STCF Track Fitting

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Outline

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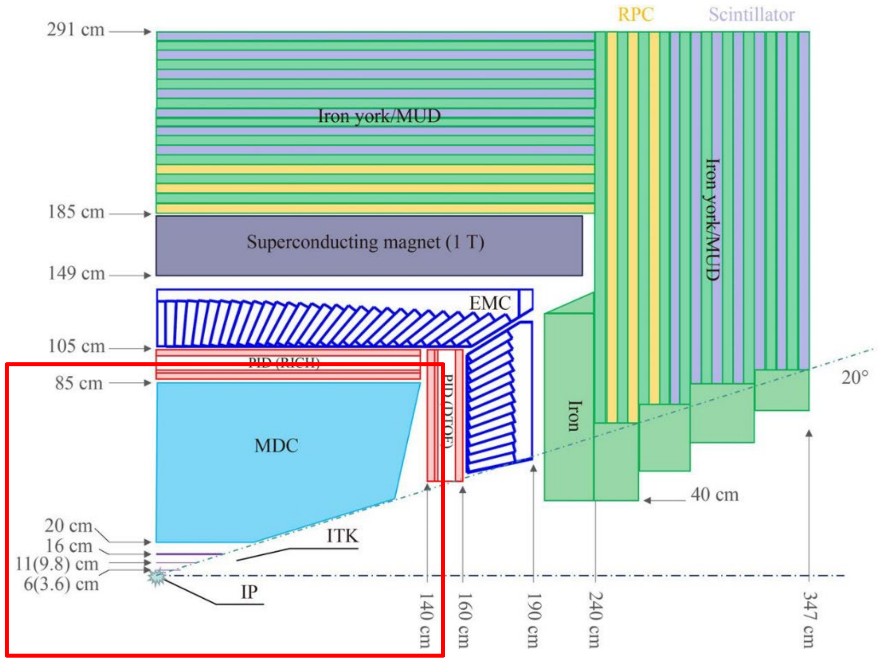
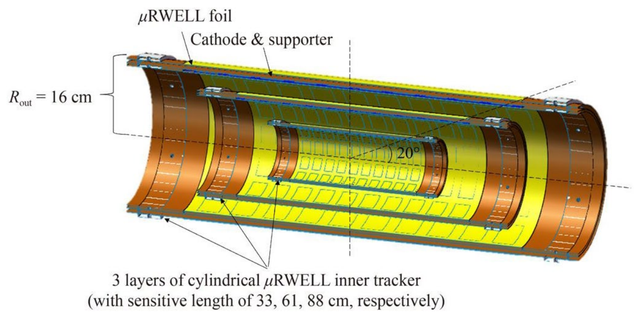
1. Tracking at STCF
2. Track Fitting with GenFit
   ① Extrapolate method
   ② Fitting algorithm
3. Performance
4. Ongoing study

STCF Tracking System

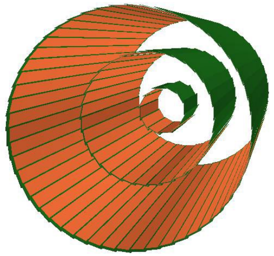
- The STCF tracking system is composed of two parts, the inner tracker(ITK) and the main drift chamber(MDC).
  - ITK is the innermost part surrounding the interaction point
    - 3 layers
    - two options : μRWELL-based ITK / MAPS-based ITK
  - MDC is the main part of the tracking system
    - consists of eight super-layers, 4 stereo super-layers, 4 axial super-layers, and each super-layer contains six layers of cells
    - radii ranging from 200 mm to 840mm



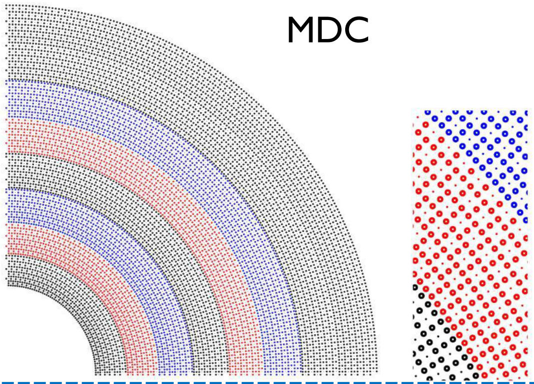
μRWELL-based ITK (ITKW)



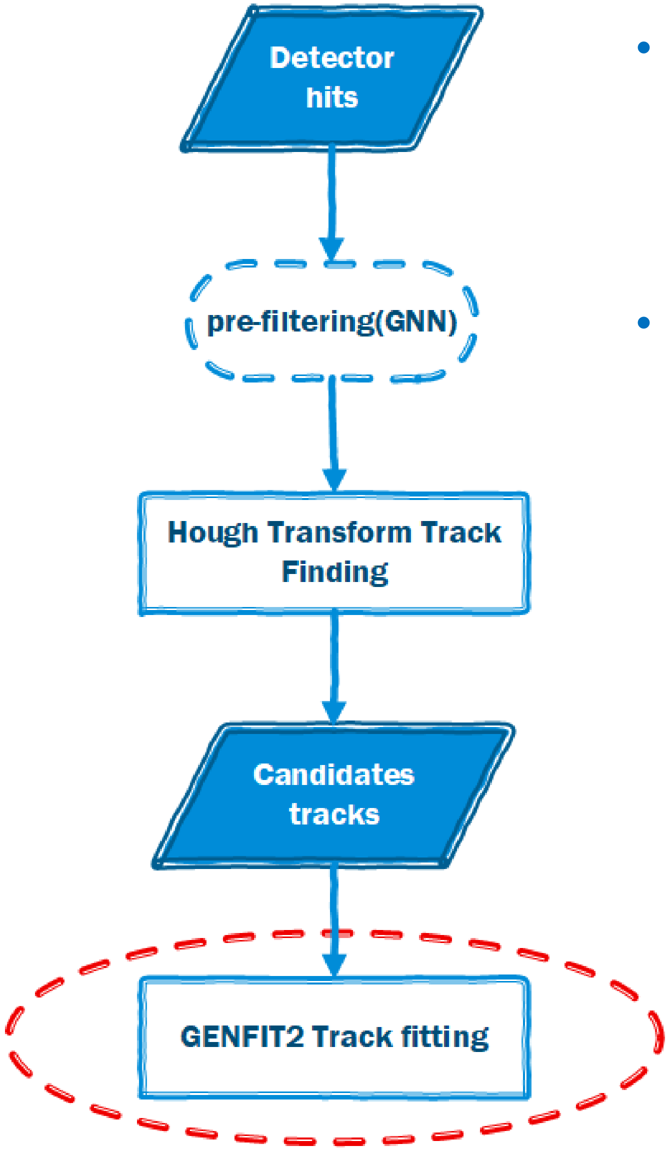
MAPS-based ITK (ITKM)



MDC



Tracking at STCF



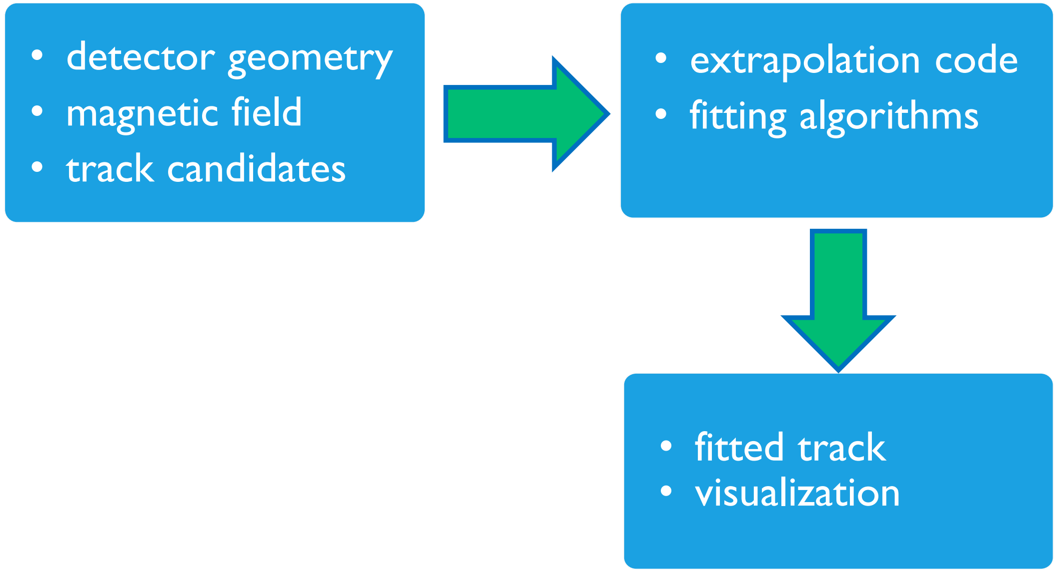
- **Tracking task**: reconstruct charged particles with high efficiency and good resolution (from 50 MeV to 3.5 GeV)

- **STCF tracking baseline**: Hough finder + GenFit2
  - Input: detectors hits from ITK and MDC
  - Firstly, graph neural network (GNN) is employed to effectively filter out noise hit.
  - Then the surviving hits are used for a global track finding based on the Hough transform.
  - At last, Track fitting takes track candidates as input, to obtain more precise parameters.

Introduction to GENFIT

- **GENFIT2** – A Generic Track Reconstruction toolkit
  - Experiment-independent, modular track-fitting framework
  - Open source C++ code
  - Larger user community(e.g., BelleII, PANDA, SHiP, AFIS …)
  - Providing some typical track fitting tools, e.g., Kalman Filter, Deterministic Annealing Filter

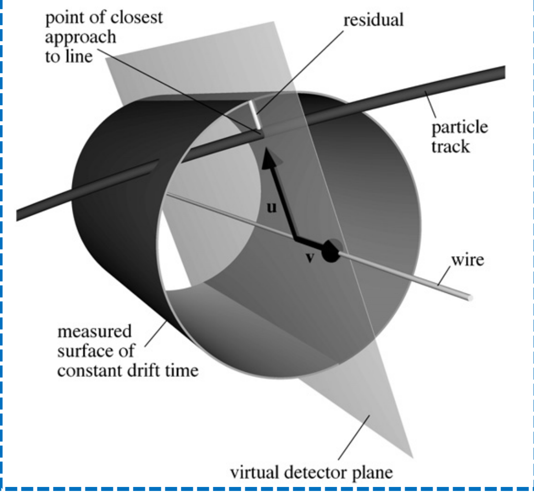
- In GENFIT2, track fitting is based on the following three components:
  - measurements
  - track representations
  - fitting algorithms



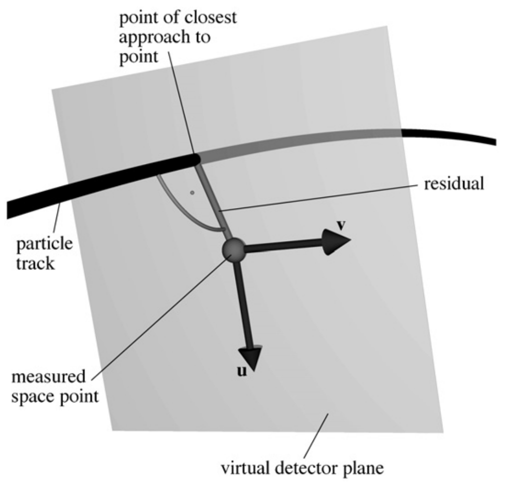
Measurements

- All detector measurements are defined in detector planes.
  - Planar detector: Use their physical detector plane
  - Non-planar detectors: Construct virtual detector plane
    - wire-based drift detector
      - Plane contains the point of closest approach of the track to the wire and passes through the entire wire
      - $\vec{v}$ along the wire; $\vec{u}$ perpendicular to the wire
    - space-point detector
      - Plane contains the hit position and the point of closest approach of the track to the hit point
      - $\vec{v}$ and $\vec{u}$ is chosen arbitrarily in the plane

wire-based drift detectors



space-point detectors



track representations

- GENFIT2 can actually use 3 different coordinate systems:

  The variables below are defined as the space coordinates $\vec{x}(x, y, z)$; the momentum $\vec{p}(p_x, p_y, p_z)$; the charge q; the absolute value of the momentum p; the momentum direction unit vector $\vec{a}$.

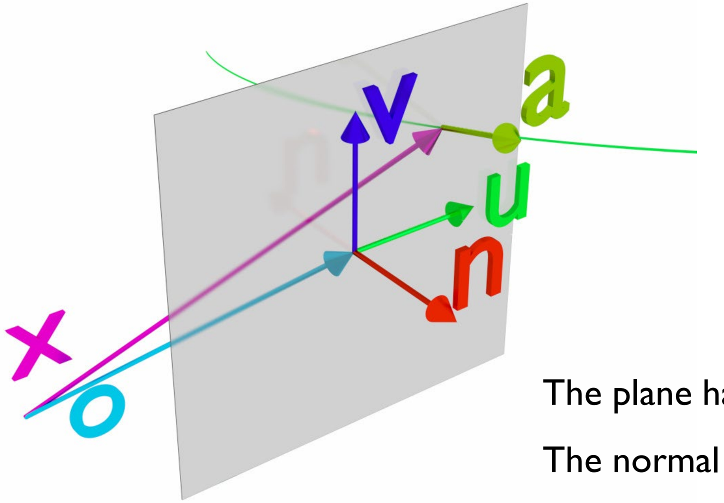
  - 6D-coordinates (x, y, z, p_x, p_y, p_z)
  - global coordinates $(x, y, z, \vec{a}, \frac{q}{p})$
  - local coordinates $(\frac{q}{p}, u', v', u, v)$

$$u' = \frac{\vec{a} \cdot \vec{u}}{\vec{a} \cdot \vec{n}}$$

$$v' = \frac{\vec{a} \cdot \vec{v}}{\vec{a} \cdot \vec{n}}$$

$$u = (\vec{x} - \vec{o}) \cdot \vec{u}$$

$$v = (\vec{x} - \vec{o}) \cdot \vec{u}$$

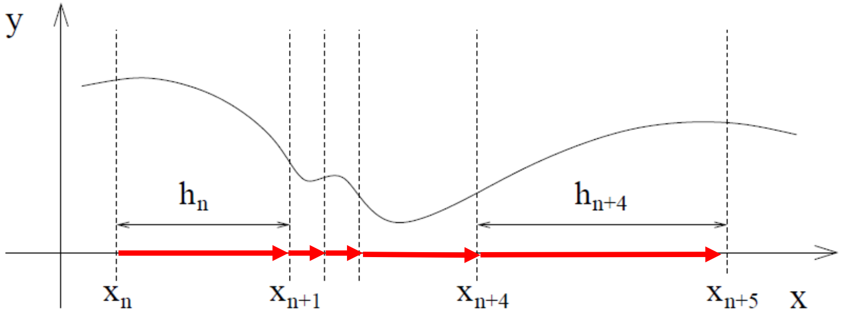


The plane has an origin $\vec{o}$, and is spanned by two orthogounit vectors $\vec{u}$ and $\vec{v}$.

The normal vector $\vec{n}$ is then equal to $\vec{u} \times \vec{v}$. And u', v' are the direction cosines.

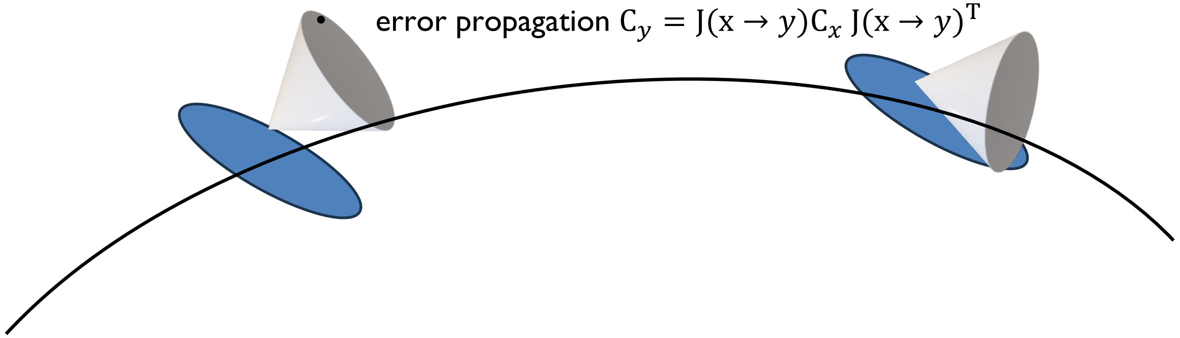
Extrapolate method

- GENFIT2 tool implements a Runge-Kutta extrapolator to propagate the parameters.



propagate step by step

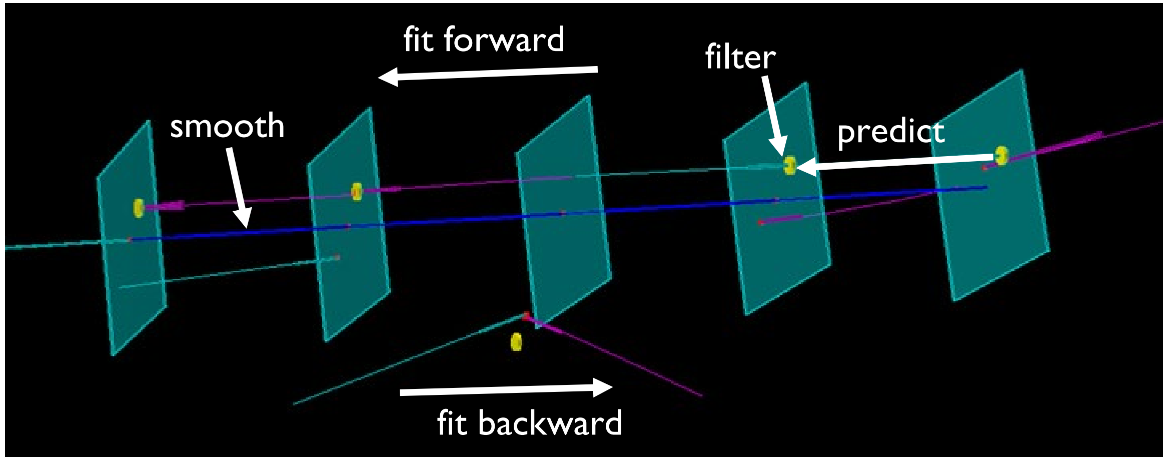
each step:
- calculate energy loss
- updates the transport Jacobians along the track $J_1, J_2, \ldots J_{n-1}, J_n$
- error propagation $C_y = J(x \rightarrow y) C_x \, J(x \rightarrow y)^T$



- taking into account field inhomogeneities
  - adjust the step size dynamically
- Consider material effects
  - the mean energy loss and its straggling for charged
  - the multiple scattering

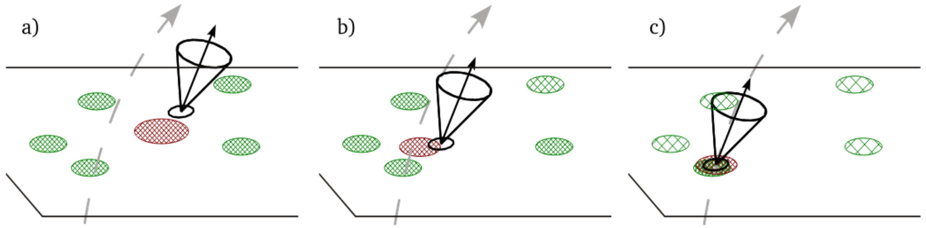
Fitting algorithm

- ## Kalman Filter
  - Iterates in 3 steps: prediction, filter, and smoothing
  - The iterative bi-directional Kalman filter is applied in GENFIT
    - Forward fitting: from inner detection module to the outer
    - Backward fitting: fit in the backwards direction
    - Smoothing in GENFIT:
      - averaging the forward and backward fit



- ## Deterministic Annealing Filter
  - Iterative Kalman filter with weighting and annealing process
  - assignment probabilities for each measurement
  - Can be used to reject outliers or to resolve left/right ambiguities

Diagram of DAF



a) At first, all measurements get similar weights, and all will be considered.
b) After update, measurement with large errors are assigned smaller weight.
c) As the temperature decreases, measurements with large errors are given even less weight.
   - the weight drops below the threshold, reject

Fitting algorithm

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Deterministic Annealing Filter

- when using the DAF algorithm, the weights of measurements need to be initialized.
- **Basic solution**: to assign both left and right measurements a weight = 0.5
  - Wire positions are taken as measurements in the first iteration, covariance is twice the mean of the individual covariances
    - all wire positions have same covariance
    - systematic false estimate of the covariance biases the fit
- **Genfit2 implements a technique to initialize the weights:**
  - measurements with larger drift radii are assigned smaller weights, since the wire position is expected to be farther away from the trajectory.
  - In contrast, measurements with smaller drift radii, which are closer to the trajectory, get larger weights.

$$w = \frac{1}{2}\left(1 - \frac{r_{drift}}{r_{drift,max}}\right)^2$$

w is the given weight, and r_{drift} is the distance of the measurement from trajectory

Performance: pull distributions at the point of closest approach(POCA)

