



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

Hall C Collaboration Meeting, June 28-29, 2020

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Spokespeople: Drs. Werner Boeglin and Mark Jones

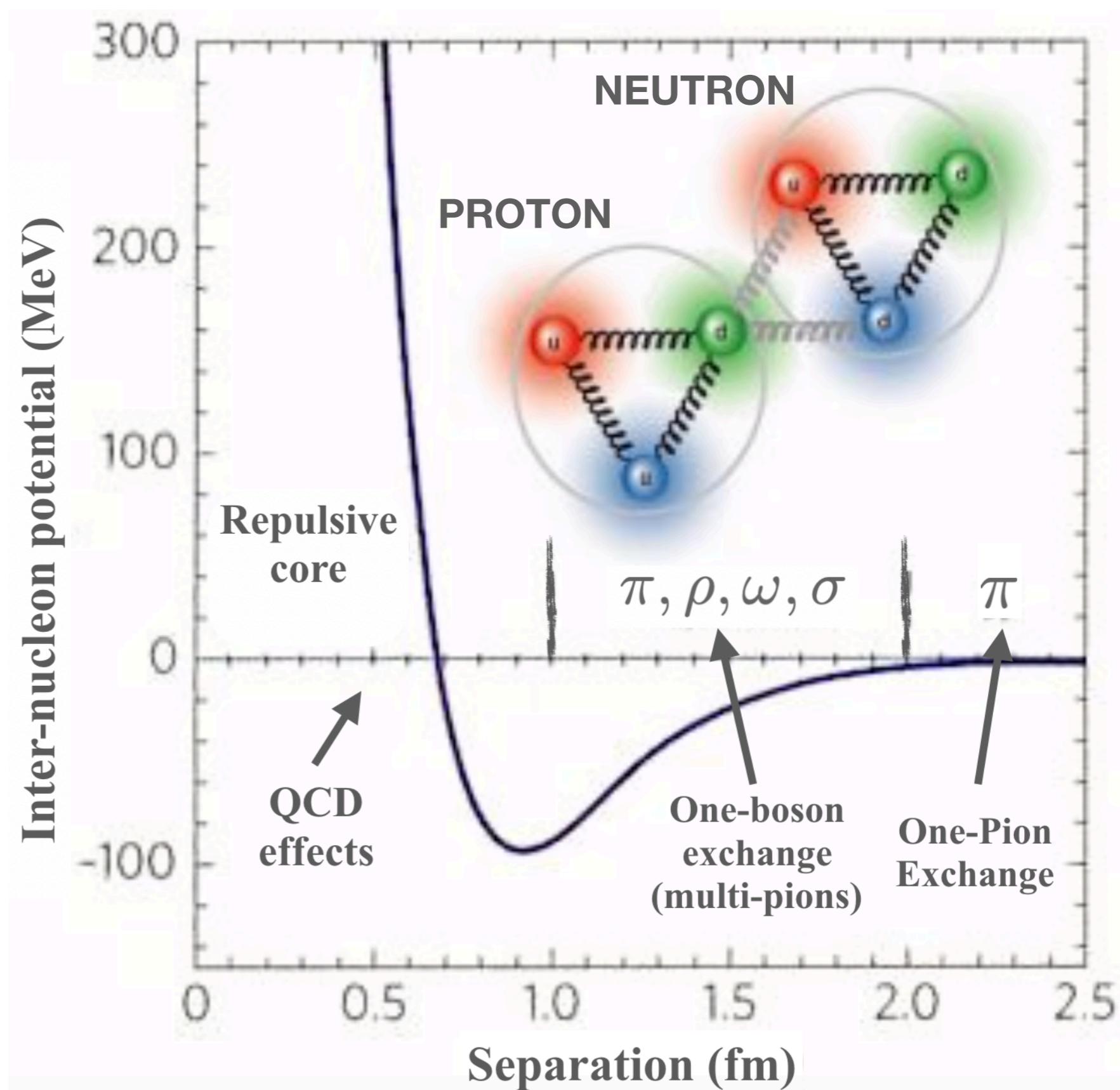
Motivation

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

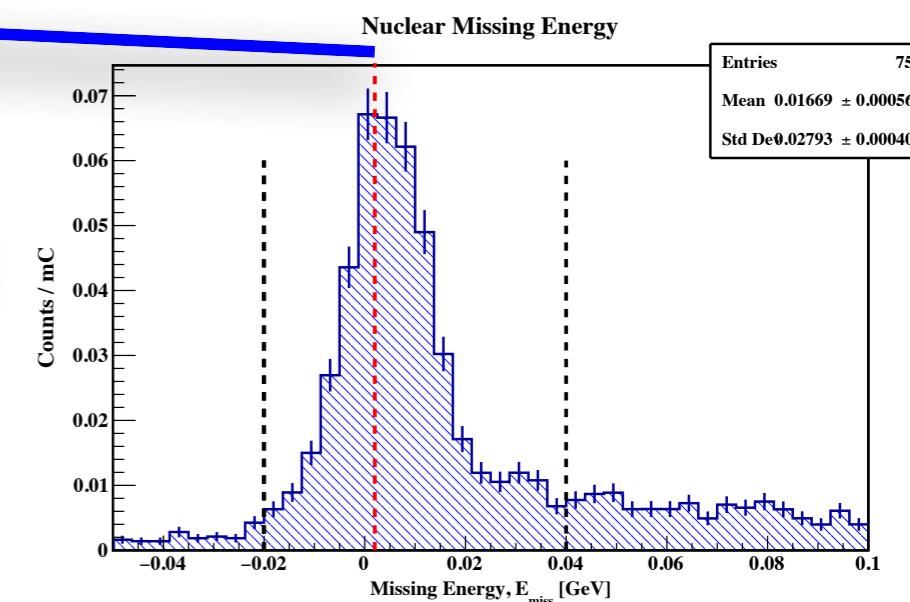
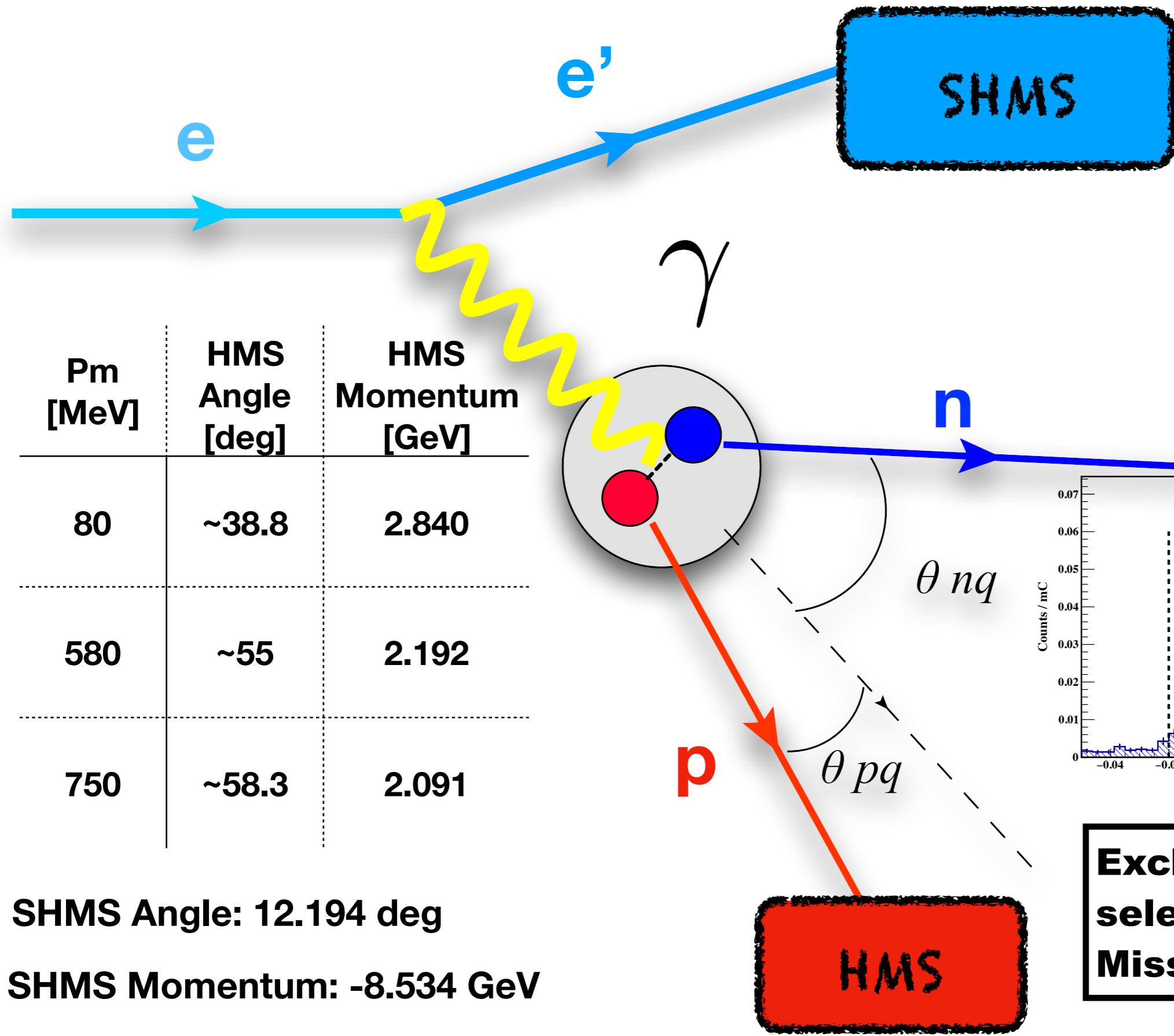
Understand the short range structure of the D2 by probing its high momentum tails

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

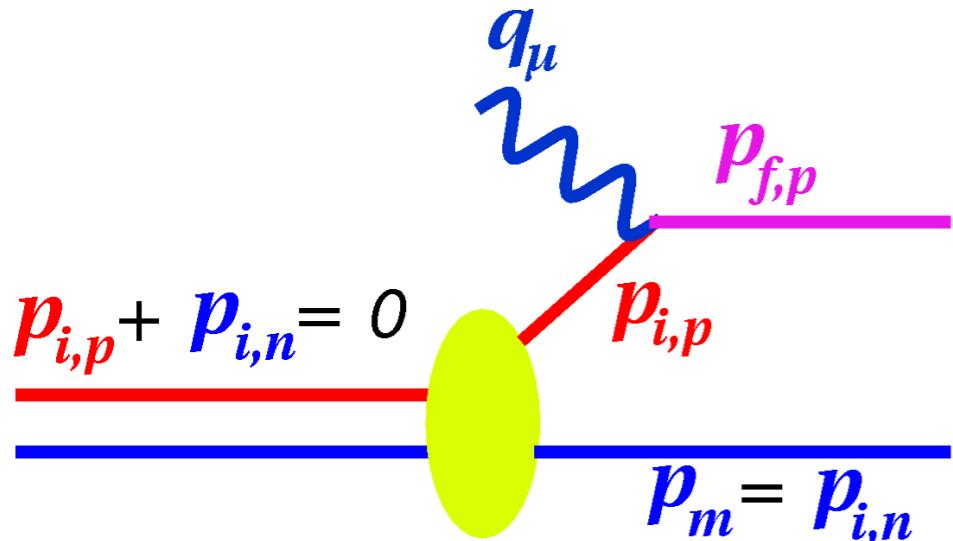


D(e,e'p)n Kinematics

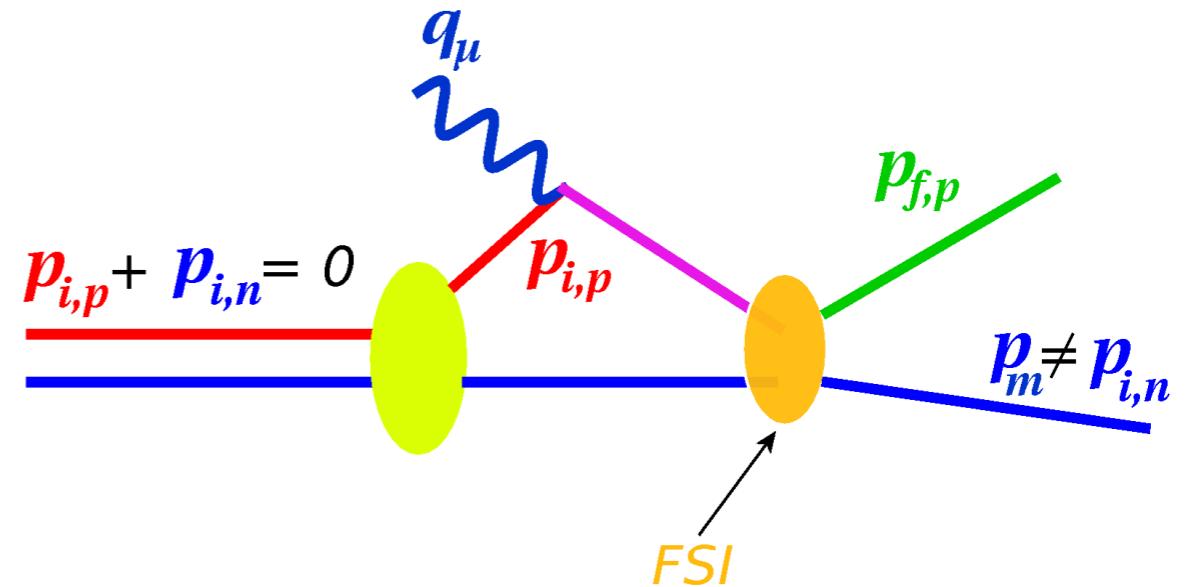


**Exclusive reaction
selected via
Missing Energy Cut**

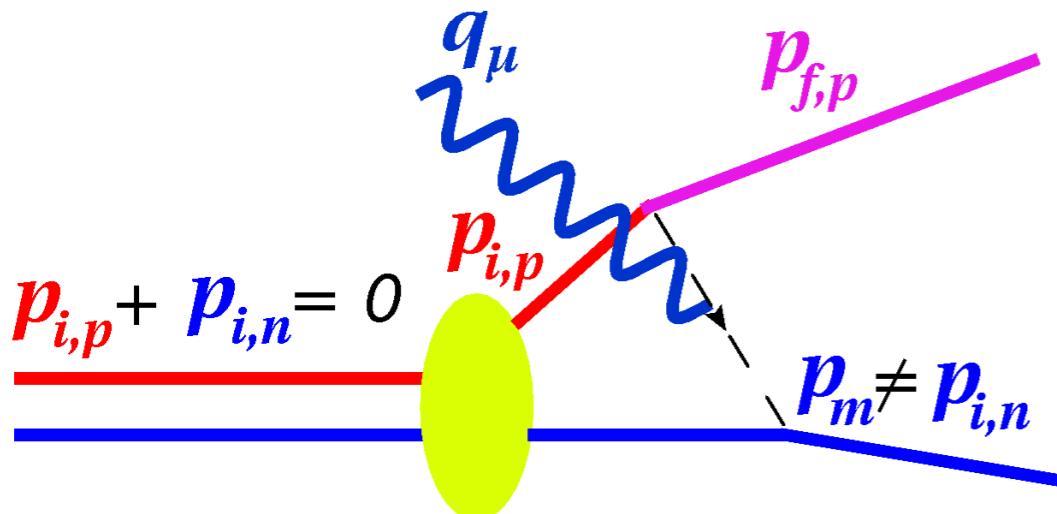
D(e,e'p)n Feynman Diagrams



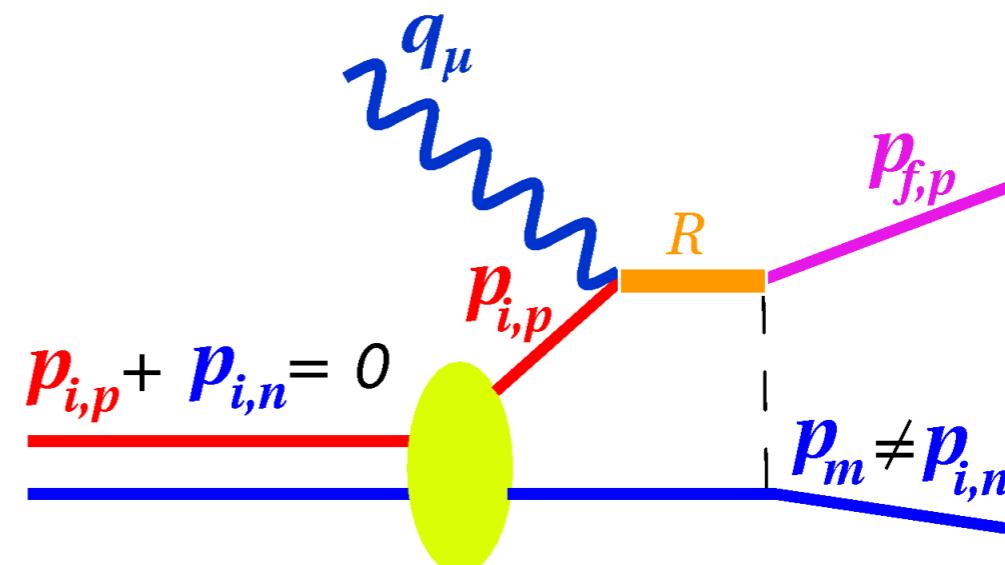
Plane Wave Impulse Approximation
(PWIA)



