Reconstruction of faint non-standard model particles in IceCube

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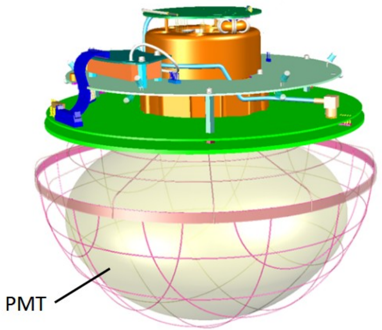
11.10.2023

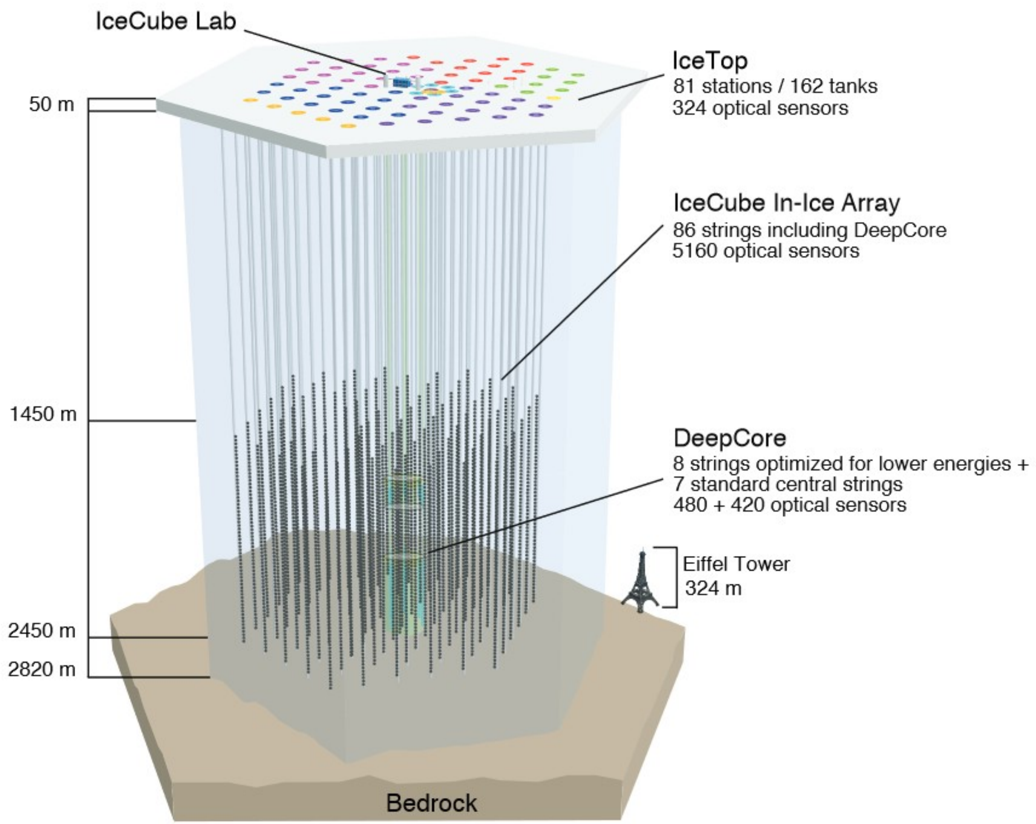
IceCube
Neutrino Observatory

Bergische
Universität
Wuppertal

The IceCube Neutrino Observatory



- Different types of events possible:
  - Track-like events
  - Spherical events, cascades
- Prior to high level analyses events need to be reconstructed, e.g. direction, position, energy



Raw data → Trigger → Cleaning → Recon-struction

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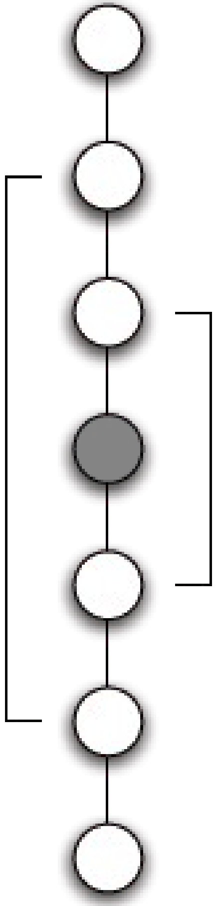
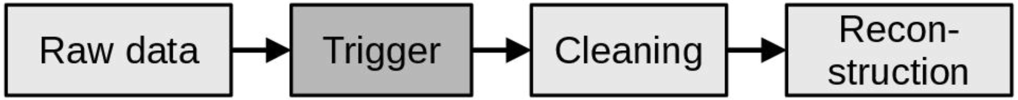
The faint particle trigger (FPT)



- Usual triggers based on local coincidences
- Problematic for search of **faint signals**,
  e.g. low energy events or fractionally charged particles
  → produce **multiple isolated hits**
- Trigger uses isolated hits
- **Will be deployed for IceCube DeepCore in November**
- Looks for **direction and velocity consistent signal-combinations**
- **Existing reconstruction algorithms** also based on local coincidences → **needs to be adjusted**



