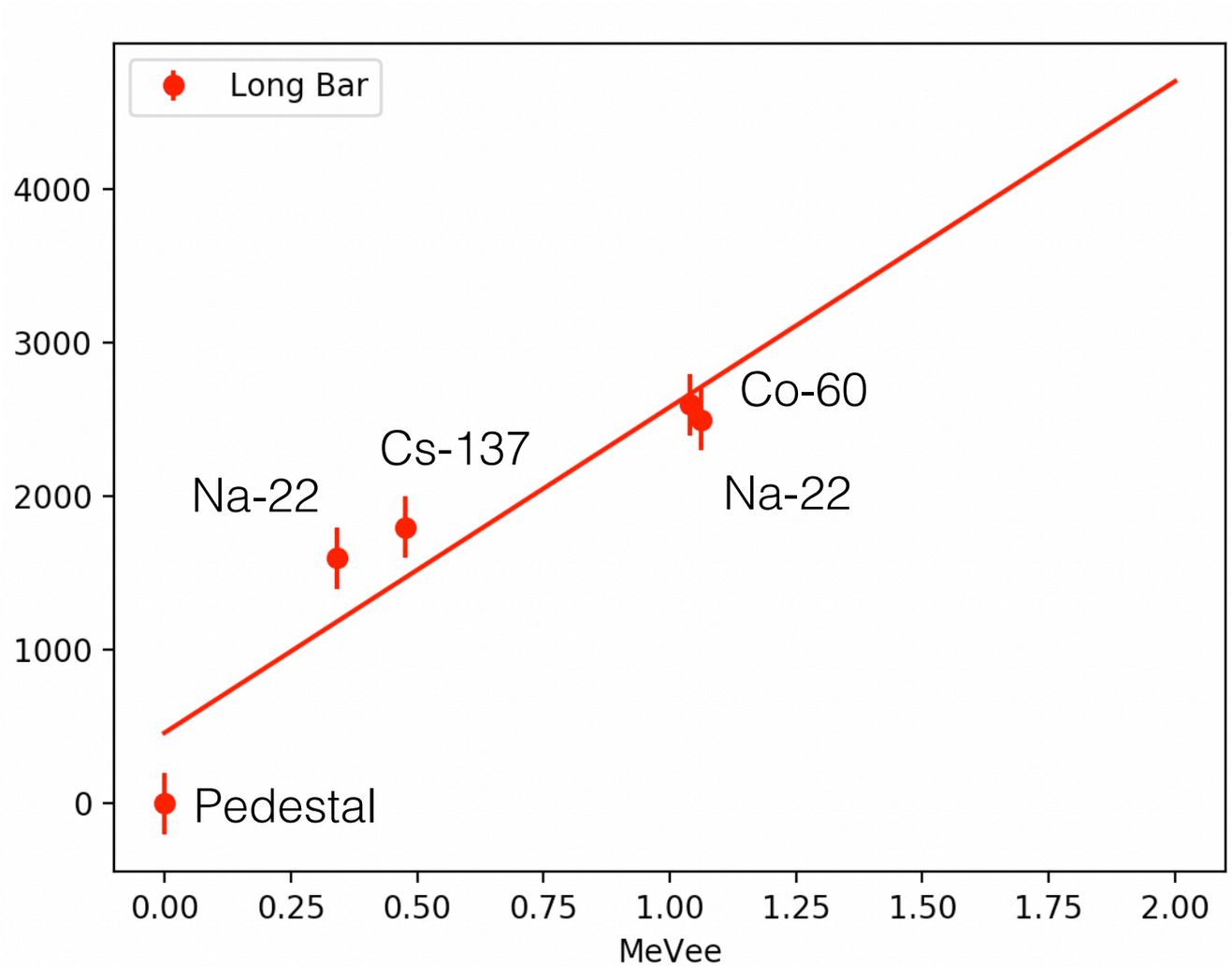




Calibrating ADC to MeVee

(MeVee =MeV Electron-Equivalent)

