ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

Updates on The CaFe Experiment

National Science Foundation

C. Yero
(On behalf of the CaFe collaboration)

Workshop:
SHORT-DISTANCE NUCLEAR STRUCTURE AND PDFS

July 17, 2023

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

Jefferson Lab
Exploring the Nature of Matter

OLD DOMINION UNIVERSITY

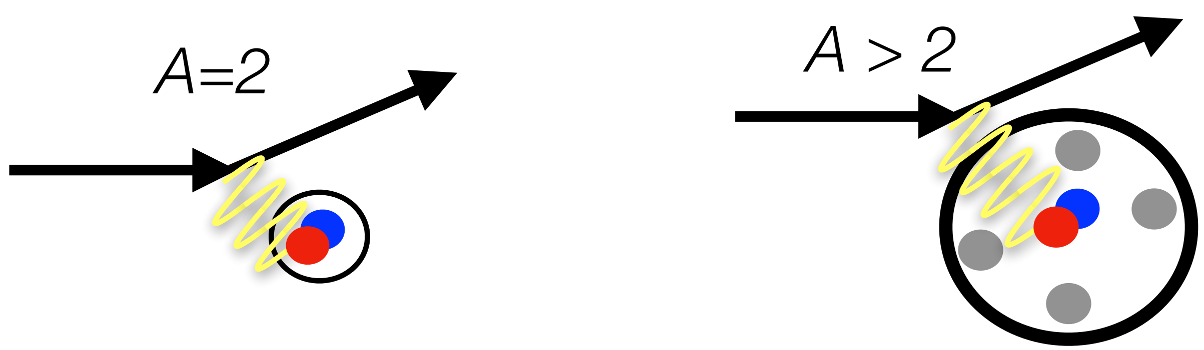
What have we learned about SRCs?

- (e,e’): scaling

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

- (e,e’p): np-dominance

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



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)

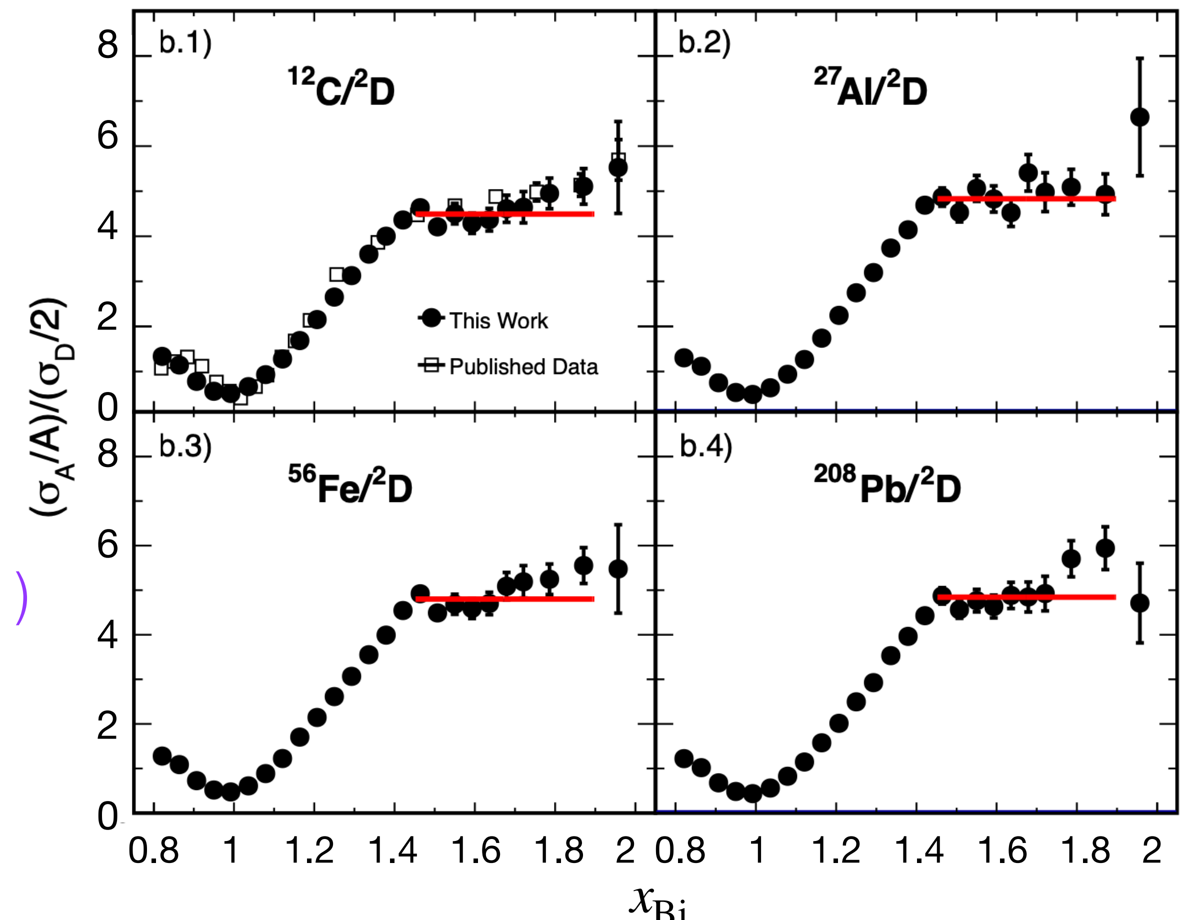
E. Piasetzky, M. Sargsian, L. Frankfurt, M. Strikman, and J. W. Watson Phys. Rev. Lett. 97, 162504 (2006)

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

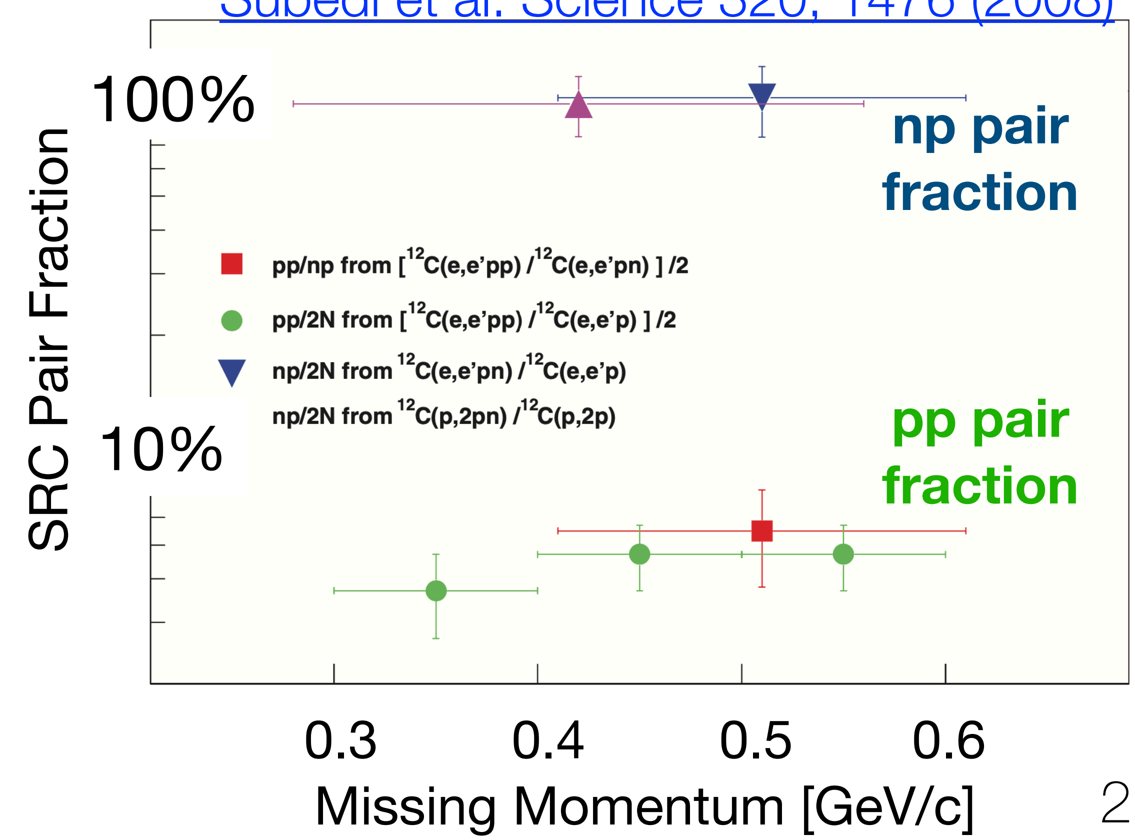
N. Fomin et al. Phys.Rev.Lett.108, 092502 (2012)

Ryckebusch et al.PLB79221 (2019)

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



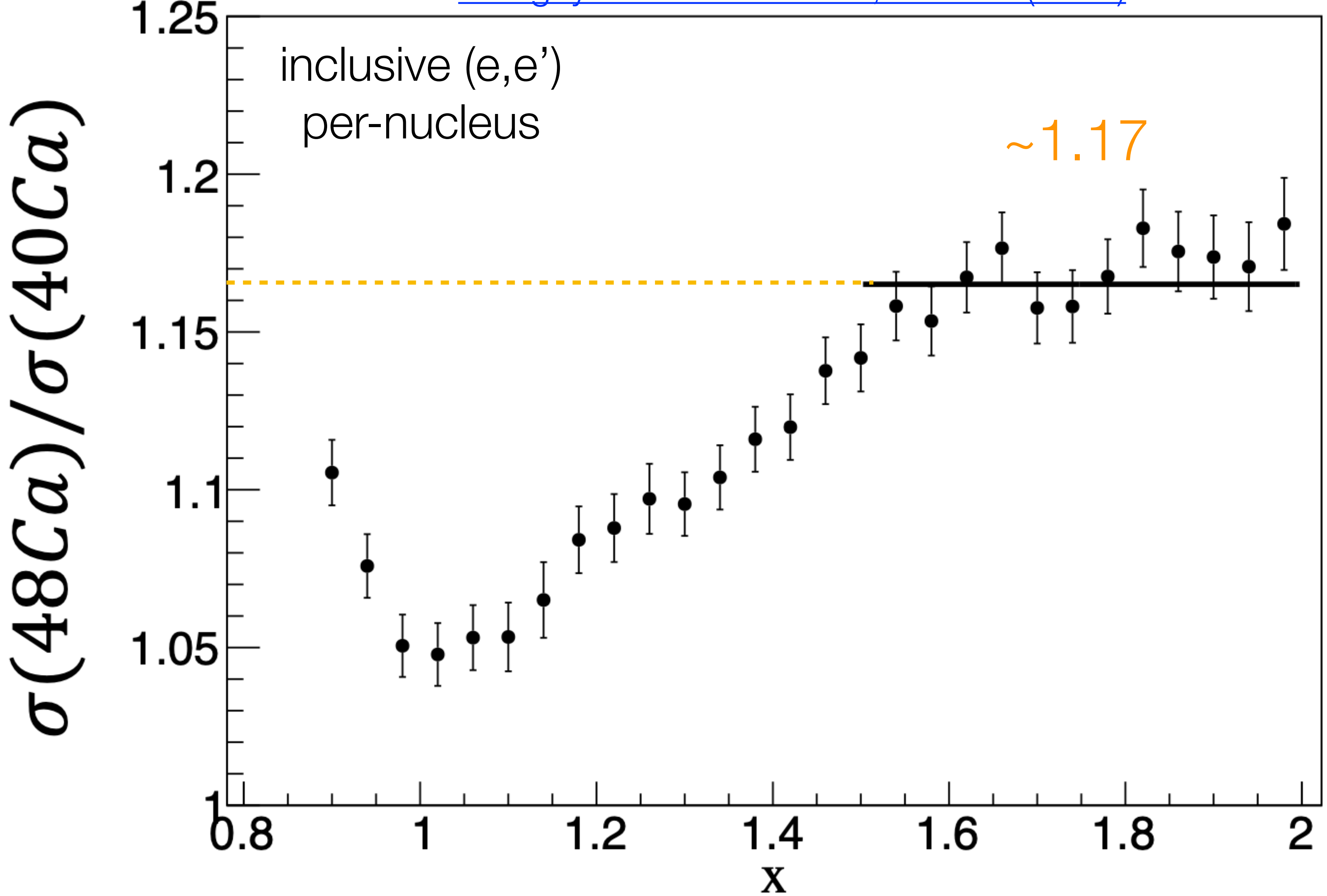
Subedi et al. Science 320, 1476 (2008)



Motivation

- (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

Motivation

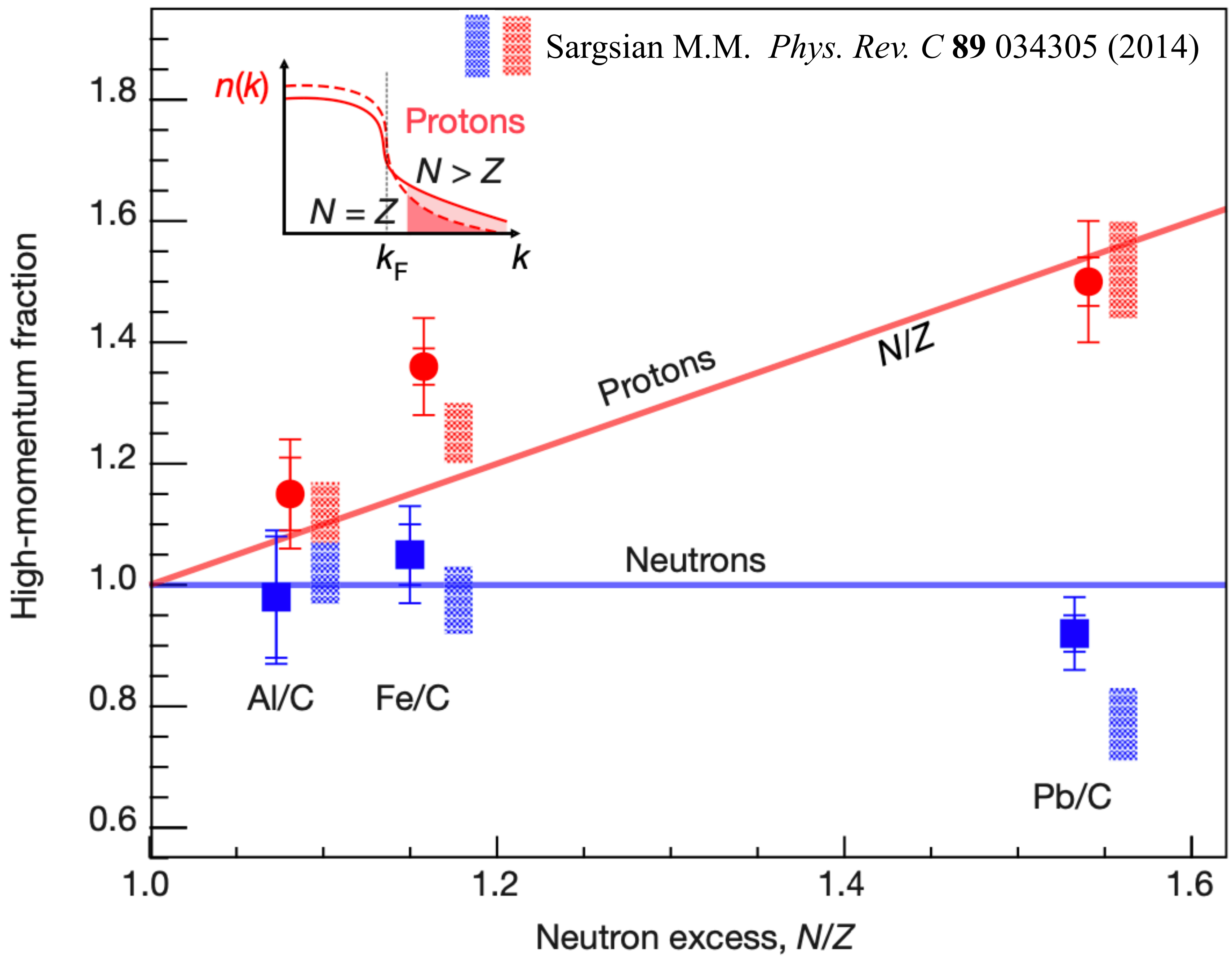
- (e,e'N):

SRC pairs:

- account for almost all high-p (>250 MeV/c) nucleons in nuclei
- are predominantly *np*, even in neutron-rich nuclei

Target	Z (protons)	N (neutrons)
C12	6	6
Al27	13	14
Fe56	26	30
Pb208	82	126

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



Motivation

- (e,e'p):

CaFe will answer:

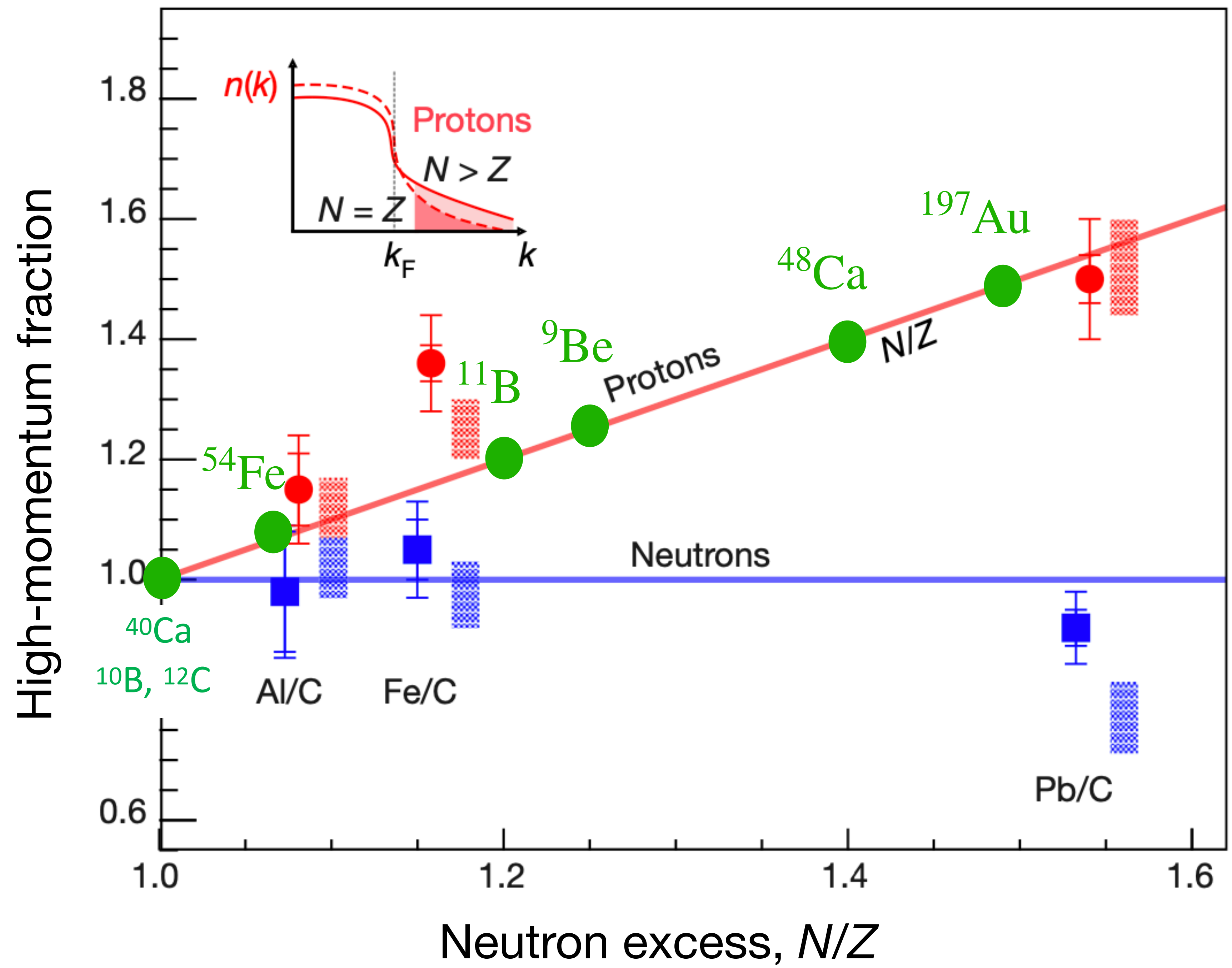
- Which nucleons form pairs?
- How does adding neutrons speed up protons?
- How does NN-SRC pairing change with A and N/Z?

Target	Z (protons)	N (neutrons)
Be9	**4**	**5**
B10	**5**	**5**
B11	**5**	**6**
C12	**6**	**6**
Al27	13	14
Ca40	**20**	**20**
Ca48	**20**	**28**
Fe54	**26**	**28**
Fe56	26	30
Au197	**79**	**118**
Pb208	82	126

← NEW data taken Spring 2023 !

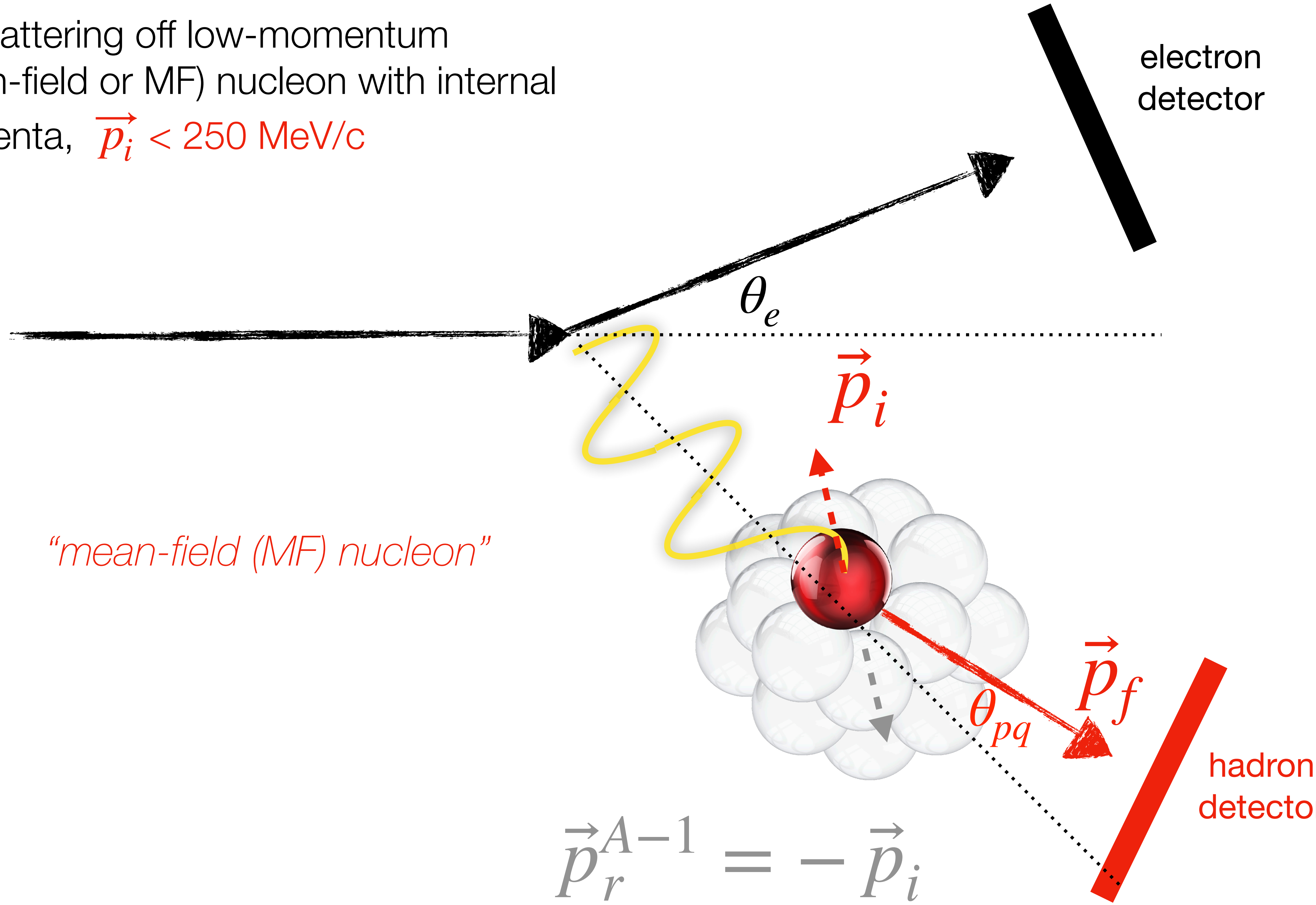
Projected CaFe Results

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



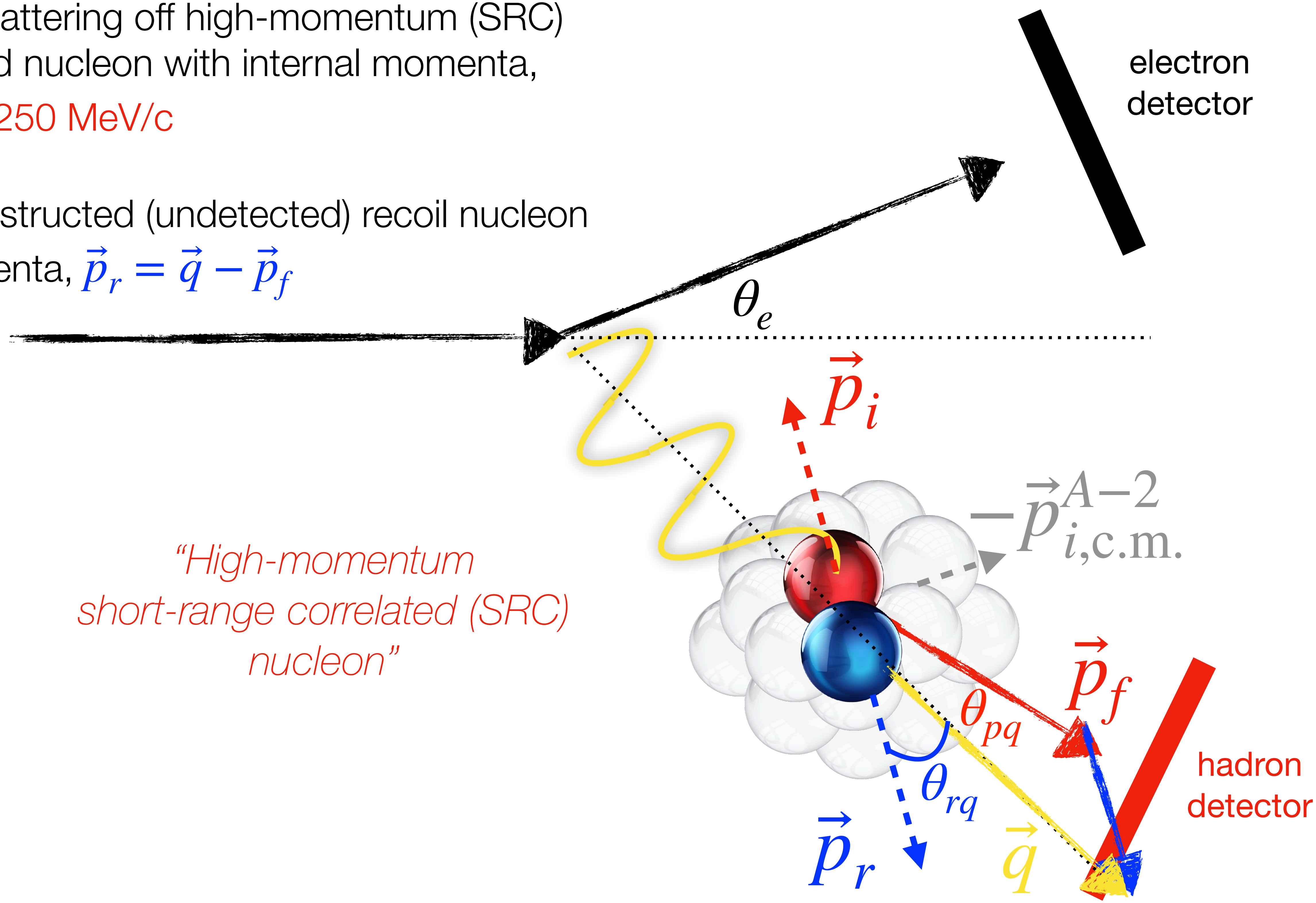
CaFe Experiment Setup

- e- scattering off low-momentum (mean-field or MF) nucleon with internal momenta, $\vec{p}_i$ < 250 MeV/c



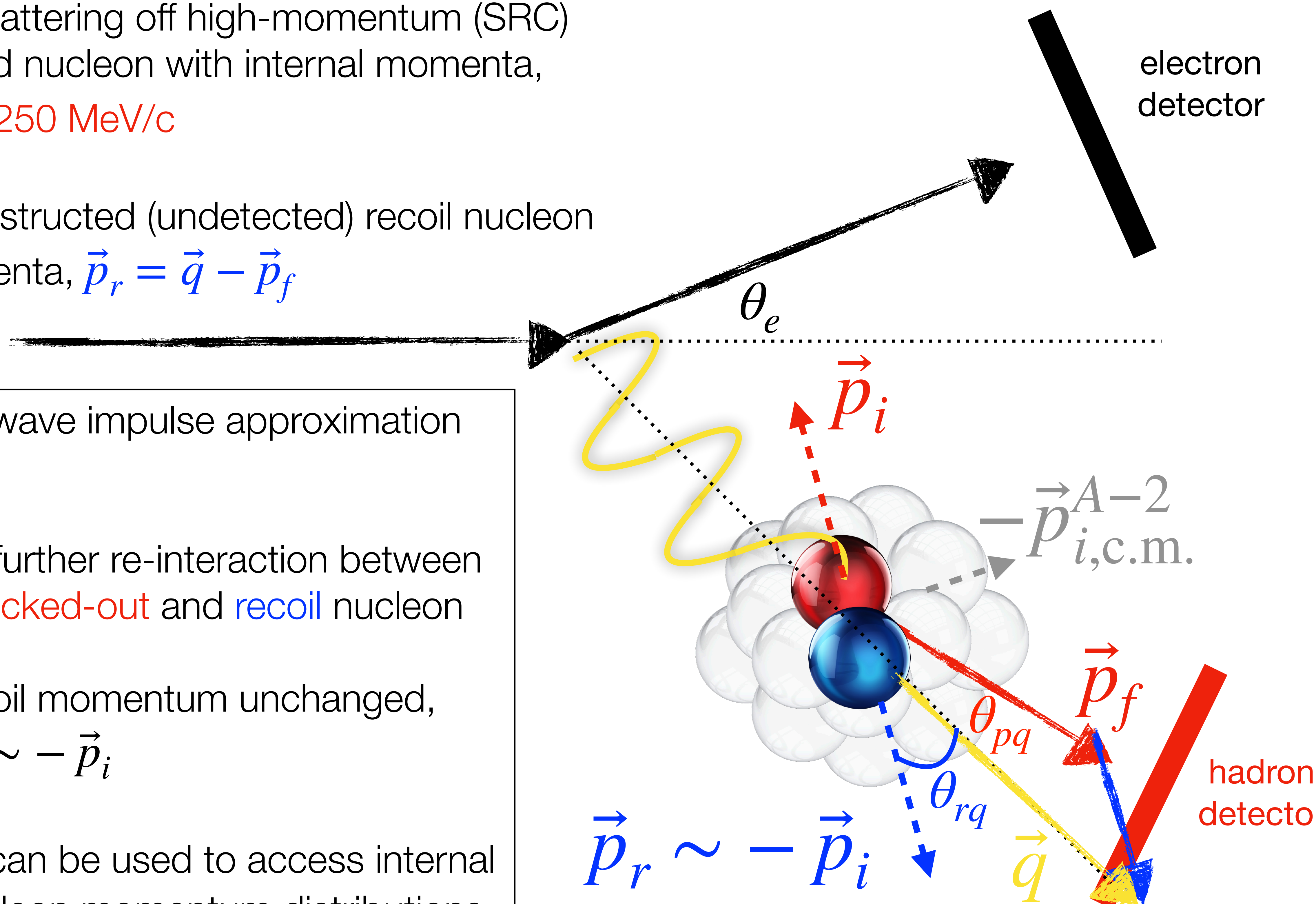
CaFe Experiment Setup

- e- scattering off high-momentum (SRC) bound nucleon with internal momenta, $\vec{p_i} > 250$ MeV/c
- reconstructed (undetected) recoil nucleon momenta, $\vec{p}_r = \vec{q} - \vec{p}_f$



