ND-GAR-LITE PERFORMANCE STUDY:
SINGLE SPILL SAMPLES

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MOTIVATION FOR THE STUDY

- This is an update on a previous study which concentrated on momentum resolution analyzed for primary muons generated in neutrino interactions in ND-LAr (https://indico.fnal.gov/event/46503/contributions/215080/attachments/143152/181005/l2g_Presentation_DUNE-Collaboration_May2021.pdf)

- We compare the results obtained for a single interaction sample of 10^6 events, with a sample of 10^5 single spill events

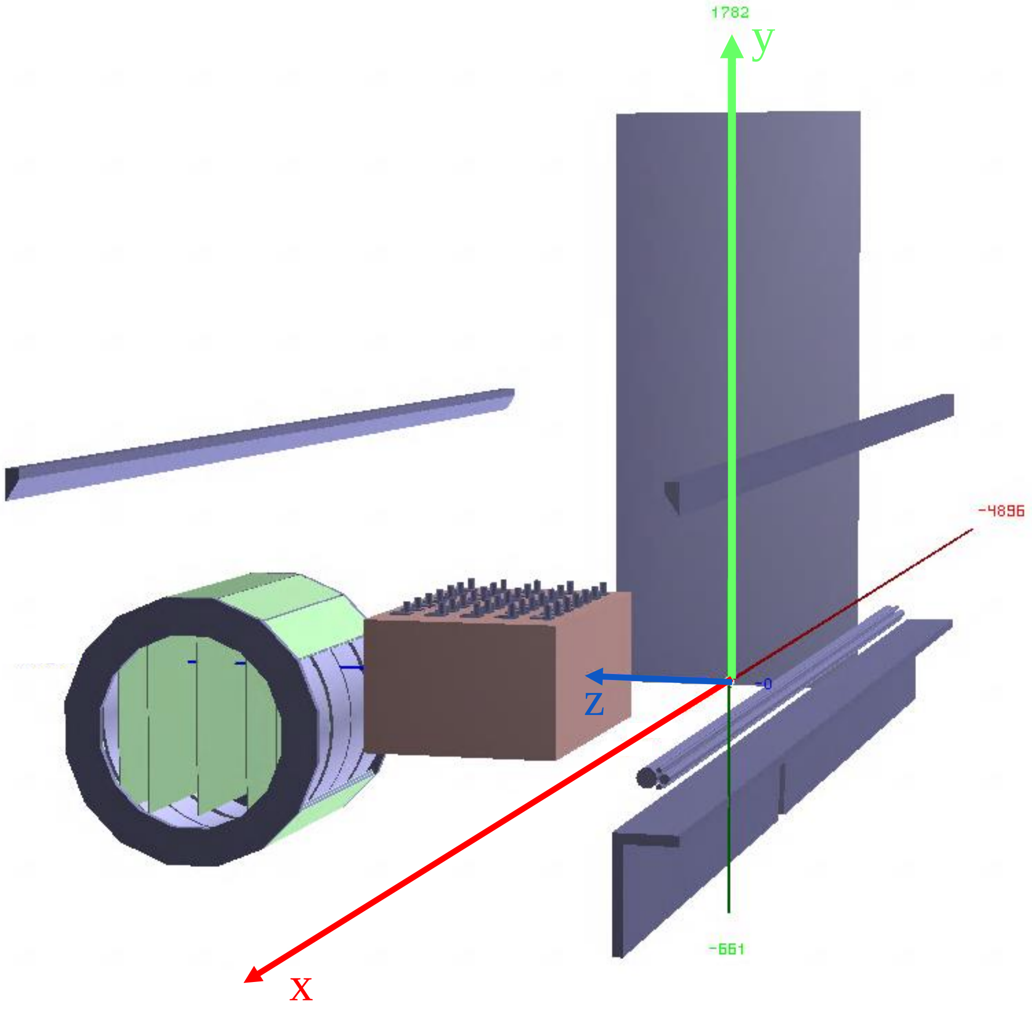
- For the single spill sample we also compare the results for an analysis where a fiducial cut on the interaction point in ND-LAr was applied and one where it wasn't

- To match reconstructed tracks with their Monte Carlo trajectories we use a simple track matching algorithm

GENERATED SAMPLE: GEOMETRY

- Geometry used:
  - ➢ Baseline ND-LAr from dunendggd
  - ➢ ND-GAr-Lite detector with SPY magnet
    - ➢ 5 Scintillator planes (Minerva-like) of 6mx5mx4cm at (-240, -150, 0, 150, 240) //Not Optimized yet!
    - ➢ Segmented with triangular shapes strips in X/Y (2 cm triangle base)
    - ➢ Includes a muon detector (3 planes of Sc of 2 cm around the magnet yoke of the ND-GAr) with 2x7.5cm iron for mu/pi separation over 500 MeV/c

- Coordinate sytem: z roughly the flux direction, y is the vertical direction and x is the drift direction (i.e. the magnetic field direction)



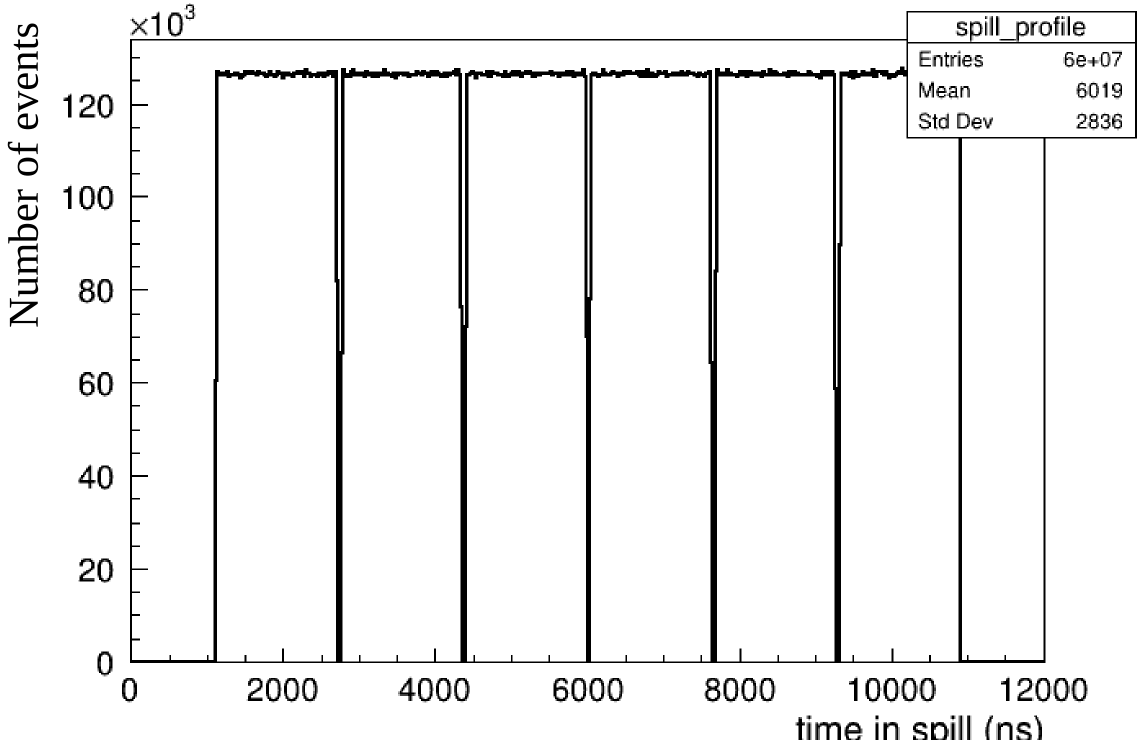
Find geometry on dunegpvm here:
/pnfs/dune/scratch/users/battisti/garlite_std/Geom/nd_hall_mpd_lar_only/nd_hall_dayone_lar_SPY_v2_wMuID.gdml

GENERATED SAMPLE: SINGLE SPILL VS SINGLE INTERACTION

- Spill sample (9.16×10^5 total spills) :
  - Single neutrino events generated with Genie v2 with vertex in volArgonCubeActive
  - Spills built with Genie Overlay using standard spill time structure (5 batch time structure, no real bunch structure yet, $7.5 \times 10^5 pot$ worth of events per spill)
  - Propagation with edep-sim v3
  - Reconstruction algorithm modified to divide spills in 19ns “wide” time groups: track finding applied to each time group separately

- Single event sample (10^6 events):
  - Produced by Eldwan on same geometry, same as the one used in: https://indico.fnal.gov/event/46503/contributions/215080/attachments/143152/181005/l2g_Presentation_DUNE-Collaboration_May2021.pdf

SPILL TIME STRUCTURE



Thanks to Andrew Cudd for this

TRACK MATCHING ALGORITHM

Based on work by Leo Bellantoni

- Primary muon track matching algorithm:

    1. Event by event get all MC primary muon trajectories that have at least one point in a defined cylinder volume

    2. For each muon thus found, cycle over all the ND-GAr reconstructed tracks for the event (currently only 1 or 0) and evaluate the angle between the reconstructed track momentum and the MC momentum taken at the first MC trajectory point in the cylinder volume. Save the track with the smallest angle θ

    3. Calculate the distance Δx between the saved track and trajectory in the plane transverse to the direction of the MC momentum

    4. Impose the cuts:($\cos\theta > 0.997$ && $\Delta x < 3\text{cm}$). If these are passed the track was matched

Same as in https://indico.fnal.gov/event/46503/contributions/215080/attachments/143152/181005/l2g_Presentation_DUNE-Collaboration_May2021.pdf)

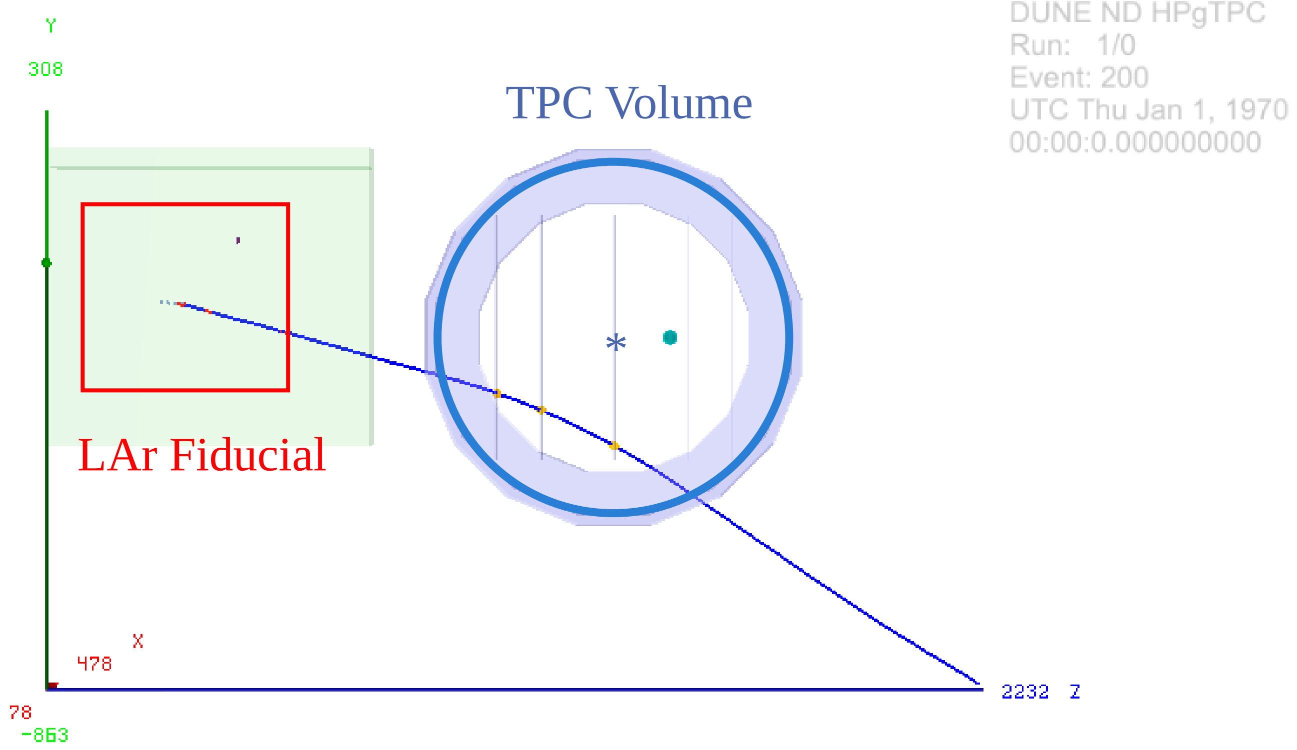
SAMPLE SELECTION

- Two volumes were defined:

  1. TPC Volume: Cylinder having $(Radius, Length) = (349.9{,}669.6)$cm and centered in $(x, y, z) = (0{,}-150.473{,}1486)$cm

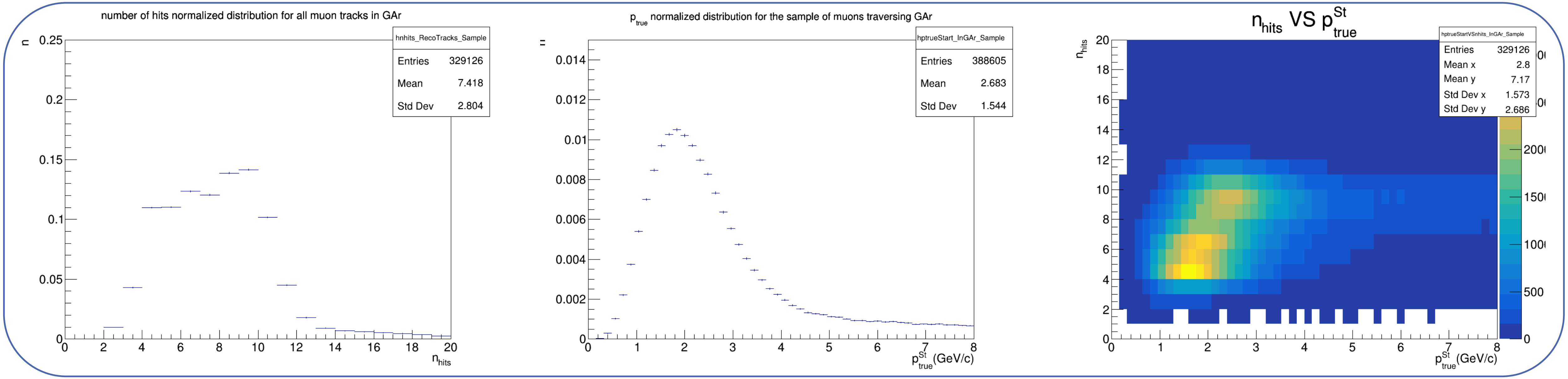
  2. LAr Fiducial Volume : A parallelepiped within ND-Lar: $x \in (-300; 300)cm$; y $\in$ $(-167; 33)cm$; z $\in (-465{,}765)cm$

- We define three samples:
  1. Single event TPC: Single event sample TPC cut only (all primary muons that have at least a point in TPC Volume; same as in previous study)
  2. Single Spill TPC: Single spill sample TPC cut only
  3. Single Spill TPC+LAr: TPC cut+LAr fiducial cut (only primary muons that have their first trajectory point in Lar Fiducial Volume)



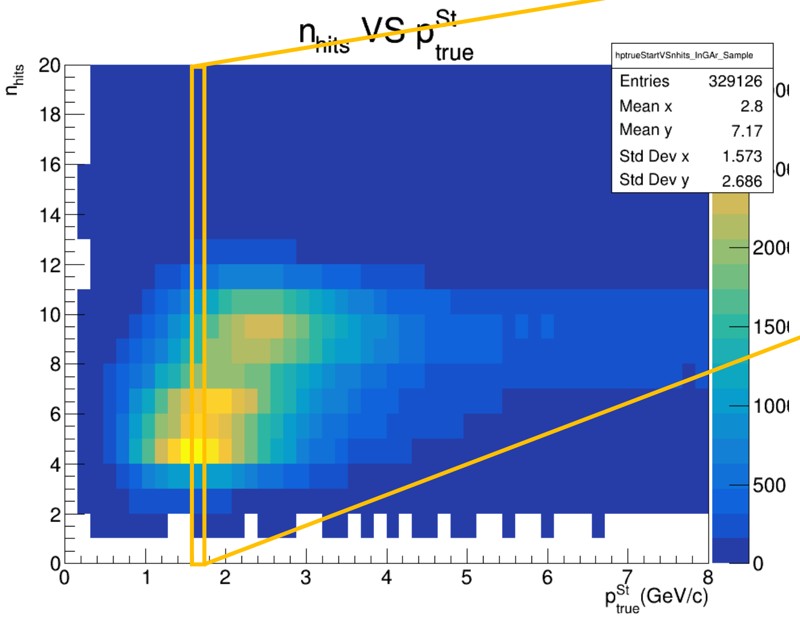
SAMPLE DEFINING DISTRIBUTIONS

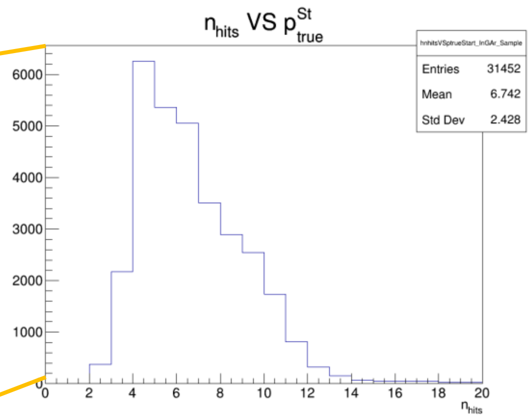
Single event TPC



- To characterize the samples, we consider two fundamental characteristics:
    1. n_{hits} = Number of hits on the scintillator planes that are associated to the tracks found in events having at least one MC trajectory in the volume. In first approximation we expect two hits for each plane traversed by the particle ("reconstructed quantity")
    2. p^{St}_{true} = Initial true MC muon momentum in [GeV/c] for all MC trajectories in the volume ("MC truth quantity")

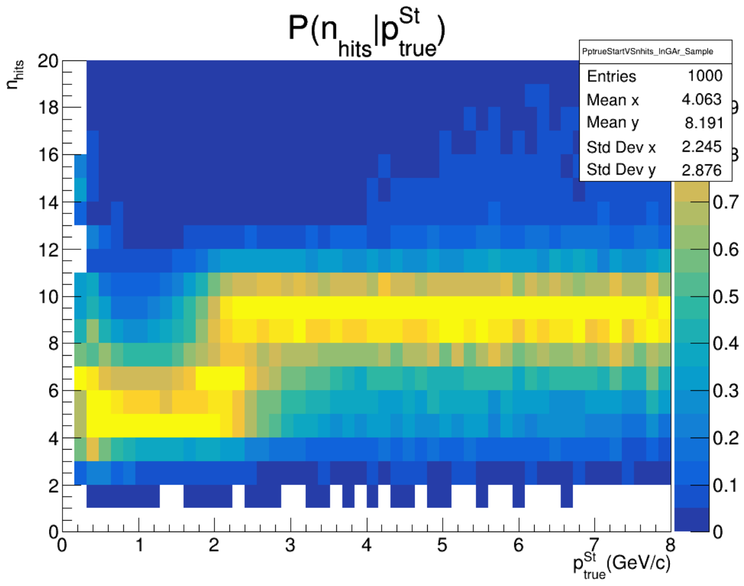
CONDITIONAL PROBABILITY DISTRIBUTIONS





Devide all bin contents in the slice by the maximum value in the distribution

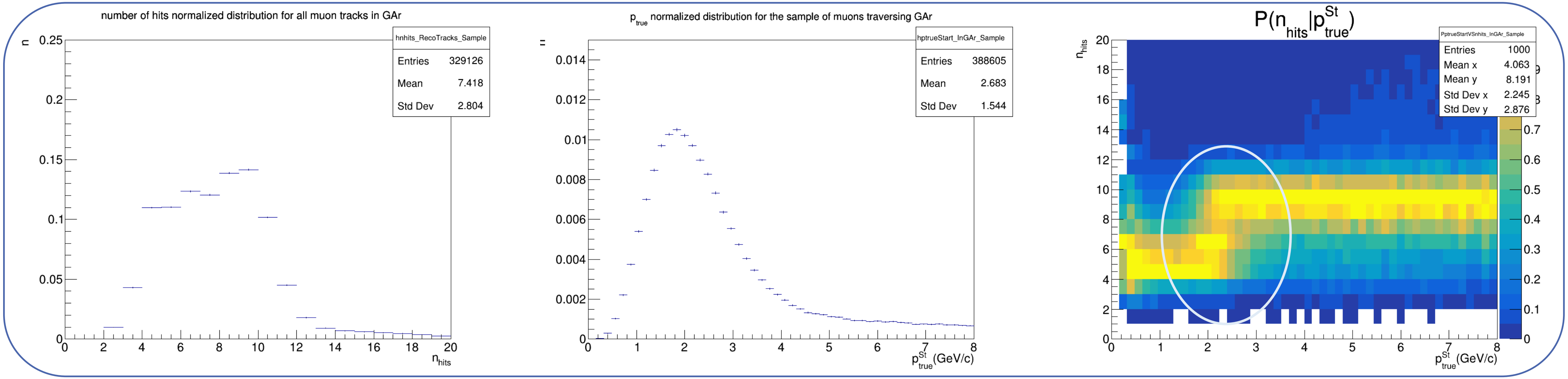
Conditional probability



Select slices in terms of one of the relevant quantities and get the histogram projection

