The CaFe Experiment:

Isospin Dependence of Short-Range Correlations in Nuclei

C. Yero
(On behalf of the CaFe collaboration)

4th EMC & SRC Workshop
Jan 30 - Feb 04, 2023

Proposal: PR12-16-004

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

What have we learned about SRCs?

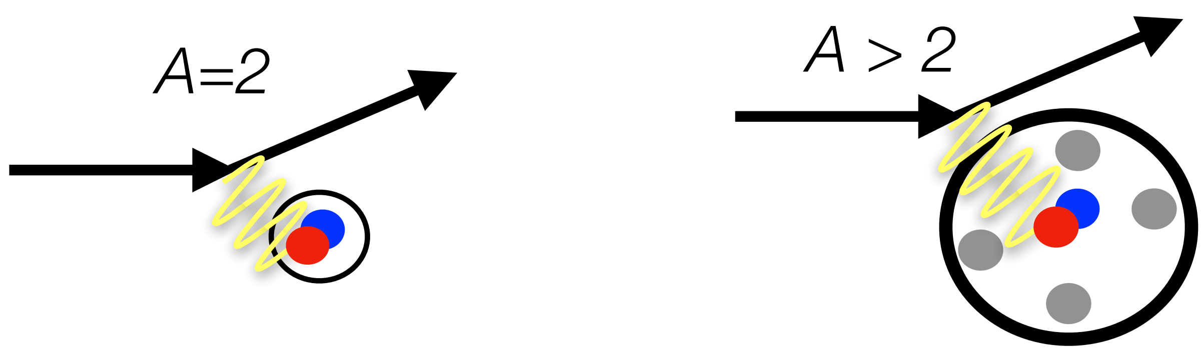
See Eli/ Or's intro !

- (e,e'): scaling **See Douglas Higinbotham's talk**

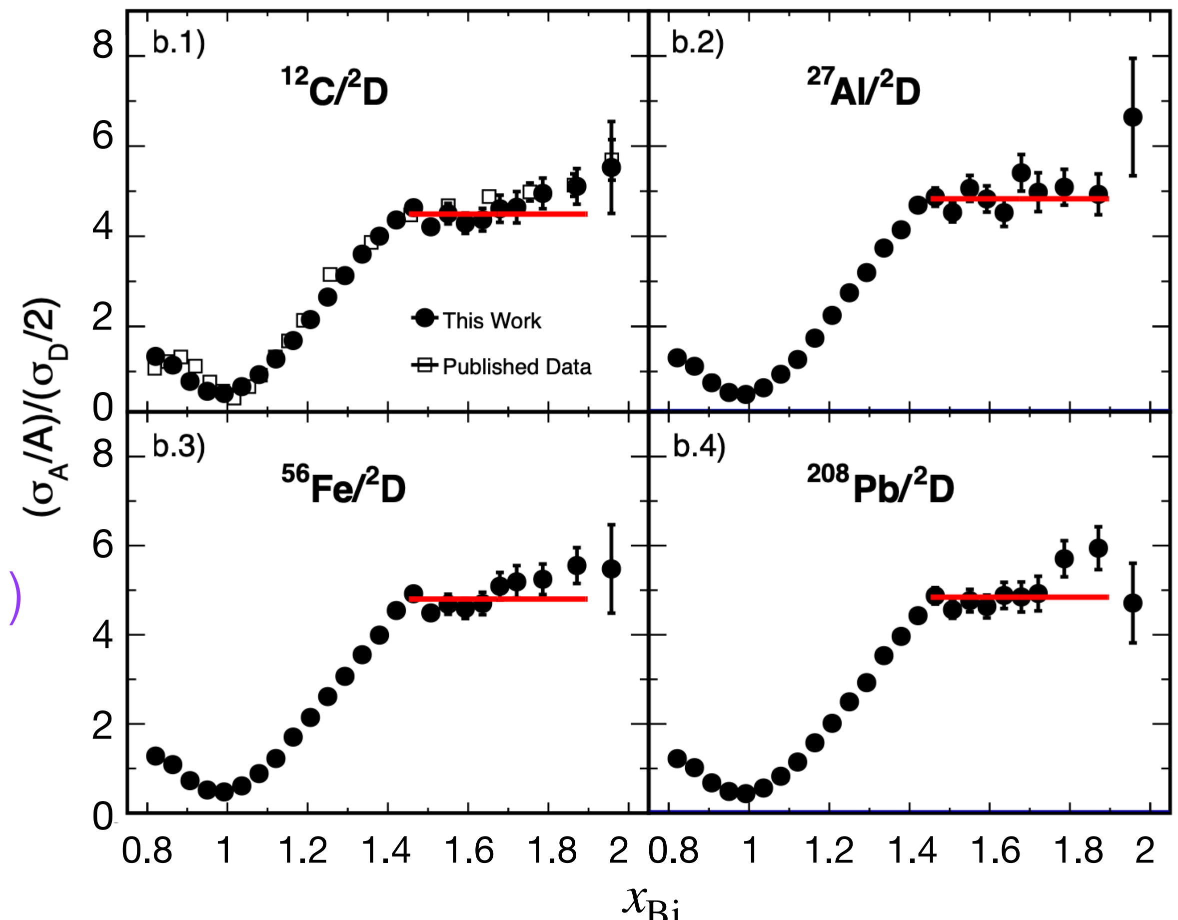
  above $k_F \sim 250$ MeV/c all nuclei have similar nucleon momentum distributions (i.e., scaling)

- (e,e'p): np-dominance **See Andrew Denniston's talk**

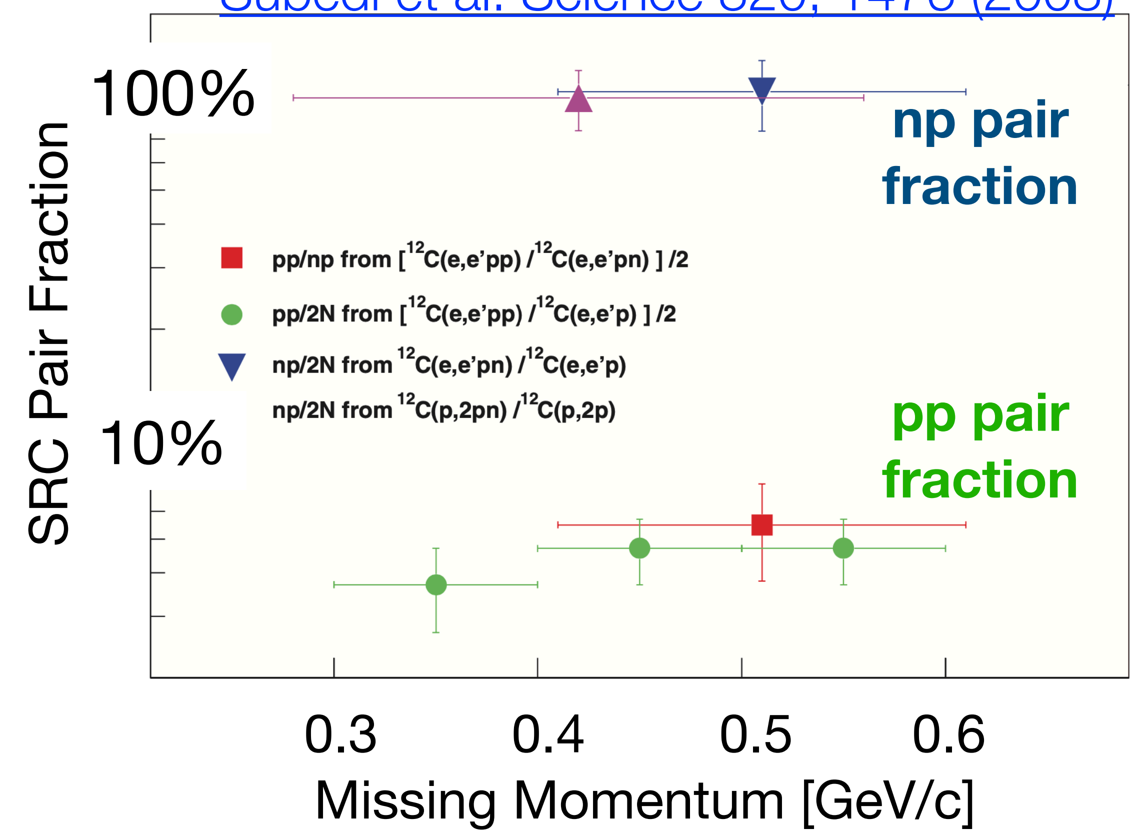
  almost all high-momentum nucleons ($k_F > 250$ MeV/c) belong to np-SRC pairs ("np-dominance")



Schmookler et al. Nature, 566, 354 (2019)



Subedi et al. Science 320, 1476 (2008)



L.L. Frankfurt, M.I. Strikman, D.B. Day, and M.M. Sargsyan, Phys. Rev. C 48, 2451 (1993)

K. Sh. Egiyan et al. Phys.Rev.C 68, 014313 (2003)

E. Piasetzky, M. Sargsian, L. Frankfurt, M. Strikman, and J. W. Watson Phys. Rev. Lett. 97, 162504 (2006)

K. S. Egiyan et al.Phys.Rev.Lett.96, 082501 (2006)

N. Fomin et al. Phys.Rev.Lett.108, 092502 (2012)

Ryckebusch et al.PLB79221 (2019)

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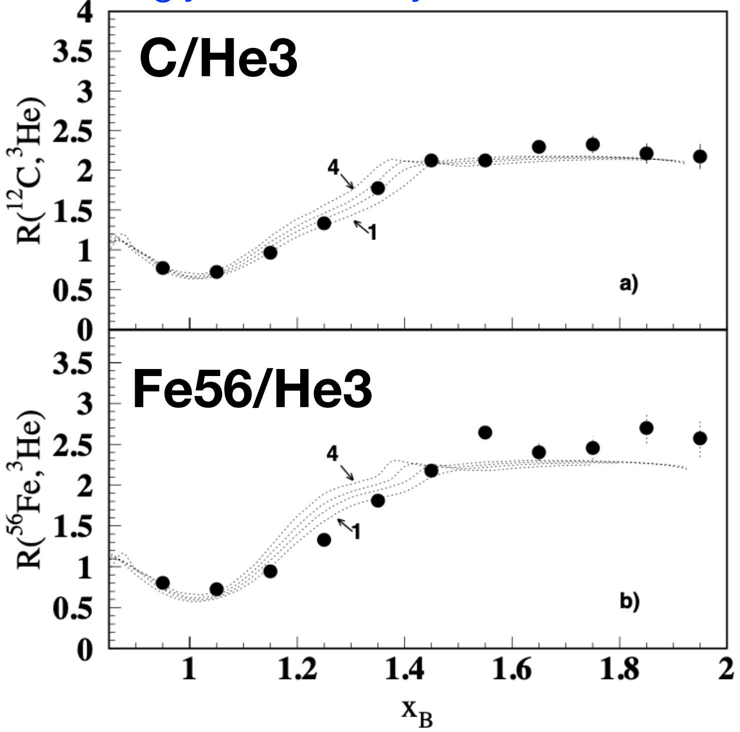

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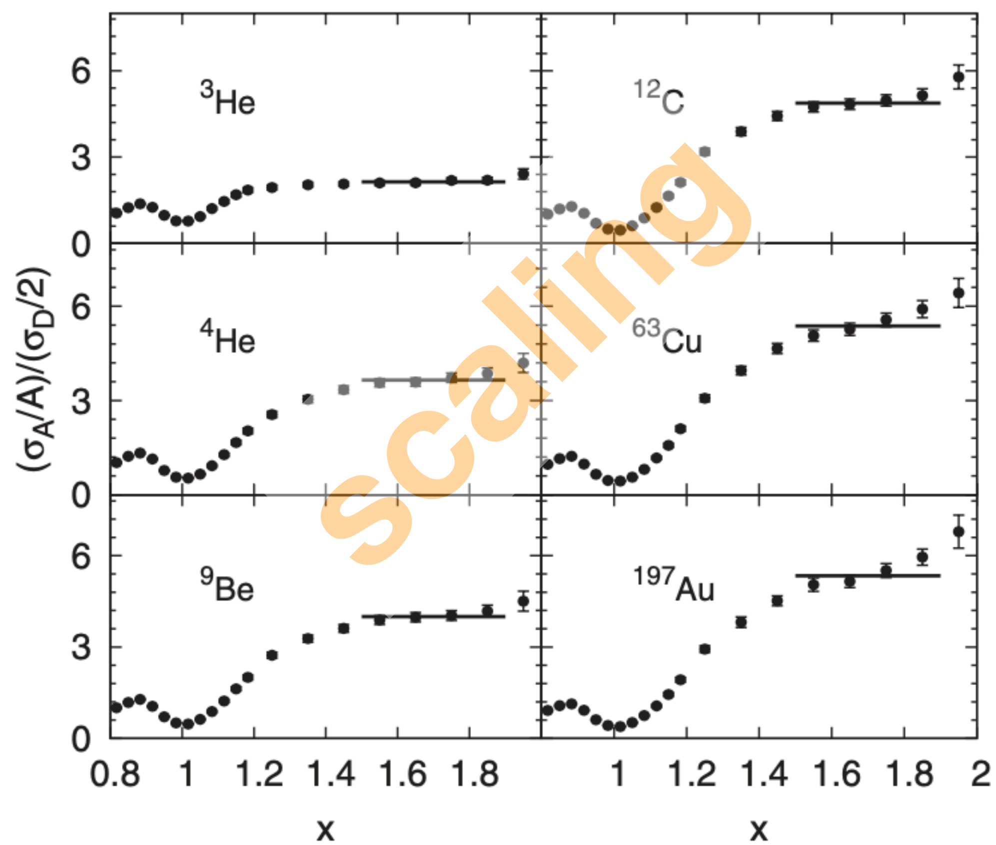
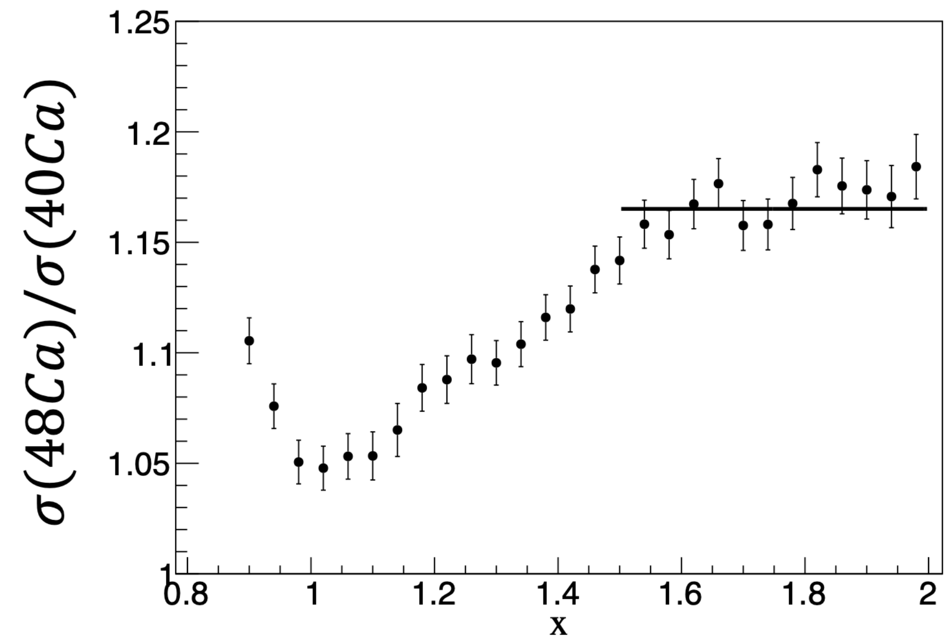
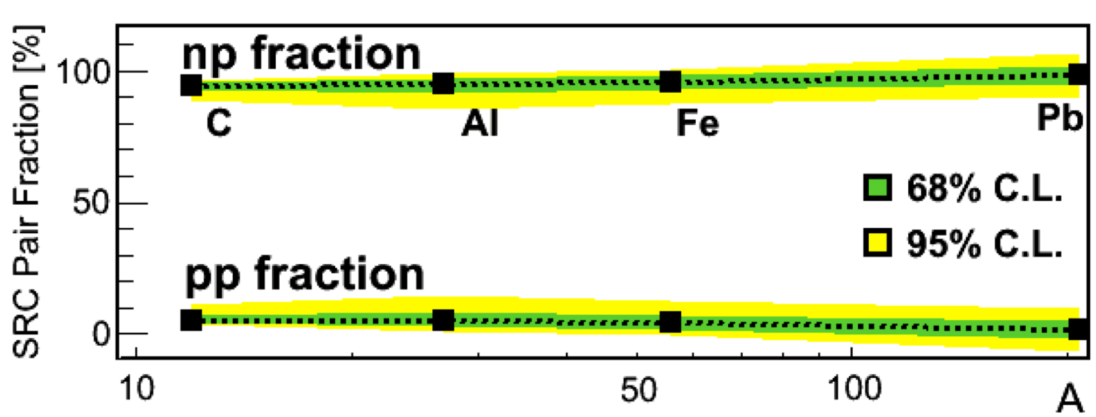


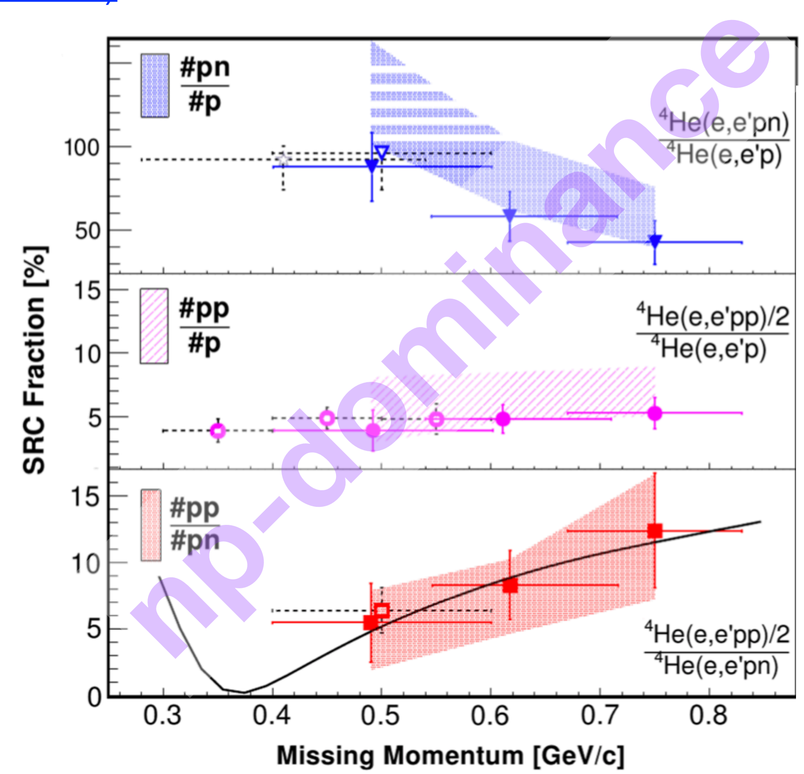
D. Nguyen et al. PRC 102, 064004 (2020)



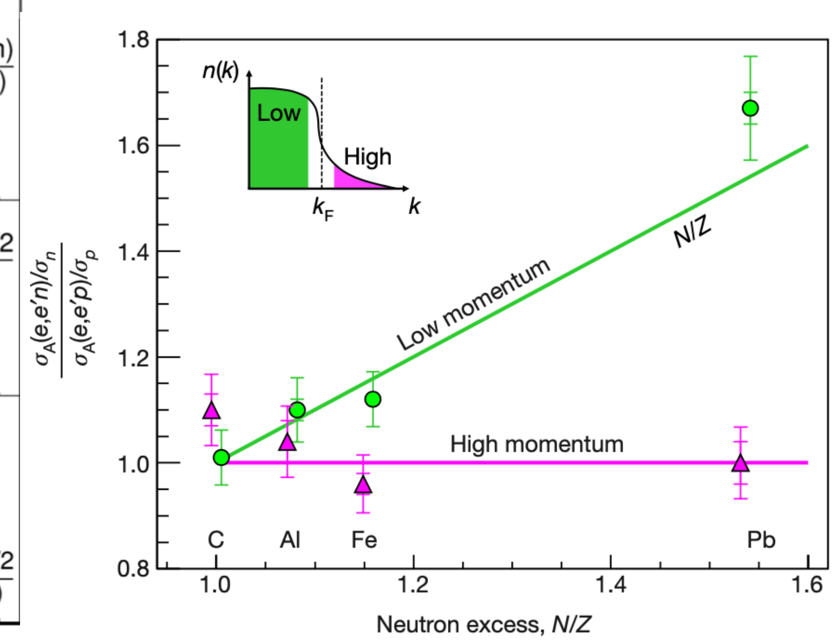
Hen et al. (CLAS Collaboration), Science 346, 614 (2014)



Korover et al. PRL 113, 022501 (2014)



Duer et al. PRL 122, 172502 (2019)



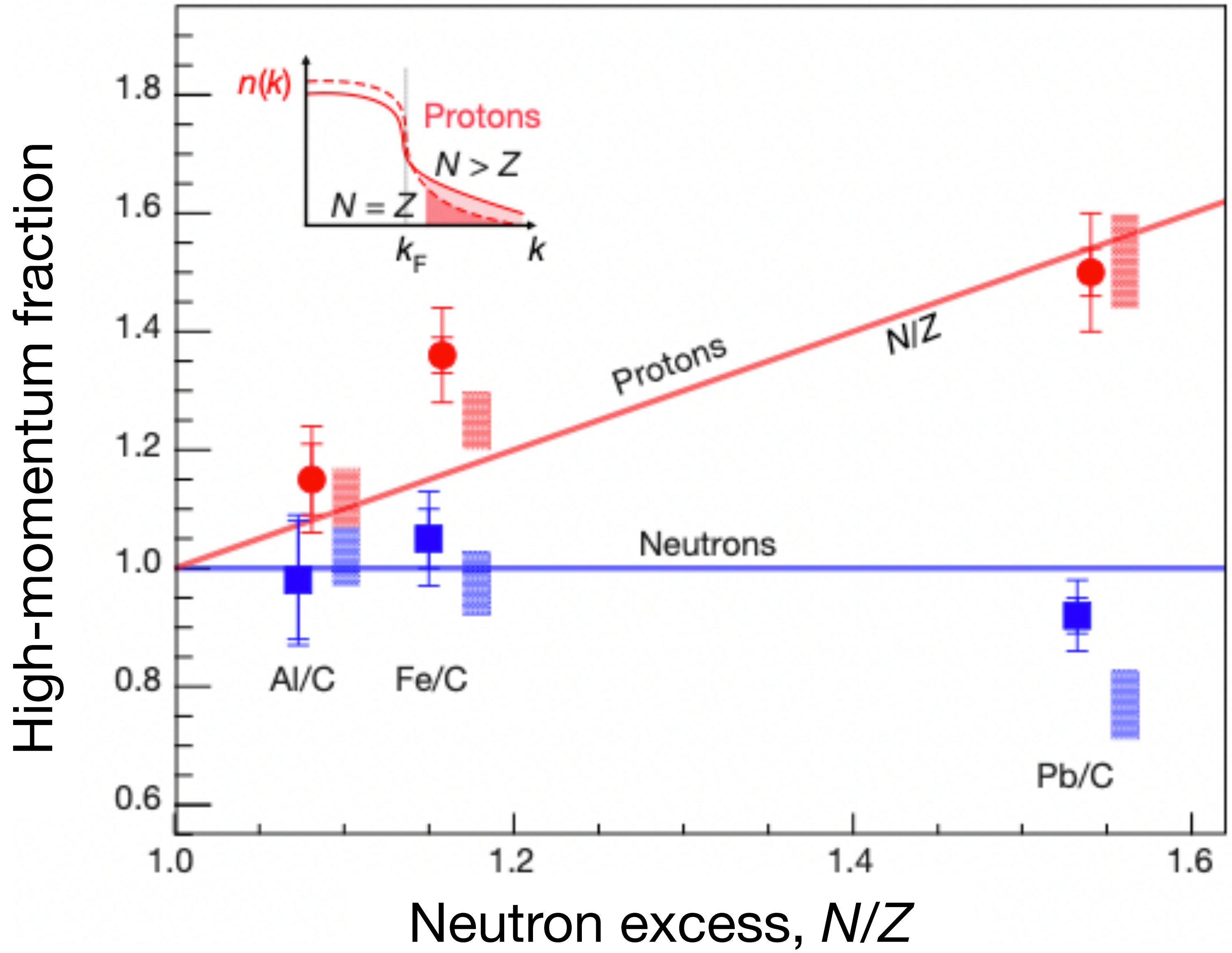
Motivation: Which nucleons form SRC pairs?

CaFe will answer:

→Which nucleons form pairs?

→How does adding (n or p) change NN pairing?

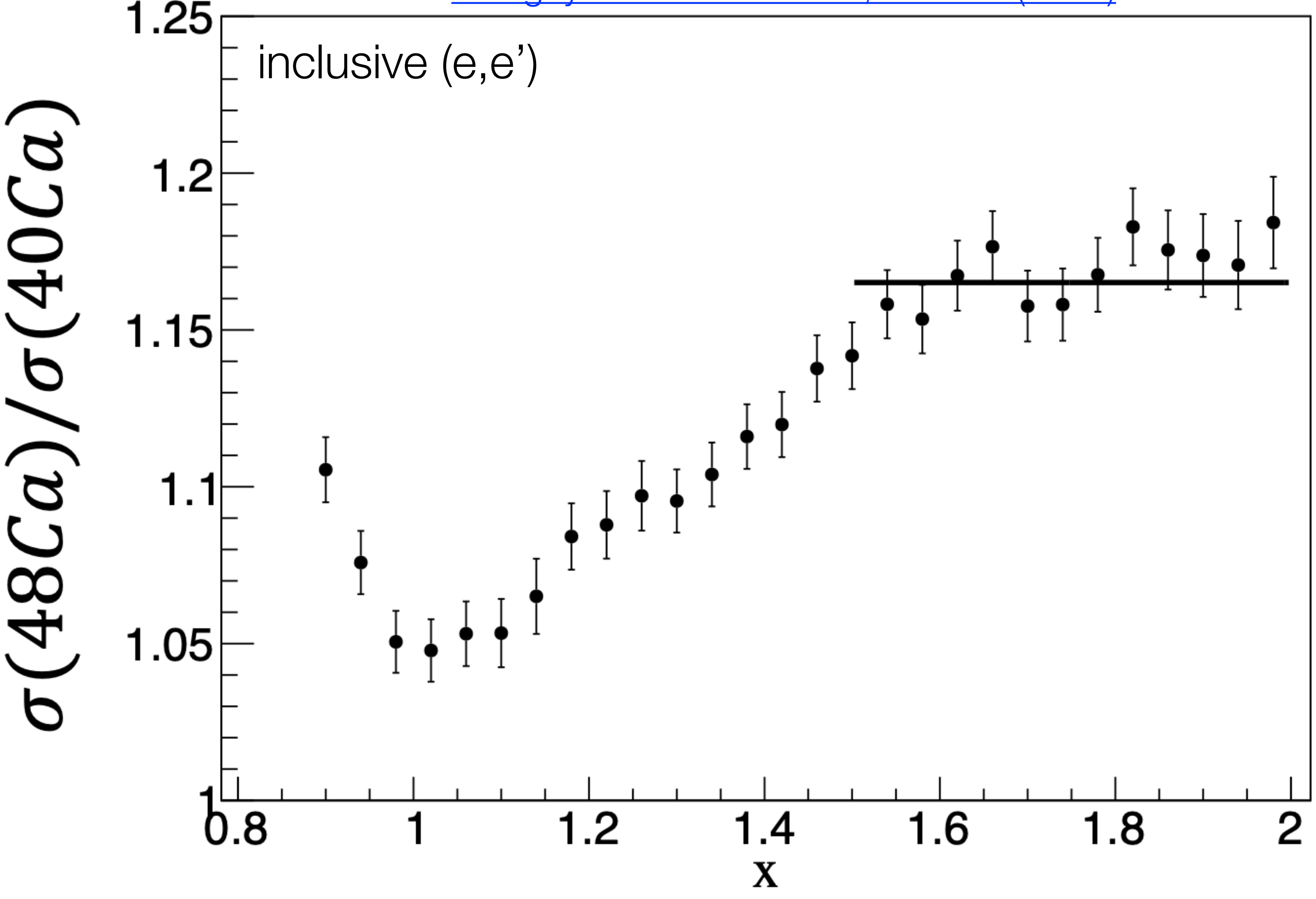
M. Duer et al. (CLAS collaboration), Nature 560, 617 (2018)



Motivation: Which nucleons form SRC pairs?

