The CaFe Experiment:

Isospin Dependence of Short-Range Correlations in Nuclei

C. Yero
(On behalf of the CaFe collaboration)

Hall C Winter Collaboration Meeting

Jan 12 - 13, 2023

Proposal: PR12-16-004

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

CaFe Experiment Overview

- 8-day measurement of (e, e'p) cross sections on:

  d, [^{9}Be - ^{10}B - ^{11}B - ^{12}C], [^{40}Ca - ^{48}Ca - ^{54}Fe]

  (… still need 1 PAC day of data-taking to complete experiment)

- A(e, e'p) at selected kinematics:
  - mean-field (MF) nucleons (k_{rel} < 250 MeV/c)
  - short-range correlated (SRC) pairs ($k_{rel} \gtrsim$ 250 MeV/c)

- what will CaFe extract?
  - double ratios (SRC/MF)_A1 / (SRC/MF)_A2

    => relative pairing probability of high-p protons in different nuclei

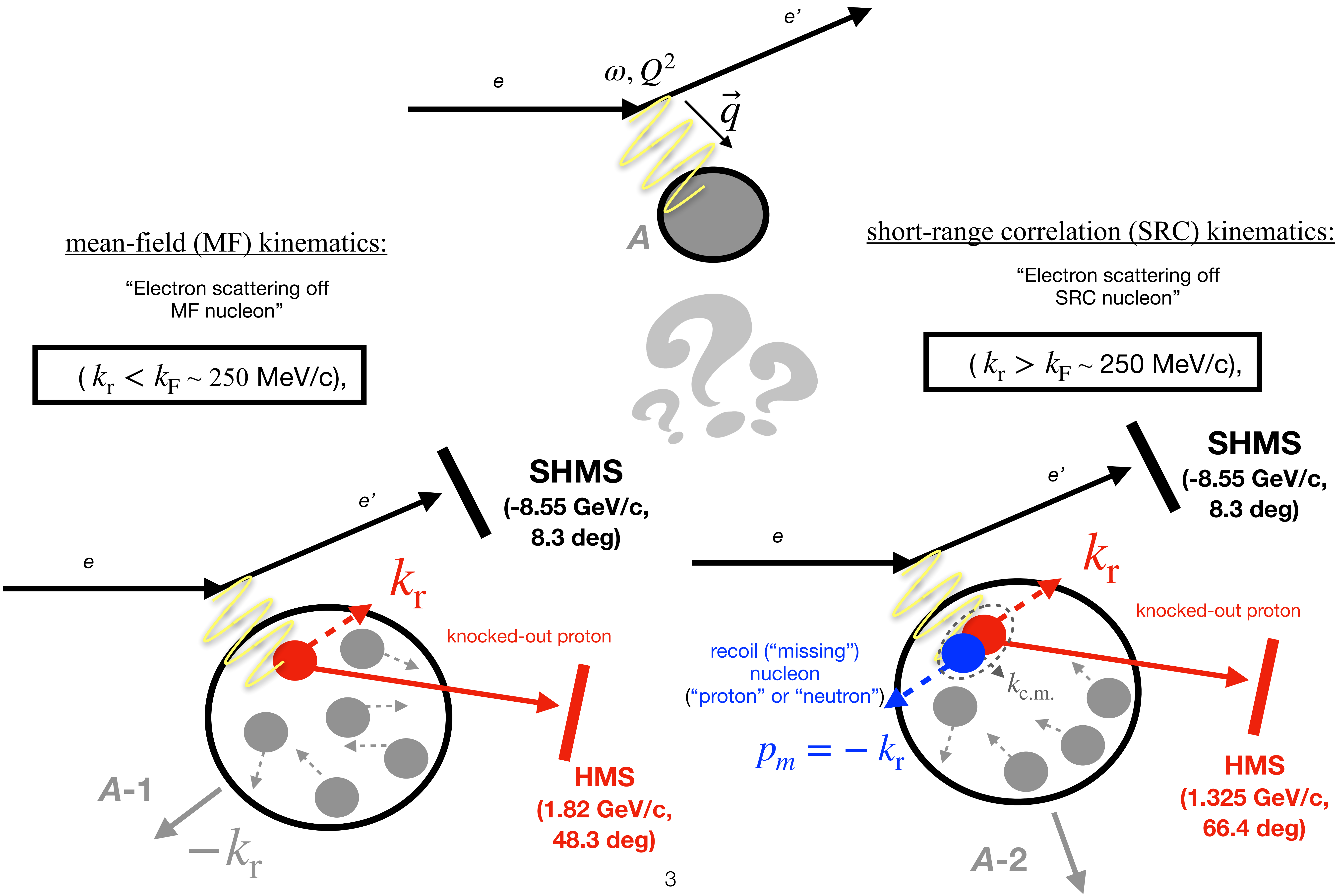
  - single ratios SRC (high-p) / MF (low-p)

    => proton pairing probability

  - absolute & reduced cross sections

    => distorted spectral function (not observable)

CaFe Experiment Kinematics



Motivation: Which nucleons form SRC pairs?

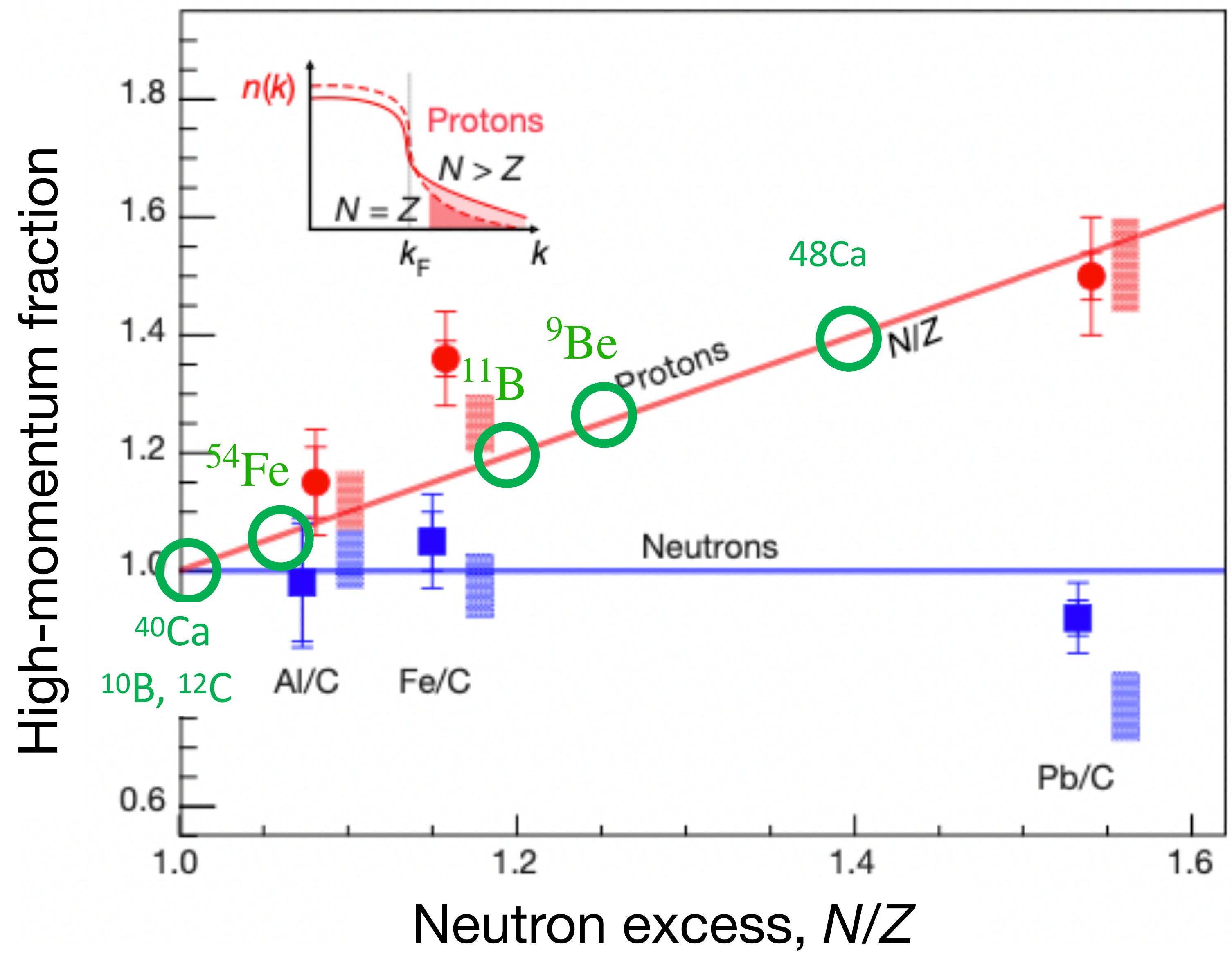
SRC pairs:

- account for almost all high momentum nucleons in nuclei
- are predominantly np

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?

Projected CaFe Results



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

Data Analysis

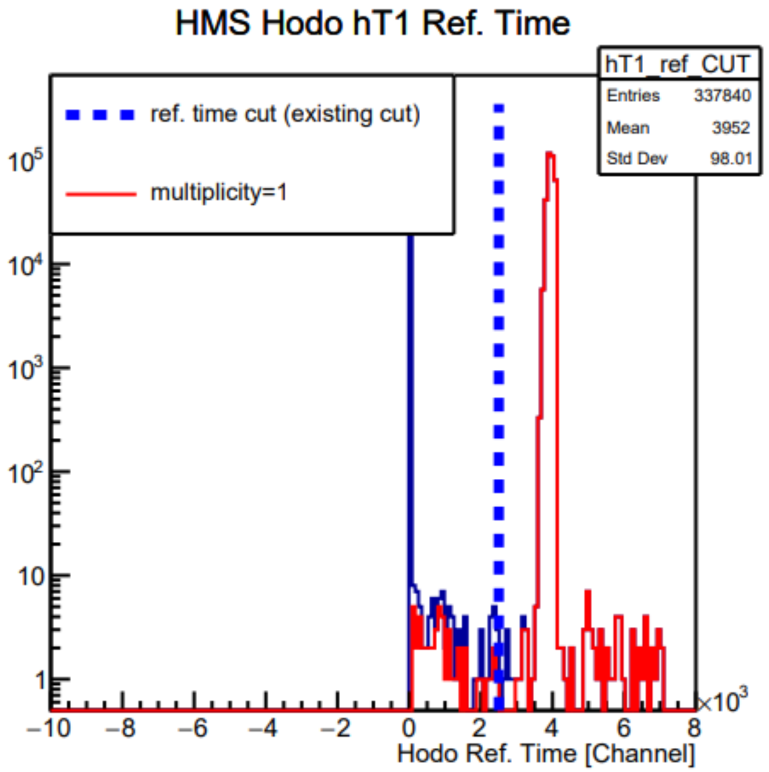
- Set Ref. Times / Detector Time Windows / Calibrations (COMPLETED)
- Quality Check of Kinematics (COMPLETED)
- SHMS Optics Delta Optimization (IN-PROGRESS)
  - H(e, e'p), d(e, e'p), C(e, e'p) data-to-simulation (PENDING)

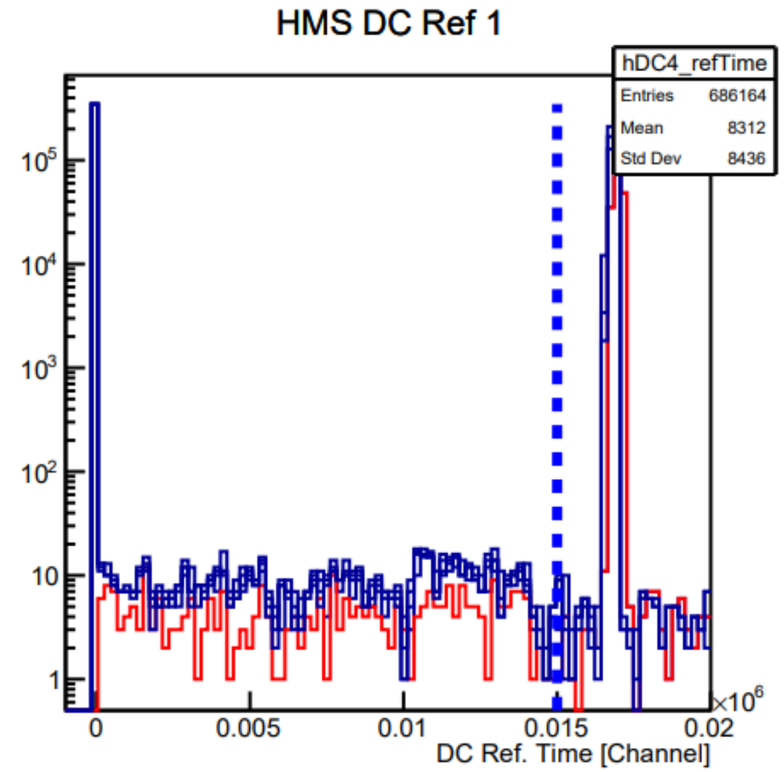
Analysis Challenges

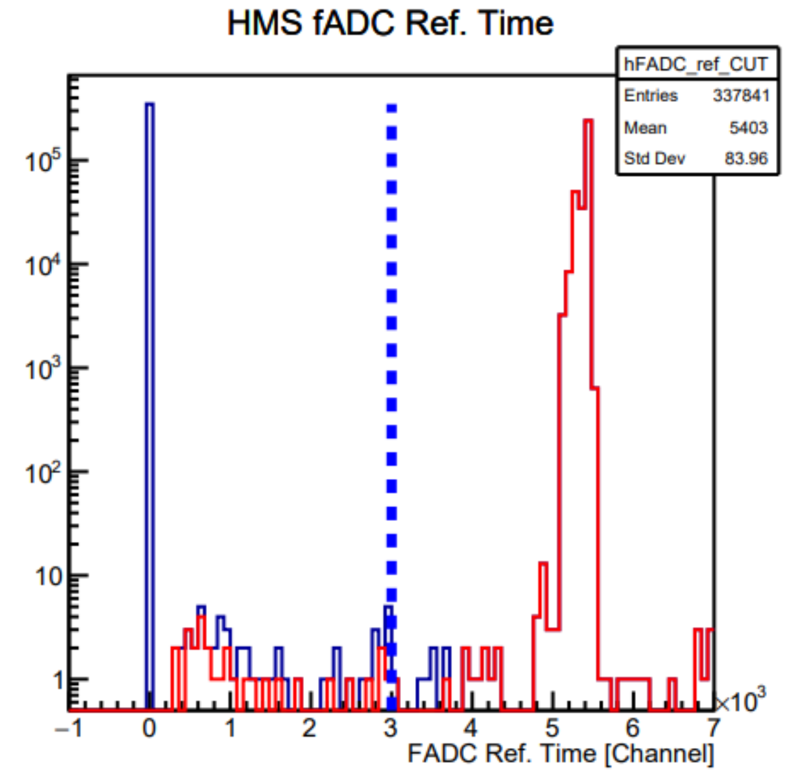
- Ca-48 Contamination Studies (IN-PROGRESS)
  - Estimate (Hydrogen, Carbon) contamination fraction (COMPLETED)
  - Results of chemical analysis of mineral oil from lab (IN-PROGRESS) (results needed to confirm our estimates)
- Beam Current Dependency (IN-PROGRESS)
  - BCM Linearity? HCANA tracking algorithm @ high rates ?

Set Reference Times

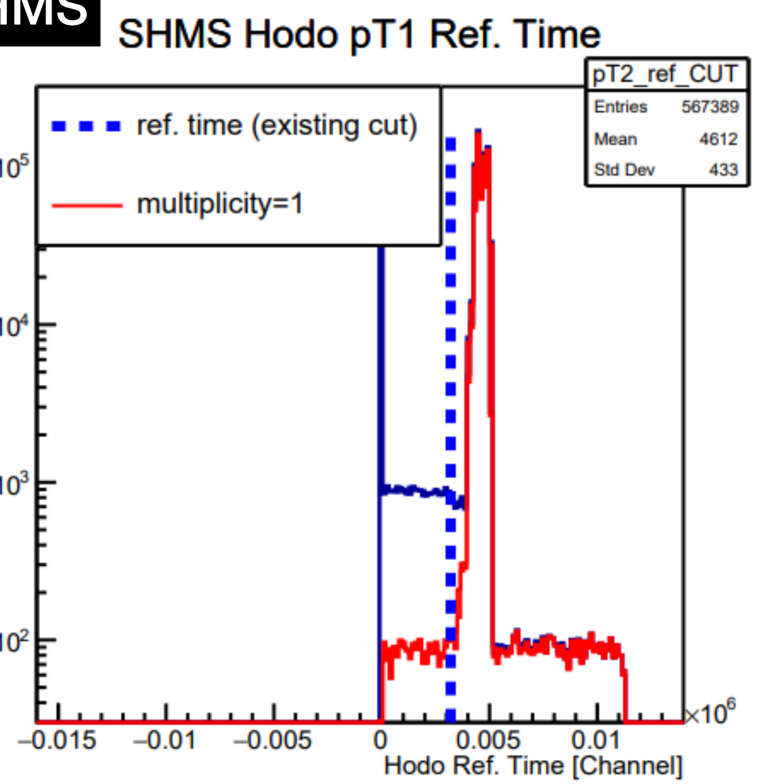
HMS

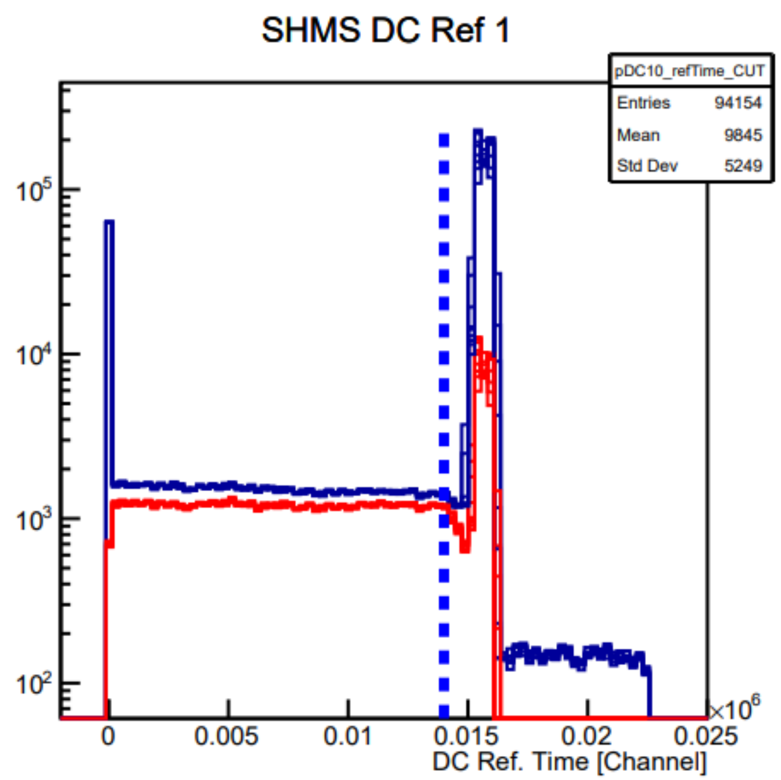


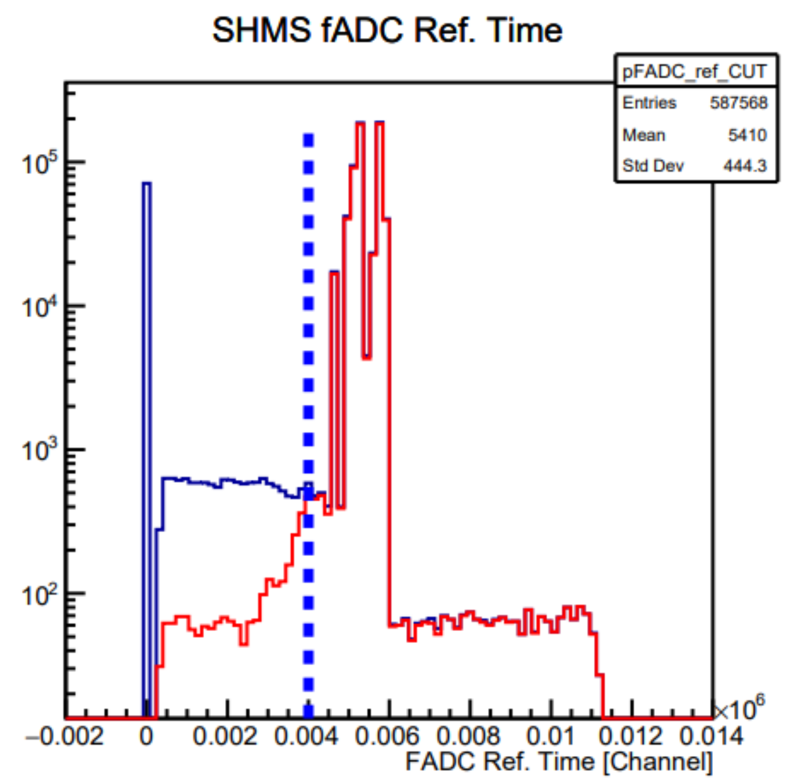




SHMS





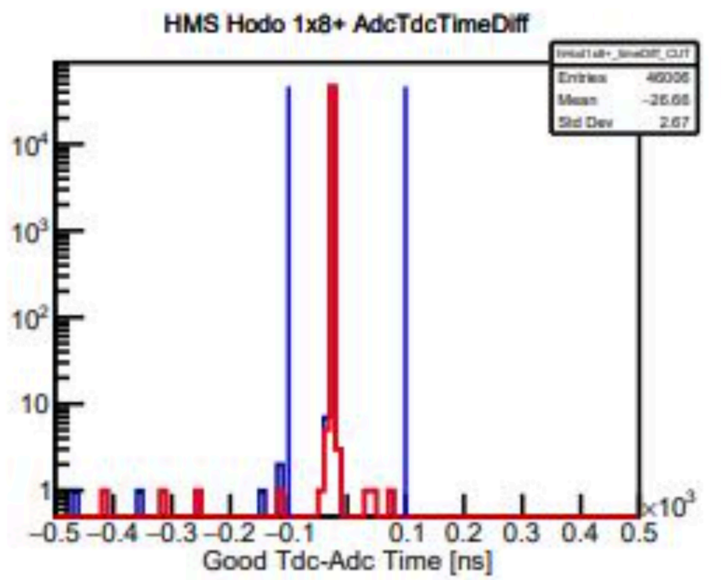


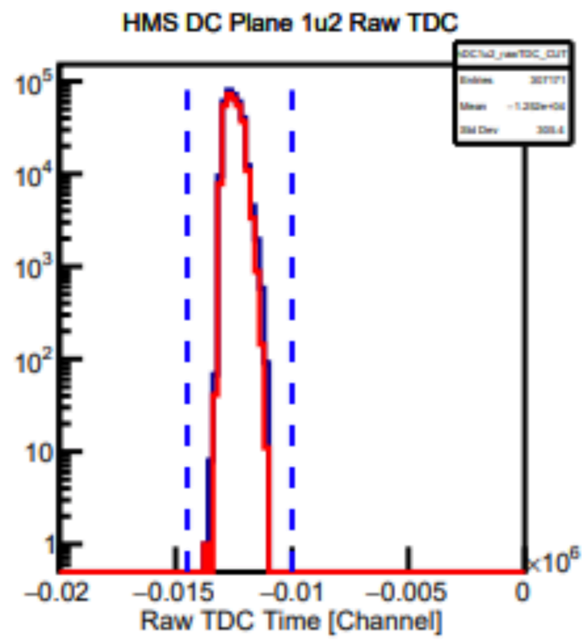
Plots made by: Noah Swan

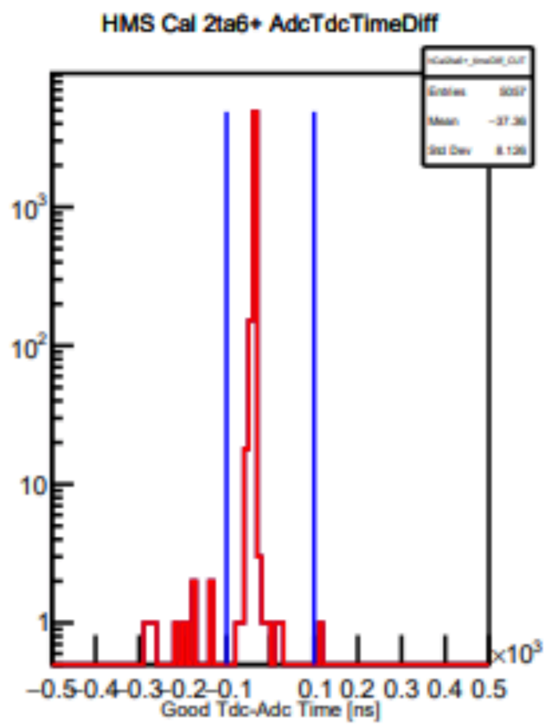
Set Detector Time Windows

(a single detector element per detector is shown for illustration purposes)