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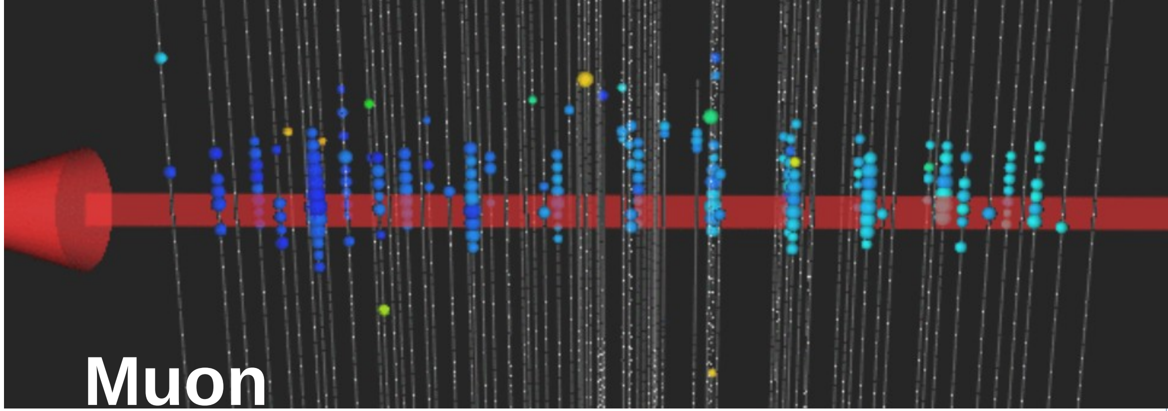
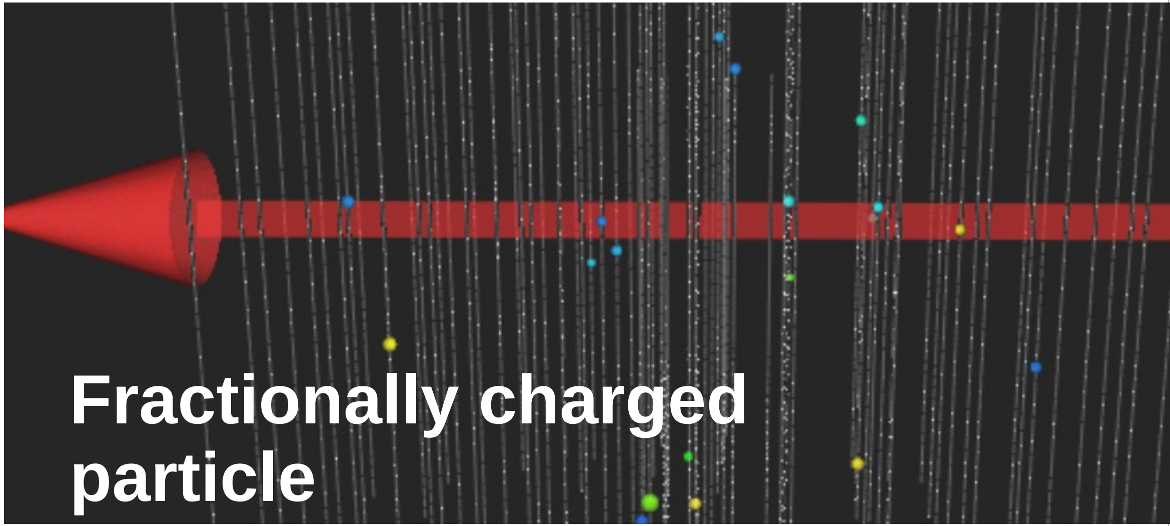
Signal events

- **Simulate** fractionally charged particles
- Charge 1/3 e

→ lower signal-to-noise ratio

- Homogeneous distribution around detector
- Use faint particle trigger on events





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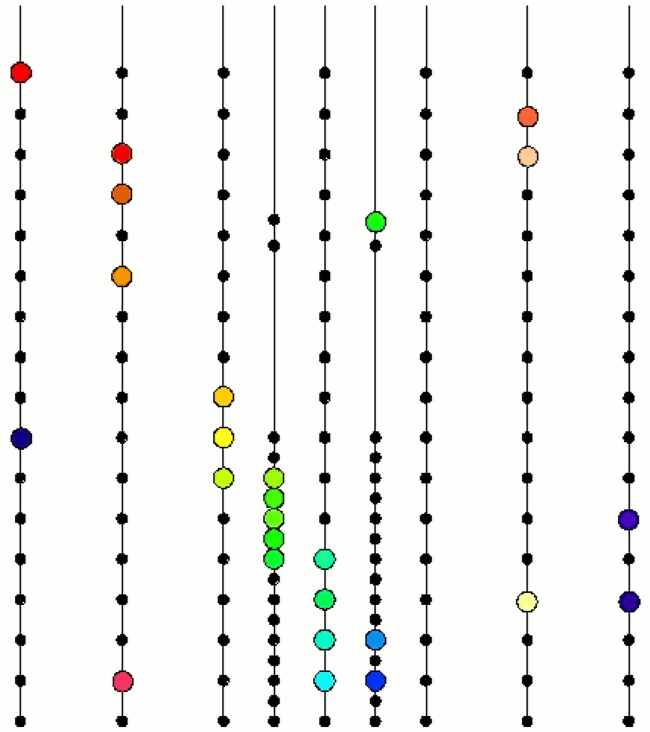
Seeded RT Cleaning

- Standard cleaning algorithm
  → reduce noise before reconstructions
- Use local coincidences as seed
- Look for hit pairs within radius *R* and time *T*
- Neglect other hits
- **Problem: Cleaning based on local coincidences, which are not likely in FPT-triggered events**



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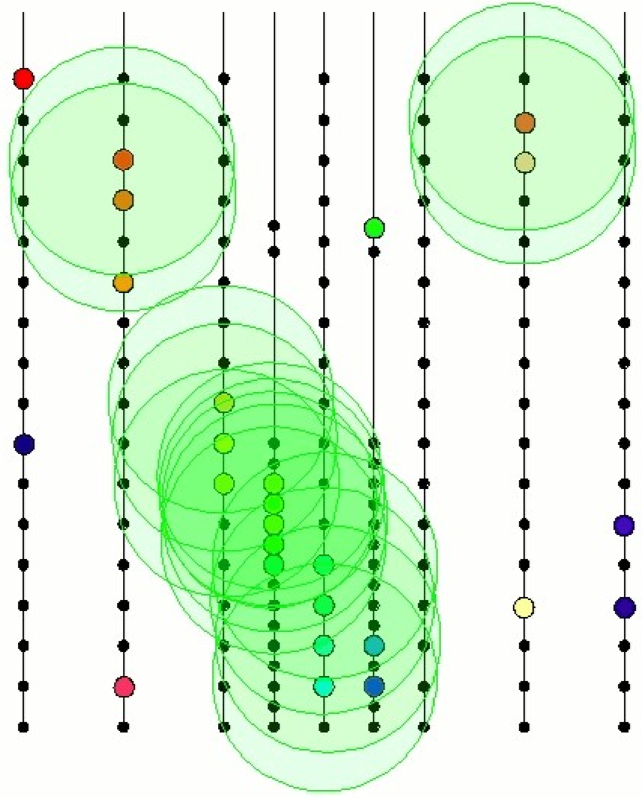
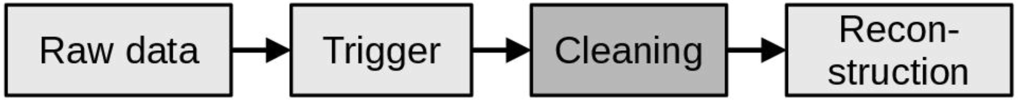
Looking for hits in RT-range of HLC hits ...