- (e,e'):

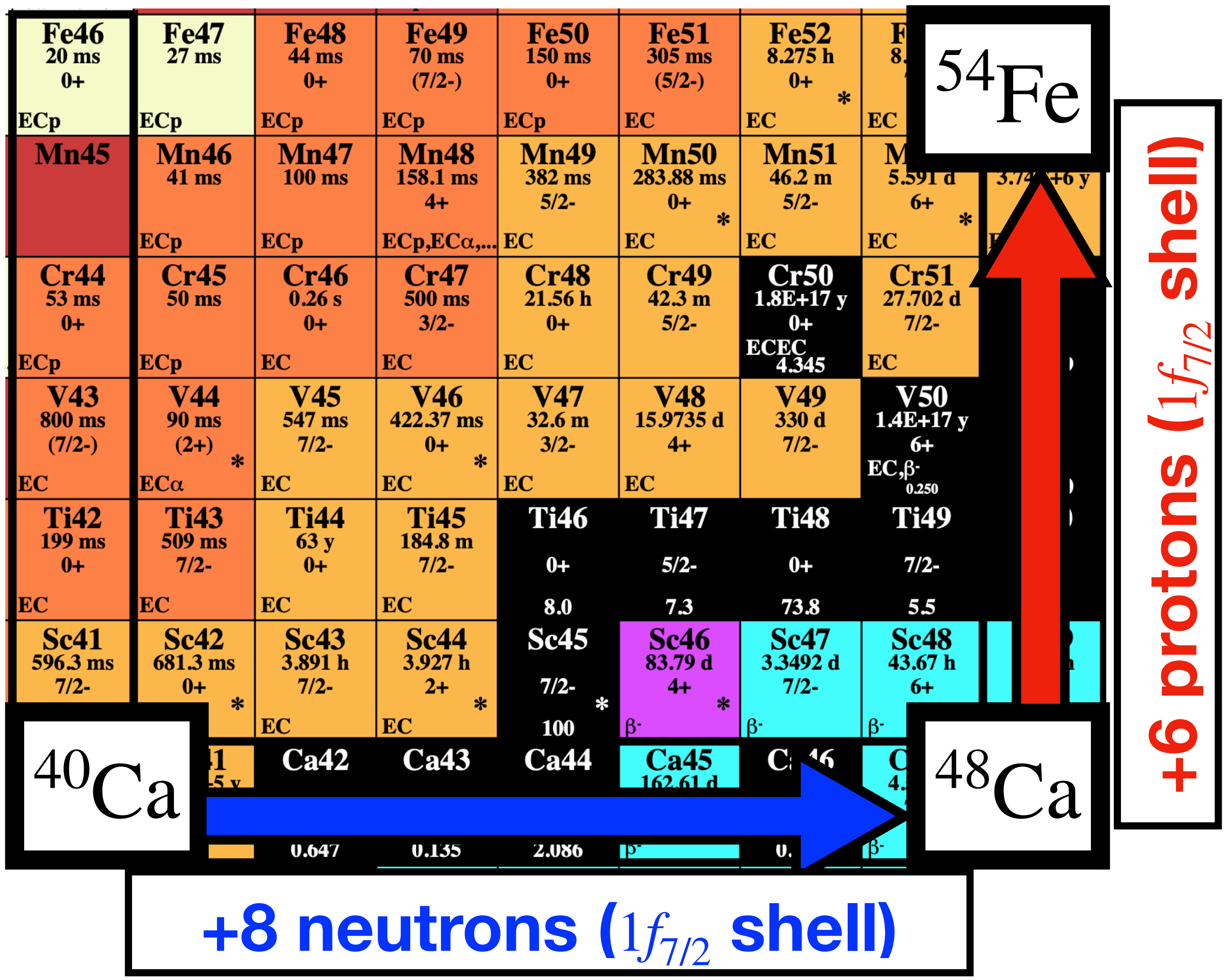
D. Nguyen et al. PRC 102, 064004 (2020)

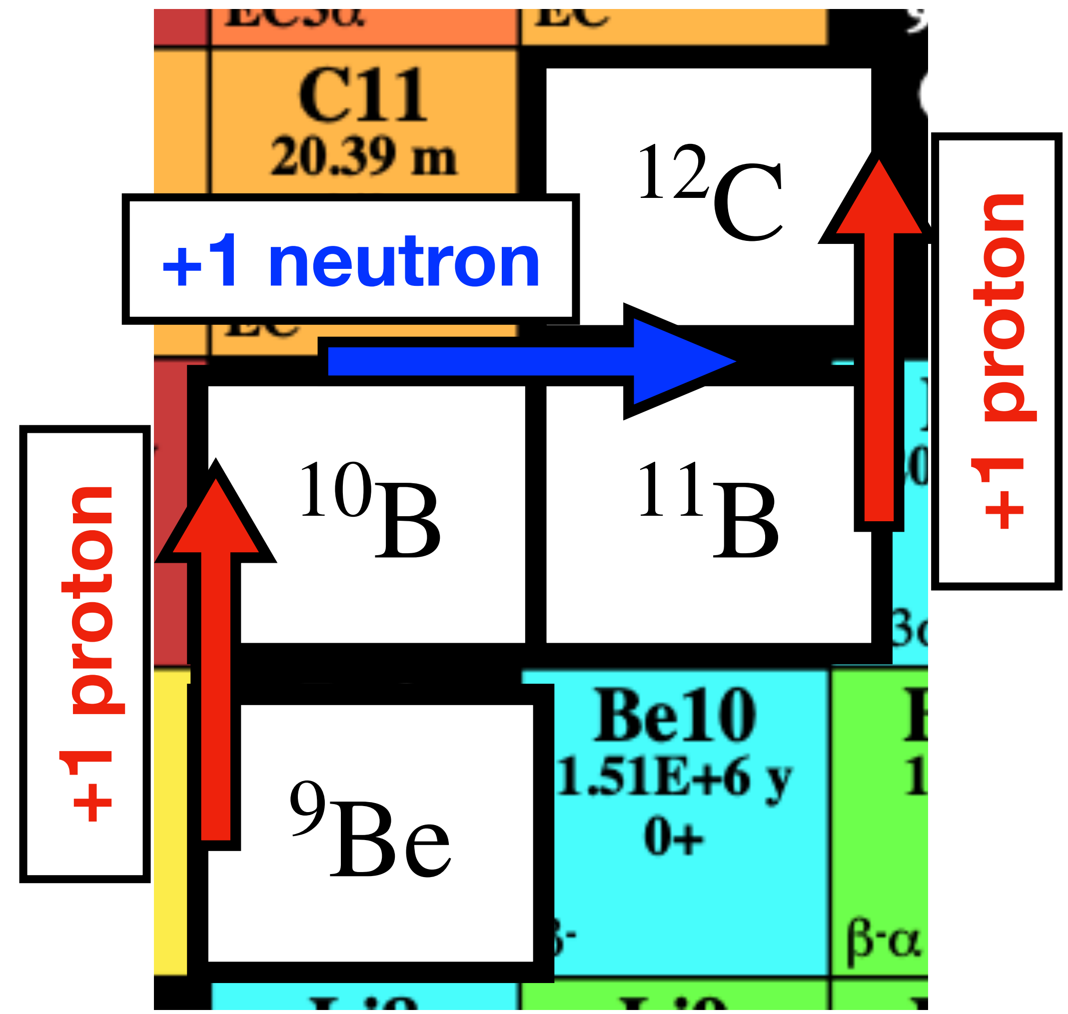


tells us abundances, but cannot distinguish *pp, nn, np*

—> need (e, e'p) for different A and N/Z

CaFe: Which nuclei to investigate?



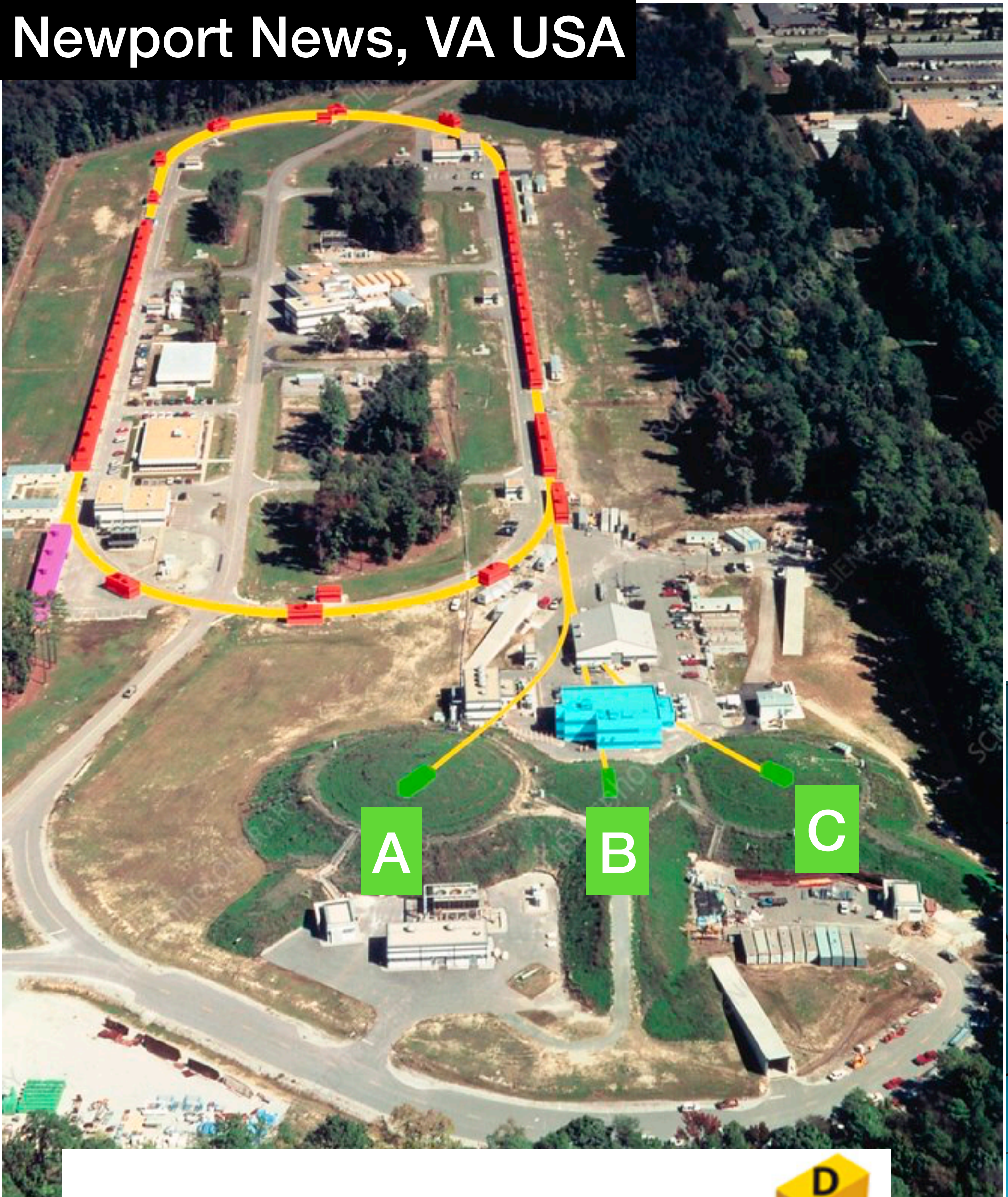


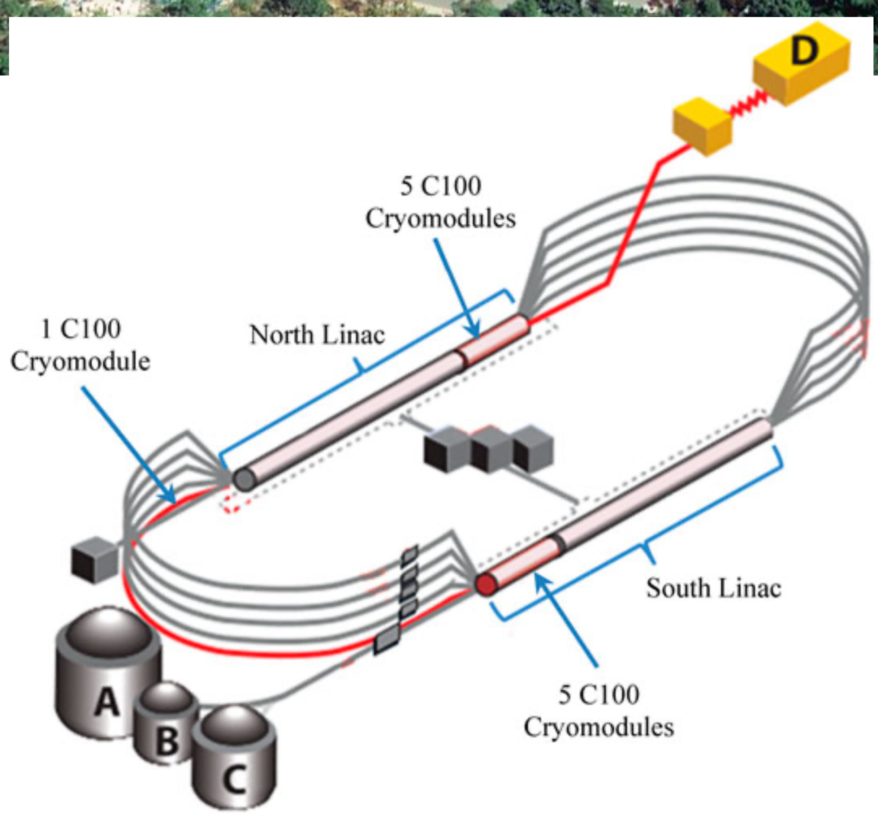
Which nucleons form pairs?

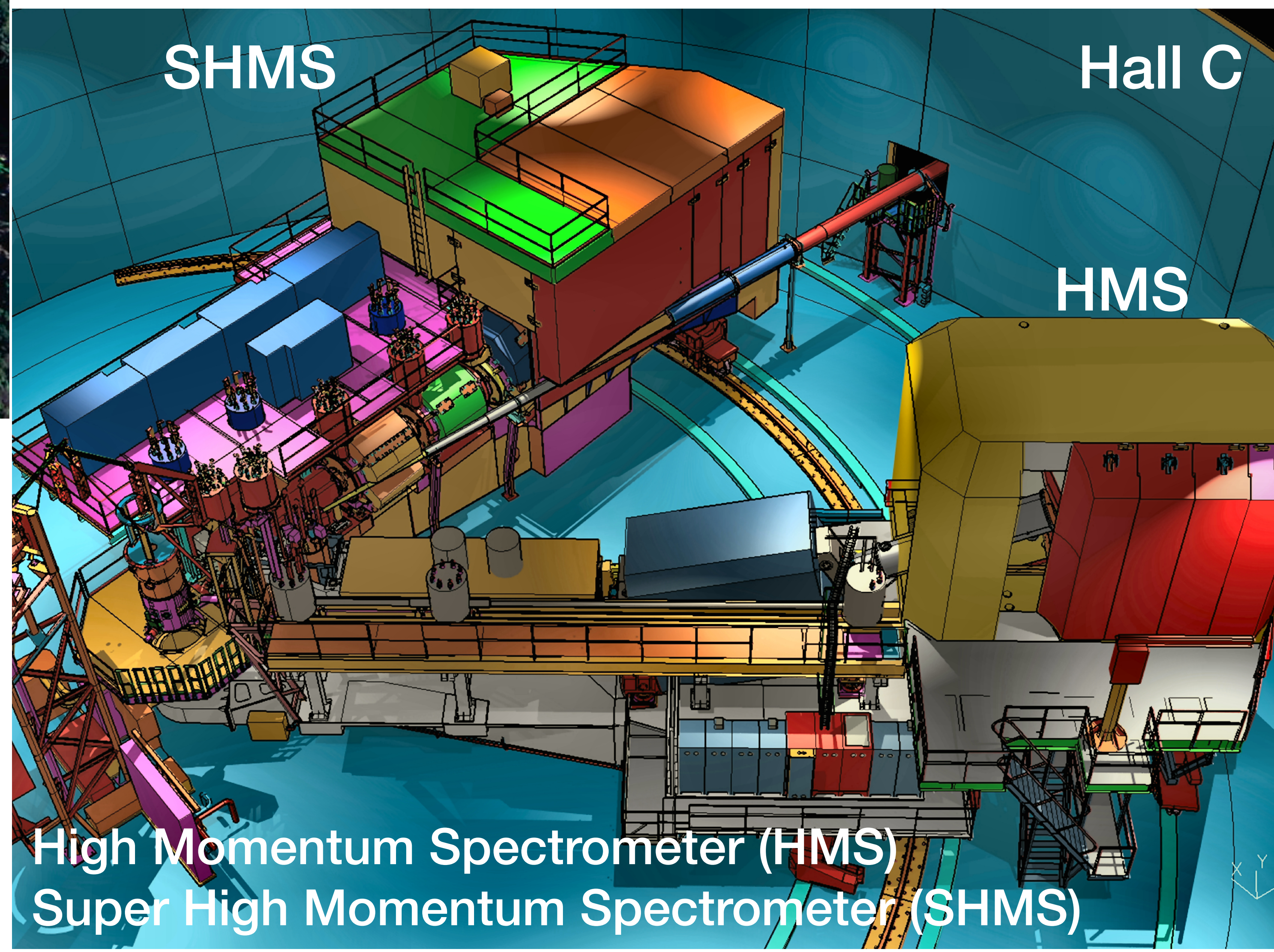
- How does adding +8 $1f_{7/2}$ neutrons to a $2s1d$ closed shell ^{40}Ca change the proton pairing?
- How does adding +6 $1f_{7/2}$ protons to ^{48}Ca change the proton pairing?
- light nuclei? 9Be → 10B → 11B → 12C

Jefferson Lab

Thomas Jefferson National Accelerator Facility

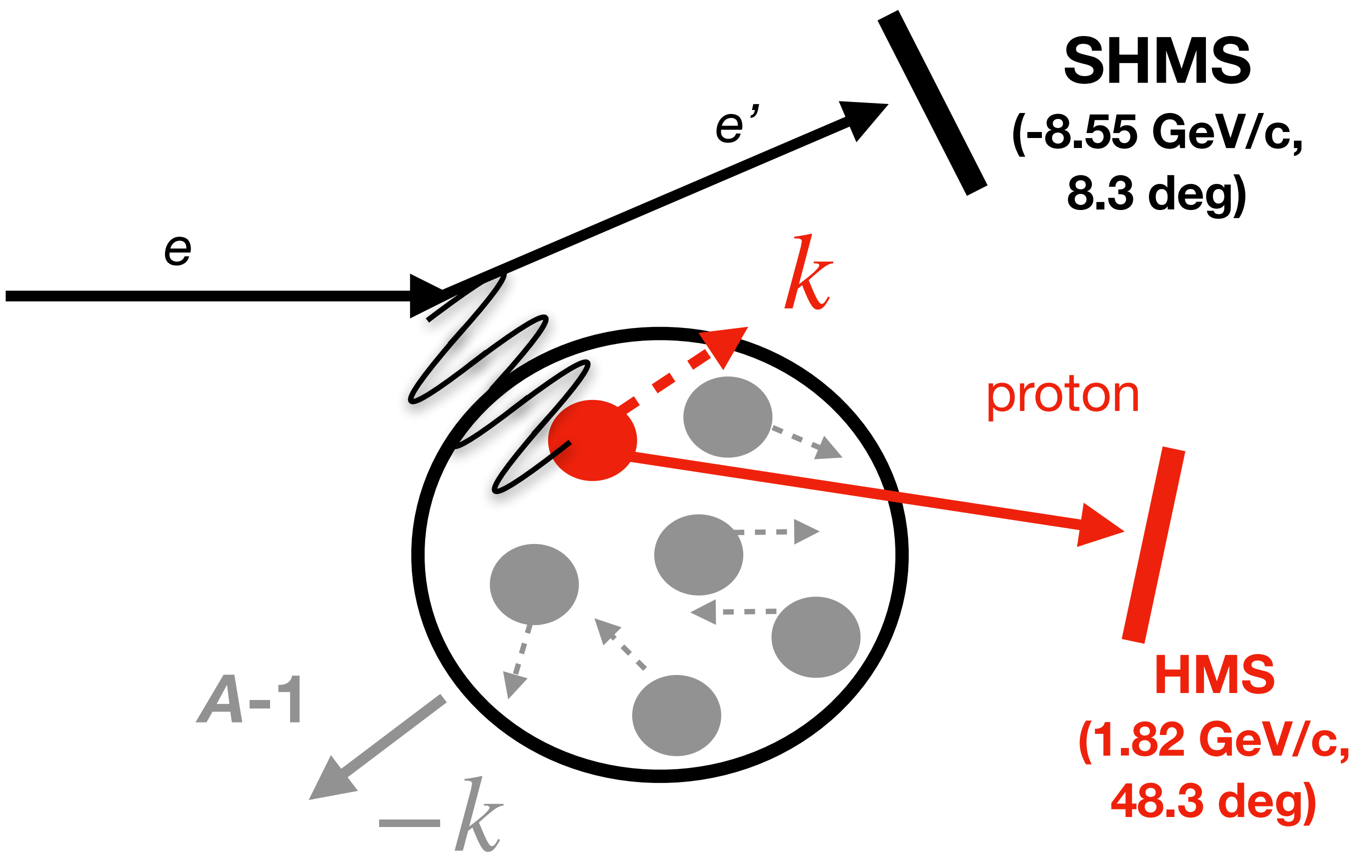




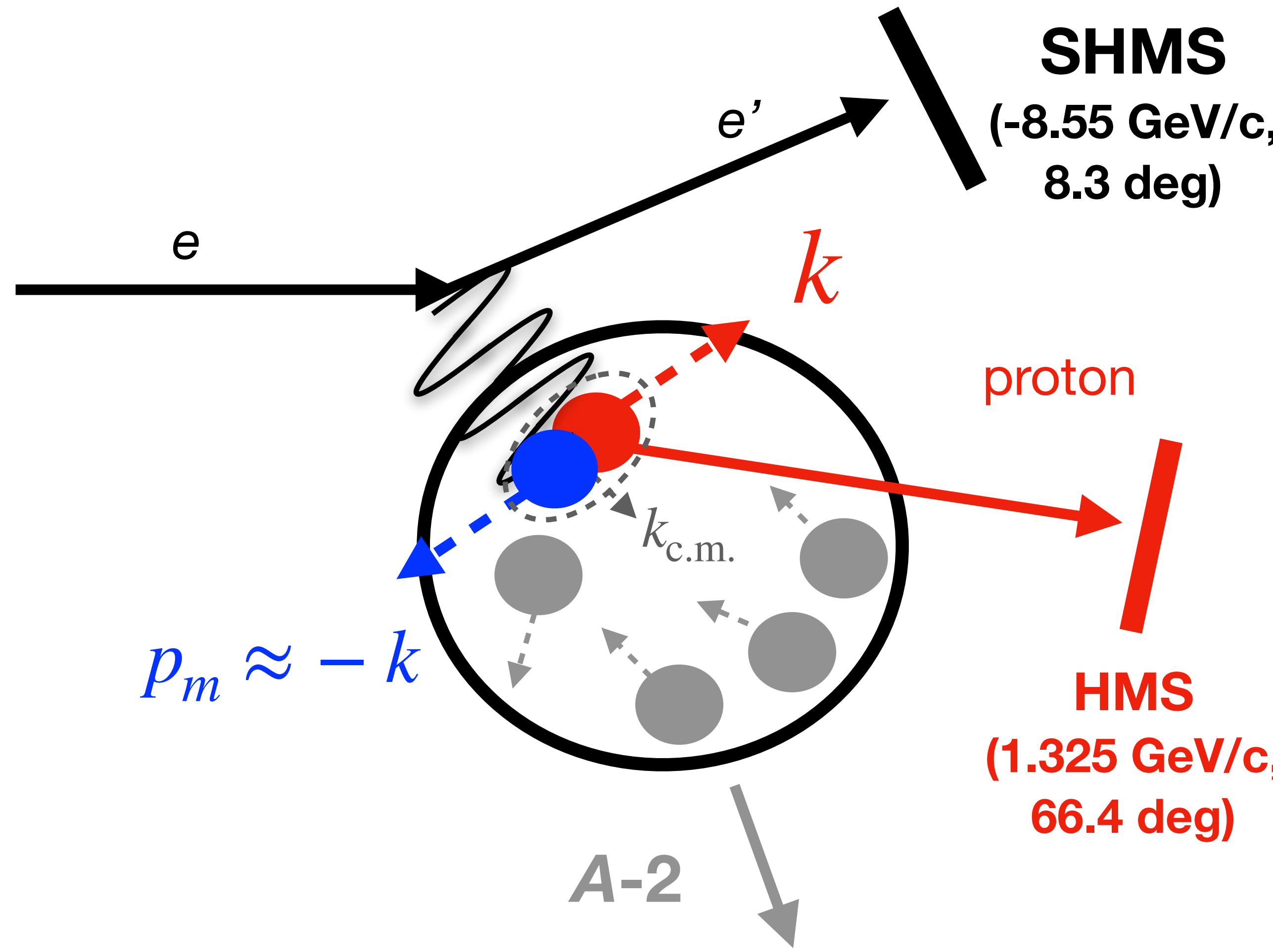


CaFe (e, e'p) Kinematics

mean-field (MF): $k < 250$ MeV/c



SRC: $350 < k < 700$ MeV/c



Event Selection Cuts and Kinematic Distribution

general cuts

Event / Particle identification

- coincidence time
- SHMS calorimeter (e-)

SHMS+HMS:

- momentum acceptance
- angular acceptance (collimator)

