PR12-23-013:

Measuring Short-Range Correlations with ALERT

Or Hen (MIT)

PAC51 Meeting

07/24/23

Executive Summary

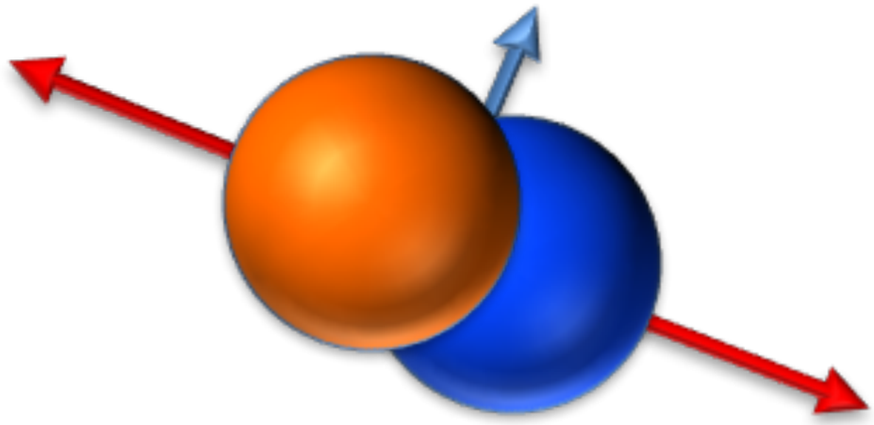
- 17 PAC days
- CLAS12+ALERT
- 6.4 GeV, 500nA
- Standard ALERT He-4 target

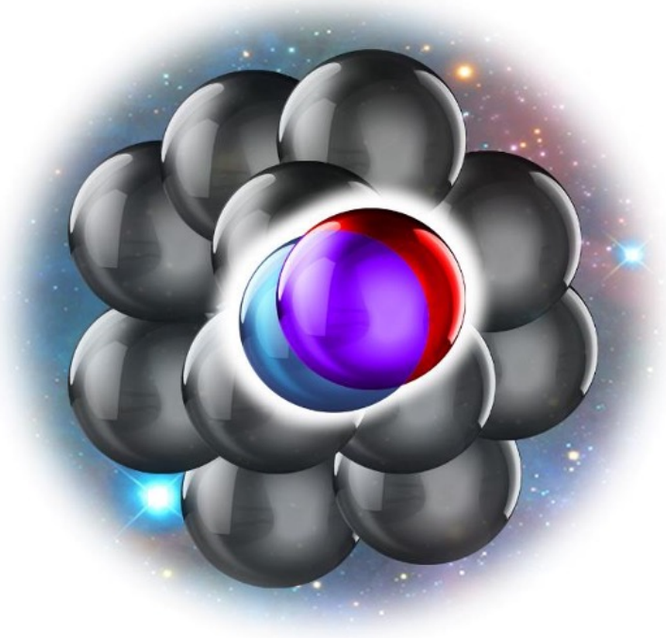
Jefferson Lab GW ODU MIT TEL AVIV UNIVERSITY אוניברסיטת תל אביב université PARIS-SACLAY

Short-Range Correlations (SRC)

<u>Correlated Nucleon pair with:</u>

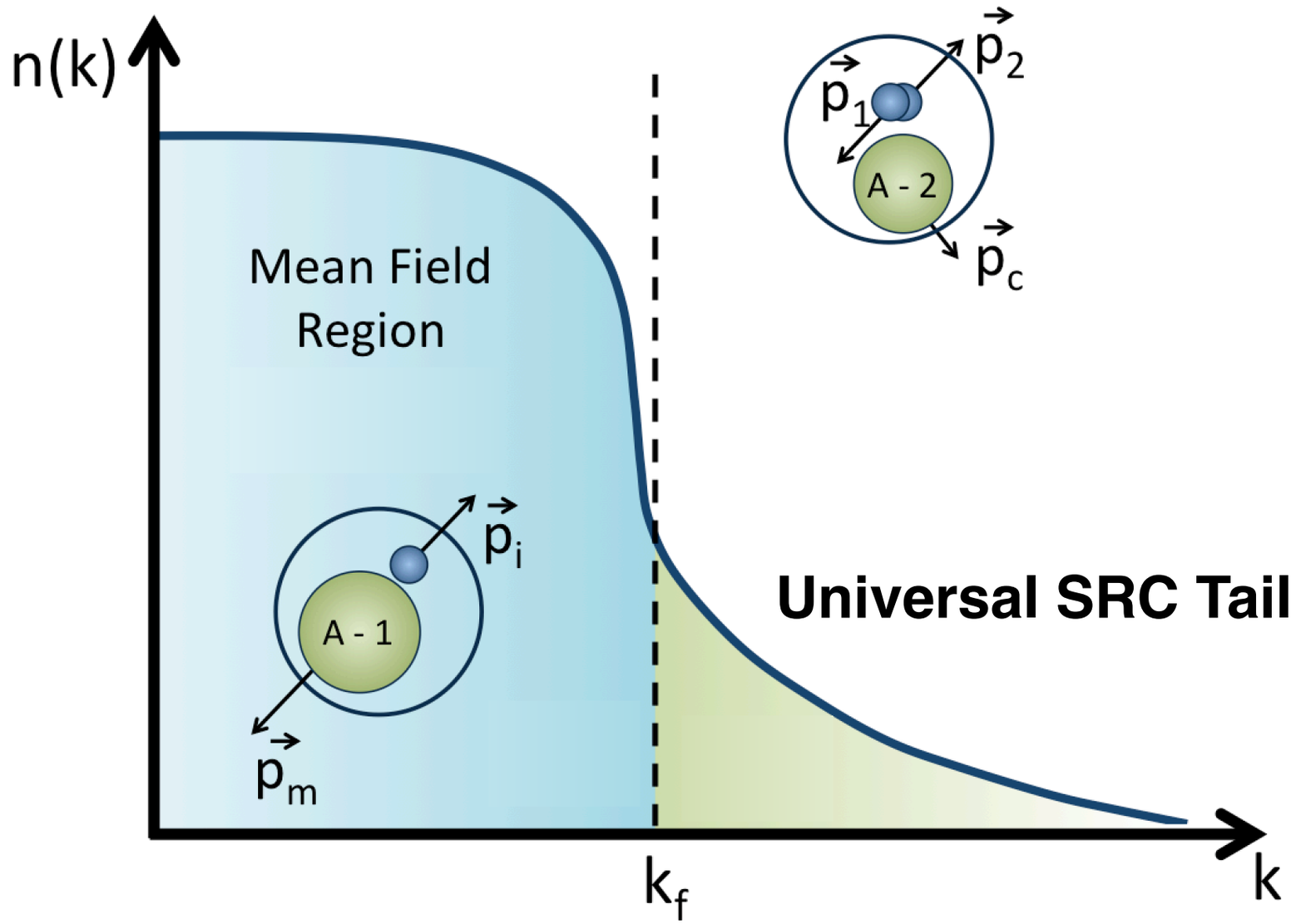
- high relative momentum
  > Fermi momentum
- lower c.m momentum





PRL (2006), PRL (2007), Science (2008), PRL (2014), Science (2014),
Nature (2018), PRL (2019), Nature (2020), PLB (2021), PRC (2023), <u>Review:</u> RMP (2017)

SRC —> Universal High-momentum Tail



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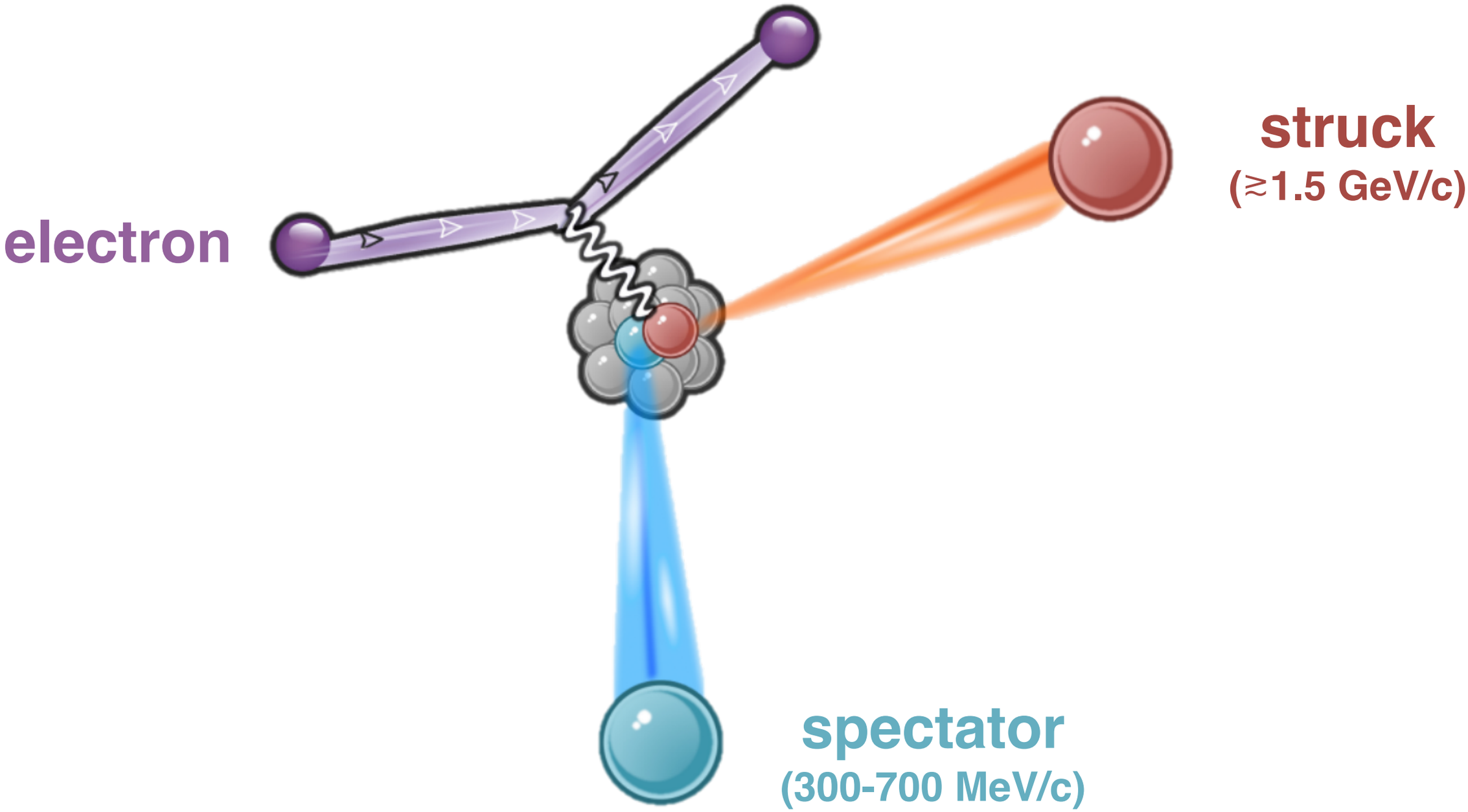
SRC Measurements



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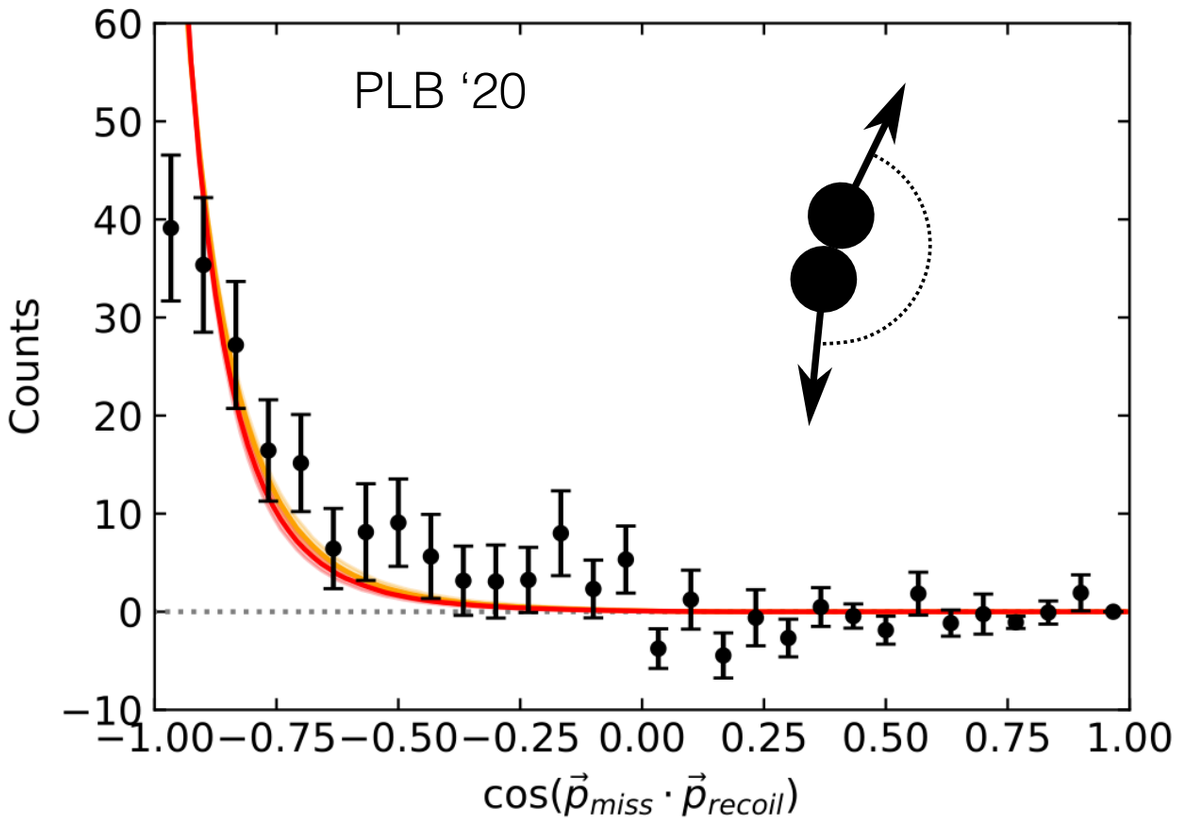
SRC Measurements

- Breakup of SRC pairs lead to correlated nucleon emission



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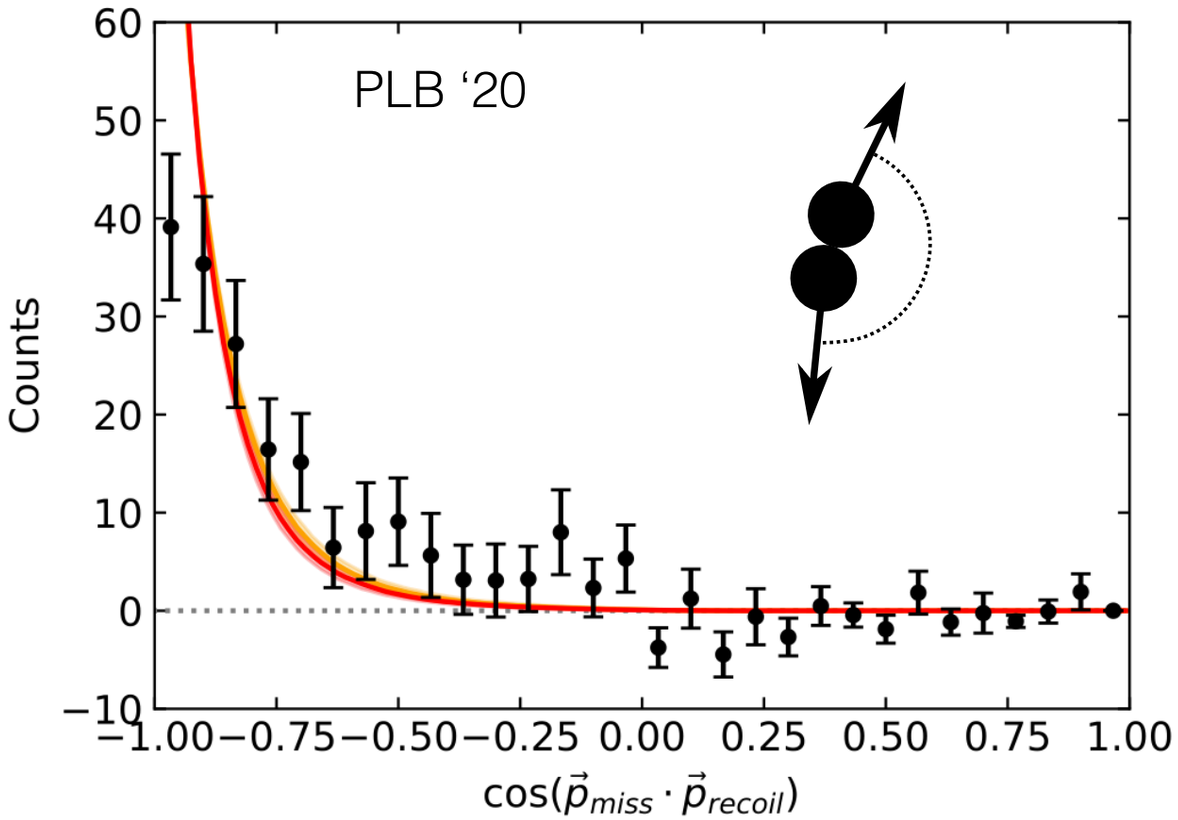
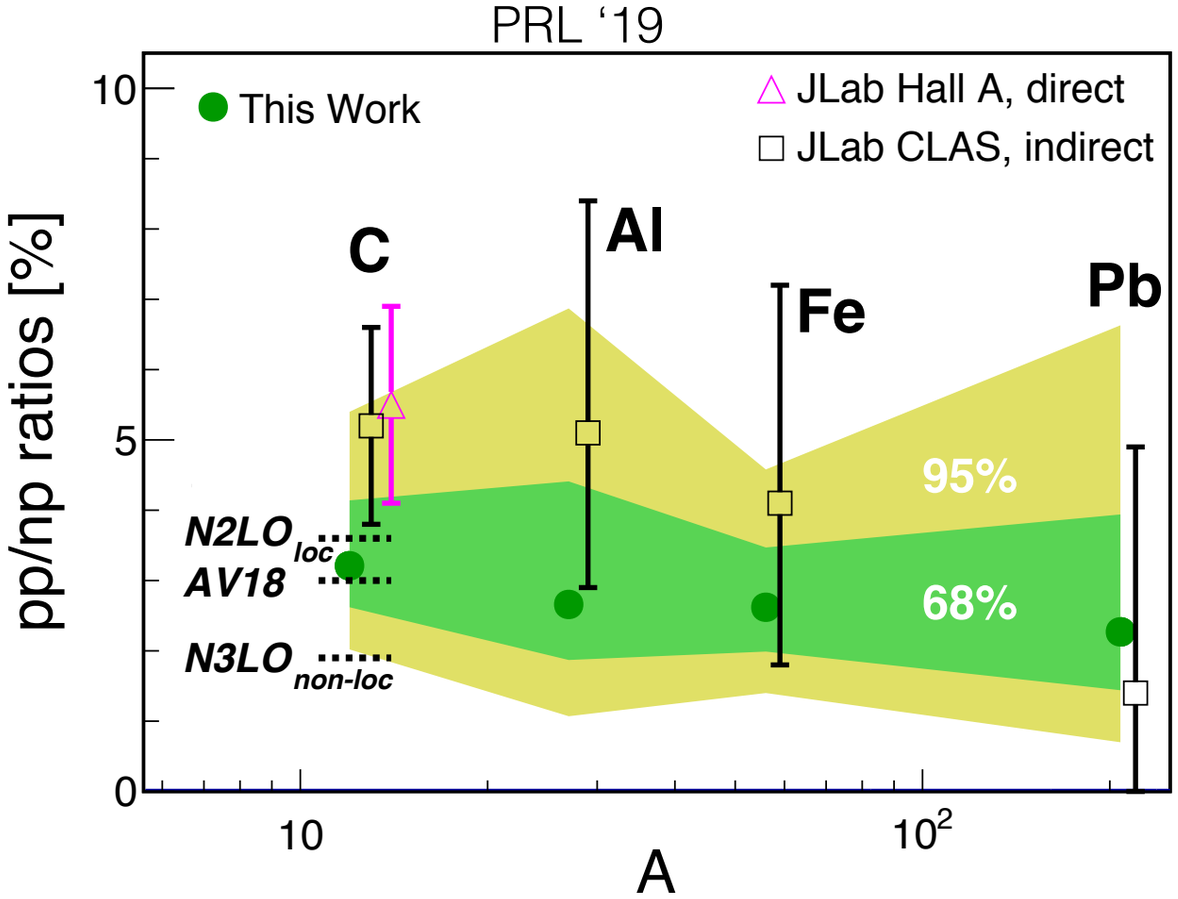


- Predominantly proton-neutron pairs



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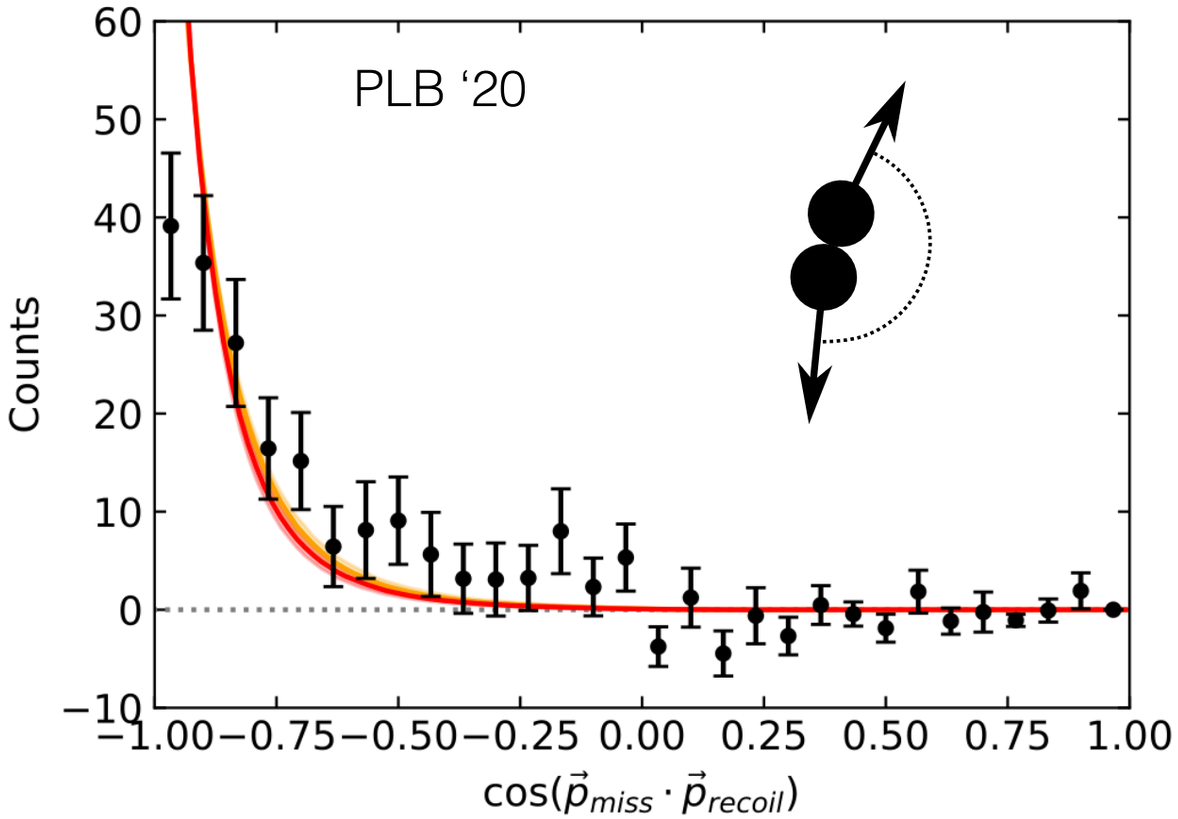

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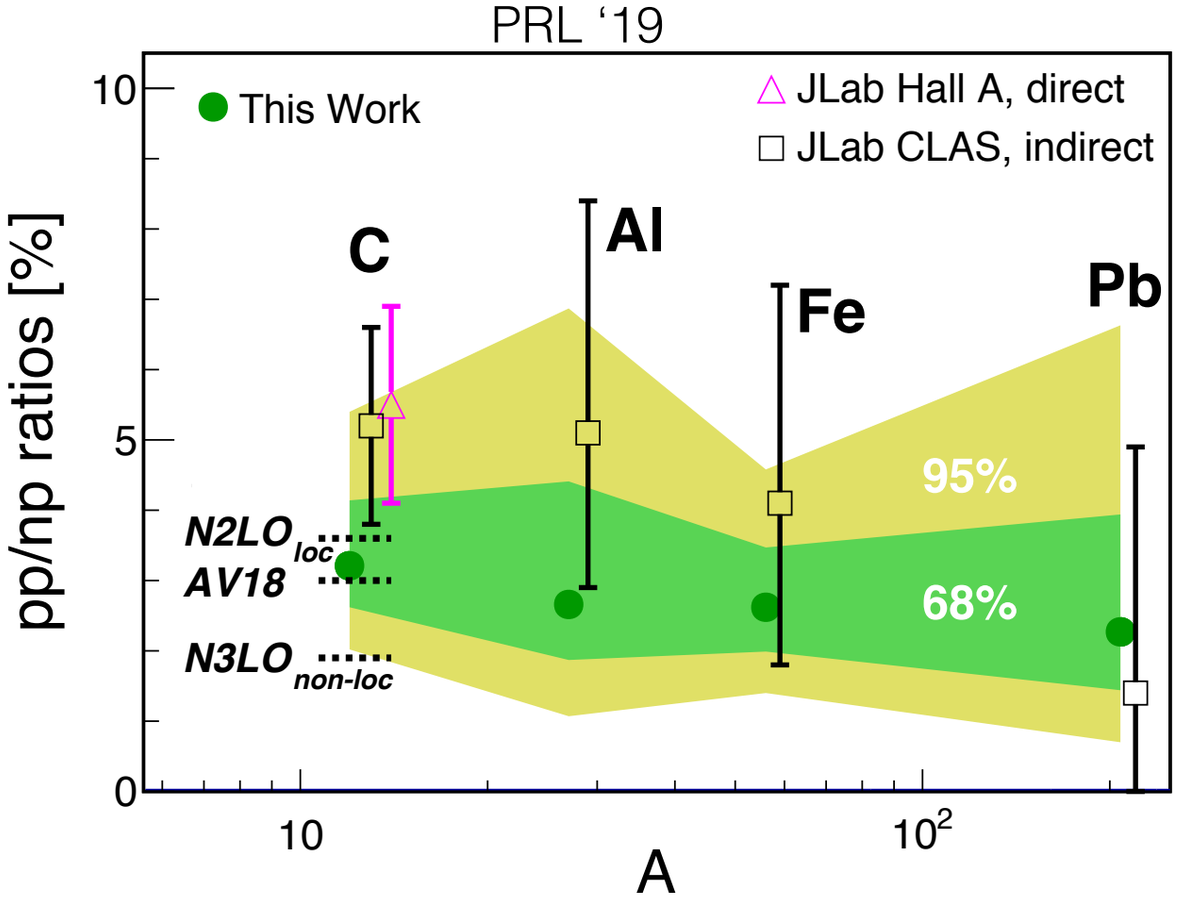


+

Quantum Numbers, Mass, Asymmetry Dependence:

Phys. Rev. C 103, L031301 (2021)
Phys. Lett. B 780, 211 (2018)
PRC 92, 024604 (2015)
PRC 92, 045205 (2015)

Isospin Structure:

Phys. Rev. Lett. 122, 172502 (2019)
Nature 560, 617 (2018)
Science 346, 614 (2014)
Phys. Rev. Lett. 113, 022501 (2014)

C.M. Motion:

Phys. Rev. Lett. 121, 092501 (2018)