SAMPLE DEFINING DISTRIBUTIONS

Single Event TPC

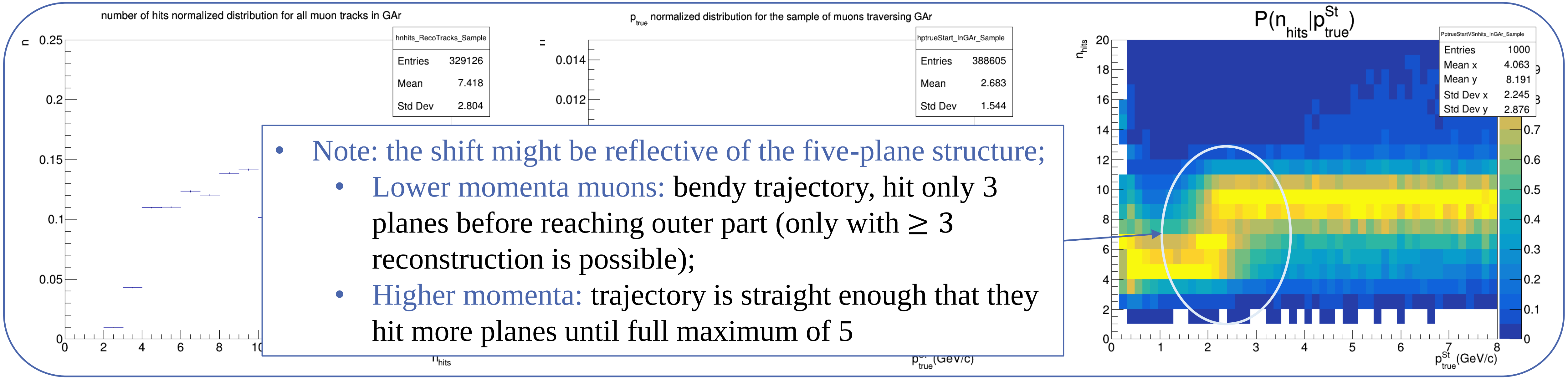


- Looking at the $P(n_{hits}|p^{St}_{true})$ distribution we clearly see a shift in the n_{hits} peak from ~ 4.5 to ~ 9.5 happening right around the oscillation peak $p^{St}_{true} \sim 2.5$ GeV$/c$

- This shift implies that the tracking performance will likely strongly depend on p^{St}_{true} and n_{hits} in the most interesting region for analysis: important to study tracking performance dependence on p^{St}_{true} and n_{hits}

SAMPLE DEFINING DISTRIBUTIONS

Single Event TPC



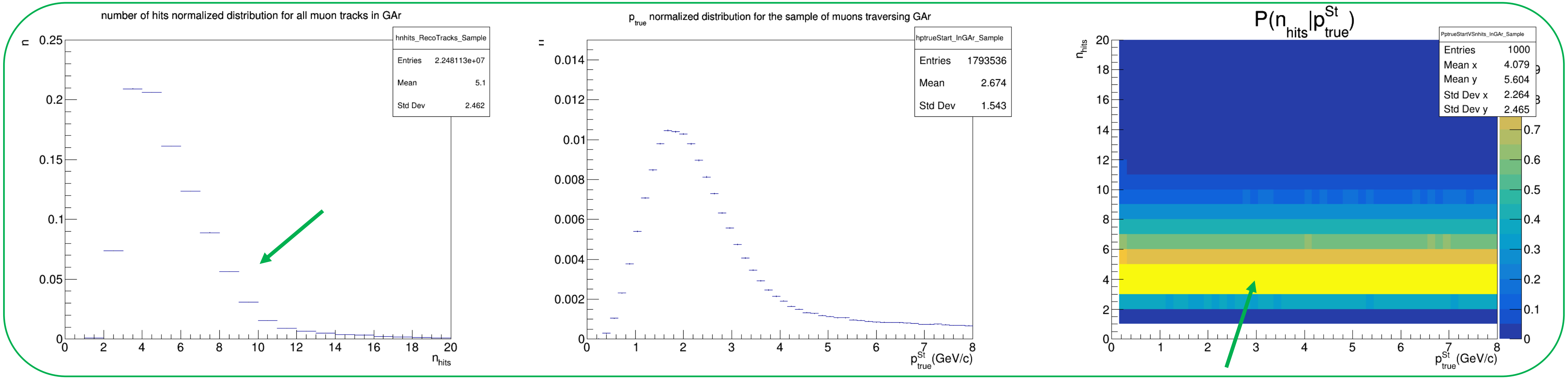
- Note: the shift might be reflective of the five-plane structure;
  - Lower momenta muons: bendy trajectory, hit only 3 planes before reaching outer part (only with ≥ 3 reconstruction is possible);
  - Higher momenta: trajectory is straight enough that they hit more planes until full maximum of 5

- Looking at the $P(n_{hits}|p^{St}_{true})$ distribution we clearly see a shift in the n_{hits} peak from ~ 4.5 to ~ 9.5 happening right around the oscillation peak $p^{St}_{true} \sim 2.5\ \mathrm{GeV}/c$

- This shift implies that the tracking performance will likely strongly depend on p^{St}_{true} and n_{hits} in the most interesting region for analysis: important to study tracking performance dependence on p^{St}_{true} and n_{hits}

SAMPLE DEFINING DISTRIBUTIONS

Single Spill TPC

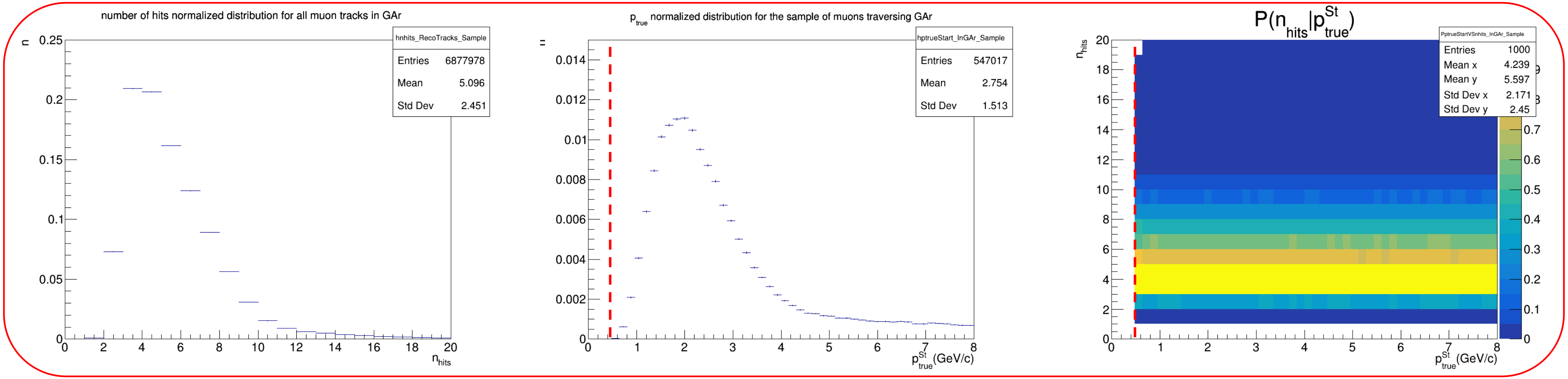


- For the Single Spill $P(n_{hits}|p^{St}_{true})$ distribution we note that the double peak structure seen in the single event sample is not present anymore

- Note: absence of the shift might be linked to the fact that we observe many less high n_{hits} tracks in the single spill sample; this might be a consequence of incorrect track splitting in the “bunching” phase of the new track finding algorithm

SAMPLE DEFINING DISTRIBUTIONS

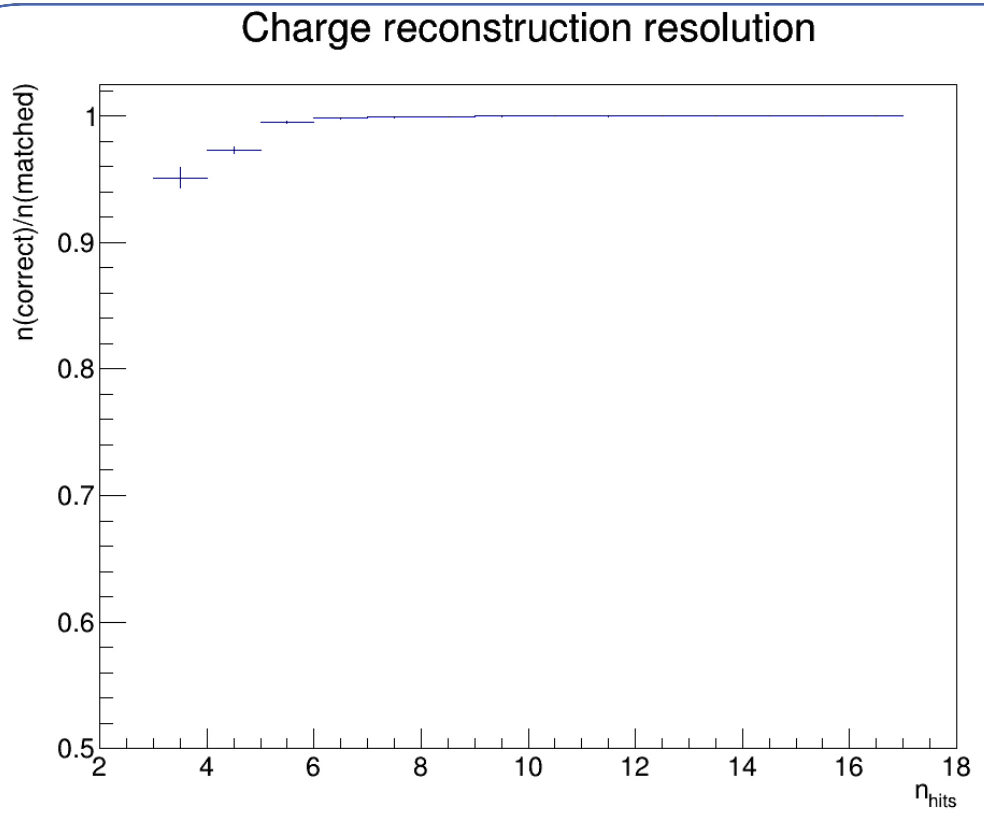
Single Spill TPC+LAr

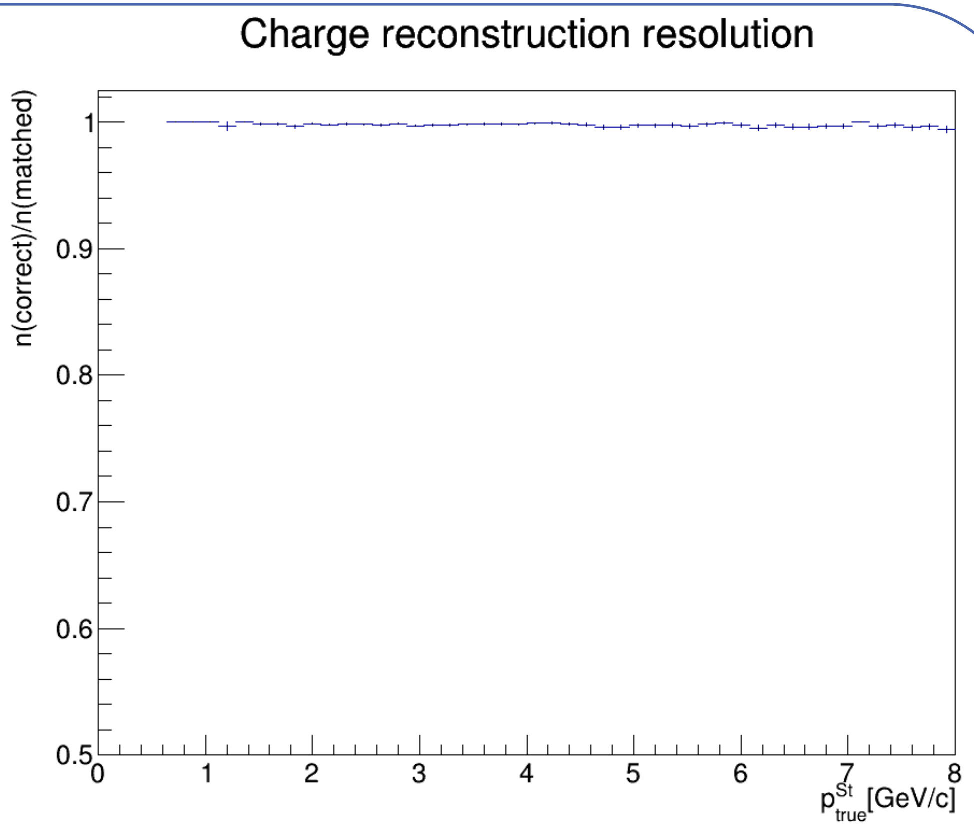


- For the Single Spill distribution with the added LAr cut we can see how we have a cut in the momentum distribution at around 0.5 GeV/c

CHARGE RECONSTRUCTION RESOLUTION

Single event TPC

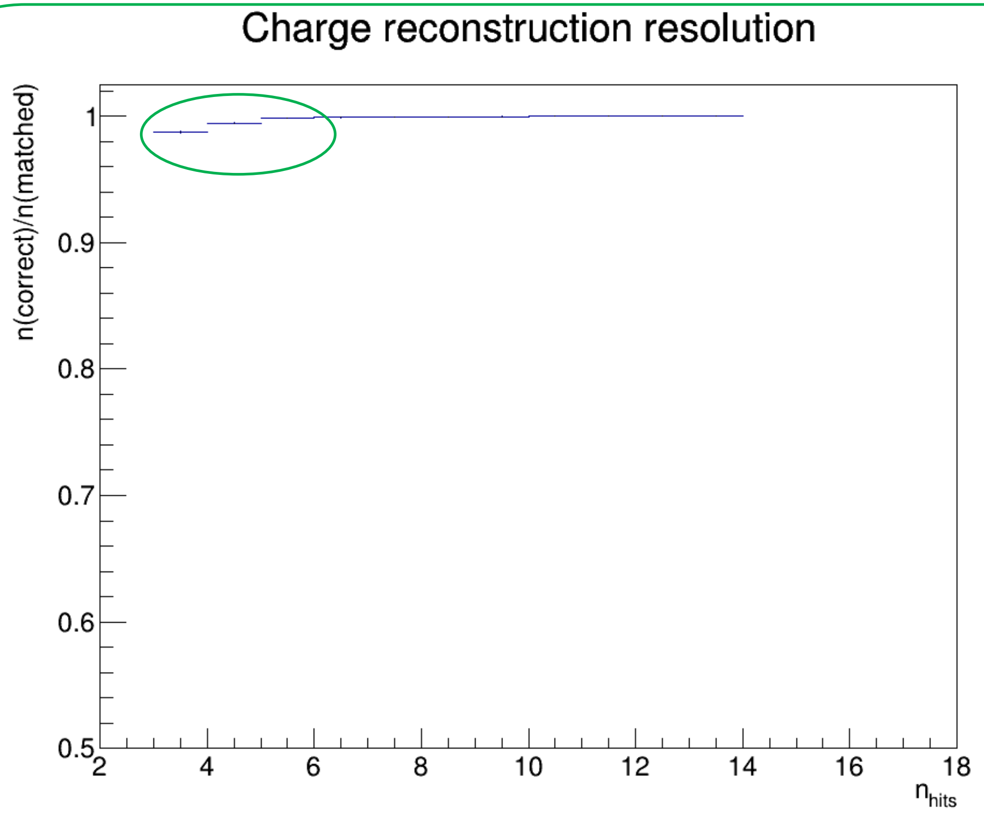


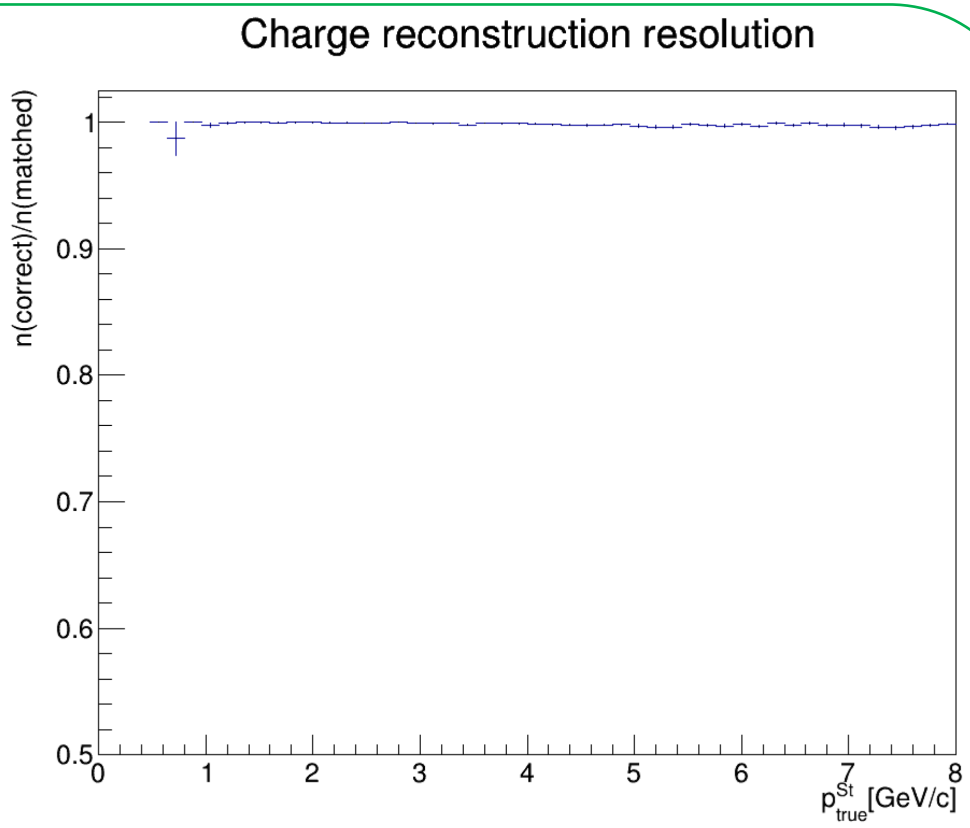


- We define the Charge Resolution as the ratio between the number of correctly reconstructed charges among the tracks that were matched and the total number matched tracks
- We see that this quantity seems mostly sensitive to the n_{hits}