- Pull distribution

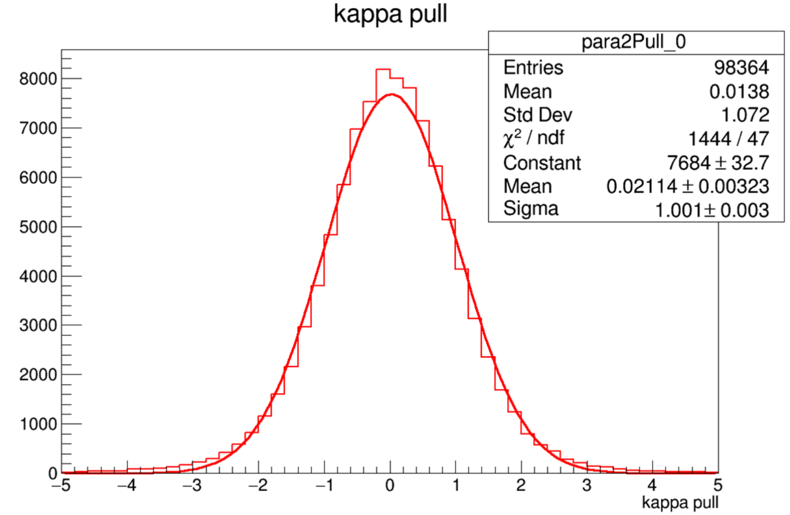
simulated 1GeV muons at θ=20° ~ 160° (ITKW+MDC)

$$Pull = \frac{v_{fit} - v_{truth}}{\sigma_v}$$

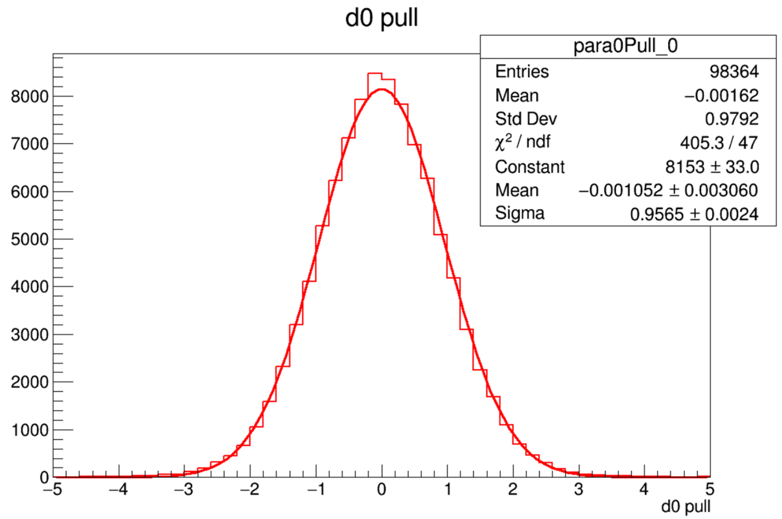
v_{fit} : the estimated value

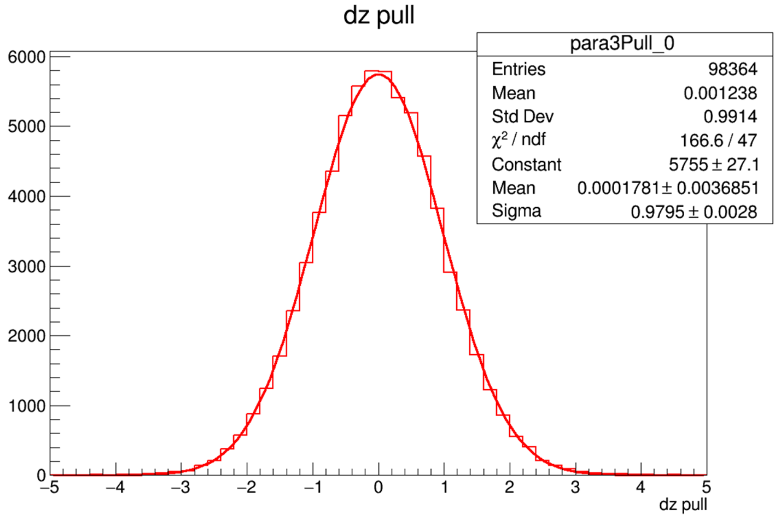
v_{truth} : the true simulated value

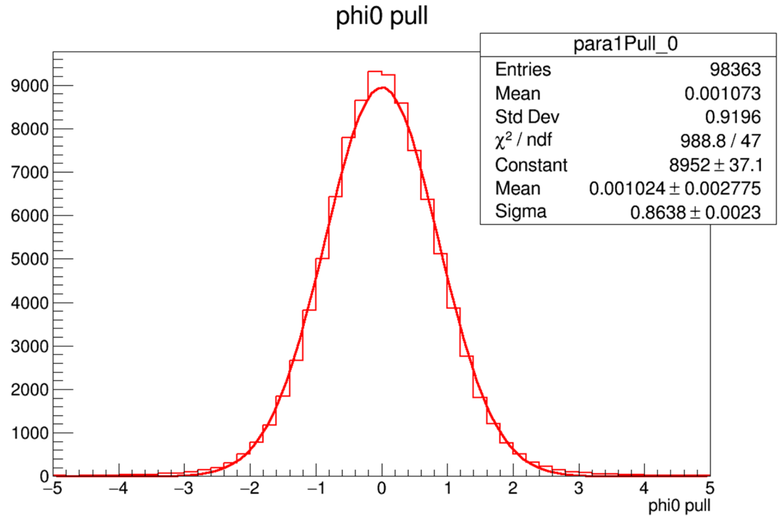
σ_v : the estimated uncertainty of the reconstructed track

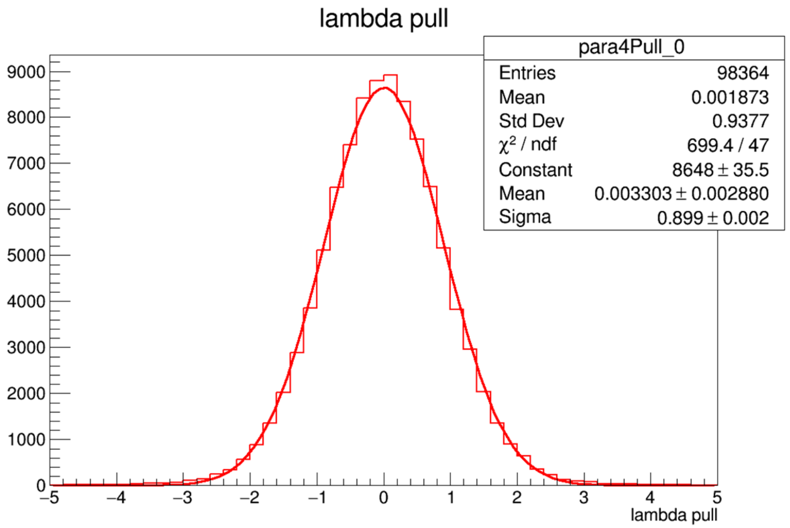


the pull distributions are approximately consistent with standard normal distributions, demonstrating that the track parameters and their uncertainties are estimated correctly.









Performance: pull distributions at the 1st measurement

- Pull distribution

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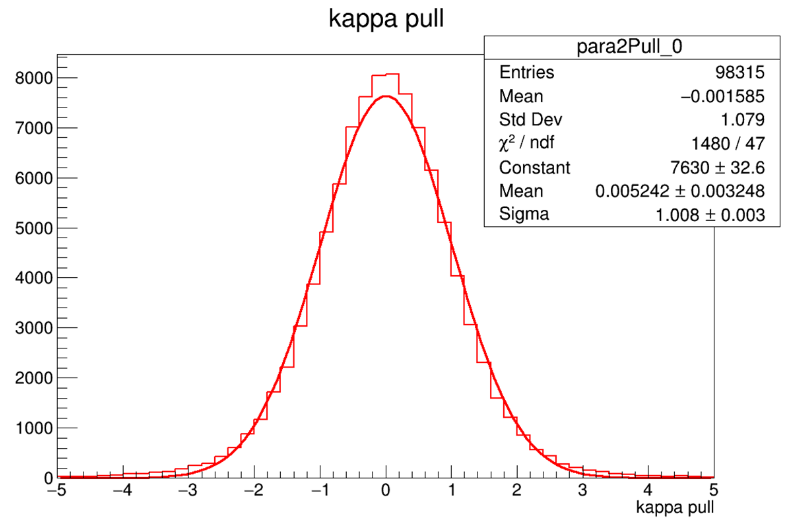
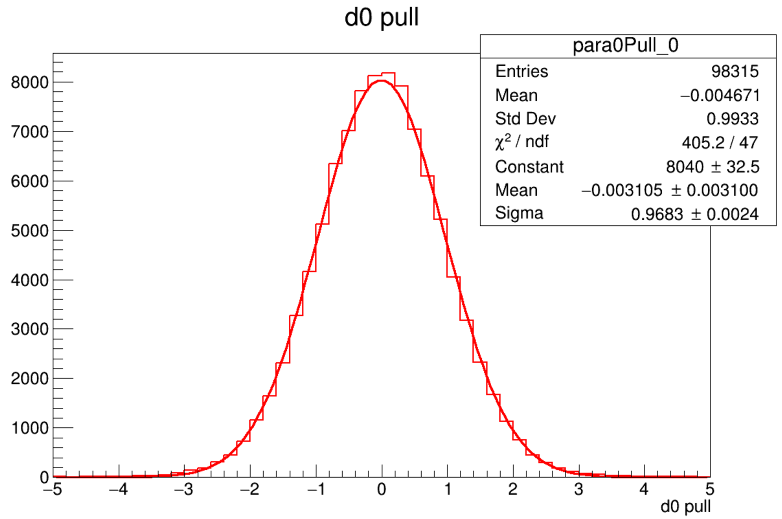
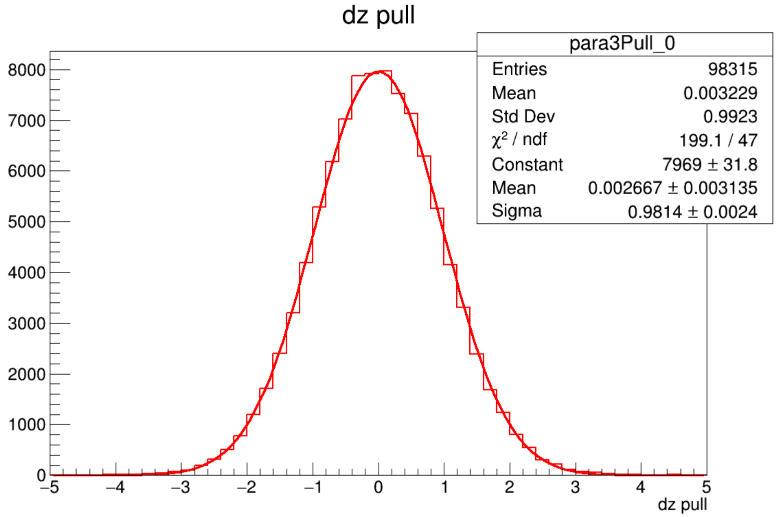
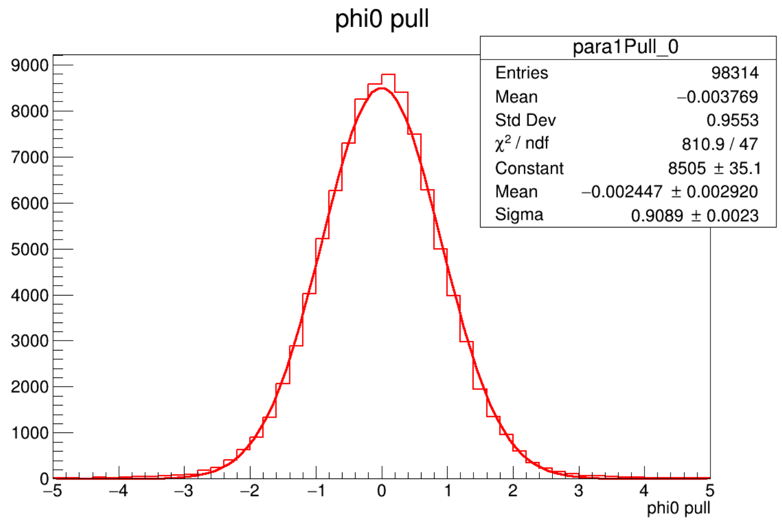
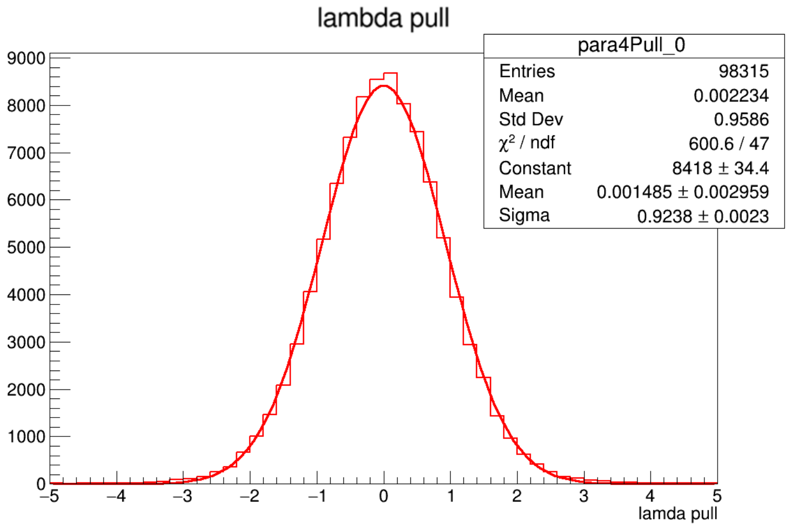






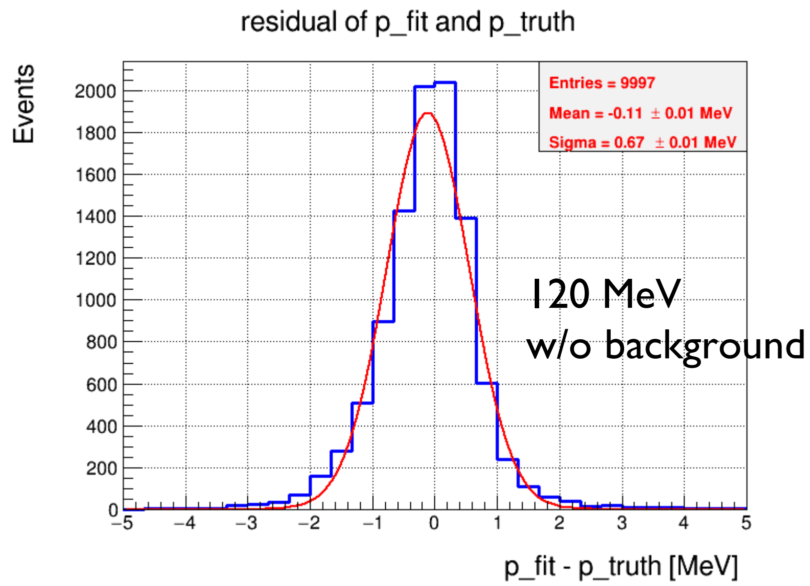


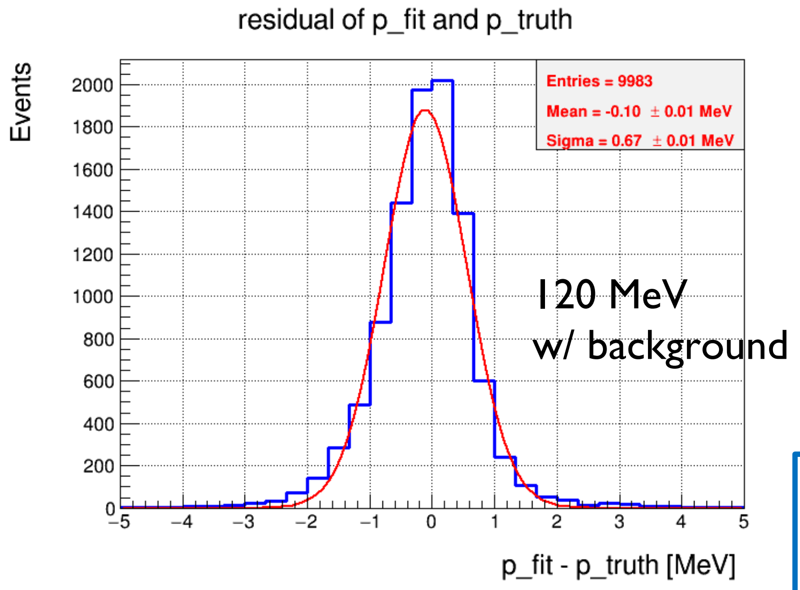


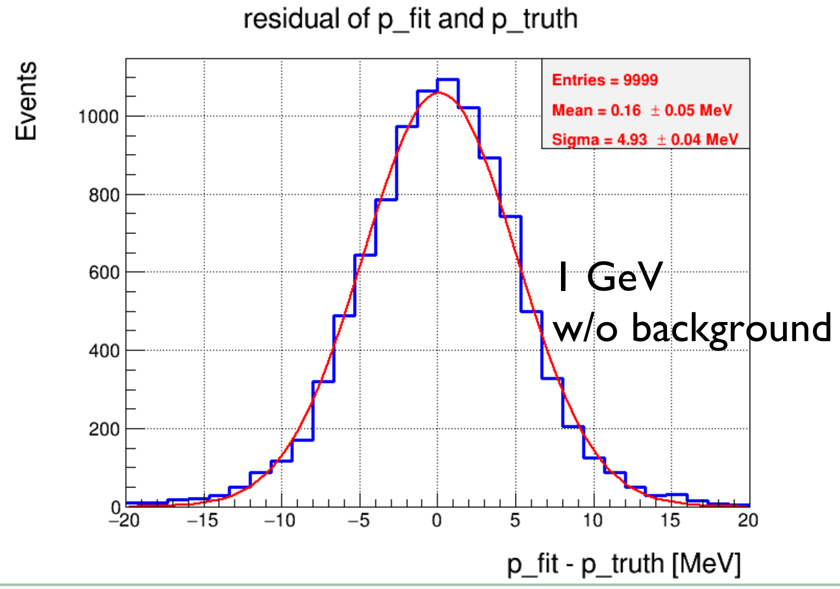
the pull distributions are approximately consistent with standard normal distributions, demonstrating that the track parameters and their uncertainties are estimated correctly.

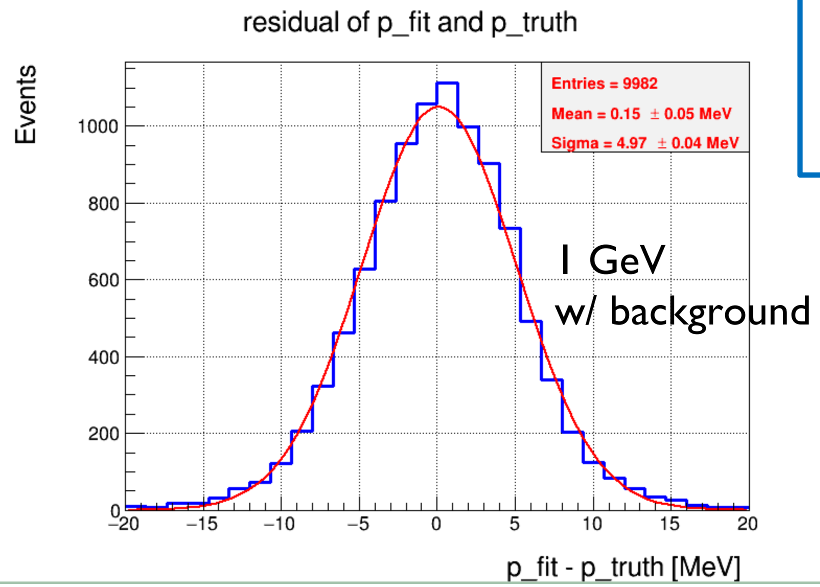
Performance

Fitting results for 10000 muons events (ITKW+MDC)









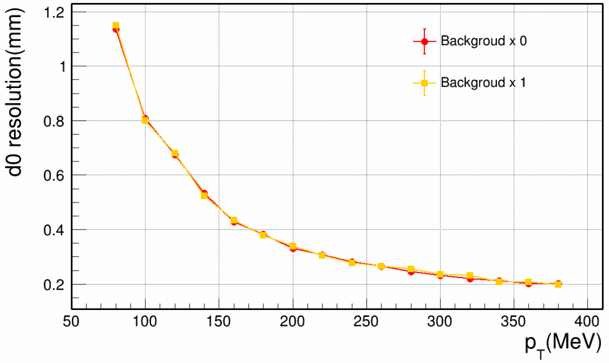
achieves good momentum resolution for both High/Low momentum tracks (<0.5% @ 1GeV, w/ w/o background)

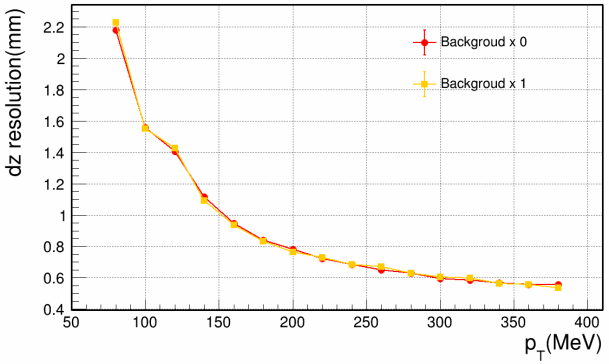
Performance: Vertex and momentum resolution form $\psi(3686) \to \pi^+\pi^- J/\psi,\ J/\psi \to \mu^+\mu^-$

