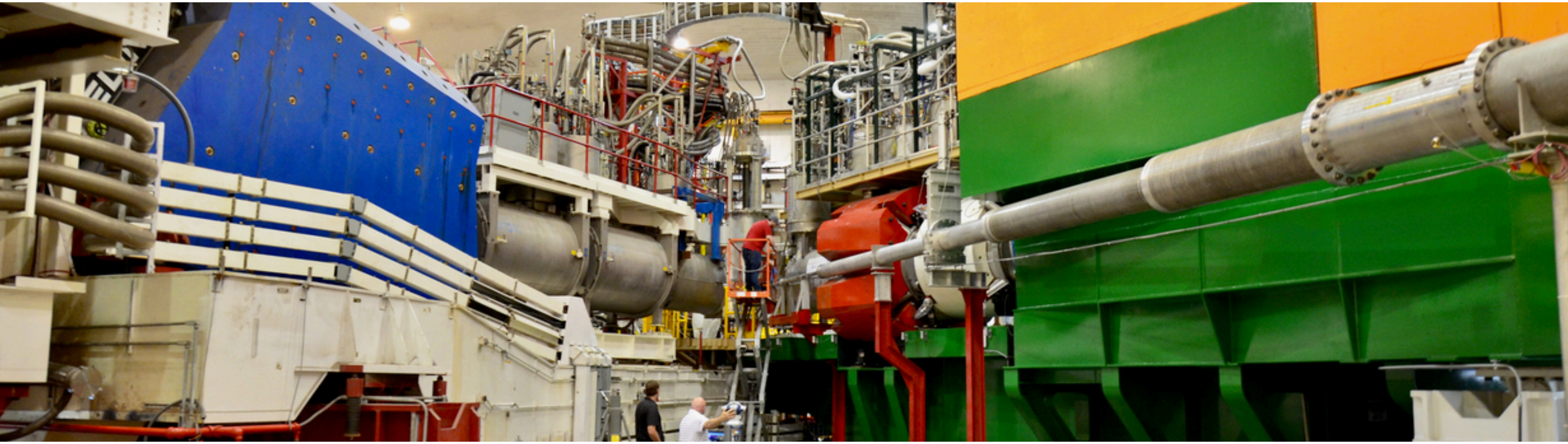


Results on the D(e,e'p)n Commissioning Experiment and Outlook

Hall C Collaboration Meeting, January 28-29, 2020

Carlos Yero

Spokespeople: Drs. Werner Boeglin and Mark Jones

Jefferson Lab
Exploring the Nature of Matter

FIU

Hall-C

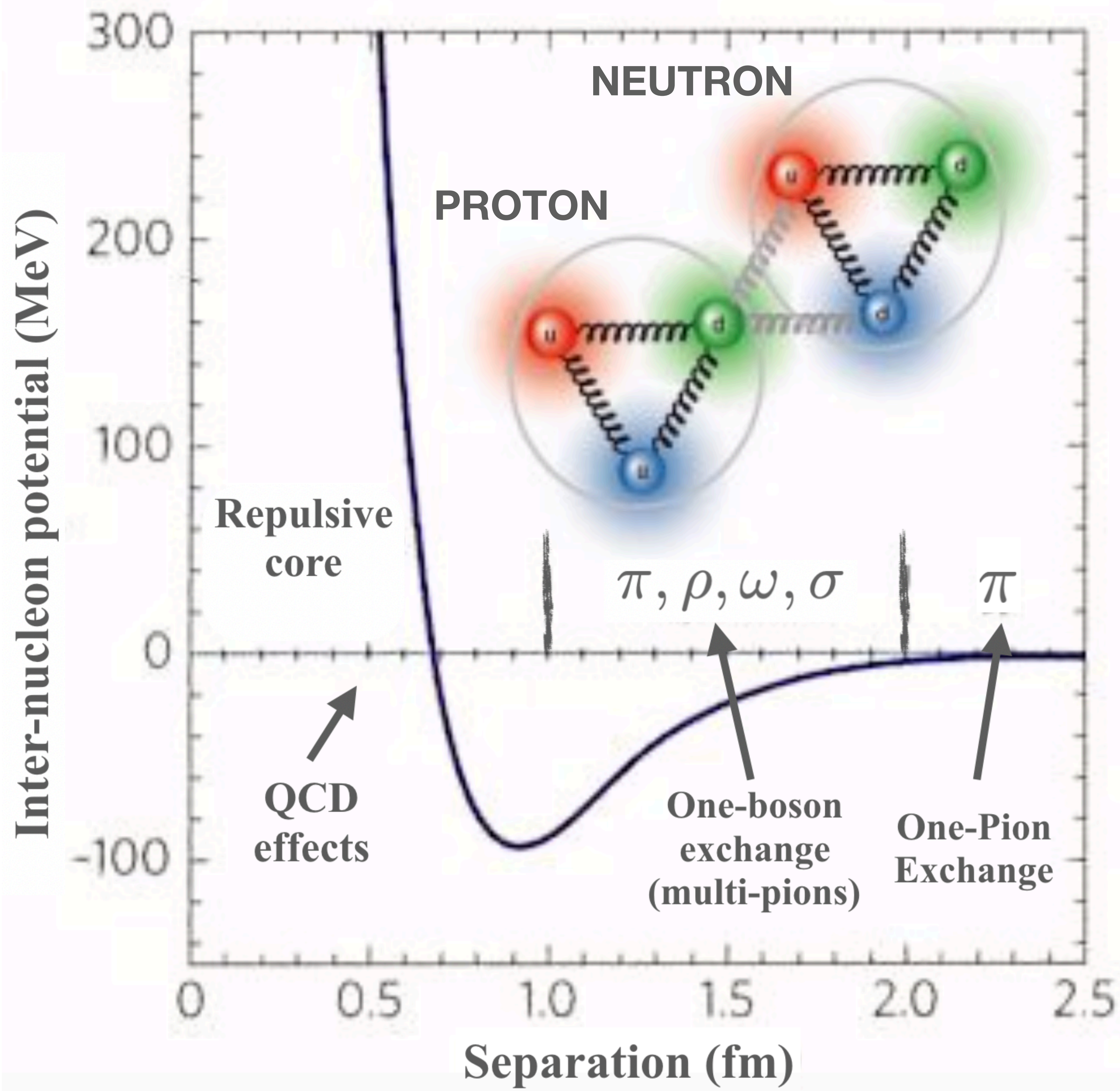
Motivation

- ☑ **Deuteron is the simplest np bound state: starting point to study nuclear force (or NN potential)**

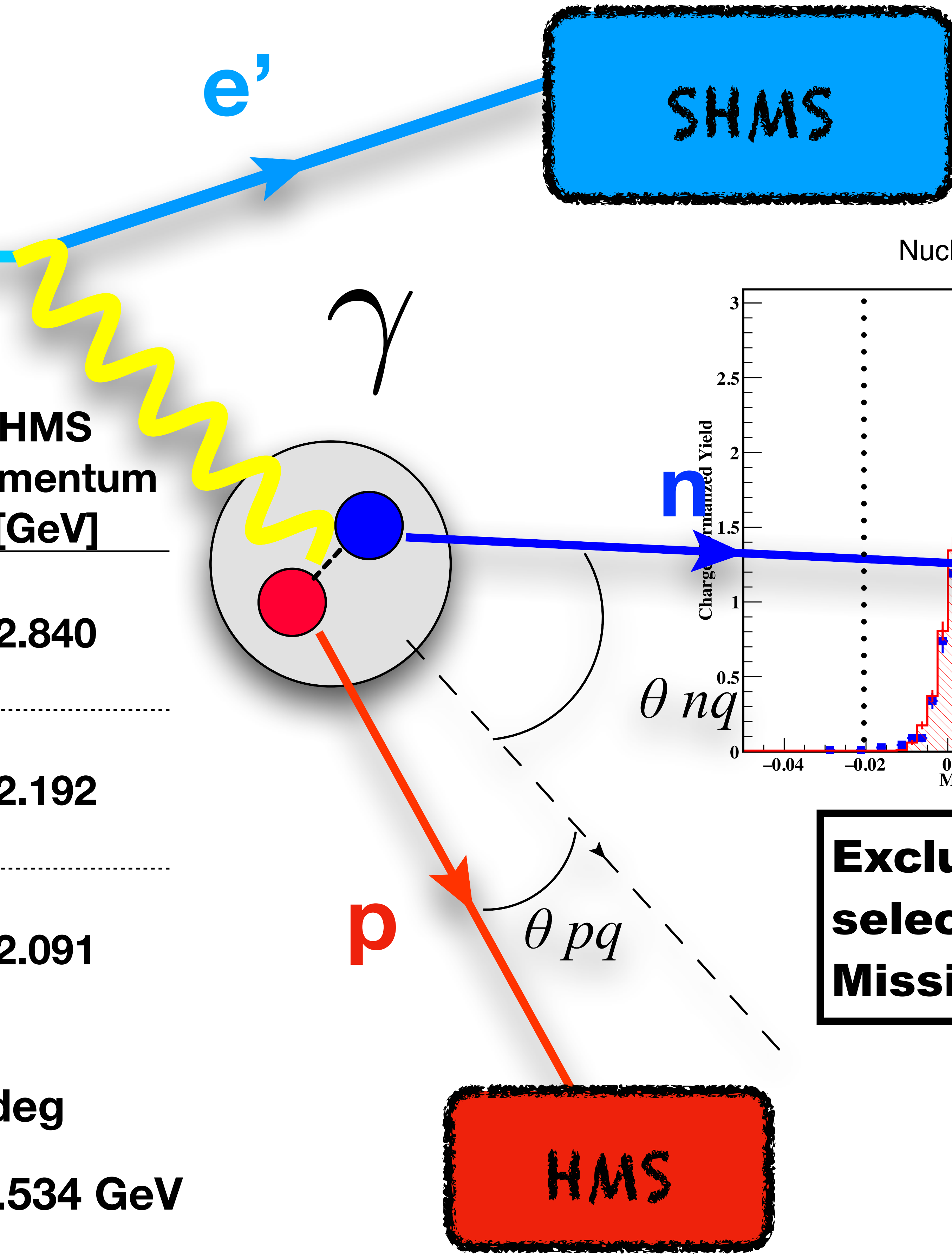
- ☑ **Understand the short range structure by probing high momentum tails**

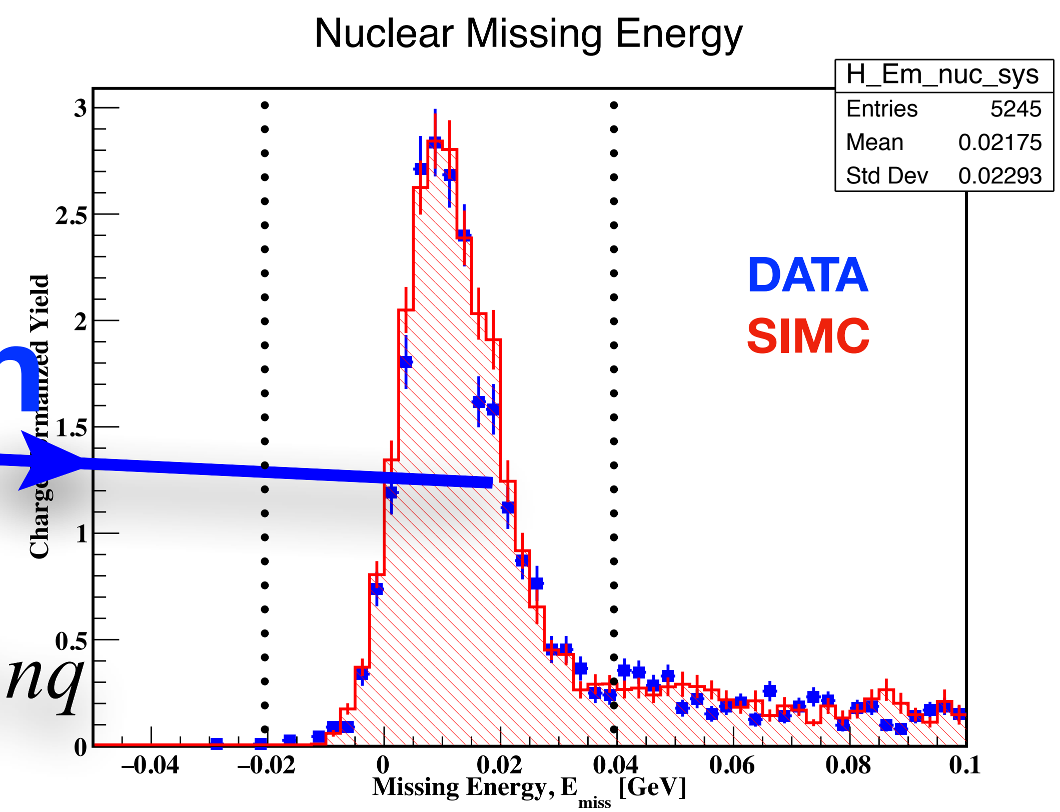
- ☑ **At short ranges, np start overlap: overlap is directly related to SRCs in A>2 nuclei**

- ☑ **Extract momentum distributions beyond 500 MeV/c recoil momenta at PWIA kinematics**



D(e,e'p)n Kinematics





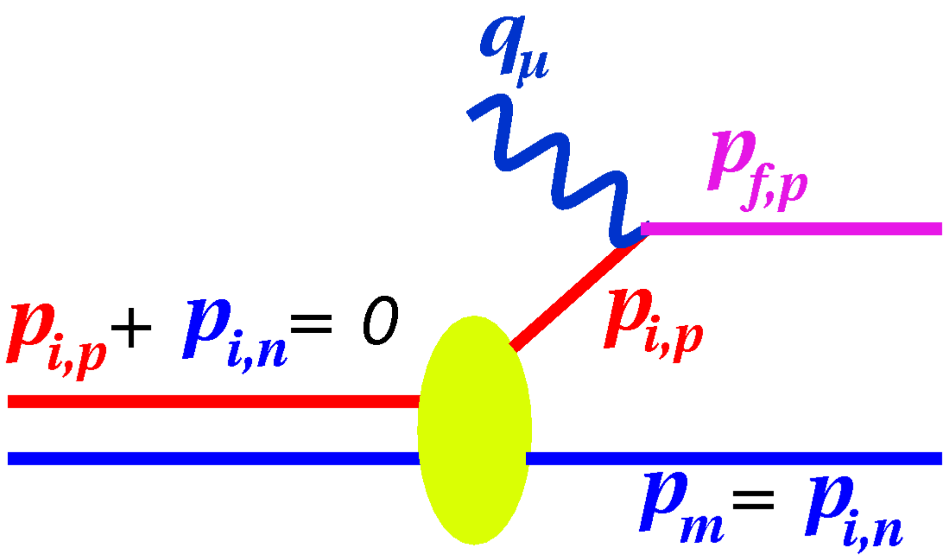
Pm [MeV]	HMS Angle [deg]	HMS Momentum [GeV]
80	~38.8	2.840
580	~55	2.192
750	~58.3	2.091

SHMS Angle: 12.194 deg

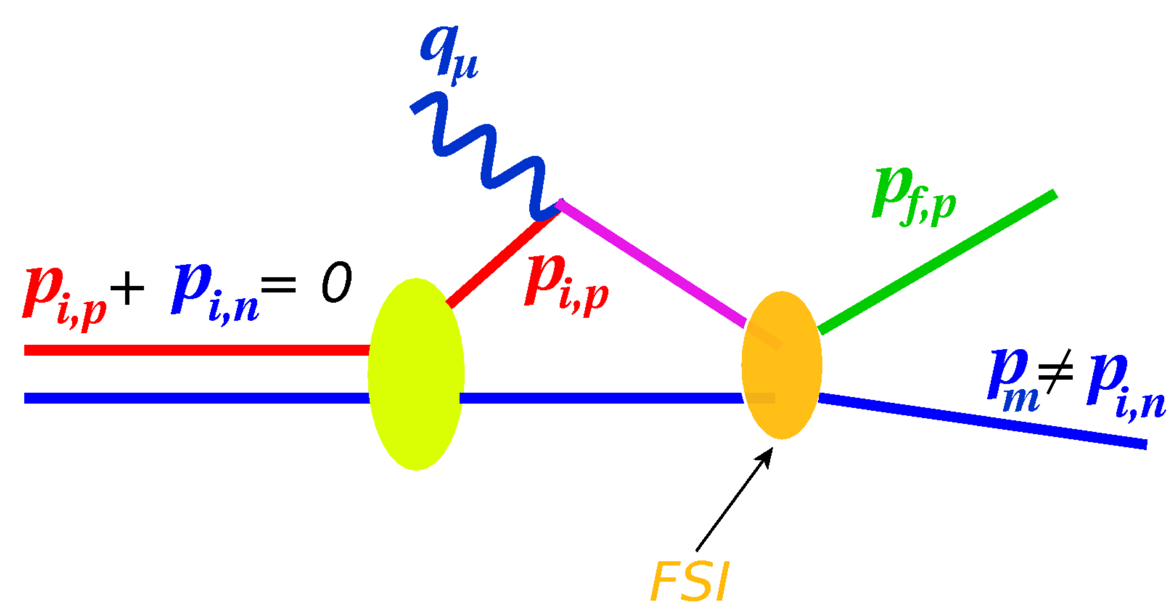
SHMS Momentum: -8.534 GeV

Exclusive reaction selected via Missing Energy Cut

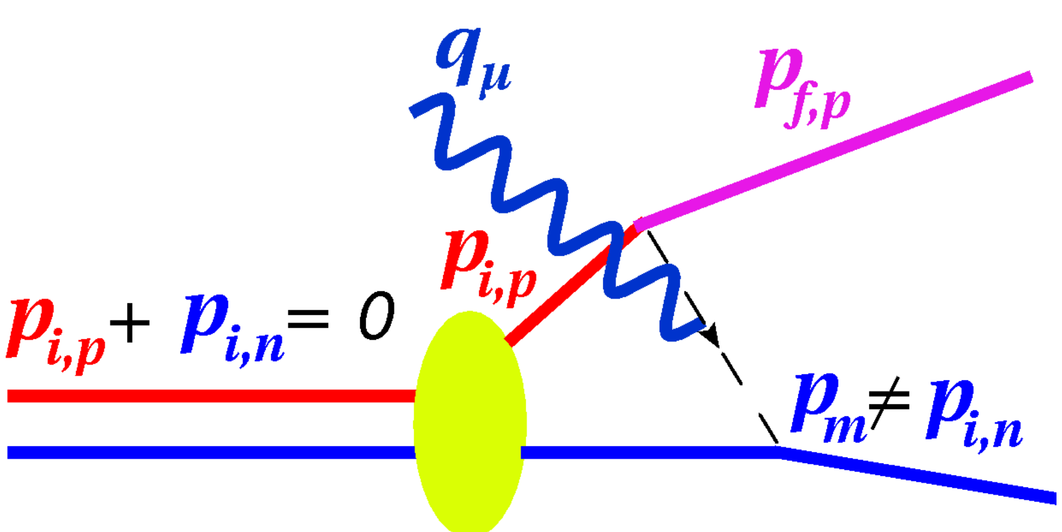
D(e,e'p)n Feynman Diagrams



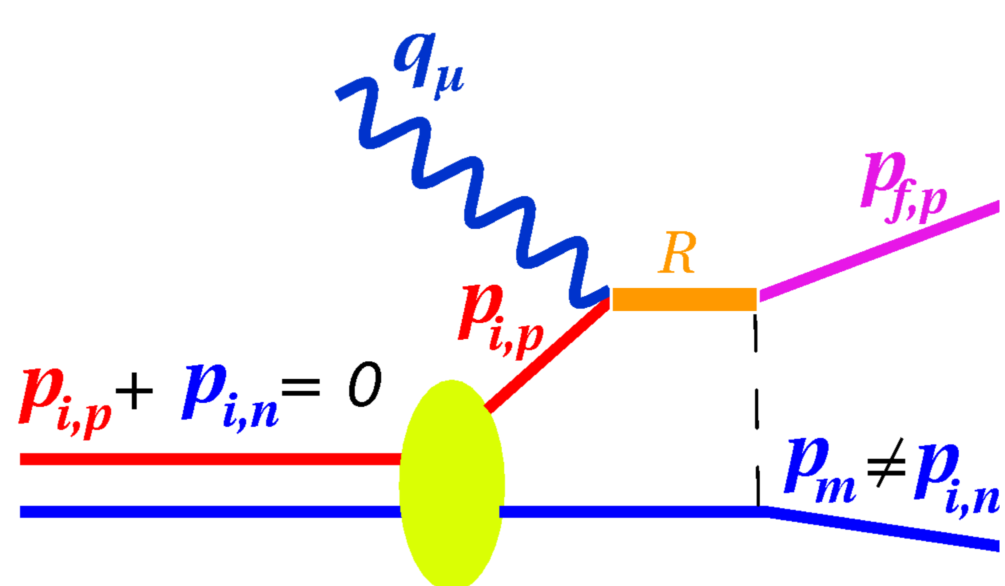
Plane Wave Impulse Approximation (PWIA)



Final State Interactions (FSI)



Meson-Exchange Currents (MEC)



Isobar Configurations (IC)

Deuteron Momentum Distribution

Experiment

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

Theory

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

Factorization ONLY possible in PWIA

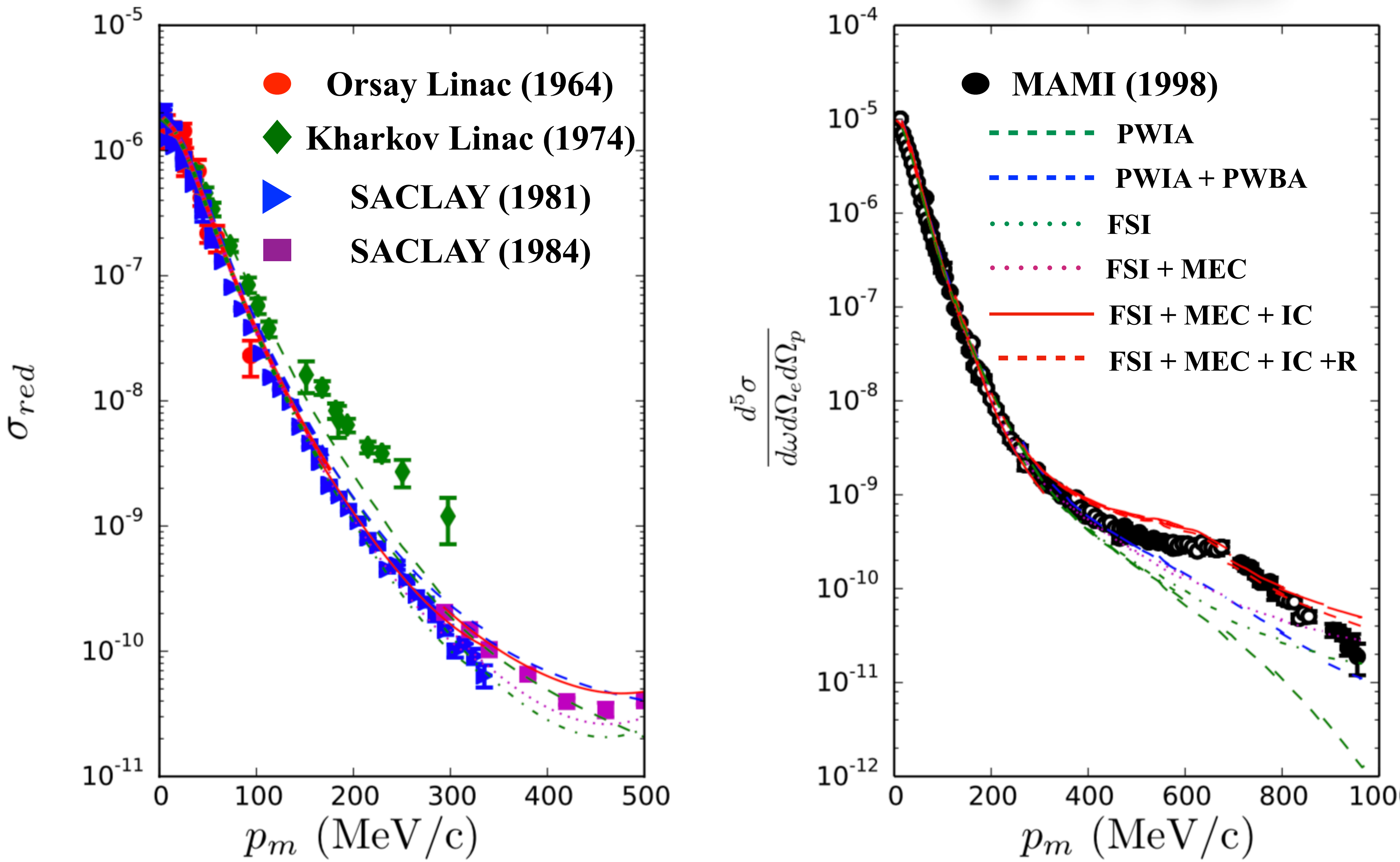
ep off-shell cross section

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

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



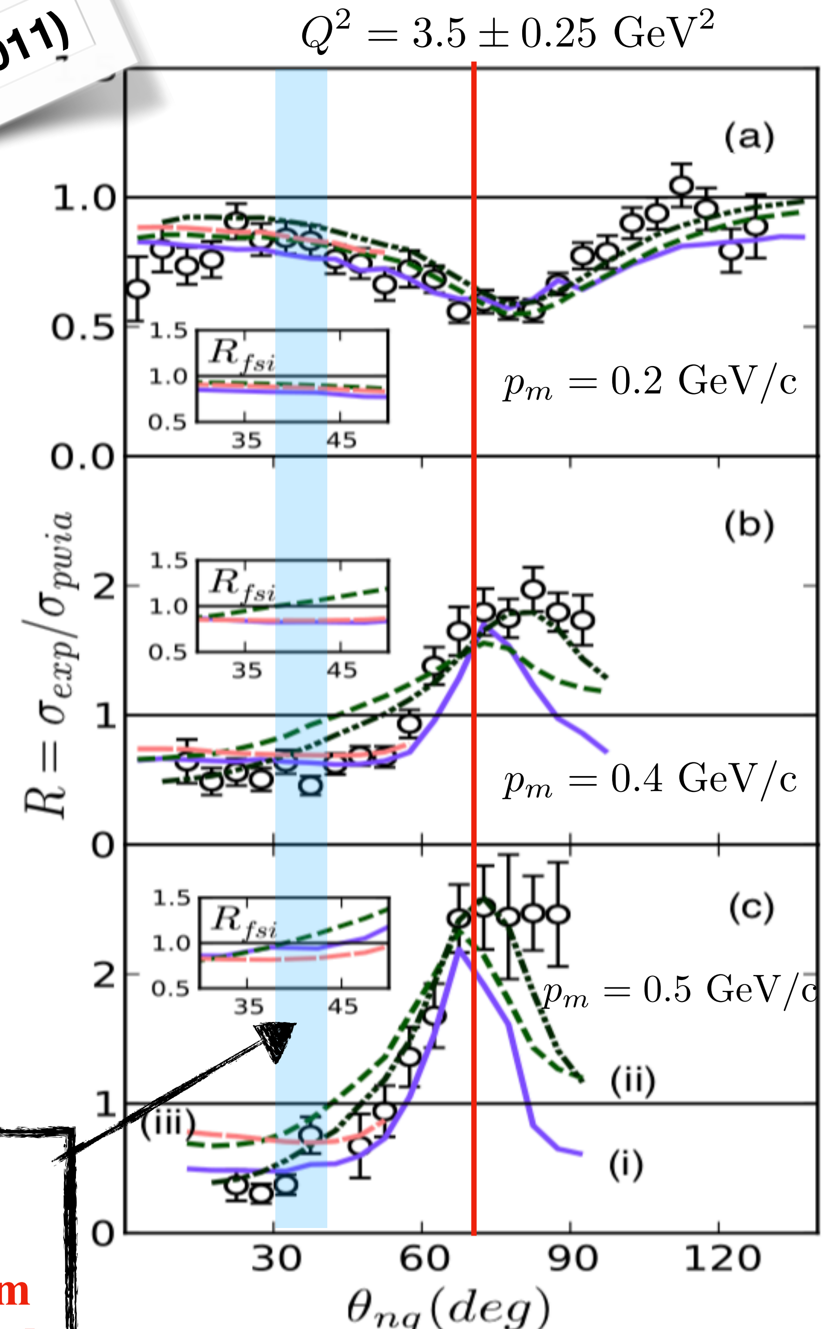
Theoretical Calculations
W. Fabian and H. Arenhovel,
Nucl.Phys. A258, 461 (1976)

