Proton reconstruction at Mu2e

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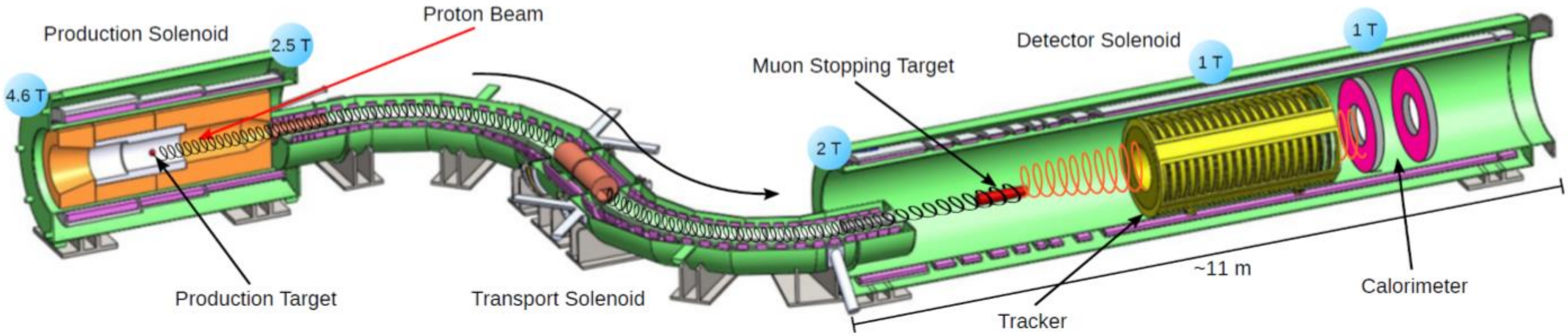
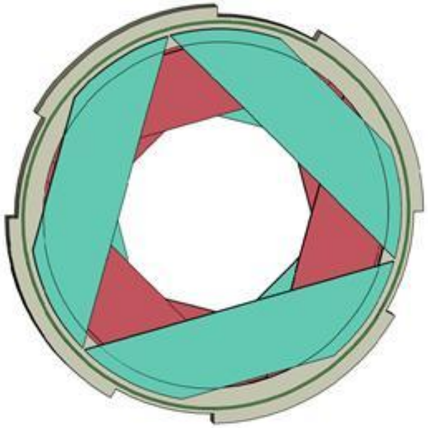
Mu2e Experiment



Goal

Reduce the upper limit for the Charged Lepton Flavour Violation process: $\mu N \rightarrow eN$ with a Single Event Sensibility $< 2.5 \cdot 10^{-17}$

The Tracker

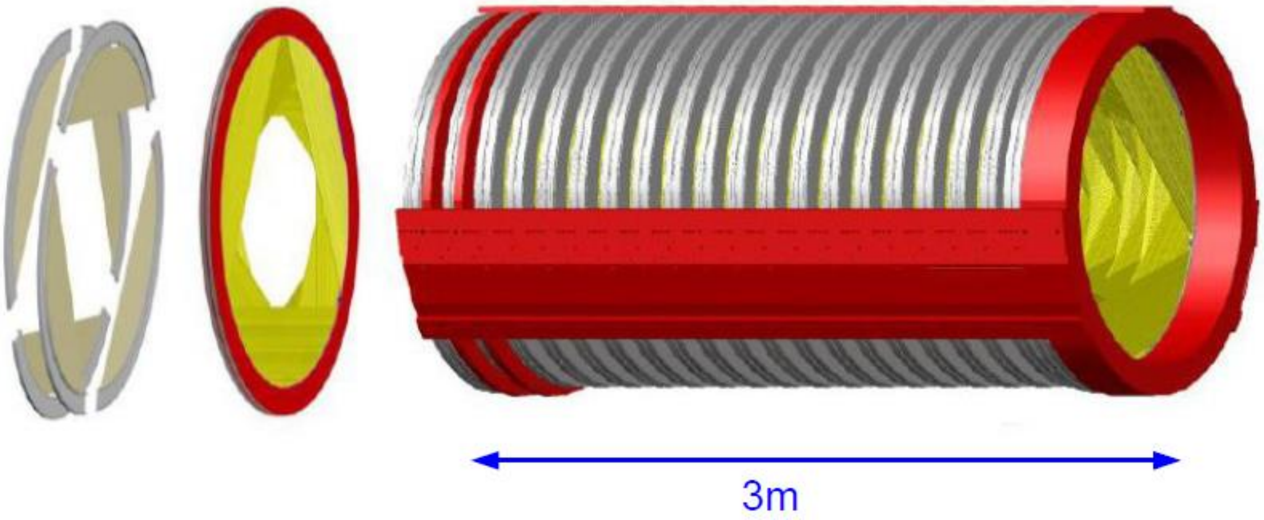


Structure

- 6 panels each plane, 2 planes each station, 18 stations in total
- Plane: 96 straw tubes

Hits

- Straw hits
- Stereo hits

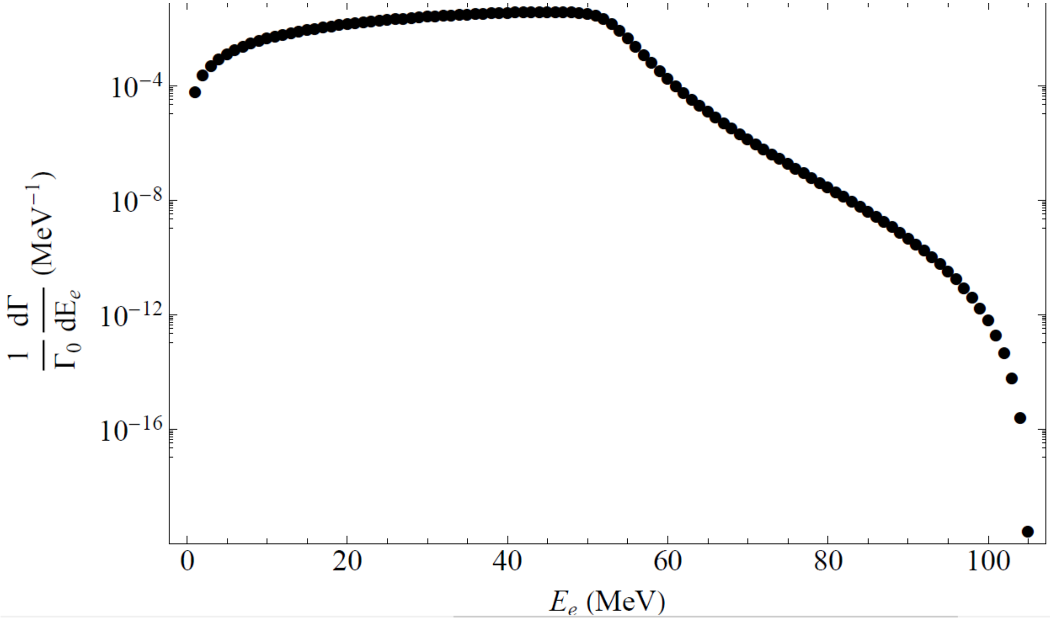


Muon Flux and Intensity fluctuations

- Fluctuations in muon flux >10% affect the sensitivity of the experiment
- Batch by batch fluctuations can reach 50-100%
- Using current method (germanium detector) is difficult to go under 10% of uncertainty

Monitor the flux:

- Need a high rate channel
- DIO electrons have a reconstruction rate of 4.6 Hz



impossible to monitor the flux batch by batch (ms time-scale)

Protons

Source

Nuclear disintegration after muon capture

Spectrum

Known with finite accuracy → mainly studied proton above 100 MeV

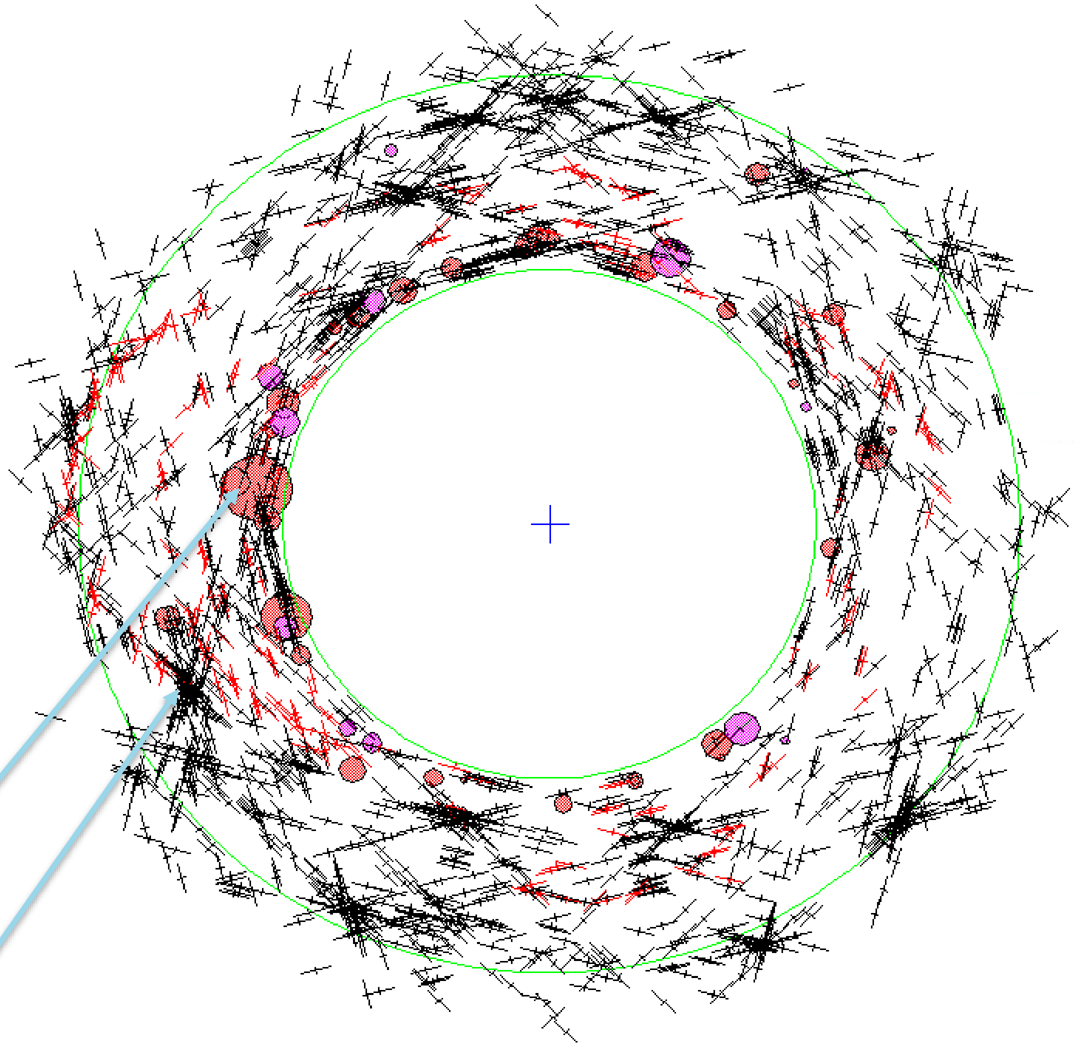
Signal Properties

- Low energy protons → non relativistic → high energy loss (Bethe-Block $1/\beta^2$ trend)
- Multiple scattering effect on trajectory
- large TOF
- No calorimeter information
- Delta-rays production

Event Reconstruction, full background

Full background simulation:

- (from MC-truth) proton generate hits
- High occupancy → It is not possible to immediately identify protons
- Protons tracks are not reconstructed

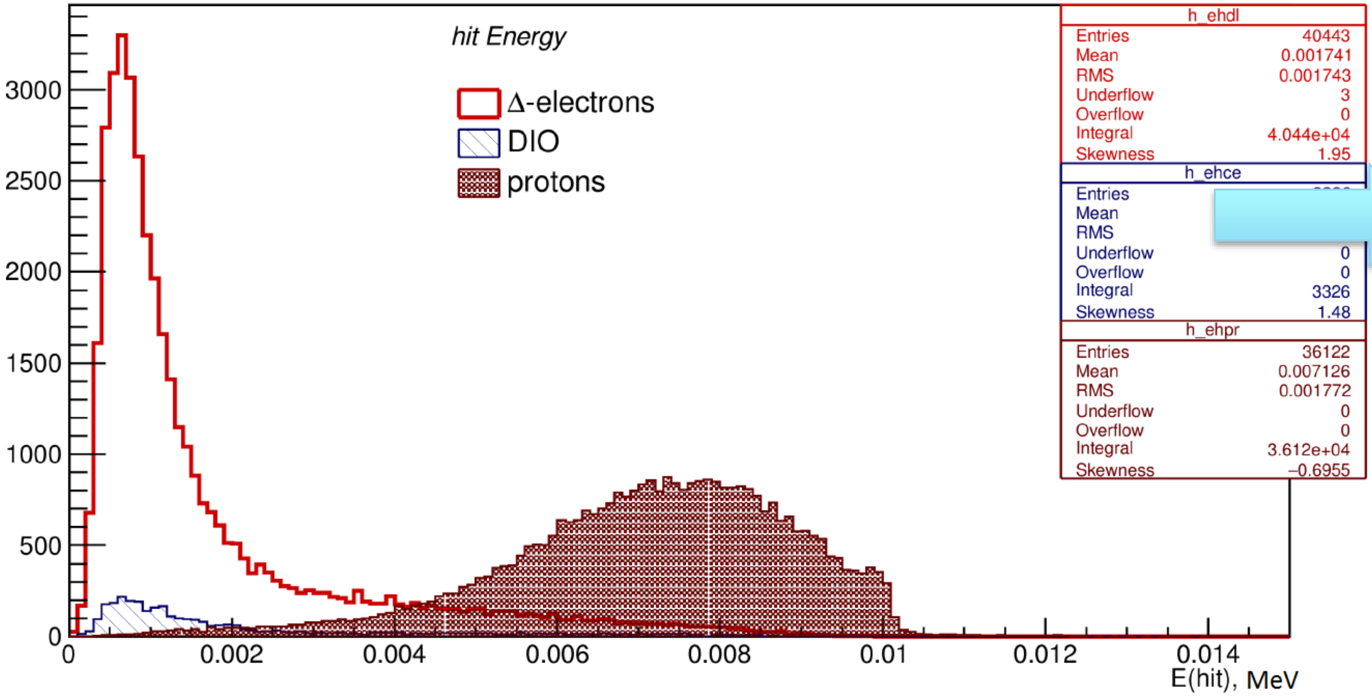


Calorimeter cluster

Delta ray

Event Reconstruction – Energy deposition

- By default energy range accepted is from 0 to 3.5 keV (per hits)
- Hit charge distribution:



Most of proton tracks are removed

- Set new range: from 3.5 keV to 110 keV → proton selection

Single Proton

Selection

Known how select protons (energy deposition tagging) is possible to study the most simple proton event and reconstruct it.

