The CaFe Experiment:

Isospin Dependence of Short-Range Correlations in Nuclei

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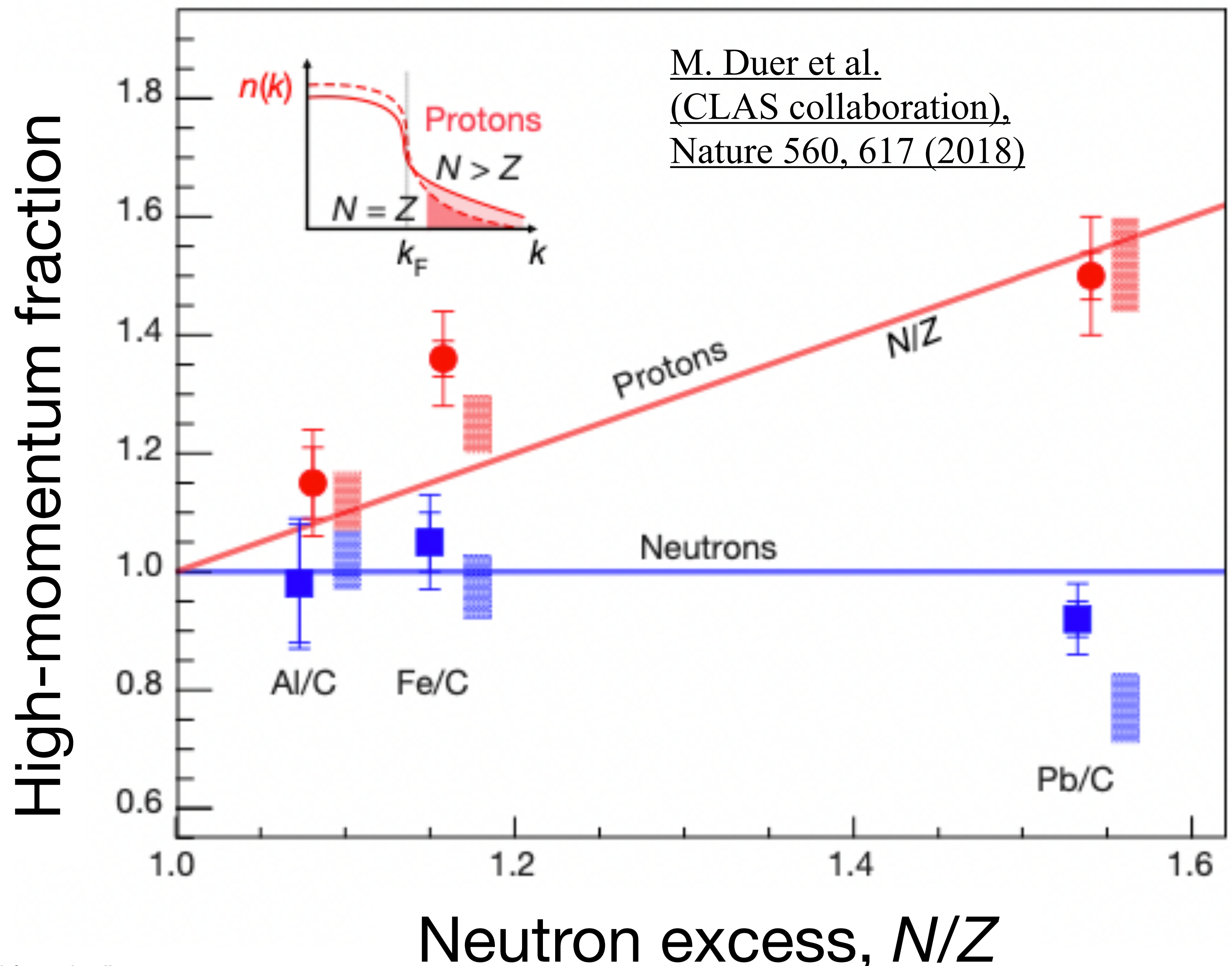
Hall C Experiment-Theory Working Group Meeting

April 15, 2024

Proposal: PR12-16-004

Spokespeople: D. Higinbotham (JLab), F. Hauenstein (JLab), O. Hen (MIT), L. Weinstein (ODU)

which nucleons form SRC pairs ?



correlated
protons increase
(*np* pair dominated)

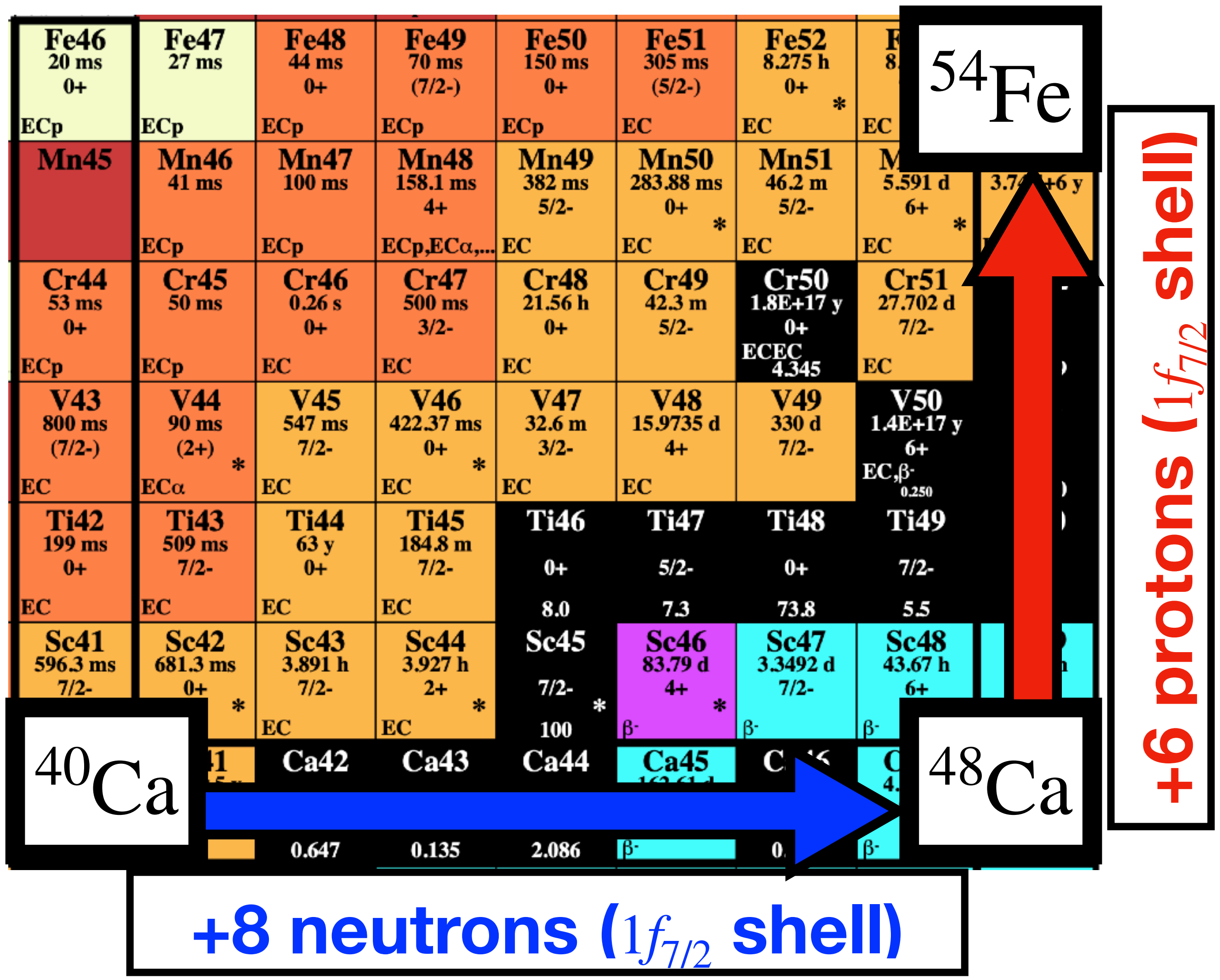
correlated
neutrons saturate

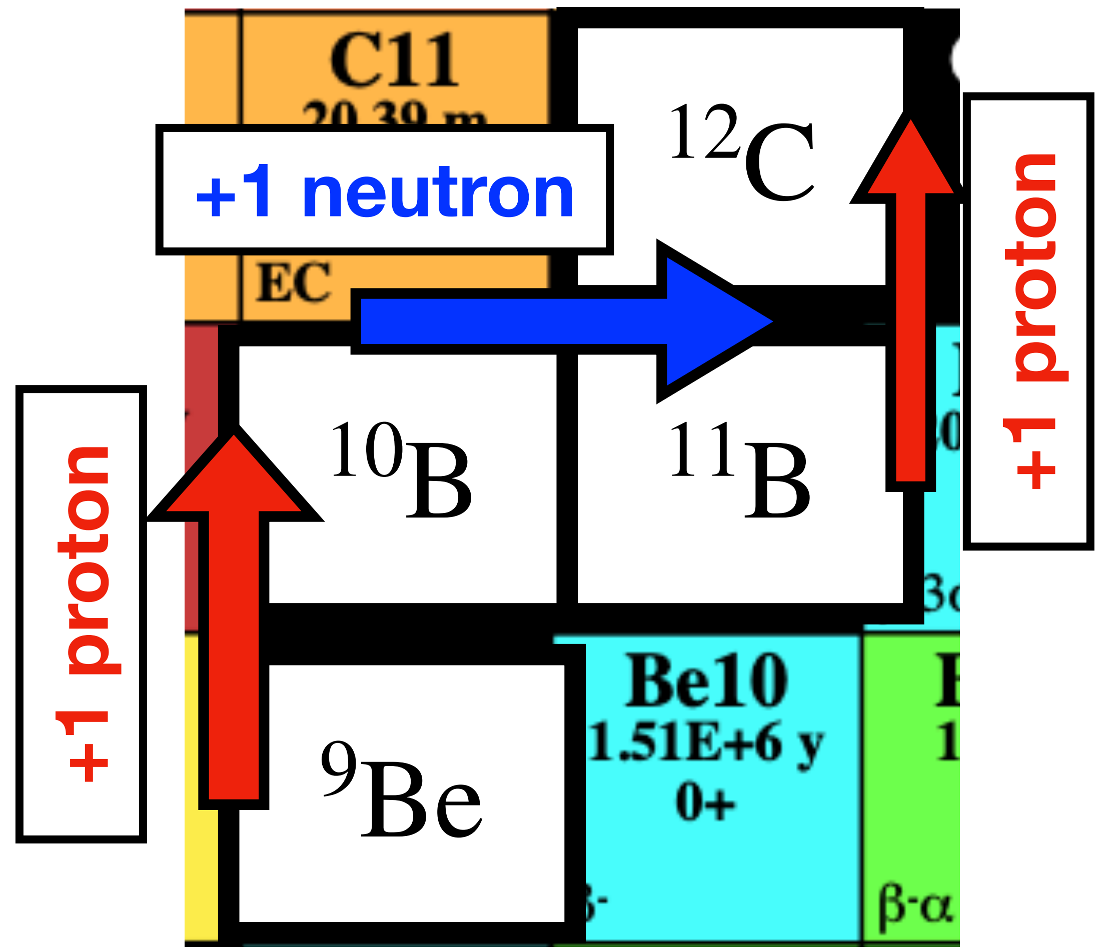
High-momentum fraction a.k.a. “double ratios”

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

How does NN-SRC pairing change
with mass (A) and asymmetry (N/Z) ?

which nuclei to investigate ?





- Which nucleons form pairs?
  - How does adding +8 $1f_{7/2}$ neutrons to a $2s1d$ closed shell ^{40}Ca change the proton pairing?
  - How does adding +6 $1f_{7/2}$ protons to ^{48}Ca change the proton pairing?
  - What about adding $+1p$, $+1n$ in light nuclei? 9Be → 10B → 11B → 12C

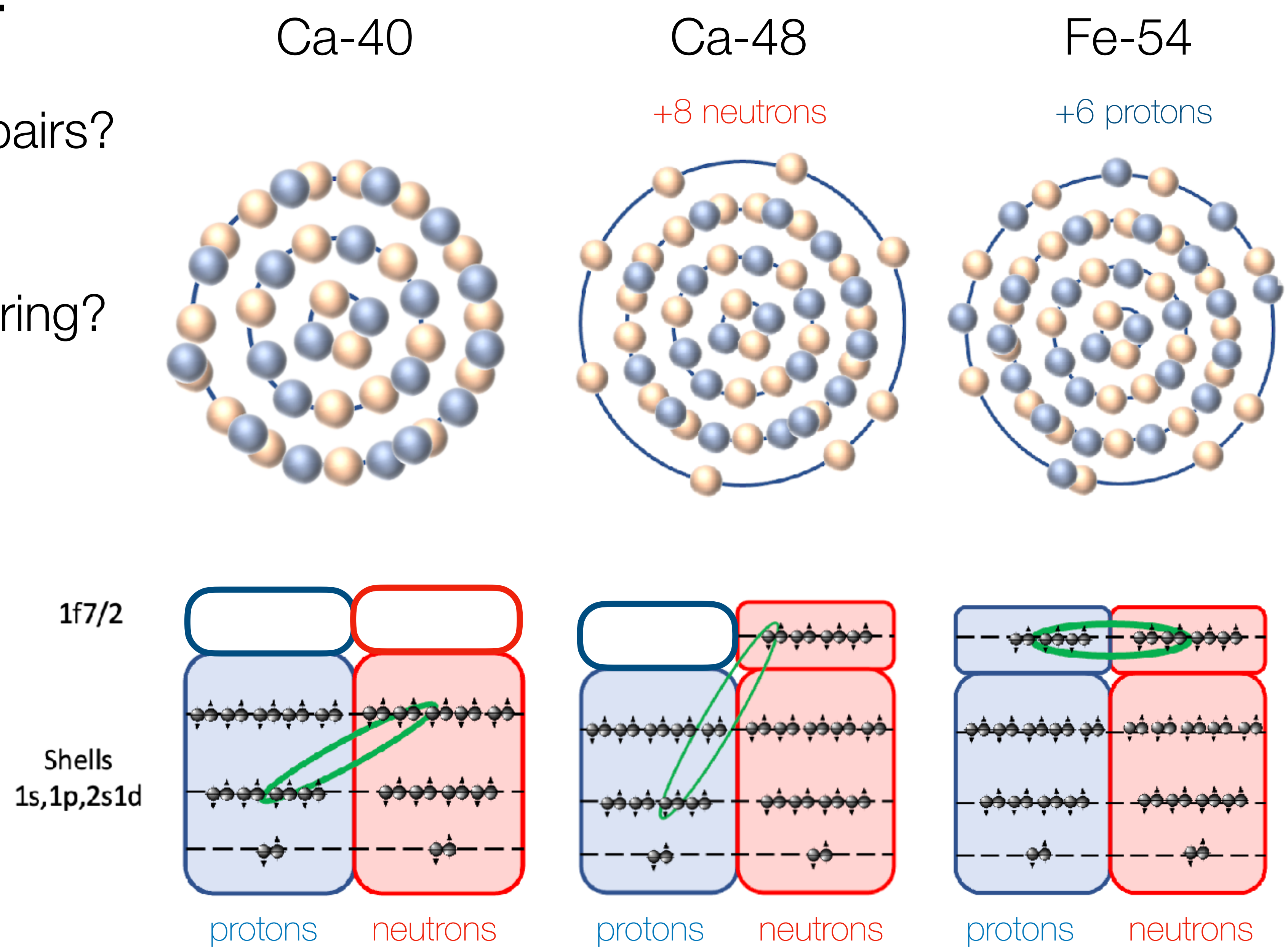
* *we also took data on Au197*

CaFe Triplet Shell Diagram

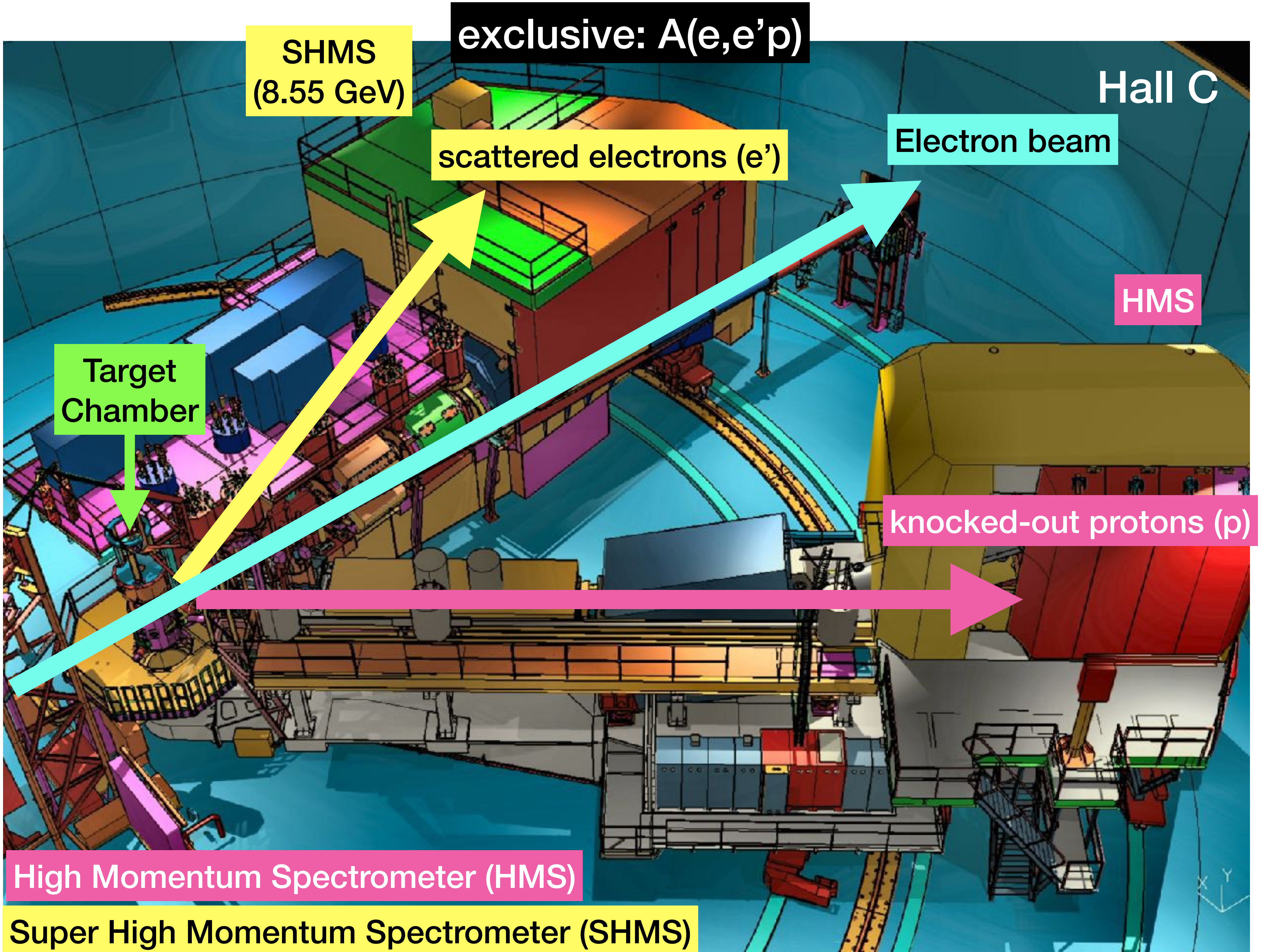
CaFe @ Hall C will answer:

- Which bound nucleons form pairs?
- How does adding (*n* or *p*) independently change *NN* pairing?

Diagram/Picture by: Larry Weinstein / Or Hen

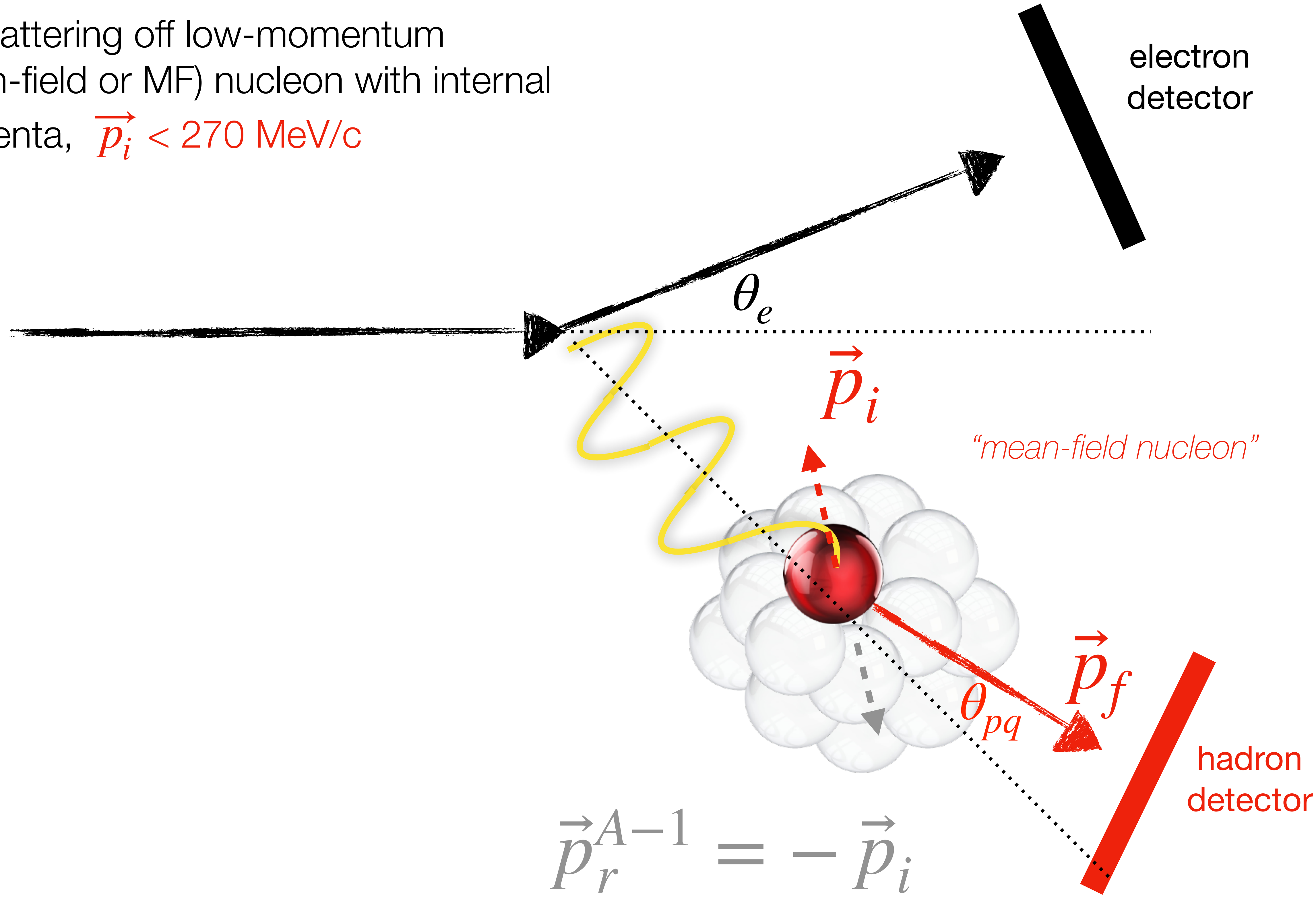


CaFe Experiment Setup @ Hall C



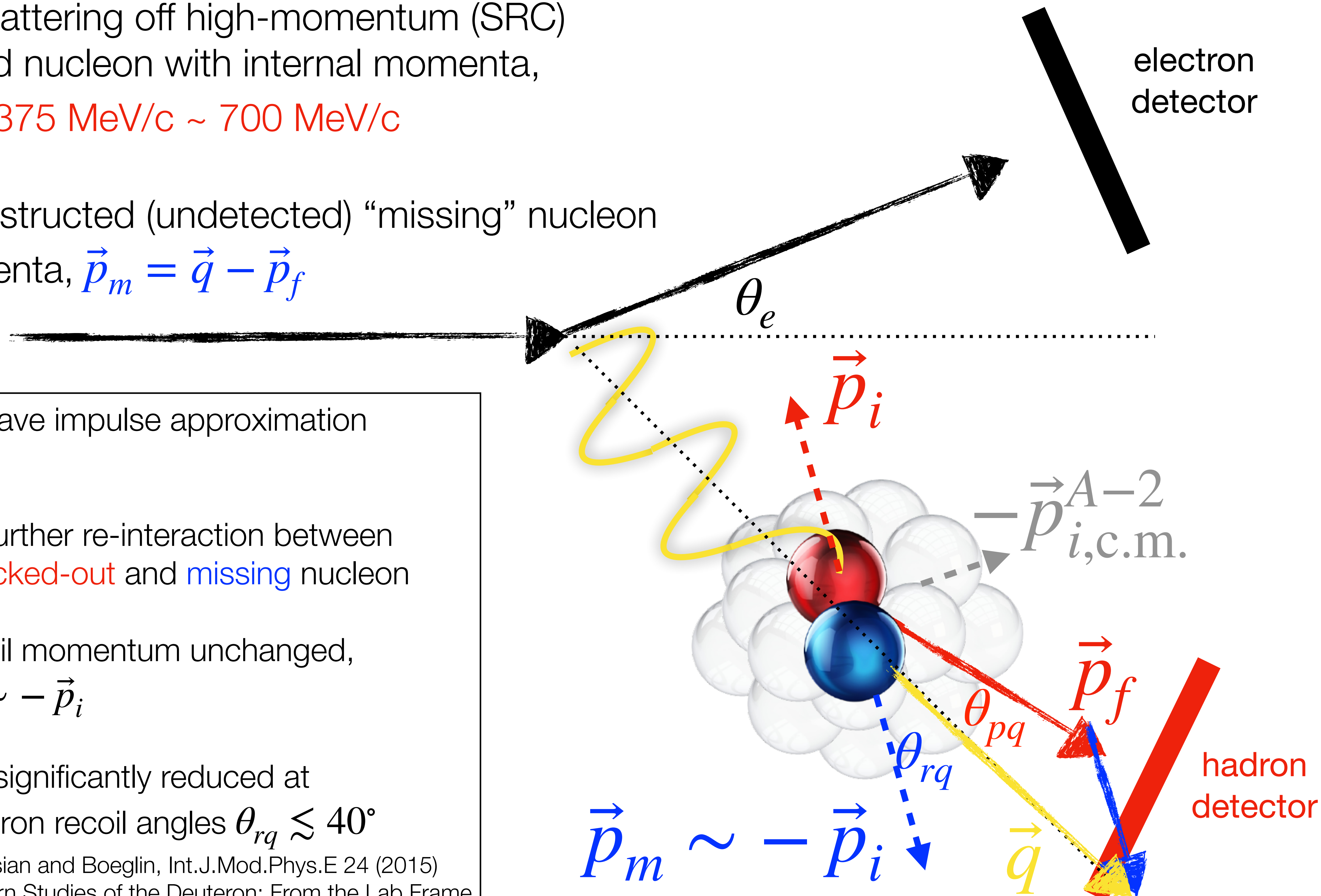
exclusive: A(e,e'p) @ MF

- e- scattering off low-momentum (mean-field or MF) nucleon with internal momenta, $\vec{p}_i$ < 270 MeV/c



exclusive: A(e,e'p) @ SRC

- e- scattering off high-momentum (SRC) bound nucleon with internal momenta, $\vec{p_i}$ > 375 MeV/c ~ 700 MeV/c
- reconstructed (undetected) “missing” nucleon momenta, $\vec{p}_m = \vec{q} - \vec{p}_f$



- plane-wave impulse approximation (PWIA)
  - no further re-interaction between knocked-out and missing nucleon
  - recoil momentum unchanged, $\vec{p}_r \sim -\vec{p}_i$
  - FSI significantly reduced at neutron recoil angles $\theta_{rq} \lesssim 40^{\circ}$
    (Sargsian and Boeglin, Int.J.Mod.Phys.E 24 (2015) Modern Studies of the Deuteron: From the Lab Frame to the Light Front)

Kinematics

NOTE: put the actual central momentum used (based on histos)

Beam Energy: $E_b = 10.6$ GeV

Targets: 9Be, 10B, 11B, 12C, 40Ca, 48Ca, 54Fe, 197Au

KIN	k_e (GeV/c)	θ_e (deg)	p_f (GeV/c)	θ_p (deg)	Q^2 (GeV^2)	P_{miss} (GeV/c)
MF	9.4	8.3	1.820	48.3	>1.8	0.150
SRC	9.4	8.3	1.325	66.4	>1.8	0.400

