Track Reconstruction in IceCube

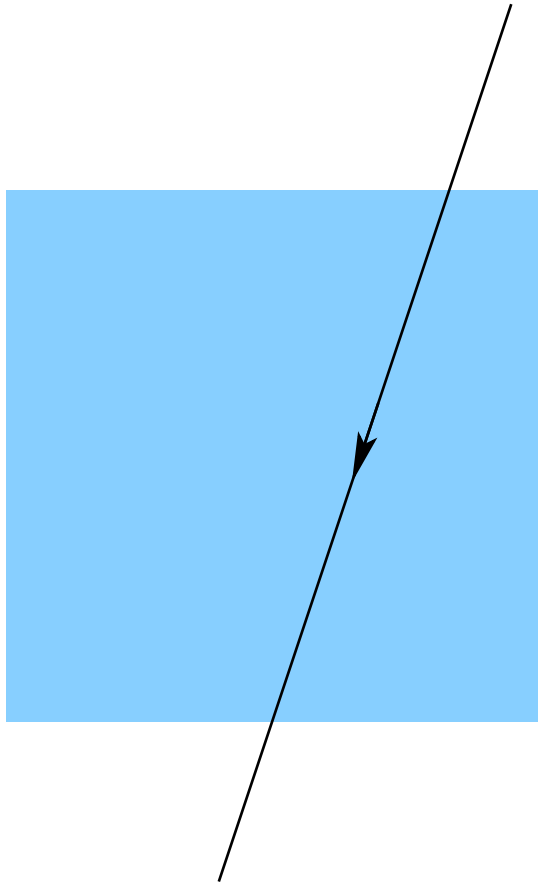
David J. Boersma

The IceCube Project

MANTS 2009, September 26

Outline

Event Types (1): single muon



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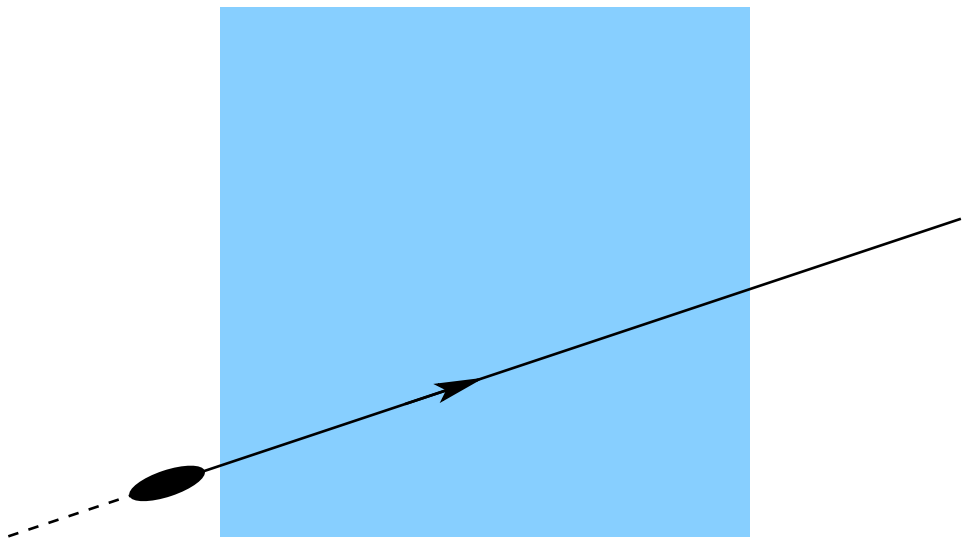

