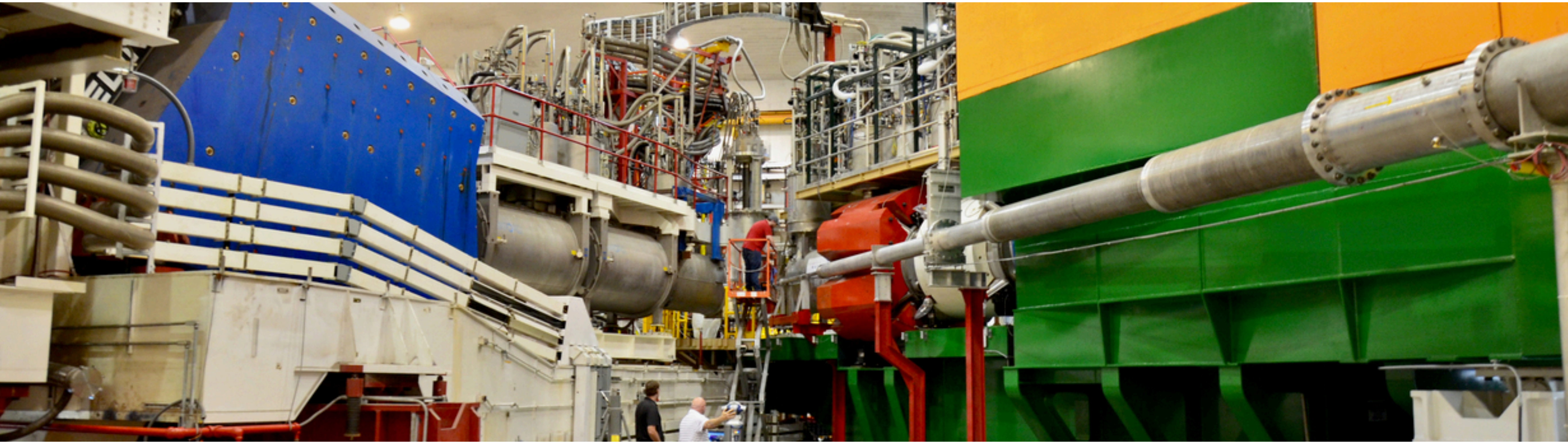


Results on the D(e,e'p)n Commissioning Experiment and Outlook

Hall C Collaboration Meeting, June 27-28, 2020

Carlos Yero

Spokespeople: Drs. Werner Boeglin and Mark Jones

Jefferson Lab
Exploring the Nature of Matter

FIU

Hall C

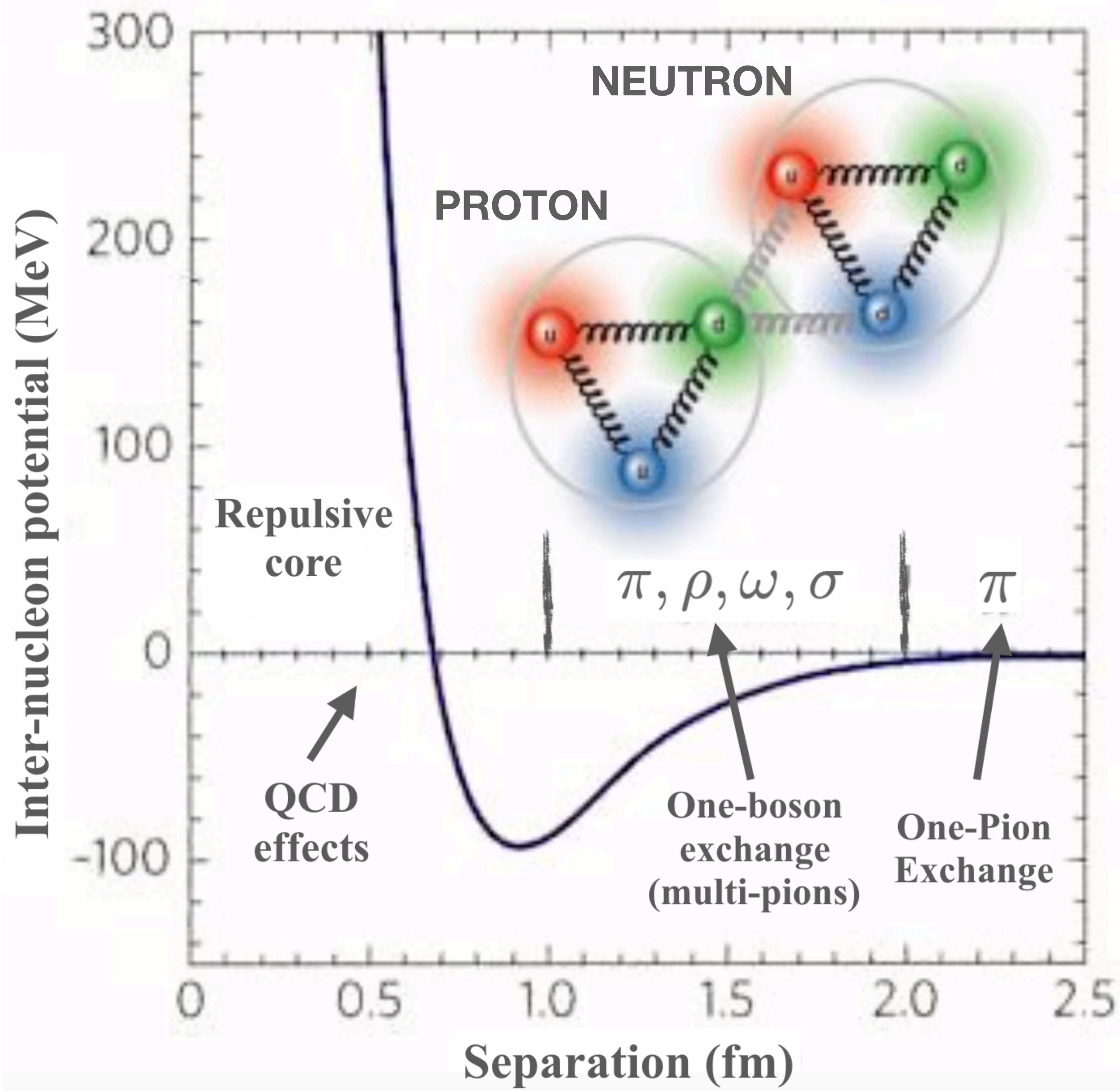
Motivation

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

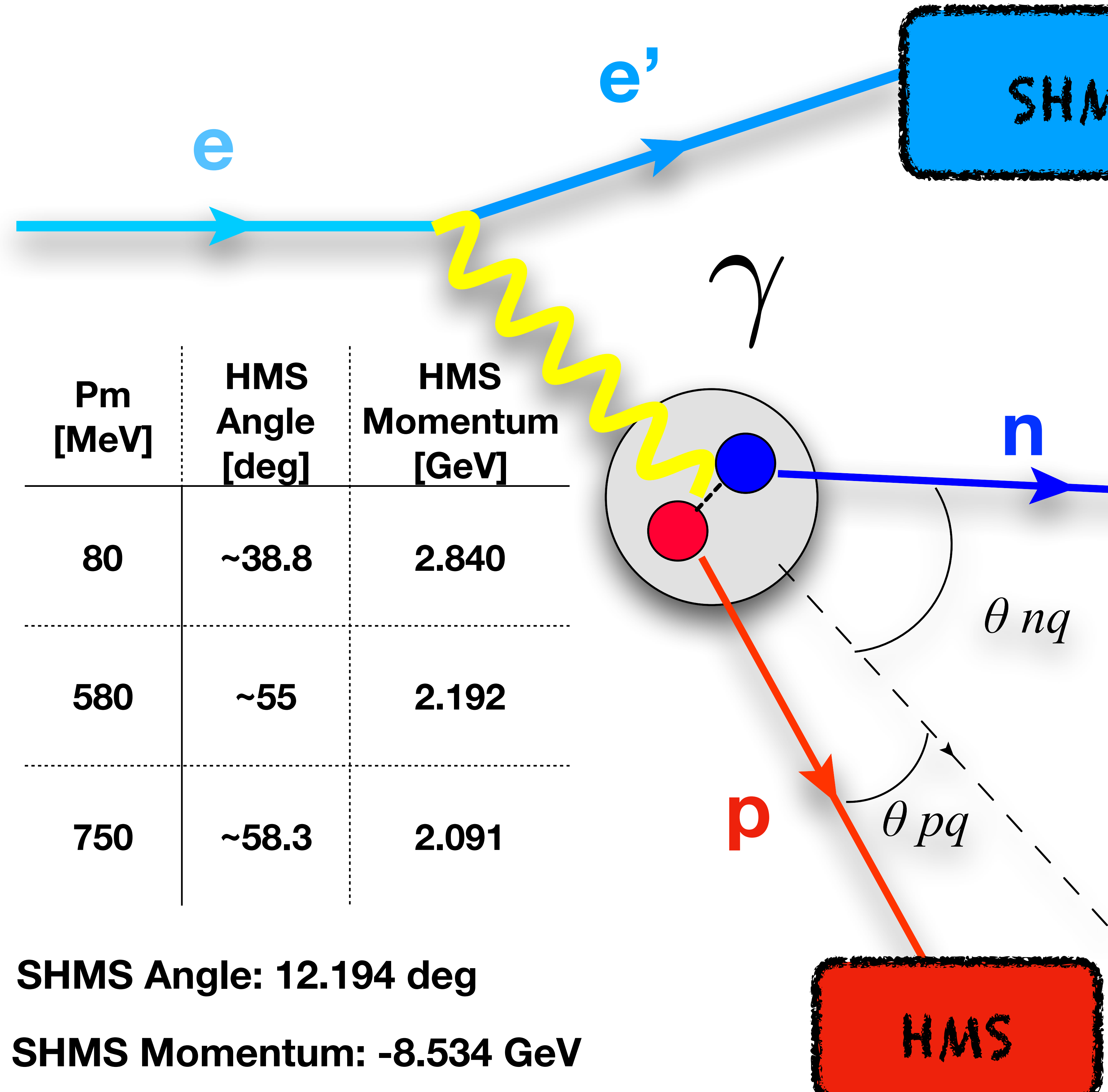
☑ Understand the short range structure of the D2 by probing its high momentum tails

