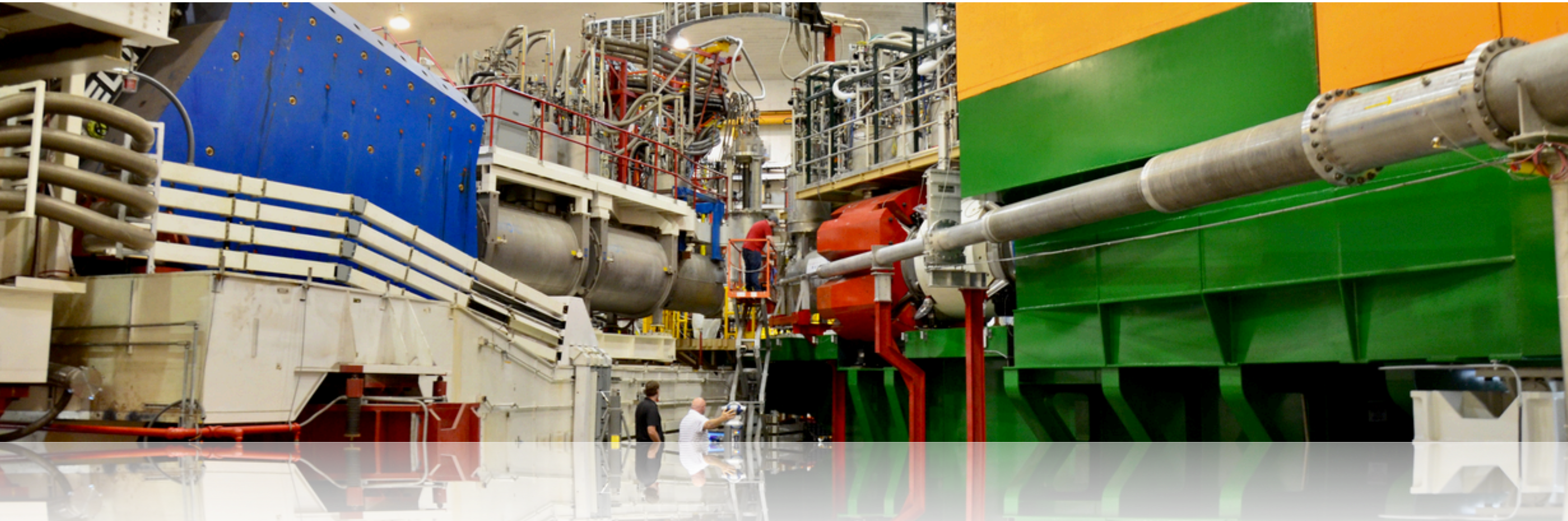


Results and Outlook of the D(e,e’p)n Commissioning Experiment

Hall C Virtual Collaboration Meeting
January 29, 2021

Carlos Yero

Spokespeople: Drs. Werner Boeglin and Mark Jones

Jefferson Lab
Exploring the Nature of Matter

FIU

Hall C

Current Status of the D(e,e'p)n (E12-10-003) Experiment

- Commissioning part of the experiment completed
  3 PAC days of the 21 PAC days requested in the
  original proposal [PR12-10-003](PR12-10-003)

- Focused on getting publishable results, although
  not at the precision originally planned (statistical uncertainty
  ~ 5 - 20 % corresponding to recoil momenta between 0.5 and 1.0 GeV/c)
  * original proposal 21 PAC days: Pr_central = 0.5, 0.6, 0.7 0.8, 0.9, 1.0 GeV/c
  * completed (commissioning part) --> 3 PAC days: Pr_central = 0.580, 0.750 GeV/c

- We demonstrated that these measurements can be done with
  the new Hall C Super High Momentum Spectrometer (SHMS)
  and requires minimal effort (standard Hall C equipment and software)
  to complete the remaining 18 PAC days

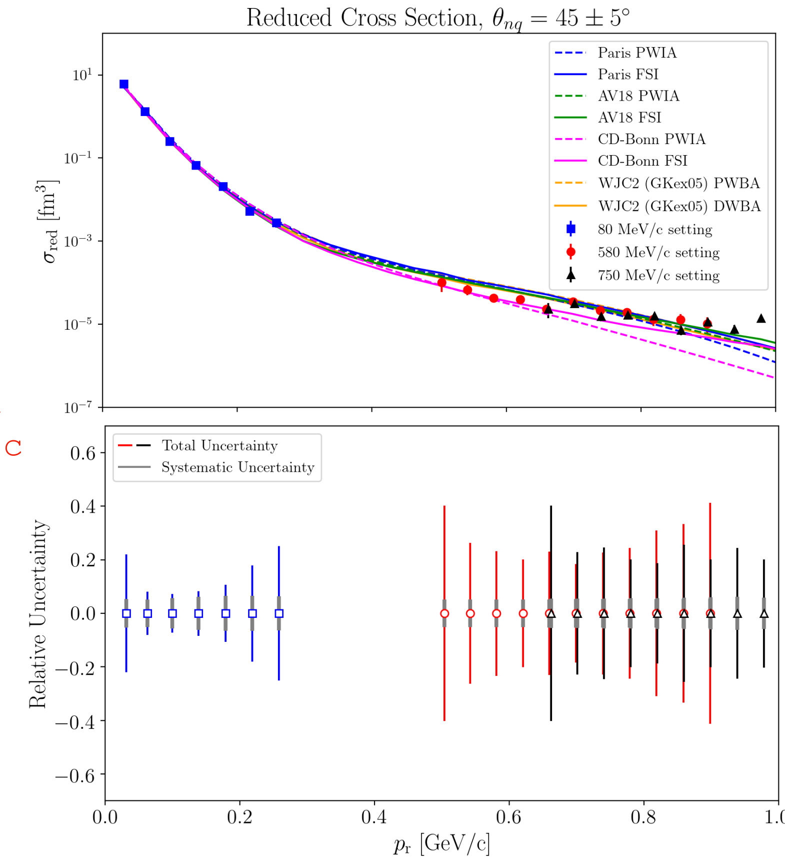
- The experiment analysis code already exists as it was
  developed for the commissioning part of the experiment,
  so the analysis of the full experiment is expected to be
  relatively quick.

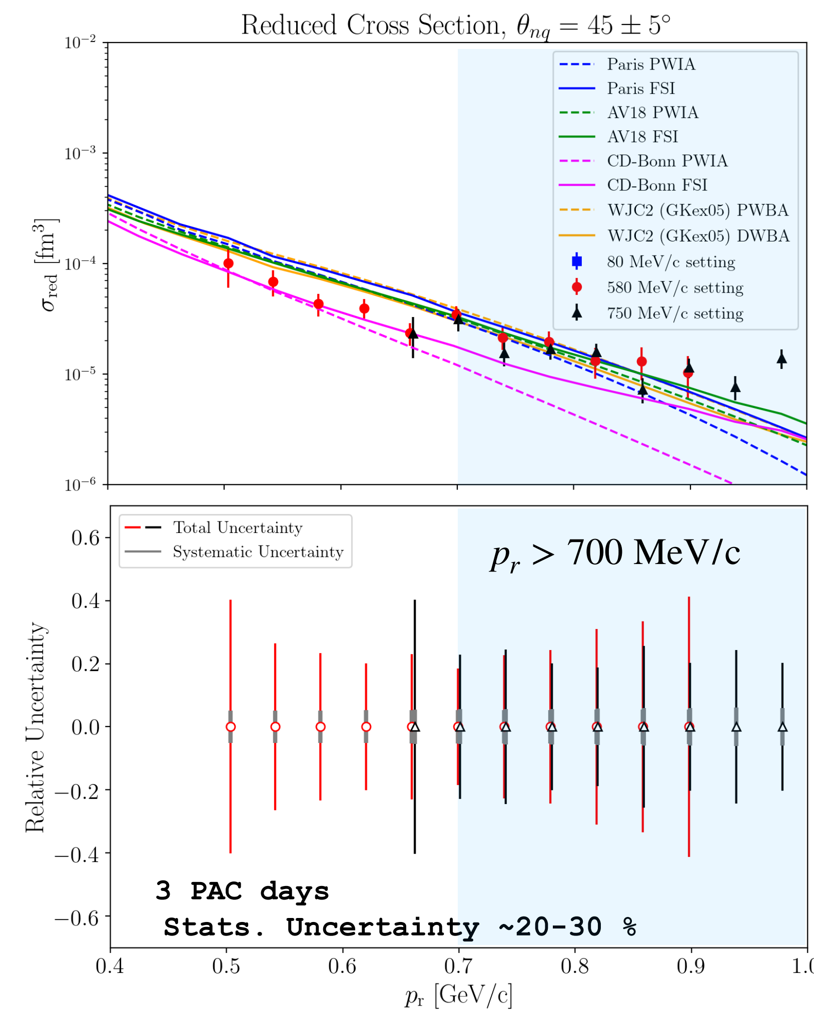
- For the remaining 18 PAC days, we will focus on the highest
  missing momentum region (Pr > 700 MeV / c):

  * **experiment point-of-view:** most difficult region to access
    as these correspond to the nucleon momentum tails where cross
    sections are extremely small (more time is needed for precise
    cross-section measurements)

  * **theoretical point-of-view:** most interesting region as
    relativistic models become increasingly important and
    high-precision data will be able to pin down which theoretical
    model provides a better description of the underlying physics

  * **extraction of light-cone $\rho_d(\alpha)$:** extraction of momentum
    distributions, $\rho_d(\alpha)$, in the light-cone frame at high Q^2 will be
    beneficial for both experiment and theory. For experiment, the
    extracted $\rho_d(\alpha)$ can be used as input in DIS studies of the deuteron
    F_{2d} structure function. For theory, will be possible to check the
    validity of different approaches in calculating the deuteron $\psi_d^{LC}(\alpha, p_t)$
    Within the light-cone dynamics. See Sec. IX of Int.J.Mod.Phys. E24 (2015)





First Results Have Been Published !

PHYSICAL REVIEW LETTERS **125**, 262501 (2020)

Probing the Deuteron at Very Large Internal Momenta

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We measure $^2\mathrm{H}(e,e'p)n$ cross sections at 4-momentum transfers of $Q^2 = 4.5 \pm 0.5$ $(\mathrm{GeV}/c)^2$ over a range of neutron recoil momenta p_r, reaching up to ~ 1.0 GeV/c. We obtain data at fixed neutron recoil angles $\theta_{nq} = 35°$, 45°, and 75° with respect to the 3-momentum transfer $\vec{q}$. The new data agree well with previous data, which reached $p_r \sim 500$ MeV/c. At $\theta_{nq} = 35°$ and 45°, final state interactions, meson exchange currents, and isobar currents are suppressed and the plane wave impulse approximation provides the dominant cross section contribution. We compare the new data to recent theoretical calculations, where we observe a significant discrepancy for recoil momenta $p_r > 700$ MeV/c.

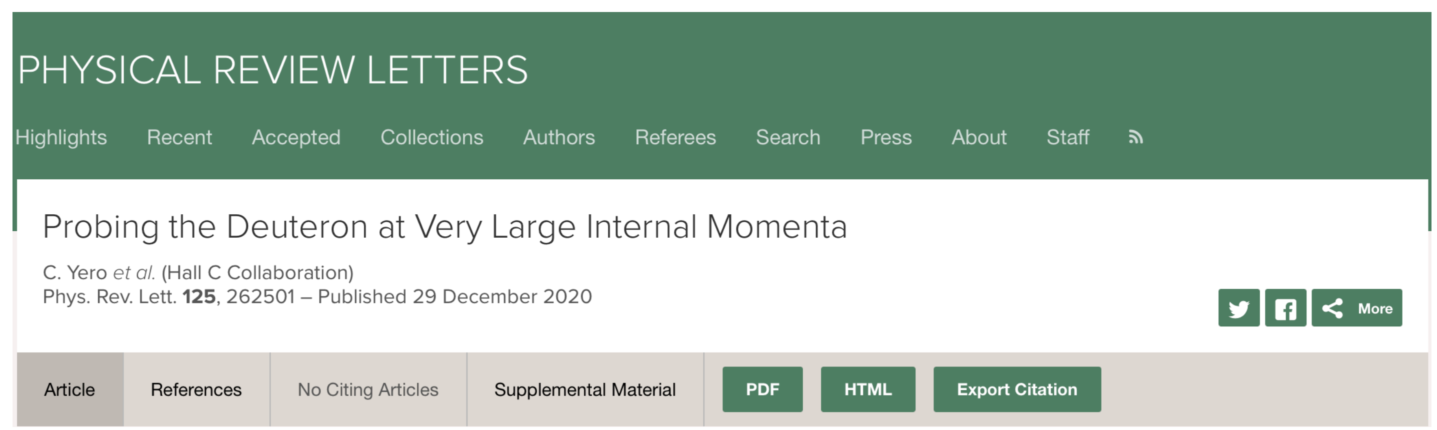
DOI: 10.1103/PhysRevLett.125.262501

- The manuscript was published in the Physical Review Letters (PRL) journal on Dec. 29, 2020

  DOI: [10.1103/PhysRevLett.125.262501](https://doi.org/10.1103/PhysRevLett.125.262501)

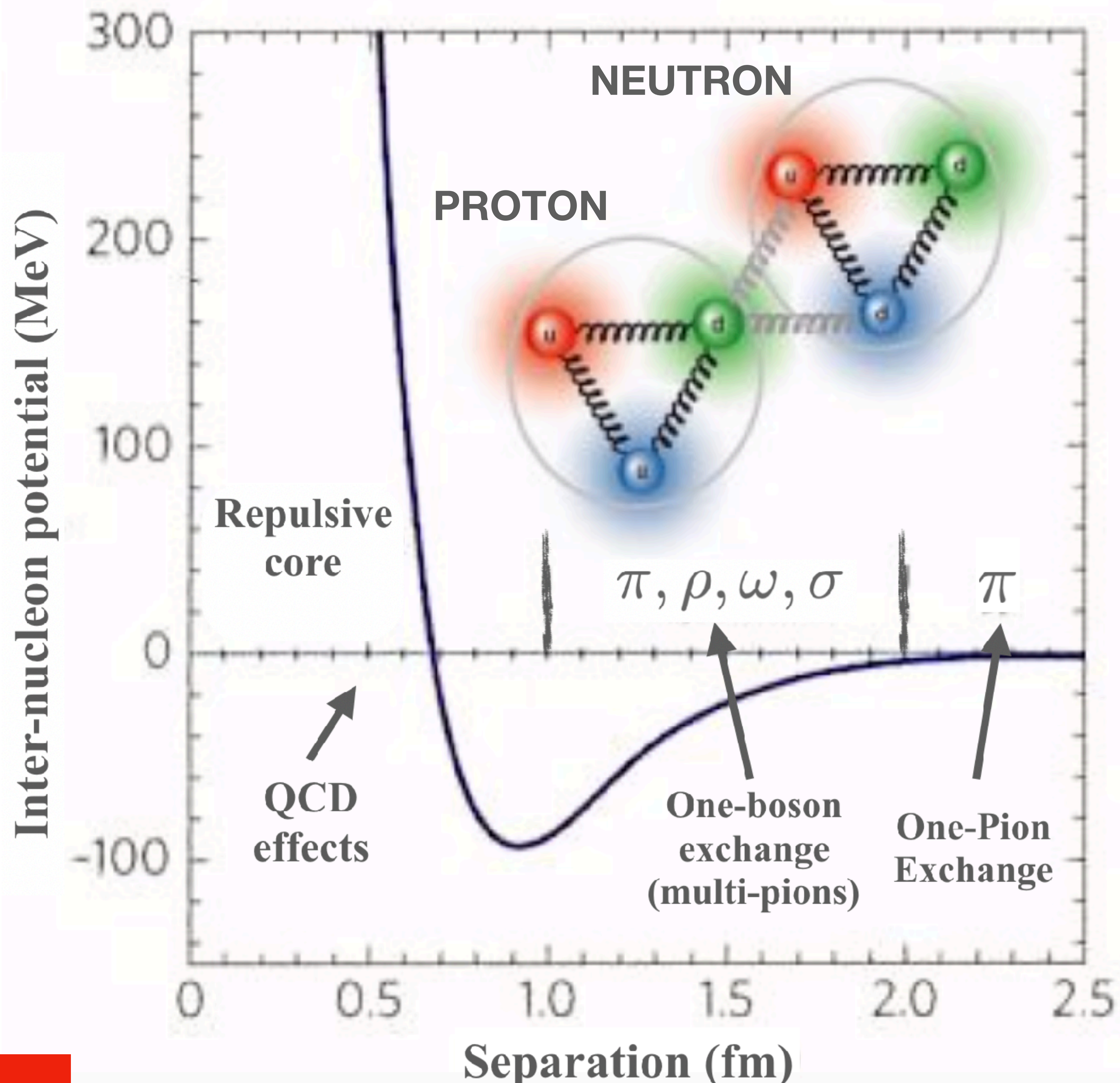
- In addition to main article, supplemental material has been included where analysis details are discussed.

  * Raw numerical data files are also provided



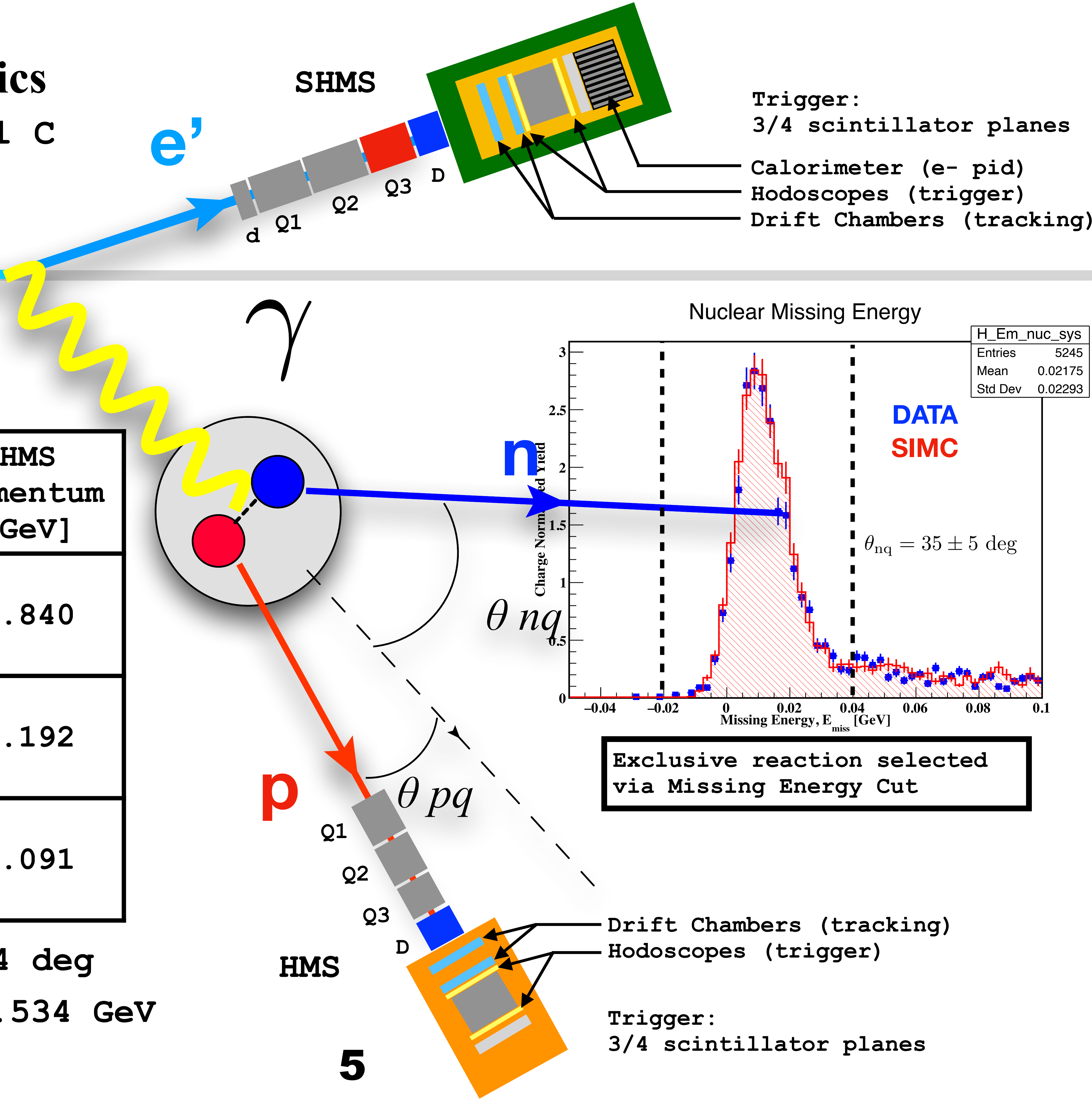
Motivation

- Deuteron is the simplest np bound state: starting point to study nuclear force (or NN potential)
- Understand the short range structure by probing high momentum tails of the deuteron
- At short ranges, *np* system starts to overlap which is directly related to SRCs in A>2 nuclei
- Extract momentum distributions beyond 500 MeV/c recoil momenta at PWIA kinematics



For historical overview of the nuclear force: SEE BACKUP SLIDES

E12-10-003
D(e,e'p)n Kinematics
Experimental Hall C



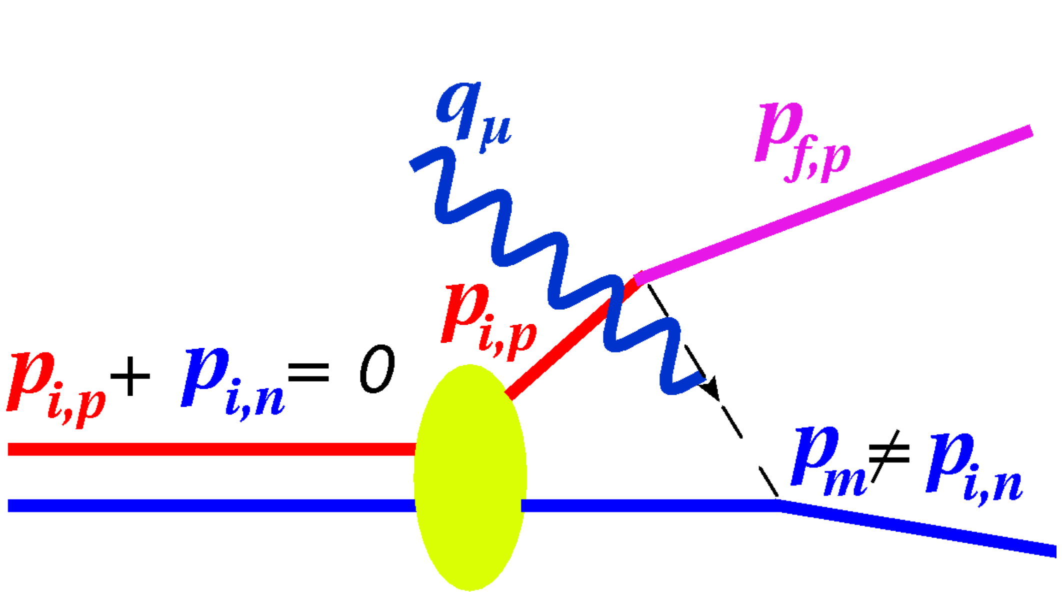
Beam Energy: 10.6 GeV

Pm [MeV]	HMS Angle [deg]	HMS Momentum [GeV]
80	~38.8	2.840
580	~55	2.192
750	~58.3	2.091

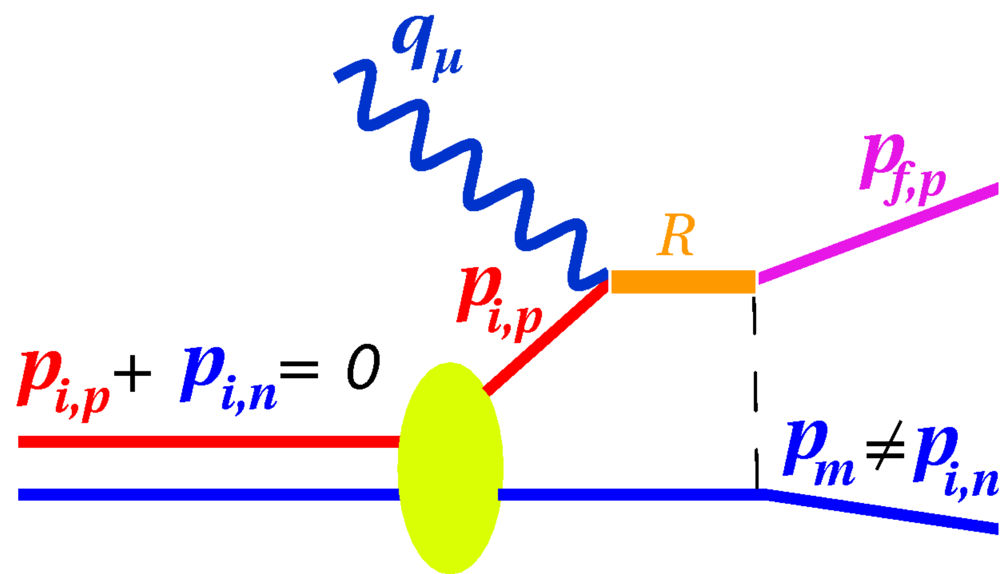
SHMS Angle: 12.194 deg

SHMS Momentum: -8.534 GeV

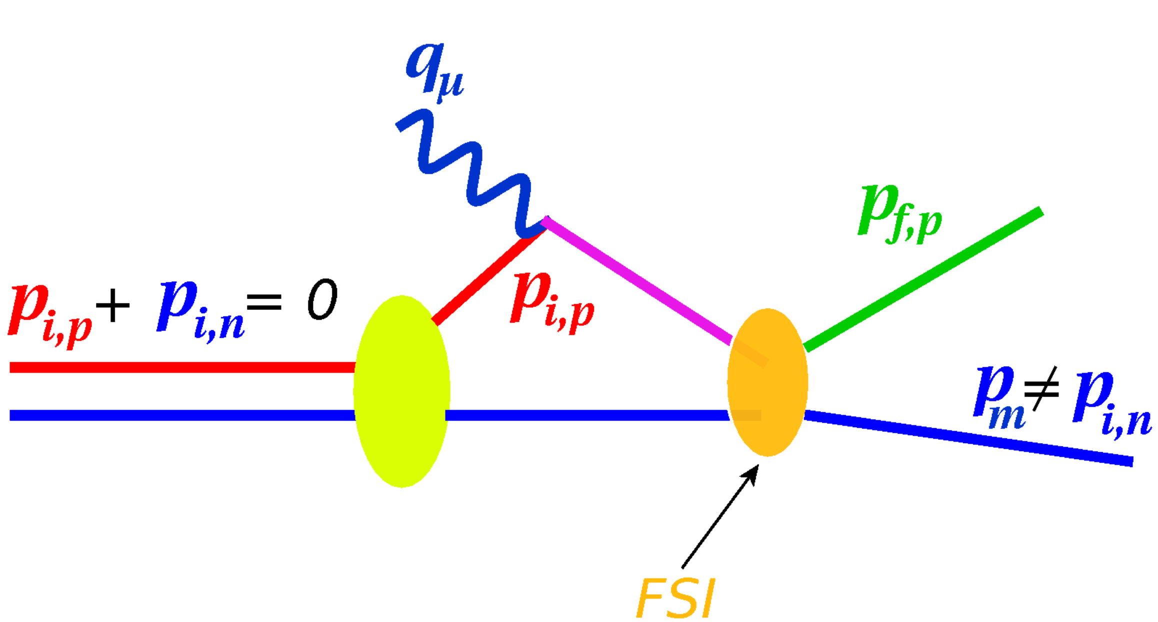
D(e,e'p)n Feynman Diagrams



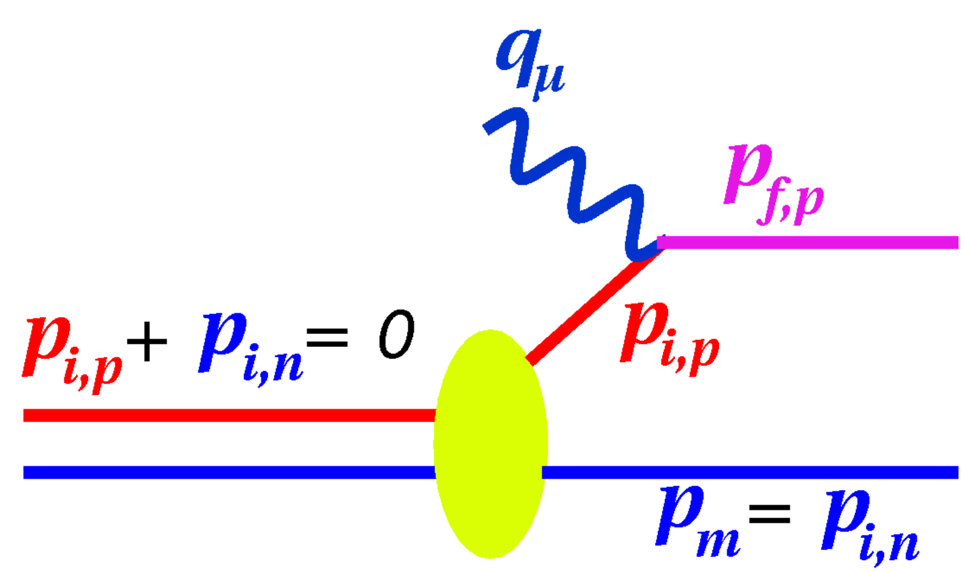
(a) Meson-Exchange Currents (MEC)



(b) Isobar Configurations (IC)



(c) Final State Interactions (FSI)



(d) Plane Wave Impulse Approximation (PWIA)

Deuteron Momentum Distribution

Experiment

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

Theory

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

Factorization ONLY possible in PWIA

ep off-shell cross section

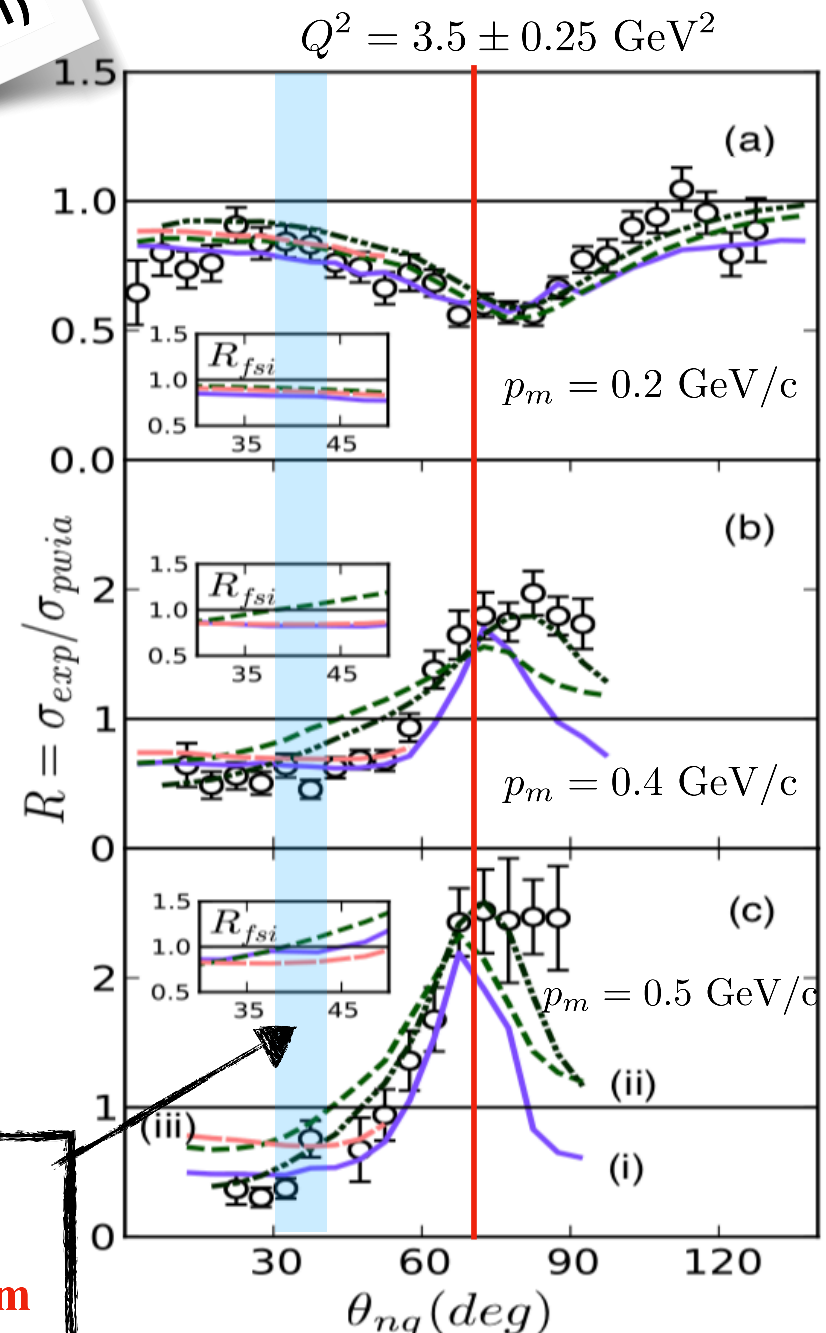
electron scatters off a bound proton within the nucleus; usually, de Forest σ_{cc1} or σ_{cc2} is prescribed

Spectral Function, $S(p_m)$

the momentum distribution inside the deuteron is interpreted as the probability density of finding a bound proton with momentum p_i

First D(e,e'p)n Experiments at: $Q^2 > 1\ \mathrm{GeV}^2$

JLab Hall A (2011)



CD-Bonn FSI (MS)

JVO Model (J.W. Van Orden)

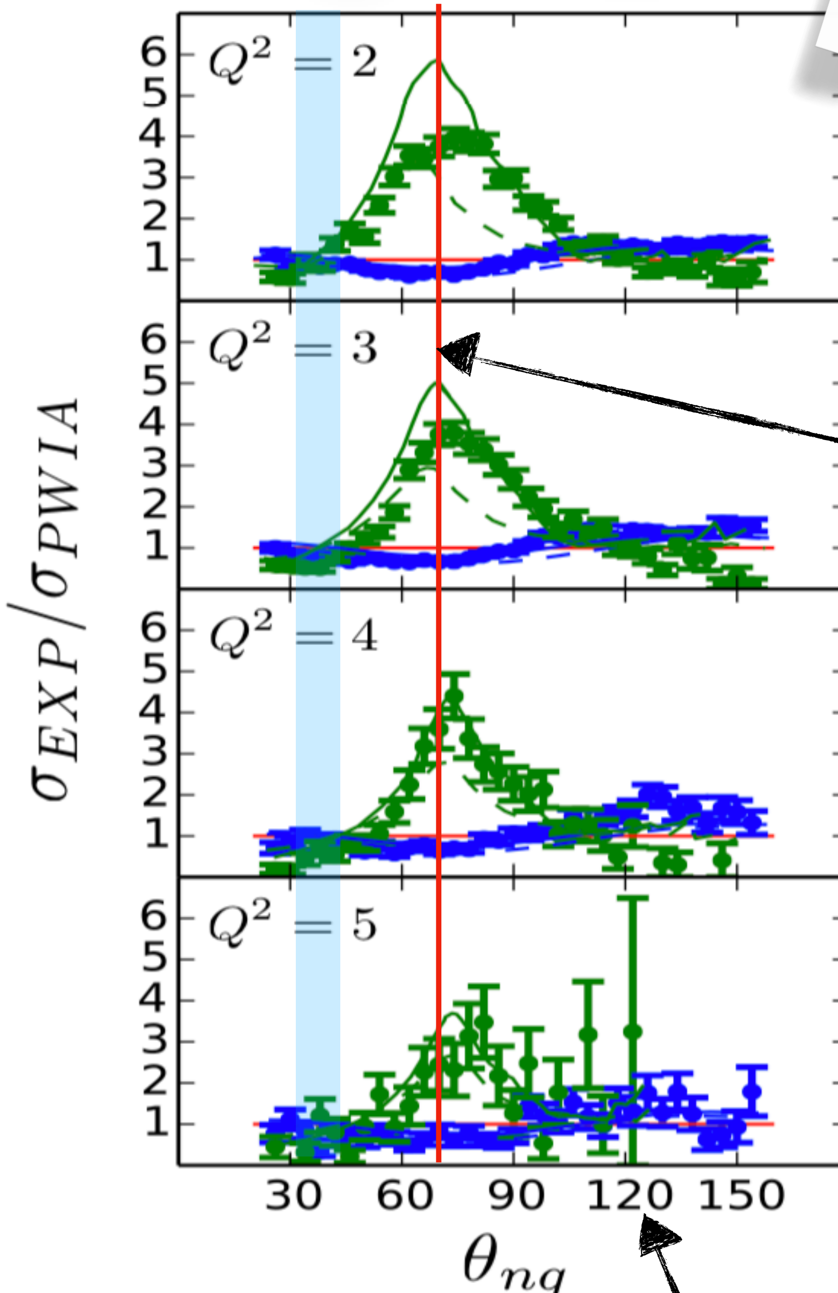
Paris FSI (J.M. Laget)

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

DATA

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

JLab Hall B (2007)



FSI peaks at ~70 deg (predicted by GEA)

$0.2 \le p_m \le 0.3$ GeV/c

$0.4 \le p_m \le 0.6$ GeV/c

Paris FSI (J.M. Laget)

CD-Bonn FSI (MS)

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

- Data shows FSI peaks at ~70 deg (predicted by GEA and J.M Laget)
- FSI greatly reduced at ~40 and ~120 deg

Plots Reference:
W.U.Boeglin and M. Sargsian Int.J.Mod.Phys. E24 (2015) no.03, 1530003

D(e,e’p)n Cross Section Experiment Results

D(e,e'p)n Momentum Distributions

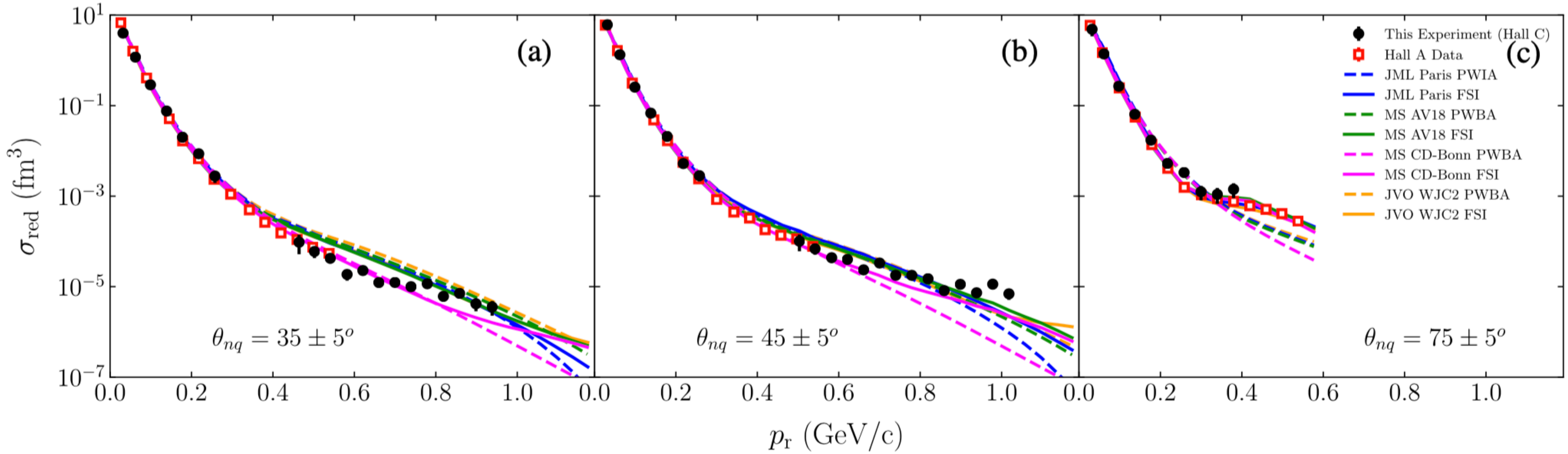


FIG. 1. The reduced cross sections $\sigma_{\rm red}(p_r)$ as a function of neutron recoil momentum p_r are shown in (a)–(c) for recoil angles $\theta_{nq} = 35°, 45°$, and $75°$, respectively, with a bin width of $\pm 5°$. The data are compared to the previous Hall A experiment (red square) results [11], as well as the theoretical reduced cross sections using the Paris (blue), AV18 (green), CD-Bonn (magenta), and WJC2 (orange) *NN* potentials. The plane wave born approximation (PWBA) includes the PWIA and the process in which the virtual photon couples to the neutron and the proton emerges as a spectator without subsequent reinteractions (no FSIs).

- Pr < 250 MeV/c, FSIs small and NN dominated by "One Pion Exchange Potential (OPEP) (for 35 and 45 deg)
- Pr > 250 MeV/c, CD-Bonn differs from Paris/AV18 models (for 35 and 45 deg)
- Hall C data reproduces previous Hall A data very well

J.M. Laget, Phys. Lett. B609, 49 (2005) (**JML Paris: Galster parametrization)**

M.M. Sargsian, Phys. Rev. C82, 014612 (2010) (**MS CD-Bonn/MS AV18: JJK parametrization)**

W.P. Ford, S. Jeschonnek and J.W.V. Orden, Phys. Rev. C90, 064006 (2014) (**JVO WJC2: GKex05 parametrization)**

Reference (Fig. 1): 10.1103/PhysRevLett.125.262501

D(e,e'p)n Reduced Cross Section Ratio to MS CD-Bonn PWIA

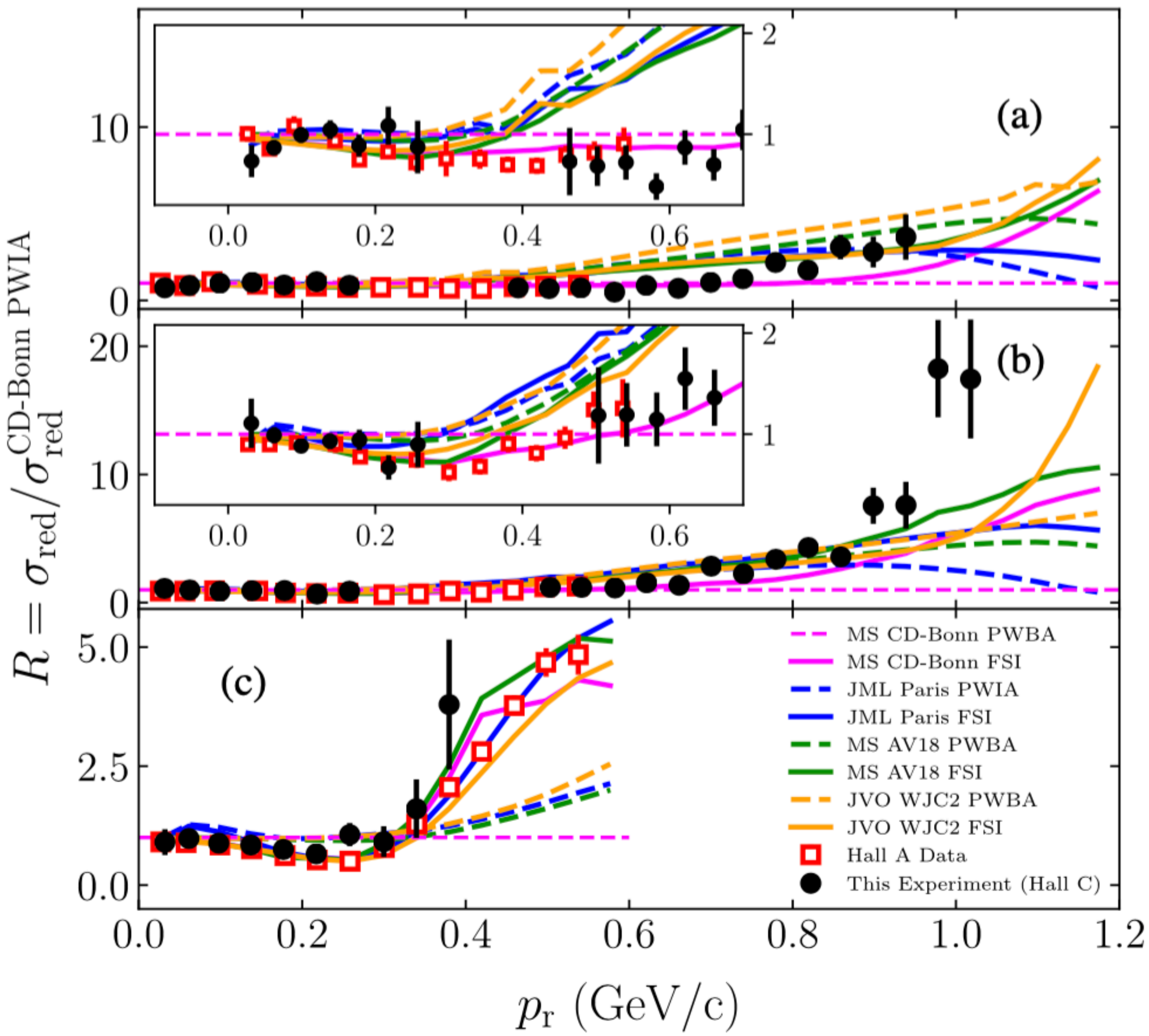


FIG. 2. The ratio $R(p_r)$ is shown in (a)–(c) for $\theta_{nq} = 35°, 45°$, and $75°$, respectively, each with a bin width of $\pm 5°$. The dashed reference (magenta) line refers to MS CD-Bonn PWIA calculation (or momentum distribution) by which the data and all models are divided. Insets: enlargement of the subfigures for $p_r \leq 0.7$ GeV/c.

