The CaFe Experiment

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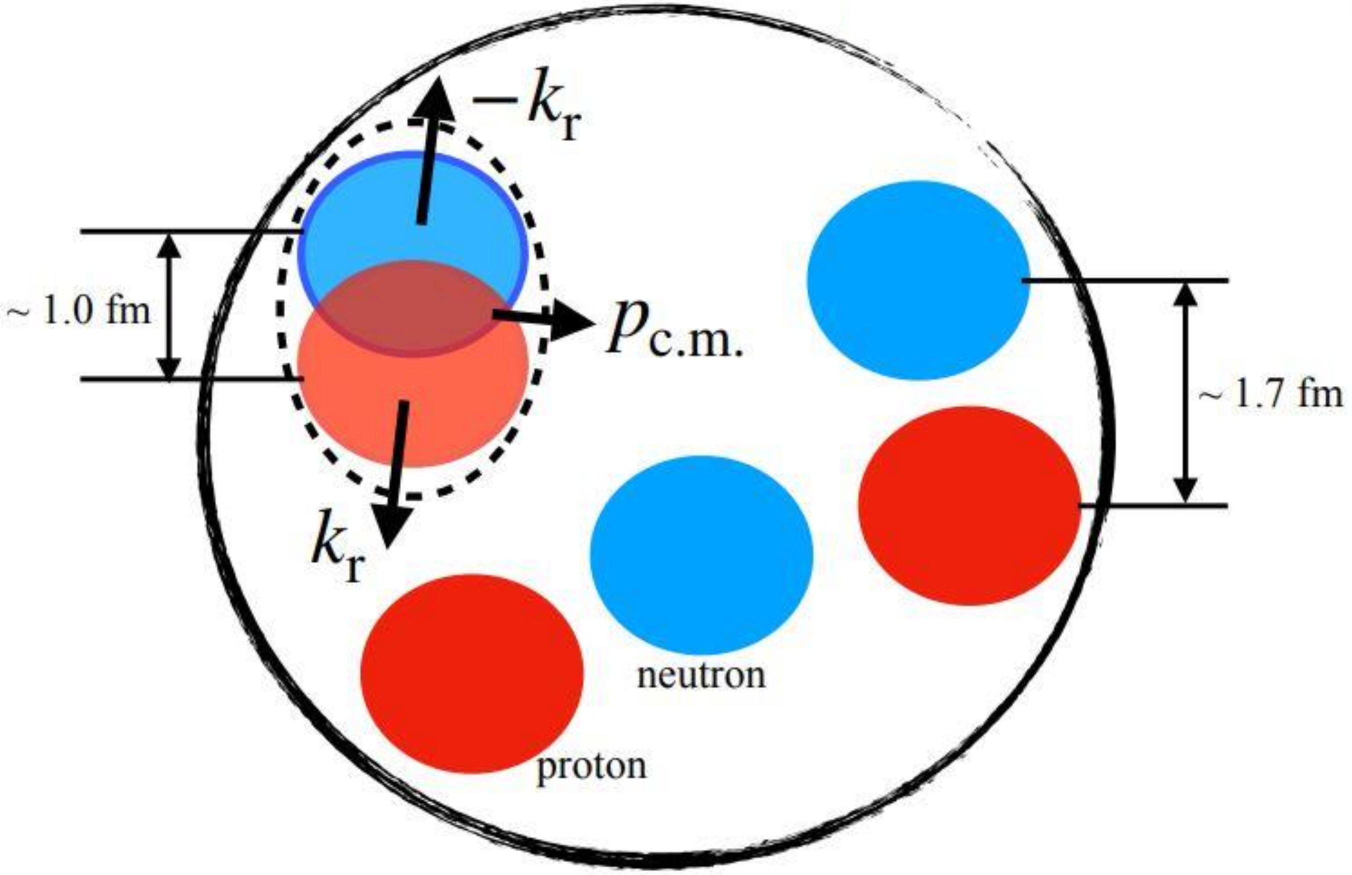
Outline

- Motivation
- Spectrometer Normalization H(e,e')
- HMS Proton Efficiency (Absorption)
- Radiative Corrections
- Nuclear Transparency
- Systematic Uncertainties
  - Cut Variations
- Results

Short Range Correlations

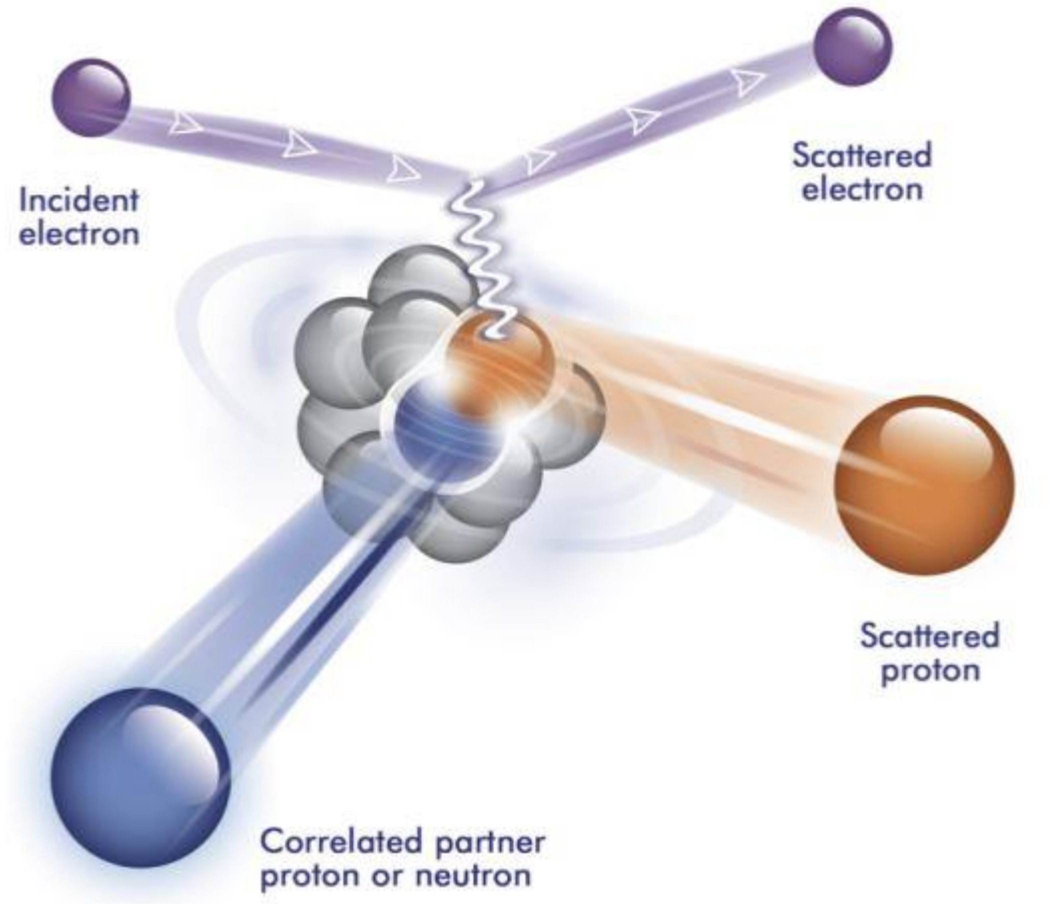
- SRCs are temporary short distance high momentum fluctuations
- High relative momentum (k_r>k_F~250 MeV/c)
  - Depends on the short-range part of the N-N interaction
- Unchanged center-of-mass momentum
- Open questions
  - Momentum structure
  - 3 nucleon correlations
  - Which nucleons pair



CaFe Motivation

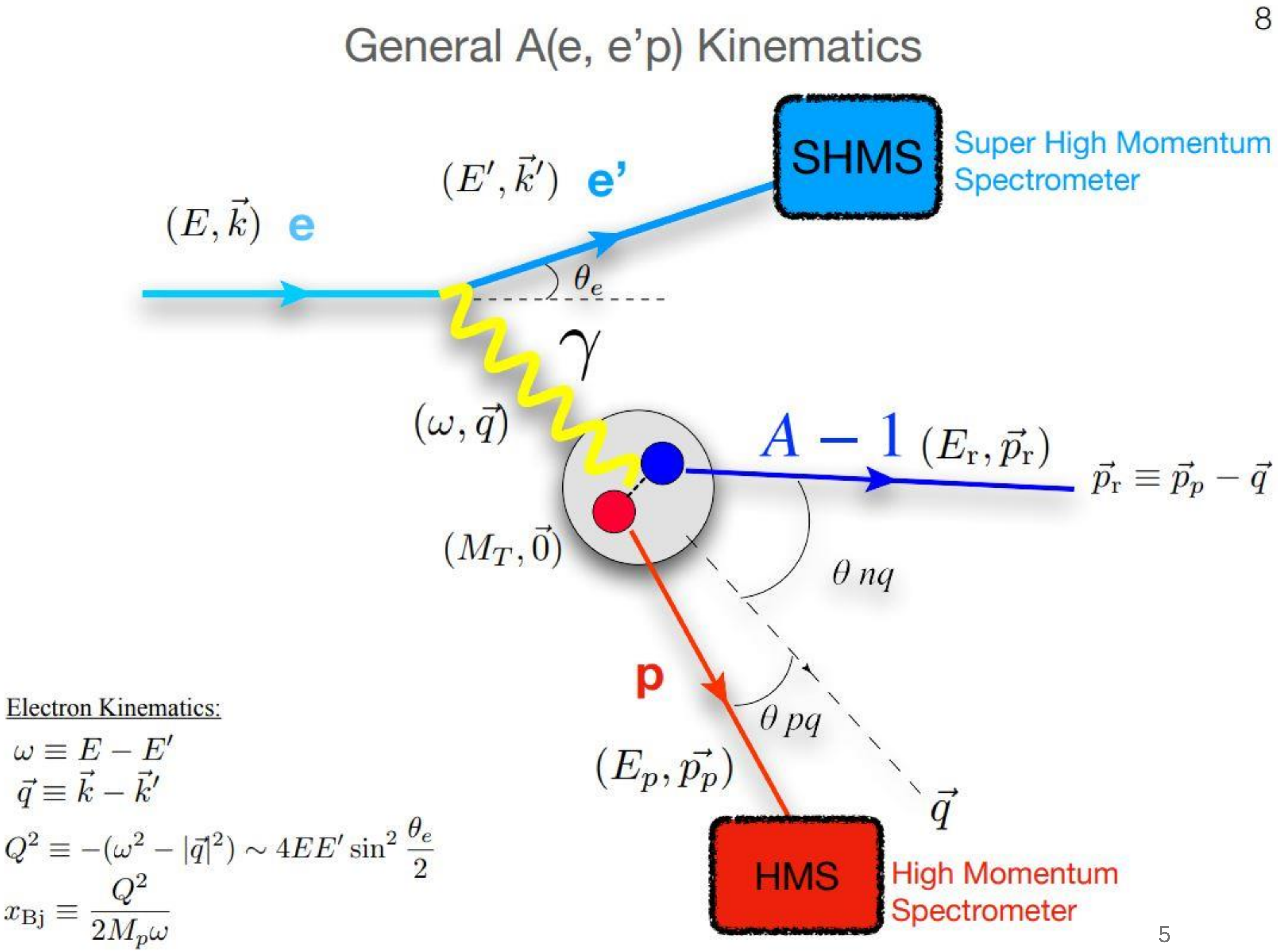
Which nucleons form SRC pairs?

- Compare number of high-momentum (paired) protons in ^{40}Ca, ^{48}Ca, and ^{54}Fe
  - ^{40}Ca: filled 1s, 1p, and 2s/1d p and n shells
  - ^{48}Ca: add 8 $f_{7/2}$ neutrons
  - ^{54}Fe: add 6 $f_{7/2}$ protons
  - First Paper
- Measure A(e,e'p) on d, ^{9}Be, $^{10,11}B$, ^{12}C, $^{40,48}Ca$, ^{54}Fe, and ^{197}Au at high and low missing momentum
  - ^{9}Be-^{10}B-^{11}B-^{12}C quartet and ^{40}Ca-^{48}Ca-^{54}Fe triplet
  - Separate A and N/Z dependence on pairing



Hall C A(e,e'p): Experimental Setup

- E_o = 10.6 GeV
- E'=8.55 GeV
- Θ_e =8.3 Deg
- Q^2 =2.1 $(GeV/c)^2$
- High P_{miss} (SRC)
  - $P_{miss} \approx$ 400 MeV/c
  - $|P_p|$ = 1.325 GeV/c
  - Θ_p = 66.4°
- Low P_{miss} (Mean Field)
  - $P_{miss} \approx$ 150 MeV/c
  - $|P_p|$ = 1.820 GeV
  - Θ_p = 48.3 Deg

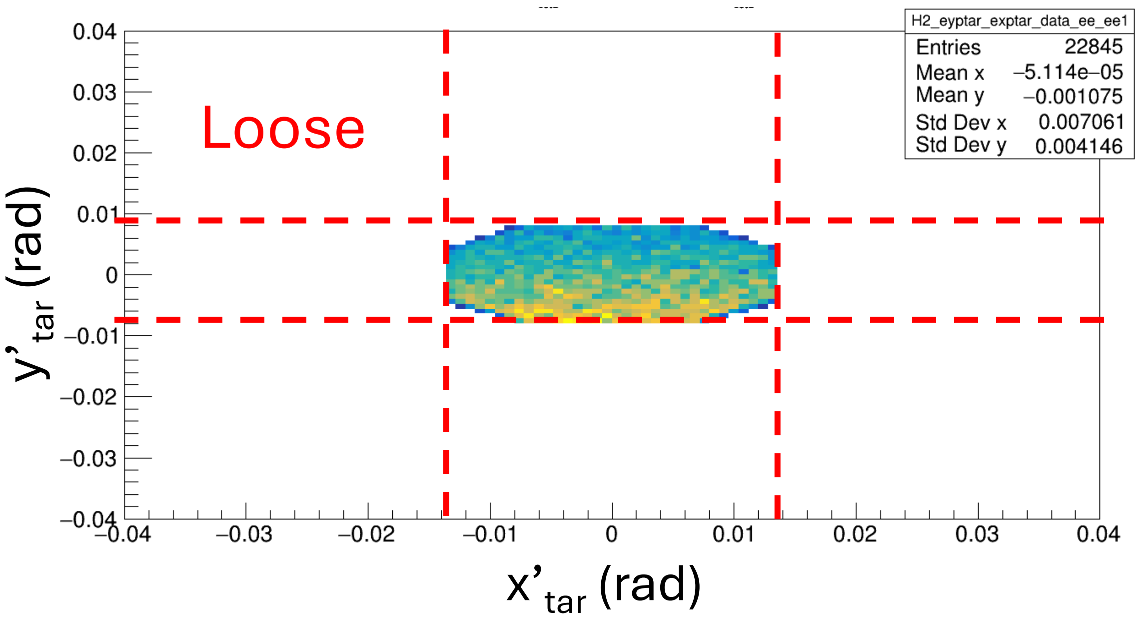


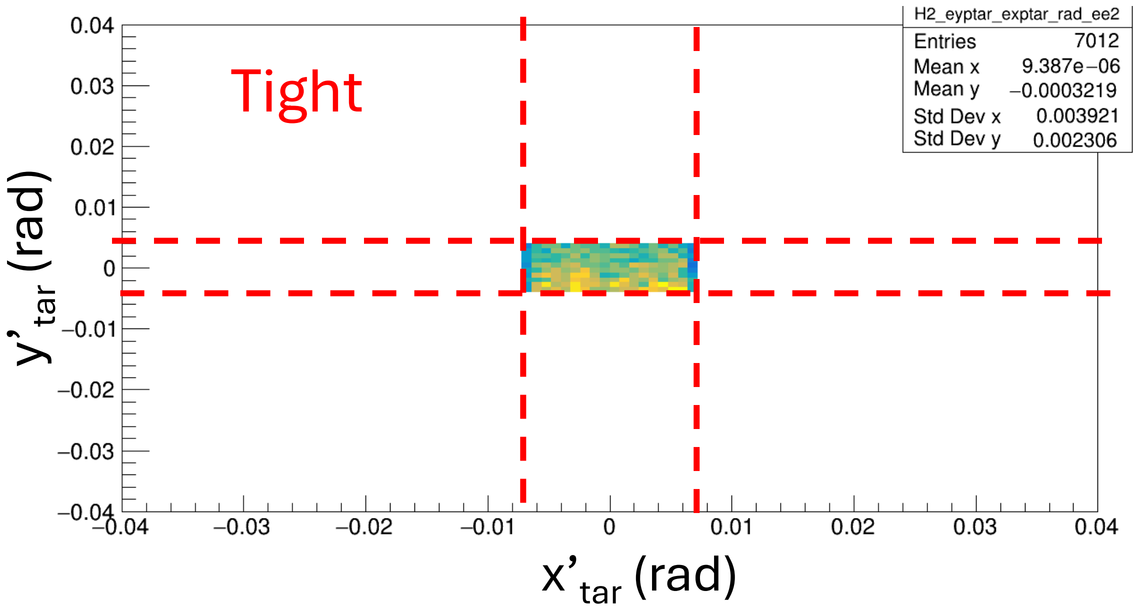
Spectrometer Normalization H(e,e’)

- H(e,e’) is the simplest system
- If the H(e,e’) cross section is correct then we have verified
  - Detector Calibrations
  - Optics Calibrations
  - Efficiencies
  - Cuts

Spectrometer Normalization H(e,e') Cuts

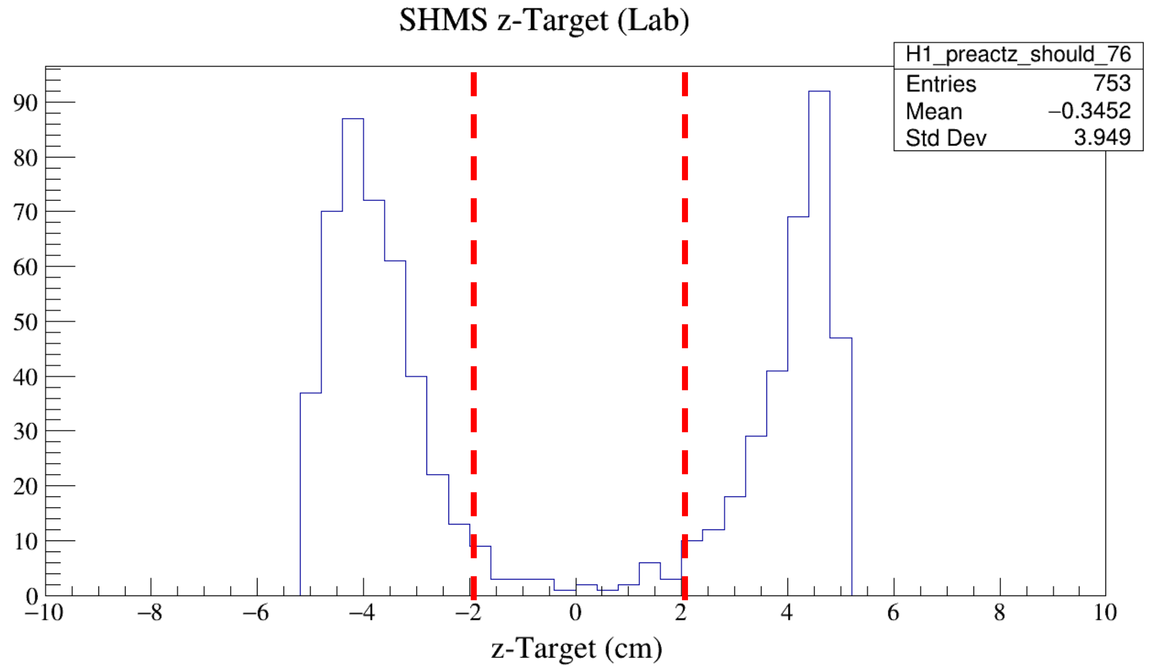
- $0.8 < \frac{E_{tot}}{P_{cent}} < 1.3$
- $0.92 < W < 0.97$ GeV
- Loose
  - $-5 < z - \text{Target} < 5$ cm
  - $-0.0135 < \text{SHMS } x'_{tar} < 0.0135$ rad
  - $-0.008 < \text{SHMS } y'_{tar} < 0.008$ rad
- Tight
  - $-2 < z - \text{Target} < 2$ cm
  - $-0.0068 < \text{SHMS } x'_{tar} < 0.0068$ rad
  - $-0.004 < \text{SHMS } y'_{tar} < 0.004$ rad

