Topological Track Reconstruction in Unsegmented Multi-Kiloton Liquid Scintillator Neutrino Detectors

- Sebastian Lorenz[1] -

on behalf of

Felix Benckwitz[2], Christoph Genster[3], Caren Hagner[2], Daniel Hartwig[2], David Meyhöfer[2], Björn Opitz[2], Henning Rebber[2], Michaela Schever[3], Hauke Schmidt[2], Alexander Tietzsch[4], Katharina Voss[2], Björn Wonsak[2], Michael Wurm[1]

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Group Report, DPG Spring Meeting – Münster, March 29th 2017

Introduction

- General idea for track reconstruction in liquid scintillator (LS) is fairly young; this talk presents one sophisticated method
  J.G. Learned, *"High Energy Neutrino Physics with Liquid Scintillation Detectors"*, [arXiv: 0902.4009]
- Working group emerged during LENA project
  M. Wurm et al., *"The next-generation liquid-scintillator neutrino observatory LENA"*, Astropart. Phys. 35 (2012) 685-732
- Experience on data- / MC-based (muon) track reconstruction in Borexino, Double Chooz, JUNO, LENA, (OPERA) present
- Current focus: **JUNO,** Borexino
  group embedded into / partially funded by DFG reseach unit
  „Bestimmung der Neutrino-Massenhierarchie mit dem JUNO-Experiment"
  F. An et al., *"Neutrino Physics with JUNO"*, J. Phys. G43 (2016) no.3, 030401
  Z. Djurcic et al., *"JUNO Conceptual Design Report"*, [arXiv: 1508.07166]
  DFG Deutsche Forschungsgemeinschaft
- Also: some interest in collaboration with water-based LS project THEIA in the USA
  G.D. Orebi Gann, *"Physics Potential of an Advanced Scintillation Detector: Introducing THEIA"*, [arXiv: 1504.08284]

Outline

- Motivation
- Reconstruction Method in a Nutshell
- Current Status
- Summary

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- Track reconstruction in LS, e.g., for muons, is required for an efficient rejection of cosmogenic radionuclide background in low-energy neutrino event searches

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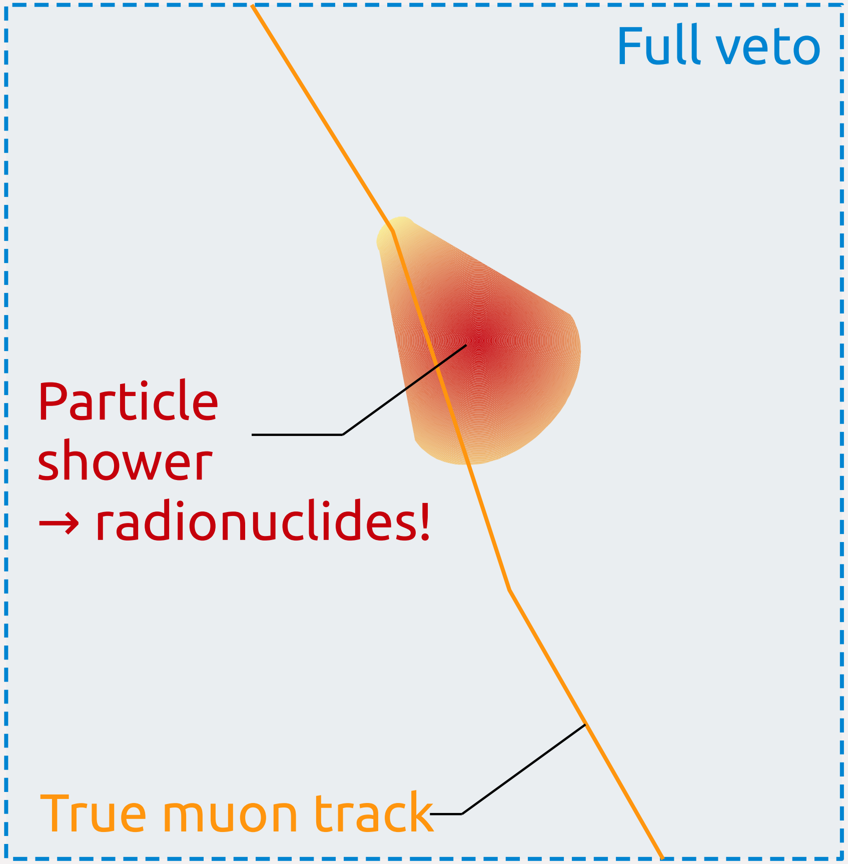
- Usually: full detector veto
  (**showering** muons; muon bundles)



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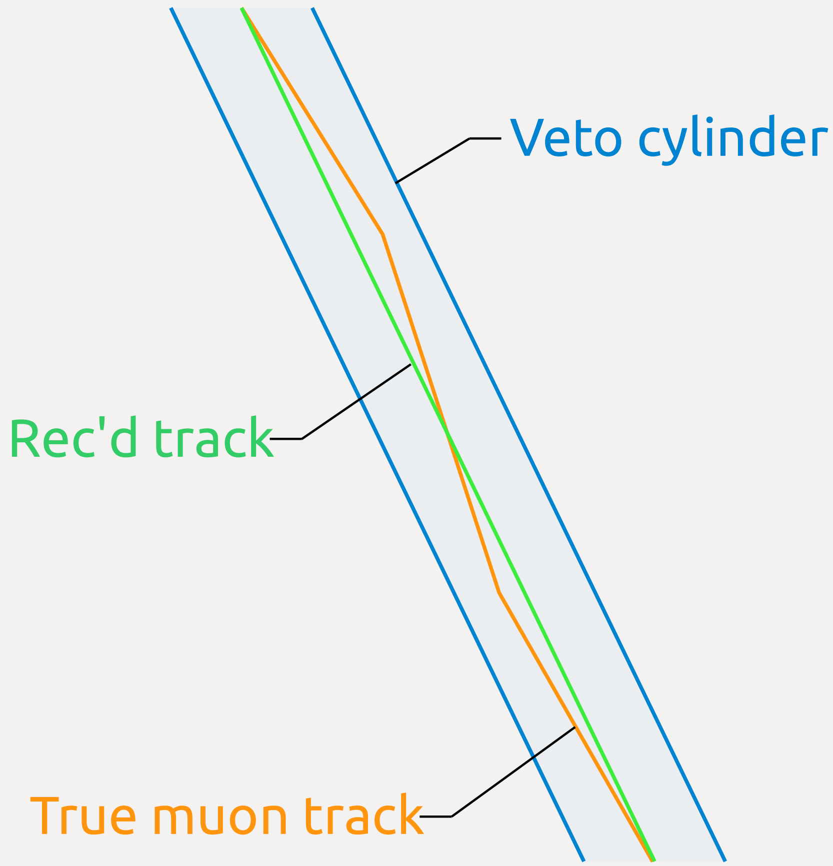
  (**showering** muons; muon bundles)

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

  (through-going or stopping muons)

Christoph Genster - T 80.4, Wed 29.03, 17:40-17:55,
“Studies on muon track reconstruction with the JUNO liquid scintillator neutrino detector“



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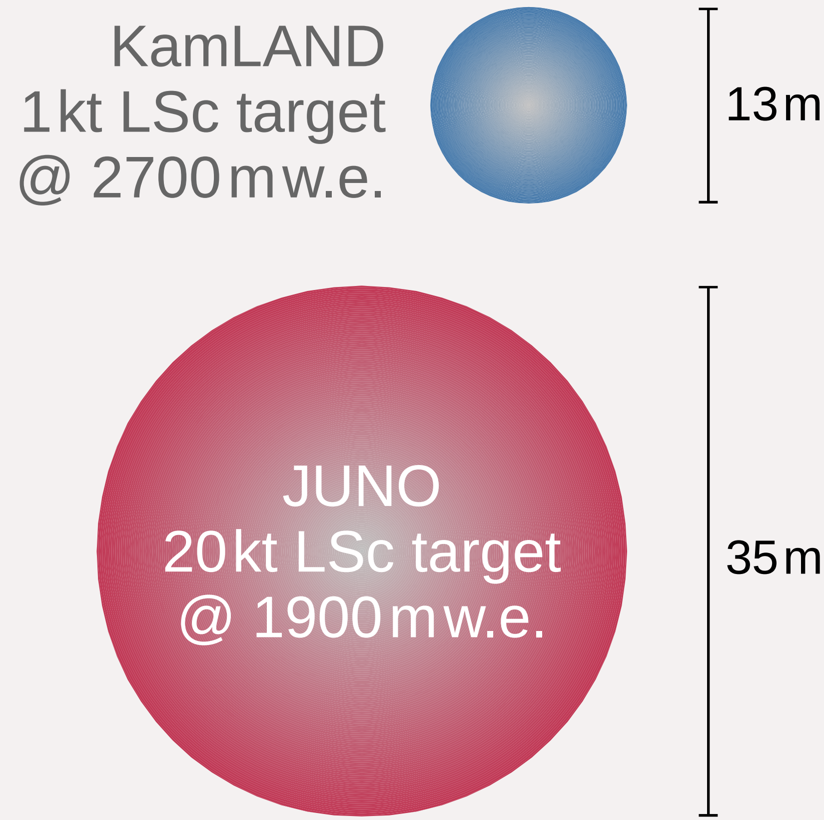

- Especially important for future large-volume LS detectors
  JUNO (20 kt with ~730 m overburden)
  ~3 s^{-1} muon event rate
  1:1 signal to cosm. bkg. ratio expected

Henning Rebber - T 80.1, Wed, 29.03., 16:45-17:05, *"Neutrino Physics with JUNO"*

Paul Hackspacher - HK 43.1, Thu, 30.03, 14:00-14:30, *"The Jiangmen Underground Neutrino Observatory"*

Motivation

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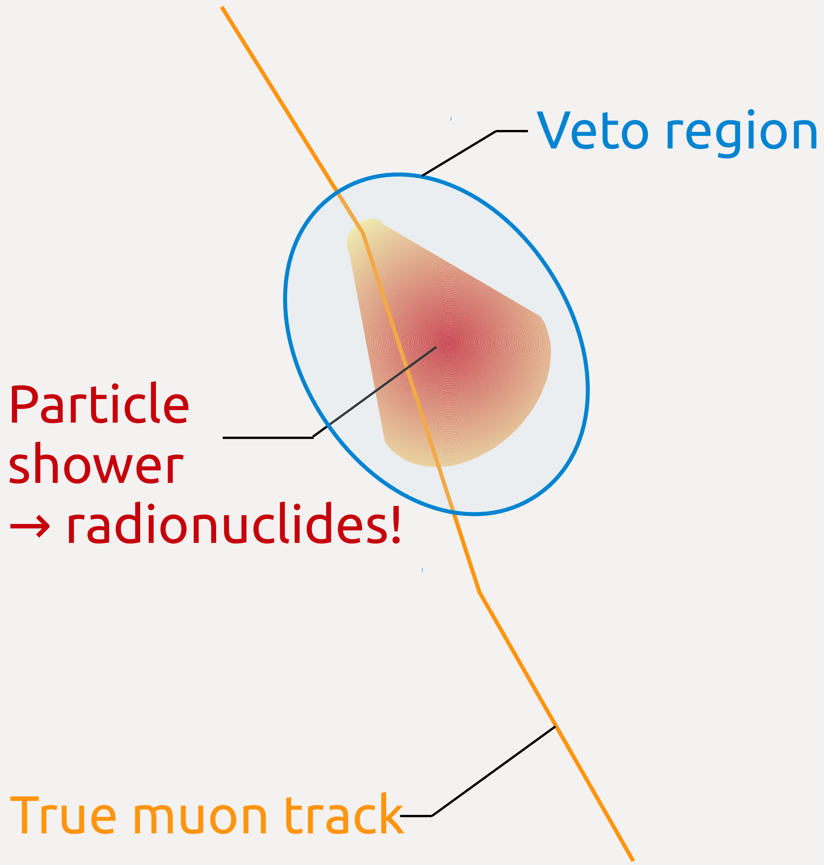
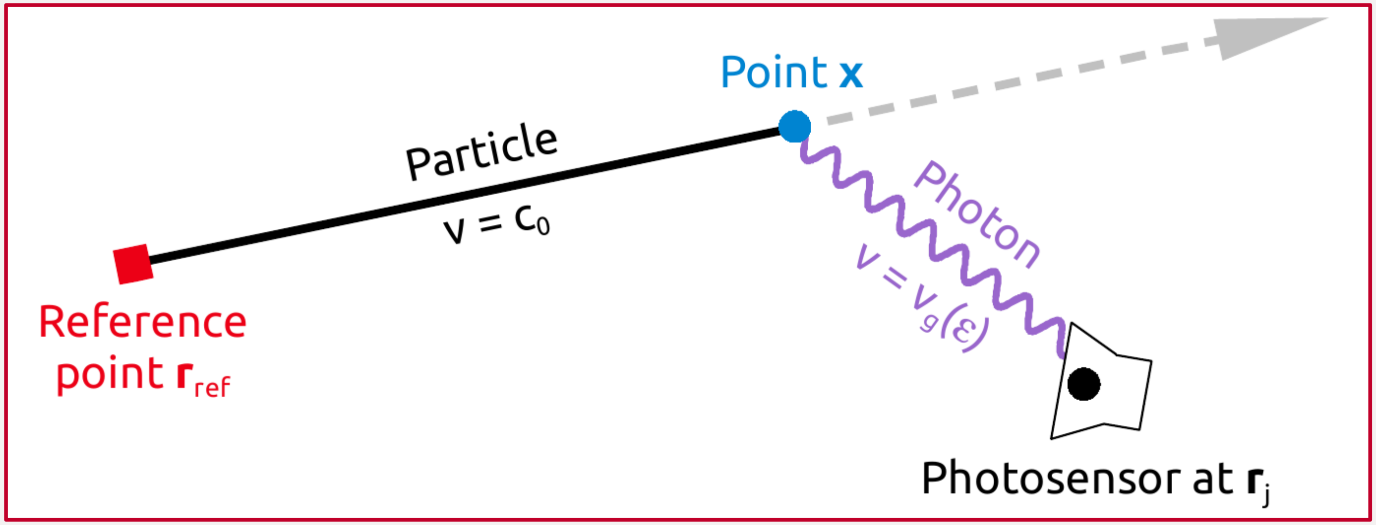