CHARGE RECONSTRUCTION RESOLUTION

Single Spill TPC

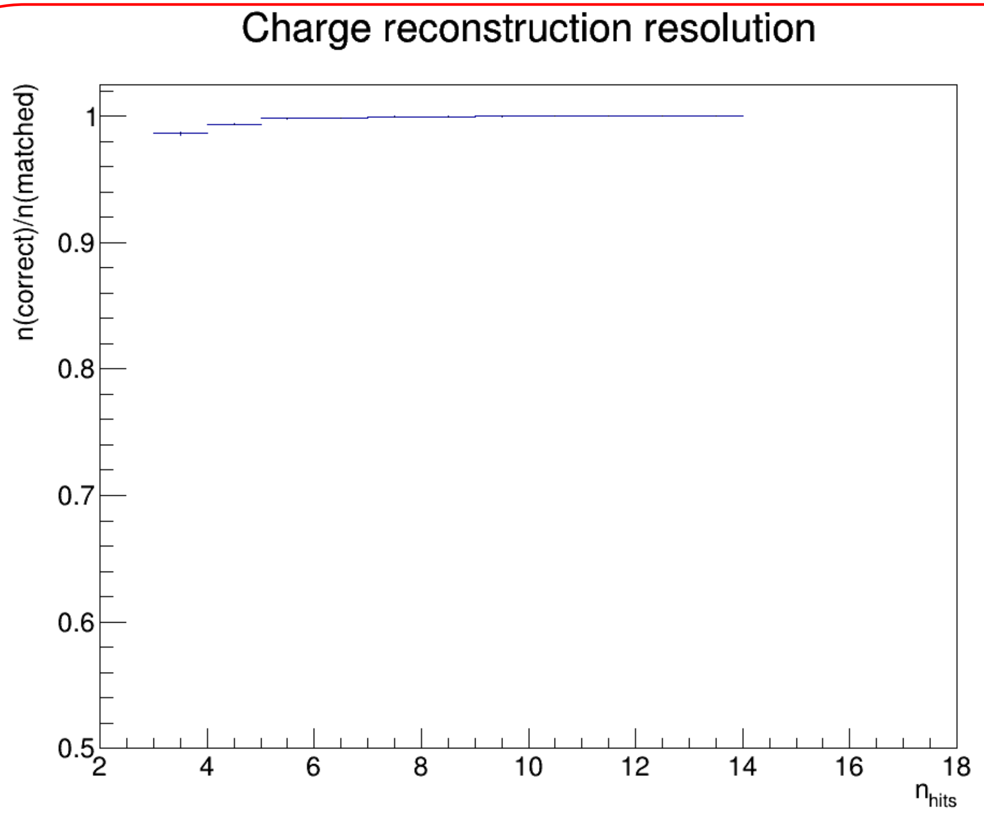


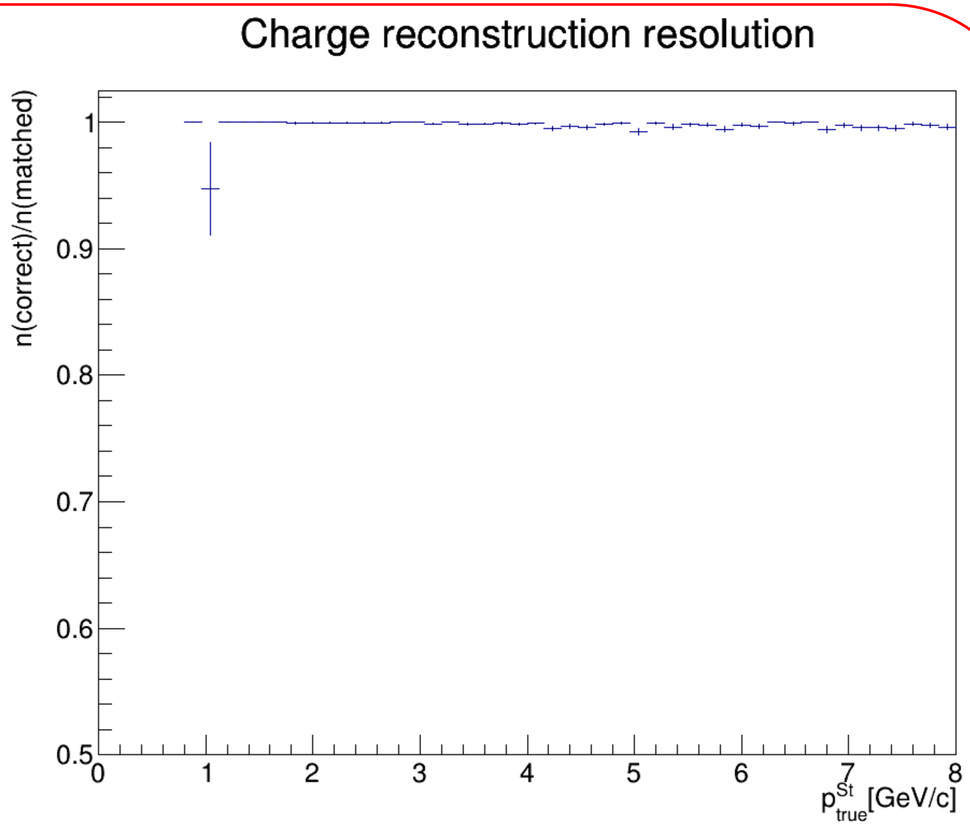


- We see how in the Single spill sample the charge resolution at lower n_{hits} is slightly higher. This might be a byproduct of track "chopping": some of the low hit tracks might be tracks that would have been longer in reality and likely "bendy"

CHARGE RECONSTRUCTION RESOLUTION

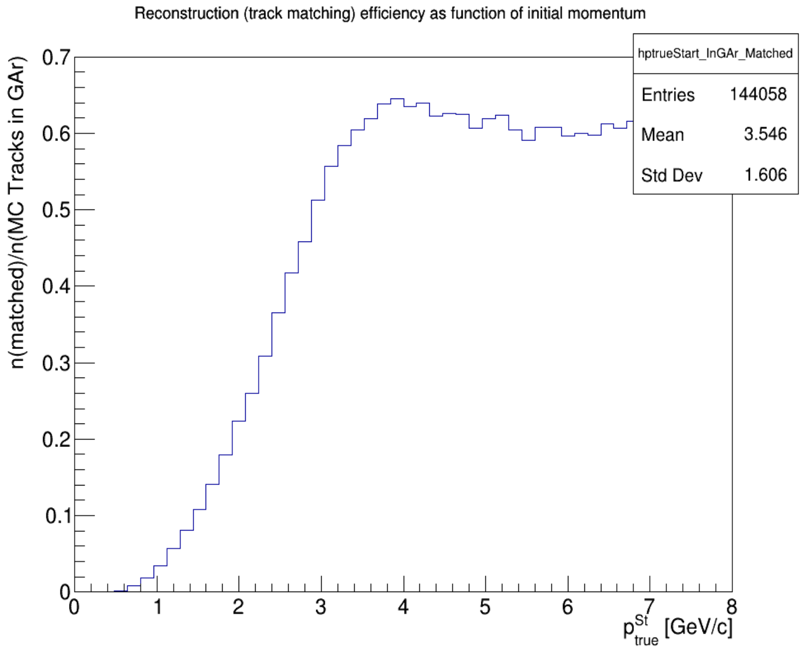
Single Spill TPC+LAr



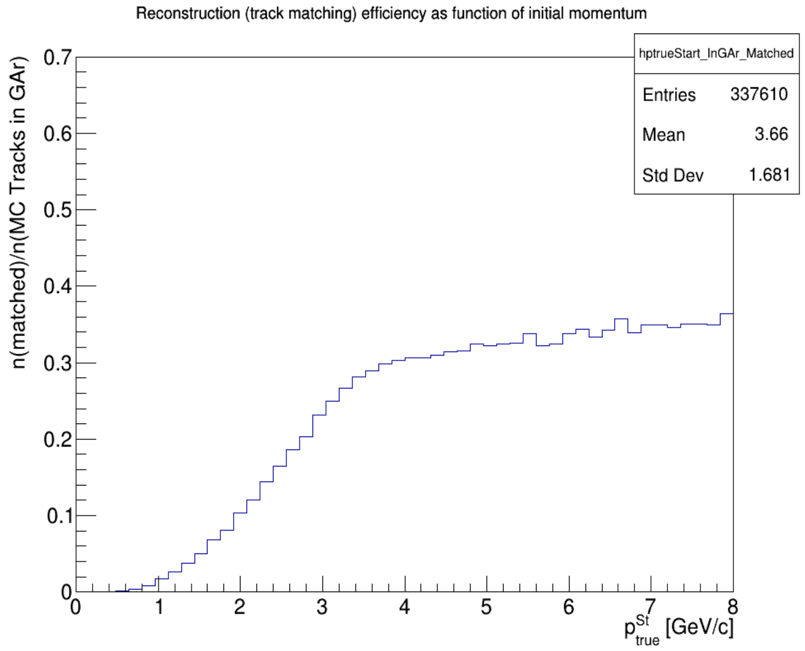


- We see no significant change after the cut

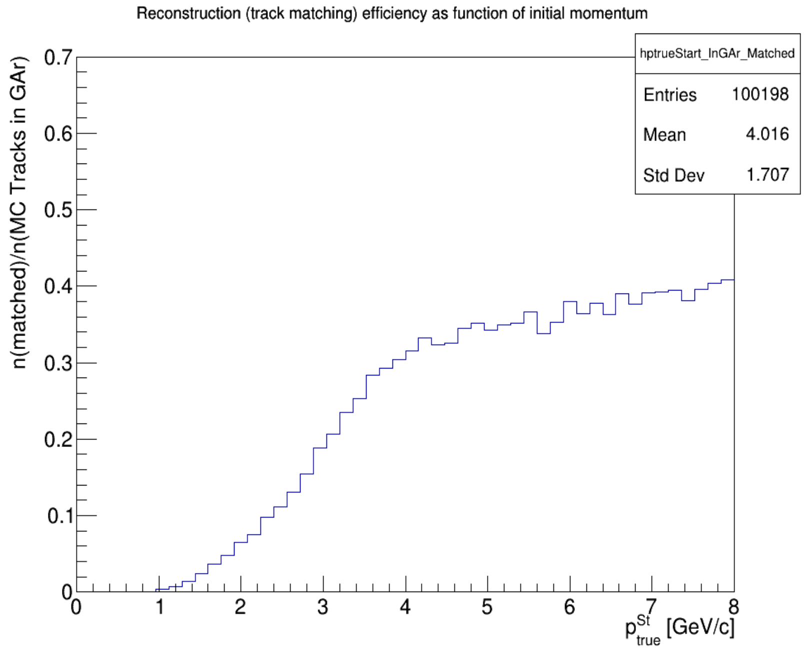
TRACK MATCHING EFFICIENCY



Single event TPC



Single Spill TPC

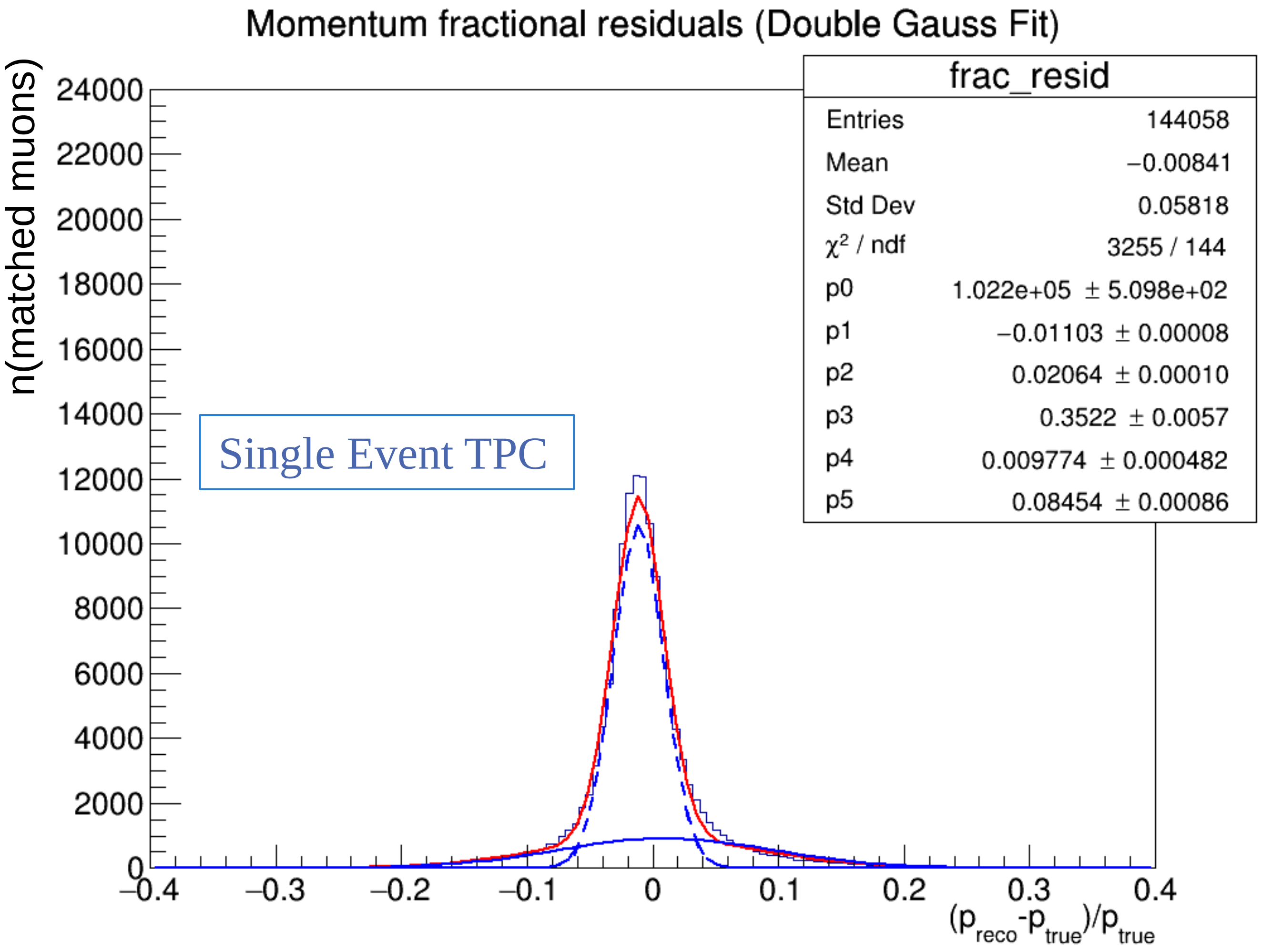


Single Spill TPC+LAr

- $\epsilon(p^{St}_{true})$ = Ratio between the number of matched trajectories and the total number of MC primary muon trajectories traversing the TPC volume

- Lower efficiency in single spill might be linked to busier events (i.e. remnants of a previous event interfering with the following one); this would explain increase in efficiency after LAr cut

MOMENTUM RESOLUTION: FRACTIONAL RESIDUALS



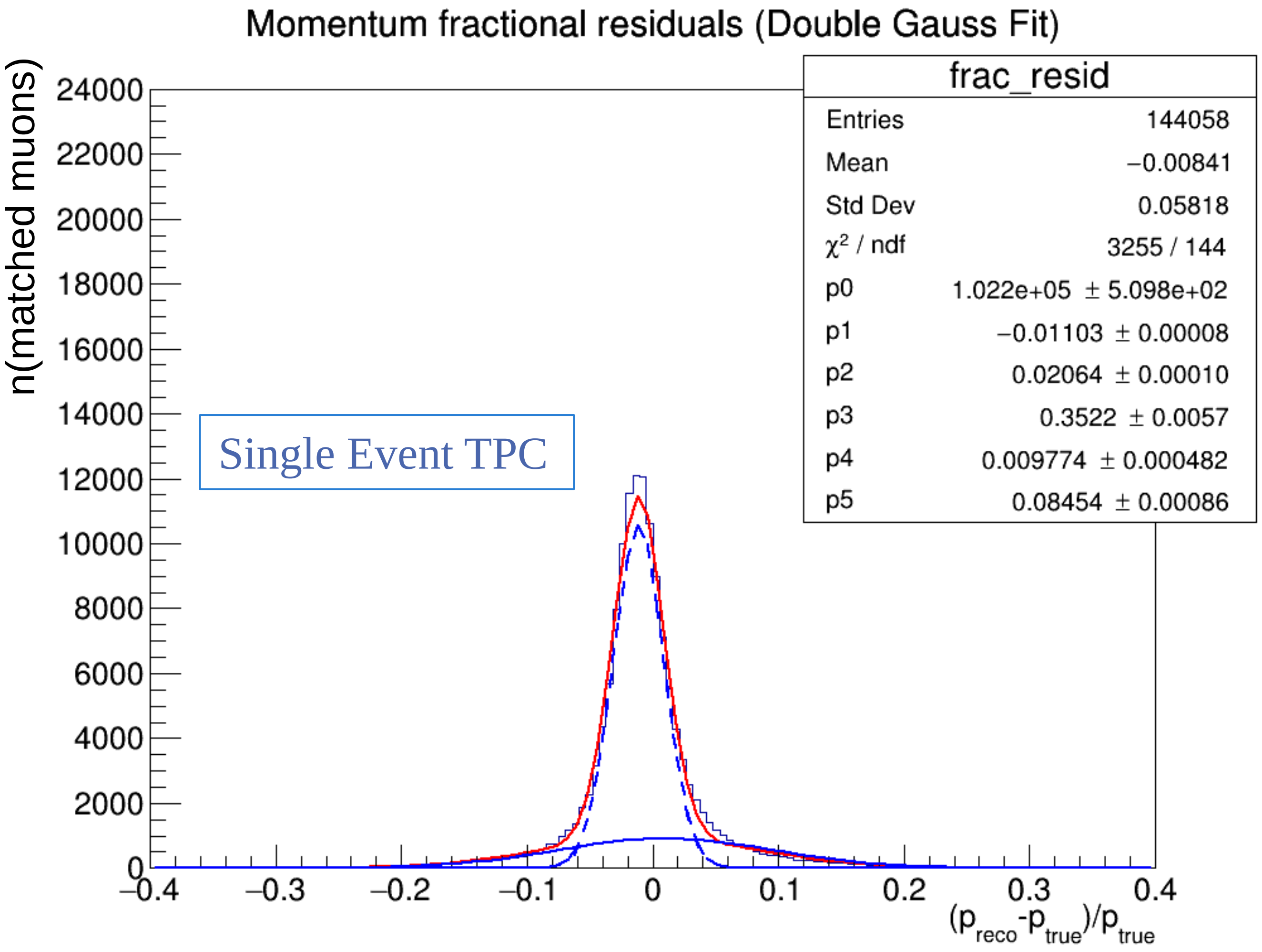
- We define the momentum resolution in terms of fractional residuals:

$$Residual = \frac{p_{reco} - p_{true}}{p_{true}}$$

- Where p_{true} and p_{reco} in this case are evaluated at the entering point in the TPC Volume
- We then fit the distribution with a double Gaussian function:

$$G = \left(\frac{\delta x_{bin}}{\sqrt{2\pi}}\right) p_0 \times \left\{ \begin{array}{c} \frac{1}{p_2}\exp\left(-\frac{1}{2}\left(\frac{x-p_1}{p_2}\right)^2\right) + \\ \frac{p_3}{p_5}\exp\left(-\frac{1}{2}\left(\frac{x-(p_1+p_4)}{p_5}\right)^2\right) \end{array} \right\}$$