Final State Interactions (FSI)



Meson-Exchange Currents (MEC)



Isobar Configurations (IC)

Deuteron Momentum Distribution

Experiment

$$\sigma_{exp} \equiv \frac{d^5\sigma}{d\omega d\Omega_e d\Omega_p}$$

Theory

$$= K \cdot \sigma_{ep} \cdot S(p_m)$$

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

Factorization **ONLY**
possible in PWIA

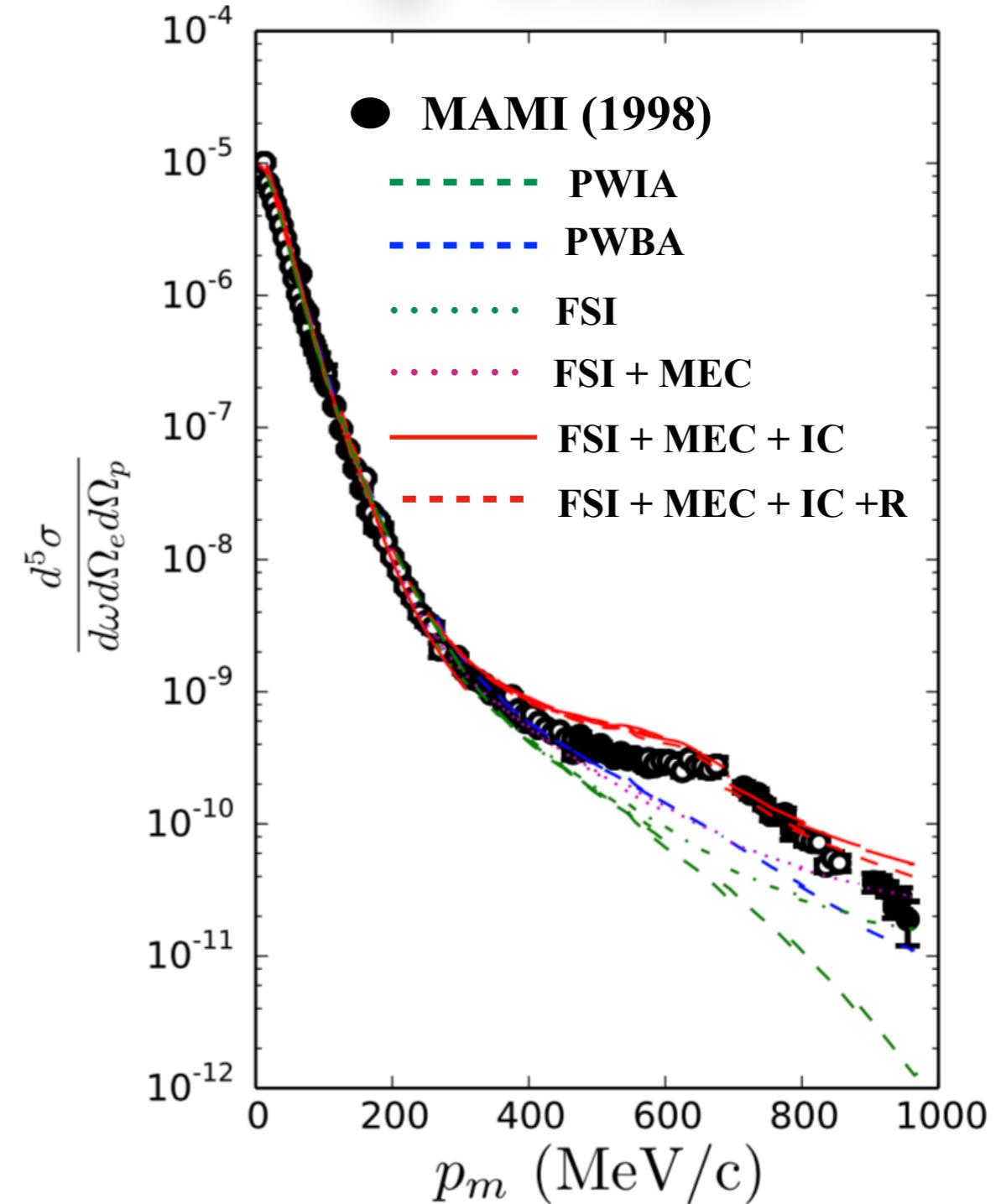
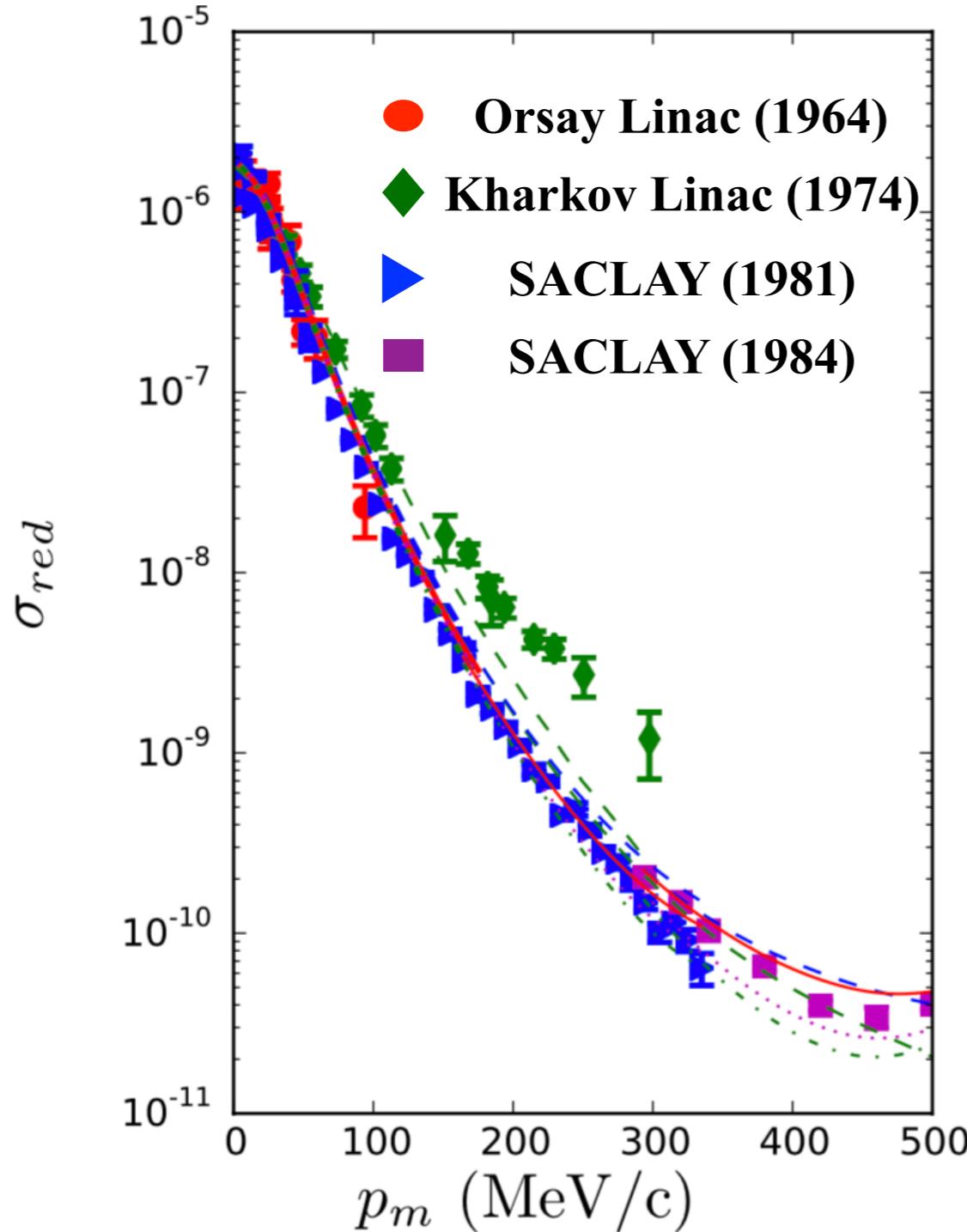
ep off-shell cross section

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: $Q^2 < 1 \text{ GeV}^2$



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: $Q^2 > 1$ GeV 2

JLab Hall A (2011)

CD-Bonn FSI (MS)

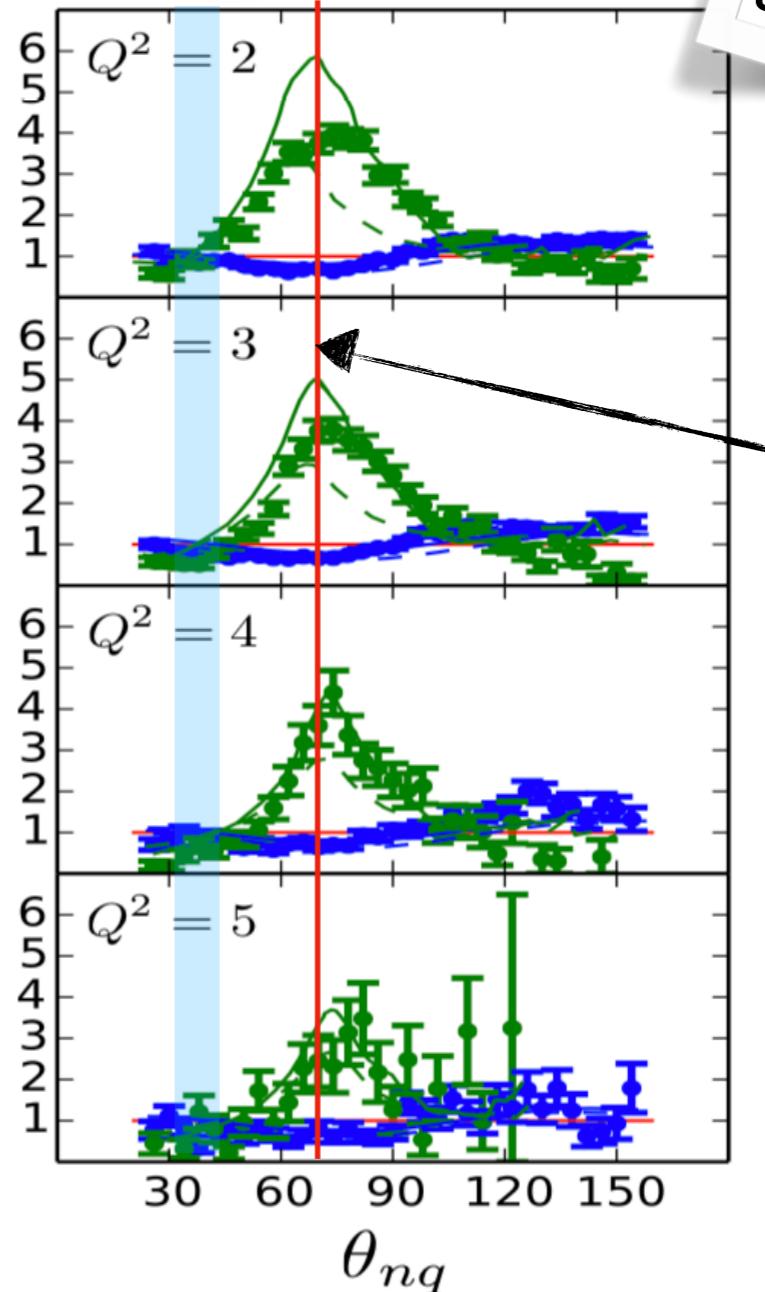
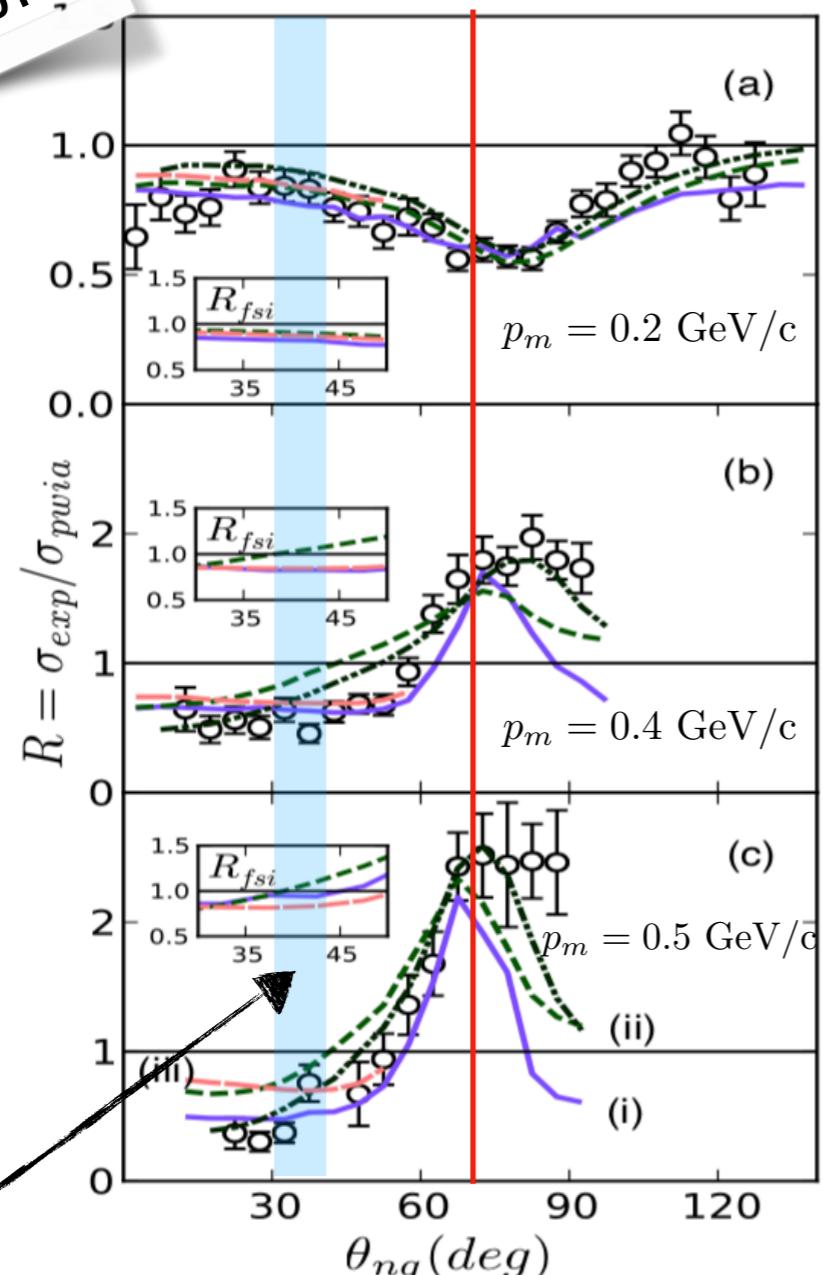
JVO Model
(J. Van Orden)