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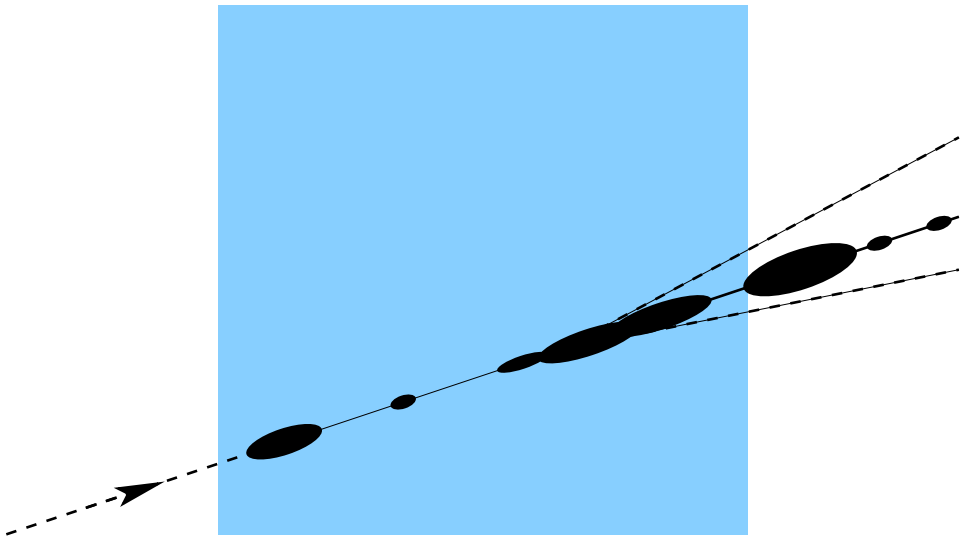

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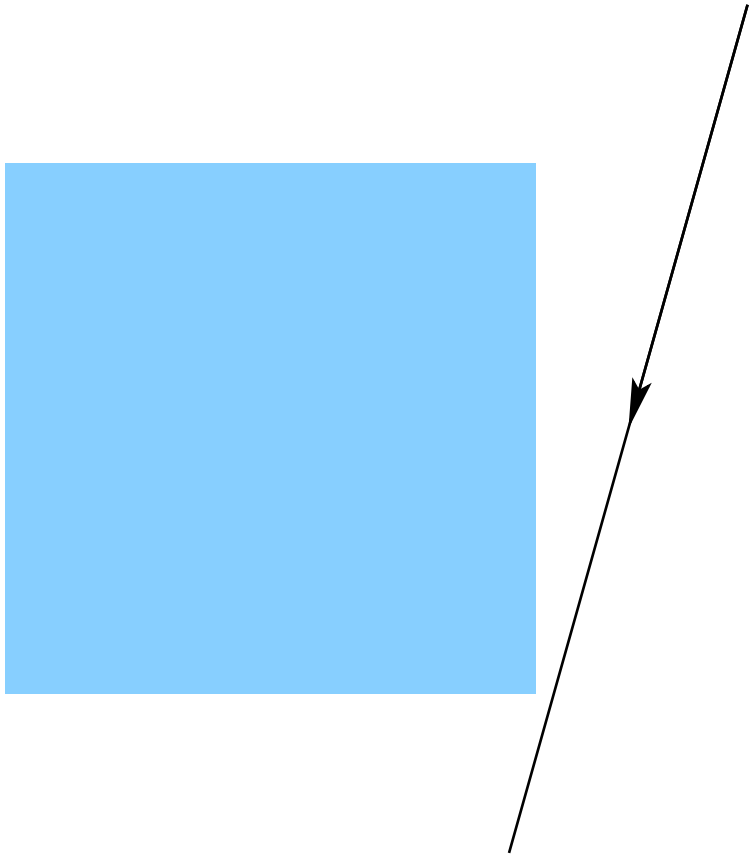

