Deuteron Electro-Disintegration at Very High Missing Momenta (E12-10-003)

PAC 49 Meeting

(July 21, 2021)

C. Yero
(Spokesperson)
Thomas Jefferson National Accelerator Facility

M.K. Jones
(Spokesperson)
Thomas Jefferson National Accelerator Facility

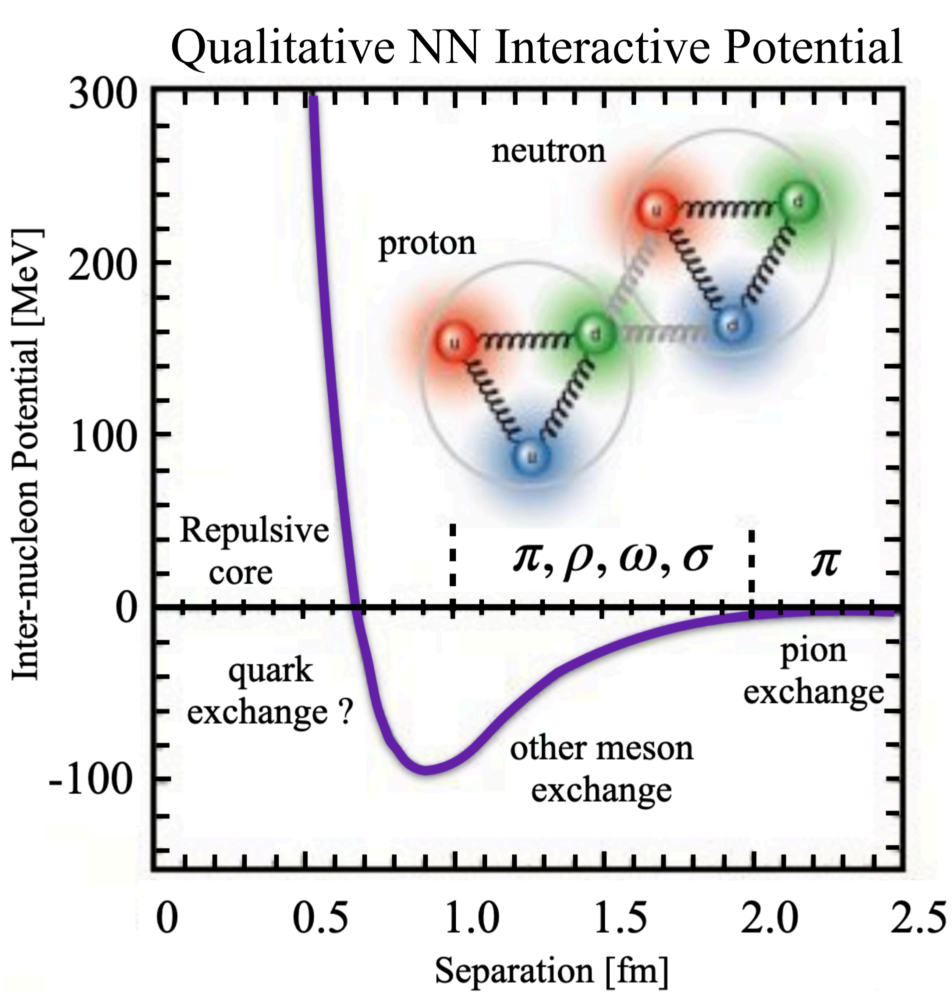
W.U. Boeglin
(Spokesperson, contact)
Florida International University

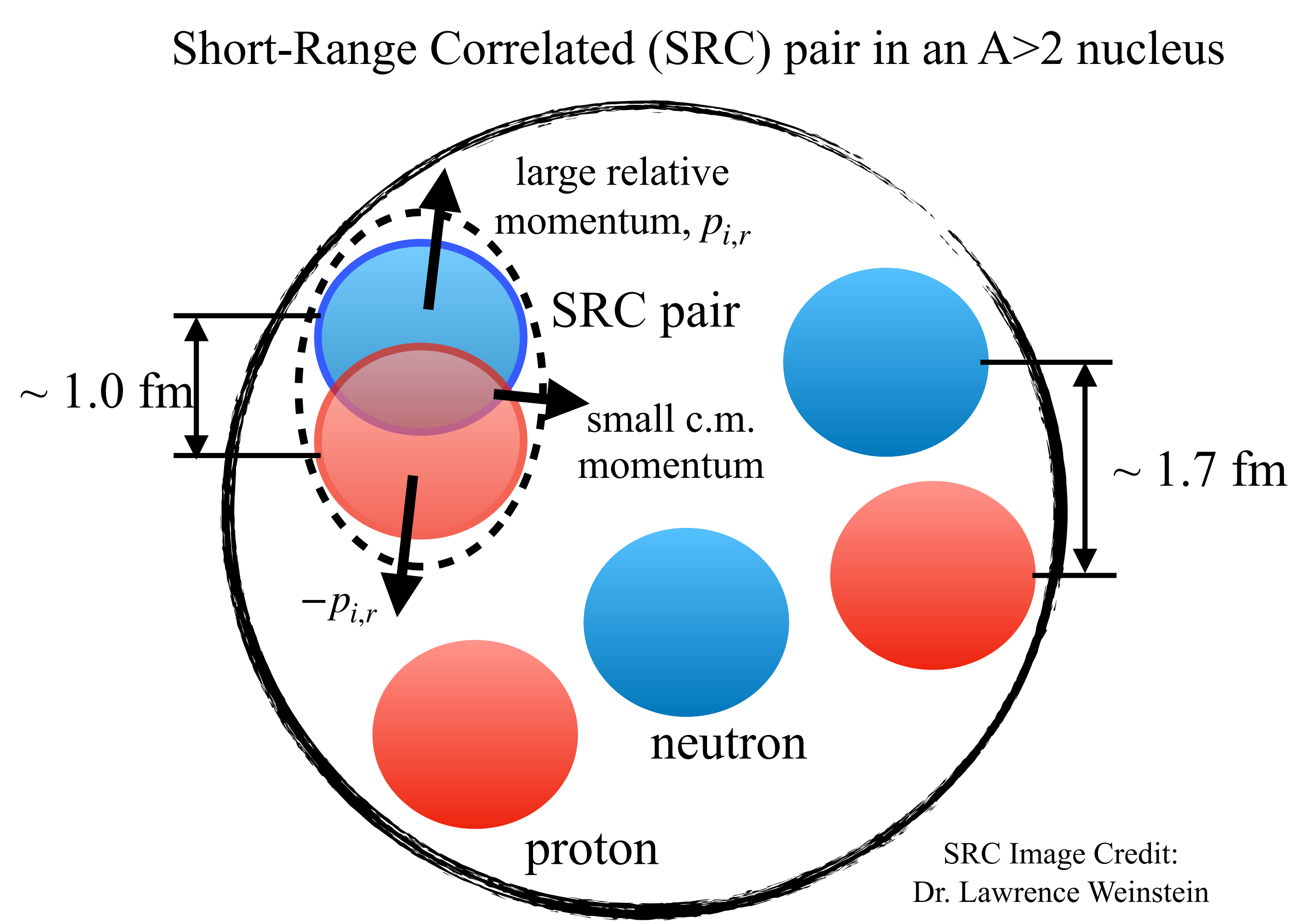
☑ Goal of this experiment (E12-10-003)

- **measure d(e, e'p)n cross sections with good statistical precision (~10%) at p_m ~ 600 - 1000 MeV/c**

☑ Motivation

- NN interaction NOT well understood at the sub-Fermi (<1 fm) distance scale
- **lack of experimental data beyond relative nucleon momenta $p_{i,r}$ ~ 500 MeV/c**
- non-nucleonic degrees of freedom, relativistic treatment of deuteron becomes important
- deuteron most simple np bound system, d(e, e'p)n ideal for probing repulsive part of NN interaction, solid understanding of final state interactions (FSI) required, theoretical calculations of FSI not as reliable for A>2





Previous d(e, e'p)n Measurements / Theoretical Support

JLab Hall A (2011)

Theory

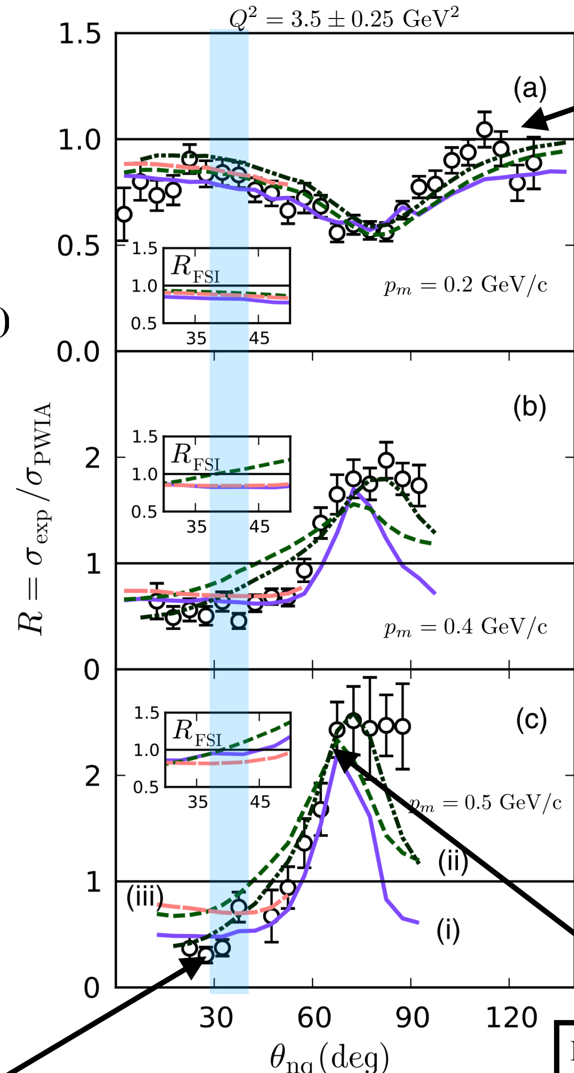
CD-Bonn FSI (MS) (Calculations: Misak Sargsian)

JVO Model (Calculations: J.W. Van Orden & S. Jeschonnek)

Paris FSI (Calculations: J.M. Laget)

Paris FSI+MEC+IC (Calculations: J.M. Laget)

DATA

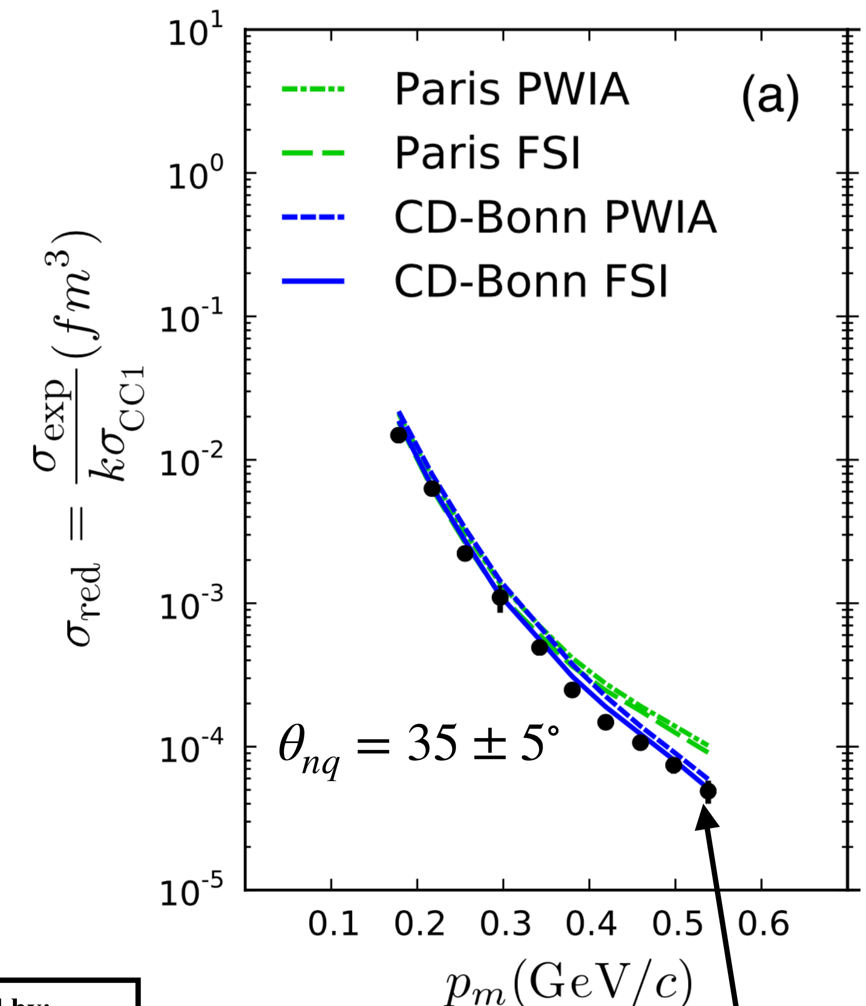


Reduced FSIs at ~120 deg (R ~ 1), But ICs are significant

Reduced FSIs at ~40 deg (R ~ 1) genuine momentum distributions probed

FSI peaks at ~70 deg, predicted by:

1. **Misak Sargsian using the Generalized Eikonal Approximation or GEA)**
2. **J.M. Laget using a diagrammatic approach**



small FSI, enhanced sensitivity of cross-section to different models

data above ~500 MeV/c needed to probe repulsive part of the NN interaction

- Data confirmed theoretical predictions by M. Sargsian and J.M. Laget:
  - Strong angular anisotropy of FSI peaking at ~70 deg
  - **FSI significantly reduced at ~40, 120 deg**

- Our experiment (E12-10-003) used kinematic window $\theta_{nq} \sim 30 - 40$ deg to probe the deuteron (for the first time) at relative momenta beyond ~500 MeV/c while keeping FSI at a minimum

J.M. Laget Phys. Lett. B 609, 49 (2005)

S. Jeschonnek and J.W. Van Orden, Phys. Rev. C 78, 014007 (2008)

M. M. Sargsian Phys. Rev. C 82, 014612 (2010)

W. U. Boeglin et al. Phys.Rev.Lett. 107, 262501 (2011)

What is new since the PAC approval of E12-10-003 ?

- PAC 36 Comments: "*Overall the experiment was viewed very highly; the lower rating simply reflects the likelihood that **the data will not reveal any particular surprise** and that their impact may thus be limited to experts in the field.* "
- **commissioning results show strikingly different behavior than any of the theoretical models > 700 MeV/c (no model calculation reproduces the observed trend as a function of missing momentum)**
- Hall C commissioning experiment (April 2018), completed 3 of the 21 PAC days (See Table below)
- data analysis completed, published (PRL) results: C. Yero et al. PhysRevLett 125, 262501 (2020)
- published results compared to most up-to-date deuteron theoretical calculations from M. Sargsian, J.W.Van Orden and S. Jeschonnek
  See references: M. M. Sargsian Phys. Rev. C 82, 014612 (2010) J.M. Laget Phys. Lett. B 609, 49 (2005)
  William P. Ford, Sabine Jeschonnek, and J. W. Van Orden Phys. Rev. C 90, 064006 (2014)

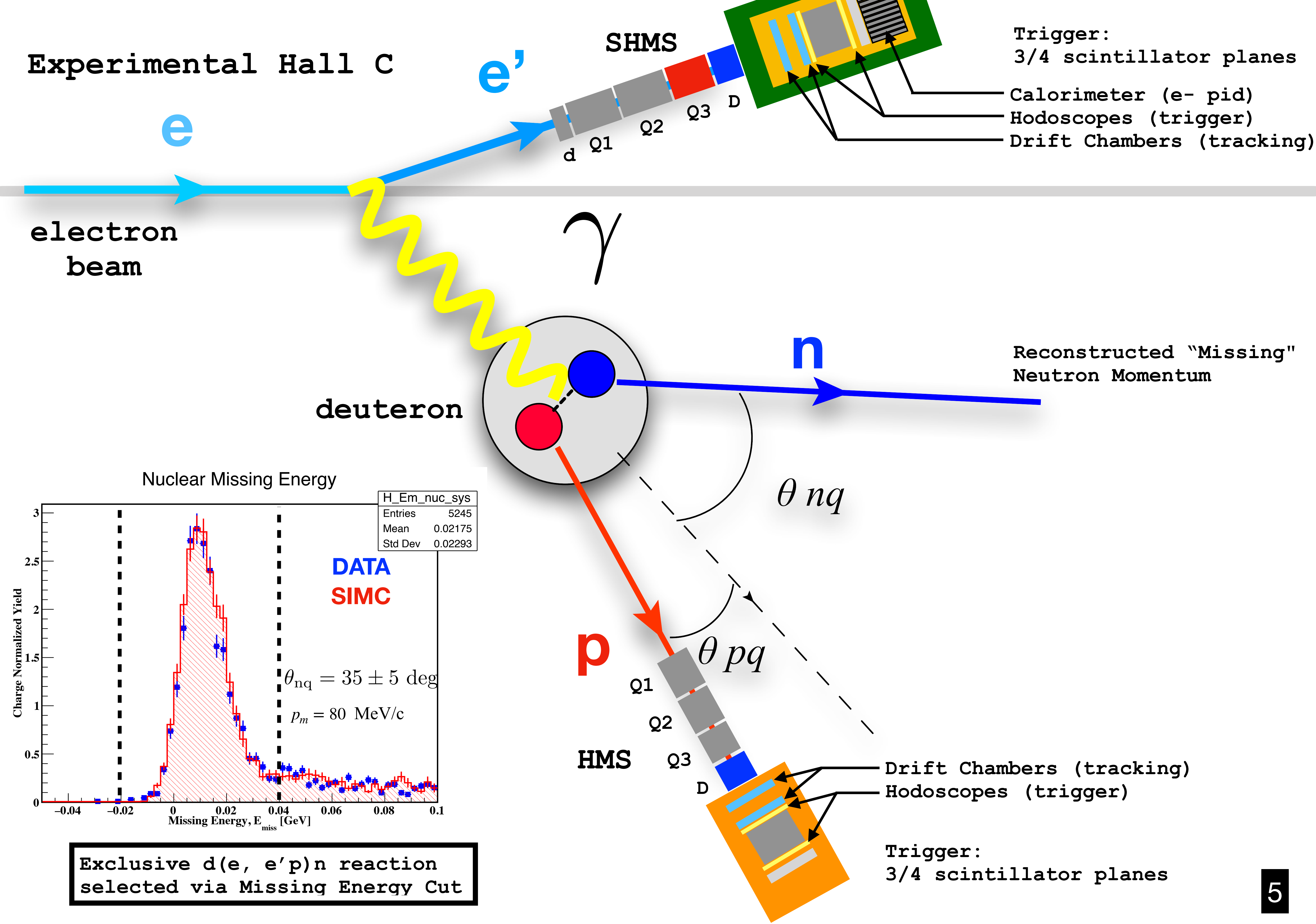
d(e, e'p)n commissioning kinematics

Beam Energy: 10.6 GeV
Beam Current: 45-60 μA

p_m (GeV/c)	k_f (GeV/c)	θ_e (deg)	$\lvert\vec{q}\rvert$ (GeV/c)	p_f (GeV/c)	θ_p (deg)	θ_{pq} (deg)	Charge (mC)	Time (hrs)
0.08	8.534	12.19	2.89	2.84	38.8	1.21	142.14	1.48
0.58	8.534	12.19	2.89	2.19	54.99	11.2	3618.6	36
0.75	8.534	12.19	2.89	2.09	58.39	14.7	8307.2	84
Total Charge							12068	
optics checkout								
hydrogen elastics								
proton absorption								22.6
Total Time								144 hrs (3 PAC days)

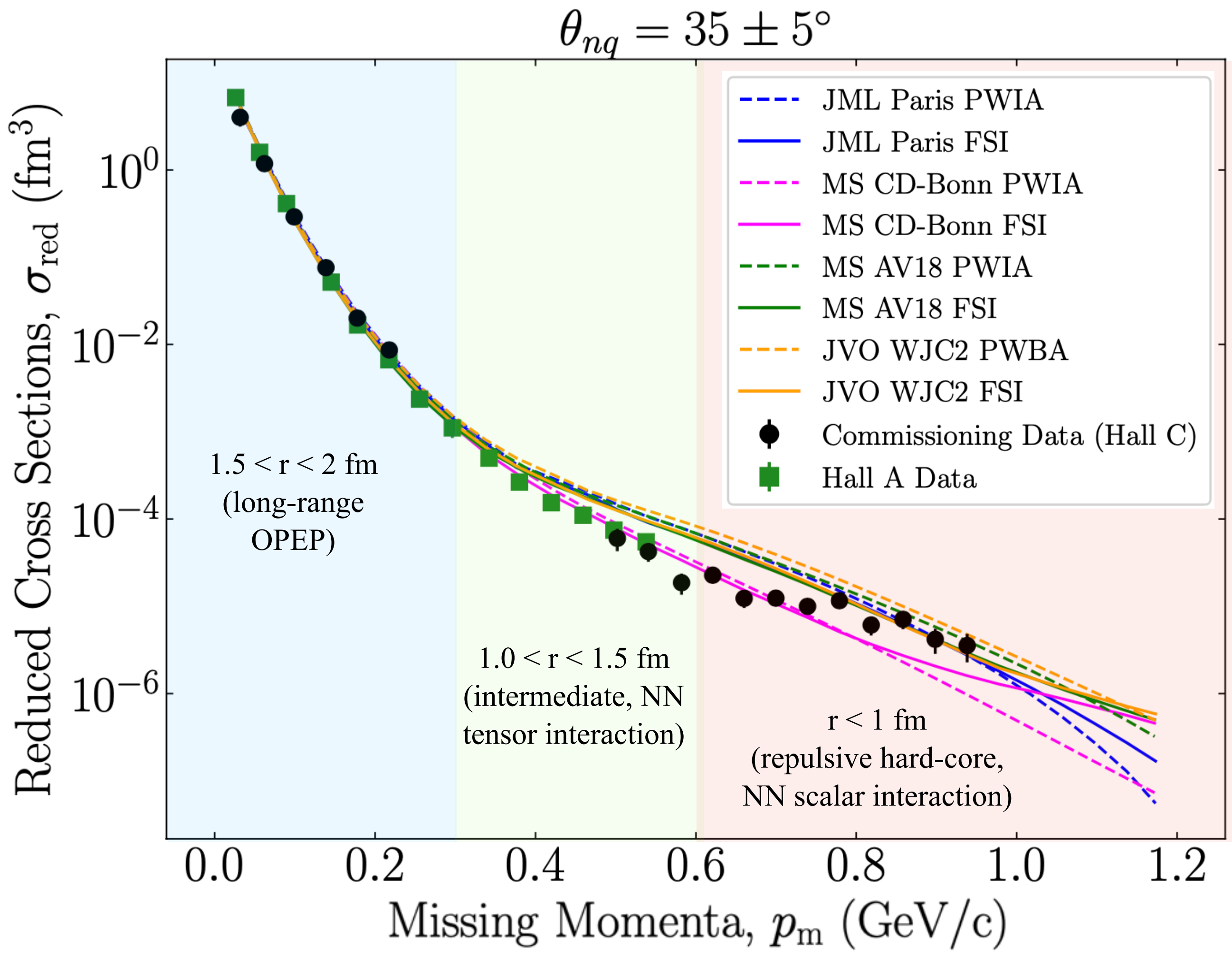
Definitions (central settings) :
p_m : central missing momentum setting
k_f : scattered electron momentum
θ_e : scattered electron angle
$|\vec{q}|$: virtual photon 3-momentum transfer
p_f : scattered proton momentum
θ_p : scattered proton angle
θ_{pq} : relative in-plane angle between p_f and $\vec{q}$

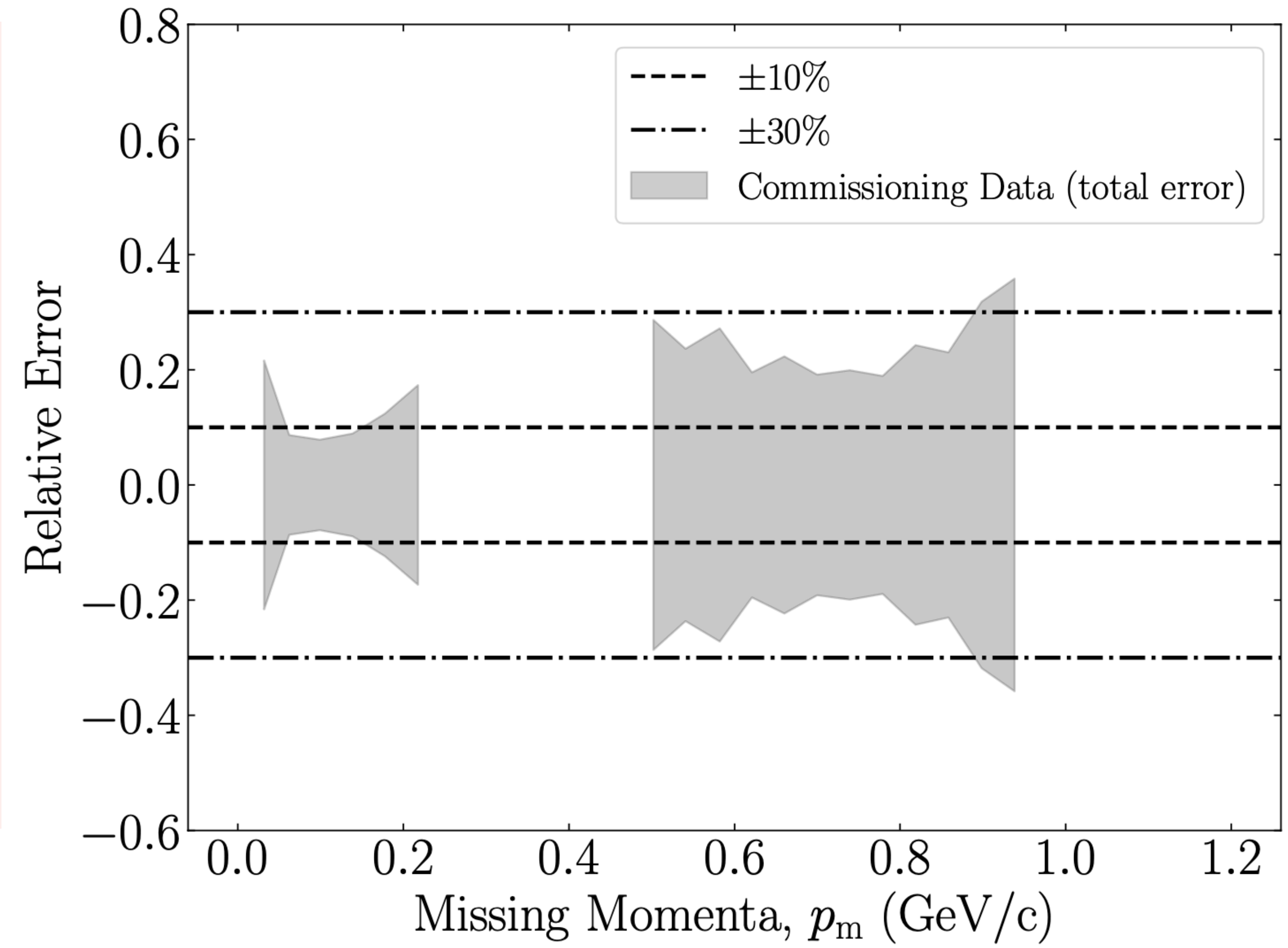
E12-10-003 Experimental Setup



Exclusive d(e, e'p)n reaction
selected via Missing Energy Cut

E12-10-003 Commissioning Experiment Results





- *above ~700 MeV/c, data shows a strikingly different behavior than predicted by any of the models*
- discrepancy above ~700 MeV/c reveals the limits in the range of validity of the theoretical calculations See page 2 of Ref.