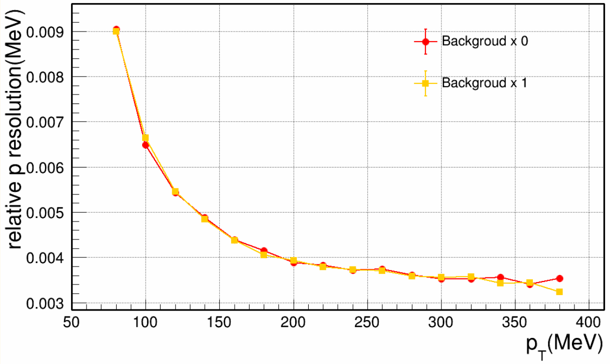
(ITKW+MDC)

shows stable performance w and w/o noise

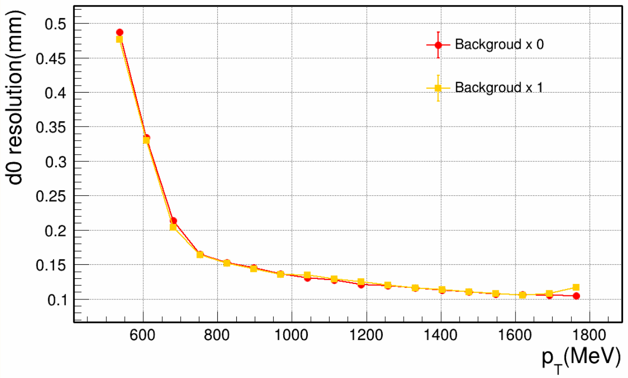
pion

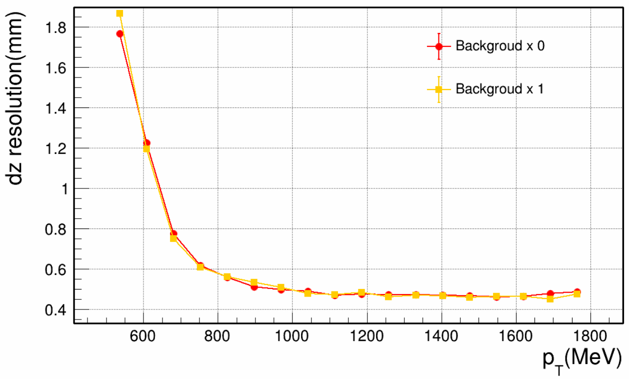


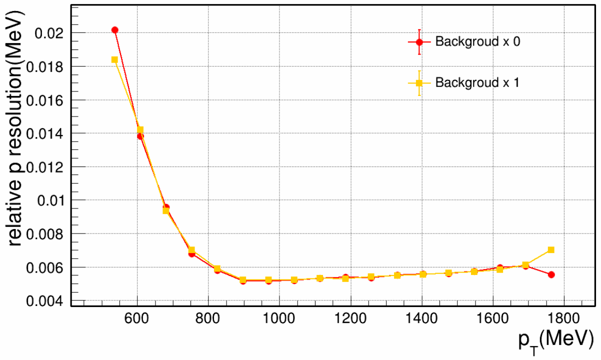




muon







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(ITKM+MDC)

shows stable performance w and w/o noise

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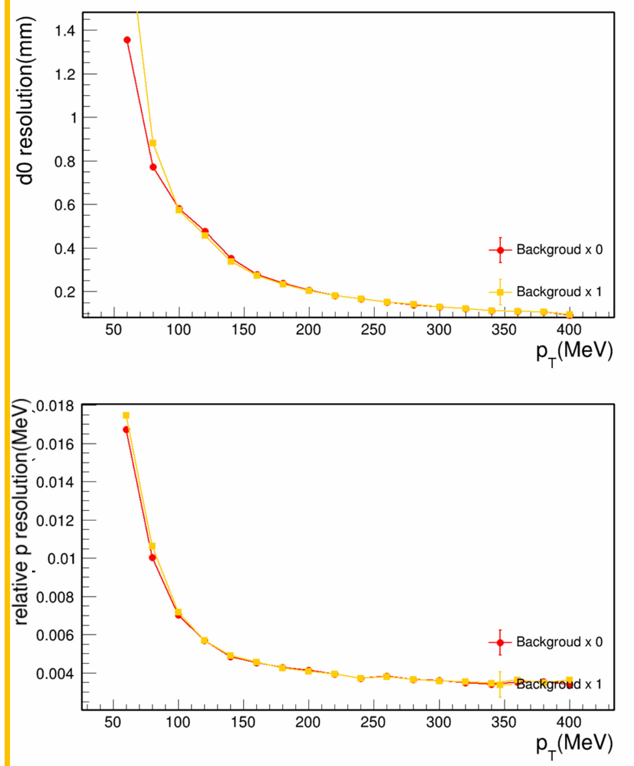
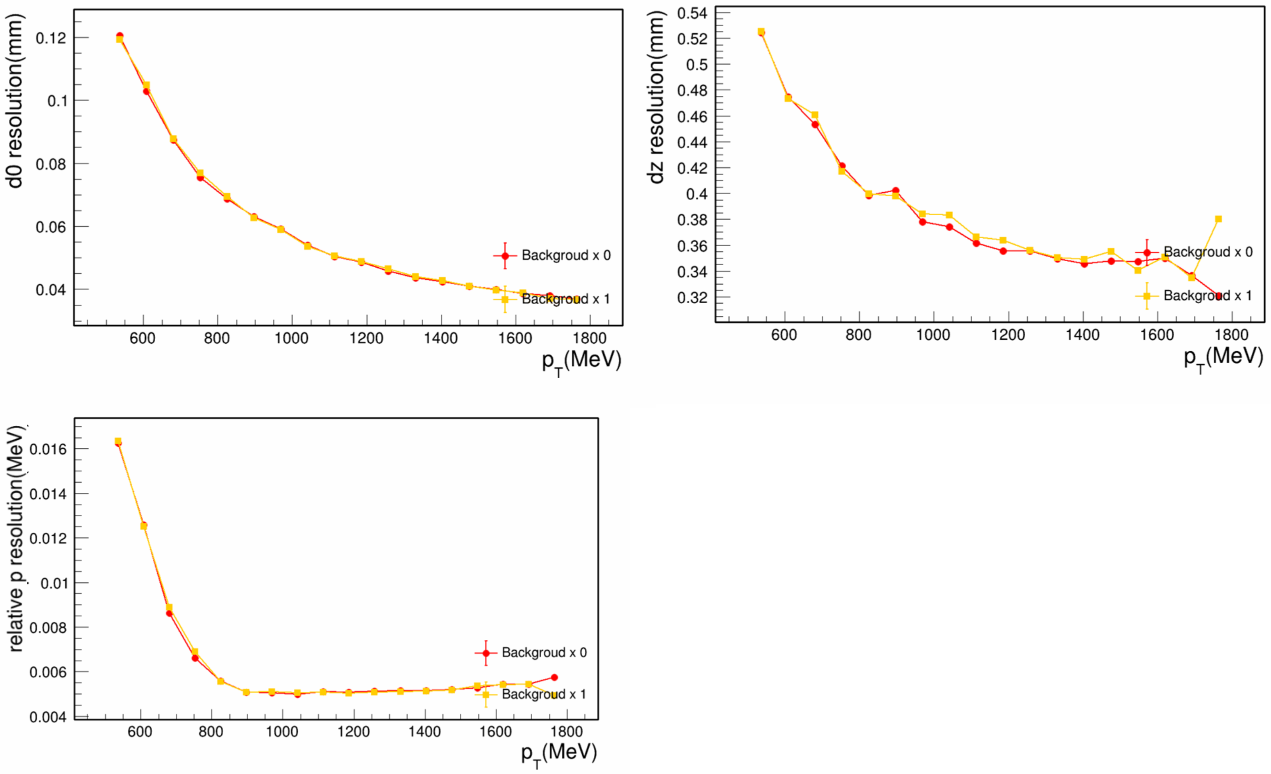


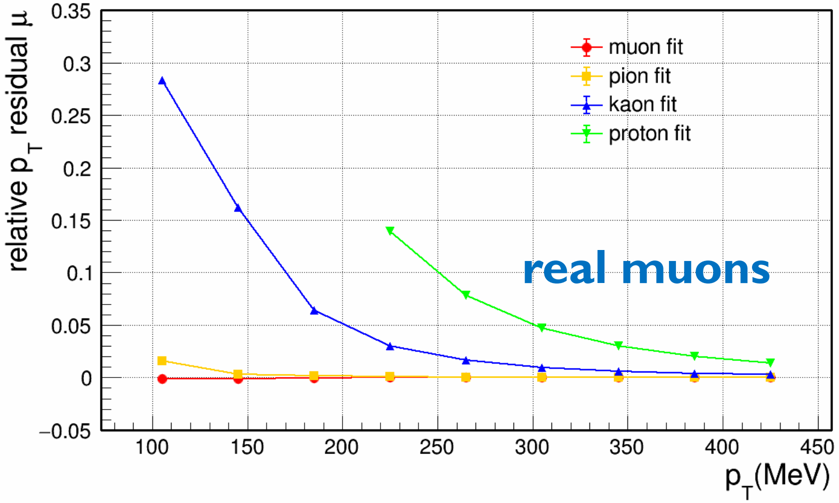
muon

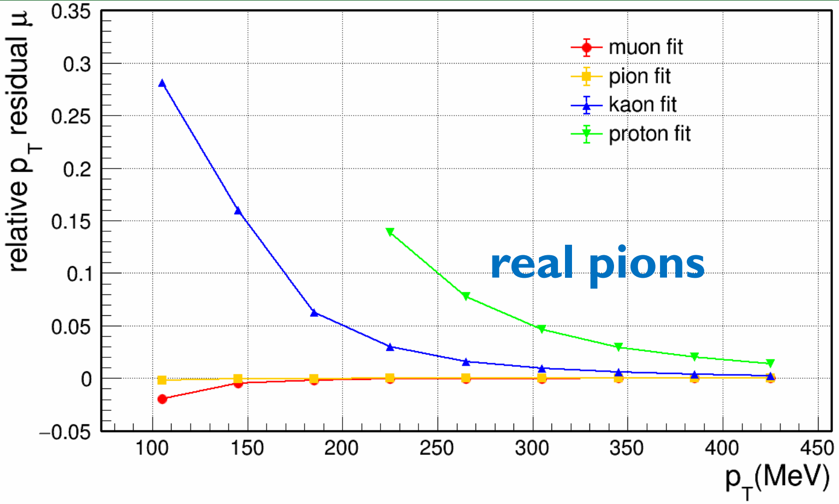


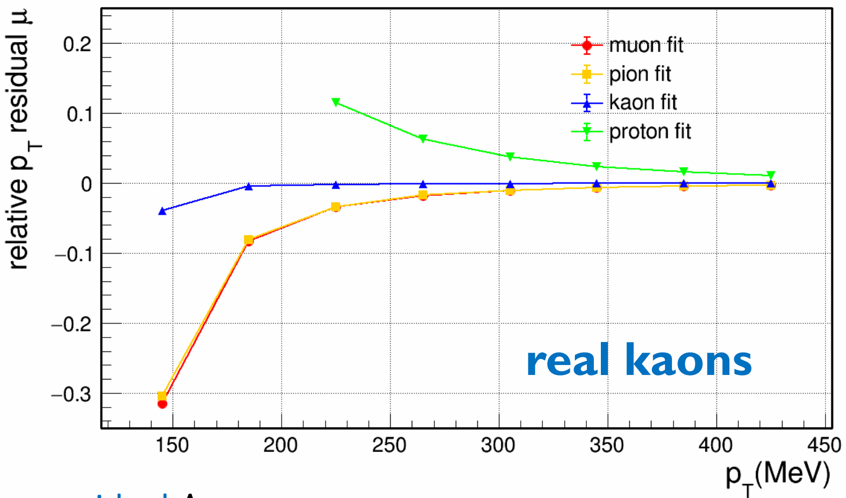
Ongoing study: multi hypotheses

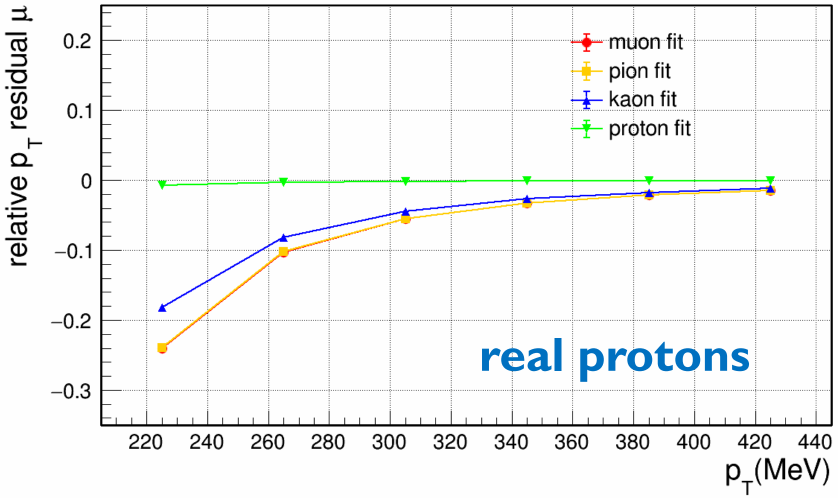
- The different particle hypotheses mainly differ in their **masses**, which translates to **different energy loss** assumptions.
- Using all five hypotheses increases computational cost.
- Thus, their impact was studied to determine if one of the particle hypotheses can be omitted.

> - the correct hypothesis provides the best estimation for the particle
> - The lower the particle momentum, the greater the difference between particle hypotheses with significantly different masses.









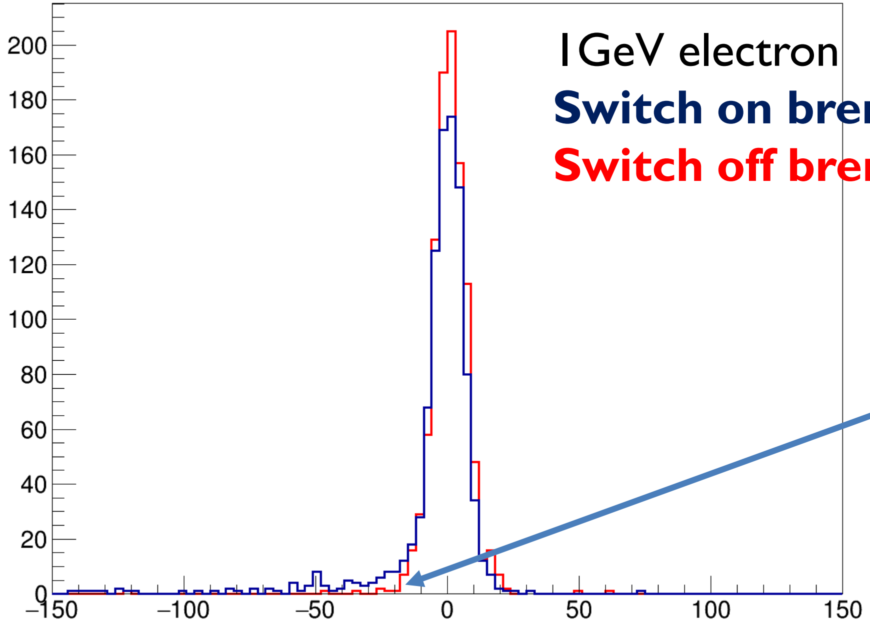
residual $\Delta v = v_{fit} - v_{truth}$

relative residual $\Delta v_{rel} = \frac{v_{fit} - v_{truth}}{v_{truth}}$

v_{fit} : the estimated value

v_{truth} : the true simulated value

Ongoing study: Fitting Performance w/ w/o brem in simulation



- When bremsstrahlung is disabled in the simulation, the ~11% of events deviating by more than 3σ from the Gaussian fit disappear
- the tail is caused by bremsstrahlung effects
- To do: Correct electron energy loss due to bremsstrahlung

	$J/\psi \to \mu^+ \mu^-$		$J/\psi \to e^+ e^-$	
Cut Flow	Eff	Rel.Eff	Eff	Rel.Eff
$N_{good\text{-}charged}=4$	66.07%	66.07%	63.99%	63.99%
$\pi^+ \pi^-$ l+l- assignment	66.03%	99.93%	63.95%	99.93%
EMC PID	64.22%	97.25%	55.53%	86.83%
$chi_{4c}^2 < 60$	59.75%	93.04%	42.05%	75.73%
Mass Window	59.65%	99.83%	41.98%	99.84%

Ongoing study: retrieve ITK hits

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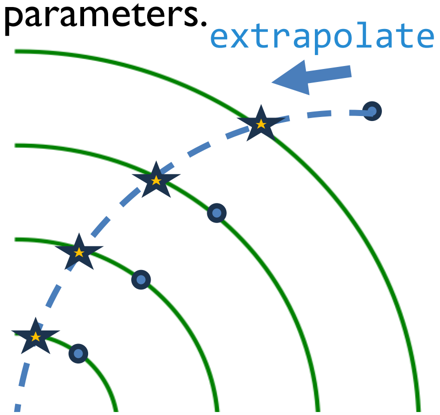
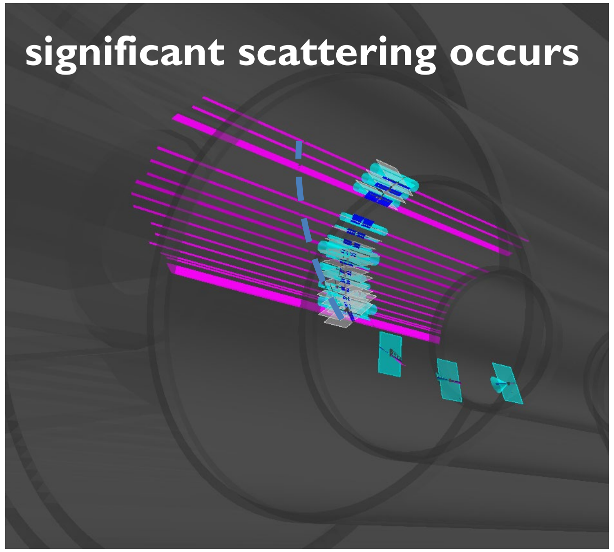
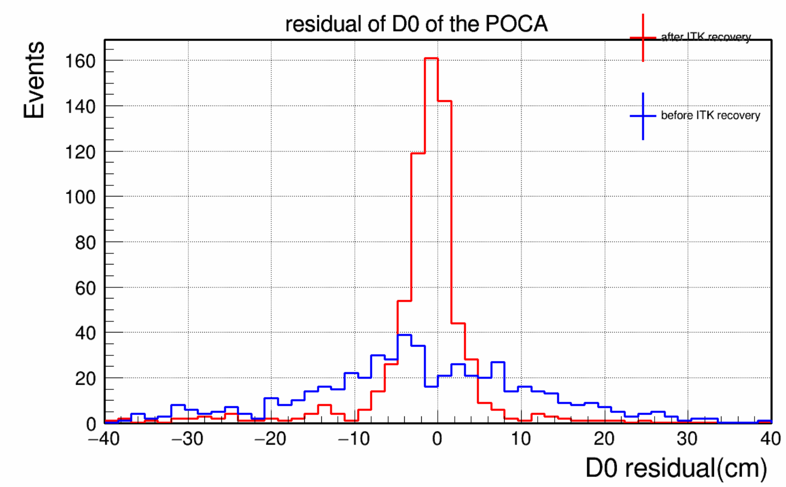
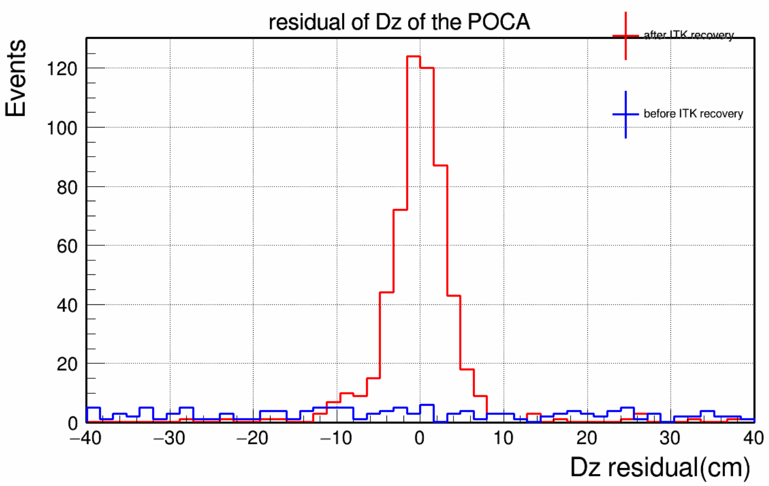
- Low-momentum particles suffer from significant material effects
  - In some cases, only tracks in MDC are found; ITK hits are lost
- A **retrieve ITK hits** algorithm is under development to reconstruct complete tracks to improve the accuracy of track parameters.

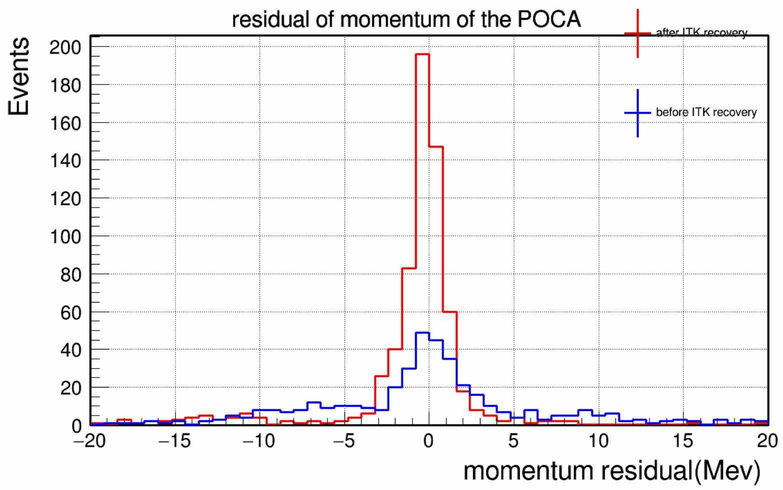




parameters residual distribution after/before ITK recovery



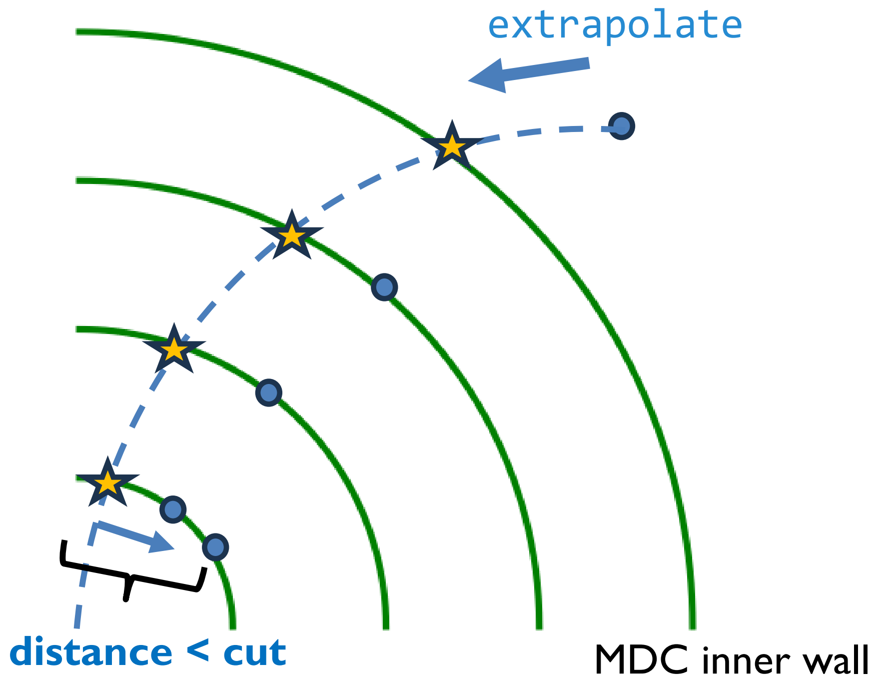


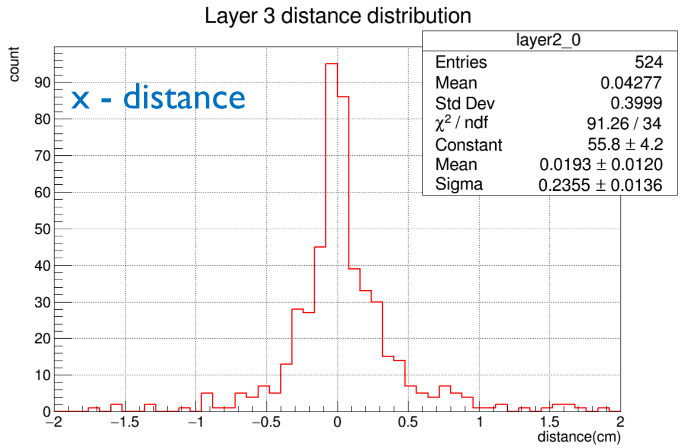


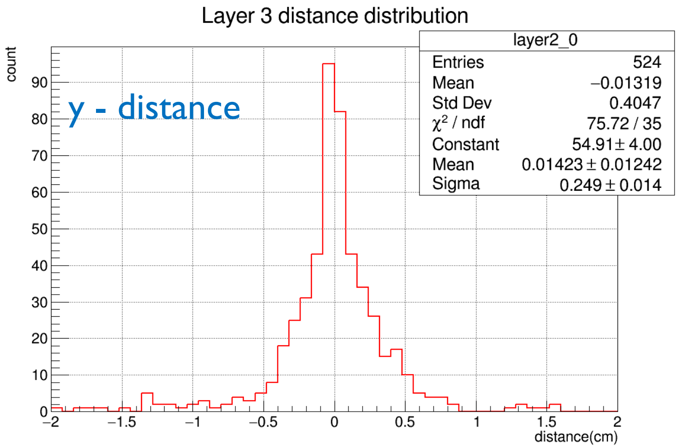
Ongoing study: retrieve ITK hits

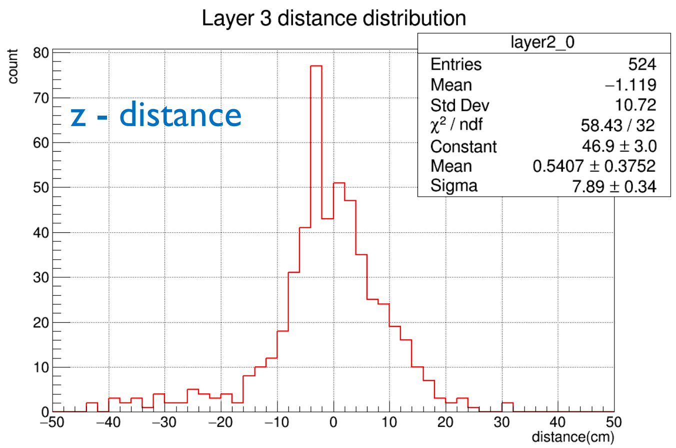
1. extrapolate to the MDC inner wall firstly
2. extrapolate backward layer by layer
3. decide whether to retrieve the ITK hits (according to the distance between extrapolated and measured hit position)