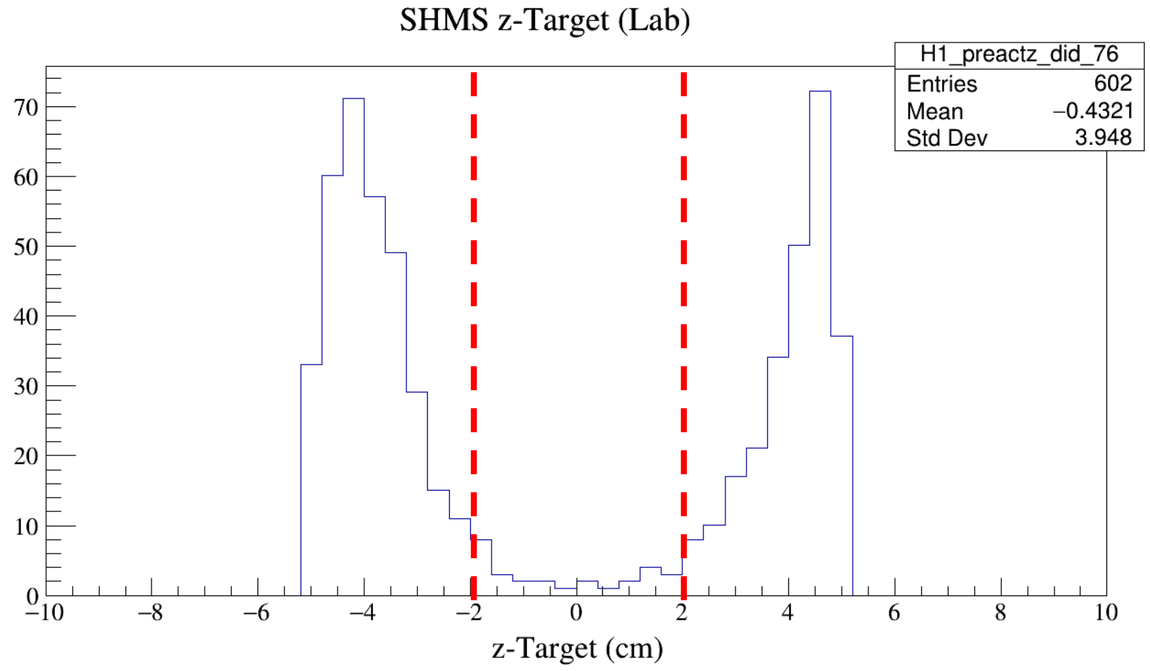




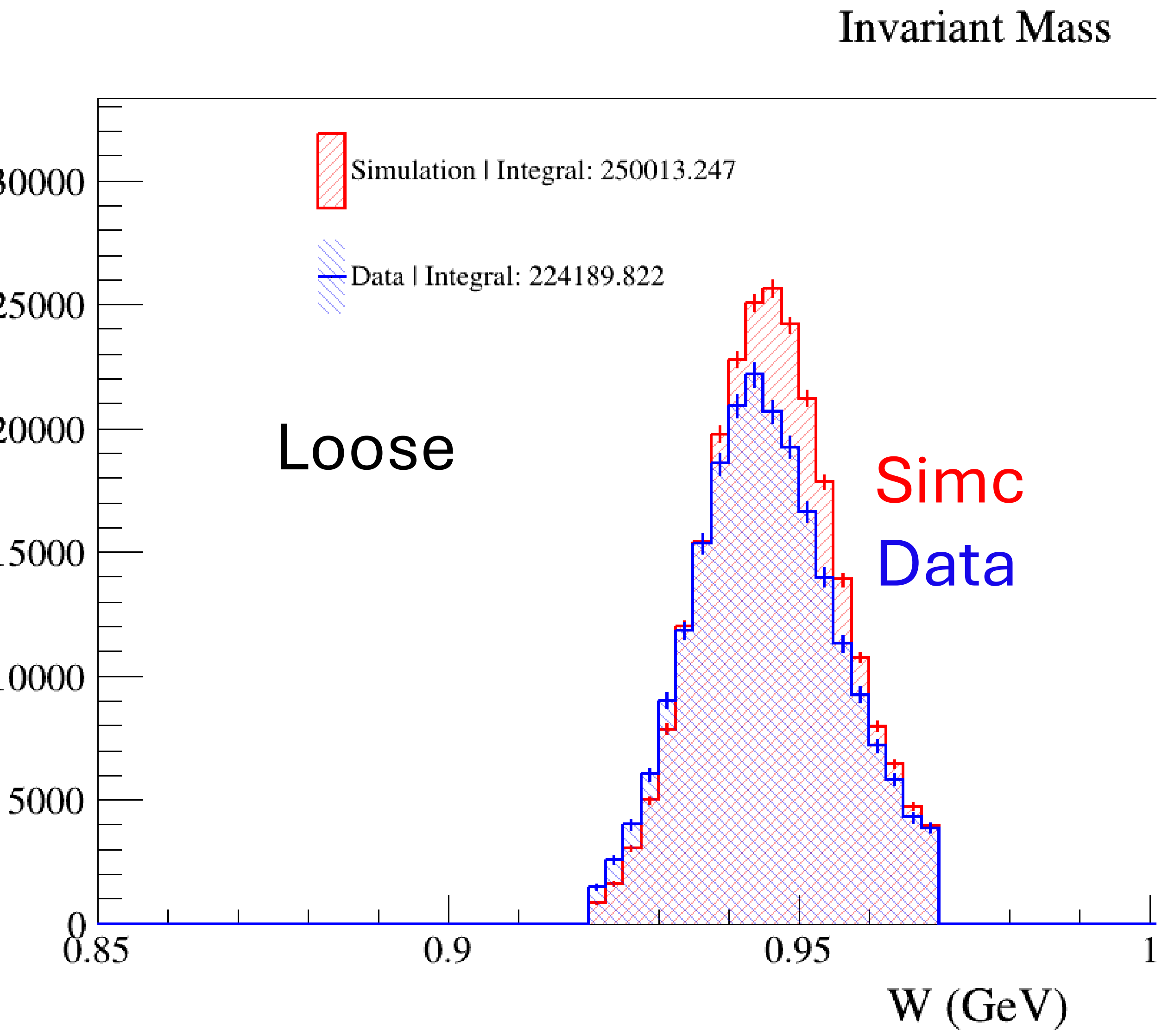
SHMS Dummy z-Target

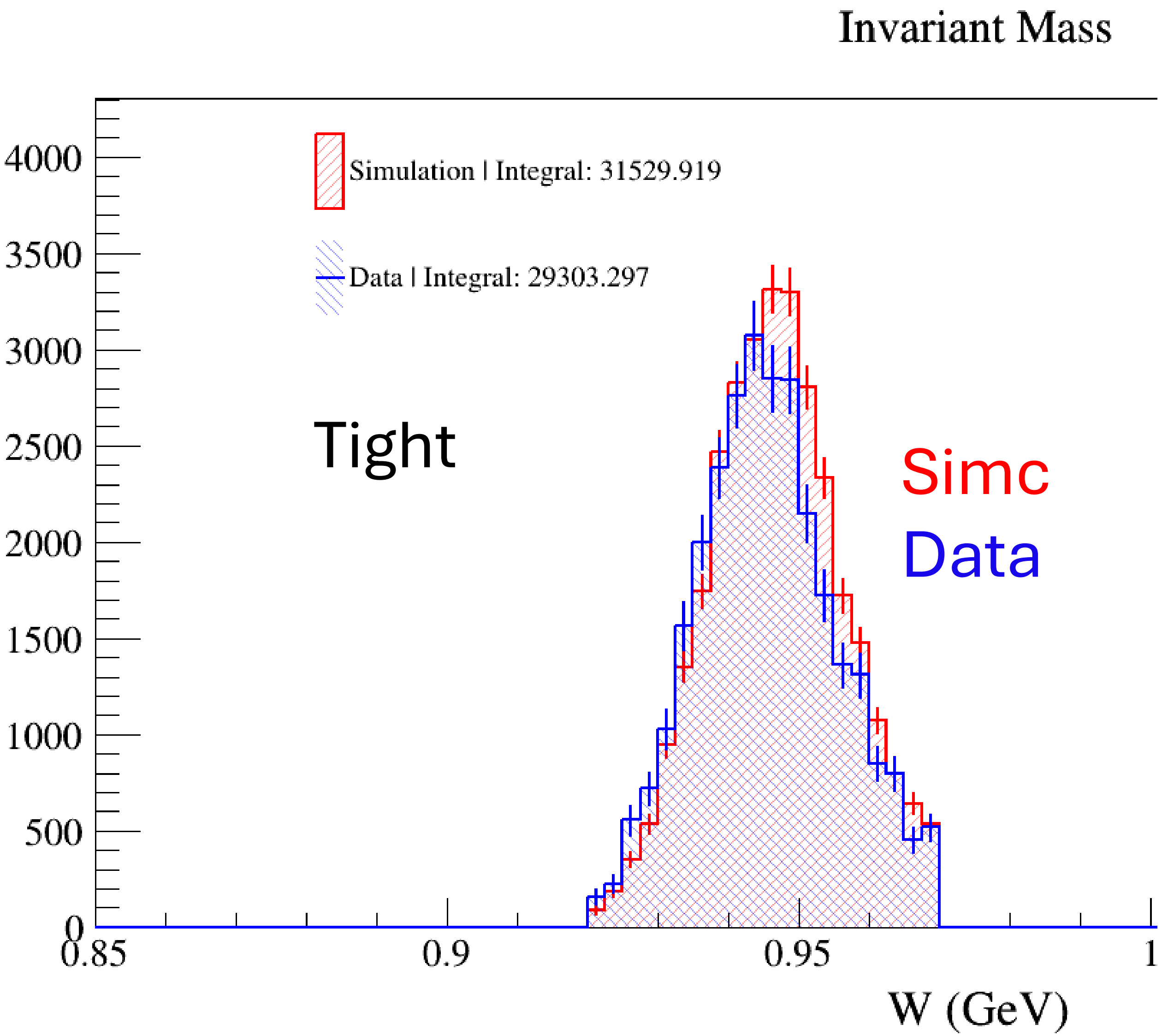
-2 < z-Target (lab) < 2 (cm) to eliminate target walls





H(e,e’) Simulation vs Data





H(e,e') Cross Sections

- Units: $10^{-2}\ \frac{\mu\text{b}}{\text{sr}}$
- World Data (J. Arrington)
  - 2.41
- Loose
  - Data: 2.07
  - Simulation: 2.17
- Tight
  - Data: 2.37
  - Simulation: 2.38

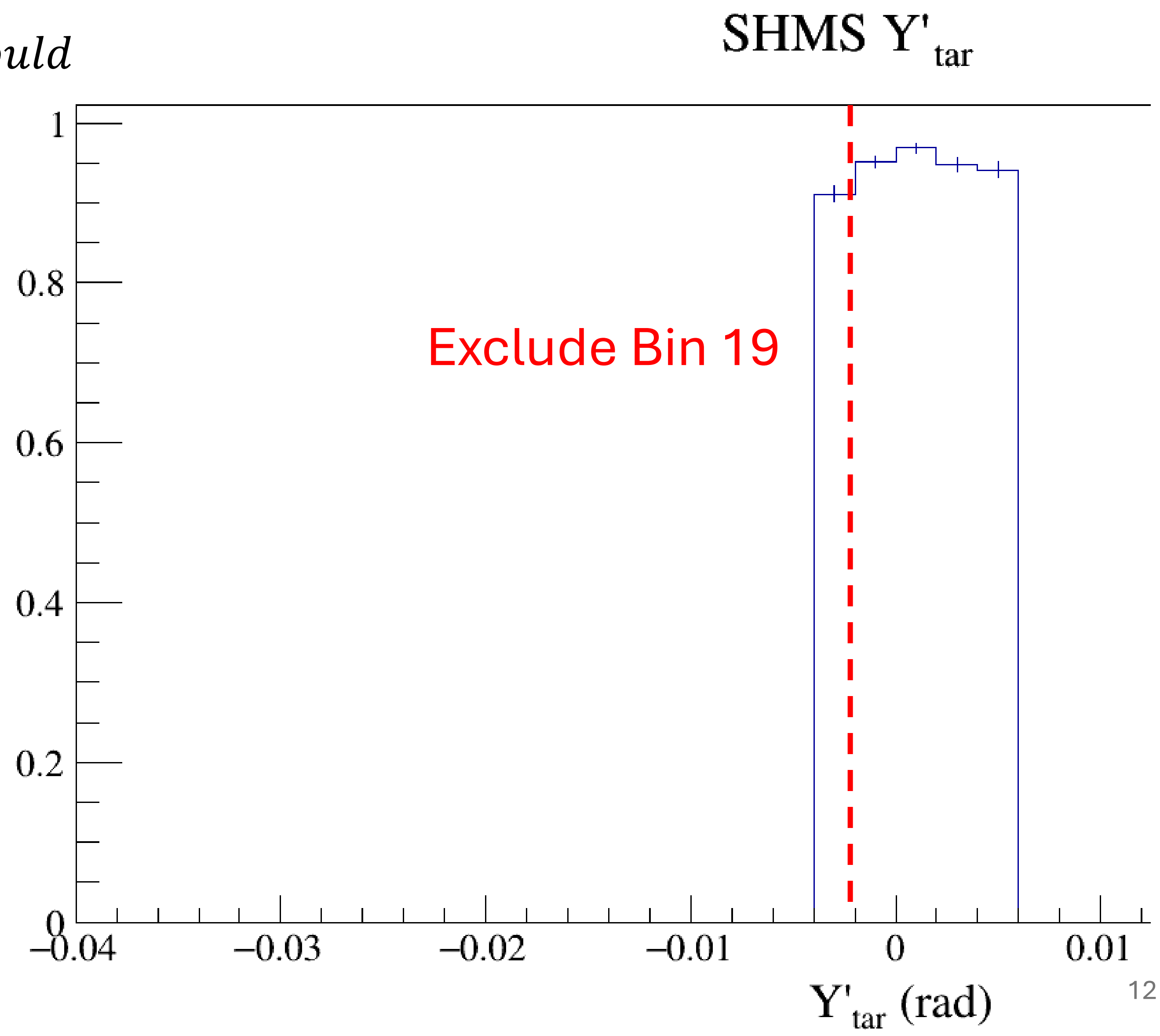
HMS Proton Efficiency

- Measure H(e,e’p)/H(e,e’)p
- Select H(e,e’) events that should have a proton in the HMS
  - $0.92 < W < 0.97$ GeV
  - $-2 < z - \text{Target} < 2$ cm
  - $-0.01 < \text{SHMS } x'_{tar} < 0.01$ rad
  - $-0.002 < \text{SHMS } y'_{tar} < 0.006$ rad
  - $0.8 < \frac{E_{tot}}{P_{cent}} < 1.8$
- H(e,e’p) events
  - Should +
  - $-5 < \text{ep Coin Time} < 5$ ns
  - $-0.02 < E_m < 0.9$ GeV
- Iteratively tightened cuts until ratios became flat

HMS Proton Efficiency

$$\sigma_{ratio}^{exact} = \sqrt{should\frac{did}{should}(1-\frac{did}{should})}\Big/should$$

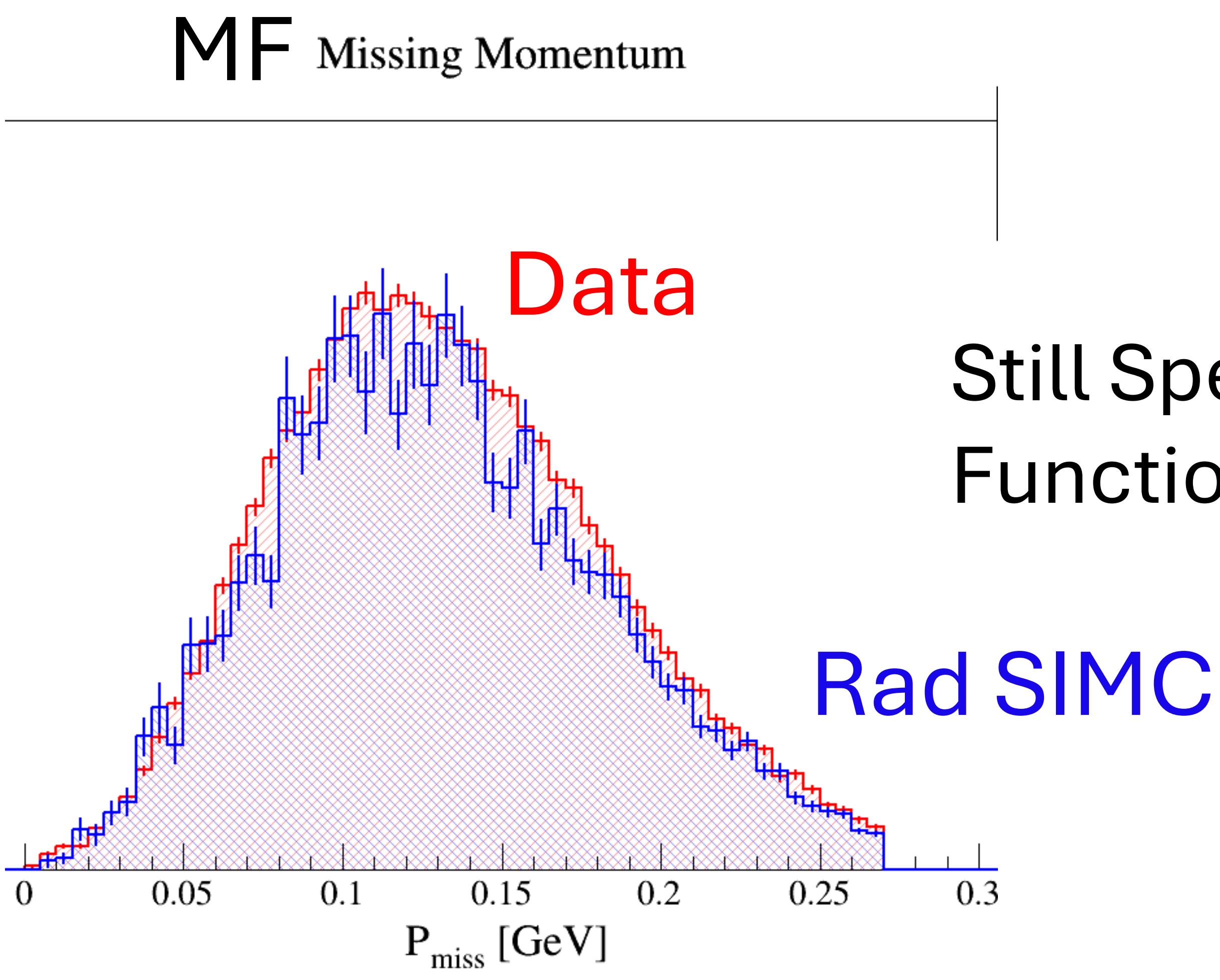
Proton Efficiency: 0.952 ± 0.004



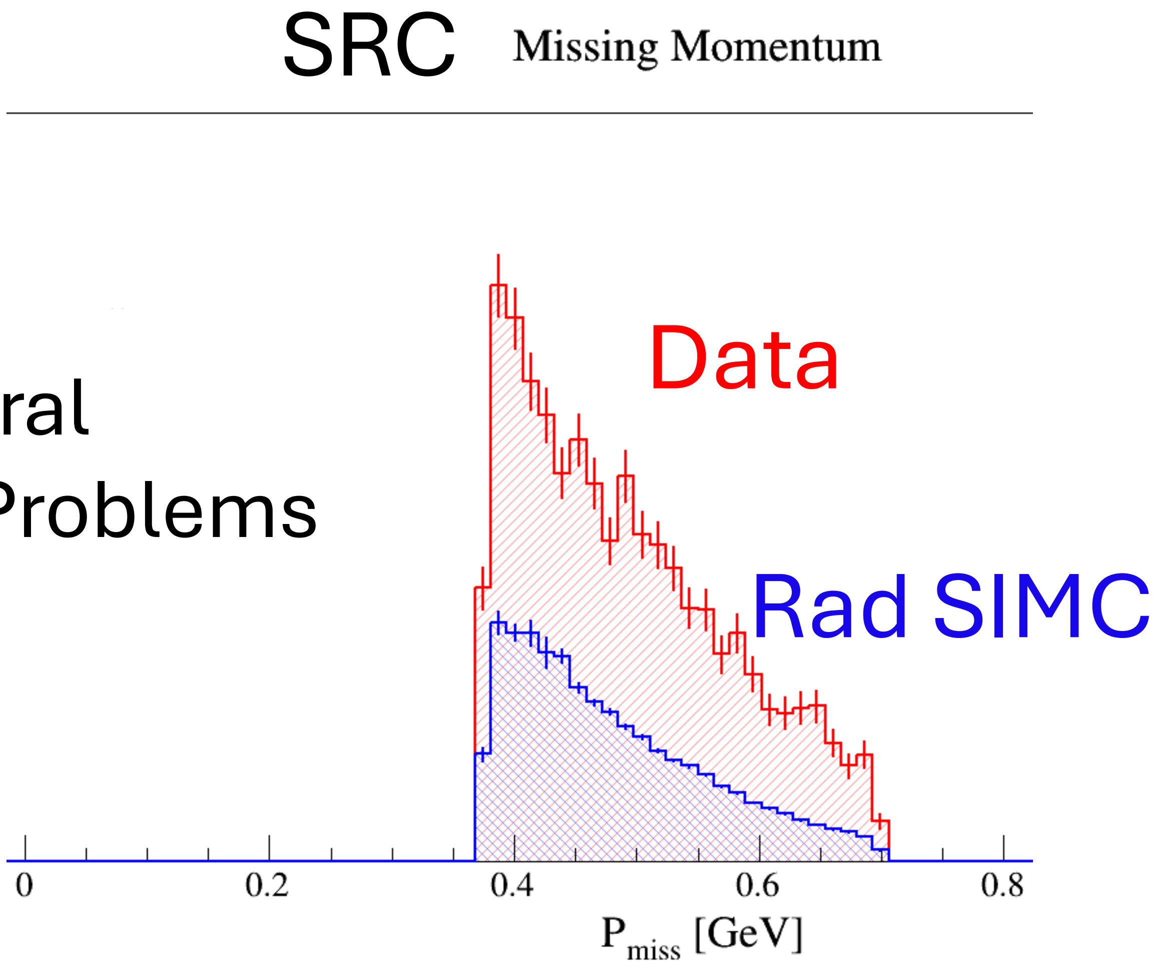
Radiative Corrections

- Take ratio of radiated / non-radiated SIMC cross sections
- Using Benhar Spectral Function because default SIMC does not account for SRCs