☑ 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



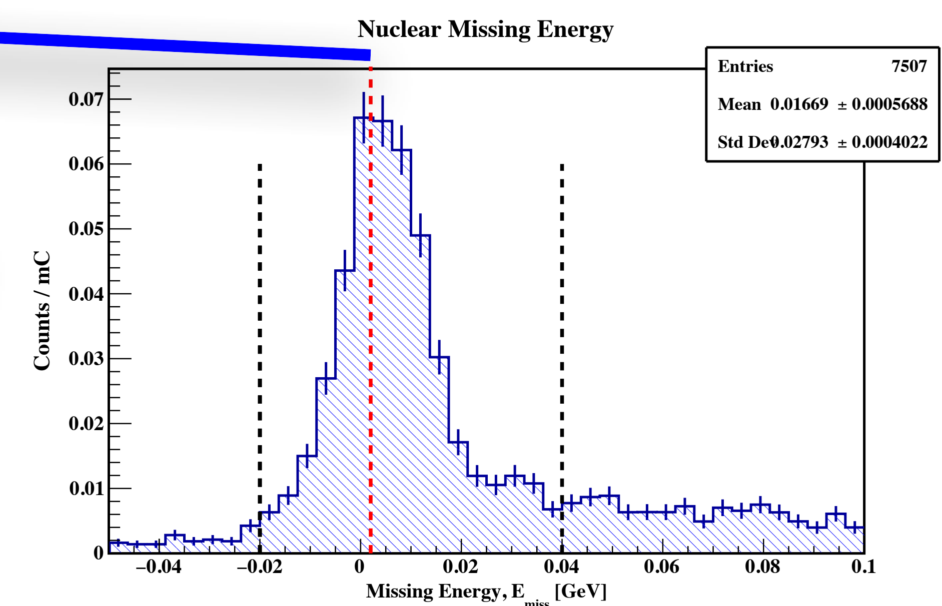
D(e,e'p)n Kinematics



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

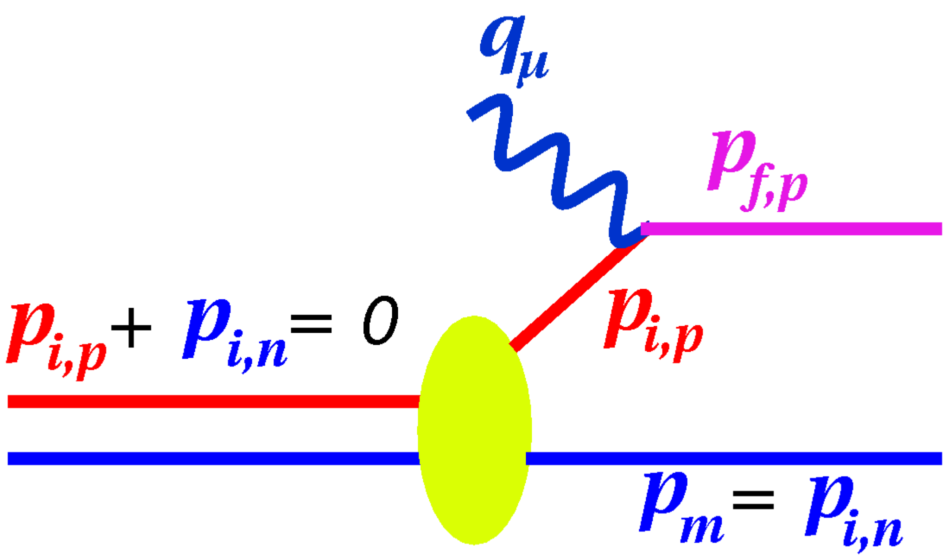
SHMS Angle: 12.194 deg

SHMS Momentum: -8.534 GeV

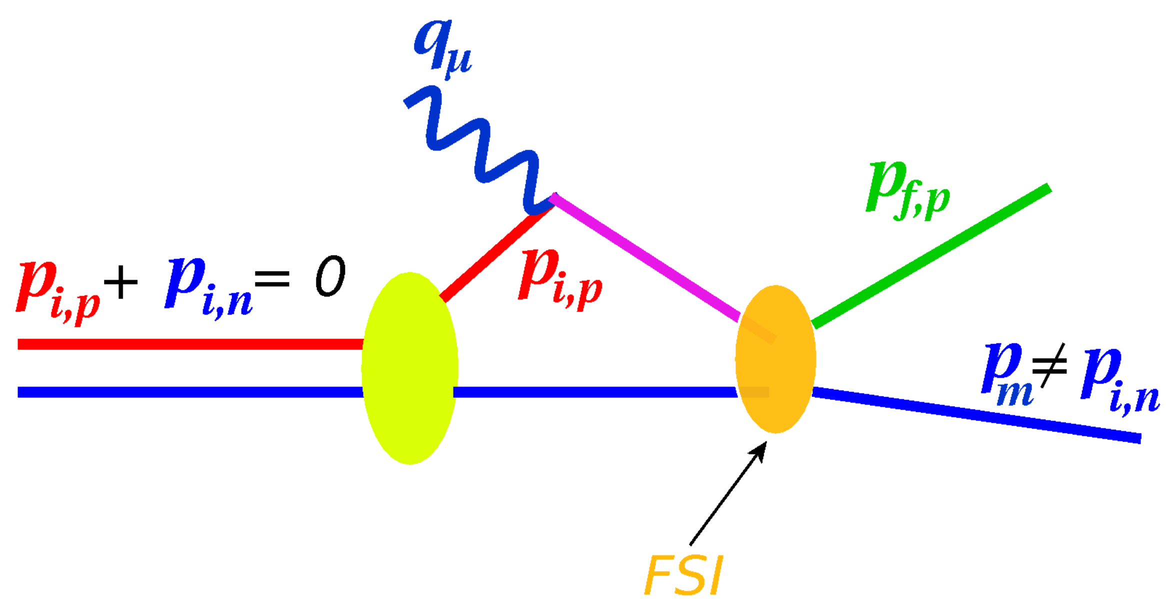


Exclusive reaction selected via Missing Energy Cut

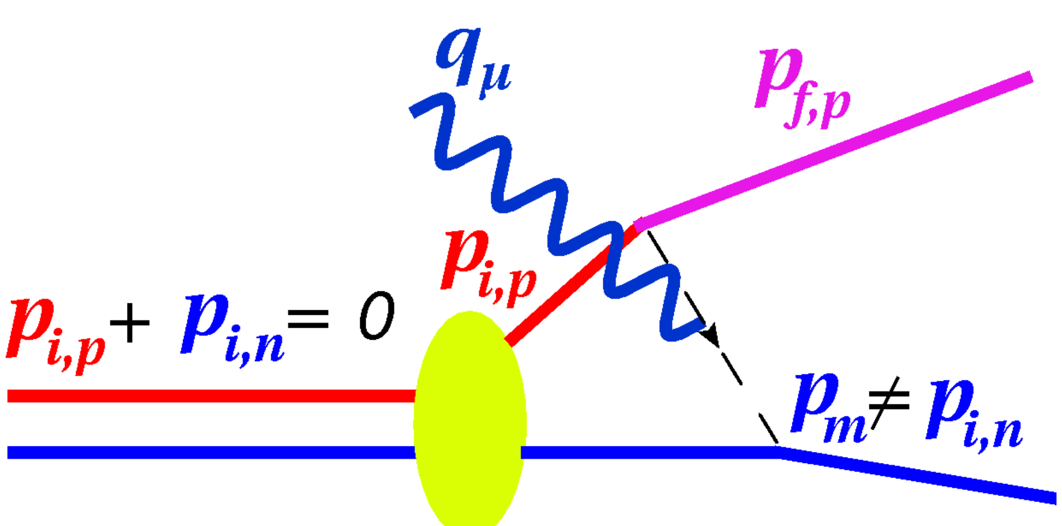
D(e,e'p)n Feynman Diagrams



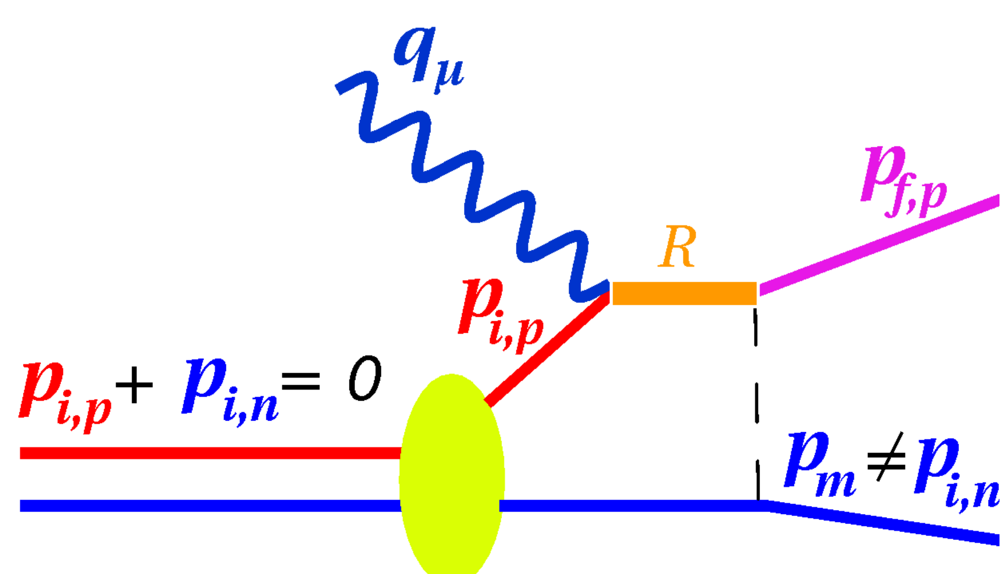
Plane Wave Impulse Approximation (PWIA)



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

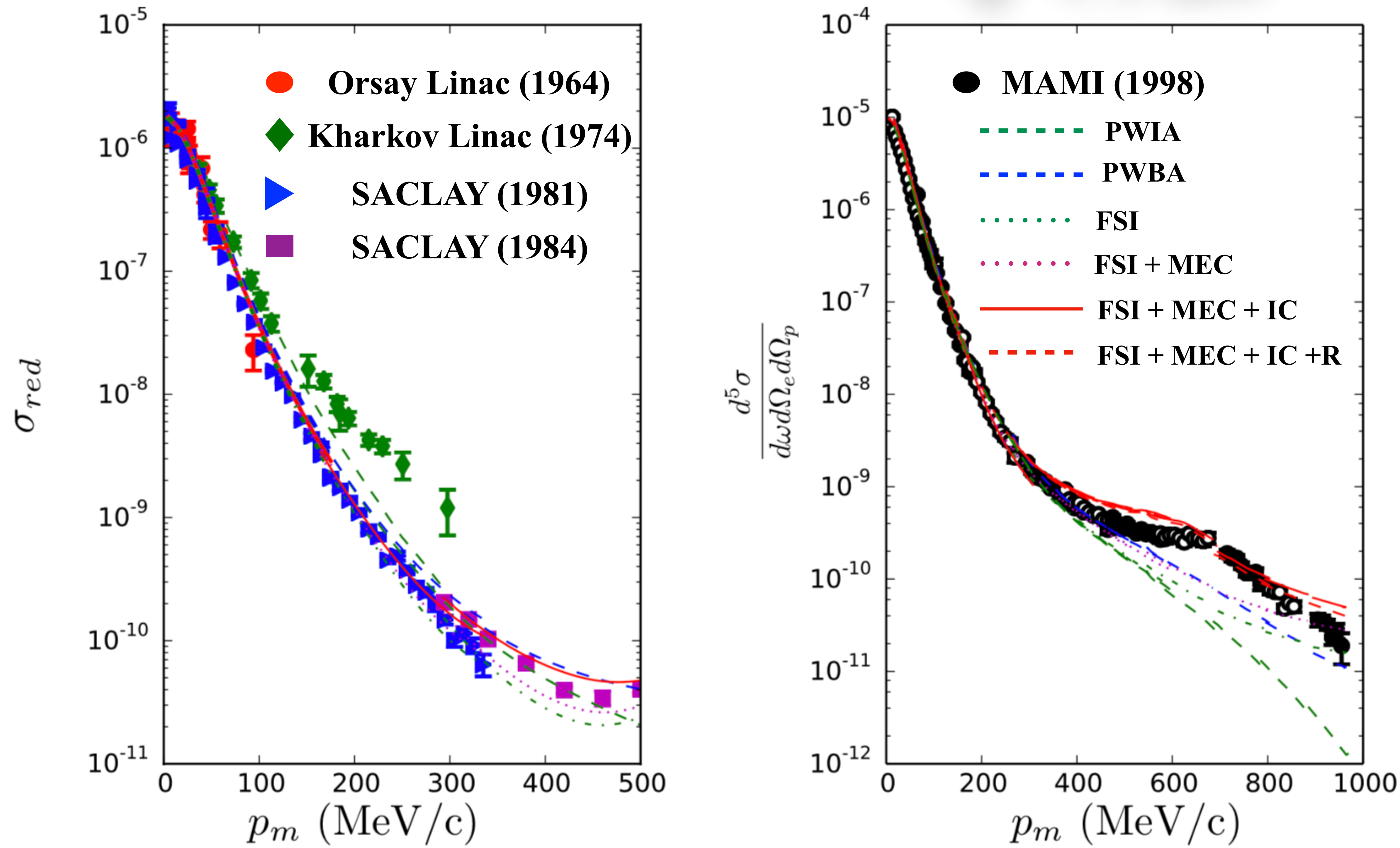
ep off-shell cross section

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

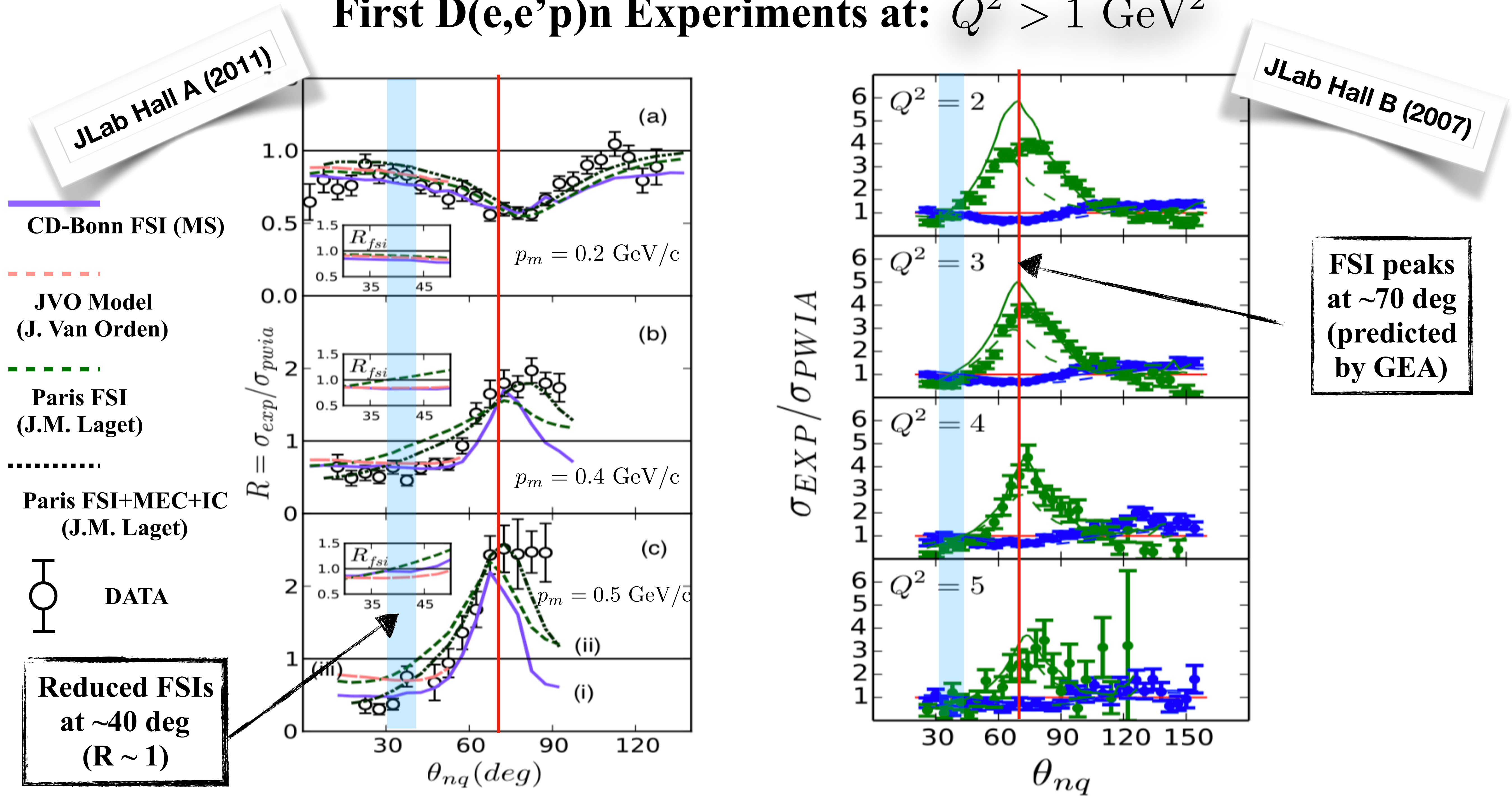
Previous D(e,e'p)n Experiments at: $Q^2 < 1\ \mathrm{GeV}^2$



Theoretical Calculations: H. Arenhovel
(Legend is same for both plots)

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

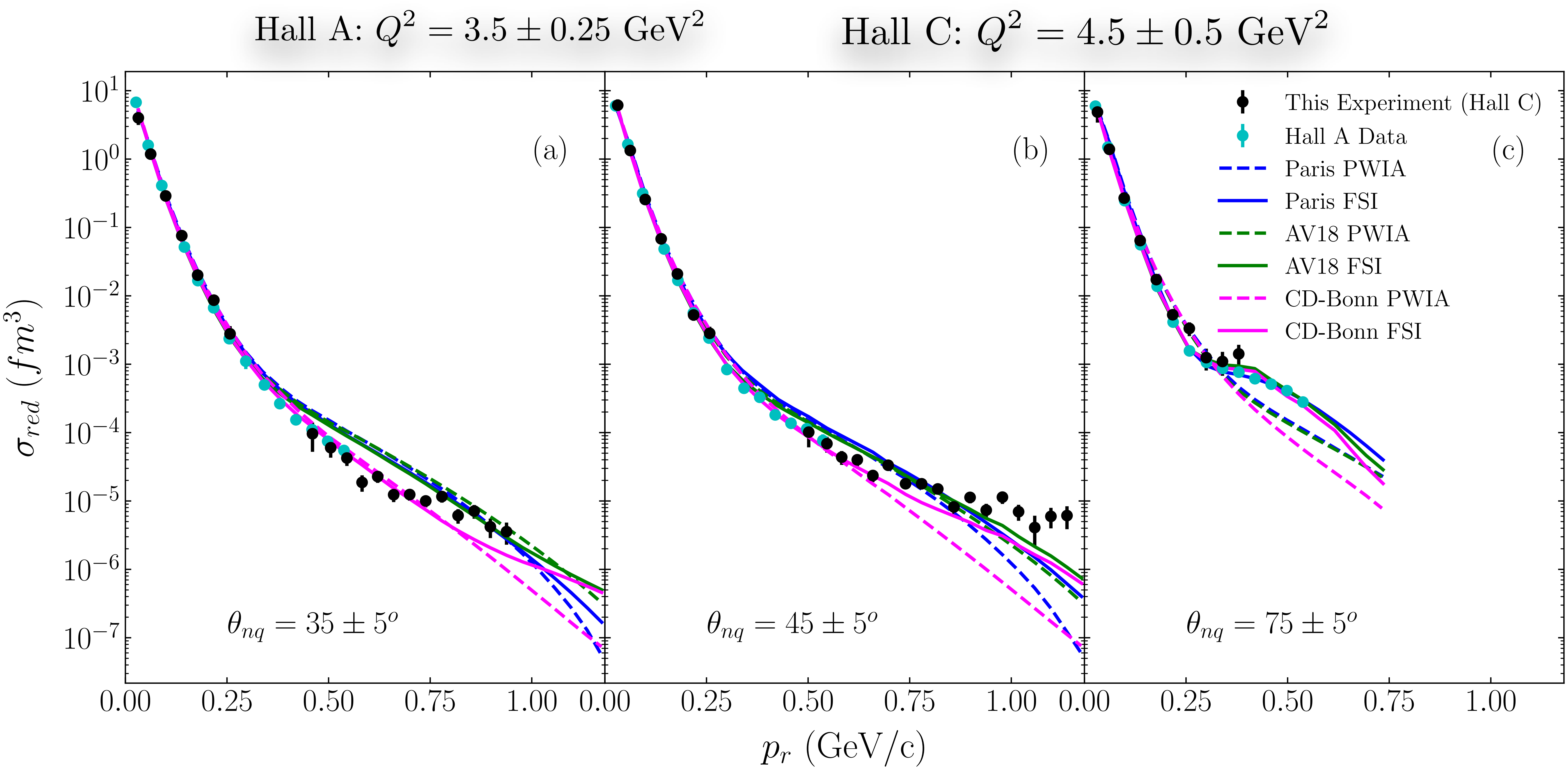
First D(e,e'p)n Experiments at: $Q^2 > 1\ \mathrm{GeV}^2$