Reference (Fig. 2): 10.1103/PhysRevLett.125.262501

- Data agrees with CD-Bonn FSI up to Pr ~ 700 MeV/c at 35 and 45 deg
- At Pr ~300 - 700 MeV/c, R ~ 0.5 - 1 for 35 and 45 deg compared to R ~ 2 - 5 for 75 deg
  (FSIs largely reduced at smaller angles)
- Pr > 700 MeV/c data is NOT described by any model

Approximate cancellation of FSI/PWIA amplitudes leads to reduction in FSI at specific kinematics

$$\sigma \sim |A_{PWIA} + iA_{FSI}|^2 \sim A_{PWIA}^2 - 2A_{PWIA}A_{FSI} + A_{FSI}^2$$

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

$$\longrightarrow \quad \frac{\sigma}{\sigma_{PWIA}} \sim 1 \boxed{- 2\frac{A_{FSI}}{A_{PWIA}} + \frac{A_{FSI}^2}{A_{PWIA}^2}}$$

Summary and Future Plans to Complete the D(e, e'p)n Experiment

- Commissioning part (3 PAC days) of the experiment was successfully completed and published in the Physical Review Letters (PRL) scientific journal.
- DATA was best described by CD-Bonn models at smaller recoil angles (35 deg) and recoil momenta up to ~700 MeV/c
- Above recoil momenta of ~700 MeV/c, NO calculation describes the data and this discrepancy is worth exploring further in the full experiment

---

- Complete the remaining 18 PAC days of the experiment
- Focus on higher missing momentum setting (Pr > 700 MeV/c) to achieve better statistical precision to pin down theoretical models
- Potentially explore new relativistic effects at the highest missing momentum region by comparing data to truly relativistic models (i.e., Light-cone formulation of the deuteron by M. Sargsian)

ACKNOWLEDGMENTS

I would like to thank my advisor and co-advisor, Drs. Werner Boeglin and Mark Jones for their constant support and useful discussions on this topic.

In addition, I would like to acknowledge the entire Accelerator Division and Hall C staff and technicians and all graduate students, users and staff who took shifts or contributed to the equipment for the Hall C upgrade making all four commissioning experiments possible.

Last (but not least) thanks to Misak Sargsian, J.M. Laget, Sabine Jeschonnek and J.W. Van Orden for providing the theoretical calculations for this experiment.

This work was in part supported by:

- **the Nuclear Regulatory Commission (NRC) Fellowship grant No: NRC-HQ-84-14-G-0040 to Carlos Yero**
- **the Doctoral Evidence Acquisition (DEA) Fellowship to Carlos Yero**
- **the DOE grant No: DE-SC0013620 to FIU**

THANK YOU !

Jefferson Lab
Exploring the Nature of Matter

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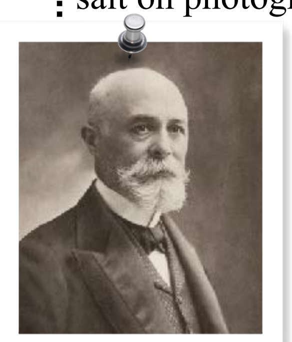
Hall-C

BACK-UP SLIDES

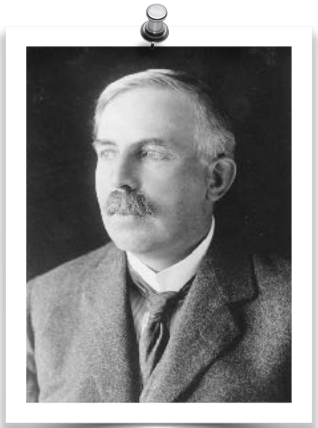
A Brief History of the Nuclear Force: From Meson Theory to Phenomenology

1896:
H. Becquerel discovers radioactivity from Uranium salt on photographic plates



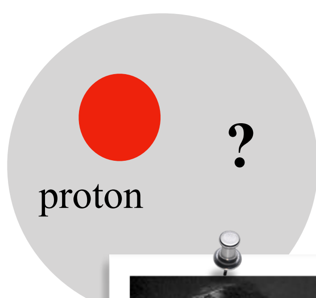
1897:
- J.J. Thompson discovers the electron (beta rays deflected by an electric field),
-the electron indicated the atom had internal structure

1911:
E. Rutherford discovers the atomic nucleus by "scattering alpha particles from Au foil." In 1917, he proved the ^{1}H nucleus is present in the nuclei of all other atoms

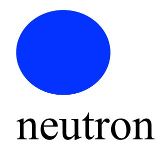


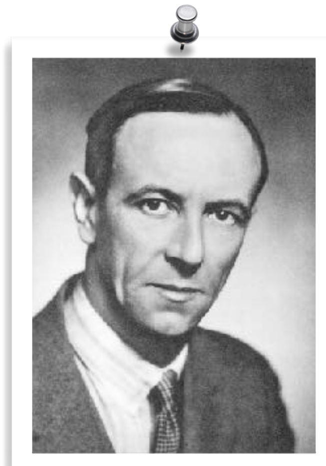
1930s:

1931:
H. Urey discovers deuterium present in a residue of distilled liquid hydrogen

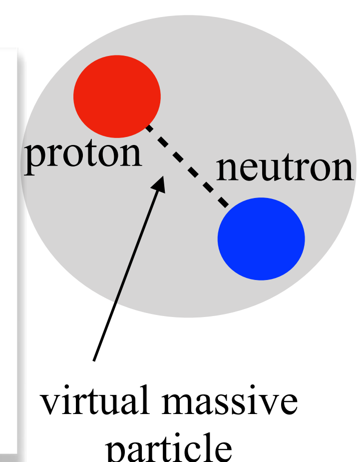


1932:
J. Chadwick discovers the neutron in a scattering experiment



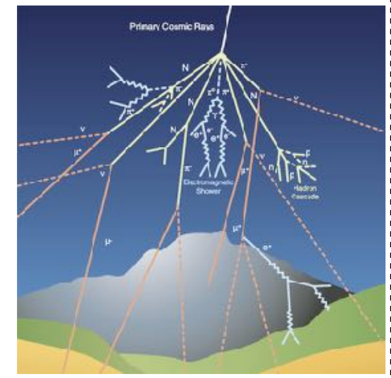


1935:
H. Yukawa proposes the NN interaction to be mediated by the exchange of a massive virtual particle



1940s:

1947,1948:
Charged pion discovered in cosmic rays (1947) and later artificially produced in Berkeley Lab (1948)

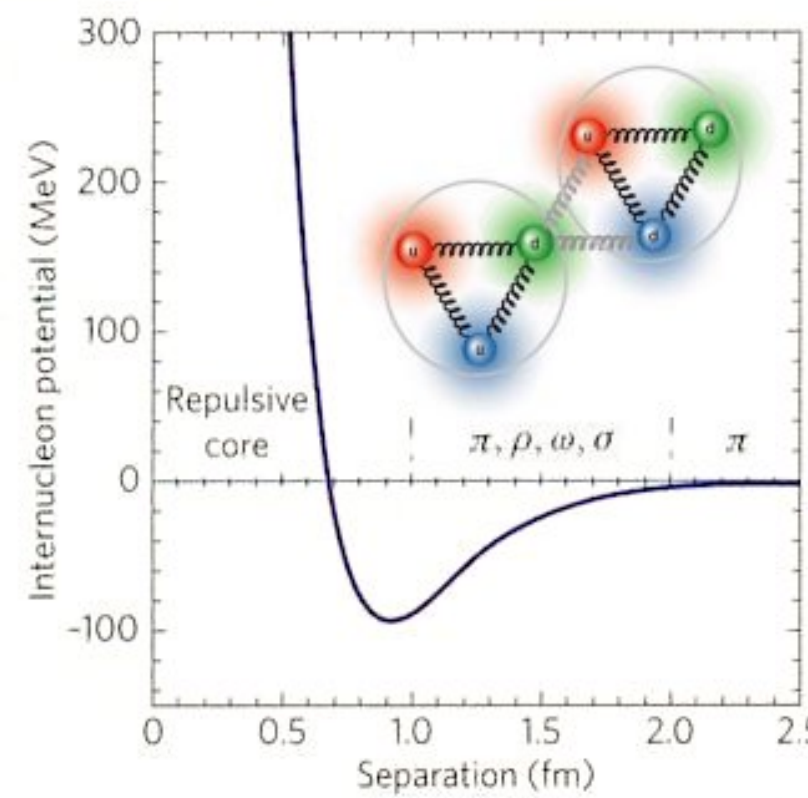


1950s:

1950s:

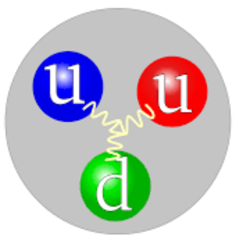
Efforts devoted to develop pion (meson) field theories motivated by pion discovery
- -One-Pion Exchange Potential (OPEP) described NN scattering data successfully
- -Meson Theory failed to describe multi-pion exchange (Meson Theory is NOT the fundamental theory of strong interactions)

1951:
M. Taketani, S. Nakamura and M. Sasaki propose to divide the NN potential into 3 sub-ranges



A Brief History of the Nuclear Force: From Meson Theory to Phenomenology

Quark Model (1964)
- M. Gell-Mann and G. Zweig propose that baryons & mesons are bound states of sub-atomic particles termed "quarks" by Gell-Mann



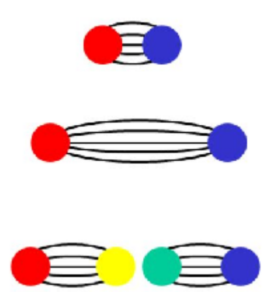
1960s:

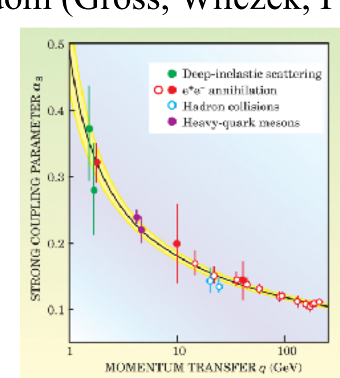
- large amounts of NN scattering data accumulated since 1955
- Discovery of heavier mesons in experiments $\rho(770), \omega(783)$,
- Development of the One-Boson Exchange Potential (OBEP)
  e.g., Hamada-Johnston (HD), Yale-Group, Bryan-Scott (BS), Reid (1969) potentials

1970s:

Refined OBEP models
- relativistic OBE models developed
- sophisticated OBE models to include 2π exchange
- Paris potential (1972, 1979)

Quantum Chromodynamics (QCD) (1973)
QCD established as the QFT of strong interactions
QCD exhibits 2 main properties:
- Color confinement
- Asymptotic Freedom (Gross, Wilczek, Politzer)





1980s:

More sophisticated OBEP models constructed
- Argonne V14,V28 (AV14, AV28) potential
  - 2π exchange contributions
- Full Bonn potential
  - 2π exchange contributions,
  - relativistic effects

1990s:

High-precision NN potentials based on improved *nn, pp, np* scattering database
e.g., Argonne V18 (AV18), Nijmegen I & II, Charge-dependent Bonn (CD-Bonn)

1990:
- Effective Field Theory (EFT) applied to low energy QCD (where nuclear physics operates) by S. Weinberg (1990)
- Meson theory revisited in terms QCD EFT (chiral perturbation theory)

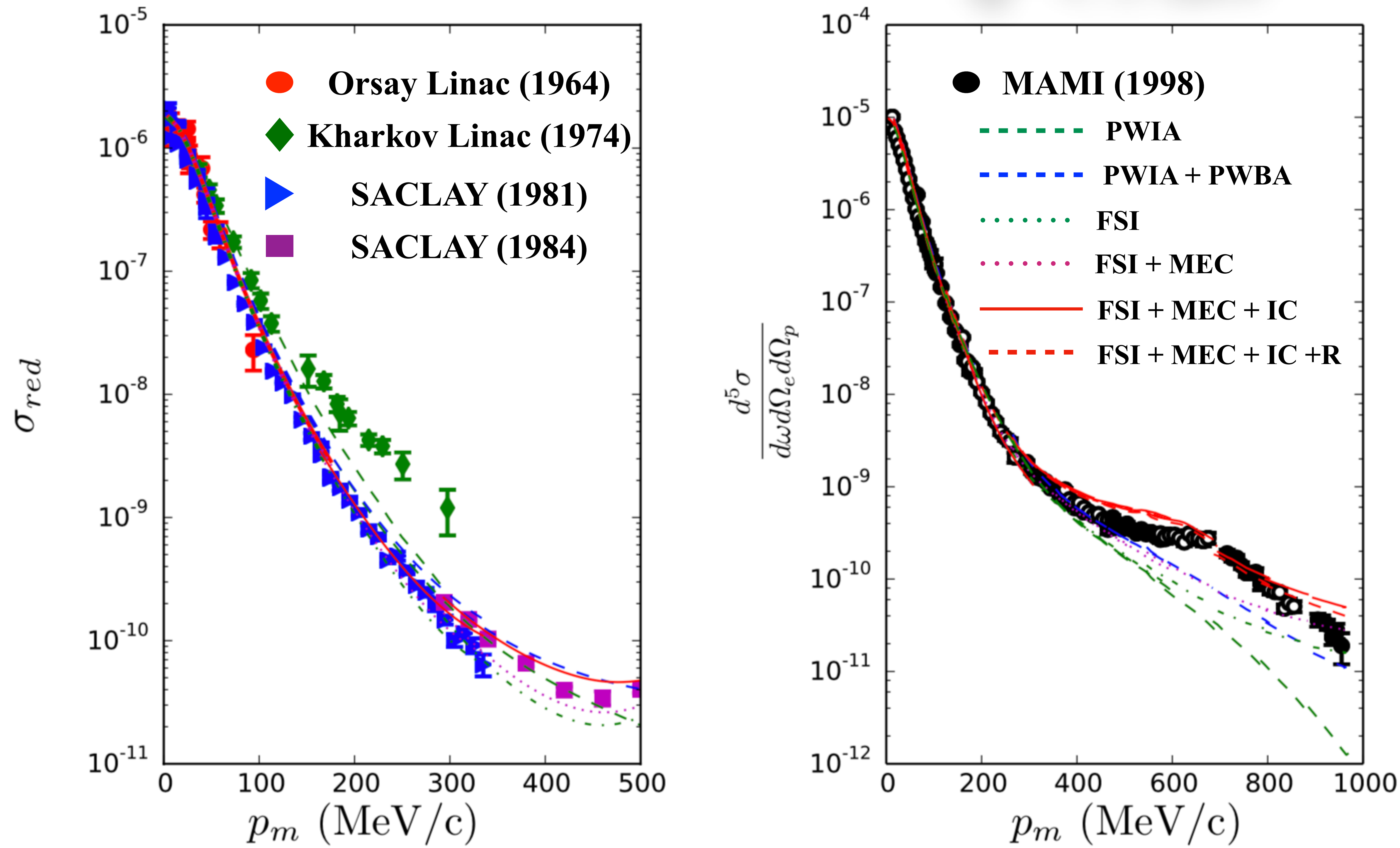
2000s:

Chiral Effective Field Theories
- development of NN potentials based on χEFT (experimental scattering data is used as input)
- QCD-based approaches are still a set of models and do NOT represent a true fundamental progress in understanding nuclear forces

Fundamental problem of nuclear physics in present day: **derive the NN interaction from fundamental QCD principles**

D(e,e'p) Experiments At $Q^2 < 1$ GeV^2

Previous D(e,e'p)n Experiments at: $Q^2 < 1\ \mathrm{GeV}^2$



<u>Theoretical Calculations</u>
W. Fabian and H. Arenhovel, Nucl.Phys. A258, 461 (1976)

- At Pm>300 MeV/c, FSI+MEC+IC all dominate the cross section

Plots Reference: <u>W.U.Boeglin and M. Sargsian Int.J.Mod.Phys. E24 (2015) no.03, 1530003</u>

Data Analysis of the E12-10-003 Commissioning Experiment at Hall C

- The E12-10-003 experiment was carried out on April 3-9
  (only 6 out of 21 days of the requested beam time for full experiment)

See Backup Slides for first steps in general analysis:

1. Set reference times cuts
2. Set detector time window cuts
3. Perform detector calibrations
4. Optics Optimization
5. Data-to-Simulation Comparison

D(e,e'p)n
Data Analysis Cuts

- These cuts are used to select a clean sample of e- in the SHMS coincident with protons in the HMS that correspond to D(e,e'p)n
- Exact cuts are also applied to simulation (except for PID cuts)
- All plots shown have been integrated over all neutron recoil angles

SEE BACKUP SLIDES
for plots of data analysis cuts
(shown only for 80 MeV setting but are
also applied to high missing momentum data)

Extraction of D(e,e'p)n Coincidence Cross Sections at Hall C

Extraction of the D(e,e'p)n Cross Section

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

Corrected Data Yield

Phase Space Volume

Radiative Correction

Correct for Inefficiencies

Normalize data by total charge

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

Luminosity

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

Monte-Carlo Generated events

Jacobian operator

Spectrometer momentum (e-) and "Solid Angles"

D(e,e'p)n Coincidence rates

Cross section

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

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

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

<u>SEE BACKUP SLIDES</u> for details on the determination of each correction factor

D(e,e'p) 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**

Error Analysis of D(e,e'p)n Coincidence Cross Sections at Hall C

Kinematic Uncertainties

$\delta\theta_e[mr]$	± 0.17
$\delta\theta_p[mr]$	± 0.24
$\delta E_f/E_f$	$\pm 9.1 \times 10^{-4}$
$\delta E_b/E_b$	$\pm 7.5 \times 10^{4}$
$d\sigma_{exp}^{kin}$	$\leq 6.5\,\%$

Normalization Uncertainties

$\delta(\epsilon_{htrk}, \epsilon_{etrk}, \epsilon_{tgtBoil})$	$\sim 0.81\,\%$ (avg/setting)
$\delta\epsilon_{pAbs}$	$0.49\,\%$
$(\delta\epsilon/\epsilon)_{tLT}$	$3.0\,\%$
$(\delta\epsilon/\epsilon)_{Q}$	$2.0\,\%$
$\delta\epsilon_{tgt}$	$\leq 2.9\,\%$
$\delta\epsilon_{spec.Acc}$	$1.4\,\%$
$d\sigma_{exp}^{norm}$	$\leq 5.3\,\%$

See Backup Slides

Estimate made by M. Jones

Stat. Uncertainty

$d\sigma_{exp}^{stats}$	$\sim 20 - 30\,\%$

- $(d\sigma_{exp}^{syst})^2 = (d\sigma_{exp}^{kin})^2 + (d\sigma_{exp}^{norm})^2$ **: total systematic error is quadrature sum of kinematics and normalization errors**
- $(d\sigma_{exp}^{tot})^2 = (d\sigma_{exp}^{stats})^2 + (d\sigma_{exp}^{syst})^2$ **: total error is quadrature sum of statistical and systematic errors**
- **Total cross section error is dominated by statistical error**

See Backup Slides
for detailed Tables and Plots of Statistical/Systematic Errors

Summary of Theoretical Calculations for E12-10-003

Theoretical Calculation	Final State Interactions (np parametrization)	Nucleon Form Factors (parametrization)	Deuteron Wave Function
J.M. Laget	SAID	Galster: GEn Hall A Exp: GEp	Paris
M.M. Sargsian	SAID	JJK	CD-Bonn AV18
S. Jeschonnek & J.W.V. Orden	SAID/Regge	GKex05 AMT	WJC2 CD-Bonn AV18

S. Galster, et al., Nucl. Phys. B32 (1971) 221 **(Galster, neutron electric form factor, GEn)**

O. Gayou, et al., Phys. Rev. Lett. 88 (2002) 092301 **(Hall A Exp. proton electric form factor, GEp)**

J.J. Kelly, Phys. Rev. C70, 068202 (2004) **(JJK)**

E.L. Lomon, Phys. Rev. C66, 045501 (2002) **(GKex05)**

J. Arrington, W. Melnitchouk, and J.A. Tjon, Phys. Rev. C76, 035205 (2007) **(AMT)**

R.A. Arndt, W.J. Briscoe, I.I. Strakovsky, and R.L. Workman, Phys. Rev. C76, 025209 (2007) **(SAID)**

W.P. Ford, S. Jeschonnek, and J.W.V. Orden, Phys. Rev. C 87, 054006 (2013) **(Regge)**

M. Lacombe, B. Loiseau, J. M. Richard, R. Vinh Mau, J. Côté, P. Pirès, and R. de Tourreil
Phys. Rec. C21, 861 (1980) **(Paris Potential)**

R.B. Wiringa, V.G.J. Stoks, and R. Schiavilla, Phys. Rev. C51, 38 (1995) **(AV18)**

R. Machleidt, Phys. Rev. C63, 024001 (2001) **(CD-Bonn)**

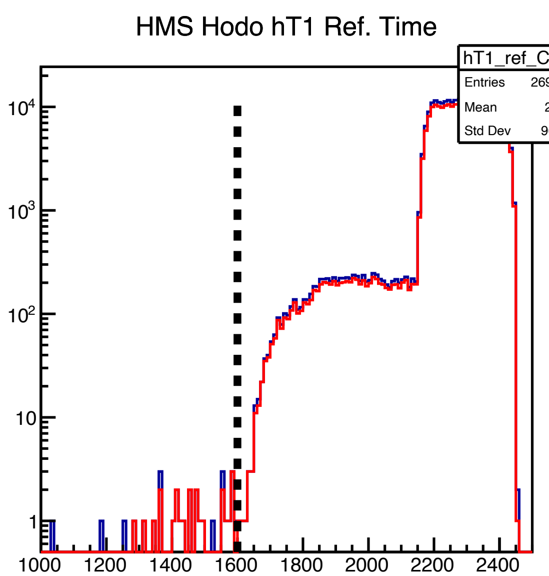
F. Gross and A. Stadler, Few Body Syst. 44, 295 (2008) **(WJC2)**

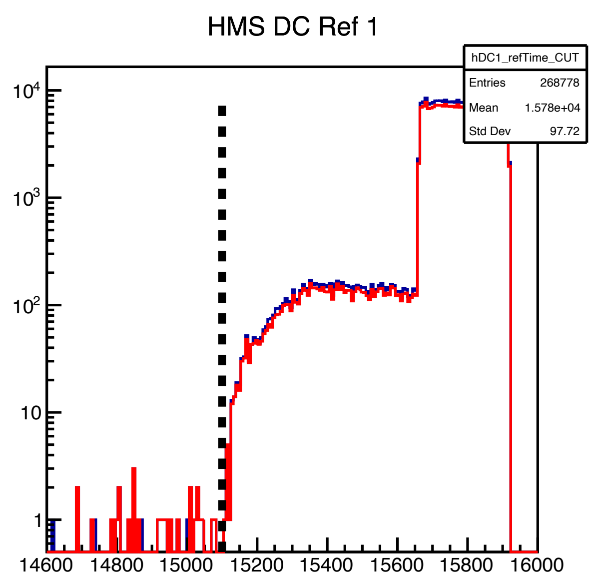
See Backup Slides: Overview of Theoretical Potentials to Theoretical Cross Sections

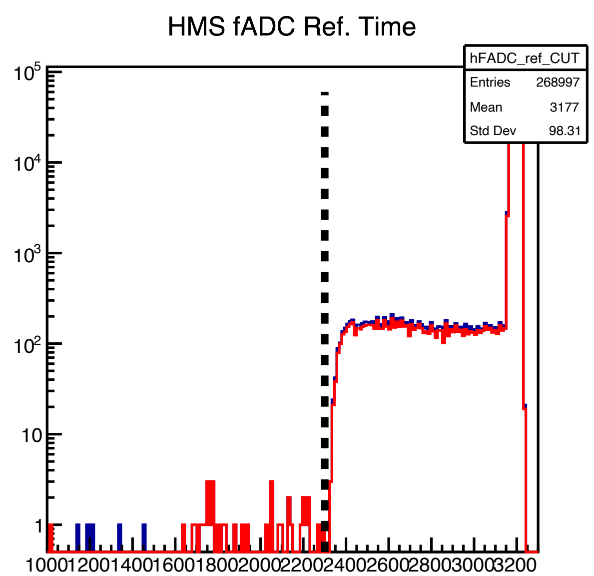
Data Analysis of the E12-10-003 Commissioning Experiment at Hall C

Reference Time Cuts

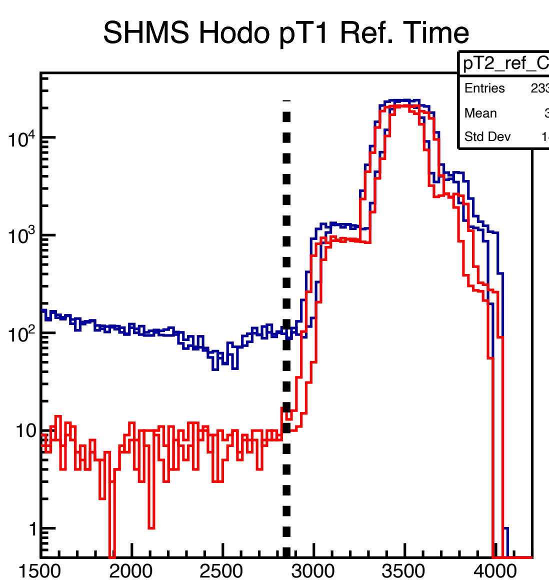
☑ **Correct reference time (copy of the trigger) must be chosen so that the ADCs/TDCs subtract the correct reference time (to the right of the cut dashed line)**

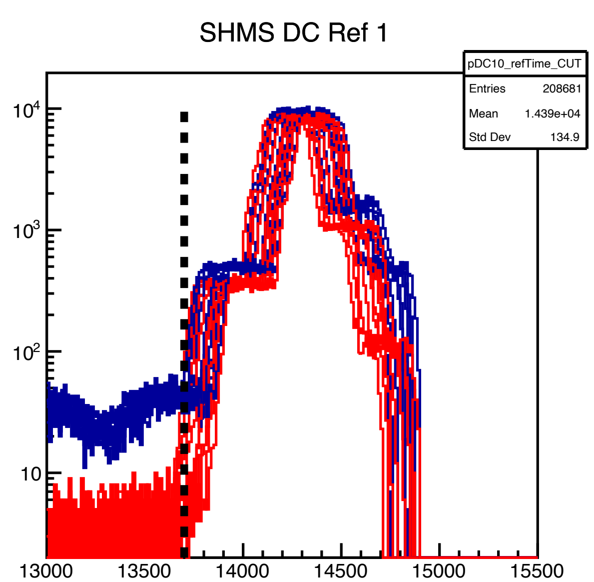


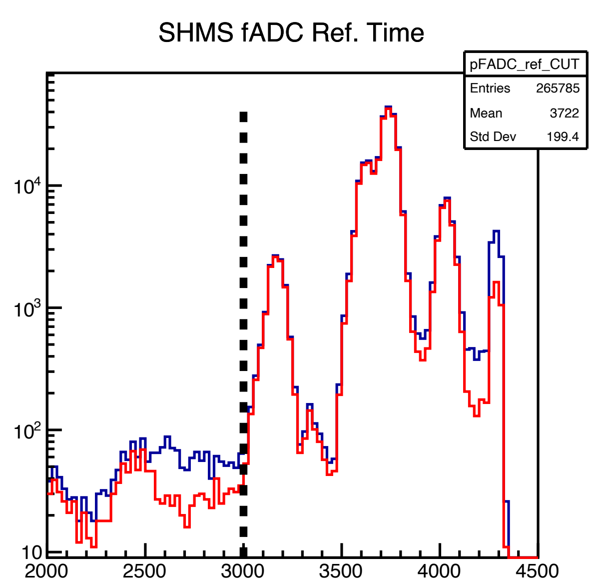




HMS Reference Times





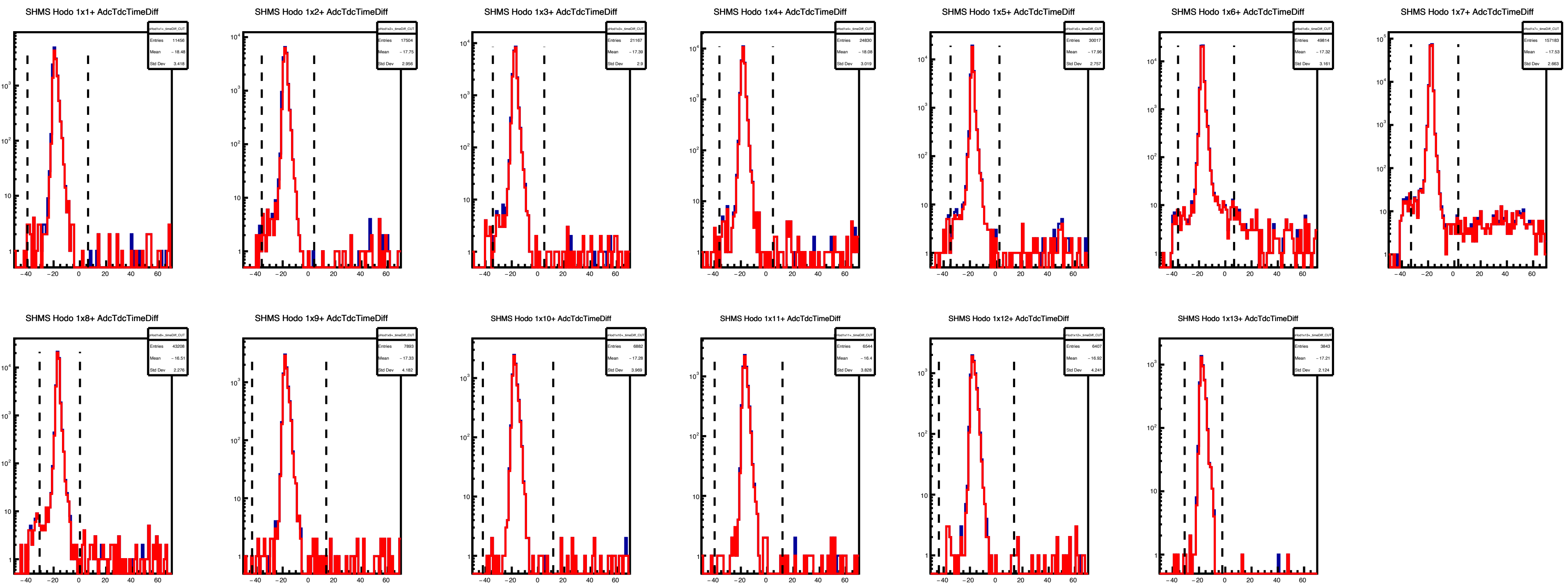


SHMS Reference Times

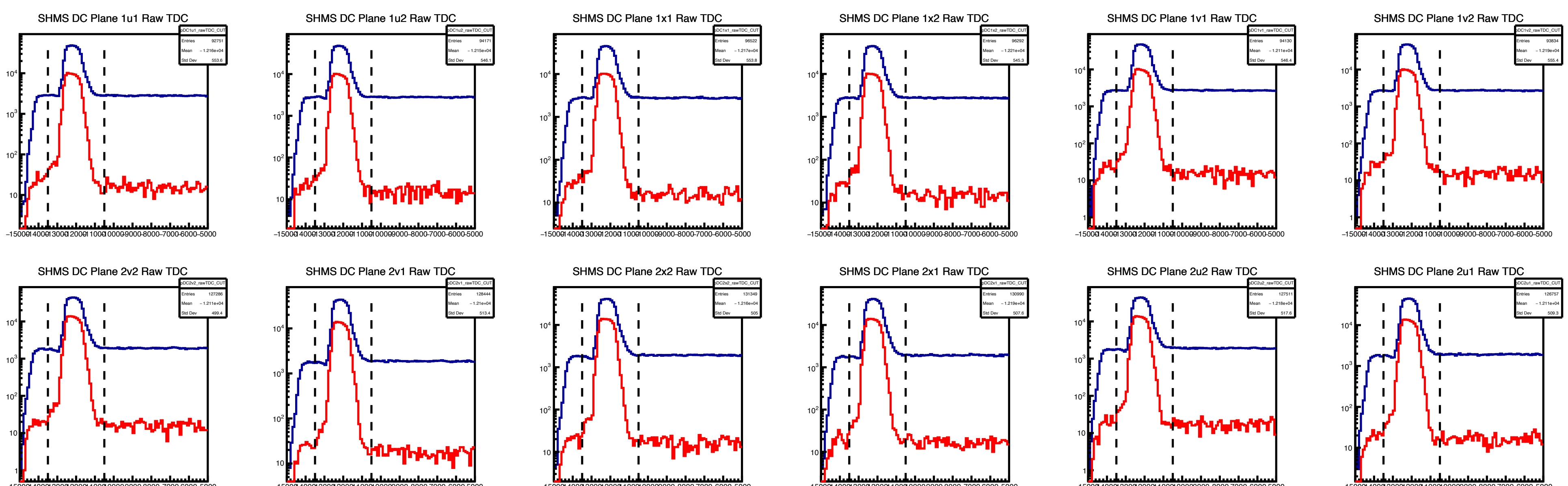
TDC Time Window Cuts

☑ **A time window cut MUST be made around the main signal peak to reduce background from possible out-of-time events.** **(Specially on the DCs)**

Legend: No Mult. Cut Multiplicity==1

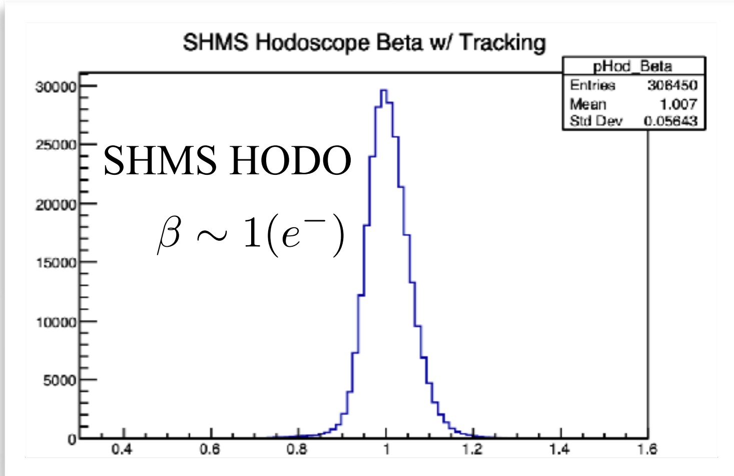


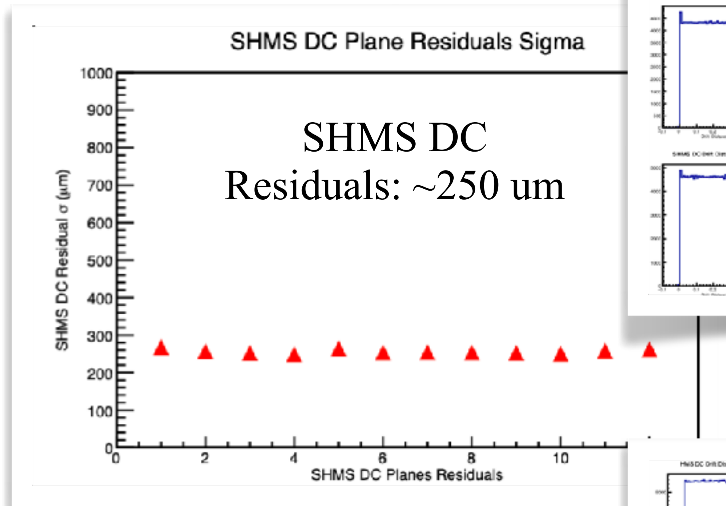
SHMS Hodoscope 1X+ (ADC-TDC) Time Difference

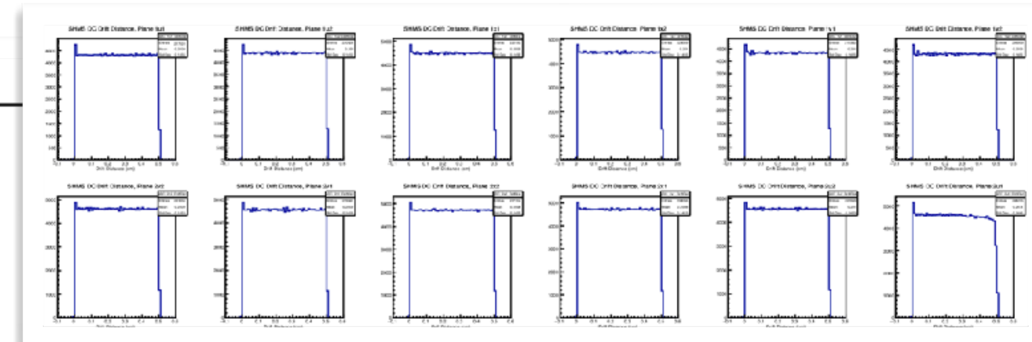


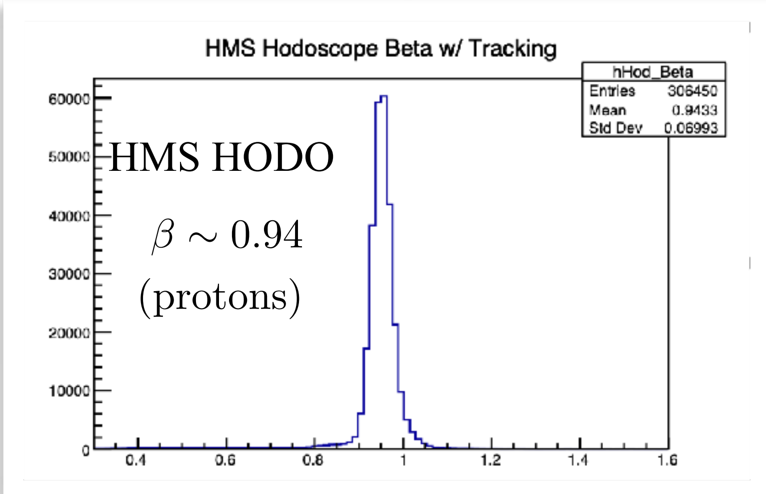
SHMS Drift Chambers Raw TDC Time

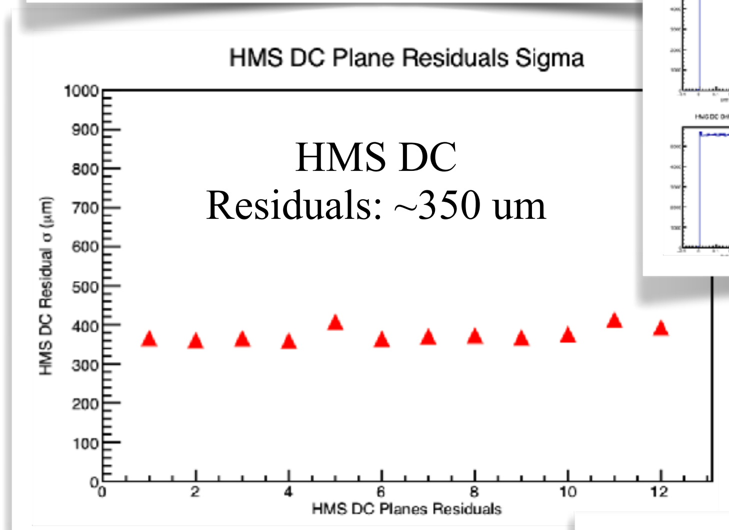
Detector Calibrations

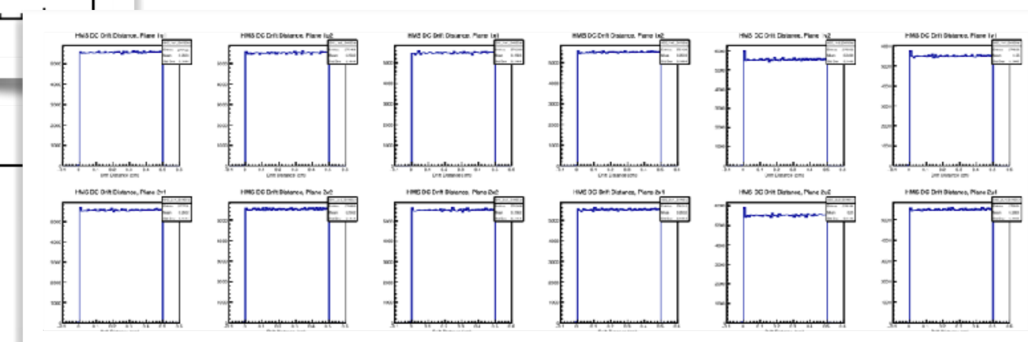


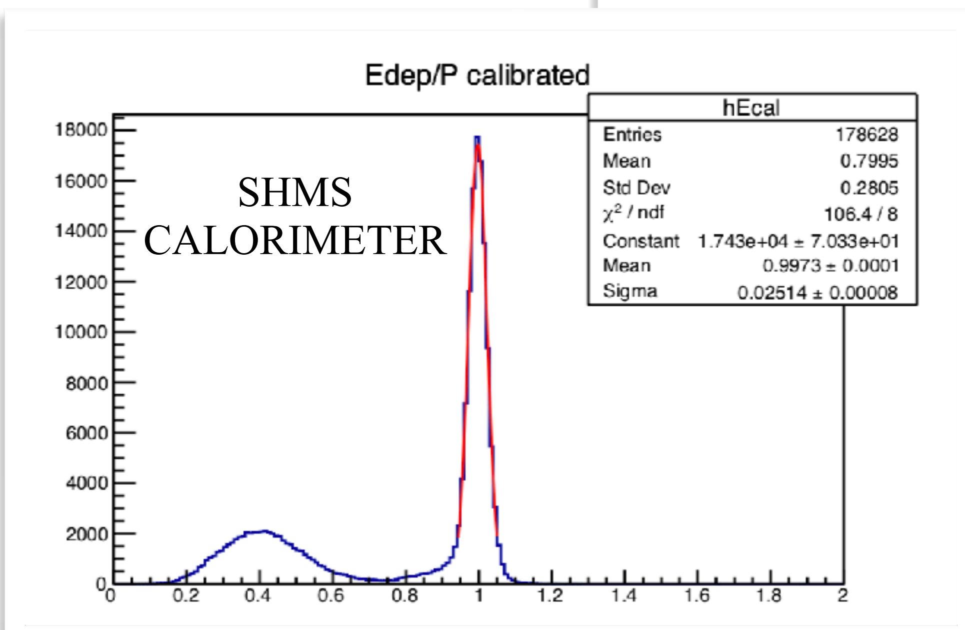


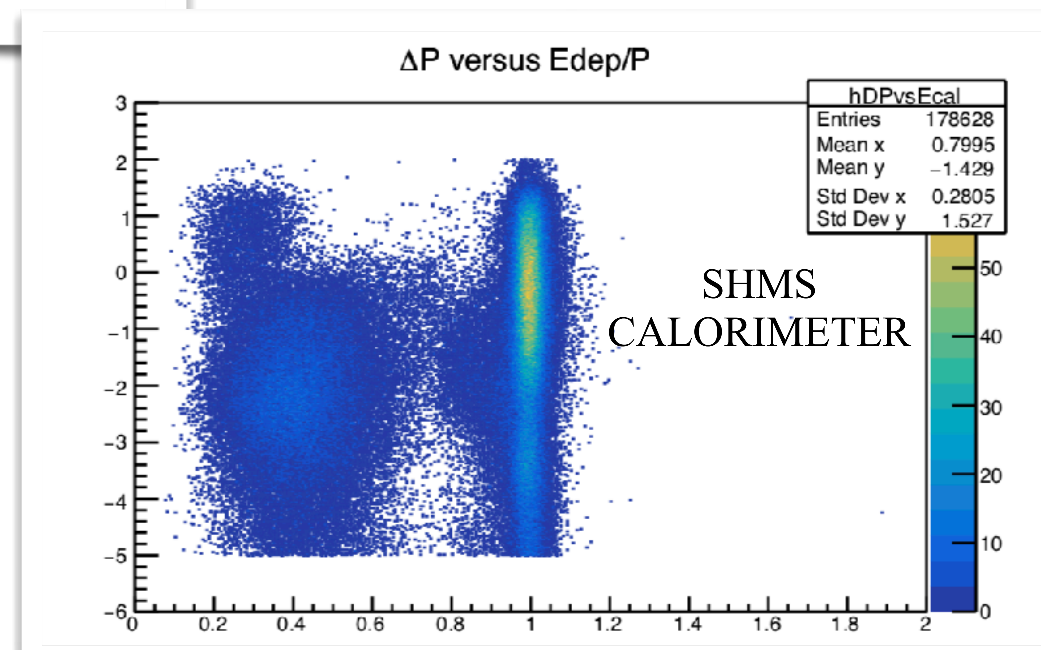




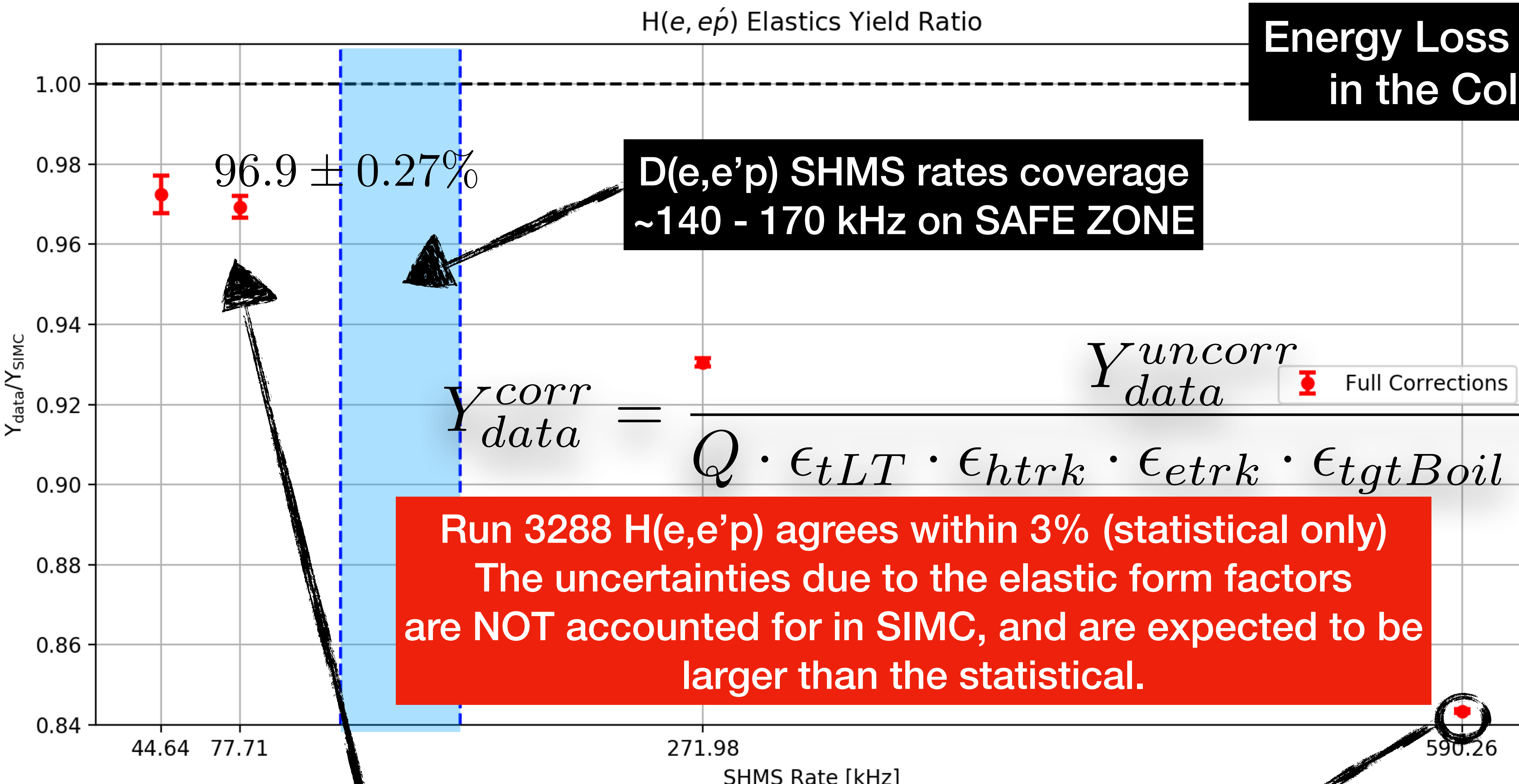








H(e,e’p) Yield Ratio Check



Energy Loss Simulated in the Collimator

D(e,e’p) SHMS rates coverage ~140 - 170 kHz on SAFE ZONE

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

Run 3288 H(e,e’p) agrees within 3% (statistical only)
The uncertainties due to the elastic form factors are NOT accounted for in SIMC, and are expected to be larger than the statistical.