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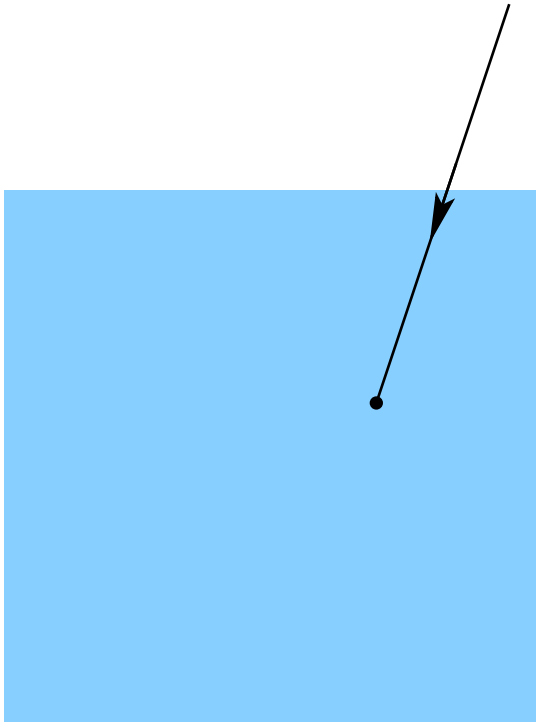

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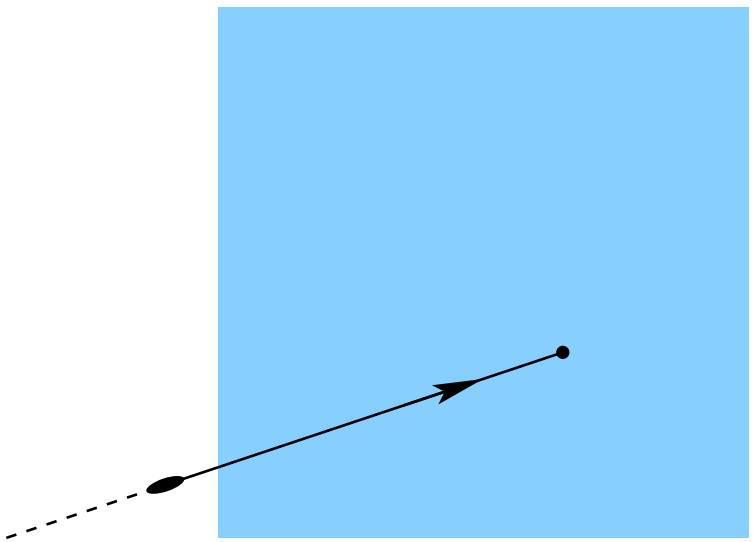

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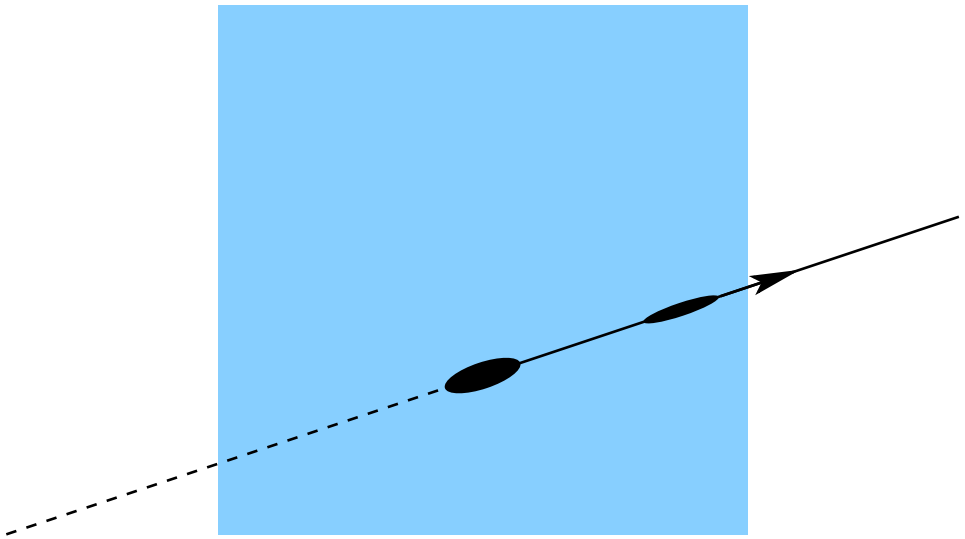

