New Reconstruction Method for Liquid Scintillator – First Results for Muon Tracks

- Sebastian Lorenz[1,2] -

on behalf of
Caren Hagner[2], Björn Wonsak[2], Michael Wurm[1]

[1] JGU Mainz – Institut für Physik – ETAP / PRISMA

[2] Universität Hamburg – Institut für Experimentalphysik

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Outline

- Motivation
- New Reconstruction Method
- First Results for Simulated Muons in LENA
- Summary & Conclusion

Motivation

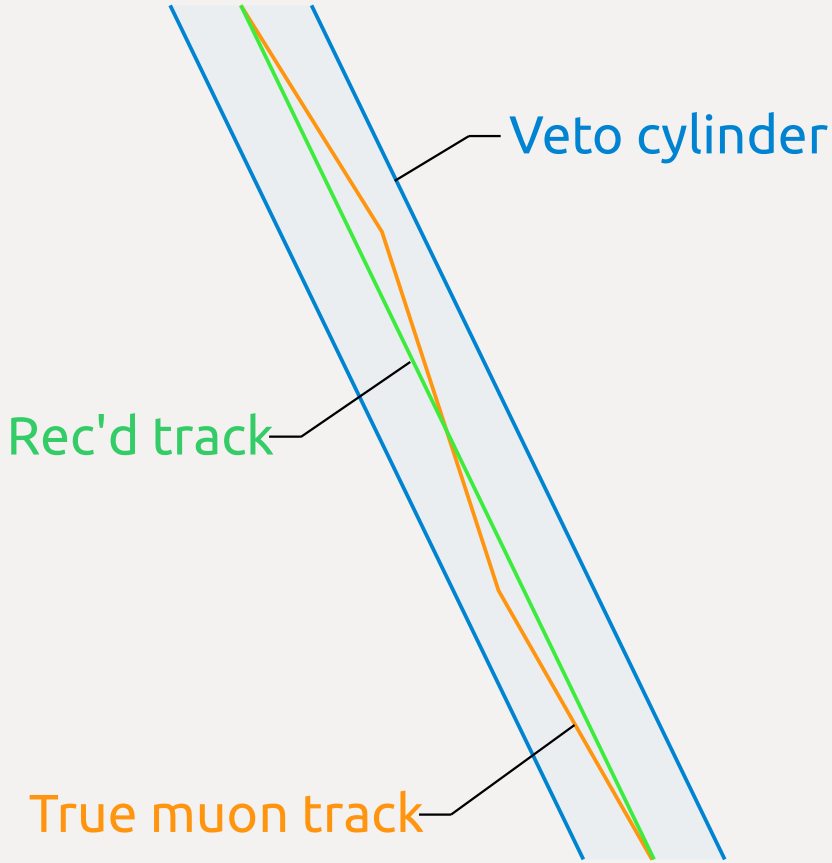
- Muon track reconstruction in LSc is required for an efficient rejection of cosmogenic radionuclide background in low-energy neutrino event searches

- Usually: full detector veto

  (**showering** muons; muon bundles)

  or cylindrical veto around rec'd track for several lifetimes; O(s)

  (through-going or stopping muons)



- Especially important for future large-volume LSc detectors

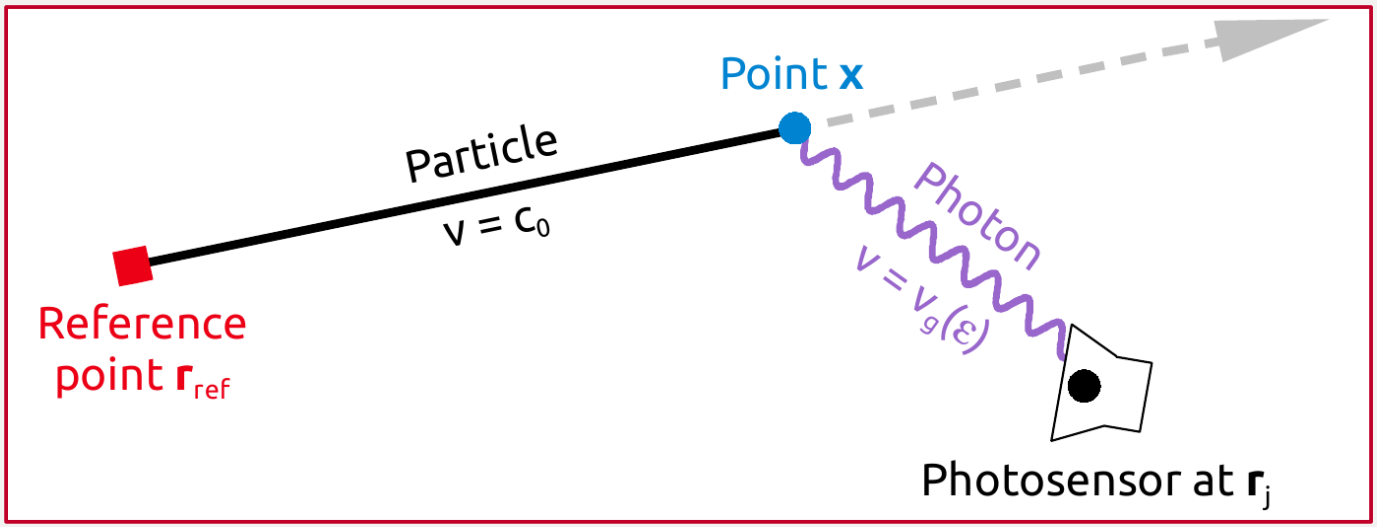
  JUNO (20 kt with ~730 m overburden)
  ~3 s^{-1} muon event rate
  1:1 signal to cosm. bkg. ratio expected

- Can we do better (e.g., dE/dx or focus on showers)?

New Reconstruction Method in a Nutshell

Goal: Reconstruction of spatial number density distribution of isotropic, optical photon emissions.

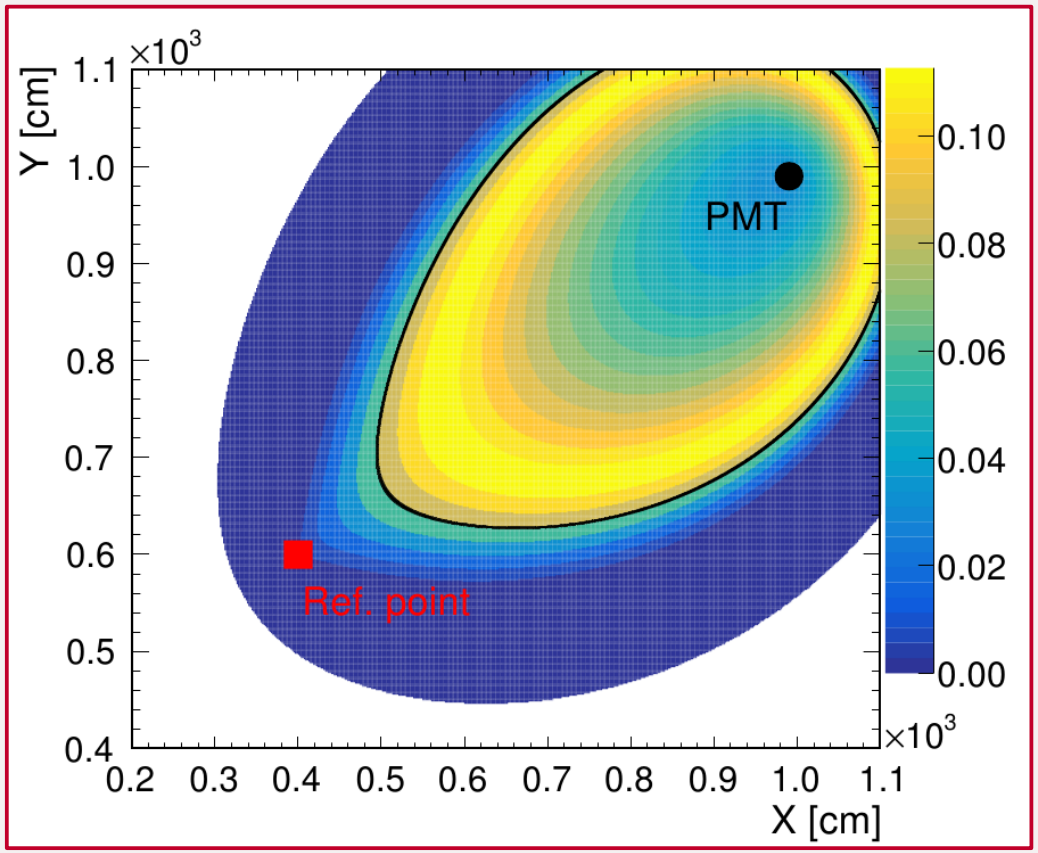
Approach: Based on a simple model,…

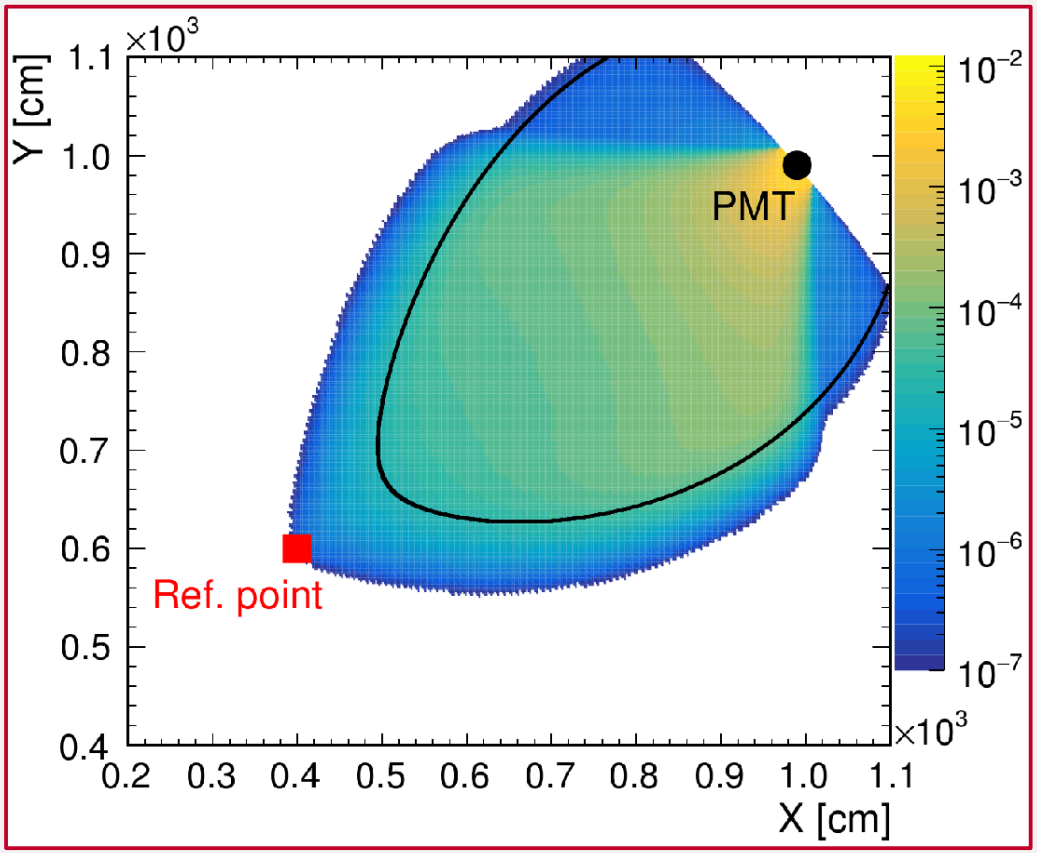


$$t(\mathbf{x}) \equiv t_{\mathrm{ref}} \pm \underbrace{\frac{|\mathbf{x}-\mathbf{r}_{\mathrm{ref}}|}{c_0}}_{\text{particle}} + \underbrace{\frac{|\mathbf{r}_j-\mathbf{x}|}{v_g(\epsilon)}}_{\text{photon}}$$