CaFe Experiment Setup

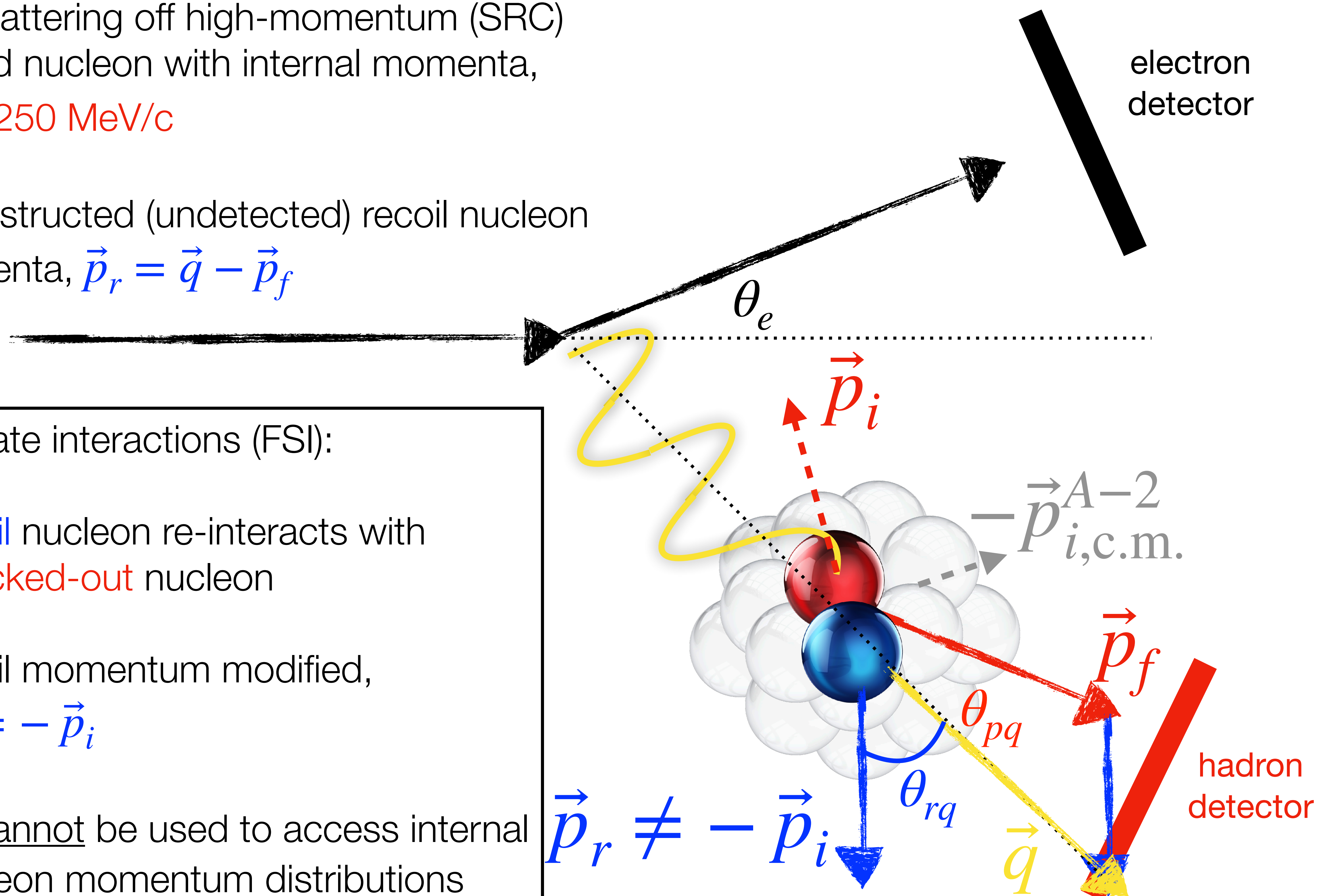
- e- scattering off high-momentum (SRC) bound nucleon with internal momenta, $\vec{p_i}$ > 250 MeV/c
- reconstructed (undetected) recoil nucleon momenta, $\vec{p}_r = \vec{q} - \vec{p}_f$



- plane-wave impulse approximation (PWIA)
  - no further re-interaction between knocked-out and recoil nucleon
  - recoil momentum unchanged, $\vec{p}_r \sim -\vec{p}_i$
  - $\vec{p}_r$ can be used to access internal nucleon momentum distributions

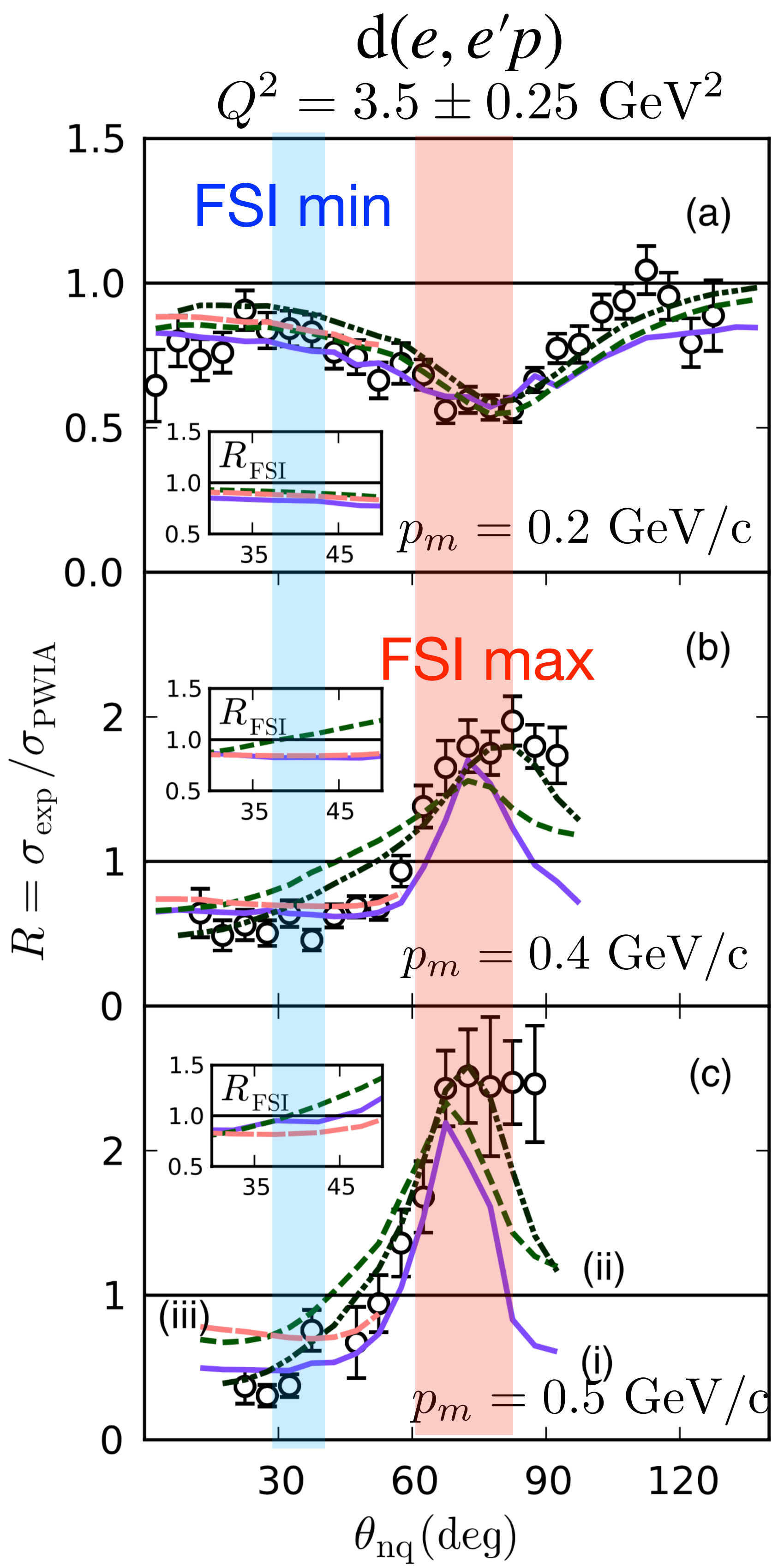
CaFe Experiment Setup

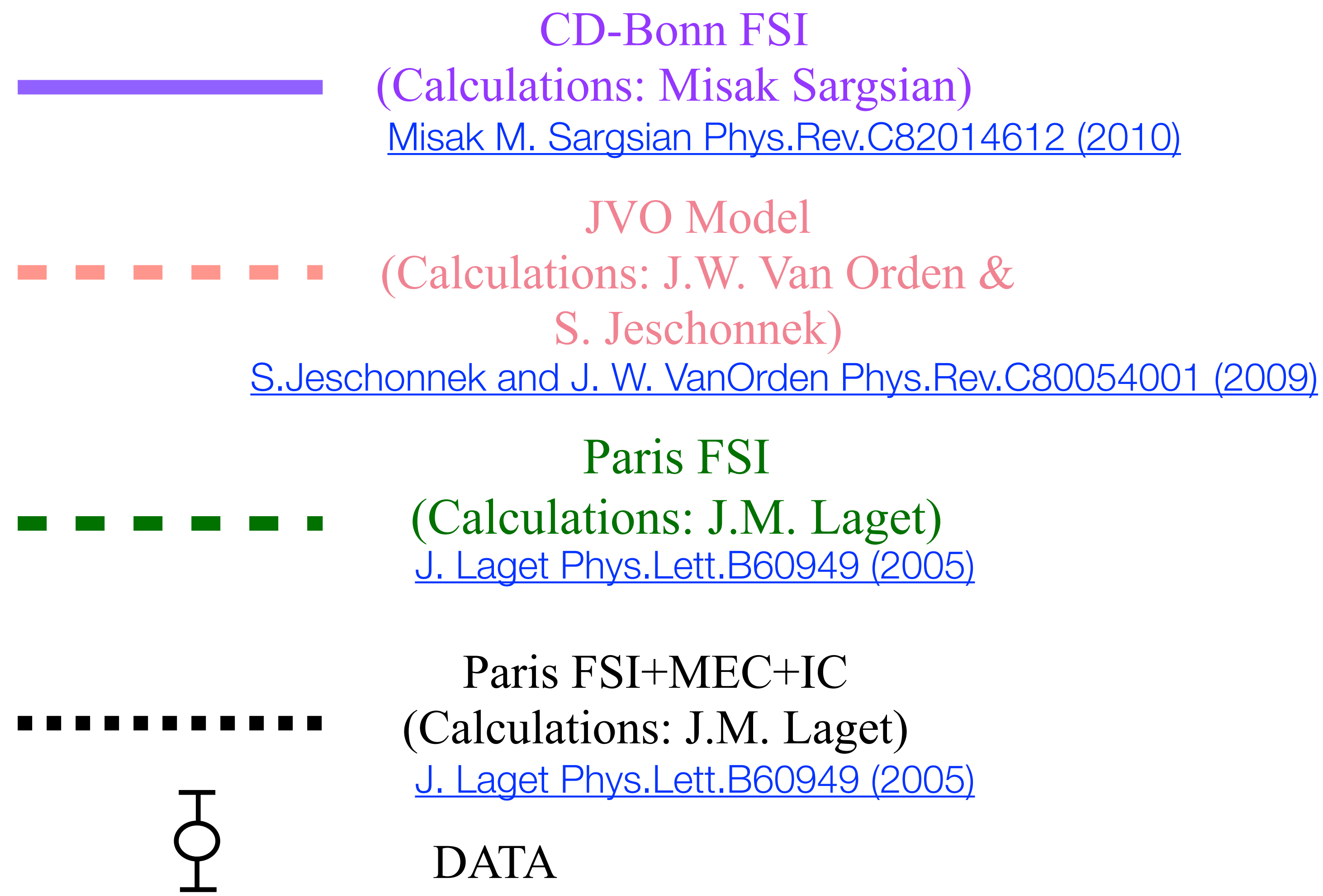
- e- scattering off high-momentum (SRC) bound nucleon with internal momenta, $\vec{p}_i$ > 250 MeV/c
- reconstructed (undetected) recoil nucleon momenta, $\vec{p}_r = \vec{q} - \vec{p}_f$



- Final-state interactions (FSI):
  - recoil nucleon re-interacts with knocked-out nucleon
  - recoil momentum modified, $\vec{p}_r \neq -\vec{p}_i$
  - $\vec{p}_r$ cannot be used to access internal nucleon momentum distributions

controlling final-state interactions (FSI)





FSI strongly anisotropic (angular-dependent):

- Sargsian uses GEA, Laget uses fully relativistic
- FSI peak at $\theta_{nq} \sim 70°$
- minimal FSI at $\theta_{nq} \sim 35 - 45°$ (CAFE uses $\theta_{nq} < 40°$)

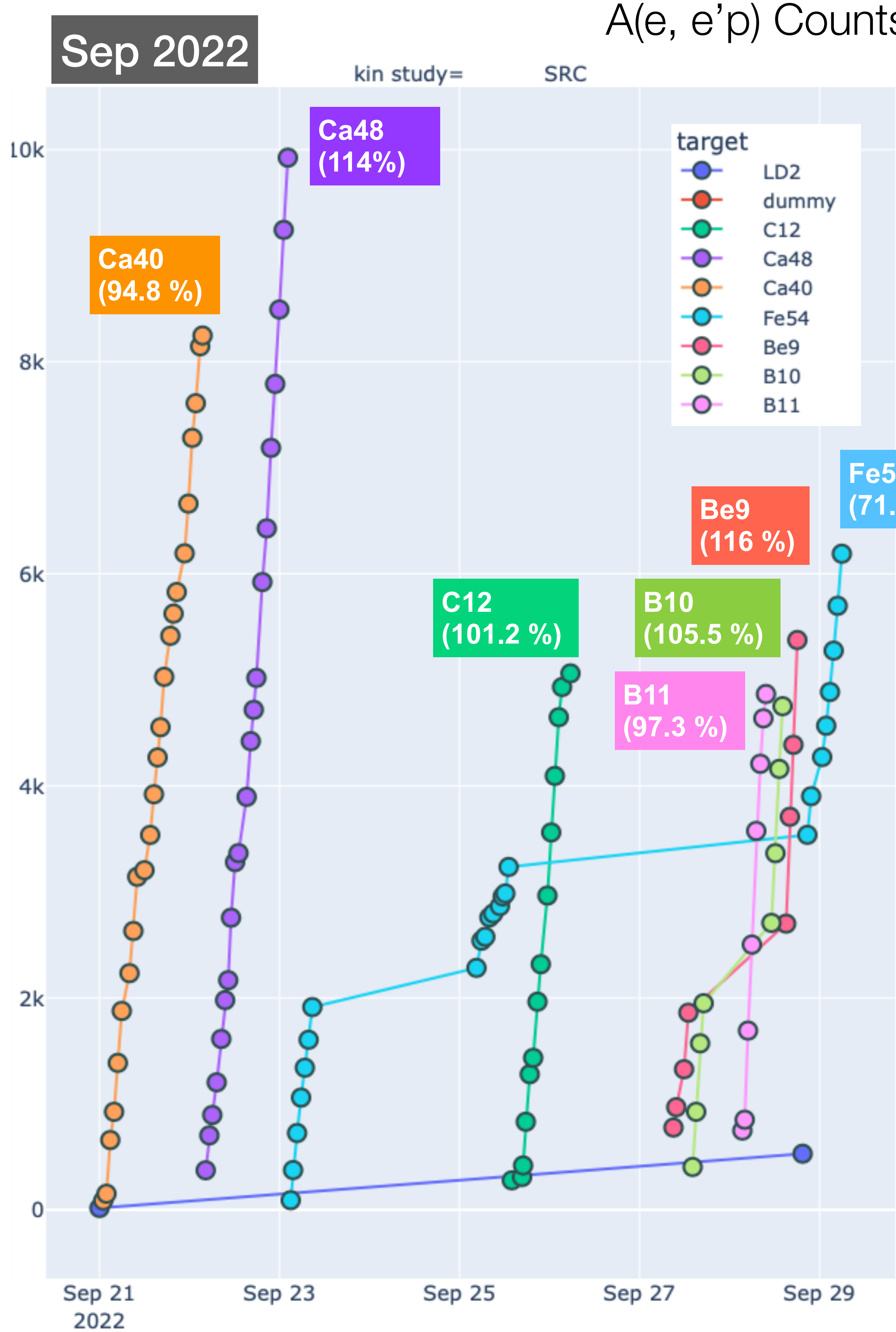
GEA theory:

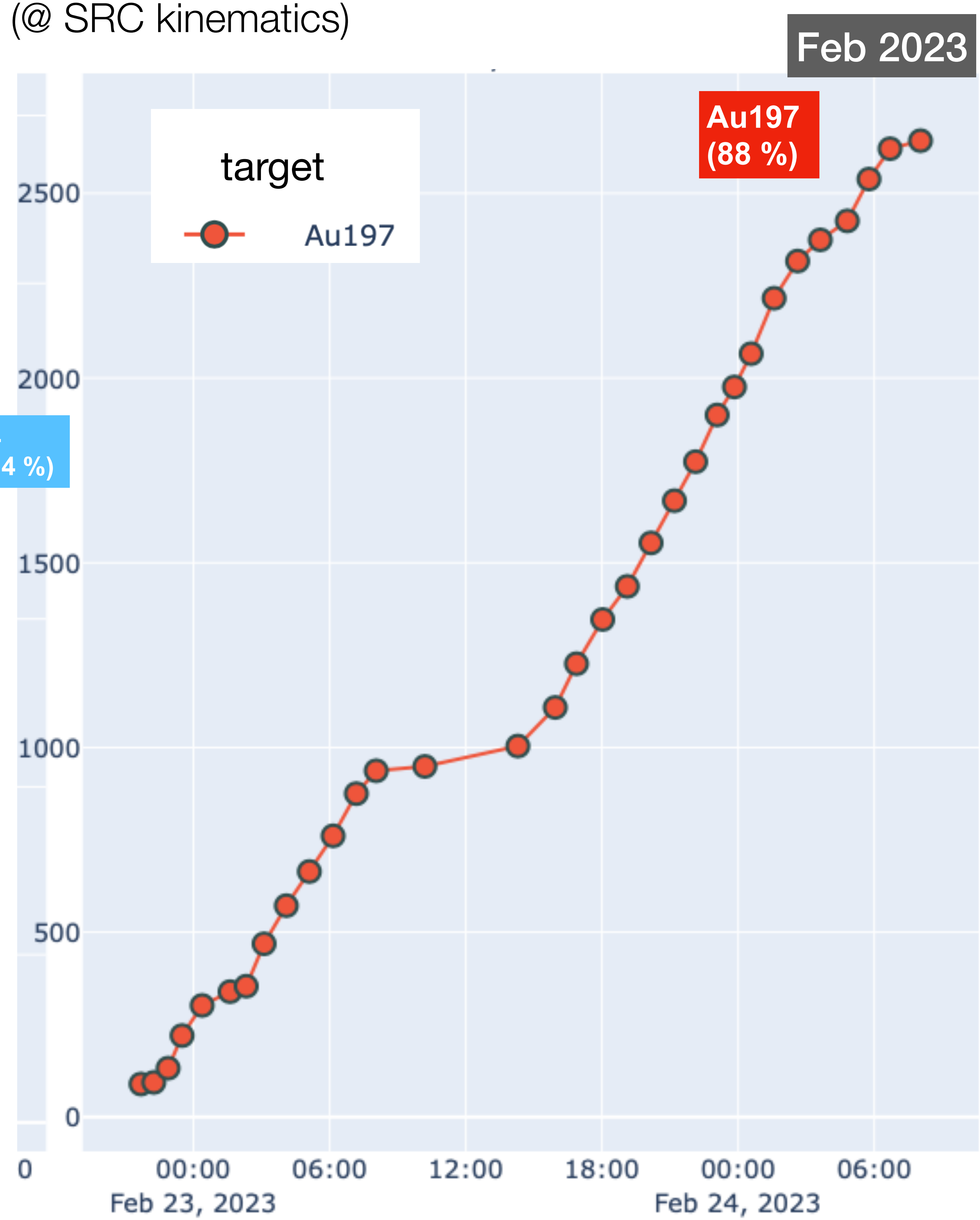
L. L. Frankfurt, M. M. Sargsian, and M. I. Strikman Phys.Rev.C561124 (1997)

Boeglin et al. (Hall A) Phys.Rev.Lett. 107, 262501 (2011)
K. S. Egiyan et al. (CLAS) Phys. Rev. Lett. 98, 262502 (2007)

CaFe (online) statistics collected

A(e, e'p) Counts (@ SRC kinematics)

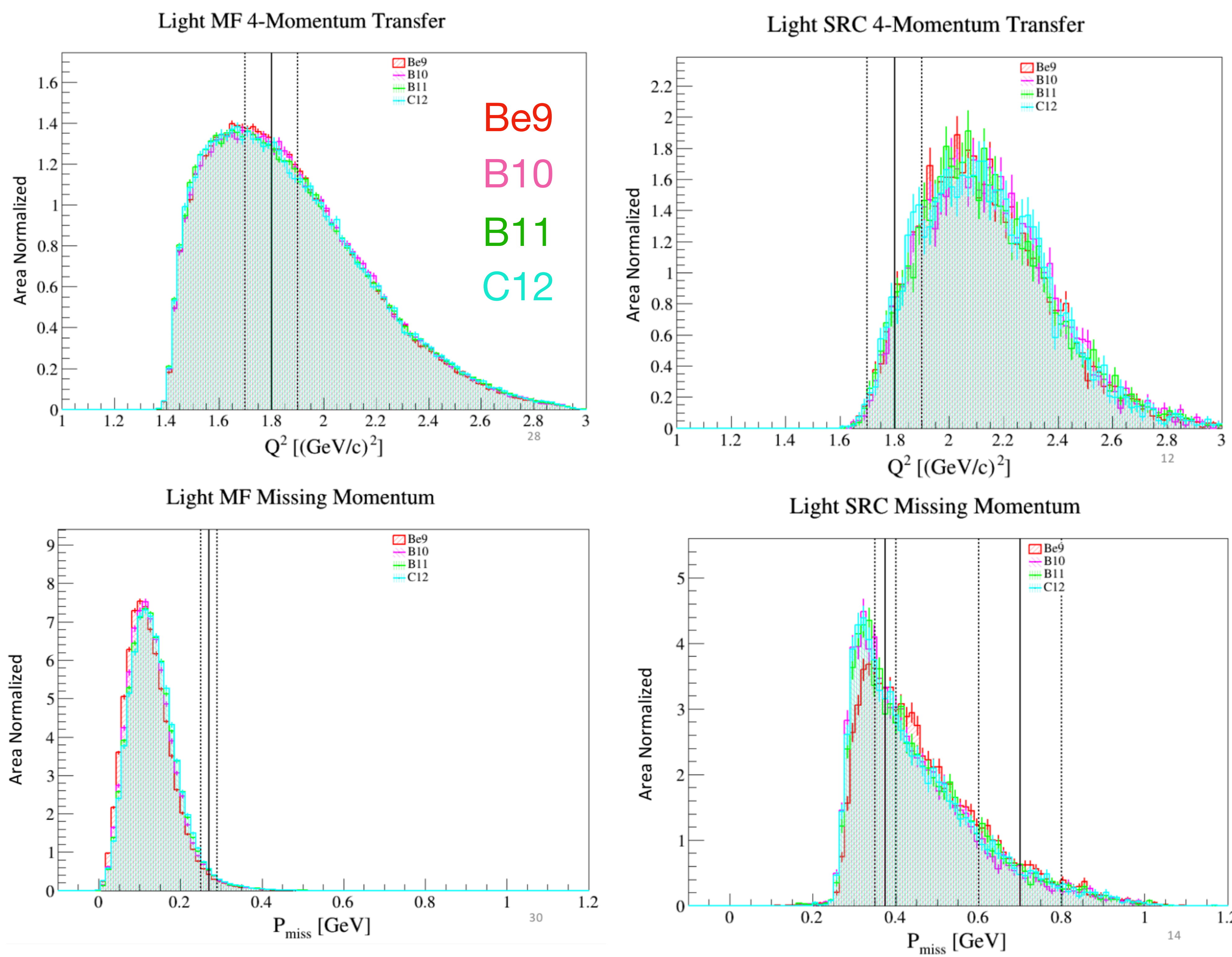




CaFe Analysis Status

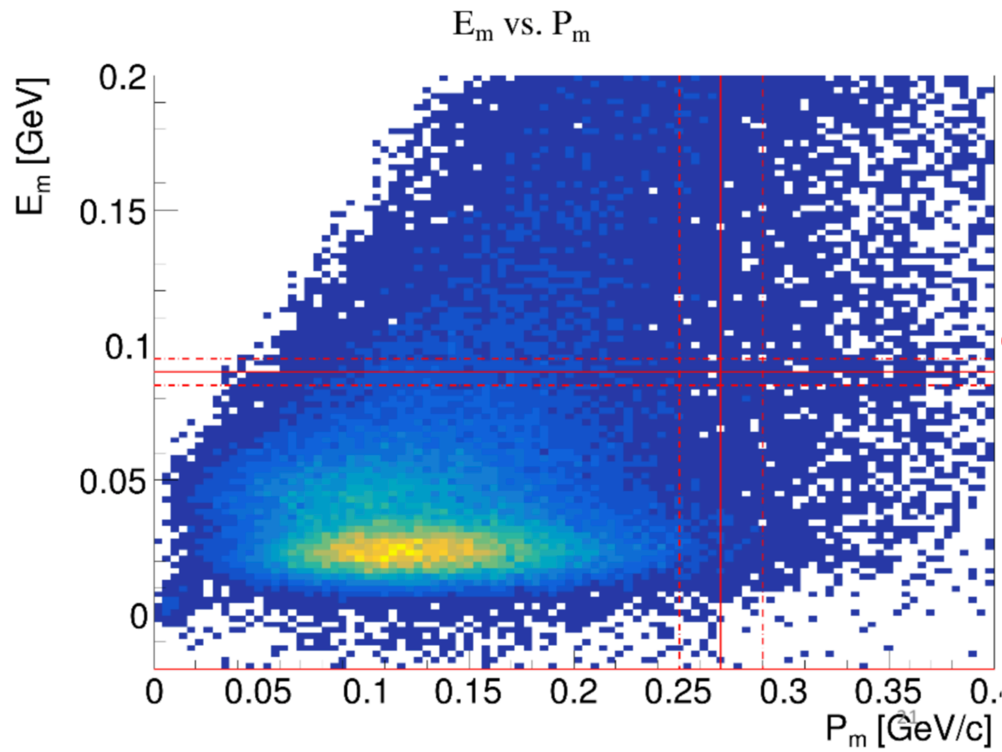
Study	Status	Leading Effort
BCM calibration	COMPLETE	C. Yero
ref. times / time windows / detector calibrations	COMPLETE	C. Yero / N. Swan
SHMS optics	COMPLETE	H. Szumila-Vance
proton absorption	IN-PROGRESS	N. Swan
cuts sensitivity studies (analysis cuts systematics)	IN-PROGRESS	C. Yero
data-to-simulations h(e,e’p), c(e,e’p) checks	IN-PROGRESS	C. Yero / D. Nguyen / N. Swan
other sources of systematics (BCM, live time, efficiencies, kinematics, etc.)	PENDING	D. Nguyen
target boiling	PENDING	N. Swan / D. Nguyen

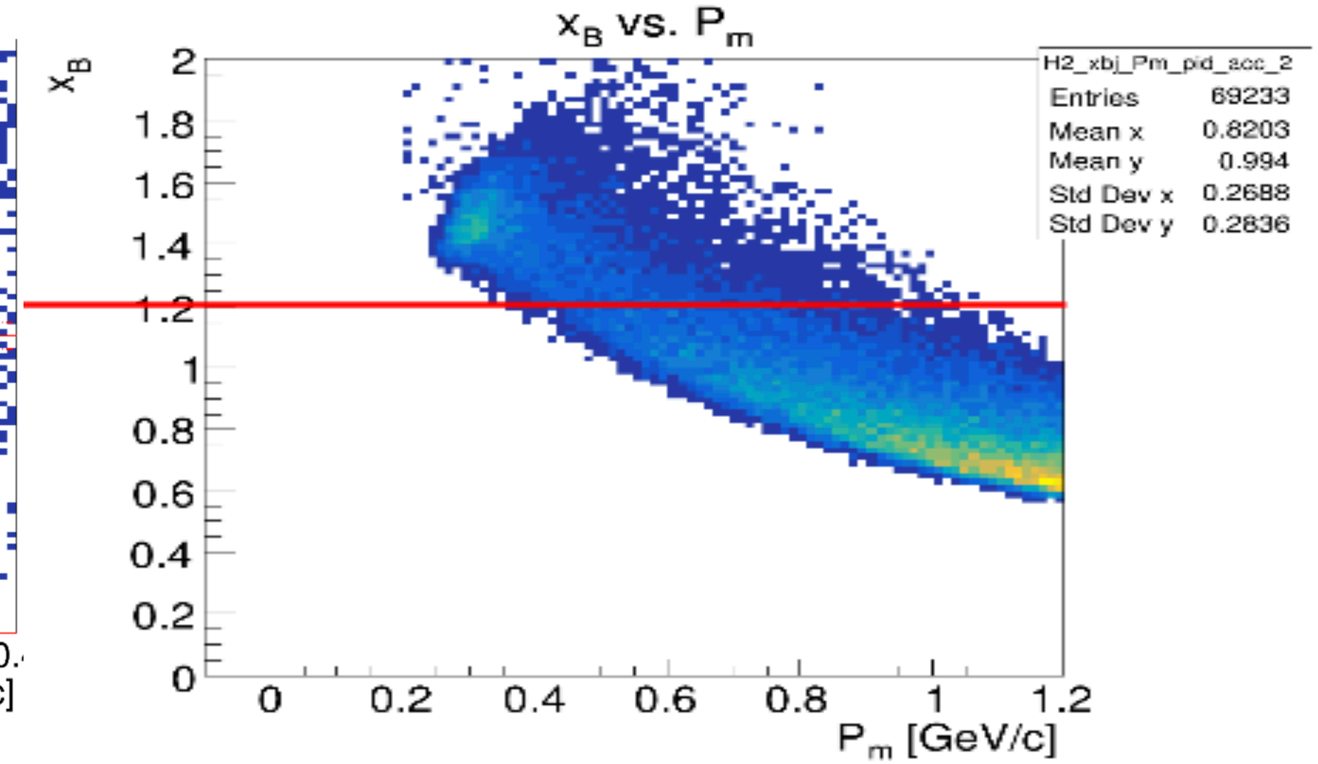
Data Quality Checks

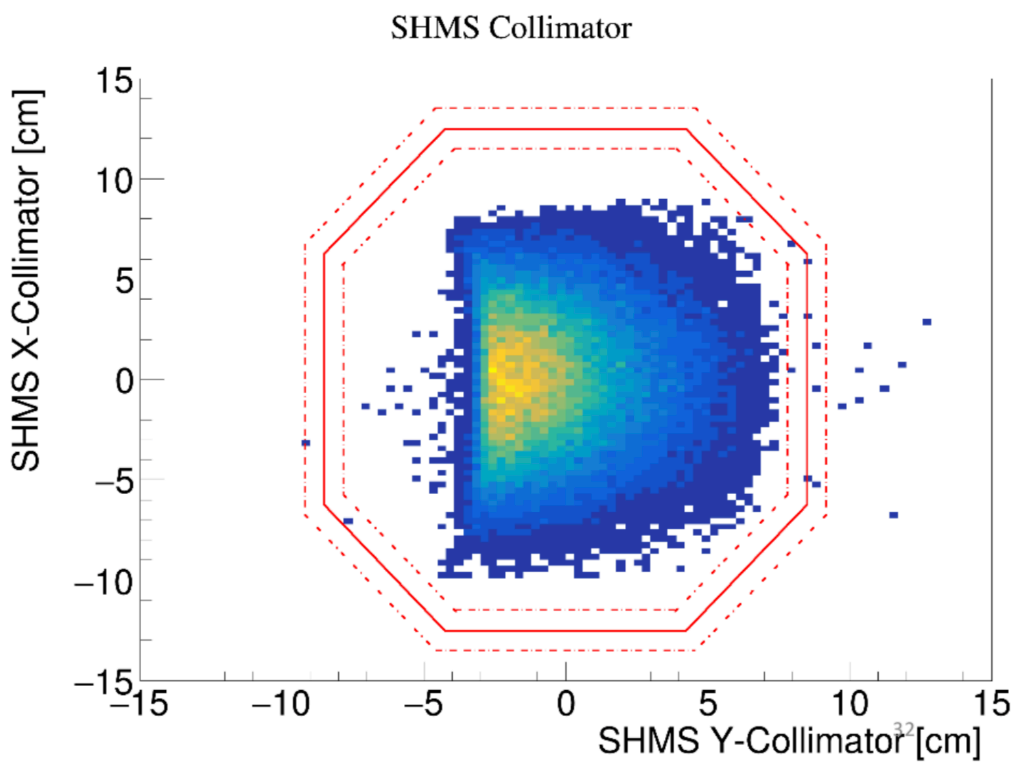


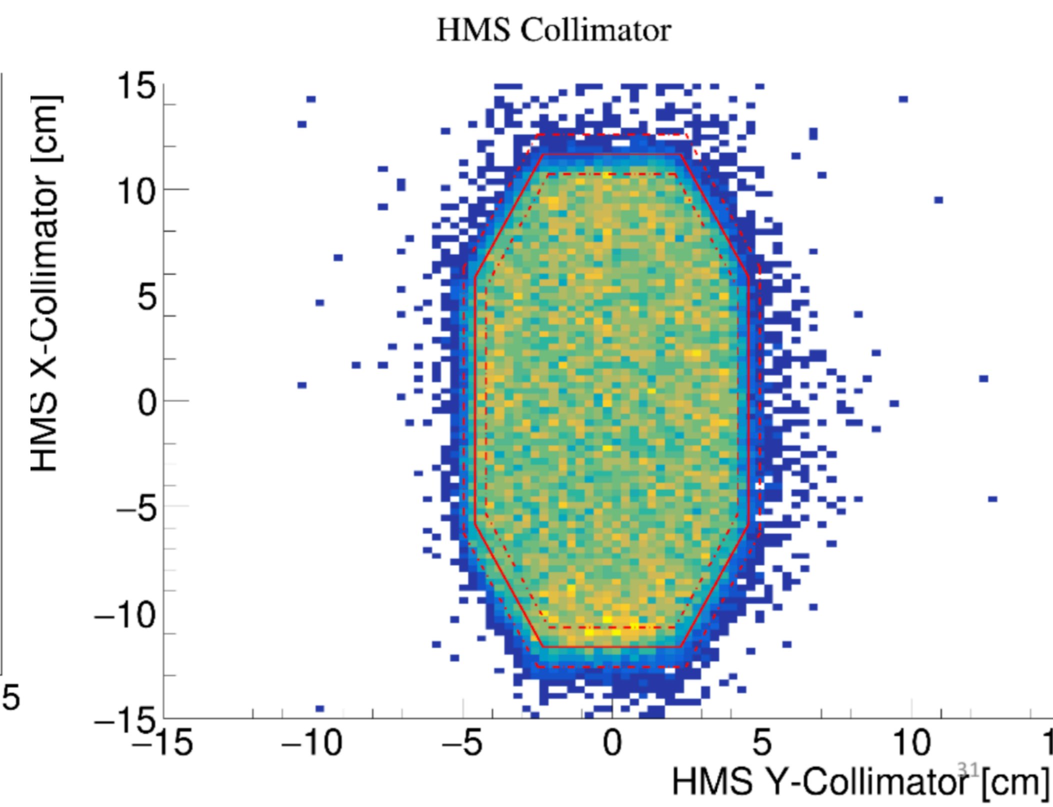
Data Quality Checks performed by Noah Swan (Hall C CaFe graduate student)

