Forward Tracking to High Luminosity

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July 8, 2025

CLAS Collaboration Meeting

Jefferson Lab
Thomas Jefferson National Accelerator Facility

clas
CEBAF Large Acceptance Spectrometer

Outline

- Status of forward tracking
- Update for covariance matrix (CM)
- Status of DC-uRWell tracking
- Summary and Next

Software Updates for Forward Tracking

Software for forward tracking has been comprehensively updated at three stages:

- Tracking-related algorithms
- Clustering-related algorithms
- Adding conventional tracking into AI-assisted tracking as complementary

RGA Fall18

Tracking Efficiency for RGA 2018 Fall

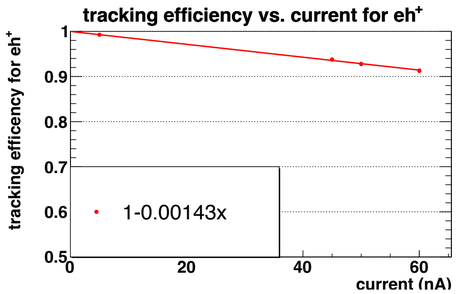
Cuts for event selection:

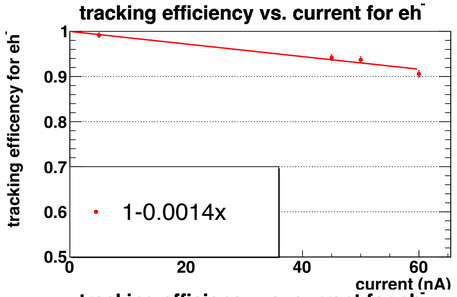
- All particles: $V_z \in [-15, 5]$ cm
- Electron: $p \in [2.5, 5.2]$ GeV
- Others: p > 0.5 GeV, |chi2pid| < 3 and $\theta < 40^0$

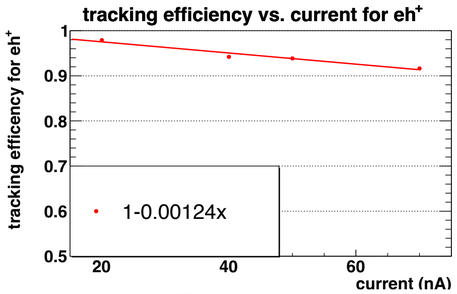
Inbending

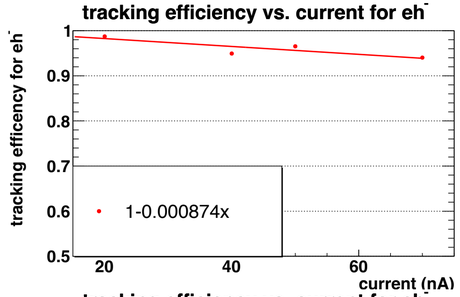
Outbending

pass2 including AI-denosing and AI-assisted tracking

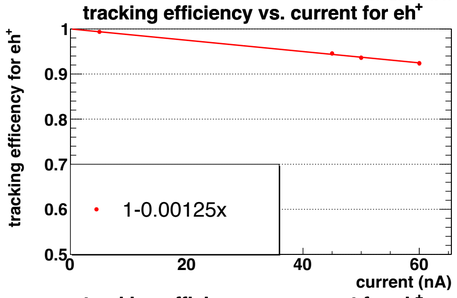


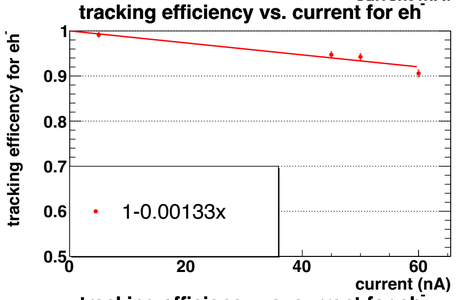


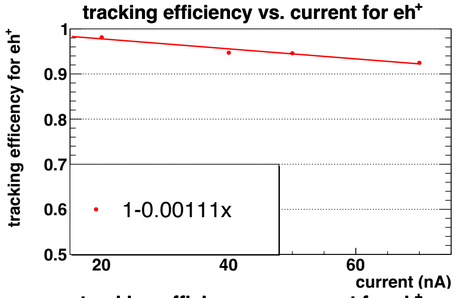


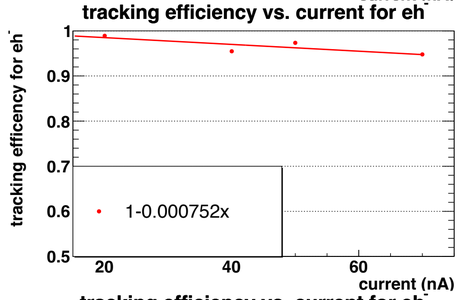


Updates with new tracking

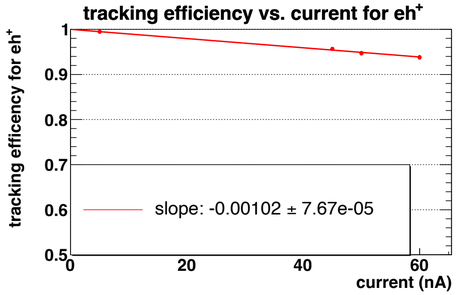


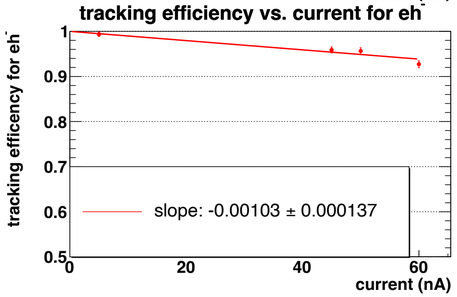


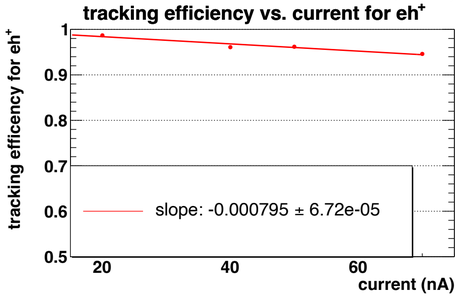


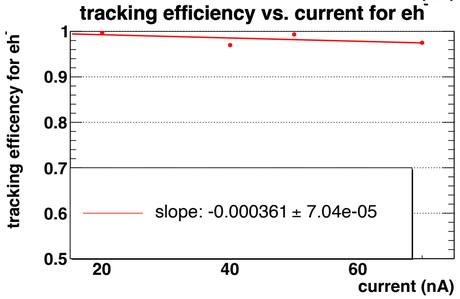


Further updates with new clustering

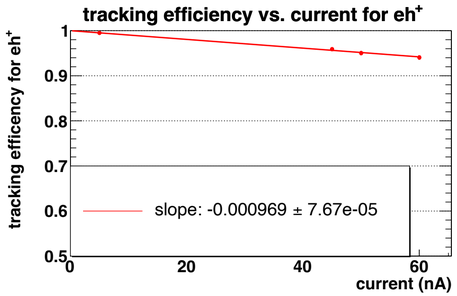


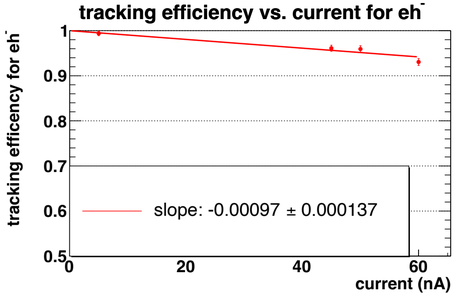


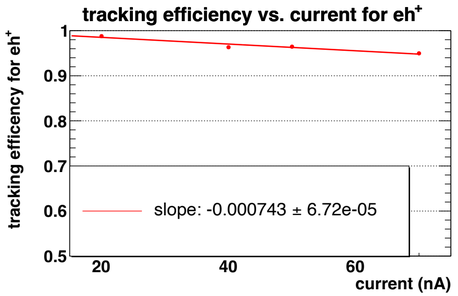


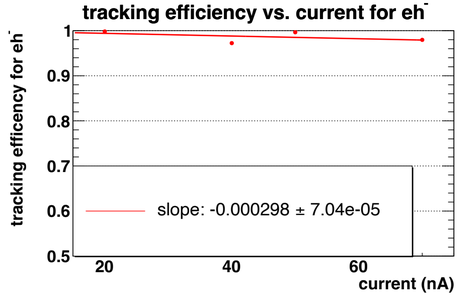


Further updates with conventional tracking as complementary to AI-assisted tracking









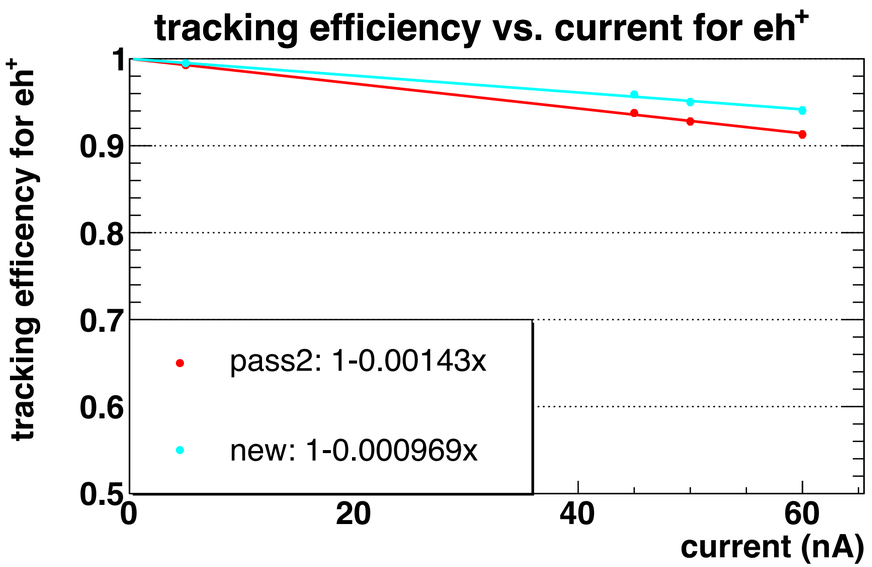
RGA Fall18

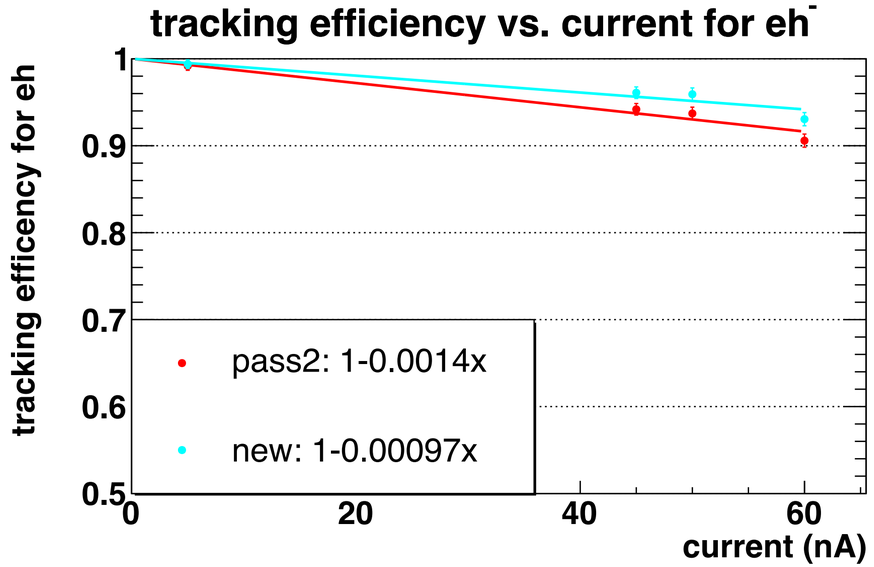
Tracking Efficiency Comparison between Pass2 and New

Cuts for event selection:

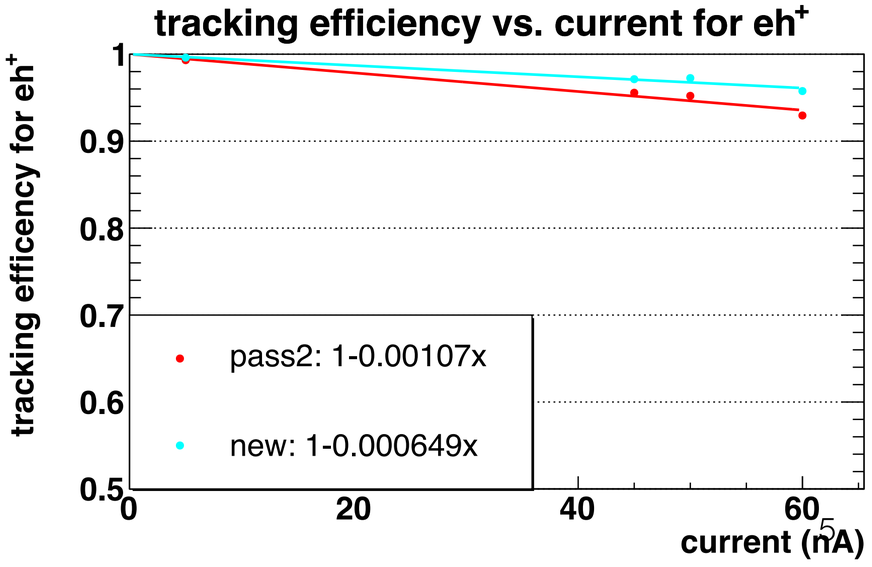
- **All particles: $V_z \in$ [-15, 5] cm**
- **Electron: p $\in$ [2.5, 5.2] GeV**
- **Others: p > 0.5 GeV, |chi2pid| < 3 and $\theta < 40^0$**