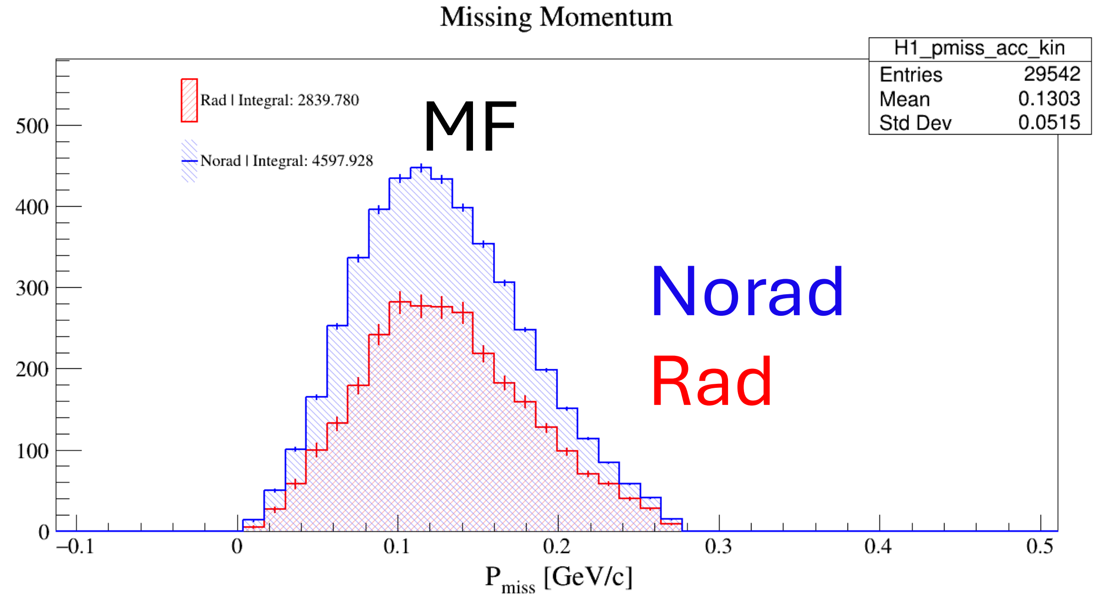
MF & SRC C12 pmiss: Benhar Simc vs Data

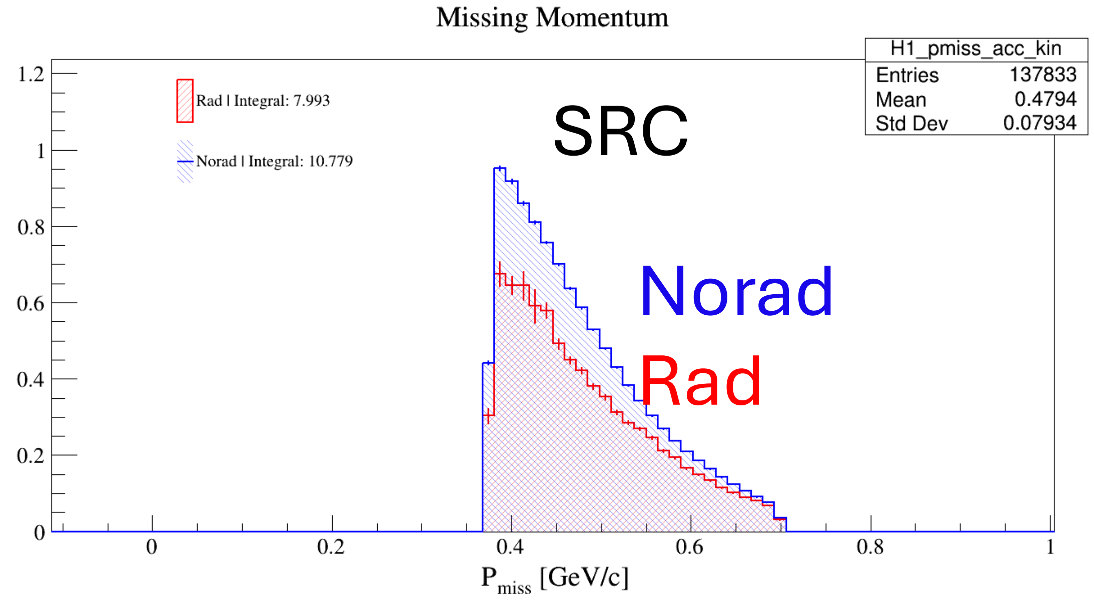


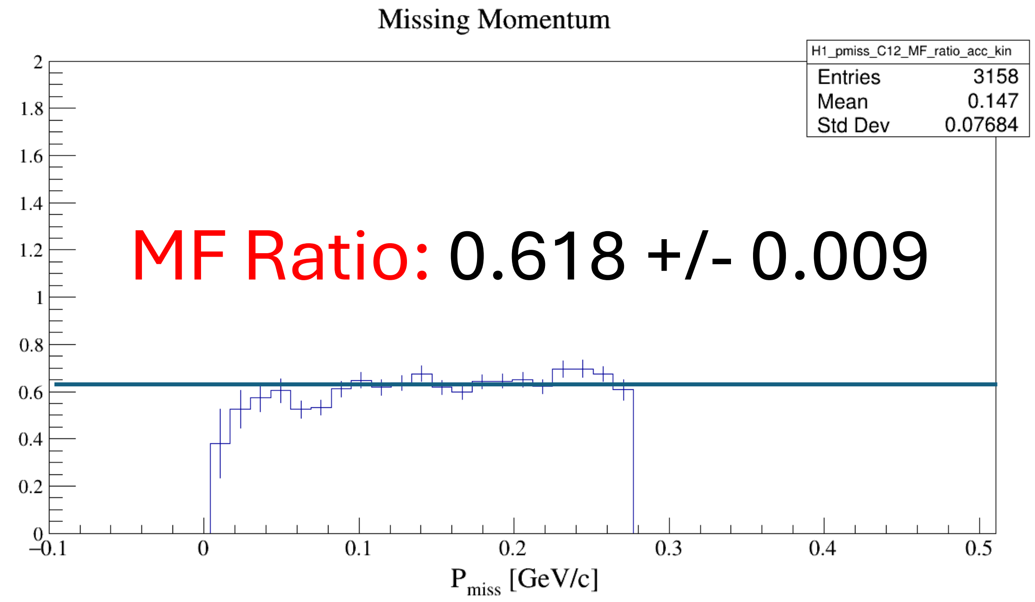
Still Spectral
Function Problems

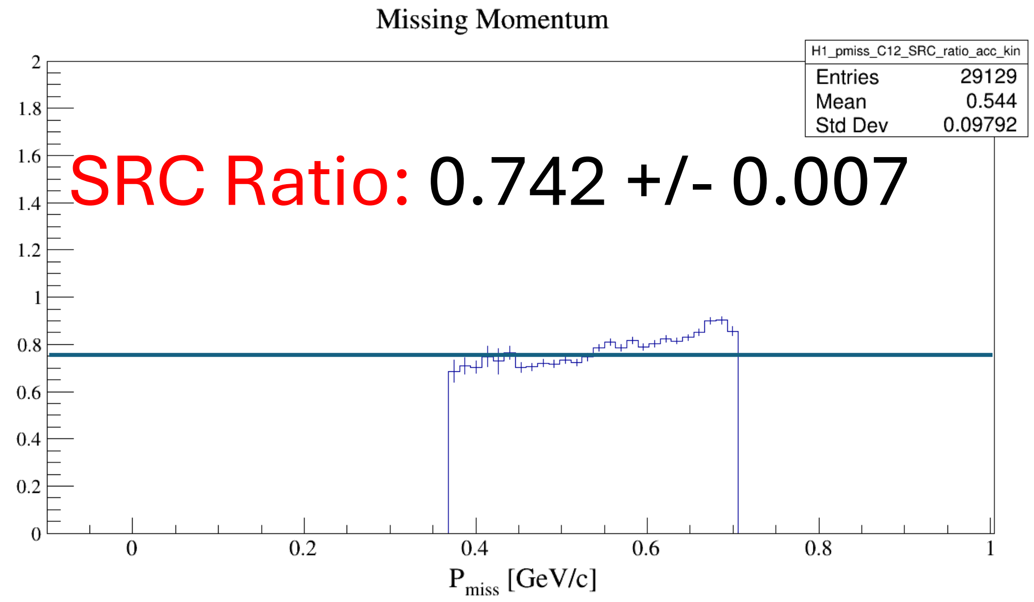


MF & SRC C12 p_{miss} Benhar Sim Radiative Correction









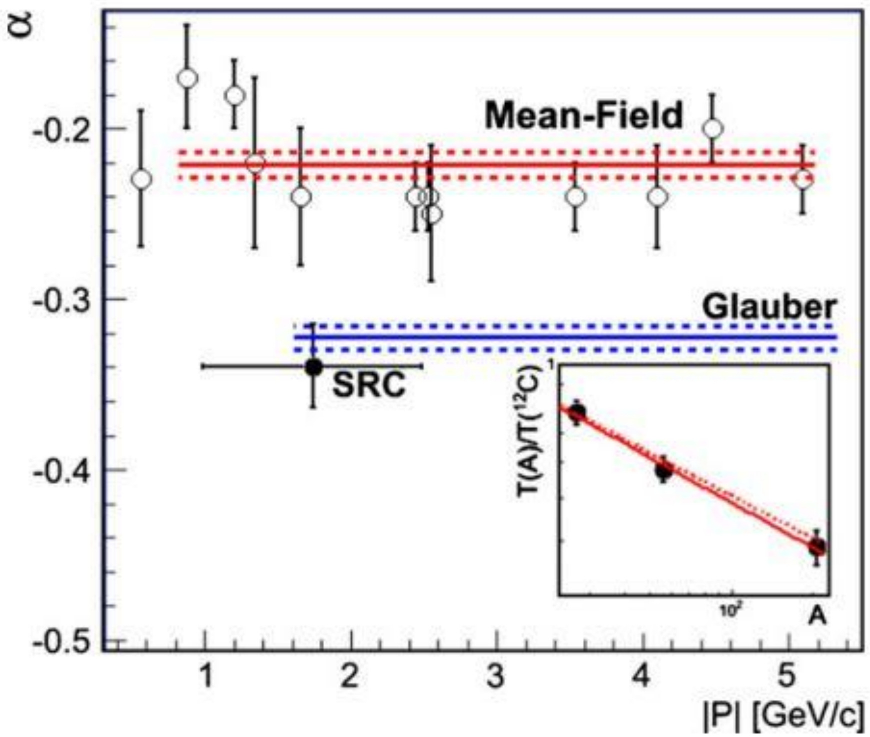
Radiative Correction Factors

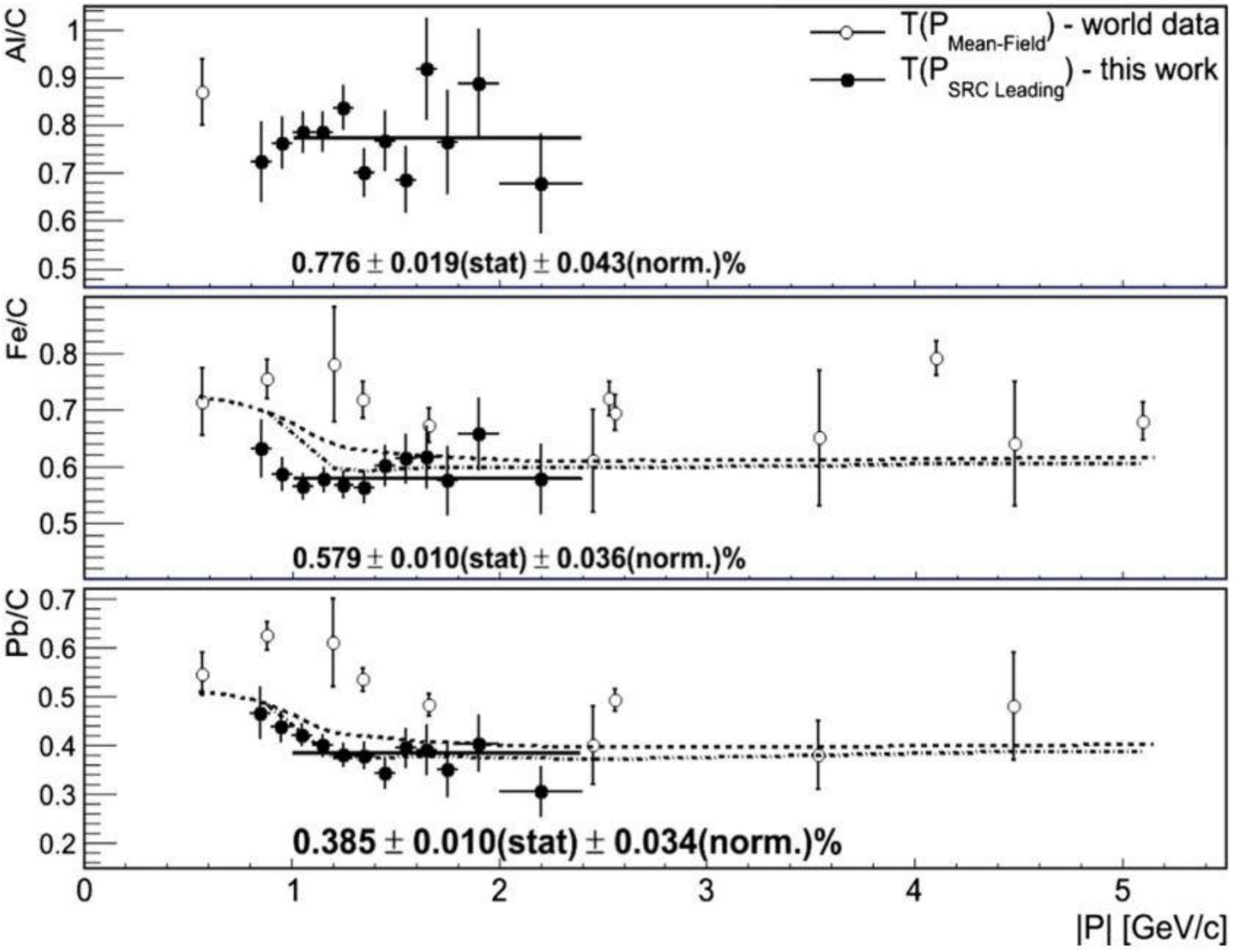
Kinematics	MF			SRC		
Target	C12	Fe56	Au197	C12	Fe56	Au197
Rad/Norad Ratio	0.618	0.577	0.451	0.742	0.734	0.604
Stat Uncertainty	0.009	0.006	0.005	0.007	0.012	0.014

- Ratios of corrections are important
  - MF to SRC
  - Different Nuclei
  - Small A dependence implies corrections mostly cancel

Proton Transparency

- Cancels in SRC to MF ratio
- Use measured ratios to C
- $T(A) \propto A^{-0.34\pm0.02}$



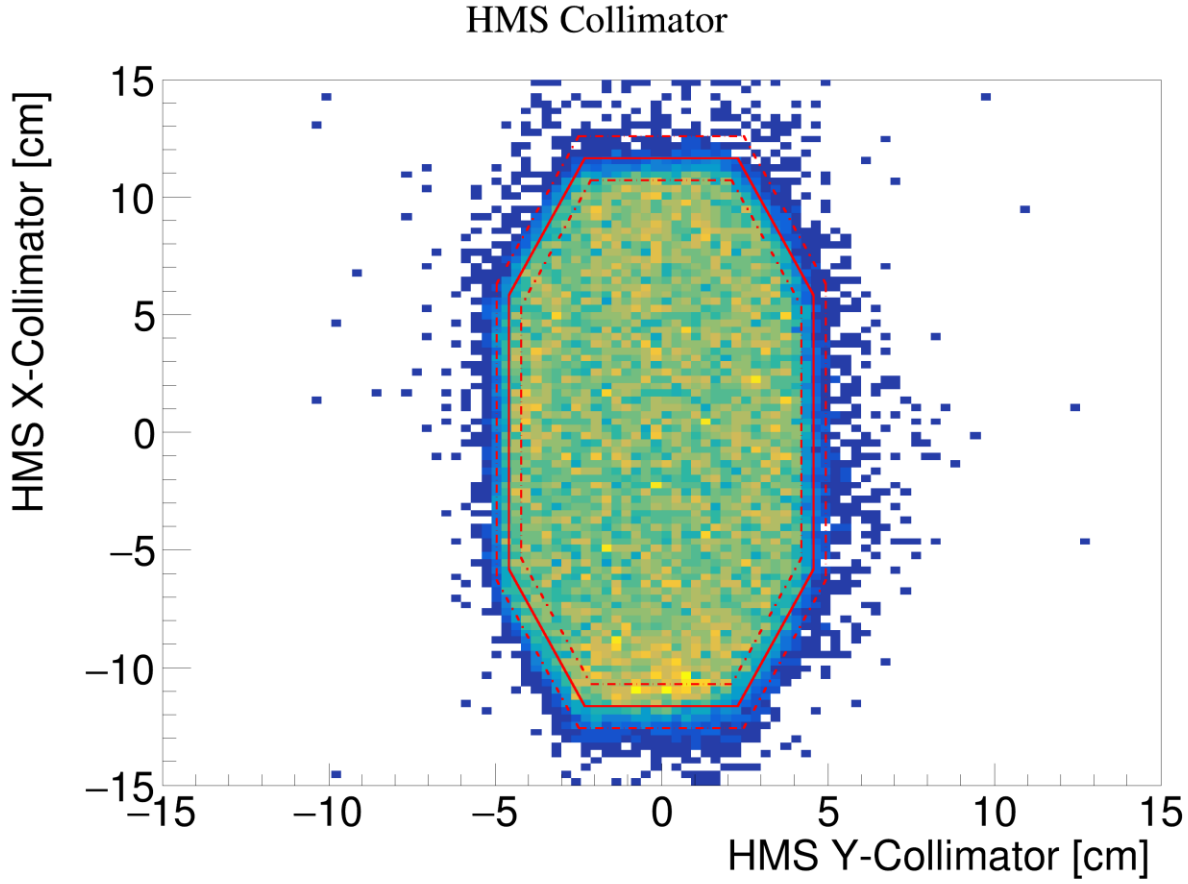


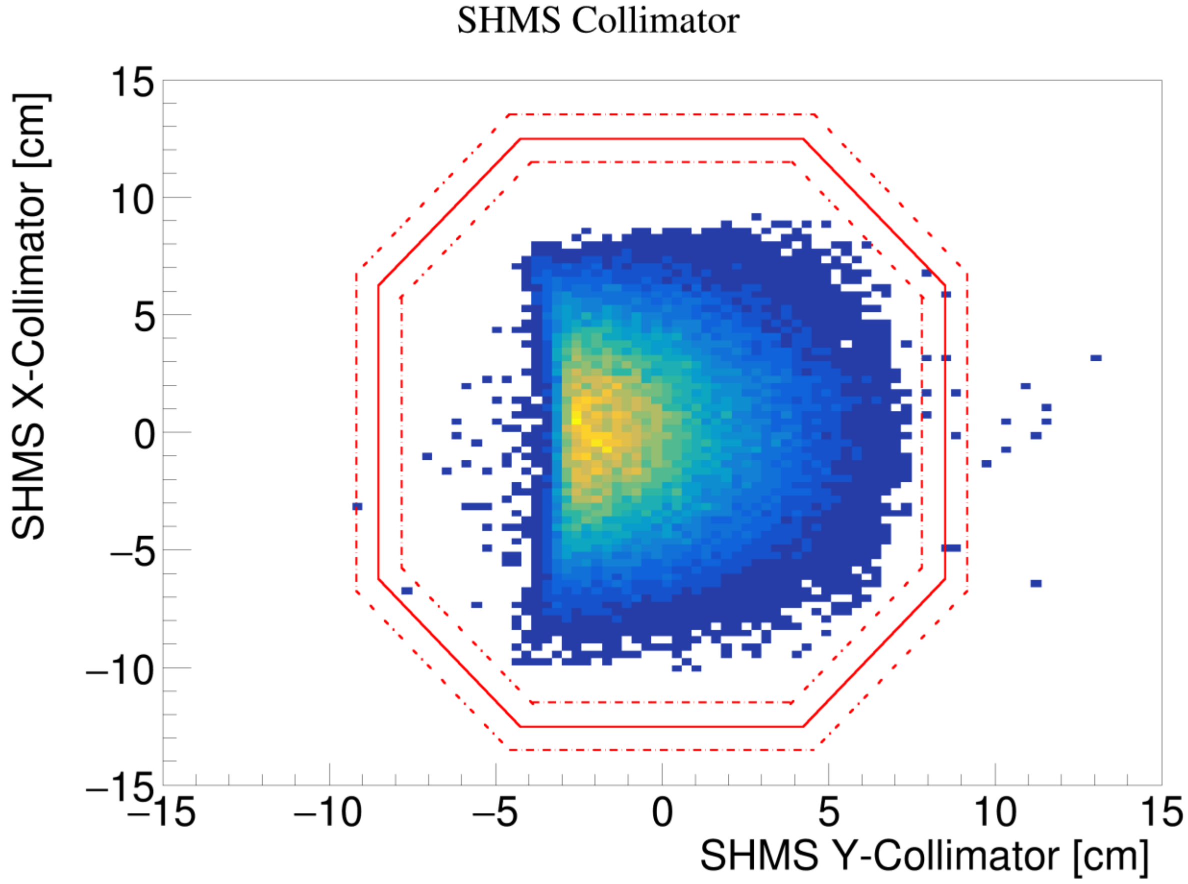
Hen et al, Physics Letters B 722 (2013) 63–68