  M. M. Sargsian Phys. Rev. C 82, 014612 (2010)
- additional data > 900 MeV/c needed to see if the trend continues

- **commissioning data (3 PAC days) statistically dominated, 20 ~ 40 % relative error**
- kinematic+normalization systematics contribution is $\lesssim 8\,\%$ and well understood from commissioning work

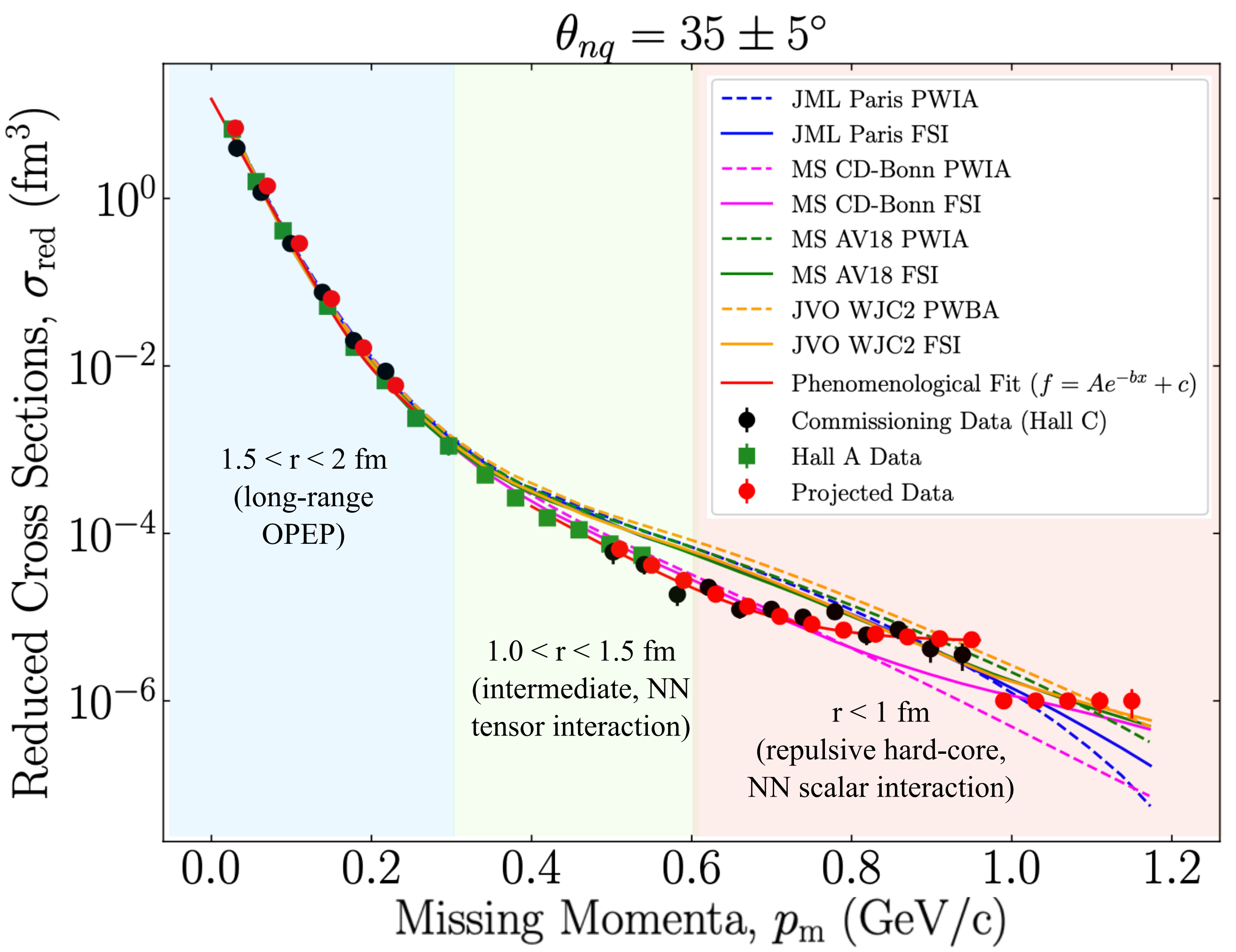
Definition of "Reduced Cross Sections"

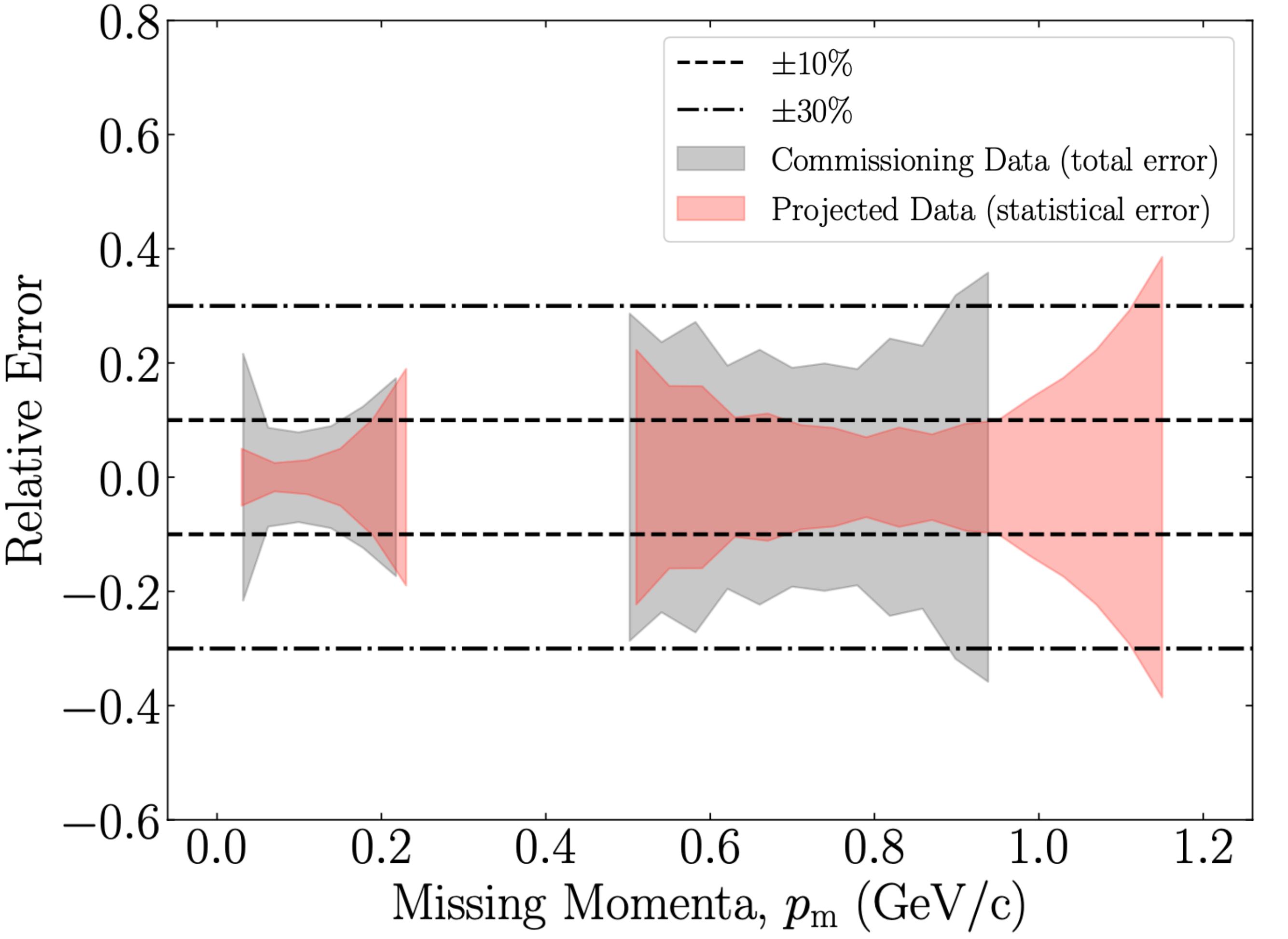
$$\sigma_{exp} \equiv \frac{d^5\sigma}{d\omega d\Omega_e d\Omega_p} = K \cdot \sigma_{ep} \cdot S(p_m)$$

$$S(p_m) \approx \sigma_{red} \equiv \frac{\sigma_{exp}}{K\sigma_{ep}}$$

C. Yero et al. PhysRevLett 125, 262501 (2020)

E12-10-003 Projected Data





☑ Phenomenological Fit

- overlay projected data/errors on phenomenological fit curve to commissioning data
- above ~900 MeV/c, no fit was made (no data), projected data conservatively placed at placed at 10^{-6}

☑ Projected Data / Errors (Assuming 18 PAC days allocated)

- simulated d(e, e'p)n reaction using central settings: 0.120, 0.580, 0.700, 0.800, 0.900 (based on Jean-Marc Laget Paris FSI calculations)
- actual inefficiencies from commissioning applied to simulated yields for realistic statistical error estimates
- yield corrections applied to correct for differences between the measured data and JML Paris FSI model
- **projected statistical error improvement down to ~10 % between $p_m \sim 600 - 1000$ MeV/c**

C. Yero et al. PhysRevLett 125, 262501 (2020)

E12-10-003 Beam Time Request

Beam Energy: 10.6 GeV
Beam Current: 70 μA

Target: 10-cm Liquid Deuterium (LD2)

p_m (GeV/c)	k_f (GeV/c)	θ_e (deg)	$\lvert\vec{q}\rvert$ (GeV/c)	p_f (GeV/c)	θ_p (deg)	θ_{pq} (deg)	Charge (mC)	Time (hrs)
0.12	8.335	12.59	3.06	3.05	38.63	2.24	252	1.0
0.58	8.922	12.17	2.66	2.26	54.96	9.92	6048	24.0
0.7	8.922	12.17	2.66	2.19	57.41	12.37	27216	108.0
0.8	8.922	12.17	2.66	2.12	59.39	14.34	27216	108.0
0.9	8.922	12.17	2.66	2.05	61.33	16.30	42084	167.0
Total Charge							102816	
optics checkout								
hydrogen elastics								
target boiling								
proton absorption								24
Total Time								432 hrs (18 PAC days)

Definitions (central settings) :
p_m : central missing momentum setting
k_f : scattered electron momentum
θ_e : scattered electron angle
$|\vec{q}|$: virtual photon 3-momentum transfer
p_f : scattered proton momentum
θ_p : scattered proton angle
θ_{pq} : relative in-plane angle between p_f and $\vec{q}$

- analysis code infrastructure was developed for commissioning part (analysis + publication expected to be quick for complete experiment)
- **d(e, e'p)n experiment at Hall C (E12-10-003) ONLY requires standard equipment (HMS+SHMS) with standard detectors (i.e., hodoscopes, drift chambers, calorimeter)**
  No special requirements or additional support from Hall C staff needed to complete the experiment

Summary

- ☑ commissioning part (3 PAC days) of E12-10-003 experiment successfully completed and published in the Physical Review Letters (PRL) scientific journal.

- ☑ **above missing momenta of ~700 MeV/c, NO calculation describes the data**
  ** this observed behavior is new and unexpected **

- ☑ cross-section uncertainties statistically dominated by ~20 - 40 %

- ☑ systematic uncertainties well understood and below ~ 8 %

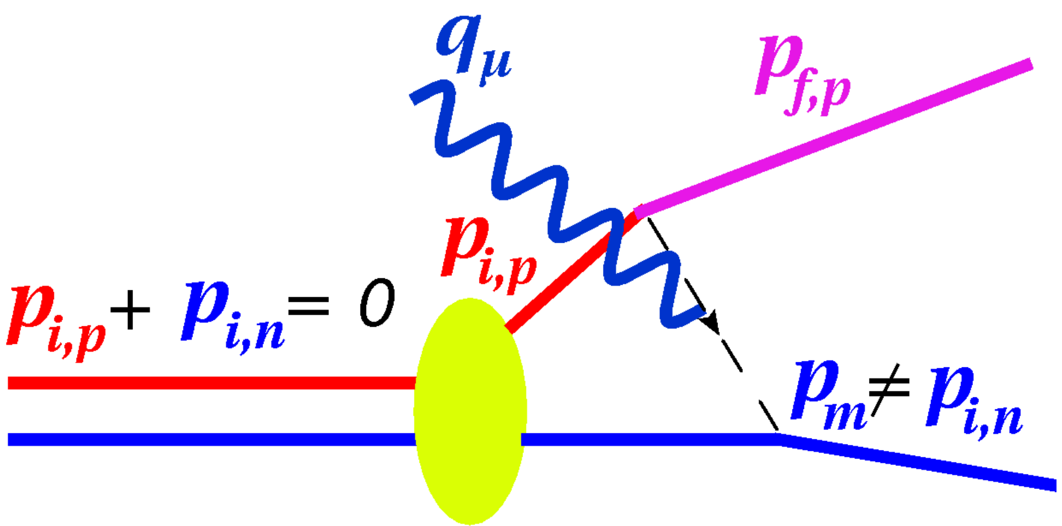
- ☑ **new, higher-precision data are crucial to understand the new behavior**

- ☑ all necessary tools available for quick analysis and publication

Back-Up Slides

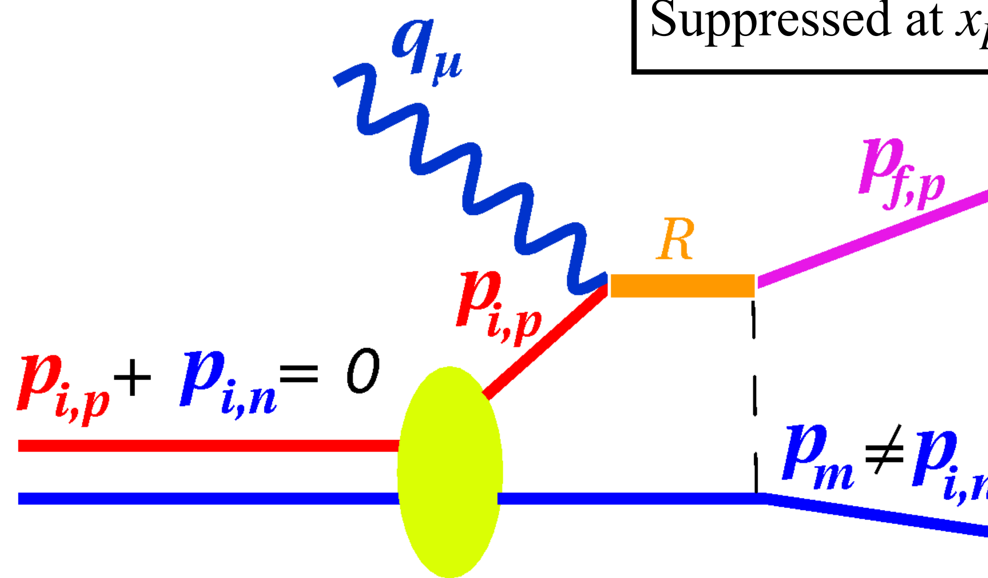
d(e, e'p)n Reaction Kinematics

Suppressed at $Q^2 > 1$ (GeV/c)^2

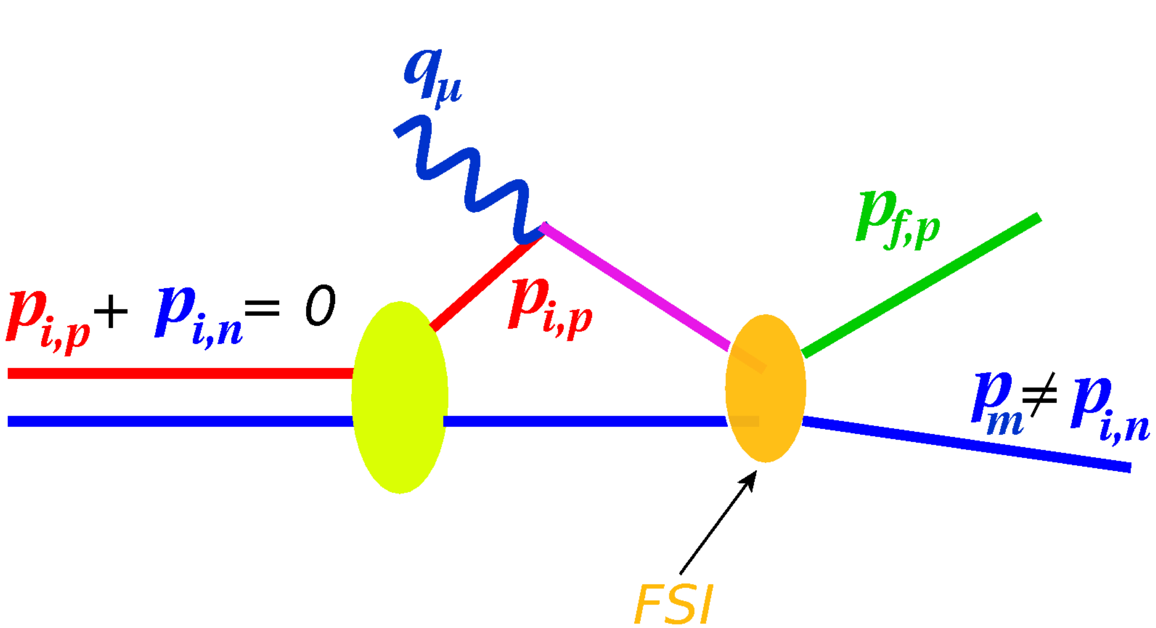


(a) Meson-Exchange Currents (MEC)

Suppressed at $x_{Bj} > 1$

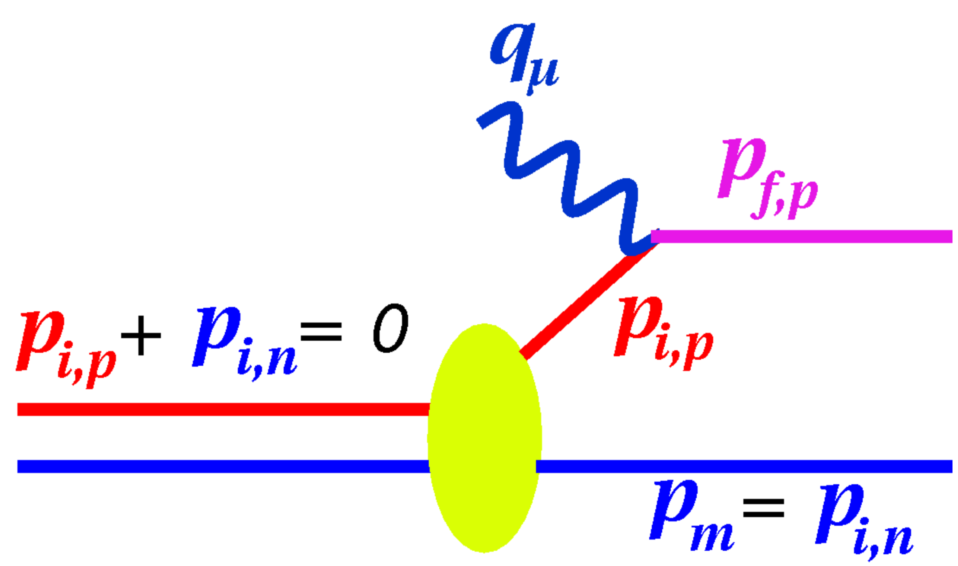


(b) Isobar Configurations (IC)



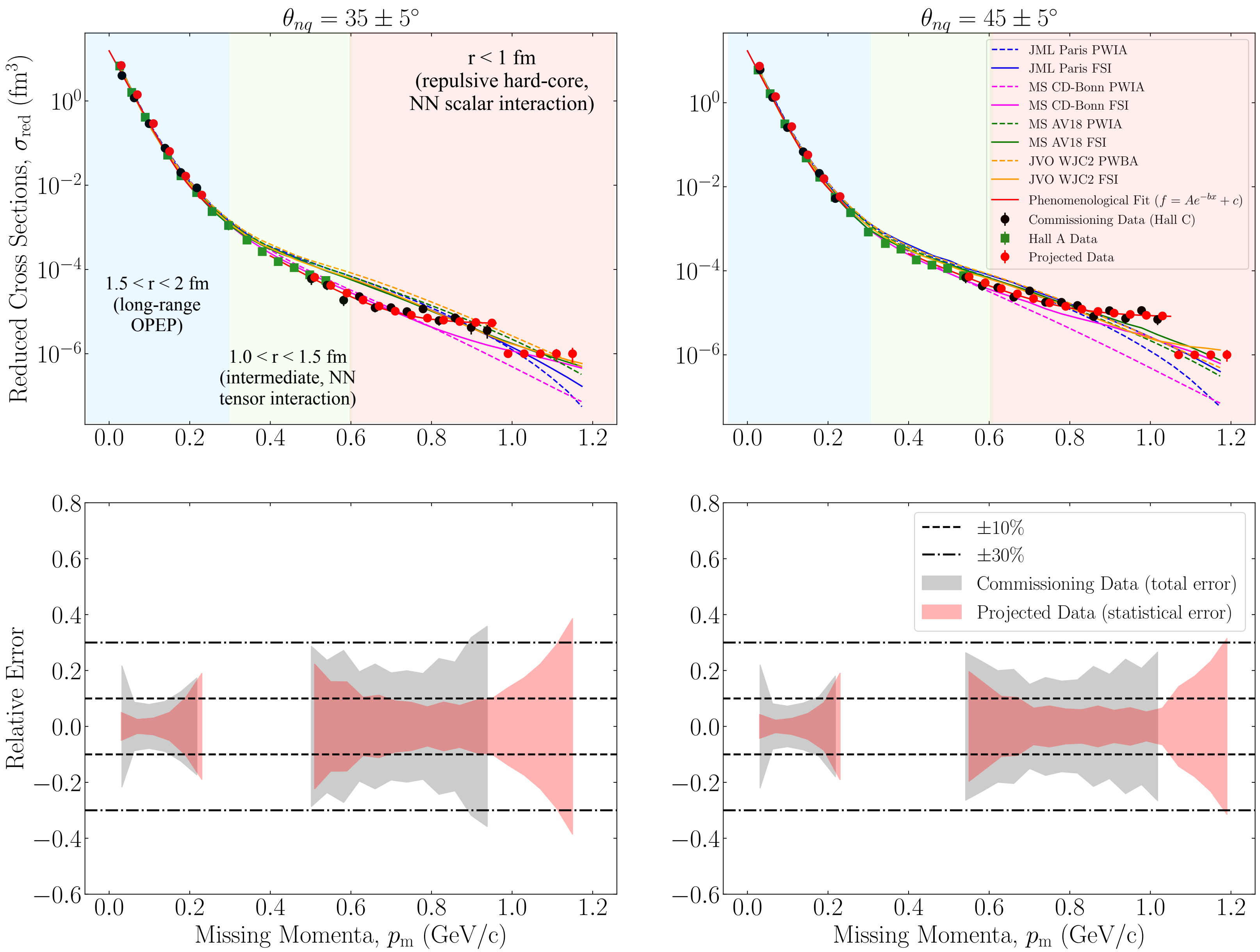
(c) Final State Interactions (FSI)

Suppressed at selected kinematics: $\theta_{nq} \sim 35 - 45°$



(d) Plane Wave Impulse Approximation (PWIA)

E12-10-003 Commissioning Experiment Results (and Projected Errors) | Part 1



☑ Pm < 250 - 300 MeV/c

- Long-range One-Pion Exchange Potential (OPEP) is well-known and widely used in most NN potentials.
- Data confirms the long-range description of the NN interaction

☑ 300 < Pm < 600 MeV/c

- Intermediate, tensor-dominated part of NN interaction
- CD-Bonn greatly differs from the other potentials (Paris, AV18, WJC2)
- Data favors the theoretical calculations by M. Sargsian using the CD-Bonn potential

☑ Pm > 600 MeV/c

- Short-range, scalar-dominated part of NN interaction corresponding to the repulsive hard-core (possible quark-gluon effects as well as relativistic effects become relevant)
- Data favors the CD-Bonn model up to ~700 MeV/c. Above 700 MeV/c, all theoretical calculations are unable to describe data
- *This behavior is completely new and unexpected and potentially shows the limits at which a valid description of the nucleus break down and the inclusion of explicit quark-gluon effects becomes a necessity in the theoretical calculations*

☑ Relative Errors

- Commissioning data (3 PAC days) dominated by statistical errors of 20 ~ 40 % (only ~ 5 % systematics contribution)
- Projected Data significantly reduces statistical uncertainty to ~10 % from missing momenta ~600 - 1000 MeV/c

Definition of "Reduced Cross Sections"

$$\sigma_{exp} \equiv \frac{d^5\sigma}{d\omega d\Omega_e d\Omega_p} = K \cdot \sigma_{ep} \cdot S(p_m)$$

$$S(p_m) \approx \sigma_{red} \equiv \frac{\sigma_{exp}}{K\sigma_{ep}}$$

☑ Why data partially favors CD-Bonn over other NN potentials ?