MF cuts

$$Q^2 \geq 1.8\ \mathrm{GeV}^2$$

$$-20 \leq E_m \leq 100\ \mathrm{MeV}$$

$$P_m \leq 250\ \mathrm{MeV/c}$$

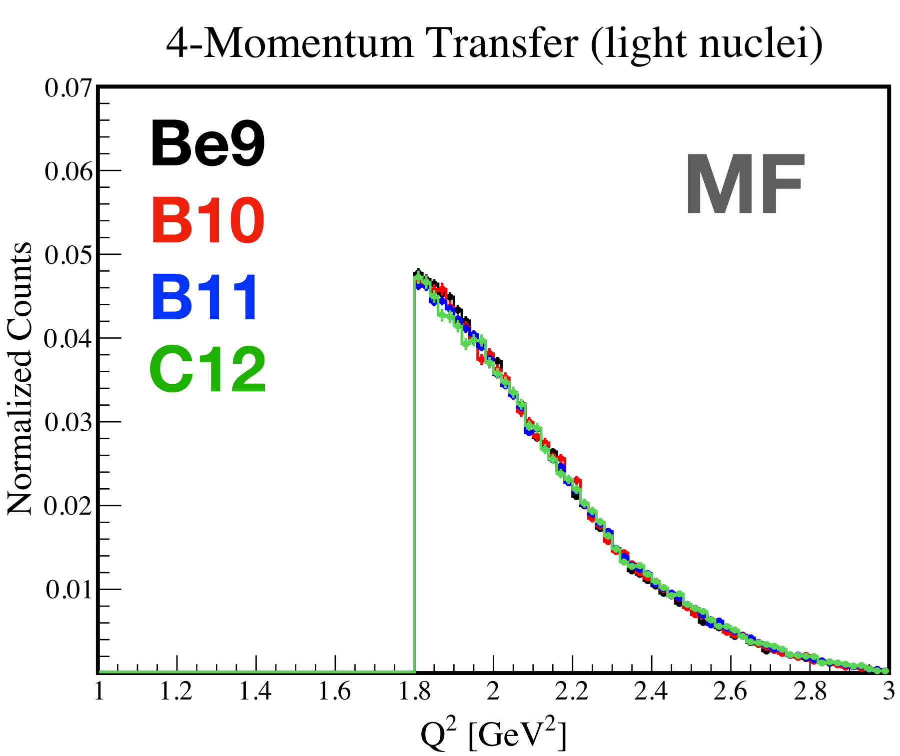
SRC cuts

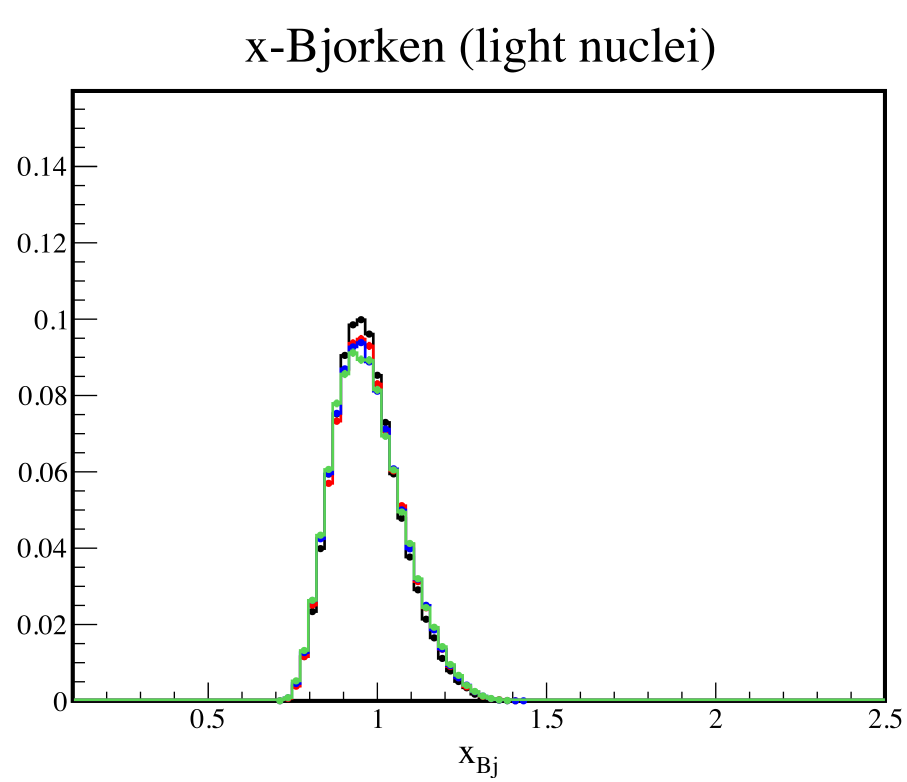
$$Q^2 \geq 1.8\ \mathrm{GeV}^2$$

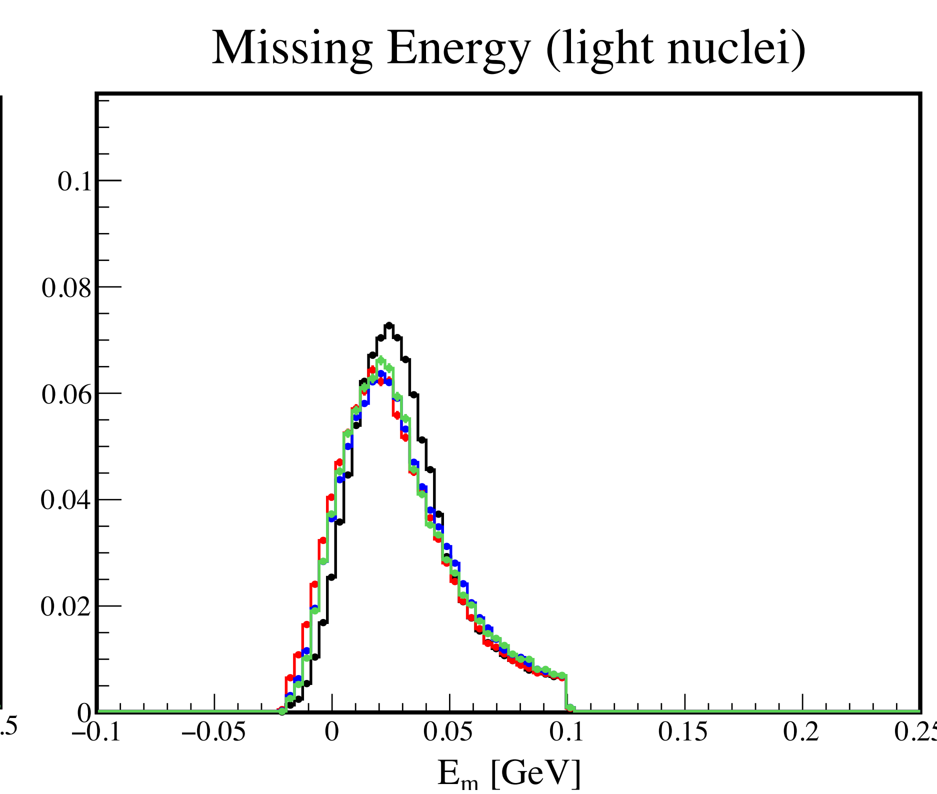
$$x_{Bj} \geq 1.2$$

$$\theta_{rq} \leq 40^\circ$$

$$350 \leq P_m \leq 700\ \mathrm{MeV/c}$$







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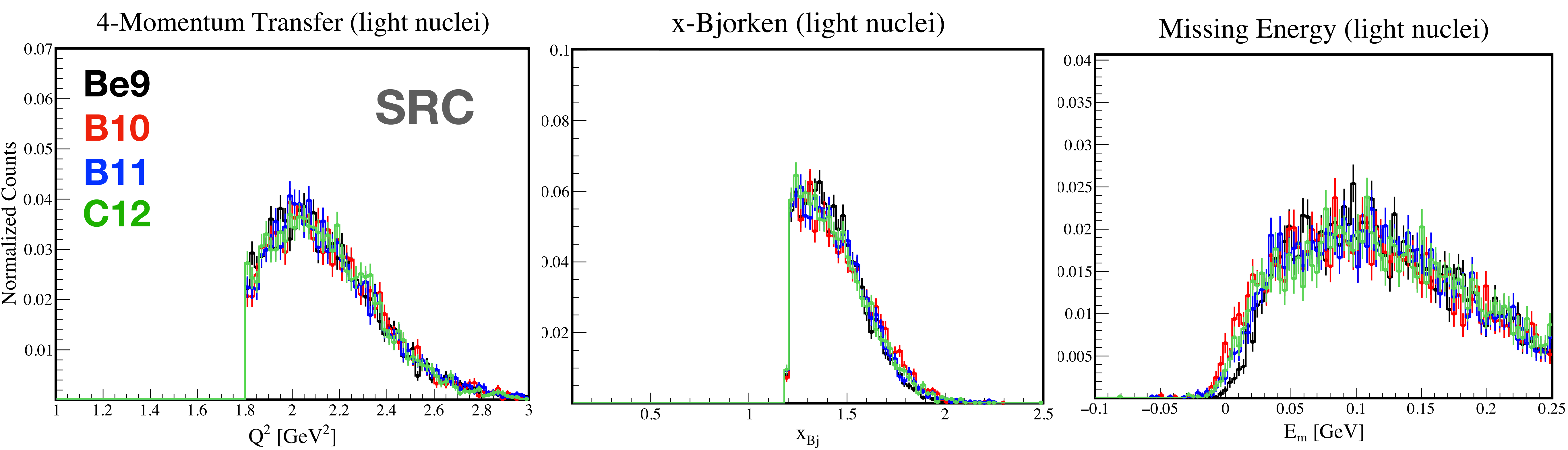
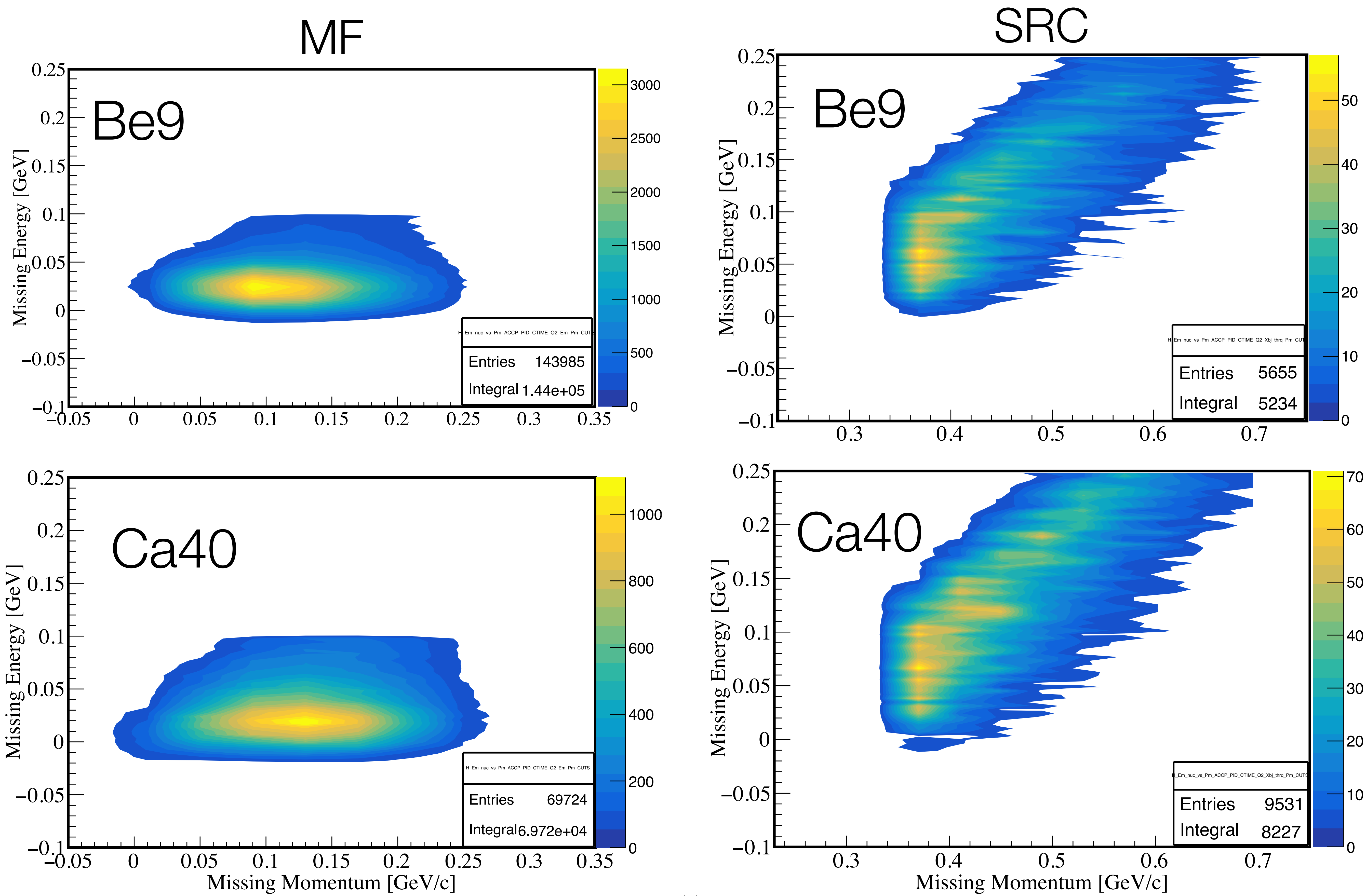


Missing Energy vs. Missing Momentum



What we measured ?

"single ratios"

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

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

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

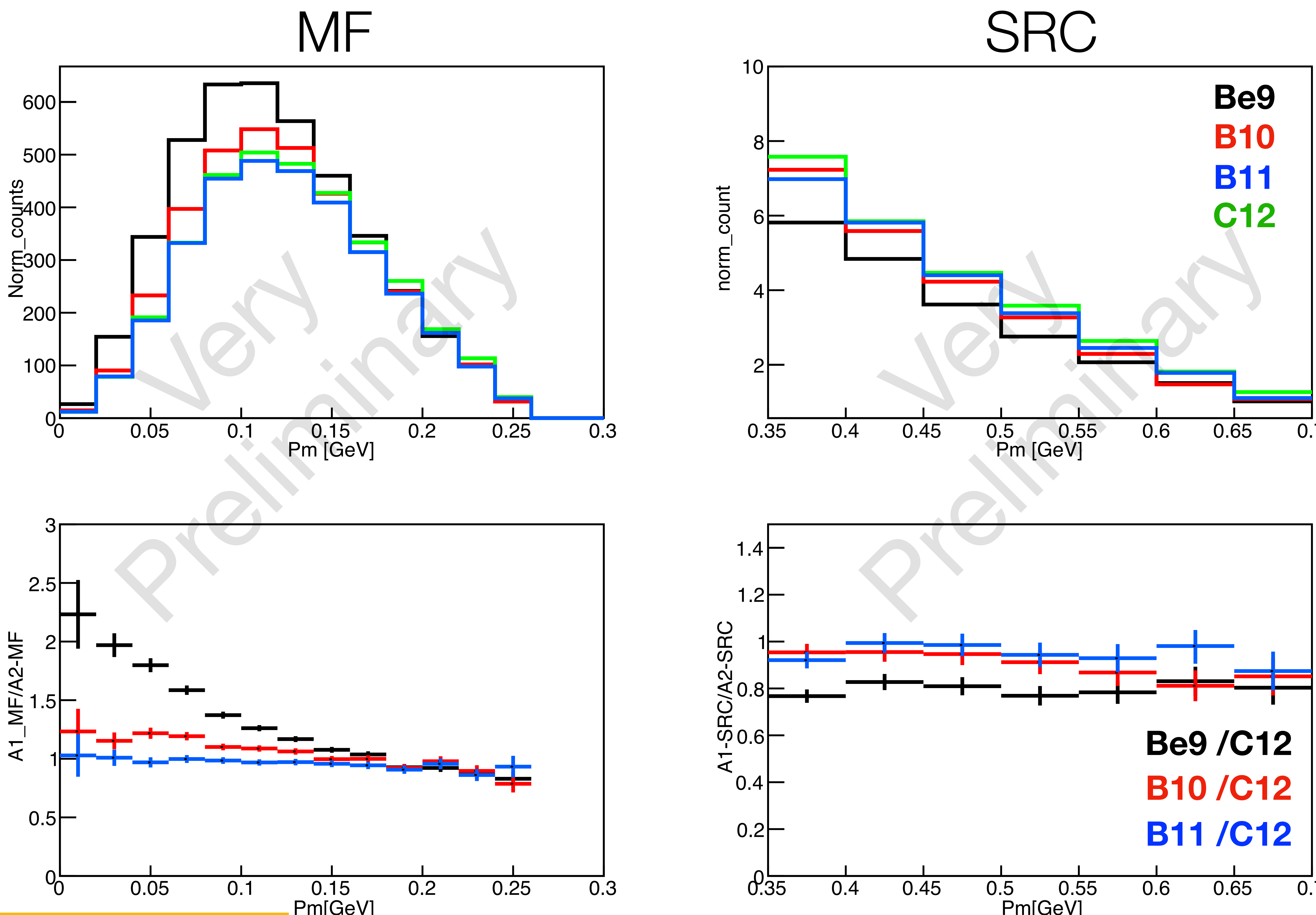
Q : total charge [mC]

ϵ_i : detector/DAQ efficiencies

T_N : nuclear transparency

ρ_t : target thickness [g/cm^2]

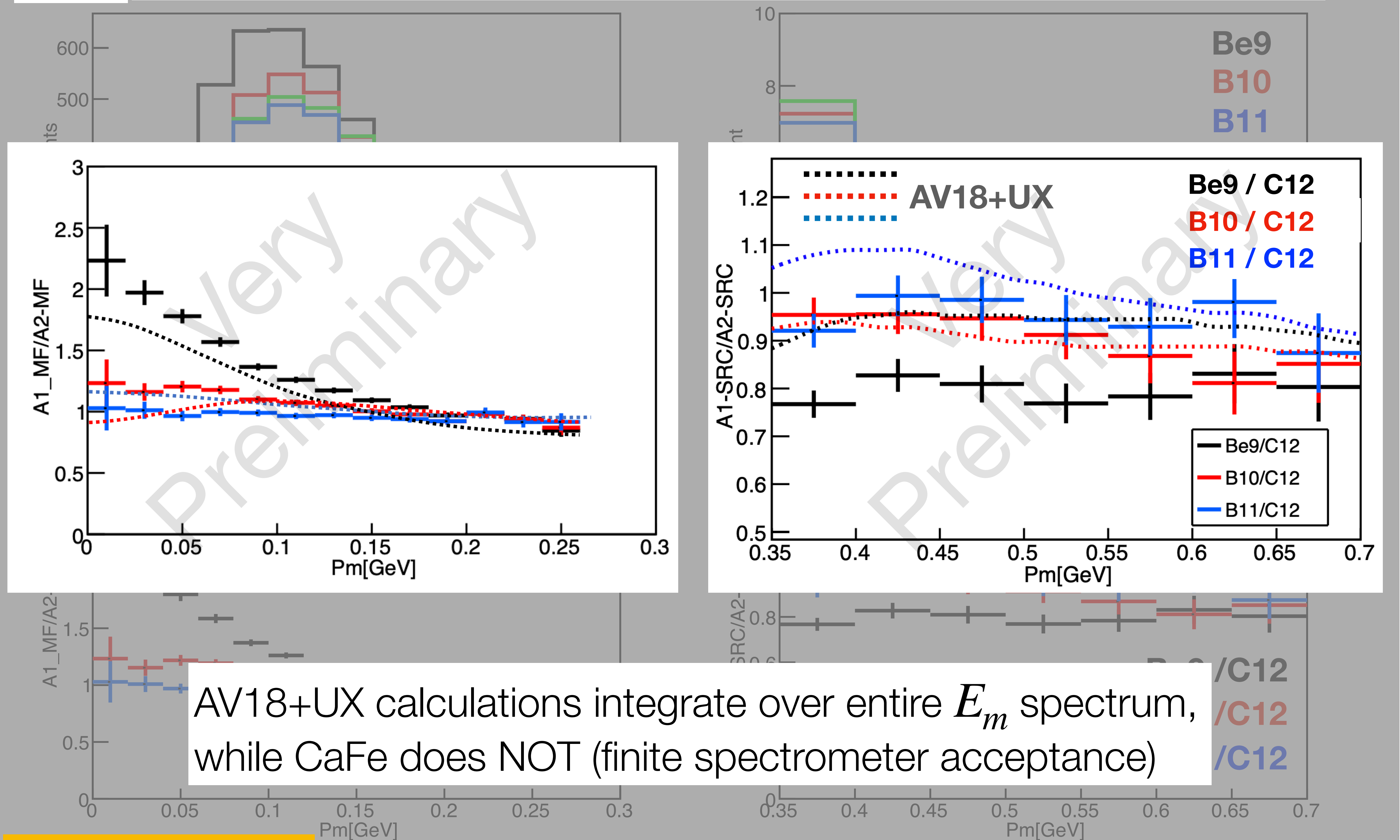
Missing Momentum and Single Ratios (light)



Plots by Dien Nguyen

Missing Momentum and Single Ratios (light)

theory: R. B. Wiringa, R. Schiavilla, Steven C. Pieper, and J. Carlson Phys. Rev. C 89, 024305 (2014)



AV18+UX calculations integrate over entire E_m spectrum, while CaFe does NOT (finite spectrometer acceptance)

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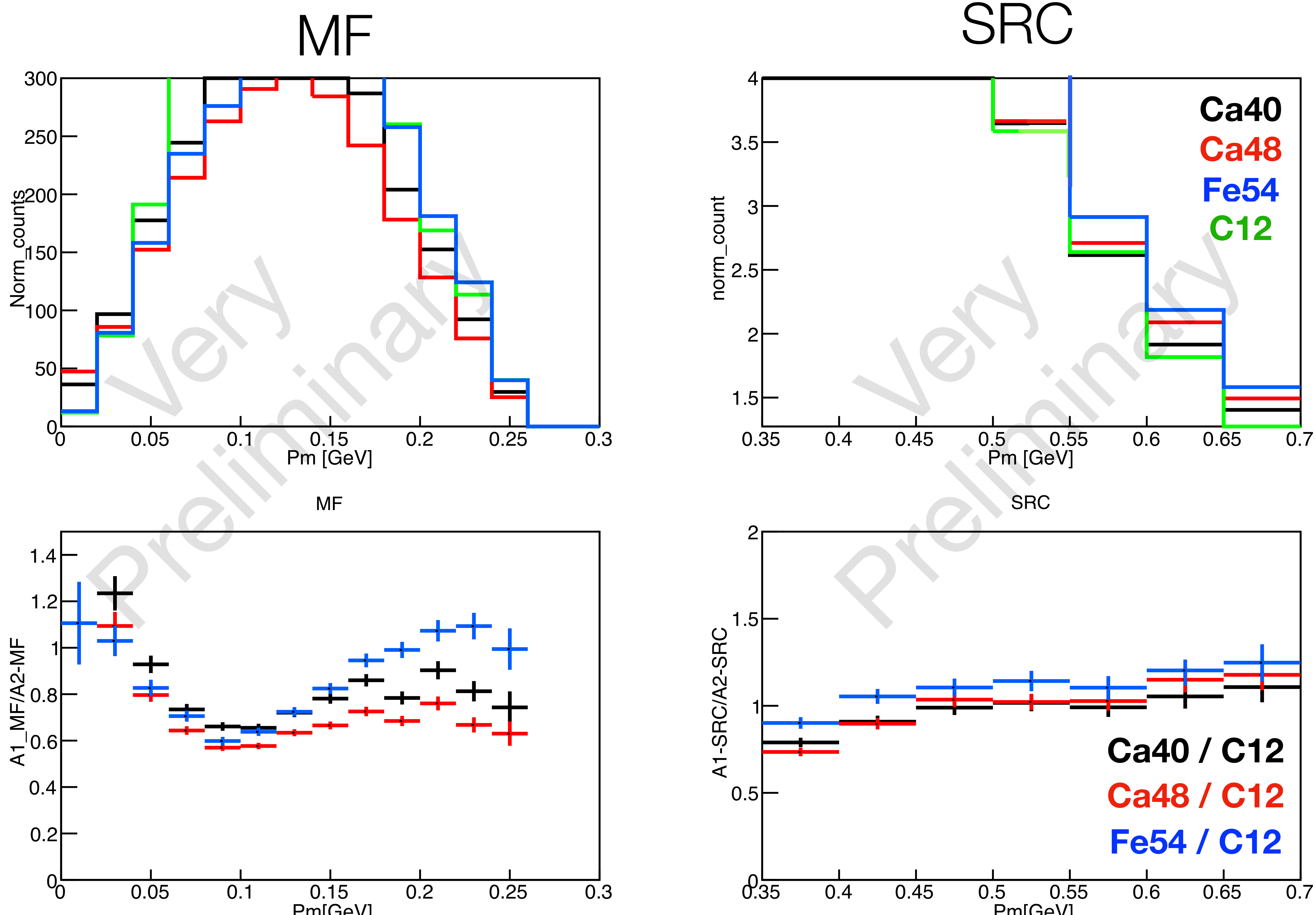
Missing Momentum and Single Ratios (heavy)



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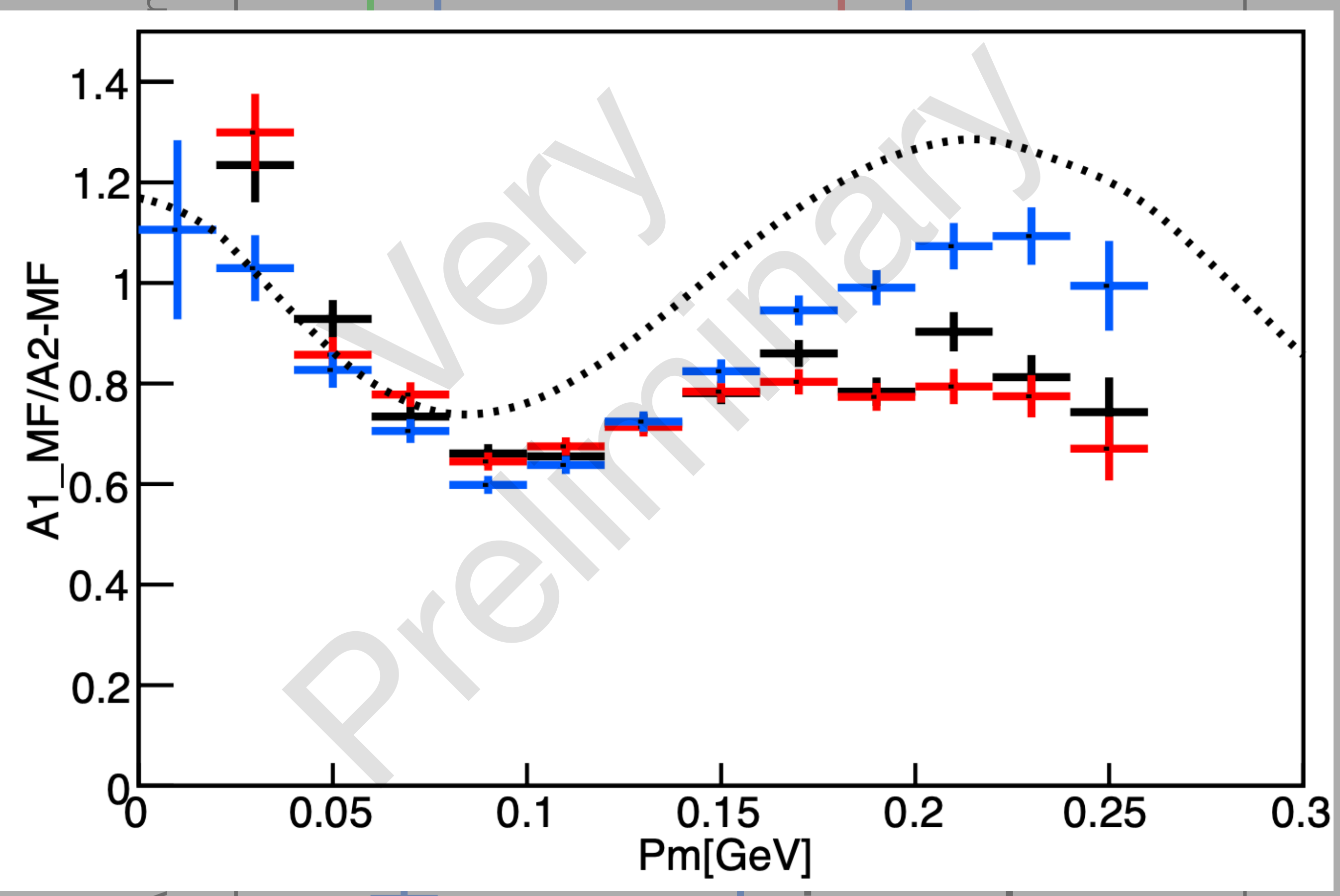

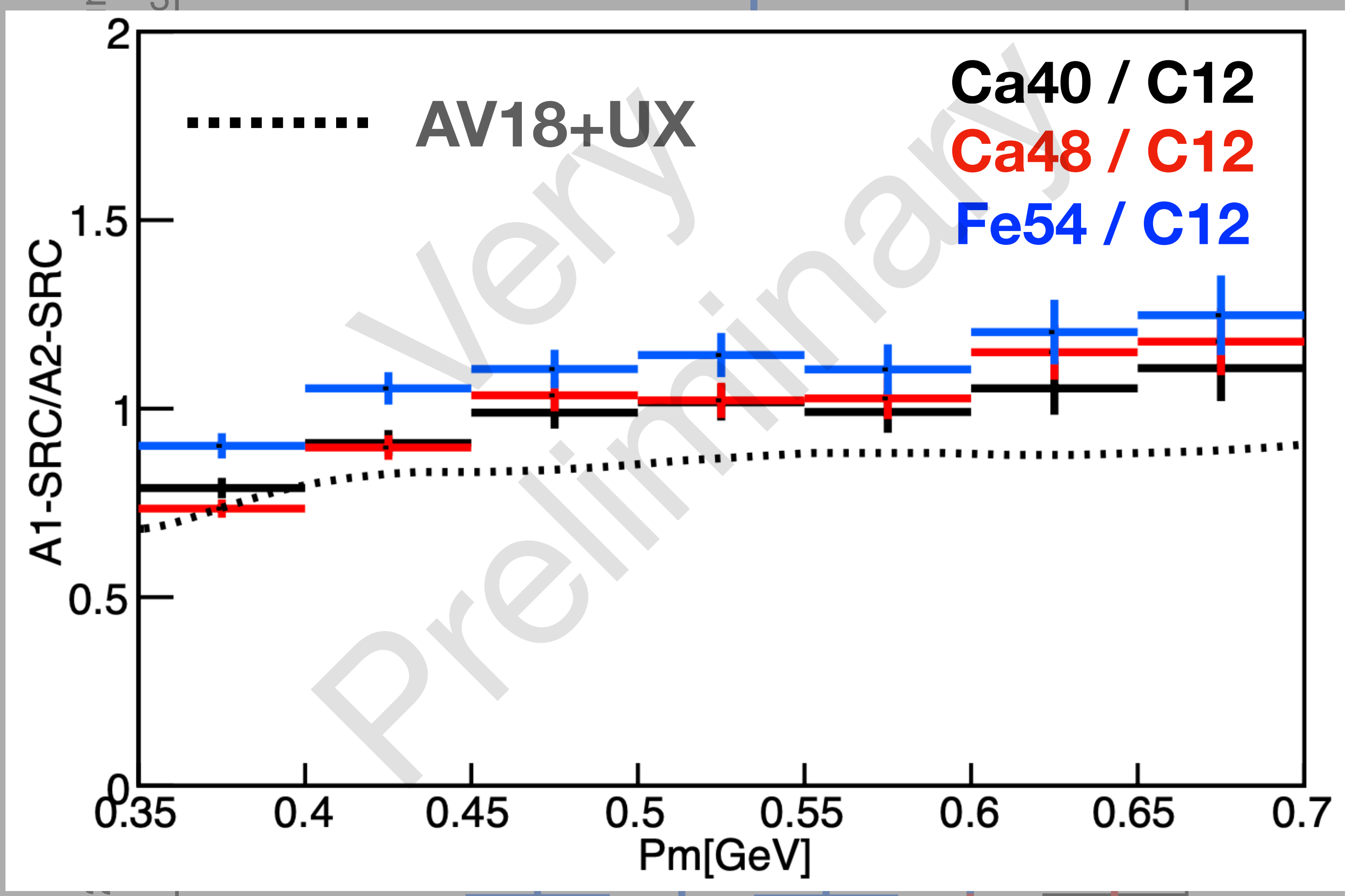

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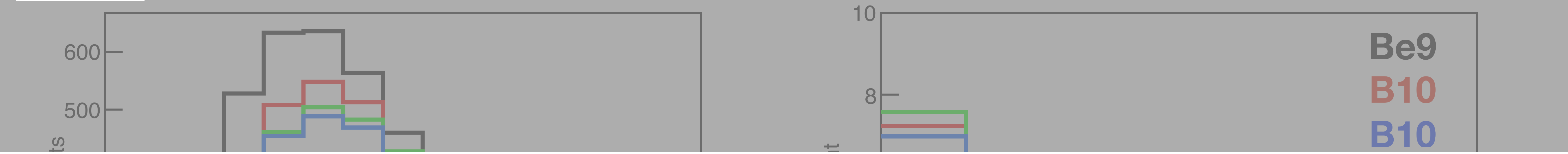