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

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

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. Van Orden)

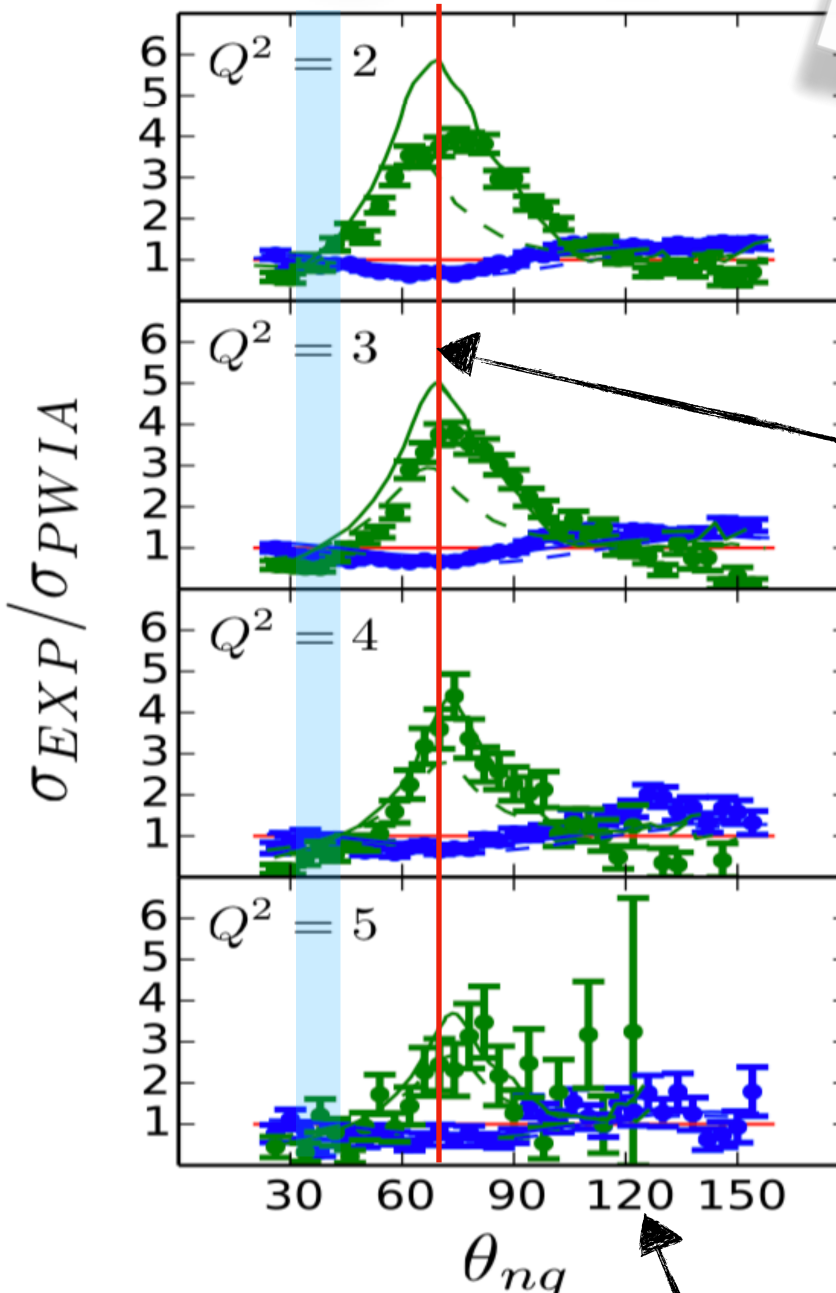
Paris FSI
(J.M. Laget)

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)

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

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

Paris FSI
(J.M. Laget)

CD-Bonn FSI (MS)

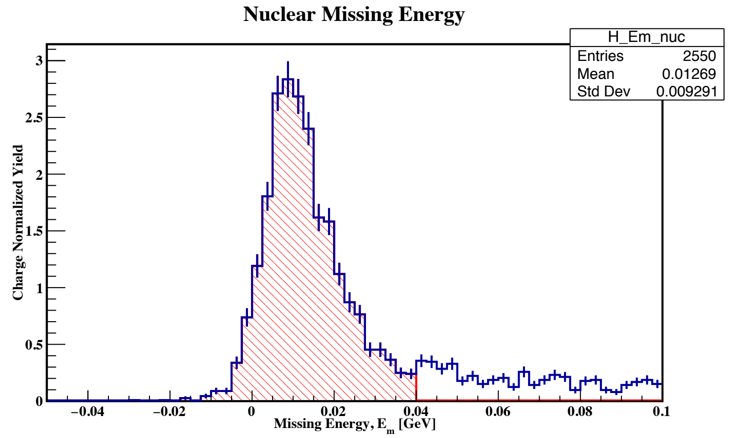
Reduced FSIs
at ~120 deg
(R ~ 1),
But ICs are significant

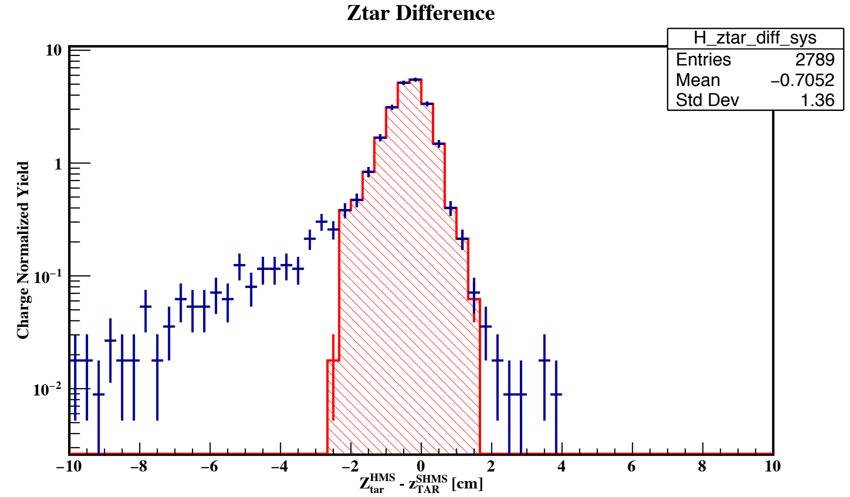
Plots Reference:
W.U.Boeglin and M. Sargsian
Int.J.Mod.Phys. E24 (2015)
no.03, 1530003

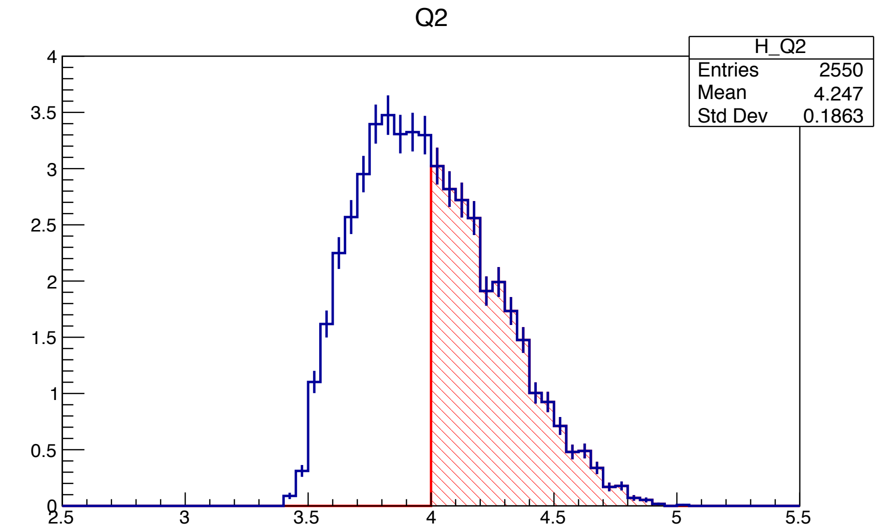
DATA ANALYSIS CUTS

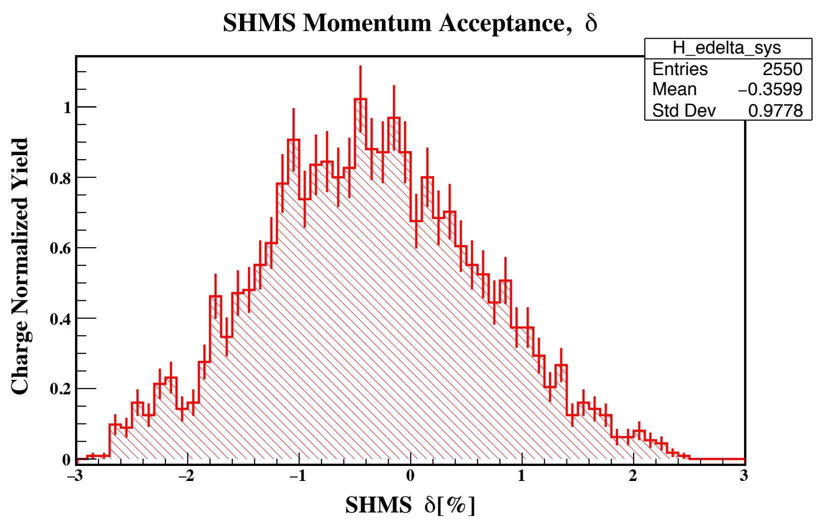
(shown only for 80 MeV setting but are also applied to high missing momentum data)

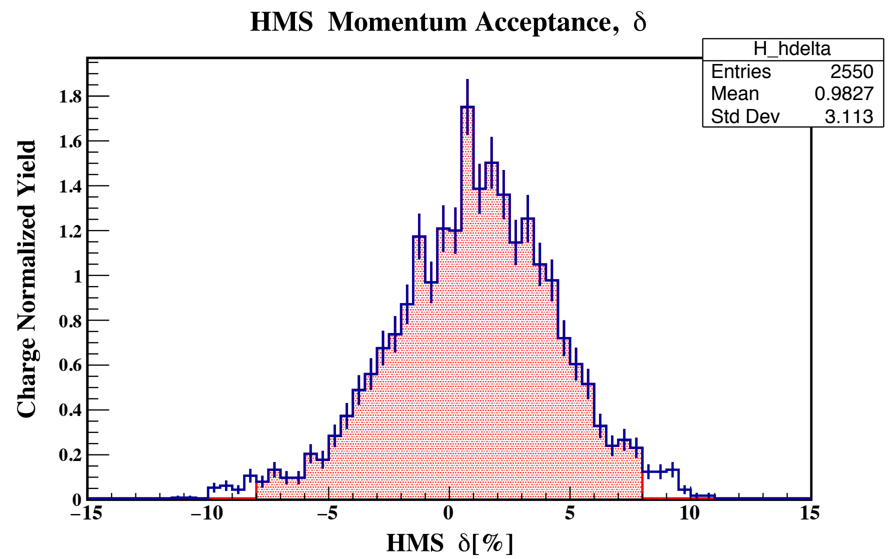
EXACT CUTS ARE ALSO APPLIED TO SIMULATION
(except for PID cuts)

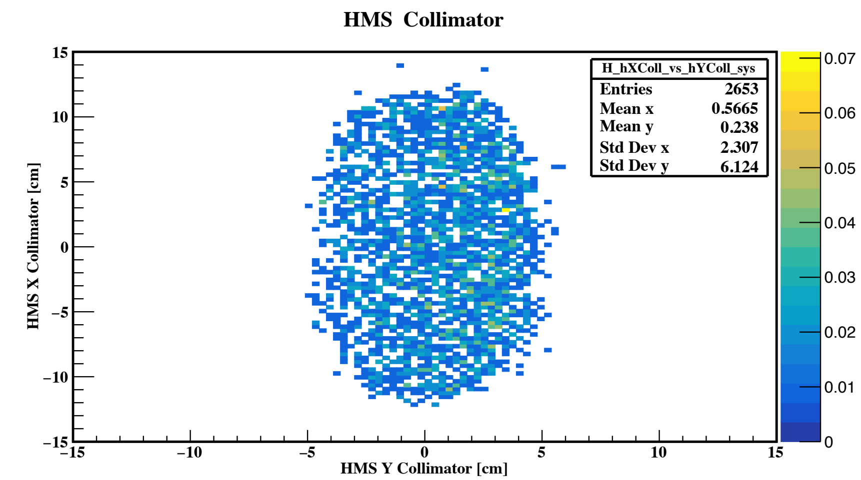


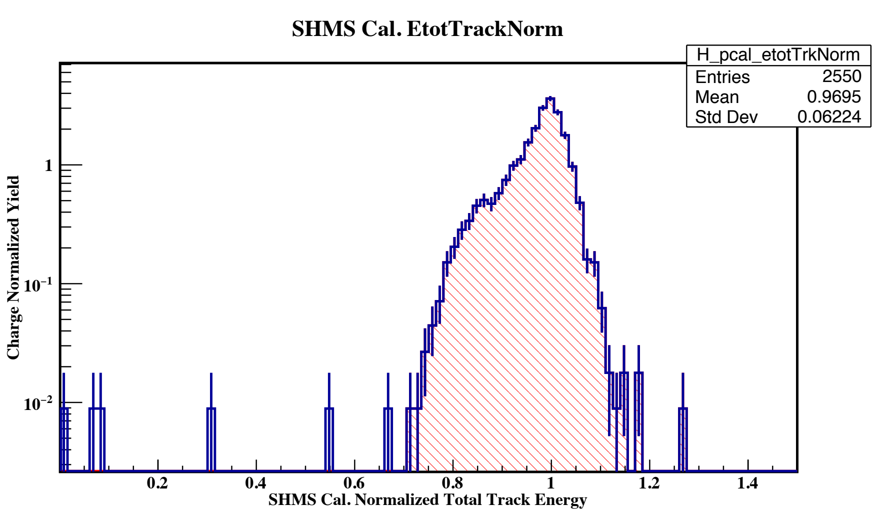


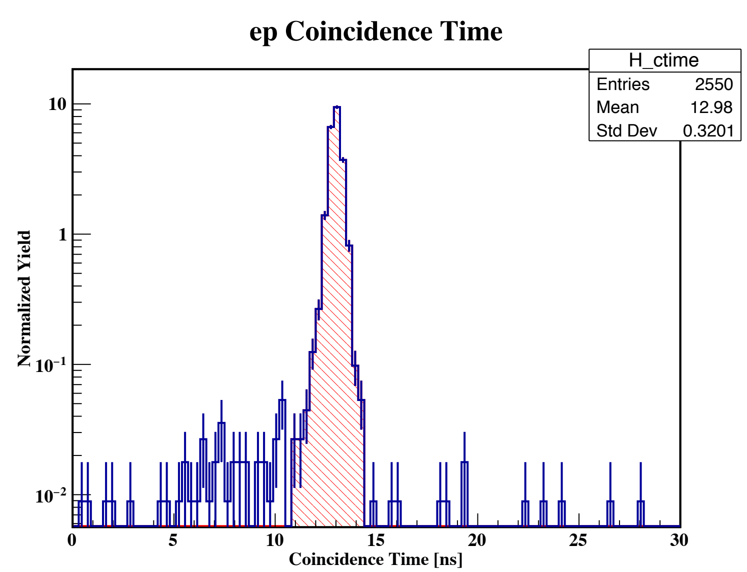












Refer to Backup Slides for details Of the cuts made

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

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

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

Corrected Data Yield

Phase Space Volume

Radiative Correction

$$\boxed{Y^{corr}_{data}} = \frac{Y^{uncorr}_{data} \cdot \boxed{f_{rc}}}{\boxed{Q_{tot}} \cdot \boxed{\epsilon_{tLT} \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{tgtBoil} \cdot \epsilon_{pAbs}}}$$

Normalize data by total charge

Correct for Inefficiencies

****See Backup Slides for details of efficiencies and correction factors**

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

Spectrometer Acceptance (or Phase Space) Definition

$$V^{P.S.} = \frac{N_f}{N_{acc}} \mathcal{J}_{corr} \rightarrow \frac{N_f}{N_{acc}} \equiv \frac{\mathcal{L}}{N_{gen}} d\omega d\Omega_e d\Omega_p$$

Normalization Factor

Accepted Events within spec. Acceptance

Jacobian Correction (convert spec. solid angles to physics angles)

Luminosity

Spectrometer "Solid Angles"

Generated Events

*(See simc.f in SIMC) for definition of luminosity

D(e,e'p) Momentum Distributions

$$\sigma_{red} \equiv \frac{\sigma_{bc}^{exp}}{K \sigma_{cc1}}$$

Fully Corrected Experimental cross sections

Kinematic Factor times deForest ep cross section

Reduced cross section (momentum distributions in PWIA)

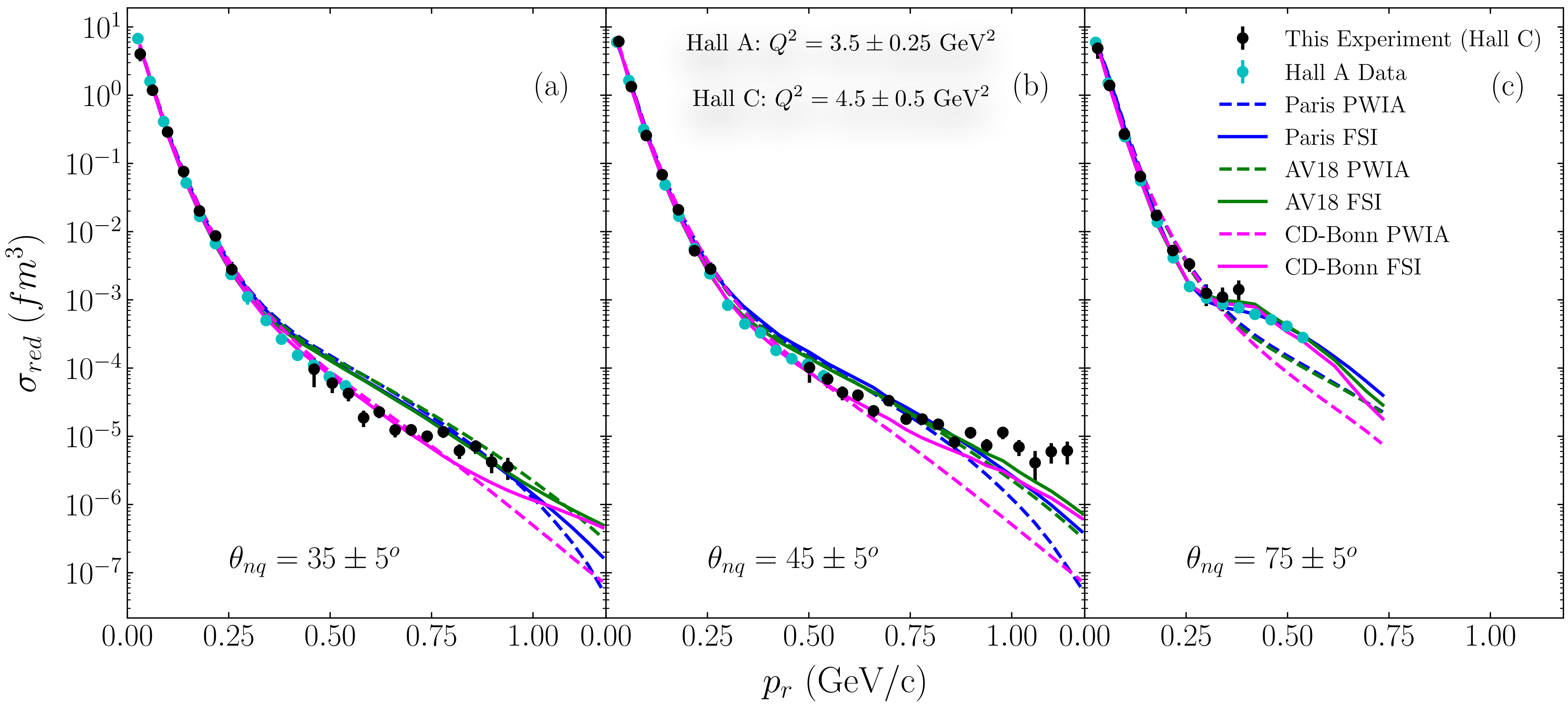
$$K \equiv k \cdot f_{rec} \sim P_f, P_m, q$$

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

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

Hall C D(e,e'p)n
Experiment Results

D(e,e'p)n Momentum Distributions

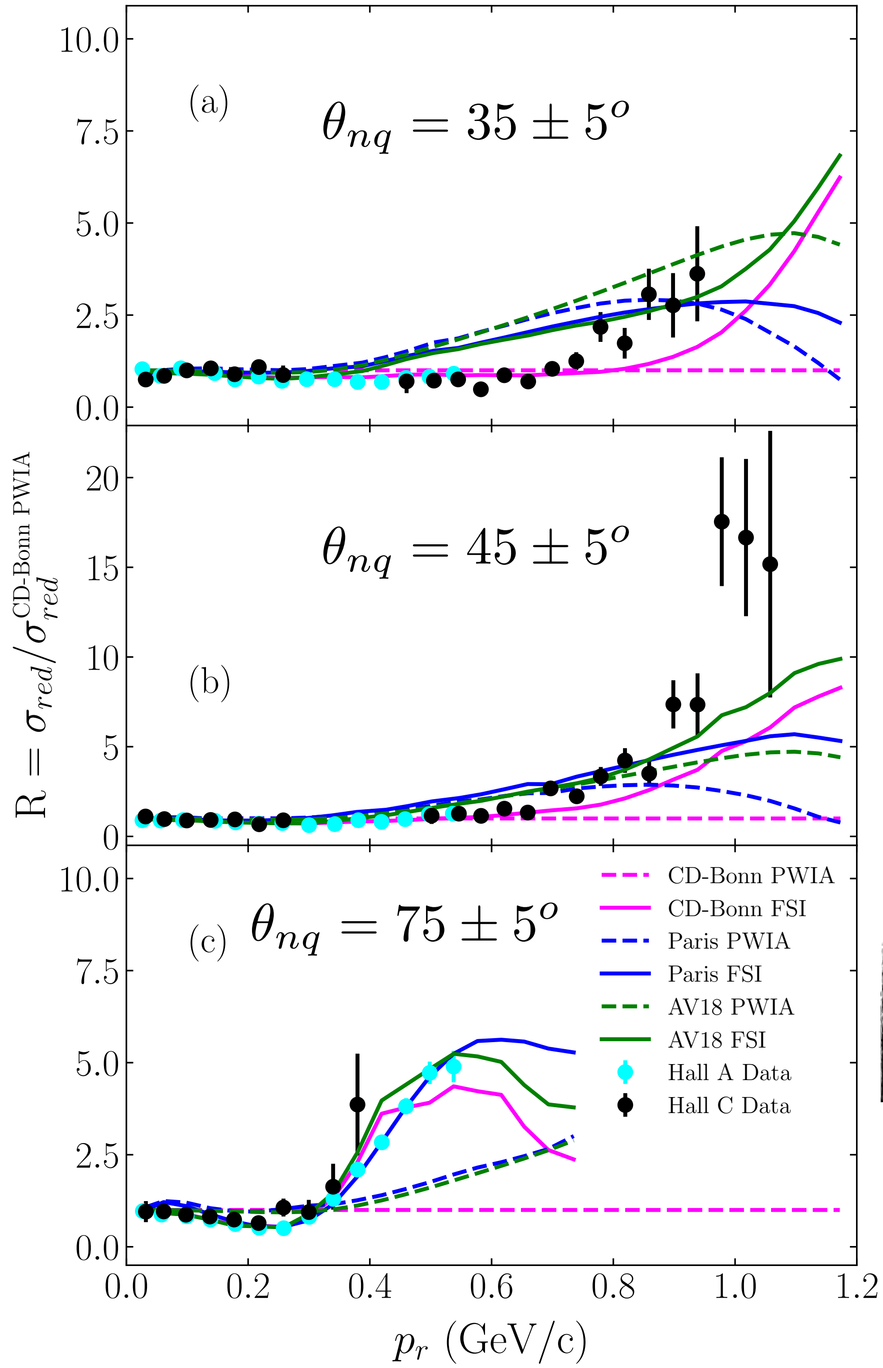


- ☑ Pr < 300 MeV/c, FSIs small and NN dominated by OPEP
- ☑ Pr > 300 MeV/c, CD-Bonn differs from Paris/AV18 models
- ☑ Hall A data agrees with Hall C data well

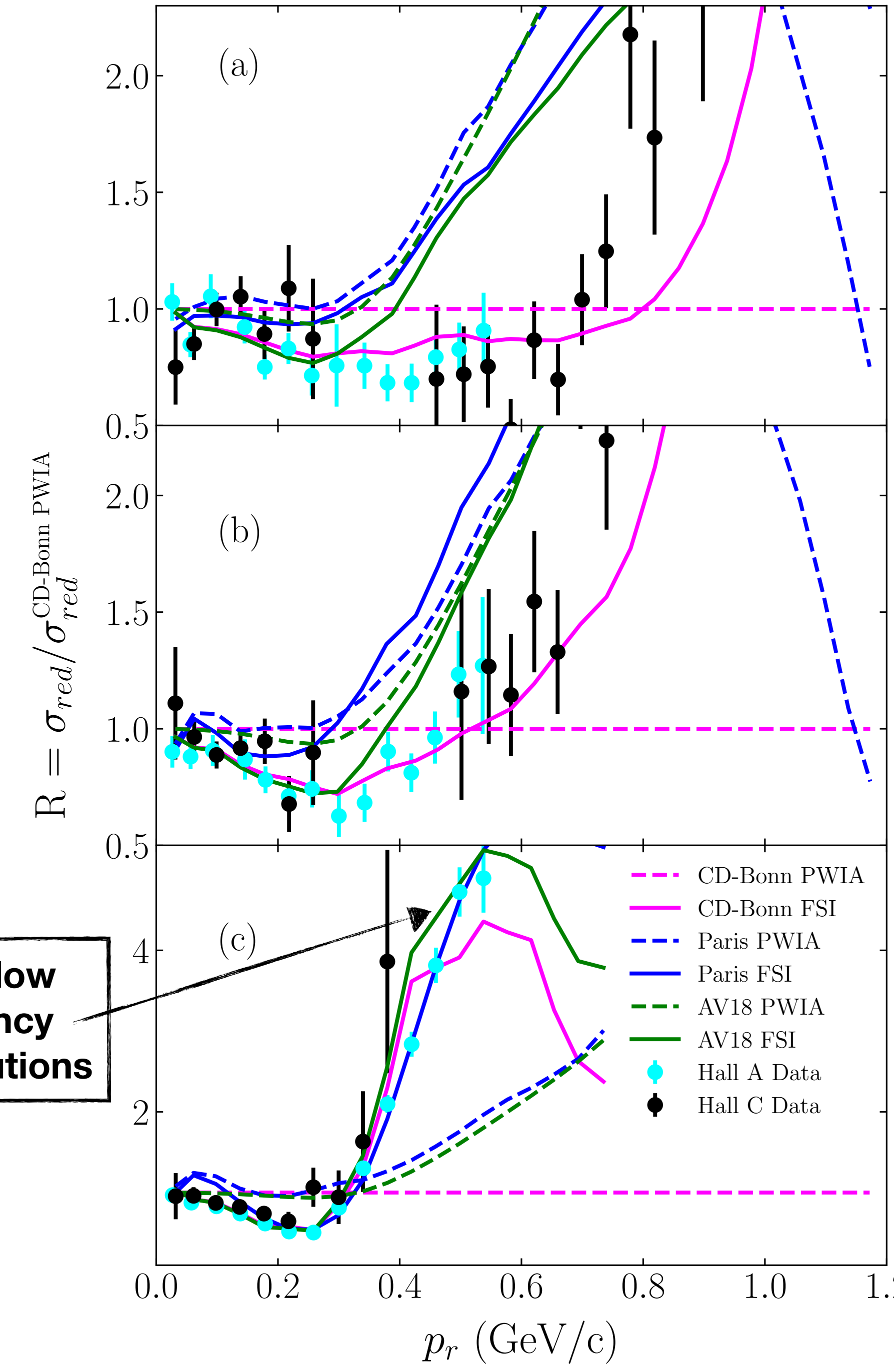
* **Paris calculations are done by J.M.Laget** J. Laget, Phys.Lett. **B609**, 49 (2005)

* **AV18/CD-Bonn calculations are done by M. Sargsian** M. M. Sargsian, Phys. Rev. **C82**, 014612 (2010)

D(e,e’p)n Ratio to CD-Bonn PWIA



ZOOM



Large FSIs overshadow any model dependency on momentum distributions

- ☑ **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 —> 35, 45 deg compared to R ~ 2 - 5 —> 75 deg (FSIs largely reduced at smaller angles)**
- ☑ **Pr > 700 MeV/c data is NOT described by any model**

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

Approximate cancellation of Scattering Amplitudes leads to reduction in FSI

SUMMARY

- **The experiment measured cross sections for the exclusive D(e,e'p)n reaction at $Q2 = 4.5\ (GeV/c)2$ for neutron recoil momentum up to 1.0 GeV/c and neutron recoil angles between 35 to 75 deg**
- **At large angles ~75 deg, FSIs dominate above 300 MeV/c, and there is virtually no difference between the models due to large FSIs which overshadow the true momentum distributions**
- **DATA was best described by CD-Bonn potential at smaller recoil angles (35 deg) and recoil momenta up to ~700 MeV/c**
- **Above 700 MeV/c, NO calculation describes the data**

The draft Physics Review Letters (PRL) paper is being prepared and expected to be sent to the Hall C Collaboration by the end of February 2020

Overall, given that this was a 6-day commissioning and statistically limited experiment, it has very interesting results, as no model seems to describe the data above recoil momenta of 700 MeV/c . This discrepancy is worth exploring further in the full experiment.