- The CD-Bonn potential uses the full, original, nonlocal Feynman amplitude as compared to local approximations used by other NN potentials (i.e., Paris, AV18) which leads to the CD-Bonn having a weaker tensor force as compared to all other potentials. This predicts a much softer repulsive interaction at short distances, which result in a smaller high-momentum component of the deuteron wave function in momentum space

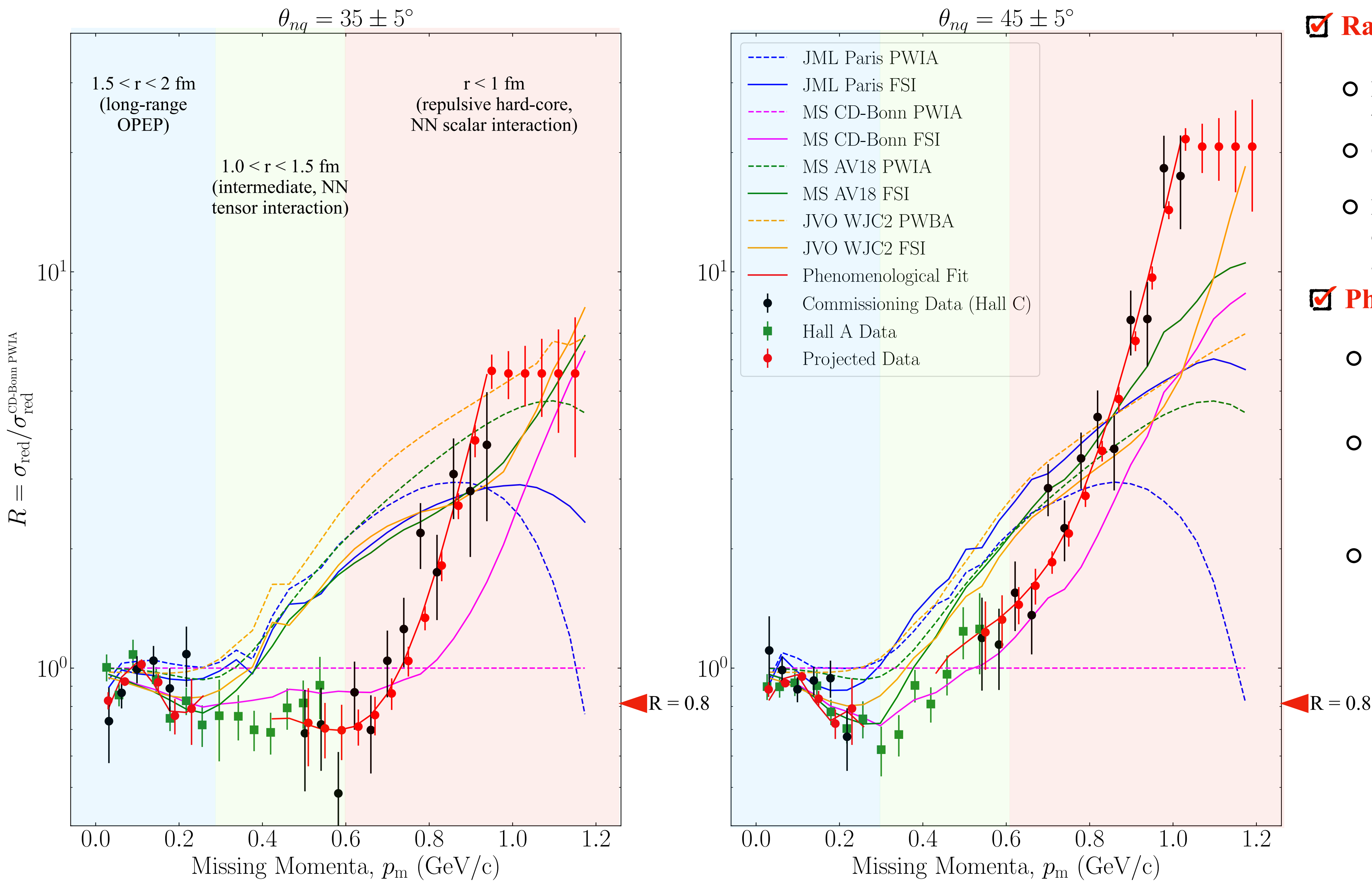
☑ Why are theoretical calculations using CD-Bonn unable to describe data above ~700 MeV/c ?

- Scattering amplitudes calculated in the theoretical framework of the generalized eikonal approximation (limited to high-Q2) using the virtual nucleon approximation (VNA). The VNA is based certain assumptions that define the limits of its validity to neutron recoil momenta $p_m \leq 700$ MeV/c. The discrepancy observed between data and CD-Bonn potentially reveal the limits imposed by the VNA assumptions

C. Yero et al. PhysRevLett 125, 262501 (2020)

M. M. Sargsian Phys. Rev. C 82, 014612 (2010)

E12-10-003 Commissioning Experiment Results (and Projected Errors) | Part 2



Ratio of data (and theory) to CD-Bonn PWIA

- Data confirms CD-Bonn FSI calculations up to ~650 - 700 MeV/c at forward angles, θ_{nq} ~ 35,45 deg
- CD-Bonn FSI is significantly small (R ~ 0.8 - 1) below 800 MeV/c for 35 deg, and below ~600 MeV/c for 45 deg
- Recoil angles at 35 +/- 5 deg better suited for directly probing high-momentum component of deuteron as FSI are small over a larger missing momentum range

Phenomenological Fit / Projected Data

- Projected data (full red circles), assuming 18 PAC days, displayed on phenomenological fit (red curve) show a significant improvement in the projected statistical errors
- Projected data at pm>900 MeV/c) shows completely new, unexplored missing momentum with statistical uncertainty comparable to the commissioning data (black points)
- Significantly smaller projected statistical errors will help pin down the behavior observed in commissioning data above ~700 MeV/c, as well as put stricter constraints on the theoretical calculations

With the GEA calculations by M. Sargsian, it can be shown that approximate cancellation of FSI/PWIA (interference "screening" term) with the FSI^2 (re-scattering term) amplitudes leads to reduction in FSI at specific kinematics

$$\sigma \sim |A_{PWIA} + iA_{FSI}|^2 \sim A_{PWIA}^2 - 2A_{PWIA}A_{FSI} + A_{FSI}^2 \longrightarrow R = \frac{\sigma}{\sigma_{PWIA}} \sim 1 - 2\frac{A_{FSI}}{A_{PWIA}} + \frac{A_{FSI}^2}{A_{PWIA}^2}$$

where $A_{FSI} \sim i|A_{FSI}|$

C. Yero et al. PhysRevLett 125, 262501 (2020)

E12-10-003 Commissioning Data Analysis

SHMS Optics Optimization for E12-10-003 Using H(e,e'p) Elastics

Optics Optimization for the D(e,e'p)n Experiment (E12-10-003)

Carlos Yero

July 29, 2019

1 Introduction

The commissioning of the HMS/SHMS optics took place on the 2017-18 run period and underwent multiple revisions of the reconstruction matrix elements for both spectrometers during that period.[3, 4] This document presents the optics optimization checks and procedures done on the High Momentum Spectrometer (HMS) and superHMS (SHMS) for the Deuteron Electro-Disintegration Commissioning Experiment (E12-10-003) on April 2018. At the time, this experiment also served as part of the general optics commissioning as during data-taking, it was found that the SHMS Q3 magnet had an un-ncecessary correction in the matrix elements. As a result, the data for this experiment is divided into two sections. Only the section after the fix in the SHMS optics was used in the optimization procedure.

The problem of optics optimization can be approached in different ways, depending on the circumstances of the experiment. In this particular experiment, a series of H(e,e'p) elastic runs were taken at different configurations such as to cover the entire HMS momentum range in the D(e,e'p)n reaction kinematics. The original and corrected H(e,e'p) kinematics are summarized below.

Run	HMS Angle [deg]	HMS Momentum [GeV]	SHMS Angle [deg]	SHMS Momentum [GeV]
3288	37.338	2.938	12.194	8.7
3371	33.545	3.48	13.93	8.7
3374	42.9	2.31	9.928	8.7
3377	47.605	1.8899	8.495	8.7

Table 1: Original H(e,e'p) Elastic Kinematics in E12-10-003.

Run	HMS Angle [deg]	HMS Momentum [GeV]	SHMS Angle [deg]	SHMS Momentum [GeV]
3288	37.338	2.9355	12.194	8.5342
3371	33.545	3.4758	13.93	8.5342
3374	42.9	2.3103	9.928	8.5342
3377	47.605	1.8912	8.495	8.5342

Table 2: Corrected H(e,e'p) Elastic Kinematics in E12-10-003.

Spec	$\delta\theta$[rad]	$\delta\phi$[rad]	X'_{tar}-offset[rad]	Y'_{tar}-offset[rad]
HMS	0.0	1.521×10^{-3}	2.852×10^{-3}	9.5×10^{-4}
SHMS	0.0	0.0	0.0	0.0

Table 3: Spectrometer Offsets determined from H(e,e'p) Elastic Run 3288 in E12-10-003. See Section 4 of this document for more information.

Since this is a coincidence experiment, the spectrometers are highly correlated which makes the optics optimization more complicated, as changes in one spectrometer can affect the other. Based on the kinematics, it was determined to focus on the HMS first, as the momentum is well below the Dipole saturation (~5 GeV), and the optics are much better understood from the 6 GeV era.

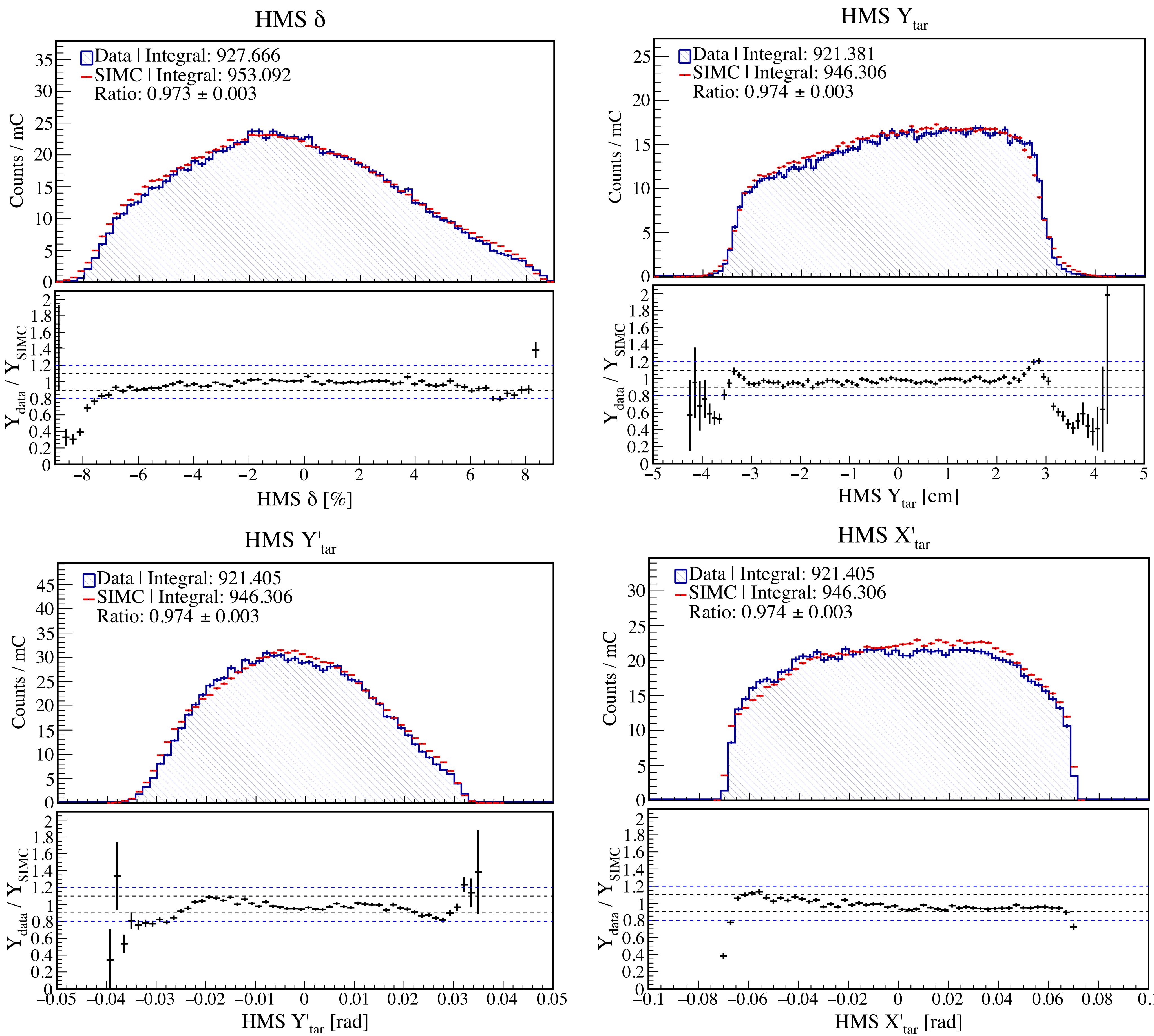
1

- Optimize SHMS delta matrix
- Used sieve data to optimize Ytar
- Determined spectrometer kinematics offsets

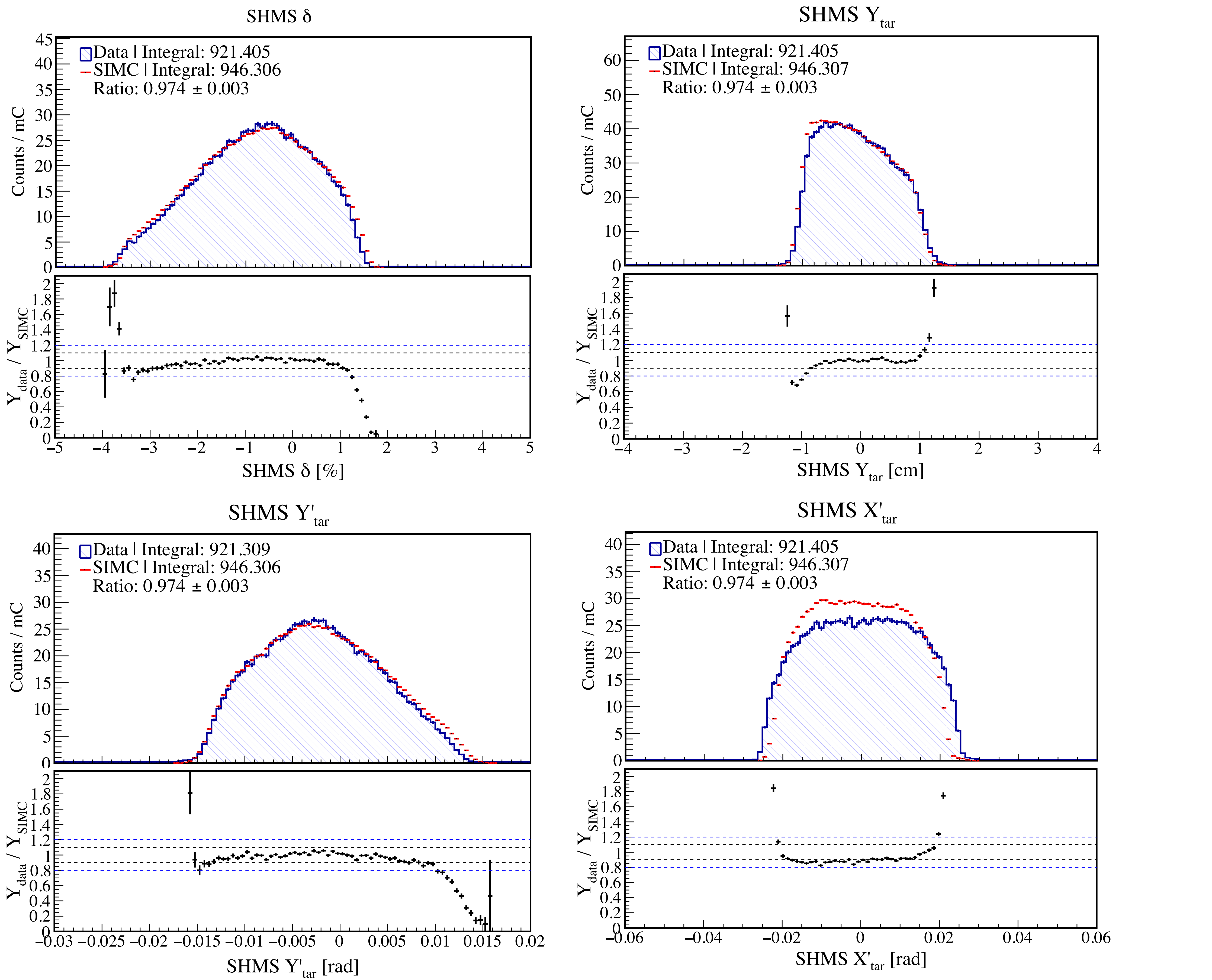
Details can be found in documentation link:

Hall C Document Database: E12-10-003 SHMS Optics Optimization

H(e, e’p) Elastics HMS Acceptance Plots



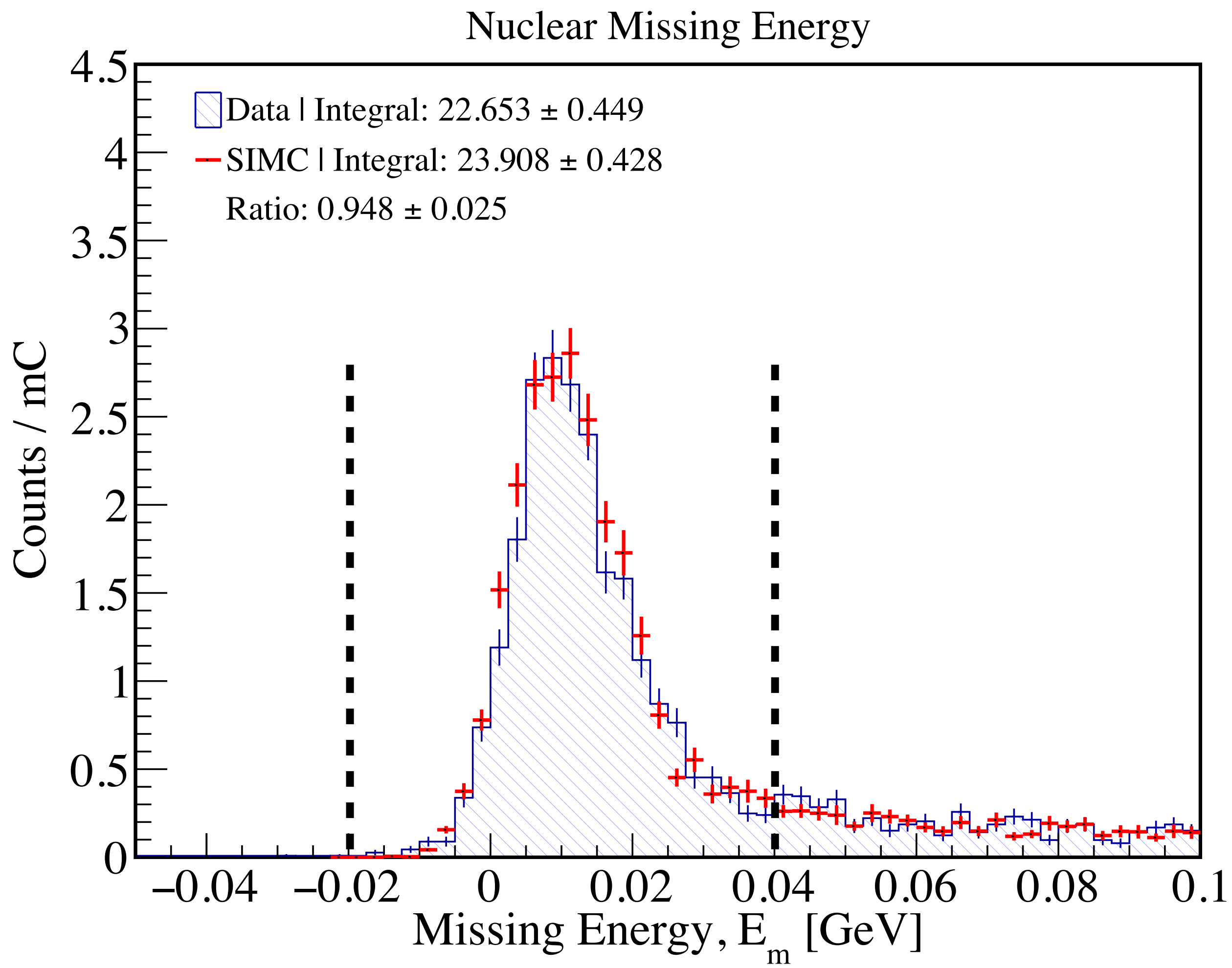
H(e, e'p) Elastics SHMS Acceptance Plots



d(e, e'p)n Event Selection Cuts

Cuts shown in next slides are for the 80 MeV/c central missing momentum setting

The exact cuts were also placed on the 580 and 750 MeV/c settings



Missing Energy Cut: (-20, 40) MeV

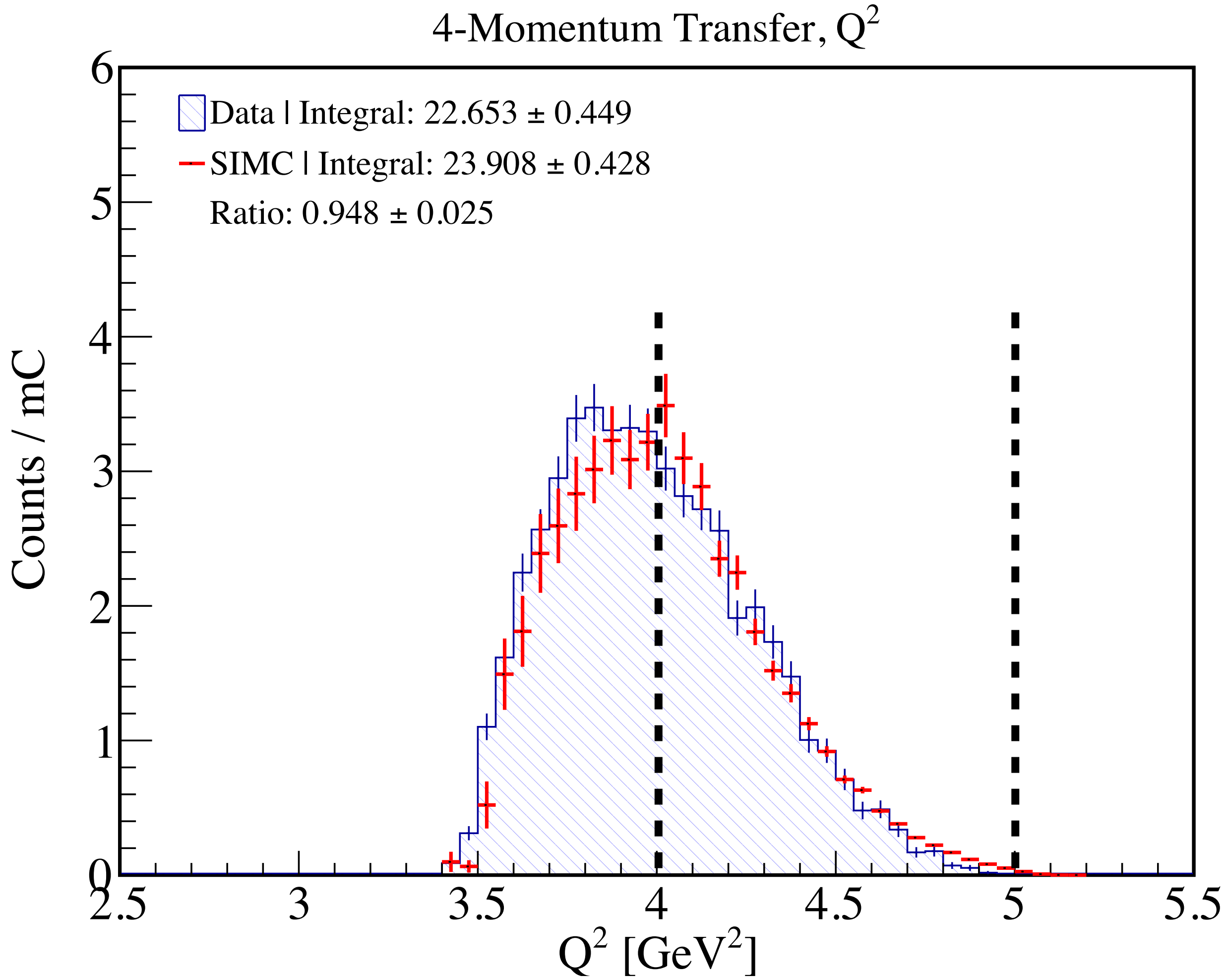
Select true d(e,e'p)n events

$$E_{\rm m} = \omega - T_{\rm p} - T_{\rm r}$$

Missing energy is the B.E. of deuteron (~2.22 MeV)