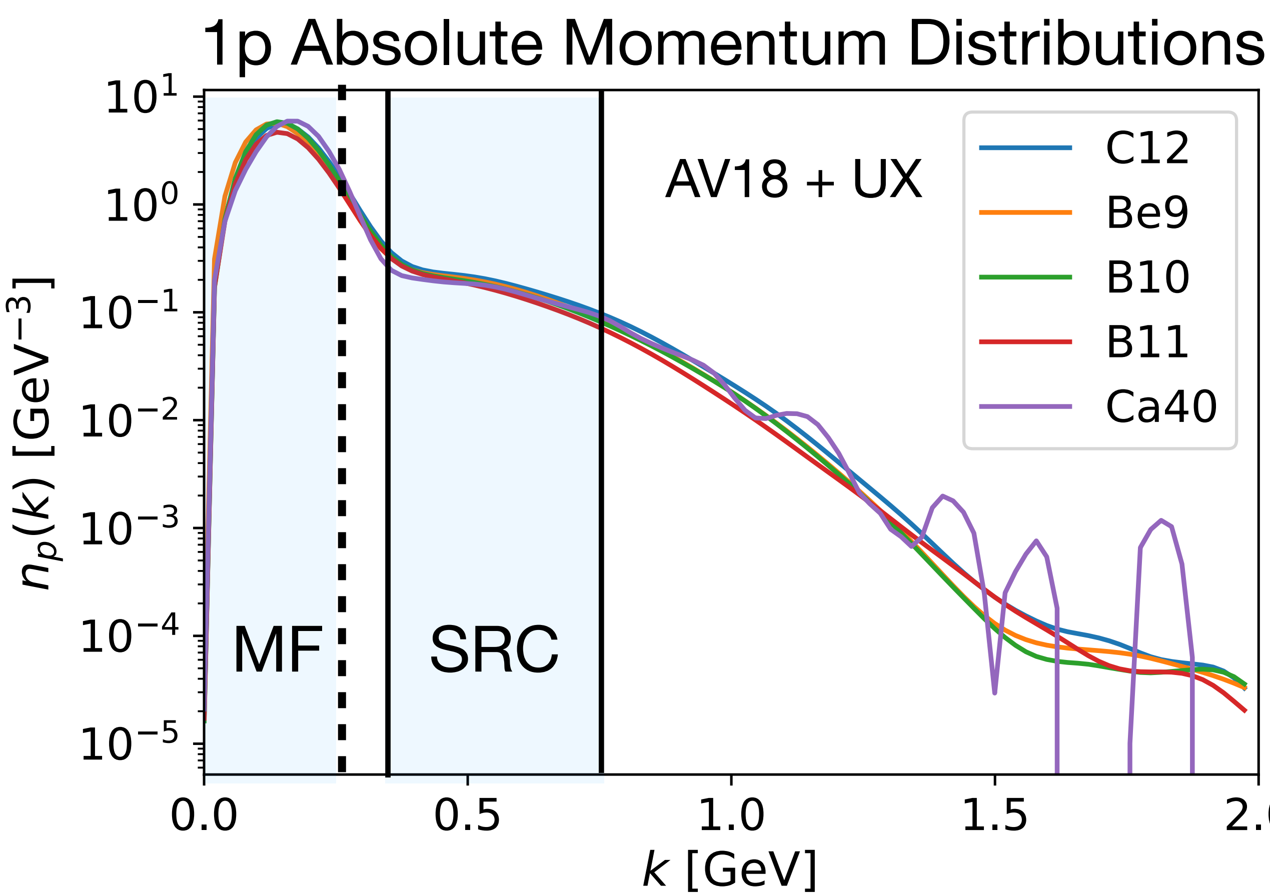

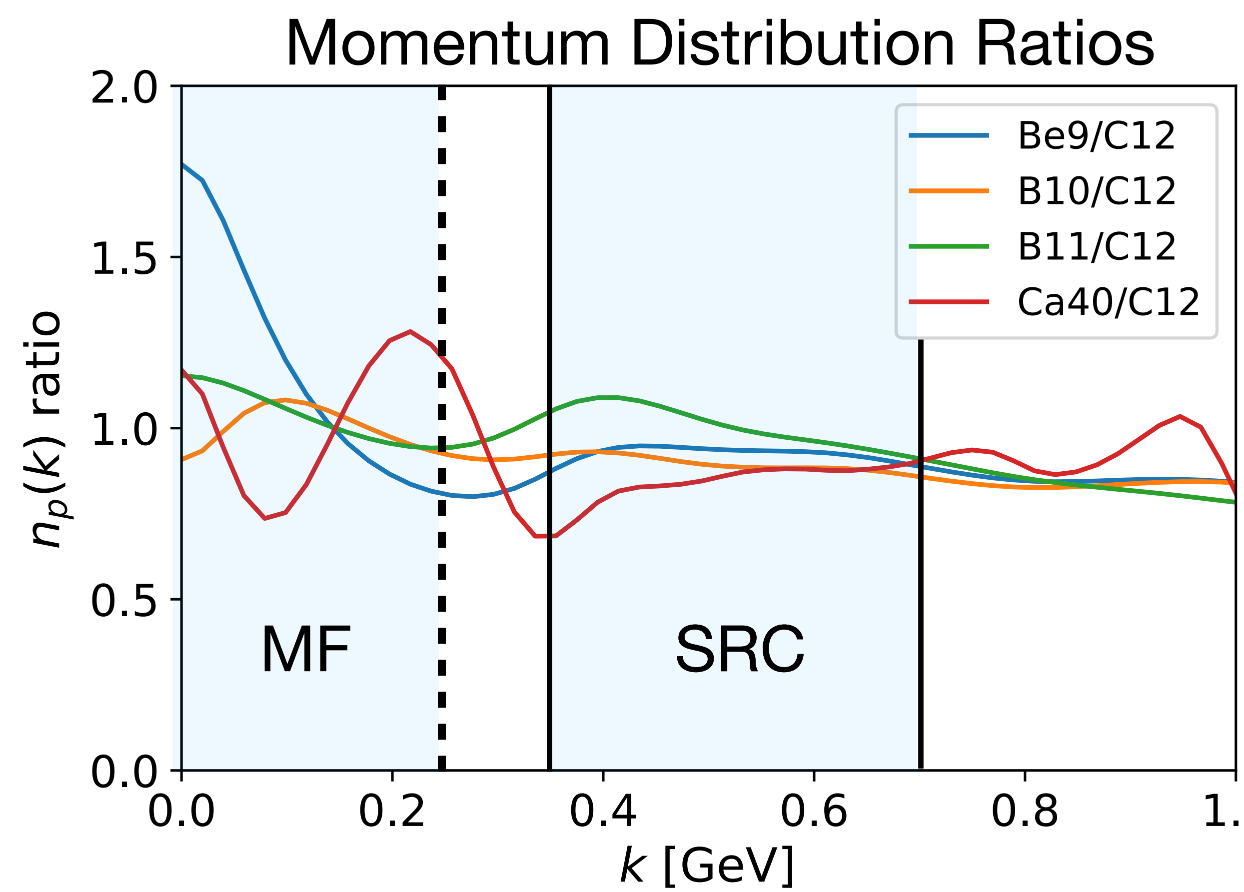

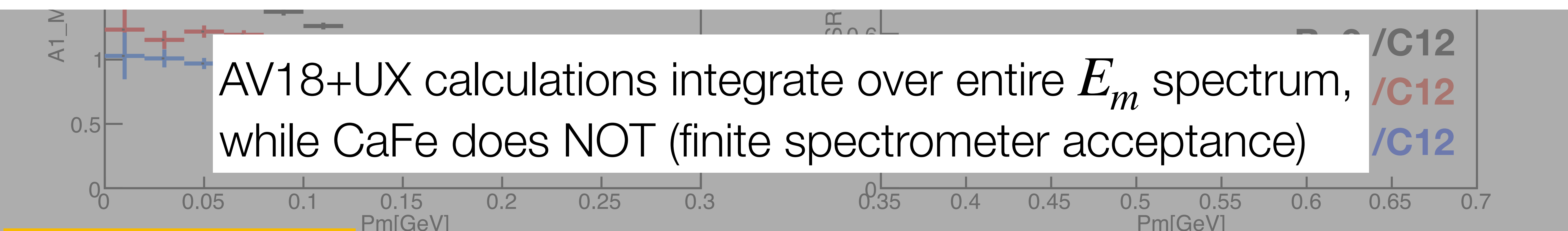

AV18+UX calculations integrate over entire E_m spectrum, while CaFe does NOT (finite spectrometer acceptance)

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What we measured ?

"high-momentum fraction"

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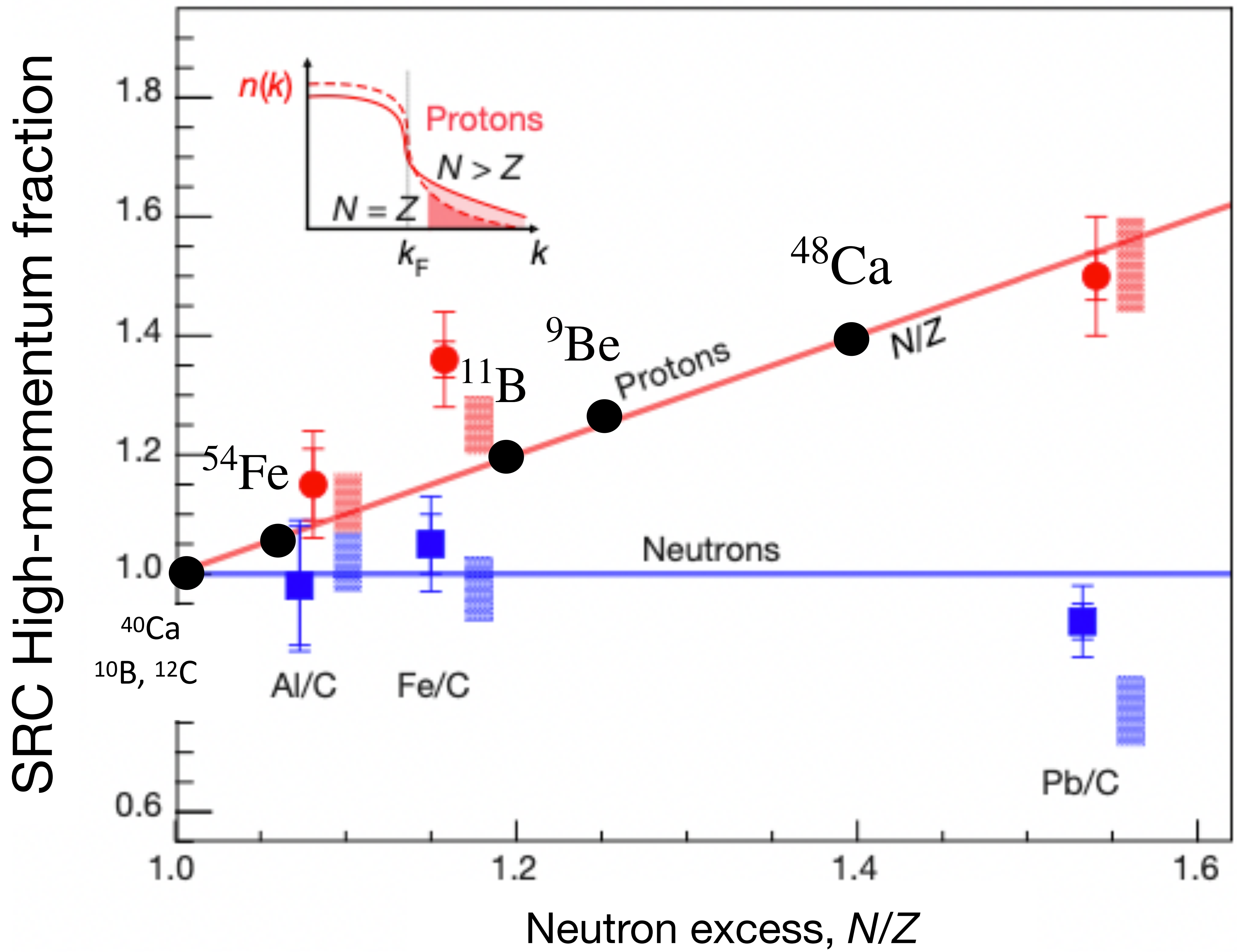
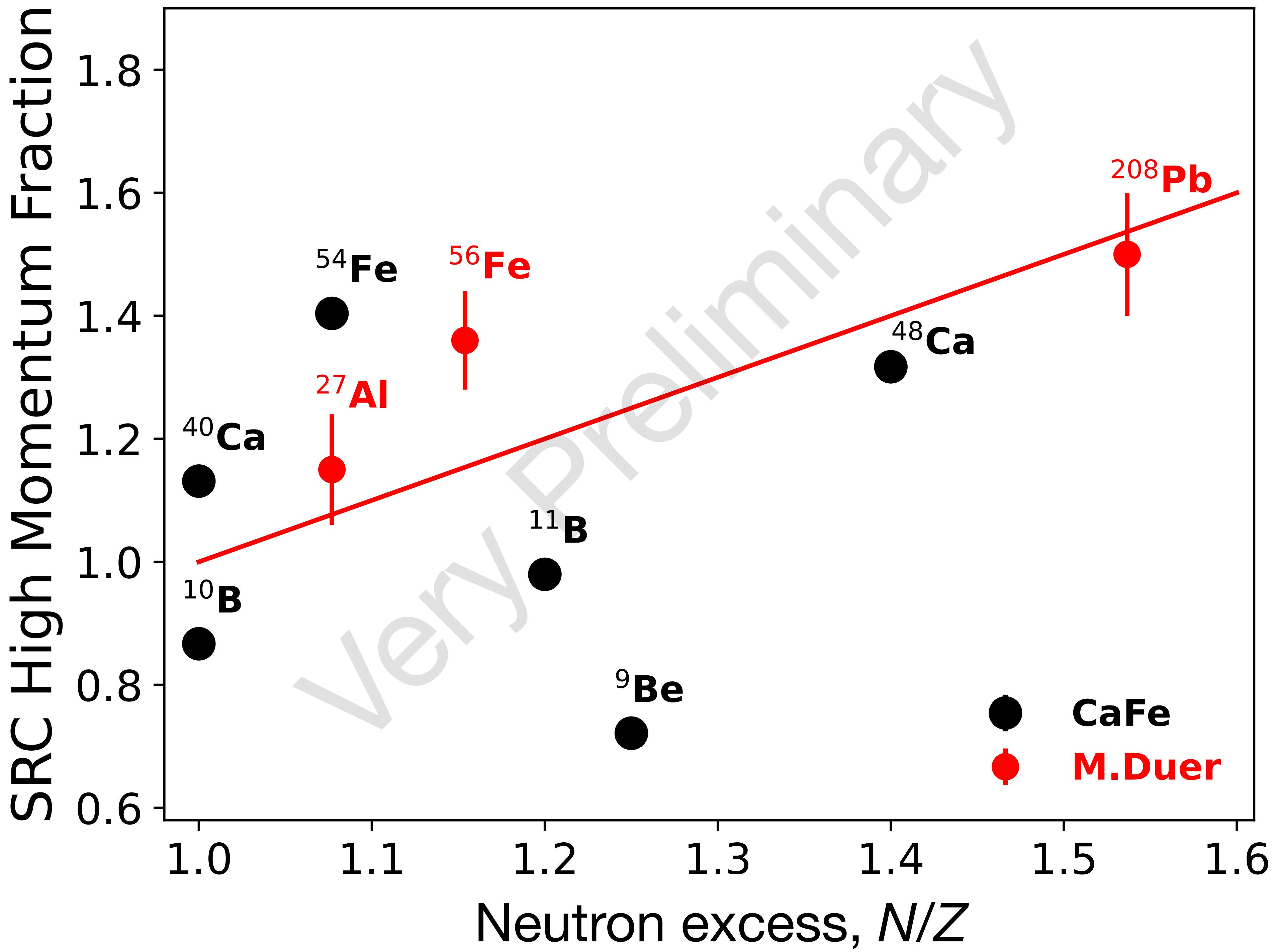
cancel in double ratio

Simple CaFe Projection



M. Duer et al. (CLAS collaboration), Nature 560, 617 (2018)

Results



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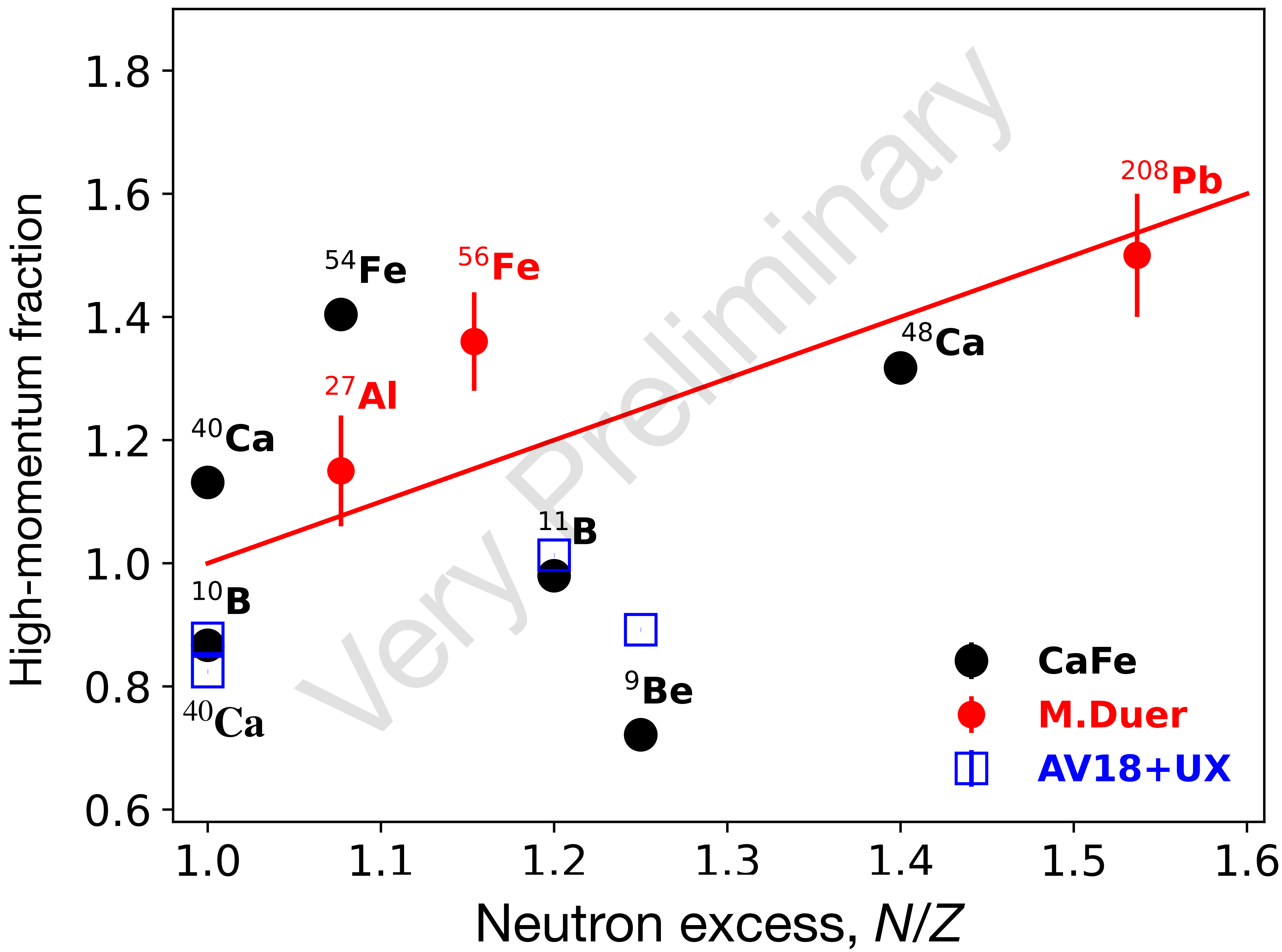

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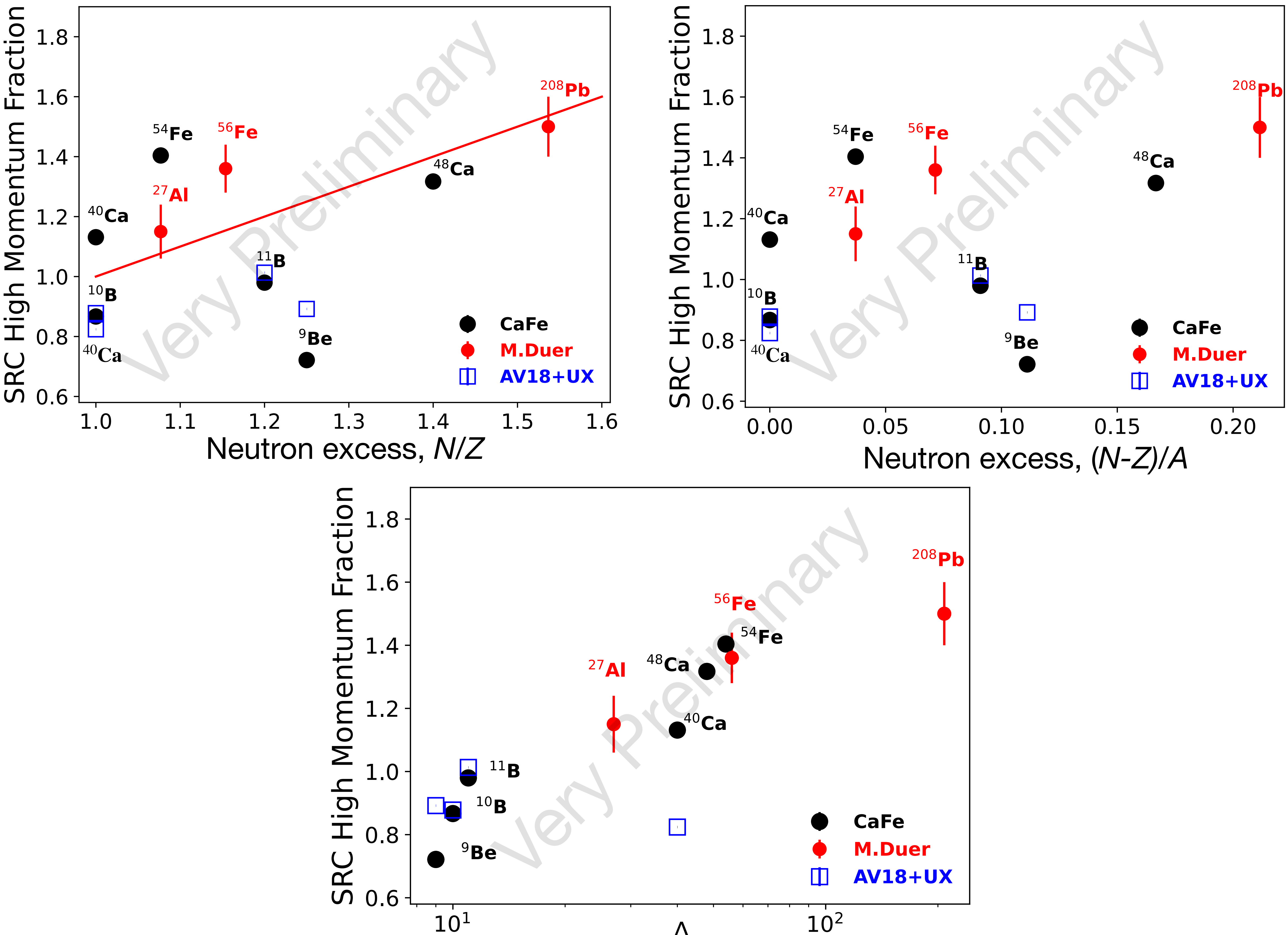


M. Duer et al. (CLAS collaboration), Nature 560, 617 (2018)

Summary

- great data collected

- needs more analysis
  - *rate dependence*
  - *target impurities*
  - *systematic uncertainties*

- unexpected results imply importance of nuclear structure

- expect final results this spring !

Holly Szumila-Vance (Staff)

Florian Hauenstein (Staff)

Dien Nguyen (Isgur Fellow)

Carlos Yero (NSF Fellow)

Noah Swan (PhD student)

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

Systematic Estimates

beam-current dependency:

< 6%

Additional Target Corrections

(*effect on double ratio*)

^{48}Ca: oil contamination +
10% ^{40}Ca subtraction

~ +0.6 %

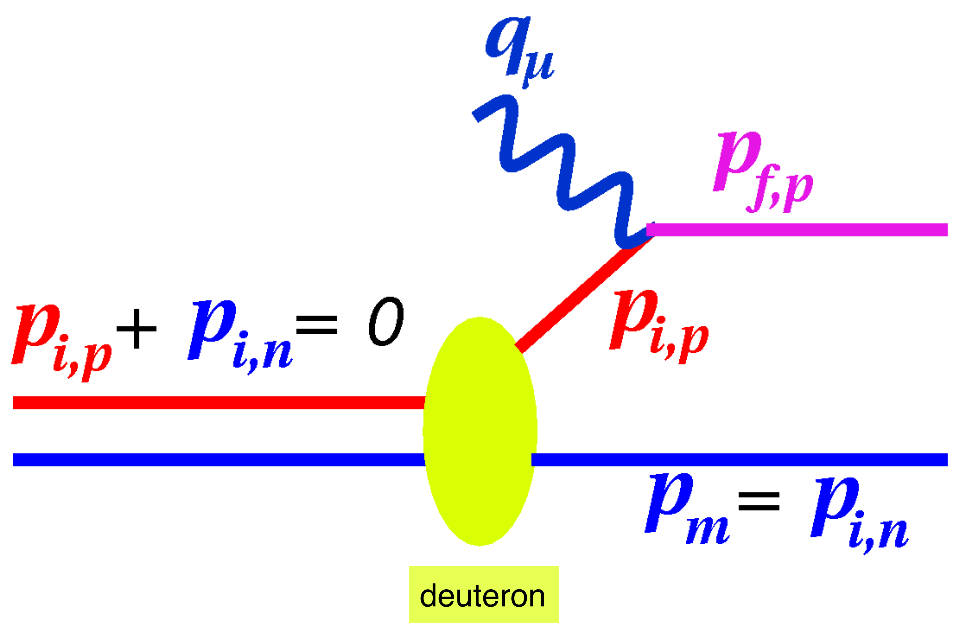
^{10}B : C in $^{10}B_4C$

- 3 %

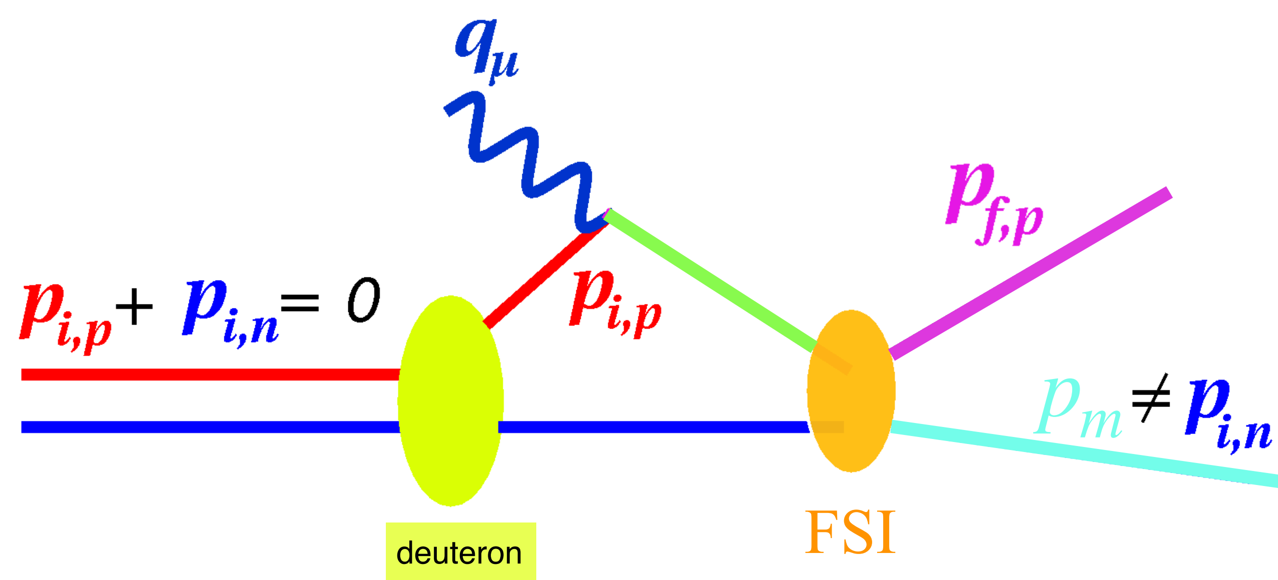
^{11}B : C in $^{11}B_4C$

~ - 0.45 %

virtual photon - nucleus interactions

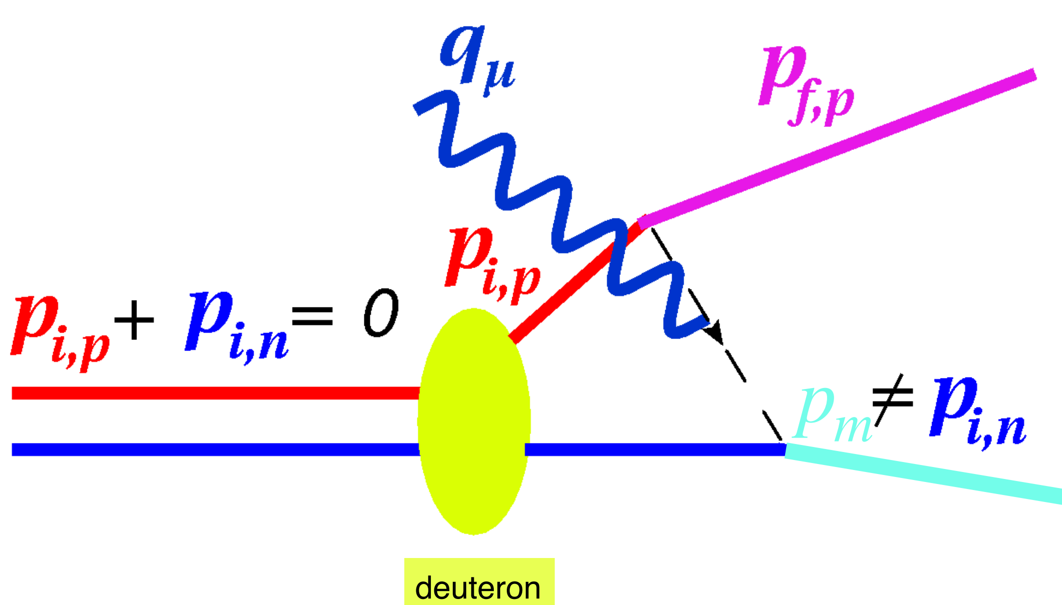


Plane Wave Impulse Approximation (PWIA)