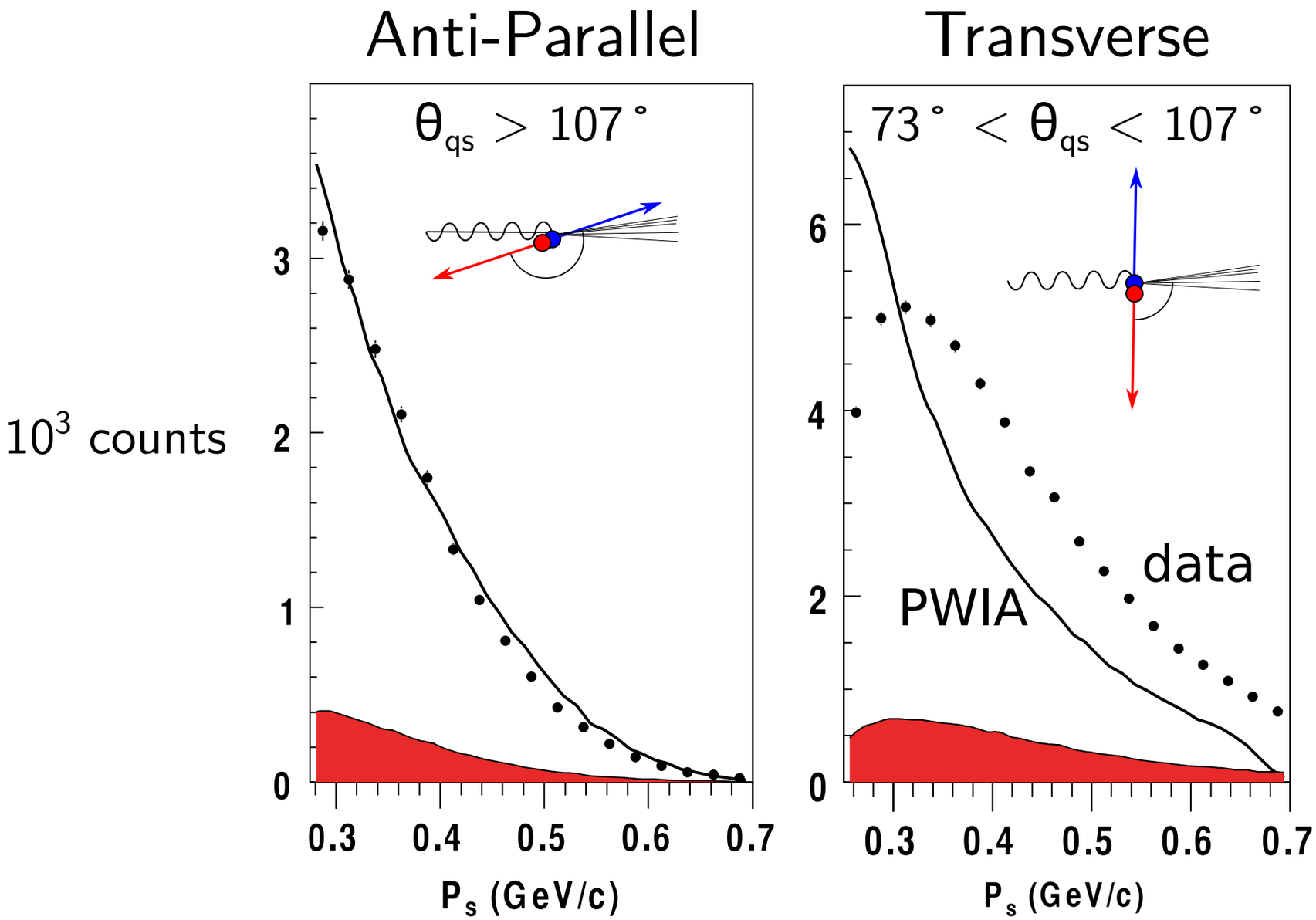




E. Segarra et al, NIM A978 (2020)

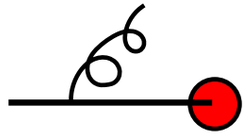
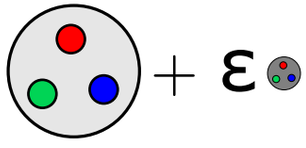
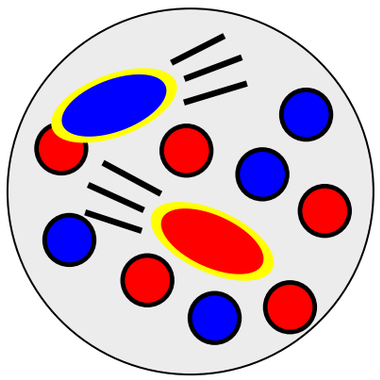
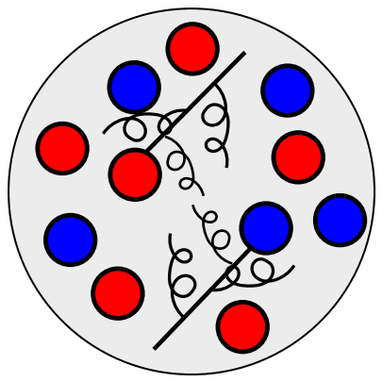
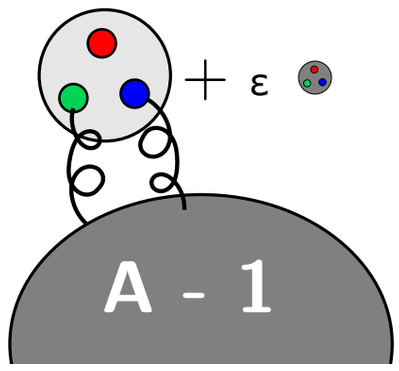
FSI in Tagged DIS

DEEPS showed little FSI at back angles.