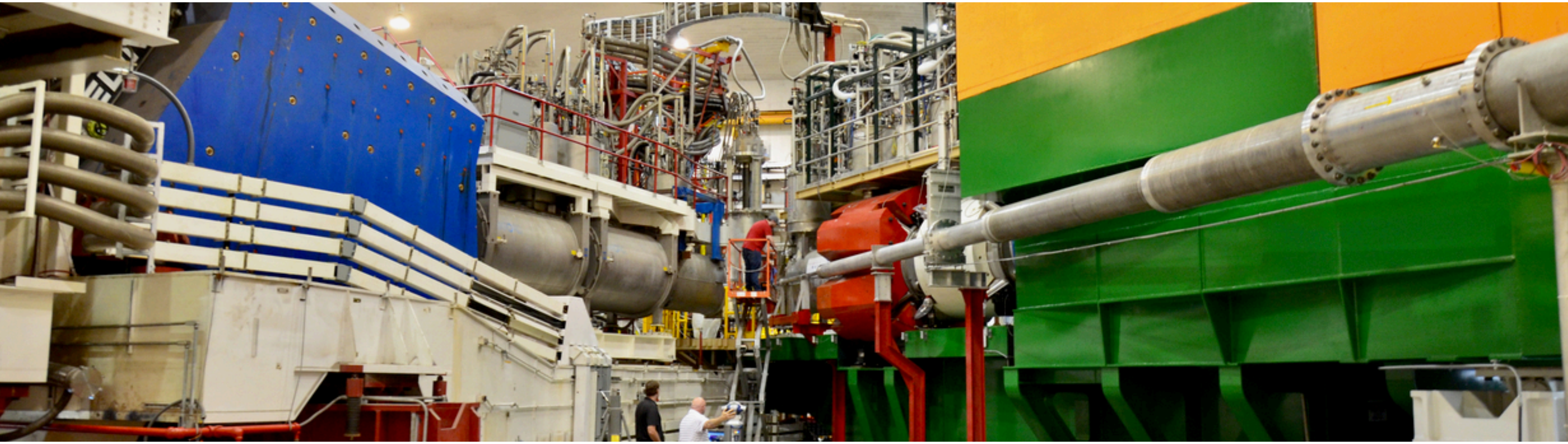
ACKNOWLEDGMENTS

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.

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 !

BACK-UP SLIDES

NORMALIZATION SYSTEMATIC UNCERTAINTIES on D(e,e’p)n

HMS Tracking Efficiency (%)	0.40
sHMS Tracking Efficiency (%)	0.59
Target Boiling (%)	0.39
Total Live Time (%)	3.0
Total Charge (%)	2.0
Overall Normalization (%)	3.7

☑ Overall normalization uncertainty is the quadrature sum of the individual normalization uncertainties

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

$\delta\theta_e[mr]$	**0.1659**	Uncertainty in SHMS angle
$\delta\theta_p[mr]$	**0.2369**	Uncertainty in HMS angle
$\delta E_f/E_f$	**9.132E-04**	Uncertainty in SHMS momentum
$\delta E_b/E_b$	**7.498E-04**	Uncertainty in Beam Energy
$d\sigma_{exp}$	**6.5%**	Max. Systematic Error on Cross Section

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

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.

SHMS Optics Optimization for D(e,e'p)n

** 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-nceccessary 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.

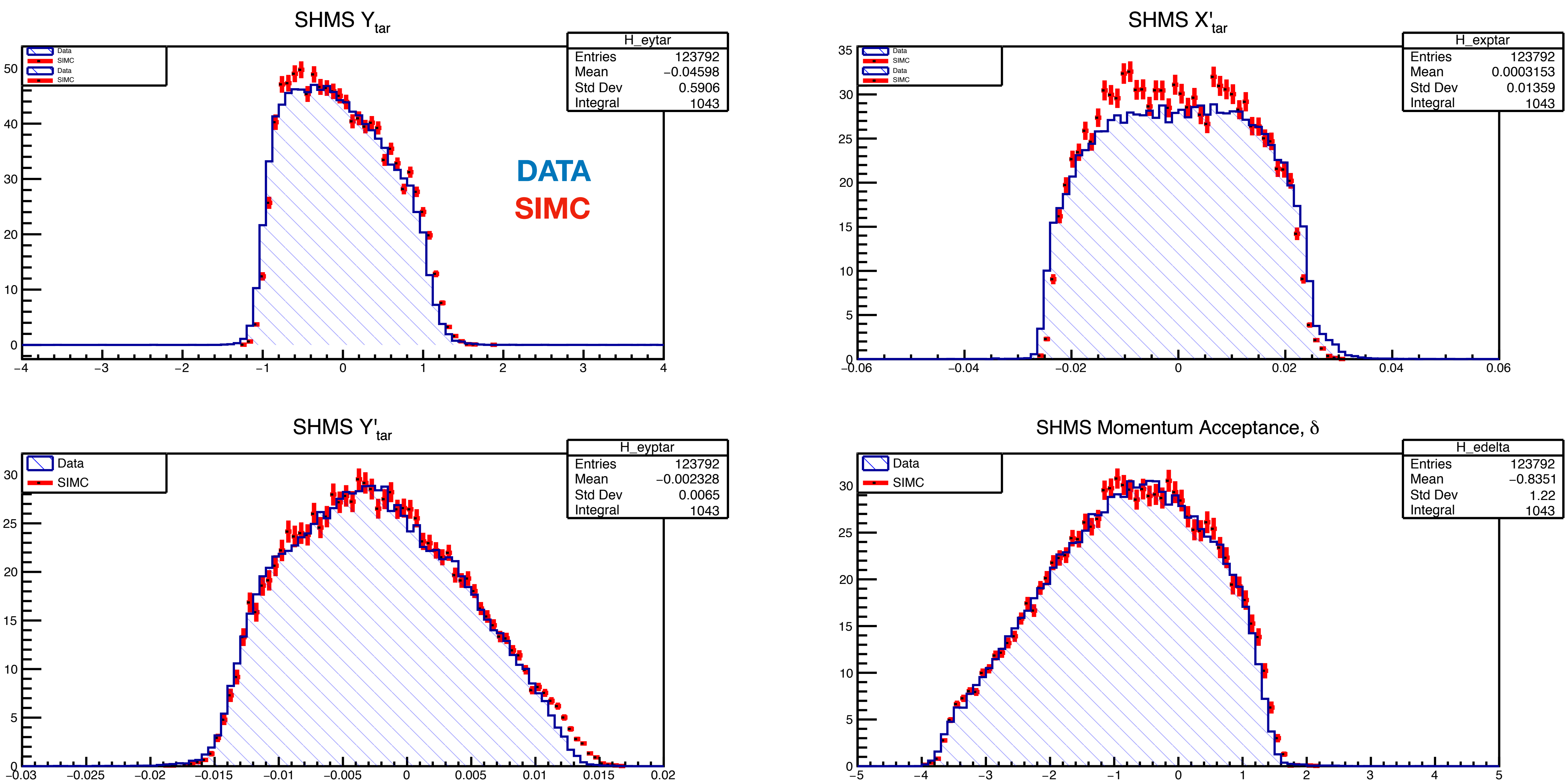
1

HALLC DOC-DB LINK

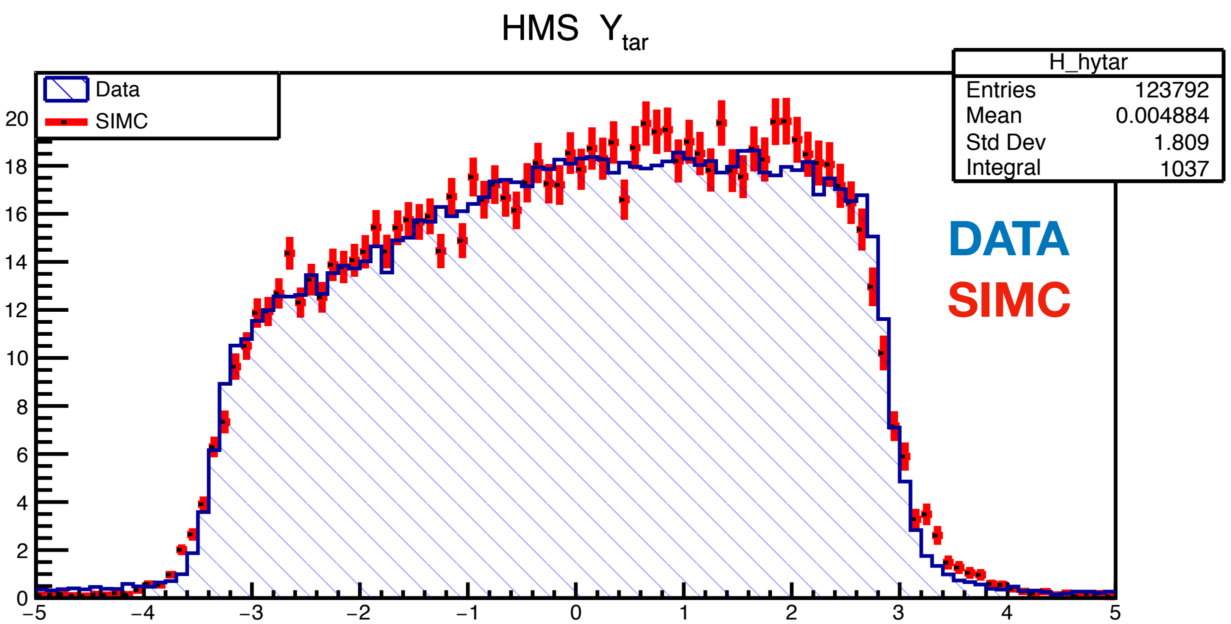
Spectrometer Acceptance
DATA/SIMULATION

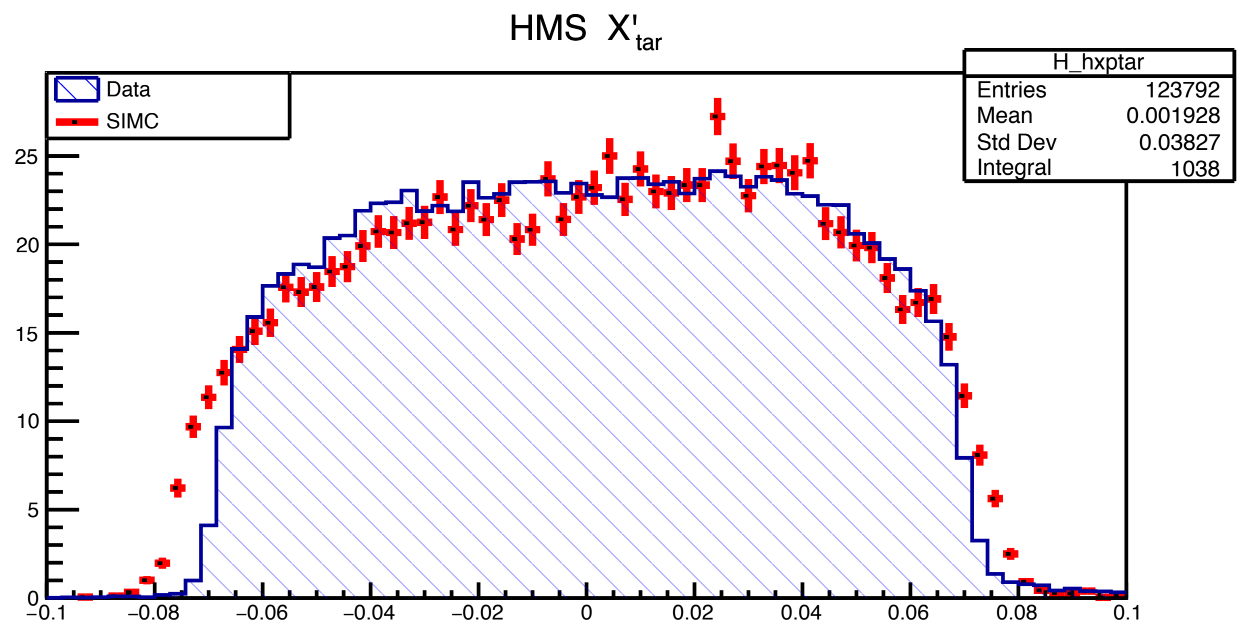
(used H(e,e'p) Elastics data taken on D(e,e'p)n Experiment