Spectrometer acceptance is studied in detailed for this run (3288), due to its proximity to the D(e,e’p)n 80 MeV kinematics

NOT Understood:

* How does the tracking algorithm perform at very high rates?

The general cuts applied were:
|HMS Delta| < 8 % SHMS Delta: (-10, 22) %
Inv. Mass W : (0.85, 1.05), HMS Coll. Cut

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

The SHMS optics optimization work done for the D(e,e'p)n experiment can be found at Hall C Document Database

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 ($\sim$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

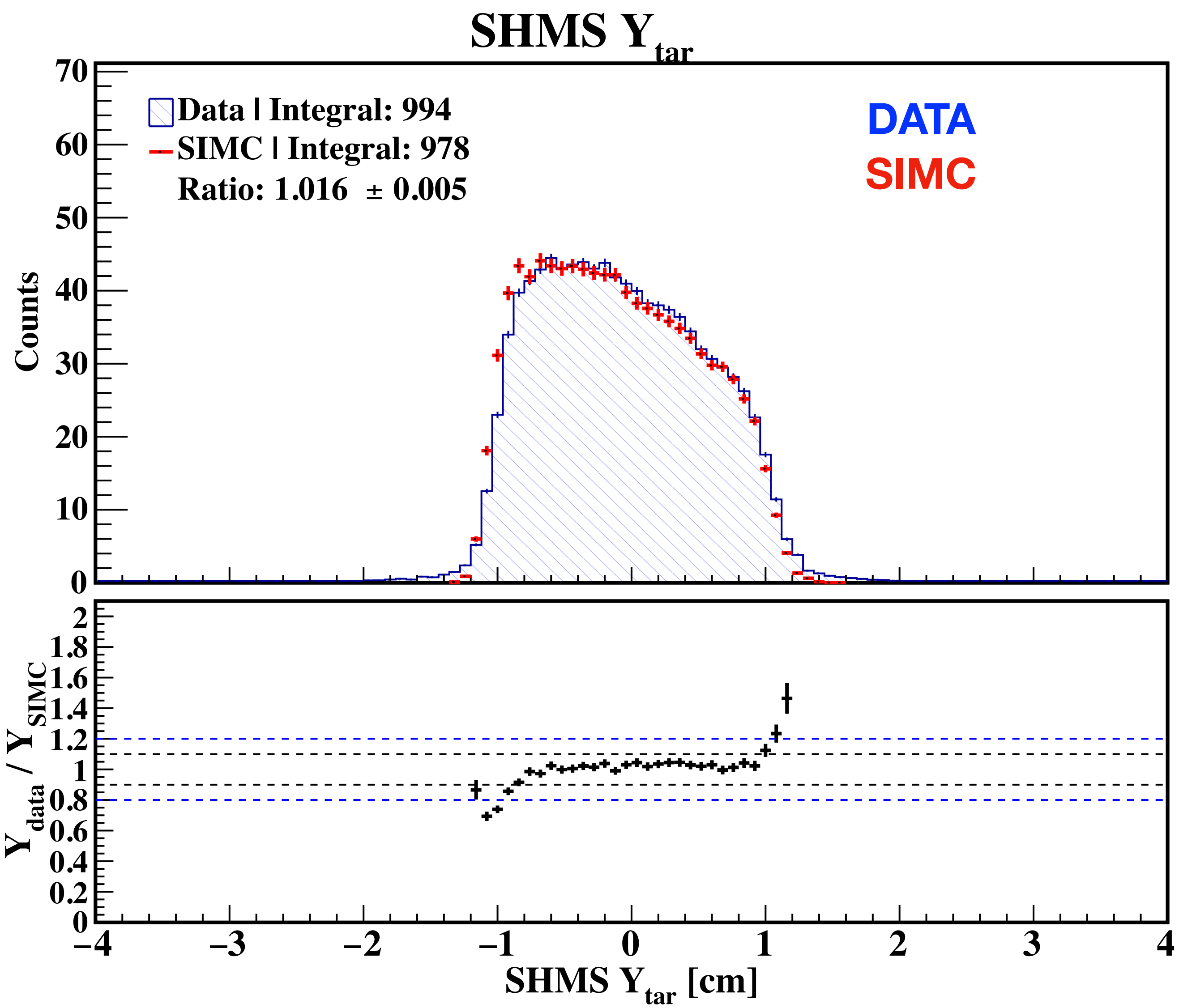
HALLC DOC-DB LINK

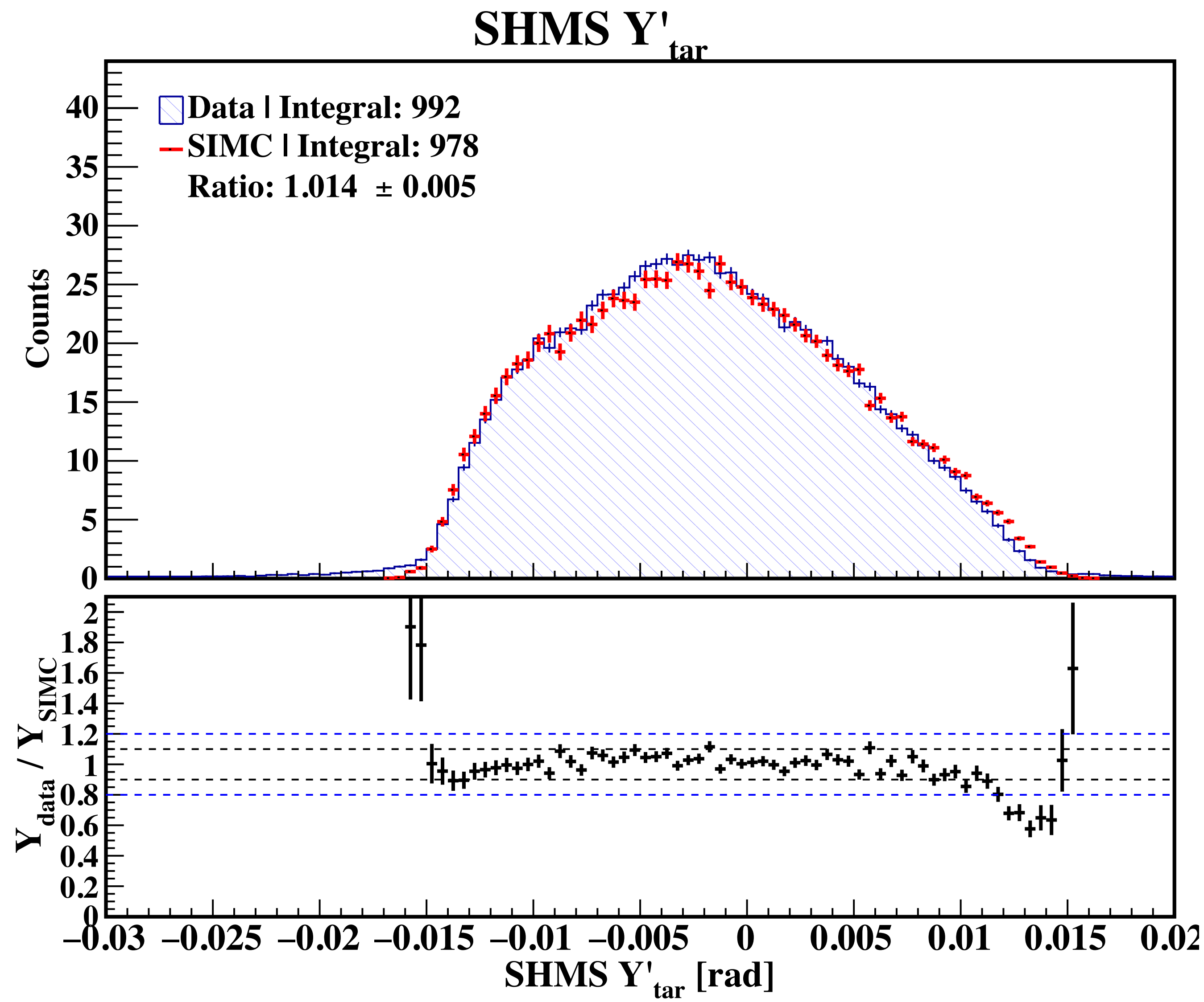
Spectrometer Acceptance
DATA/SIMULATION

(used H(e,e'p) Elastics data taken on D(e,e'p)n Experiment)

SHMS Reconstructed Variables

**** Data is fully corrected for inefficiencies**

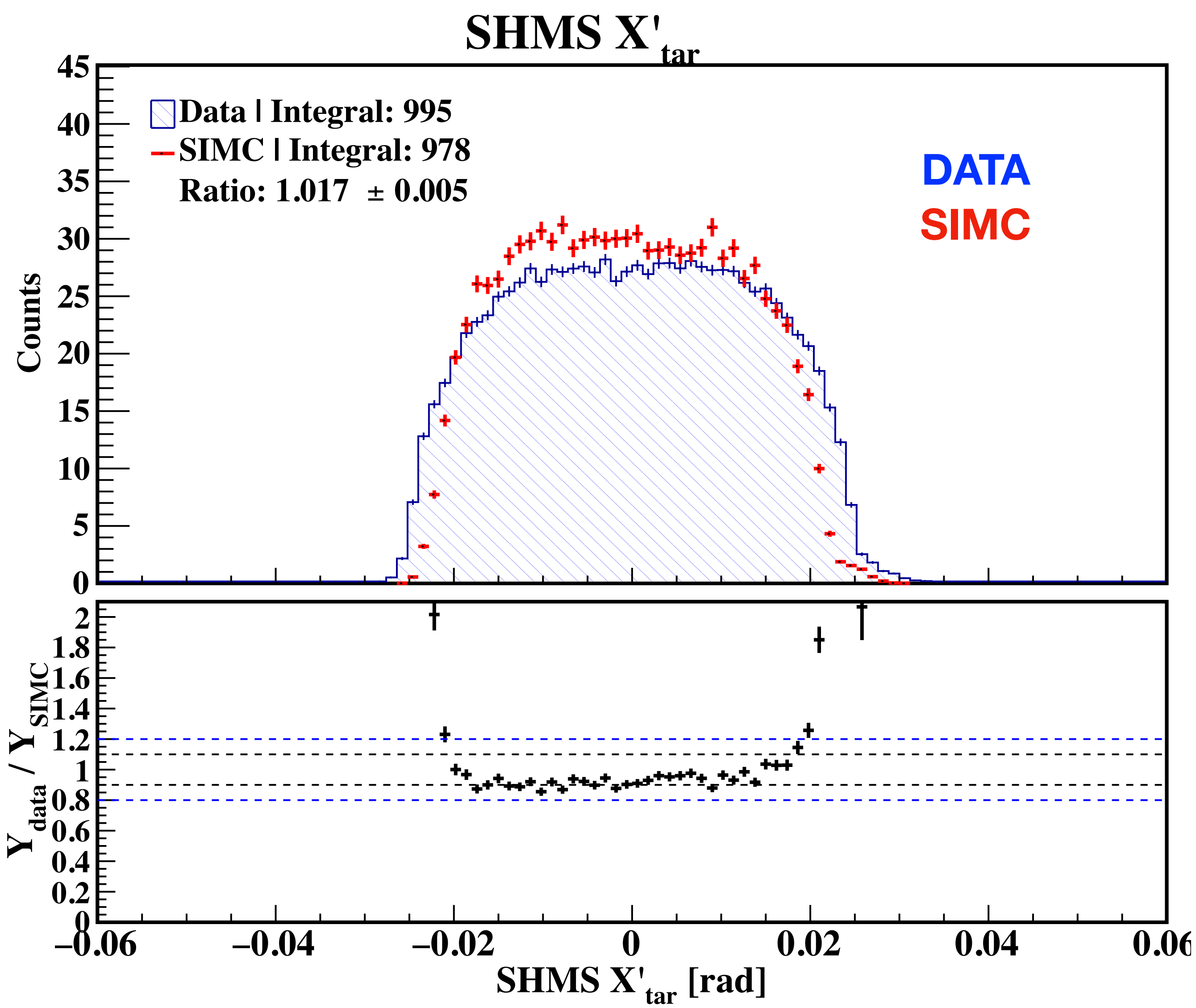


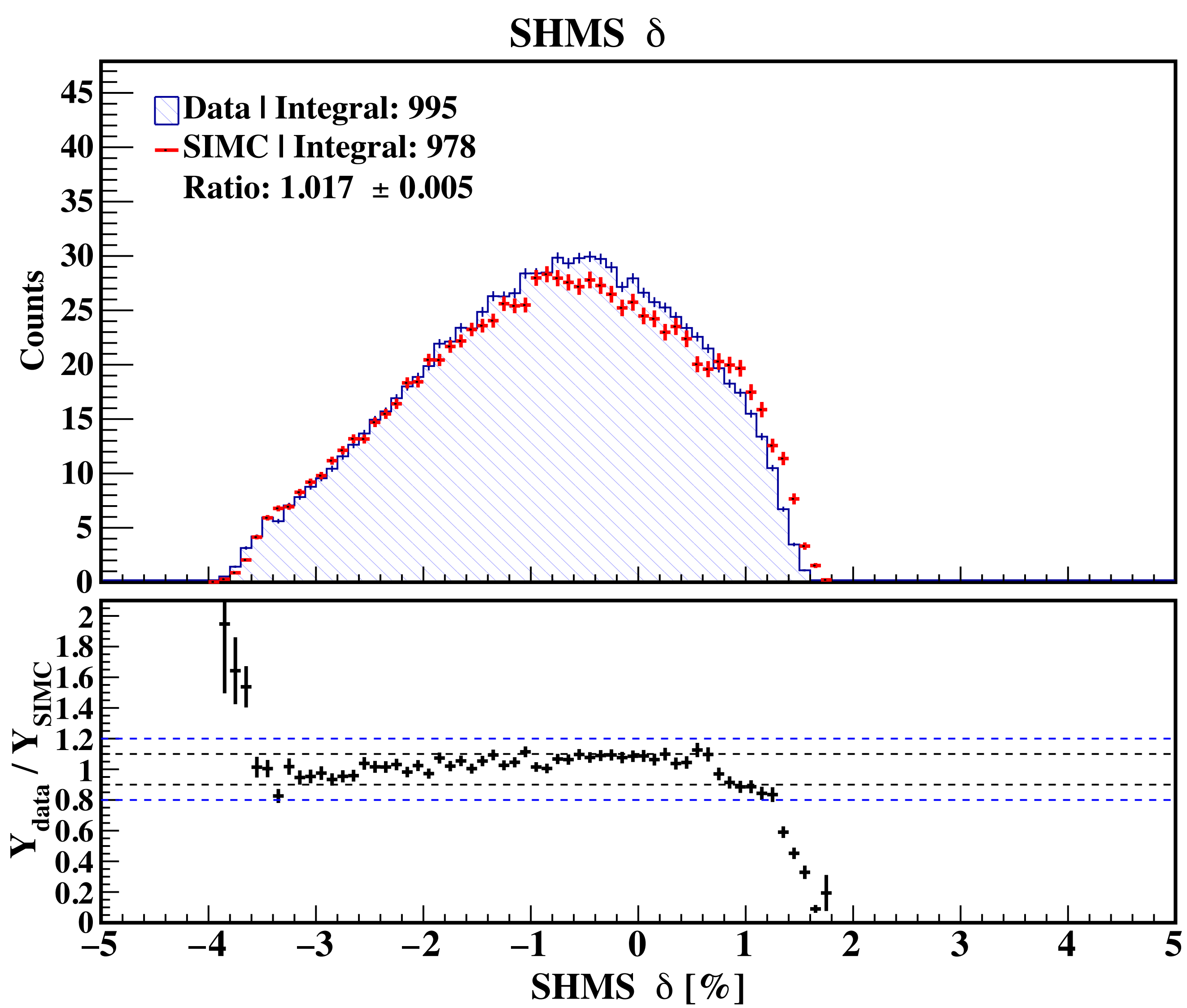


Spectrometer Acceptance
DATA/SIMULATION
(used H(e,e'p) Elastics data taken on D(e,e'p)n Experiment)

SHMS Reconstructed Variables

** Data is fully corrected for inefficiencies



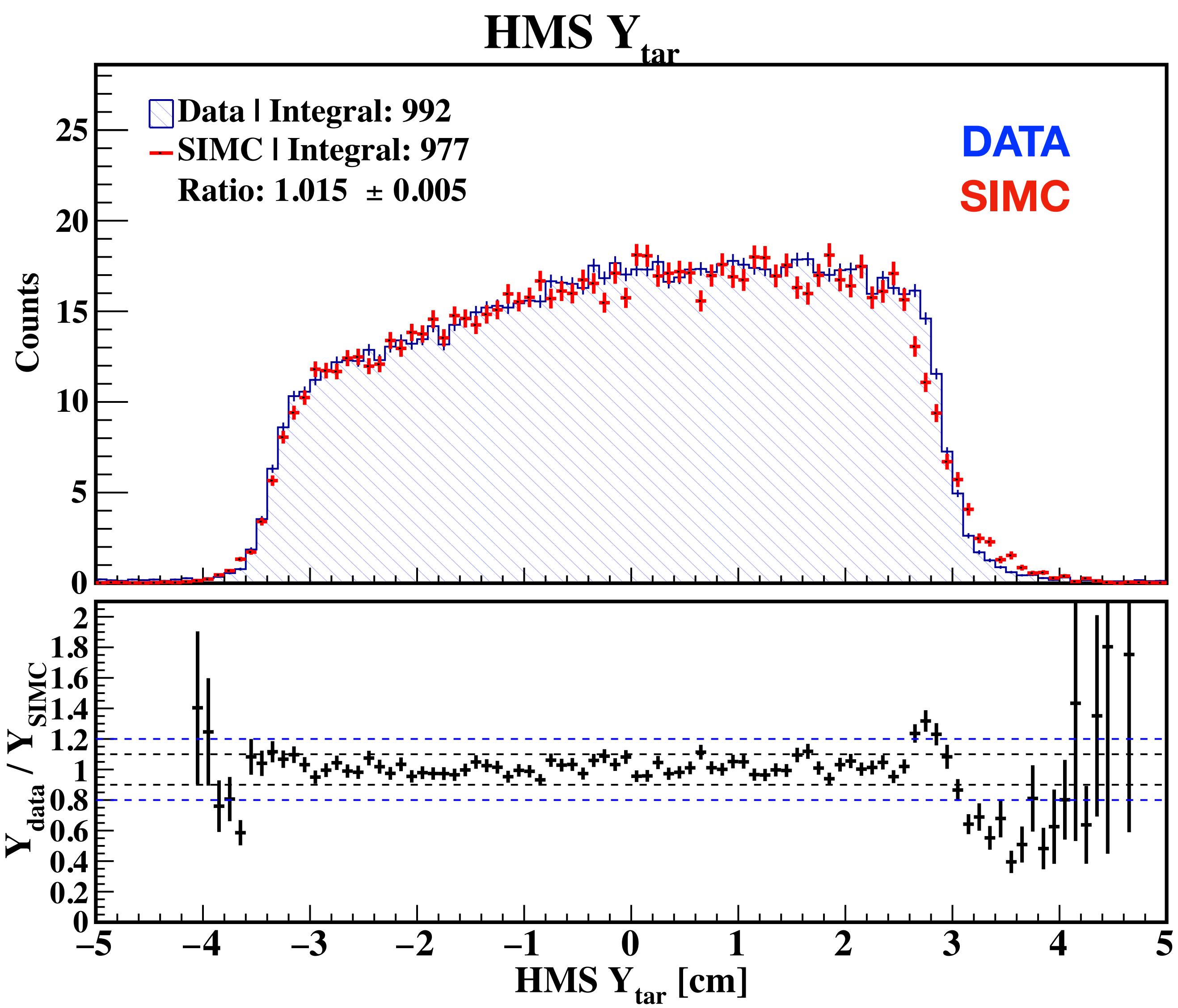


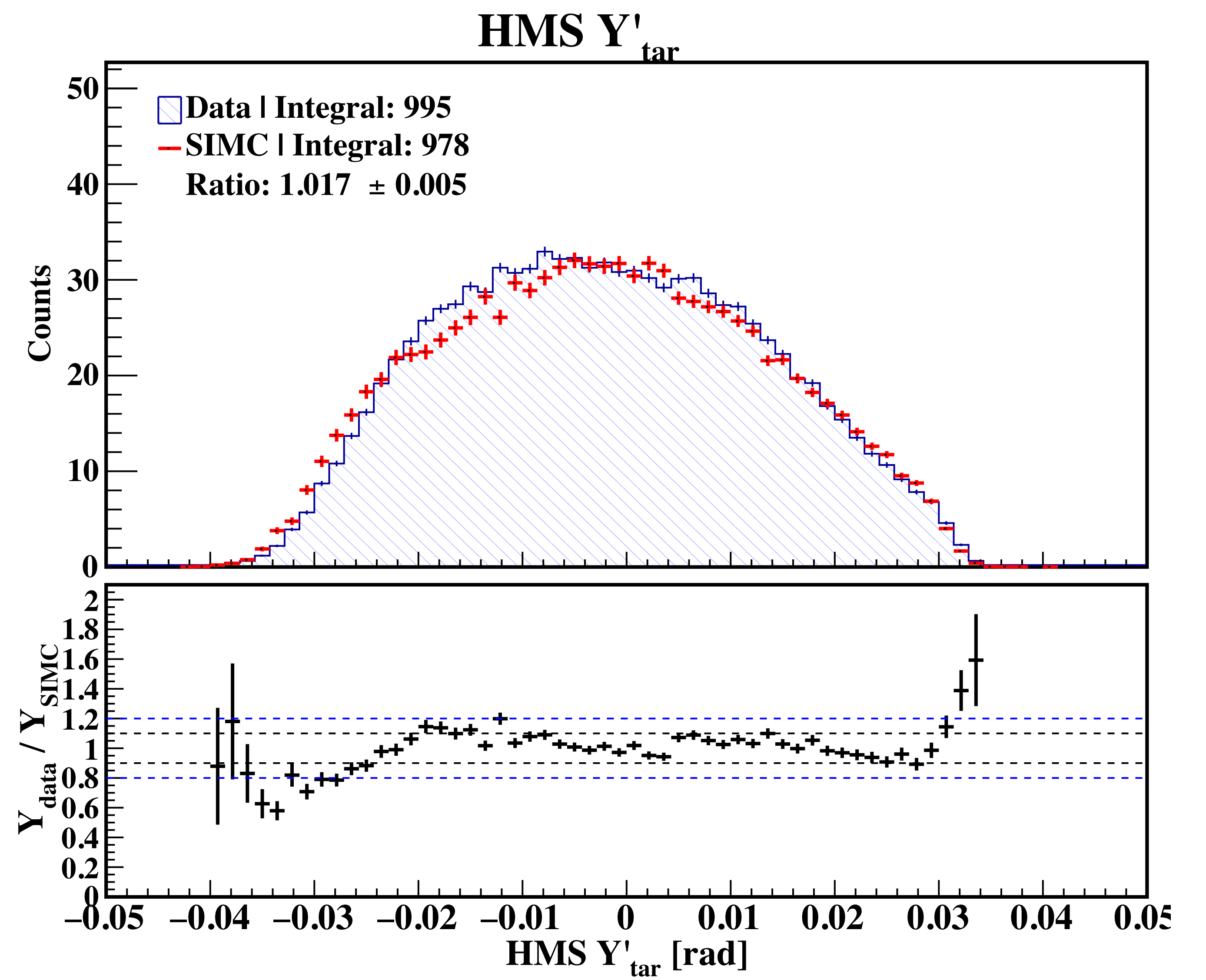
Spectrometer Acceptance
DATA/SIMULATION

(used H(e,e'p) Elastics data taken on D(e,e'p)n Experiment

HMS Reconstructed Variables

**** Data is fully corrected for inefficiencies**



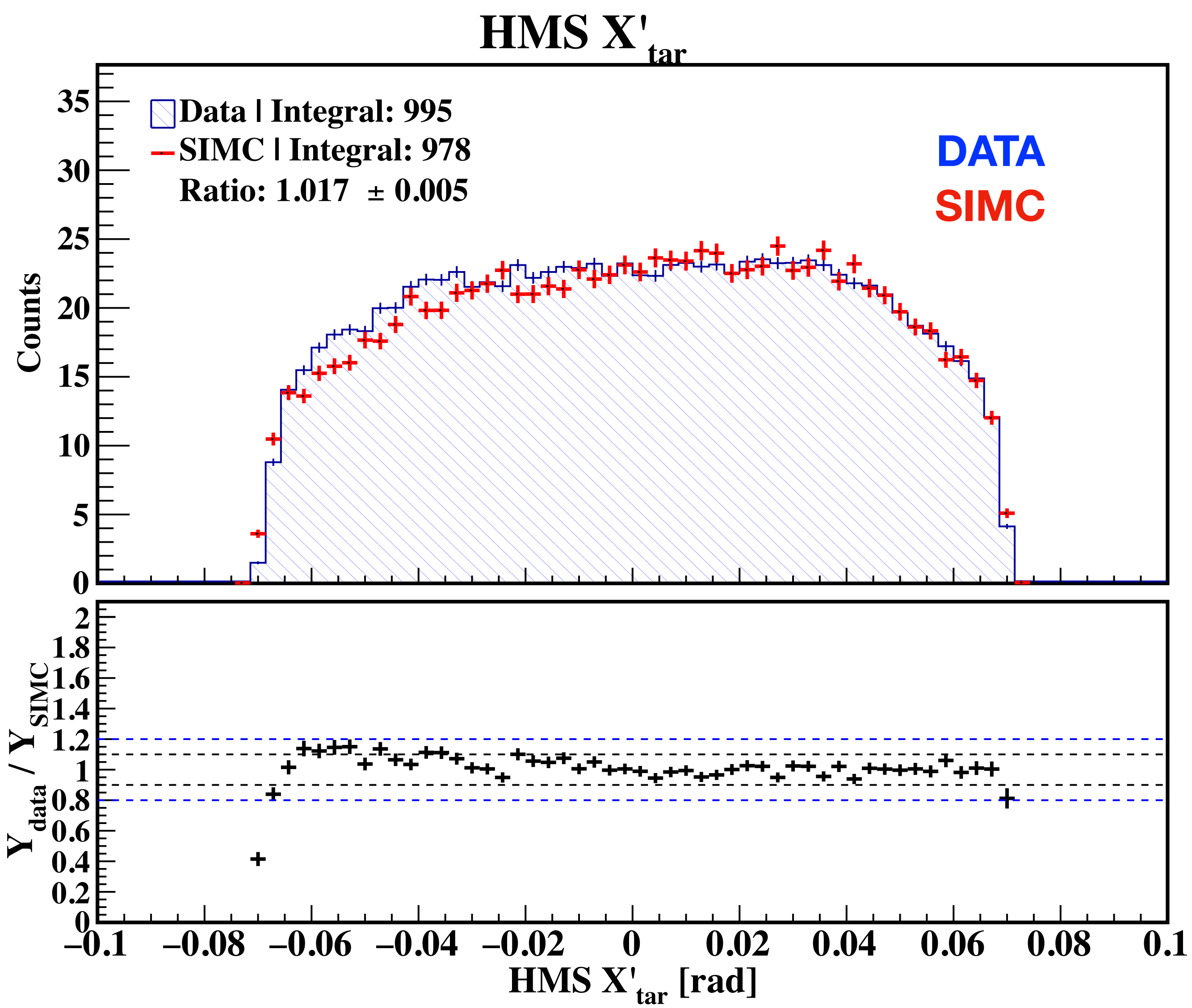


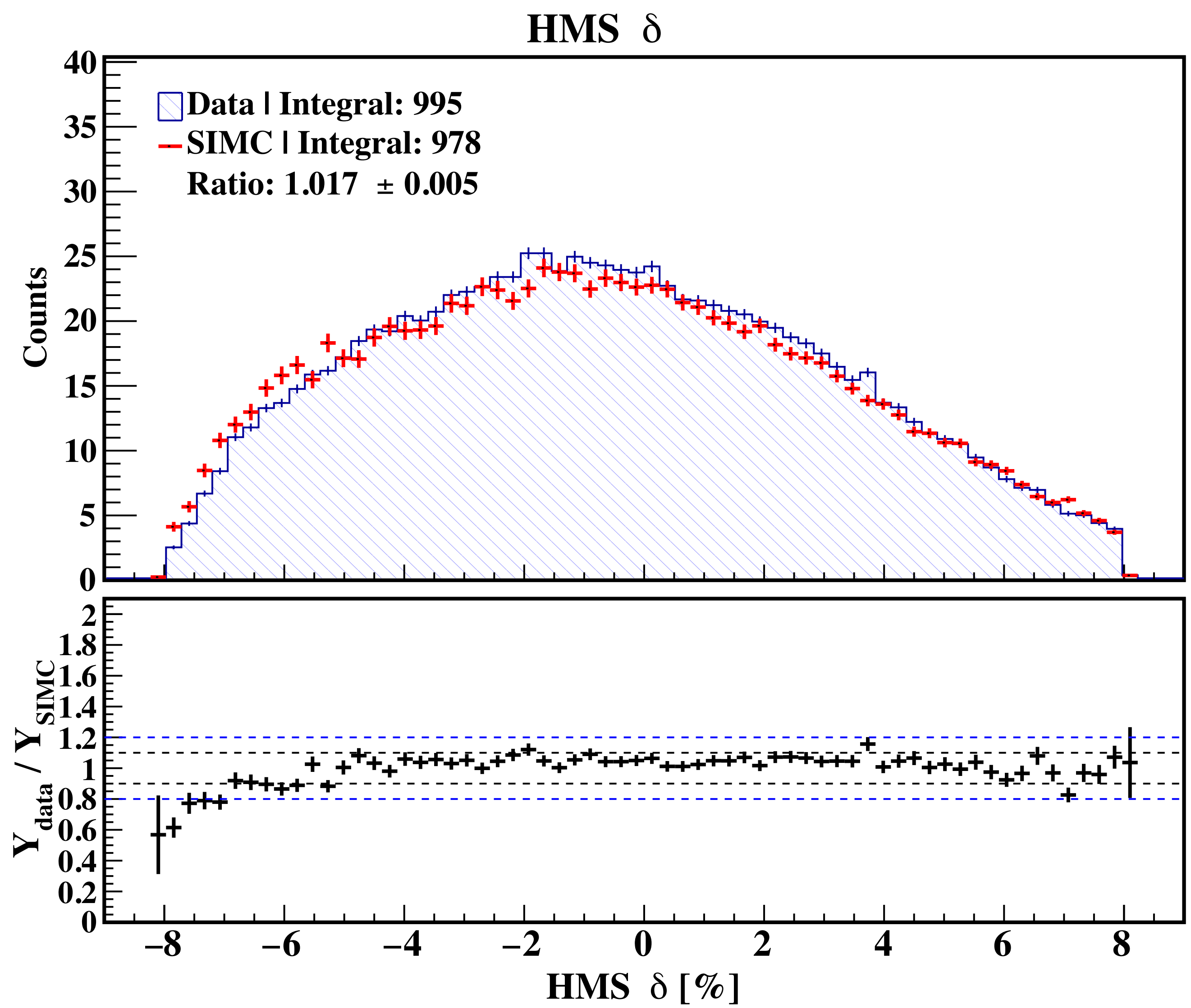
Spectrometer Acceptance
DATA/SIMULATION

(used H(e,e'p) Elastics data taken on D(e,e'p)n Experiment

HMS Reconstructed Variables

** Data is fully corrected for inefficiencies



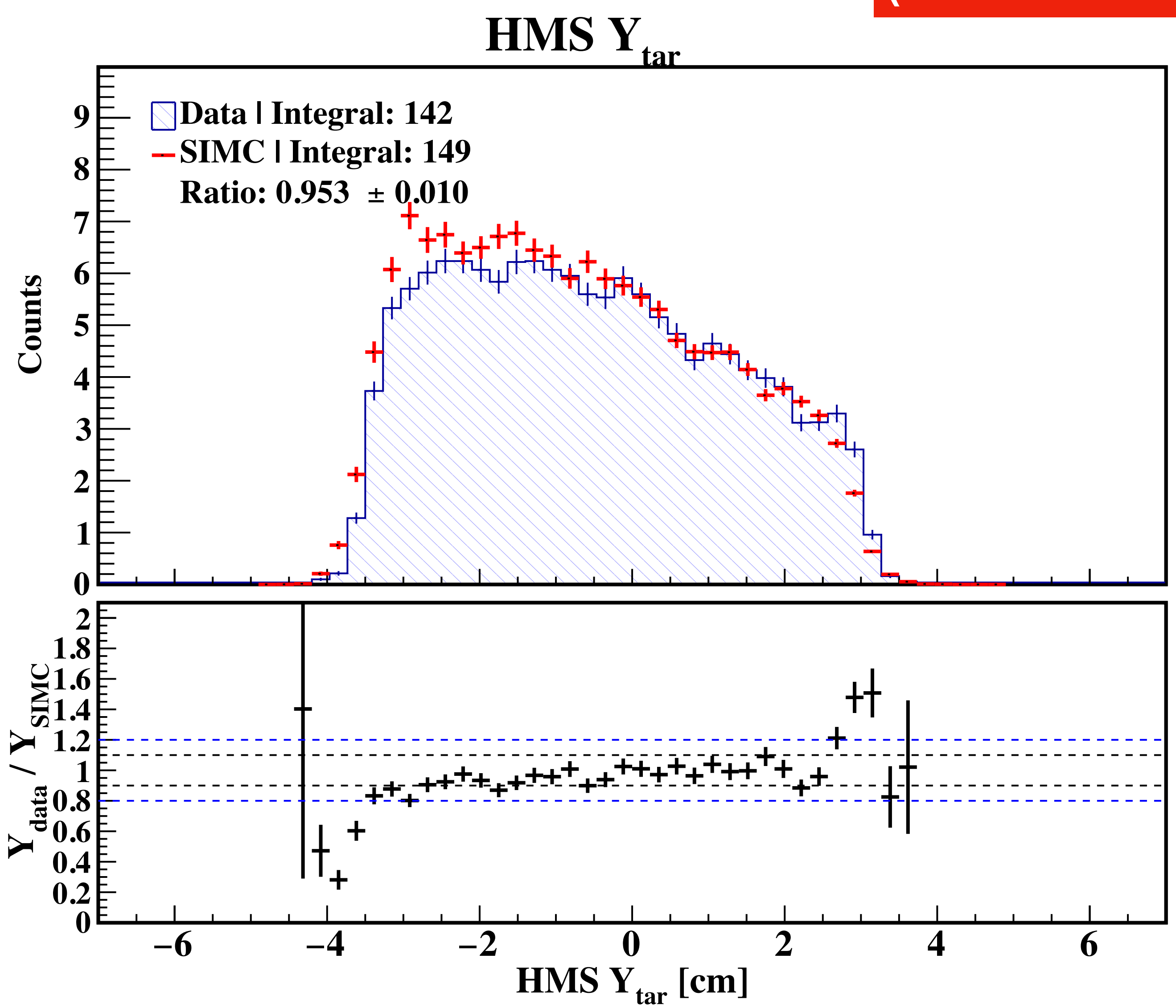


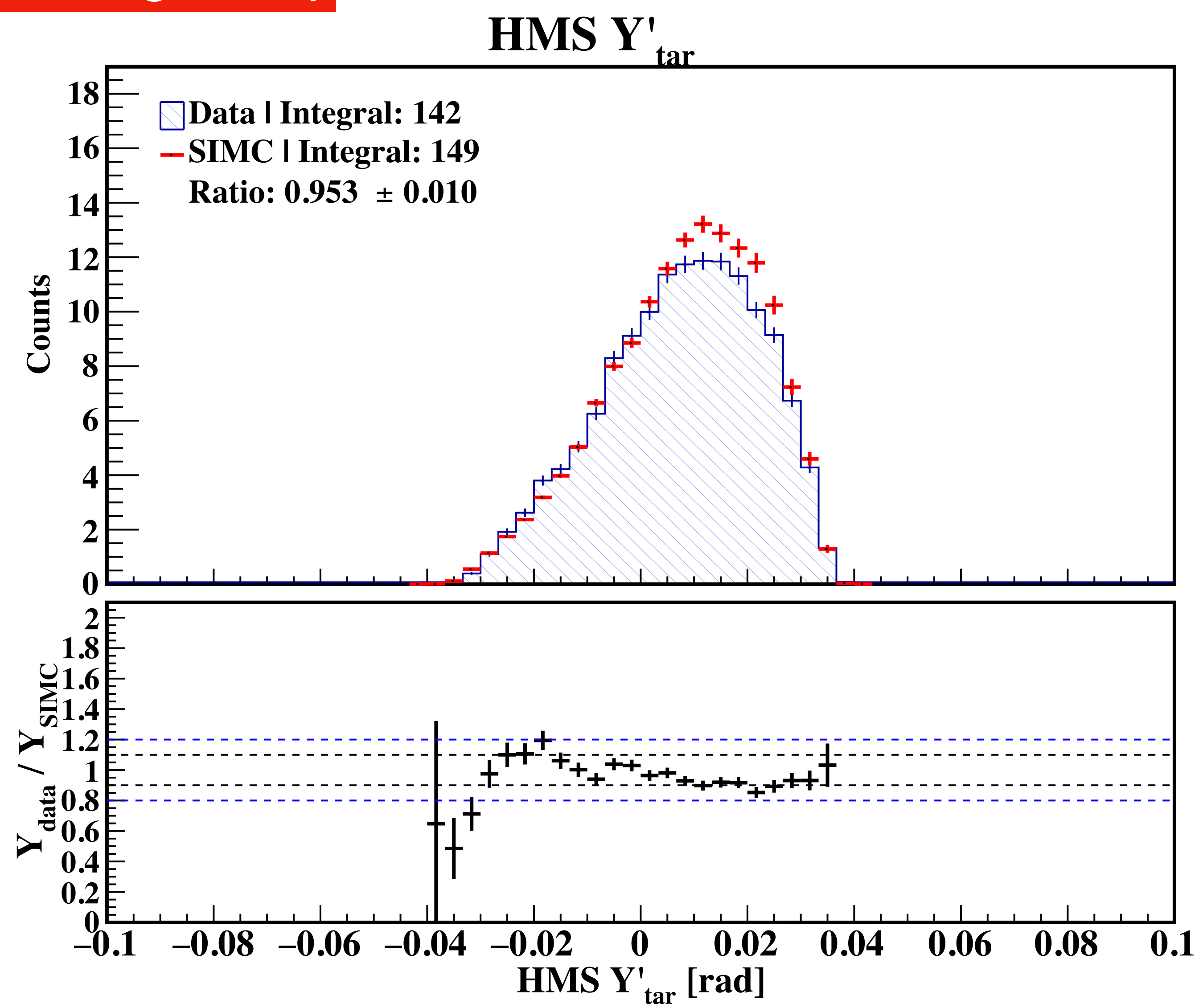
Spectrometer Acceptance
Checks on D(e,e’p)n using 80 MeV setting

HMS Reconstructed Variables

**** Data is fully corrected for inefficiencies**

(SIMC MODEL: Laget FSI)



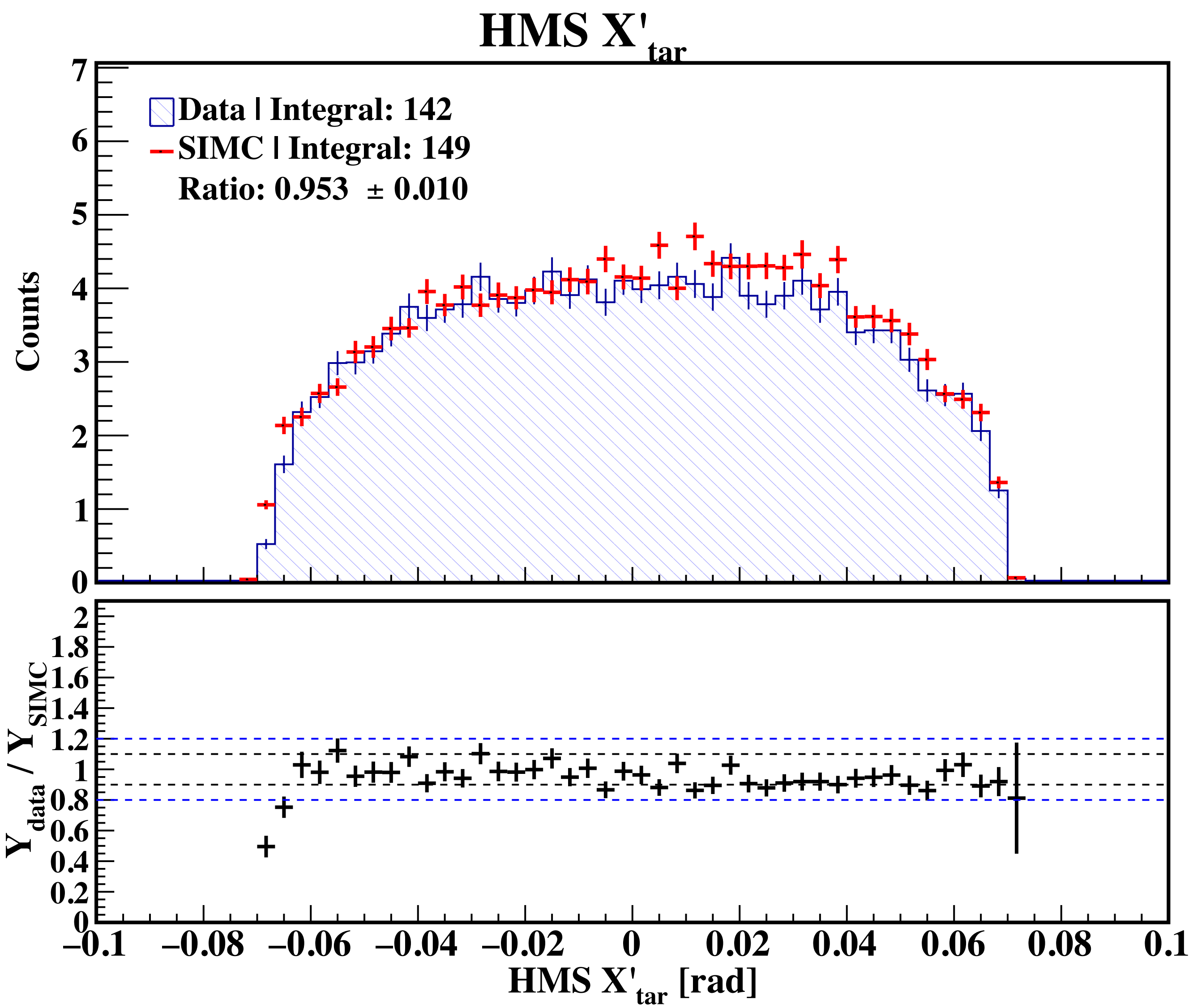


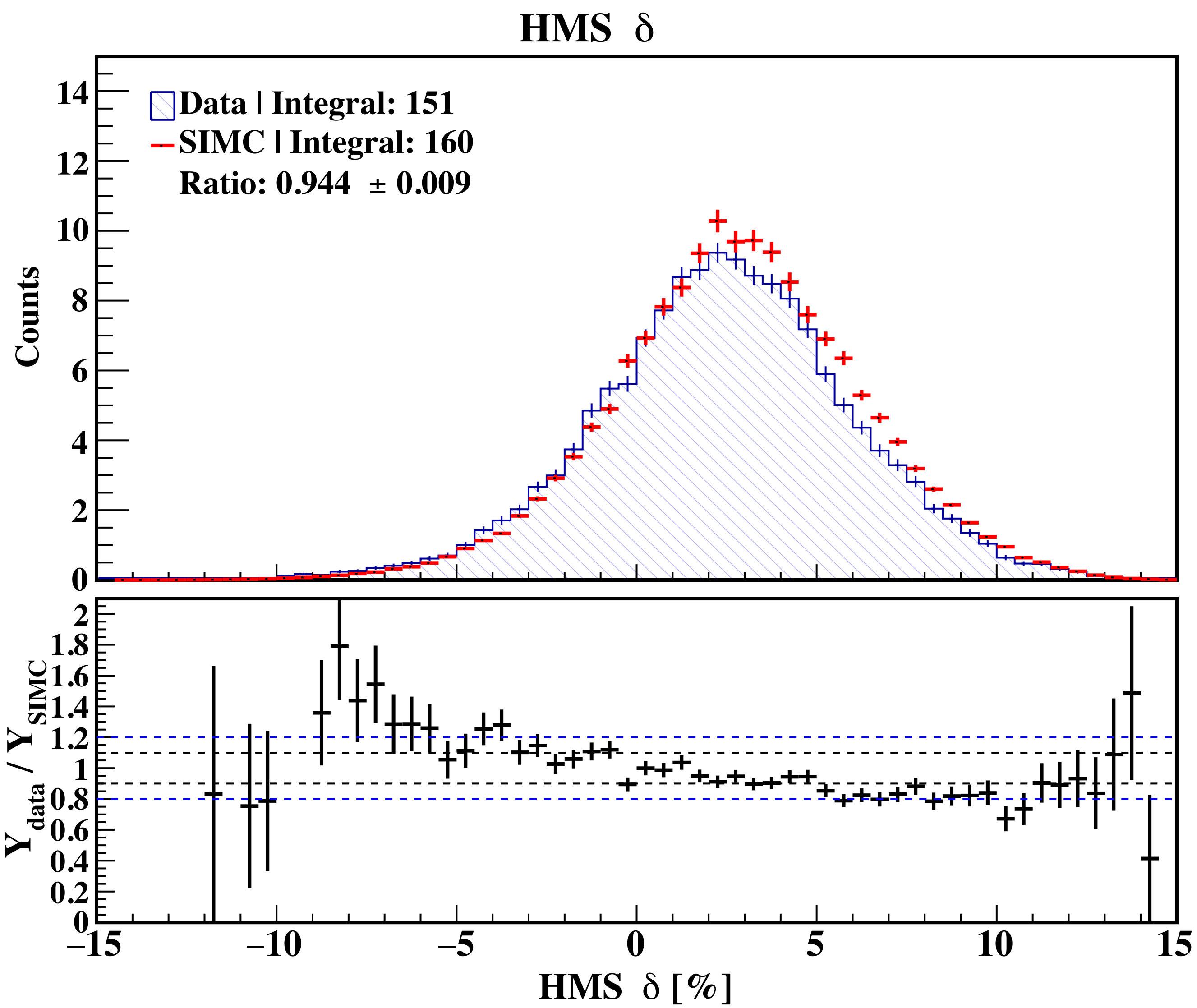
Spectrometer Acceptance
Checks on D(e,e'p)n using 80 MeV setting