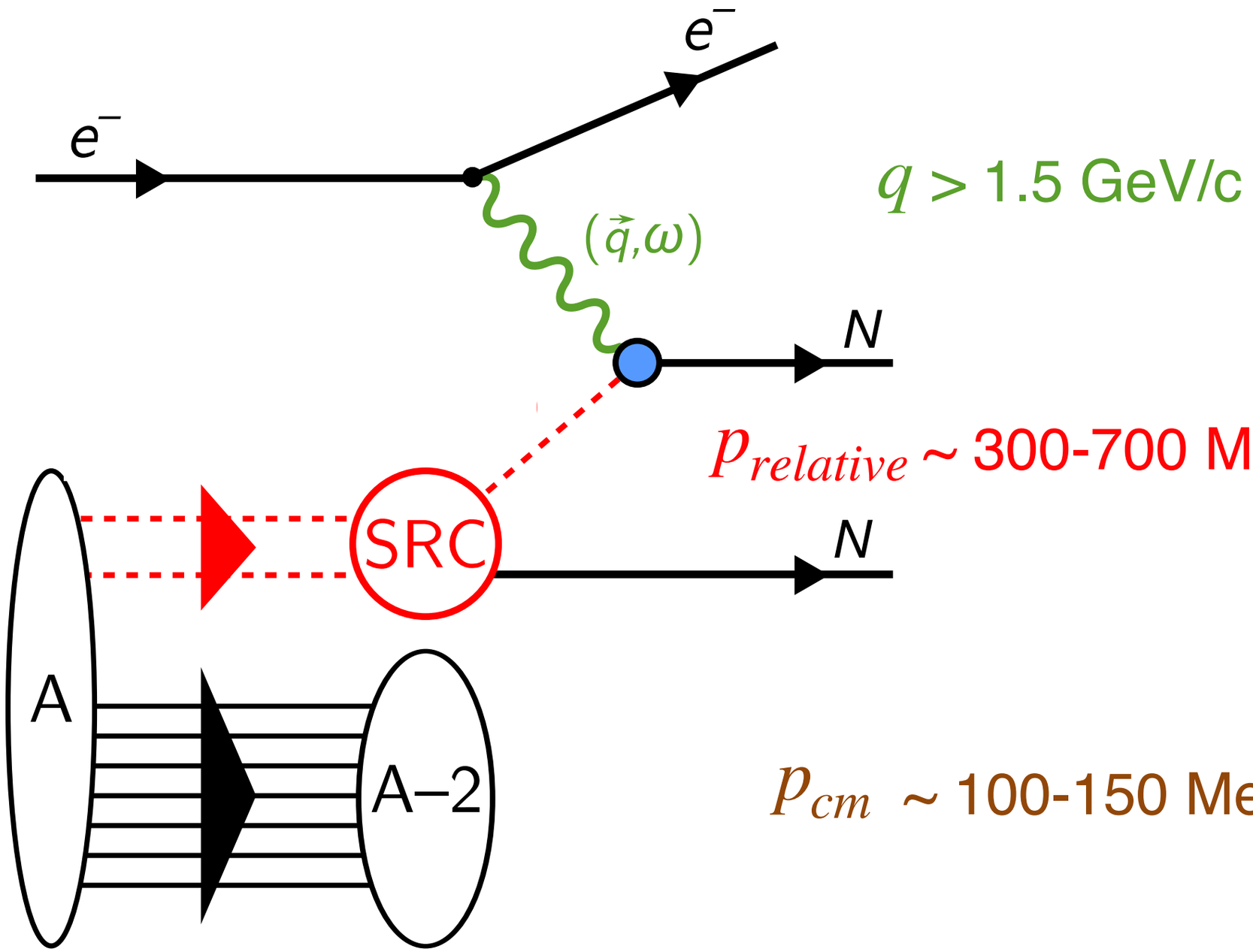
Hard-Reaction Dynamics:

Nature Physics 17, 693 (2021)
Phys. Lett. B 797, 134792 (2019)
Phys. Lett. B 722, 63 (2013)

Effective Theory:

Nature Physics 17, 306 (2021)
Phys. Lett. B 805, 135429 (2020)
Phys. Lett. B 791, 242 (2019)

Scale Separation: q >> $p_{relative}$ >> p_{cm}



q > 1.5 GeV/c

$p_{relative}$ ~ 300-700 MeV/c

p_{cm} ~ 100-150 MeV/c

PRC 92 (2015), PLB 780 (2018), PLB 791 (2019), PLB 792 (2019), JPG 47 (2020), Nature Physics 17 (2021), PRC 104 (2021), PRC 53 (1996), PRL 119 (2017)

Scale Separation

$$q \gg p_{relative} \gg p_{cm}$$

Factorization of many-body wave function

PRC 92 (2015), PLB 780 (2018), PLB 791 (2019), PLB 792 (2019), JPG 47 (2020), Nature Physics 17 (2021), PRC 104 (2021), PRC 53 (1996), PRL 119 (2017)

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Factorization of many-body wave function

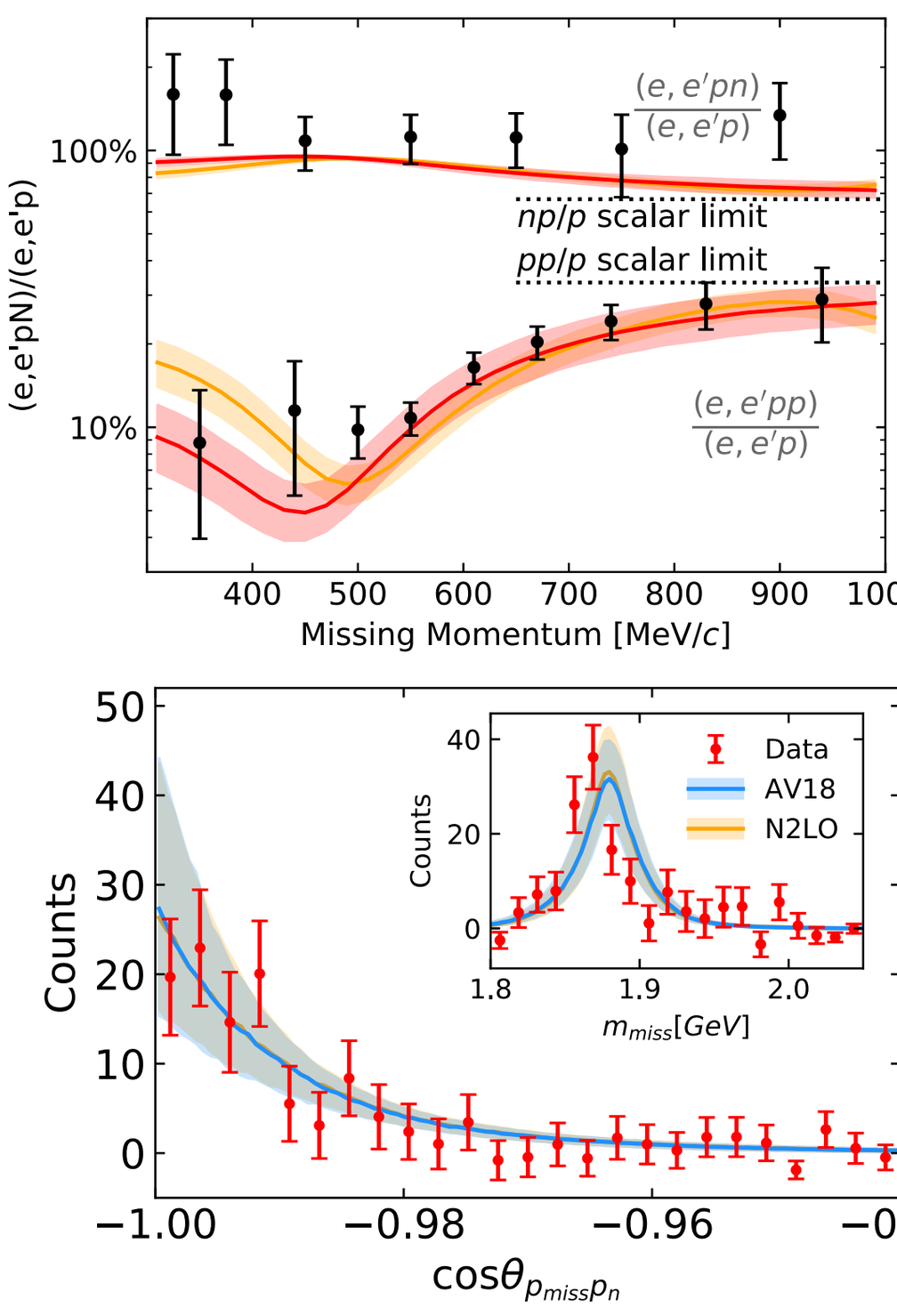
Elementary eN cross section | **Nuclear Contacts** | **Two-body wave function** | **Center of mass motion**

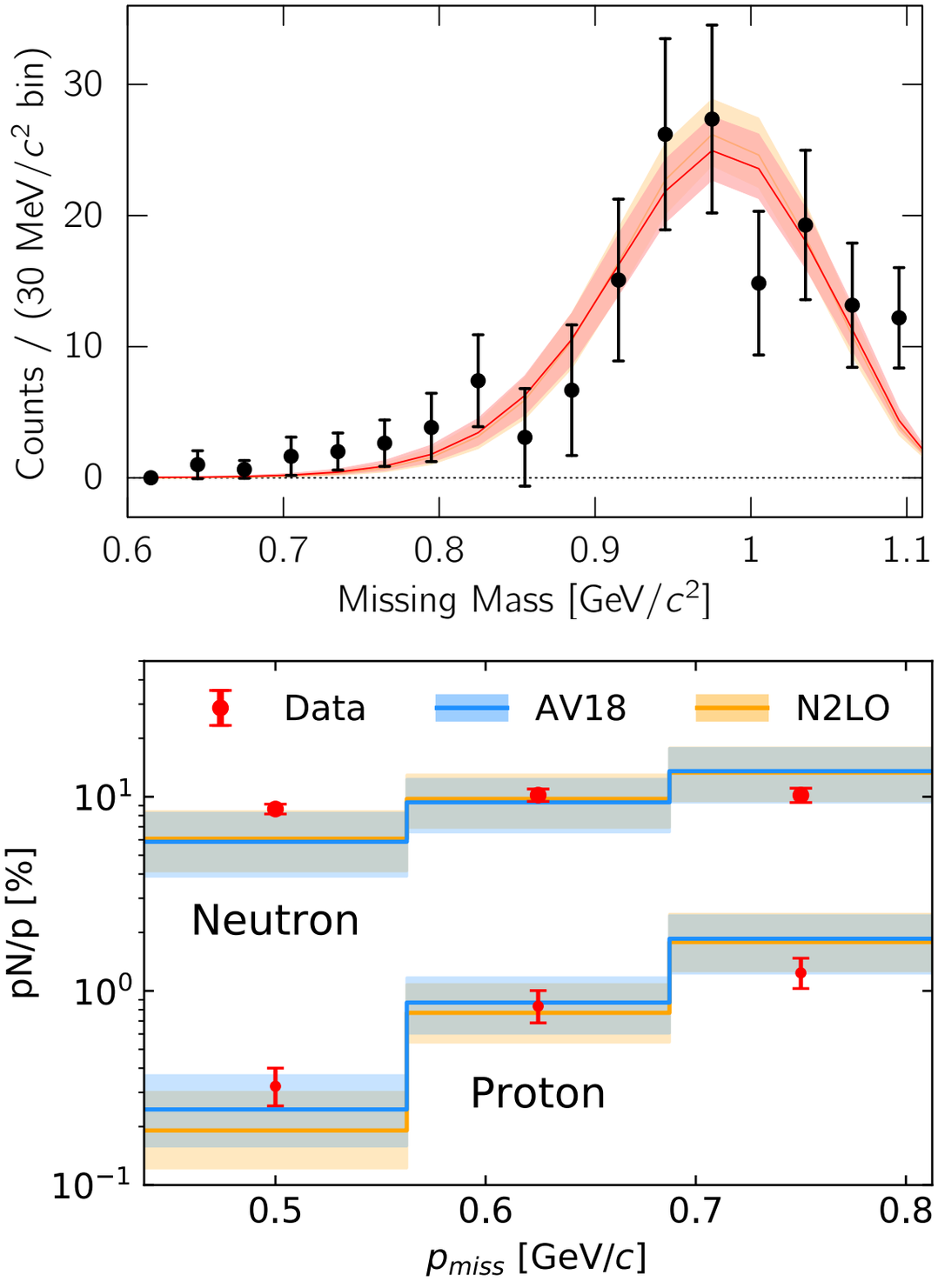
$$\sigma_{eA} = \sigma_{eN}(q) \cdot \sum_{NN-pairs} \cdot C_A^{NN} \cdot |\phi(p_{relative})|^2 \cdot n(p_{cm})$$

PRC 92 (2015), PLB 780 (2018), PLB 791 (2019), PLB 792 (2019), JPG 47 (2020), Nature Physics 17 (2021), PRC 104 (2021), PRC 53 (1996), PRL 119 (2017)

Formalism works very well!

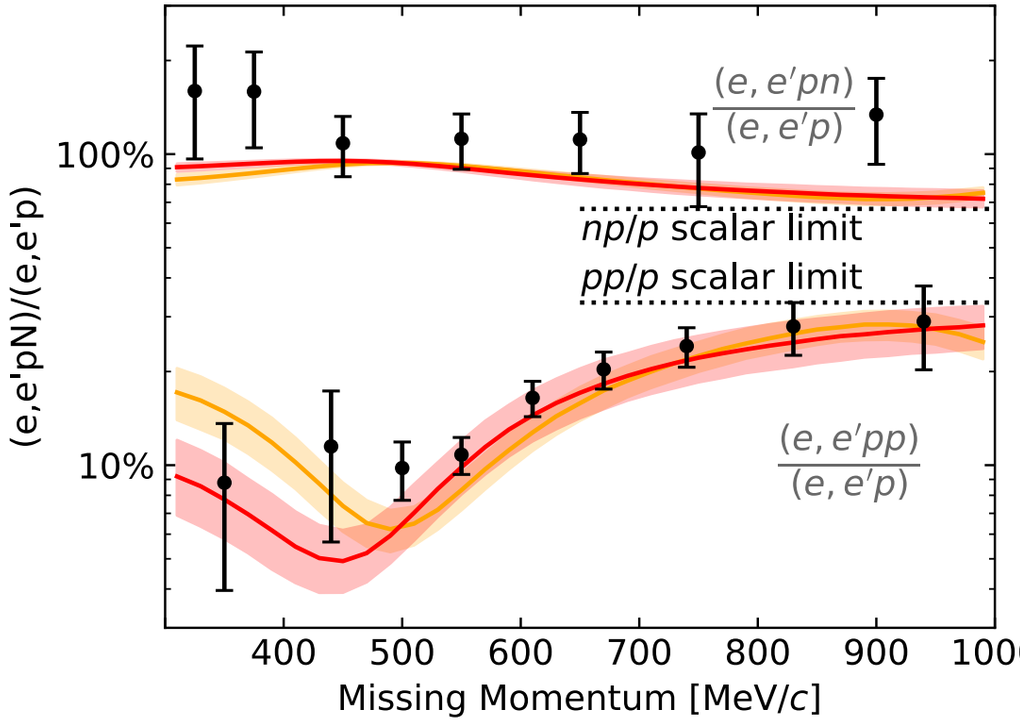
PRL ’19, Nature ’20, PLB ’20, Nature Phys. ’21, PLB ’21, PRC Lett. ’21, PRC lett. ’23

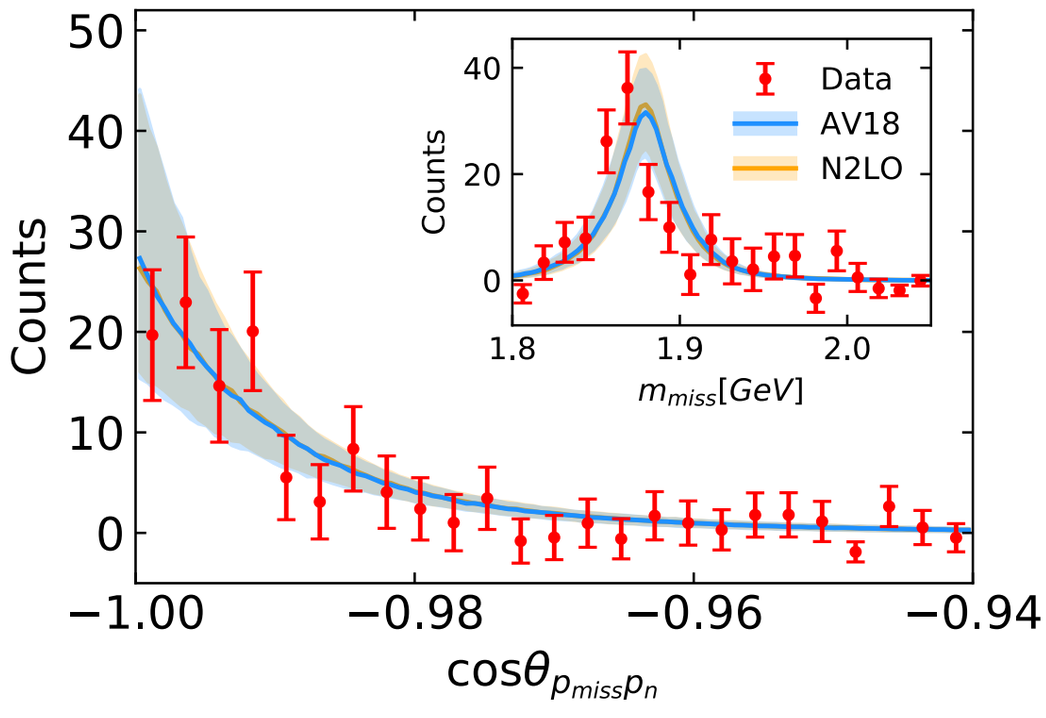


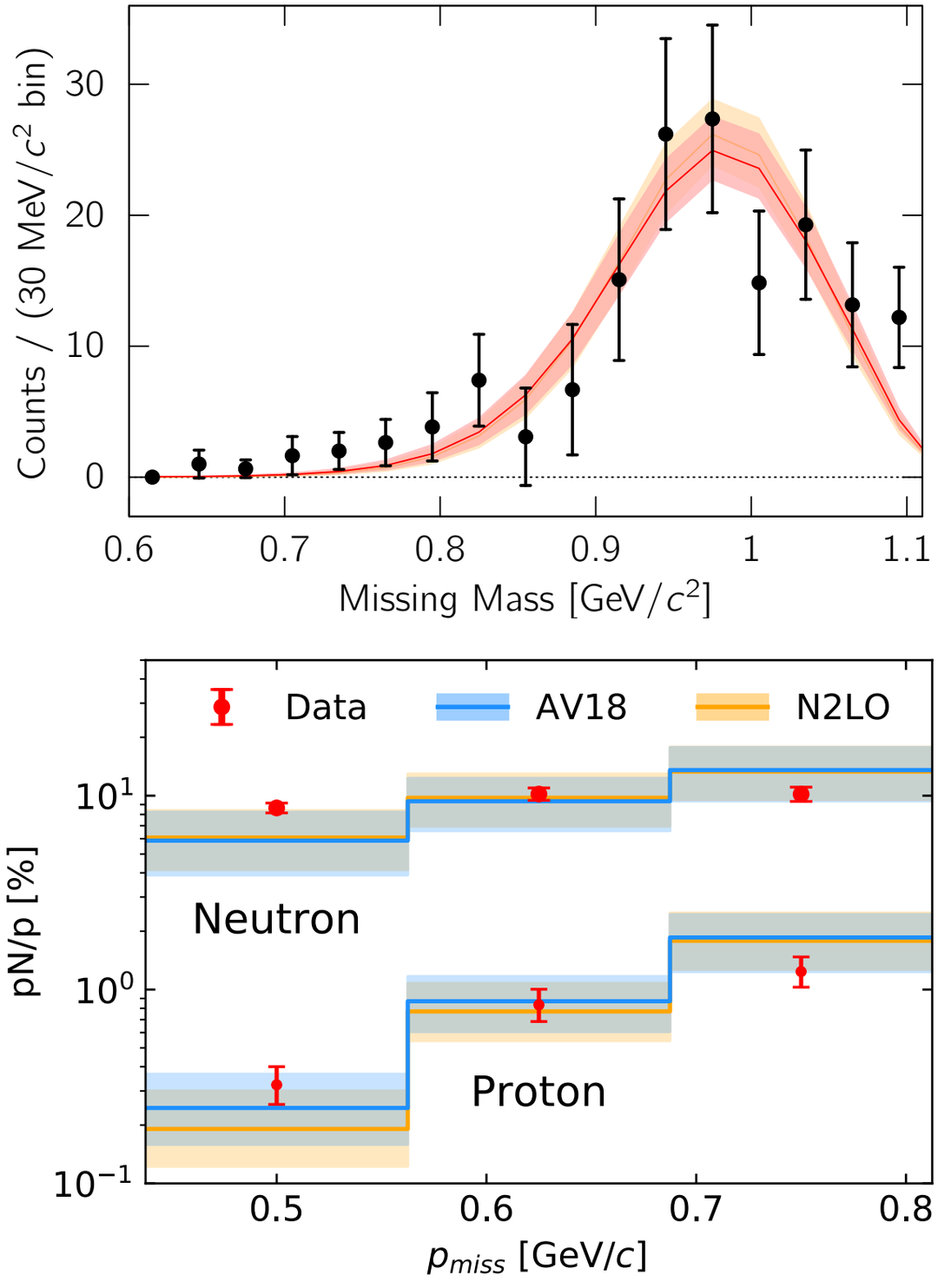


Formalism works very well … <u>where tested</u>

PRL ’19, Nature ’20, PLB ’20, Nature Phys. ’21, PLB ’21, PRC Lett. ’21, PRC lett. ’23







Question 1: SRC pair Factorization

Elementary eN cross section | **Nuclear Contacts** | **Two-body wave function** | **Center of mass motion**

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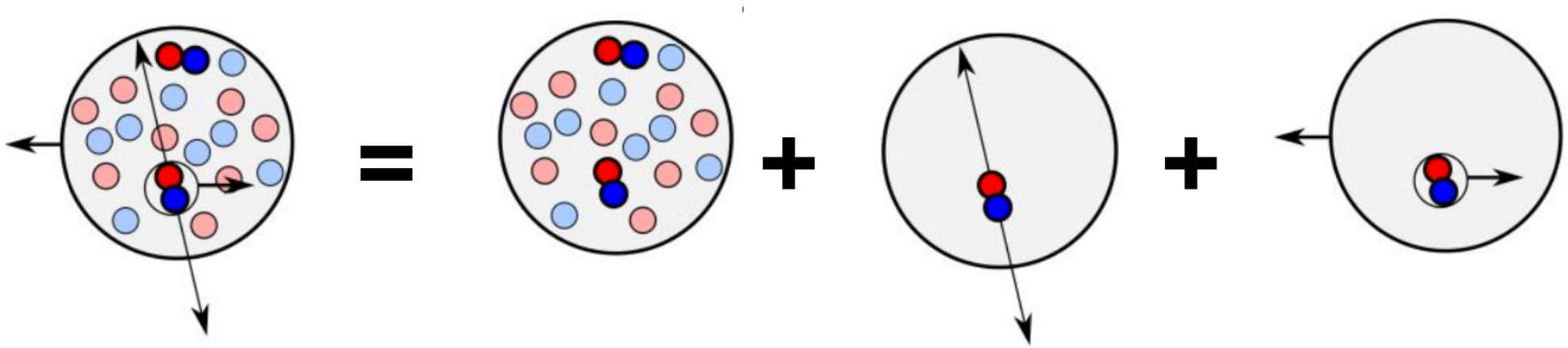

PRC 92 (2015), PLB 780 (2018), PLB 791 (2019), PLB 792 (2019), JPG 47 (2020), Nature Physics 17 (2021), PRC 104 (2021), PRC 53 (1996), PRL 119 (2017)

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Factorization test: uncorrelated relative and c.m. motions

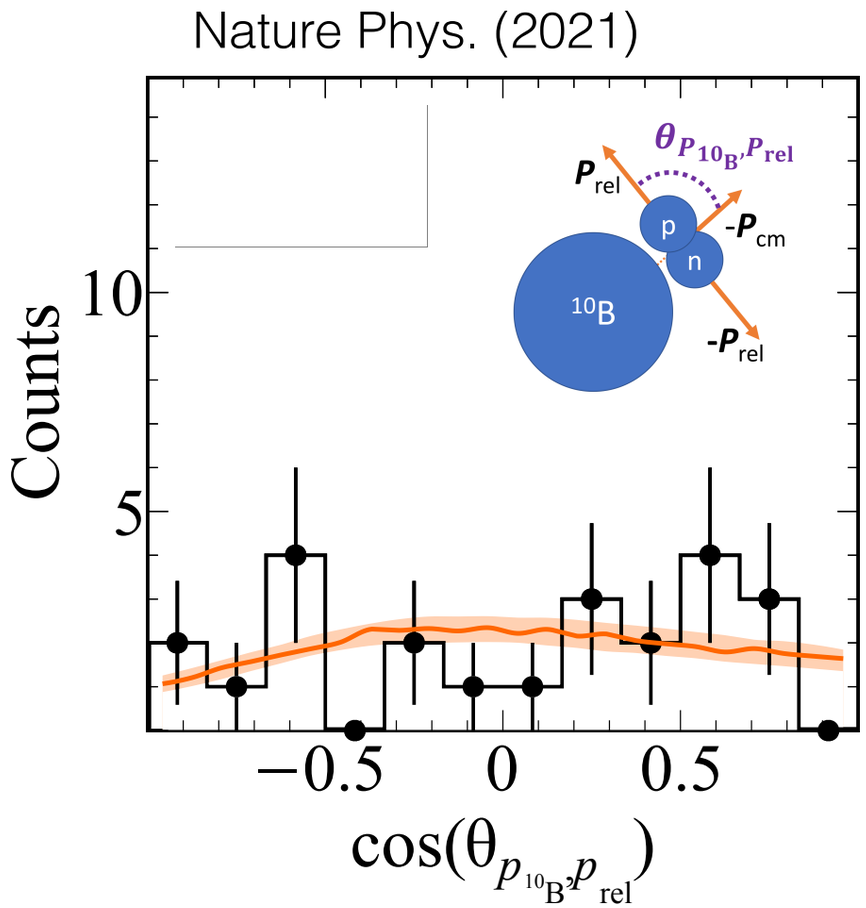
[C.Ciofi degli Atti, Phys. Rep. 2015]

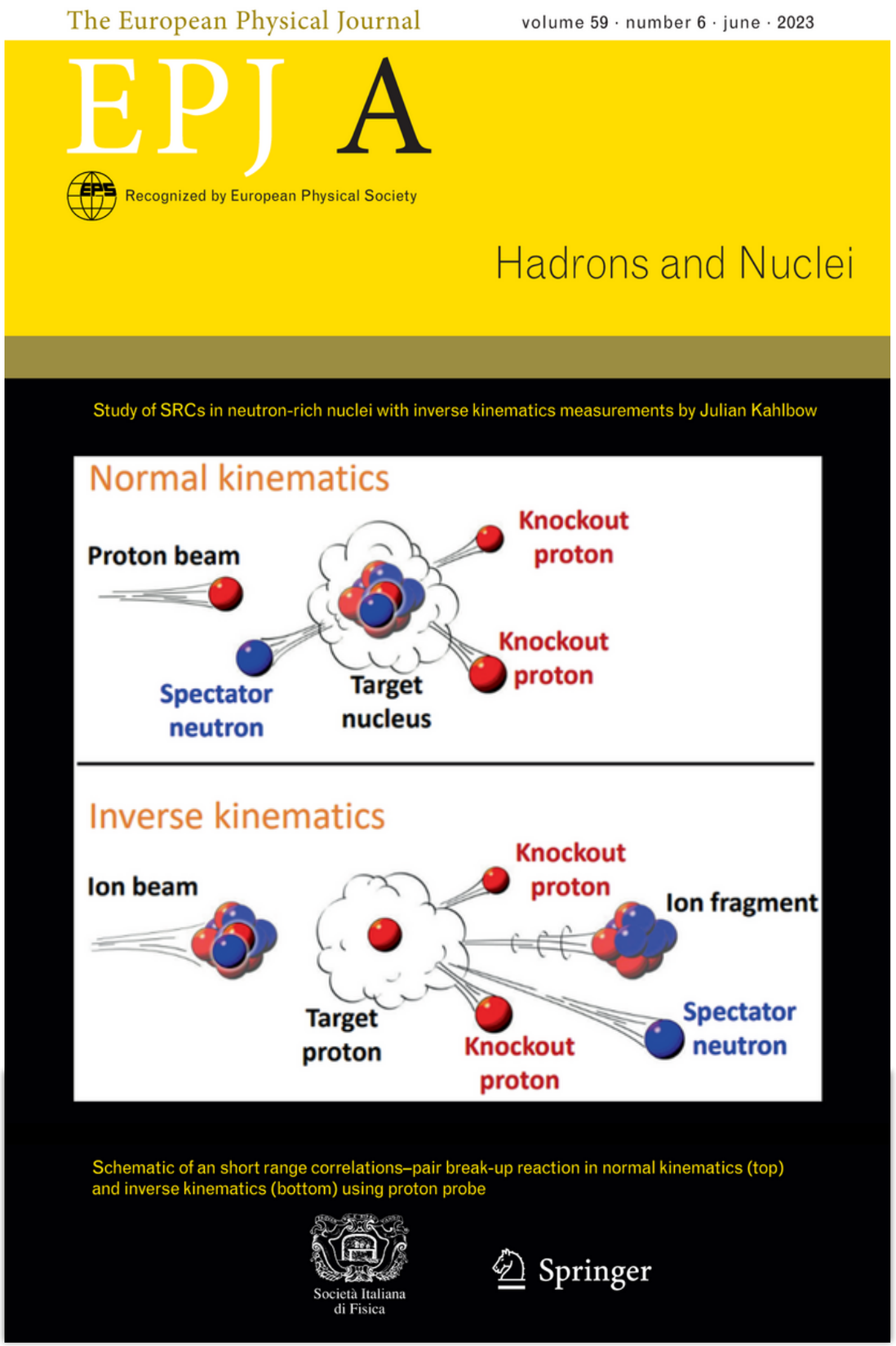
PRC 92 (2015), PLB 780 (2018), PLB 791 (2019), PLB 792 (2019), JPG 47 (2020), Nature Physics 17 (2021), PRC 104 (2021), PRC 53 (1996), PRL 119 (2017)