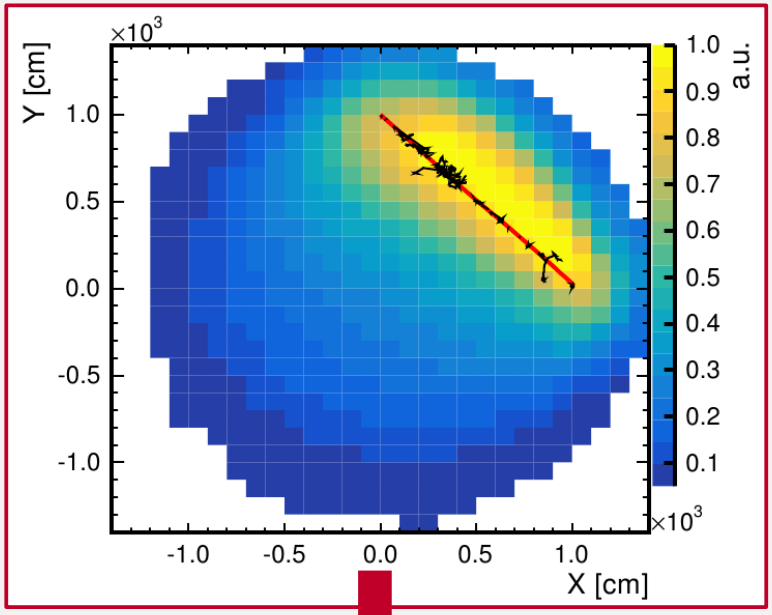
New Reconstruction Method in a Nutshell

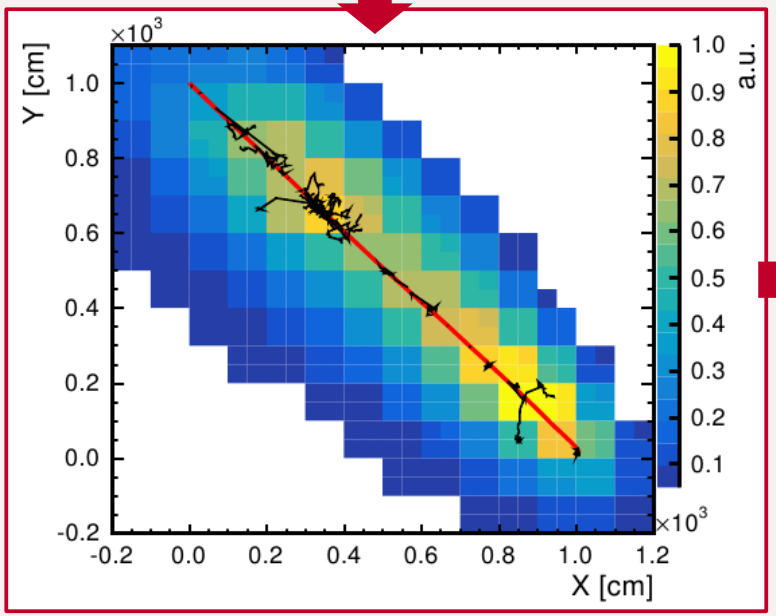
…create a PDF for the origin of each detected photon inside the detector that takes temporal and spatial constraints into account.



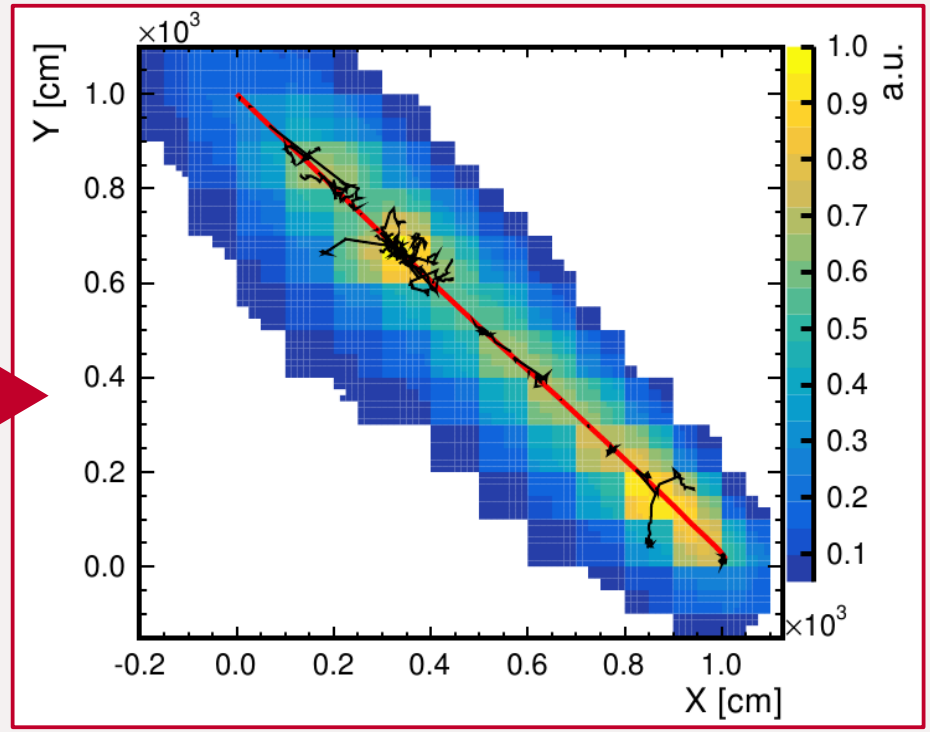


New Reconstruction Method in a Nutshell





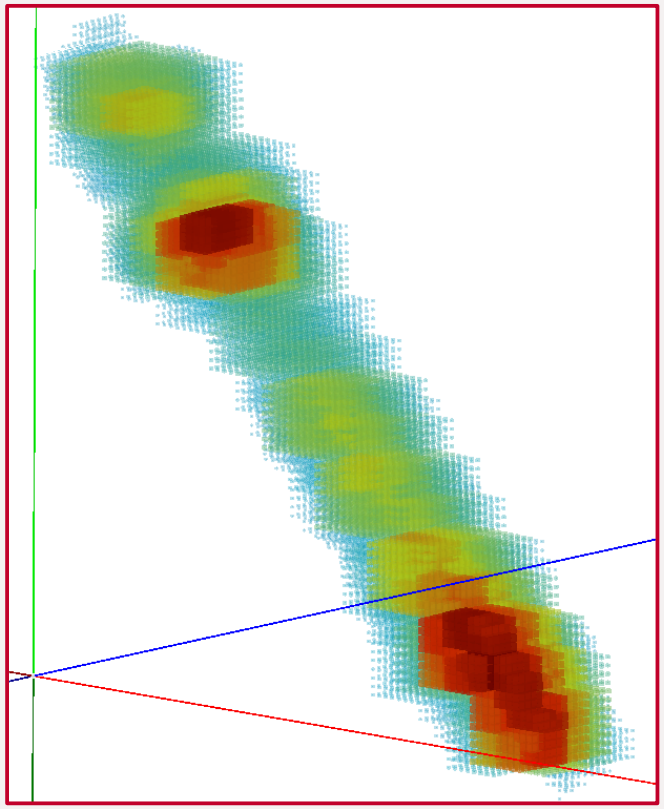
- Use photon hits from all PMTs.
- Divide result by local detection efficiency.
  - → Number density of emitted photons
- "Connect" information in multiple iterations.
  - → Use prior result as "prior information" in next iteration.

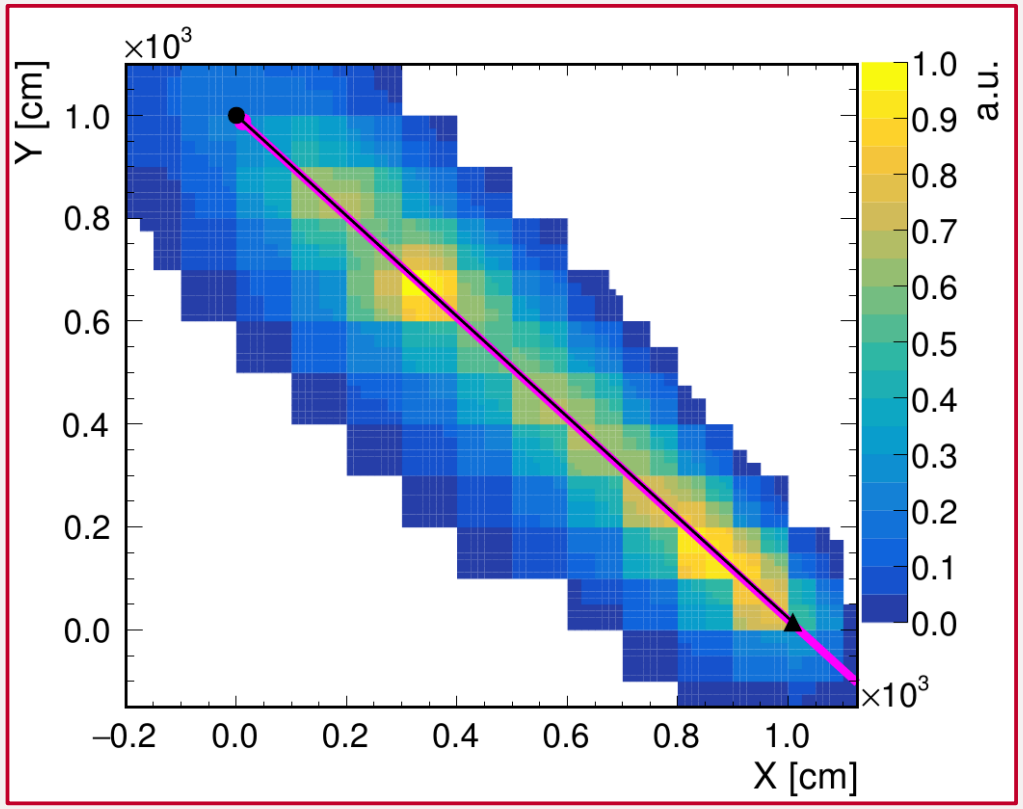


Simulated 3 GeV muon in LENA; started at (10,0,0) m with direction (1,-1,0)

