DEEP UNDERGROUND NEUTRINO EXPERIMENT

Status of Kalman Filter in Heavy Neutral Lepton study

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11-12 Nov Bologna

BEYOND STANDARD MODEL PHYSICS

$$\mathcal{L}_{\nu\mathrm{MSM}} = \mathcal{L}_{\mathrm{MSM}} + \bar{\tilde{N}}_I i\partial_\mu \gamma^\mu \tilde{N}_I - F_{\alpha I}\, \bar{L}_\alpha \tilde{N}_I \tilde{\Phi} - M \bar{\tilde{N}}_2^{\,c} \tilde{N}_3 - \frac{\Delta M_{IJ}}{2}\, \bar{\tilde{N}}_I^{\,c} \tilde{N}_J + \mathrm{h.c.}$$

model I : $f_e^2 : f_\mu^2 : f_\tau^2 \approx 52 : 1 : 1\,, \quad \kappa = 1\,,$

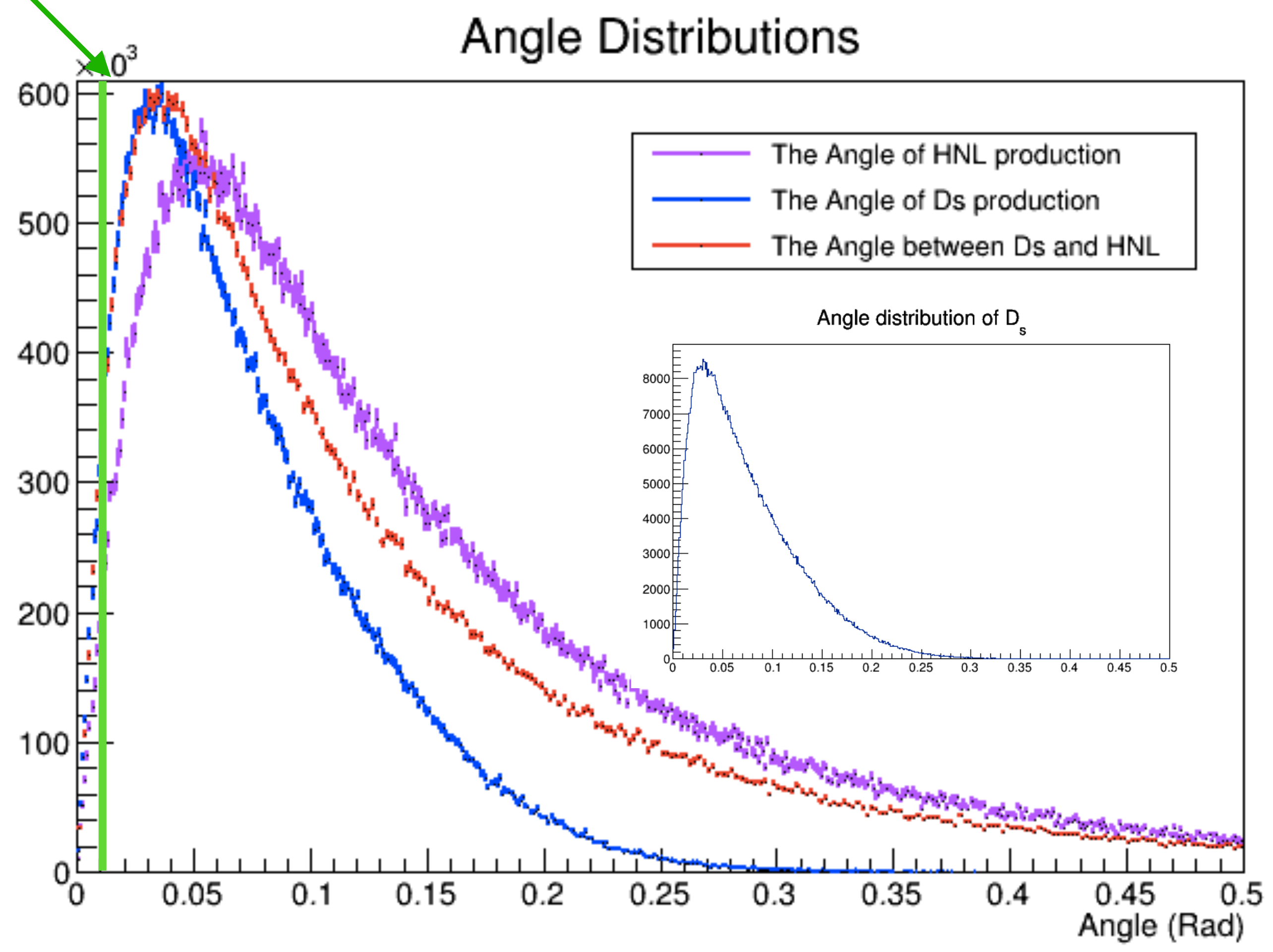
model II : $f_e^2 : f_\mu^2 : f_\tau^2 \approx 1 : 16 : 3.8\,, \quad \kappa = 2\,,$

model III : $f_e^2 : f_\mu^2 : f_\tau^2 \approx 0.061 : 1 : 4.3\,, \quad \kappa = 2\,.$

	Channel	BR (%)	m_N/MeV
$D_s^+ \to$	$\tau^+\nu_\tau$	5.48	191.42
	$\mu^+\nu_\mu$	0.55	1862.63
	$e^+\nu_e$	0.008	1967.78
$\tau^+ \to$	$\pi^+\pi^0\bar{\nu}_\tau$	25.49	1502.31
	$\bar{\nu}_\tau e^+\nu_e$	17.82	1776.35
	$\bar{\nu}_\tau \mu^+\nu_\mu$	17.39	1671.20
	$\pi^+\bar{\nu}_\tau$	10.82	1637.29

$$N \to \pi^\mp \mu^\pm$$

Acceptance

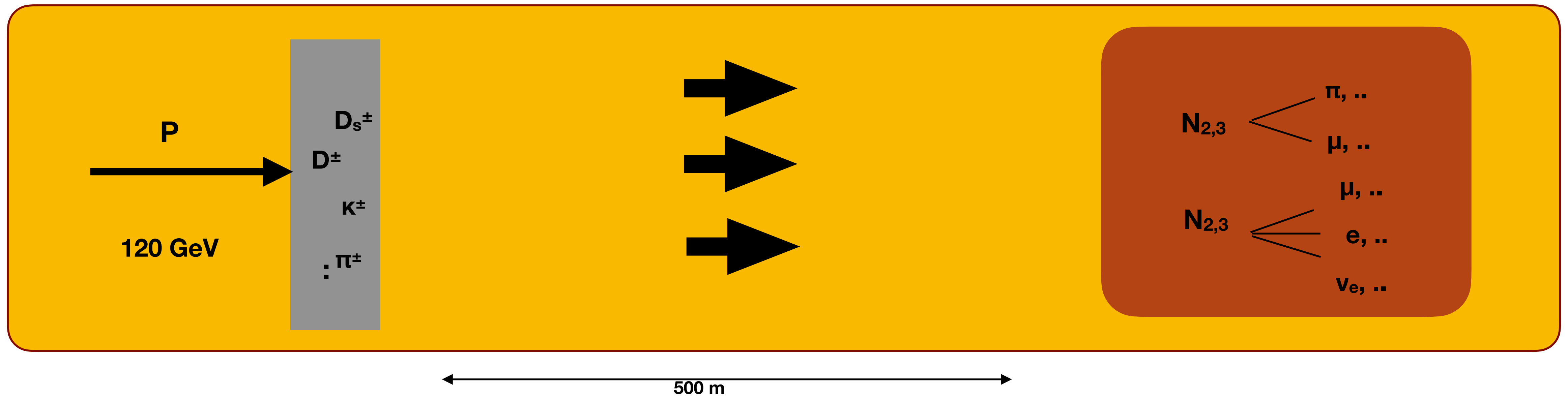


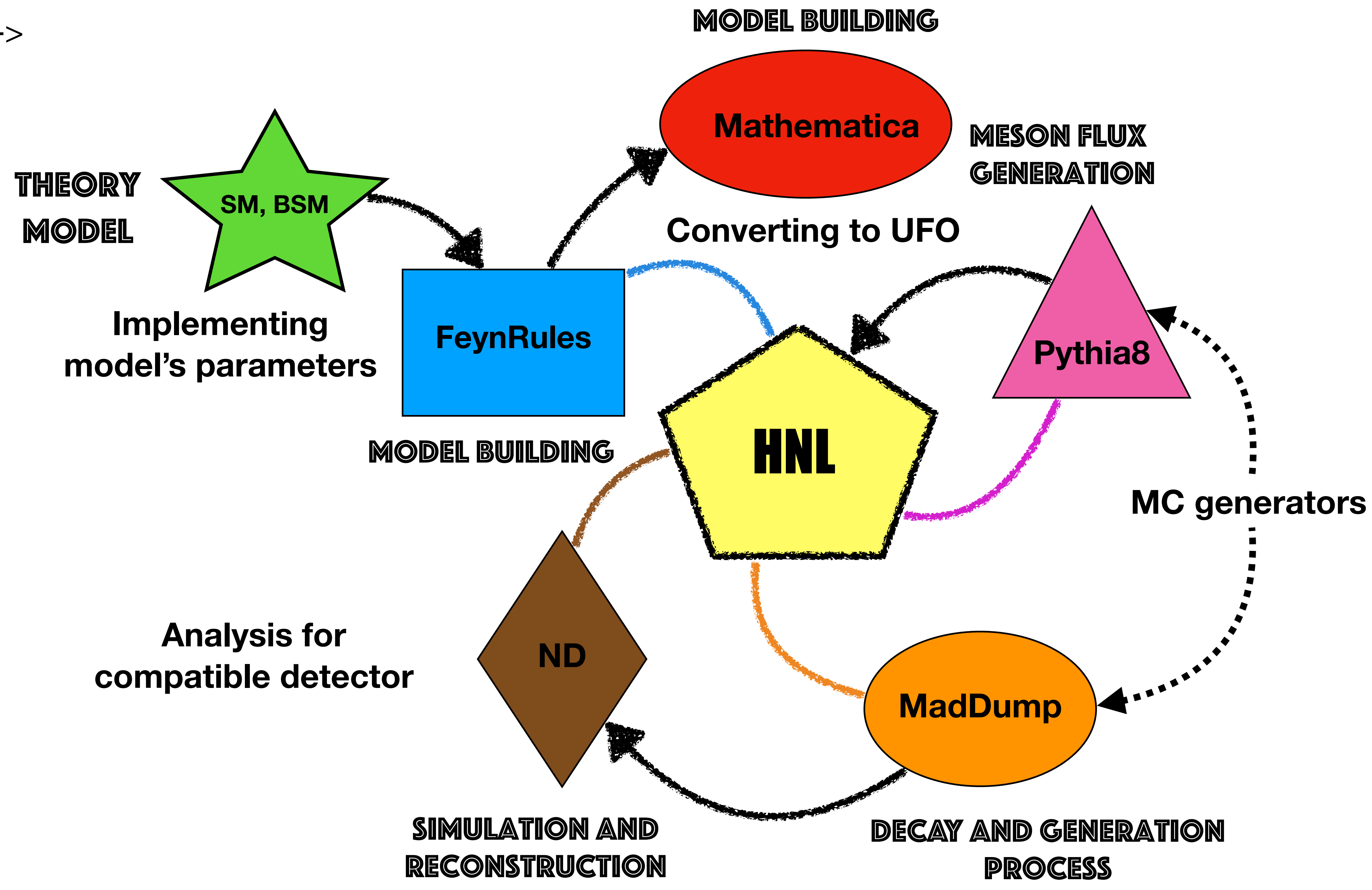
- **# Mesons:**
  - Primary
  - Secondary

❋Steps

- Building the model, choosing the right parameters ->(Channels, Coupling, Mass, Mixing,…)
- Generating external meson(s) flux -> Heavy Meson (Ds)
- Final check of the parameters
- Launching Mad-dump
- Analyzing the results

- **# Heavy Fermions:**
  - Long lived.





https://arxiv.org/abs/0705.1729 https://arxiv.org/abs/1812.06771

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$D_s^\pm \to N\mu^\pm$

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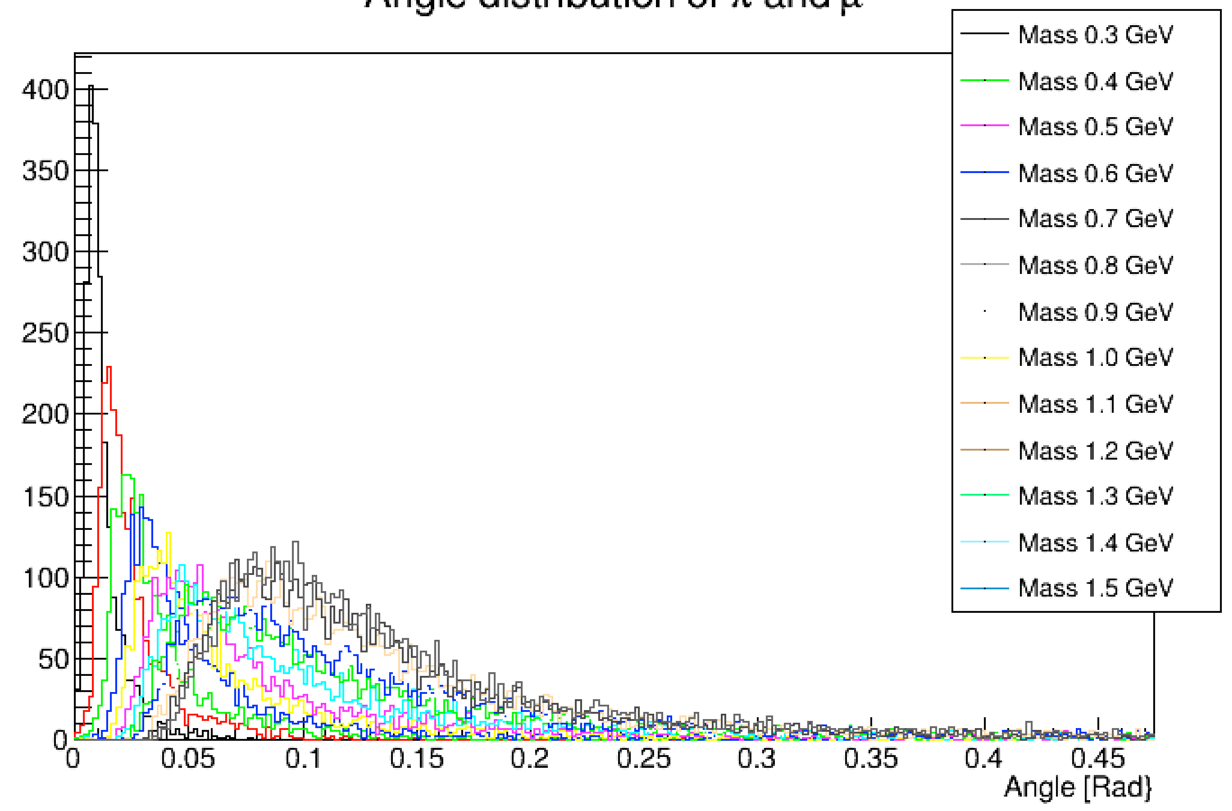

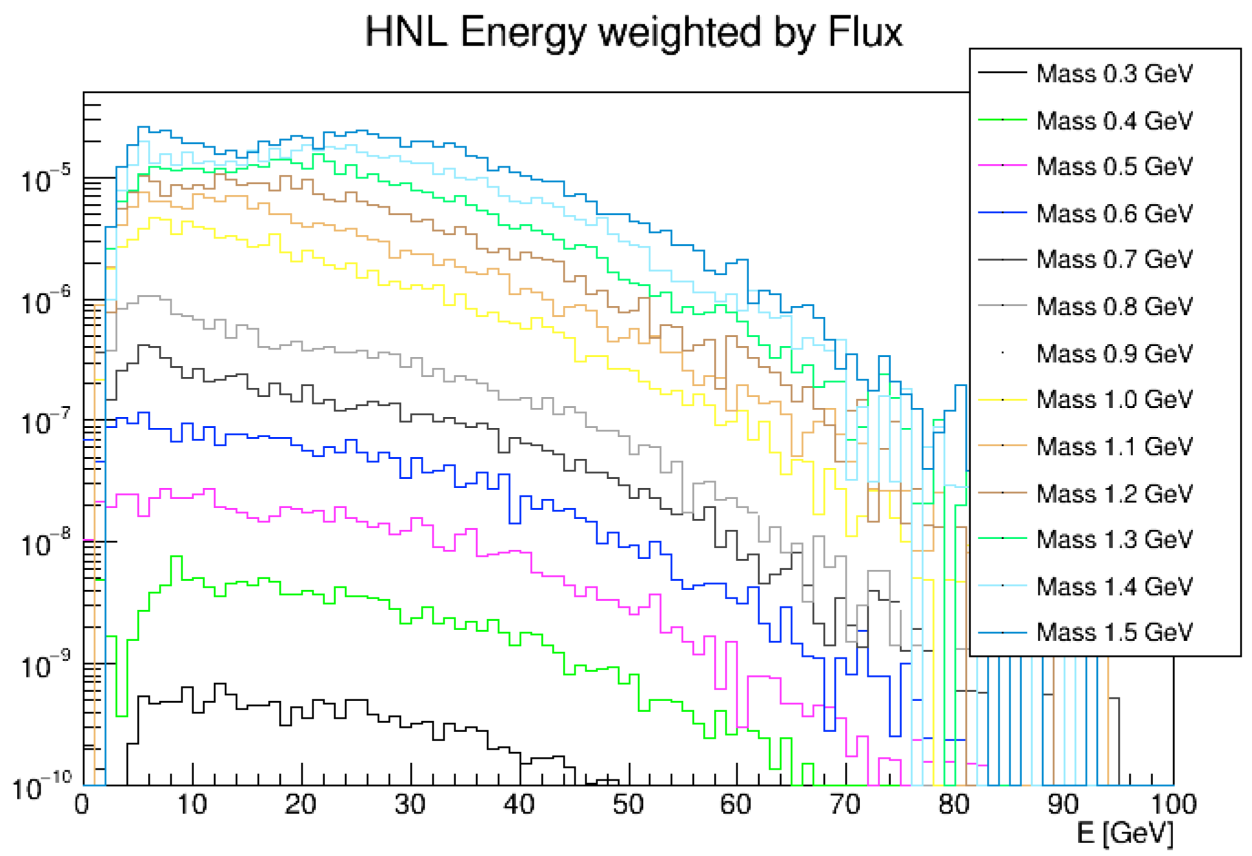

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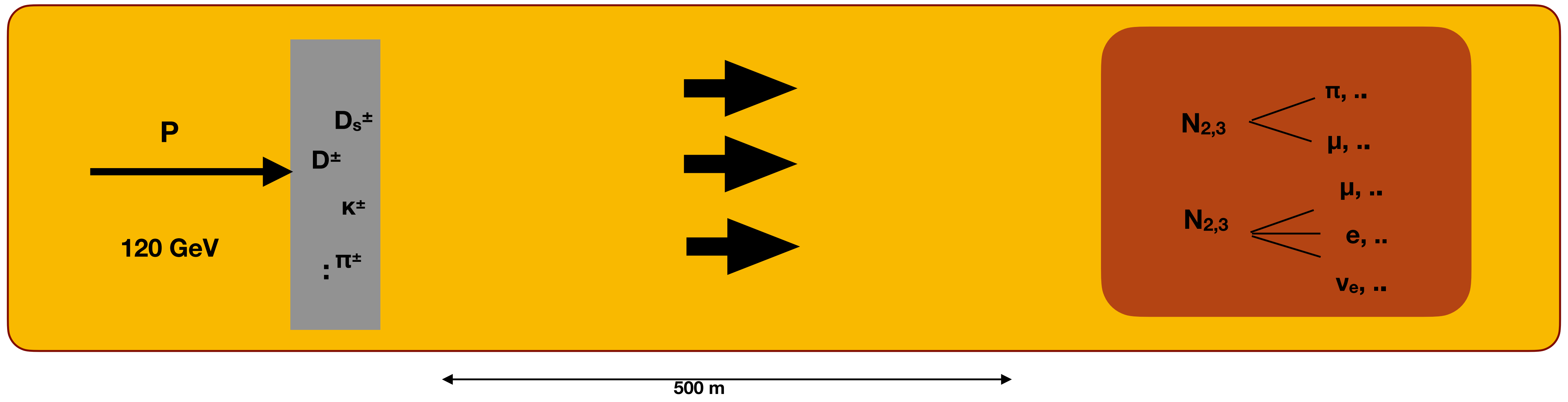