Goal 1: Precision Test of Factorization

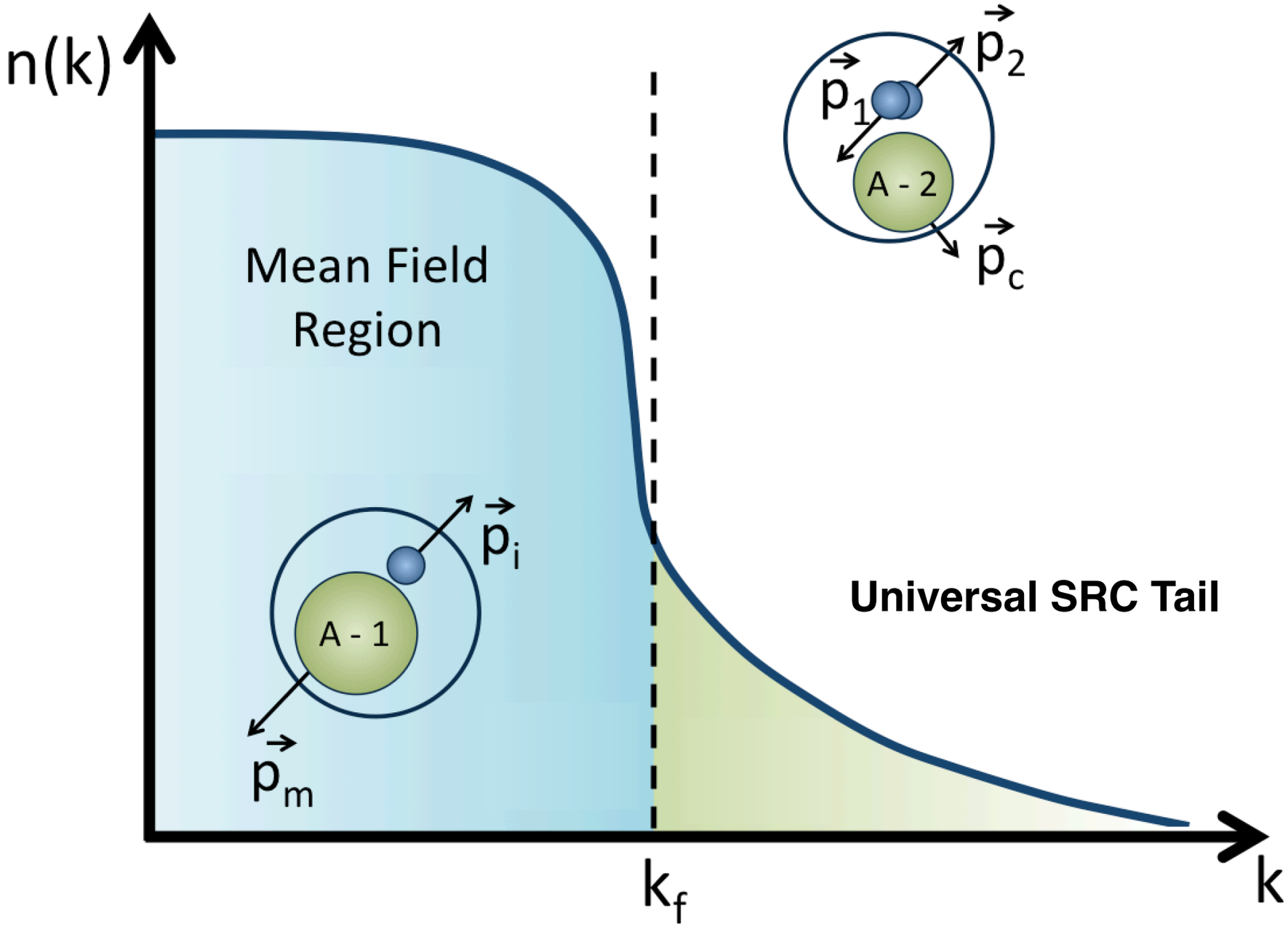
- 23 inverse kinematics $^{12}C(p,2p)^{10}B$ events
- Consistent with factorization but… limited statistics
- Need better data with spectator nucleus tagging

Nature Phys. (2021)





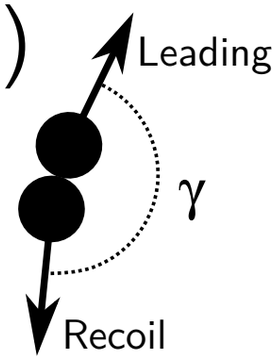
Question 2: Mean-field to SRC Transition

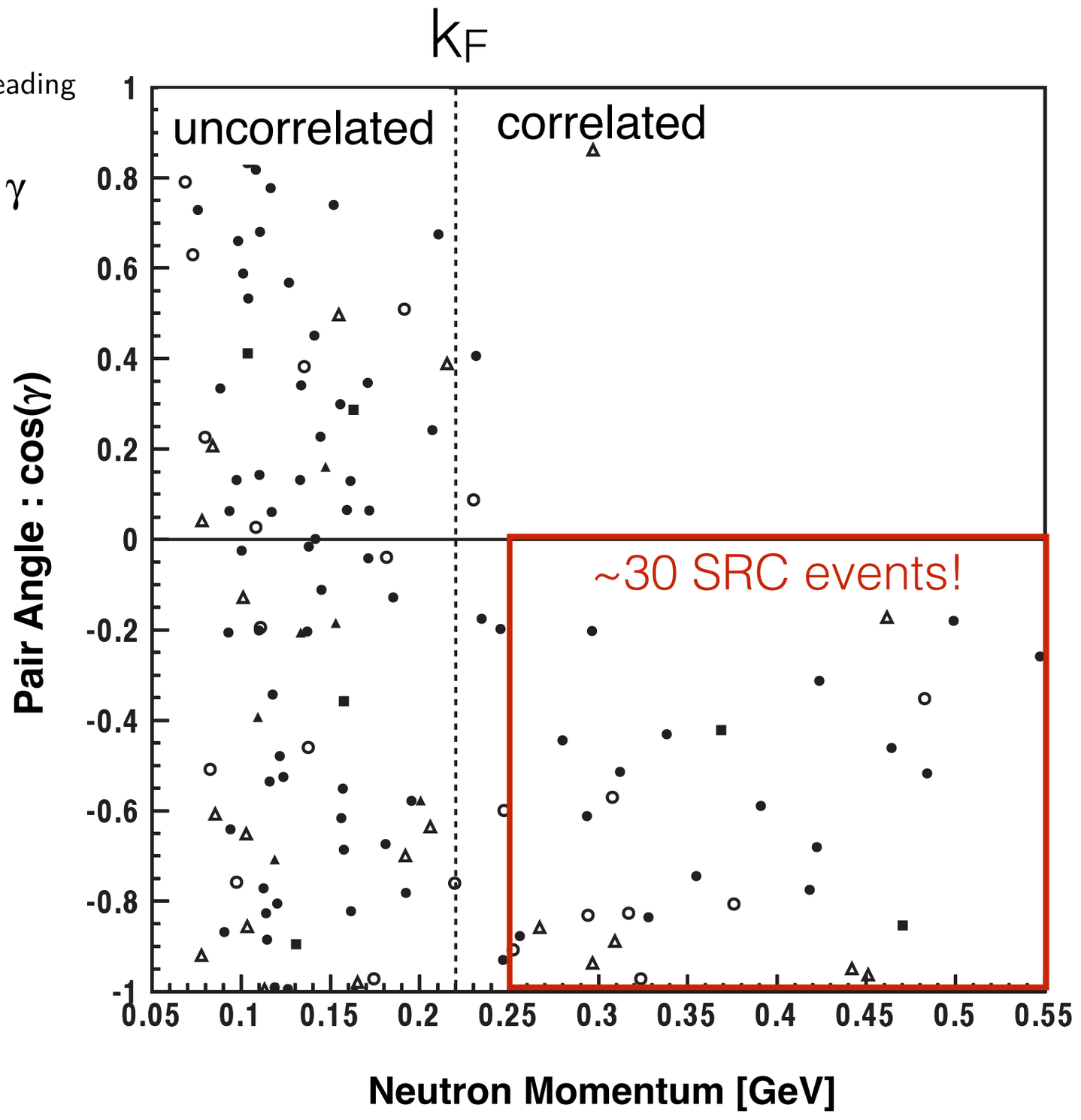


Goal 2: High-statistics, Exclusive Mapping of Transition Region

PRL 97 (2006), PLB 453 (1999), PRL 90 (2003)

C(p,2pn)





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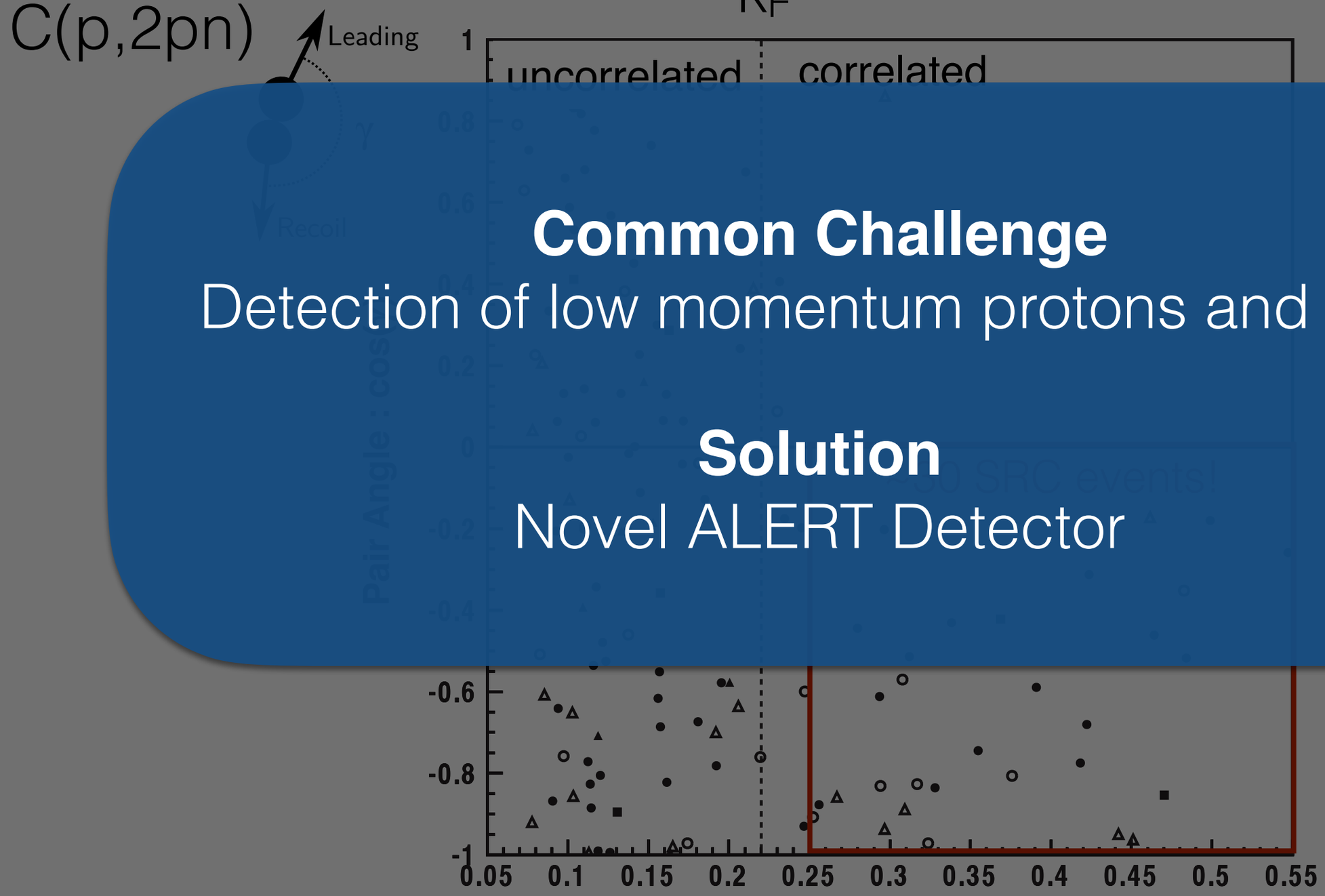


Common Challenge

Detection of low momentum protons and ions

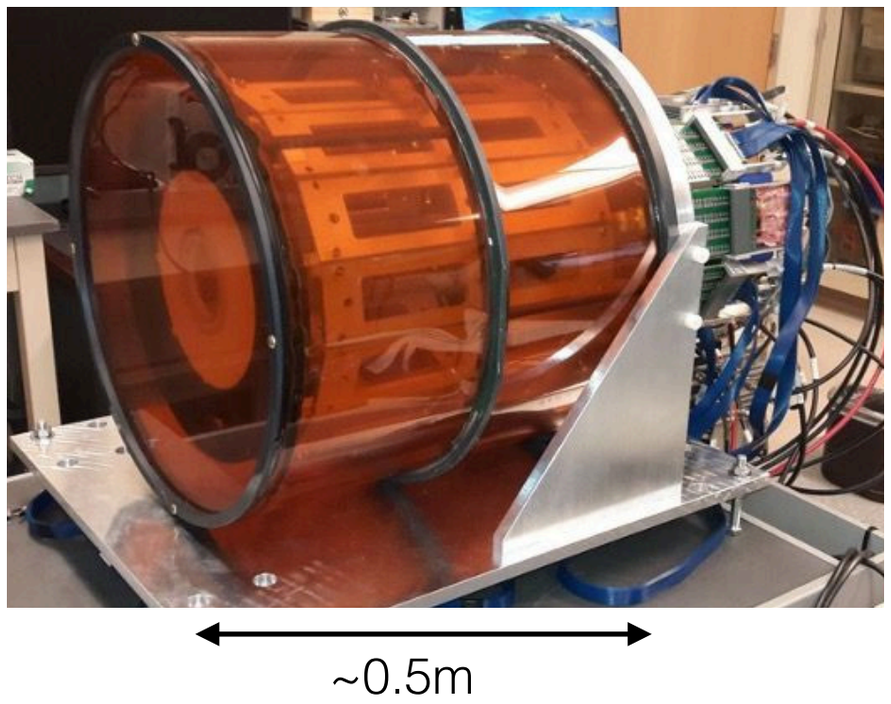
Solution

Novel ALERT Detector

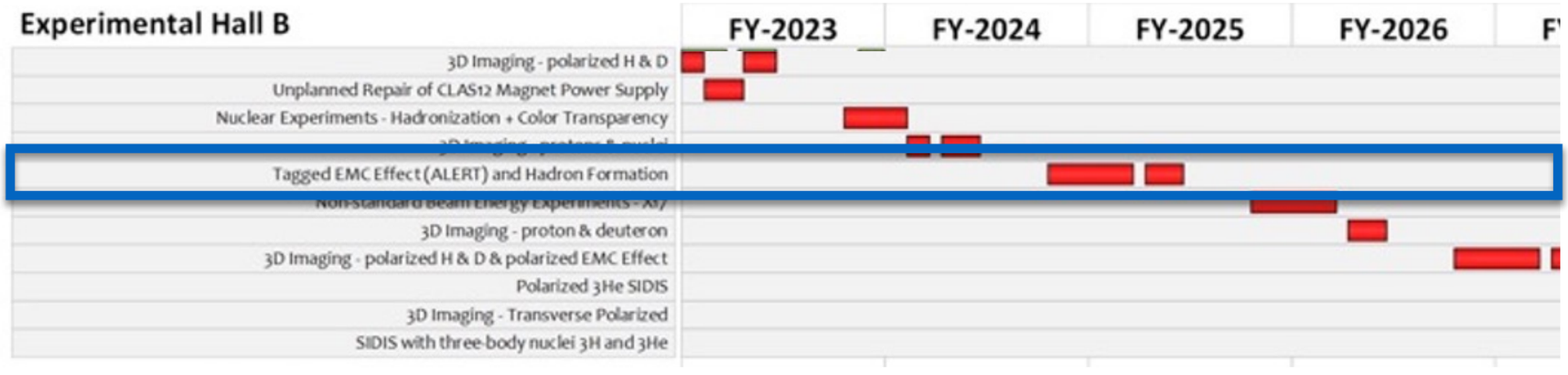
ALERT Detector - Unique Opportunity

- A Low Energy Recoil Tracker (ALERT)
  - deuteron: 100 - 300 MeV/c
  - triton:120 - 300 MeV/c
  - blind to minimum ionizing particles

- Large angular acceptance
  - 25-160° polar
  - ~340° azimuthal

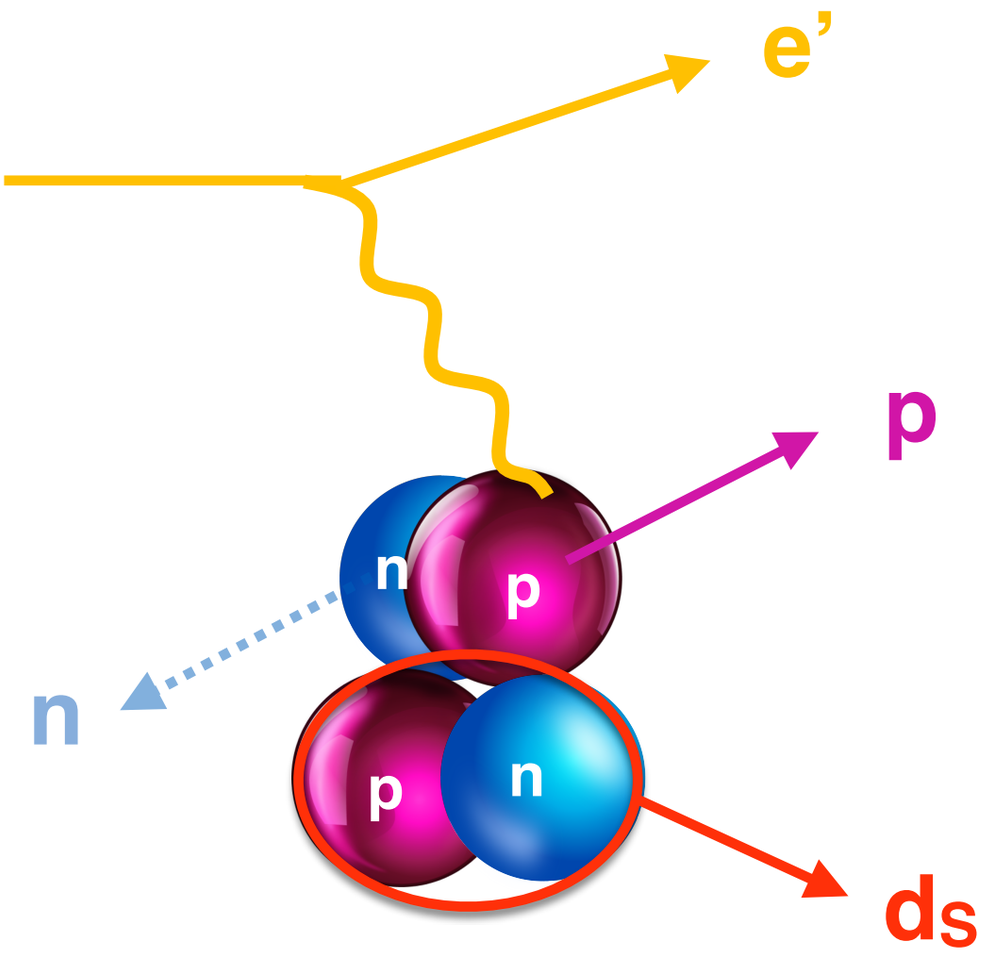


- Expected to run next year with 11 GeV beam



2023 JLab Users meeting, David Dean

Main Channel ^{4}He(e,e'pd$_S$)n



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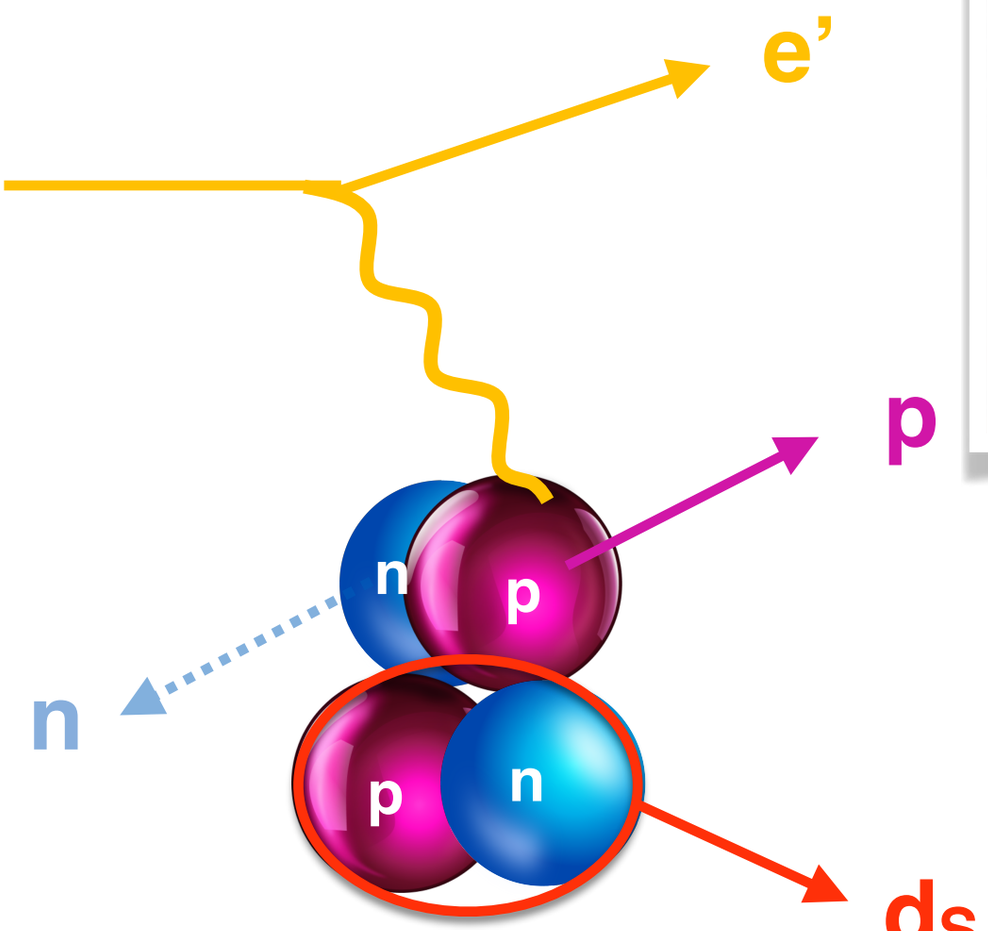
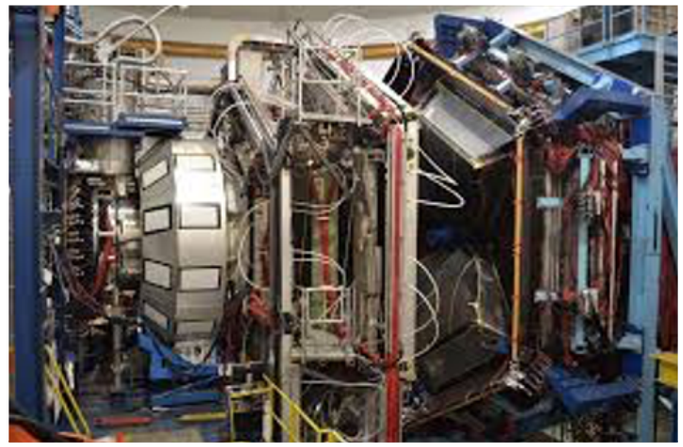
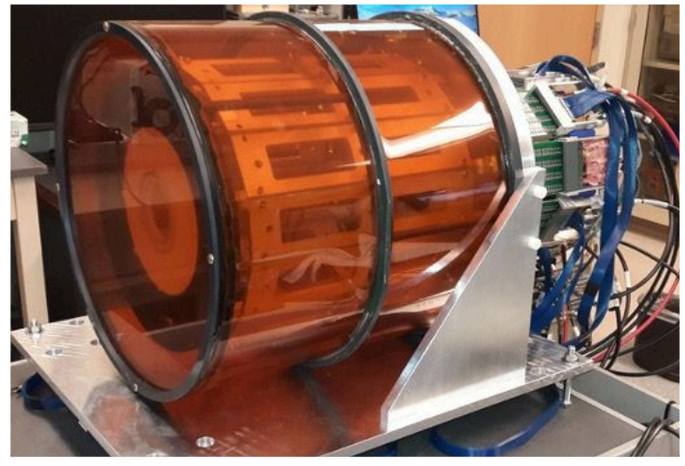


CLAS12

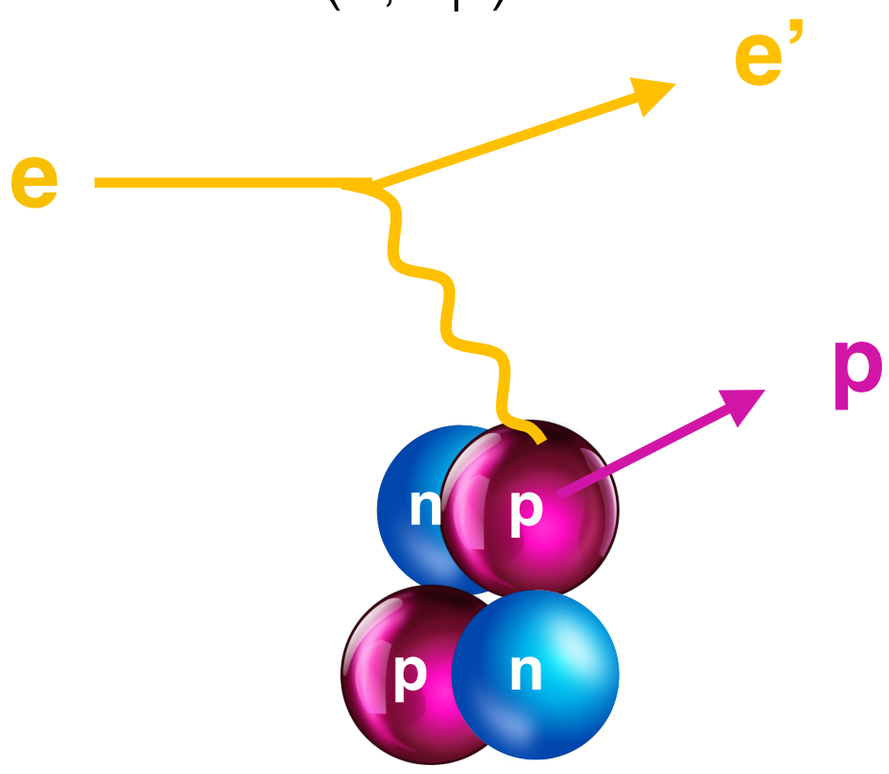


ALERT

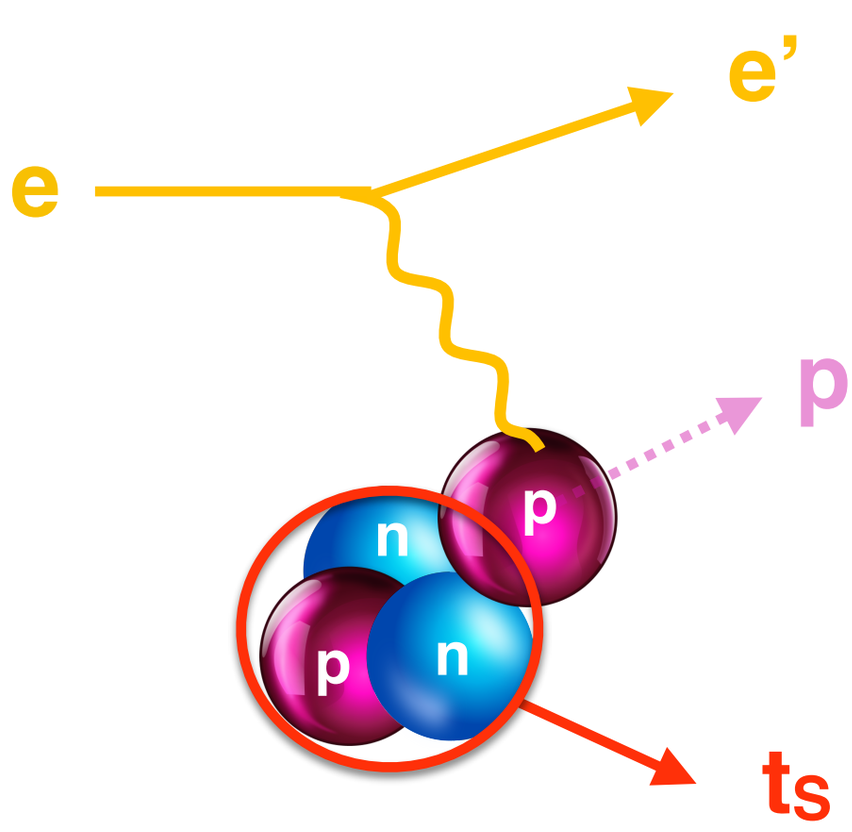


Other Channels

^{4}He(e,e'p)