The simulation

Monte-Carlo with “single proton gun”: one proton per event, with complete detector simulation

Analysis

We want run the existing reconstruction code on single proton generated events and understand why and where the reconstruction algorithm fails.

Reconstruction code steps

- Step 1: **Hit Preparation** → energy flagging
- Step 2: **Time Peak Finder** (discussed later)
- Step 3: **Patter Recognition** → helix finder
  - Different energy deposition → different hit distribution
  - Multiple scattering → relaxed constrains on circle pattern
- Step 4.1: **Seed Fit** → starts from helix, simplified fit
- Step 4.2: **Kalman Filter Fit** → material and field effect, 10 iterations
  - Most of parameter relaxed, no material effect

↓

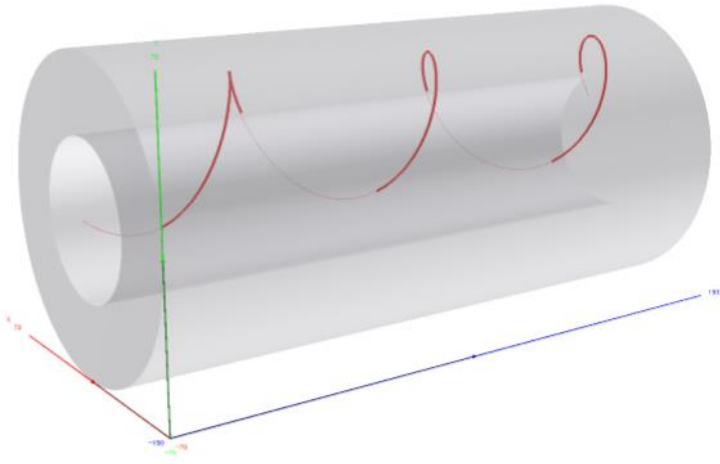
The fit converges, first reconstructed proton!

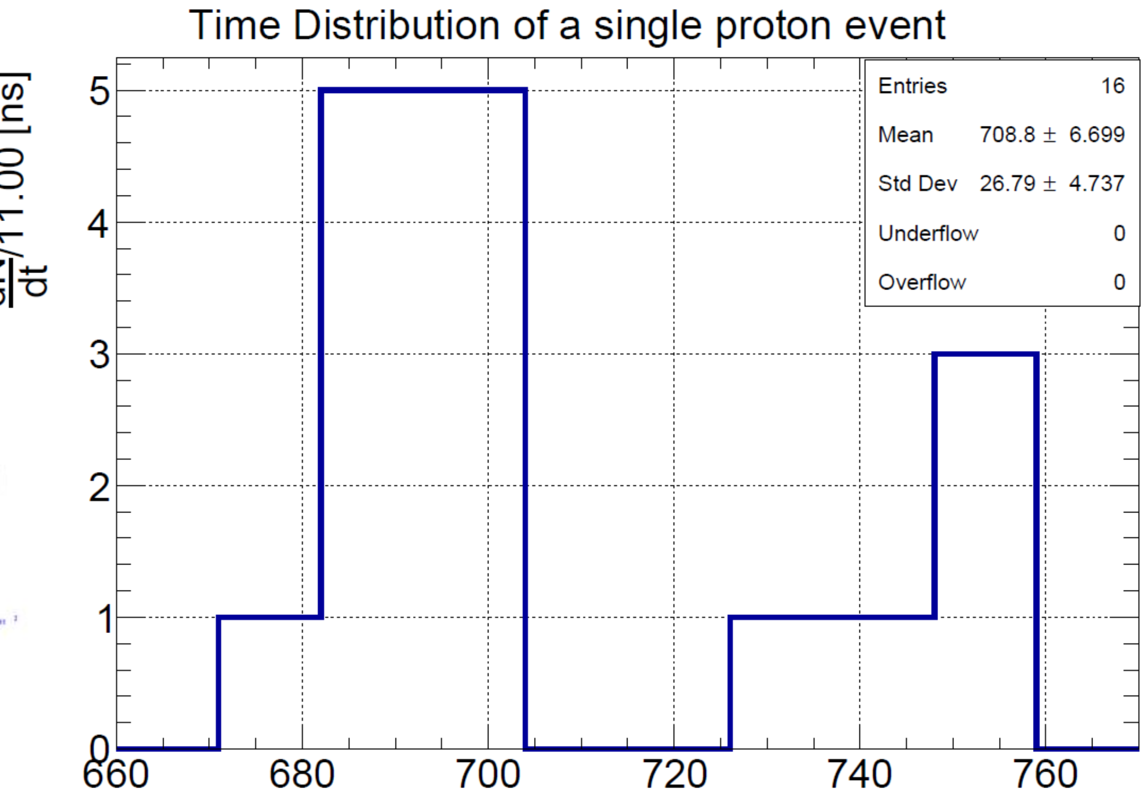
Time Peak Finder

The algorithm searches for sets of hits close each other

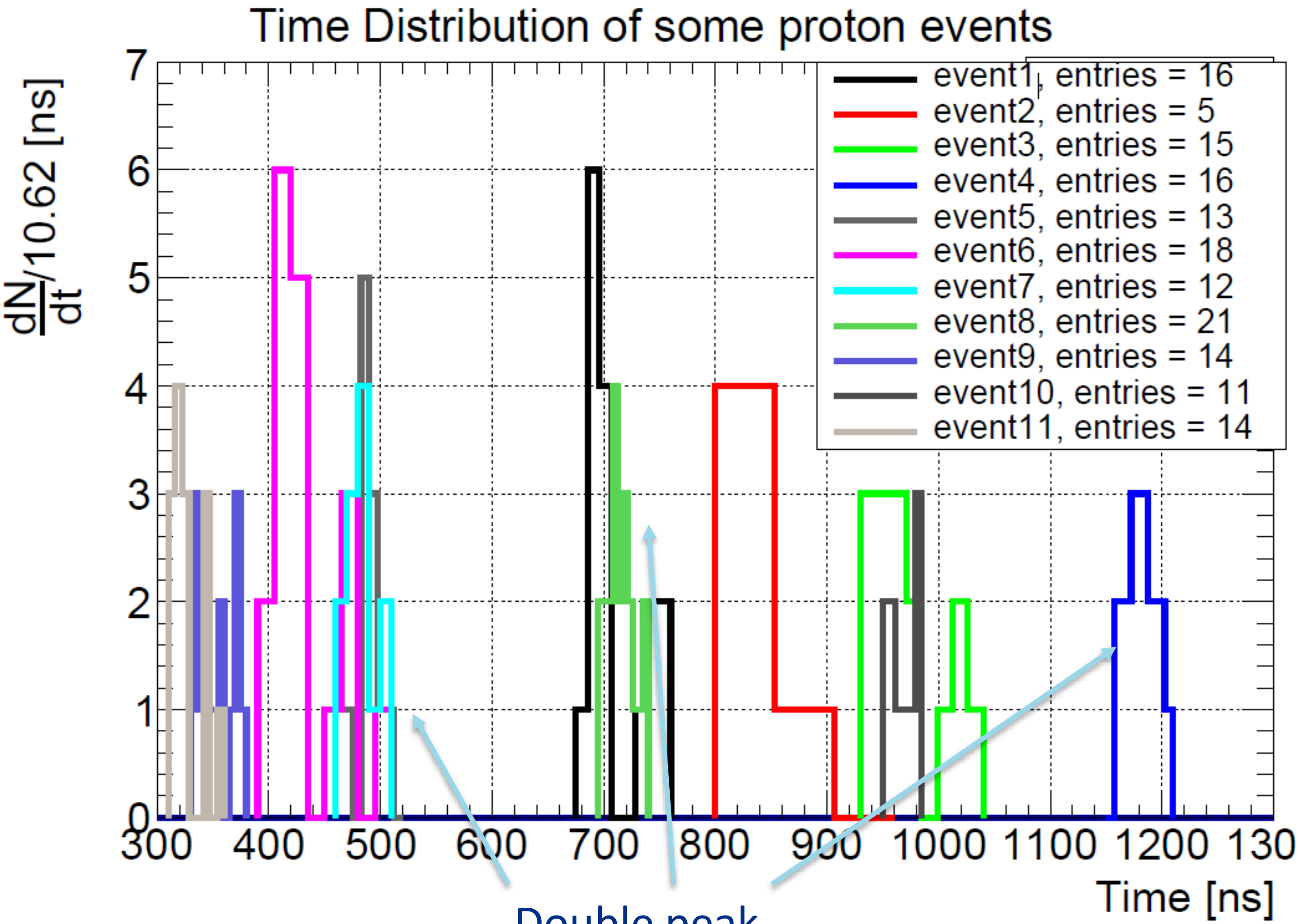
Proton peaks features:

- Larger width: not negligible TOF (70 ns VS 30 ns of drift time)
- Double peaks





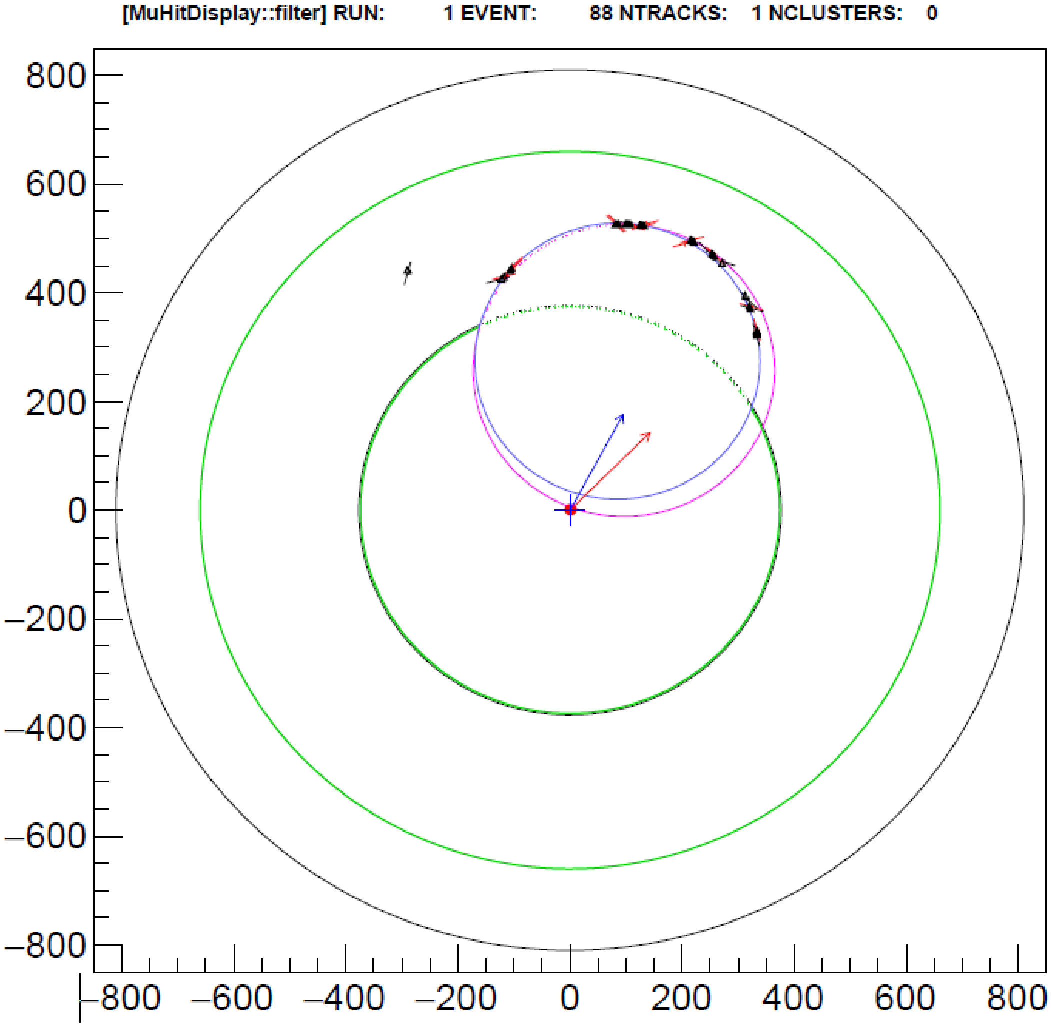
Time Peak Finder (2)