- **Can we do better (e.g., dE/dx or focus on showers)?**

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

Approach: Based on a simple model,…



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

Reference point / time from external system or method

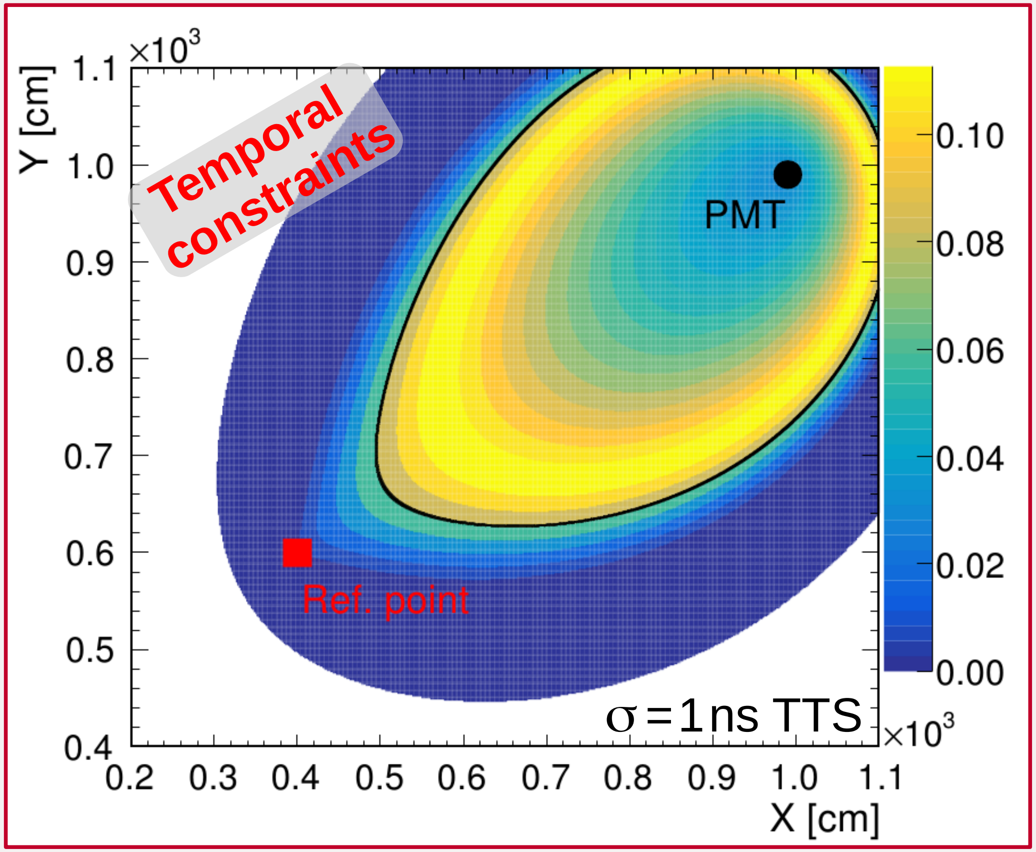
David Meyhöfer - T 80.9, Mi, 29.03., 18:55-19:10
"Vertex reconstruction in unsegmented liquid scintillator detectors"

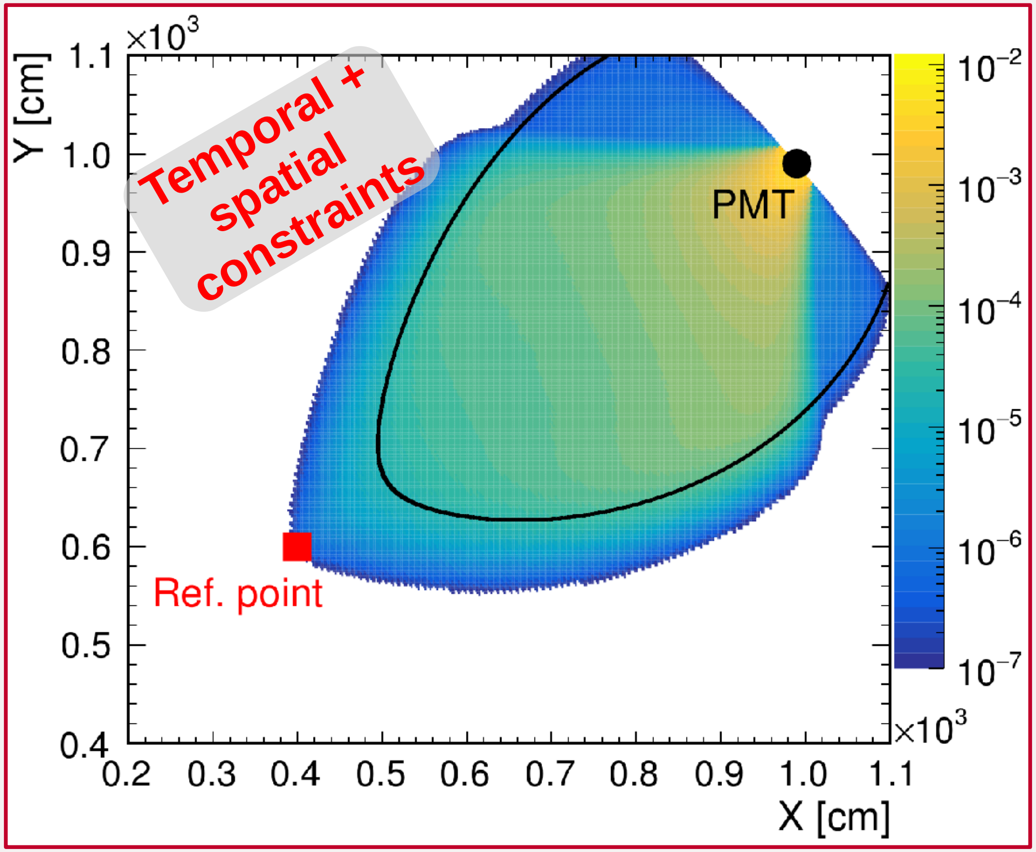
Reconstruction Method in a Nutshell

…create a PDF for the origin of each detected photon inside the detector that takes temporal (scintillator, PMT timing) and spatial constraints (acceptance, opt. properties, light concentrators, ...) into account.

Single photon counting assumed!

Michaela Schever - T 57.9, Tue, 28.03., 18:50-19:05, *“Waveform reconstruction with the deconvolution method for JUNO“*





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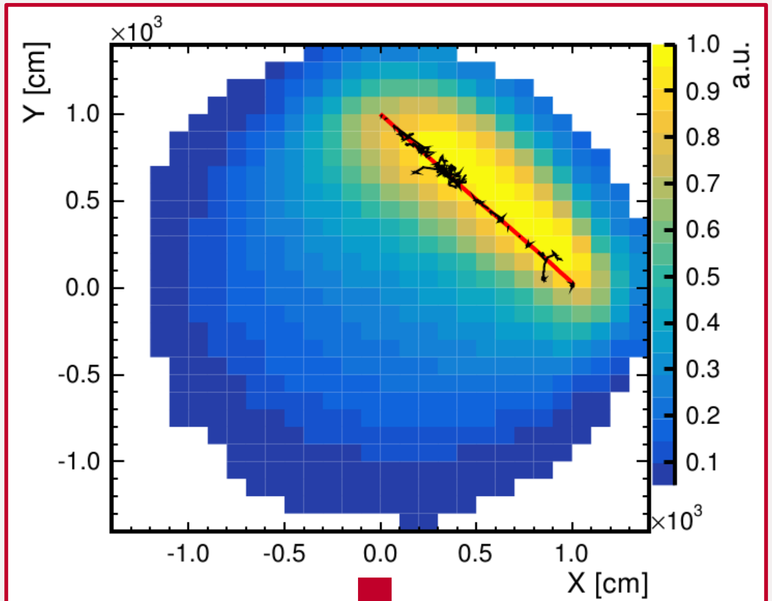
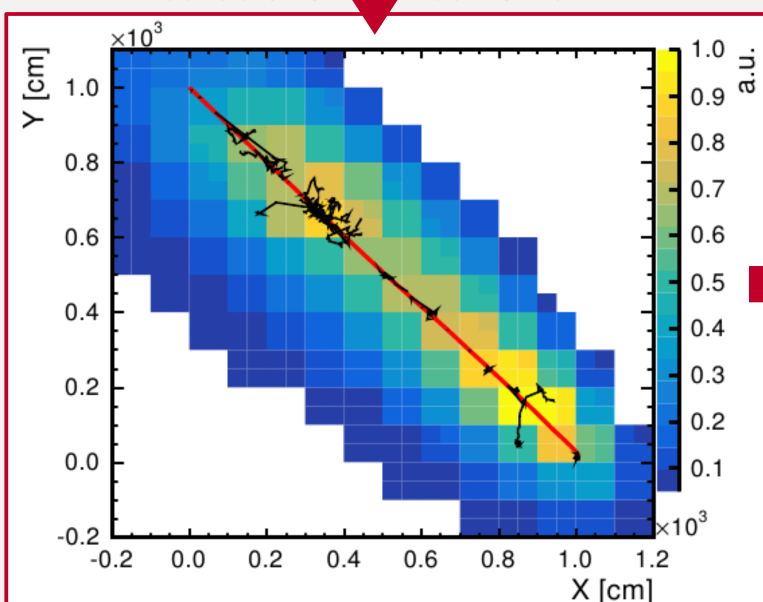


Some iterations

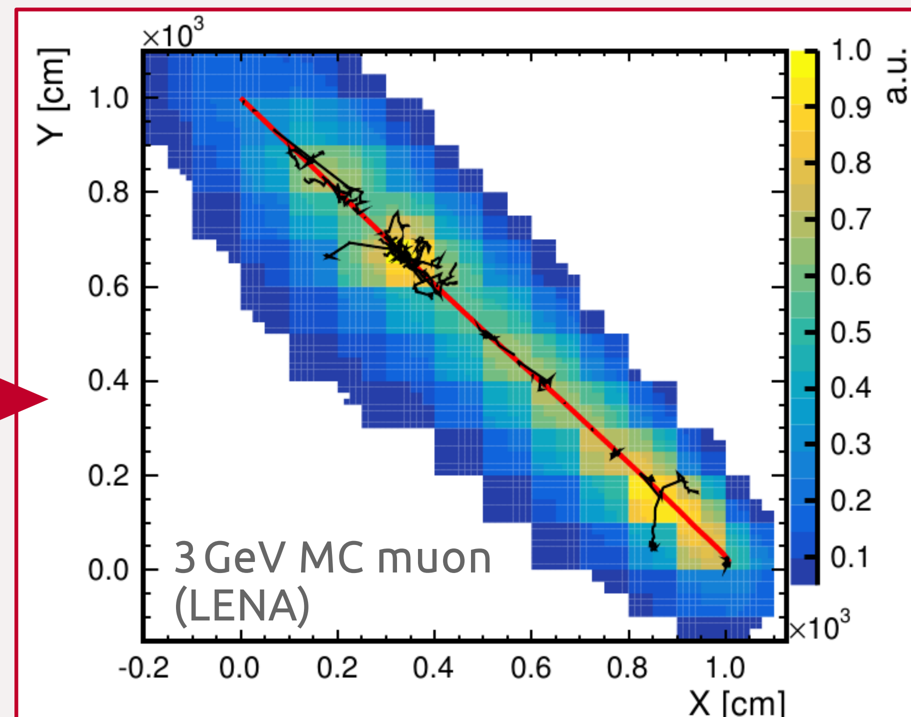
Decrease cell size



- 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.

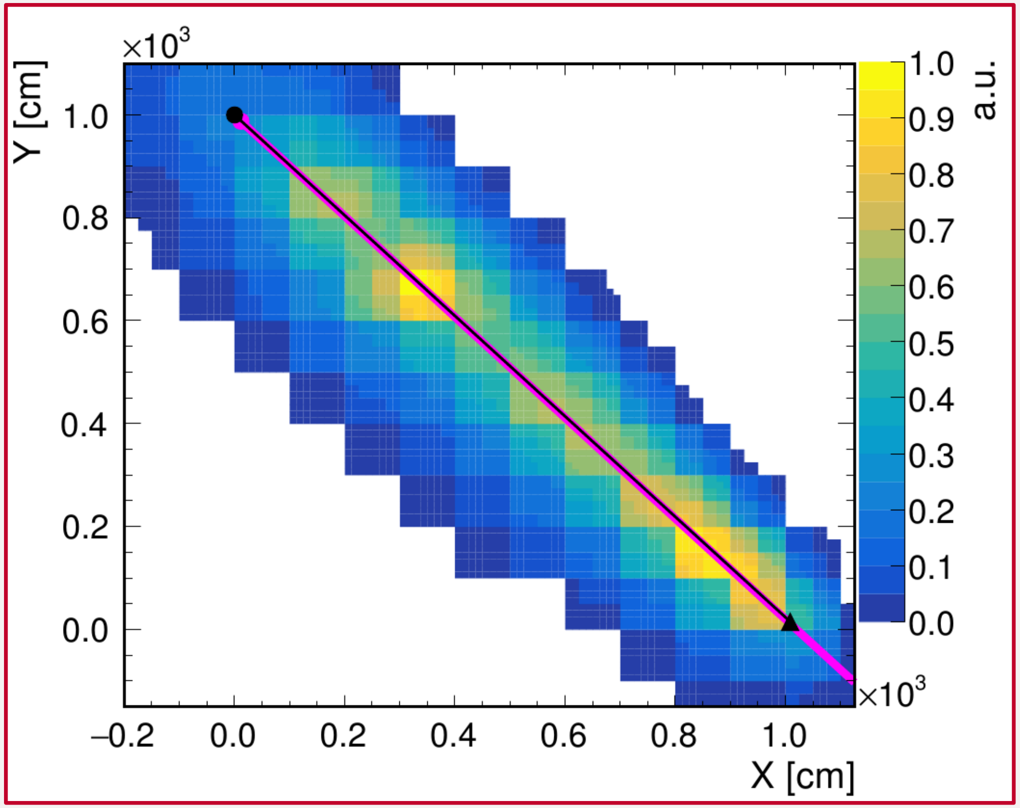
Some iterations

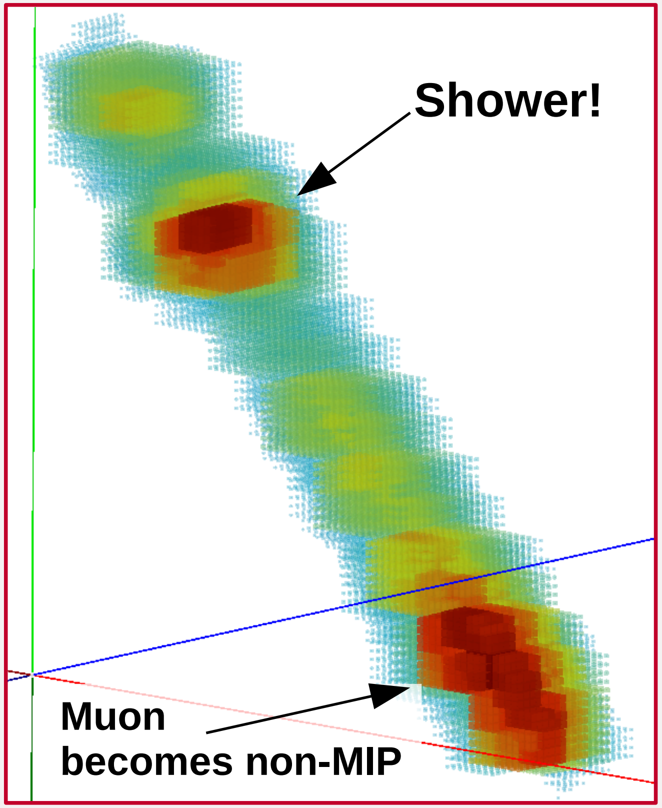
Decrease cell size



Reconstruction Method in a Nutshell

- After computation of 3D data: analysis to extract physics parameters
- Use methods from 3D data / image processing
- For example: find / fit linear tracks; find increased energy depositions
- Computationally expensive method (optimization possible / ongoing)
  → final, optional step in reconstruction chain