FRACTIONAL RESIDUALS FIT PARAMETERS



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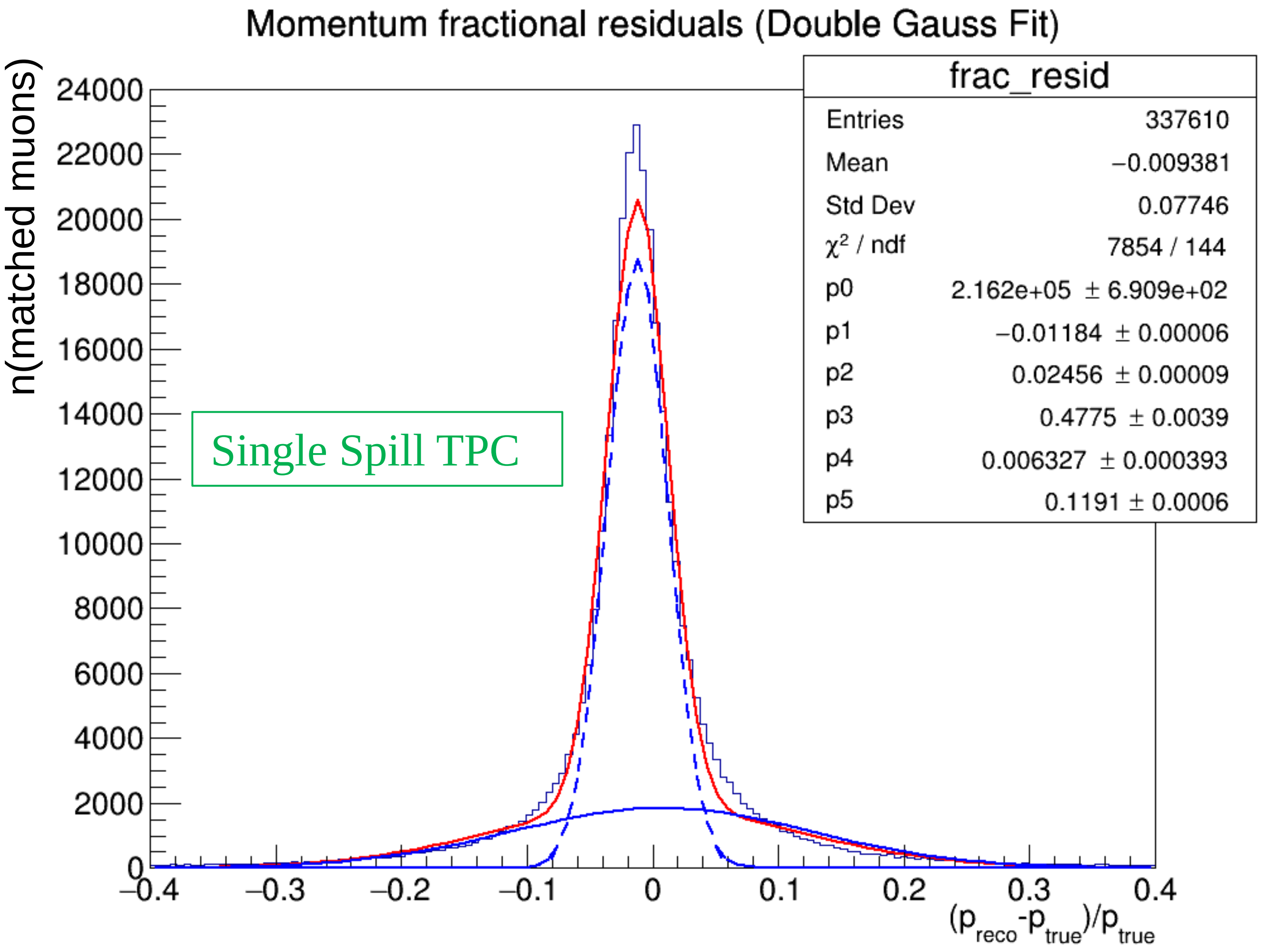
- Where:
  - $p_0 = \mathrm{n_{events}}$ belonging to the main slender Gaussian
  - p_1 = Center of the main slender Gaussian (bias)
  - $p_2 = \sigma$ of the main Gaussian (resolution)
  - p_3 = Ratio between the number of events belonging to the second and first Gaussian
  - p_4 = distance between the centers of the two Gaussians (bias)
  - $p_5 = \sigma$ of the wider, shorter Gaussian (resolution)
  - $p_0(1+p_3)$ = Total $\mathrm{n_{events}}$

FRACTIONAL RESIDUALS FIT PARAMETERS



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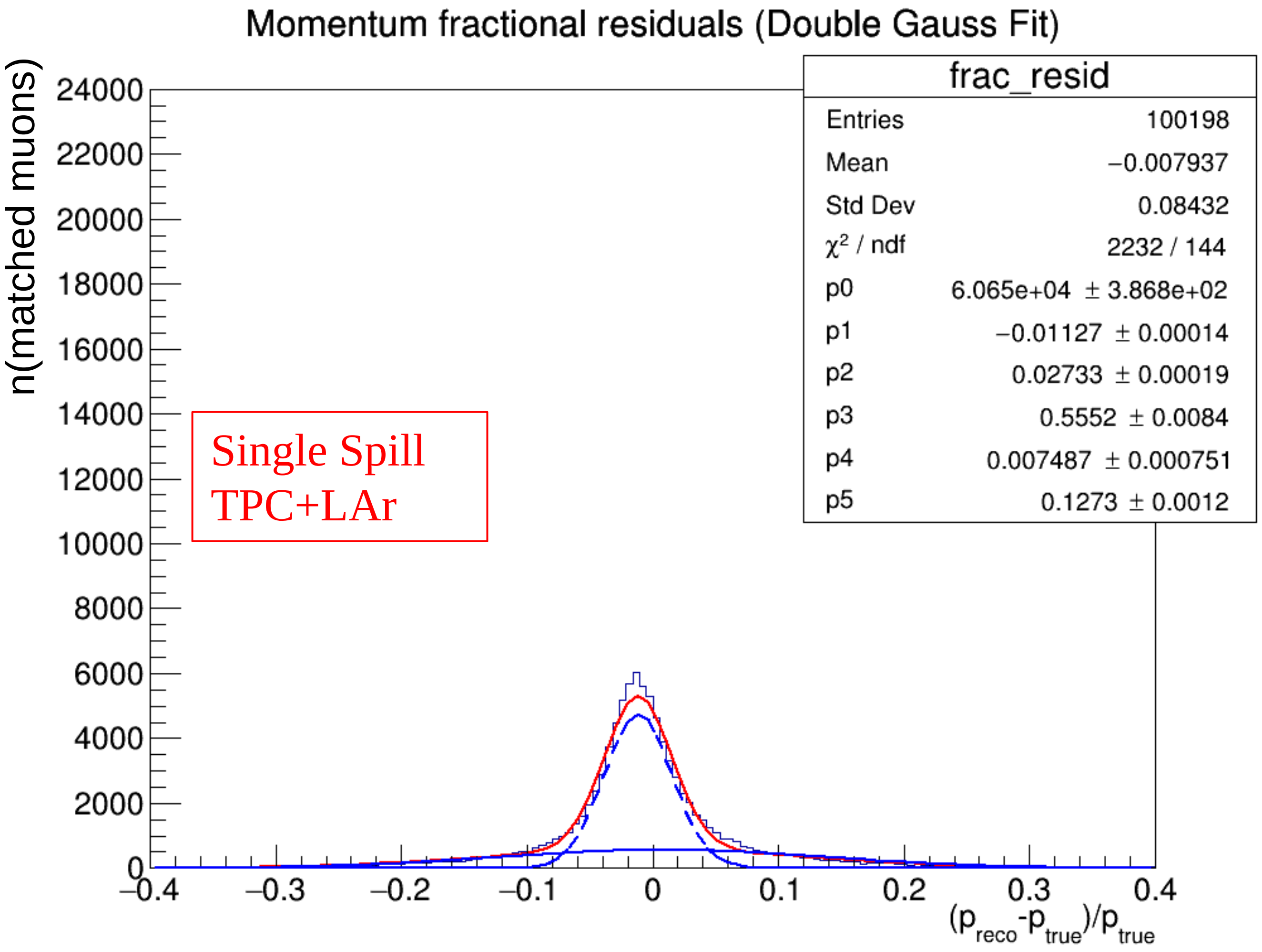
FRACTIONAL RESIDUALS FIT PARAMETERS



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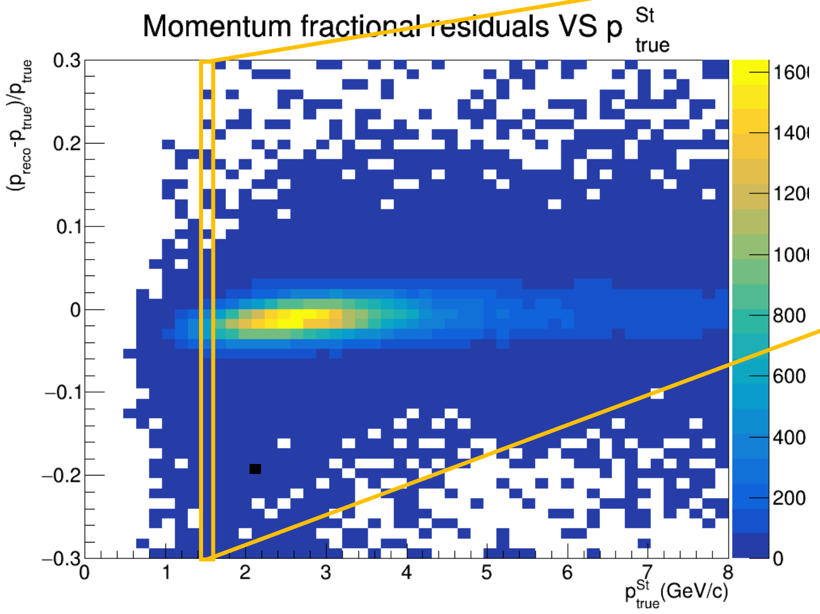
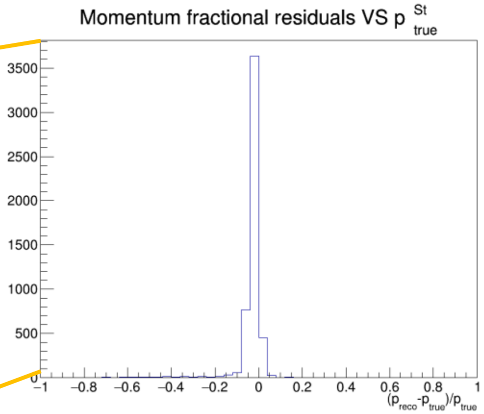
  - $p_5 = \sigma$ of the wider, shorter Gaussian (resolution)
  - $p_0(1 + p_3) = \text{Total } \mathrm{n_{events}}$

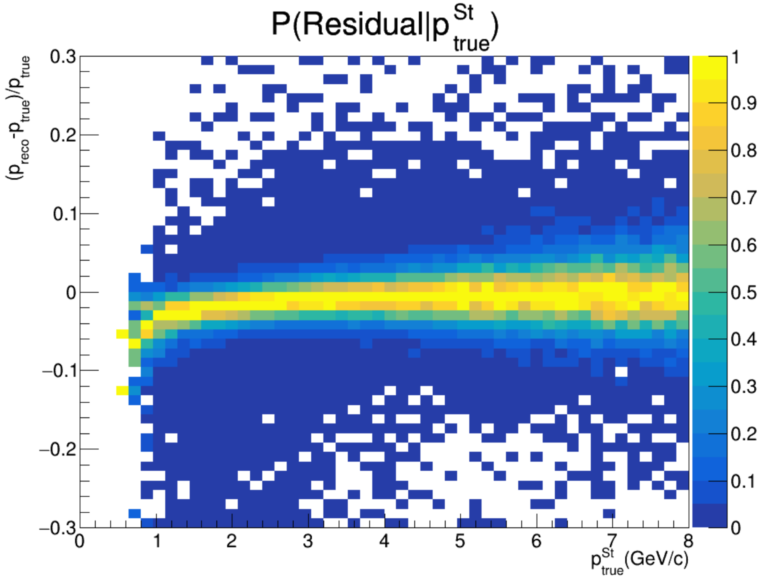
CONDITIONAL PROBABILITY DISTRIBUTIONS





Devide all bin contents in the slice by the maximum value in the distribution

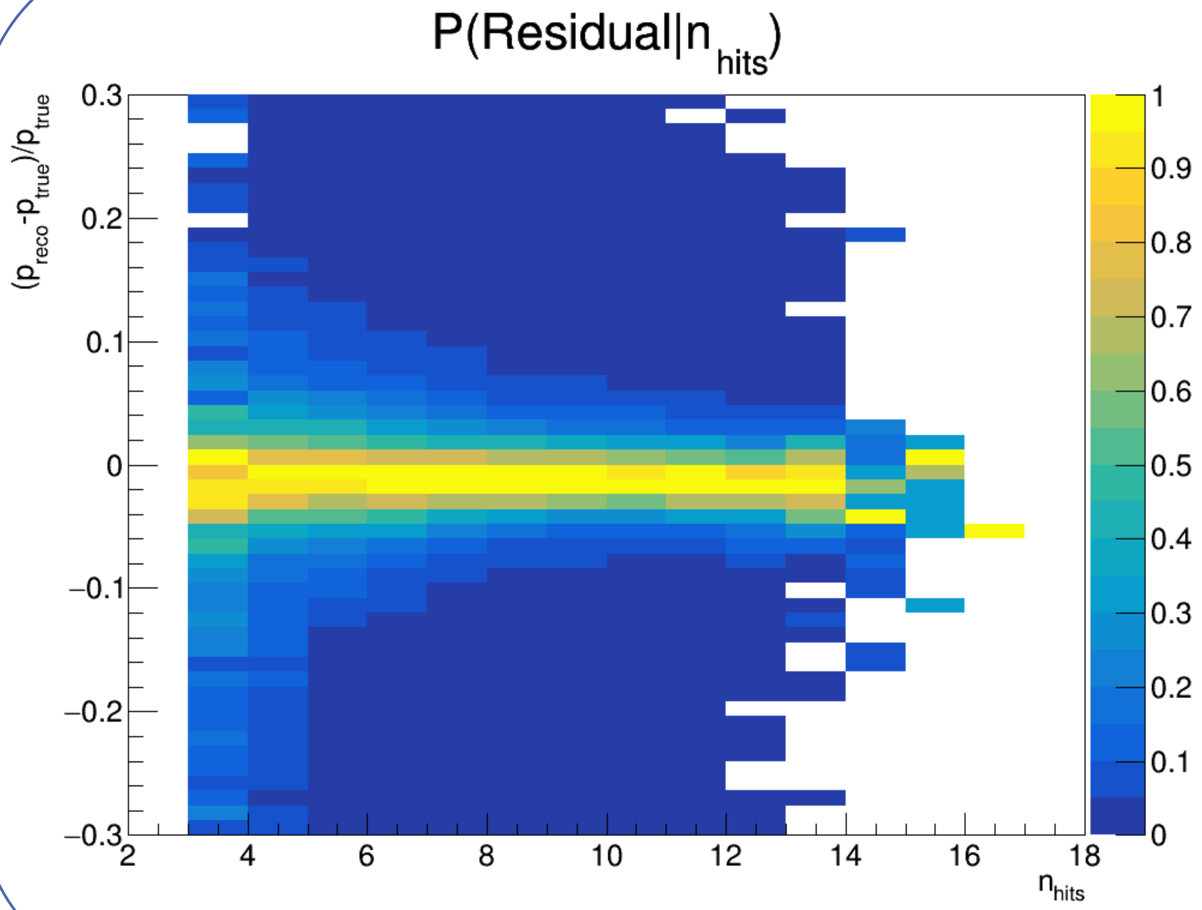
Select slices in terms of one of the relevant quantities and get the histogram projection