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

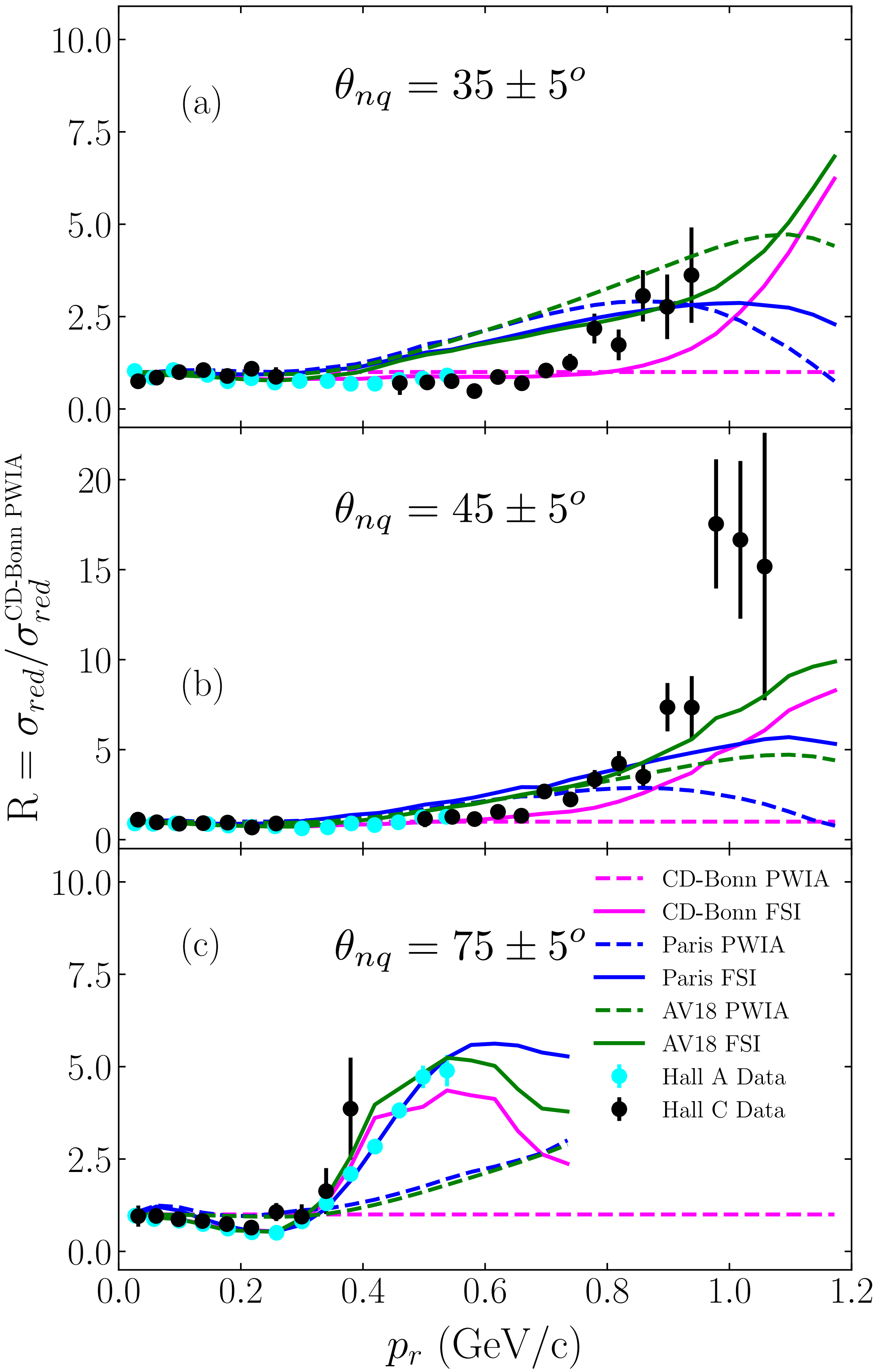
Hall C D(e,e'p)n Experiment Results

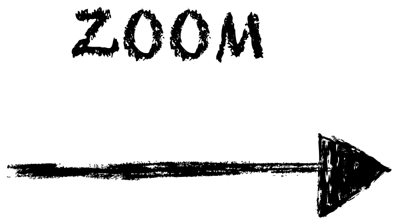
D(e,e'p)n Momentum Distributions

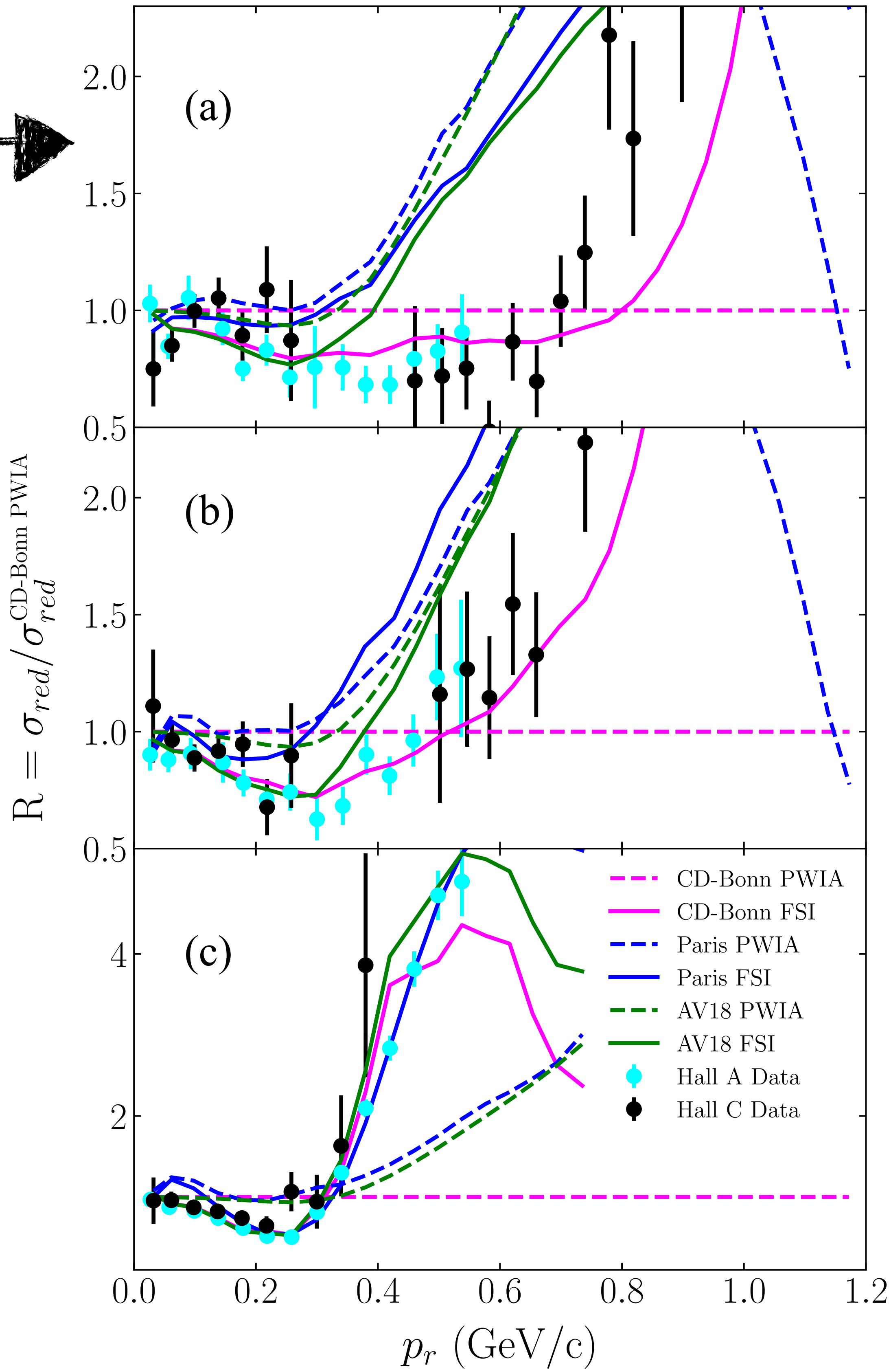


- Paris calculations are done by J.M.Laget
- AV18/CD-Bonn calculations are done by M. Sargsian

D(e,e'p)n Ratio to CD-Bonn PWIA







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 0.98 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

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.

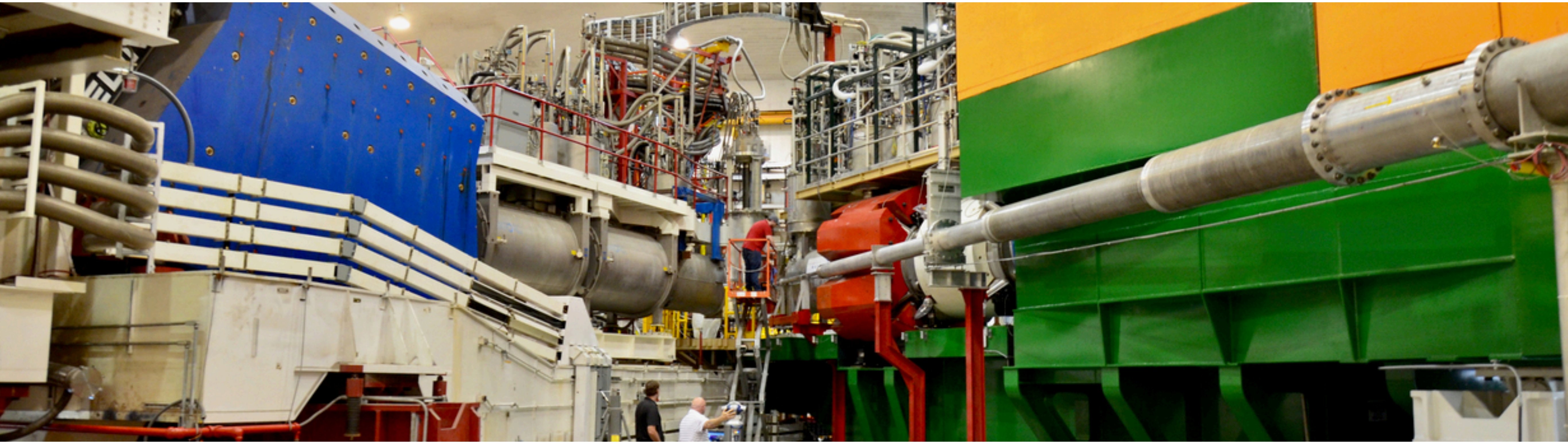
ACKNOWLEDGMENTS

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**

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

$$\text{Covariance Errors}$$

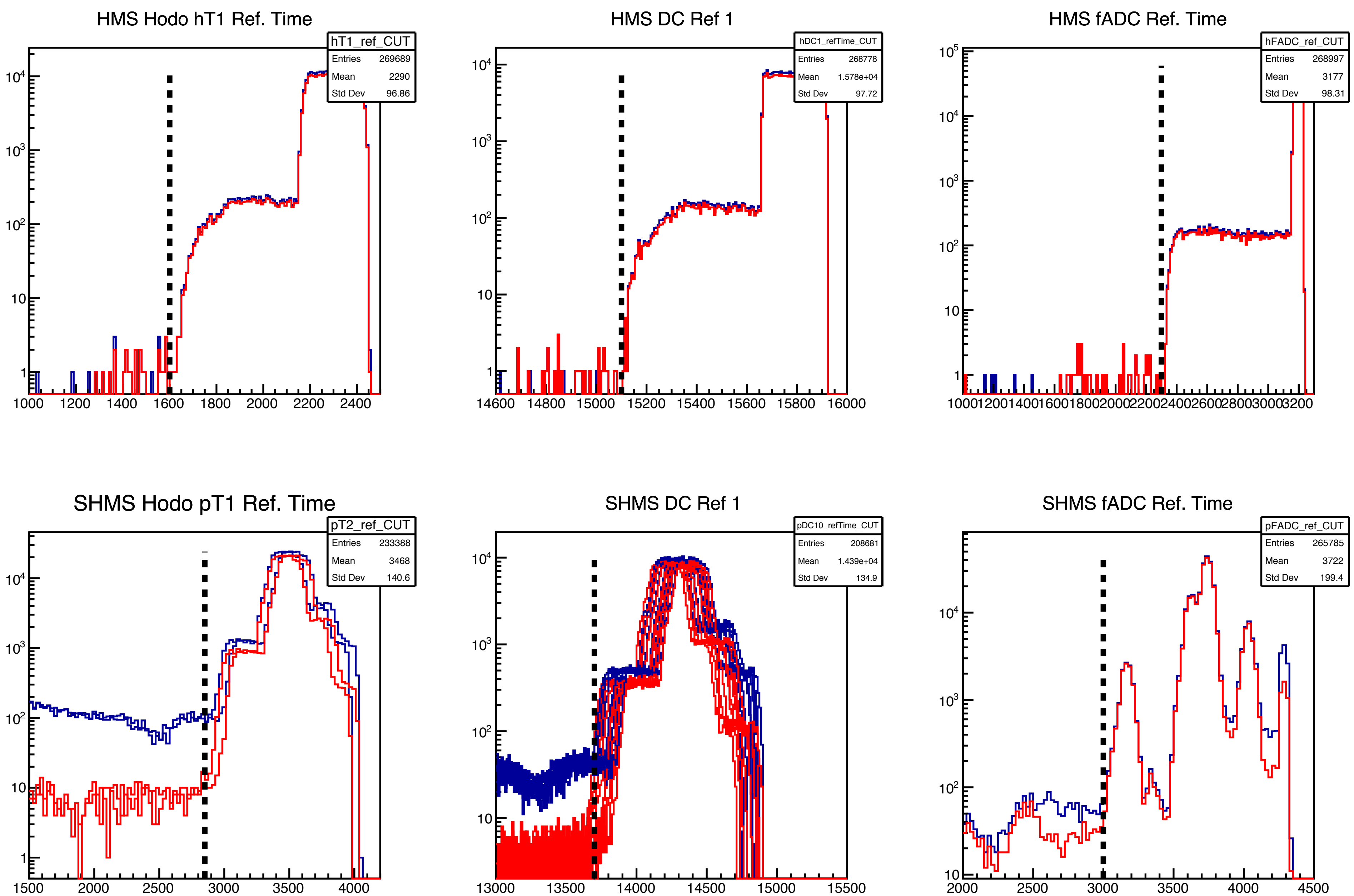
Kinematic uncertainties are due to our limited knowledge of the beam, spectrometer momenta and angles Each of these uncertainties affects our knowledge of the cross section, since the cross section depends on these kinematics

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.

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)