HMS Reconstructed Variables

**** Data is fully corrected for inefficiencies**

(SIMC MODEL: Laget FSI)



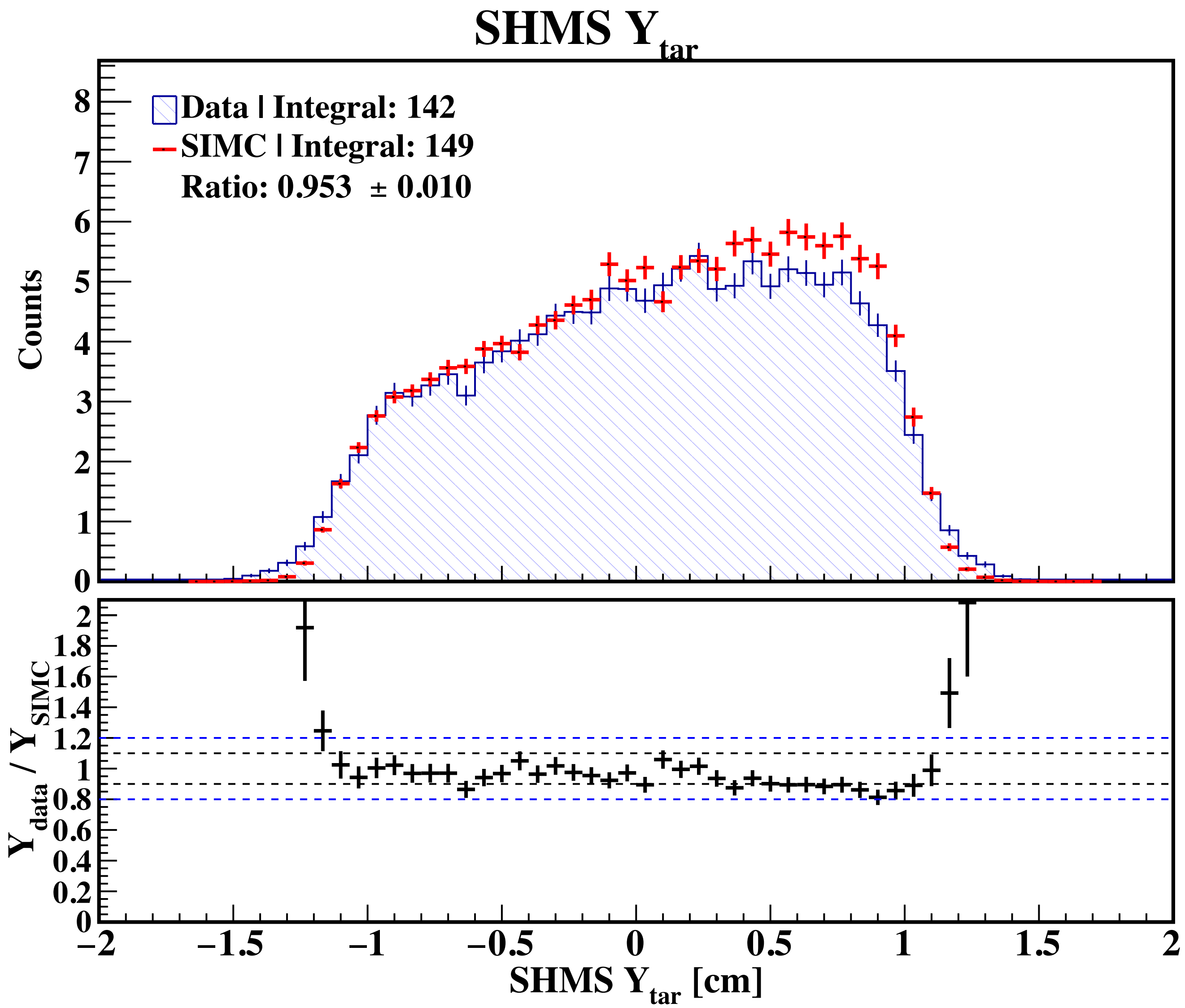


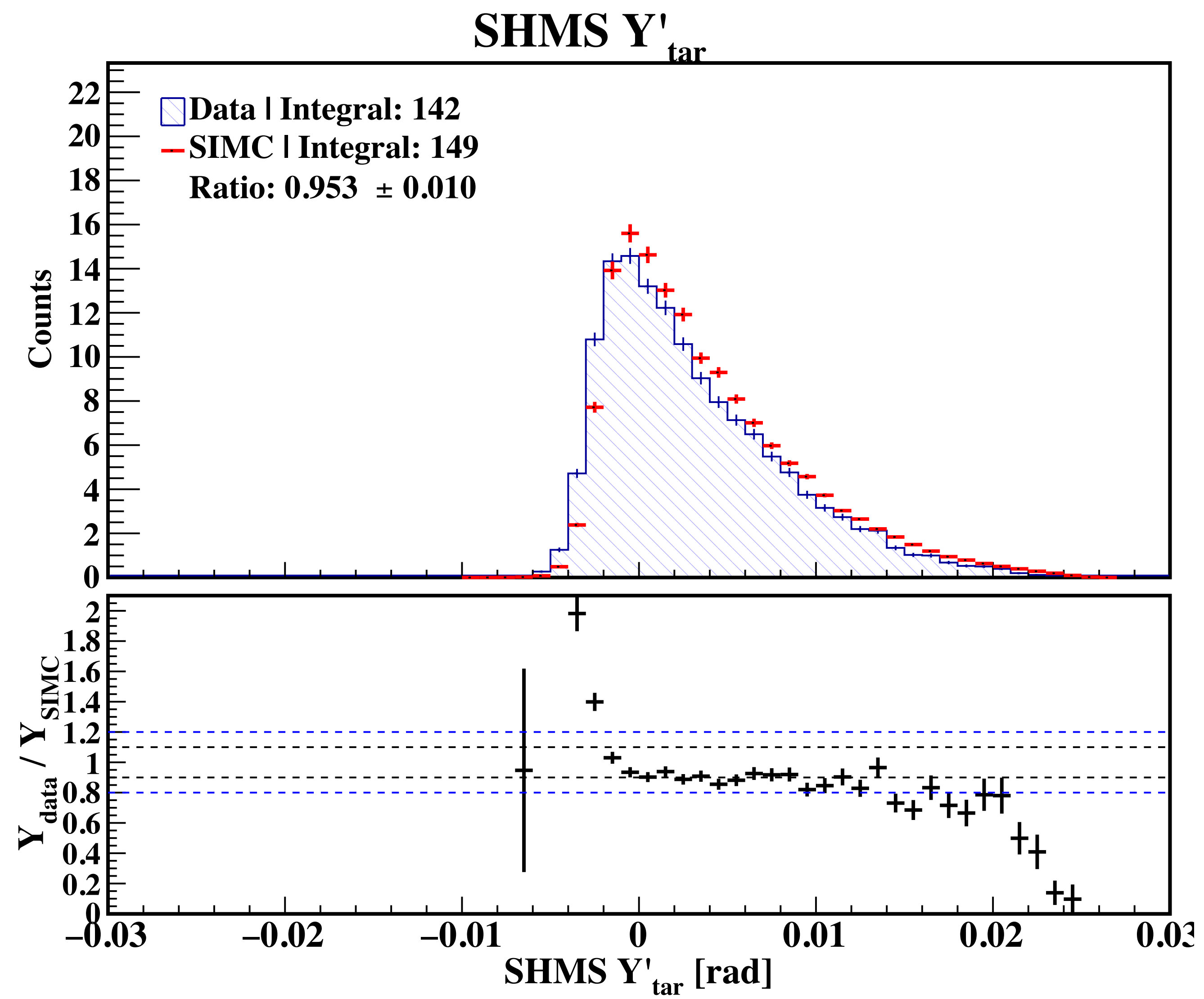
Spectrometer Acceptance
Checks on D(e,e’p)n using 80 MeV setting

SHMS Reconstructed Variables

** Data is fully corrected for inefficiencies

(SIMC MODEL: Laget FSI)



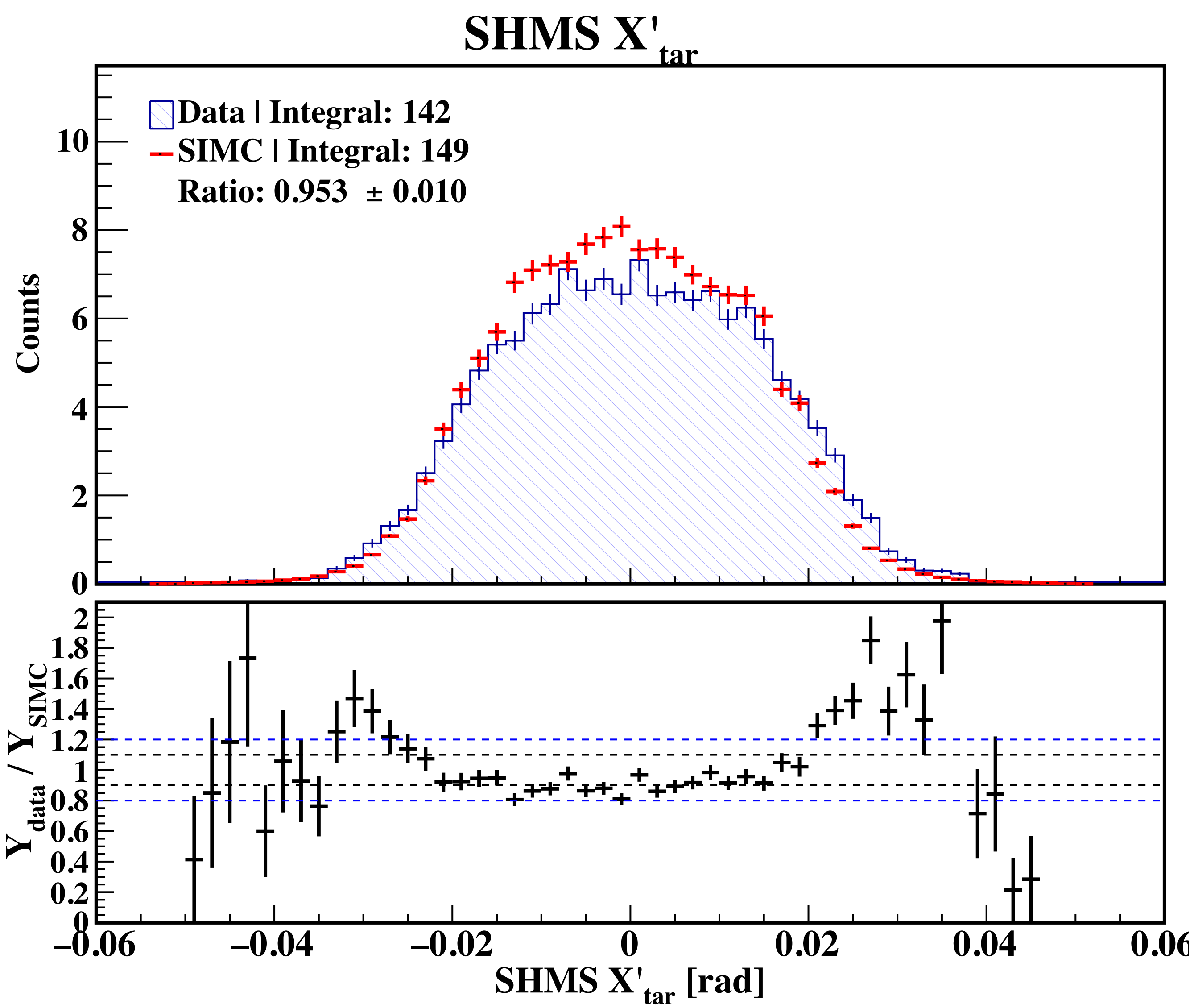


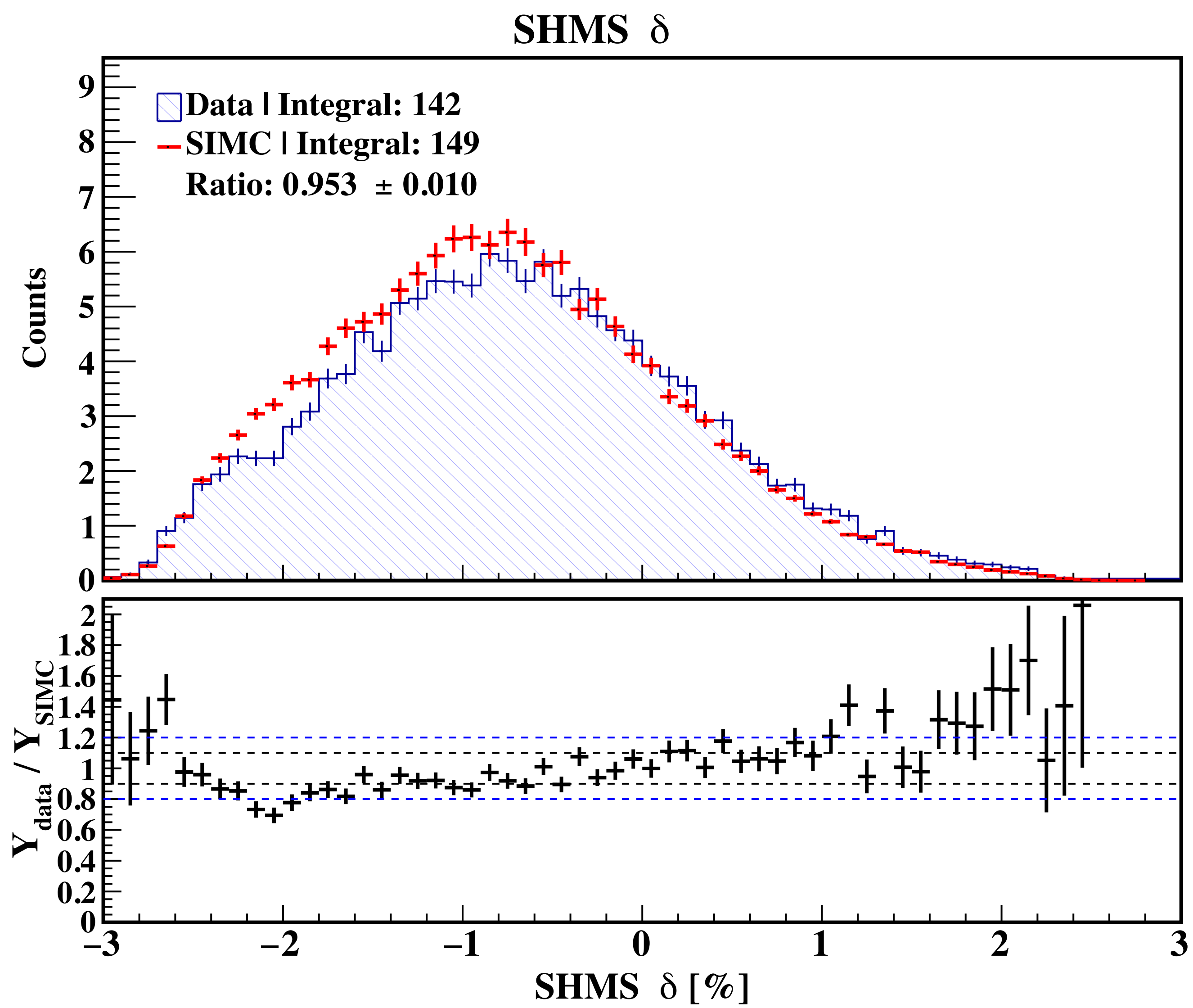
Spectrometer Acceptance
Checks on D(e,e'p)n using 80 MeV setting

SHMS Reconstructed Variables

** Data is fully corrected for inefficiencies

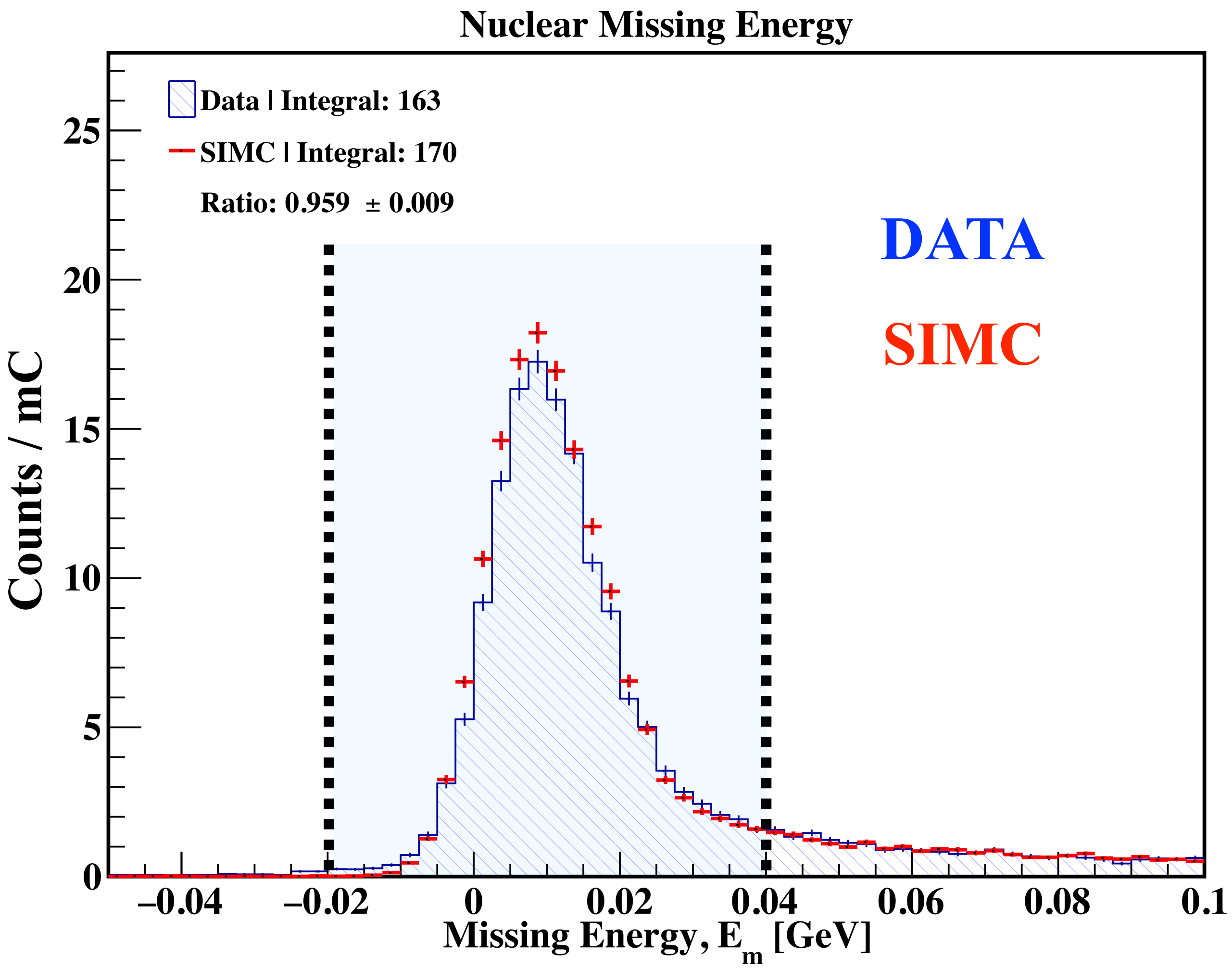
(SIMC MODEL: Laget FSI)





D(e,e'p)n
Data Analysis Cuts

(shown only for 80 MeV setting but are
also applied to high missing momentum data)



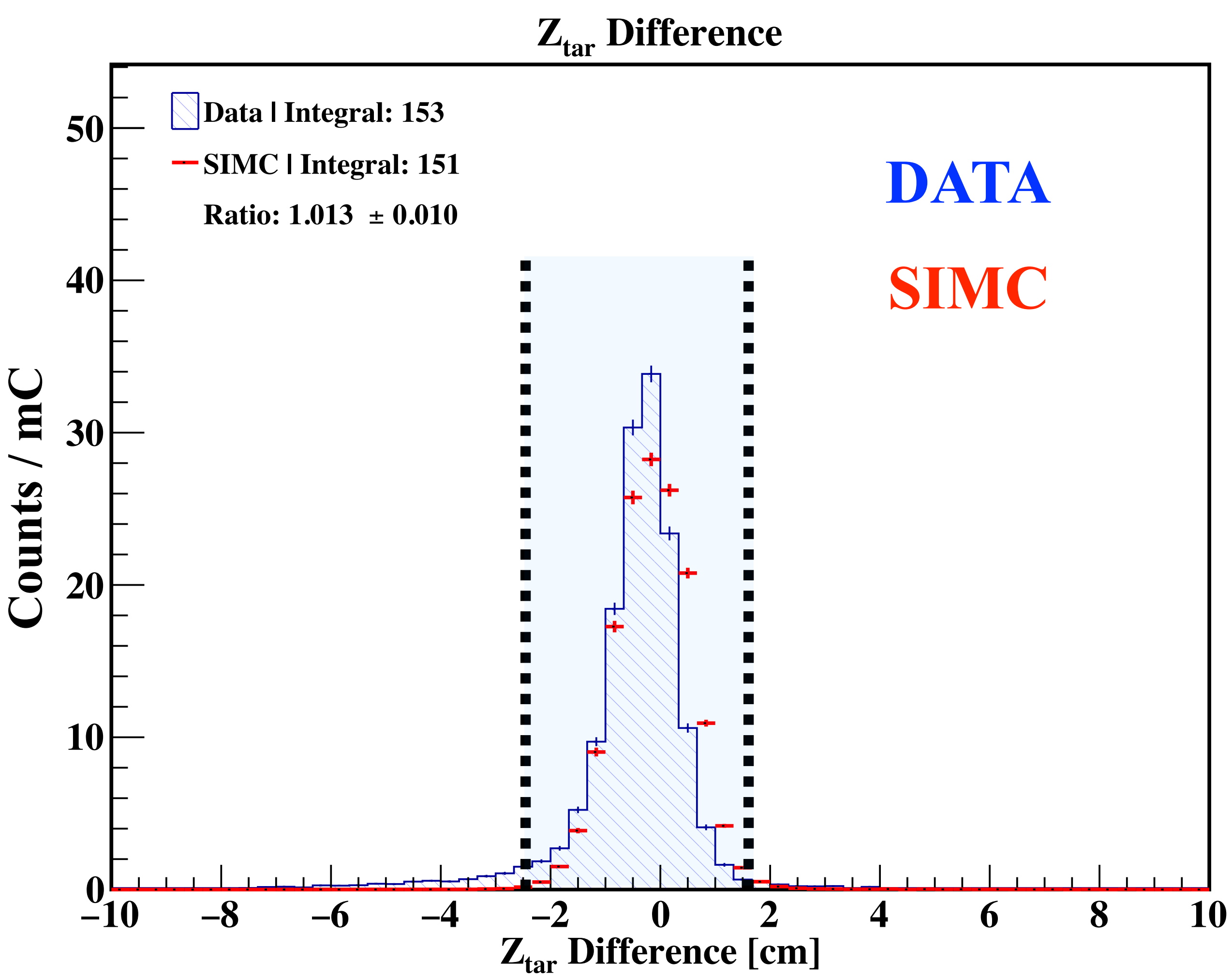
Missing Energy Cut: (-20, 40) MeV

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

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

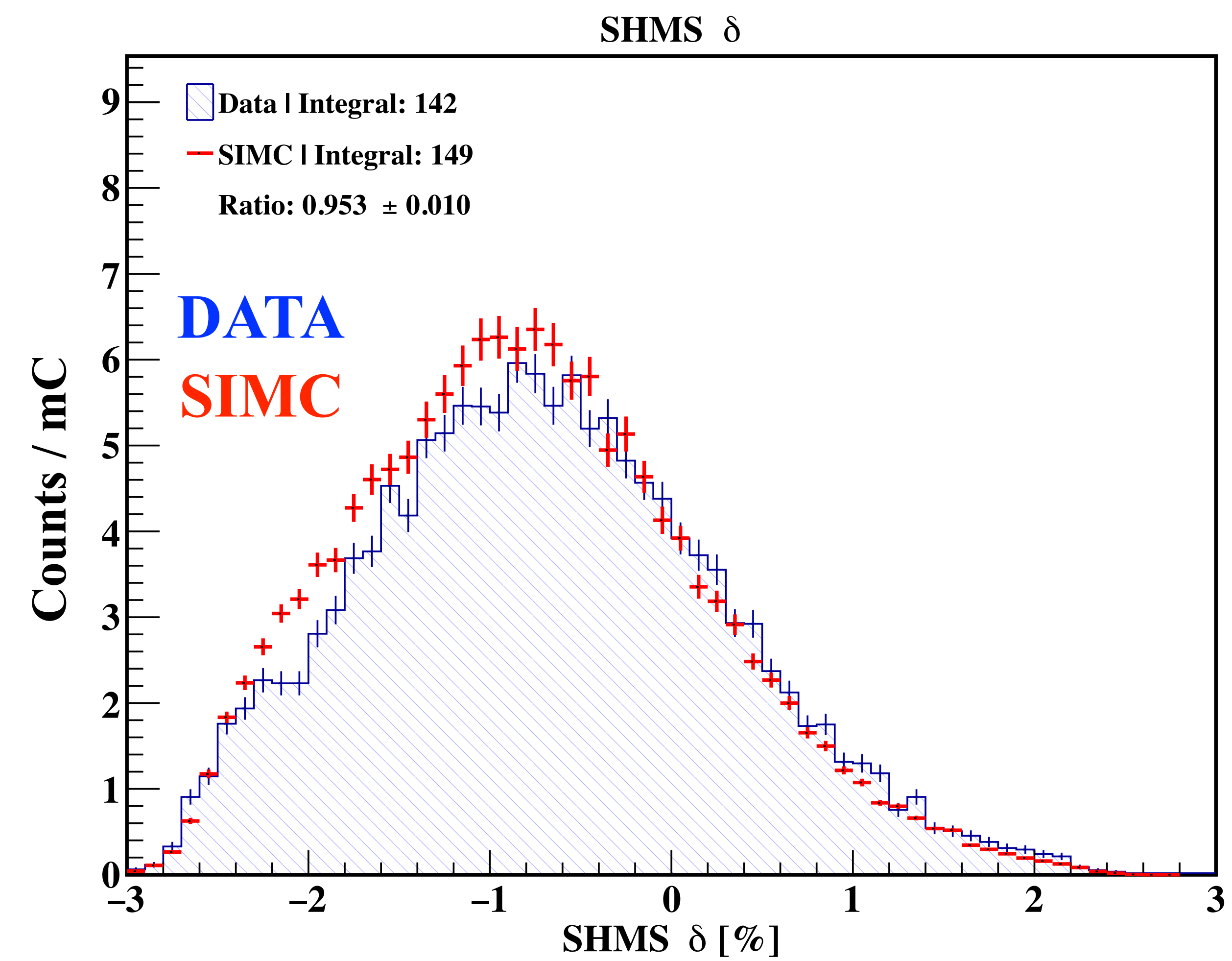
Missing energy is the B.E. of deuteron (~2.22 MeV)

Assume the mass of the neutron



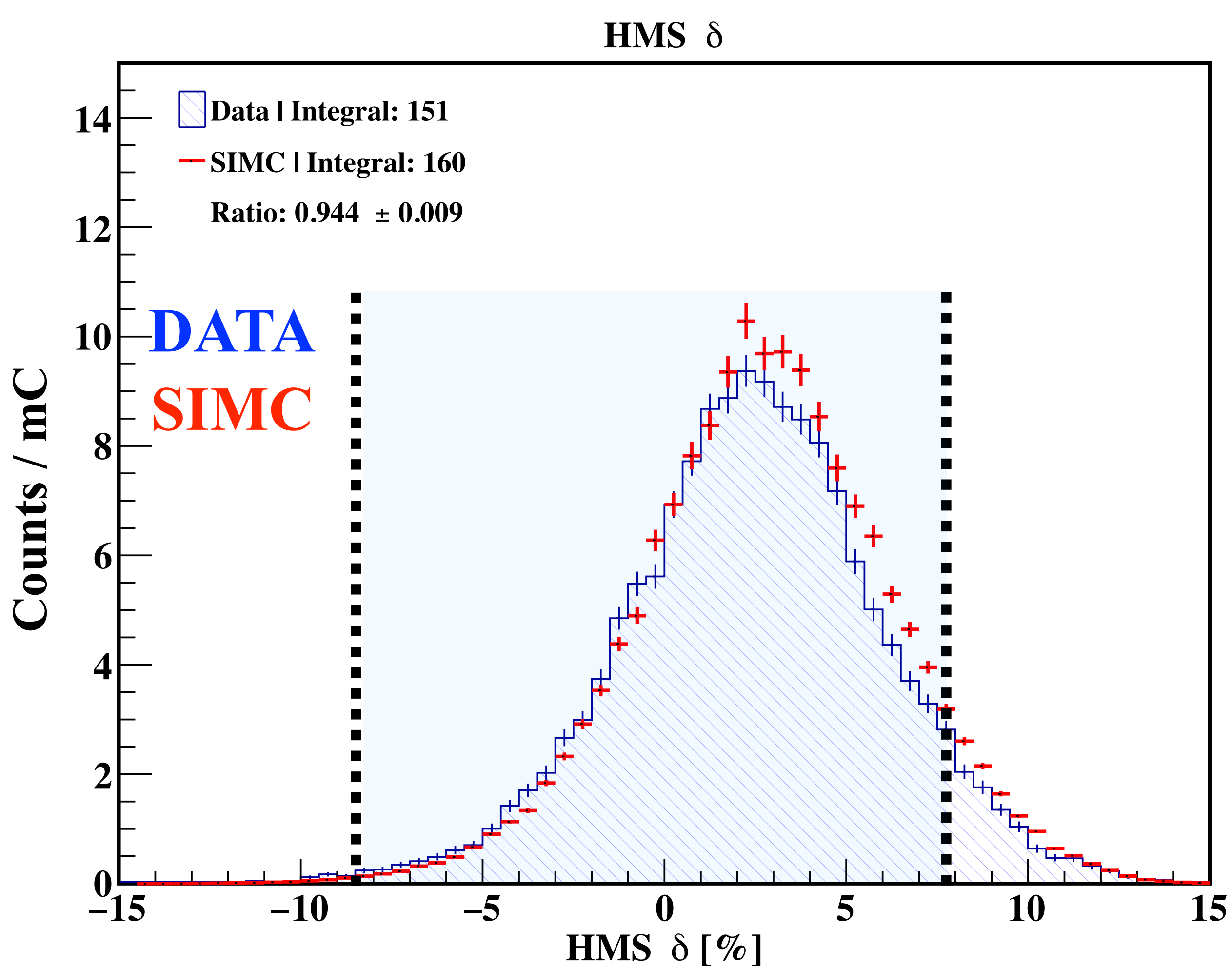
Reconstructed Z vertex difference Cut: +/- 2 cm relative the peak value

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



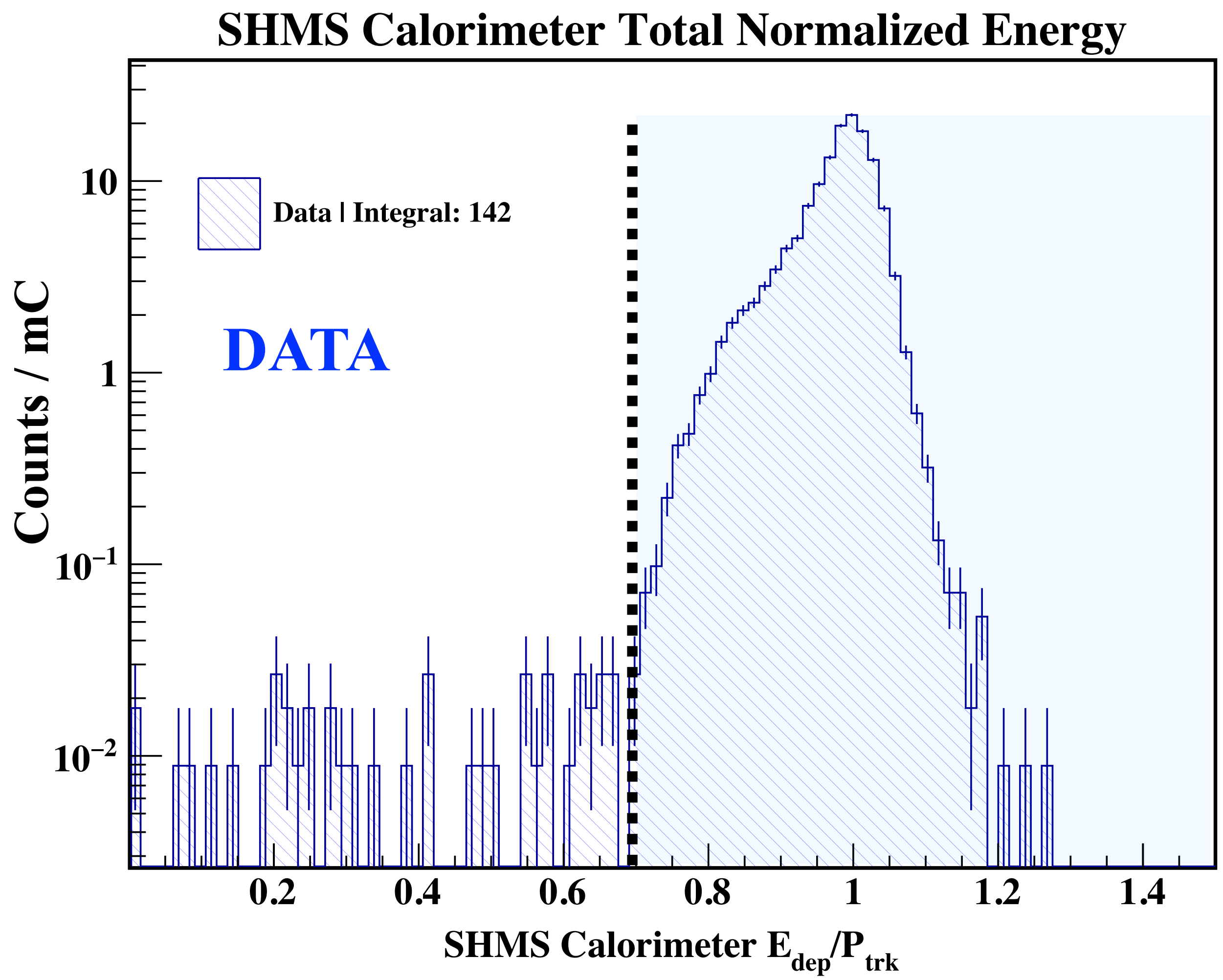
SHMS Delta Acceptance (-3, 3) %

SHMS Delta Acceptance is constrained by the HMS Acceptance to be in the range (-3, 3)%



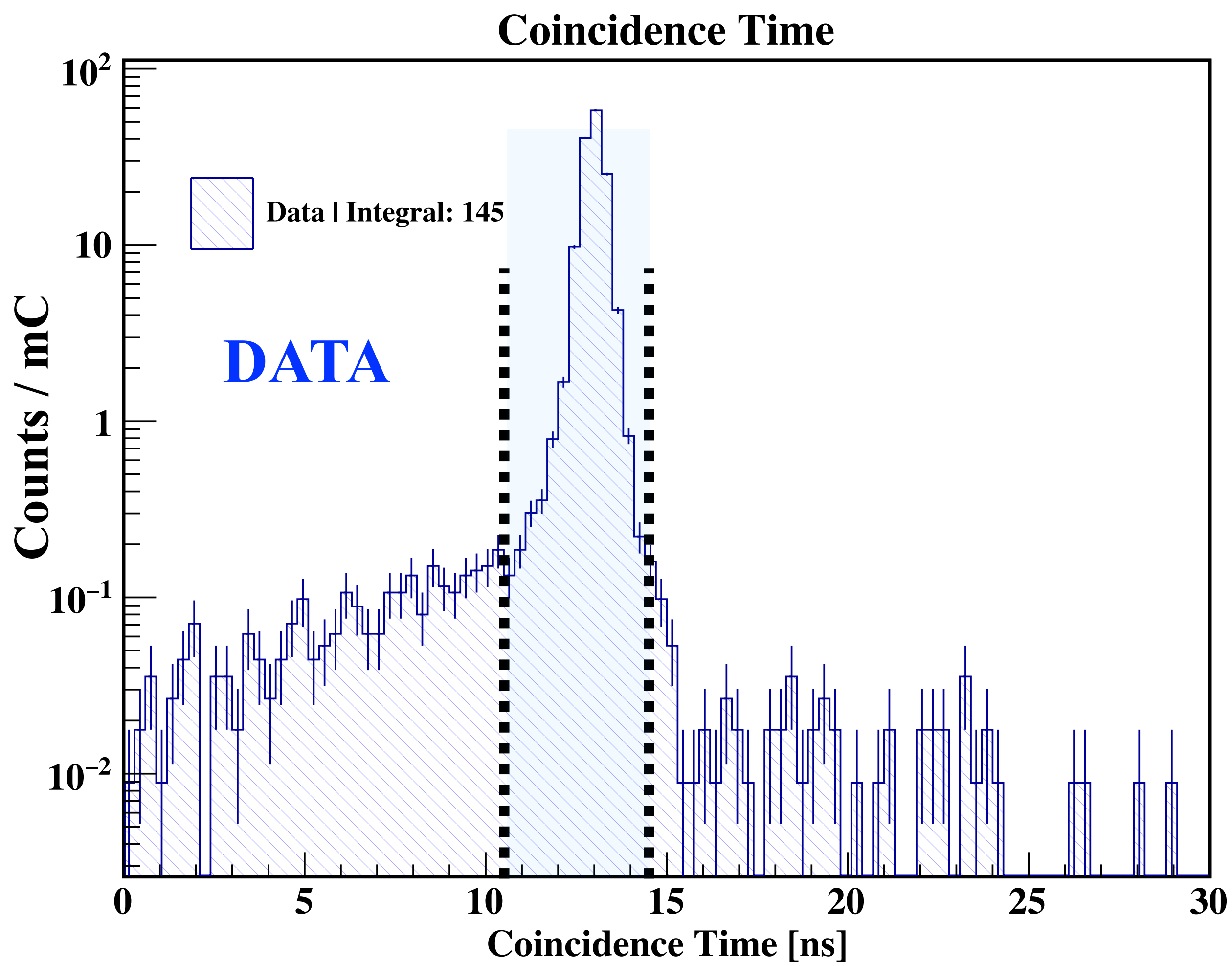
HMS Delta Acceptance Cut: (-8, 8) %

Select HMS acceptance region where Optics Reconstruction is reliable



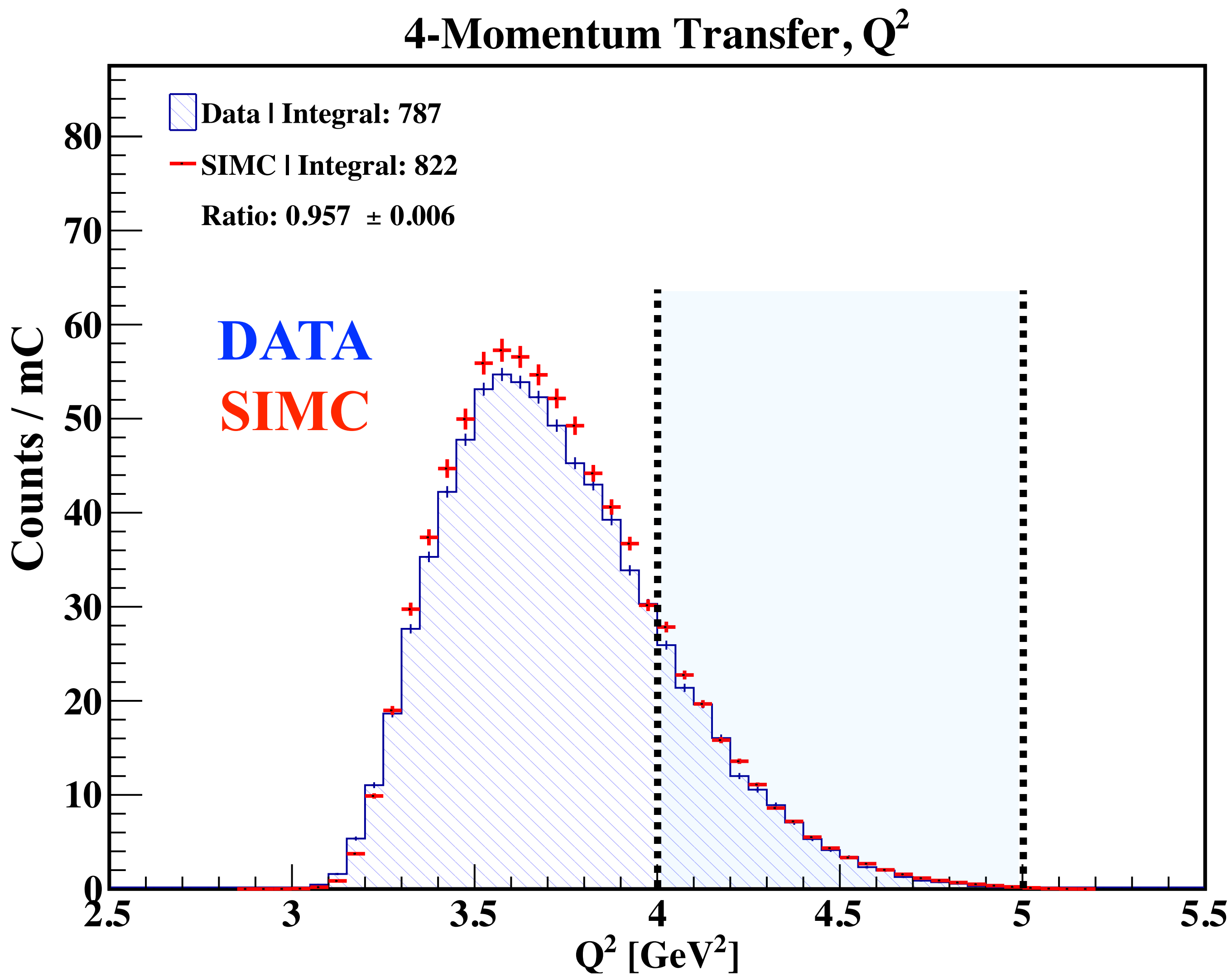
SHMS: Total energy deposited in Calorimeter normalized by the best track
CUT: > 0.7