Data Quality Checks



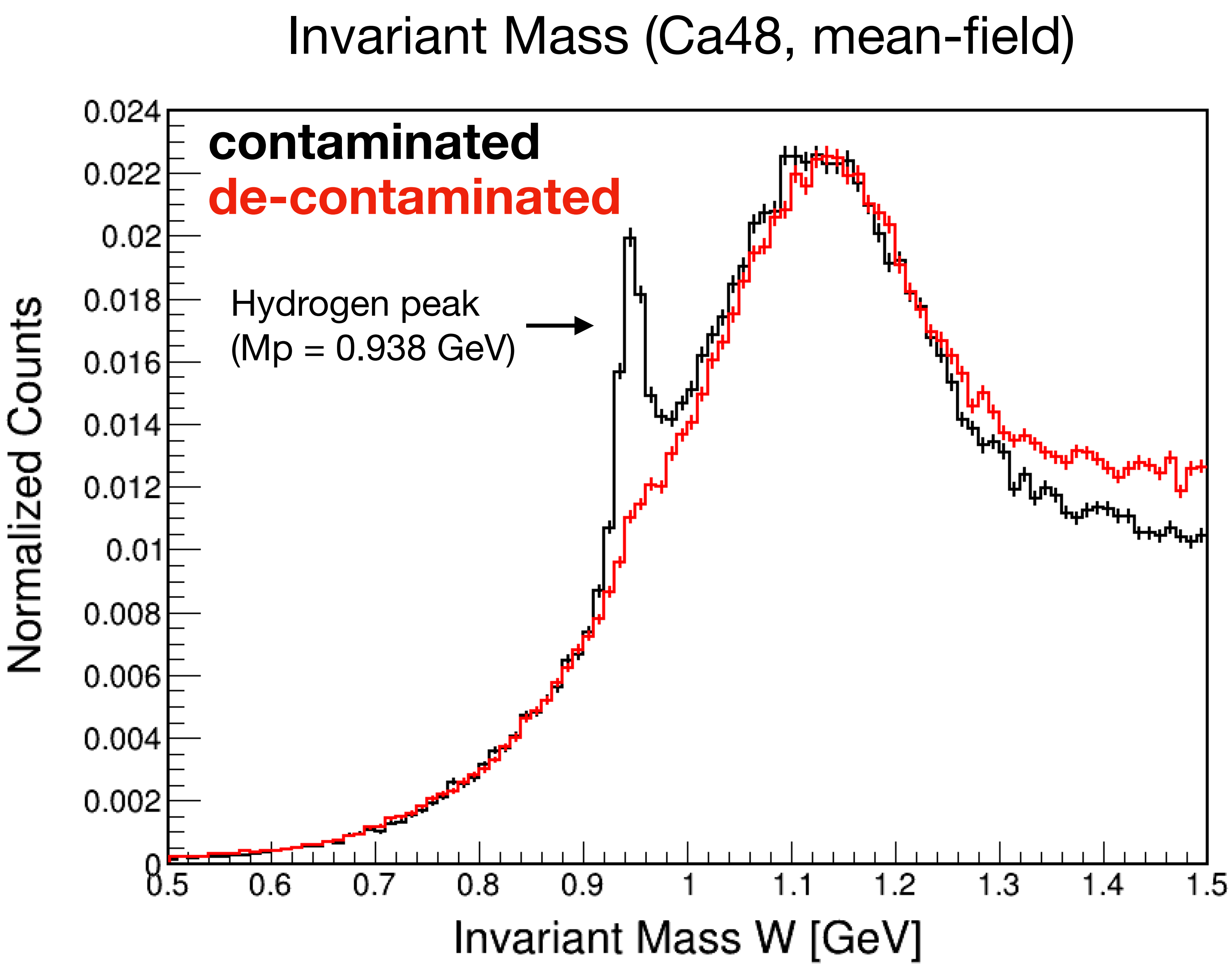






Data Quality Checks performed by Noah Swan (Hall C CaFe graduate student)

Data Analysis Challenges

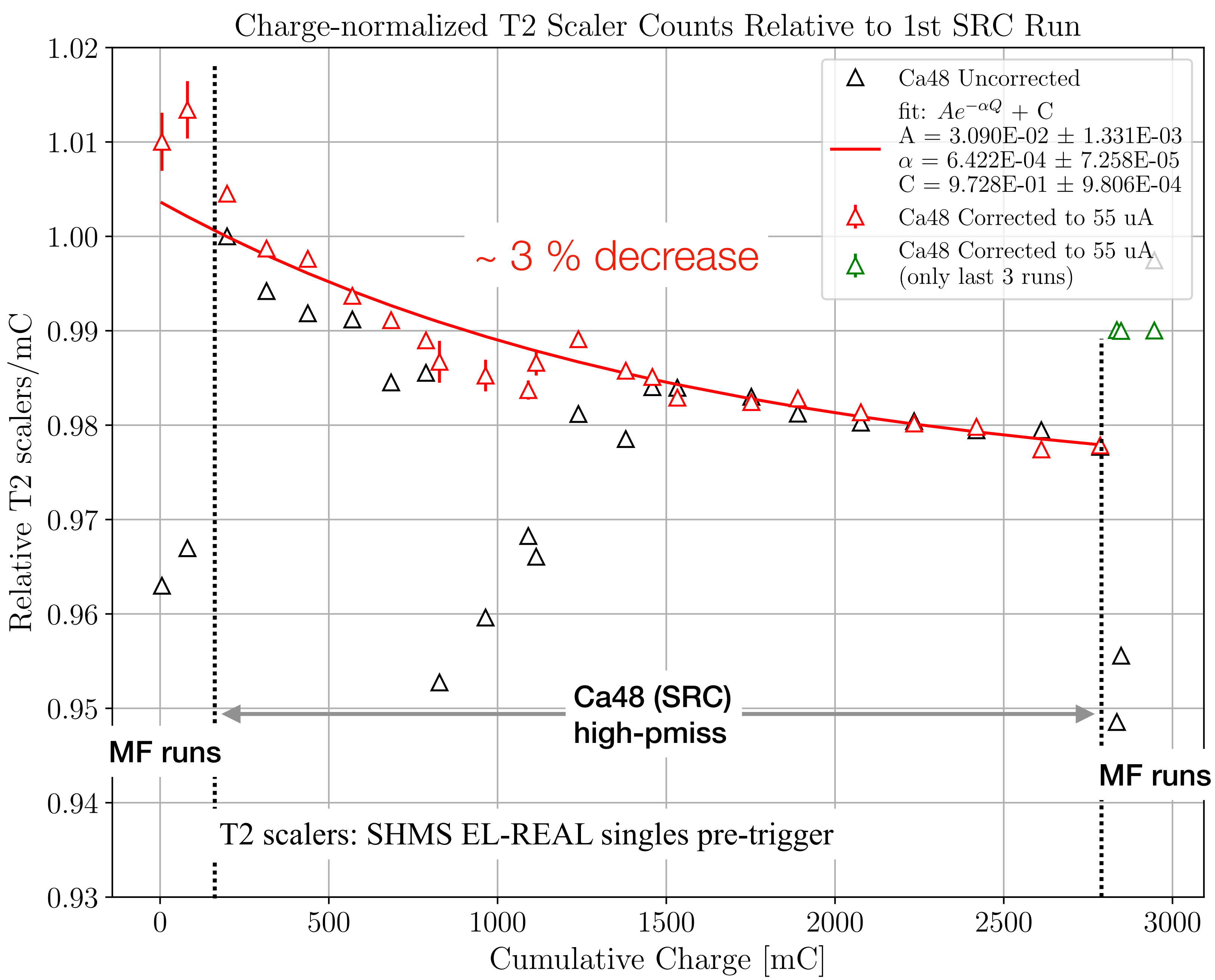


- Ca48 oil contamination
- rate-dependence
- double coin. time peak
- H(e, e’p) optics optimization
- data-to-simulation

Hypothesis:

- pure mineral oil (C + H) at surface of Ca-48 “washed off”on its own
- high beam current helped with decontamination process

Data Analysis Challenges



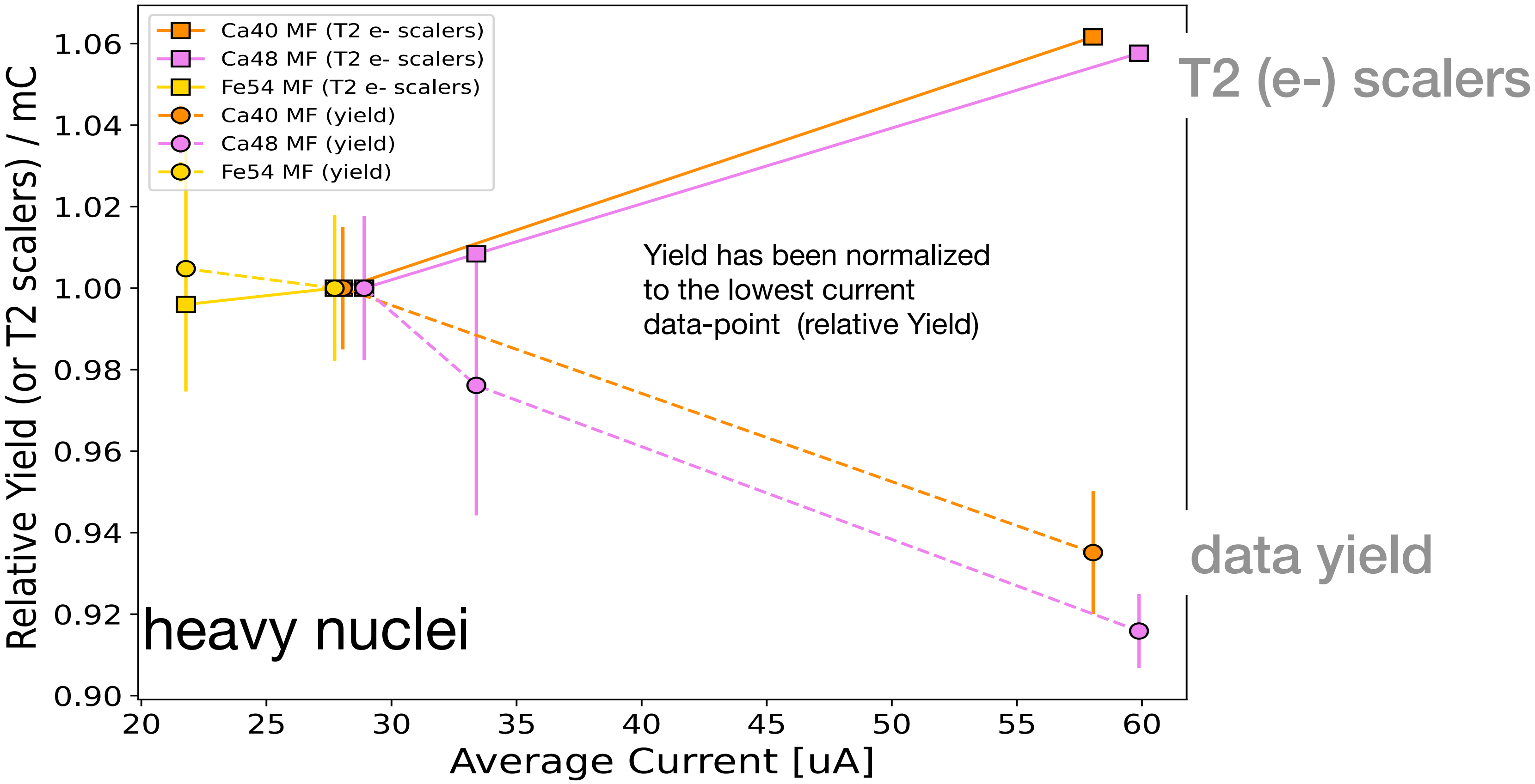
- Ca48 oil contamination
- rate-dependence
- double coin. time peak
- H(e, e'p) optics optimization
- data-to-simulation

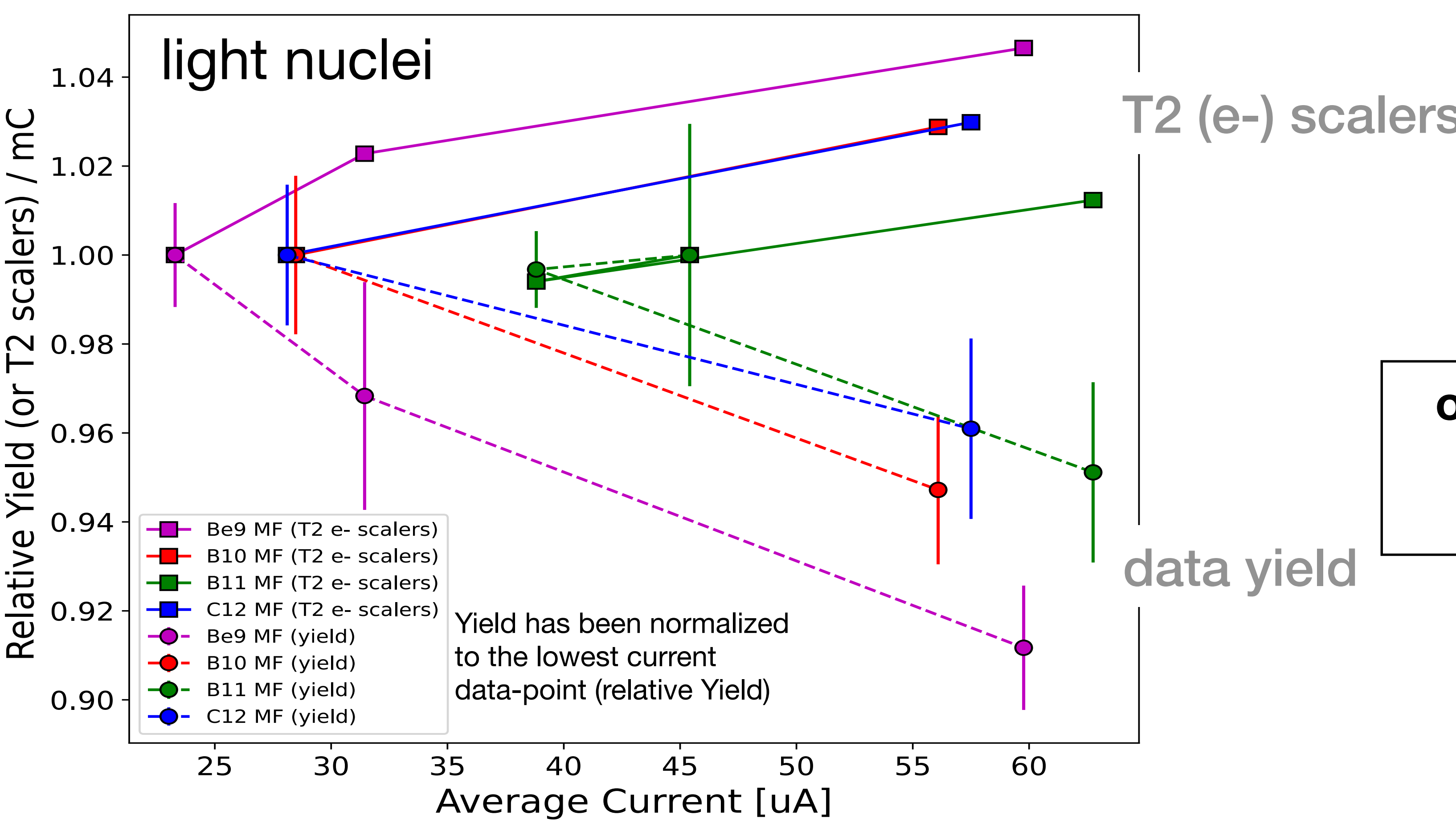
Measurements:

- ~3 % absolute drop (3.1 to 0.65 %) in H-scaled Carbon contamination @ MF kin
- ~3 % relative drop in charge-normalized T2 (e- singles) scalers @ SRC kin

independent measurements of absolute and relative contamination consistent !

Data Analysis Challenges





- Ca48 oil contamination
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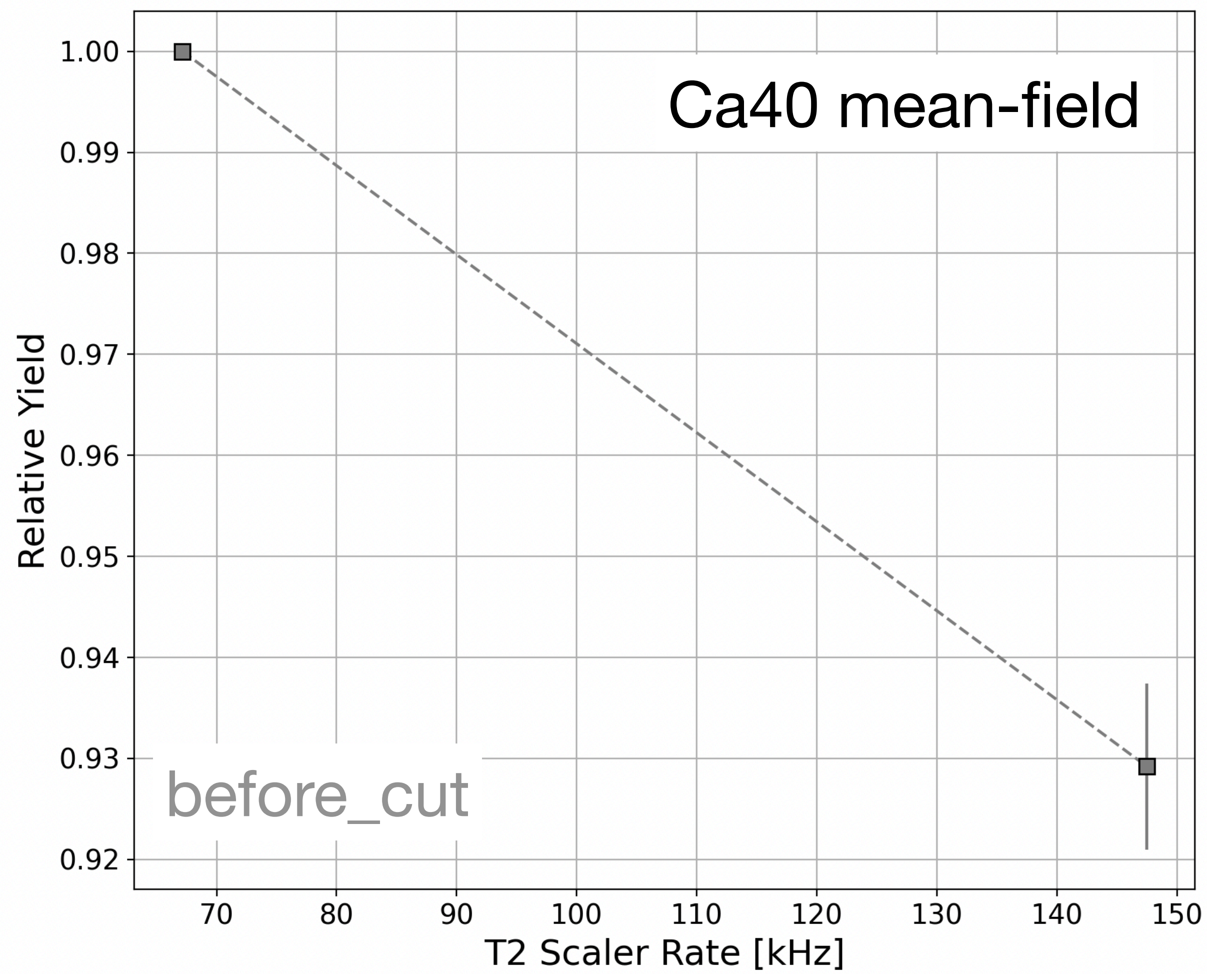
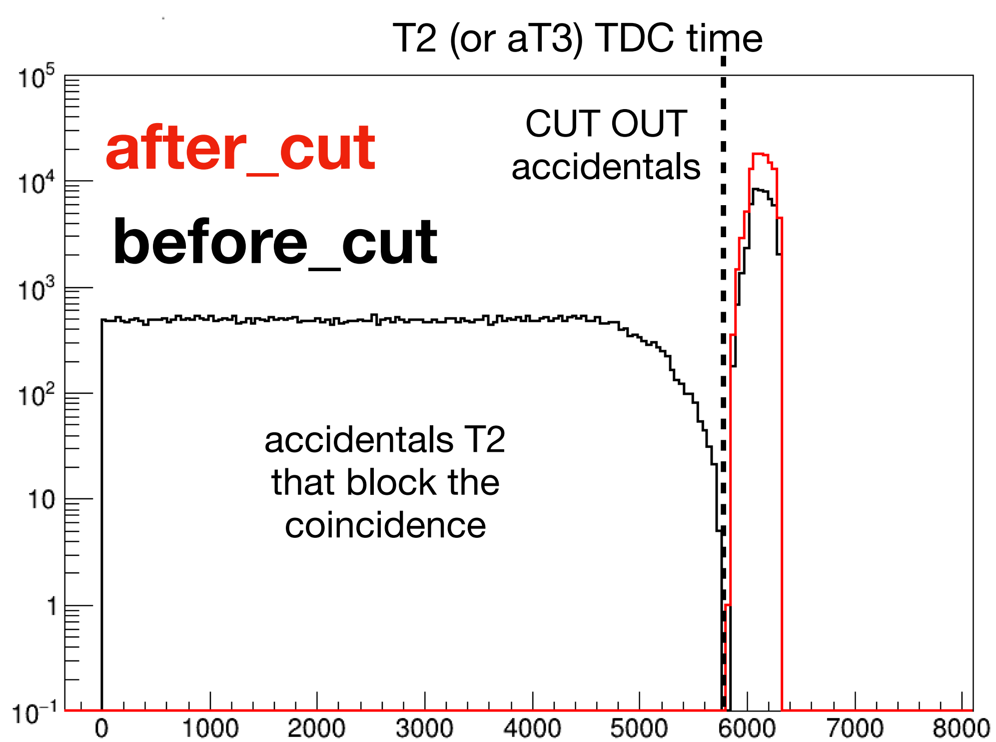
observation: charge-normalized data yield depends on trigger rate (current) for all nuclei measured

Data Analysis Challenges

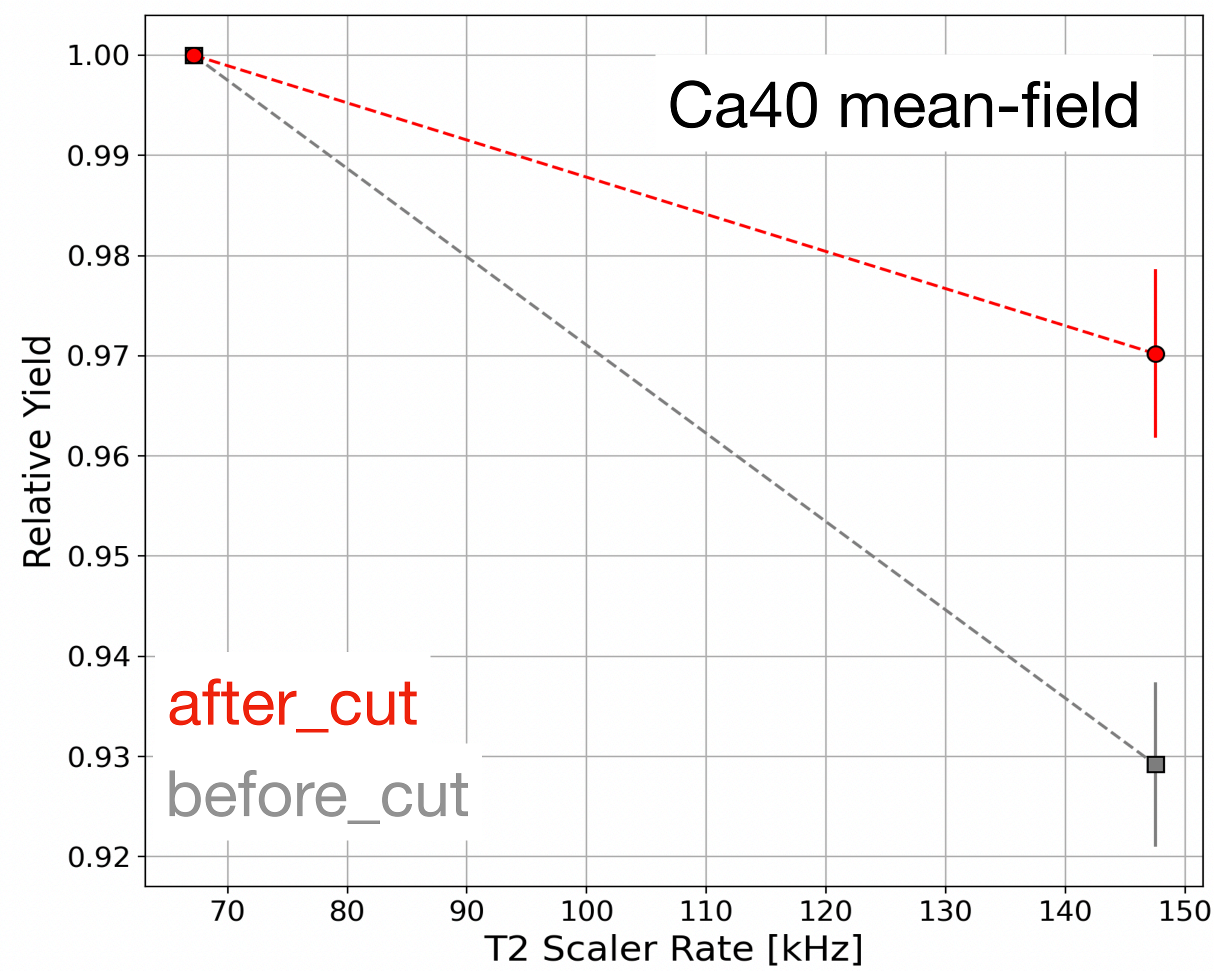




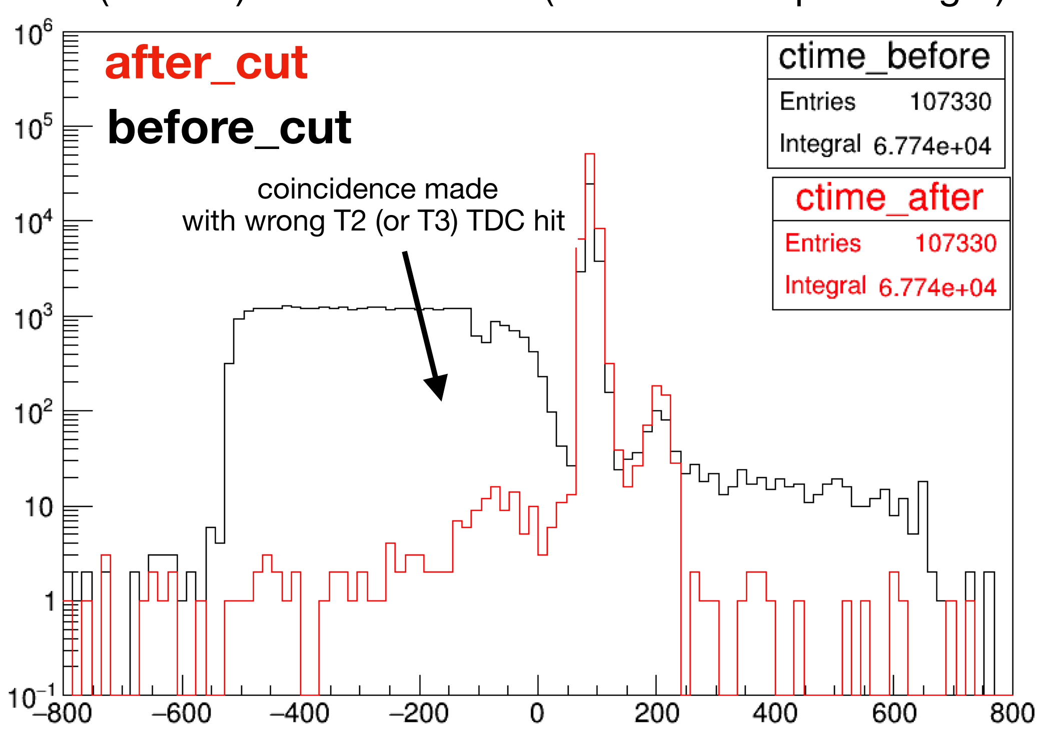
- Ca48 oil contamination
- rate-dependence
- double coin. time peak
- H(e, e'p) optics optimization
- data-to-simulation

problem: no trigger timing cuts made on T2 (and T3) triggers -> wrong (accidental) trigger used to form the coincidence lead to good coincidence signals blocked and drop of yield

Data Analysis Challenges



(T2 - T3) Coin. TDC time (corrected for path length)



- Ca48 oil contamination
- rate-dependence
- double coin. time peak
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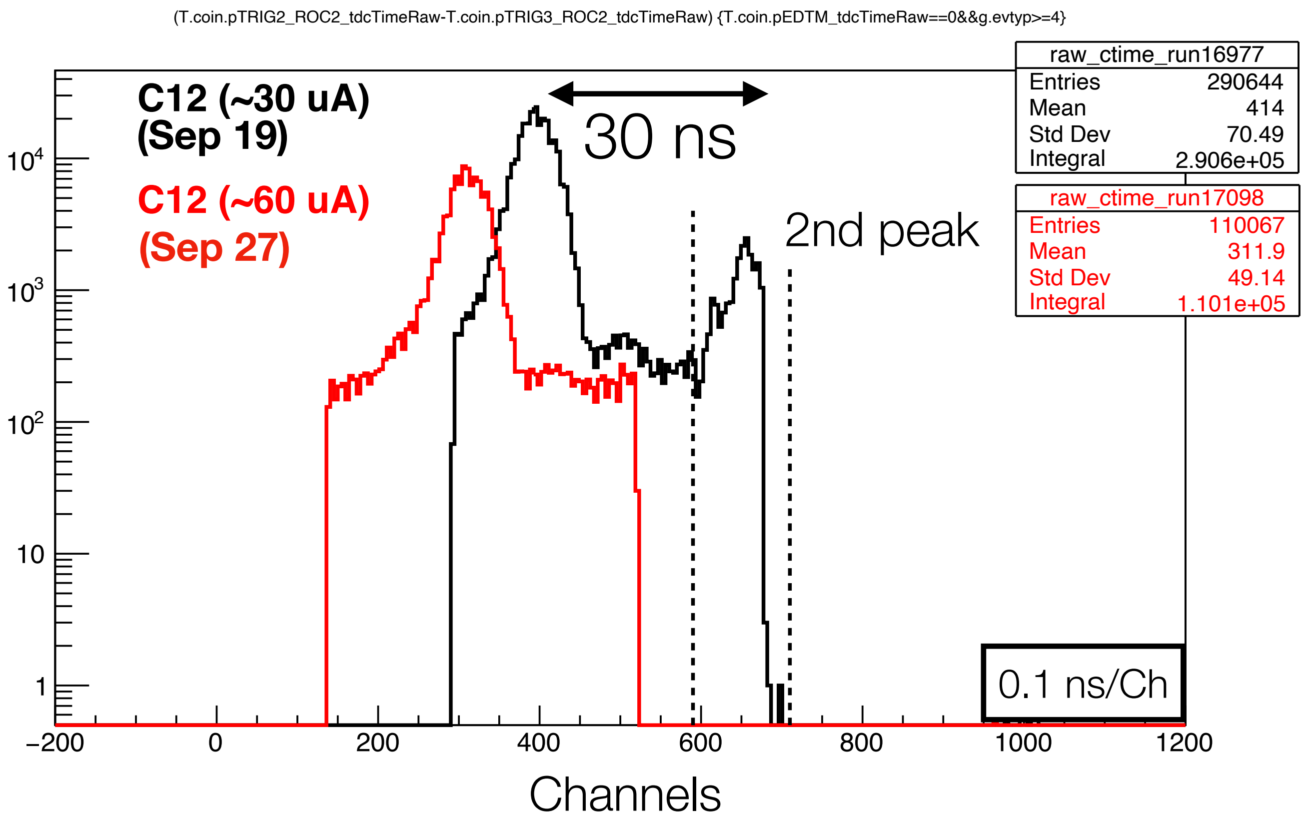
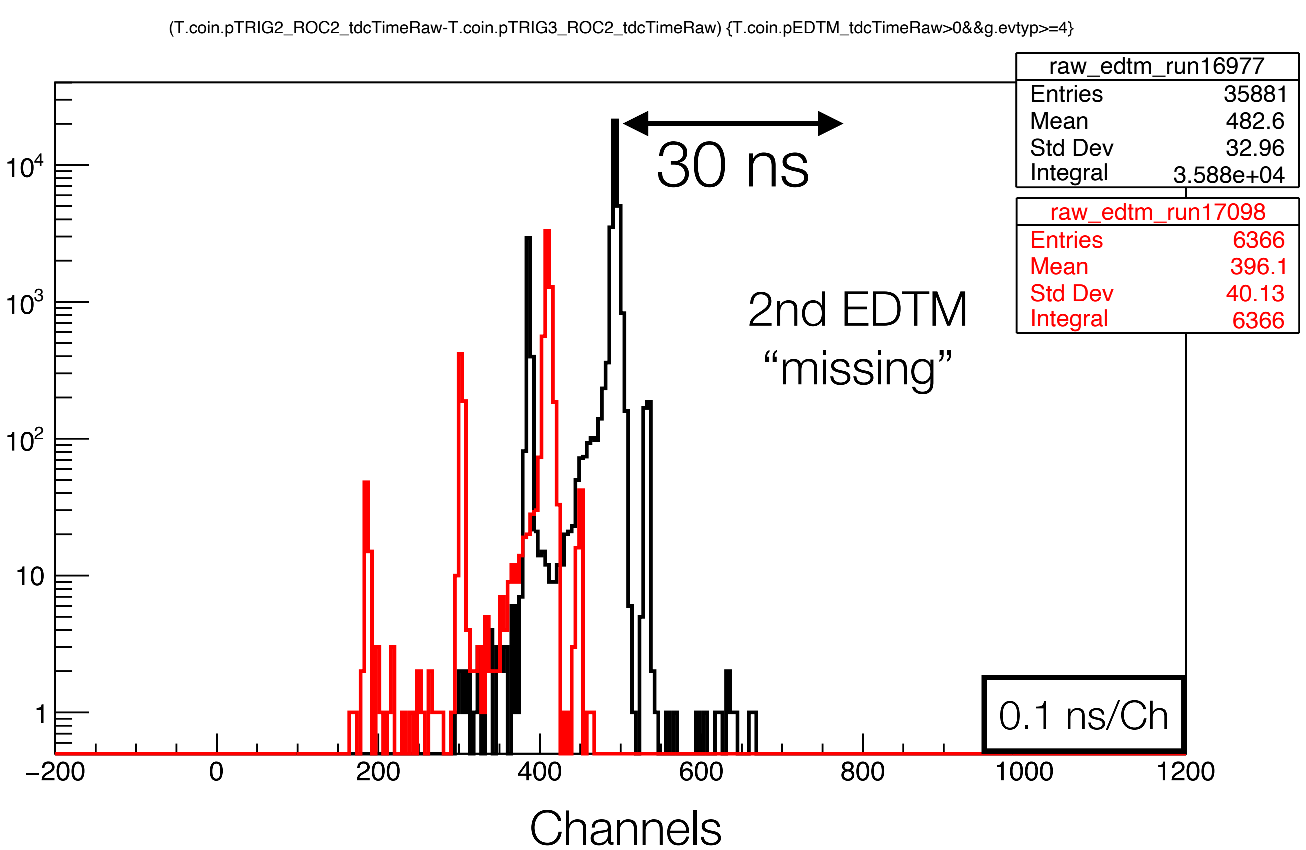
- data-to-simulation

solution: apply timing cut to triggers (T2, T3) that form the coincidence signal -> use the correct trigger time to recover coincidences (and yield)