Cut Variations

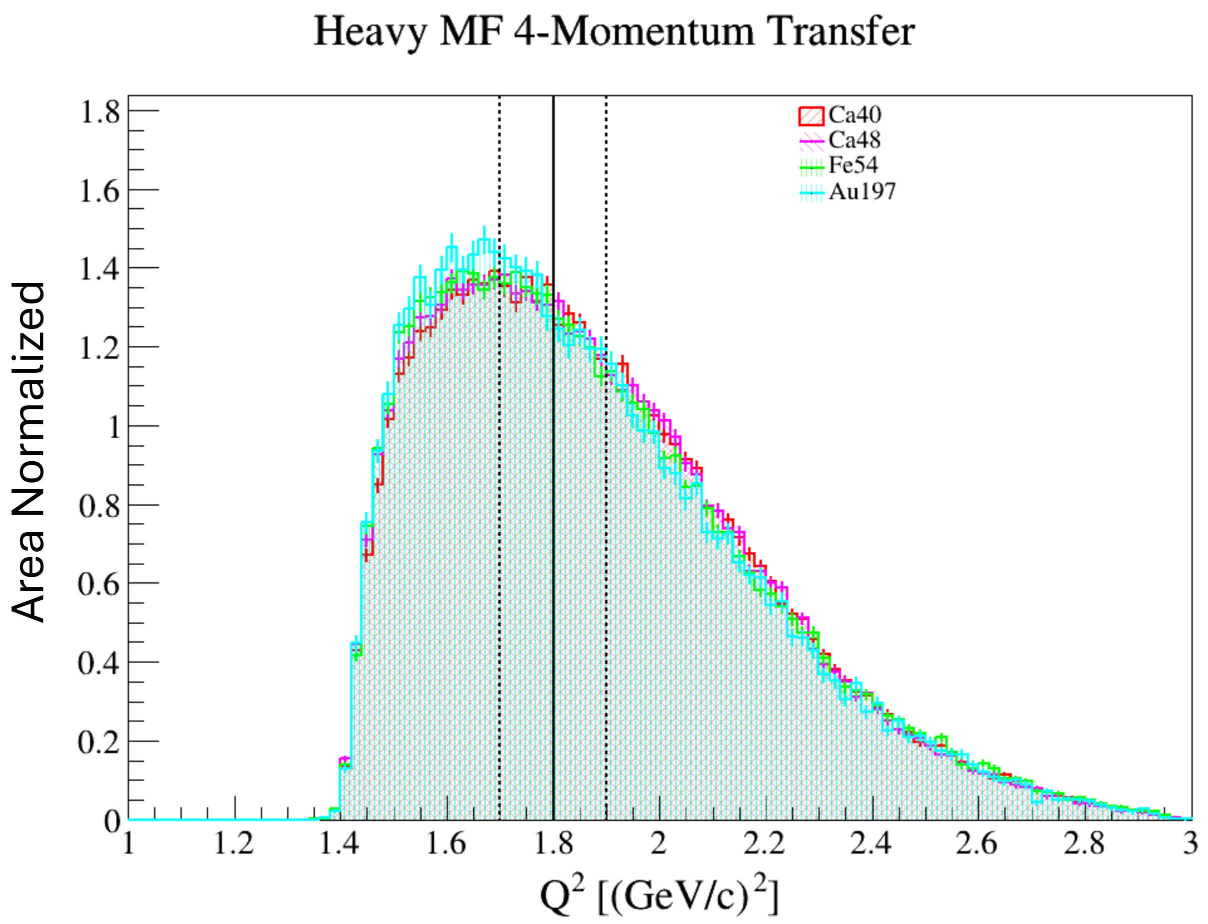
- Examine how sensitive the data is to cuts (systematic uncertainty)
- Data Selection Cuts (and 2σ cut variations)
  - PID
    - $0.8 < \frac{E_{tot}}{P_{cent}} < 1.3$
    - $-2.0 <$ ep Coin Time < 2 ns
  - Acceptance
    - Collimator Cut ± 8 %
  - Kinematics
    - $Q^2 > 1.8 \pm 0.1$ GeV/c^2
    - MF
      - $P_m < 0.27 \pm 0.02$ GeV/c
      - $-0.02 < E_m < 0.09 \pm 0.005$ GeV
    - SRC
      - $0.375 \pm 0.025 < P_m < 0.7 \pm 0.1$ GeV/c
      - $x_{bj} > 1.2 \pm 0.1$
      - $\theta_{rq} < 40 \pm 4$ deg

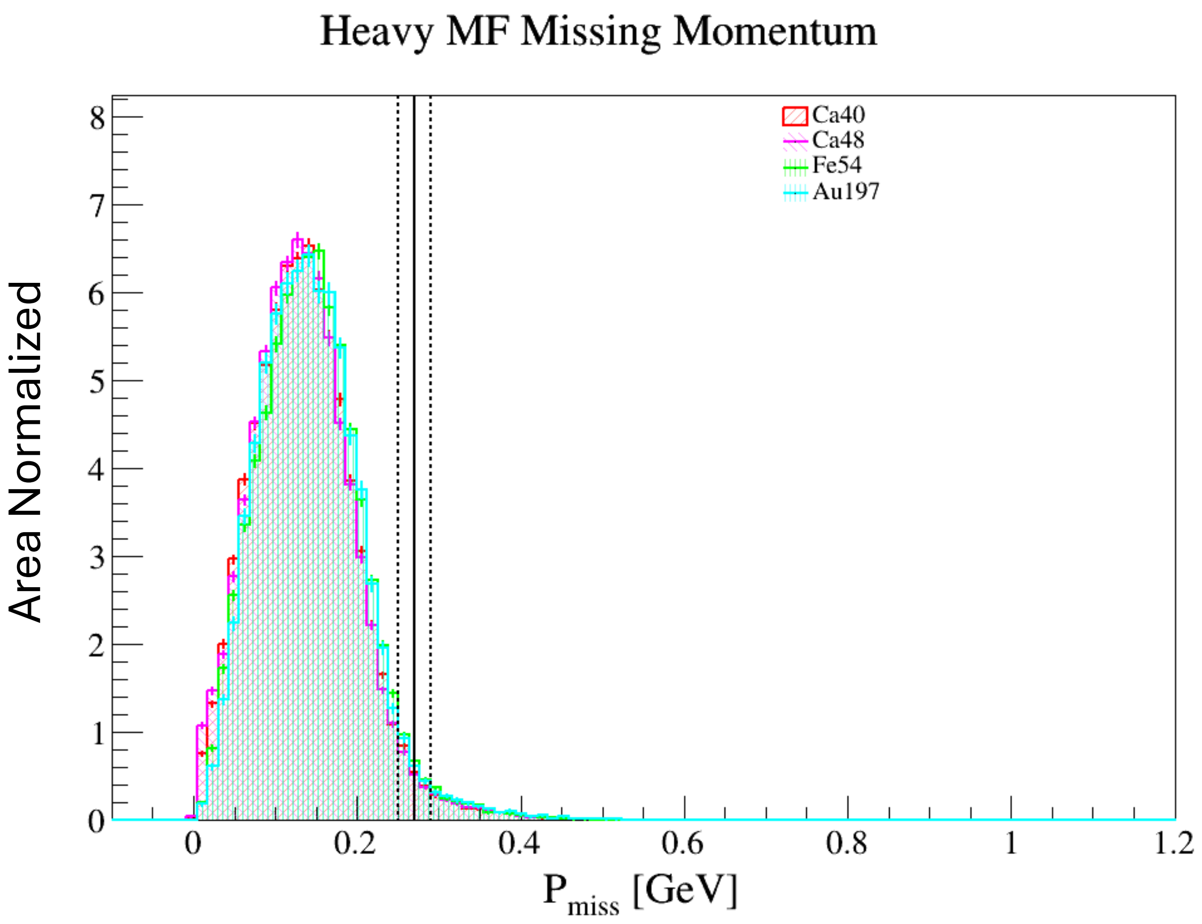
MF HMS & SHMS Collimator Cuts (±2σ)



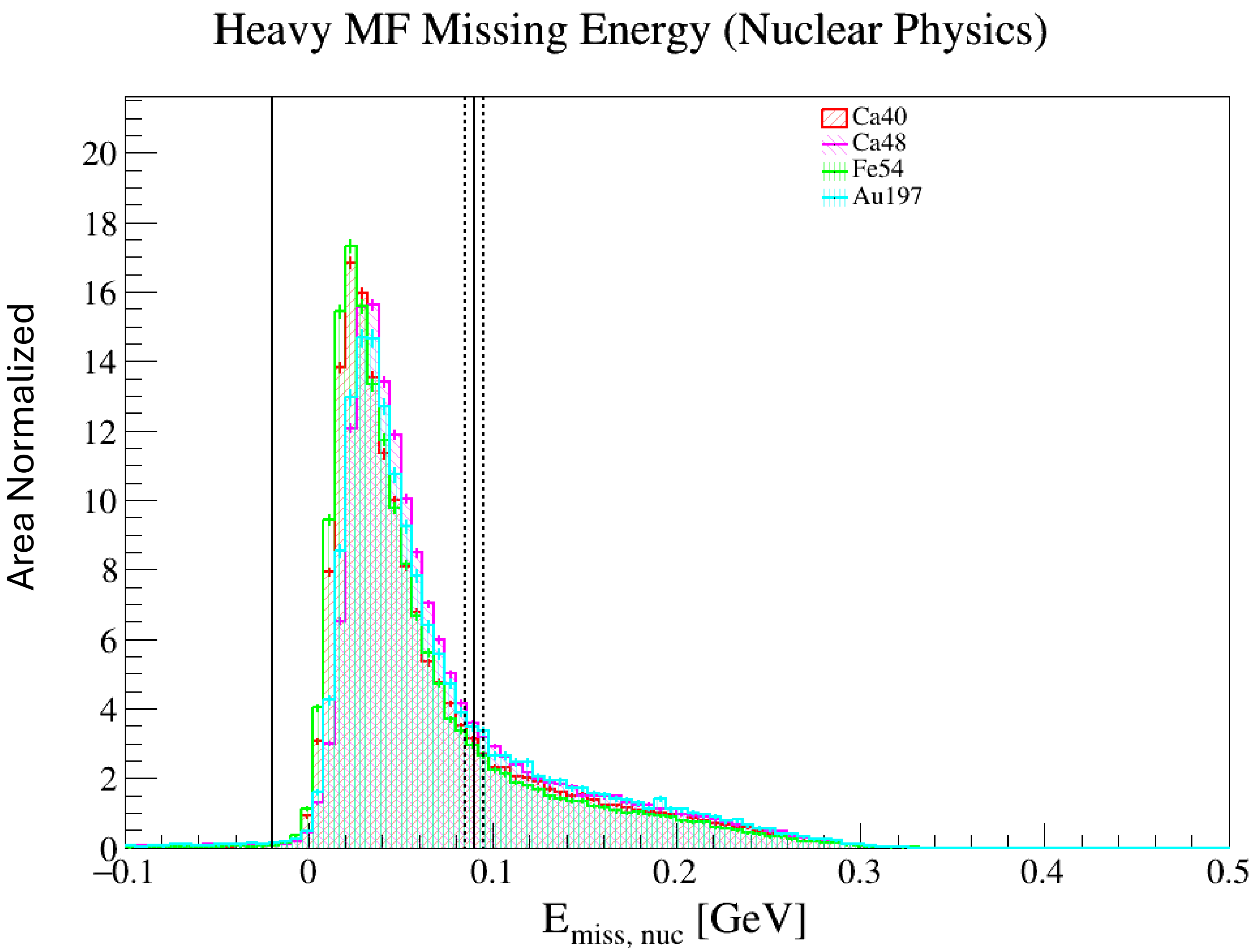


MF Q^2 & P_m Cuts (±2σ)



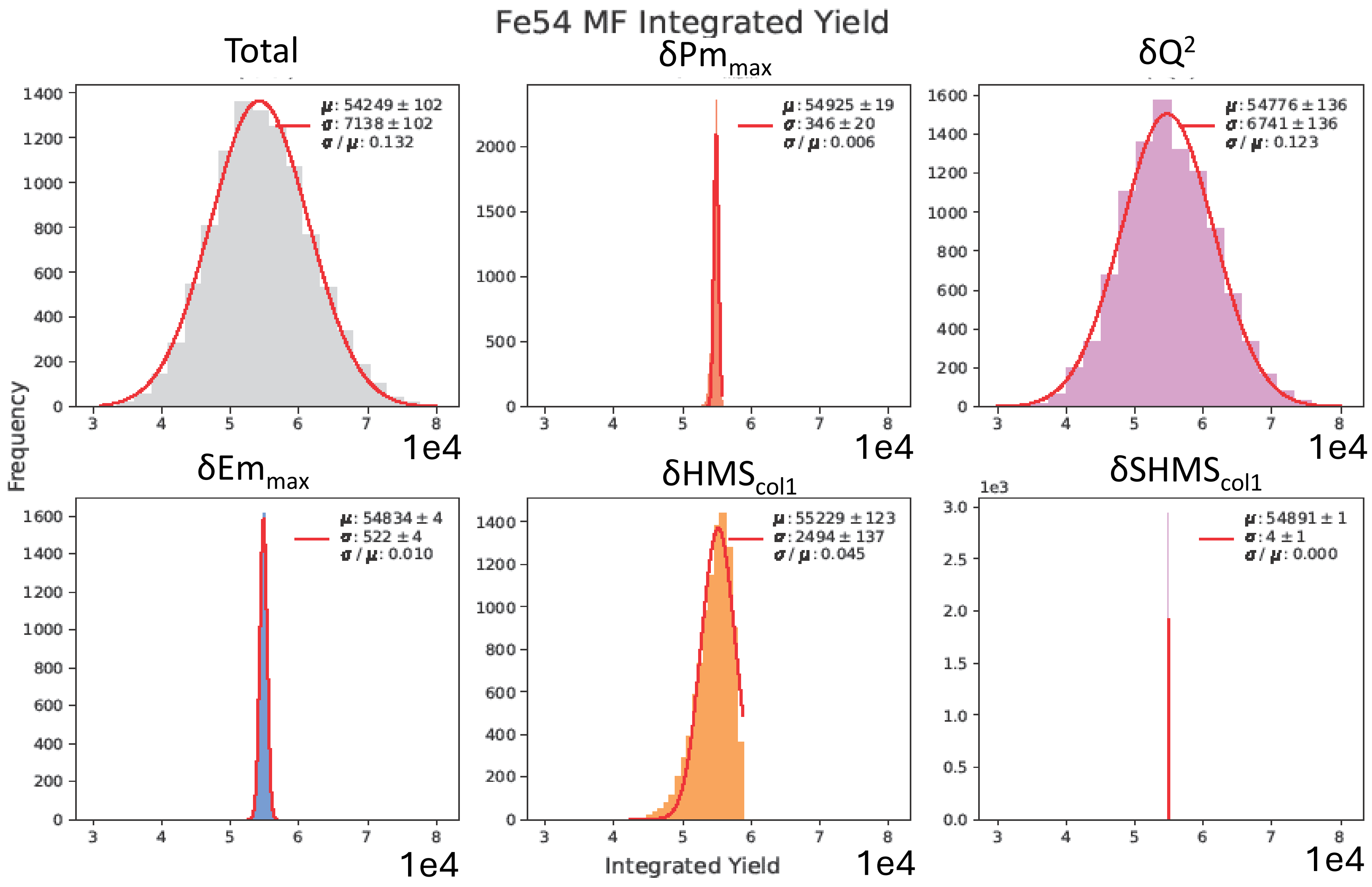


MF E_m Cuts (±2σ)



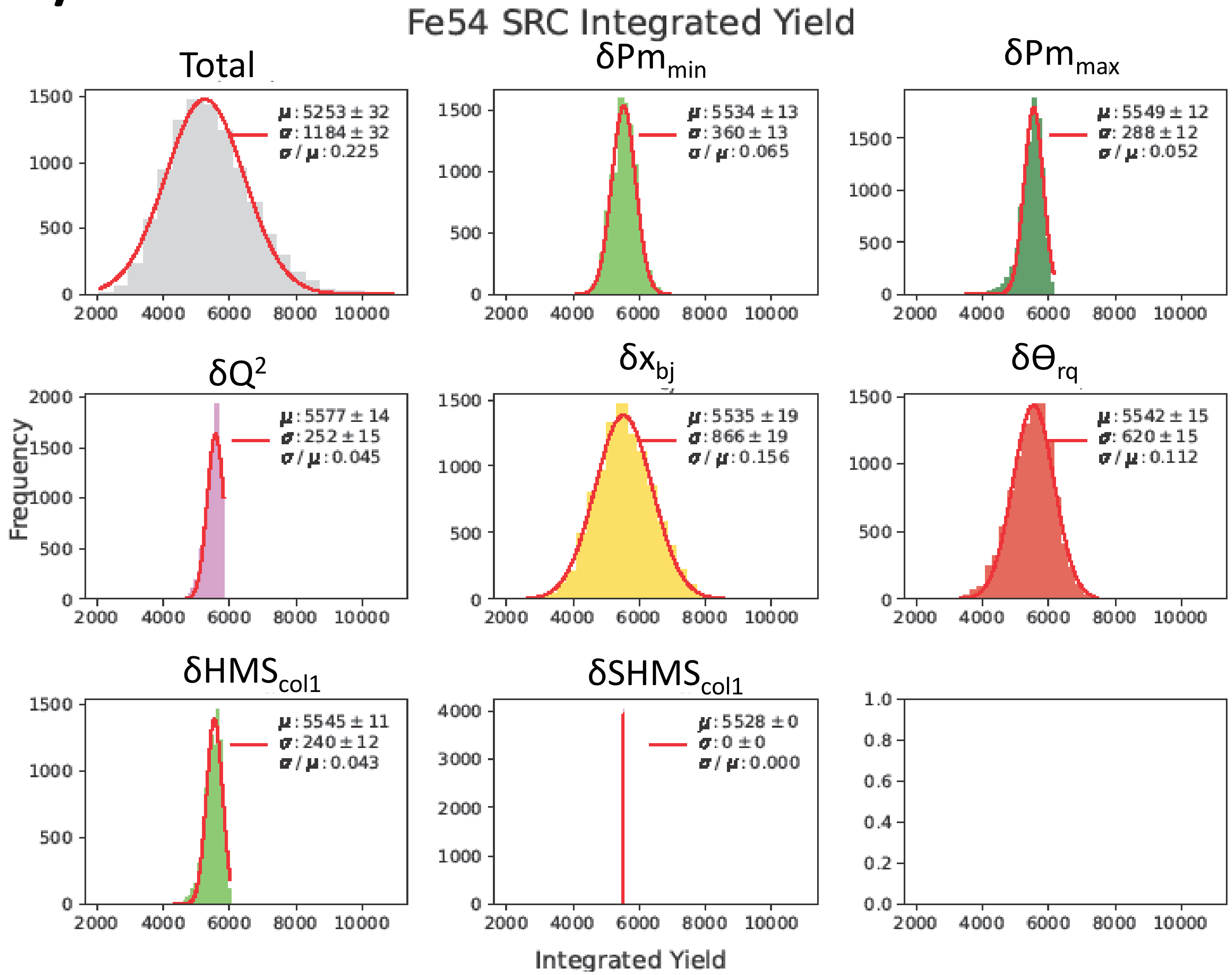
Heavy MF Missing Energy (Nuclear Physics)
Ca40
Ca48
Fe54
Au197
Area Normalized
0
2
4
6
8
10
12
14
16
18
20
−0.1
0
0.1
0.2
0.3
0.4
0.5
E_miss, nuc [GeV]

Mean and σ/mean: MF



σ/mean ≈ 13% for all targets

Mean and σ/mean: SRC



σ/mean ≈ 22% for all targets

Cut Variation: Single & Double Ratios

Ratios to C							
Single Ratio (%)	Be9/C12	B10/C12	B11/C12	Ca40/C12	Ca48/C12	Fe54/C12	Au197/C12
σ/μ (MF)	0.4	0.2	0.1	0.3	0.5	0.3	0.7
σ/μ (SRC)	1.3	1.0	0.9	2.2	3.1	2.4	4.9
Double Ratio (%)	Be9/C12	B10/C12	B11/C12	Ca40/C12	Ca48/C12	Fe54/C12	Au197/C12
σ/μ	1.4	1.0	0.9	2.2	3.1	2.4	4.9

Other Ratios			
Single Ratio (%)	Fe54/Ca48	Fe54/Ca40	Ca40/Ca48
σ/μ (MF)	0.3	0.4	0.3
σ/μ (SRC)	0.7	1.0	1.0
Double Ratio (%)	Fe54/Ca48	Fe54/Ca40	Ca40/Ca48
σ/μ	0.8	1.1	1

SRC uncertainties dominate and increase with larger differences between nuclei.