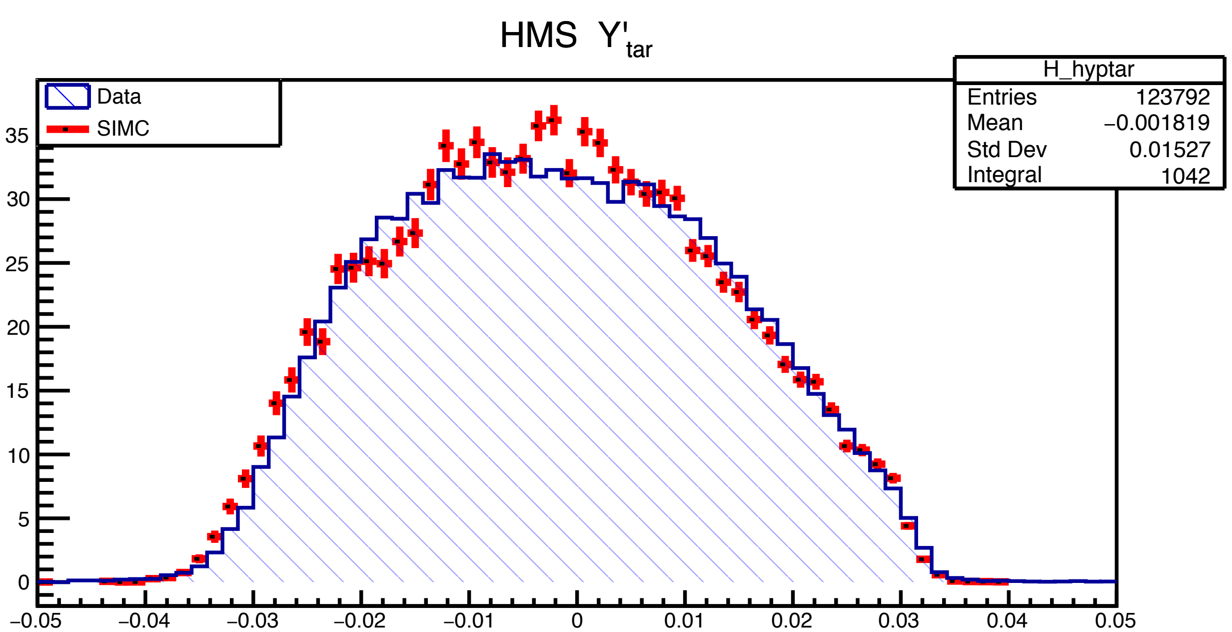
** SHMS Reconstructed Variables

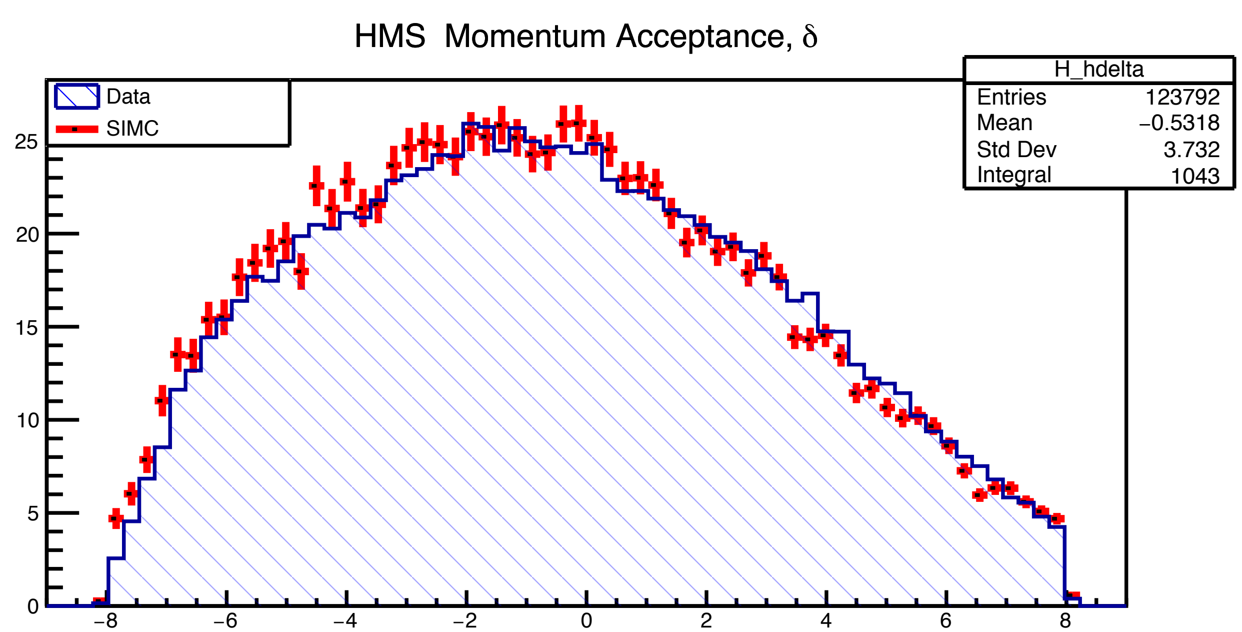


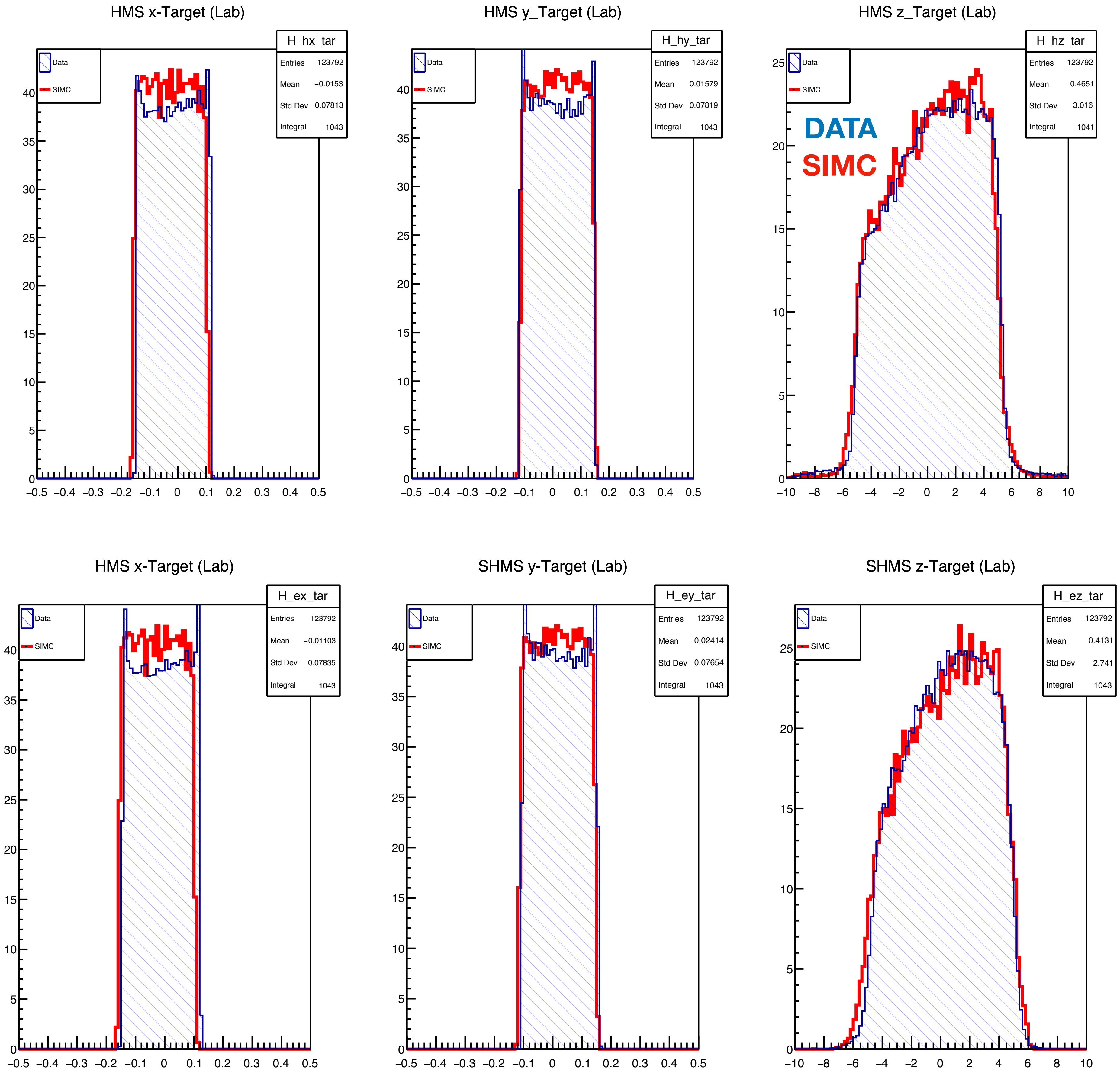
** HMS Reconstructed Variables





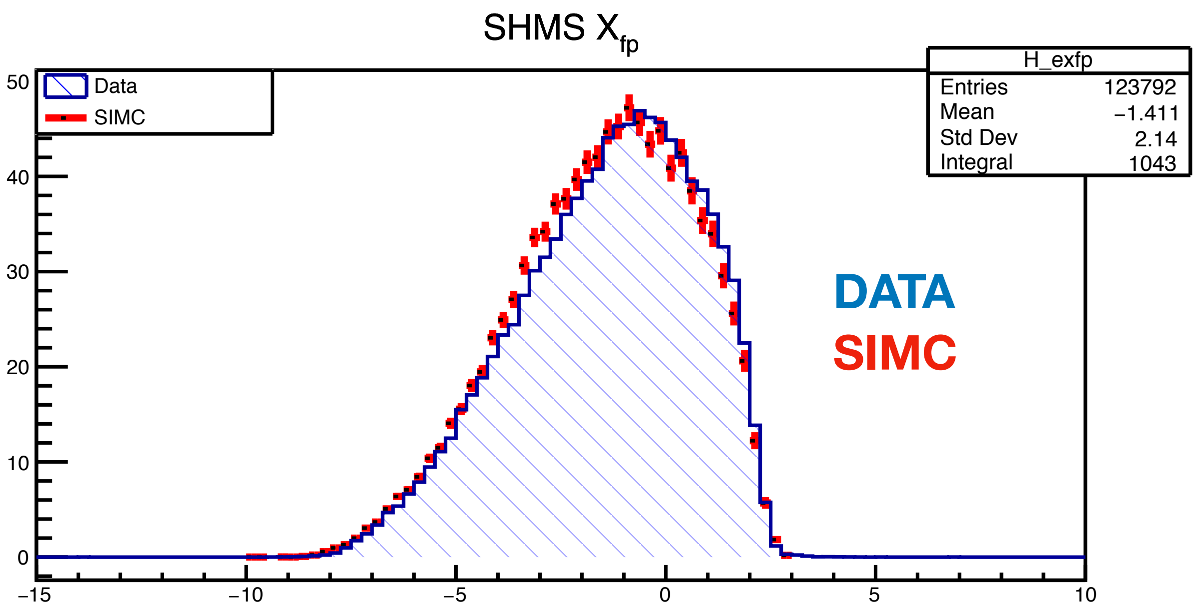


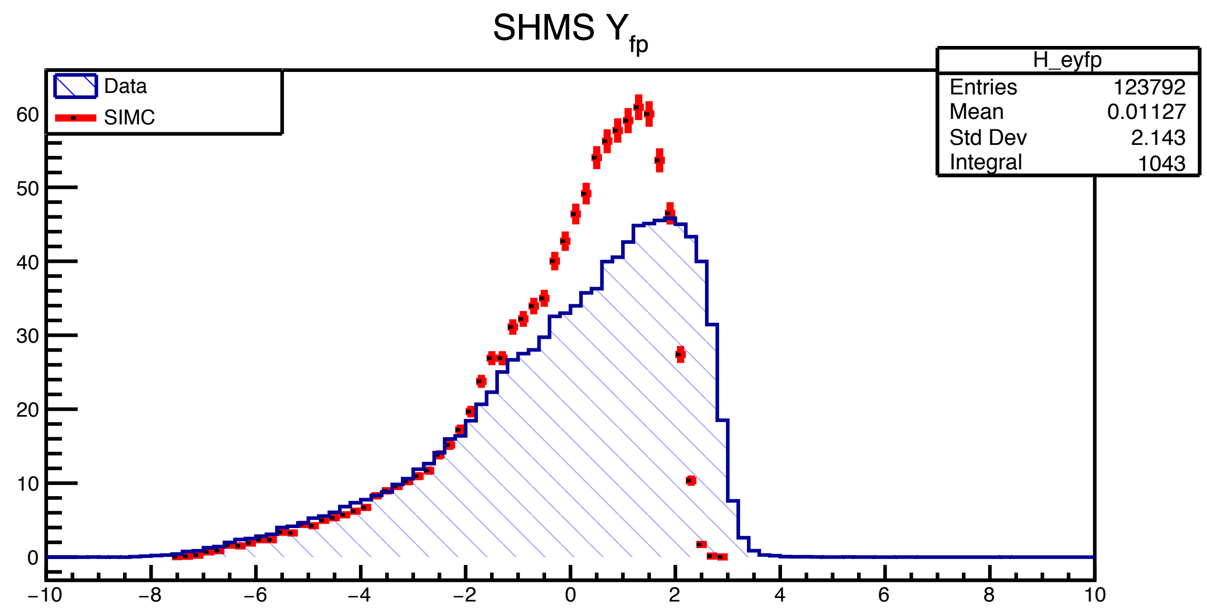


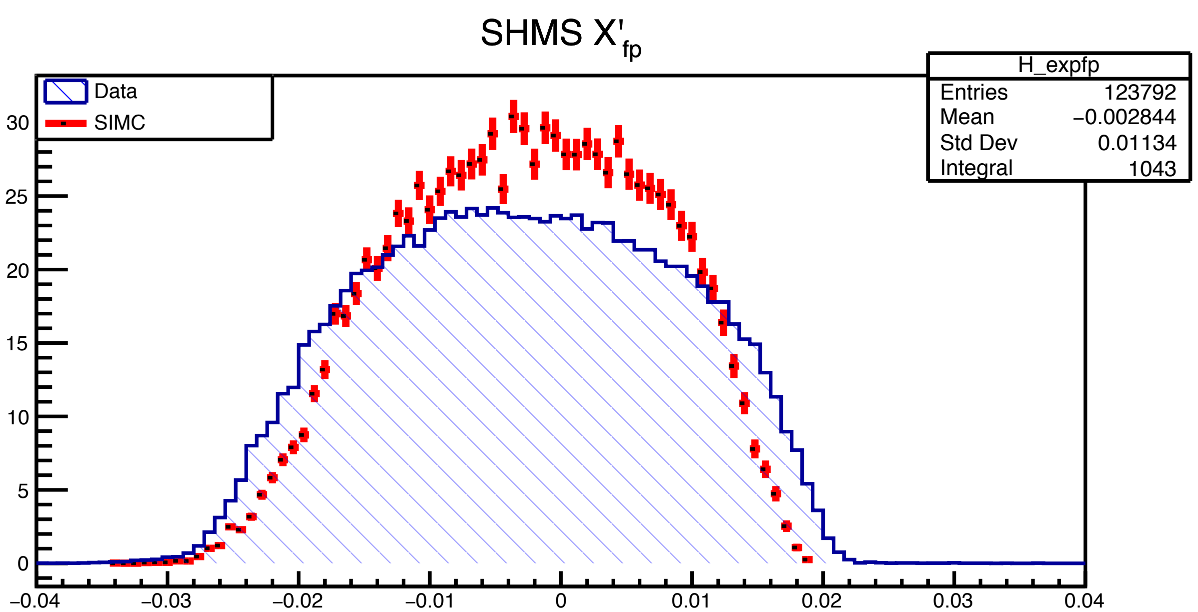


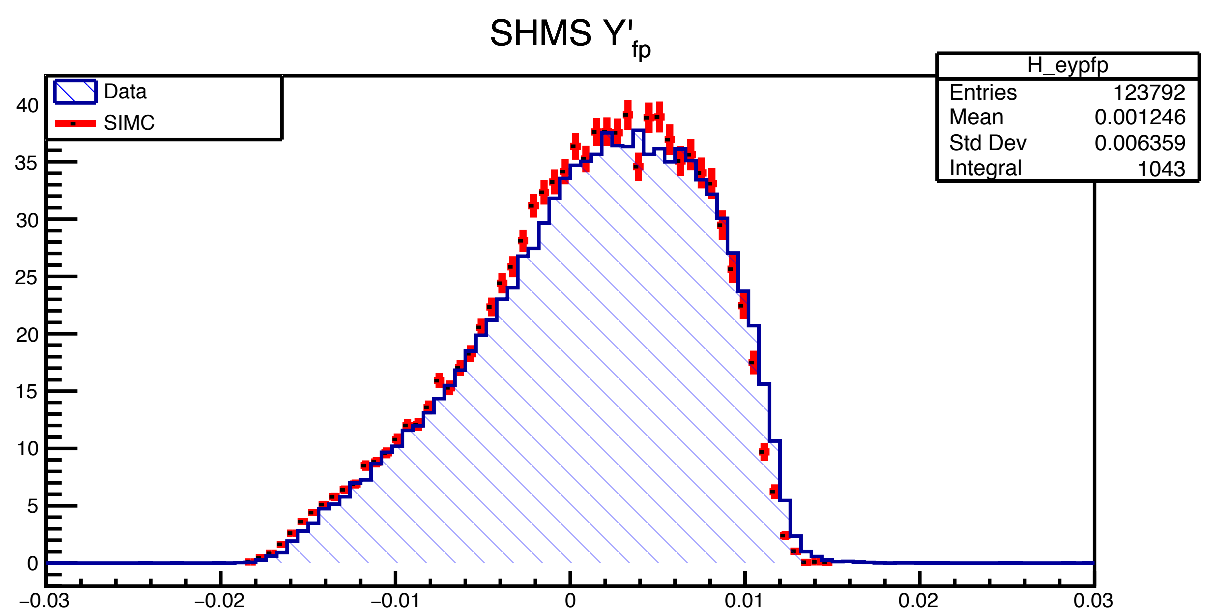
**** Reaction Vertex Reconstruction**

** SHMS Focal Plane Variables

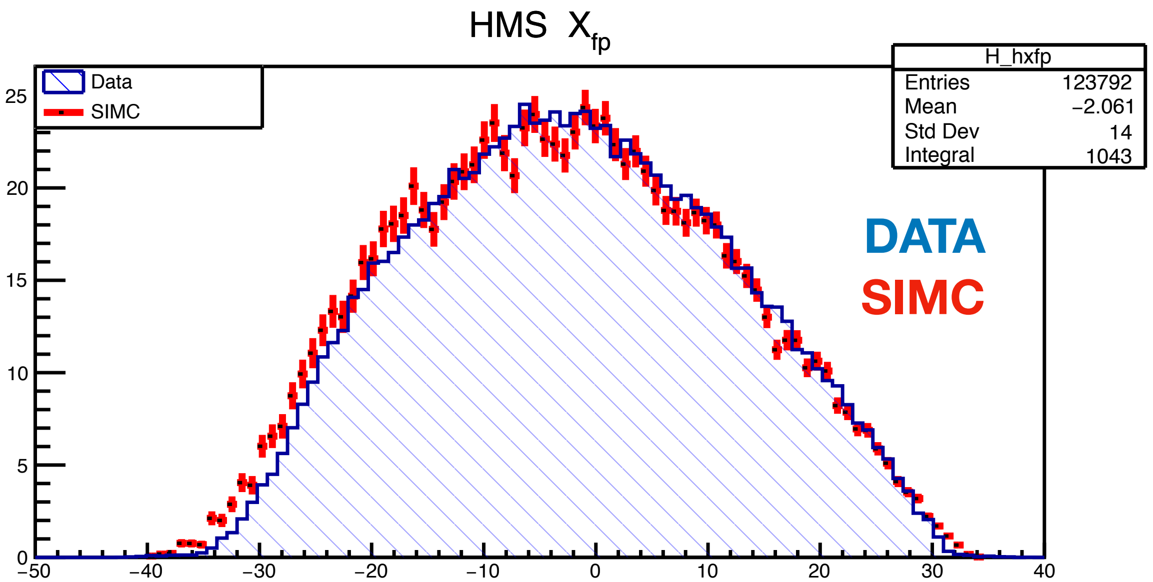


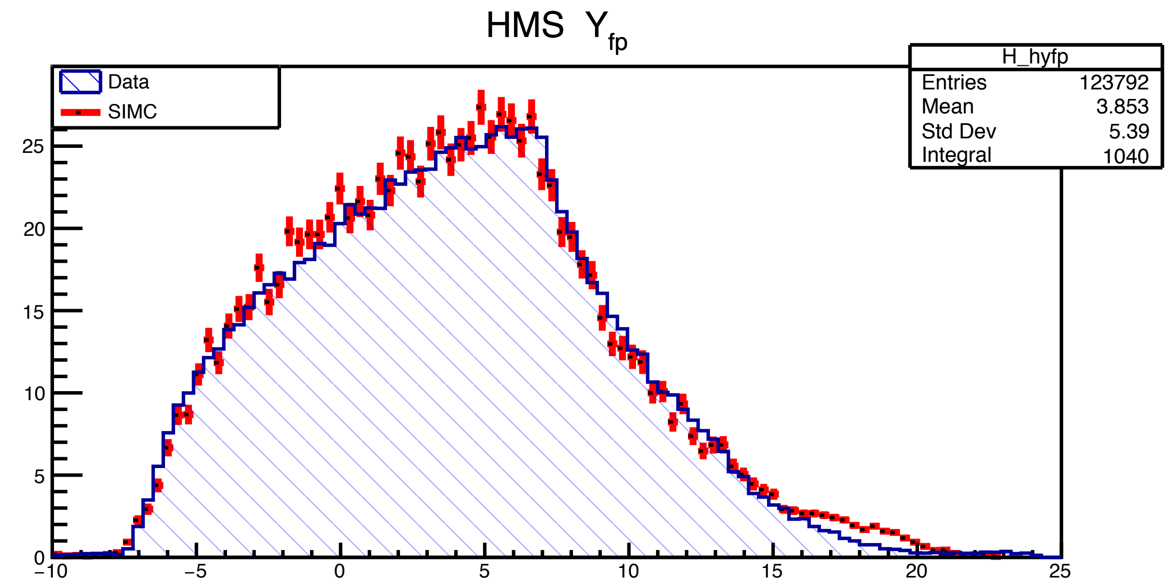


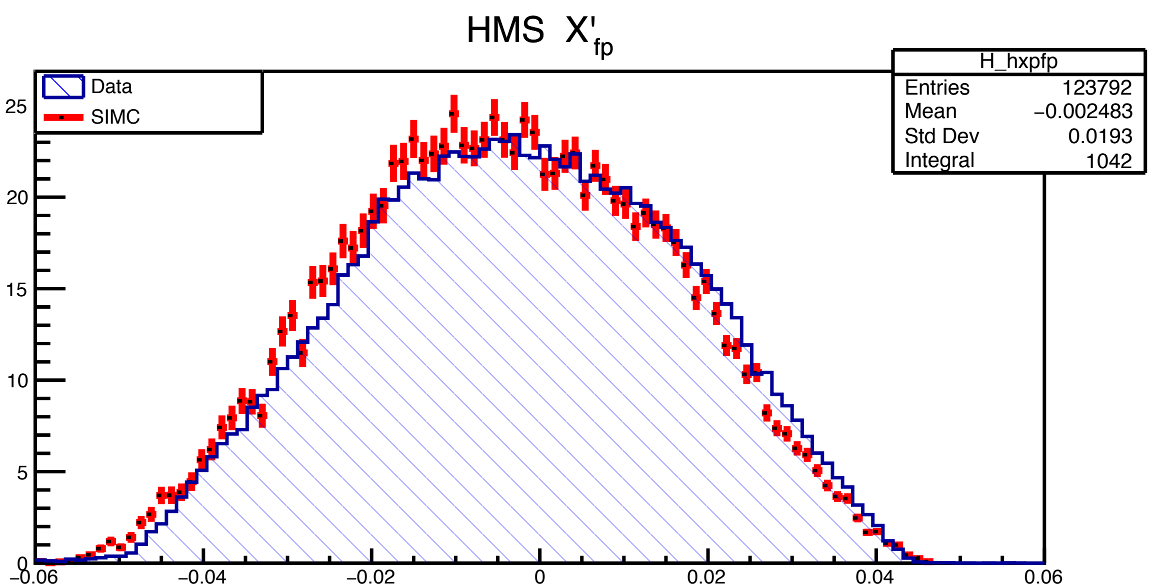


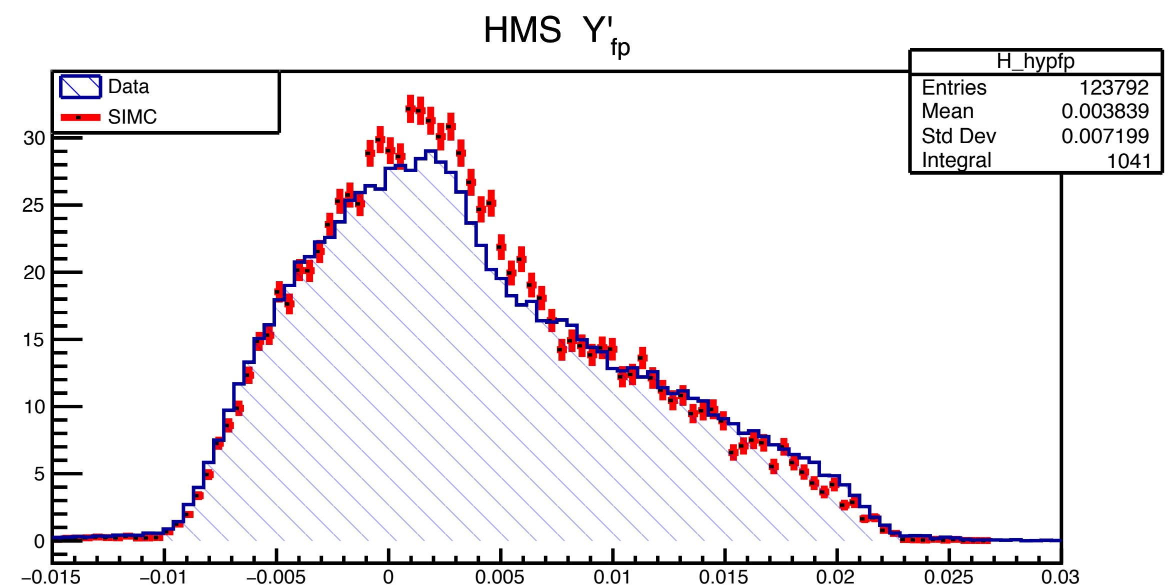


** HMS Focal Plane Variables





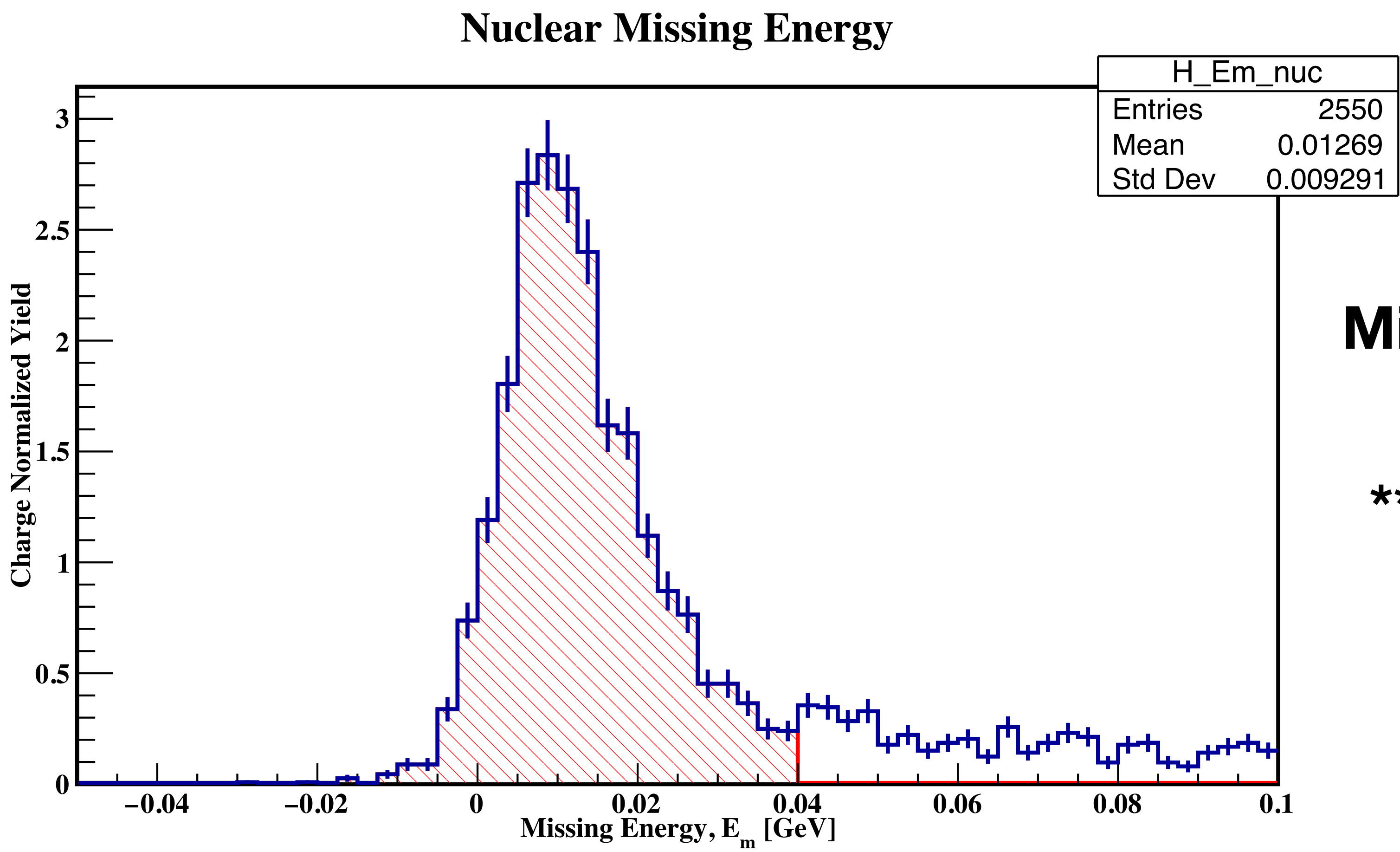




DATA ANALYSIS CUTS

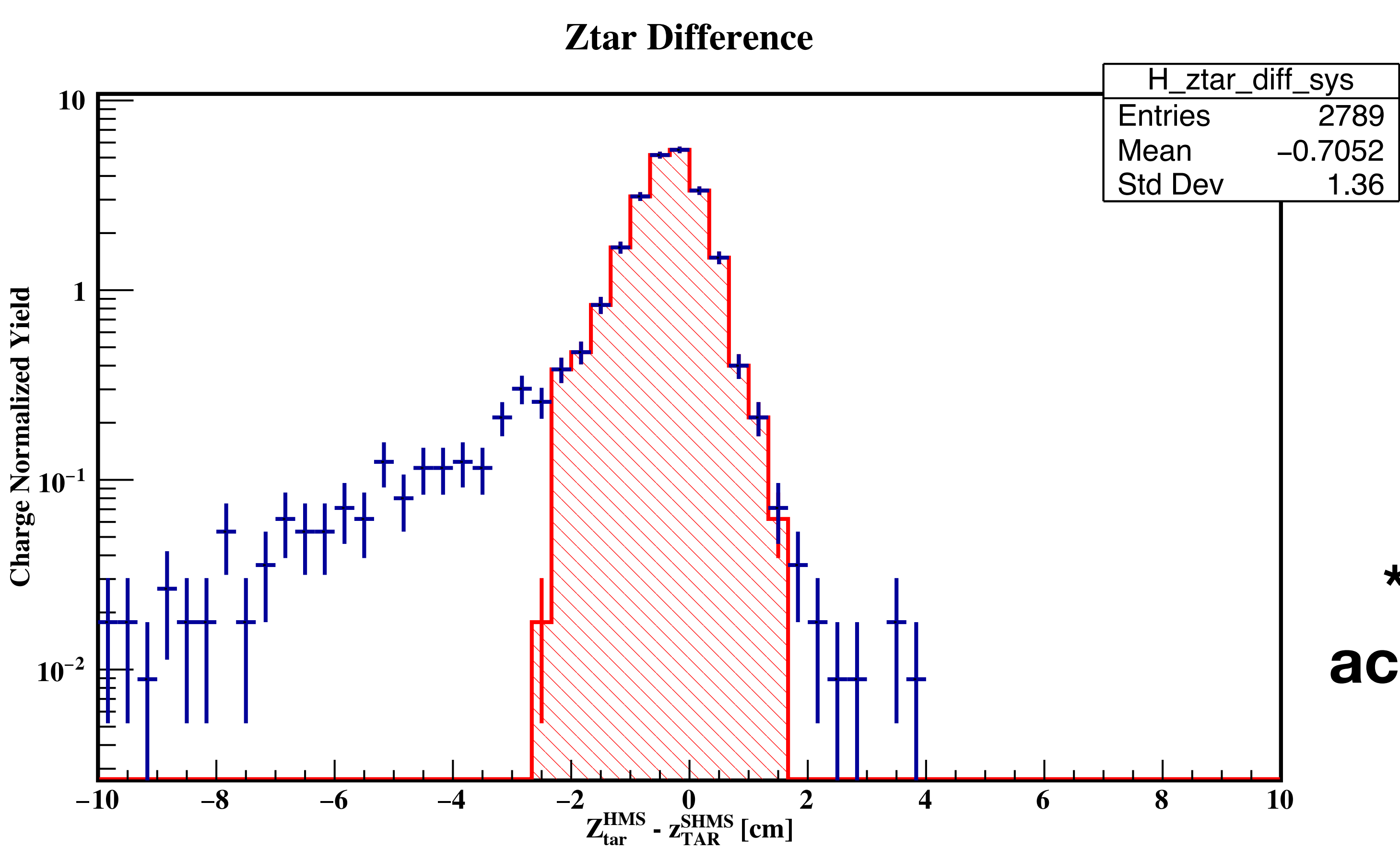
(shown only for 80 MeV setting but are also applied to high missing momentum data)

EXACT CUTS ARE ALSO APPLIED TO SIMULATION
(except for PID cuts)