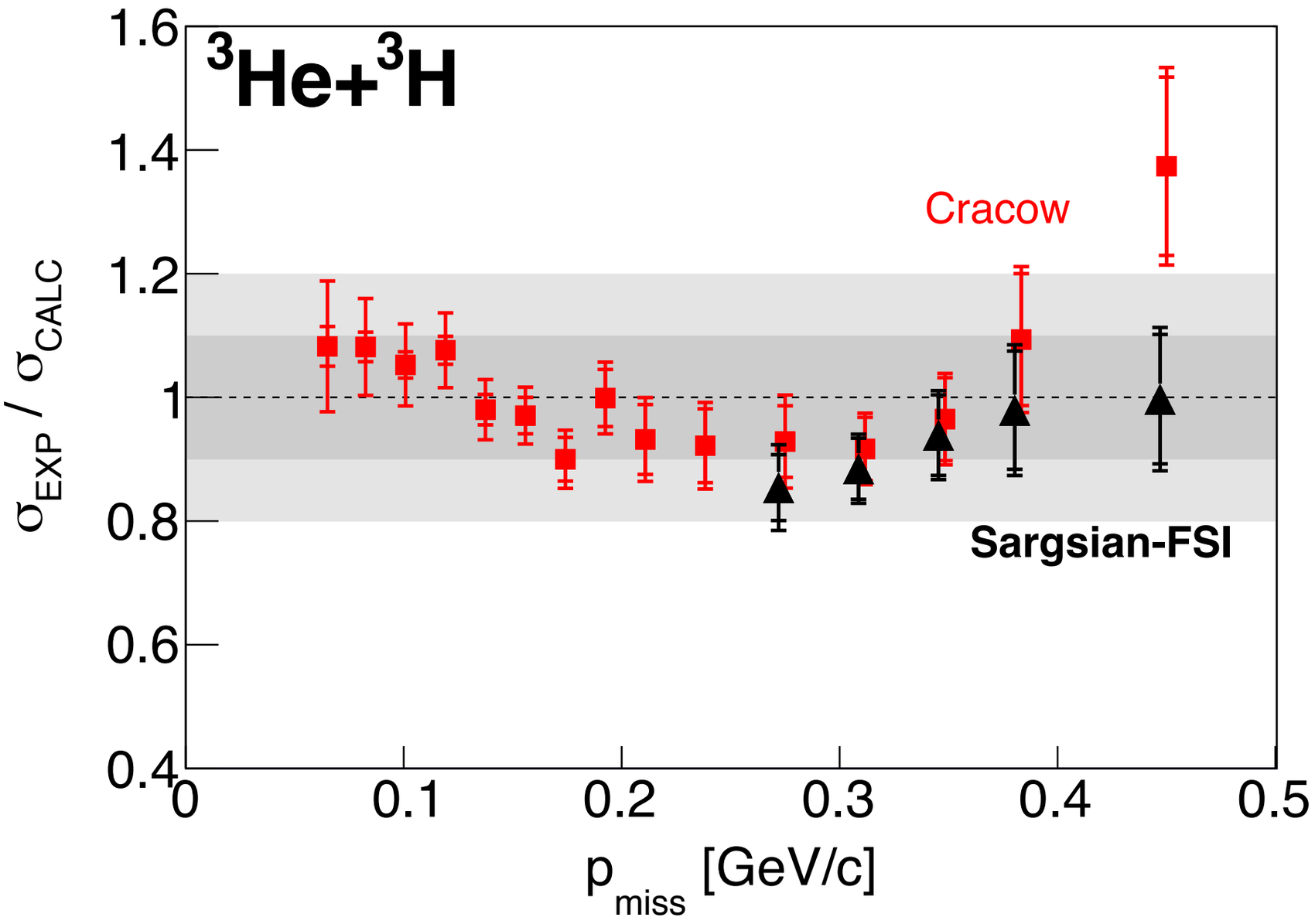


^{4}He(e,e't$_s$)p



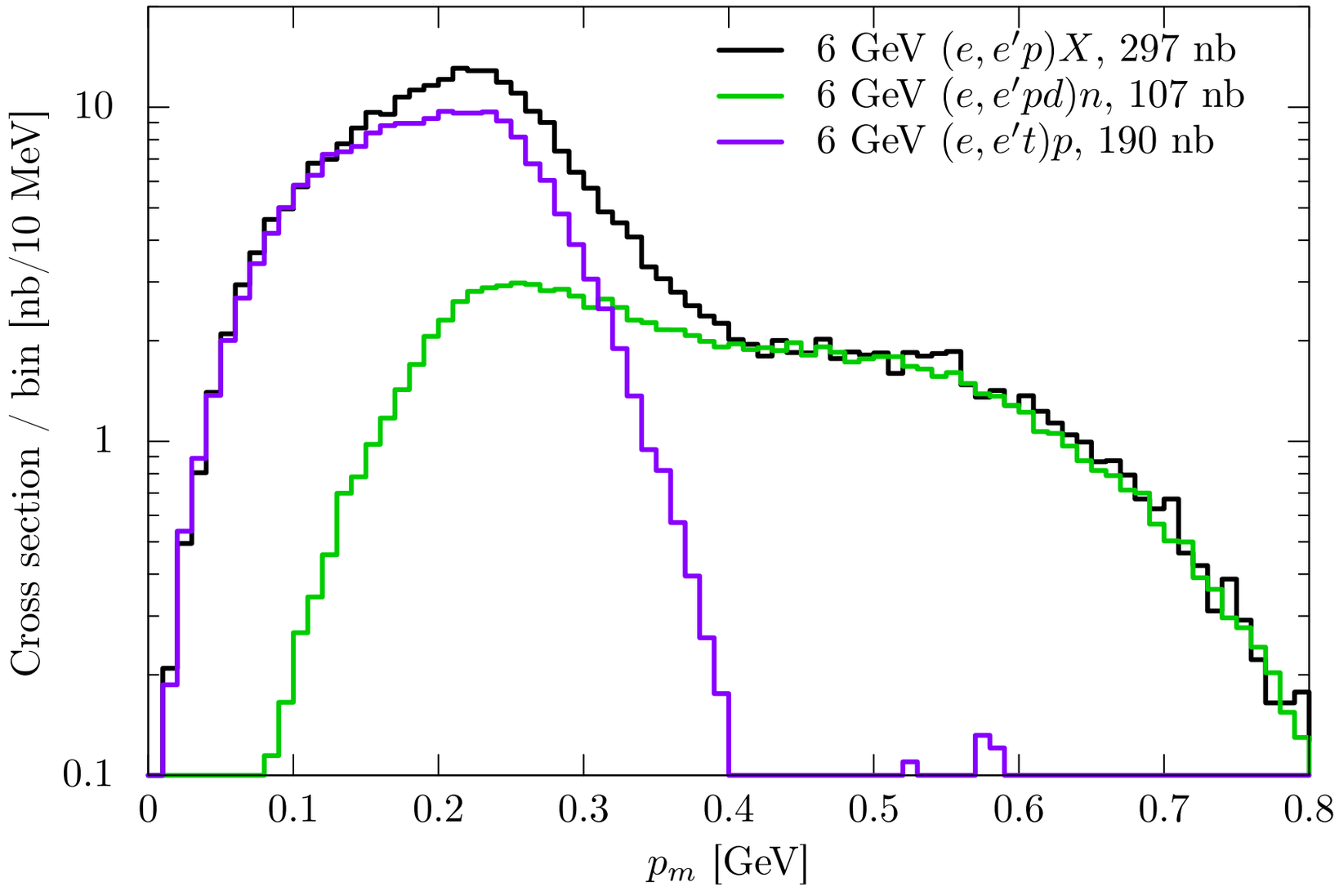
Interlude: ^{3}He + Tritium Cross Sections

PRL124 (2020) **Editors' Suggestion**



- Validation of A=3 ground state up to 500 MeV/c!

Bonus Goal: Validation of ^{4}He Model



- Simulations with Plane-Wave-Impulse-Approximation
  - ^{4}He spectral function (N. Rocco and A. Lovato)
  - Two-body and three-body breakup
- Triton momentum acceptance ~120 - 300 MeV/c

Supportive TAC Reports

- Technical Report:

There are no technical issues to run the CLAS12 Forward Detector with the ALERT detector installed in the solenoid at 6.6 GeV. The experiment proposes to run in the same configuration as planned for the 5-pass RG-L experiment. The identification of deuteron and triton recoils will be even cleaner at the lower energy compared to running at 11 GeV. This beam time, if approved, should be integrated into the already scheduled RG-L experiment due to the overhead associated with installing and configuring the ALERT detector in CLAS12, for example immediately following after the RG-L 11 GeV beam time scheduled in Hall B in 2024.

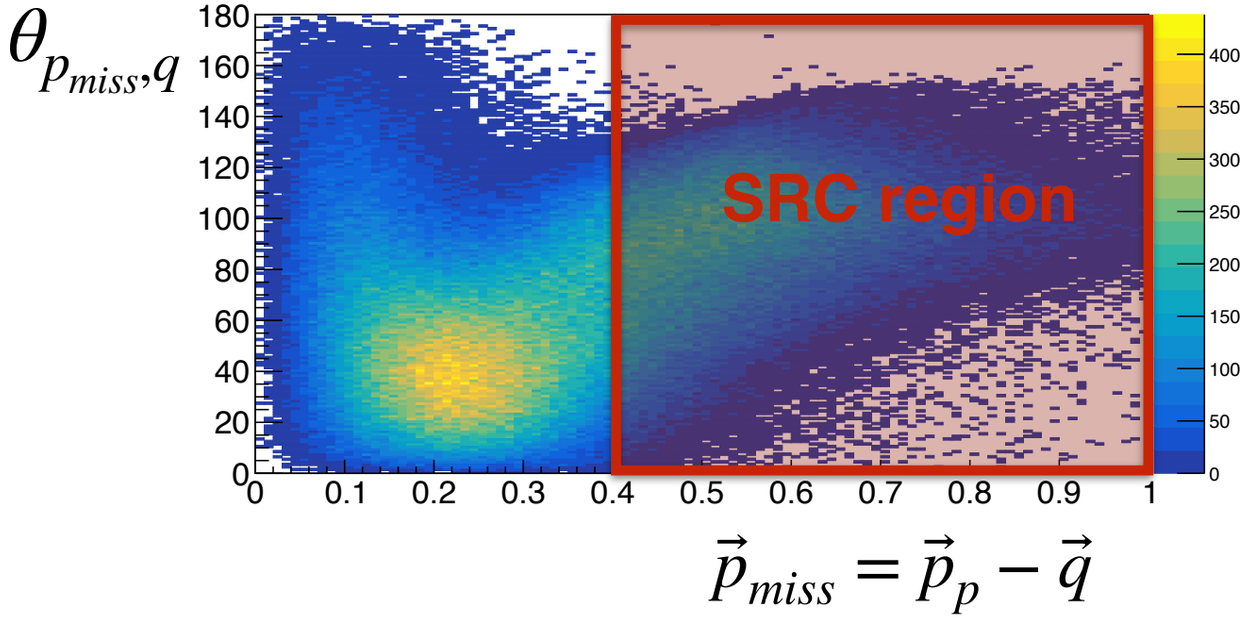
- Theory Report:

It is of significant importance to establish factorization and understand how it sets in as $\vec{p}_{rel}$ increases. This endeavor is certainly part of a program that should eventually be carried out from light to heavier nuclei.

The measurements in the experiment are important for the understanding of SRCs, and the setup seems to make an optimal use of the Hall B capabilities, as shown by the detailed analysis of section III B of the proposal.

Rate Estimates

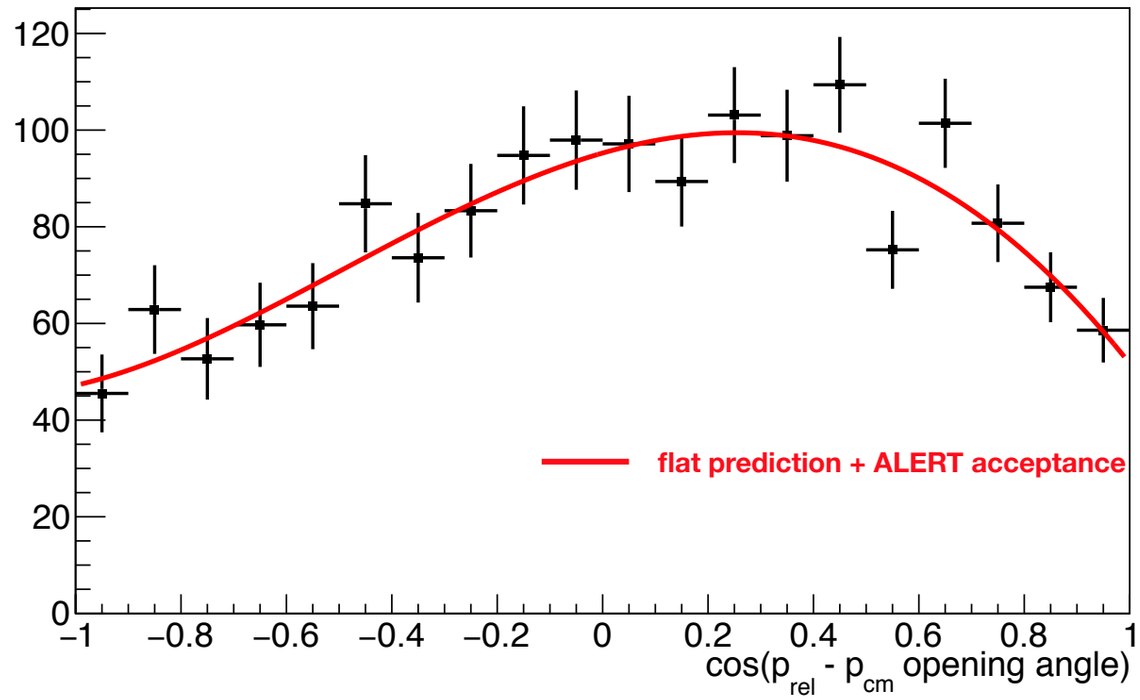
- Measured CLAS12 rates (RGM ^{4}He(e,e'p) data), scaled to ALERT luminosity
- Standard CLAS12 SRC events selection cuts
- Account for recoil ion tagging using ab-initio spectral function event generator and a ALERT simulation



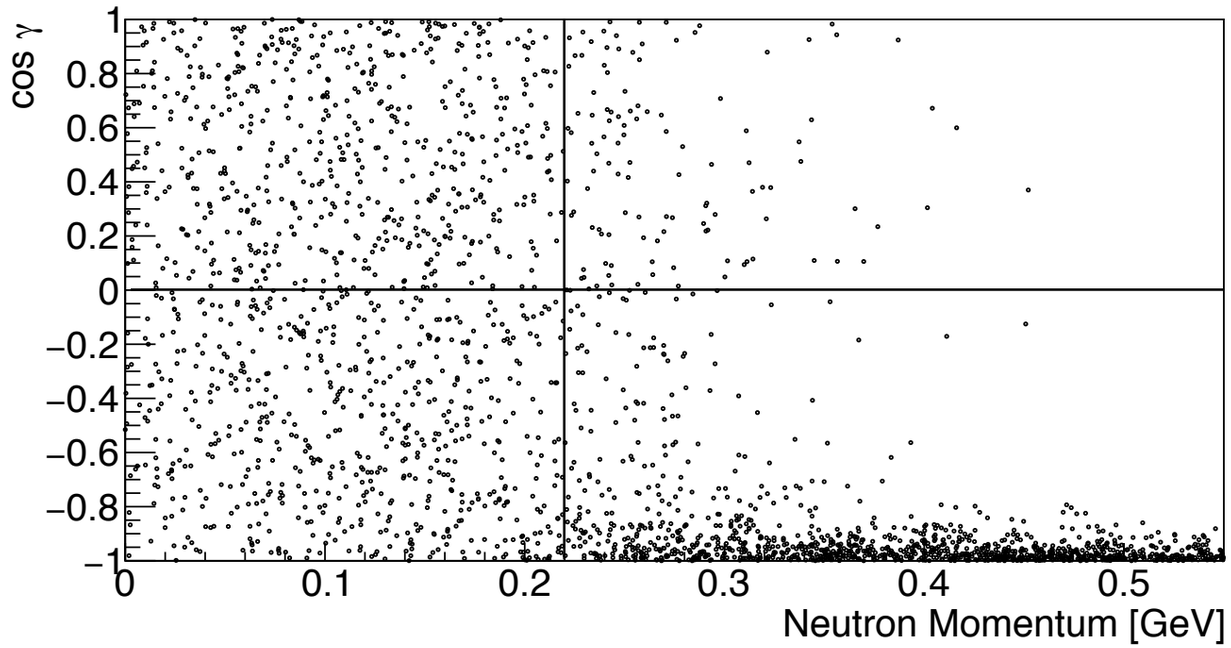
- 3 x 10^{34} luminosity
- **17 PAC days**
- 1600 SRC events with deuteron tagging

Projected Results: ^{4}He(e,e'd$_s$p)n

- **Test of Factorization**
  - 1600 SRC events from ^{4}He(e,e'pd$_s$)n
  - Based on flat prediction folded with ALERT deuteron acceptance

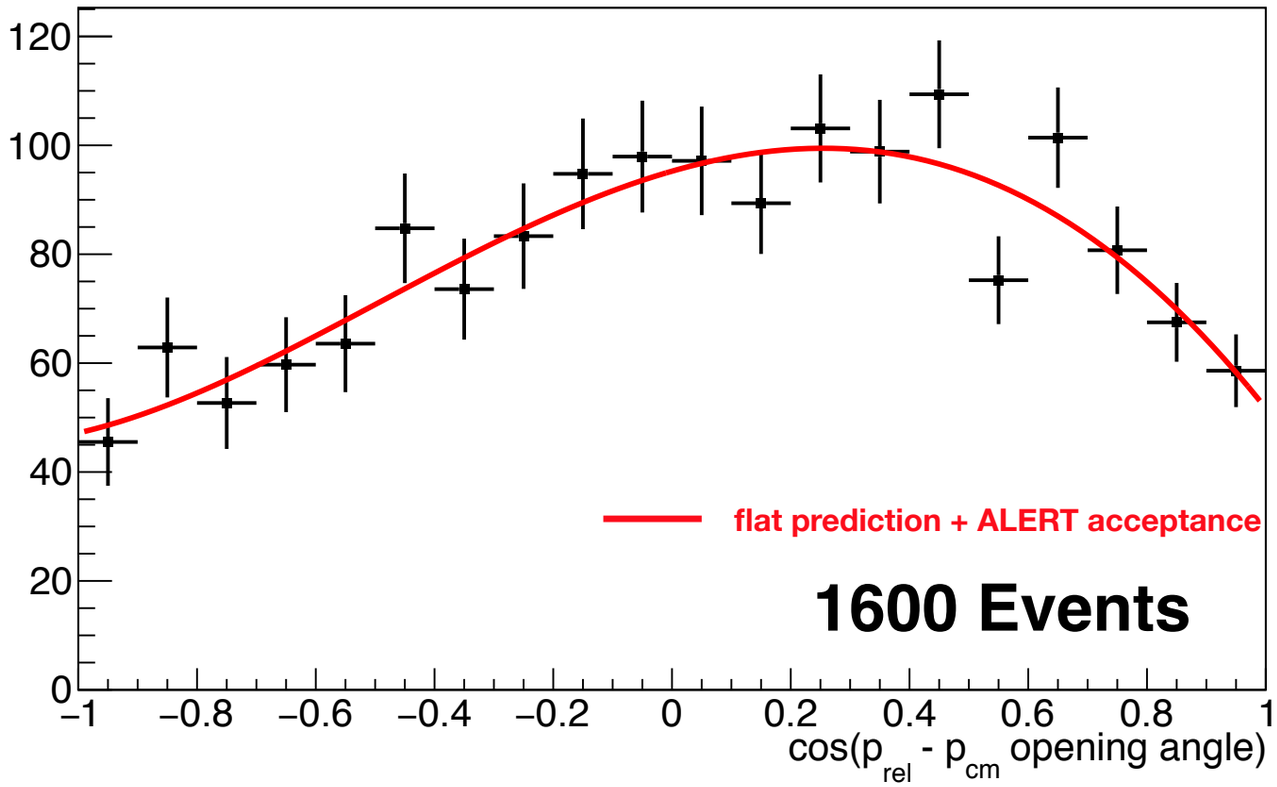


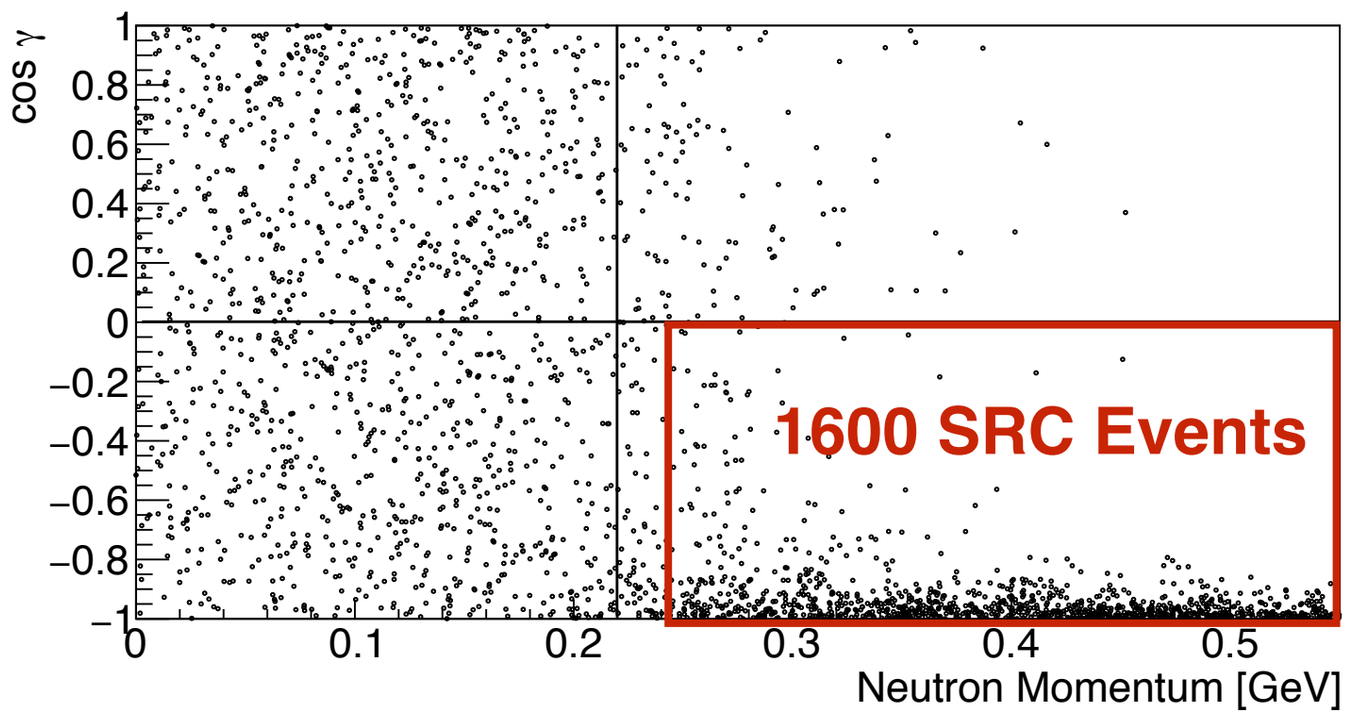
- **Transition Mapping**
  - 1600 SRC events from ^{4}He(e,e'pd$_s$)n
  - Similar or more uncorrelated MF events
  - 80 MeV/c neutron momentum resolution



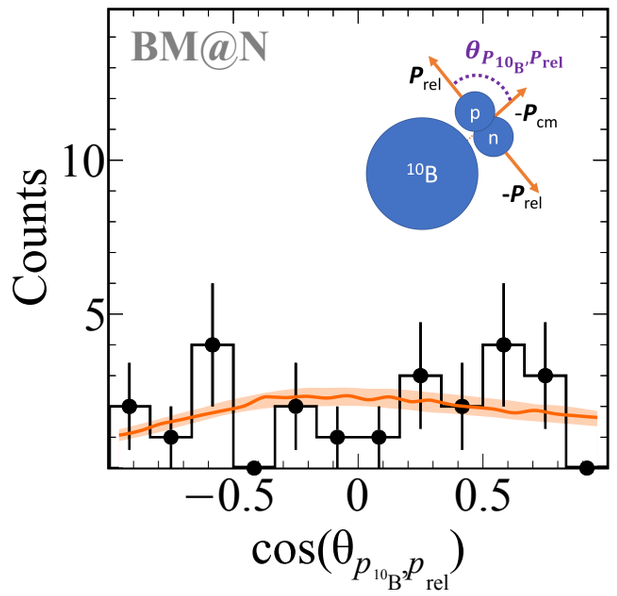
Projected Results: ^{4}He(e,e'd$_s$p)n

This Proposal

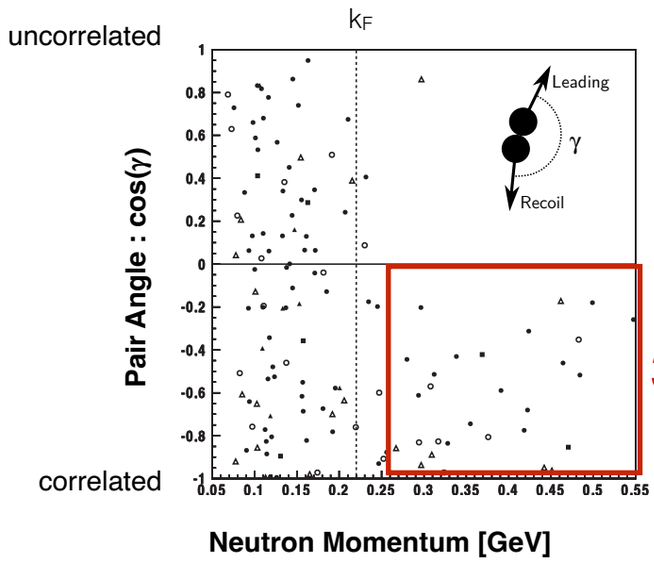




Previous Experiments

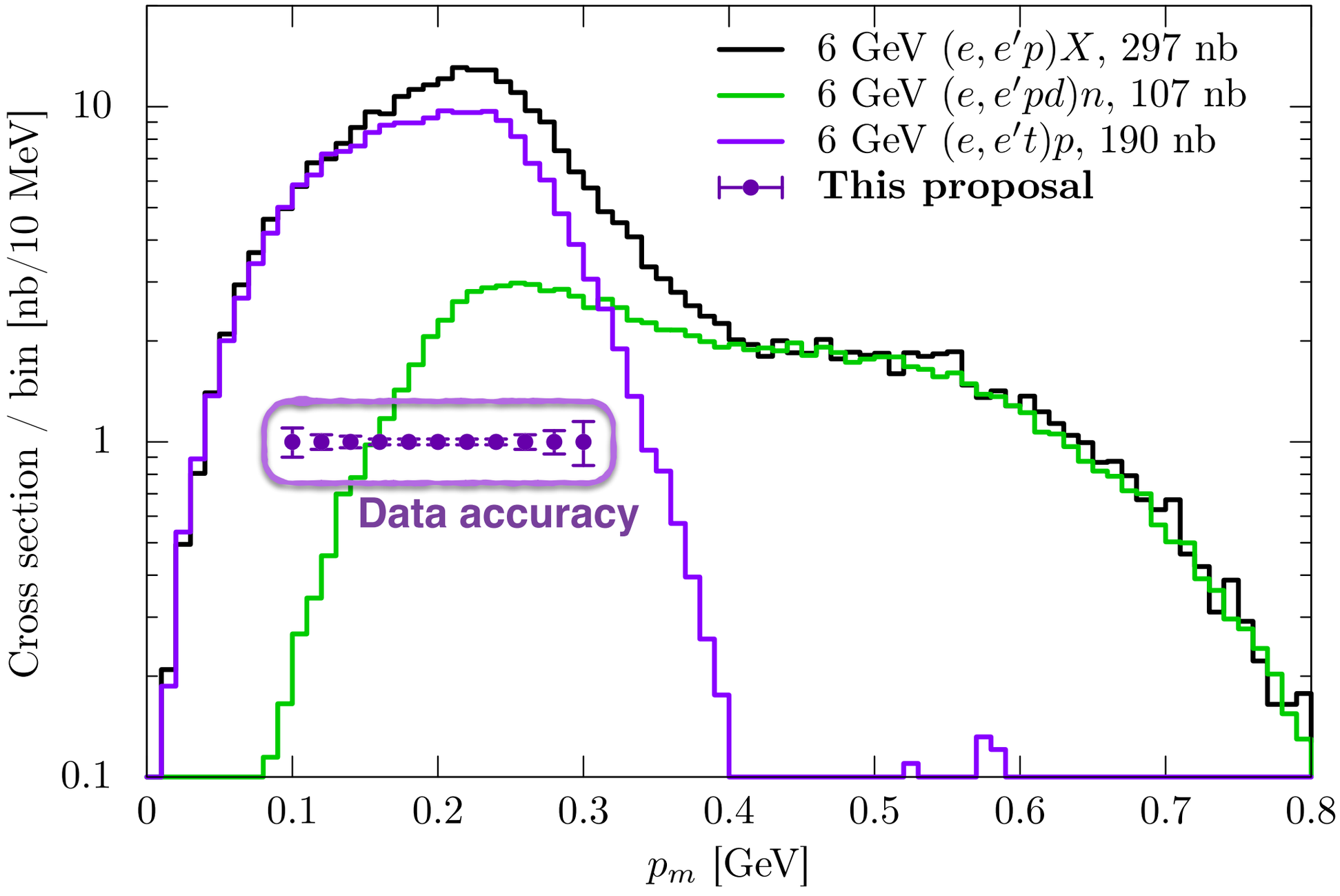


23 events



30 Events

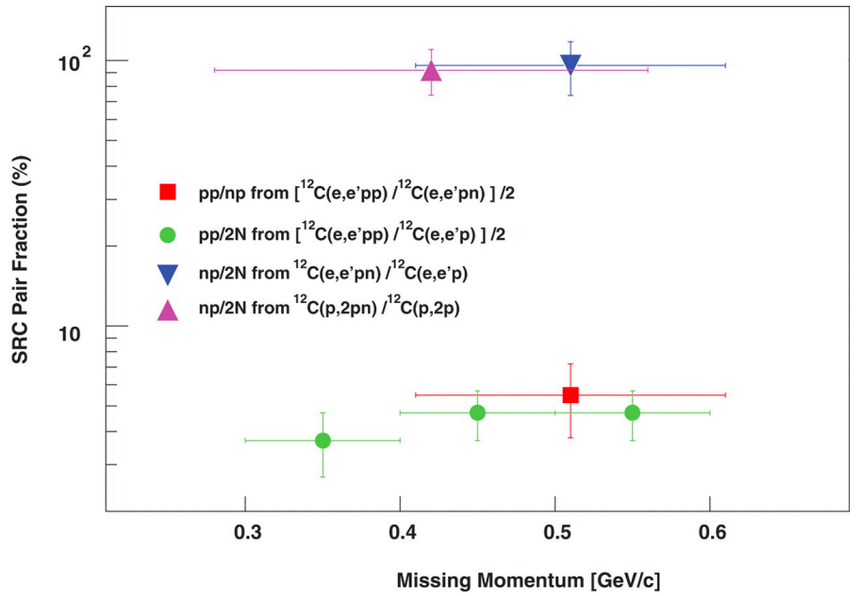
Projected Results ^{4}He(e,e't_s)p



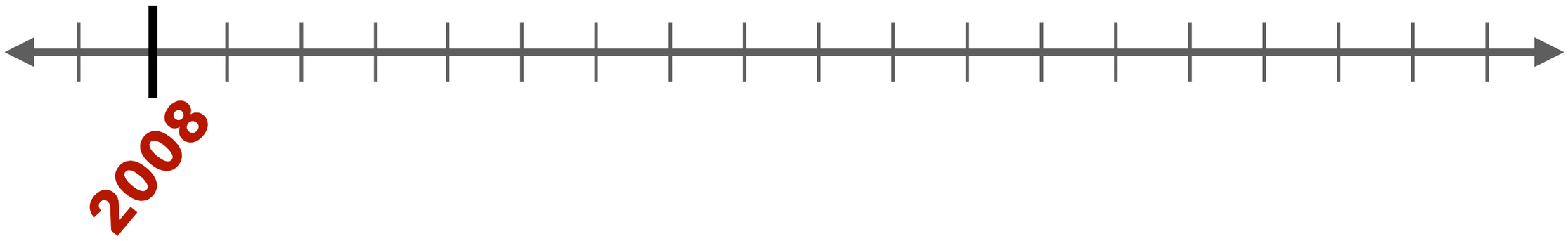
Next frontier in the JLab SRC Program

1) Established np-dominance in ^{12}C

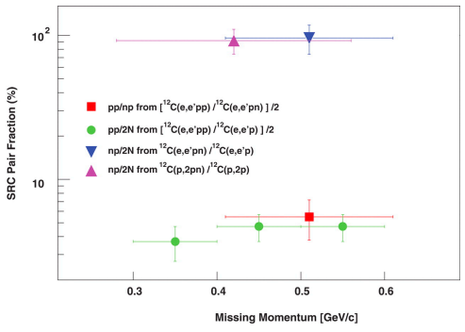
Science (2008)