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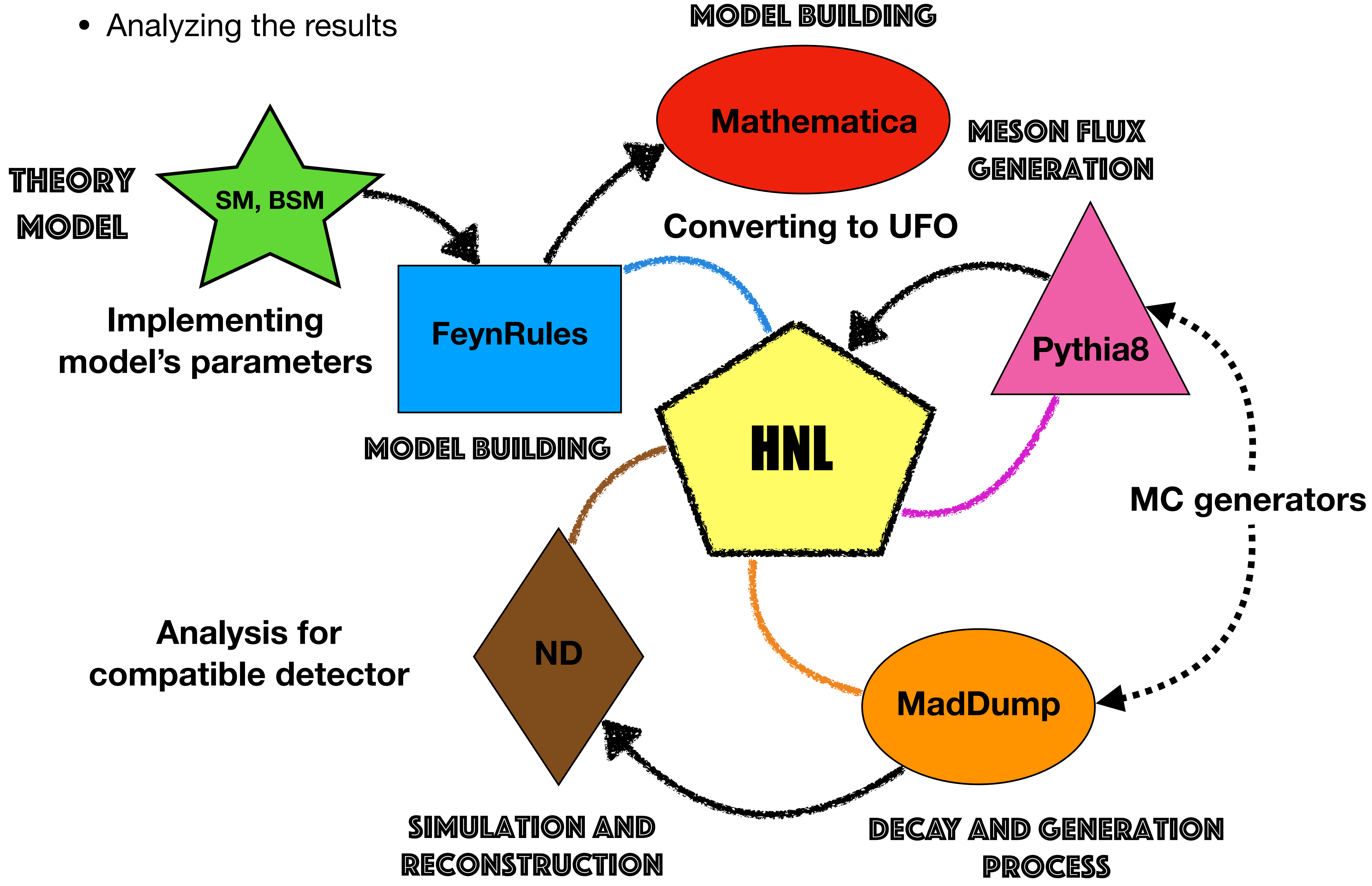
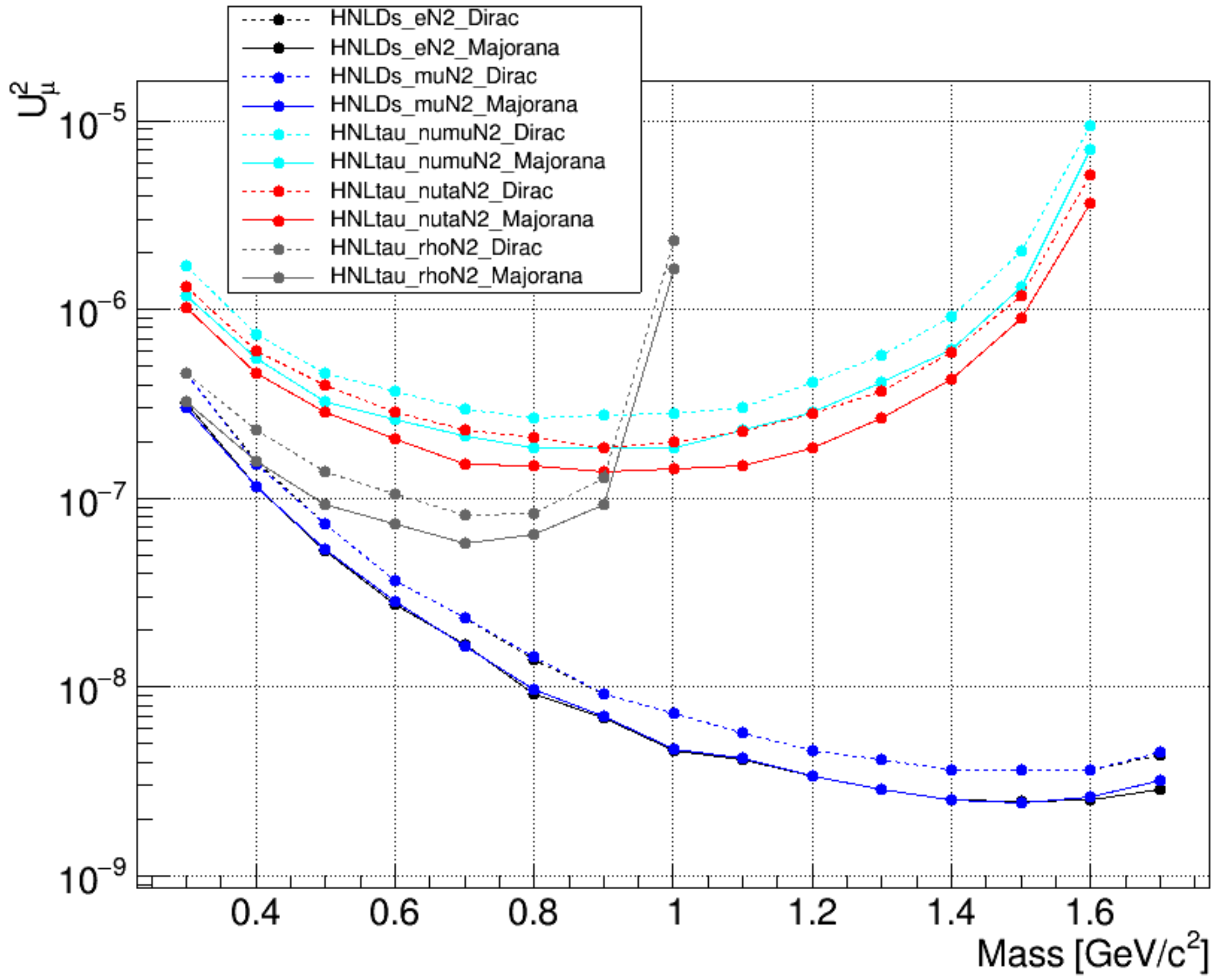
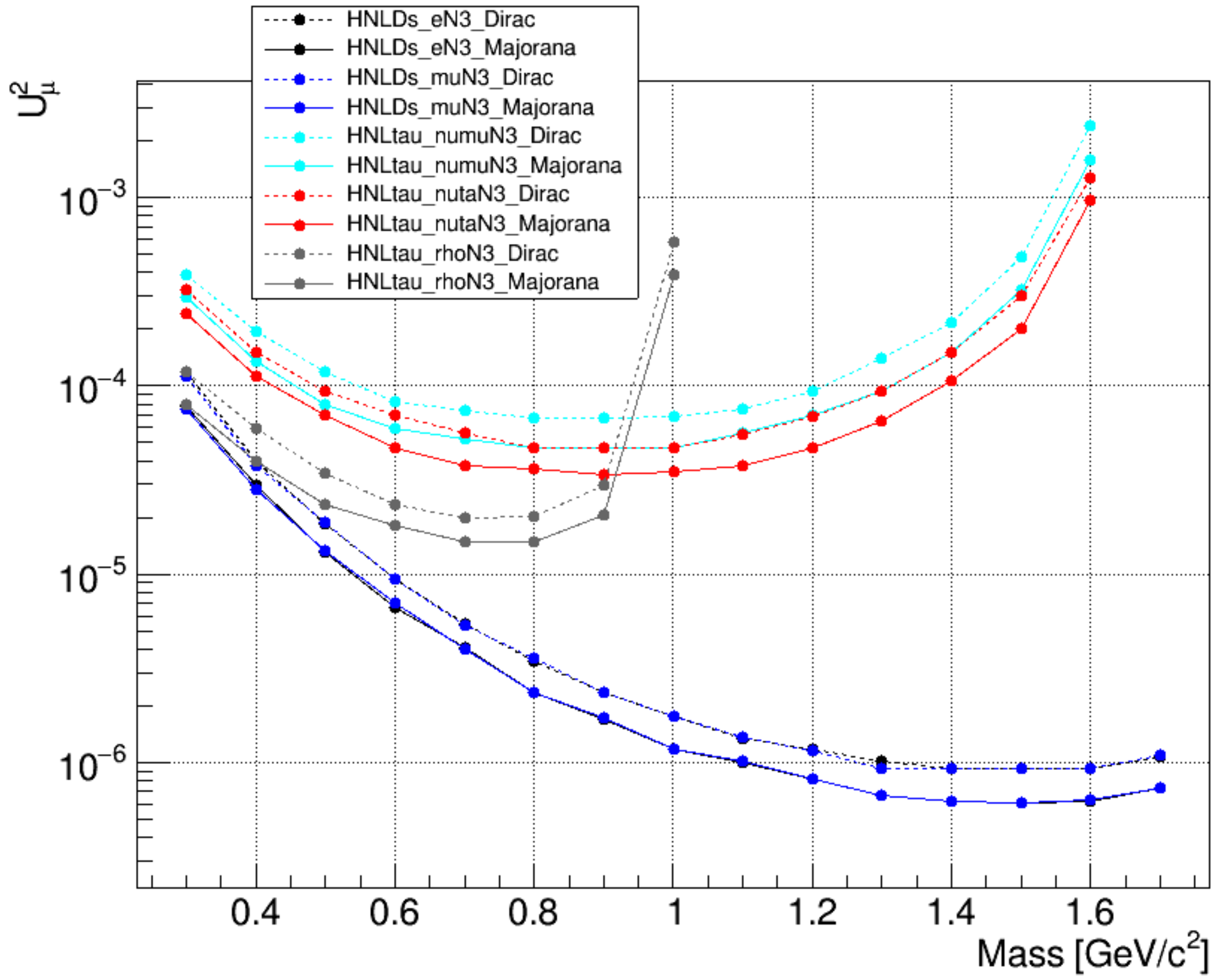
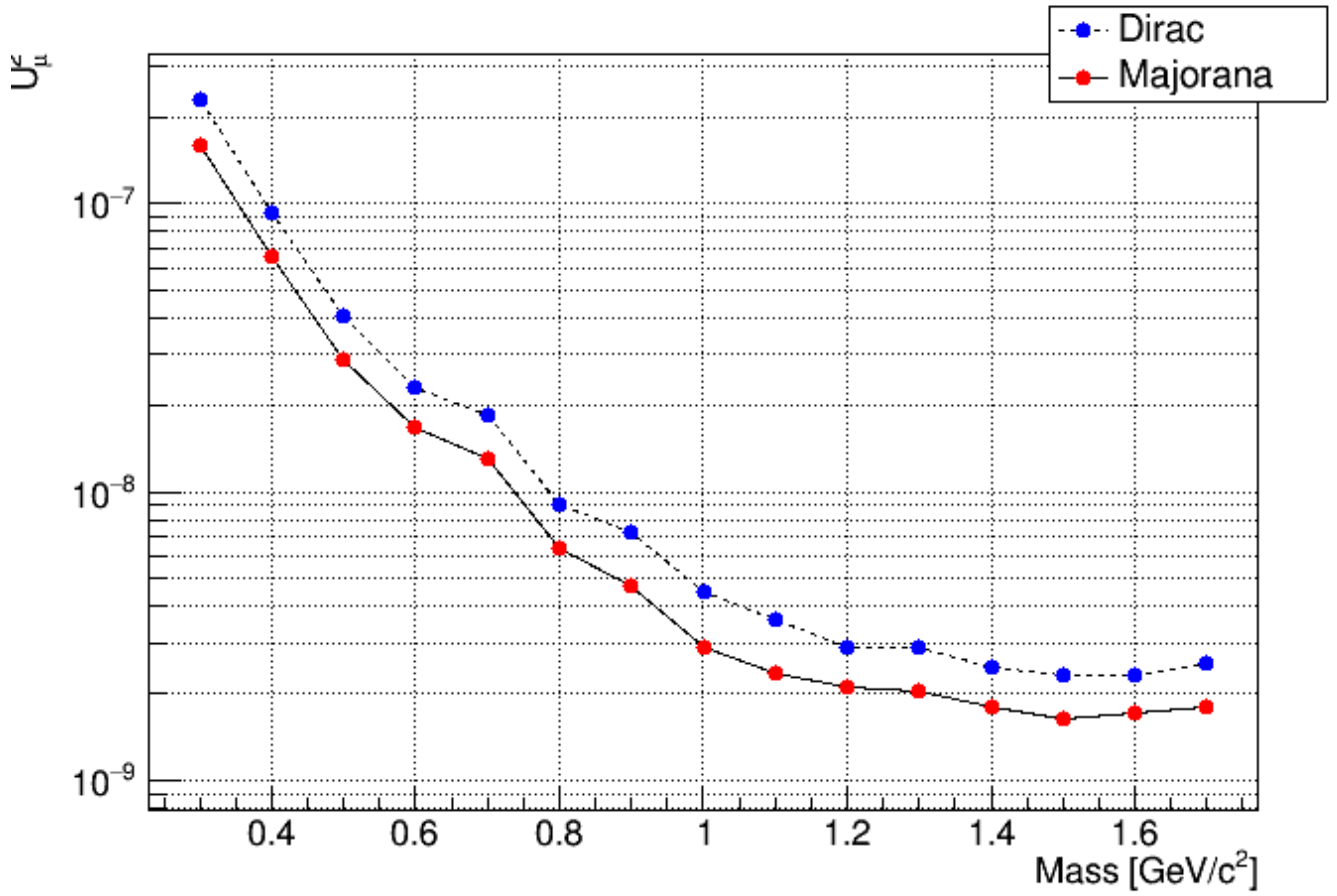
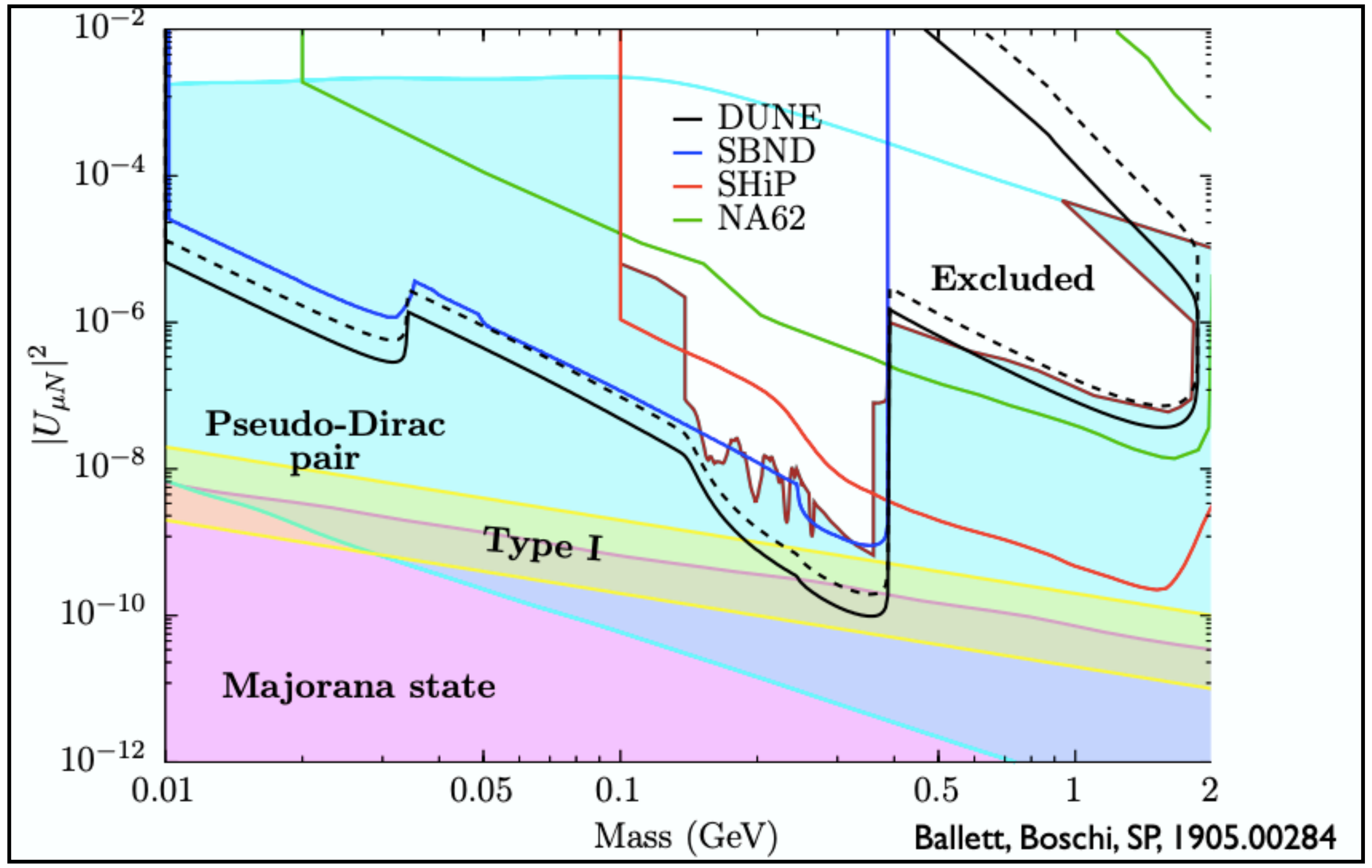








- 6 years exposure, 1.1×10^{21} NPOT/1yr
- Coupling follows Benchmark II, mass range is extended to 1.7 GeV
- Very small mixing between N2 and N3 due BAU lower bound
- Detector's Geometry has been modified to fit with SAND transversally
- All correction has been checked
- All Ds channels has been covered



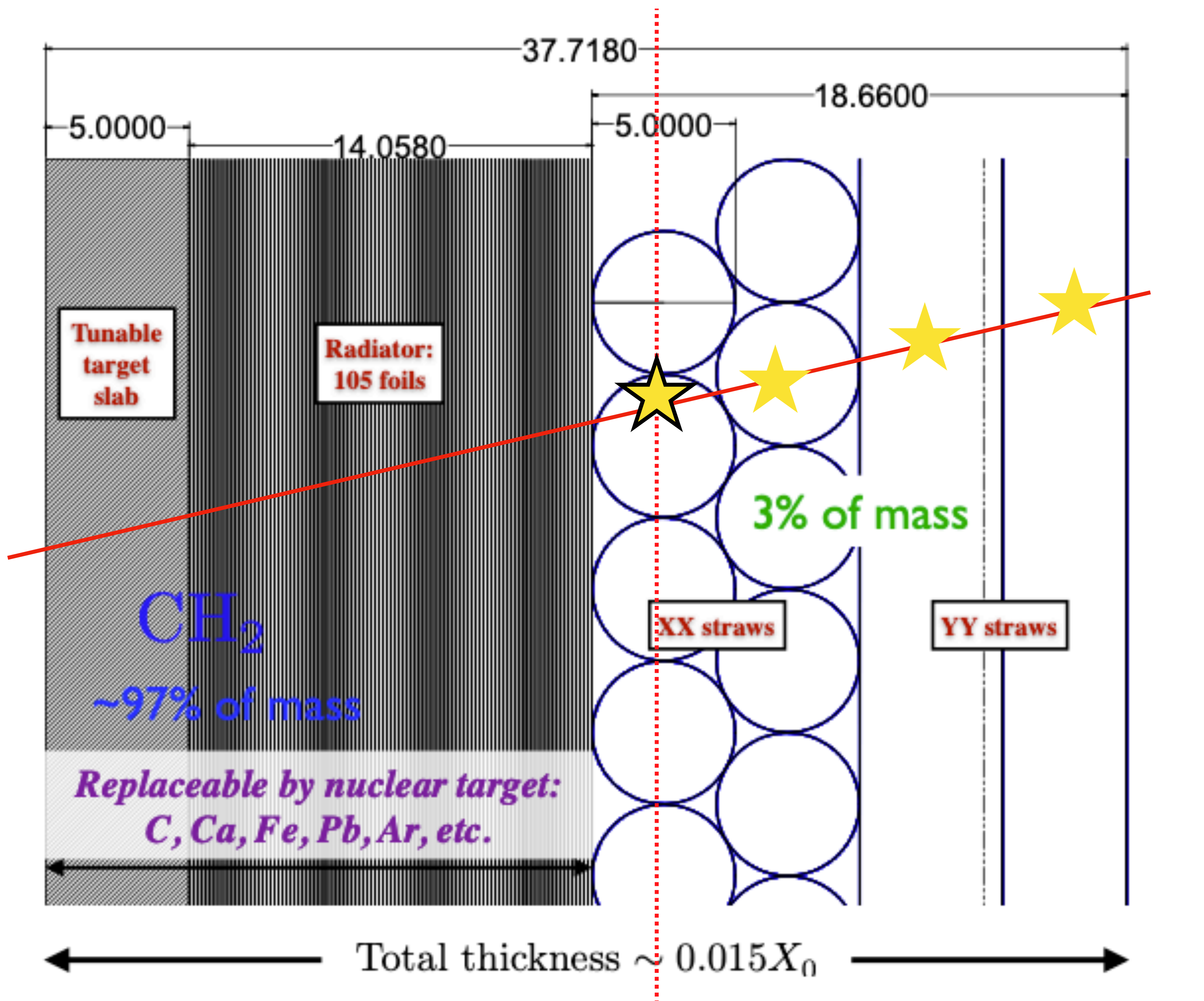
⁕Reconstruction

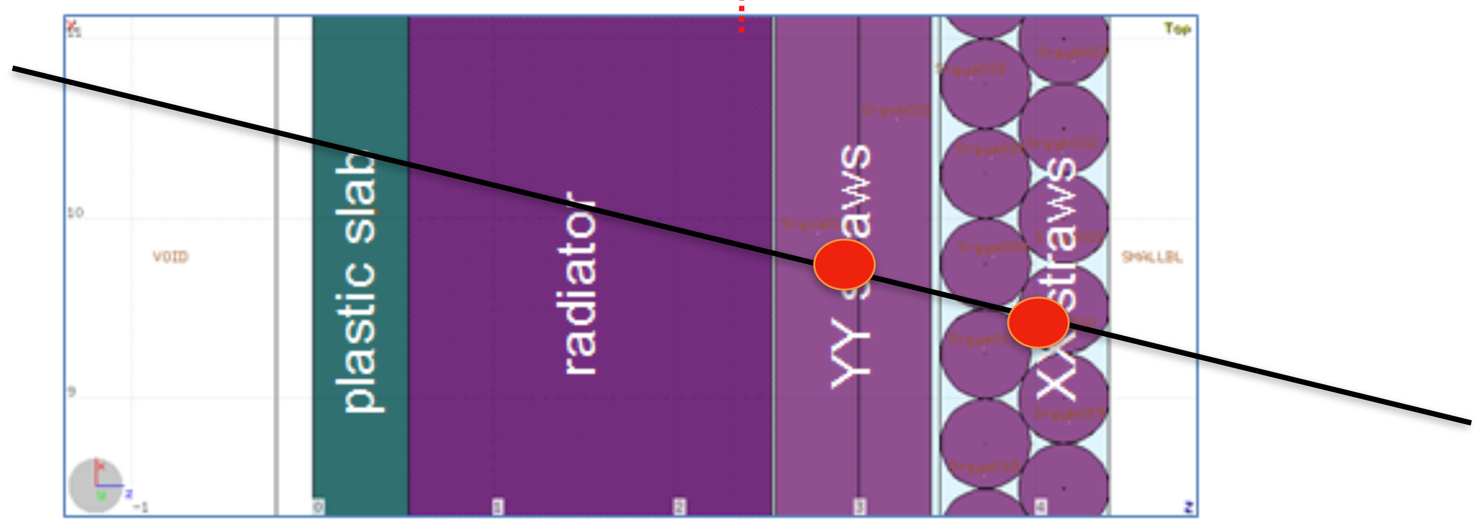
- Mad-Dump output file gets transformed to Genie-like output
- Genie-like output processed with EdepSim : edepsim output
- Digitization
- Existing Reco didn't work for me -> Motivation for implementing Kalman Filter for my work

DUNE, Near detector, SAND, Designs

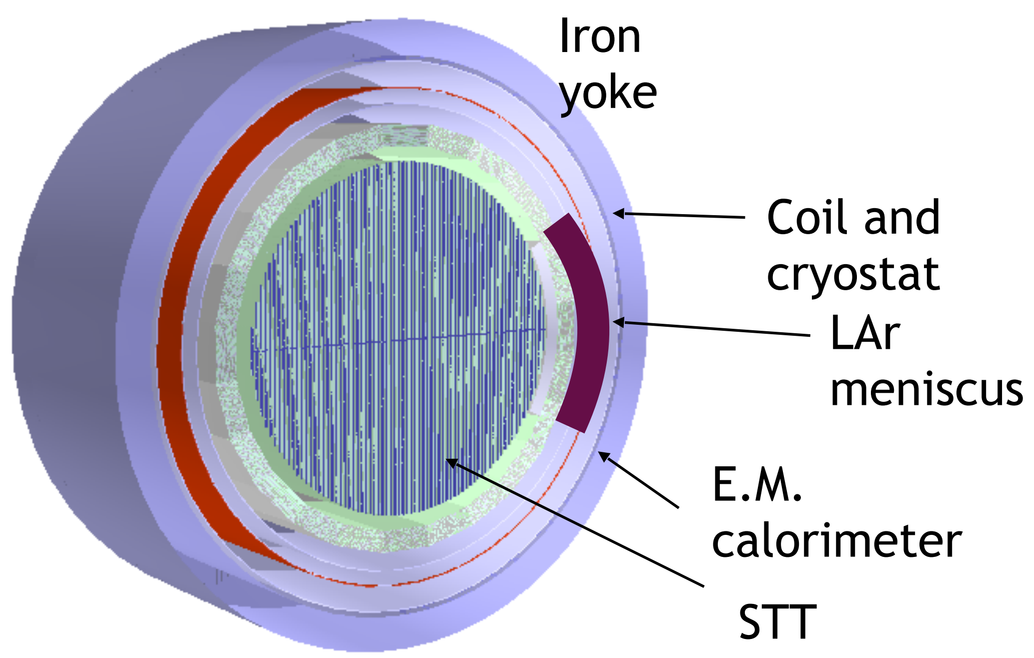
Geometry of the Tracker

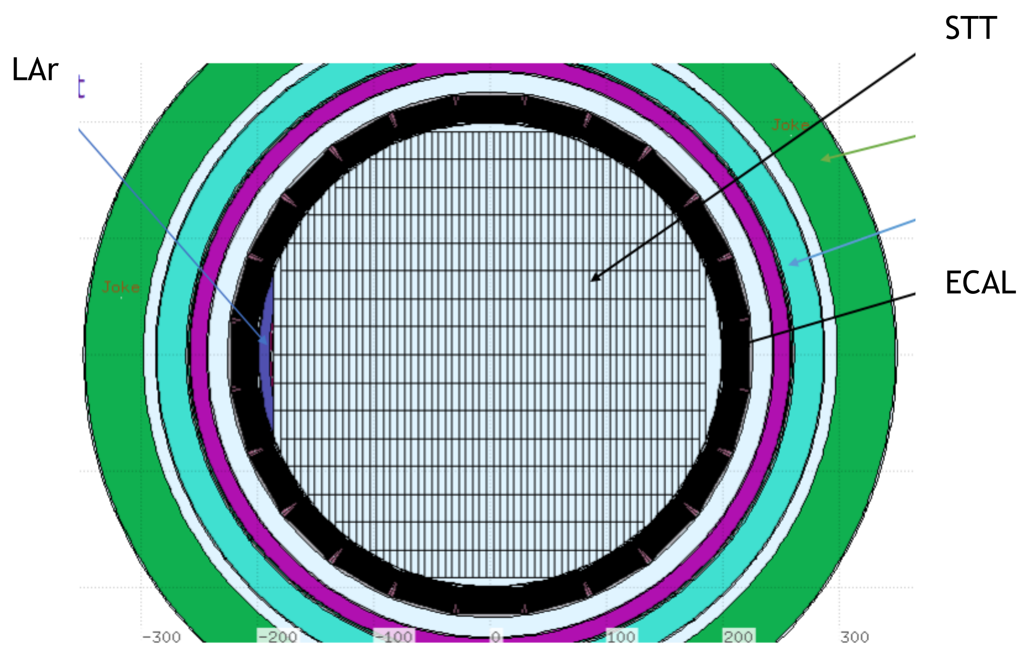
ECAL + STT + Grain (LAr meniscus) → GEANT4 and FLUKA

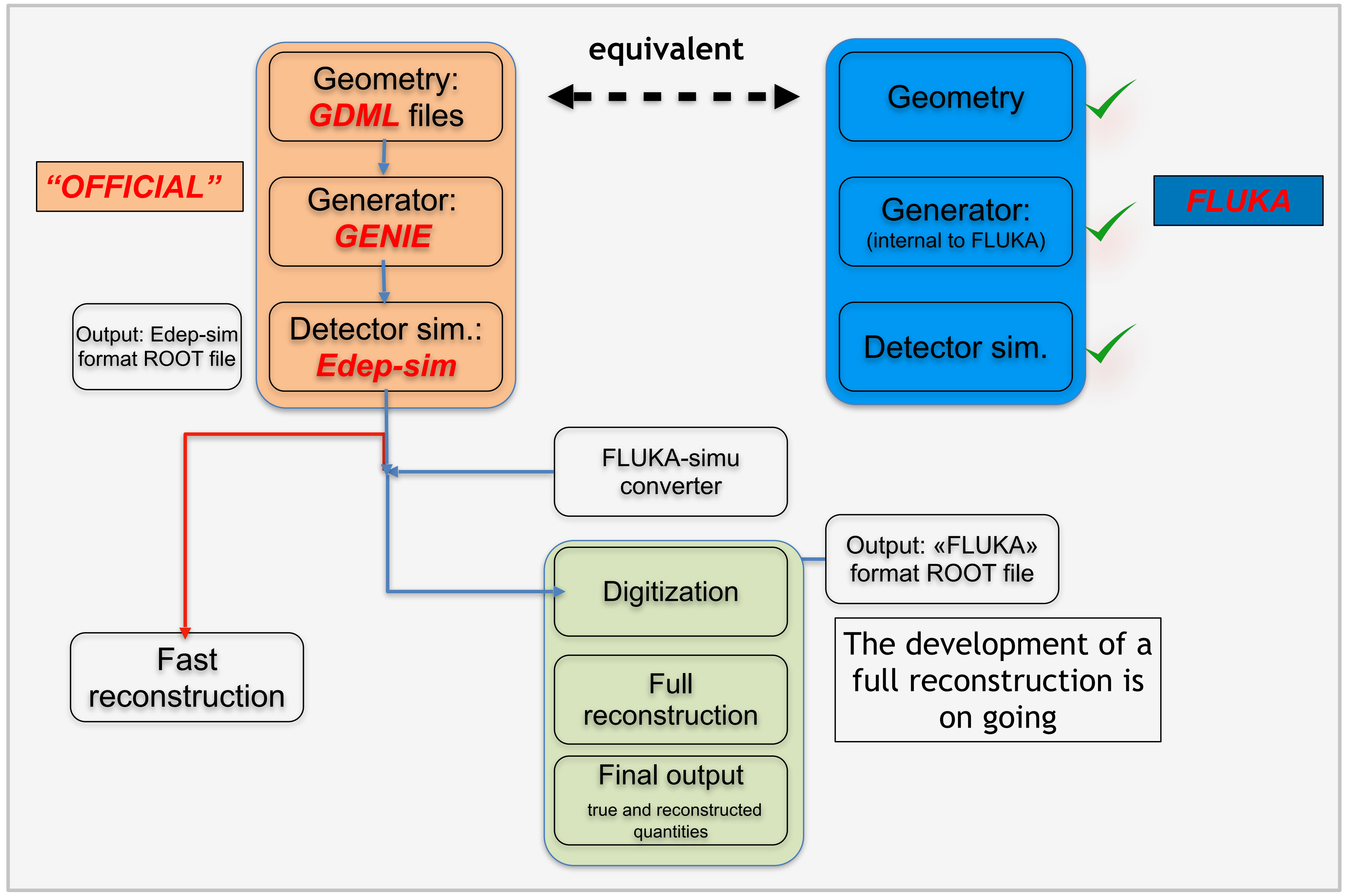


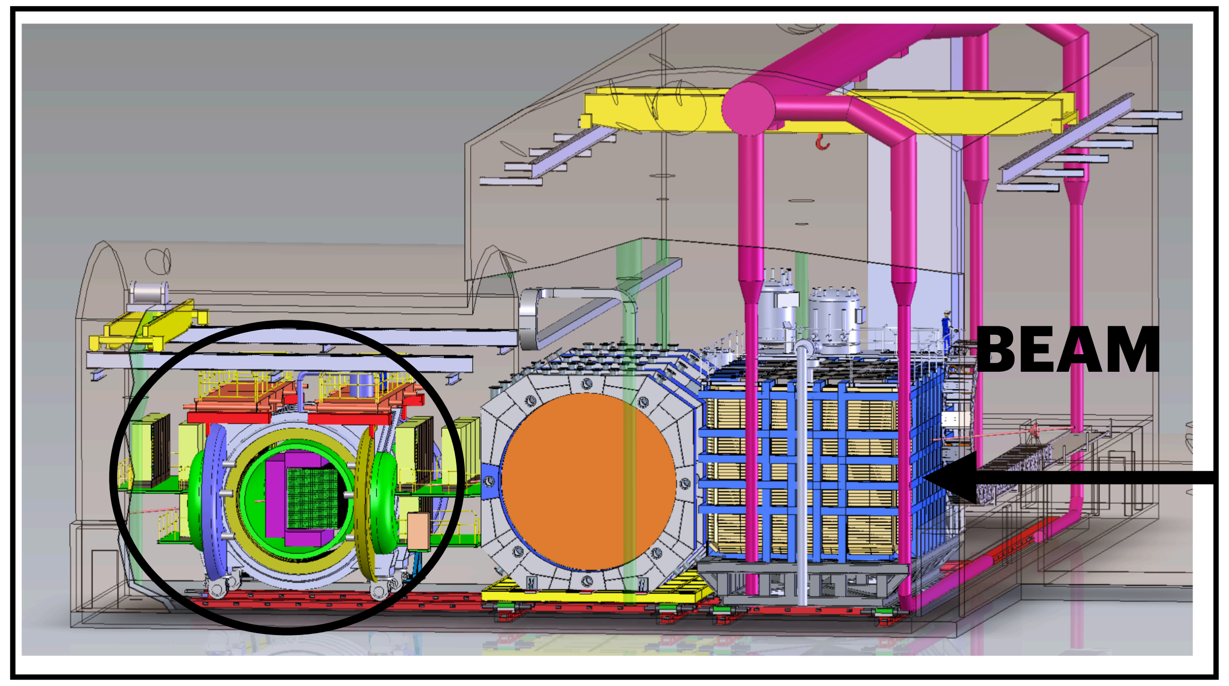


- FLUKA
  - HeaderTree
  - HitsTree
  - CellTree
  - STTTree
- EDEPSIM
  - TG4PrimaryVertex
  - TG4Trajectories
  - TG4HitSegment









Reconstruction, Kalman Filter

- Kalman Filter is an algorithm that determines the trajectory of a state vector of a dynamical system from a set of measurements taken at different times, taking into account gaussian fluctuations
- It proceeds progressively from one measurement to the next, improving the knowledge about the trajectory with each new measurement.
- There are three steps for Kalman Filter
  - **Predicting** : an estimate is made for the next measurement from current knowledge of the state vector
  - **Filtering/Updating** : Kalman Filter in Theory updates the state vector using the measurement
  - **Smoothing** : recursive operation, step by step in the direction opposite to that of filter