Data Analysis Challenges





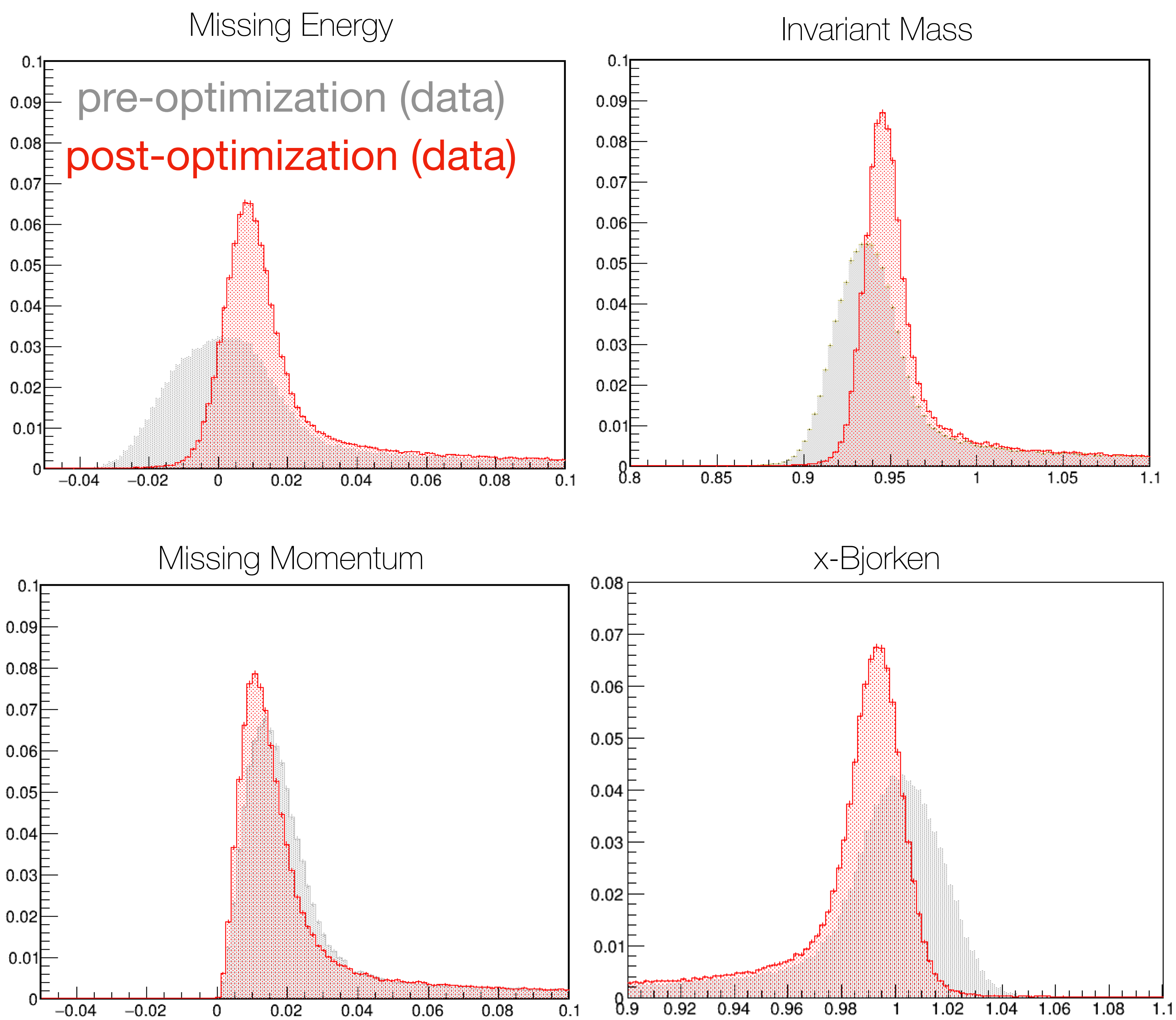
- Ca48 oil contamination
- rate-dependence
- double coin. time peak
- H(e, e’p) optics optimization
- data-to-simulation

problem:
- hardware trigger component offset +30 ns coincidence
  - part of good coincidence trigger offset
  - corresponding EDTM signal also offset (and missing)

solution:
- “missing EDTM” signal leads to lower DAQ live time and this also accounts for the lost (2nd peak) coincidence signals when correcting for the live time

Data Analysis Challenges

H(e, e'p) kinematics (after optimization+centroid alignment)

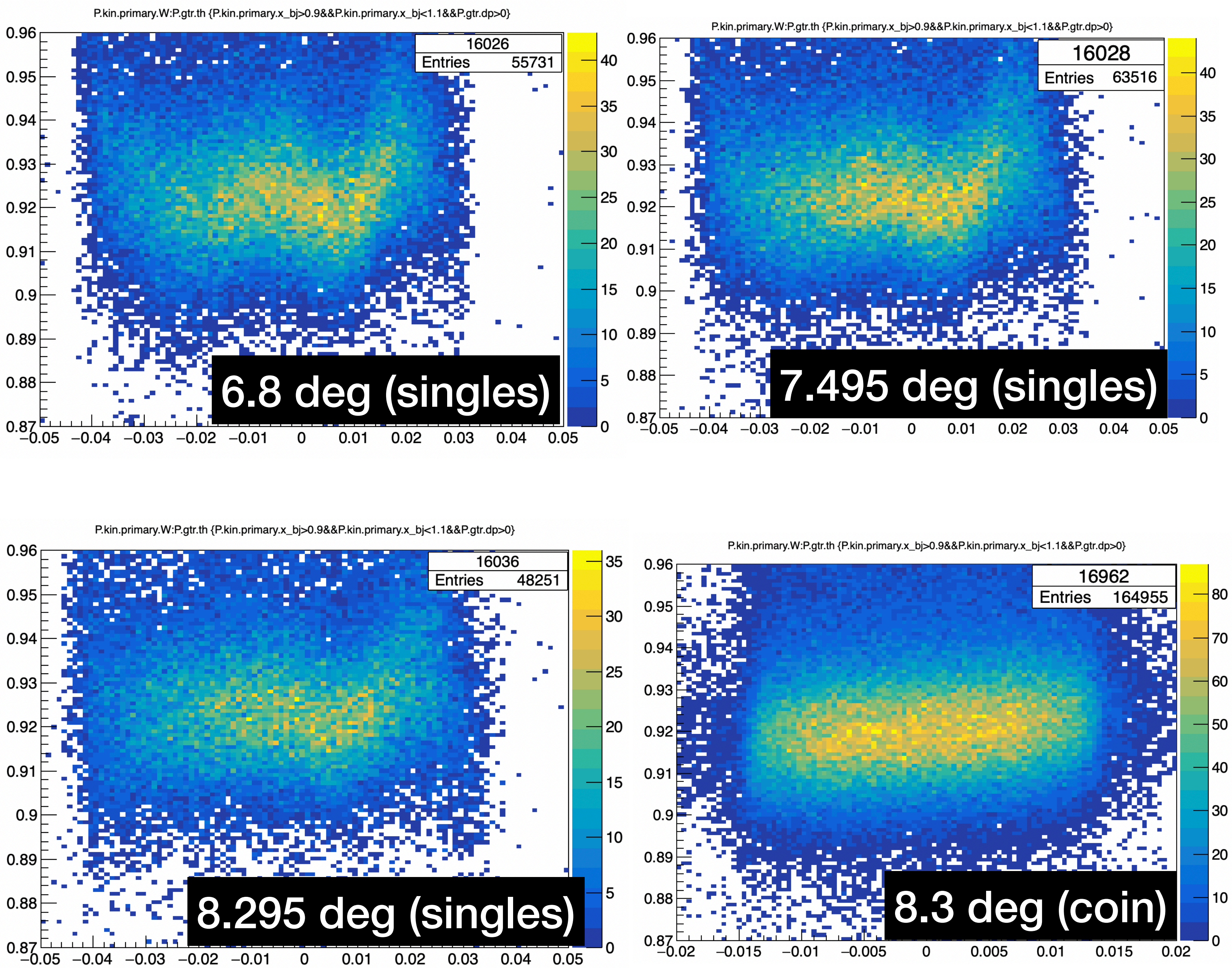


- Ca48 oil contamination
- rate-dependence
- double coin. time peak
- H(e, e'p) optics optimization
- data-to-simulation

*Thanks to **Holly Szumila-Vance** for H(e, e'p) angle/delta optimization*
(See references: [1] , [2])

Data Analysis Challenges

Invariant Mass W vs. SHMS x'tar (DATA)

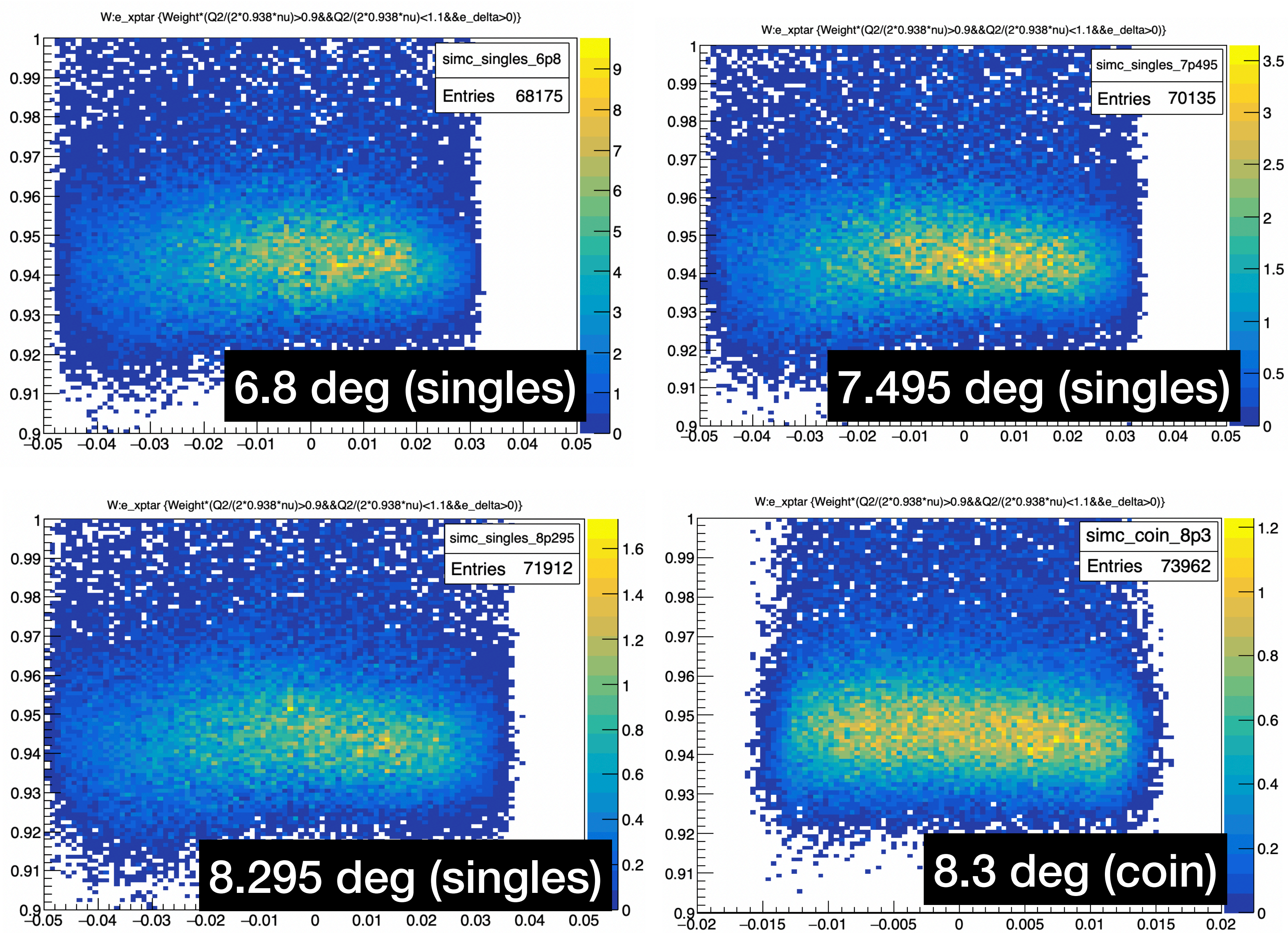


- Ca48 oil contamination
- rate-dependence
- double coin. time peak
- H(e, e'p) optics optimization
- data-to-simulation

DATA W dependence on x'tar (relative out-of-plane) could distort location of W peak in each of the singles elastics runs (largest effect @ 6.8 deg)

Data Analysis Challenges

Invariant Mass W vs. SHMS x’tar (SIMC)

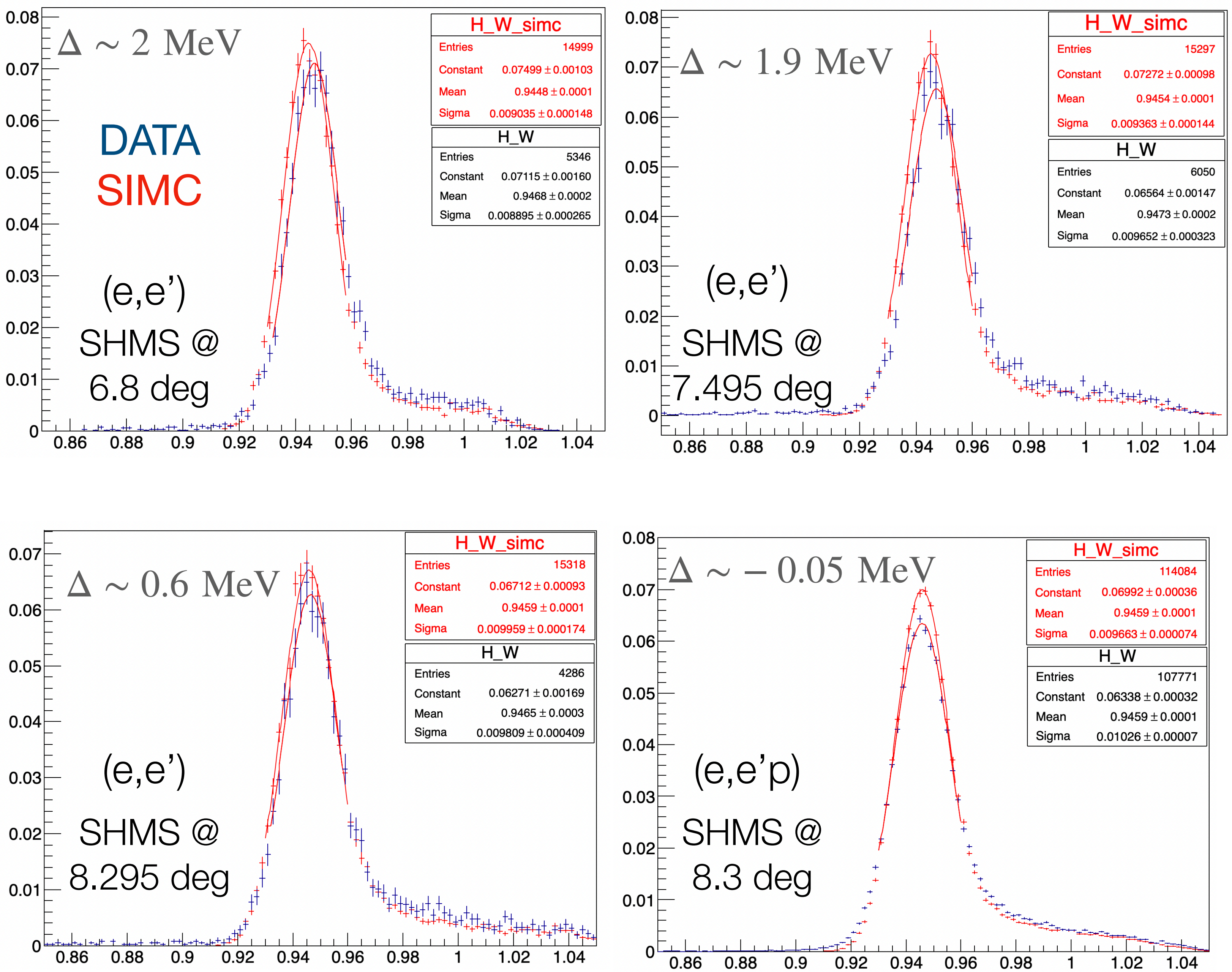


- Ca48 oil contamination
- rate-dependence
- double coin. time peak
- H(e, e’p) optics optimization
- data-to-simulation

NO SIMC W dependence on x’tar (relative out-of-plane) as expected, but since DATA has dependence, can affect centroid alignment of W

Data Analysis Challenges

Invariant Mass W (after optimization+centroid alignment)



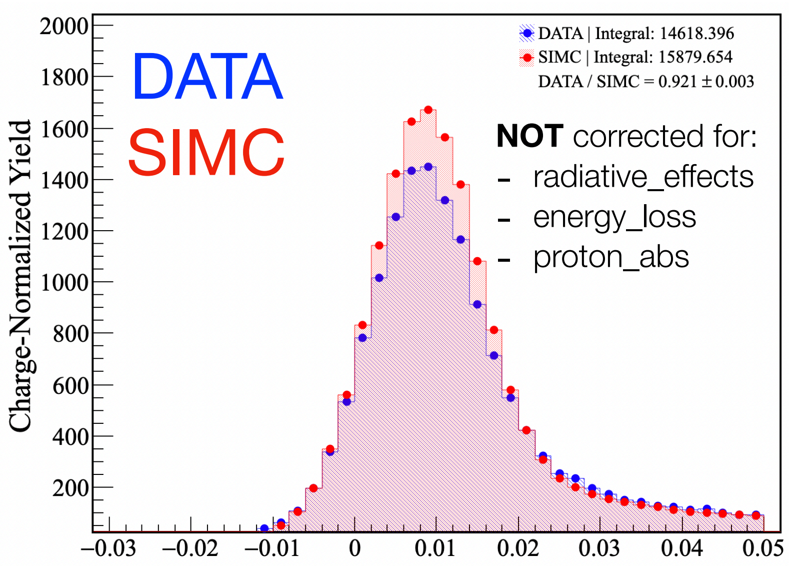
- Ca48 oil contamination
- rate-dependence
- double coin. time peak
- H(e, e'p) optics optimization
- data-to-simulation

- ~1-2 MeV data/simc mis-alignment
- difficulty fitting higher order matrix elements to reduce x'tar dependence
  (may be best optimized matrix that can be done ?!)

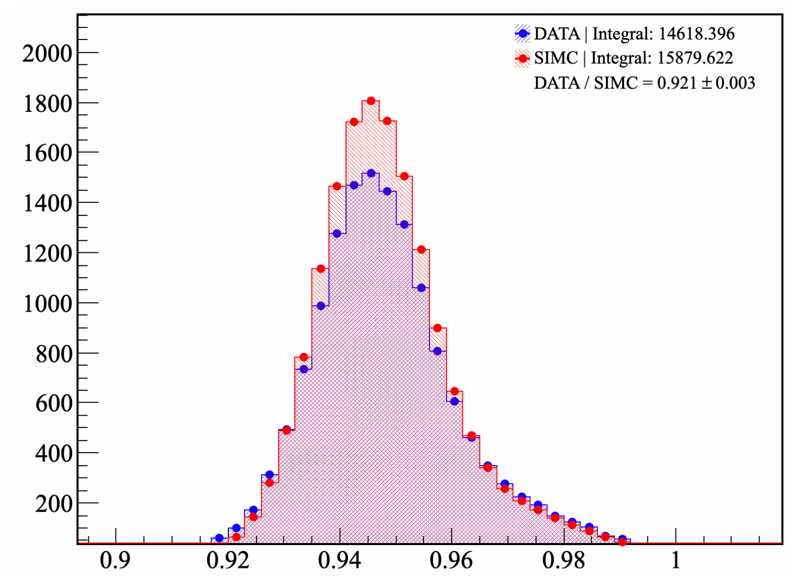
Data Analysis Challenges

H(e, e’p) Data / SIMC Yields

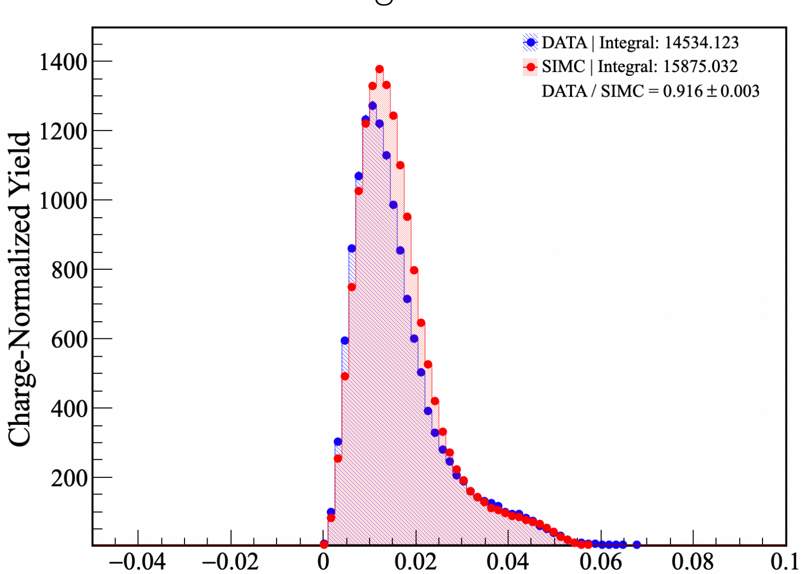
Missing Energy



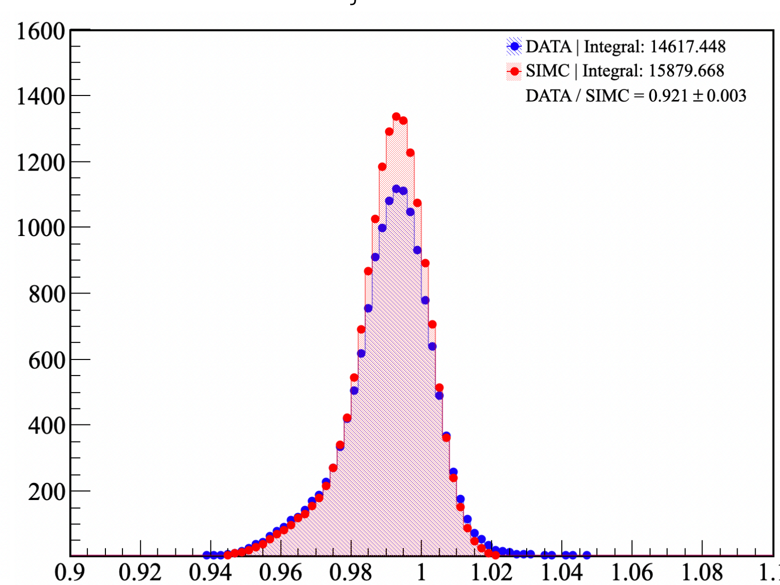
Invariant Mass



Missing Momentum



x-Bjorken



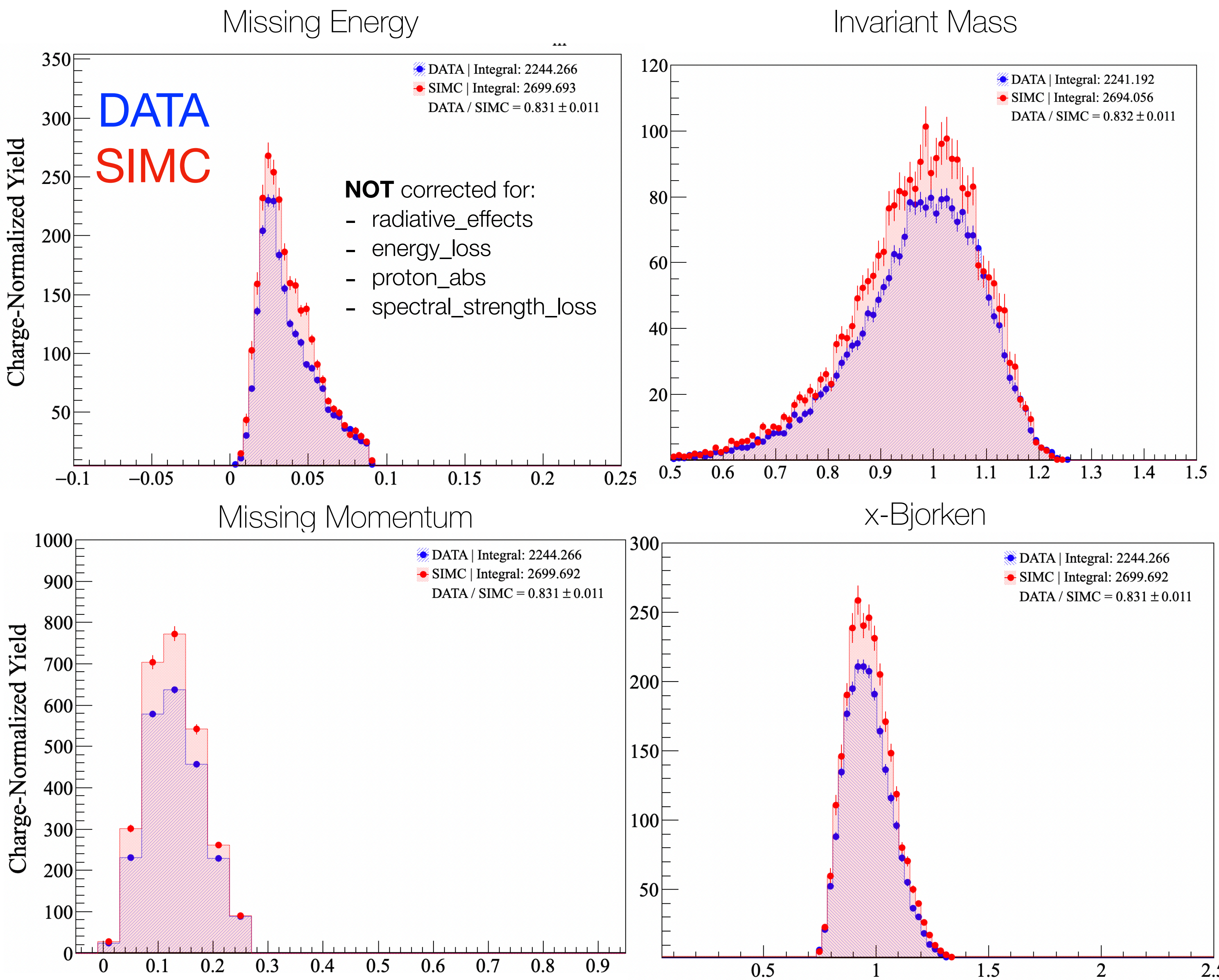
- Ca48 oil contamination
- rate-dependence
- double coin. time peak
- H(e, e’p) optics optimization
- data-to-simulation

- Measured DATA/SIMC ~ 92 %
  (where are remaining counts?)
  - HMS proton absorption expected ~ 5%

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

Data Analysis Challenges

C(e, e'p) Data / SIMC Yields



- Ca48 oil contamination
- rate-dependence
- double coin. time peak
- H(e, e'p) optics optimization
- data-to-simulation

- Measured DATA/SIMC ~ 83%, (where are remaining counts ?)
  - HMS proton absorption expected ~ < 5%
  - Loss of C12 spectral strength due to SRC ? (Hall C CT exp. Estimated ~11%)

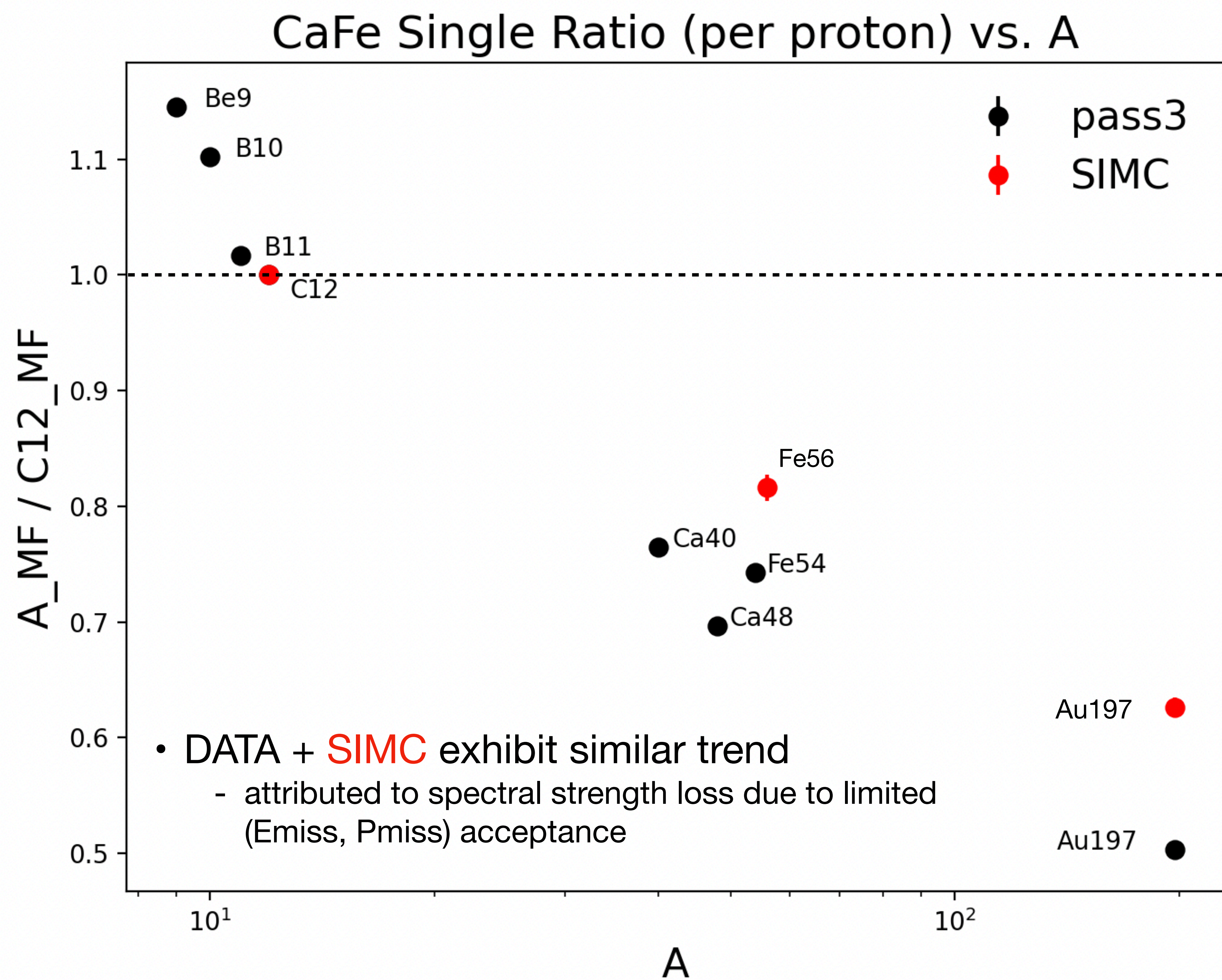
$$Y = \frac{N_{A(e,e'p)}}{Q \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{mult.trk} \cdot \epsilon_{LT} \cdot T_N \cdot \sigma_{thick} \cdot Z/A}$$