- Ongoing task: find the suitable cut to decide whether to retrieve ITK hits





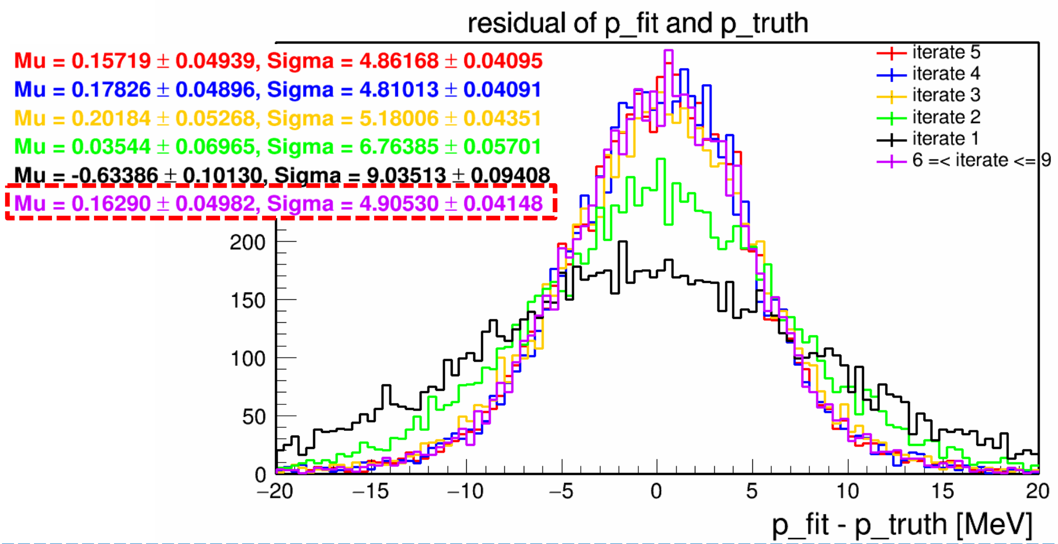




Ongoing study: DAF noise rejection

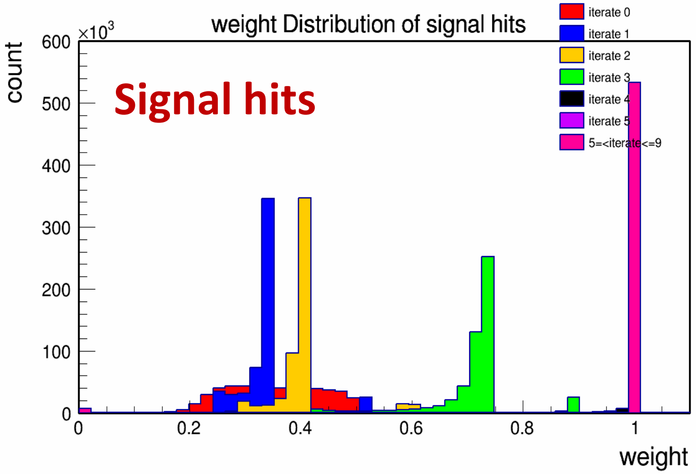
- The noise rejection capability is studied with 1GeV muon, with 1X background

fitting iteration process

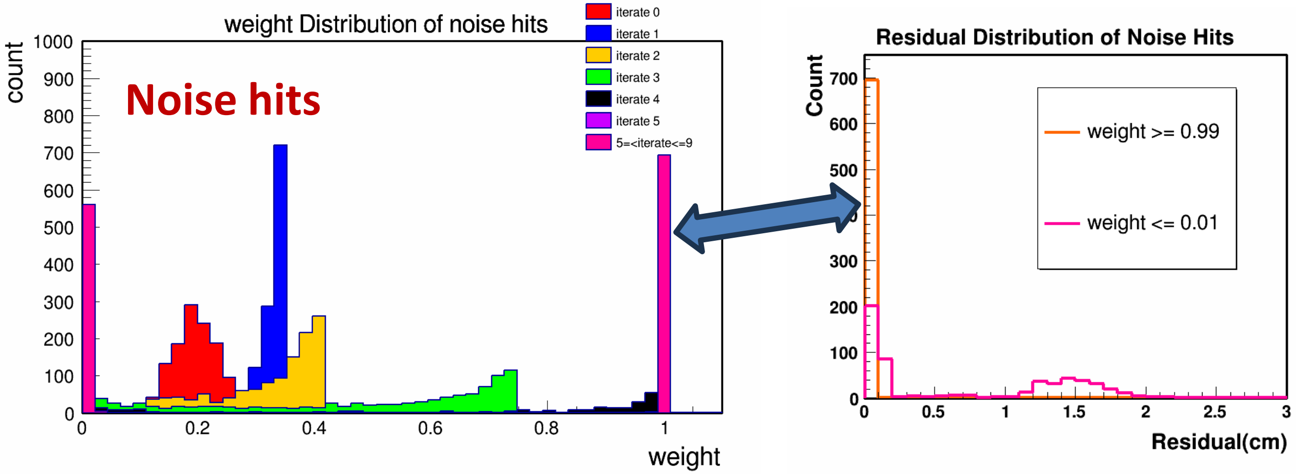


- **The ambiguity of hits is not initialized before fitting, it is managed in DAF**
- **The fitter generally converges after 5 iterations**

- the weight of signal hits converges to 1



- The weight of noise hits with large residual converges to 0
- the remaining noise hits are very close to real tracks(residual<0.05cm)



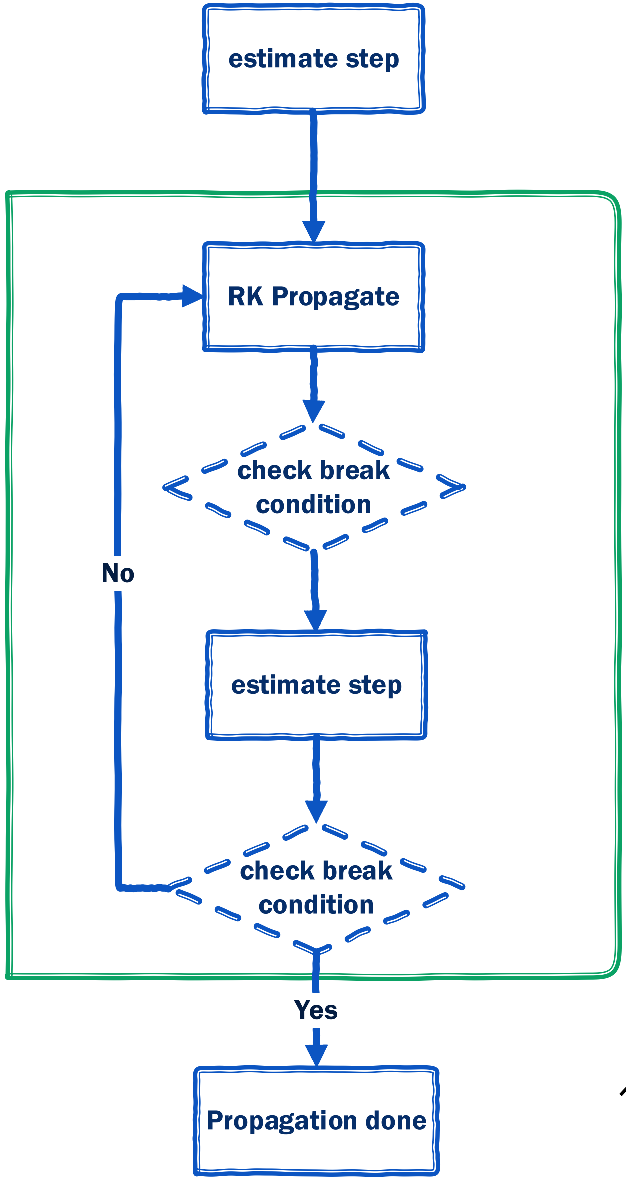
Summary

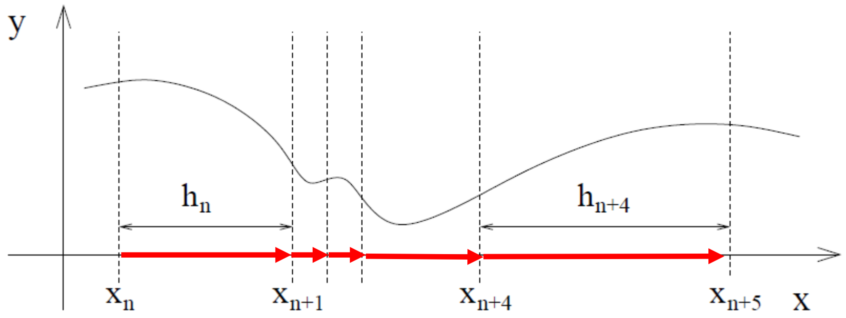
- DAF is adopted as the default track fitting algorithm in STCF offline software framework, **providing good momentum resolution for both High/Low momentum**

- Ongoing study
  - combine the information from ITK and MDC to improve the reconstruction accuracy in low-momentum cases
  - Optimize the fitting criteria to reject noise and reduce fake and duplicate tracks.
  - determine the proper number of particle hypotheses to balance computing cost and performance
  - correct electron bremsstrahlung energy loss

BACK UP

Extrapolate method

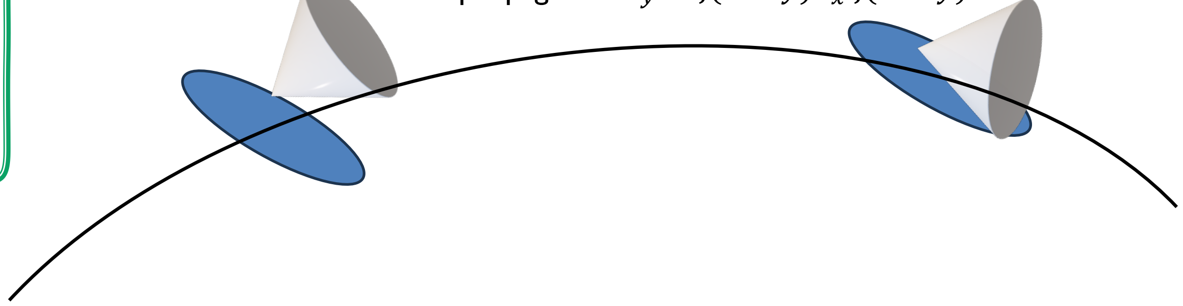




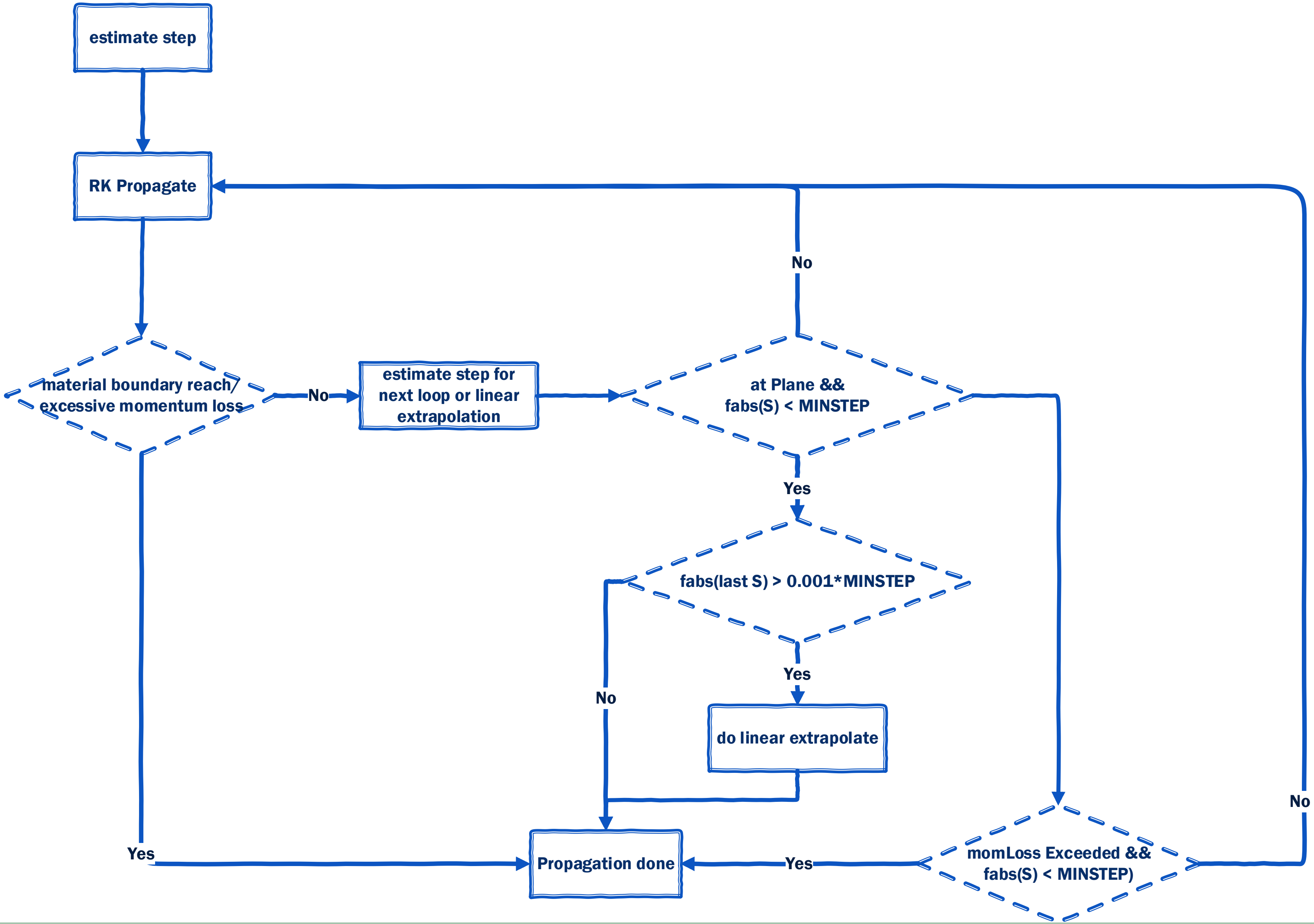
propagate step by step

each step:

- calculate energy loss
- updates the transport Jacobians along the track $J_1, J_2, \ldots J_{n-1}, J_n$
- error propagation $C_y = J(x \to y) C_x \, J(x \to y)^T$



Extrapolate method



Estimate step

- step size is limited by:

  ① maximum step setting

  ② maximum momentum loss

  - do not maximal exceed relative momentum loss in the material

  ③ material boundary

  - extrapolation stops at material boundaries

  ④ distance to the target plane

  ⑤ field inhomogeneities

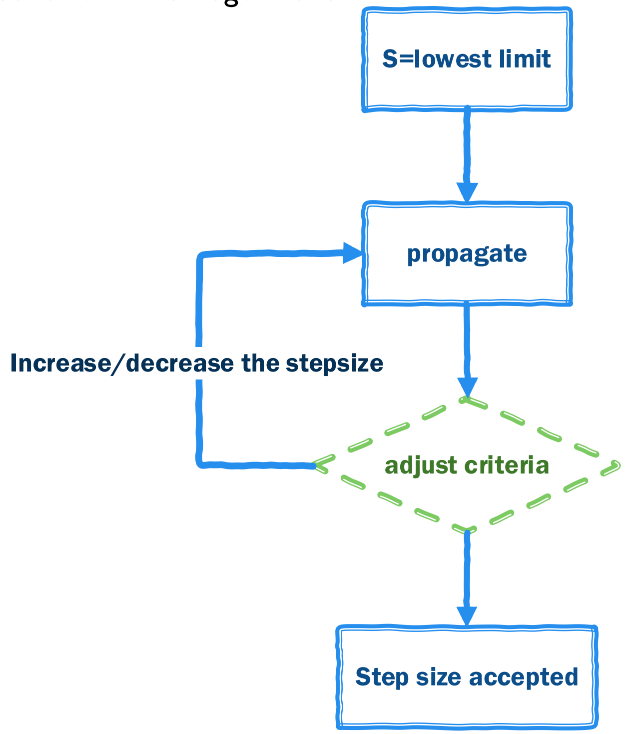
  - local error estimate $\epsilon = y_{n+1} - \hat{y}_{n+1}$
  - new step length $h_{n+1} = h_n(\frac{\tau}{|\epsilon|})^{\frac{1}{q+1}}$
  - the step is only accepted if the criteria is fulfilled. (eg. $\frac{h_n}{4} \leq h_{n+1} \leq 4h_n$ and $|\epsilon| < 4\tau$)

higher (y_{n+1}) and lower ($\hat{y}_{n+1}$) order solution

user-specified error tolerance τ

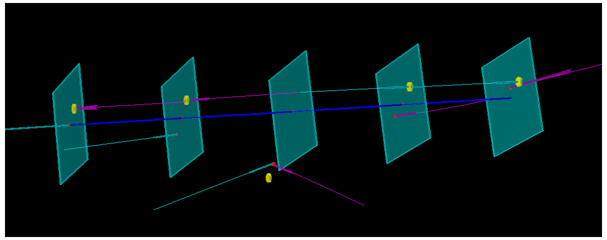
lower order q

estimate step size taking into account field inhomogeneities



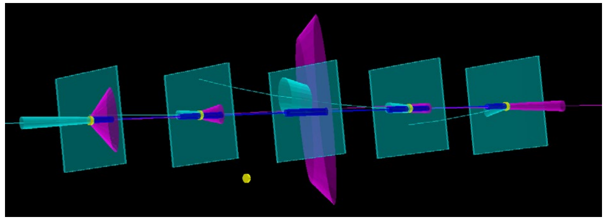
DAF iteration

iteration 1



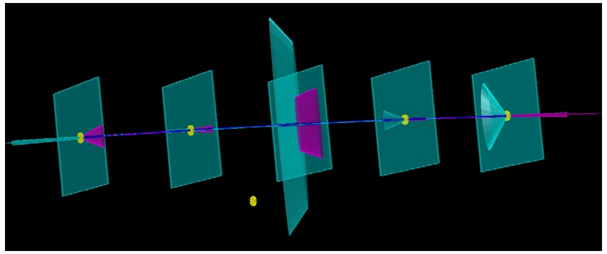
old weights	1	1	1	1	1
new weights	0.0805671	0.0466704	**7.64619e-20**	0.0620372	0.0620372

iteration 2



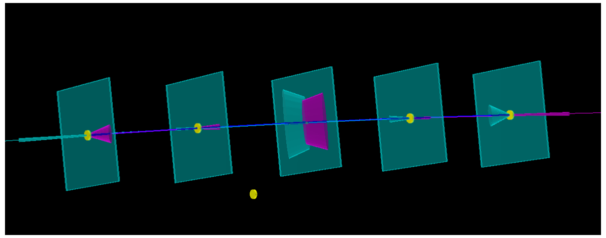
old weights	0.0805671	0.0466704	**7.64619e-20**	0.0620372	0.0620372
new weights	0.594671	0.585524	**3.81322e-171**	0.585042	0.592371

iteration 3



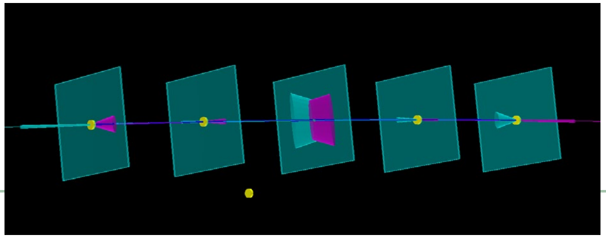
old weights	0.594671	0.585524	**3.81322e-171**	0.585042	0.592371
new weights	0.896426	0.887211	**0**	0.884235	0.895077

iteration 4



old weights	0.896426	0.887211	**0**	0.884235	0.895077
new weights	0.999995	0.999991	**0**	0.999989	0.999994

iteration 5

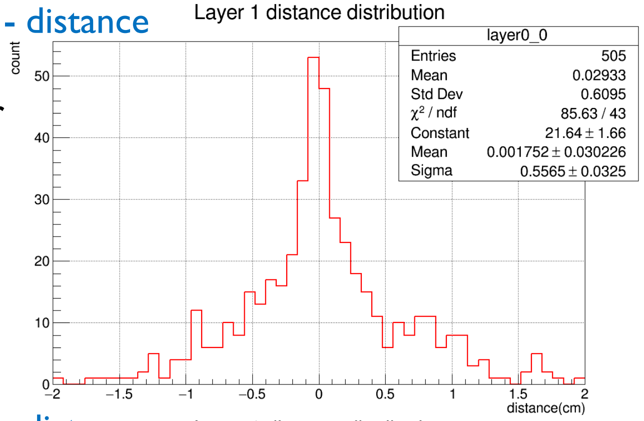


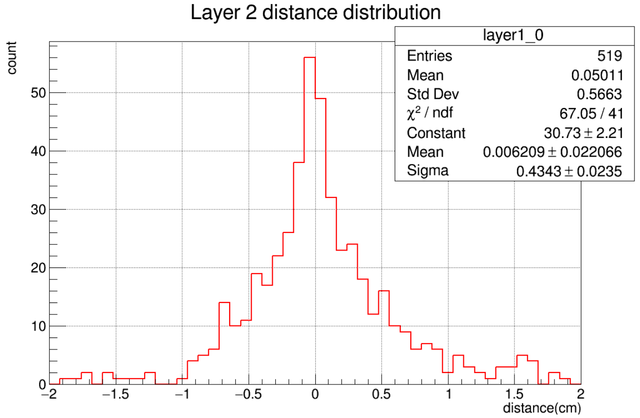
old weights	0.999995	0.999991	**0**	0.999989	0.999994
new weights	1	1	**0**	1	1