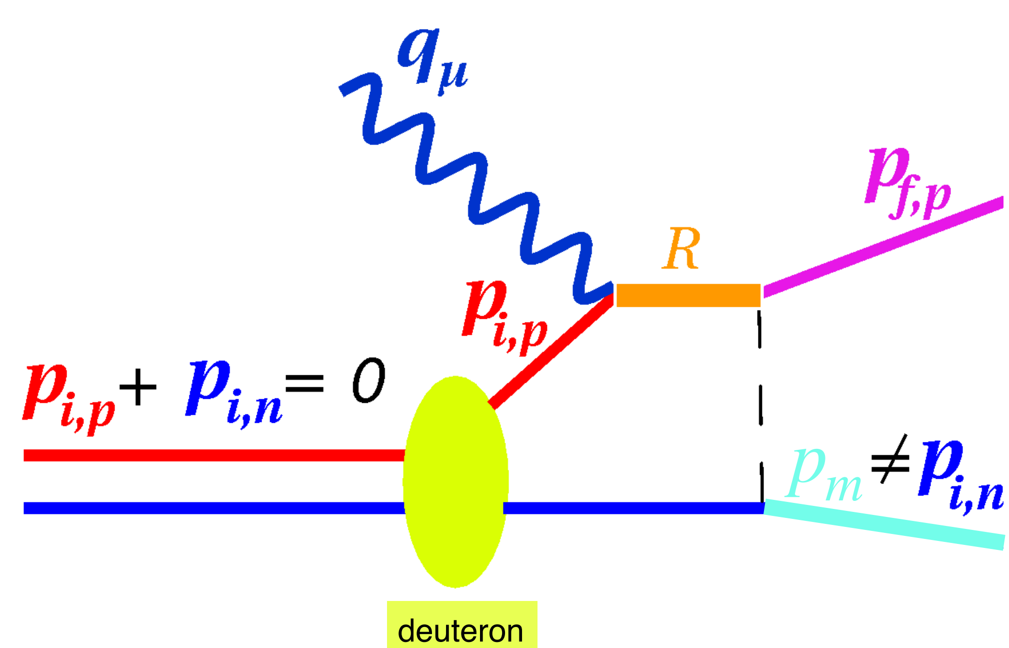
Final State Interactions (FSI)

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



Meson-Exchange Currents (MEC)

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

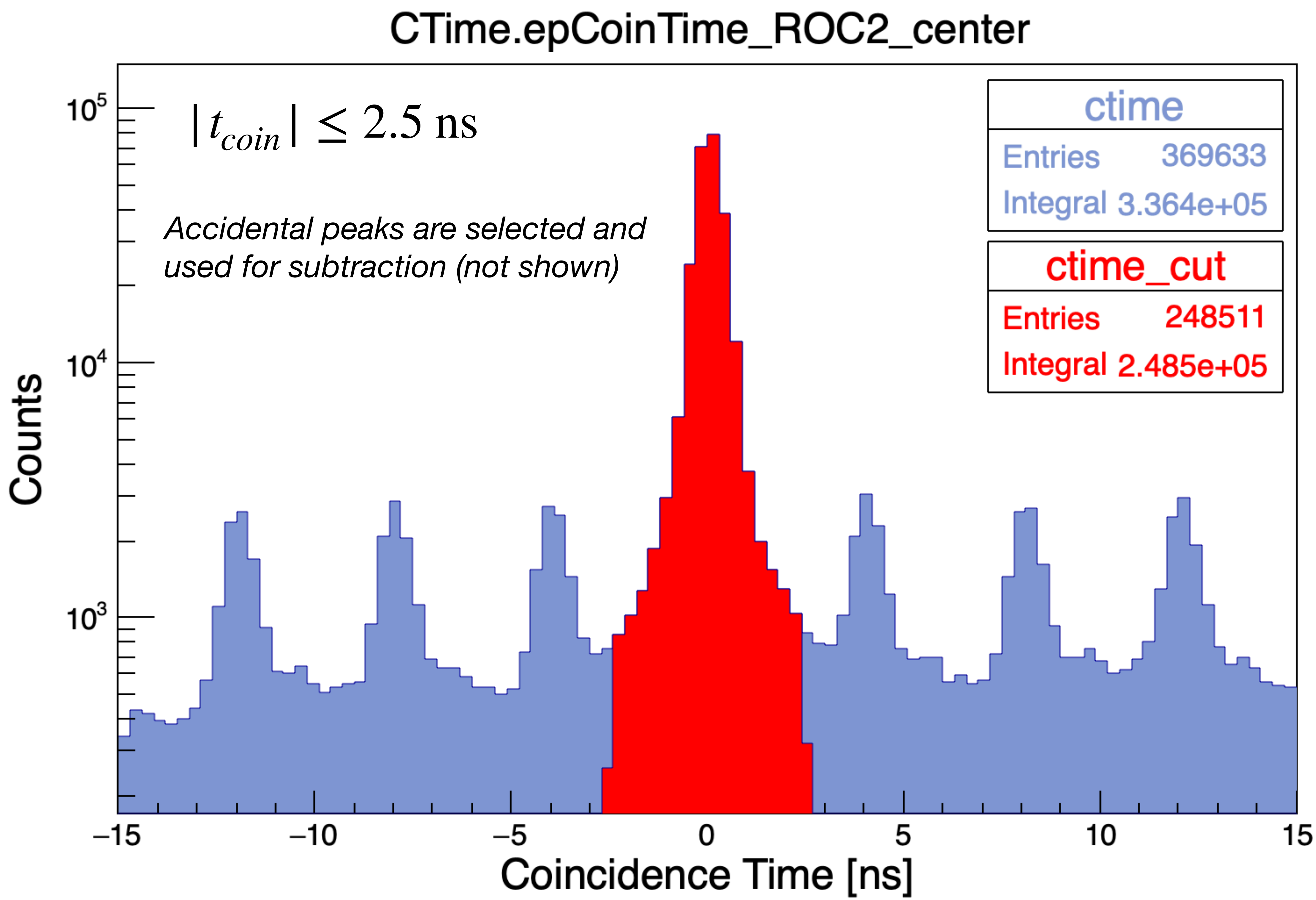


Delta, N* Resonance Excitations (IC)

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

Event Selection (MF)

(For illustration purposes, Ca48 MF run 17096 is used)



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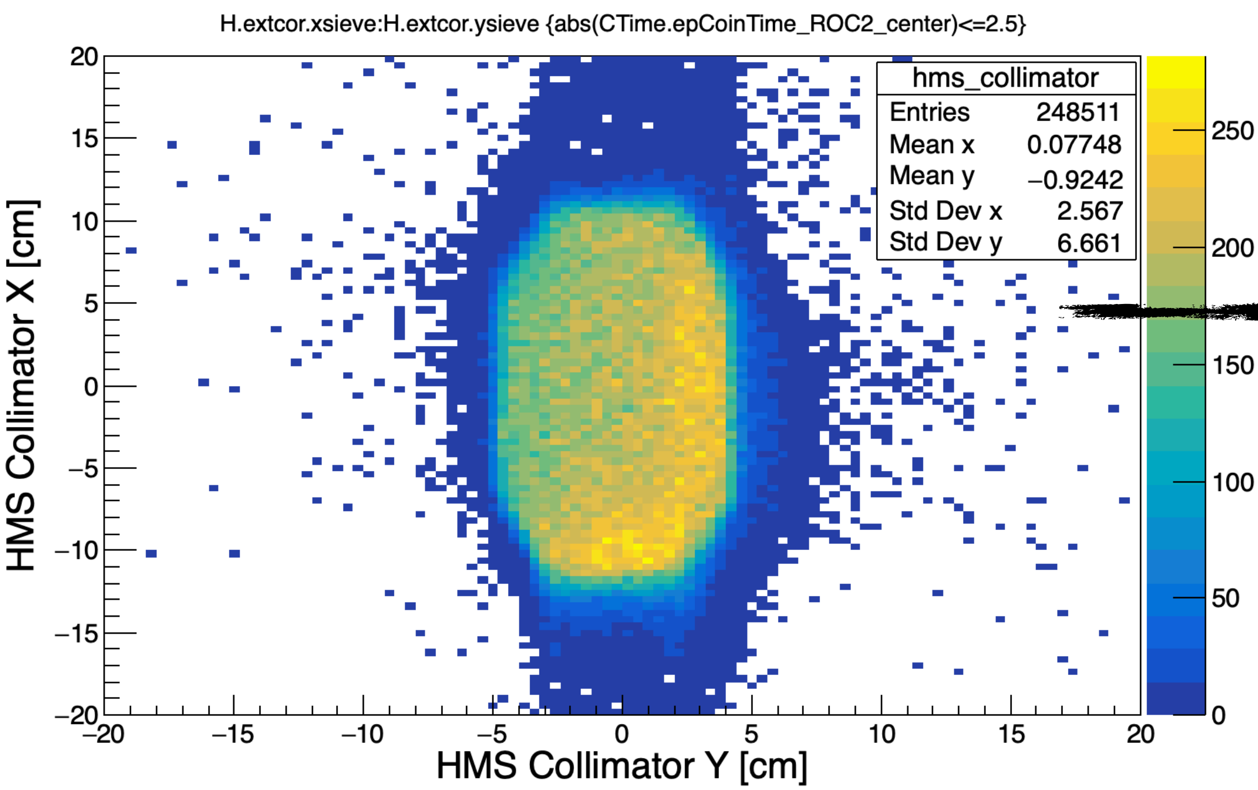
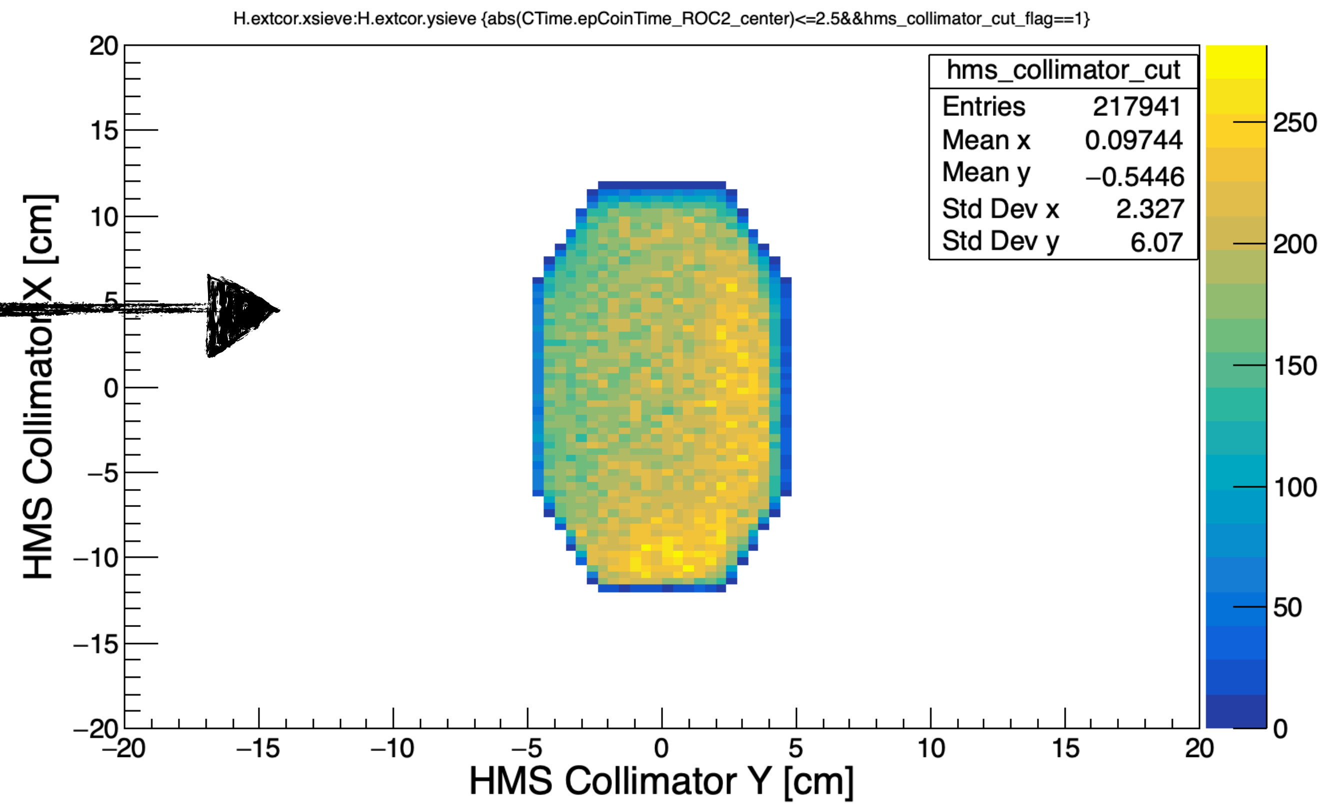
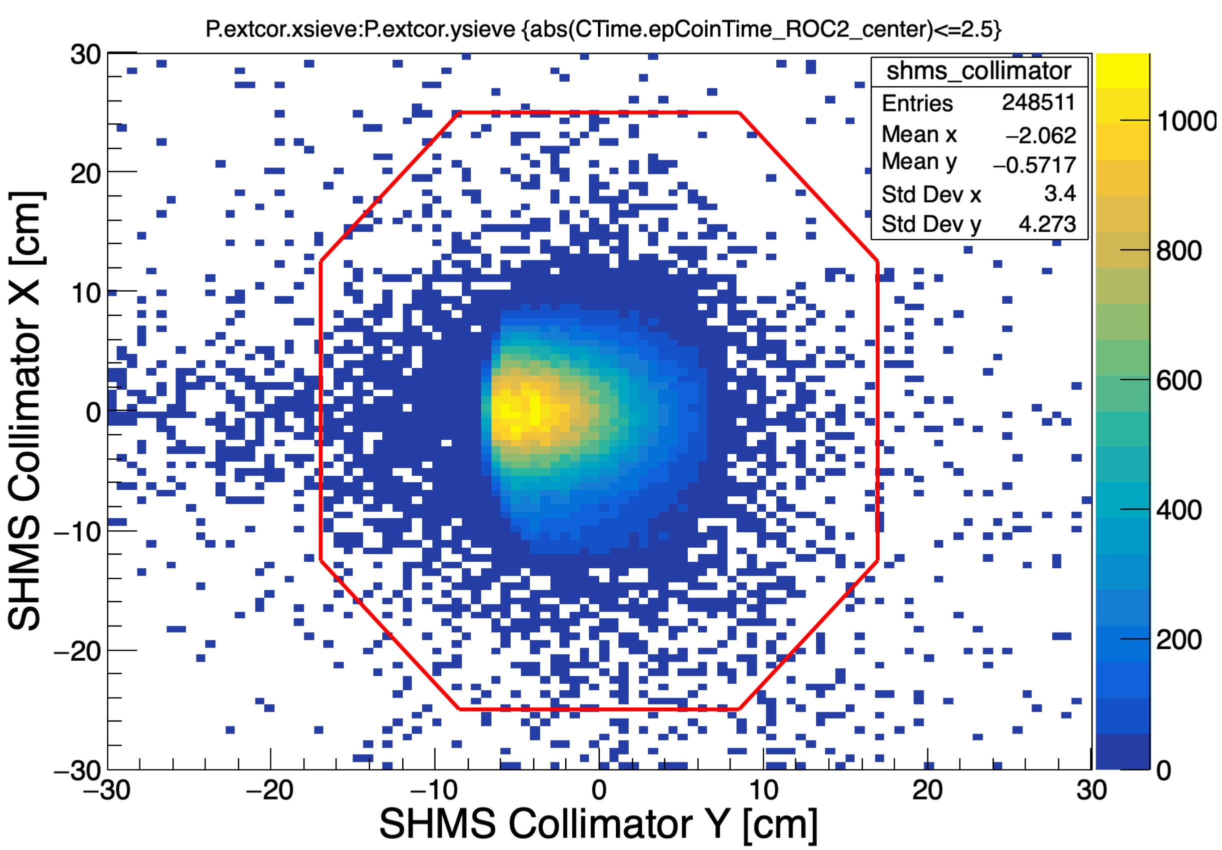
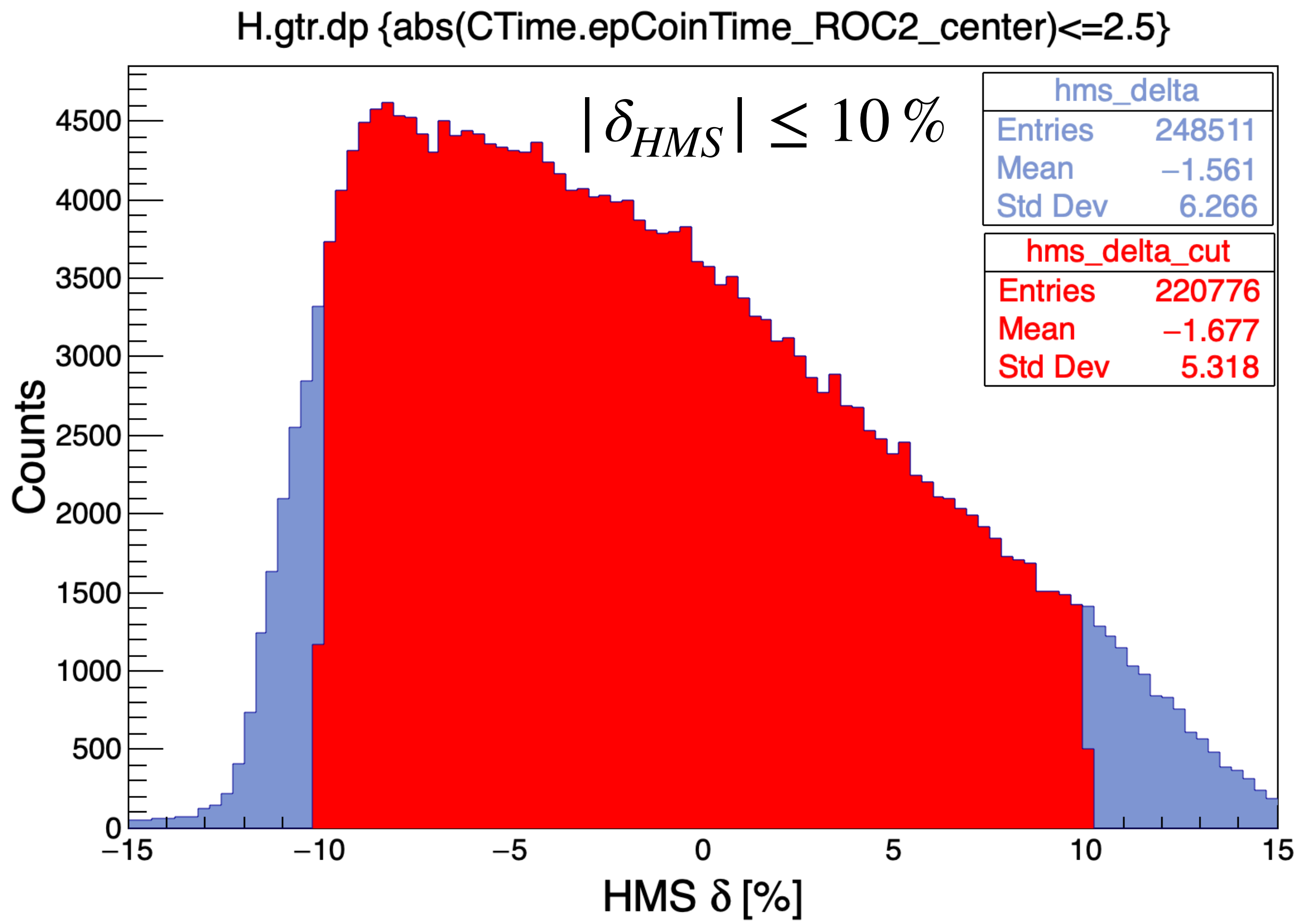






- SHMS acceptance determined (OR SET) by HMS (*angular cut will not do much, but is still applied*)

Event Selection (MF)

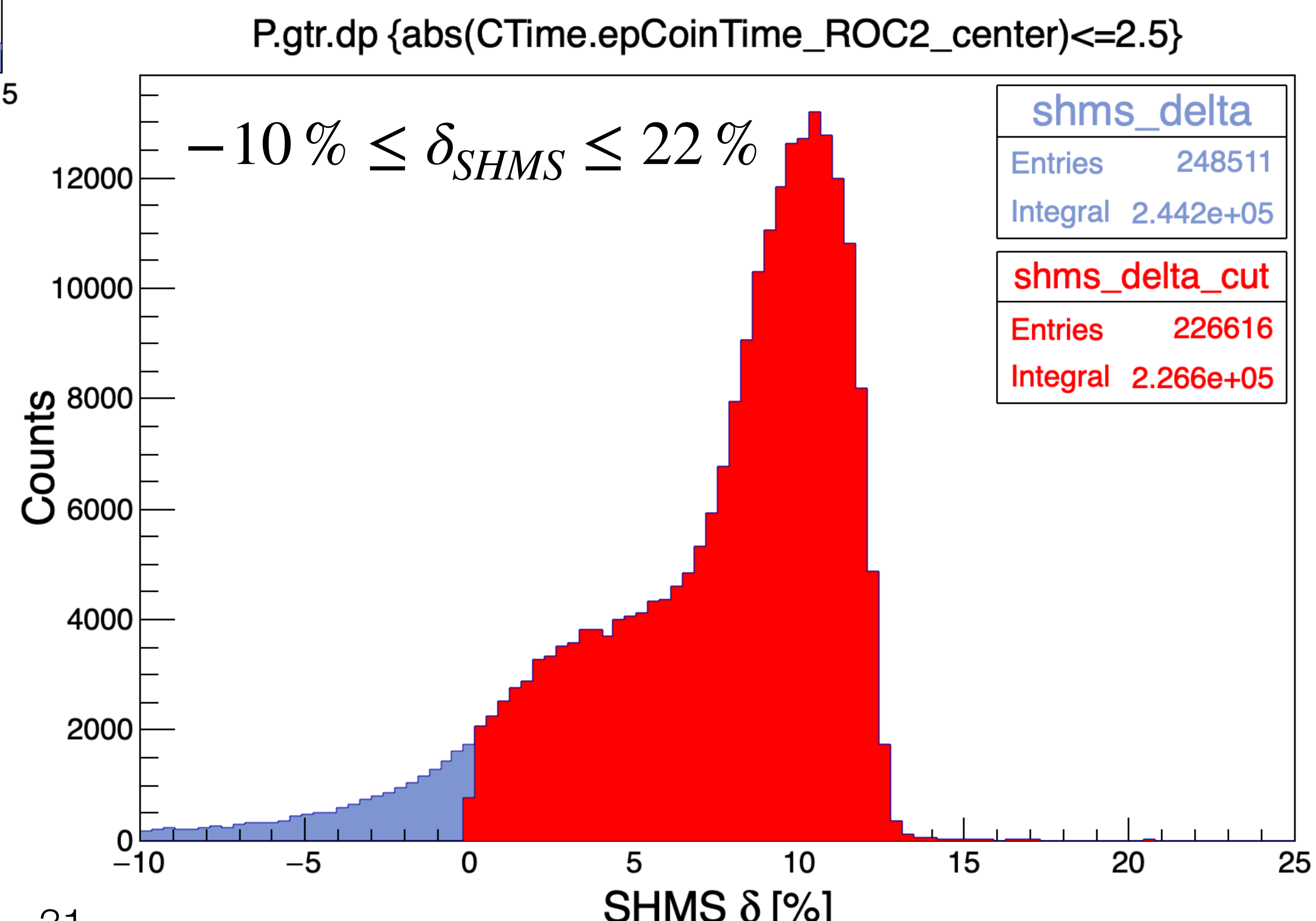


Momentum Acceptance Definition

$$\delta \equiv \frac{P - P_0}{P_0}$$

P_0 : Spectrometer central momentum

P : Particle track momentum



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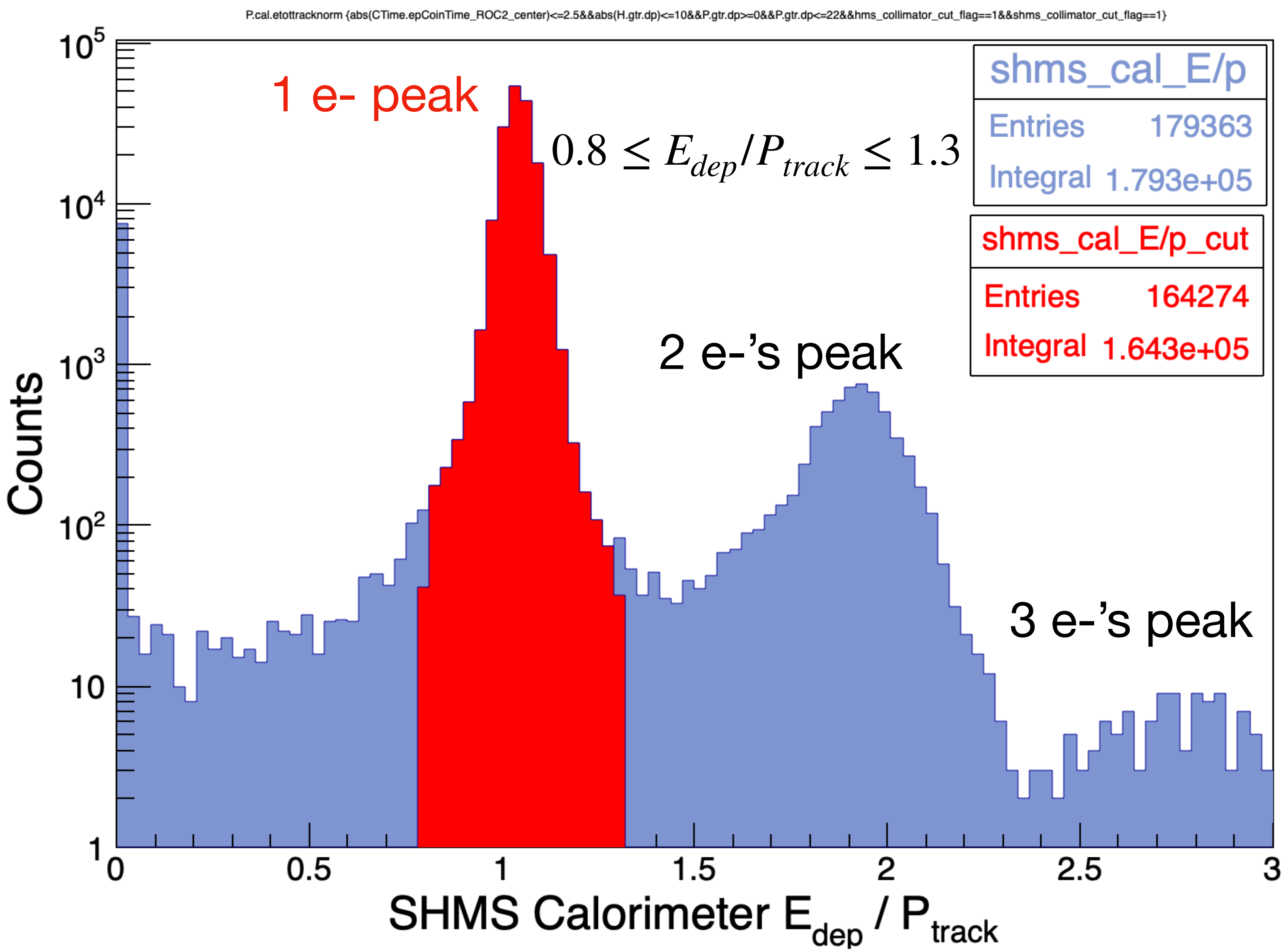
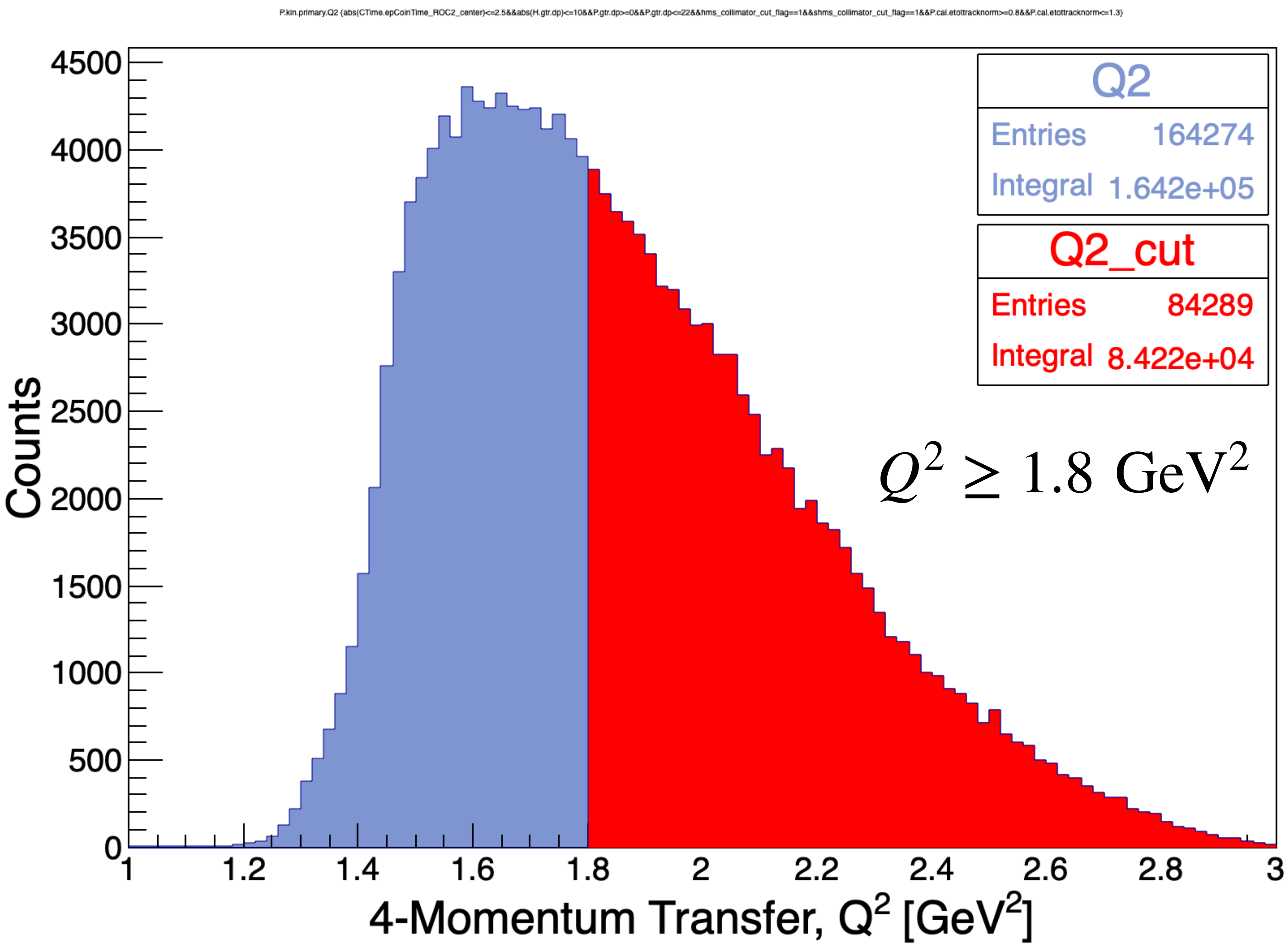