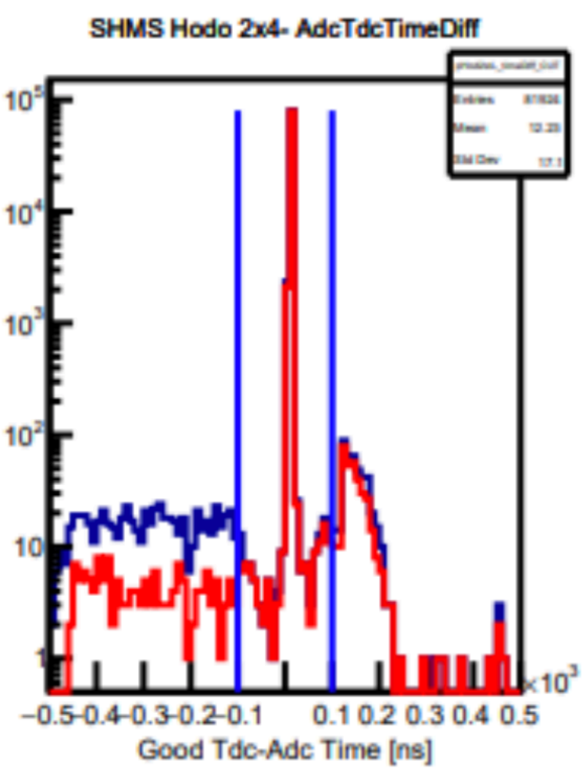
HMS

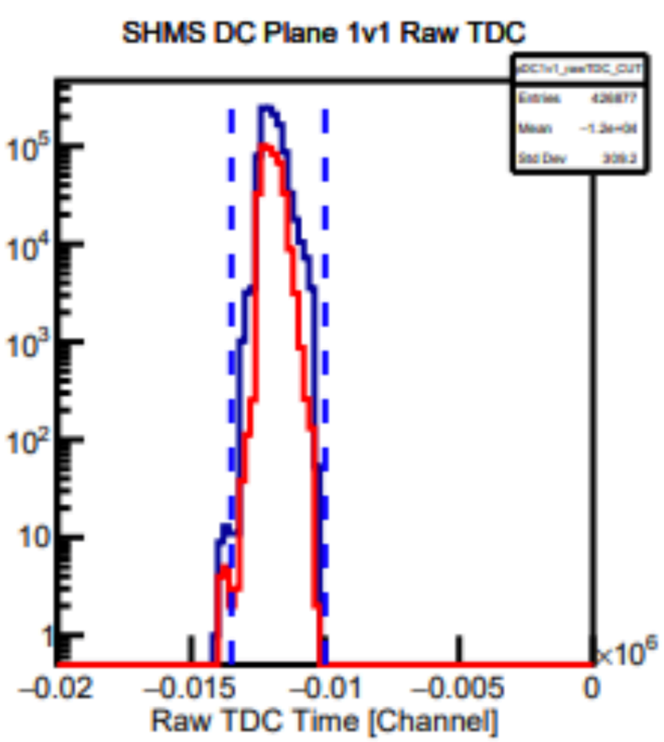


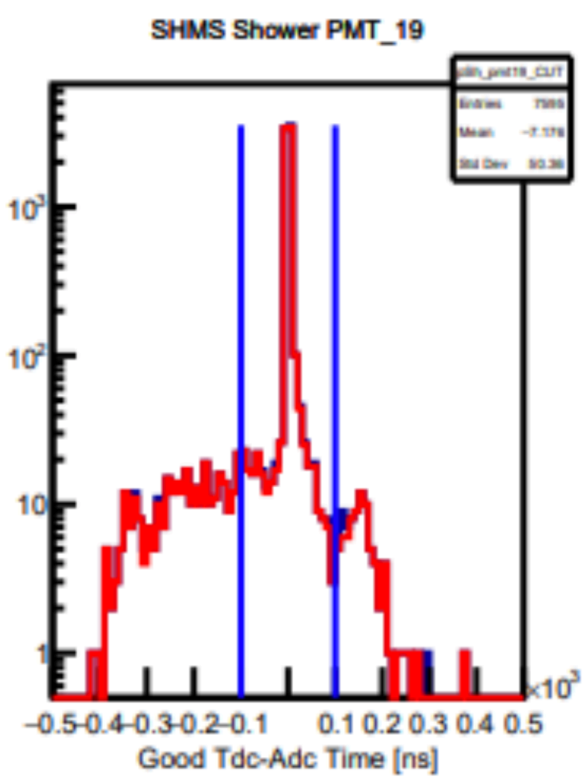




SHMS



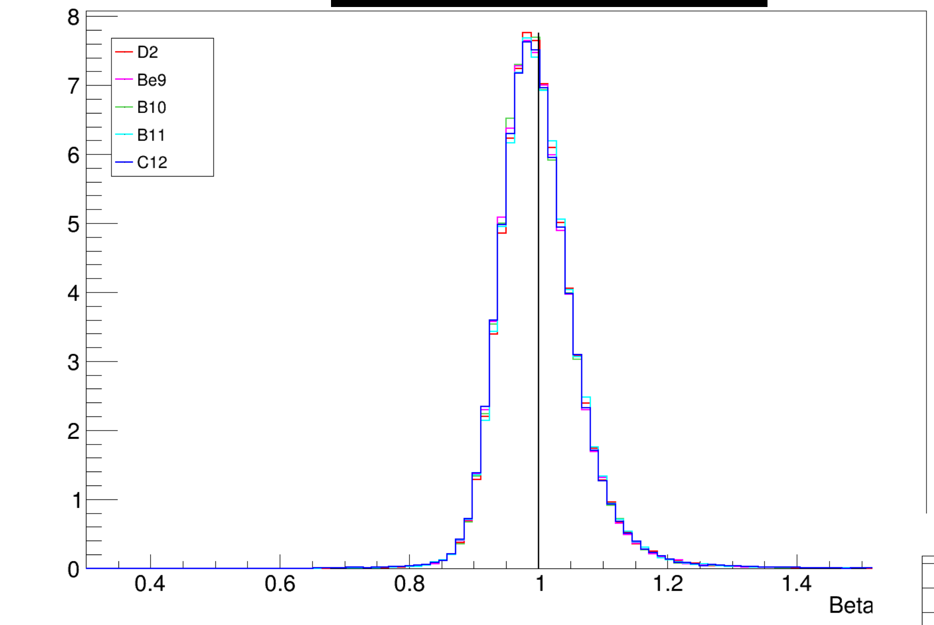




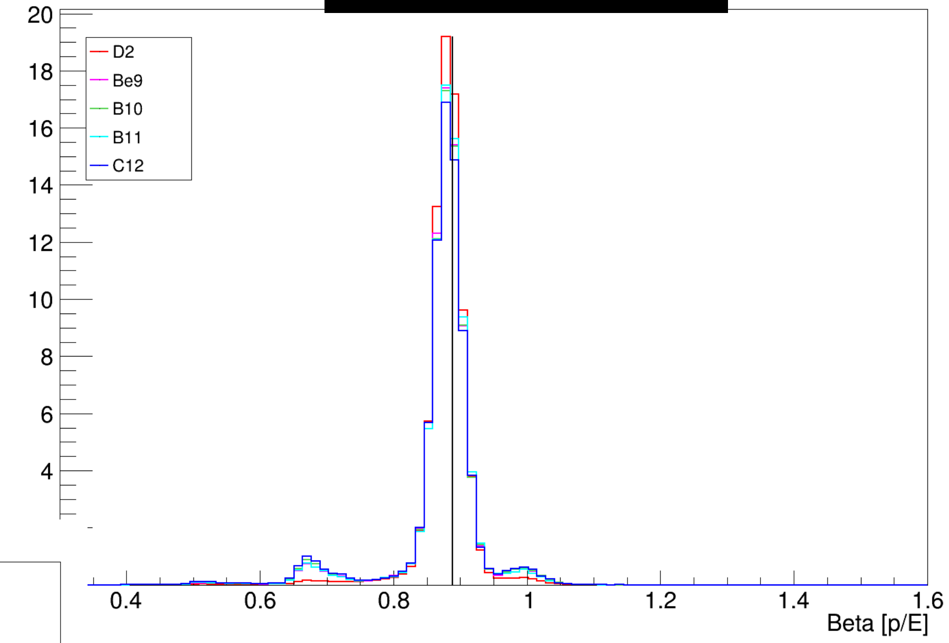
Plots made by: Noah Swan

Detector Calibrations

SHMS Hodo Beta



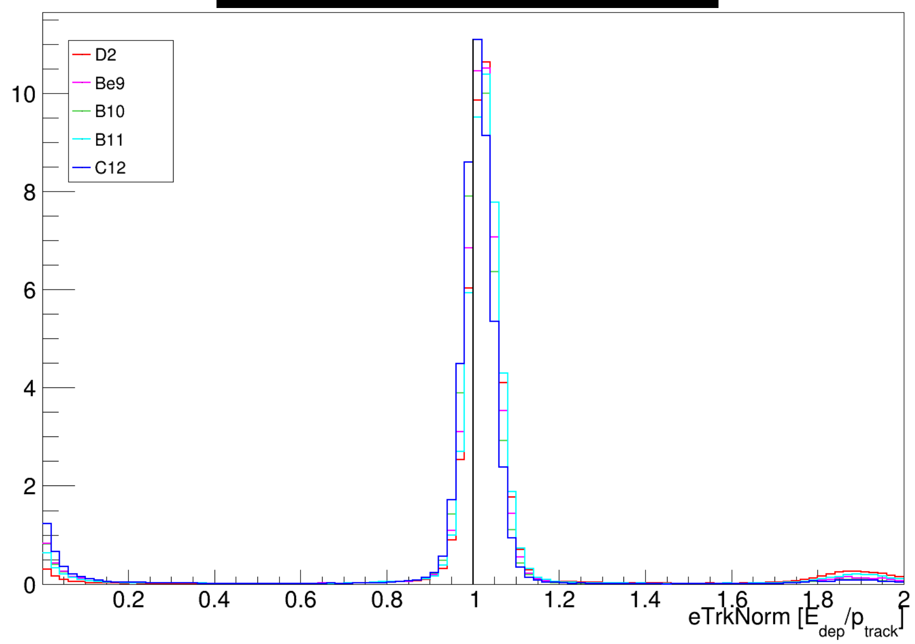
HMS Hodo Beta



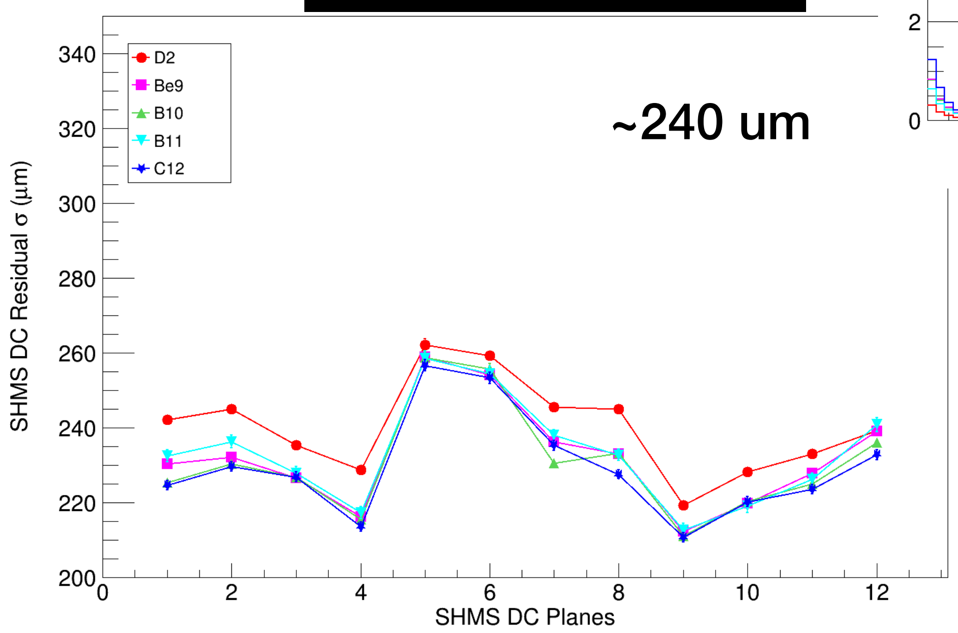
Legend

D2
Be9
B10
B11
C12

SHMS Calorimeter

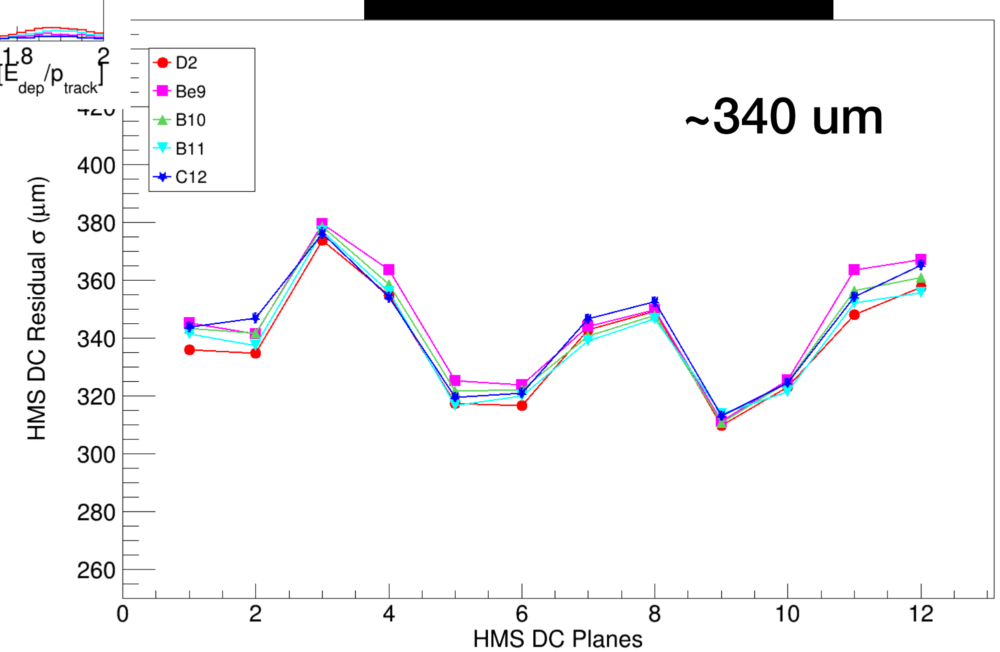


SHMS DC Residuals



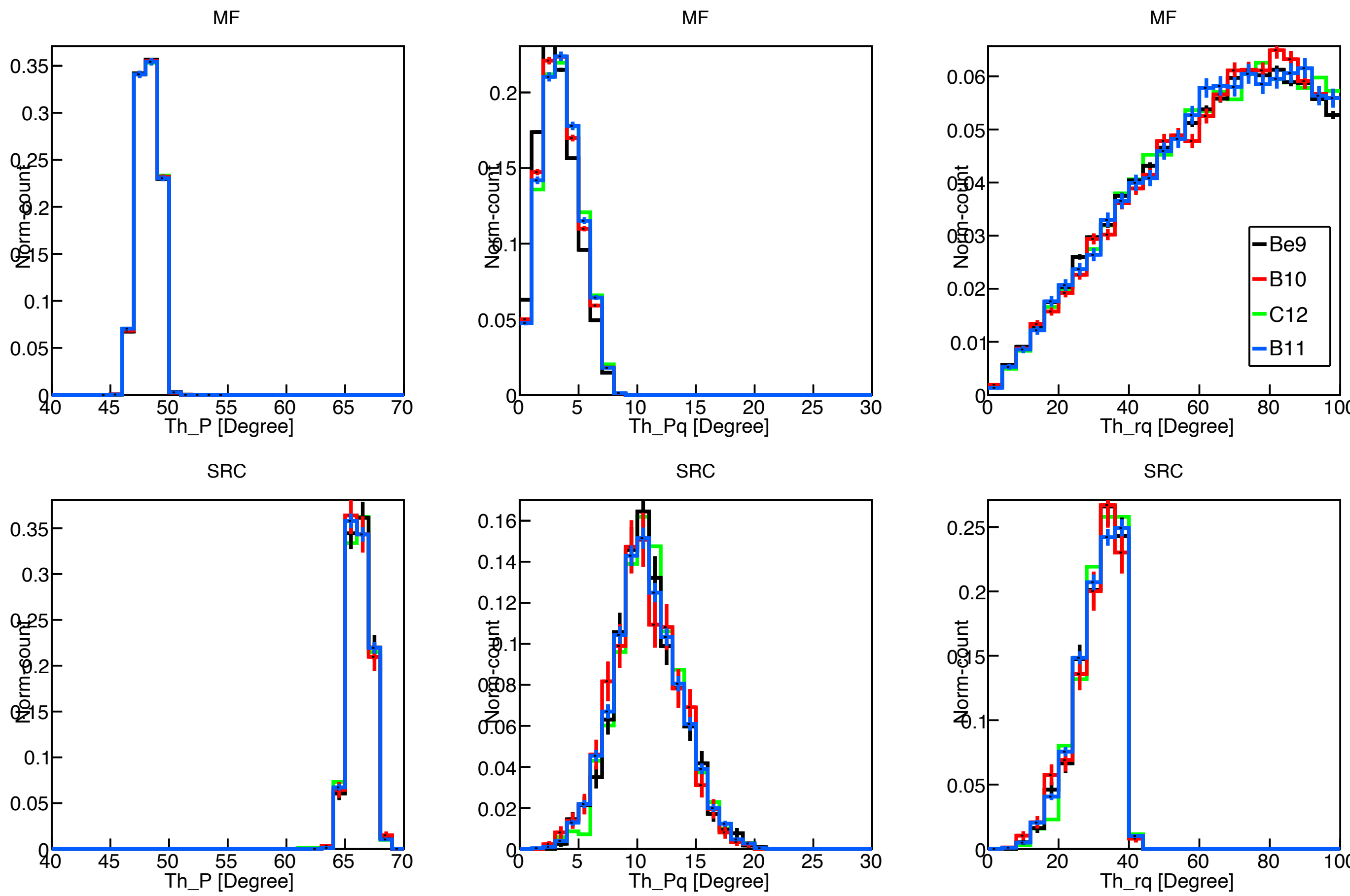
(ONLY light nuclei @ MF kinematics is shown for illustration purposes)

HMS DC Residuals

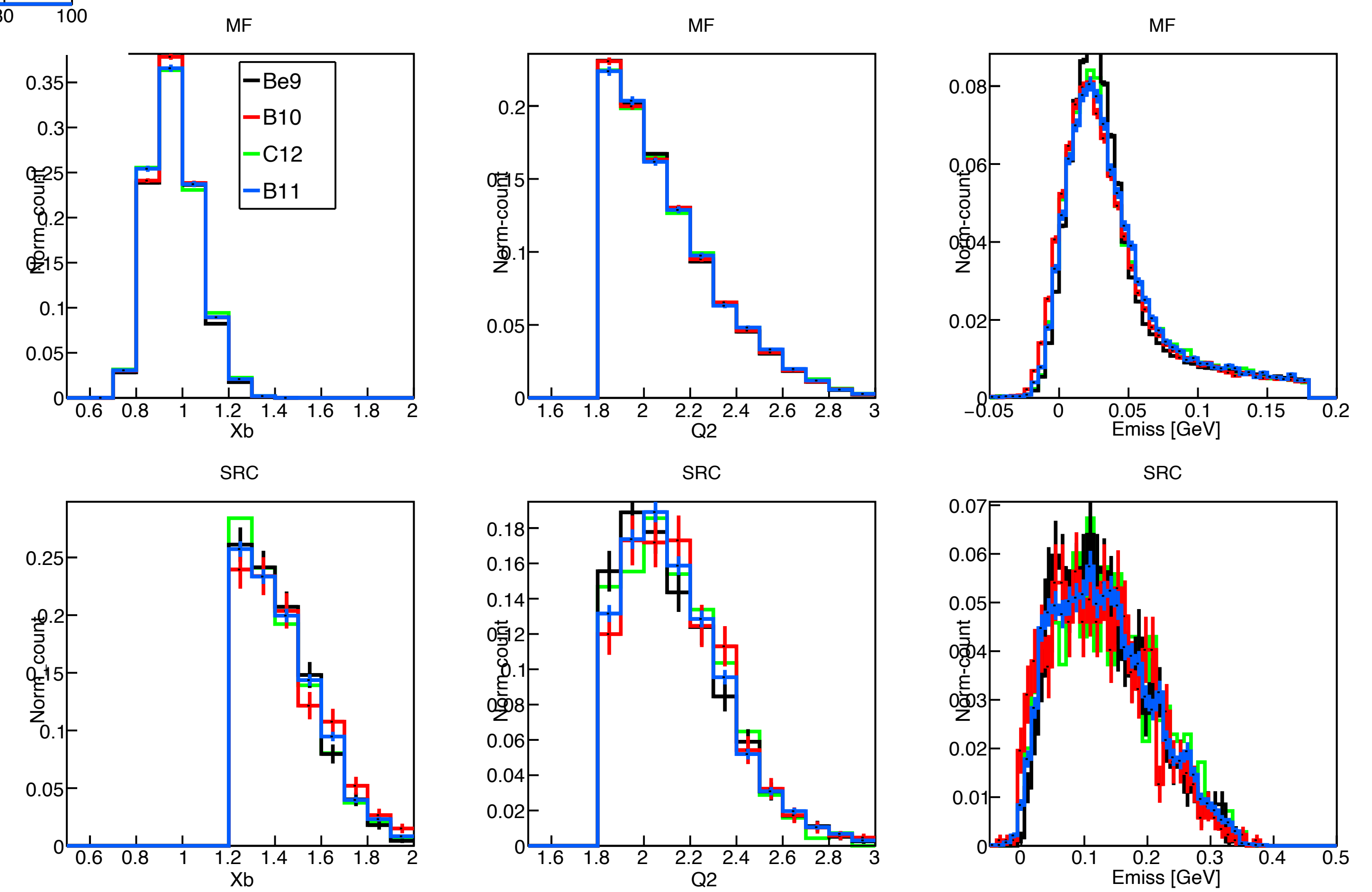


Plots made by: Noah Swan

Kinematics Quality Check: Light Nuclei

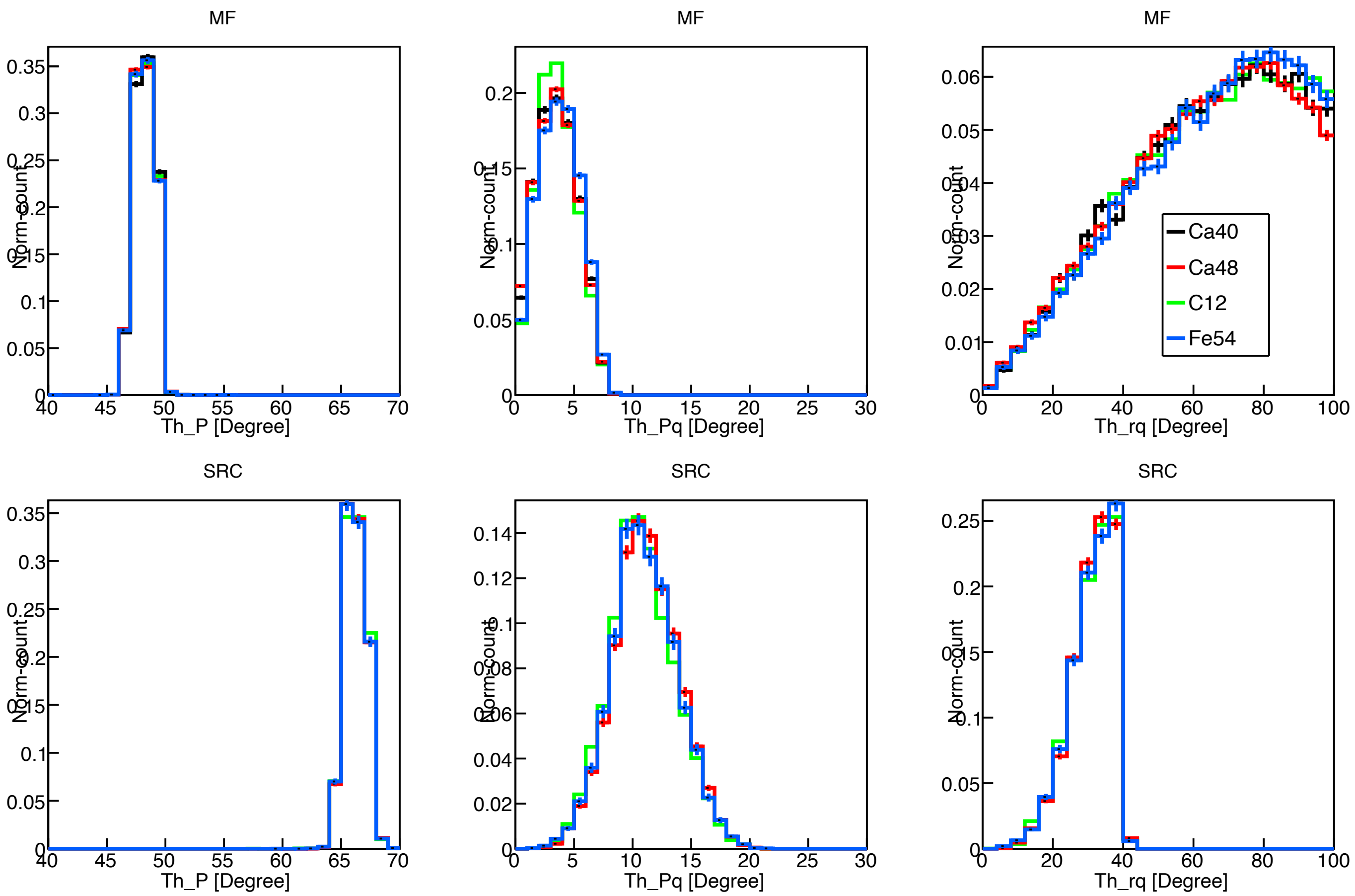


- Overlayed kinematics for light targets at (MF) and (SRC)
- histograms normalized to 1