Analysis of Reconstruction Output

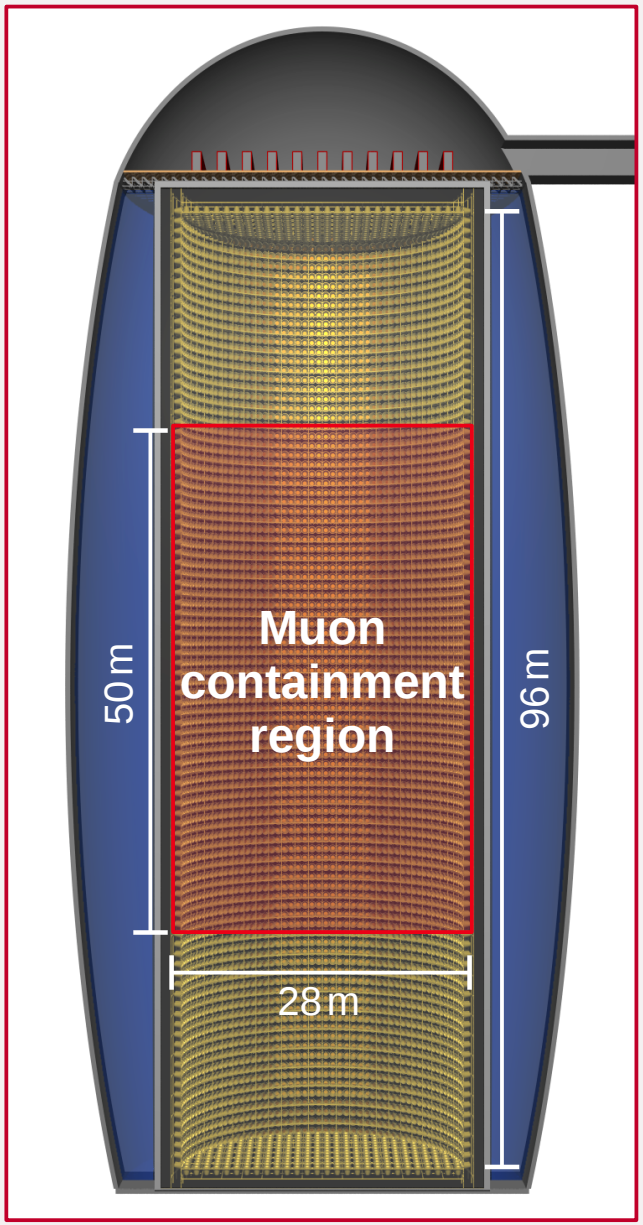
- Analysis of 3D output to extract descriptive physics parameters
- Both the reconstruction and the analysis part are work in progress:
  - Preparation for JUNO; improvement of optical model
  - So far: basic analysis to estimate performance





- Example: Find “primary blob“ and make line fit to get direction

Simulated Muons in LENA



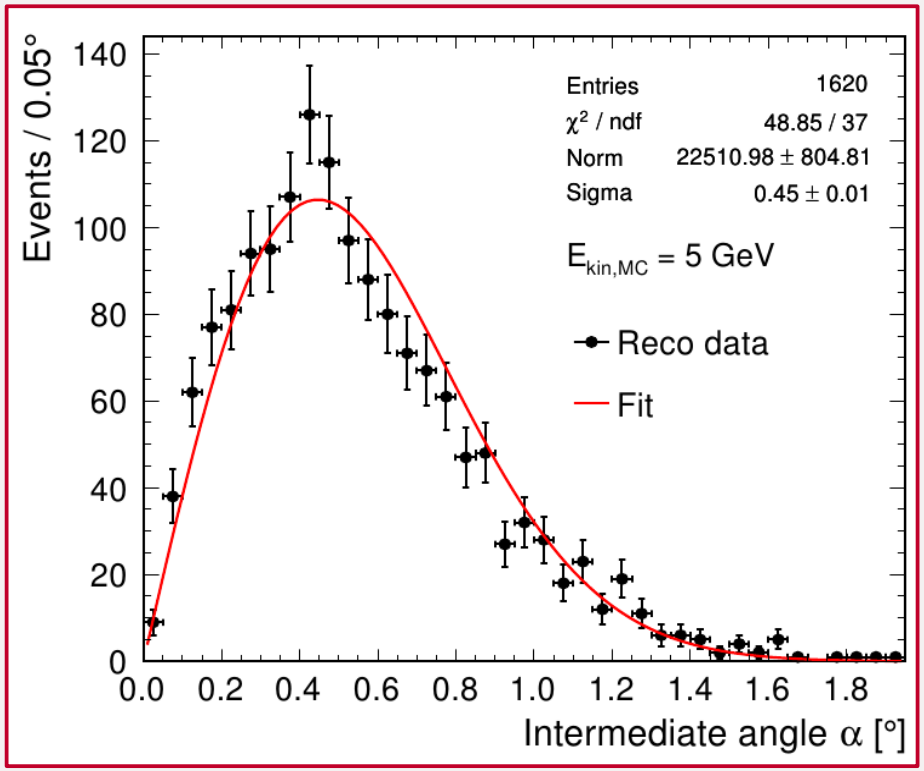
LENA Design

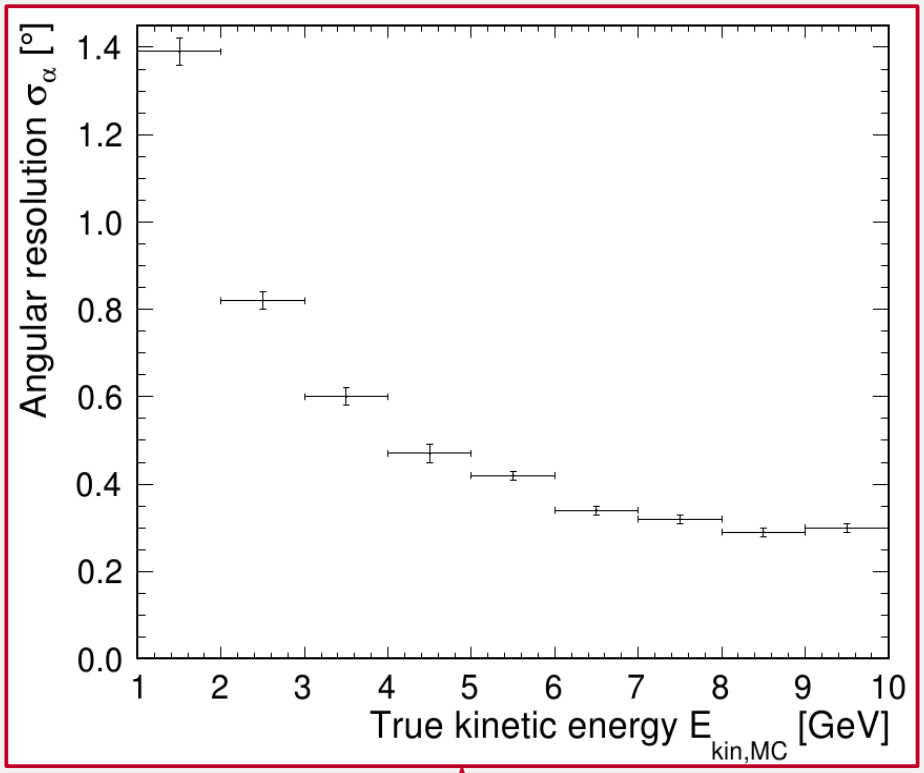
- For simplicity, reconstruction was tested with single muons
- LENA Geant4 detector simulation
- About 12k events in the energy range from 1 to 10 GeV
- Required muon containment in central half of detector (based on MC truth)

  → tracks become more aligned with cylinder axis at higher energies

Angular Resolution

- Angle between reconstructed track line and MC mean direction





Fit-function: $$F(\alpha) = \sin(\alpha)\, A\, \exp\left(-\frac{\alpha^2}{2\sigma_\alpha^2}\right)$$

Borexino tracking (inner vessel): ~2.5° [JINST 6 (2011) P05005 / arXiv: 1101.3101]