Residuals

Predict

$$\tilde{x}_k^{k-1} = F_k \tilde{x}_{k-1}$$

$$\tilde{C}_k^{k-1} = F_k C_{k-1} F_k^T + Q_k$$ (=MCS)

$$\tilde{r}_k^{k-1} = m_k - H_k \tilde{x}_{k-1}^k$$

$$\tilde{R}_k^{k-1} = V_k + H_k C_{k-1}^k H_k^T$$

Update

$$K_k = C_{k-1}^k H^T (V_k + H_k C_{k-1}^k H_k^T)^{-1}$$

$$\tilde{x}_k = \tilde{x}_k^{k-1} + K_k (m_k - H_k \tilde{x}_{k-1}^k)$$

$$C_k = (1 - K_k H_k) C_{k-1}^k$$

$$r_k = (1 - K_k H_k) r_{k-1}^k$$

$$R_k = (1 - K_k H_k) V_k$$

$$\chi^2_{k,F} = r_k^T R_k^{-1} r_k$$

Smooth

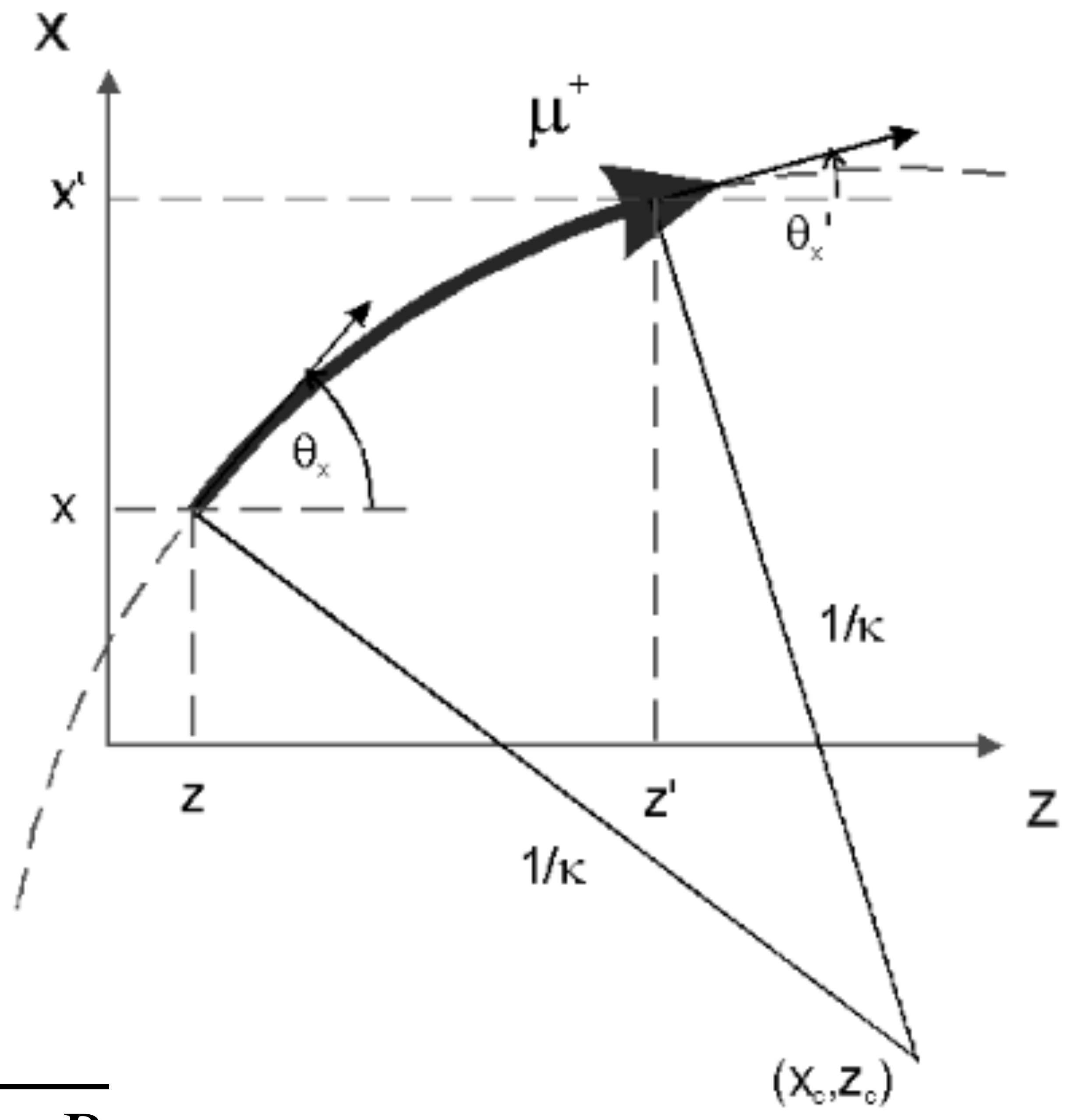
$$A_k = C_k F_{k+1}^T (C_{k+1}^k)^{-1}$$

$$\tilde{x}_k^n = \tilde{x}_k + A_k (\tilde{x}_{k+1}^n - \tilde{x}_{k+1}^k)$$

$$C_k^n = C_k + A_k (C_{k+1}^n - C_{k+1}^k) A_k^T$$

$$r_k^n = m_k - H_k \tilde{x}_k^n$$

$$R_k^n = R_k - H_k A_k (C_{k+1}^n - C_{k+1}^k) A_k^T H_k^T$$



$$X = (x, y, t_x, t_y, \frac{q}{P_T})$$

$$\frac{q}{P_T}[\frac{e}{GeV}] = \frac{1}{R \times 0.3 \times B}$$

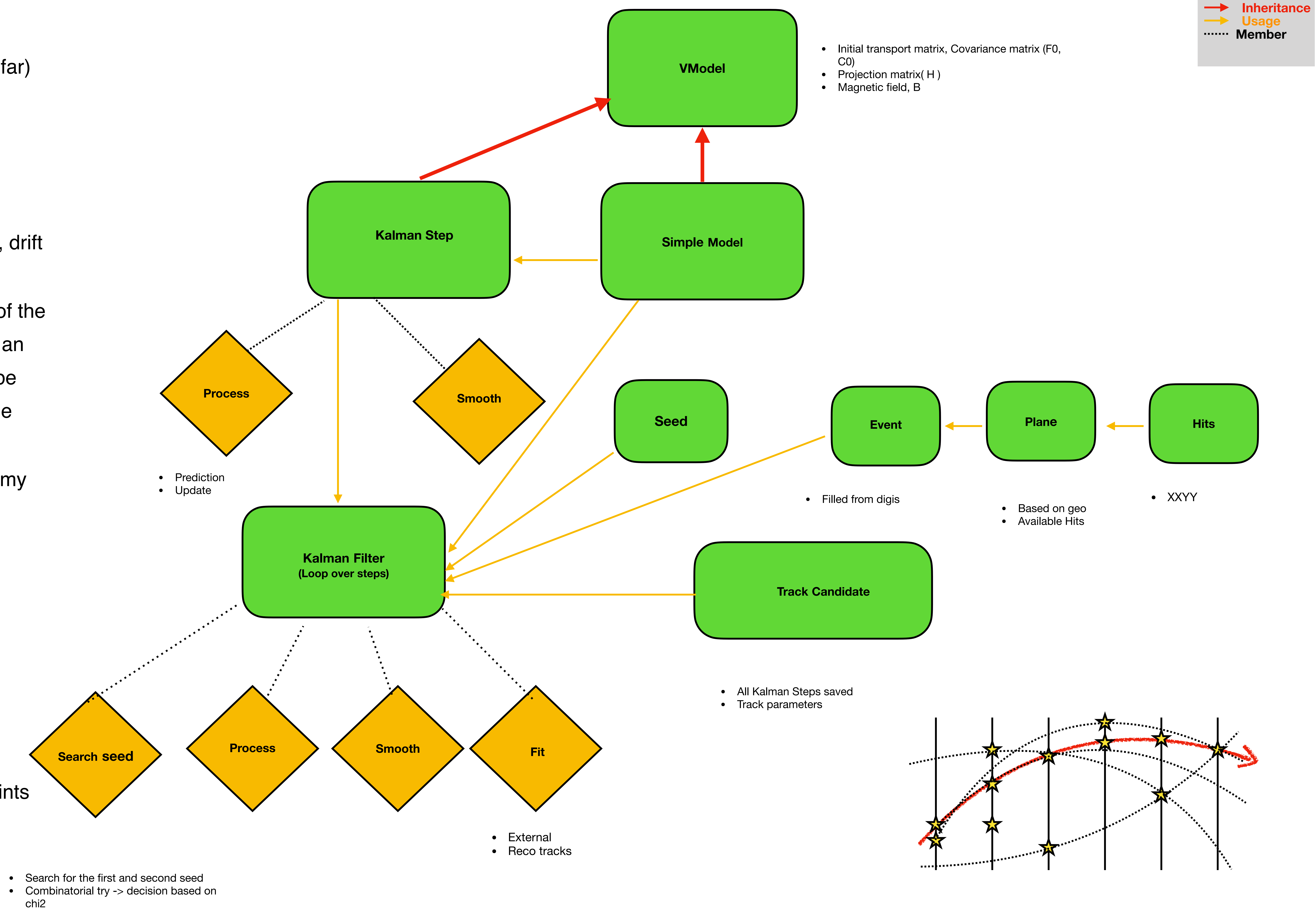
Kalman Filter, Obj Oriented Coding

Coding structure

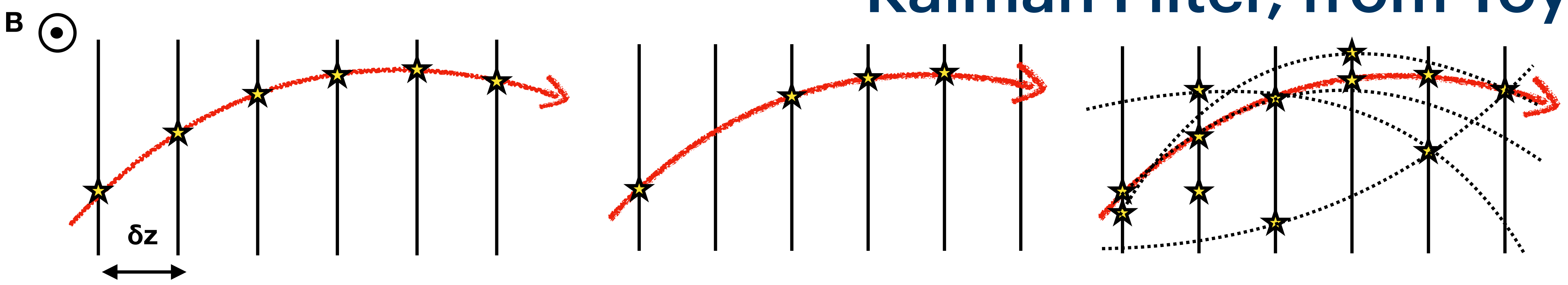
- Started with simple code (it cannot go far)
- Progressed to Object Oriented

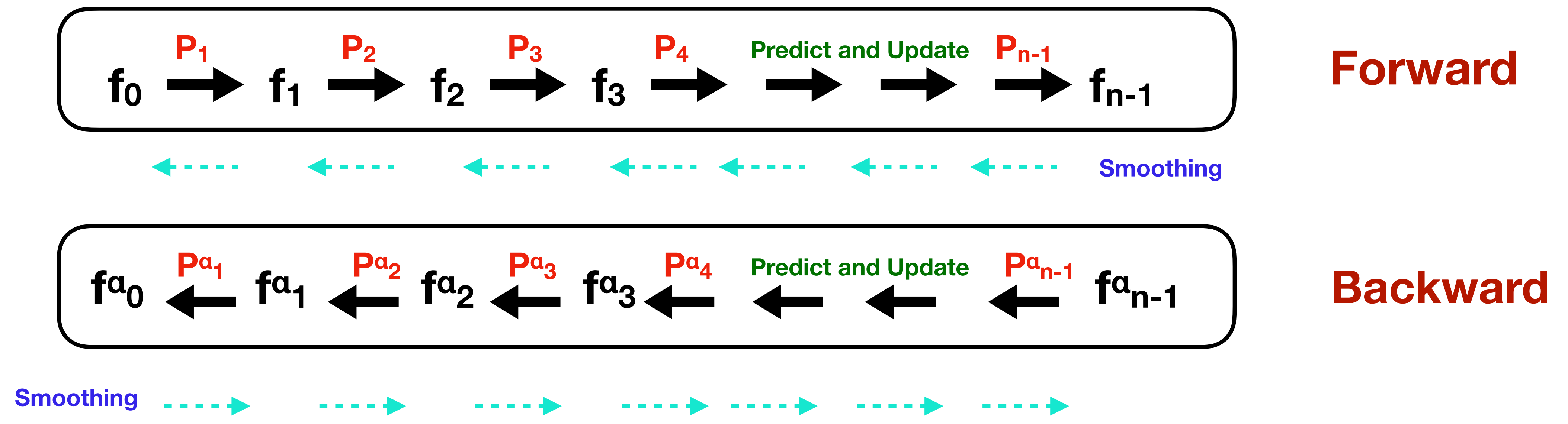
Procedure

- Hits
  - Digitization provides 1-D hits (X,Y), drift radius is not stored
    - Having the drift radius instead of the coordinate directly, leaves with an ambiguity on left and right (to be solved using the other hits in the same coordinate)
  - Not very realistic but it’s still ok for my study
- Kalman Step
  - In each step Kalman Process and Smooth acts
- Kalman Filter
  - Search Seed
    - Two hits combinations
  - Build potential tracks
    - Discard candidates with < 6 points
  - Fit
  - Save the track



Kalman Filter, from Toy MC to Geant4 MC





⁕ Toy MC

- Toy MC starting with one single track, moved to multiple tracks, noise hits added
- Forward (Backward) Kalman
- **Measurements**
  - Assuming uniform B field, 0.6 T, constant δz for the planes (ideal, zero thickness)
  - RN generation with uniform distribution for initial position and initial momentum
  - For each plane x , y according to analytic extrapolation, with 95% efficiency.
  - Smearing 0.1mm for x and y

⁕ Preparation for Geant4 MC

- Mad-Dump -> Genie-like output
- EdepSim (nd_hall_kloe_sttonly.gdml) -> Edep-Sim output
- Digitization (200 µm smearing)-> wire position added (to meet with Kalman Filter discrete process that goes in steps, e.g. zero uncertainty on z coordinate of the plane)
- XY hits are combined into an extrapolated measurement at the z of the wire of the upstream plane of the module

⁕ Kalman Filter Geant4 MC

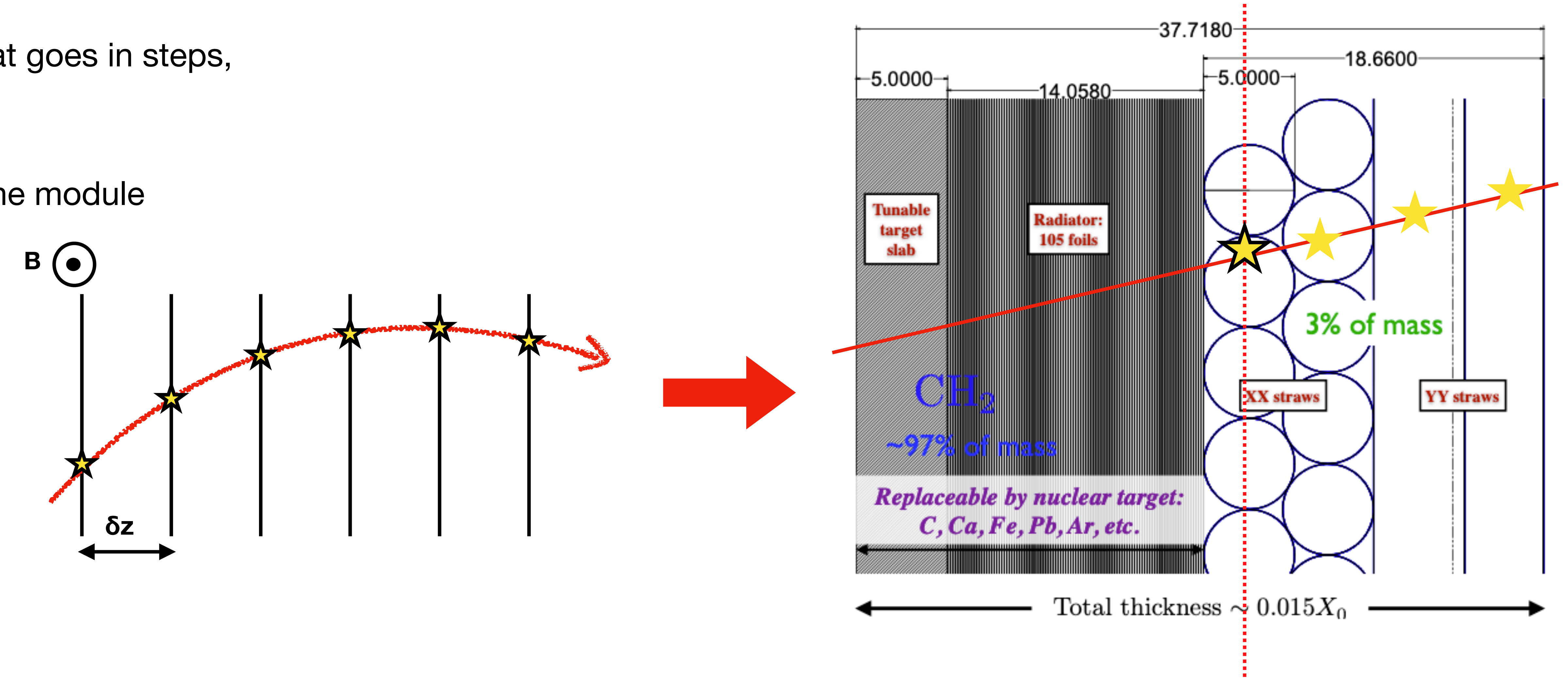
- HNL sample 1 GeV mass
- Forward/Backward
- **My Kalman Filter Assumptions**
  - Straw modules -> XXYY or XXYYXX (present in this geometry)
  - Uniform B field
  - Processing hits
    - Separate measurement for X and Y are recombined to (X, Y) referring to the Z of the first straw layer of each module

⁕ Kalman Filter Procedure:

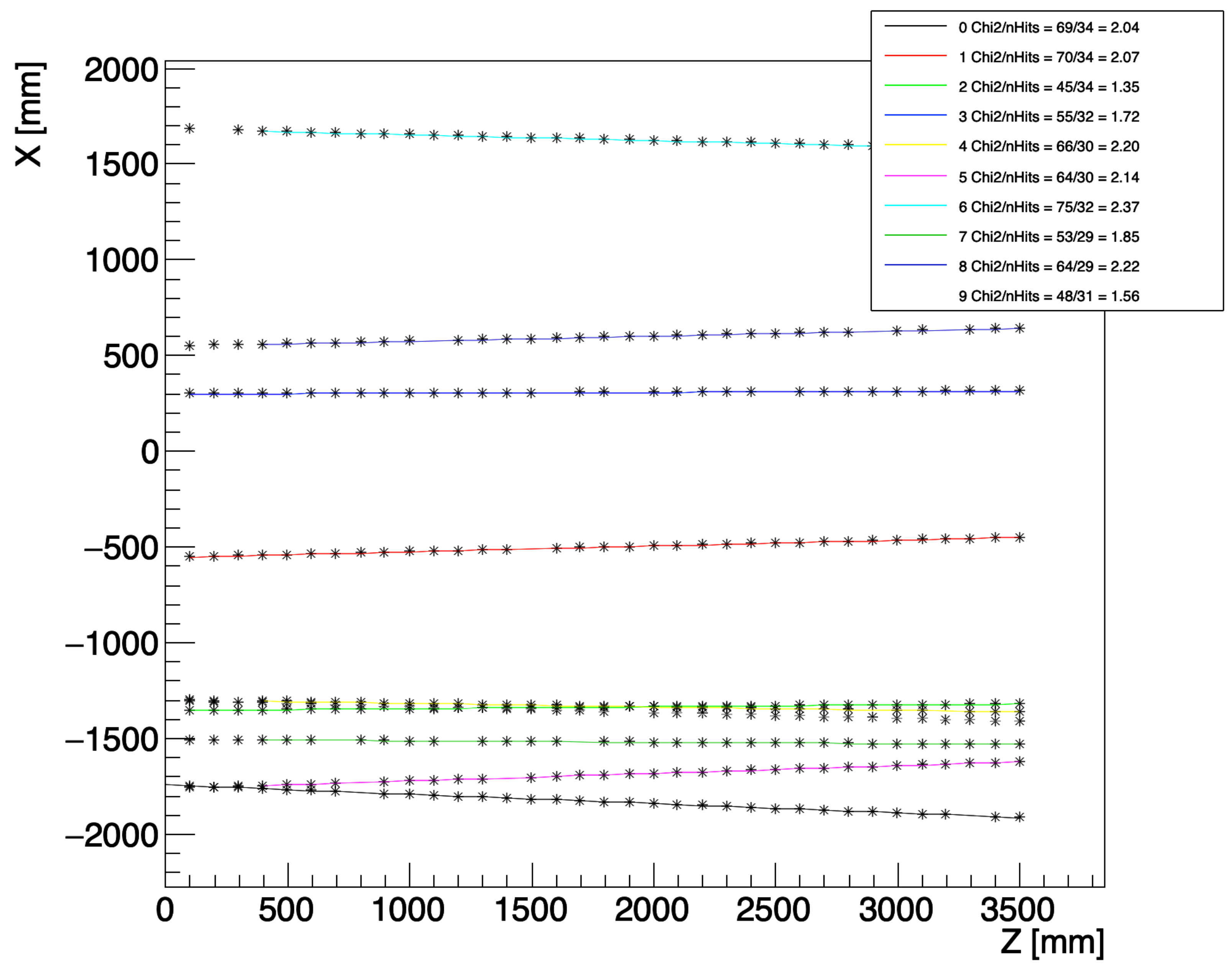
- Sequentially adding new information on each hits to get an optimal track
- **Strategy:**
  - Prediction and Update (Filtering, Residual , χ^2) -> forward and backward, Smoothing

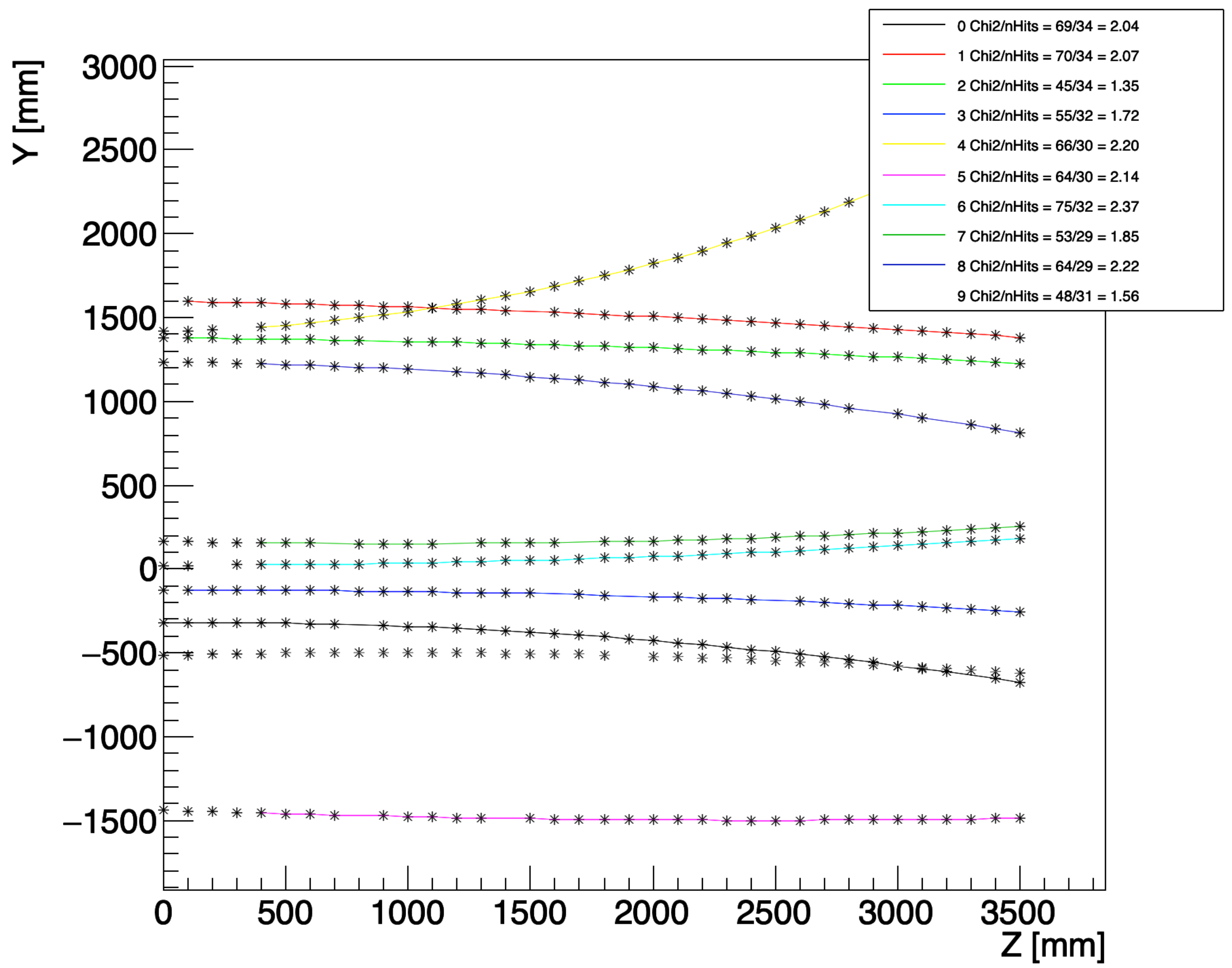
⁕ Kalman Filter Assumptions

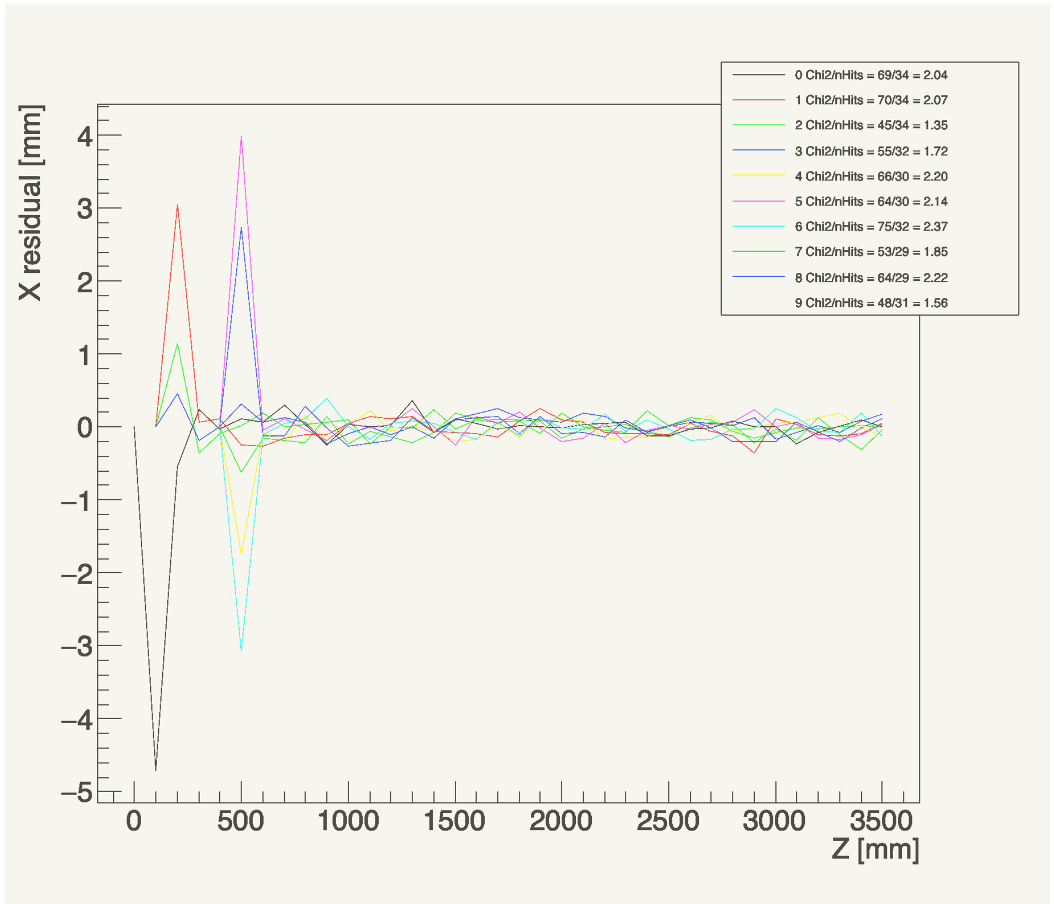
- Uniform B field
- Prediction step is an analytical extrapolation