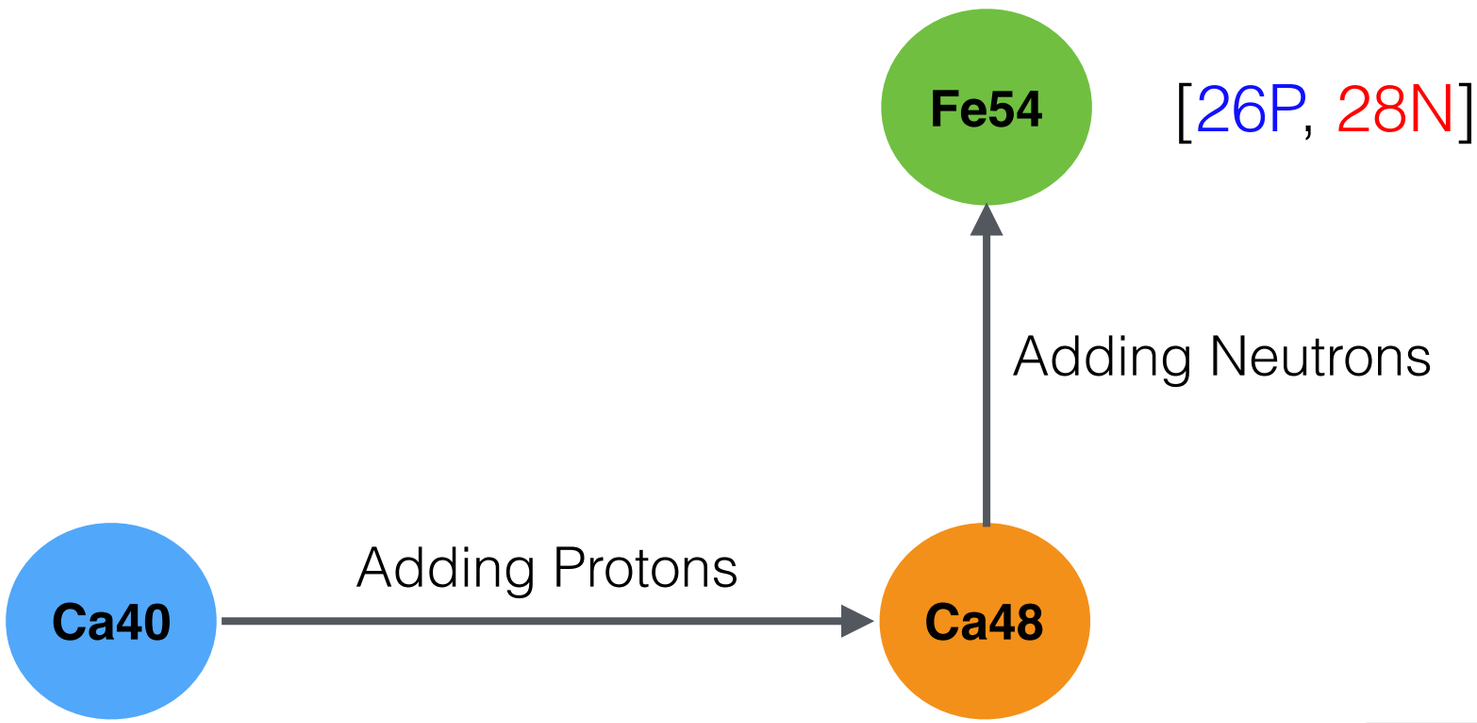


Klimenko et al., PRC 73 035212 (2006)