Single Ratio Checks (per proton)

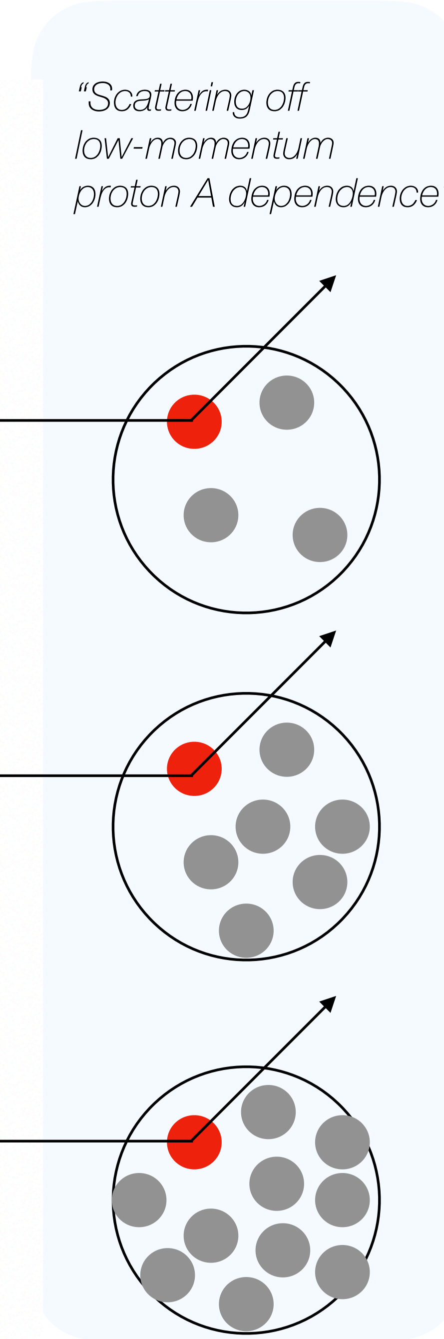
$$R \equiv \left.\frac{Y_A}{Y_{C12}}\right|_{MF}$$

$$Y_A \equiv \frac{N_{A(e,e'p)}}{Q \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{mult.trk} \cdot \epsilon_{LT} \cdot T_N \cdot \sigma_{thick} \cdot Z/A}$$

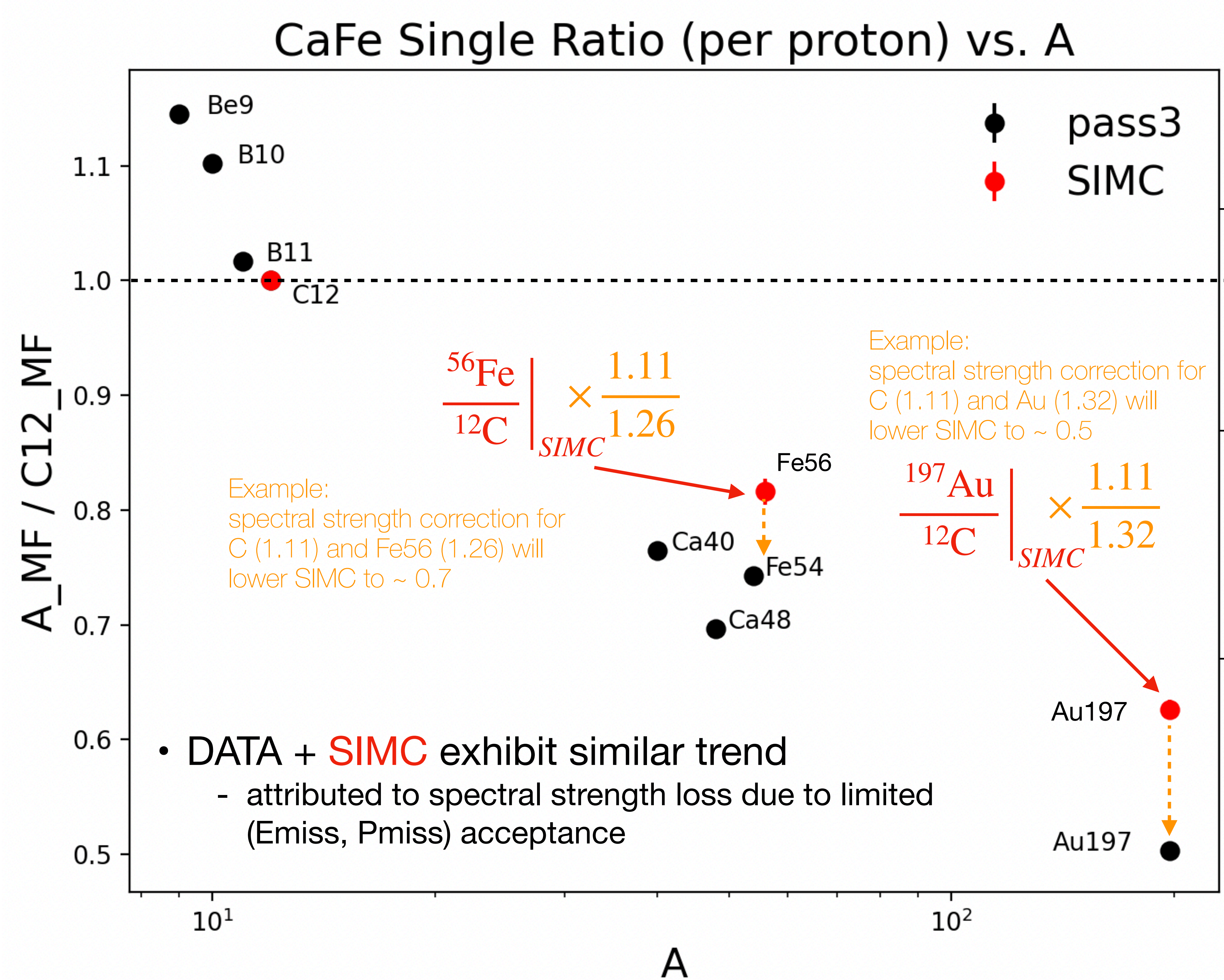
MF Single Ratio A/C12
(for **data** and **simc**)



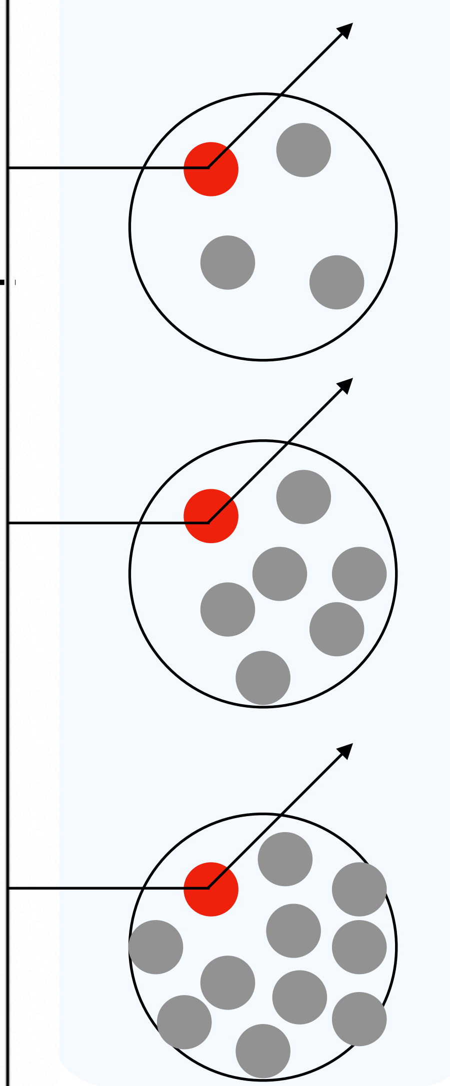
- DATA + SIMC exhibit similar trend
  - attributed to spectral strength loss due to limited (Emiss, Pmiss) acceptance



MF Single Ratio A/C12
(for **data** and **simc**)



"Scattering off low-momentum proton A dependence"



See D. M. ONeill Thesis (1994) , Table 11 (p. 122), Table 12 (p. 126) for spectral function strength corrections

Spectral Function Strength Correction

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

"spectral strength correction factor"
(Integrated over finite acceptance range, *R*)

$$I_{correl} = 0.5 \left(\int_{\mathcal{R}} dE_s d^3p S_{correl}(E_s, \mathbf{p}) + \int_0^{\infty} dE_s \int_{p_{m,min}}^{p_{m,max}} d^3p S_{correl}(E_s, \mathbf{p}) \right)$$

"due to uncertainties in the amount of correlated spectral function strength at large *Em,* the integral over R is averaged with the integral over all *Em"*

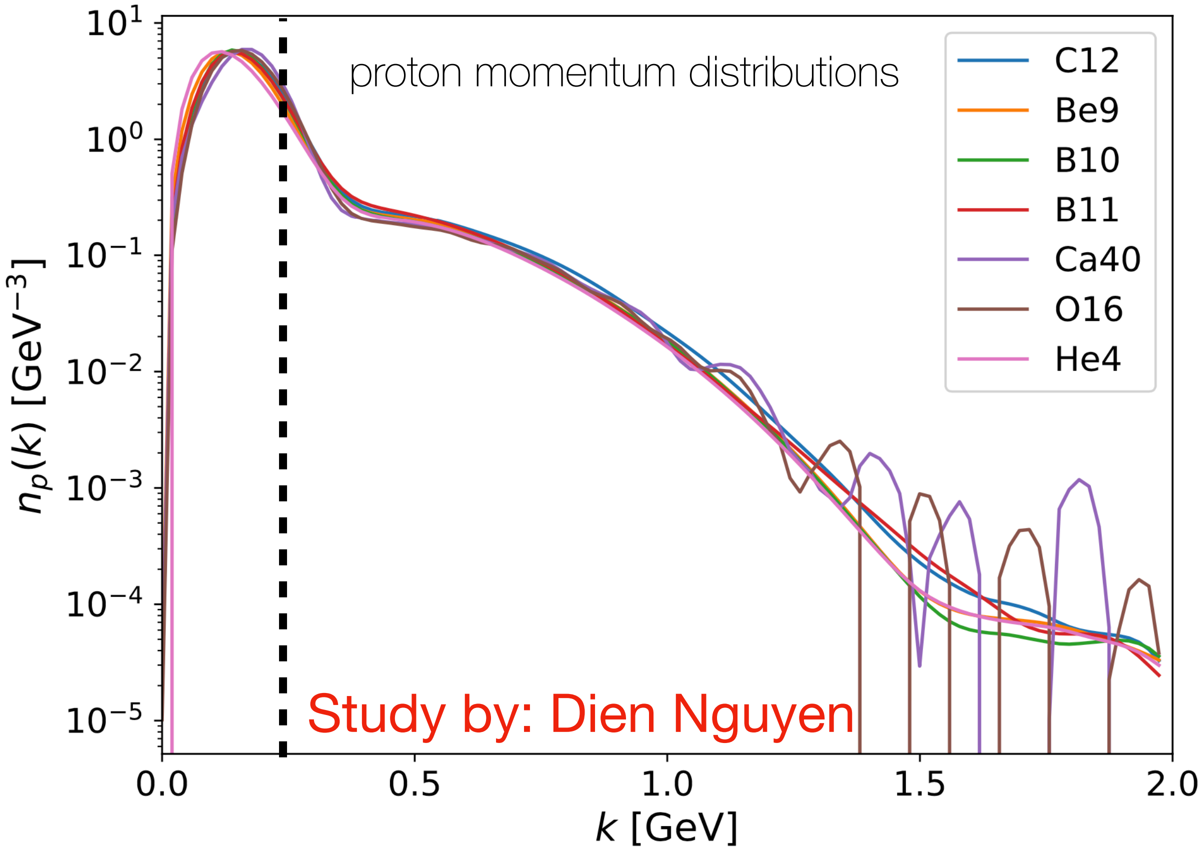
- after applying corrections to CaFe, data/simc ~ 97 %, in good agreement with previous CT experiments
- D. Nguyen currently finalizing the data-to-simulation comparisons

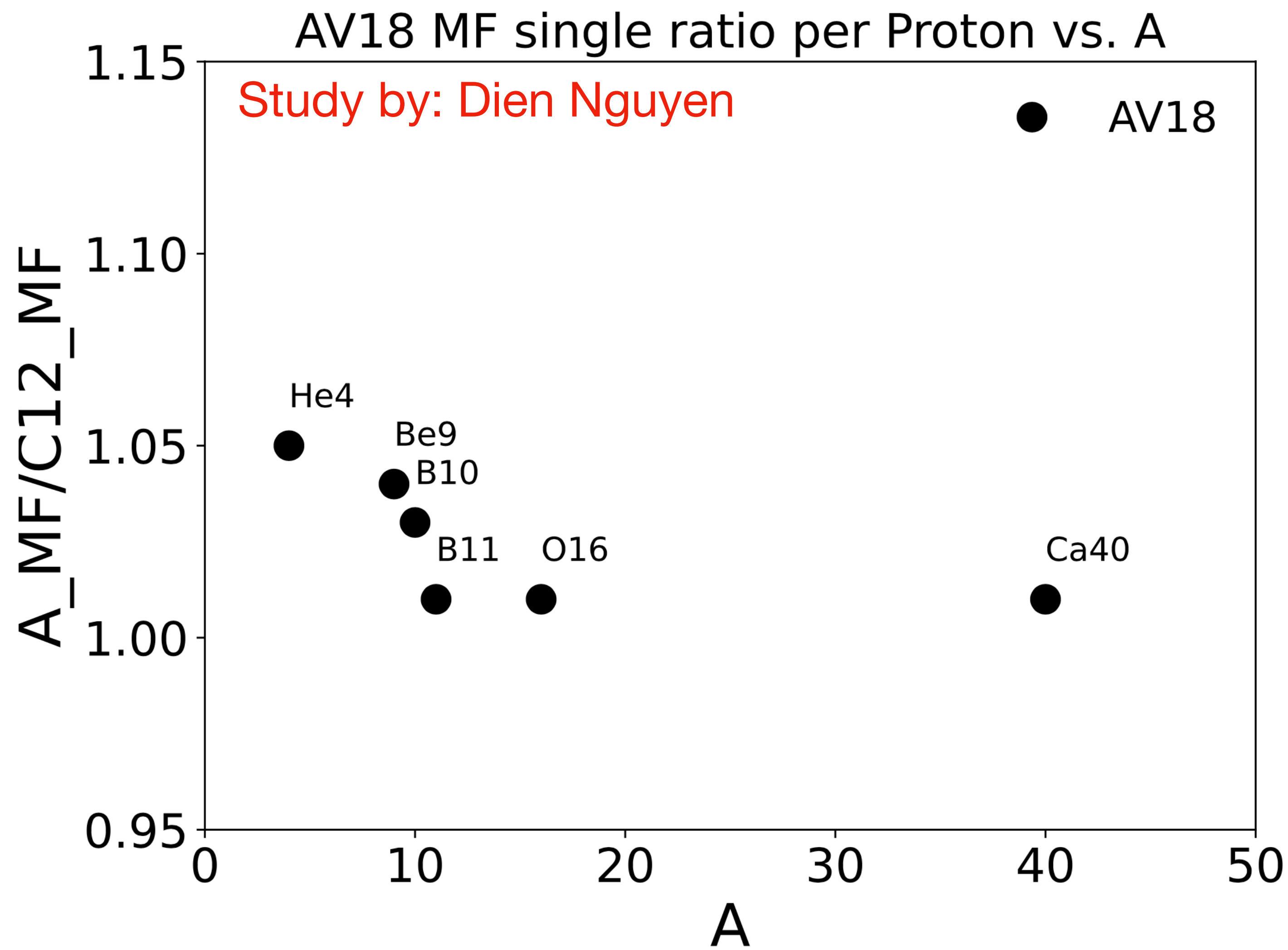
TABLE 12. Correlation tail correction to the PWIA calculation

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

See D. M. ONeill Thesis (1994) , Table 11 (p. 122), Table 12 (p. 126) for spectral function strength corrections

MF Single Ratio A/C12 (momentum distributions)





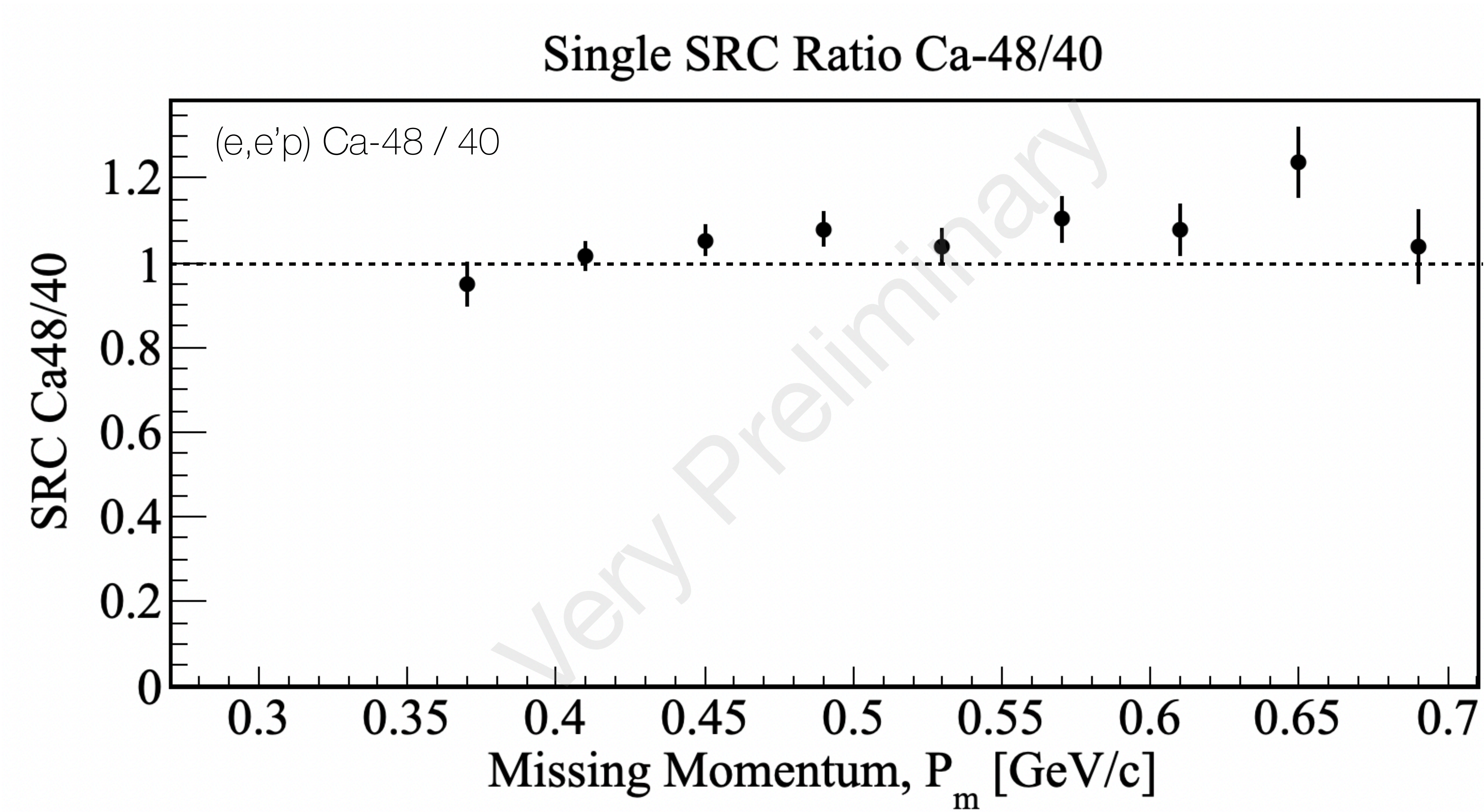
- proton momentum distributions integrated up to k~250 MeV/c, and full Emiss range
- single ratios of A/C12 momentum distributions show ratio R ~ 1
  - Why A/C12 for Hall C data and SIMC shows A dependence?
    a) could be due to finite acceptance of spectrometer (cut-off in Emiss range)
    b) collaboration with RGM Hall B to verify A-dependence

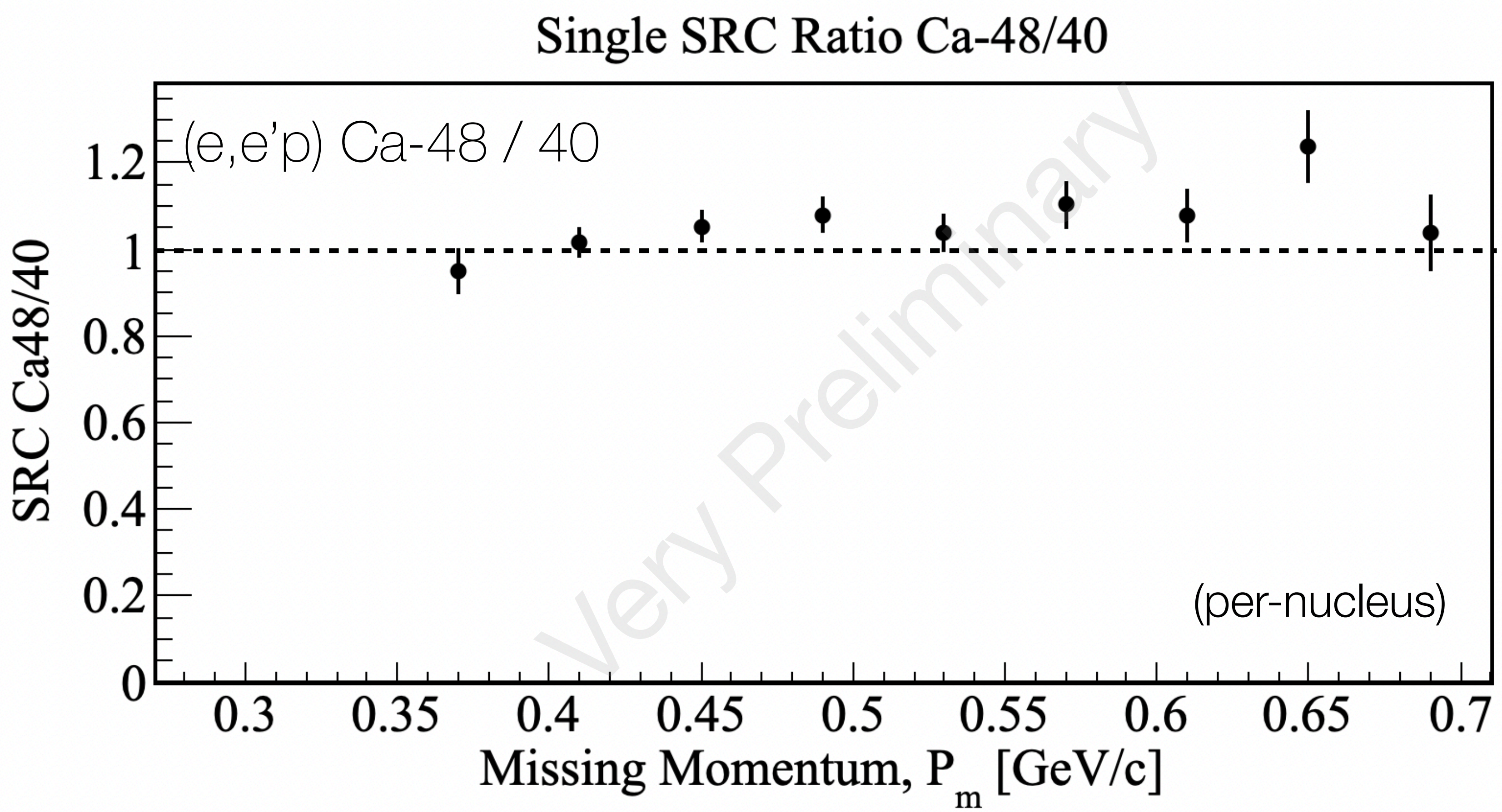
High-Momentum (SRC)
Single Ratio (per proton)

$$R \equiv \left.\frac{Y_{\text{Ca48}}}{Y_{\text{Ca40}}}\right|_{SRC}$$

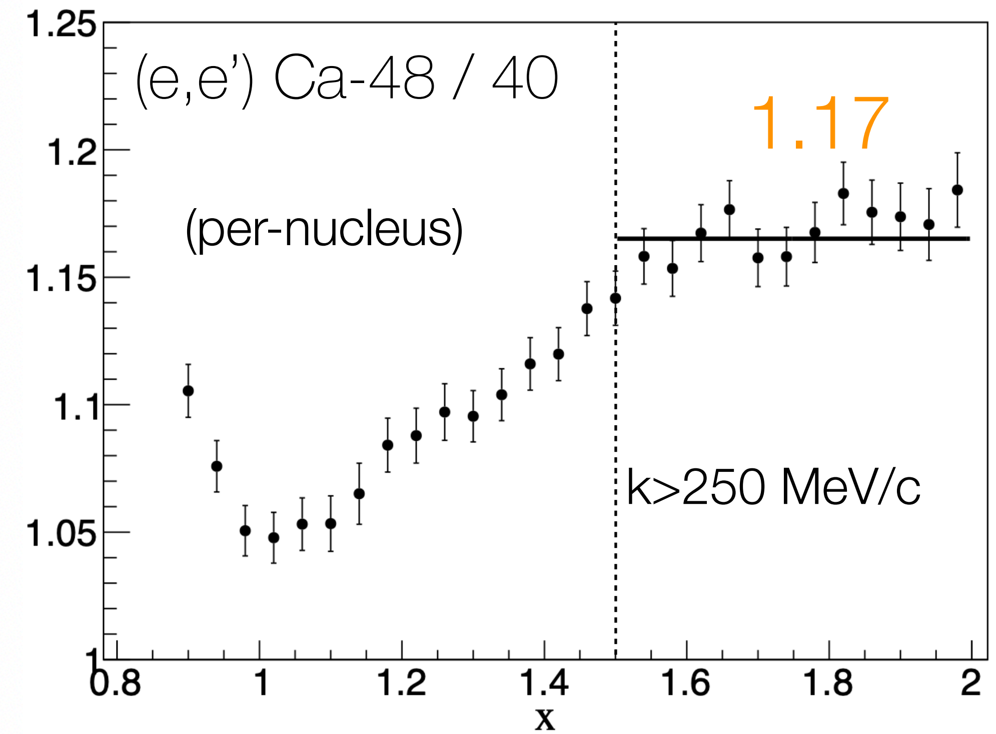
$$Y_A \equiv \frac{N_{A(e,e'p)}}{Q \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{mult.trk} \cdot \epsilon_{LT} \cdot T_N \cdot \sigma_{thick} \cdot Z/A}$$

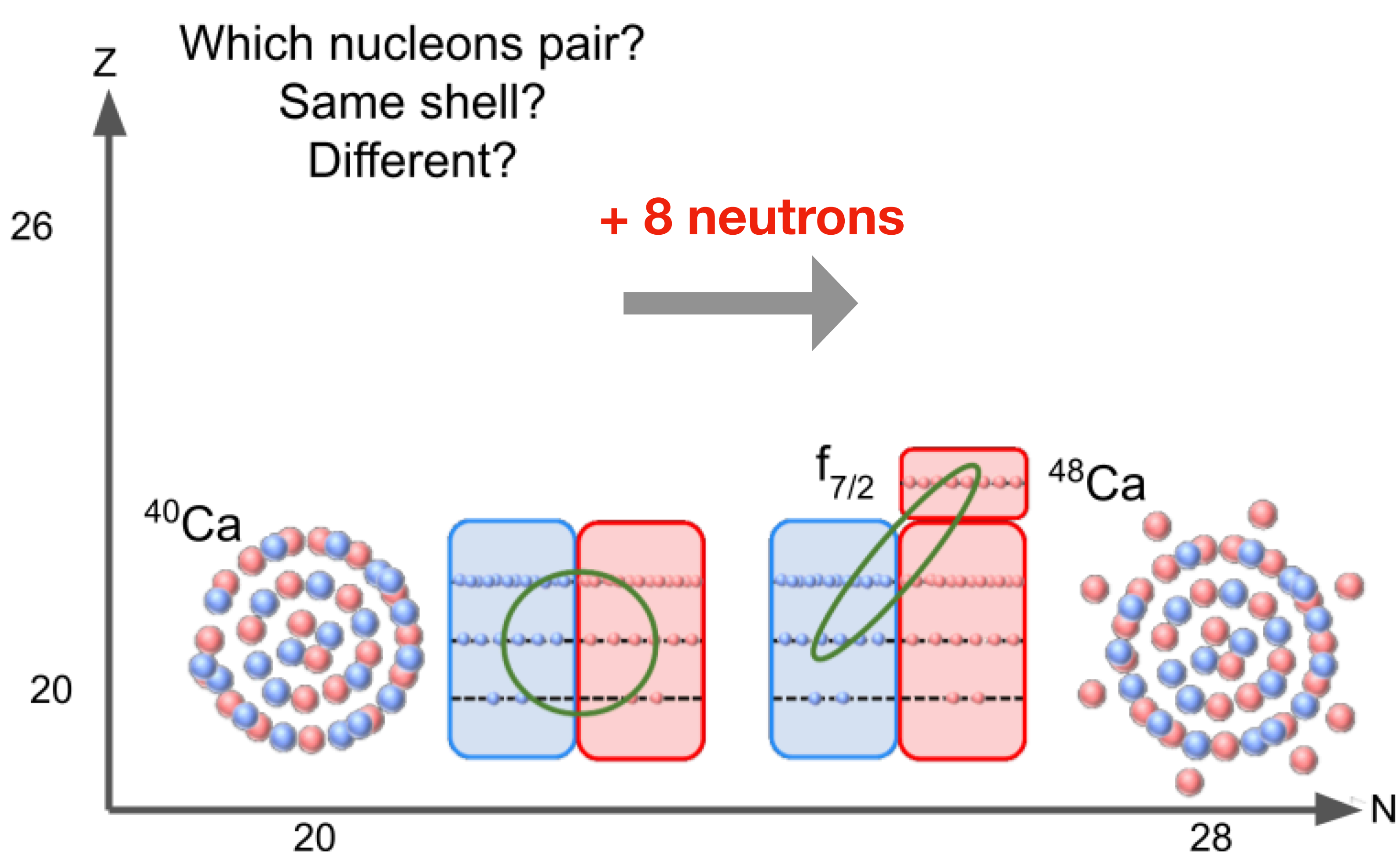
SRC Ca-48 / 40 Single Ratio (per proton)





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





Summary

- great data collected

- need to finalize analysis
  - *data/simulation*
  - *proton absorption*
  - *systematic uncertainties*

- unexpected and interesting Ca-48/40 results imply importance of nuclear structure

- expect final results this fall !