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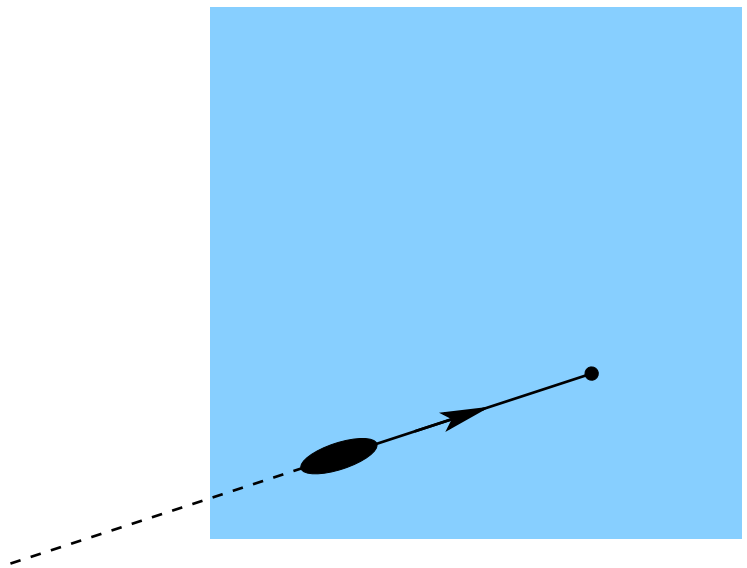

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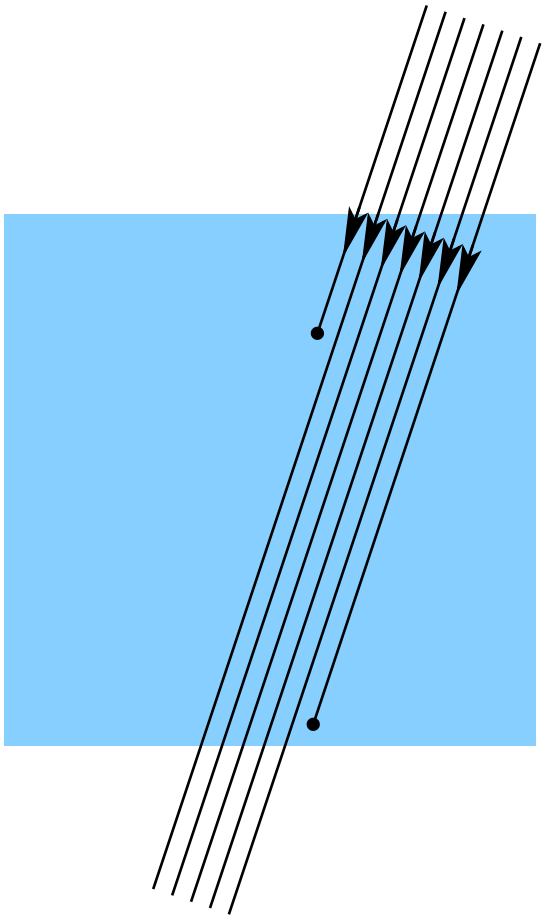

- CR $\rightarrow \mu$ bundle
- CR $\rightarrow \mu$ (HE, high p_T)
- 2CR $\rightarrow 2\mu$ (coinc)
- μ pairs from decay of microscopic black holes

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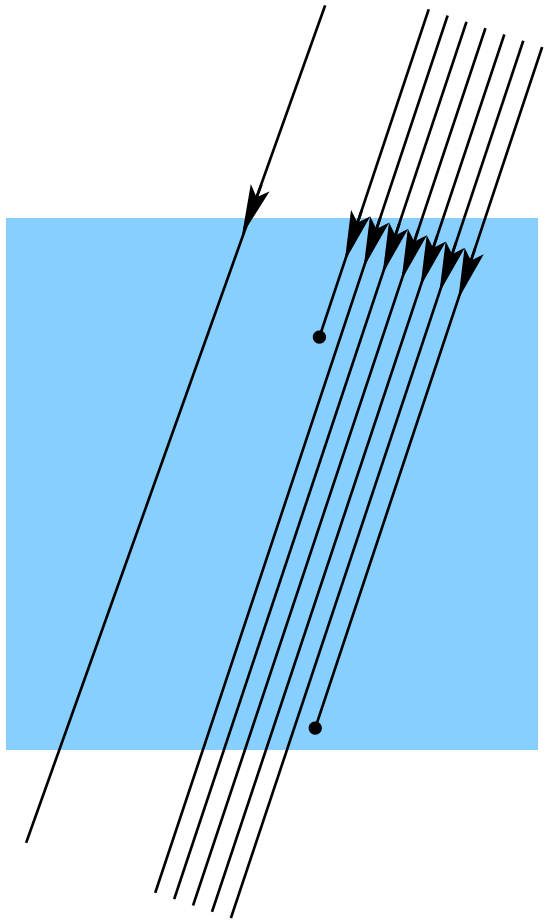