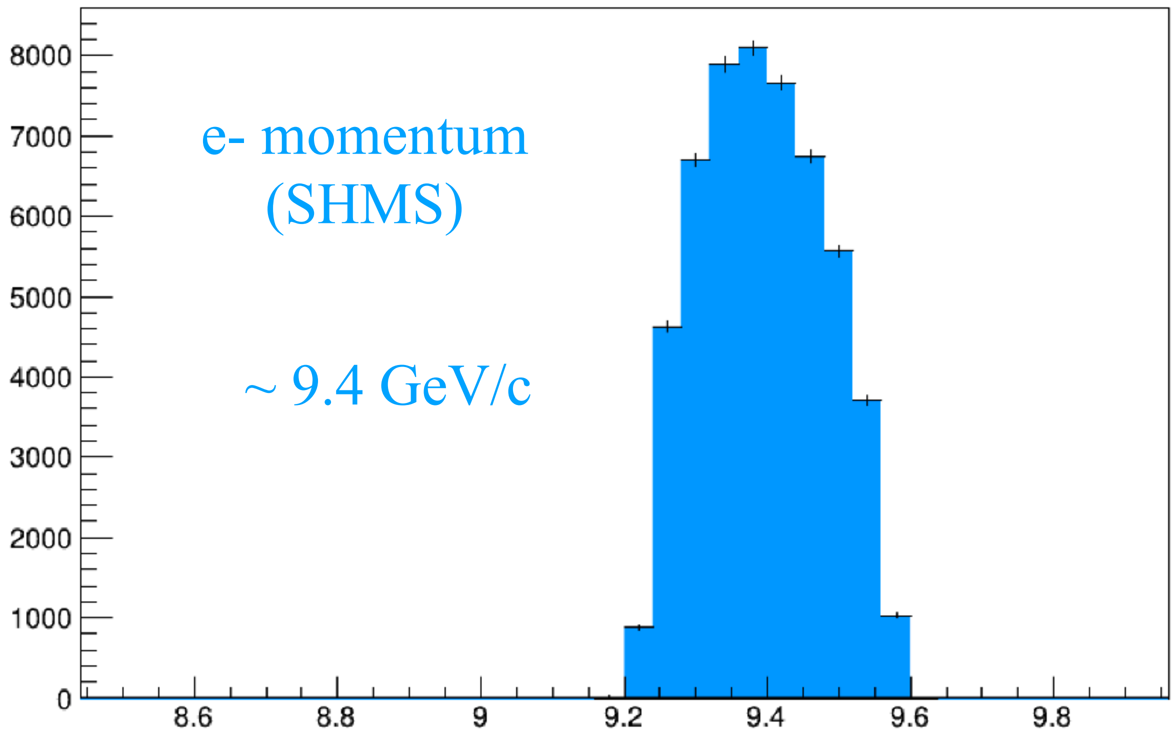
Mean Field (MF) Kinematics

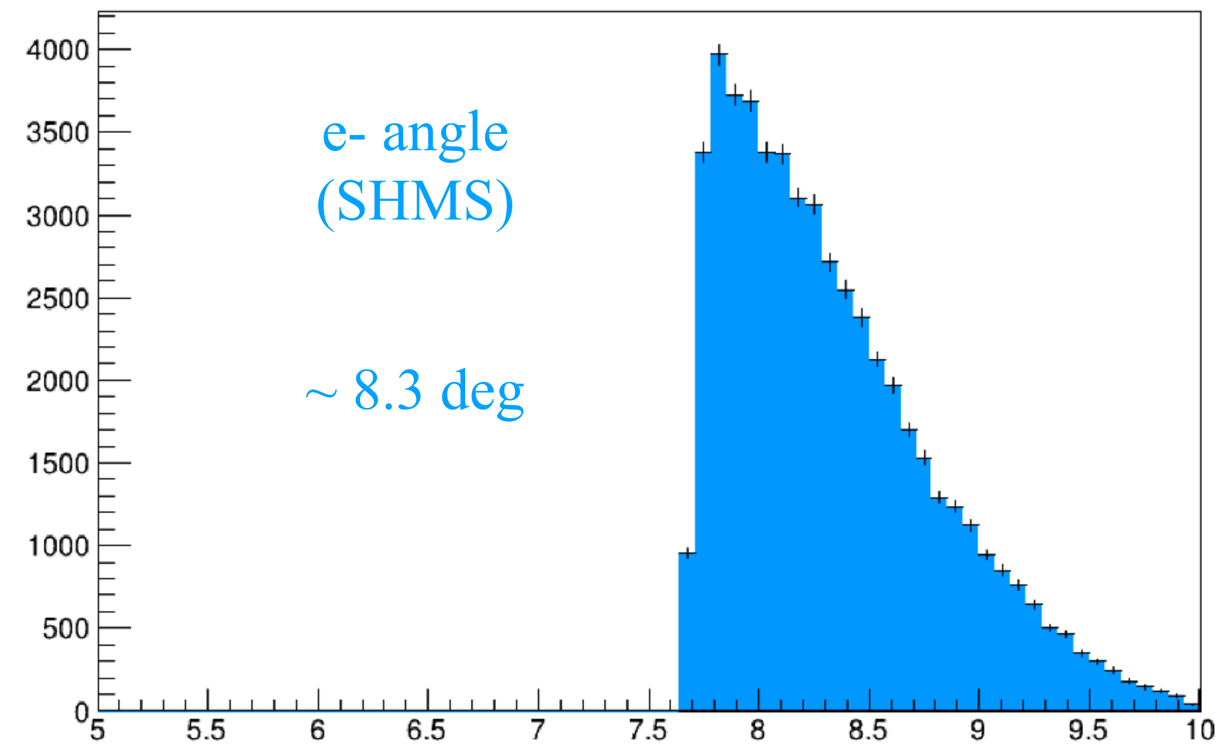
- $Q^2 > 1.8$ GeV^2
- $P_{miss} < 0.270$ GeV/c
- $-0.02 < E_{miss} < 0.09$ (GeV)

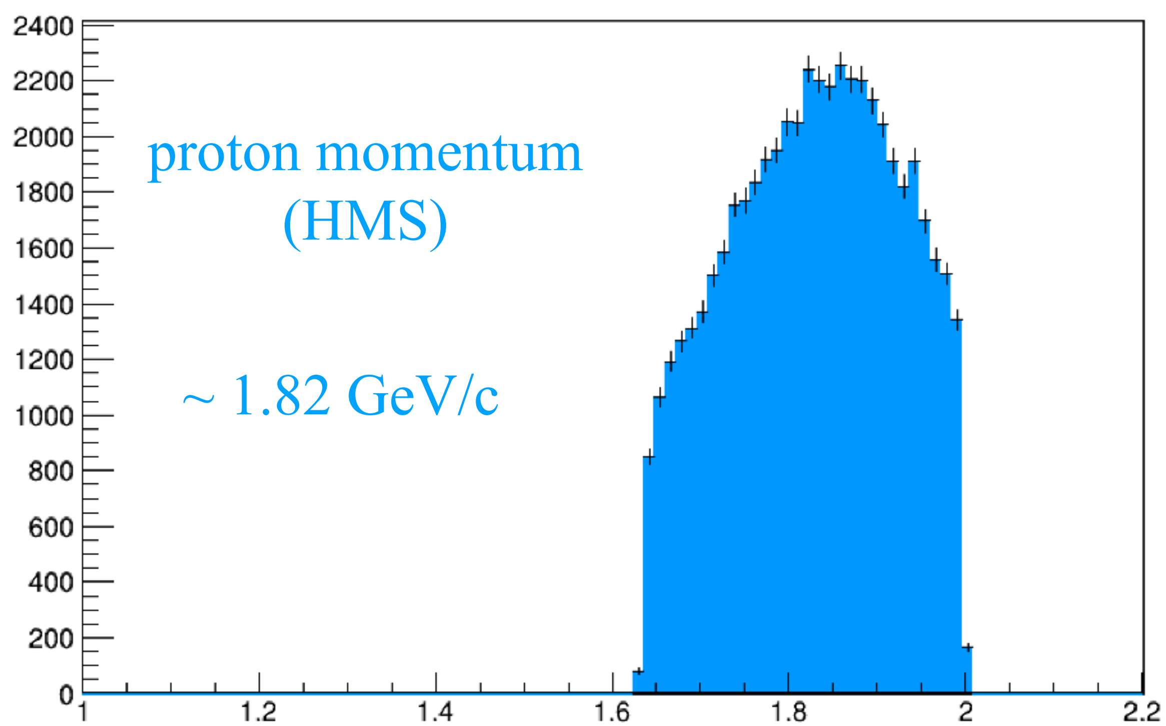
SRC Kinematics

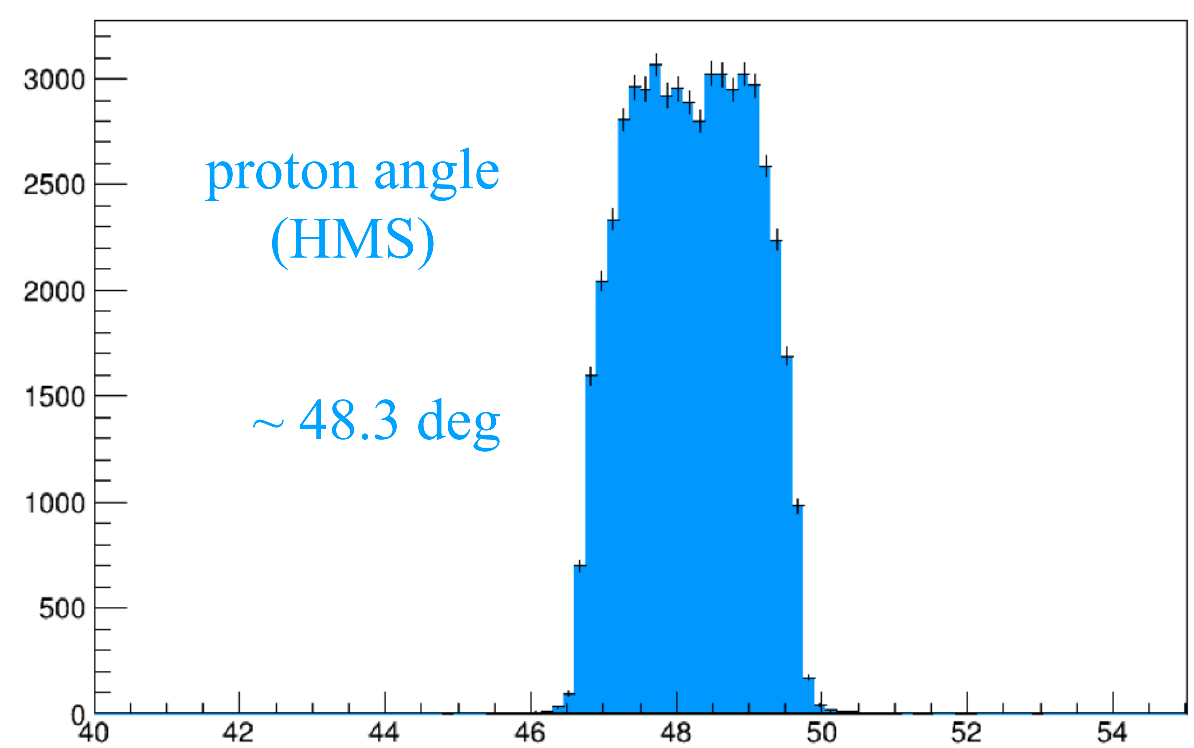
- $Q^2 > 1.8$ GeV^2
- $x_B > 1.2$
- $\theta_{rq} < 40°$
- $0.375 < p_{miss} < 0.7$ GeV/c

Kinematics (C12 MF)



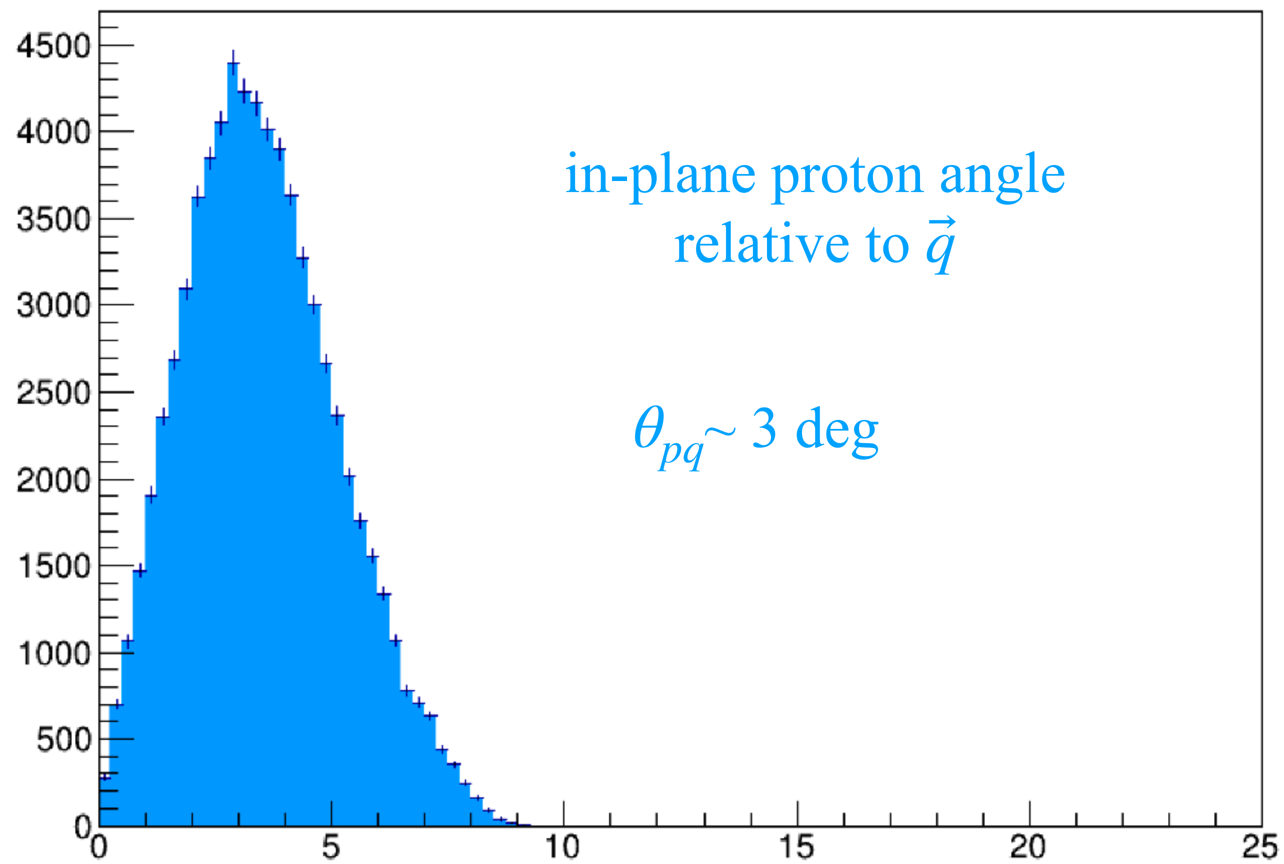


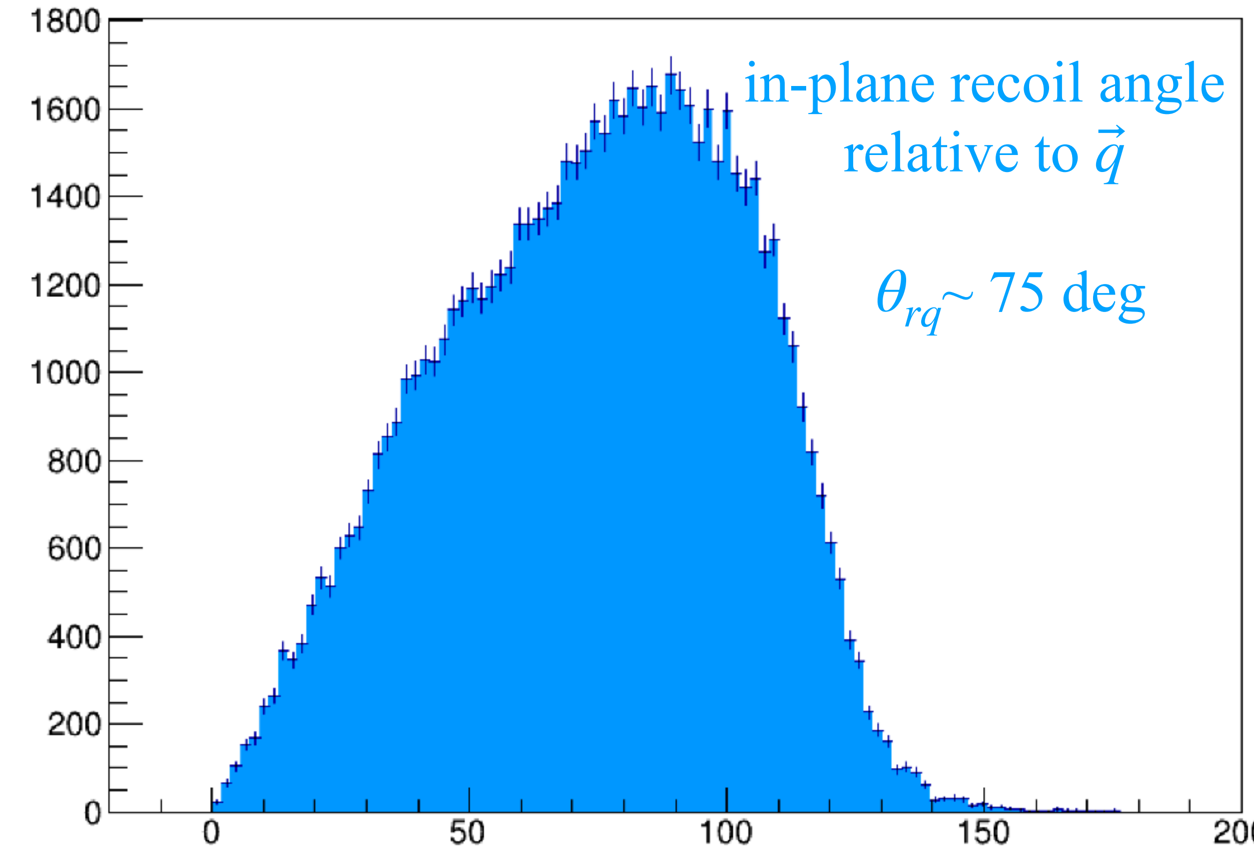


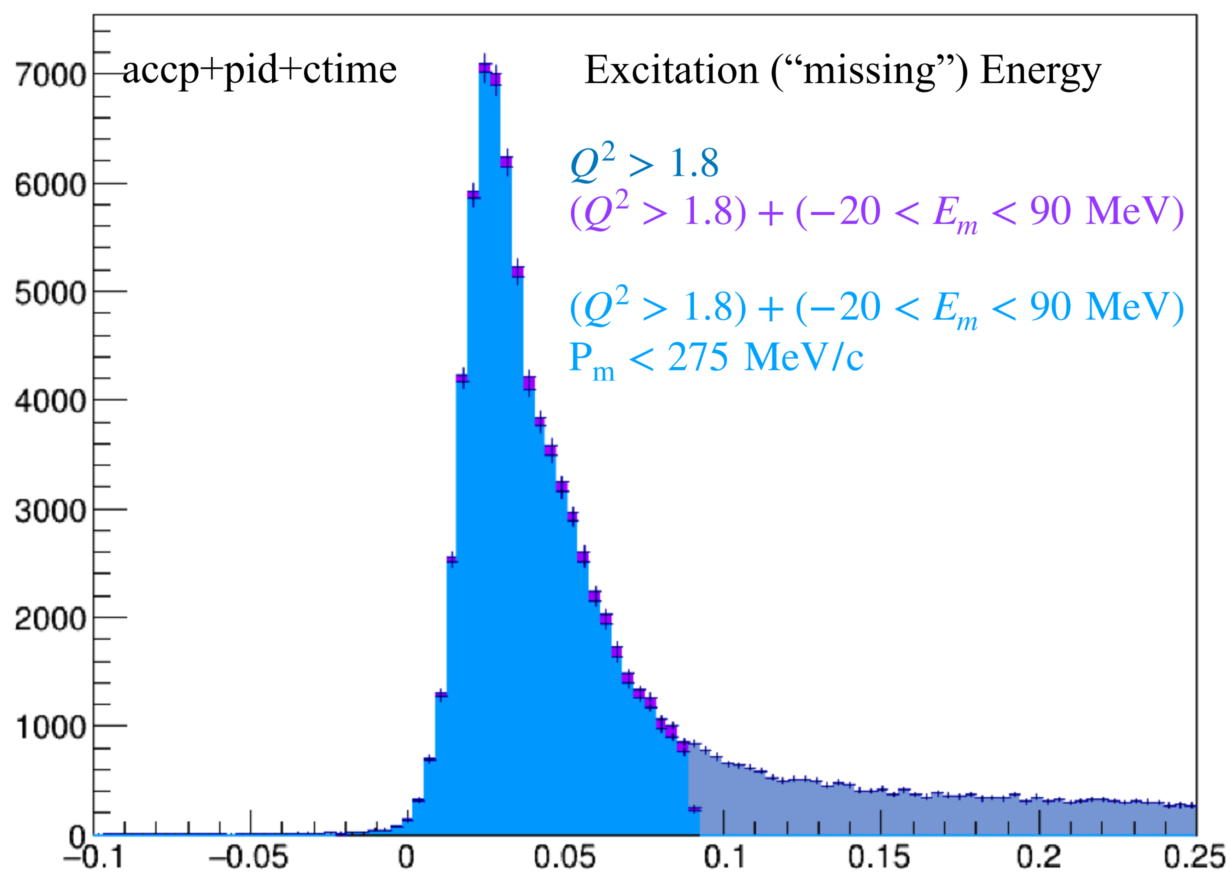


all analysis cuts applied

Kinematics (C12 MF)



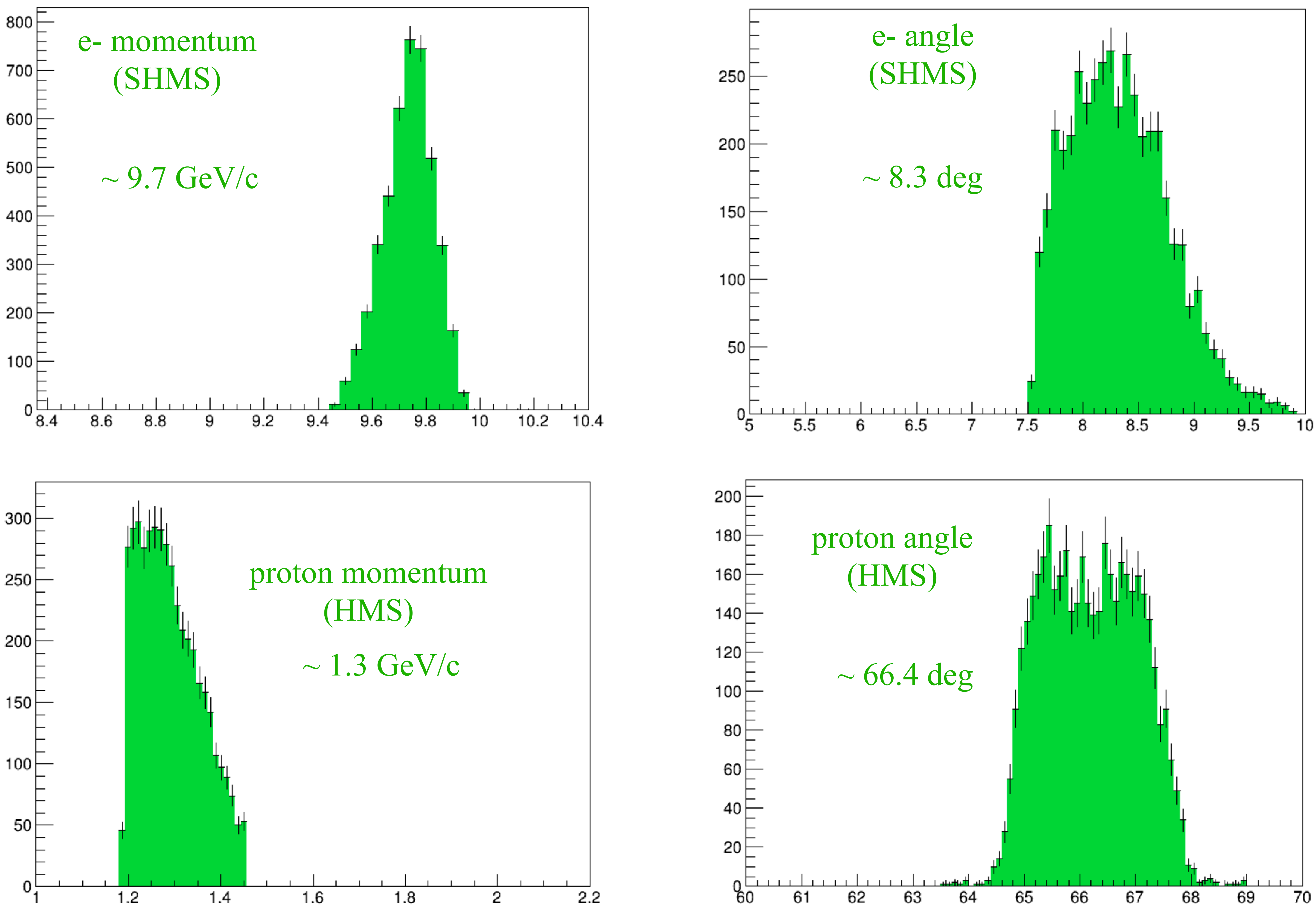




$$E_{miss} = \nu - T_p - T_{rec}$$

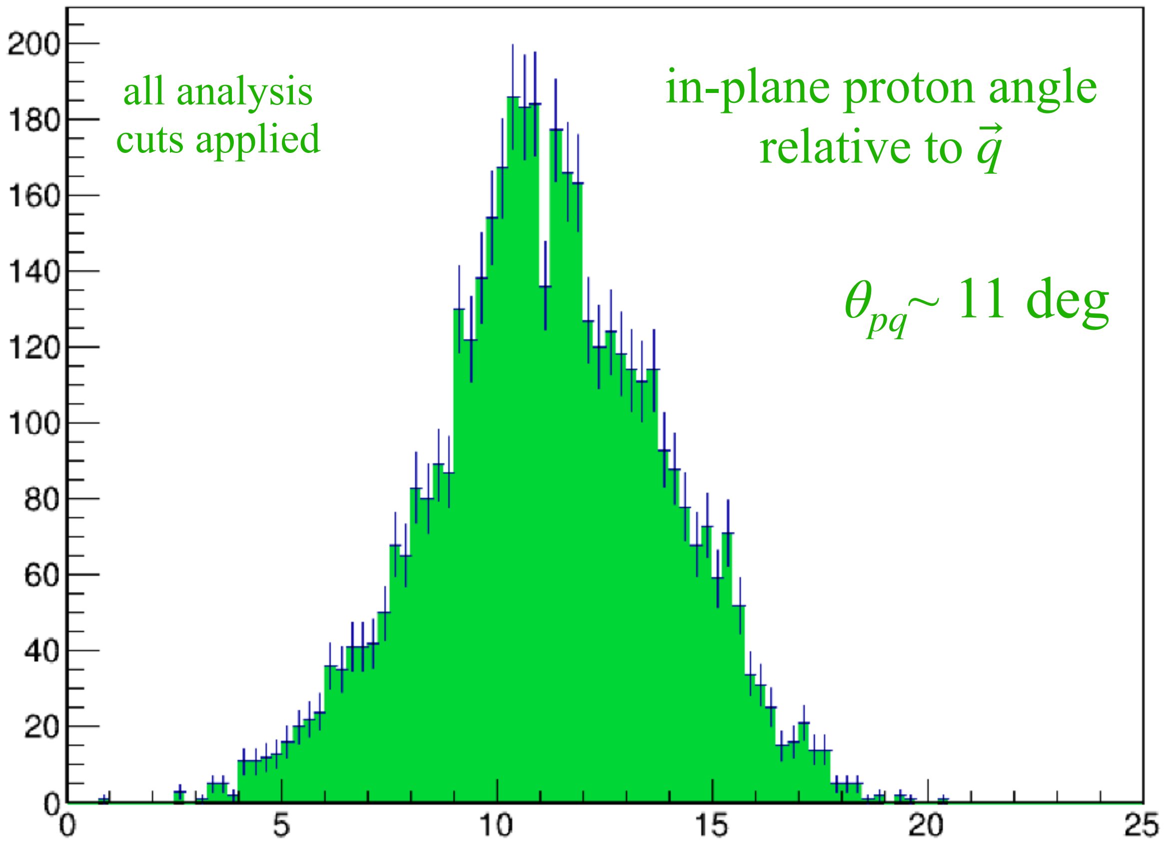
all analysis cuts applied

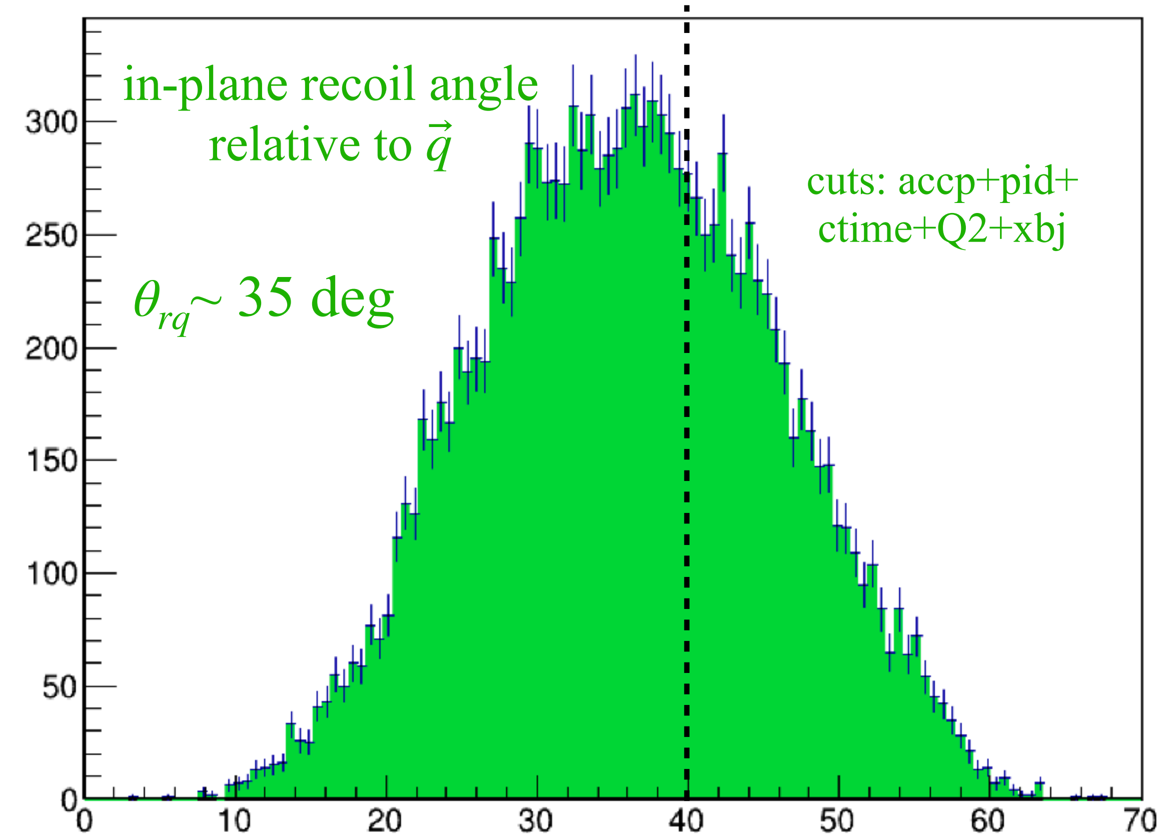
Kinematics (C12 SRC)