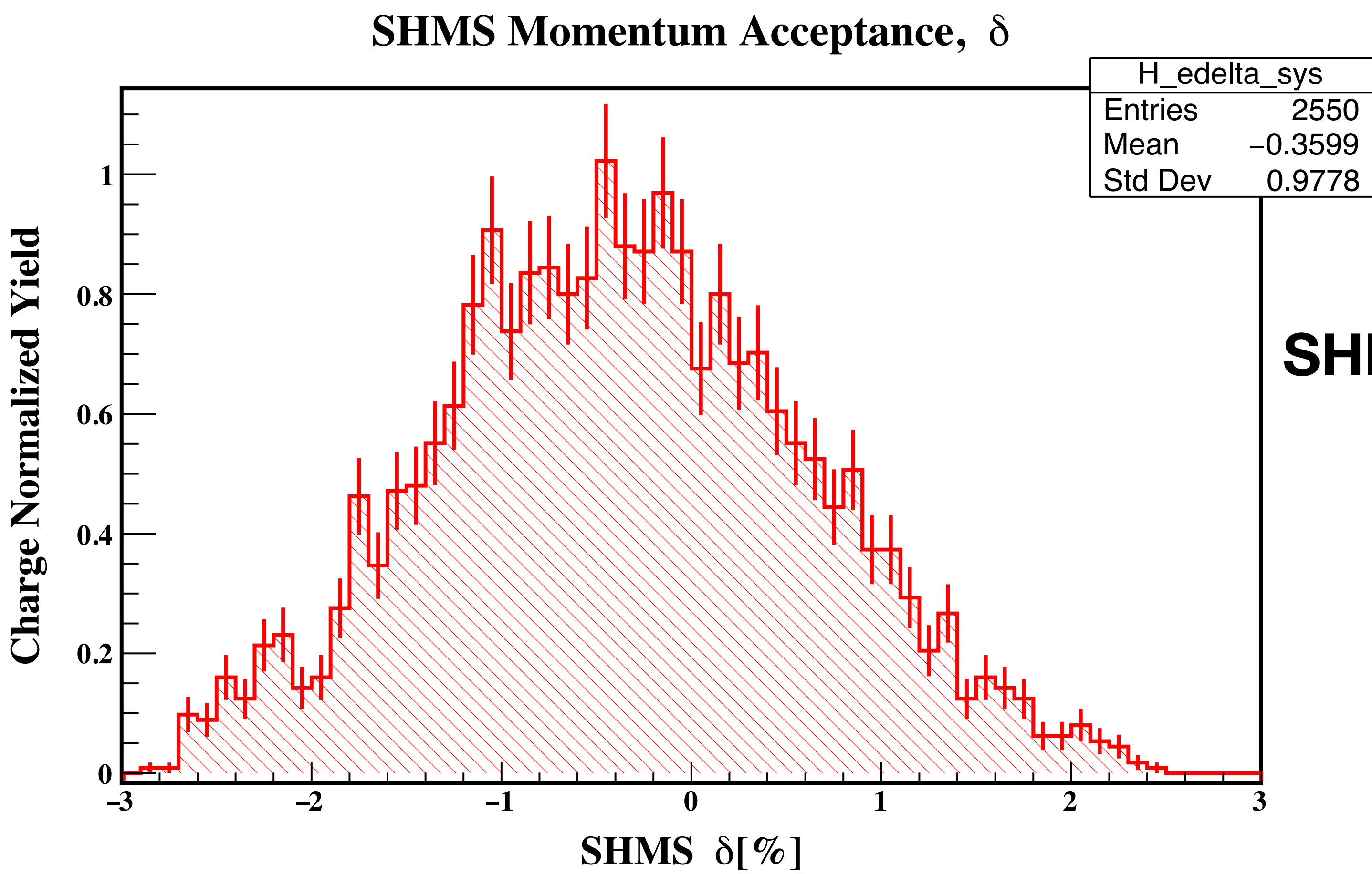
Missing Energy Cut: (-20, 40) MeV

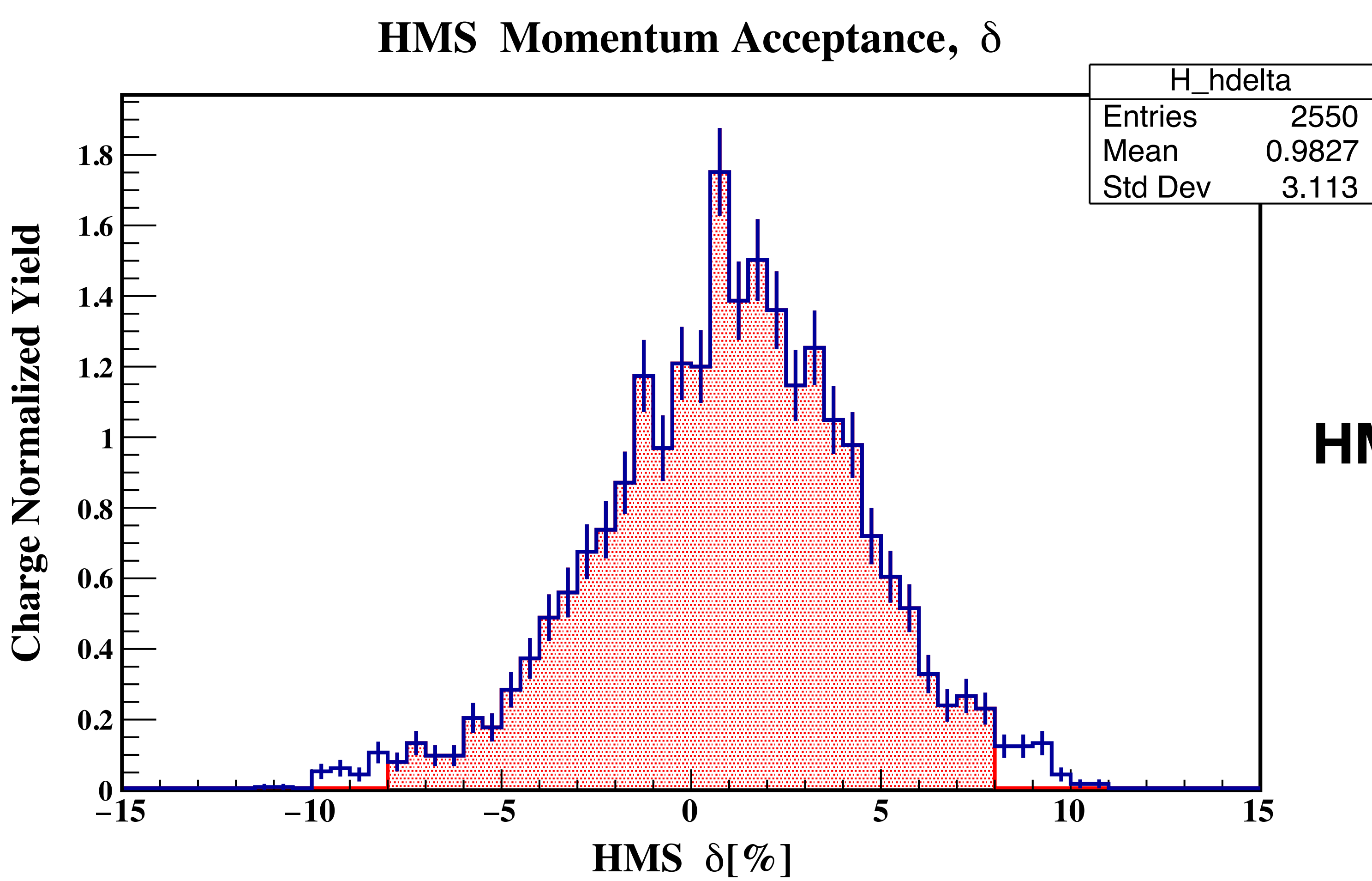
**** Select true D(e,e’p)n events**



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

****select true coincidences and not accidentals from another beam bunch**

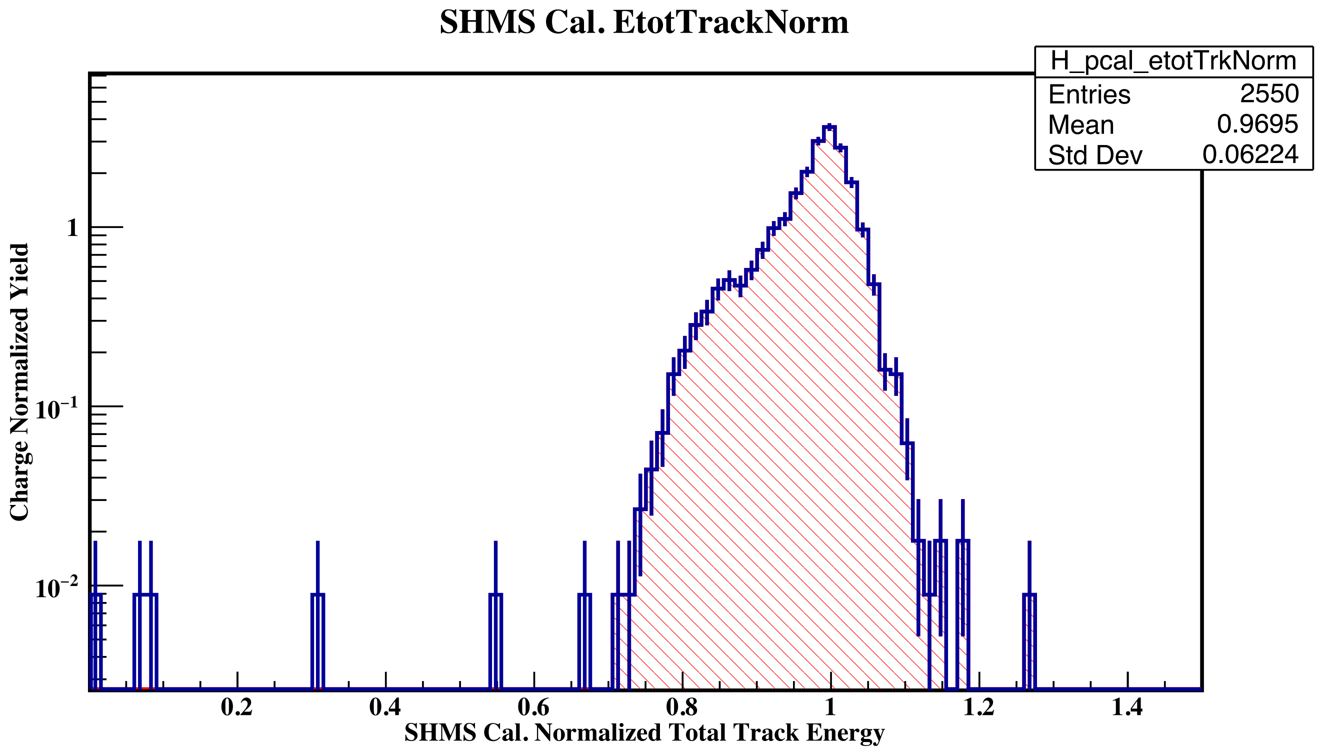




SHMS Delta Acceptance Cut: (-10, 22) %

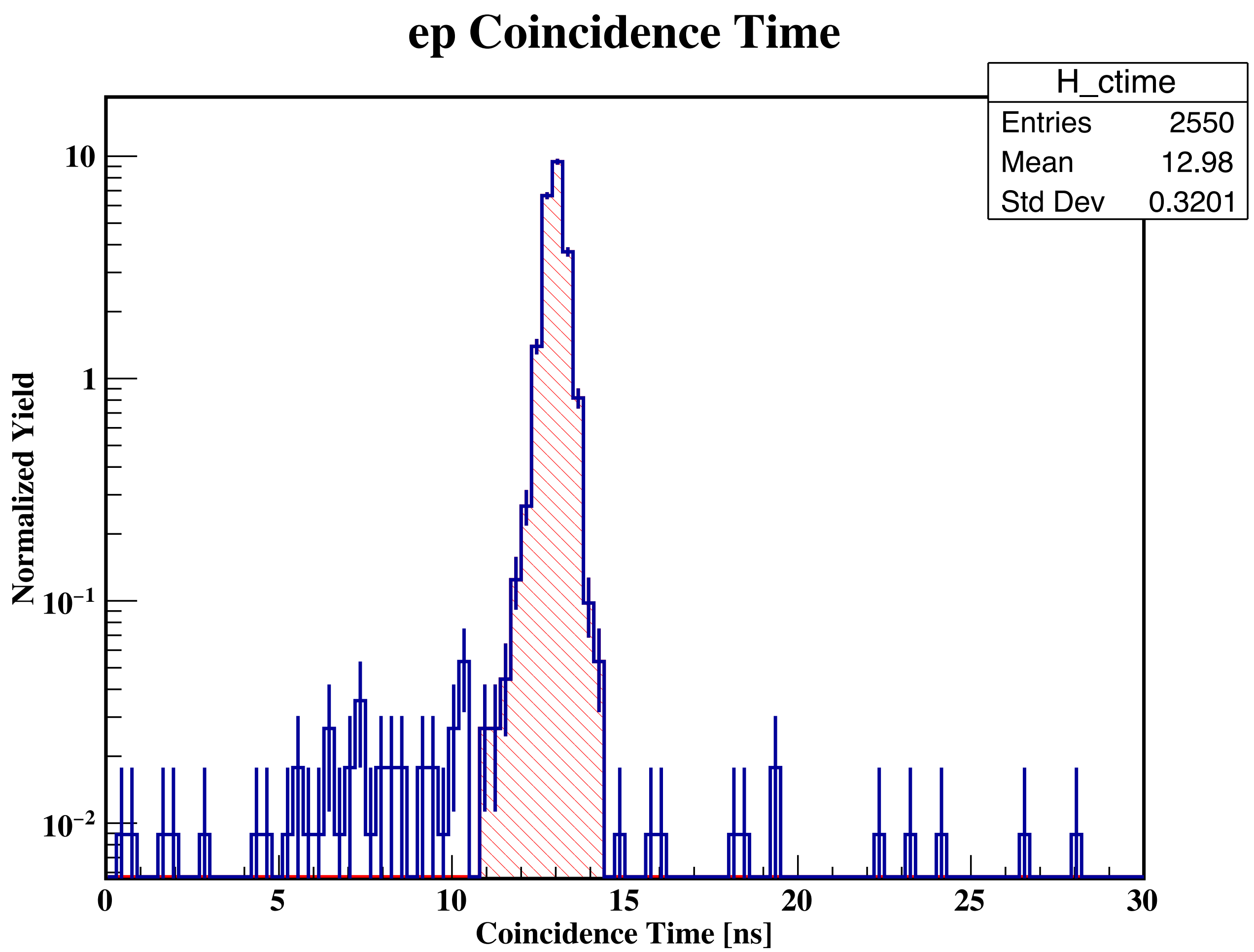
**** Select acceptance region where Optics Reconstruction is reliable**

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



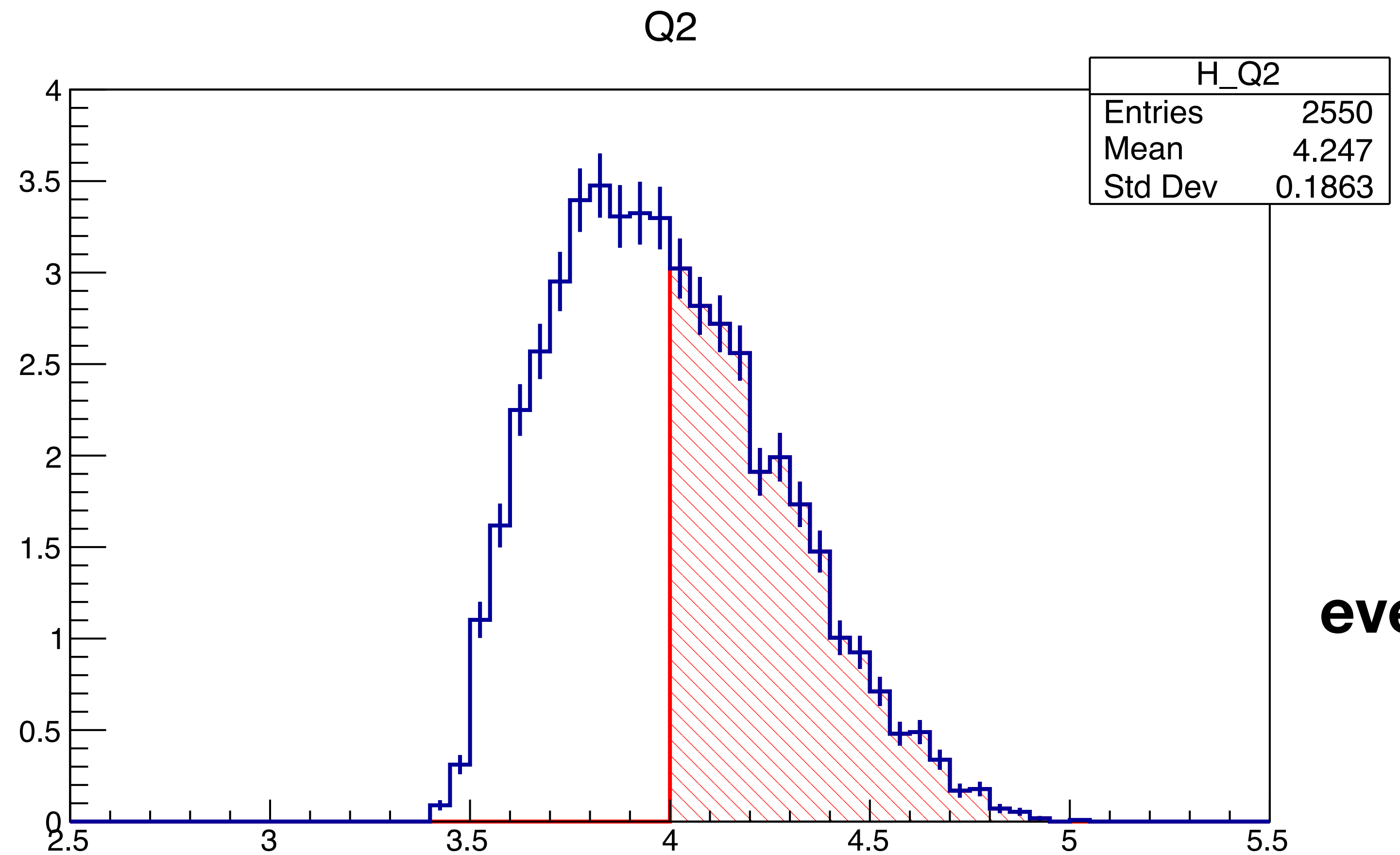
SHMS Calorimeter Normalized Total Energy of Track Cut (0.7, 5.0)

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



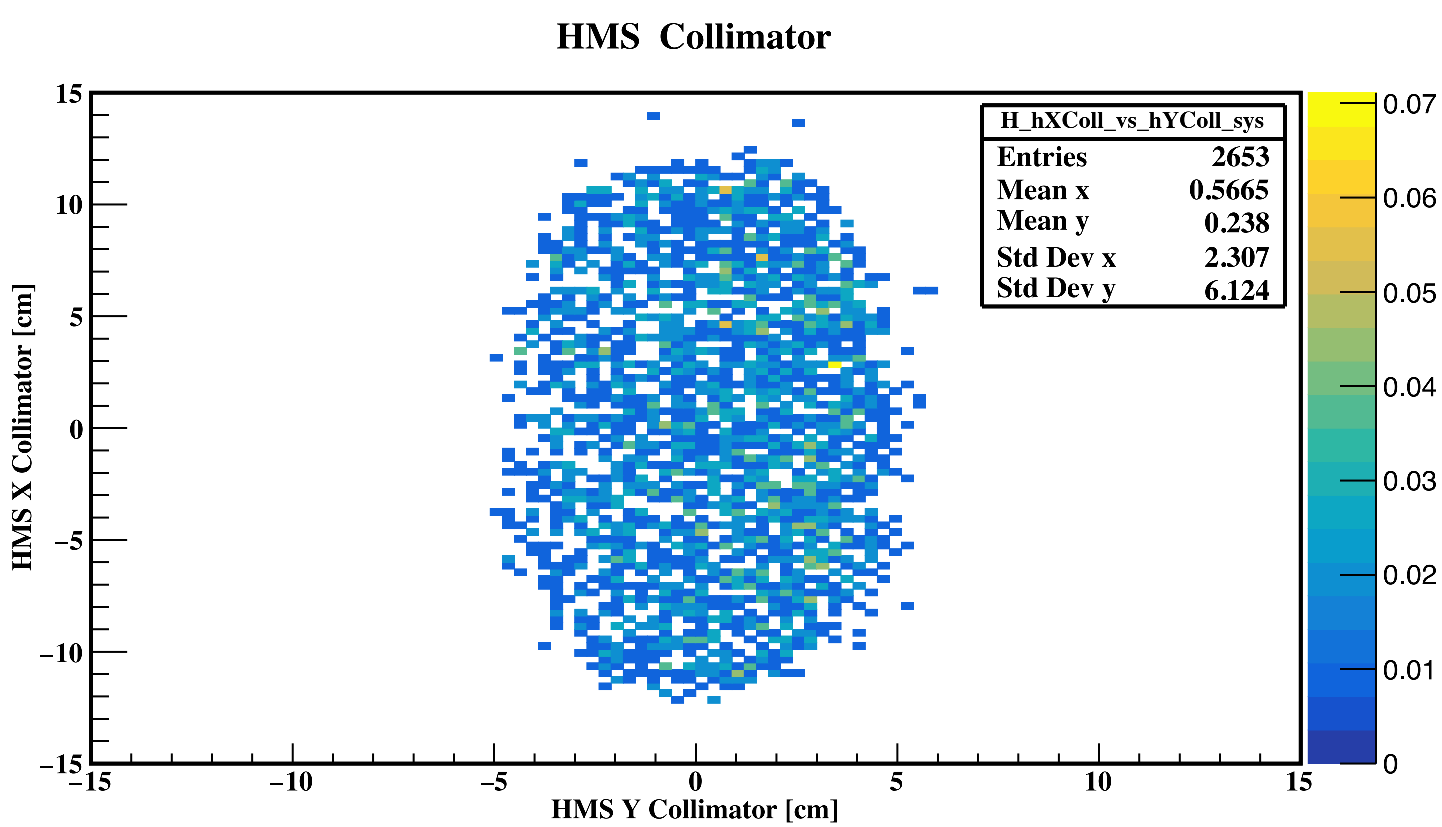
Coincidence Time Cut (10.5, 14.5) ns

**** select true electron-proton coincidences**



4-Momentum Transfer Cut
(4, 5) GeV^2

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



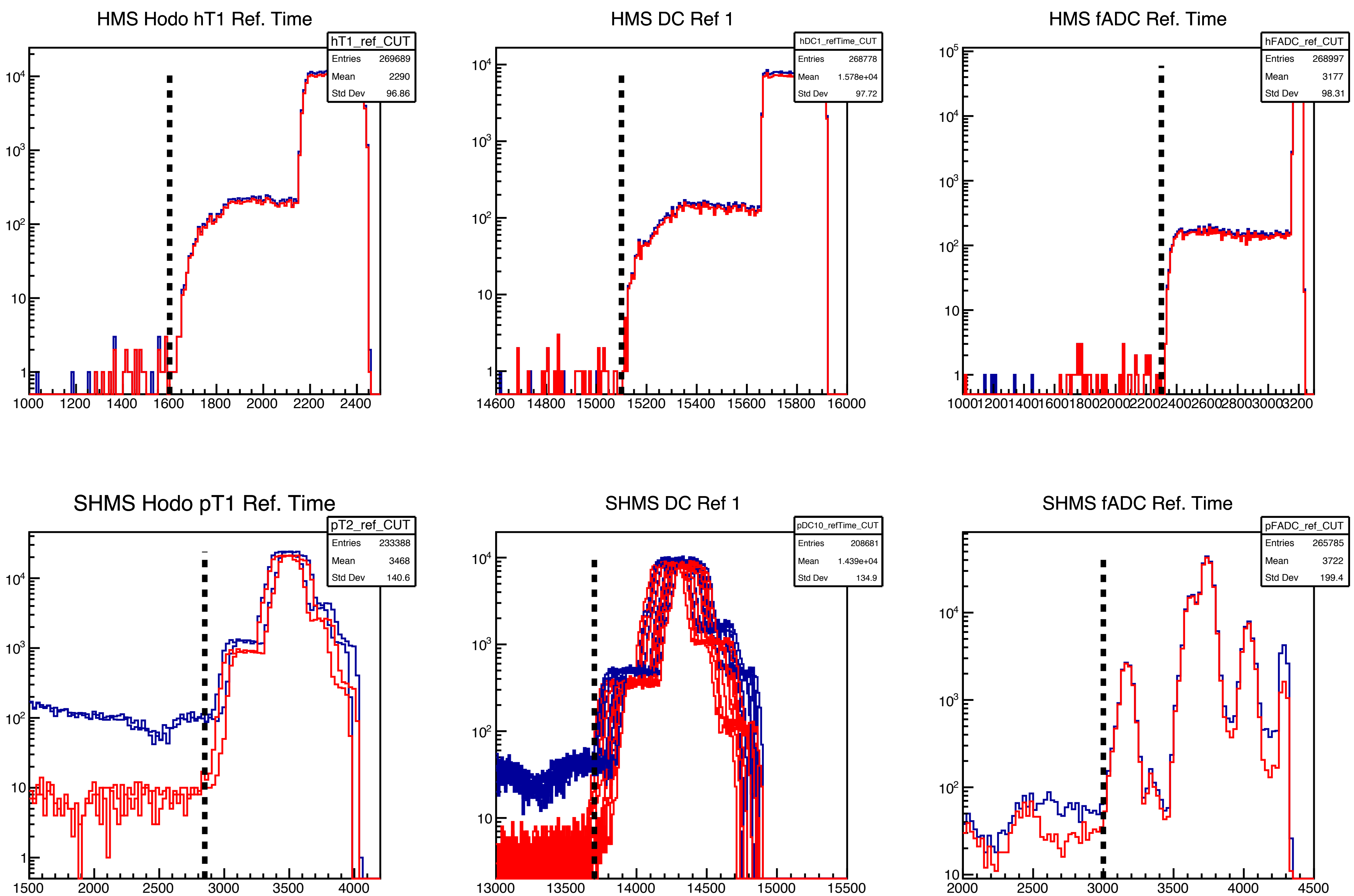
HMS Collimator Cut
(Geometrical cut on collimator dimensions)

****Select events that passed through collimator and did Not hit the edges of collimator**

Hall C Experimental Analysis on D(e,e’p)n

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)**



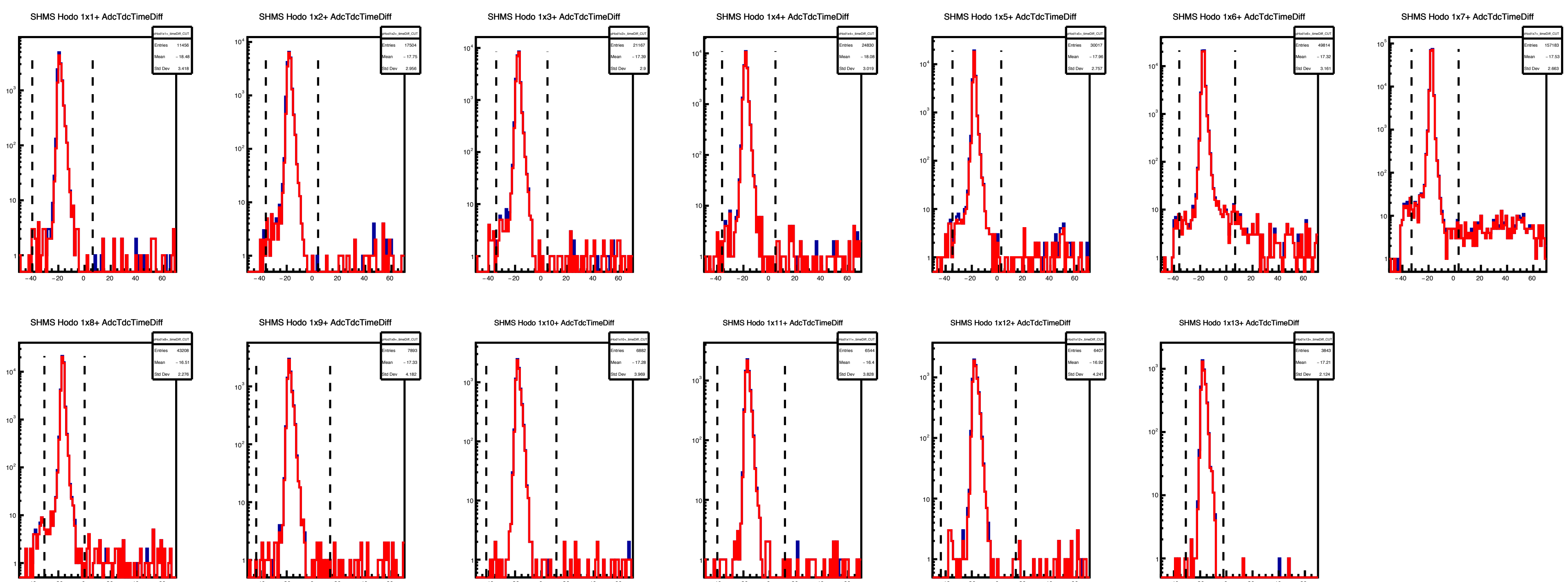
HMS Reference Times

SHMS Reference Times

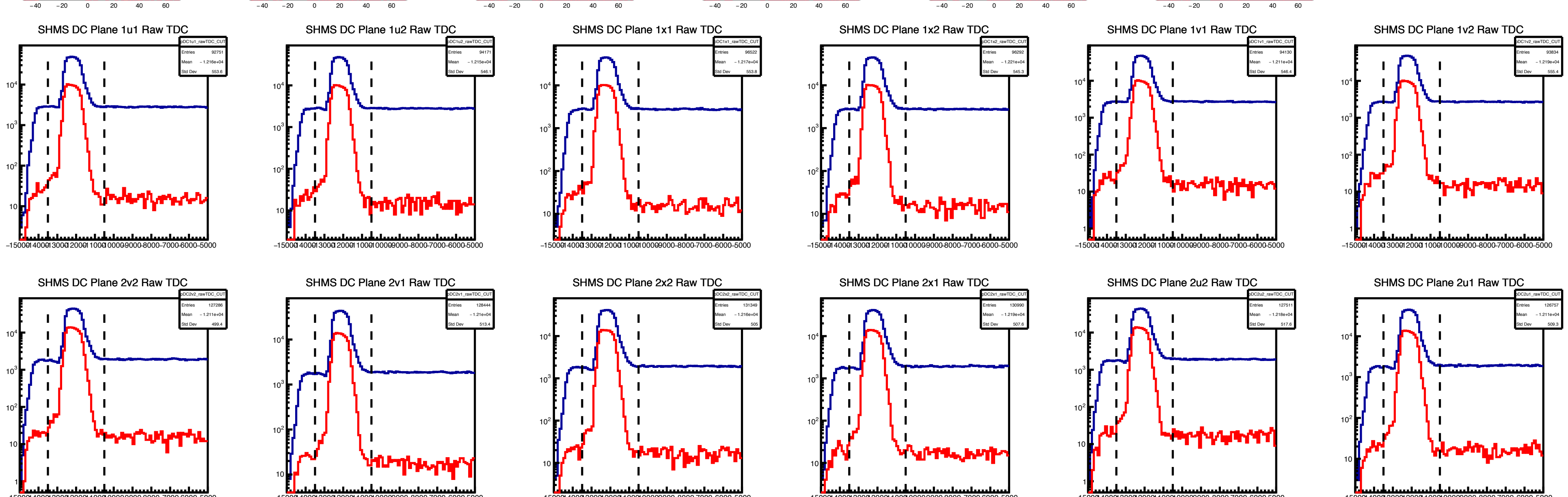
TDC Time Window Cuts

☑ 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

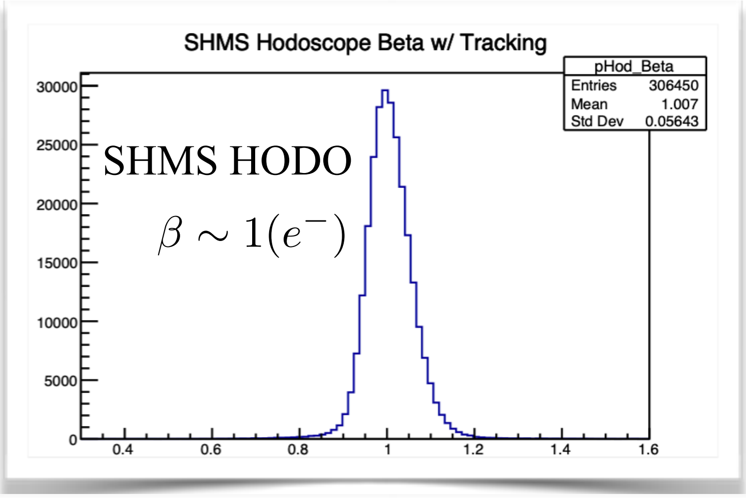


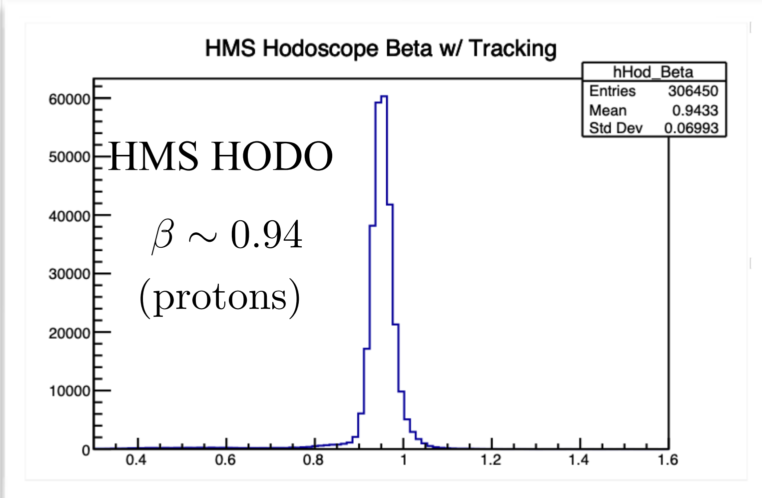
SHMS Hodoscope 1X+ (ADC-TDC) Time Difference