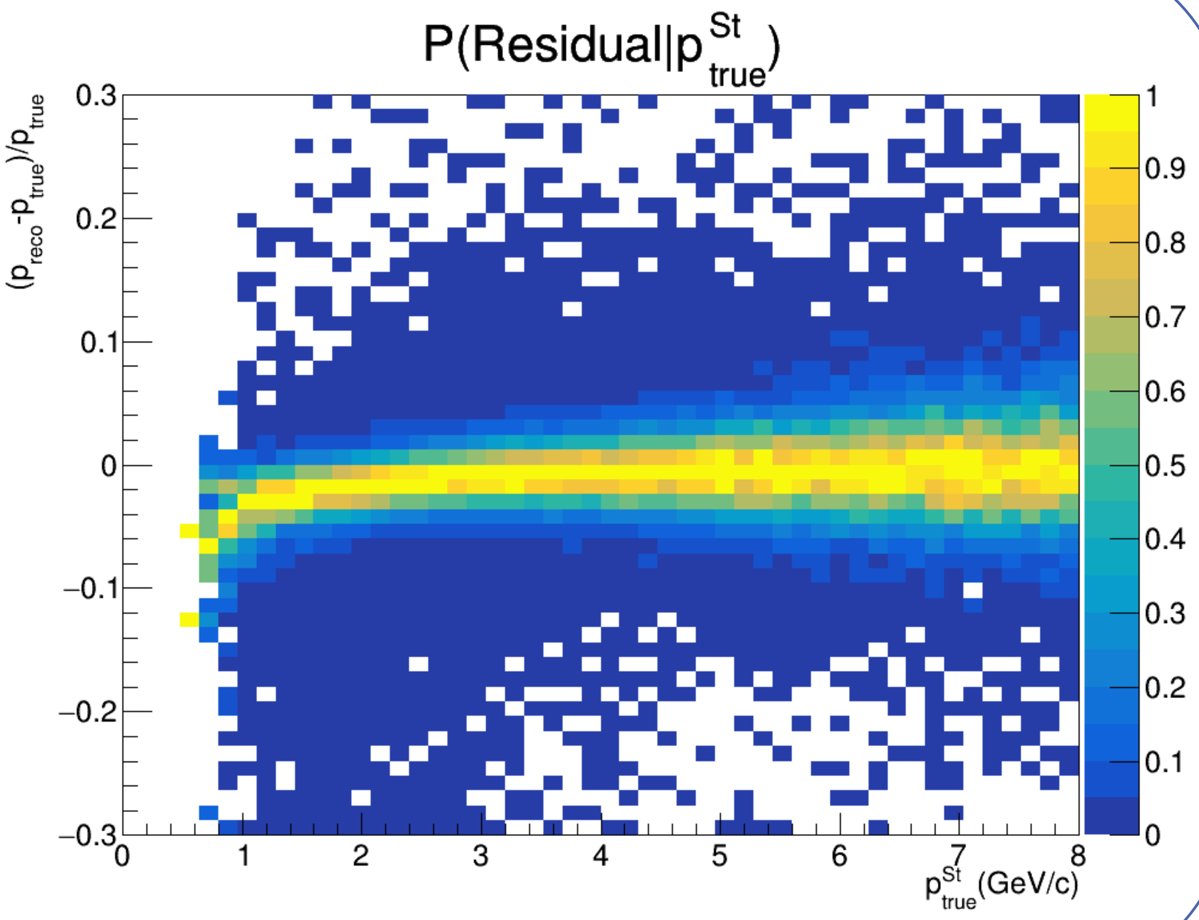


Conditional probability

FRACTIONAL RESIDUALS: PROBABILITY DISTRIBUTIONS

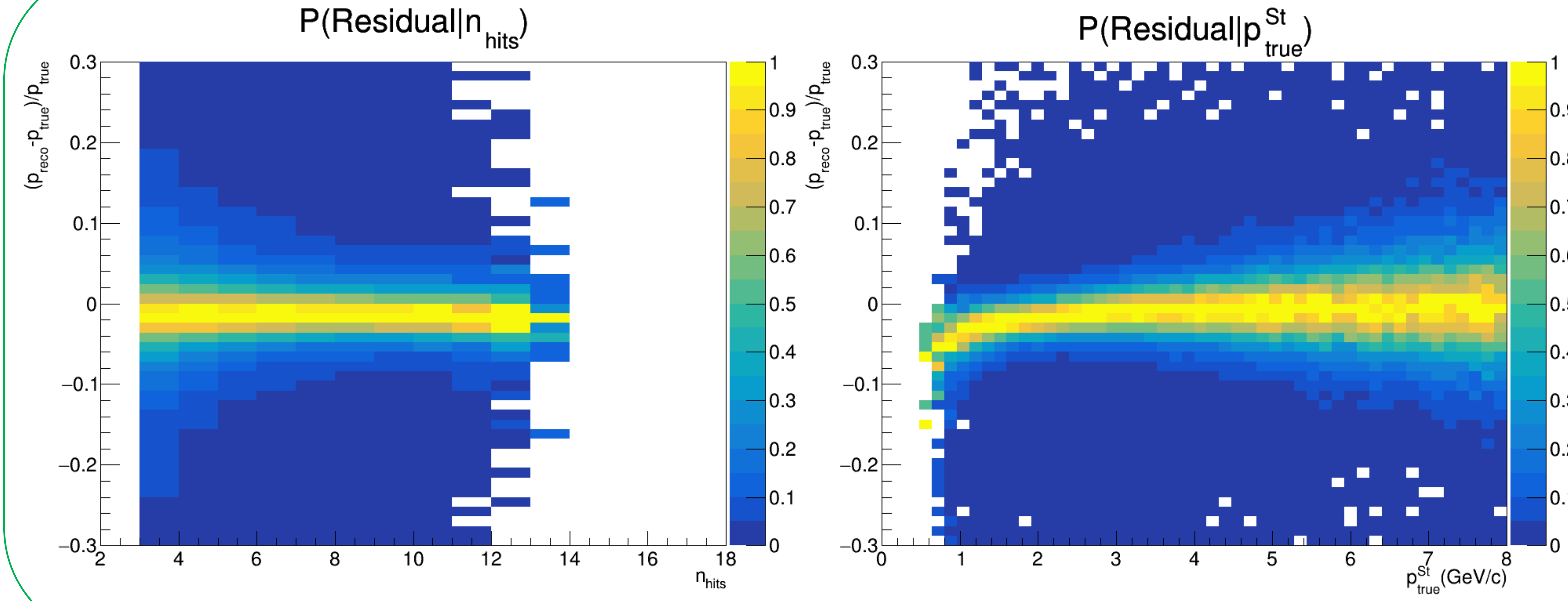
Single Event TPC





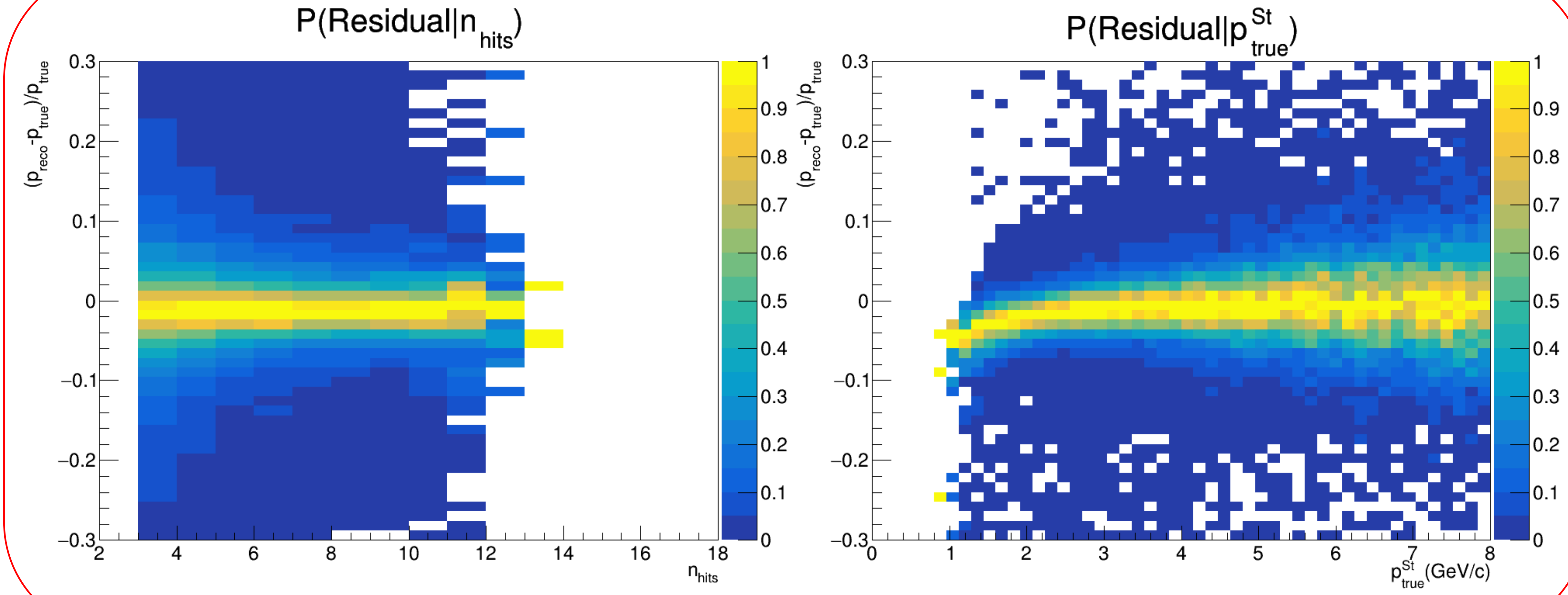
FRACTIONAL RESIDUALS: PROBABILITY DISTRIBUTIONS

Single Spill TPC

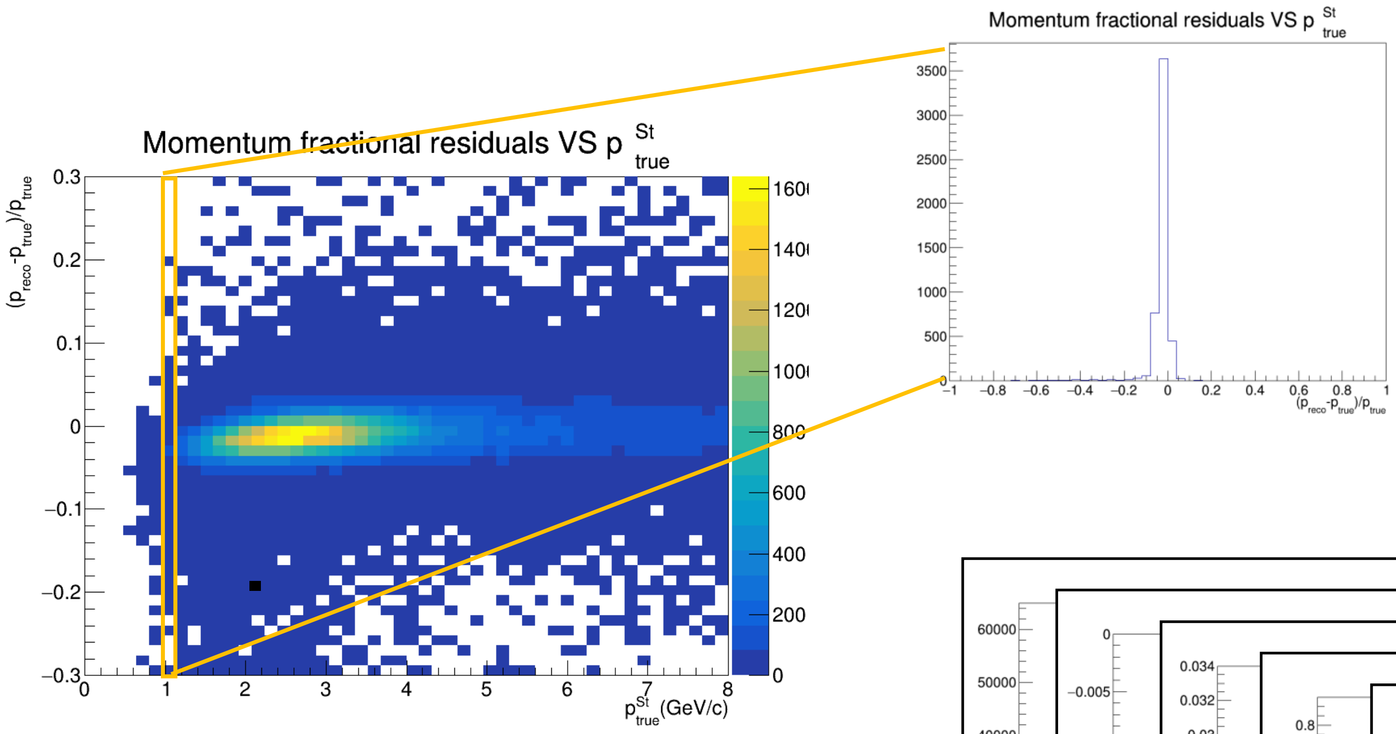


FRACTIONAL RESIDUALS: PROBABILITY DISTRIBUTIONS

Single Spill LAr



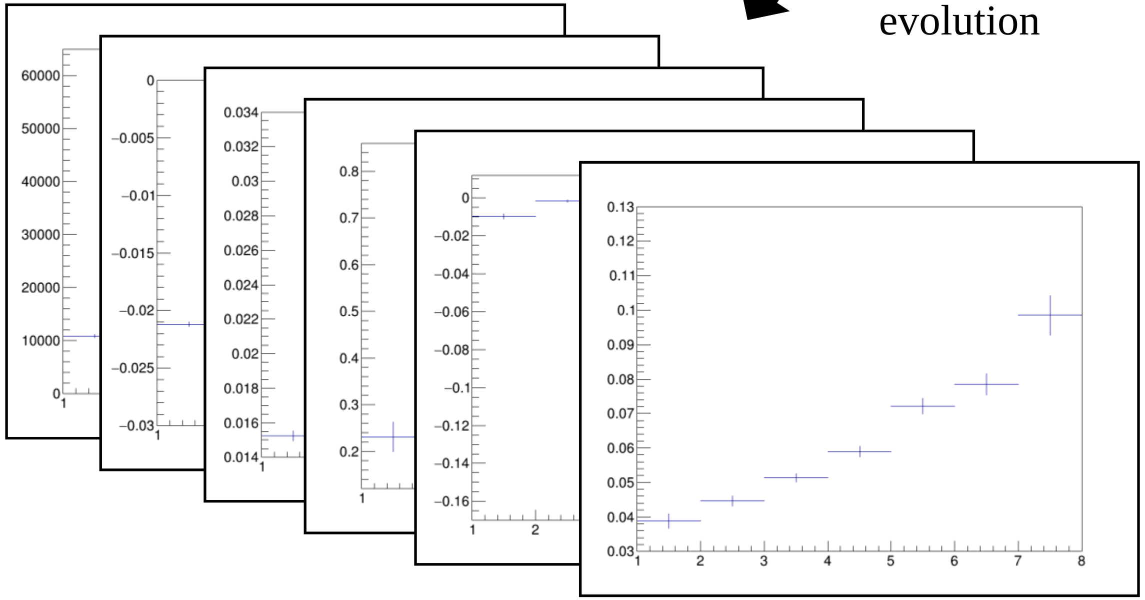
FIT PARAMETERS EVOLUTION



Select slices in terms of one of the relevant quantities and get the histogram projection

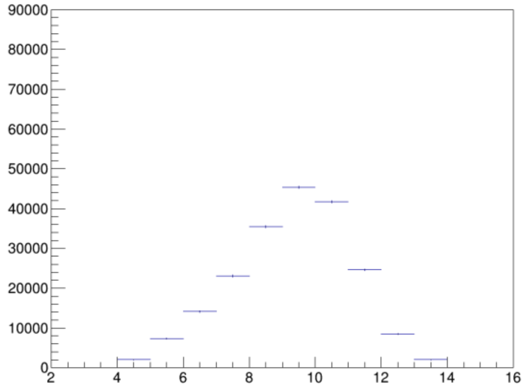
$$G = \left(\frac{\delta x_{bin}}{\sqrt{2\pi}}\right) p_0 \times \left\{ \frac{1}{p_2} \exp\left(-\frac{1}{2}\left(\frac{x-p_1}{p_2}\right)^2\right) + \frac{p_3}{p_5} \exp\left(-\frac{1}{2}\left(\frac{x-(p_1+p_4)}{p_5}\right)^2\right) \right\}$$

Parameter fit evolution

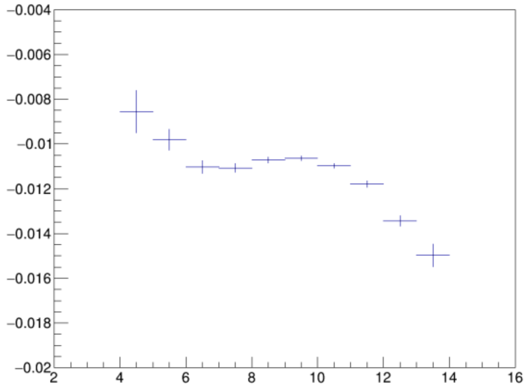


FIT PARAMETERS EVOLUTIONS n_{hits}: SINGLE EVENT TPC

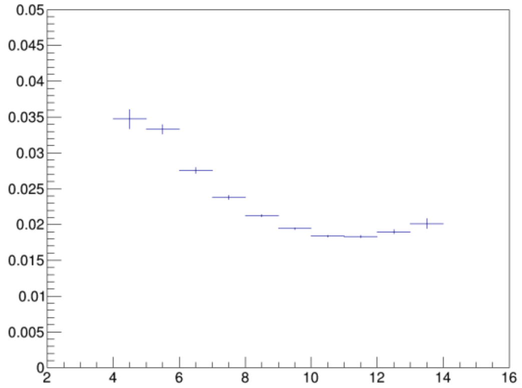
Fitted value of p_0



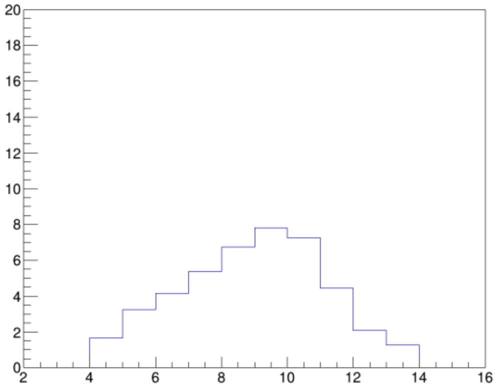
Fitted value of p_1



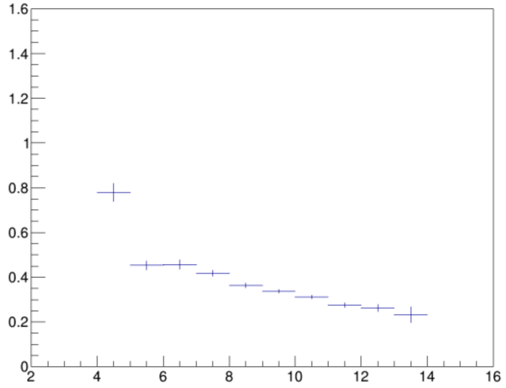
Fitted value of p_2



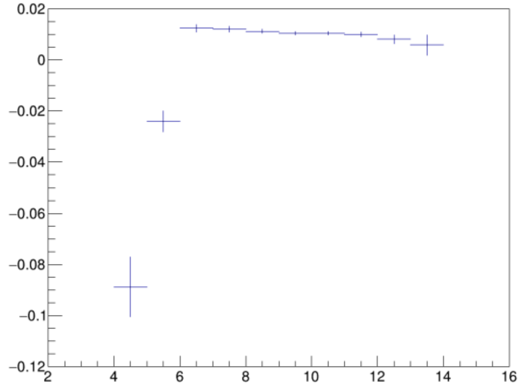
χ^2/NDF



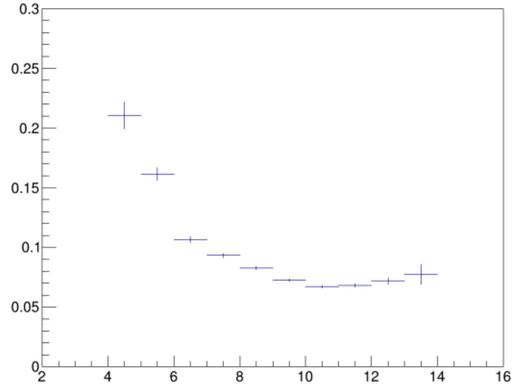
Fitted value of p_3

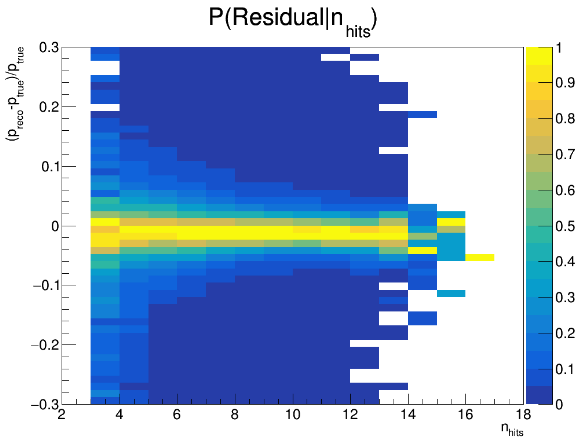


Fitted value of p_4



Fitted value of p_5

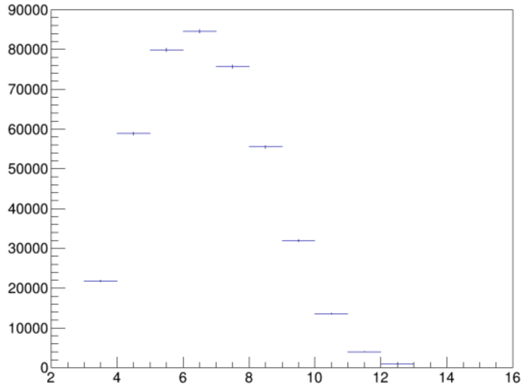




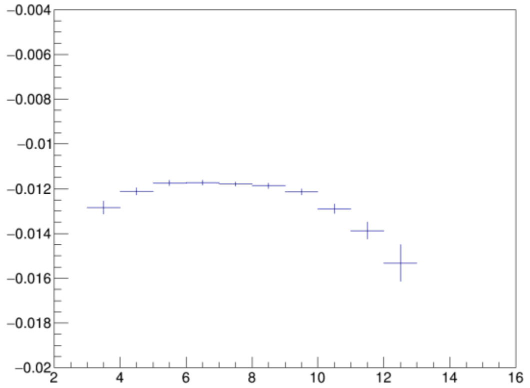
$$G = \left(\frac{\delta x_{bin}}{\sqrt{2\pi}}\right) p_0 \times \left\{ \frac{1}{p_2} \exp\left(-\frac{1}{2}\left(\frac{x - p_1}{p_2}\right)^2\right) + \frac{p_3}{p_5} \exp\left(-\frac{1}{2}\left(\frac{x - (p_1 + p_4)}{p_5}\right)^2\right) \right\}$$

FIT PARAMETERS EVOLUTIONS n_{hits}: SINGLE SPILL TPC

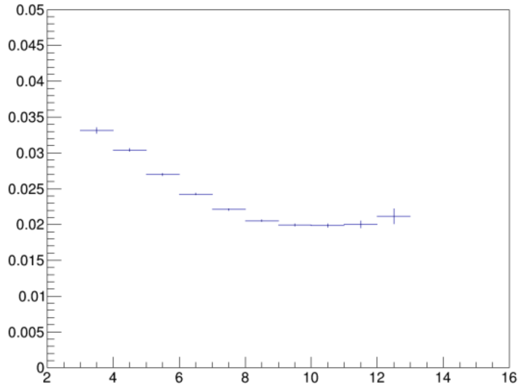
Fitted value of p_0



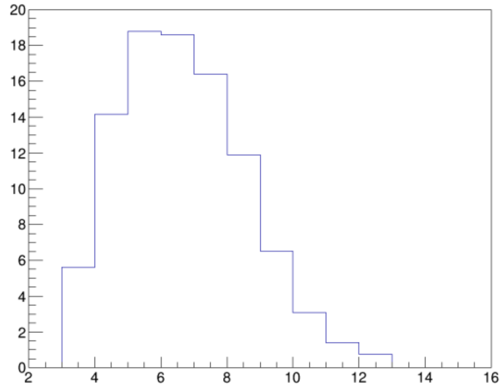
Fitted value of p_1



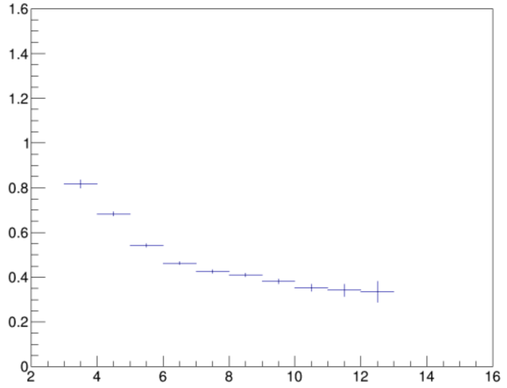
Fitted value of p_2



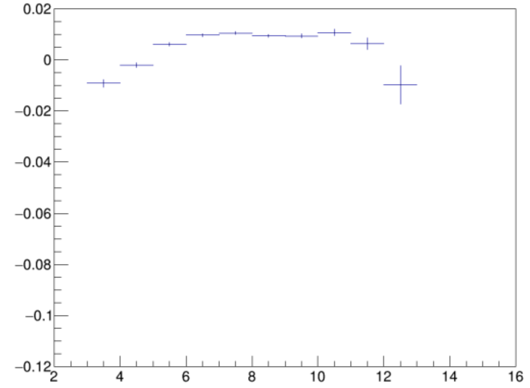
χ^2/NDF



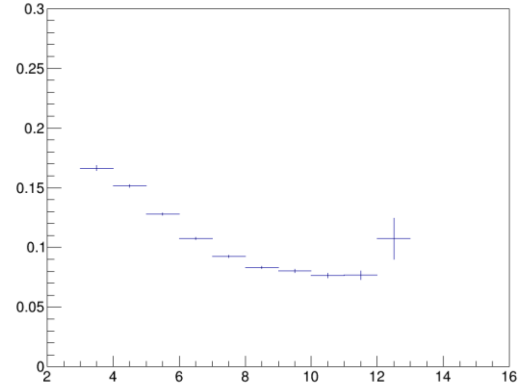
Fitted value of p_3

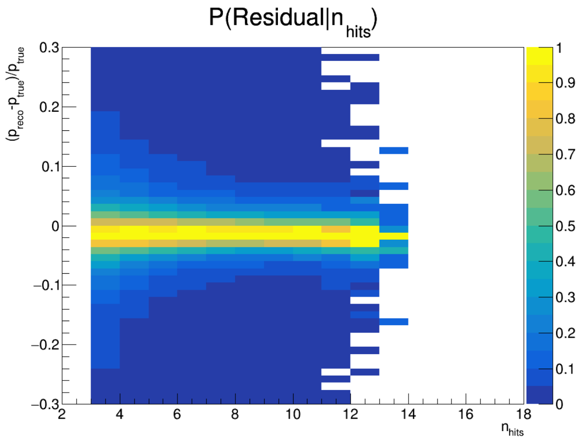


Fitted value of p_4



Fitted value of p_5

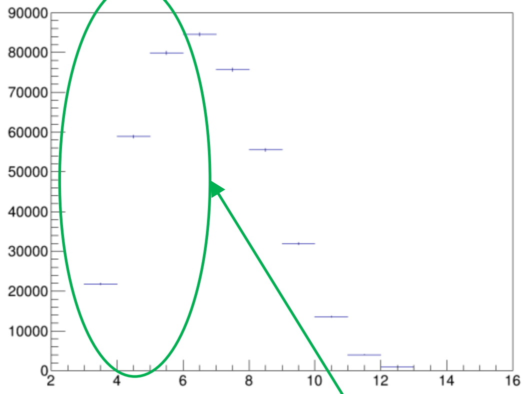




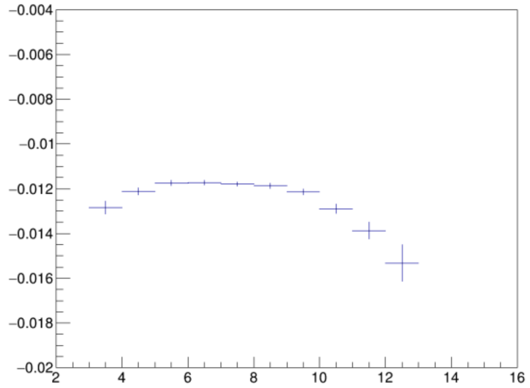
$$G = \left(\frac{\delta x_{bin}}{\sqrt{2\pi}}\right) p_0 \times \left\{ \frac{1}{p_2} \exp\left(-\frac{1}{2}\left(\frac{x-p_1}{p_2}\right)^2 \right) + \frac{p_3}{p_5} \exp\left(-\frac{1}{2}\left(\frac{x-(p_1+p_4)}{p_5}\right)^2 \right) \right\}$$