Paris FSI
(J.M. Laget)

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

DATA

Reduced FSIs
at ~40 deg
(R ~ 1)



JLab Hall B (2007)

FSI peaks
at ~70 deg
(predicted
by GEA)

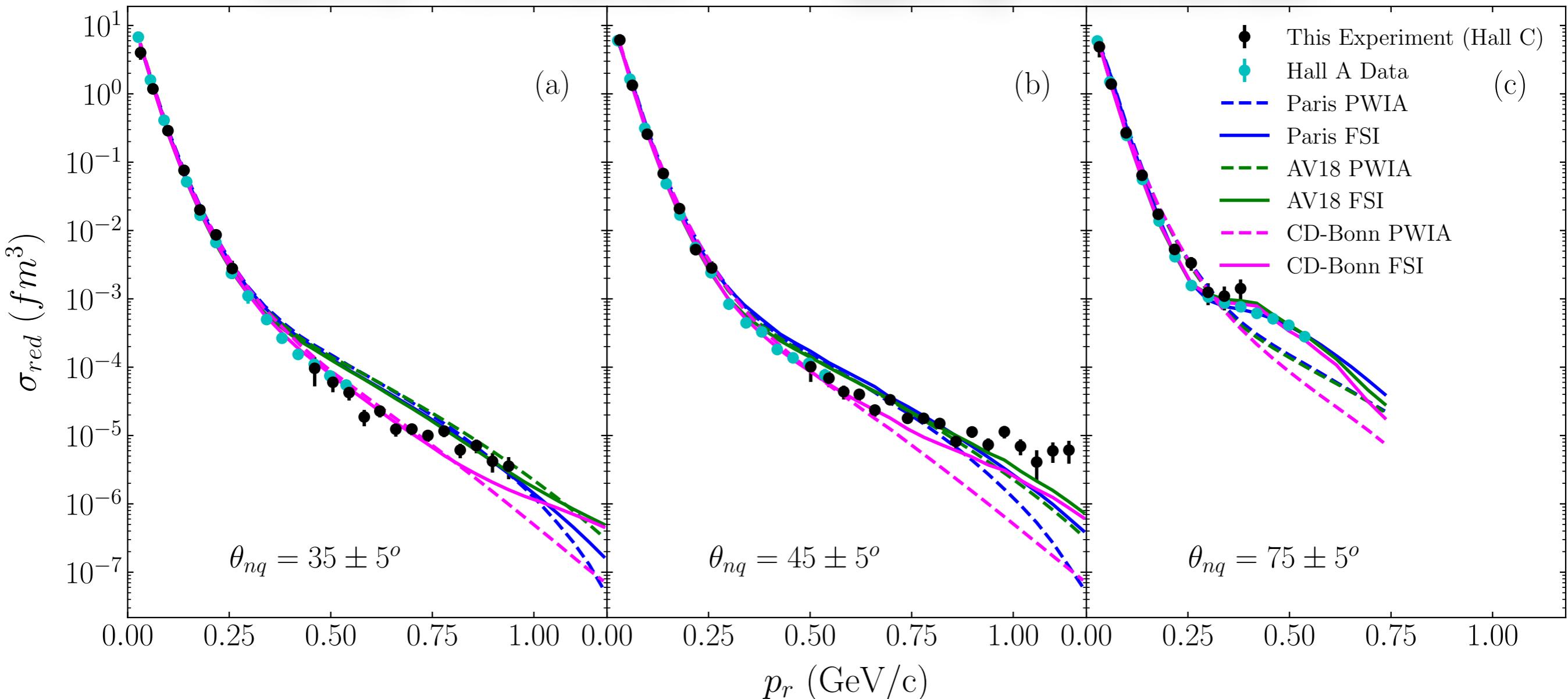
Plots Reference:
W.U.Boeglin and M. Sargsian
Int.J.Mod.Phys. E24 (2015)
no.03, 1530003

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

D($e, e' p$)n Momentum Distributions

Hall A: $Q^2 = 3.5 \pm 0.25 \text{ GeV}^2$

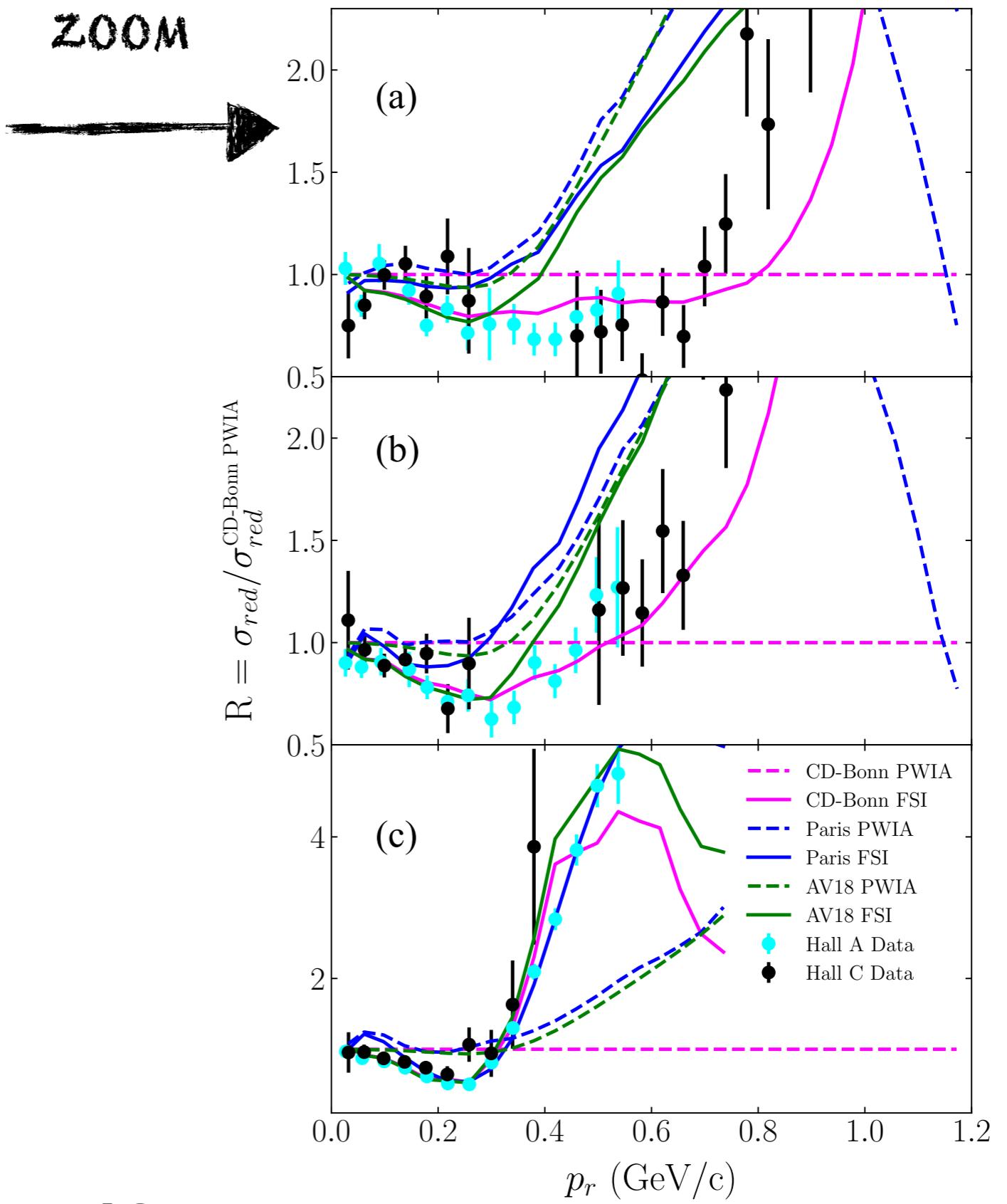
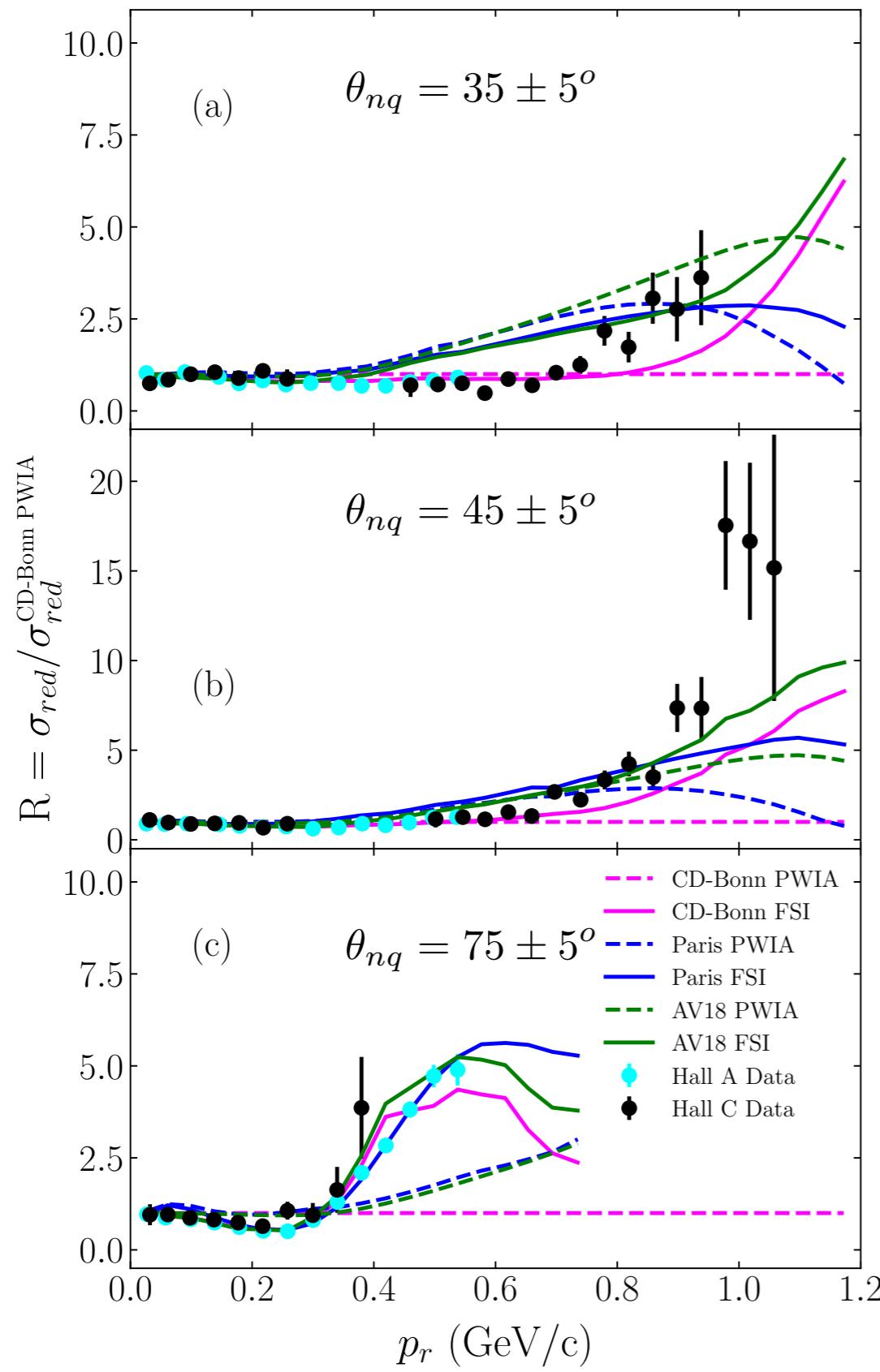
Hall C: $Q^2 = 4.5 \pm 0.5 \text{ GeV}^2$



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 $Q^2 = 4.5 \text{ (GeV/c)}^2$ 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

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

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.

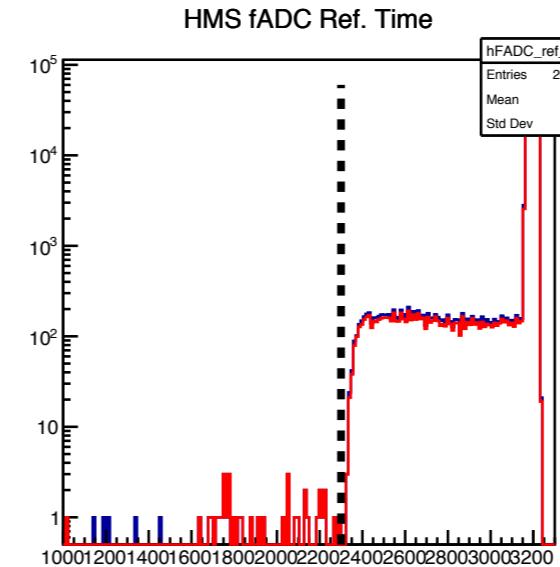
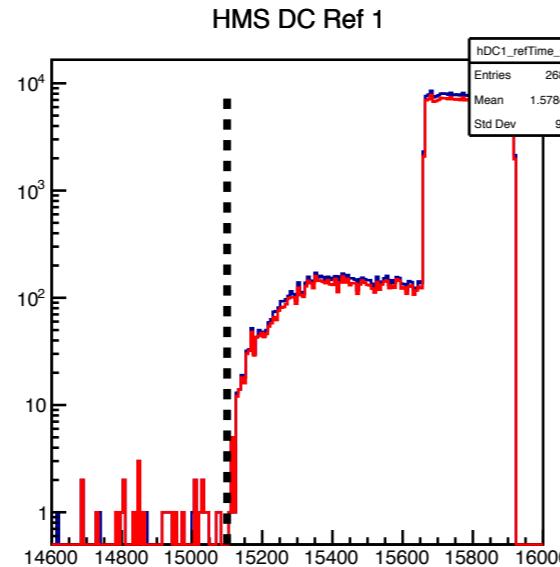
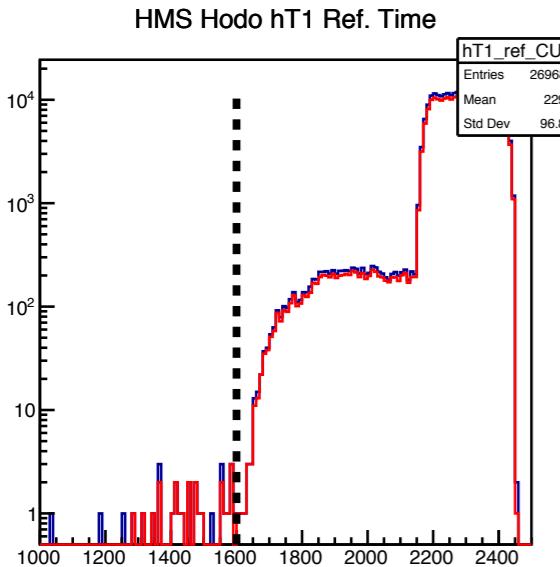
Hall C Experimental Analysis

on

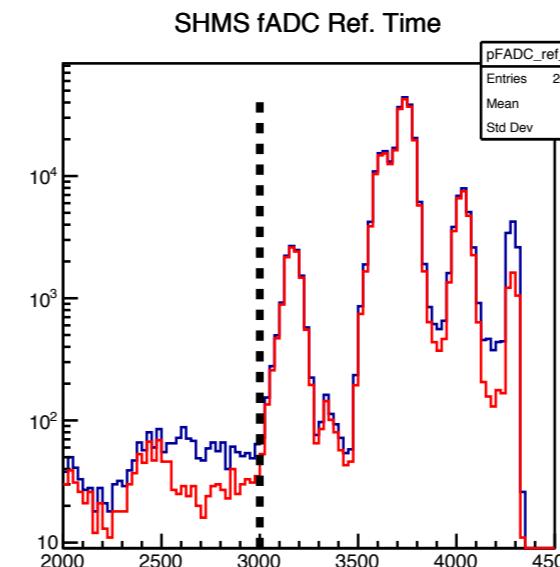
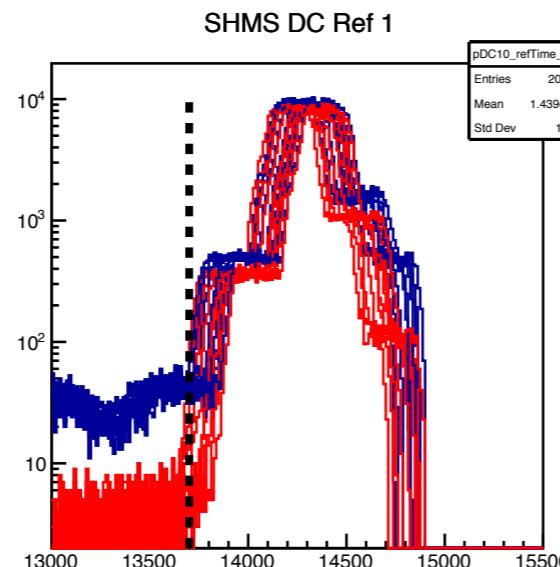
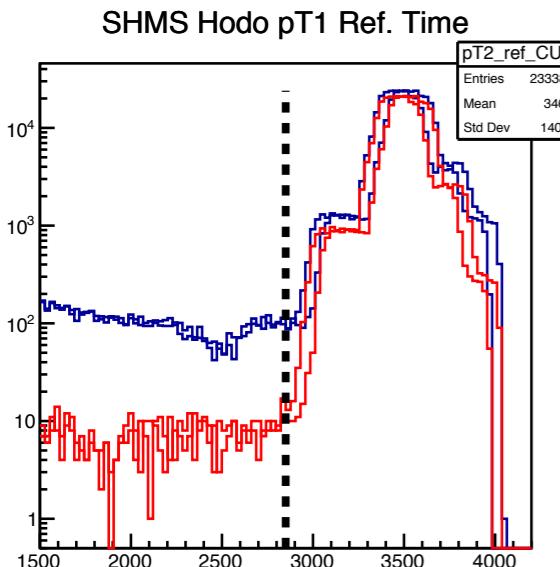
D(e,e'p)n