Systematic Uncertainties CaFe Triplet

Systematic Uncertainties (%)				
Ratio	Radiative Correction	Transparency	Cut Variation	Total
MF Single Ratio				
Ca40/Ca48	0	1	1	**1.4**
Fe54/Ca48	2.5	1	1	**2.9**
SRC Single Ratio				
Ca40/Ca48	0	1	1	**1.4**
Fe54/Ca48	2.5	1	1	**2.9**
Double Ratio				
Ca40/Ca48	1	1	0	**1.4**
Fe54/Ca48	1	1	0	**1.4**

Ratios

$$Y_A : \frac{N}{Q \cdot \epsilon_i \cdot T_N \cdot \sigma_t \cdot Z/A}$$

Y_A : nucleus A yield

N : $(e, e'p)$ coincidence counts

Q : total charge [mC]

ϵ_i : detector/DAQ efficiencies

T_N : nuclear transparency

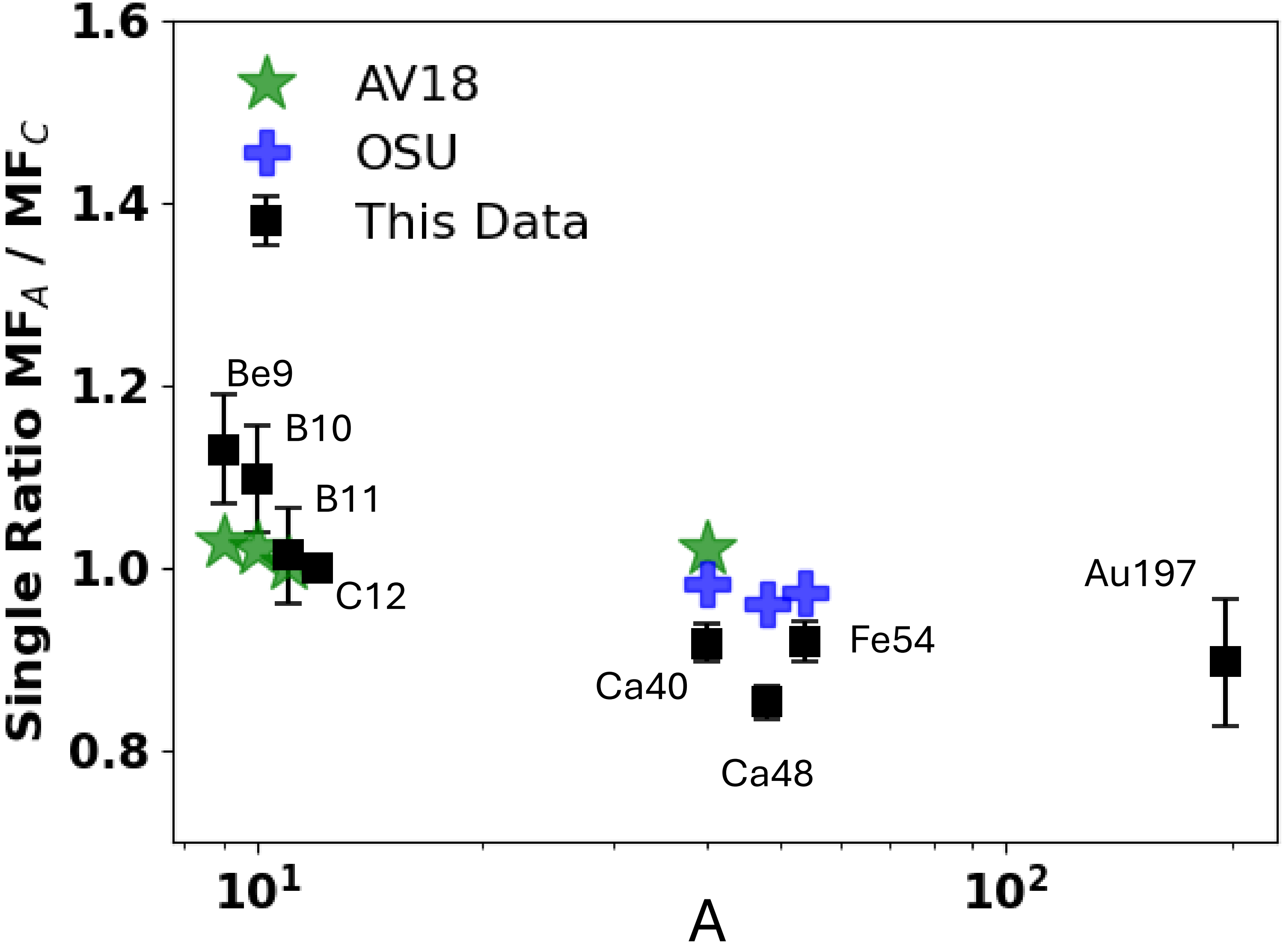
σ_t : target thickness [g/cm^2]

- Single
  - $R = \frac{Y_A}{Y_{C12}}$
- Double
  - Normalization Factors Cancel
- MF should be proportional to number protons
- SRC should reflect probability of being in SRC
- Additional Corrections for
  - Random coincidences
  - Oil contamination (Ca targets)
  - Isotopic Impurity (Ca48 90.5%)
  - Chemical Impurity (B_4C)

Double Ratios

$$\frac{A(e,e'p)^{SRC}/A(e,e'p)^{MF}}{{}^{12}C(e,e'p)^{SRC}/{}^{12}C(e,e'p)^{MF}}$$

MF Single Ratio

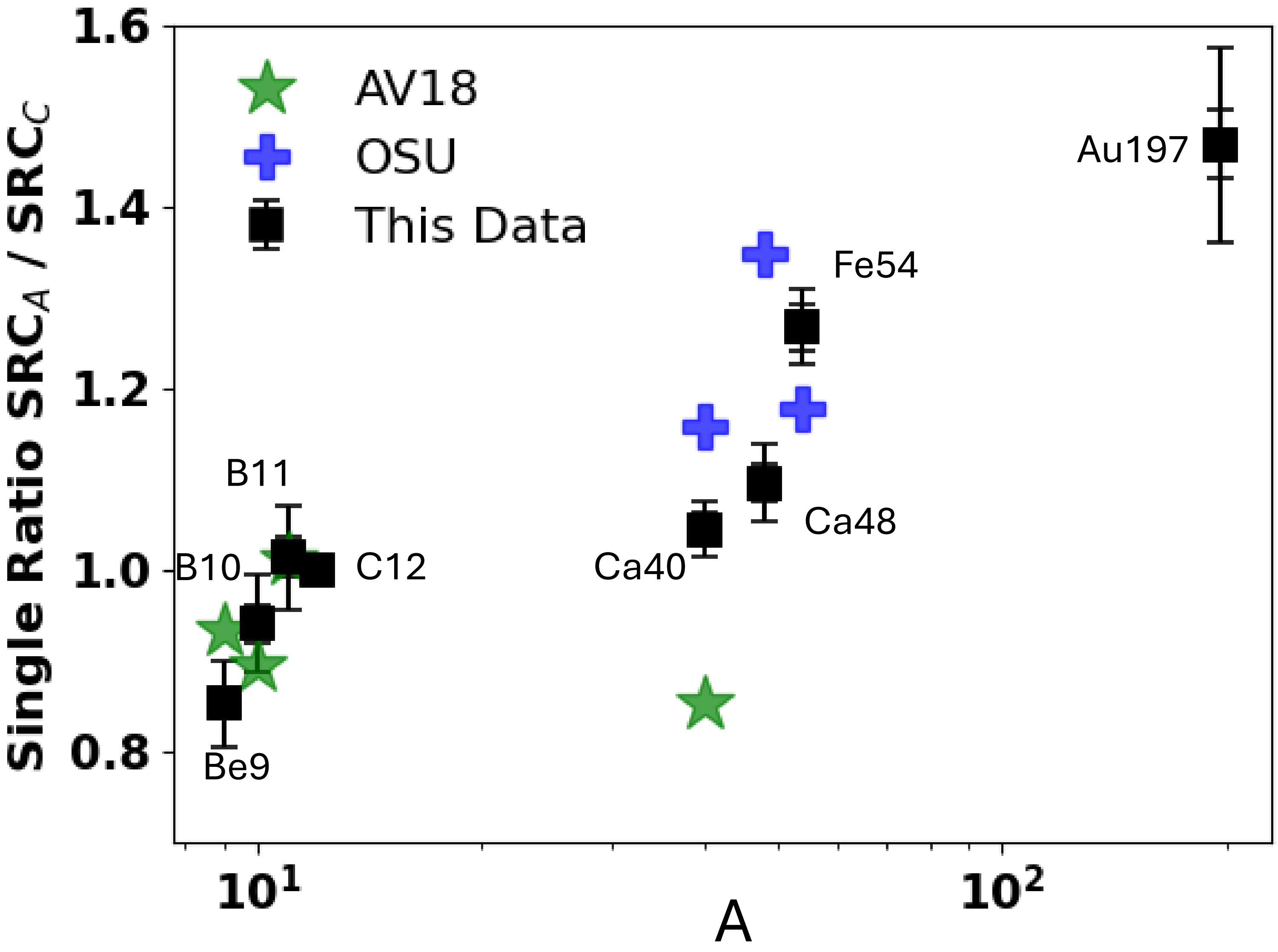


- MF Single Ratio decreases with A
- Models are flat

R.J.Furnstahl et al. arXiv:2402.00634v2 (OSU)

Wiringa et al. Phys.Rev.C89 (AV18)

SRC Single Ratios



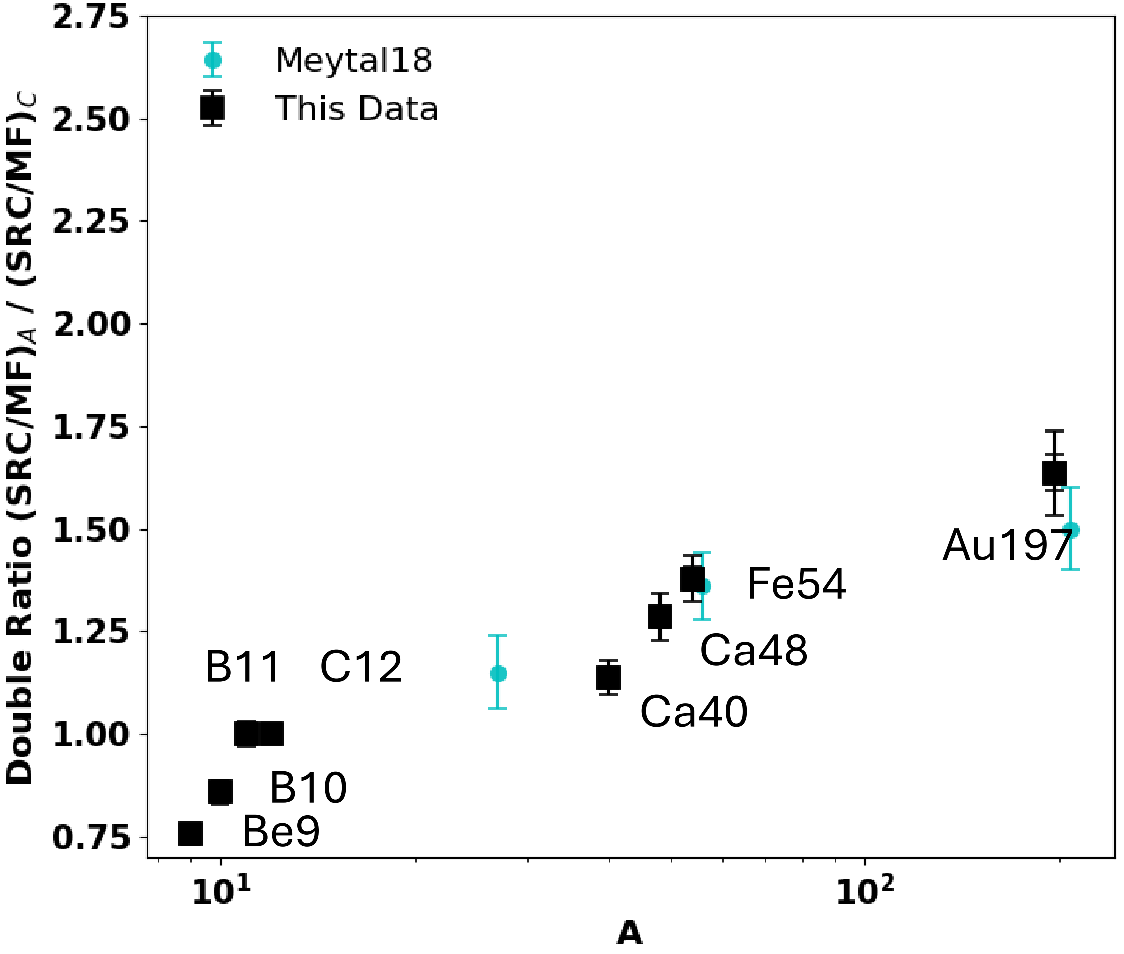
- SRC Single Ratio increases with A

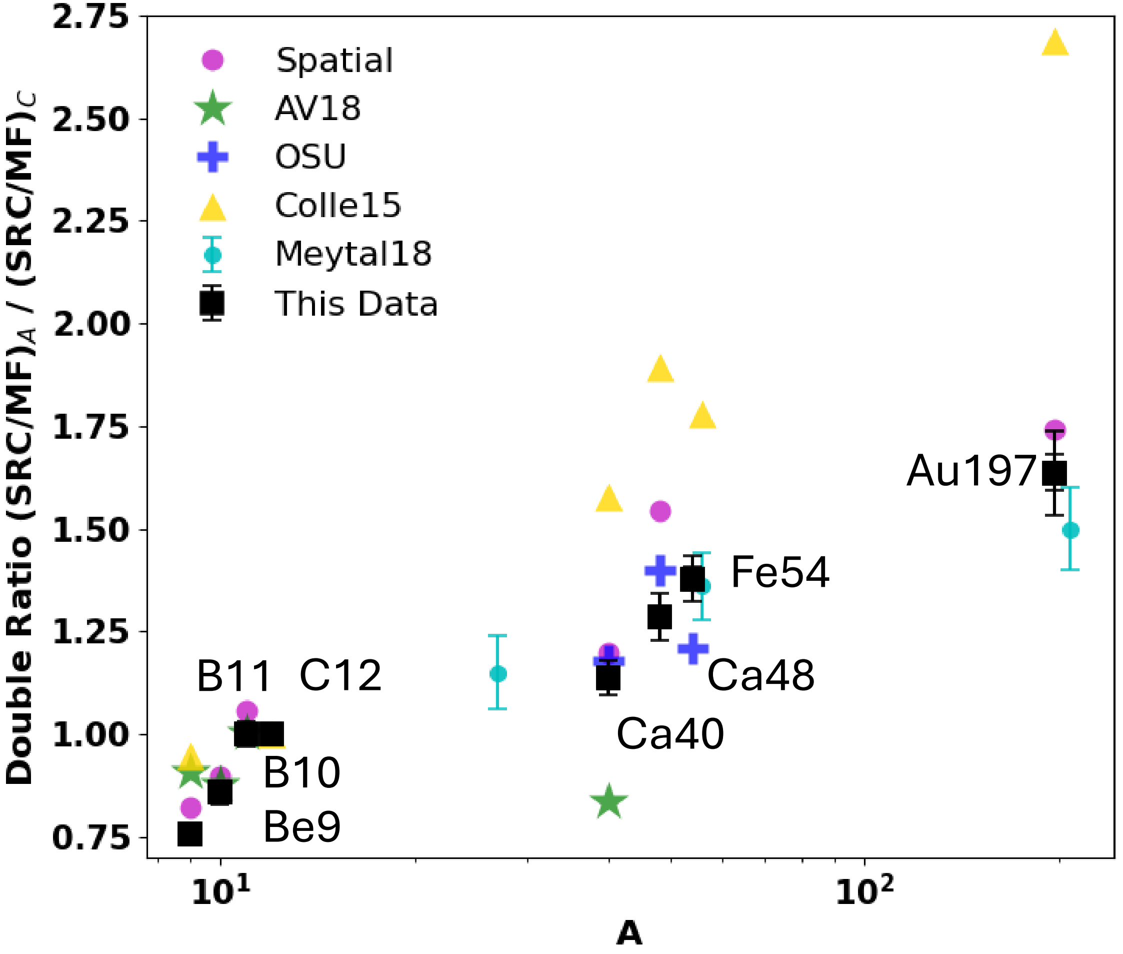
R.J.Furnstahl et al. arXiv:2402.00634v2 (OSU)

Wiringa et al, Phys.Rev.C89 (AV18)

Double Ratio vs A

Double Ratio increases with A



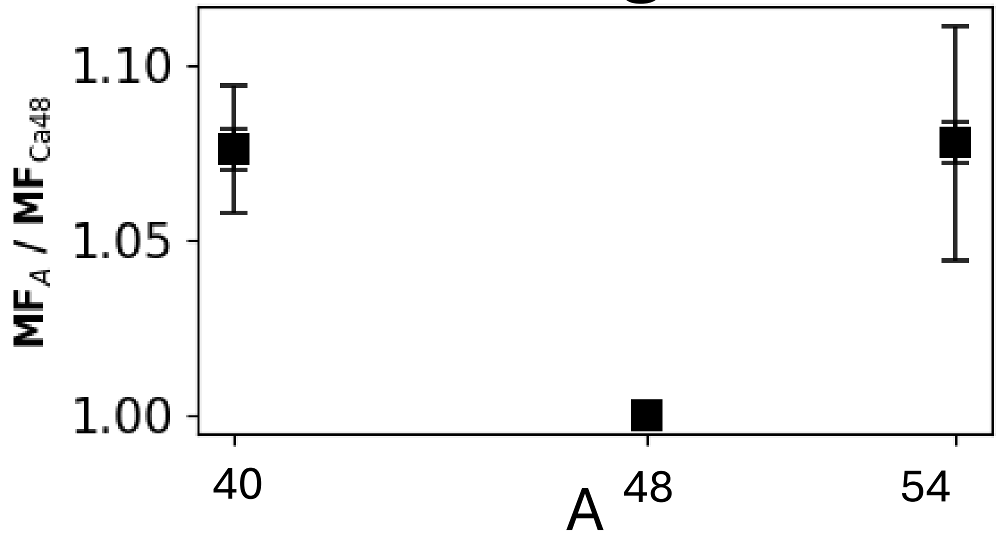


M. Duer et al. (CLAS collaboration), Nature 560, 617 (Meytal 18)

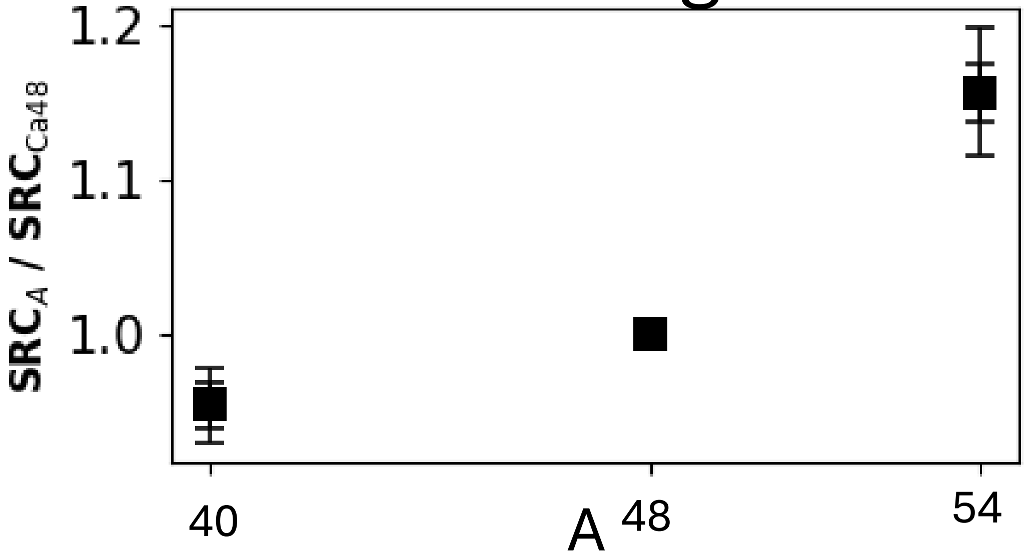
Triplet Ratios

- The MF accounts for ~70% of all nucleons
- Therefore, a small decrease in the MF single ratio should correspond to a large increase in the SRC single ratio
- We don't see this
- Ca48 target made in house

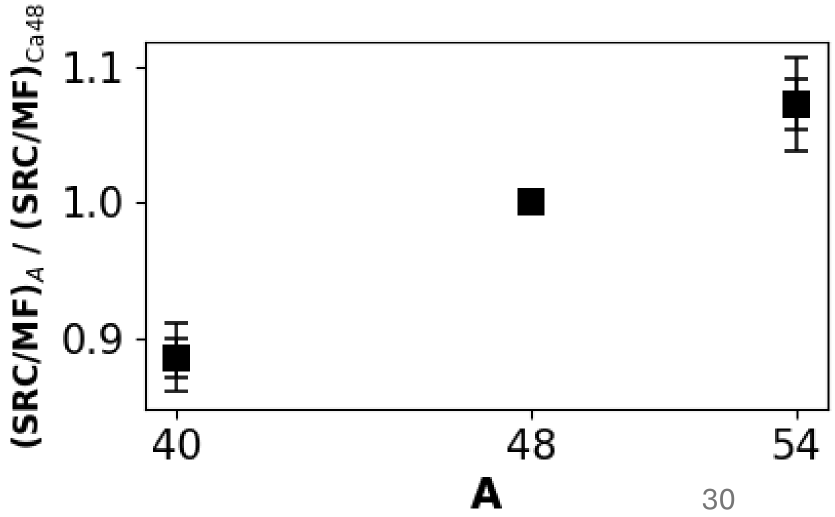
MF Single



SRC Single



Double



Conclusion

- Double Ratio generally increase with A
  - Linear increase within both Be9-B10-B11-C12 and Ca40-Ca48-Fe54
- Possible Ca48 target thickness issue?
- CaFe Triplet Double Ratio
  - Adding 8 neutrons increases correlated protons by ~11%
  - Adding 6 protons increases correlated protons by ~7%
    - Calculations predict decrease
  - Importance of shell effects?

Questions?