Double peak algorithm behaviour: 2 cloned peak

Double peak not always present

Example of the results

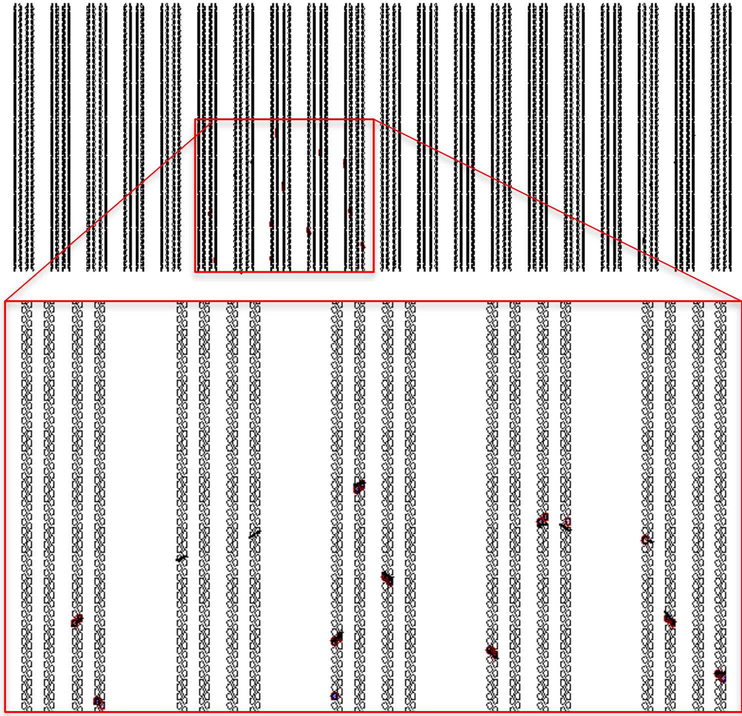


$$p = 115 \pm 2\ \mathrm{MeV}/c$$

$$p_\perp = 77 \pm 2\ \mathrm{MeV}/c$$

$$[\ldots]$$

$$\chi^2/\mathrm{dof}= 4.6$$



Fast Optimization of reconstruction algorithm

General method:

- Single proton simulation analysis and debug of rejected event
- Advantages: every time MC-truth well known (event by event), efficiency under control
- Disadvantages: no purity check

Time Peak Finder: increase efficiency from 40% to 80%

- number of hits give an upper limit to efficiency
- tracks duplicate not easily solvable at configuration level

Helix Finder: efficiency >90%

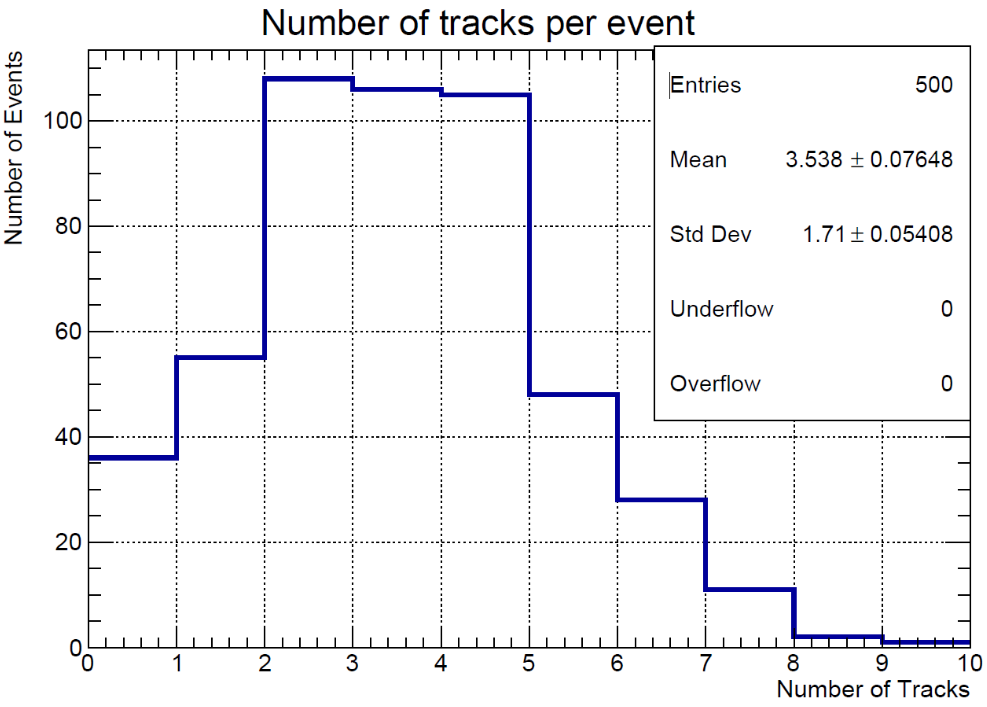
NB: all efficiencies evaluated for 150 MeV/c protons

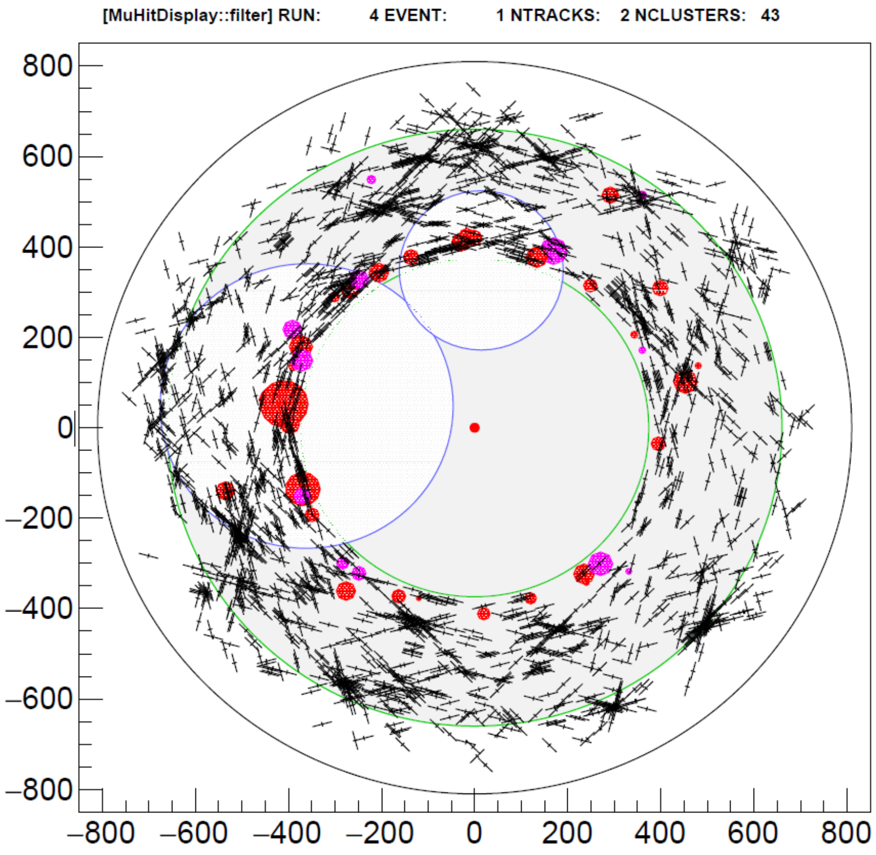
Fitter: efficiency about 50%

- not solvable at configuration level
- Stronger cut on hit number (20) ⇒ fitter efficiency >90%

Background frame test

Reconstruction of proton tracks on full-background sample of events:



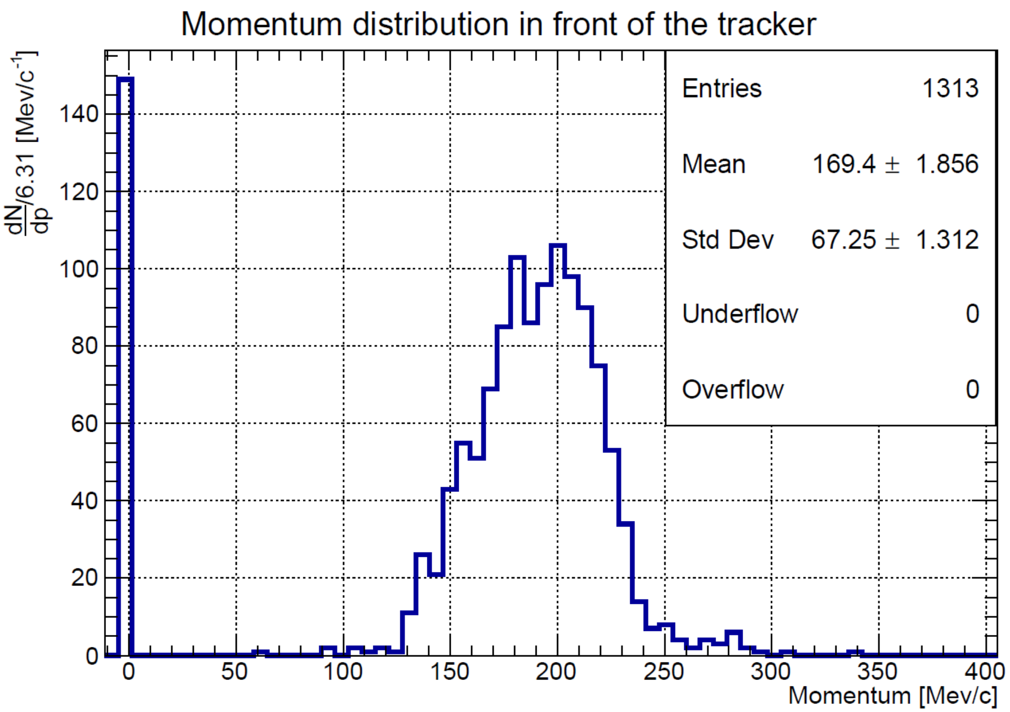


It works, but studies on track quality are necessary:

Purity

Method:

- comparing track-ID and generated particle-ID and associate
- evaluate momentum of generated particle in front of the tracker (p_{front})
- If generate particle is not a proton set $p_{\text{front}} = -1$

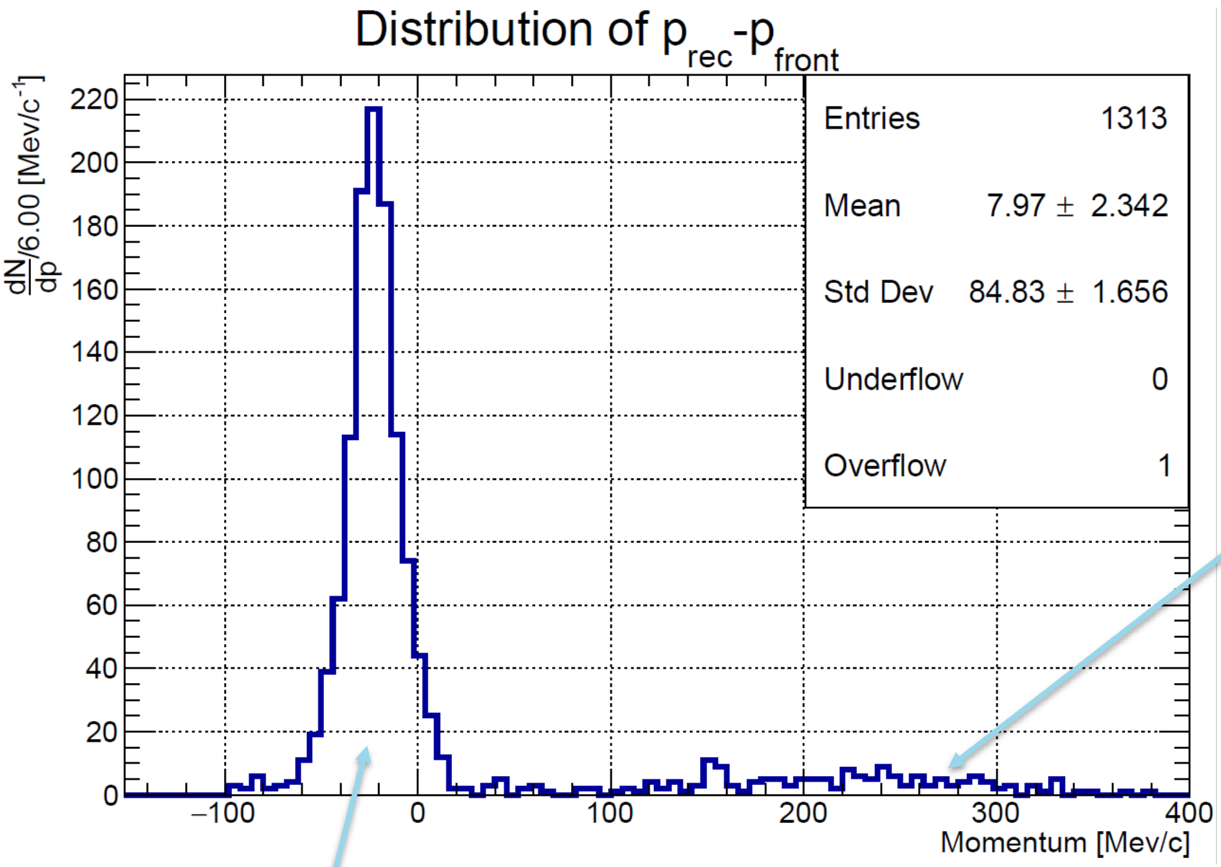


About 10% of events are not protons → ID-checking → deutons

Deutons:

- indistinguishable from protons in reconstruction
- Are not a problem for main purpose

Purity (2)