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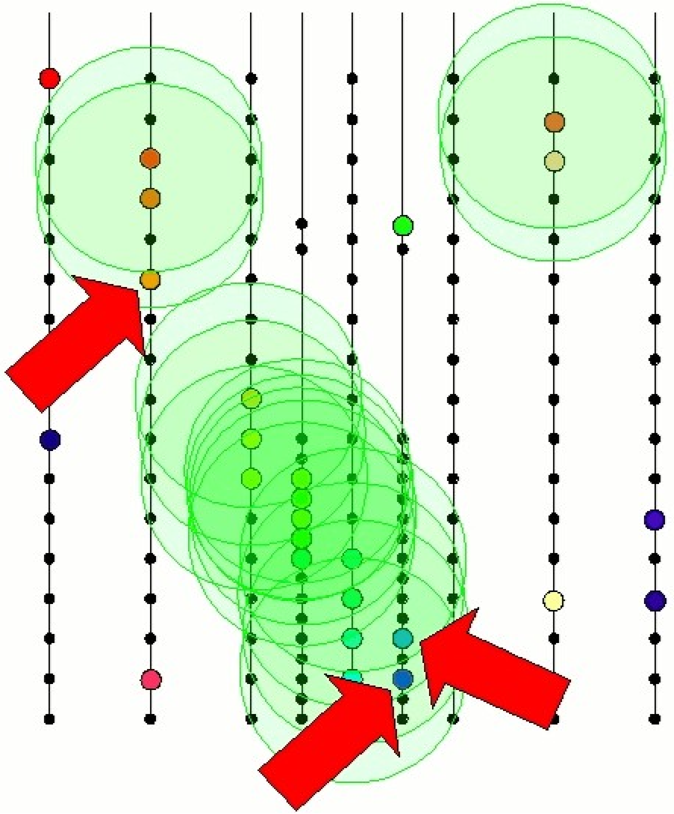
… keep these hits and look for further hits in their RT-range ...



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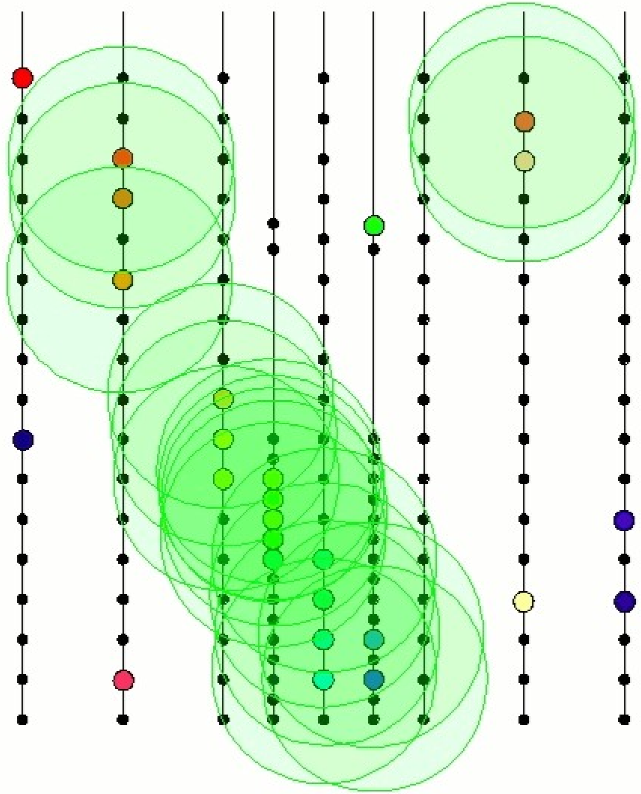

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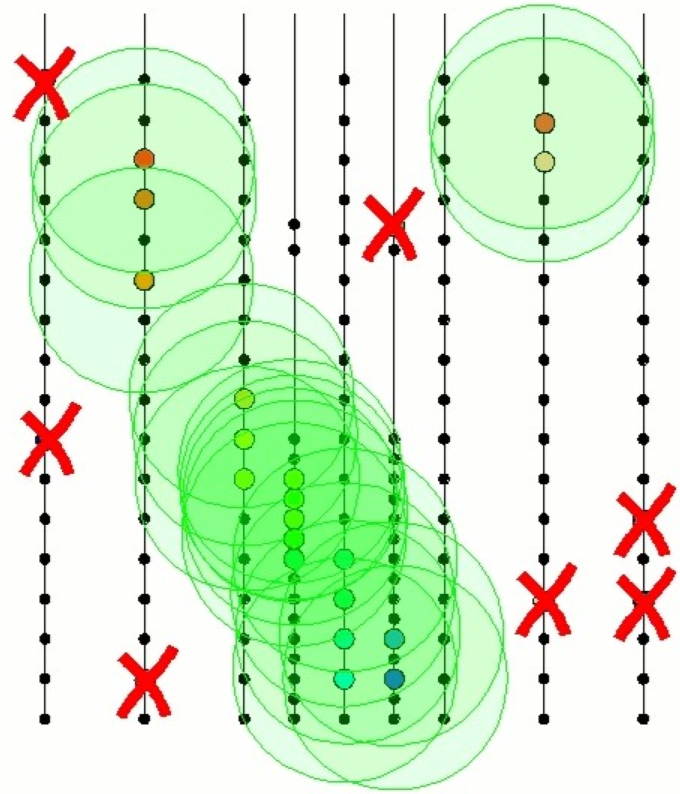
… iterate until there are no more changes.