Current Status

- C++ framework for different LS detectors
- Currently: LENA, JUNO, Borexino

> Björn Opitz - T 80.5, Wed, 29.03, 17:55-18:10,
> *“Topological track reconstruction for Borexino“*

- Basic performance analysis with events from LENA Geant4 detector simulation

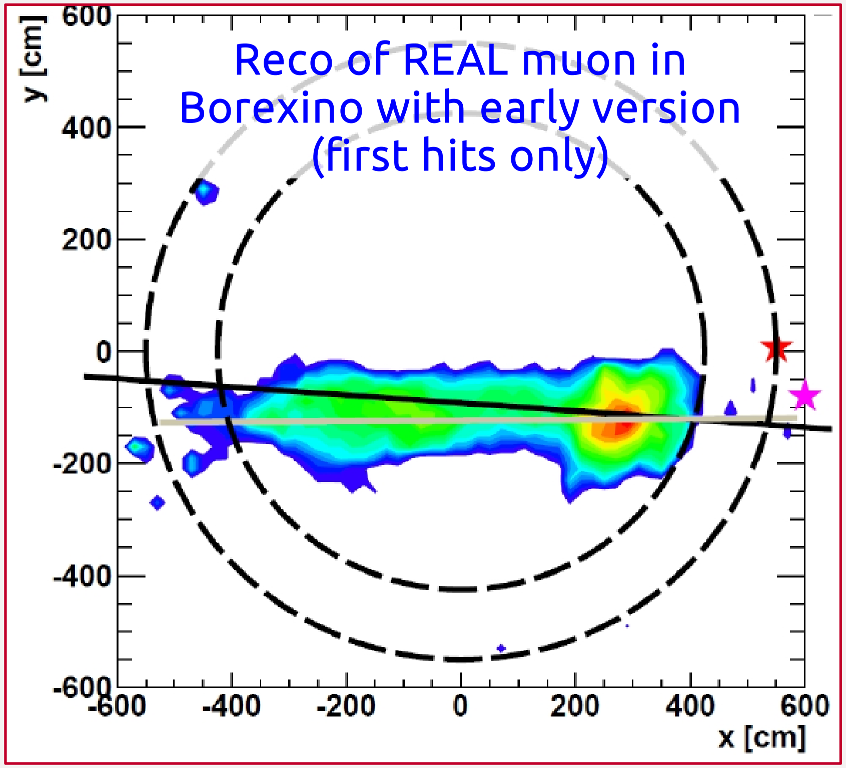
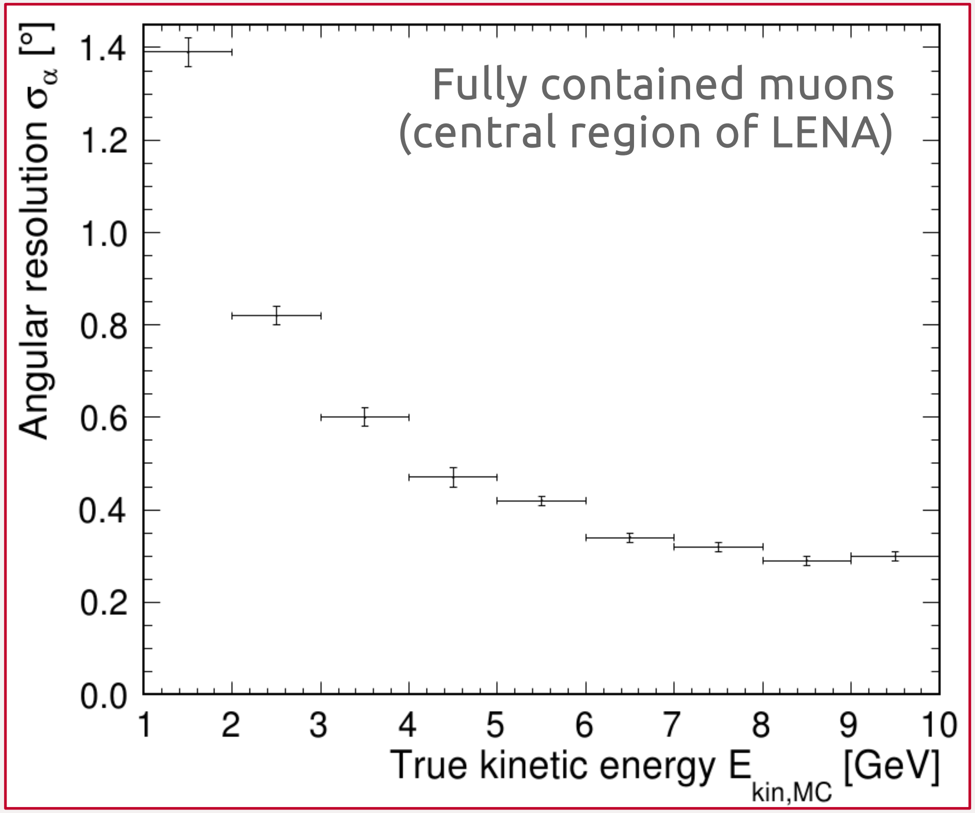


Figure courtesy of Björn Wonsak (Uni Hamburg)



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

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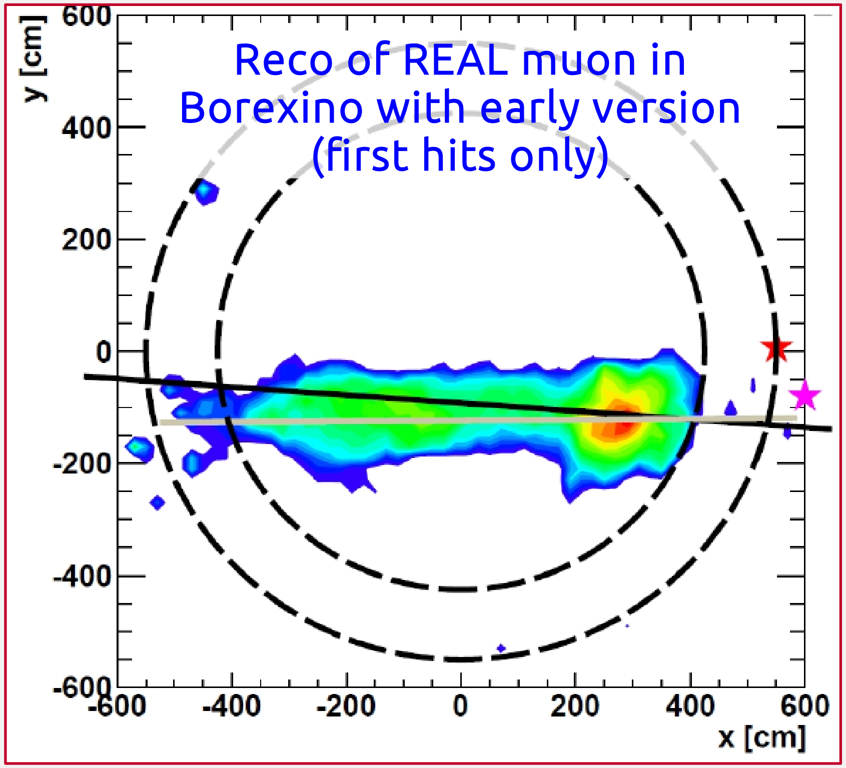

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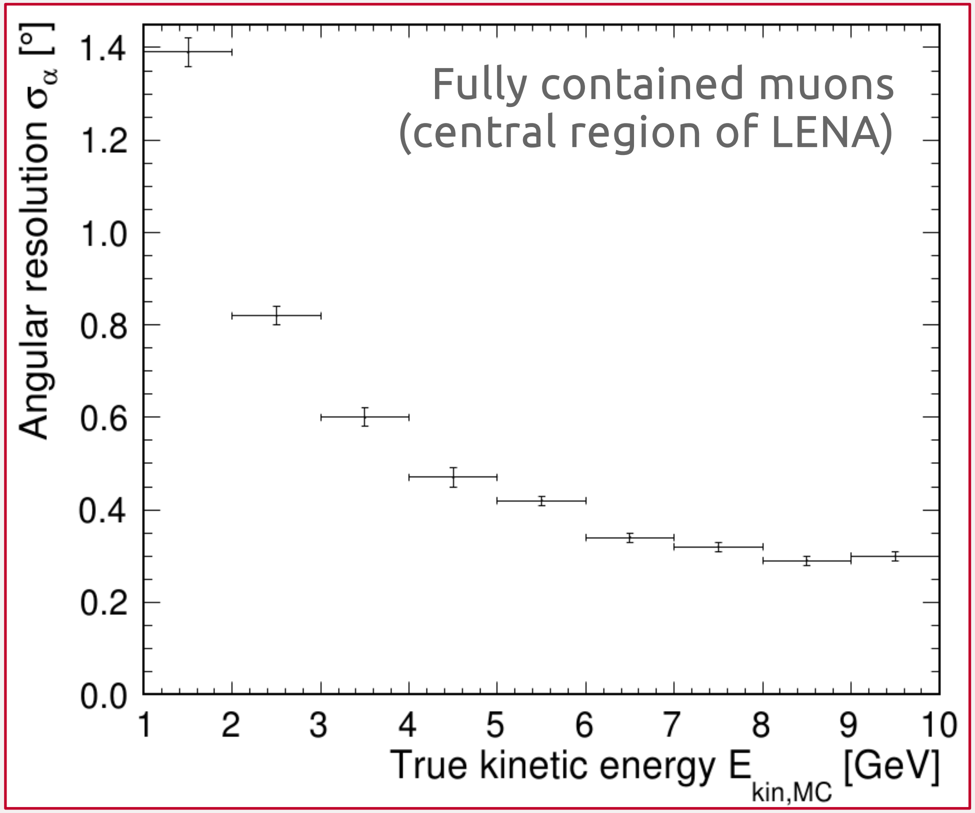

Current hot topic:

Balancing speed and precision
➔ optical model is important!

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

Optical Model

- Key to a good event (topology) reconstruction!
- Description of **photon production** (scintillation, Cherenkov), **propagation** (scattering, absorption) and **detection** (PMT acceptance, QE, light concentrator)
- **Pre-compute look-up-tables**; validate with Monte Carlo

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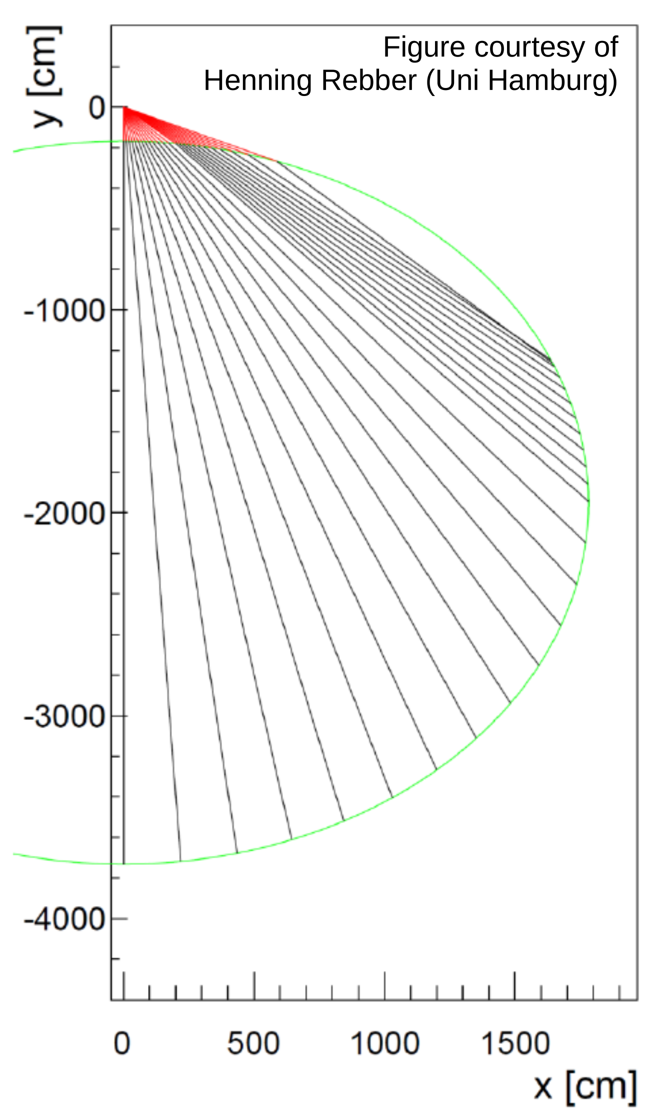
- For JUNO: Respect the details!
  - wavelength dependencies
  - acrylic sphere
  - three different PMT types
  - photons traverse three media
  - shadowing from construction elements
  - ...