FIT PARAMETERS EVOLUTIONS n_{hits}: SINGLE SPILL TPC

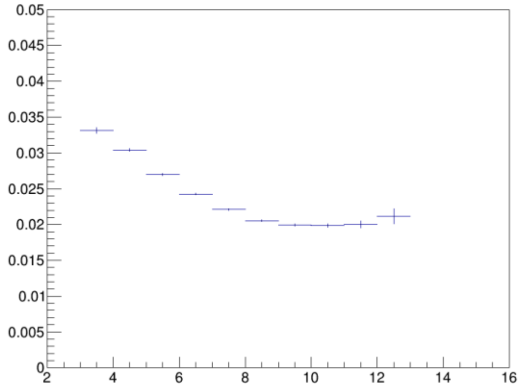
Fitted value of p_0



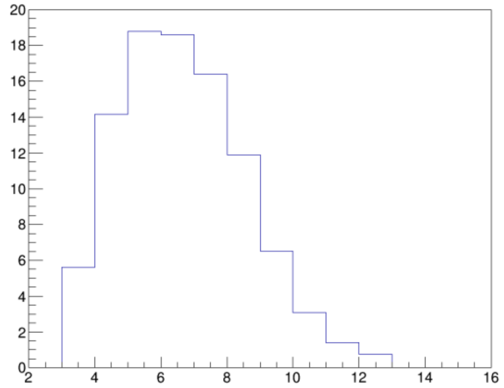
Fitted value of p_1



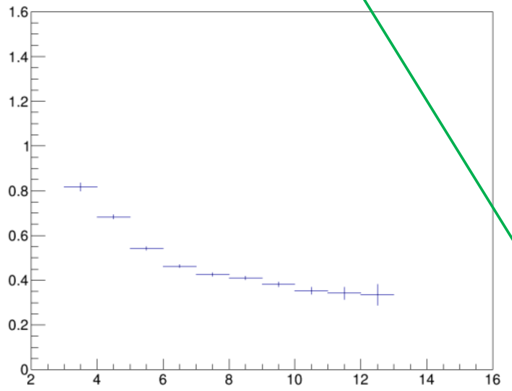
Fitted value of p_2



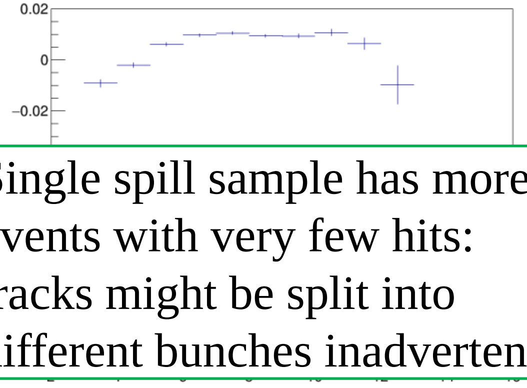
χ^2/NDF



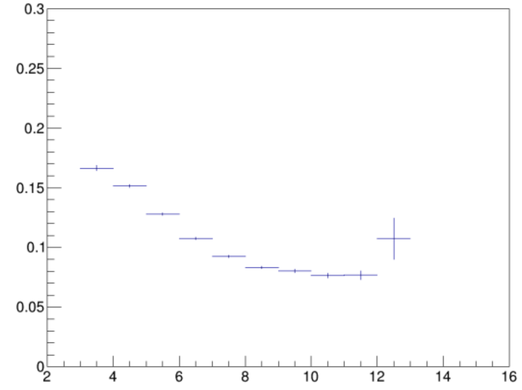
Fitted value of p_3

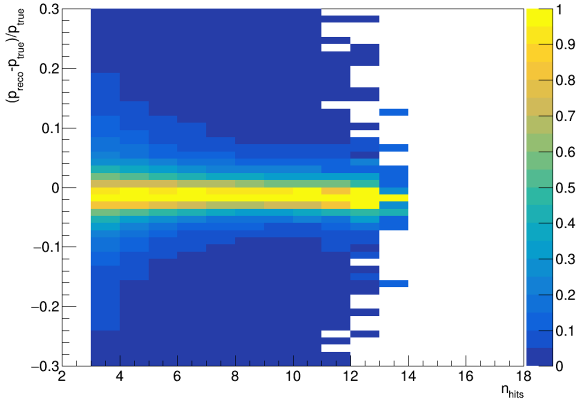


Fitted value of p_4



Fitted value of p_5





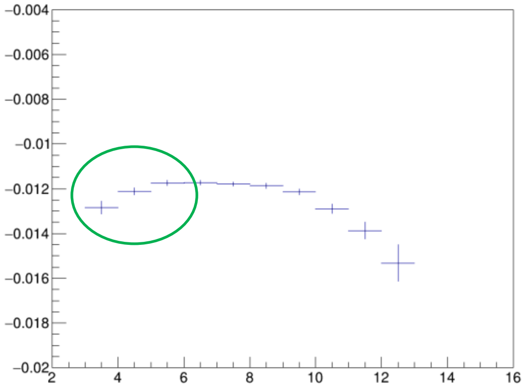
- Single spill sample has more events with very few hits: tracks might be split into different bunches inadvertently

$$G = \left(\frac{\delta x_{bin}}{\sqrt{2\pi}}\right) p_0 \times \left\{ \frac{1}{p_2} \exp\left(-\frac{1}{2} \left(\frac{x - p_1}{p_2} \right)^2 \right) + \frac{p_3}{p_5} \exp\left(-\frac{1}{2} \left(\frac{x - (p_1 + p_4)}{p_5} \right)^2 \right) \right\}$$

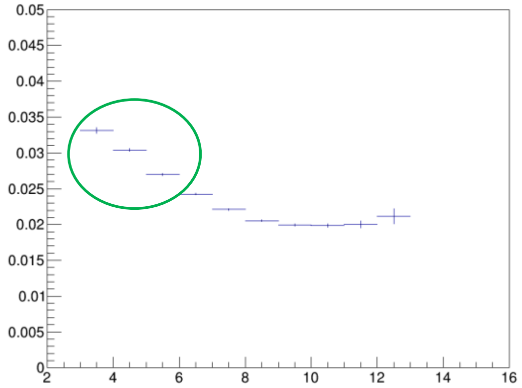
FIT PARAMETERS EVOLUTIONS n_{hits}: SINGLE SPILL TPC

- These low n_{hits} events lead to a worse overall performance: larger bias (p_1 and p_4) and larger spread (p_2, p_3 and p_5)

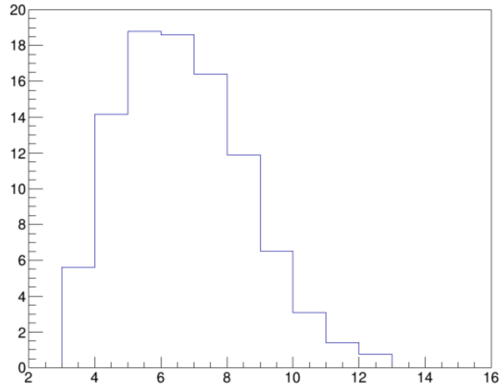
Fitted value of p_1



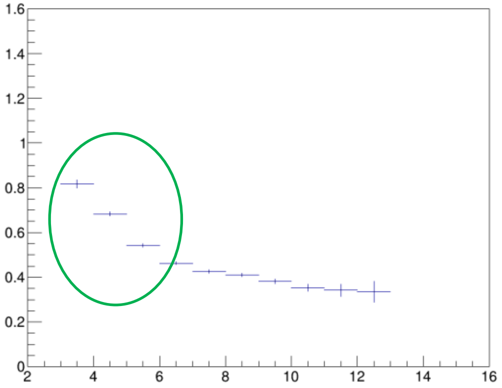
Fitted value of p_2



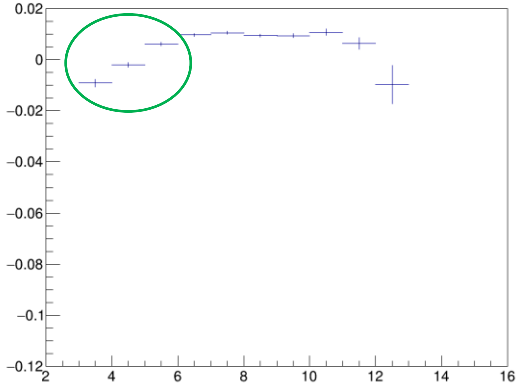
χ^2/NDF



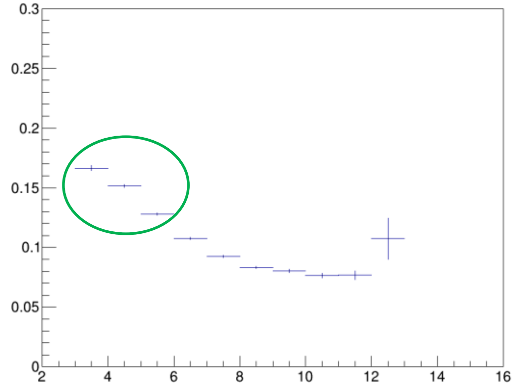
Fitted value of p_3

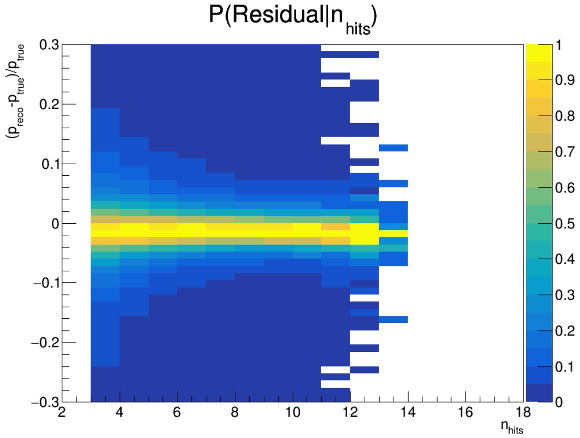


Fitted value of p_4



Fitted value of p_5

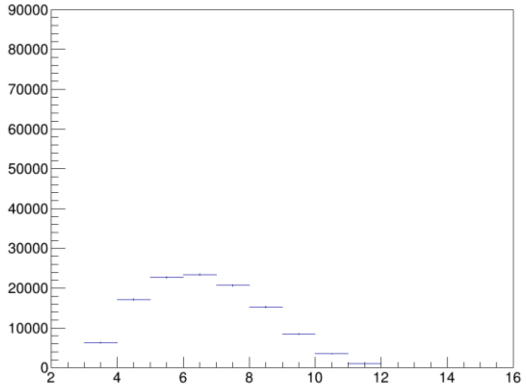




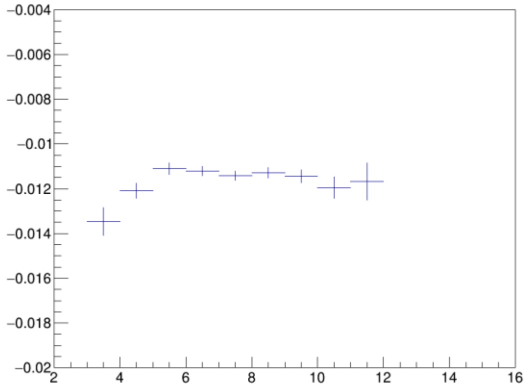
$$G = \left(\frac{\delta x_{bin}}{\sqrt{2\pi}}\right) p_0 \times \left\{\frac{1}{p_2}\exp\left(-\frac{1}{2}\left(\frac{x-p_1}{p_2}\right)^2\right) + \frac{p_3}{p_5}\exp\left(-\frac{1}{2}\left(\frac{x-(p_1+p_4)}{p_5}\right)^2\right)\right\}$$

FIT PARAMETERS EVOLUTIONS n_{hits}: SINGLE SPILL TPC+LAR

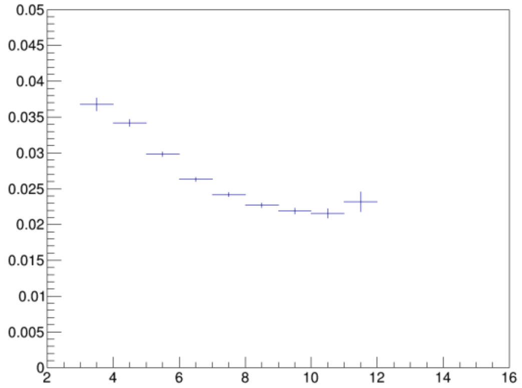
Fitted value of p_0



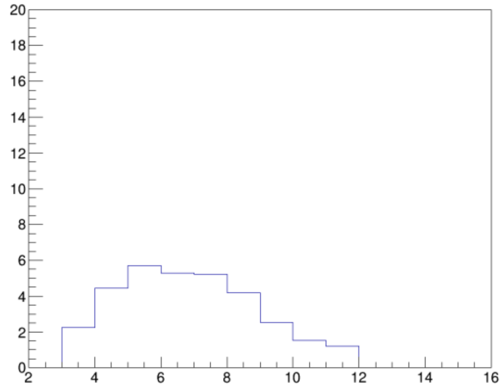
Fitted value of p_1



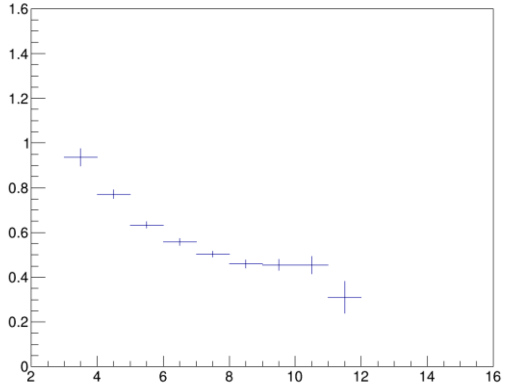
Fitted value of p_2



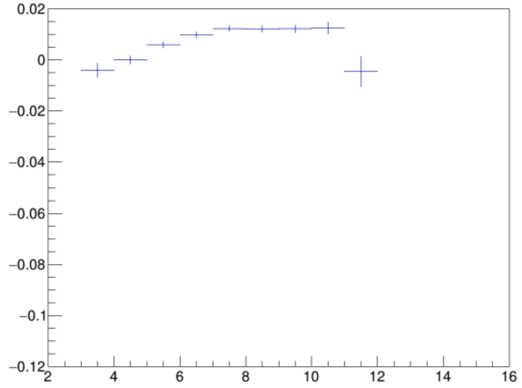
χ^2/NDF



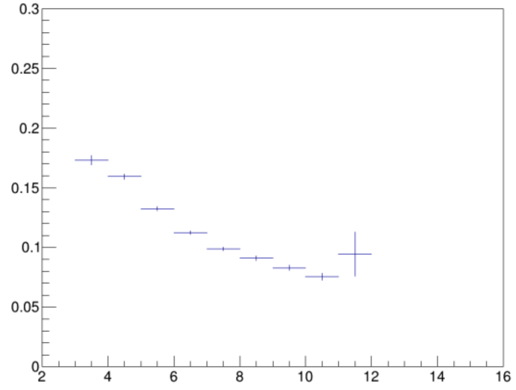
Fitted value of p_3

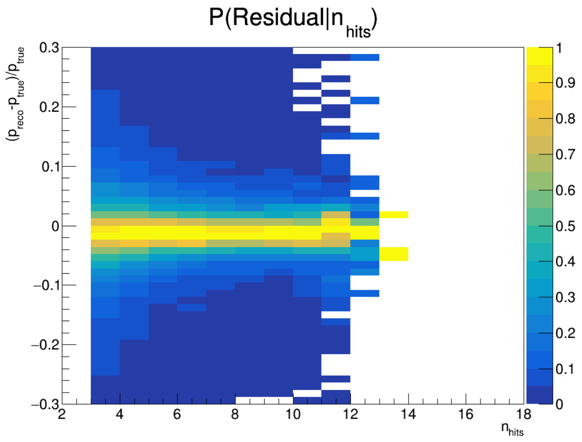


Fitted value of p_4



Fitted value of p_5

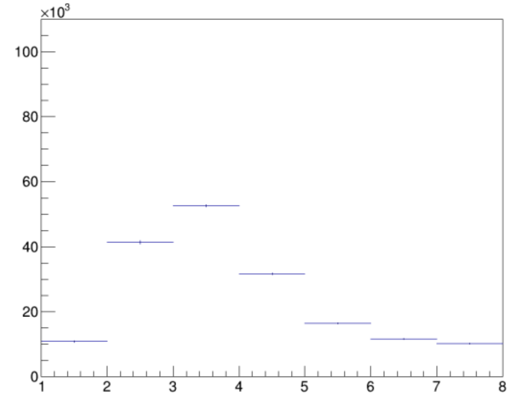




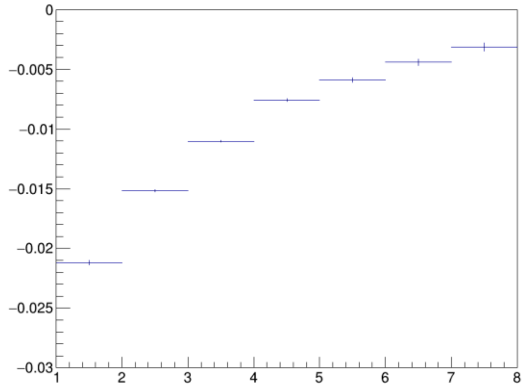
$$G = \left(\frac{\delta x_{bin}}{\sqrt{2\pi}}\right) p_0 \times \left\{\frac{1}{p_2}\exp\left(-\frac{1}{2}\left(\frac{x-p_1}{p_2}\right)^2\right) + \frac{p_3}{p_5}\exp\left(-\frac{1}{2}\left(\frac{x-(p_1+p_4)}{p_5}\right)^2\right)\right\}$$