- Particle Identification: select electrons in SHMS
- multiple peaks constitue (~4-5%)
- *n* peak: *n times* the energy deposited (*n* valid electrons) *n*=1,2,3
- Account for multi-peak events: (multi-track efficiency)

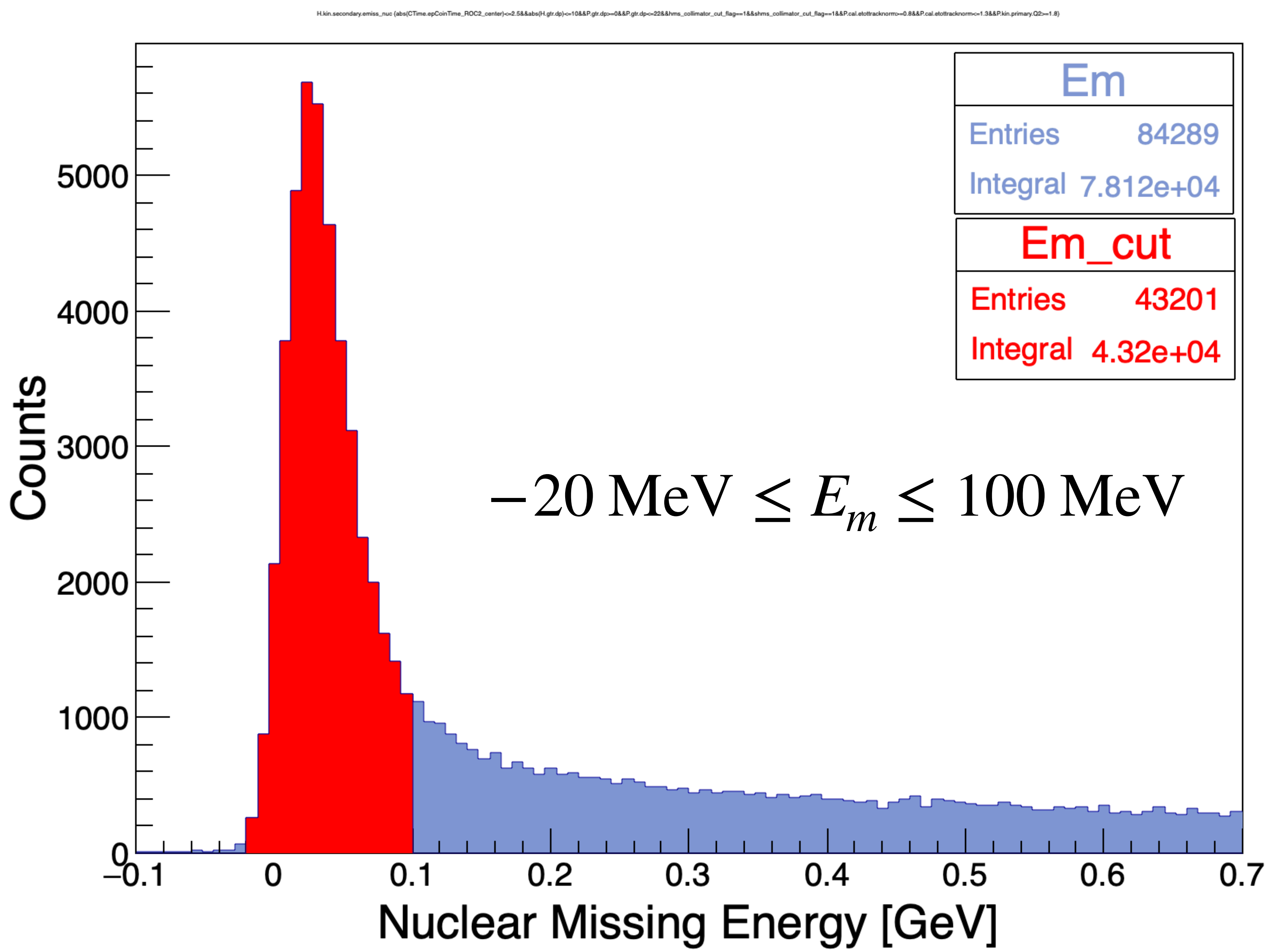
$$\epsilon_{\mathrm{multi.trk}} = \frac{\sum_{n=2,3} E_{dep}/P_0}{\sum_{n=1} E_{dep}/P_0}$$

Event Selection (MF)



- Kinematic Cut to Suppress Meson-Exchange Currents (MEC)

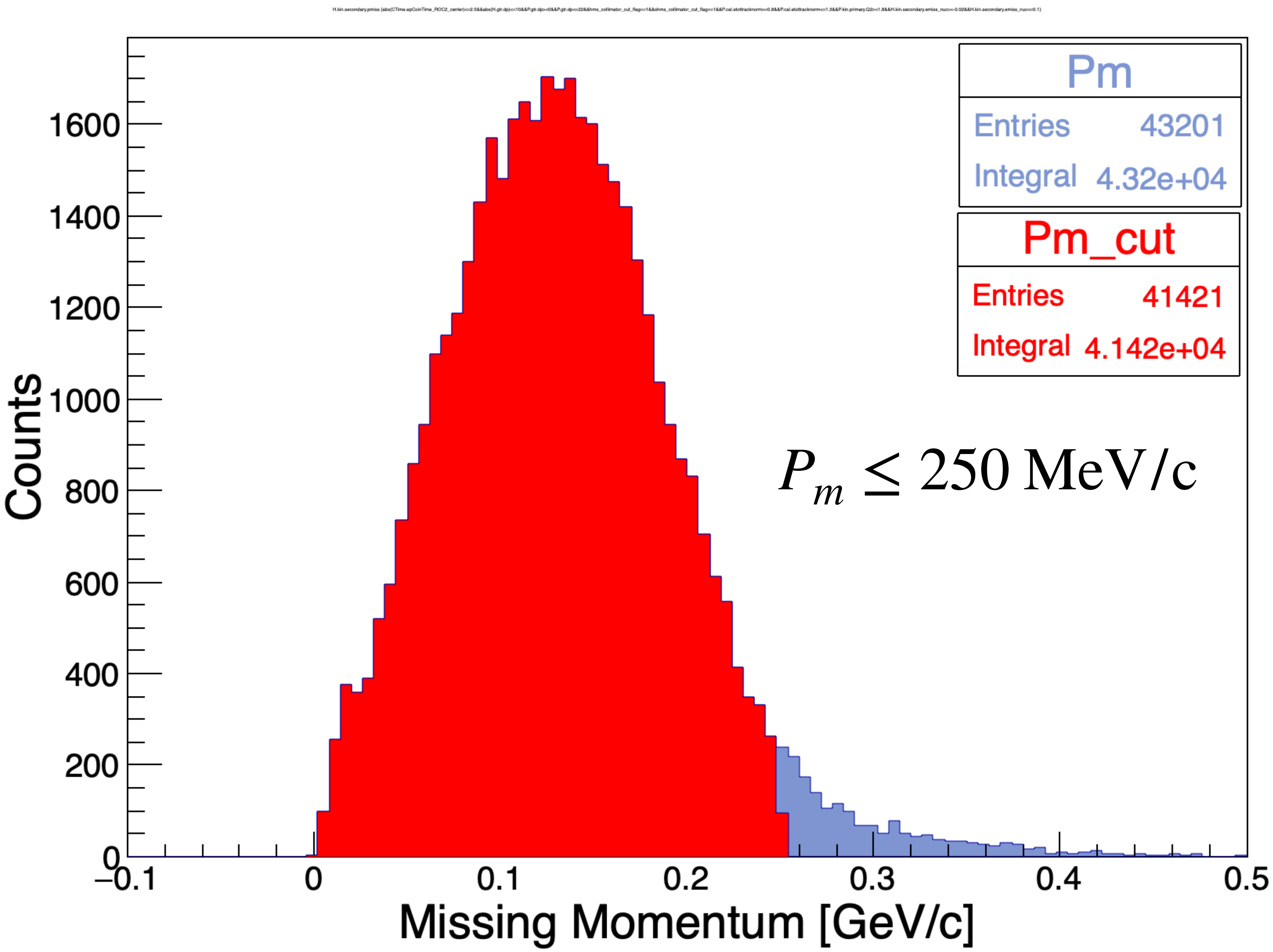
Event Selection (MF)



- Kinematic Cut to suppress radiative tail/ select (e, e’p) events

$$E_m = \nu - T_p - T_r$$

Event Selection (MF)

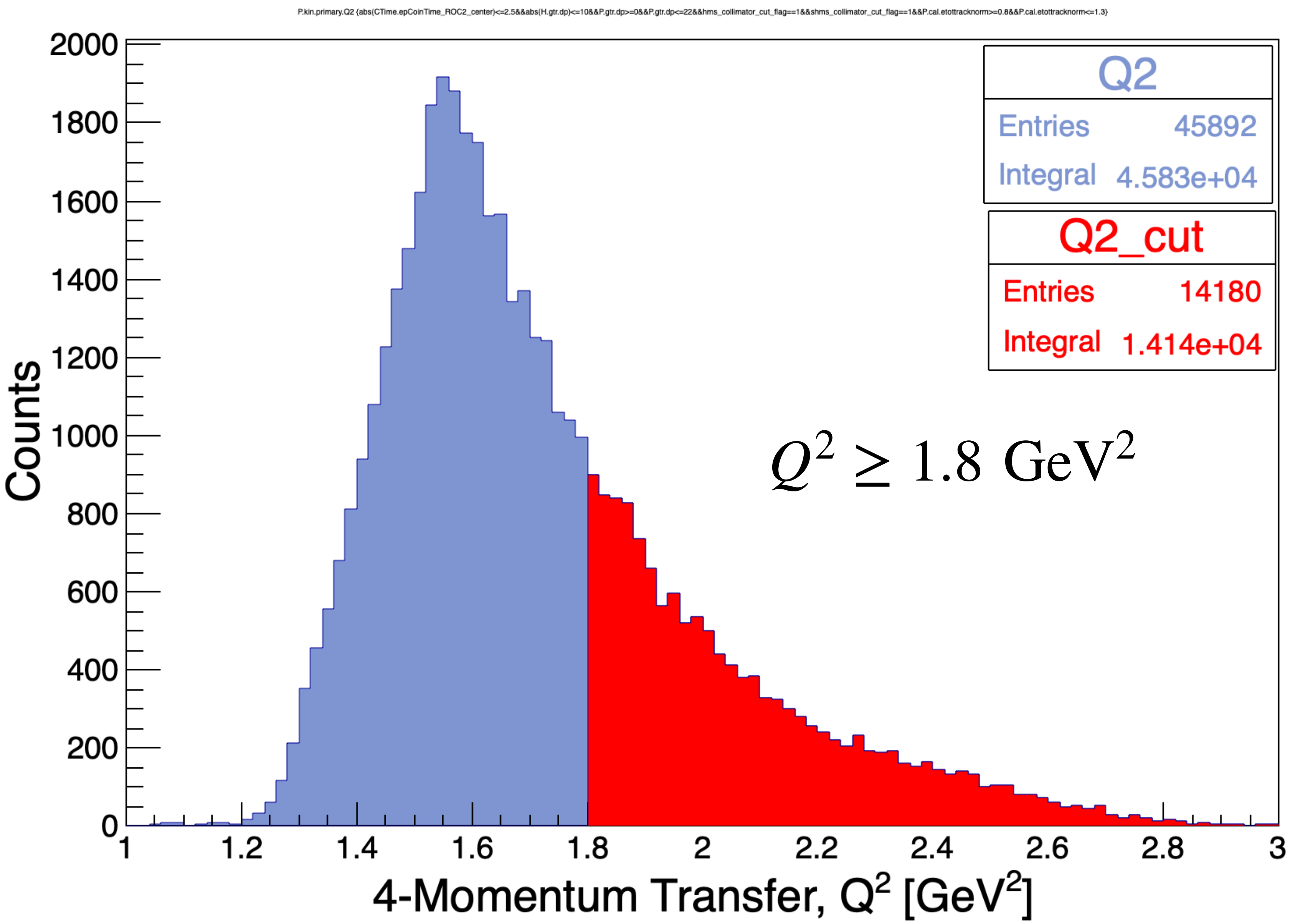


- Kinematic Cut to select mean-field (MF) nucleons

Event Selection (SRC)

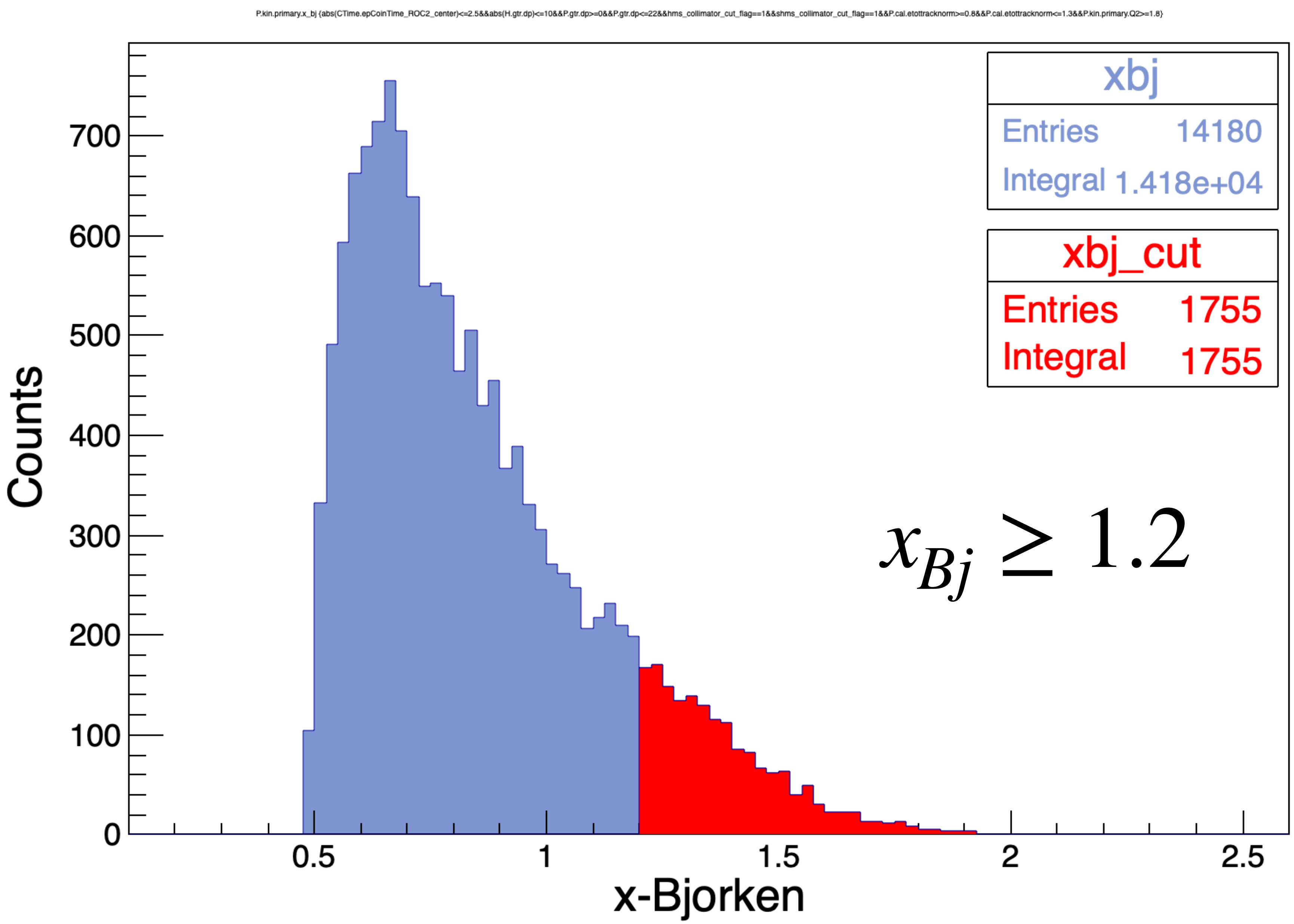
(For illustration purposes, Ca48 SRC run 17057 is used)

*** coincidence time + acceptance + PID cuts are same as (MF) kinematics*



- Kinematic Cut to Suppress Meson-Exchange Currents (MEC)

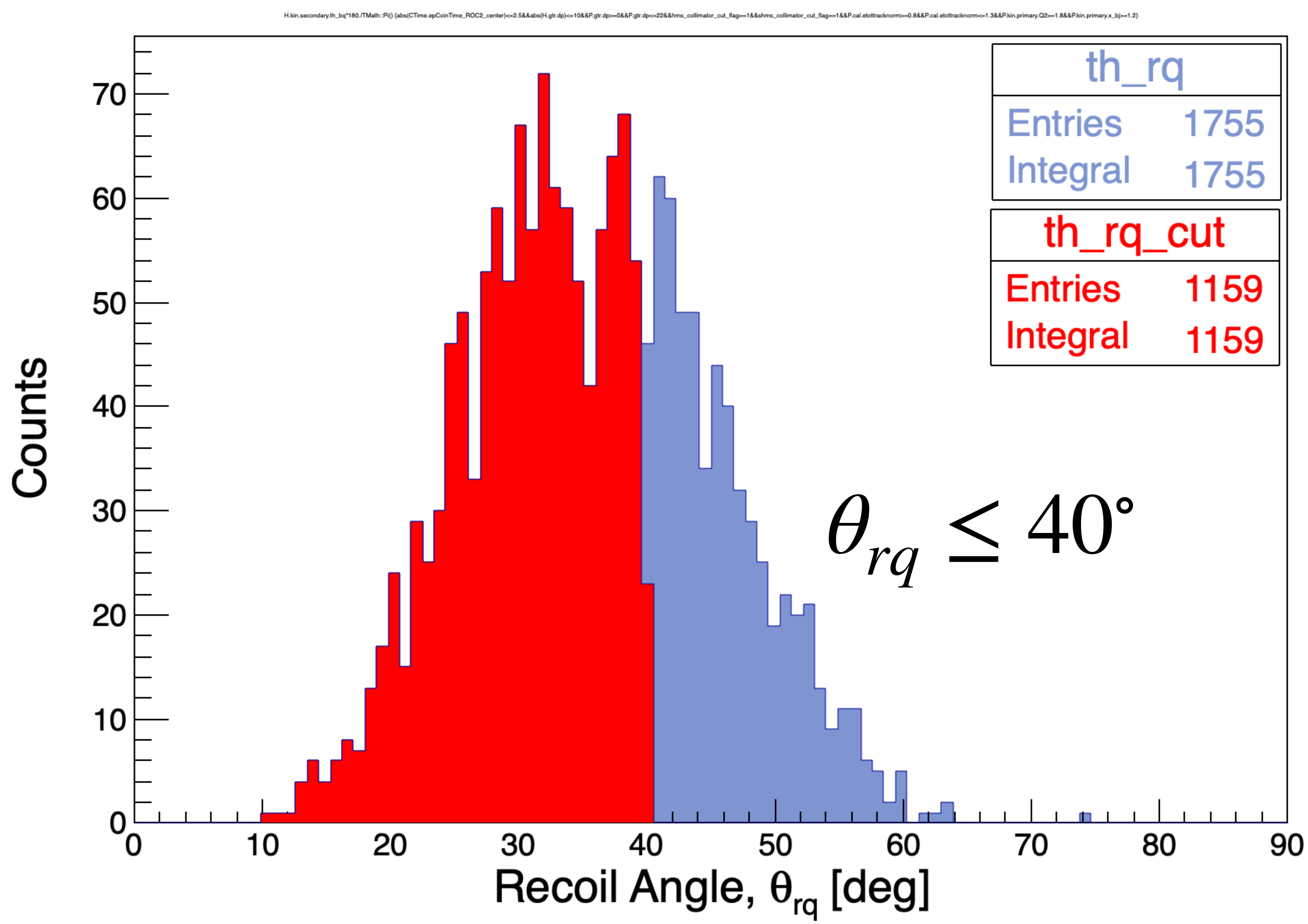
Event Selection (SRC)



- Kinematic Cut to suppress inelastic + DIS events at x<1

  (i.e., suppress Δ, N^* excitations)

Event Selection (SRC)



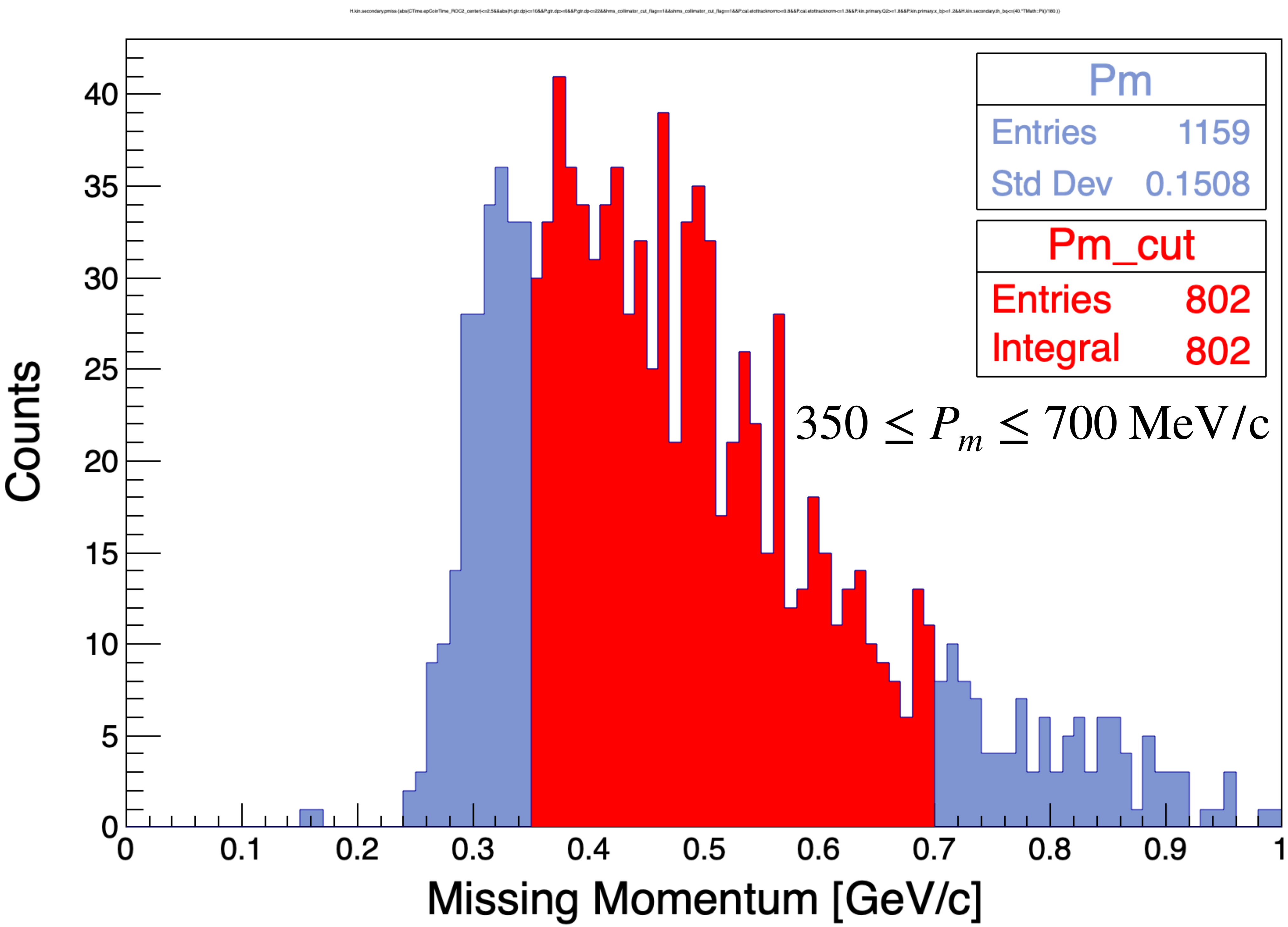
θ_{rq} :

- Angle between recoil system
- and virtual photon direction

- Kinematic Cut to suppress re-scattering of recoil SRC nucleon

  (i.e., suppress final-state interactions)

Event Selection (SRC)



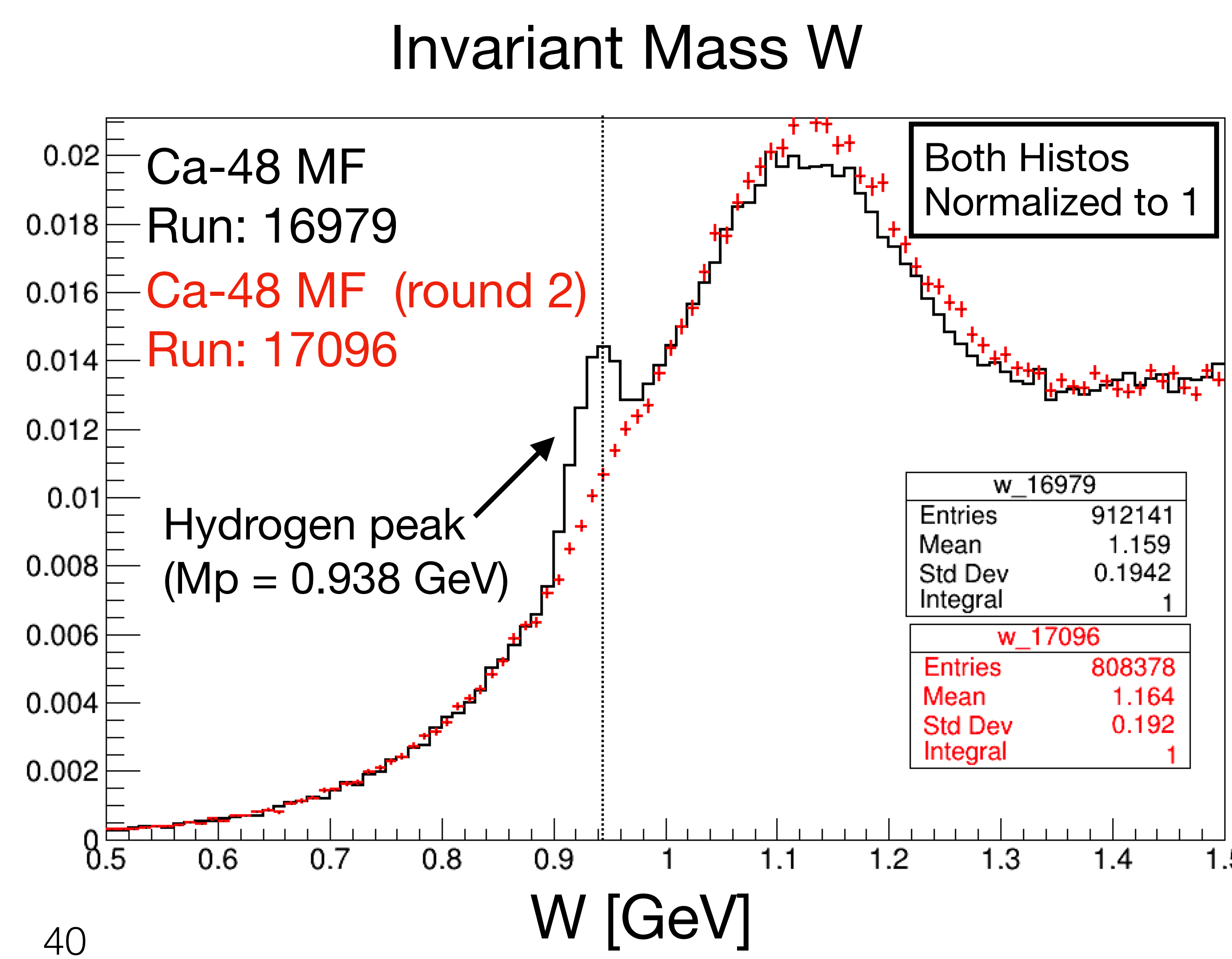
- Kinematic Cut to select short-range correlated nucleon

Ca-48 Contamination Studies: Background

- Ca-48 target found to be contaminated with hydrogen (H) during initial 2 runs @ mean-field (MF) kinematics
- During Ca-48 short-range correlation (SRC) running, target received ~50-55 uA beam throughout ~ 22 hr period (with occasional beam trips, and few runs < 50 uA)
- Ca-48 MF data (3 runs) was taken again and found that the H-contamination peak had been significantly reduced

Hypothesis:
pure mineral oil was only present on the surface of Ca-48 and was "washed off" on its own + high-current beam received during SRC running helped with decontamination process.