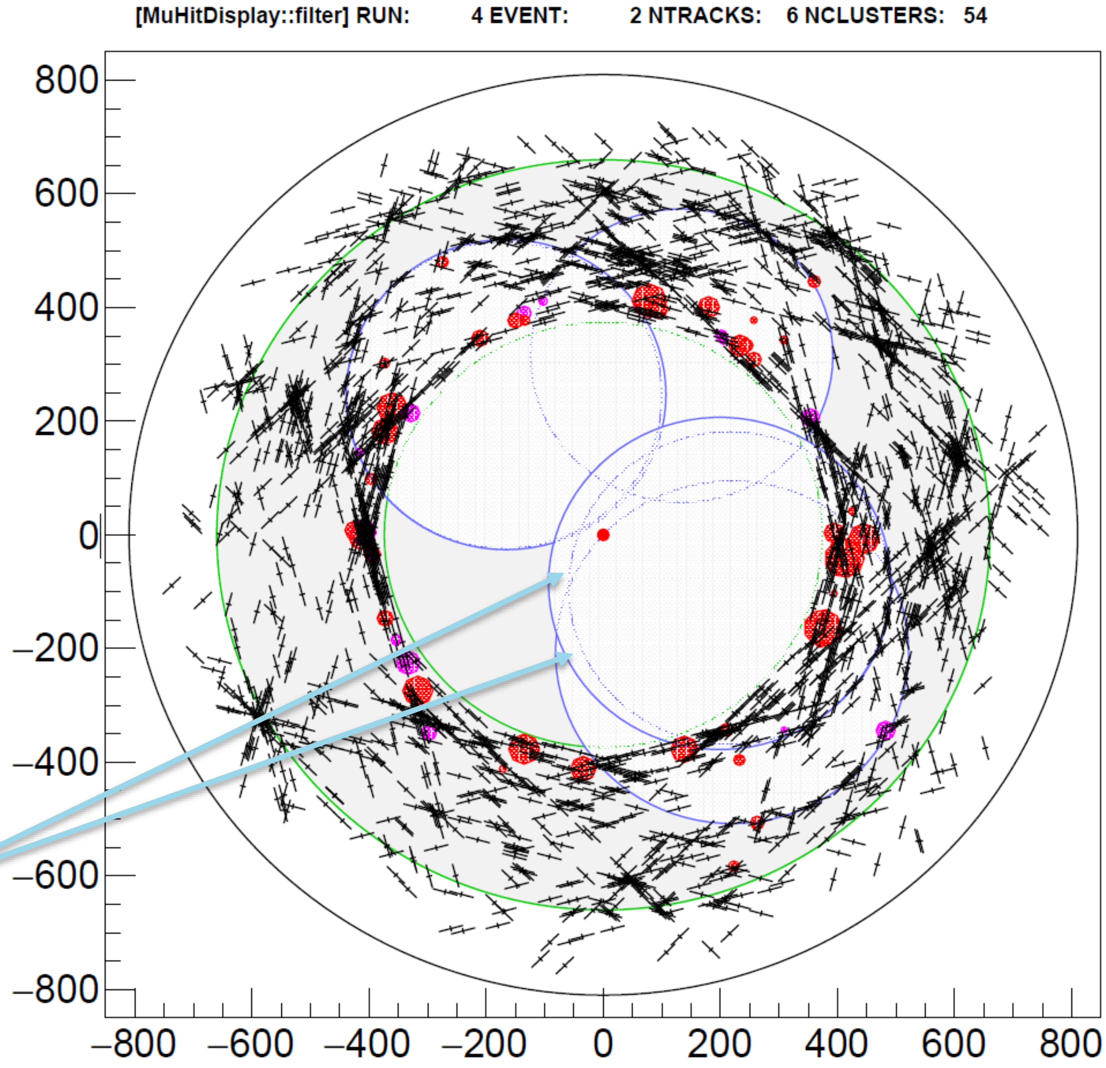


Deutons (shifted by 1 MeV)

- Negative mean ($\simeq -20\ \mathrm{MeV/c}$) for energy losses
- RMS ($\simeq 18\ \mathrm{MeV/c}$) is the scale of uncertainty in momentum

Tracks duplicate problem

- Easy to study statistically using particle ID of tracks
- Are statistically relevant: about 20% of tracks are cloned

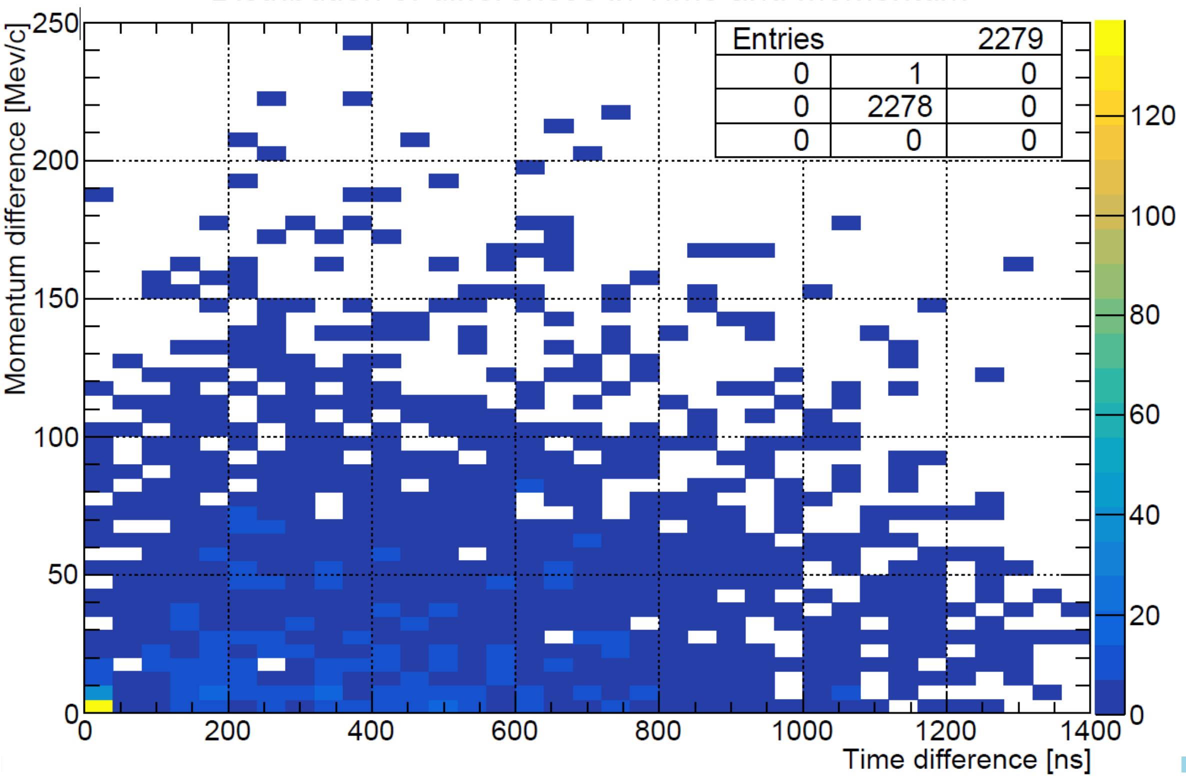


Cloned tracks

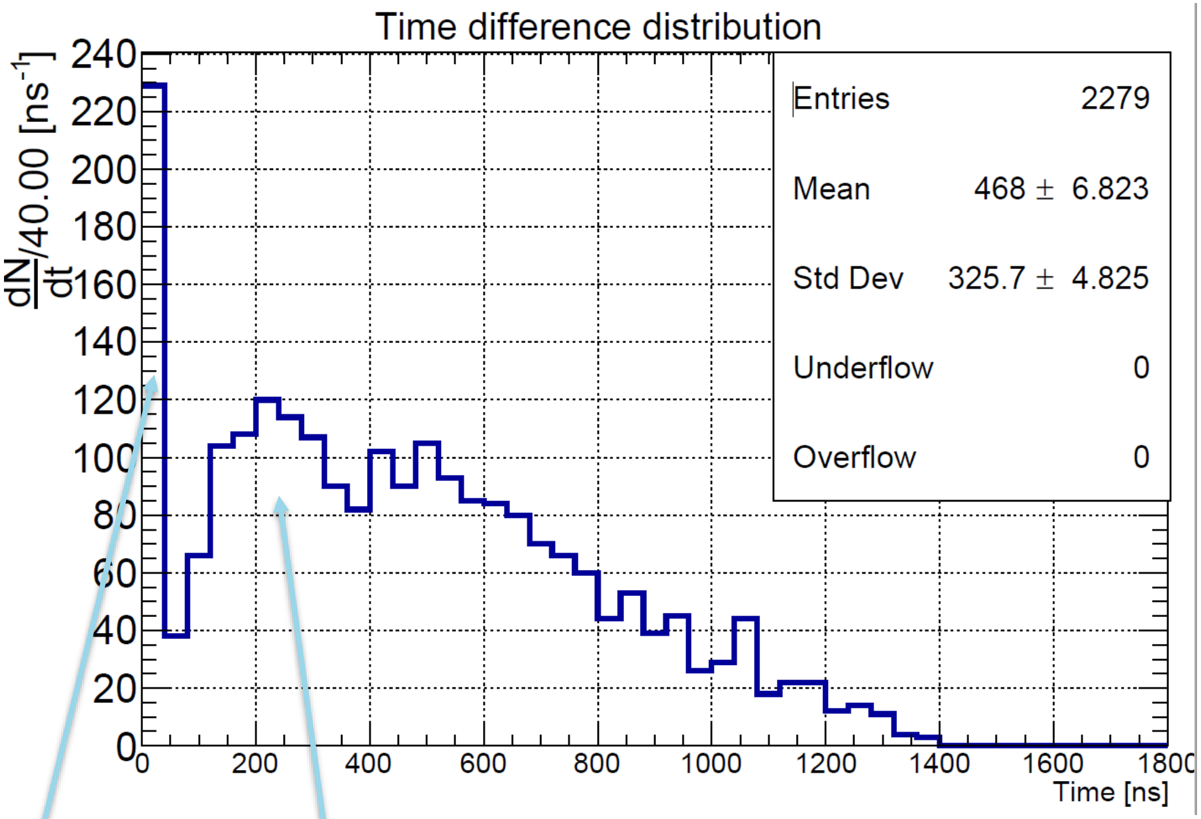
Tracks duplicate problem (2)

Solution method

- Find best parameters to recognize cloned tracks: T_0, p for tracks duplicate are nearly the same
- Analyze distribution on $\Delta p \times \Delta T_0$ plane, where differences are evaluated between all the tracks of the event
- Make a cut using MC-truth information of track duplicate too



Tracks duplicate problem (3)



- Only one peak around zero
- Momentum not add information integrated

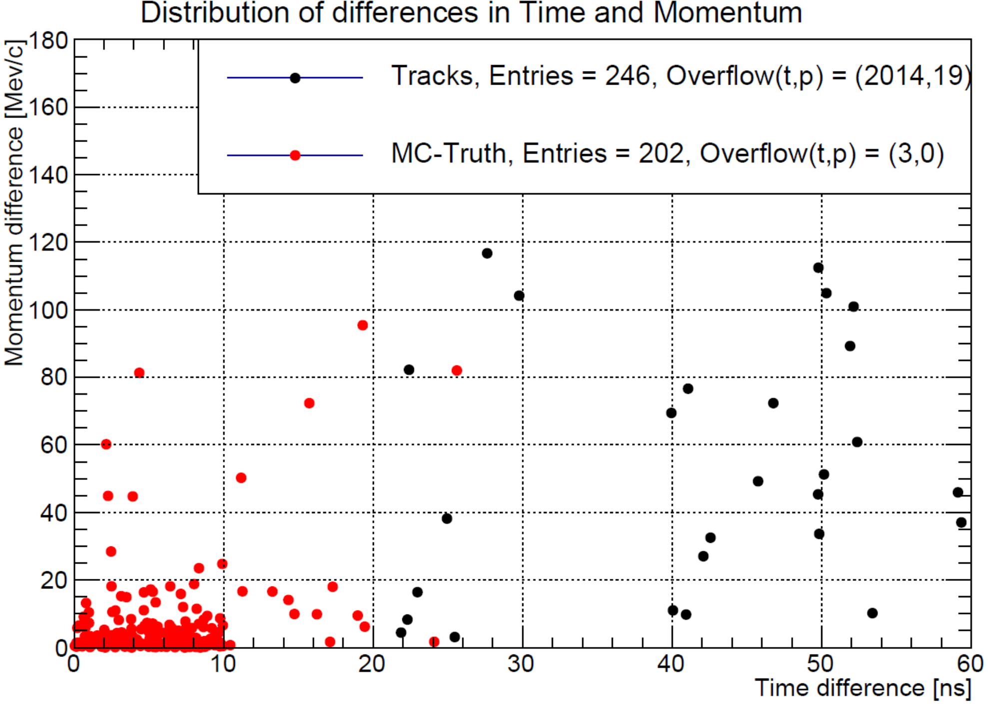
Distribution of real tracks

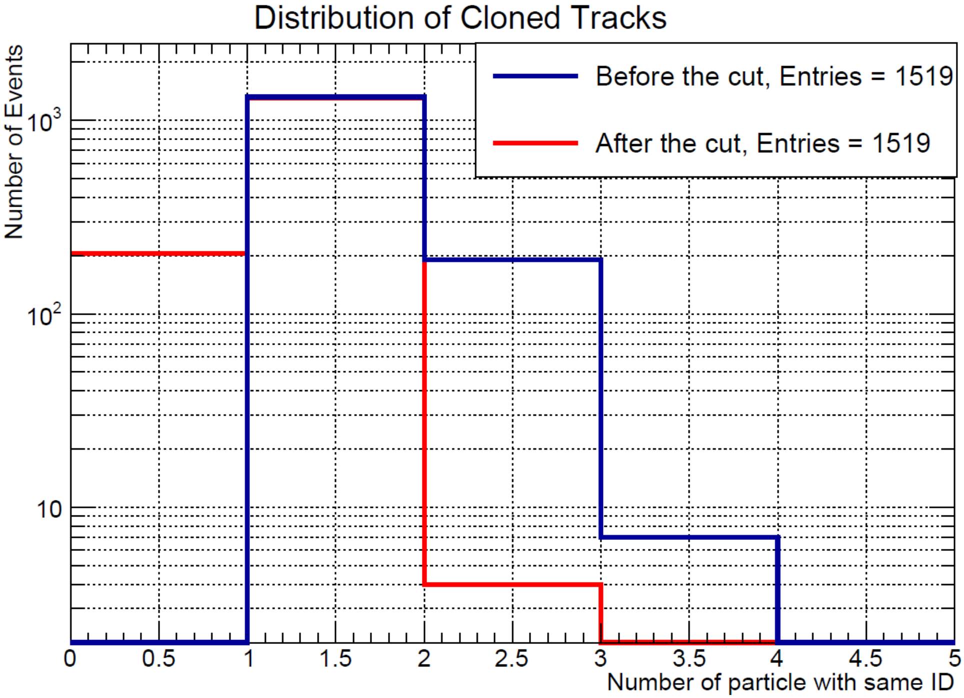
Track duplicate peak

Tracks duplicate problem

Monte-Carlo Truth:

- Most of track duplicate has $\Delta T_0 < 20\ \mathrm{ns}$
- In used simulation real track has $\Delta T_0 < 20\ \mathrm{ns}$