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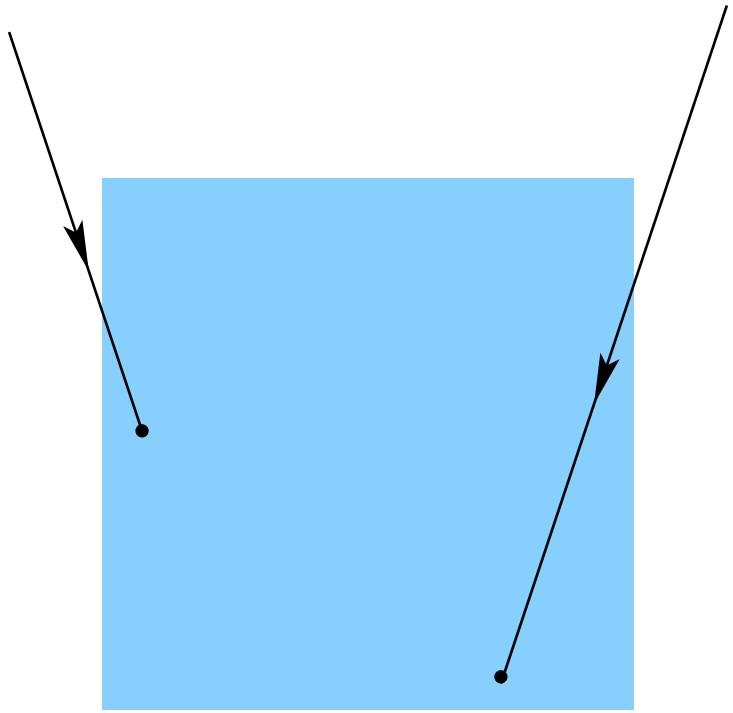

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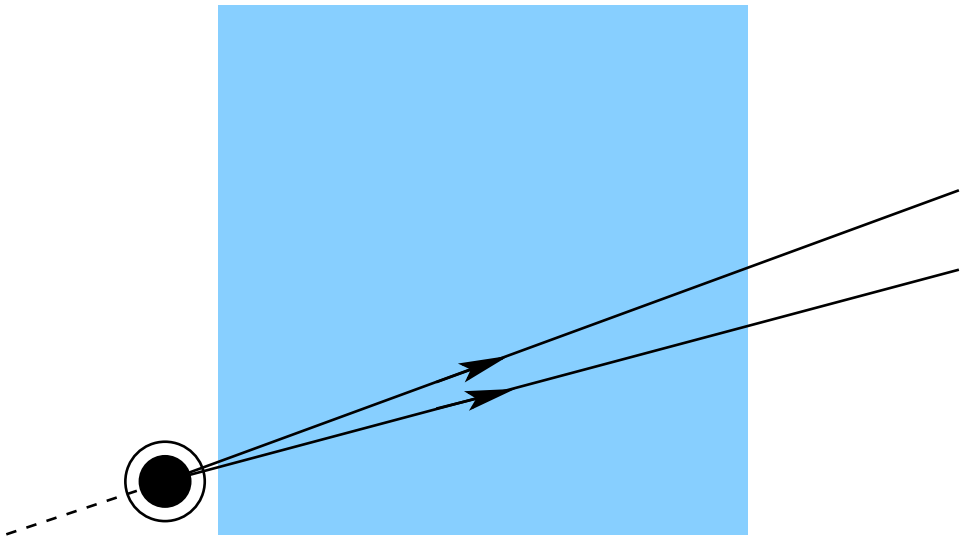