proton kinetic energy

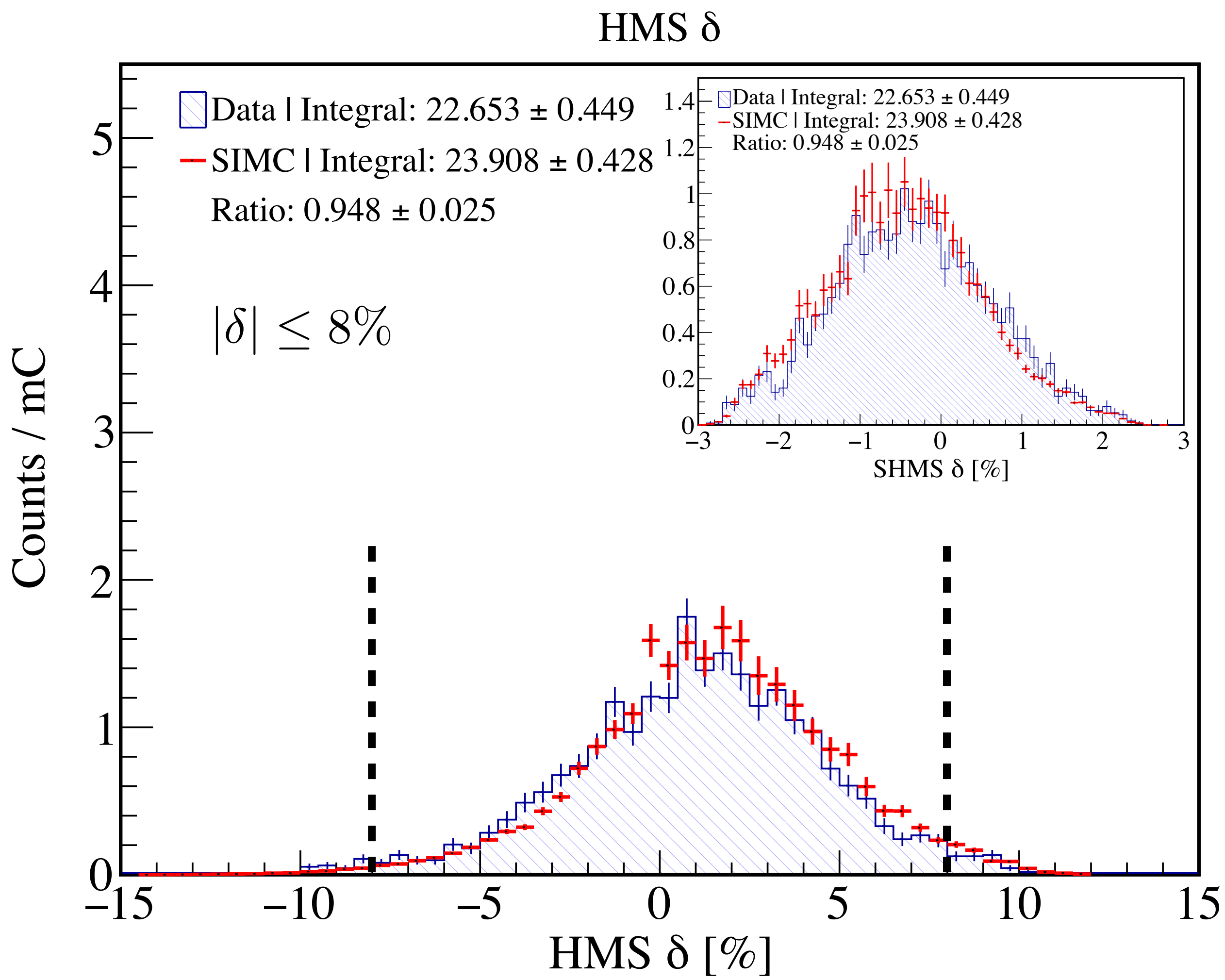
recoil kinetic energy (Assume the mass of the recoil neutron)



4-Momentum Transfer Cut

CUT: $Q^2 = 4.5 \pm 0.5\ \mathrm{GeV}^2$

Kinematics cut to select only events with high momentum transfer



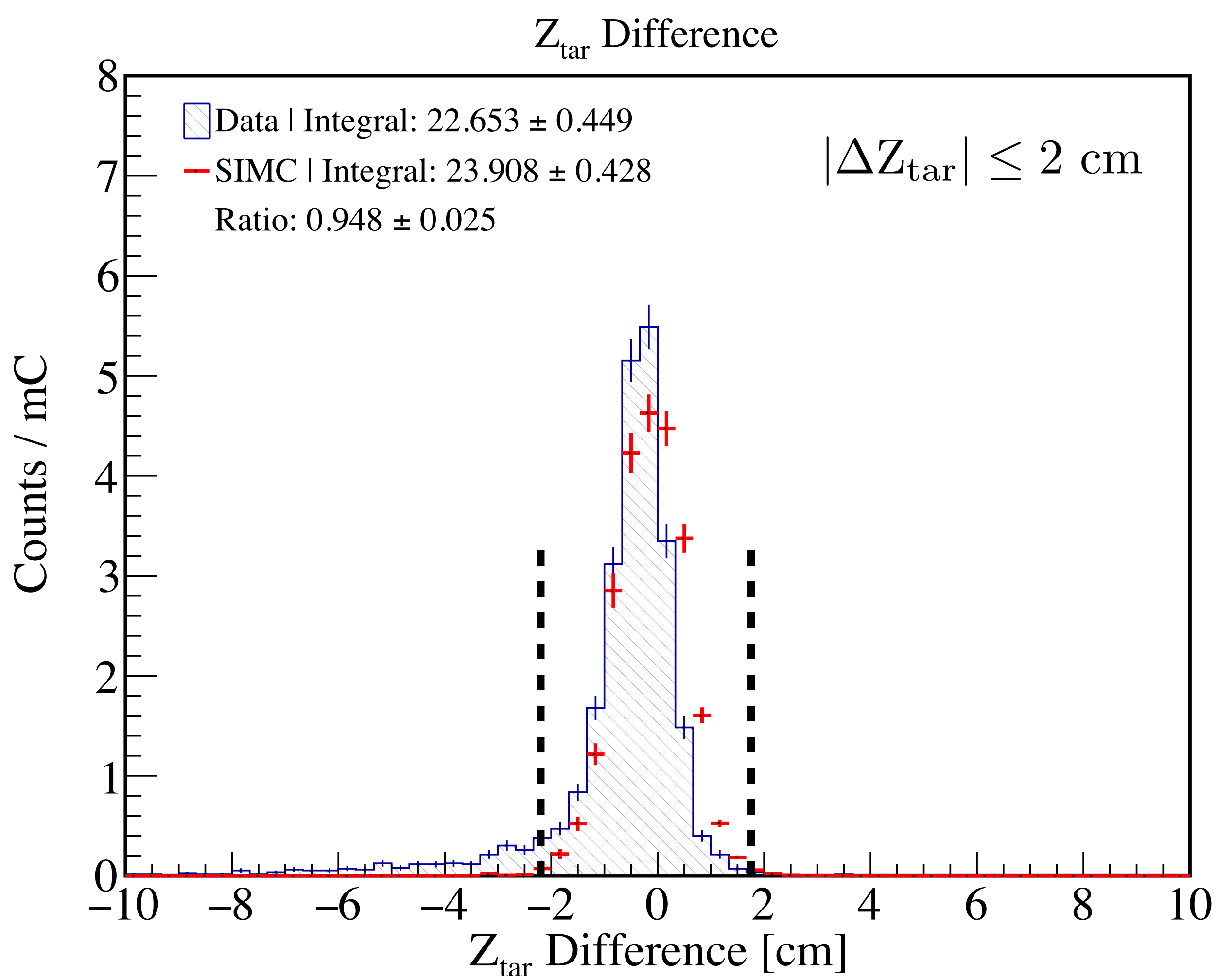
HMS Delta Acceptance Cut: (-8, 8) %

Select HMS momentum acceptance region where Optics Reconstruction is reliable

Inset: SHMS momentum acceptance is constrained by HMS acceptance to be within (-3, 3) %

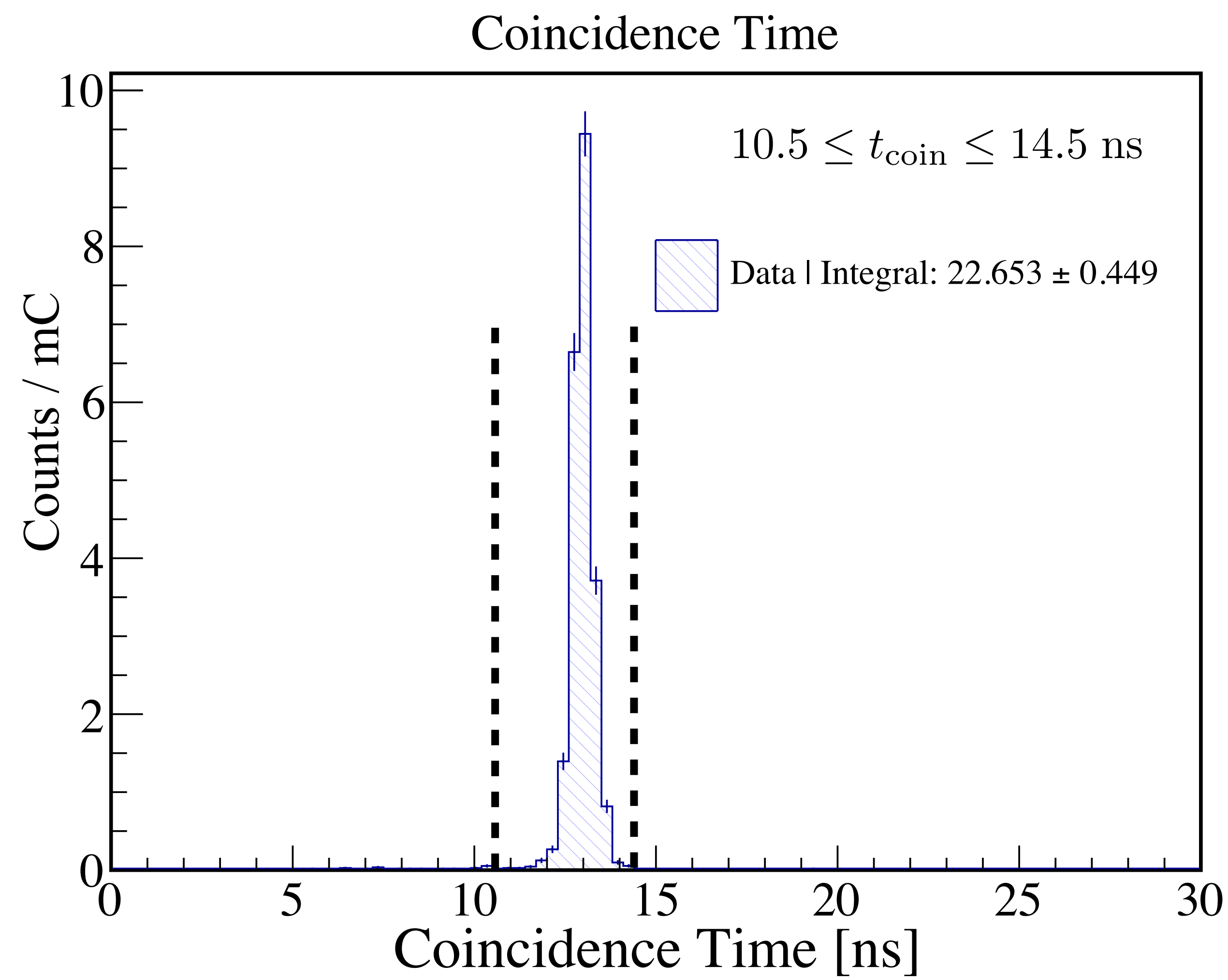
particle momentum **central spectrometer momentum**

$$\delta \equiv \frac{P - P_0}{P_0} \times 100$$



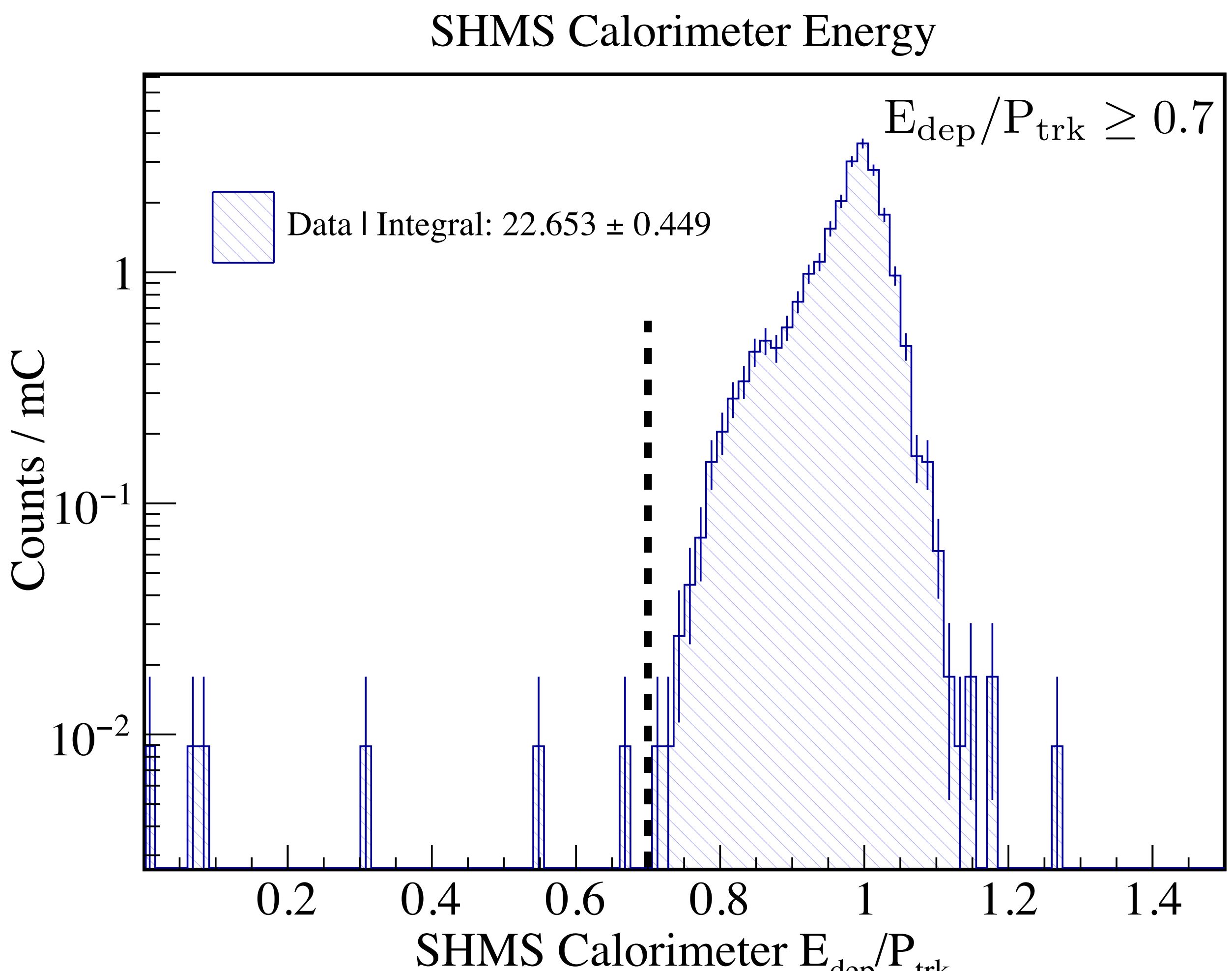
Reconstructed Z vertex difference Cut: +/- 2 cm relative the peak value

require event Z-vertex (target) position to be the same for both HMS and SHMS to select true coincidences and not accidental events



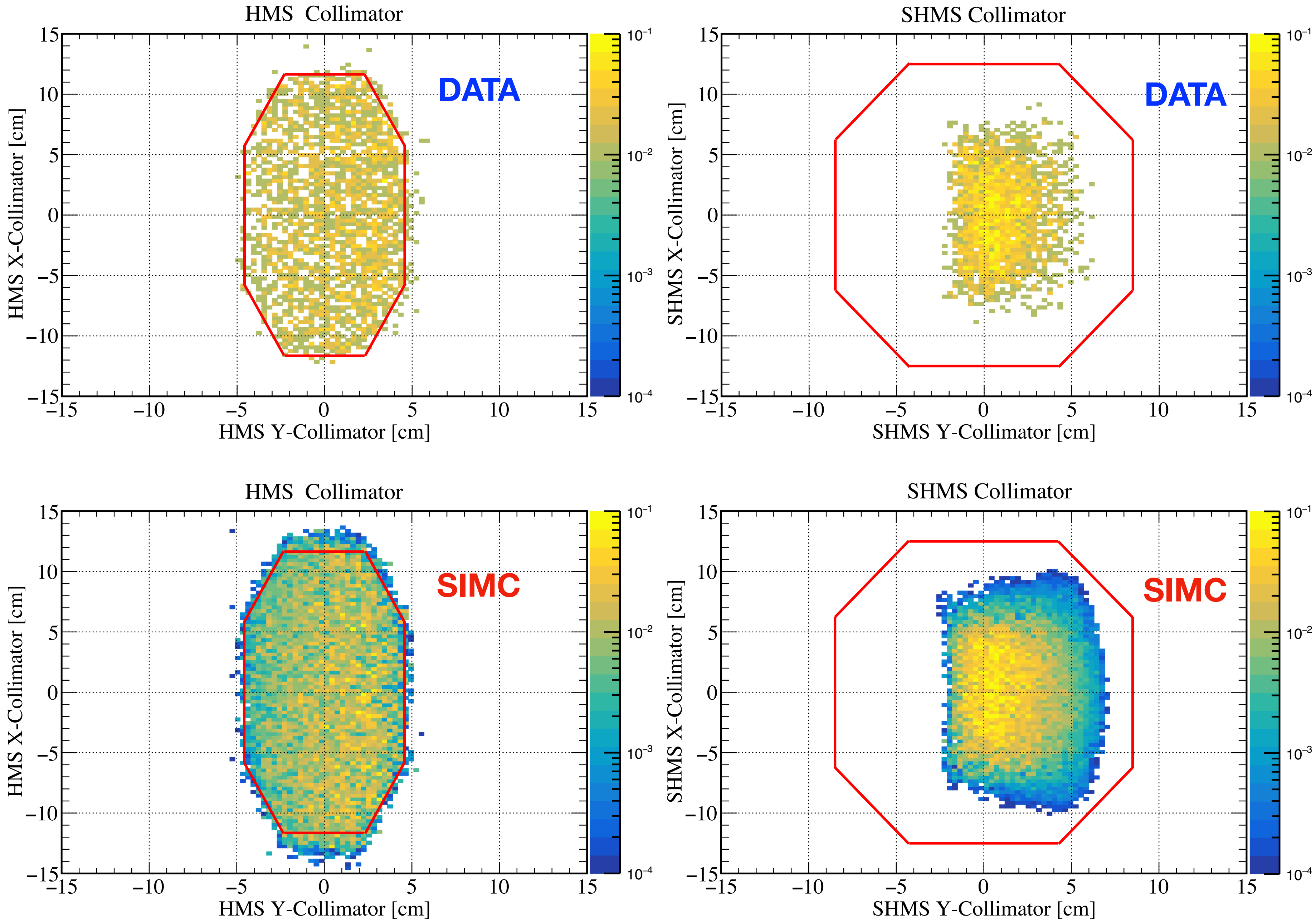
Coincidence Time Cut
CUT: (10.5, 14.5) ns

select true electron-proton coincidences



SHMS: Total energy deposited in Calorimeter normalized by the best track
CUT: >= 0.7

select true electrons in SHMS and not pions (looks very clean!)



HMS Collimator Cut
(Geometrical cut on
collimator dimensions)

Select events that passed through HMS collimator and NOT scattered at the edges of the collimator

SHMS Collimator:

events in SHMS are constrained by the HMS acceptance to be well within the collimator edges (not cut was necessary, this just illustrates where the events are)

d(e, e'p)n Cross-Section Extraction

$$\bar{\sigma}^{exp} \equiv \frac{Y^{corr}_{data}}{V^{P.S.}}$$

Corrected Data Yield

Phase Space Volume

Average Experimental Cross-Section

Radiative Correction

Correct for Inefficiencies

Normalize data by total charge

$$Y^{corr}_{data} = \frac{Y^{uncorr}_{data} \cdot f_{rad}}{Q \cdot \epsilon_{tLT} \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{tgtBoil} \cdot \epsilon_{pAbs}}$$

Luminosity

$$V^{P.S.} = \frac{\mathcal{L}}{N_{\mathrm{gen}}} \mathcal{J}_{\mathrm{corr}} \Delta E' \Delta\Omega_{\mathrm{e}} \Delta\Omega_{\mathrm{p}}$$

Monte-Carlo Generated events

Jacobian operator

Spectrometer momentum (e-) and "Solid Angles"

D(e,e'p)n Coincidence rates

Cross section

$$\mathcal{L} \equiv \frac{1}{\sigma} \frac{dN_{\mathrm{coin}}}{dt}$$

$$= \frac{\#\ \text{beam particles}}{\text{sec}} \times \frac{\#\ \text{target particles}}{\text{cm}^2}$$

- luminosity can be expressed in terms of beam and target parameters, usually in units of $\mathrm{s}^{-1}\mathrm{cm}^{-2}$

Averaged Experimental Cross Section ($\bar{\sigma}^{exp}$)

- missing momentum yield (top) and phase space (bottom) binned in (P_m, θ_{nq}) bins, and divided to extract the cross sections

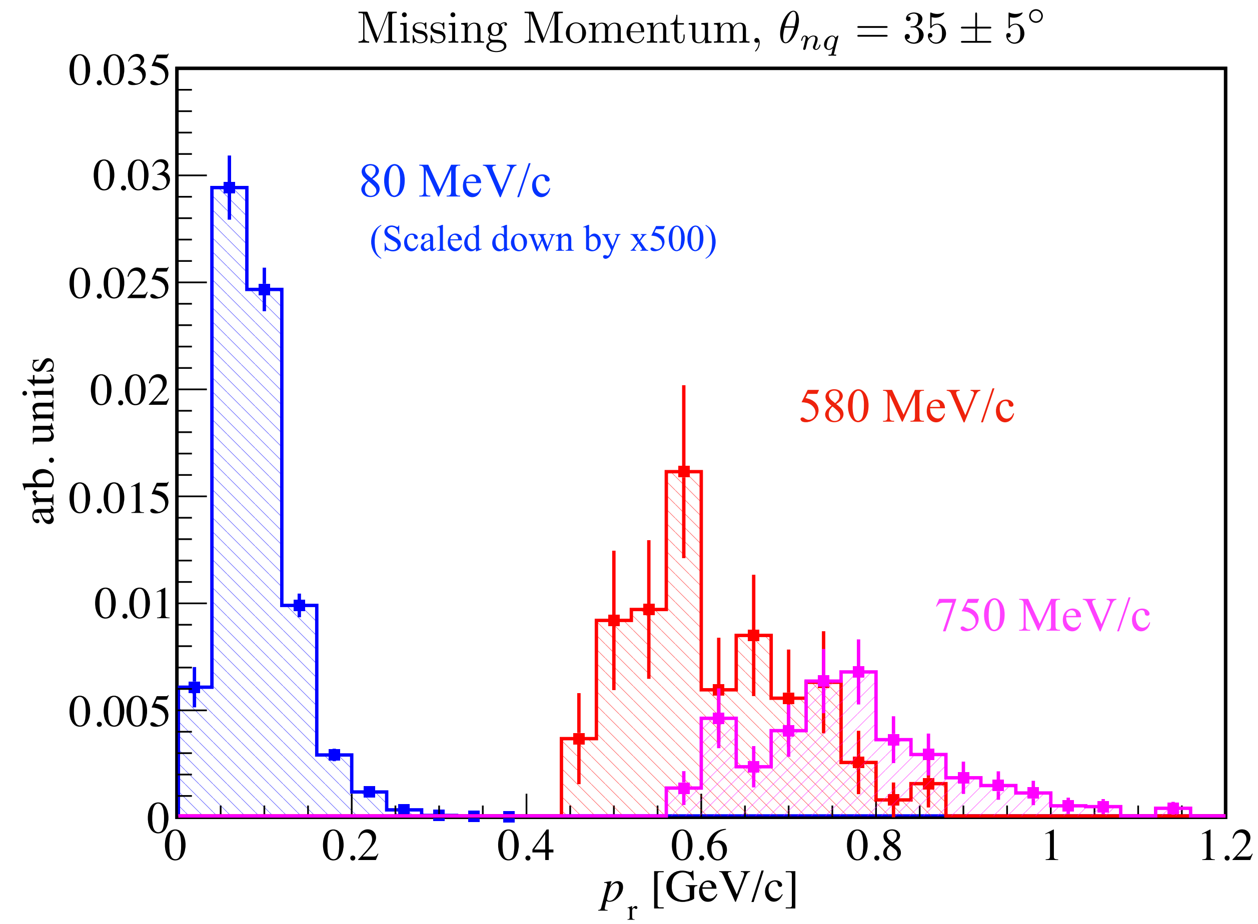
- in this example, only a specific bin: $\theta_{nq} = 35 \pm 5^{\circ}$ is shown