Theories

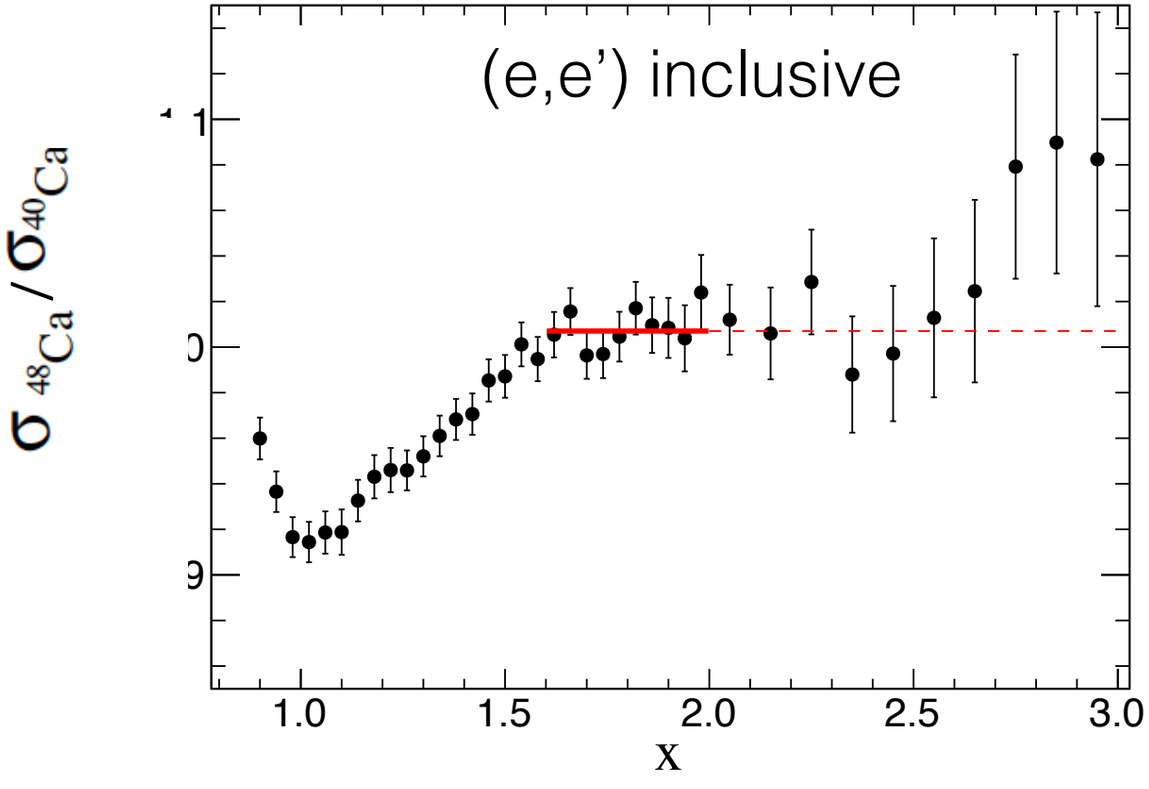
Binding	Rescaling	Point-like Configuration Suppression
Free 	Free 	Free 
Bound 	Bound 	Bound 

Understanding Pairing - CaFe (e,e'p)



- Pairing from different orbits
- Asymmetry dependence
- Separate pairing probabilities