Back up

Calculating Electron Cross Section

- $N_{events\ into\ solid\ angle\ \Delta\Omega} = Data\ Counts\ * SIMC\ Ratio$
- $N_{incident} = \frac{Q\ (C)}{1.602 * 10^{-19} (C)}$
- $nx = \rho_{H2} * Target\ Length\ * N_A$
  - Target Length modified by z-Target cut
- Electron solid angle modified by hxptar and hyptar cuts

Central Kinematics

```
------------------------------
H(e,e'p) Elastics for
Beam Energy (Eb) = 10.549 GeV
e- angle (th_e)  = 8.300 deg
------------------------------
e- momentum (kf)           = 9.438 GeV/c
proton angle (th_p)        = 48.384 deg
proton momentum (Pf)       = 1.822 GeV/c
4-momentum transfer (Q2)   = 2.086 (GeV/c)^2
3-momentum transfer (|q|)  = 1.822 GeV/c
energy transfer            = 1.111 GeV
x-Bjorken                  = 1.000

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H(e, e') Cross Section @ Central Kinematics

```
H(e,e') Elastic Cross Section:
 Eb = 10549.0 MeV
 kf = 9438.0 MeV
 th_e = 8.3 deg
d_sig/d_omega_e [ub/sr] (Bosted parametrization) = 2.449E-02
d_sig/d_omega_e [ub/sr] (Arrington parametrization)= 2.409E-02
```

- Use J. Arrington form-factor parametrization (more recent)

Definition of cross section for scattering or reactions

Let $N_{incident}$ = number of incident (beam) particles

N_{events} = number of events (beam−target interactions)

n = target atoms per unit volume = $\frac{\rho N_{Avogadro}}{A}$

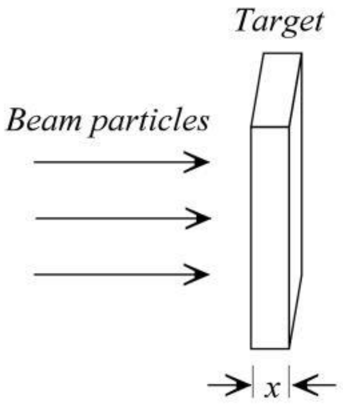
A = mass number of target (assuming a single pure isotope)

ρ = mass density of target (g/cm^3)

x = thickness of target (cm)

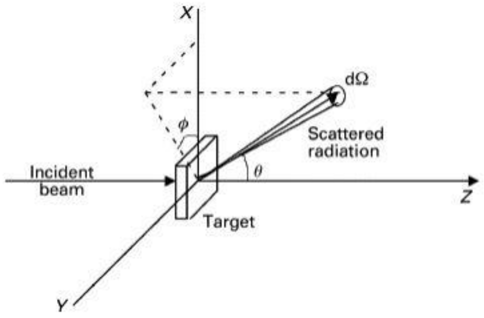
ρx = areal density of target (g/cm^2)

nx = areal number density (atoms/cm^2) = $\frac{\rho x N_{Avogadro}}{A}$



$$N_{\text{events into solid angle } \Delta\Omega_e} = N_{\text{incident}}\, nx \frac{d\sigma}{d\Omega_e} \Delta\Omega_e$$

Need to determine total # of H atoms per area that contaminate the Ca48 target



Ref. Physics 537/635 – D. Sober "An Introduction to Cross Sections" January 2005 (rev. 2007)

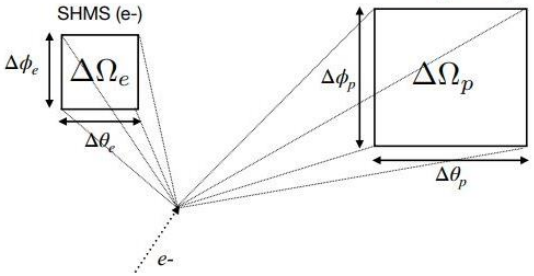
Solid Angle

$$N_{\text{events into solid angle } \Delta\Omega_e} = N_{\text{incident}} nx \frac{d\sigma}{d\Omega_e} \Delta\Omega_e$$

$$\Delta\Omega_e = \Delta\Omega_p \times \frac{d\theta_e}{d\theta_p} \times \frac{d\phi_e}{d\phi_p}$$

"HMS Solid Angle" "In-plane" "Out-of-plane"

Hall C spectrometers angular acceptance

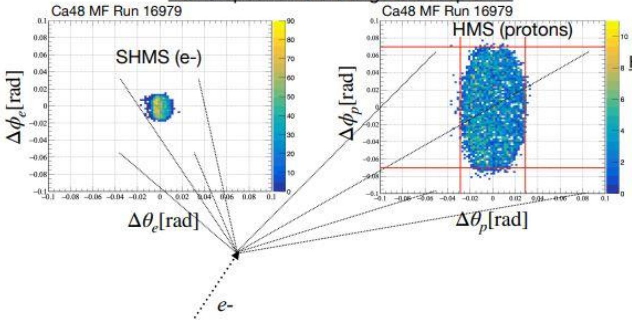


$$N_{\text{events into solid angle } \Delta\Omega_e} = N_{\text{incident}} nx \frac{d\sigma}{d\Omega_e} \Delta\Omega_e$$

$$\Delta\Omega_e = \Delta\Omega_p \times \frac{d\theta_e}{d\theta_p} \times \frac{d\phi_e}{d\phi_p}$$

"HMS Solid Angle"

Hall C spectrometers angular acceptance



HMS "Large" Collimator

$\Delta\theta_p = \pm 0.0275$ rad

$\Delta\phi_p = \pm 0.07$ rad

$\Omega_p = 0.00674$ sr

$$N_{\text{events into solid angle } \Delta\Omega_e} = N_{\text{incident}} nx \frac{d\sigma}{d\Omega_e} \Delta\Omega_e$$

$$\Delta\Omega_e = \Delta\Omega_p \times \frac{d\theta_e}{d\theta_p} \times \frac{d\phi_e}{d\phi_p}$$

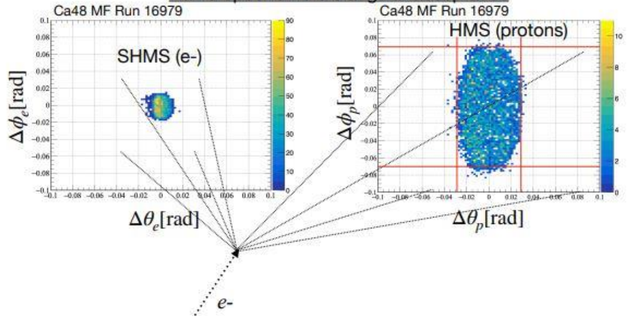
"Out-of-plane"

Momentum conservation (out-of-plane):

$$k_{i,\perp} = |k_f|\sin(\phi_e) + |p_f|\sin(\phi_p) = 0 \implies \frac{\delta\phi_e}{\delta\phi_p} \sim \frac{|p_f|}{|k_f|} = \frac{1.822 \text{ GeV/c}}{9.438 \text{ GeV/c}} \sim 0.193$$

"⊥ component of beam momentum is zero"

Hall C spectrometers angular acceptance



$$N_{\text{events into solid angle } \Delta\Omega_e} = N_{\text{incident}} nx \frac{d\sigma}{d\Omega_e} \Delta\Omega_e$$

numerical approach

```
---------------------------------
H(e,e'p) Elastics for
Beam Energy (Eb) = 10.549 GeV
e- angle (th_e)  = 8.200 deg
---------------------------------
e- momentum (kf)          = 9.461 GeV/c
proton angle (th_p)       = 48.730 deg
```