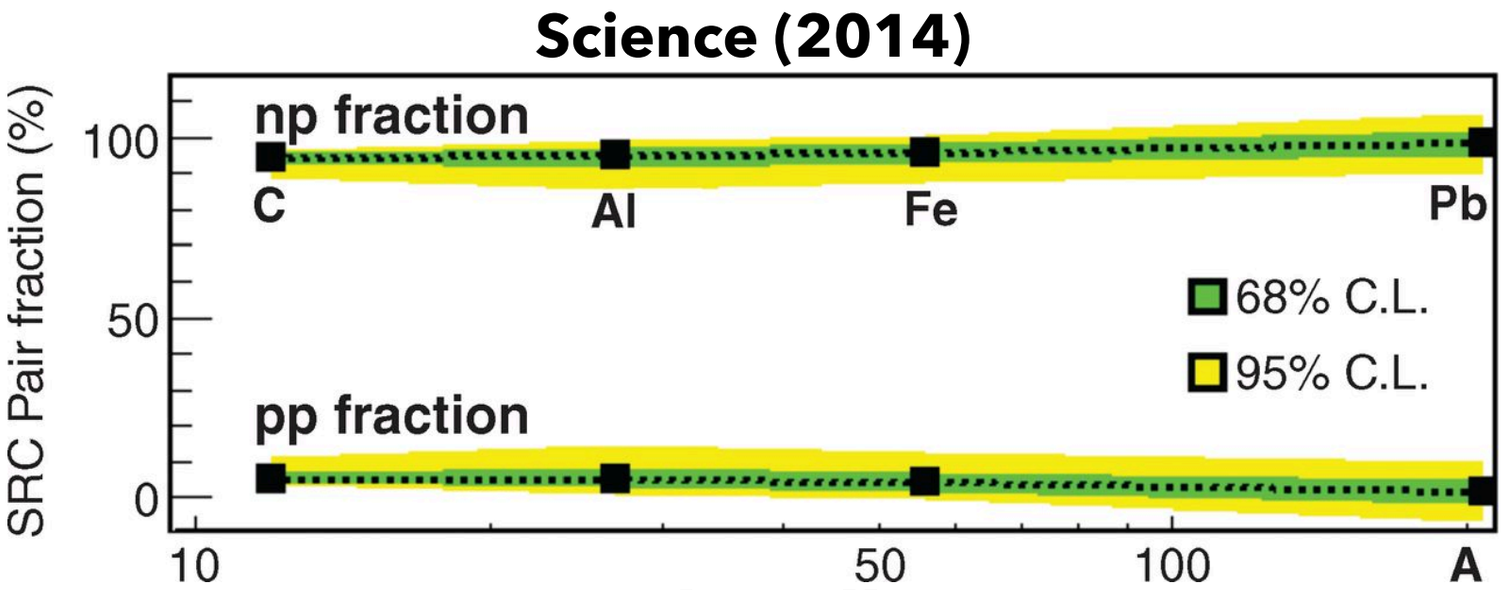


JLab Hall A, BNL

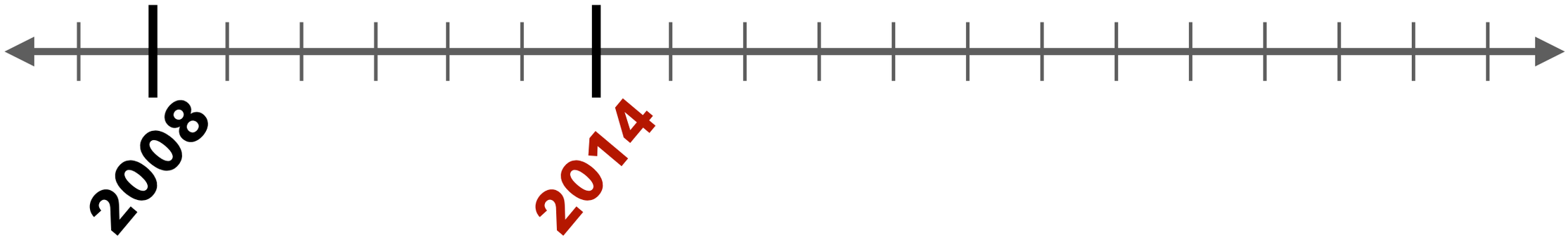


2) Universal np-dominance up to lead

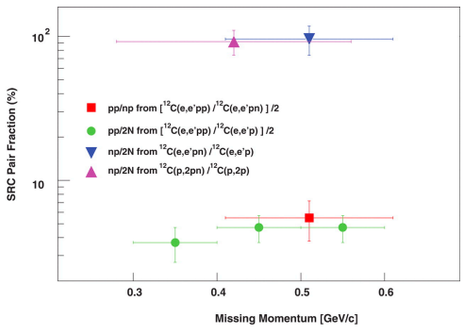


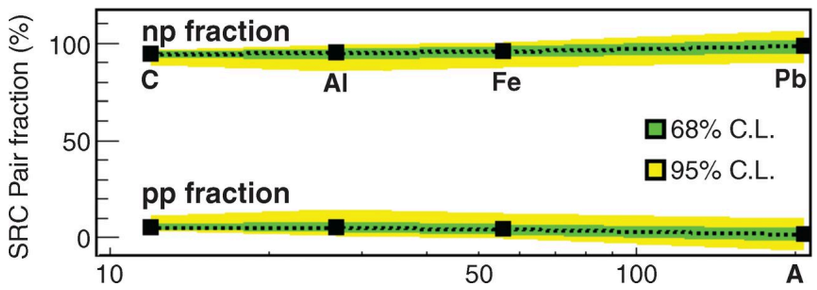


Science

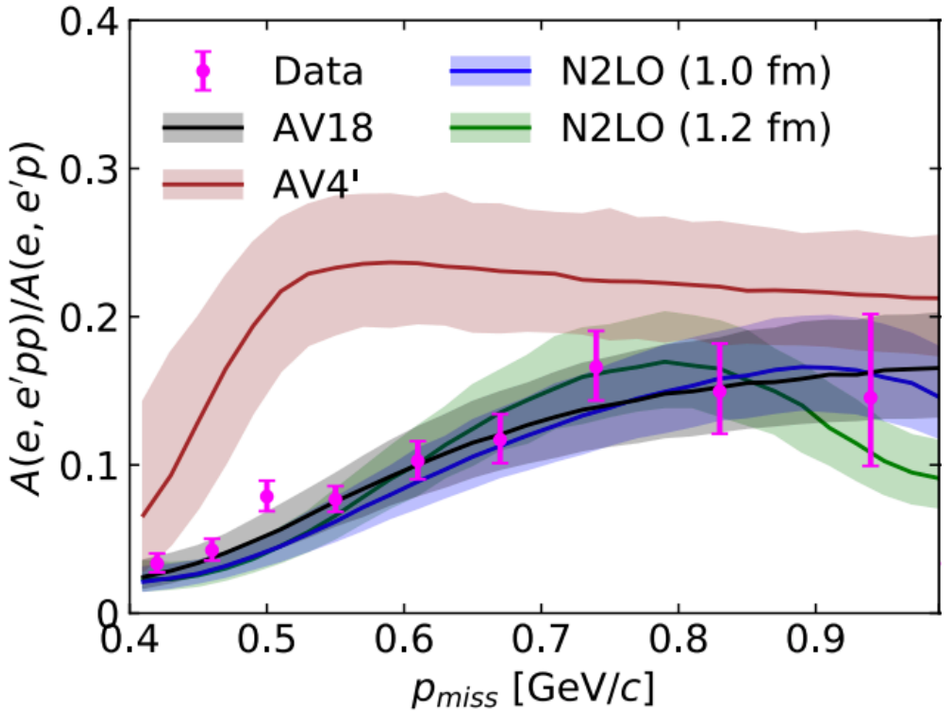


3) First map of SRC Isospin evolution





Nature (2020)



Science **Science**

JLab Hall B

2008 **2014** **2020**

Many more results…

2018:
Nature 560, 617 (2018)
Phys. Rev. Lett. 121, 092501 (2018)
Phys. Lett. B 785, 304 (2018)
Phys. Lett. B 780, 211 (2018)

2019:
Nature 566, 354 (2019)
Phys. Rev. Lett, 122, 172502 (2019)
Phys. Lett. B 797, 134890 (2019)
Phys. Lett. B 797, 134792 (2019)
Phys. Lett. B 793, 360 (2019)
Phys. Lett. B 791, 242 (2019)

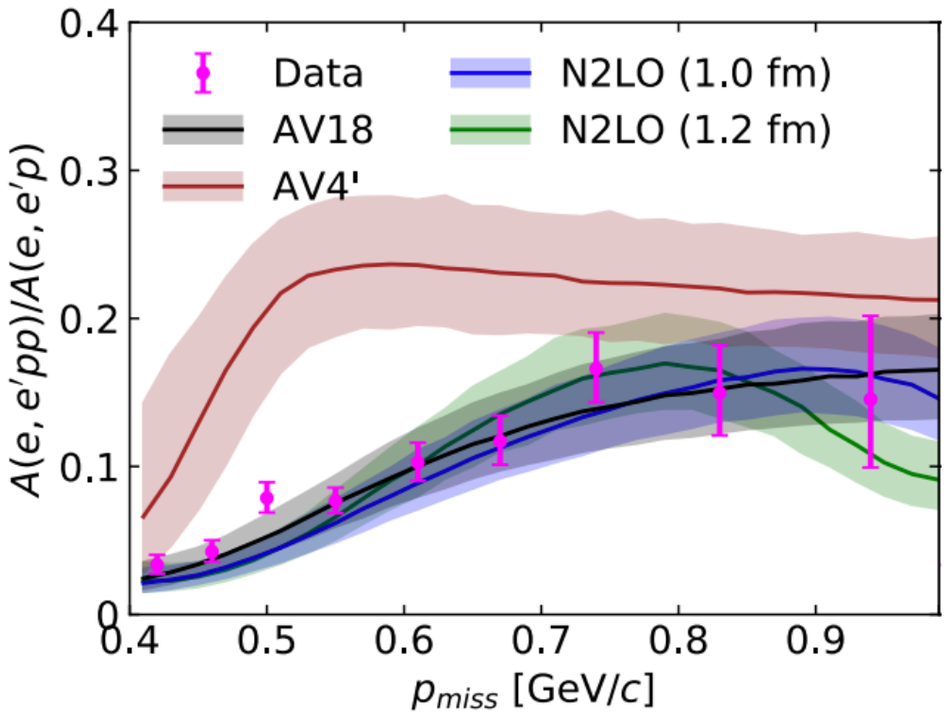
2020:
Nature 578, 540 (2020)
Phys. Rev. Lett. 124, 212501 (2020)
Phys. Rev. Lett. 124, 092002 (2020)
Phys. Lett. B 805, 135429 (2020)
Phys. Lett. B 811, 135877 (2020)
Phys. Lett. B 800,135110 (2020)

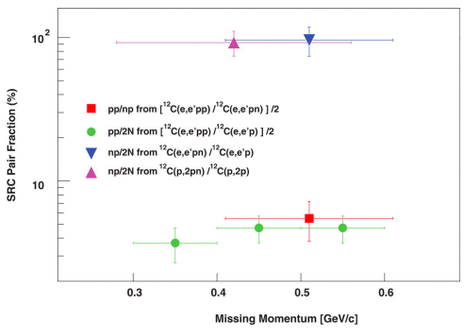
2021:
Nature Physics 17, 693 (2021)
Nature Physics 17, 306 (2021)
Phys. Lett. B 820, 136523 (2021)
Phys. Rev. Research 3, 023240 (2021)
Phys. Rev. C Lett. 103, L031301 (2021)

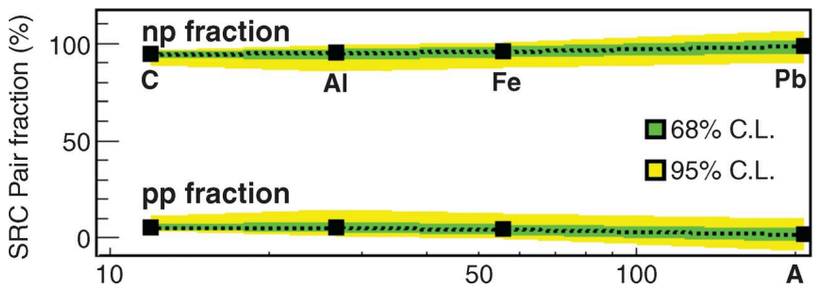
2022:
Phys. Rev. C 105, 034001 (2022)

2023:
Phys. Rev. C 107, L061301 (2023)
Nucl. Instrum. Meth. A 1052, 168238 (2023)

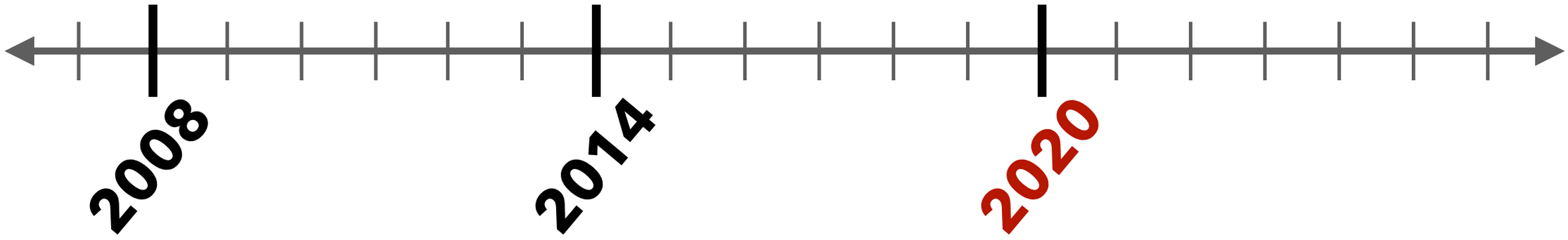
Nature (2020)



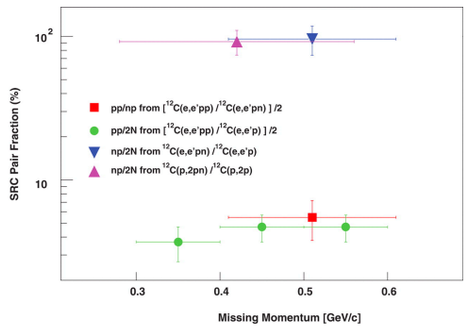


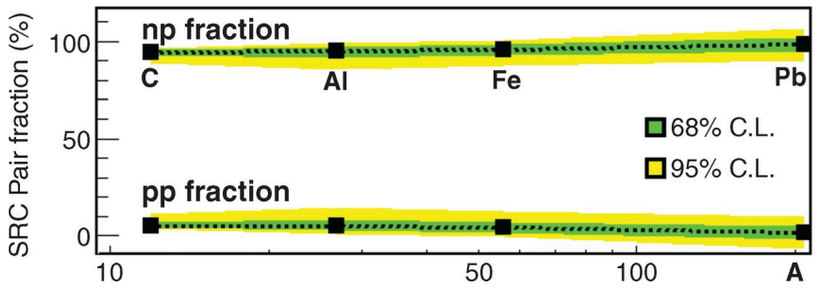


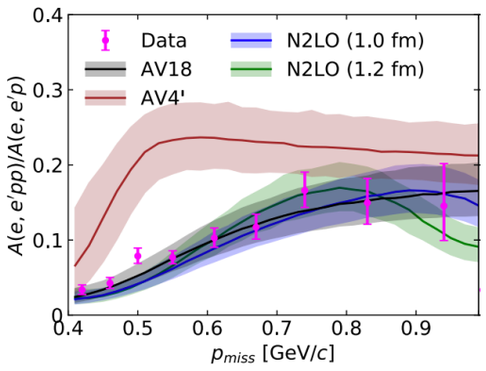
Science **Science** **JLab Hall B**

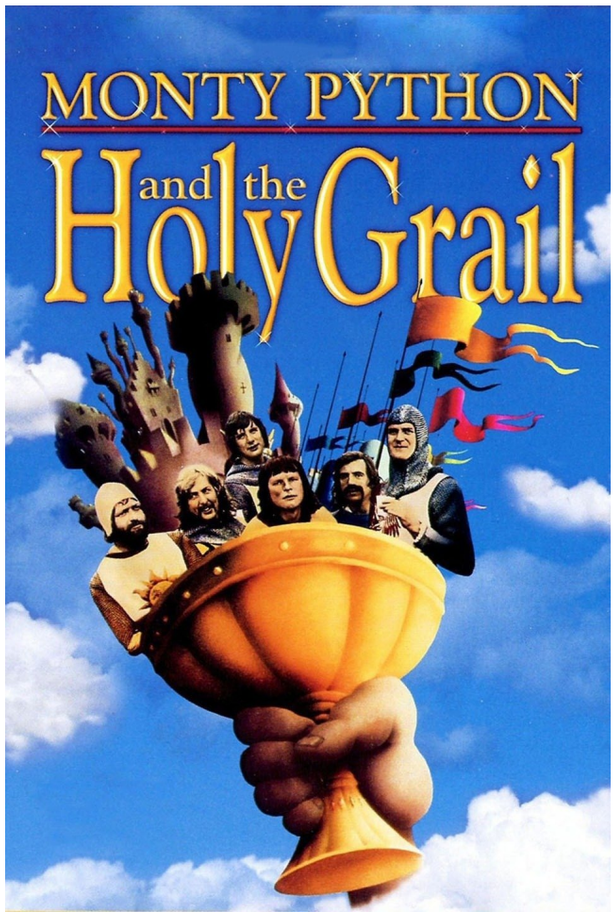


Precision SRC Measurements and comparisons with ab-initio theory

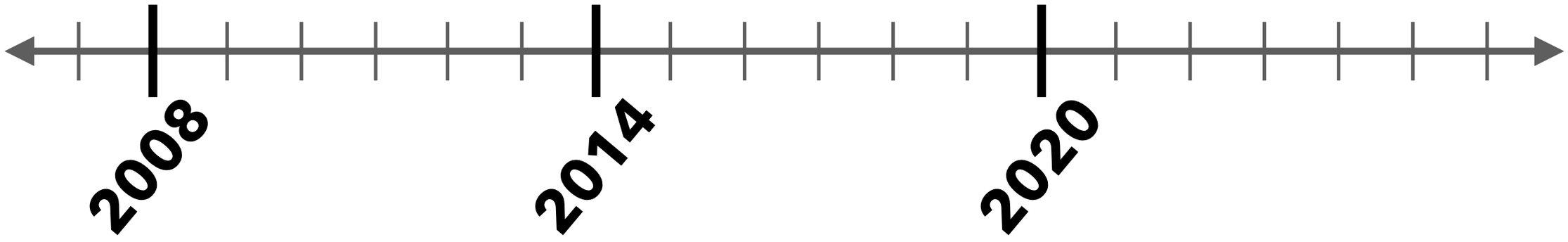




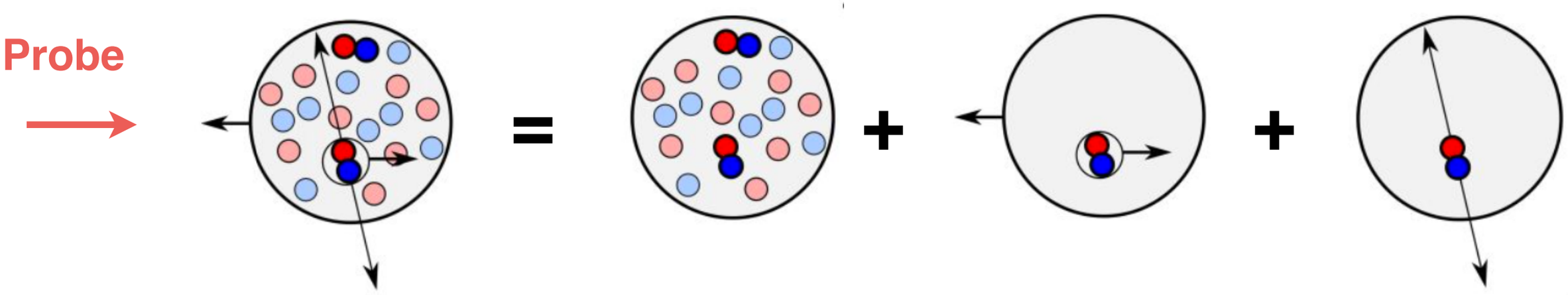




Science **Science** **Nature**



Open Questions and Worldwide SRC Program



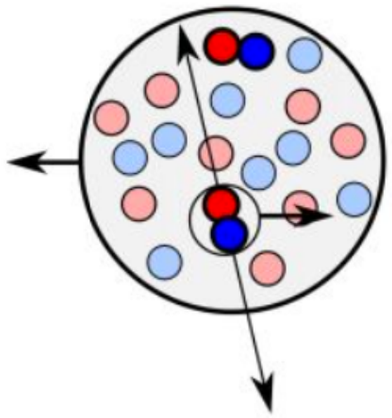
Pair abundance Pair properties NN interaction

Open Questions and Worldwide SRC Program

Probe Independence

CLAS12/RGM
GSI/JINR
SRC@HallD

e
p
γ

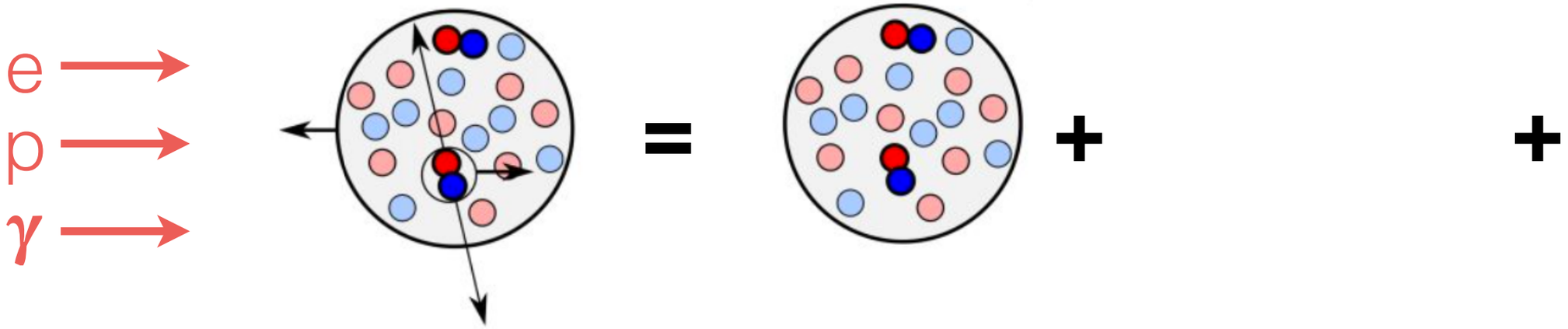


Open Questions and Worldwide SRC Program

Probe Independence

CLAS12/RGM
GSI/JINR
SRC@HallD

Pair Abundance
CLAS12/RGM
CaFe@HallC
Inclusive@HallC
GSI



Open Questions and Worldwide SRC Program

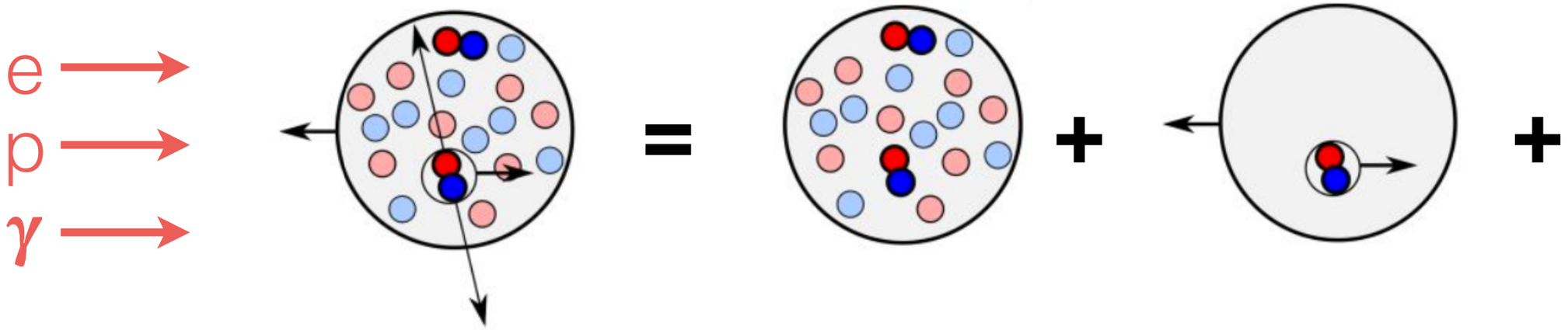
Probe Independence

CLAS12/RGM
GSI/JINR
SRC@HallD

Pair Abundance
CLAS12/RGM
CaFe@HallC
Inclusive@HallC
GSI

Pair Properties

CLAS12/RGM
SRC@Hall D



Open Questions and Worldwide SRC Program

Probe Independence

CLAS12/RGM
GSI/JINR
SRC@HallD

Pair Abundance

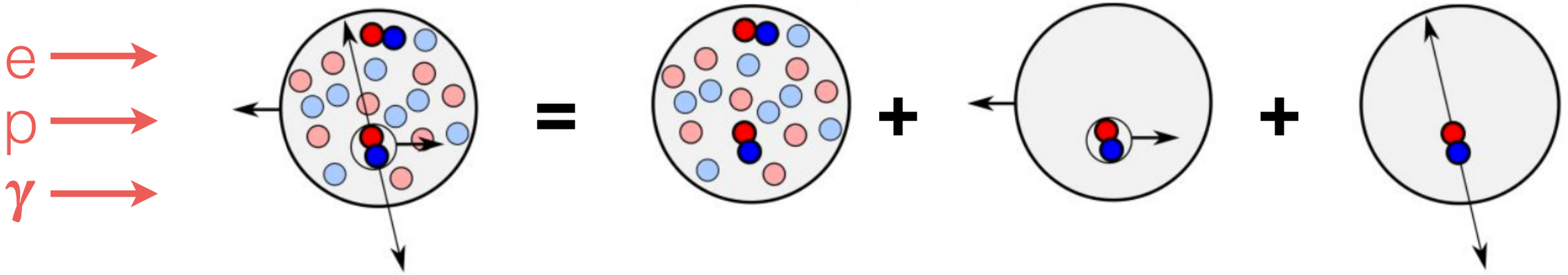
CLAS12/RGM
CaFe@HallC
Inclusive@HallC
GSI

Pair Properties

CLAS12/RGM
SRC@Hall D

NN Interaction

CLAS12/RGM
SRC@Hall D



Open Questions and Worldwide SRC Program

Probe Independence

CLAS12/RGM
GSI/JINR
SRC@HallD

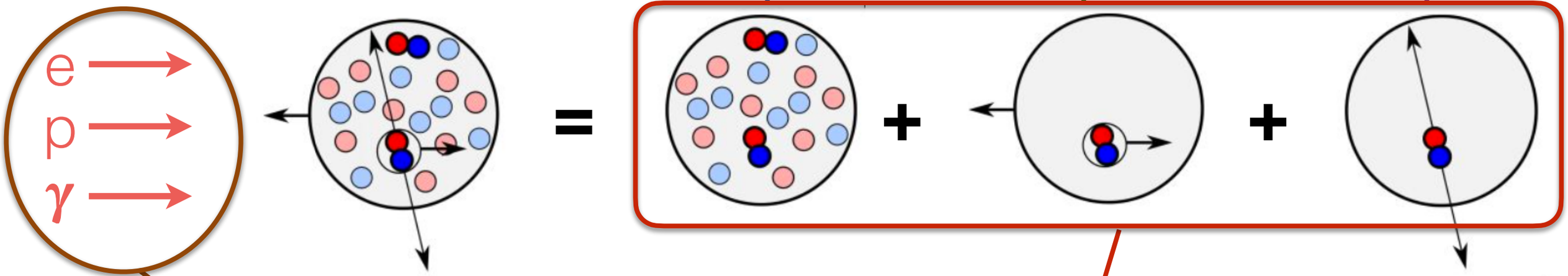
Pair Abundance
CLAS12/RGM
CaFe@HallC
Inclusive@HallC
GSI