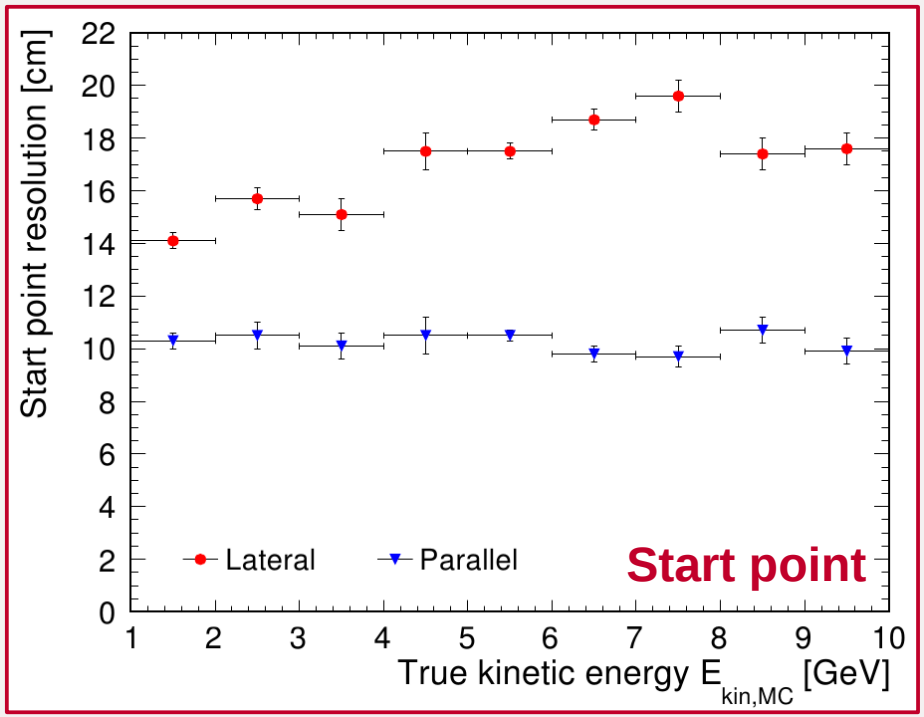
Start Point / End Point Resolution

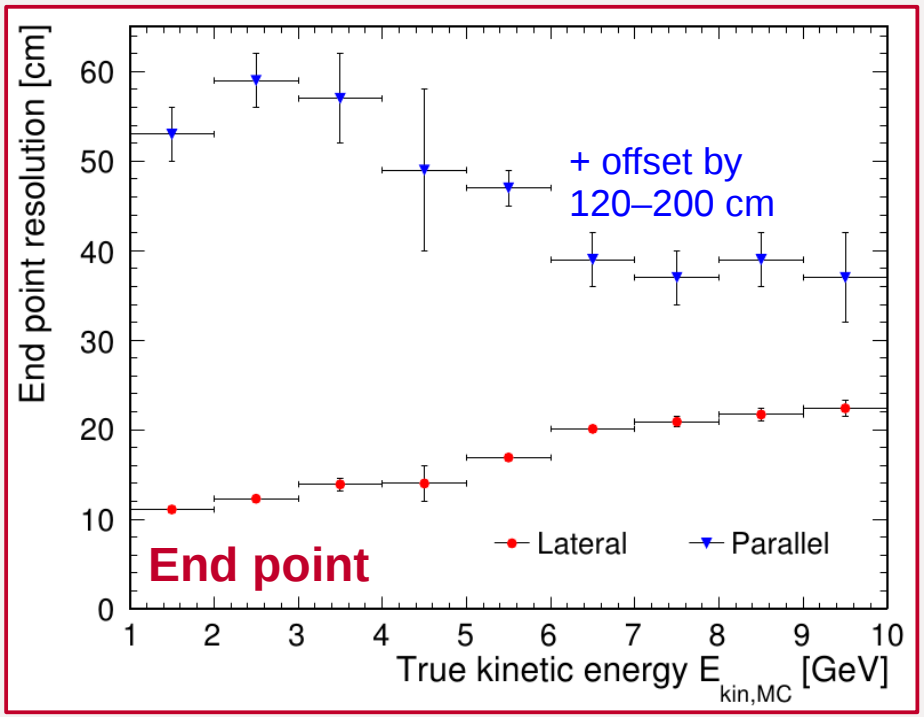
Start point

- Resolution ≤ 20 cm in x, y, z
- Total: ≤ 30 cm

End point

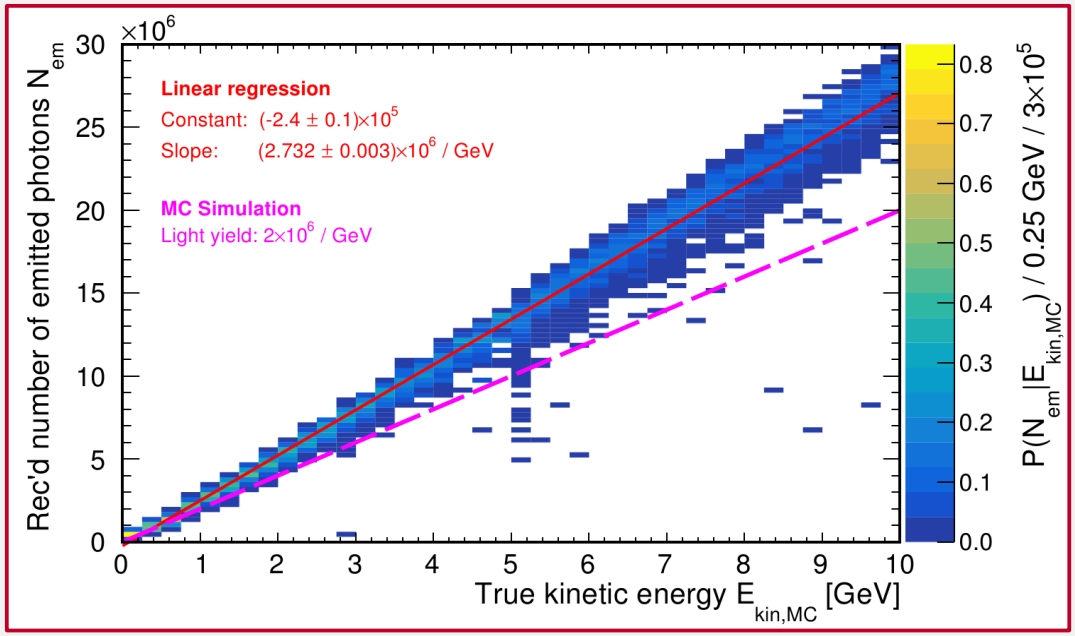
- Systematic offset in parallel direction (from “primary blob“ selection)
- Offset decreases with rising energy

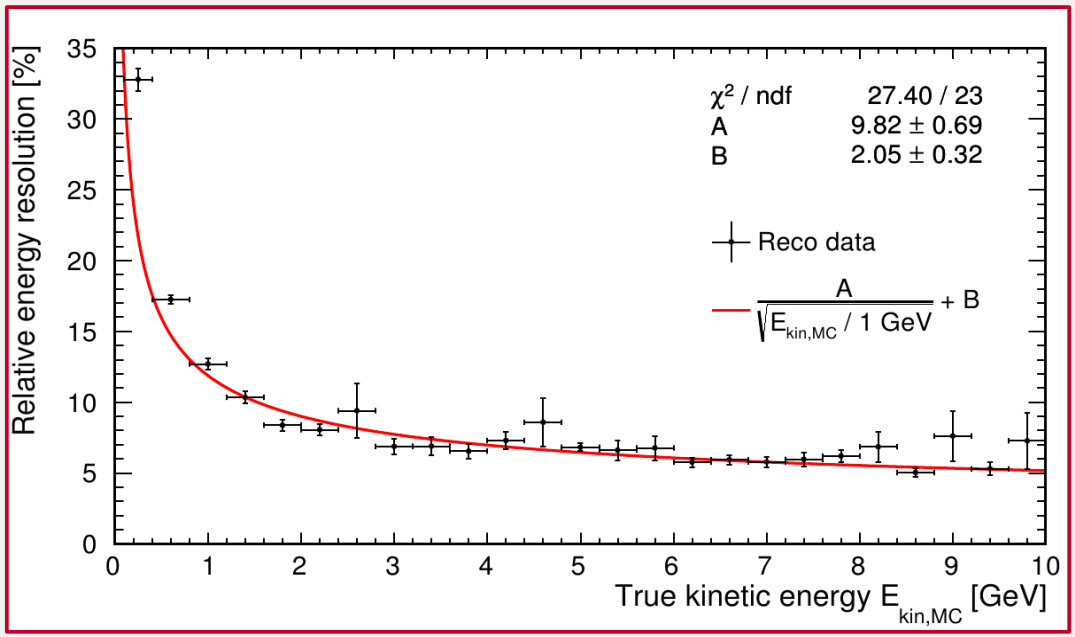




Borexino tracking (inner vessel): ~35 cm lateral [JINST 6 (2011) P05005 / arXiv: 1101.3101]

Relative Energy Resolution





- Volume integral over 3D result = rough estimate for total number of emitted photons N_{rec}
- Scattered photons treated as absorbed in current optical model
  → local detection efficiency too low
  → too many photons reconstructed
- Relative energy resolution: standard deviation over mean for N_{rec} distribution per energy bin
- In analyzed energy range:

$$\sigma_E / E \approx 10\% \times (E / 1\,\mathrm{GeV})^{1/2} + 2\%$$

Summary & Conclusion

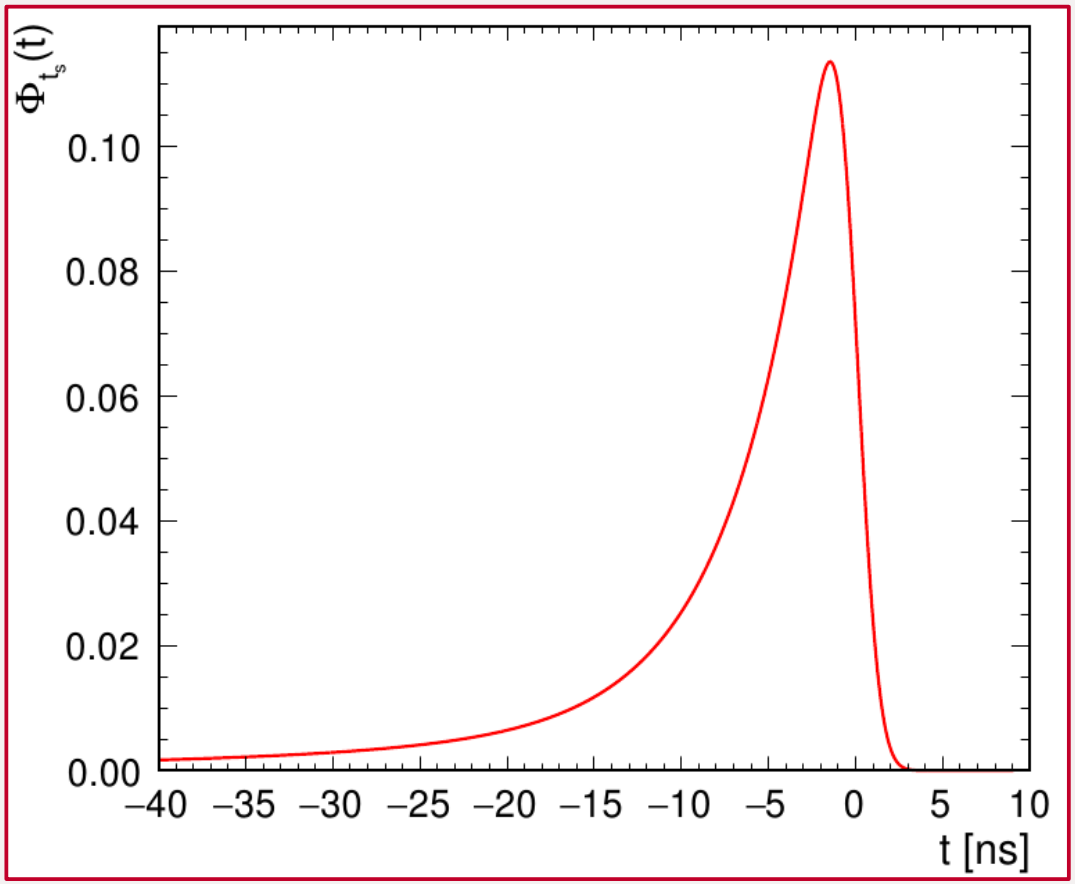
- Muon **track reconstruction** inside (future) LSc detectors is important for an **efficient rejection of cosmogenic background**
- **Novel reconstruction approach** in development; it produces 3D output data, which require further analysis
- First performance estimate with **simulated muons in LENA**
- Identified **some issues** in current post-processing, but there are ways to **improve robustness**
- Current results indicate that the new approach can be a **competitive alternative** to existing reconstruction methods
- Full potential (**shower identification, dE/dx**,…) not yet explored

Thank you for your kind attention!

Further information

Temporal Smearing PDF

- Convolution of PMT timing PDF – Norm (0, 1ns) – and exponential decay function with three components:
  4.6 ns [71%], 18 ns [22%] and 156 ns [7%]
- Direction of tail for “historical reasons“ to the left



Test with Borexino

- Test of new reconstruction method with **real data** from Borexino
- First hits only