```
---------------------------------
H(e,e'p) Elastics for
Beam Energy (Eb) = 10.549 GeV
e- angle (th_e)  = 8.300 deg
---------------------------------
e- momentum (kf)          = 9.438 GeV/c
proton angle (th_p)       = 48.384 deg
```

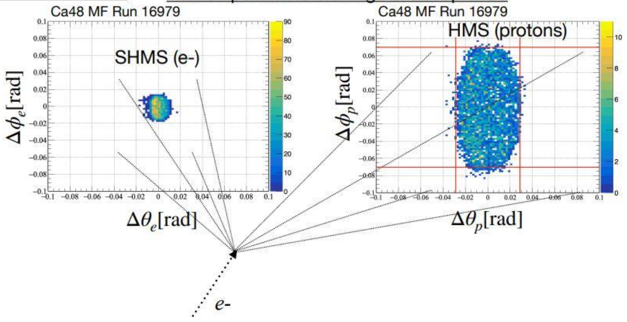
```
---------------------------------
H(e,e'p) Elastics for
Beam Energy (Eb) = 10.549 GeV
e- angle (th_e)  = 8.400 deg
---------------------------------
e- momentum (kf)          = 9.414 GeV/c
proton angle (th_p)       = 48.042 deg
```

$$\Delta\Omega_e = \Delta\Omega_p \times \frac{d\theta_e}{d\theta_p} \times \frac{d\phi_e}{d\phi_p}$$

"In-plane"

"In-plane" (numerical approach): vary in-plane (e-) angle by ~ +/- 0.1 deg and determine the variation in proton angle $\frac{\delta\theta_e}{\delta\theta_p} \sim 0.2907$

Hall C spectrometers angular acceptance



$$N_{\text{events into solid angle } \Delta\Omega_e} = N_{\text{incident}} nx \frac{d\sigma}{d\Omega_e} \Delta\Omega_e$$

$$\Delta\Omega_e = \Delta\Omega_p \times \frac{d\theta_e}{d\theta_p} \times \frac{d\phi_e}{d\phi_p}$$

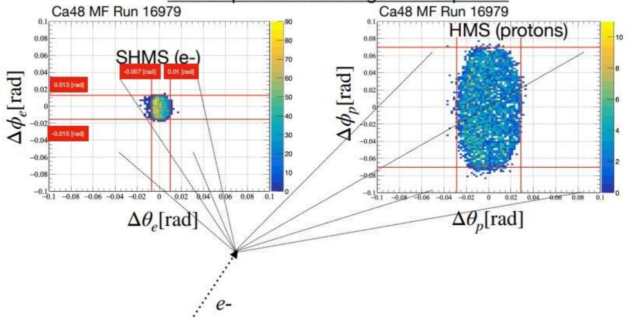
$\Omega_p \sim 0.00674$ sr

$\frac{\delta\theta_e}{\delta\theta_p} \sim 0.2907$

$\frac{\delta\phi_e}{\delta\phi_p} \sim 0.193$

$\Delta\Omega_e \sim 0.000378$ sr

Hall C spectrometers angular acceptance



Electron Cross Section Ratio (e,e') Data

- $\frac{d\sigma}{d\Omega_e} = \frac{N_{events\ into\ solid\ angle}}{N_{incident} * nx * d\Omega_e}$

e,e'									
loose rad (e,e') cuts									
Raw Count	Norad Count	Rad Count	Rad Corr	q (mC)	Nicident	nx (atoms / cm^2)	ΔΩe (sr)	dσ/dΩe (μb/sr)	Norm
26293	410267.38	224189.82	1.83	19.284	1.20E+17	4.35E+23	3.78E-04	2.07E-02	0.859
tight rad (e,e') cuts									
Raw Count	Norad Count	Rad Count	Rad Corr	q (mC)	Nicident	nx (atoms / cm^2)	ΔΩe (sr)	dσ/dΩe (μb/sr)	Norm
2996	53625.03	29303.30	1.83	19.284	1.20E+17	1.74E+23	1.08E-04	2.37E-02	0.983

Electron Cross Section Ratio (e,e'p) Data

- $\frac{d\sigma}{d\Omega_e} = \frac{N_{events\ into\ solid\ angle}}{N_{incident} * nx * d\Omega_e}$

e,e'p									
loose rad (e,e'p) cuts									
Raw Count	Norad Count	Rad Count	Rad Corr	q (mC)	Nicident	nx (atoms / cm^2)	ΔΩe (sr)	dσ/dΩe (μb/sr)	Norm
205041	500254.81	273363.28	1.83	26.61	1.66E+17	4.35E+23	3.78E-04	1.83E-02	0.760
tight rad (e,e'p) cuts									
Raw Count	Norad Count	Rad Count	Rad Corr	q (mC)	Nicident	nx (atoms / cm^2)	ΔΩe (sr)	dσ/dΩe (μb/sr)	Norm
30823	81242.86	44395.01	1.83	26.61	1.66E+17	1.74E+23	1.08E-04	2.60E-02	1.079

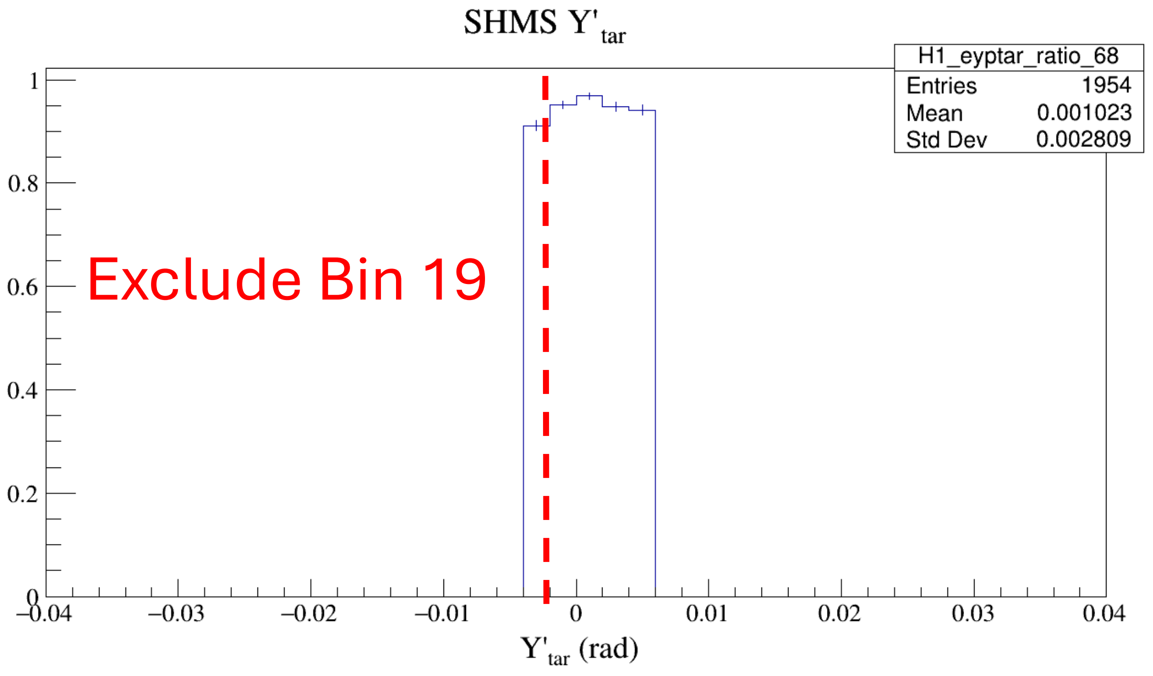
Electron Cross Section Ratio SIMC

- $\frac{d\sigma}{d\Omega_e} = \frac{N_{events\ into\ solid\ angle}}{N_{incident} * nx * d\Omega_e}$

Simulation									
loose rad (e,e'p) cuts									