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

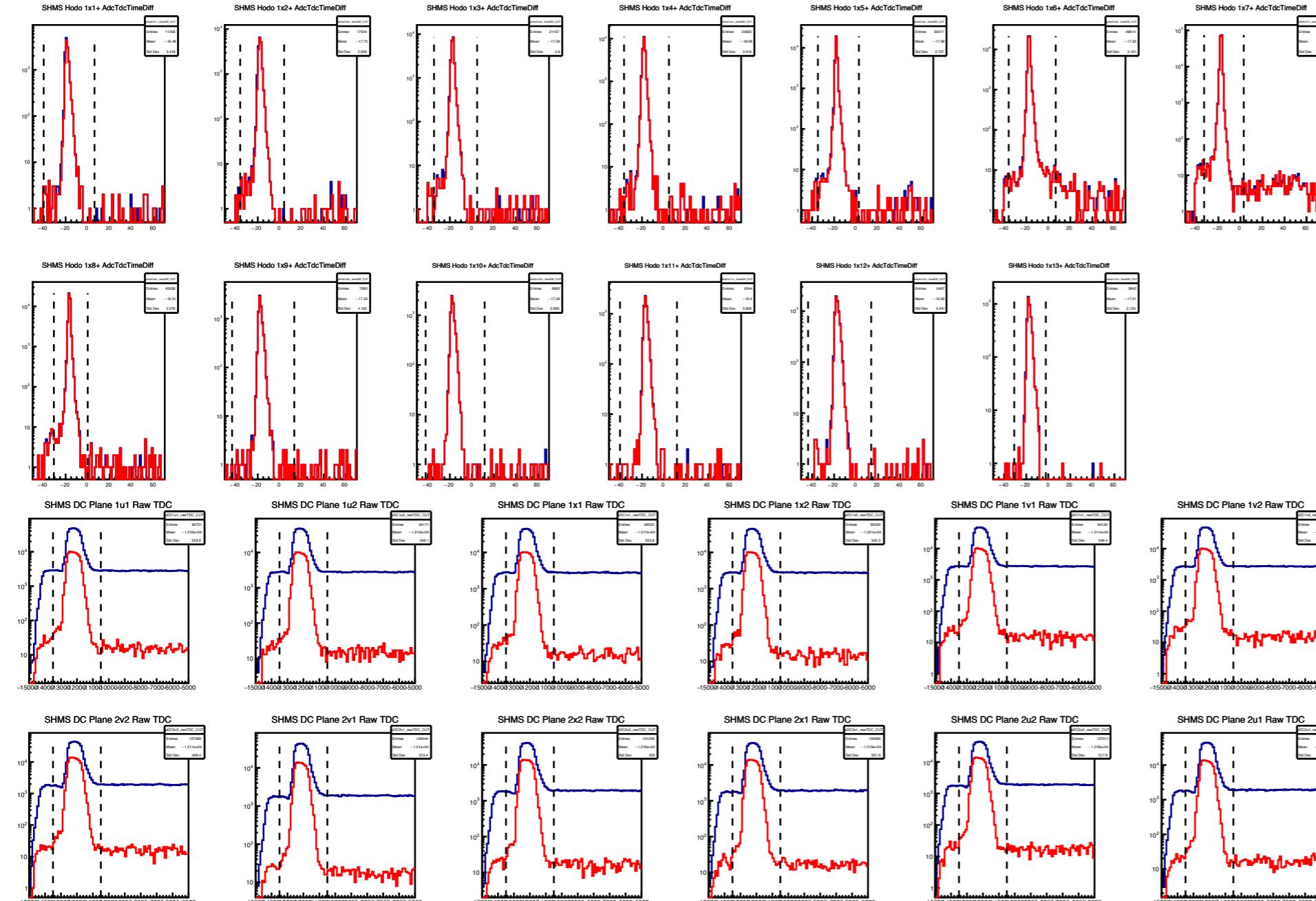


SHMS
Reference Times

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)

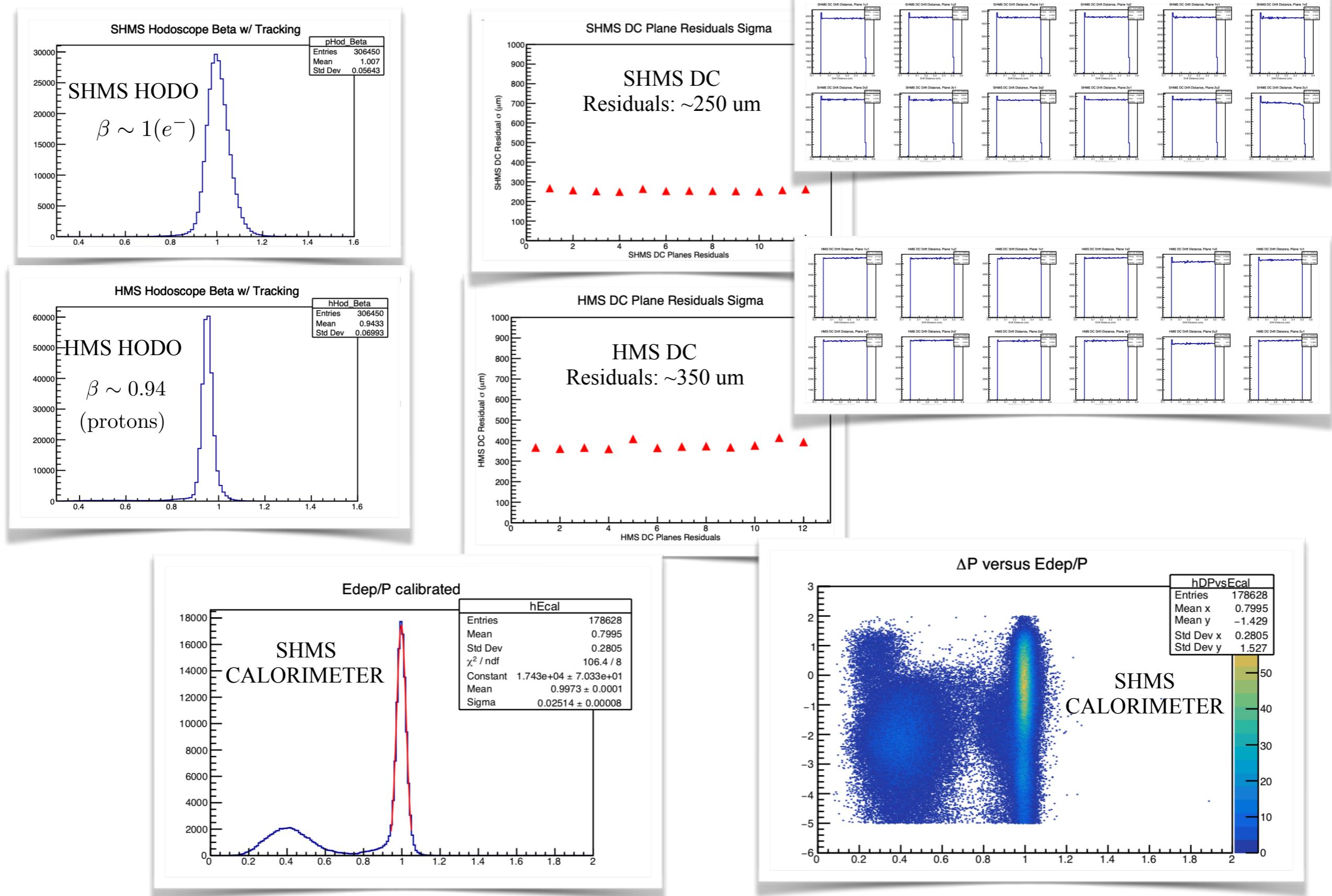
Legend: No Mult. Cut Multiplicity==1



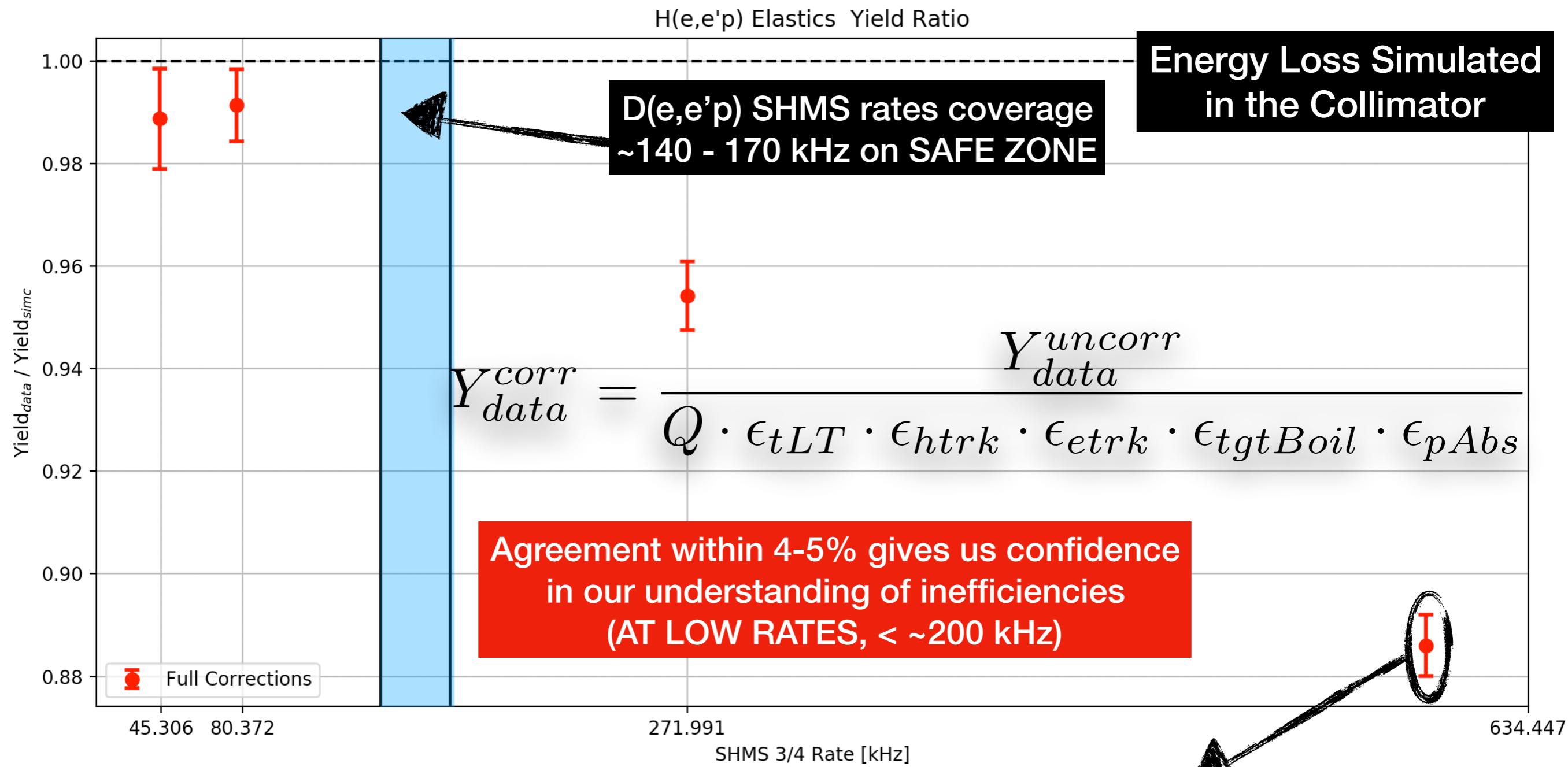
**SHMS
Hodoscope 1X+
(ADC-TDC) Time
Difference**

**SHMS
Drift Chambers
Raw TDC Time**

Detector Calibrations



H(e,e'p) Yield Ratio Check



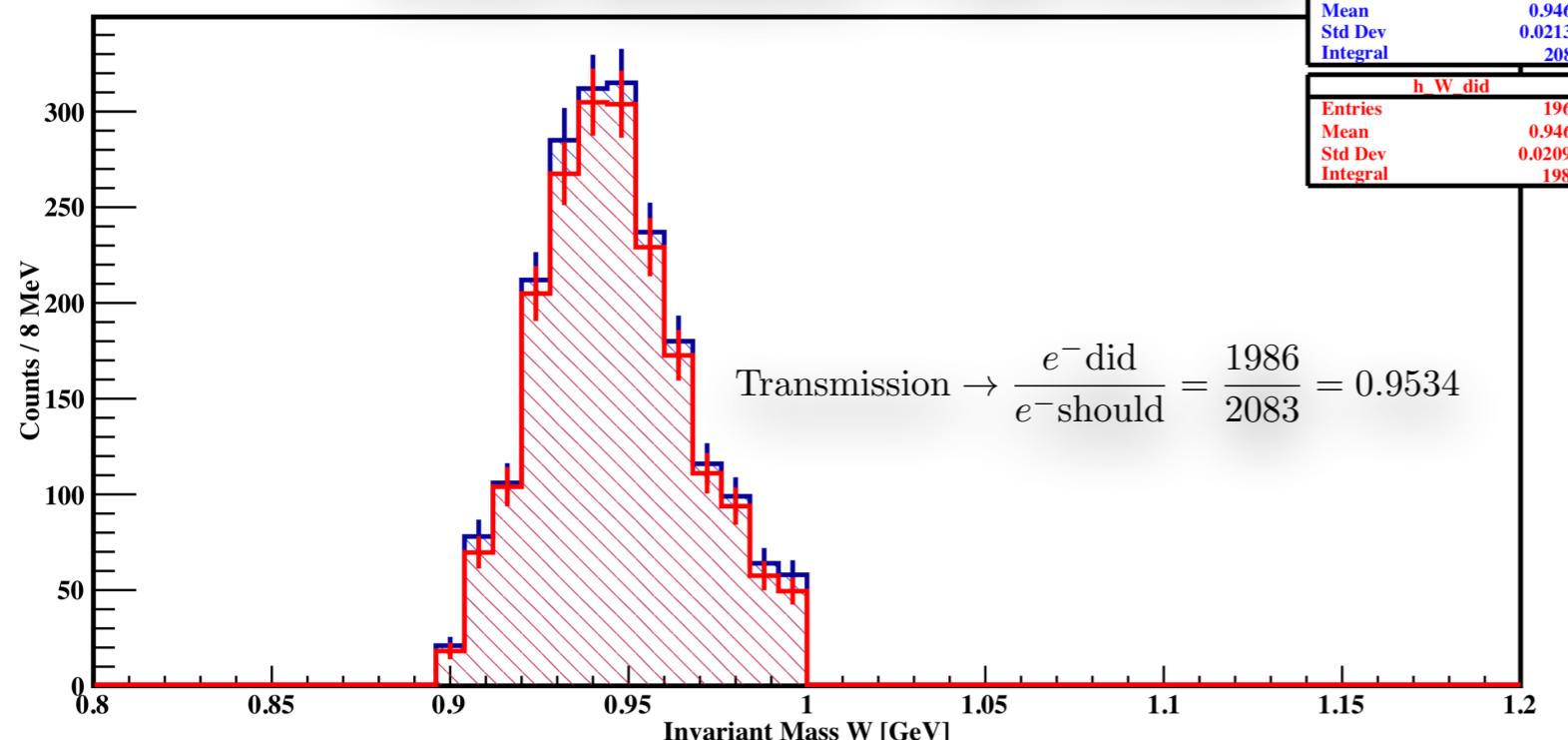
The general cuts applied were:

$|HMS\ Delta| < 8\%$ SHMS Delta: (-10, 22) %

Inv. Mass W : (0.85, 1.05), HMS Coll. Cut

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

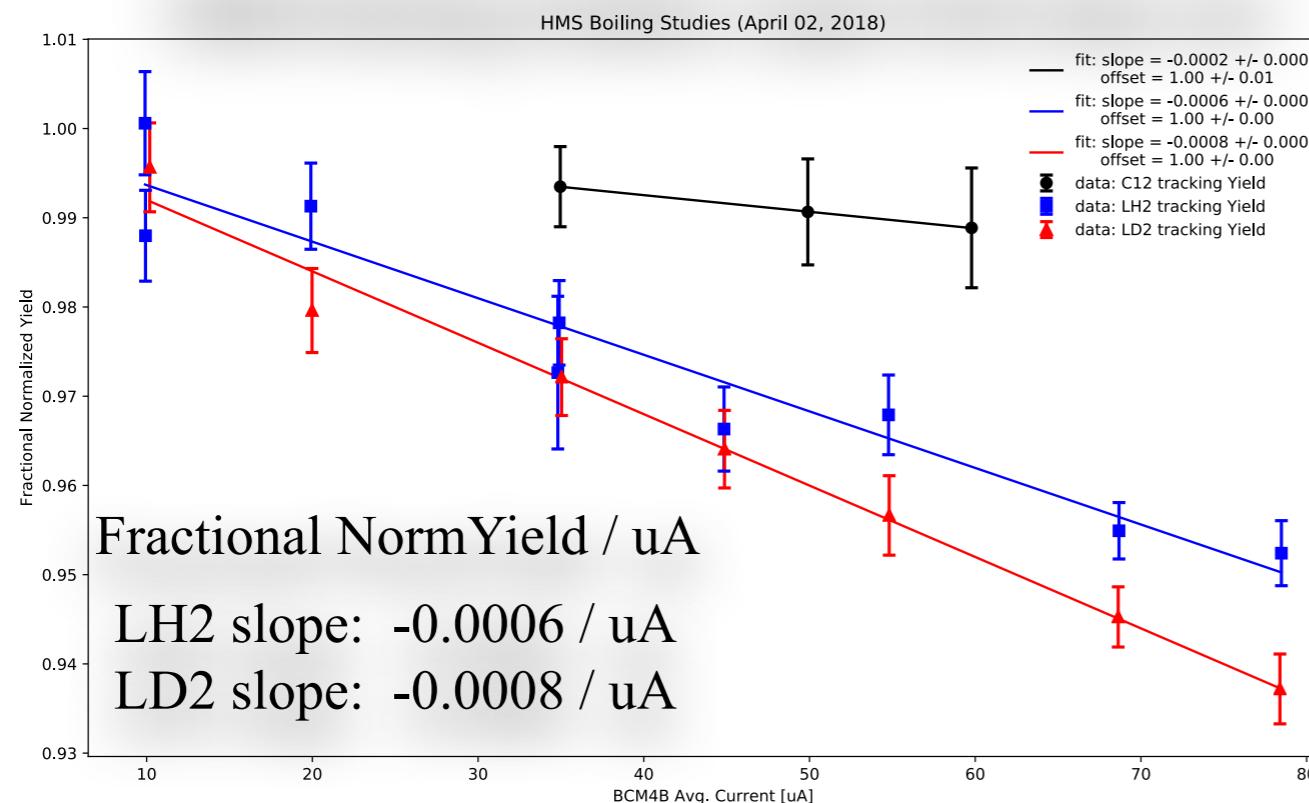
Proton Absorption = $4.66 \pm 0.472\%$



For Full Description of
Proton Absorption Analysis,
See DOC DB Link [HERE !](#)

(ONLY relevant for coincidence
experiments)

HMS Boiling Studies (April 2018 data set)



For Full Description of
Target Boiling Corrections
See DOC DB Link [HERE !](#)