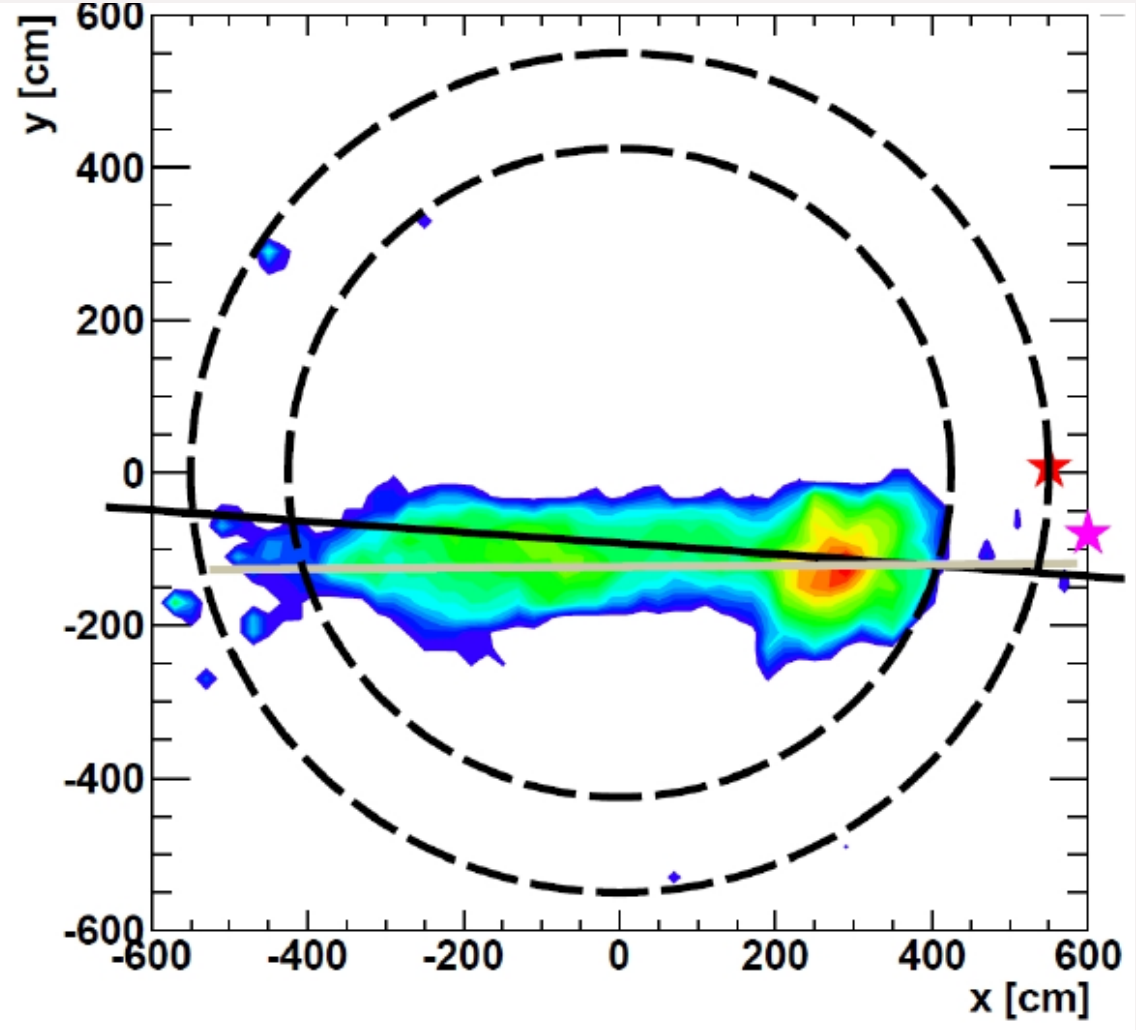
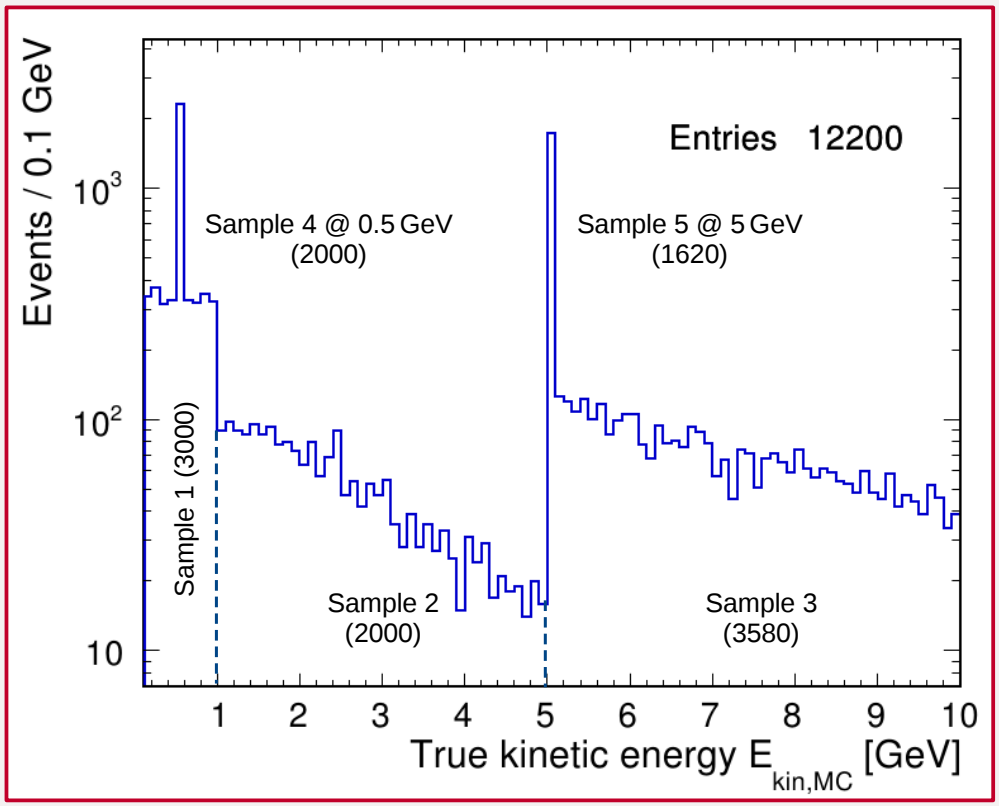
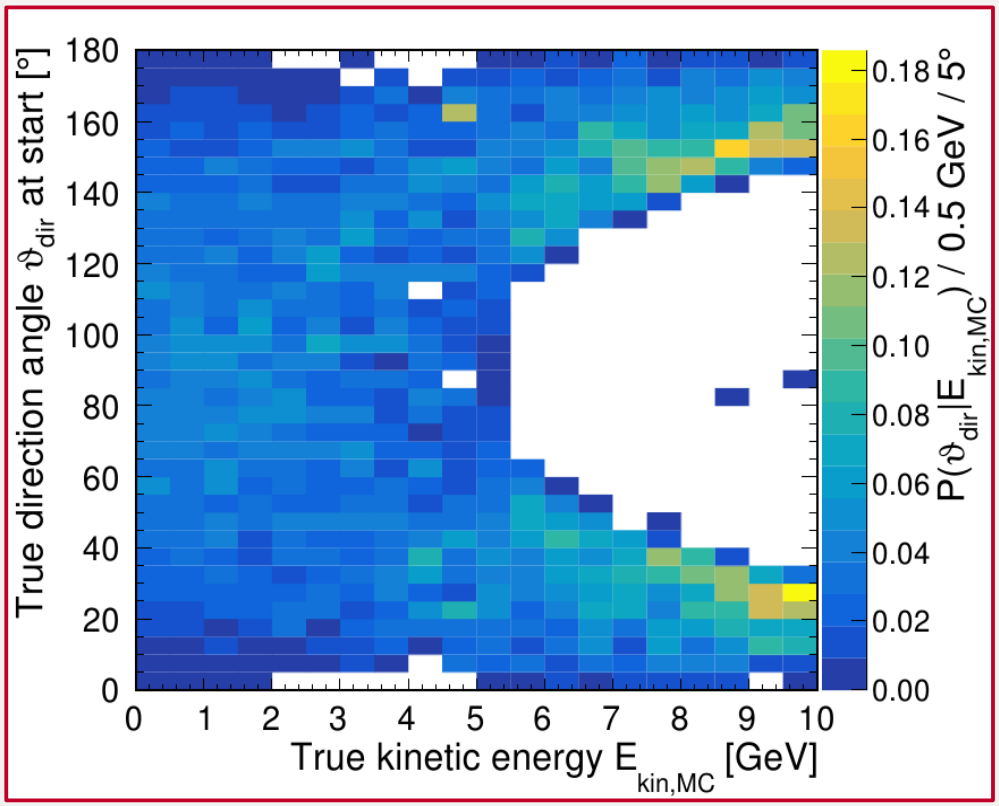