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



Coincidence Time Cut
CUT: (10.5, 14.5) ns

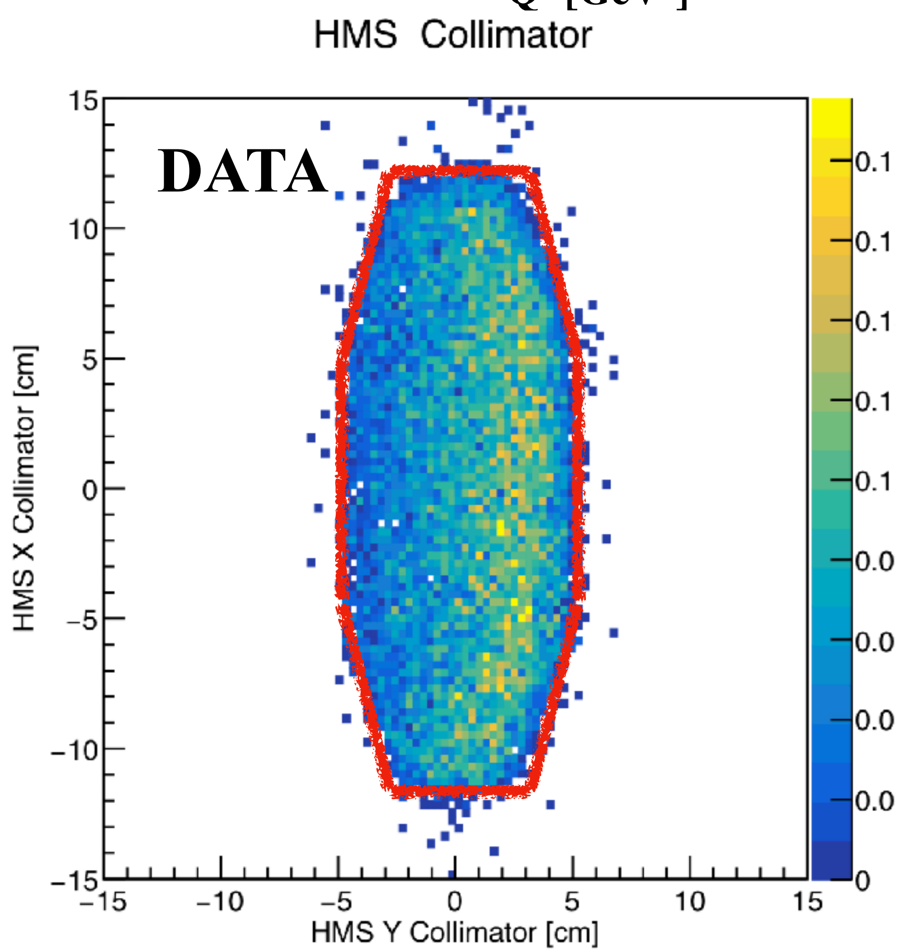
select true electron-proton coincidences



4-Momentum Transfer Cut

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

Kinematics cut to select only events with high momentum transfer (as stated on the proposal)



HMS Collimator Cut (Geometrical cut on collimator dimensions)

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

Extraction of the D(e,e'p)n Cross Section

Efficiencies and Correction Factors Determination

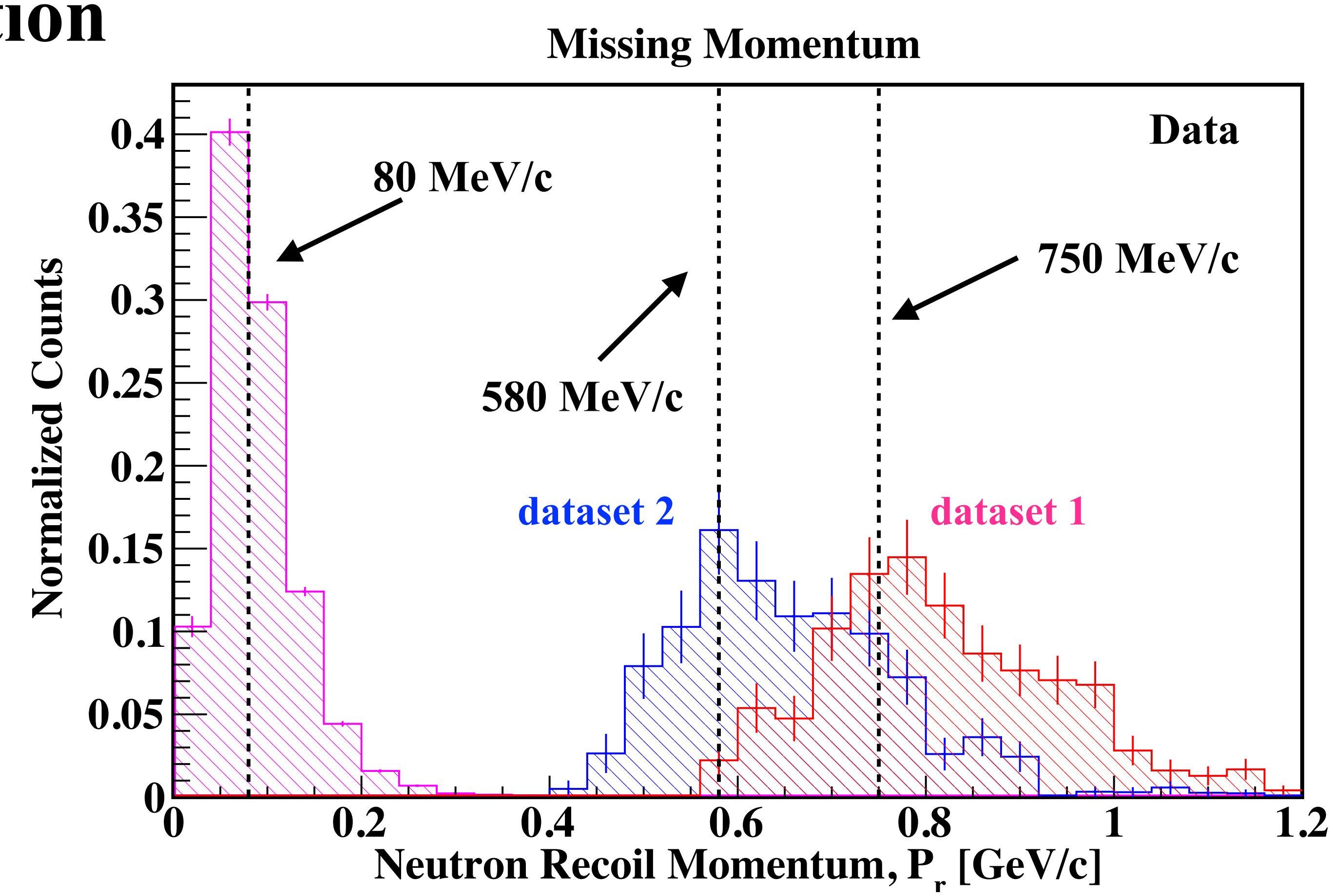
$$Y^{corr}_{data} = \frac{Y^{uncorr}_{data} \cdot f_{rad} \cdot f_{bc}}{Q \cdot \epsilon_{tLT} \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{tgtBoil} \cdot \epsilon_{pAbs}}$$

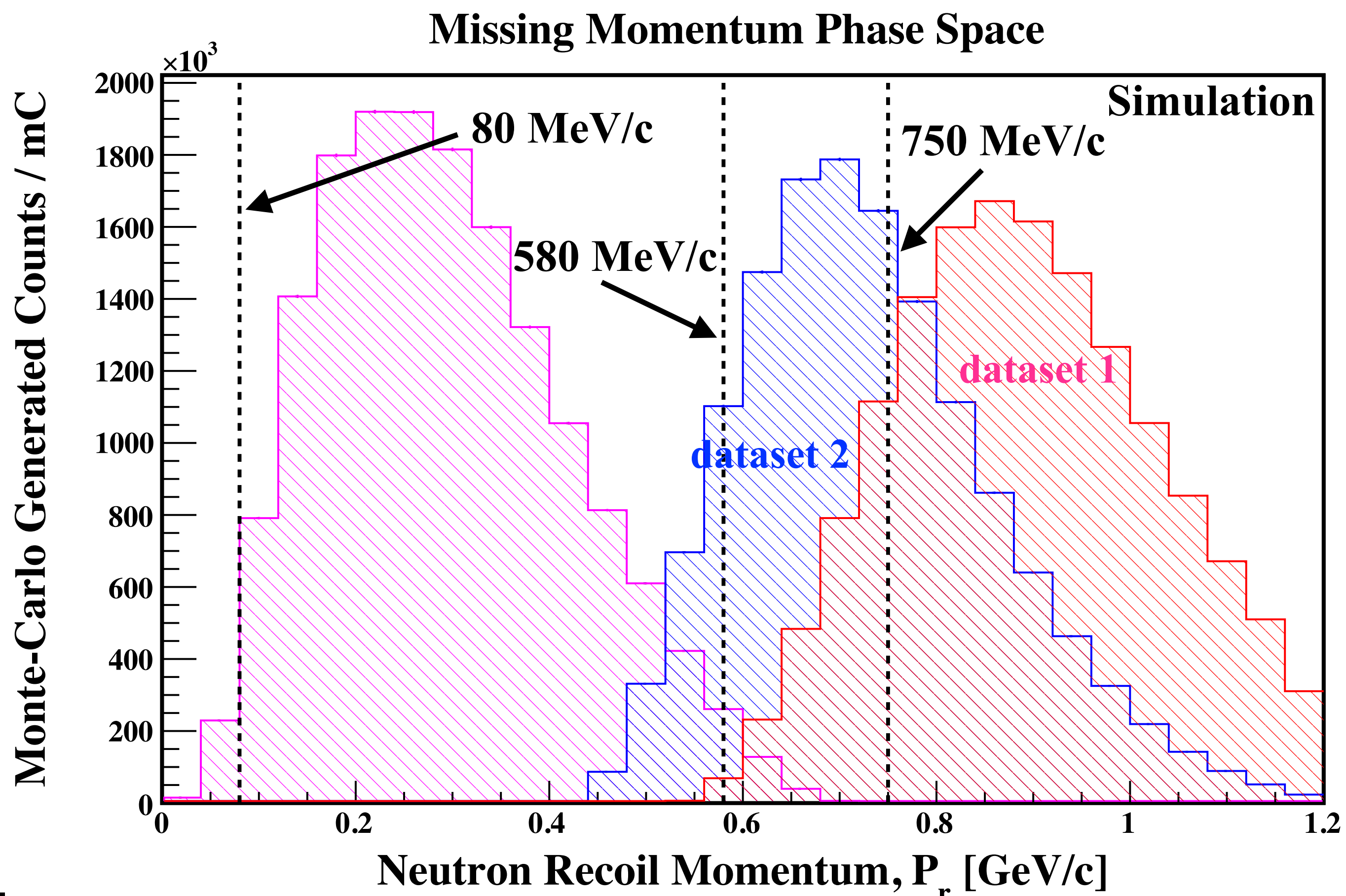
Extraction of the D(e,e'p)n Cross Section

Corrected Data Yield

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

Phase Space Volume

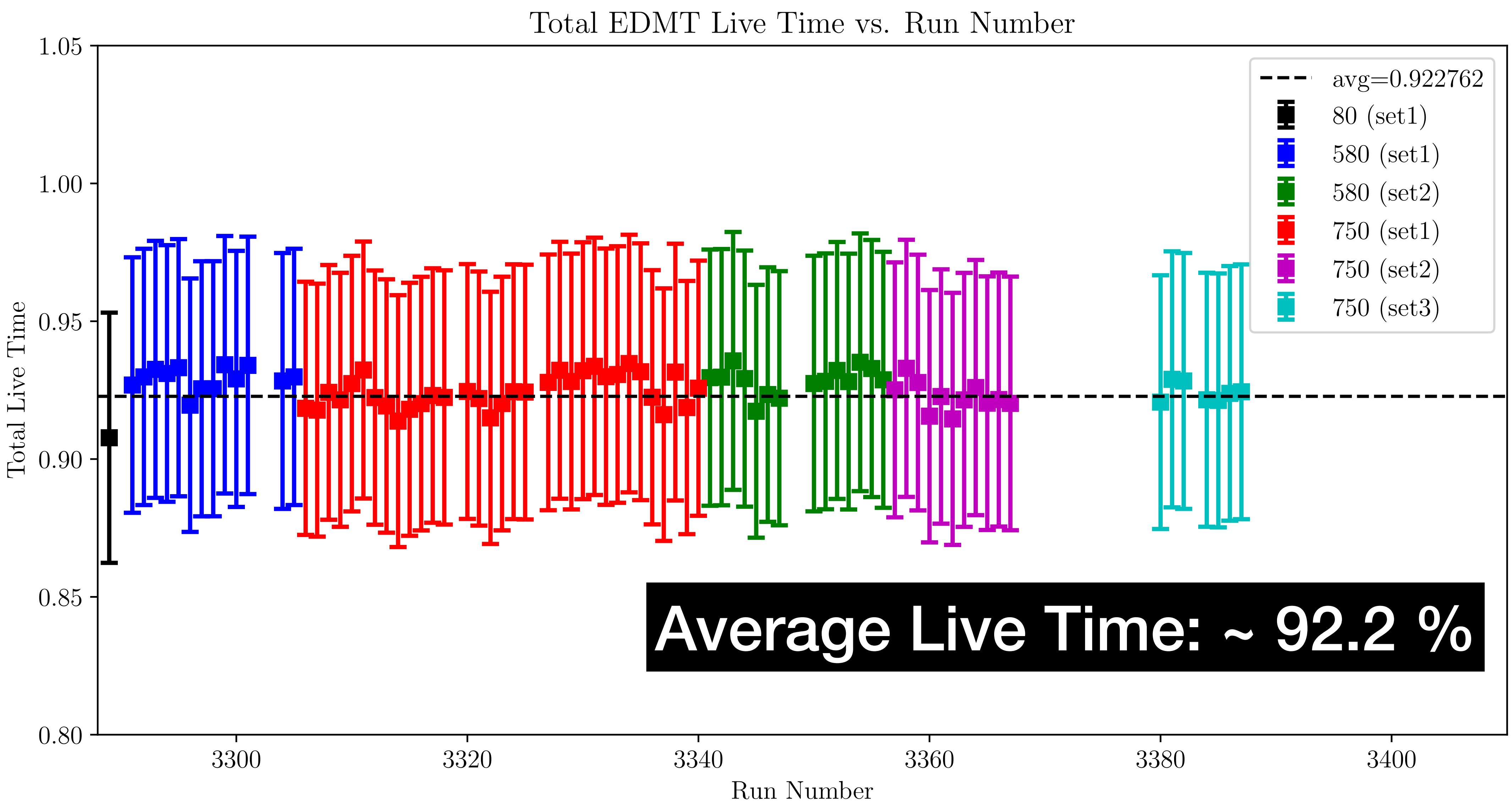




$$Y_{data}^{corr} = \frac{Y_{data}^{uncorr} \cdot f_{rad}}{Q \cdot \epsilon_{tLT} \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{tgtBoil} \cdot \epsilon_{pAbs}}$$

Correct for total Data Acquisition (DAQ) dead time

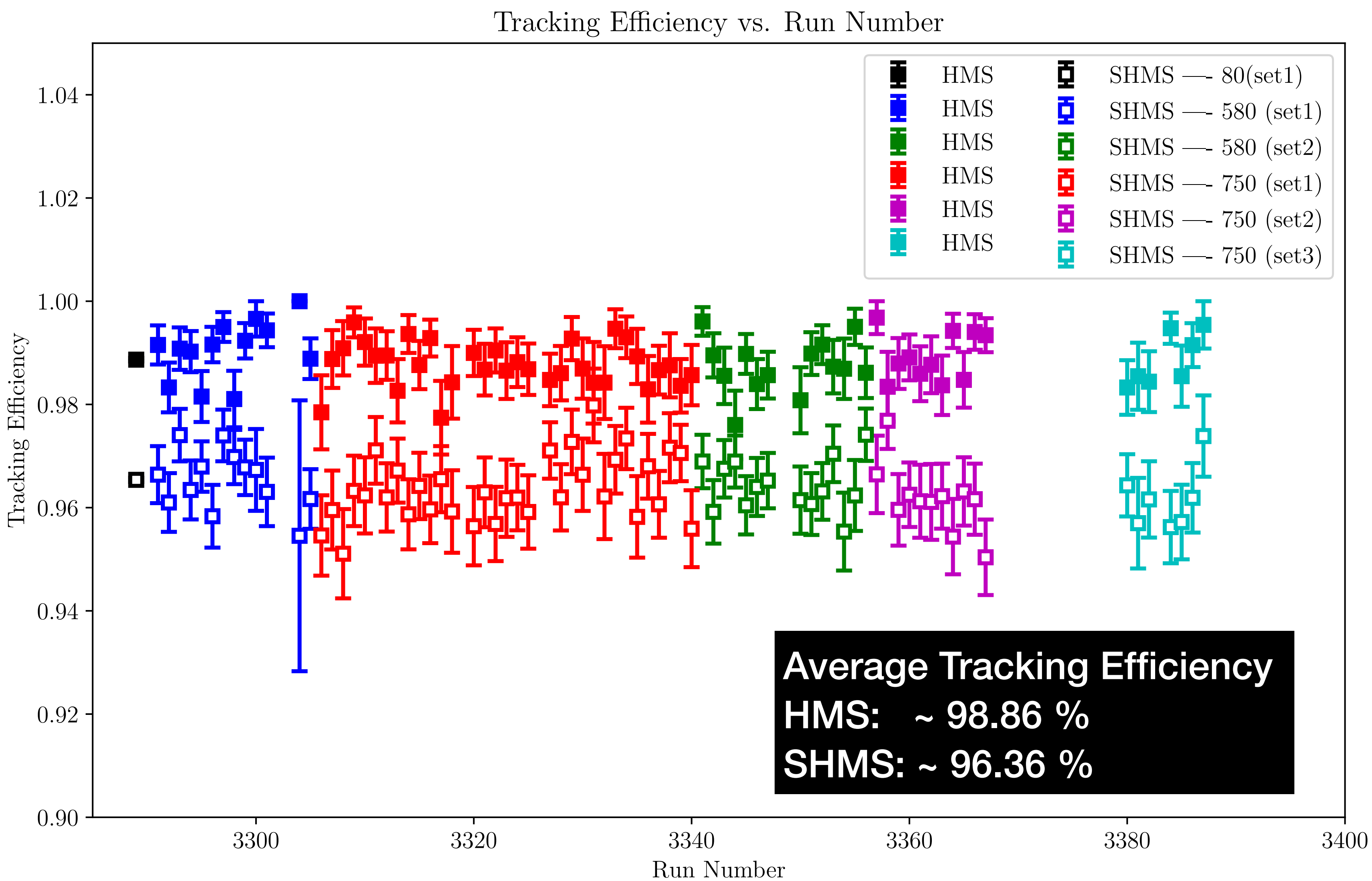
- **Time that the DAQ is unable to register/process triggers results in event loss which must be accounted for**



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

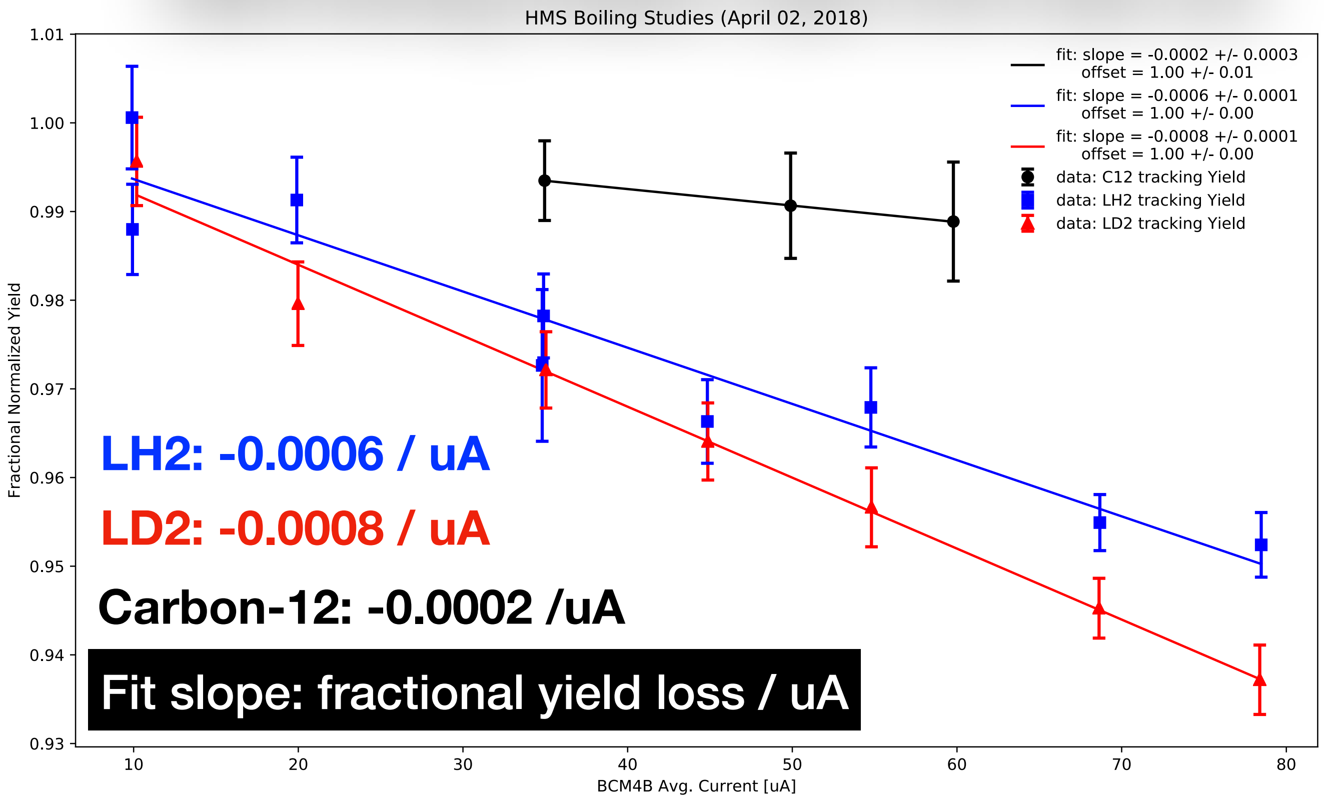
Correct for inefficiency due to tracking reconstruction

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

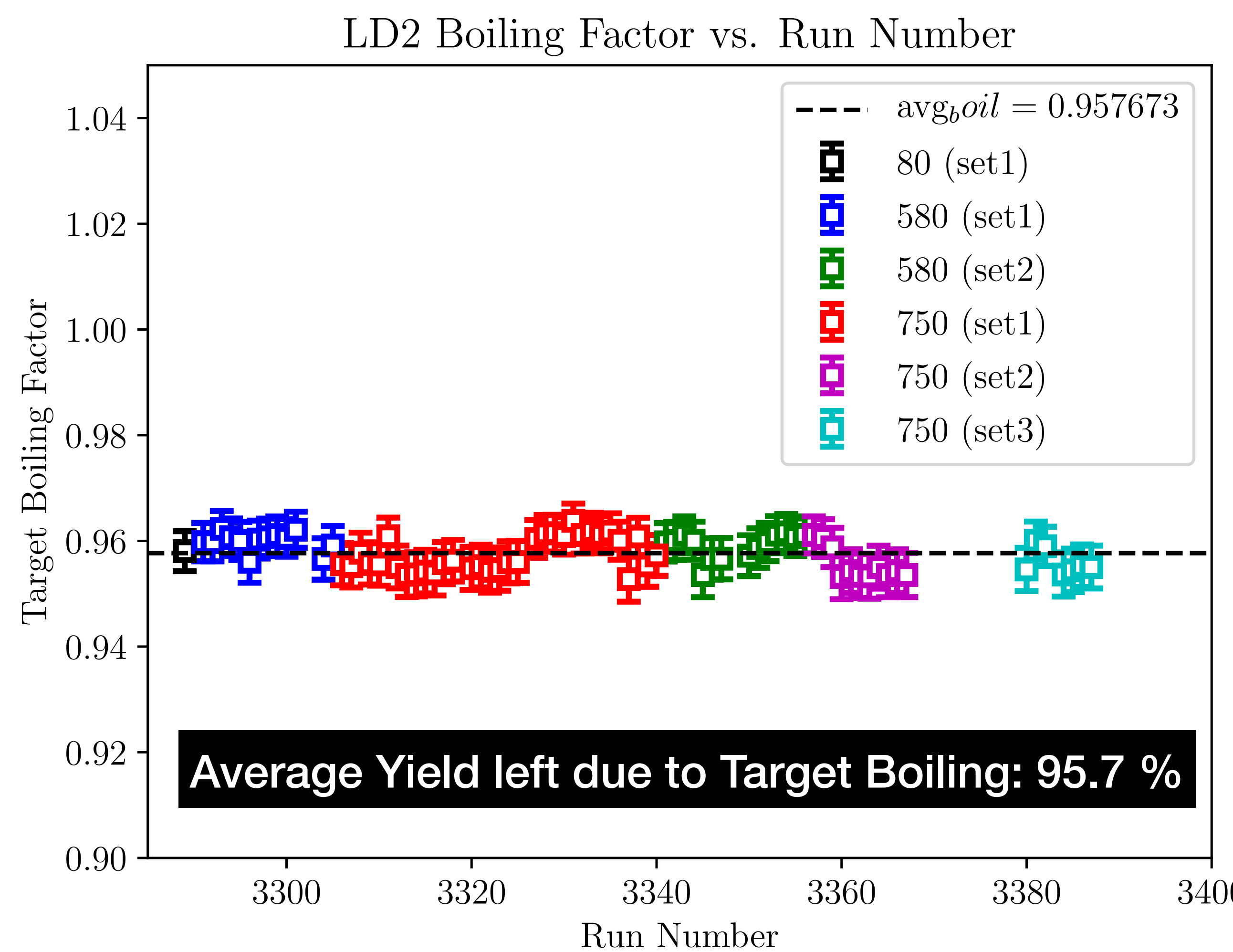


$$Y_{data}^{corr} = \frac{Y_{data}^{uncorr} \cdot f_{rad}}{Q \cdot \epsilon_{tLT} \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{tgtBoil} \cdot \epsilon_{pAbs}}$$

HMS Boiling Studies (April 2018 data set)



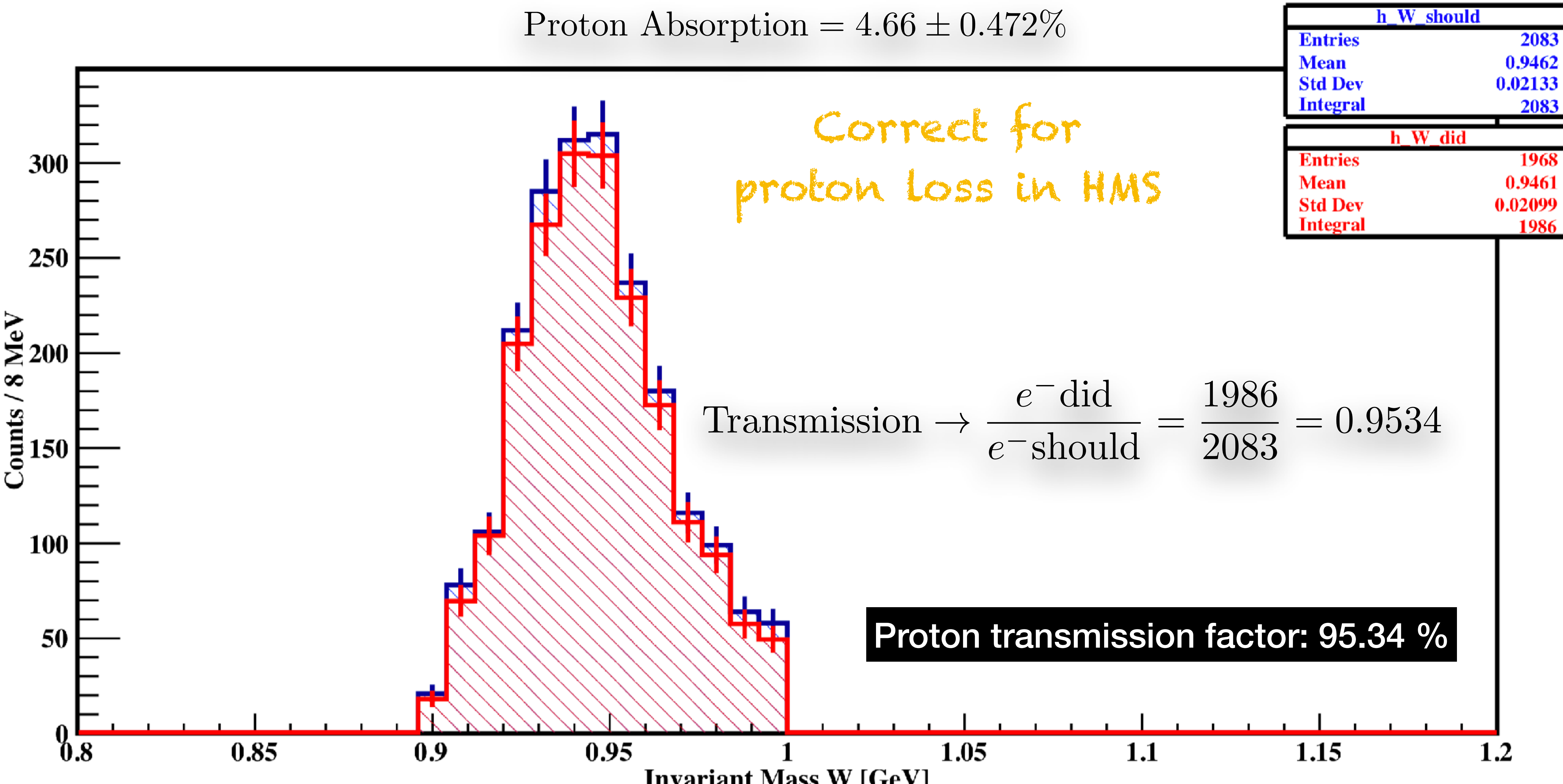
Correct for yield loss due to target boiling



Target Boiling Corrections
See DOC DB Link HERE !

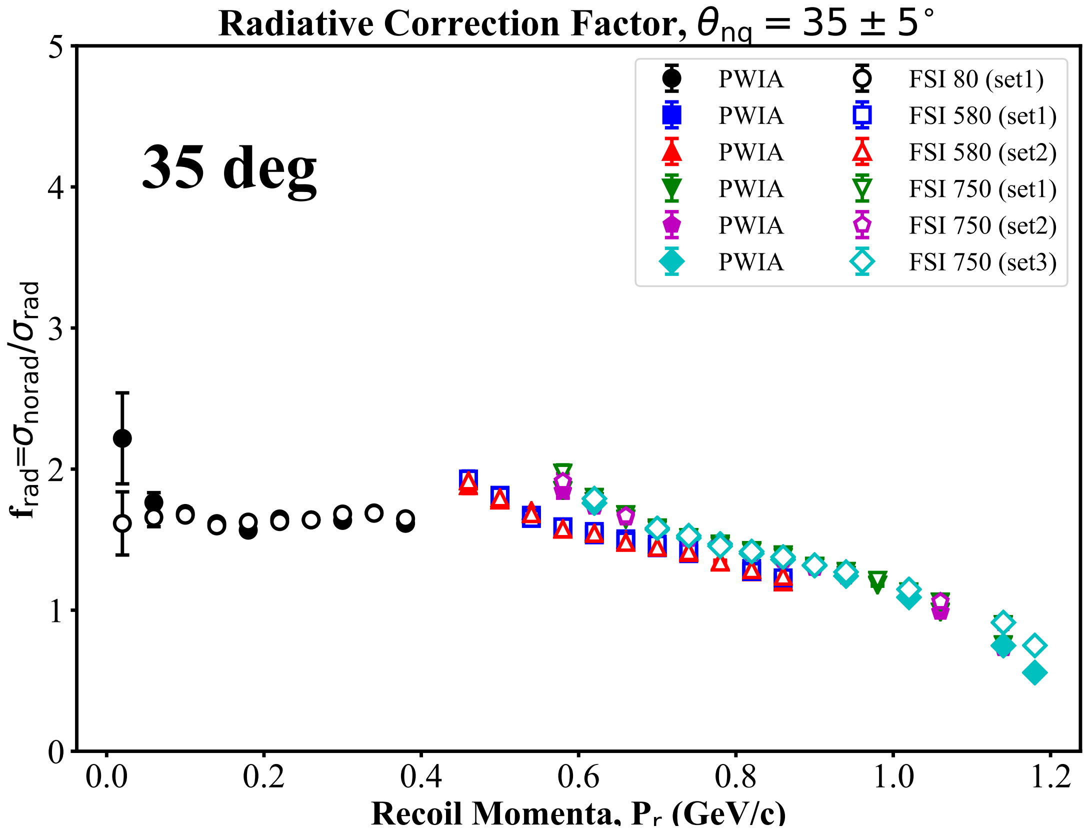
$$Y^{corr}_{data} = \frac{Y^{uncorr}_{data} \cdot f_{rad}}{Q \cdot \epsilon_{tLT} \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{tgtBoil} \cdot \epsilon_{pAbs}}$$

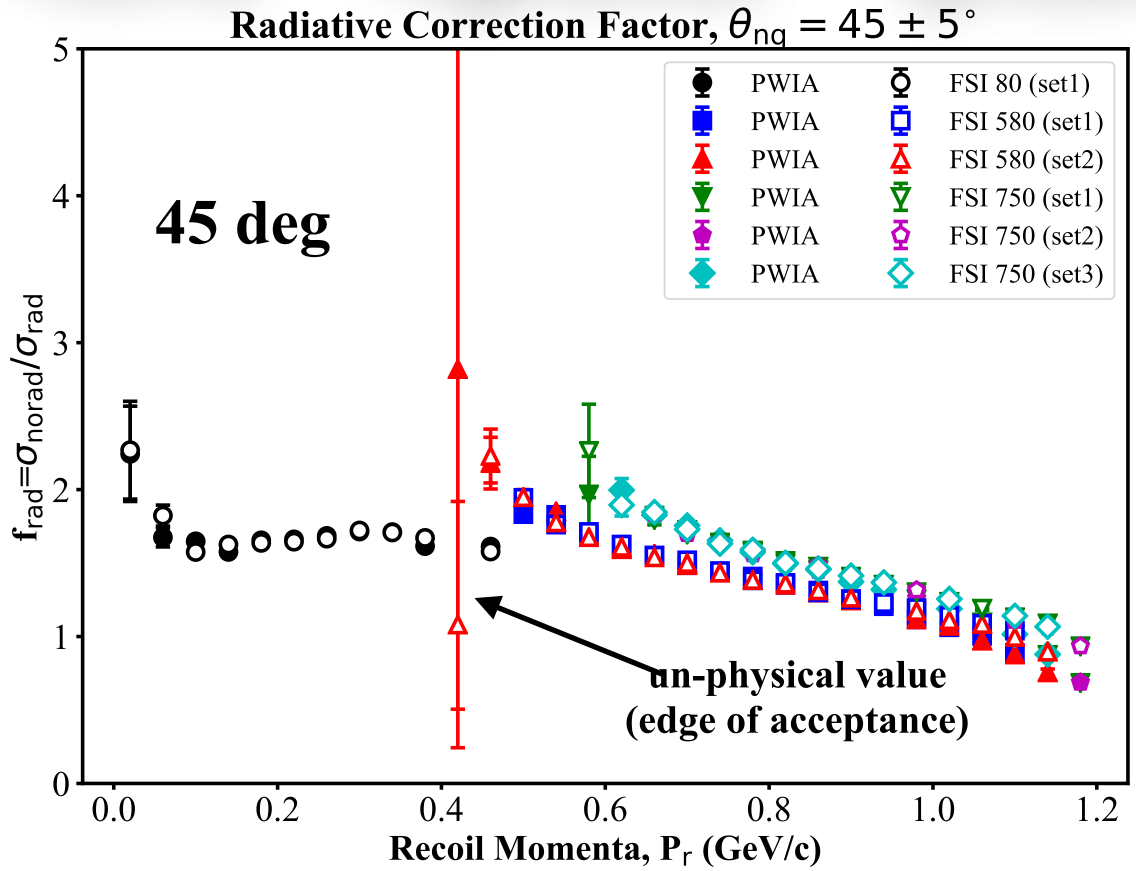
Proton Absorption $= 4.66 \pm 0.472\%$

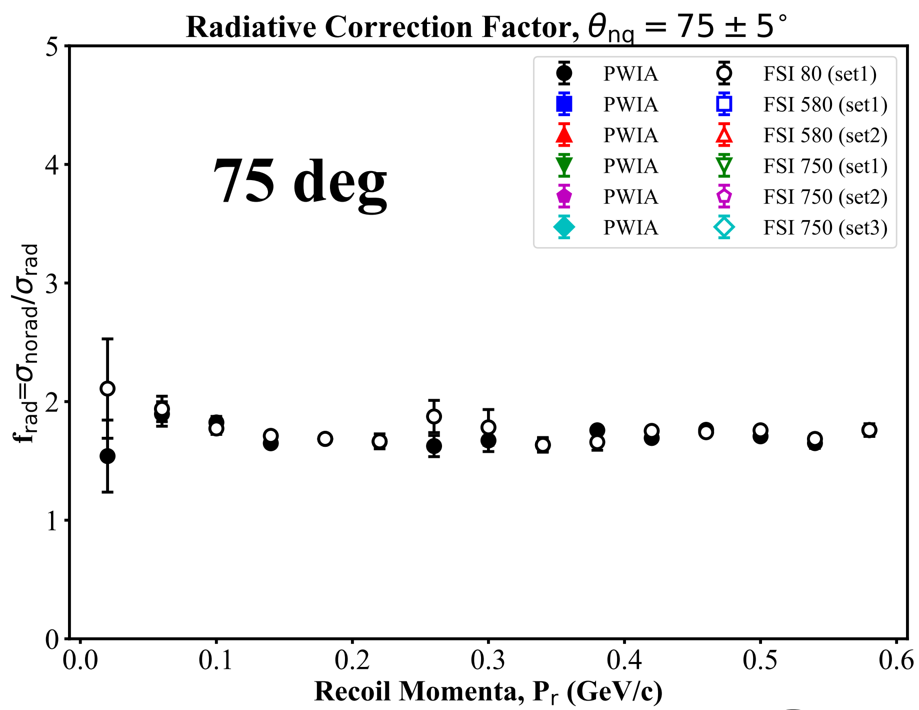


For Full Description of Proton Absorption Analysis, See DOC DB Link HERE !