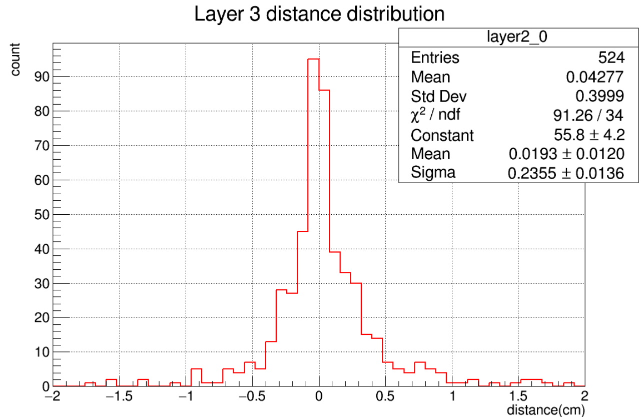
retrieve ITK hits

- Global distance of each ITK layer

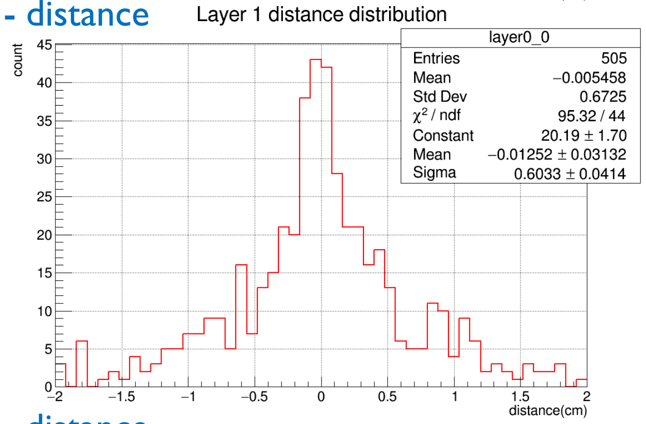
x - distance

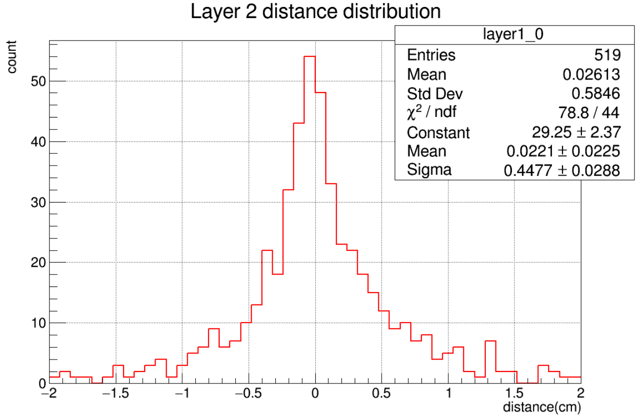


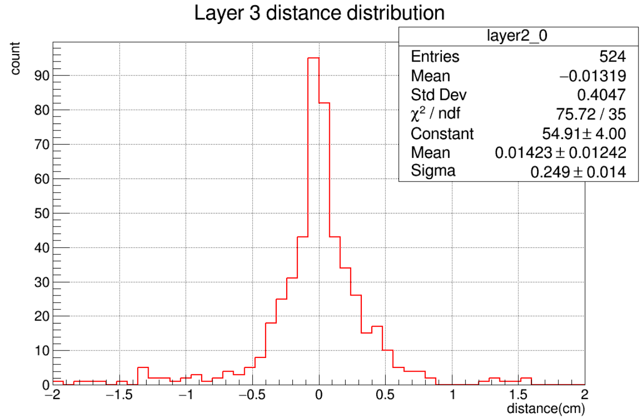




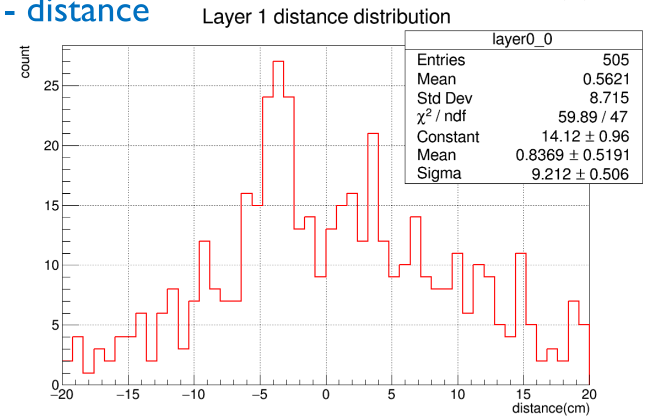
y - distance

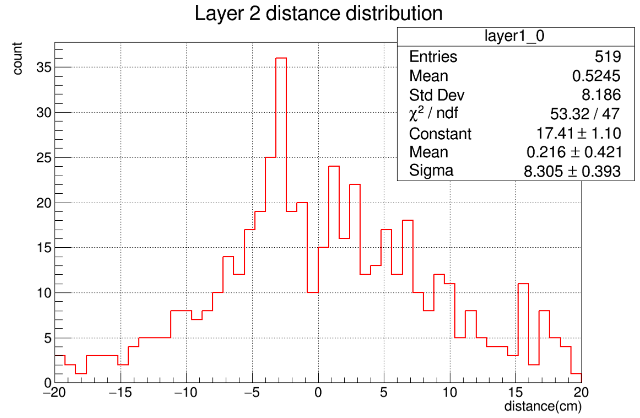


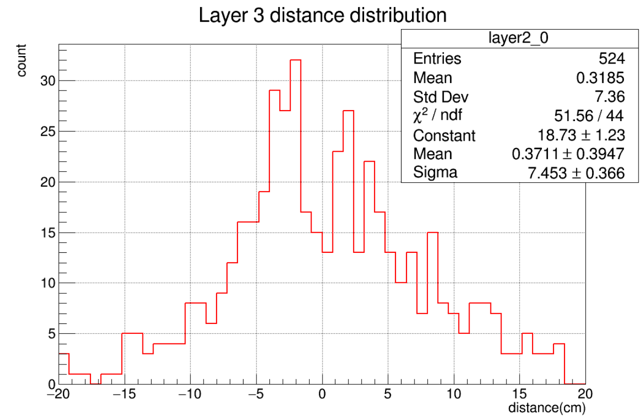




z - distance







retrieve ITK hits

- firstly attempted to use global distance for filter decision
- significant deviations were observed in the z-direction
- switch to a weighted distance

$$\bar{d} = (d_i)^T (V_i)^{-1} d_i$$

$$V_i = H^T C_i H + V_m$$

d_i :distance vector

C_i: uncertainty of track parameters

V_i: uncertainty of measurements

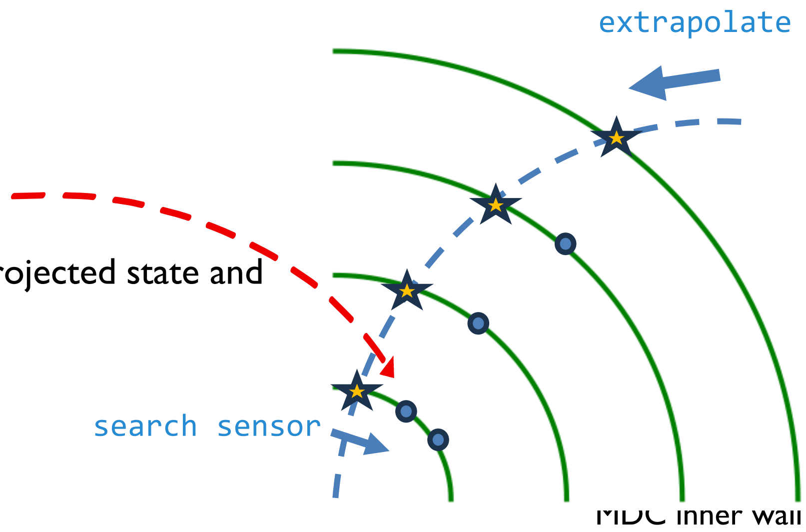
  - the uncertainty defined on the measurement plane is needed

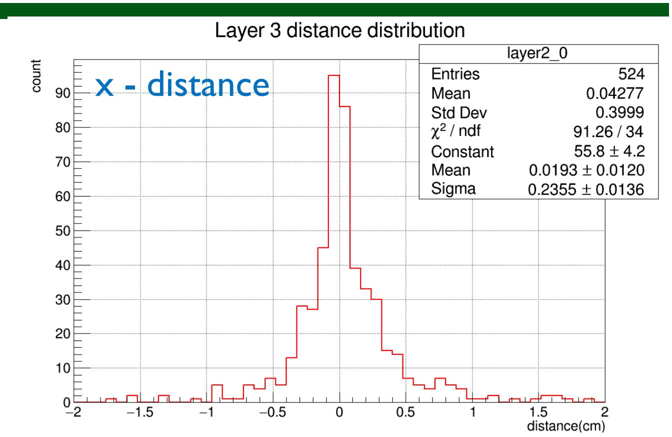
- switch to local weighted distance

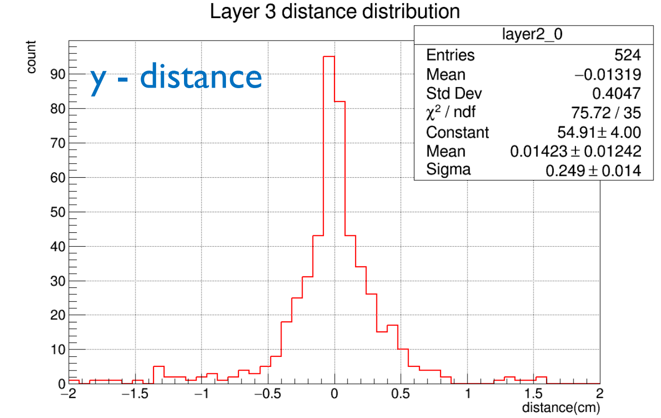
① search detector plane firstly

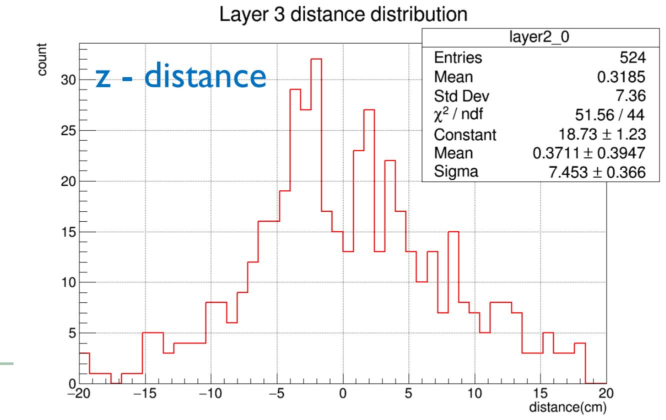
② propagate the extrapolated state to the plane

③ calculate local weighted distance between the projected state and measurement

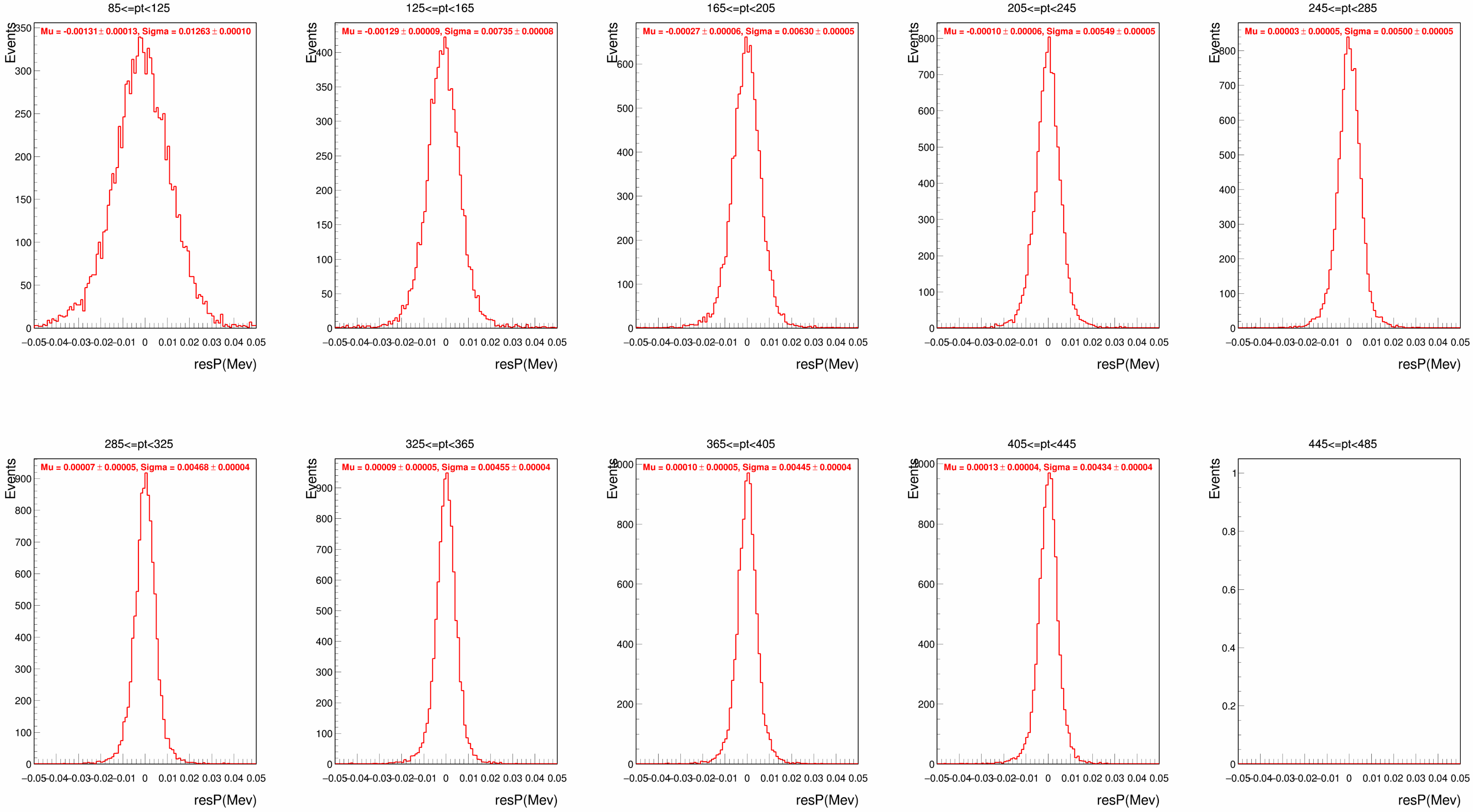




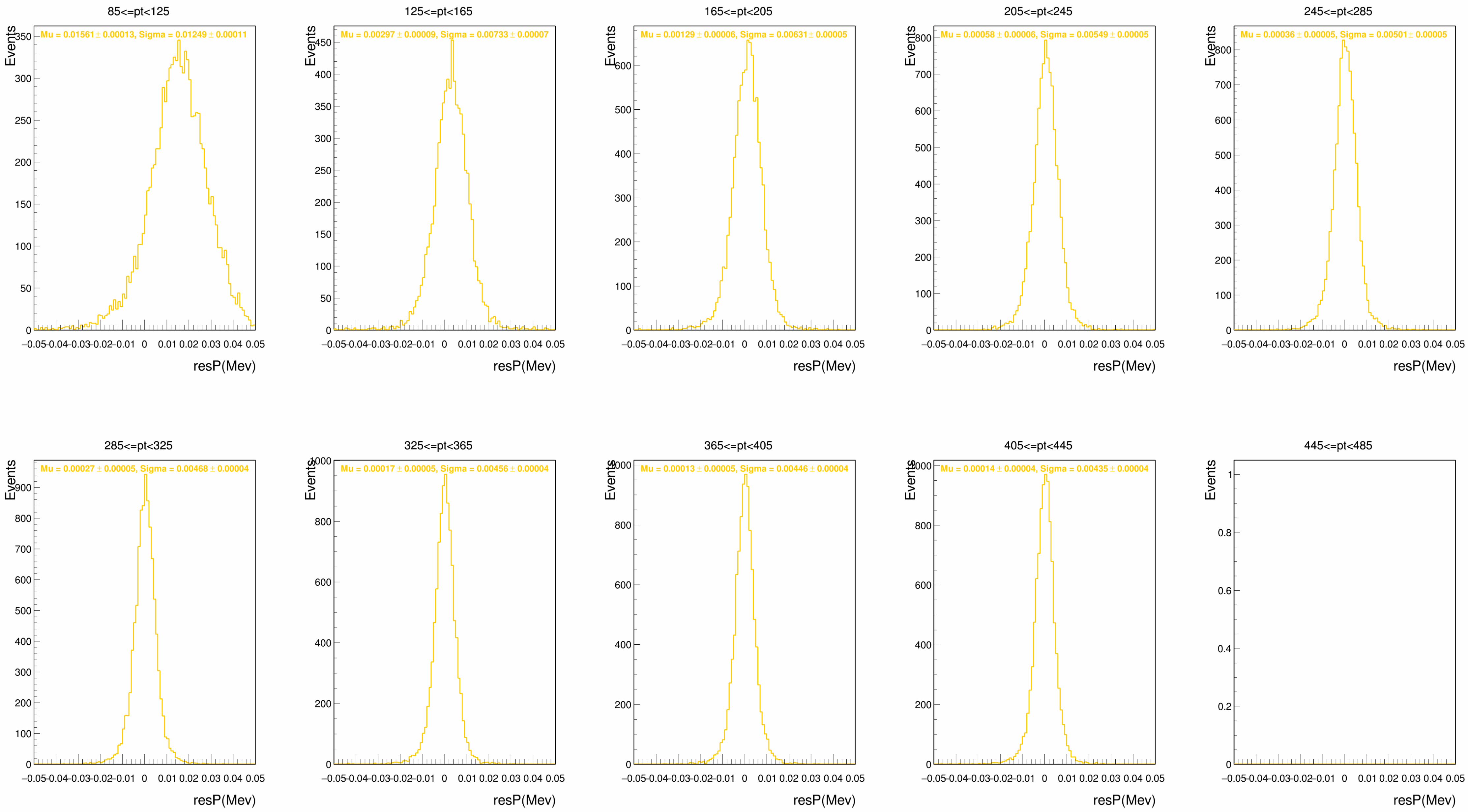




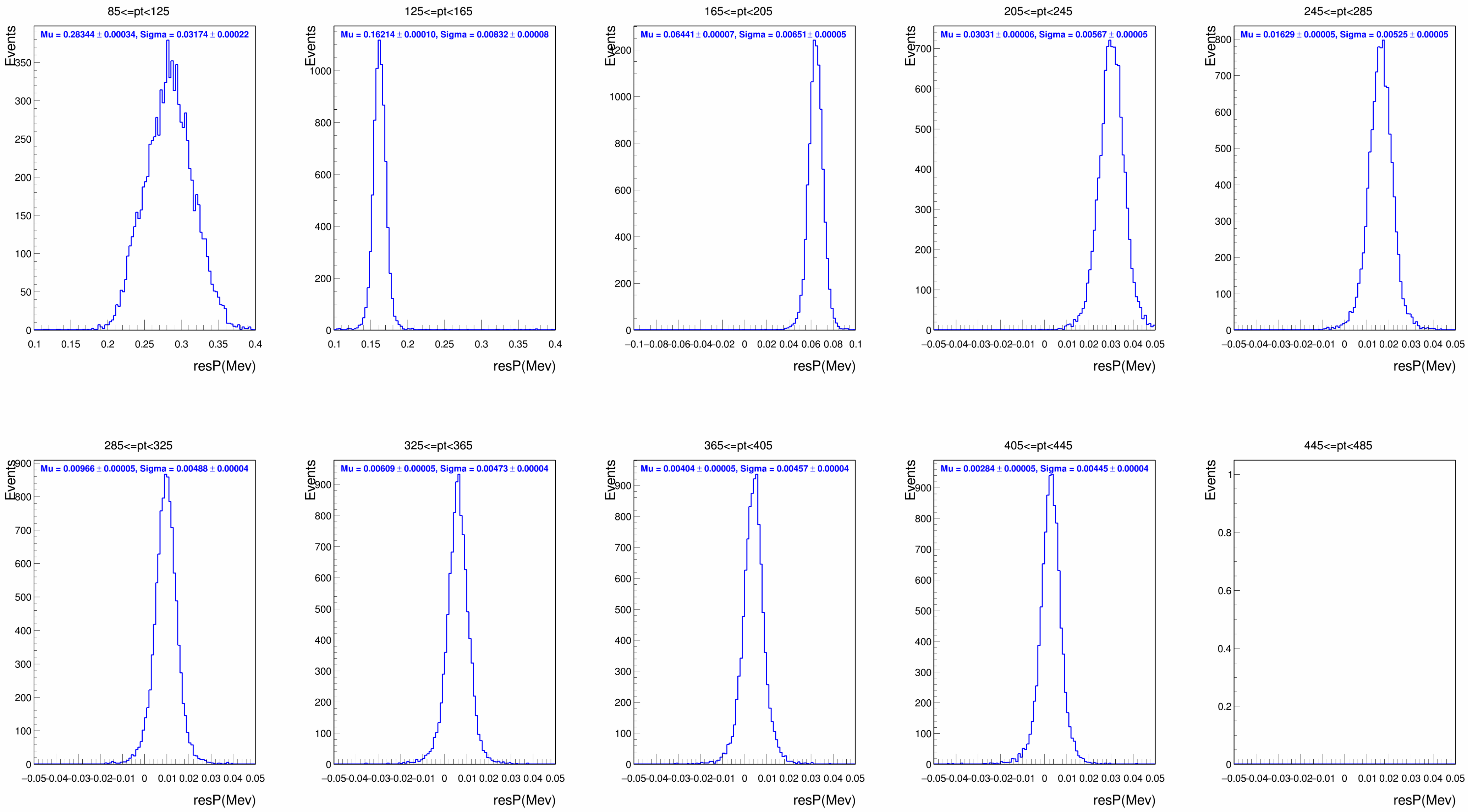
- real muons were fitted with the muon hypothesis