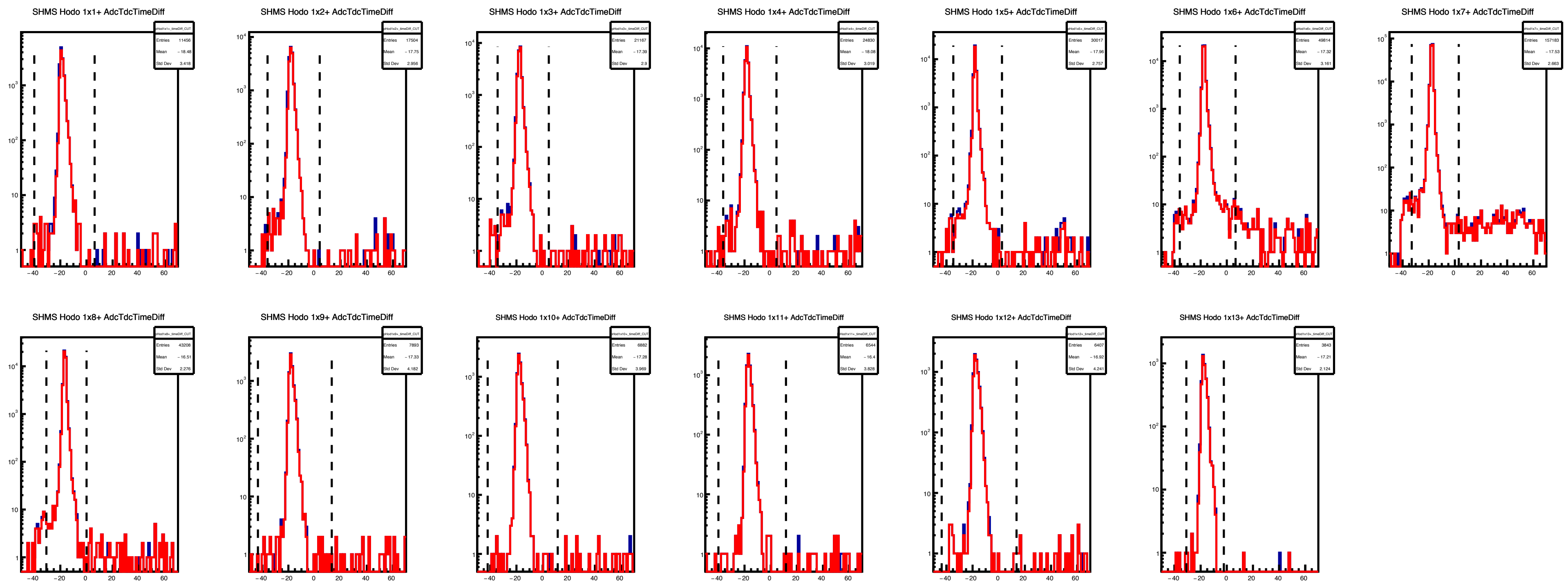
HMS Reference Times

SHMS Reference Times

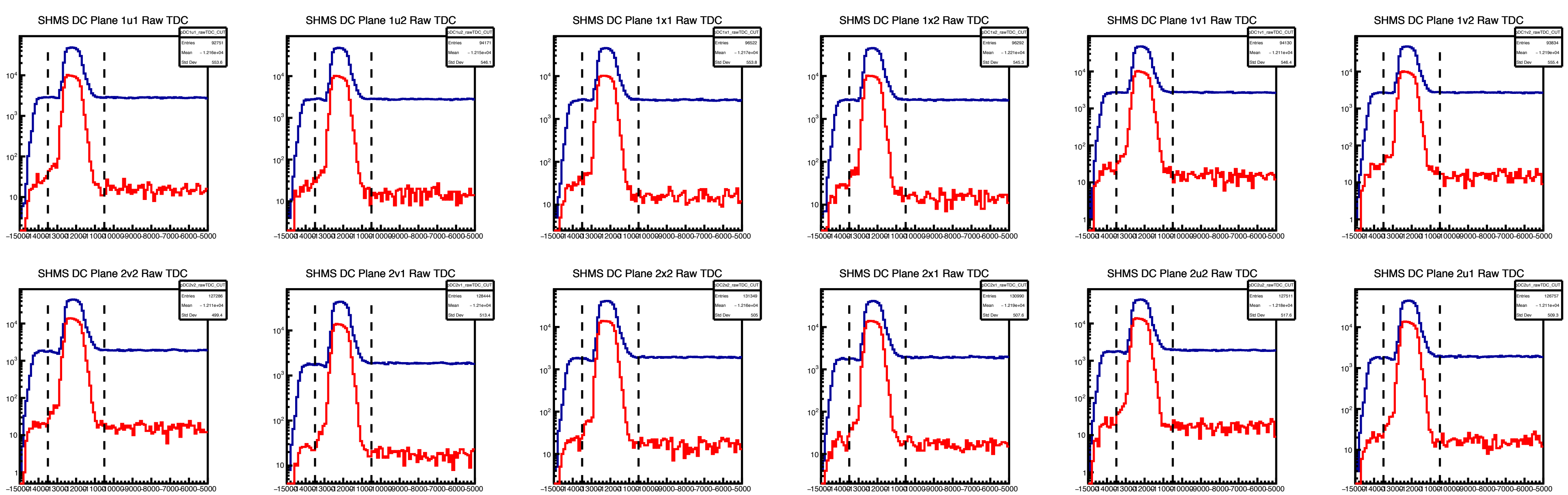
TDC Time Window Cuts

☑ 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

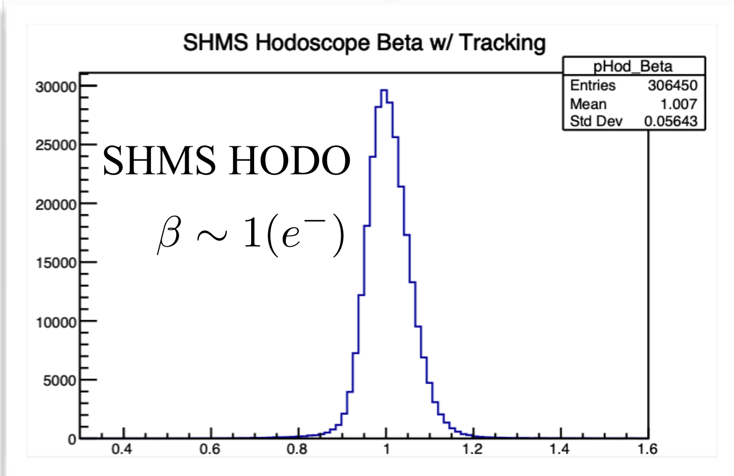


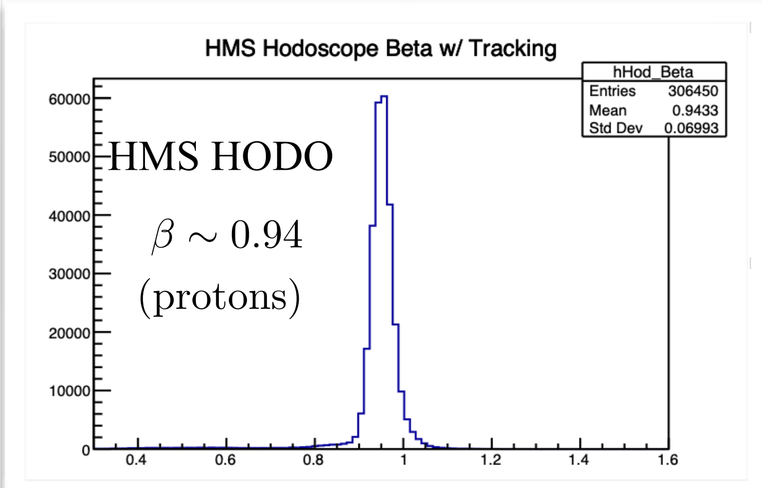
SHMS Hodoscope 1X+ (ADC-TDC) Time Difference