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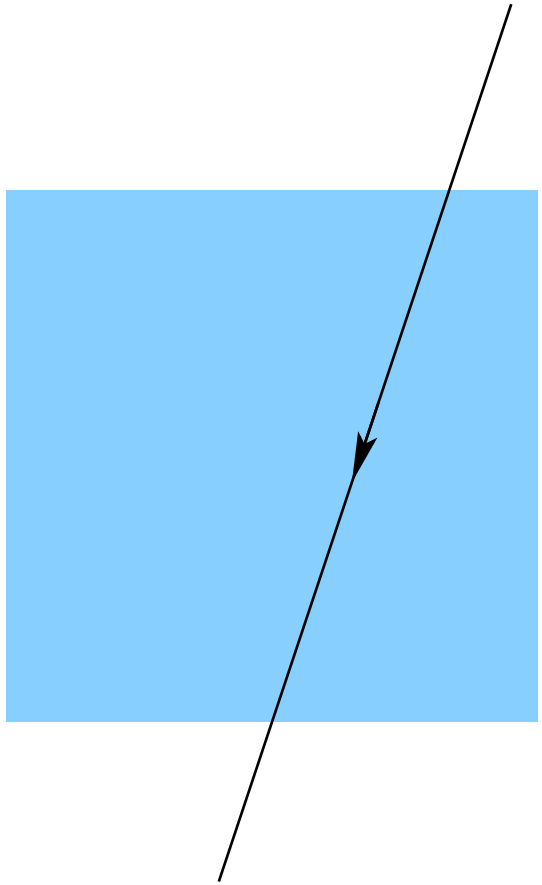
Event Types (3): energy range



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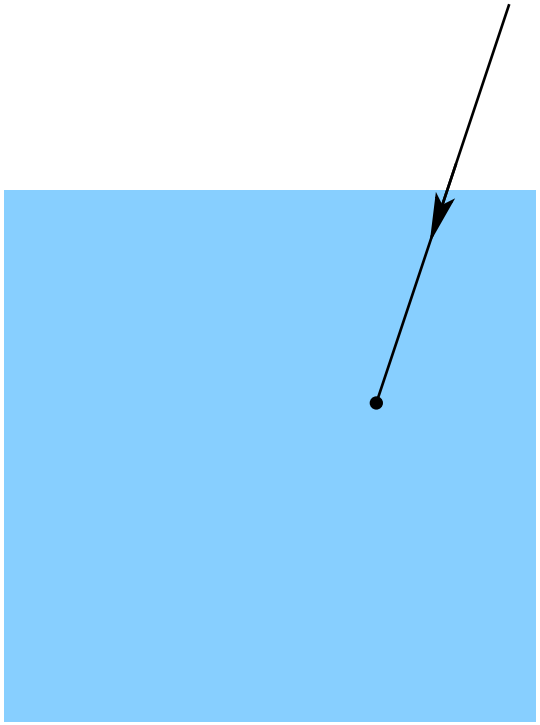