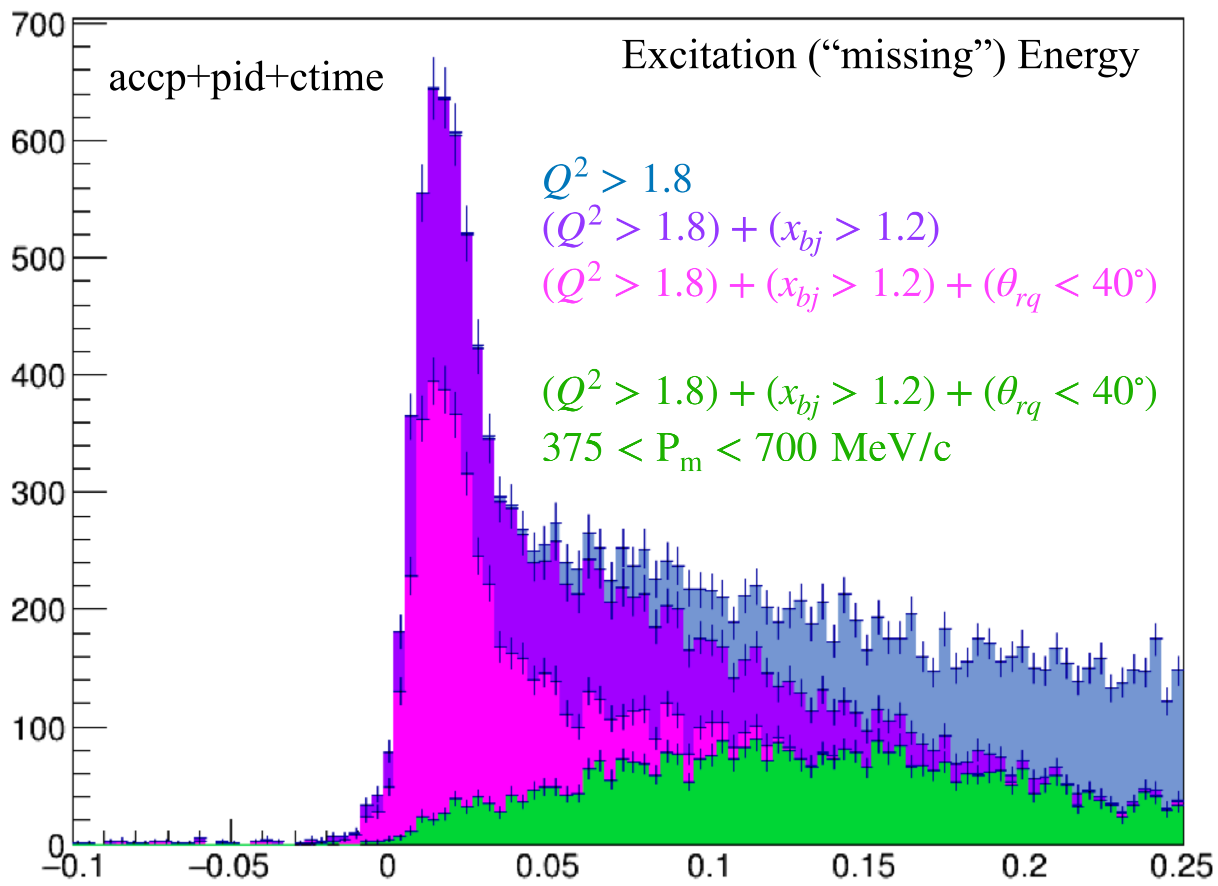


all analysis cuts applied

Kinematics (C12 SRC)

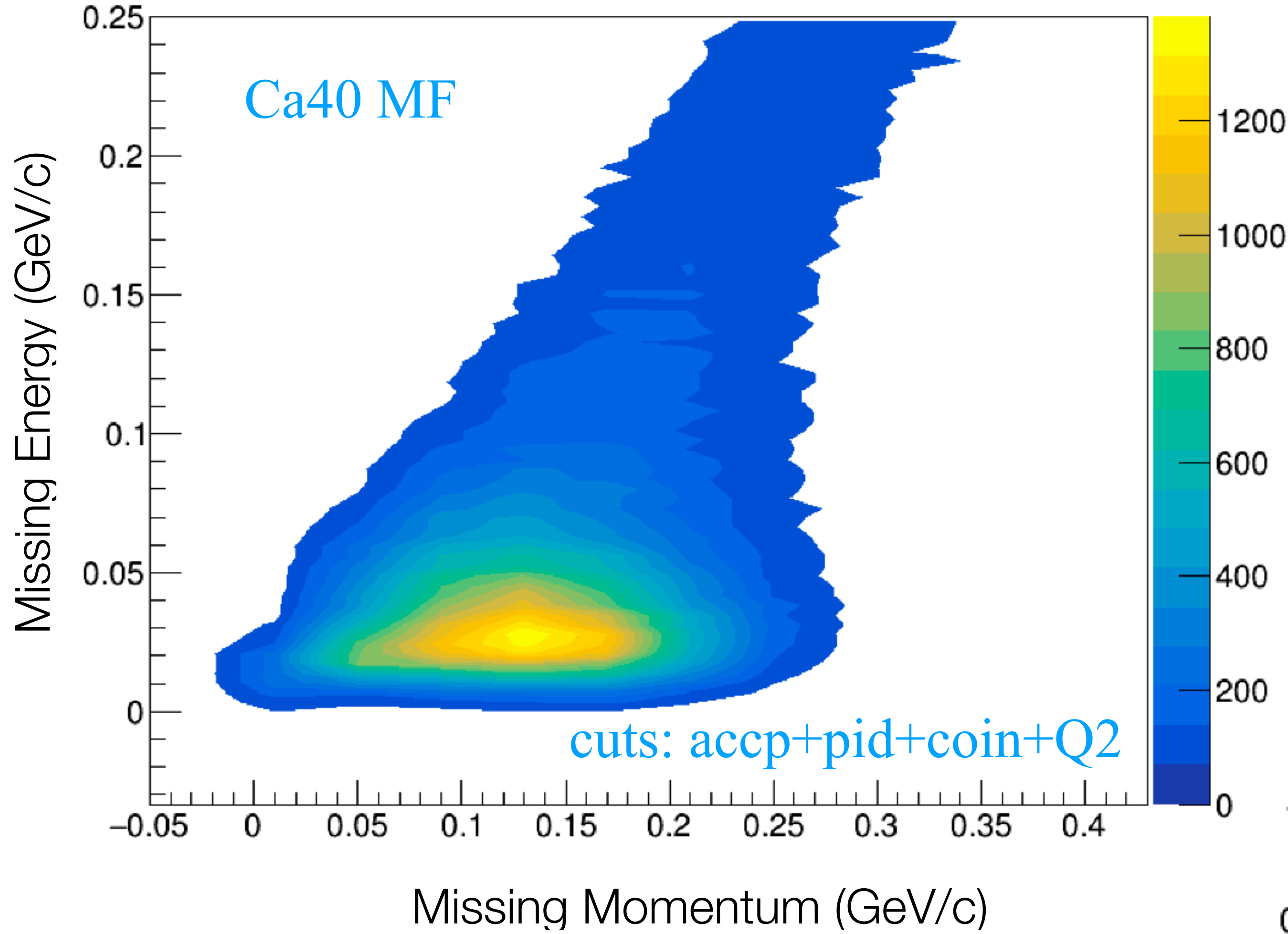


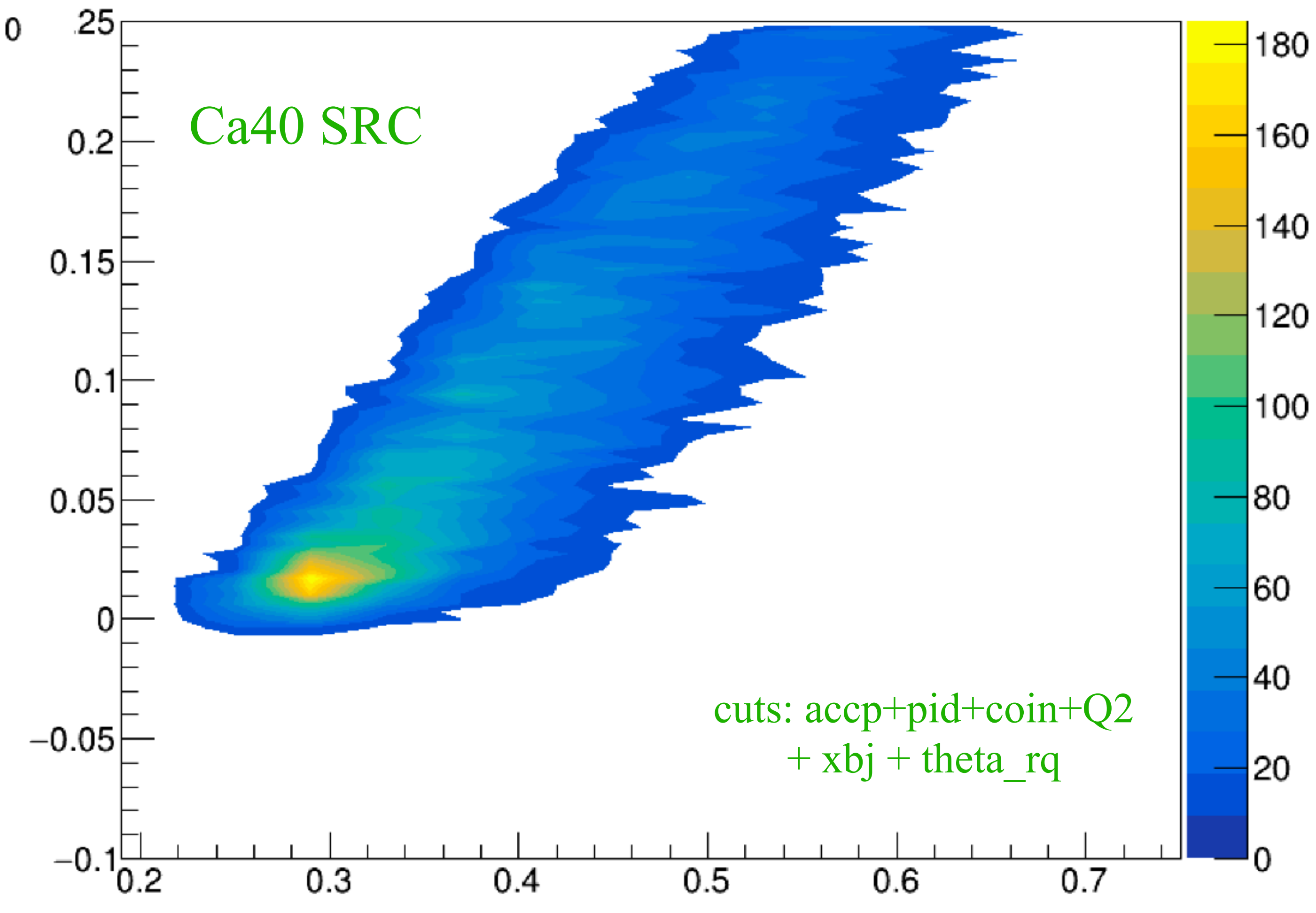




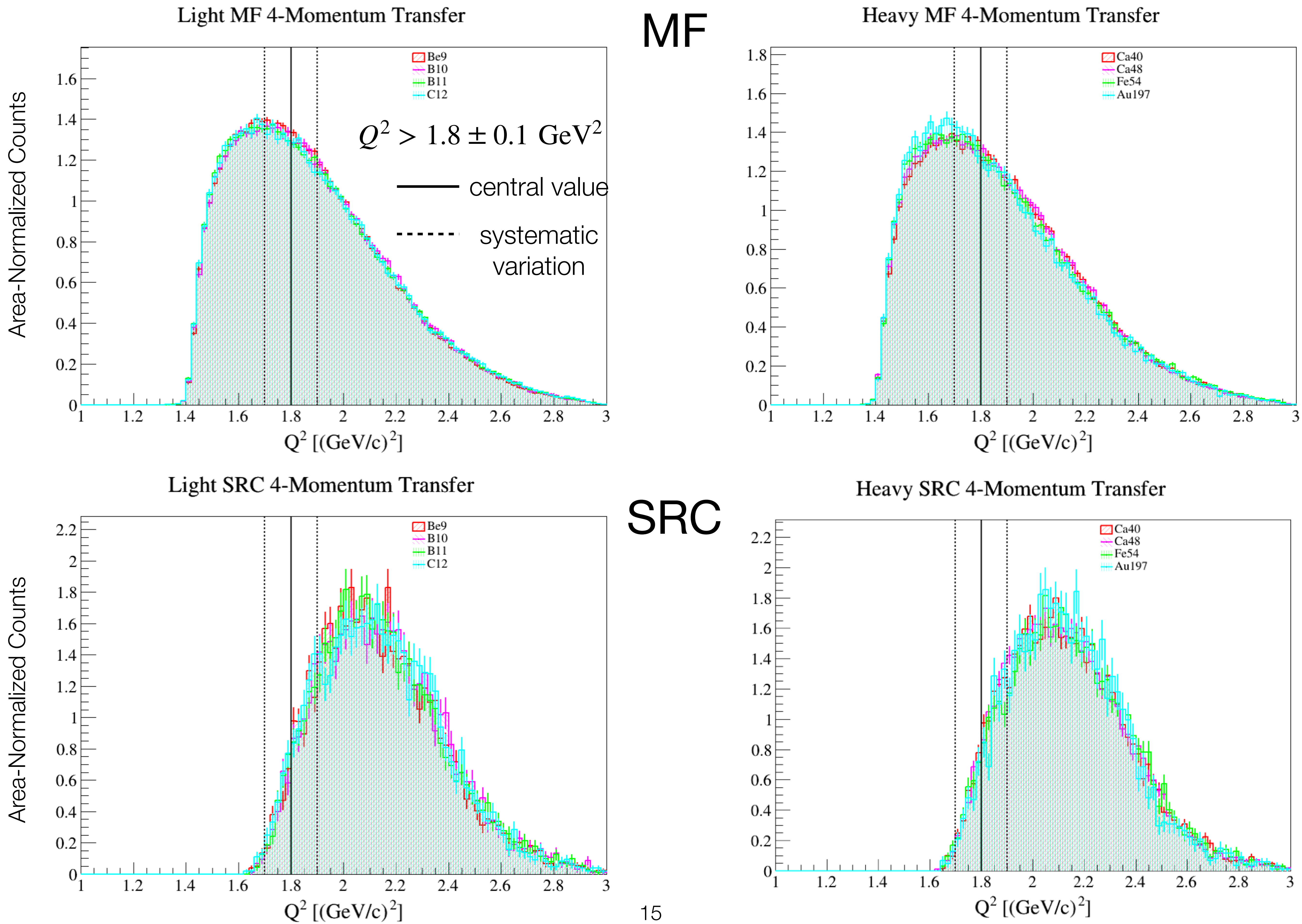
$$E_{miss} = \nu - T_p - T_{rec}$$

Missing Energy vs. Missing Momentum

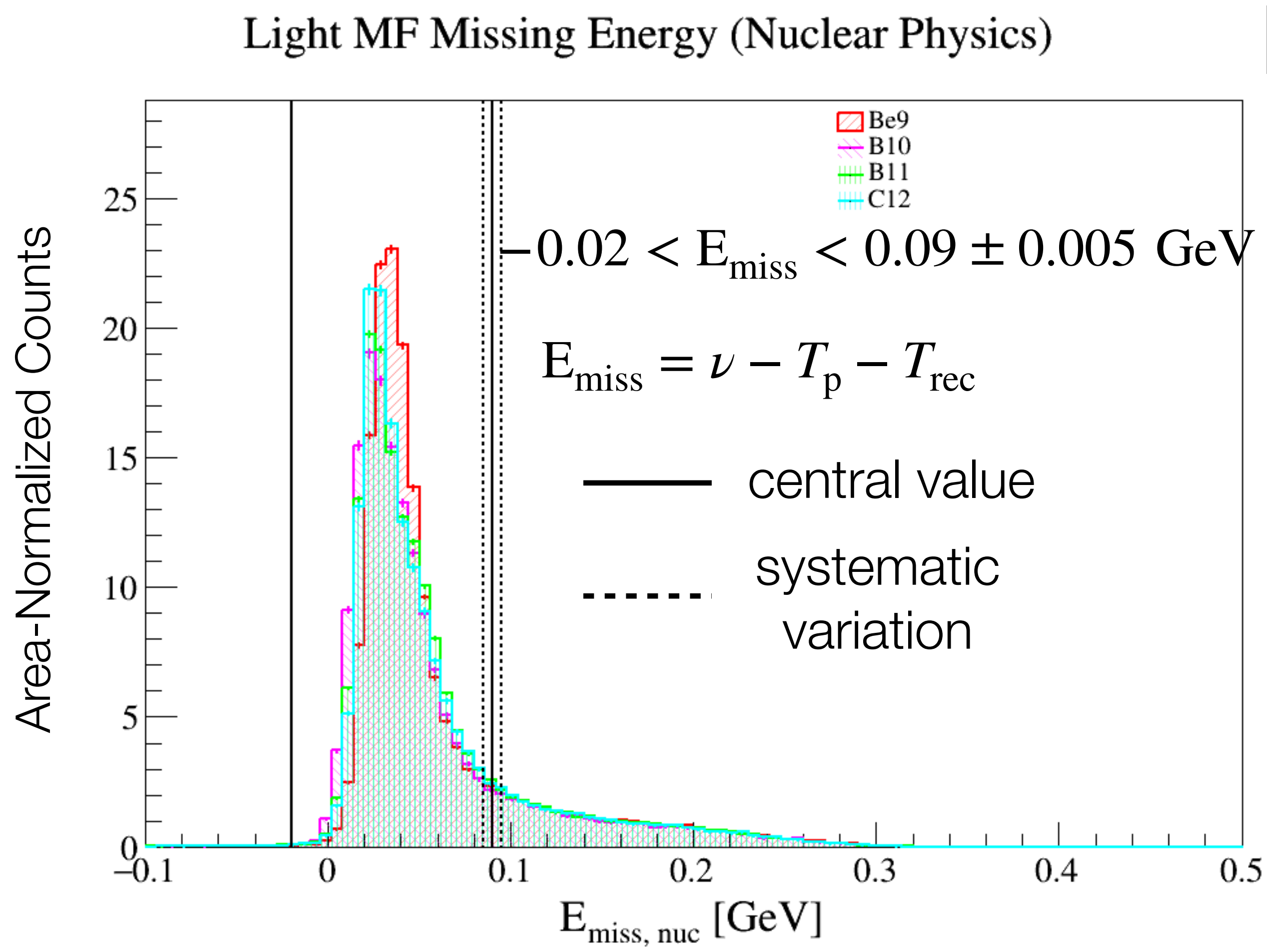


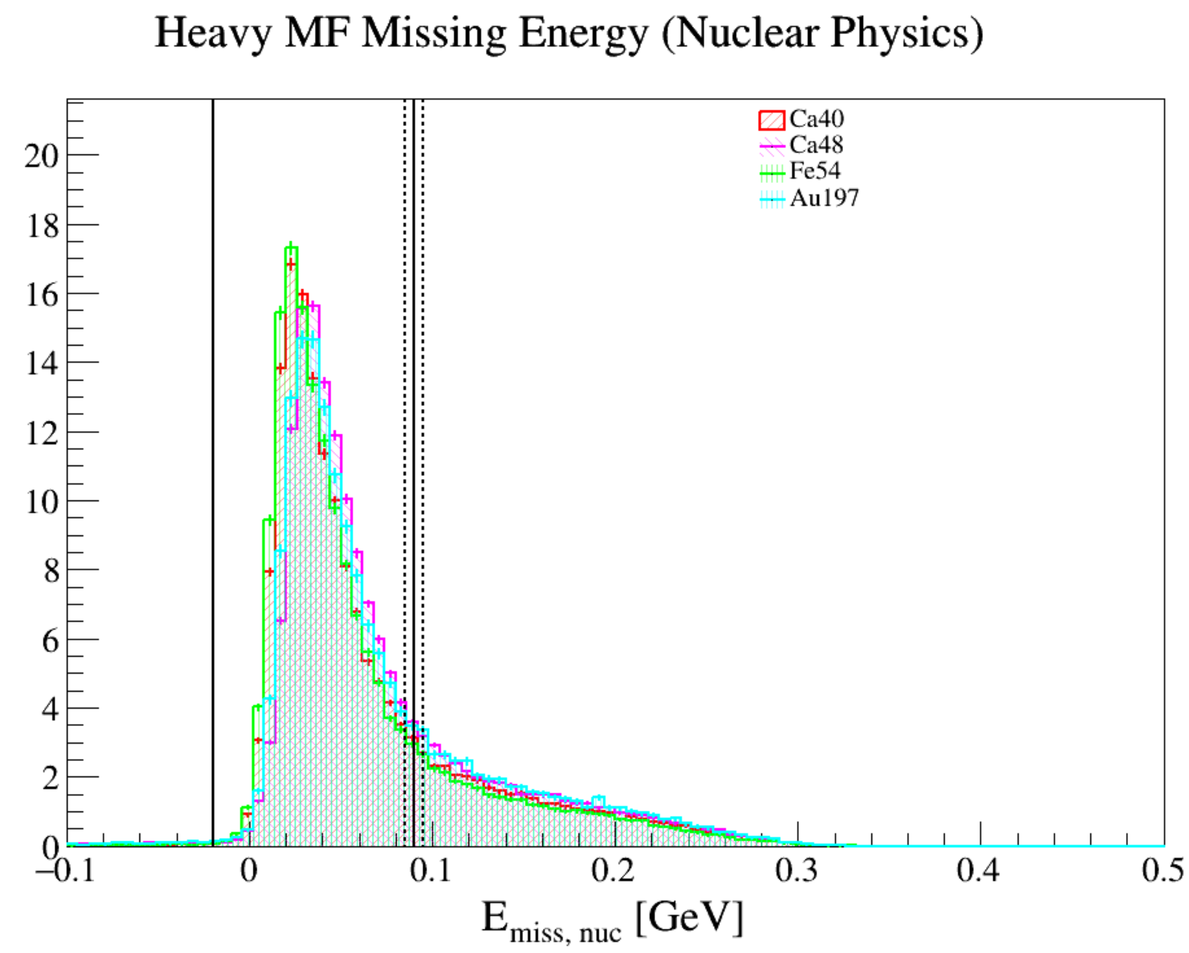


Data Analysis Cuts

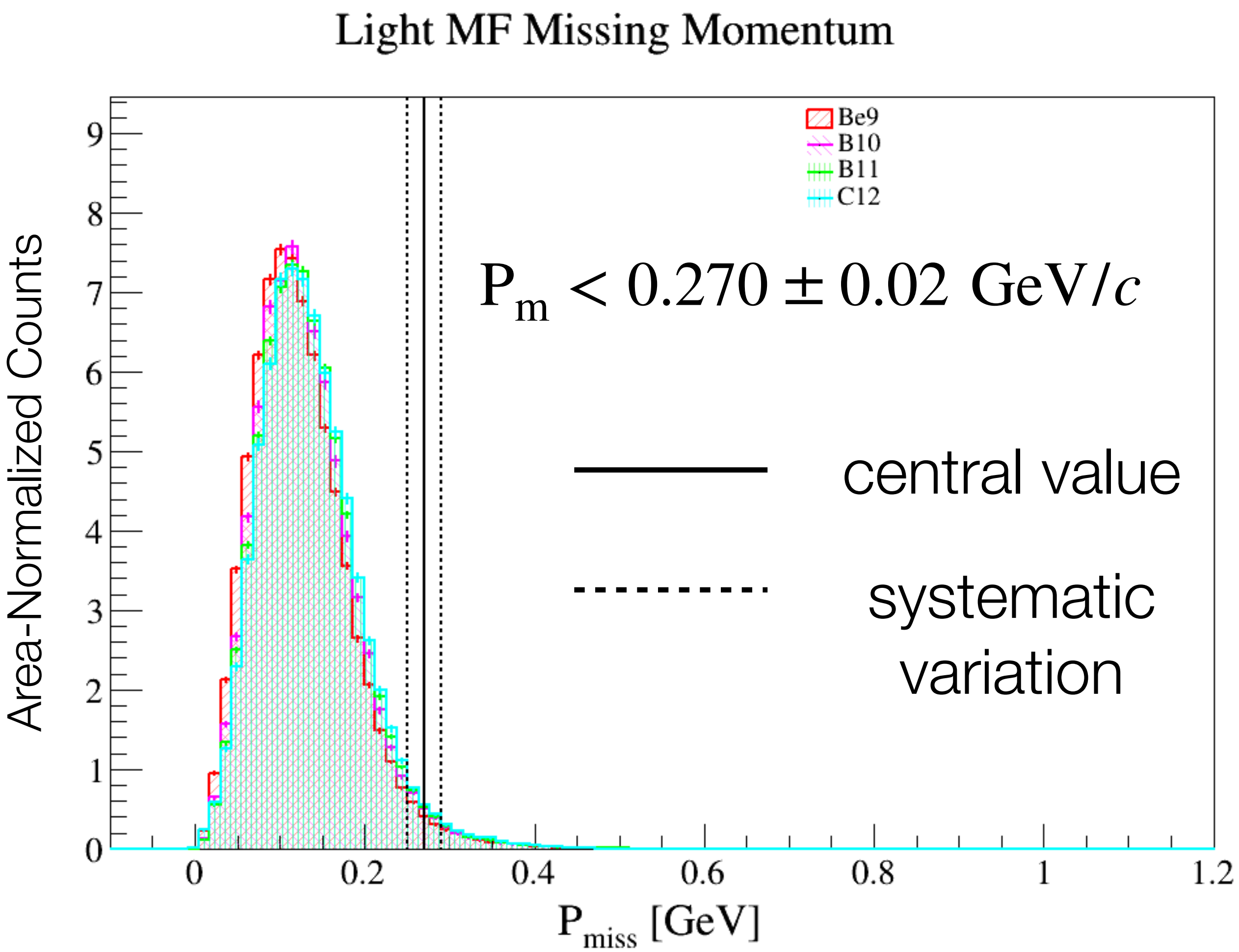

MF
SRC
Light MF 4-Momentum Transfer
Heavy MF 4-Momentum Transfer
Light SRC 4-Momentum Transfer
Heavy SRC 4-Momentum Transfer
Area-Normalized Counts
Q^2 [(GeV/c)^2]
Be9
B10
B11
C12
Ca40
Ca48
Fe54
Au197
$Q^2 > 1.8 \pm 0.1$ GeV^2
central value
systematic variation

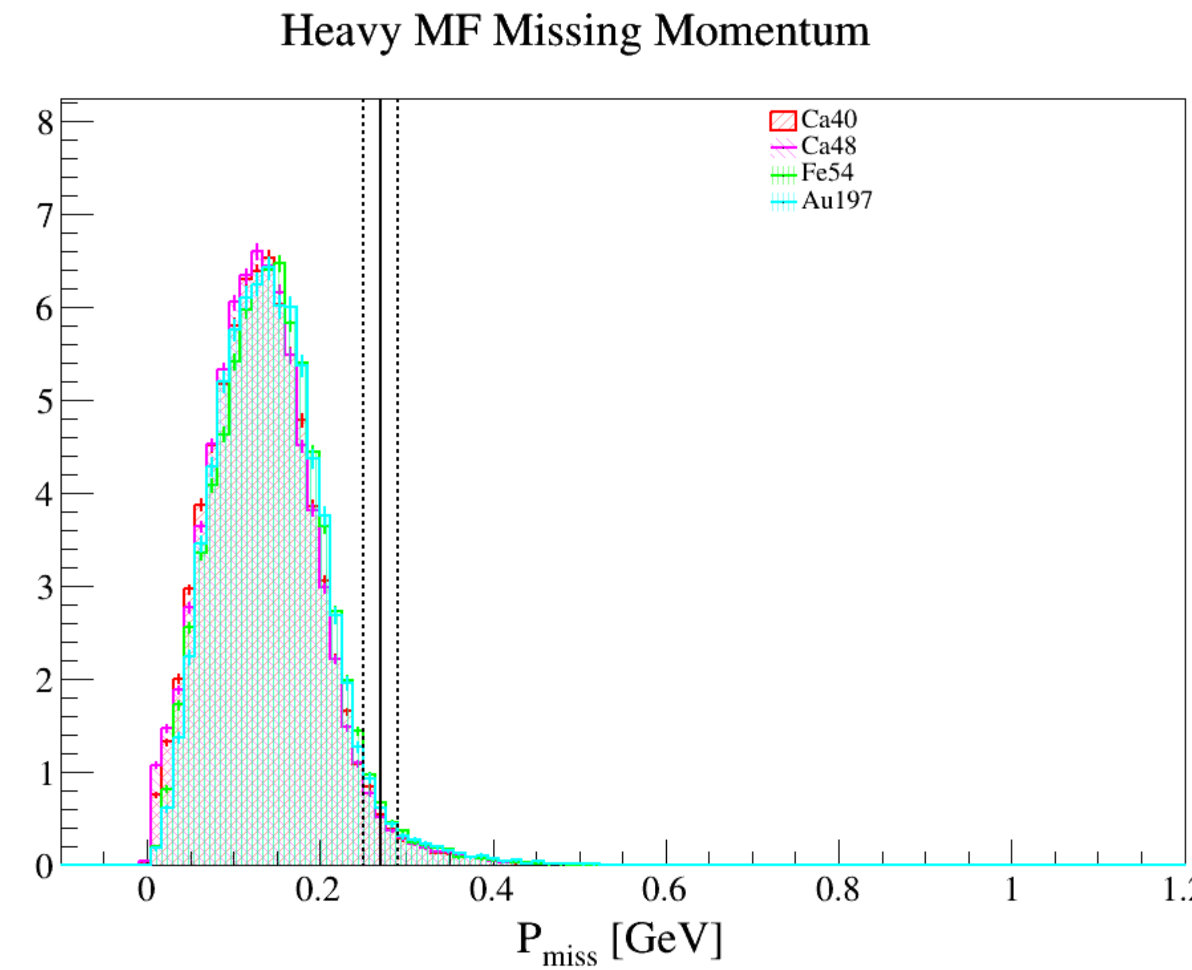
MF


Light MF Missing Energy (Nuclear Physics)
Be9
B10
B11
C12
−0.02 < E_miss < 0.09 ± 0.005 GeV
E_miss = ν − T_p − T_rec
central value
systematic
variation
Area-Normalized Counts
E_miss, nuc [GeV]