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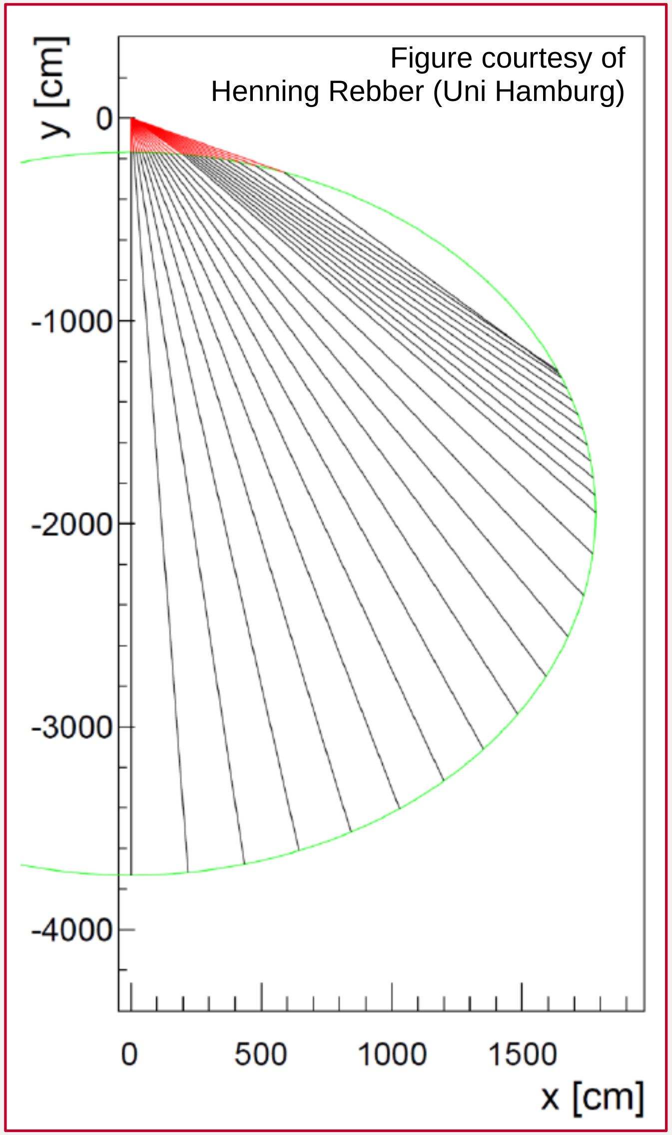
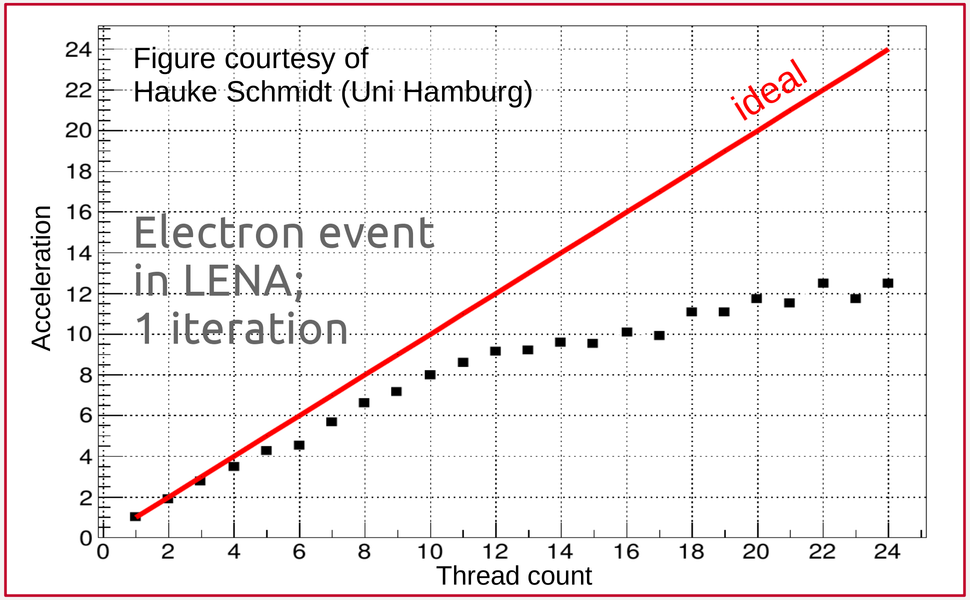
  - …
- Essential for statistical removal of scattered photons → improve preformance / speed!

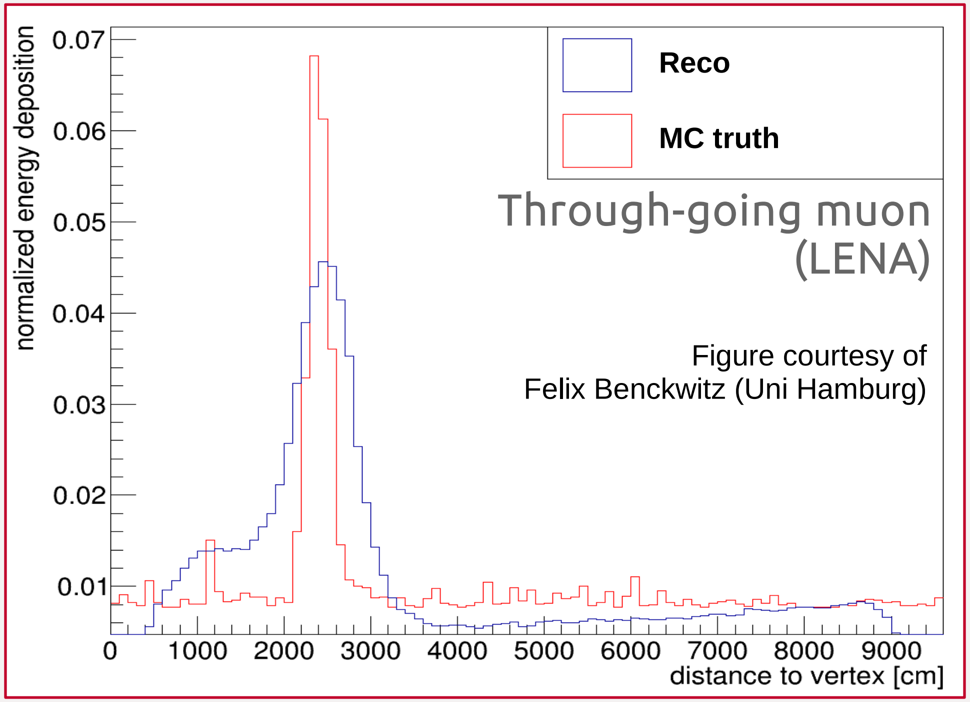


Further Developments

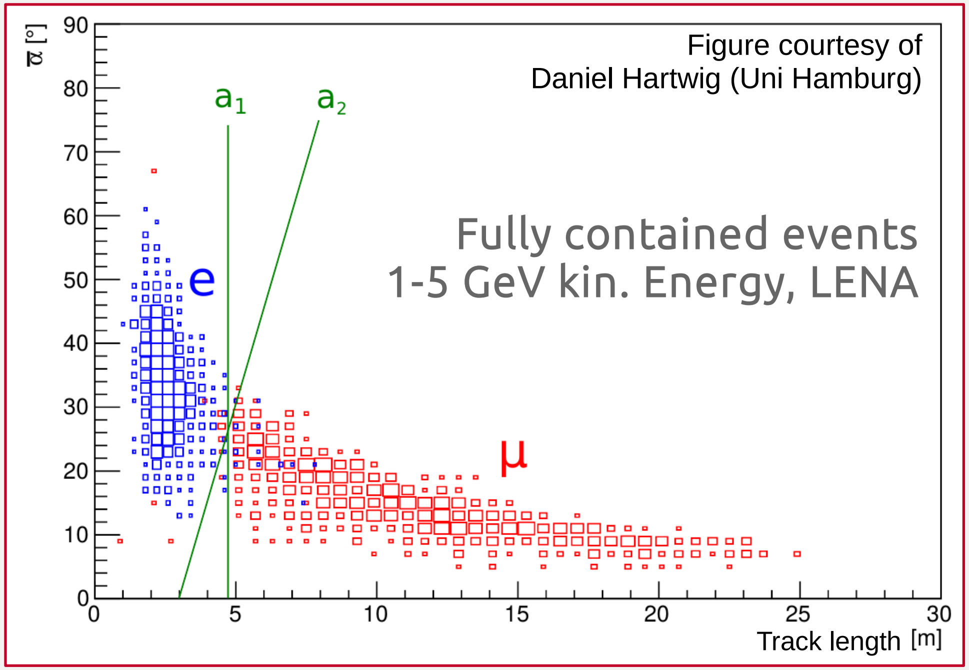
- Hardware-based acceleration of the reconstruction
  → CPU-based multithreading
- The dream for the future: GPU-based parallelization

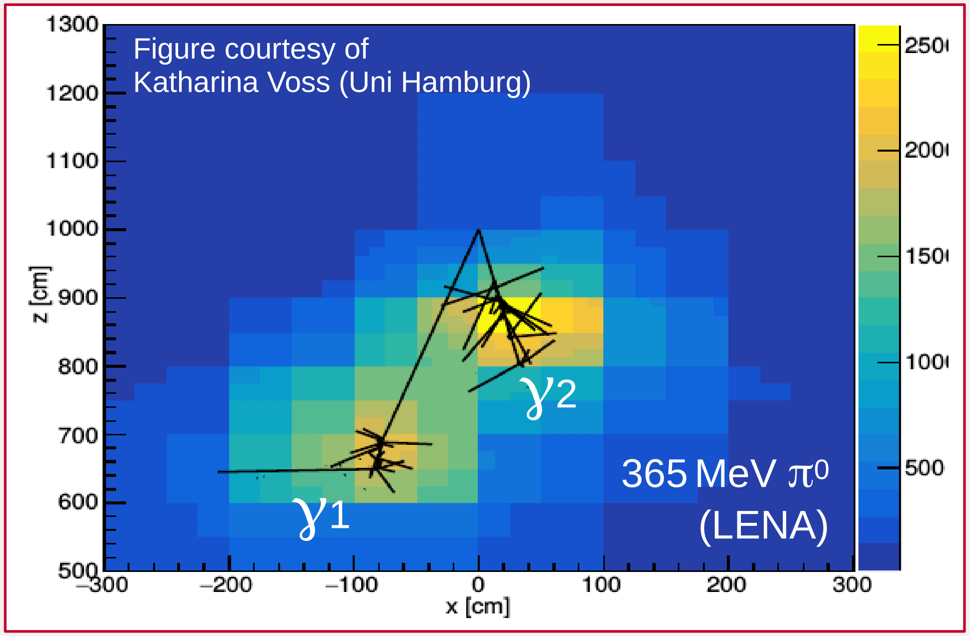


- Estimate for dE / dx along track



- Particle discrimination at GeV energies, e.g., e vs. μ or e vs. π^0
- Atmospheric or beam neutrino studies with LSc detectors





Summary

- Muon **track reconstruction** inside (future) LS detectors is important for an **efficient rejection of cosmogenic background**
- Development of **new, “generic“ topological track reconstruction method for LS** detectors by **German working group**
- Development started for LENA; now: **JUNO** and **Borexino**
- First performance measurement with MC muon events in LENA
- Hot topic: **balancing speed and precision**
- Ongoing activities: **optical model** implementations, hardware-based acceleration, **dE / dx** estimation, particle discrimination

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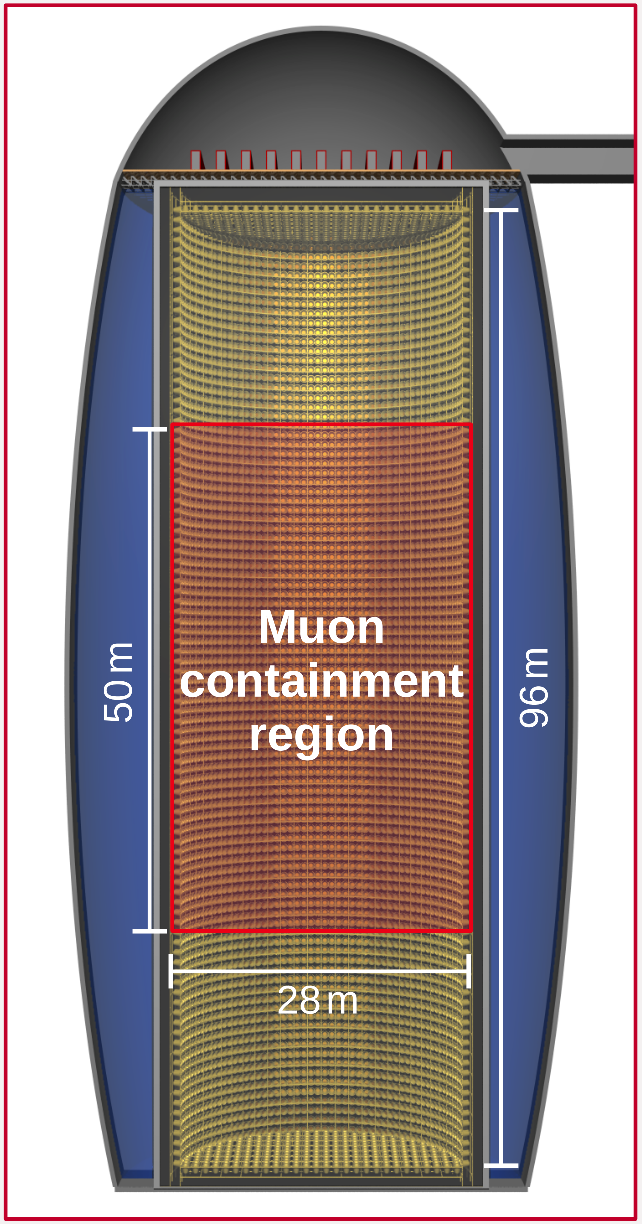
Thank you for your kind attention!