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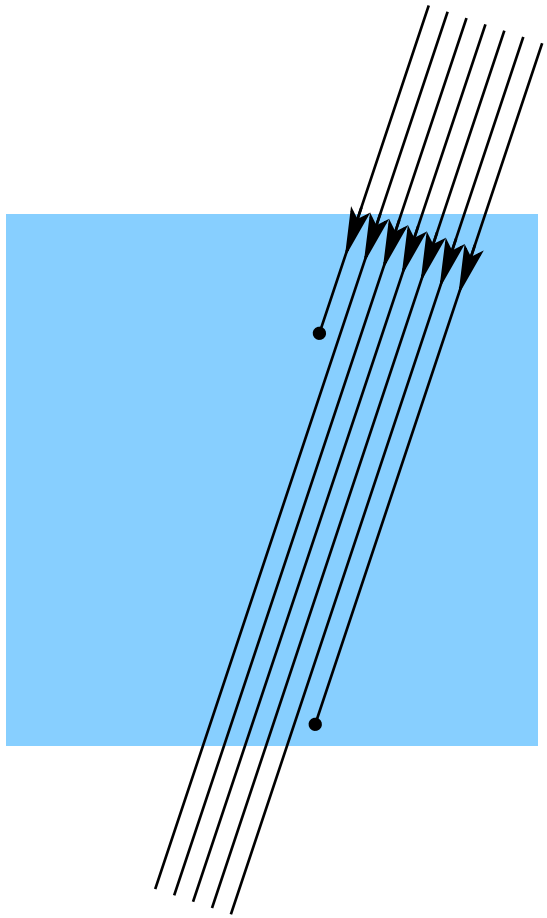

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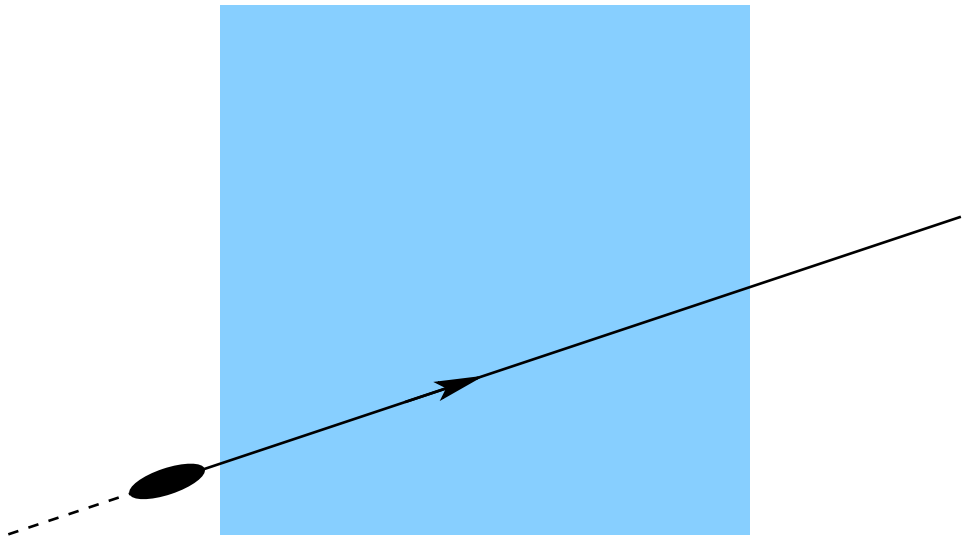

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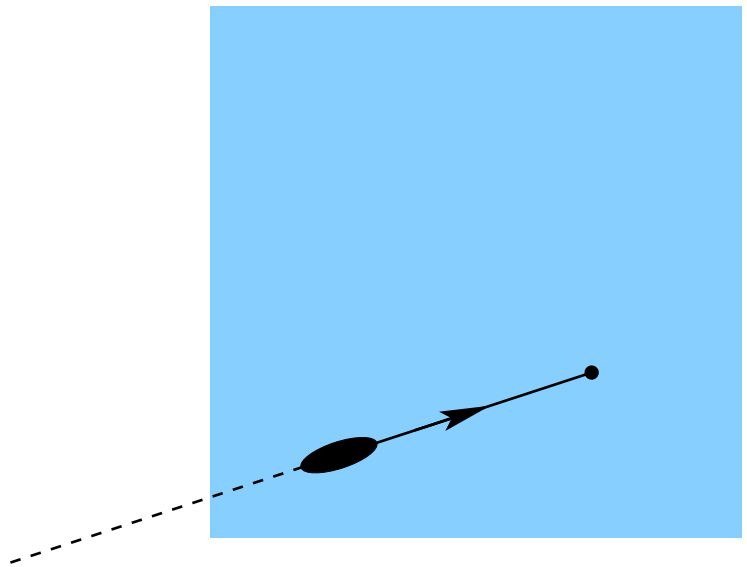