Figure courtesy of Björn Wonsak – Universität Hamburg

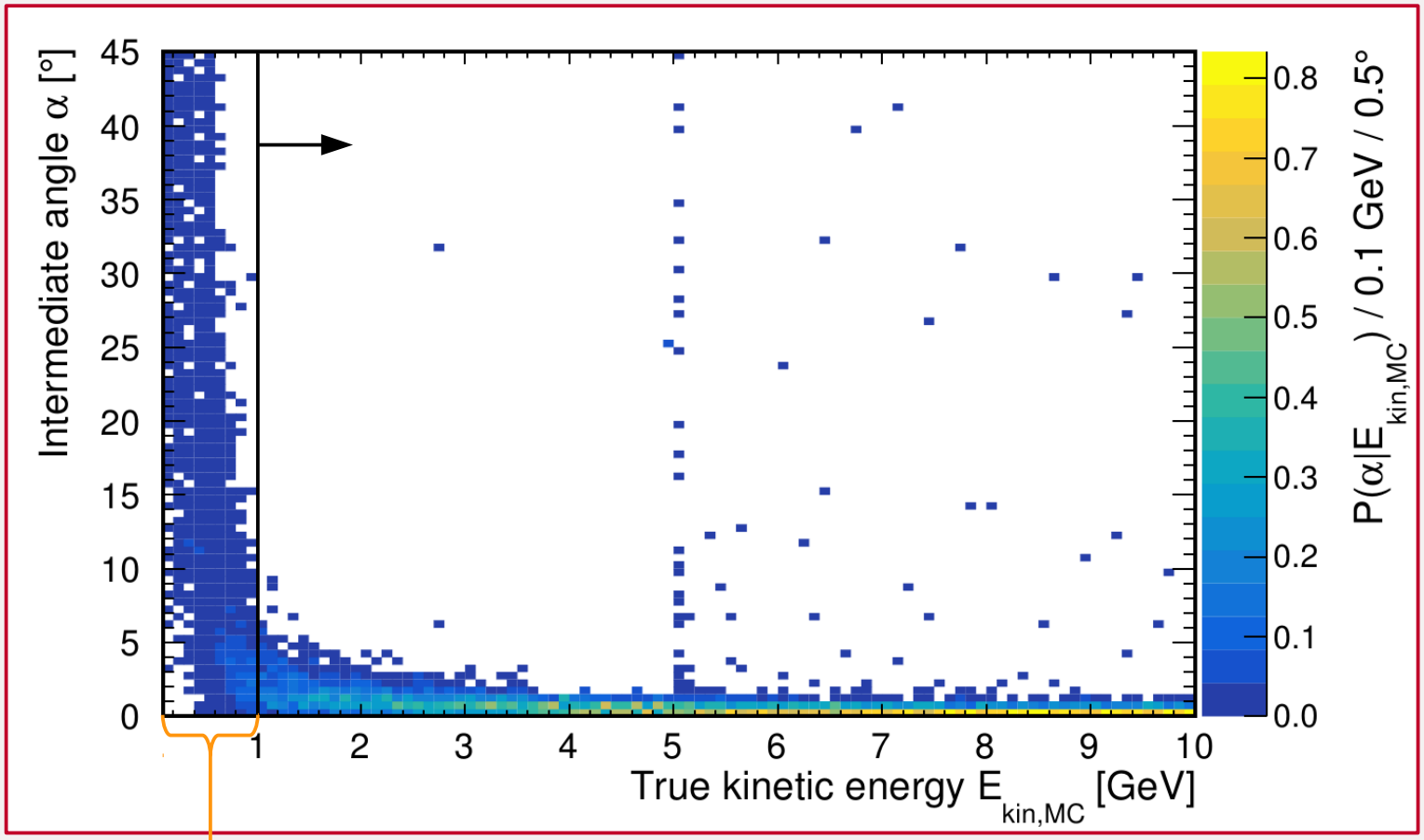
Event Sample





Intermediate Angle

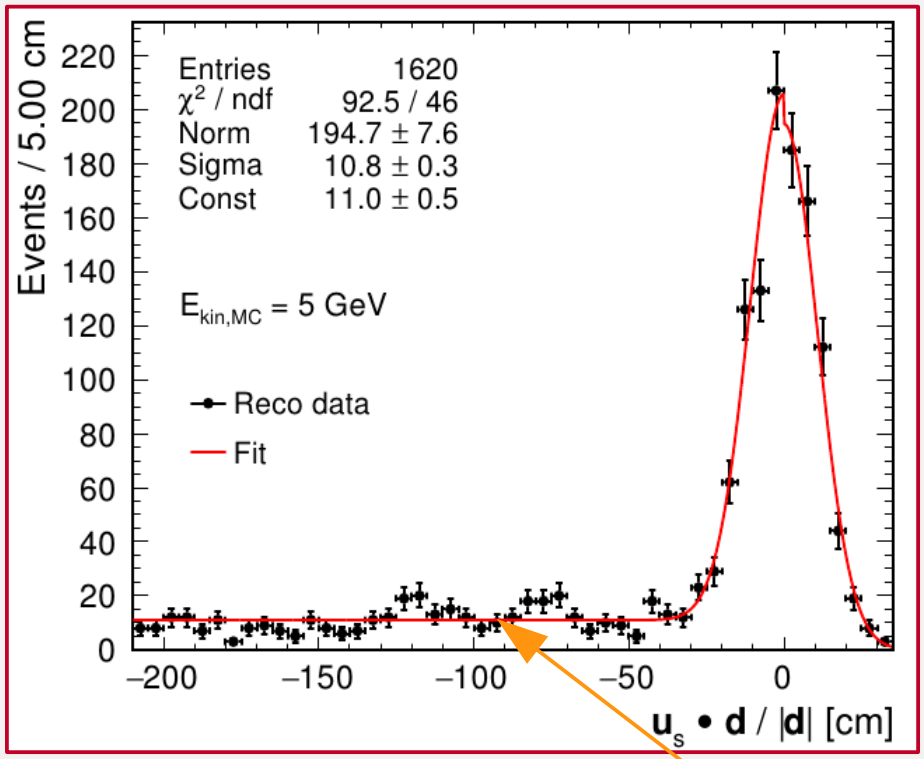
- Angle between reconstructed track line and MC mean direction

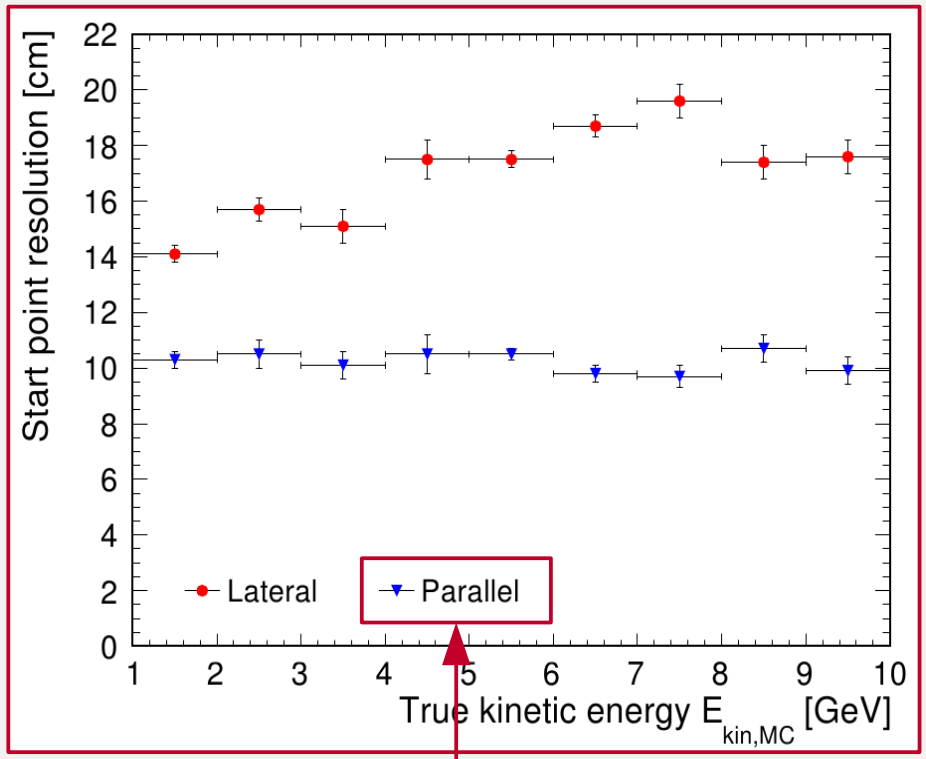


- Tracks too short
- Cells in reconstruction too large
- Random shift of ref. point w.r.t. true start point comparable to blob extension

Start Point Resolution (Parallel)

- Projection of connecting vector from rec. start to MC start onto rec. track



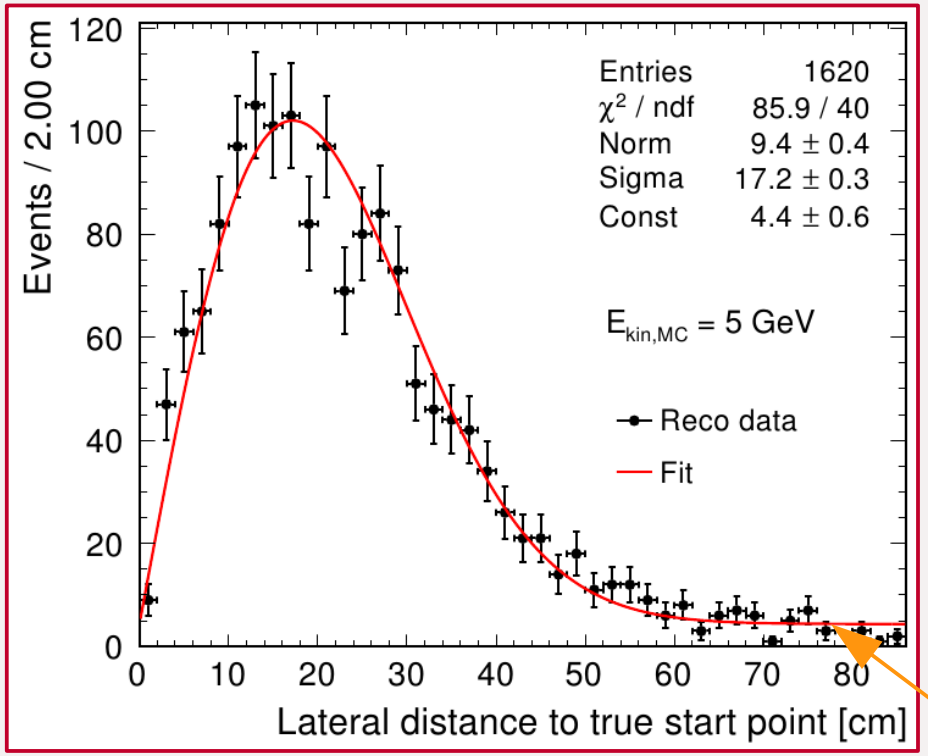


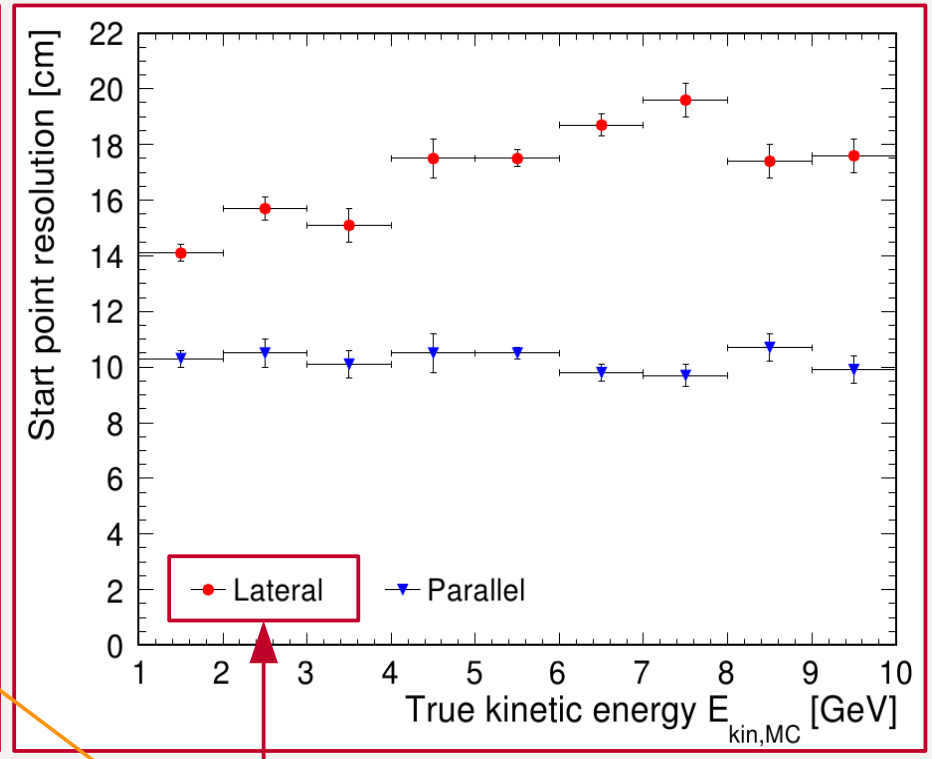
Systematic effects in start point finding

Fit-function:

$$F(u_{s,\mathrm{para}}) = \begin{cases} A \exp\left(-\frac{u_{s,\mathrm{para}}^2}{2\sigma_{s,\mathrm{para}}^2}\right), & \text{if } u_{s,\mathrm{para}} \geq 0 \\ A \exp\left(-\frac{u_{s,\mathrm{para}}^2}{2\sigma_{s,\mathrm{para}}^2}\right) + B, & \text{if } u_{s,\mathrm{para}} < 0 \end{cases}$$

Start Point Resolution (Lateral)