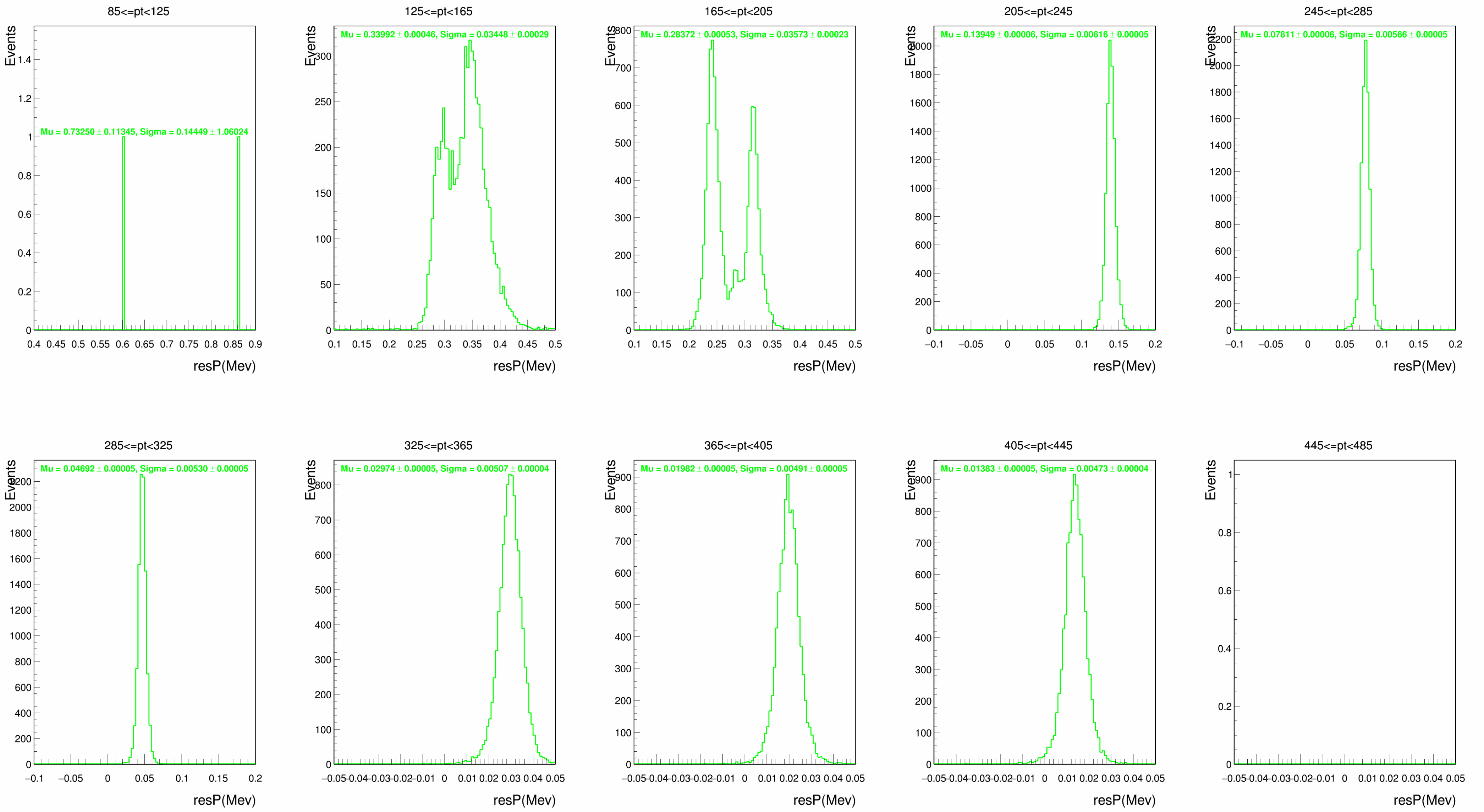
- real muons were fitted with the pion hypothesis



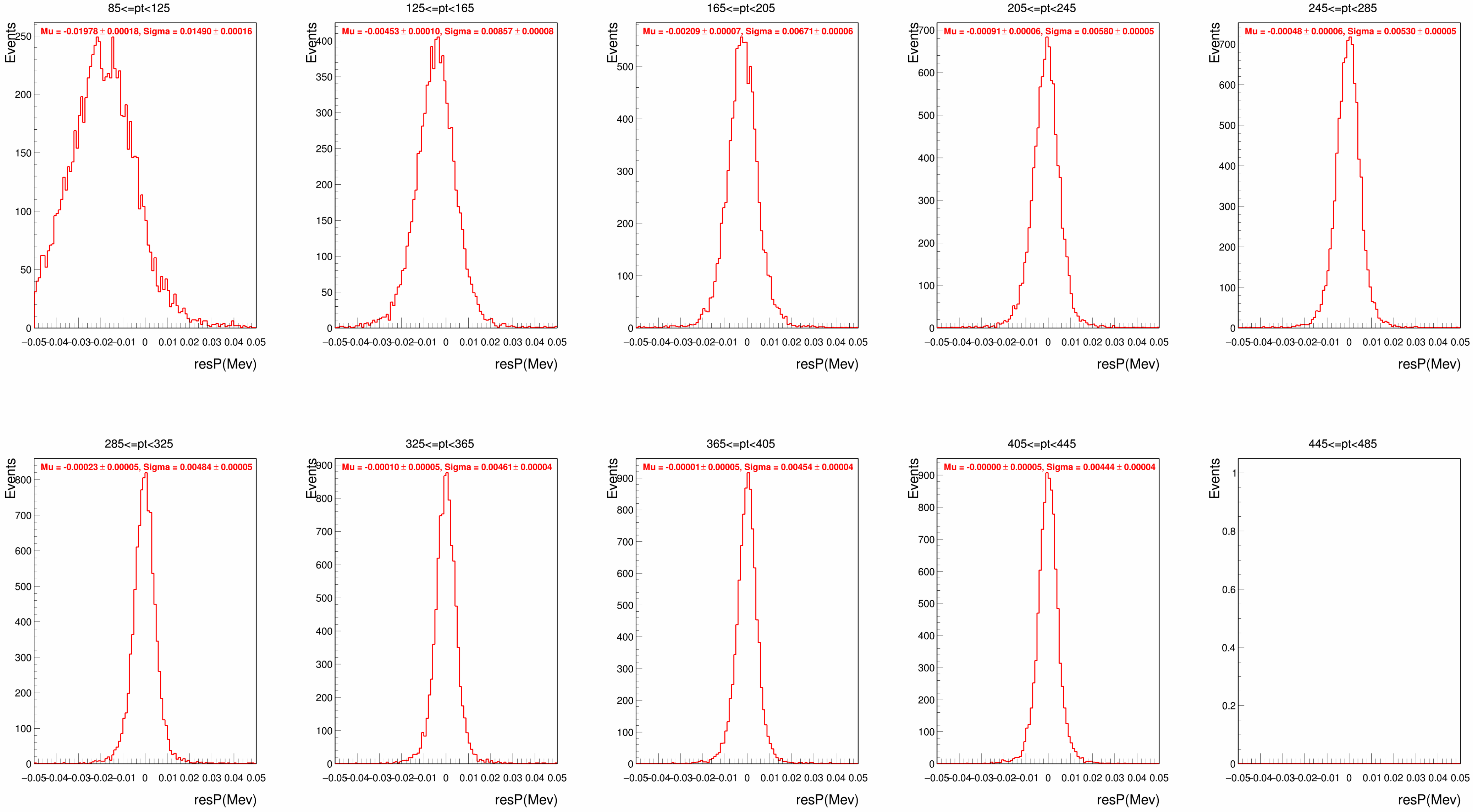
- real muons were fitted with the kaon hypothesis



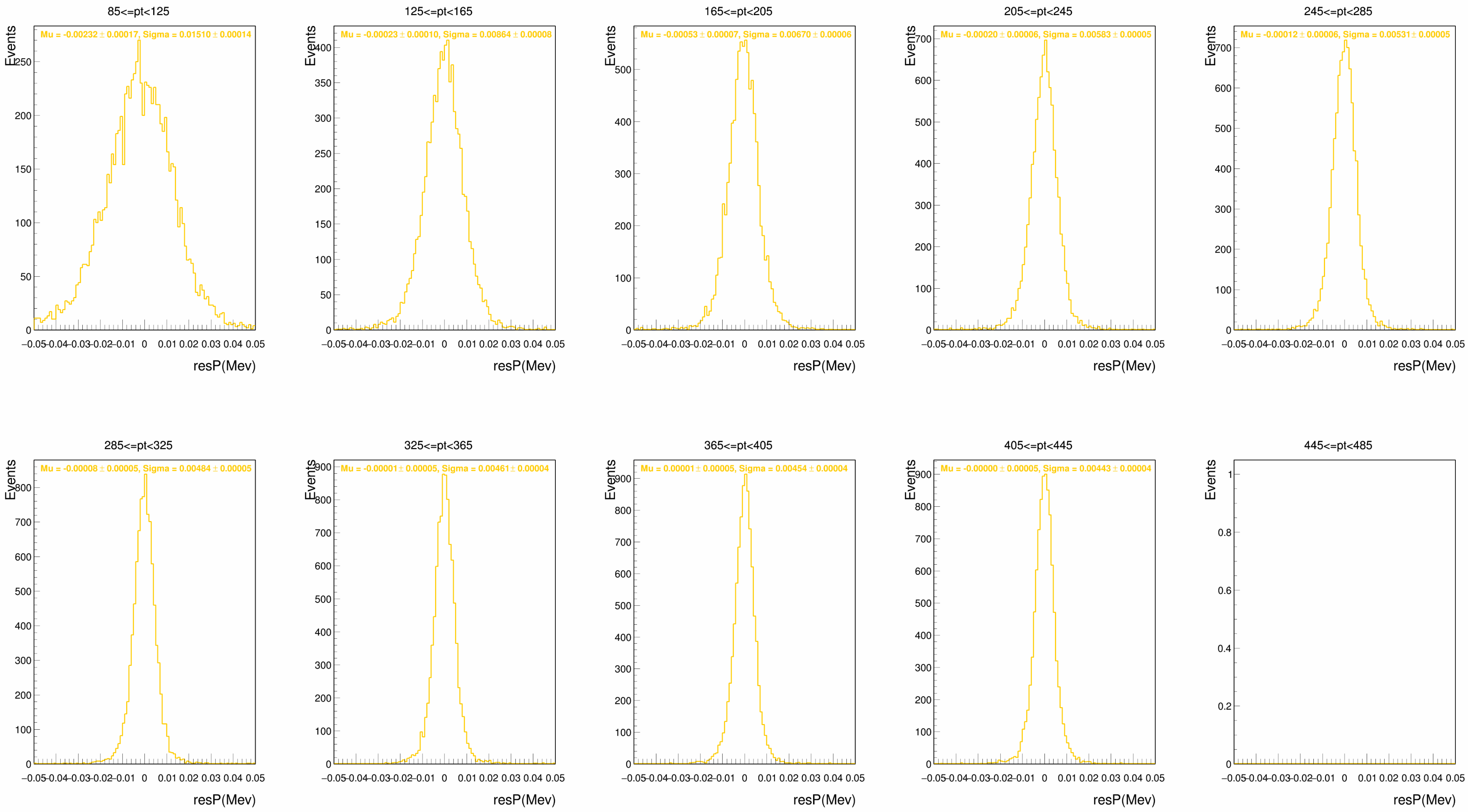
- real muons were fitted with the proton hypothesis



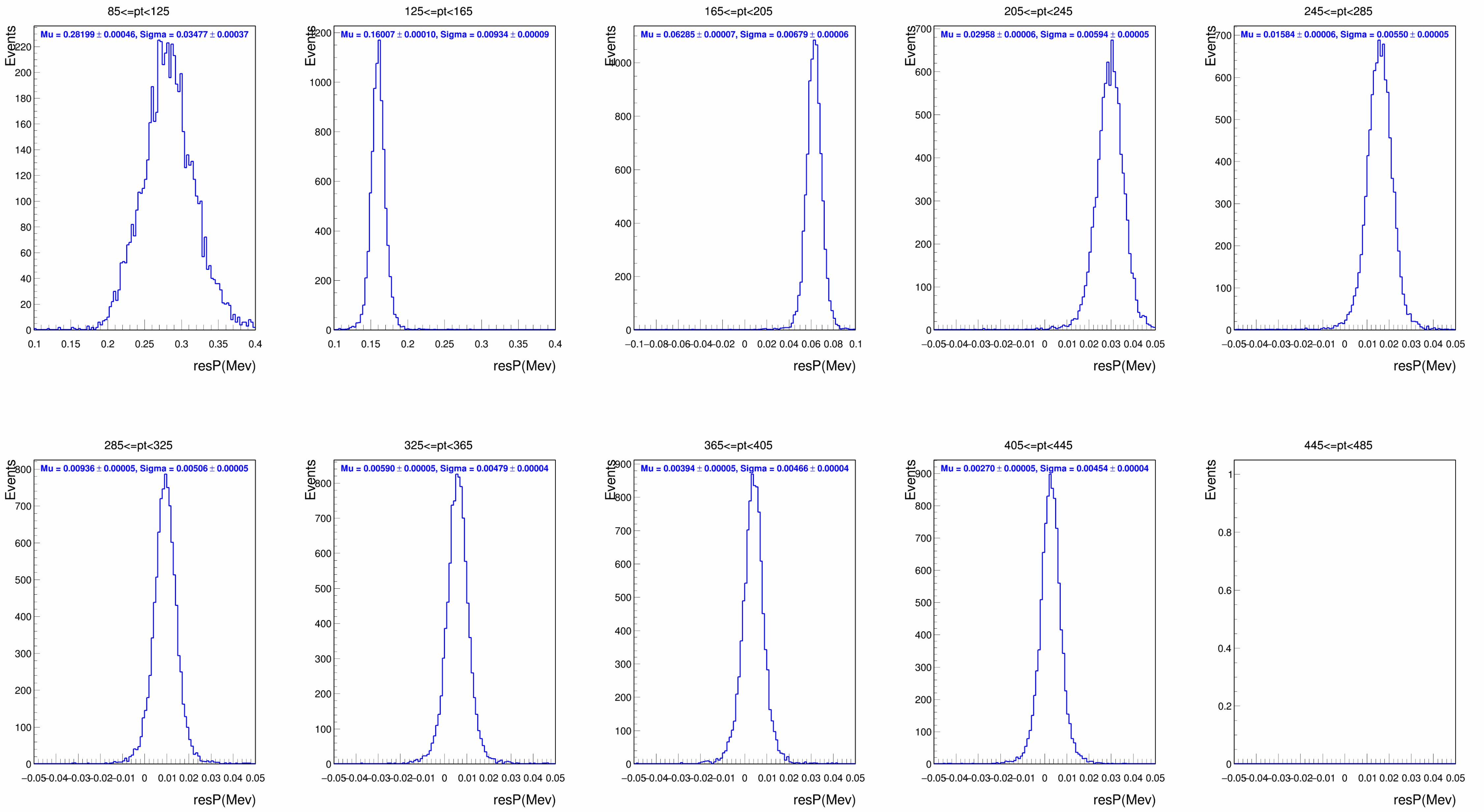
- real pions were fitted with the muon hypothesis



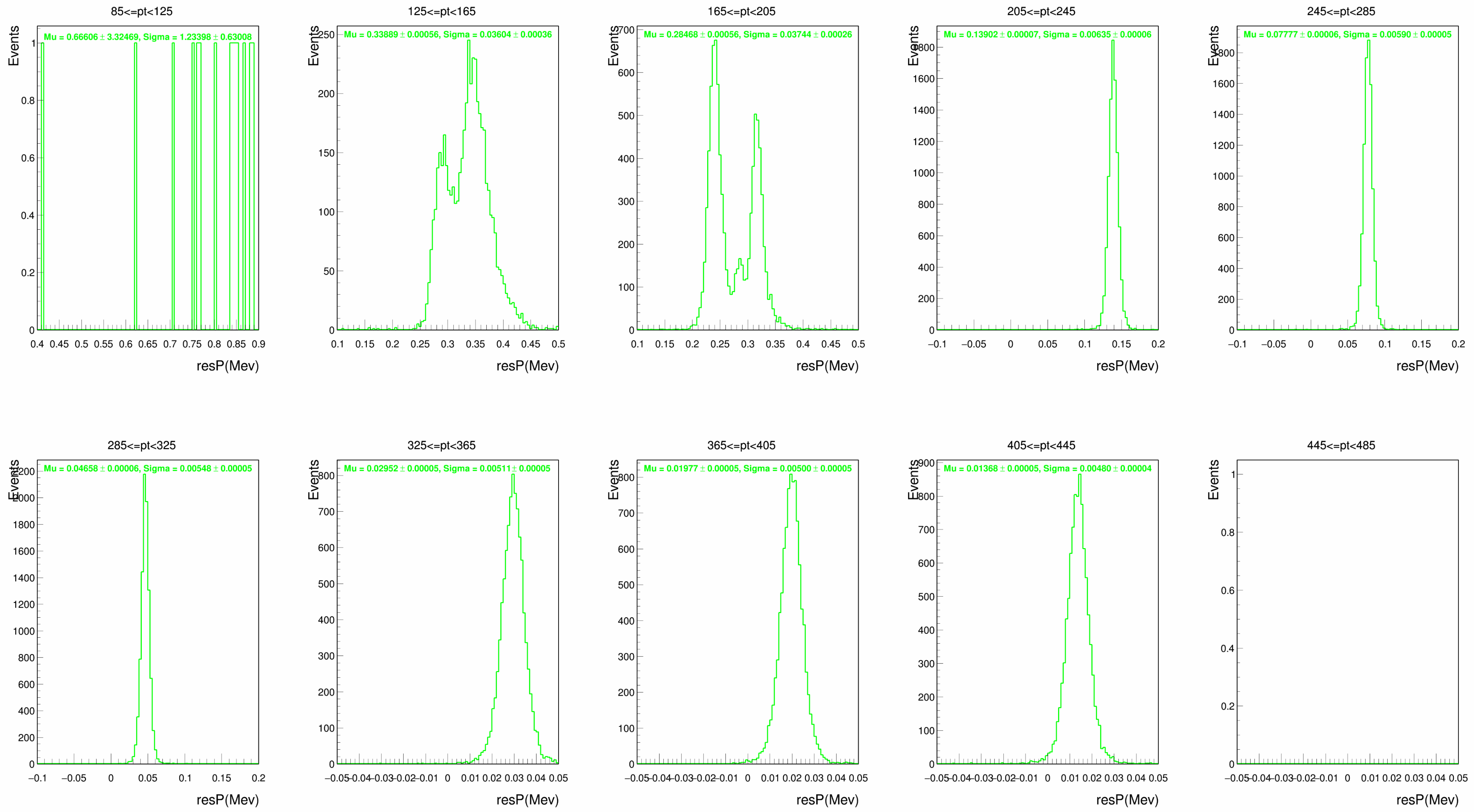
- real pions were fitted with the pion hypothesis



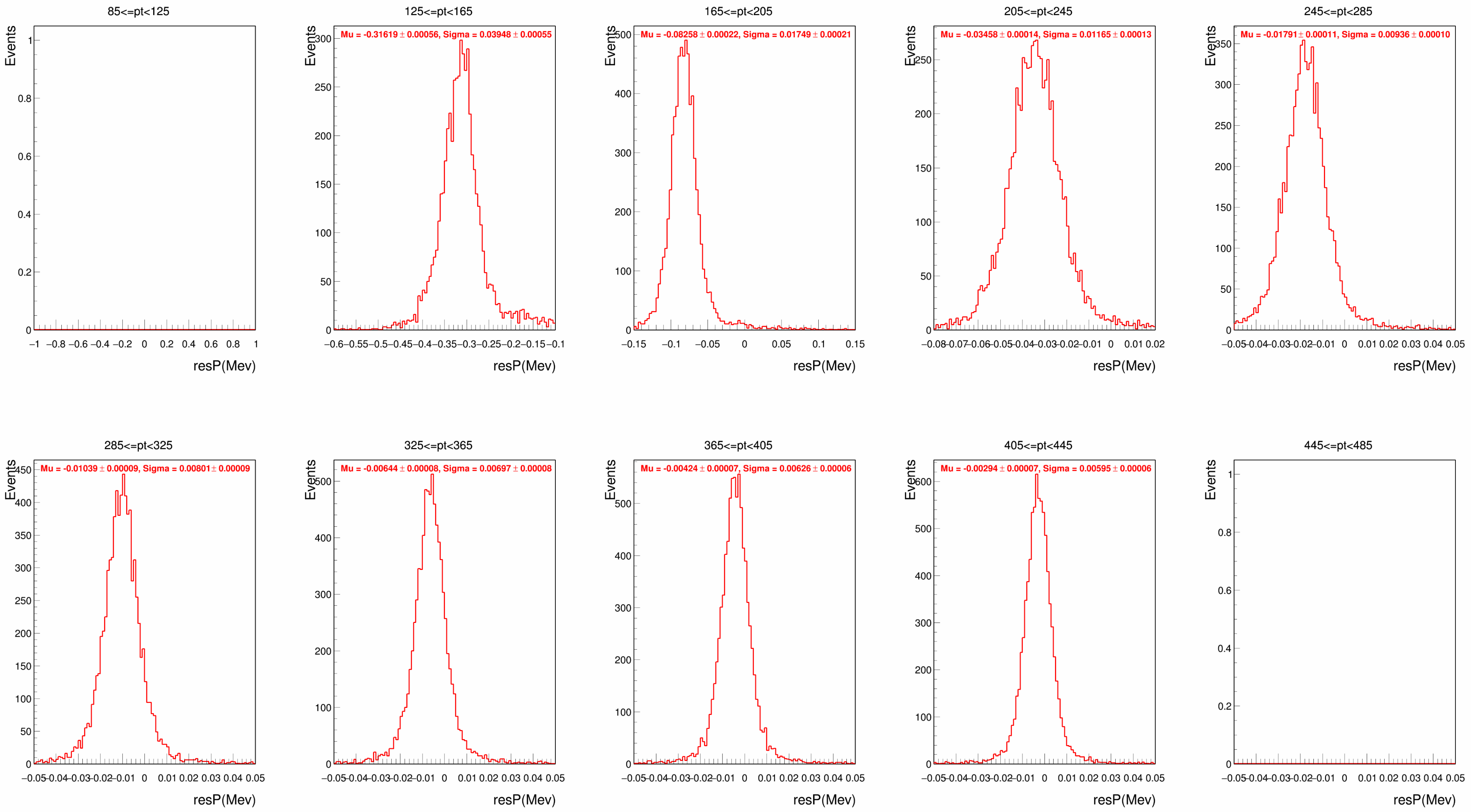
- real pions were fitted with the kaon hypothesis