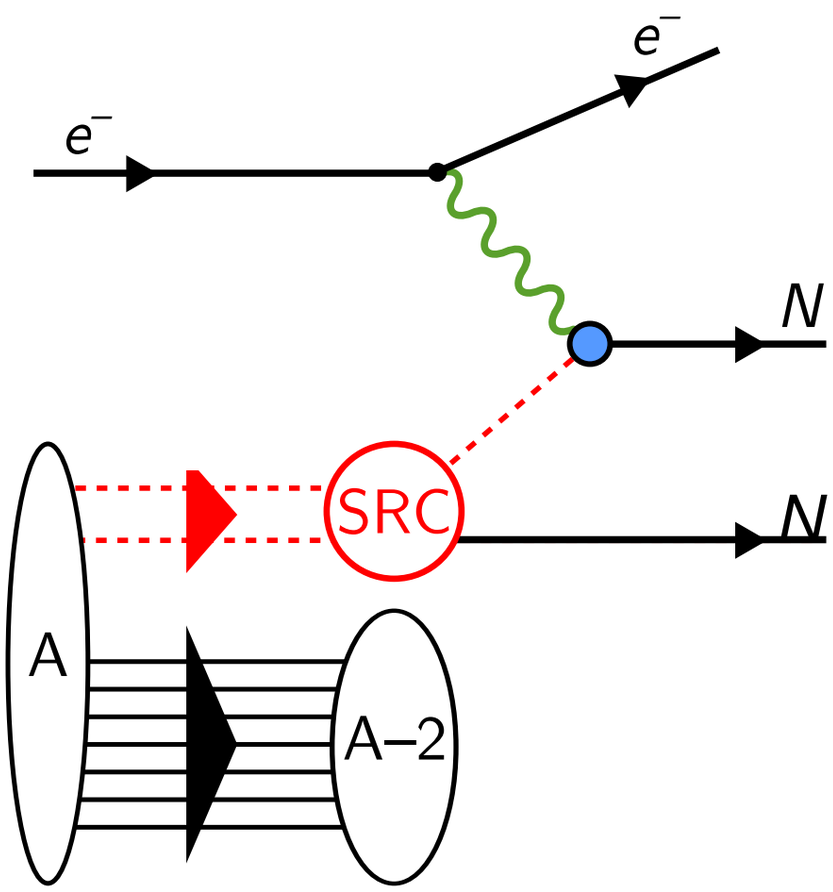
- Run in HallC in 2021



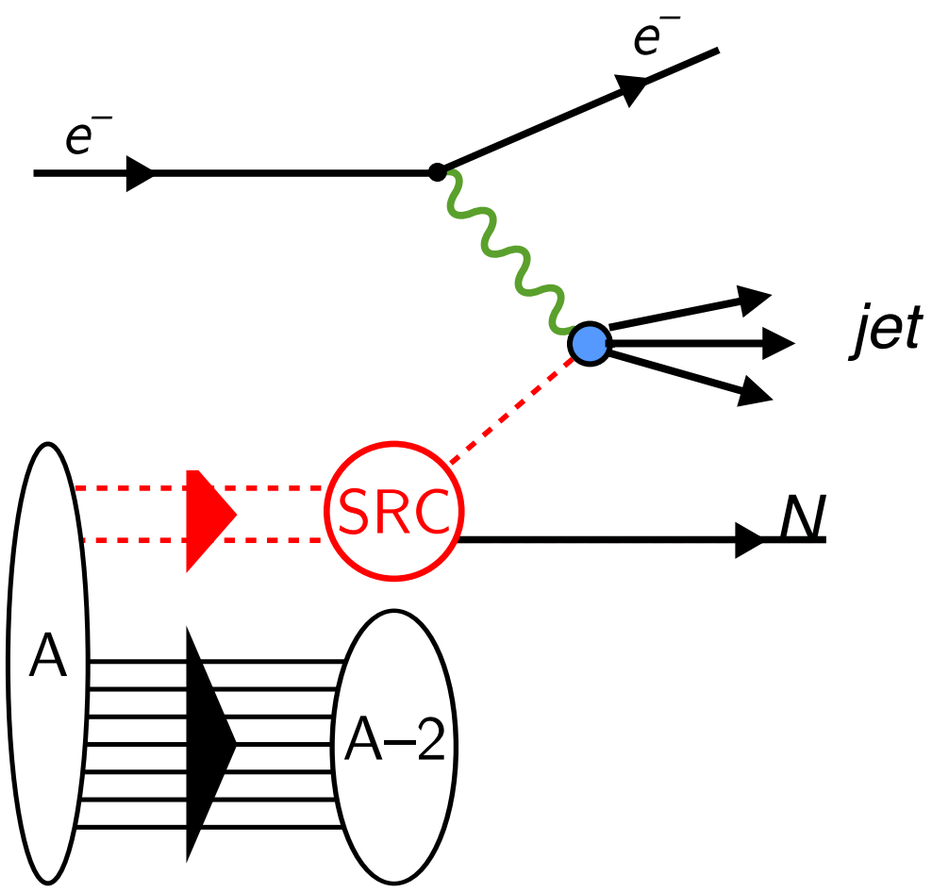
D. Nguyen et al., paper in preparation

GCF for different reactions

GCF-QE



GCF-DIS



- Recoil and A-2 distributions independent on photon interaction