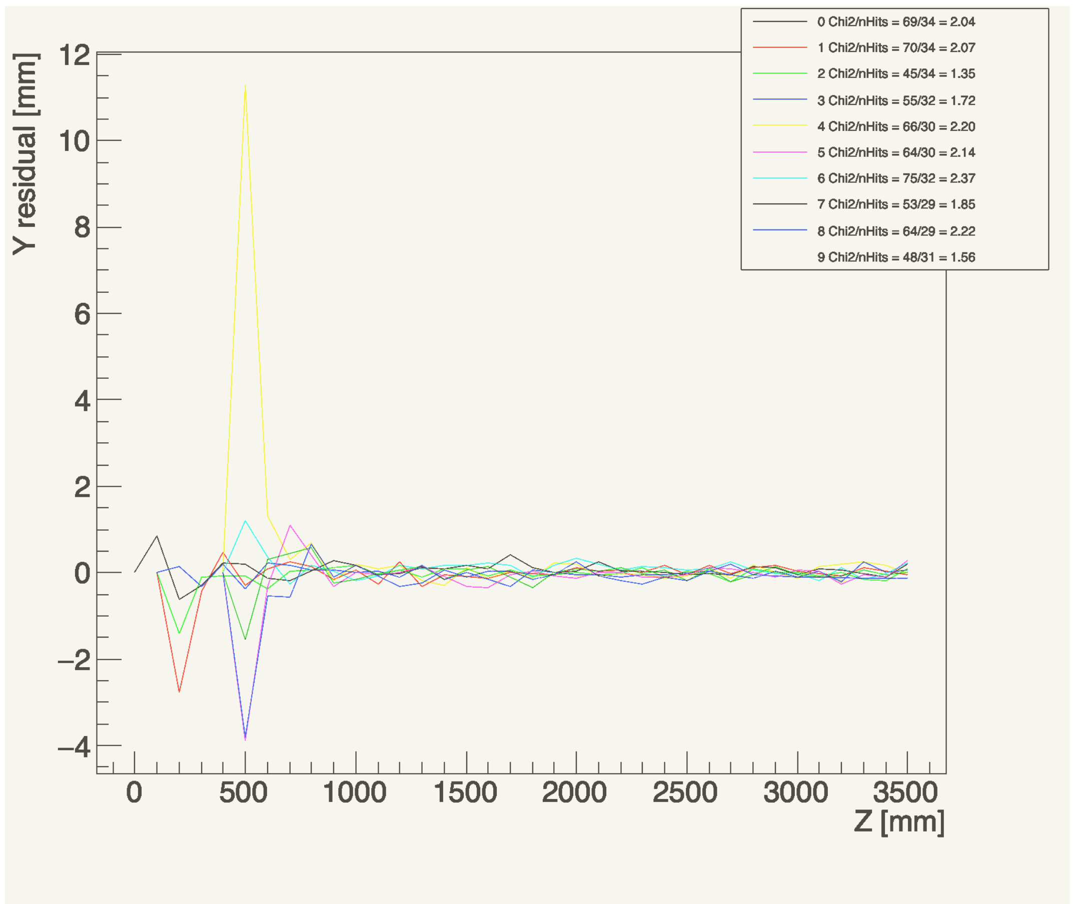


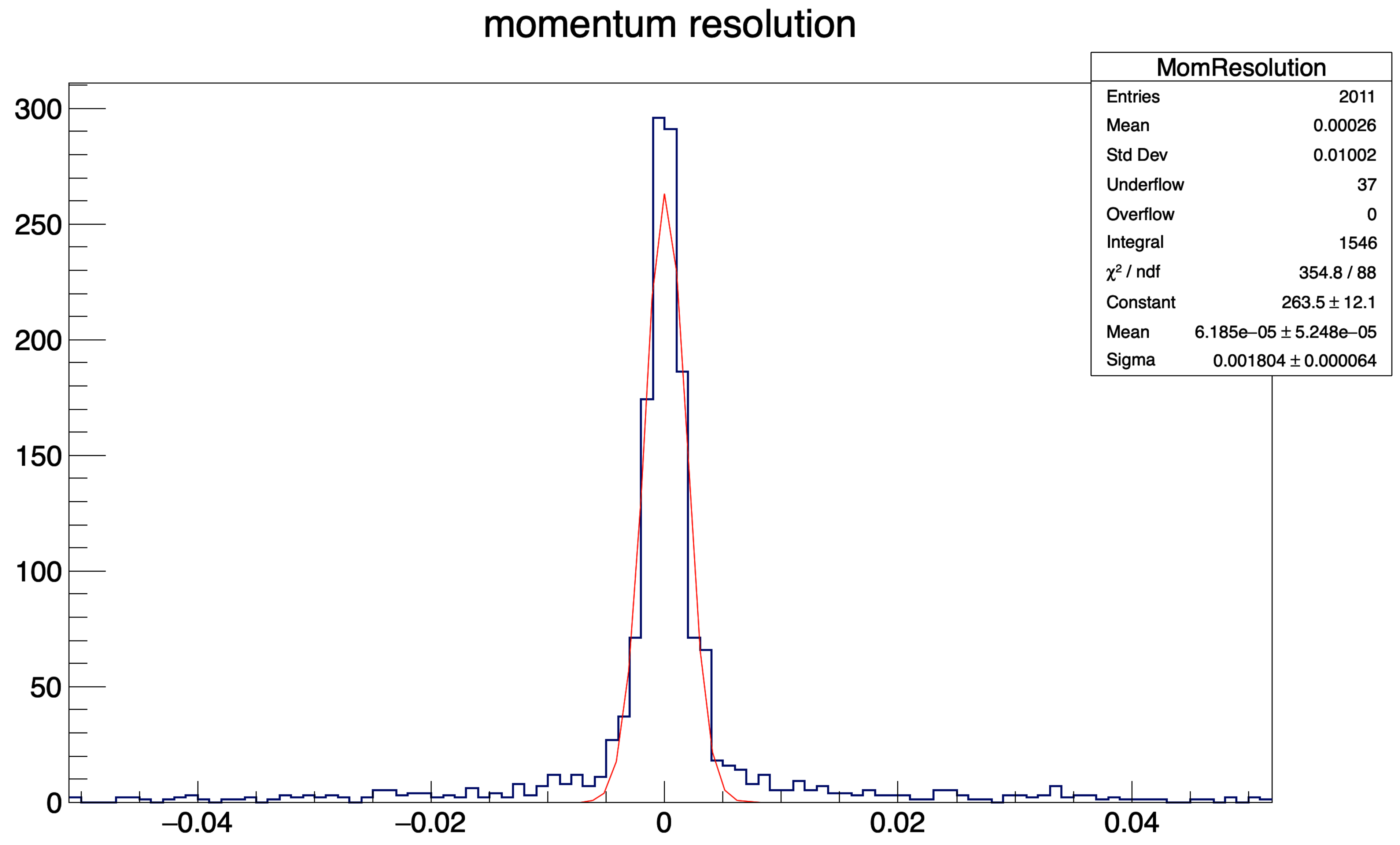
Kalman Filter, Toy MC











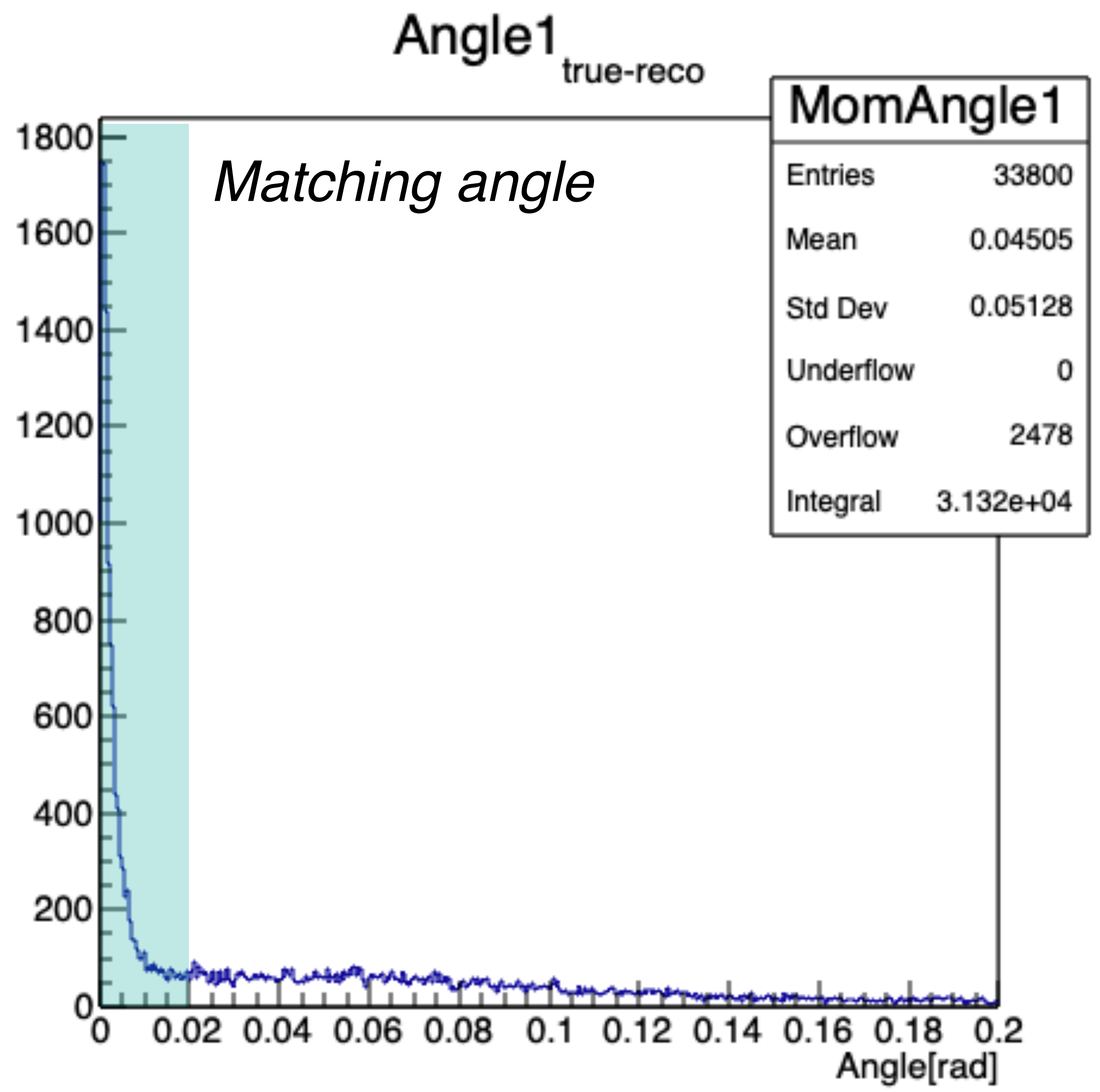
Momentum Resolution

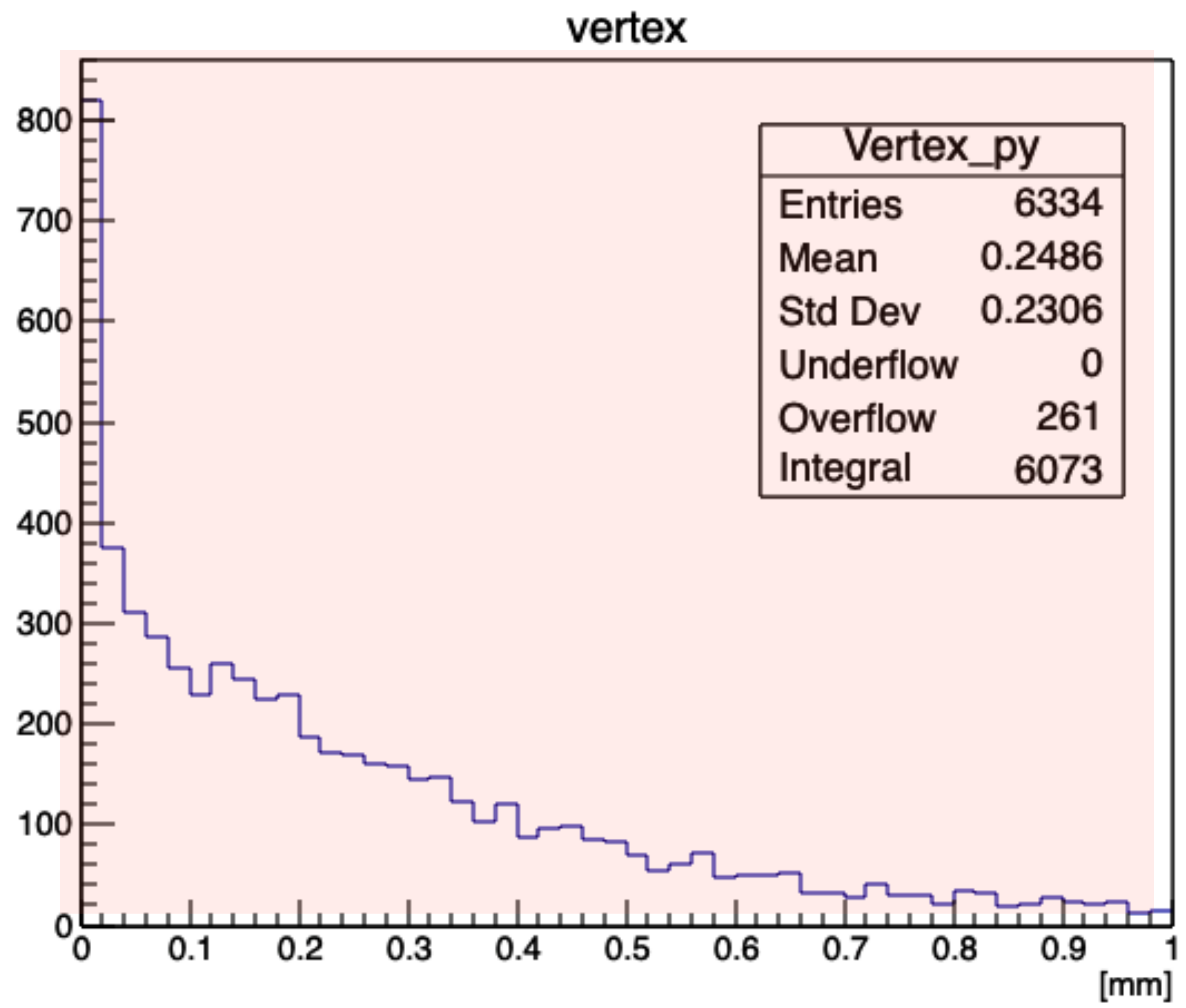
- Sigma 0.2% -> contribution of the Kalman Filter process to momentum resolution
  - Detector's contribution under estimated by the simple simulation approach
- Toy MC could be improved:
  - mimic a closer geometry to the real one, e.g. the separate measurements for X and Y
  - Individual effects like MS can be studied

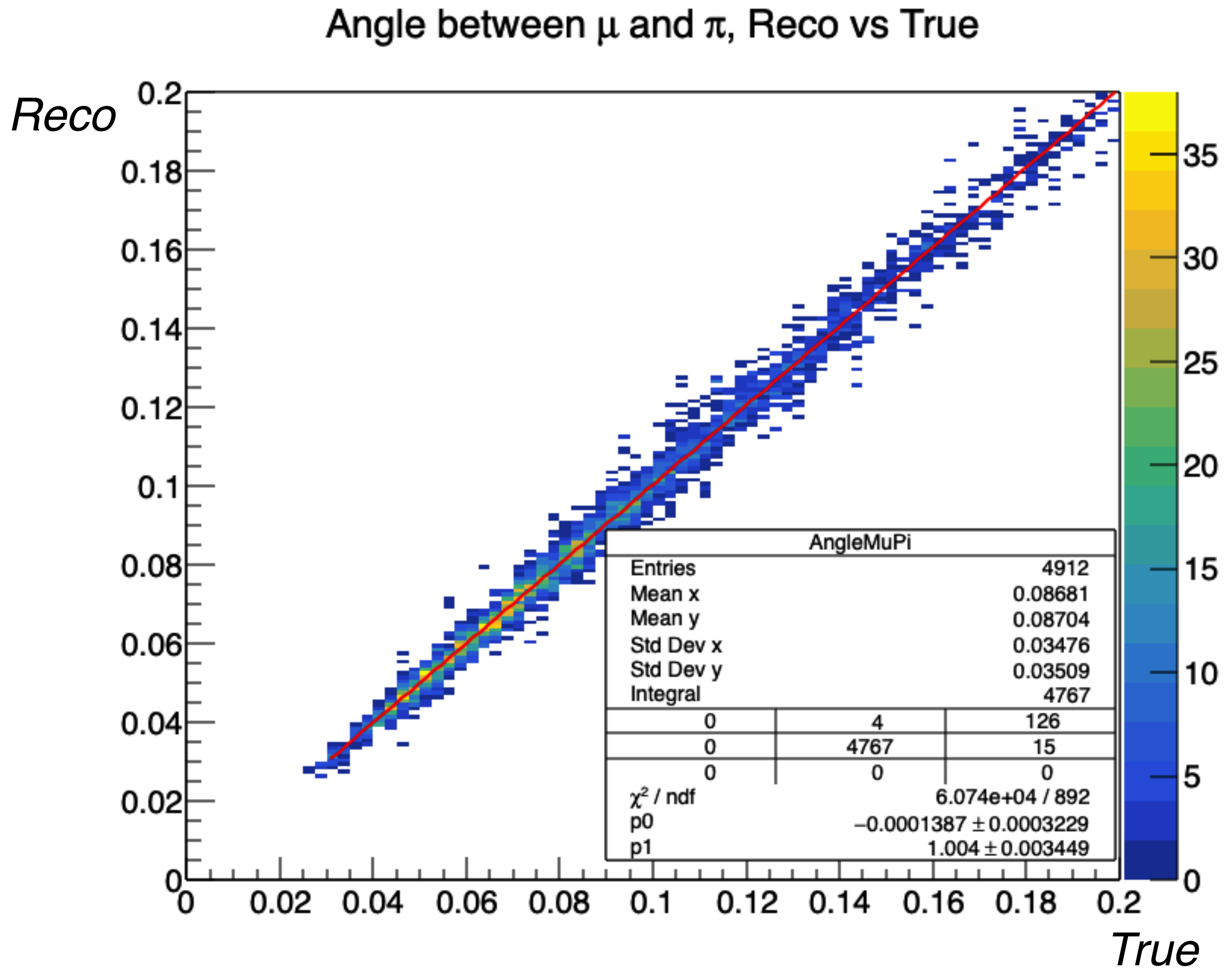
Efficiency

- Seems to find all tracks up to 10 tracks but a realistic estimate on efficiency is not worth for this toy MC

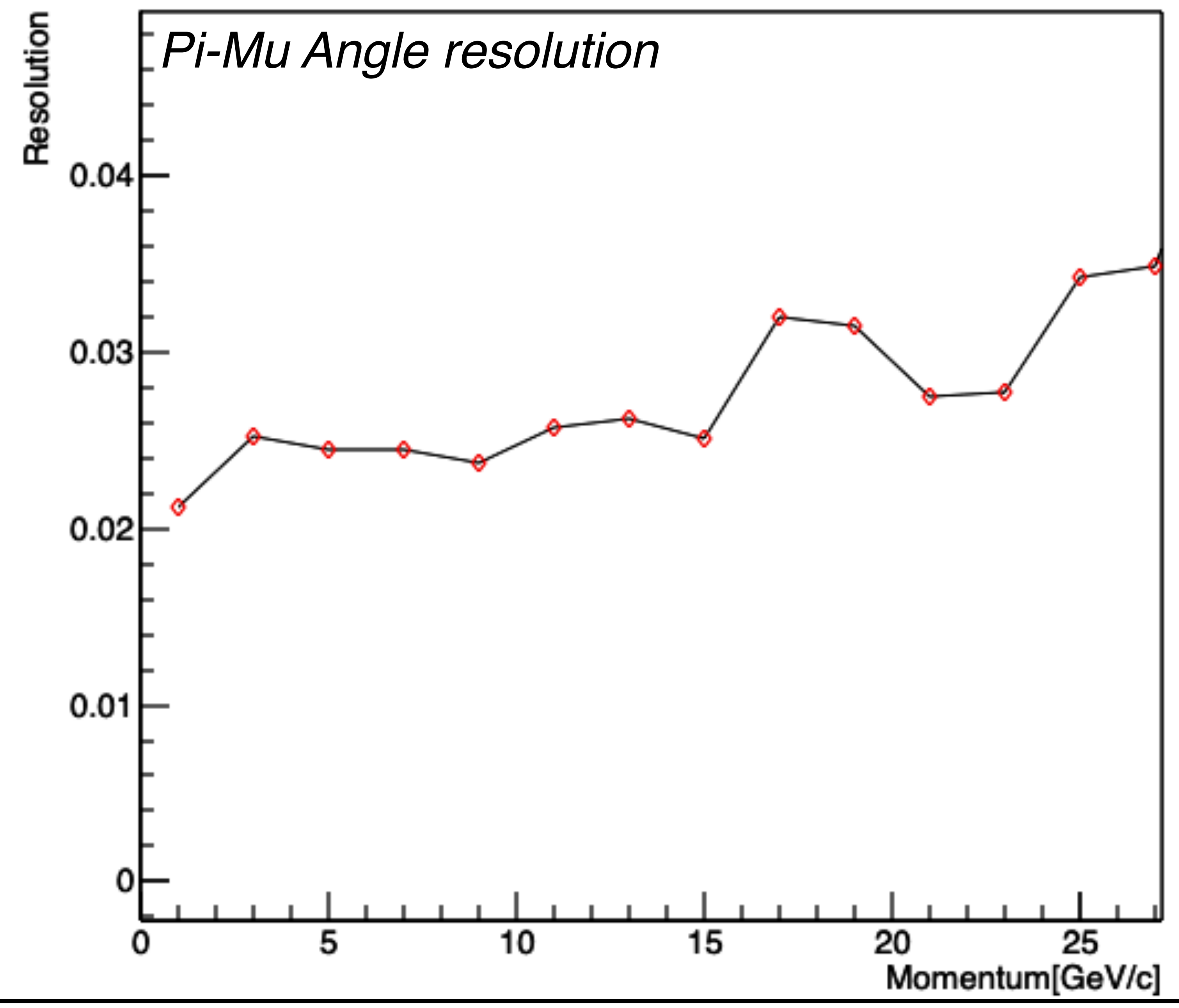
Kalman Filter, Angles and Vertex







- **Dominant contributions to Invariant Mass (besides Momentum)**
  - **Quality of the Vertex:**
    - cut is < 1mm (most of statistics)
  - **Quality of the Reco final product angle:**
    - The final product angle resolution is around 30 [mrad] up to 25 [GeV]
  - **MC truth Matching angle (preliminary):**
    - Significant tail on the single particle angle resolution (currently cut by MC truth matching ~ 20 [mrad])



Kalman Filter, GEANT4 MC

Improvements

- Backward Kalman direction implemented, in this case backward is more efficient: the initial hit is found easier and more precise (MCS not messing with the hits much)
- Multiple scattering has been added (changing the resolution by 0.1%)
- For better precision, external helical fit has been used (hits are coming from Kalman Filter, the used fit is the external one)

Items to have an eye on:

- Invariant Mass resolution
- Momentum resolution
- Kalman Filter parameters (Pull plots)
- Goodness of the fit (χ^2)

Procedure:

- Kalman Filter
  - Forward/Backward Kalman and smoothing.
    - External helical fit.
    - Reco tracks:
      A. Choosing either forward or backward as Reco tracks.
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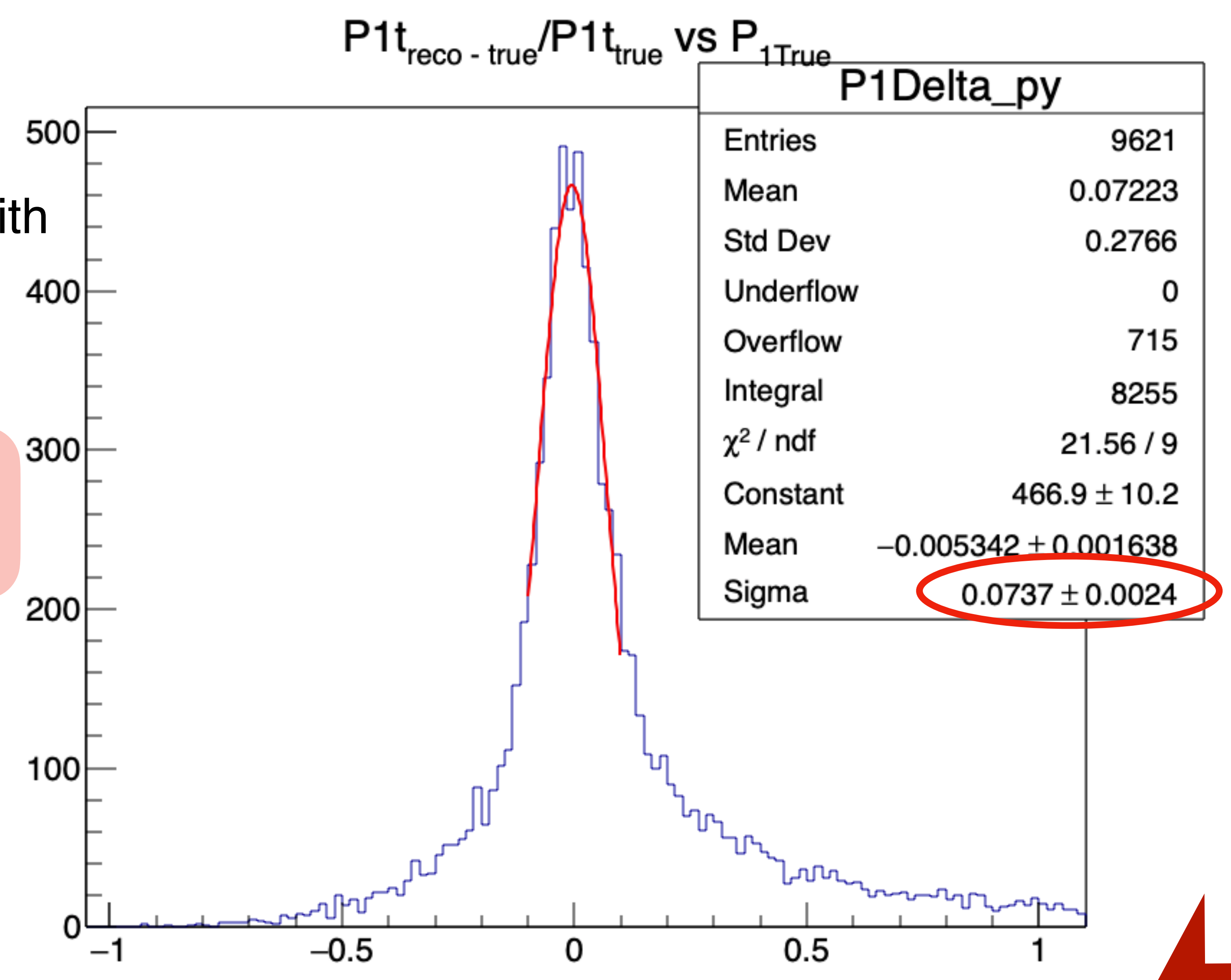
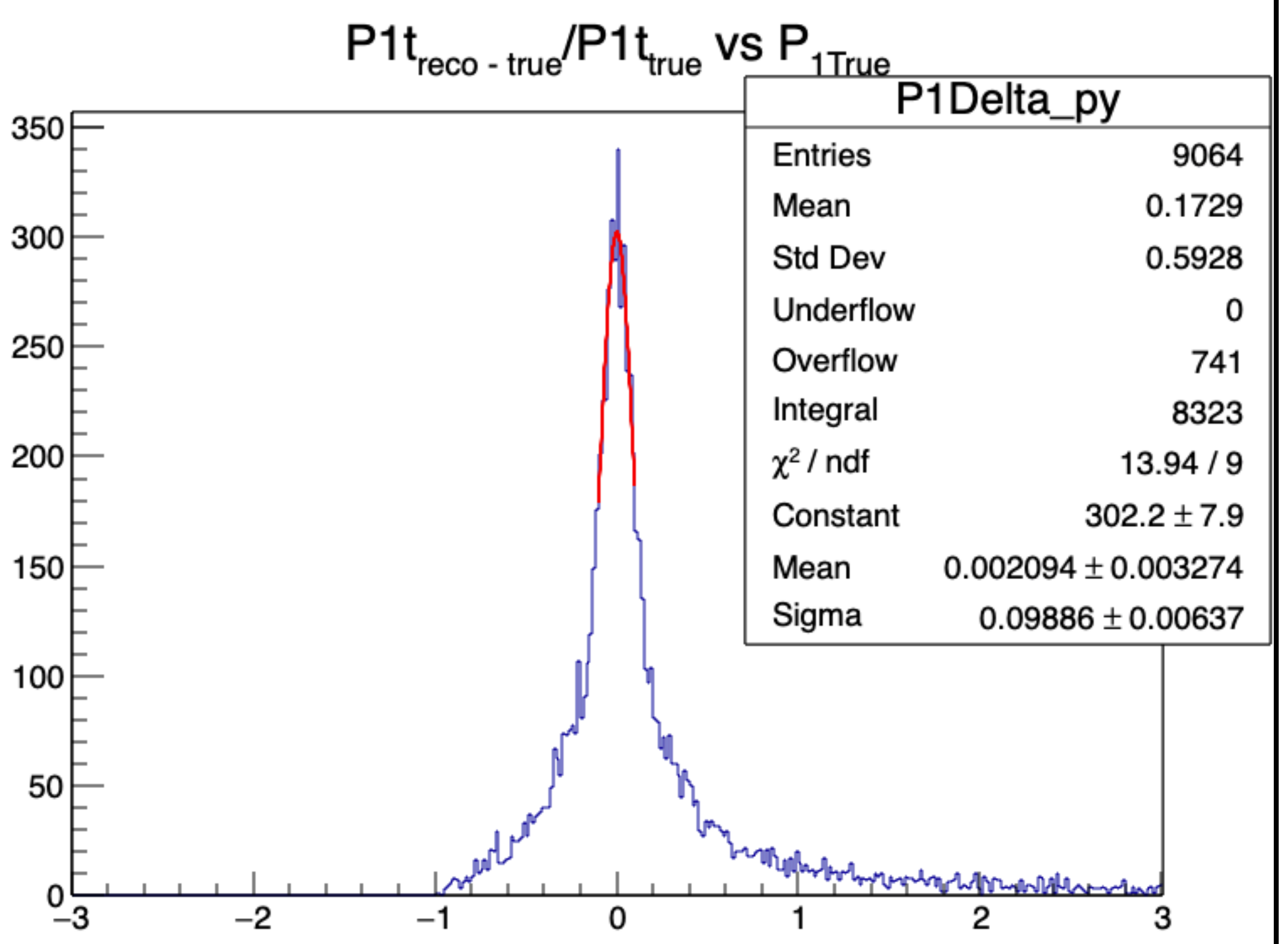
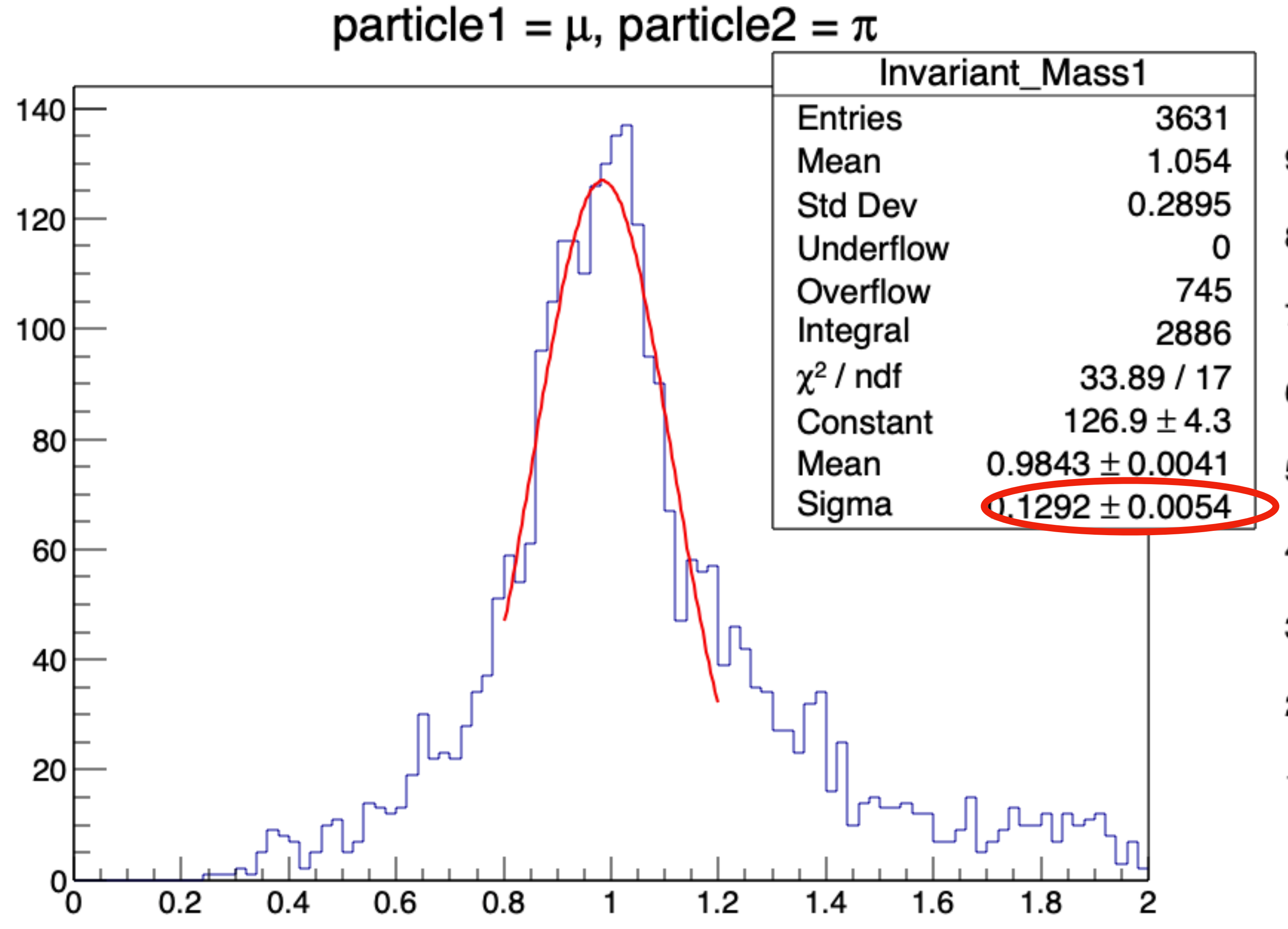
- Matching the Reco and the True.
- Momentum resolution, Invariant mass resolution, Pull plots