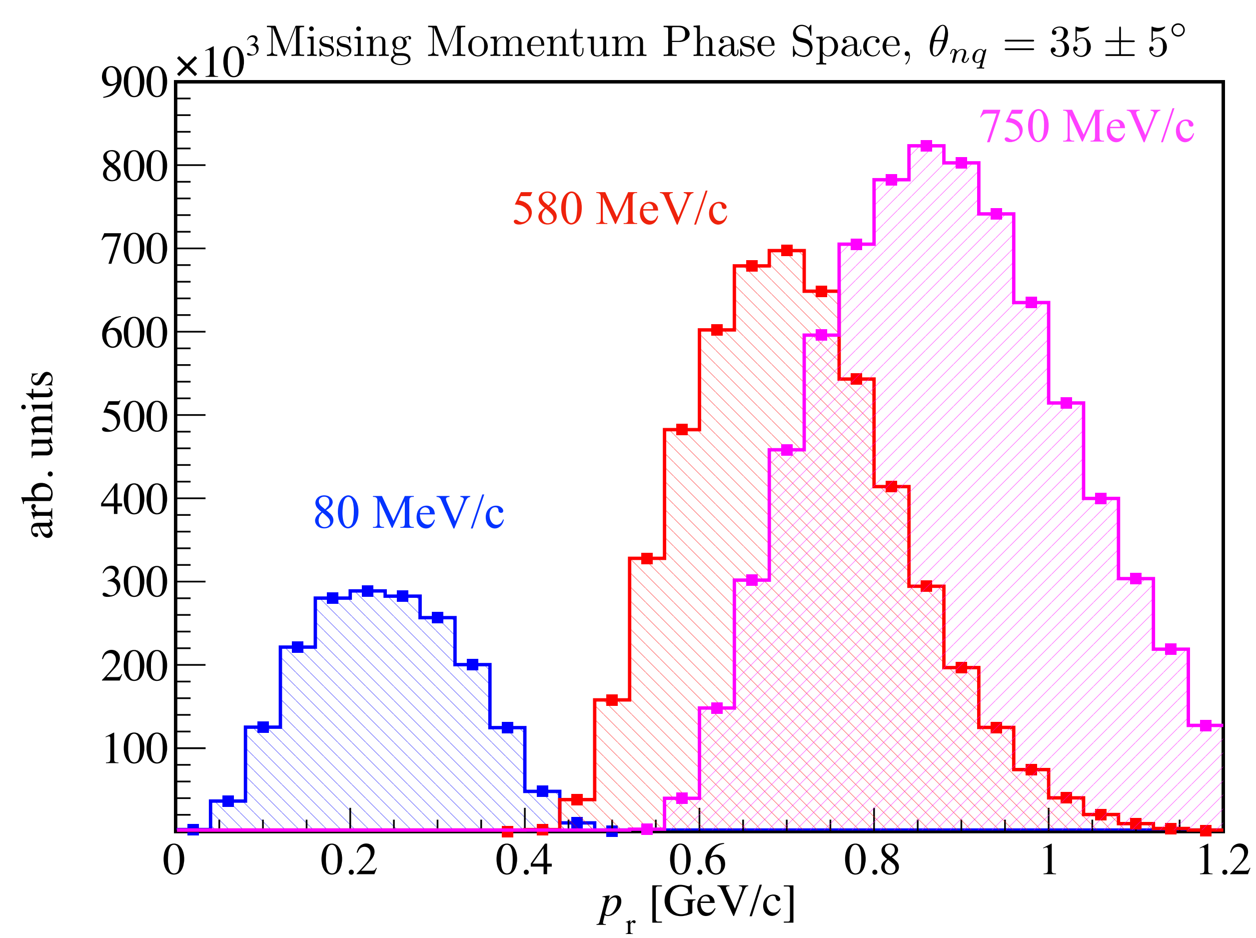
- corrected data yield (Y^{corr}_{data}) has been radiatively corrected, normalized by total charge and corrected for inefficiencies

Corrected Data Yield

$$\bar{\sigma}^{exp} \equiv \frac{Y^{corr}_{data}}{V^{P.S.}}$$

Phase Space Volume





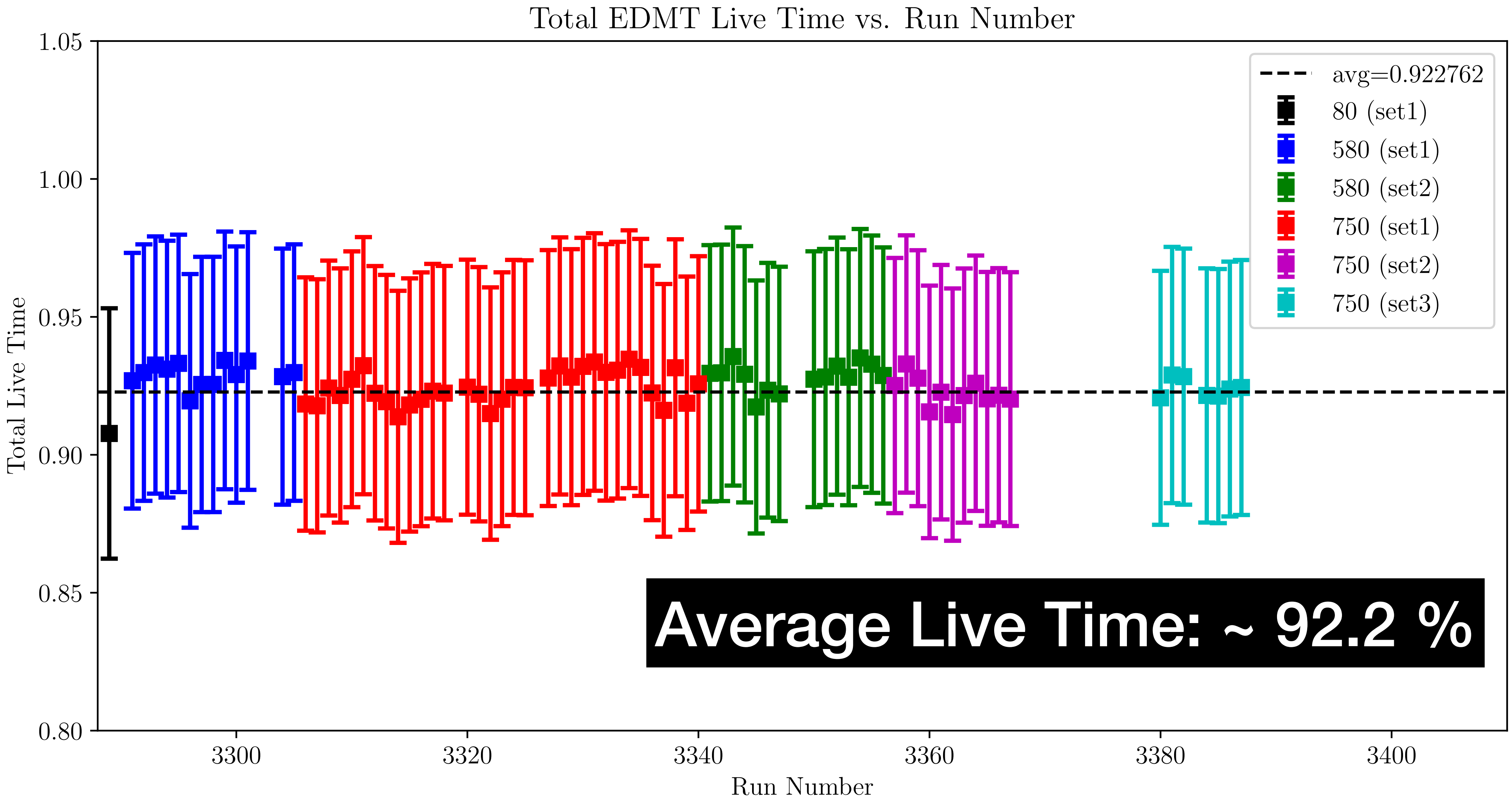
- randomly-generated Monte Carlo events have populated the HMS-SHMS spectrometers acceptance at the d(e, e'p)n reaction kinematics

NOTE: Missing momentum (P_m) and recoil momentum (p_r) are used interchangeably when referring to the recoiling neutron momentum

$$Y_{data}^{corr} = \frac{Y_{data}^{uncorr} \cdot f_{rad}}{Q \cdot \epsilon_{tLT} \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{tgtBoil} \cdot \epsilon_{pAbs}}$$

Correct for total Data Acquisition (DAQ) dead time

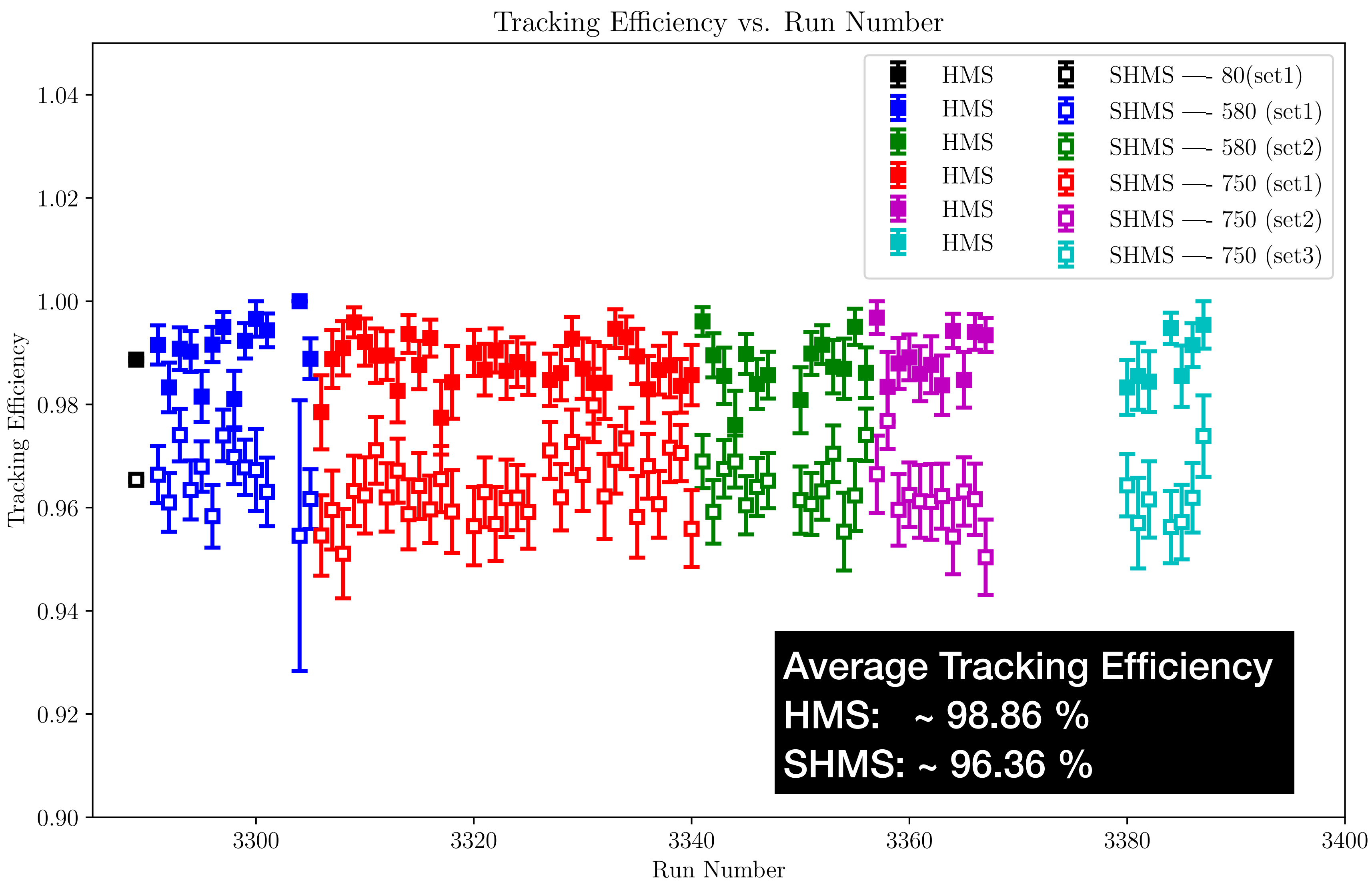
- dead time is the time that the DAQ is unable to register/process triggers which results in event loss that must be accounted for



$$Y_{data}^{corr} = \frac{Y_{data}^{uncorr} \cdot f_{rad}}{Q \cdot \epsilon_{tLT} \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{tgtBoil} \cdot \epsilon_{pAbs}}$$

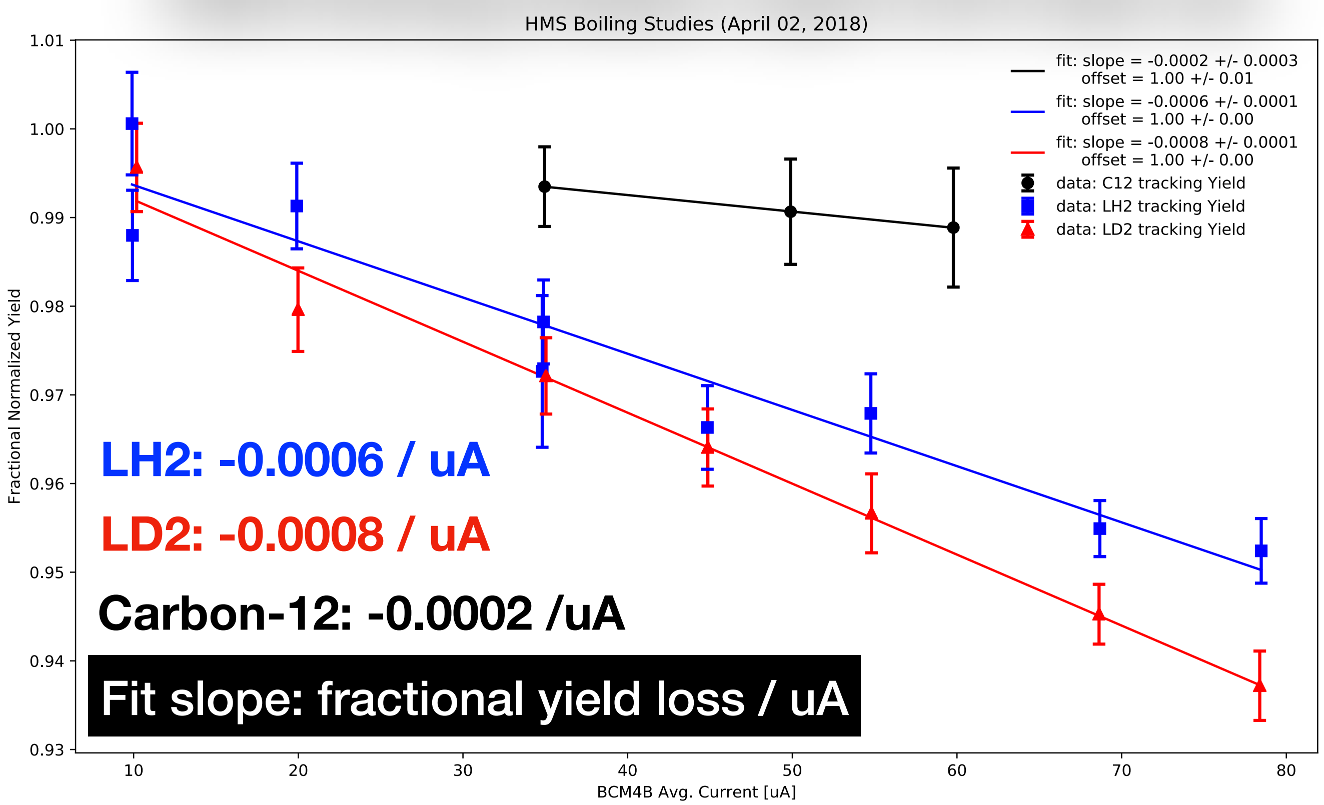
Correct for inefficiency due to tracking reconstruction algorithm

- Account for potential lost tracks due to bad track reconstruction by the tracking algorithm

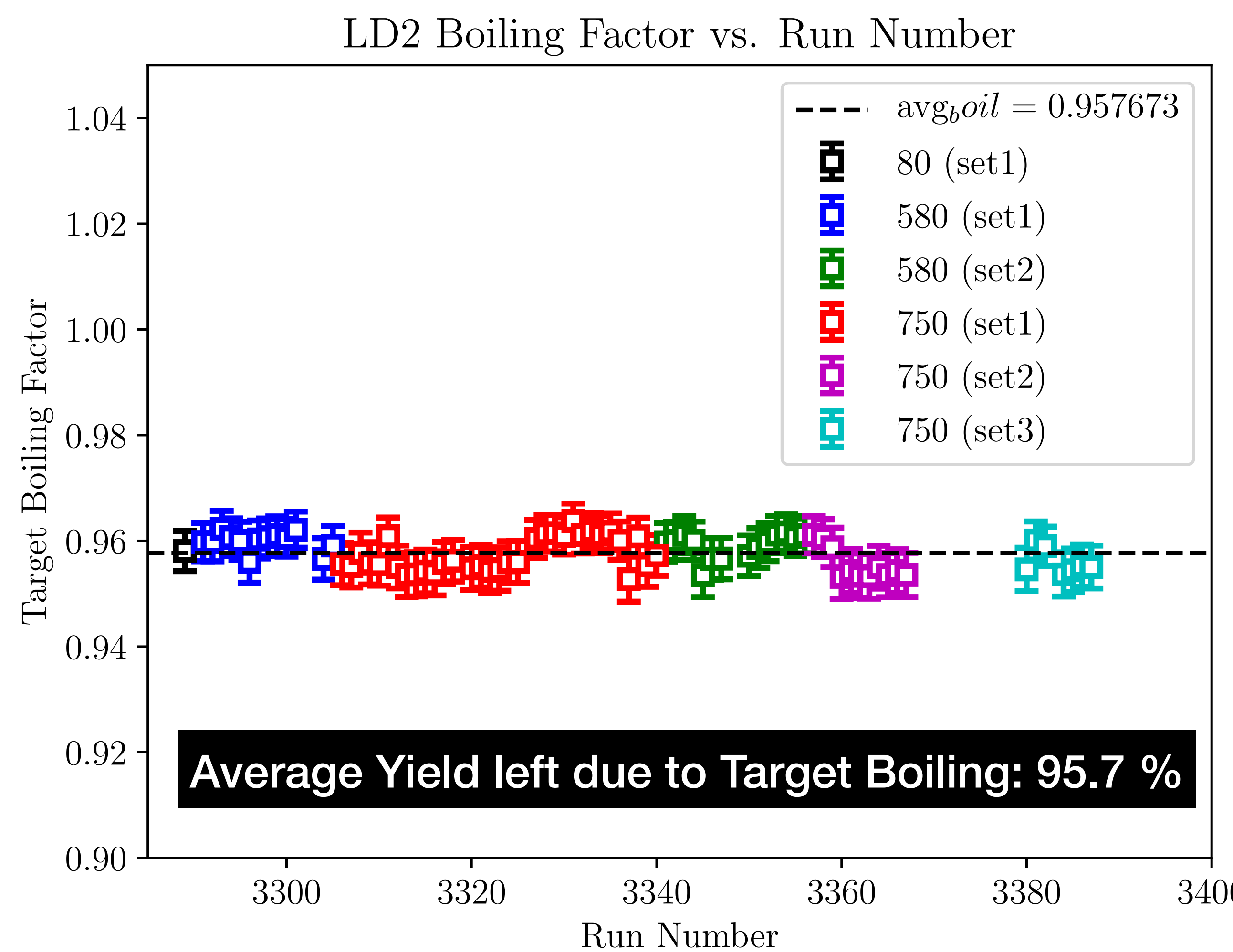


$$Y_{data}^{corr} = \frac{Y_{data}^{uncorr} \cdot f_{rad}}{Q \cdot \epsilon_{tLT} \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{tgtBoil} \cdot \epsilon_{pAbs}}$$

HMS Boiling Studies (April 2018 data set)



Correct for yield loss due to target density fluctuations



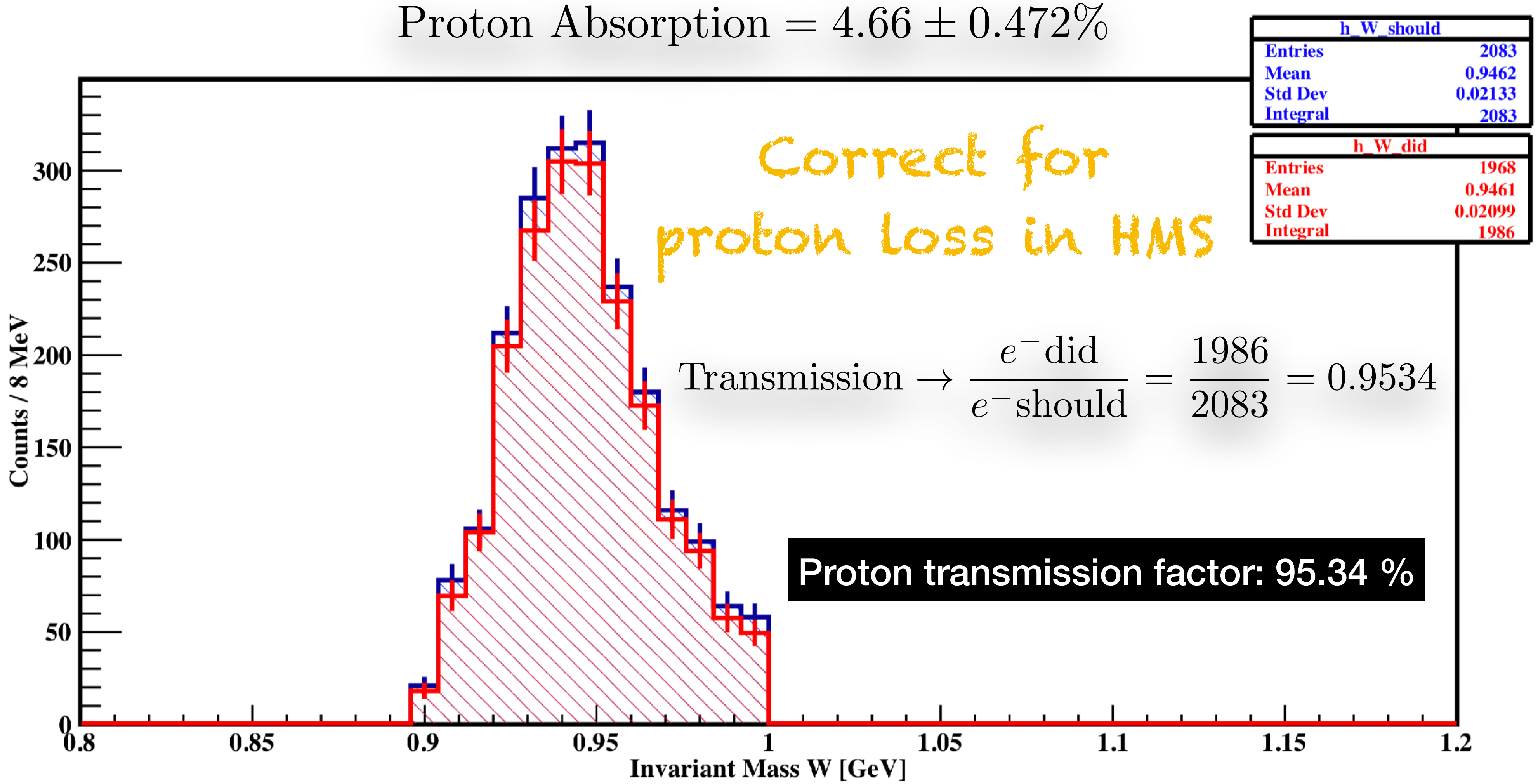
- Account for event loss at the reaction vertex due to target density fluctuations in the 10-cm liquid deuterium target

Details can be found in documentation link:

[Hall C Document Database: E12-10-003 Target Boiling Studies]

$$Y_{data}^{corr} = \frac{Y_{data}^{uncorr} \cdot f_{rad}}{Q \cdot \epsilon_{tLT} \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{tgtBoil} \cdot \epsilon_{pAbs}}$$