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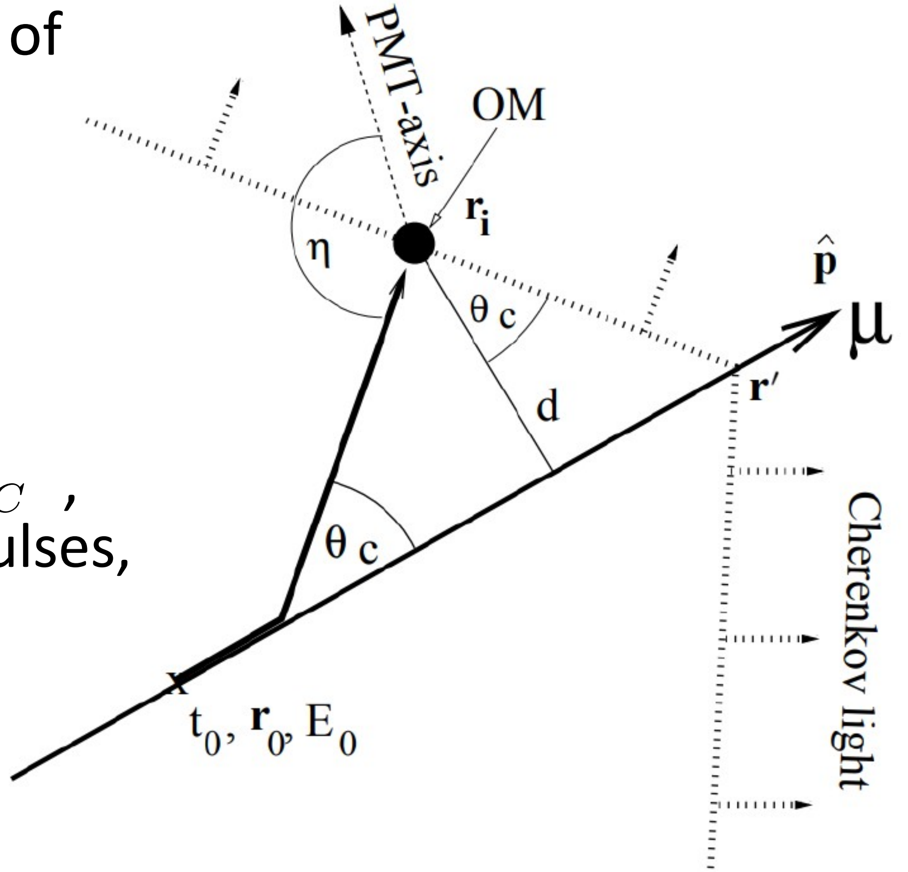
Track reconstruction

- Used as a **basic direction reconstruction** of events
- Use **Line-Fit as seed**, which estimates simple particle track $\vec{r'} = \vec{r} + \vec{v}t$ by assuming perpendicular wavefront
- Improve seed by including sensor-orientation η , Cherenkov-cone θ_C , time-consistency, Multi-Photoelectron pulses, etc.
- Use **angular deviation** $\Delta\Phi$ between reconstructed direction and simulated direction to **check precision of reconstruction**



Source: Van Driessche, Ward: Search for particles with anomalous charge in the IceCube detector, 2019, p. 123

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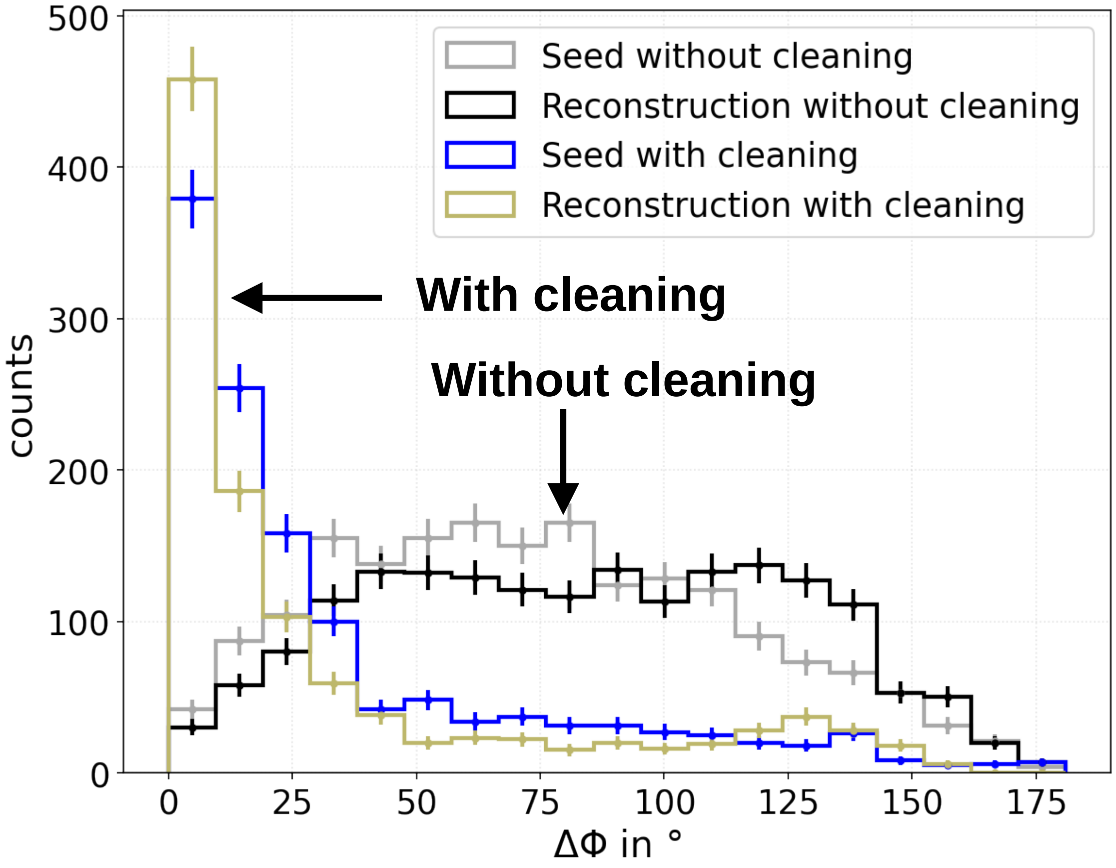
Influence of cleaning (1)