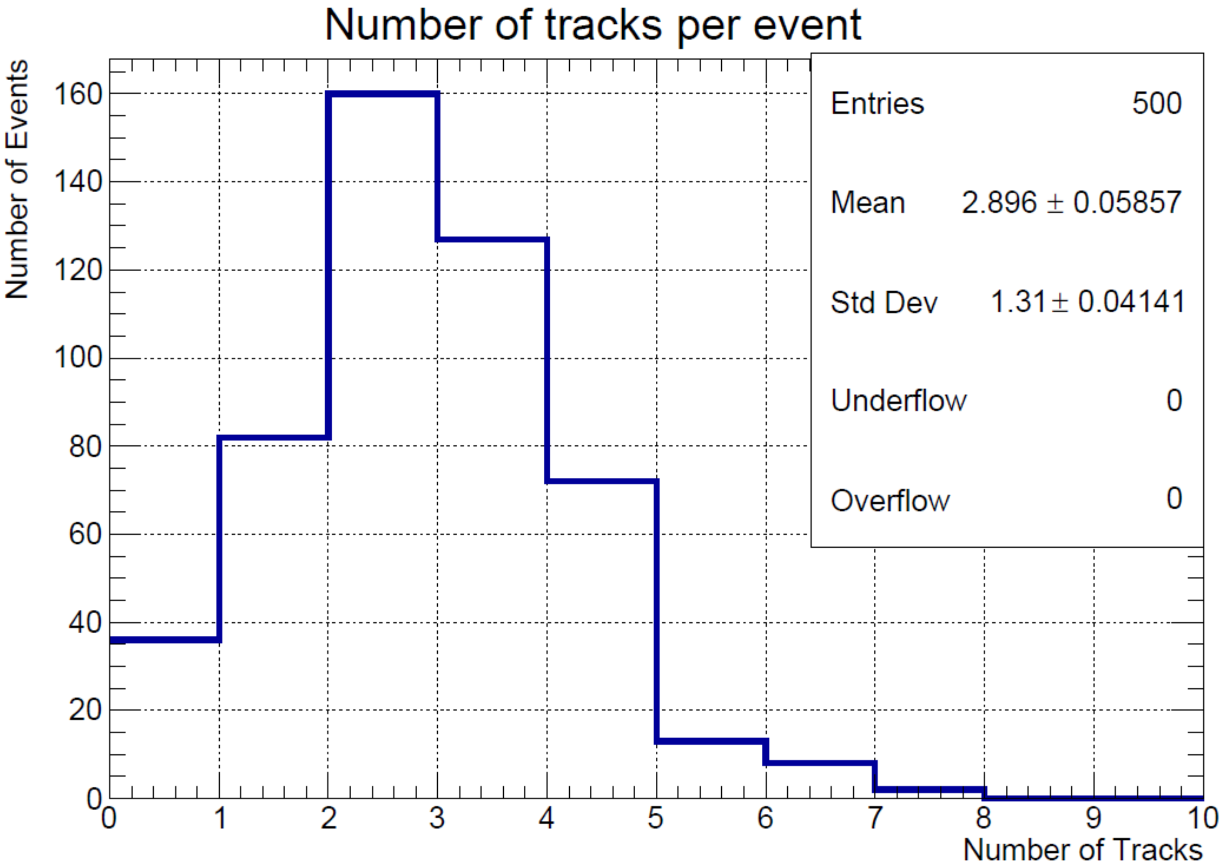




The Cut:

- Applied a cut at 20 ns
- Efficiency of the cut >99%

Number of tracks reconstructed



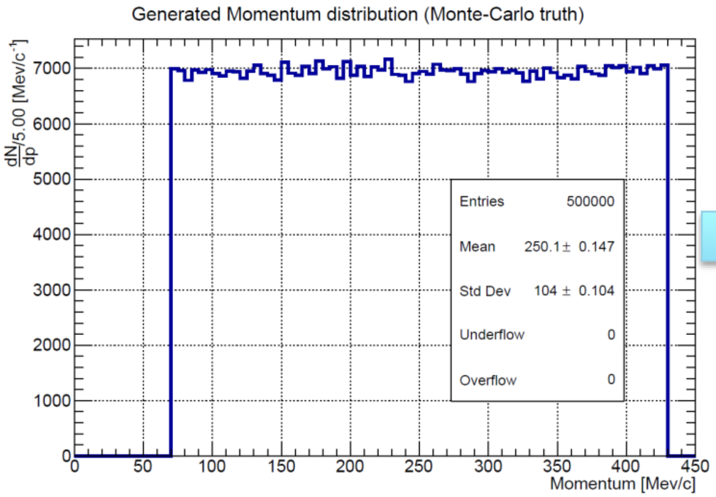
We could monitor the flux every 180 microbunch $(\simeq 300\,\mu s)$ with precision about 4.4%

Monitoring Method

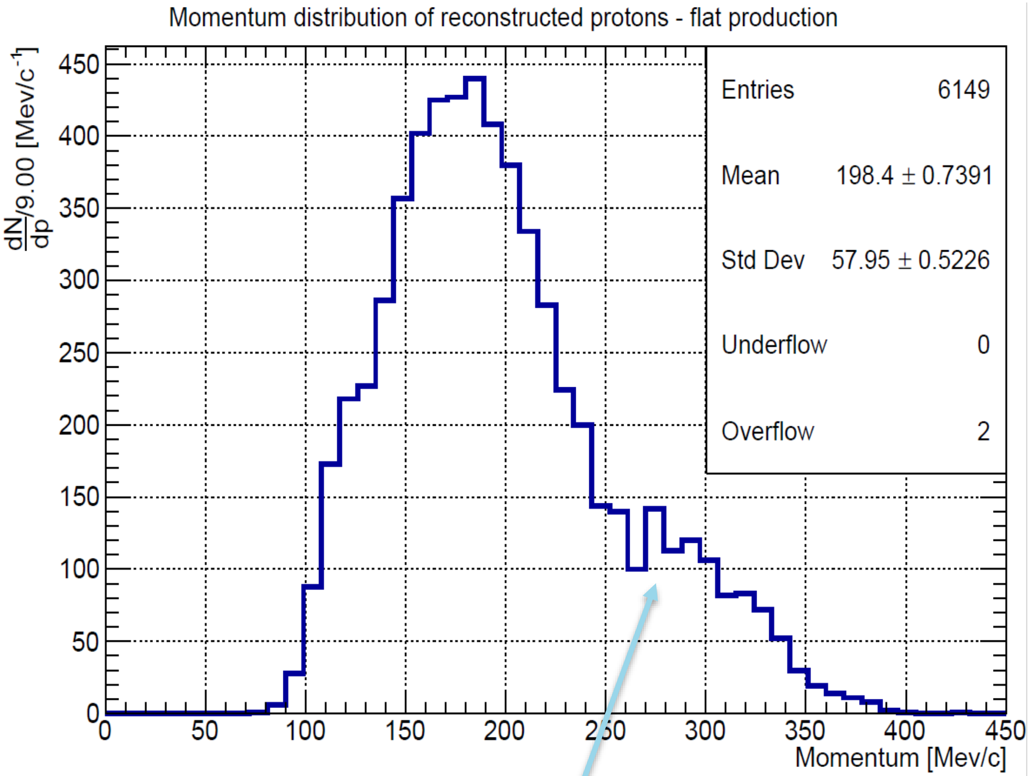
- Absolute normalization: counting DIO muons in a long period T (efficiency stopping and decay fraction well known) $\longrightarrow N_\mu(T)$
- Assumption: reconstruction efficiency for protons is constant in time
- $\frac{N_p}{N_\mu}(t) \equiv f = \mathrm{const} = \frac{N_p(T)}{N_\mu(T)}$ from absolute normalization
- Measuring protons in time $N_\mu(t) = N_p(t)/f$

Flat generator

For further analysis are generated protons with a flat momentum distribution and analyse the result of reconstruction using Monte Carlo truth information

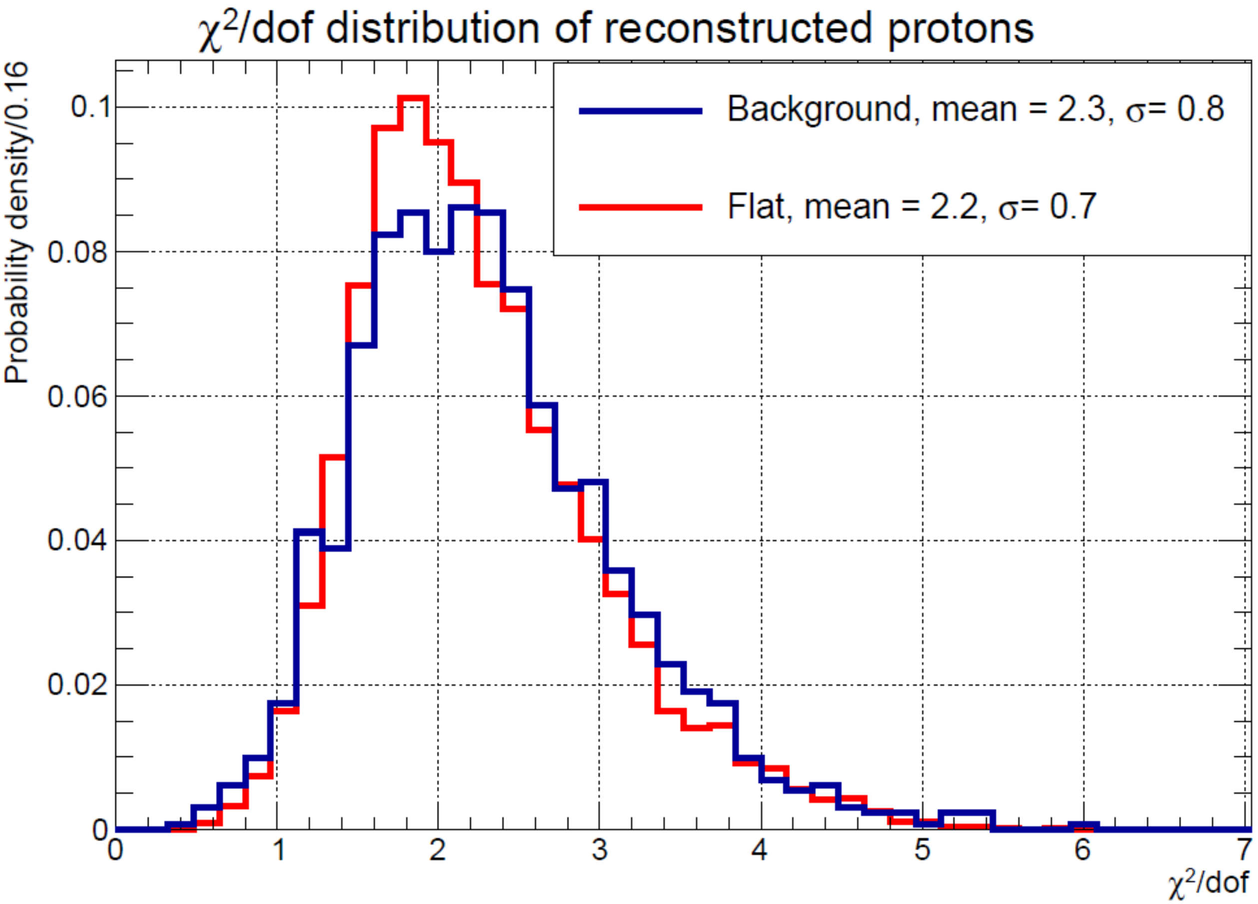


reco



Not well understood bump

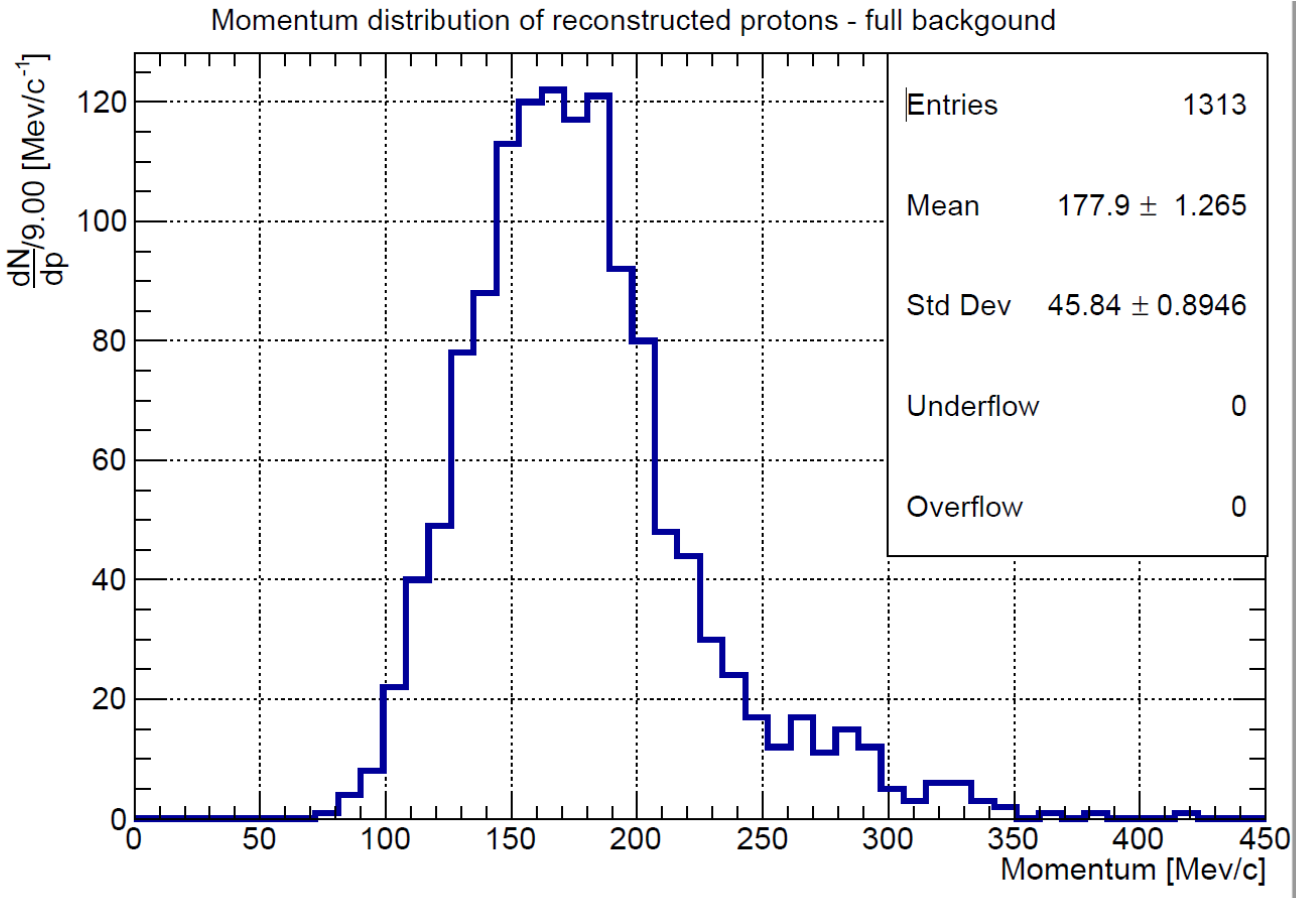
χ^2 distribution



Good : Same behaviour ⇨ convenient to use flat production to understand reconstruction properties