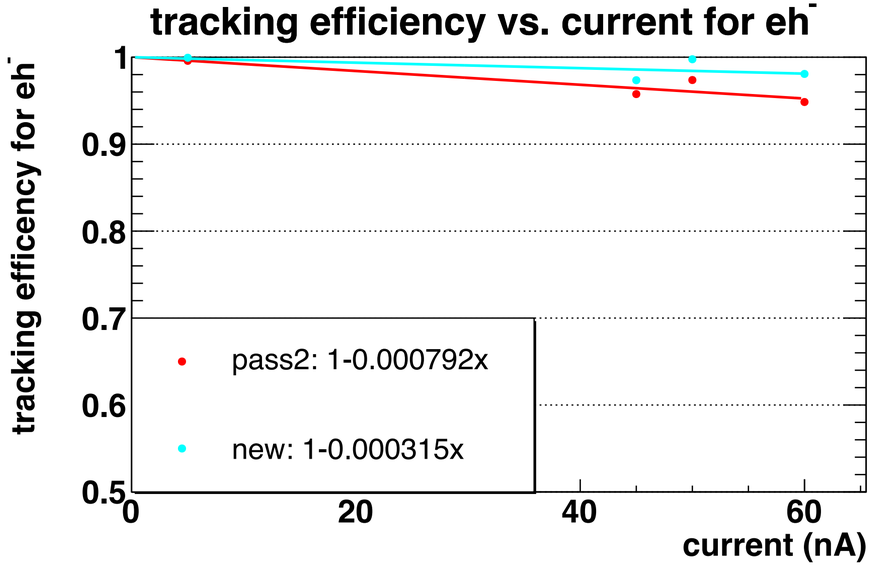
In-bending





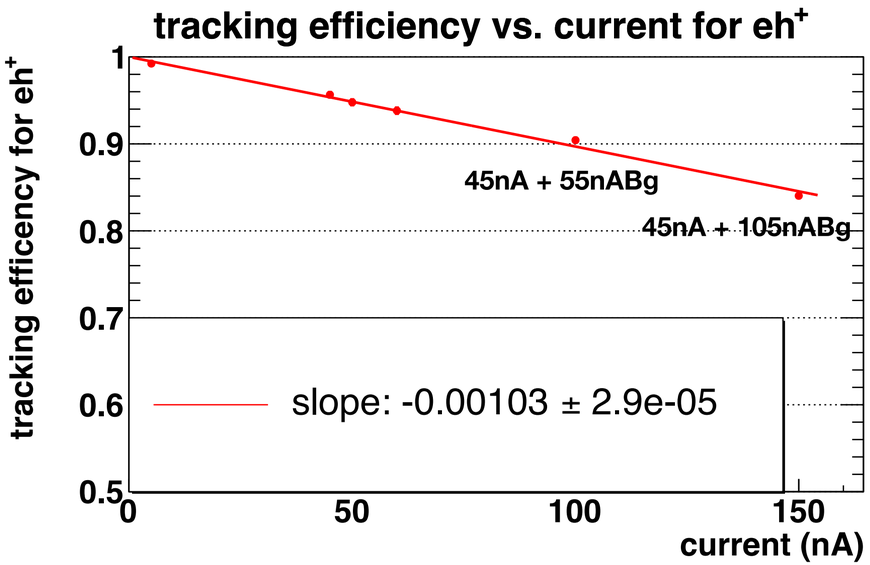
Out-bending

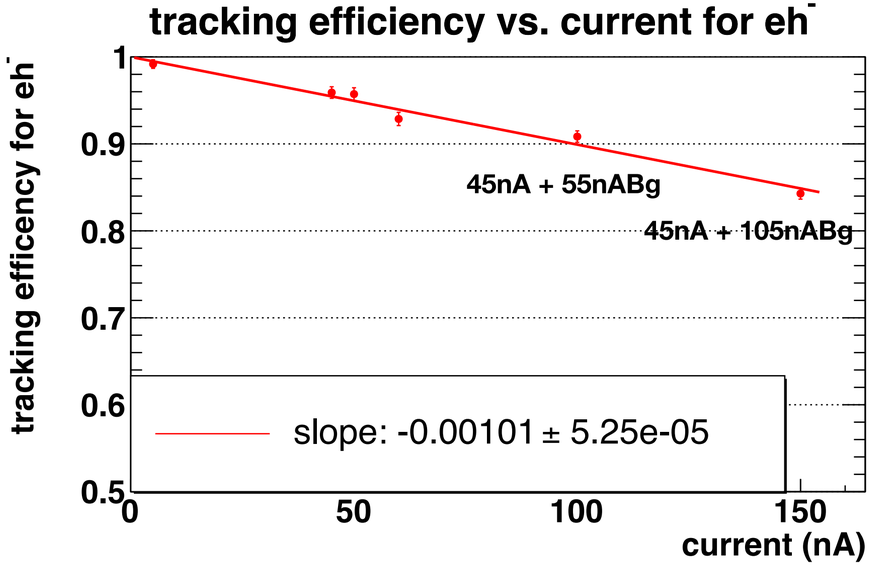




Tracking Efficiency at High Luminosity

In-bending





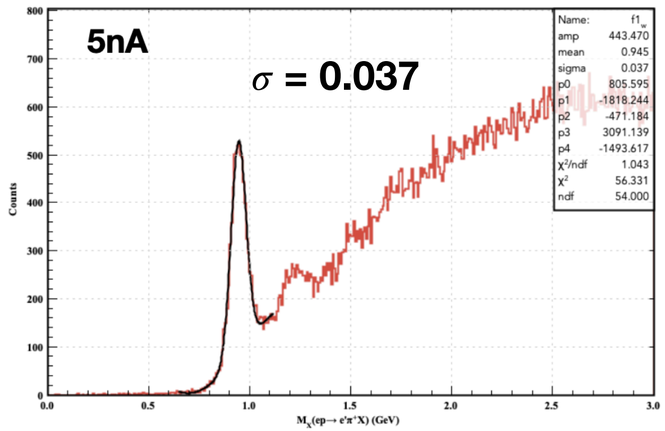
- Tracking efficiency is still linear as beam current at high luminosity.
- Tracking efficiency for RGA is estimated to be ~84% with 150nA beam.

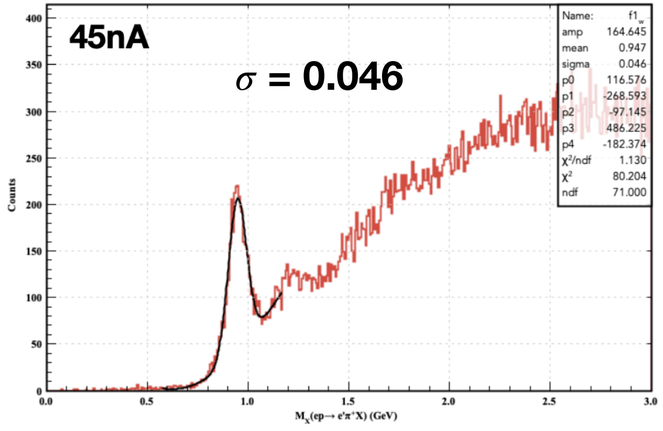
RGA Fall18; In-bending

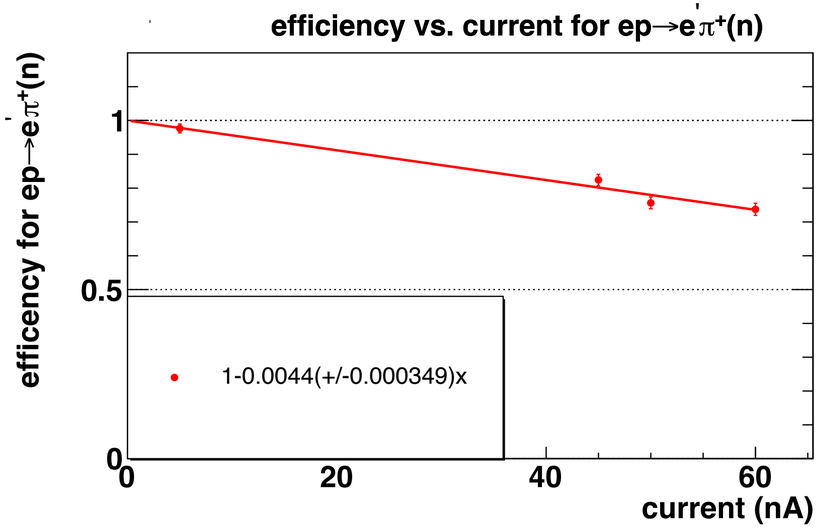
Efficiency for Exclusive Reaction: $ep \rightarrow e'\pi^+X$

Events are selected with cuts for all final-state particles: $V_z \in [-15, 5]$ cm, p > 0.5 GeV and |chi2pid| < 3. All π^+s are used to calculate missing mass if multiple exist.

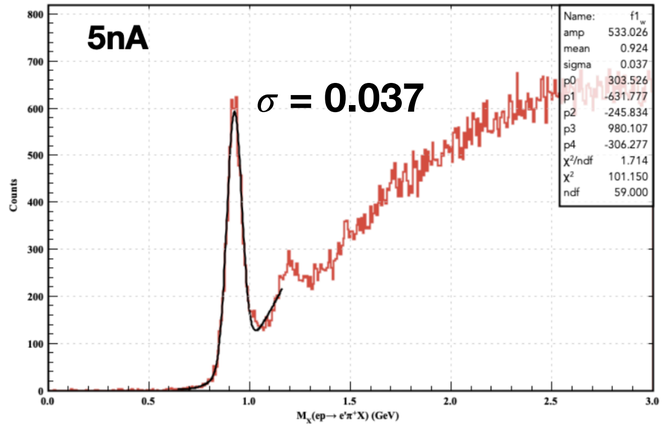
Pass2

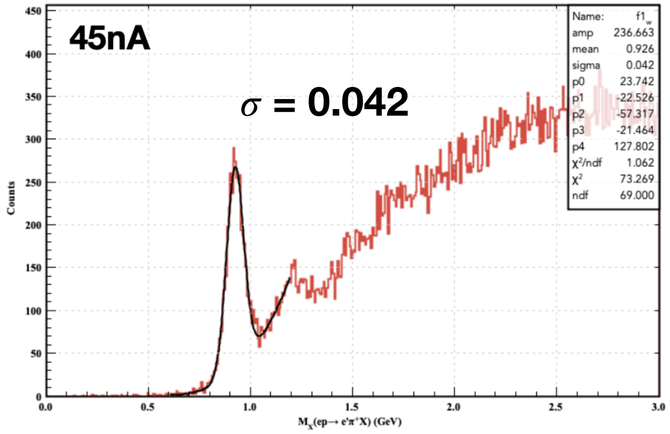


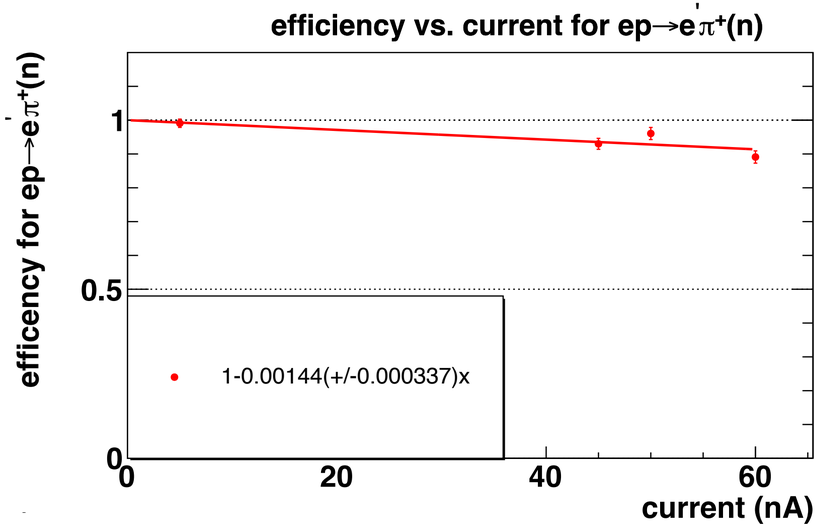




New





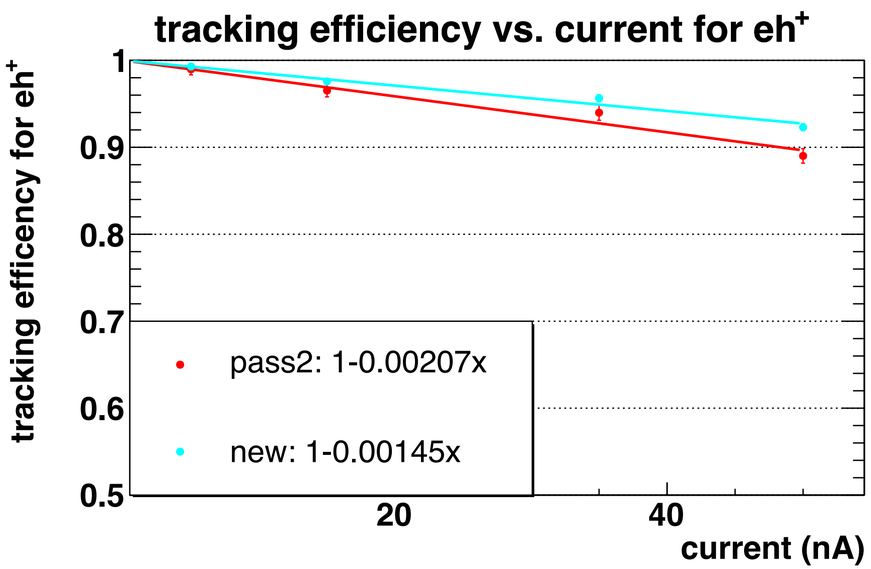


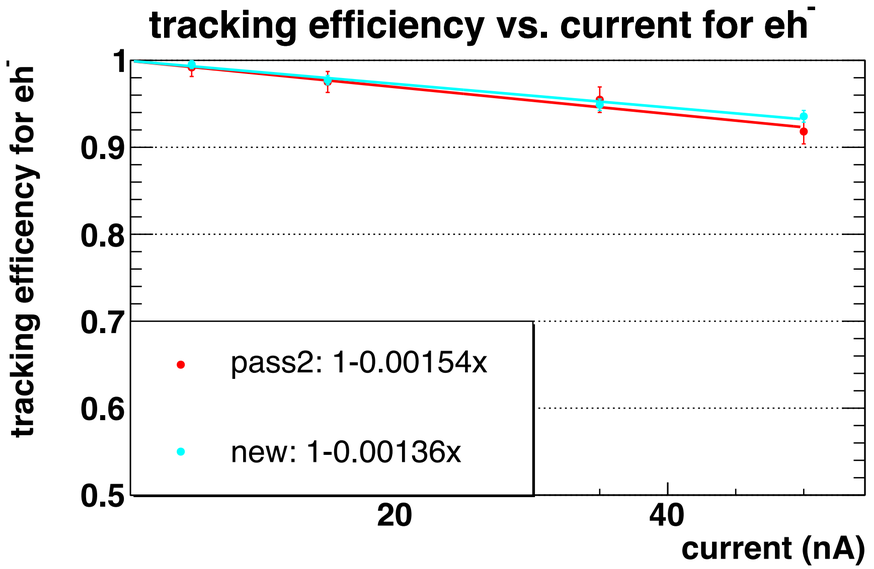
RGB Spring2019

Cuts for event selection:
- **All particles: $V_z \in$ [-15, 5] cm**
- **Electron: p $\in$ [2.5, 5.2] GeV**
- **Others: p > 0.5 GeV, |chi2pid| < 3 and $\theta < 40^0$**

Tracking Efficiency Comparison between Pass2 and New

In-bending





Tracking efficiency for RGB is worse since FT is on.

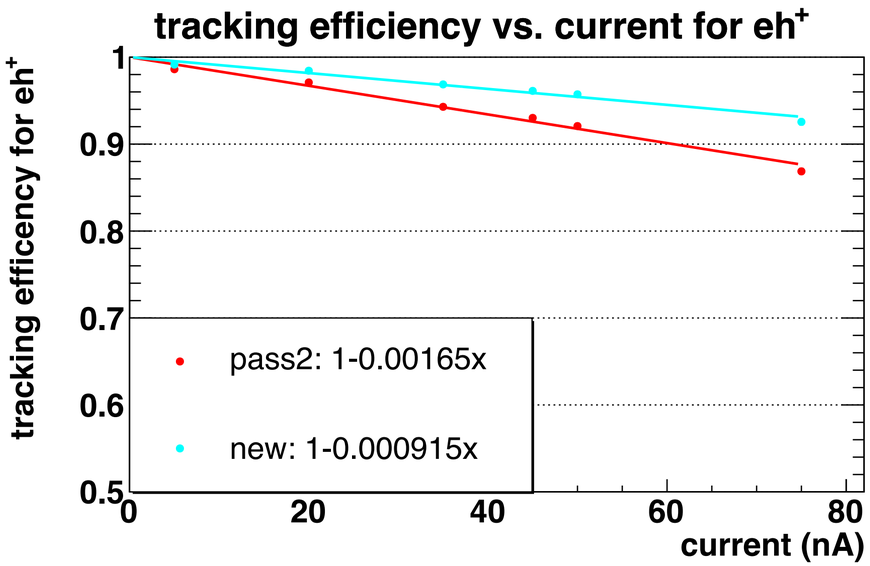
RGD Fall2023

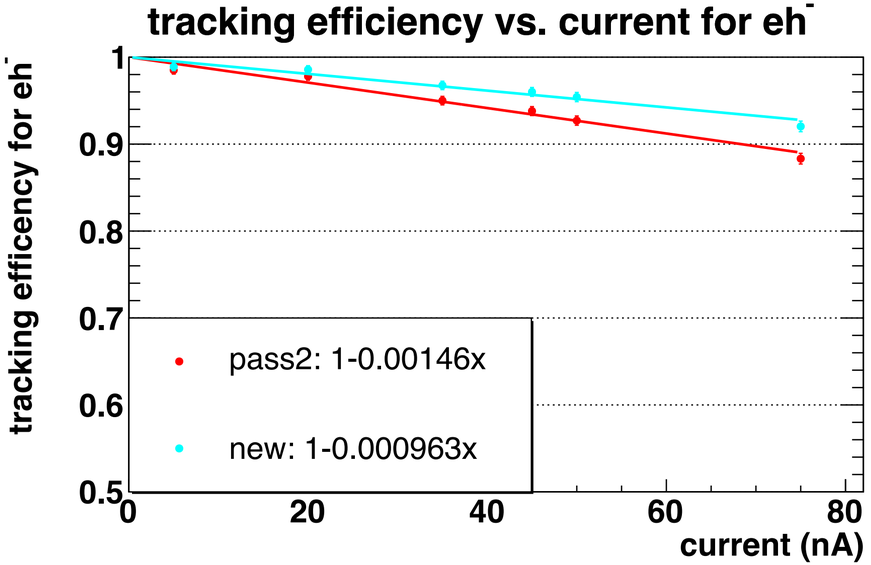
Tracking Efficiency Comparison between Pass2 and New