Further information

Simulated Muons in LENA



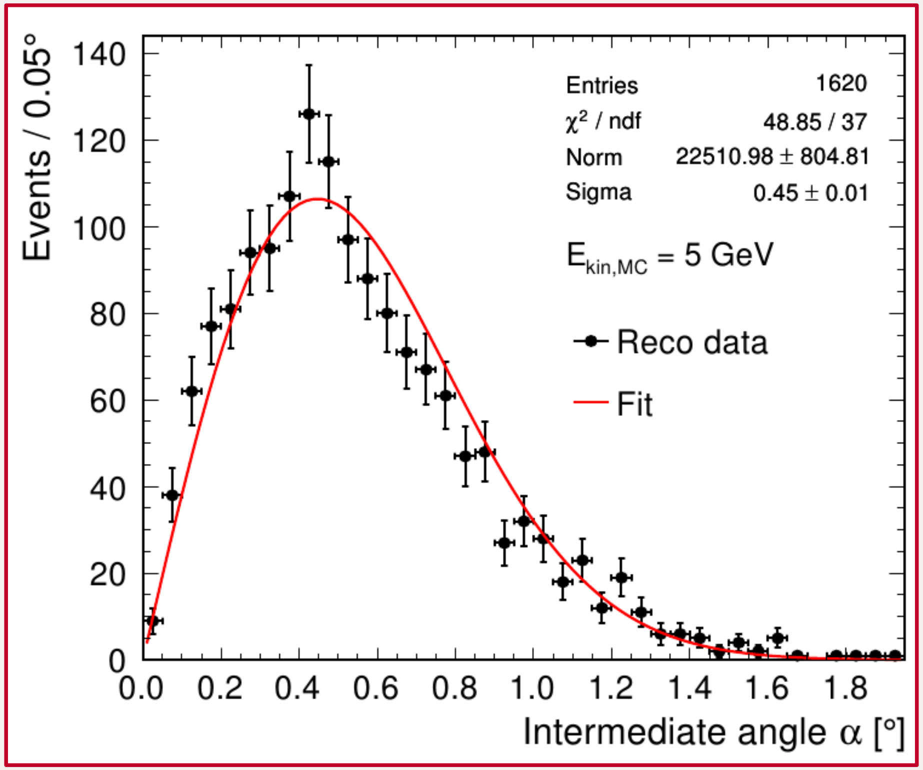
LENA Design

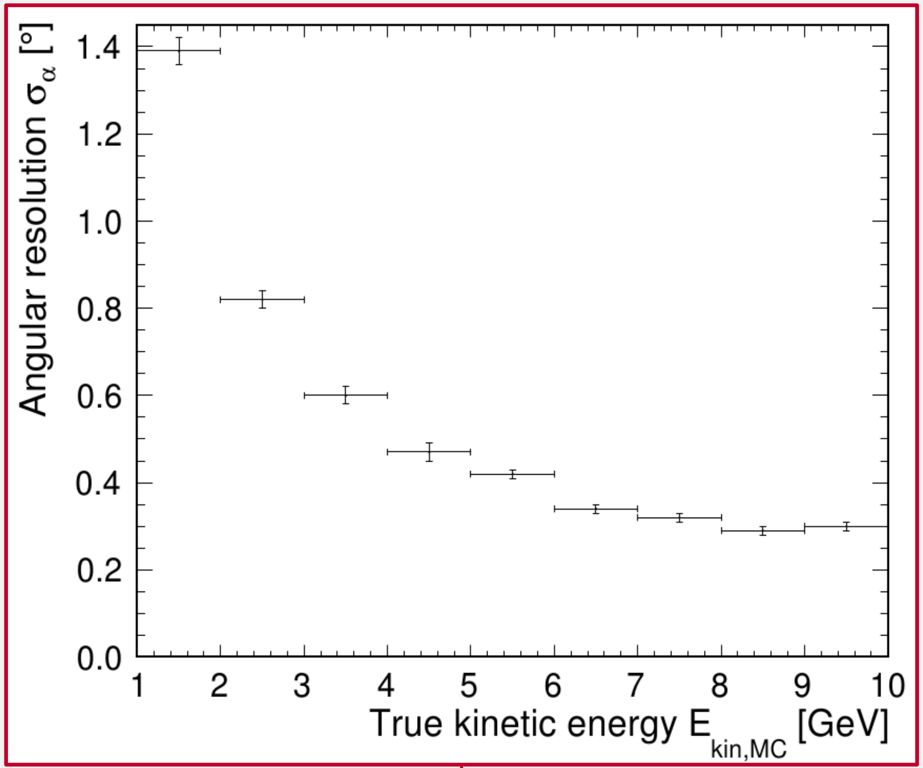
- For simplicity, reconstruction was tested with single muons
- LENA Geant4 detector simulation
- About 12k events in the energy range from 1 to 10 GeV
- Required muon containment in central half of detector (based on MC truth)

  → 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]

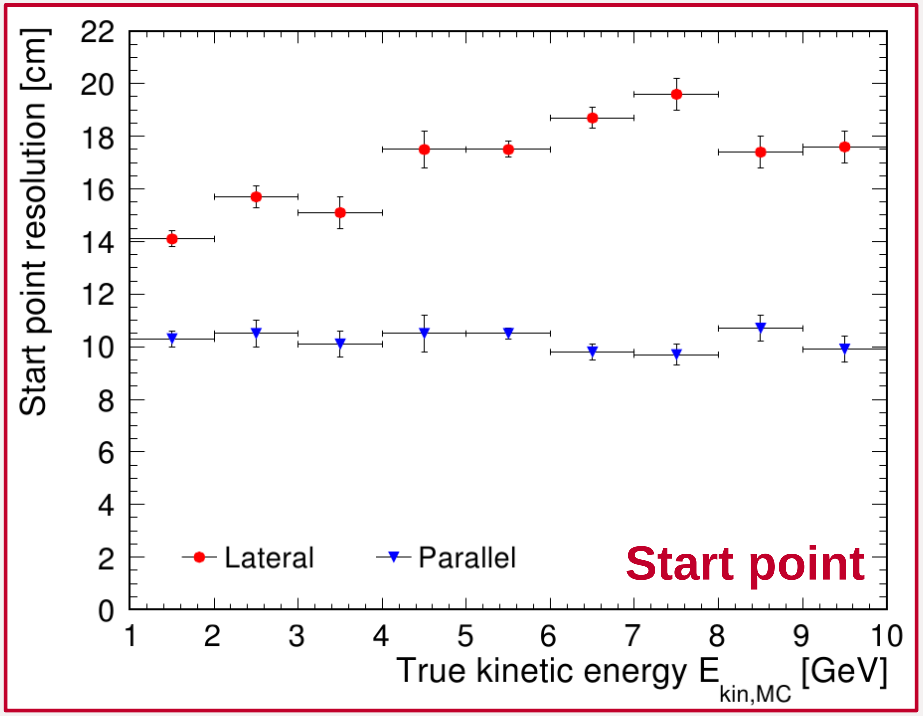
Start Point / End Point Resolution

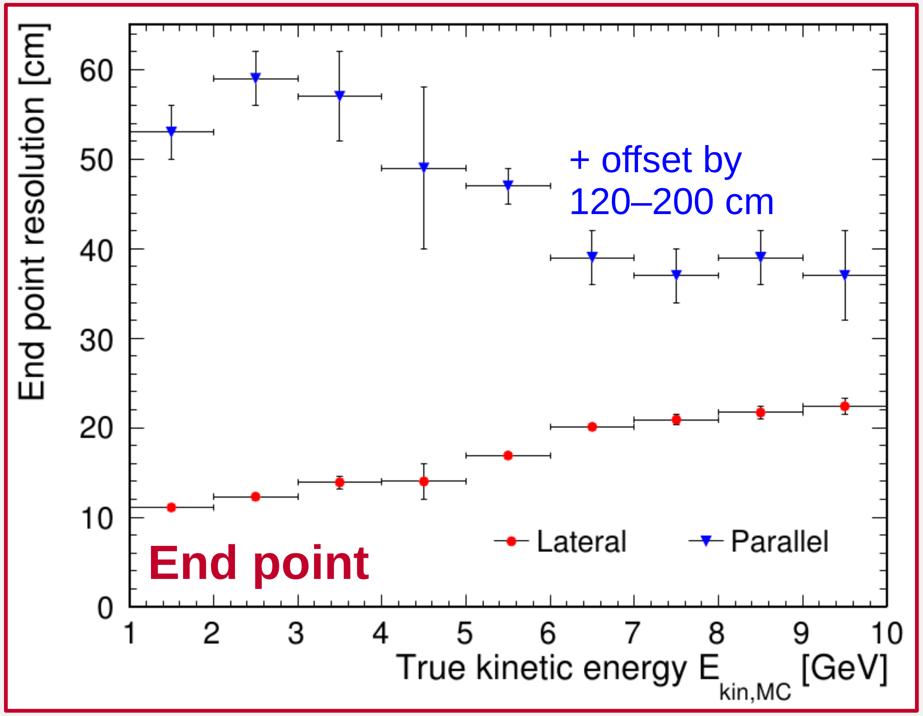
Start point

- Resolution $\leq$ 20 cm in x, y, z
- Total: $\leq$ 30 cm

End point

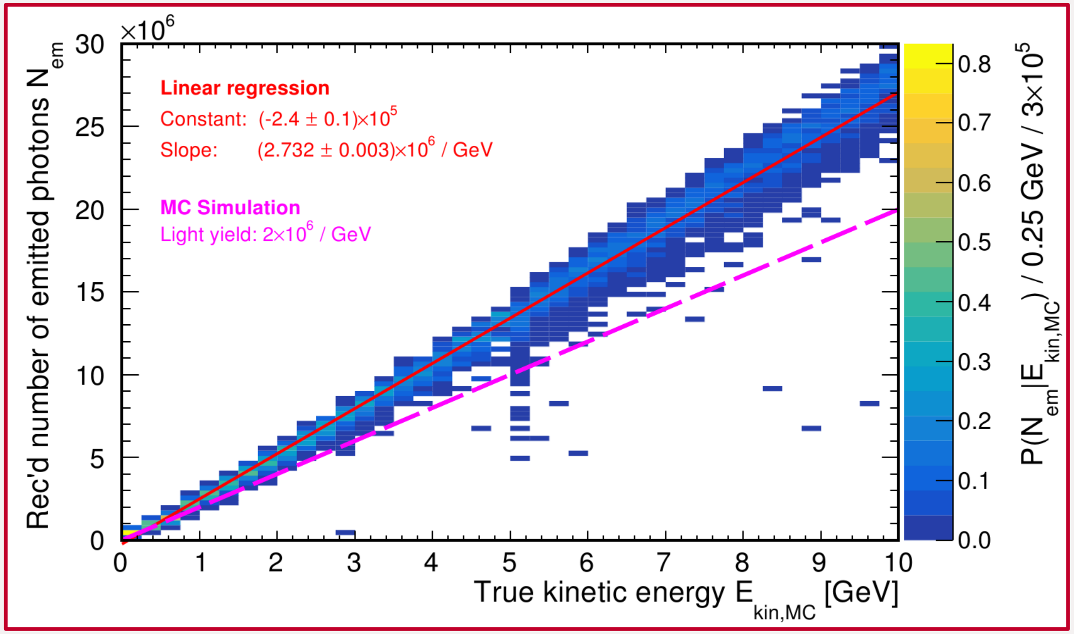
- Systematic offset in parallel direction (from “primary blob“ selection)
- Offset decreases with rising energy



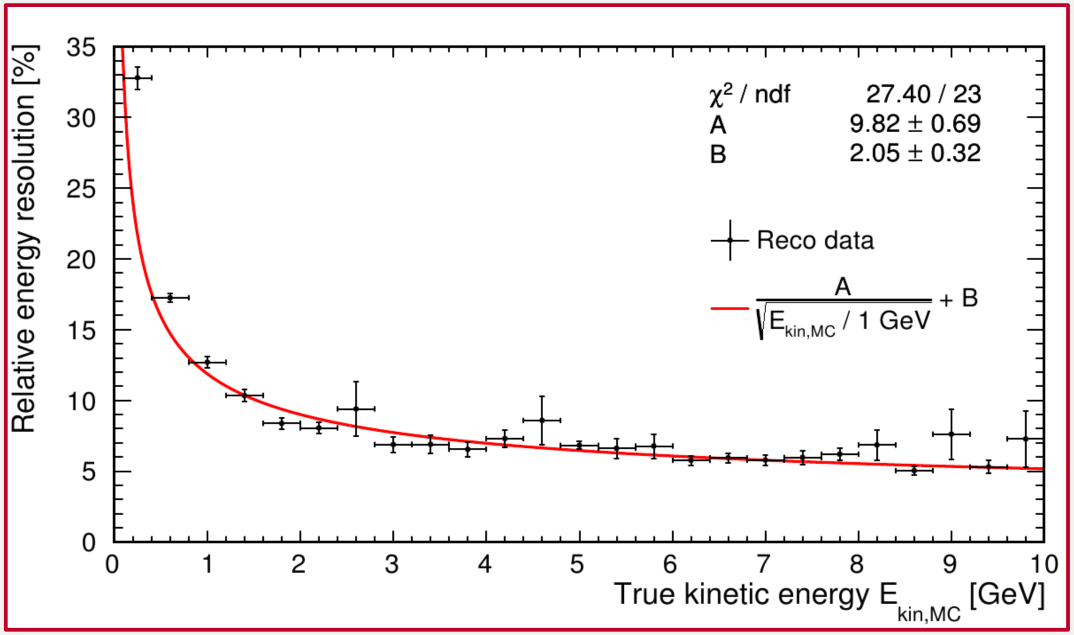


Borexino tracking (inner vessel): ~35 cm lateral [JINST 6 (2011) P05005 / arXiv: 1101.3101]