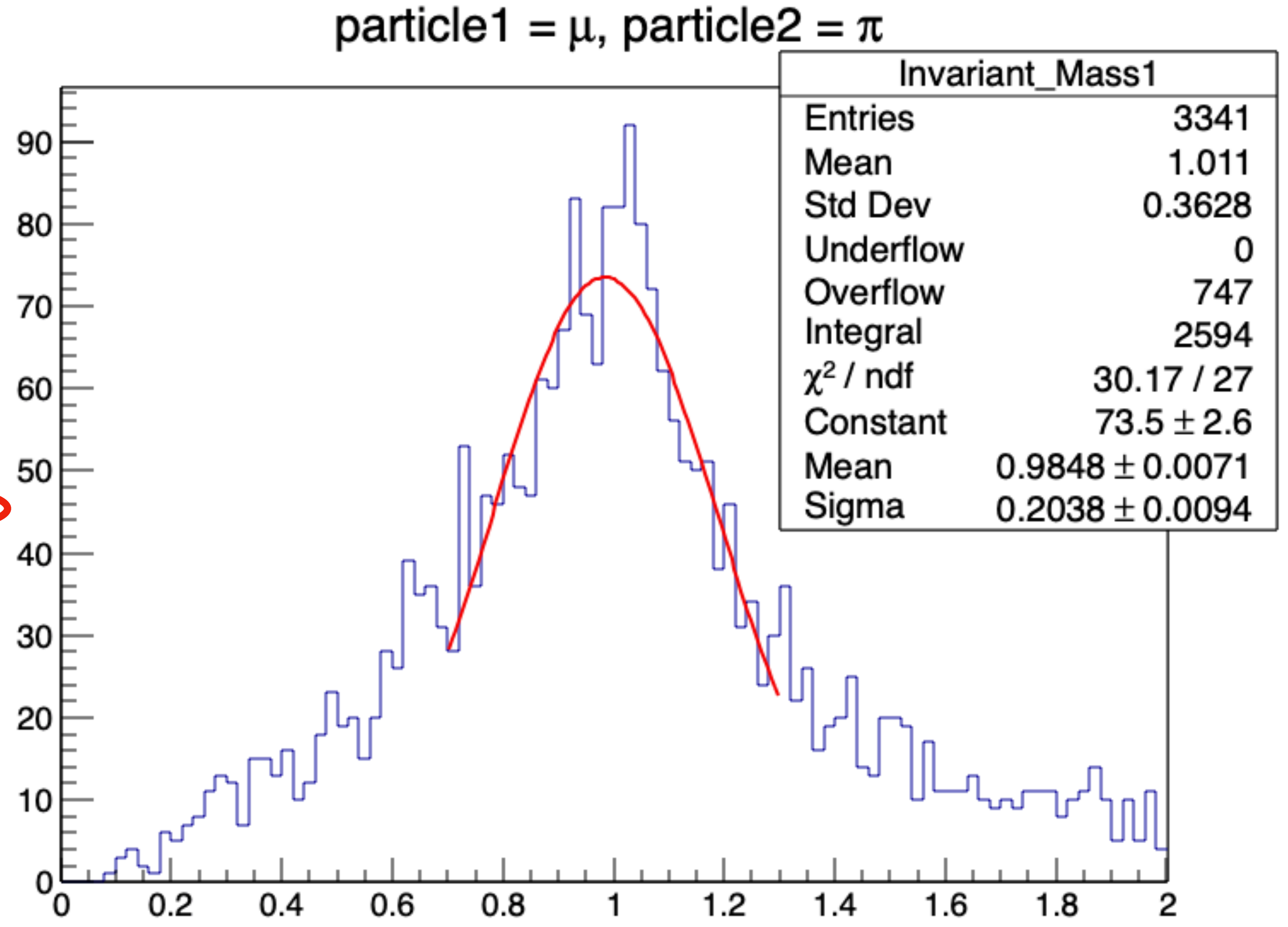
External Fit



Kalman Fit







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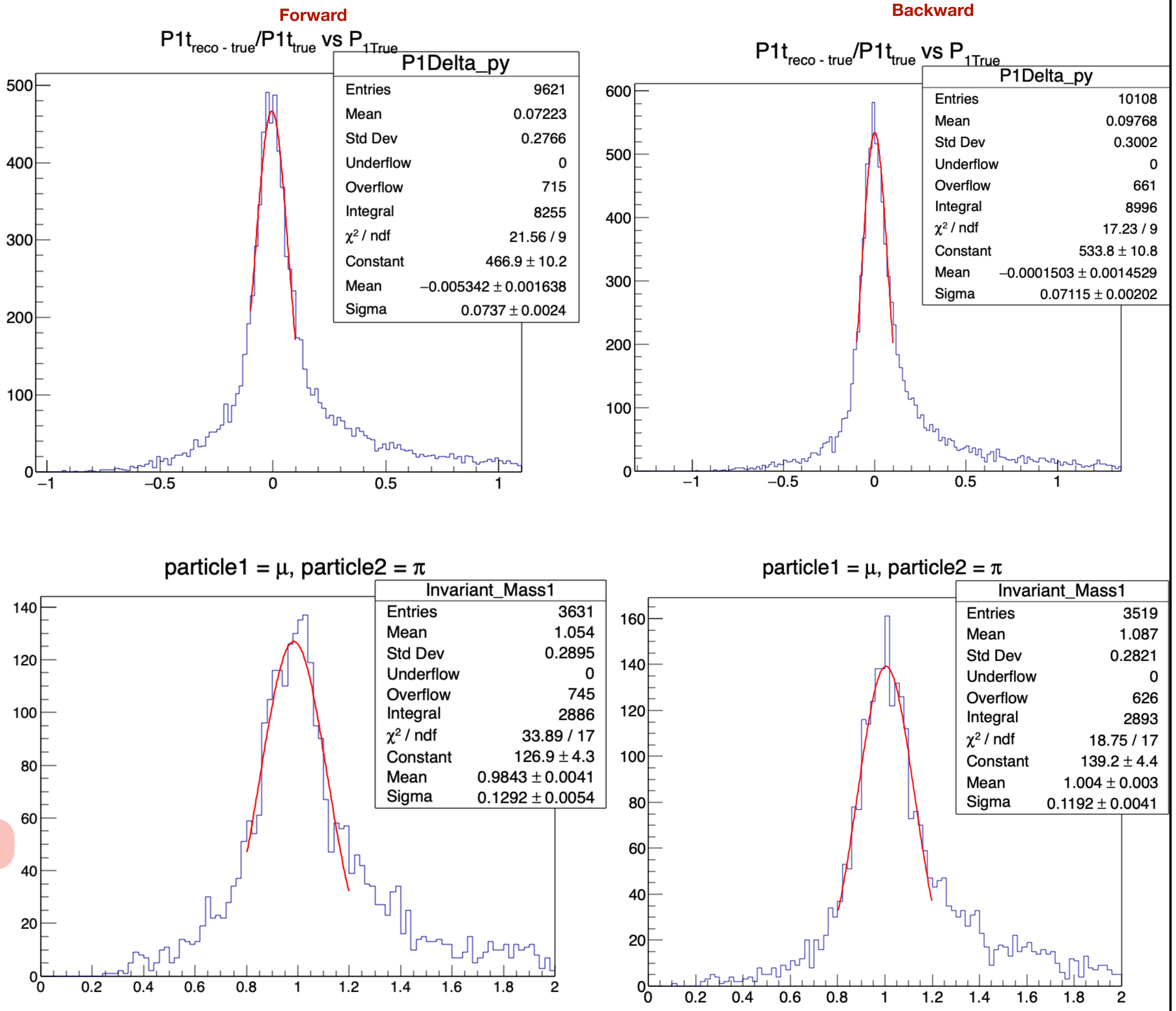

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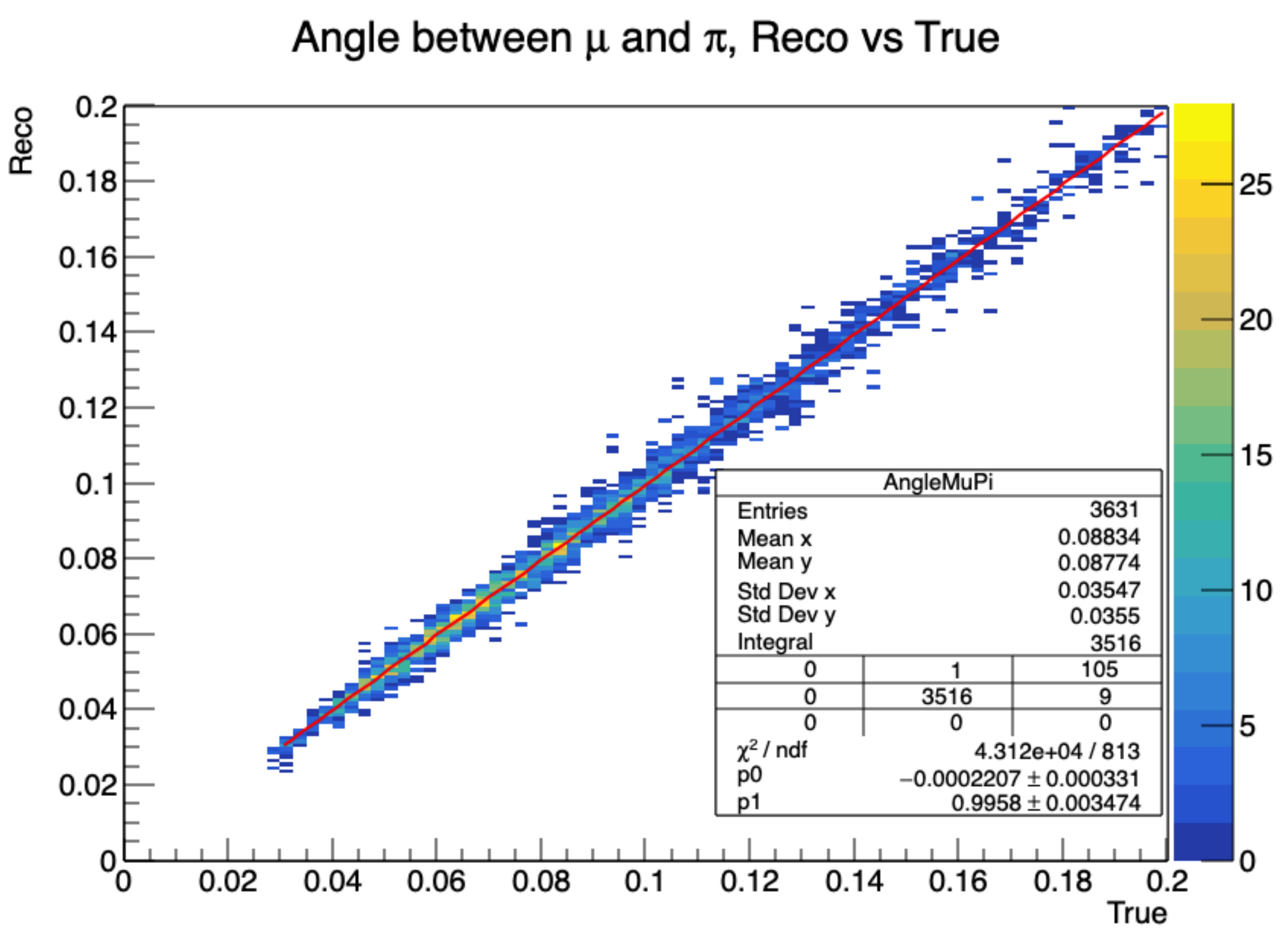
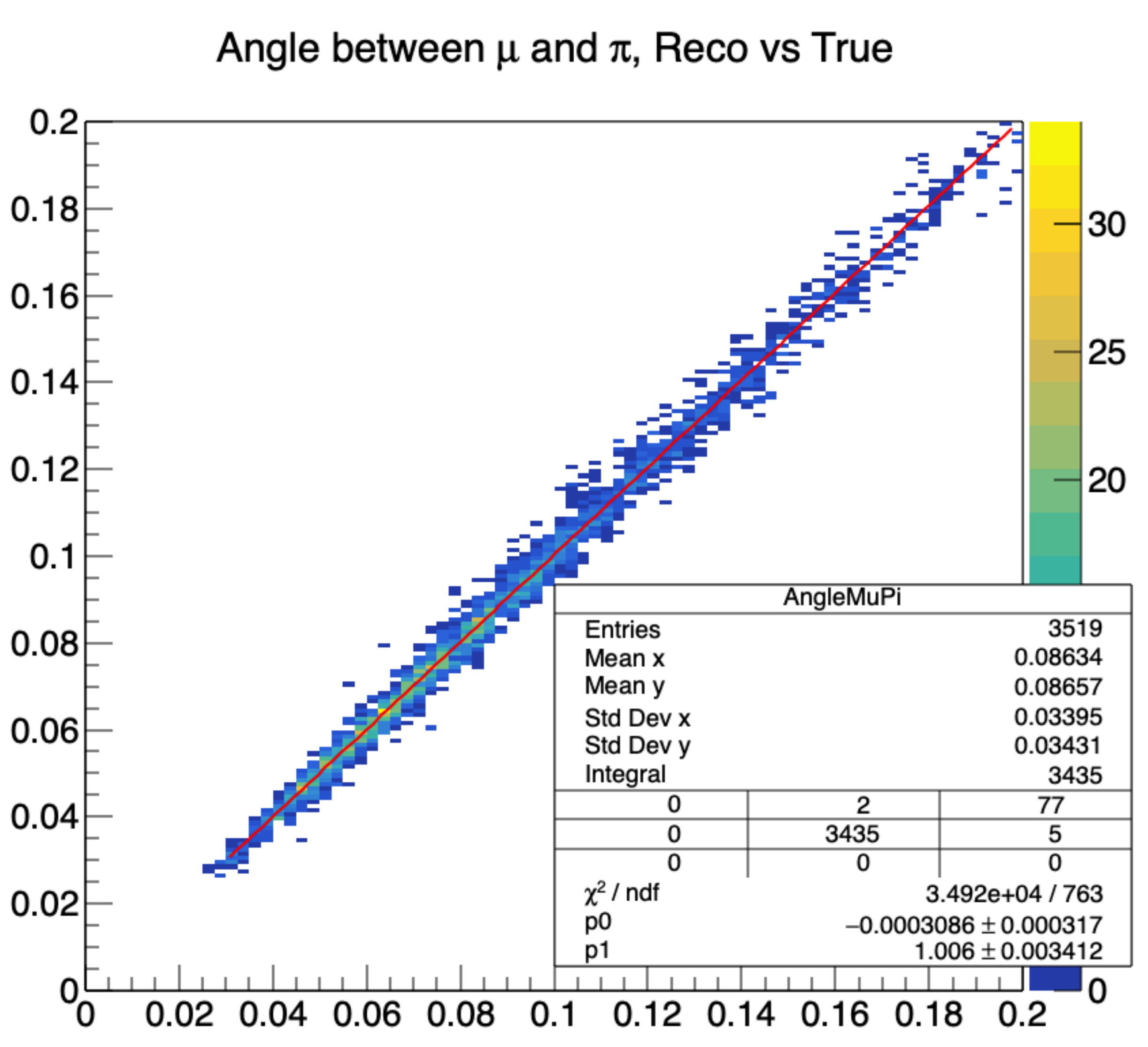
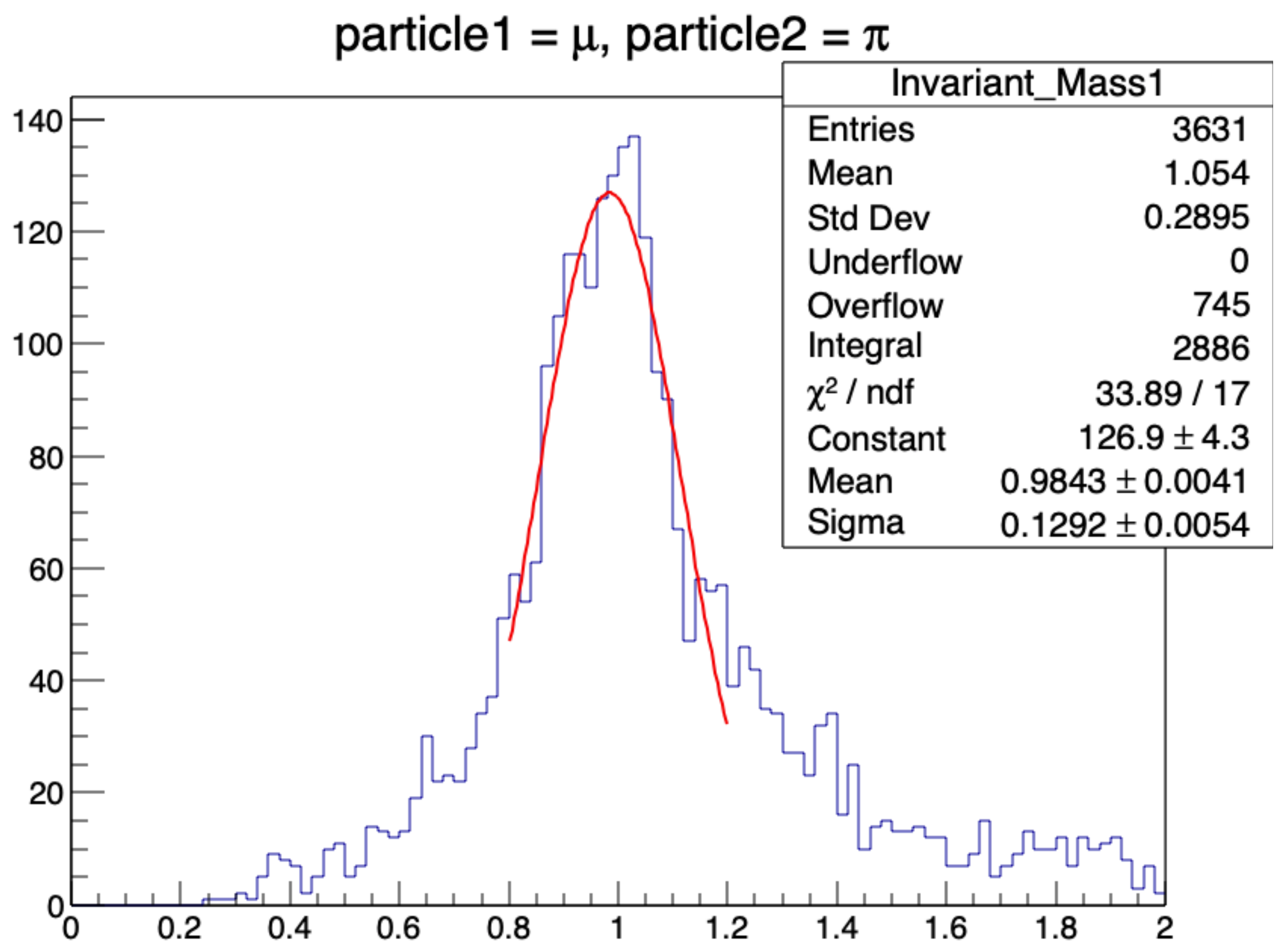
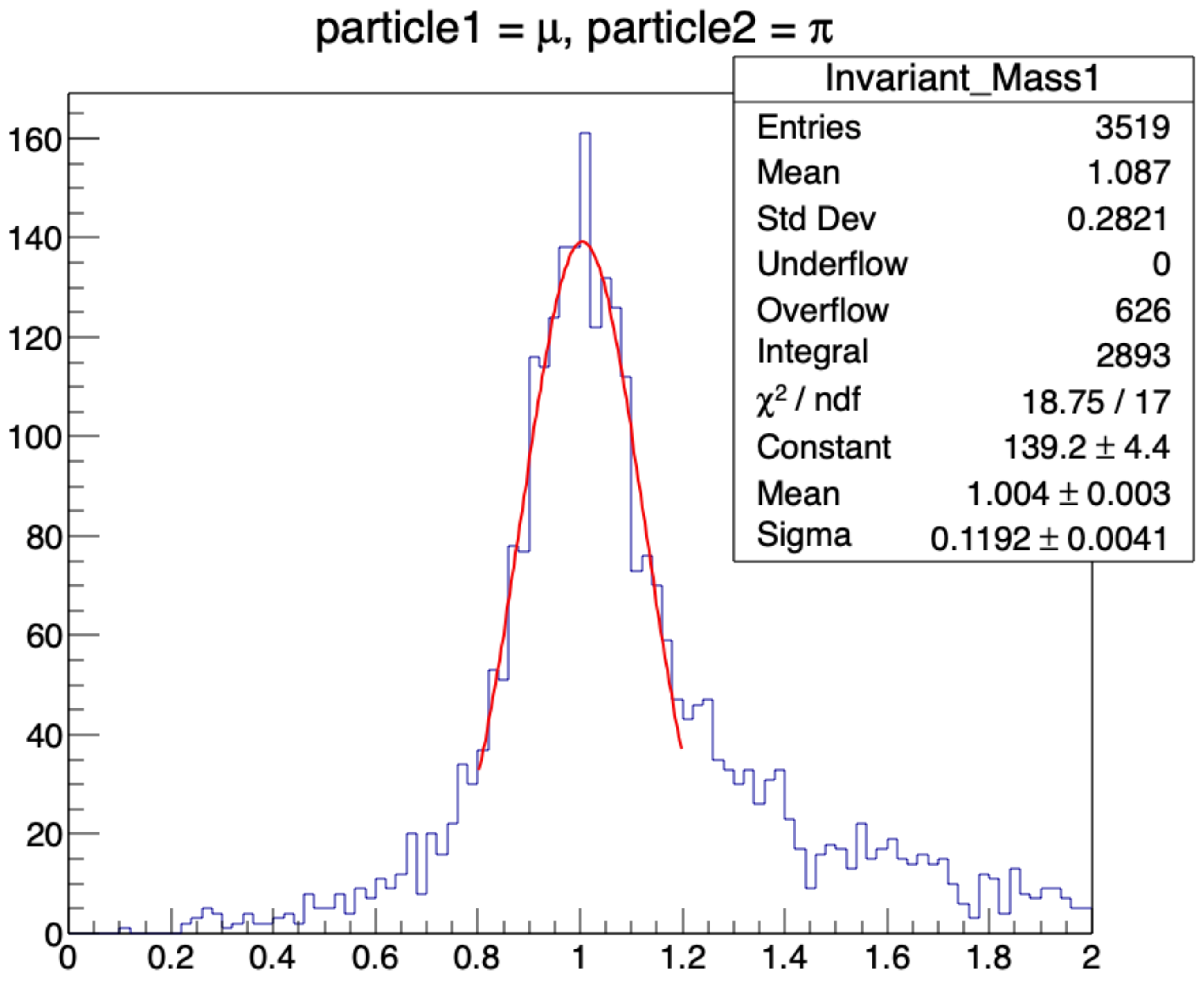
Forward



Backward







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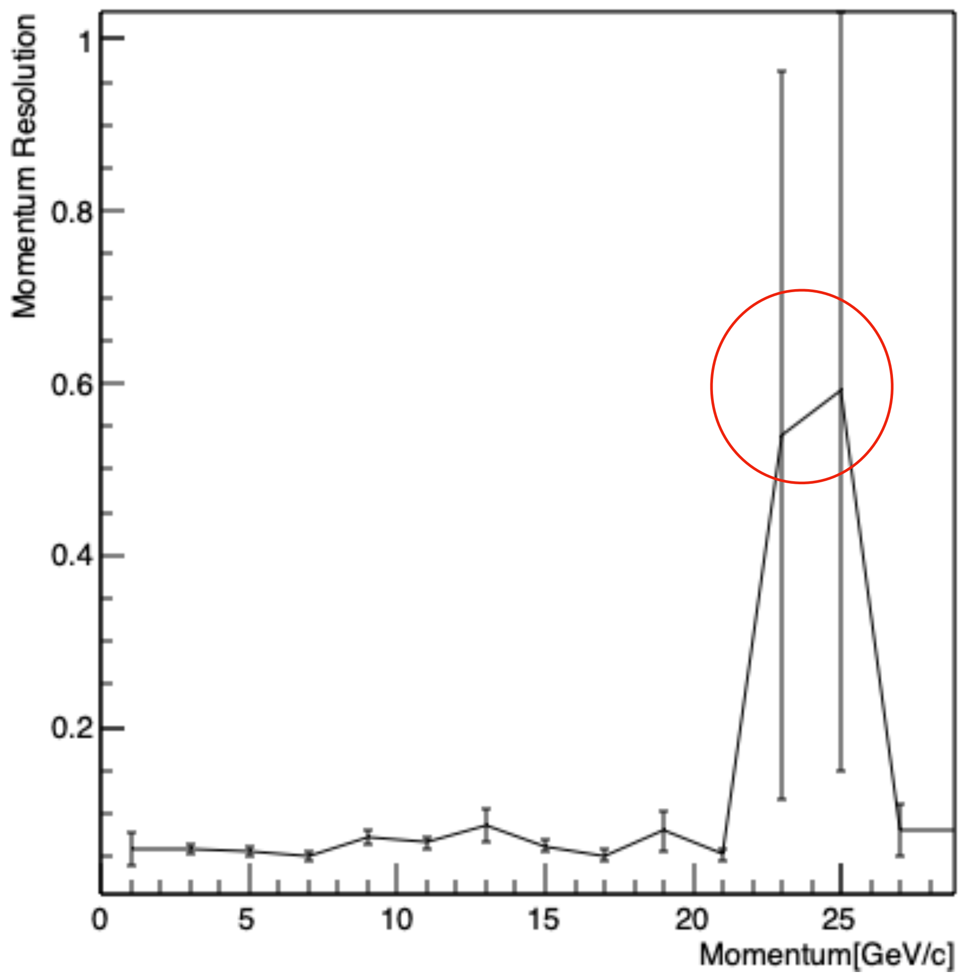
Improvements

- Backward Kalman direction implemented, in this case backward is more efficient: the initial hit is found easier and more precise (MCS not messing with the hits much)
- Multiple scattering has been added (changing the resolution by 0.1%)
- For better precision, external helical fit has been used (hits are coming from Kalman Filter, the used fit is the external one)