Holly Szumila-Vance (Staff)

Florian Hauenstein (Staff)

Dien Nguyen (Isgur Fellow)

Carlos Yero (NSF Fellow)

Noah Swan (PhD student)

National Science Foundation

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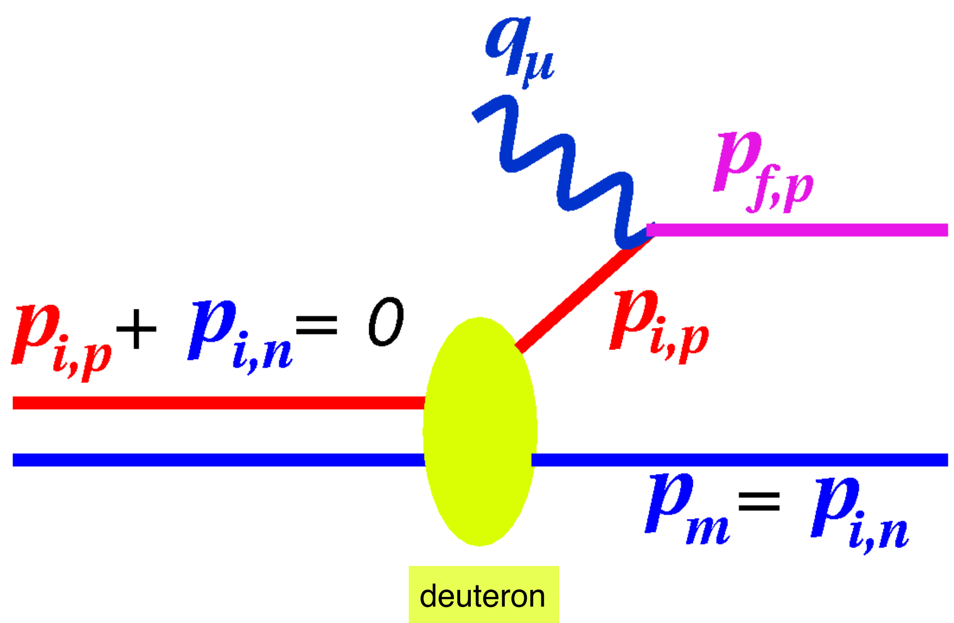
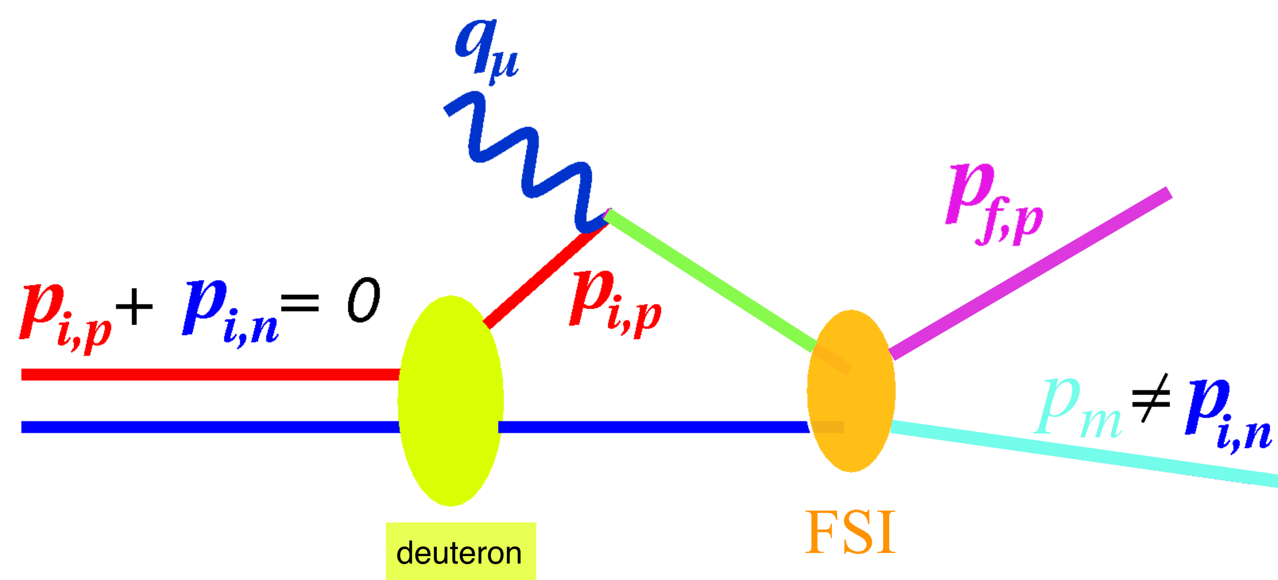
Spokespeople: D. Higinbotham (JLab), F. Hauenstein (JLab), O. Hen (MIT), L. Weinstein (ODU)

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

virtual photon - nucleus interactions

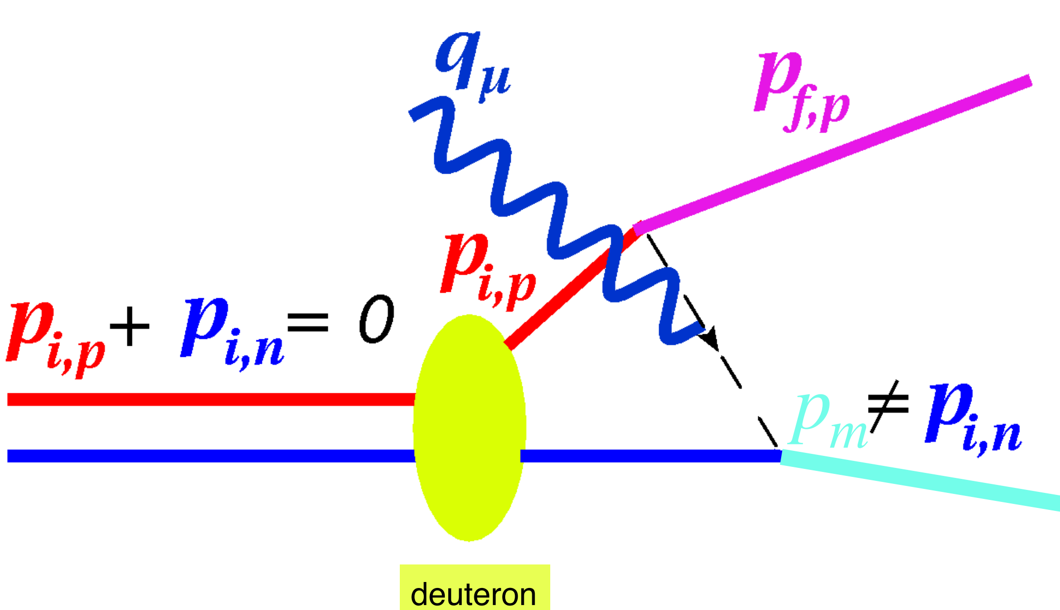


Plane Wave Impulse Approximation (PWIA)



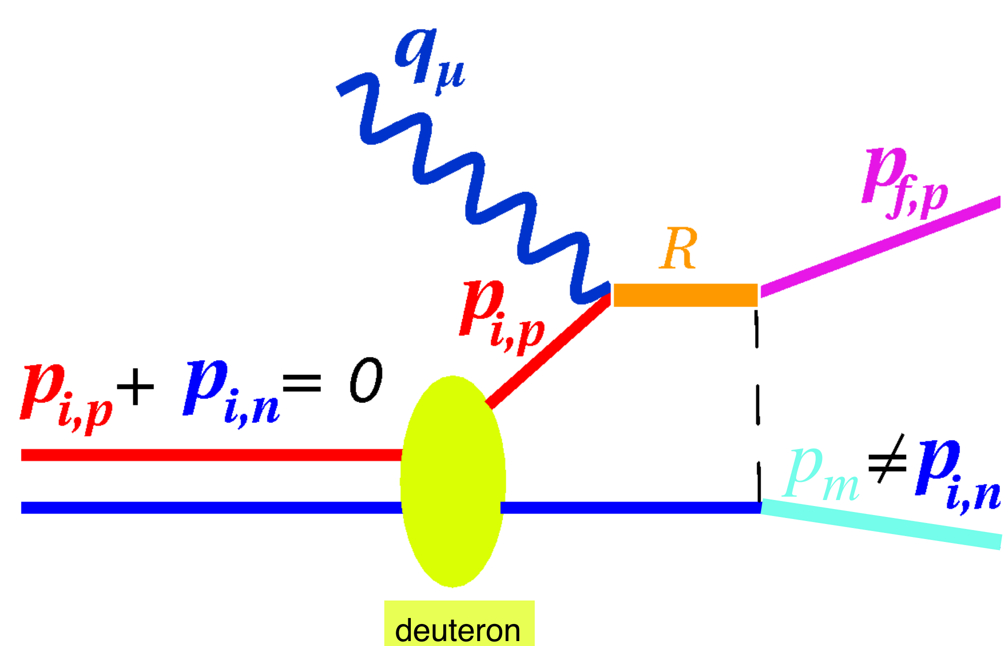
Final State Interactions (FSI)

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



Meson-Exchange Currents (MEC)

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

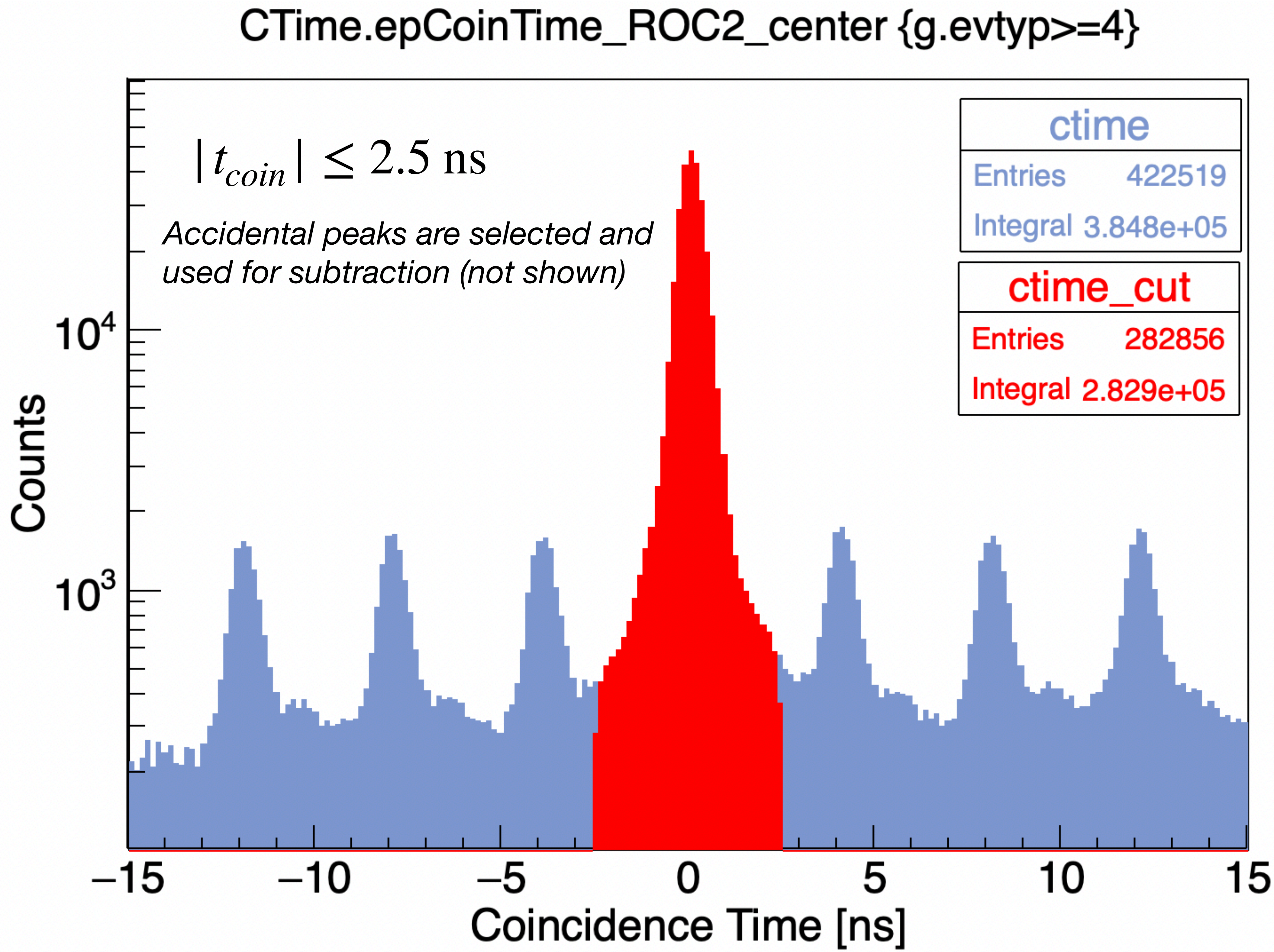


Delta, N* Resonance Excitations (IC)

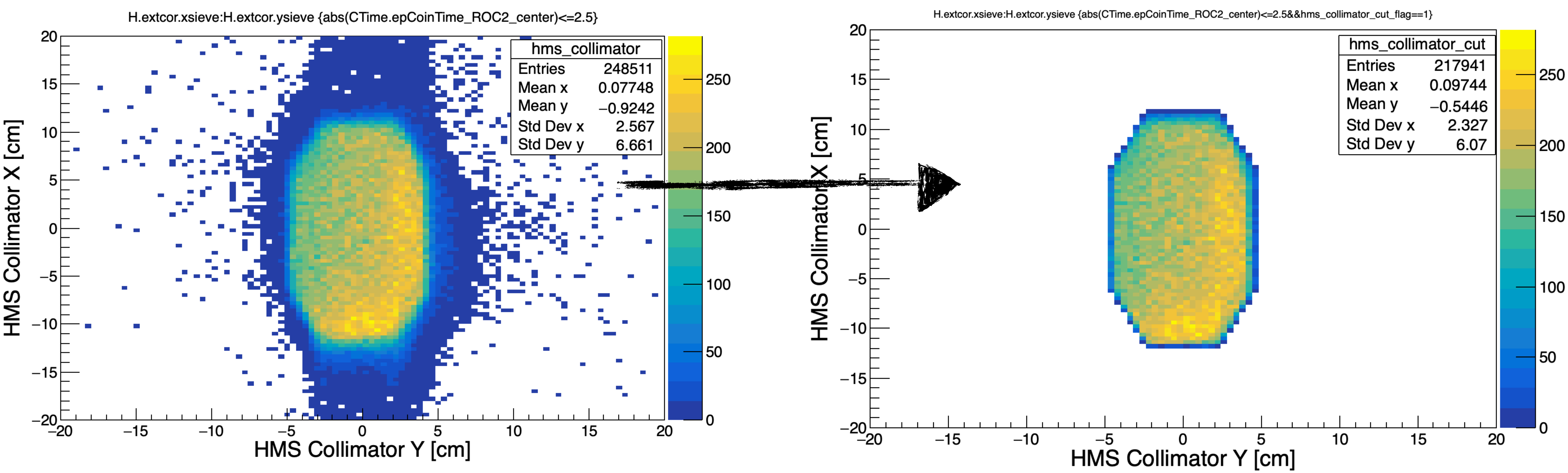
suppressed at $x_{\mathrm{Bj}} > 1$

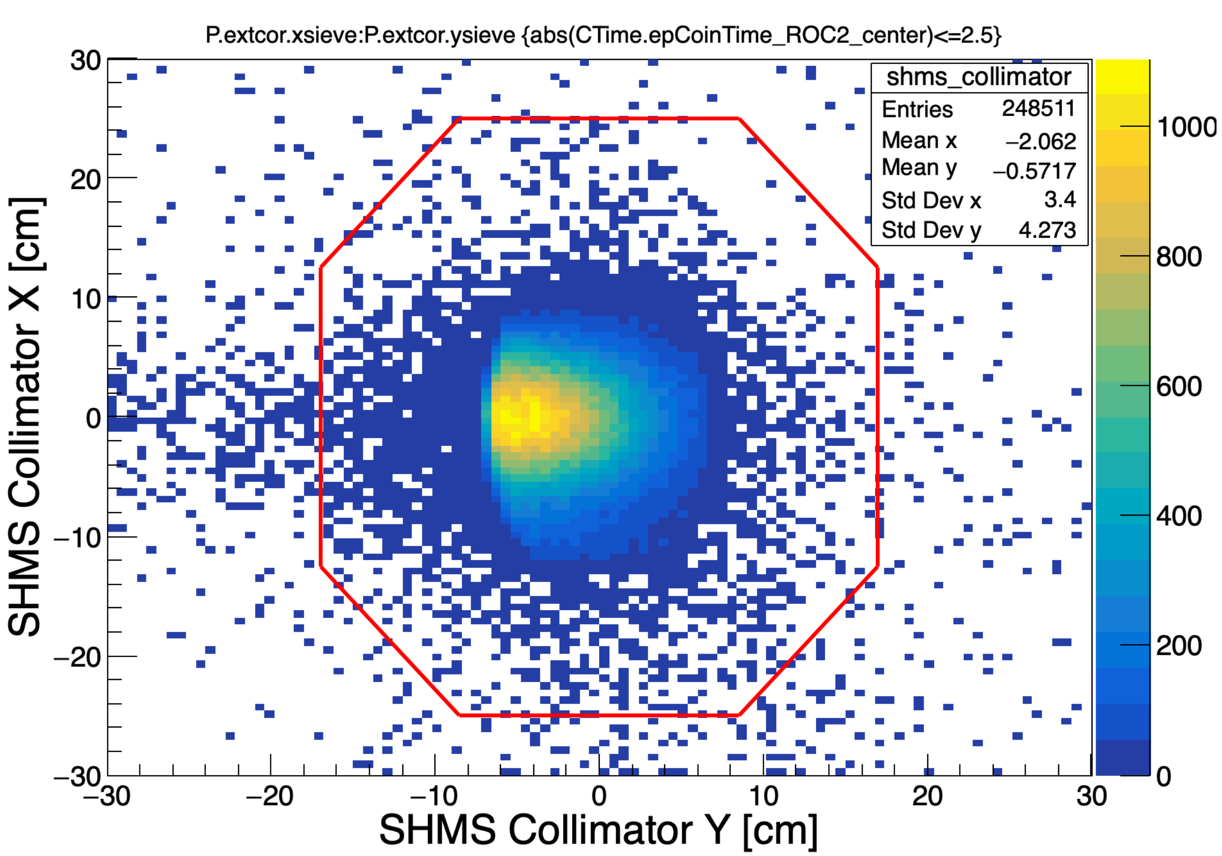
Event Selection (MF)

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



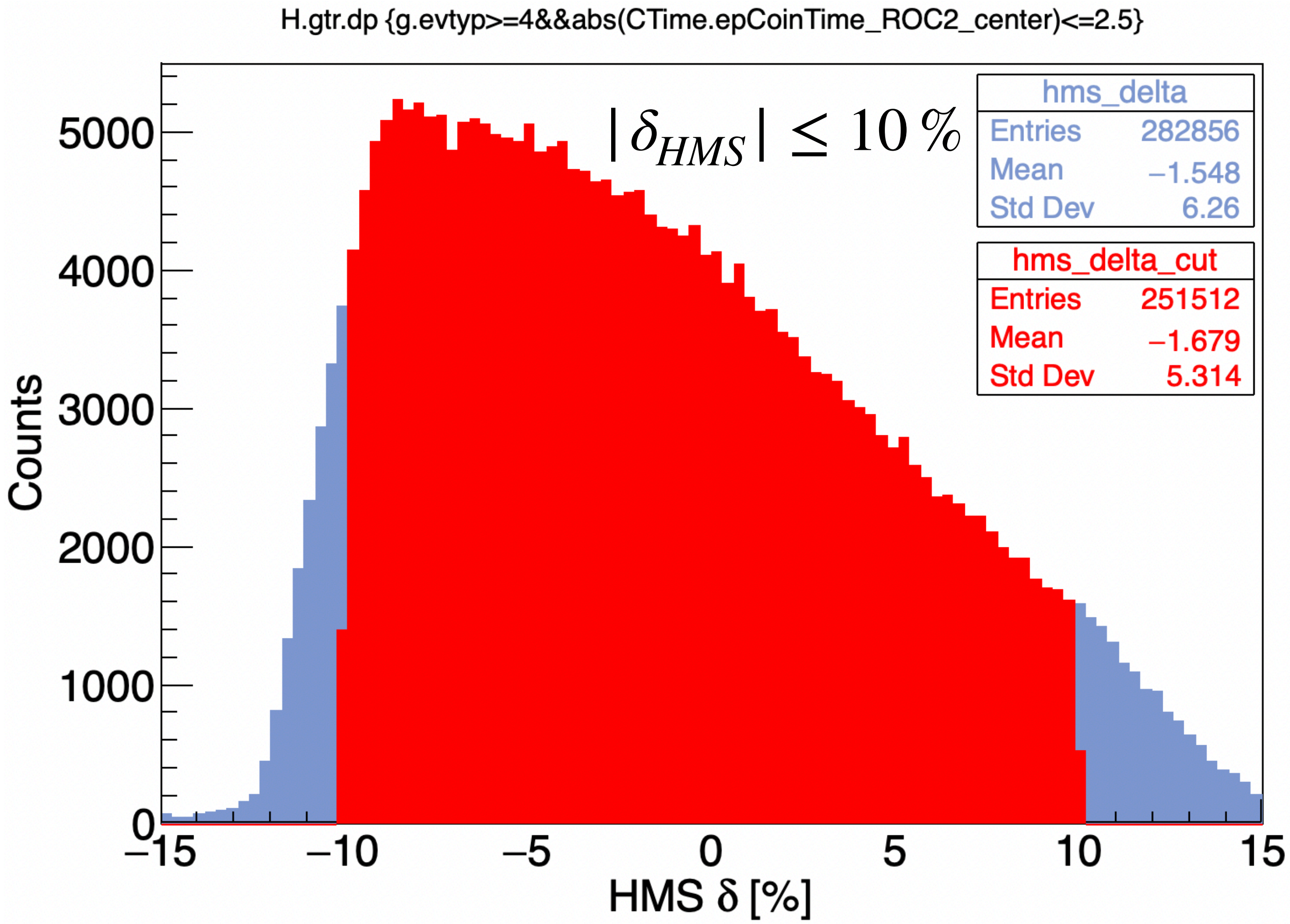
Event Selection (MF)





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

Event Selection (MF)

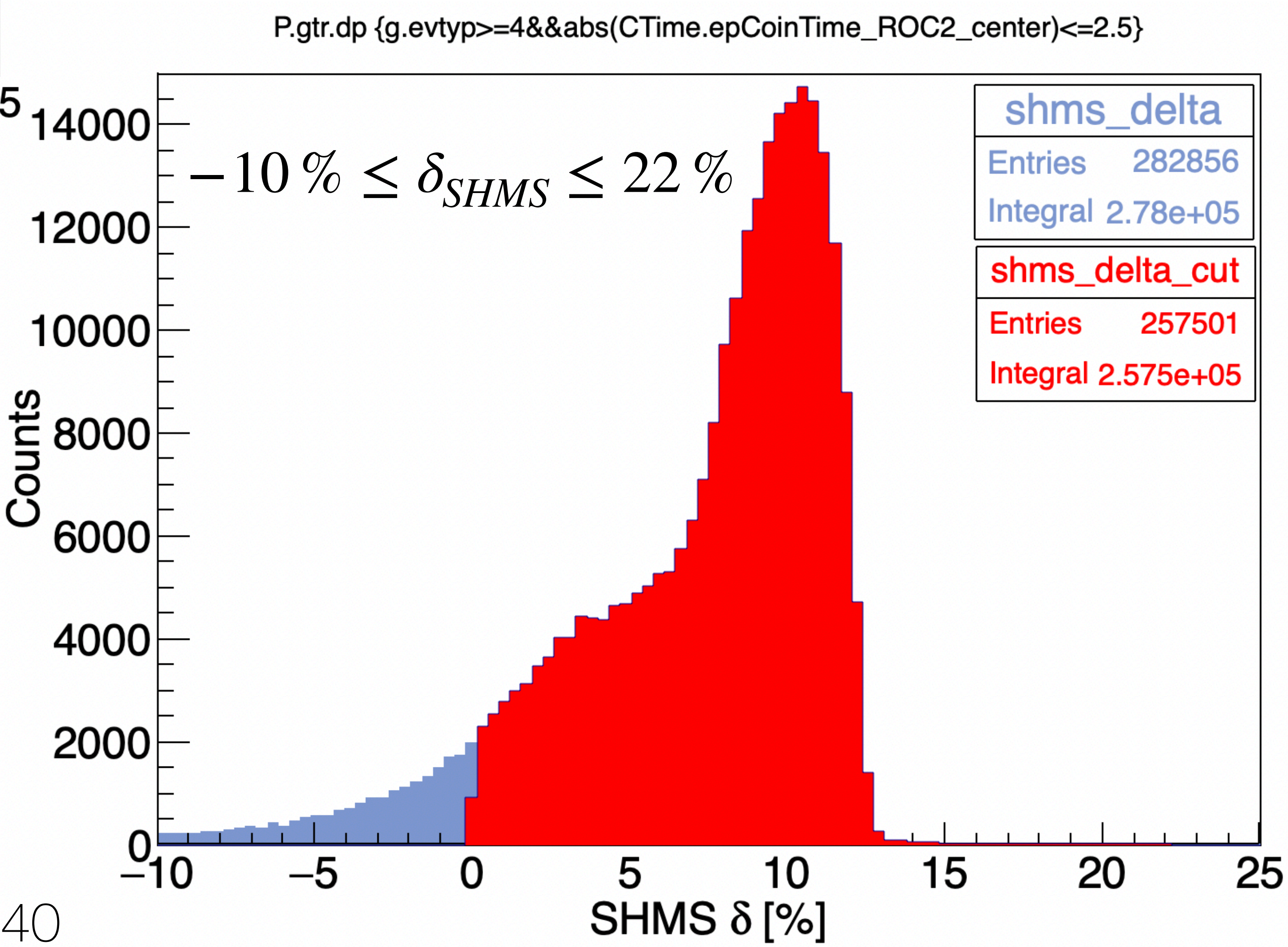


Momentum Acceptance Definition

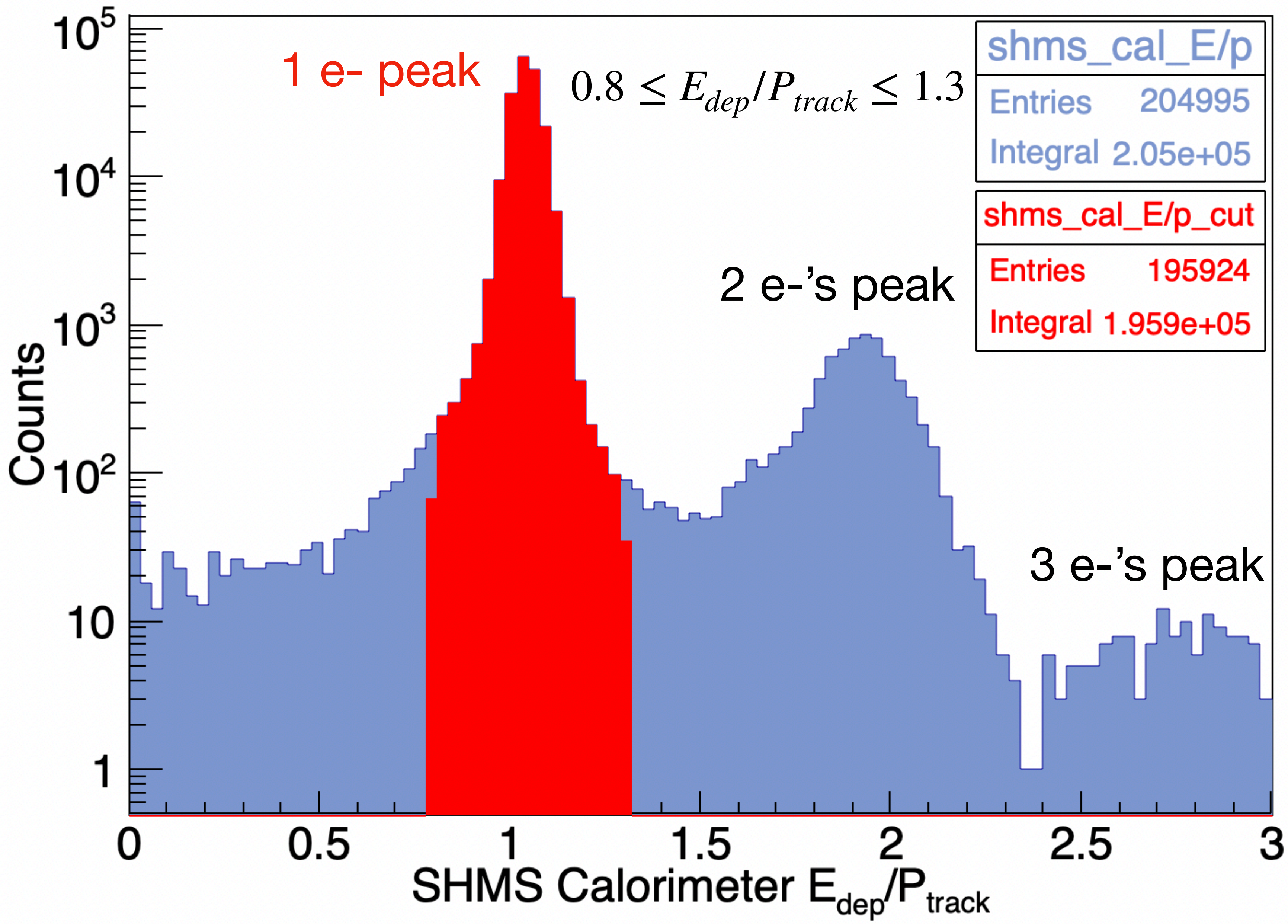
$$\delta \equiv \frac{P - P_0}{P_0}$$

P_0 : Spectrometer central momentum

P : Particle track momentum



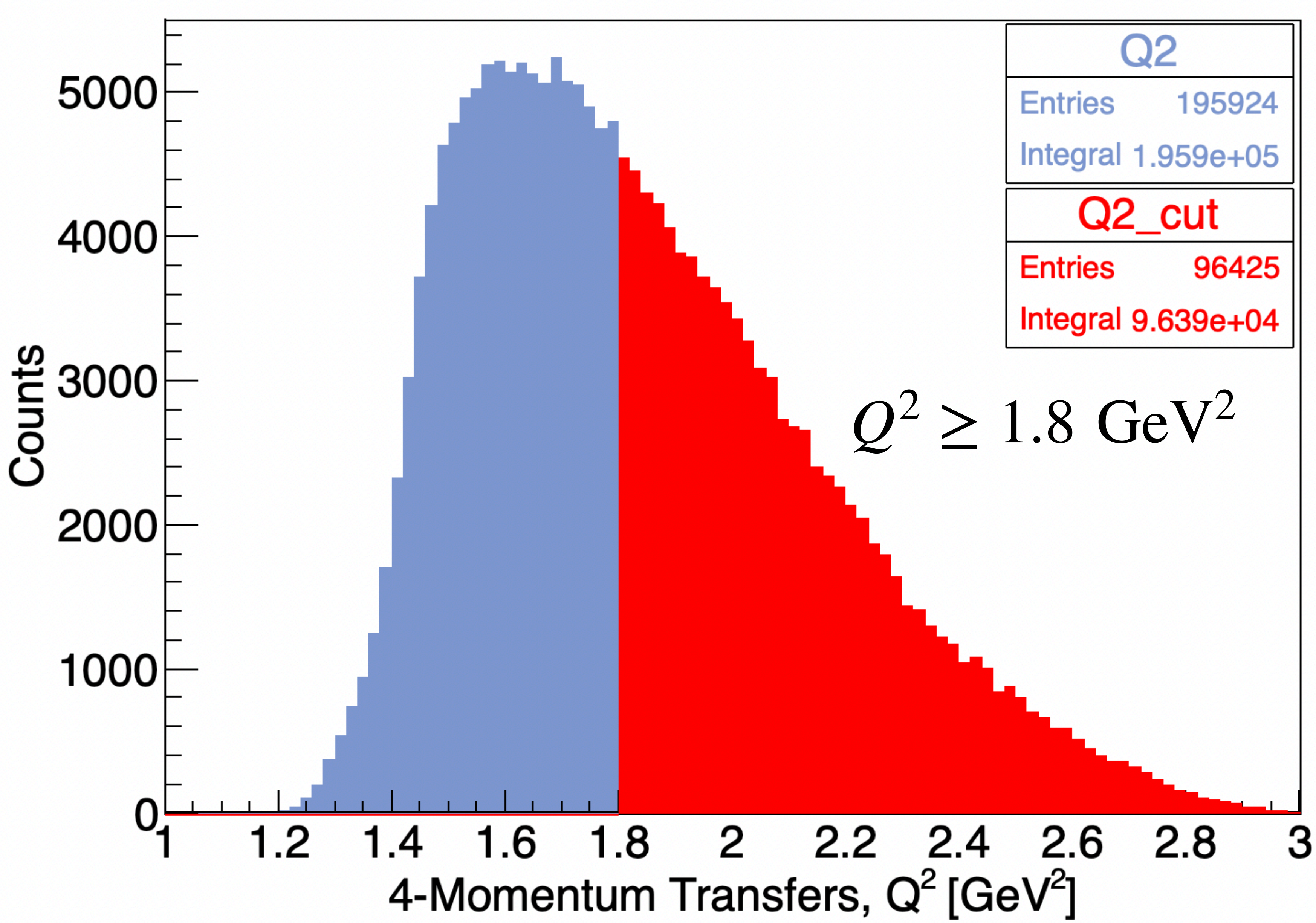
Event Selection (MF)



- 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)

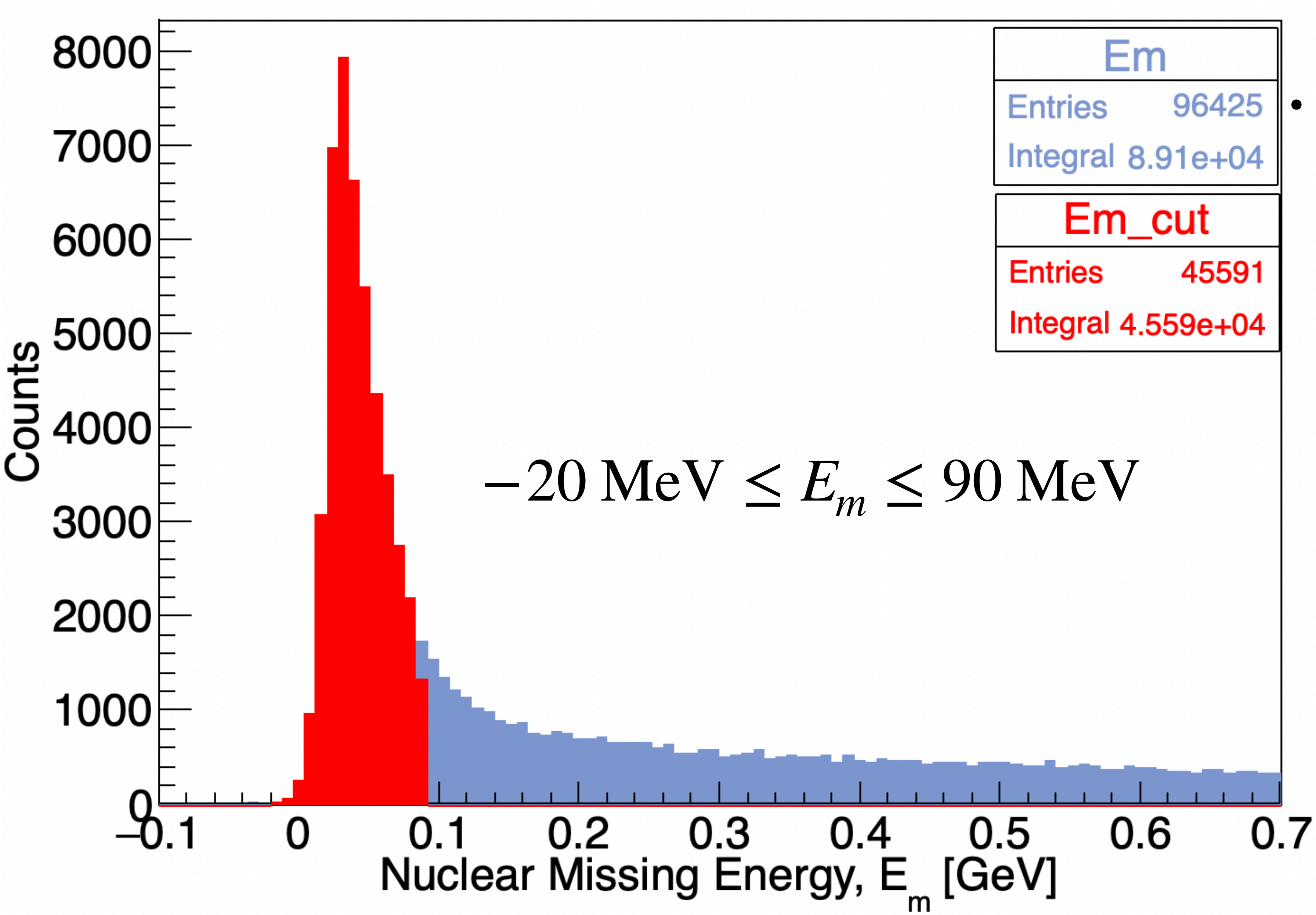
$$\epsilon_{\text{multi.trk}} = \frac{\sum_{n=2,3} E_{dep}/P_0}{\sum_{n=1} E_{dep}/P_0}$$