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

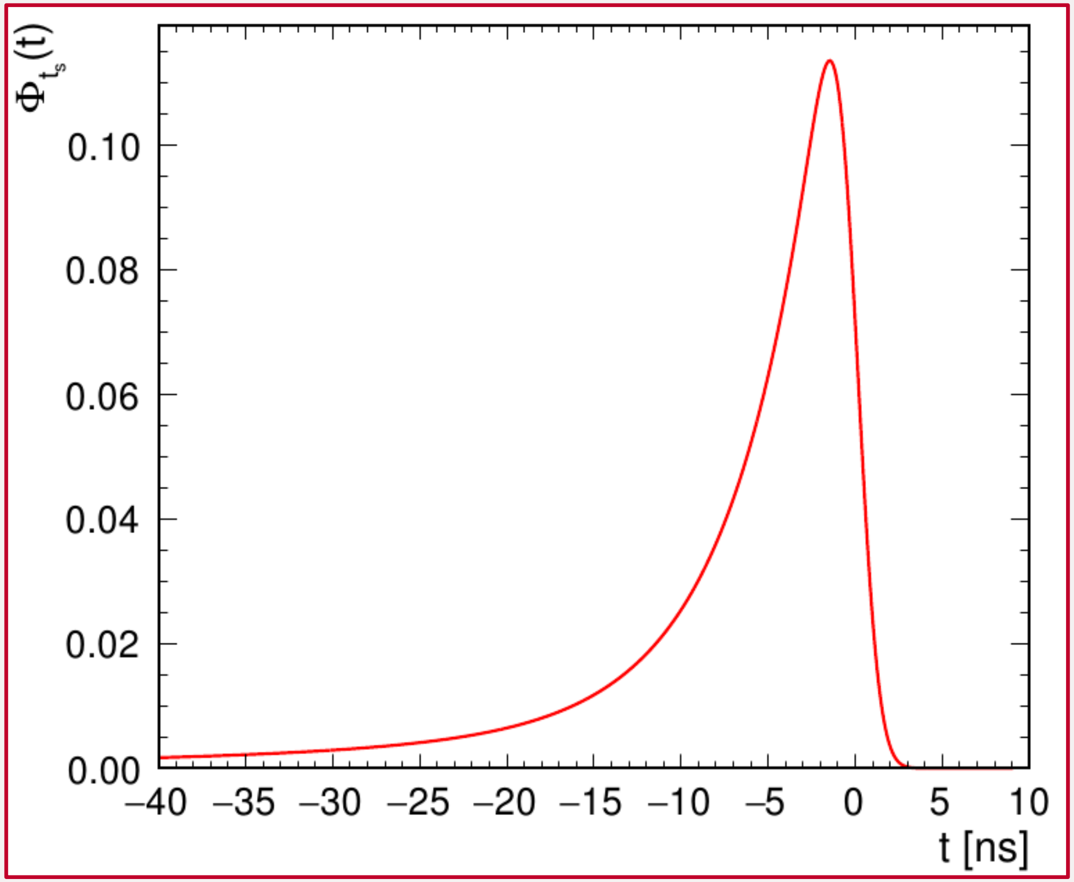


- Relative energy resolution: standard deviation over mean for N_{rec} distribution per energy bin
- In analyzed energy range:

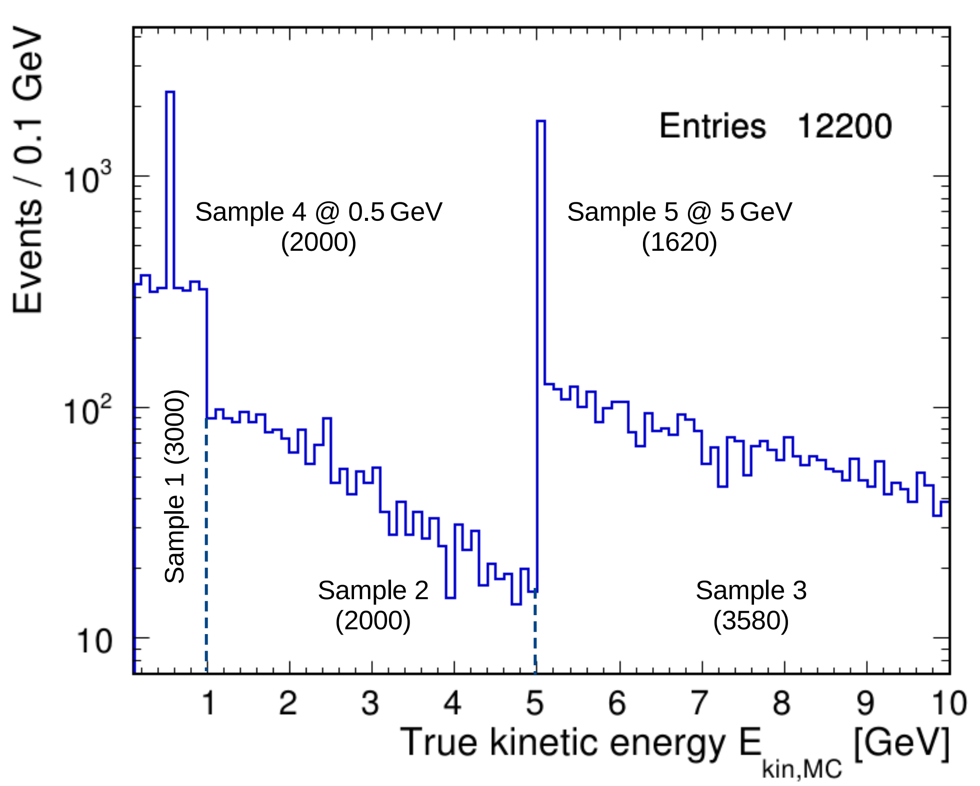
$$\sigma_E / E \approx 10\% \times (E / 1\,\mathrm{GeV})^{1/2} + 2\%$$

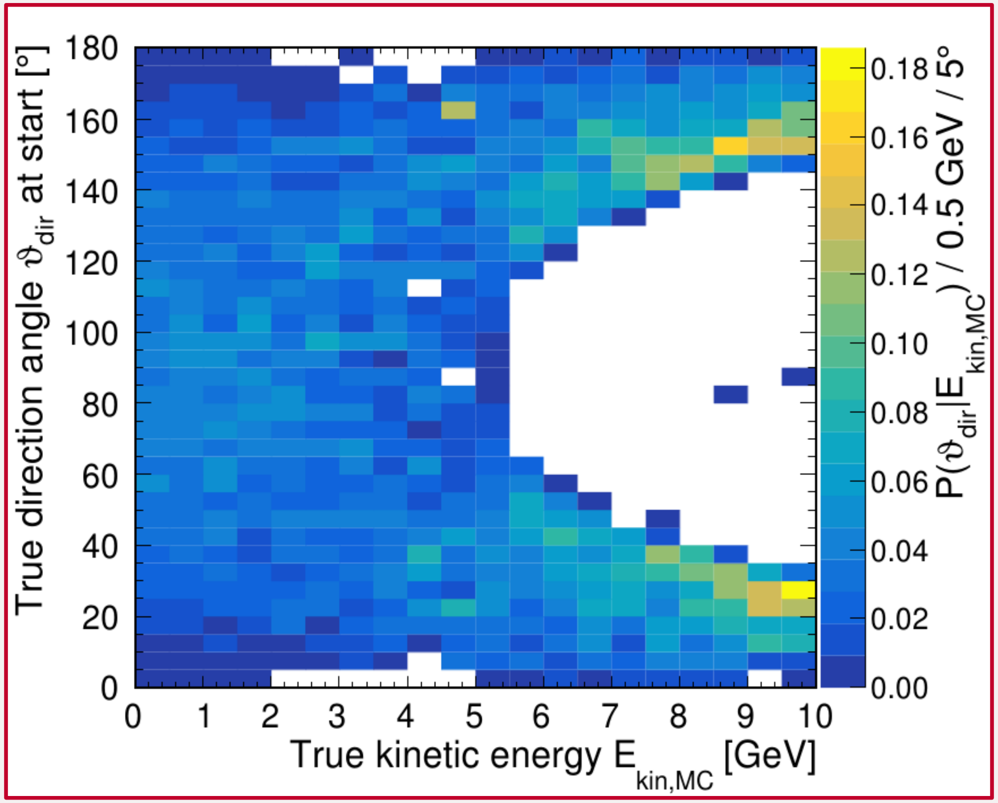
Temporal Smearing PDF

- Convolution of PMT timing PDF – Norm (0, 1 ns) – 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



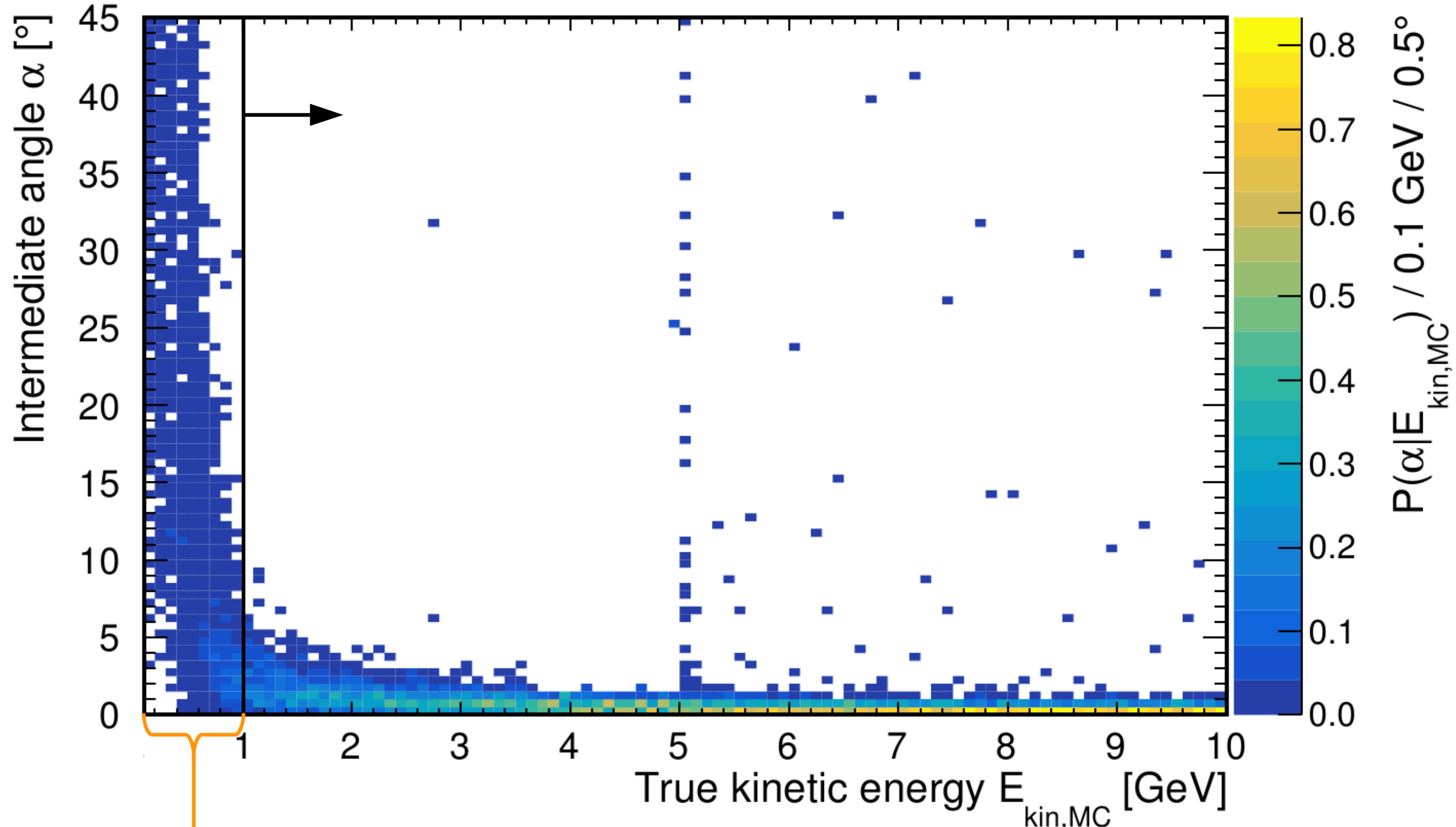
Event Sample





Intermediate Angle

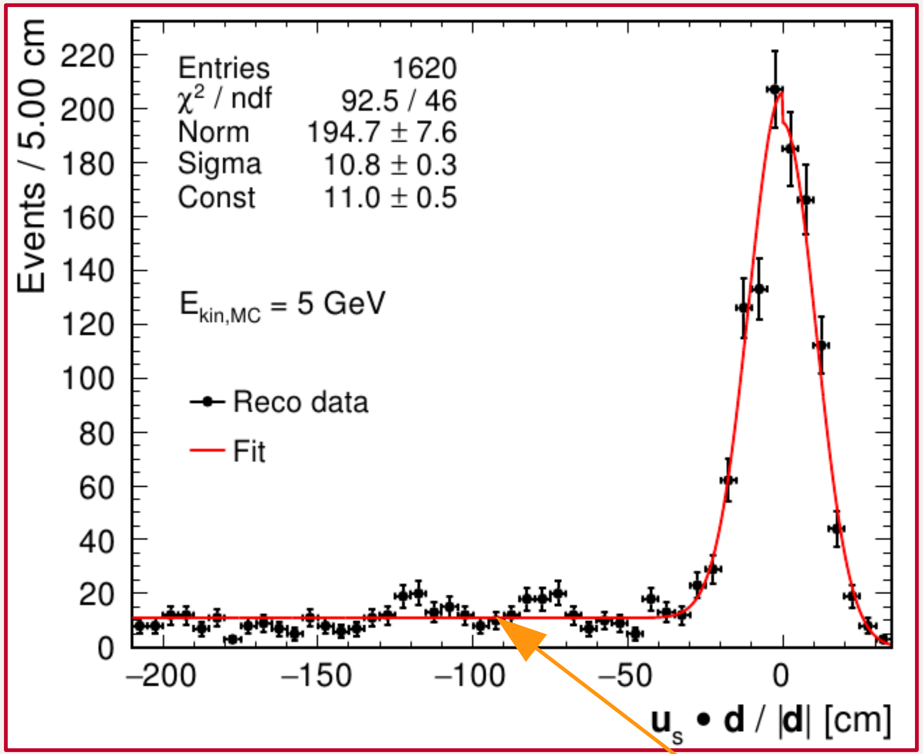
- Angle between reconstructed track line and MC mean direction