Proton Absorption $= 4.66 \pm 0.472\%$

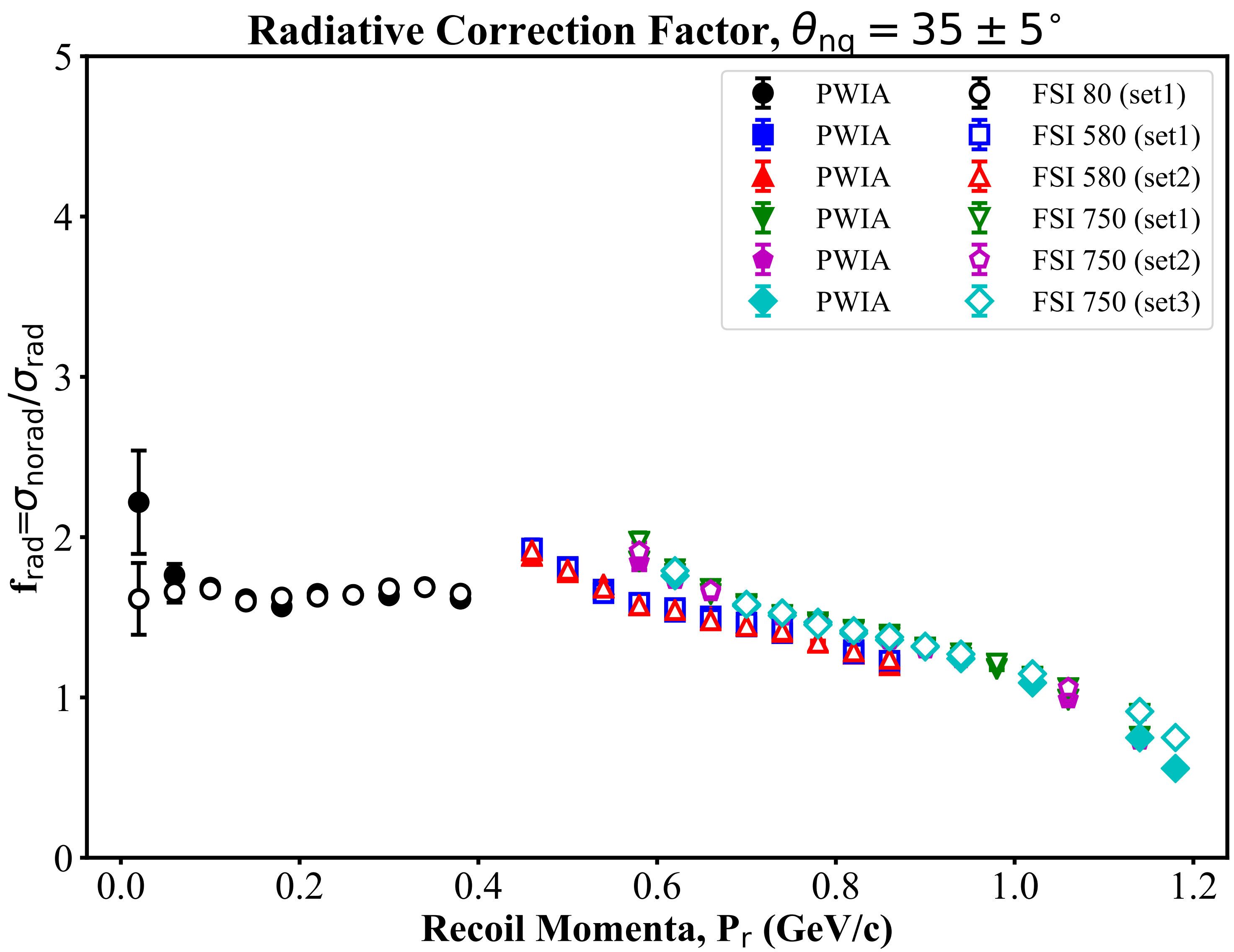


- Account d(e, e’p)n coincidence events lost due to a small fraction of the protons undergoing nuclear interactions in the spectrometer medium to lose all its energy before being detected and forming a coincidence trigger

Details can be found in documentation link:

[Hall C Document Database: E12-10-003 Proton Absorption Studies]

$$Y_{data}^{corr} = \frac{Y_{data}^{uncorr} \cdot f_{rad}}{Q \cdot \epsilon_{tLT} \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{tgtBoil} \cdot \epsilon_{pAbs}}$$



Radiative Correction factor

$$f_{rad} = \frac{Y_{\mathrm{norad}}^{\mathrm{SIMC}}}{Y_{\mathrm{rad}}^{\mathrm{SIMC}}}$$

- Correct for the radiative effects before and after the electron interaction with the target
- Radiative effects (either internal or external bremsstrahlung) in the initial and final states of the reaction modify the kinematics of the detected particles, and thus the true cross section

d(e, e’p)n Bin-Centering Corrections

Bin-center corrected experimental cross sections →

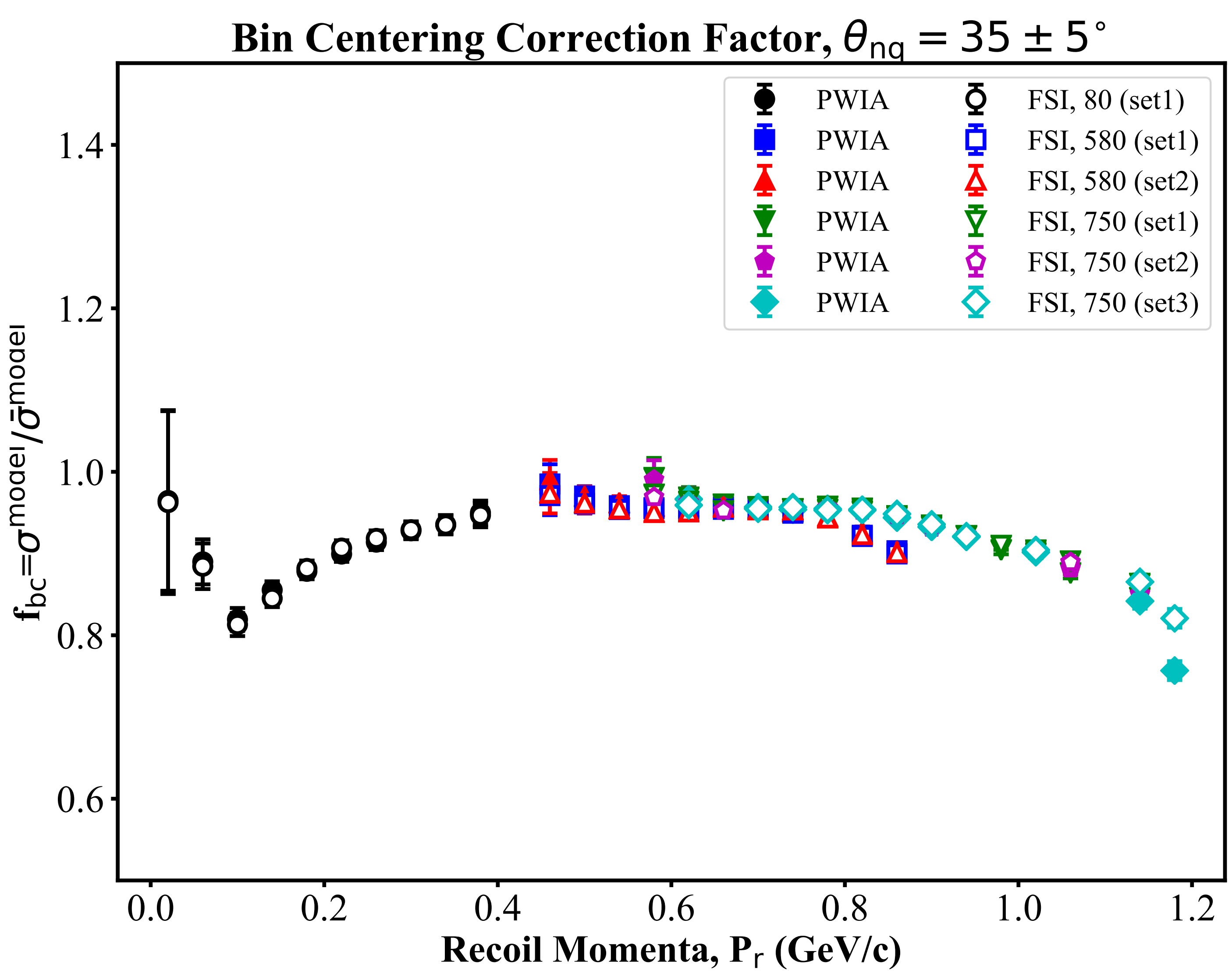
$$\sigma_{bc}^{exp} = \bar{\sigma}^{exp} \cdot f_{bc}$$

$$\bar{\sigma}^{exp} \equiv \frac{Y_{data}^{corr}}{V^{P.S.}}$$

$$f_{\mathrm{bc}} \equiv \frac{\sigma^{\mathrm{model}}(\bar{\mathrm{k}})}{\bar{\sigma}^{\mathrm{model}}(\mathrm{k})}$$

Model cross sections evaluated at the average kinematics, $\bar{\mathrm{k}} : (\bar{P}_m, \bar{\theta}_{nq})$

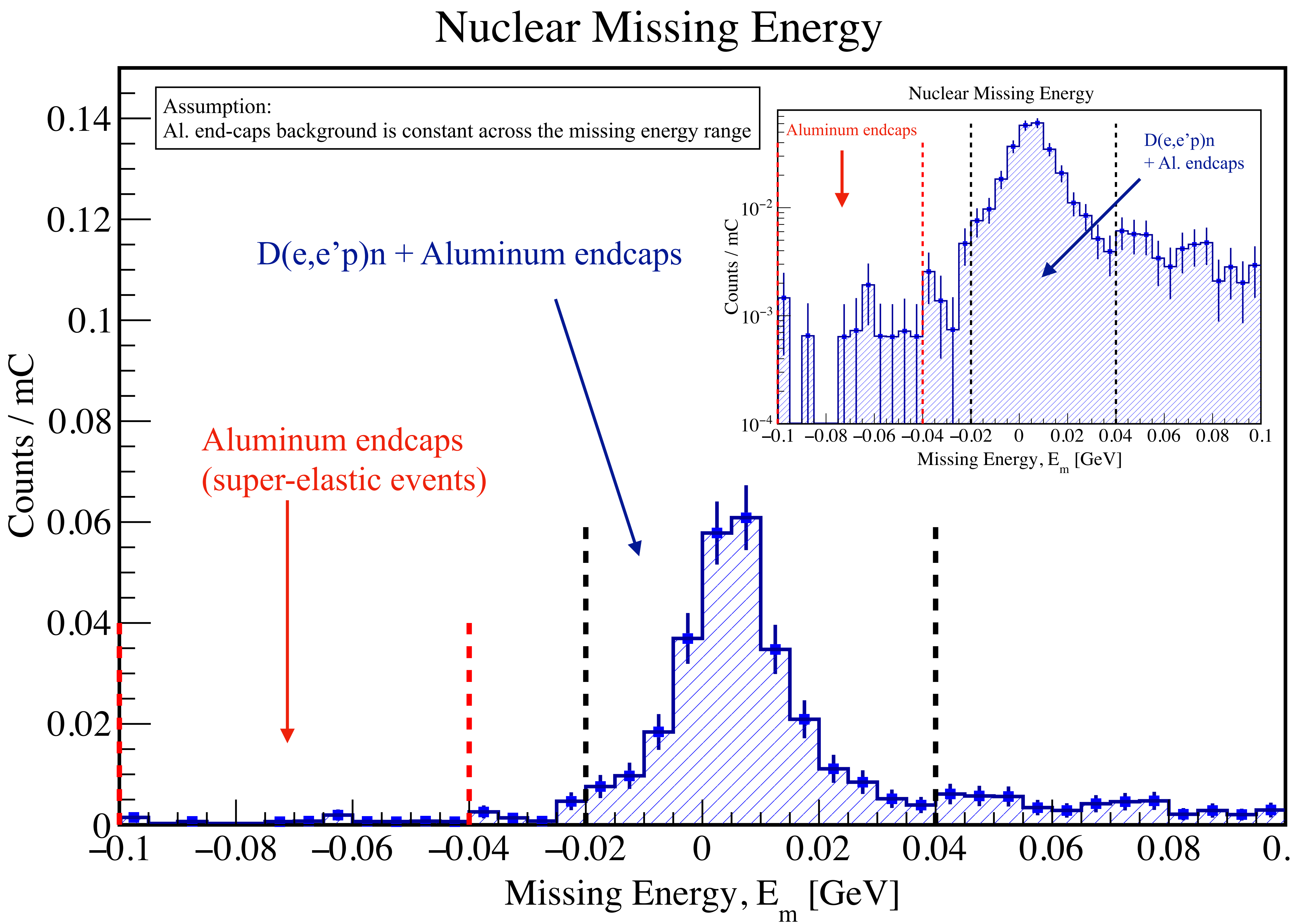
Average model cross sections evaluated at the central kinematics, $\mathrm{k} : (P_m, \theta_{nq})$



- Bin centering corrections account for the fact that the the average cross sections by the simulation program are determined at the bin-center, when in reality, the cross section at a kinematic bin might not necessarily correspond to the central value but some averaged kinematic value, depending on how fast the cross-section changes across that kinematic bin in question.
- The Jean-Marc Laget (JML) Paris model cross-sections were used in the bin-centering corrections

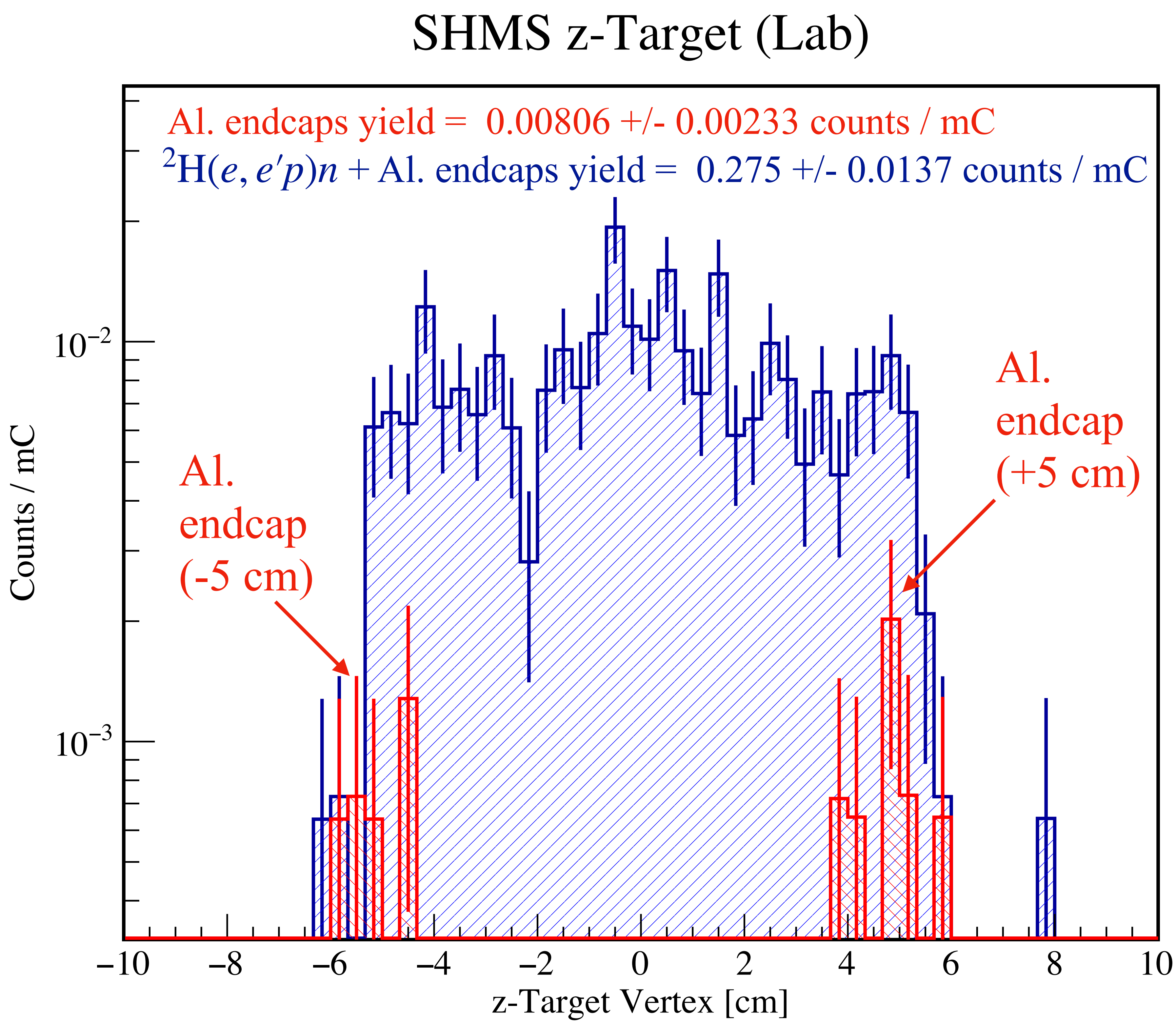
d(e, e’p)n Target Background Studies

580 MeV/c setting
Integrated over all θ_{nq}



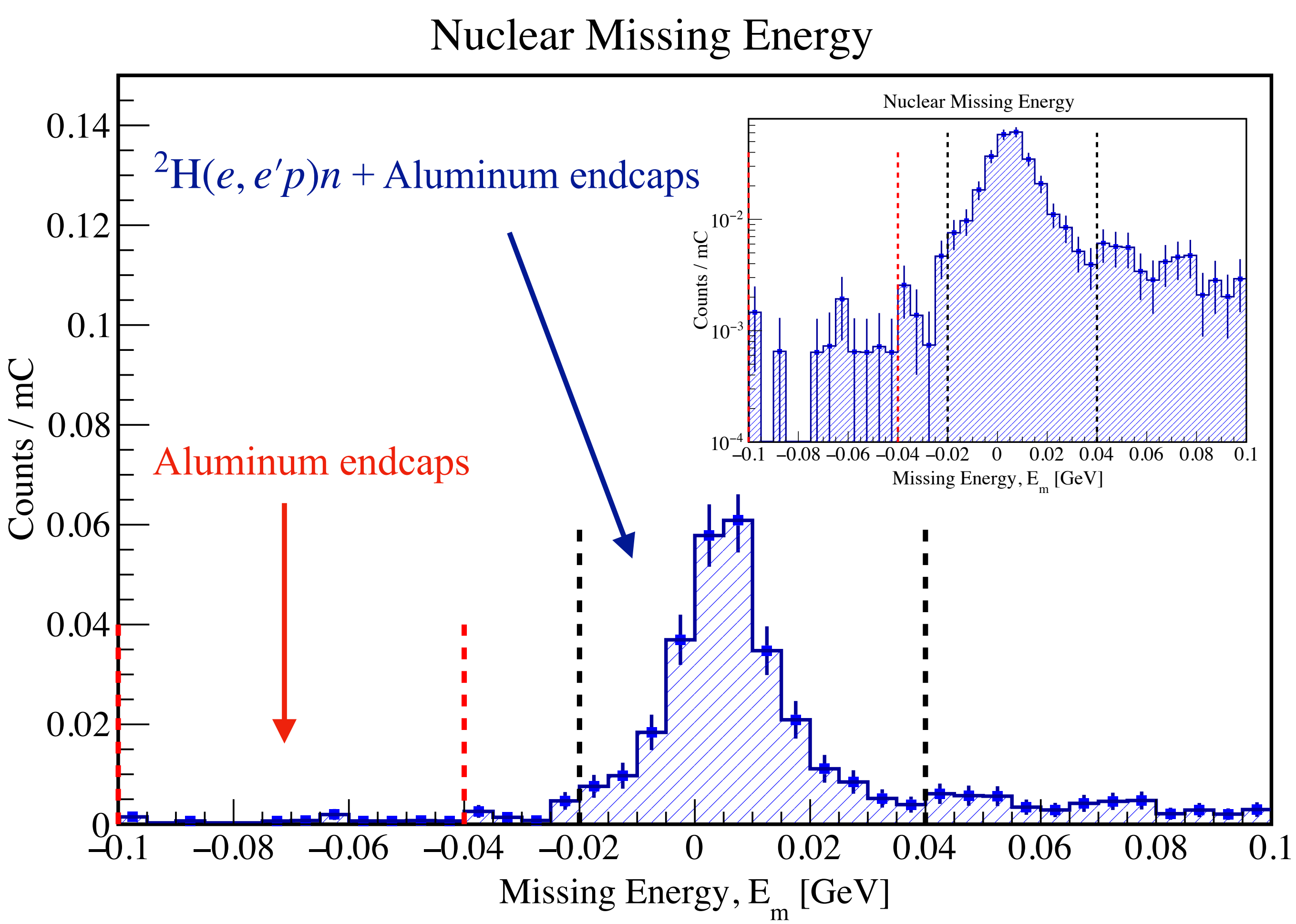
d(e, e’p)n Target Background Studies

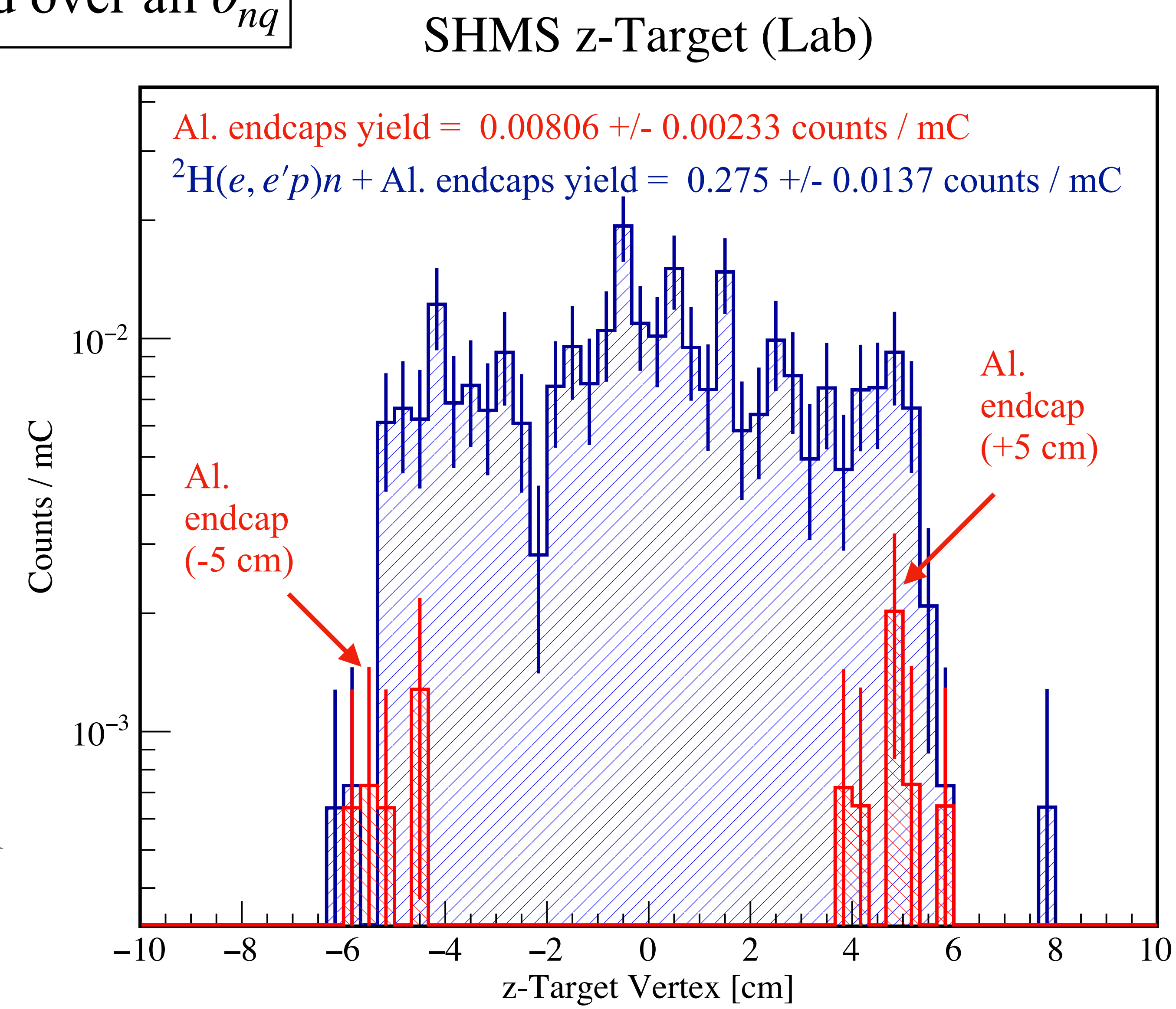
580 MeV/c setting
Integrated over all θ_{nq}



d(e, e'p)n Target Background Studies

580 MeV/c setting
Integrated over all θ_{nq}





- The background underneath the missing energy spectrum was estimated to contribute:

$$\frac{\text{Al. endcaps yield}}{^2\text{H}(e,e'p)n + \text{Al. endcaps yield}} = \frac{0.00806}{0.275} = 0.0293 \longrightarrow \boxed{2.93\%}$$

- The background contribution was added as an overall normalization systematic uncertainty to the d(e, e'p)n cross sections

d(e, e'p)n Momentum Distributions

Reduced cross section (theoretical momentum distributions within PWIA)

$$\sigma_{red}^{(p_r,\theta_{nq})} \equiv \frac{\sigma_{bc}^{exp}}{K\sigma_{cc1}}$$