Bad : χ^2/dof peak in 2 ⇨ uncorrect assignment of errors in fit (not-easy solvable)

Proton momentum spectrum



Comparison with flat production:

- Peak at lower momentum
- No significant bump in tail

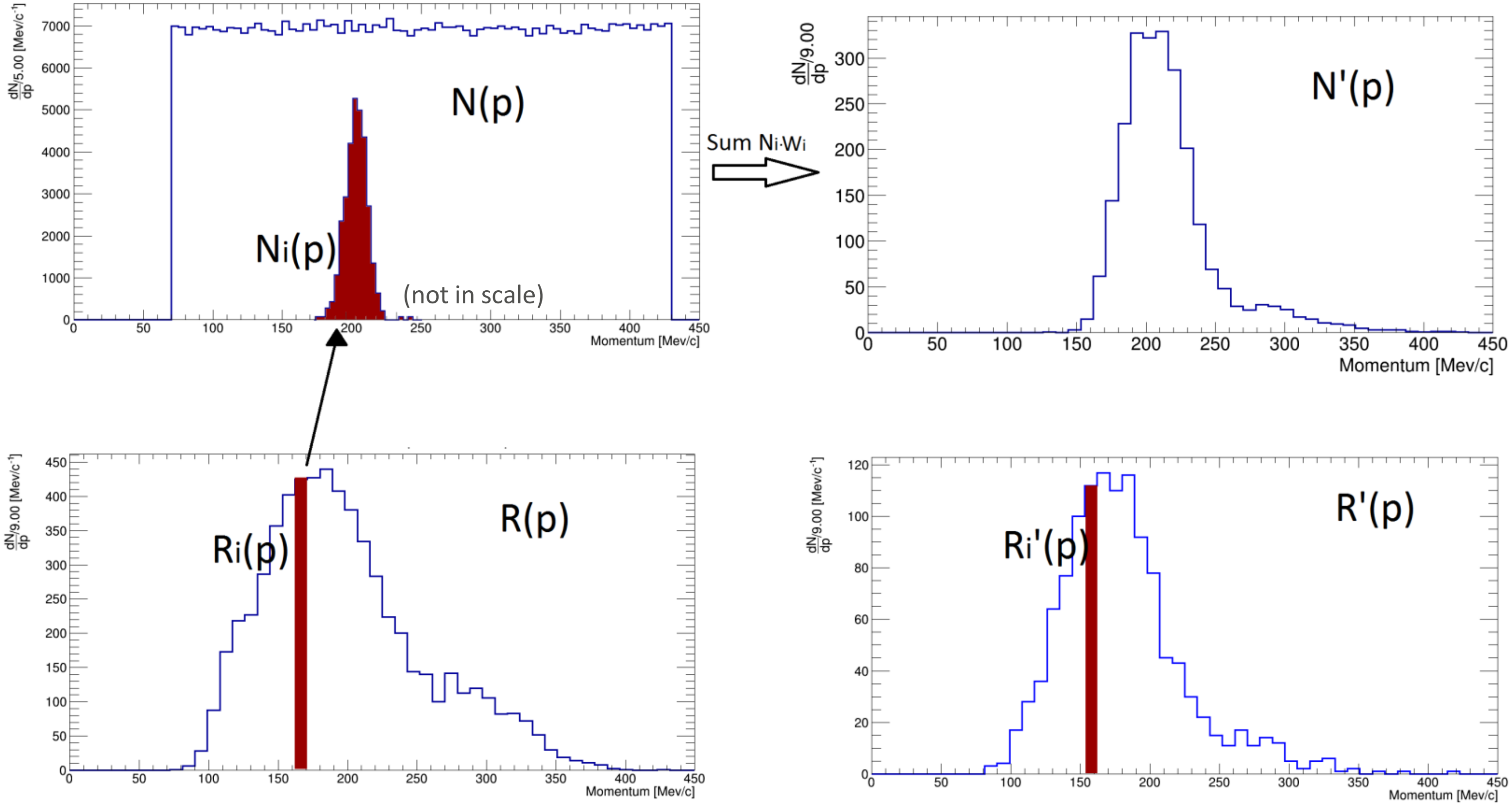
Input momentum distribution

Purpose:

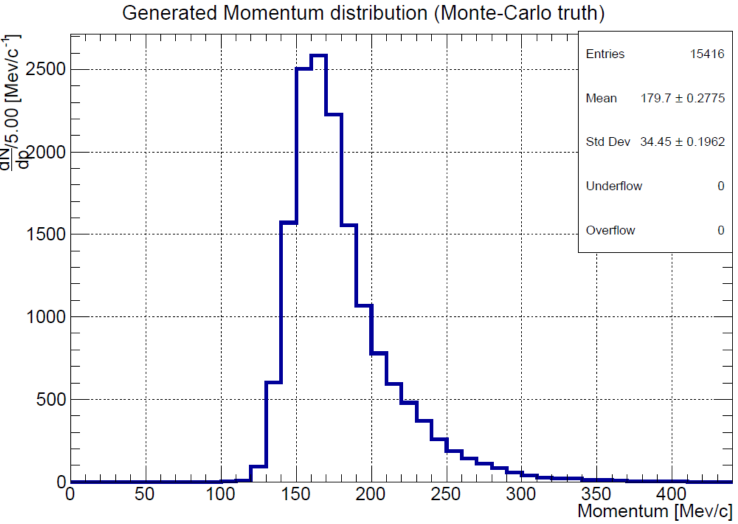
-consider 4 distributions:

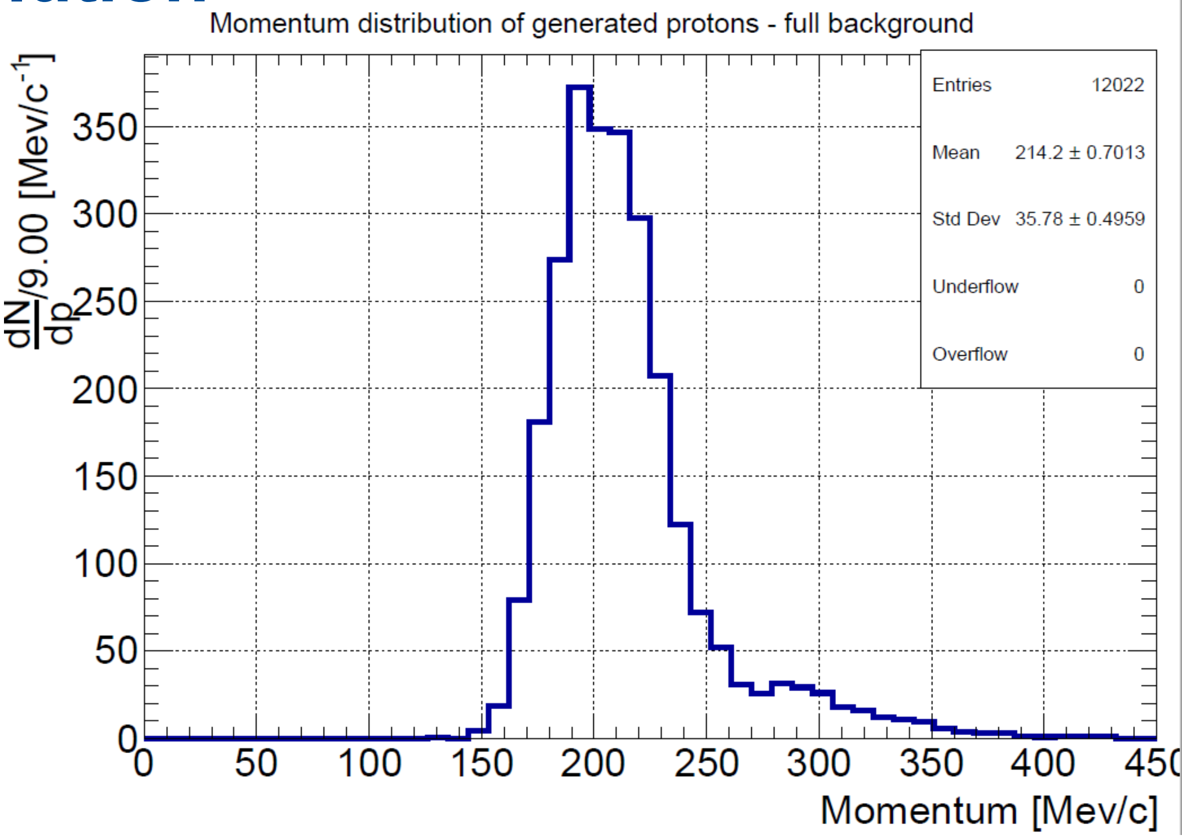
- -Generated flat N(p) and generated from background frames N’(p)
- -Reconstructed from flat R(p) and from background R’(p)

-We want to obtain N’(p) to check the reconstruction



First try of deconvolution





- similar qualitative shape
- Same width
- different peak (shift)

- Useful to make the method iterative
- Needed efficiency studies

Summary and results

- The current reconstruction method of mu2e, with some modification is able to reconstruct protons
- Reconstruction in nominal background: about 3 proton/microbunch
  - an alternative method for monitoring the muon flux intensity
  - adequate for bunch-to-bunch intensity monitoring
- Studied and optimized the purity: there are 10% of deutons
- reconstructed momentum spectrum of protons
- Deconvolution of input spectrum – work in progress

Next Steps

- Optimizing the fitting algorithm for protons and understand how to improve χ^2 distribution
- Study and optimize the reconstruction efficiency
- Quantitative study on muon flux and its fluctuations
- Improve a deconvolution method to obtain proton momentum distribution at production level

BACKUP SLIDES

Background of the experiment

Signal

Monoenergetic electron $$E_e = m_\mu c^2 - B_\mu - \frac{(m_c^2)^2}{2 m_N c^2}$$

Background

- DIO electrons: $\mu^- N \rightarrow e^- \overline{\nu}_e \nu_\mu N$
- Radiative muon capture: $\mu^- \mathrm{Al} \rightarrow \gamma \nu_\mu \mathrm{Mg}$
- Decay in flight muons: $\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu$
- Cosmic rays
- Radiative pion capture: $\pi^- \mathrm{Al} \rightarrow \gamma X$
- Antiprotons: $pp \rightarrow ppp\overline{p}$
- Protons from nucleus disintegration

Singal numbers

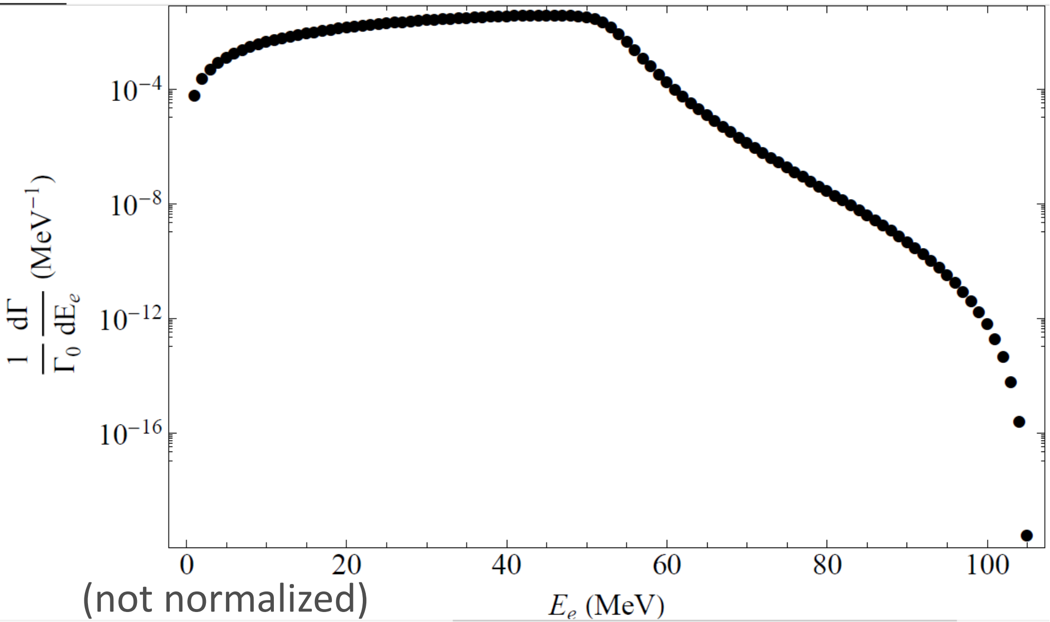
Microbunch: $T \simeq 1.7\ \mu\mathrm{s} \quad N_p = 10^7$, duration= 200 ns