Pair Properties

CLAS12/RGM
SRC@Hall D

NN Interaction

CLAS12/RGM
SRC@Hall D



Probe Universality and precision SRC properties

Hall D proposal

Open Questions and Worldwide SRC Program

Probe Independence

CLAS12/RGM
GSI/JINR
SRC@HallD

Pair Abundance

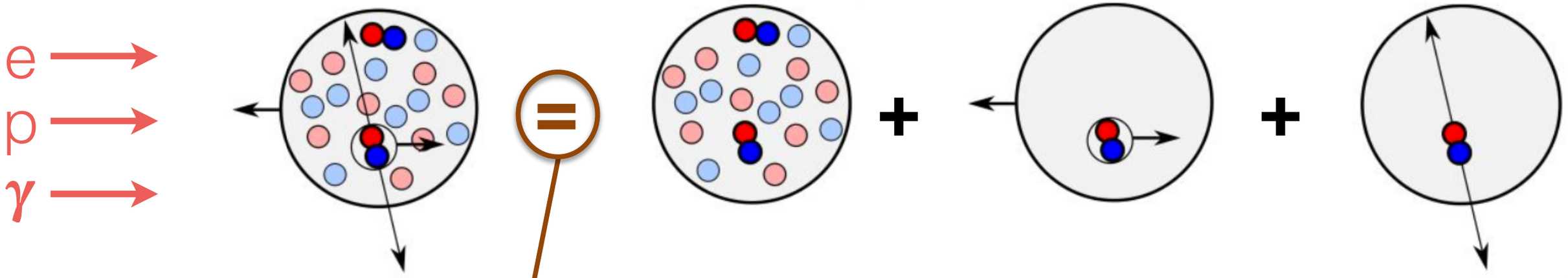
CLAS12/RGM
CaFe@HallC
Inclusive@HallC
GSI

Pair Properties

CLAS12/RGM
SRC@Hall D

NN Interaction

CLAS12/RGM
SRC@Hall D

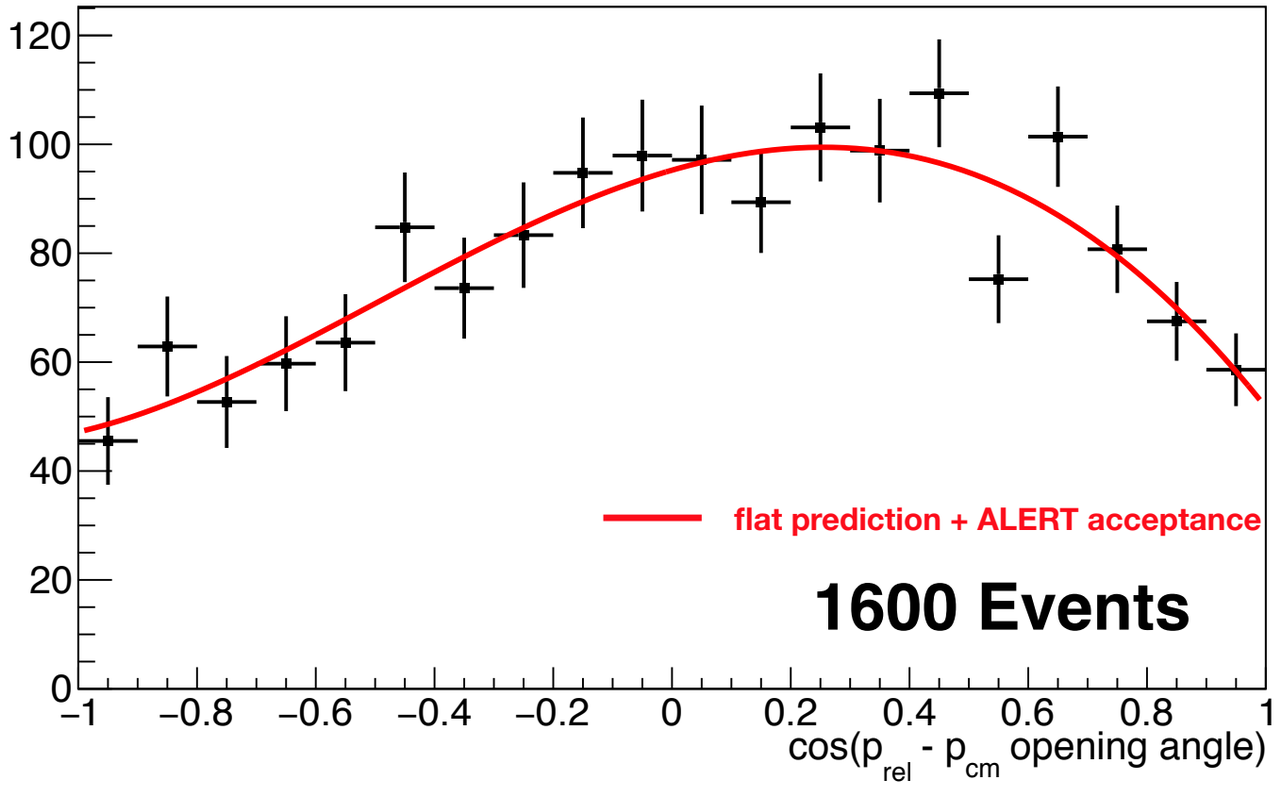


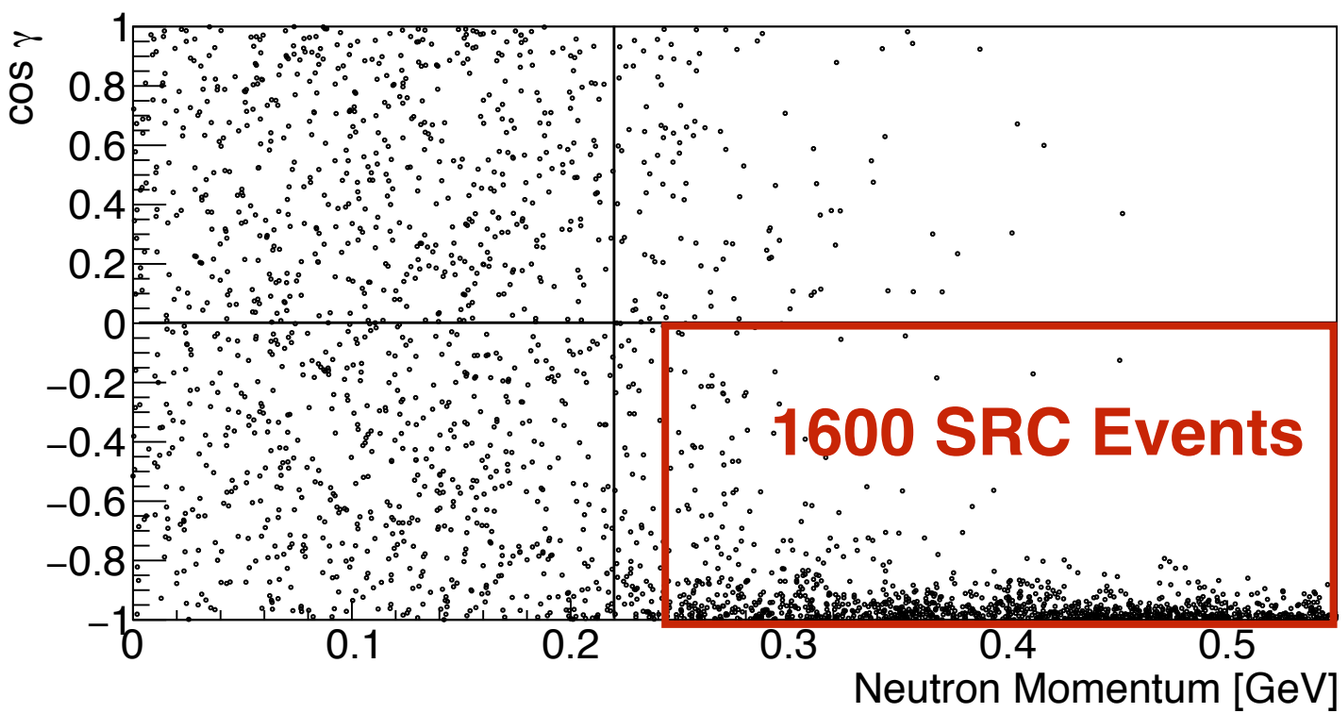
Factorization + Onset of SRC Dominance

This proposal!

Executive Summary

Projected Results: ^{4}He(e,e'pd$_S$)n





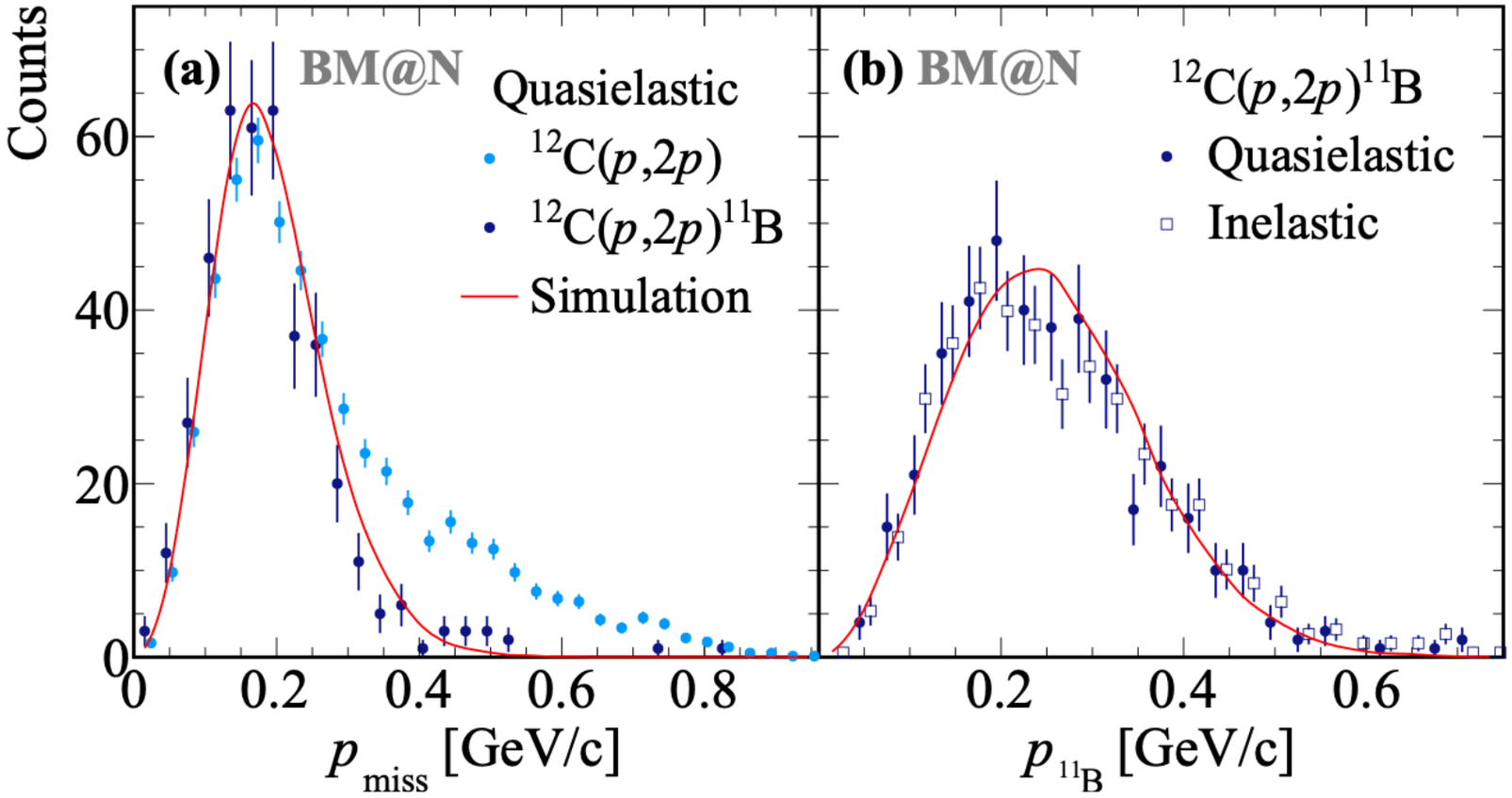
Experimental Details

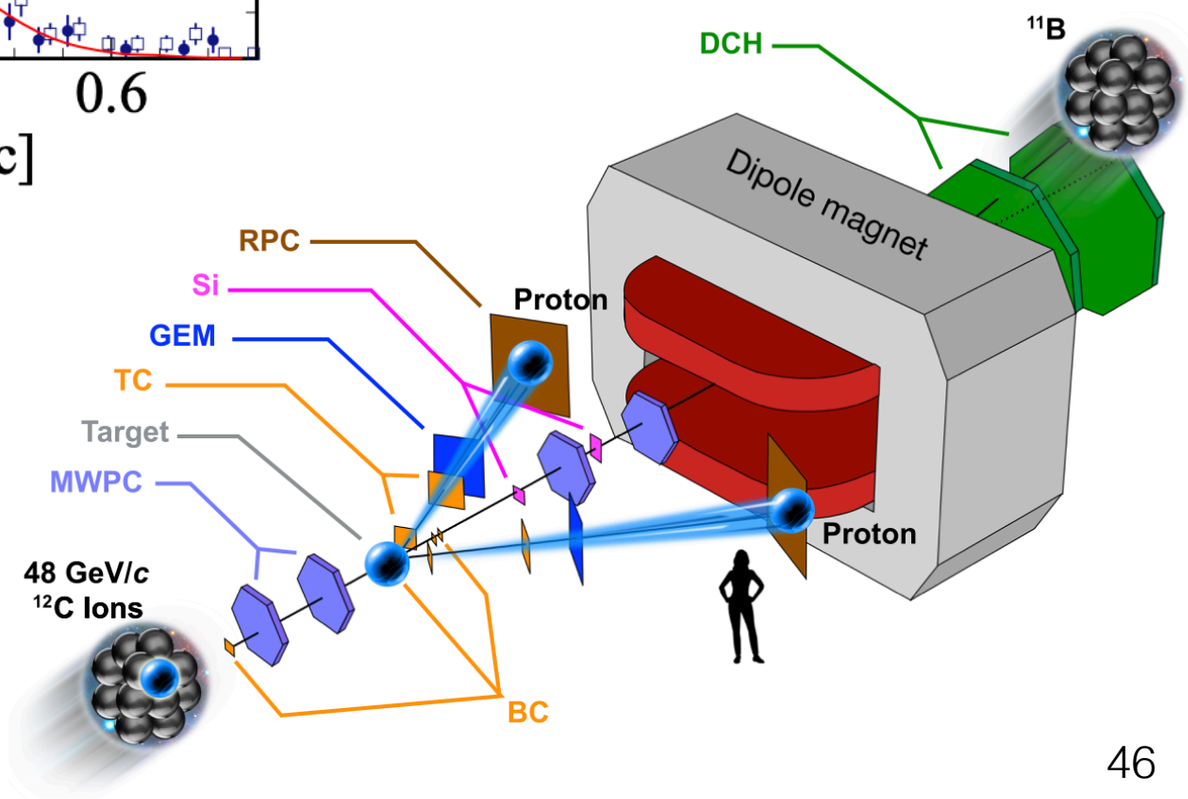
- 17 PAC days
- CLAS12+ALERT
- 6.4 GeV
- 500nA
- Standard ALERT He-4 target

Backup slides

FSI and bound fragment tagging

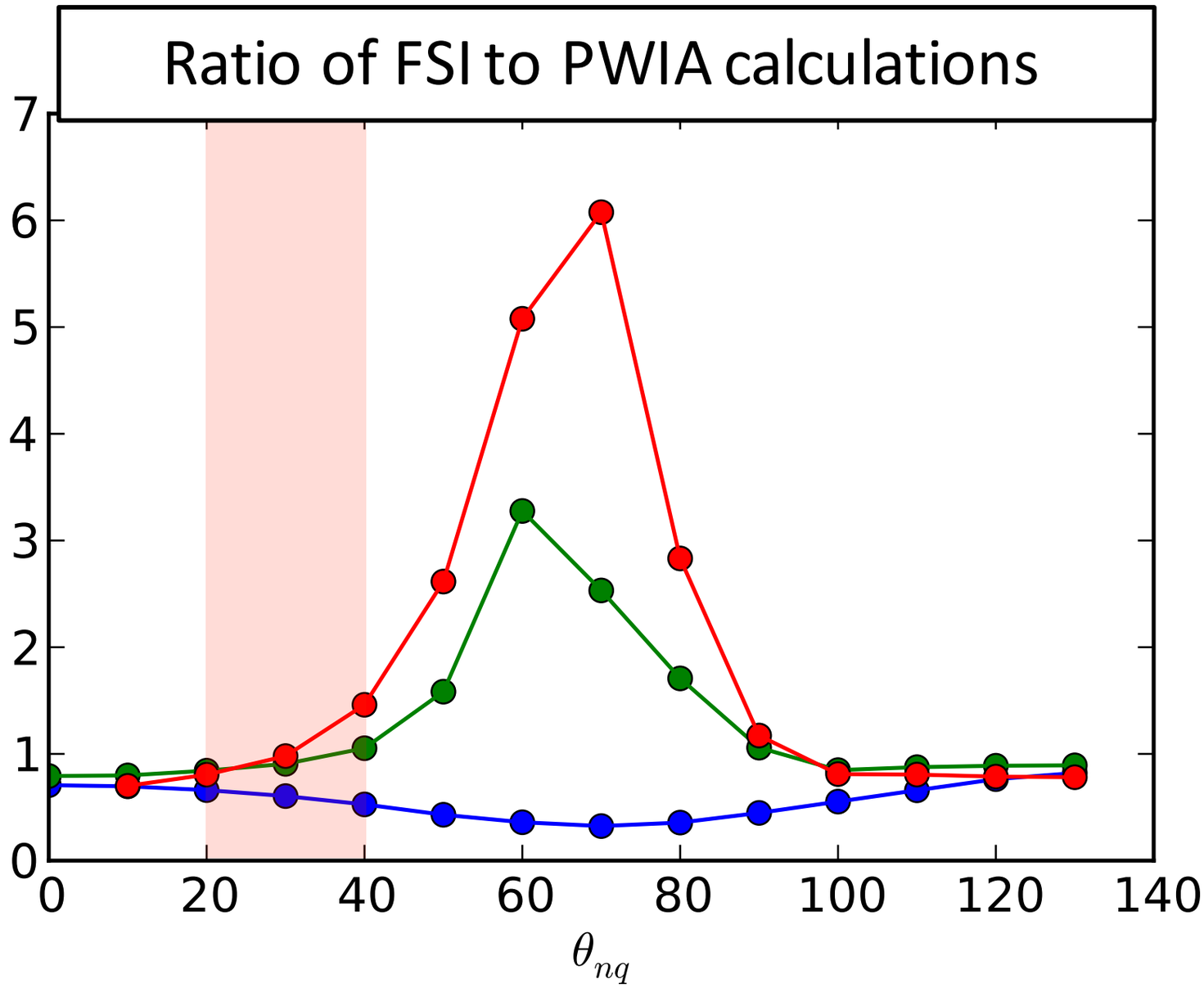
Fragment tagging reduce FSI leading to consistent extractions from quasi-elastic and inelastic reactions





Patsyuk et al. (BM@N Collaboration), Nature Physics 2021

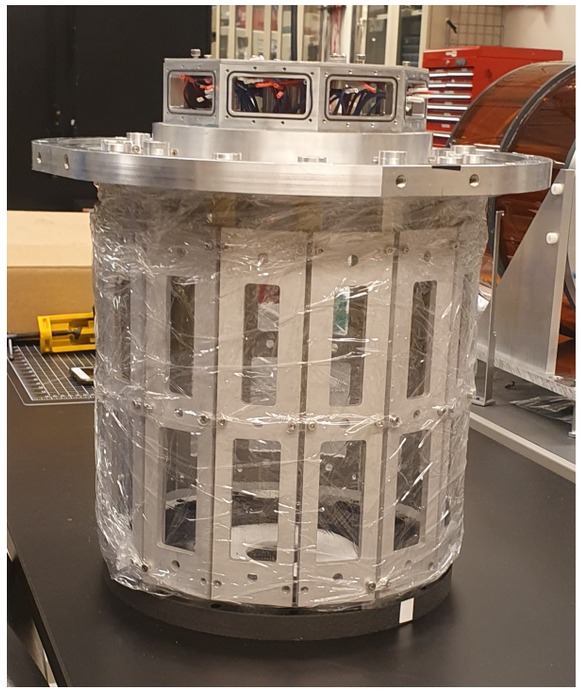
Choosing the right kinematics help suppress FSI

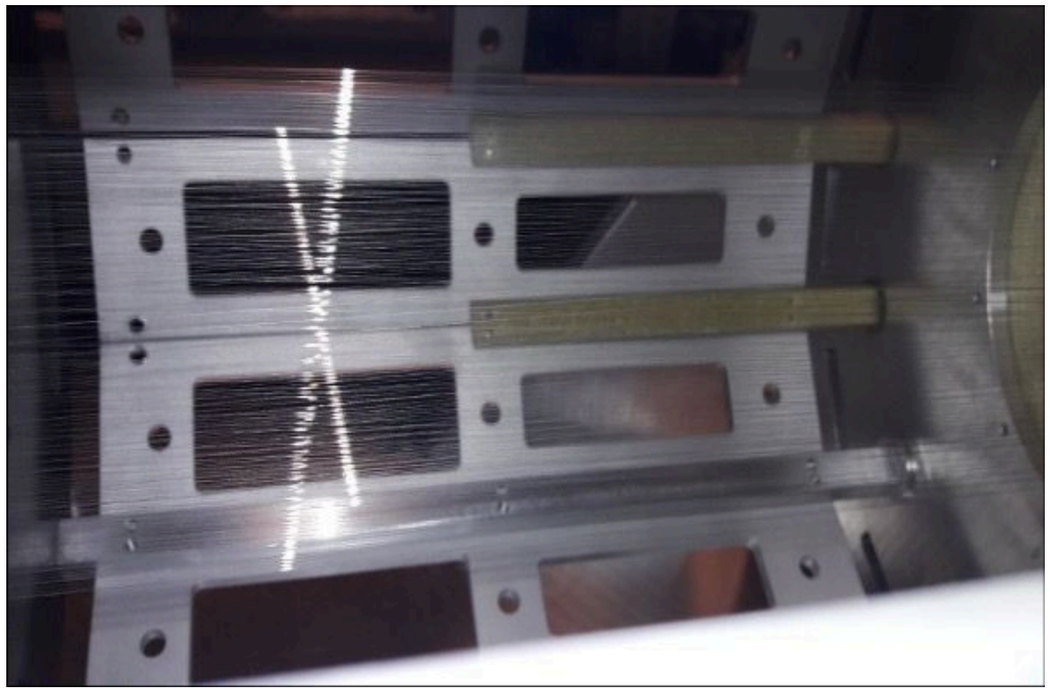


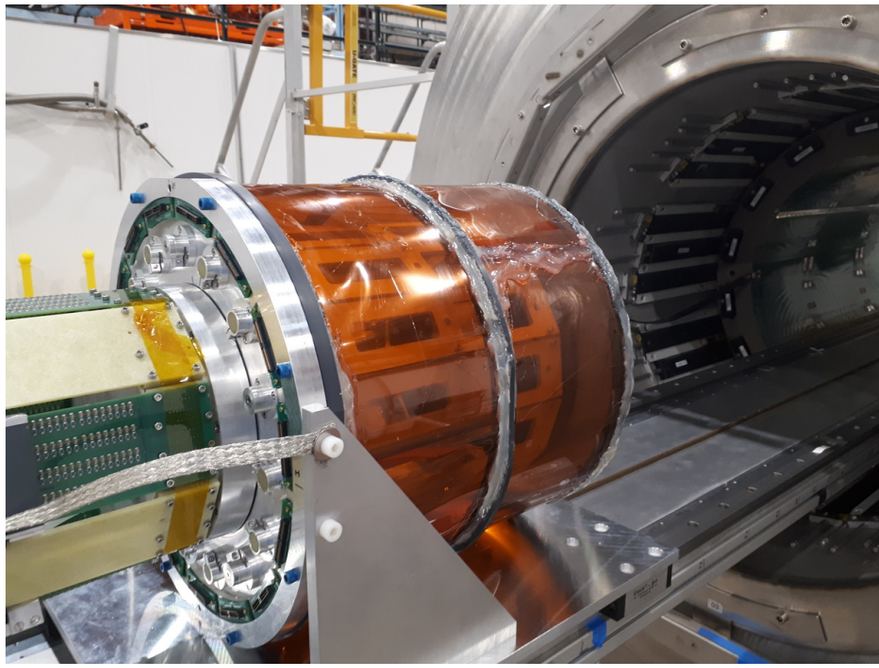
Calculations by Misak Sargsian.
Overarching features insensitive to model / calculation details