Cuts for event selection:

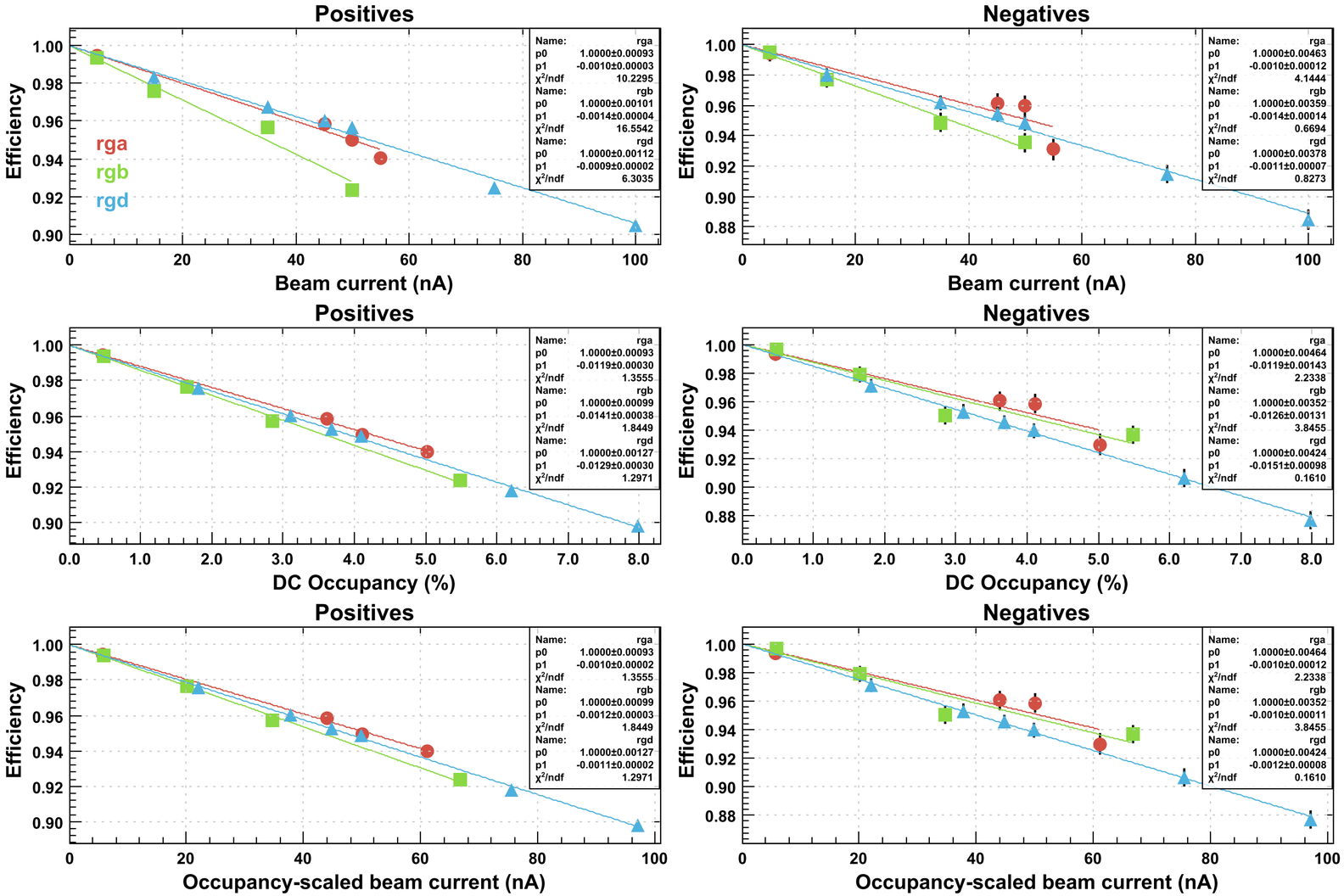
- **All particles: $V_z \in$ [-15, 5] cm**
- **Electron: p $\in$ [2.5, 5.2] GeV**
- **Others: p > 0.5 GeV, |chi2pid| < 3 and $\theta < 40^0$**

In-bending





Tracking Efficiency vs. Occupancy-Scaled Beam Current

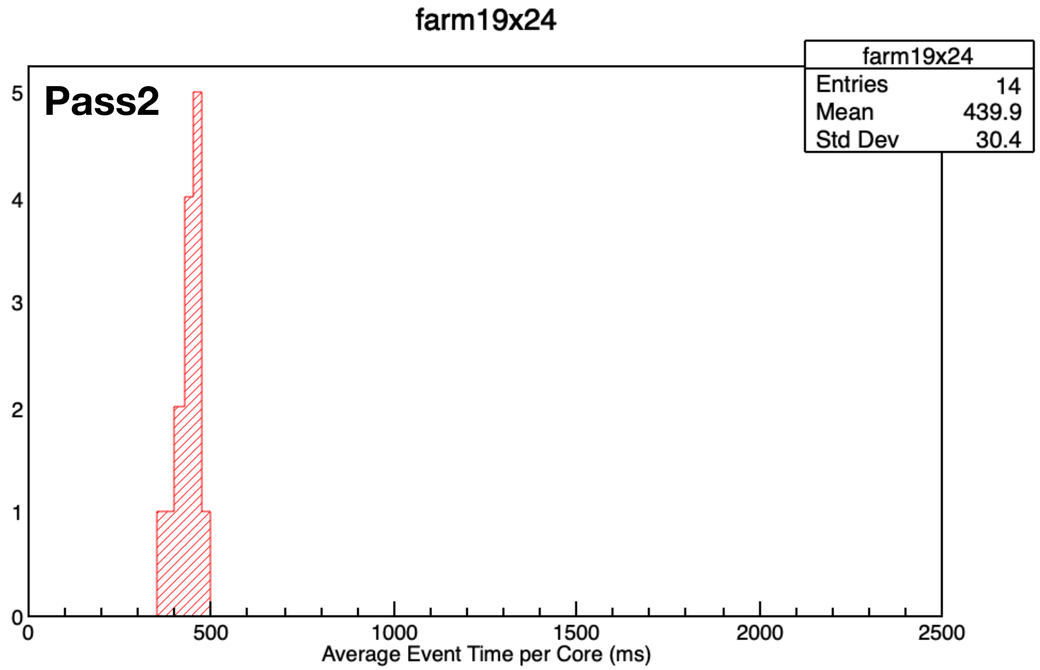


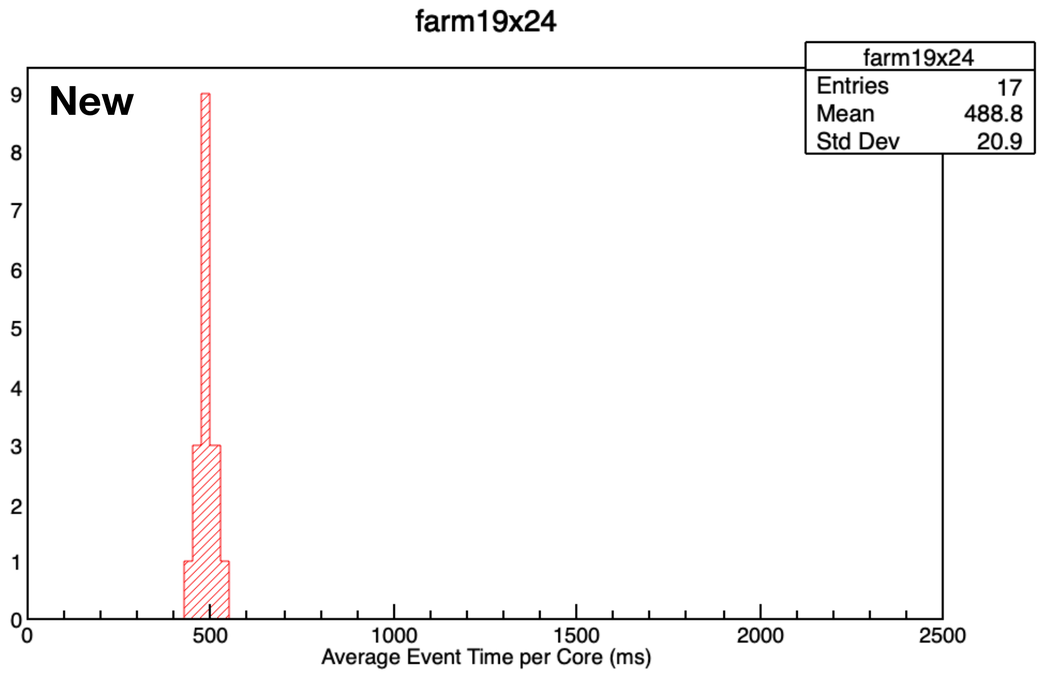
Plots from Raffaella

Tracking efficiency reduction rate is nearly 0.1% per nA.

CPU Time

RGD run 18324 (50nA); DST cooking



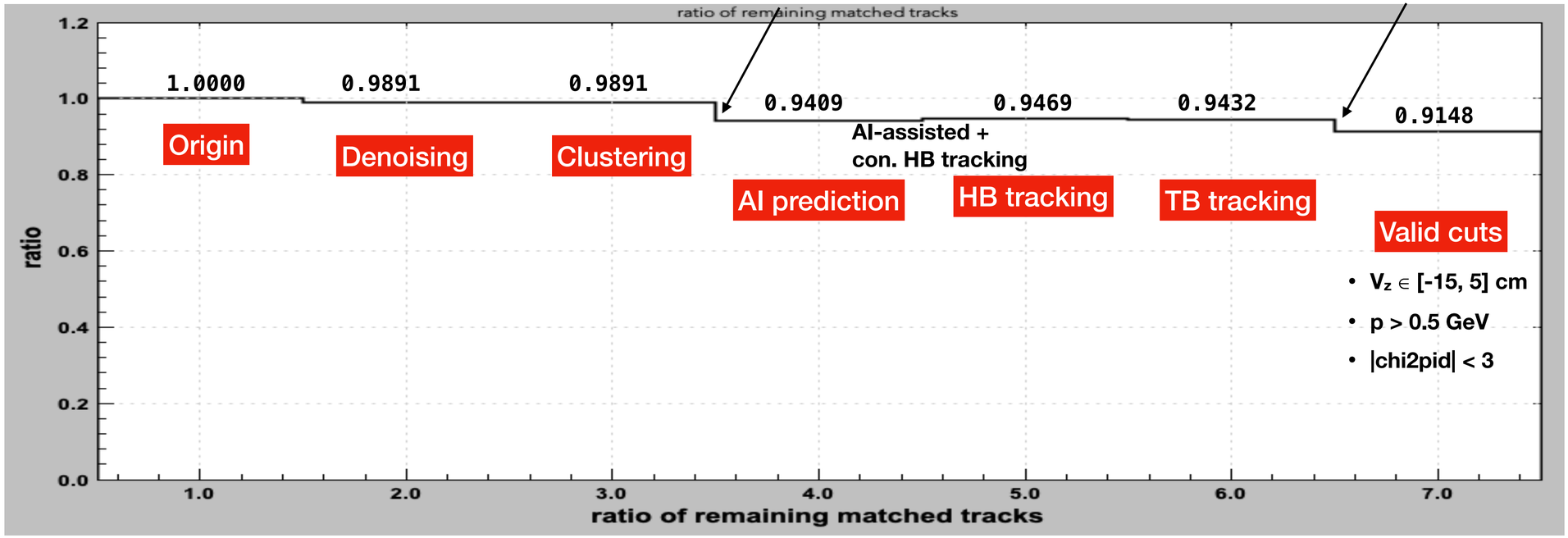


~11% more CPU time

Background Effects on Tracking Efficiency

- Effects of noise or mixed clusters
- Routine for selection of cluster combos

- Effects of noise and lost hits on tracking
- TB hit measures depending on rough HB tracking



- Study for background effects on tracking efficiency is taken through track-by-track comparison between pure RGA-MC and RGA-MC merged with 100nA background at all levels of DC reconstruction.
- The study reveals that track efficiency mainly drops at the levels of AI prediction for cluster combos and kinematic cuts for selection of valid tracks.

Discussion

- To relief the issue for cluster combo selection,
  - new AI model with double cluster features for cluster combo prediction is in progress.
  - the road algorithm, which is applied in the trigger system, plans to be attempted to predict cluster combos.
- Besides, an attempt for third-pass tracking after TB tracking is in plan to relief effects that TB hit measures depend on rough HB tracking.

About Covariance Matrix

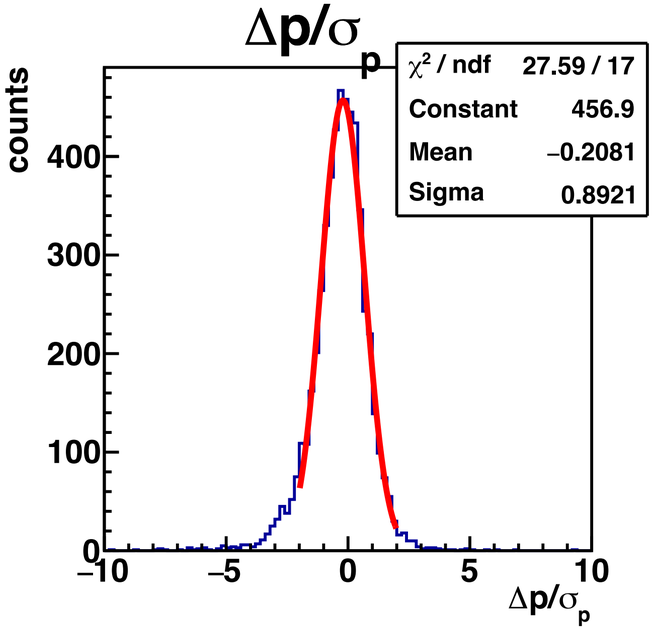
- Current CM bank for forward tracking is not available since it is for state at vertex from tracking in the tilted sector frame. Tracking representation is (x, y, t_x, t_y, Q) with reference of z, so CM is a 5*5 matrix.
- To be available for kinematic fitting and other studies, CM in the tilted sector frame needs to be transformed into a 6*6 CM for vertex and momentum (x'', y'', z'', θ'', φ'', p'') in the lab frame.
- Transformation formula is $C' = J_s J_t J_m C J_m^T J_t^T J_s^T$
  - J_m: Jacobi matrix for transformation from (x, y, t_x, t_y, Q) to (x, y, z, θ, φ, p) in the tilted sector frame
  - J_t: Jacobi matrix for transformation from (x, y, z, θ, φ, p) in the tilted sector frame to (x', y', z', θ', φ', p') in the sector frame (rotate 25^0 around y)
  - J_s: Jacobi matrix for transformation from (x', y', z', θ', φ', p') in the sector frame to (x'', y'', z'', θ'', φ'', p'') in the lab frame (rotate around z')