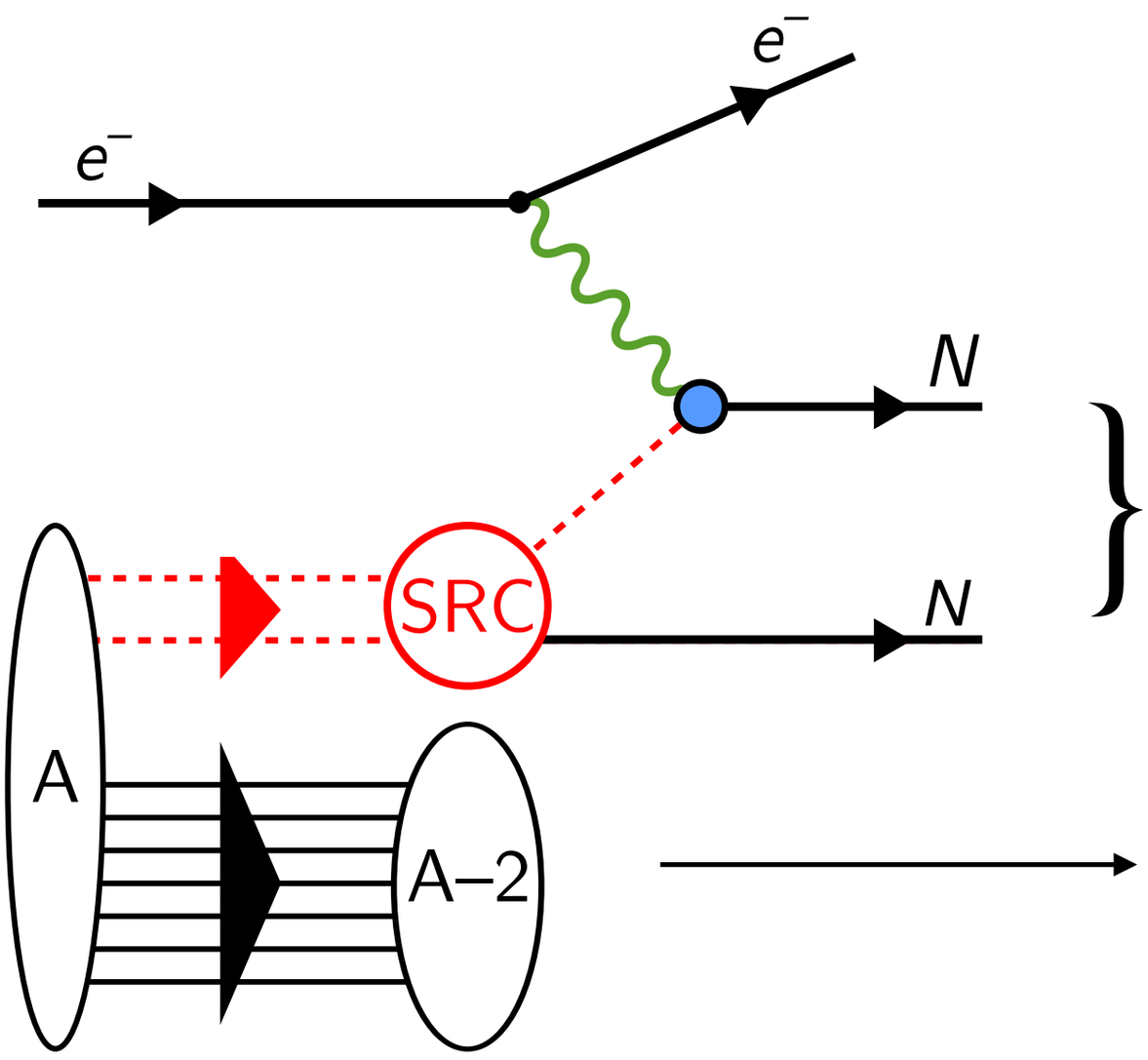
—> GCF-QE to learn about recoil tagging

GCF and BeAGLE

- GCF-DIS in development
- GCF-Quasielastic (QE) implemented
- (A-2)-system handled by BeAGLE's DPMJET3+FLUKA