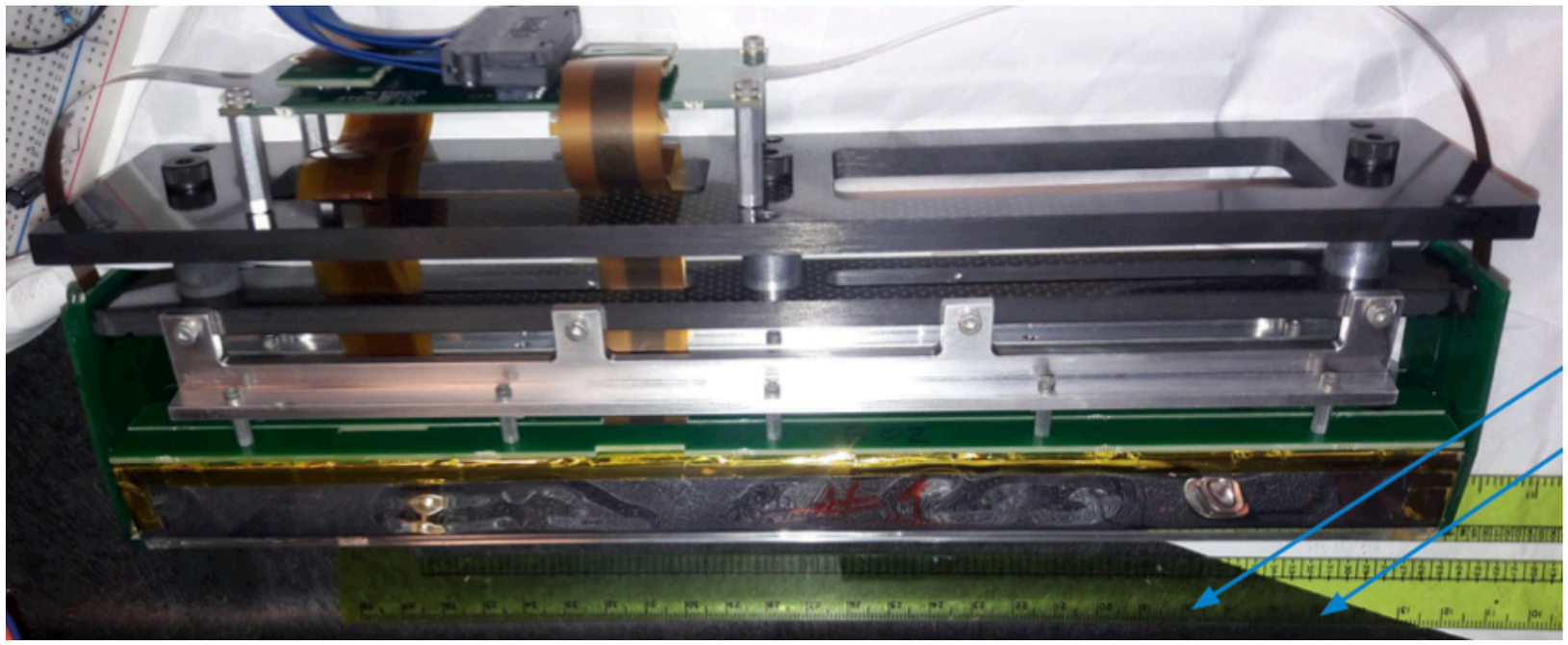
ALERT Detector

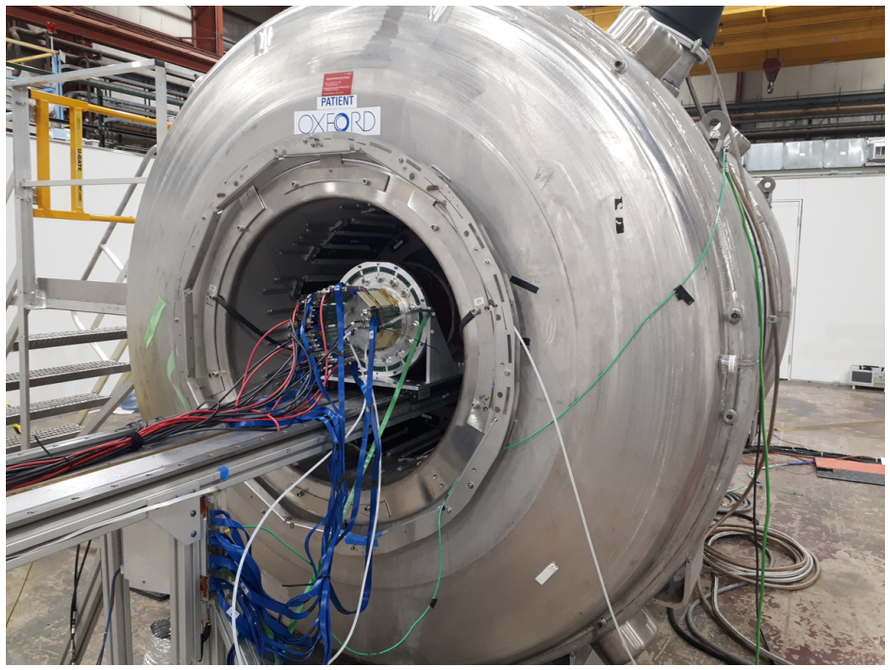
ALERT construction and testing underway





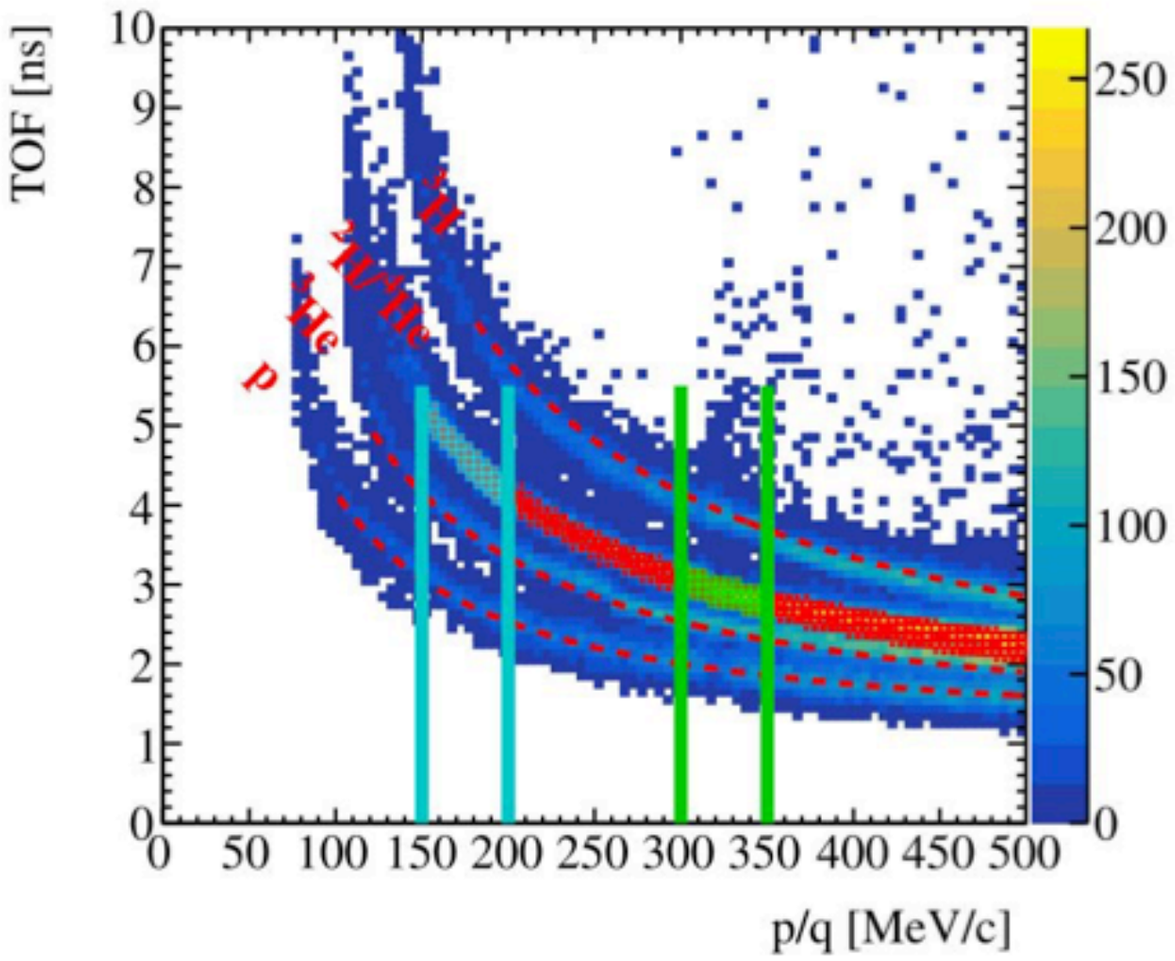






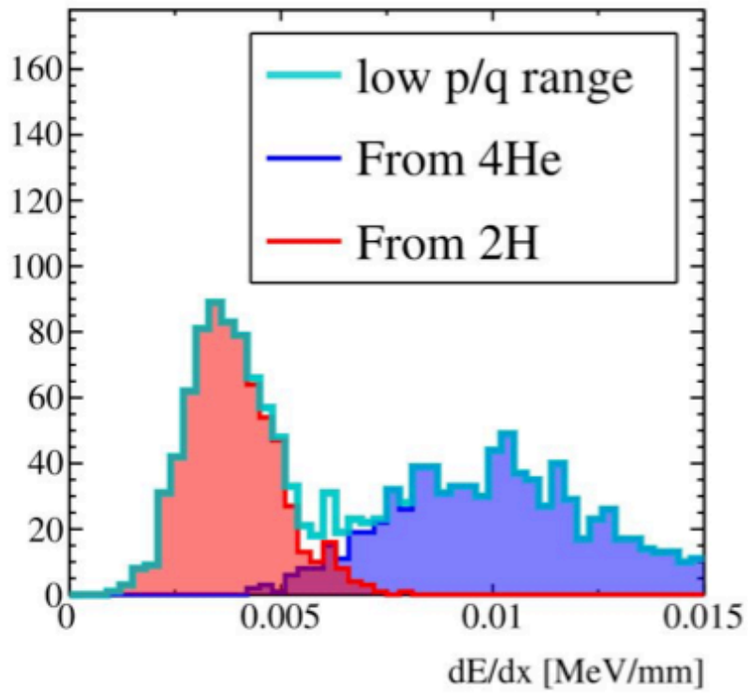
ALERT PID

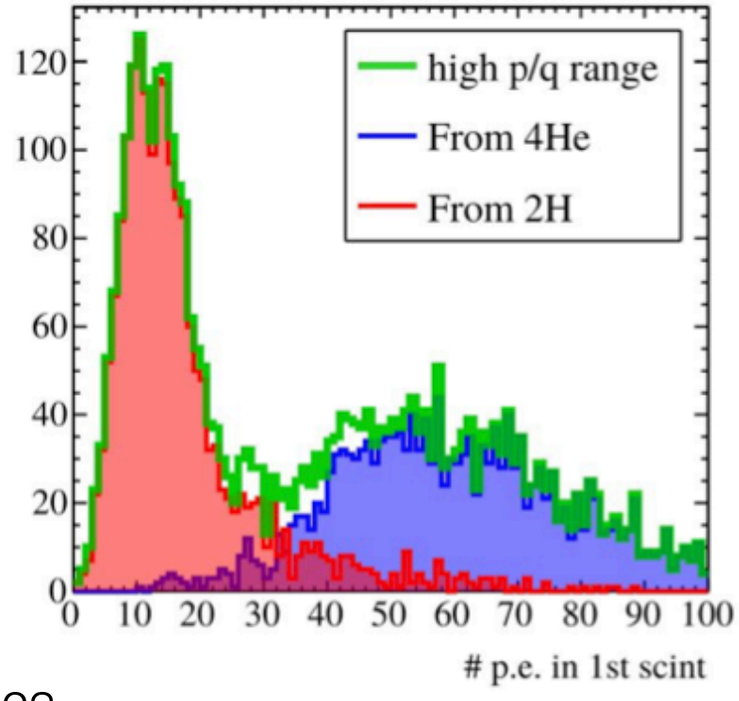
- PID from ToF (<150ps resolution)



- well separated p, ^{3}He, d/^{4}He and ^{3}H bands

- d and 4He seperation via dE/dx

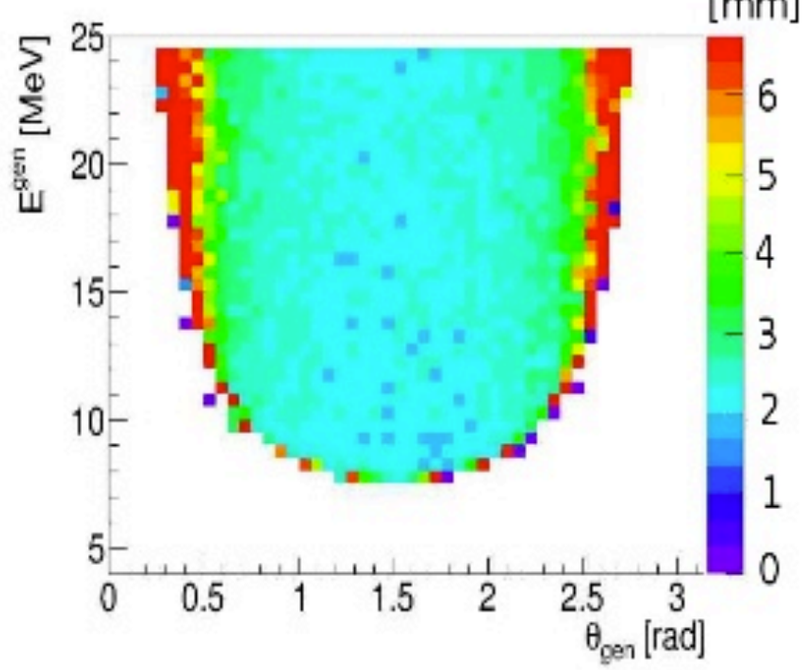




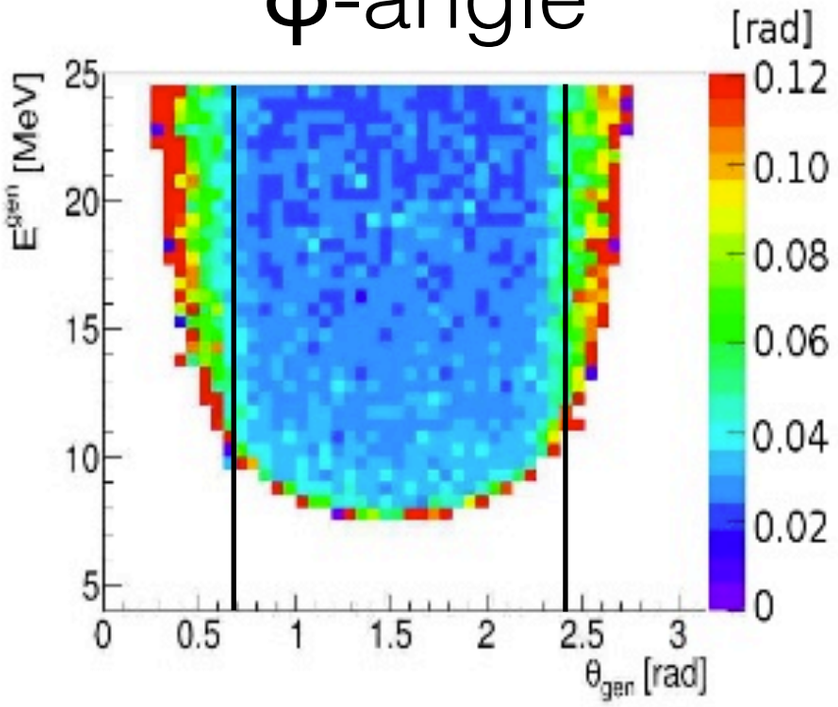
Figures courtesy of W. Armstrong, CLAS collaboration meeting June 2023

Expected ALERT Resolutions ^{4}He

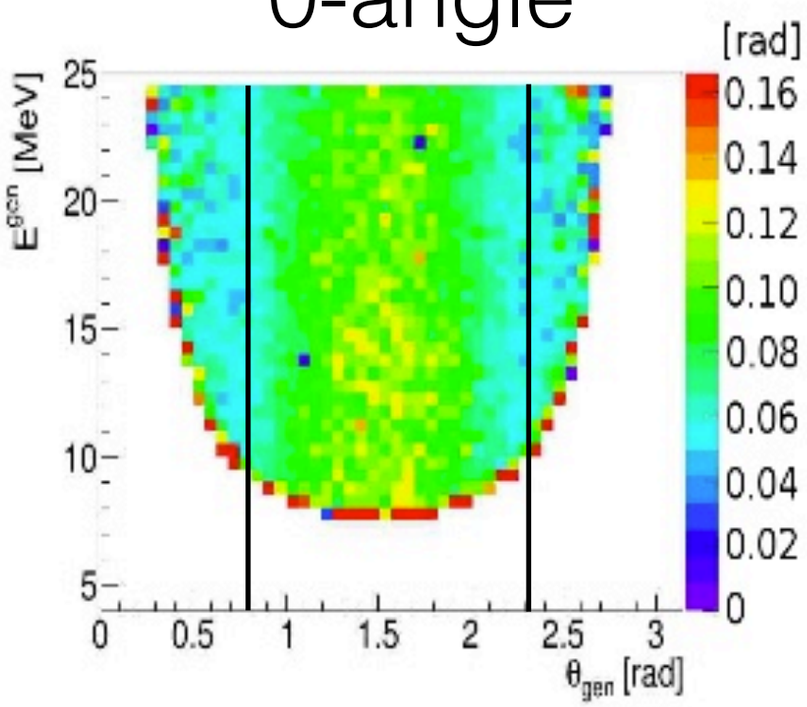
z-vertex



ϕ-angle



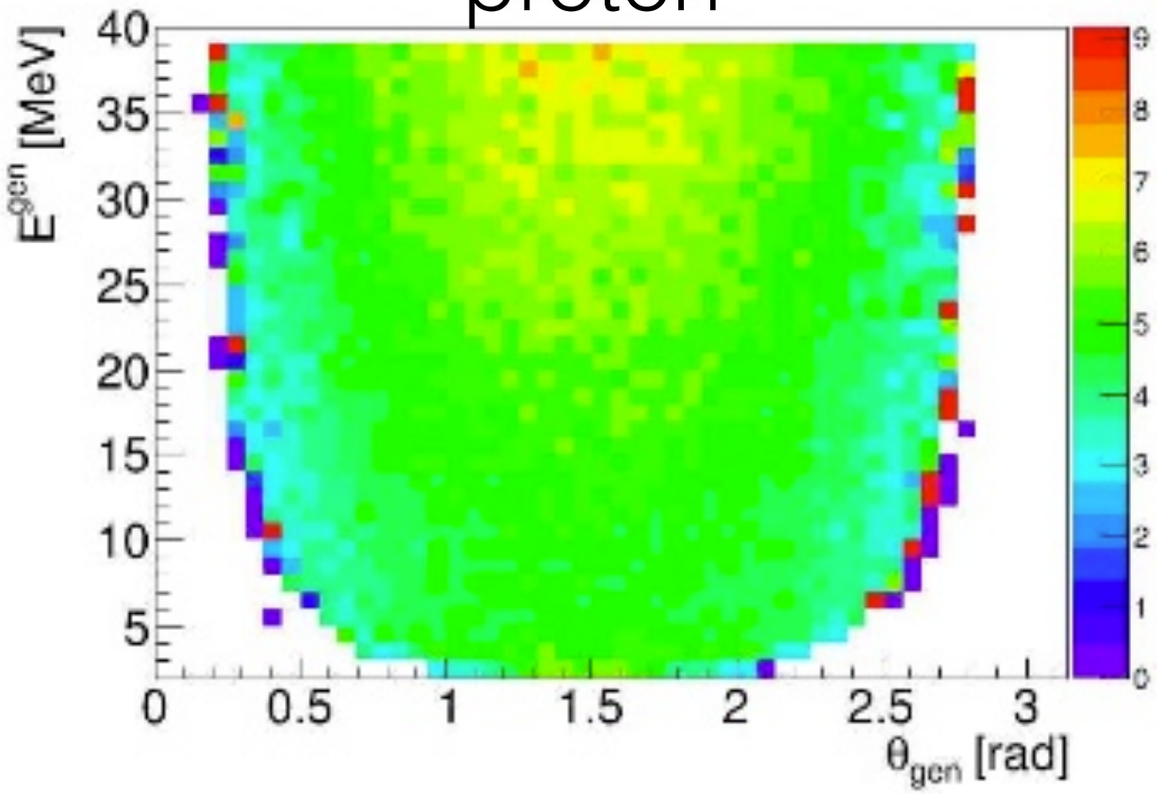
θ-angle



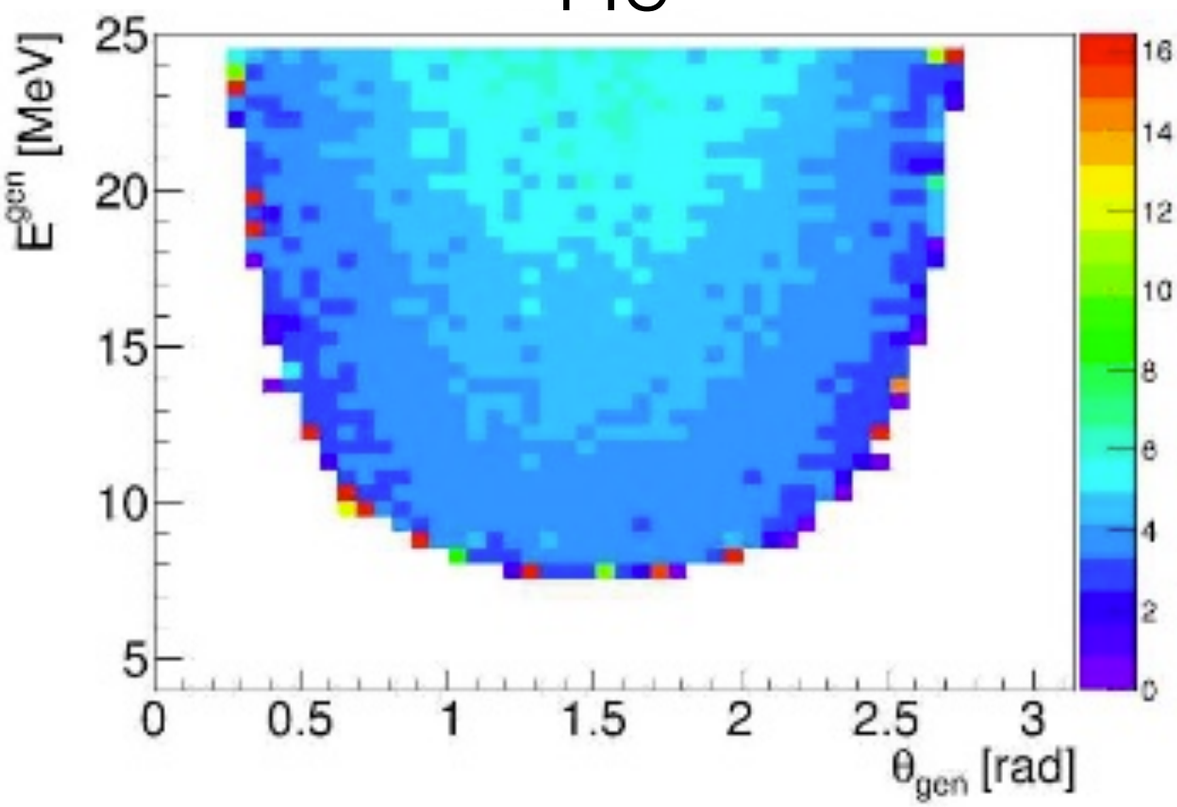
- Resolutions from approved ALERT proposal E12-17-012 (https://misportal.jlab.org/pacProposals/proposals/1338/attachments/98370/Proposal.pdf)
- Assumed resolutions for deuterons/tritons within acceptance
  - ϕ = 0.1 rad
  - θ = 0.1 rad

ALERT Momentum Resolutions

proton



^{4}He

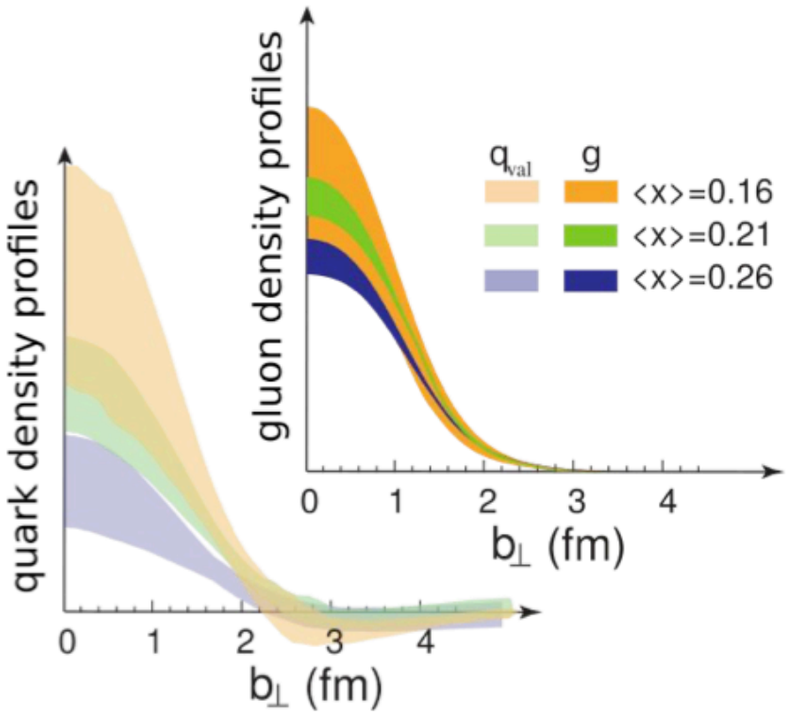


- Resolutions from approved ALERT proposal E12-17-012 (https://misportal.jlab.org/pacProposals/proposals/1338/attachments/98370/Proposal.pdf)
- Assumed resolution for deuterons/tritons will be between protons and 4He —> ~4%

ALERT 11 GeV Program

W. Armstrong, CLAS collaboration meeting June 2023

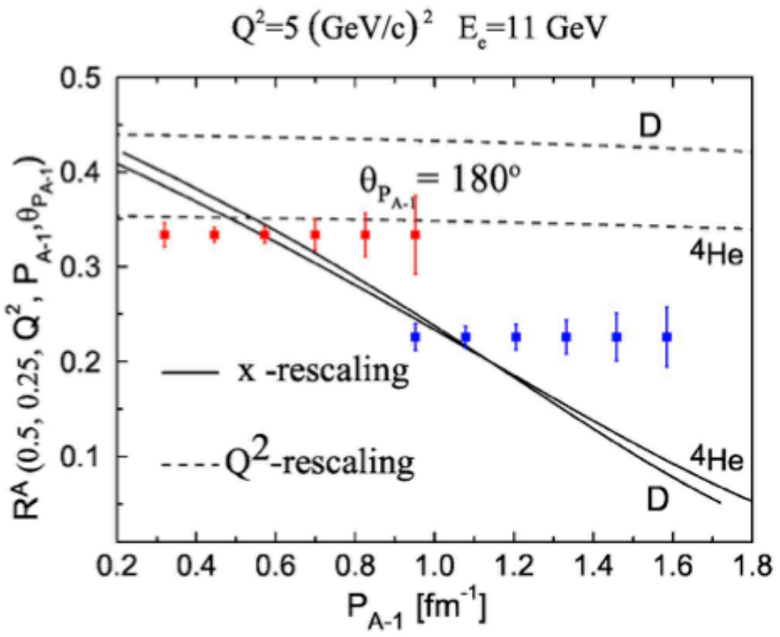
Nuclear GPDS



Explore the quark and gluon structure of ^{4}He

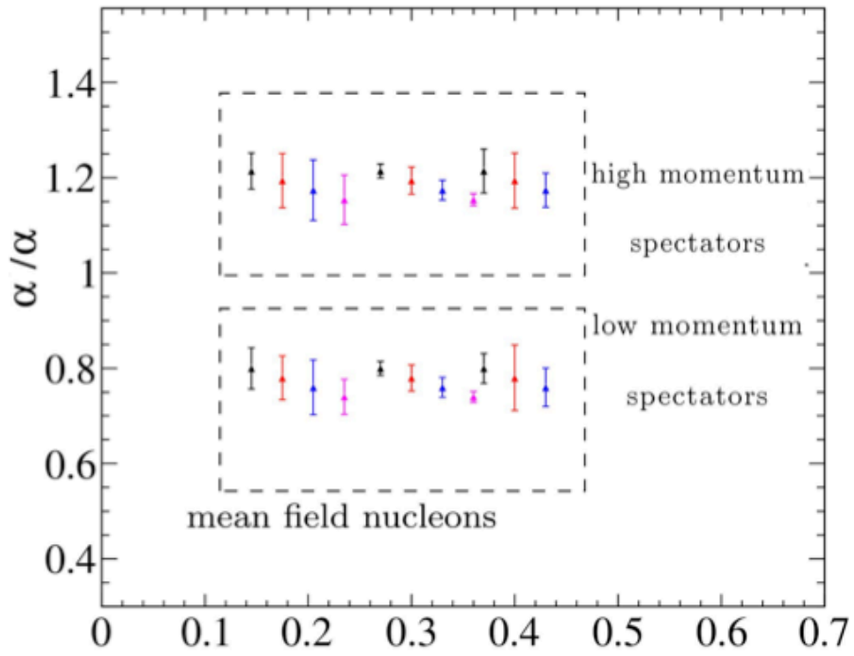
Compare quark and gluon radii

Tagged EMC Effect



Address key questions about the EMC Effect with spectator tagging

Tagged DVCS



Unravel EMC Effect[x]

Connect partonic and nucleonic modification

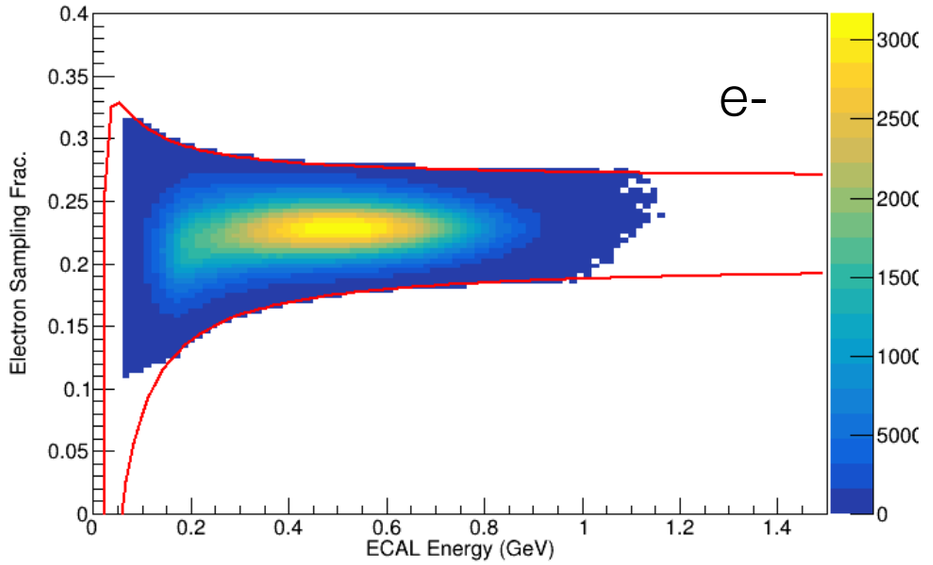
Simulations and Rates

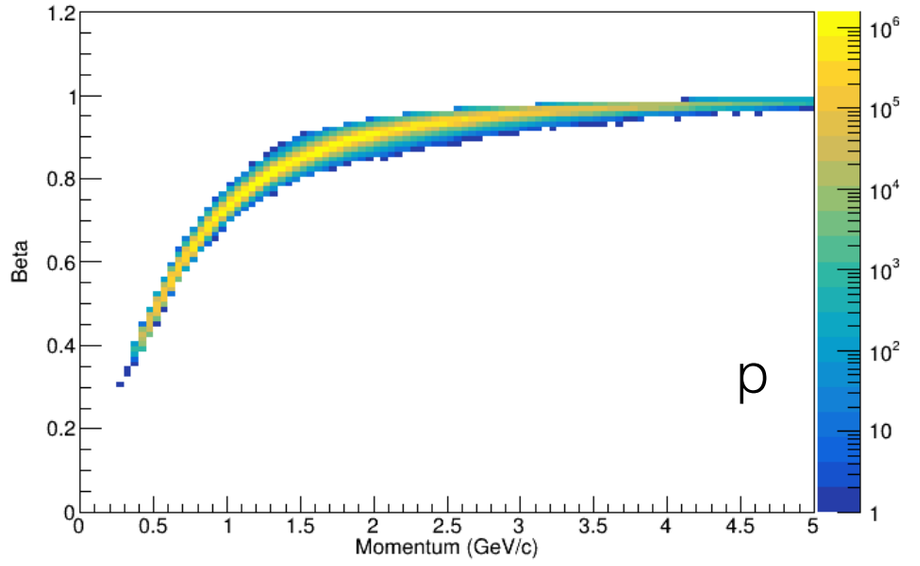
RGM (e,e'p) Event Selection

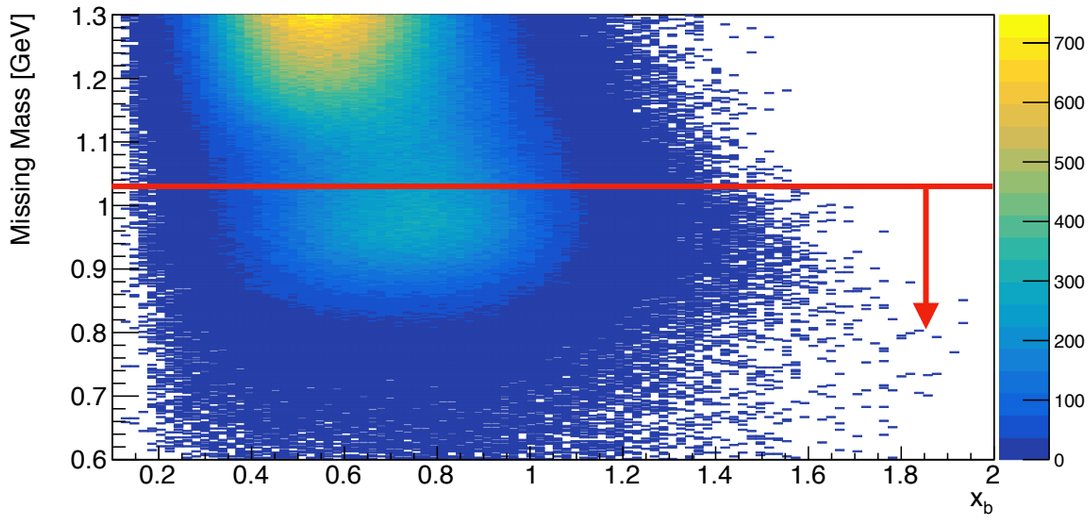
- Electron in Forward Detector
  - Calorimeter sampling fraction cut
  - PCAL fiducials