<u>With Cleaning:</u>

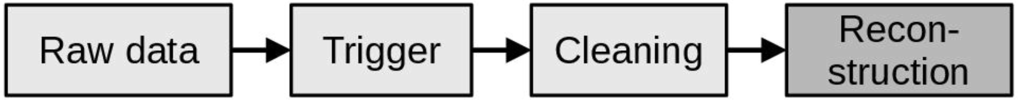
- **~1/3 of events are lost**
- Especially events only triggered by FPT → no local coincidences

<u>Without Cleaning:</u>

- Reconstruction much worse
- Data dominated by noise



Notice: Seed also not precise



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Influence of cleaning (2)

Idea:

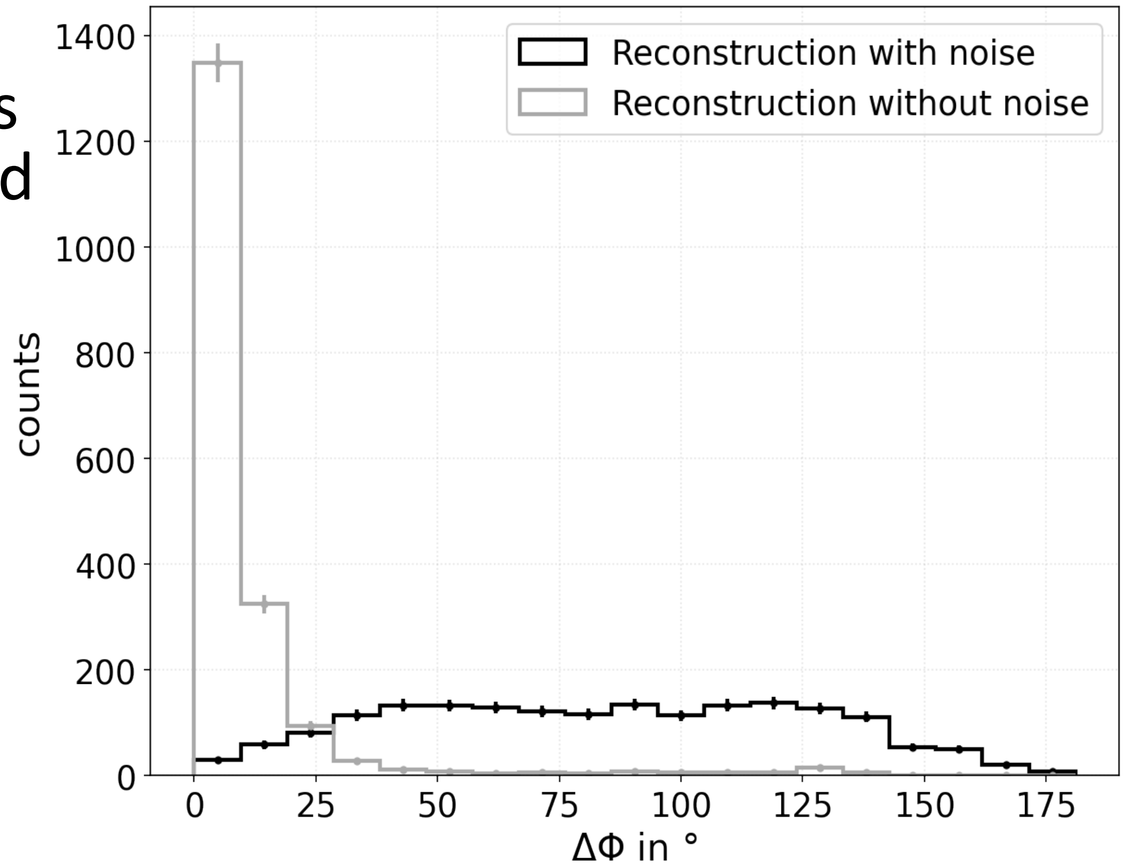
Adjust Cleaning to new events
→ Include isolated hits as seed

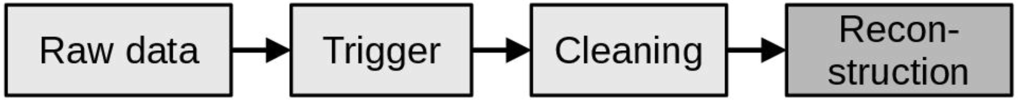
Problem:

Not possible with existing algorithm
→ work in progress

Goal:

Reduce noise hits





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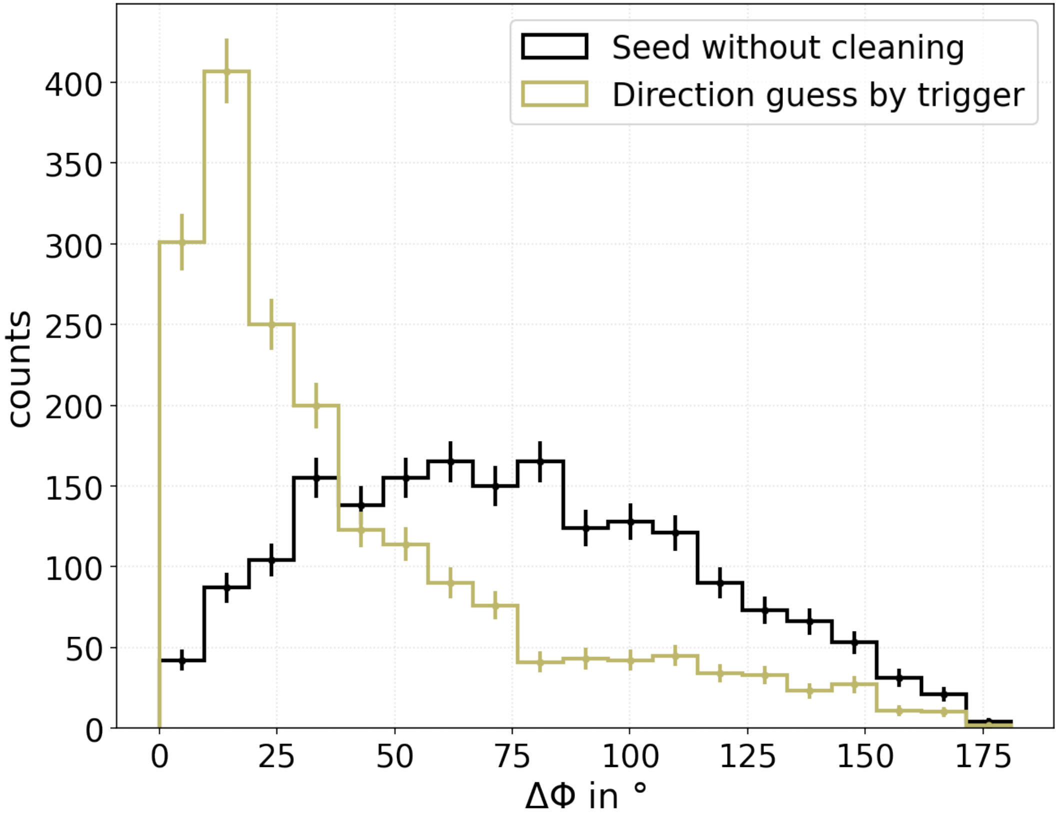
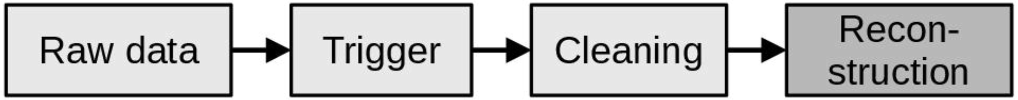
Direction guess by trigger (1)

- Faint particle trigger able to give first direction guess
- Looks at clustering of hit pairs in zenith and azimuth
- Better as seed which is used without the cleaning
- Can maybe be used as seed for reconstruction





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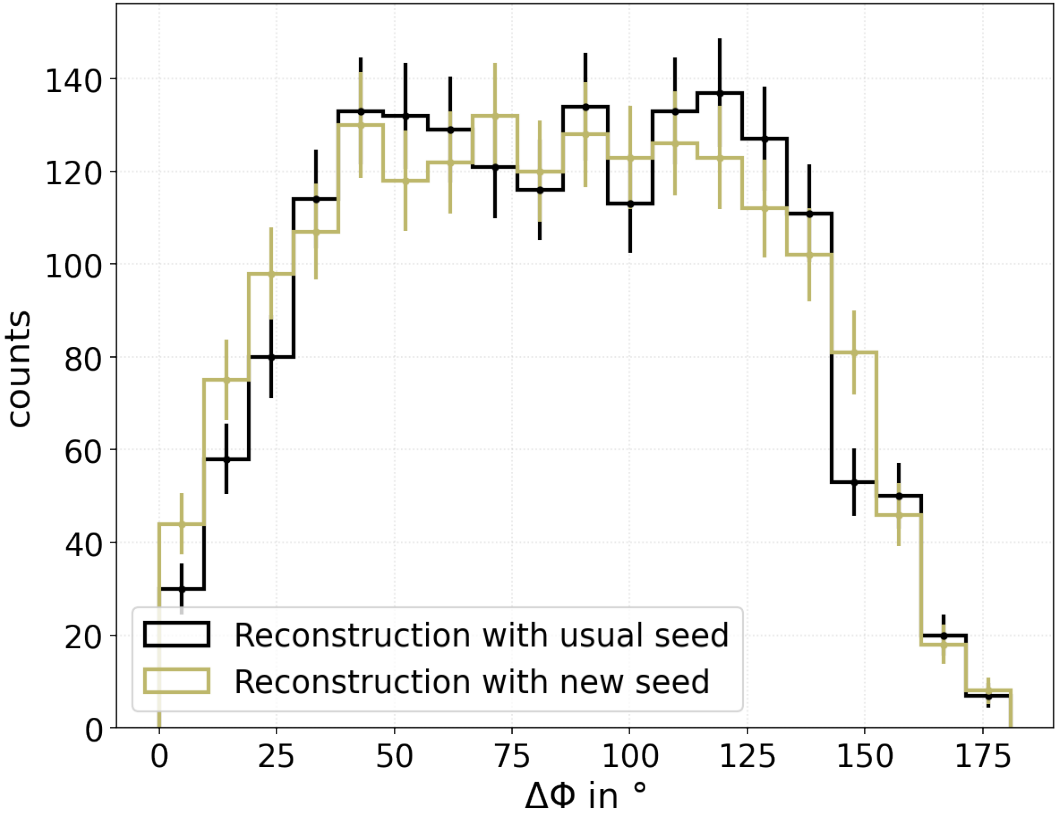
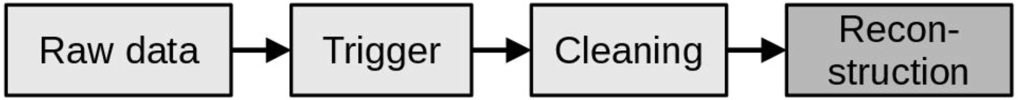
Direction guess by trigger (2)

- Use direction guess as seed for reconstruction
- Gives small improvement
- Reconstruction still bad