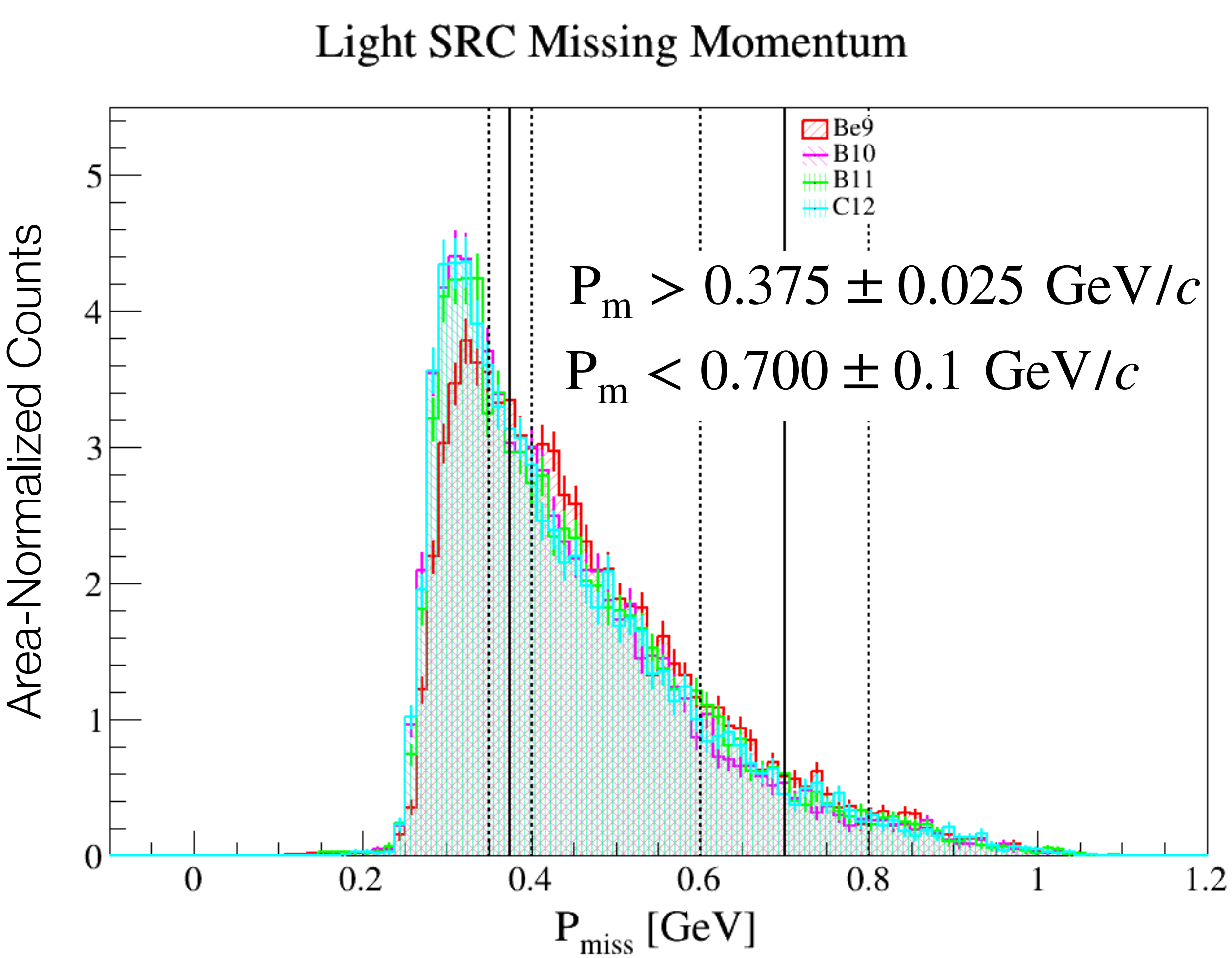

Heavy MF Missing Energy (Nuclear Physics)
Ca40
Ca48
Fe54
Au197
E_miss, nuc [GeV]

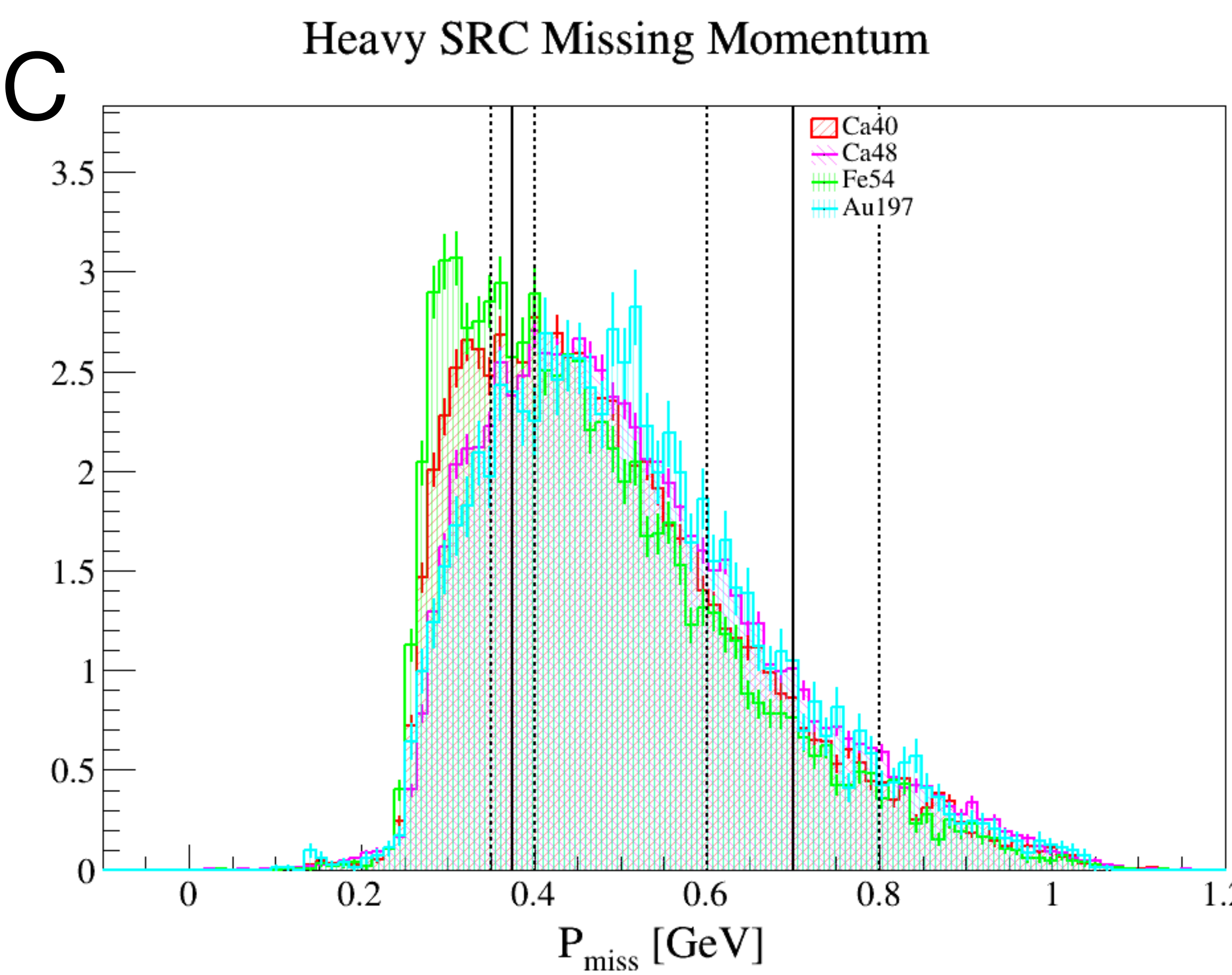
MF


Light MF Missing Momentum
Be9
B10
B11
C12
$P_m < 0.270 \pm 0.02$ GeV/c
central value
systematic variation
Area-Normalized Counts
P_{miss} [GeV]

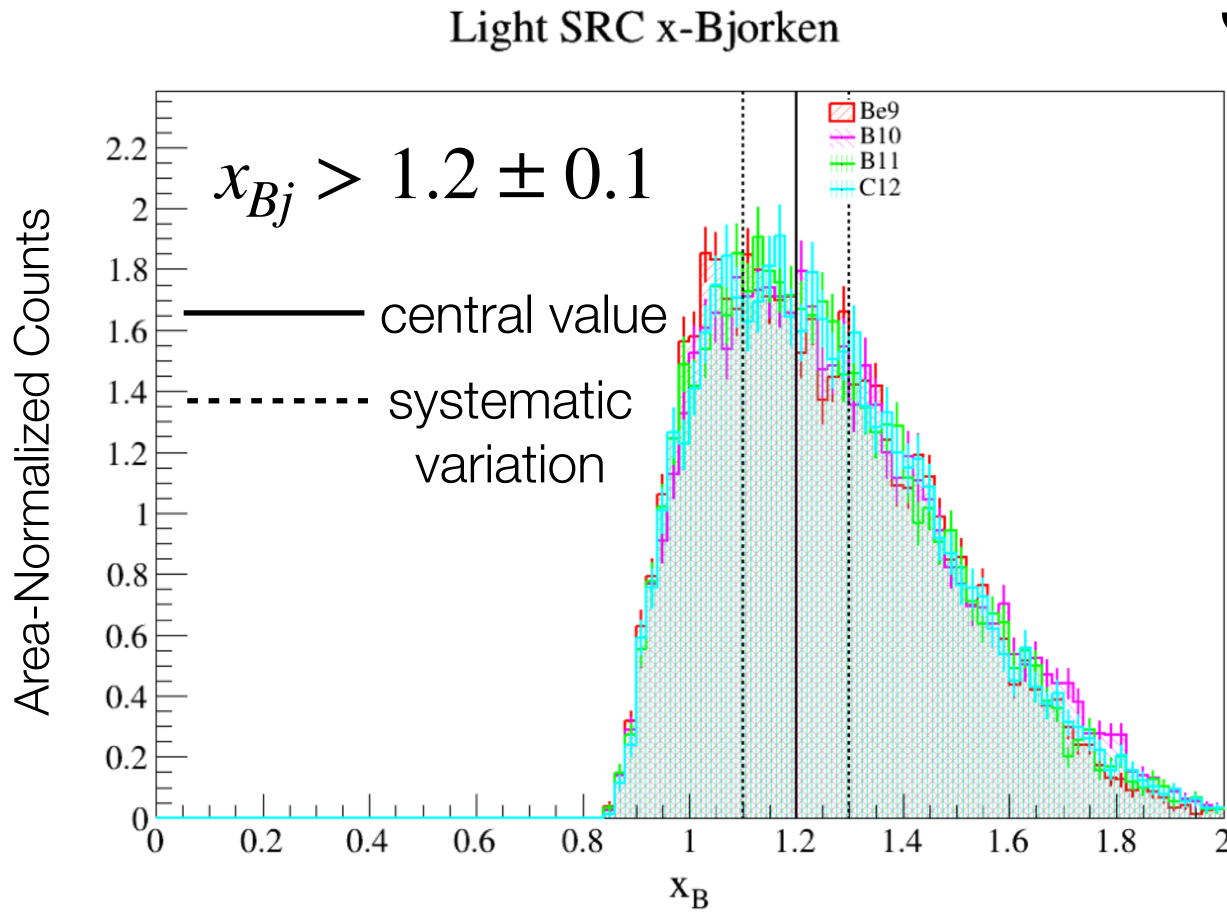

Heavy MF Missing Momentum
Ca40
Ca48
Fe54
Au197
P_{miss} [GeV]

SRC

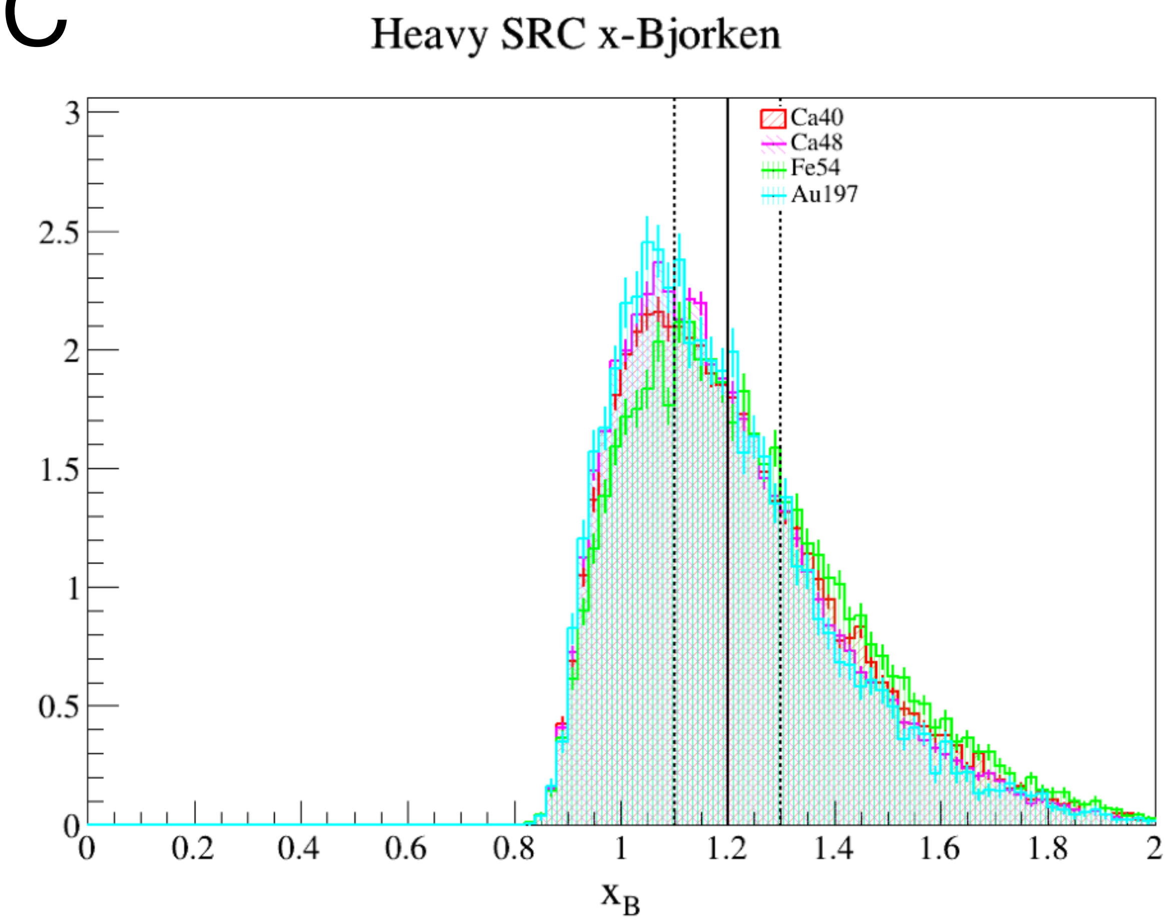

Light SRC Missing Momentum
Be9
B10
B11
C12
$P_m > 0.375 \pm 0.025$ GeV/c
$P_m < 0.700 \pm 0.1$ GeV/c
Area-Normalized Counts
P_{miss} [GeV]


Heavy SRC Missing Momentum
Ca40
Ca48
Fe54
Au197
P_{miss} [GeV]

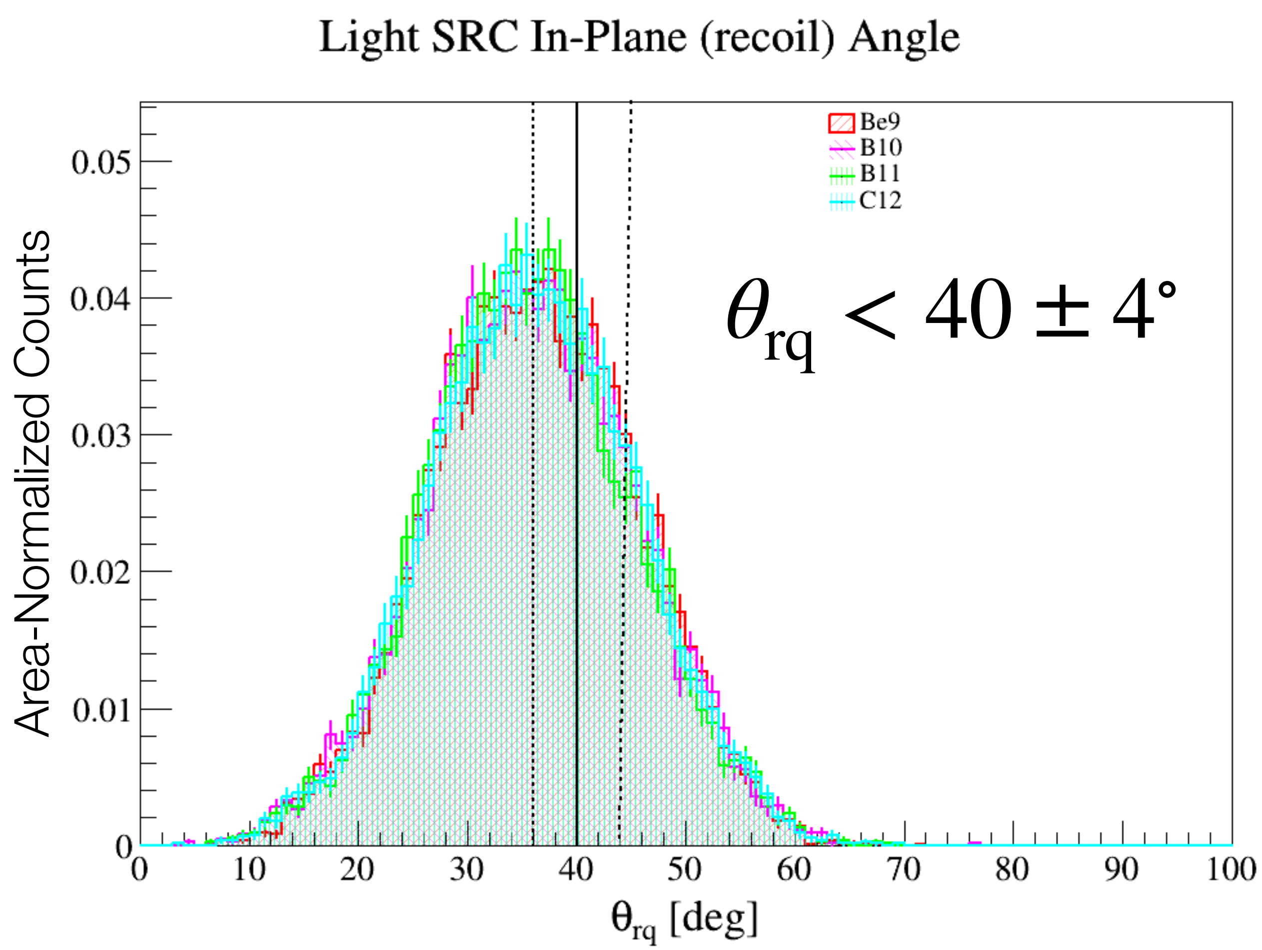
SRC



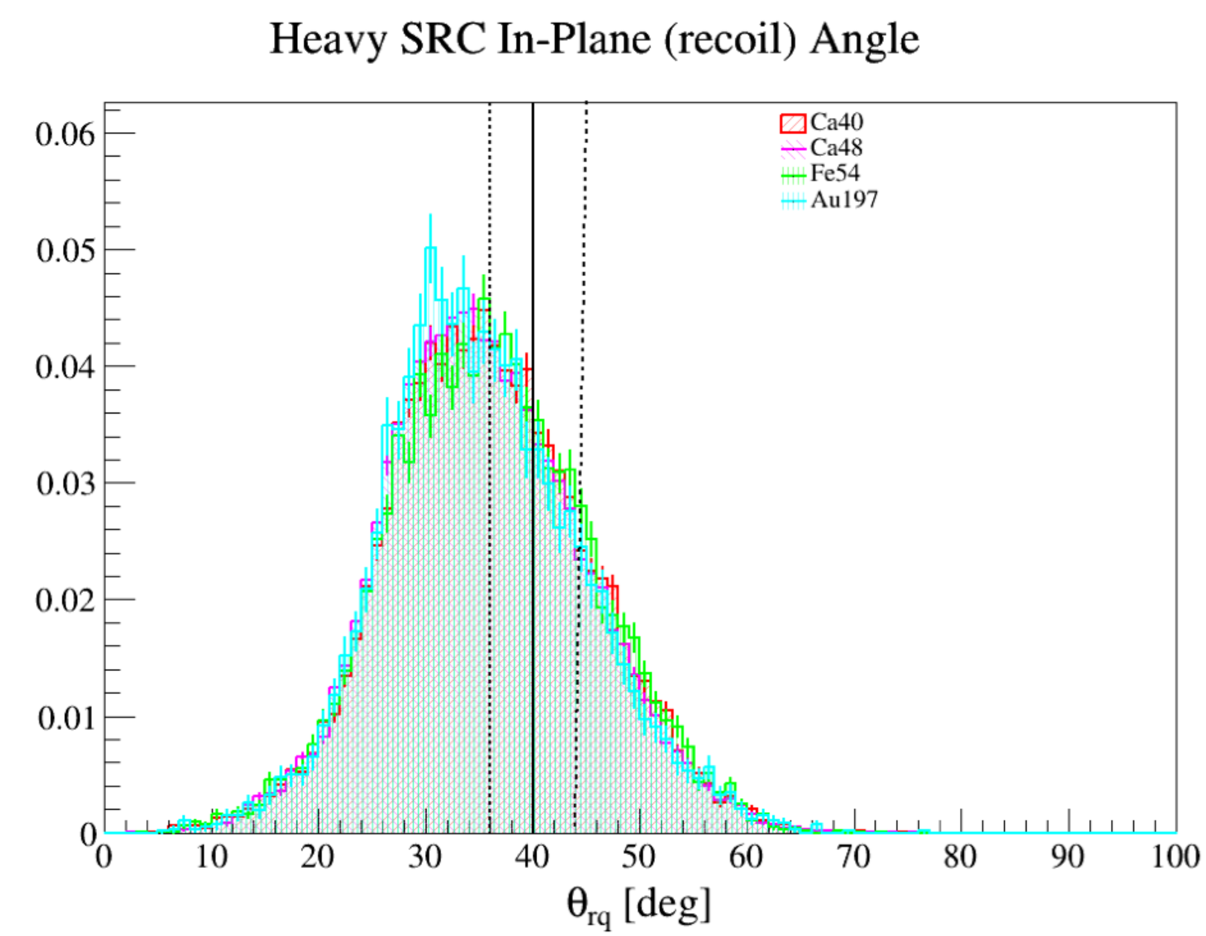
Light SRC x-Bjorken
$x_{Bj} > 1.2 \pm 0.1$
central value
systematic variation
Be9
B10
B11
C12
Area-Normalized Counts
x_B



Heavy SRC x-Bjorken
Ca40
Ca48
Fe54
Au197
x_B



Light SRC In-Plane (recoil) Angle
Be9
B10
B11
C12
$\theta_{rq} < 40 \pm 4°$
Area-Normalized Counts
θ_{rq} [deg]



Heavy SRC In-Plane (recoil) Angle
Ca40
Ca48
Fe54
Au197
θ_{rq} [deg]

Single Ratios to C12 (per proton)

$$R_{MF} \equiv \left.\frac{Y_A}{Y_{C12}}\right|_{MF} \qquad R_{SRC} \equiv \left.\frac{Y_A}{Y_{C12}}\right|_{SRC}$$

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

Y_A : nucleus A yield

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

Q : total charge [mC]

ϵ_i : detector/DAQ efficiencies

T_N : nuclear transparency

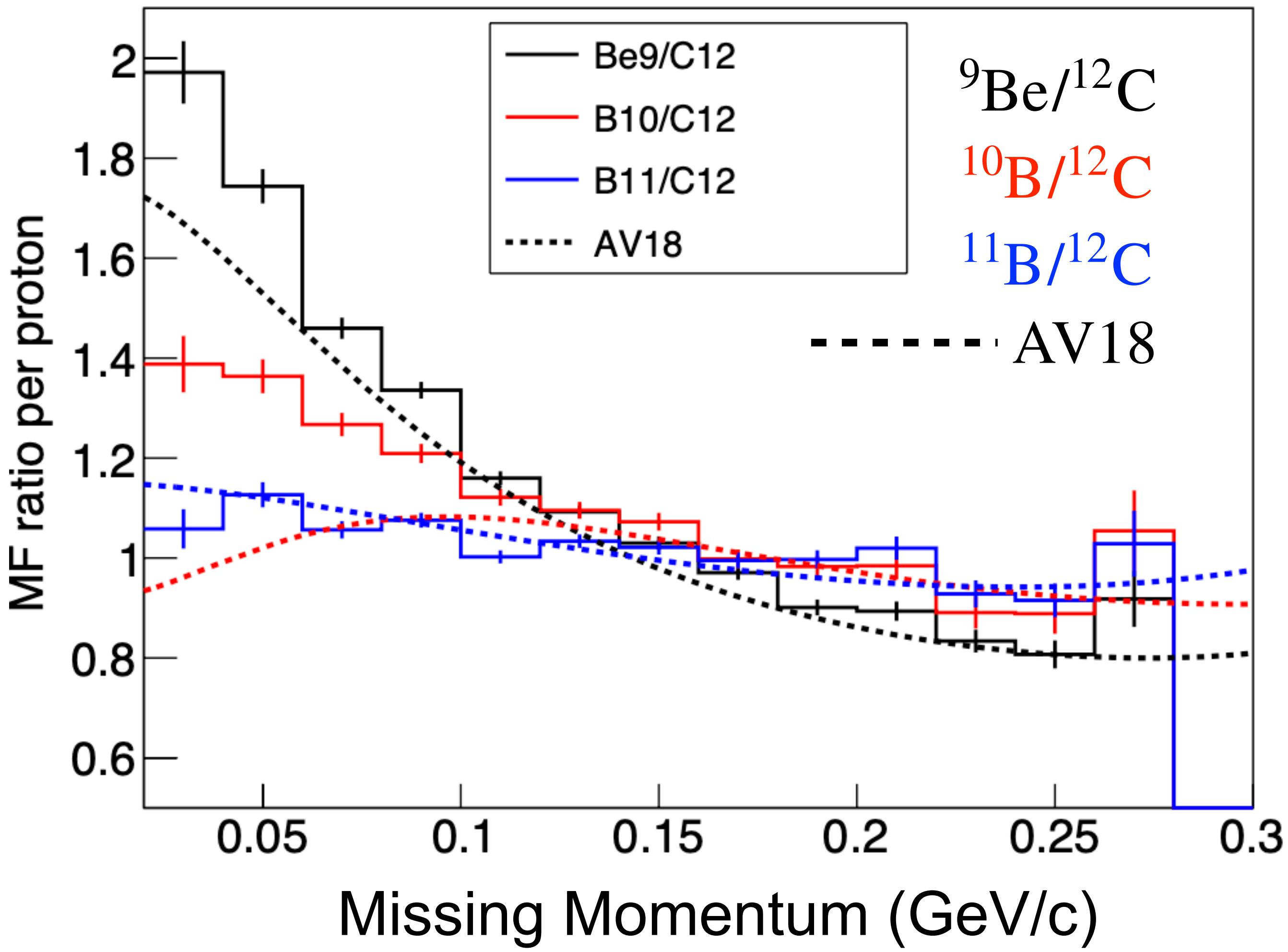
σ_t : target thickness [g/cm^2]