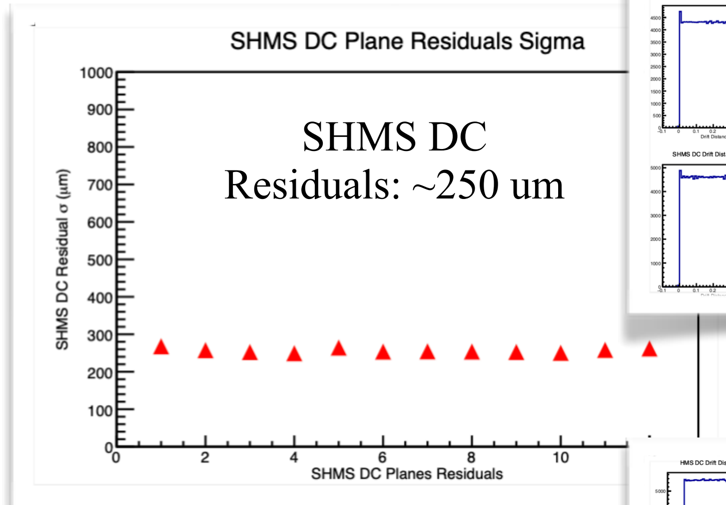


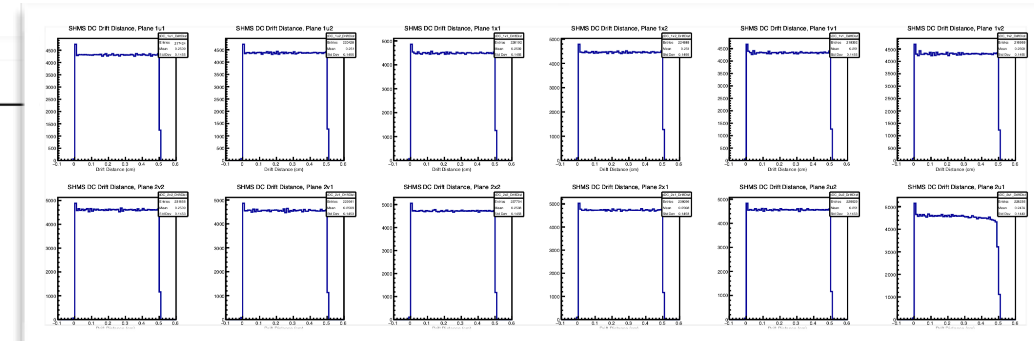
SHMS Drift Chambers Raw TDC Time

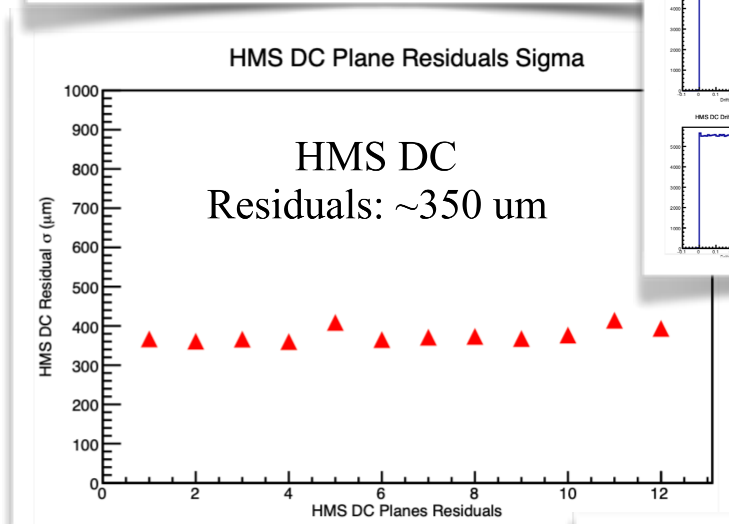
Detector Calibrations

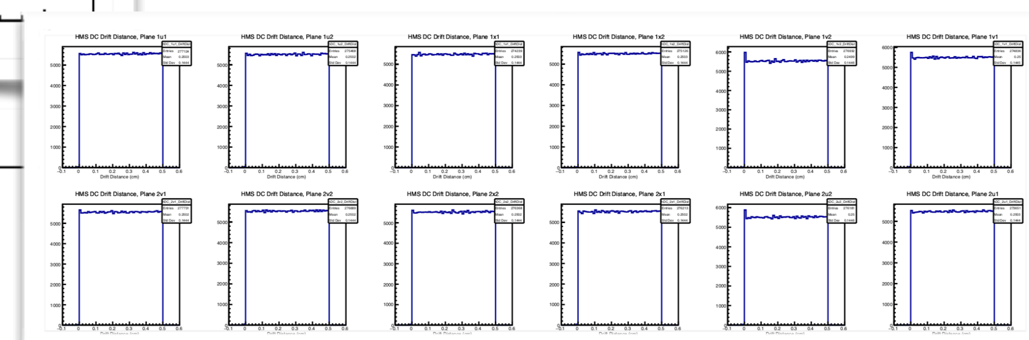


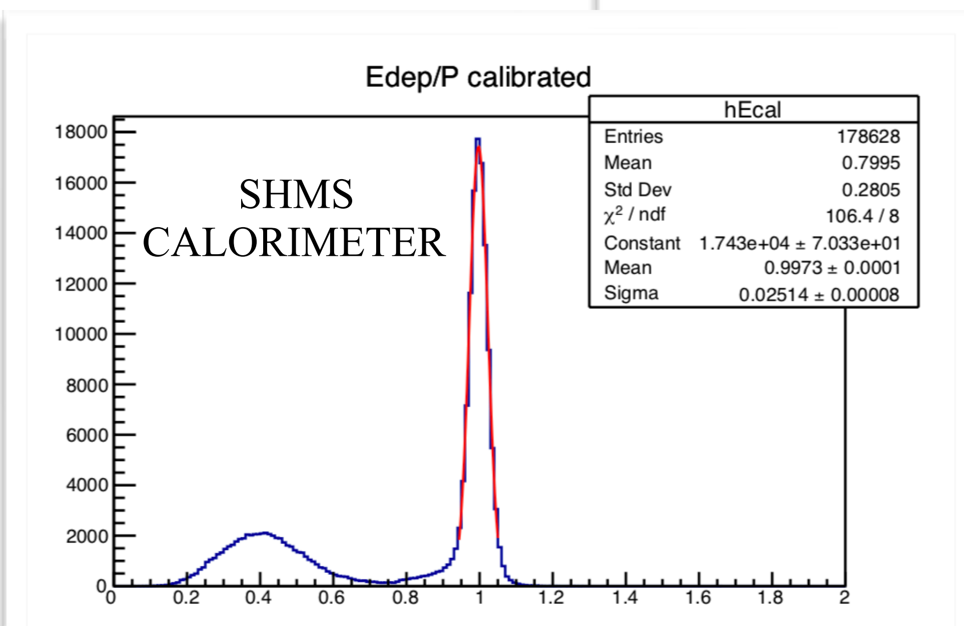


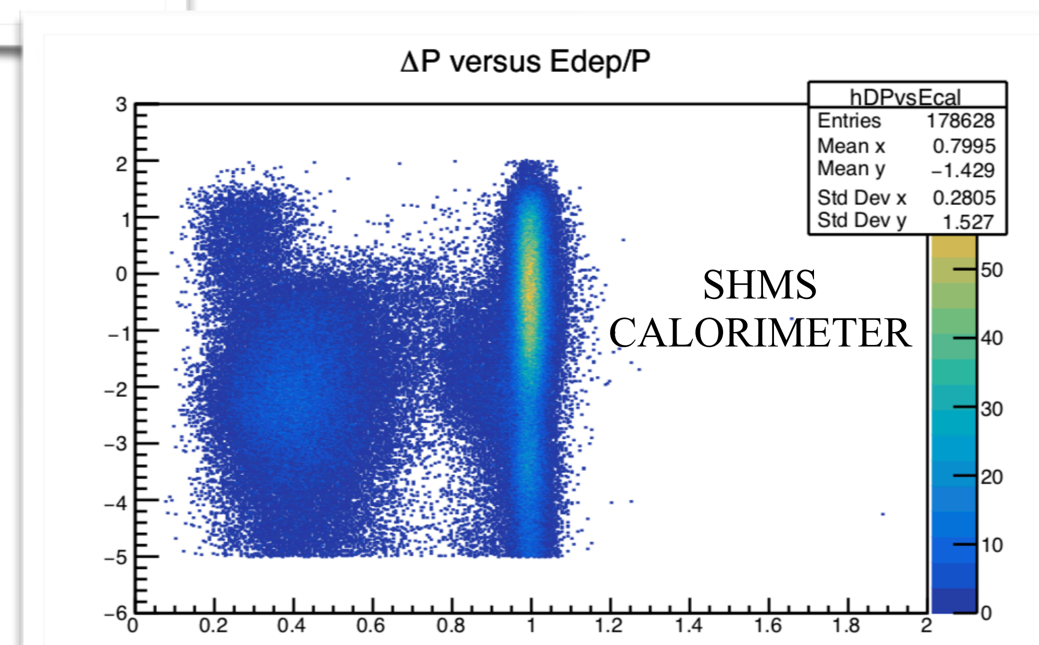




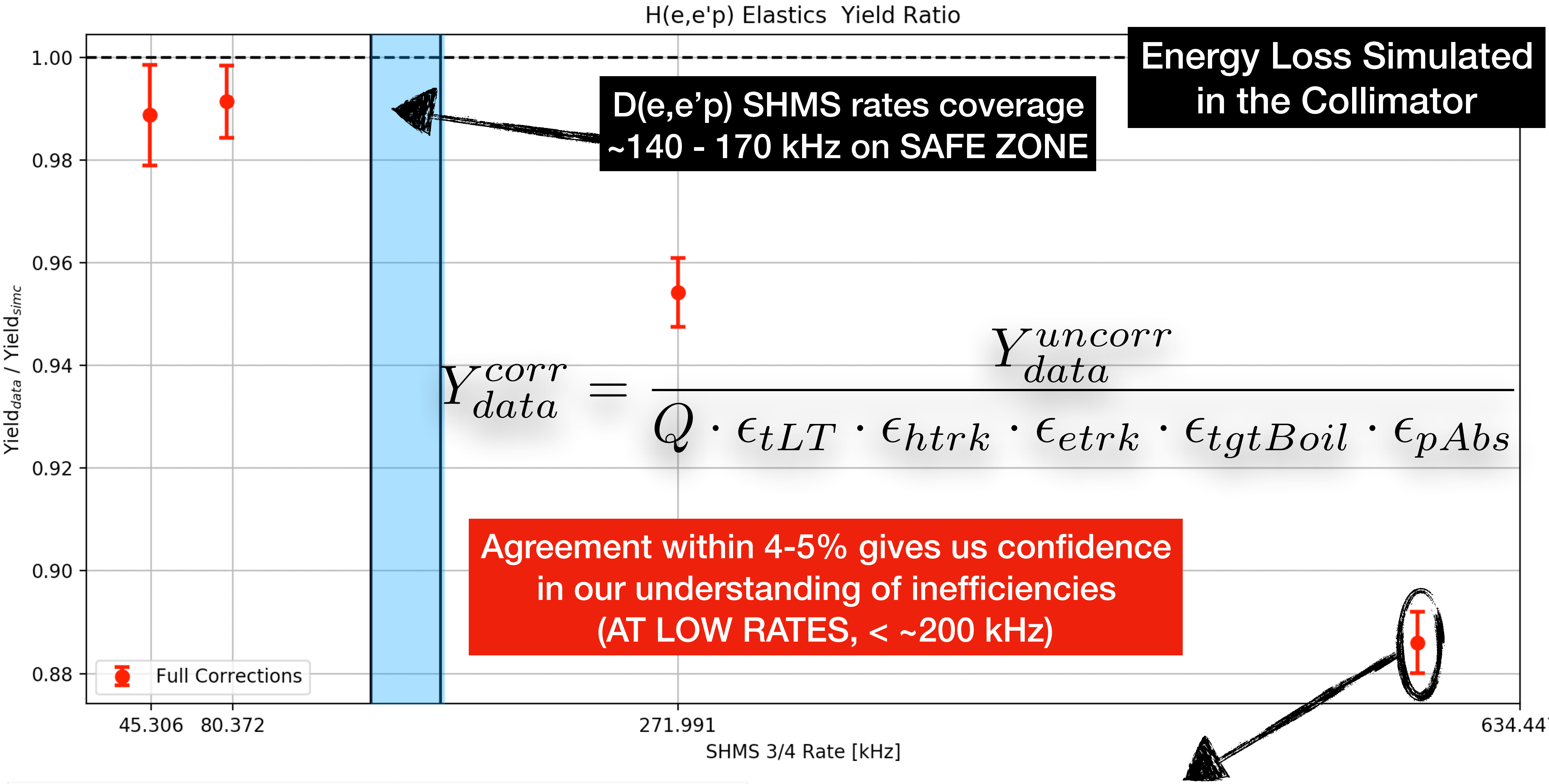








H(e,e’p) Yield Ratio Check

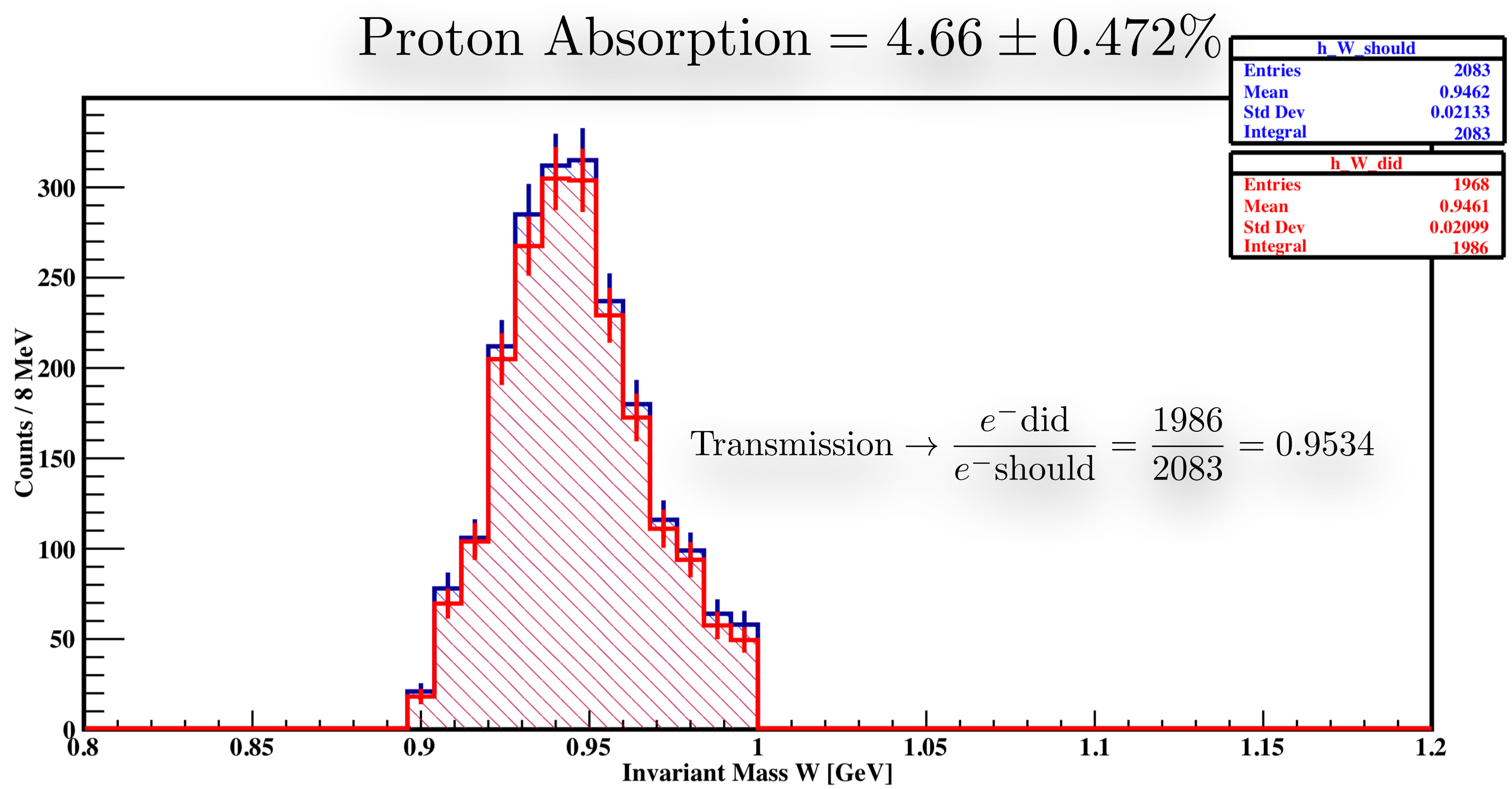


The general cuts applied were:
|HMS Delta| < 8 % SHMS Delta: (-10, 22) %
Inv. Mass W : (0.85, 1.05), HMS Coll. Cut

NOT Understood:

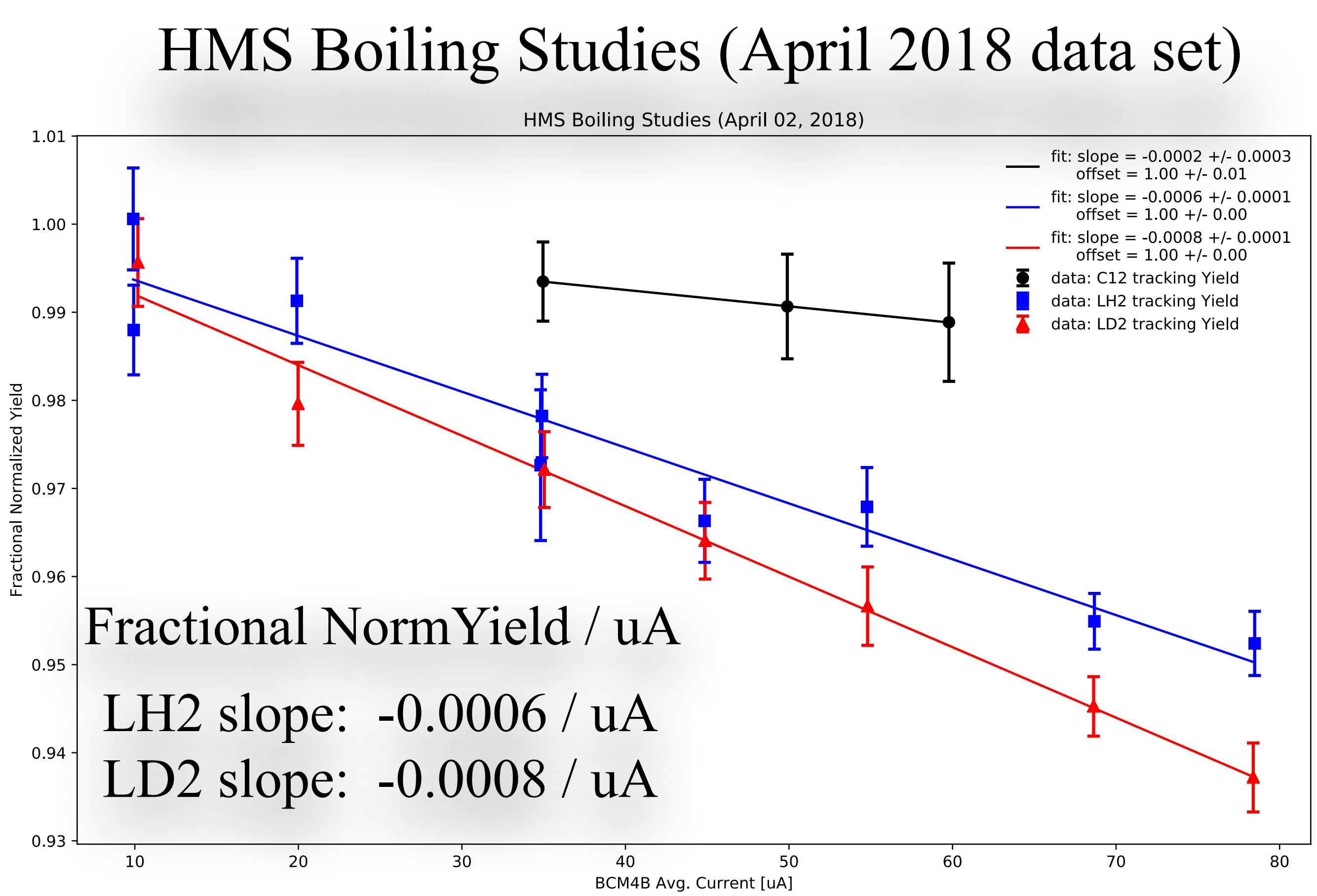
* How does the tracking algorithm perform at high rates?

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

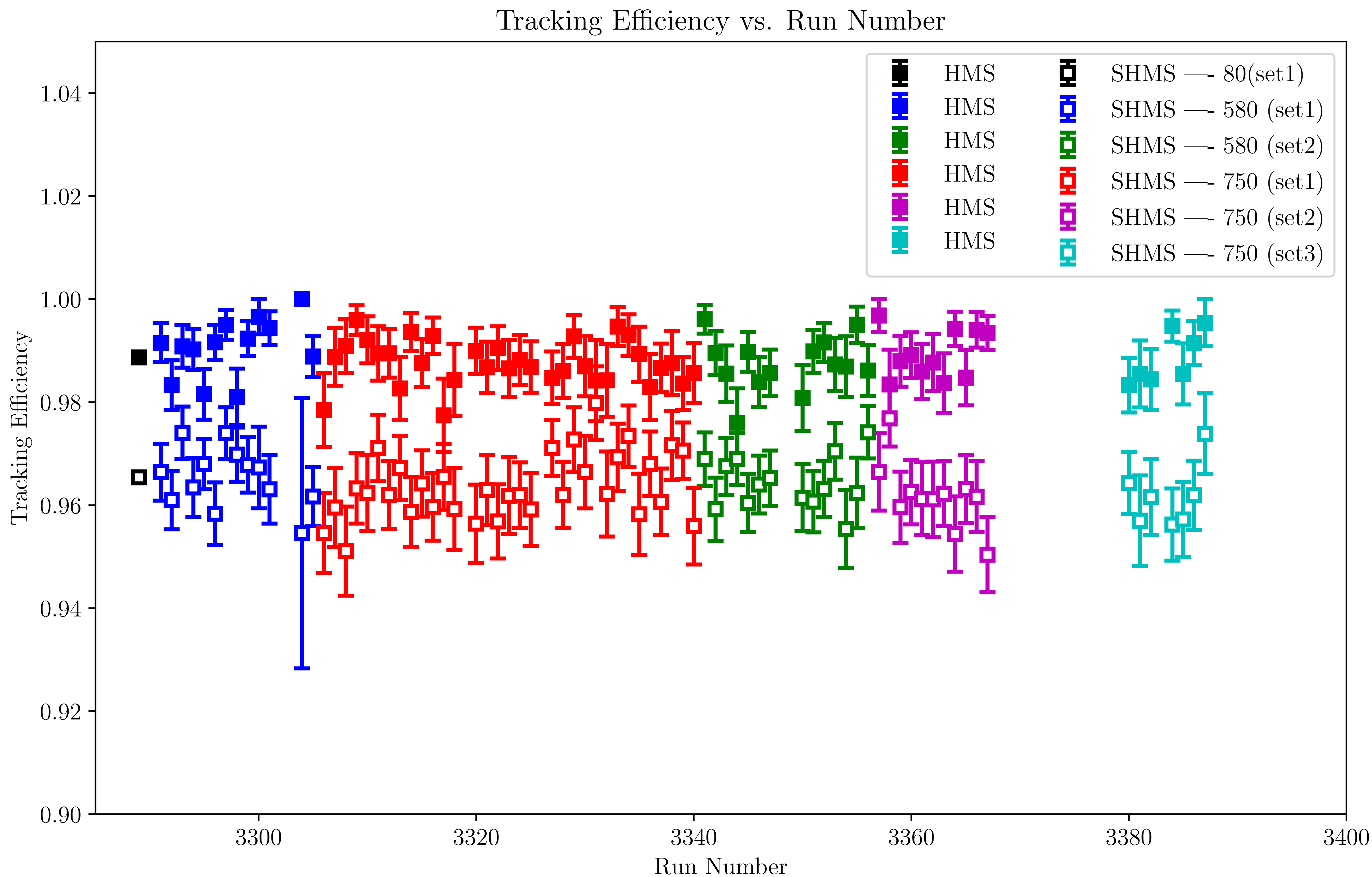
- ❖ Corrected data Yield for inefficiencies and charge
  (explain basic definition of experimental cross section)