  → still influenced by noise





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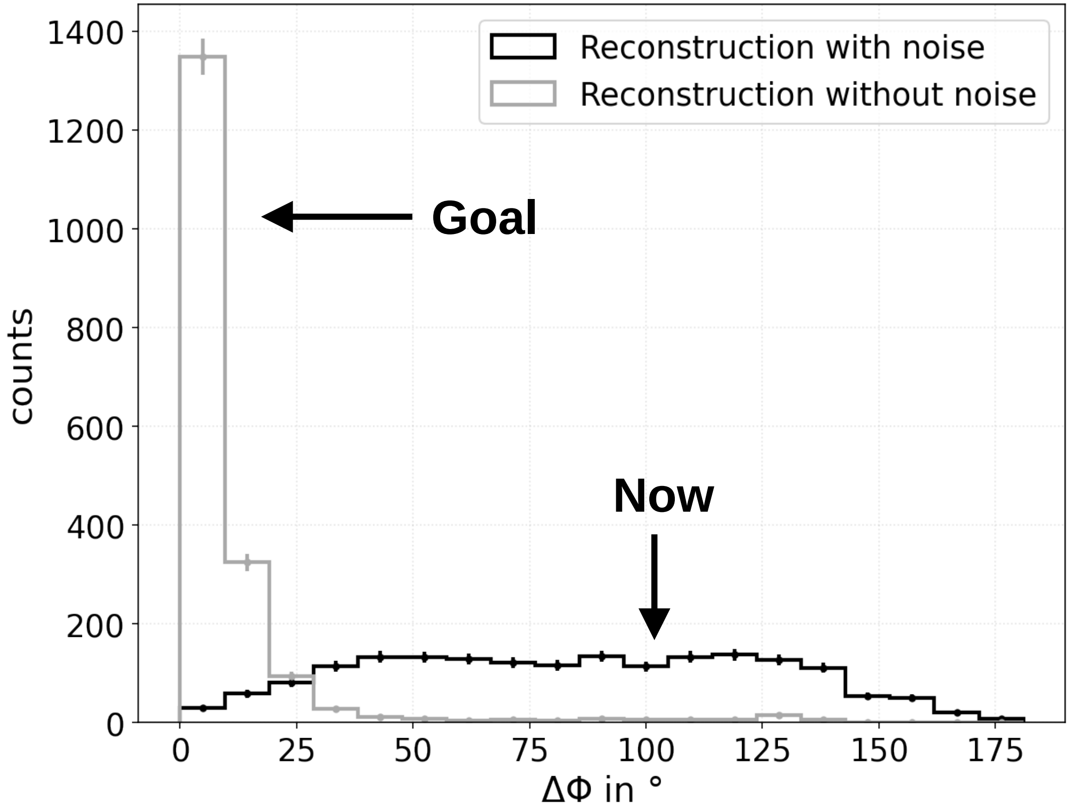
Conclusion and outlook

- Adjustment of existing reconstruction algorithms needed
  → especially cleaning
- Maybe more information from trigger can be used as seed
- Check energy reconstruction
- Goal: Implement adjustments into standard processing pipeline
  so that events by new trigger can be used for analysis
- Later: Reconstruction with graph neural network for comparison



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Back-Up

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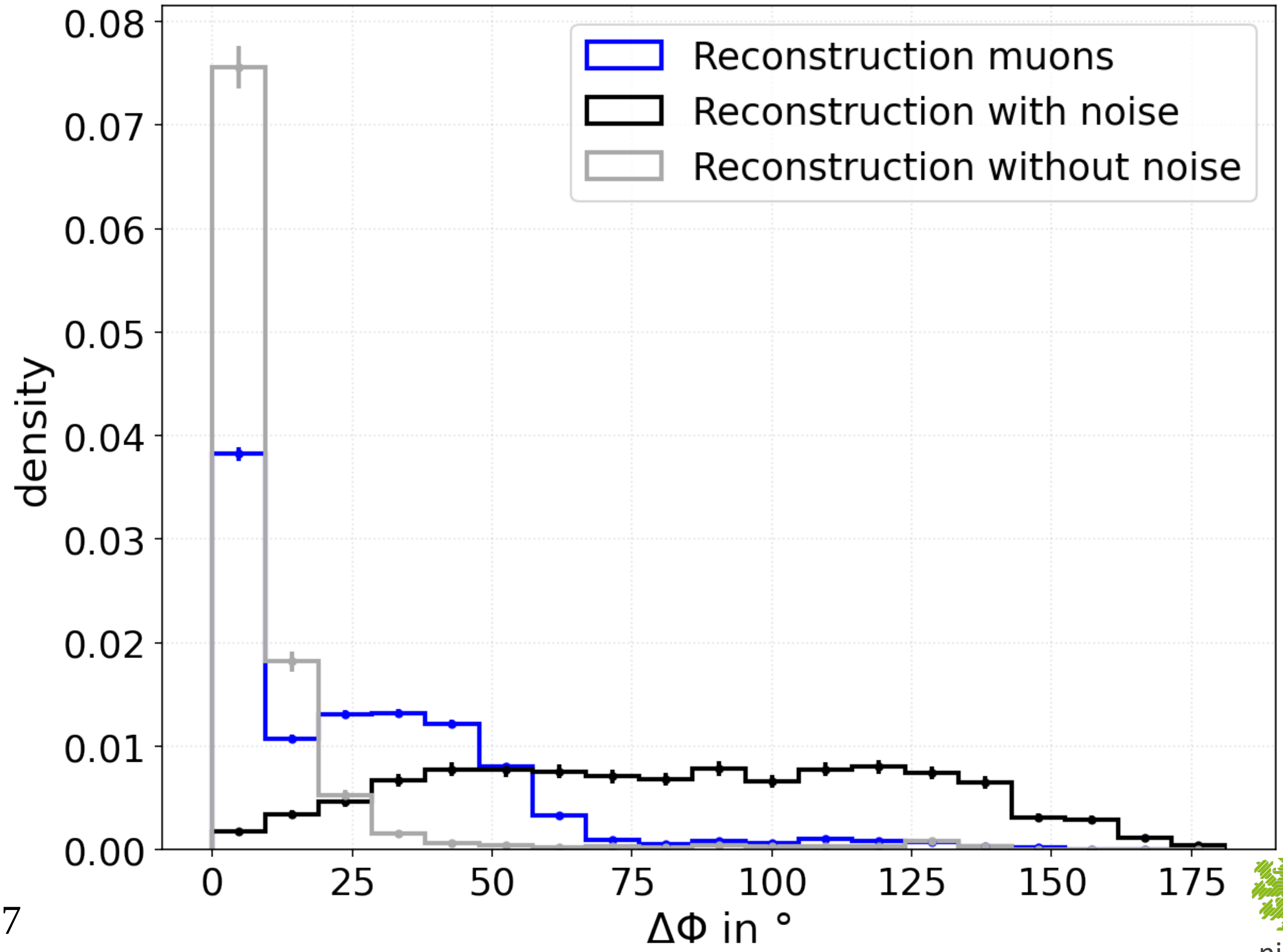