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



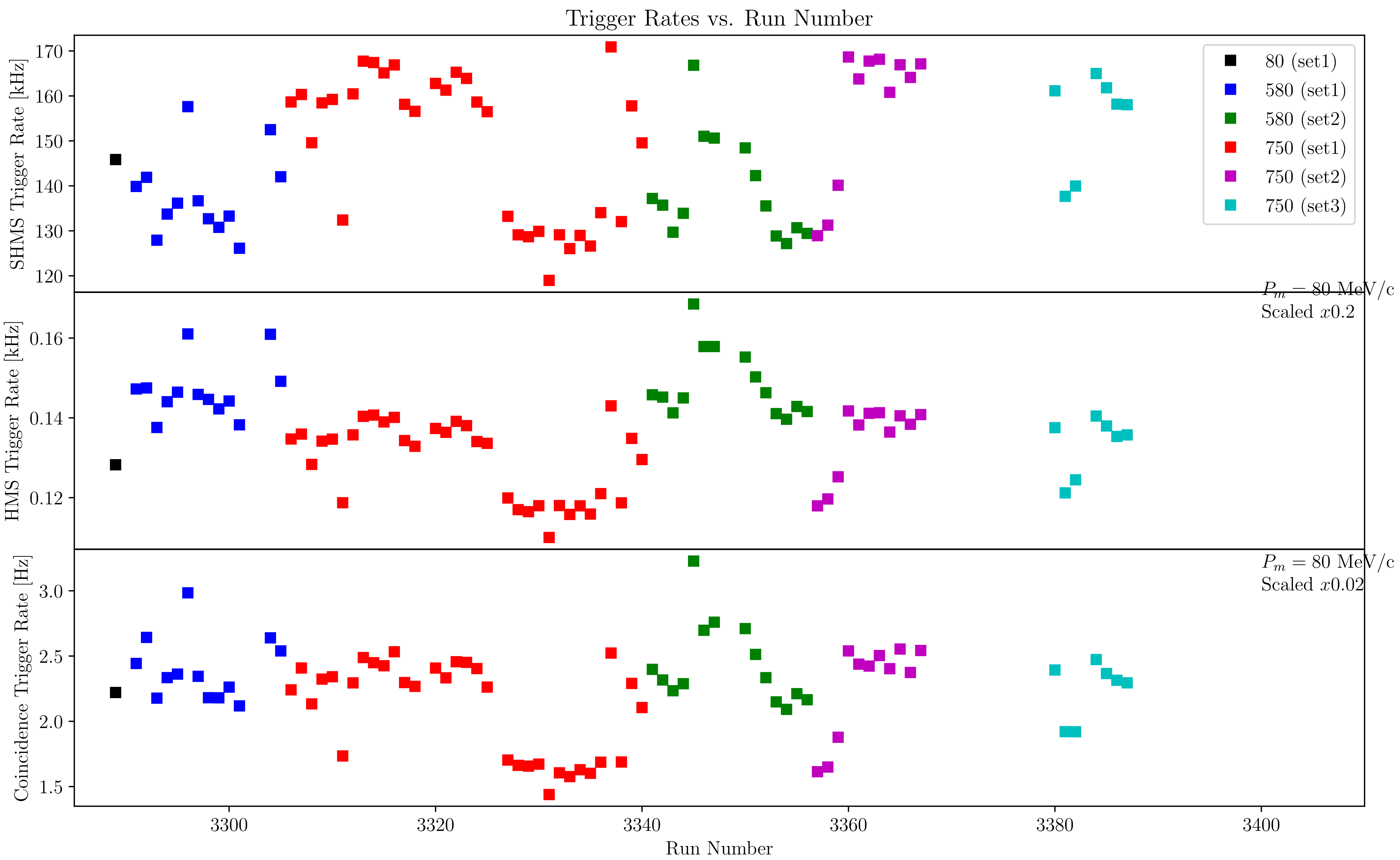




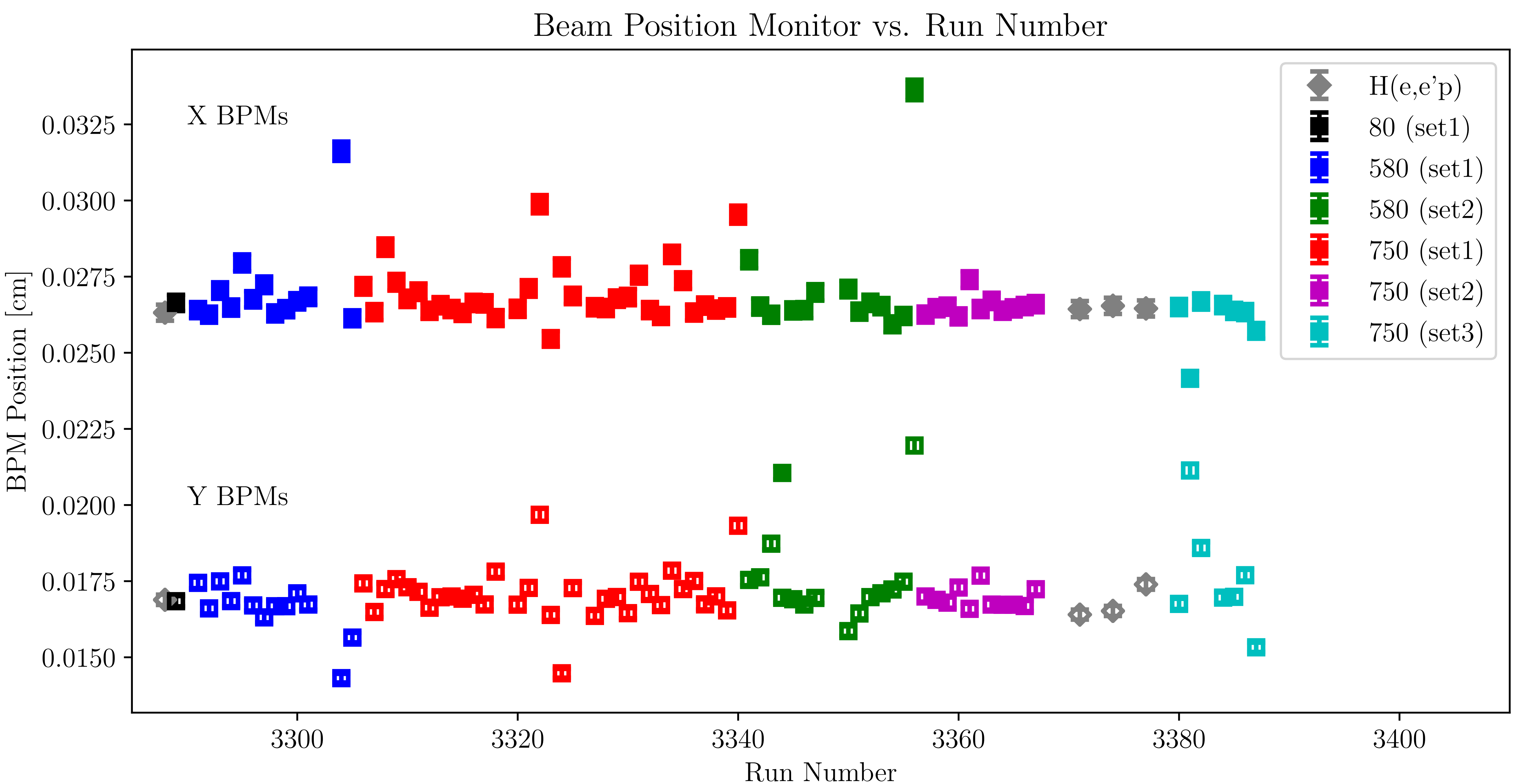
Radiative Correction factor

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

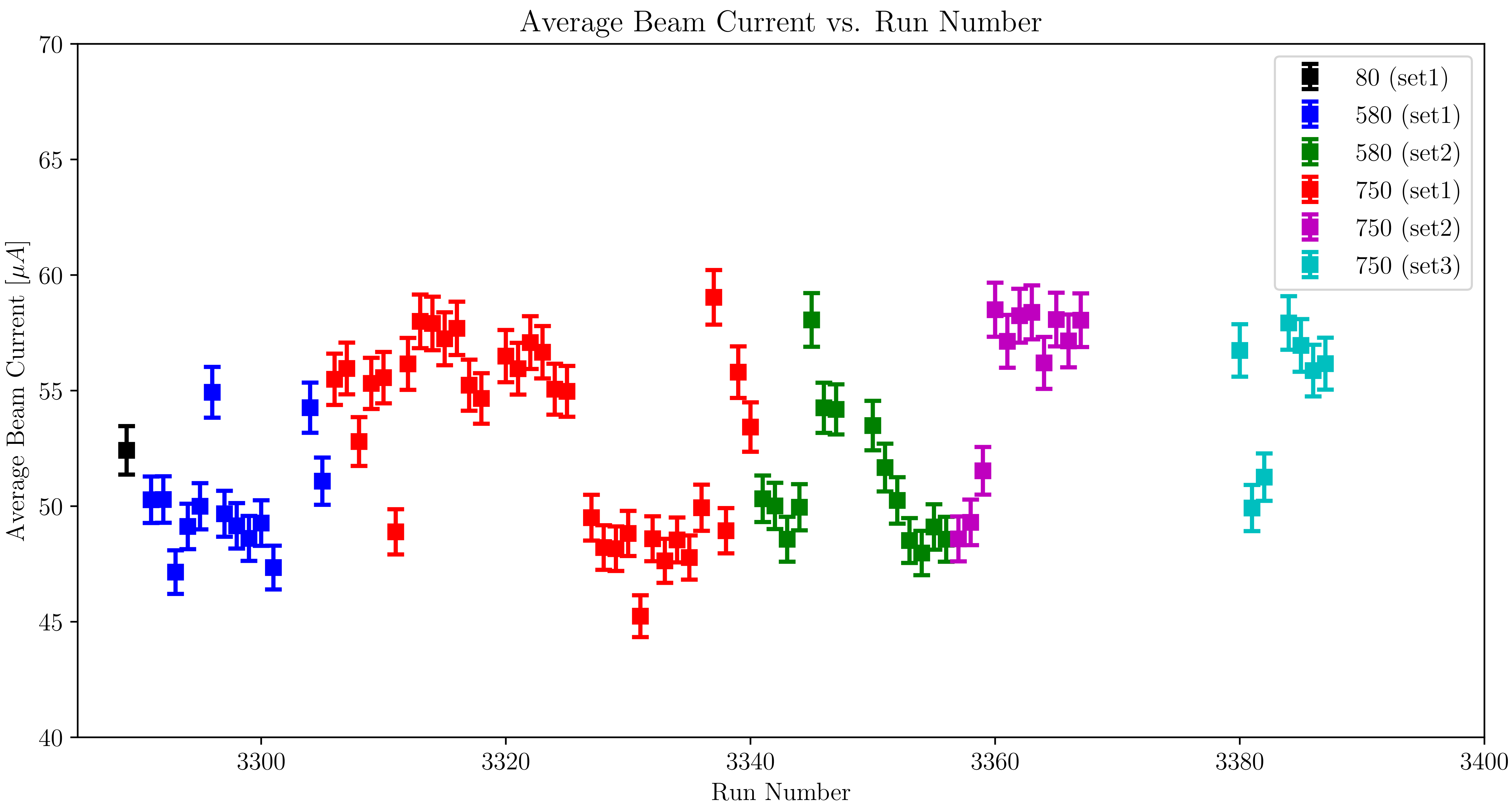
TRIGGER RATES



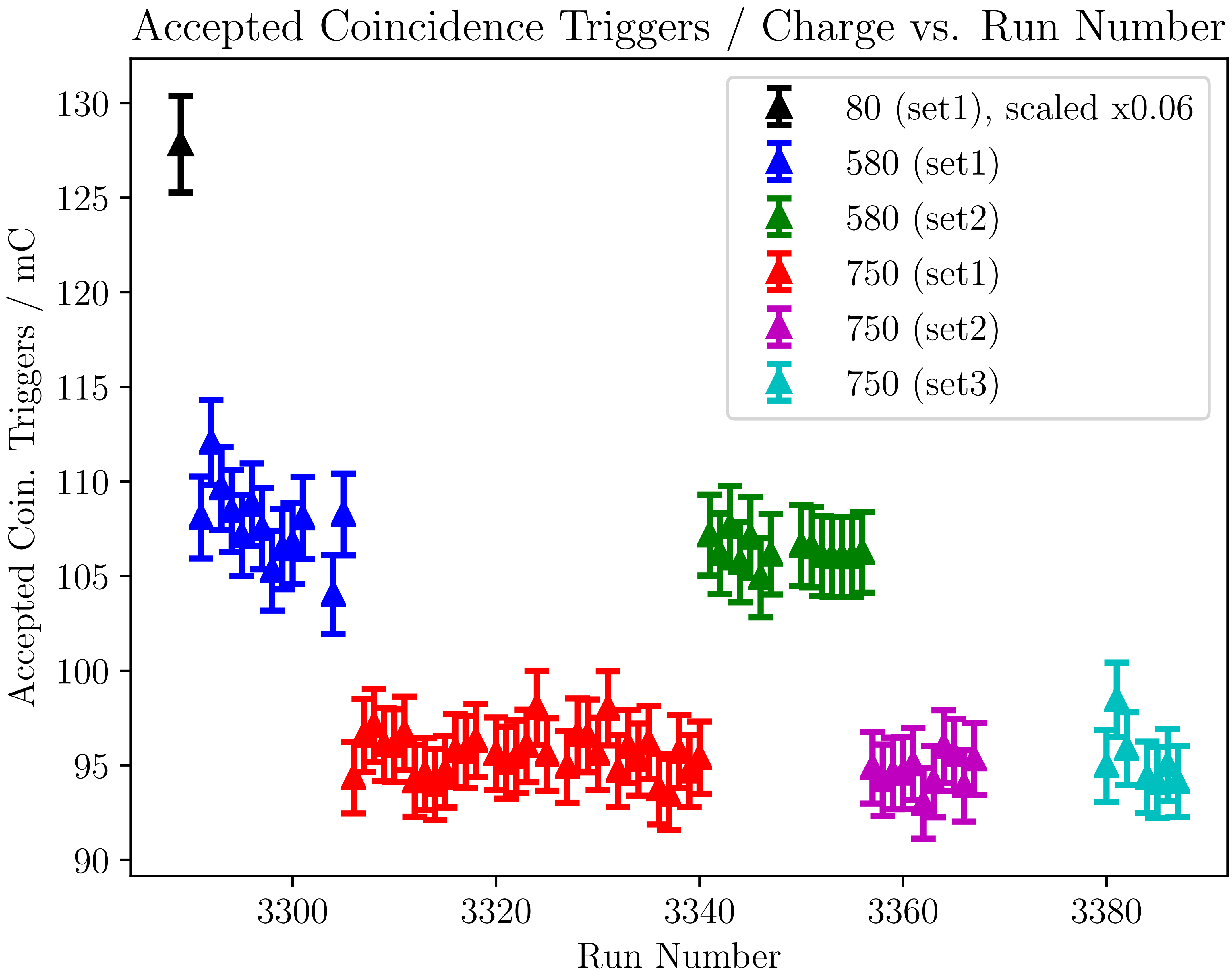
BEAM POSITION MONITORING (BPMs)



AVERAGE BEAM CURRENT



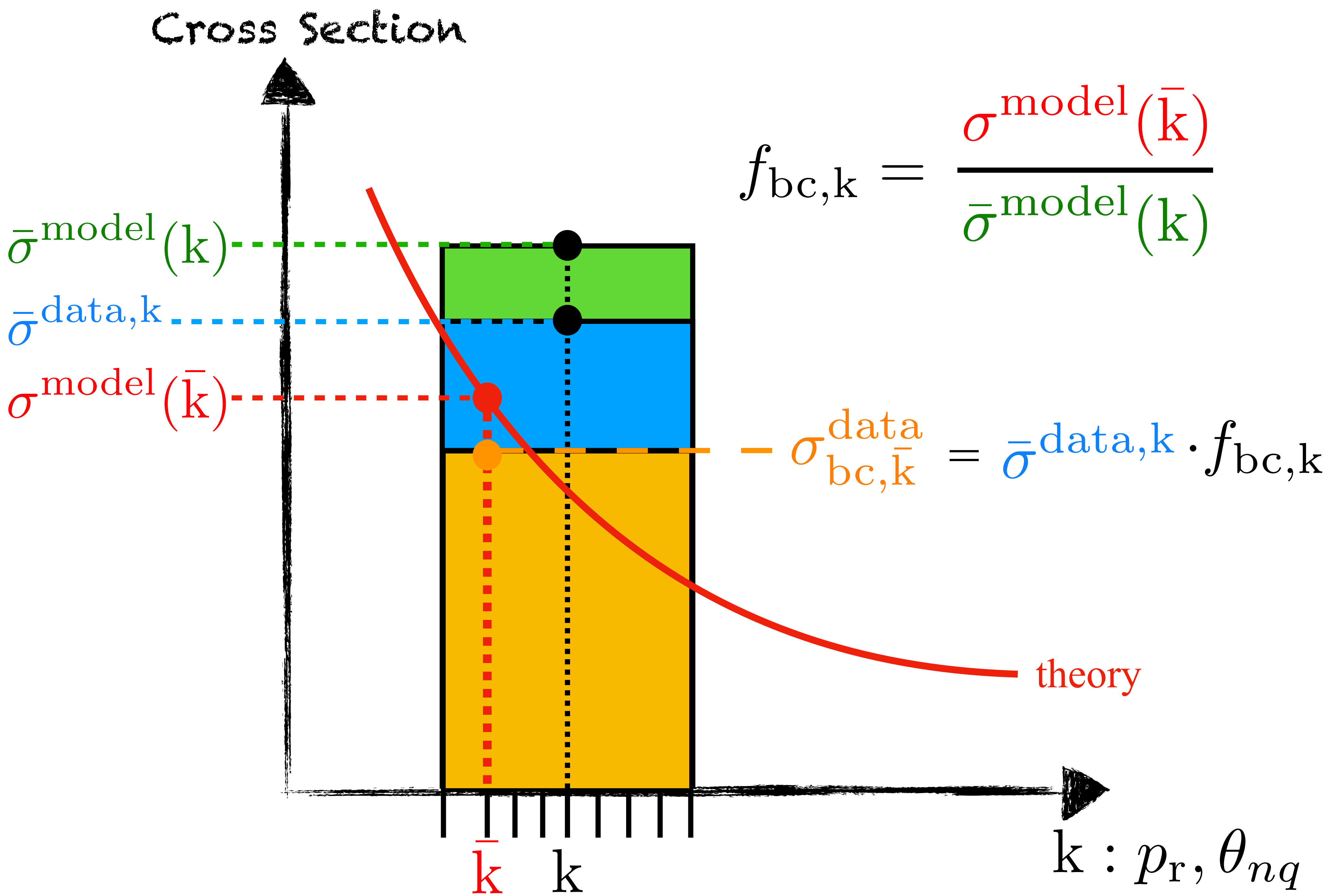
ACCEPTED COUNTS / CHARGE



BIN-CENTERING

CORRECTIONS

Bin Centering Corrections



$\sigma^{\mathrm{model}}(\bar{\mathrm{k}})$ **Model cross section evaluated at the averaged kinematic bin**

$\bar{\sigma}^{\mathrm{model}}(\mathrm{k})$ **Average (SIMC) model cross section evaluated over a kinematic bin, k**

$\sigma^{\mathrm{data}}_{\mathrm{bc},\bar{\mathrm{k}}}$ **Bin-center corrected data cross section at kinematic bin, k**

Bin Centering Corrections

- Currently, Hall C software does **NOT** do energy loss corrections, therefore, the average kinematics were calculated from vertex quantities in simulation.

Kinematic bin (e.g. Pm bin where cross section is stored)

$$\bar{x}_k = \left(\frac{\sum_i w_i x_i}{\sum_i w_i} \right)_k$$

Averaged kinematic variable x over kinematic bin k

Weight times kinematic variable summed over all events

Sum of the weights over all events

Bin Centering Corrections

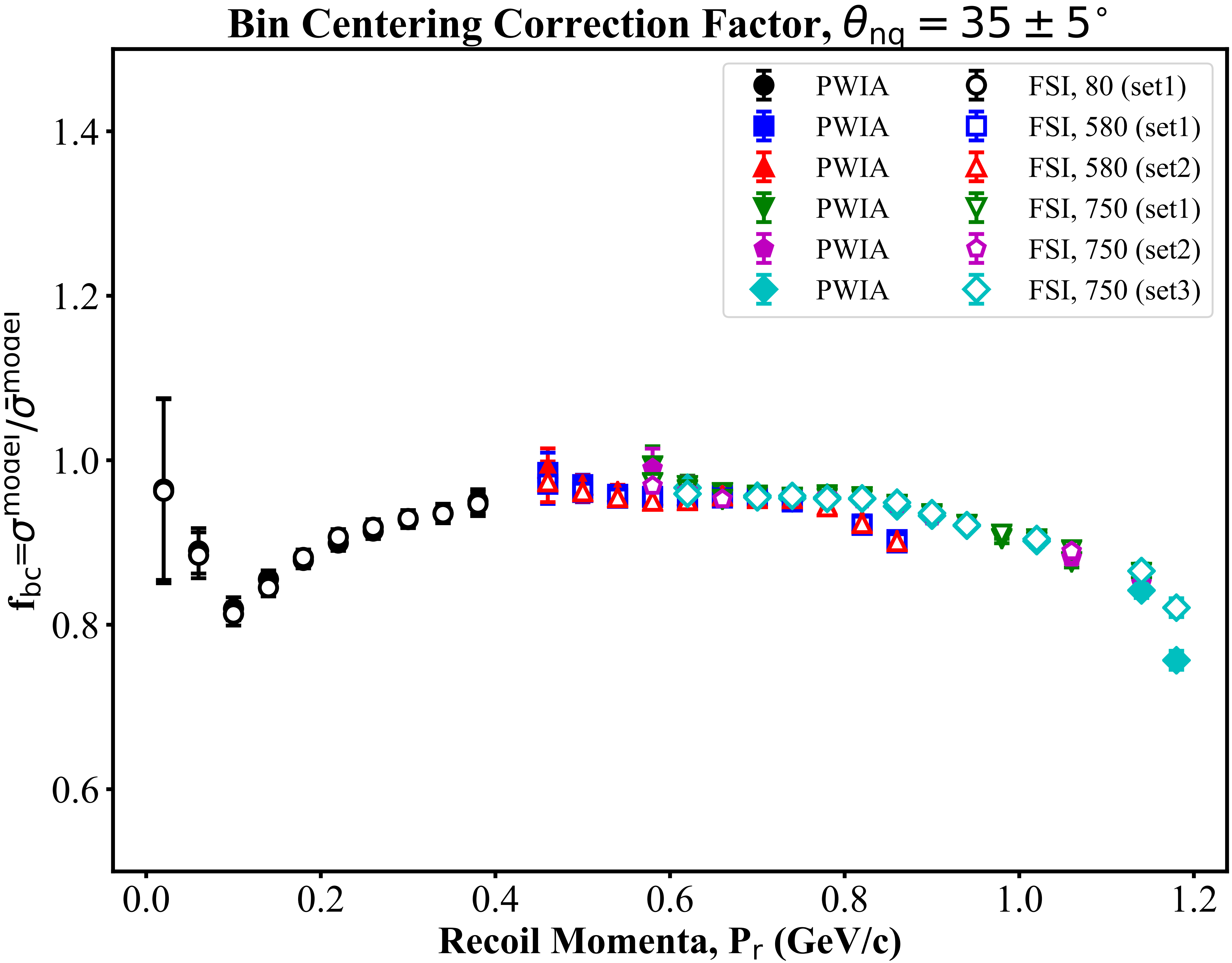
- **Once the averaged kinematics have been calculated, . . .**

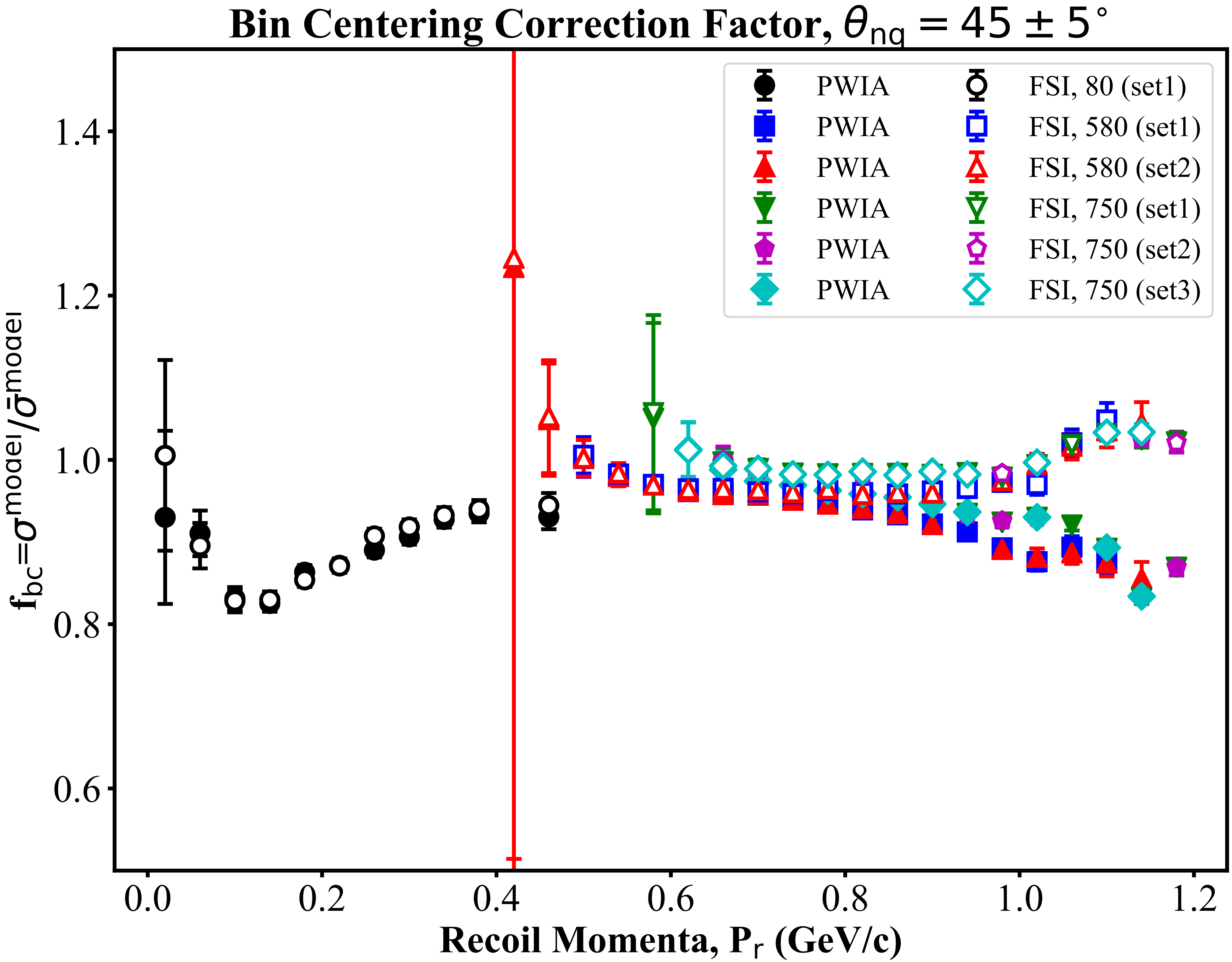
$\bar{x}$: avg. kinematics $\xrightarrow{\textbf{IN}}$ **Theoretical Model (usually a code that takes the input)** $\xrightarrow{\textbf{OUT}}$ $\sigma^{model}(\bar{E_b}, \bar{Q^2}, \bar{\omega}, \bar{\theta}^{cm}_{pq}, \bar{\phi}_{pq})$

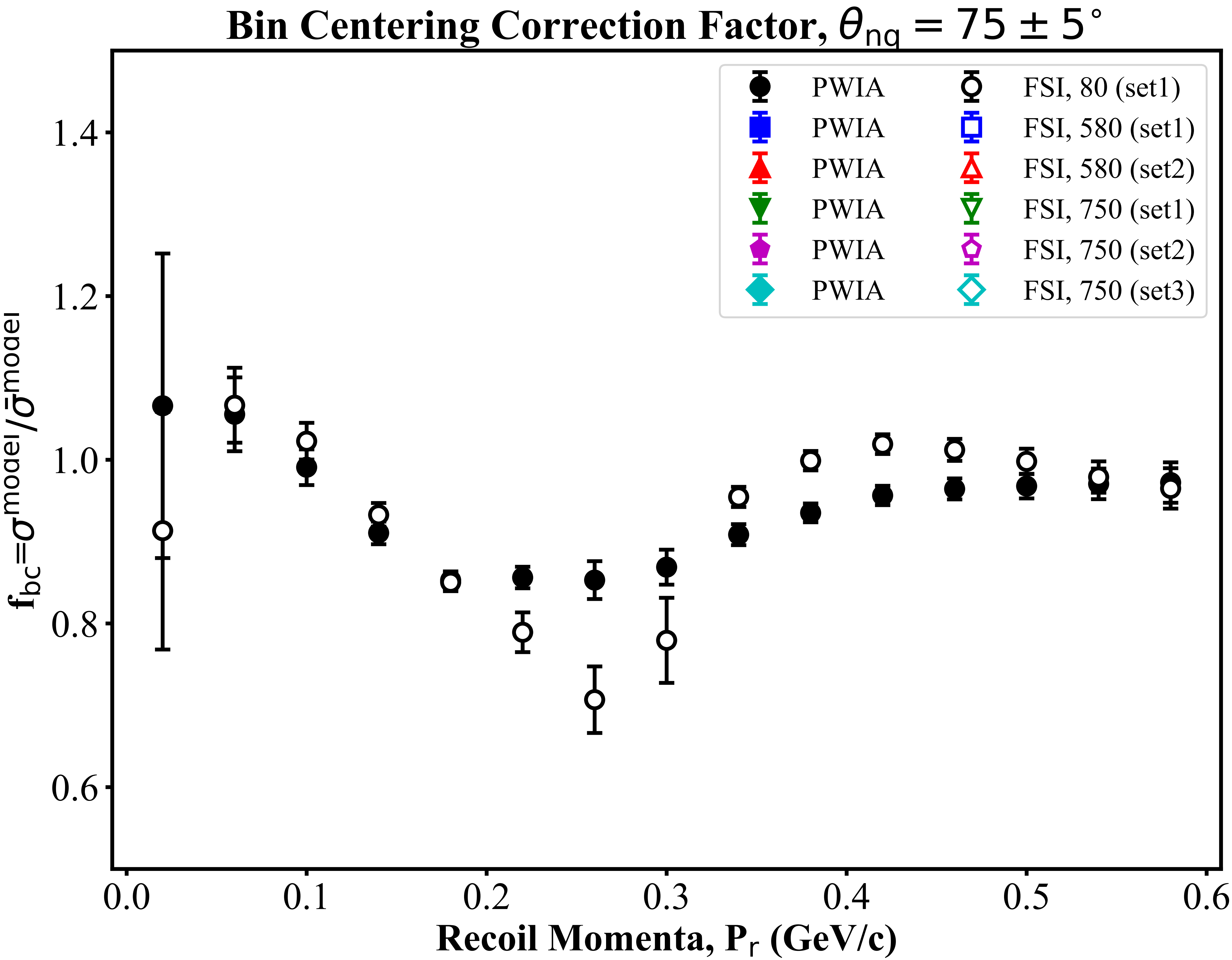
$$\bar{\sigma}^{model} \equiv \frac{Y^{\mathrm{SIMC}}}{V^{P.S.}}$$ $\longrightarrow$ **Averaged Model Cross Section**

- **Correct the data bin-by-bin using the model cross sections ratio . . .**

$$\sigma^{exp}_{bc} = \bar{\sigma}^{exp} \cdot \frac{\sigma^{model}(\bar{E_b}, \bar{Q^2}, \bar{\omega}, \bar{\theta}^{cm}_{pq}, \bar{\phi}_{pq})}{\bar{\sigma}^{model}}$$


Bin Centering Correction Factor, $\theta_{nq} = 35 \pm 5^{\circ}$
PWIA
PWIA
PWIA
PWIA
PWIA
PWIA
FSI, 80 (set1)
FSI, 580 (set1)
FSI, 580 (set2)
FSI, 750 (set1)
FSI, 750 (set2)
FSI, 750 (set3)
$f_{bc}=\sigma^{model}/\bar{\sigma}^{model}$
Recoil Momenta, P_r (GeV/c)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.6
0.8
1.0
1.2
1.4

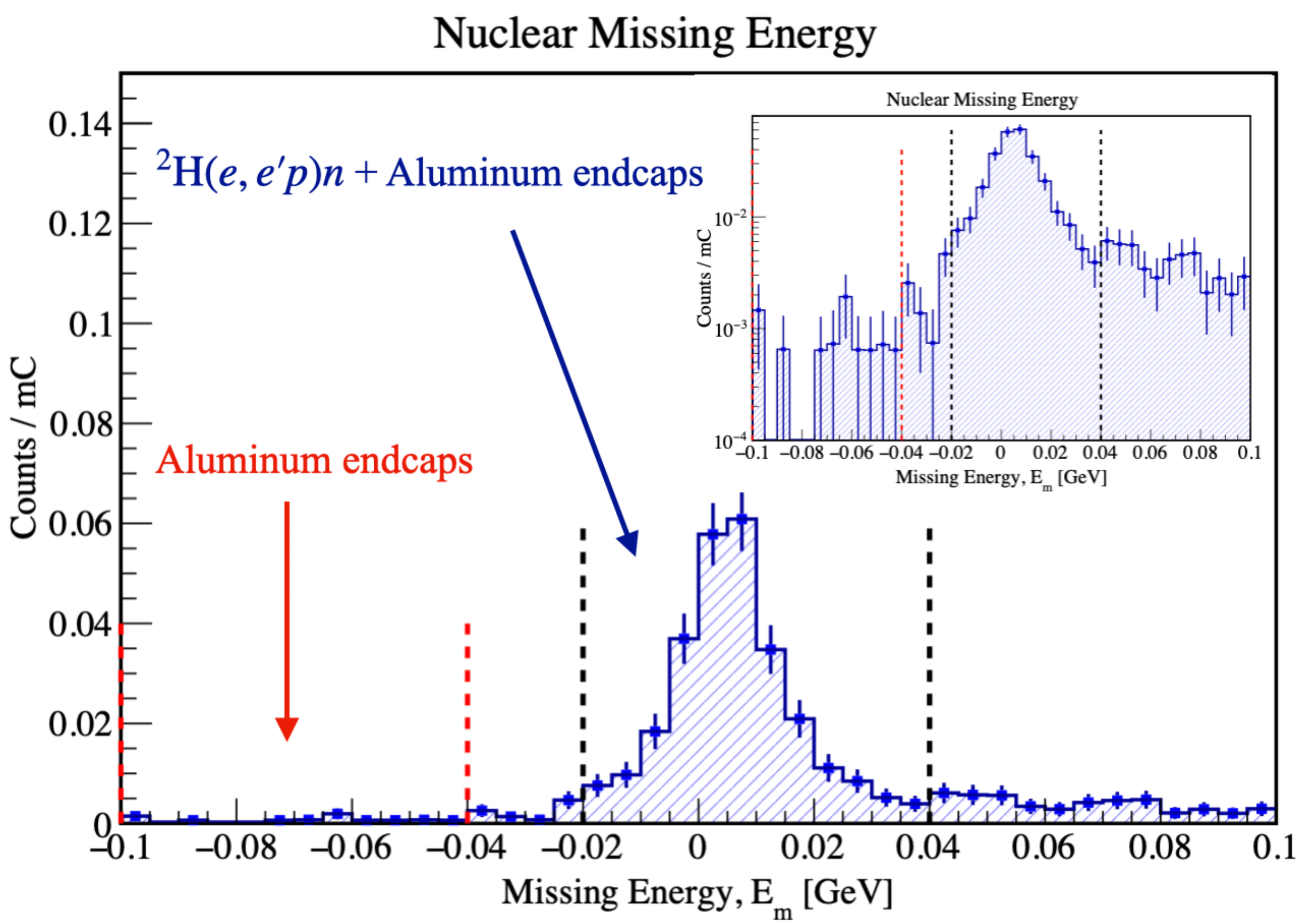

Bin Centering Correction Factor, $\theta_{nq} = 45 \pm 5^{\circ}$
$f_{bc}=\sigma^{model}/\bar{\sigma}^{model}$
Recoil Momenta, P_r (GeV/c)
PWIA
FSI, 80 (set1)
FSI, 580 (set1)
FSI, 580 (set2)
FSI, 750 (set1)
FSI, 750 (set2)
FSI, 750 (set3)

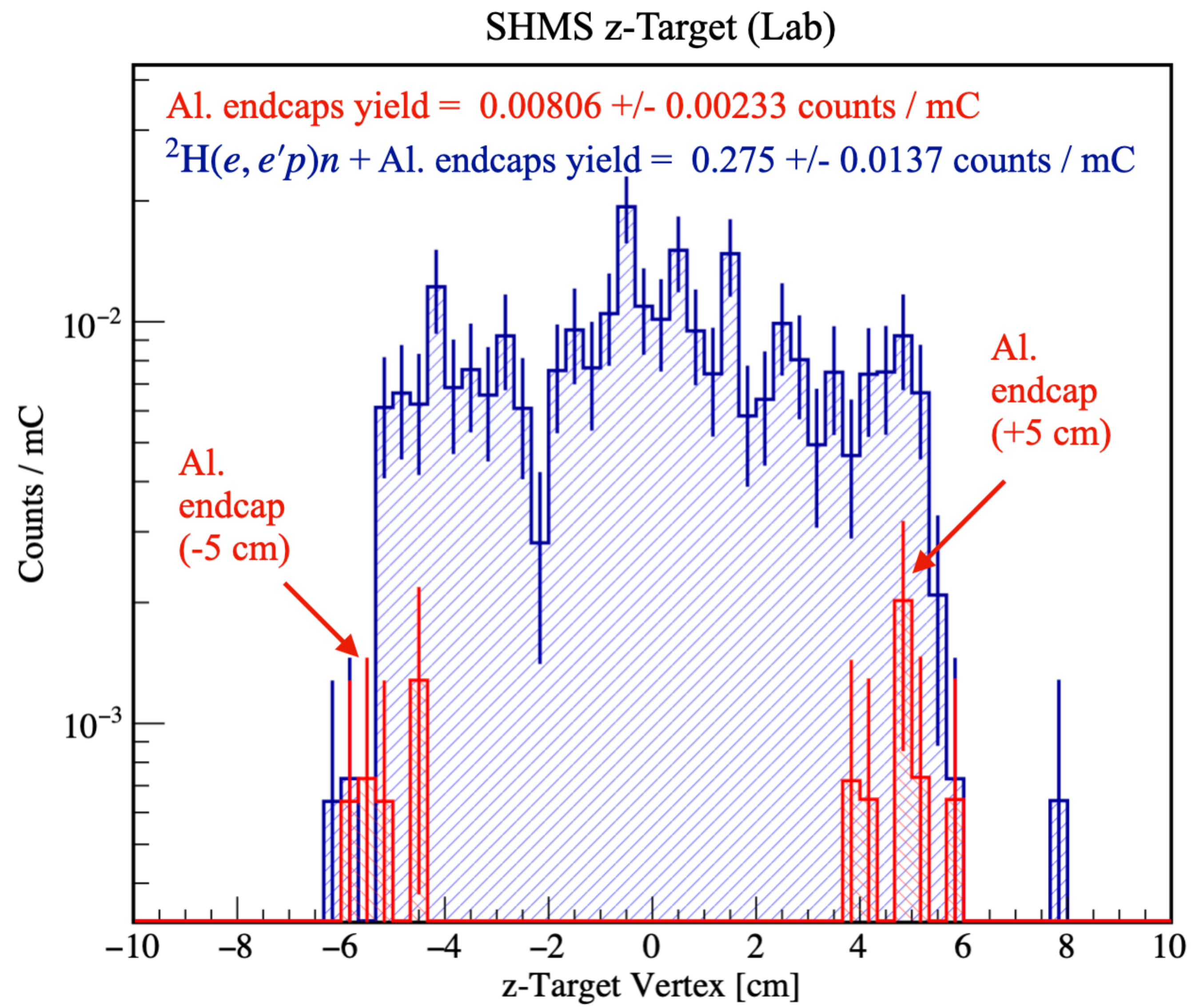


Bin Centering Correction Factor, $\theta_{nq} = 75 \pm 5^{\circ}$
PWIA
PWIA
PWIA
PWIA
PWIA
PWIA
FSI, 80 (set1)
FSI, 580 (set1)
FSI, 580 (set2)
FSI, 750 (set1)
FSI, 750 (set2)
FSI, 750 (set3)
$f_{bc}=\sigma^{model}/\bar{\sigma}^{model}$
Recoil Momenta, P_r (GeV/c)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.6
0.8
1.0
1.2
1.4

Error Analysis of D(e,e'p)n Cross Section

Estimate of Target Wall Contribution to the D(e,e'p)n Cross Section





- No dedicated target dummy runs were taken for the high missing momentum settings during the experiment
- Target wall contributions Al(e, e')p show up in the missing energy spectrum
- Assume contribution due to target wall is uniform across the missing energy spectrum
- Selected a sample of Al(e, e')p events from -0.1 to -0.04 GeV and used it to estimate the background underneath the main missing energy peak (-0.02, 0.04 GeV)

NORMALIZATION CORRECTION FACTORS for D(e,e'p)n

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 were averaged over all runs of individual data sets**

ABSOLUTE UNCERTAINTY (%) IN NORMALIZATION CORRECTION FACTORS for D(e,e'p)n

Pm	HMS Tracking Efficiency Err.	sHMS Tracking Efficiency Err.	Target Boiling Correction Err.	Proton Absorption Correction Err.	Total Live Time Err.	Total Charge (mC) Err.
80	0.034%	0.040%	0.378%	0.472%	—	—
580 (set 1)	0.396%	0.732%	0.362%	0.472%	—	—
580 (set 2)	0.473%	0.583%	0.369%	0.472%	—	—
750 (set 1)	0.526%	0.689%	0.384%	0.472%	—	—
750 (set 2)	0.467%	0.682%	0.401%	0.472%	—	—
750 (set 3)	0.507%	0.729%	0.397%	0.472%	—	—

** Uncertainty on EDTM and BCM is not finalized. Conservative estimates on the relative cross section error were made (See next slide)

SYSTEMATIC UNCERTAINTY ON NORMALIZATION

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

f_i : normalization correction factors

df_i : error in normalization correction factors

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

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%	≤ 2.9 %	1.4%
580 (set 1)	0.3999%	0.7586%	0.3766%	0.4951%	3.0%	2.0%	≤ 2.9 %	1.4%
580 (set 2)	0.4786%	0.6041%	0.3842%	0.4951%	3.0%	2.0%	≤ 2.9 %	1.4%
750 (set 1)	0.5329%	0.7155%	0.4013%	0.4951%	3.0%	2.0%	≤ 2.9 %	1.4%
750 (set 2)	0.4719%	0.7089%	0.4196%	0.4951%	3.0%	2.0%	≤ 2.9 %	1.4%
750 (set 3)	0.5127%	0.7584%	0.4150%	0.4951%	3.0%	2.0%	≤ 2.9 %	1.4%
AVG	0.4026%	0.5978%	0.3985%	0.4951%	3.0%	2.0%	≤ 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

SPECTROMETER KINEMATIC SYSTEMATIC UNCERTAINTIES on D(e,e'p)n

$\delta\theta_e[mr]$	± 0.17
$\delta\theta_p[mr]$	± 0.24
$\delta E_f/E_f$	$\pm 9.1 \times 10^{-4}$
$\delta E_b/E_b$	$\pm 7.5 \times 10^{4}$
$d\sigma_{exp}^{kin}$	$\leq 6.5\ \%$

Uncertainty in SHMS angle

Uncertainty in HMS angle

Uncertainty in SHMS momentum

Uncertainty in Beam Energy

Max. Kin. Systematic Error on Cross Section

Determined from fit to H(e,e'p) coincidence elastic data. (<u>See DOC DB link HERE!</u>)

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

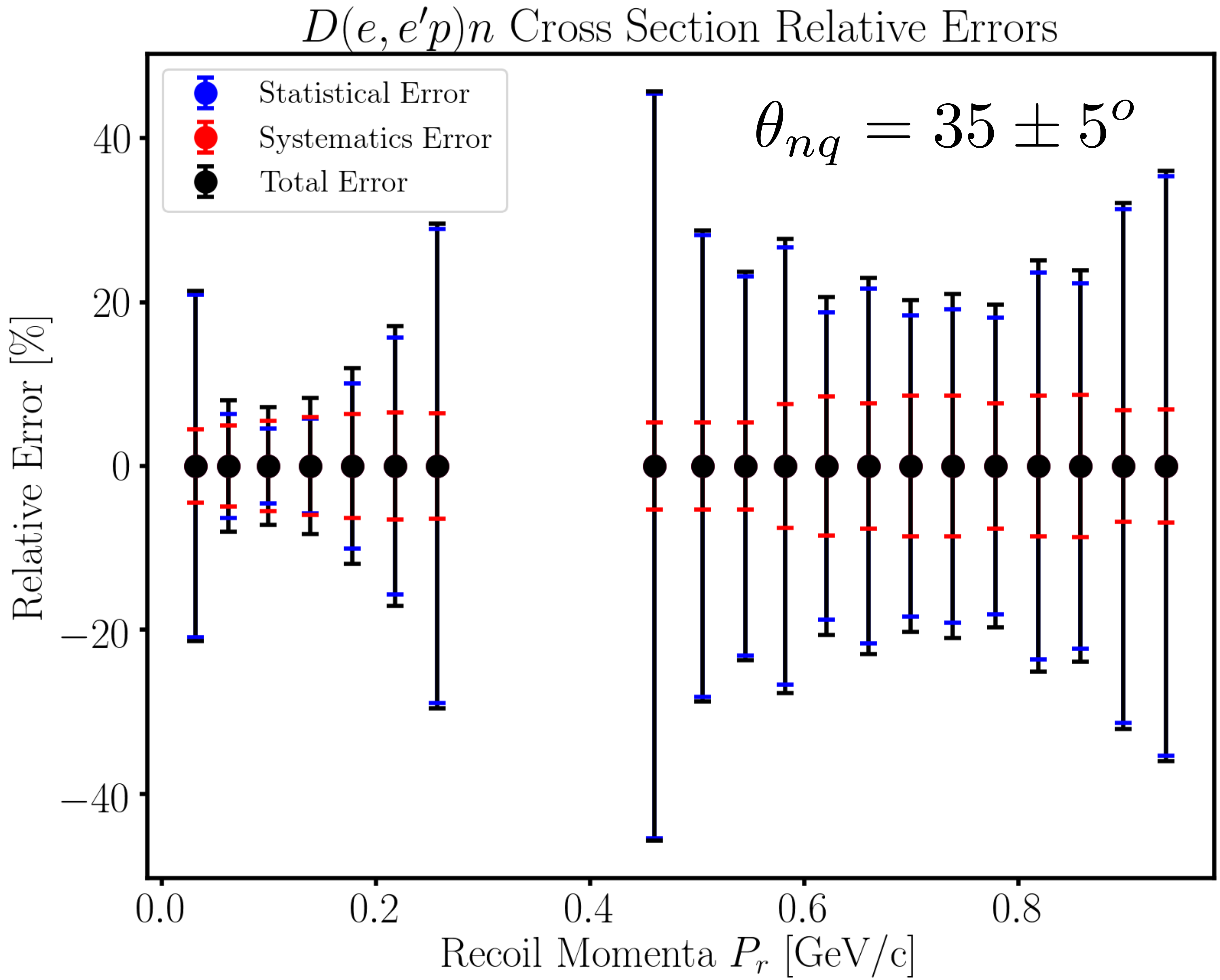
Covariance Errors

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

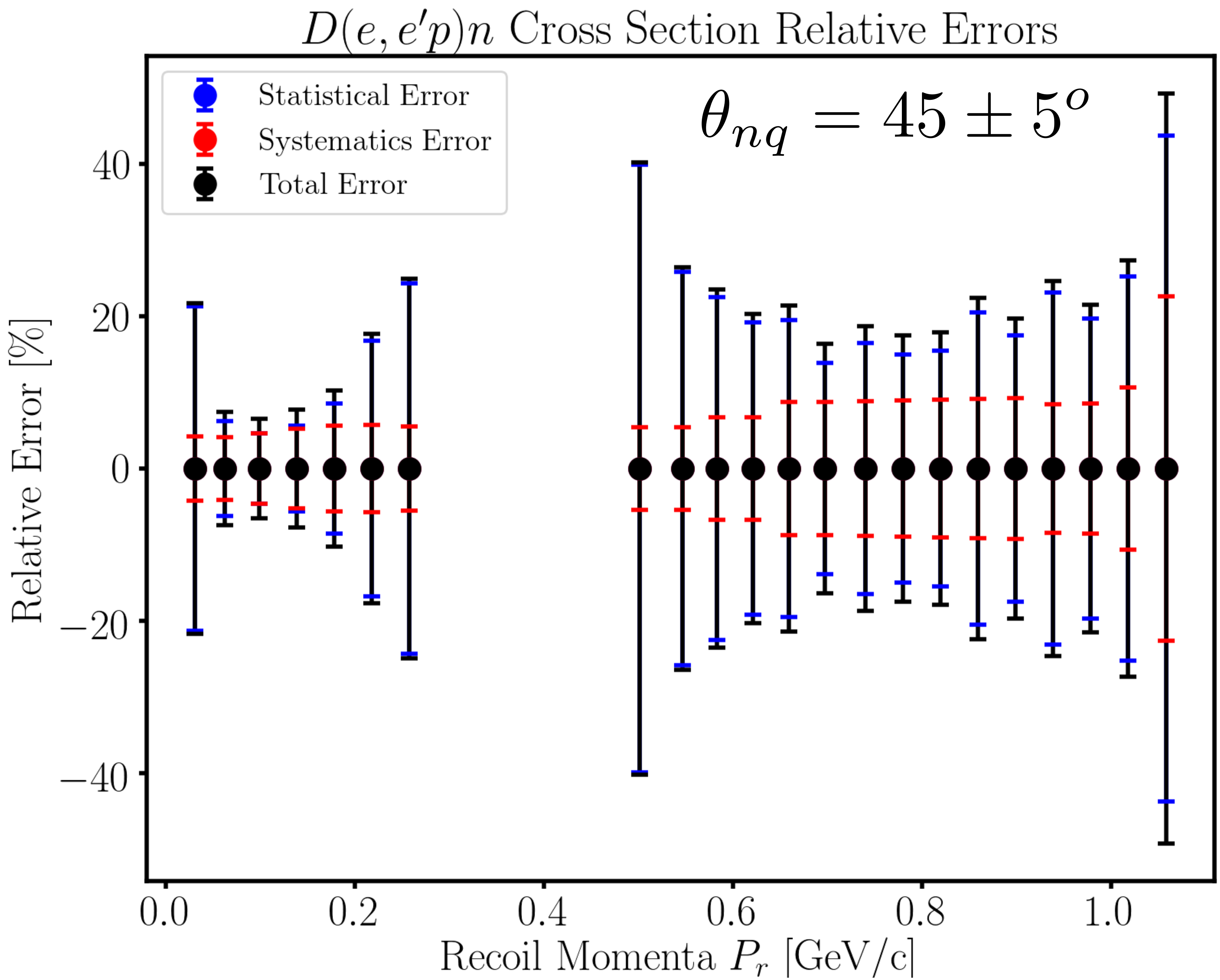
The kinematic uncertainties are point-to-point which means they vary depending for each data point, as each corresponds to a different missing momentum kinematic bin.