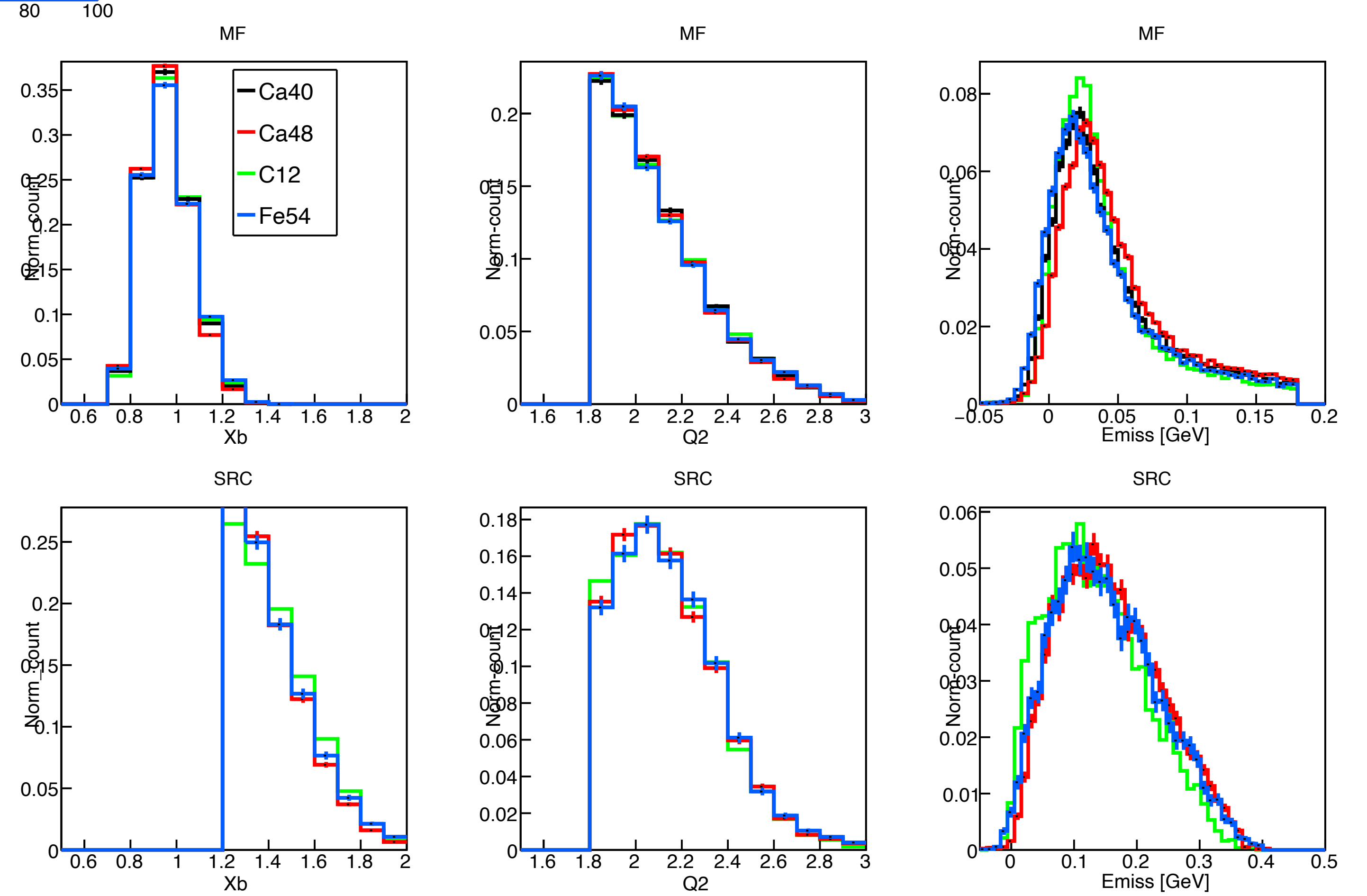


Plots made by: Dien Nguyen

Kinematics Quality Check: Heavy Nuclei



- Overlayed kinematics for heavy targets at (MF) and (SRC)
- histograms normalized to 1



Plots made by: Dien Nguyen

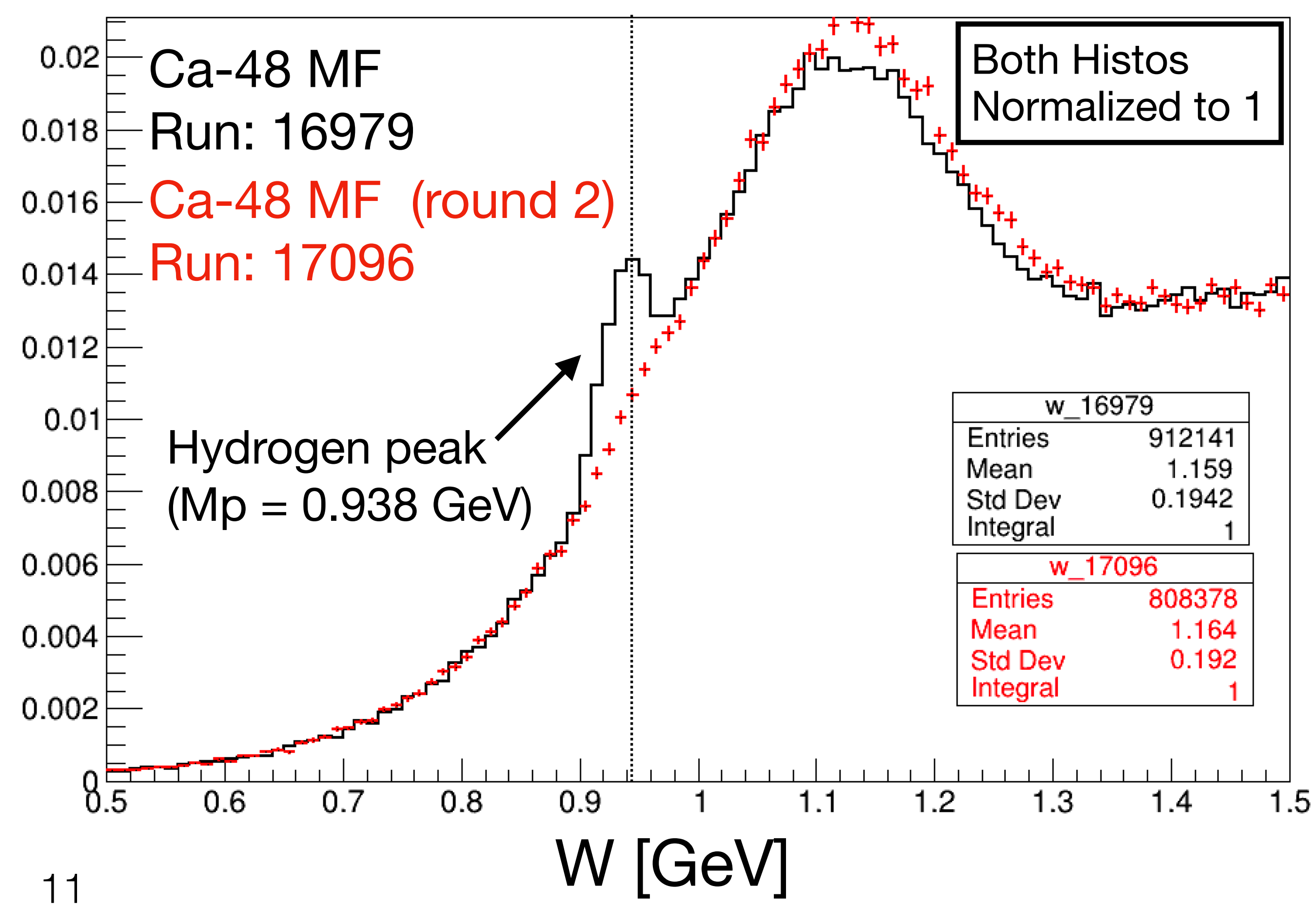
Ca-48 Contamination Studies: Background

- 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

Invariant Mass W

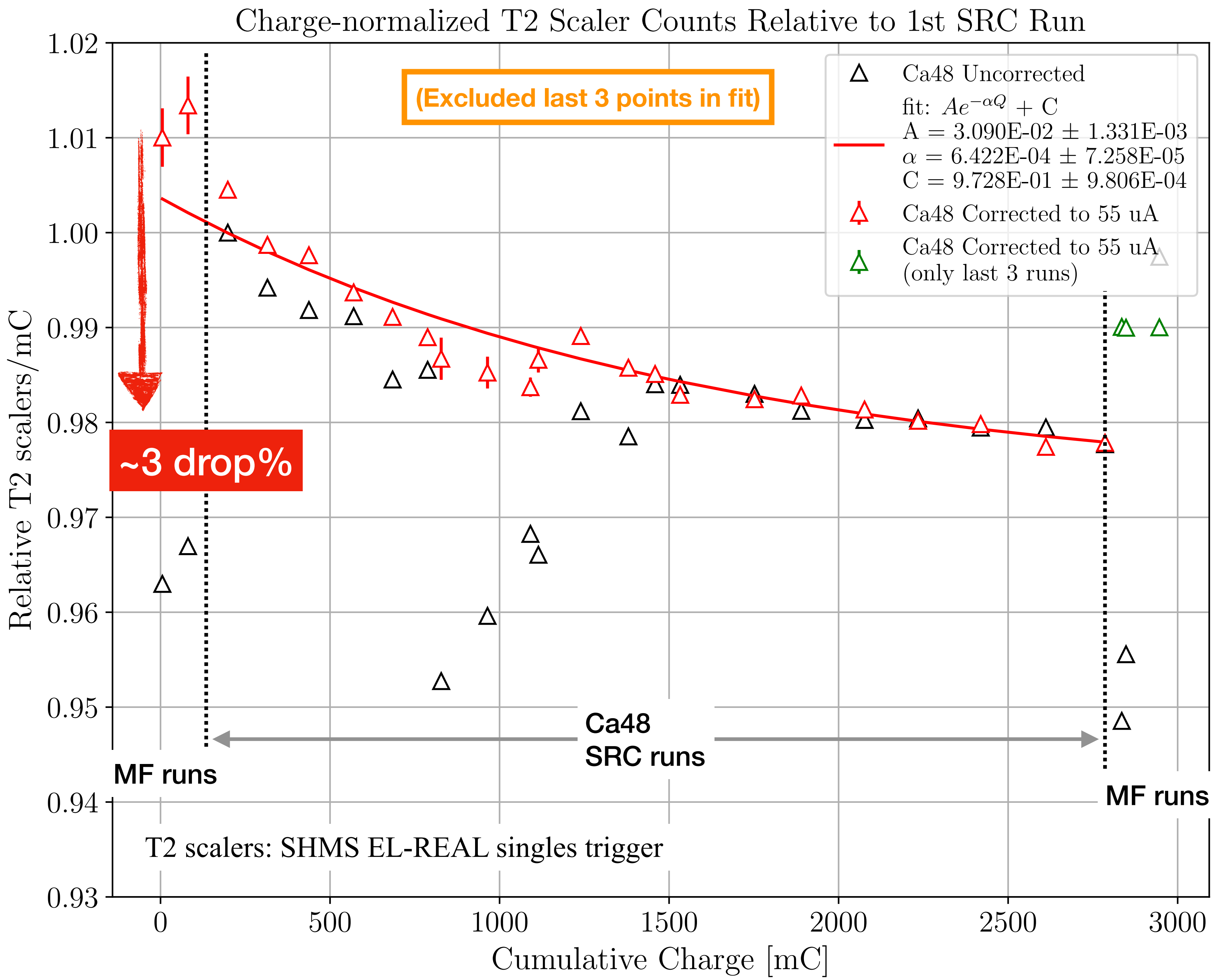


Ca-48 Contamination Studies Analysis Steps

- 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)

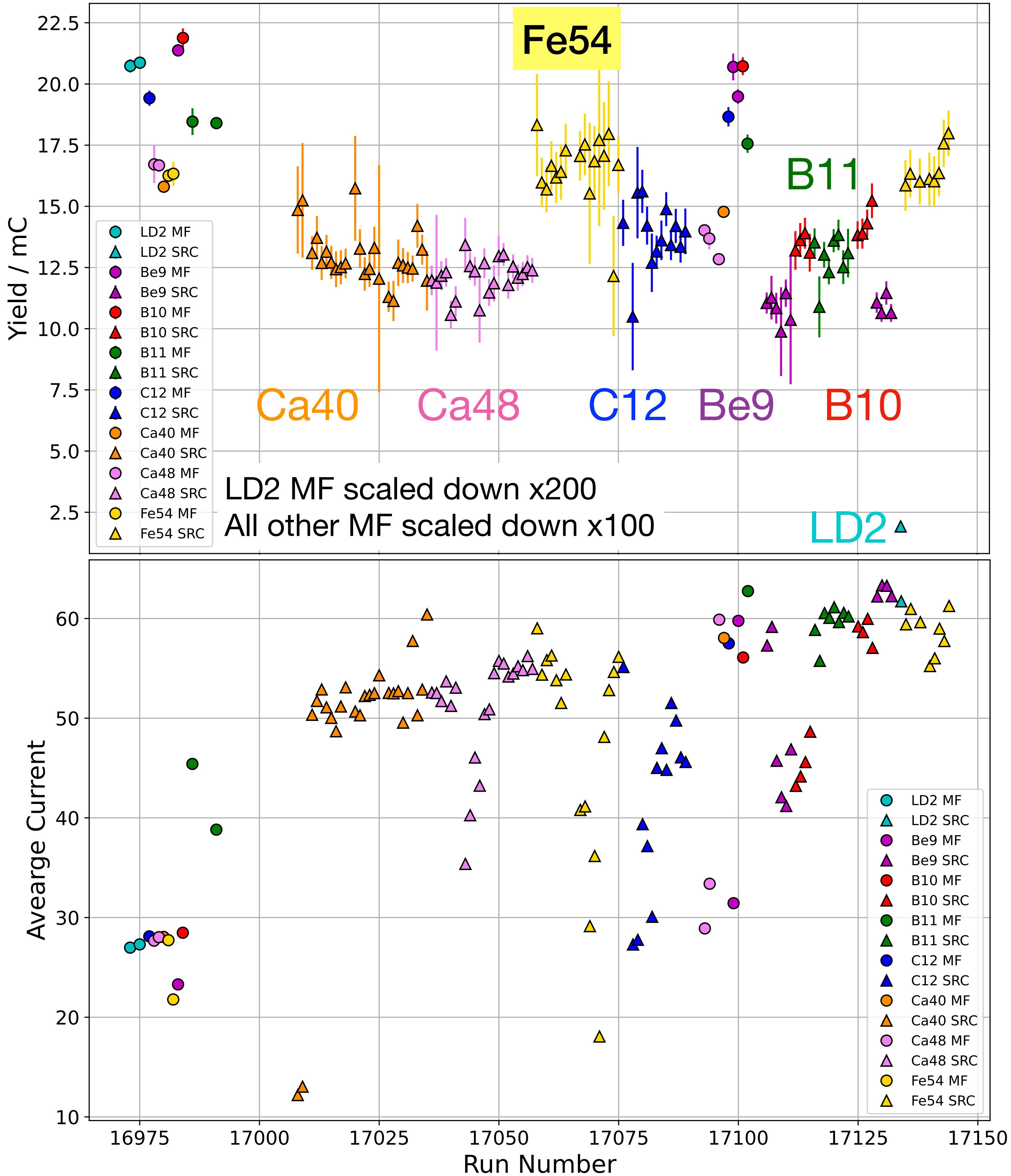


Ca48 Absolute Carbon Contamination Limiting Cases

	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:

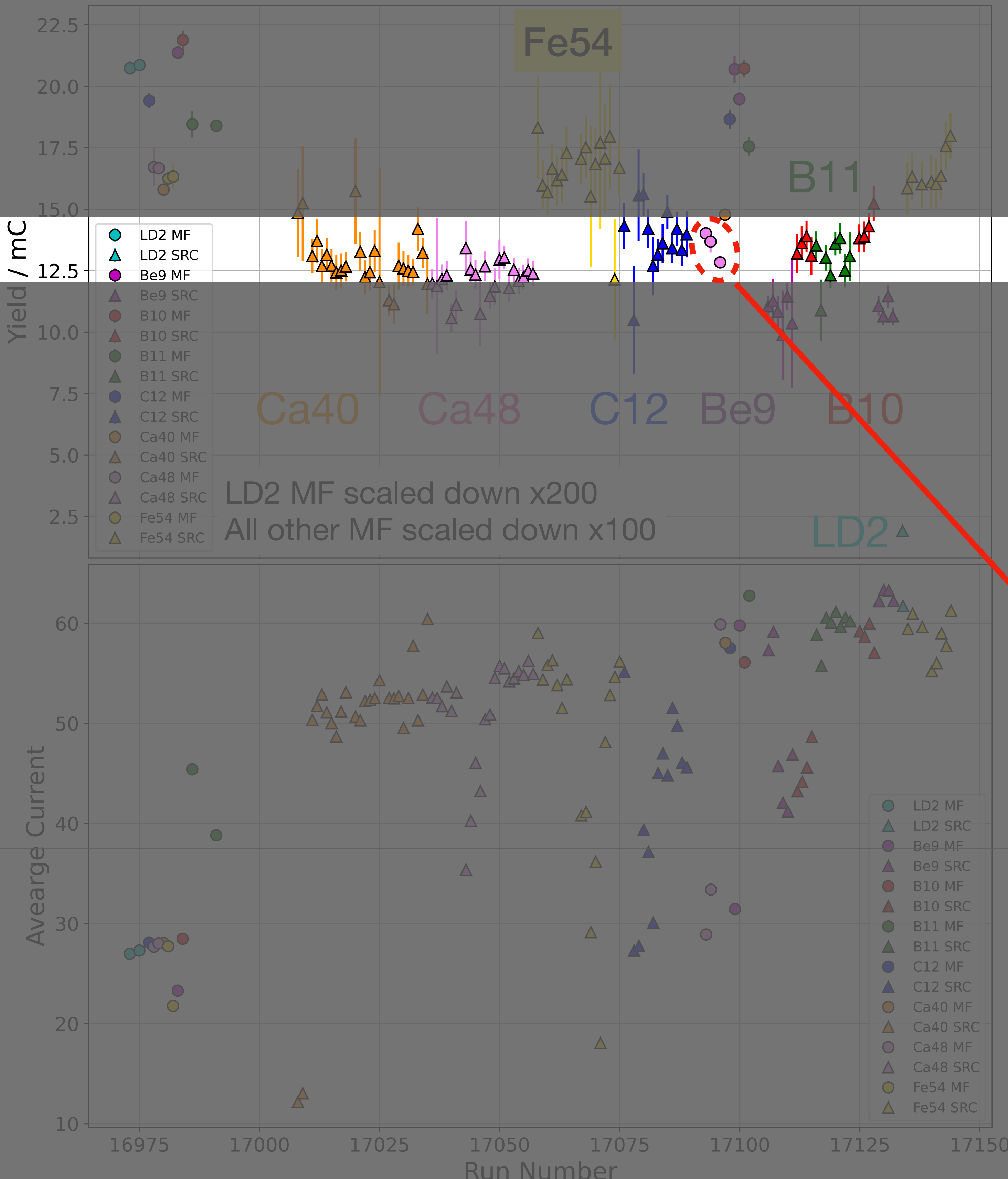
$$Y = \frac{N_c}{Q \cdot \epsilon_{htrk} \cdot \epsilon_{etrk} \cdot \epsilon_{multi.trk} \cdot \epsilon_{LT} \cdot \sigma_A \cdot T}$$

- 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)