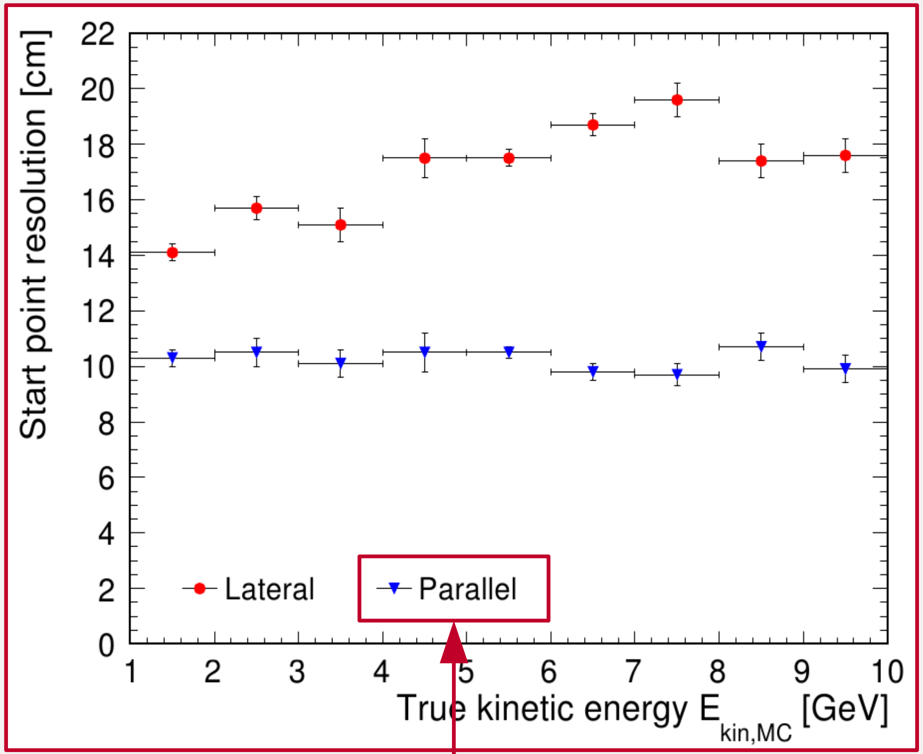


- Tracks too short
- Cells in reconstruction too large
- Random shift of ref. point w.r.t. true start point comparable to blob extension

Start Point Resolution (Parallel)

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



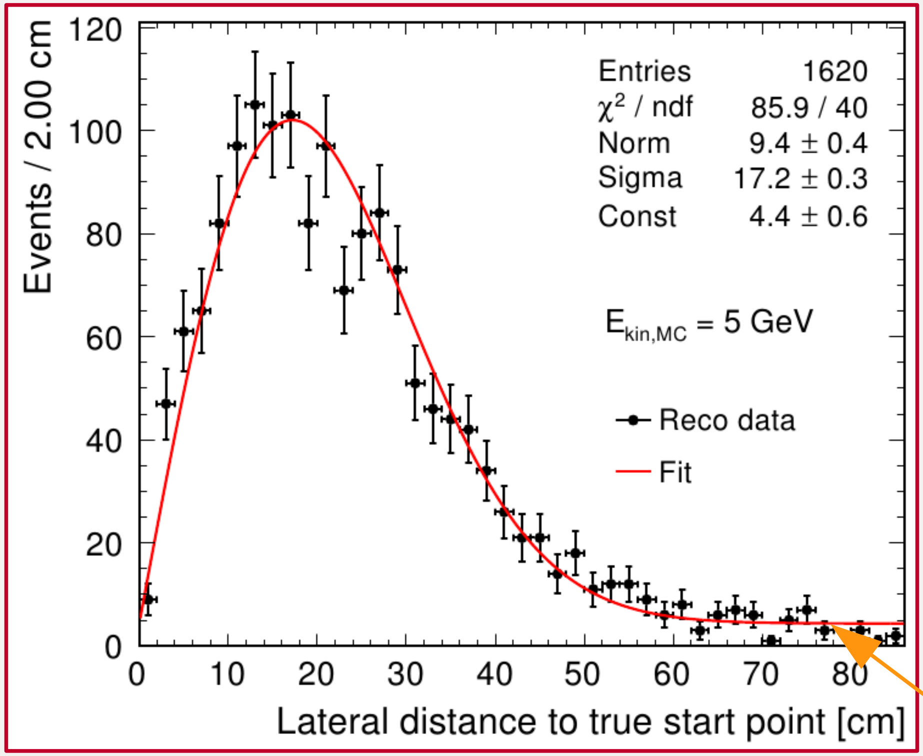


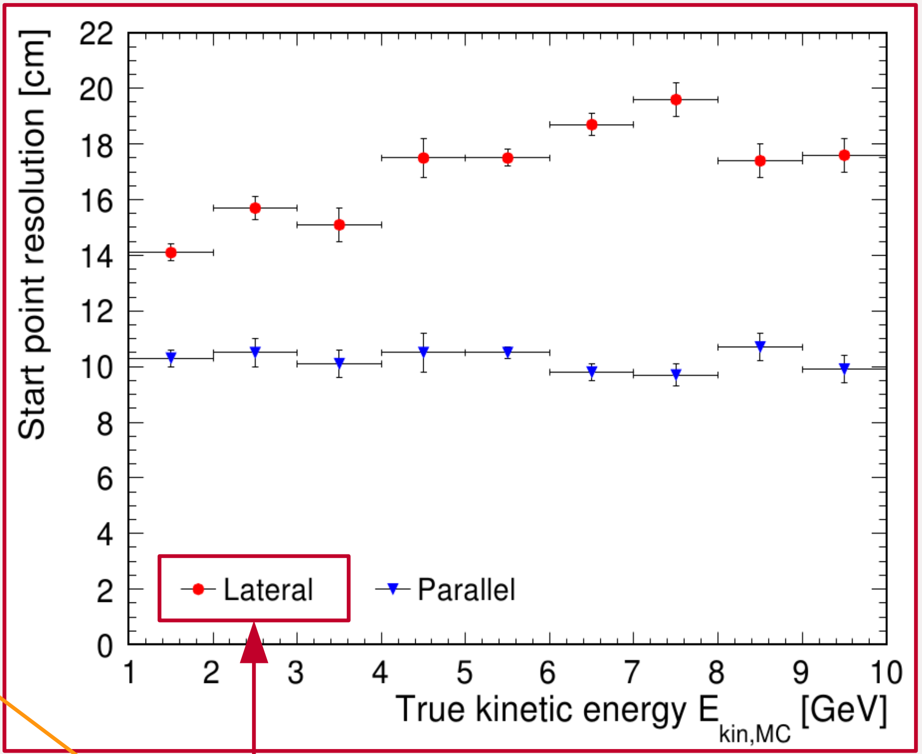
Systematic effects
in start point finding

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)



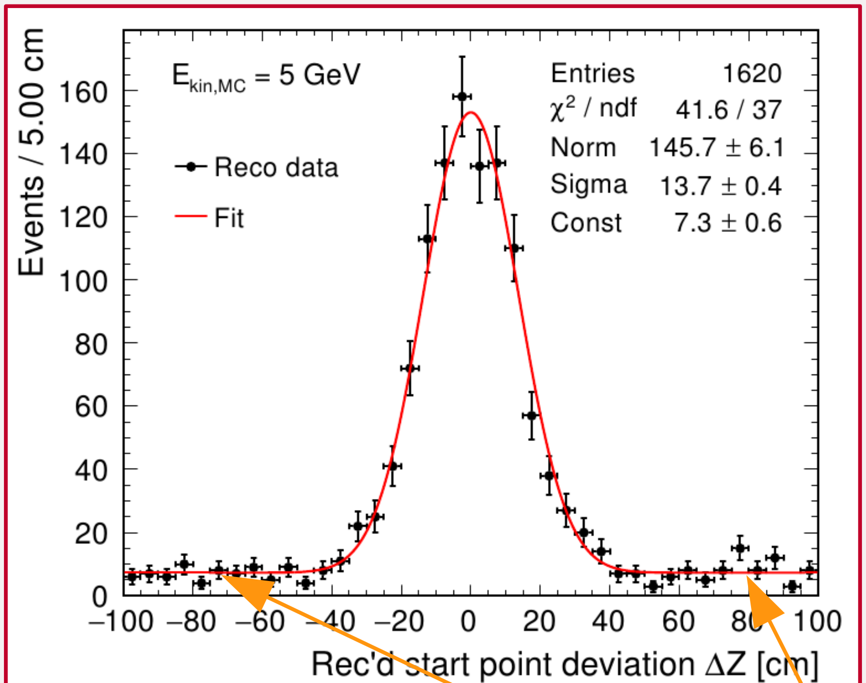


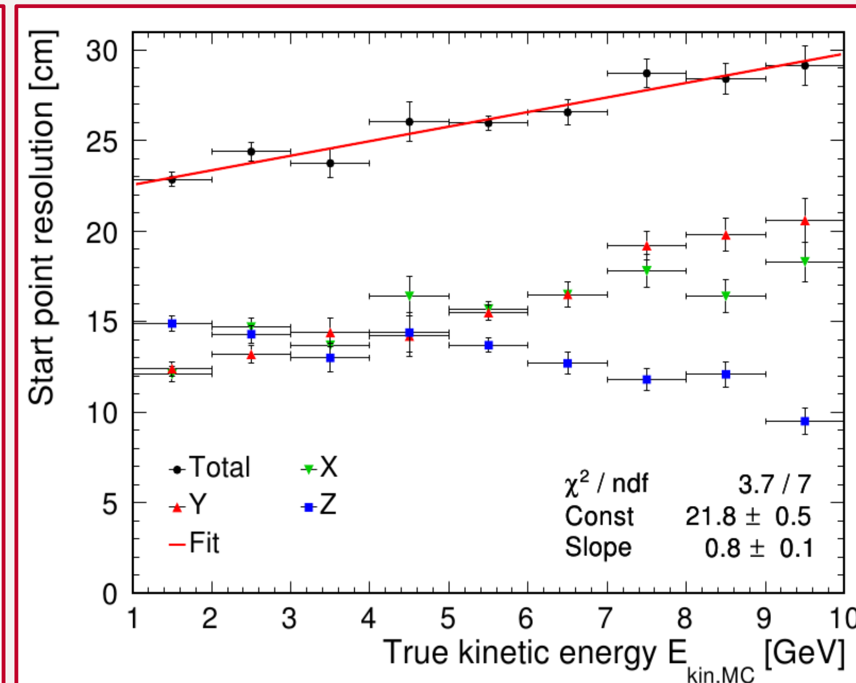
Fit-function:

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

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



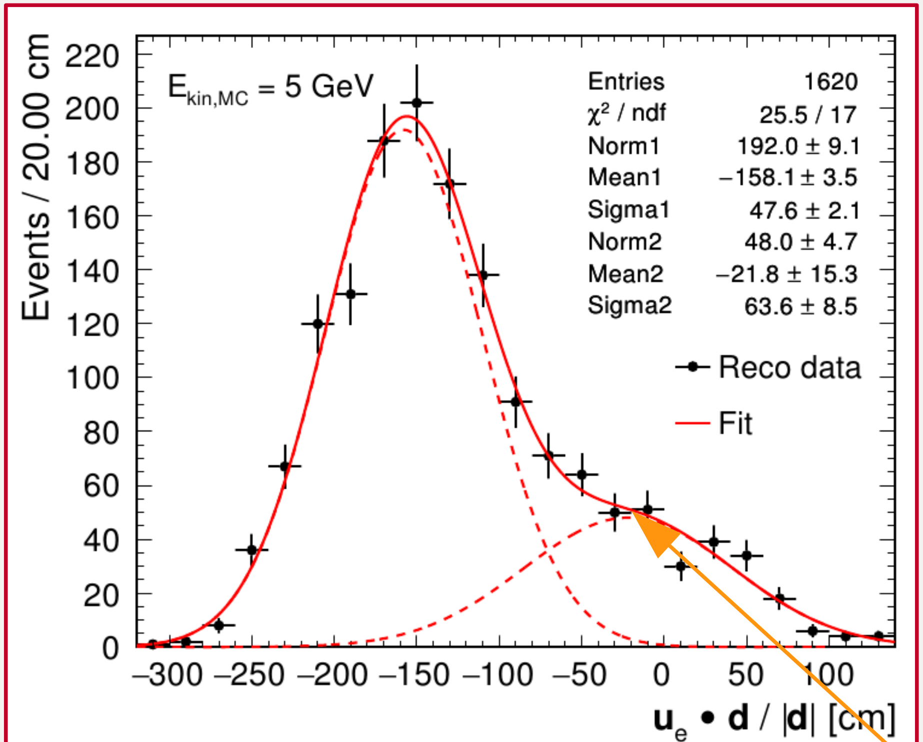


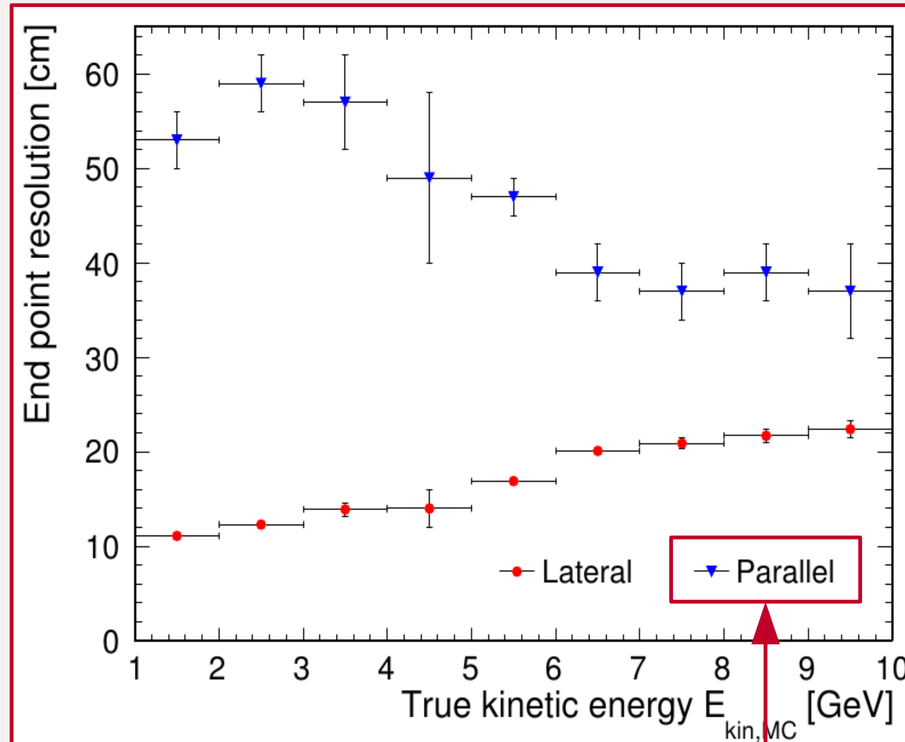
Systematic effects in start point finding