Bin-center Corrected Experimental cross sections

Kinematic Factor times deForest ep cross section

$$K \equiv k \cdot f_{rec} \sim P_f, P_m, q$$

kinematic factor

final proton momentum

neutron recoil momentum

3-momentum transfer

$$\sigma_{cc1} \sim G_{Ep}(Q^2), G_{Mp}(Q^2)$$

deForest Off-shell *ep* cross-section

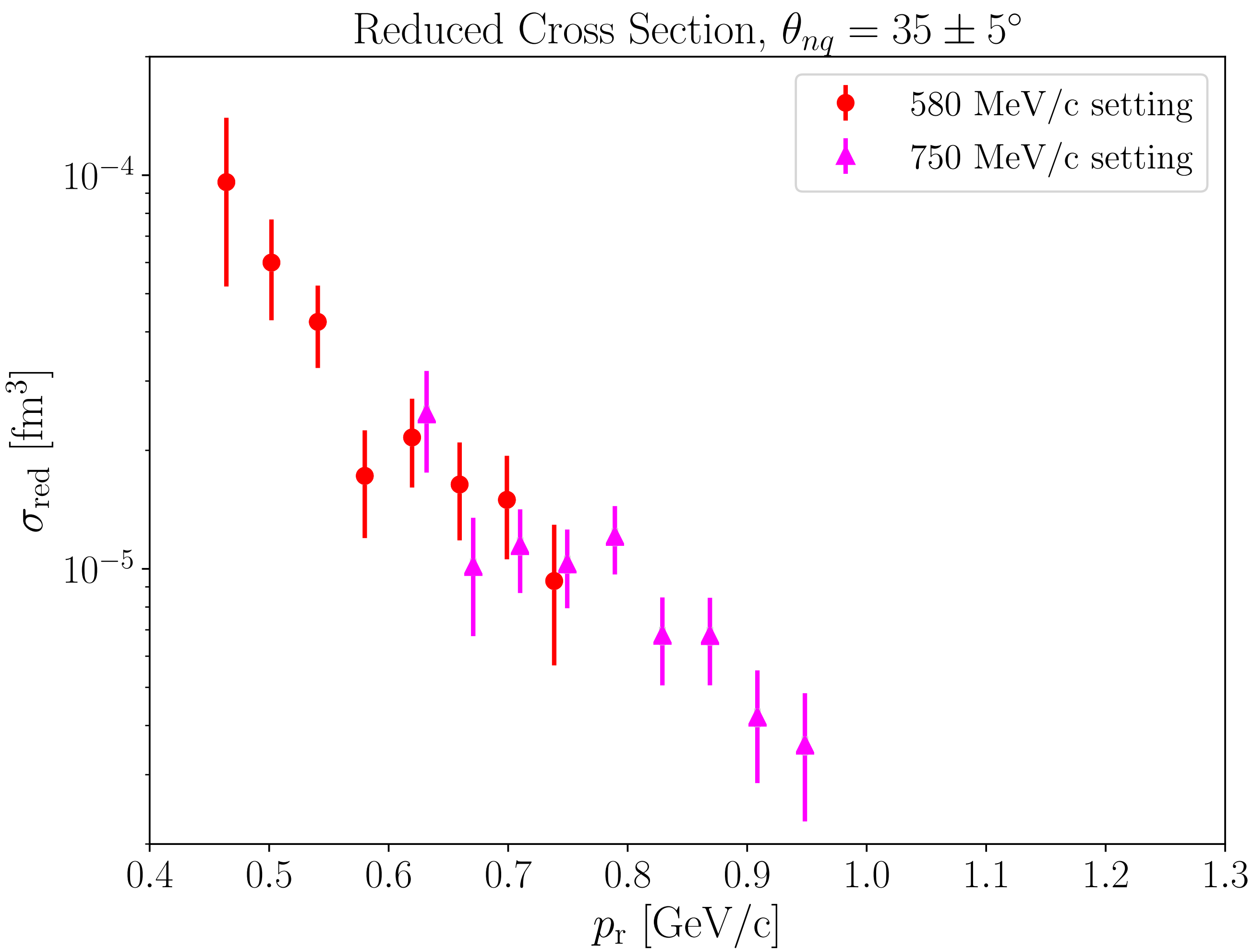
(Proton form factor parametrization)

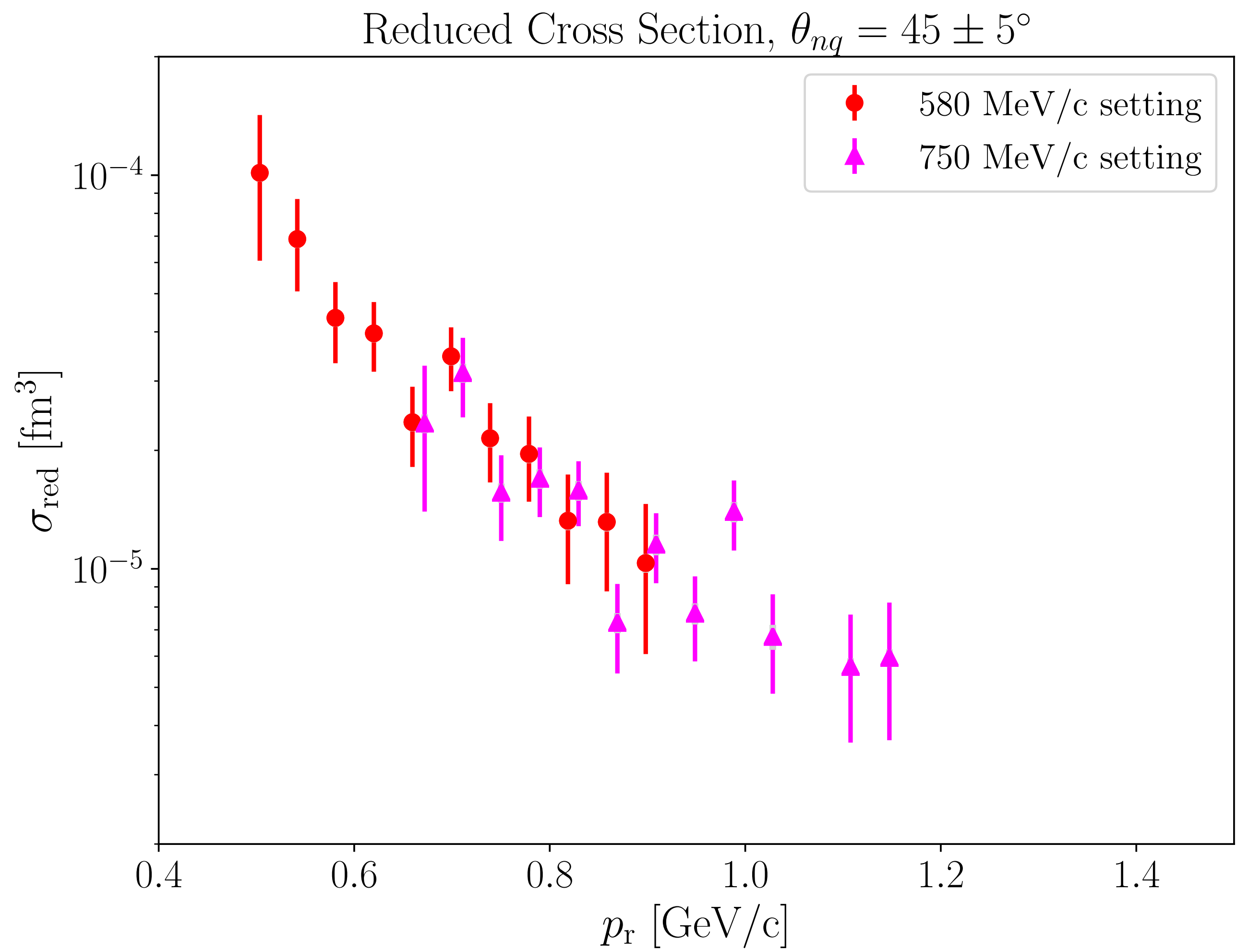
J. Arrington, Implications of the discrepancy between proton form factor measurements, Phys. Rev. C69, 022201 (2004)

- Division by deForest cross section and kinematic factor removes kinematical dependencies on reduced cross section

d(e, e'p)n Reduced Cross-Sections

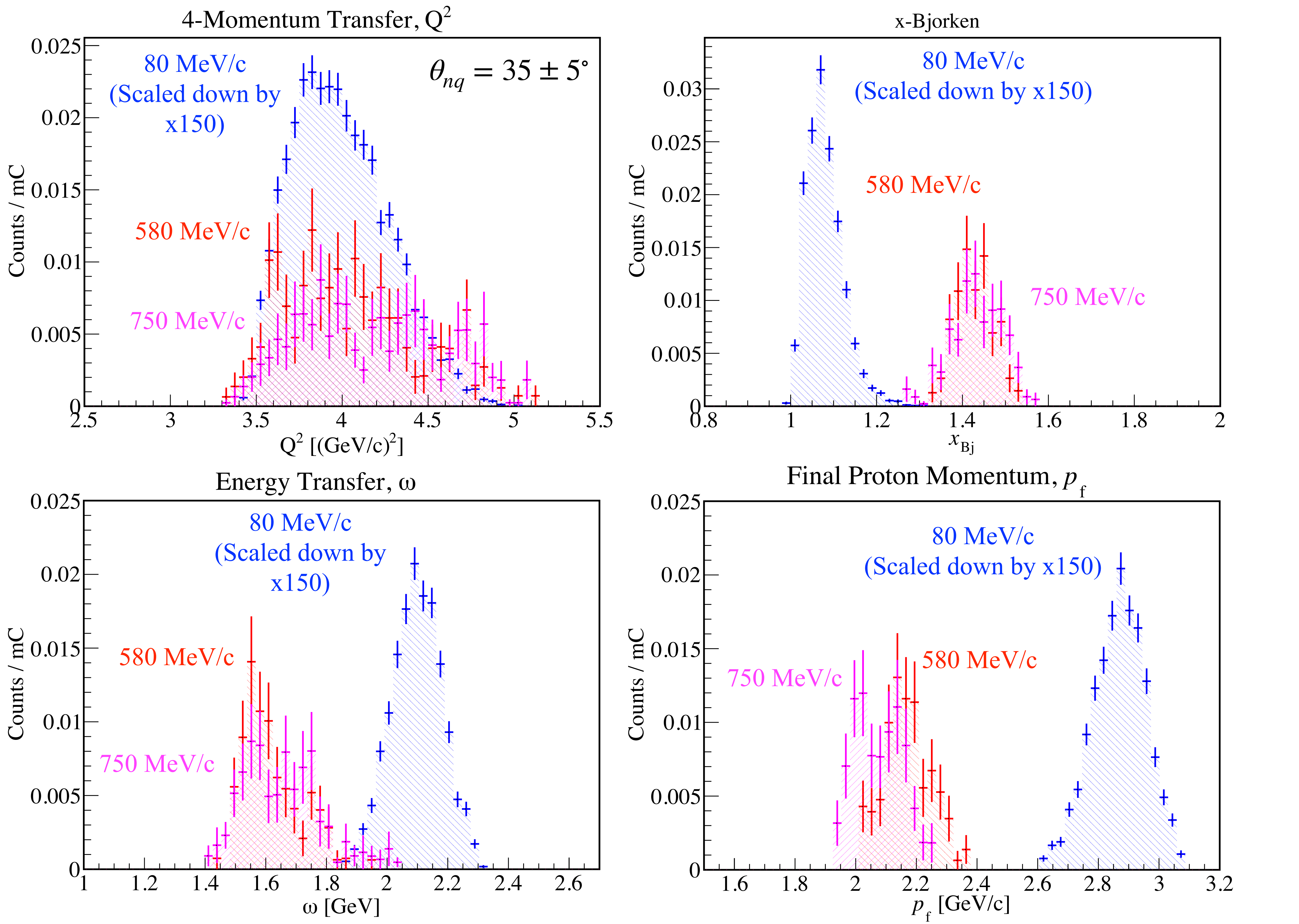
Before combining overlapping missing momentum bins





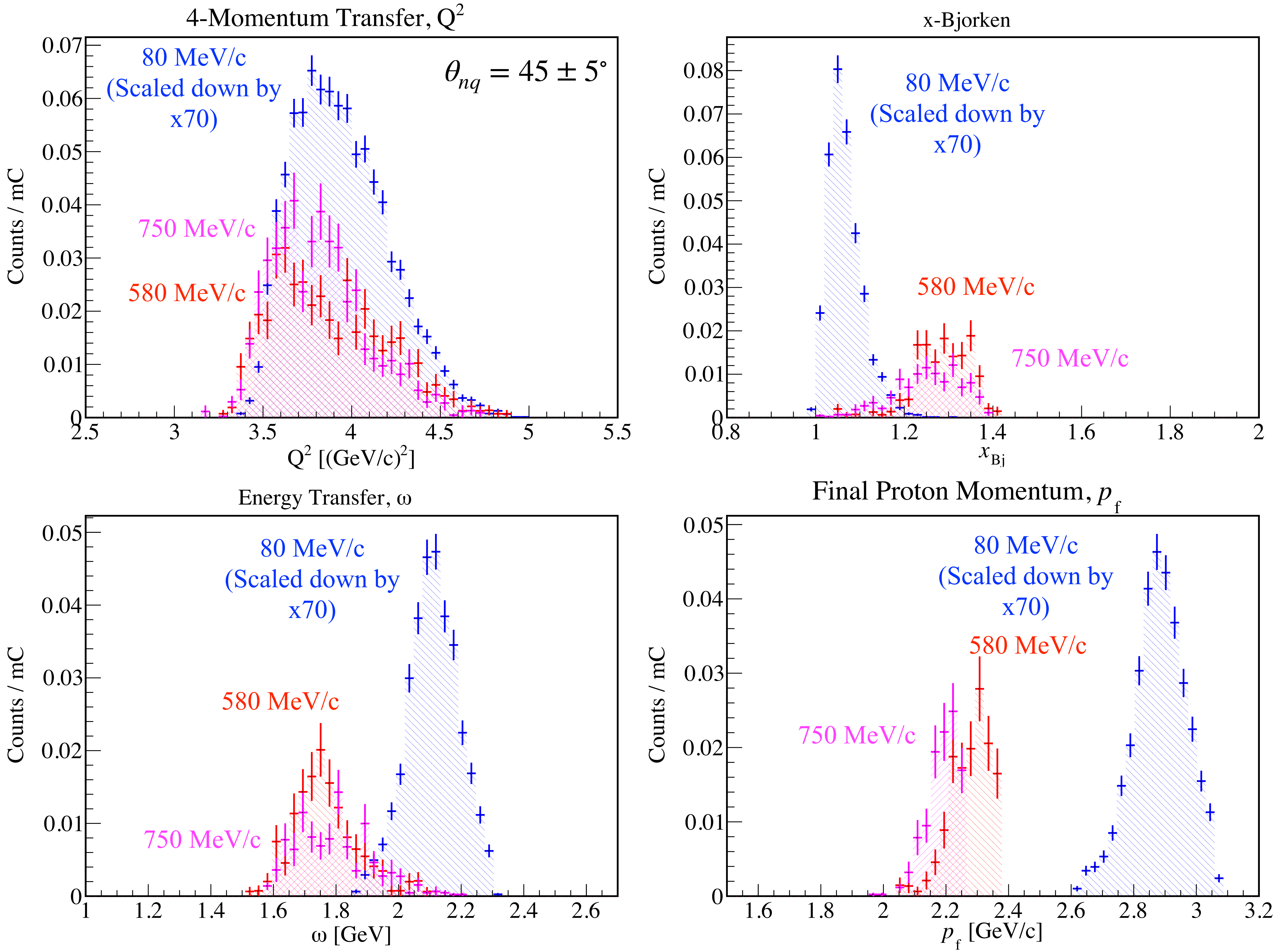
Additional d(e, e'p)n Kinematic Distributions

Recoil angle bin: $\theta_{nq} = 35 \pm 5°$



Additional d(e, e'p)n Kinematic Distributions

Recoil angle bin: $\theta_{nq} = 45 \pm 5°$



d(e, e’p)n Normalization Correction Factors

&

Statistical/Systematic Uncertainty Tables

Normalization Correction Factors for d(e, e'p)n

$$Y^{corr}_{data} = \frac{Y^{uncorr}_{data} \cdot f_{rad}}{Q \cdot \epsilon_{tLT} \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{tgtBoil} \cdot \epsilon_{pAbs}}$$

Pm	HMS Tracking Efficiency	sHMS Tracking Efficiency	Target Boiling Correction	Proton Absorption Correction	Total Live Time	Total Charge (mC)
80	0.989	0.965	0.958	0.953	0.908	142.140
580 (set 1)	0.990	0.965	0.960	0.953	0.929	1686.830
580 (set 2)	0.987	0.964	0.959	0.953	0.929	1931.770
750 (set 1)	0.988	0.964	0.957	0.953	0.924	5329.490
750 (set 2)	0.989	0.962	0.956	0.953	0.923	1894.010
750 (set 3)	0.989	0.962	0.956	0.953	0.924	1083.700

- Correction factors in table were averaged over all runs of individual data sets

Systematic Uncertainty on Normalization Correction Factors for d(e, e'p)n

$$\bar{\sigma}^{exp}_{corr} = \bar{\sigma}^{exp}_{uncorr} \cdot f_1 \cdot f_2 ... f_i \longrightarrow \left.\frac{d\bar{\sigma}^{exp}_{corr}}{\bar{\sigma}^{exp}_{corr}}\right|_i = \frac{df_i}{f_i}$$

f_i : normalization correction factors
df_i : error in normalization correction factors

Relative Systematic Error (%) on the Cross Section due to: f_i

Pm	HMS Tracking Efficiency	sHMS Tracking Efficiency	Target Boiling Correction	Proton Absorption Correction	Total Live Time	Total Charge (mC)	Target Wall Corrections	Spectrometer Acceptance
80	0.0344%	0.0413%	0.3948%	0.4951%	3.0%	2.0%	$\leq$ 2.9 %	1.4%
580 (set 1)	0.3999%	0.7586%	0.3766%	0.4951%	3.0%	2.0%	$\leq$ 2.9 %	1.4%
580 (set 2)	0.4786%	0.6041%	0.3842%	0.4951%	3.0%	2.0%	$\leq$ 2.9 %	1.4%
750 (set 1)	0.5329%	0.7155%	0.4013%	0.4951%	3.0%	2.0%	$\leq$ 2.9 %	1.4%
750 (set 2)	0.4719%	0.7089%	0.4196%	0.4951%	3.0%	2.0%	$\leq$ 2.9 %	1.4%
750 (set 3)	0.5127%	0.7584%	0.4150%	0.4951%	3.0%	2.0%	$\leq$ 2.9 %	1.4%
AVG	0.4026%	0.5978%	0.3985%	0.4951%	3.0%	2.0%	$\leq$ 2.9 %	1.4%

added in quadrature for overlapping Pm bins

Systematic errors that DO NOT vary are added in quadrature as an overall constant to the final result

- Relative error on cross sections due to normalization correction factors (f_i) equals the relative error of normalization factor itself, $\frac{df_i}{f_i}$

Spectrometer Kinematic Systematic Uncertainties on d(e, e'p)n

$\delta\theta_e[mr]$	± 0.17	Uncertainty in SHMS angle
$\delta\theta_p[mr]$	± 0.24	Uncertainty in HMS angle
$\delta E_f/E_f$	$\pm 9.1 \times 10^{-4}$	Uncertainty in SHMS momentum
$\delta E_b/E_b$	$\pm 7.5 \times 10^{4}$	Uncertainty in Beam Energy
$d\sigma_{exp}^{kin}$	≤ 6.5 %	upper limit on relative kinematic systematic uncertainty

Details can be found in documentation link:

[Hall C Document Database: Spectrometer Offsets Studies]

$$d\sigma_{exp}^2 = \left(\frac{d\sigma}{d\theta_e}\delta\theta_e\right)^2 + \left(\frac{d\sigma}{d\theta_p}\delta\theta_p\right)^2 + \left(\frac{d\sigma}{dE_f}\frac{\delta E_f}{E_f}E_f\right)^2 + \left(\frac{d\sigma}{dE_b}\frac{\delta E_b}{E_b}E_b\right)^2 +$$

Covariance Errors

- Kinematic uncertainties are due to our limited knowledge of the beam, spectrometer momenta and angles. Each of these uncertainties affects our knowledge of the cross section, since the cross section depends on these kinematics
- The kinematic uncertainties are point-to-point which means they vary depending on each kinematic point, as each corresponds to a different missing momentum kinematic bin.
- A table of the JML Paris PWIA cross-section derivatives with respect to each of the kinematic variables was used

d(e, e'p)n Statistical/Systematic Uncertainties Summary

Kinematic Uncertainties

$\delta\theta_e[mr]$ (SHMS central angle)	± 0.17
$\delta\theta_p[mr]$ (HMS central angle)	± 0.24
$\delta E_f/E_f$ (final electron energy)	$\pm 9.1 \times 10^{-4}$
$\delta E_b/E_b$ (beam energy)	$\pm 7.5 \times 10^{4}$
$d\sigma_{exp}^{kin}$ (Overall kin. syst.)	$\leq 6.5\,\%$

Normalization Uncertainties

$\delta(\epsilon_{htrk}, \epsilon_{etrk}, \epsilon_{tgtBoil})$ (Tracking efficiencies)	$\sim 0.81\,\%$ (avg/setting)
$\delta\epsilon_{pAbs}$ (Proton absorption)	$0.49\,\%$
$(\delta\epsilon/\epsilon)_{tLT}$ (Total live time)	$3.0\,\%$
$(\delta\epsilon/\epsilon)_{Q}$ (Charge normalization)	$2.0\,\%$
$\delta\epsilon_{tgt}$ (Target background)	$\leq 2.9\,\%$
$\delta\epsilon_{spec.Acc}$ (Spectrometer acceptance)	$1.4\,\%$
$d\sigma_{exp}^{norm}$ (Overall norm. syst.)	$\leq 5.3\,\%$

← Estimate made by M.K. Jones

Stat. Uncertainty

$d\sigma_{exp}^{stats}$	$\sim 20 - 40\,\%$

- $(d\sigma_{exp}^{syst})^2 = (d\sigma_{exp}^{kin})^2 + (d\sigma_{exp}^{norm})^2$: total systematic relative error is quadrature sum of kinematics and normalization errors

  $d\sigma_{exp}^{syst} \leq 8.39\,\%$

- $(d\sigma_{exp}^{tot})^2 = (d\sigma_{exp}^{stats})^2 + (d\sigma_{exp}^{syst})^2$: total relative error is quadrature sum of statistical and systematic errors

d(e, e'p)n Reduced Cross Sections
Linear Fit Results

Statistical Significance Test on Reduced Cross Sections

- The fall-off observed in the reduced cross sections is smaller (less steep) for data compared to theory at higher recoil momenta

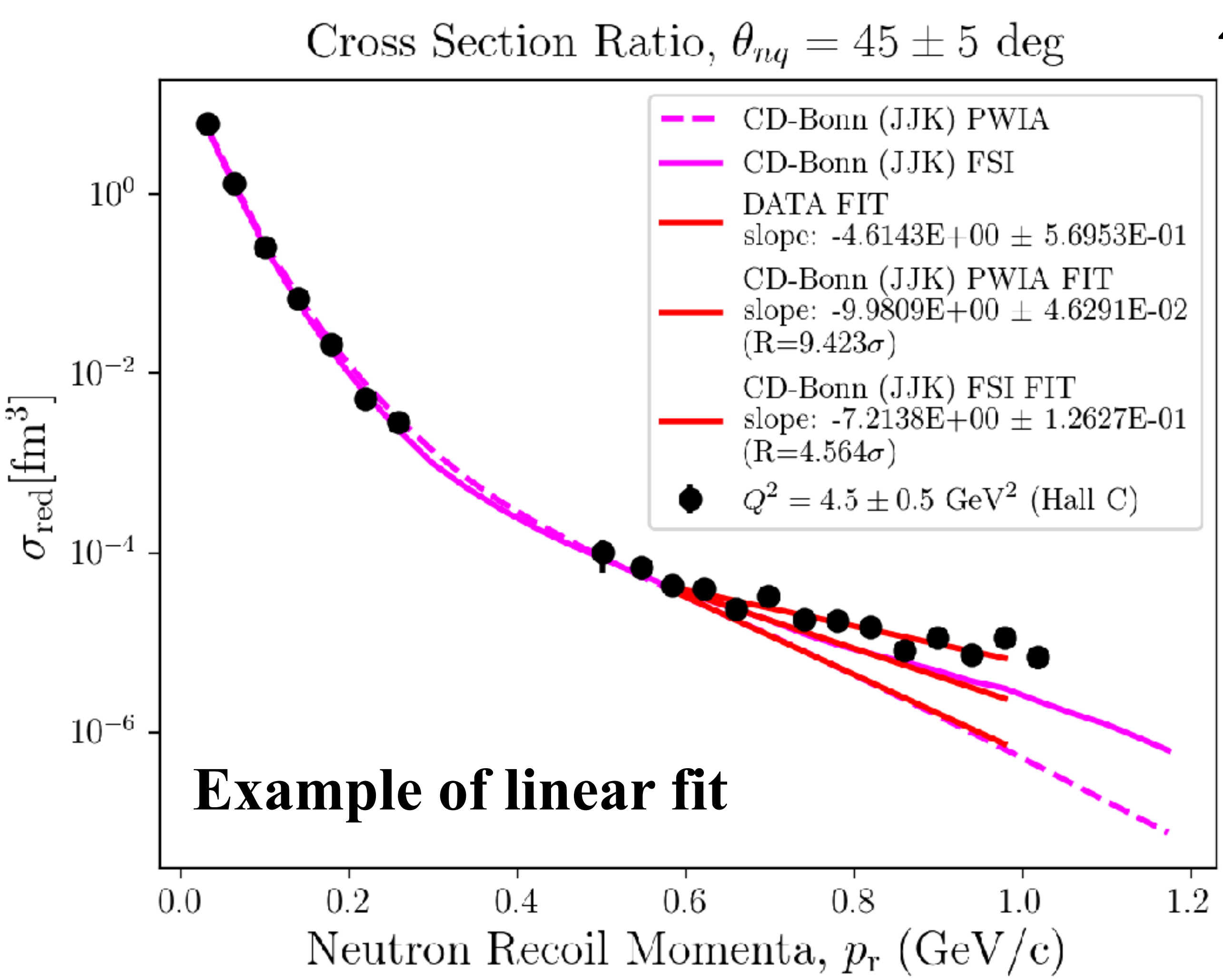
Is the discrepancy between data and theory slopes statistically significant ?