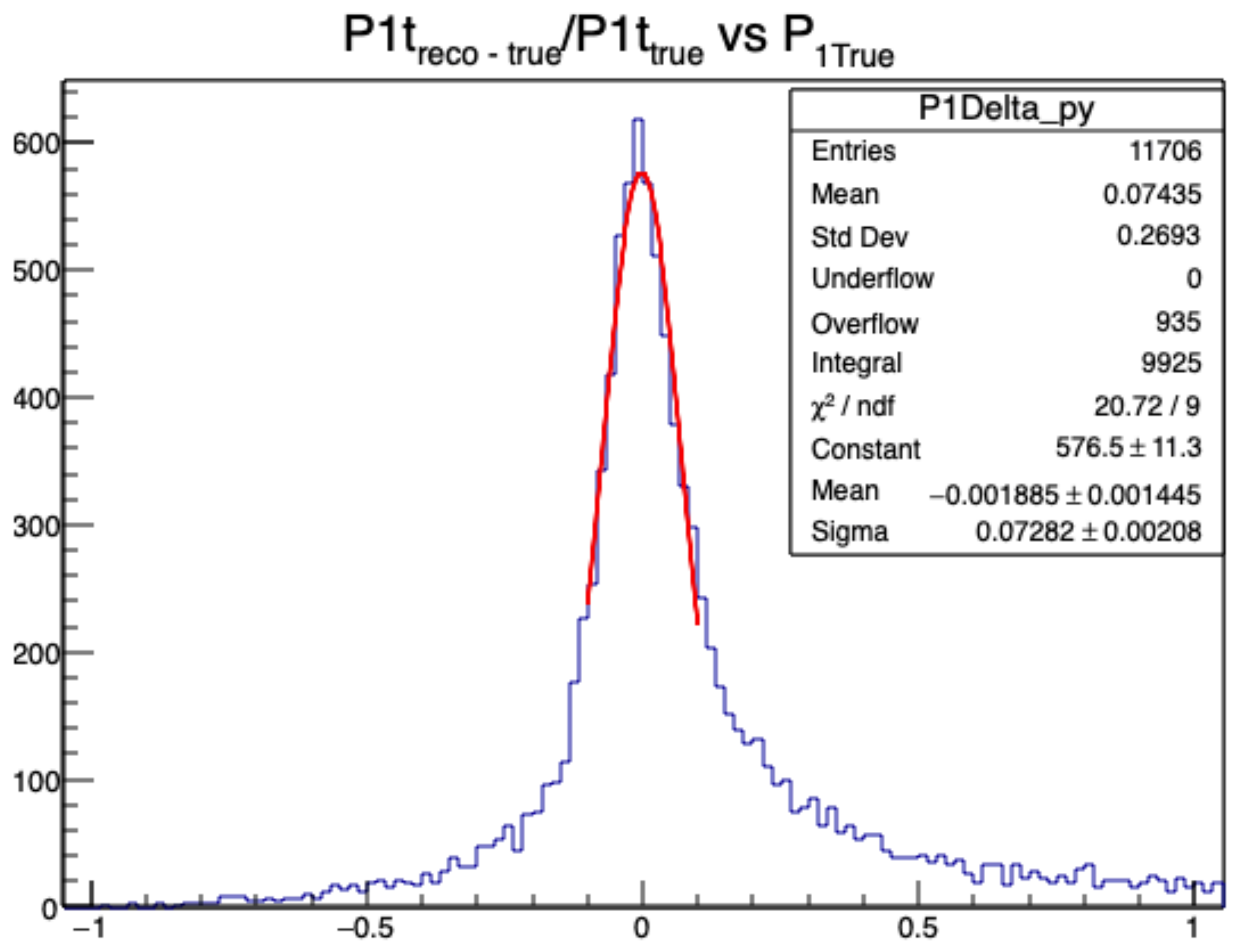
Items to have an eye on:

- Invariant Mass resolution
- Momentum resolution
- Kalman Filter parameters (Pull plots)
- Goodness of the fit (χ^2)

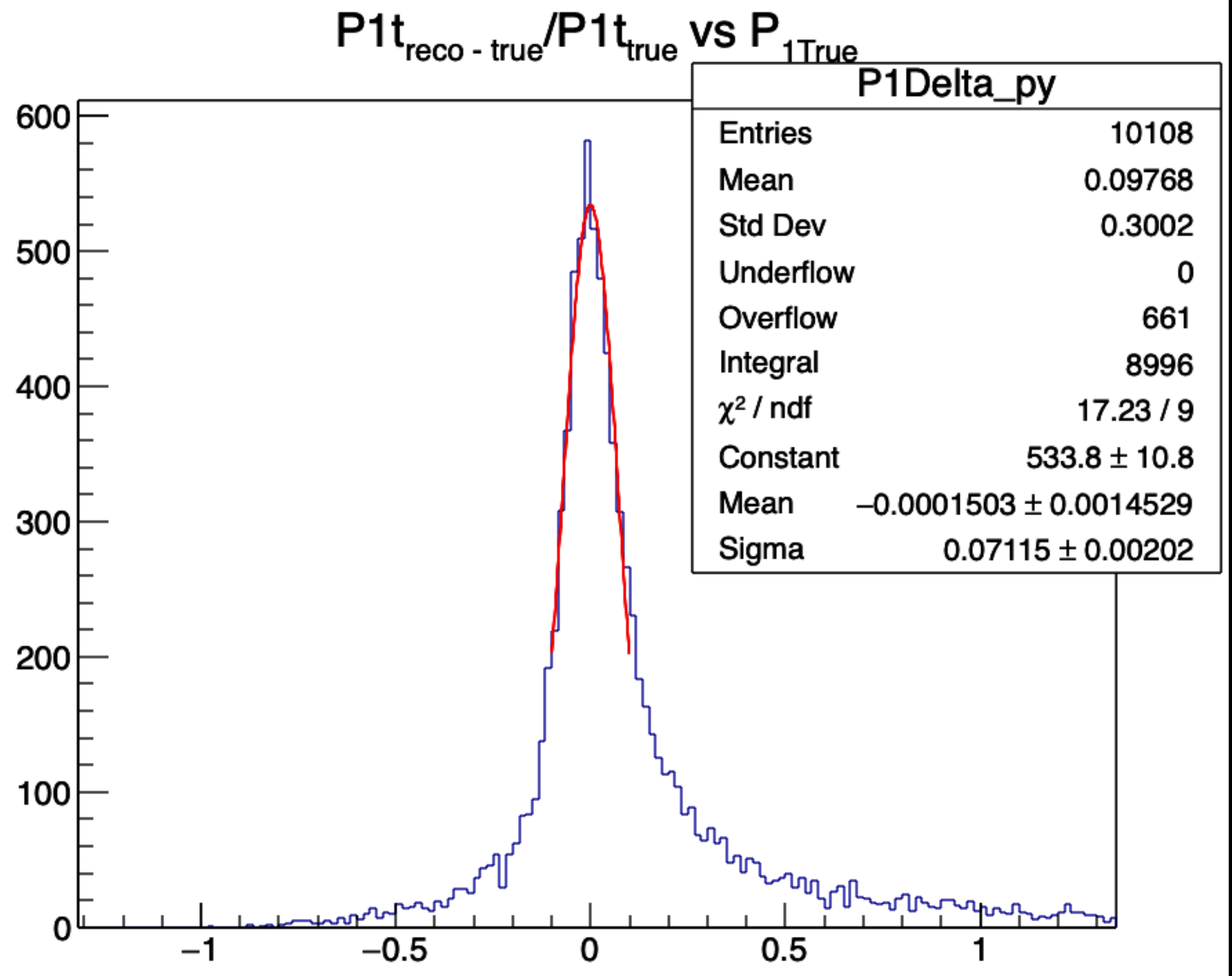
Procedure:

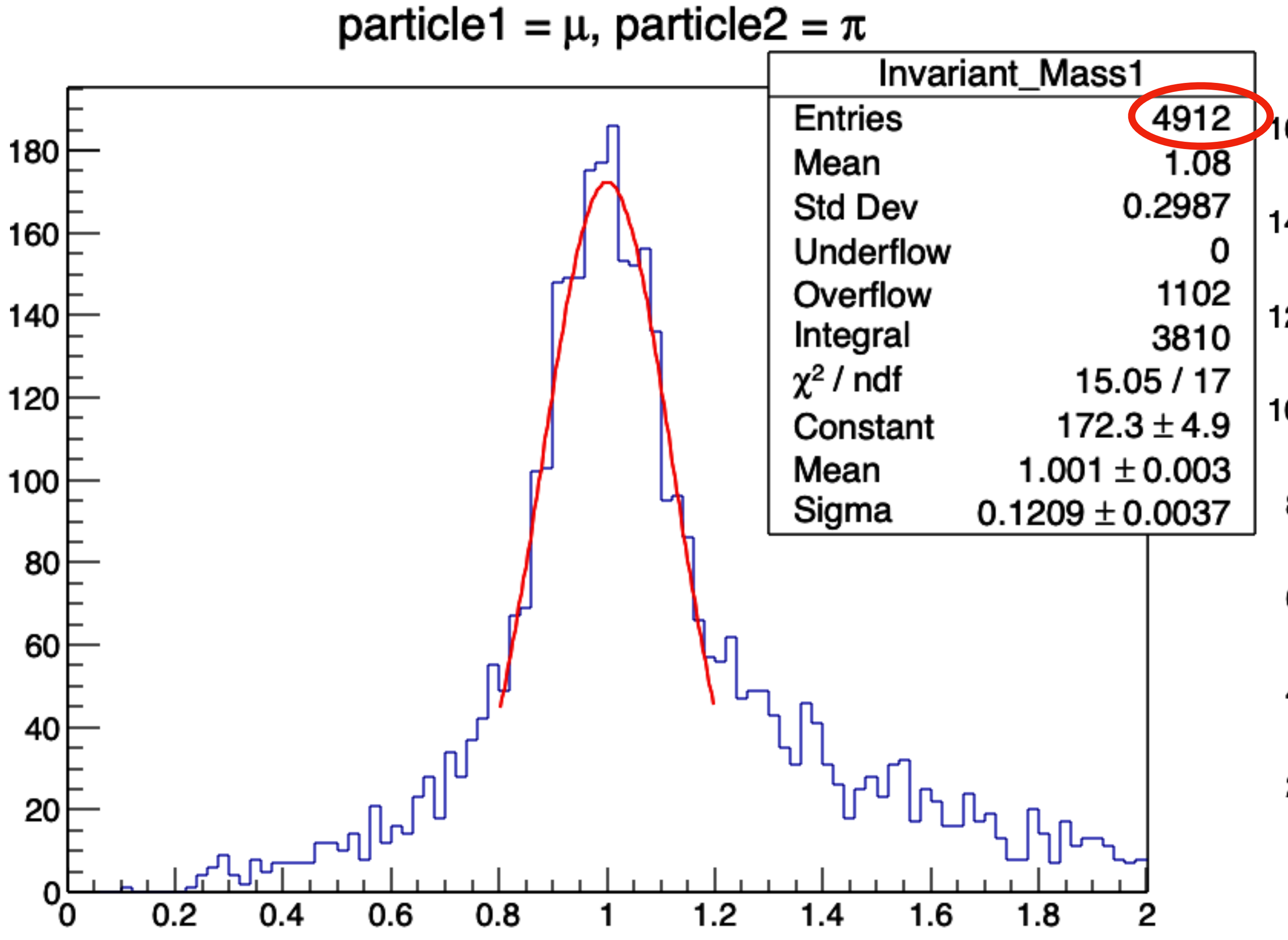
- Kalman Filter
  - Forward/Backward Kalman and smoothing.
    - External helical fit.
    - Reco tracks:
      - A. Choosing either forward or backward as Reco tracks.
      - B. Matching the forward/backward Reco tracks (>=90% shared hits), choosing the right combo for the final Reco track collection: Matched-> minChi2/Backward, Non-Matched->Both
- Matching the Reco and the True.
- Momentum resolution, Invariant mass resolution, Pull plots

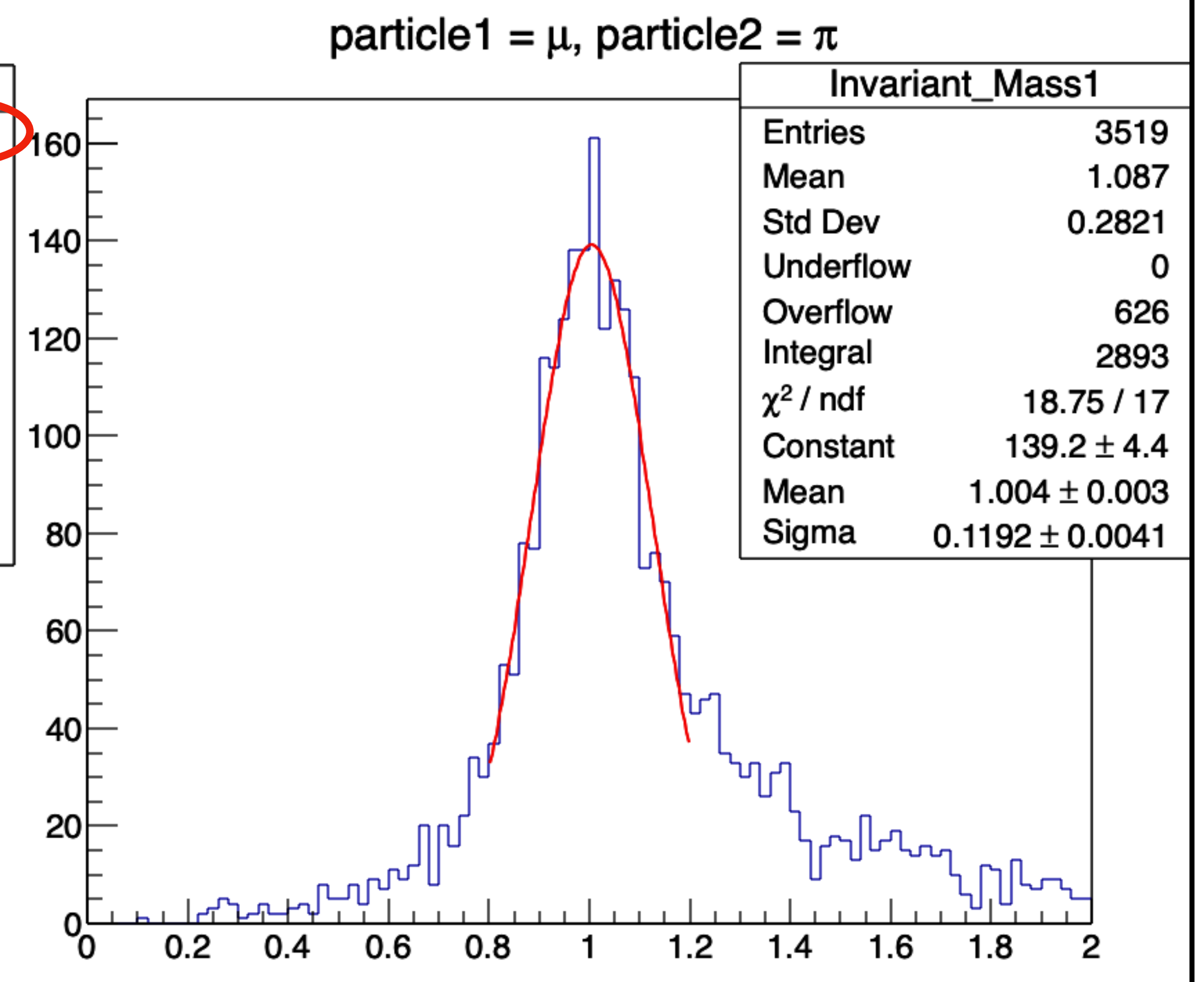
Merged



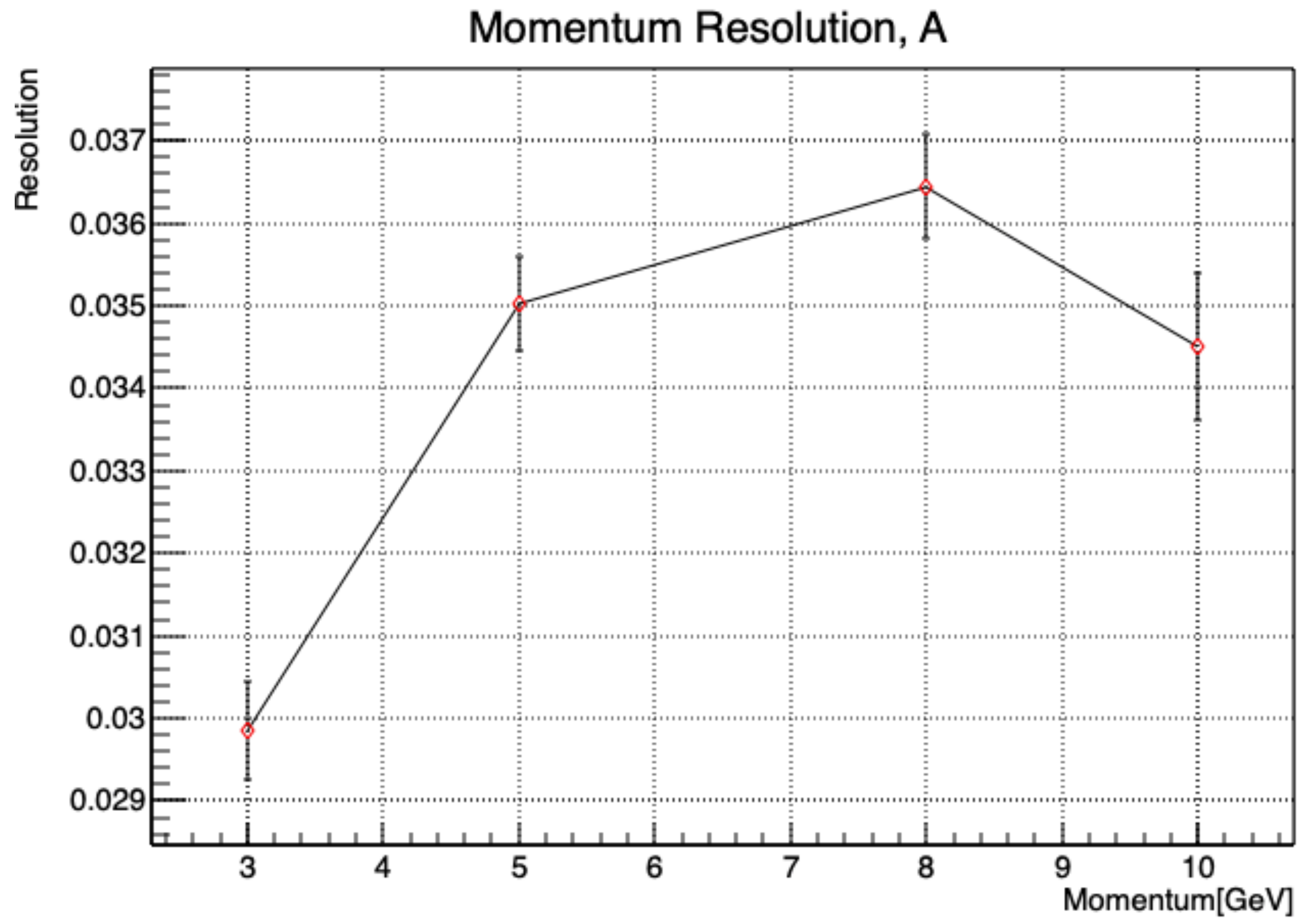
Backward



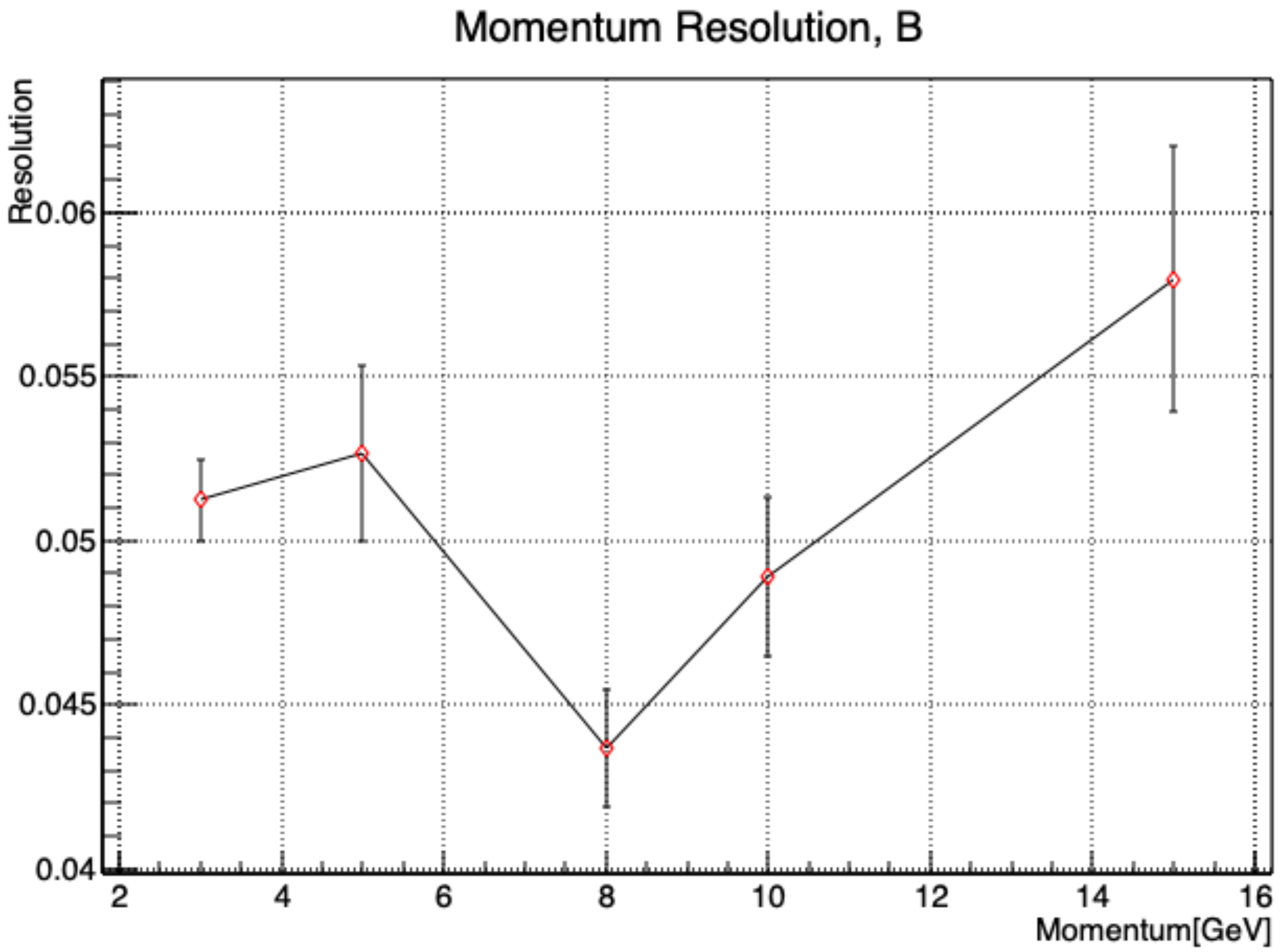


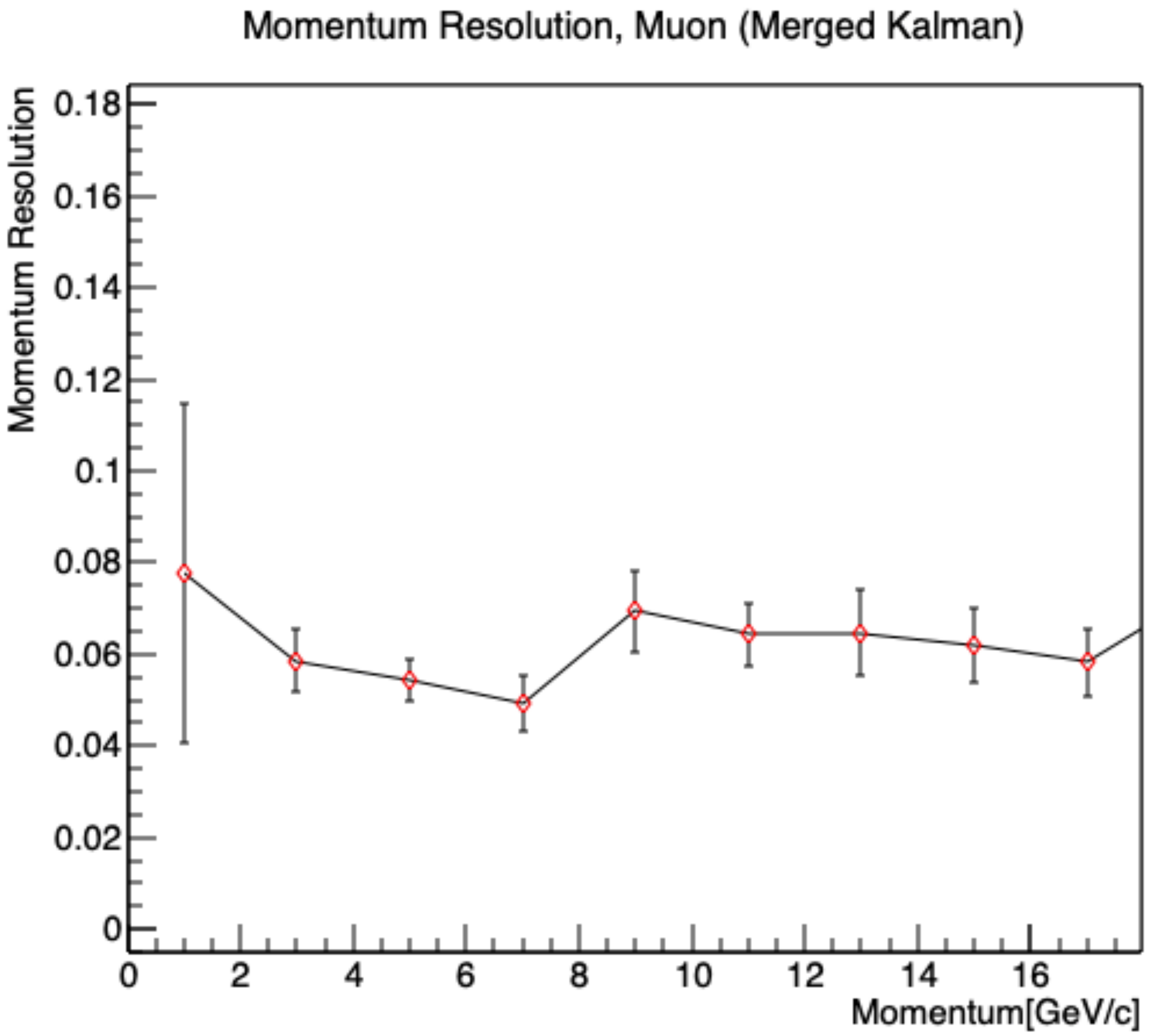


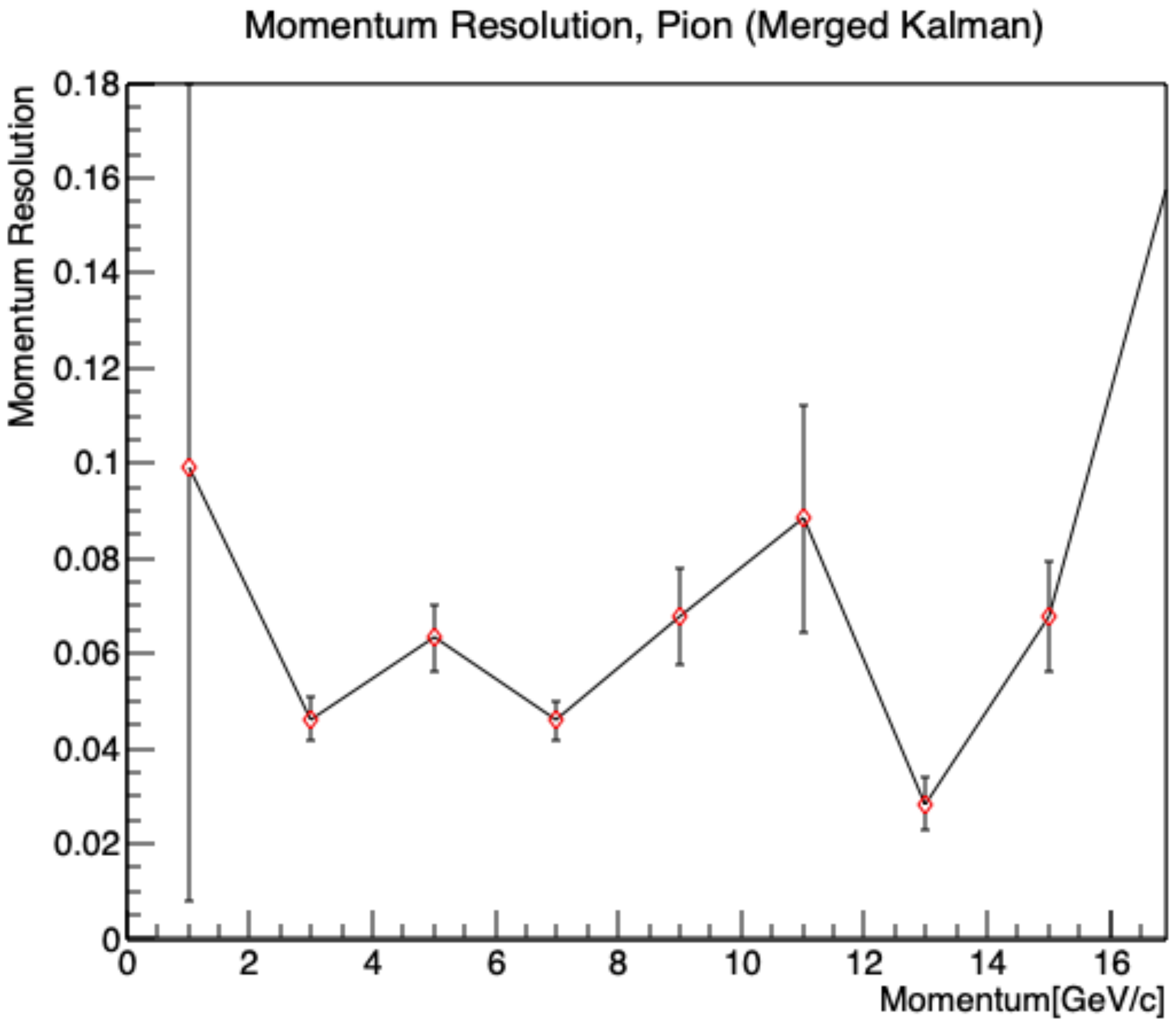
Kalman Filter, Resolution Comparison



- **Samples**
  A. Monochromatic, simple single muon: fixed point, fixed direction (horizontal)
  B. My event-like muons (Cylindrical distribution, comparable angle to my sample)
  C. HNL sample