Beam Current Dependency Study: Motivation



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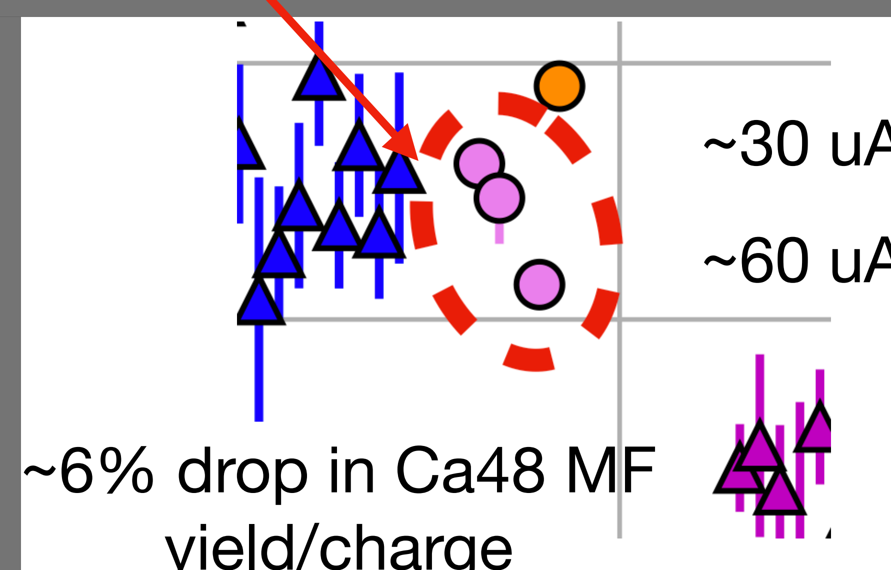
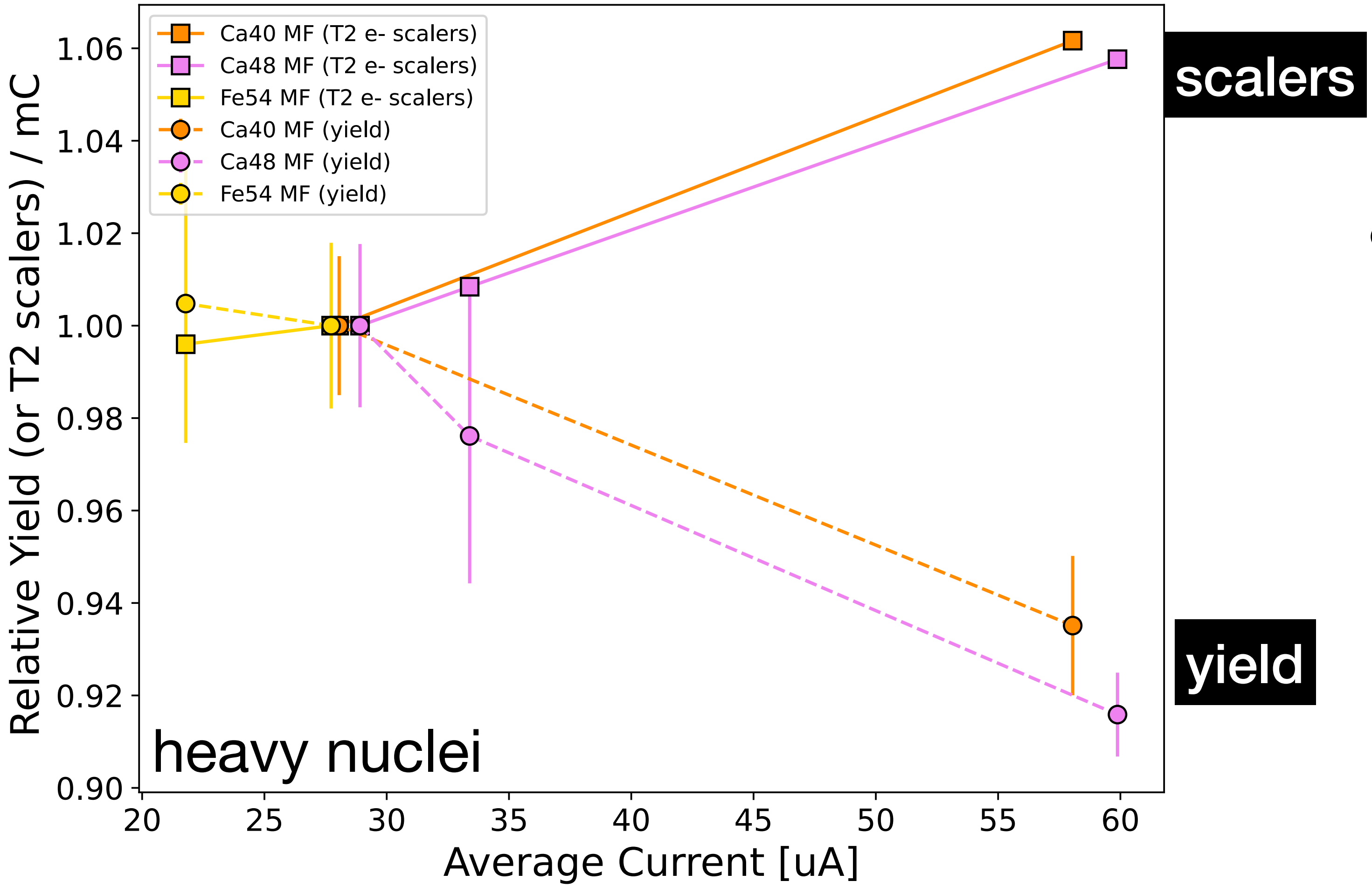
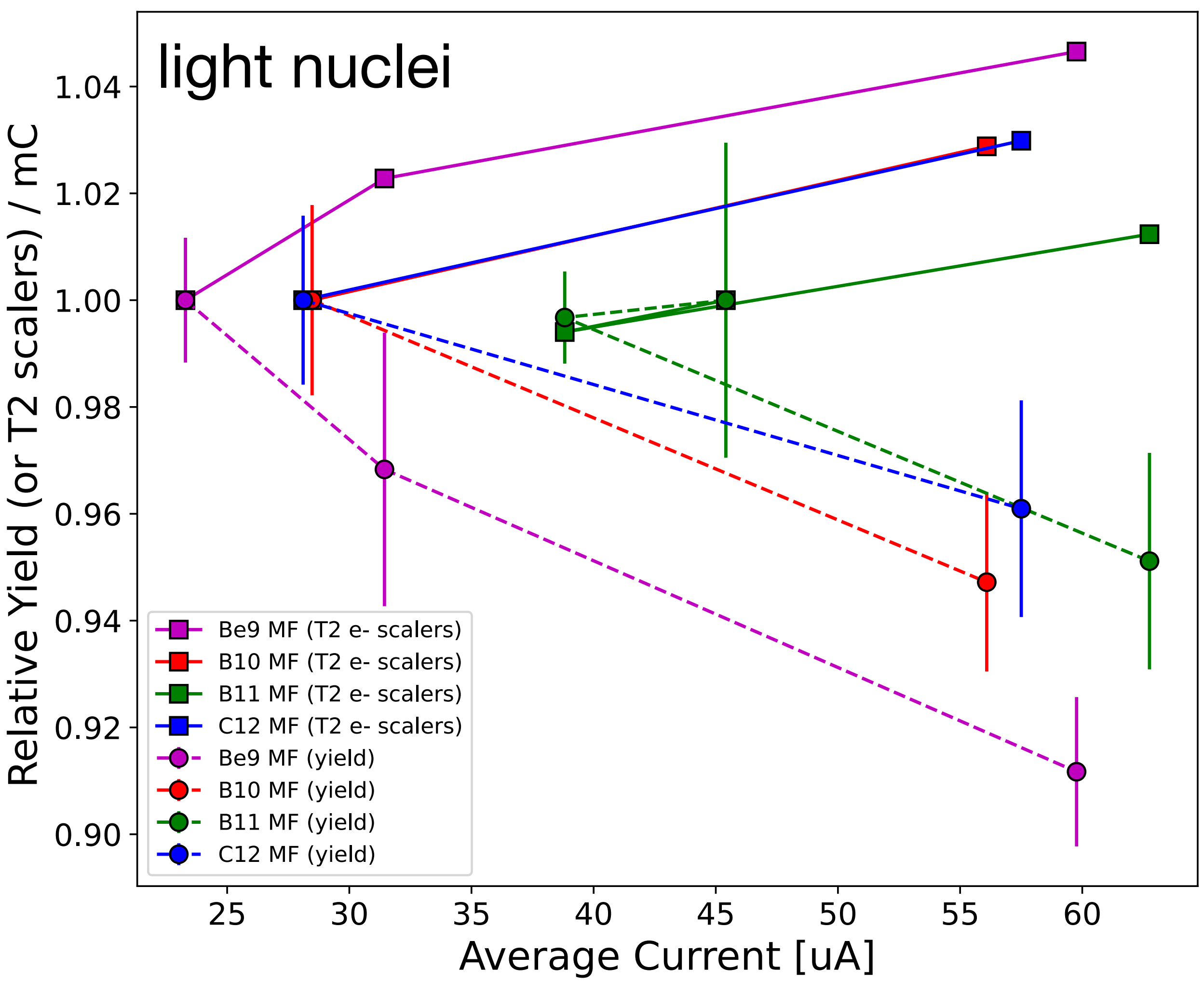
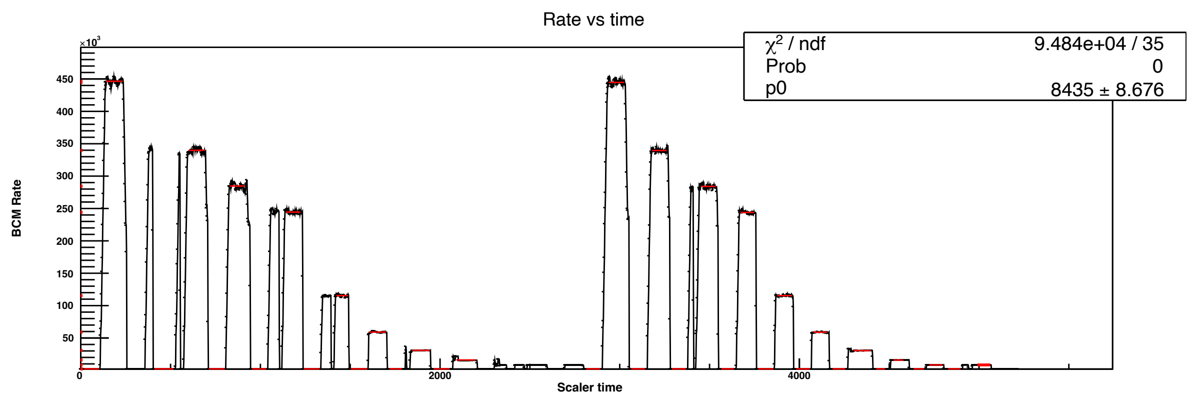


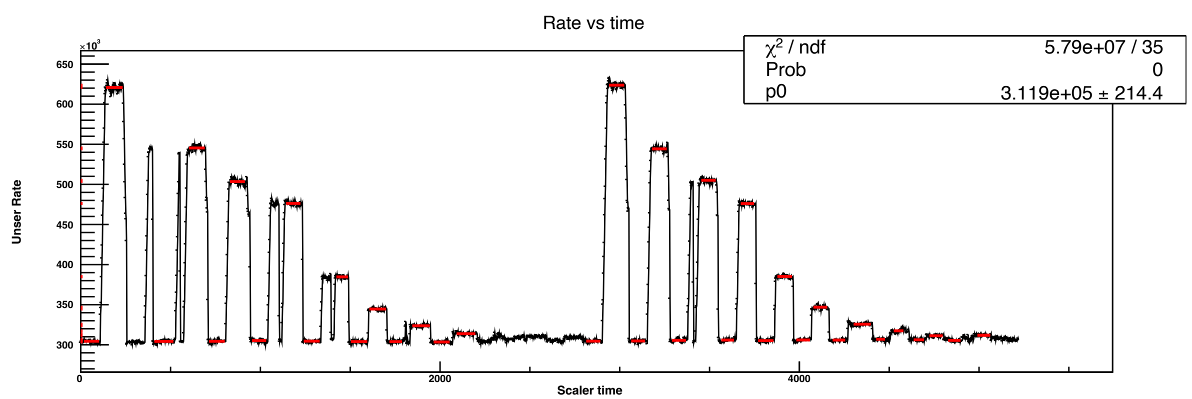


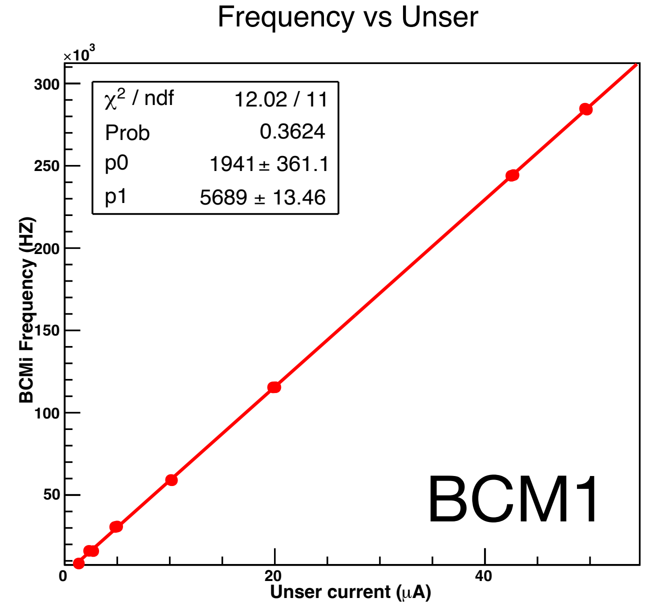


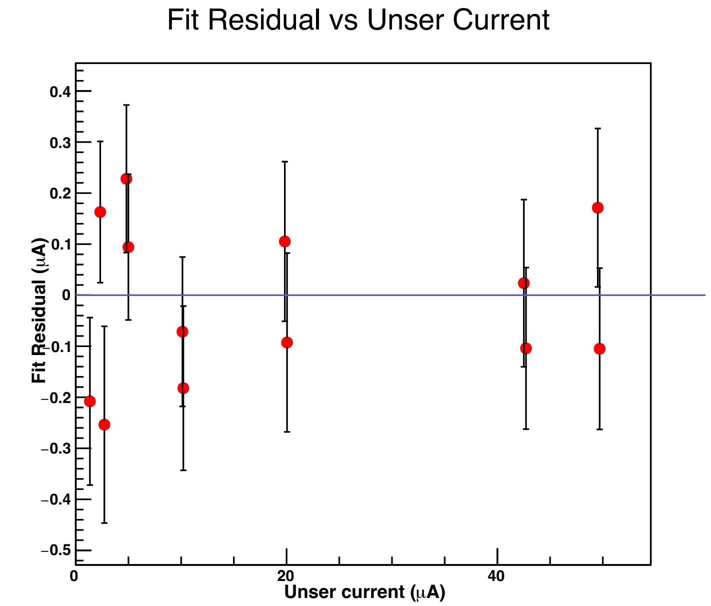
- charge-normalized data yield should **NOT** change with beam current
- relative yield drops ~6-8 % when beam current increases ~30 uA —> 60 uA (**dashed**)
- relative T2 scalers (e-) increase ~4-6 % when beam current increases ~30 uA —> 60 uA (**solid**)
- **Possible Causes of Yield Dependency on Current:**
  - BCM linearity issue ?
  - HCANA tracking algorithm?

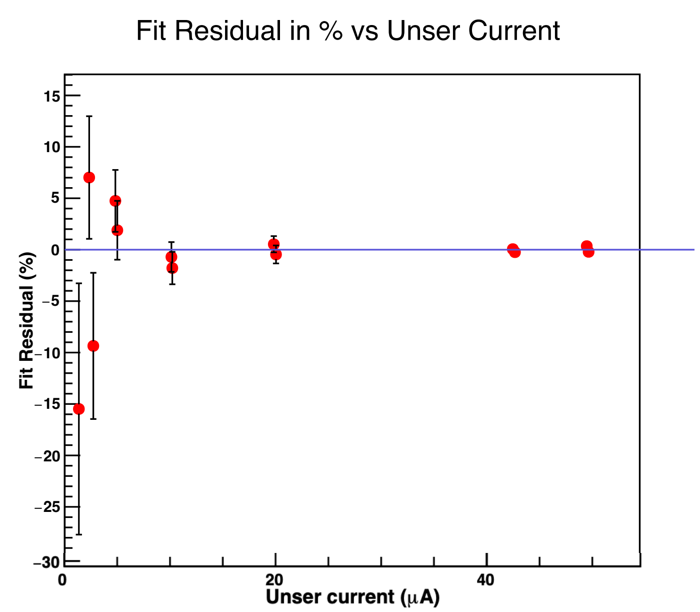
Beam Current Dependency Study: BCM Linearity?

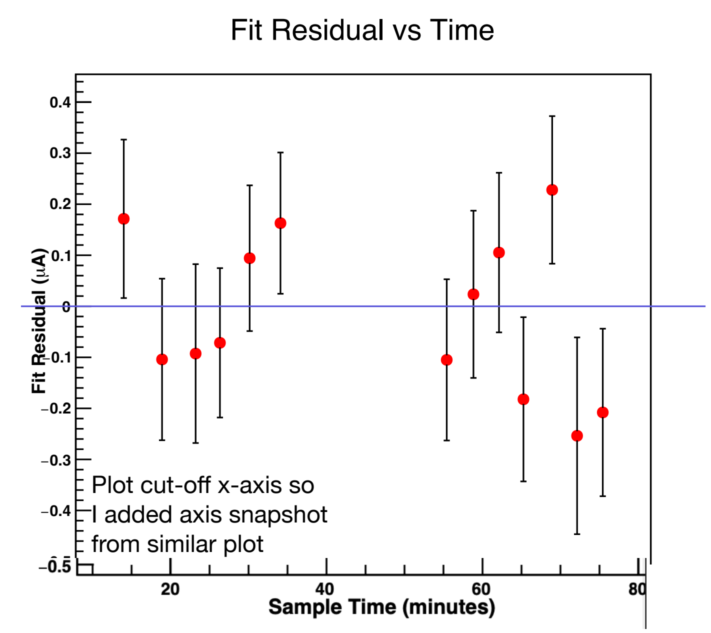








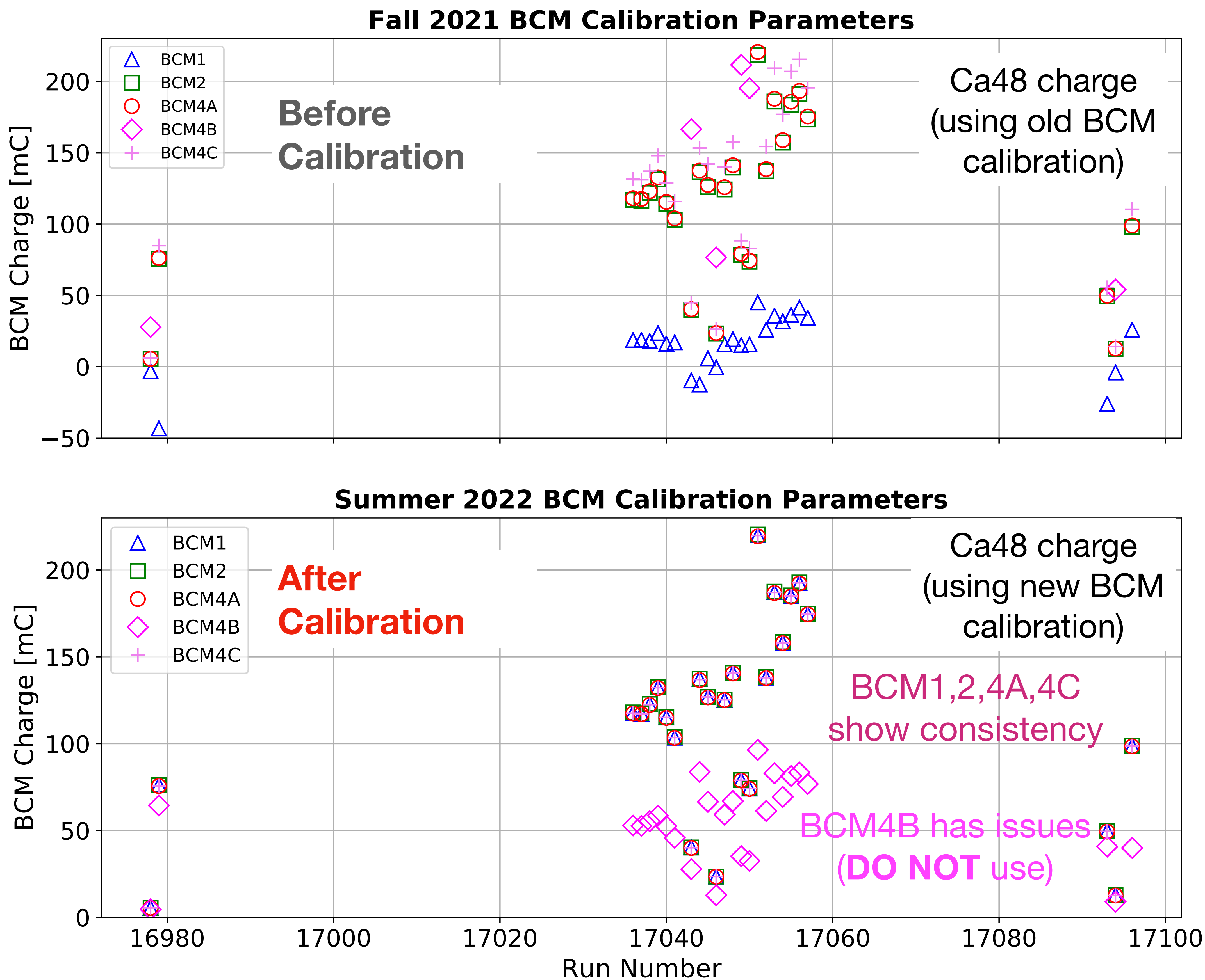




- calibrated BCMs using Aug 23, 2022 BCM run
- Fit up to 50 uA as there is non-linearity at higher currents for BCM1,2 (non-linearity correction was added by D. Mack in 2019)
- dependency on yields/charge observed also < 50 uA, so it is unlikely it is a BCM issue

** how stable is the non-linearity correction factor ?

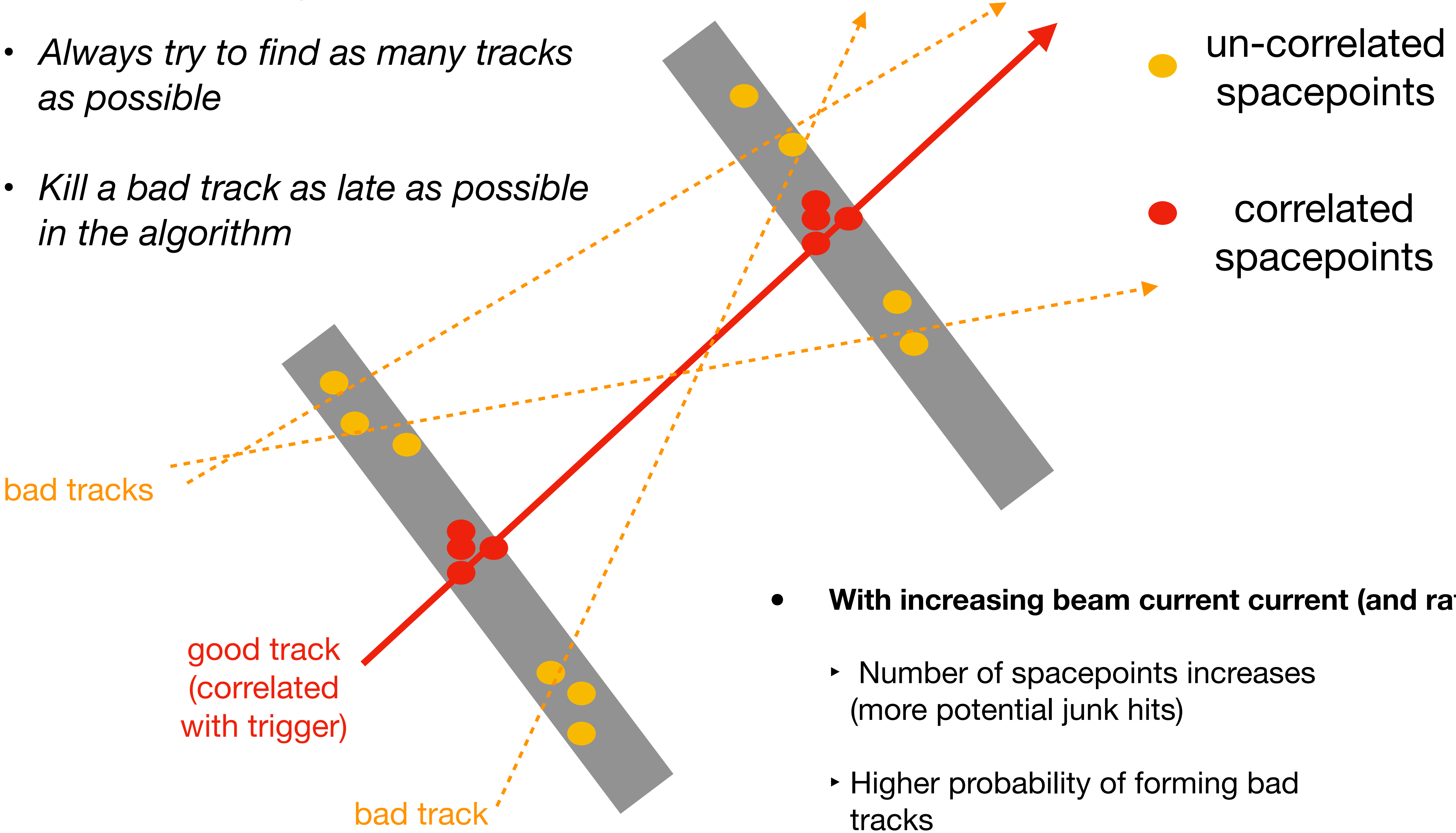
Beam Current Dependency Study: BCM Sanity Check



Beam Current Dependency Study: HCANA Track Algorithm?