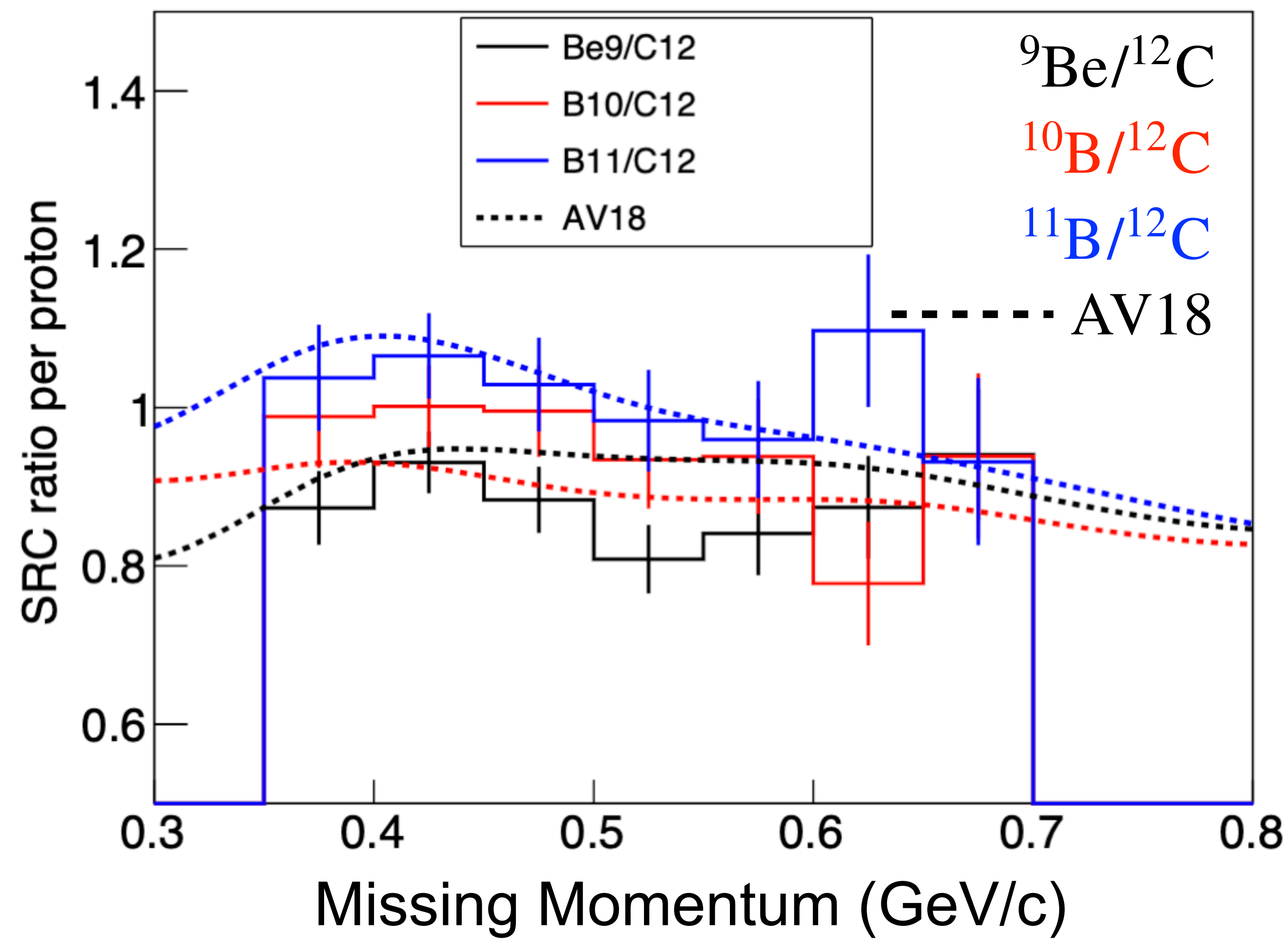
Radiative corrections were applied to ratios directly

Single Ratios to C12 (per proton)

Missing Momentum Distributions

Single Ratio to C12 (per proton): Light Nuclei



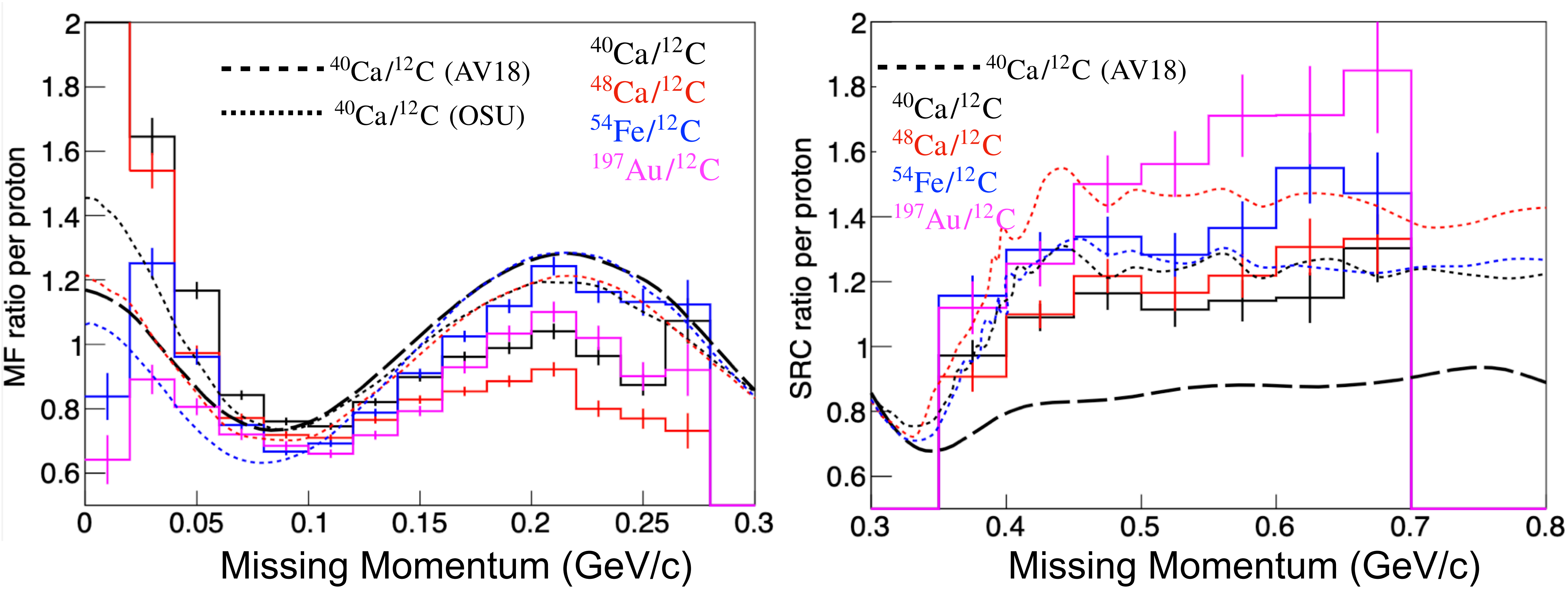


Note:

- Radiative correction included
- ONLY statistical uncertainty
- data integrated over -20 < E_{miss} < 90 MeV, calculations integrated over all E_{miss}

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

Single Ratio to C12 (per proton): Heavy Nuclei



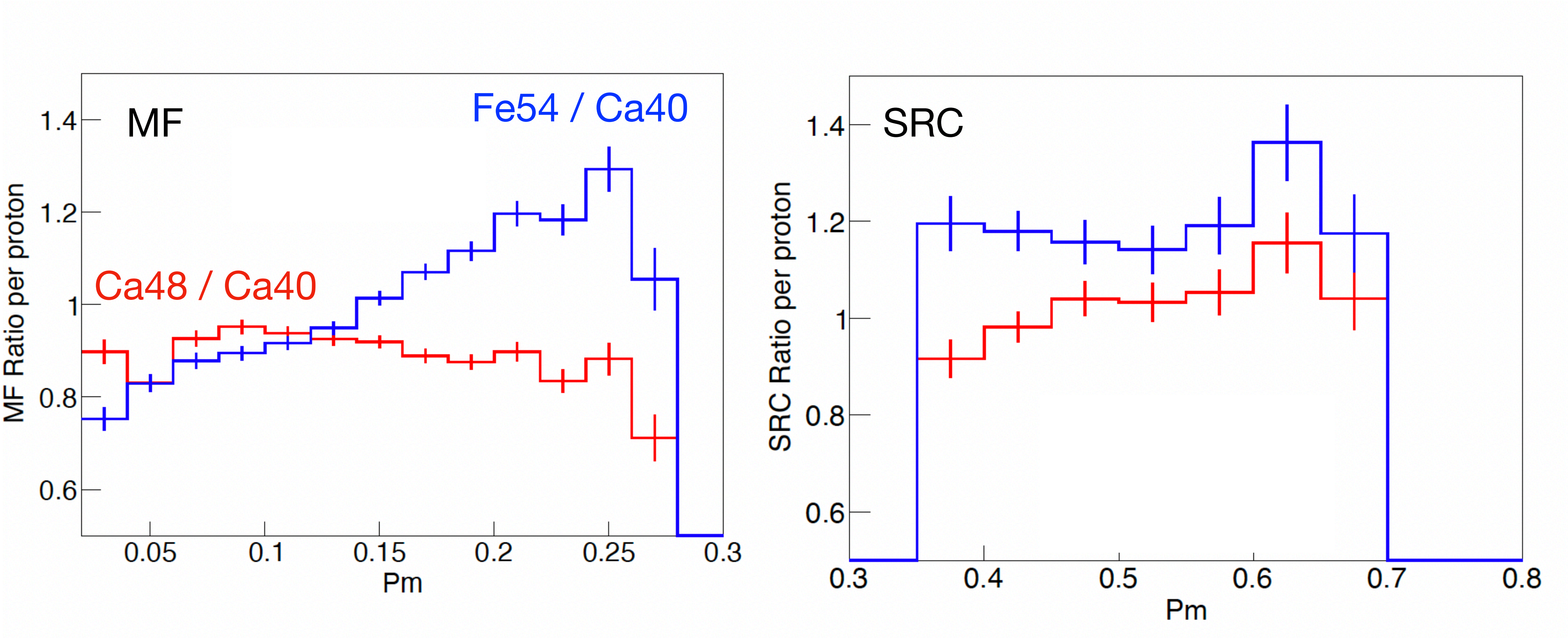
Note:

- Radiative correction included
- ONLY statistical uncertainty
- data integrated over -20 < E_{miss} < 90 MeV, calculations integrated over all E_{miss}

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

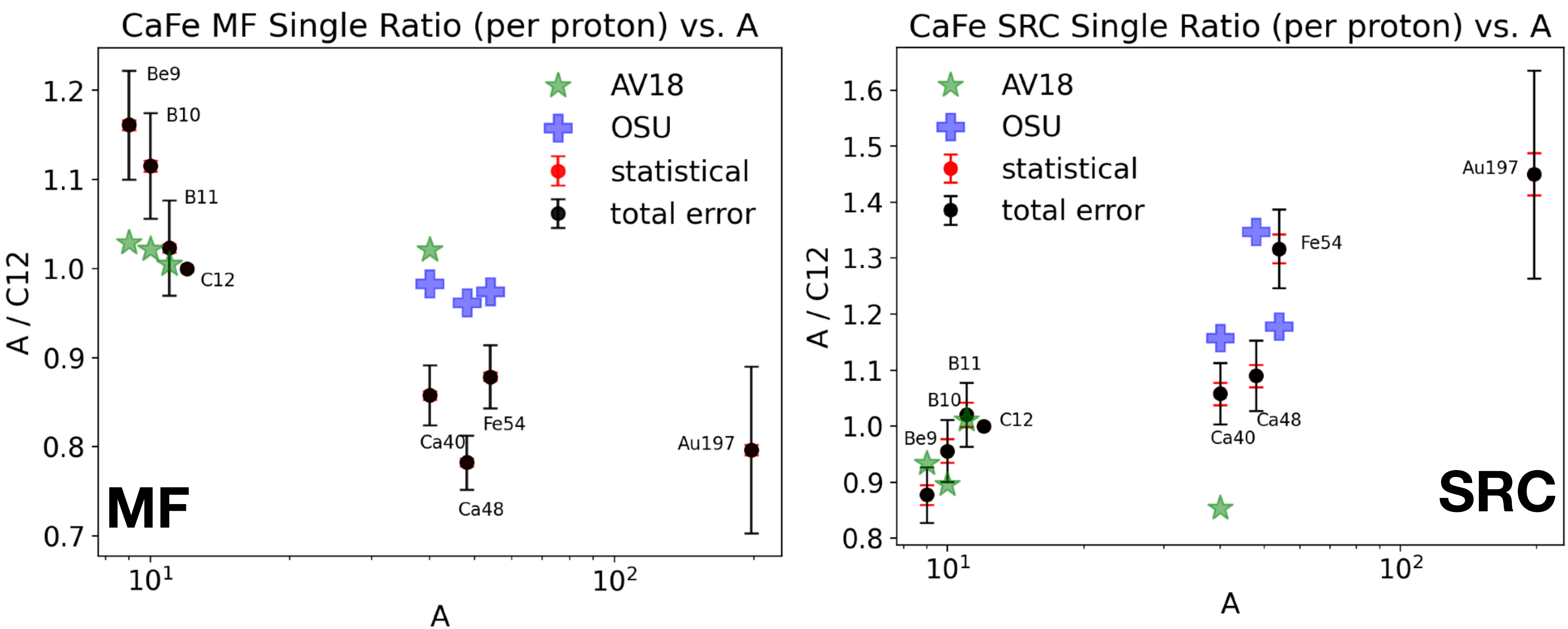
Wiringa et al, Phys.Rev.C89 (AV18)

Single Ratio to Ca40 (per proton)



Single Ratios to C12 (per proton)

Integrated over Missing Momentum



- the **data** MF single ratio decreases with *A*; models are flat

- the **data** SRC single ratio increases with *A*;

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

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

Double Ratios

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

"a.k.a. high-momentum fraction"

$$Y_A \equiv A(e,e'p) : \frac{N}{Q \cdot \epsilon_i \cdot T_N \cdot \sigma_t}$$

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

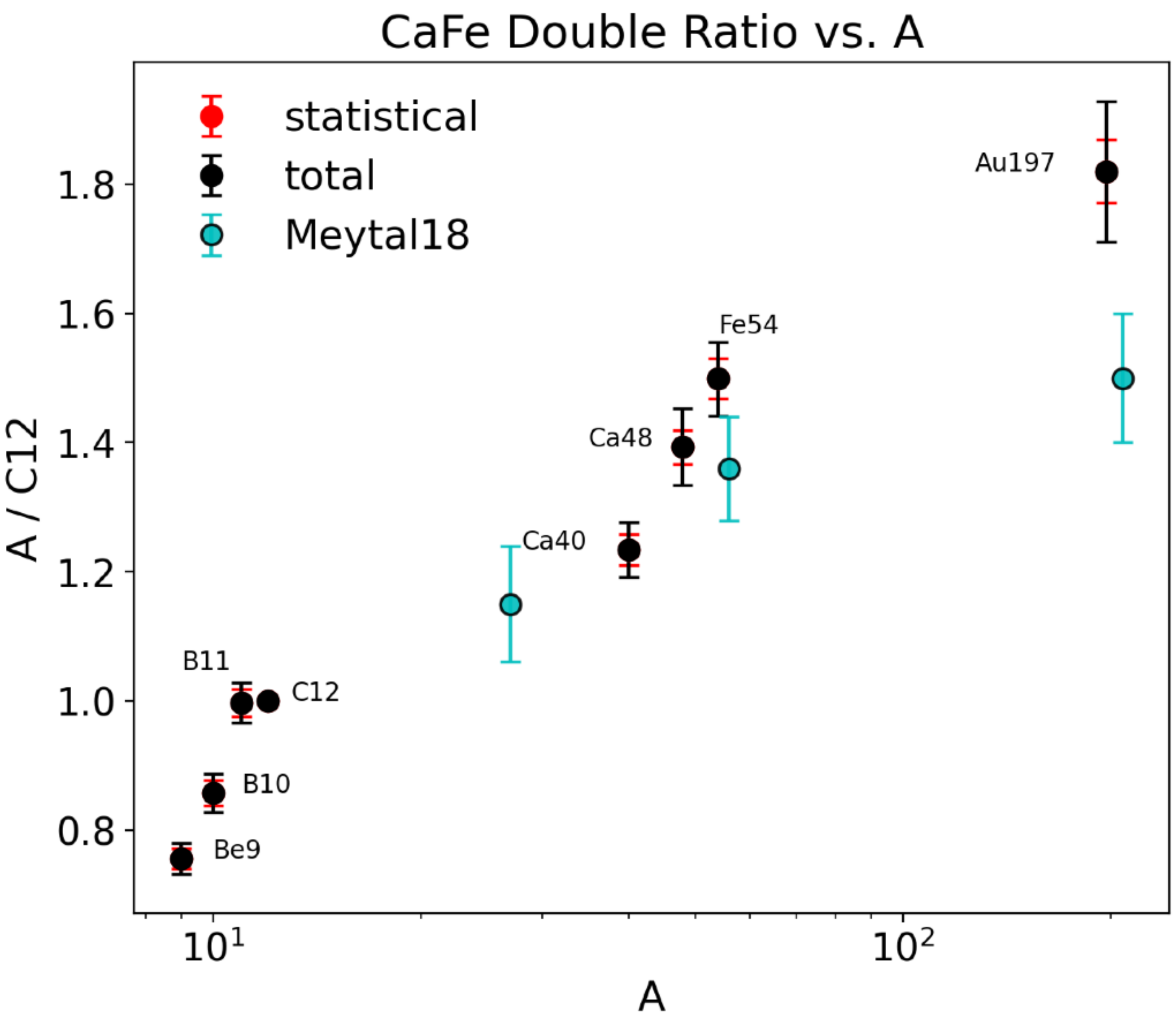
Q : total charge [mC]

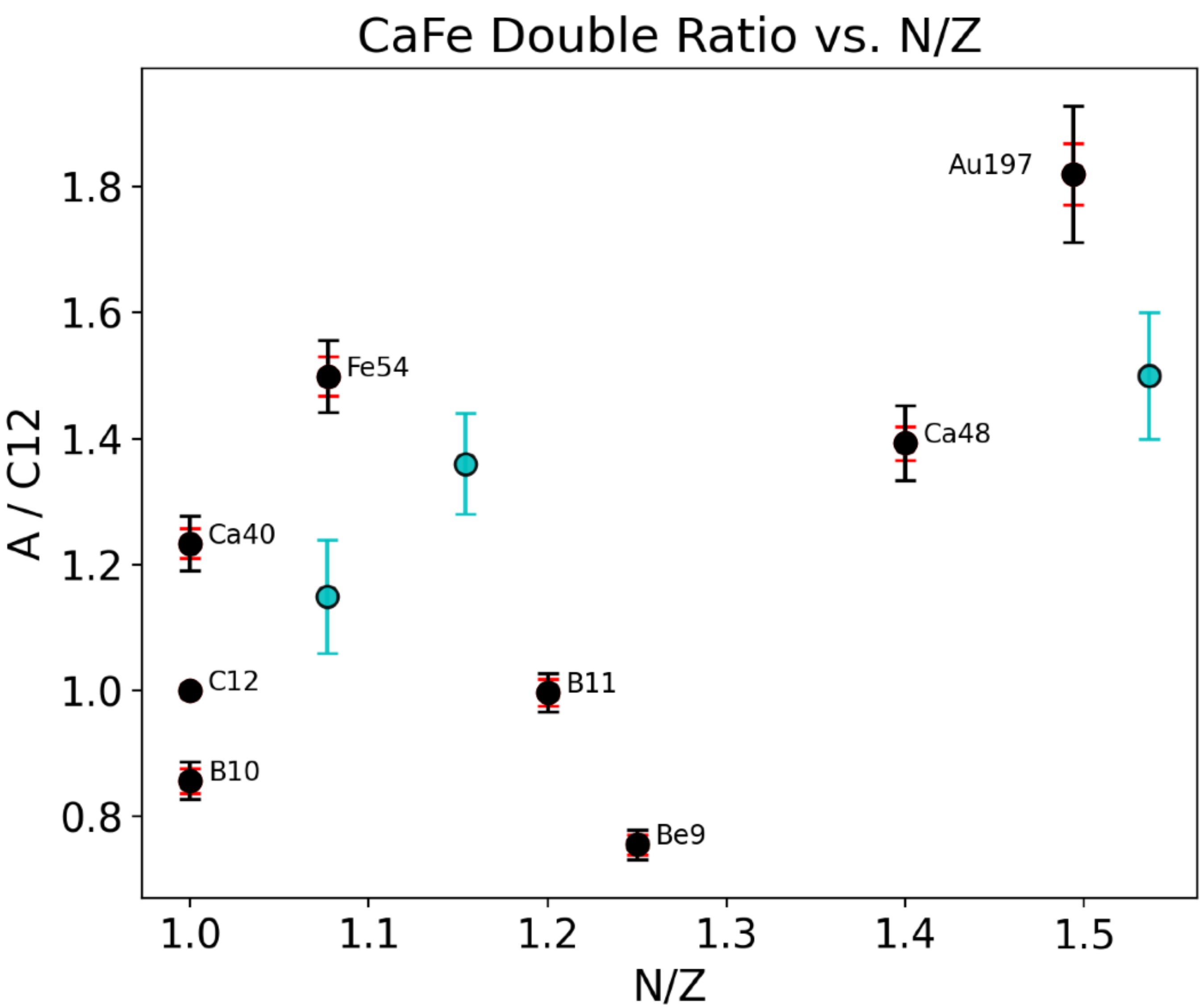
ϵ_i : detector/DAQ efficiencies

T_N : nuclear transparency

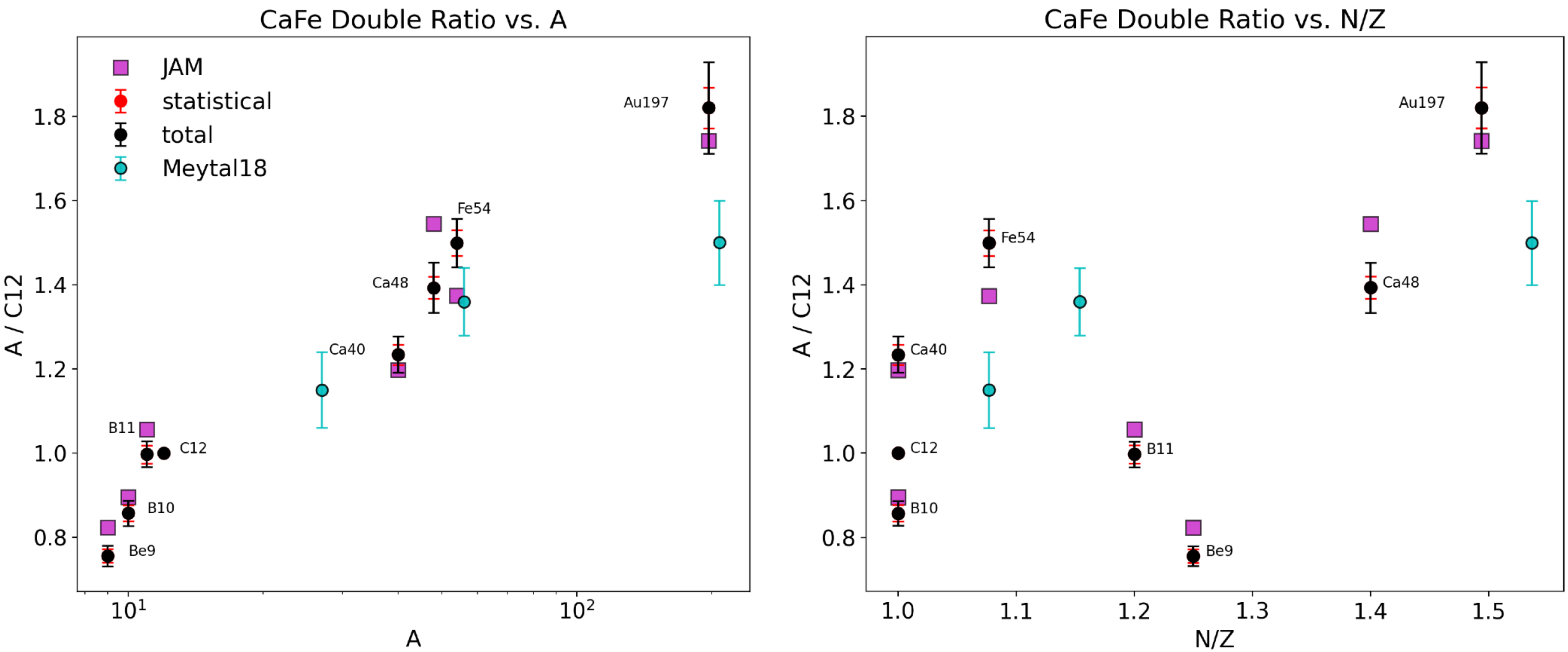
σ_t : target thickness [g/cm^2]

cancel in double ratio





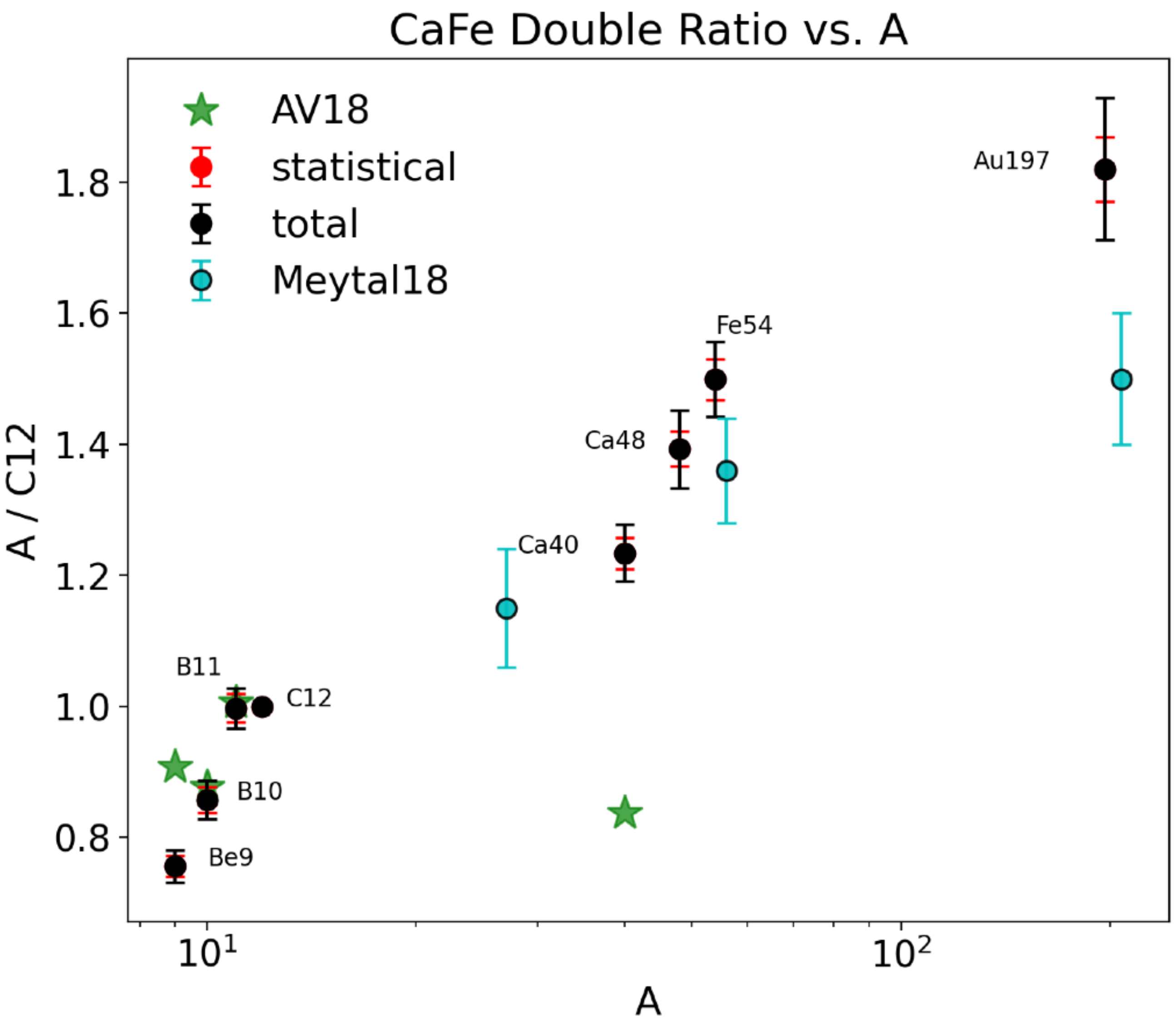
M. Duer et al. (CLAS collaboration), Nature 560, 617 (Meytal 18)

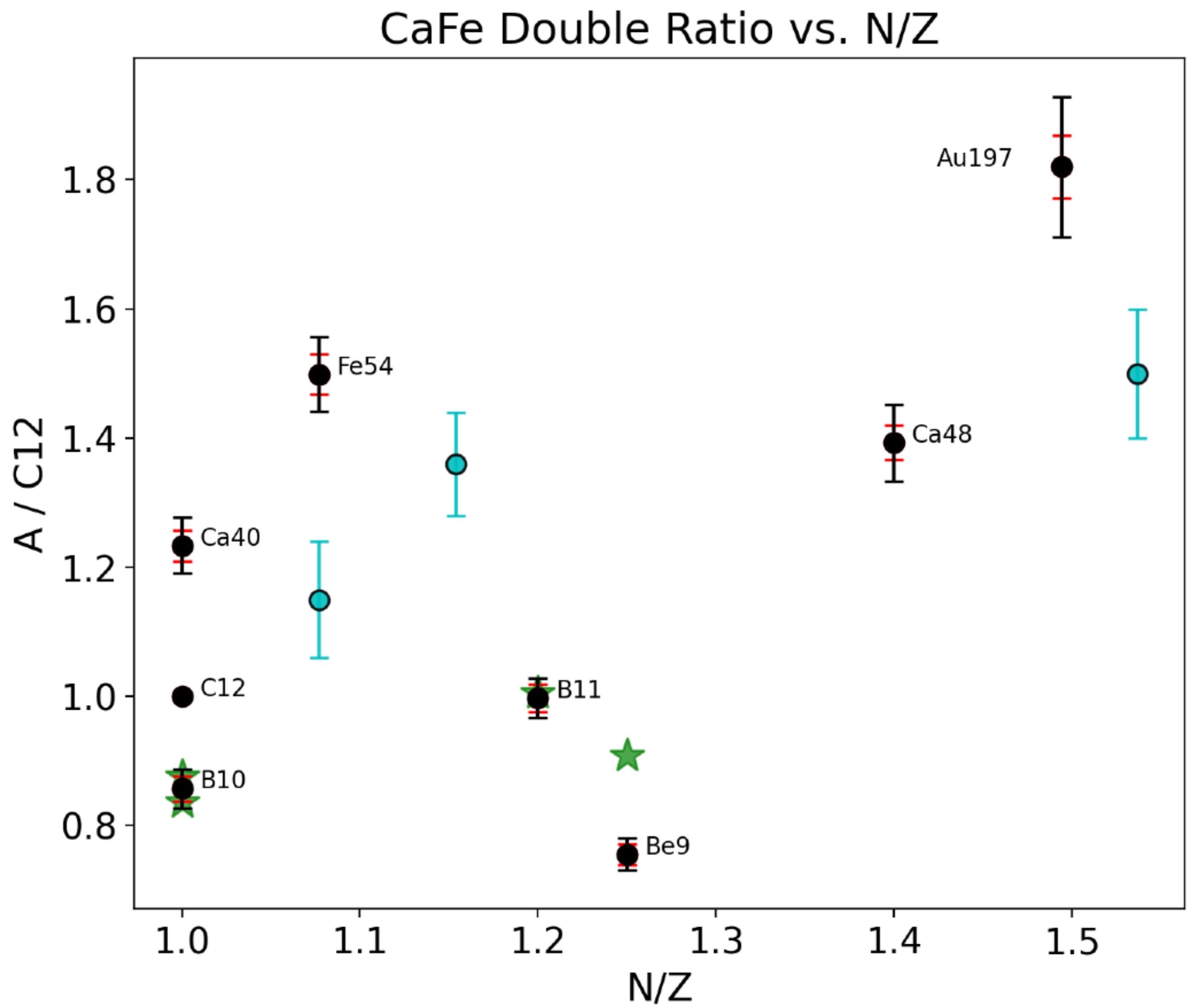


- The spatial-overlap **JAM** model describes the double-ratio data well, **BUT**
  - **OVER-PREDICTS** the Ca48 double ratio and **UNDER-PREDICTS** that of Fe54, indicating the importance of shell-closure effects