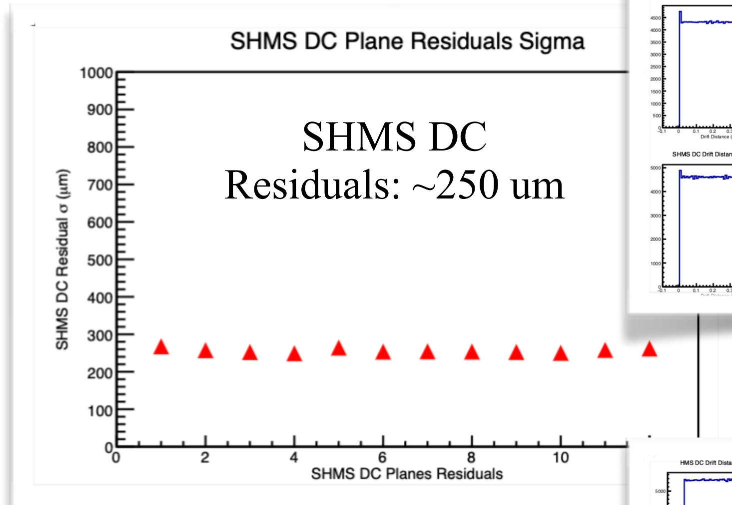


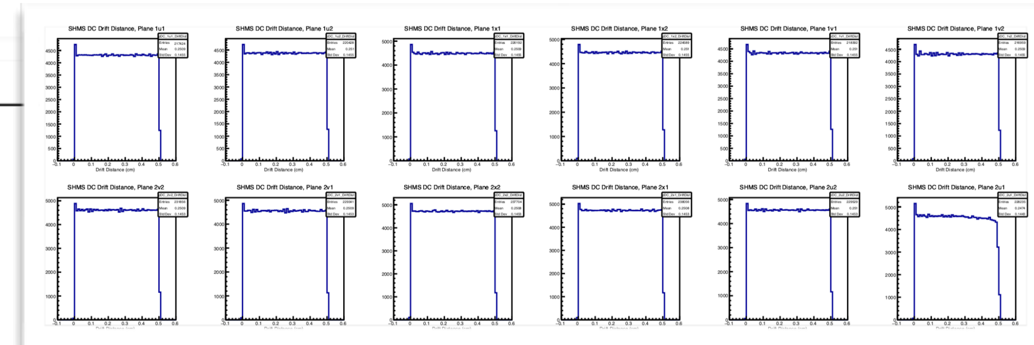
SHMS Drift Chambers Raw TDC Time

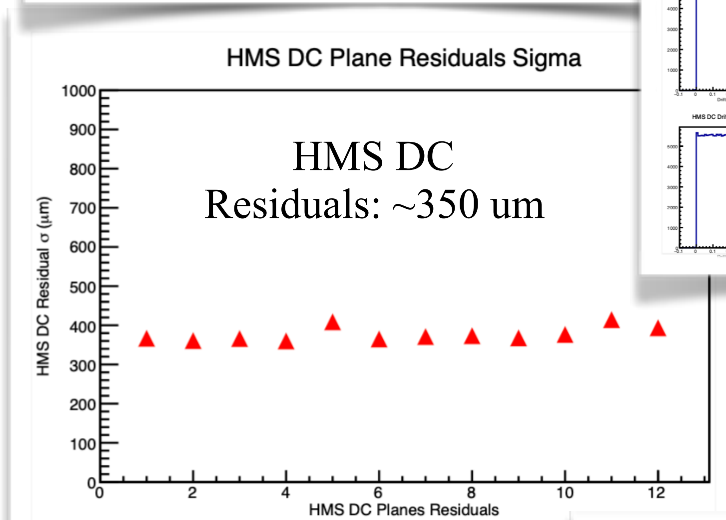
Detector Calibrations

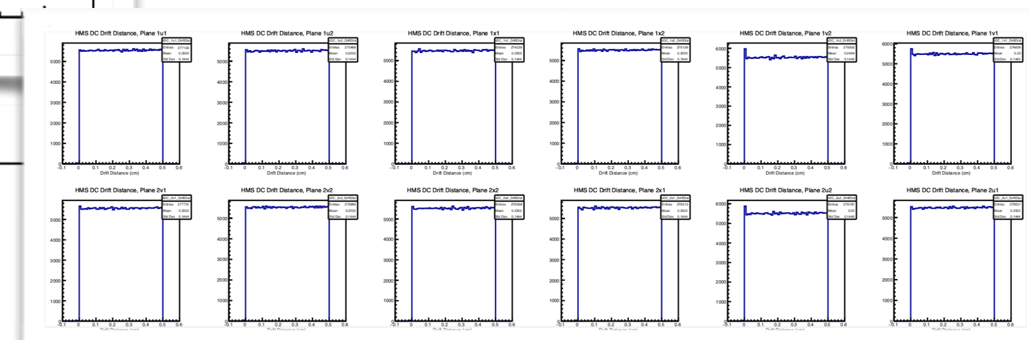


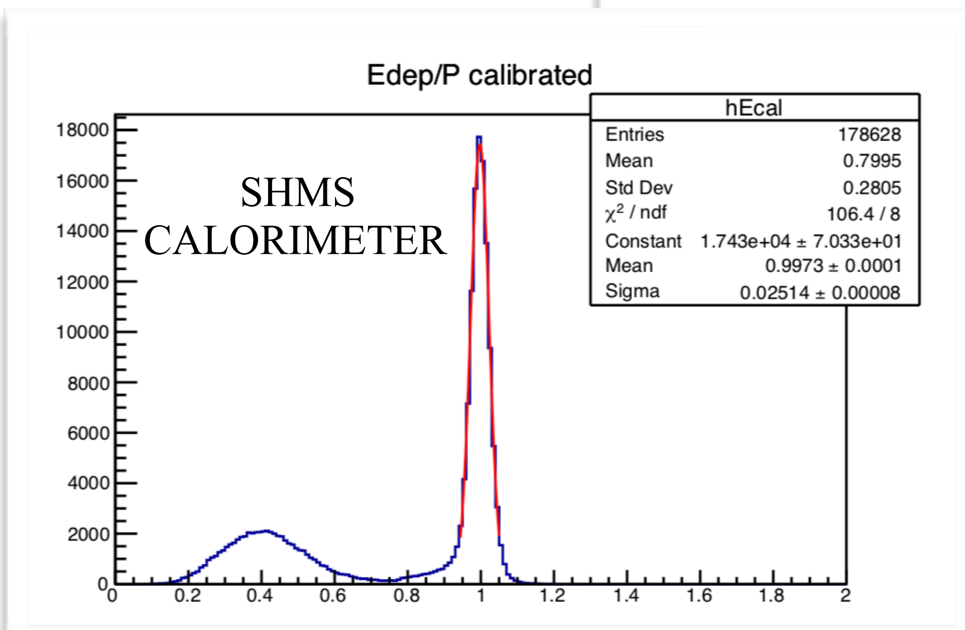


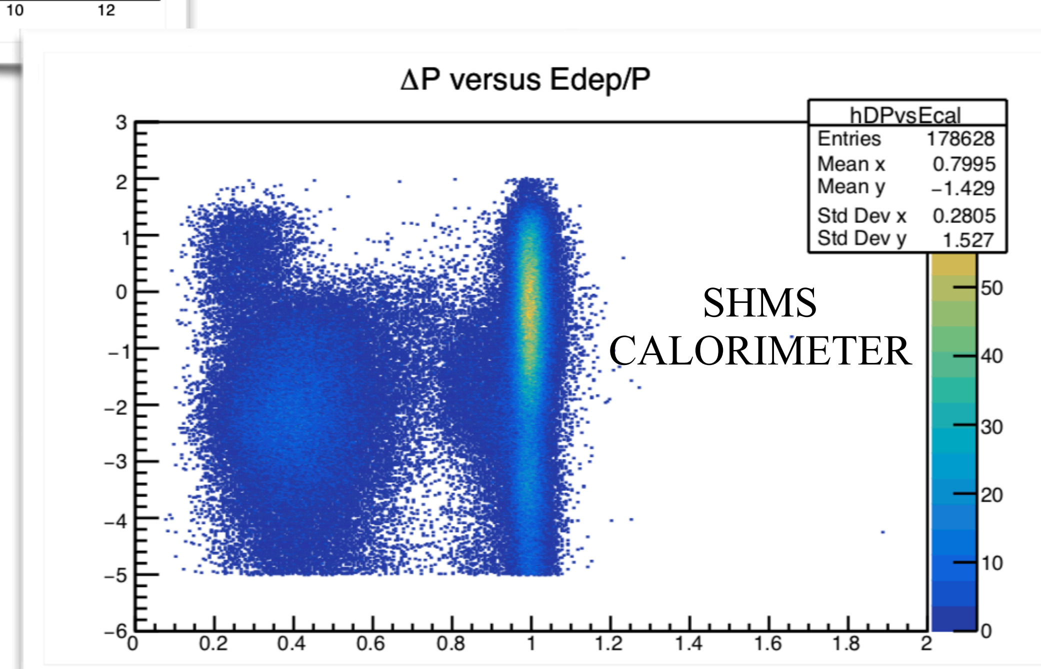




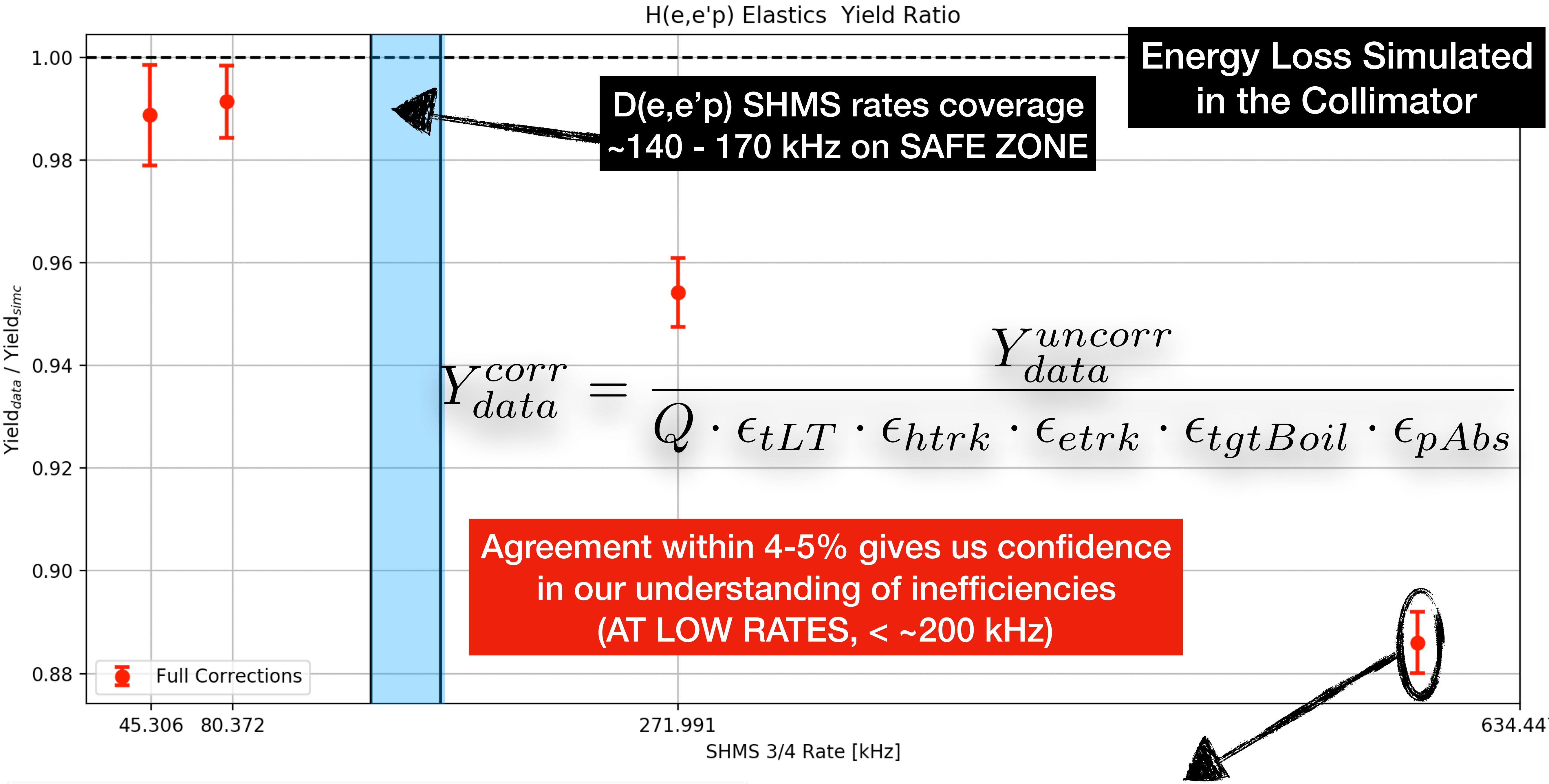








H(e,e'p) Yield Ratio Check



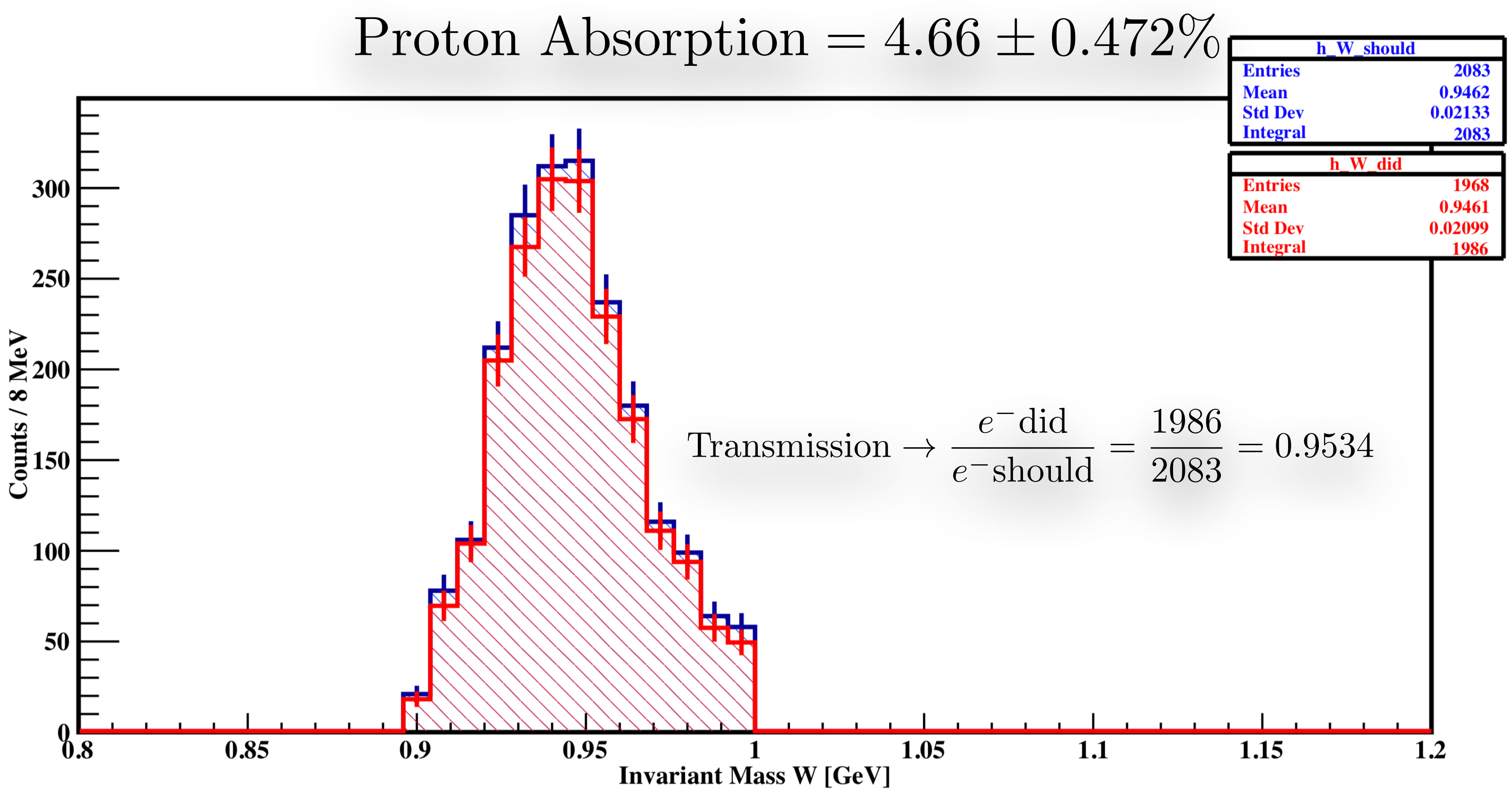
$$Y_{data}^{corr} = \frac{Y_{data}^{uncorr}}{Q \cdot \epsilon_{tLT} \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{tgtBoil} \cdot \epsilon_{pAbs}}$$

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

NOT Understood:

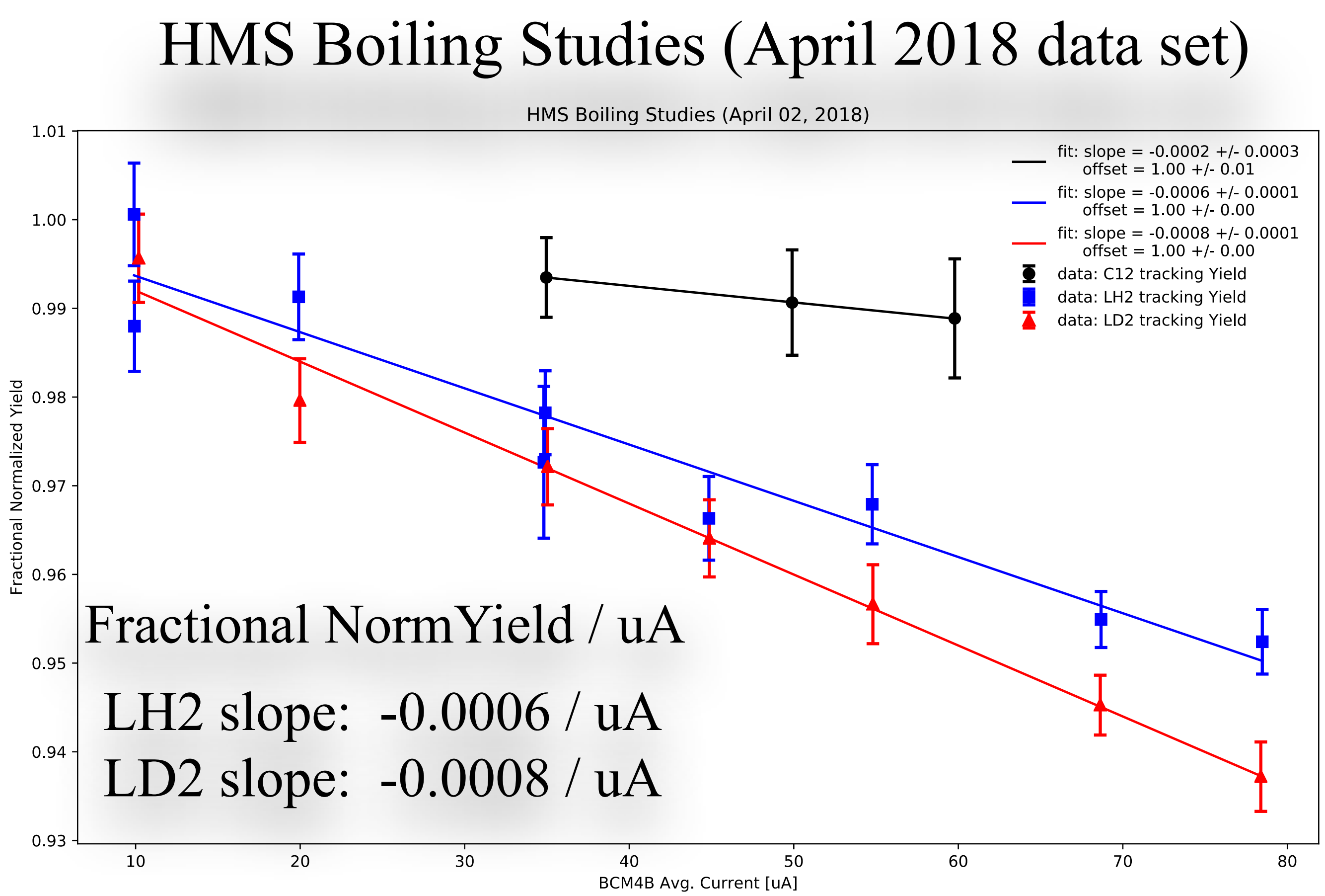
* How does the tracking algorithm perform at high rates?

Results of p-Absorption and Target Boiling Corrections to the Data Yield



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

(ONLY relevant for coincidence experiments)



For Full Description of Target Boiling Corrections See DOC DB Link HERE !

Extraction of D(e,e’p)n Cross Section

- ❖ Corrected data Yield for inefficiencies and charge
  (explain basic definition of experimental cross section)