Hall C Track Algorithm Philosophy:

- *Always try to find as many tracks as possible*
- *Kill a bad track as late as possible in the algorithm*



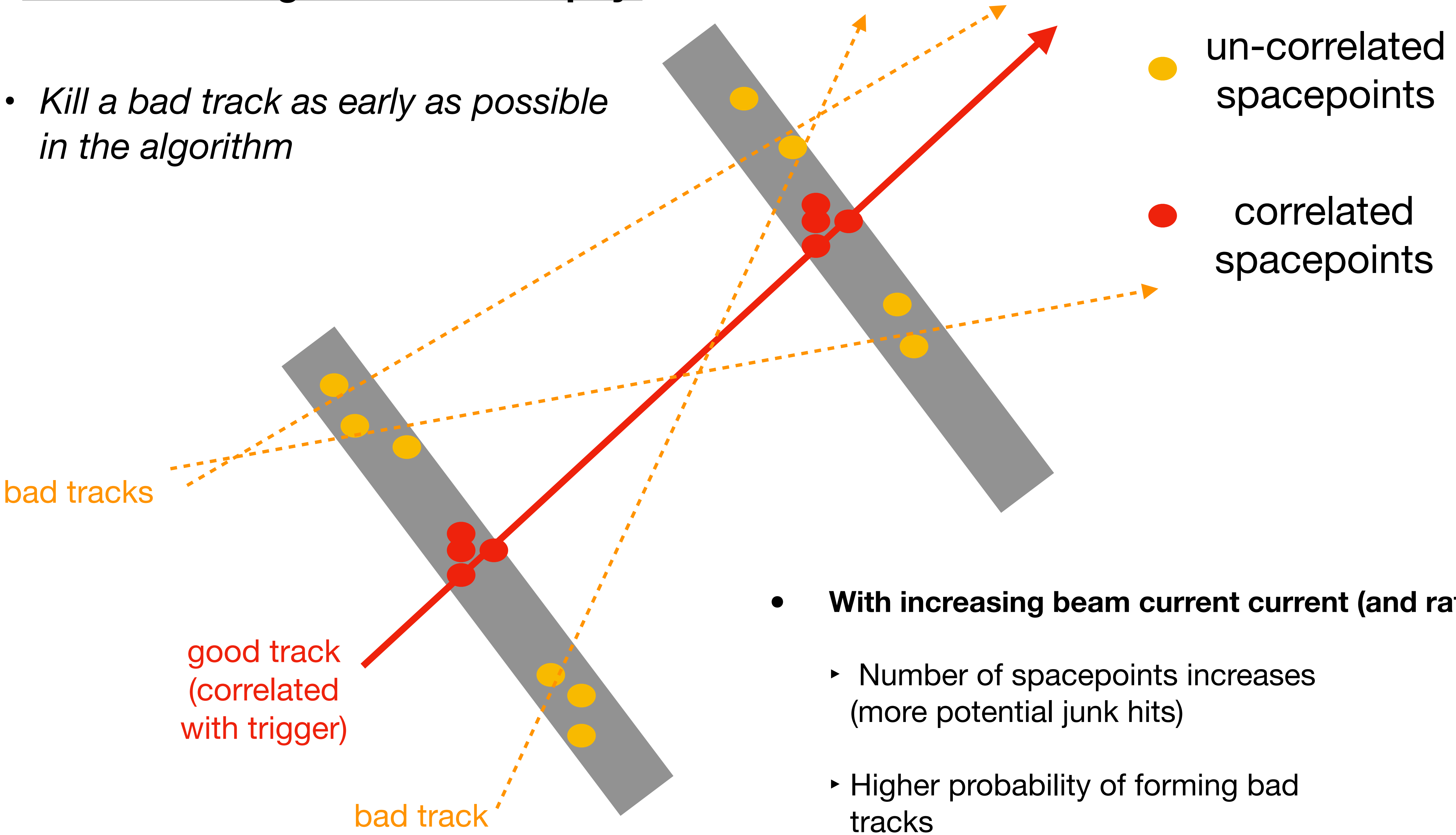
- **With increasing beam current current (and rates)**
  - Number of spacepoints increases (more potential junk hits)
  - Higher probability of forming bad tracks
  - over-estimate track efficiency (more tracks than there should be)
    —> this could lead to beam current dependency on yield/charge

Track Selection in HCANA (MKJones, 2019)

Beam Current Dependency Study: HCANA Track Algorithm?

CaFe Track Algorithm Philosophy:

- *Kill a bad track as early as possible in the algorithm*



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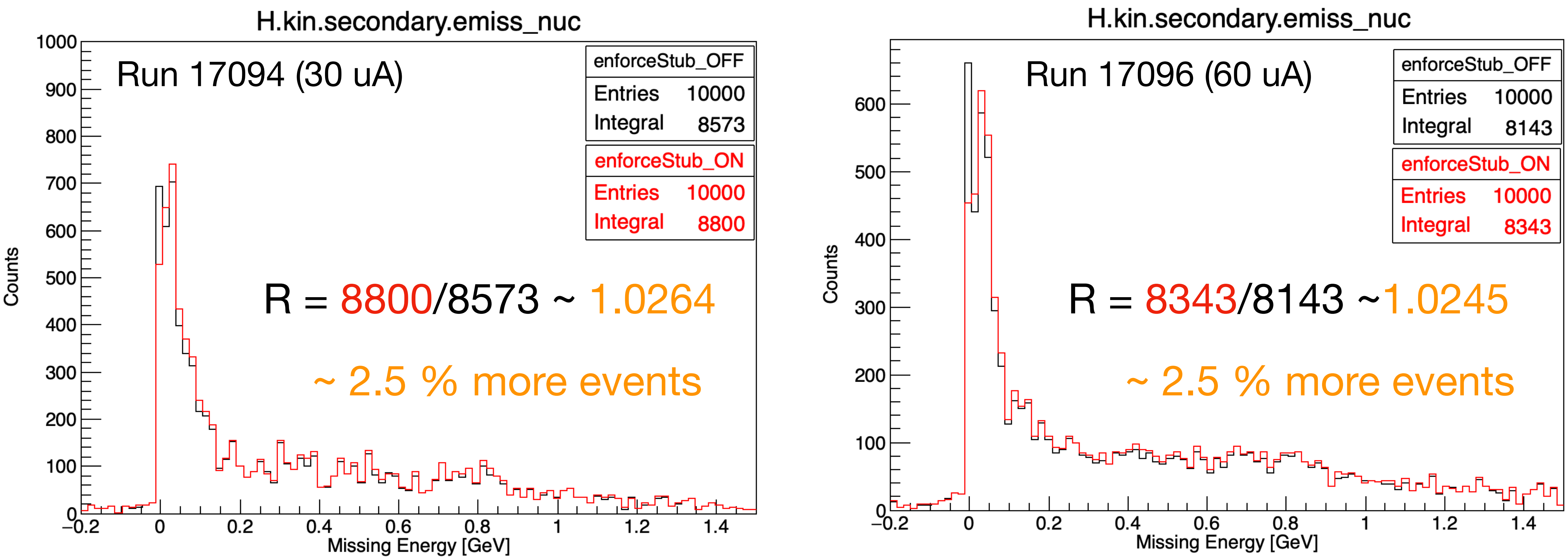
Track Selection in HCANA (MKJones, 2019)

Enforce Reduction of Possible Tracks Being Formed

(Study: *used last two Ca48 MF runs, where a bean-current dependency was observed)*



- Modified “NewLinkStubs()” method: reduced possible number of bad tracks being formed (increase probability of a good track being selected —> recovered Emiss events)

- **<u>Expectation:</u>** more “bad tracks” removed in high-current compared to low-current, leaving room for more good tracks being formed in high-current compared to low current

- **<u>Expectation NOT MET:</u>** low and high current runs increased number of good tracks by same amount
  - Implies relative change in yield/mC stays constant (rate-dependence issue NOT solved)

[Track Selection in HCANA]() (MKJones, 2019)

Beam Current Dependency Study

- Investigated ~6% drop in yield/mC on Ca48 runs 17094 (~30 uA), 17096 (~60)
- enforced stub selection criteria + tightened pruning cuts but no improvement in relative yield/charge (I expected to recover more events for high-current than low current run but did not occur)

```
phase0: baseline (cafe original tracking config parameters, deault prune npmt>=6 && hodo_2x_hit && hodo_2y_hit  )

phase1: enforce stub_criterion (actually changes number of tracks, but emiss does not change much)

phase2: phase1 + (hodo geometry fiducial region: paddles 7-14)

phase3: phase2 + tightened pruning (x'tar, y'tar, ytar, delta, beta) + tightened spacepoint criteria (0.9 -> 0.5)

phase4: phase3 + tightened shms dc tdctime to : -5, 120 ns (tight cut on drift time to cut out junk hits) -> increase number of single tracks

phase5: phase4 + tightened pmax_pr_hits from ( 35, 35 ) to ---> (10, 10),
max number of hits per chamber for forming stubs (for purposes of studing rate dependence)


definition:
norm_counts = counts / (charge *  h_trk_eff * e-_trk_eff * tLT *  e-_multi_track)
rel_norm_counts=norm_counts / norm_counts_17094
ntrk: P.dc.ntrack (total number of tracks)
```

single-tracks increase

multi-tracks decrease

relative norm yield constant

run	phase	counts	charge	h_trk_eff	e-_trk_eff	tLT	e-_multi_track	ntrk=0,	ntrk=1,	ntrk>1	norm_counts	rel_norm_counts
17094	0	6052.487	12.680	0.997	0.987	0.934	0.9760	102929	39241	46940	532.115	1.
17096	0	42541.394	98.674	0.995	0.973	0.934	0.9554	242702	244171	321505	499.0464	0.9378
17094	1	6081.145	12.680	0.997	0.981	0.934	0.976	109876	44979	34255	537.9045	1.
17096	1	42863.066	98.674	0.995	0.966	0.934	0.9554	281427	298007	228944	506.463	0.9415
17094	2	5969.434	12.680	0.997	0.981	0.934	0.976	109876	44979	34255	528.0232	1.
17096	2	41607.105	98.674	0.995	0.965	0.934	0.9554	281427	298007	228944	492.1327	0.9320
17094	3	5950.434	12.680	0.997	0.976	0.934	0.976	110431	46195	32484	529.039	1.
17096	3	41333.421	98.674	0.995	0.958	0.934	0.955	286344	305565	216469	492.6741	0.93126
17094	4	5933.092	12.680	0.997	0.972	0.934	0.975	110826	51911	26373	530.211	1.
17096	4	41339.092	98.674	0.995	0.957	0.934	0.955	284198	351674	172506	493.2566	0.93030
17094	5	4479.079	12.680	0.997	0.725	0.934	0.9731				537.6899	1.
17096	5	28005.04	98.674	0.995	0.642	0.934	0.9508				500.3101	0.93048

Beam Current Dependency Study

What next steps to take?

- Implement matching trigger to hodoscopes paddle that was hit and require this condition to form a track

  after Holly, Dien and Carlos' discussion on tracking with M. Jones :

  - there is no clear path for implementing trigger match to hodo hits

  - it is non-trivial to enforce the pruning variables as hard-cuts in the part of the code where tracks are initially formed from chamber hits

Any ideas that might give insight as to why there is a beam-current dependency with yield/charge are welcomed ! ! !

Summary

- Initial Analysis Steps
  -> completed ref. times / time windows / calibrations - N. Swan / C. Yero

- SHMS Optics Optimization
  -> in progress - Holly Szumila-Vance

- Ca48 Contamination Studies
  -> contamination estimates complete,
  -> (lab analysis of chemical composition of oil in progress - D. Meekins)

- Beam Current Dependency on Charge-Norm Yield
  -> enforced tight pruning parameters in tracking algorithm (dependence persists)
  -> need try and implement something similar to track-matching to hodoscope paddles in tracking algorithm - D. Nguyen / C. Yero

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)

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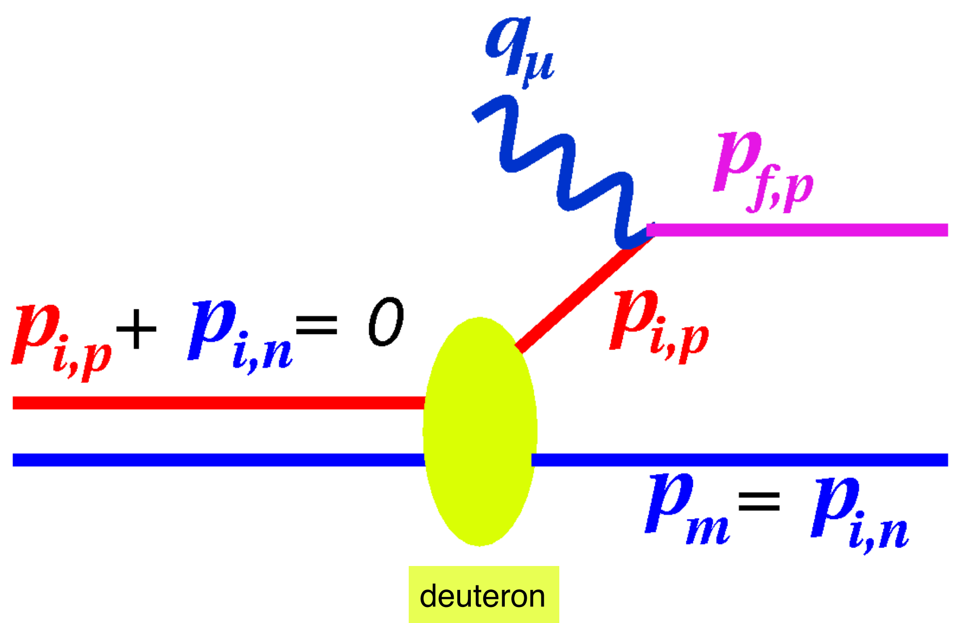
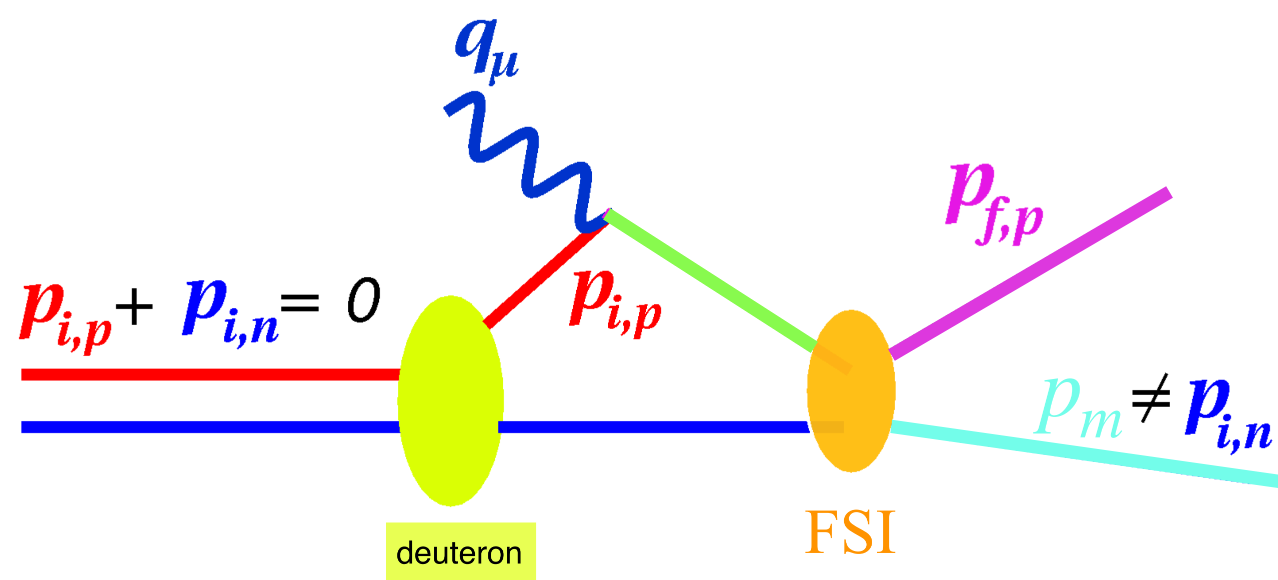
Backup Slides

virtual photon - nucleus interactions

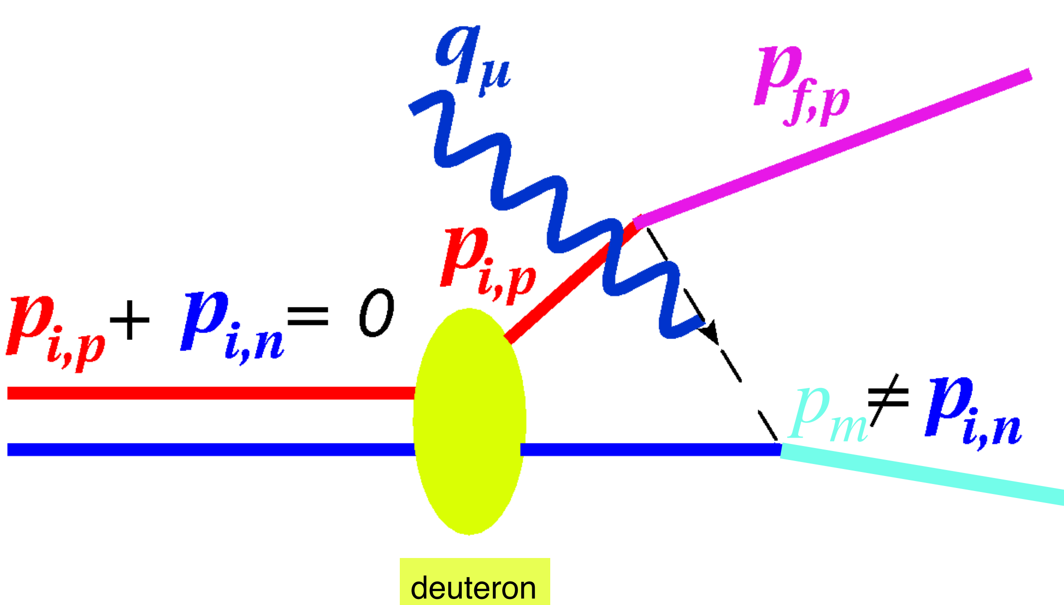


Plane Wave Impulse Approximation (PWIA)



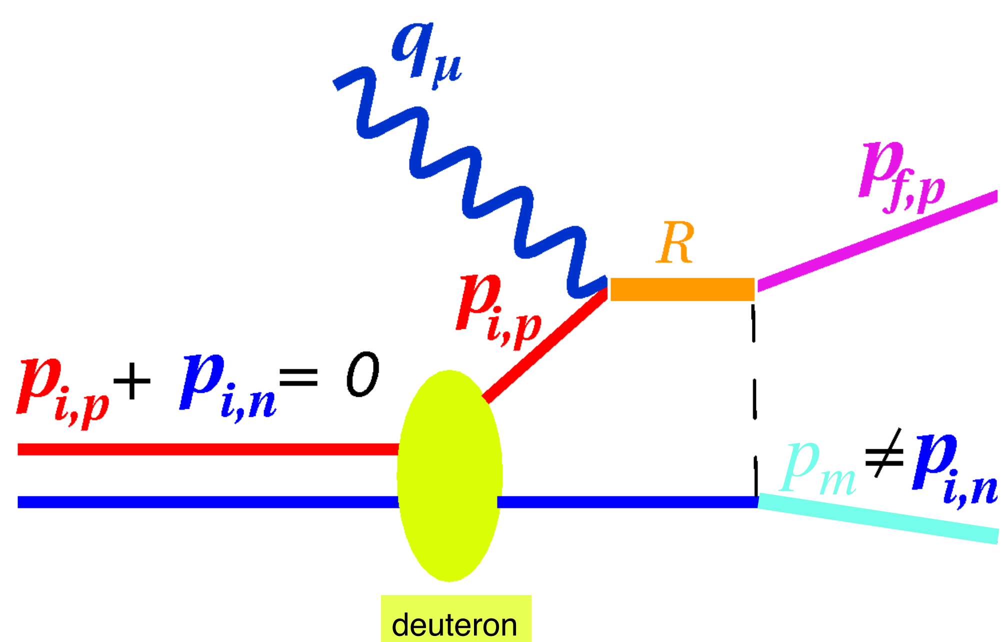
Final State Interactions (FSI)

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



Meson-Exchange Currents (MEC)

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

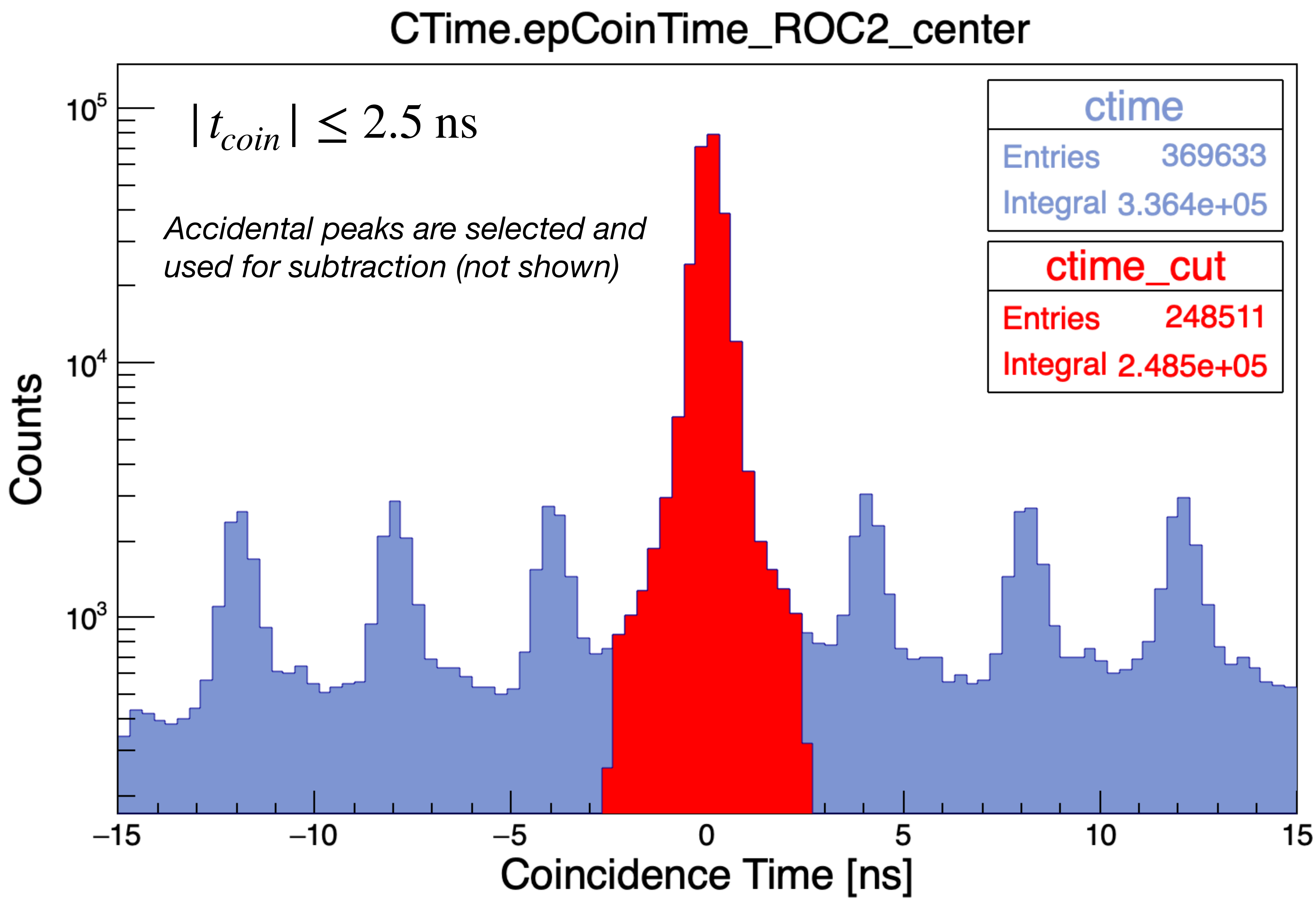


Delta, N* Resonance Excitations (IC)