FIT PARAMETERS EVOLUTIONS p_{true}^{St}: TPC SAMPLE

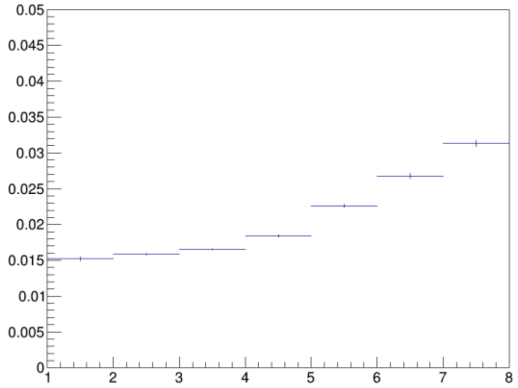
Fitted value of p_0



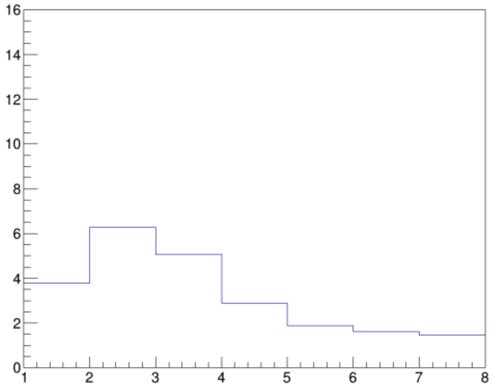
Fitted value of p_1



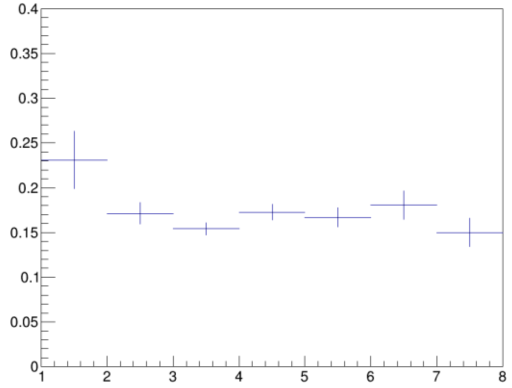
Fitted value of p_2



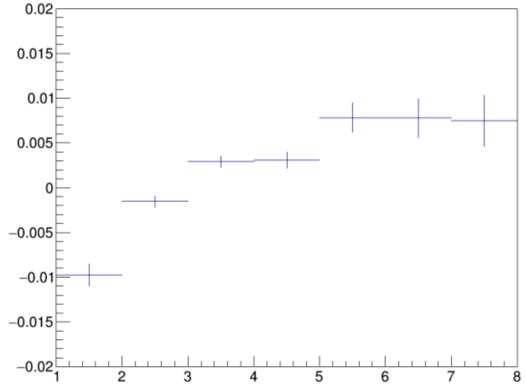
χ^2/NDF



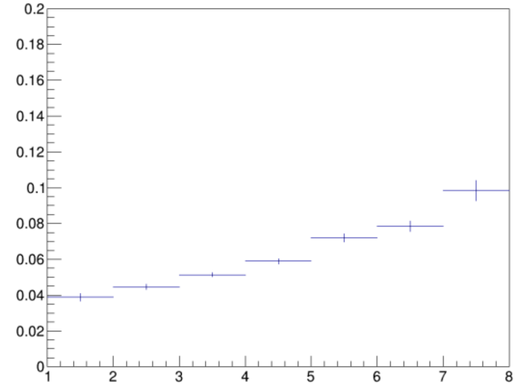
Fitted value of p_3

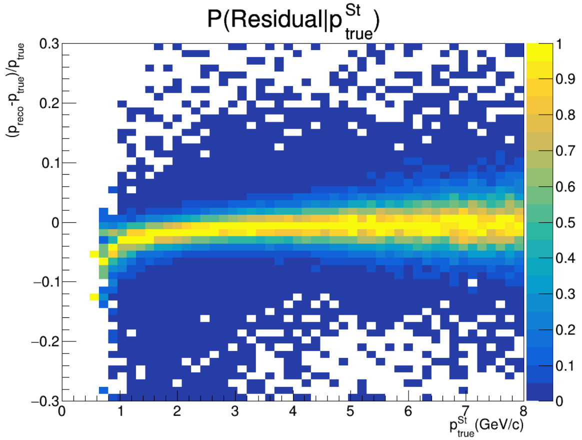


Fitted value of p_4



Fitted value of p_5

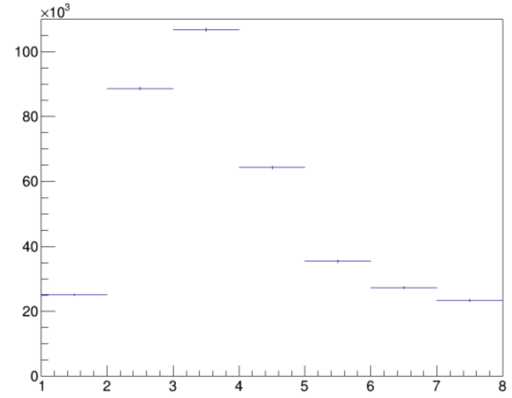




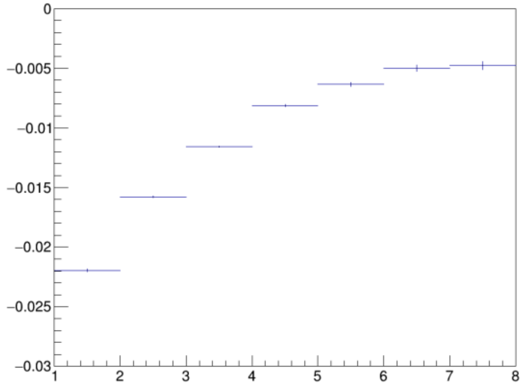
$$G = \left(\frac{\delta x_{bin}}{\sqrt{2\pi}}\right) p_0 \times \left\{\frac{1}{p_2}\exp\left(-\frac{1}{2}\left(\frac{x-p_1}{p_2}\right)^2\right) + \frac{p_3}{p_5}\exp\left(-\frac{1}{2}\left(\frac{x-(p_1+p_4)}{p_5}\right)^2\right)\right\}$$

FIT PARAMETERS EVOLUTIONS p_{true}^{St}: SINGLE SPILL TPC

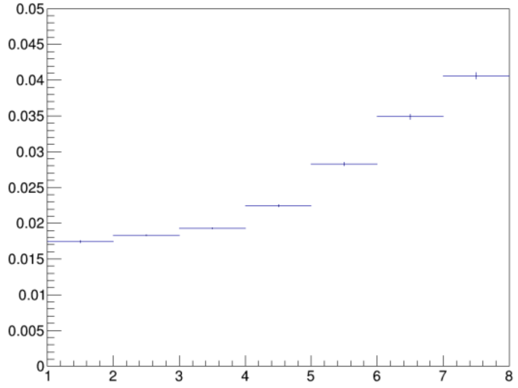
Fitted value of p_0



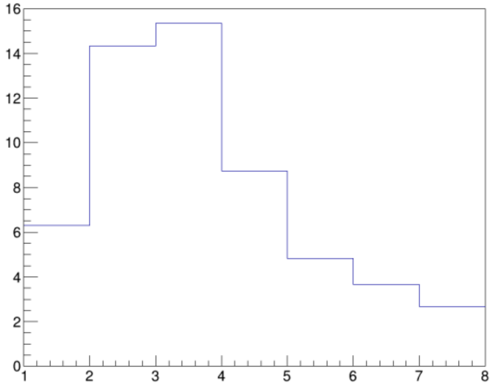
Fitted value of p_1



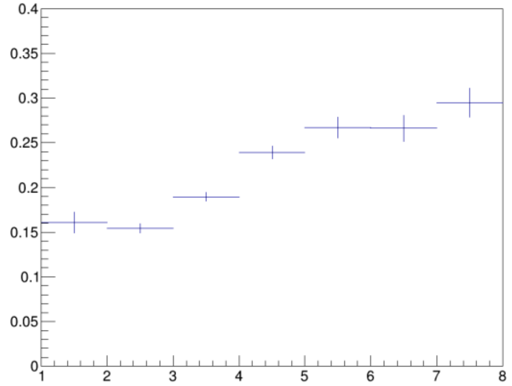
Fitted value of p_2



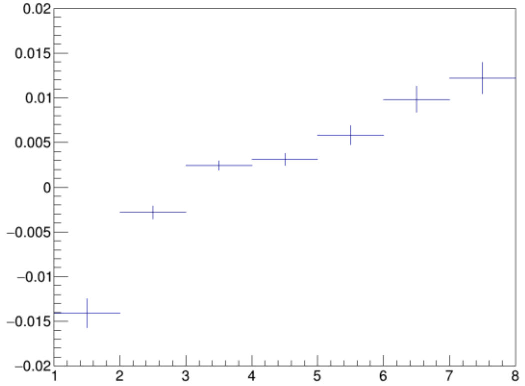
χ^2/NDF



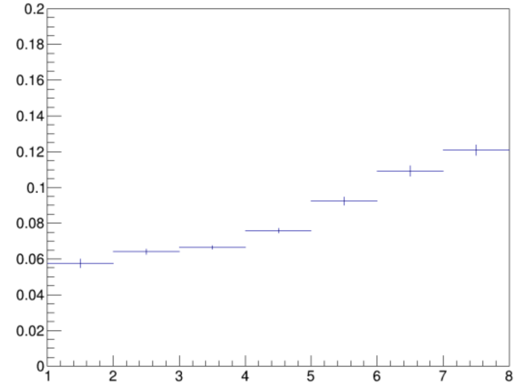
Fitted value of p_3

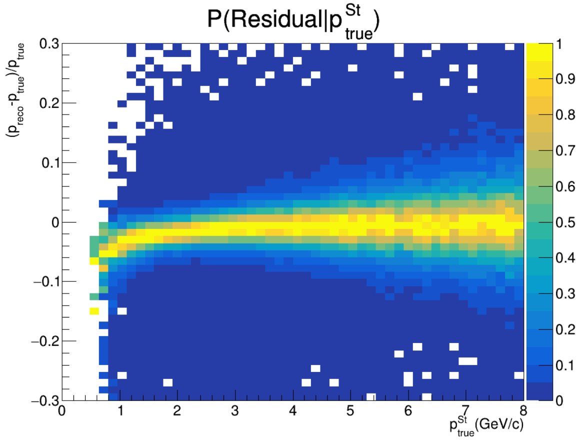


Fitted value of p_4



Fitted value of p_5





$$G = \left(\frac{\delta x_{bin}}{\sqrt{2\pi}}\right) p_0 \times \left\{\frac{1}{p_2}\exp\left(-\frac{1}{2}\left(\frac{x-p_1}{p_2}\right)^2\right) + \frac{p_3}{p_5}\exp\left(-\frac{1}{2}\left(\frac{x-(p_1+p_4)}{p_5}\right)^2\right)\right\}$$

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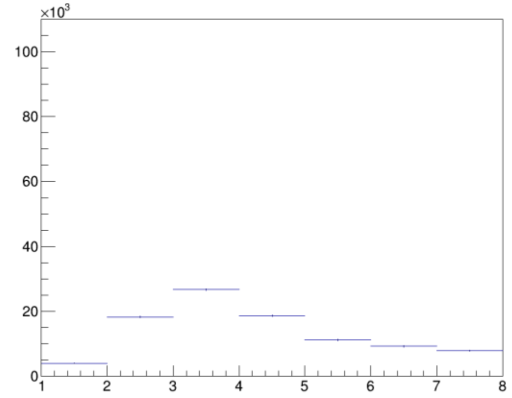
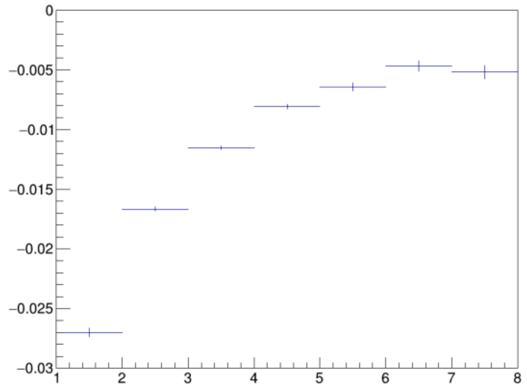
FIT PARAMETERS EVOLUTIONS p_{true}^{St}: SINGLE SPILL TPC+LAR

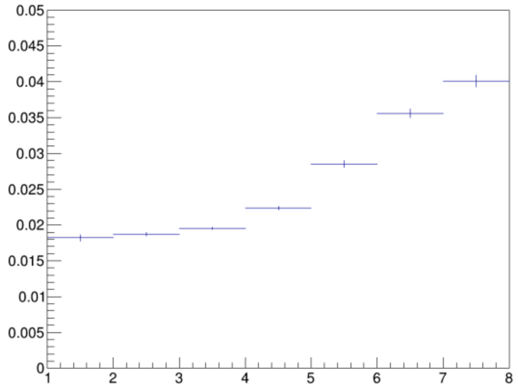
Fitted value of p_0



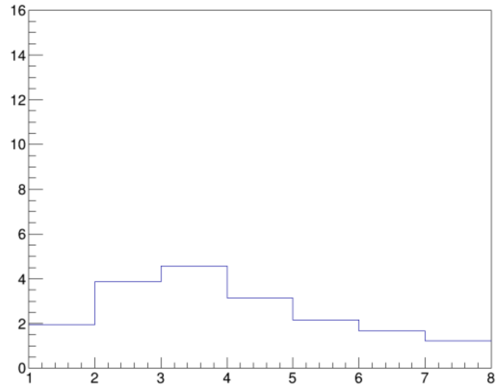
Fitted value of p_1



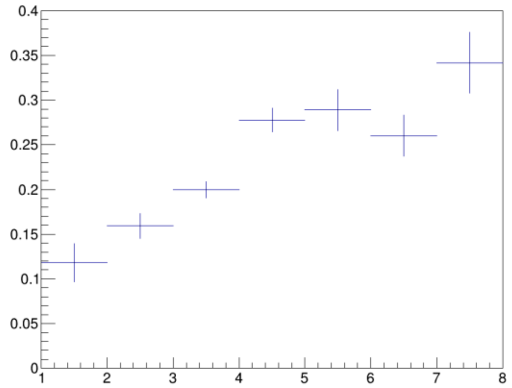
Fitted value of p_2



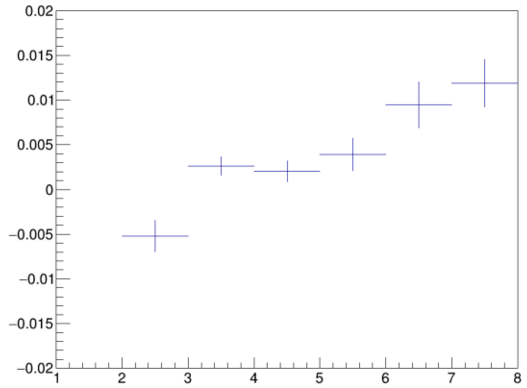
χ^2/NDF



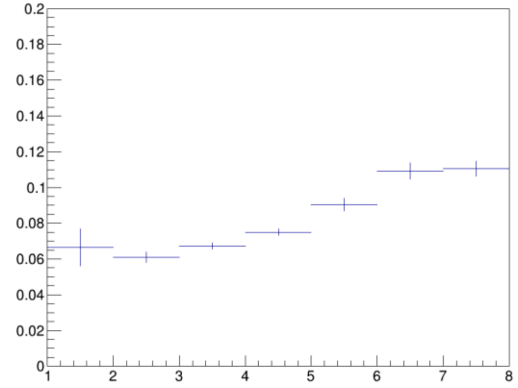
Fitted value of p_3

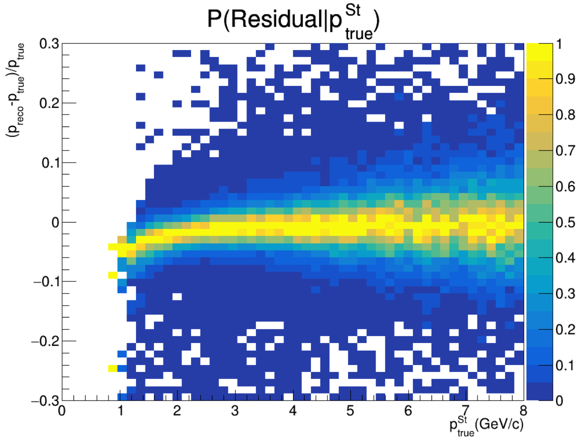


Fitted value of p_4



Fitted value of p_5

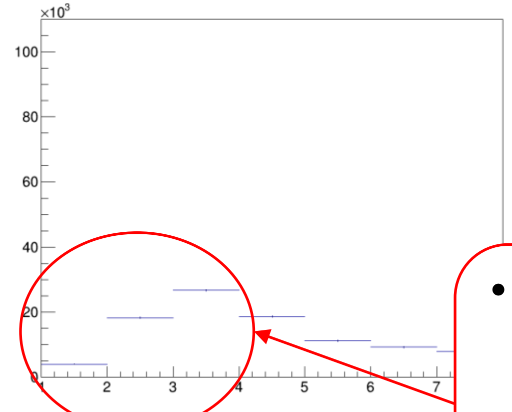




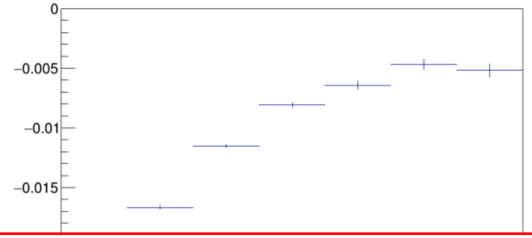
$$G = \left(\frac{\delta x_{bin}}{\sqrt{2\pi}}\right) p_0 \times \left\{ \frac{1}{p_2} \exp\left(-\frac{1}{2}\left(\frac{x-p_1}{p_2}\right)^2\right) + \frac{p_3}{p_5} \exp\left(-\frac{1}{2}\left(\frac{x-(p_1+p_4)}{p_5}\right)^2\right) \right\}$$

FIT PARAMETERS EVOLUTIONS p_{true}^{St}: SINGLE SPILL TPC+LAR

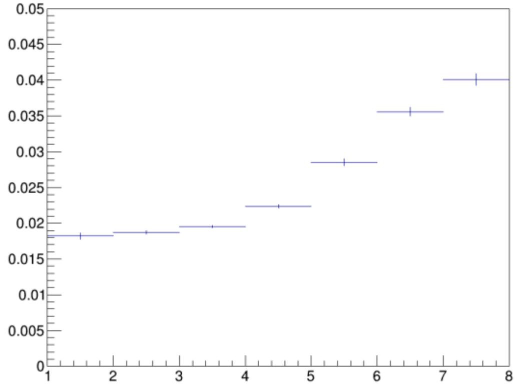
Fitted value of p_0



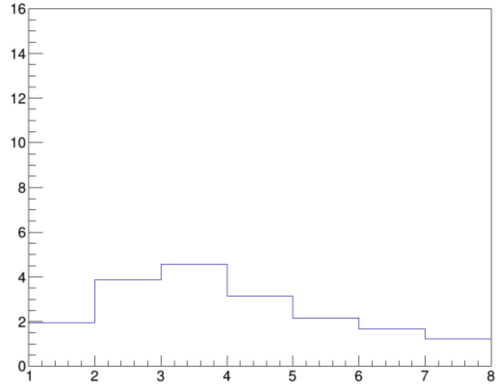
Fitted value of p_1



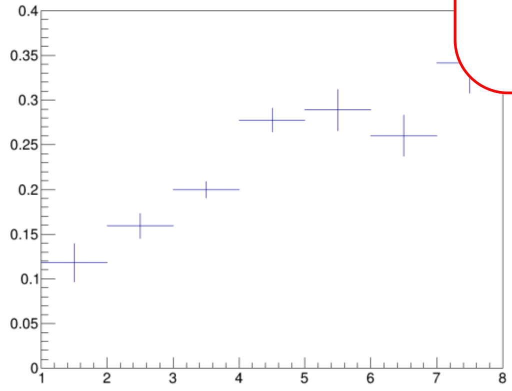
Fitted value of p_2

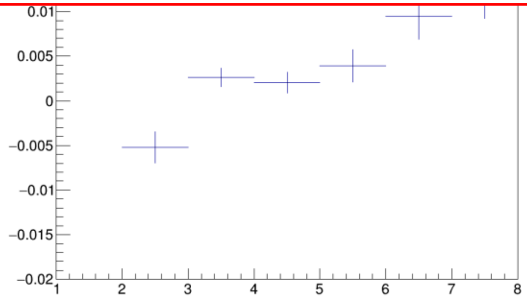


χ^2/NDF

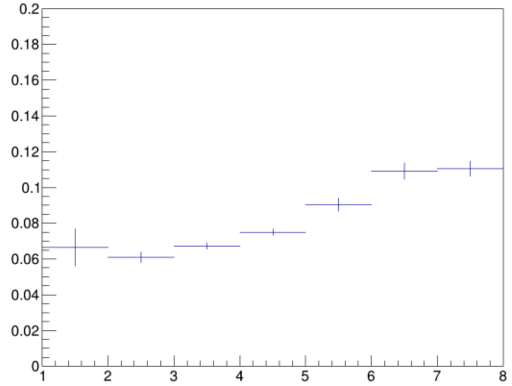


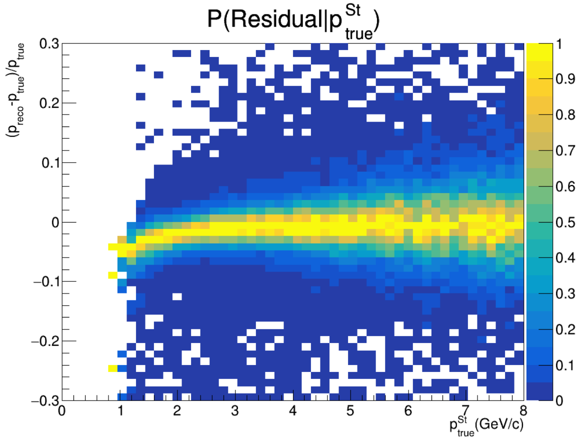
Fitted value of p_3





Fitted value of p_5





- More low momentum tracks are cut than high momentum ones: momentum reconstruction is worse for straighter tracks → worse performance

$$G = \left(\frac{\delta x_{bin}}{\sqrt{2\pi}}\right) p_0 \times \left\{\frac{1}{p_2}\exp\left(-\frac{1}{2}\left(\frac{x-p_1}{p_2}\right)^2\right) + \frac{p_3}{p_5}\exp\left(-\frac{1}{2}\left(\frac{x-(p_1+p_4)}{p_5}\right)^2\right)\right\}$$