- ❖ Radiative Corrections

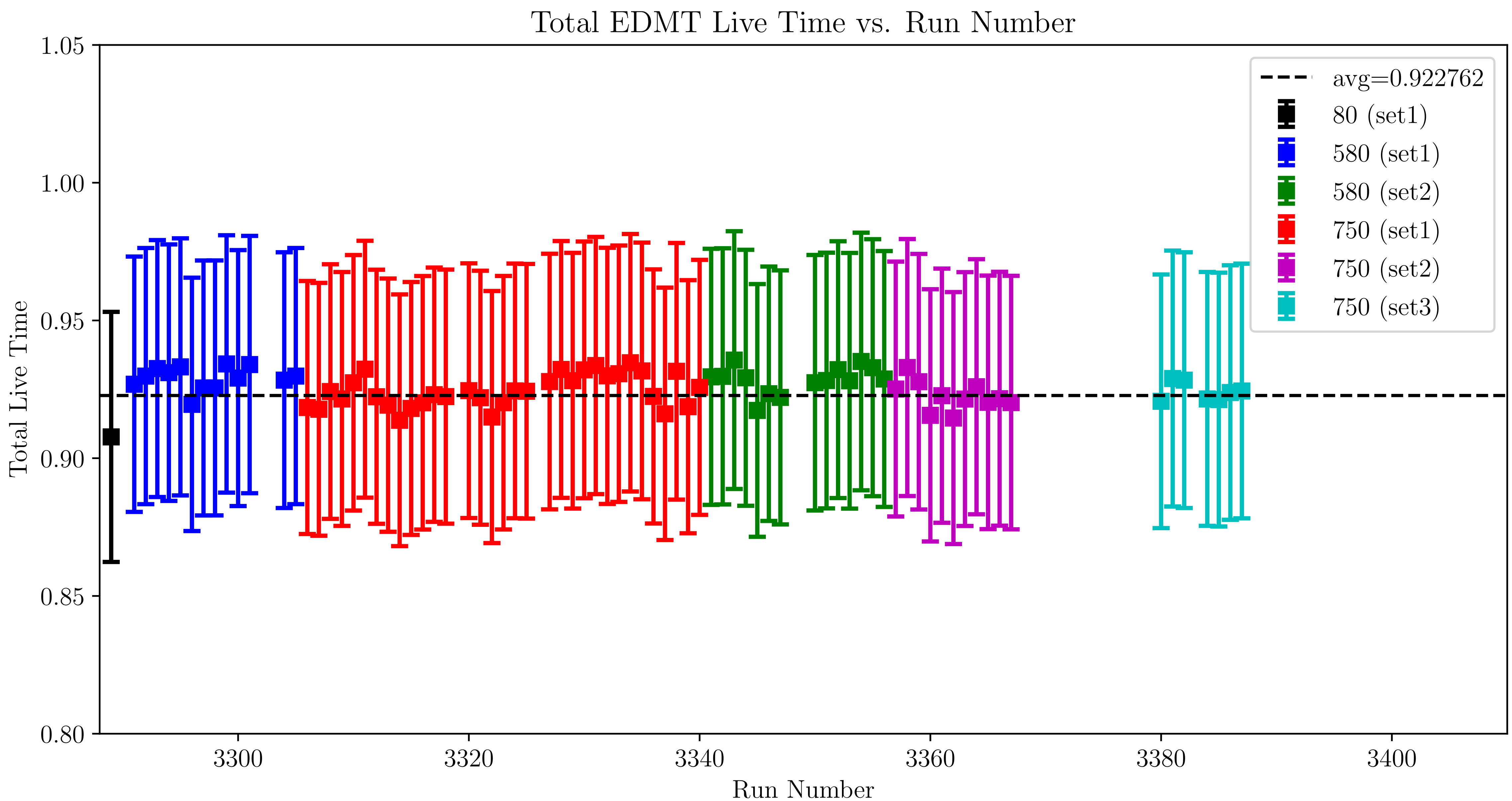
- ❖ Bin-Centering Corrections

Efficiencies and Correction Factors

TRACKING EFFICIENCY

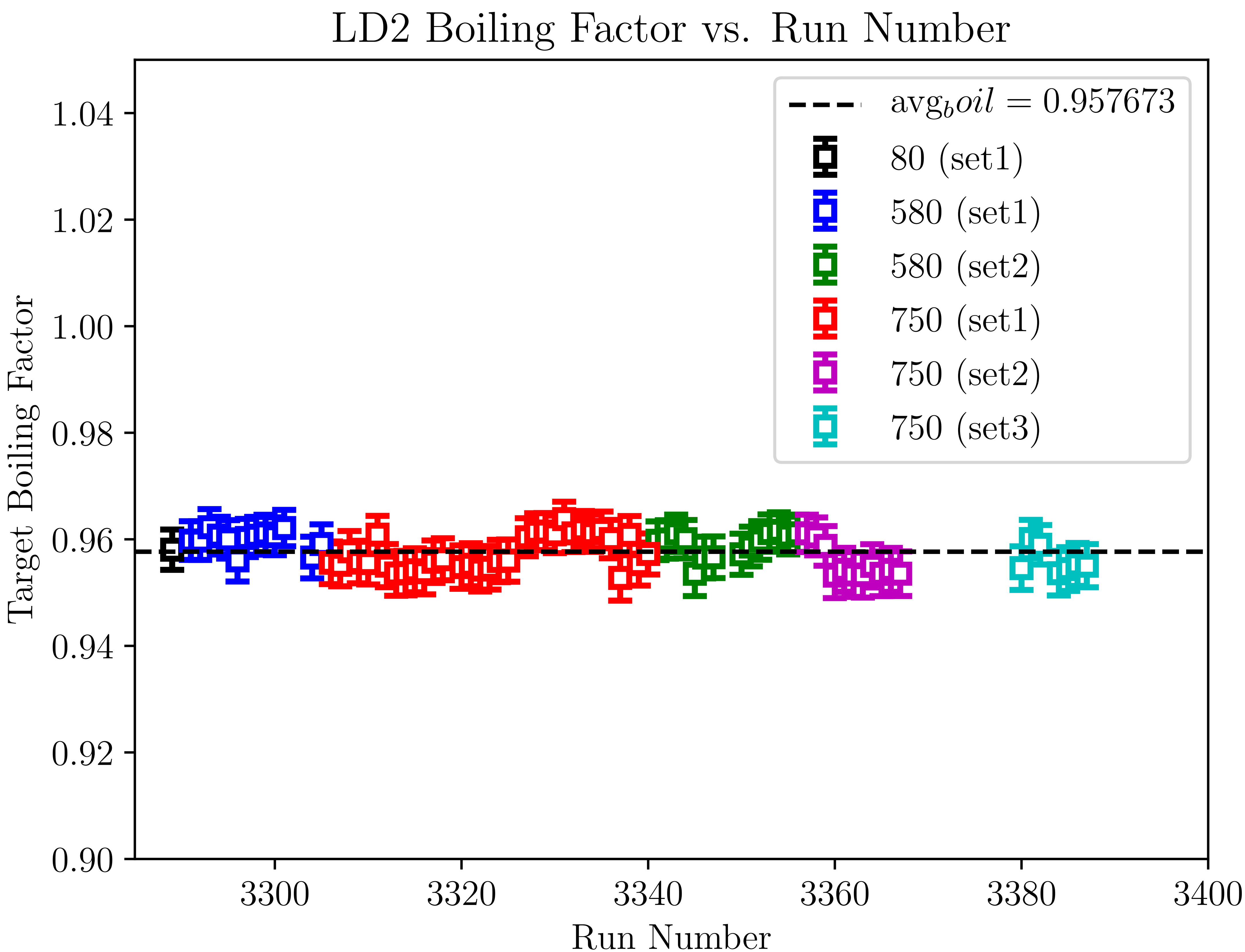


TOTAL EDTM LIVE TIME

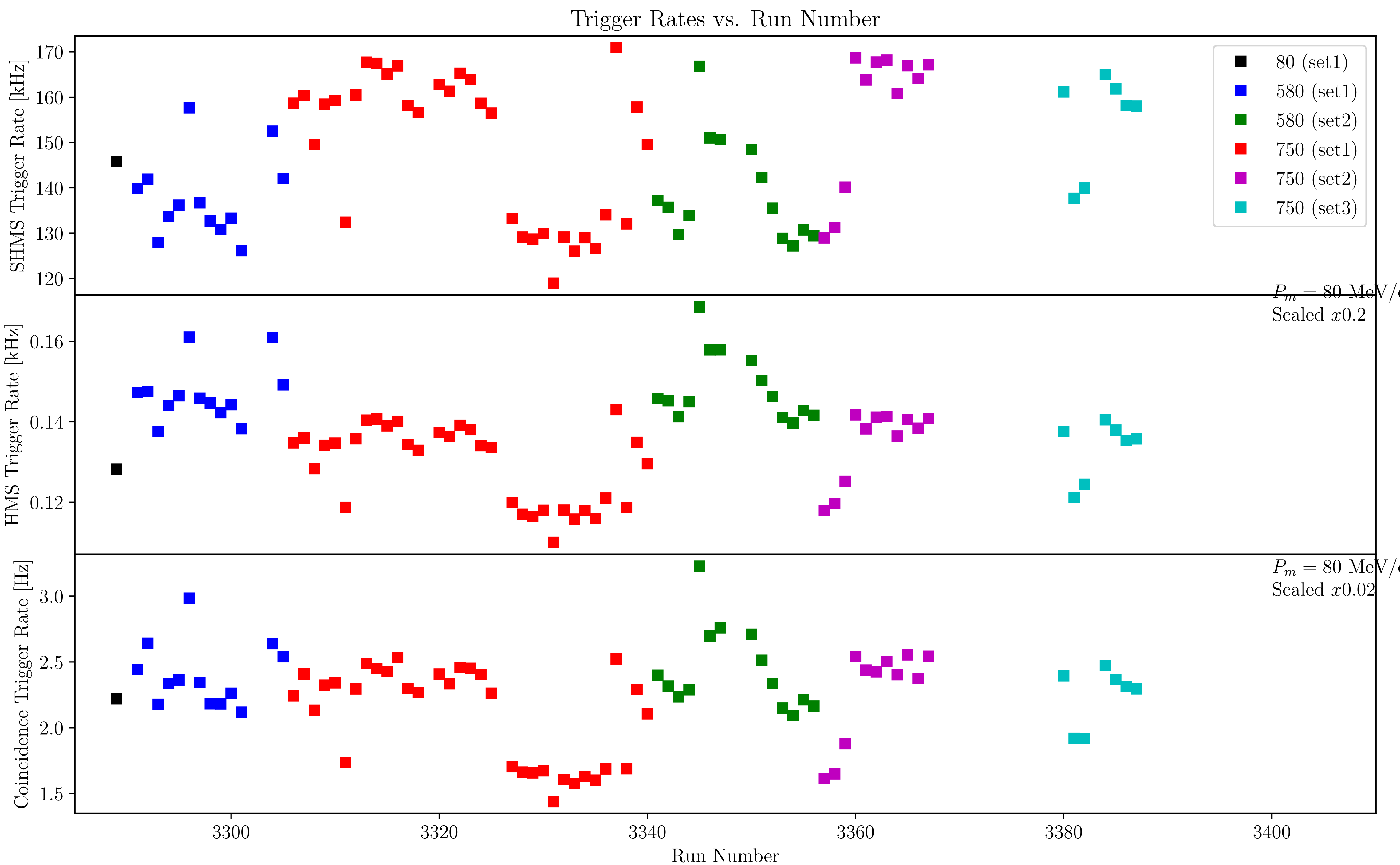


EDTM: Electronic Dead Time Monitoring

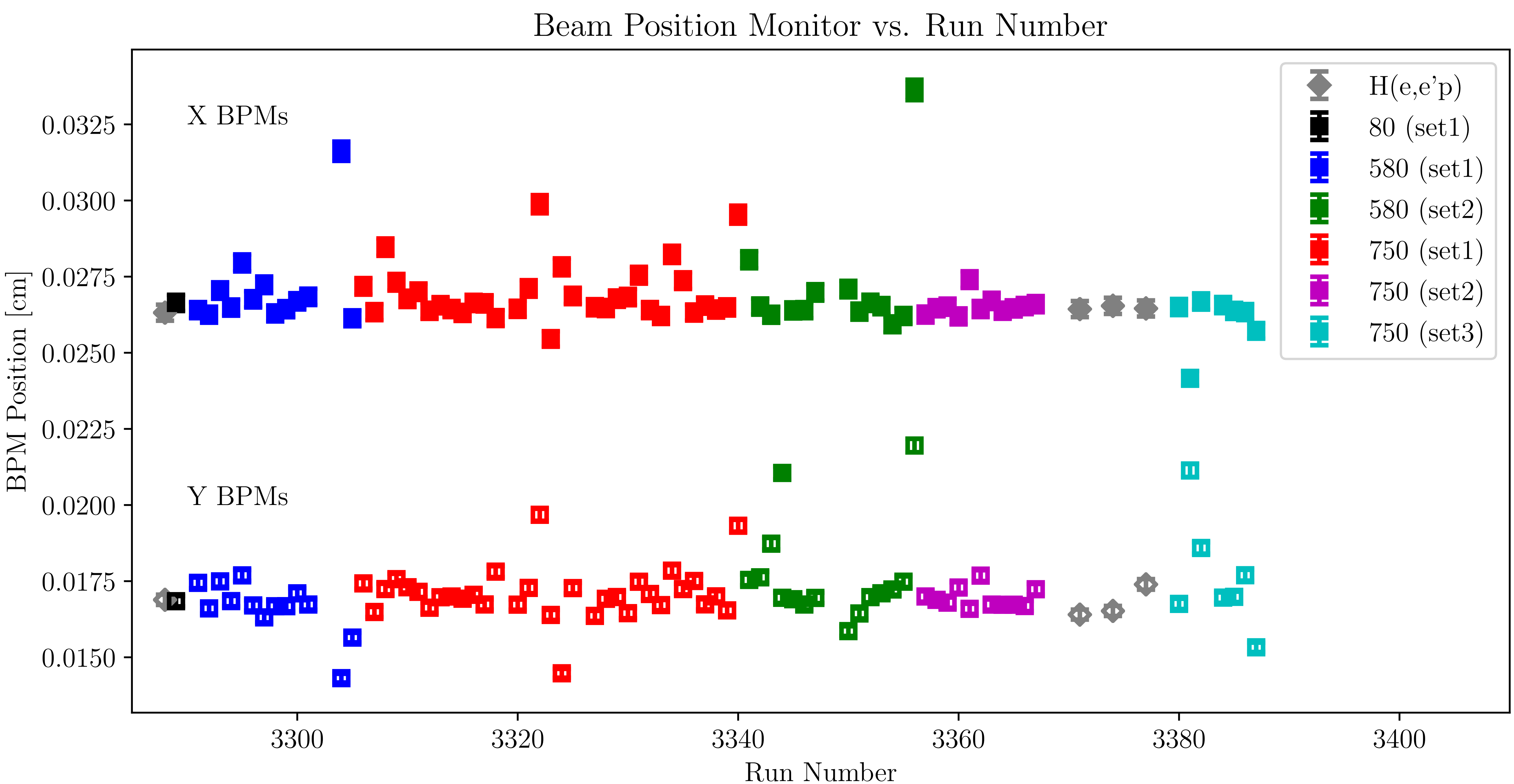
TARGET BOILING FACTOR



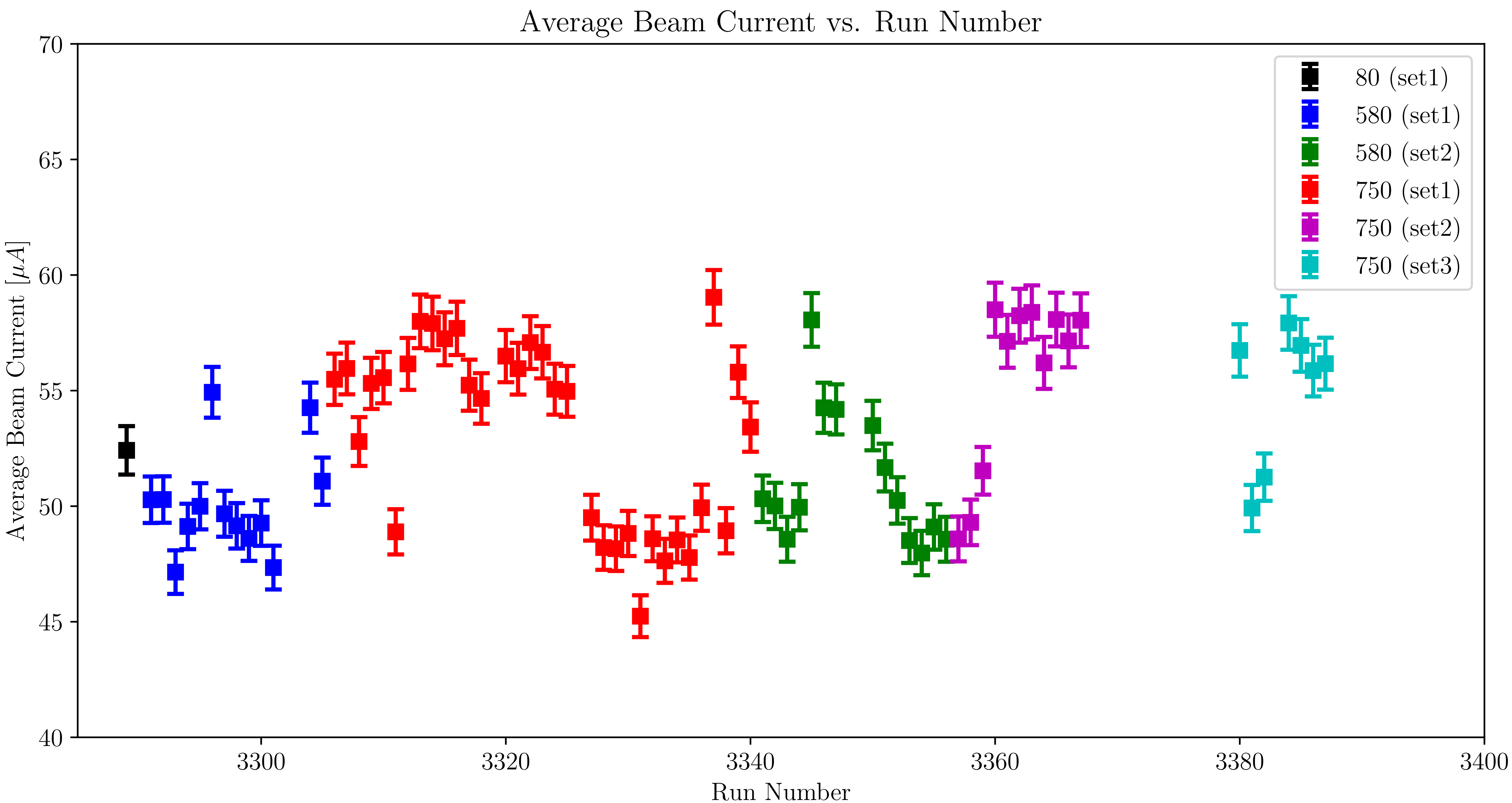
TRIGGER RATES



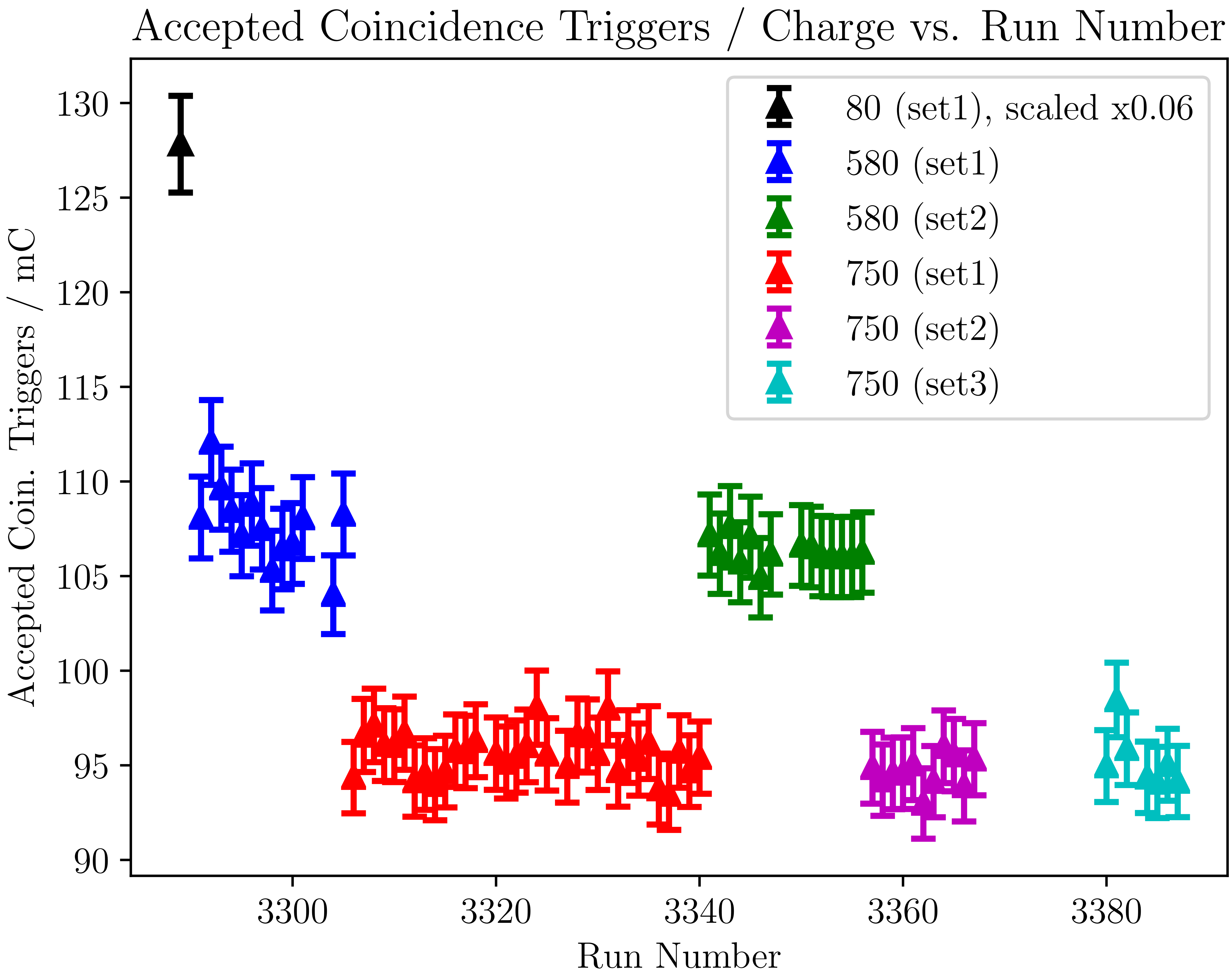
BEAM POSITION MONITORING (BPMs)