GCF-QE Generator

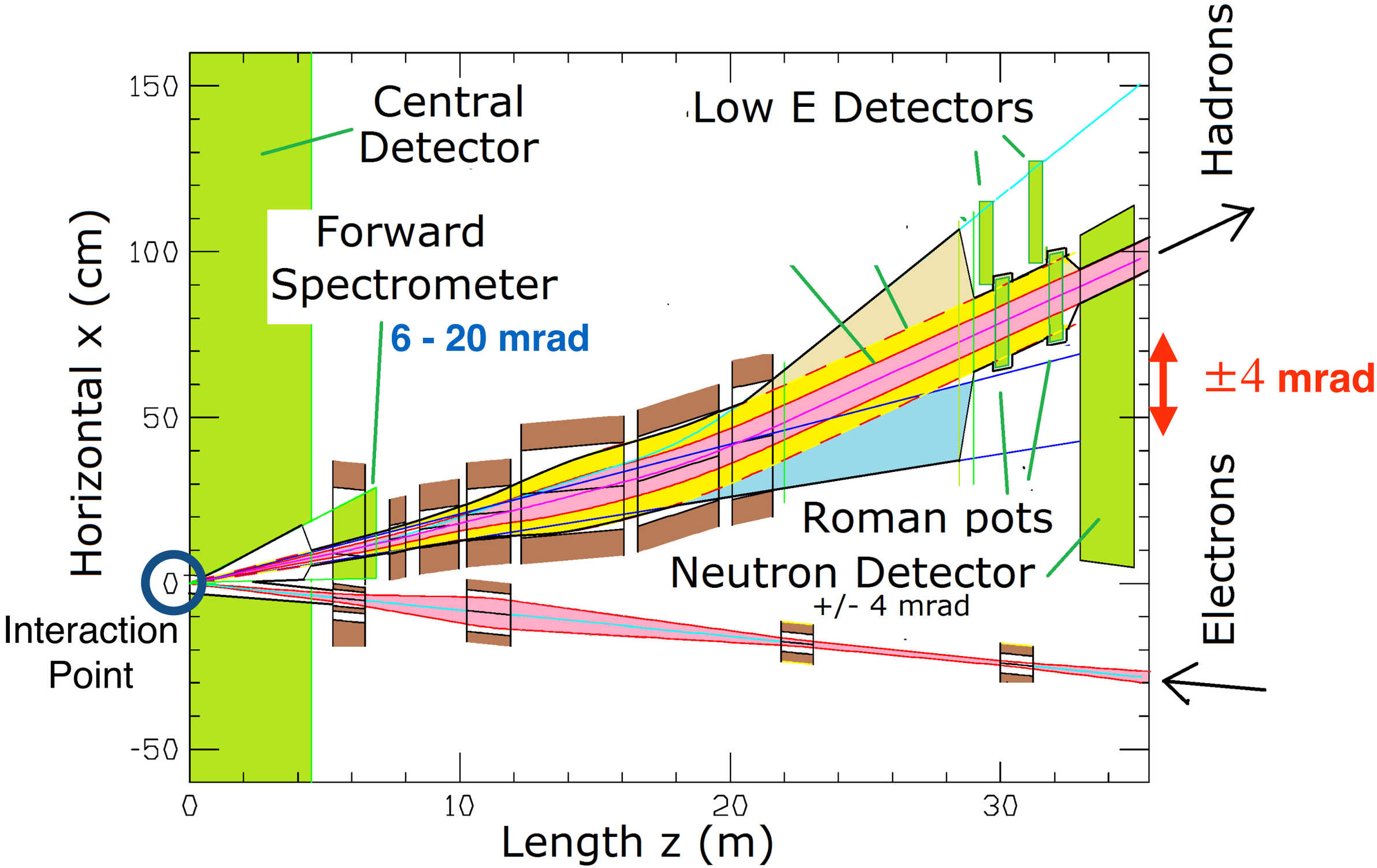
{e-,N,N, (A-2)}



Optional (BeAGLE)
- FSI
- Intranuclear cascading

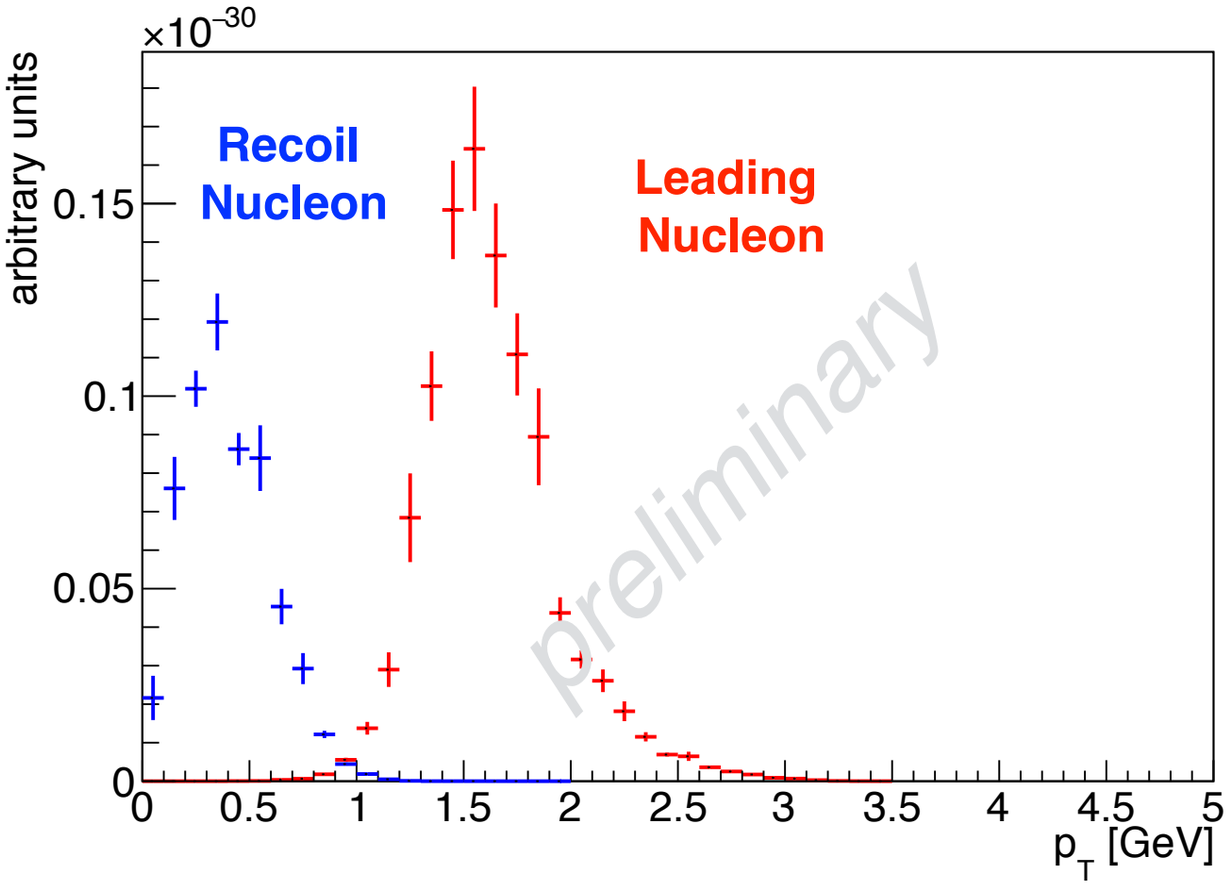
DMPJET+FLUKA

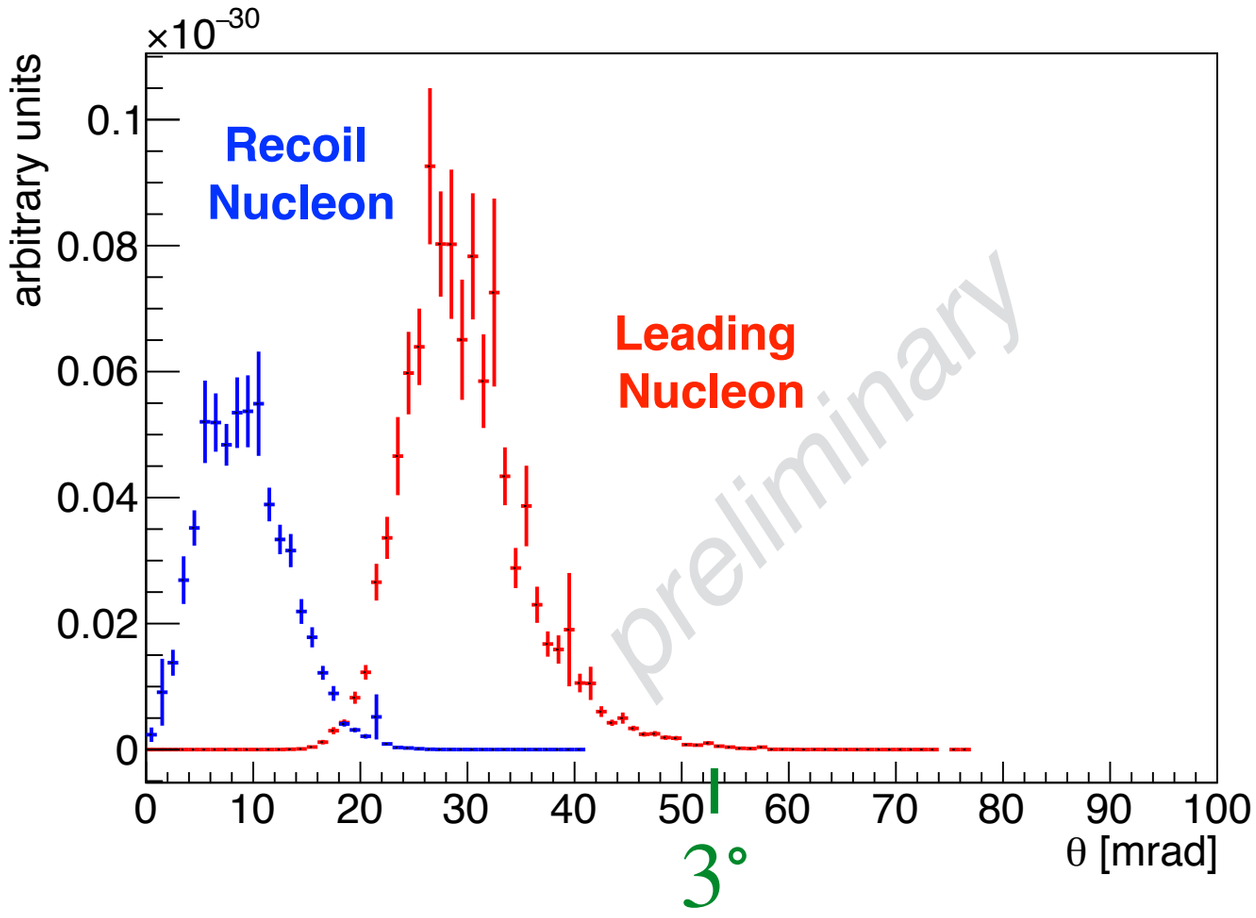
EIC Forward Ion Detection



QE Results for e+C, 10x41GeV/nucleon

no crossing angle, no intra-nuclear cascading, no FSI, QE cuts: $x_B > 1$, $Q^2 > 3$ GeV^2





- Leading and recoil nucleons well separated
- Similar for neutrons and protons

—> Geant detector simulations

—> Study of acceptances and resolutions