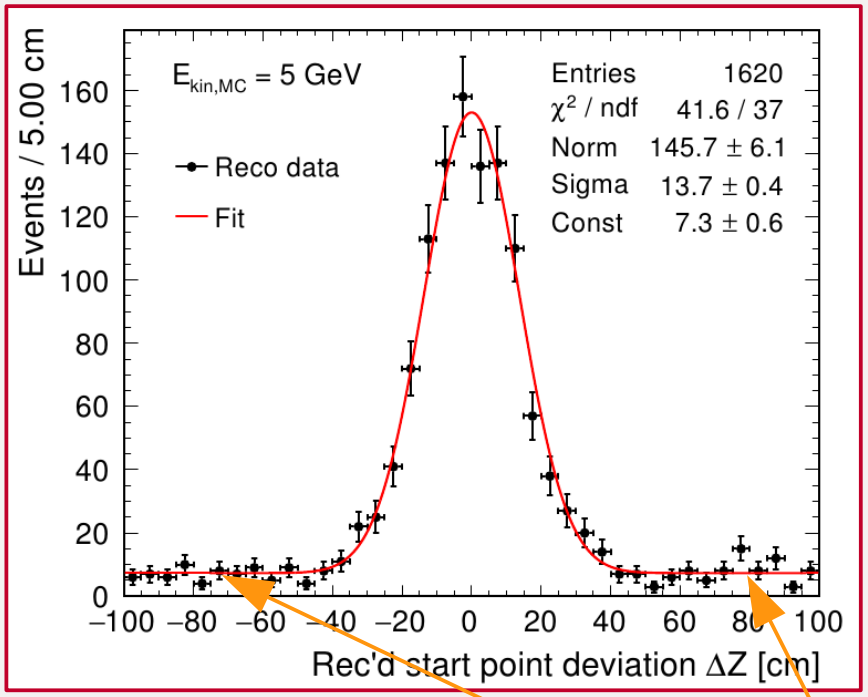


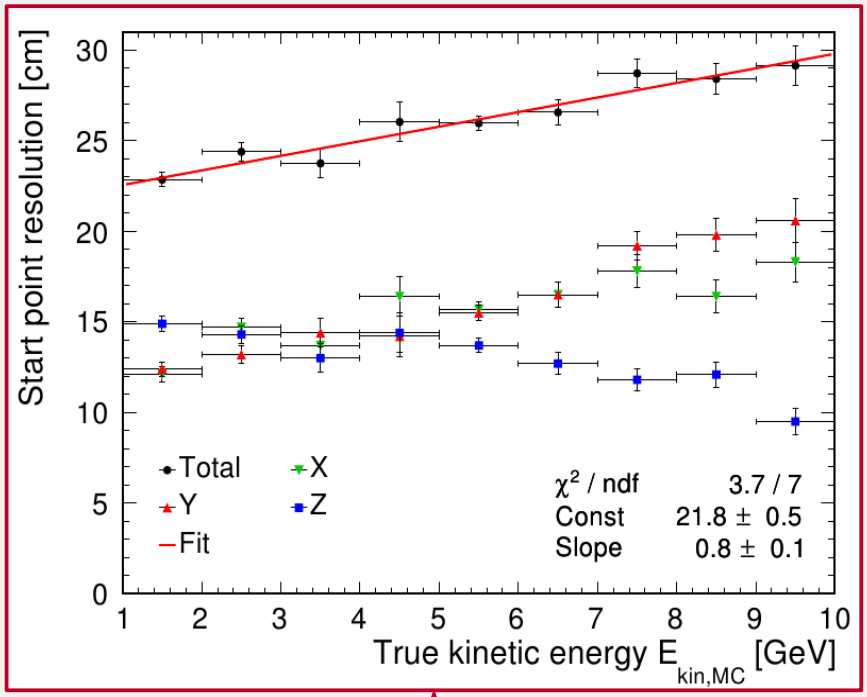
Fit-function:

$$F(u_{s,\mathrm{lat}}) = u_{s,\mathrm{lat}}\, A\, \exp\left(-\frac{u^2_{s,\mathrm{lat}}}{2\sigma^2_{s,\mathrm{lat}}}\right) + B$$

Start Point Resolution (X, Y, Z)

- Look at distance $|\mathbf{u}_s| = (u^2_{s,x} + u^2_{s,y} + u^2_{s,z})^{1/2}$ between true and reconstructed start point in detector coordinates



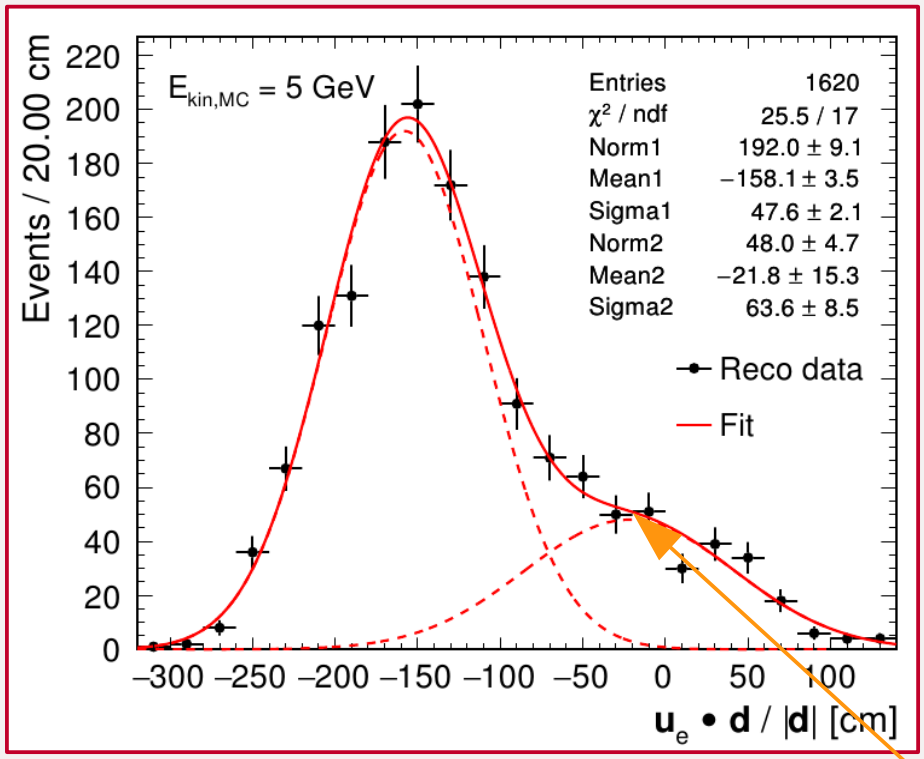


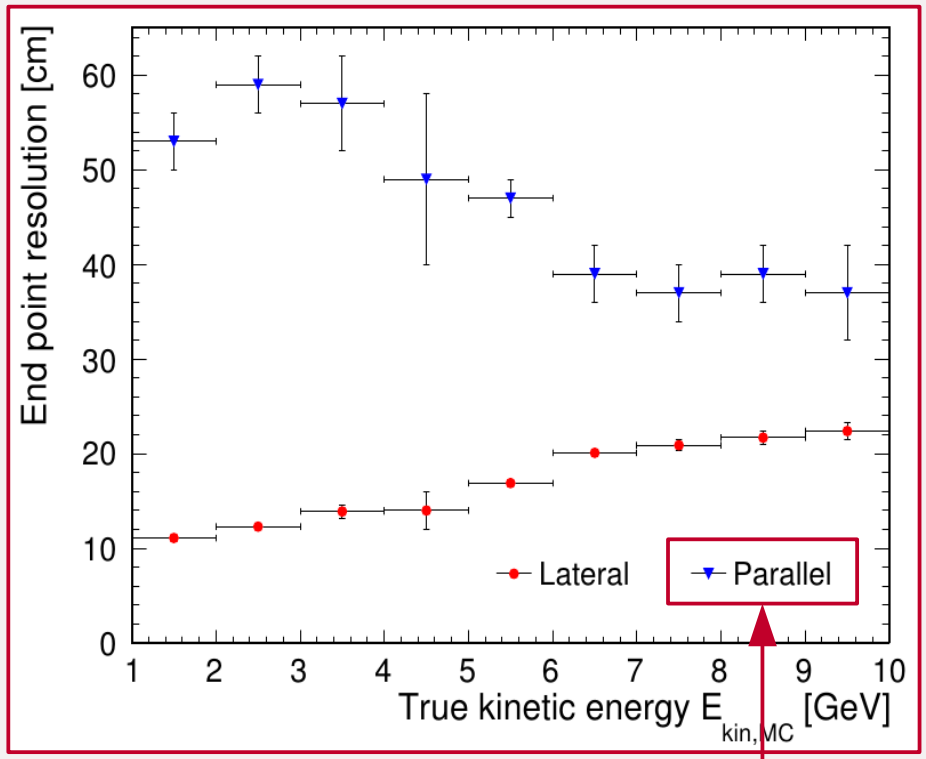
Systematic effects in start point finding

Fit-function: $$F(u_{s,c}) = A \exp\left(-\frac{u^2_{s,c}}{2\sigma^2_{s,c}}\right) + B, \quad c = x, y, z$$

End Point Resolution (Parallel)

- Projection of connecting vector from rec. end to MC start onto rec. track





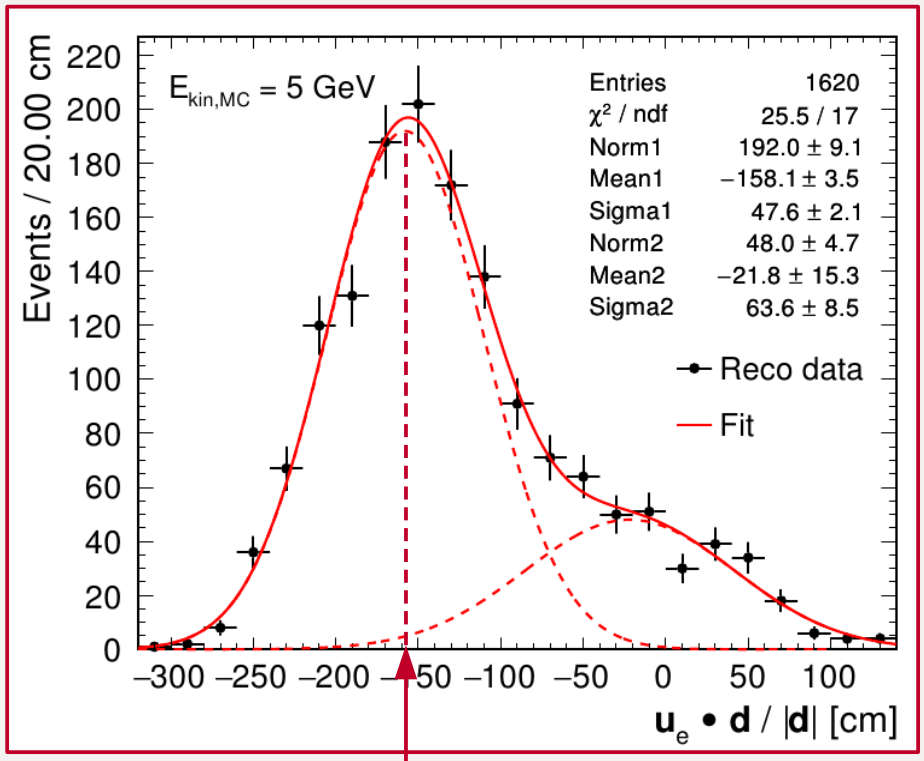
Systematic effects
in end point finding

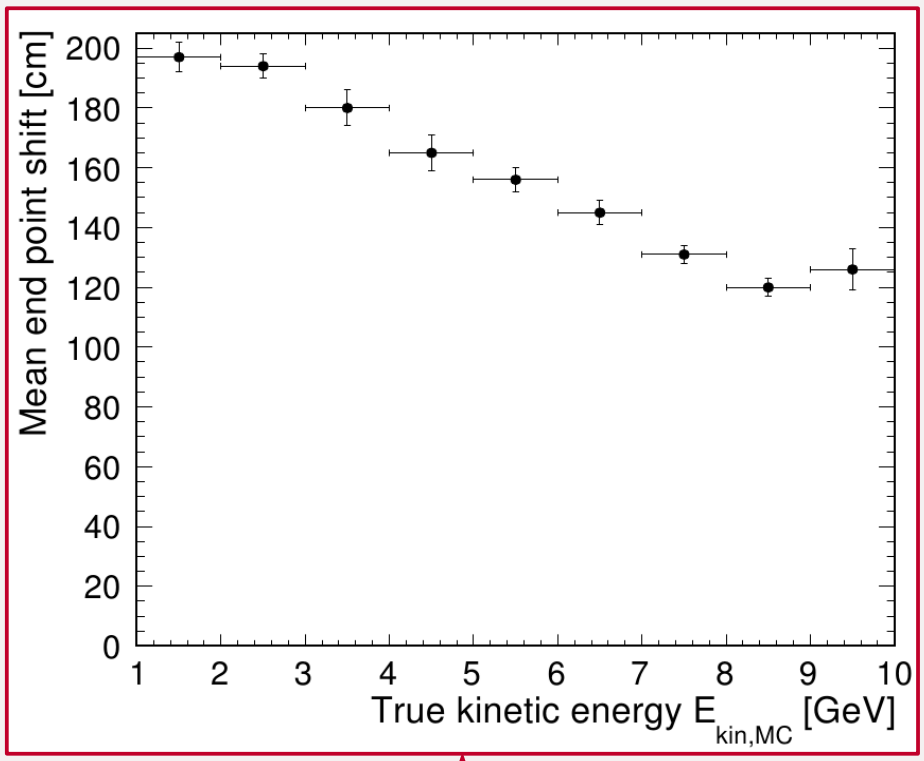
Fit-function:

$$F(u_{e,\mathrm{para}}) = A \exp\left(-\frac{(u_{e,\mathrm{para}} - \mu_{\mathrm{peak}})^2}{2\sigma^2_{\mathrm{peak}}}\right) + B \exp\left(-\frac{(u_{e,\mathrm{para}} - \mu_{\mathrm{tail}})^2}{2\sigma^2_{\mathrm{tail}}}\right)$$