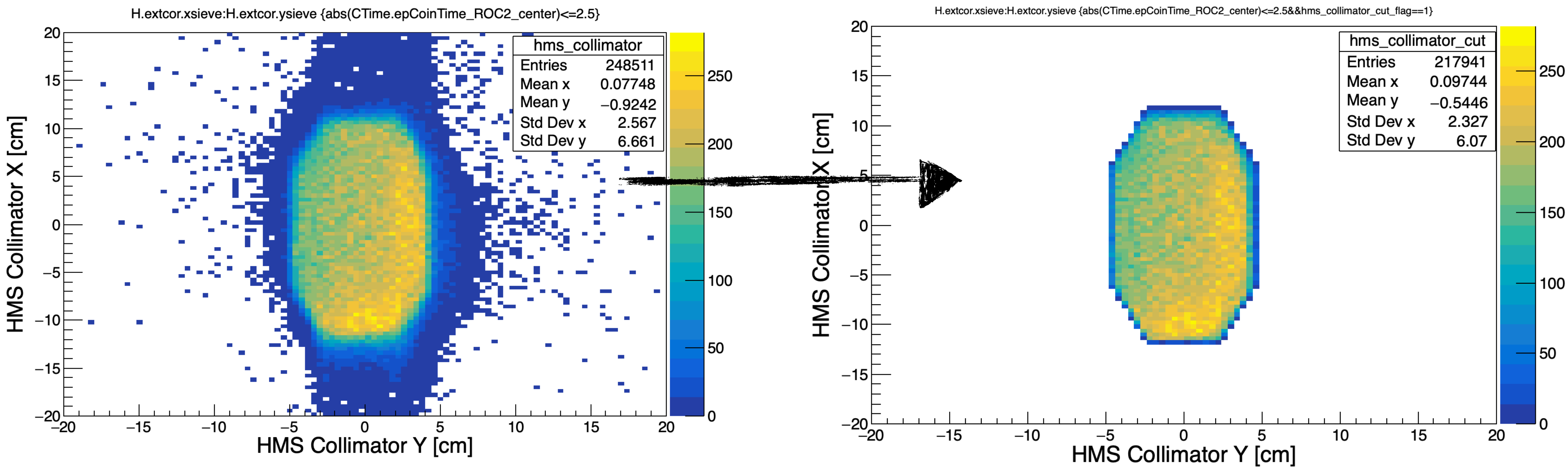
suppressed at $x_{\mathrm{Bj}} > 1$

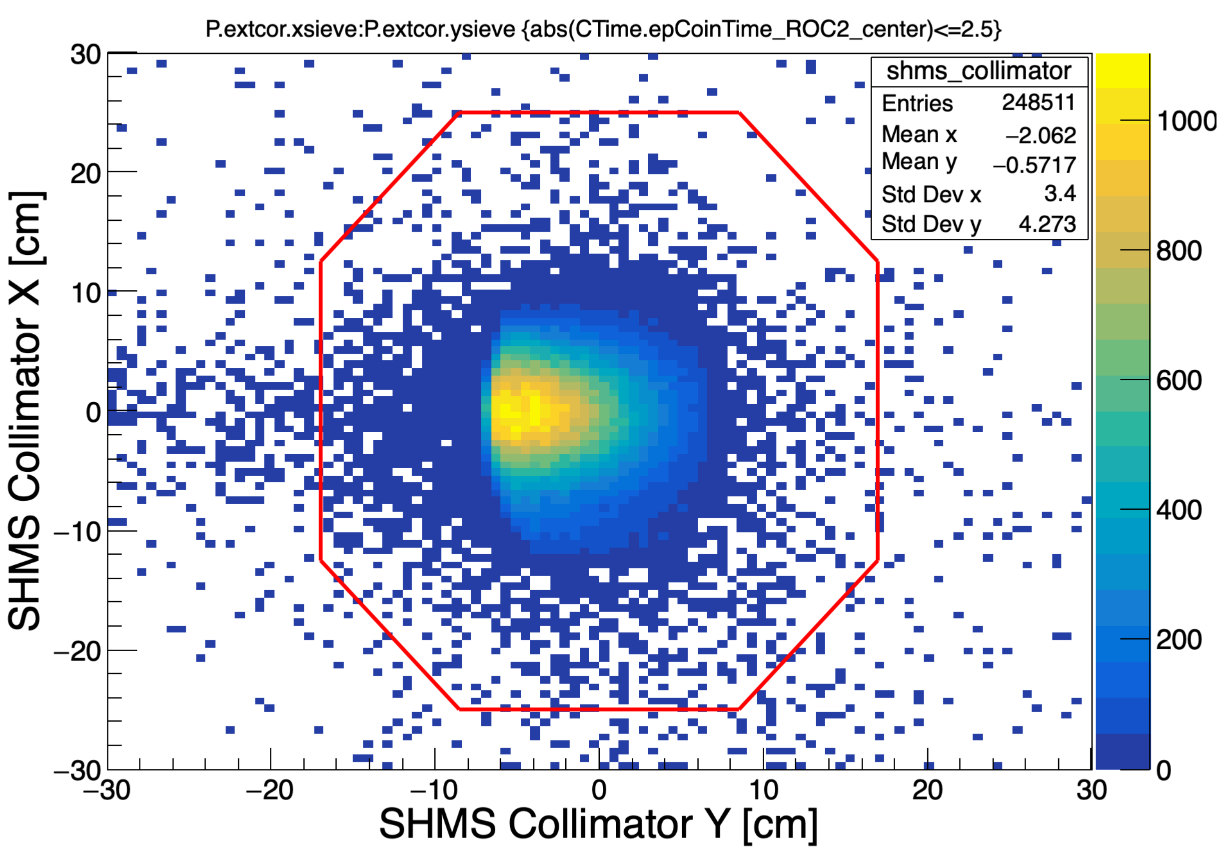
Event Selection (MF)

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



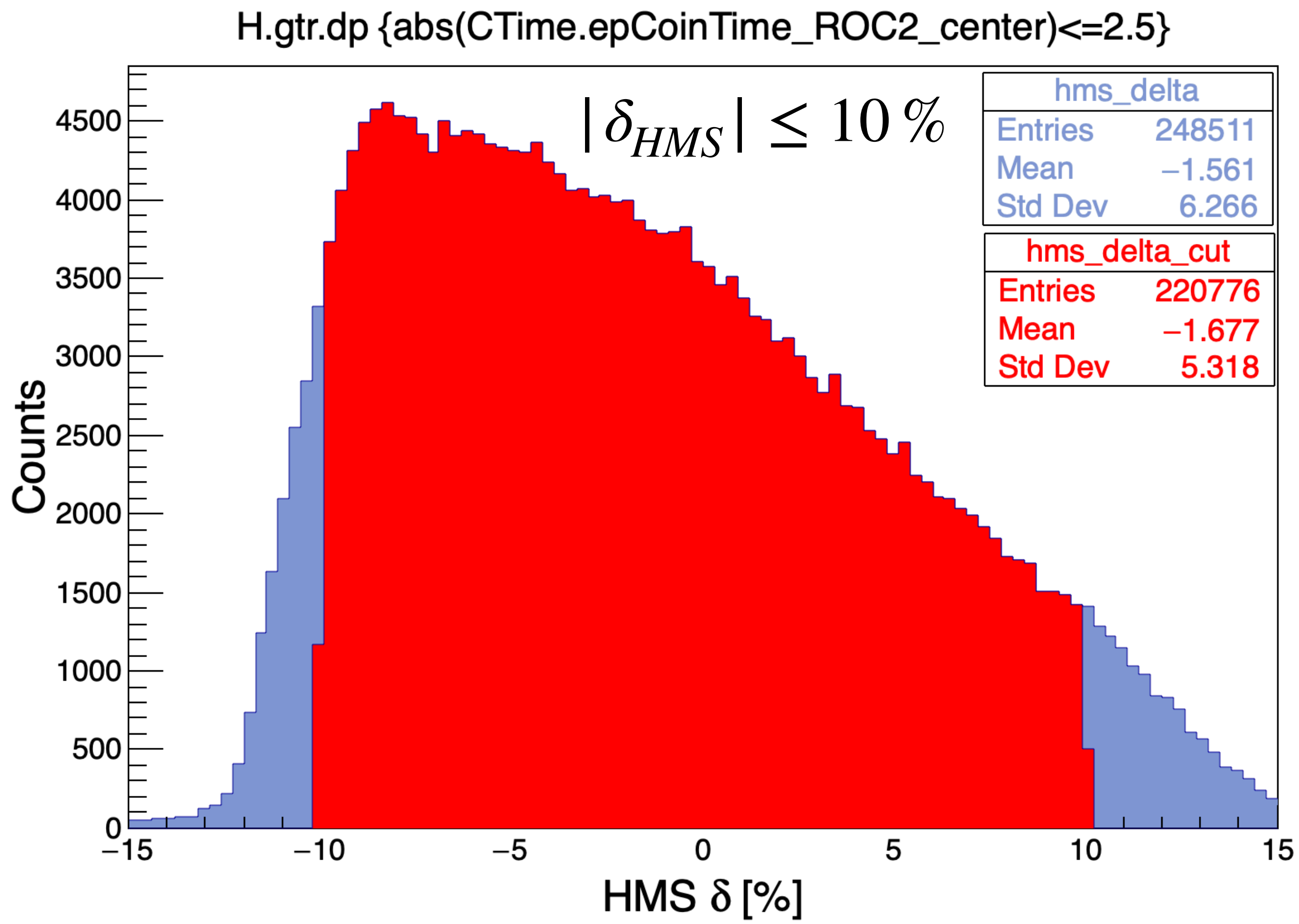
Event Selection (MF)





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

Event Selection (MF)

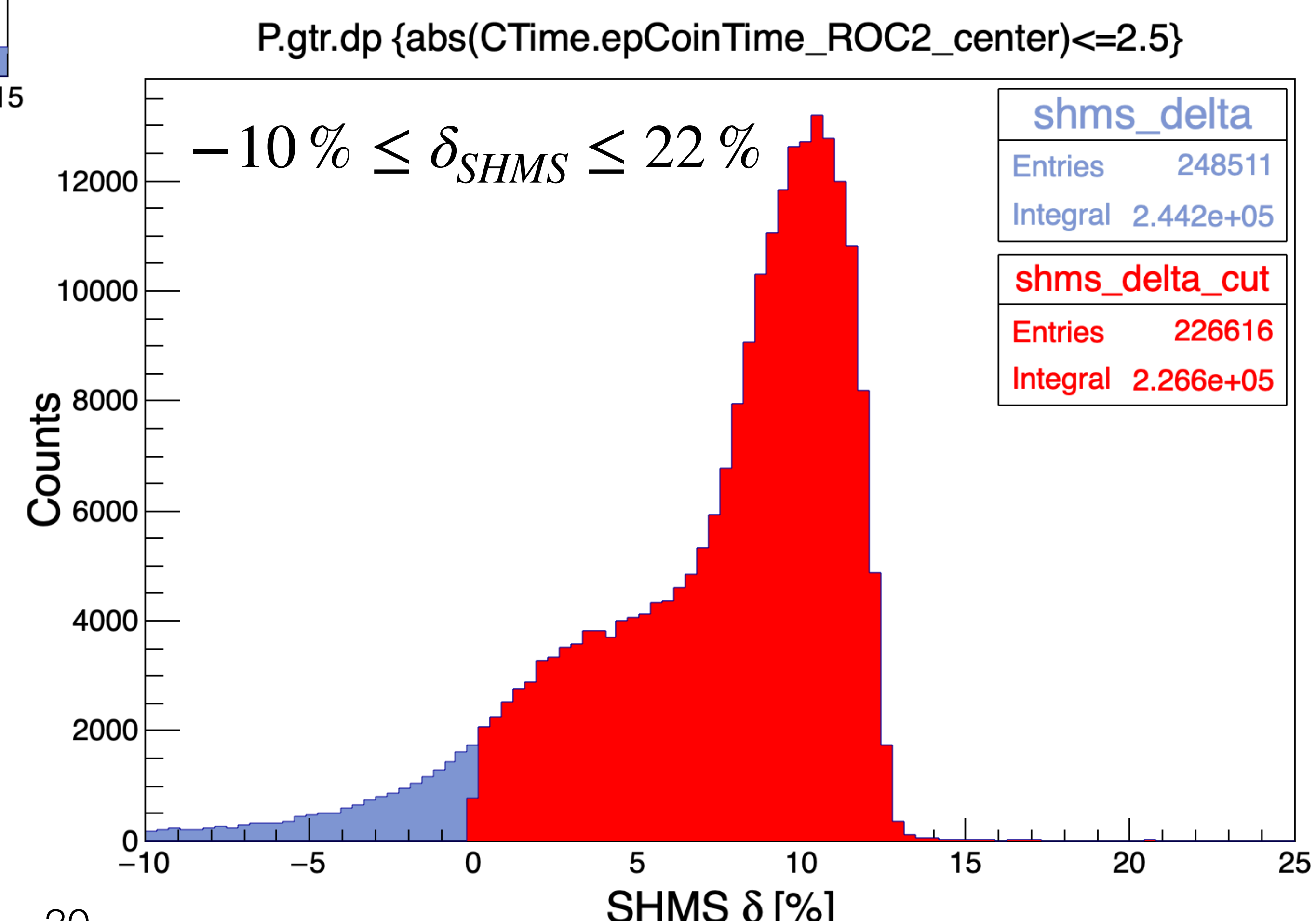


Momentum Acceptance Definition

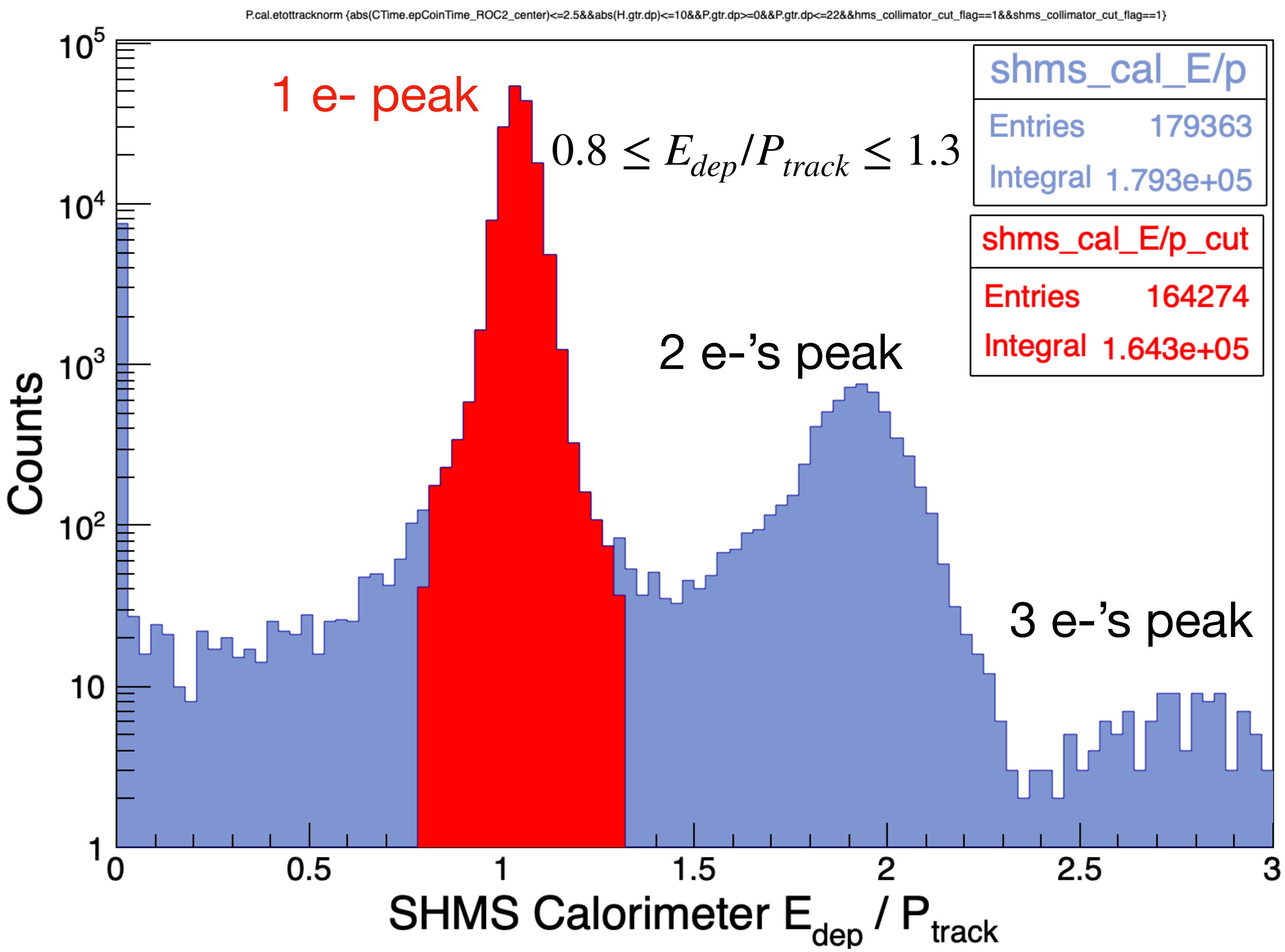
$$\delta \equiv \frac{P - P_0}{P_0}$$

P_0 : Spectrometer central momentum

P : Particle track momentum



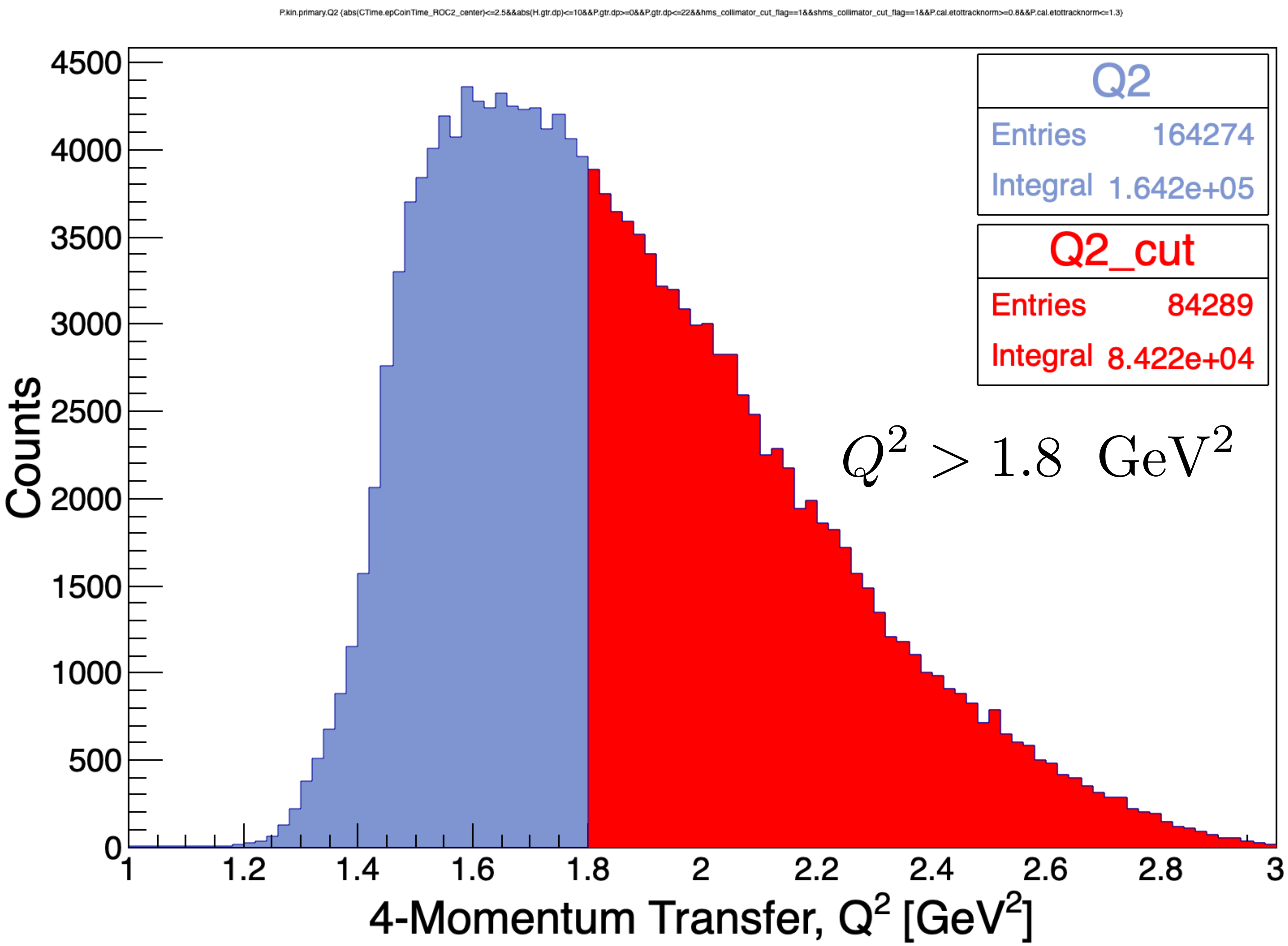
Event Selection (MF)



- 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)

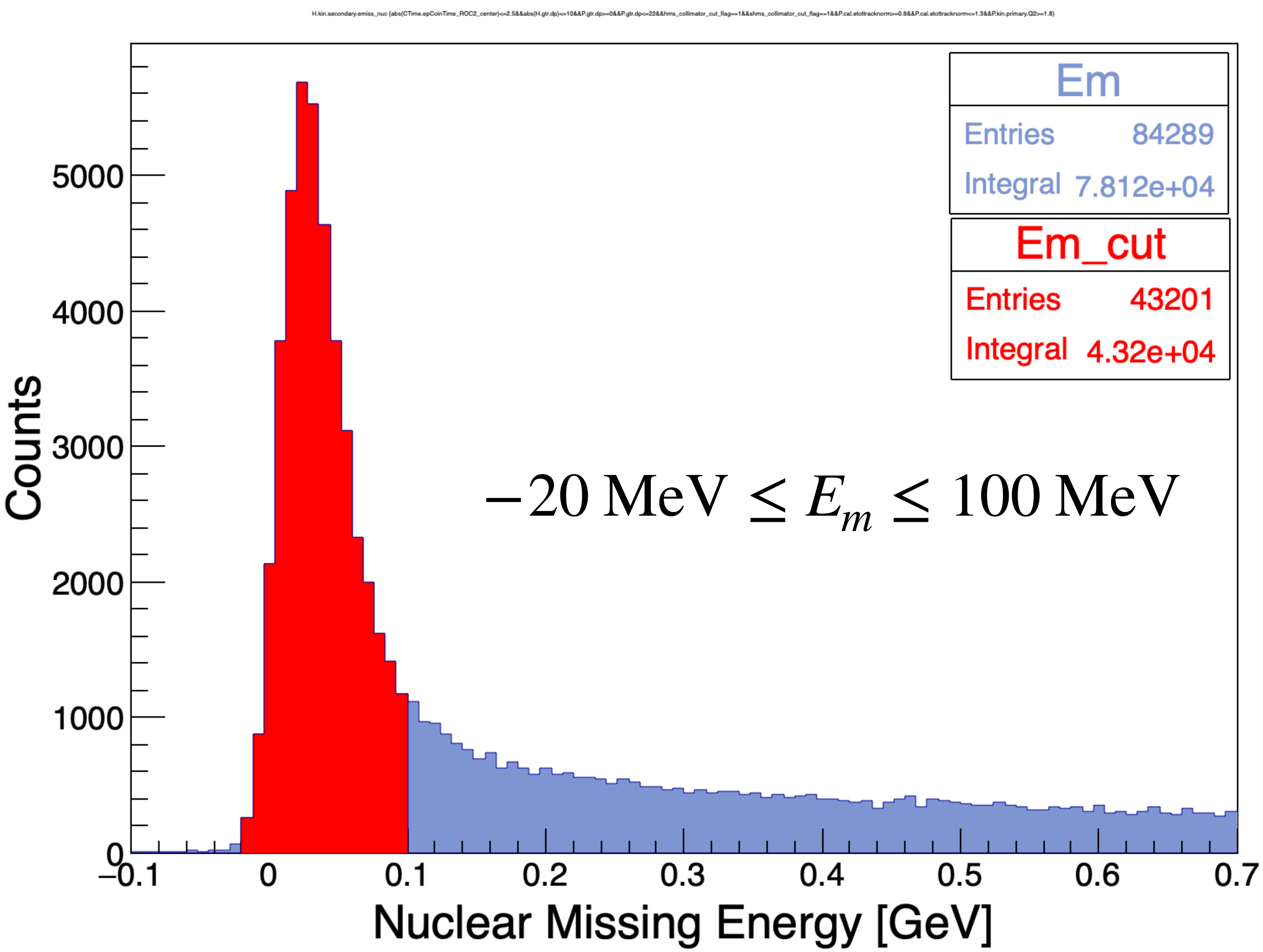
$$\epsilon_{\text{multi.trk}} = \frac{\sum_{n=2,3} E_{dep}/P_0}{\sum_{n=1} E_{dep}/P_0}$$

Event Selection (MF)