SUMMARY AND CONCLUSIONS

- Single spill production for ND-GAr-Lite on the Fermilab Grid is now available using the scripts found on the dunegpvm servers at /dune/app/users/battisti/garlite/Spill/production/Grid/

- A new track finding algorithm has been used for the spill sample which divides the track hits in time "bunches" (note that no proper bunch structure is currently implemented in the spill production)

- The momentum reconstruction performance thus obtained is comparable, but slightly worse than what was found for the single event production: this is likely due to an increase in the number of low n_{hits} tracks in the single spill samples which might be due to track hits being incorrectly divided into multiple bunches

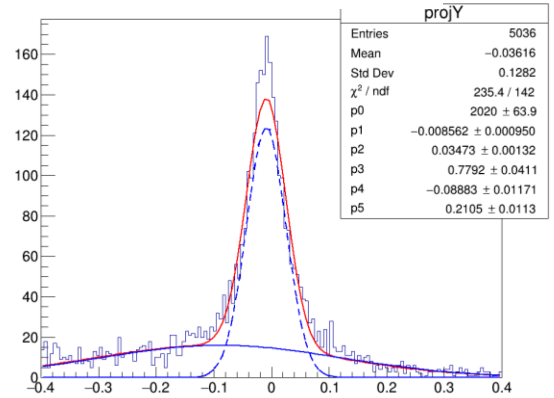
- LAr fiducial cuts introduced in the single Spill sample seem to have little effect, except for a slight decrease in performance likely due to low momentum muons being discarded from the sample and a slight increase in efficiency

- Possible future steps:
  1. Introduce proper bunch structure in the spill production;
  2. Avoid track matching with the introduction of backtracking for GArLite
  3. Reproduce the study with more up-to-date optimized geometry

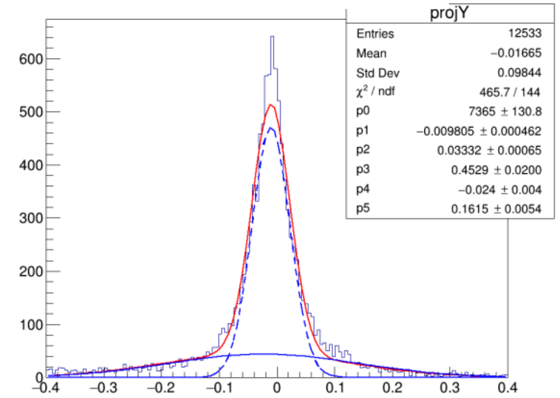
BACK-UP

SLICES FIT n_{hits}: TPC SAMPLE

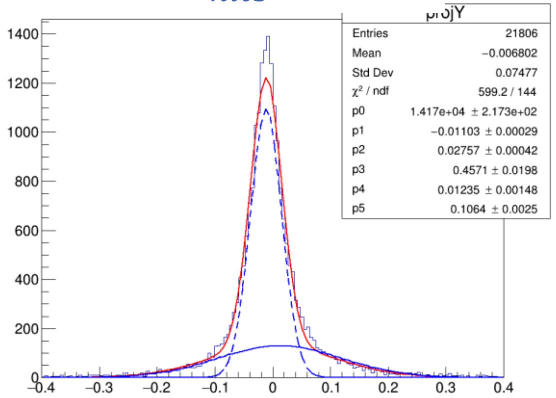
$n_{hits} = 4$



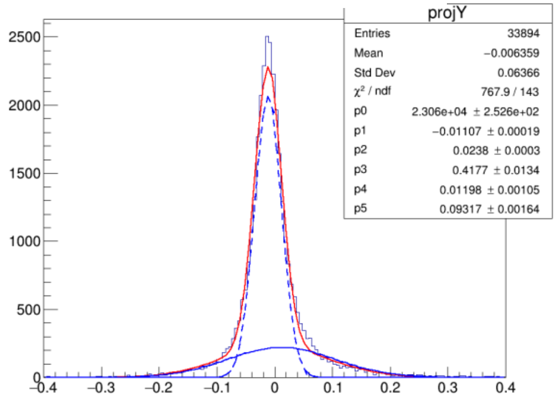
$n_{hits} = 5$



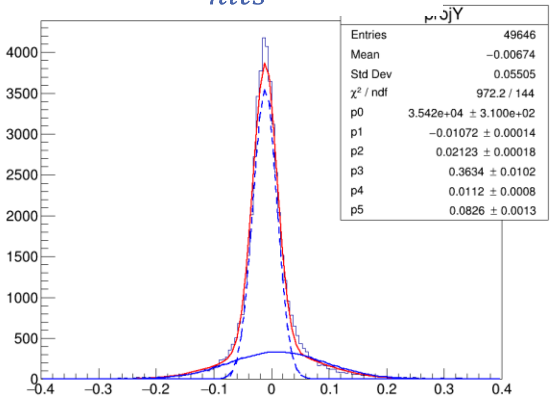
$n_{hits} = 6$



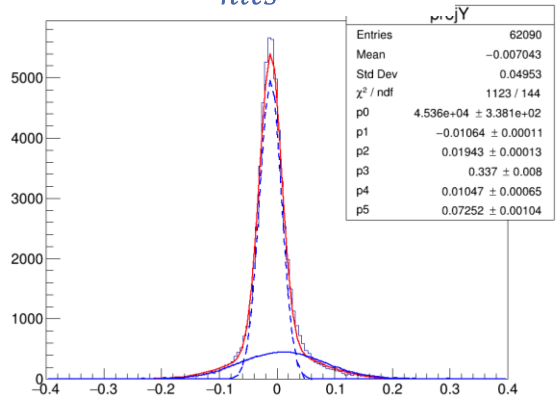
$n_{hits} = 7$



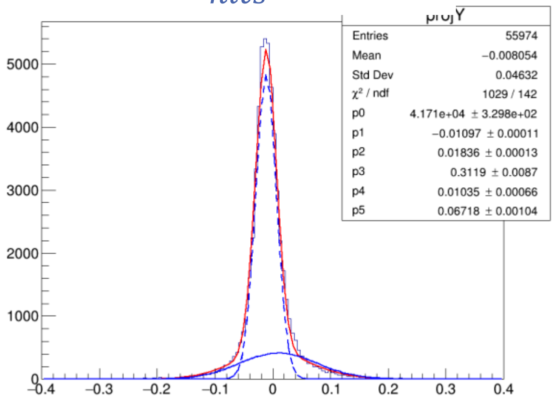
$n_{hits} = 8$



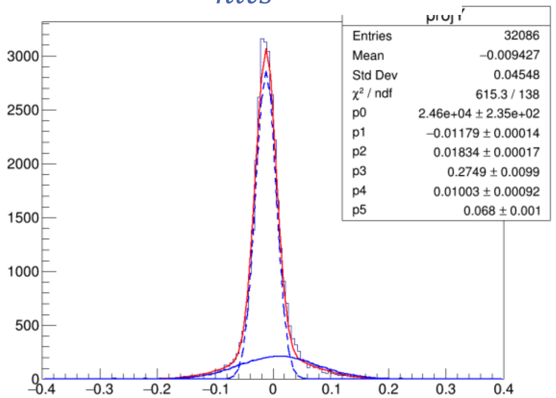
$n_{hits} = 9$



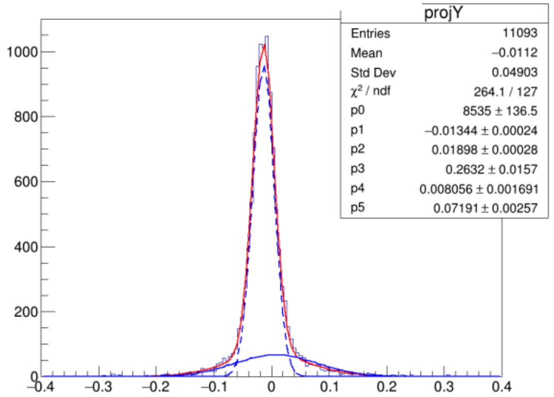
$n_{hits} = 10$



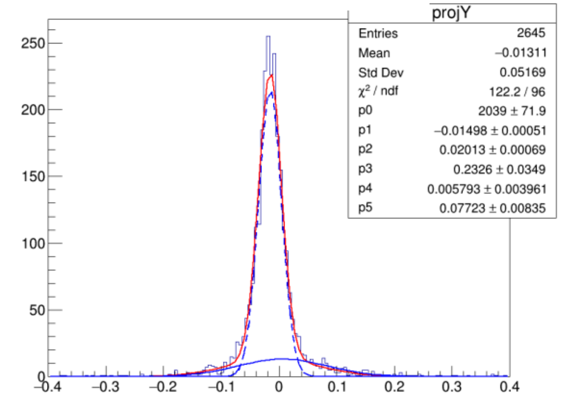
$n_{hits} = 11$



$n_{hits} = 12$

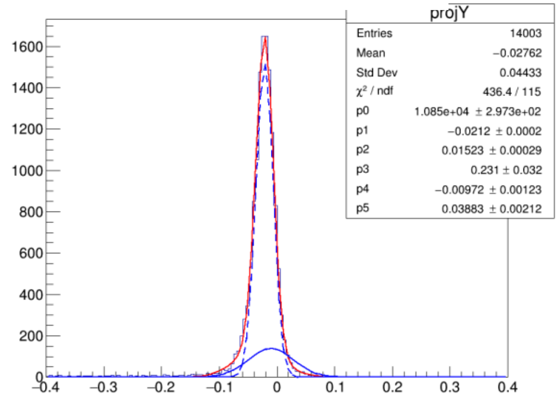


$n_{hits} = 13$

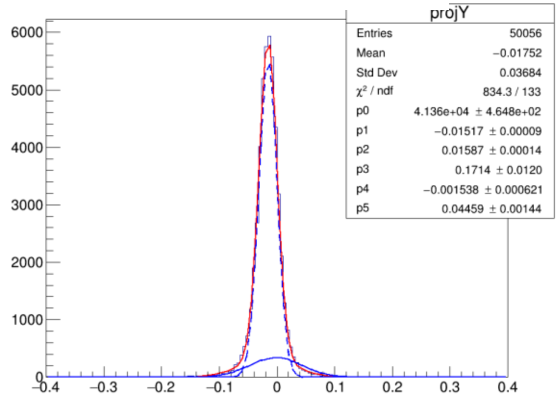


SLICES FIT p_{true}^{St}: TPC SAMPLE

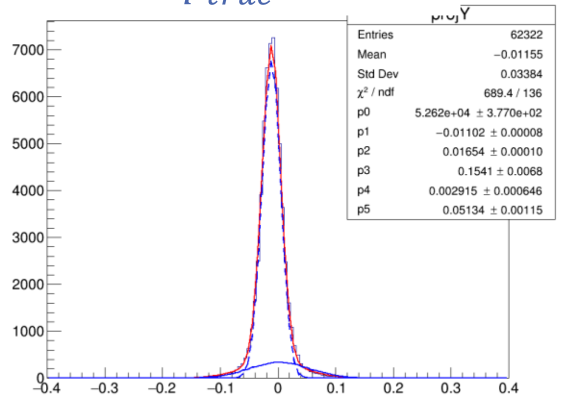
$1 < p_{true}^{St} < 2GeV$



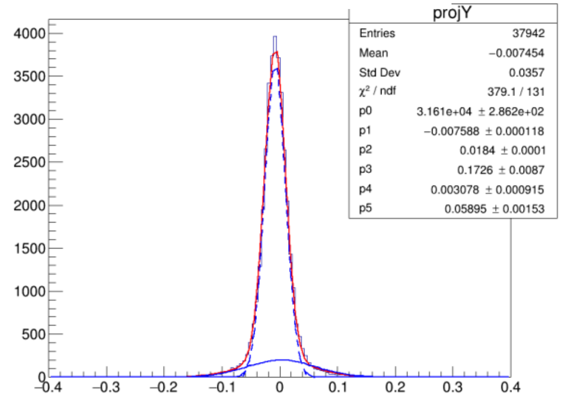
$2 < p_{true}^{St} < 3\text{GeV}$



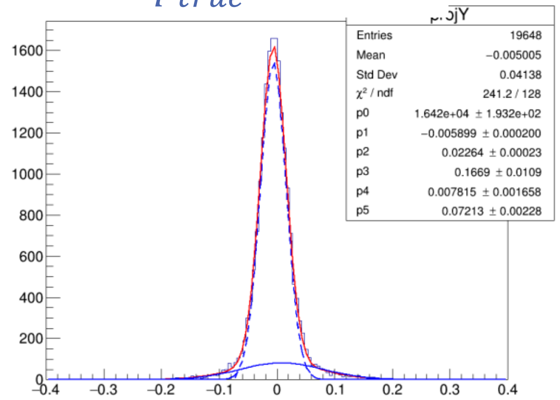
$3 < p_{true}^{St} < 4\text{GeV}$



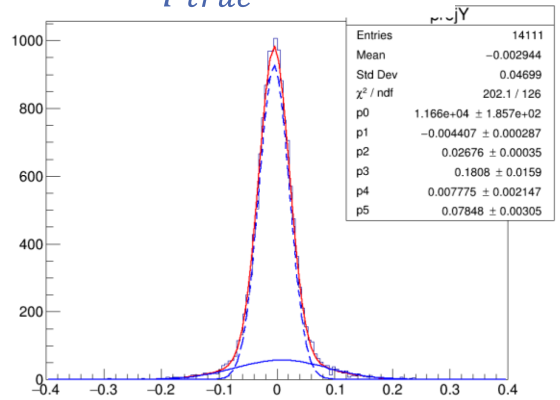
$4 < p_{true}^{St} < 5\ GeV$



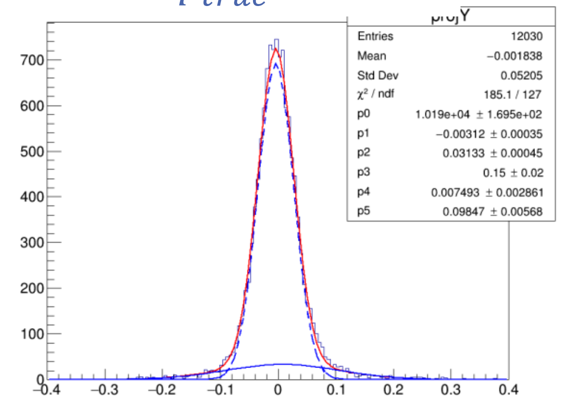
$5 < p_{true}^{St} < 6\ GeV$



$6 < p_{true}^{St} < 7\ \text{GeV}$

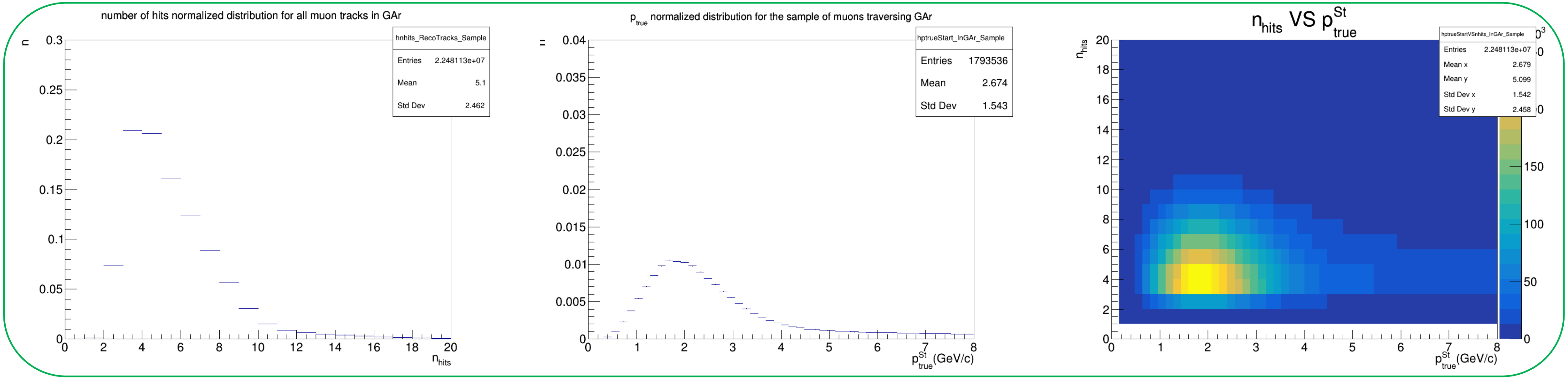


$7 < p_{true}^{St} < 8\ \text{GeV}$



SAMPLE DEFINING DISTRIBUTIONS

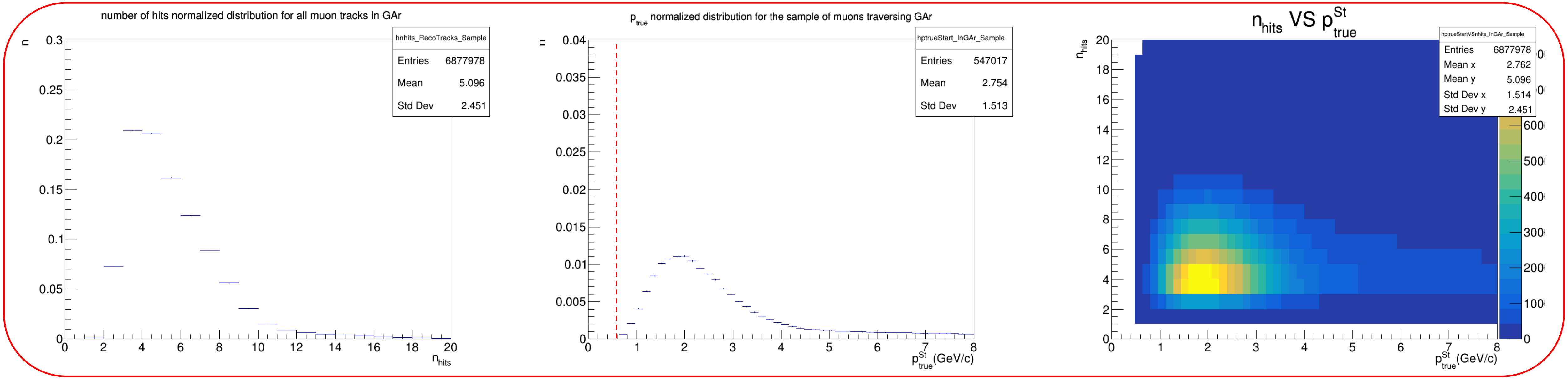
Single Spill TPC



- To characterize the samples, we consider two fundamental characteristics:
  1. n_{hits} = Number of hits on the scintillator planes that are associated to the tracks found in events having at least one MC trajectory in the volume. In first approximation we expect two hits for each plane traversed by the particle ("reconstructed quantity")
  2. p^{St}_{true} = Initial true MC muon momentum in [GeV/c] for all MC trajectories in the volume ("MC truth quantity")

SAMPLE DEFINING DISTRIBUTIONS

Single Spill TPC+LAr



- For the Single Spill distribution with the added LAr cut we can see how we have a cut in the momentum distribution at around 0.5-0.6 GeV/c