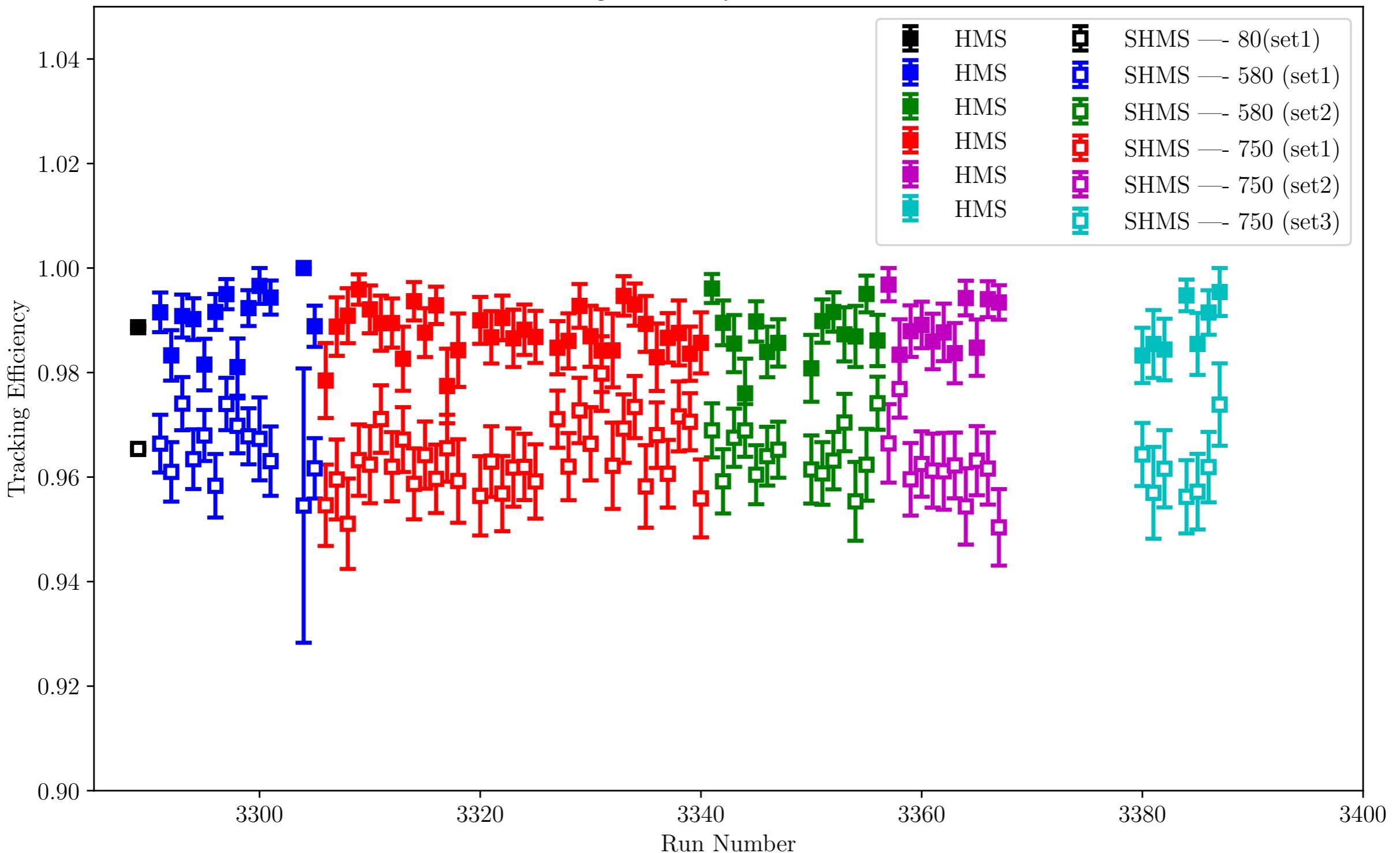
Extraction of D(e,e'p)n Cross Section

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

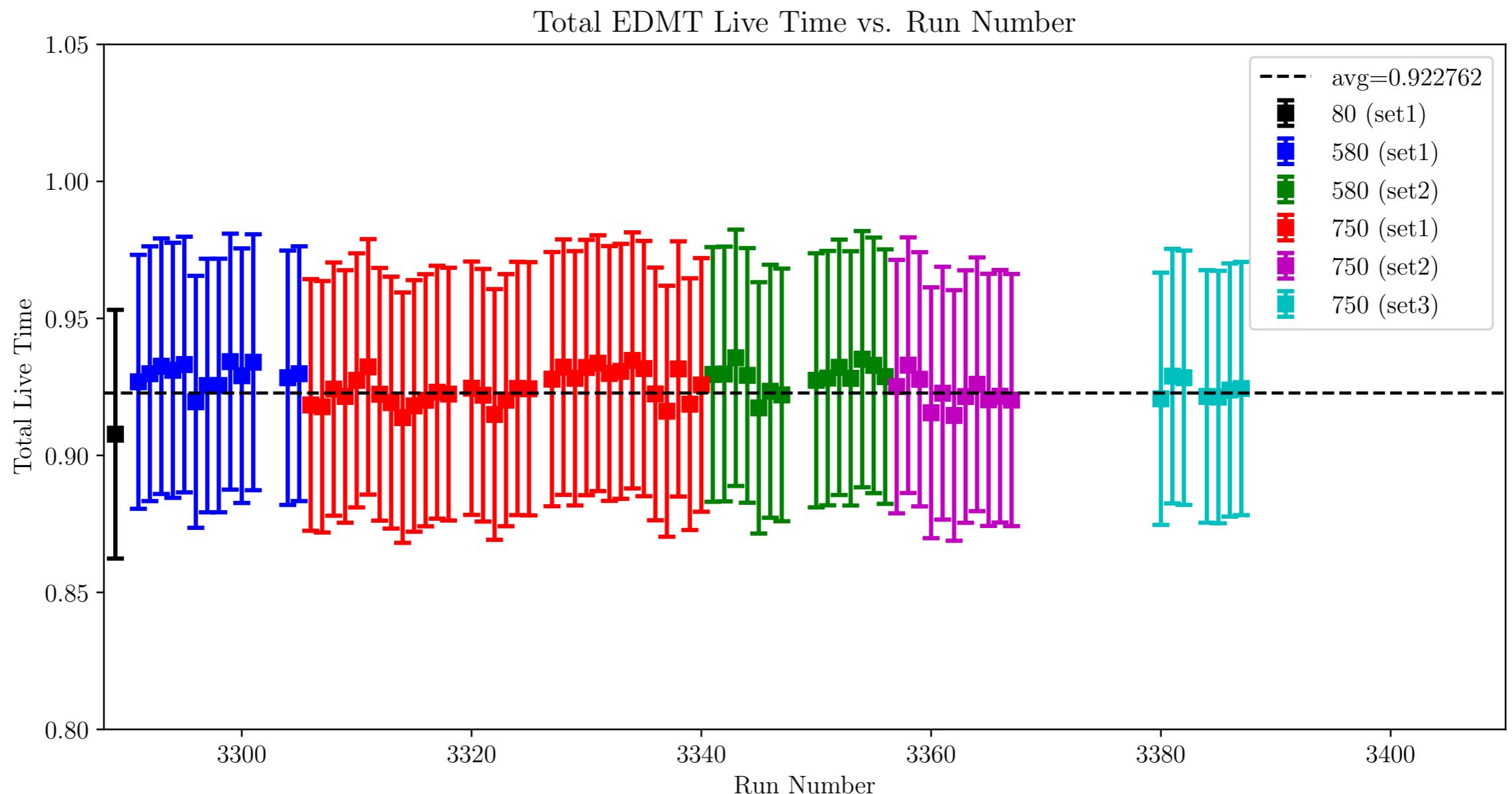
Efficiencies and Correction Factors

TRACKING EFFICIENCY

Tracking Efficiency vs. Run Number



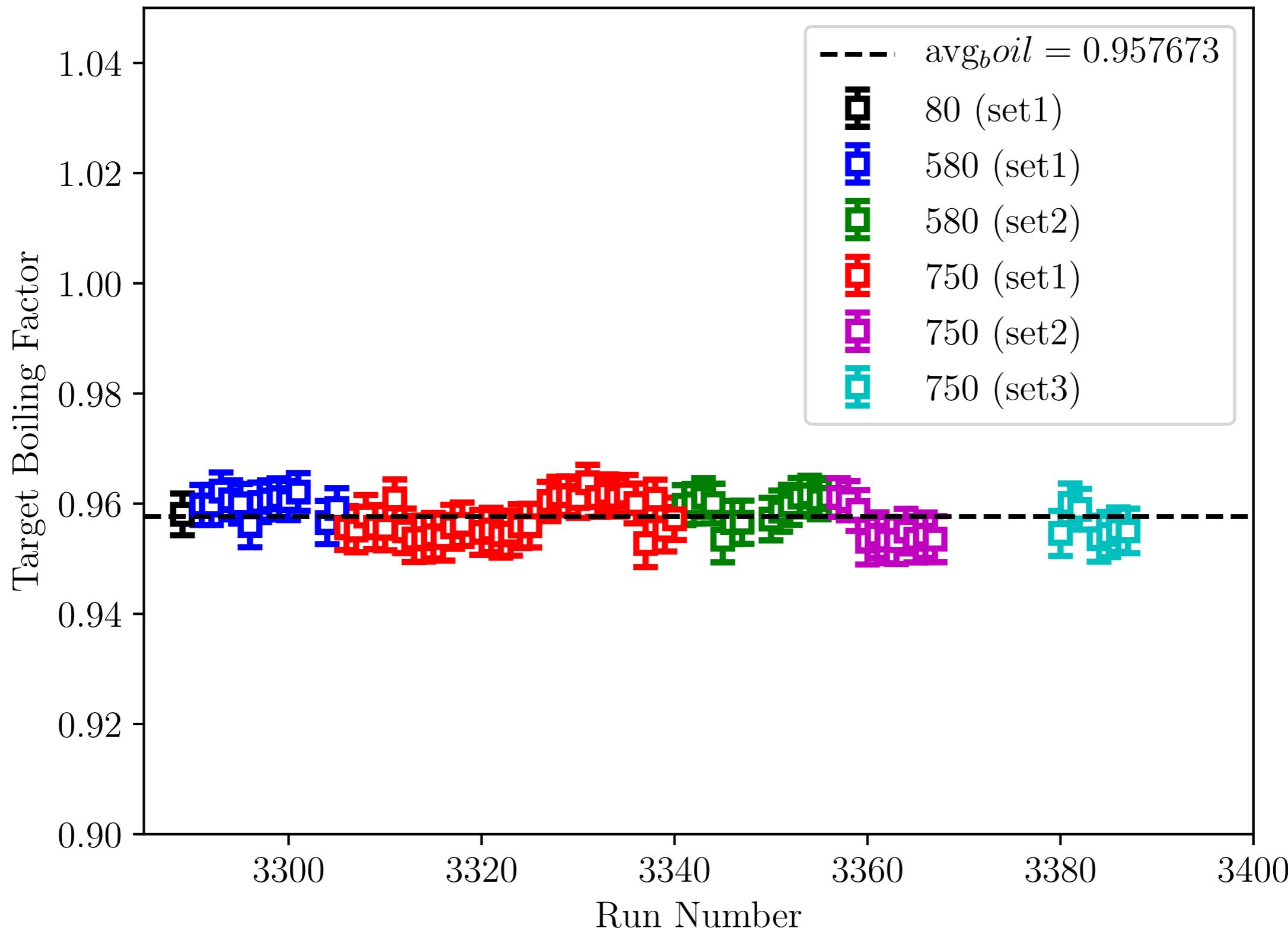
TOTAL EDTM LIVE TIME



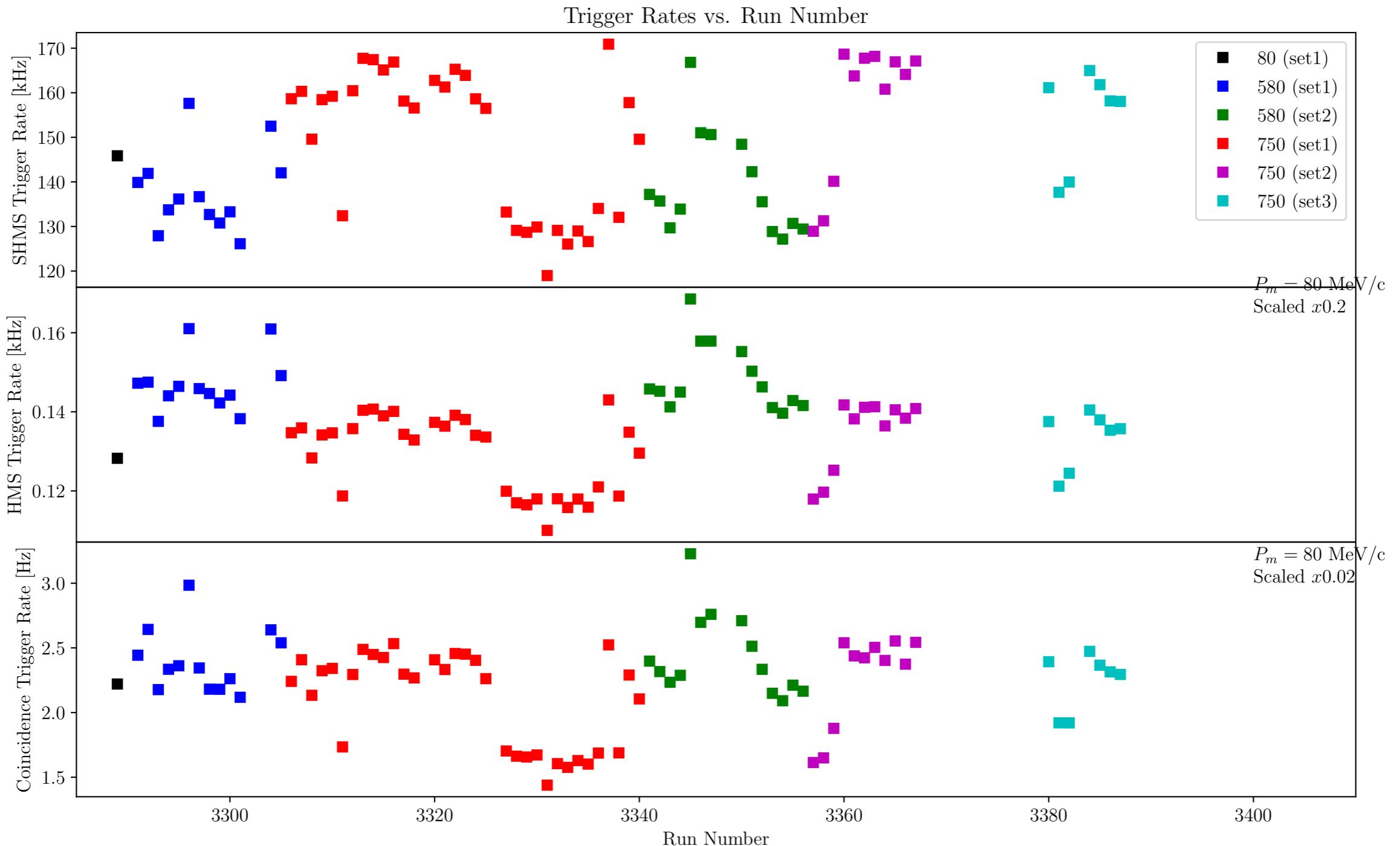
EDTM: Electronic Dead Time Monitoring

TARGET BOILING FACTOR

LD2 Boiling Factor vs. Run Number

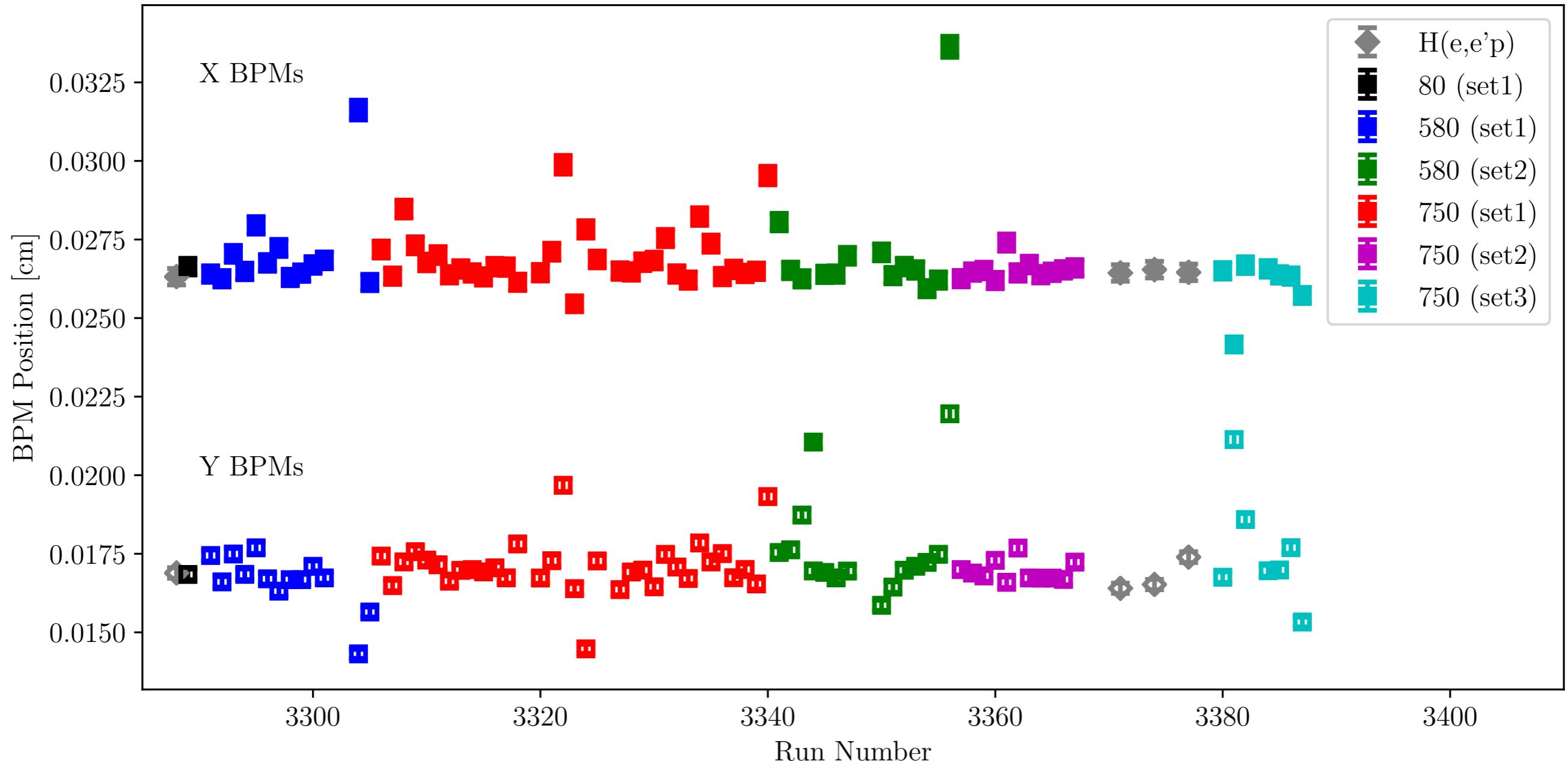


TRIGGER RATES

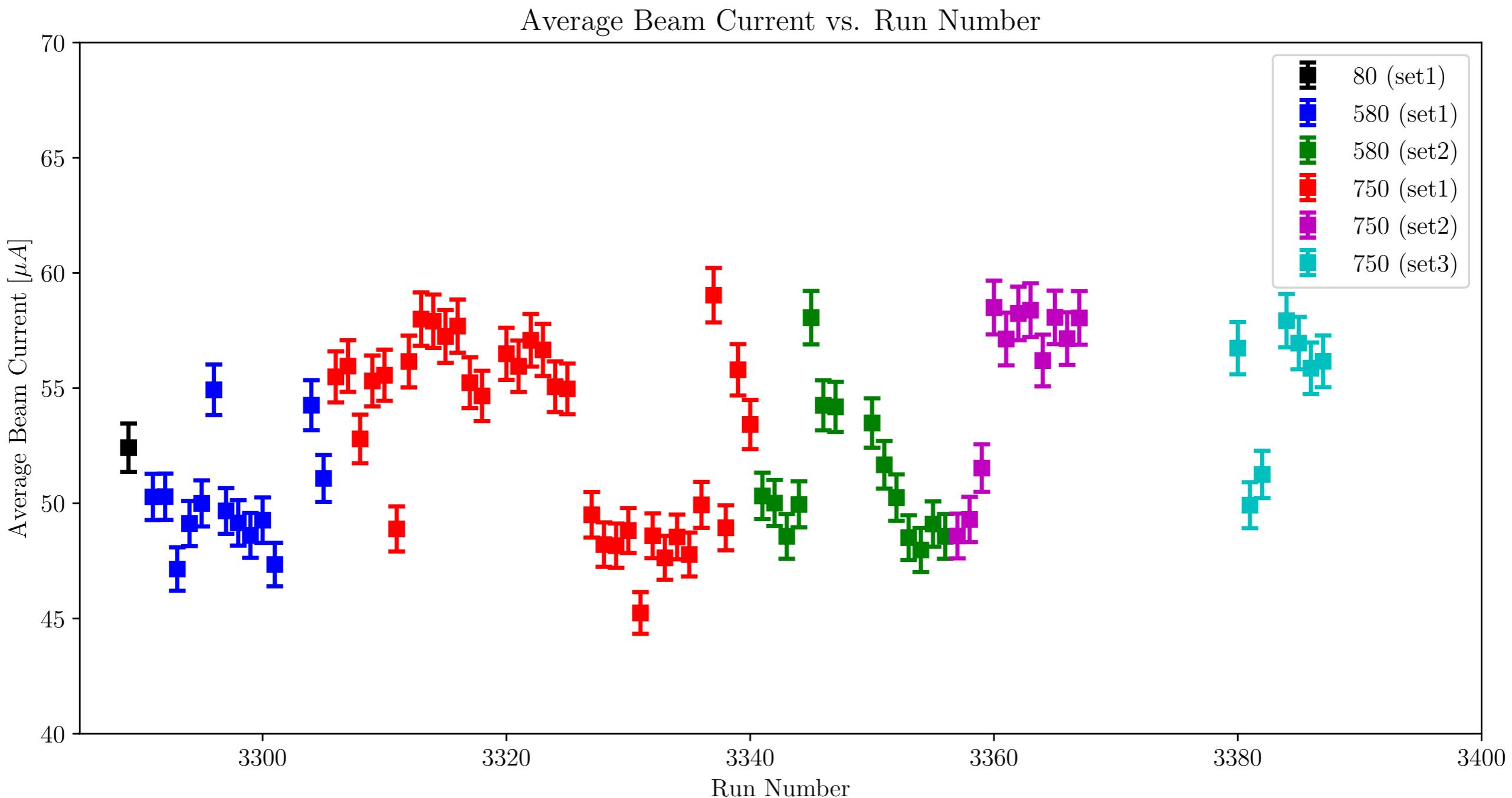


BEAM POSITION MONITORING (BPMs)

Beam Position Monitor vs. Run Number

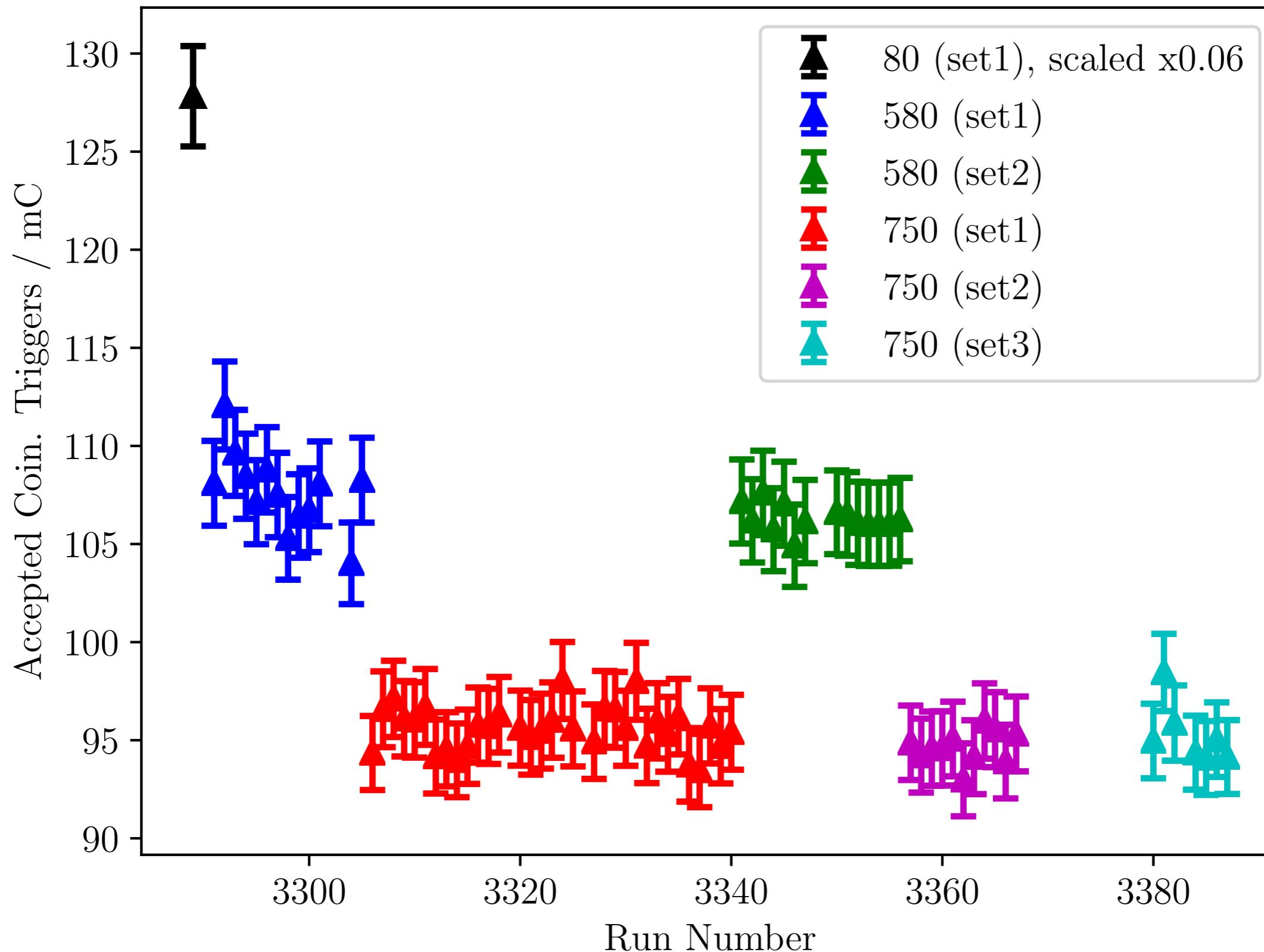


AVERAGE BEAM CURRENT



ACCEPTED COUNTS / CHARGE

Accepted Coincidence Triggers / Charge vs. Run Number



EXTRACTION OF CROSS SECTIONS: BASIC CONCEPT

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

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

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



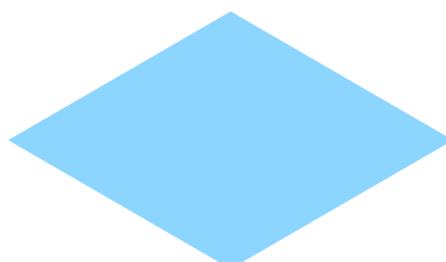
Jacobian Correction
to solid angles



Luminosity



Spectrometer
"Solid Angles"