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

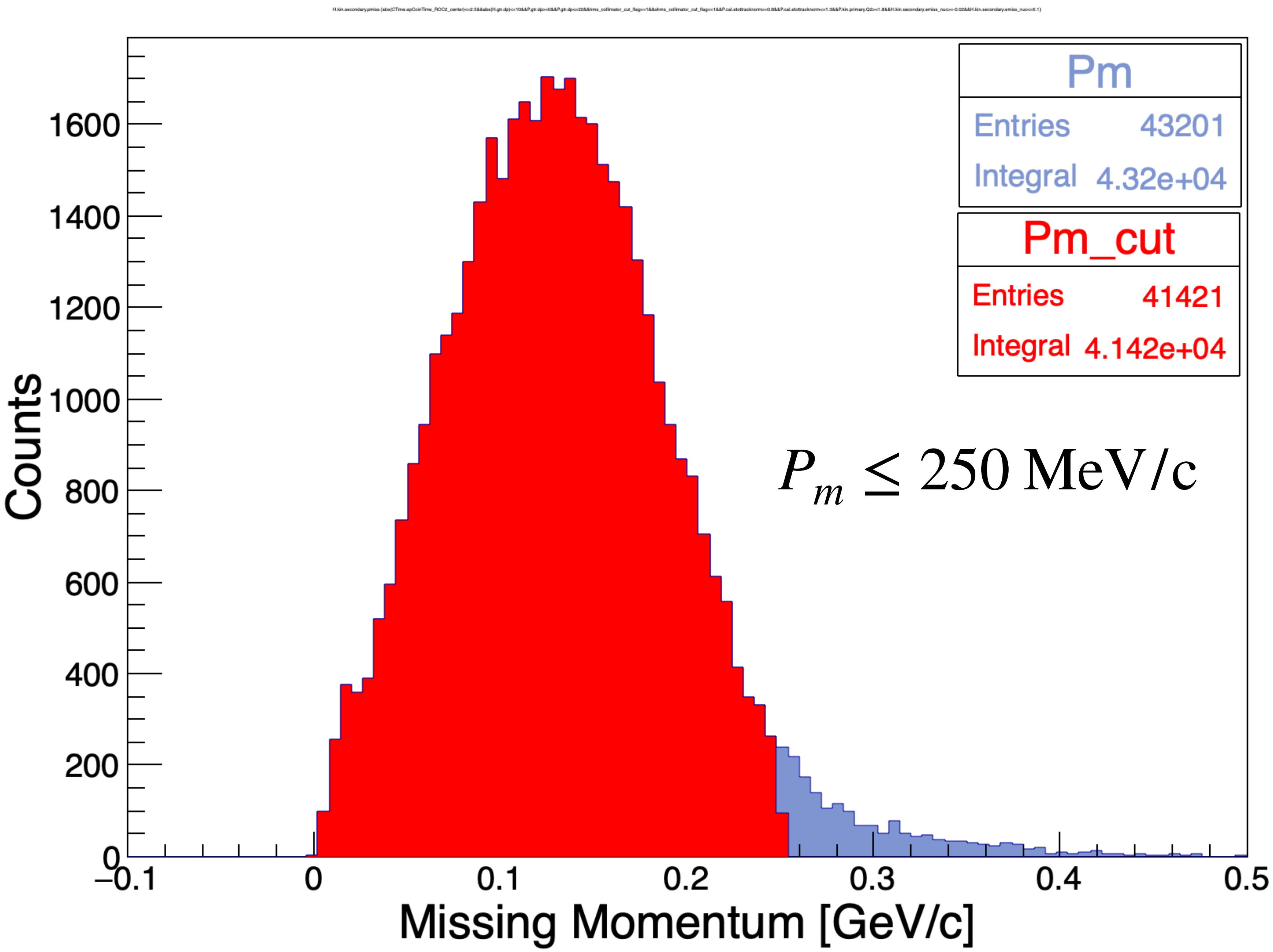
Event Selection (MF)



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

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

Event Selection (MF)

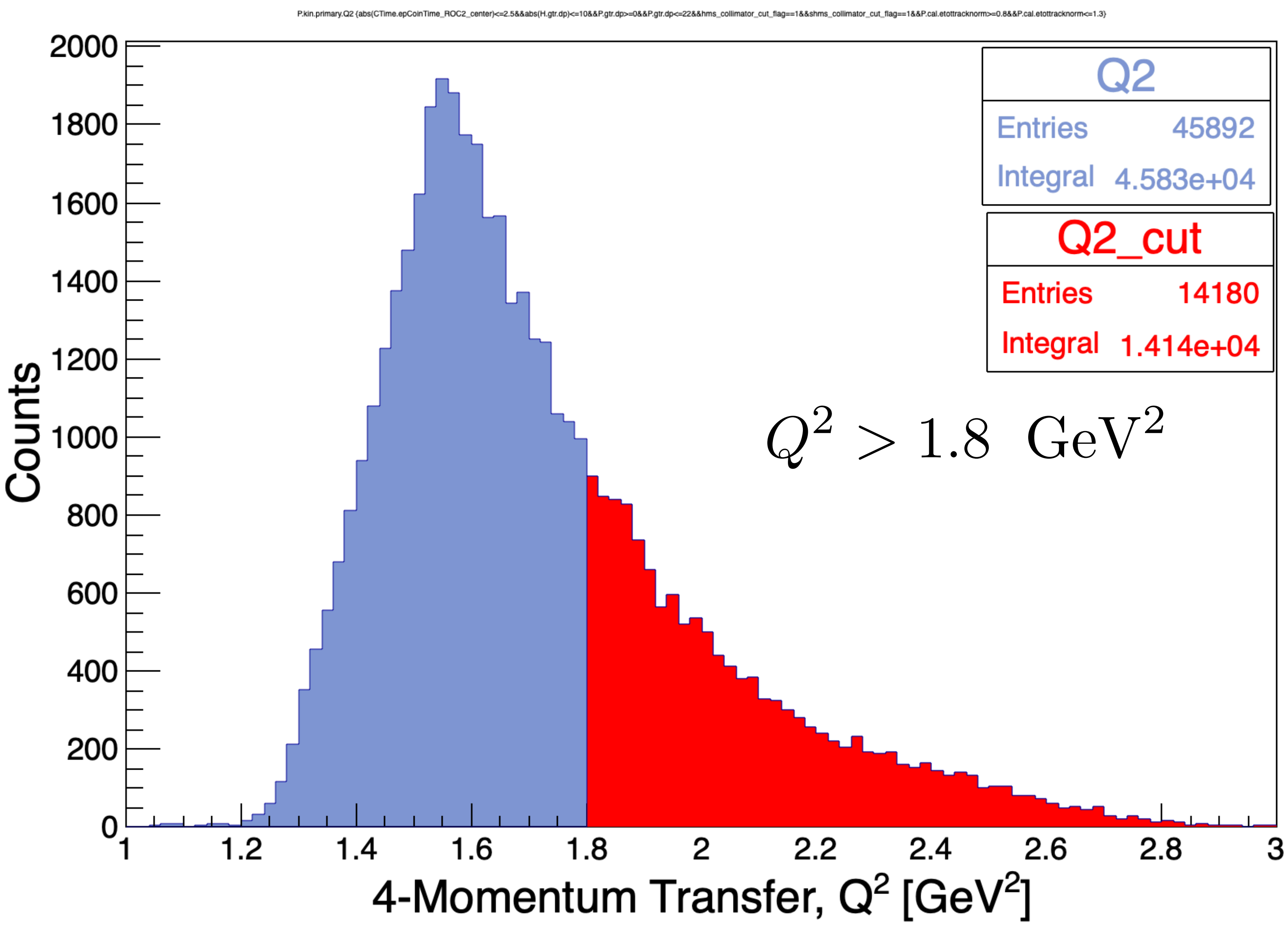


- Kinematic Cut to select mean-field (MF) nucleons

Event Selection (SRC)

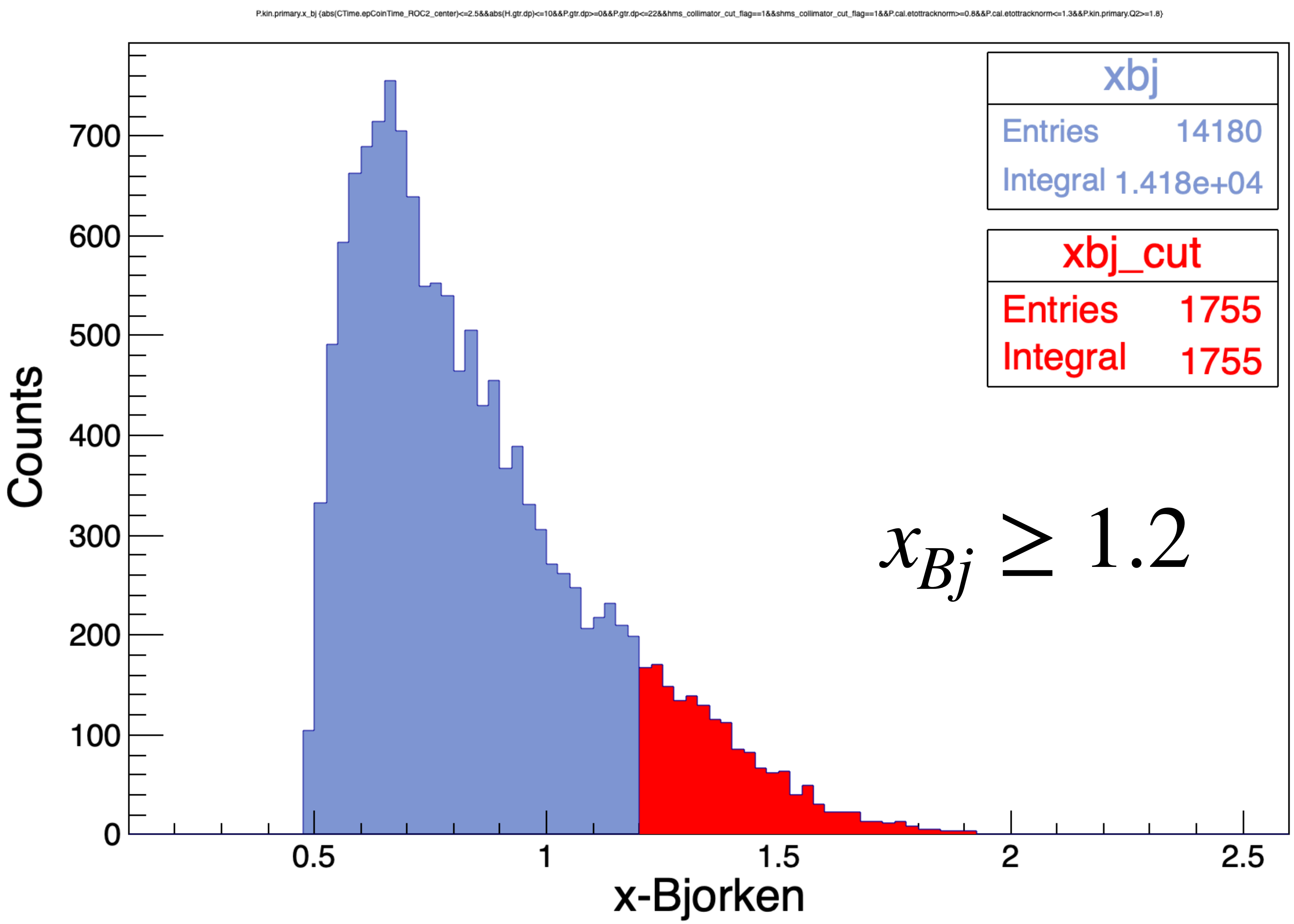
(For illustration purposes, Ca48 SRC run 17057 is used)

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



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

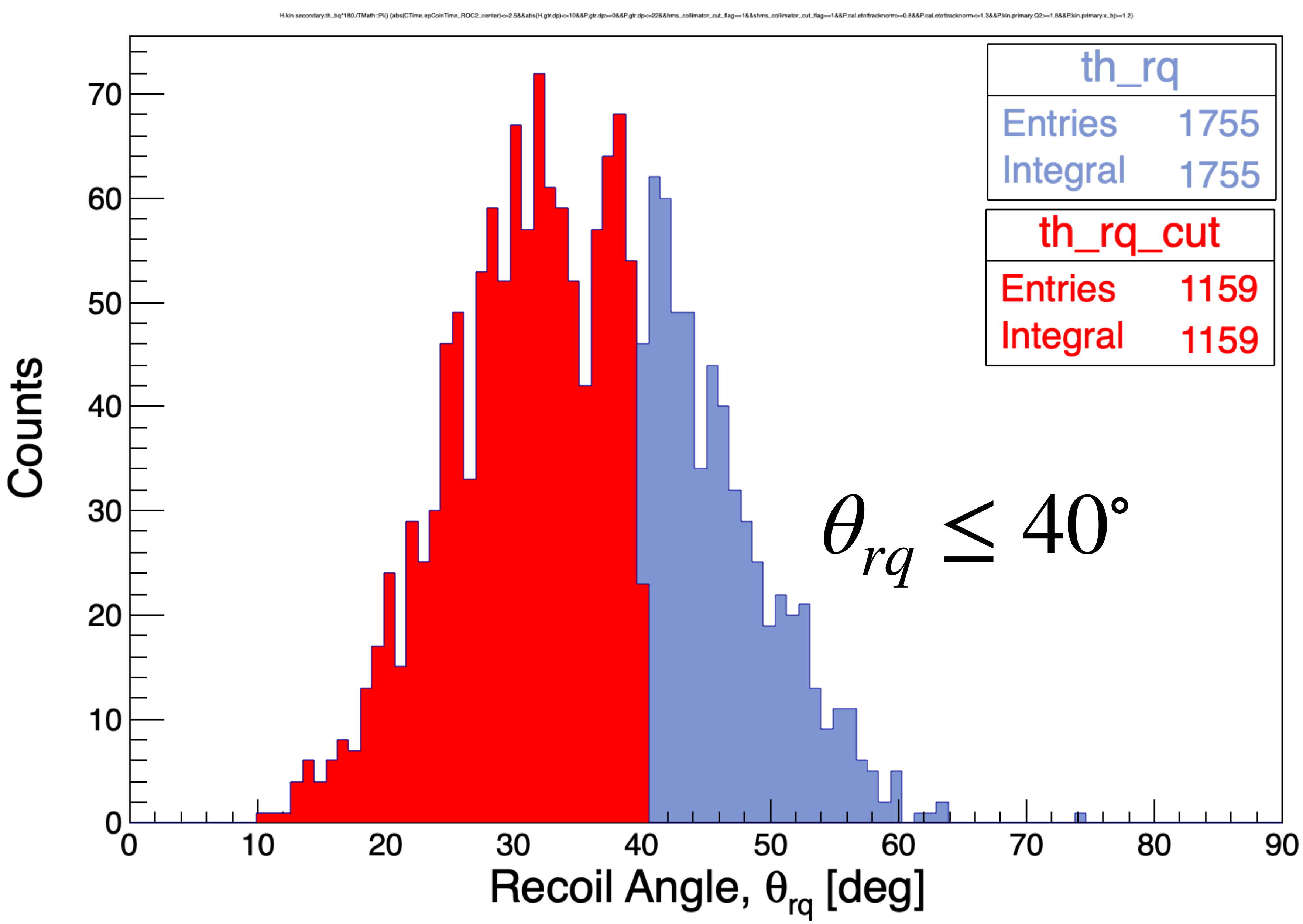
Event Selection (SRC)



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

  (i.e., suppress Δ, N^* excitations)

Event Selection (SRC)



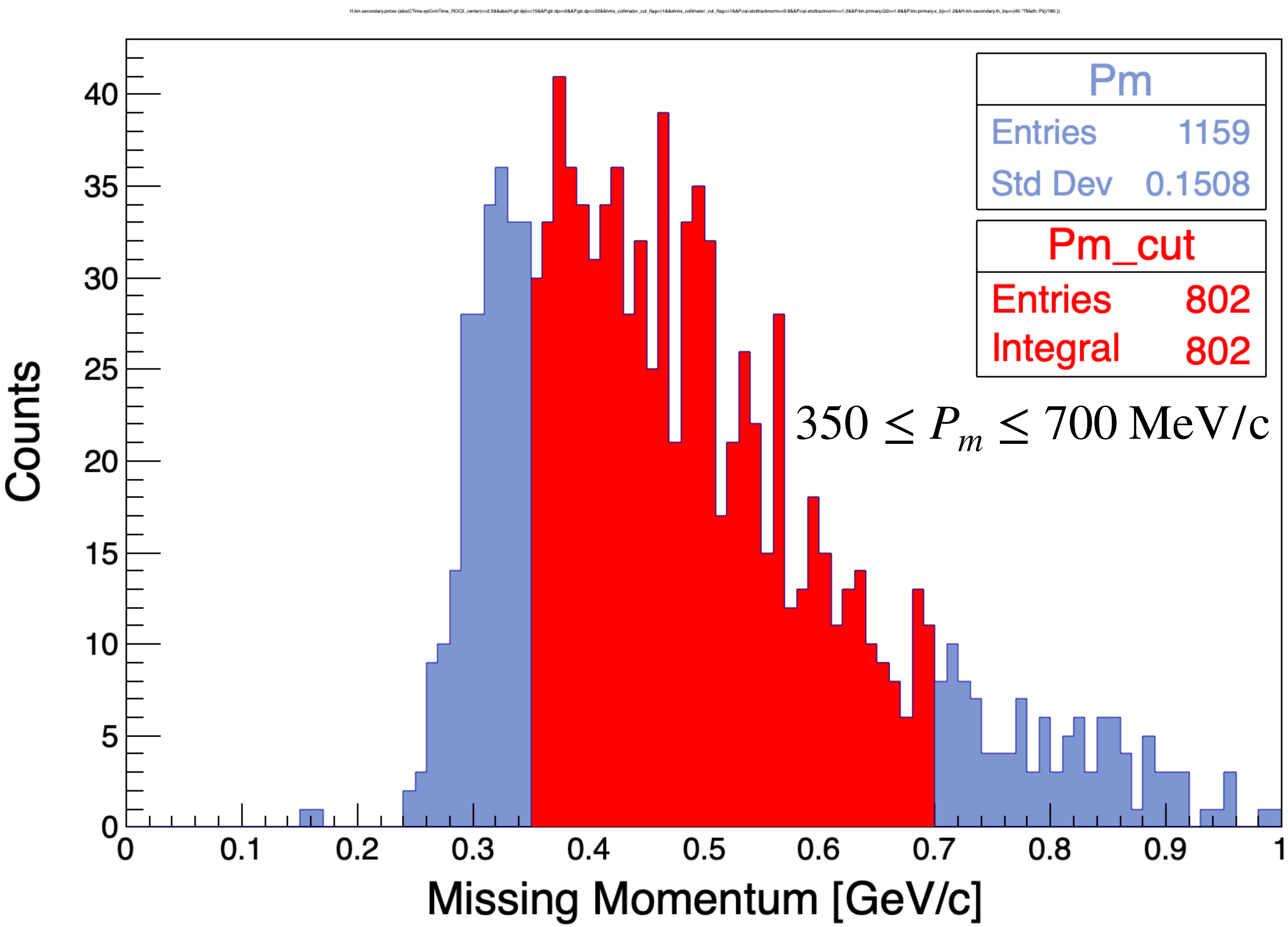
θ_{rq} :

- Angle between recoil system
- and virtual photon direction

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

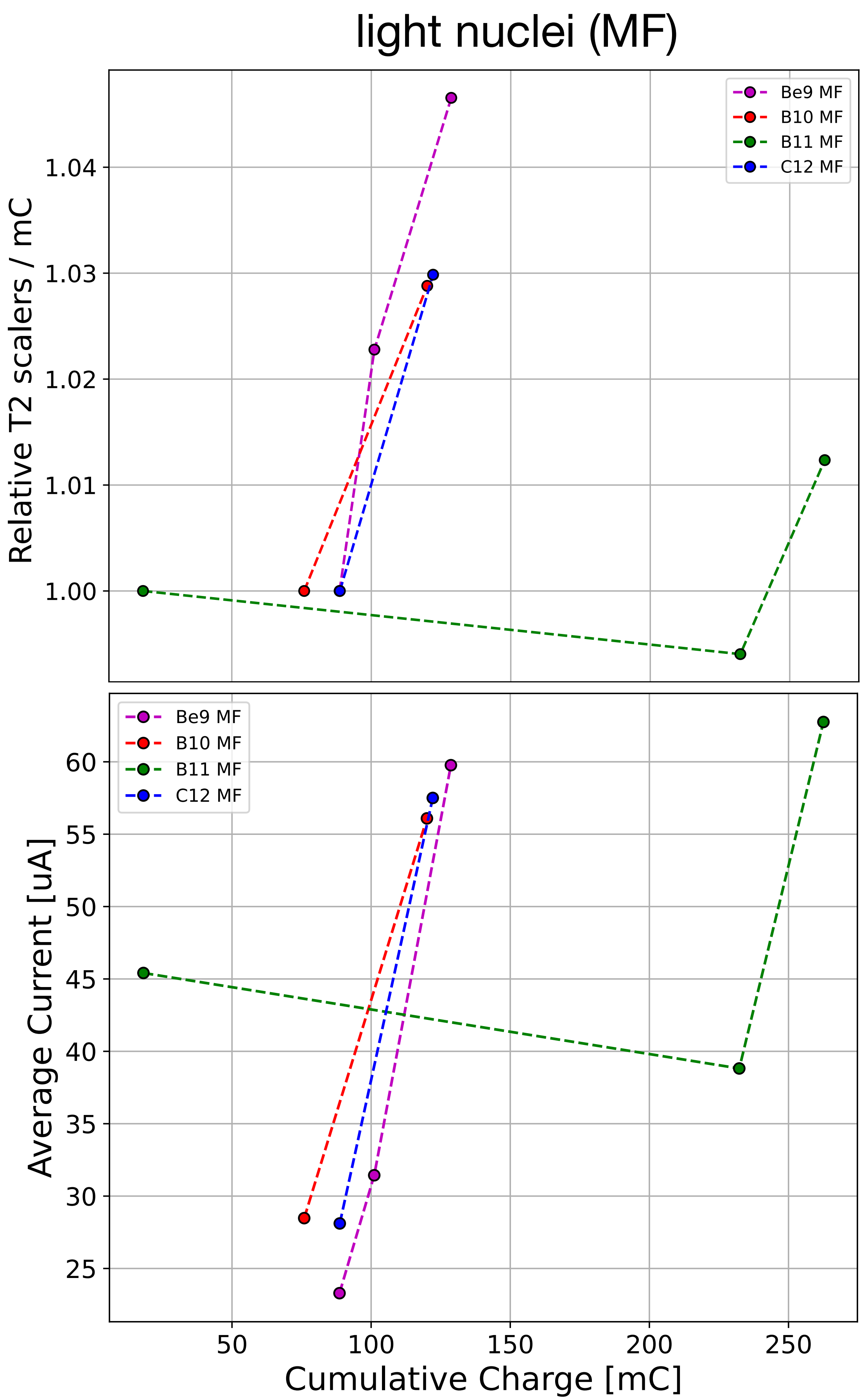
  (i.e., suppress final-state interactions)

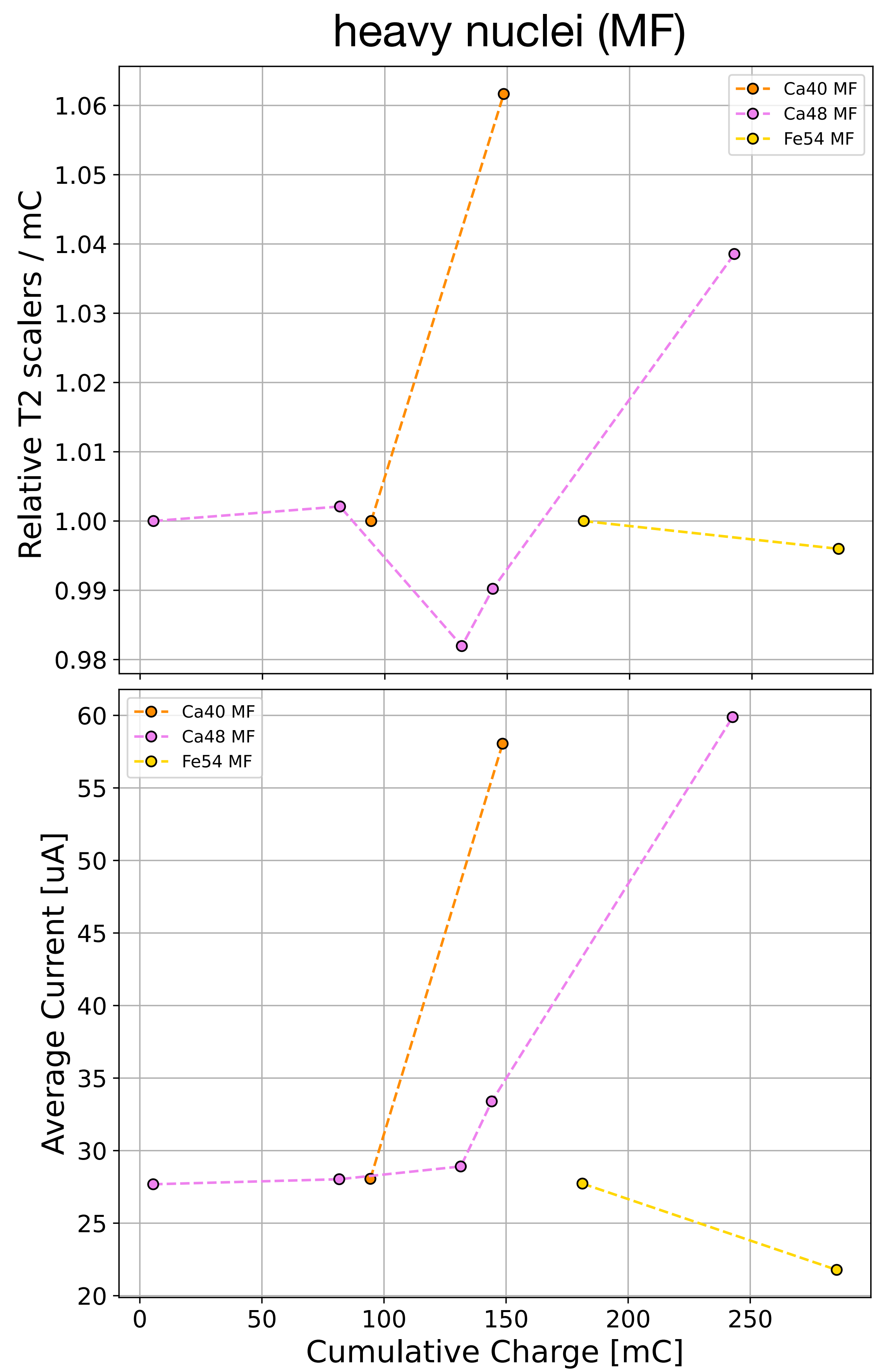
Event Selection (SRC)