AVERAGE BEAM CURRENT



ACCEPTED COUNTS / CHARGE



EXTRACTION OF CROSS SECTIONS:

BASIC CONCEPT

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

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

Corrected Data Yield

Phase Space Volume

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

Radiative Correction

Normalize data by total charge

Correct for Inefficiencies

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 to solid angles

Luminosity

Spectrometer "Solid Angles"

Generated Events

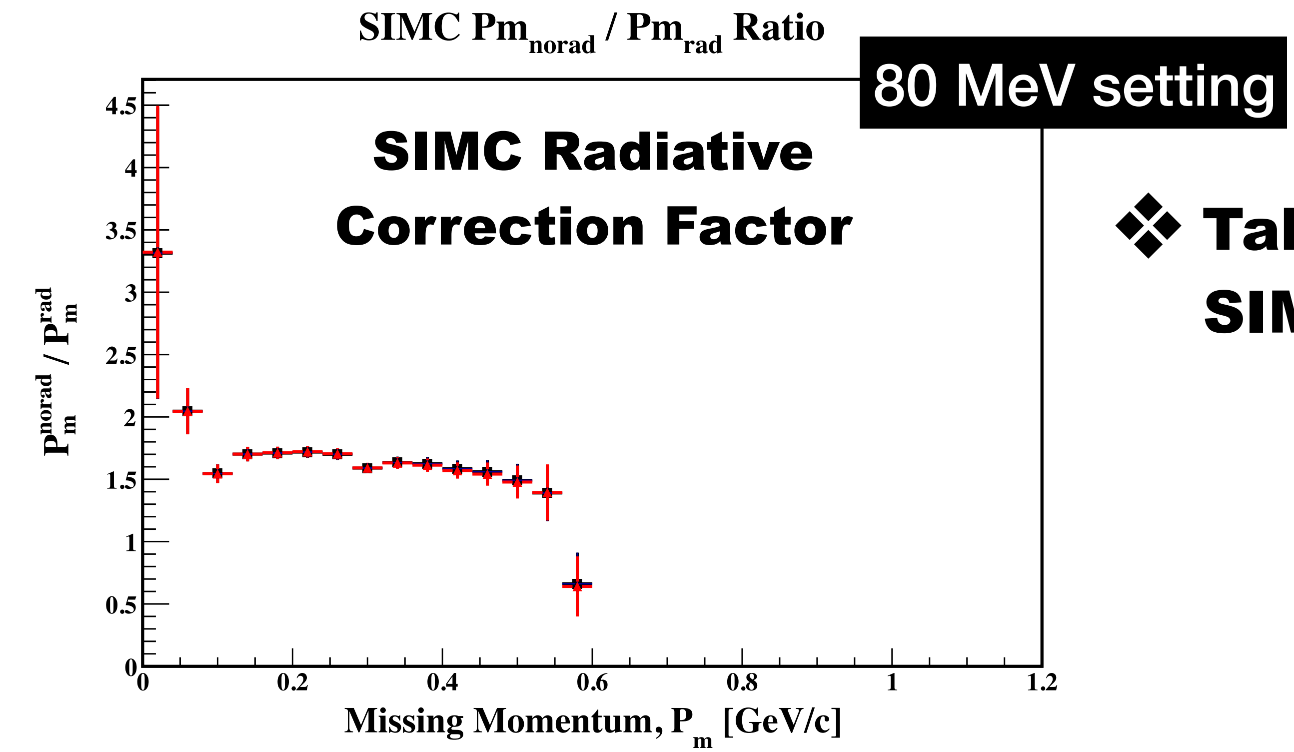
*(See simc.f in SIMC) for definition of normalization factor

RADIATIVE CORRECTIONS

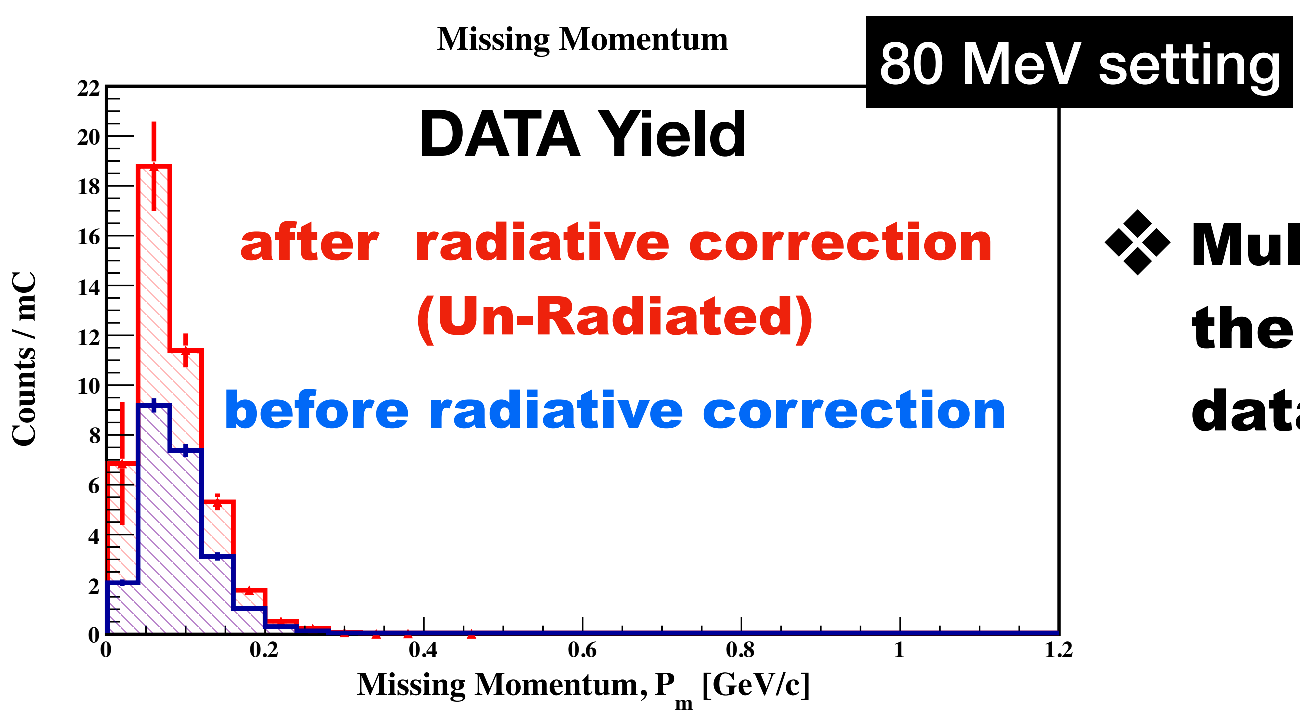
Extraction of the D(e,e’p)n Cross Section

❖ **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)

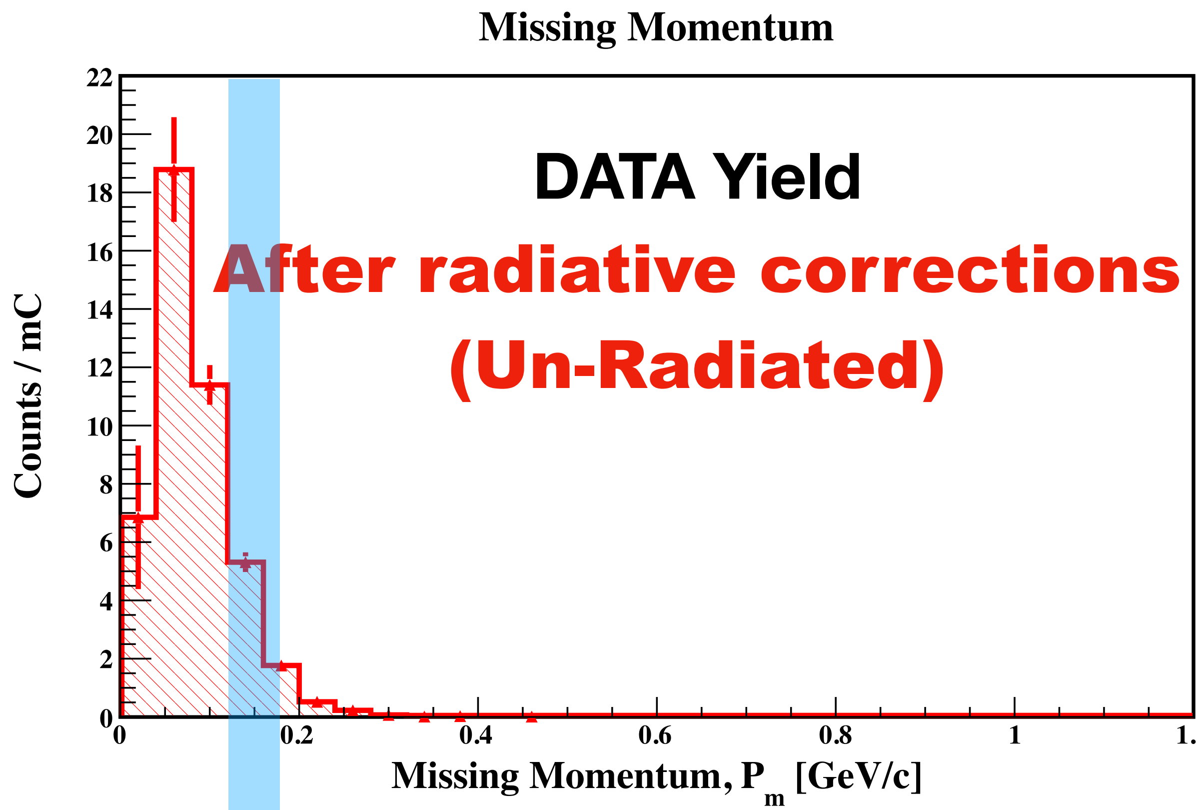


❖ **Take ratio between non-radiative to radiative SIMC Yield to get correction factor bin by bin.**

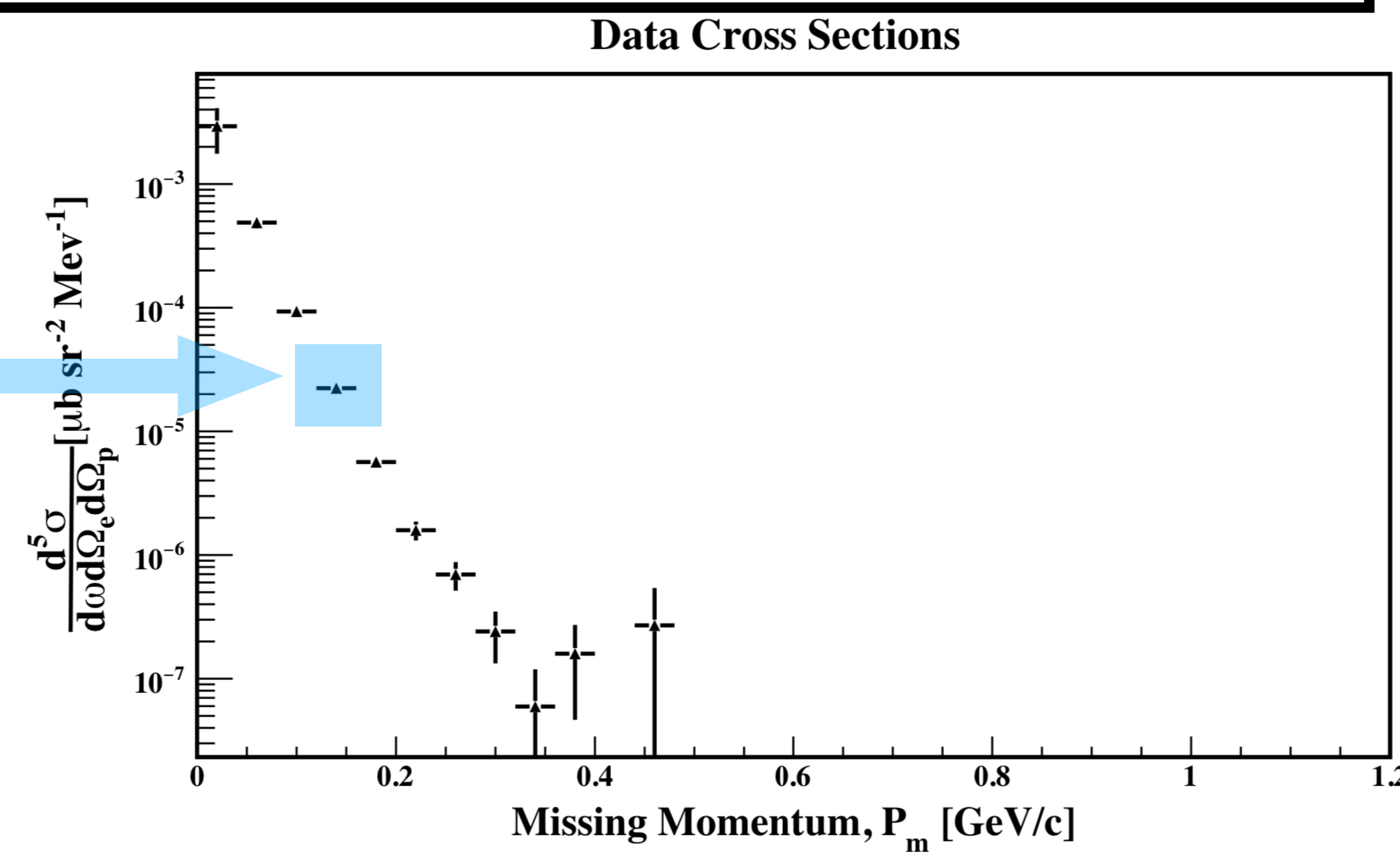


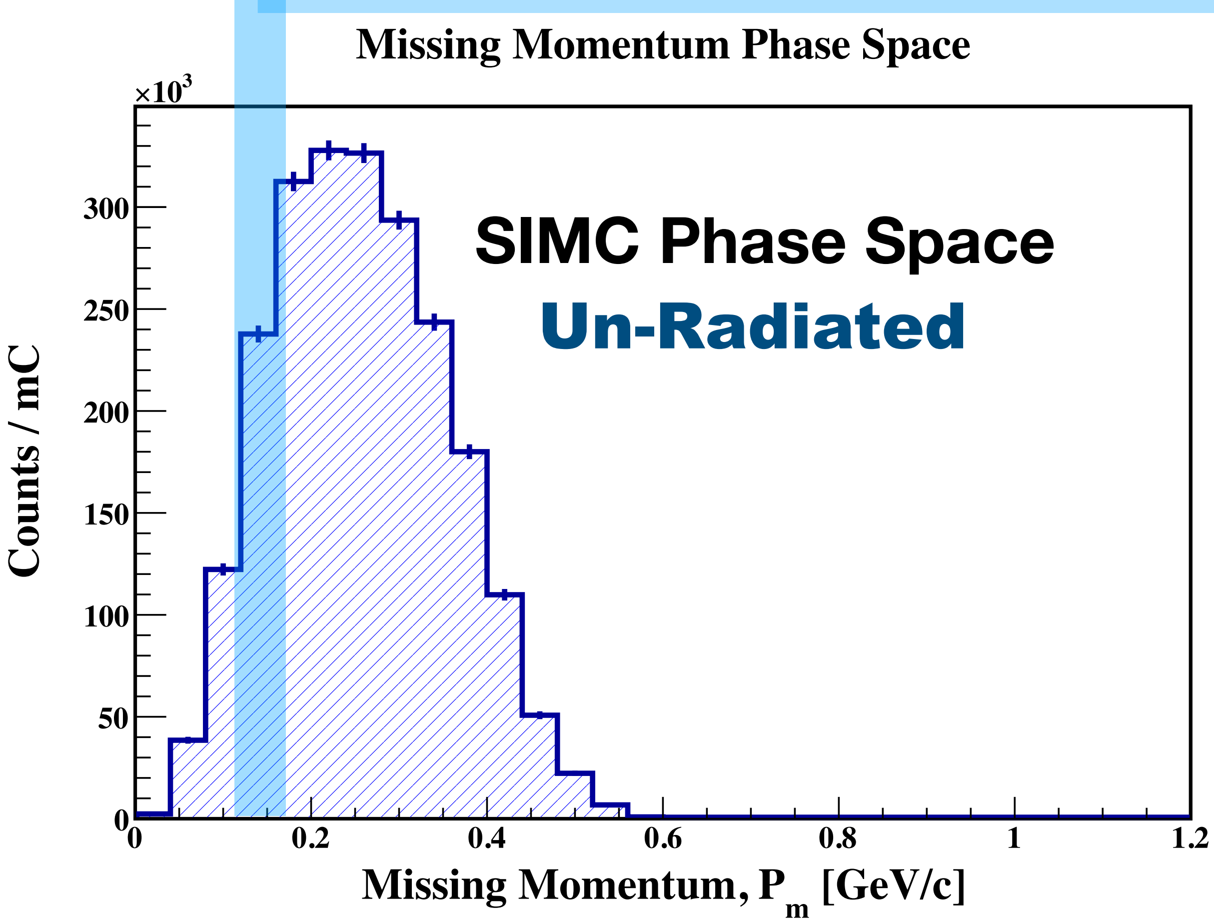
❖ **Multiply the radiative correction factor by the un-radiative data yield to get the corrected data yield bin-by-bin.**