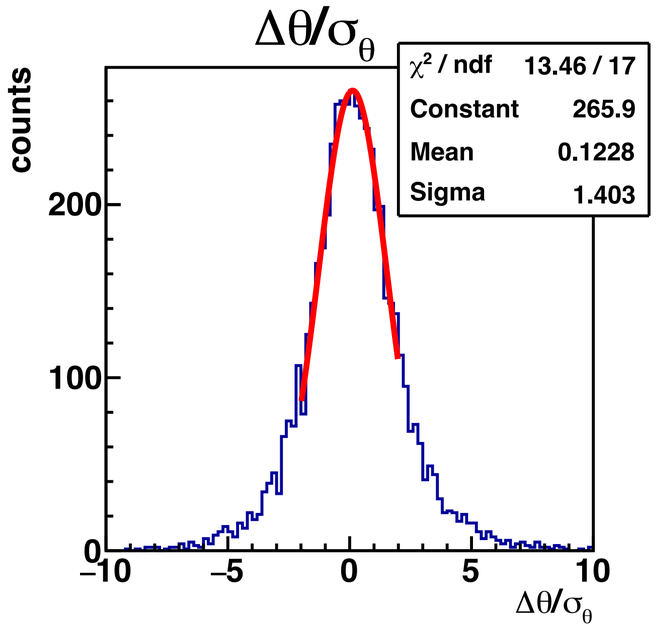
Pure Muon and zero solenoid field

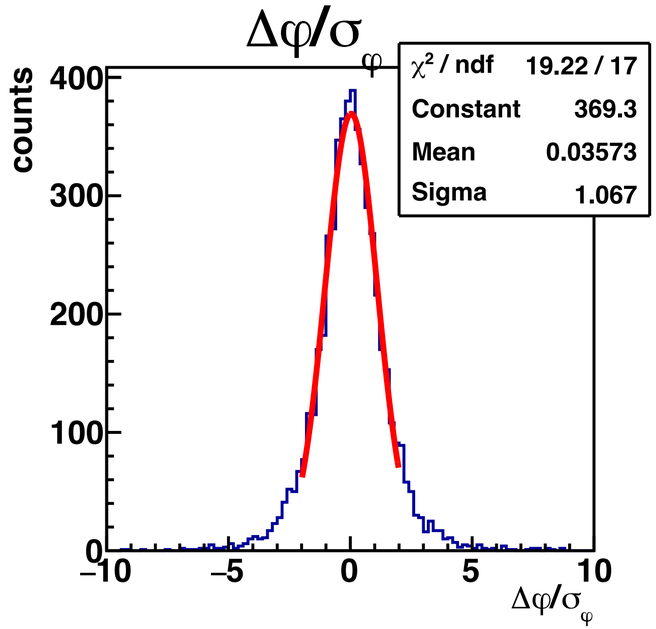
Test Transformed CM

Δ = reconstructed momentum - truth

σ = uncertainty from transformed CM



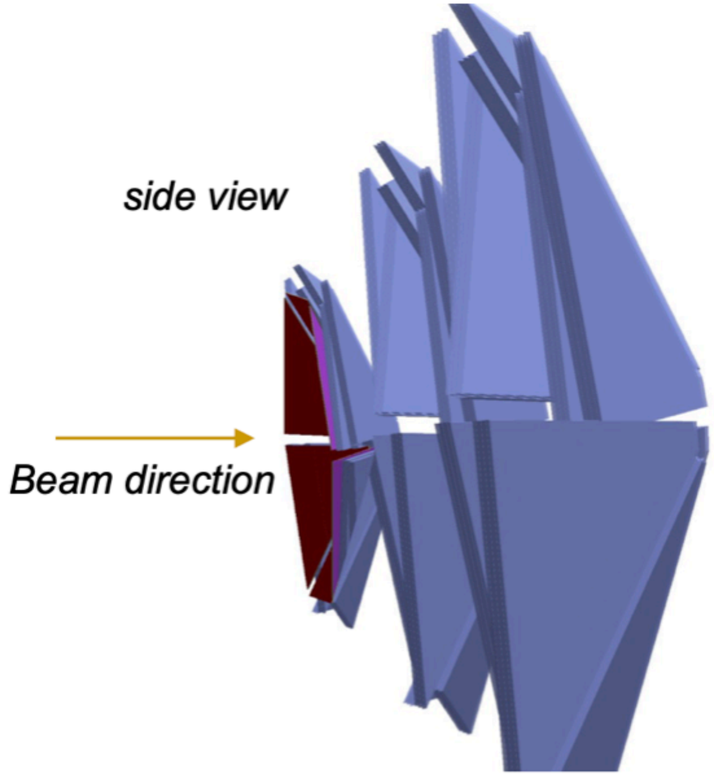




- With scaling resolution of DC hit measurements, transformed CM is close to expected.
- With new calibration, function for resolution of DC hit measurements will be re-defined. Then, CM will be re-investigated.
- Software for transformation of CM is done, but not released yet.

Status of DC-uRWell Tracking

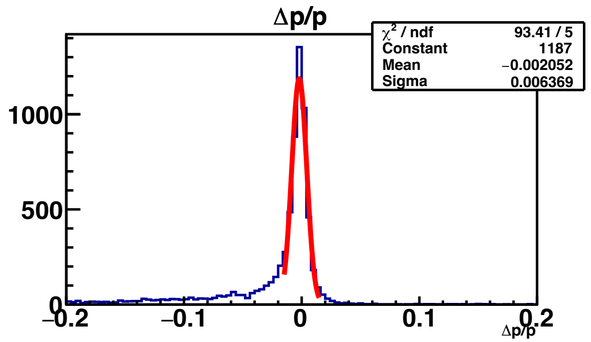
- At DC clustering level, since uRWell is close to DC-SL1, uRWell participates SL1 clustering.
- It relieves background effects at SL1 with high DC hit occupancy at high luminosity.
- Based on correlation between DC and uRWell, which is built at the clustering level, DC-uRWell tracking package for both conventional and AI-assisted tracking has been developed with input of uRWell cluster measurements and DC hit measurements.