The tables of the PWIA Laget Cross section derivatives with respect to the kinematic variables were used

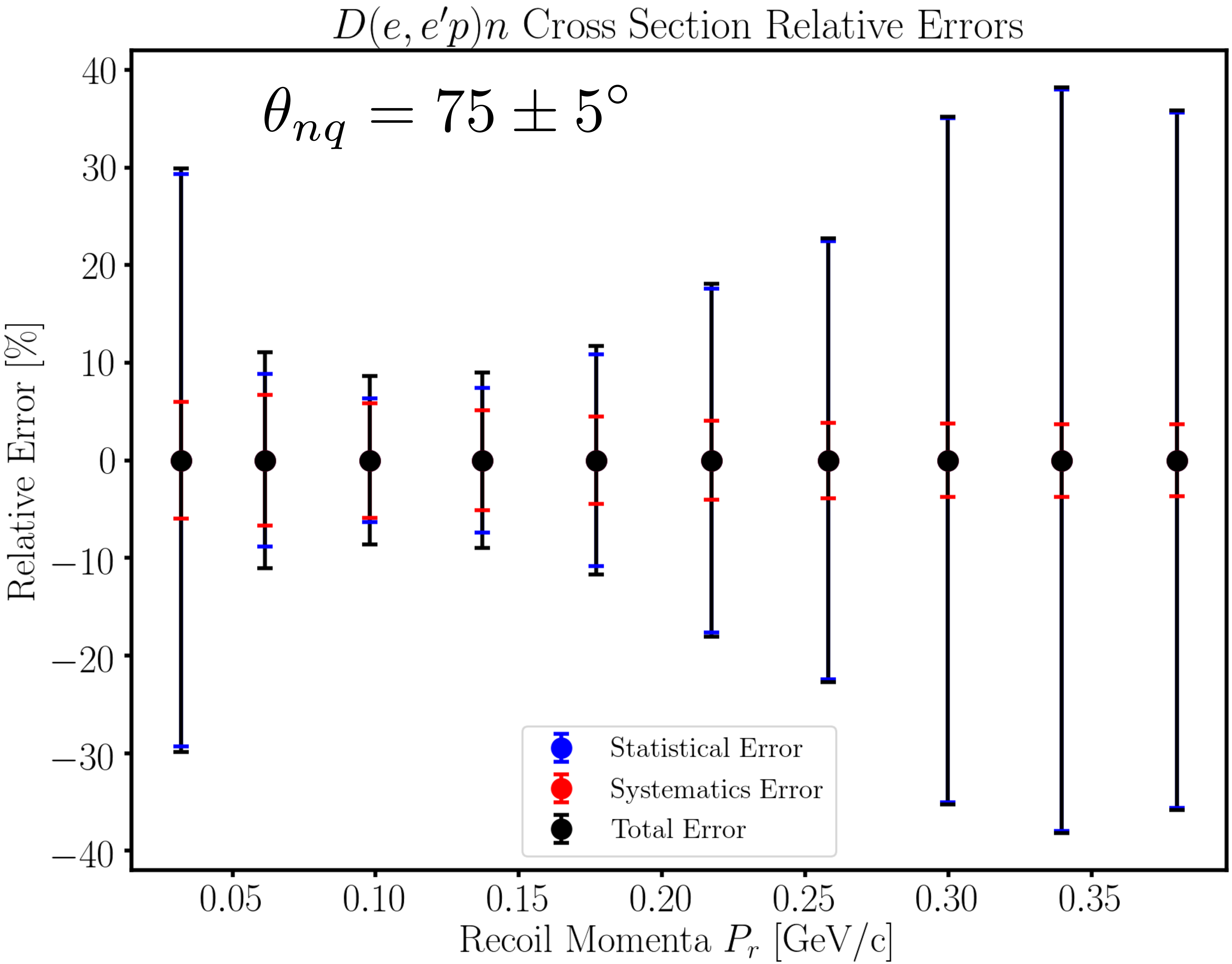
D(e,e'p)n Cross Section Relative Errors Summary Plots



D(e,e'p)n Cross Section Relative Errors Summary Plots



D(e,e'p)n Cross Section Relative Errors Summary Plots



From Theoretical Potentials to Theoretical Cross Sections

How are the theoretical cross sections determined from an *NN* potential ?

Construction of NN potential
(by theory groups)

Elastic nn, pp, np scattering data

NN theoretical potential
V_{NN}

Nuclear wave function, $\psi(\vec{r})$

Paris, CD-Bonn, AV18, WJC2, …

Theoretical cross-section
calculations from NN wave function

Nucleon form factor parametrization
e.g., Galster, JJK, GKex05, AMT

np **data parametrization for**
FSI calculations
e.g., SAID, Regge

Theoretical Calculations

J.M. Laget
Paris (Galster)

M. M. Sargsian
CD-Bonn (JJK)
AV18 (JJK)

S. Jeschonnek and J.W.V. Orden
WJC2 (GKex05)
CD-Bonn (GKex05)
AV18 (GKex05)

WJC2 (AMT)
CD-Bonn (AMT)
AV18 (AMT)

$$< \psi_p, \psi_n | A_{\mathrm{tot}} | \psi_D > = < \psi_p, \psi_n | A_{\mathrm{PWBA}} | \psi_D > + < \psi_p, \psi_n | A_{\mathrm{FSI}} | \psi_D >$$
$$+ < \psi_p, \psi_n | A_{\mathrm{MEC}} | \psi_D > + < \psi_p, \psi_n | A_{\mathrm{IC}} | \psi_D >$$

np final state wave function

total transition amplitude

initial state wave function

$$\frac{d^5\sigma}{dE' d\Omega_e d\Omega_p} \propto | < \psi_p, \psi_n | A_{\mathrm{tot}} | \psi_D > |^2$$

"5-fold theoretical differential cross section for the deuteron"

J.M. Laget, Phys. Lett. B609, 49 (2005)

M.M. Sargsian, Phys. Rev. C82, 014612 (2010)

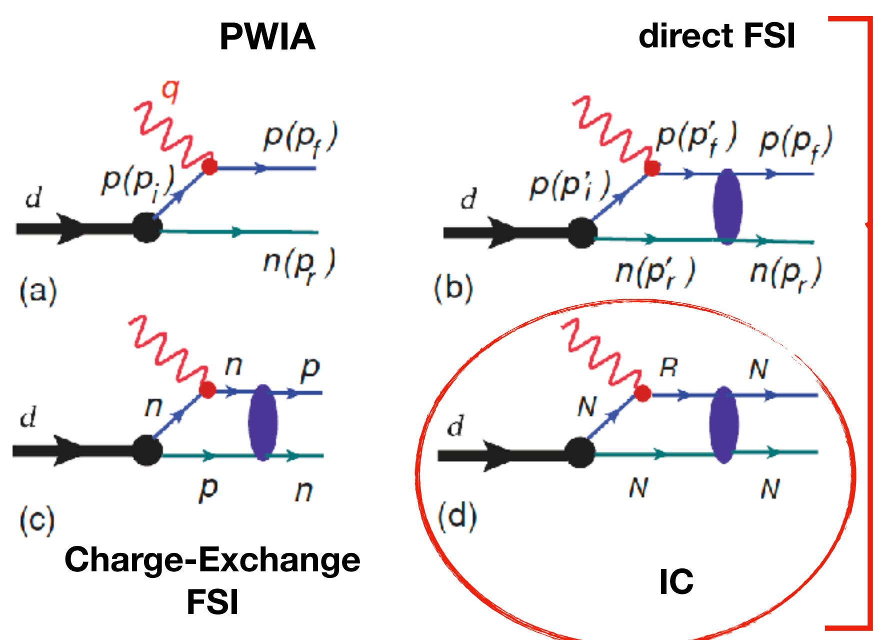
W.P. Ford, S. Jeschonnek and J.W.V. Orden, Phys. Rev. C90, 064006 (2014)

Theoretical Calculations by M. Sargsian [M.M. Sargsian, Phys. Rev. C82, 014612 (2010)]

❖ Effective Feynman Diagrammatic Approach (calculate scattering amplitudes)

- **Scattering amplitudes are calculated using the Generalized Eikonal Approximation (GEA) at high Q^2 (> 1 (GeV/c)^2) under the assumptions of the Virtual Nucleon Approximation**

Feynman diagrams under GEA



Δ resonance production suppressed at Bjorken-x > 1

$$\frac{d^5\sigma}{dE' d\Omega_e d\Omega_p} \propto |< s_f, s_r|A^\mu|s_d >|^2$$

total transition amplitude

Scattering Amplitude determined within GEA

PWIA direct FSI

$$\langle s_f, s_r|A^\mu|s_d\rangle = \langle s_f, s_r|A_0^\mu|s_d\rangle + \langle s_f, s_r|A_1^\mu|s_d\rangle + \langle s_f, s_r|A_{1,\mathrm{chex}}^\mu|s_d\rangle.$$

Charge-exchange FSI

Initial (d) and final (np) spin projections of deuteron

$$\langle s_f, s_r|A_0^\mu|s_d\rangle = \sqrt{2}\sqrt{(2\pi)^3 2E_r}\sum_{s_i} J_N^\mu(s_f, p_f; s_i, p_i) \times \Psi_d^{s_d}(s_i, p_i, s_r, p_r),$$

Total E.M. current operator (on-shell + off-shell components)

transition vertex (Deuteron to np)

$$\Psi_d^{s_d}(s_1, p_1, s_2, p_2) = -\frac{\bar{u}(p_1, s_1)\bar{u}(p_2, s_2)\Gamma_{DNN}^{s_d}\chi_{s_d}}{(p_1^2 - m^2)\sqrt{2}\sqrt{(2\pi)^3 2(p_2^2 + m^2)^{\frac{1}{2}}}}$$

General Solution to Bethe-Salpeter Equation

Wave function used for numerical estimates

$$\boxed{\Psi_d(p) = \Psi_d^{\mathrm{NR}}(p)\frac{M_d}{2(M_d - \sqrt{m^2 + p^2})}}$$

Ref: M. Sargsian and M. Strikman, Phys. Lett. B 639, 223 (2006).

Effects included in the amplitude calculations

- **Non-factorization effects**
- **Off-shell FSI re-scattering effets**
- **Charge-exchange re-scattering effects**
- **Off-shell electromagnetic interaction effects**

For the E12-10-003: AV18 and CD-Bonn wave functions were used in the calculations

Theoretical Calculations by J.M. Laget [J.M. Laget, Phys. Lett. B609, 49 (2005)]

❖ **Laget Diagrammatic Approach (calculate scattering amplitudes)**

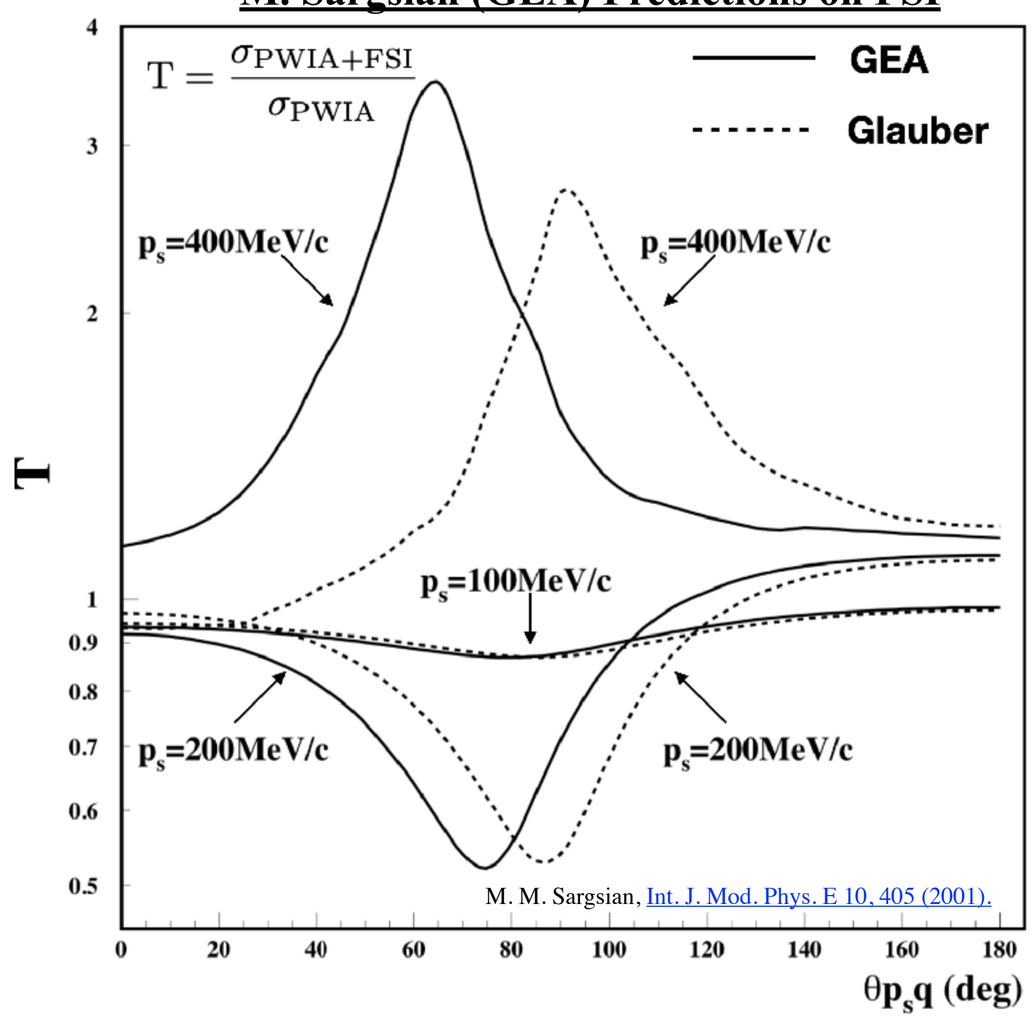
- **Scattering amplitudes are calculated using the Laget diagrammatic approach which takes into account the full kinematics from the beginning of the calculations See Ref.** [J.M. Laget, Phys. Rep. 69 (1981) 1]

Scattering Amplitude from Laget Diagrammatic Approach

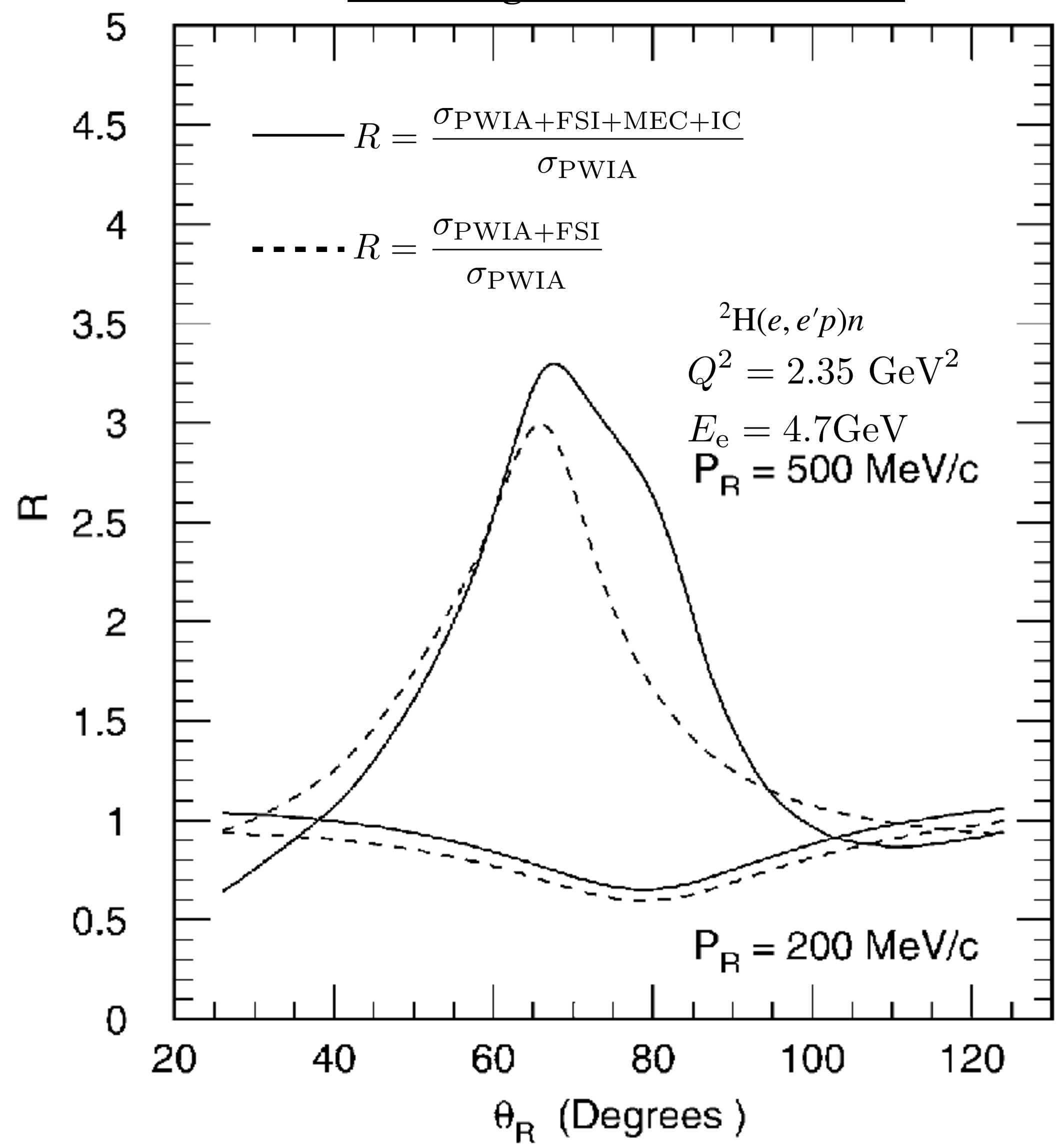
$$< \psi_p, \psi_n | A_{\rm tot} | \psi_D > = < \psi_p, \psi_n | A_{\rm PWIA} | \psi_D > + < \psi_p, \psi_n | A_{\rm FSI} | \psi_D > + < \psi_p, \psi_n | A_{\rm MEC} | \psi_D > + < \psi_p, \psi_n | A_{\rm IC} | \psi_D >$$

- **Laget calculations accounts for relativistic effects of the bound nucleons from the beginning of the calculations**
  - **Laget FSI calculations agree with GEA prediction of re-scattering peak at ~70 deg**

M. Sargsian (GEA) Predictions on FSI



J.M. Laget Predictions on FSI



Glauber Eikonal Approximation: **recoil effects are neglected (stationary bound nucleon) and FSI peak stays at neutron recoil angles ~90 deg**

Generalized Eikonal Approximation: **Accounts for the relativistic effects of bound nucleons and predicts FSI peak at neutron recoil angles of ~ 70 deg.**

Theoretical Calculations by S. Jeschonnek & J.W.V. Orden

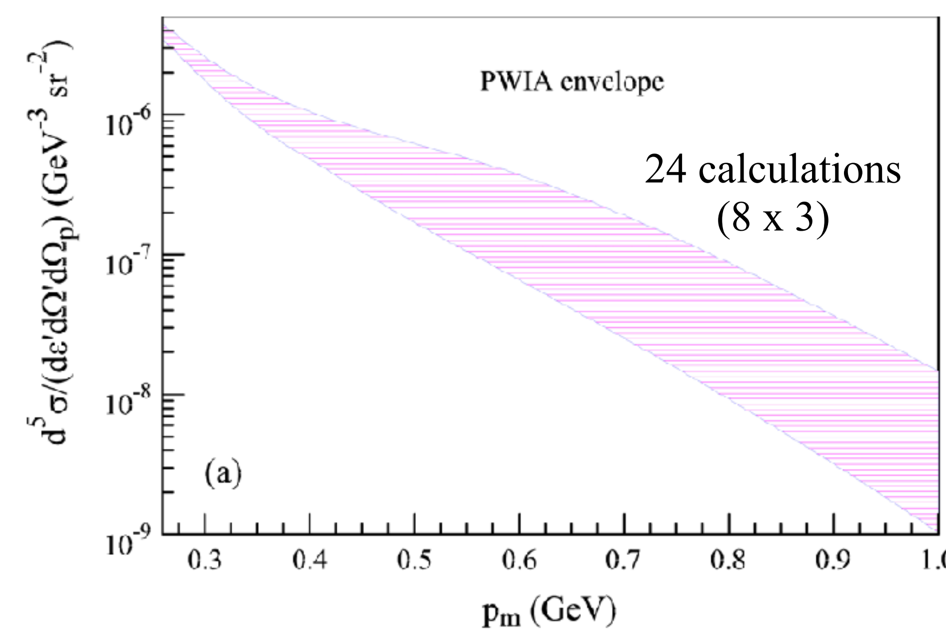
[W.P. Ford, S. Jeschonnek and J.W.V. Orden, Phys. Rev. C90, 064006 (2014)]

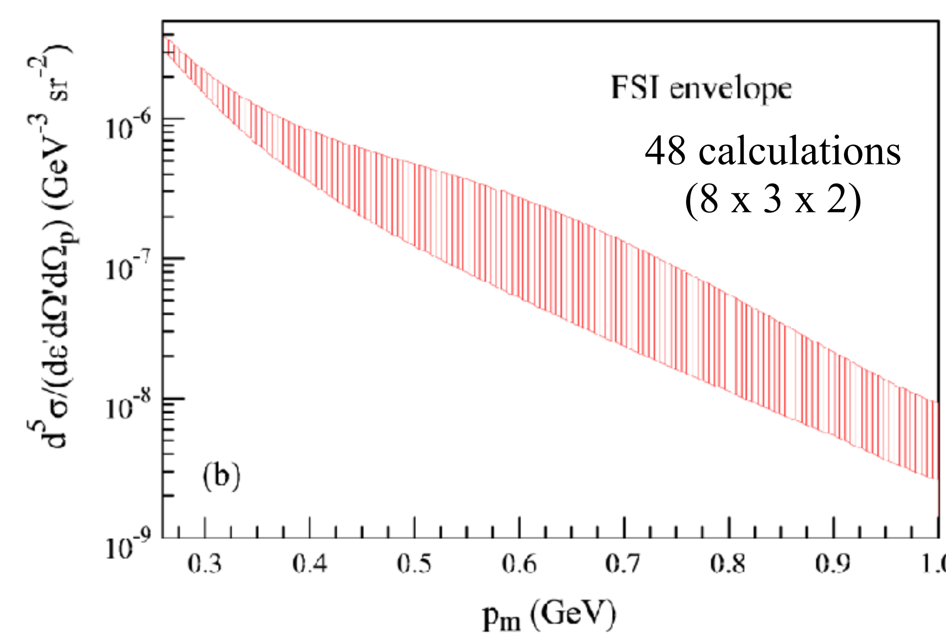
❖ **Bethe-Salpeter formalism used in the calculations of wave functions**

- **The new method of extracting the momentum distributions takes into account a variety of model inputs providing a theoretical uncertainty**
- **A wide variety of bound-state wave functions, nucleon form factors and final state interactions are used as input in the cross section calculations (band of cross section calculations)**
- **The E12-10-003 kinematics from the original proposal were used in the calculations**

Final state interactions	Form factors	Deuteron wave function
		IIB
		WJC 1
Regge	GKex05	WJC 2
SAID	AMT	AV18
	MMD	CD Bonn
		NIMJ 1
		NIMJ 2
		NIMJ 3

Cross section calculations using combinations of these parametrizations and wave functions were provided by S. Jeschonnek and J.W.V. Orden using the actual kinematics for this experiment.





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

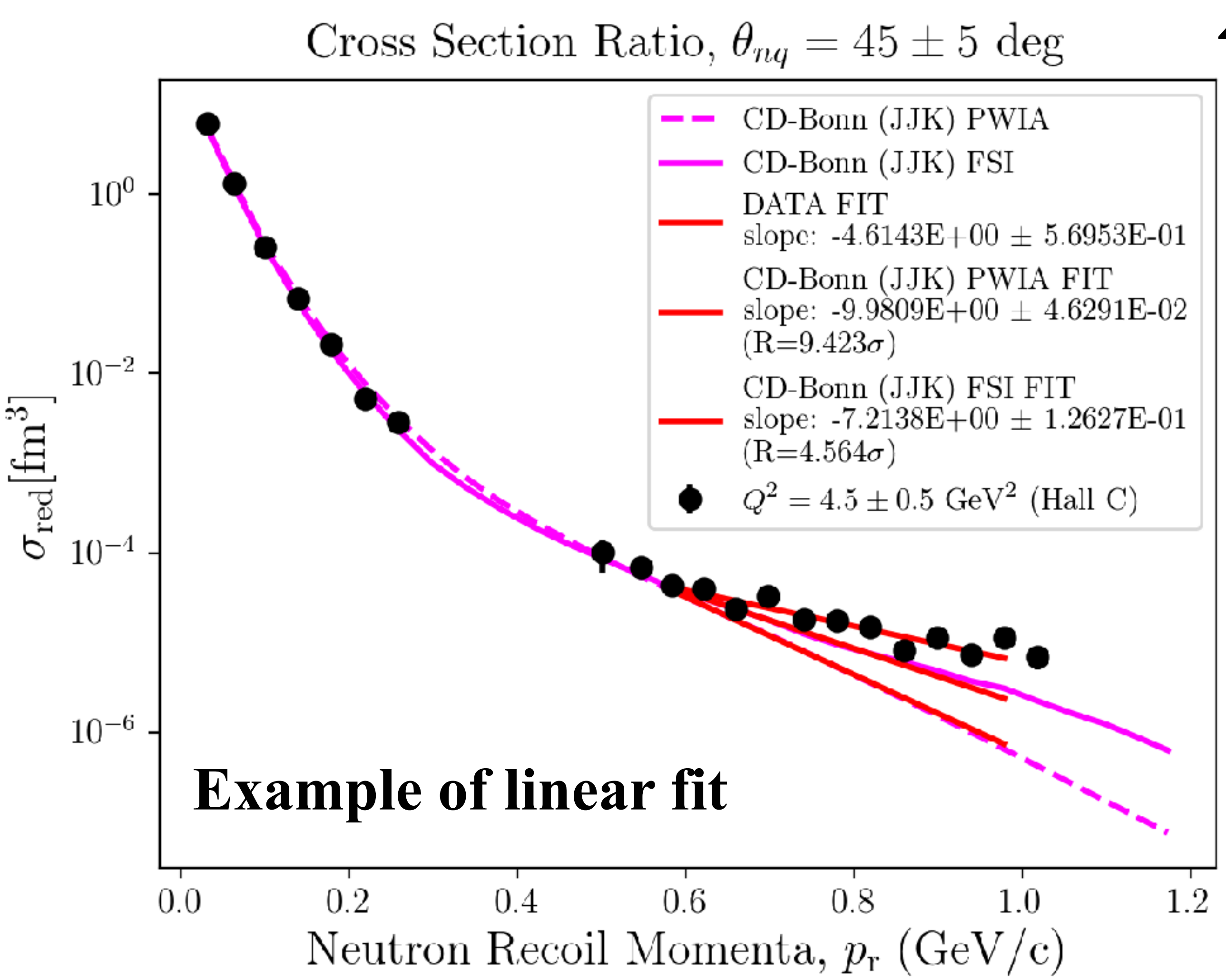
- Calculate the Z-score to determine number of standard deviations between slopes of the the data and theory linear fits.

data slope

theory slope

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

data slope error



See Backup Slides for all the plots with linear fits

Statistical Significance Test: Fit Slopes and Chi2

- **Slopes are dependent on the NN potential and approximately independent of different parametrizations within the same potential**
- **The data differs from the CD-Bonn slopes by ~ 4 - 9 standard deviations (statistical fluctuations extremely unlikely)** [See Slides 78,79]

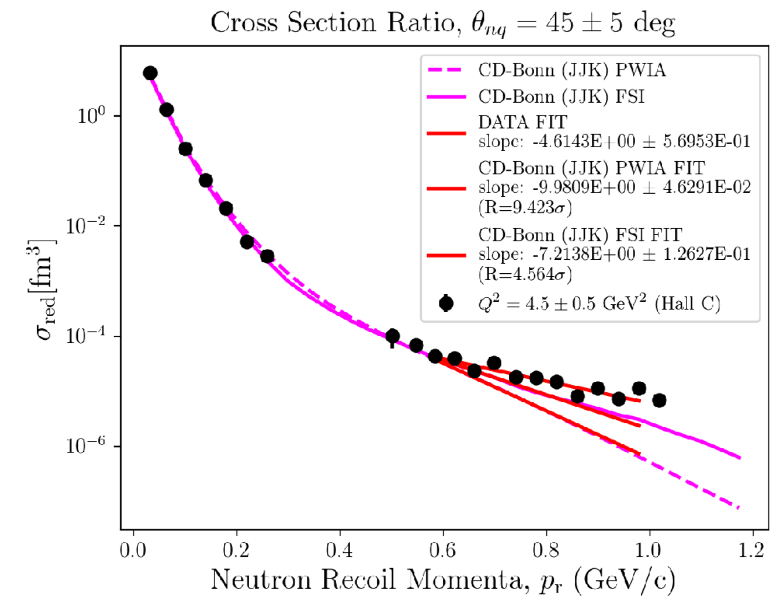
Theoretical Model	PWIA (35 deg) SLOPE	PWIA (45 deg) SLOPE	FSI (35 deg) SLOPE	FSI (45 deg) SLOPE
Paris (Galster)	-8.3	-8.3	-8.2	-7.7
AV18 (JJK)	-7.9	-7.8	-8.4	-7.3
AV18 (GKex05)	-8.1	-8.1	-8.8	-8.0
AV18 (AMT)	-8.1	-8.1	-8.8	-8.0
CD-Bonn (JJK)	-10.1	-10.0	-9.6	-7.2
CD-Bonn (GKex05)	-10.3	-10.3	-10.2	-7.7
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 slope: -4.7 χ^2_{red} : 0.66	45 deg slope: -4.6 χ^2_{red} : 1.4

Interpreting the Statistical Significance Test

p-value definition:

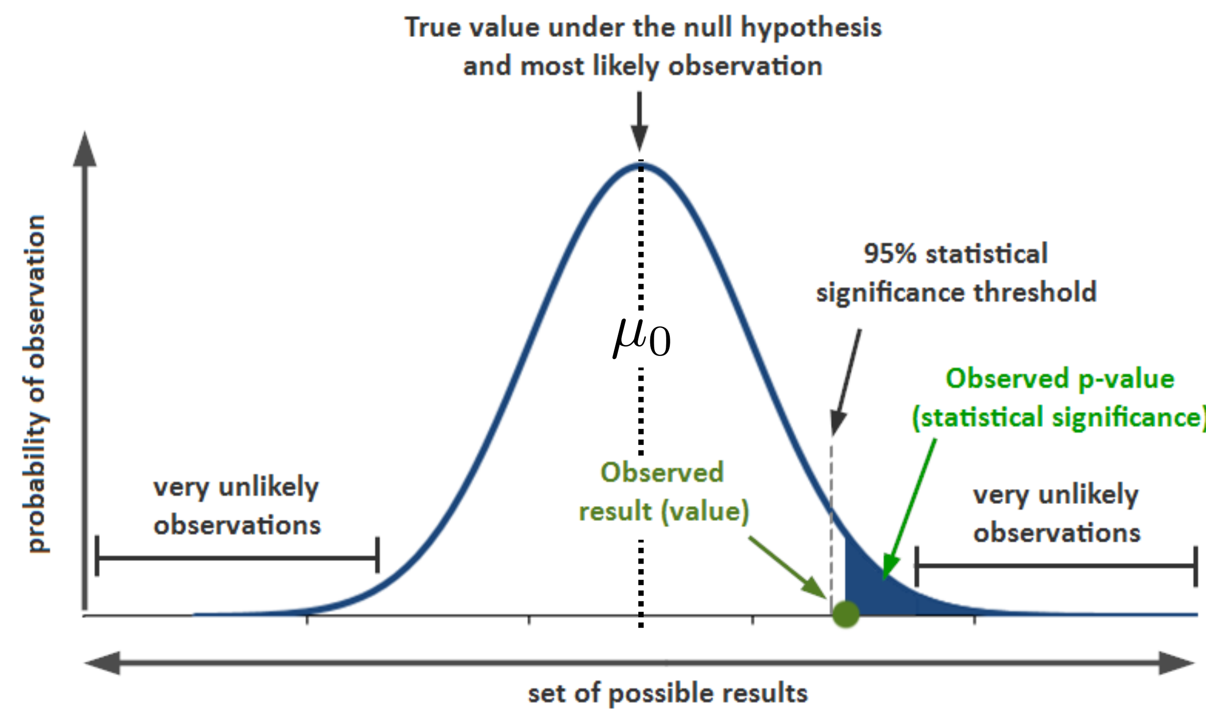
The *p*-value is the probability of getting the observed value of the test statistic, or a value with even greater evidence against *H0*, if the null hypothesis is true



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

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

Distribution of Z if H_0 is true:



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

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:

$$\bar{X} \equiv \mu_{\mathrm{data}} - \mu_{\mathrm{theory}} \quad \text{(Slope difference)}$$

$$\mu_0 = 0 \quad n = 1$$

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

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

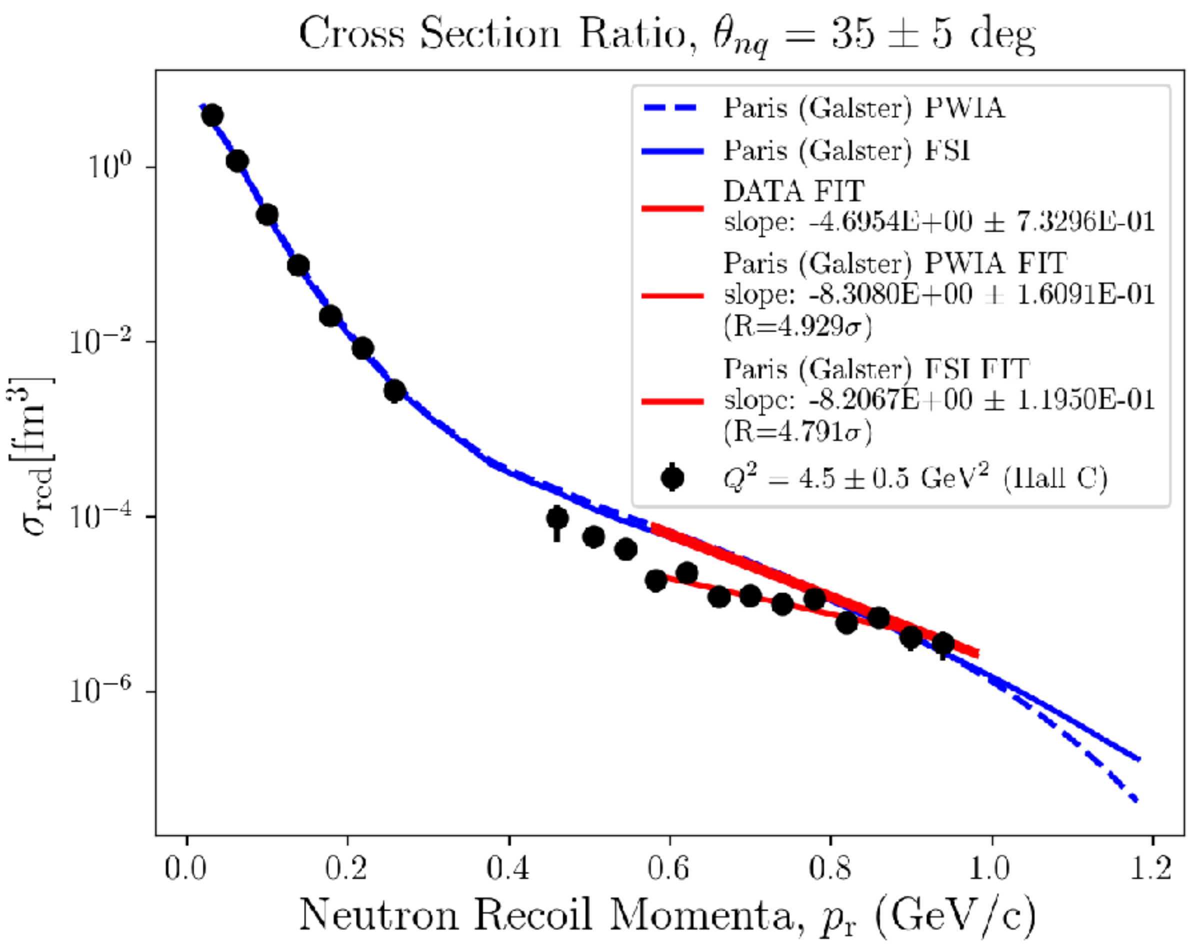
- The p-values describe the probability that the observed difference in the measurements is due to a statistical fluctuation

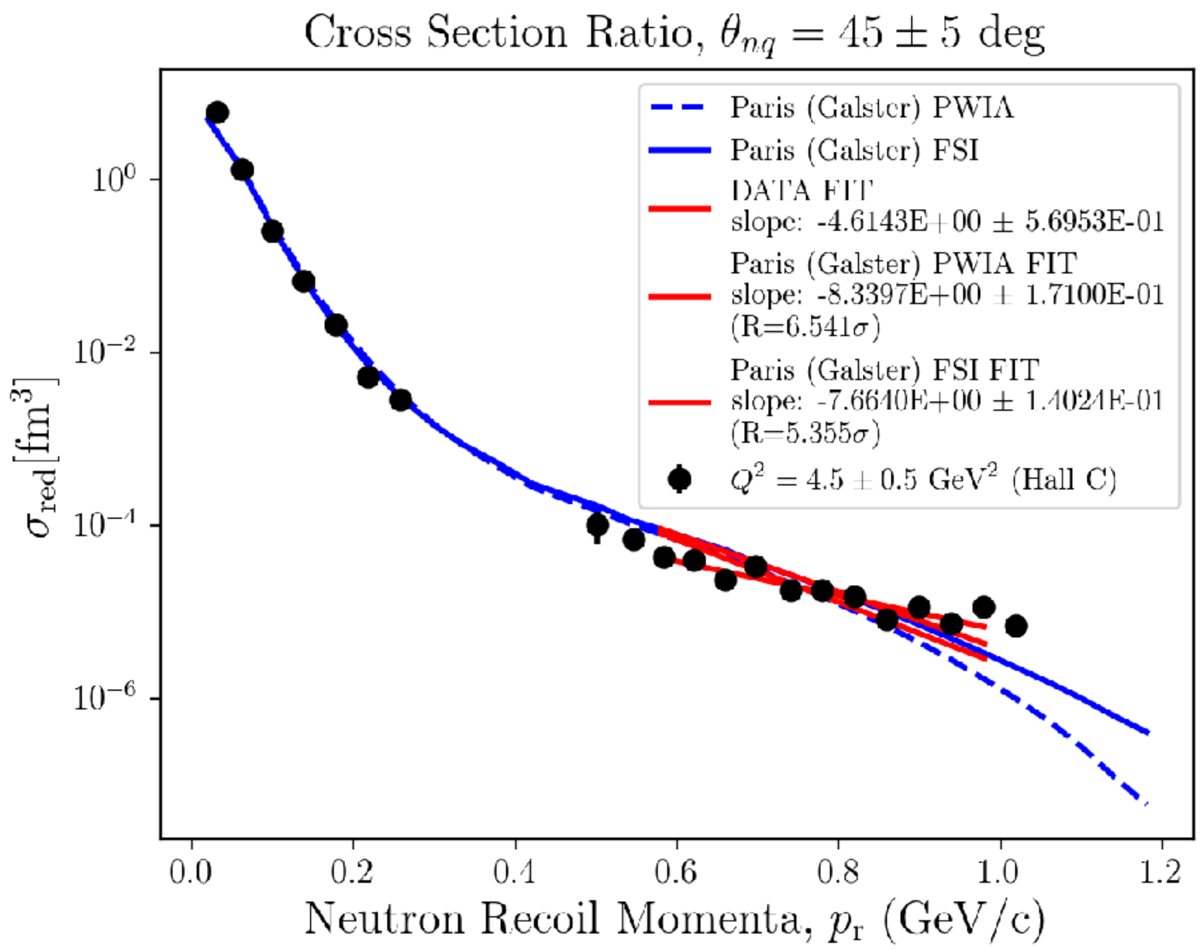
- The data differs from the CD-Bonn slopes by ~ 4 - 9 standard deviations (statistical fluctuations extremely unlikely)

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

D(e,e’p)n Linear Fit Plots

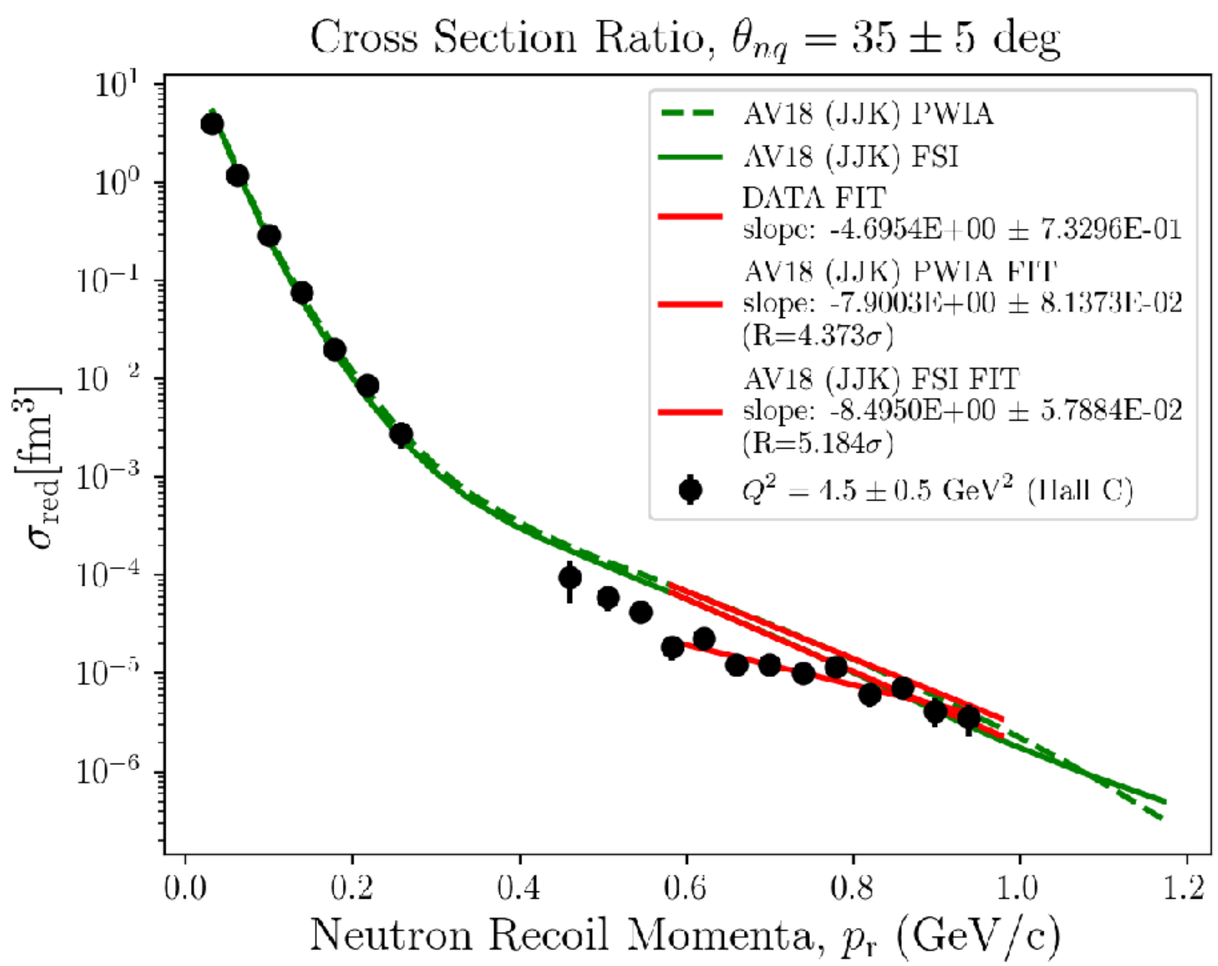
Paris Potential (Galster parametrization)