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

Justin-Andrew Model (JAM, 2023)

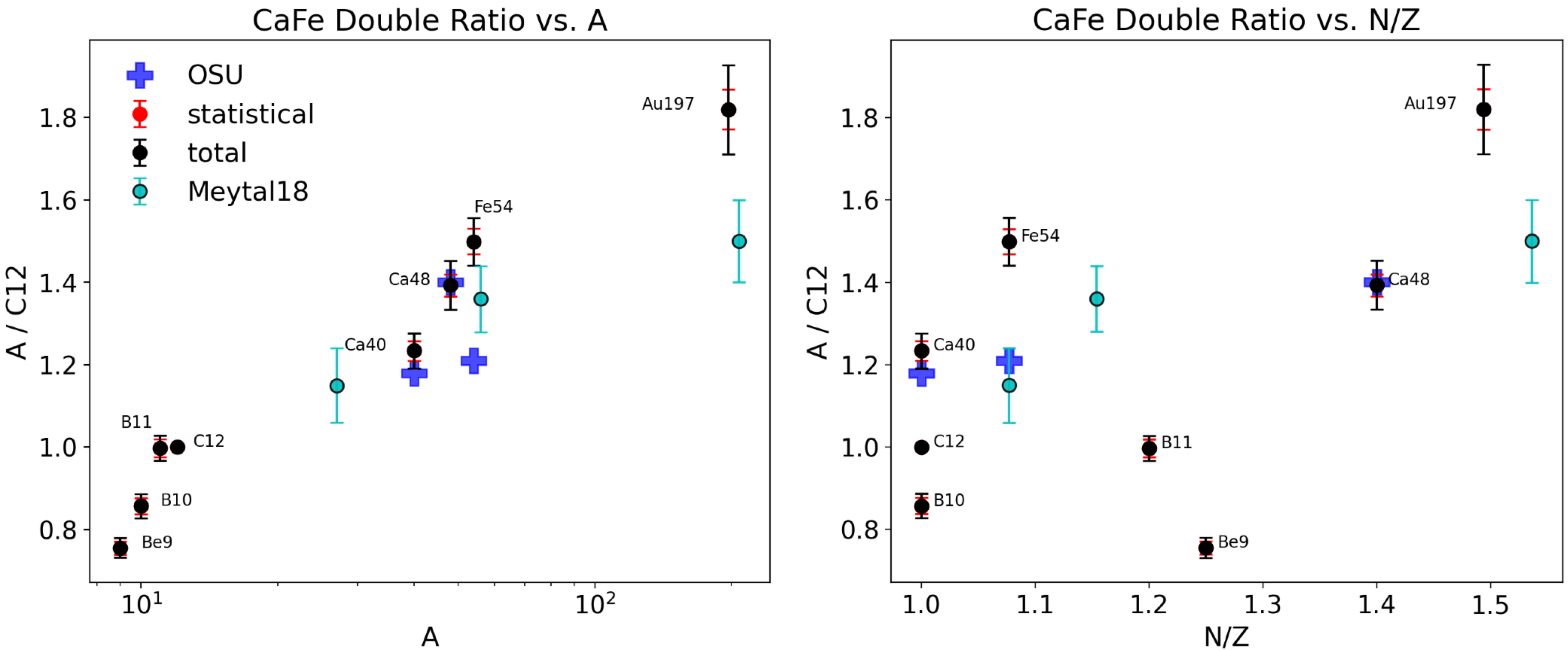




- ratios of **AV18** momentum distributions do not describe the data well; they describe B10, B11, but **DO NOT** describe Be9 or Ca40

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

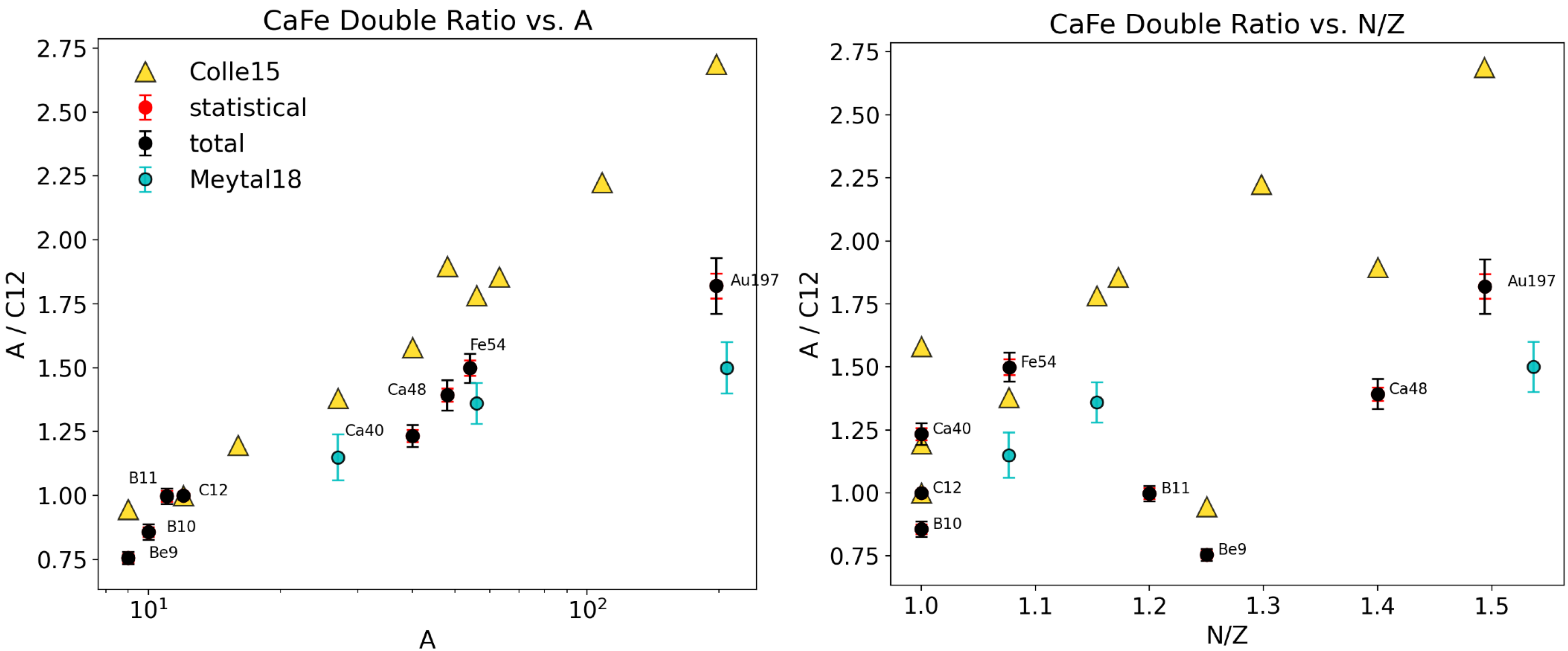
Wiringa et al, Phys.Rev.C89 (AV18)



- ratios of **OSU** momentum distributions describe Ca40 and Ca48; but **DO NOT** describe well Fe54

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

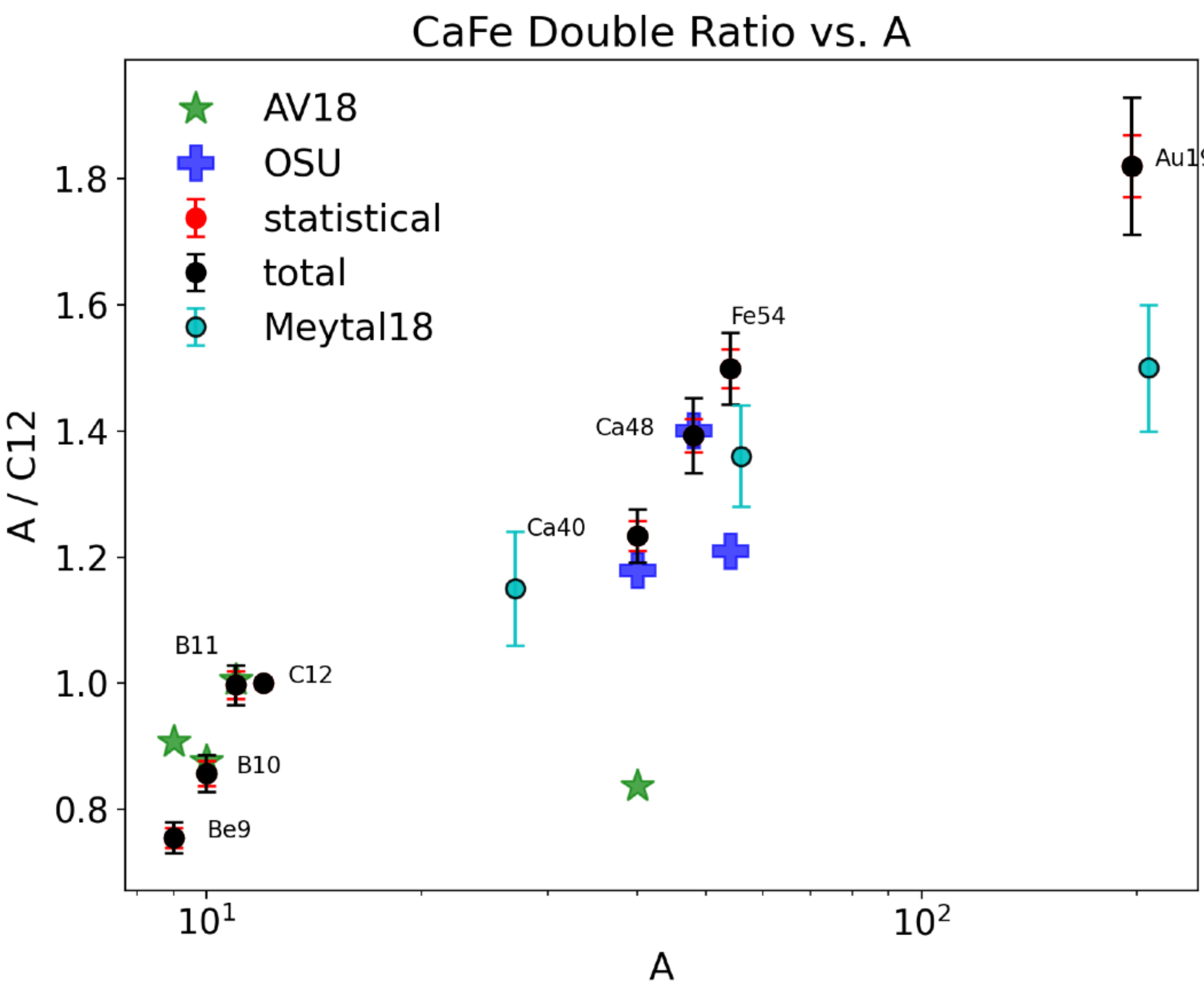
R.J.Furnstahl et al. arXiv:2402.00634v2 (OSU)

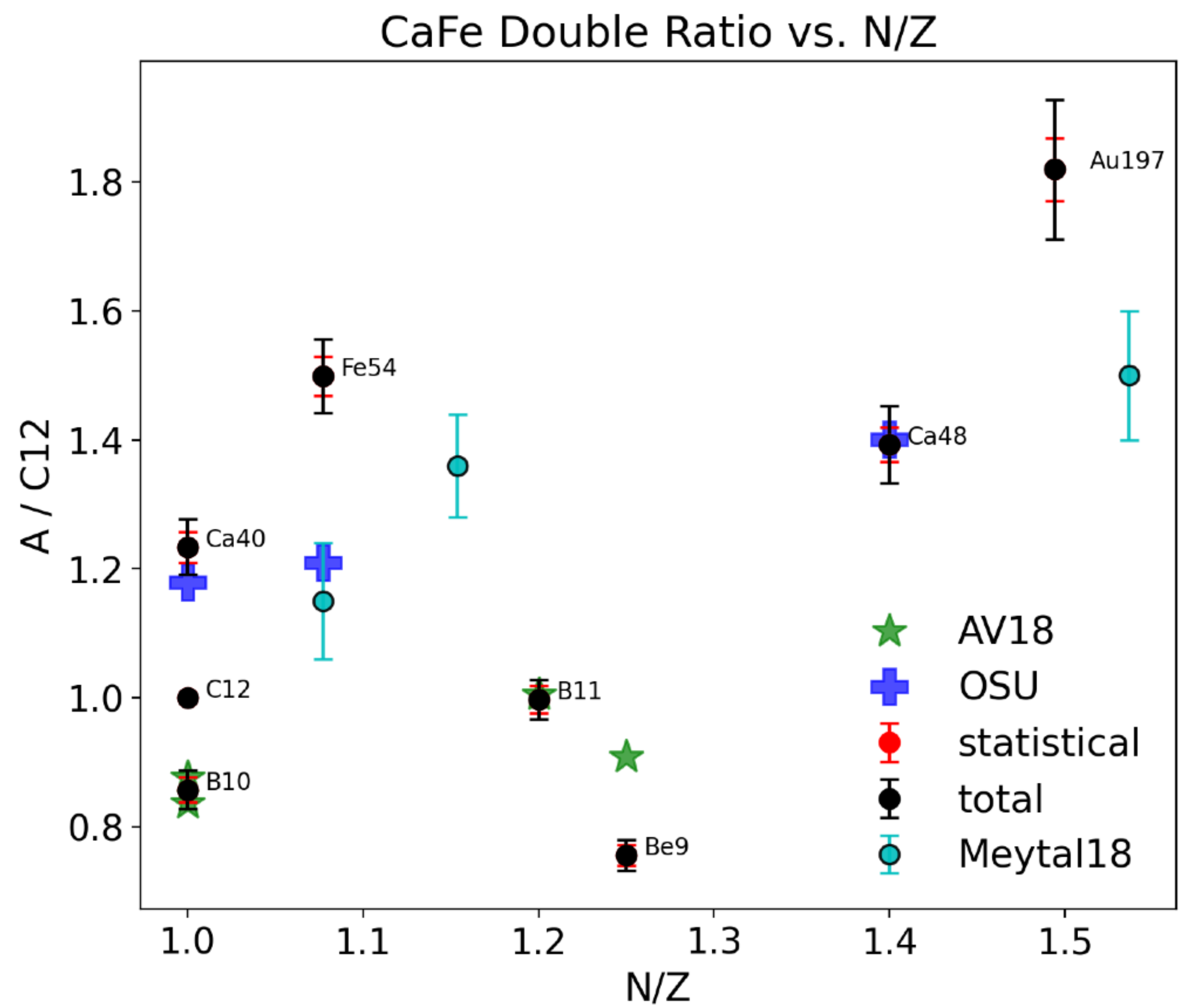


- ratios of **Colle15** **OVER-PREDICTS** almost all nuclei

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

Colle et al. Phys.Rev.C92 (Colle 15)



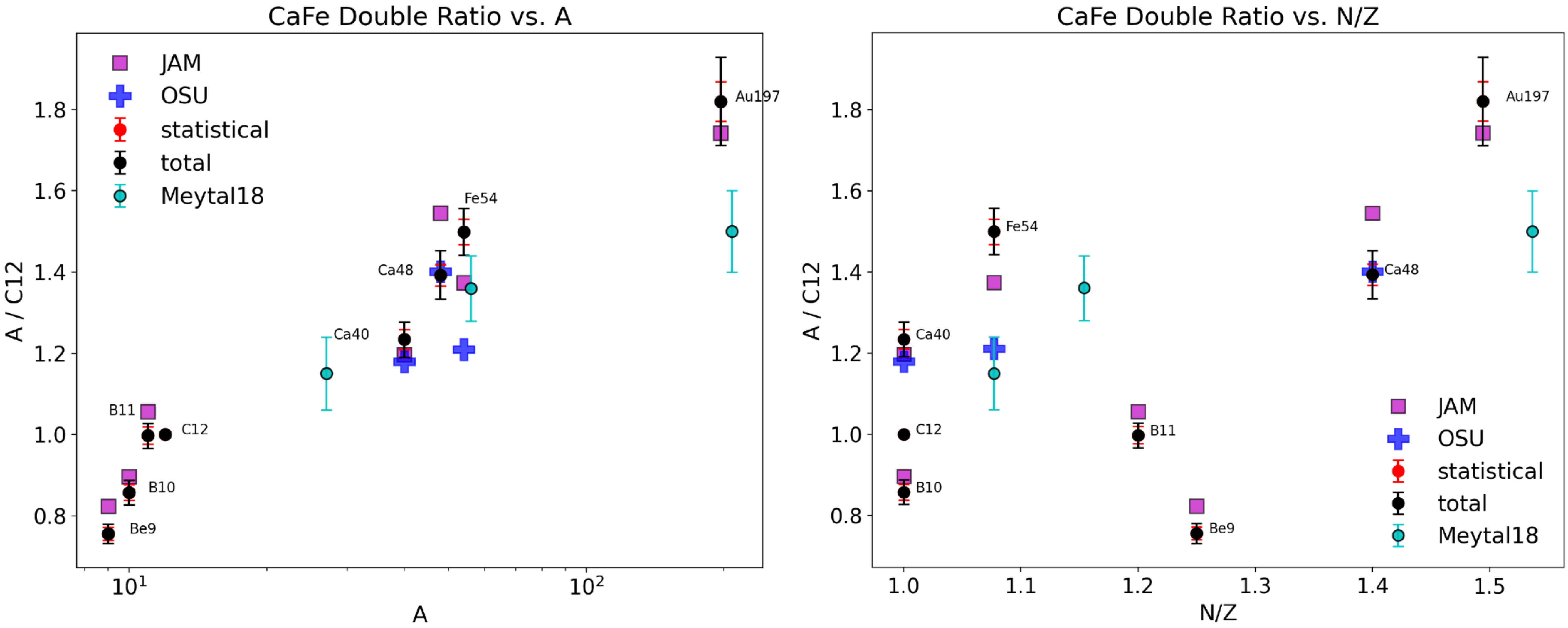


- models overlay: **OSU** + **AV18**

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

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

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

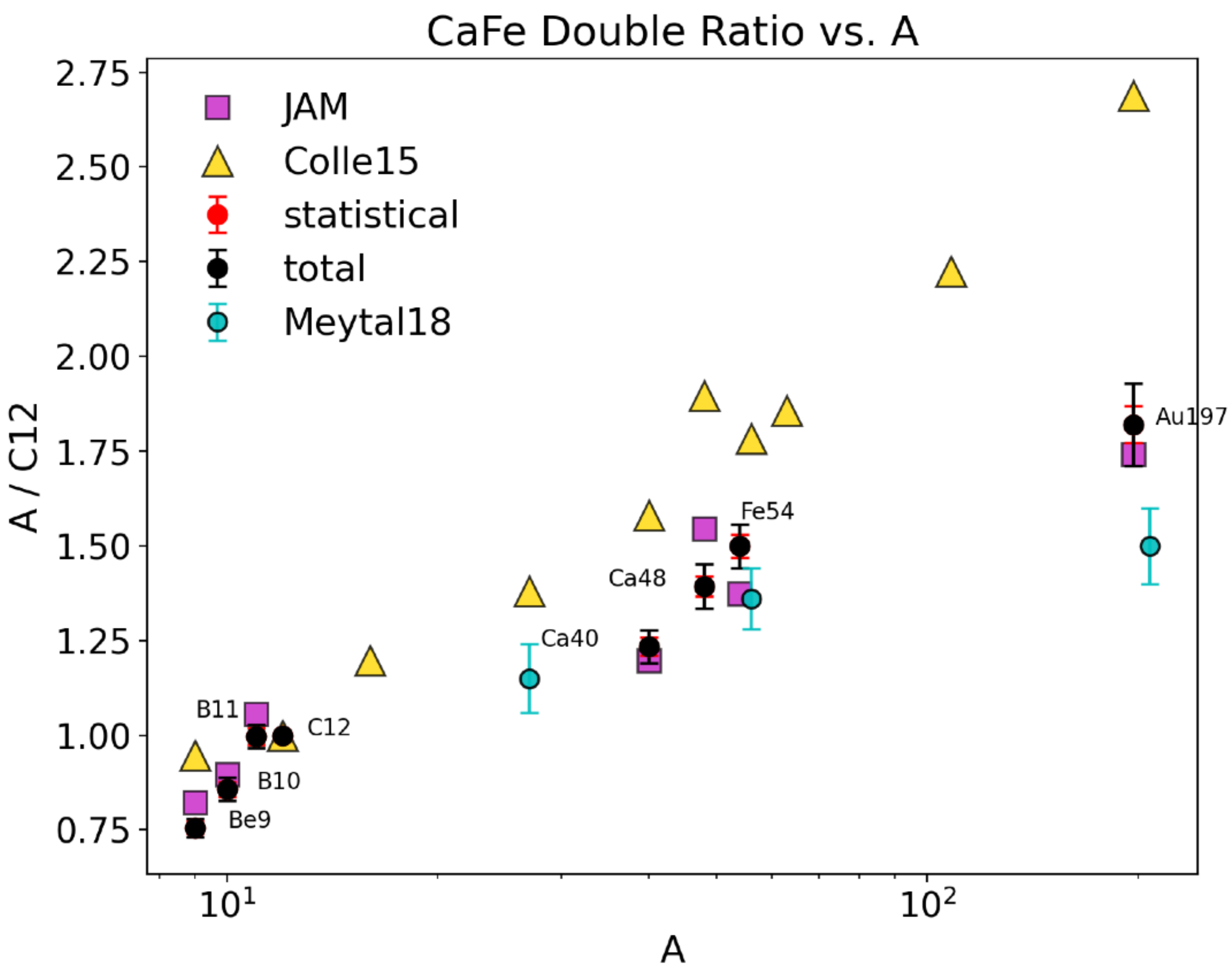


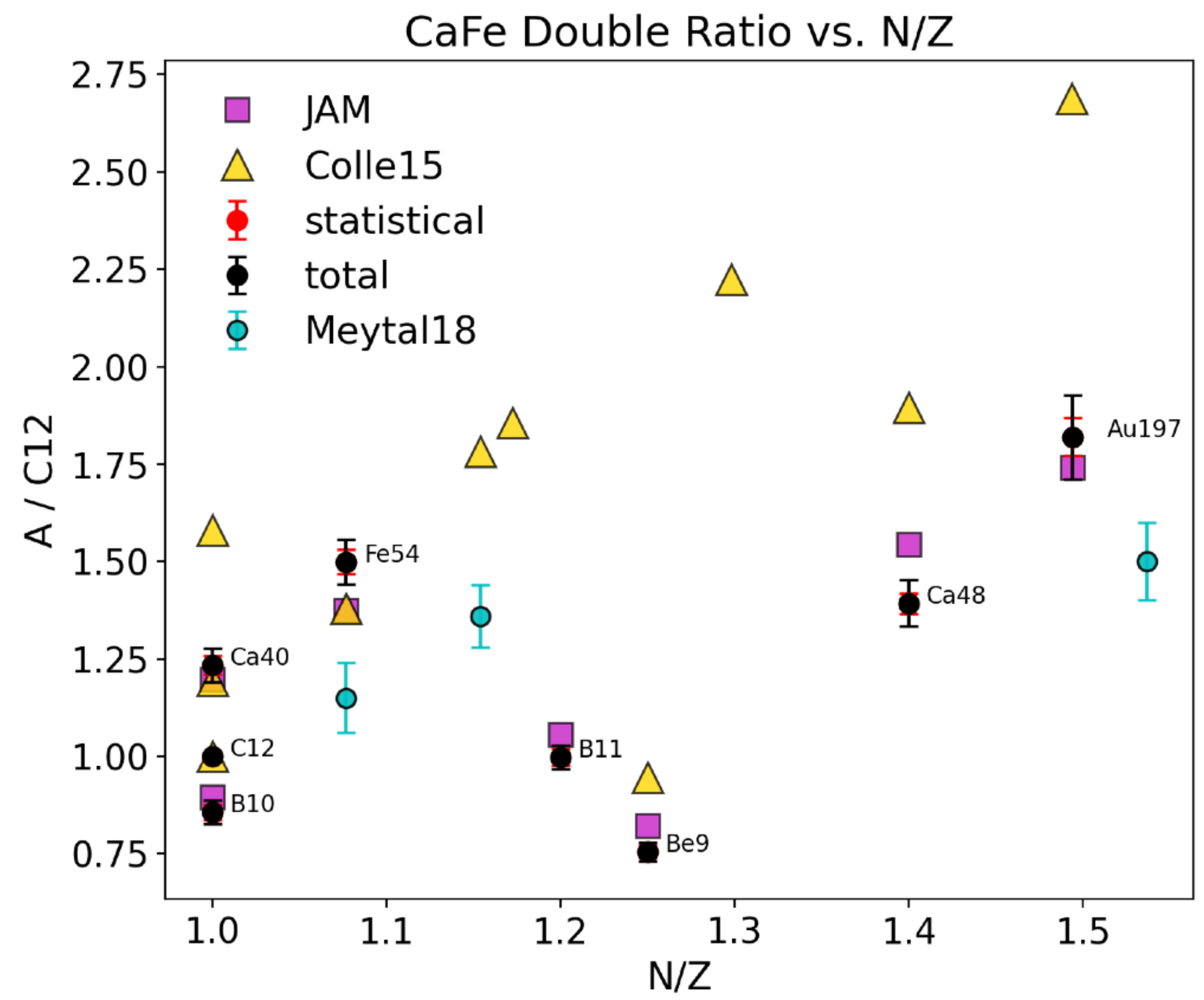
- models overlay: **OSU** + **JAM**

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

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

Justin-Andrew Model (JAM, 2023)



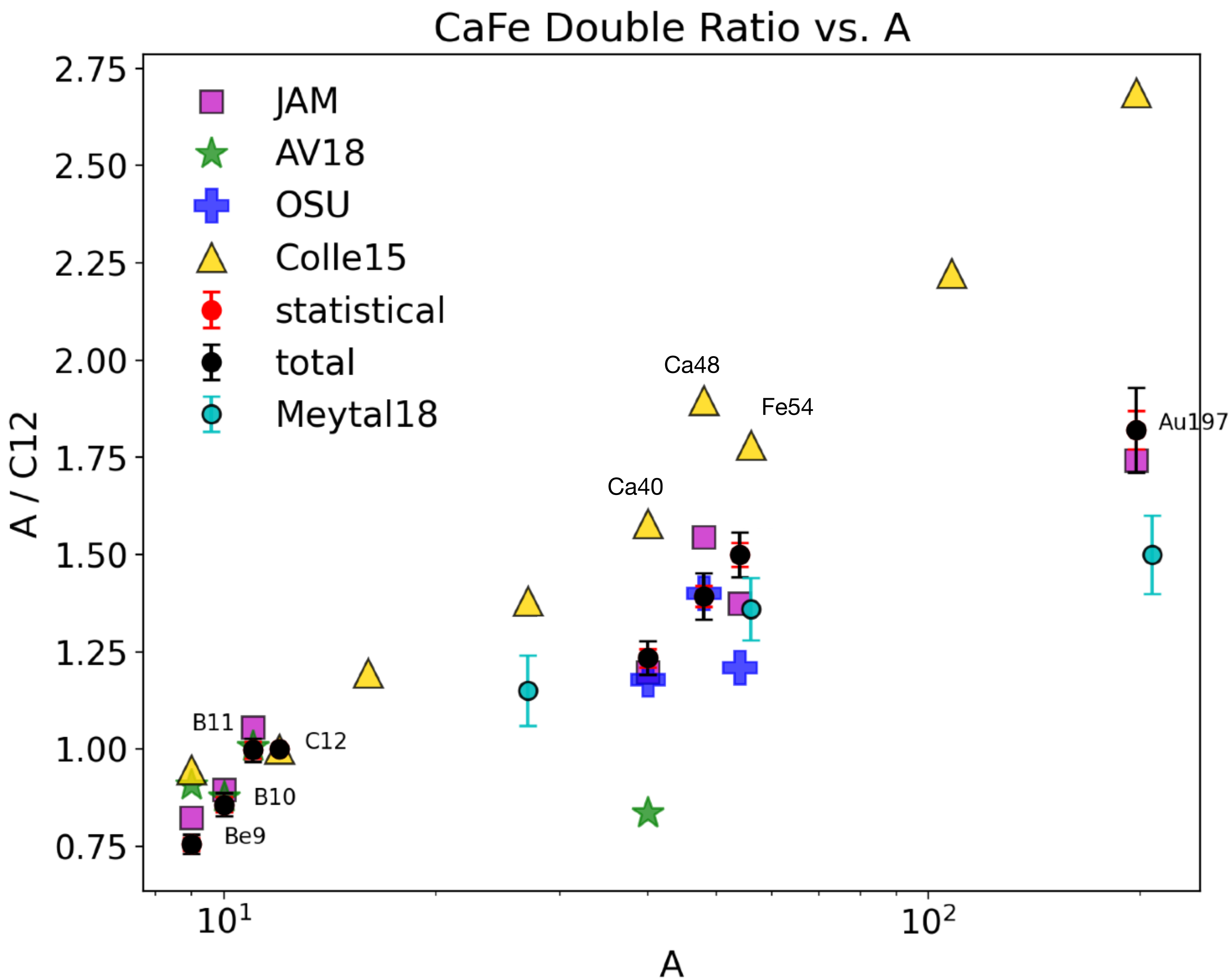


- models overlay: **JAM** + **Colle15**

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

Justin-Andrew Model (JAM, 2023)