Event Selection (MF)



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

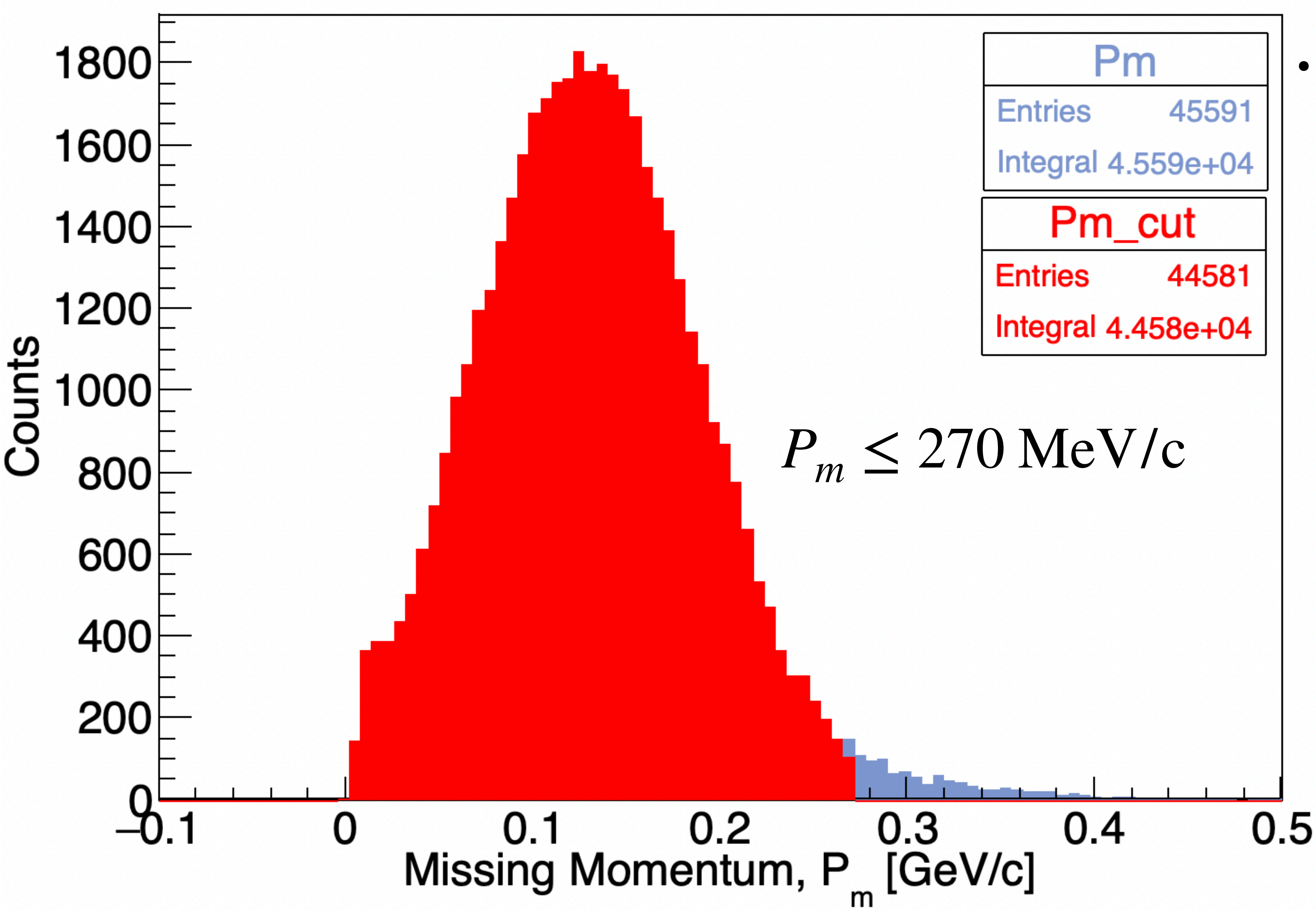
Event Selection (MF)



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

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

Event Selection (MF)

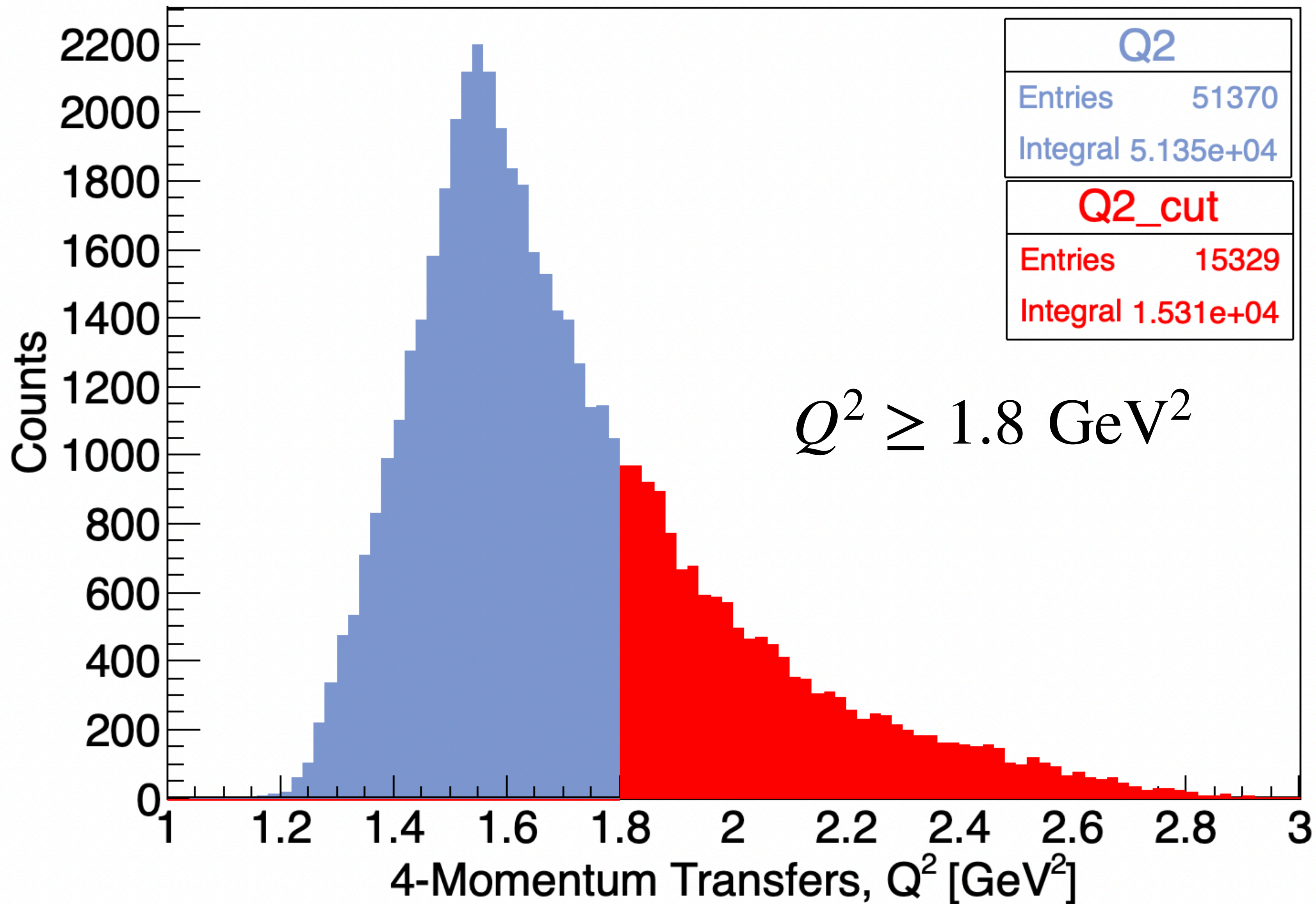


- Kinematic Cut to select mean-field (MF) nucleons

Event Selection (SRC)

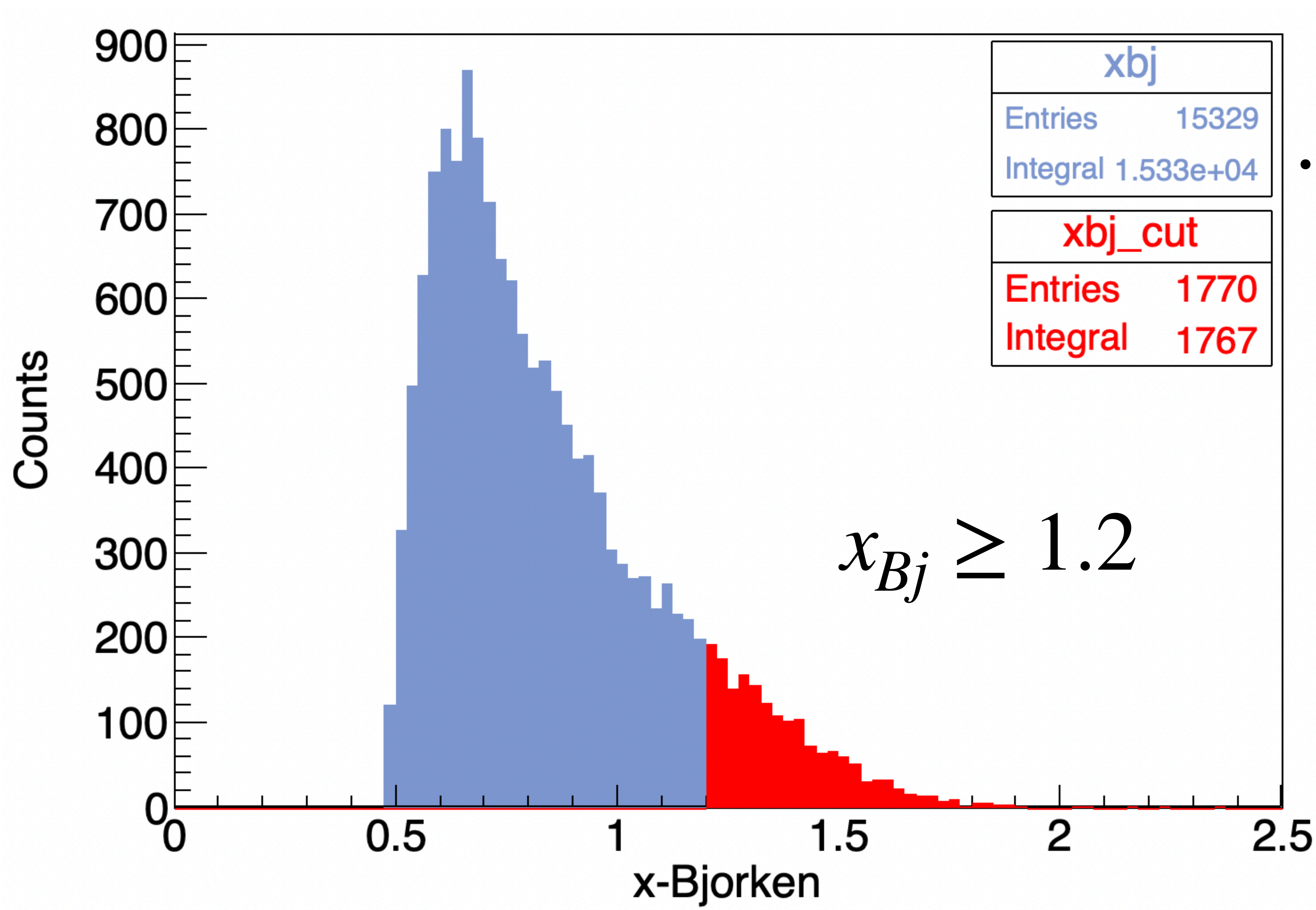
(For illustration purposes, Ca48 SRC run 17057 is used)

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



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

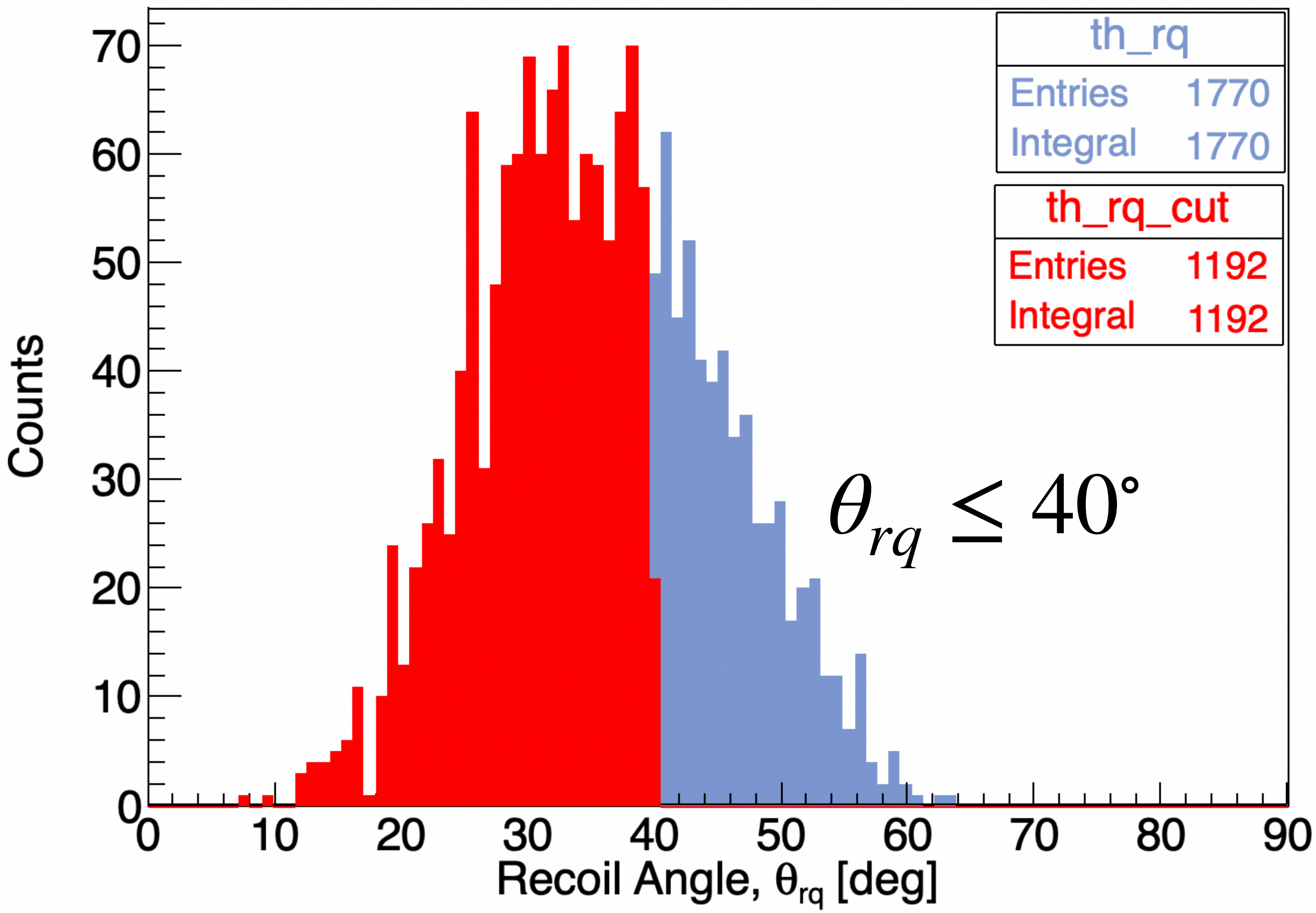
Event Selection (SRC)



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

  (i.e., suppress Δ, N^* excitations)

Event Selection (SRC)



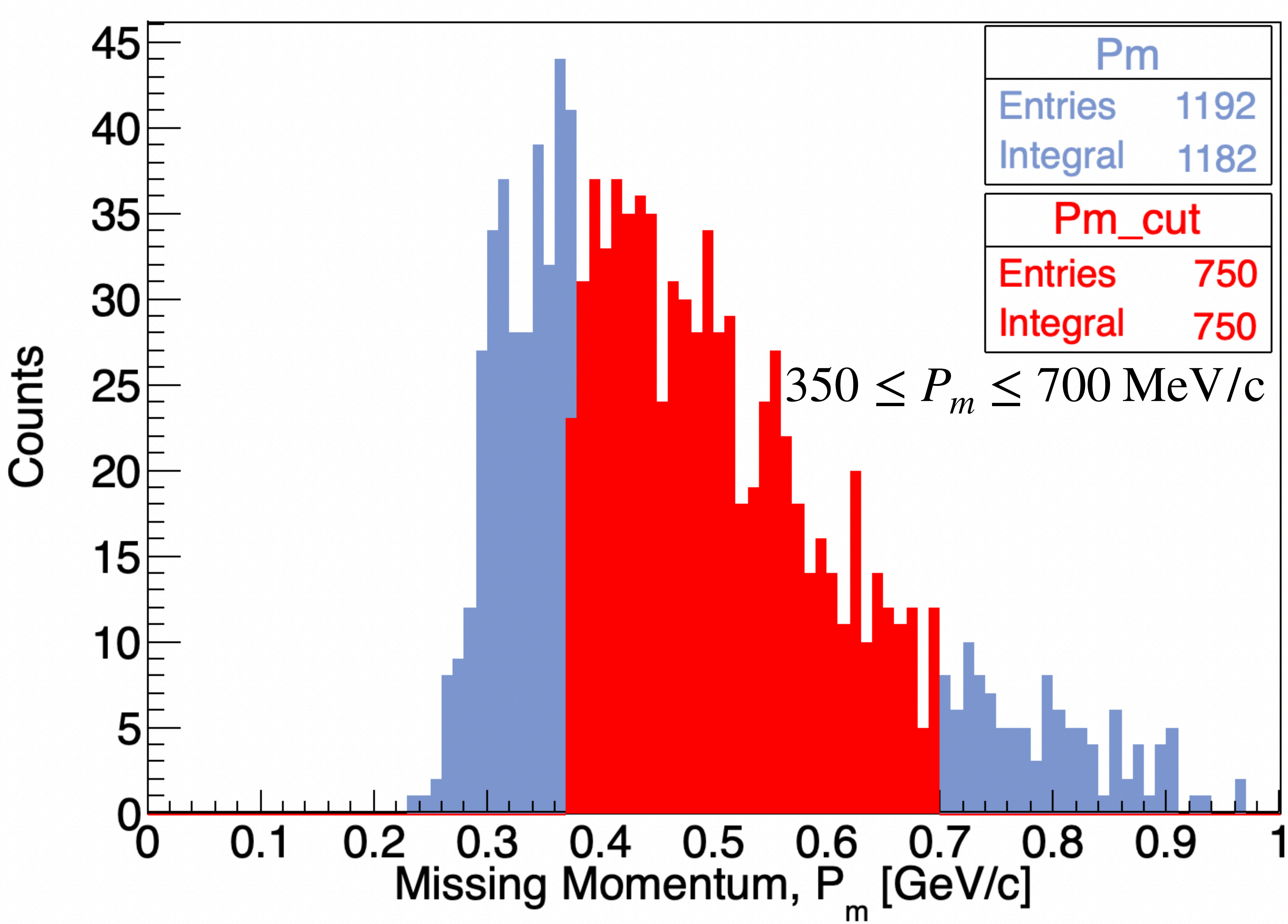
θ_{rq} :

- Angle between recoil system
- and virtual photon direction

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

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

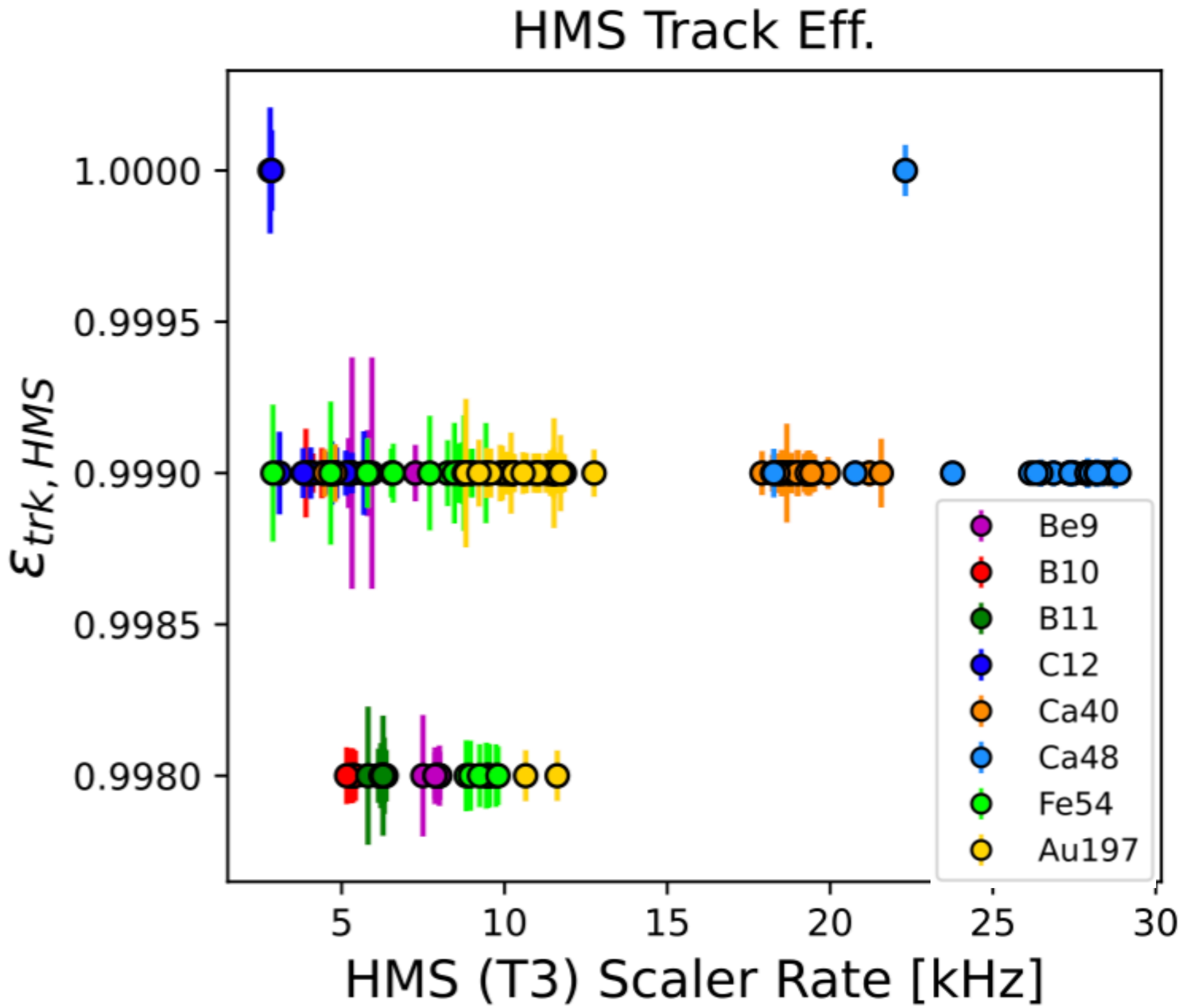
Event Selection (SRC)