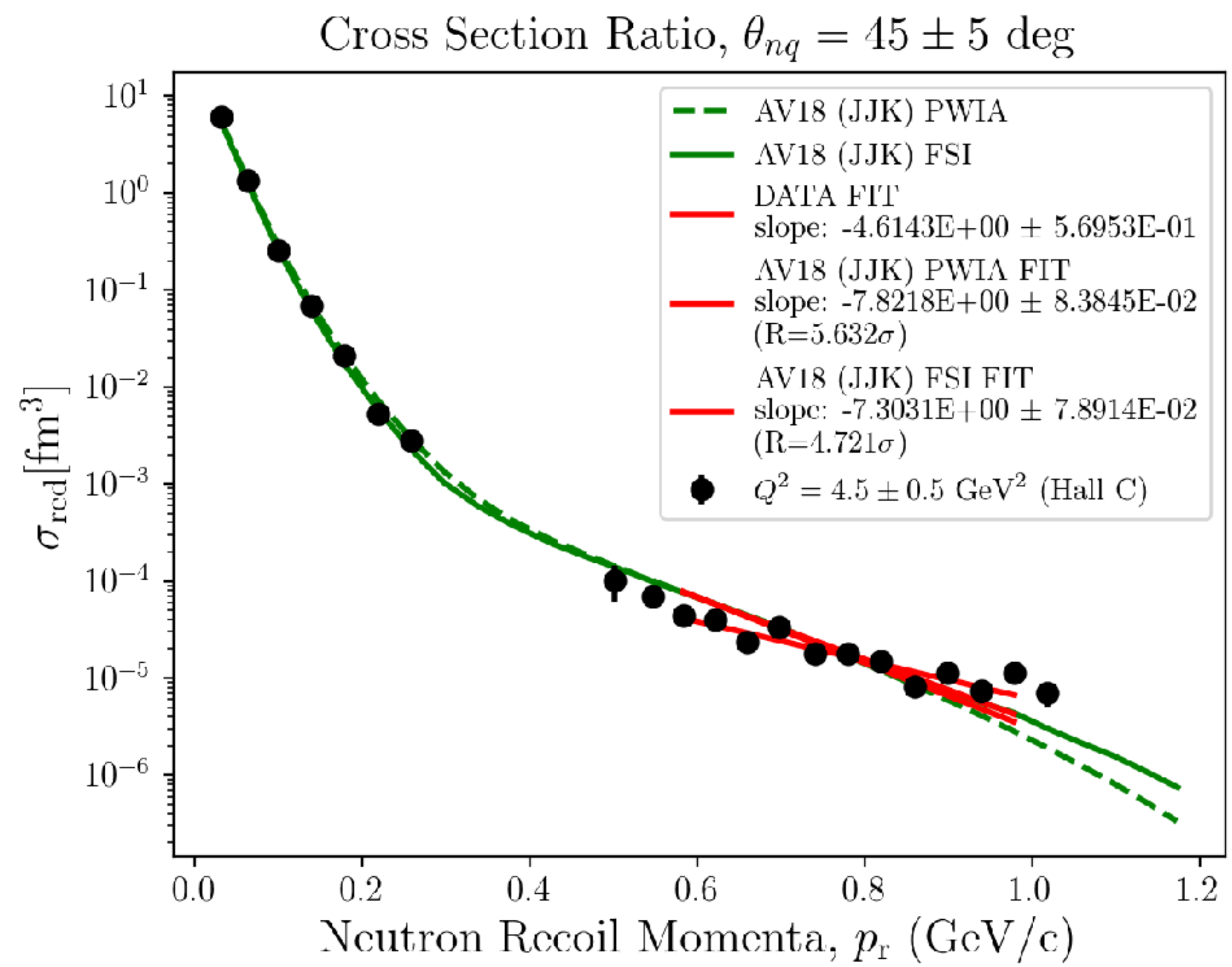




D(e,e'p)n Linear Fit Plots

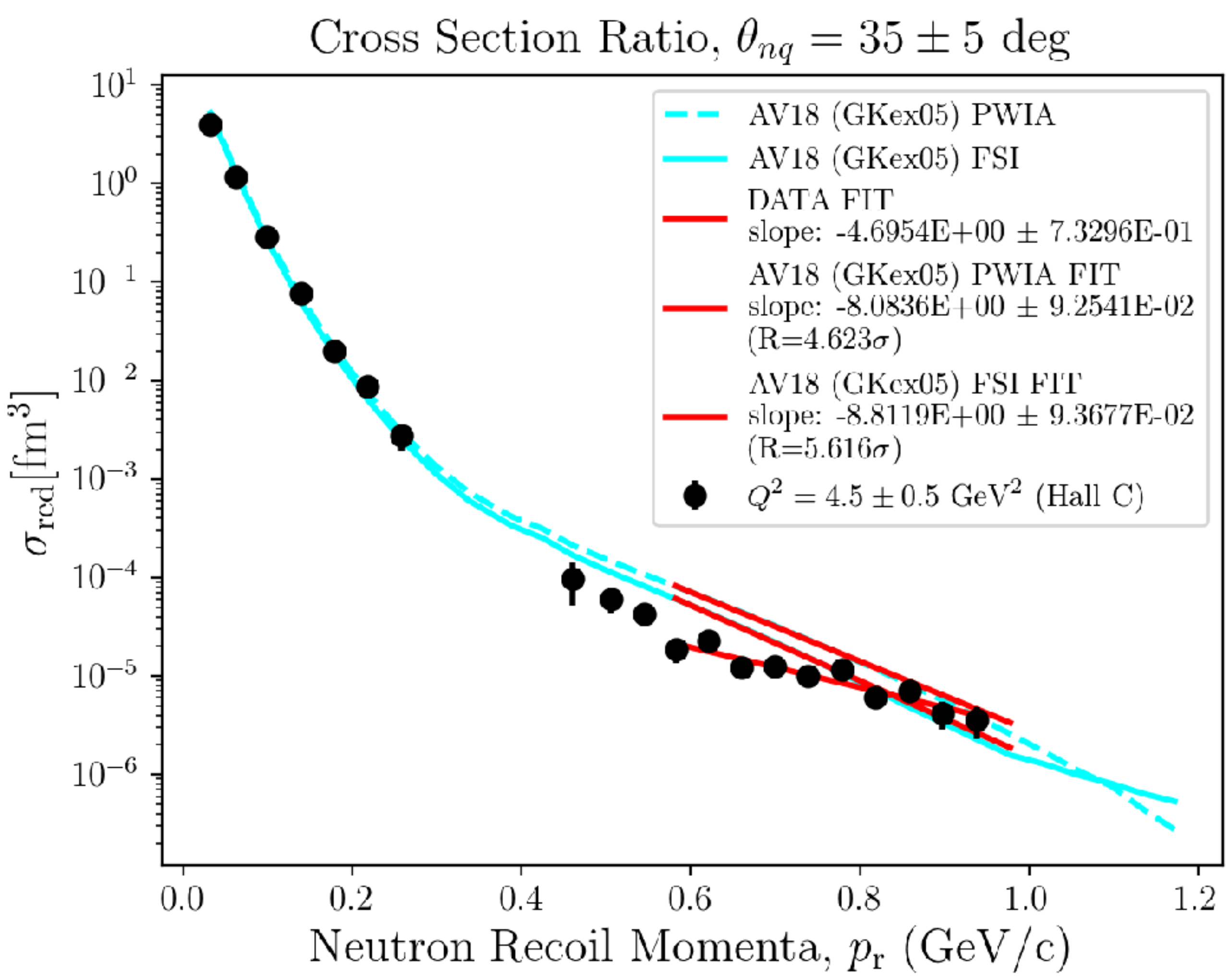
AV18 (JJK parametrization)

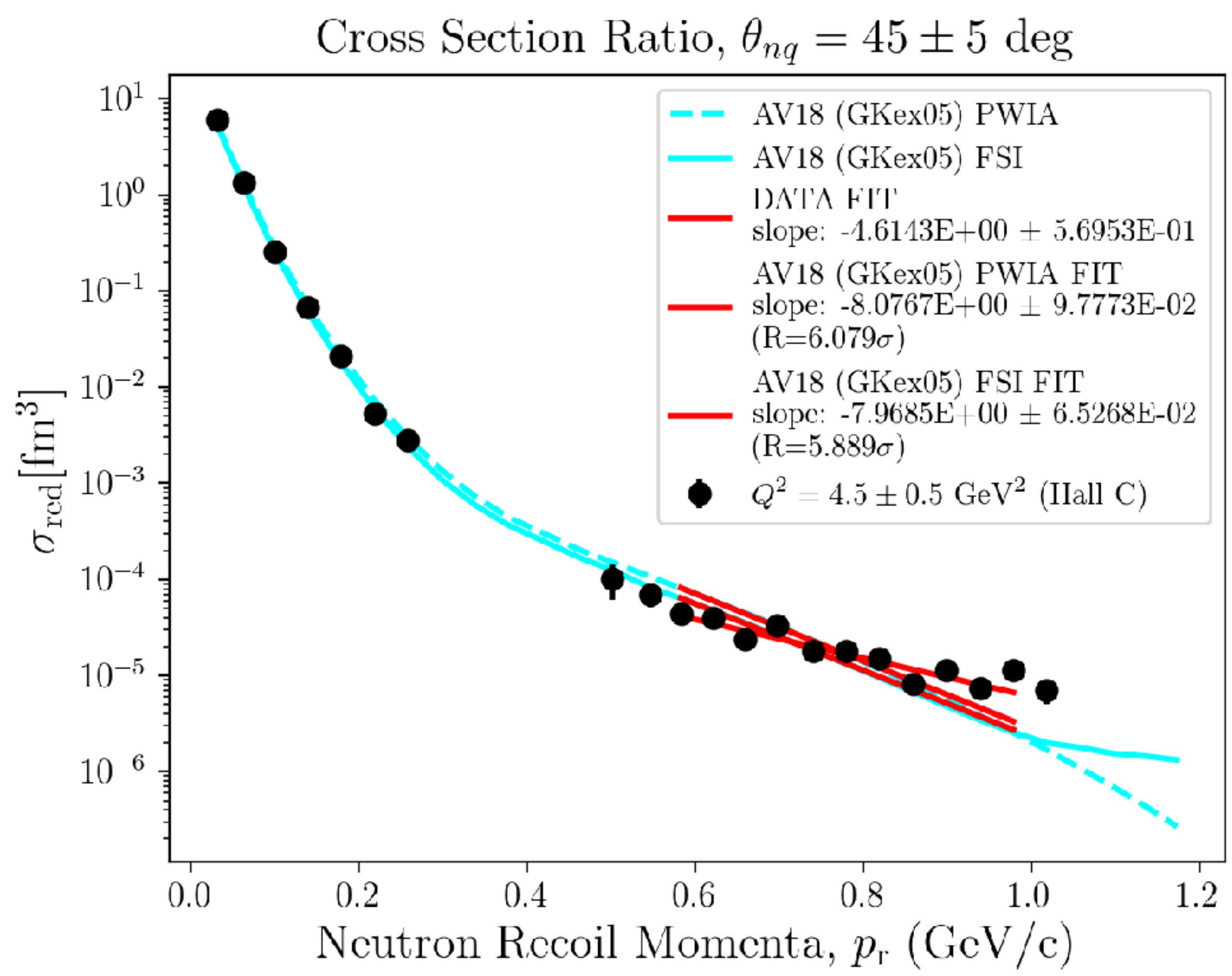




D(e,e'p)n Linear Fit Plots

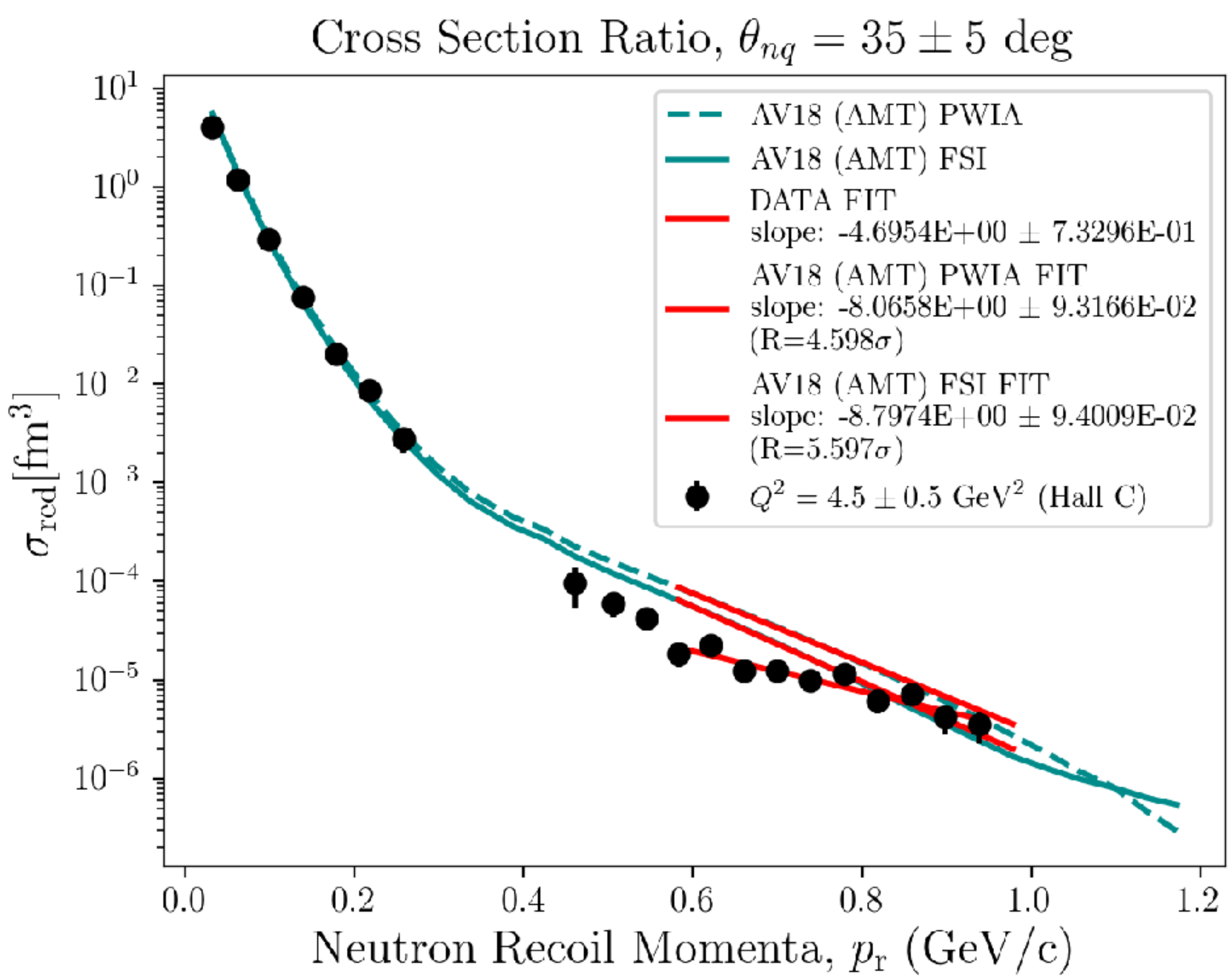
AV18 (GKex05 parametrization)

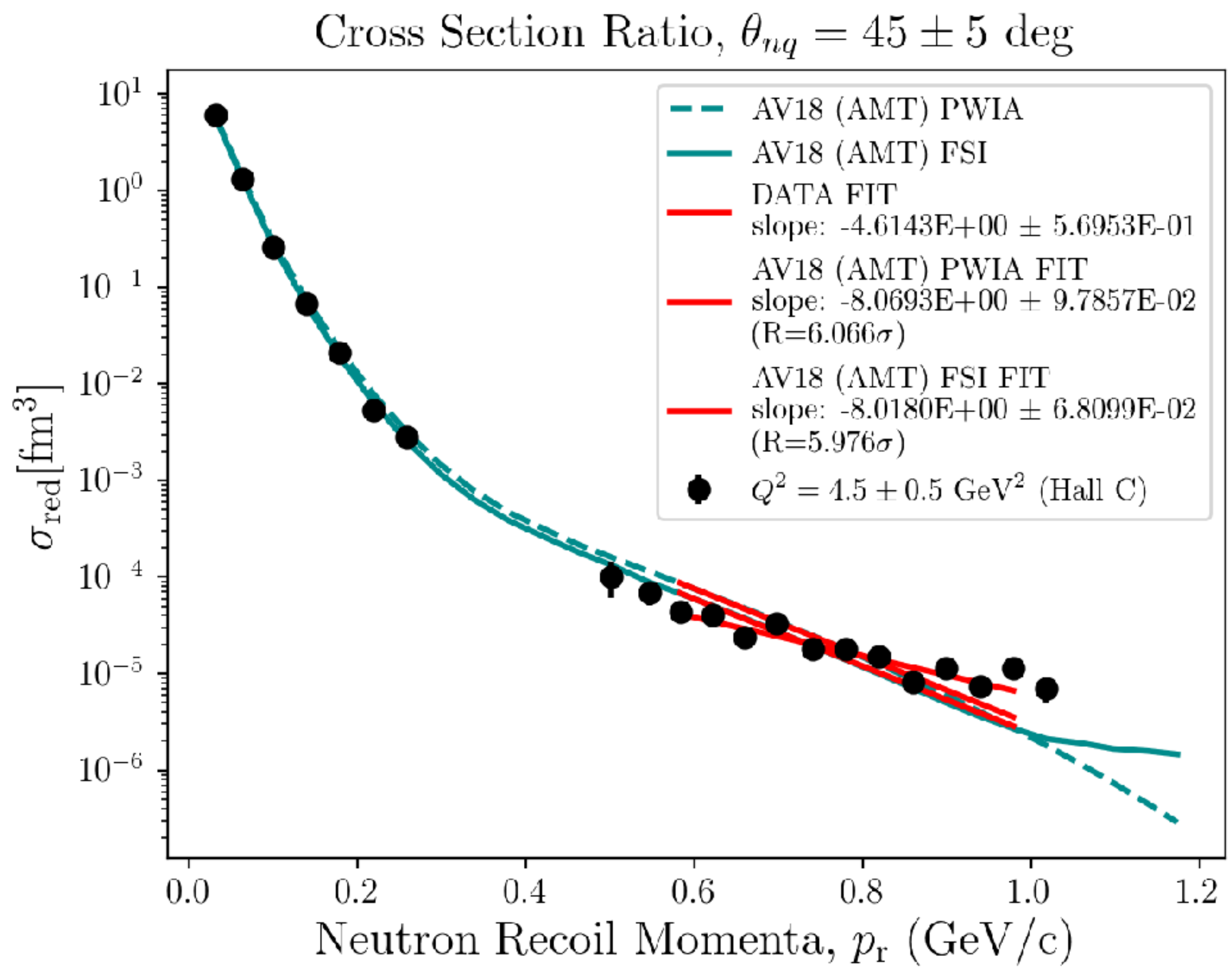




D(e,e'p)n Linear Fit Plots

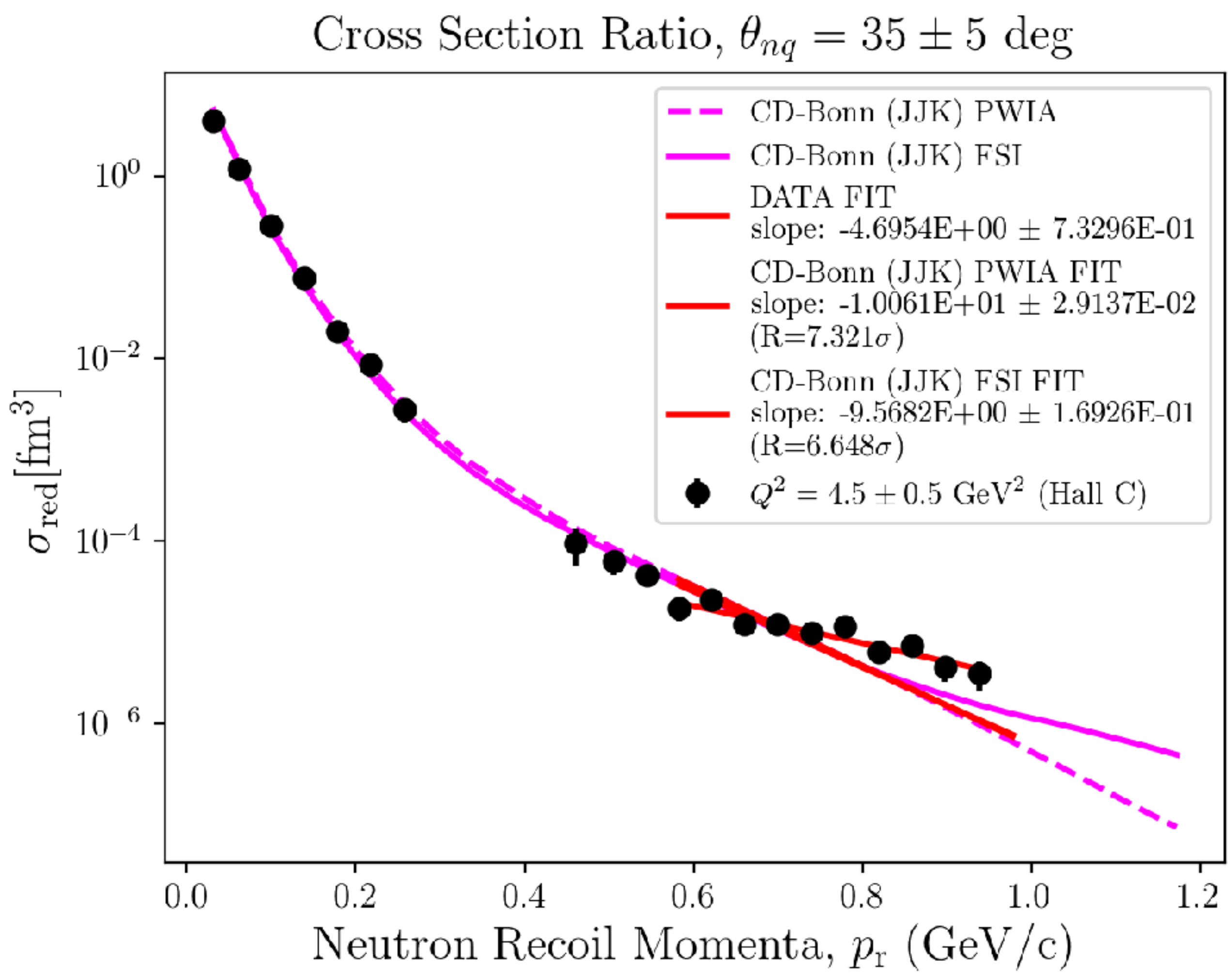
AV18 (AMT parametrization)

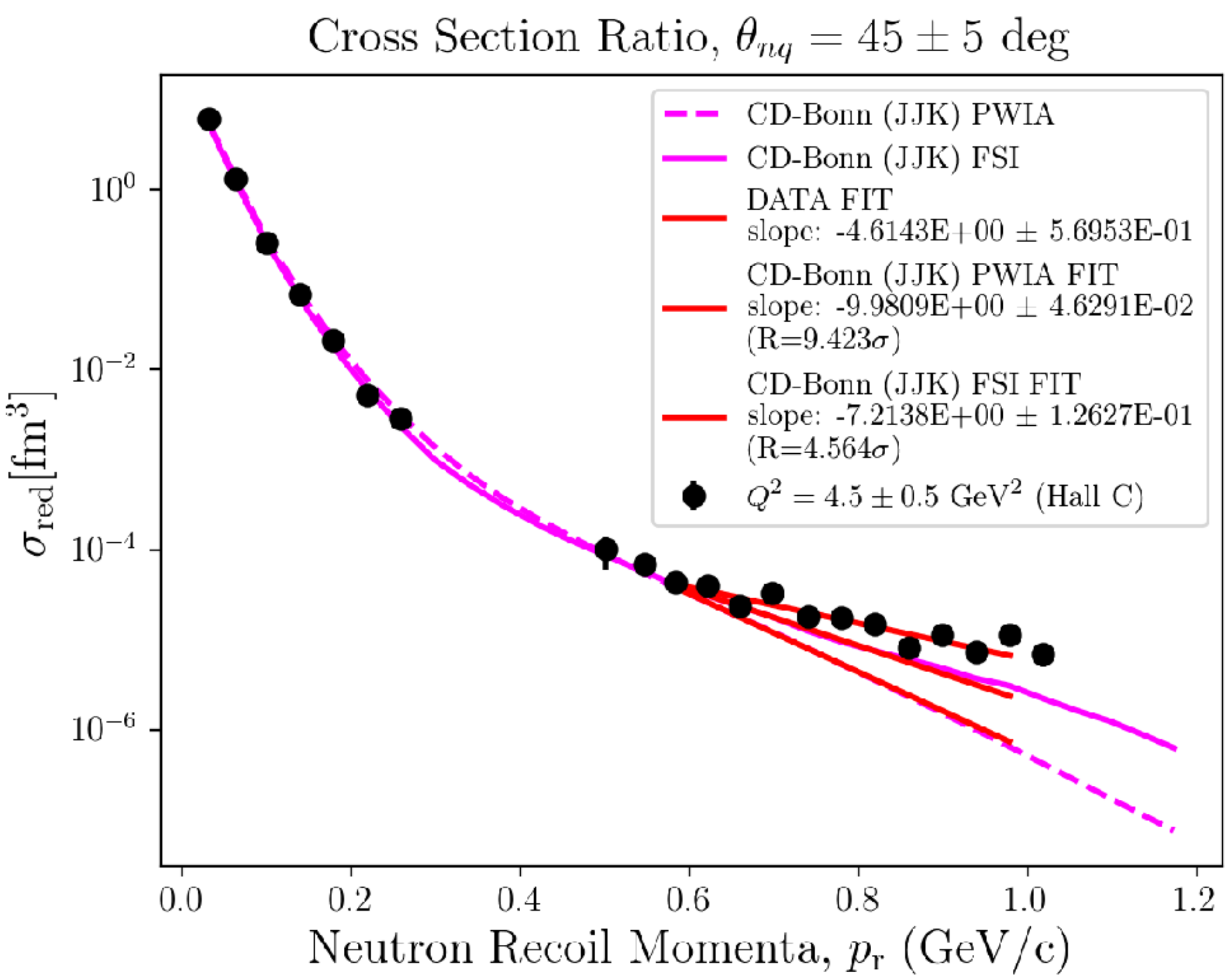




D(e,e'p)n Linear Fit Plots

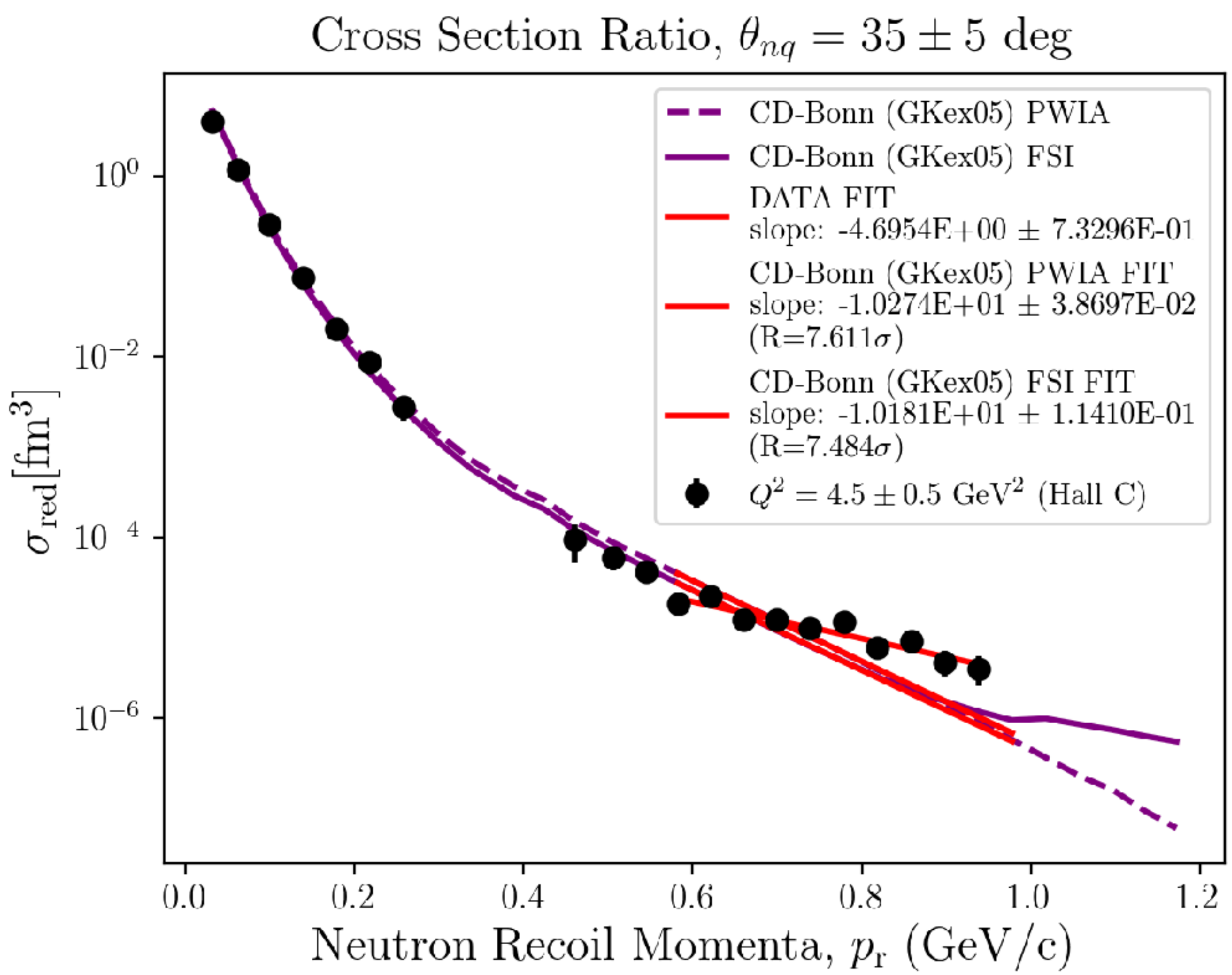
CD-Bonn (JJK parametrization)

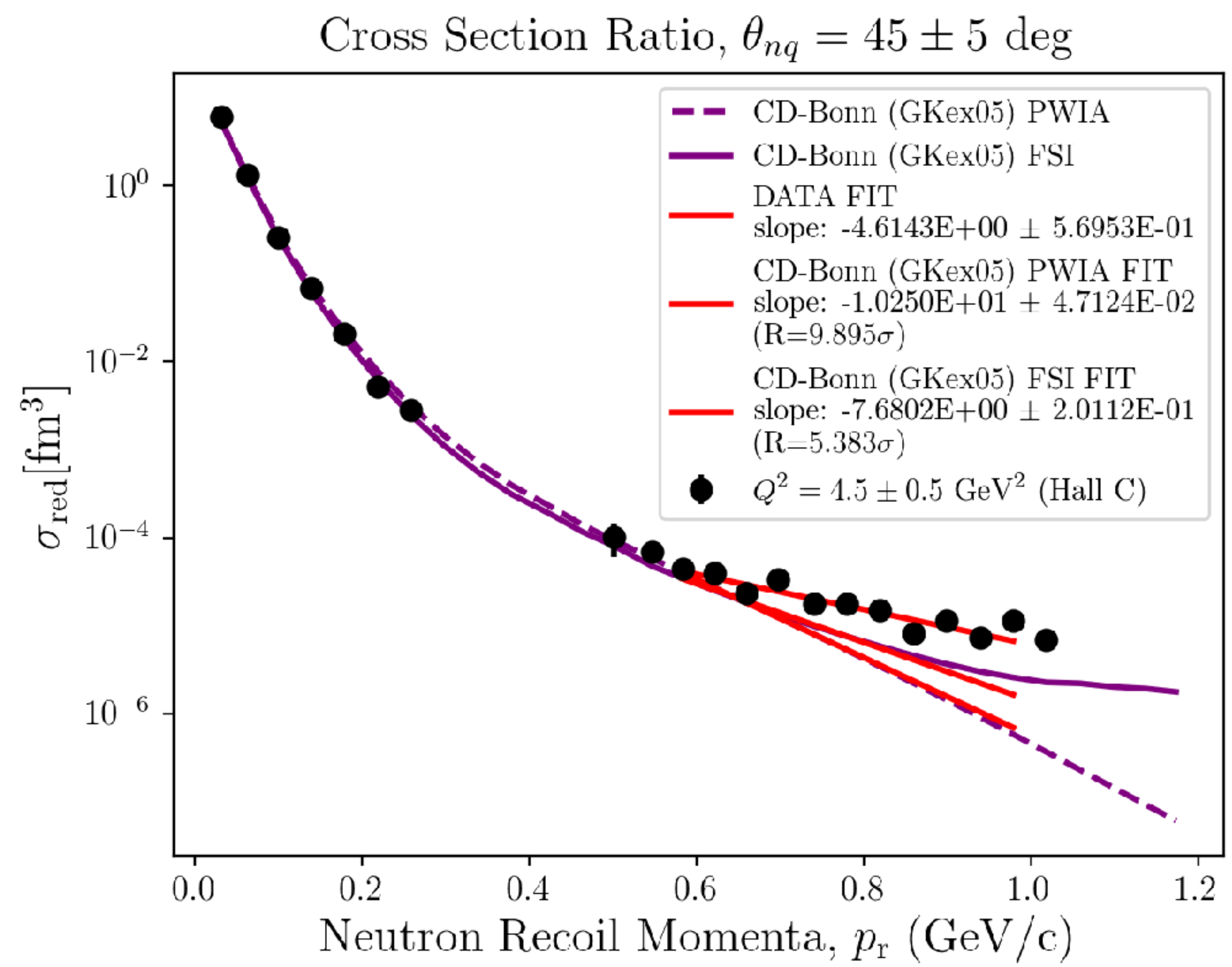




D(e,e'p)n Linear Fit Plots

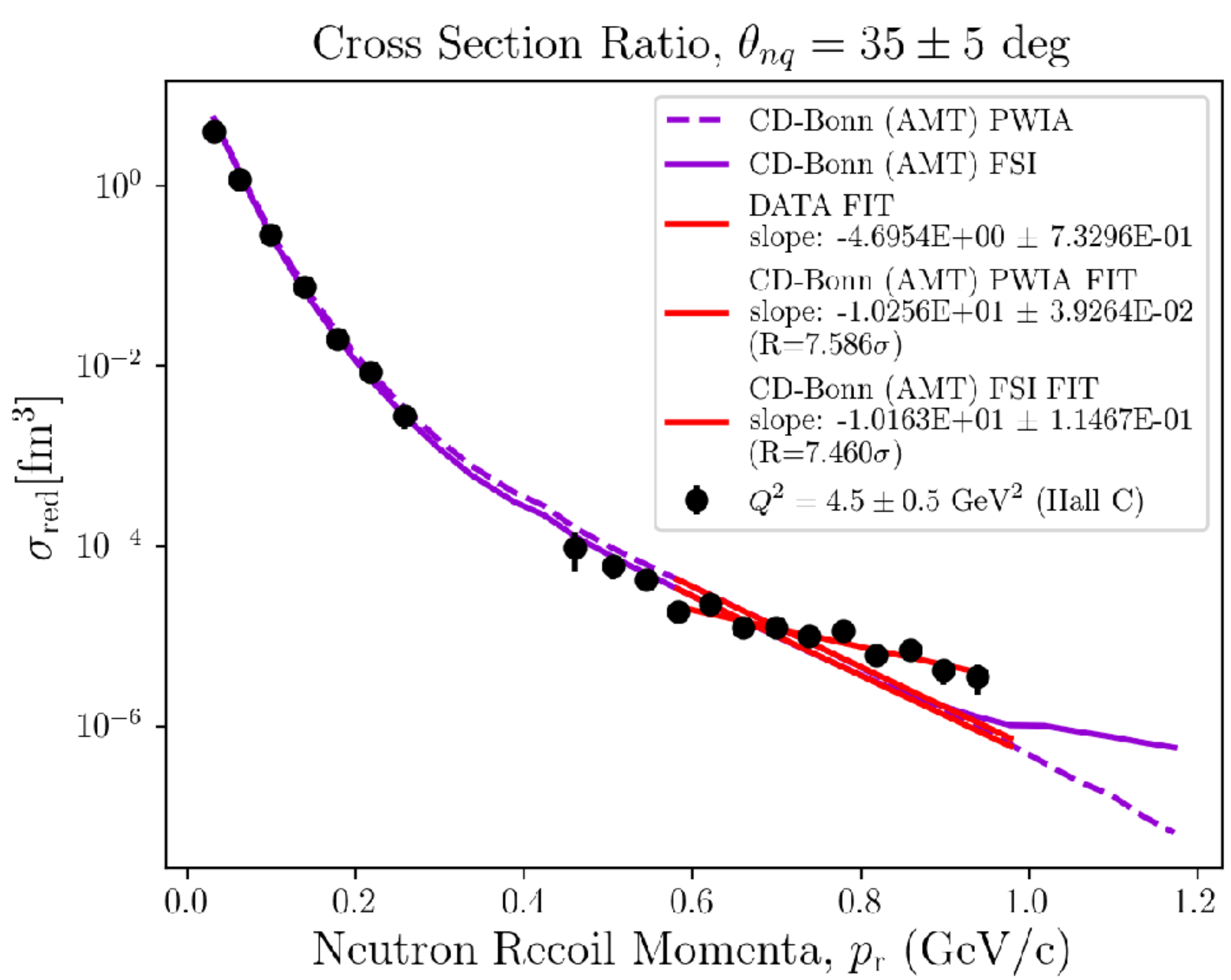
CD-Bonn (GKex05 parametrization)

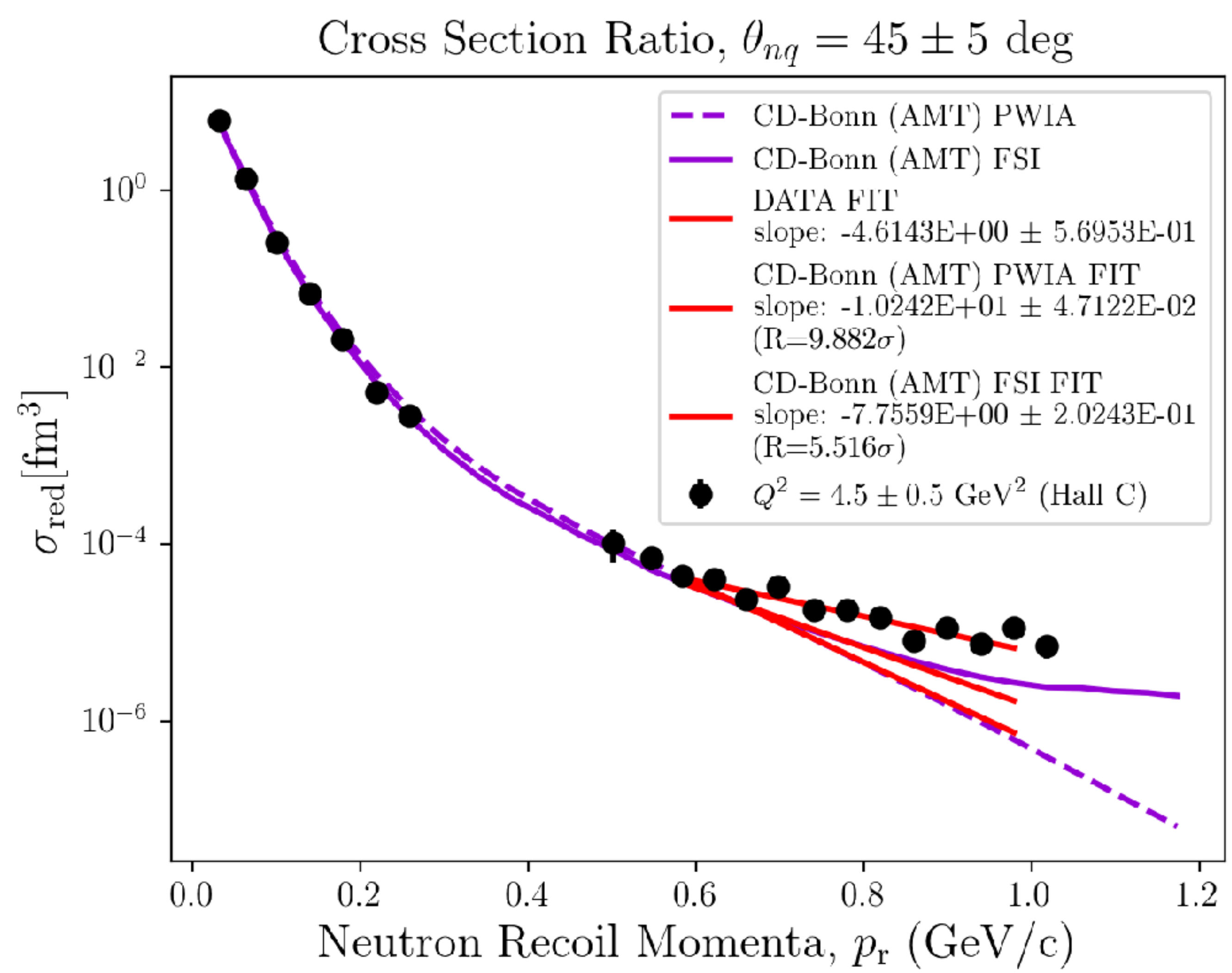




D(e,e'p)n Linear Fit Plots

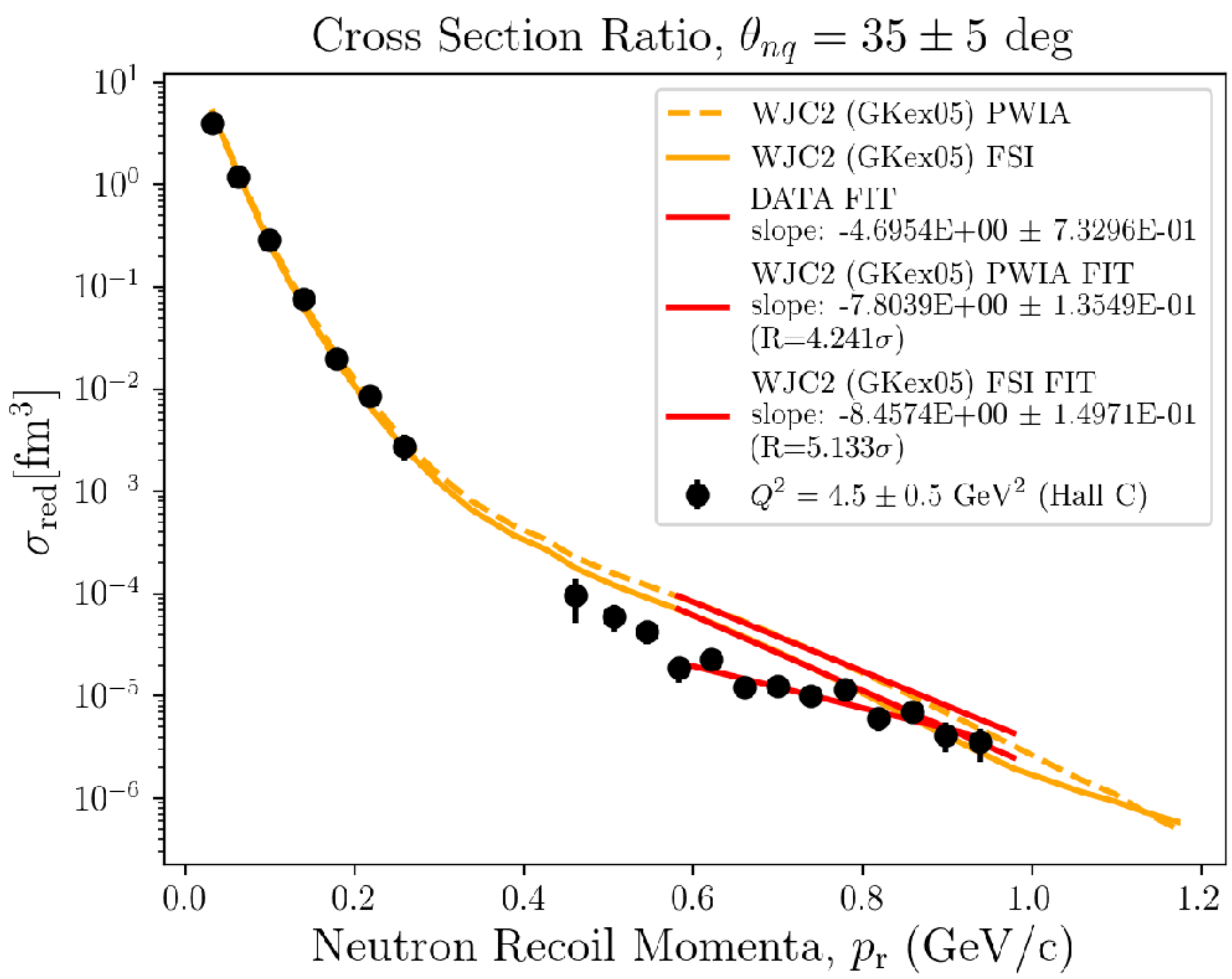
CD-Bonn (AMT parametrization)

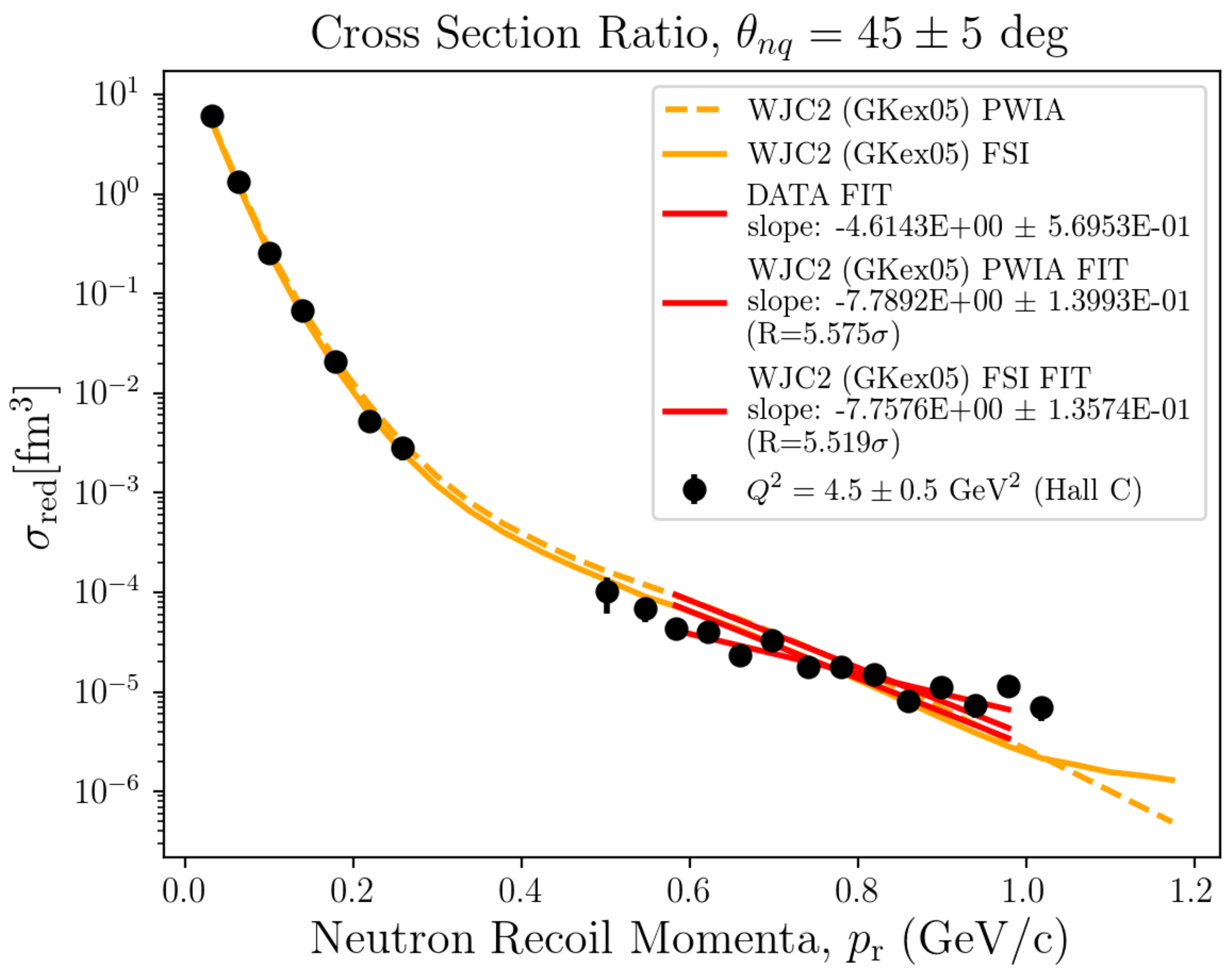




D(e,e'p)n Linear Fit Plots

WJC2 (GKex05 parametrization)





D(e,e'p)n Linear Fit Plots

WJC2 (AMT parametrization)