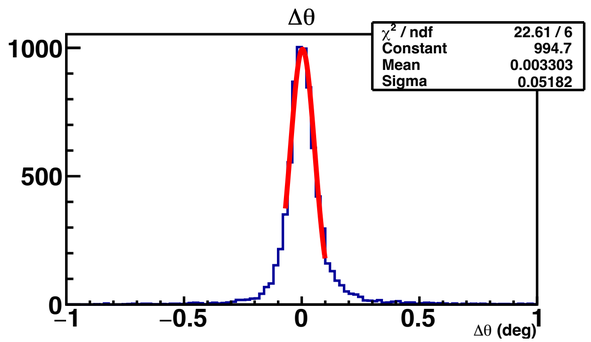


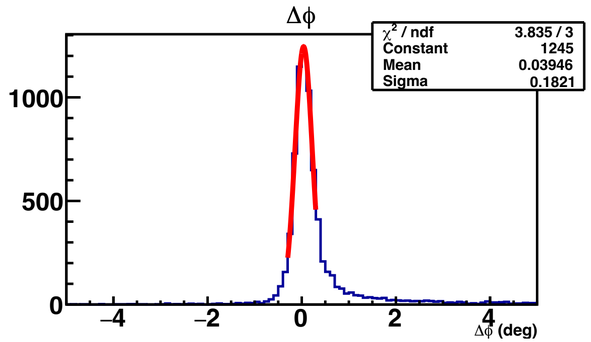
Electron + 100nA Bg

Improvement of Momentum Resolution

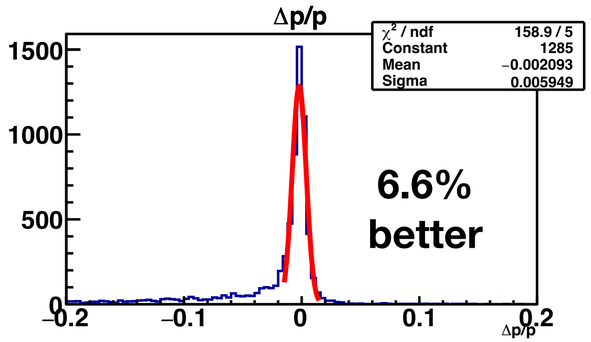
DC-only tracking

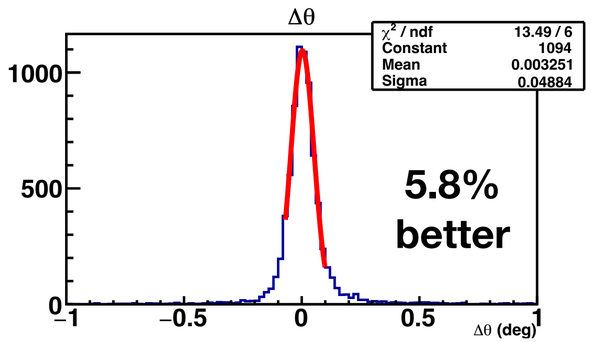


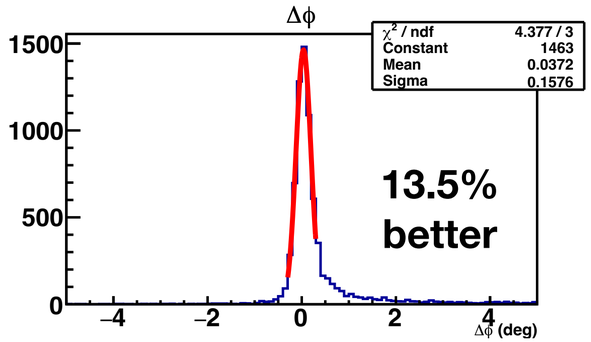




DC-uRWell tracking



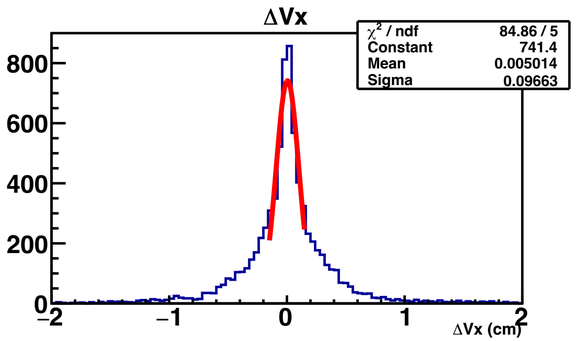


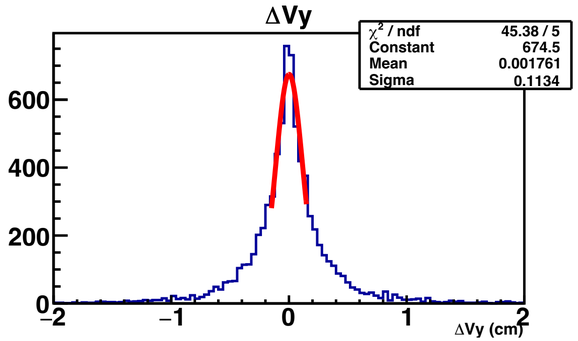


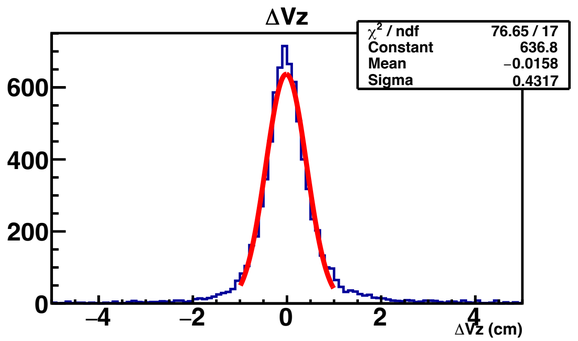
Electron + 100nA Bg

Improvement for Vertex Resolution

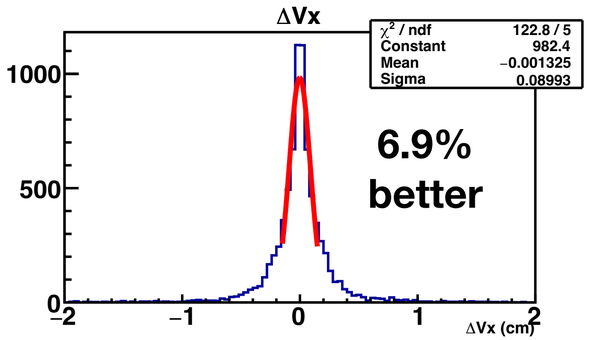
DC-only tracking

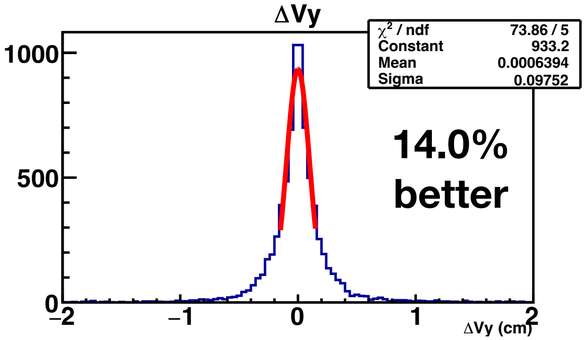


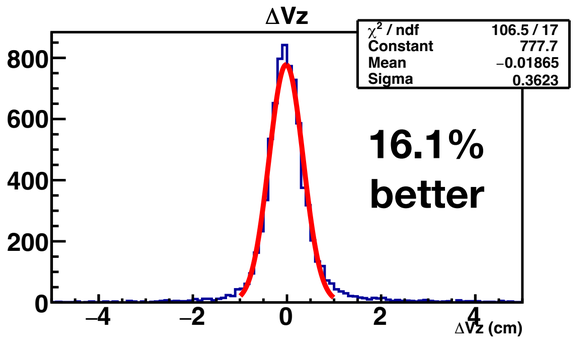




DC-uRWell tracking



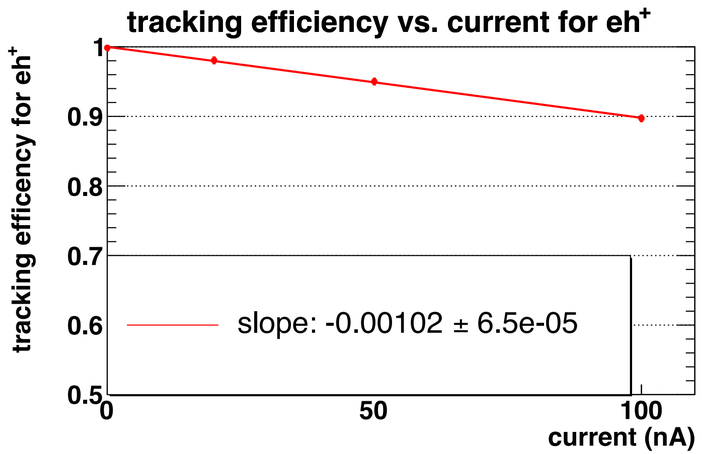


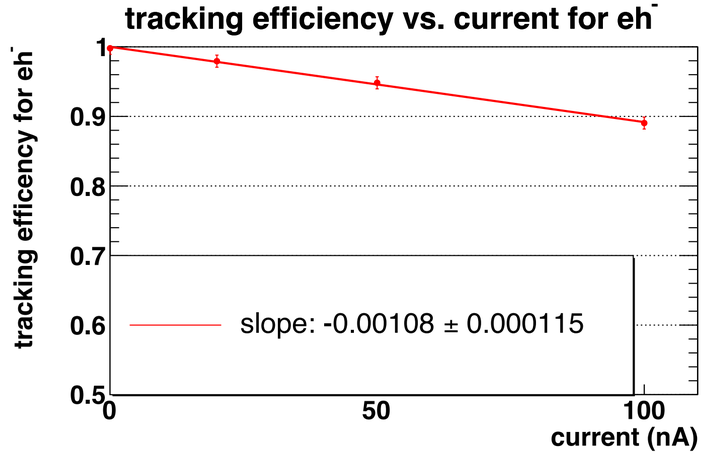


RGA MC + Bg

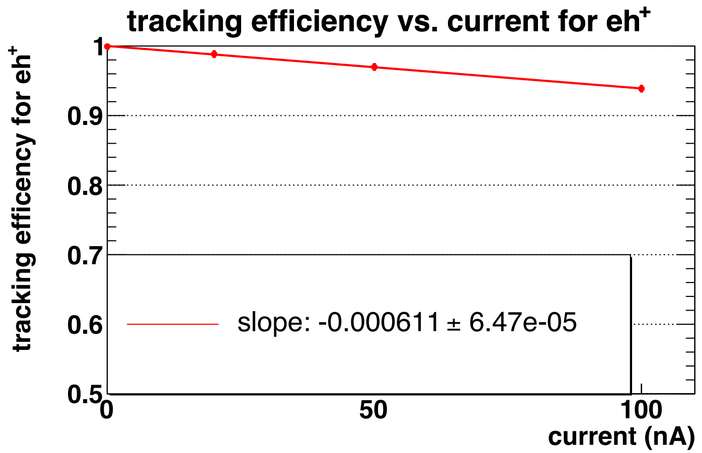
Tracking Efficiency: Conv. Tracking

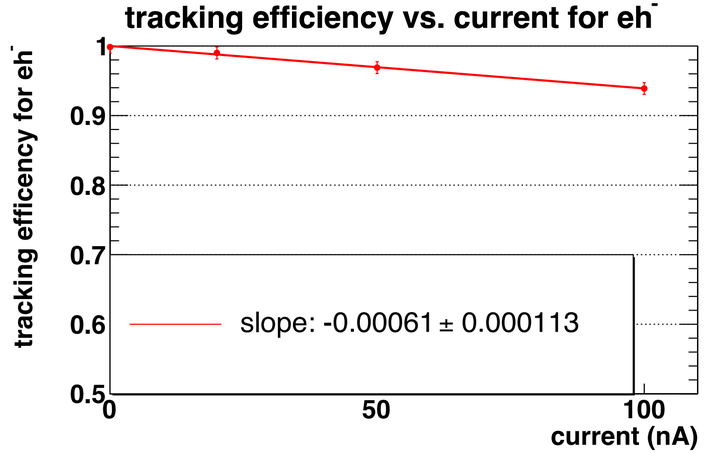
DC-only tracking





DC-uRWell tracking

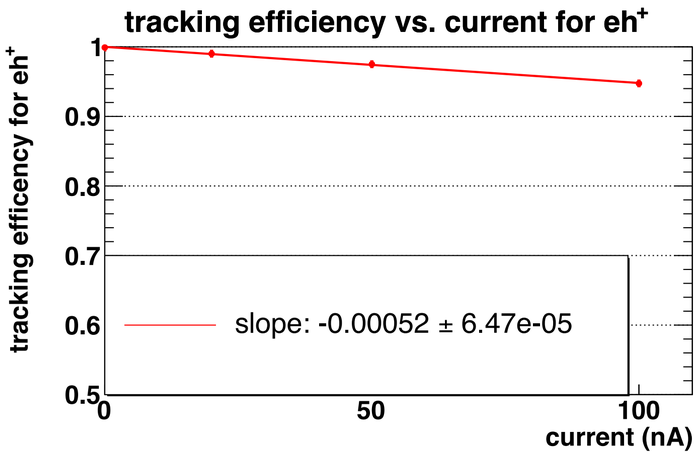


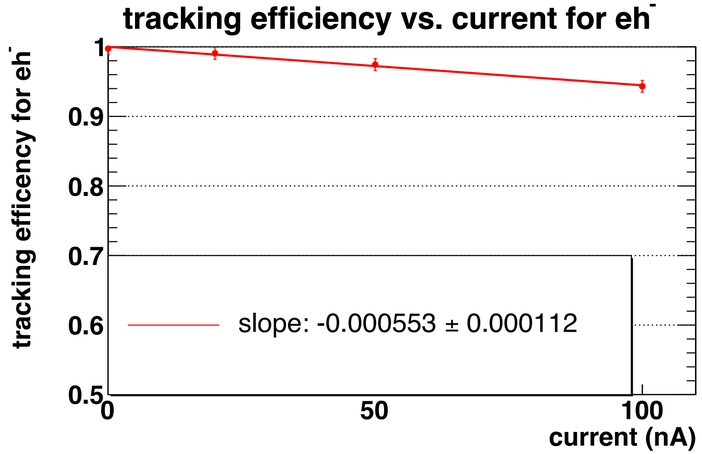


RGA MC + Bg

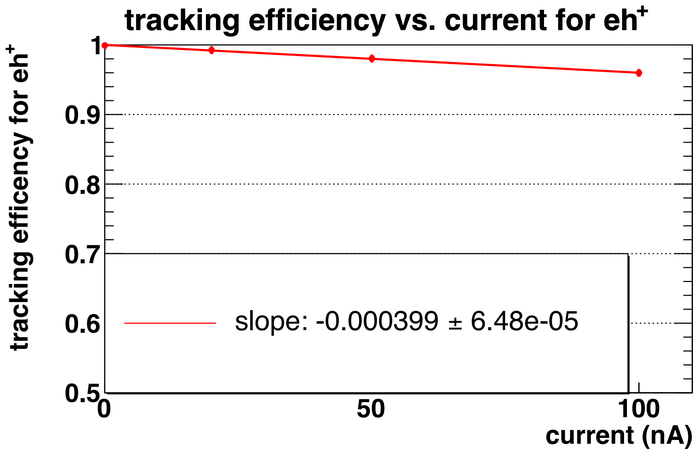
Tracking Efficiency: AI + Conv. Tracking

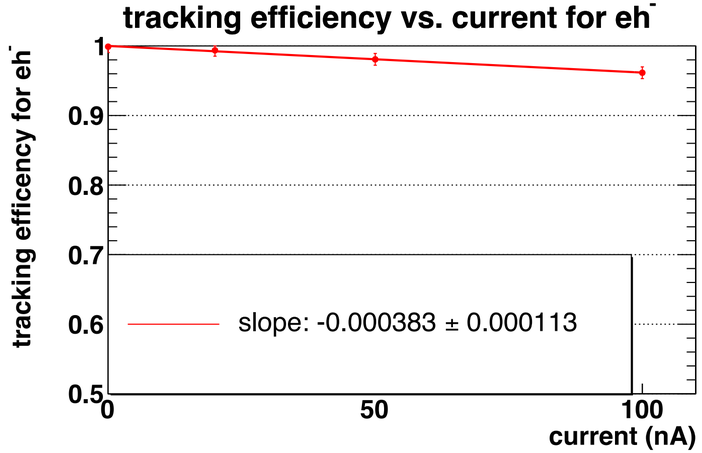
DC-only tracking





DC-uRWell tracking





- Since DC hit occupancy for MC is lower than data, tracking efficiency for MC is better than data.
- For both conventional and AI-assisted tracking, tracking efficiency is improved with participation of uRWell.
- Currently, AI-assisted DC-uRWell tracking is based on AI prediction for DC cluster combos. With uRWell participating into AI model, tracing efficiency is expected to be further improved.

Summary and Next

- With updates after pass2, kinematic resolution is improved mainly due to application of Deterministic Annealing Filter (DAF), and tracking efficiency is improved through comprehensive optimization of algorithms at various levels in DC reconstruction, such as clustering, seeding, and tracking.
- As test, tracking efficiency reduction rate for in-bending is nearly 0.1% per nA for RGA and RGD, while somewhat worse for RGB since FT is on.
- As estimation, tracking efficiency for in-bending of RGA is ~84% at double luminosity with 150nA beam.
- Tracking efficiency for out-bending is better than in-bending.
- Due to background effects on kinematic resolution, efficiency for physics channels seems not to be improved as good as tracking efficiency according to test by exclusive reaction $ep \rightarrow e'\pi^+X$. Very welcome more validations.
- To further improve tracking efficiency and resolution, more efforts are in progress or in plan, including new AI model or the road algorithm for cluster combo prediction, and attempt of third-pass tracking after TB tracking.
- Software for transformation of CM is done, and is reasonable as test. CM is sensitive to resolution of DC hit measurement. Transformed CM will be re-investigated after function for resolution of DC TB hits is re-defined with new calibration.
- New firmware for DC allows multiple hits on a DC wire. Software will be updated correspondingly.
- DC-uRWell tracking has been developed. As test, kinematic resolution and tracking efficiency are improved with participation of uRWell. Physics test will be taken after production of large-statistic sample is done.
- More explorations for uRWell are in progress or in plan, such as attempt of the same stereo-angle as DC, updates of uRWell digitization and background, attempt of double uRWells, AI model for DC and uRWell cluster combos, etc.

Backup

Review about Updates for Tracking-Related Algorithms

- Improved pattern recognition and uncertainties of initial state for seed construction
- Optimized Kalman Filter (KF) Tracking:
  - Refactored KF package
  - Reset initial covariance matrix (CM) for each iteration
  - Reset conditions for iteration termination
- Applied Deterministic Annealing Filter (DAF) to be cooperated with KF
- Tracking efficiency, resolution of kinematics and CPU efficiency are comprehensively improved by the above updates.

Review about Updates for Clustering-Related Algorithms

- Clustering updates:
  - Fixed bugs and optimized algorithms in splitter for splitting complicated hit clumps and constructing cluster candidates
  - Tuned parameters for cutting cluster candidates
  - Loosed limits of cluster size from 4 to 3 hits for exceptional cases due to dead strips, AI-denoising, edge effect, etc
  - Fixed an issue that a hit is shared by multiple clusters in clustering, but is only associated with one cluster when writing it into the hit bank

- Simple Noise Removal (SNR) was cancelled from denoising on DC hits. As test, with application of AI-denoising, SNR is not necessarily implemented.

- With the updates, plenty of missing signal clusters are saved.

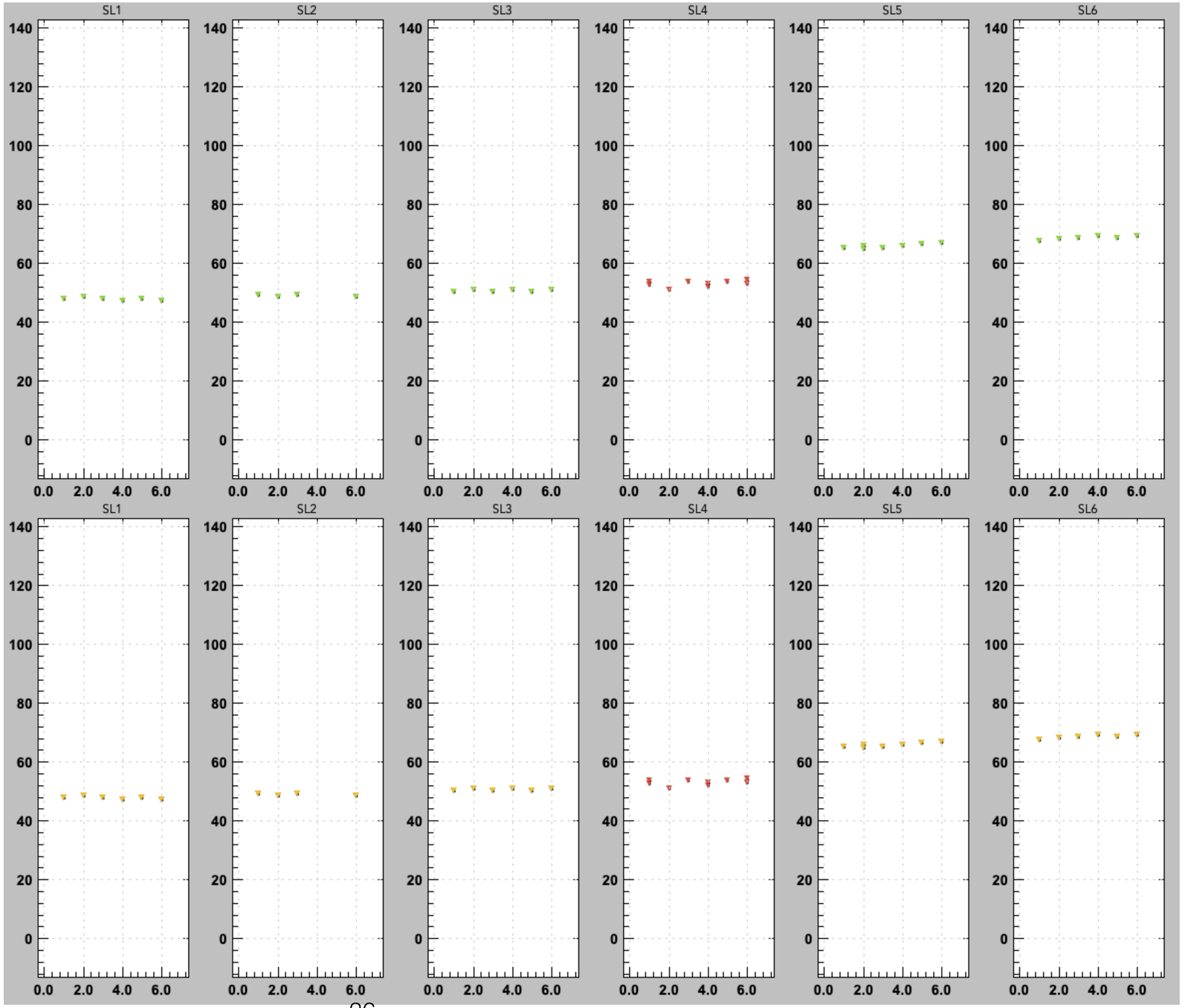
- The above updates further improve tracking efficiency, but need to cost somewhat more CPUT time.

Most Recent Update: Add Conventional Tracking into AI-assisted Tracking as Complementary

- To save missing tracks from AI-assisted tracking, conventional tracking is taken using remaining clusters after AI-assisted tracking.
- Not like general conventional tracking, to avoid 5-track lost since fake 6-cluster tracks, 6-cluster and 5-cluster conventional tracking are processed in parallel. Then, a track with best tracking quality is selected from overlapping track candidates, together with 5-cluster and 6-cluster track candidates.
- The update could save missing tracks mainly from four aspects:
  - Cluster combos are not predicted by AI model.
  - Wrong cluster combos are predicted.
  - 6-cluster combos are predicted, but HB tracking fails since one of clusters is a noise cluster, while conventional tracking succeeds with attempt of 5 signal clusters.
  - Corrected cluster combos are predicted, and hit-based (HB) tracking succeeds, but time-based (TB) tracking fails since start-time-particle in the event is missed in the HB tracking. It affects measurements of TB hits on all tracks in the event, and causes track lost. After the update, start-time-particle is restored.
- The above update further improves tracking efficiency, but need to cost somewhat more CPUT time.
- Next, some examples are provided to show examples for the above four aspects.