- Kinematic Cut to select short-range correlated nucleon

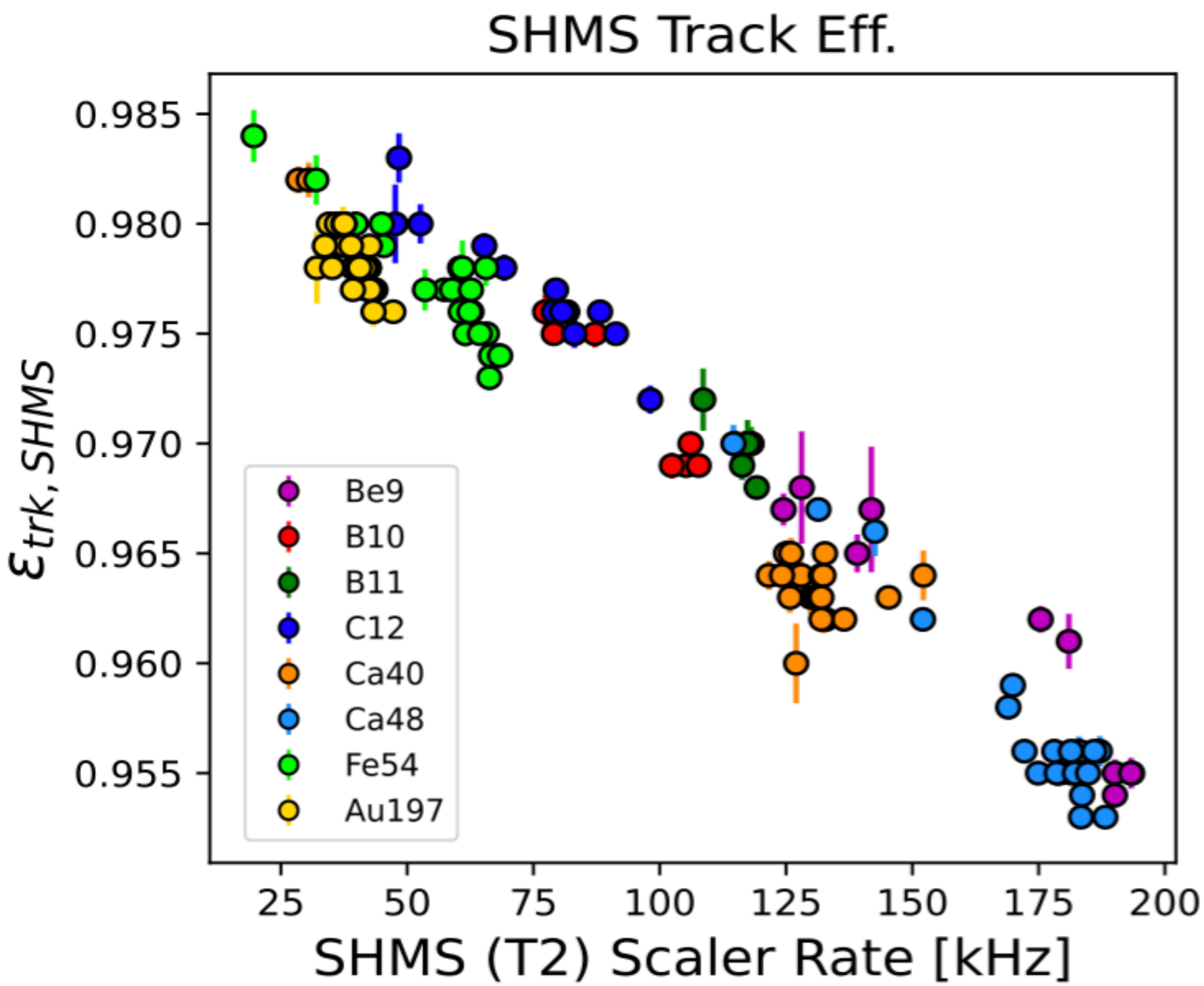
Yield Extraction

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



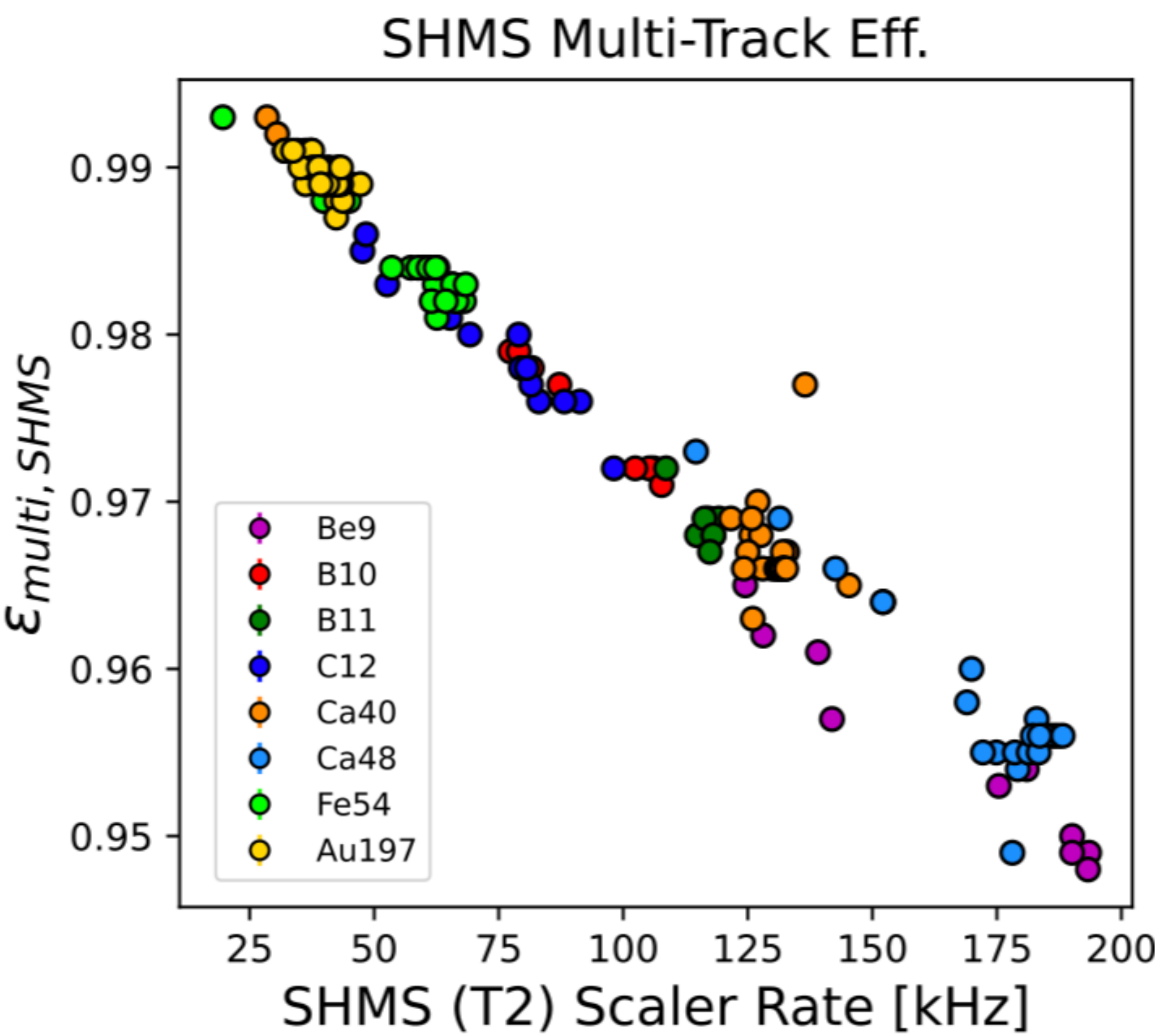
Yield Extraction

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



Yield Extraction

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



Yield Extraction

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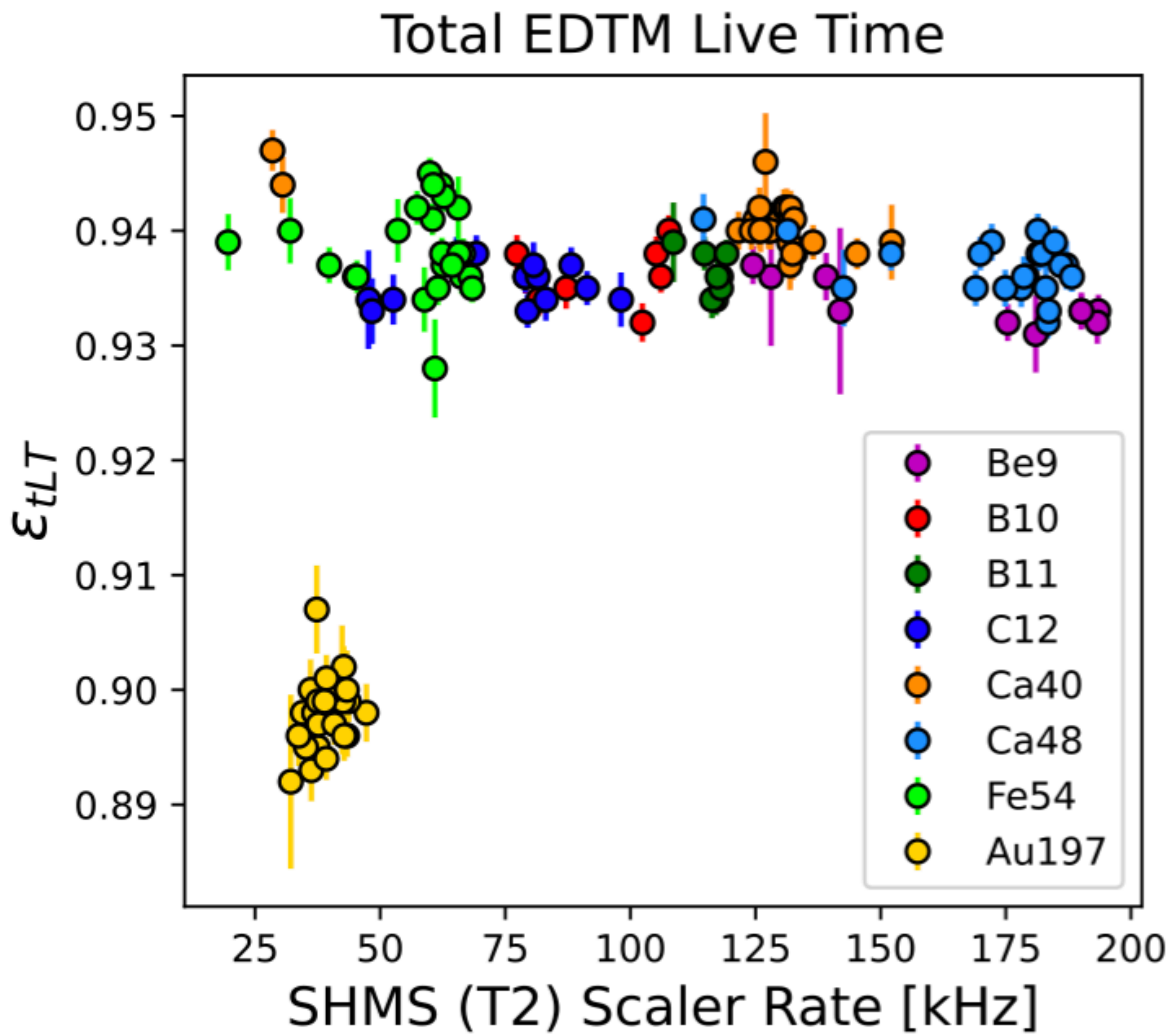
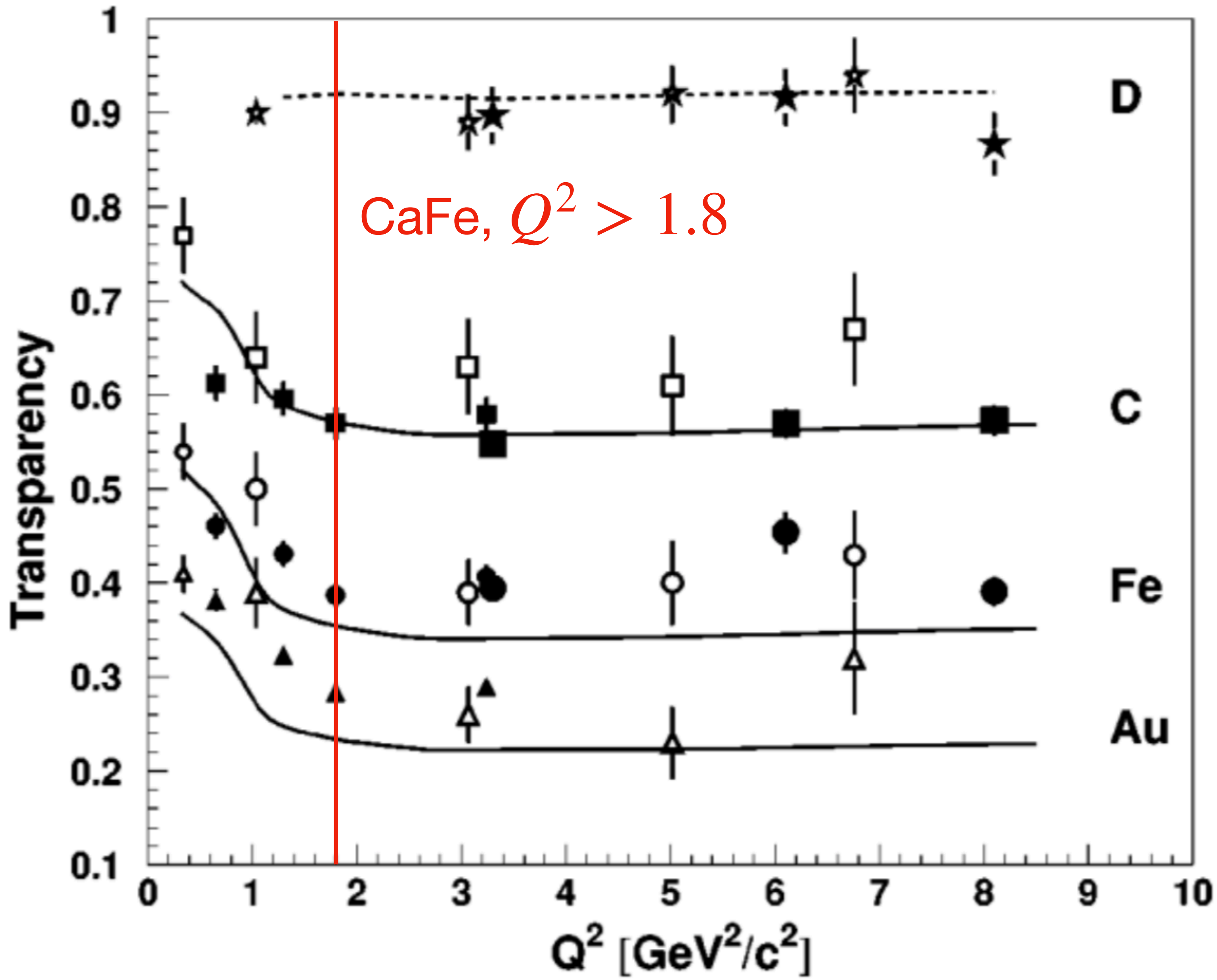


Yield Extraction

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

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



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

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

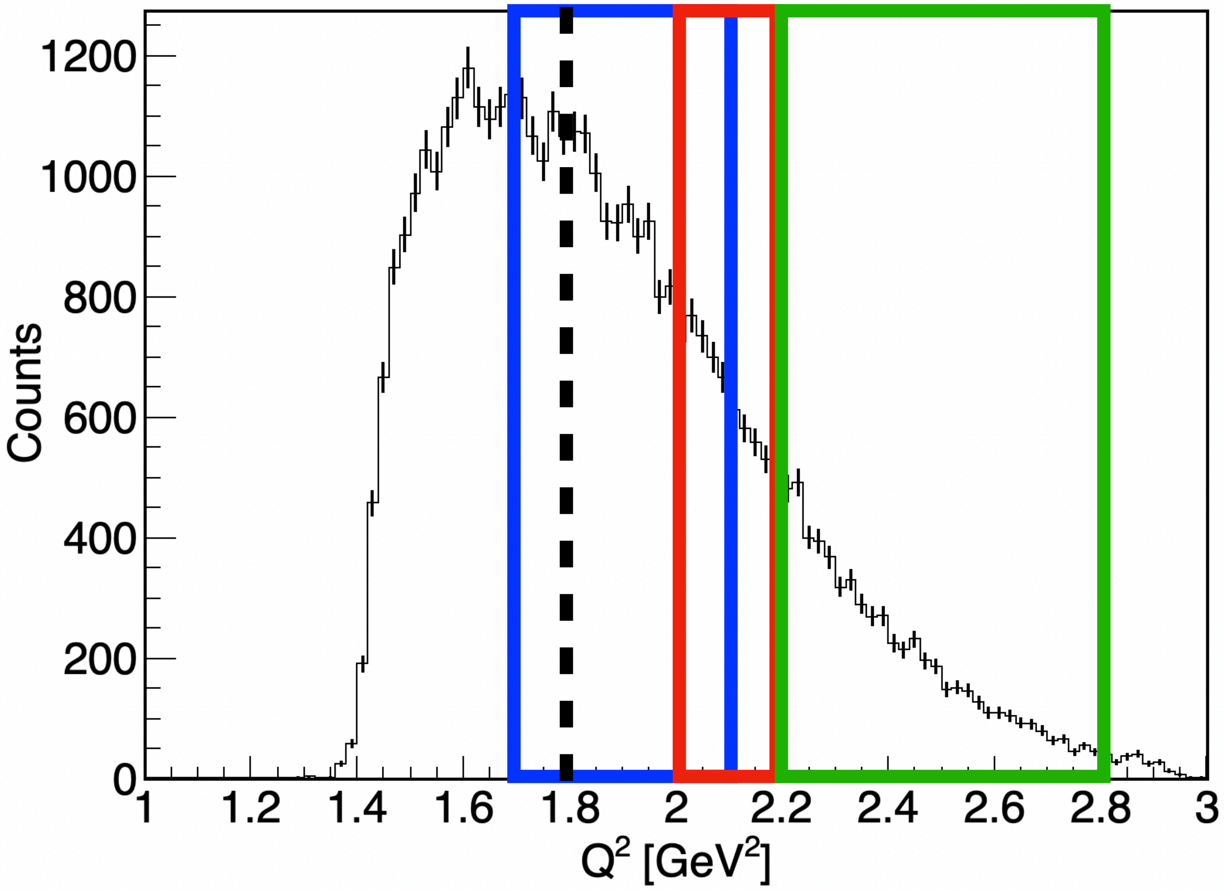
$c \to 1$

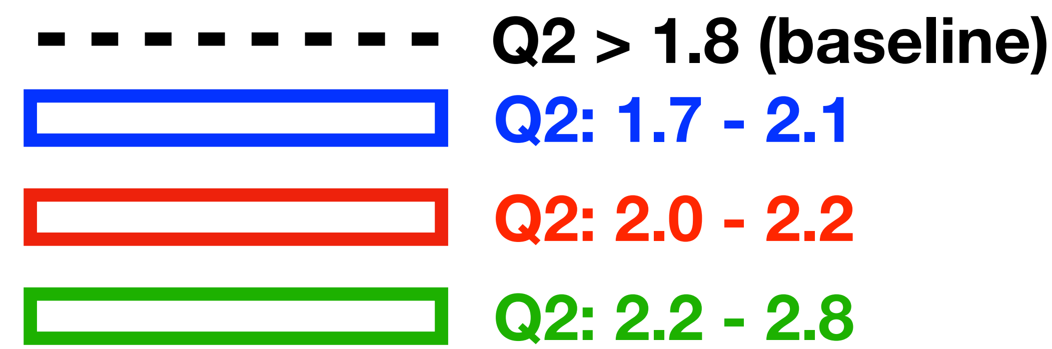
$\alpha \to 0.24$

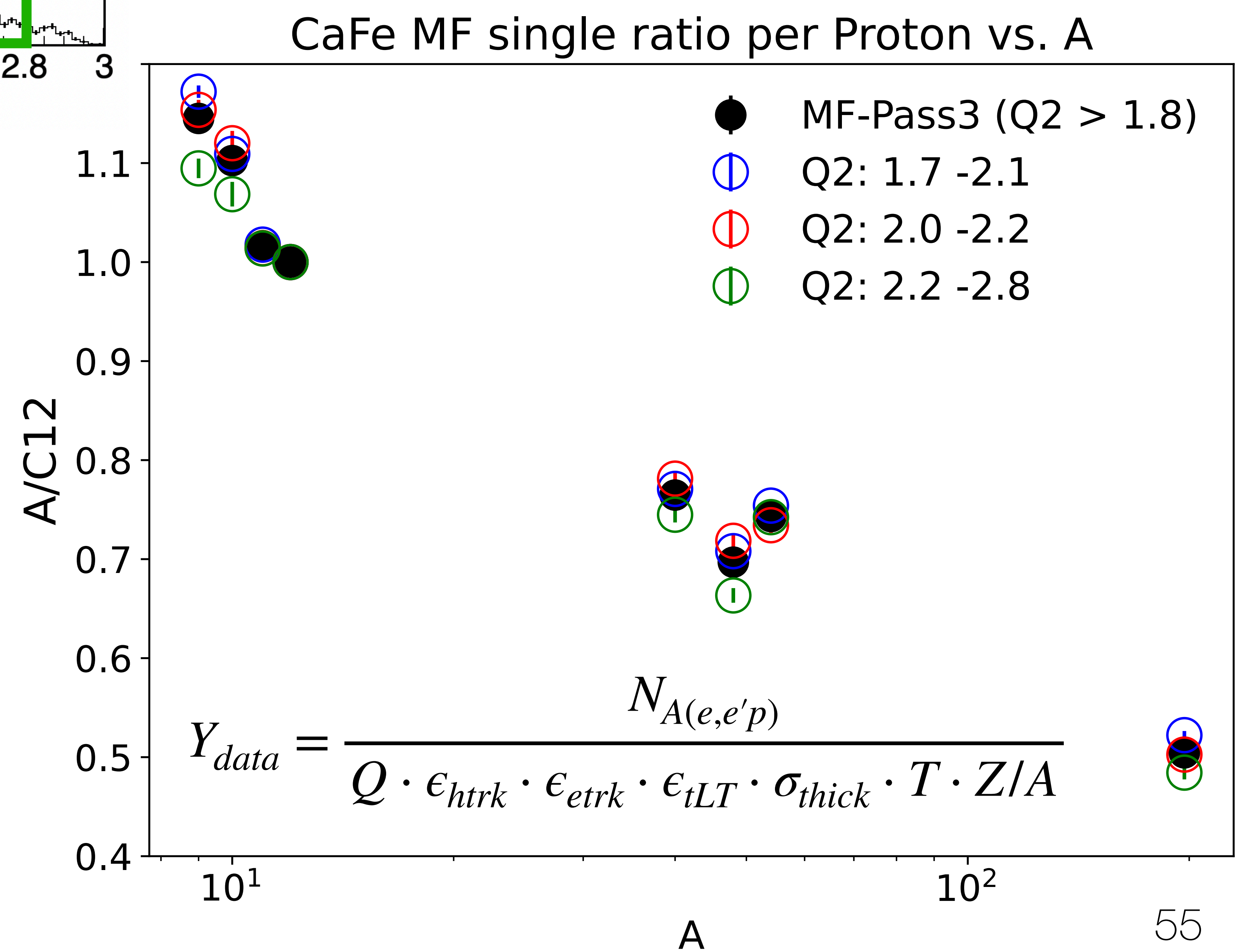
Single Ratio Checks

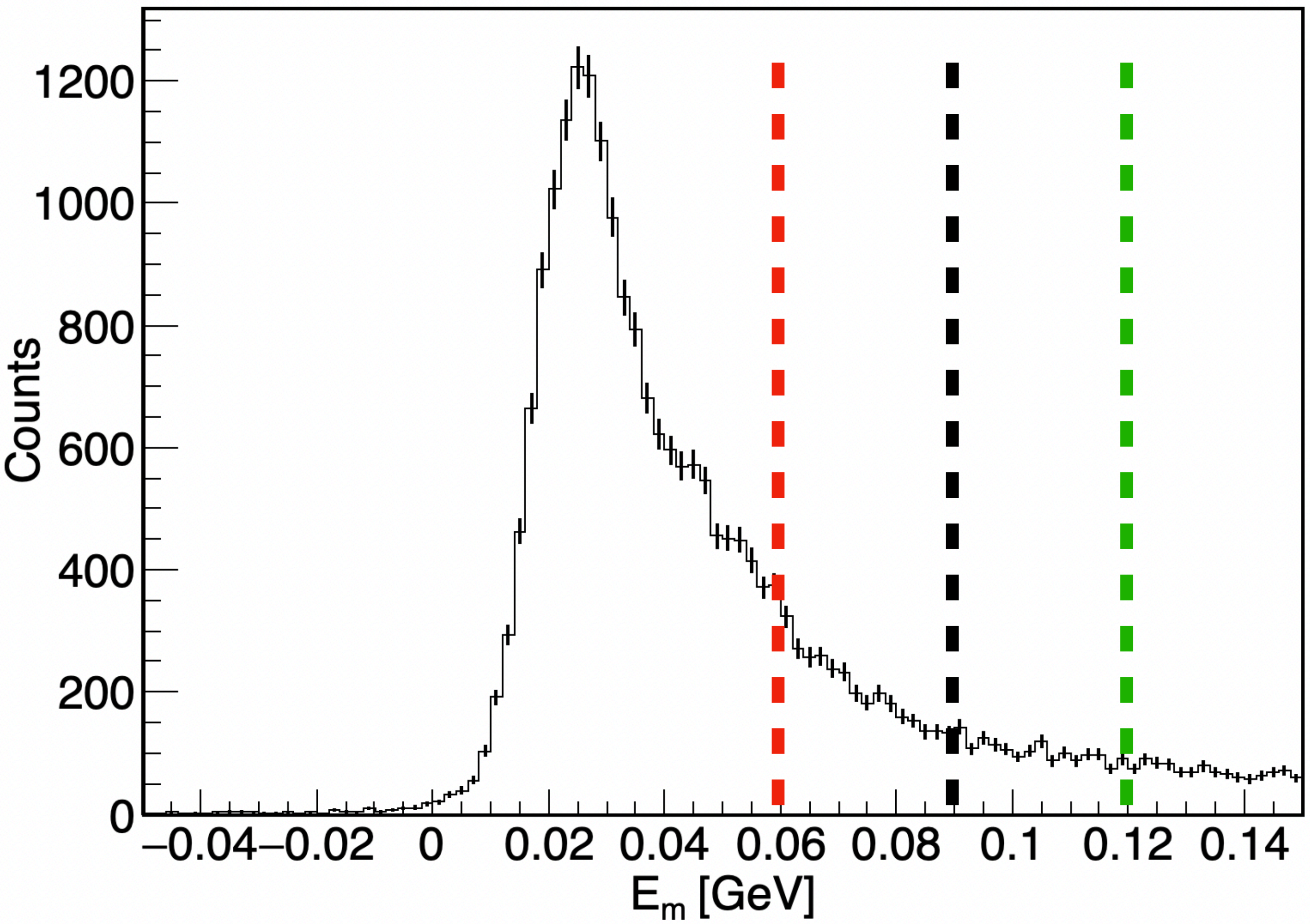
$$R = \left.\frac{Y_A}{Y_{C12}}\right|_{MF}$$

Q2 Dependence on Single Ratios: A_MF / C12_MF







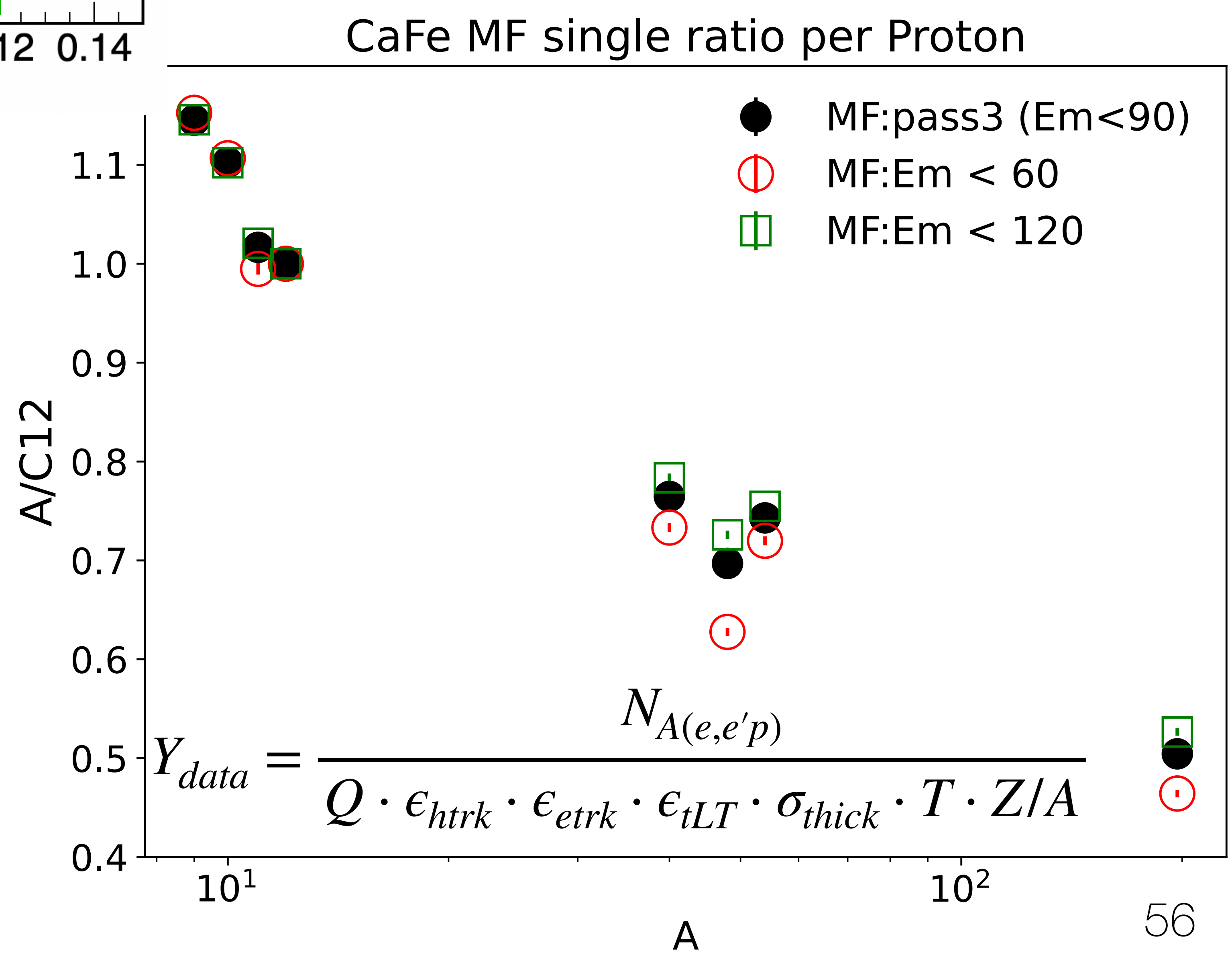


Missing Energy Dependence on Single Ratios: A_MF / C12_MF

Em < 90 MeV (baseline)

Em < 60 MeV

Em < 120 MeV

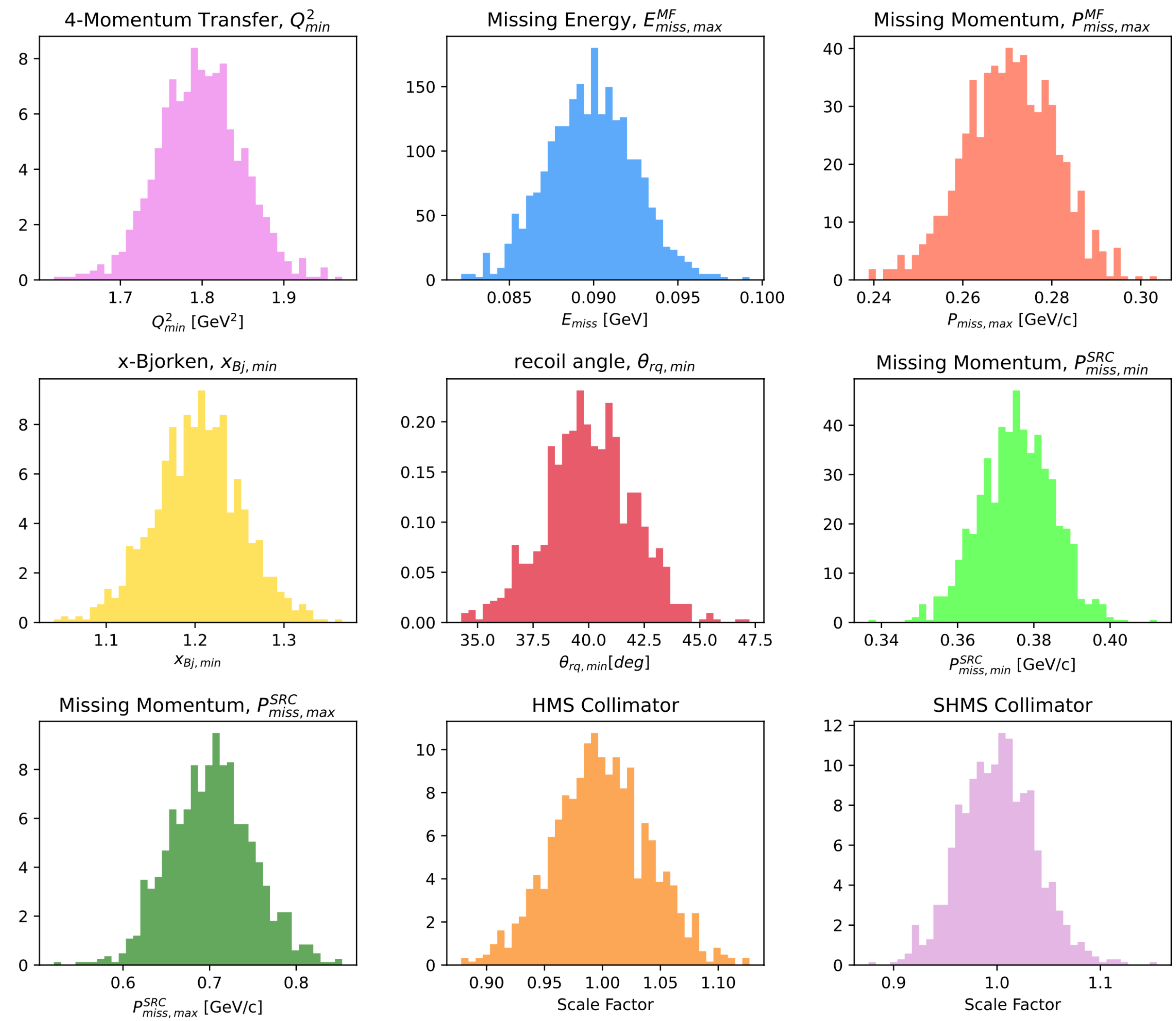


$$Y_{data} = \frac{N_{A(e,e'p)}}{Q \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{tLT} \cdot \sigma_{thick} \cdot T \cdot Z/A}$$

Systematics

example of how systematic cut sensitivity is studied in CaFe

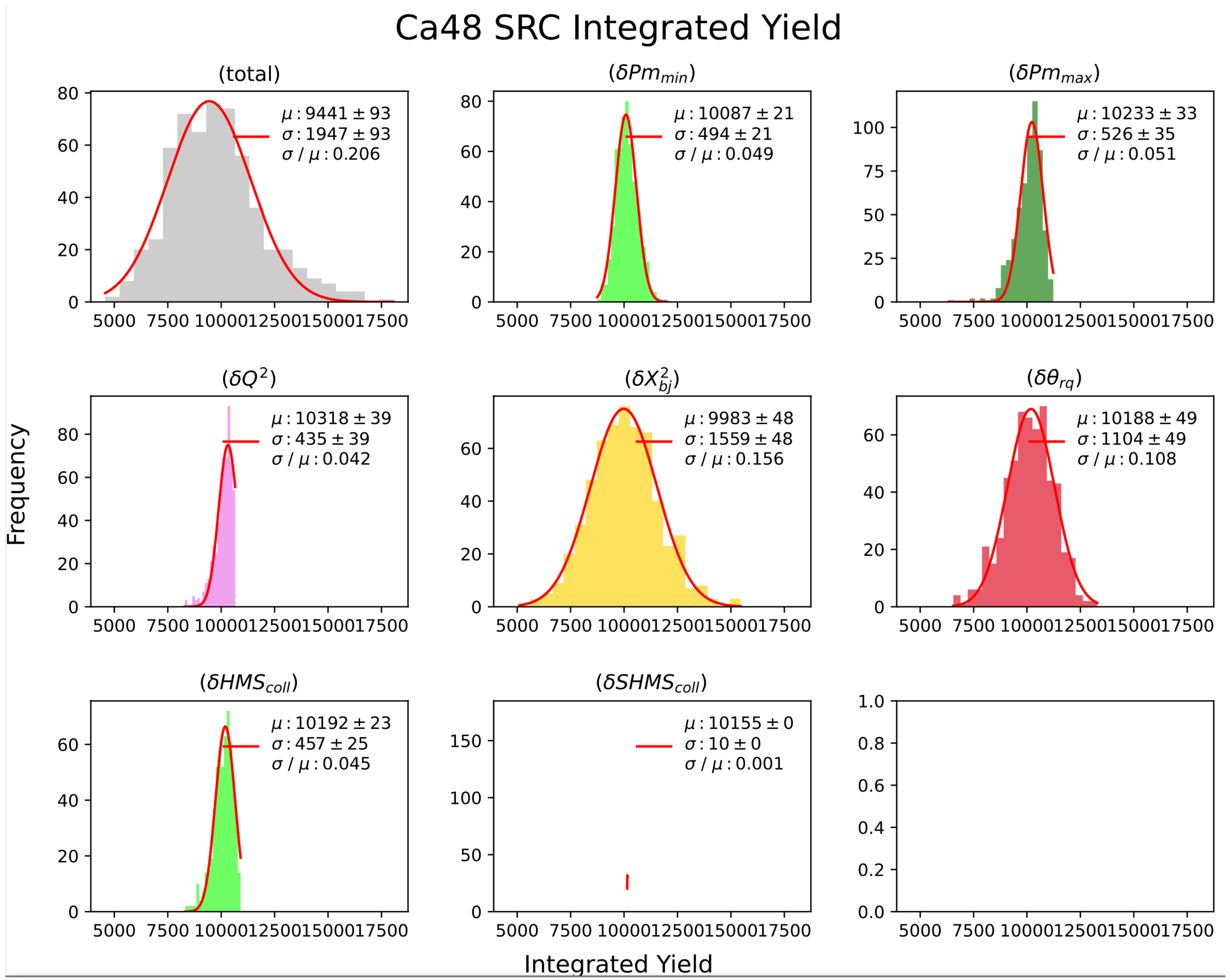
- randomly-sampled gaussian for N=1000 distinct kinematical cut variations
- central kinematical cuts were varied by +/- 2 standard deviations
- data analysis performed for every N=1000 cut variations to determine the systematic spread



Systematics

example of how systematic cut sensitivity is studied in CaFe

- systematic spread (gray) in integrated missing momentum yield due to different cut variations
- individual (colorful) contributions from each varied cut on the total integrated yield



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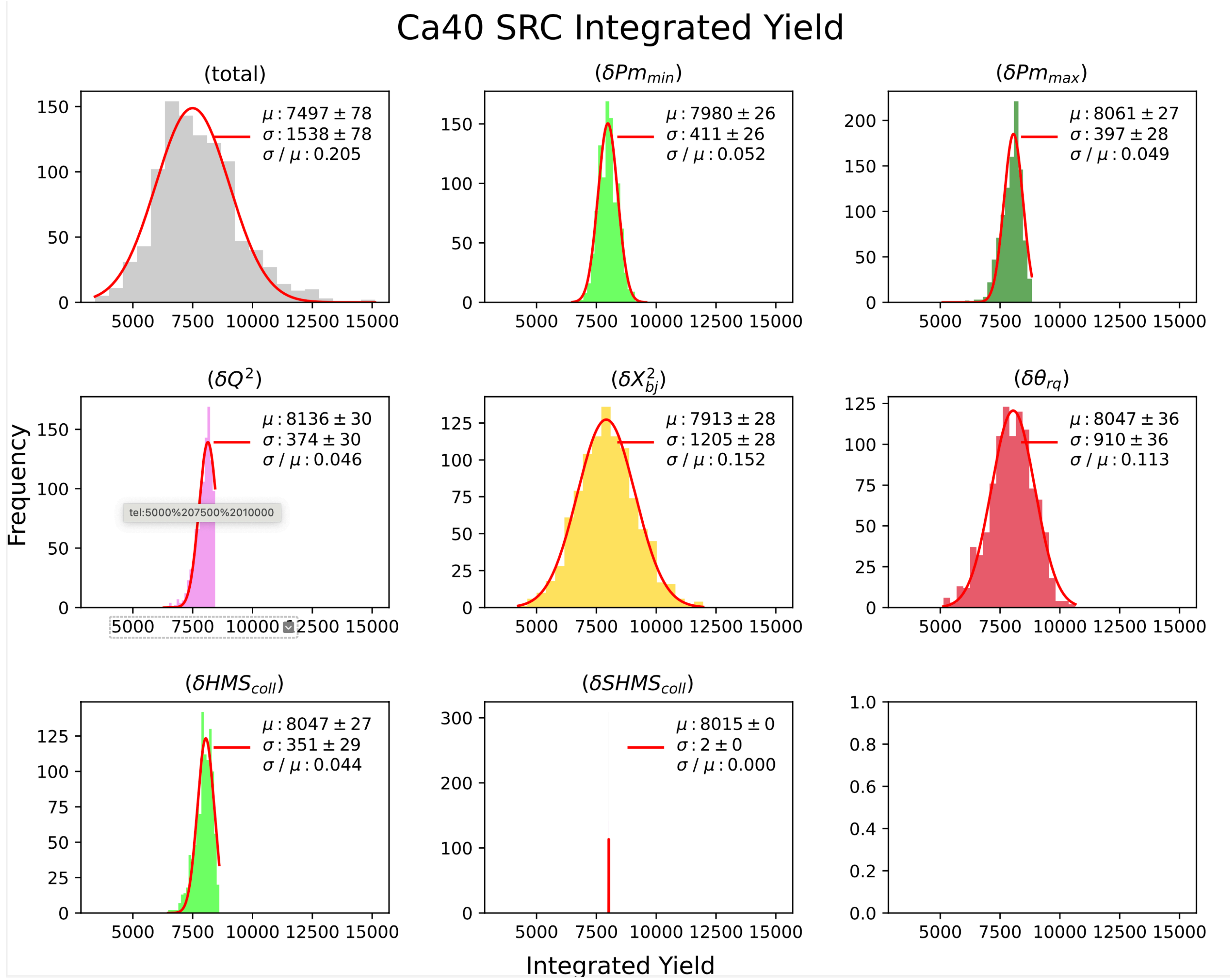

Systematics

example of how systematic cut sensitivity is studied in CaFe

- Typical systematics on single SRC ratios (example shown for SRC Ca48/40)

- Systematic effects on single ratio of SRC/SRC seem to be ~ 1 %