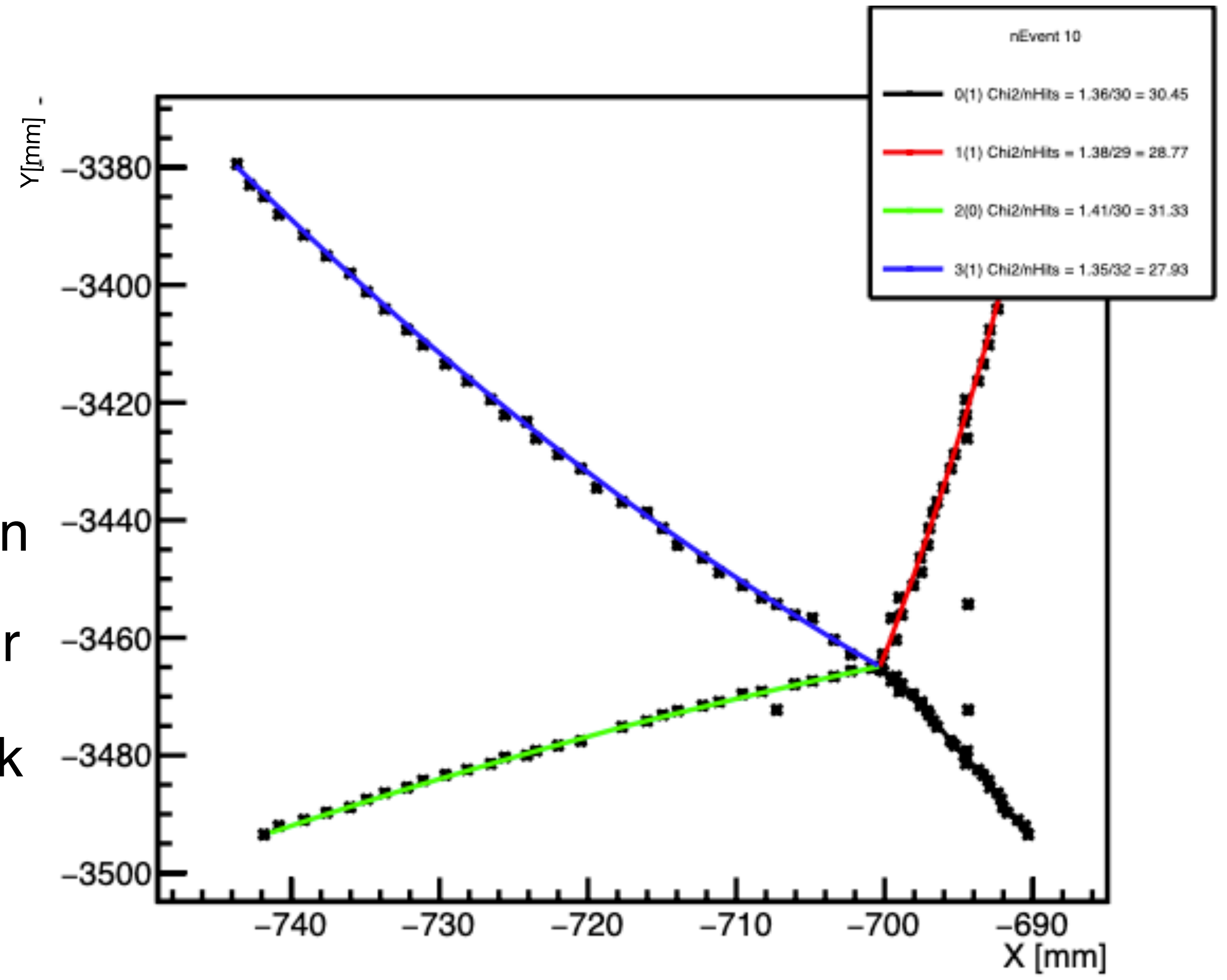


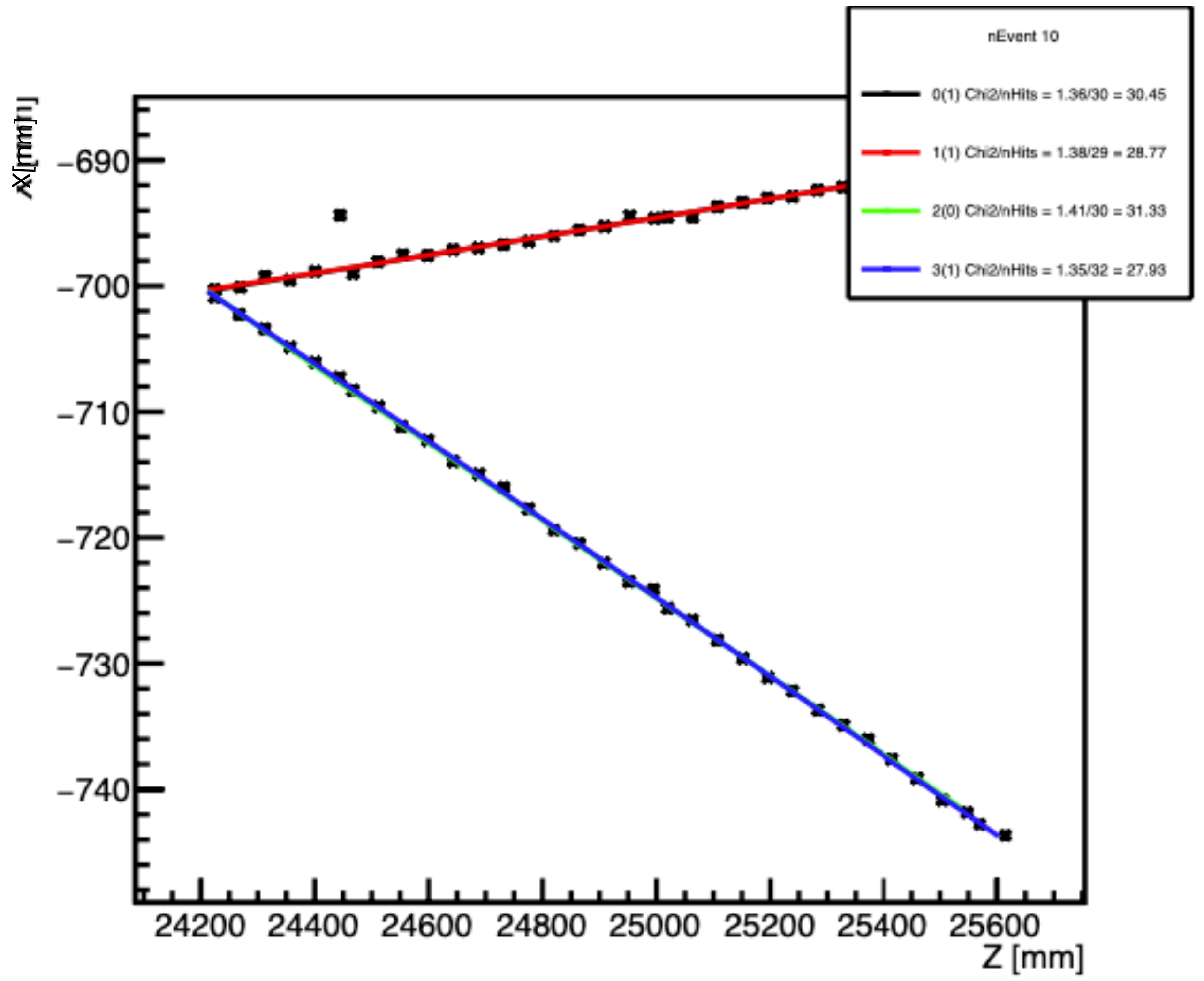


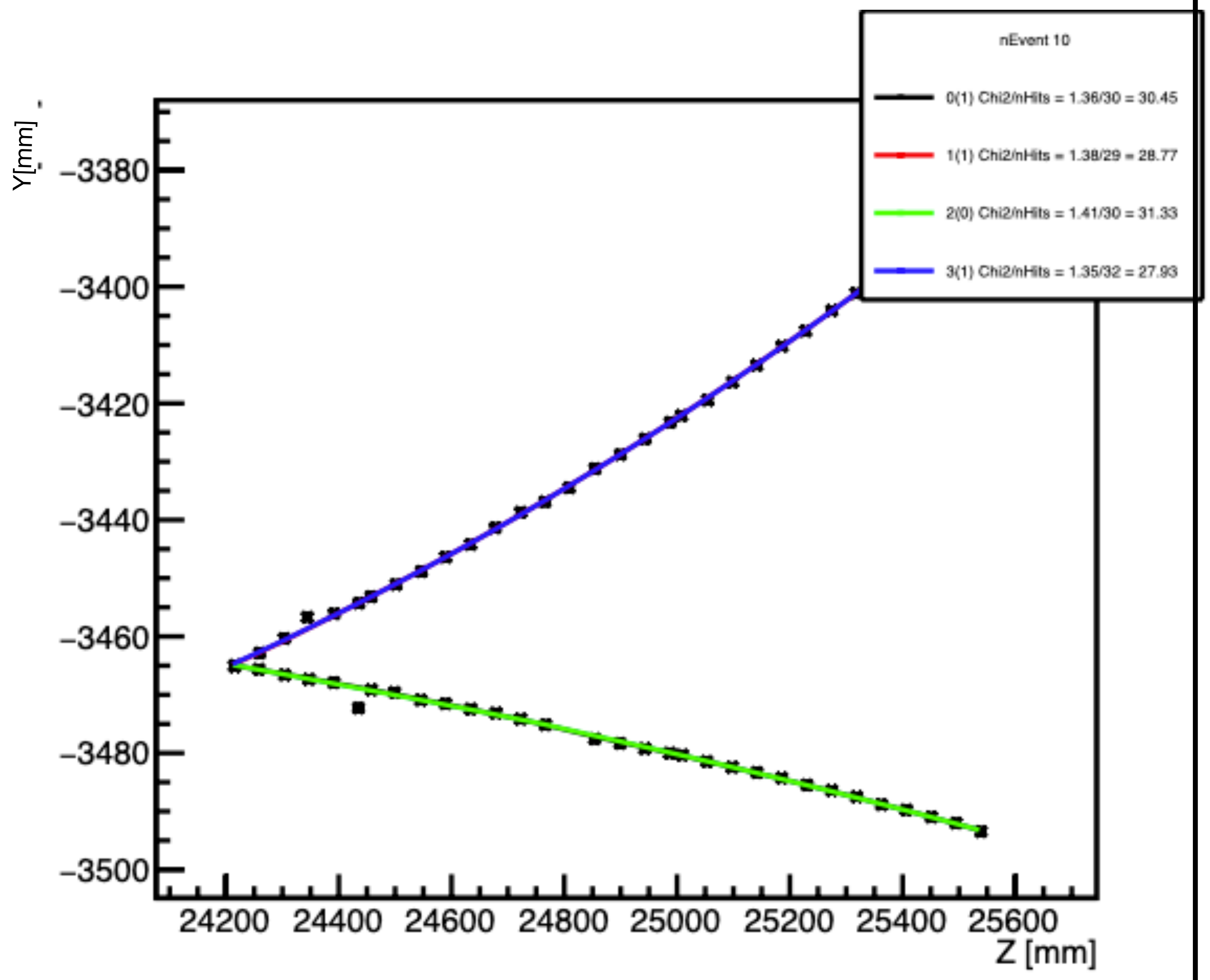


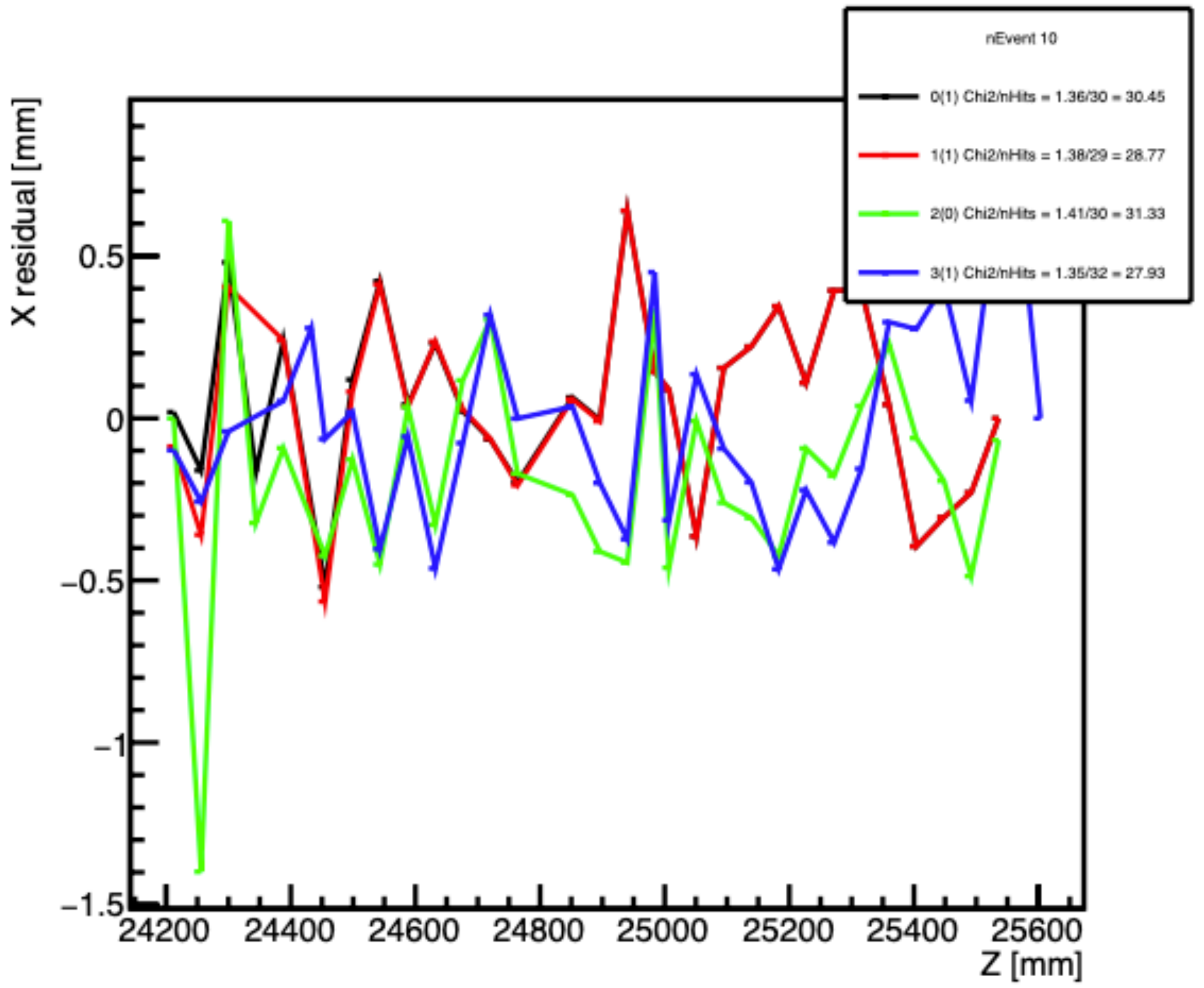
Kalman Filter, GEANT4 MC, Event Display

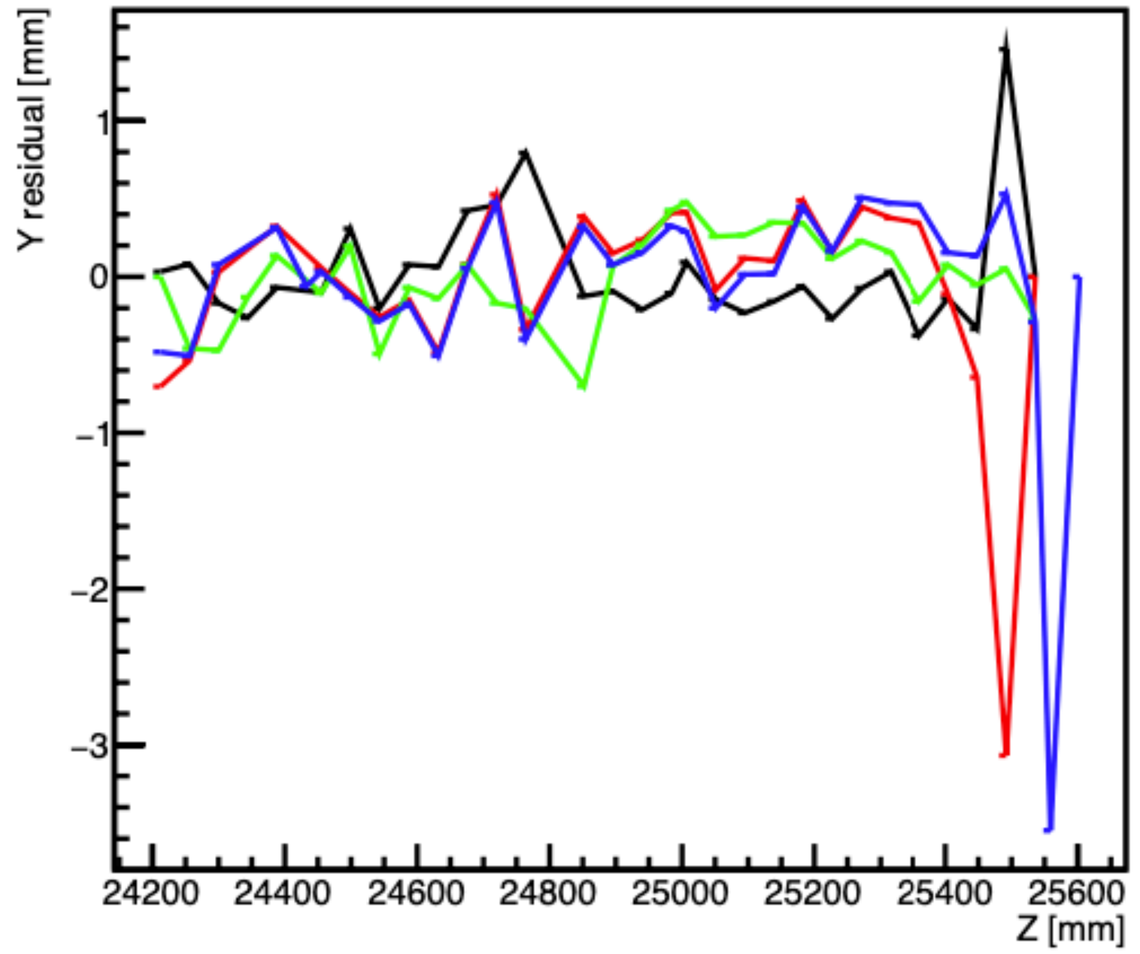
- Ignoring MC truth matching
- The hits are coming from the digitization and the solid lines are the Kalman Filter
- The ghosts usually are not back to back (potential discriminant for this channel)
- The χ^2 :
  - Point rejection chi2 (Update stage) ~ threshold 300
  - The external fit chi2 for the tracks
- The bottom graphs show the spacial residual fluctuations