- real pions were fitted with the proton hypothesis



- **real kaons** were fitted with the muon hypothesis



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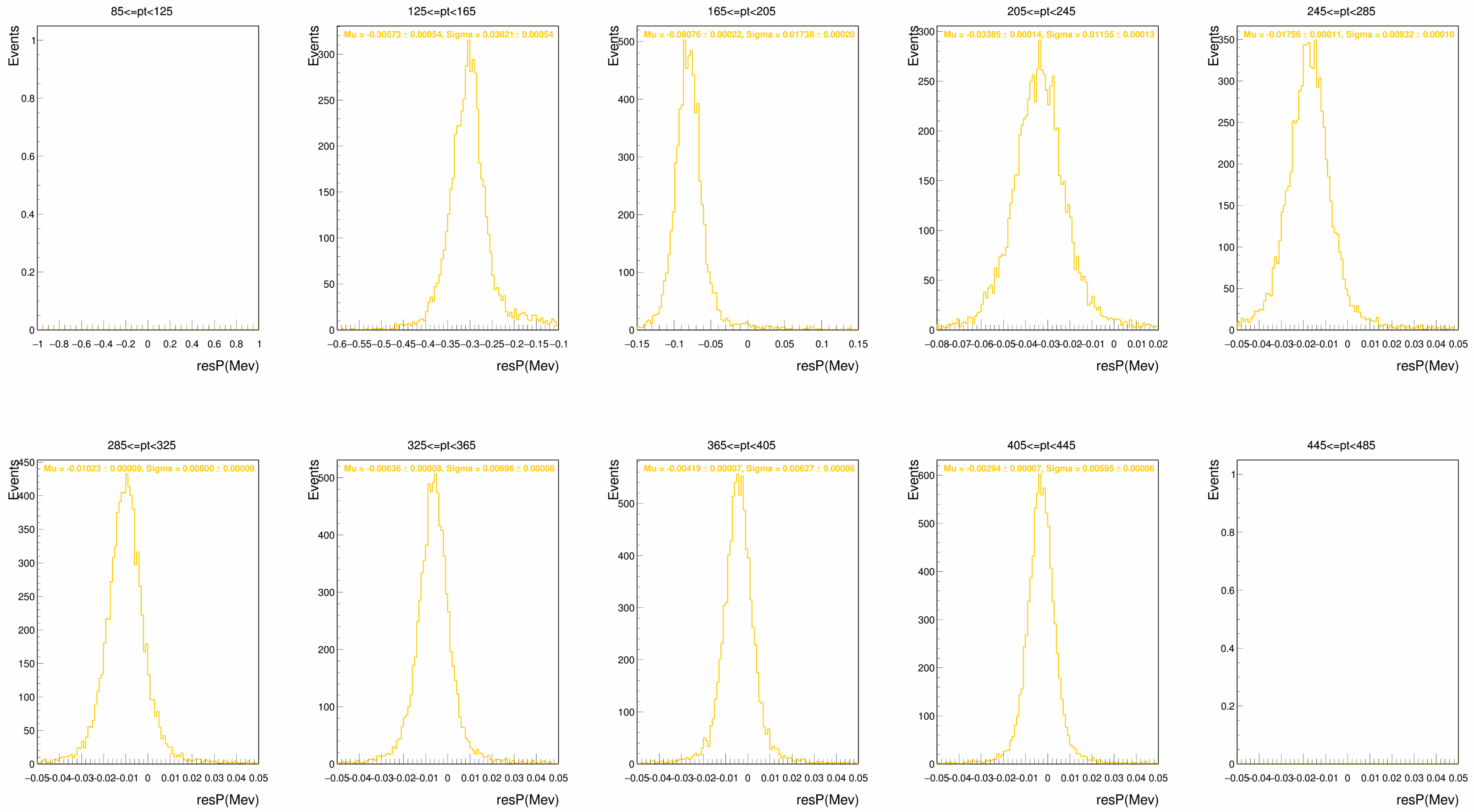

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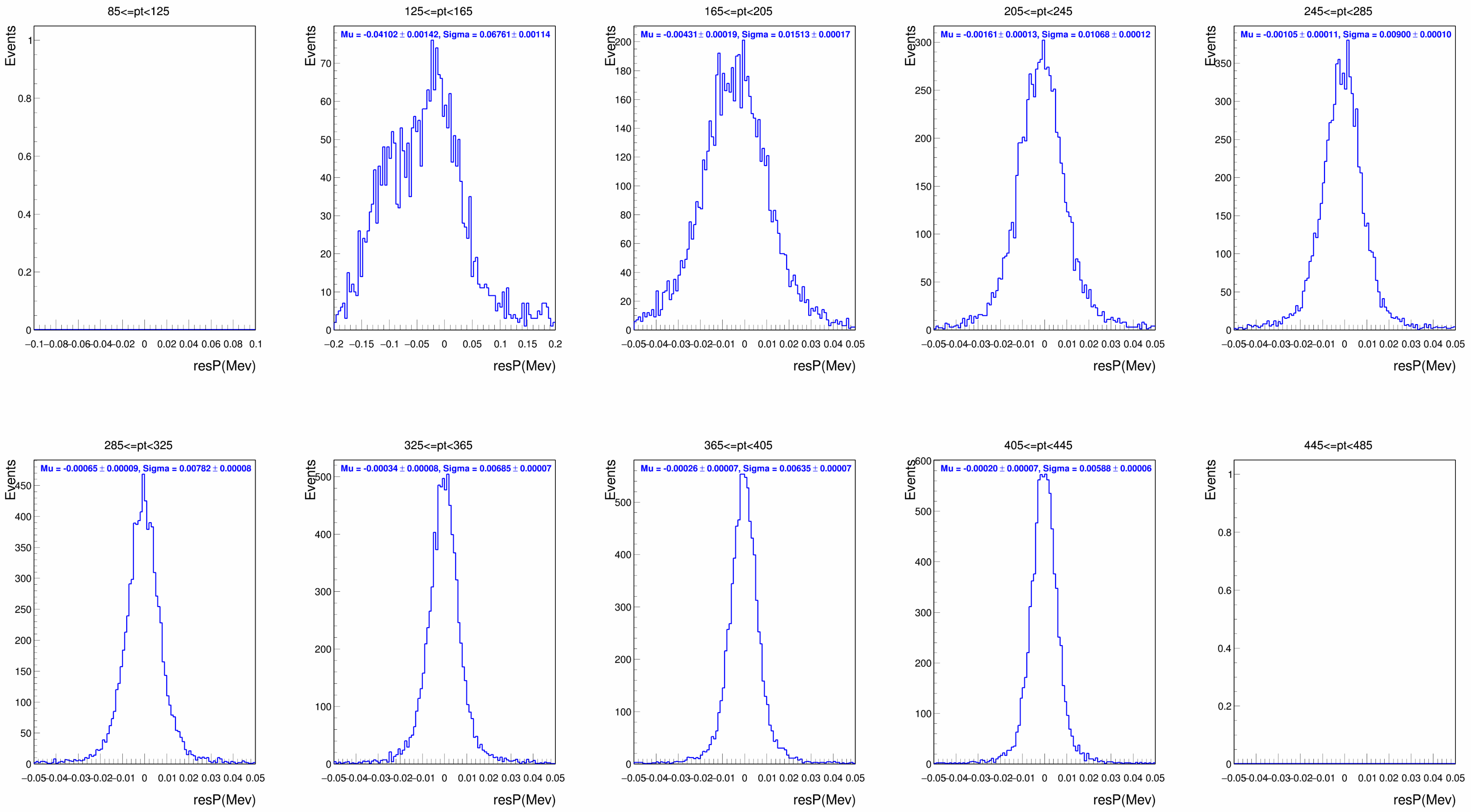
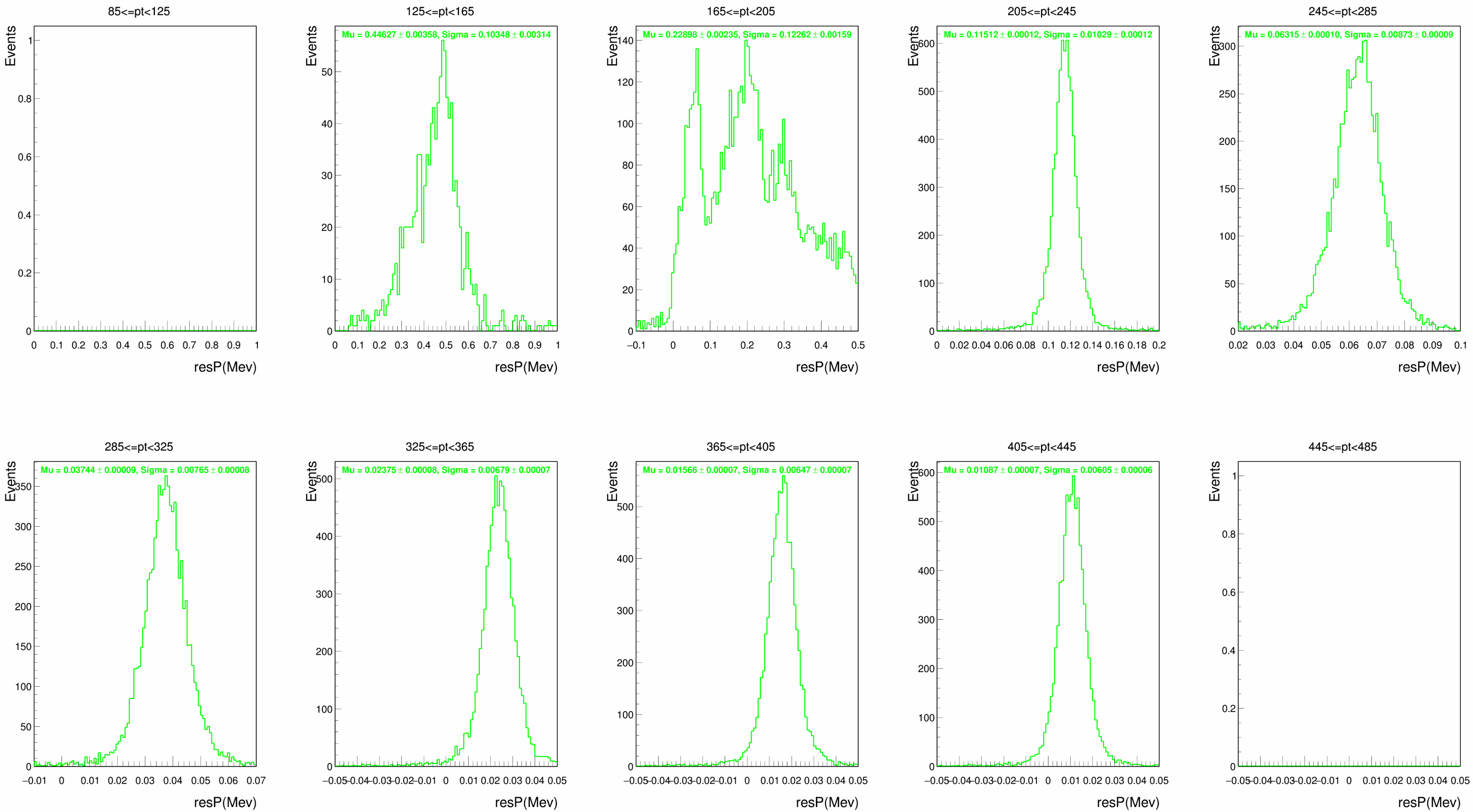
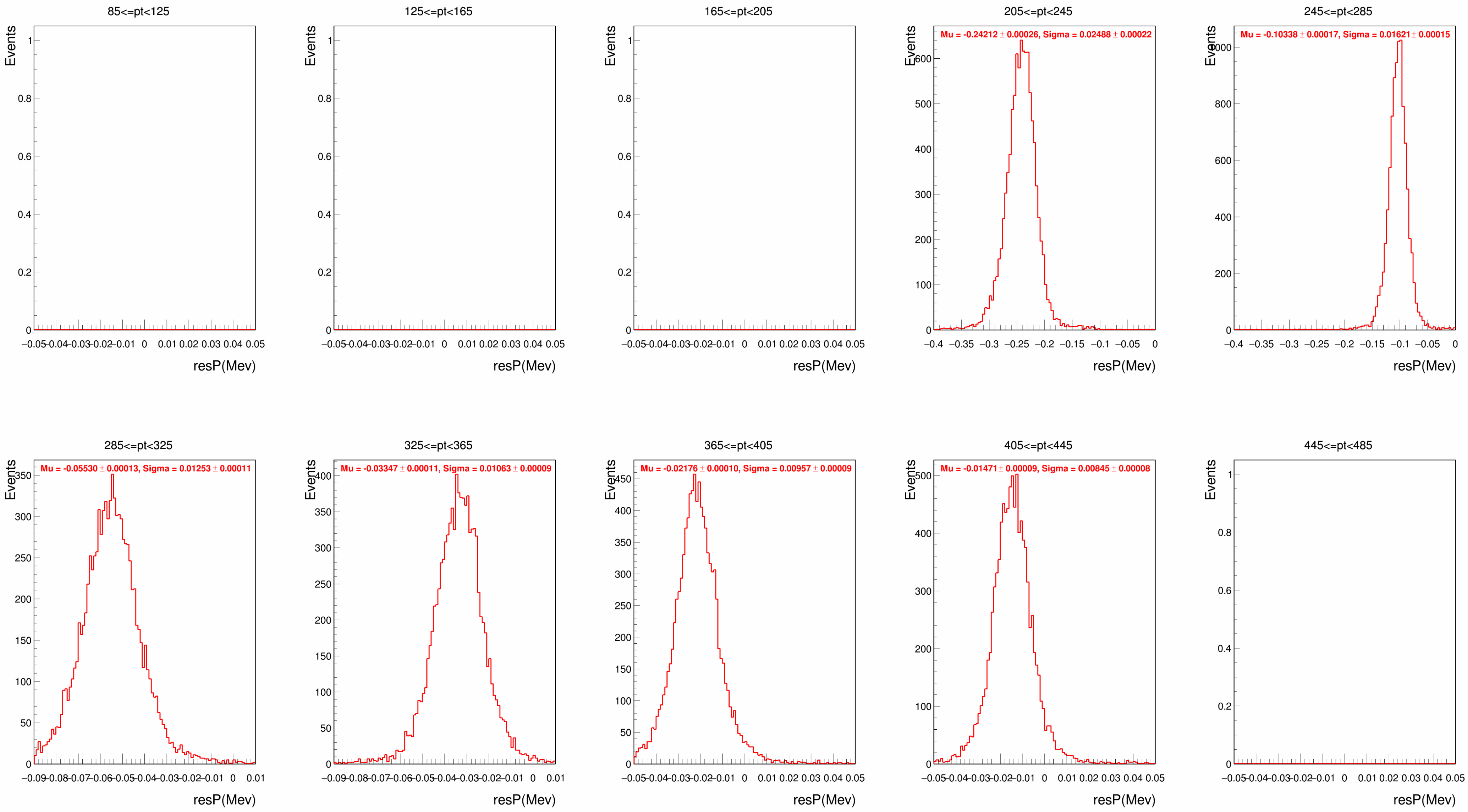


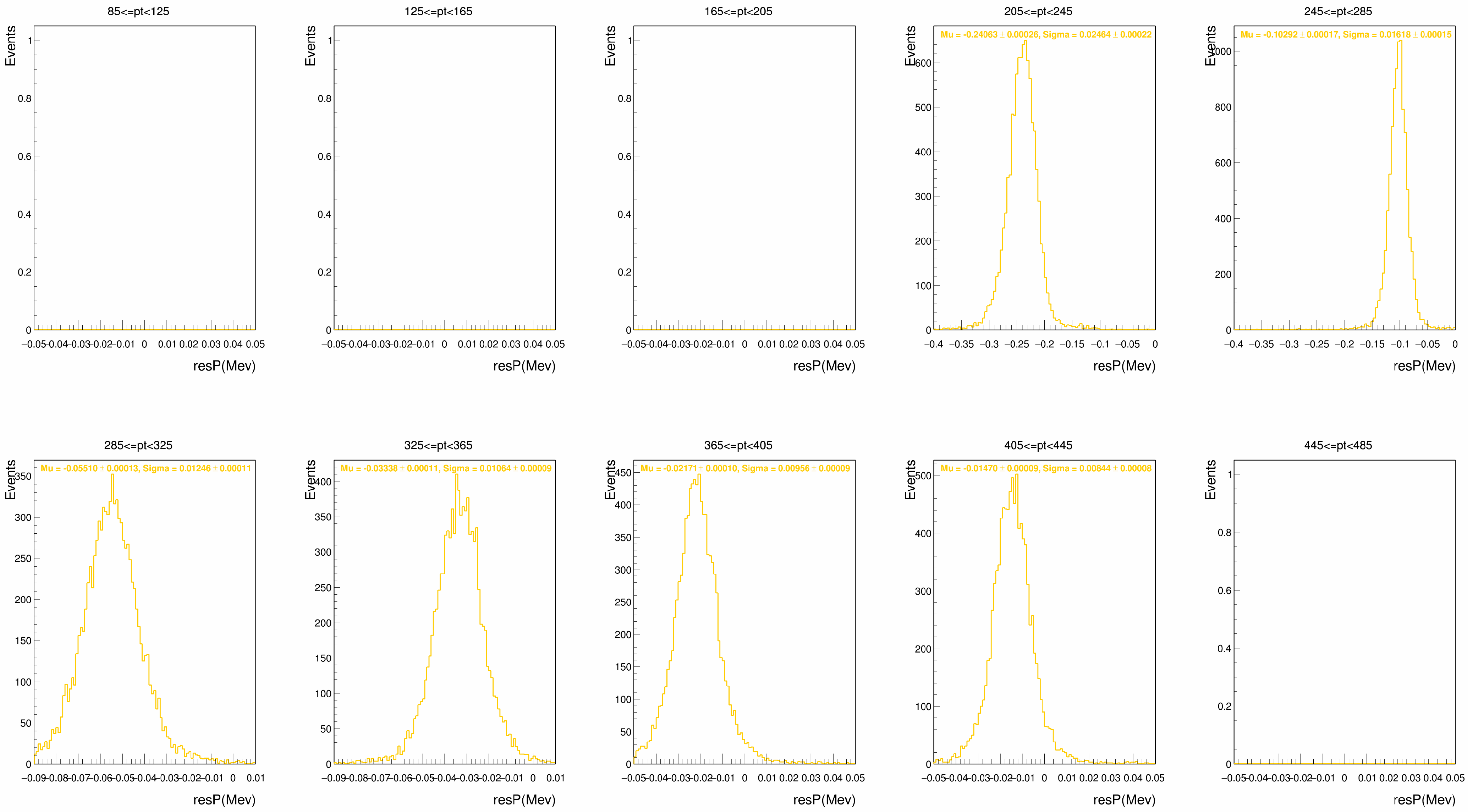
- **real kaons** were fitted with proton hypothesis



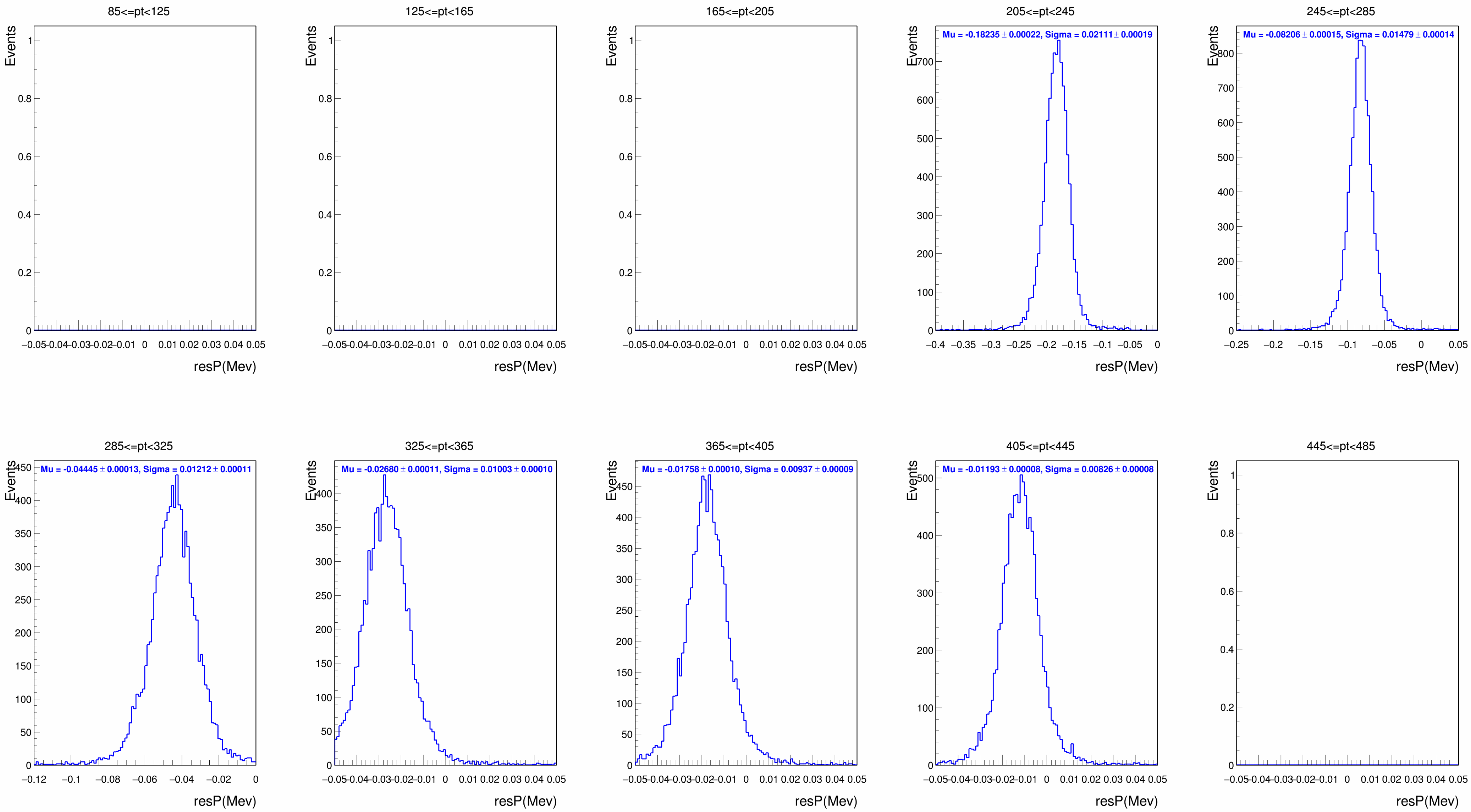
- **real protons** were fitted with the muon hypothesis