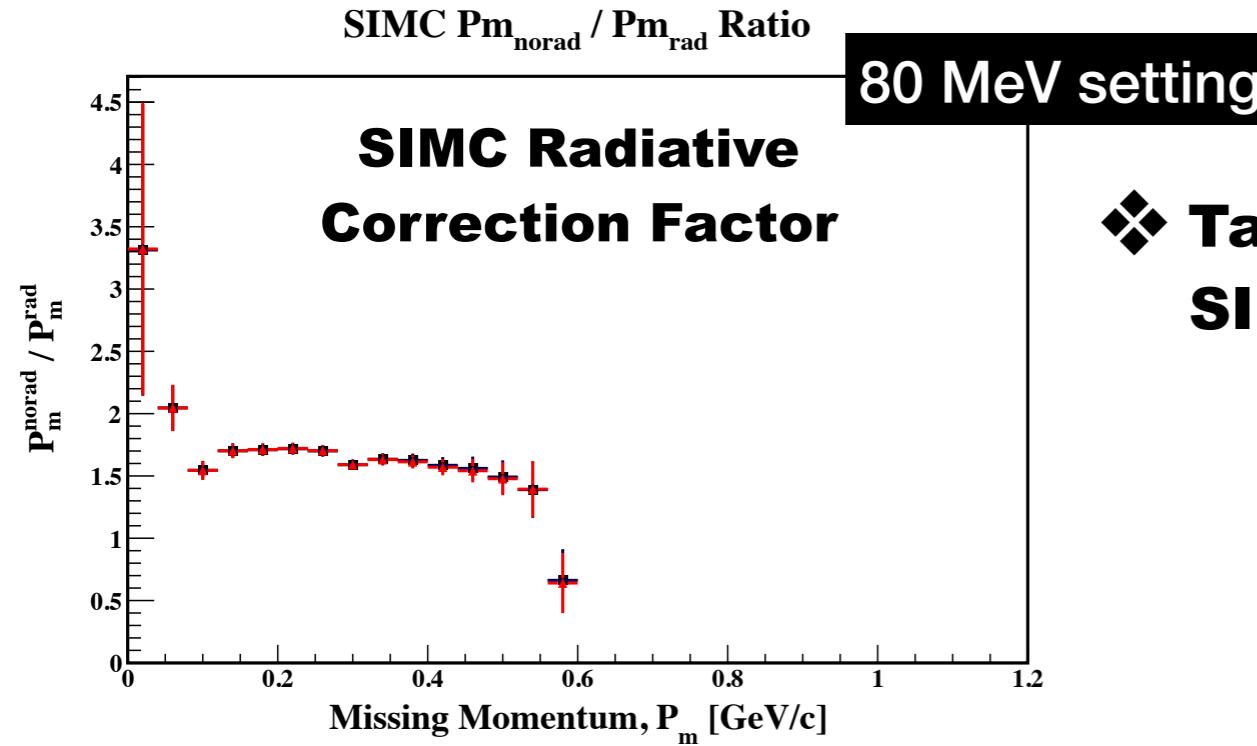
Generated Events

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

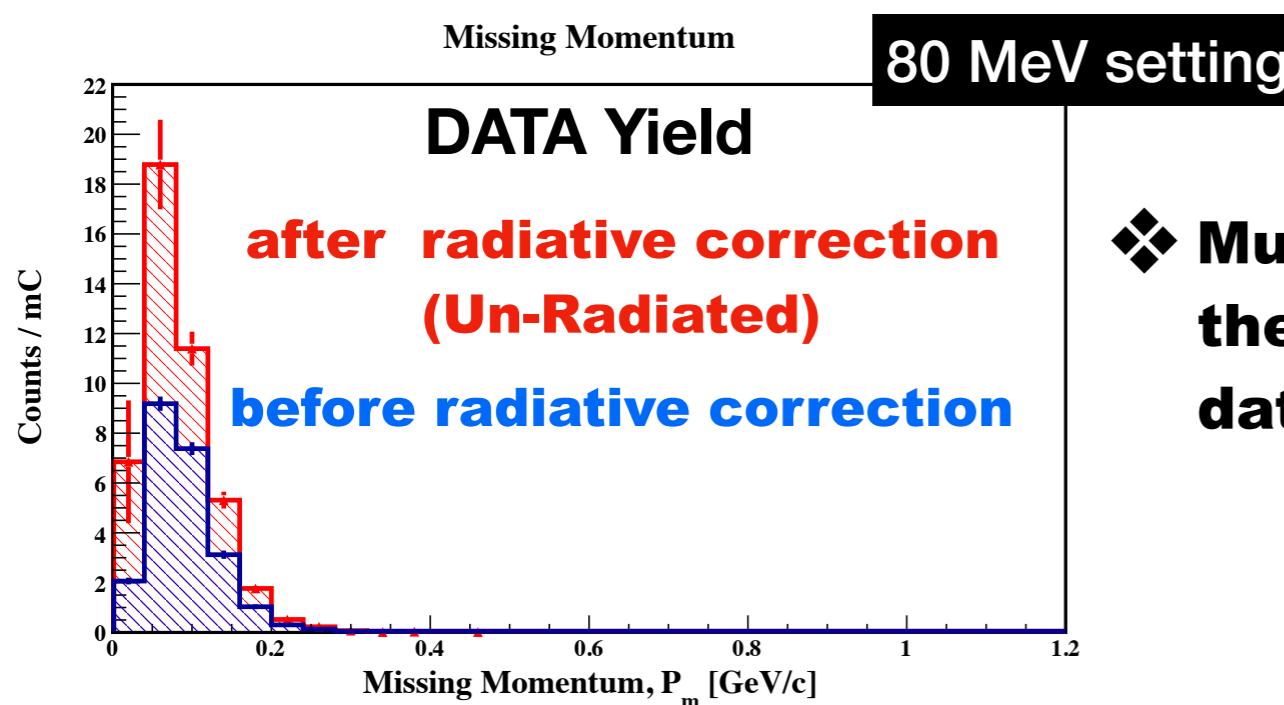
RADIATIVE CORRECTIONS

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)

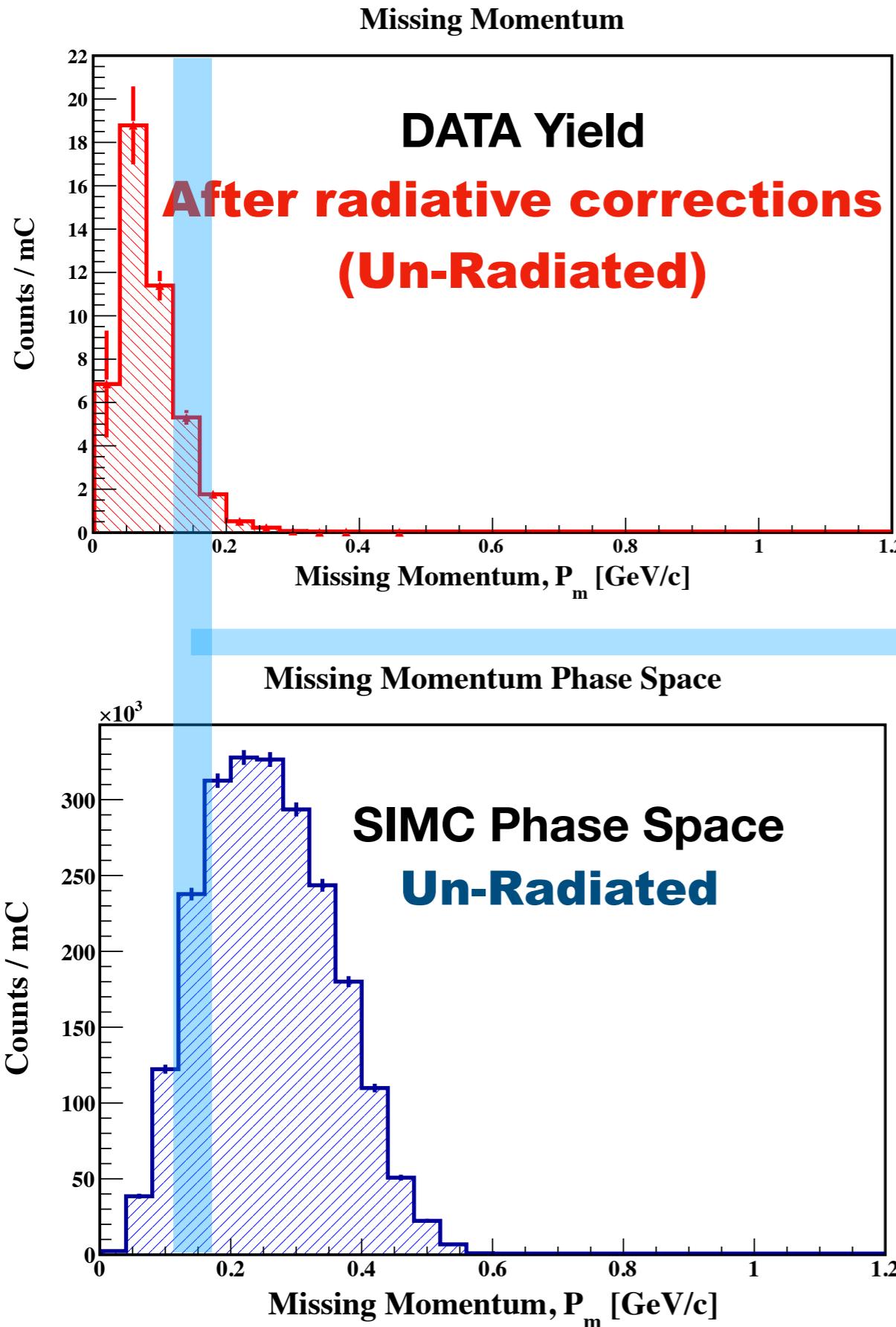


- ❖ Take ratio between non-radiative to radiative SIMC Yield to get correction factor bin by bin.

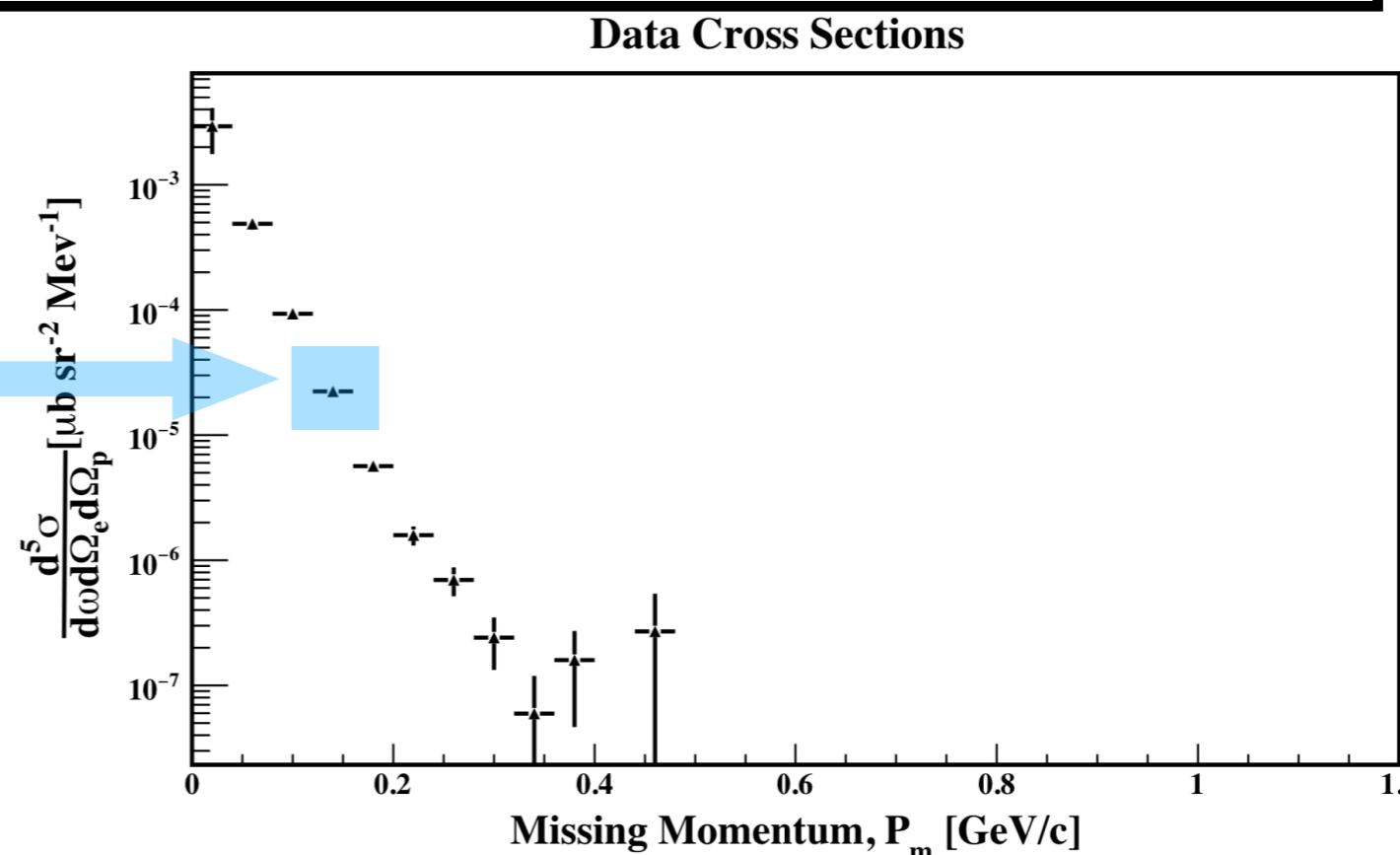


- ❖ Multiply the radiative correction factor by the un-radiative data yield to get the corrected data yield bin-by-bin.