- Hits kept after denoising
- Hits kept after clustering
- Hits kept after AI prediction
- Hits kept after HB tracking
- Hits kept after TB tracking

No cluster-combo prediction

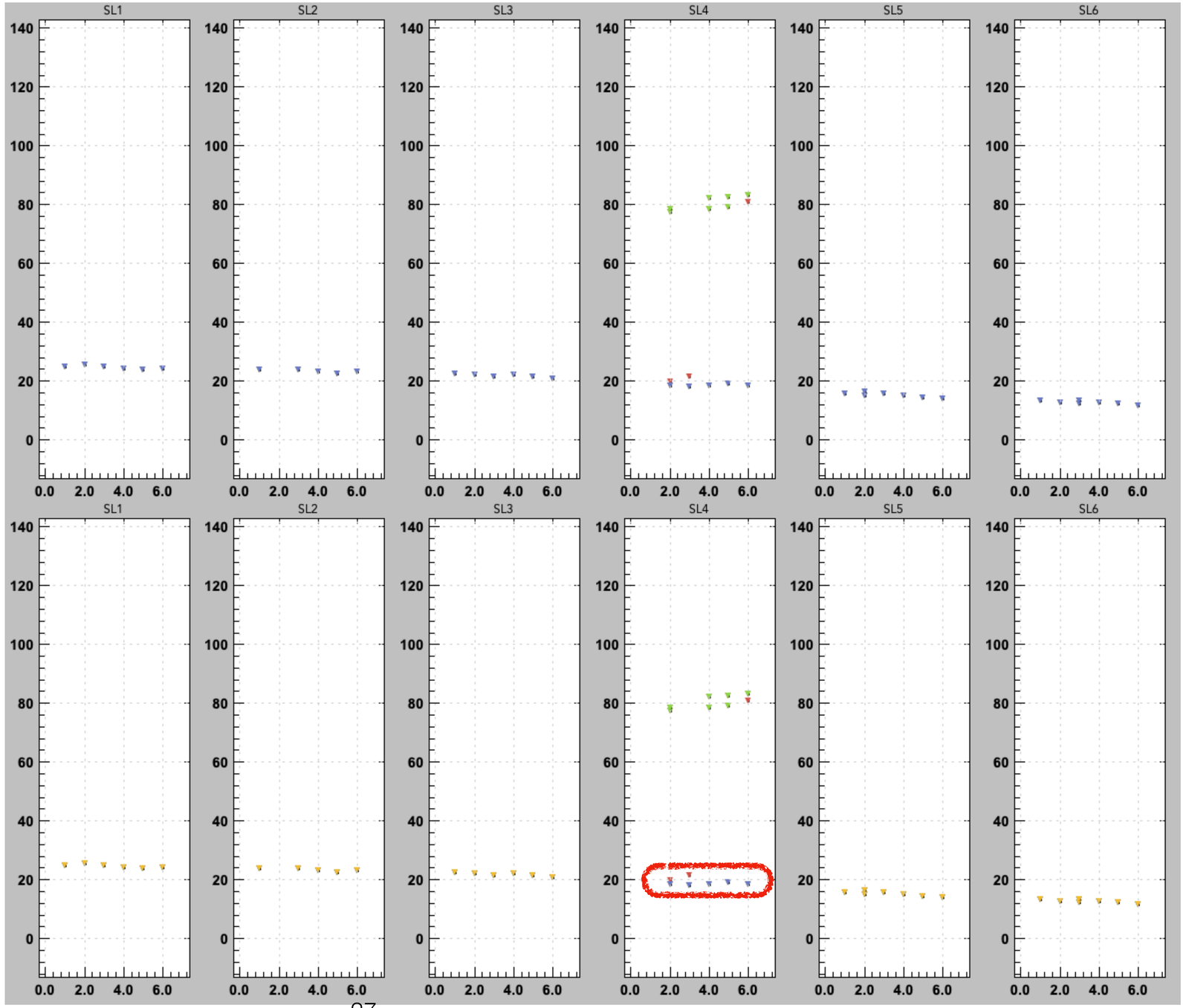


RGA run6666 (50nA)

- Hits kept after denoising
- Hits kept after clustering
- Hits kept after AI prediction
- Hits kept after HB tracking
- Hits kept after TB tracking

HB tracking fails for predicted 6-cluster-combo

HB tracking succeeds for 5-cluster combo

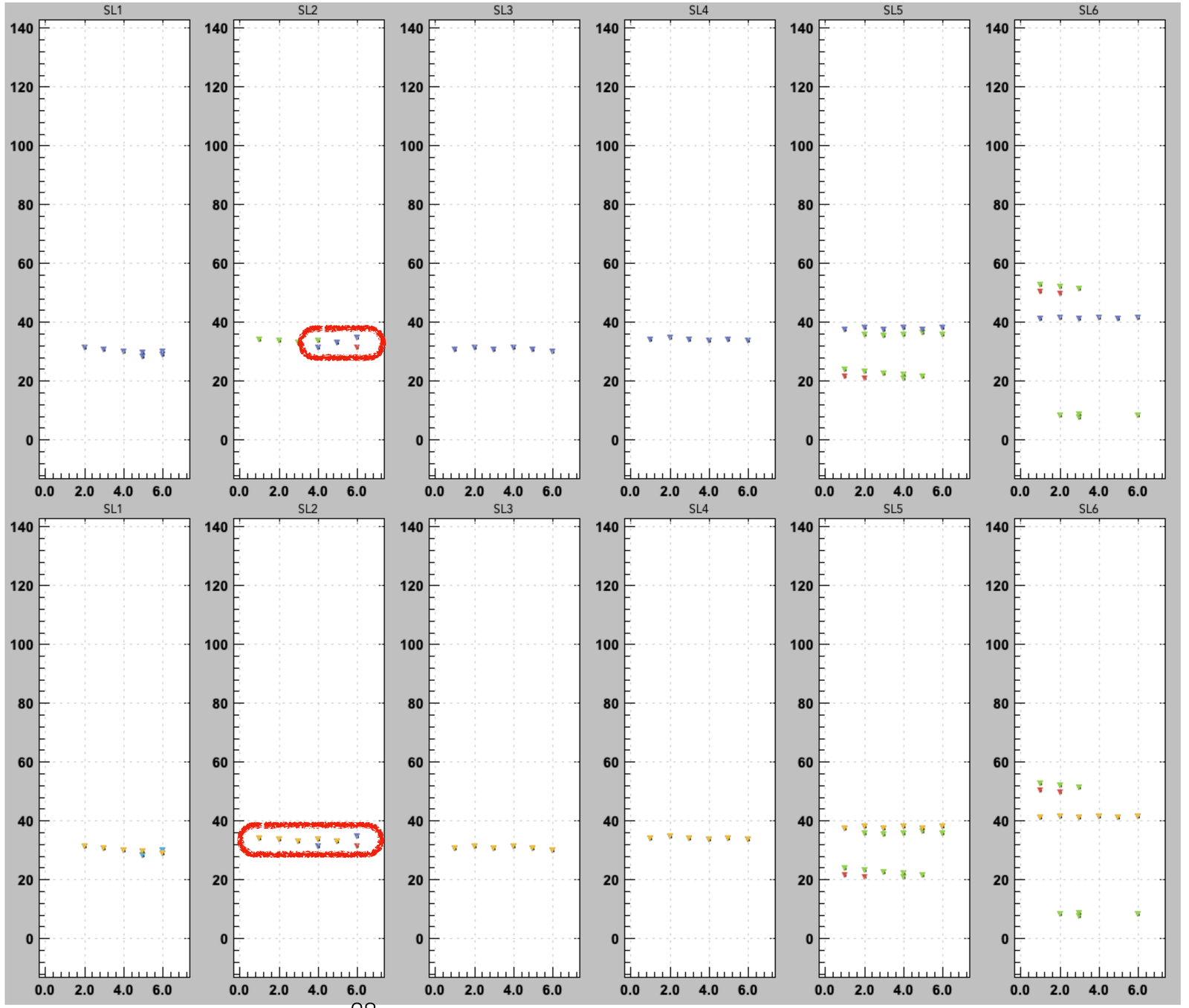


RGA run6666 (50nA)

- Hits kept after denoising
- Hits kept after clustering
- Hits kept after AI prediction
- Hits kept after HB tracking
- Hits kept after TB tracking

Wrong cluster-combo prediction

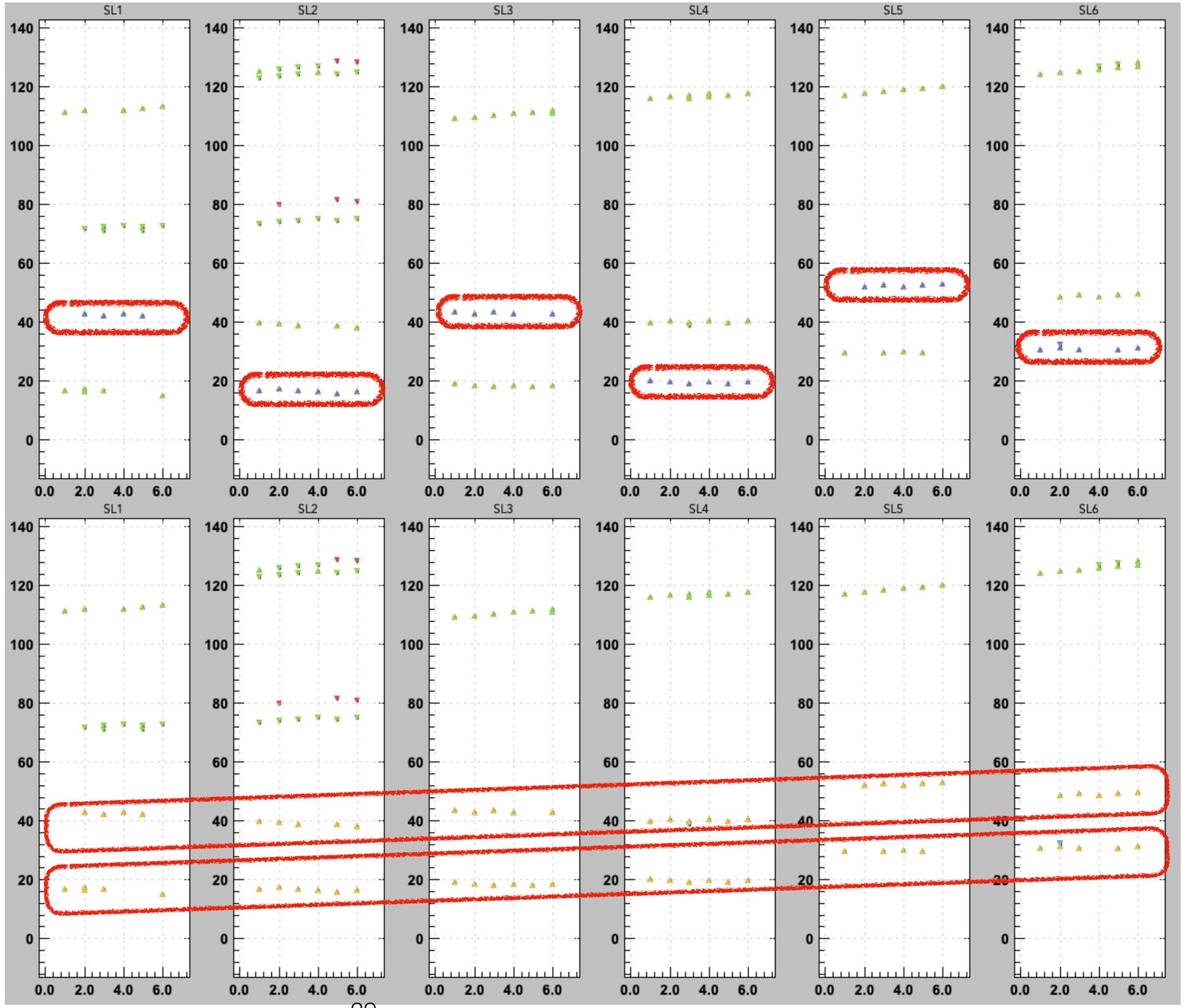
HB tracking succeeds with replacement of a cluster in SL2



RGA run6666 (50nA)

- Hits kept after denoising
- Hits kept after clustering
- Hits kept after AI prediction
- Hits kept after HB tracking
- Hits kept after TB tracking

Wrong cluster-combo prediction

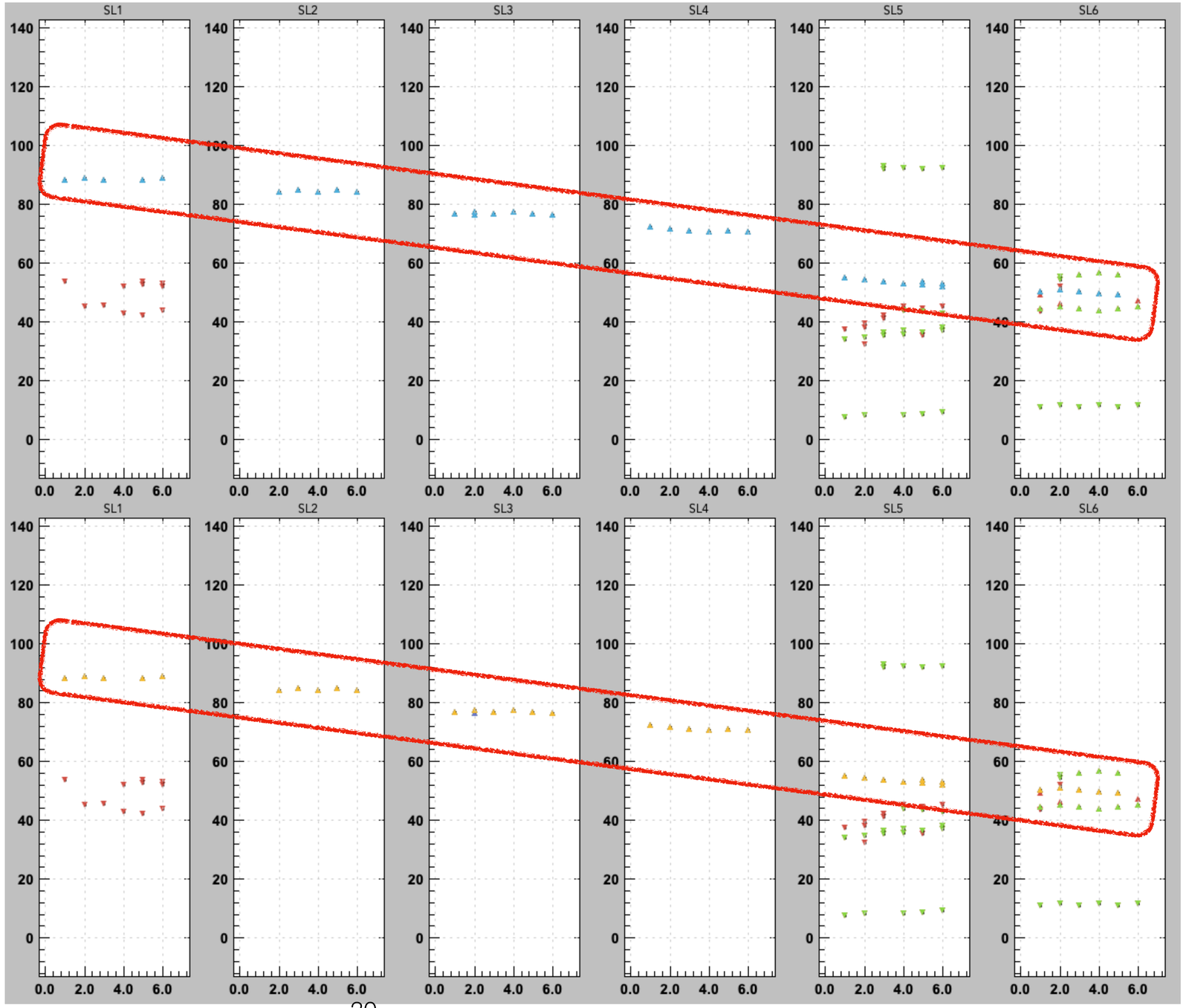


RGA run6666 (50nA)

- Hits kept after denoising
- Hits kept after clustering
- Hits kept after AI prediction
- Hits kept after HB tracking
- Hits kept after TB tracking

HB tracking succeeds for predicted 6-cluster-combo, but TB tracking fails

Start-time-particle changes in HB event reconstruction, TB tracking succeeds



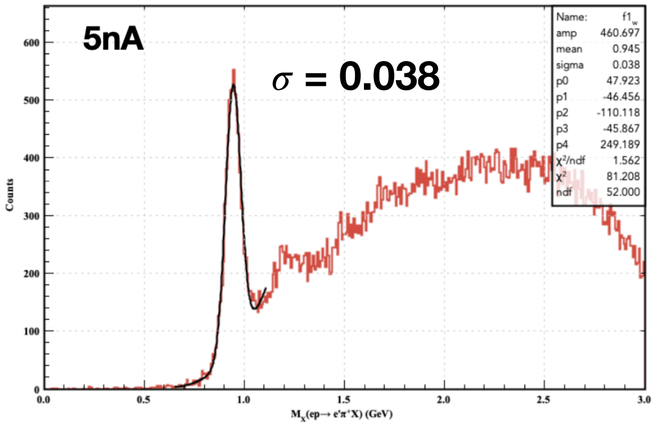
RGA run6666 (50nA)

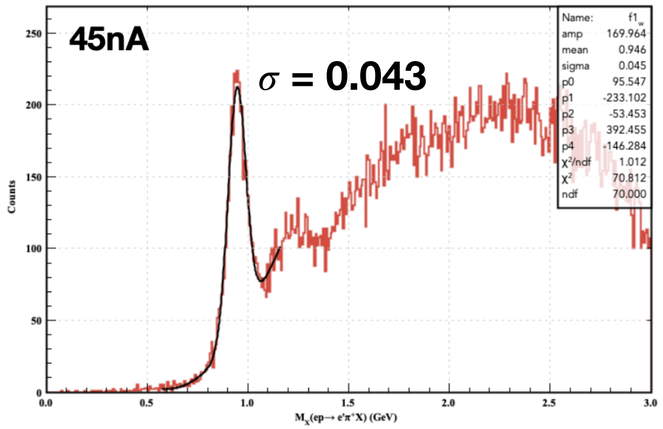
RGA Fall18; In-bending

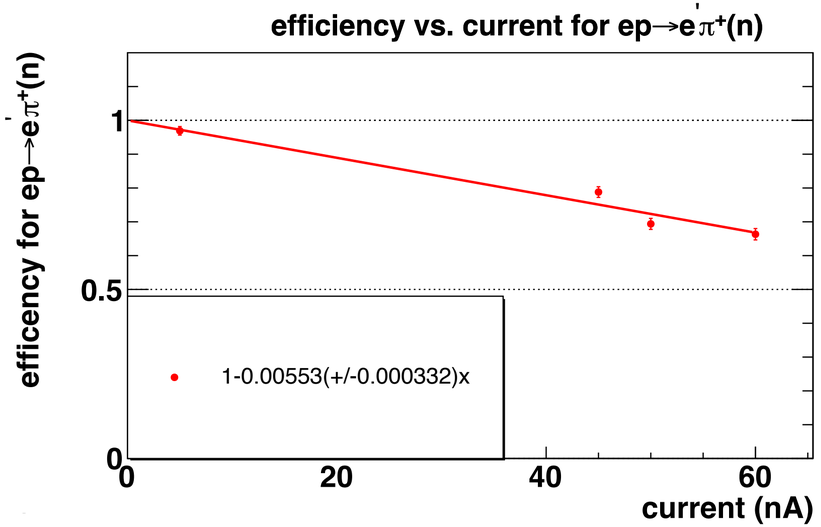
Efficiency for Exclusive Reaction: $ep \rightarrow e'\pi^+X$

Events with electron with p > 2.5 GeV, at least one π^+ with p > 1.5 GeV and |chi2pid| < 3 are used. All π^+s are used to calculate missing mass if multiple exist.