End Point – Mean Parallel Shift

- Projection of connecting vector from rec. end to MC start onto rec. track





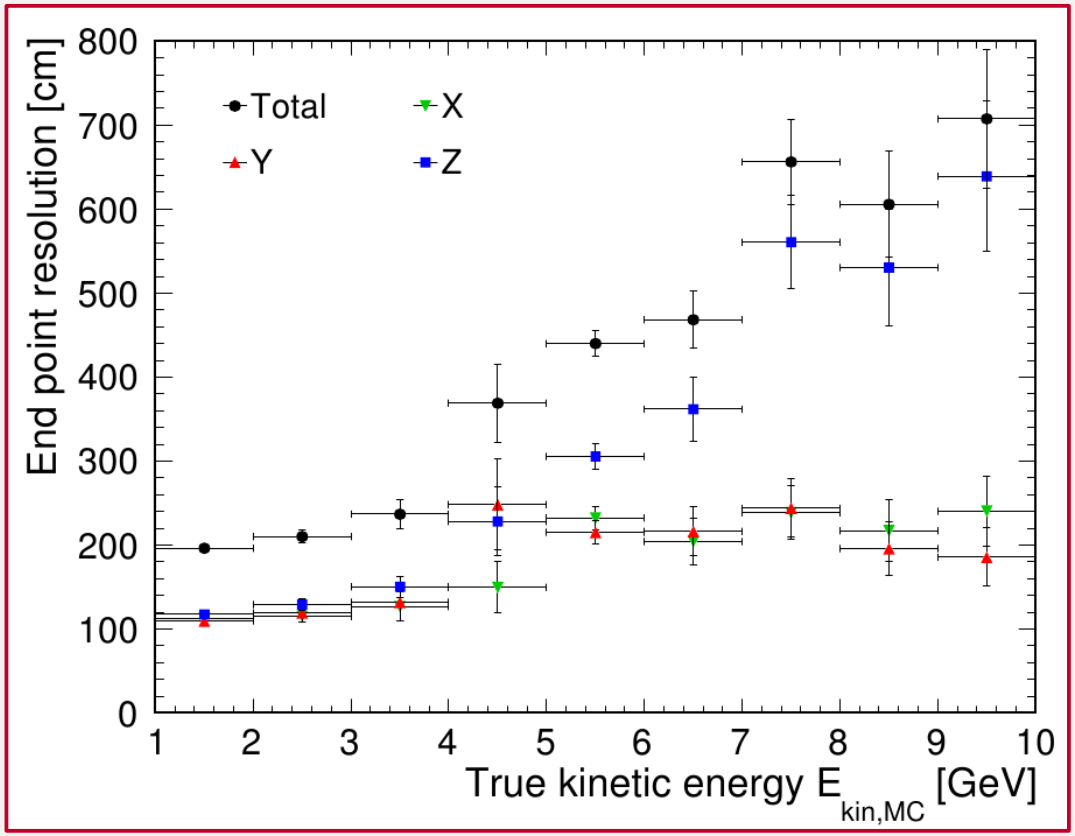
modulus

Fit-function:

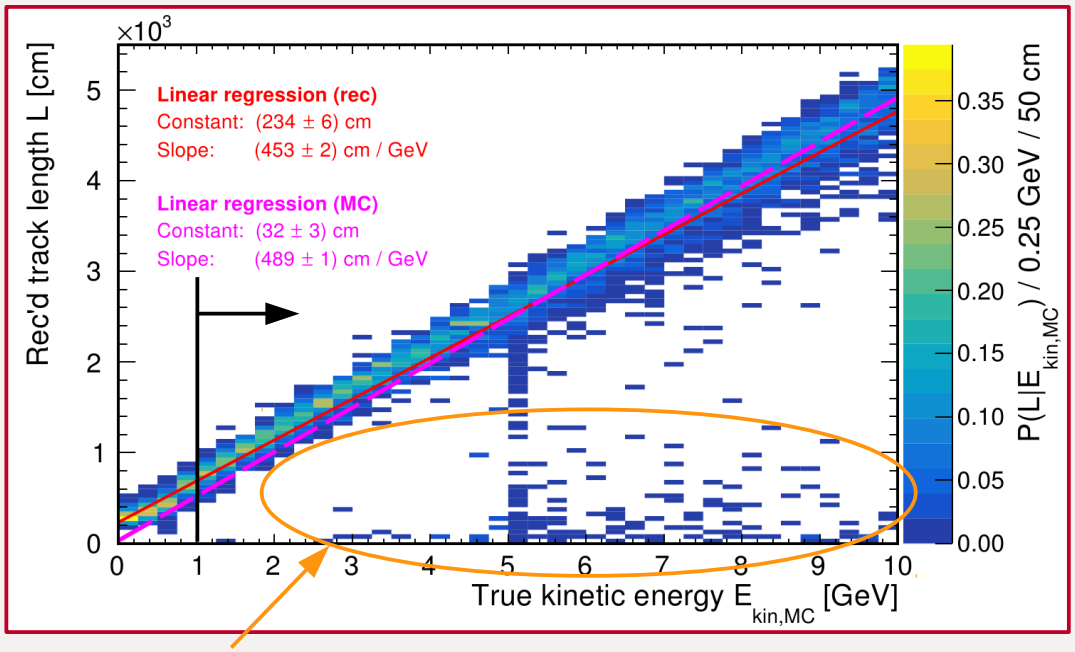
$$F(u_{e,\mathrm{para}}) = A \exp\left(-\frac{(u_{e,\mathrm{para}} - \mu_{\mathrm{peak}})^2}{2\sigma_{\mathrm{peak}}^2}\right) + B \exp\left(-\frac{(u_{e,\mathrm{para}} - \mu_{\mathrm{tail}})^2}{2\sigma_{\mathrm{tail}}^2}\right)$$

End Point Resolution (X, Y, Z)

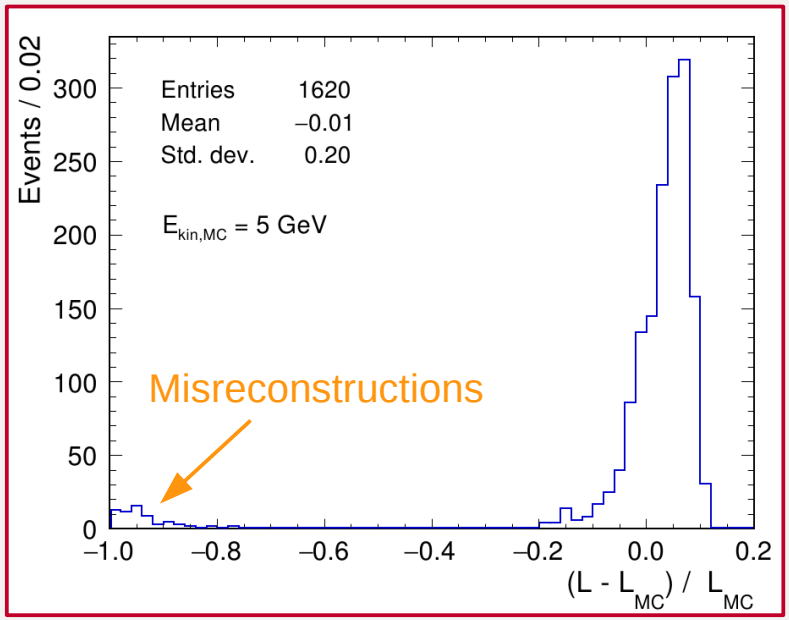
- Look at distance $|\mathbf{u_e}| = (u^2_{e,x} + u^2_{e,y} + u^2_{e,z})^{1/2}$ between true and reconstructed end point in detector coordinates
- Due to the offset, no Gaussian distribution around zero for $u_{e,x}$, $u_{e,y}$ and $u_{e,z}$
- Used sample standard deviation as resolution measure
- “Total“ is square root of the sum of the squared resolutions



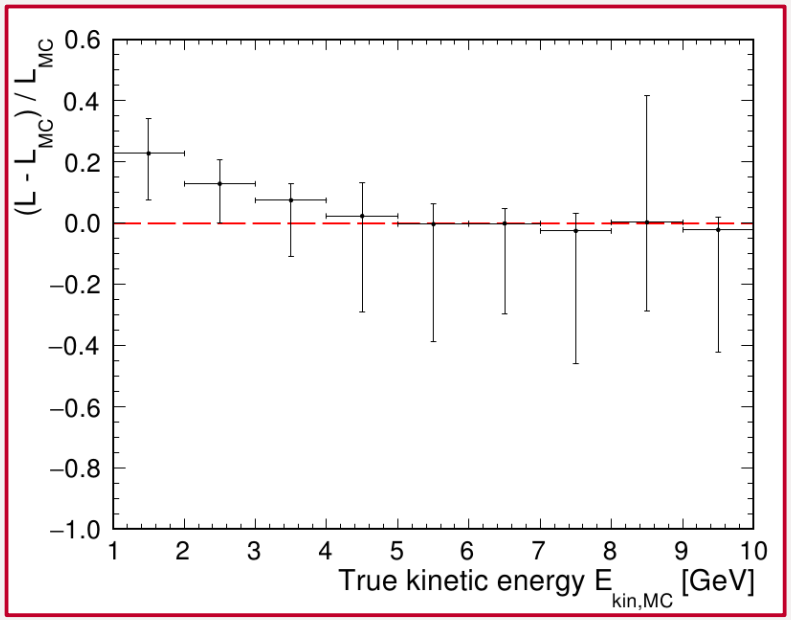
Track Length



Mostly misreconstructions



Mean +
left- and right-sided
standard deviations



Determination of Relative Energy Resolution

- Relative energy resolution: standard deviation over mean per energy bin