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



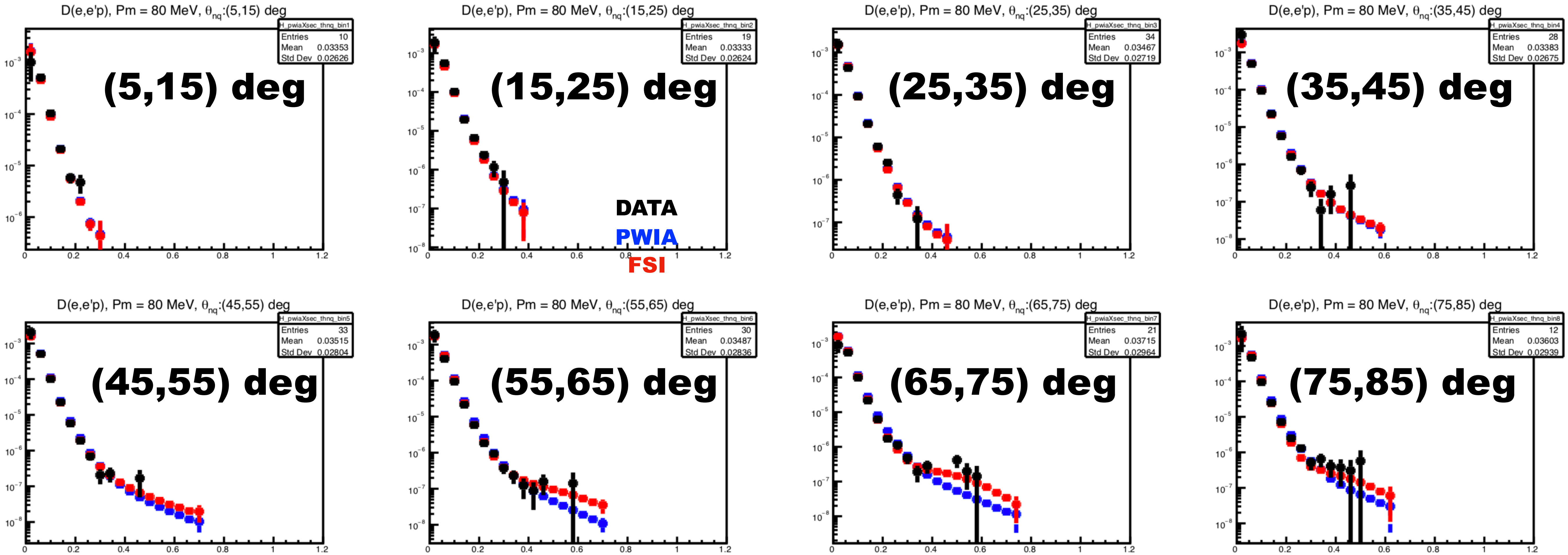
The ratio of the fully corrected data yield to the SIMC phase space will give the data cross section, bin-by-bin





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.**

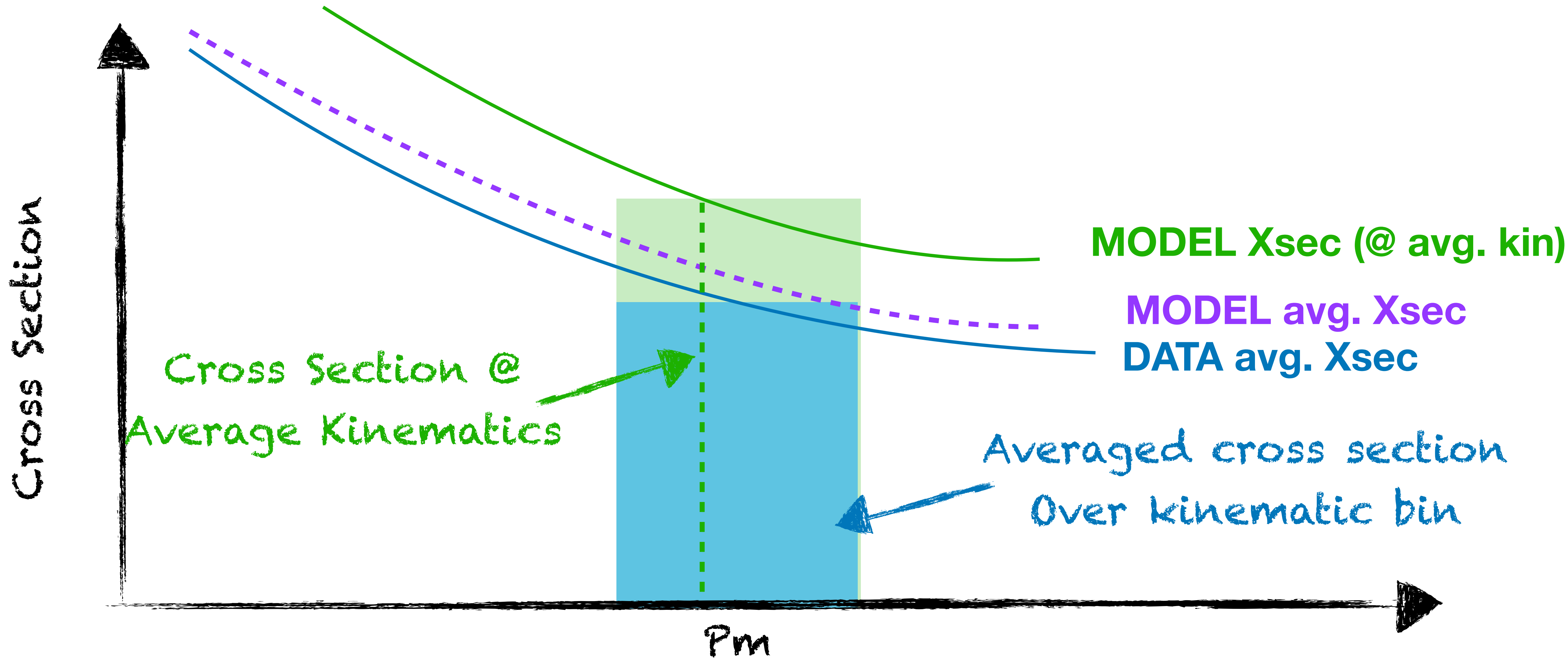


BIN-CENTERING

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)

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

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

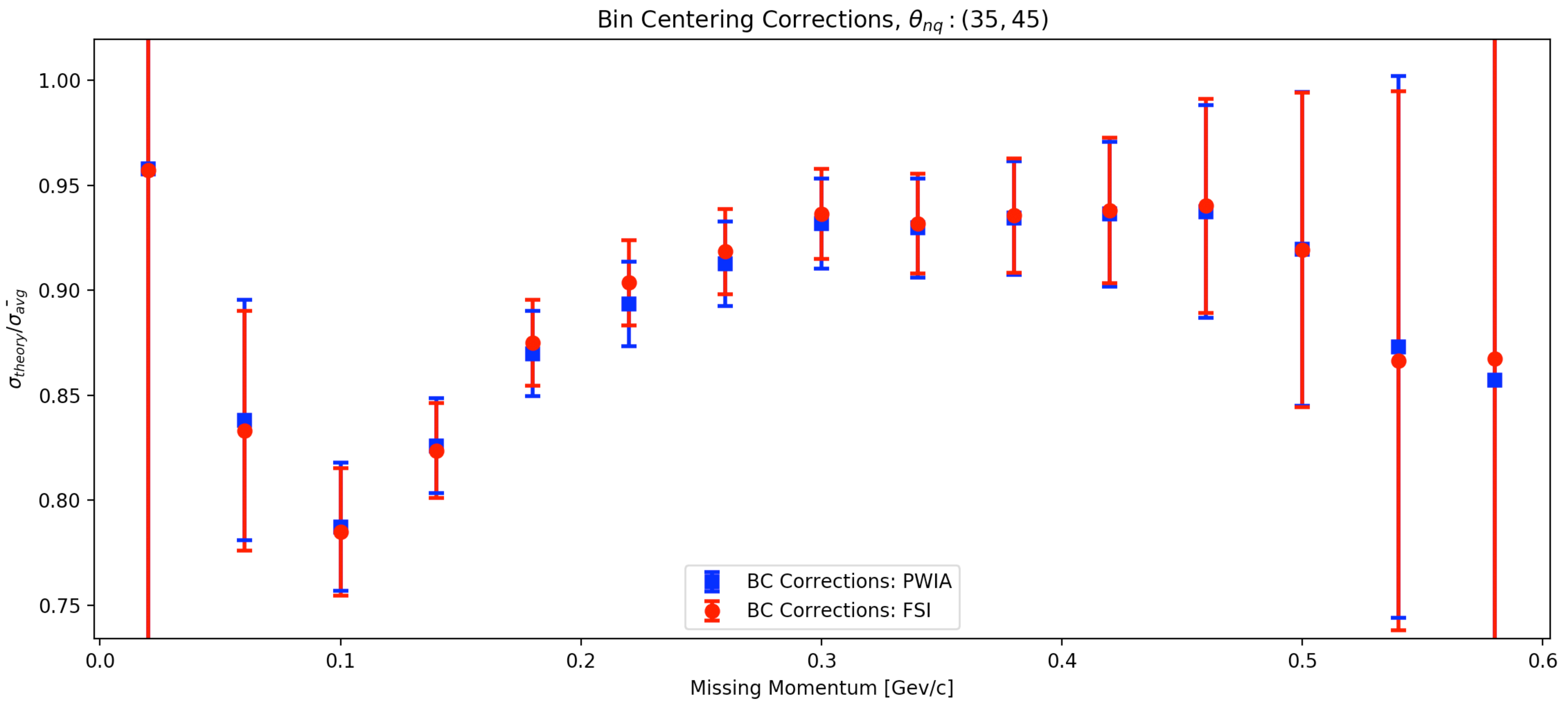
$\bar{\sigma}^{model} \equiv \dfrac{Y^{\mathrm{SIMC}}}{V^{P.S.}}$ $\longrightarrow$ **Averaged Model Cross Section**
(See Slide 21 for reference)

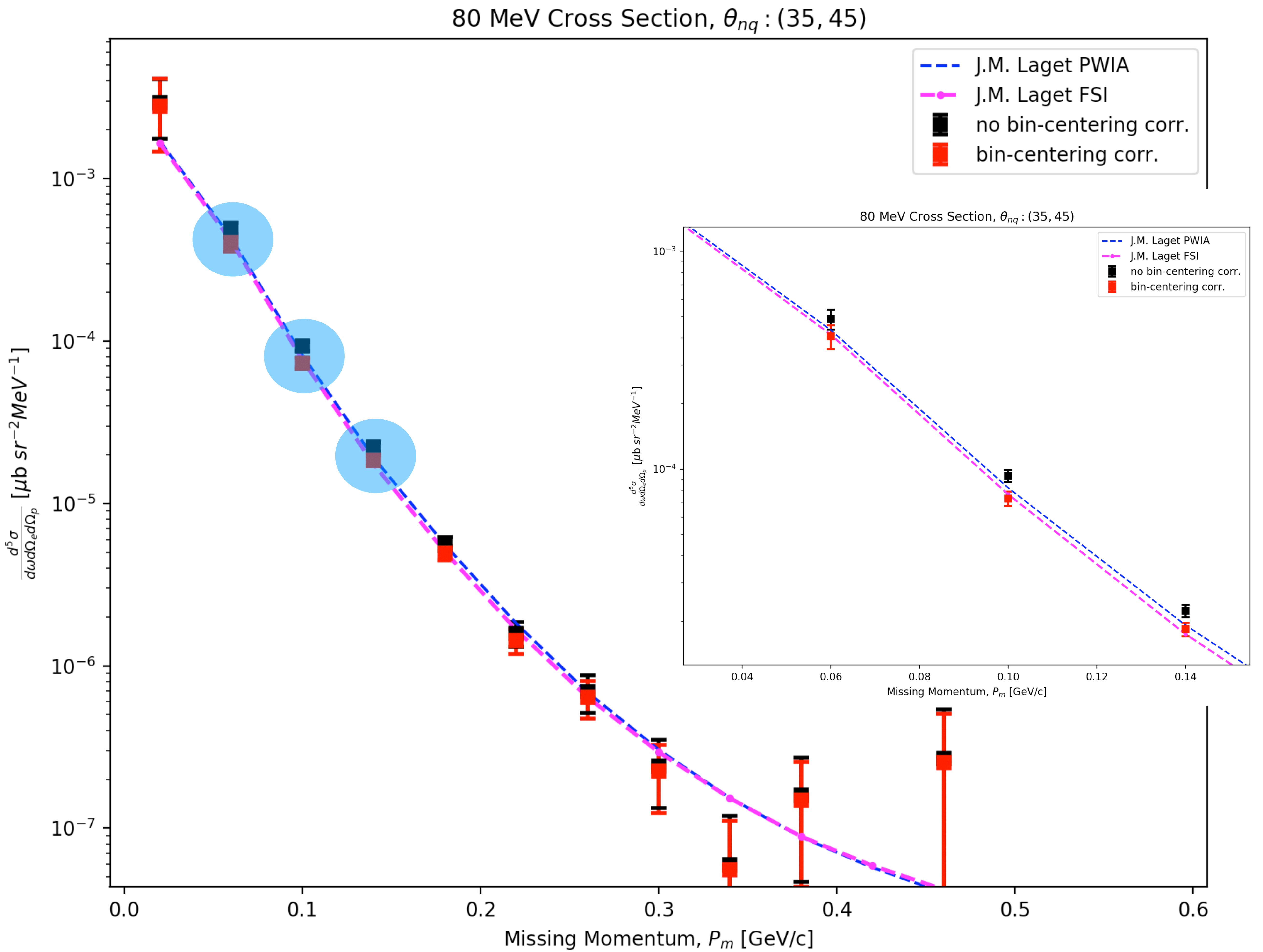
❖ **Correct the data bin-by-bin using the model cross sections ratio . . .**

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

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]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0.0
0.1
0.2
0.3
0.4
0.5
0.6
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]
0.04
0.06
0.08
0.10
0.12
0.14

D(e,e'p) Momentum Distributions

Fully Corrected
Experimental
cross sections

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

Kinematic Factor
times deForest
e-N cross section

Reduced cross section
(momentum distributions in PWIA)

deForest cross section depends on the E.M. form factors of the proton, therefore, division by Kinematical Factor eliminates all kinematical dependencies on the cross section of except for the missing momentum. Ideally, the momentum distributions should be Independent of all kinematical factors, and should only depend on the internal momentum of the proton.