Colle et al. Phys.Rev.C92 (Colle 15)



- all models overlay

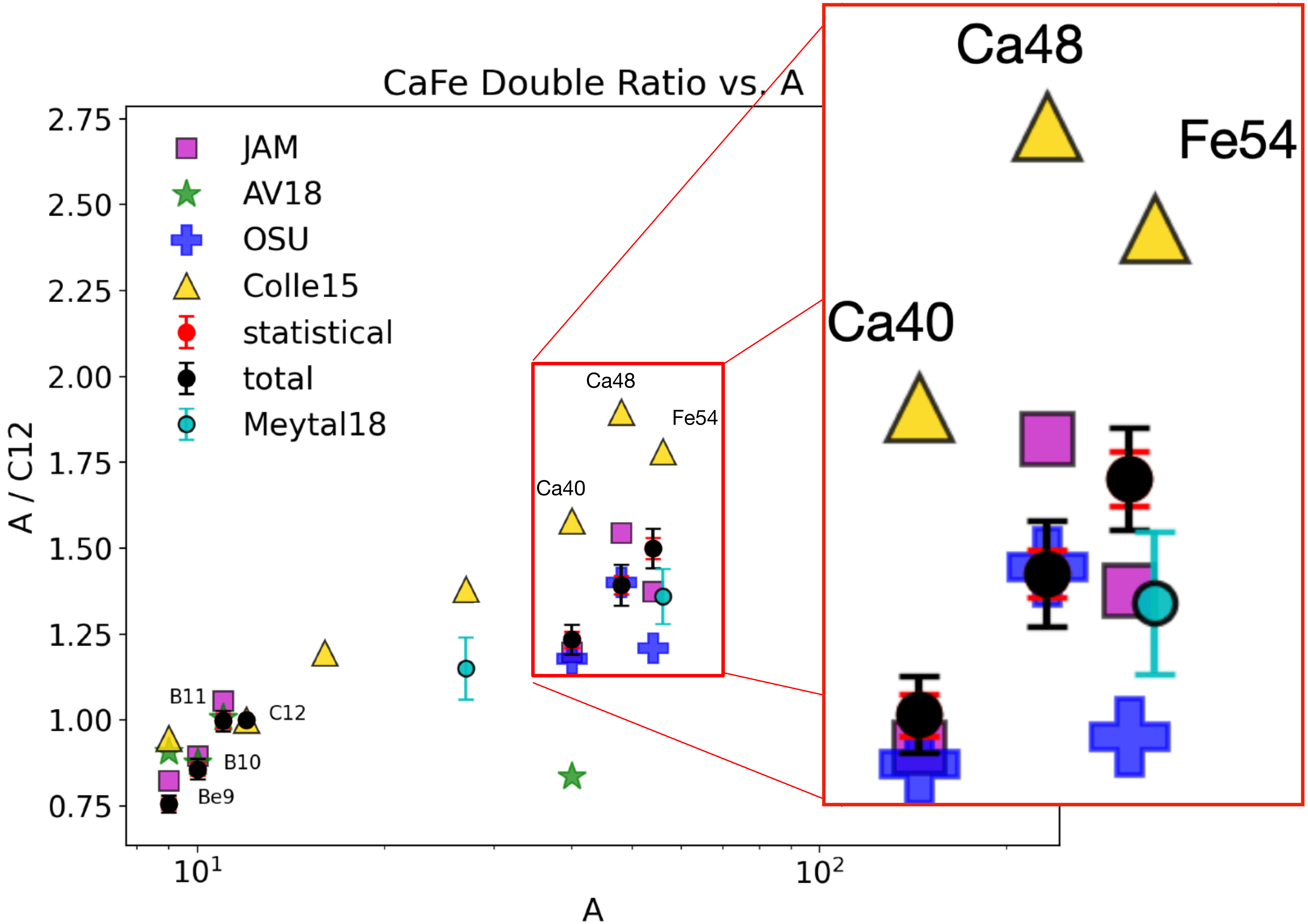
M. Duer et al. (CLAS collaboration), Nature 560, 617 (Meytal 18)

Justin-Andrew Model (JAM, 2023)

Colle et al. Phys.Rev.C92 (Colle 15)

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

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



- **OSU** + **JAM + Colle15** predict less pairing in Fe54 compared to Ca48

- **data** does NOT show this decrease
  - stronger $1f_{7/2} - 1f_{7/2}$ pairing for Fe54?

- all models overlay;

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

Justin-Andrew Model (JAM, 2023)

Colle et al. Phys.Rev.C92 (Colle 15)

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

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

Summary

Conclusions:

1. the MF single ratio to C data decreases with A; models are flat; we **DO NOT** understand this !

2. the SRC single ratio to C increases with A; models **DO NOT** show this trend;

3. the SRC/MF double ratio to C increases with A as expected
   it does not increase with N/Z; different from Duer (2018)

4. Models:
   a. The spatial-overlap (**JAM**) model describes the double-ratio data well
   b. ratios of **AV18** momentum distributions describe B10, B11, but not Be9 or Ca40
   c. ratios of **OSU** momentum distributions describe Ca40 and Ca48 but not Fe54
   d. **OSU** + **JAM** + **Colle15** predict weaker pairing for Ca48 -> Fe54; **data** predict stronger pairing

Failure of models to describe Ca40, Ca48 and Fe54 double ratios
$\Longrightarrow$ important of shell effects in SRC pairing !

More data on (*e, e'p*), (*e, e'n*), (*e, e'np*), (*e, e'pp*) coming soon from CLAS12 on C, Ca40, Ca48

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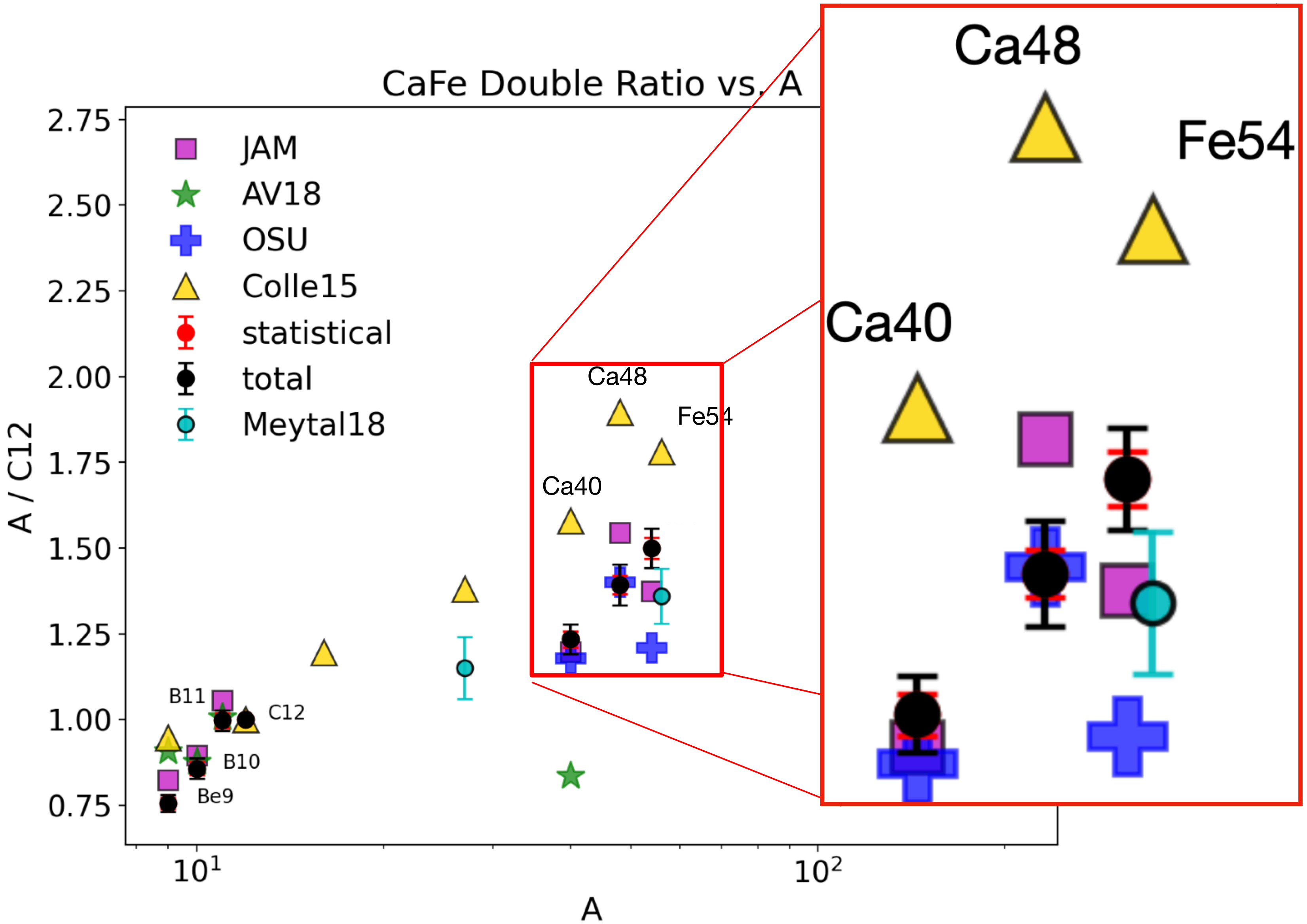
National
Science
Foundation

Thanks !

Spokespeople: D. Higinbotham (JLab), F. Hauenstein (JLab), O. Hen (MIT), L. Weinstein (ODU)

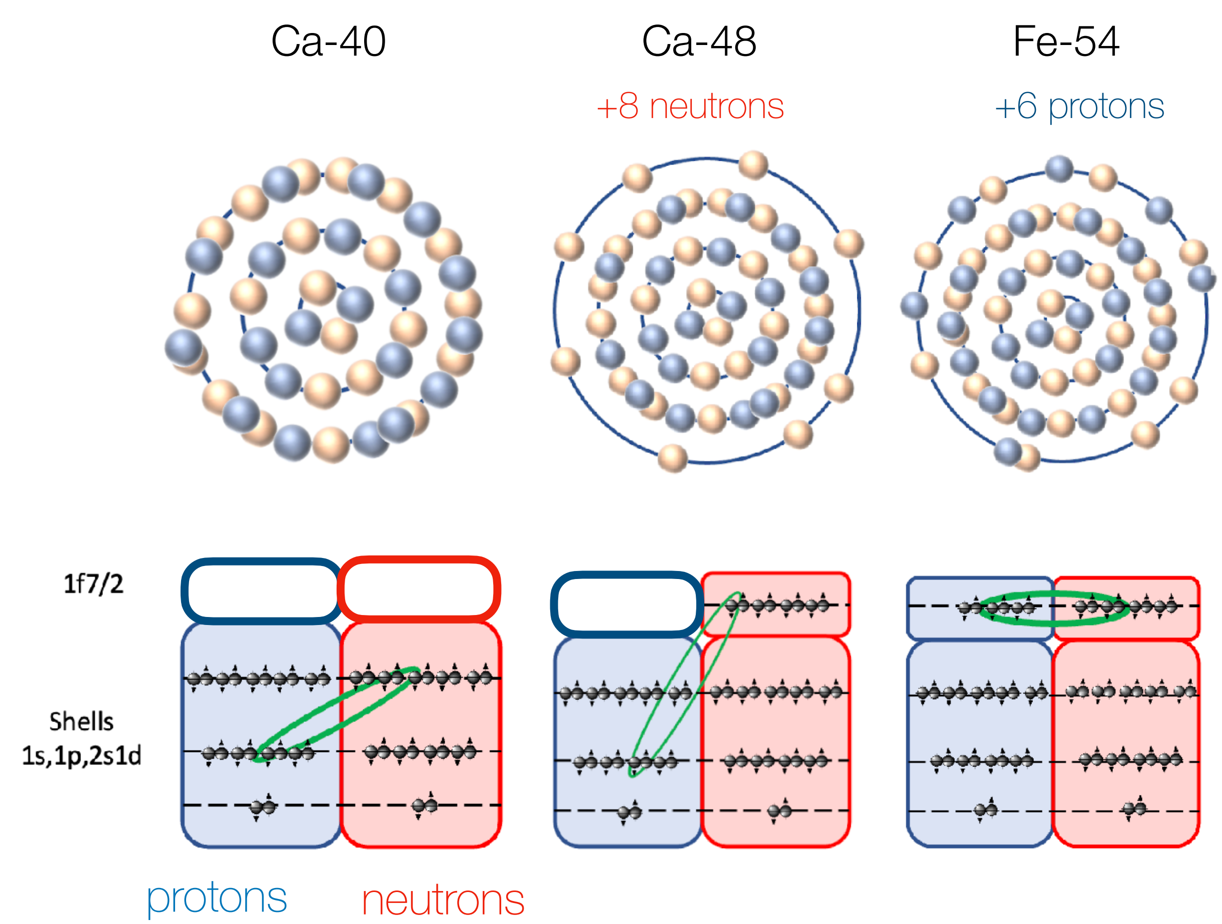
"This material is based upon work supported by the National Science Foundation under Grant No. 2137604"

Backup Slides

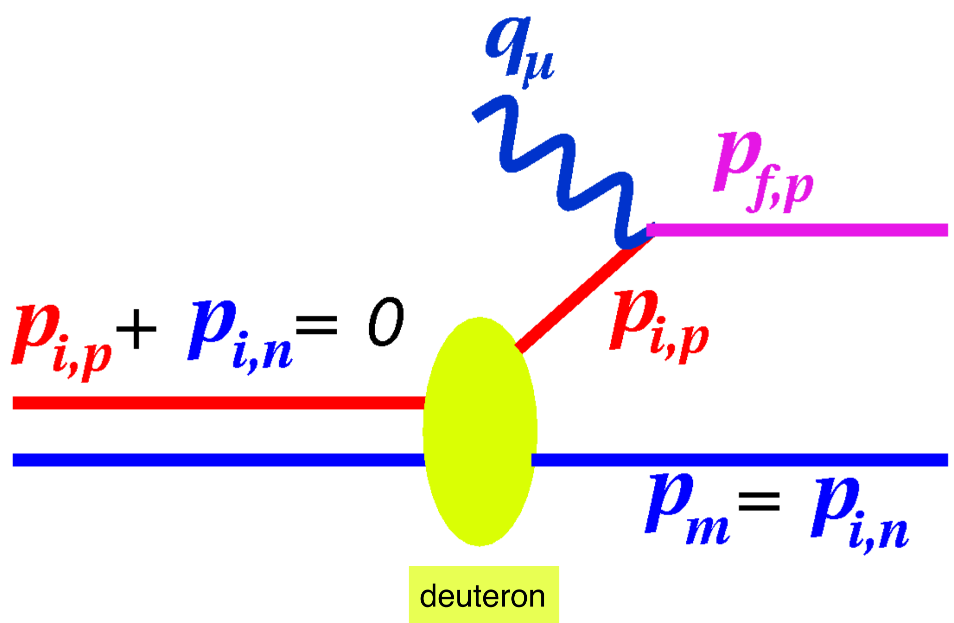


strong $1f_{7/2} - 1f_{7/2}$ pairing in Fe54?

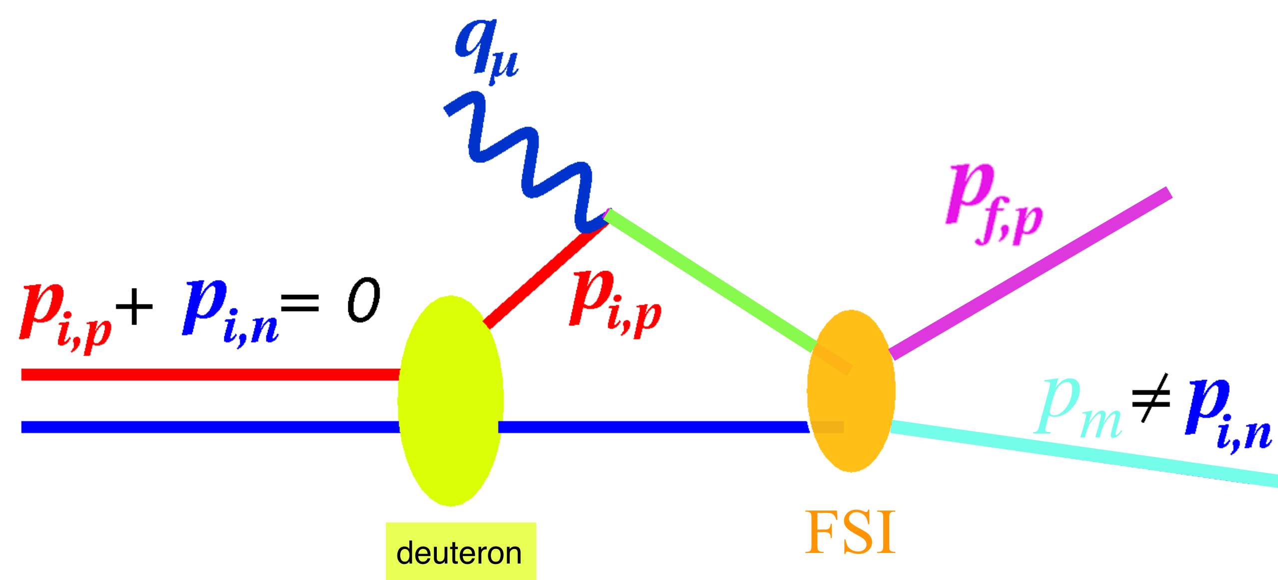
OSU + **JAM** + **Colle15**
predict less pairing in
Fe54 compared to Ca48;



virtual photon - nucleus interactions

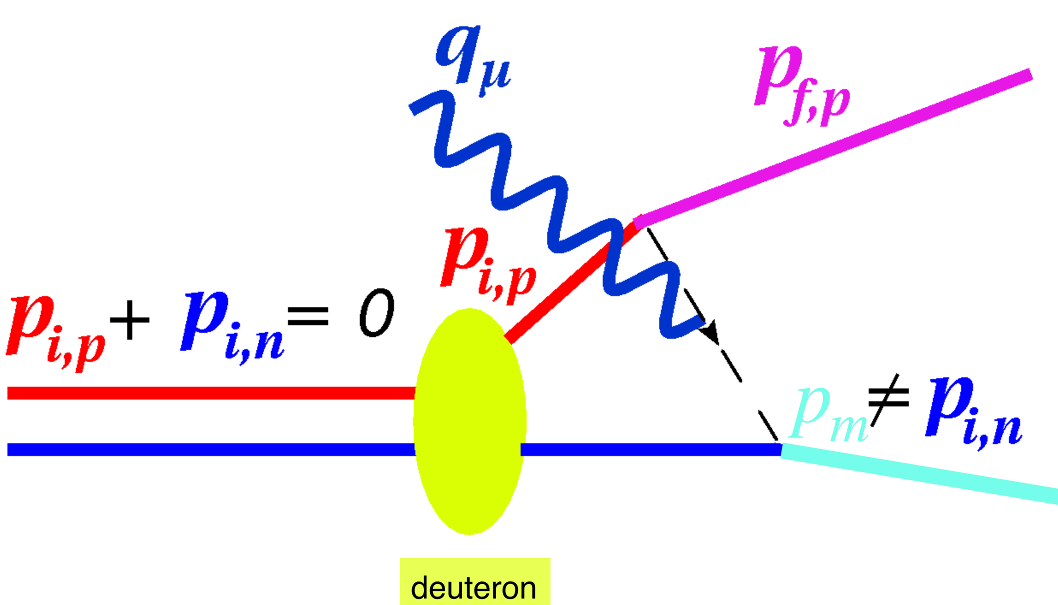


Plane Wave Impulse Approximation (PWIA)



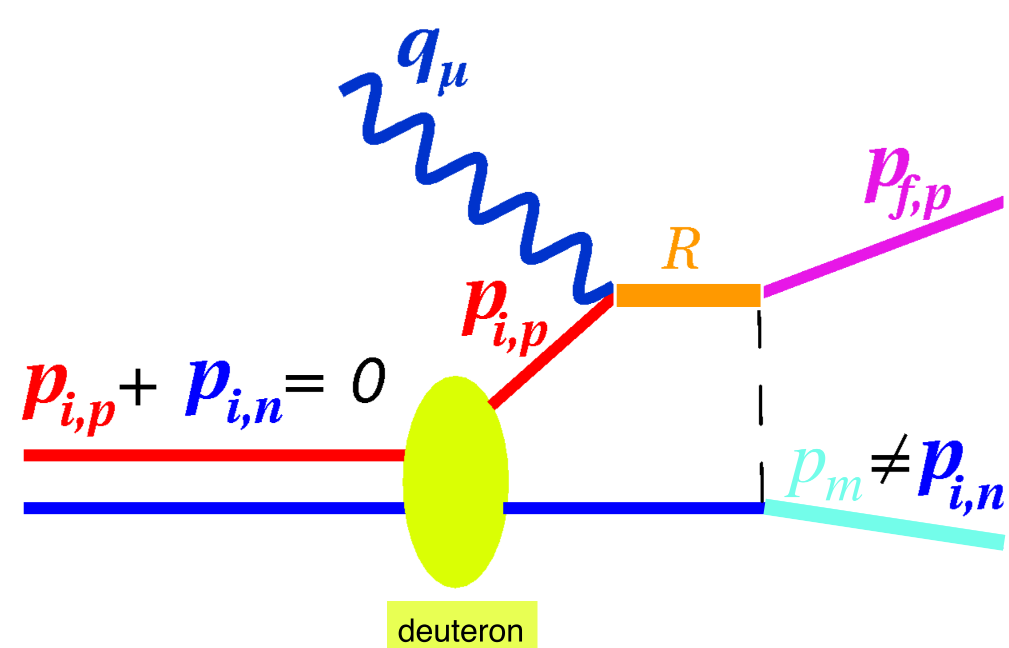
Final State Interactions (FSI)

suppressed at specific $\theta_{nq} < 40$ deg



Meson-Exchange Currents (MEC)

suppressed at $Q^2 > 1(\mathrm{GeV/c})^2$



Delta, N* Resonance Excitations (IC)

suppressed at $x_{\mathrm{Bj}} > 1$

Data/SIMC Single MF Ratios (per proton)

SIMC: Hall C standard A(e,e'p) simulation program

Purpose: Check SIMC per-proton raw cross sections for C12, Fe56, Au197 MF kinematics

$$Y = \frac{N_{e,e'p}}{T \cdot \sigma_{thick} \cdot Z/A}$$

Charge Q = 1 mC

Target (Z, A)	T	Target thickness (g/cm2)	raw counts	Yield
C12 (6, 12)	0.551	0.5738	1081	6838. +/- 208
Fe56 (56, 26)	0.381	0.367	370.6	5708. +/- 297
Au197 (79, 197)	0.281	0.4047	264.9	5808. +/- 356

SIMC Cuts (exactly same as data):

Kinematical

-20 < Em < 90 MeV

Q2 > 1.8 GeV^2

Pm < 270 MeV

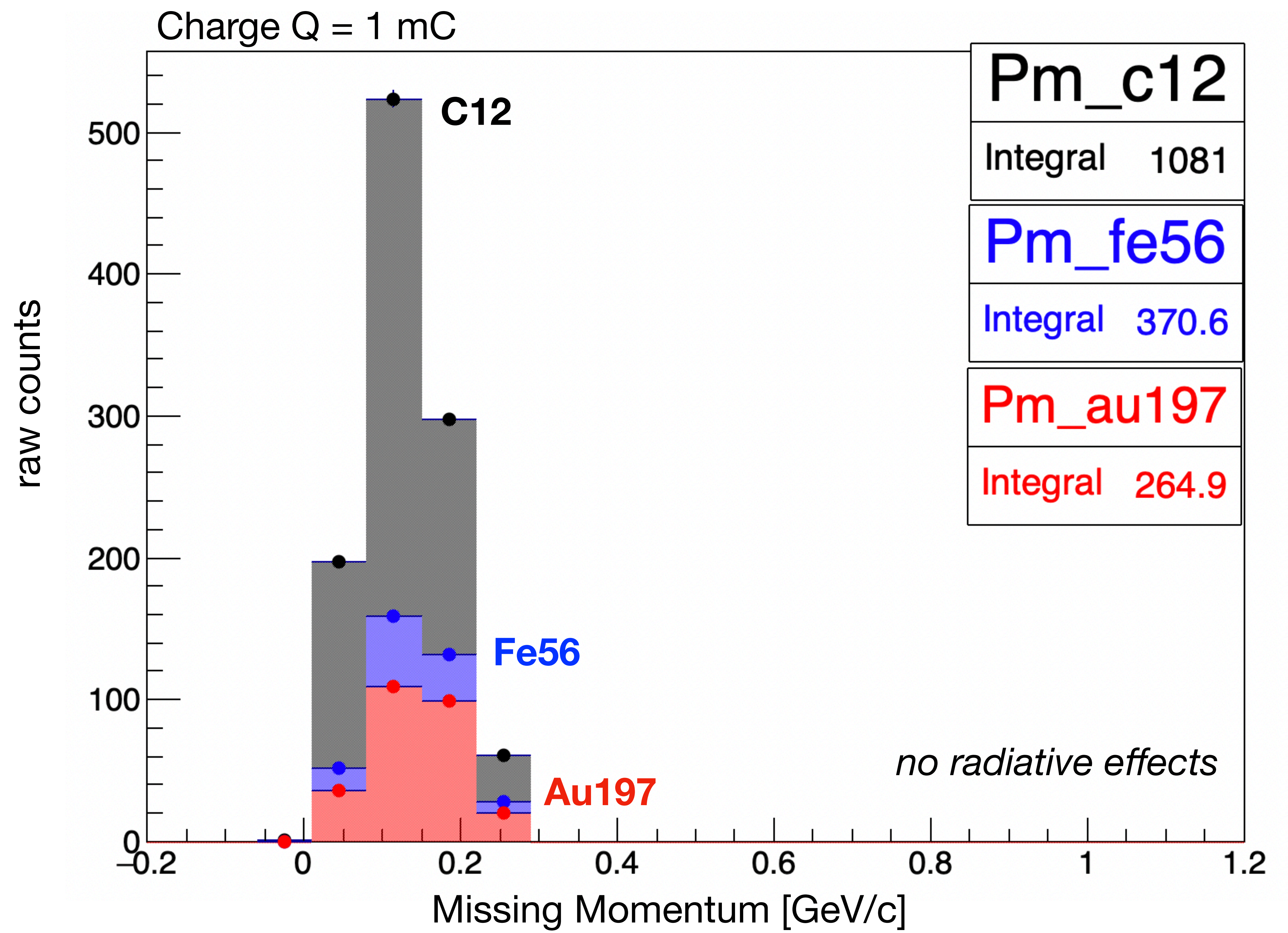
Acceptance

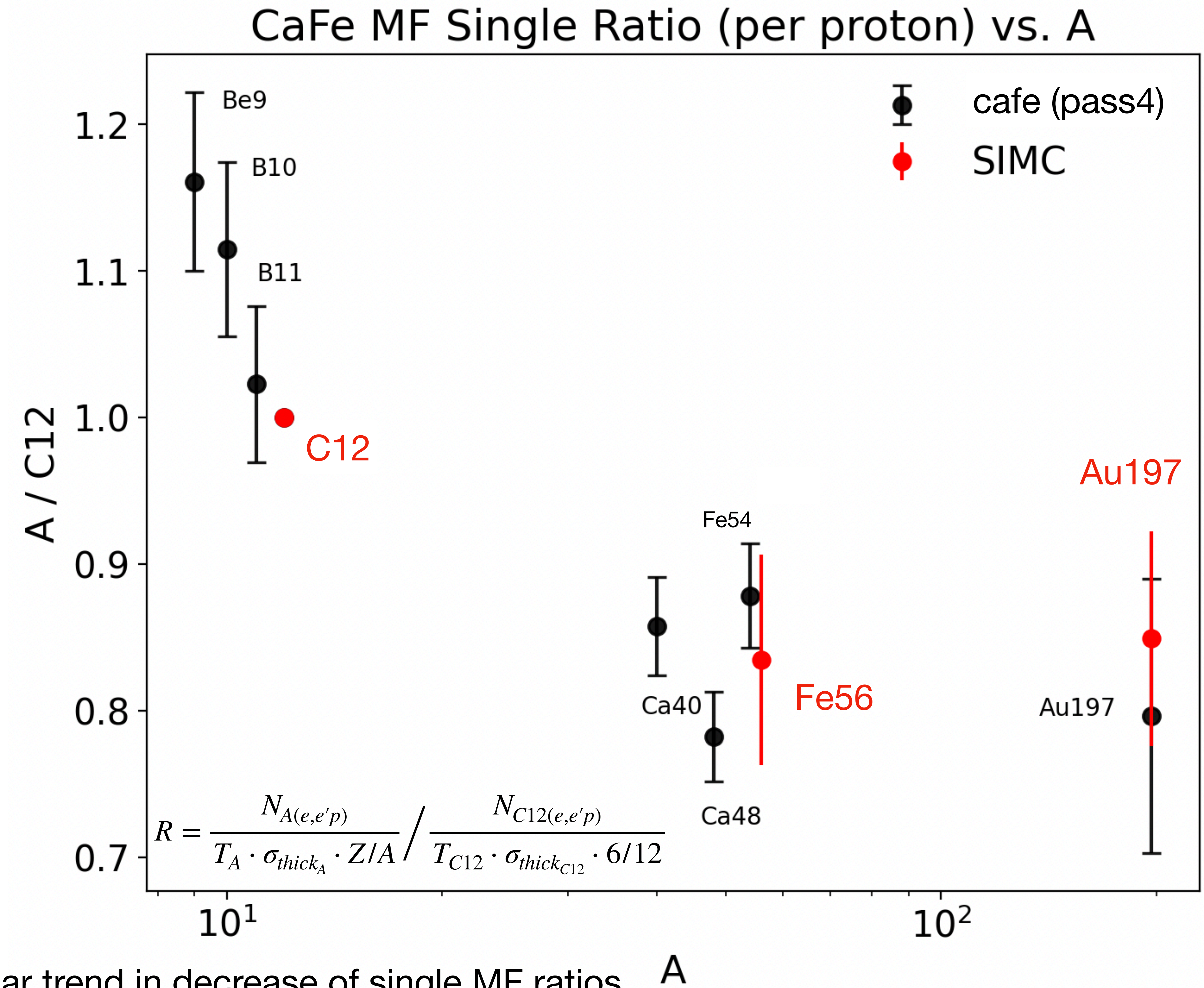
0 < SHMS delta < 22 %

| HMS delta | < 10 %

HMS/SHMS collimator (was not done in SIMC)