Raw Count	Norad Count	Rad Count	Rad Corr	q (mC)	Nicident	nx (atoms / cm^2)	ΔΩe (sr)	dσ/dΩe (µb/sr)	Norm
1034393	442391.78	260091.86	1.70	26.61	1.66E+17	4.35E+23	3.78E-04	1.62E-02	0.672
tight rad (e,e'p) cuts									
Raw Count	Norad Count	Rad Count	Rad Corr	q (mC)	Nicident	nx (atoms / cm^2)	ΔΩe (sr)	dσ/dΩe (µb/sr)	Norm
116625	74182.28	48370.63	1.53	26.61	1.66E+17	1.74E+23	1.08E-04	2.37E-02	0.986
loose rad (e,e') cuts									
Raw Count	Norad Count	Rad Count	Rad Corr	q (mC)	Nicident	nx (atoms / cm^2)	ΔΩe (sr)	dσ/dΩe (µb/sr)	Norm
625496	429131.21	250013.25	1.72	19.284	1.20E+17	4.35E+23	3.78E-04	2.17E-02	0.899
tight rad (e,e') cuts									
Raw Count	Norad Count	Rad Count	Rad Corr	q (mC)	Nicident	nx (atoms / cm^2)	ΔΩe (sr)	dσ/dΩe (µb/sr)	Norm
70140	53874.13	31529.92	1.71	19.284	1.20E+17	1.74E+23	1.08E-04	2.38E-02	0.988

HMS Proton Efficiency

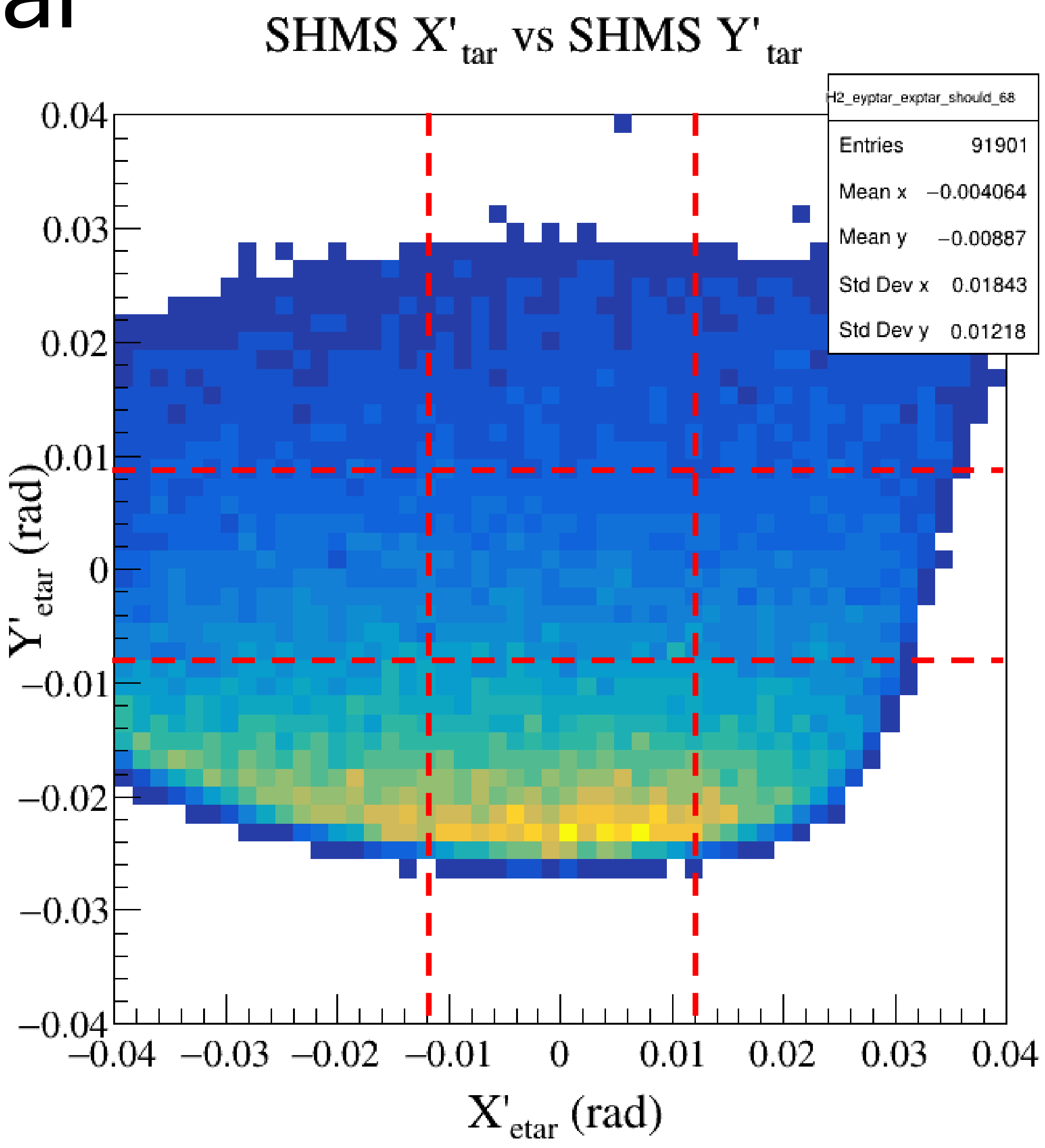
$$\sigma_{ratio}^{exact} = \sqrt{should \frac{did}{should}(1 - \frac{did}{should})} \Big/ should$$

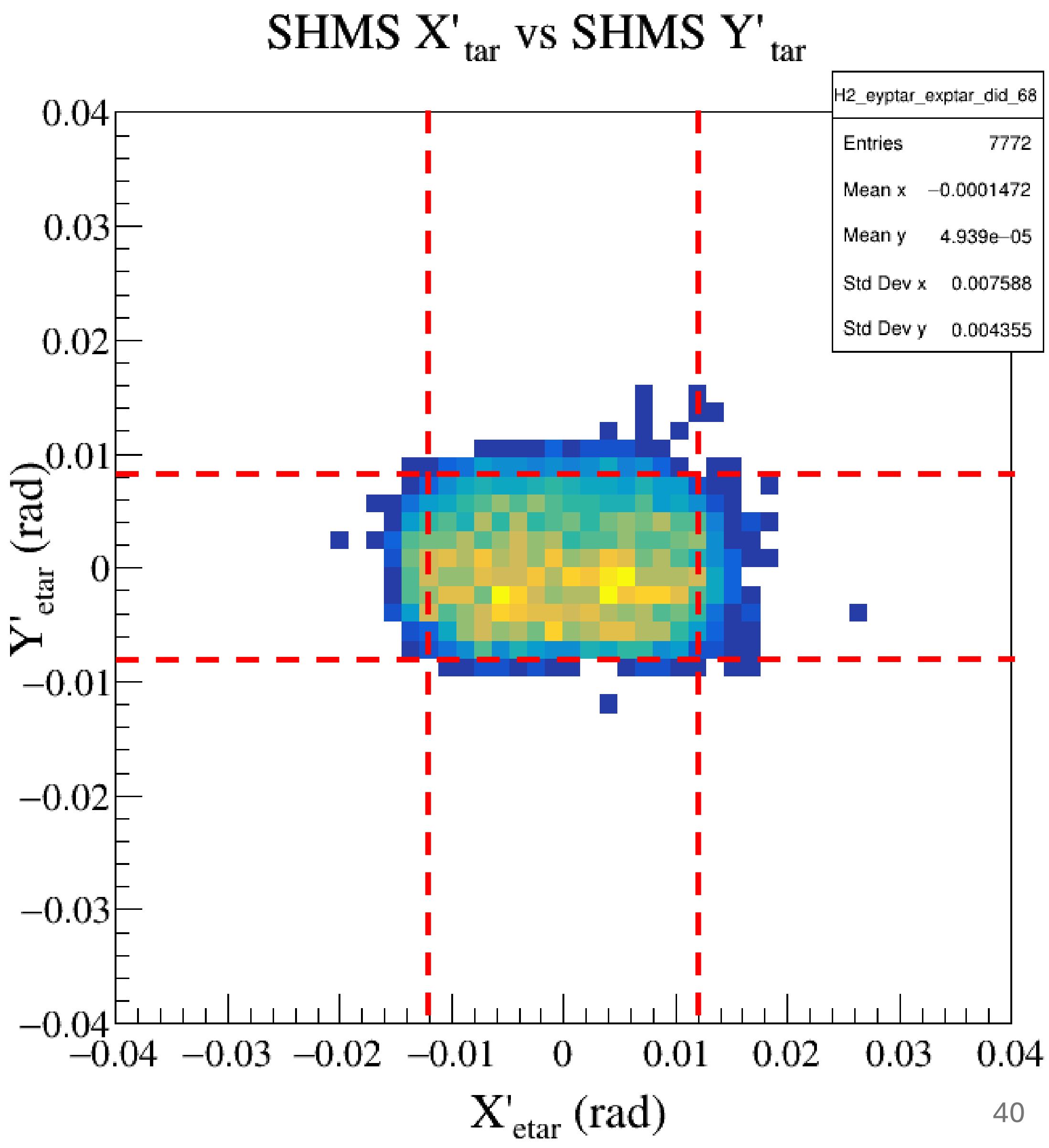


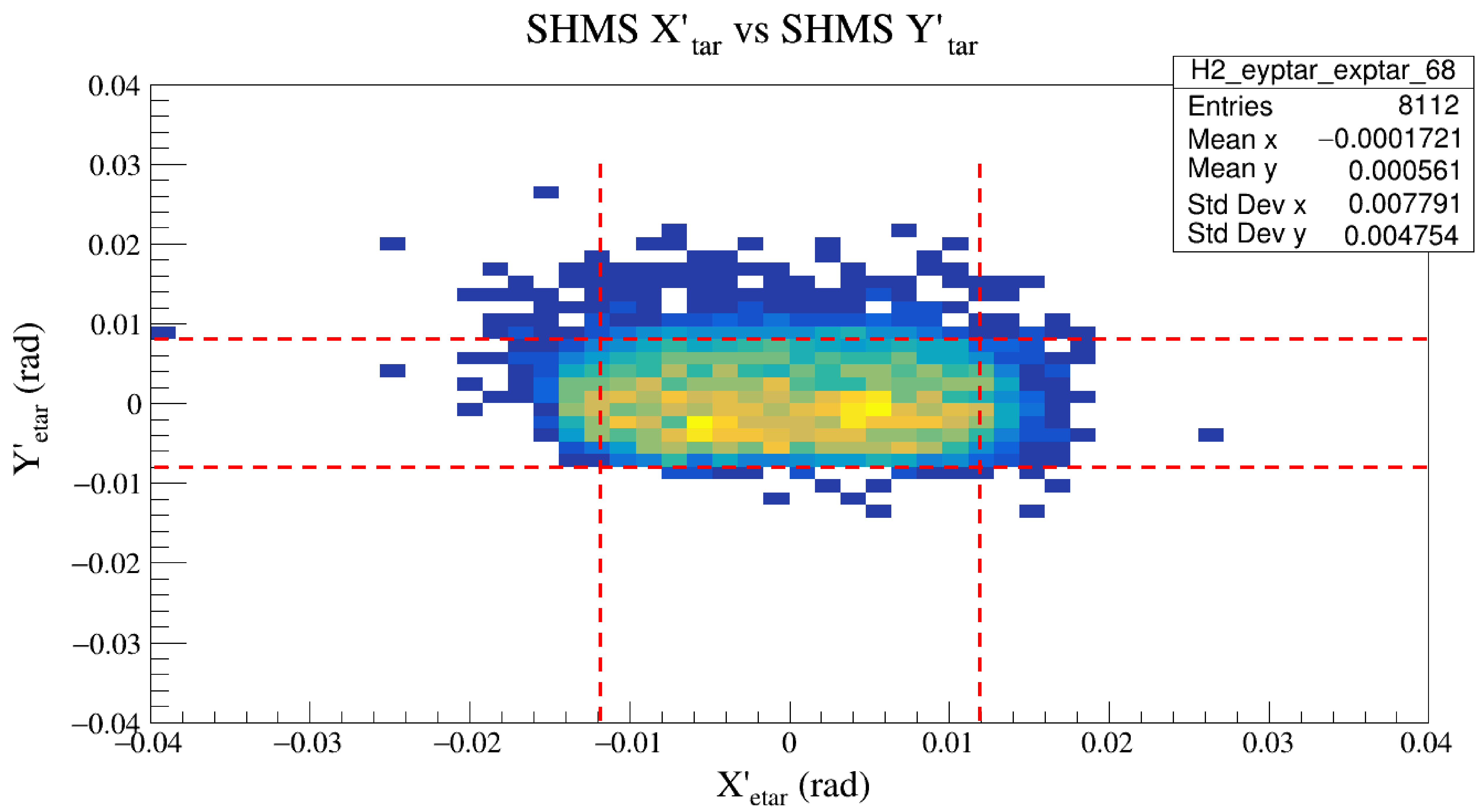
SHMS Y'tar							
Bin	Should Count	Did Count	σ_{approx}	σ_{exact}	Did/Should	Weight	Numerator
19	1012	919.8	0.009	0.009	0.91	12216.4	11102.9
20	960	907.7	0.008	0.007	0.95	18644.5	17629.2
21	873	845.5	0.006	0.006	0.97	28652.5	27751.1
22	713	680.0	0.008	0.008	0.95	16171.4	15423.8
23	669	628.9	0.009	0.009	0.94	11869.2	11157.5
Total	3215	3062.2	0.004	0.004			

Result		
Unweighted Proton Transmission	Weighted Proton Transmission	Uncertainty
0.952	0.955	0.004

SHMS X’tar vs SHMS Y’tar



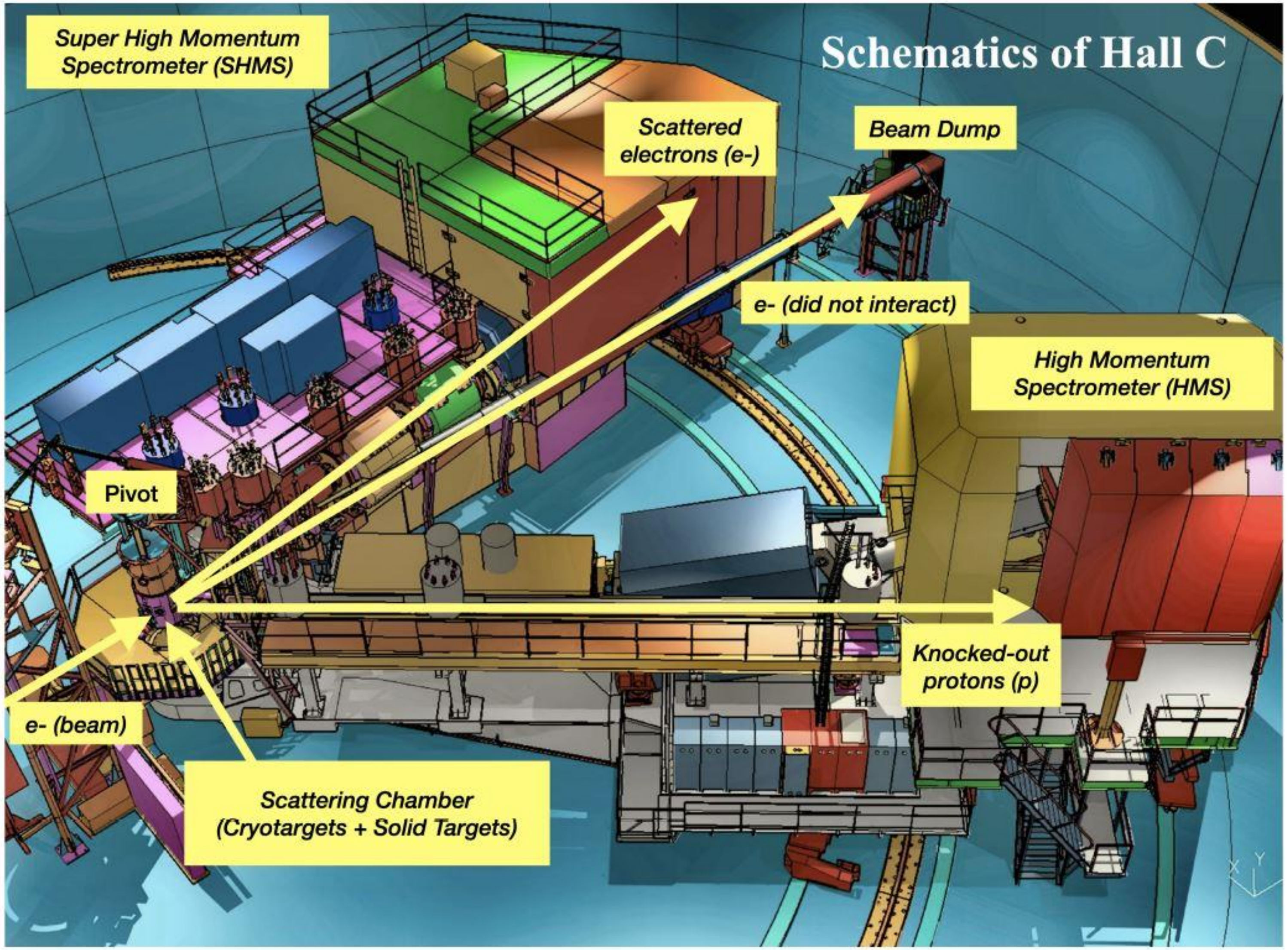




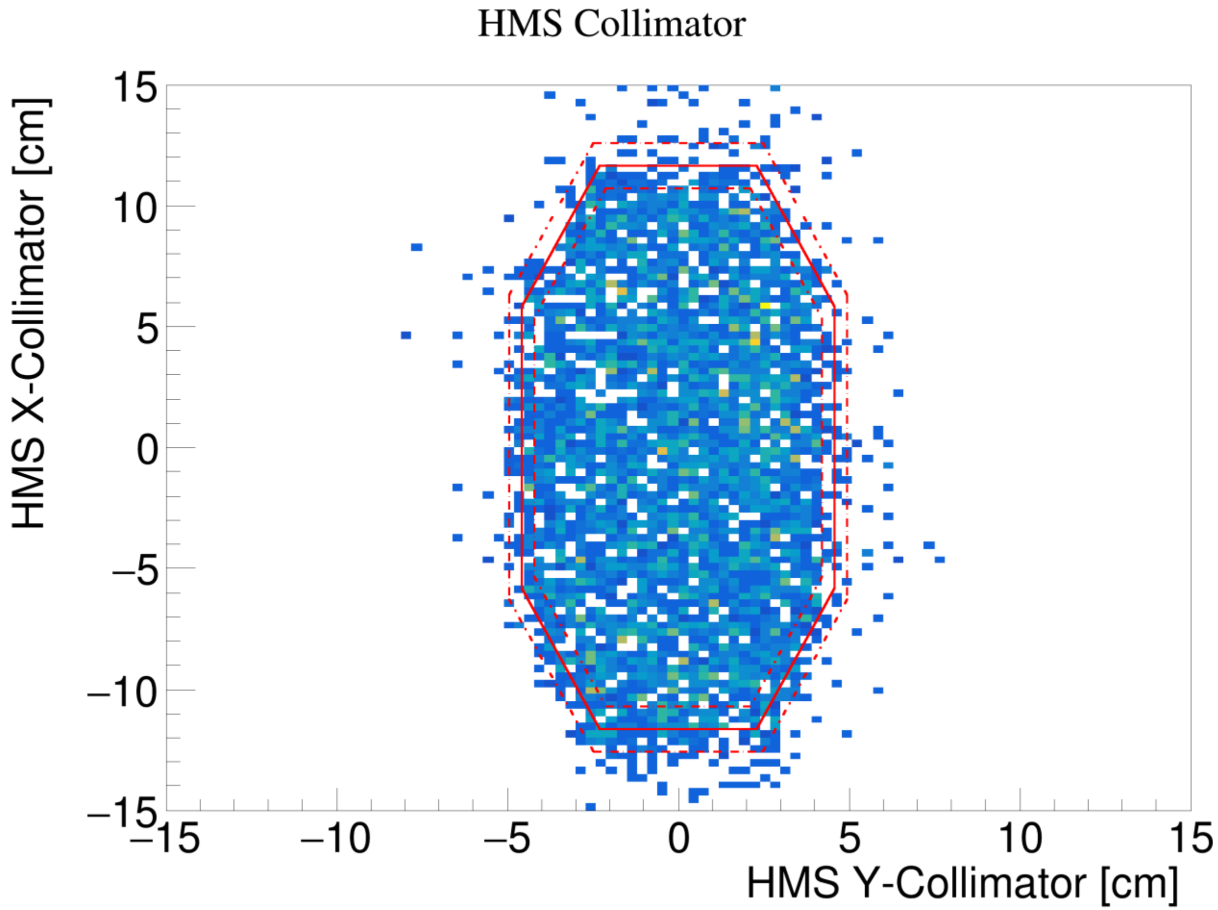
SHMS X'tar vs SHMS Y'tar
H2_eyptar_exptar_68
Entries 8112
Mean x −0.0001721
Mean y 0.000561
Std Dev x 0.007791
Std Dev y 0.004754
Y'etar (rad)
X'etar (rad)
0.04
0.03
0.02
0.01
0
−0.01
−0.02
−0.03
−0.04

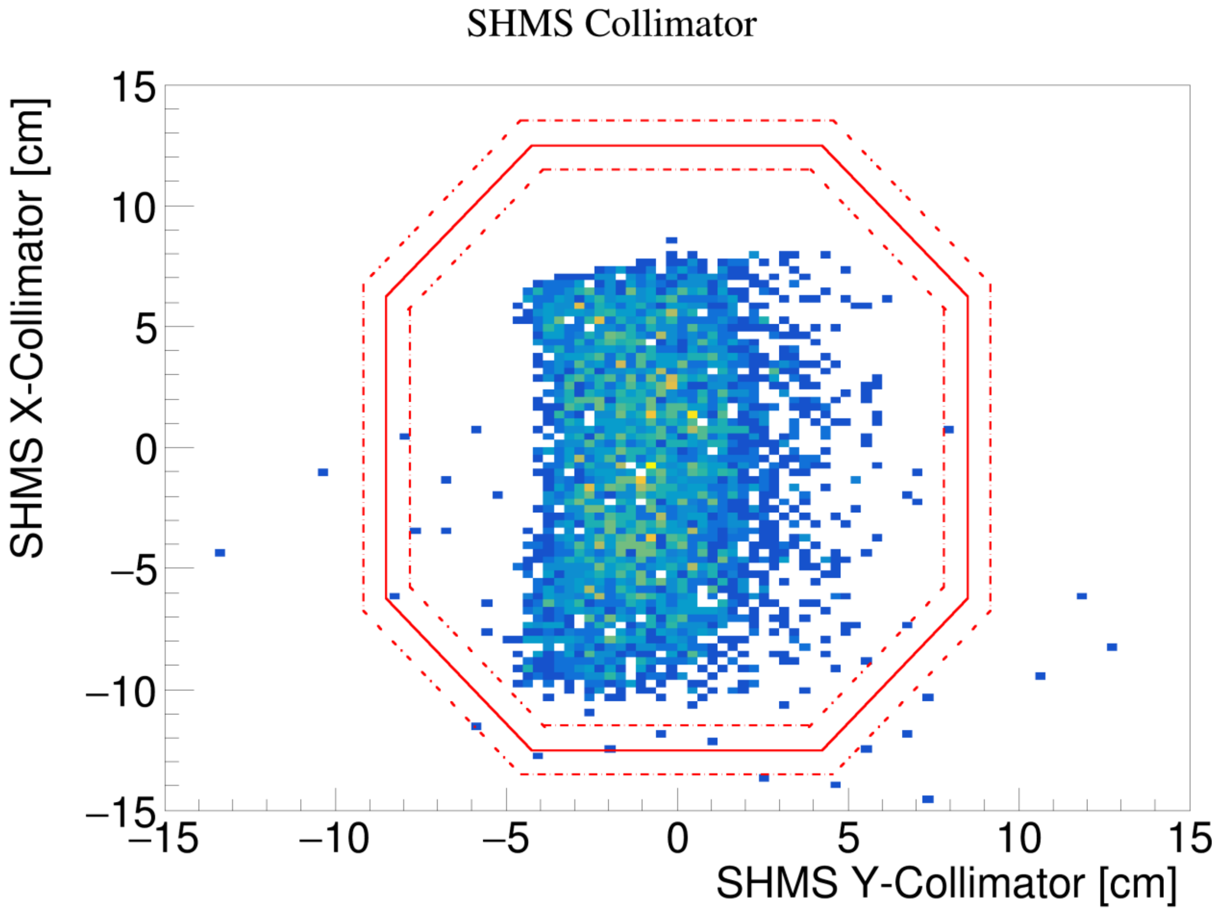
Hall C: CaFe Experimental Setup

- A(e,e'p)
- 10.6 GeV
- Detect scattered electrons in the Super High Momentum Spectrometer (SHMS)
- Detect knocked-out protons in the High Momentum Spectrometer (HMS)

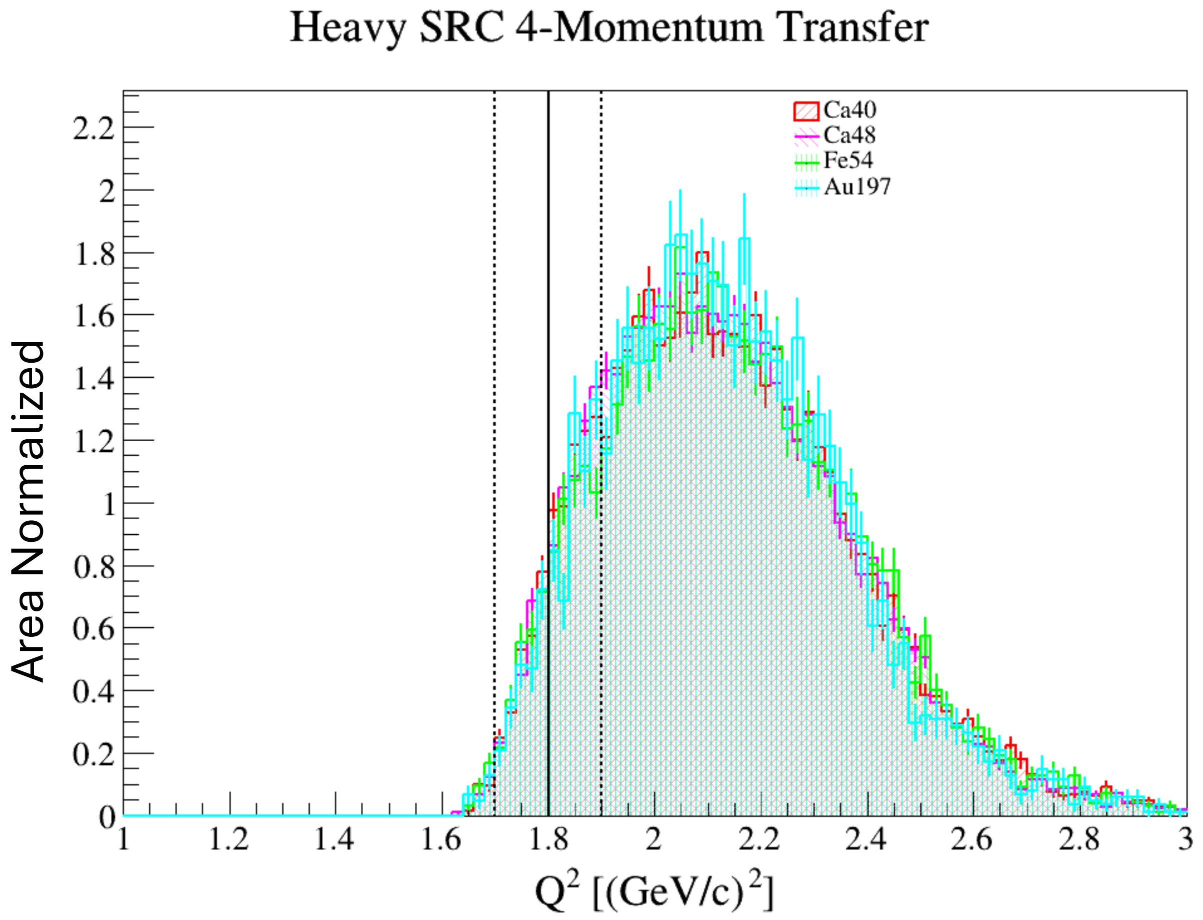


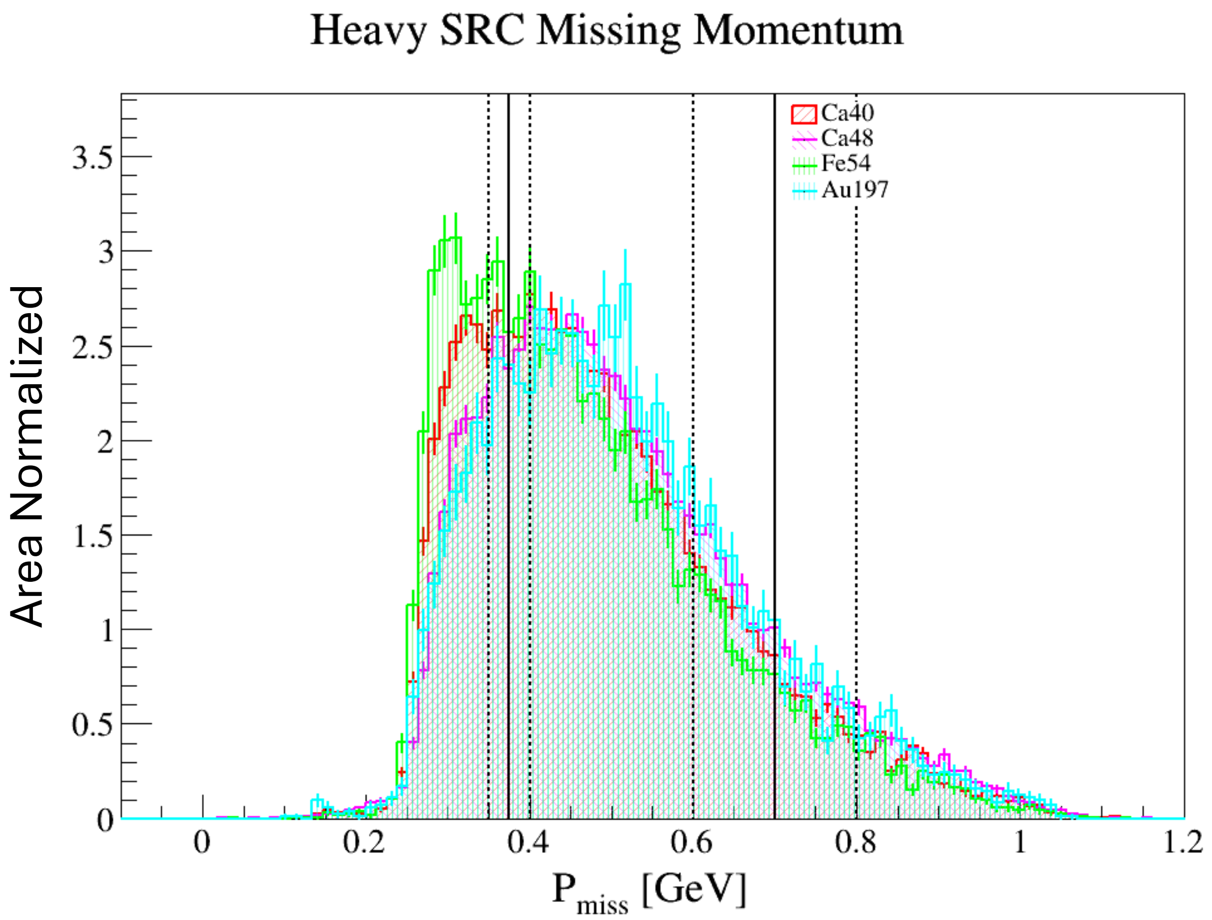
SRC HMS & SHMS Collimator Cuts (±2σ)



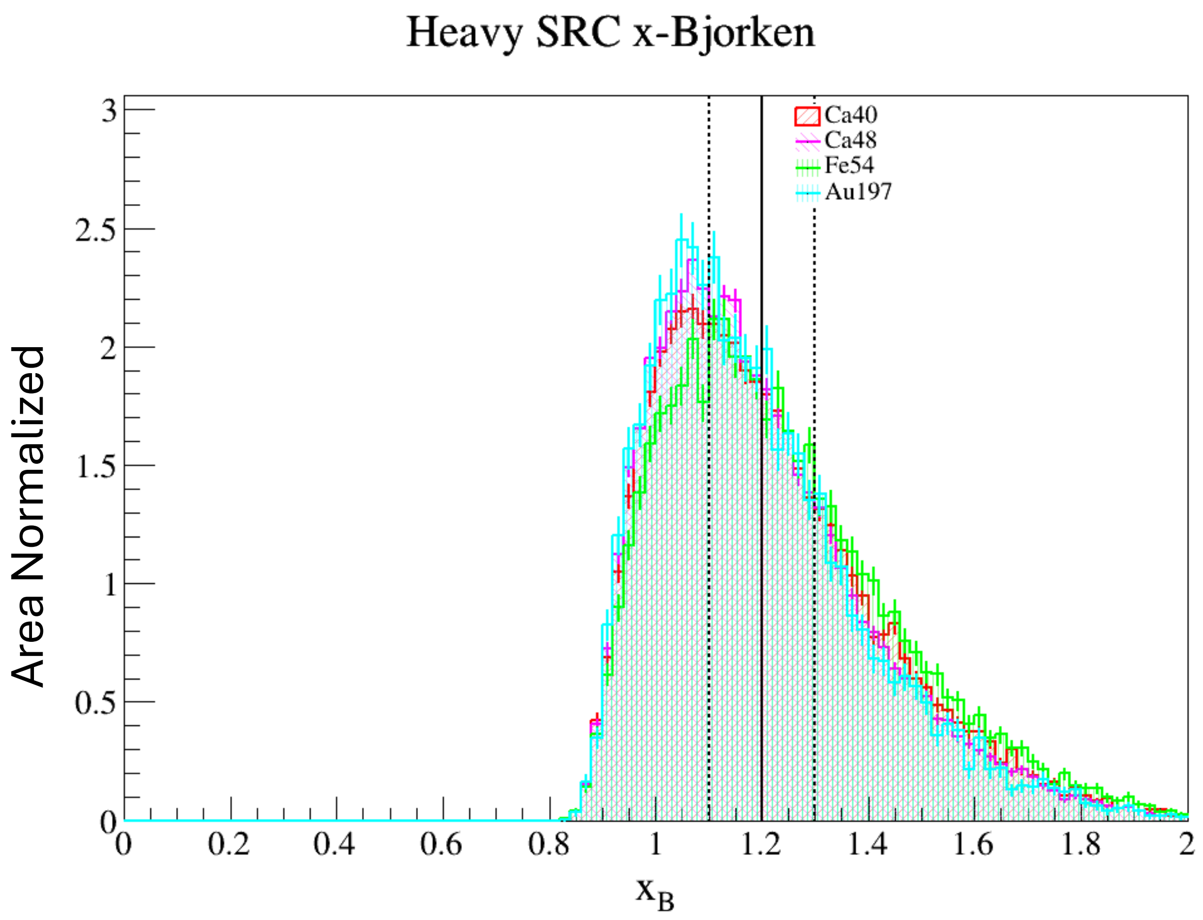


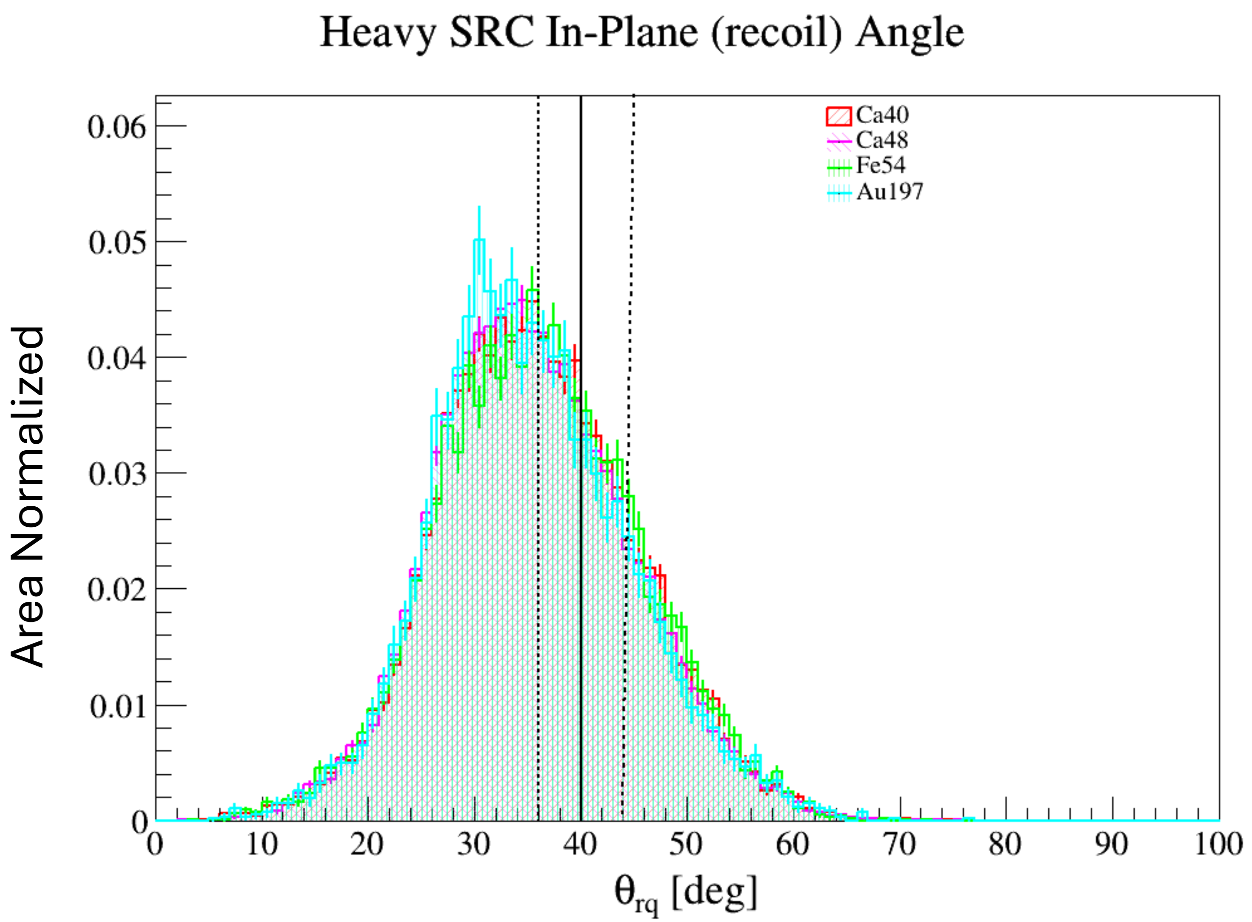
SRC Q^2 & P_m Cuts (±2σ)



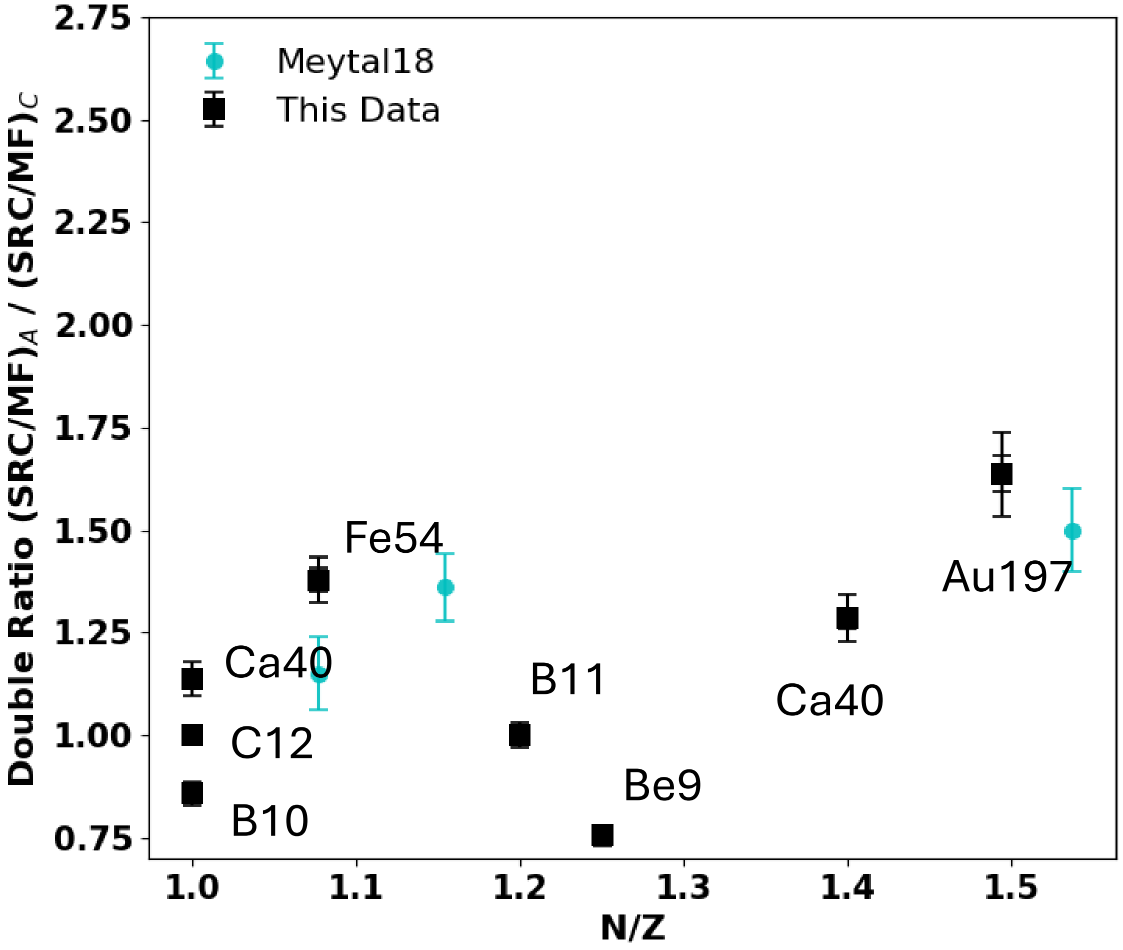


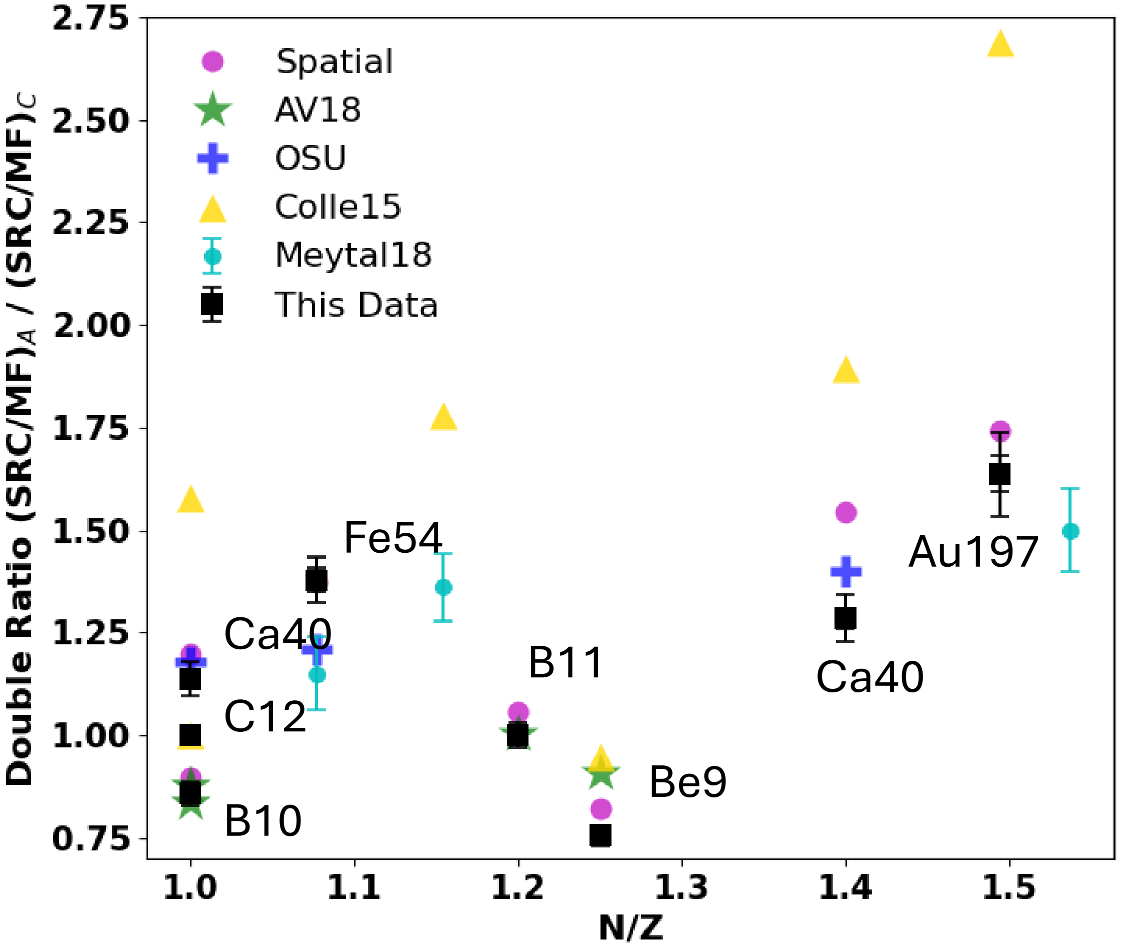
SRC x_{bj} & θ_{rq} Cuts (±2σ)



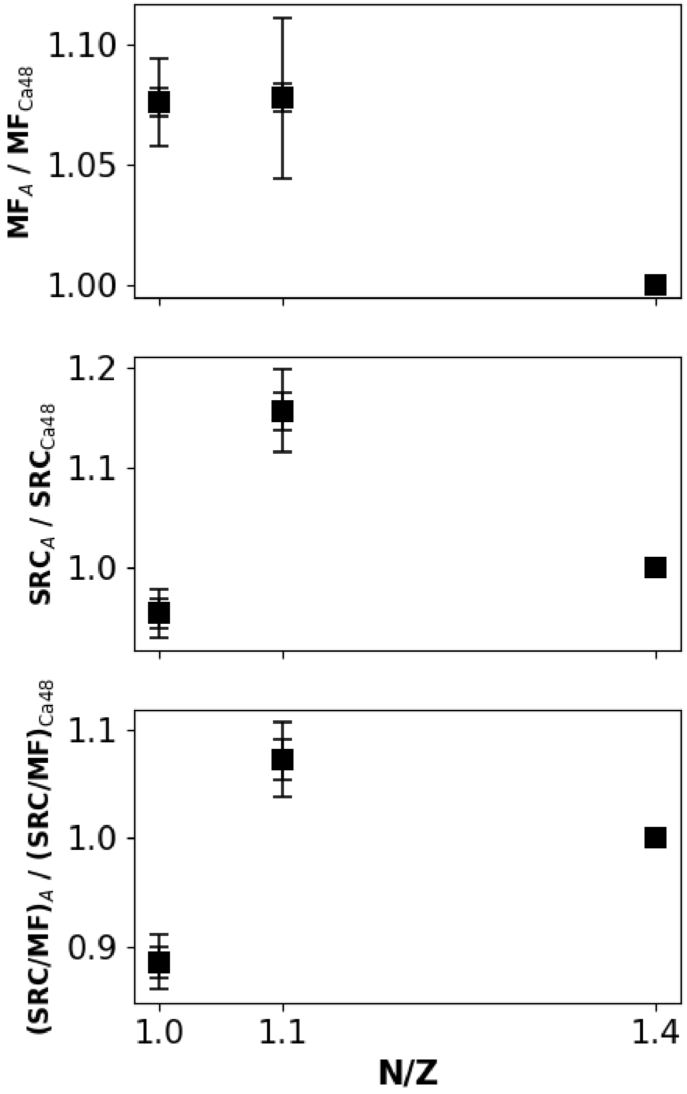


Double Ratio vs N/Z

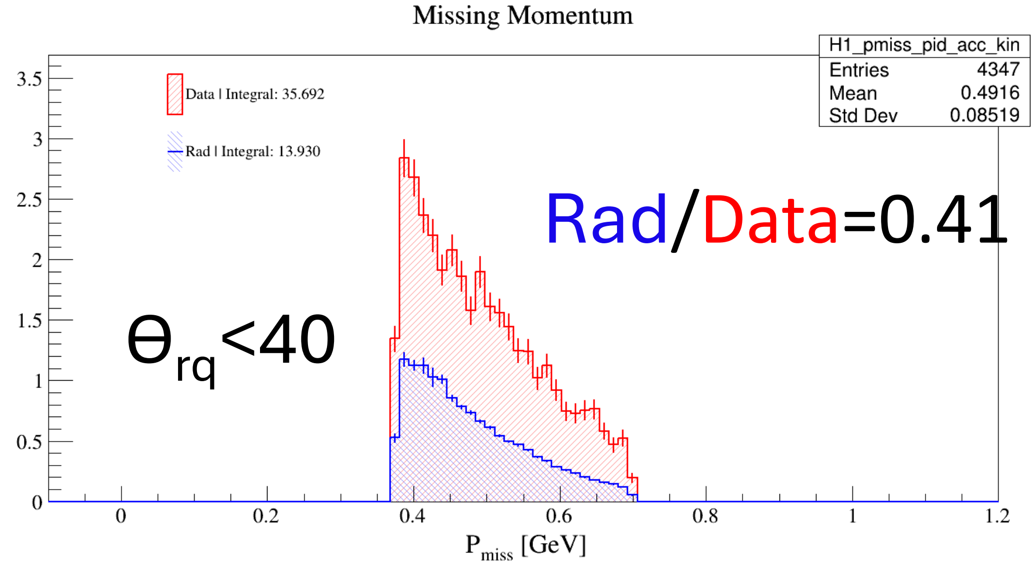


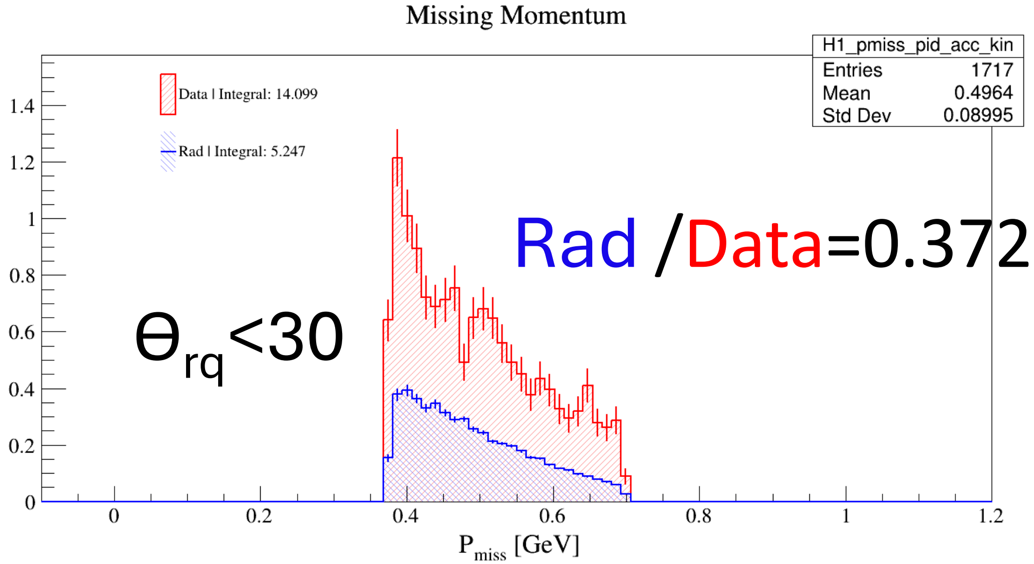


Triplet Ratios N/Z



Check C12 SRC FSI Effects





Data PWIA ratio stable for varying θ_{rq} cuts, therefore data is largely unaffected by FSI