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





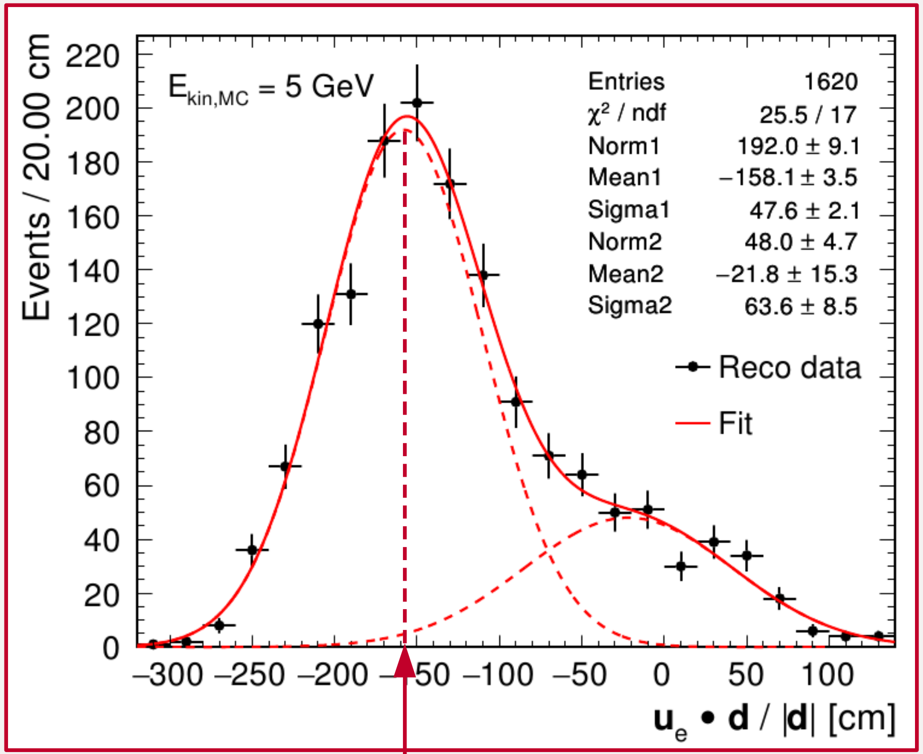
Systematic effects
in end point finding

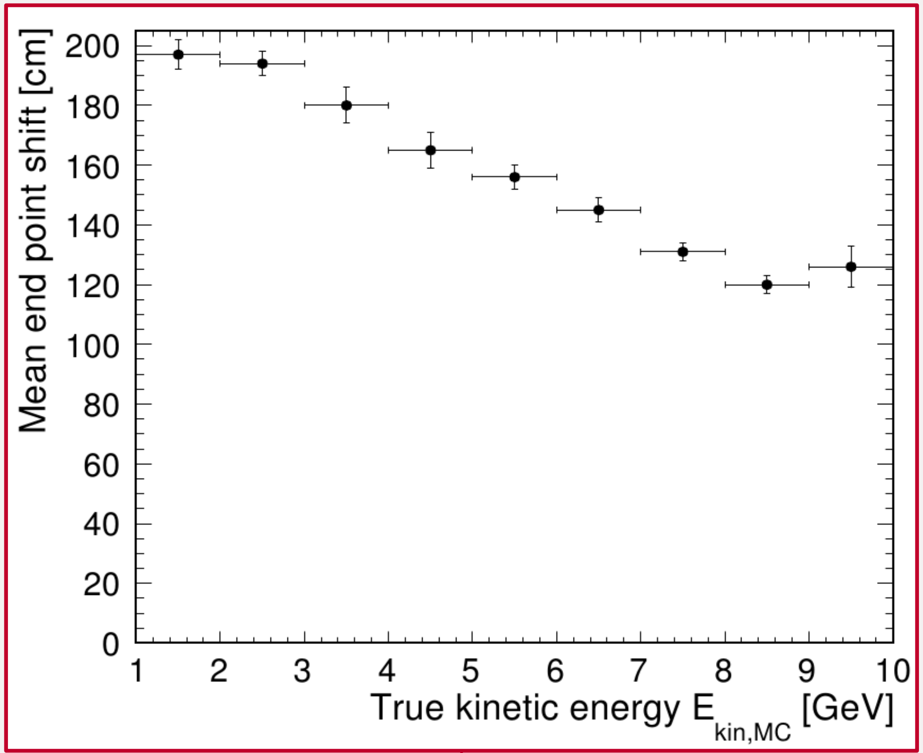
Fit-function:

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

End Point – Mean Parallel Shift

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





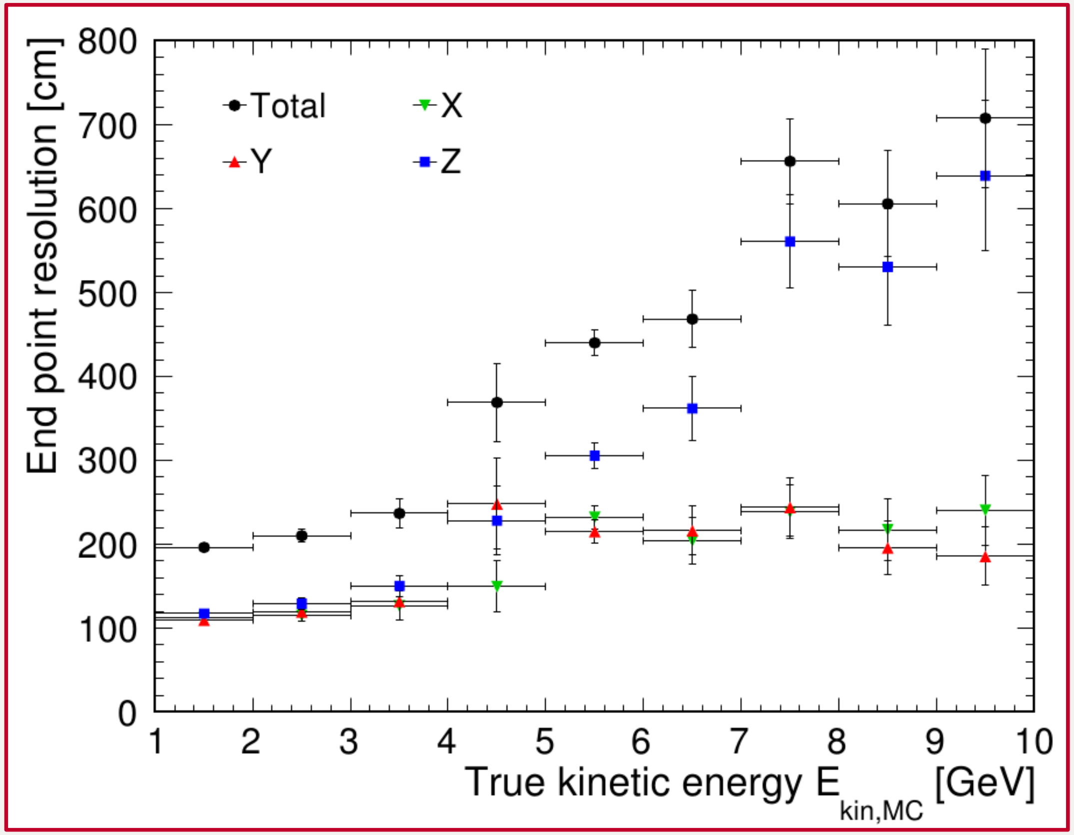
modulus

Fit-function:

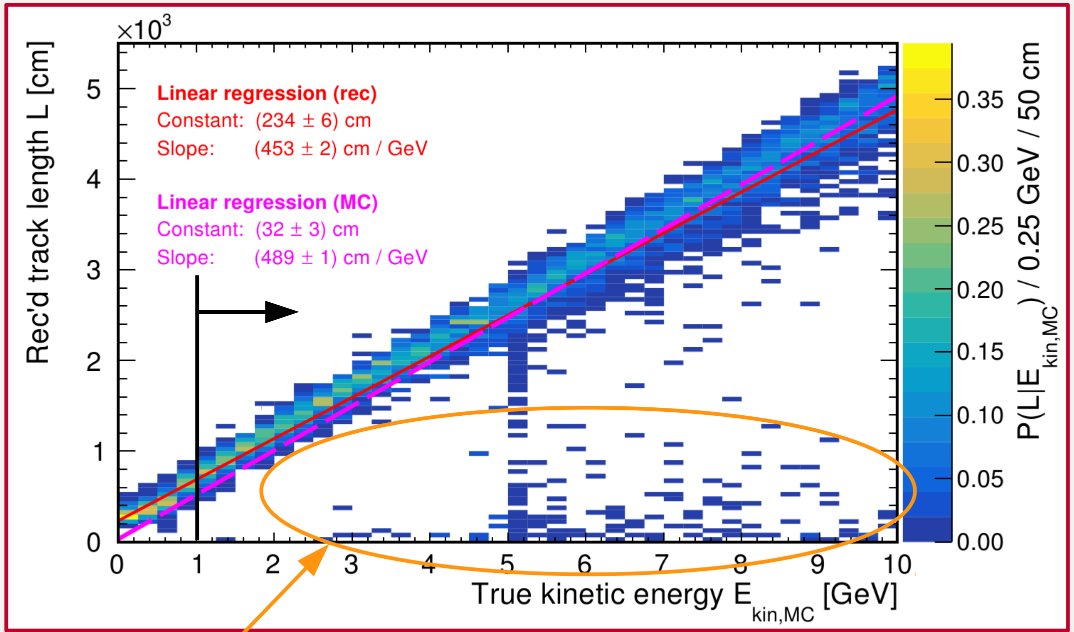
$$F(u_{e,\text{para}}) = A \exp\left(-\frac{(u_{e,\text{para}} - \boxed{\mu_{\text{peak}}})^2}{2\sigma_{\text{peak}}^2}\right) + B \exp\left(-\frac{(u_{e,\text{para}} - \mu_{\text{tail}})^2}{2\sigma_{\text{tail}}^2}\right)$$

End Point Resolution (X, Y, Z)

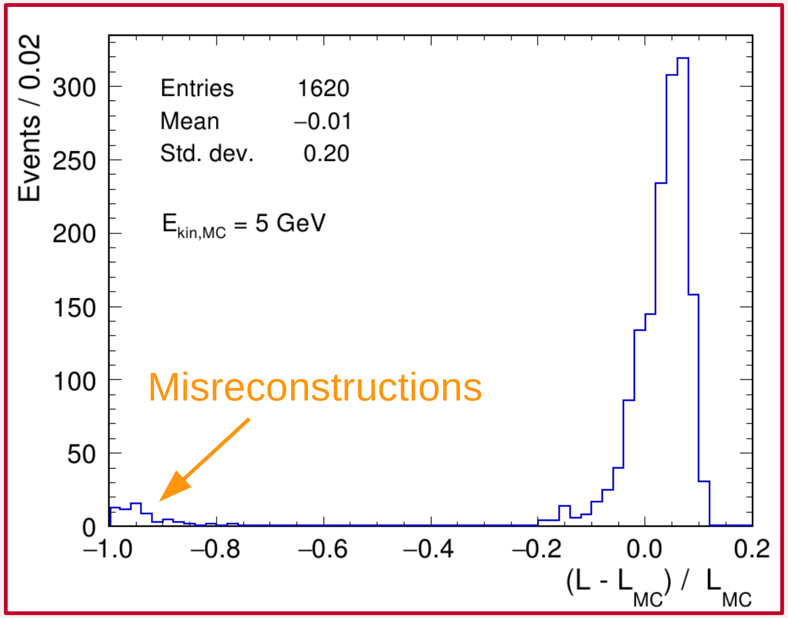
- Look at distance $|\mathbf{u_e}| = (u^2_{e,x} + u^2_{e,y} + u^2_{e,z})^{1/2}$ between true and reconstructed end point in detector coordinates
- Due to the offset, no Gaussian distribution around zero for $u_{e,x}$, $u_{e,y}$ and $u_{e,z}$
- Used sample standard deviation as resolution measure
- “Total“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



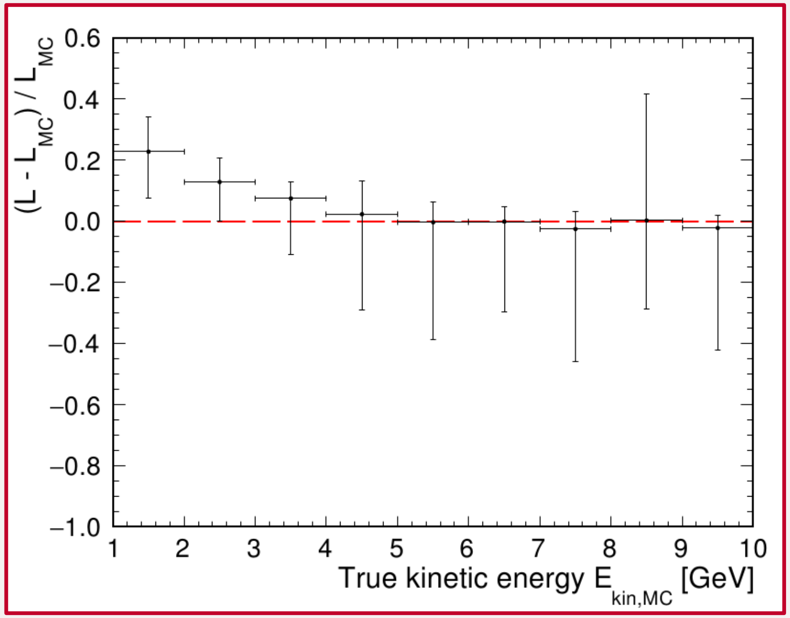
Track Length



Mostly misreconstructions



Mean +
left- and right-sided
standard deviations



Determination of Relative Energy Resolution

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