Purpose: Check SIMC per-proton raw cross sections for C12, Fe56, Au197 MF kinematics



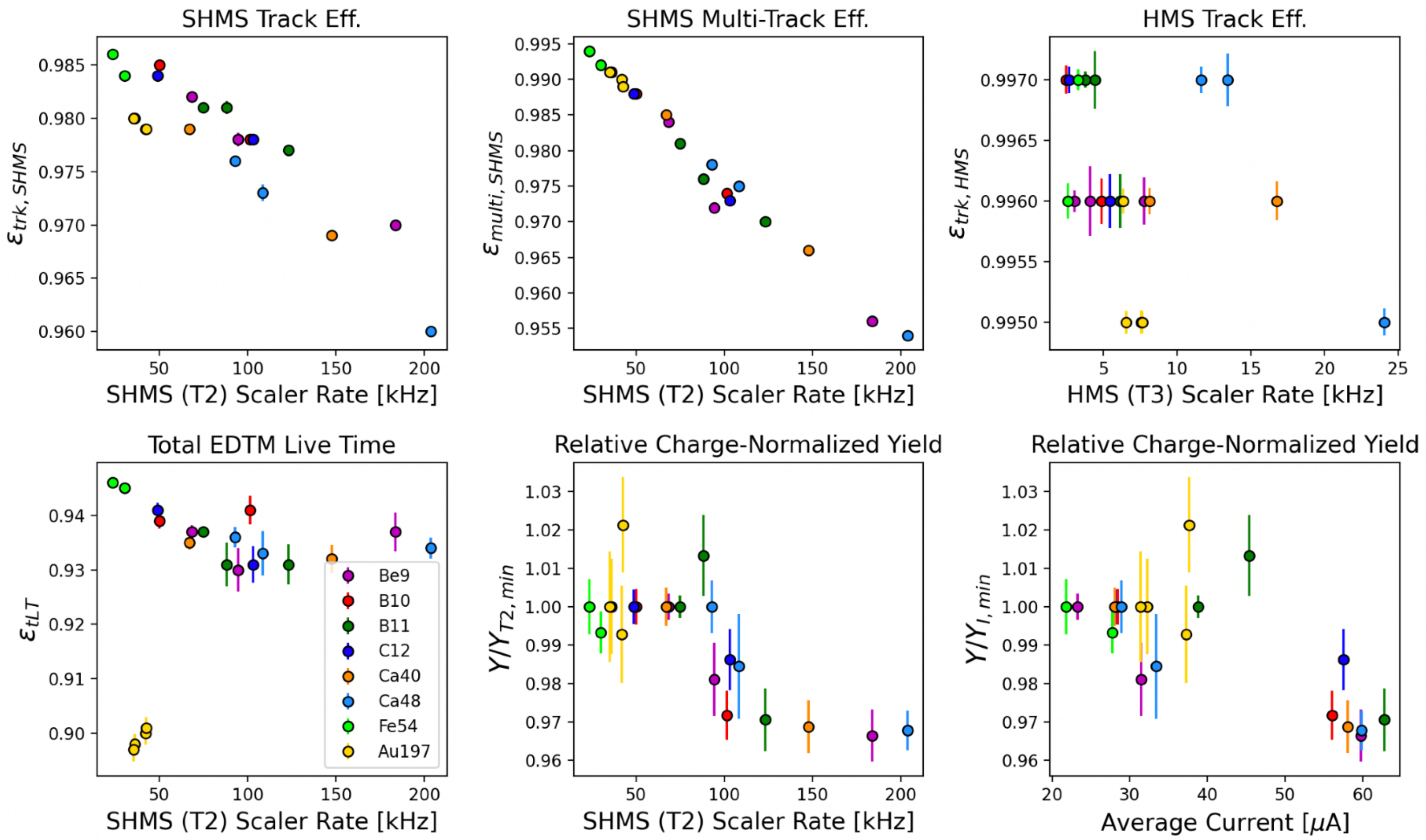


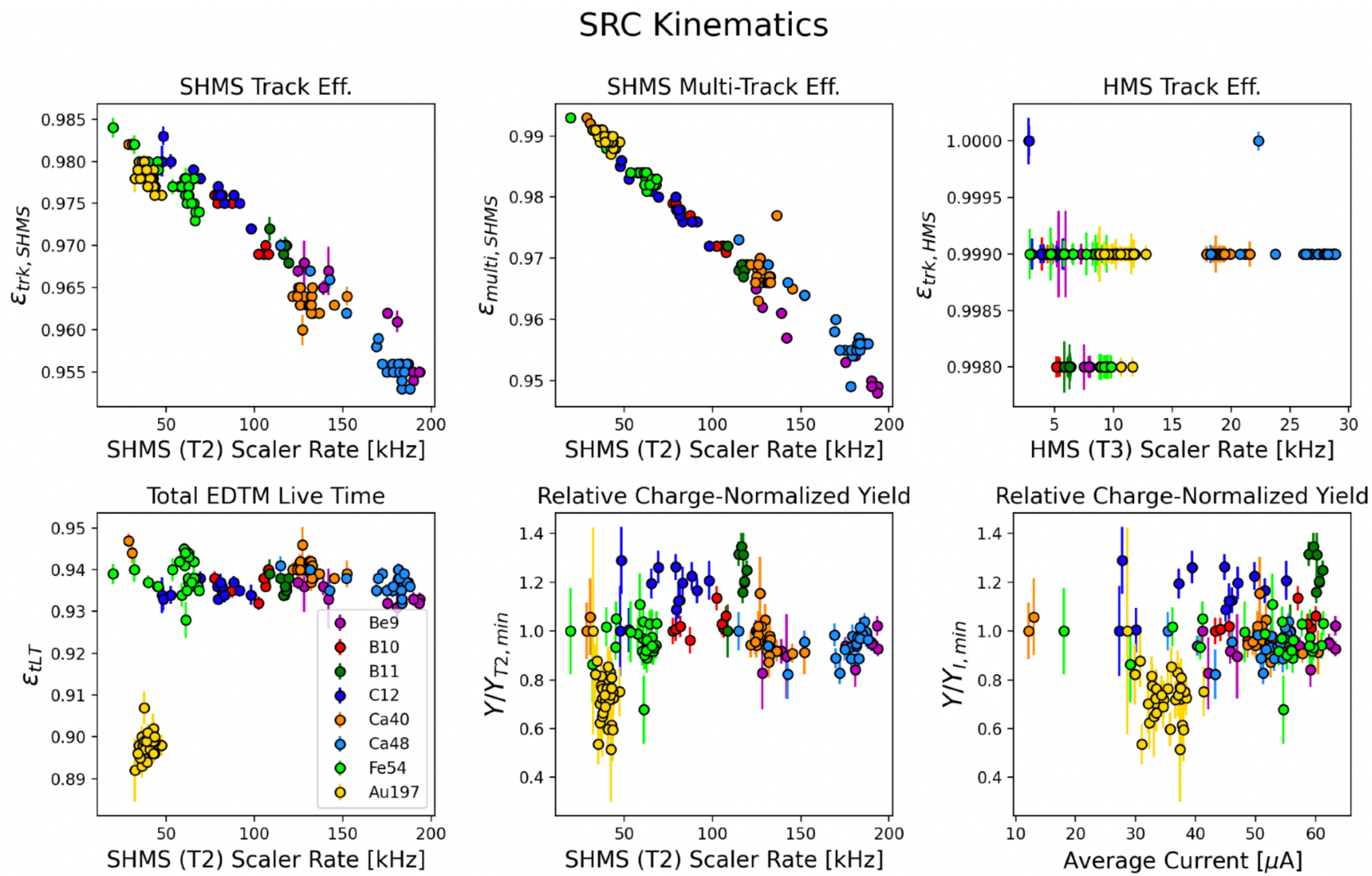
similar trend in decrease of single MF ratios between **data** and **SIMC** (why **NOT** flat ?)

data: radiative corrections
simc: no radiative effects

Corrections and Inefficiencies

MF Kinematics

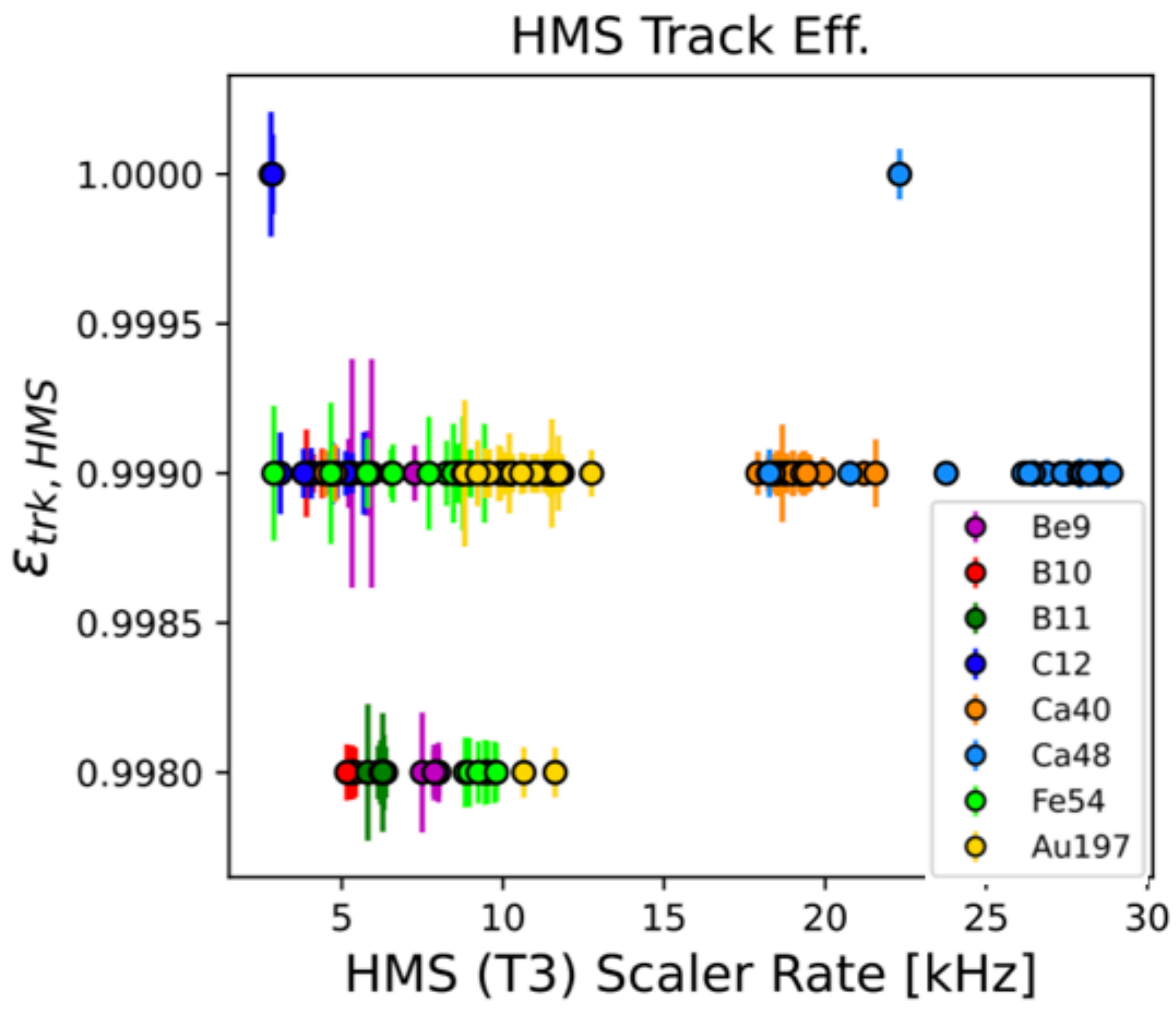




SRC Kinematics
SHMS Track Eff.
SHMS Multi-Track Eff.
HMS Track Eff.
Total EDTM Live Time
Relative Charge-Normalized Yield
Relative Charge-Normalized Yield
SHMS (T2) Scaler Rate [kHz]
HMS (T3) Scaler Rate [kHz]
Average Current [μA]
$\varepsilon_{trk,SHMS}$
$\varepsilon_{multi,SHMS}$
$\varepsilon_{trk,HMS}$
ε_{tLT}
$Y/Y_{T2,min}$
$Y/Y_{I,min}$
Be9
B10
B11
C12
Ca40
Ca48
Fe54
Au197

Yield Extraction

$$Y = \frac{N_{(e,e'p)}}{Q \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{mult.trk} \cdot \epsilon_{LT} \cdot T_N \cdot \sigma_{thick}}$$



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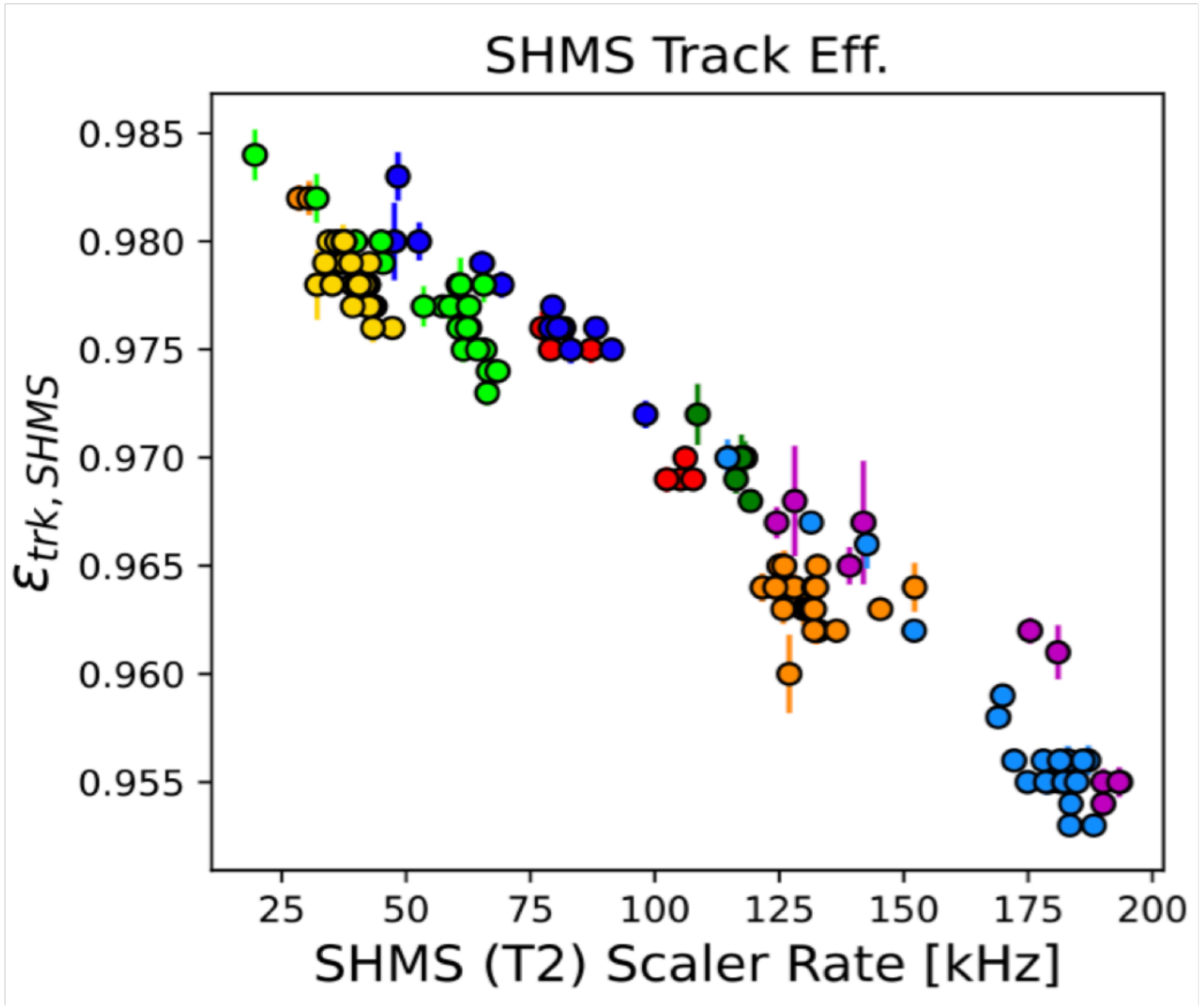

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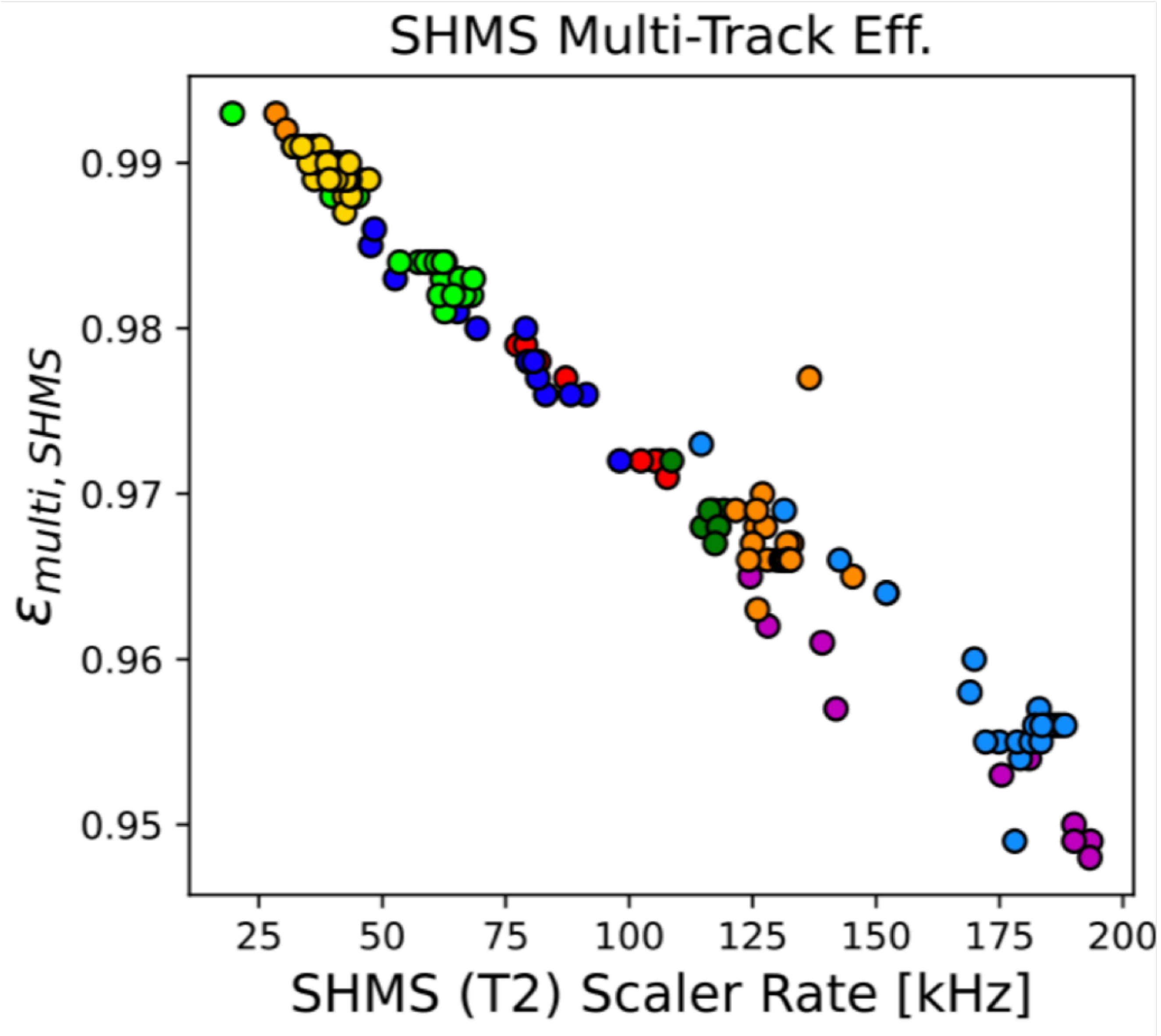

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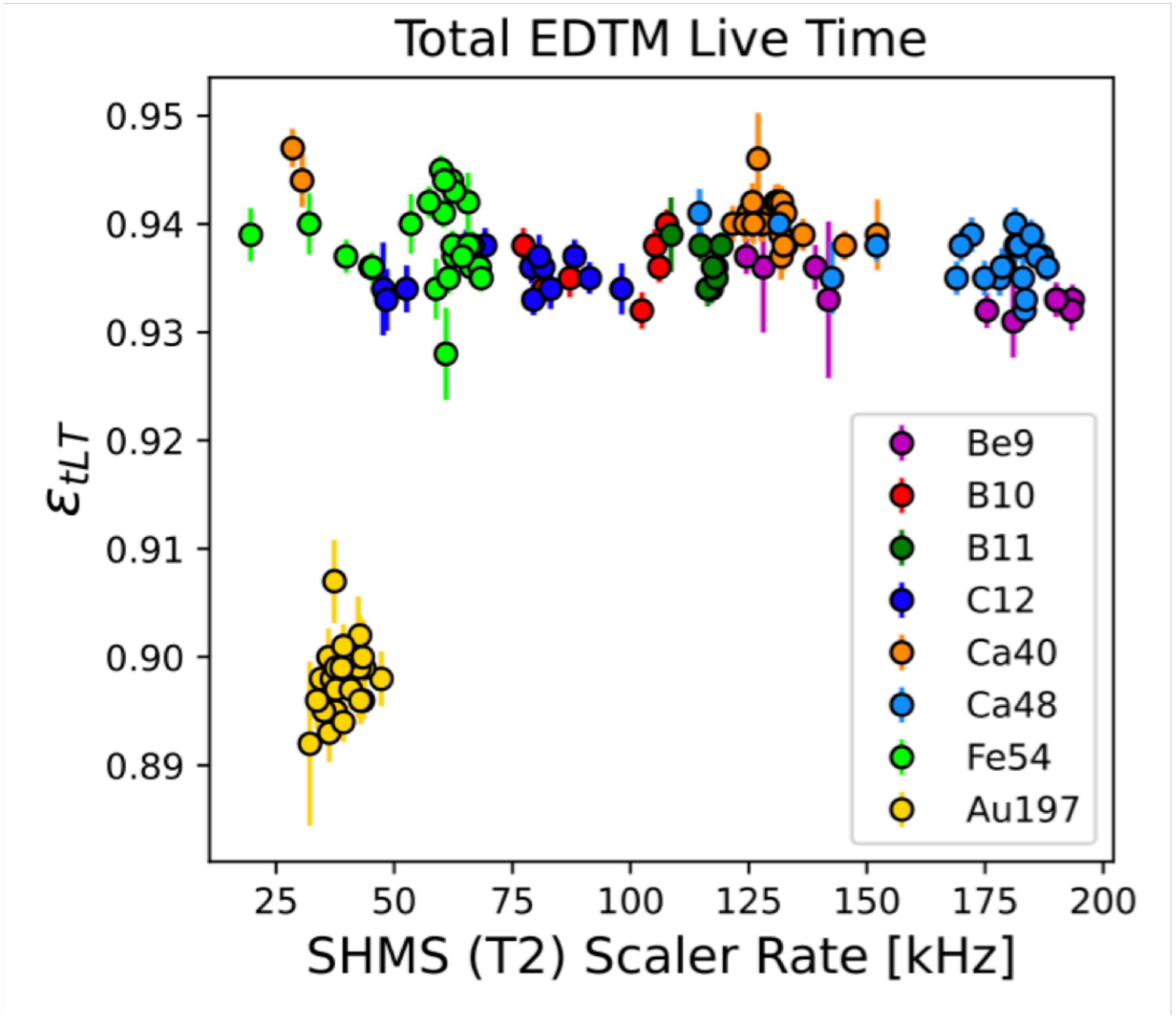
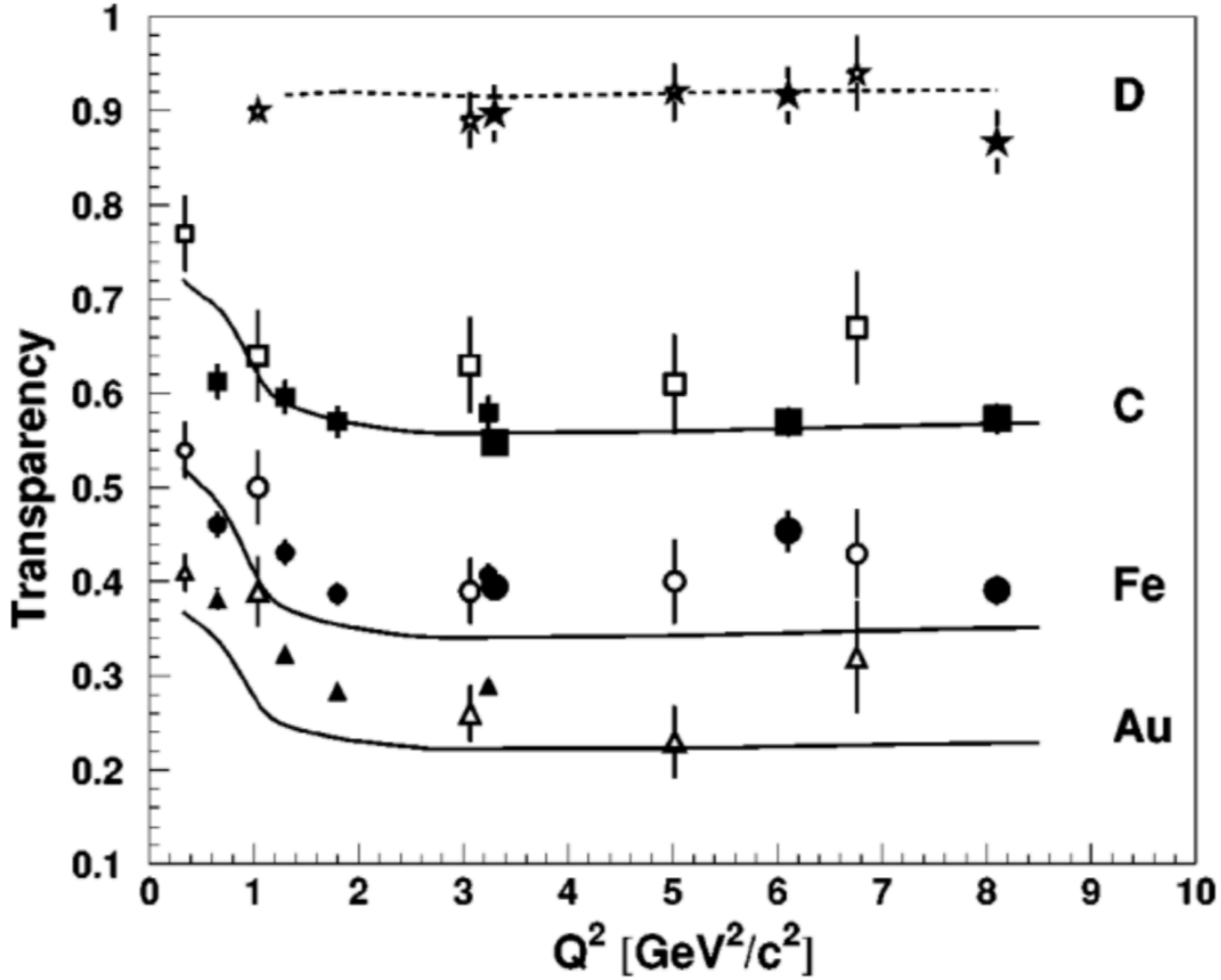


Yield Extraction

$$Y = \frac{N_{(e,e'p)}}{Q \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{mult.trk} \cdot \epsilon_{LT} \cdot T_N \cdot \sigma_{thick}}$$

K. Garrow *et al.* PHYSICAL REVIEW C **66**, 044613 (2002)



$$T_N = cA^{-\alpha(Q^2)}$$

For $Q^2 \gtrsim 2\text{GeV}^2$

$c \to 1$

$\alpha \to 0.24$

K. Garrow et al. PhysRevC66 (2002)

The IPSM spectral function does not include the effects of short-range nuclear correlations, which move strength to $|p_m| > p_f$. The measured T must be corrected by the ratio of $\int S d^3p dE_s$ for the IPSM and correlated spectral functions, integrated over the (E_m, p_m) range $\mathcal{R}$:

$$C_{correl} = \frac{1}{I_{correl}} \int_{\mathcal{R}} dE_s d^3p S(E_s, \mathbf{p}). \tag{5.7}$$

TABLE 12. Correlation tail correction to the PWIA calculation

A	C_{correl}
^1H, ^2H	1.00
^{12}C	1.11 ± 0.03
^{56}Fe	1.26 ± 0.08
^{197}Au	1.32 ± 0.08

O’Neill Hall C thesis