Purpose of this study: quantify hydrogen contamination (and scale to Carbon) present on Ca-48 during both MF and SRC kinematics runs



Ca-48 Contamination Studies Analysis Steps

- determine H-thickness (g/cm2) for each Ca48 MF run

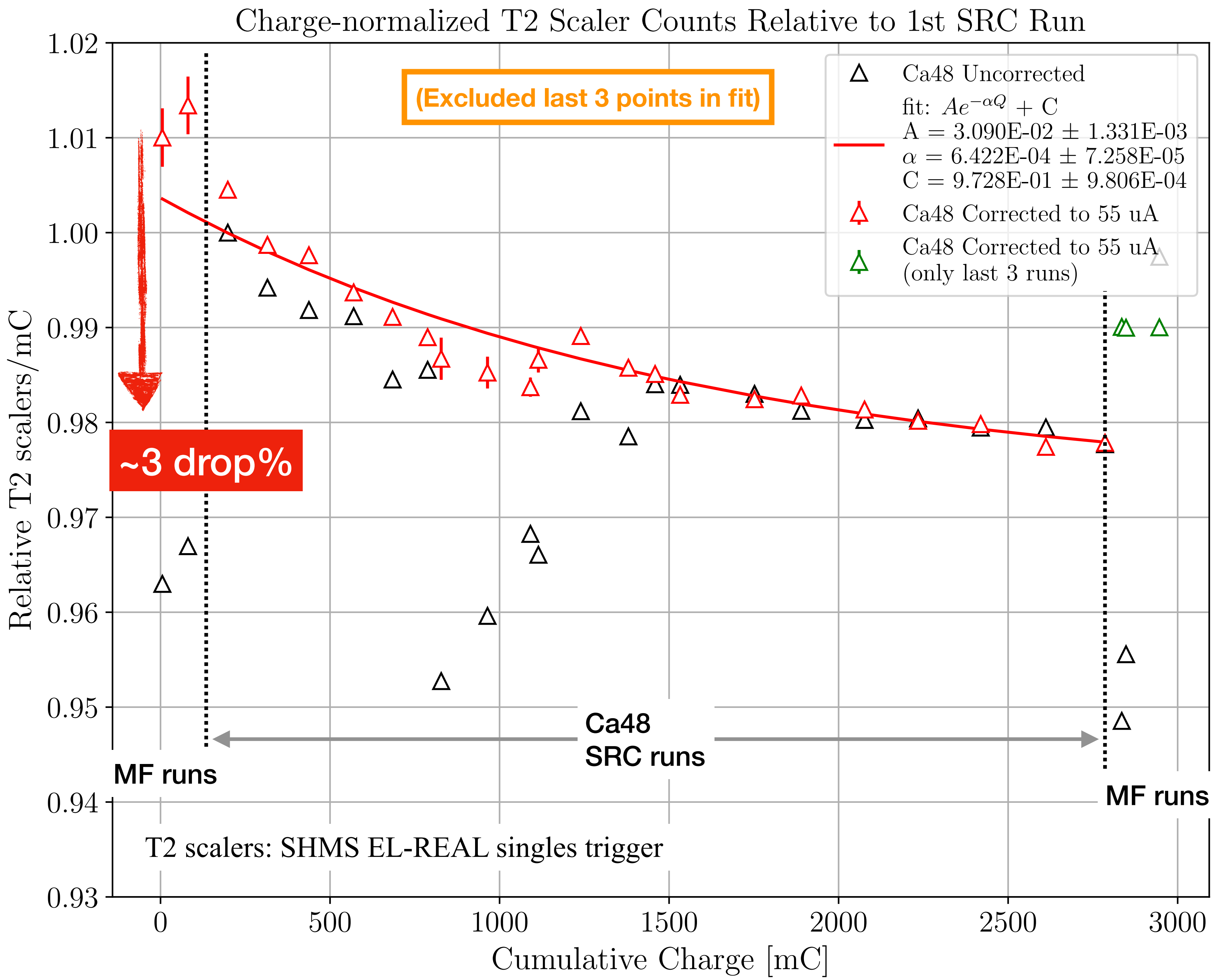
- determine C-thickness (g/cm2) : Scale H-thickness to C-thickness assuming a specific H/C ratio for mineral oil (research mineral oil chemical composition for this)

- ** Calculate T2 (e- singles) scalers / charge for all Ca48 runs to quantify relative drop in contamination for all Ca48 SRC runs

- absolute (H, C) contamination in Ca48 MF +
  relative drop in contamination in Ca48 SRC runs
  —> *absolute drop in contamination for Ca48 SRC runs*

** cannot directly measure absolute H-contamination determine @ SRC kinematics (not kinematically possible+singles were pre-scaled significantly)

Relative Contamination (using scalers)

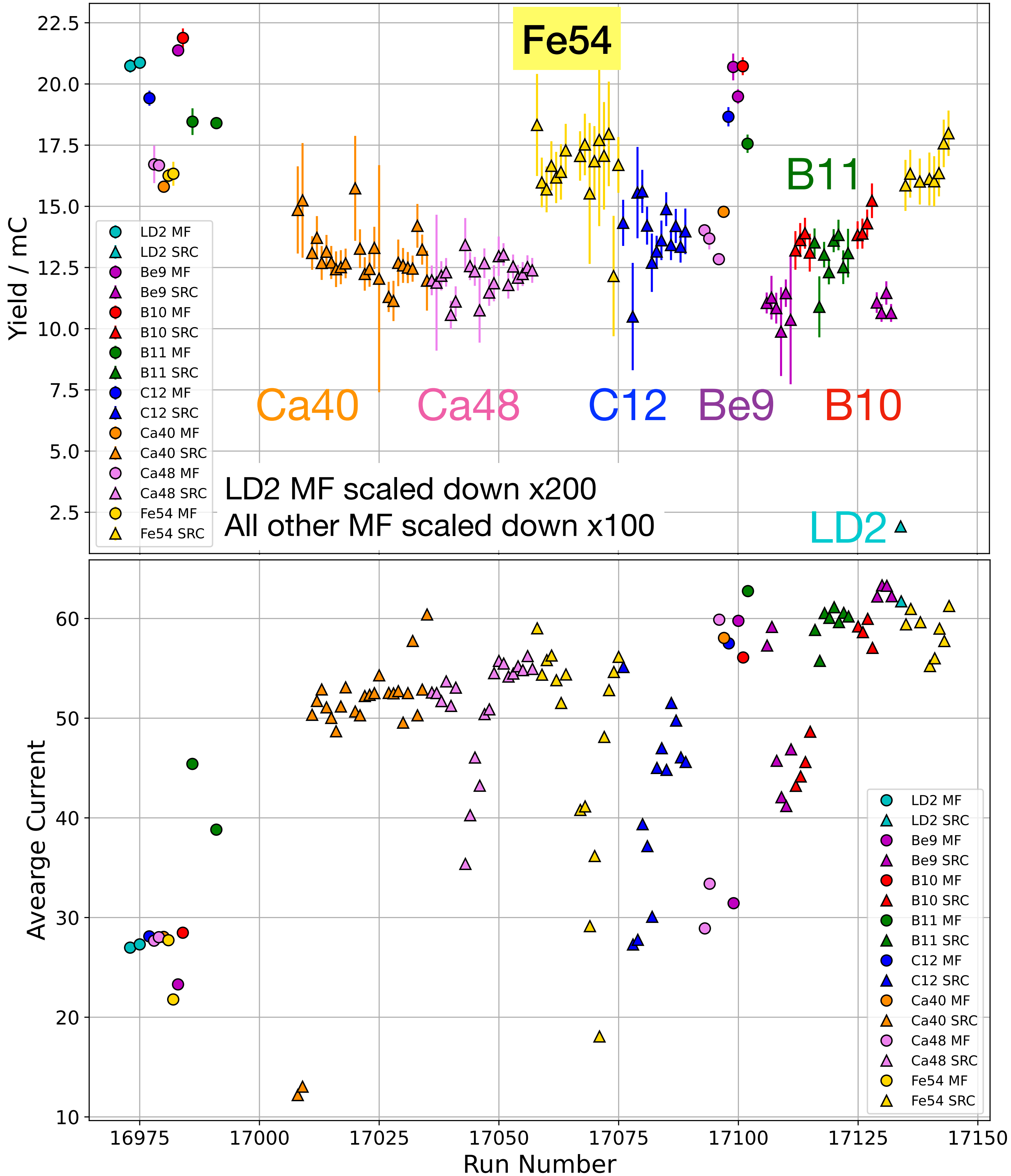


Ca48 Absolute Carbon Contamination Limiting Cases

	MF		MF	
	[16979,	. . . SRC runs . . .	17093]	
1C/2H :	[3.1 %	. . . ? . . .	0.65 %]	—> ~ 3 % drop on C-thickness (assuming 1C/2H: alkanes or cyclic alkanes)
2C/1H:	[12.3 %	. . . ? . . .	2.6 %]	—> ~ 10 % drop on C-thickness (assuming 2C/H : alkylated aromatics)

- T2 scaler analysis of relative contamination consistent with lower limit *(1C / 2H)* of absolute contamination measurements
  (expectation from chemical analysis is that there be little to none alkylated aromatics i.e., 2 C-atom / 1 H-atom ratio, and abundance of 1 C / 2 H atoms)

Beam Current Dependency Study: Motivation



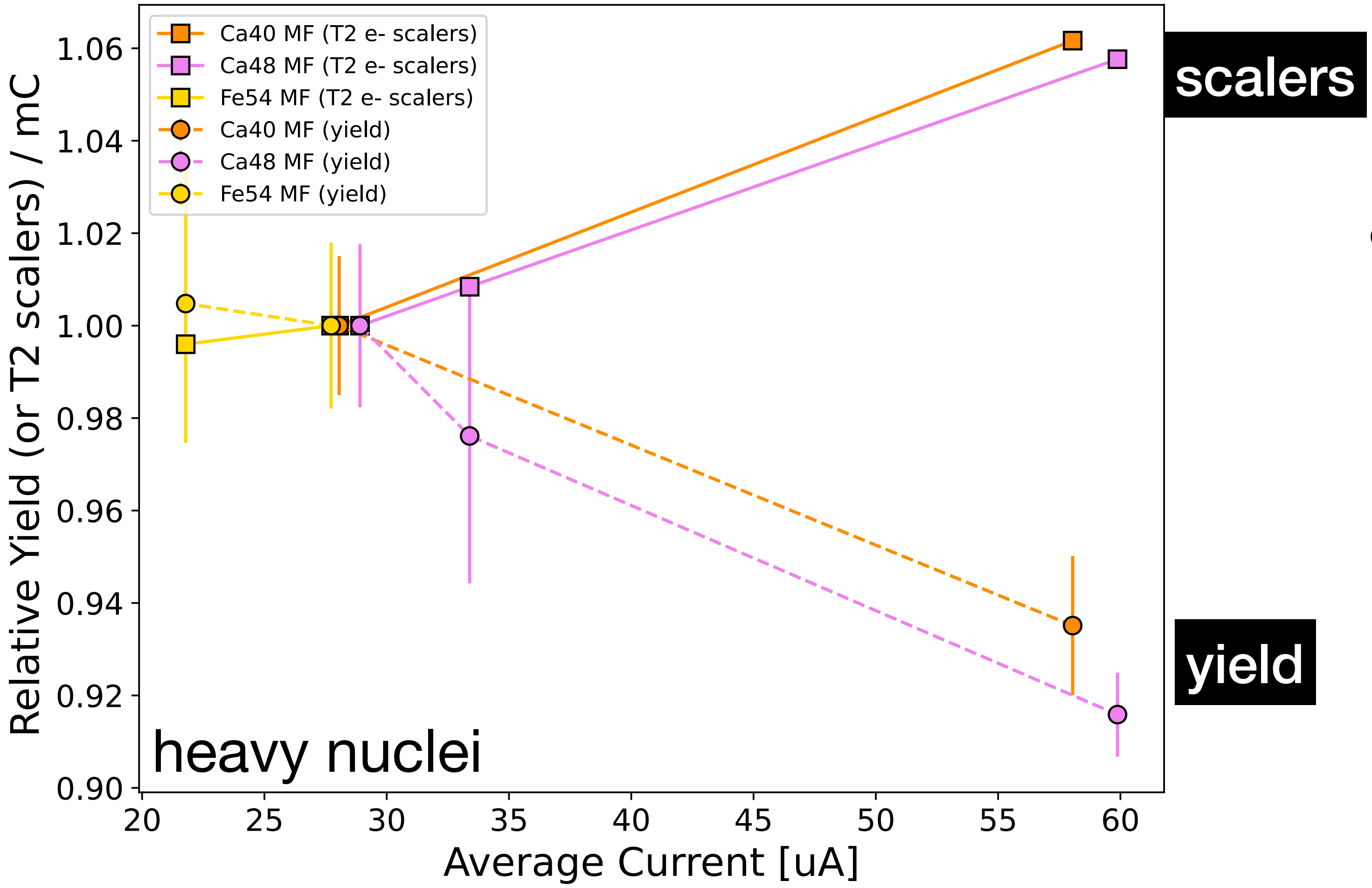
- Normalized Yield is defined as:

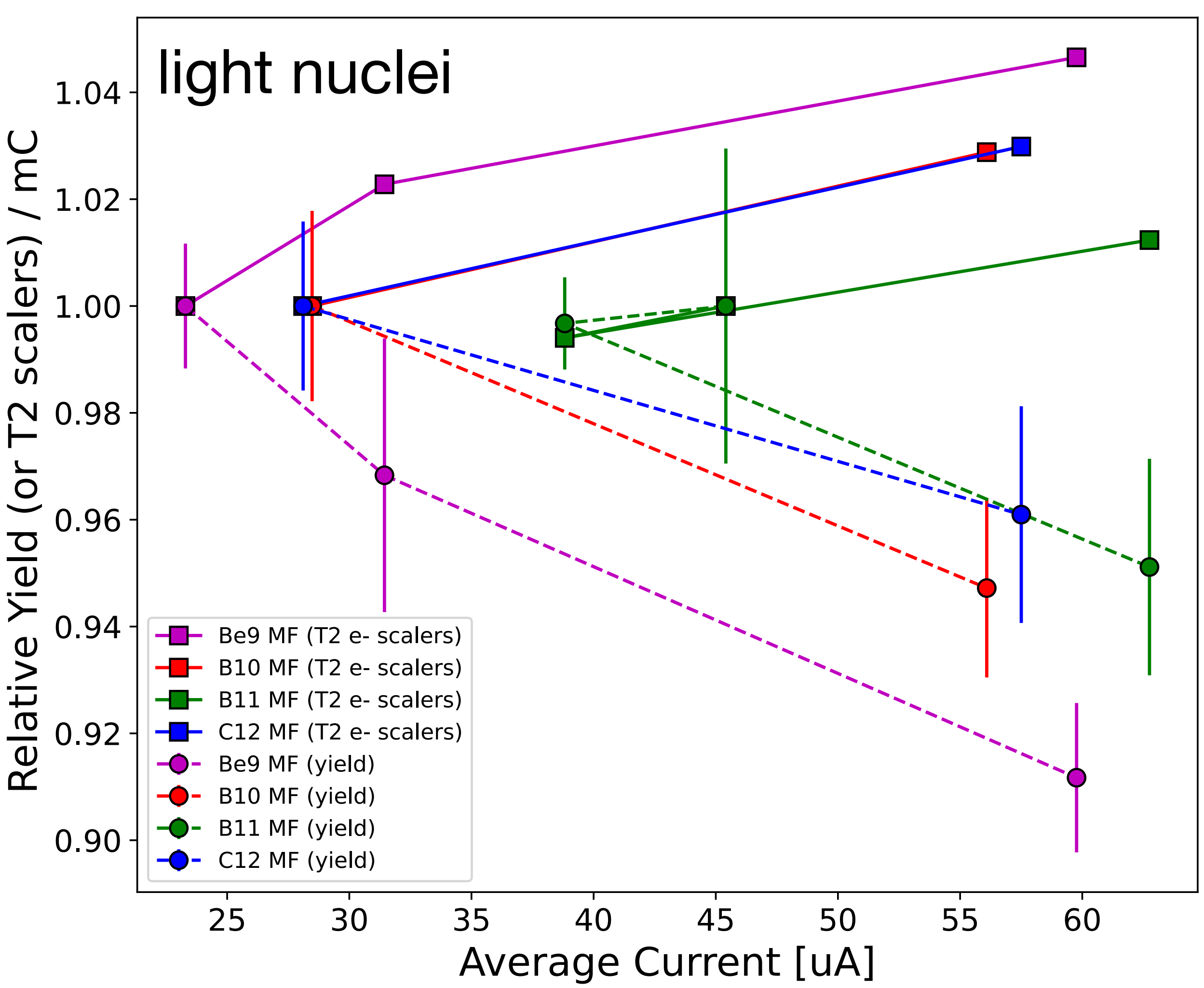
$$Y = \frac{N_c}{Q \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{multi.trk} \cdot \epsilon_{LT} \cdot \sigma_A \cdot T}$$

- Yield/charge dependence on beam-current observed !

- SRC data low stats (large error bar) so beam current dependence not obvious as it could be smaller than error bar

- MF data high stats (small error bar) so beam current dependence is obvious (next slide)





Relative Yield (or T2 Scalers) vs Average Current

- charge-normalized data yield should **NOT** change with beam current

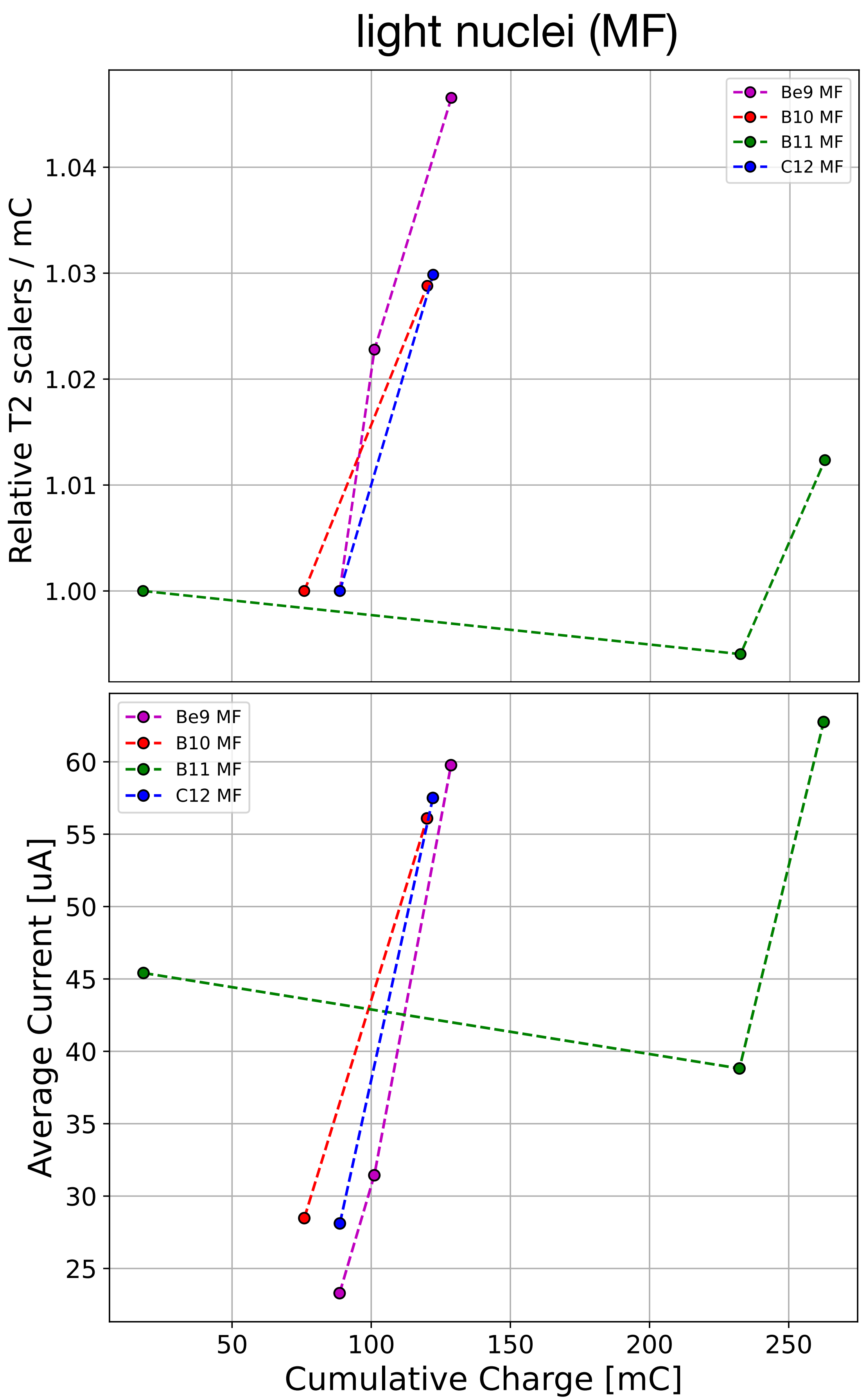
- relative yield drops ~6-8 % when beam current increases ~30 uA —> 60 uA (**dashed**)

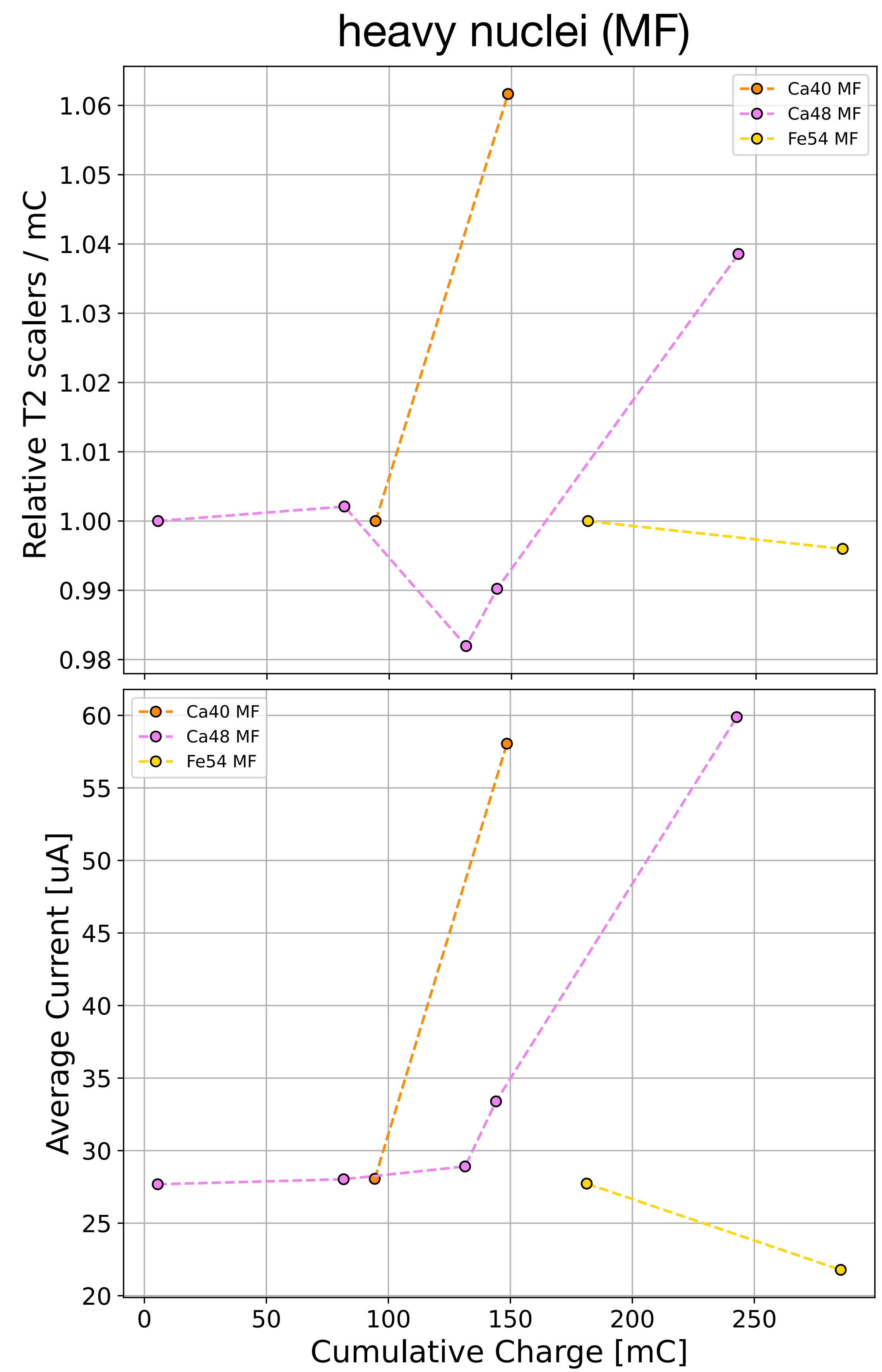
- relative T2 scalers (e-) increase ~4-6 % when beam current increases ~30 uA —> 60 uA (**solid**)

- **Possible Causes of Yield Dependency on Current:**

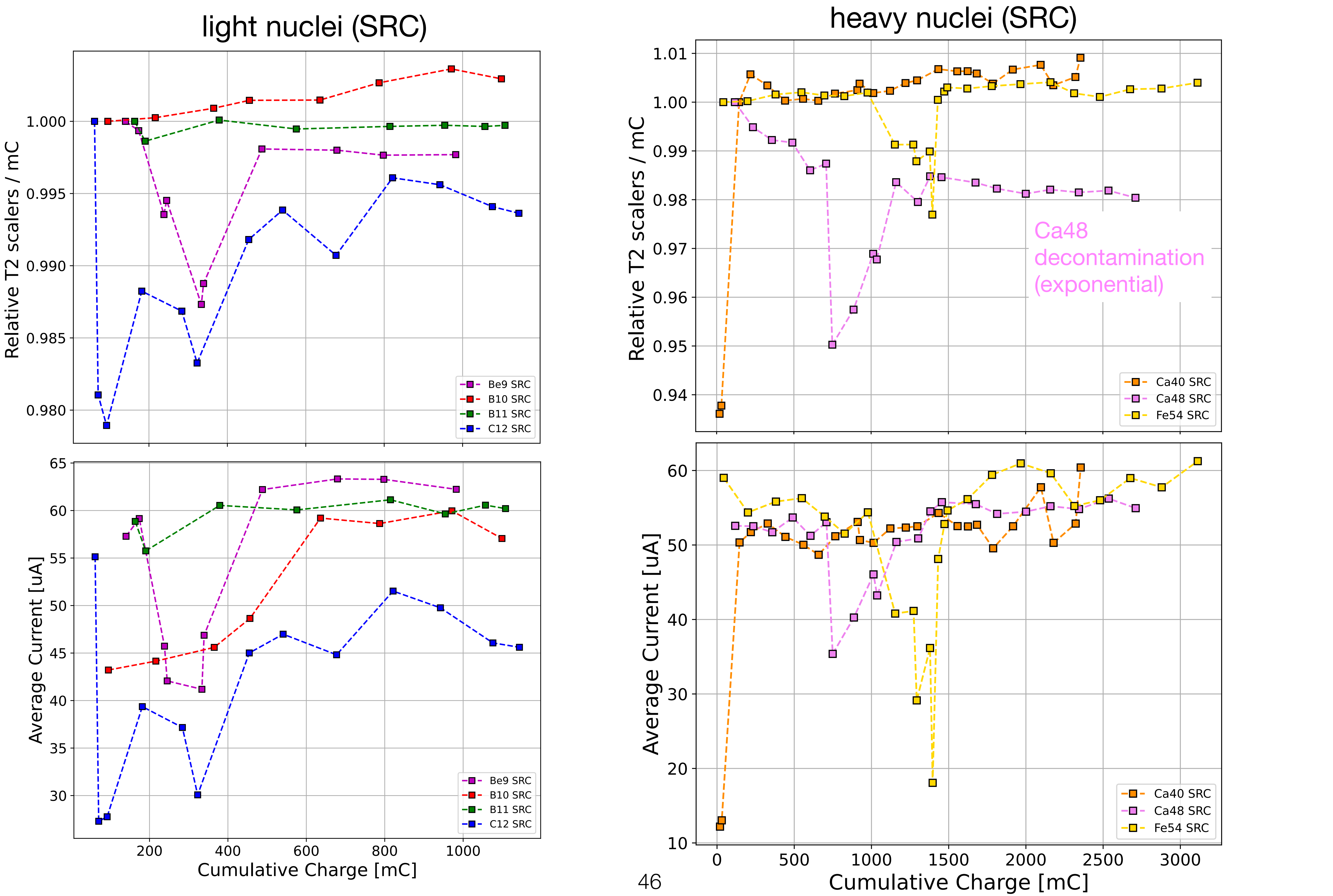
  - BCM linearity issue ?
  - HCANA tracking algorithm?