Batch: $25 \cdot 10^3$ microbunch, $T_b \simeq 43\ \mathrm{ms}$

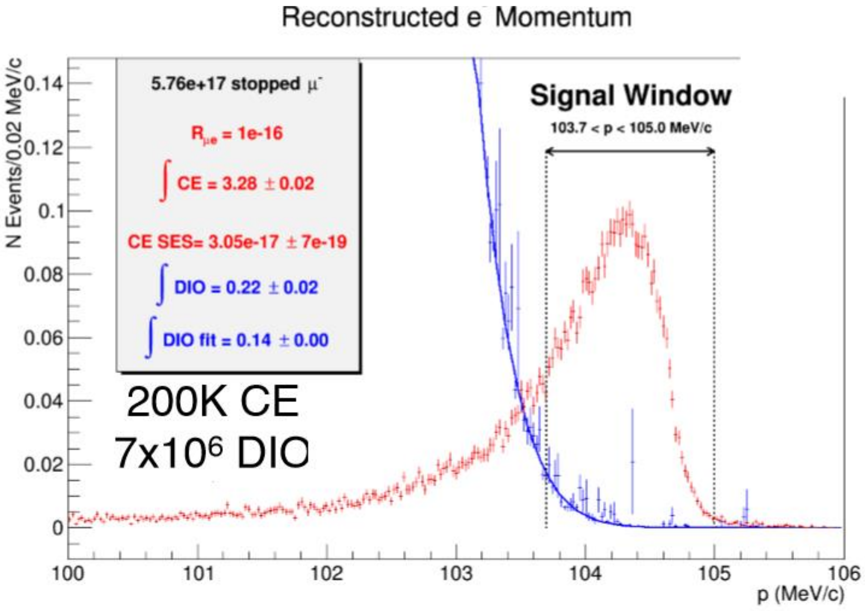
Decay-In-Orbit analysis

The Signal

$\mu^- \to e^- \overline{\nu}_e \nu_\mu$ in target nucleus orbit is one of the main background with a theoretically calculated spectrum ($\Gamma_0 = \frac{G_F^2 m_\mu^5}{192\pi^3}$)



(not normalized)



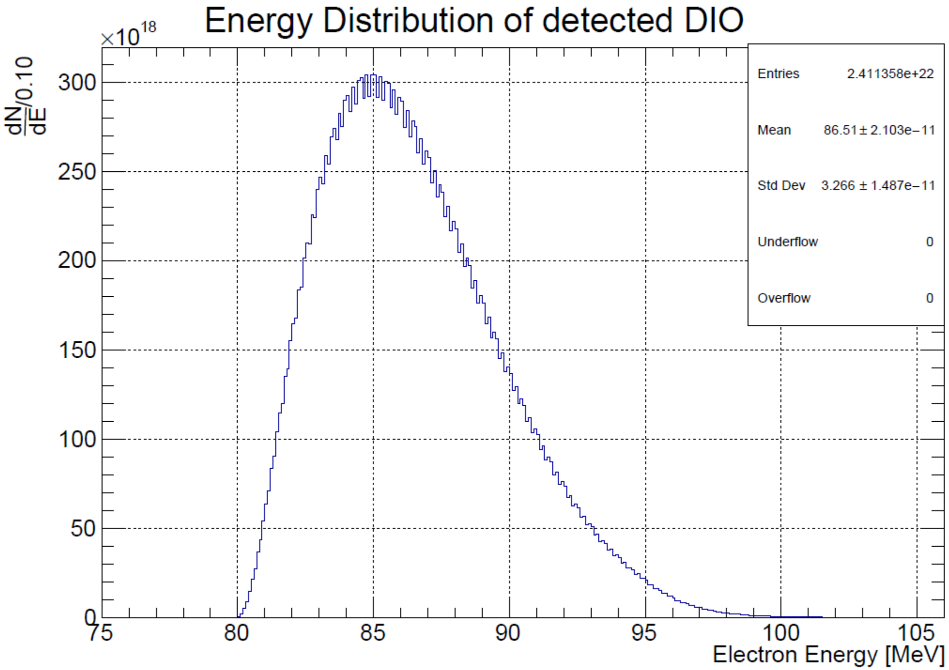
DIO Reconstruction Efficiency (approx):

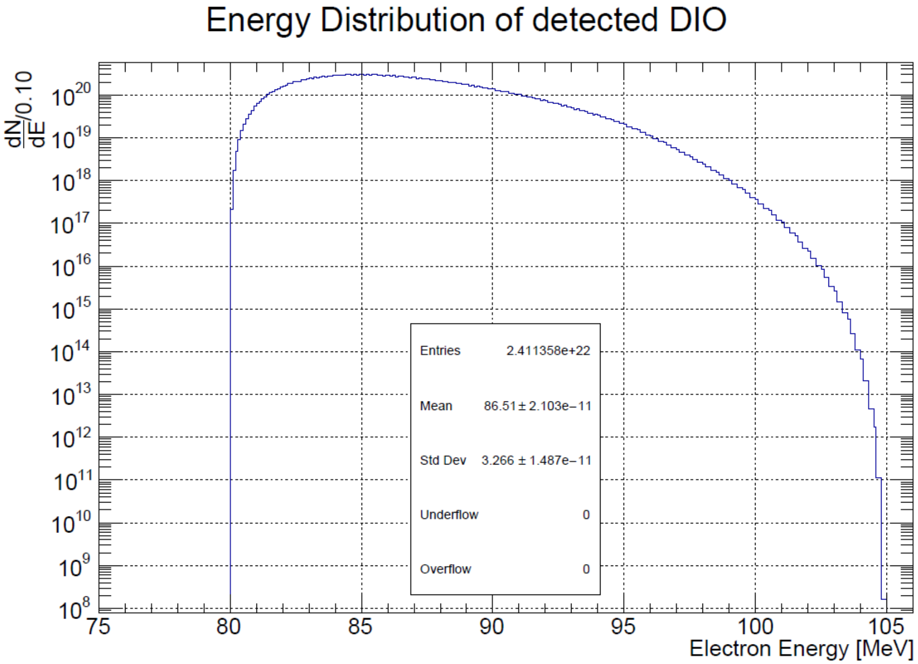
Linear from 80 MeV ($\varepsilon = 0$) to 95 MeV, ($\varepsilon = 0.1$), flat above 95 MeV

Decay-In-Orbit flux analysis (2)

$$\text{DIO total number} \ \simeq 9.0 \cdot 10^7$$

$$\text{DIO number (per second)} \ \simeq 4.6$$



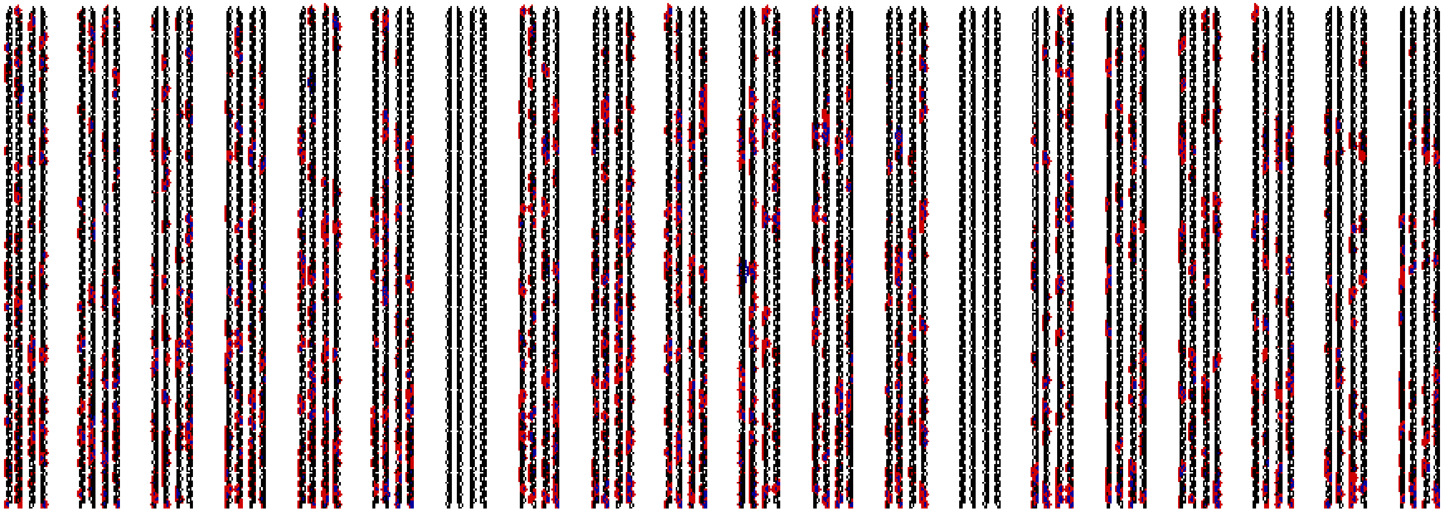


Problem:

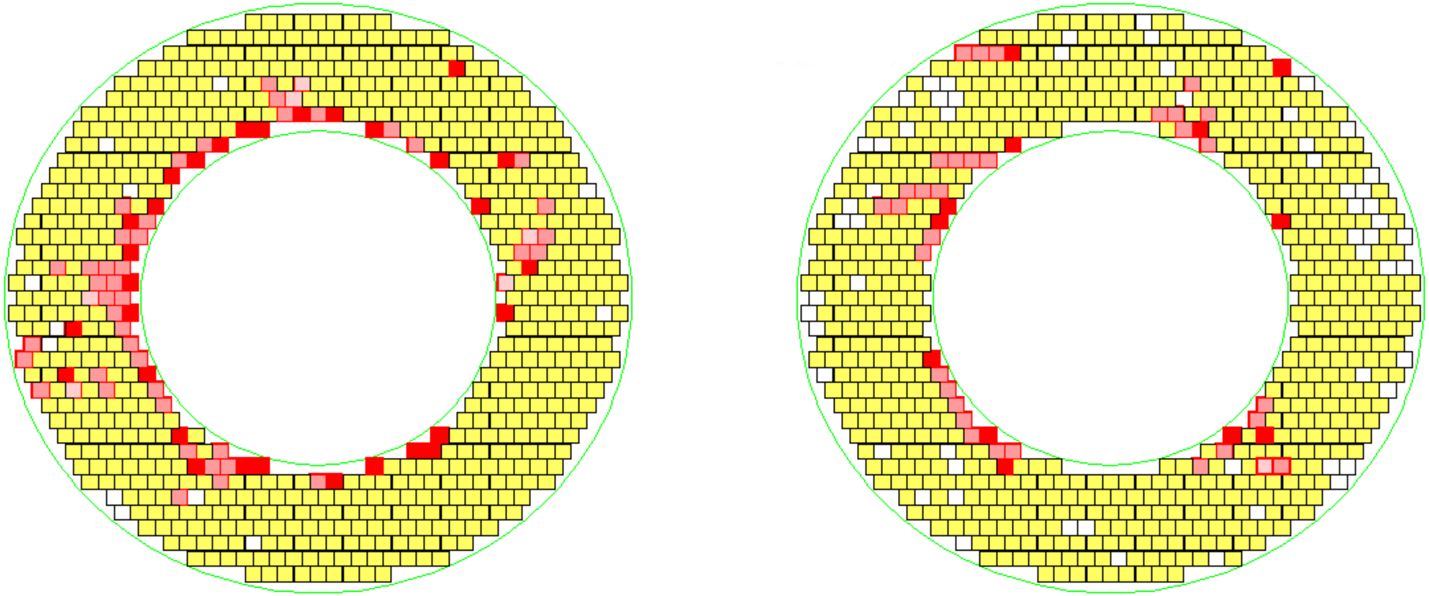
Rate of reconstructed DIO electrons is less than 1 event/microbunch, so is impossible use DIO to monitor microbunch fluctuations

History 1 - starting (failing) event reconstruction in full background

Tracker (R-z view)



Calorimeter



History 2 - Event Reconstruction – first try (energy deposition)

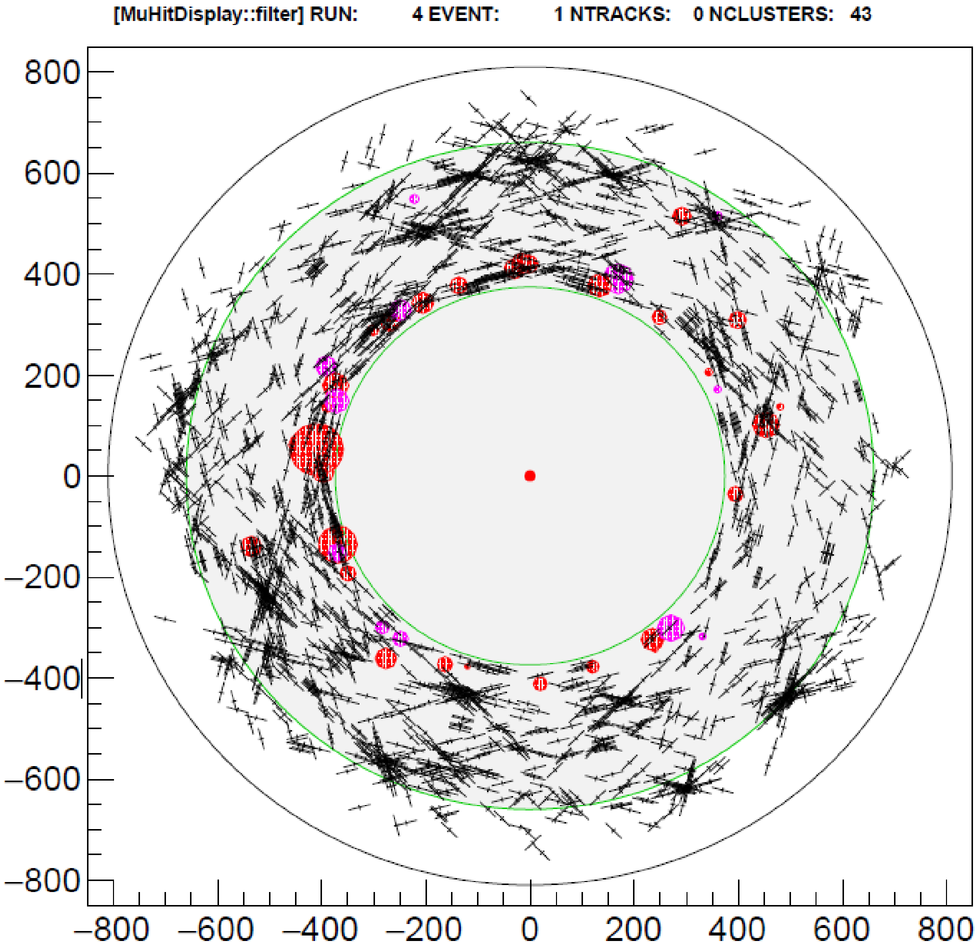
- With new energy range protons COULD be reconstructed