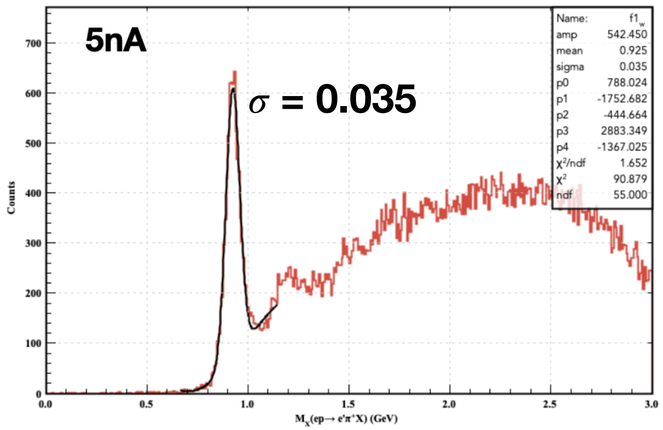
Pass2

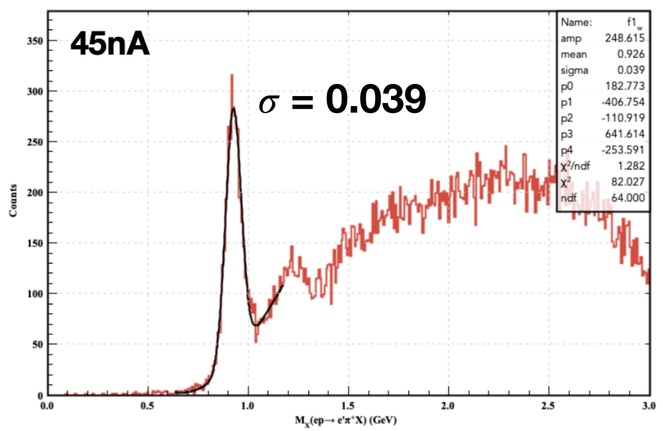


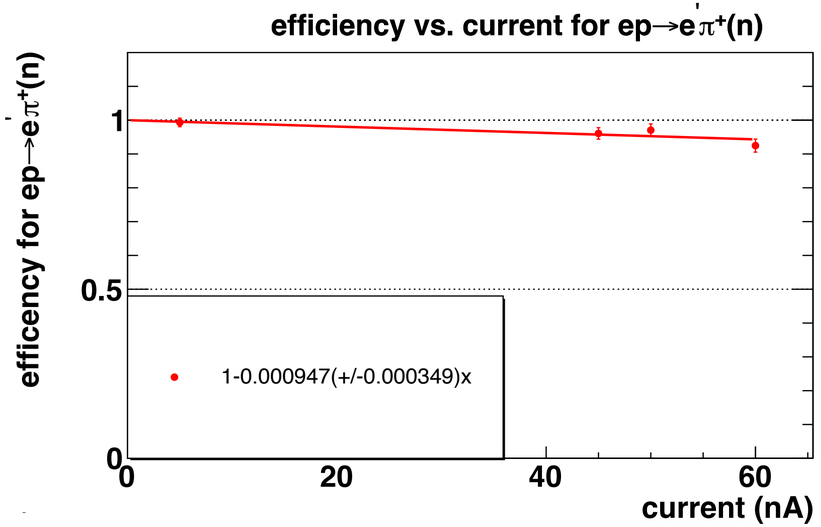




New

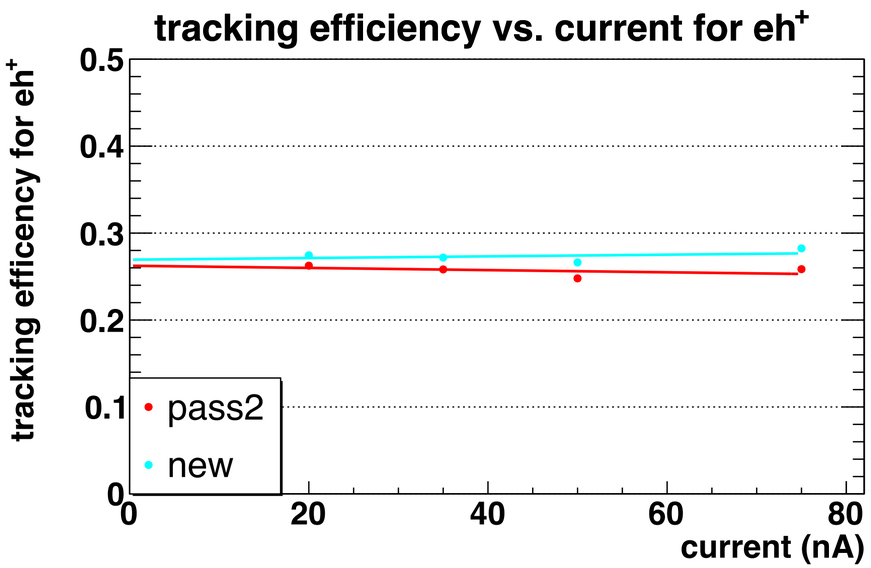


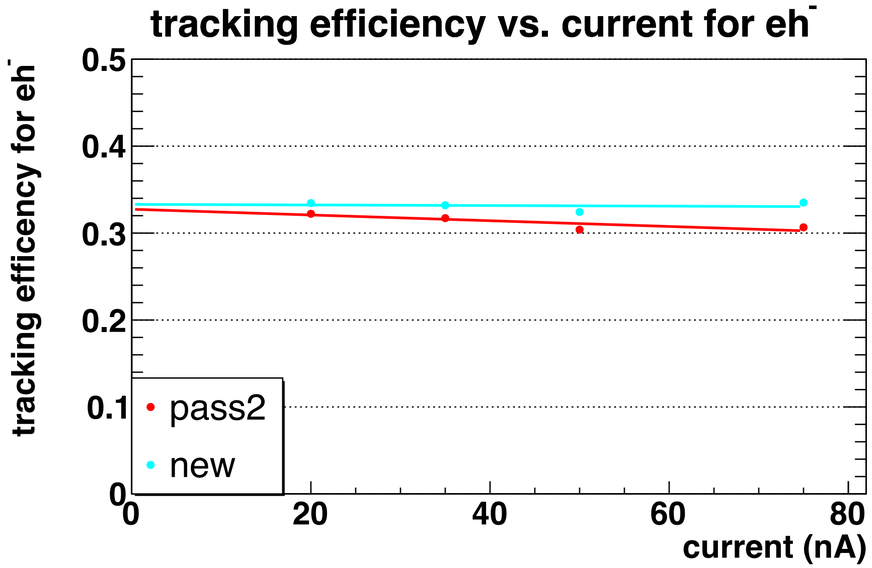




Tracking Efficiency for RGD Out-bending before Scaling

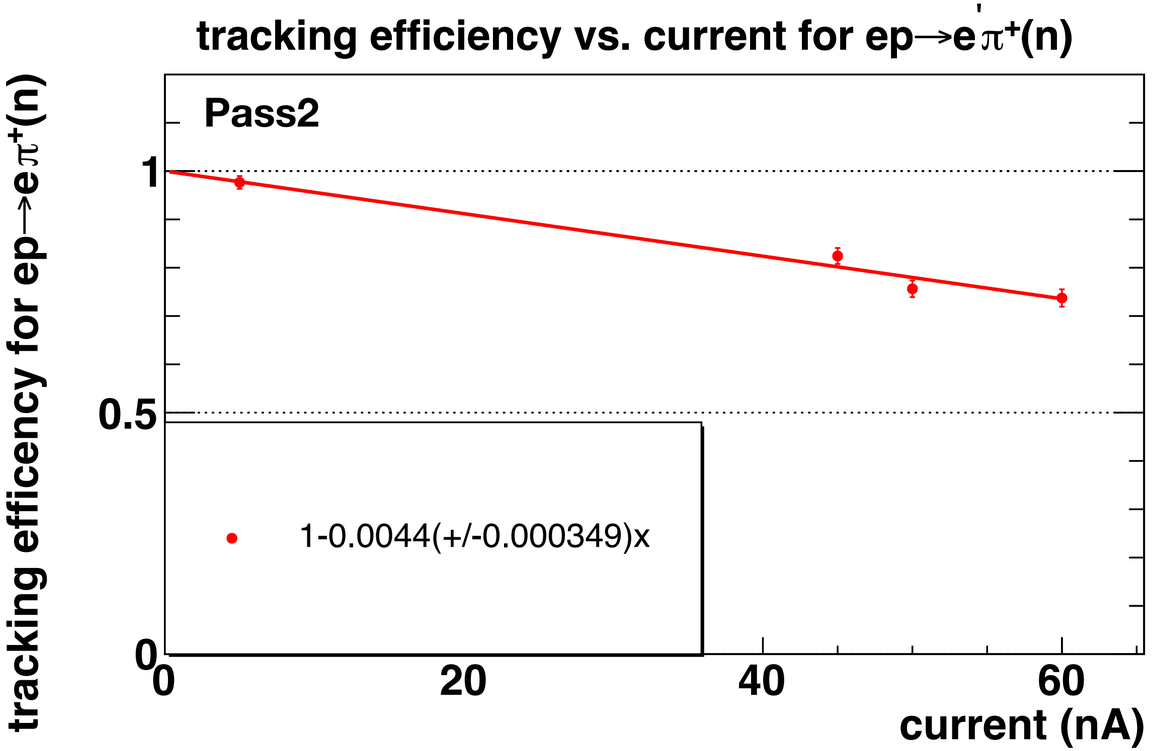
Out-bending

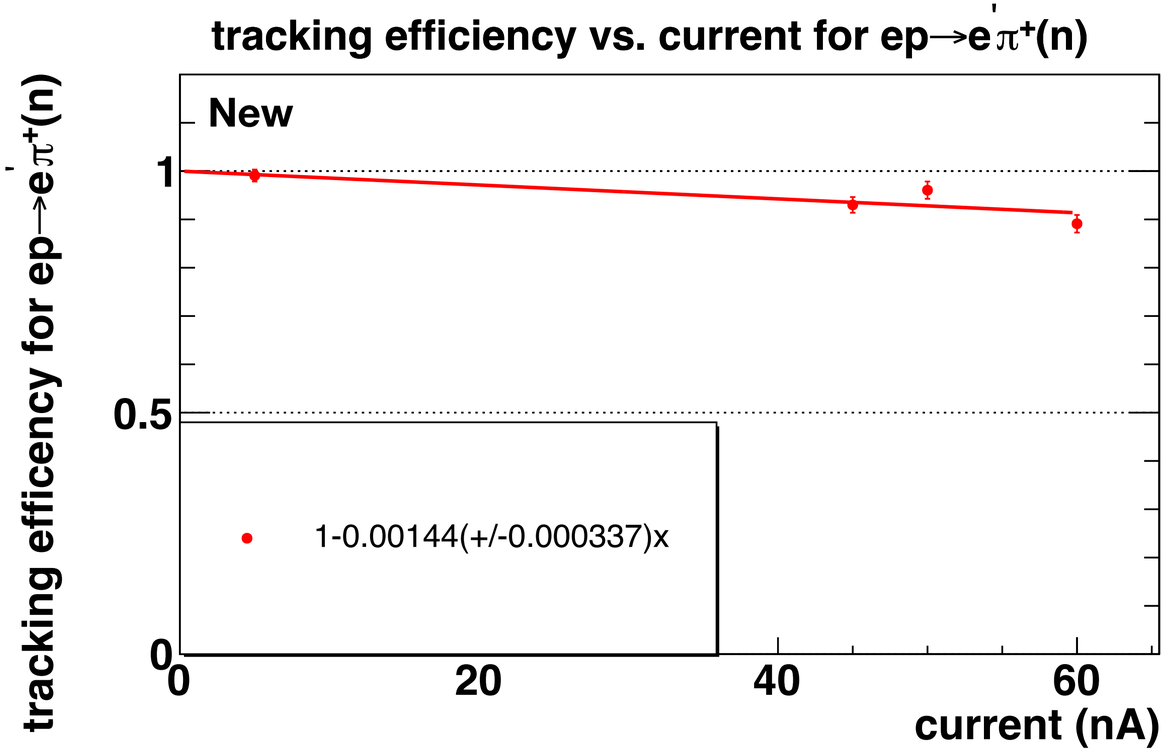




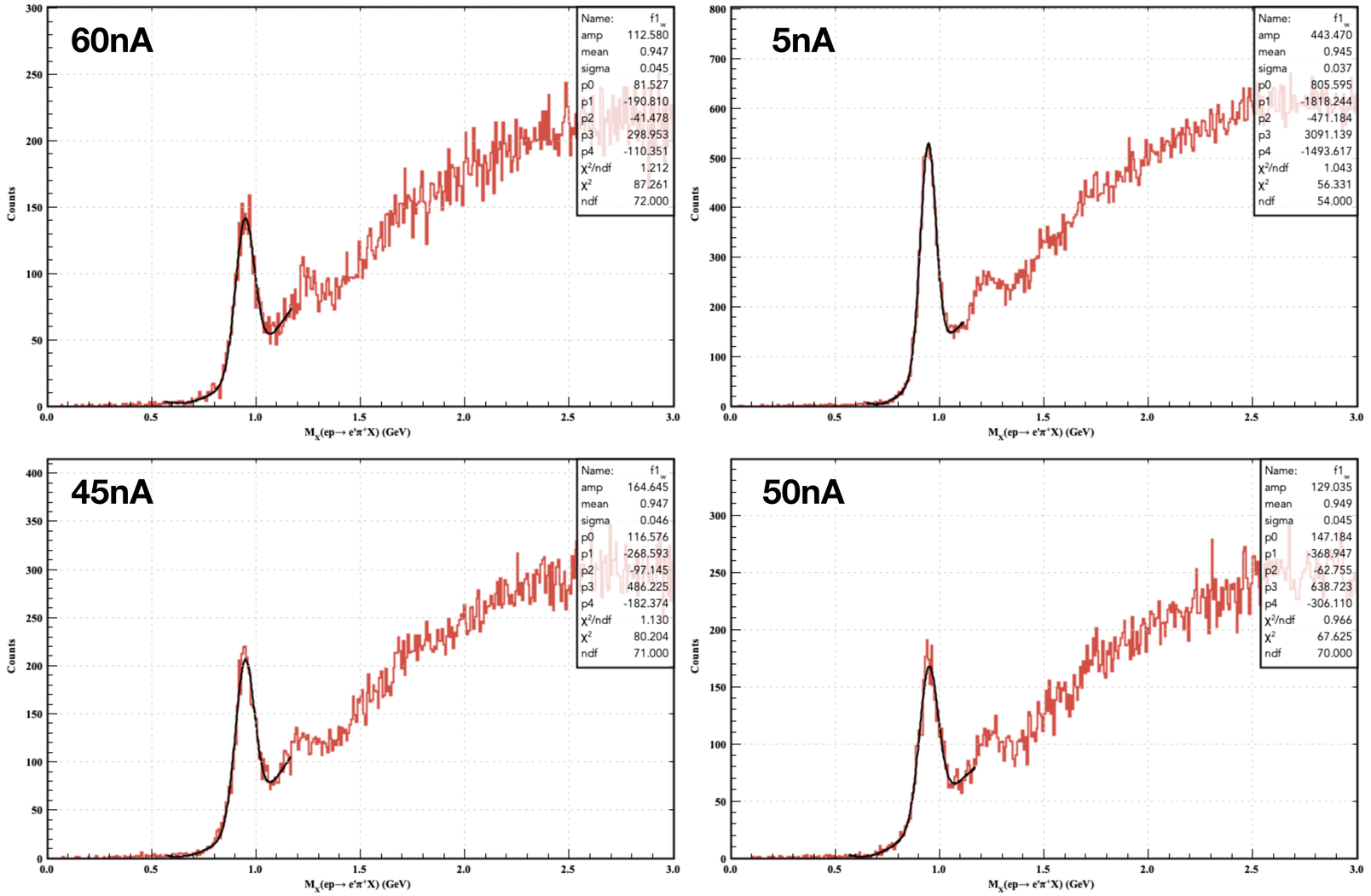
Exclusive reaction: $ep \rightarrow e'\pi^+X$

- Events are selected with cuts for all final-state particles: vz [-15, 5] cm, p > 0.5 GeV and |chi2pid| < 3. Note: all π^+s are used to calculate missing mass if multiple exist.
- The missing mass distributions at each beam current are fitted with Gaussian+pol4 function to extract number of events for the reaction. (See distributions with fitting in next slides)
- The number of exclusive events is then normalized to the number of inclusive electrons for efficiency study.