- Proton in Forward Detector
  - PID 2212
  - χ^2 PID < 3

- Kinematic Cuts for Quasi-elastic selection
  - $Q^2 > 1.2$ GeV^2
  - $\theta_{pq} < 25°$
  - $|p|/|q| > 0.6$
  - $M_{miss} < 1.03$ GeV (assuming stationary pair with deuteron mass)

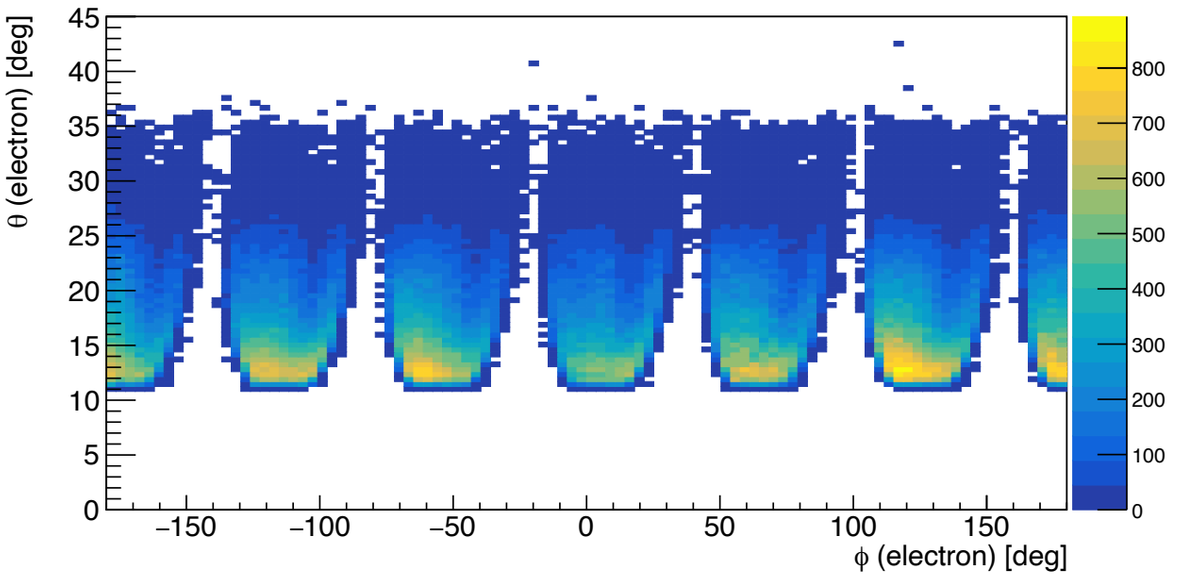


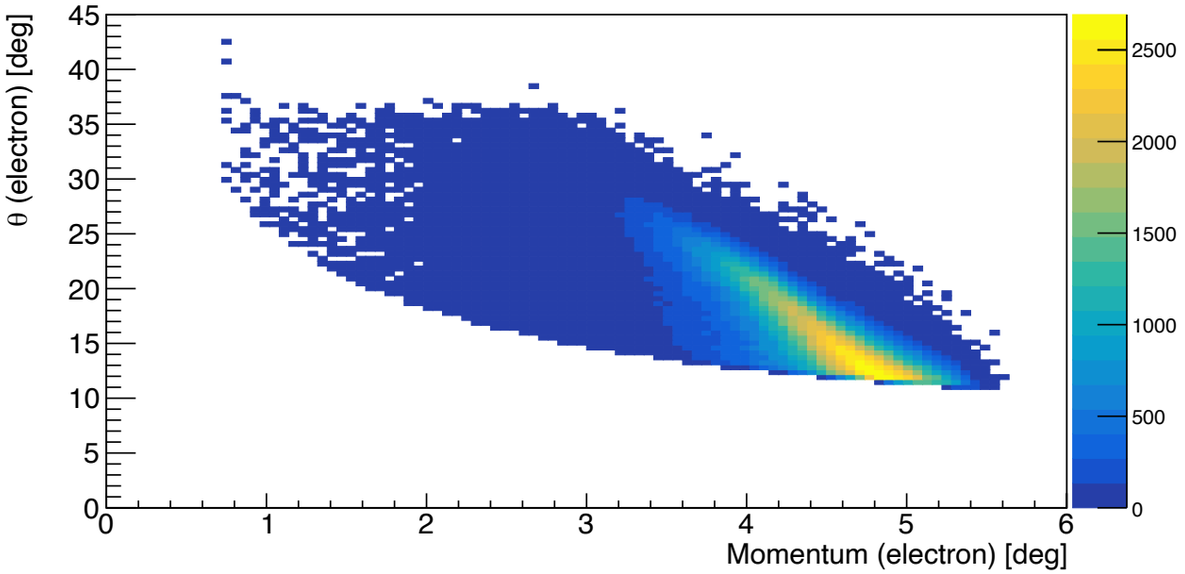




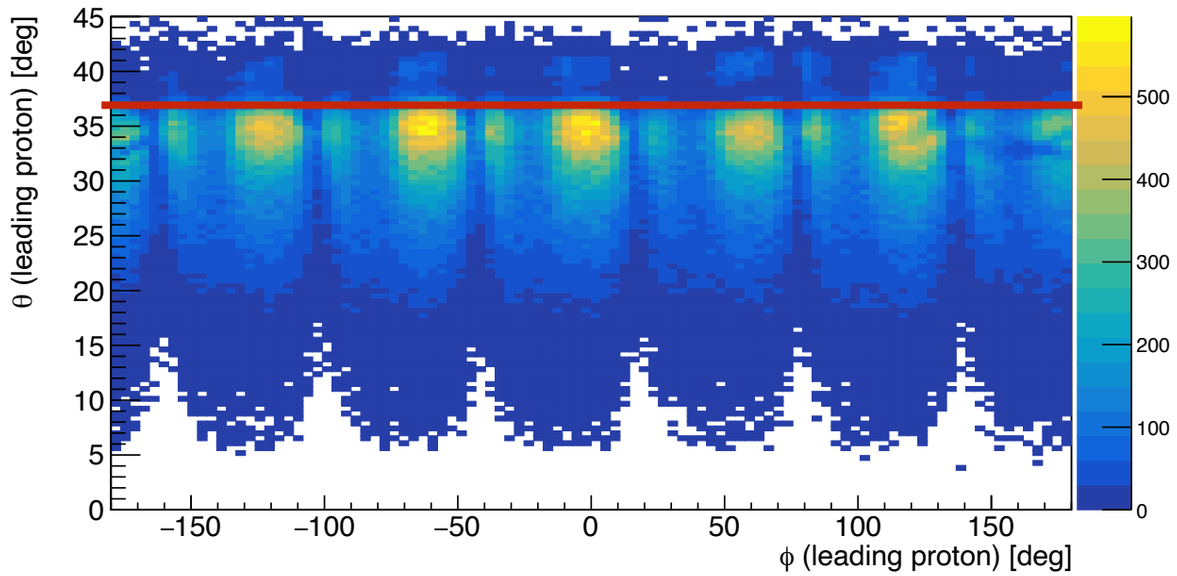
Electron and Proton Distributions

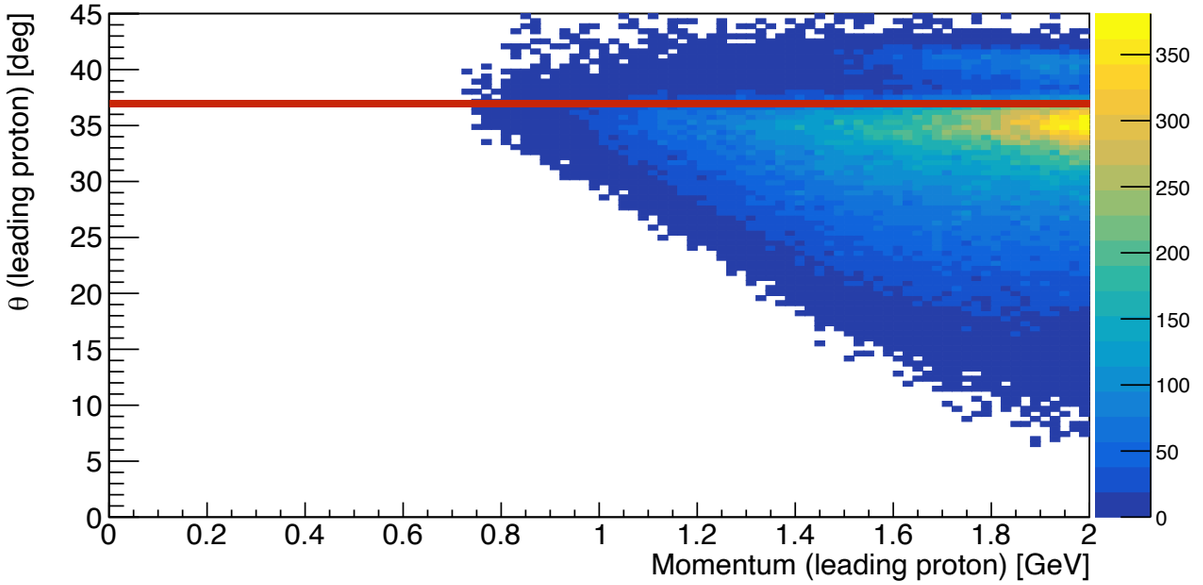
Electrons





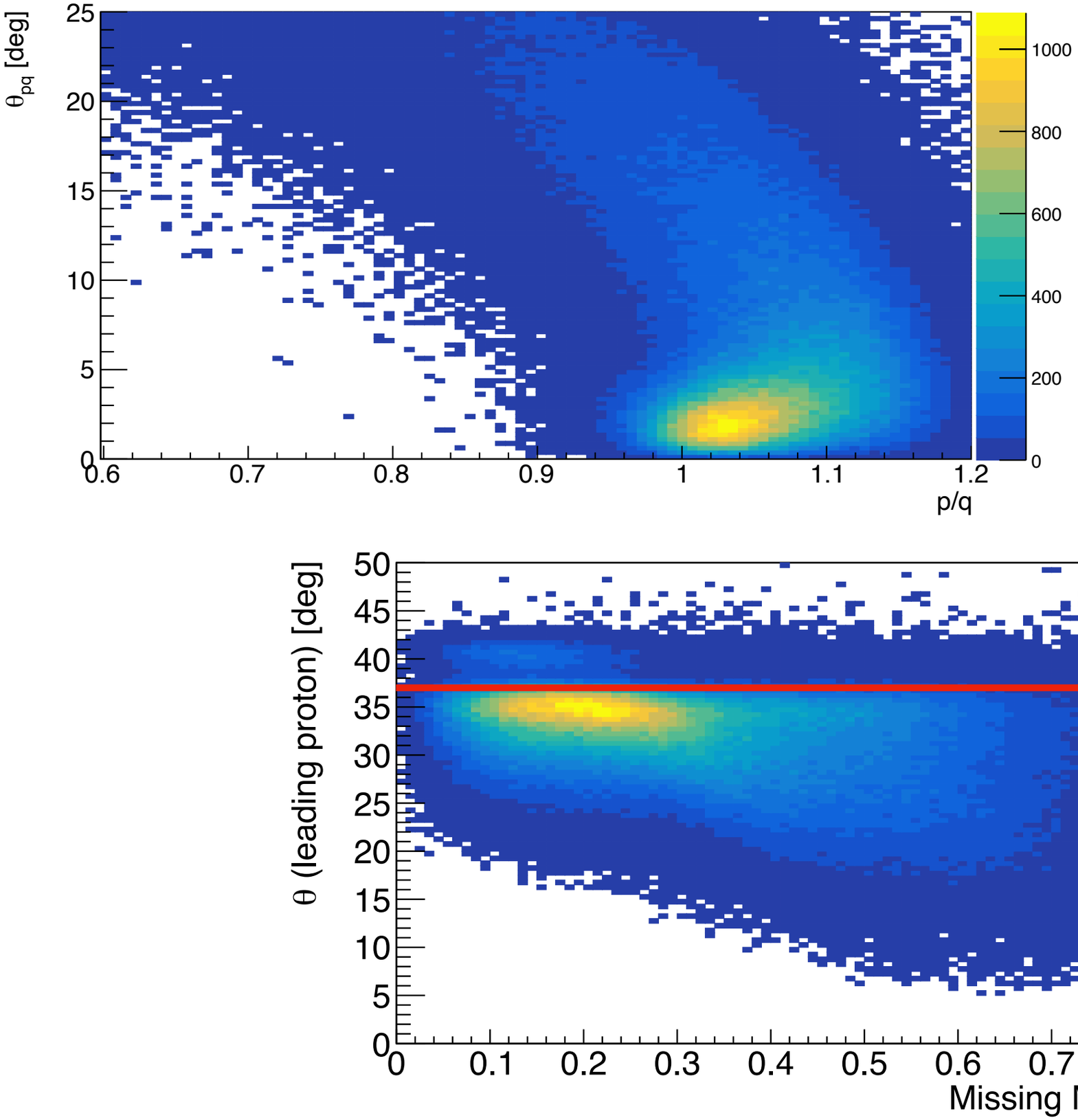
Protons





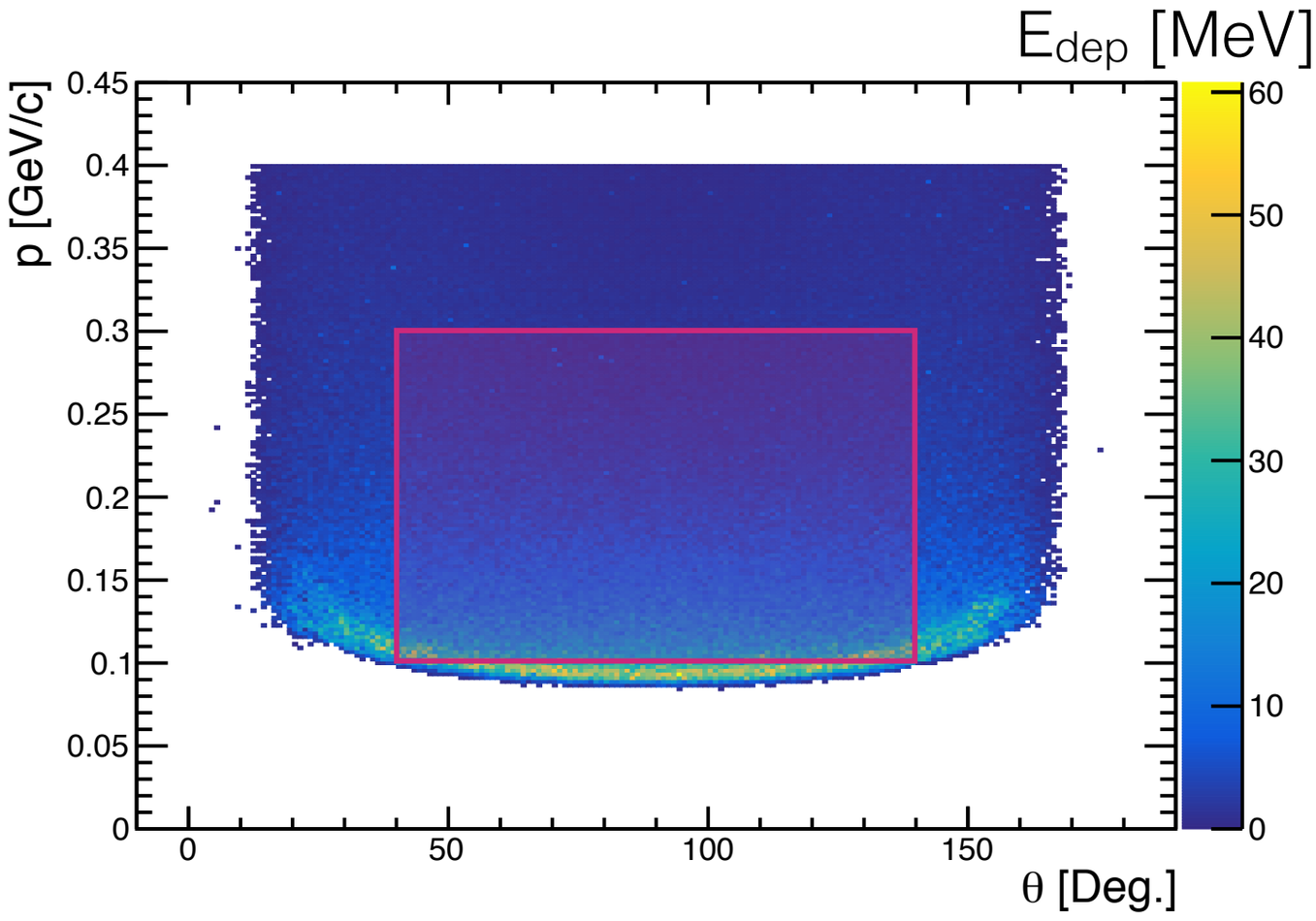
- Standard 6-fold sector structure of CLAS12
- Additional proton scattering angle cut $\theta_p < 37°$ to ensure proton only in forward detector

Other Kinematic Distributions



Deuteron Acceptance (1)

- Uniformly generated deuterons
  - 0-400 MeV/c momenta
  - 0-180° polar angle
  - 0-360° azimuthal angle

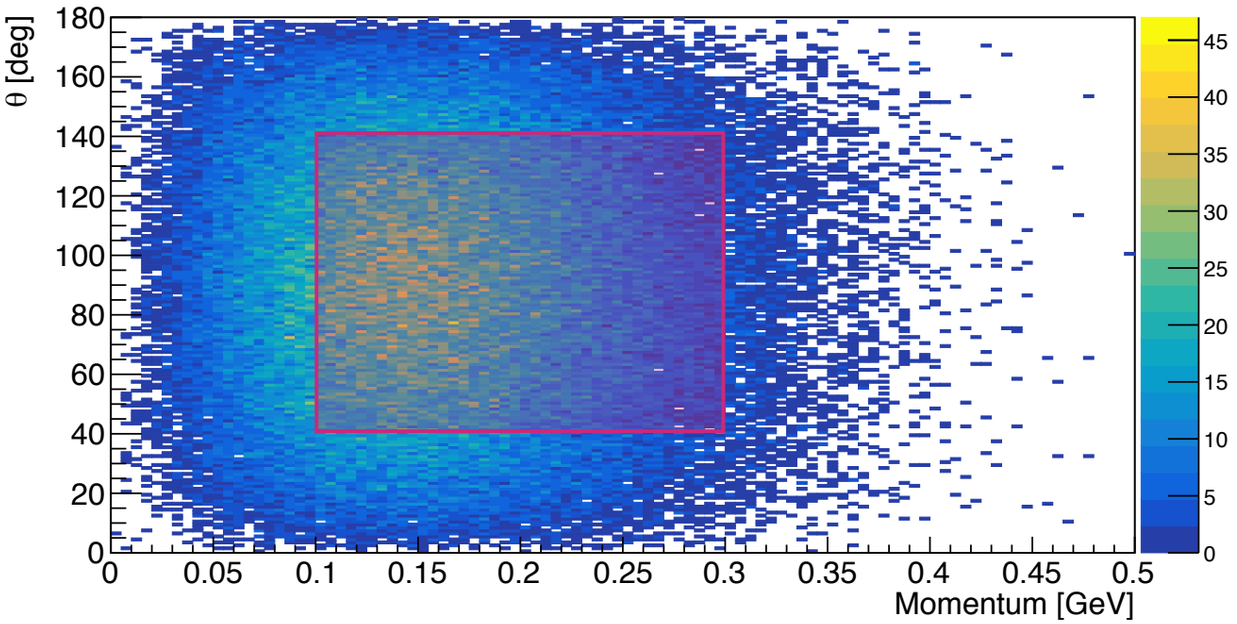


- Events through GEMC (ALERT only)
  - Accept event if hit in all DC layers
  - No explicit track reconstruction

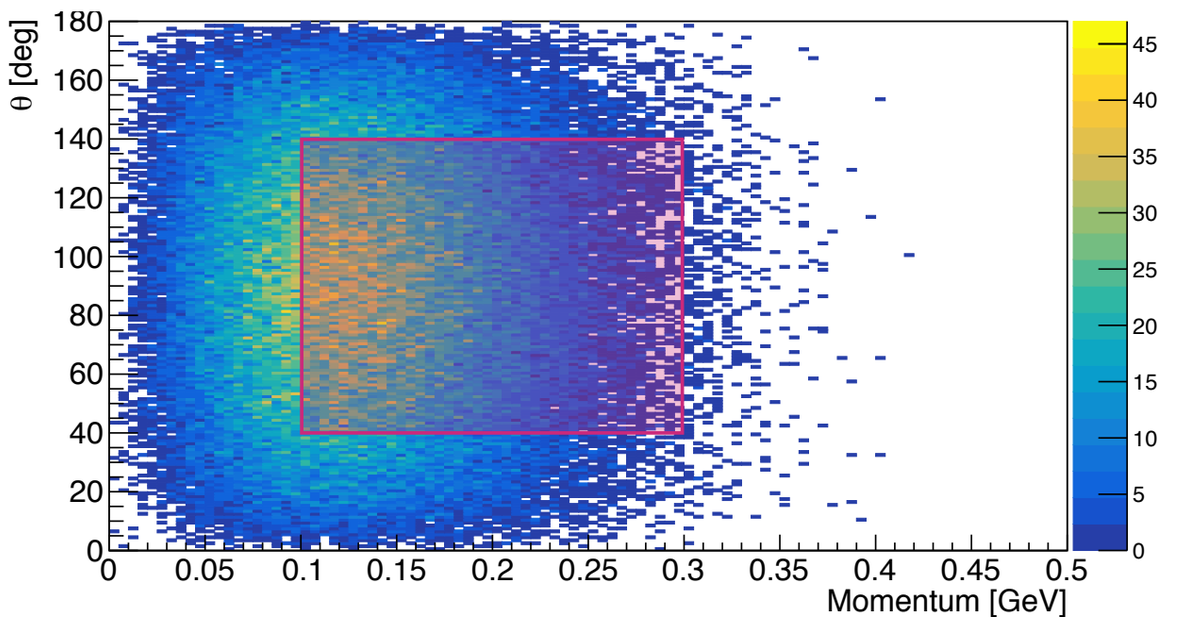
- Select conservative range with high efficiency for acceptance determination
  - 100 - 300 MeV/c
  - 40° -140°

Deuteron Acceptance (2)

- Simulated deuterons from ^{4}He(e,e'pd$_S$)n
  - isotropically emitted
  - deuteron momentum (= np-pair cms momentum) sampled from Gaussian
  - checked different values: σ = 100 MeV/c [PRL 113 (2014)] and σ = 84 MeV/c [PRC 89 (2014)]



σ = 100 MeV/c



σ = 84 MeV/c

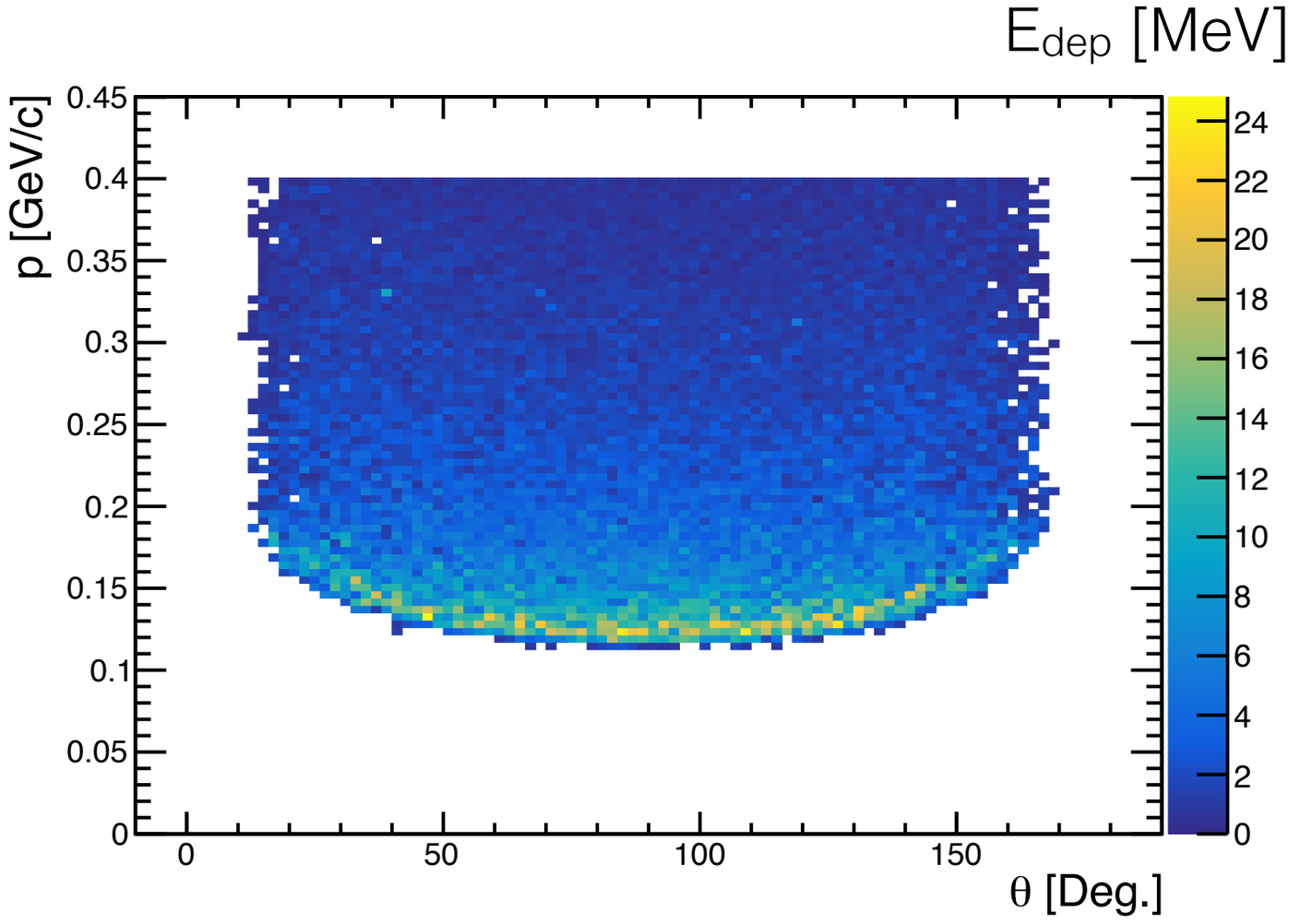
- More spread in momentum for larger σ (expected)
- 59% (100 MeV/c) or 53% (84 MeV/c) events in (conservative) ALERT acceptance box

- For rate estimate: conservative **deuteron acceptance factor = 0.5**

Triton ALERT Acceptance

- Uniformly generated tritons
  - 0-400 MeV/c momenta
  - 0-180° polar angle
  - 0-360° azimuthal angle

- Events through GEMC (ALERT only)
  - Accept event if hit in all DC layers
  - No explicit track reconstruction



- Similar acceptance range than deuterons —> can detect tritons from 120-300 MeV/c

Rate Estimate and Beam Time

$$N_{He(e,e'pd_S)n} = N_{He(e,e'p)^{RGM-SRC}} f_{acc} f_{surv} f_{pp/\phi acc} f_{FSI}$$

$$= 3.8 \cdot 10^5 \times 0.5 \times 0.1 \times 0.8 \times 0.1 = \boxed{1.6 \cdot 10^3}$$

- RGM ^{4}He data
  - 1.2 x 10^{35} luminosity
  - 4 PAC days

→

- This proposal
  - 0.3 x 10^{35} luminosity
  - **16 PAC days**
  - 1.6 x 10^3 SRC events
  - similar or more Mean-field events

Beam Time Request

Configuration	**Target**	**Luminosity** $\mathrm{cm^{-2}s^{-1}}$	**Beam current** nA	**Beam energy** GeV	**Beam time request** days
Measurement Days	^{4}He	$3 \cdot 10^{34}$	500	6.4	16
Commissioning	^{4}He	various	various	6.4	1
Total					**17**