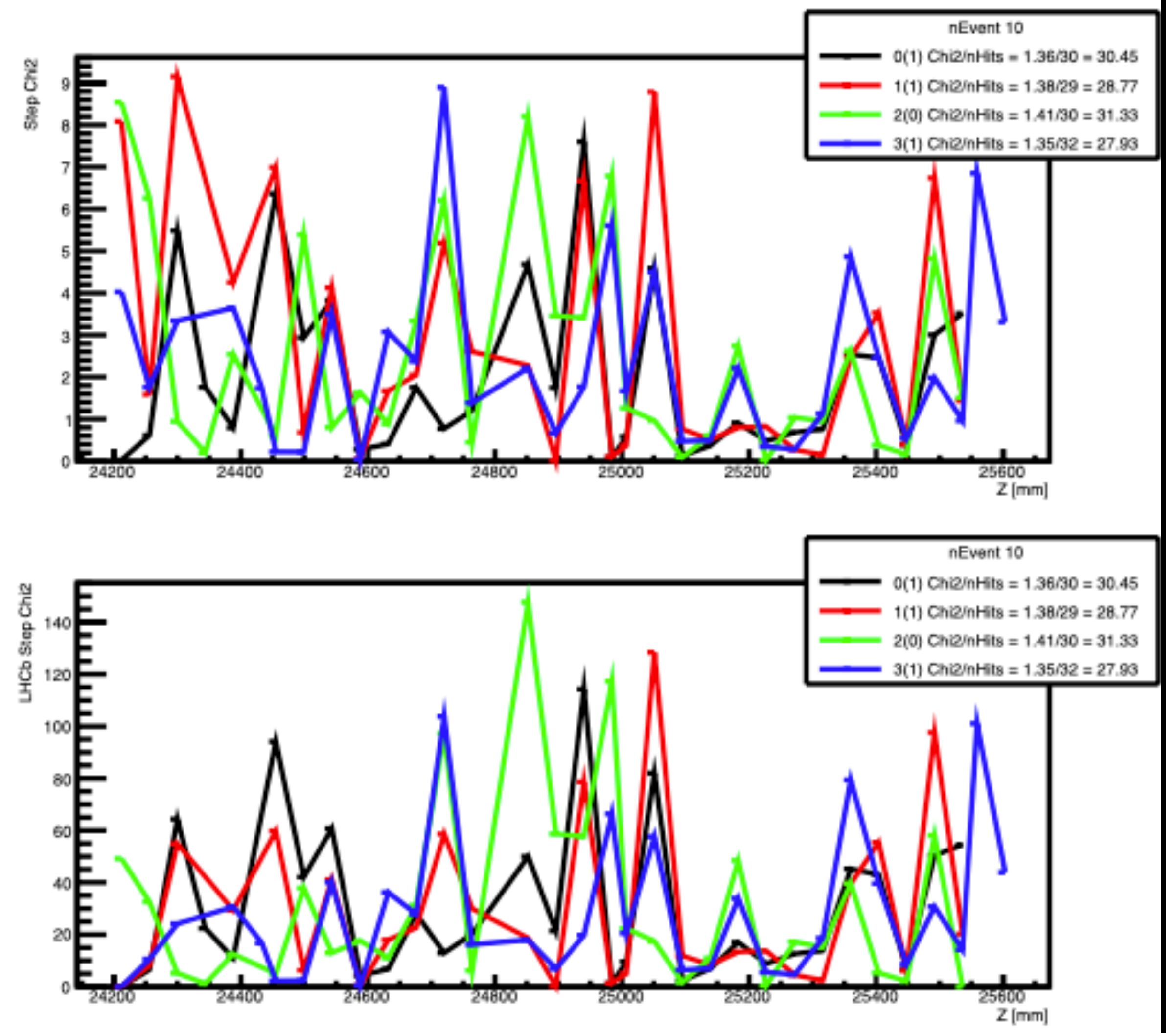






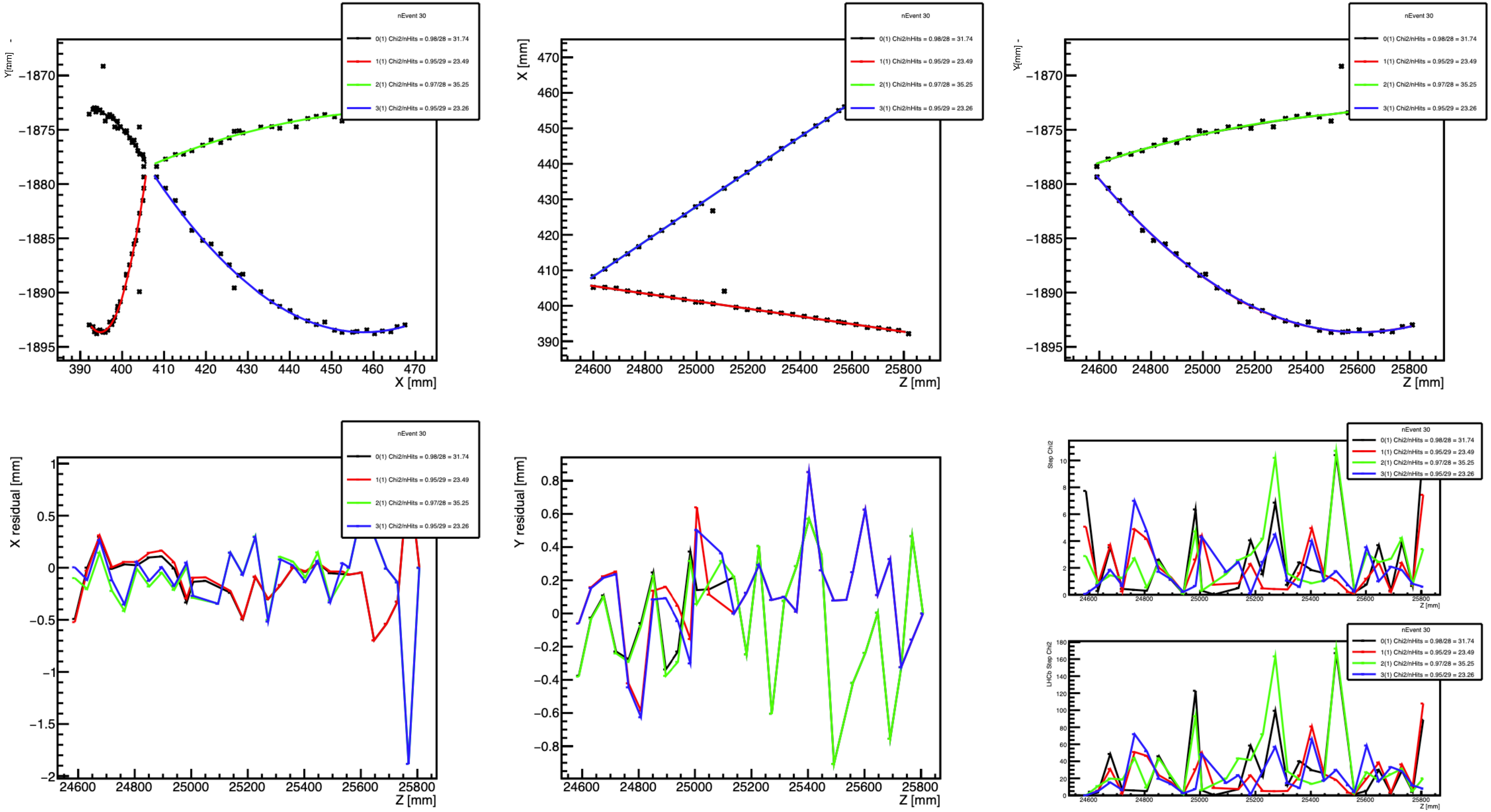




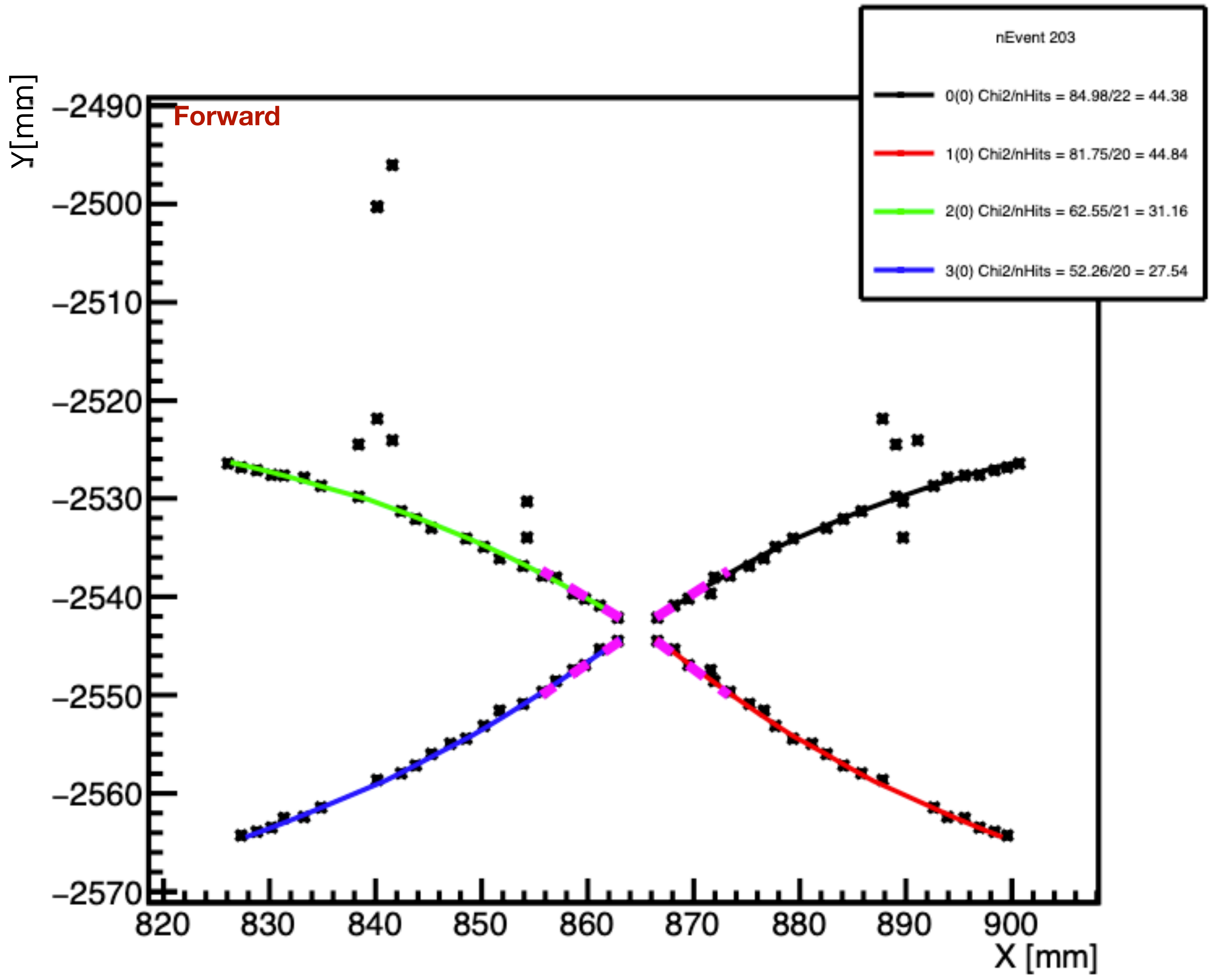


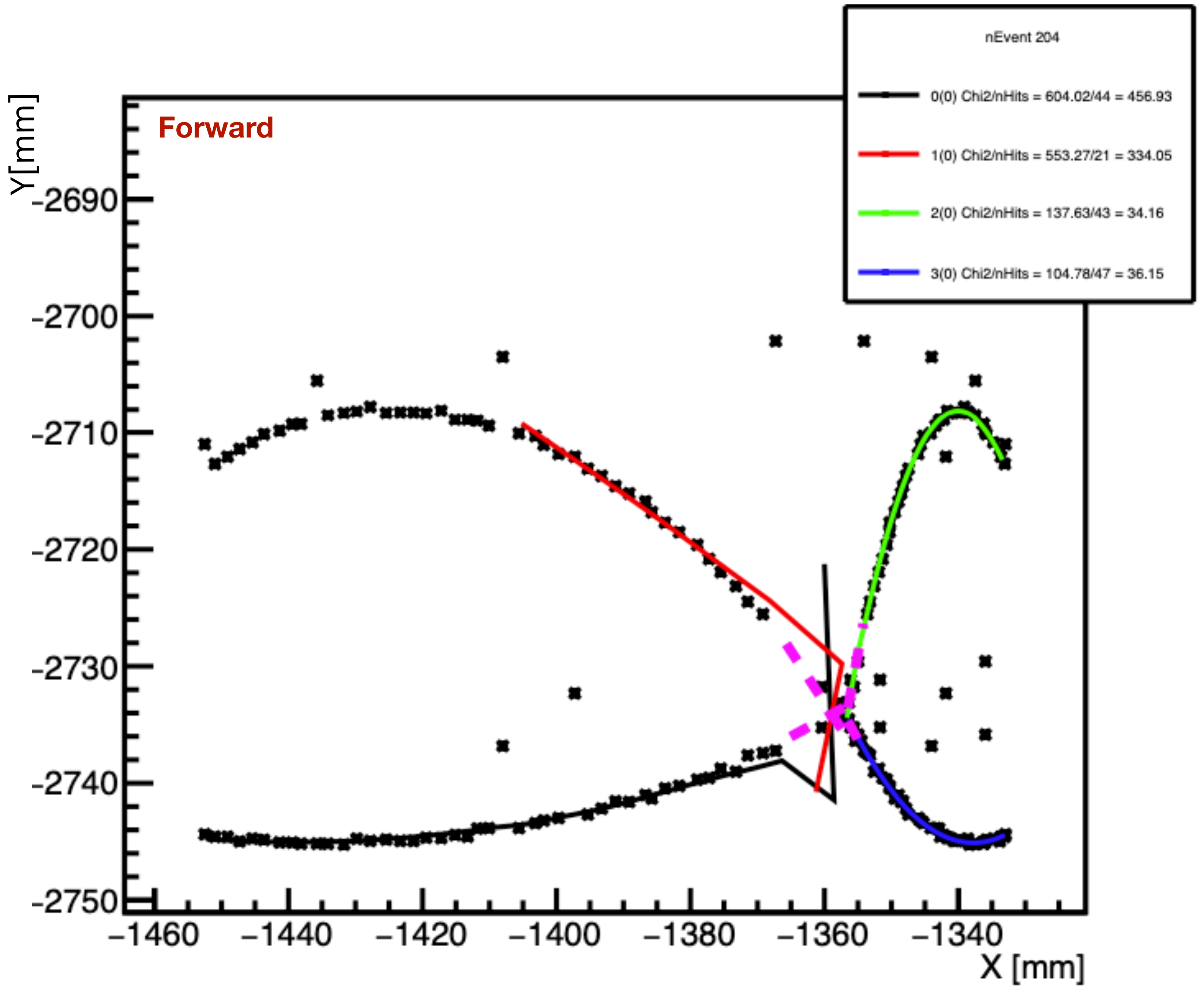
Point rejection χ^2

Kalman Filter, GEANT4 MC, Event Display



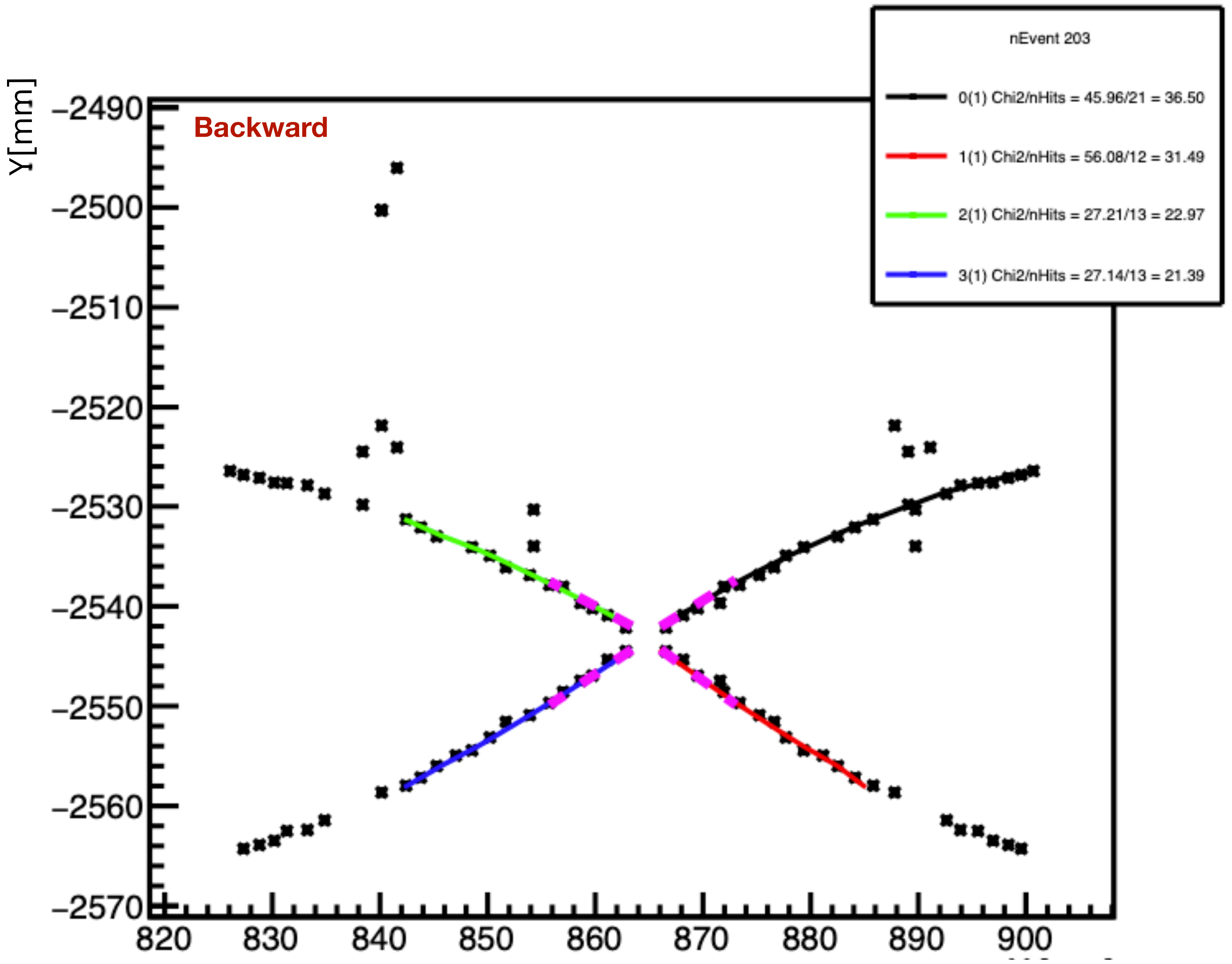
Kalman Events

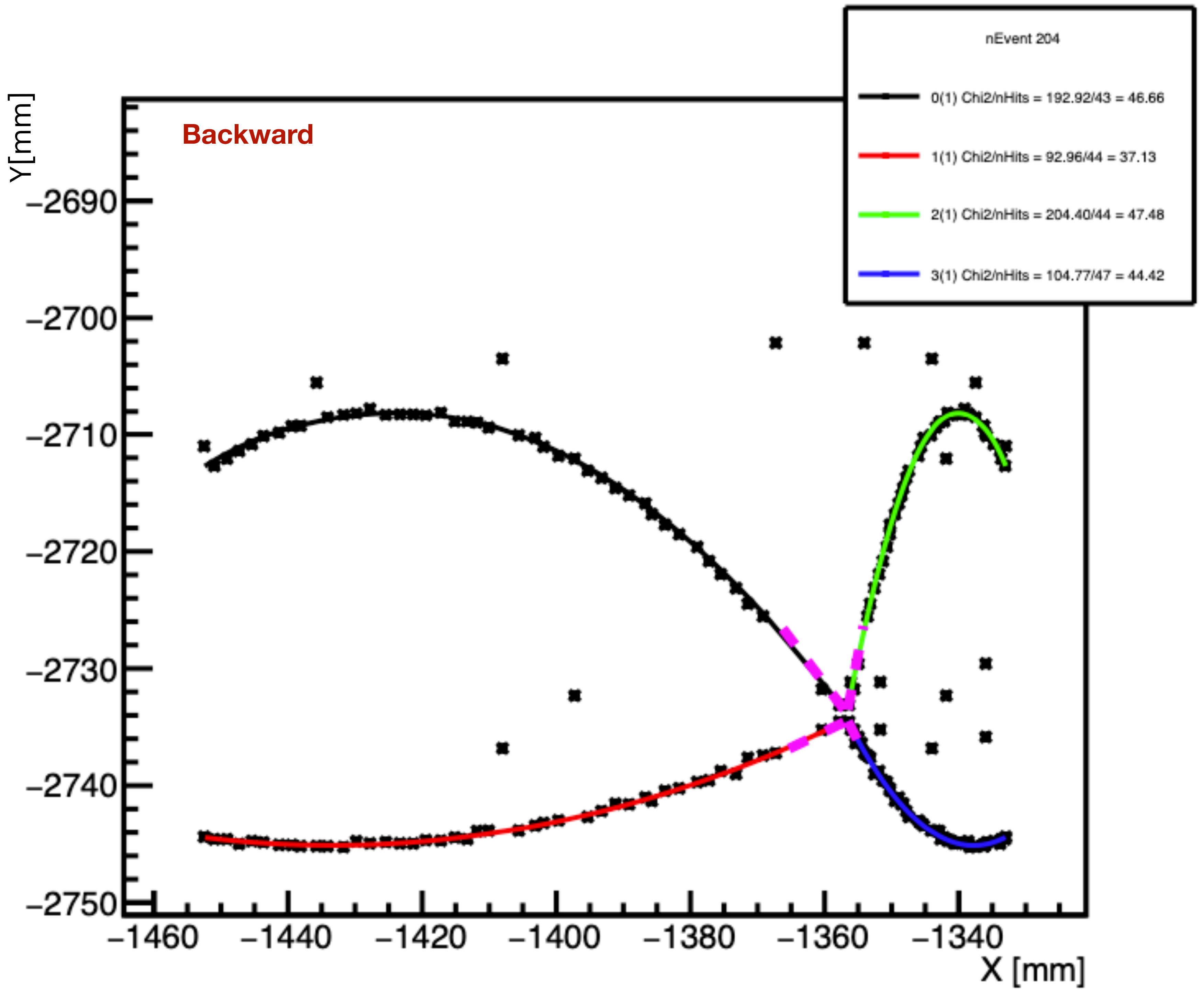




Kalman Event Selection

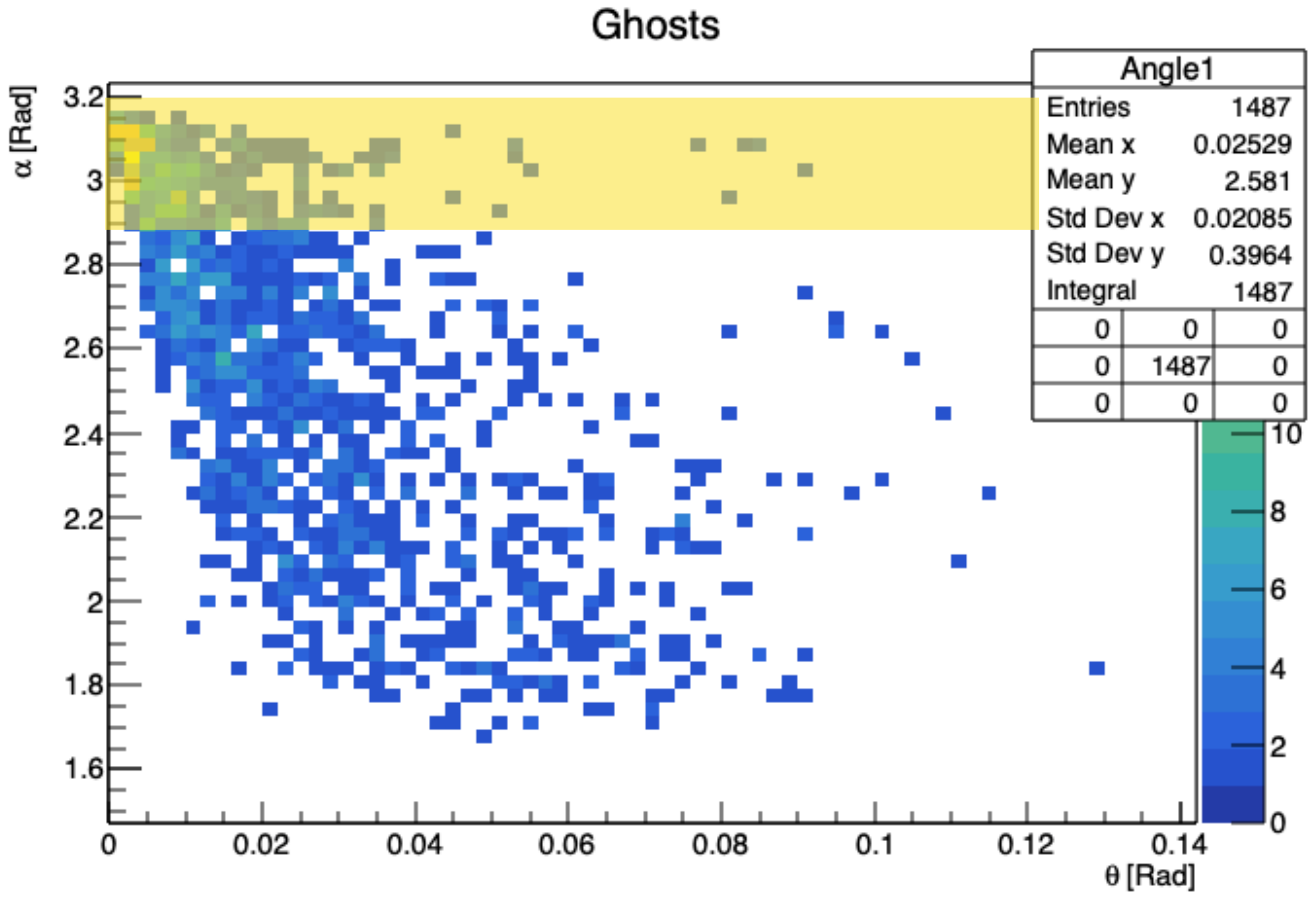
- **For/Backward tracks**
  - The more apart the hits the better the track recognition
  - Statistically, the backward Kalman is more efficient
- **Merged tracks**
  - Enhancing the InvarMass resolution
  - Recovering the events failed in either of For/Backward process
  - Saving the better reconstructed event
  - Shared hits are checked to make sure of no double counting
- **Preliminary Efficiency estimate**
  - FidCut is done:
    - Extrapolation of the track up to the exiting point, count the # plane
    - Number of planes = 6
  - Single track efficiency ~ 70%
  - Event (pair of tracks with a vertex< 1mm) efficiency ~ 80%
  - Still to investigate the apparent statistical correlation

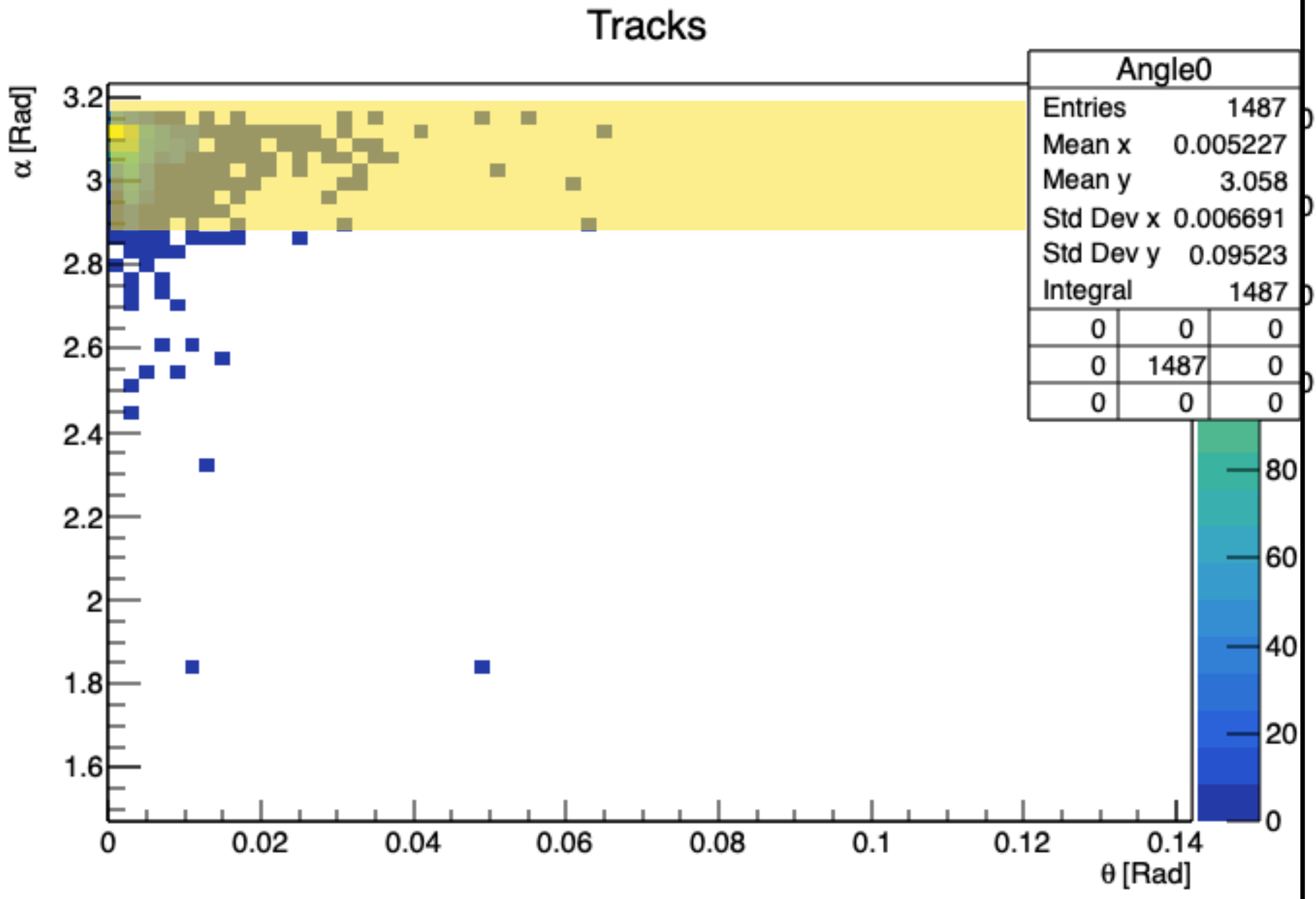


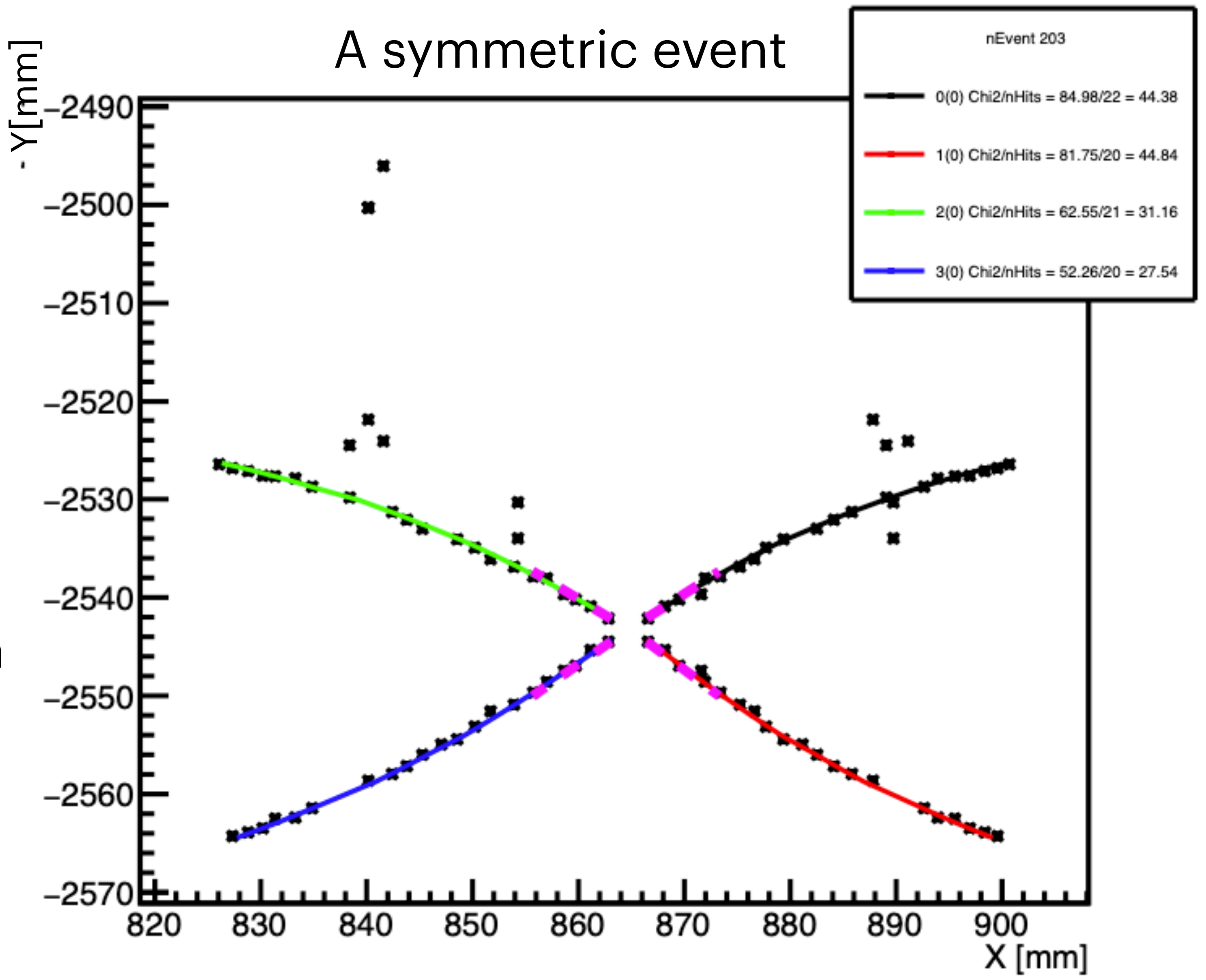


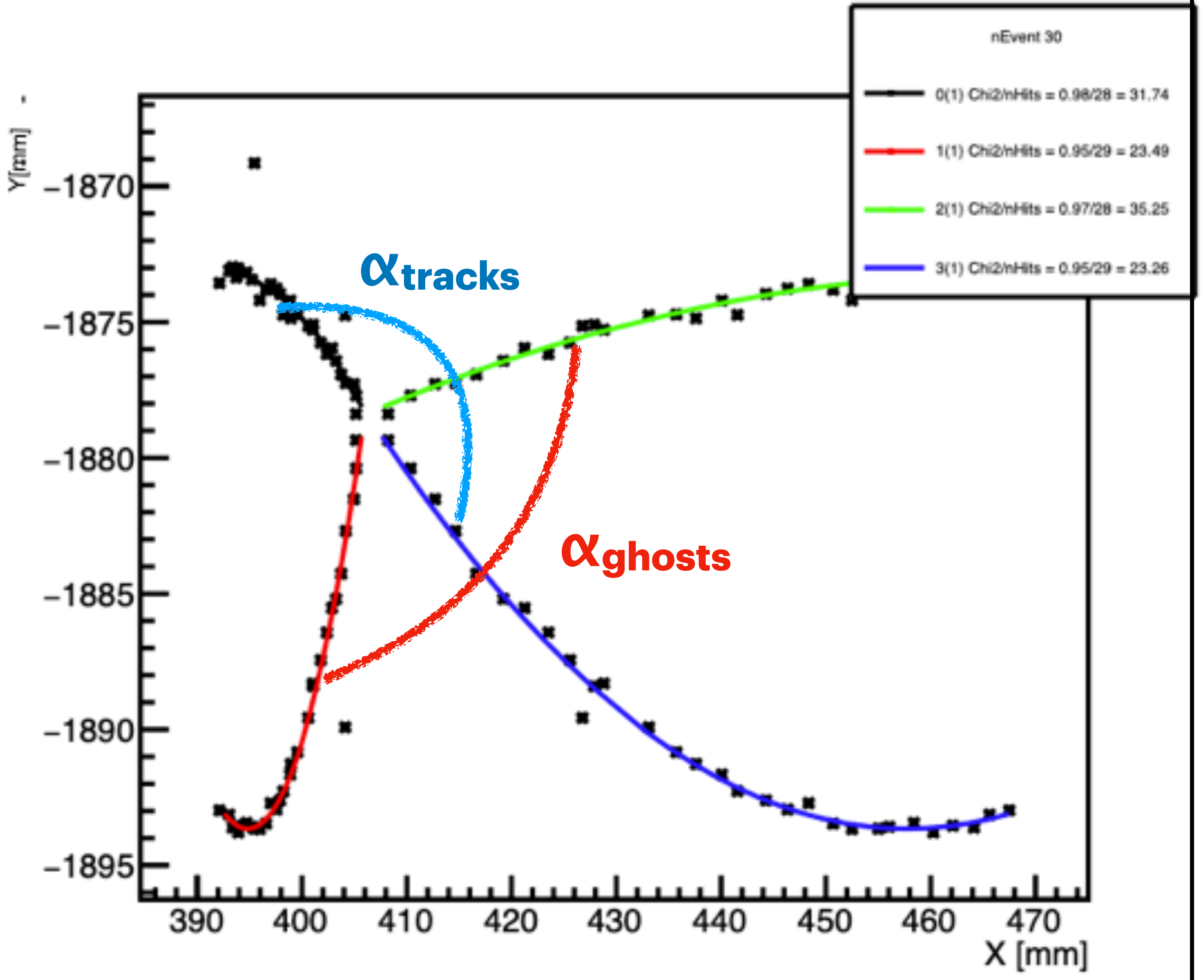
Events Selection

- **Production cut**
  - Cubic FidVol cut to mad-Dump output
- **Events Kinematic**
  - Heavy Neutrino: High P, mostly with low theta—>back to back (XY) 2-body decay
- **Treatment for Ghosts**
  - Opposite charges and tracks in opposite quadrants XY.
  - Alpha angle in XY between the ghosts or the tracks
  - Theta is the angle of HNL with respect to the z-axis
  - Alpha is geometrically correlated with theta
  - A cut can be made for selecting the tracks from ghosts -> theta < 0.02, alpha > 2.9
    - Removes most of the ghosts contaminating the signal
    - To be optimized based on Signal/Background(regular neutrino interactions)
    - The remnant ghosts:
      - No effect on the resolution (very symmetric events)
      - Compensated by a correction factor
- **Particle ID**
  - Not necessary at this stage
    - Swapping pi-mu has negligible effect on Invariant mass resolution
- **Background**
  - Working on generating a neutrino beam-like sample with the tracker geometry i'm using









Summary and Outlook

- **Kalman Filter Implementation**
  - Toy (Uniform B, Const δz, (x,y) measurement based on analytical function, 95% off, 0.1 mm smearing)
  - Geant4 (Uniform B , Geometry “nd_hall_kloe_sttonly.gdml”, XXYY, XXYYXX for δz, separate X, Y measurement, 200 µm smearing)
- **Kalman Selection**
  - Heavy Neutrino: High P, mostly with low theta—>back to back (XY) 2-body decay
  - **Ghosts treatment**
    - Angle cut in XY plane combined with the angle cut on theta
      - Removes most of the ghosts contaminating the signal
      - To be optimized based on s/b
      - The remnant ghosts:
        - No effect on the resolution (very symmetric events)
        - Compensated by a correction factor
- **Event Selection and Efficiency**
  - FidCut based on track extrapolation to the detectors walls (passing >=6 planes)
  - Efficiency (preliminary) of single track ~ of an event (pair with a vertex < 1mm)
  - **Particle ID**
      - Not needed at this stage-> highly boosted event
- **Background**
  - Working on generating a neutrino beam-like sample with the tracker geometry i’m using
  - More accurate efficiency can be estimated after the bg sample is ready

- **To be done**
  - Further Investigation on the efficiency of single and paired tracks
  - Run background and signal to assess “final” sensitivity
  - Kalman Filter optimization

THANKS!