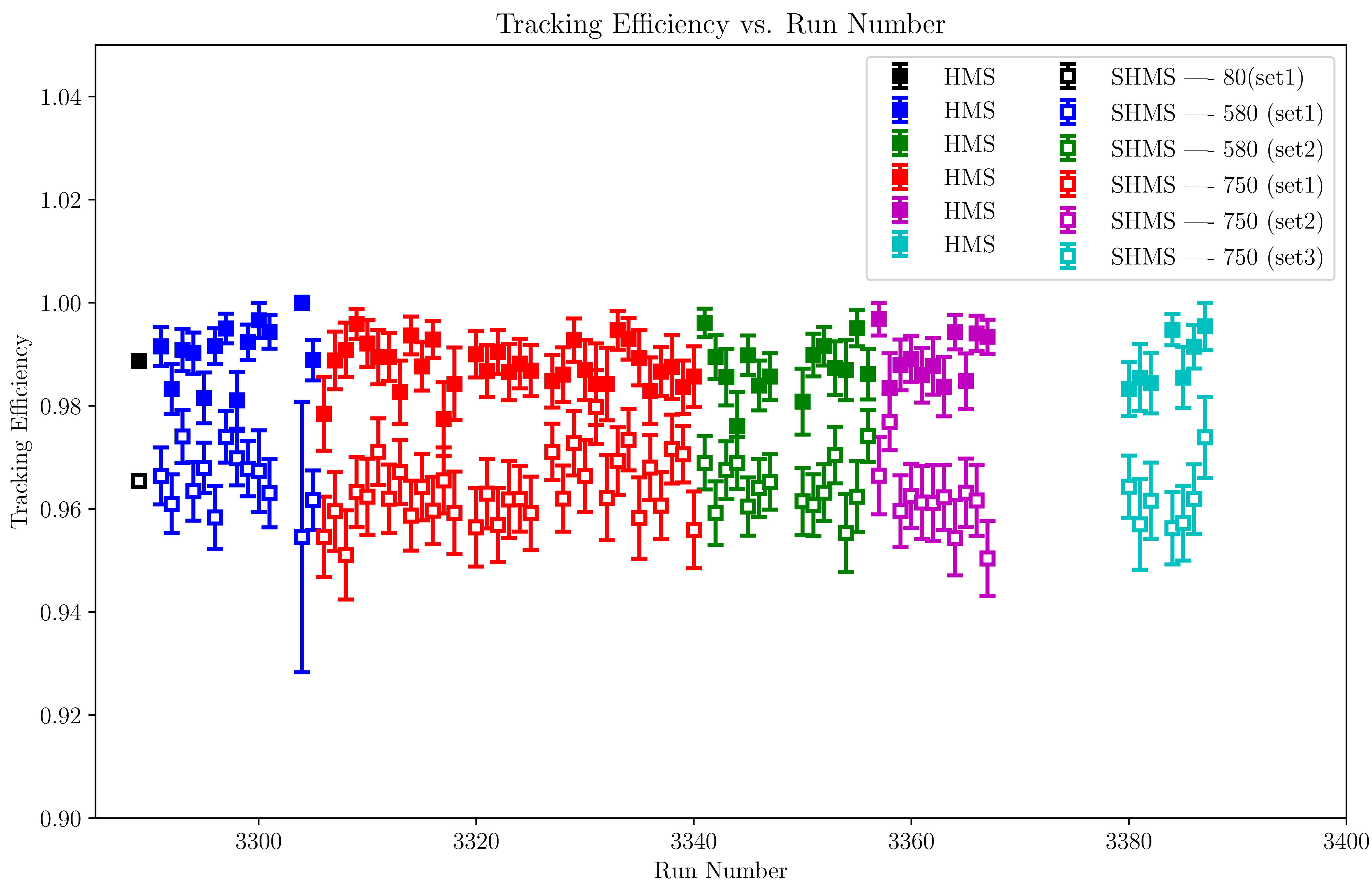
- ❖ Radiative Corrections

- ❖ Bin-Centering Corrections

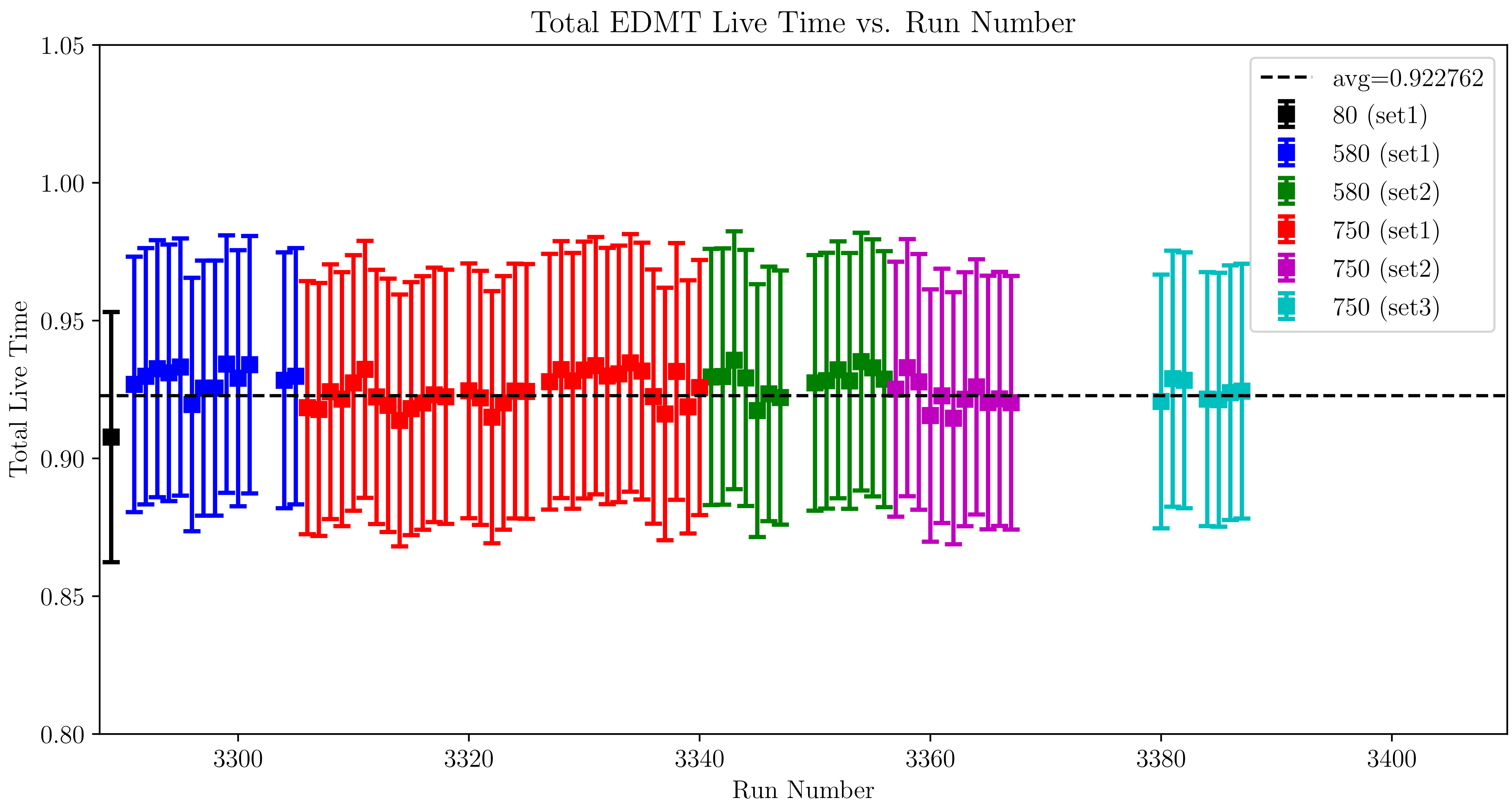
Efficiencies and Correction Factors

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

TRACKING EFFICIENCY

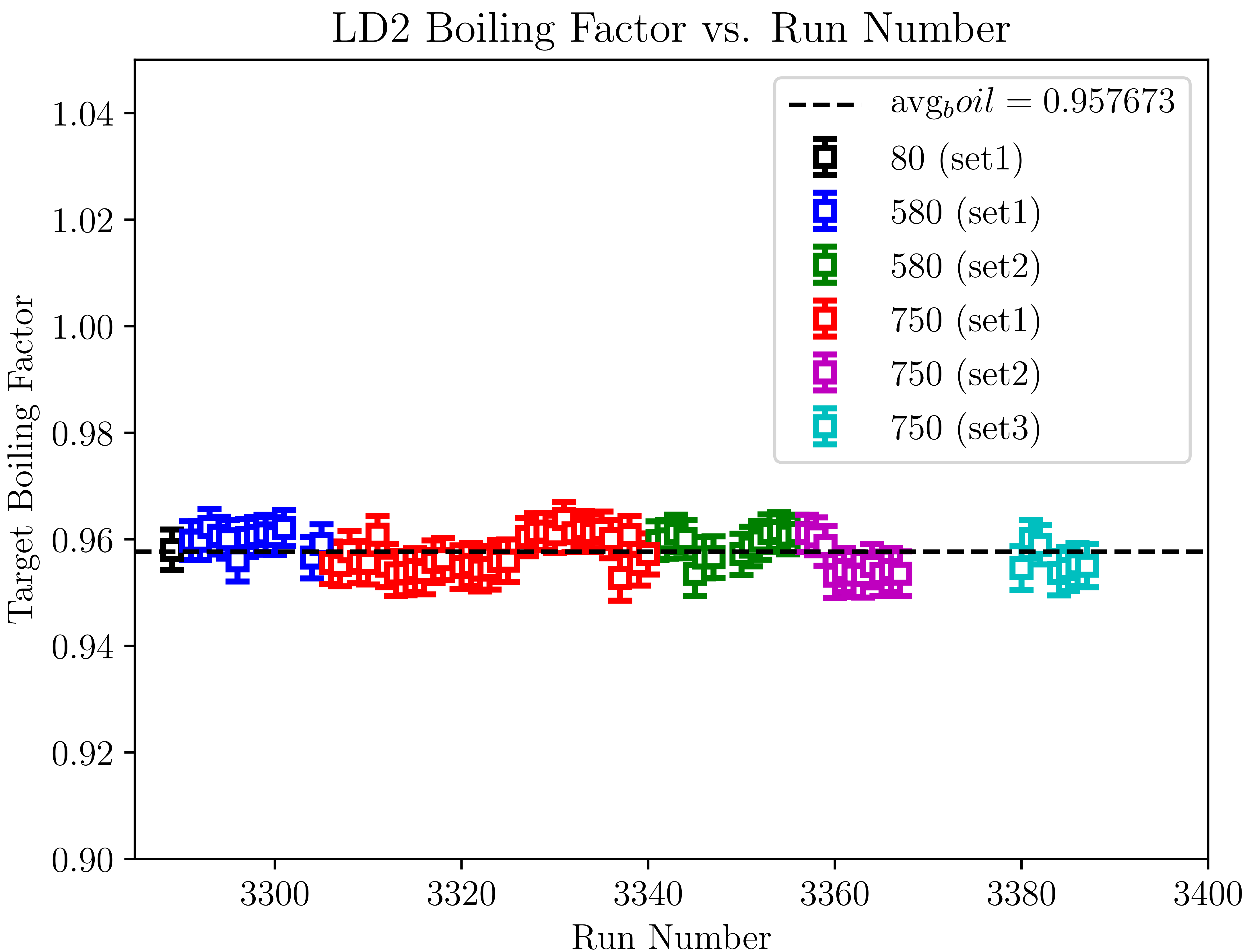


TOTAL EDTM LIVE TIME

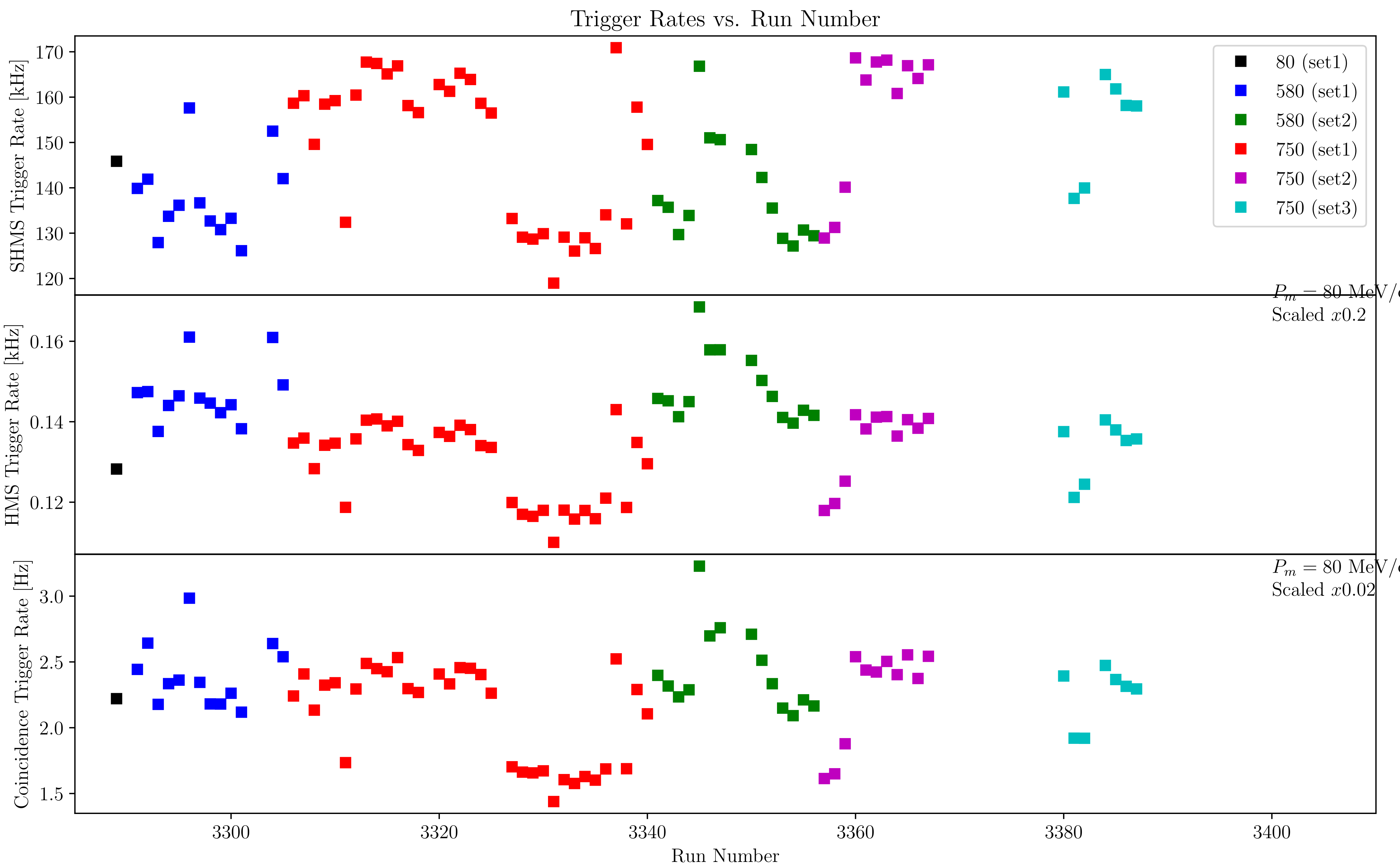


EDTM: Electronic Dead Time Monitoring

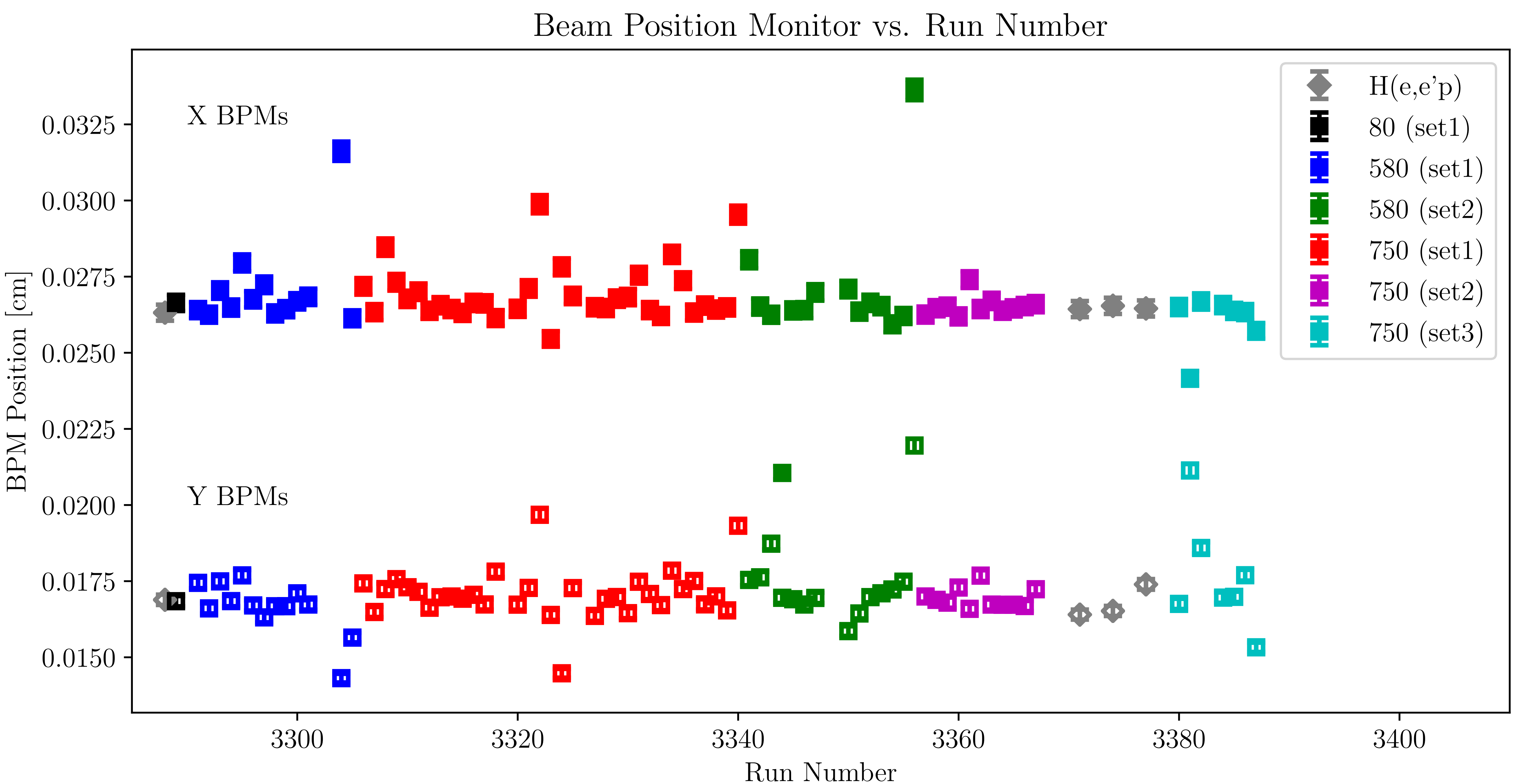
TARGET BOILING FACTOR



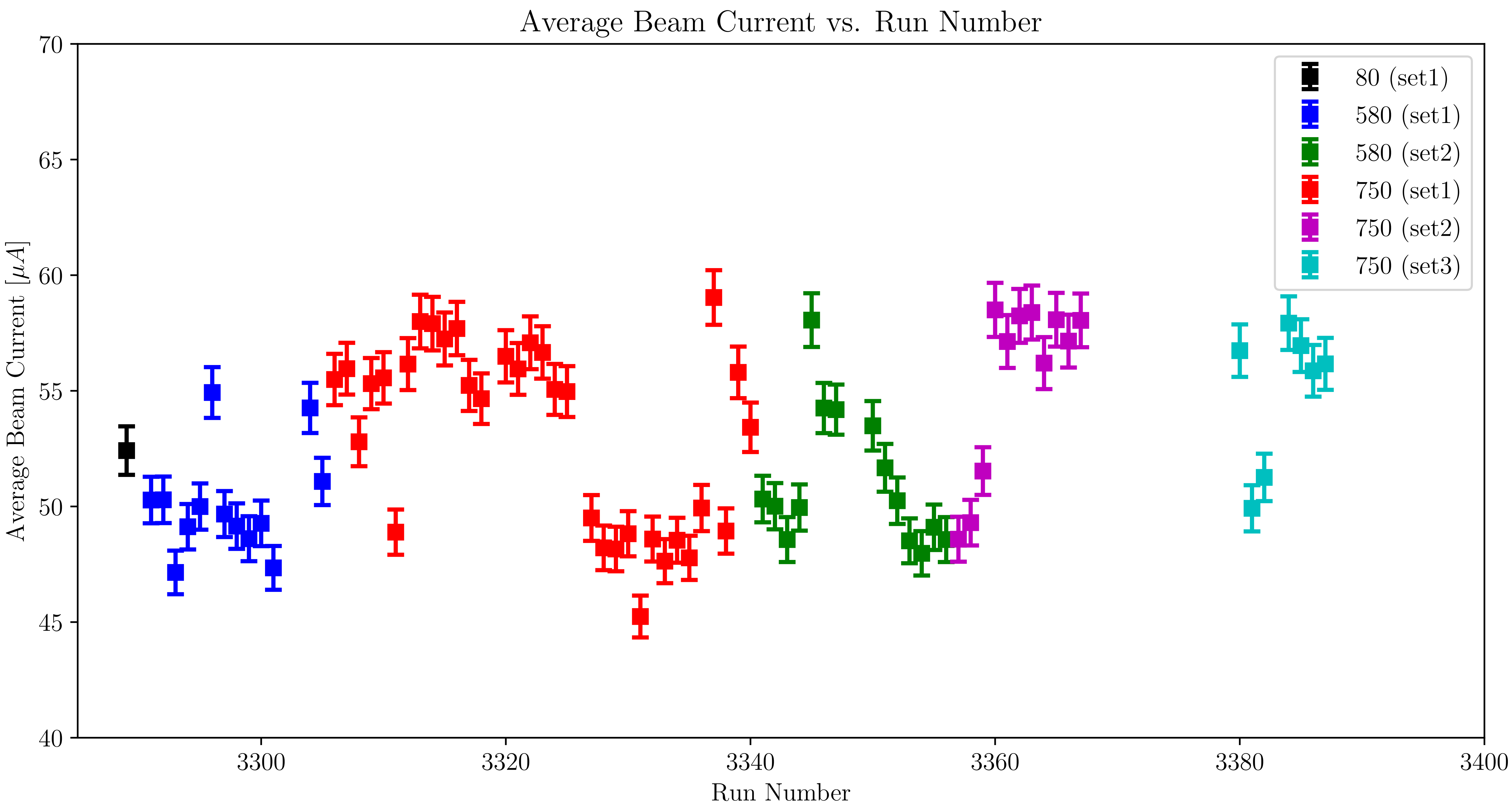
TRIGGER RATES



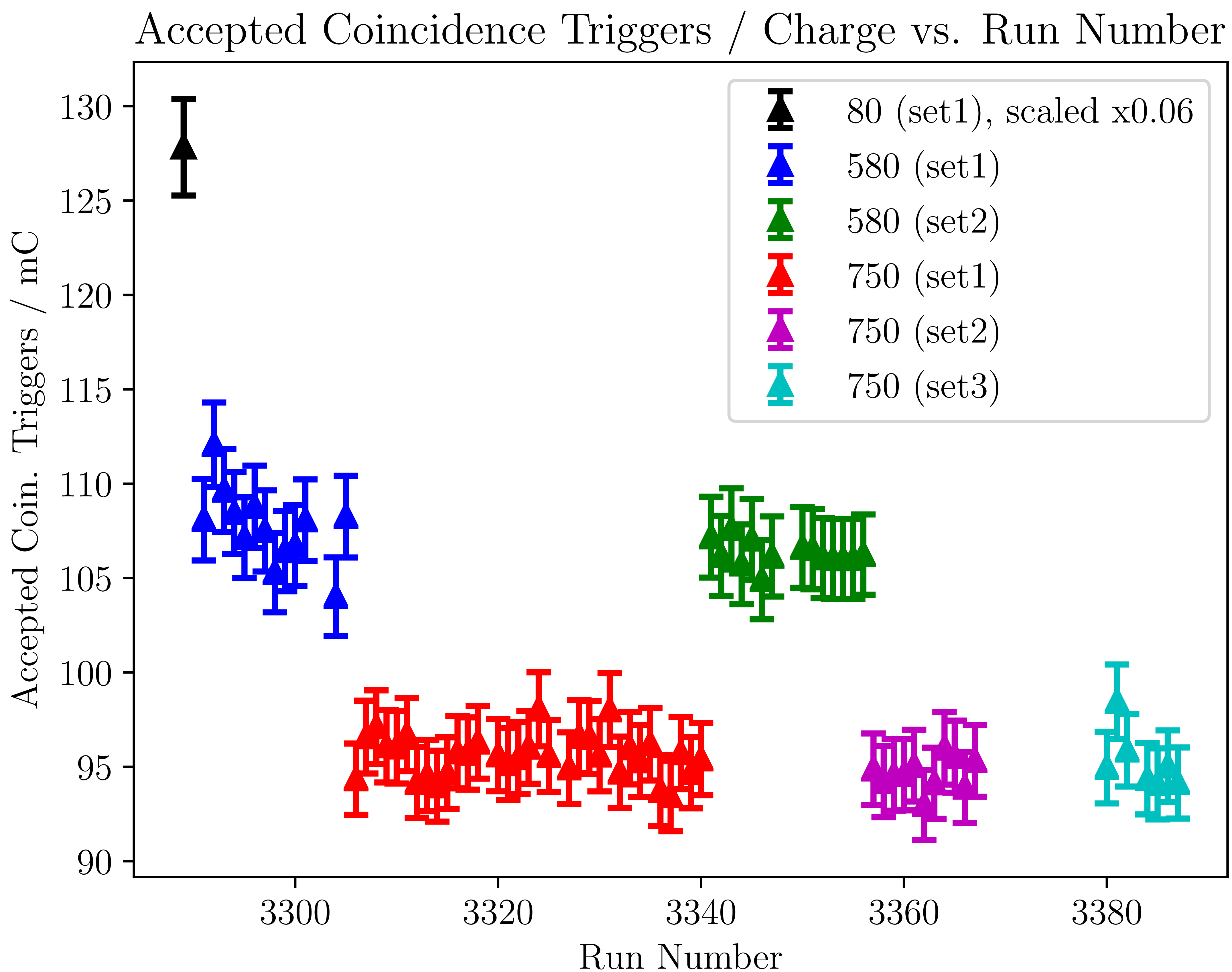
BEAM POSITION MONITORING (BPMs)



AVERAGE BEAM CURRENT



ACCEPTED COUNTS / CHARGE

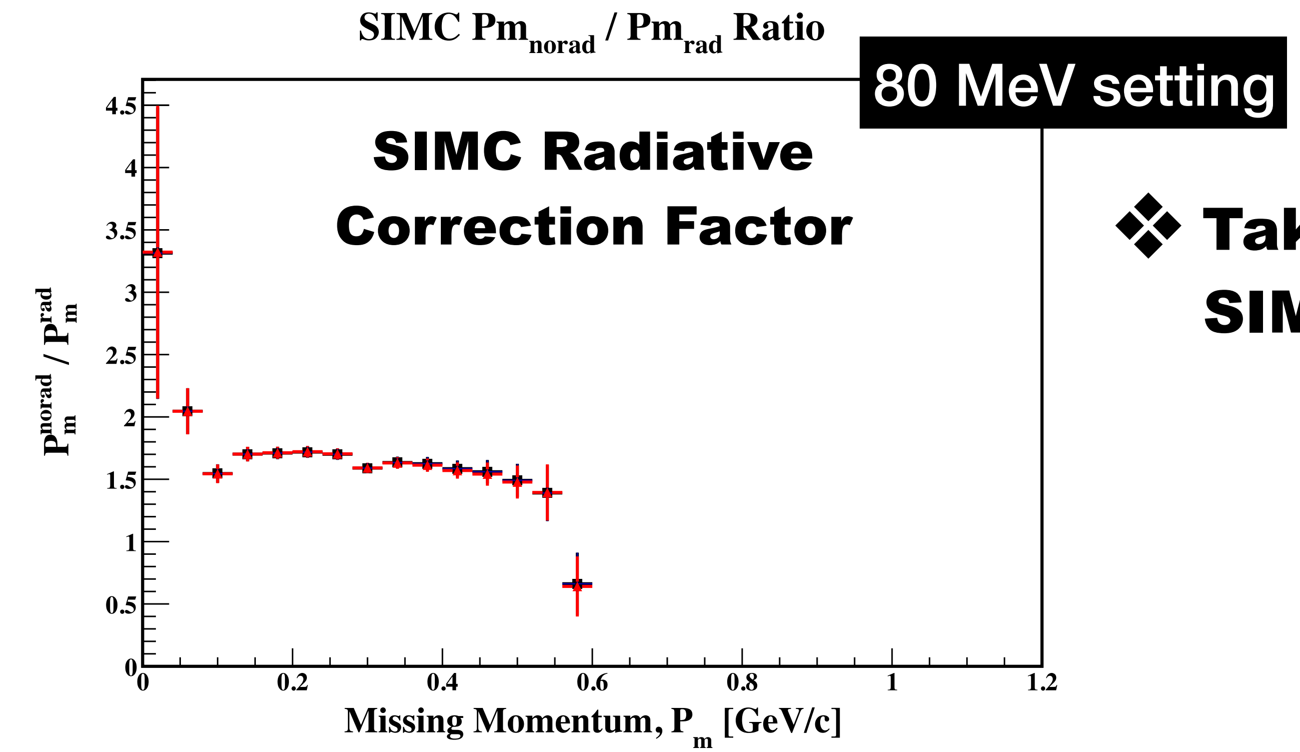


RADIATIVE CORRECTIONS

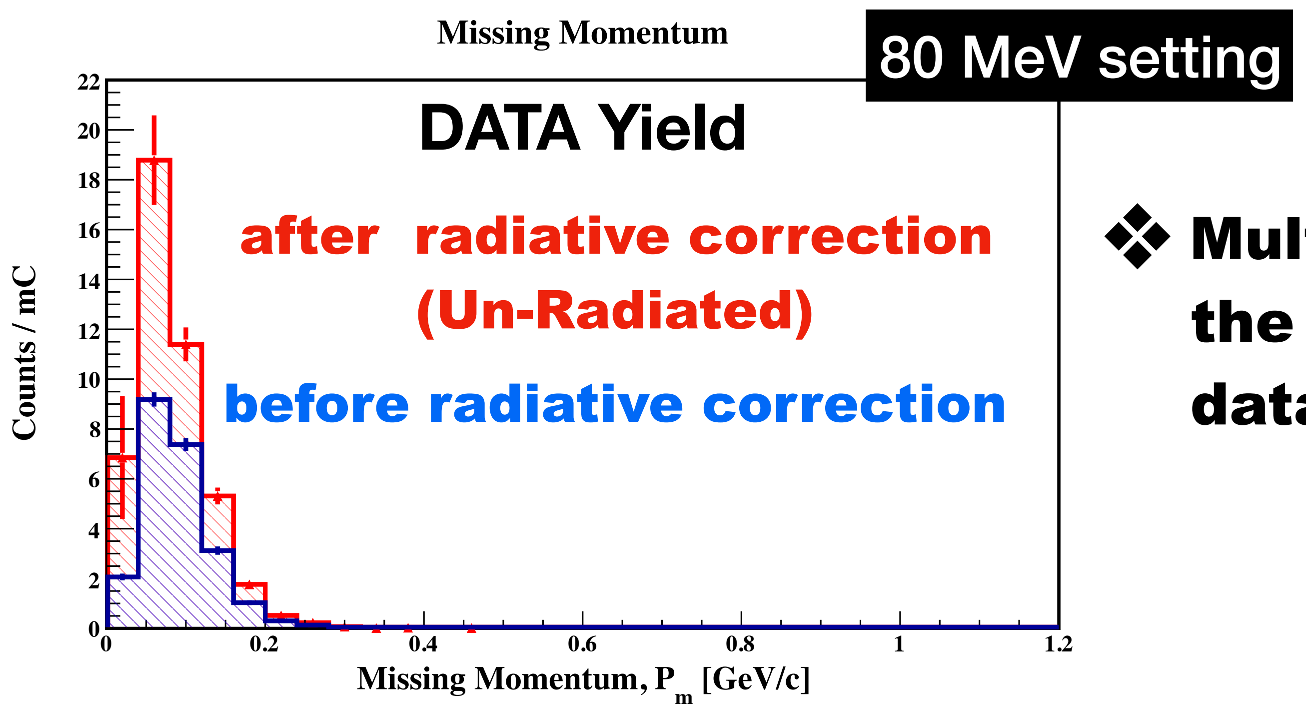
Extraction of the D(e,e'p)n Cross Section