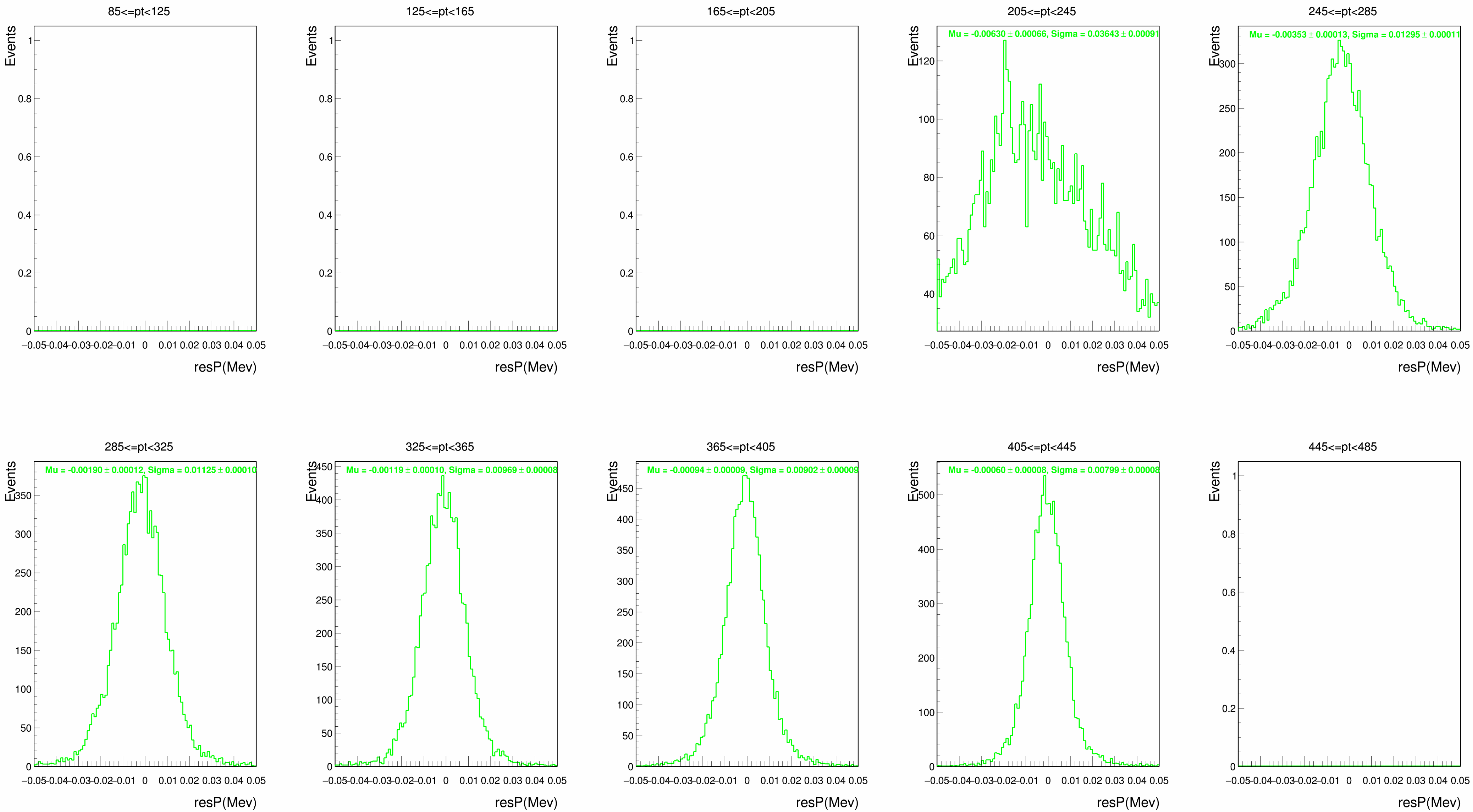
- **real protons** were fitted with the pion hypothesis



- **real protons** were fitted with the kaon hypothesis



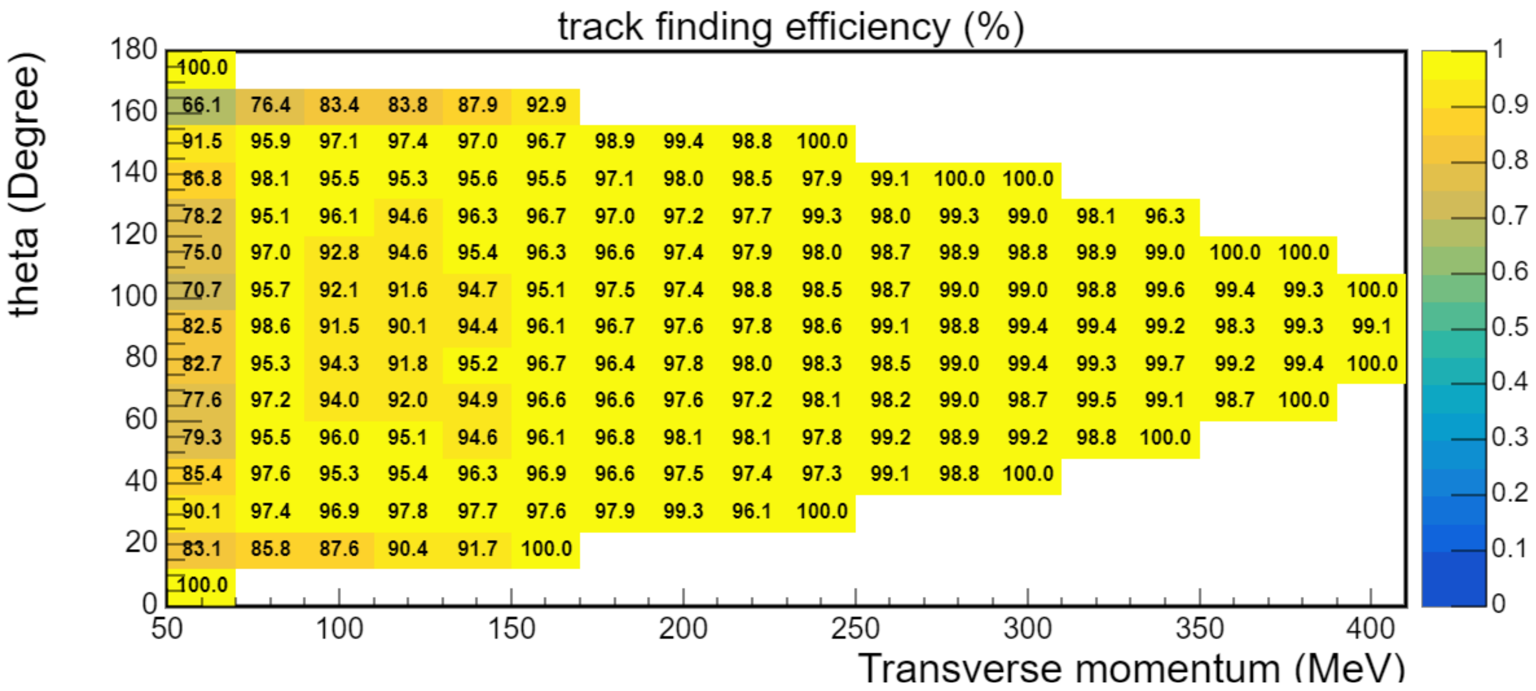
- **real protons** were fitted with the proton hypothesis

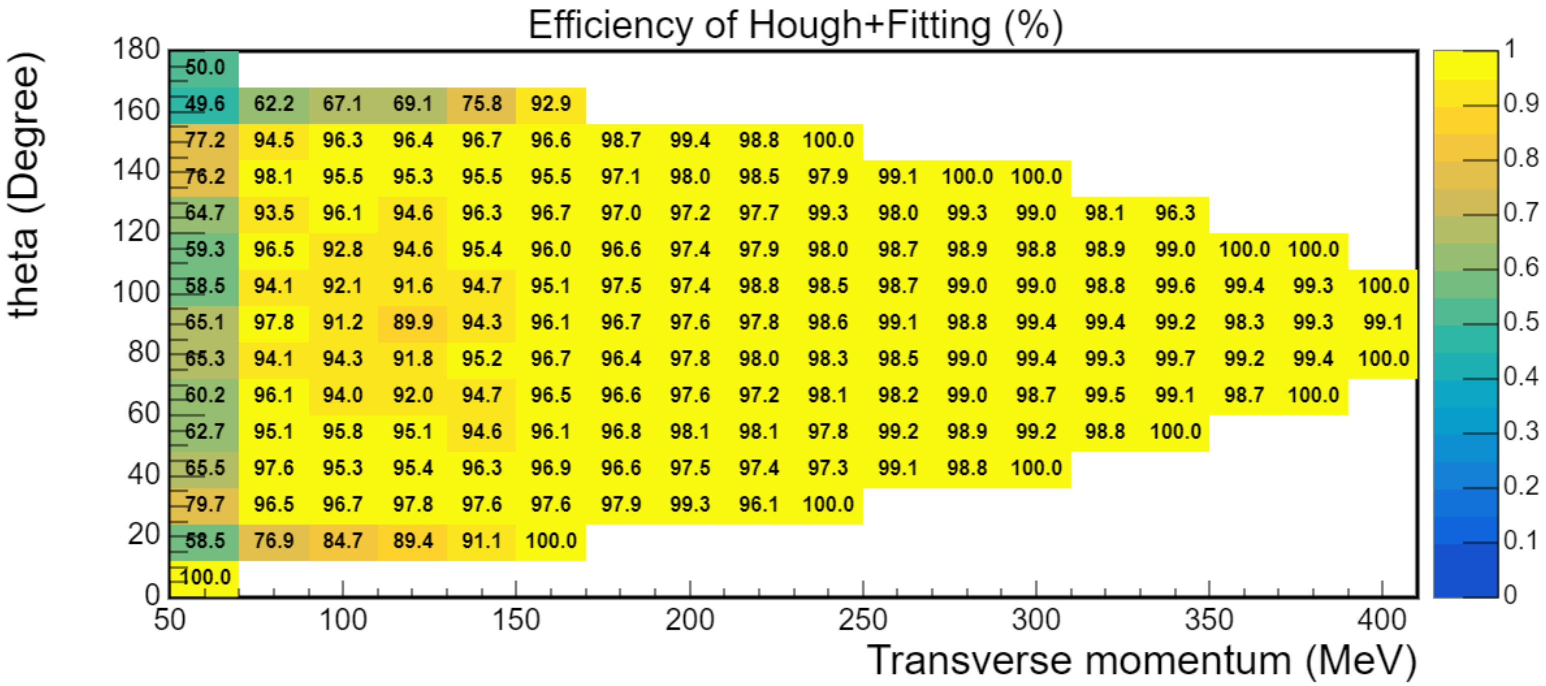


Performance

pipi mumu

- **pi**
  - background × 0

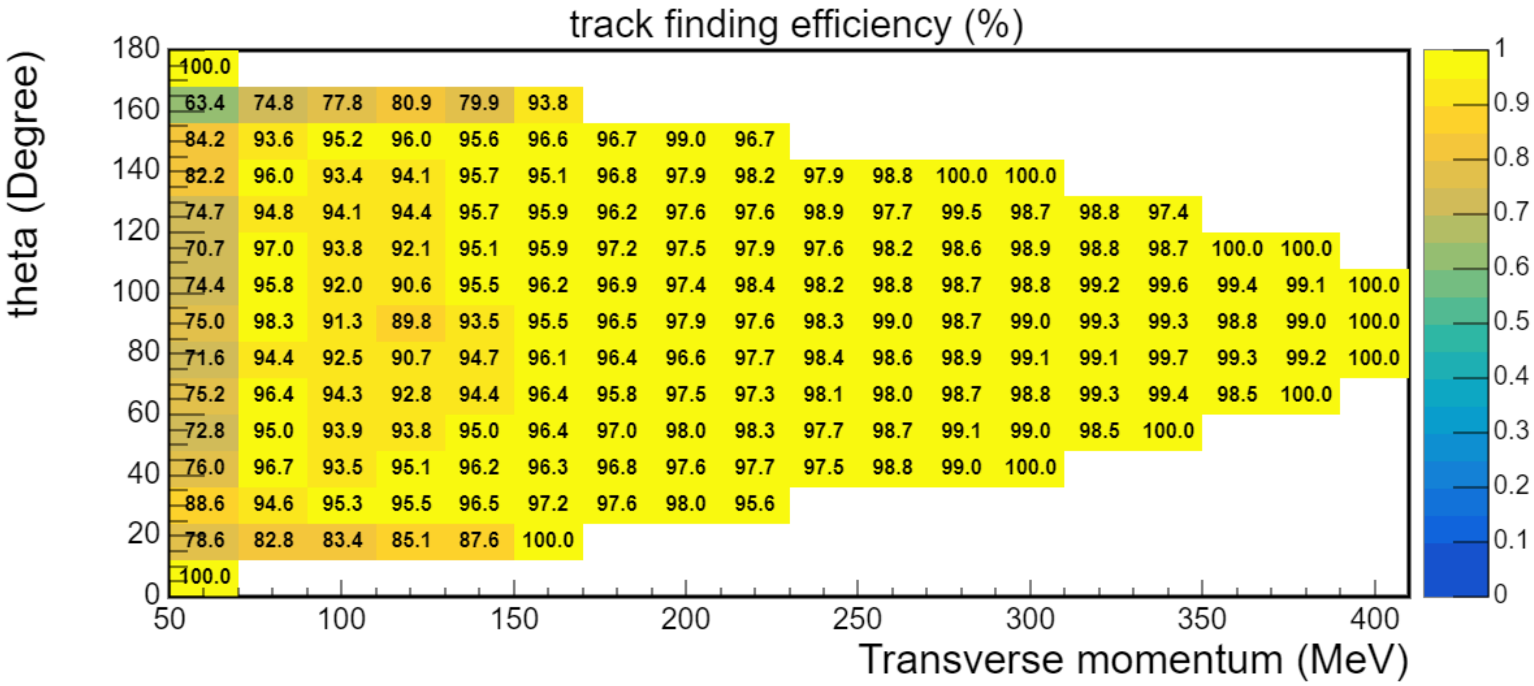


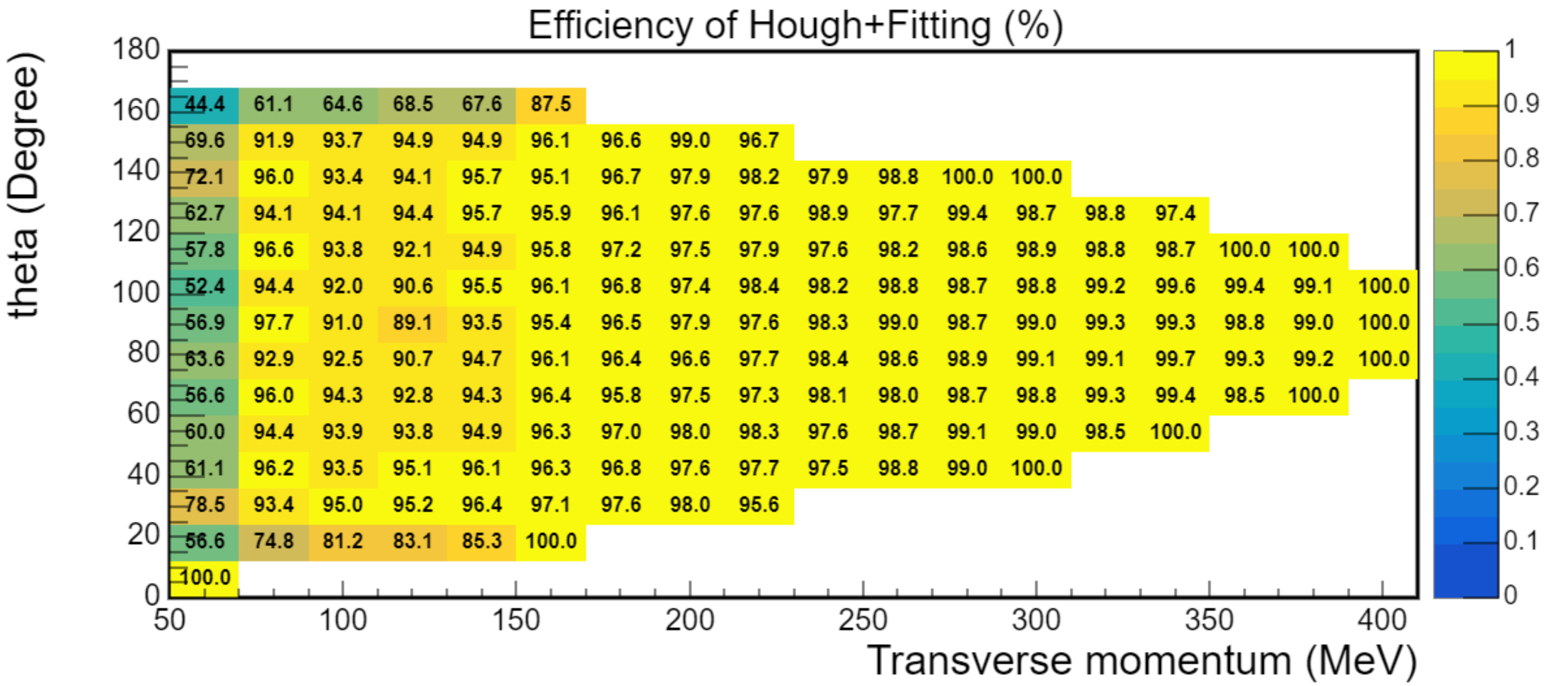


Performance

pipi mumu

- **pi**
    - background × 1

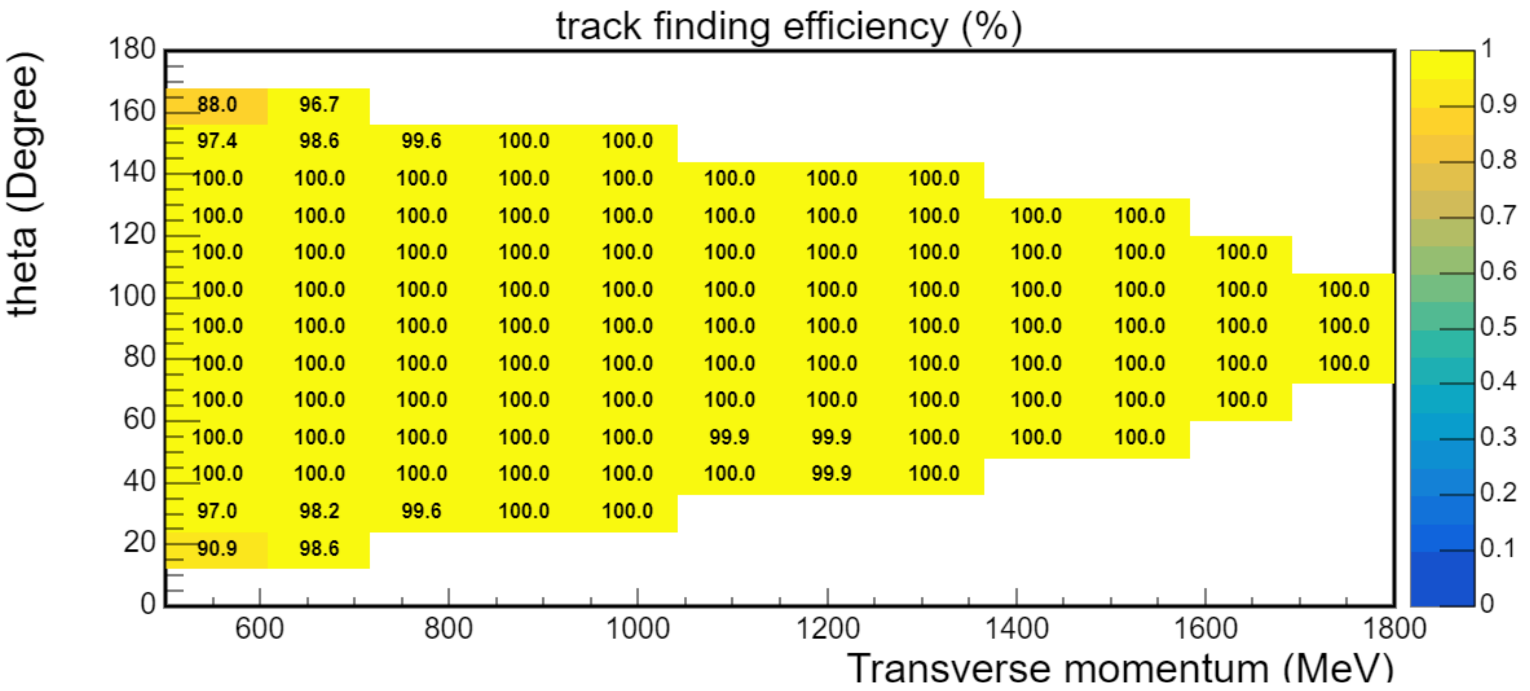


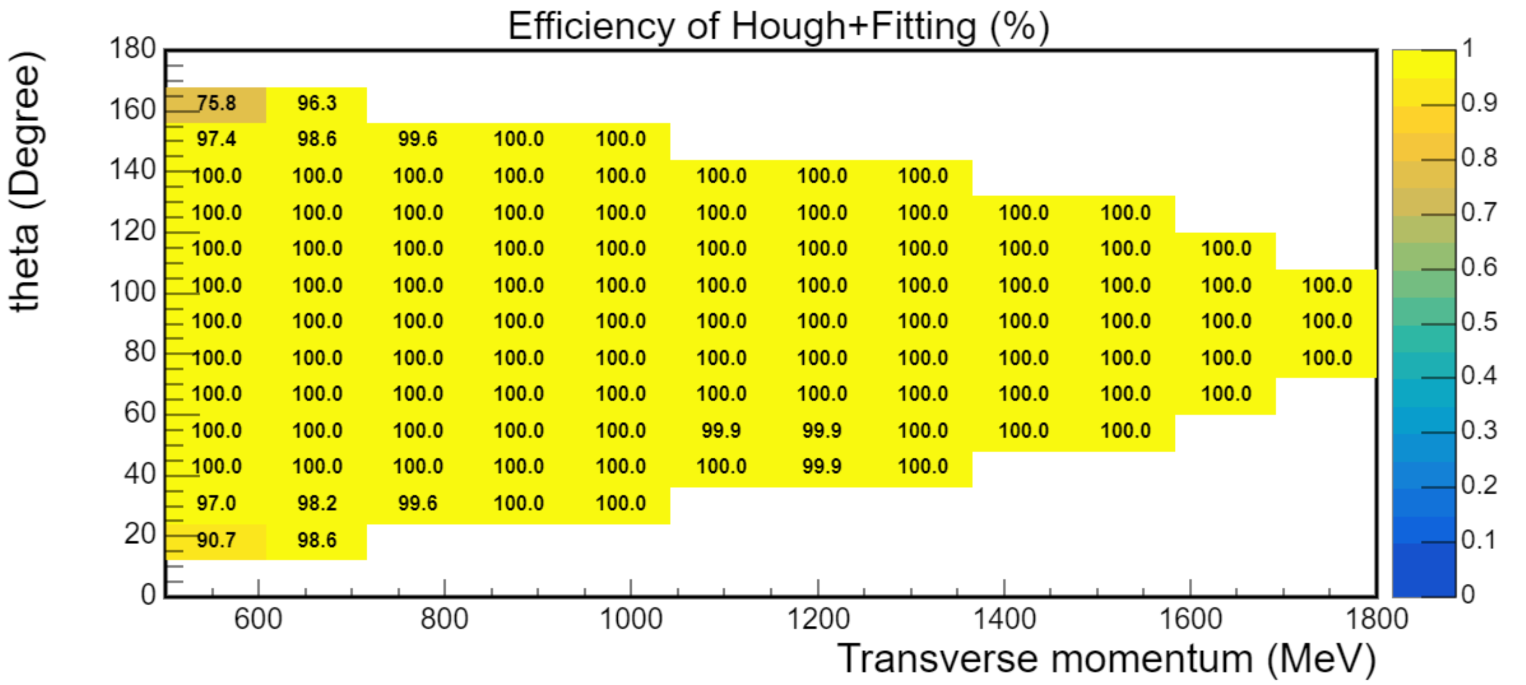


Performance

pipi mumu

- **mu**
  - background × 0





Performance

pipi mumu

- **mu**
  - background × 1