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Line-Fit

- Estimate simple particle track $\vec{r'} = \vec{r} + \vec{v}t$
- Assumes perpendicular wavefront traveling with particle
- Get analytical solutions for *r* and *v* by minimizing

$$S(\vec{r},\vec{v}) = \sum_{i=1}^{N_{hit}} \rho^2 = \sum_{i=1}^{N_{hit}} (\vec{r_i} - \vec{r'})^2 = \sum_{i=1}^{N_{hit}} (\vec{r_i} - \vec{r} - \vec{v}t_i)^2$$

- N_{hit} - number of hit modules
- Analytical solution:

$$\vec{r} = \langle \vec{r_i} \rangle - \vec{v}\langle t_i \rangle \qquad \vec{v} = \frac{\langle \vec{r_i} t_i \rangle - \langle \vec{r_i} \rangle \langle t_i \rangle}{\langle t_i^2 \rangle - \langle t_i \rangle^2}$$

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Improved Line-Fit

- Line-Fit doesn't account for the Cherenkov profile, scattering effects and noise hits which can occur far from the track
- Can improve accuracy by removing scattered hits with simple filter
- Algorithm looks for each hit h_i at all hits within neighborhood of radius μ and if there is an earlier hit in this neighborhood then h_i is considered a scattered hit
- Calculate track by minimizing $$\sum_{i=1}^{N_{hit}} \phi(\rho) = \sum_{i=1}^{N_{hit}} \phi(|\vec{r_i} - \vec{r'}|)$$

  with $$\phi(\rho) \equiv \begin{cases} \rho^2 & \text{if } \rho < \mu \\ \mu\,(2\rho - \mu) & \text{if } \rho \geq \mu \end{cases}$$

- Used as seed for following reconstructions

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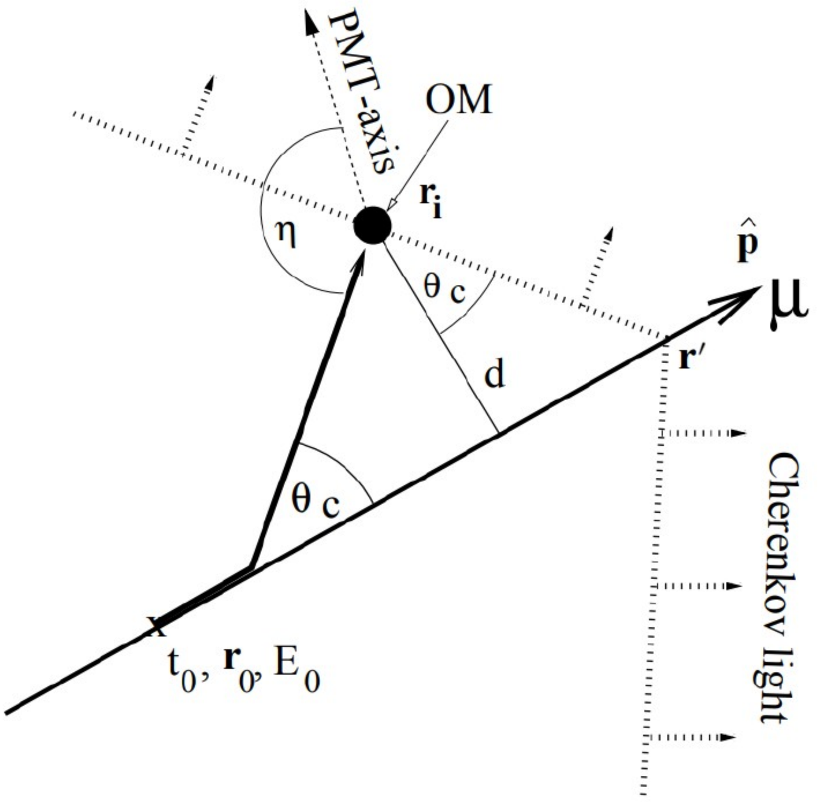
SPE Fit

- Uses Line-Fit as a seed for reconstruction
- Takes Cherenkov cone into account as well as time smearing effects due to noise effects, PMT jitter, light from secondary interactions, DOM orientation, etc.
- Initial particle position and direction found by minimizing likelihood and iterating a couple of times → global maximum
- Single PhotoElectron (SPE) fit



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MPE Fit

- Multi-PhotoElectron (MPE) fit
- Takes into account that only first pulse is recorded if multiple photons hit module in a short period of time
- Early photons scattered less in the ice
- For this likelihood function is adjusted by replacing single photon p.d.f.

- General comment: SPE-Fit and MPE-Fit in Offline Filter are normally only activated if certain filters were passed (muon, deepcore, highQ, etc.)

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Calculation of angular diviations

- From all fits as well from the original simulated particles one gets a zenith (ϑ) and azimuth (ϕ) angle
- Convert angles into unit vector with cartesian coordinates
- Calculate angle between different unit vectors

$$x = \sin(\vartheta)\cos(\phi)$$
$$y = \sin(\vartheta)\sin(\phi)$$
$$z = \cos(\vartheta)$$

$$\alpha = \arccos\left(\frac{\vec{a}\cdot\vec{b}}{|\vec{a}||\vec{b}|}\right)$$

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Seeded RT Cleaning

- Cleaning algorithm to reduce noise&outliers
- Use a subgroup of all hits as seeds → HLC-hits as standards
- For each seed hit look for hits within a radius R and time distance T → add them to the seed list
- Standard definitions: R=150 m, T=1000 ns
- Iterate this multiple times
- Remove other hits

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