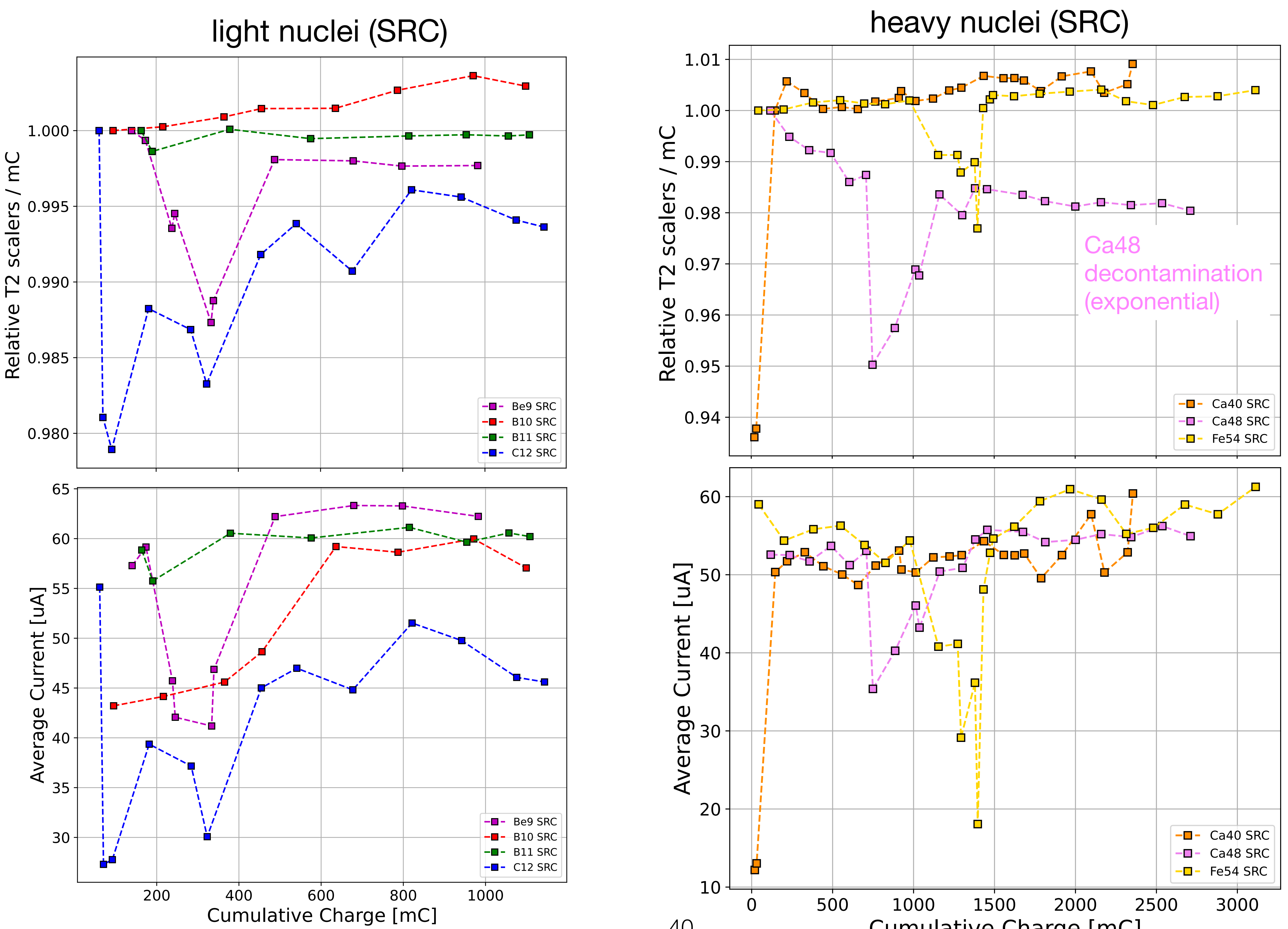
- Kinematic Cut to select short-range correlated nucleon

Relative T2 Scalers / Charge vs Cumulative Charge

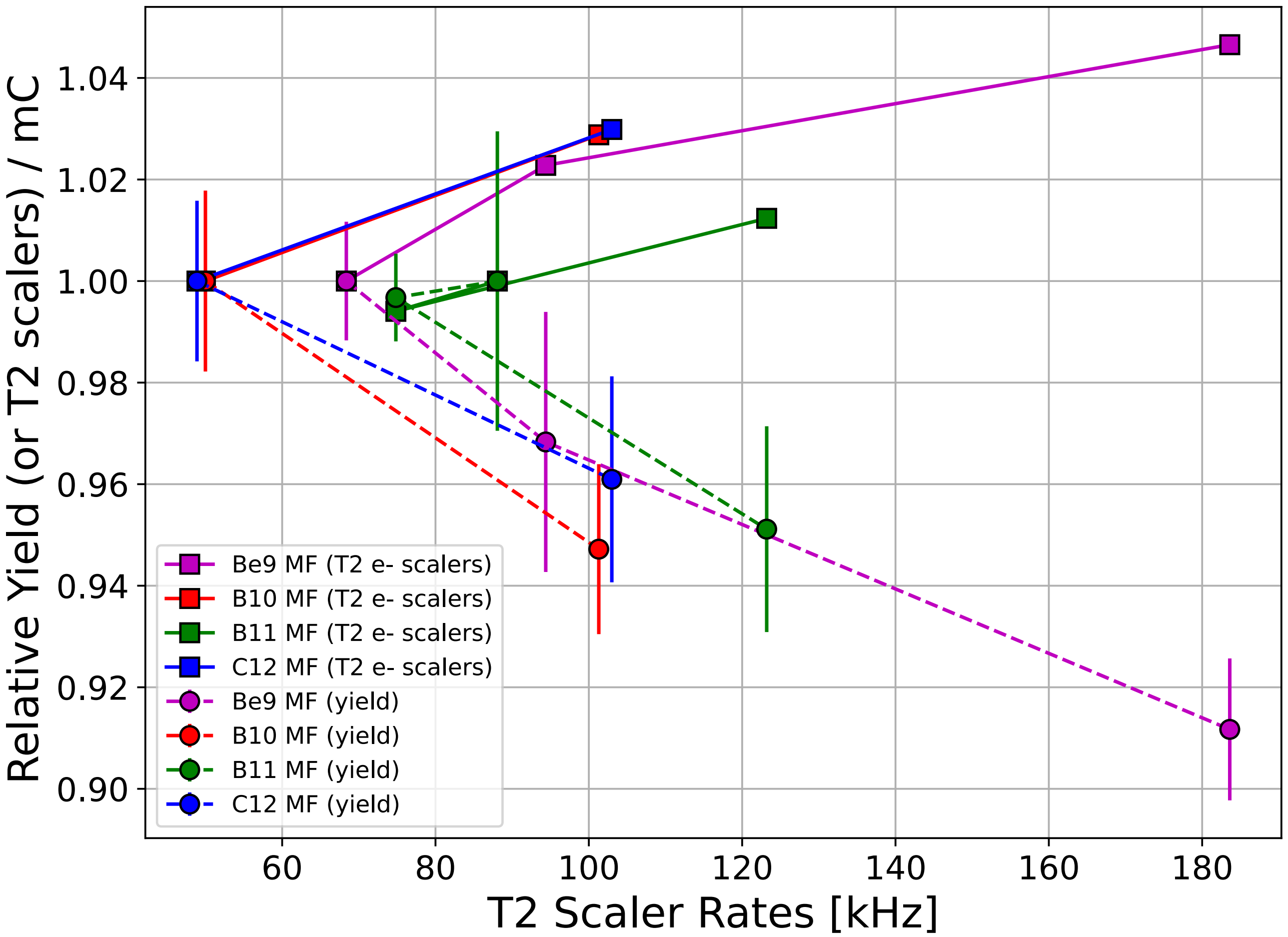


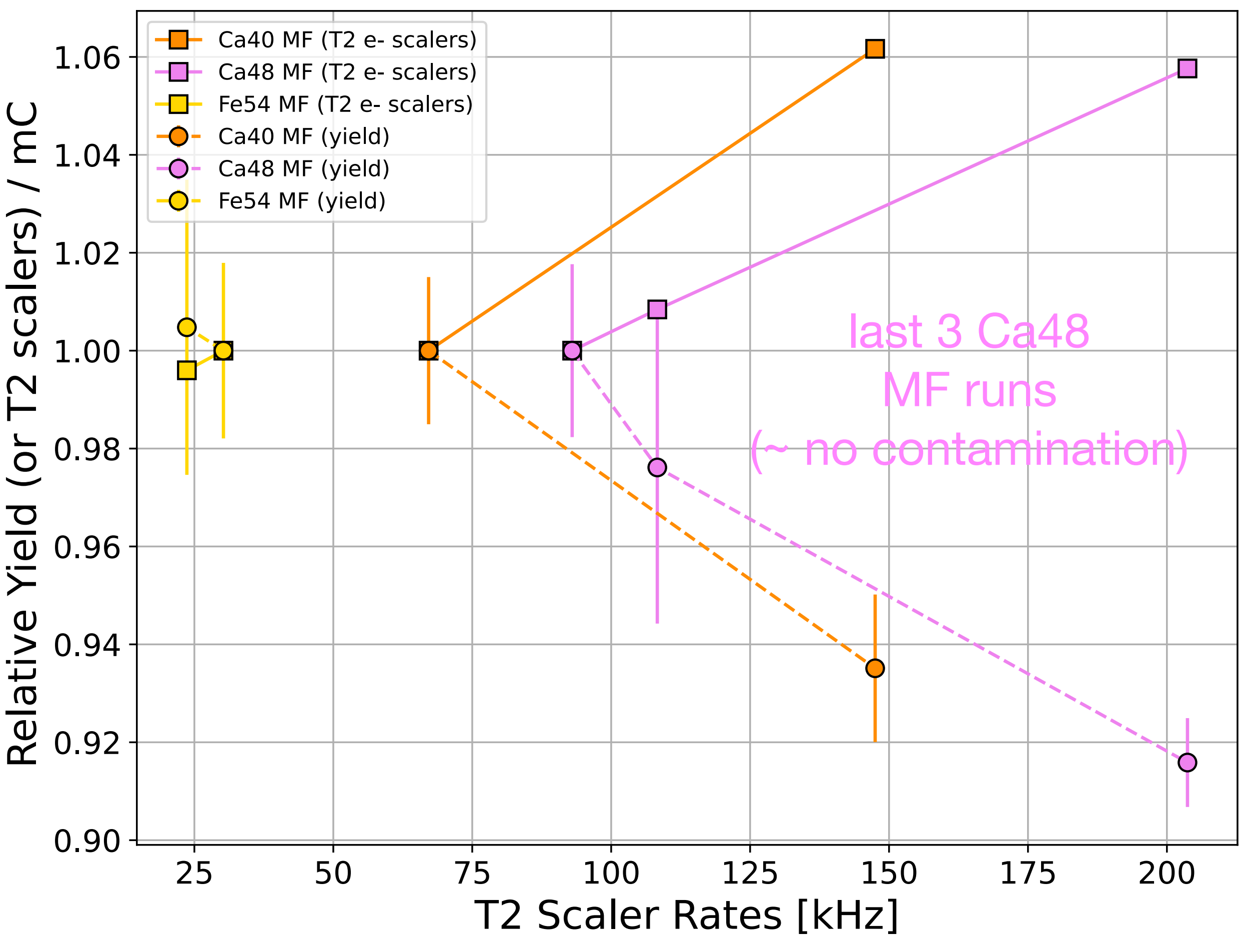


Relative T2 Scalers / Charge vs Cumulative Charge

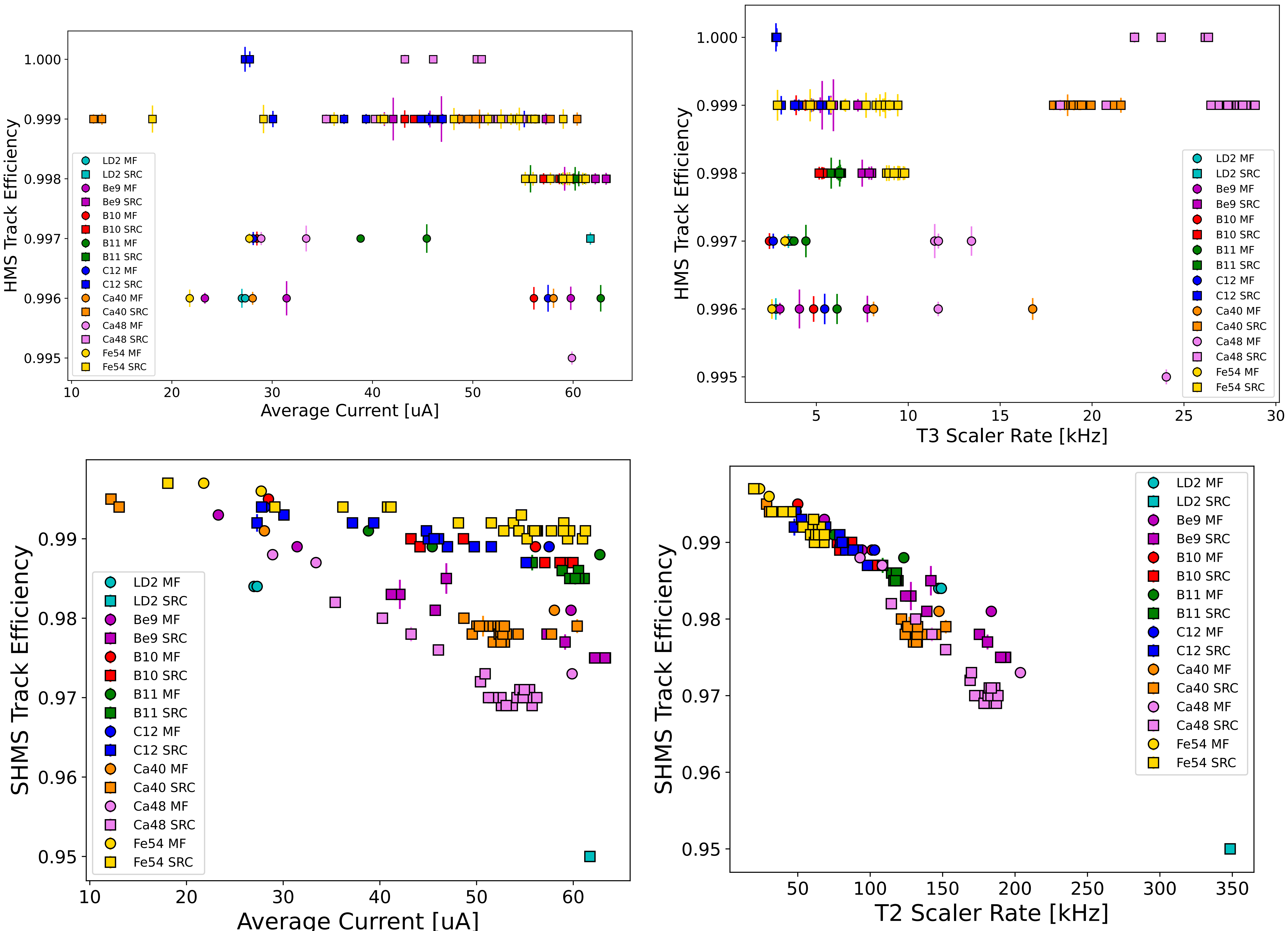


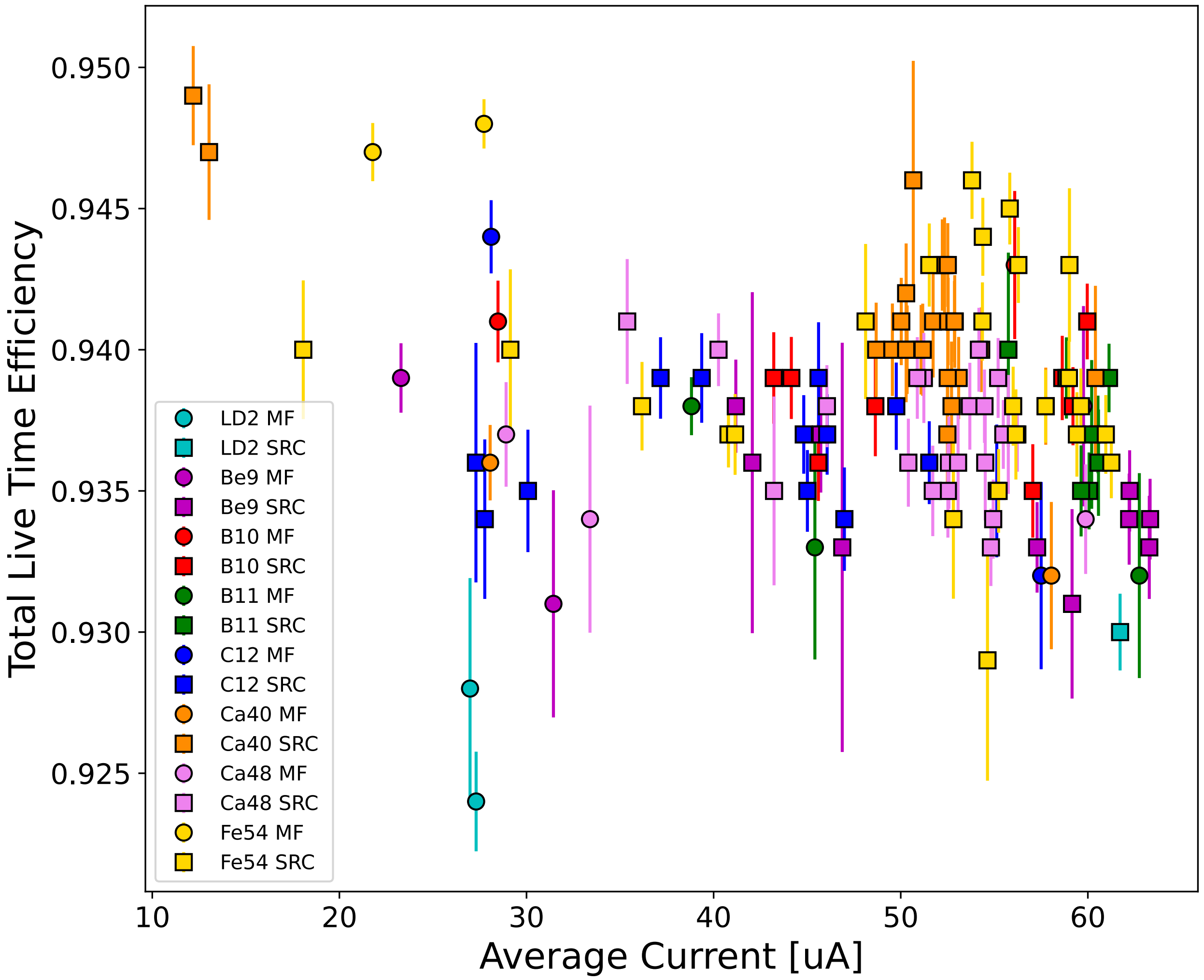
Relative T2 Scalers (or Yield) / Charge vs T2 Scaler Rates

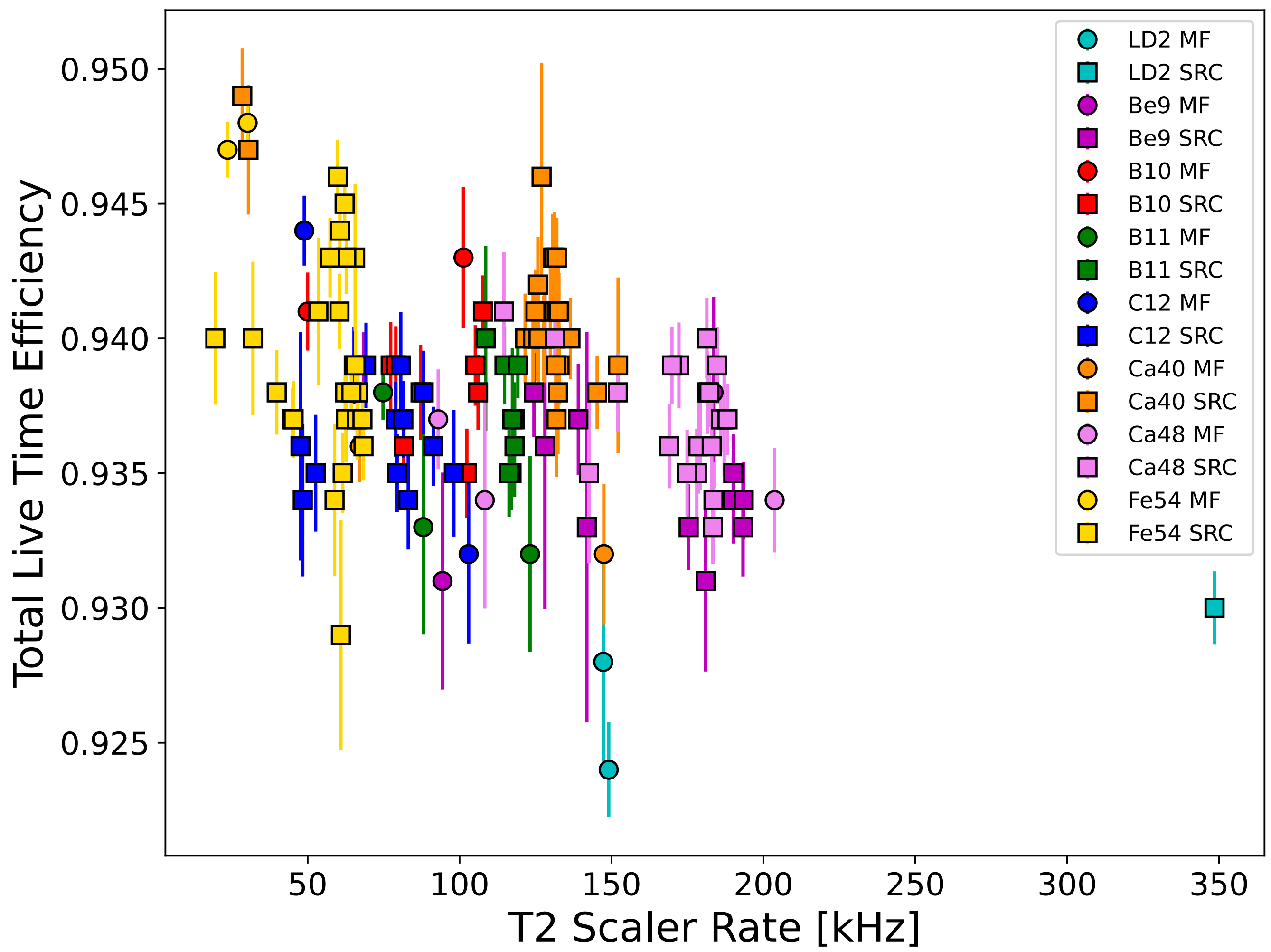




Efficiencies


HMS Track Efficiency
Average Current [uA]
T3 Scaler Rate [kHz]
SHMS Track Efficiency
Average Current [uA]
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


Total Live Time Efficiency
Average Current [uA]
0.950
0.945
0.940
0.935
0.930
0.925
10
20
30
40
50
60
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
T2 Scaler Rate [kHz]
0.950
0.945
0.940
0.935
0.930
0.925
50
100
150
200
250
300
350
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