Relative T2 Scalers / Charge vs Cumulative Charge

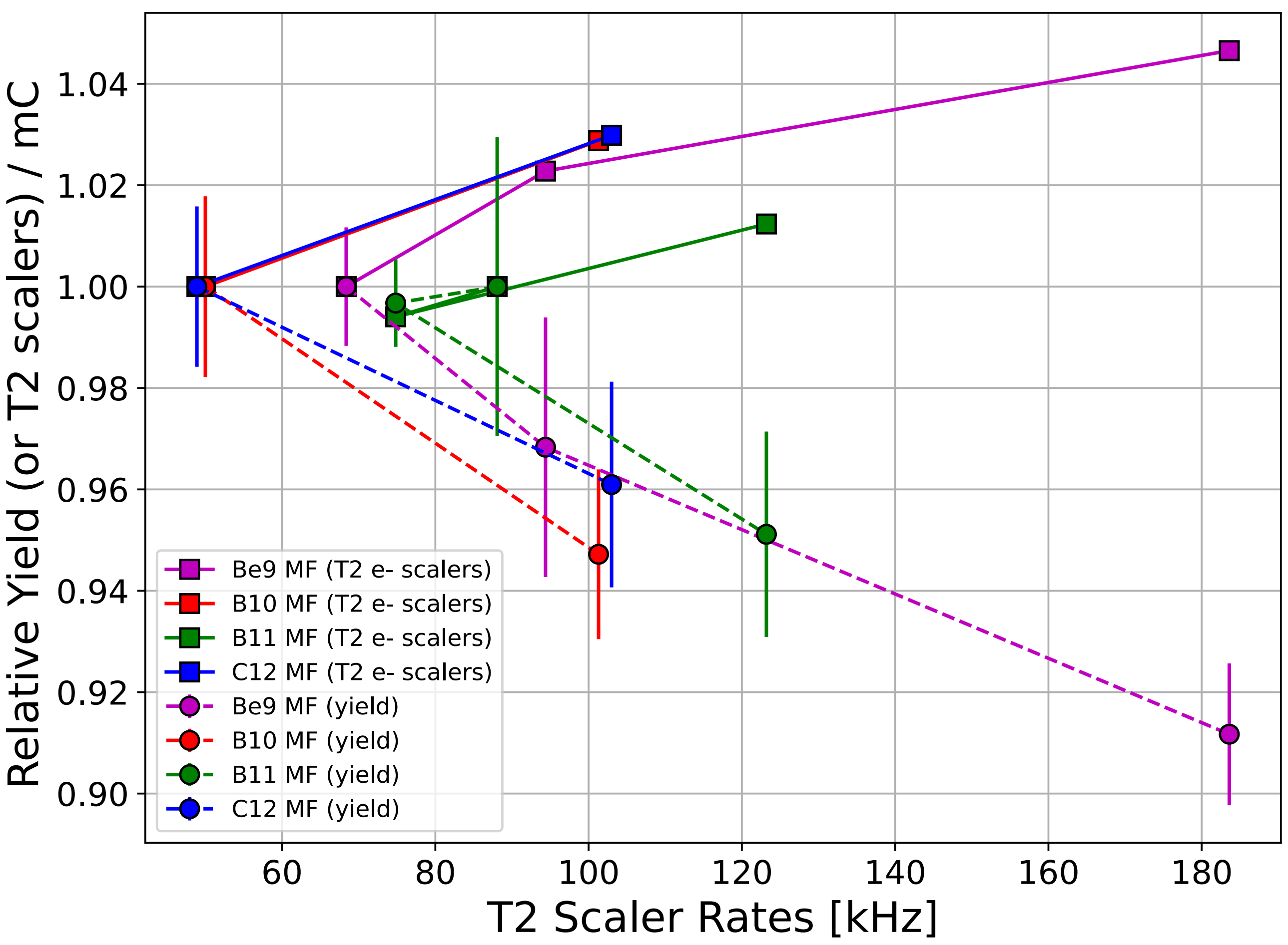


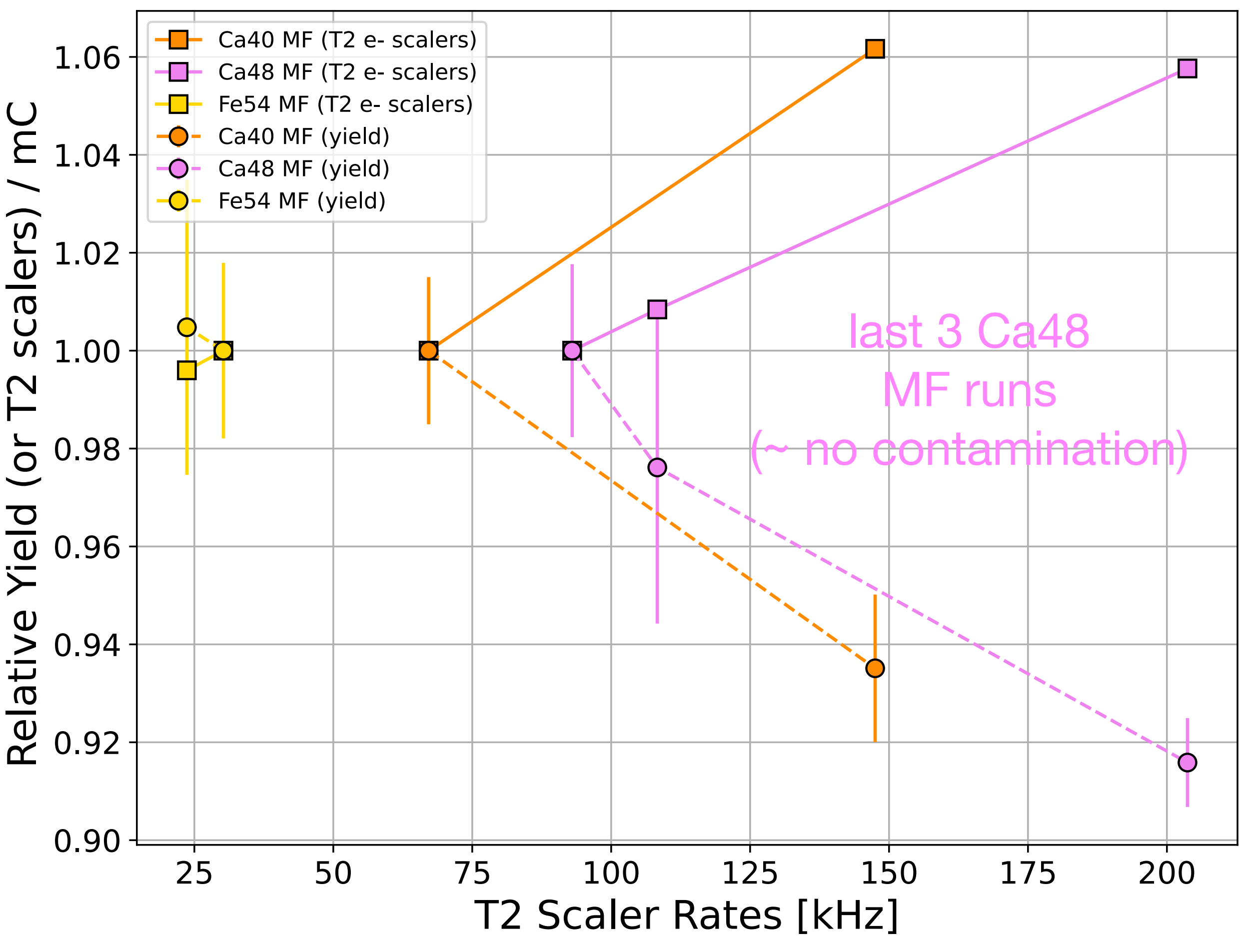


Relative T2 Scalers / Charge vs Cumulative Charge



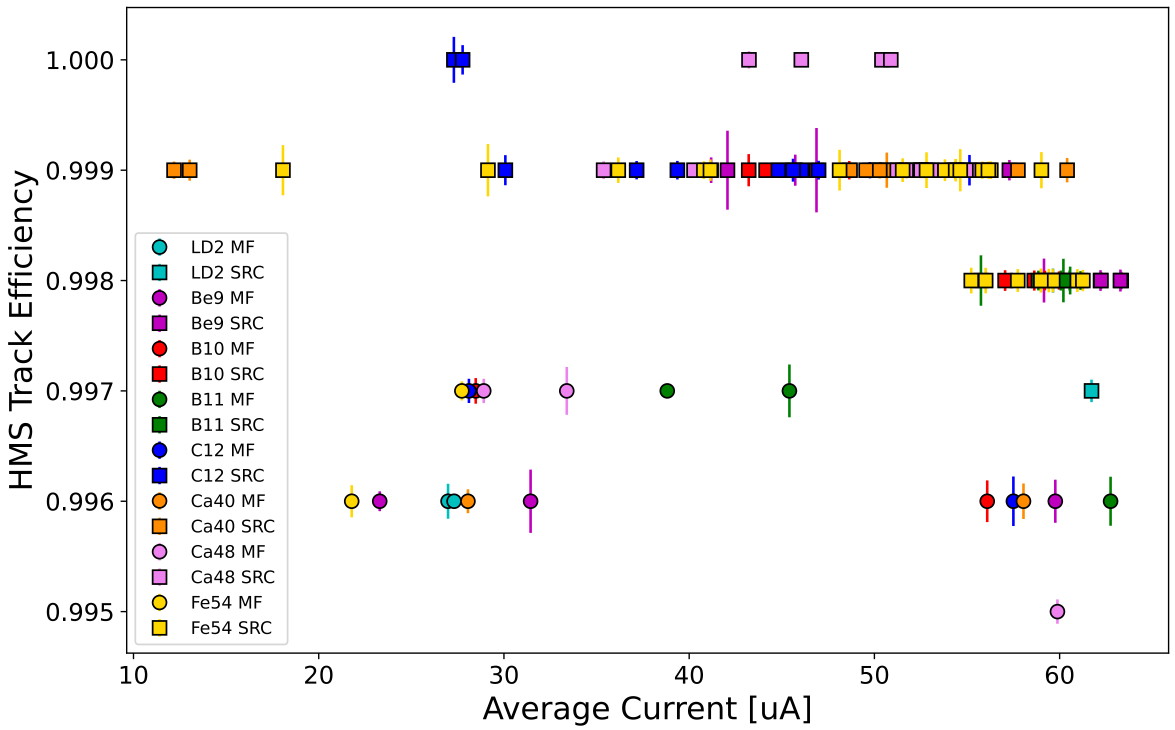
Relative T2 Scalers (or Yield) / Charge vs T2 Scaler Rates

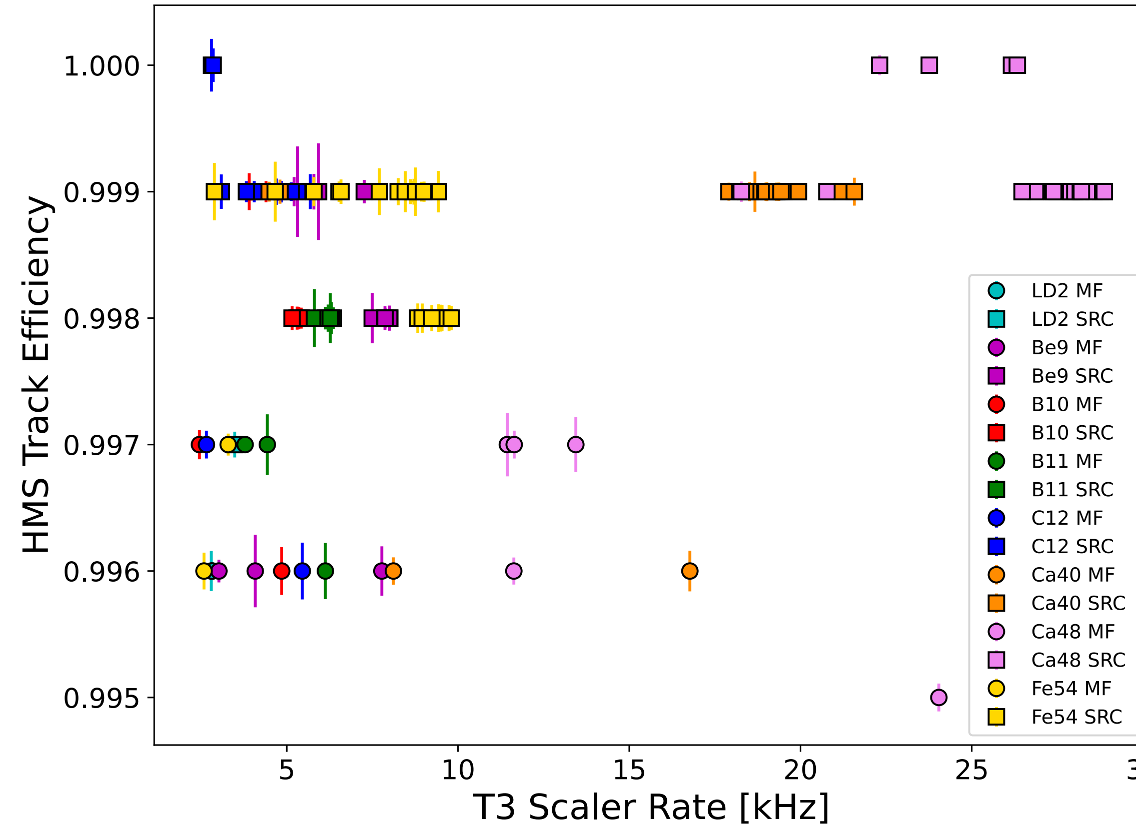


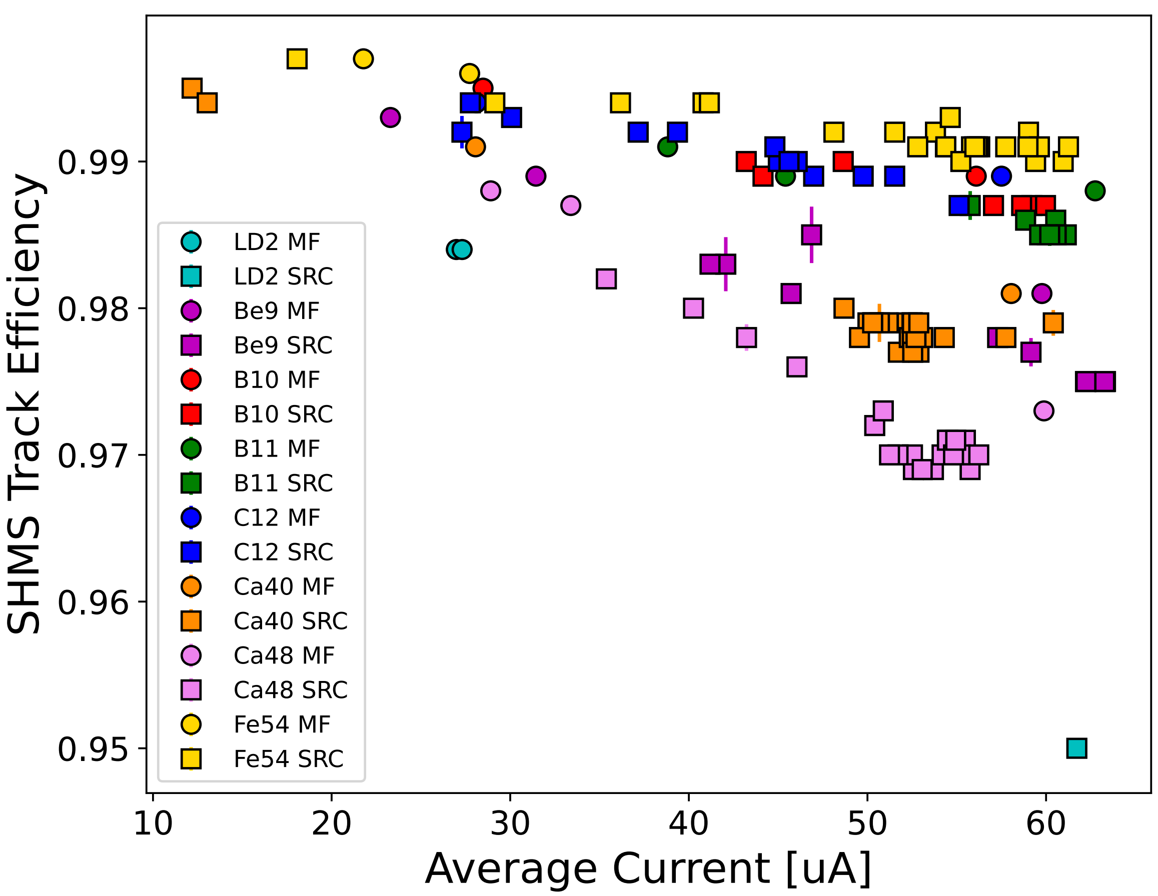


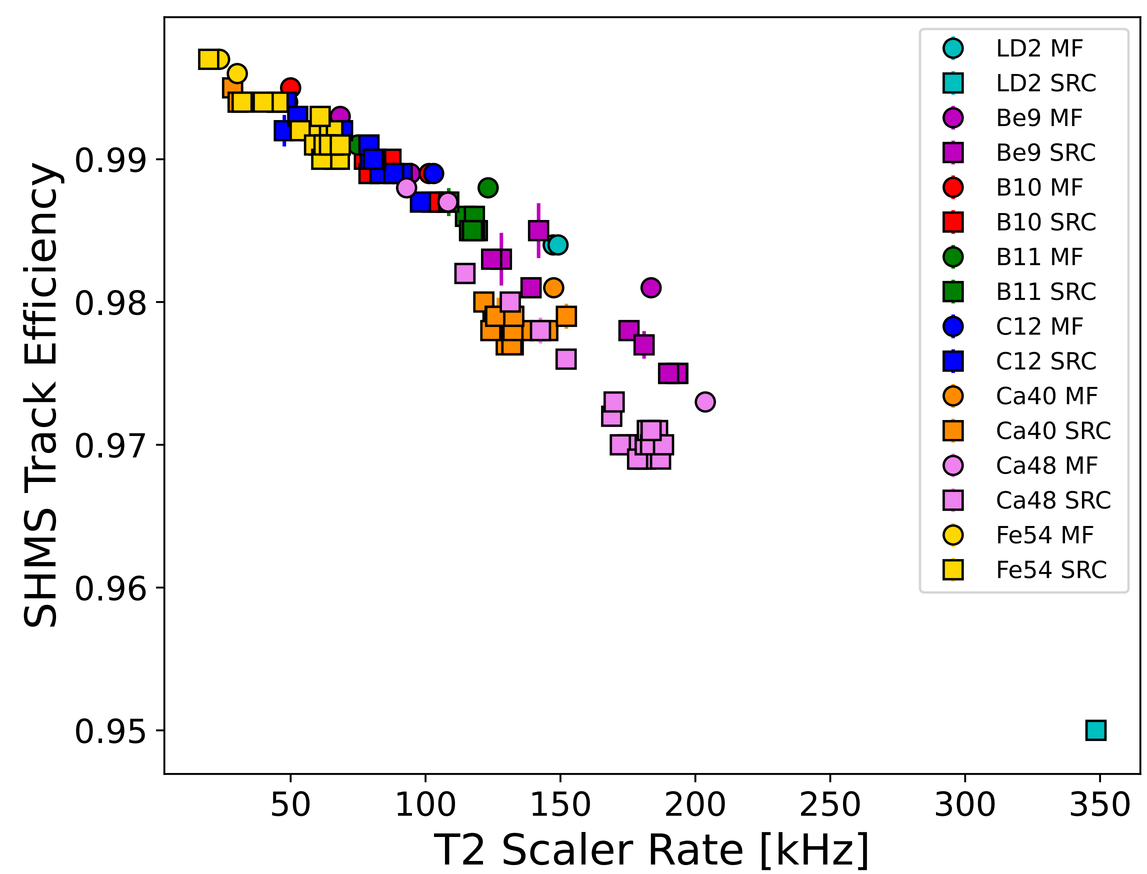
Efficiencies

Tracking Efficiencies

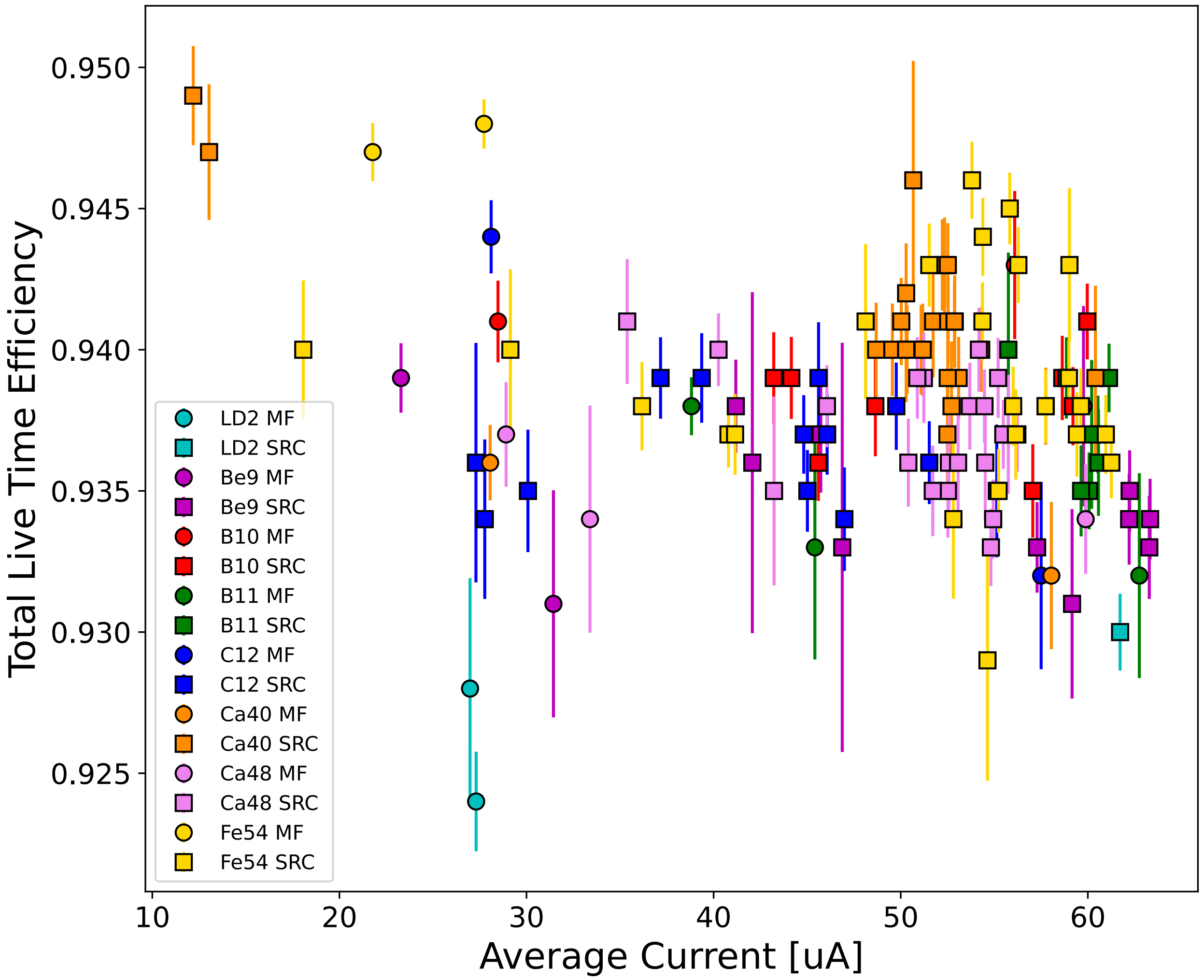




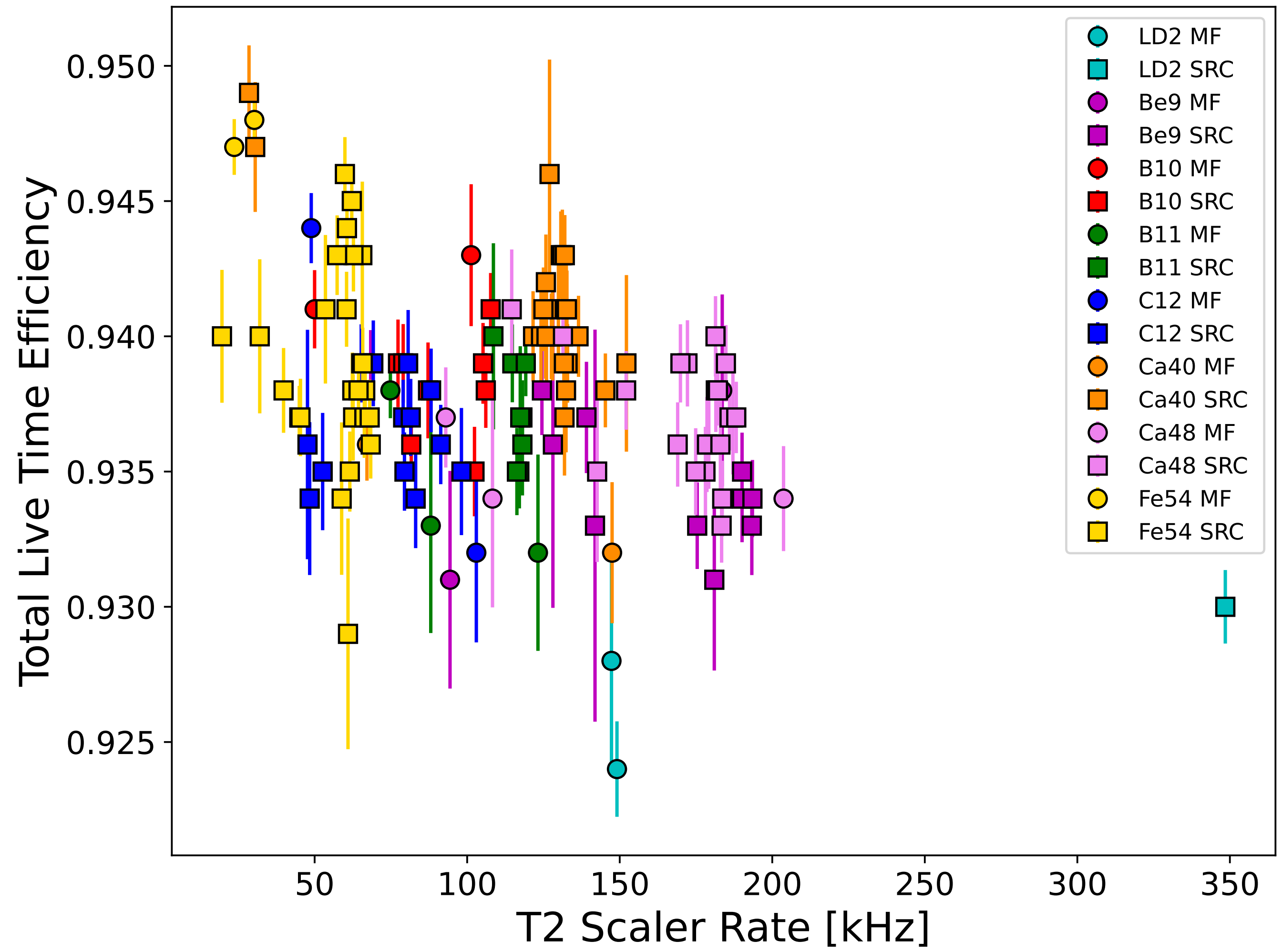




Live Time



Total Live Time Efficiency
0.950
0.945
0.940
0.935
0.930
0.925
10
20
30
40
50
60
Average Current [uA]
LD2 MF
LD2 SRC
Be9 MF
Be9 SRC
B10 MF
B10 SRC
B11 MF
B11 SRC
C12 MF
C12 SRC
Ca40 MF
Ca40 SRC
Ca48 MF
Ca48 SRC
Fe54 MF
Fe54 SRC



Total Live Time Efficiency
0.950
0.945
0.940
0.935
0.930
0.925
50
100
150
200
250
300
350
T2 Scaler Rate [kHz]
LD2 MF
LD2 SRC
Be9 MF
Be9 SRC
B10 MF
B10 SRC
B11 MF
B11 SRC
C12 MF
C12 SRC
Ca40 MF
Ca40 SRC
Ca48 MF
Ca48 SRC
Fe54 MF
Fe54 SRC

C. Colle et al. Phys.Rev.C 92, 024604 (2015)