But:

- Reconstruction in complete background event doesn't find tracks

So:

- Only proton hits has so high energy
- Needed to modify the code to reconstruct protons



Step 1 – Hit Preparation (Energy analysis)

Flagging:

Define hits in the tracker, for proton main flag is energy deposition

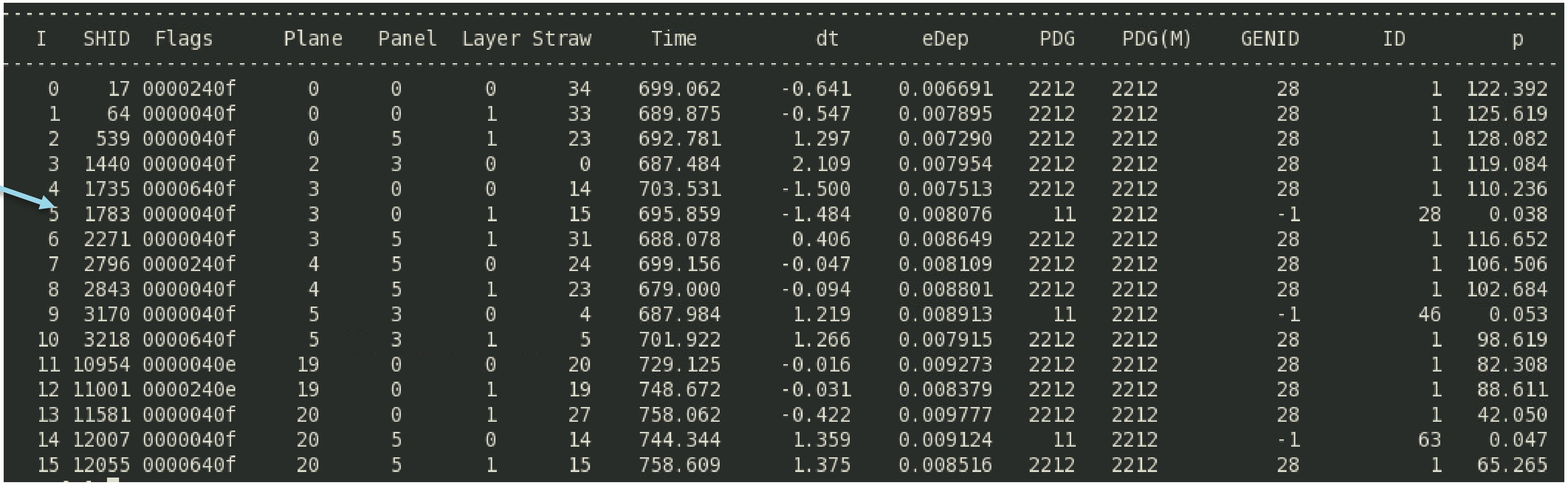
Proton absorber

- Using 100 MeV/c protons → no hits
- Generated 150 MeV/c protons

Energy deposition

- Proton simulation include delta rays production
- Energy deposition selection can't reject delta rays

MC Truth:



Delta ray

```
---------------------------------------------------------------------------------------------------------------------------
  I   SHID  Flags      Plane   Panel  Layer Straw     Time         dt        eDep     PDG    PDG(M)    GENID       ID        p
---------------------------------------------------------------------------------------------------------------------------
   0     17 0000240f      0       0       0     34    699.062     -0.641   0.006691  2212   2212         28          1  122.392
   1     64 0000040f      0       0       1     33    689.875     -0.547   0.007895  2212   2212         28          1  125.619
   2    539 0000040f      0       5       1     23    692.781      1.297   0.007290  2212   2212         28          1  128.082
   3   1440 0000040f      2       3       0      0    687.484      2.109   0.007954  2212   2212         28          1  119.084
   4   1735 0000640f      3       0       0     14    703.531     -1.500   0.007513  2212   2212         28          1  110.236
   5   1783 0000040f      3       0       1     15    695.859     -1.484   0.008076    11   2212         -1         28    0.038
   6   2271 0000040f      3       5       1     31    688.078      0.406   0.008649  2212   2212         28          1  116.652
   7   2796 0000240f      4       5       0     24    699.156     -0.047   0.008109  2212   2212         28          1  106.506
   8   2843 0000040f      4       5       1     23    679.000     -0.094   0.008801  2212   2212         28          1  102.684
   9   3170 0000040f      5       3       0      4    687.984      1.219   0.008913    11   2212         -1         46    0.053
  10   3218 0000640f      5       3       1      5    701.922      1.266   0.007915  2212   2212         28          1   98.619
  11  10954 0000040e     19       0       0     20    729.125     -0.016   0.009273  2212   2212         28          1   82.308
  12  11001 0000240e     19       0       1     19    748.672     -0.031   0.008379  2212   2212         28          1   88.611
  13  11581 0000040f     20       0       1     27    758.062     -0.422   0.009777  2212   2212         28          1   42.050
  14  12007 0000040f     20       5       0     14    744.344      1.359   0.009124    11   2212         -1         63    0.047
  15  12055 0000640f     20       5       1     15    758.609      1.375   0.008516  2212   2212         28          1   65.265
```

Step 3 – Pattern recognition

Algorithm

- Search for triplet of hits to reconstruct circles
  - Minimum hit distance and radius constrains to avoid divergences
  - Intersection with centre (the target) constrain
- Find centres
- Find helix axis

Proton helix features

- Relaxed constrains on radius
- No constrains on centre (for multiple scattering in absorber)

Double Peaks: don’t give same helix parameters

Step 4 - Fit

Algorithm

- Try to recover hit from pattern recognition
- Seed Fit: from helix of pattern reconstruction make a first simplified fit
  - No material/field effect
  - Big errors
  - 2 iterations
- Final Fit: complete Kalman filter fit
  - Material and field effects
  - 10 iteration with smaller errors
  - Drift radius reconstruction and solved left-right ambiguity
    - Combinatorial station per station, minimum χ^2 on position
    - OR Minimum χ^2 on slope of helix

Step 4 – Fit (2)

Result of fit on protons

- Using default parameters most of helix pass the seed fit but no tracks pass the final Kalman filter

First operative solution:

- Lower hit number requirement
- No material effect
- Larger error, max 3 iterations

The fit converges, first reconstructed protons!

Deconvolution method

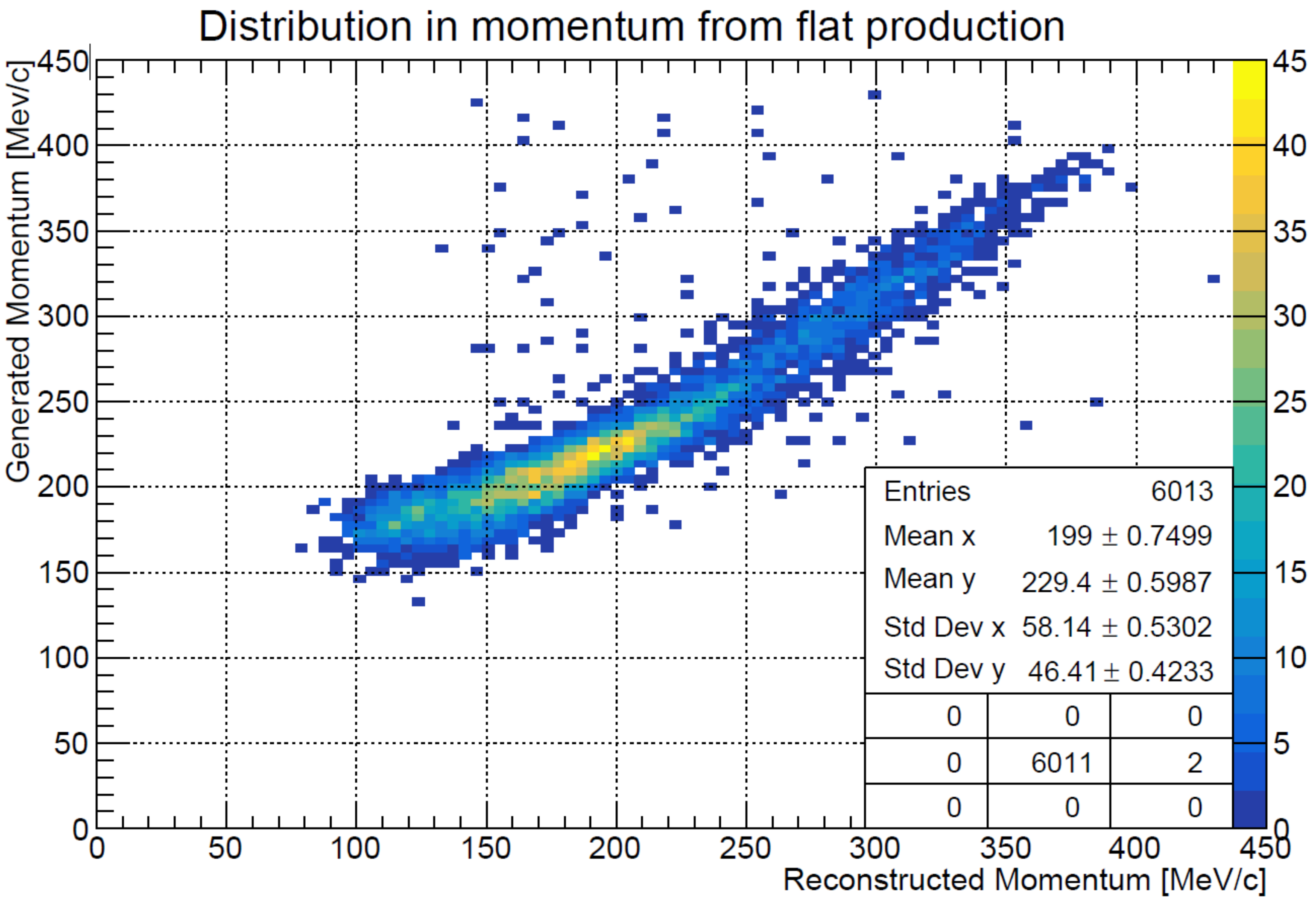
Purpose:

- consider 4 distributions:
  - Generated flat N(p) and generated from background frames N’(p)
  - Reconstructed from flat R(p) and from background R’(p)
- We want to obtain N’(p) to check the reconstruction

Method:

- Bin R(p) and obtain slices $R_i(p)$
- Using MC-truth obtain correspondent distribution $N_i(p)$
- Evaluate, bin per bin, the weights: $W_i(p) = \frac{R_i'(p)}{R_i(p)}$
- Correct using weights: $N_i'(p) = W_i(p) N_i(p)$
- Build the distribution N(p) as sum of the slices $N_i'(p)$

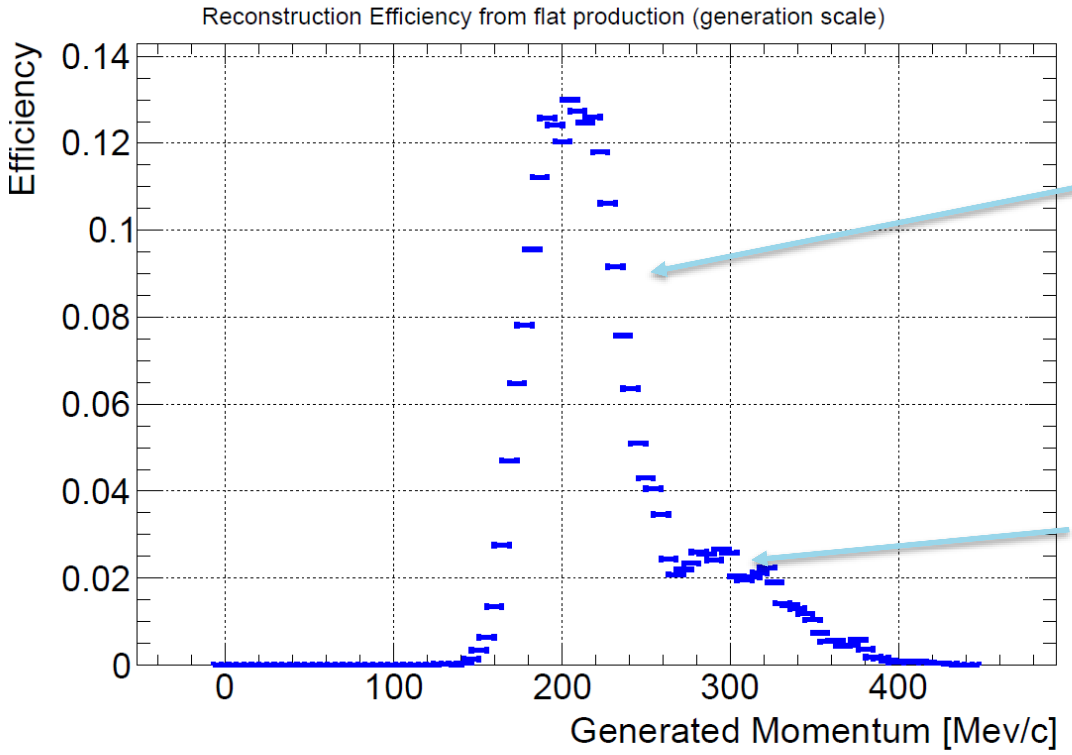
Momentum (reco and generated) distribution



Efficiency of Reconstruction – first try

Using flat producer, bin per bin $\varepsilon(p) = \frac{N_{rec}(p)}{N_{prod}} \pm \frac{1}{N_{prod}} \sqrt{N_{rec}(p)(1-\varepsilon(p))}$

- N_{gen} are number of events produced in the bin
- N_{rec} are the integral of reconstructed proton momentum distribution corresponding to the generated bin



Reasonable falling

Not well understood bump!