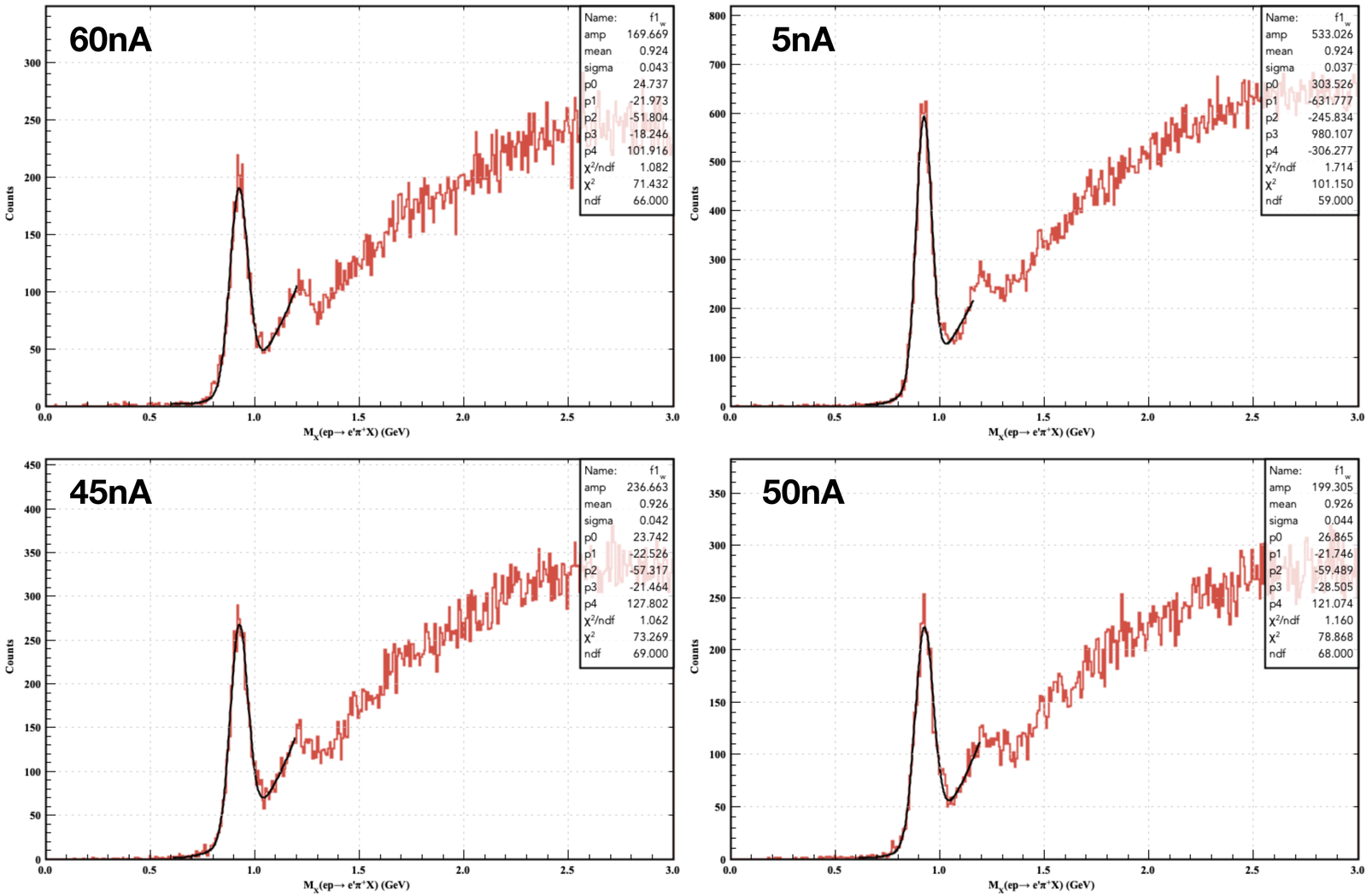




MM Distributions with Fitting for Pass2



MM Distributions with Fitting for New

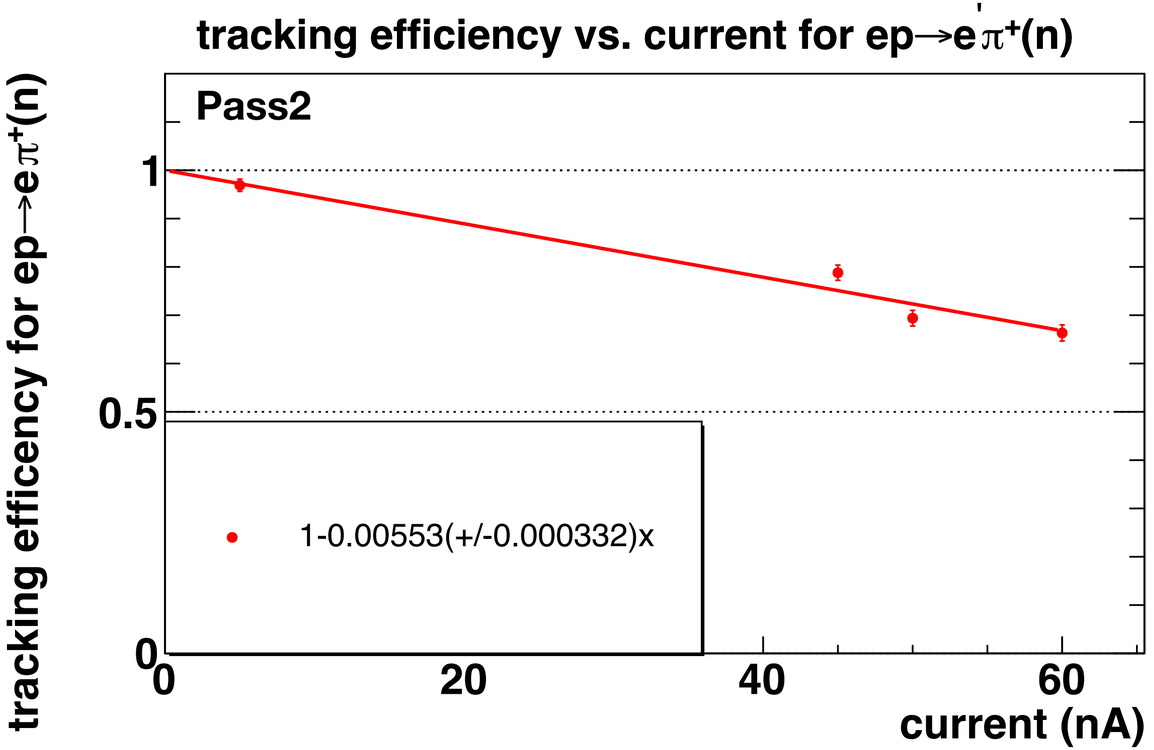


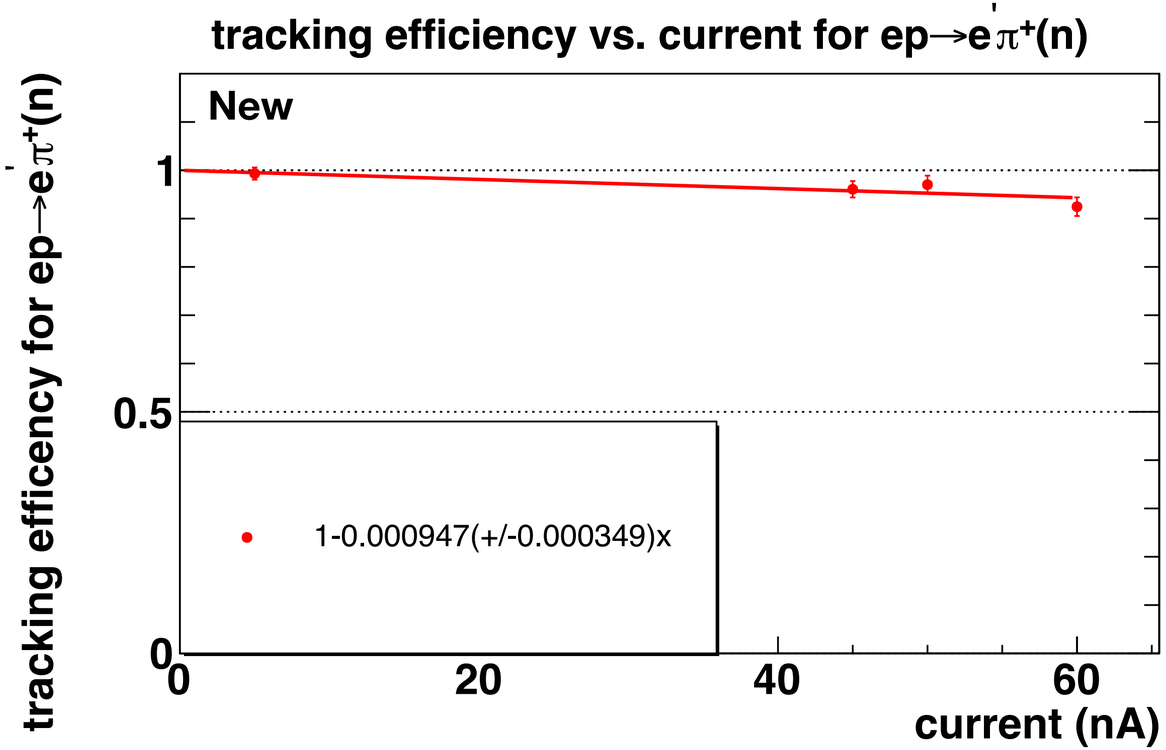
RGA Fall18; In-bending

Follow Stepan's event selection criteria

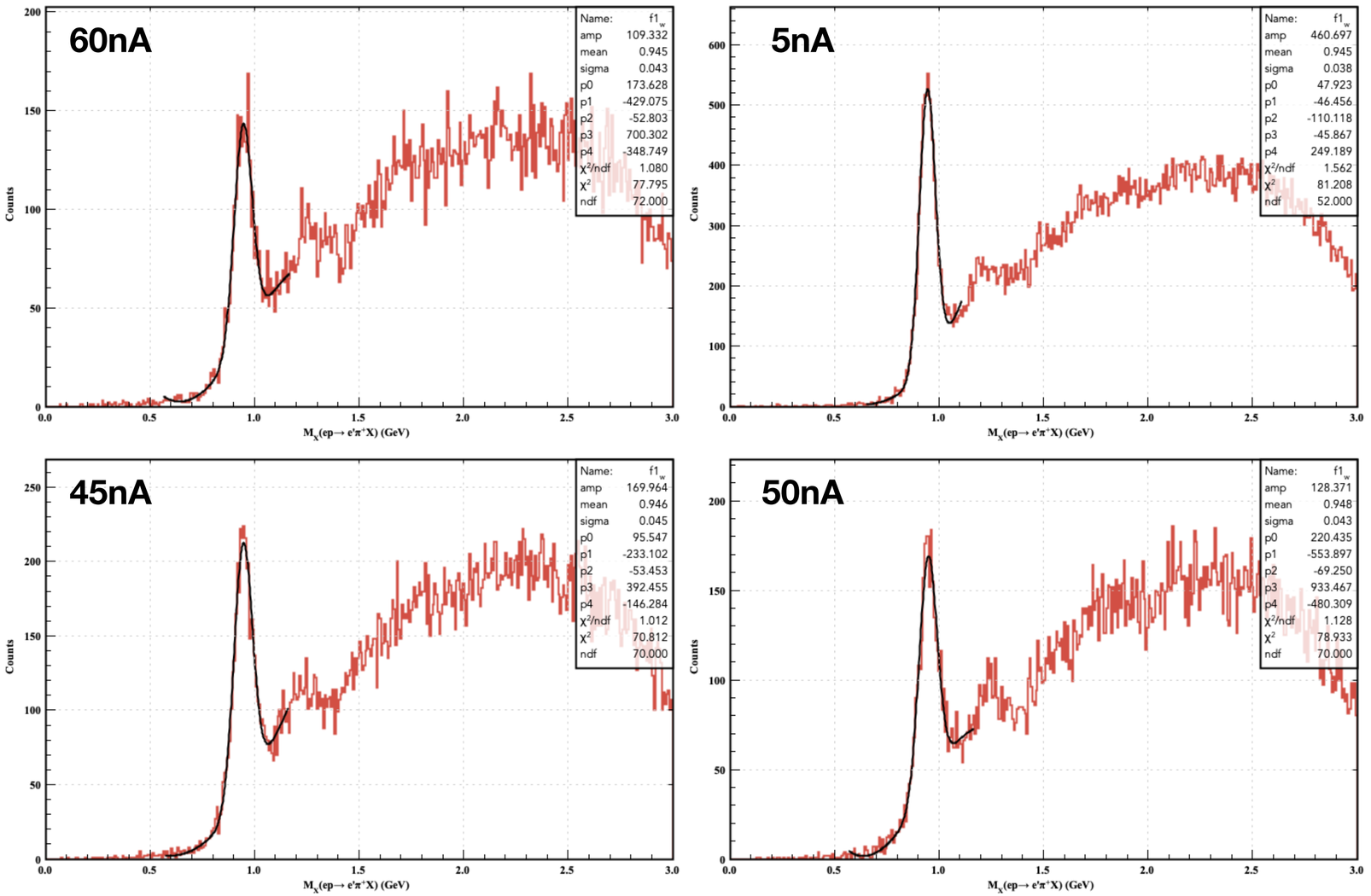
Exclusive reaction: $ep \rightarrow e'\pi^+X$

- Events with electron with p > 2.5 GeV, at least one π^+ with p > 1.5 GeV and |chi2pid| < 3 are used. Note: all π^+s are used to calculate missing mass if multiple exist.
- The missing mass distributions at each beam current are fitted with Gaussian+pol4 to extract number of events for the reaction. (See distributions with fitting in next slides)
- The number of exclusive events is then normalized to the number of inclusive electrons for efficiency study.





MM Distributions with Fitting for Pass2



MM Distributions with Fitting for New