❖ **Decide which kinematic variable to bin (or store) the cross section.**
(I choose to store the cross section in missing momentum bins)

❖ **Only apply radiative corrections to the relevant variable chosen**
(No need for unnecessary histograms)

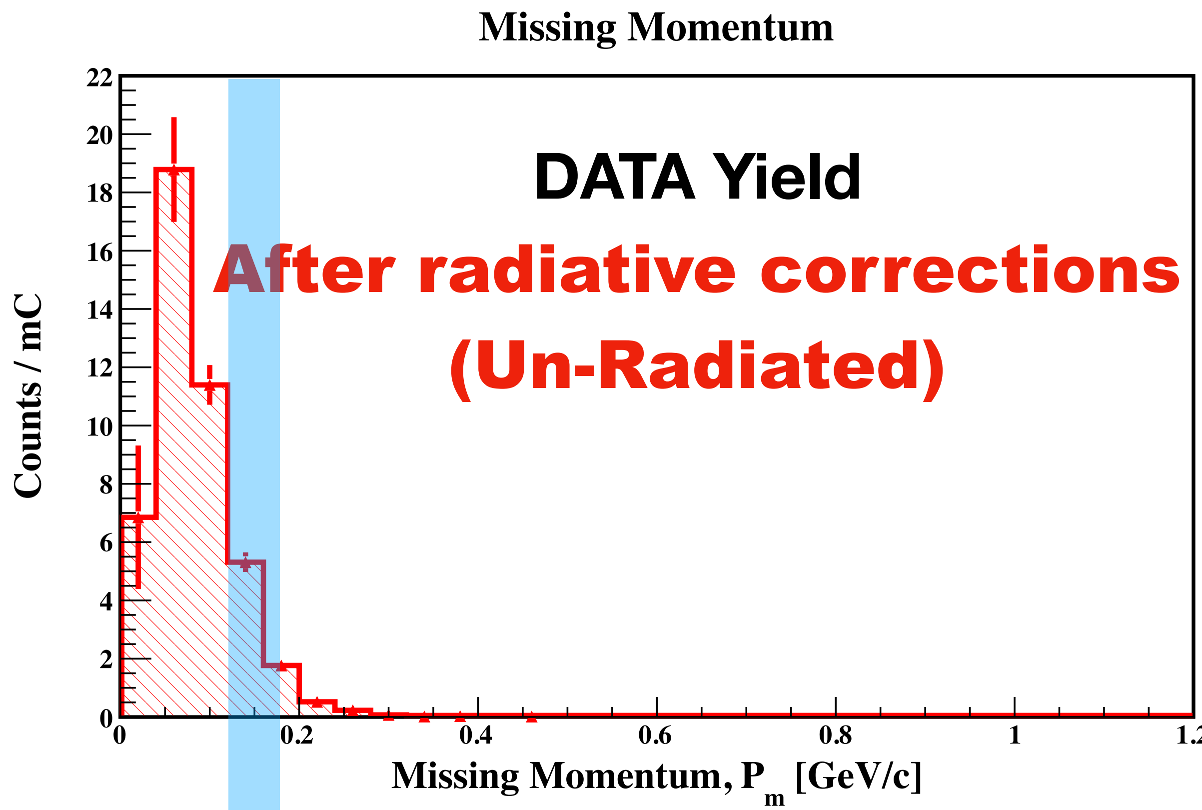


❖ **Take ratio between non-radiative to radiative SIMC Yield to get correction factor bin by bin.**

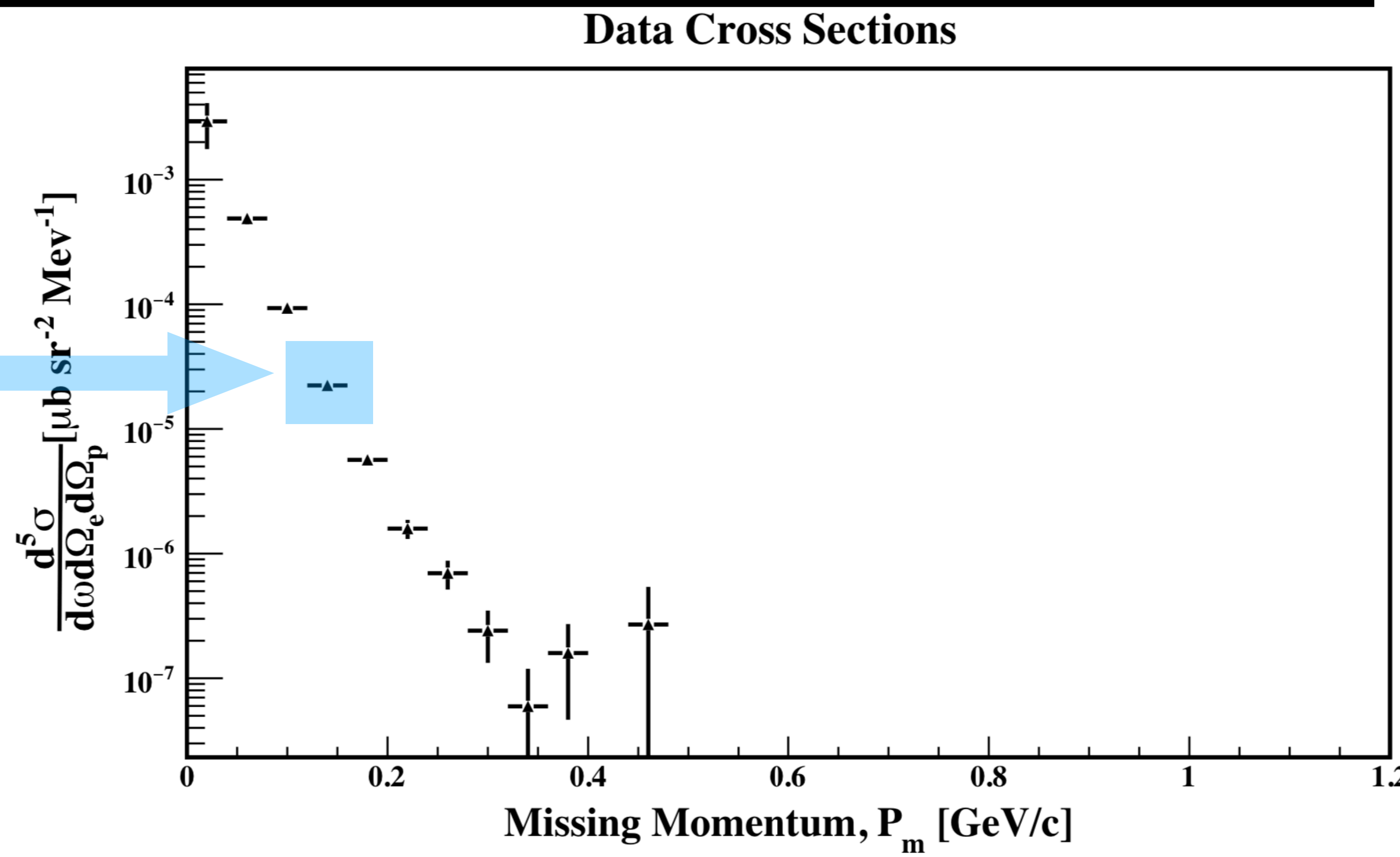


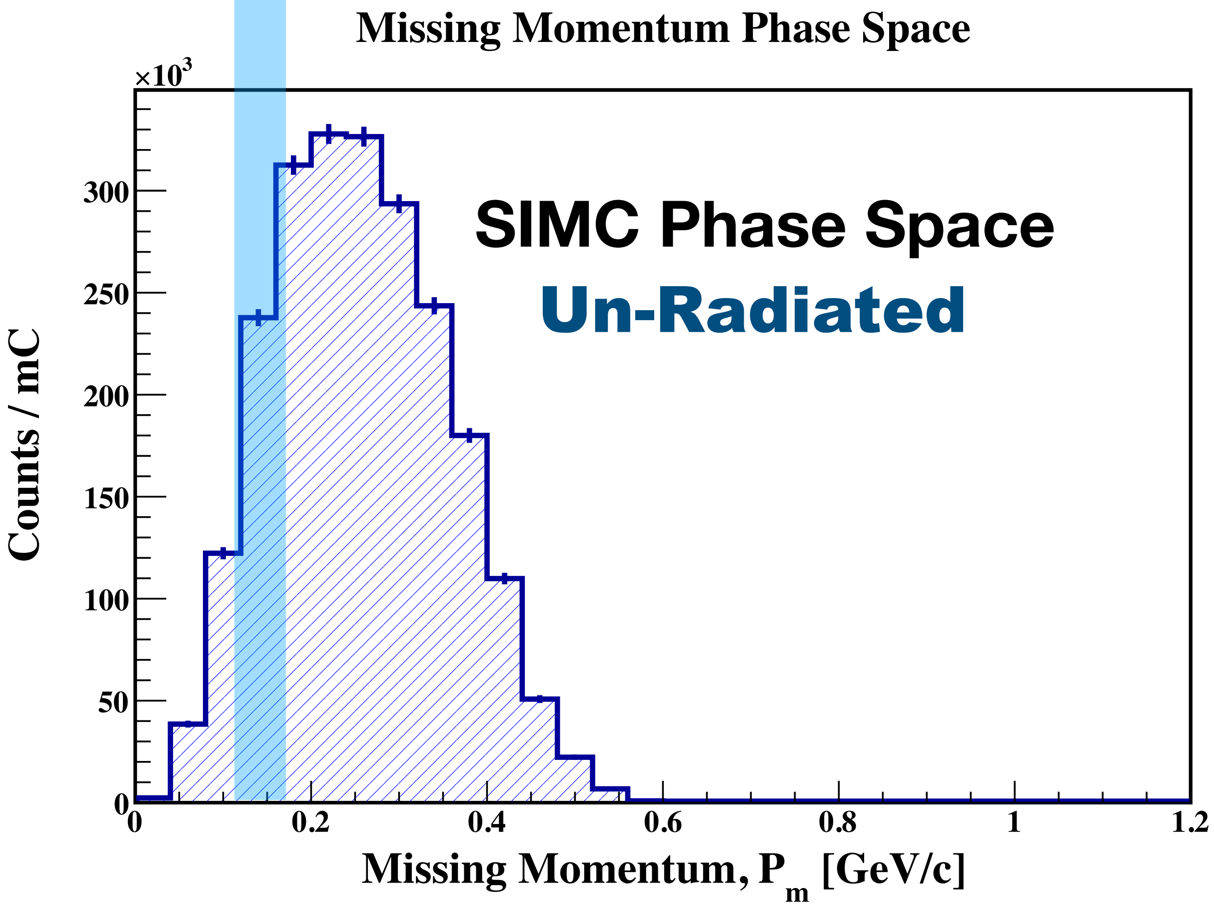
❖ **Multiply the radiative correction factor by the un-radiative data yield to get the corrected data yield bin-by-bin.**

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



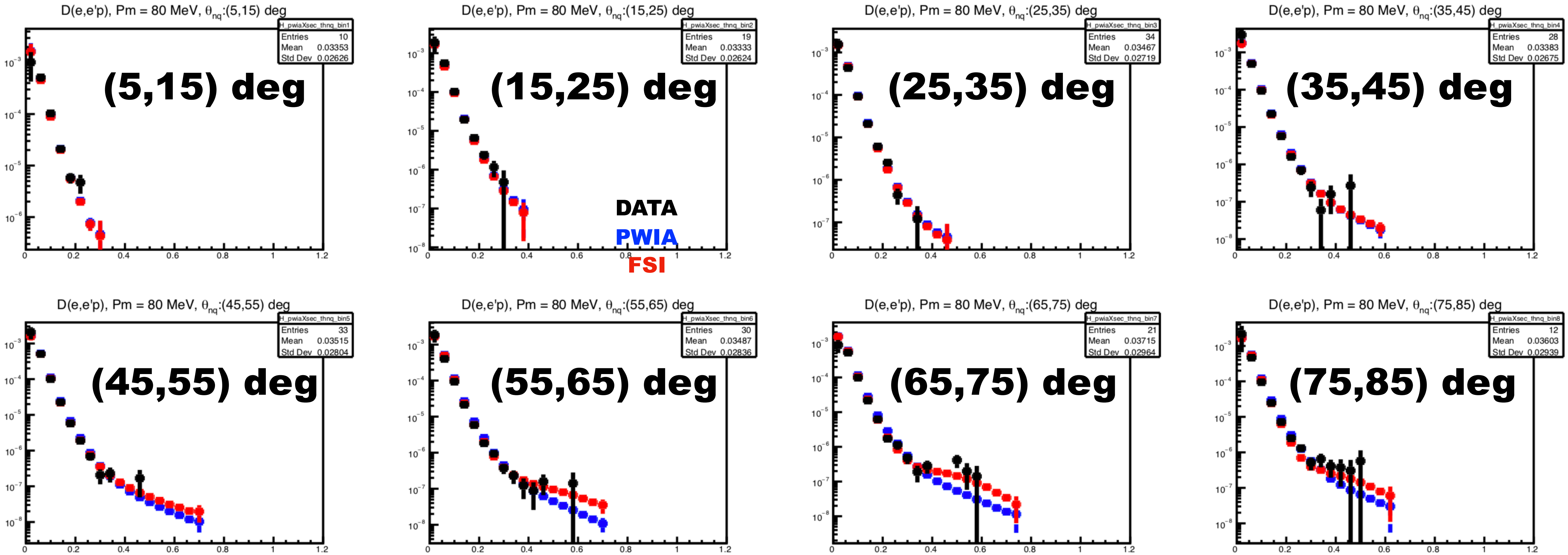
The ratio of the fully corrected data yield to the SIMC phase space will give the data cross section, bin-by-bin





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

- ❖ **D(e,e’p)n 80 MeV setting Cross Section Binned in different recoil neutron angles.**

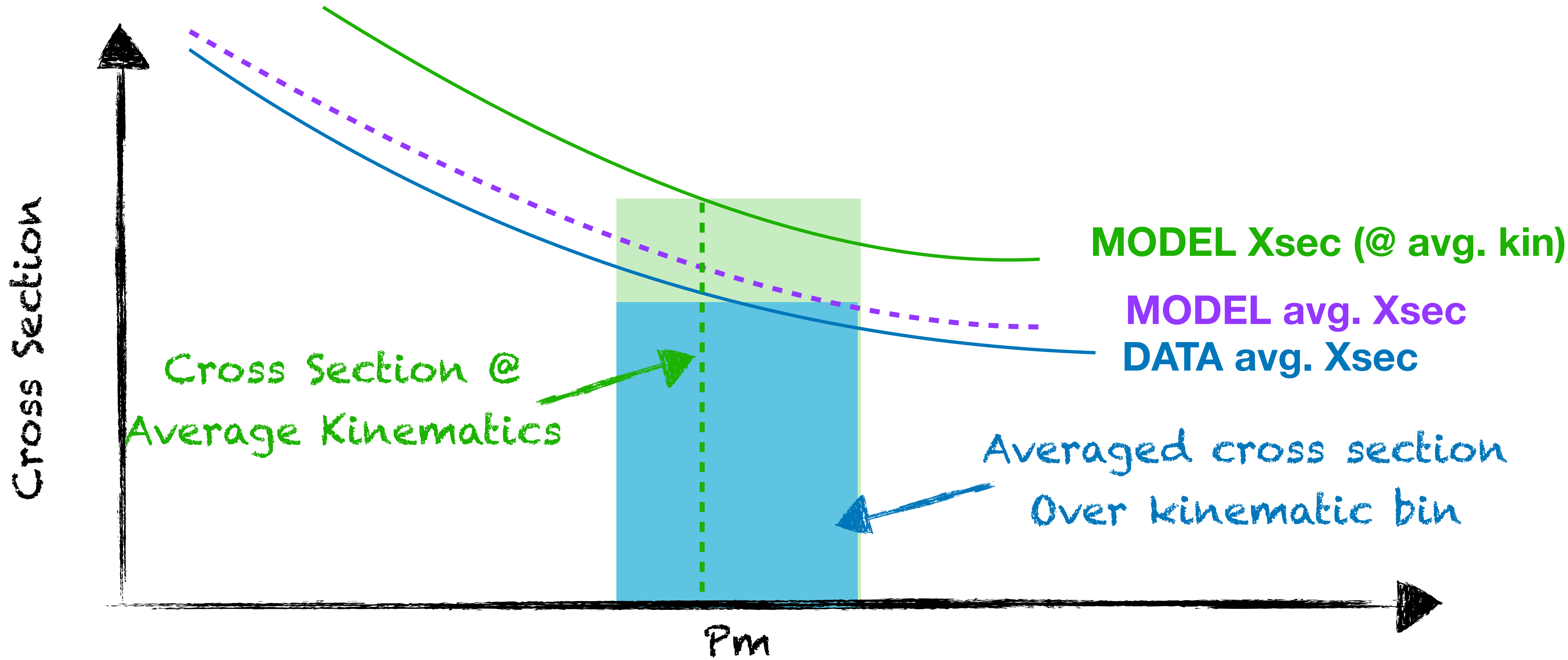


BIN-CENTERING

CORRECTIONS

Bin Centering Corrections

❖ **In reality, the measured data cross section is an average over the kinematic bin in which it is stored.**



Model cross section at the averaged kinematic variables

Model average cross section -> simcYield / PhaseSpace

(SIMC Yield does NOT have to be corrected for efficiencies or charge, as it is assumed all efficiencies are 100% and a 1 mC charge is assumed in the input file)

$$f_{bc} = \frac{\sigma^{model}(\bar{E}_b, \bar{Q}^2, \bar{\omega}, \bar{\theta}_{pq}^{cm}, \bar{\phi}_{pq})}{\bar{\sigma}^{model}}$$

Bin-centering correction

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 → **IN** → **Theoretical Model (usually a code that takes the input)** → **OUT** → $\sigma^{model}(\bar{E}_b, \bar{Q^2}, \bar{\omega}, \bar{\theta}^{cm}_{pq}, \bar{\phi}_{pq})$

$$\bar{\sigma}^{model} \equiv \frac{Y^{\mathrm{SIMC}}}{V^{P.S.}}$$

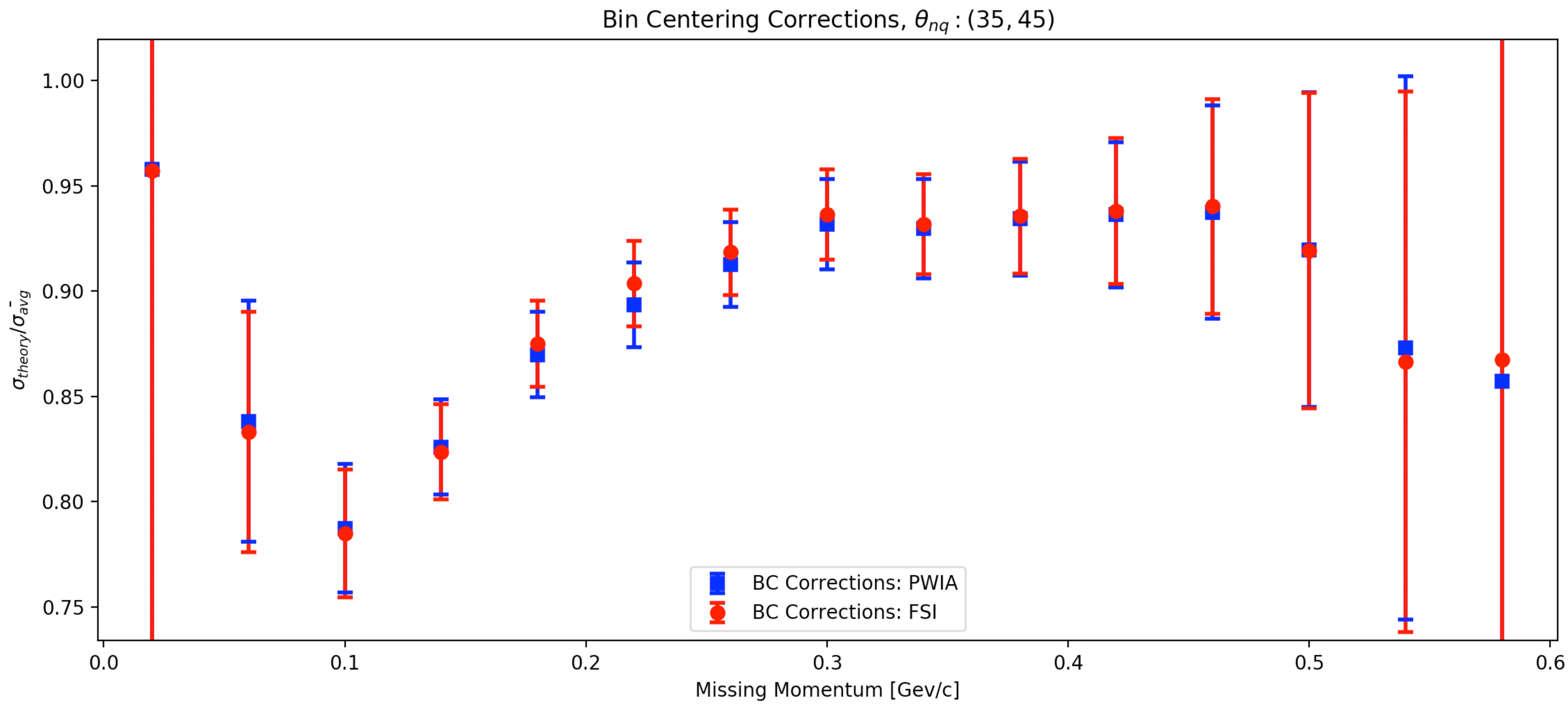
→ **Averaged Model Cross Section (See Slide 11 for reference)**

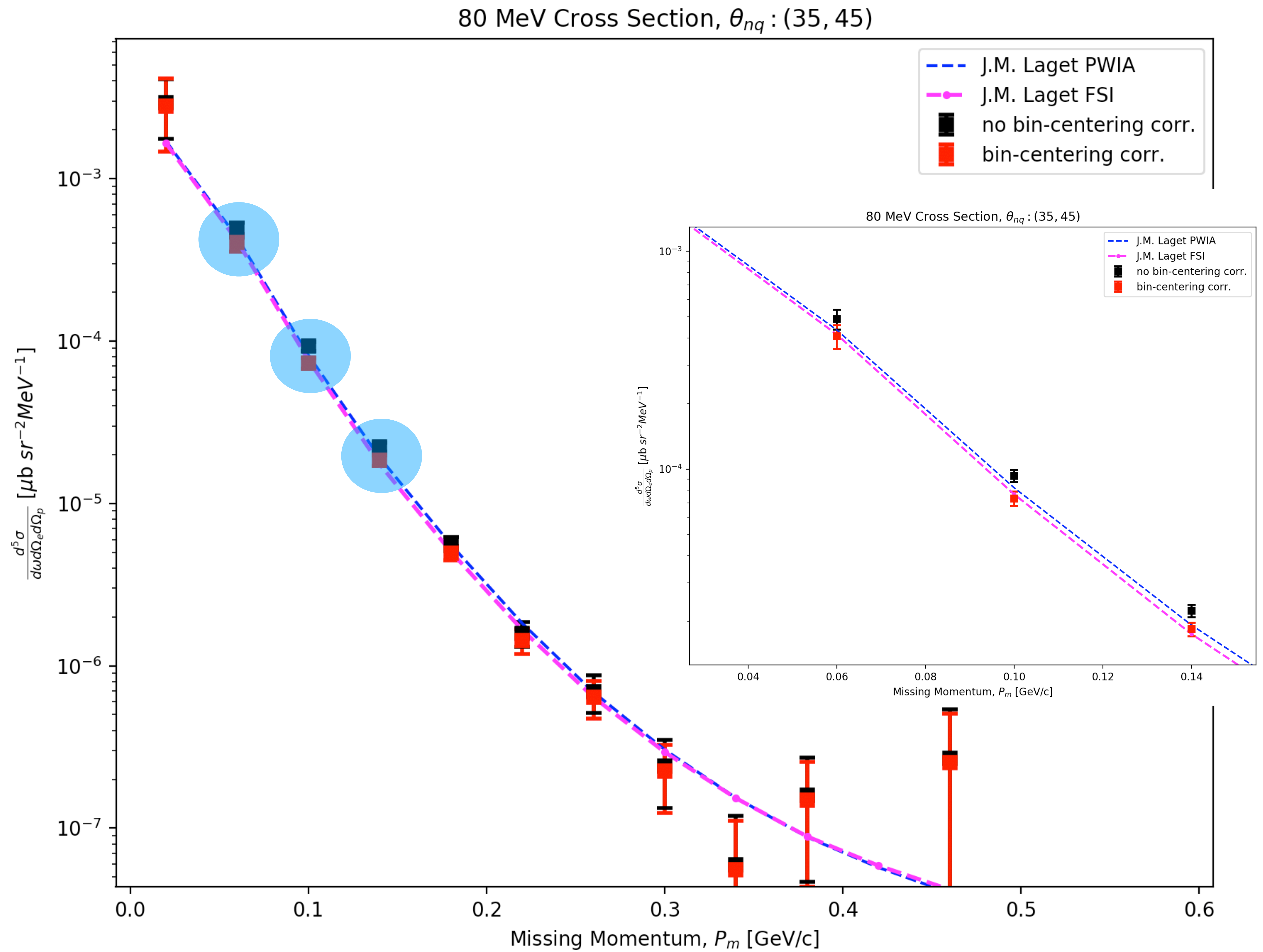
❖ **Correct the data bin-by-bin using the model cross sections ratio . . .**

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

Bin Centering Corrections

❖ **Bin-centering correction factor for the 80 MeV setting**





80 MeV Cross Section, $\theta_{nq}: (35, 45)$
J.M. Laget PWIA
J.M. Laget FSI
no bin-centering corr.
bin-centering corr.
$\frac{d^5\sigma}{d\omega d\Omega_e d\Omega_p}$ [$\mu b\ sr^{-2} MeV^{-1}$]
Missing Momentum, P_m [GeV/c]