- Compare the slopes of the theoretical and experimental reduced cross sections at neutron recoil momenta between 0.55 - 1.0 GeV/c
- Calculate the Z-score to determine number of standard deviations between slopes of the the data and theory linear fits.

data slope **theory slope**

$$Z = \frac{\mu_{\text{data}} - \mu_{\text{theory}}}{\sigma_{\mu_{\text{data}}}}$$

data slope error



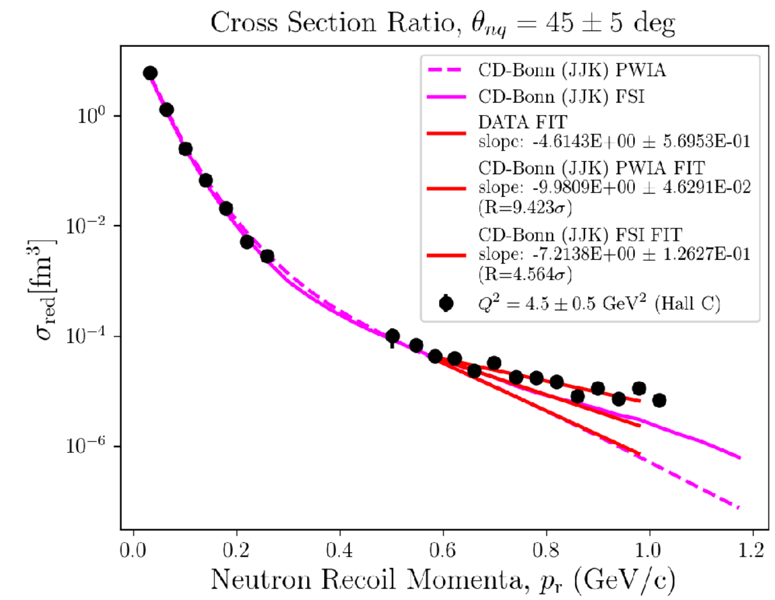
Statistical Significance Test: Fit Slopes and Chi2

- Slopes are dependent on the NN potential and approximately independent of different parametrizations within the same potential

Theoretical Model	PWIA (35 deg) SLOPE	PWIA (45 deg) SLOPE	FSI (35 deg) SLOPE	FSI (45 deg) SLOPE
Paris (Galster)	-8.3	-8.3	-8.2	-7.7
AV18 (JJK)	-7.9	-7.8	-8.4	-7.3
AV18 (GKex05)	-8.1	-8.1	-8.8	-8.0
AV18 (AMT)	-8.1	-8.1	-8.8	-8.0
CD-Bonn (JJK)	-10.1	-10.0	-9.6	-7.2
CD-Bonn (GKex05)	-10.3	-10.3	-10.2	-7.7
CD-Bonn (AMT)	-10.3	-10.2	-10.2	-7.6
WJC2 (GKex05)	-7.8	-7.8	-8.5	-7.8
WJC2 (AMT)	-7.8	-7.8	-8.4	-7.8

DATA	35 deg	45 deg
	slope: -4.7	slope: -4.6
	χ^2_{red} : 0.66	χ^2_{red} : 1.4

Interpreting the Statistical Significance Test



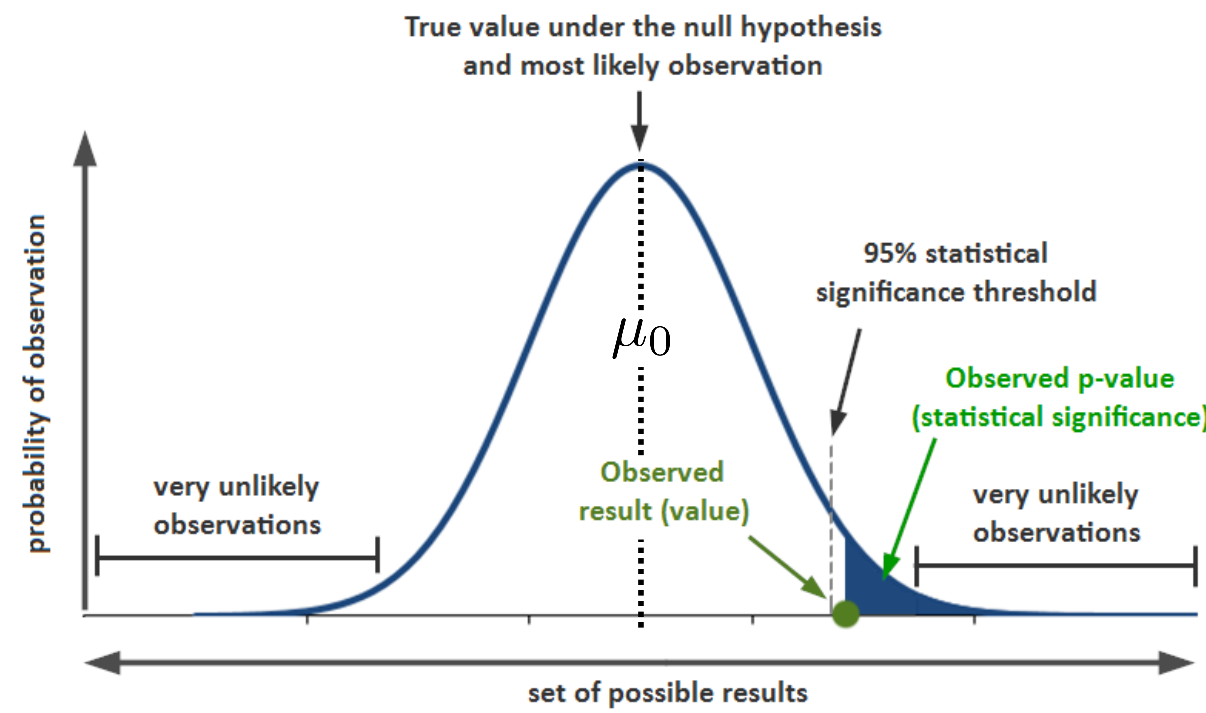
p-value definition:

The *p*-value is the probability of getting the observed value of the test statistic, or a value with even greater evidence against *H0*, if the null hypothesis is true

$$H_0 : \mu = \mu_0 \quad \text{(null hypothesis)}$$

$$H_a : \mu > \mu_0 \quad \text{(alternative hypothesis)}$$

Distribution of Z if H_0 is true:



Z $\quad$ $p\text{-value} = p(Z \geq Z_0)$

Z-test statistic

$$Z = \frac{\bar{X} - \mu_0}{\sigma/\sqrt{n}}$$

$\bar{X}$: measured variable

μ_0 : population mean of H_0

σ : population standard deviation of H_0

n : number of trials or experiments

For the E12-10-003:

$\bar{X} \equiv \mu_{\rm data} - \mu_{\rm theory}$ (Slope difference)

$\mu_0 = 0 \quad n = 1$

$\sigma \equiv \sigma_{\mu_{\rm data}}$

null hypothesis: if the E12-10-003 were to be repeated *n* times, the difference between the data and theory slopes would follow a standard normal distribution with a mean of zero. That is, the difference in the slopes would only be due to statistical fluctuations.

Statistical Significance Test: Z-score and p-values

- The p-values describe the probability that the observed difference in the measurements is due to a statistical fluctuation
- The data differs from the CD-Bonn slopes by Z-scores ~ 4 - 9 standard deviations (statistical fluctuations extremely unlikely)

Theoretical Model	PWIA (35 deg) Z-score	p-value	PWIA (45 deg) Z-score	p-value	FSI (35 deg) Z-score	p-value	FSI (45 deg) Z-score	p-value
Paris (Galster)	4.929	4.1E-07	6.541	3.0E-11	4.791	8.2E-07	5.355	4.2E-08
AV18 (JJK)	4.373	6.1E-06	5.632	8.9E-09	5.184	1.0E-07	4.721	1.1E-06
AV18 (GKex05)	4.623	1.9E-06	6.079	6.0E-10	5.616	9.7E-09	5.889	1.9E-09
AV18 (AMT)	4.598	2.1E-06	6.066	6.5E-10	5.597	1.0E-08	5.976	1.1E-09
CD-Bonn (JJK)	7.321	1.2E-13	9.423	2.1E-21	6.648	1.4E-11	4.564	2.5E-06
CD-Bonn (GKex05)	7.611	1.3E-14	9.895	2.1E-23	7.484	3.6E-14	5.383	3.6E-08
CD-Bonn (AMT)	7.586	1.6E-14	9.882	2.4E-23	7.460	4.3E-14	5.516	1.7E-08
WJC2 (GKex05)	4.241	1.1E-05	5.575	1.2E-08	5.133	1.4E-07	5.519	1.7E-08
WJC2 (AMT)	4.217	1.2E-05	5.561	1.3E-08	5.110	1.6E-07	5.598	1.0E-08

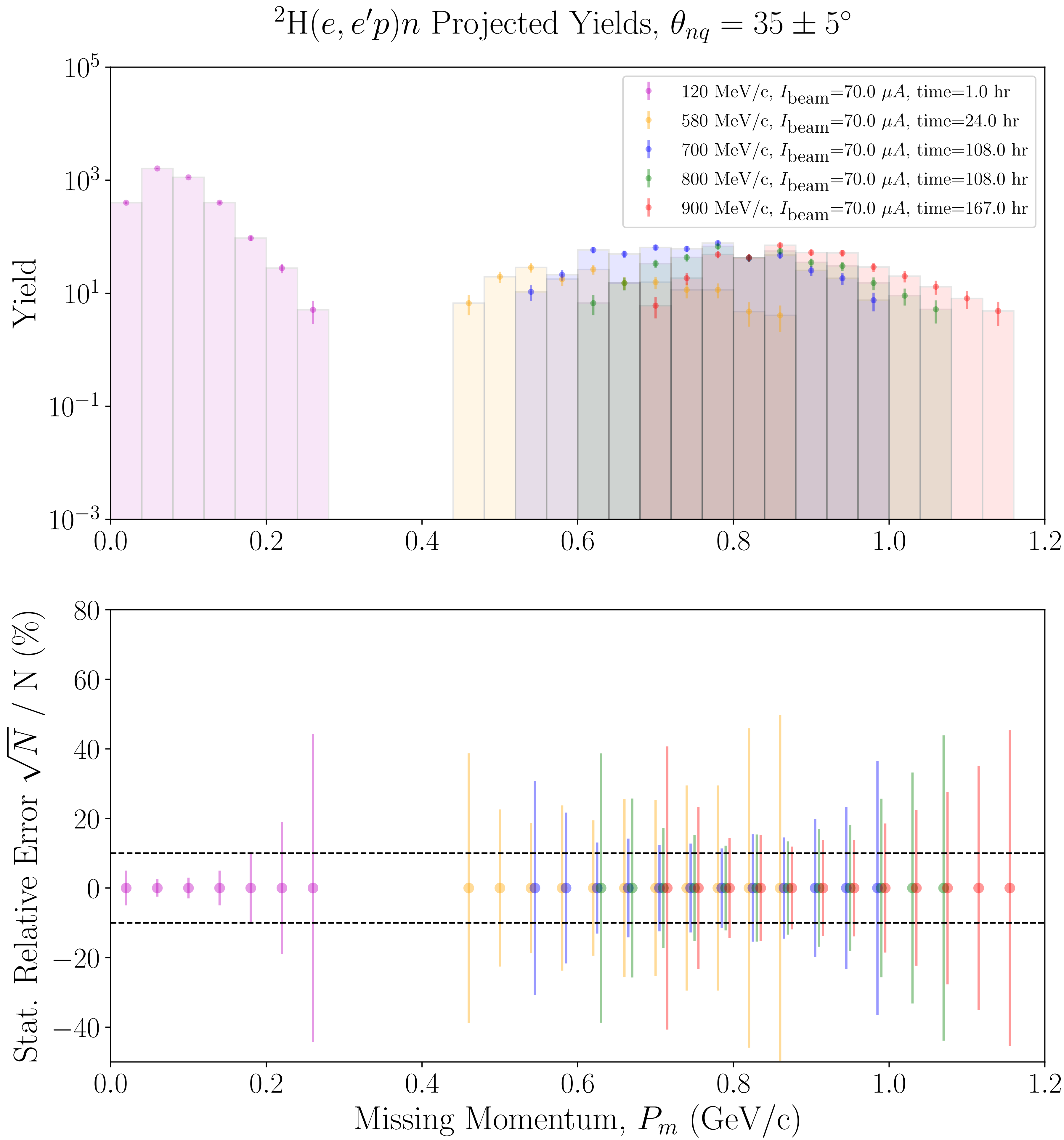
Projected d(e, e'p)n Missing Momentum Yields

- d(e, e'p)n simulation done using the JML Paris FSI theoretical calculations assuming radiative effects and energy loss at the target

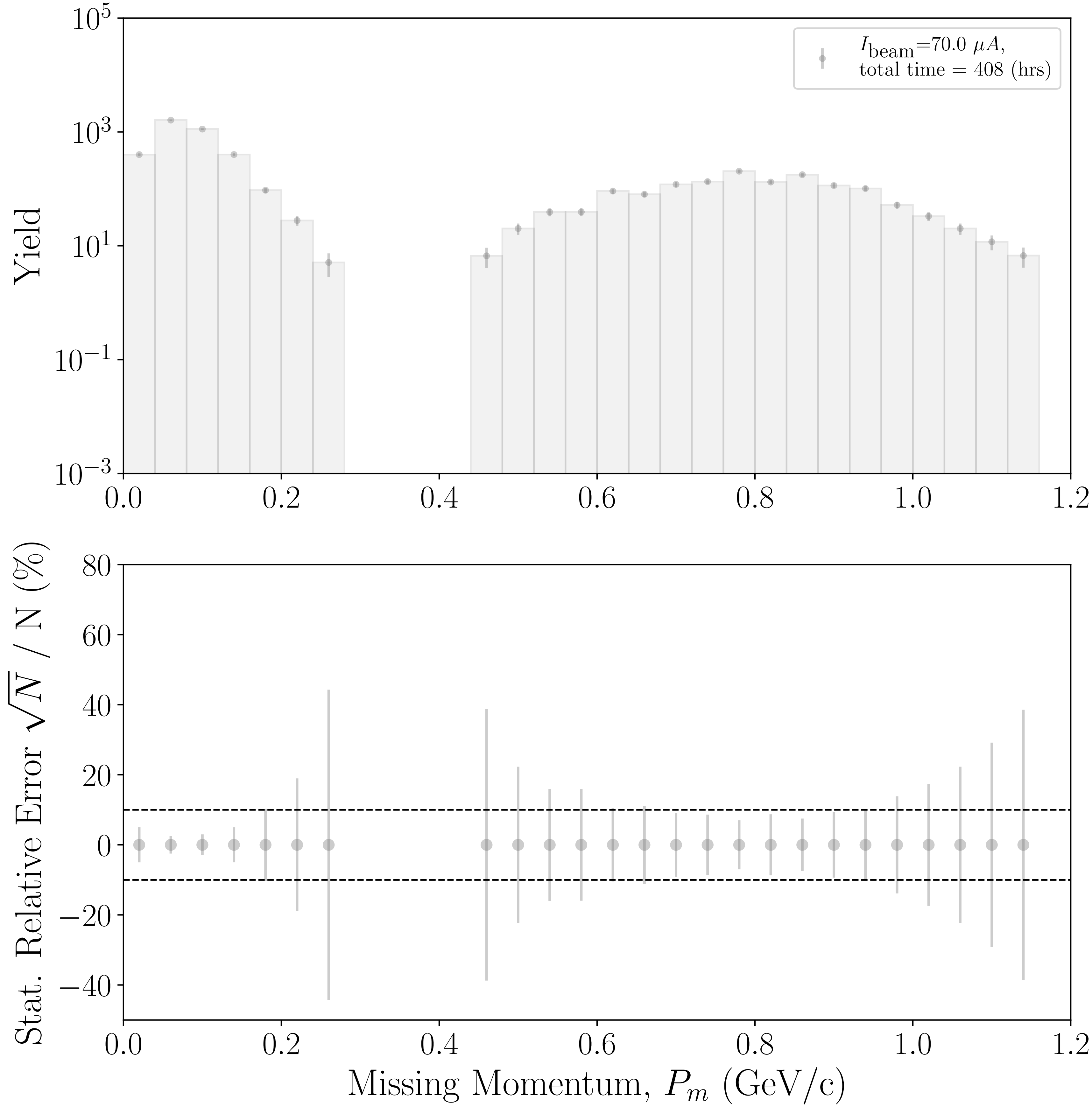
- For realistic estimation of the yields (and statistical uncertainties) :

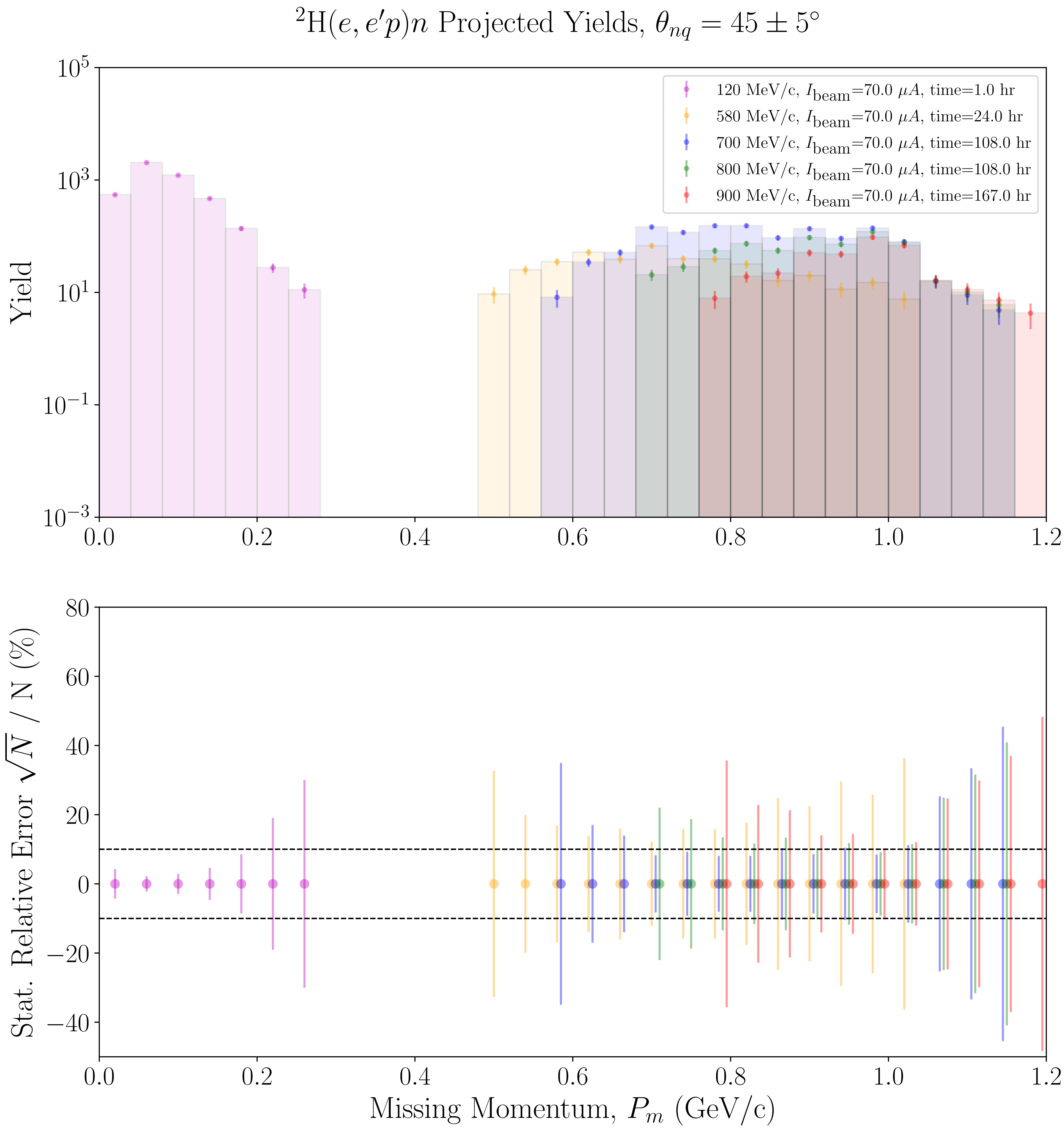
  - ☑ Correction factors based on commissioning data analysis have been applied to the yield (i.e., tracking inefficiencies, dead-time, target density corrections, proton absorption)

  - ☑ To account for the differences between the JML Paris FSI and the measured data, a ratio of R = JML Paris FSI / Commissioning Data cross sections was used as a correction factor on the simulated yields

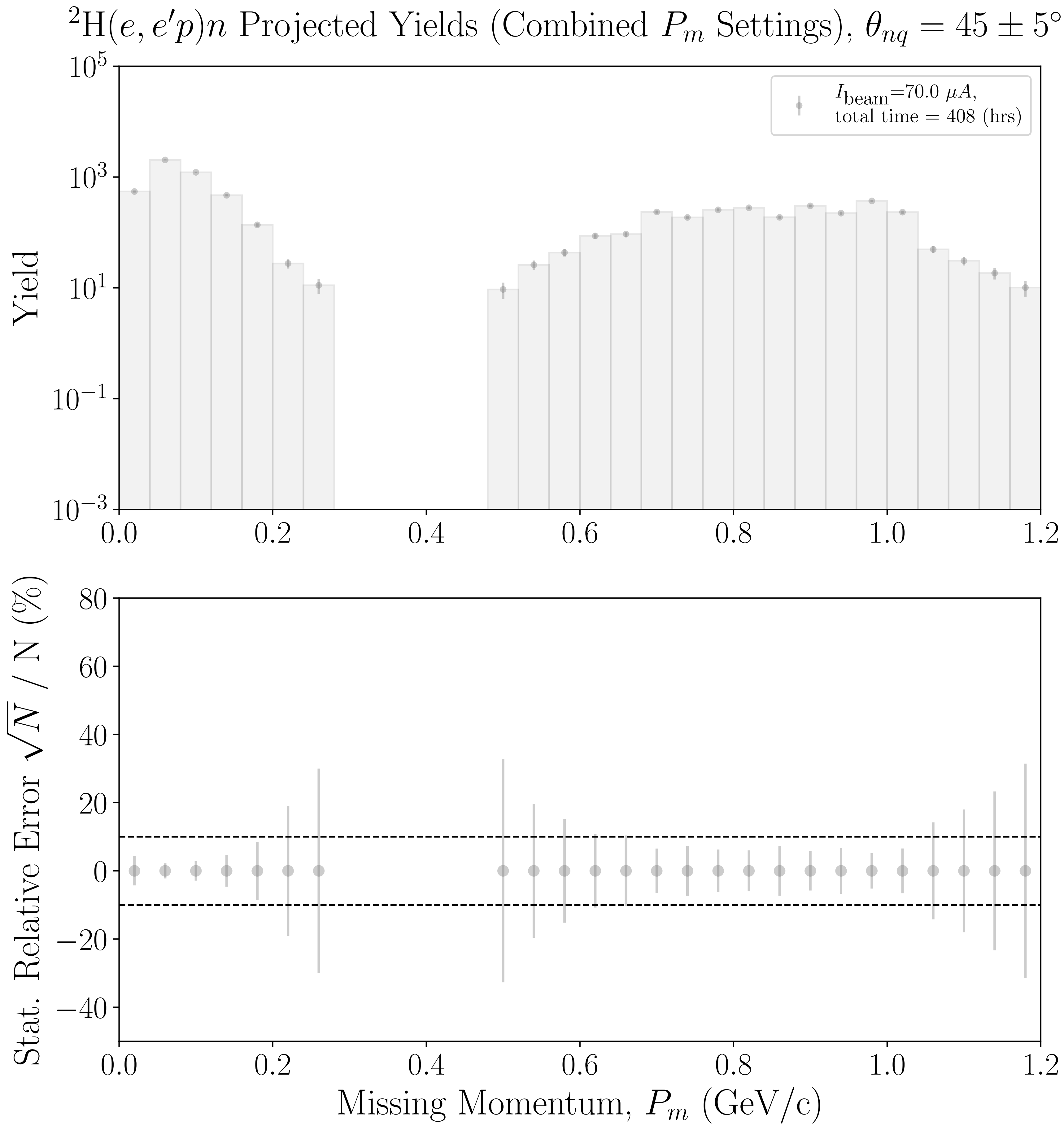

^{2}H$(e,e'p)n$ Projected Yields, $\theta_{nq} = 35 \pm 5°$
120 MeV/c, $I_{\rm beam}$=70.0 μA, time=1.0 hr
580 MeV/c, $I_{\rm beam}$=70.0 μA, time=24.0 hr
700 MeV/c, $I_{\rm beam}$=70.0 μA, time=108.0 hr
800 MeV/c, $I_{\rm beam}$=70.0 μA, time=108.0 hr
900 MeV/c, $I_{\rm beam}$=70.0 μA, time=167.0 hr
Yield
Stat. Relative Error $\sqrt{N}$ / N (%)
Missing Momentum, P_m (GeV/c)

$^2\mathrm{H}(e, e'p)n$ Projected Yields (Combined P_m Settings), $\theta_{nq} = 35 \pm 5°$





^{2}H$(e, e'p)n$ Projected Yields, $\theta_{nq} = 45 \pm 5°$
120 MeV/c, I_{beam}=70.0 μA, time=1.0 hr
580 MeV/c, I_{beam}=70.0 μA, time=24.0 hr
700 MeV/c, I_{beam}=70.0 μA, time=108.0 hr
800 MeV/c, I_{beam}=70.0 μA, time=108.0 hr
900 MeV/c, I_{beam}=70.0 μA, time=167.0 hr
Yield
Stat. Relative Error $\sqrt{N}$ / N (%)
Missing Momentum, P_m (GeV/c)


^{2}H$(e,e'p)n$ Projected Yields (Combined P_m Settings), $\theta_{nq} = 45 \pm 5°$
$I_{\rm beam}$=70.0 μA,
total time = 408 (hrs)
Yield
10^5
10^3
10^1
10^{-1}
10^{-3}
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Stat. Relative Error $\sqrt{N}$ / N (%)
80
60
40
20
0
−20
−40
Missing Momentum, P_m (GeV/c)

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