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

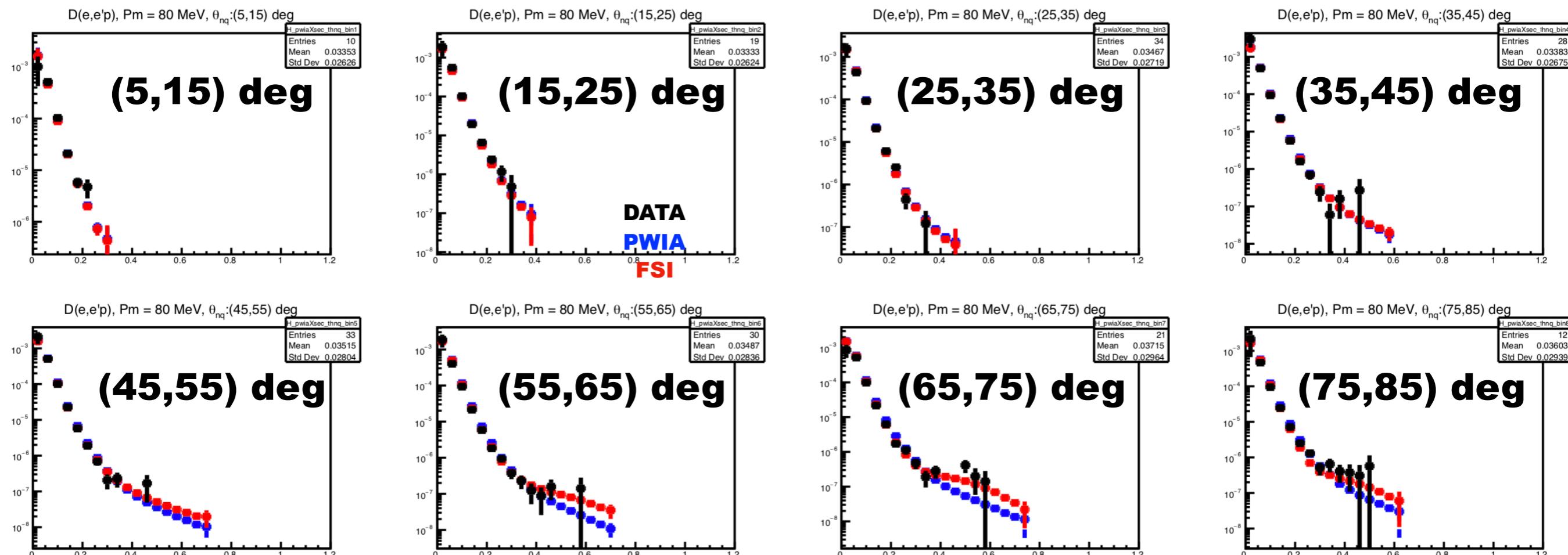


The ratio of the fully corrected data yield to the SIMC phase space will give the data cross section, bin-by-bin



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.

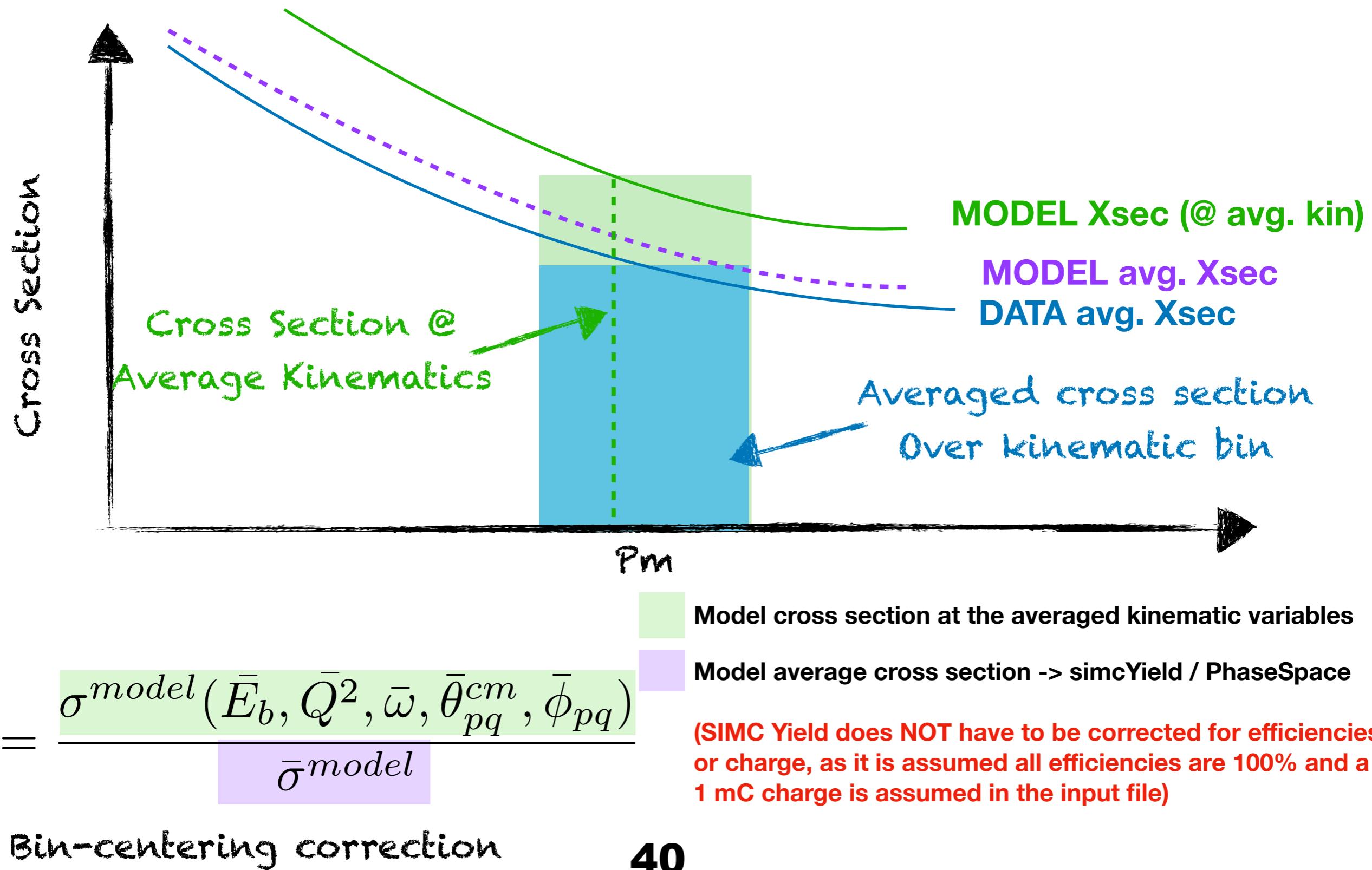


BIN-CENTERING

CORRECTIONS

Bin Centering Corrections

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

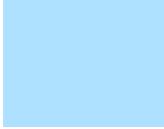


Bin Centering Corrections

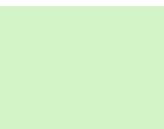
- ❖ Currently, Hall C software does **NOT** do energy loss corrections, therefore, the average kinematics were calculated from vertex quantities in simulation.

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

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

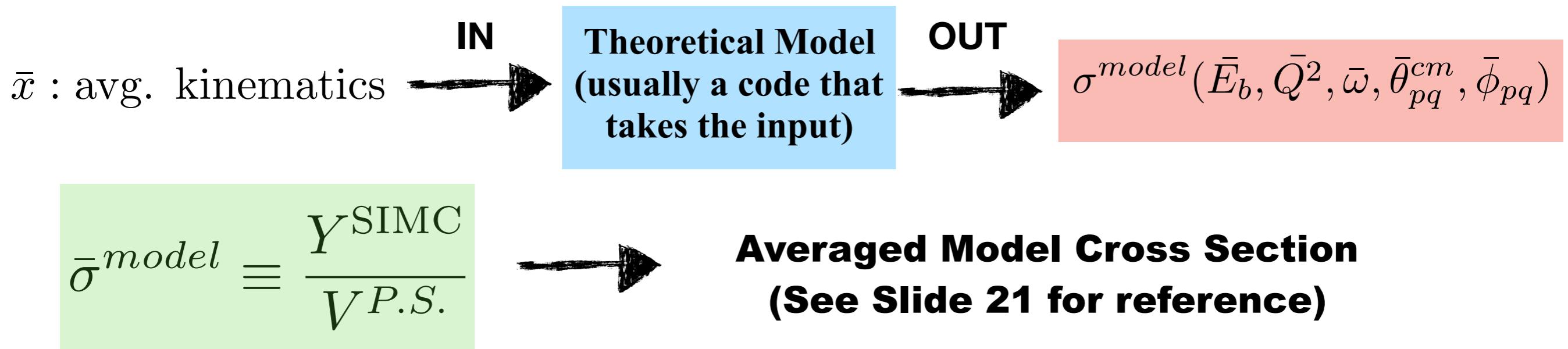
 **Averaged kinematic variable x over kinematic bin k**

 **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, . . .

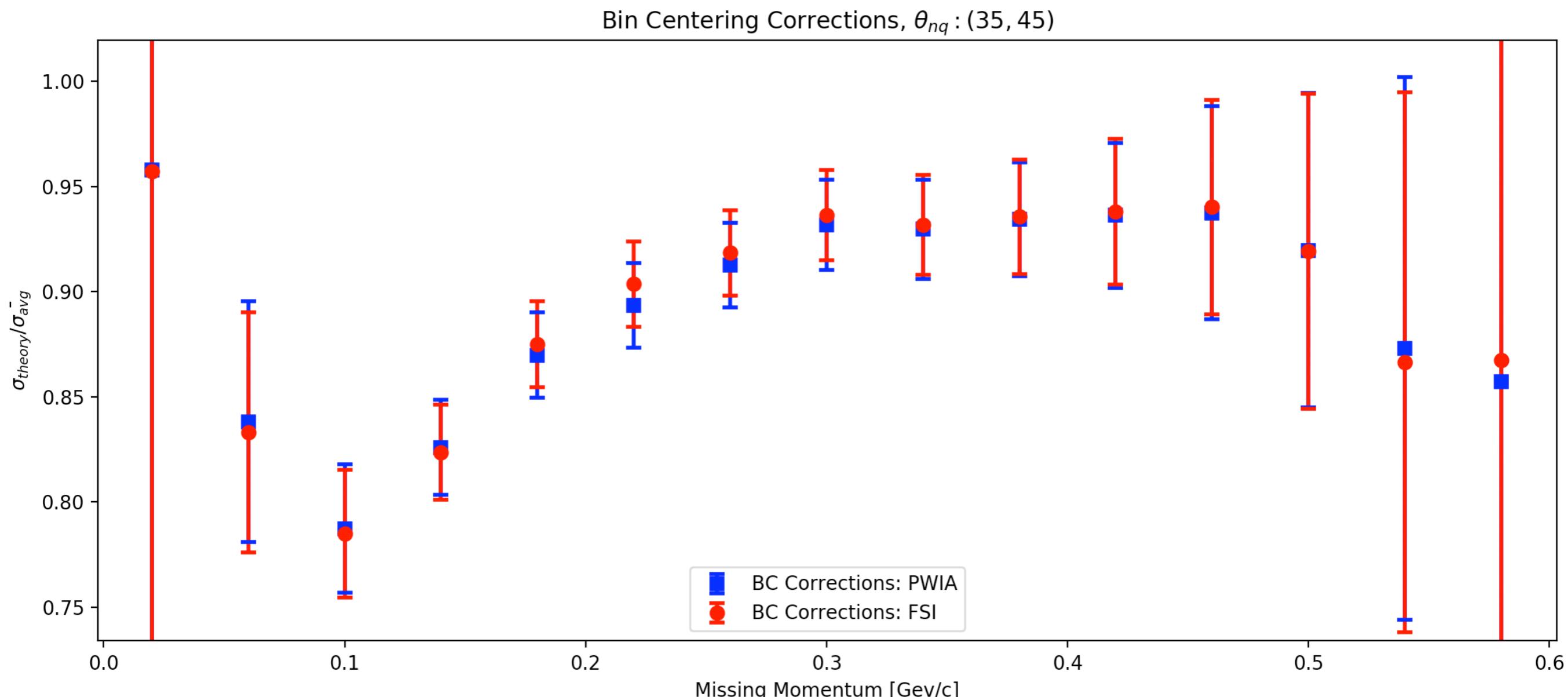


- ❖ Correct the data bin-by-bin using the model cross sections ratio . . .

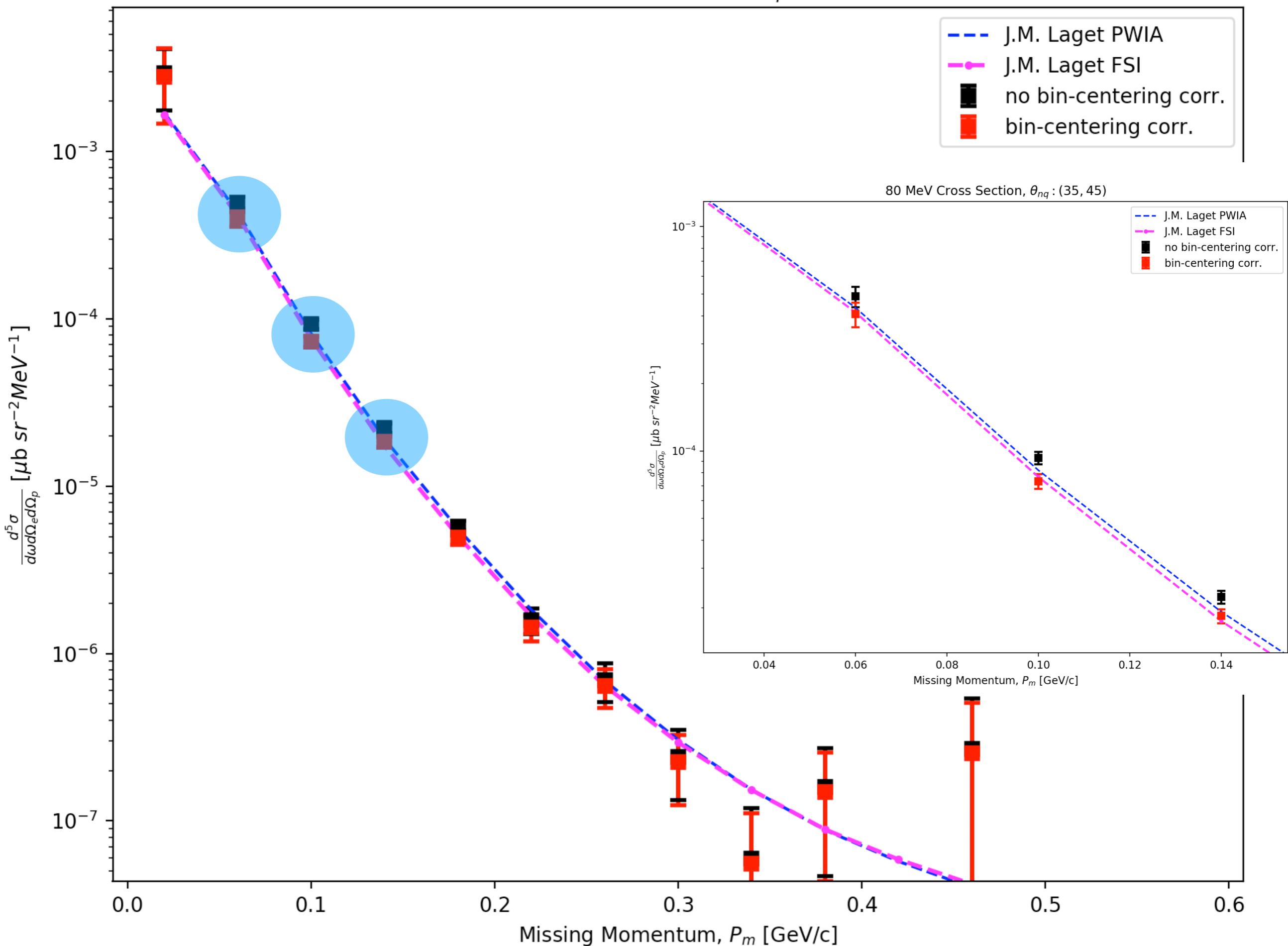
$$\sigma_{bc}^{exp} = \bar{\sigma}^{exp} \cdot \frac{\sigma^{model}(\bar{E}_b, \bar{Q}^2, \bar{\omega}, \bar{\theta}_{pq}^{cm}, \bar{\phi}_{pq})}{\bar{\sigma}^{model}}$$

Bin Centering Corrections

❖ Bin-centering correction factor for the 80 MeV setting



80 MeV Cross Section, $\theta_{nq} : (35, 45)$



D(e,e'p) Momentum Distributions

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

Reduced cross section
(momentum distributions in PWIA)

Fully Corrected Experimental cross sections

Kinematic Factor times deForest e-N cross section

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.