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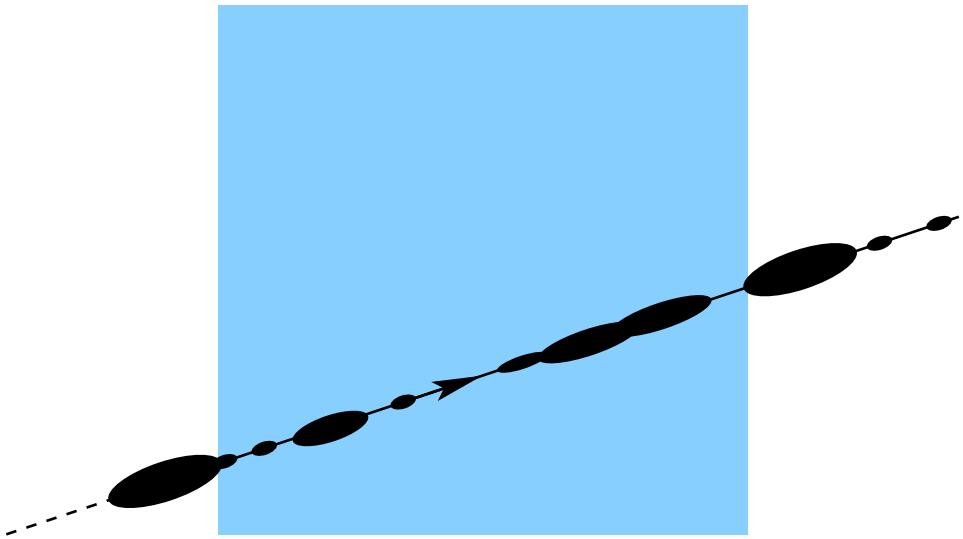

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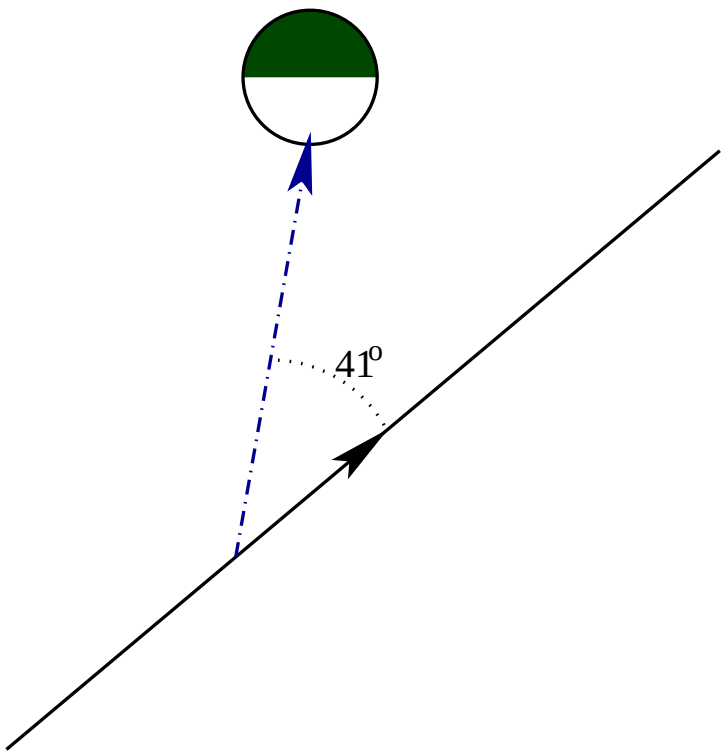
Event Types (4): many more!

. . .

Light & Photoelectrons



Phenomena:

- Direct light
- Scattering
- Absorption
- Time residual
- Arrival time distribution
- Jitter, noise

Available solutions:

- Analytic: Pandel
- Table: Photonics
- Fits: Photospline

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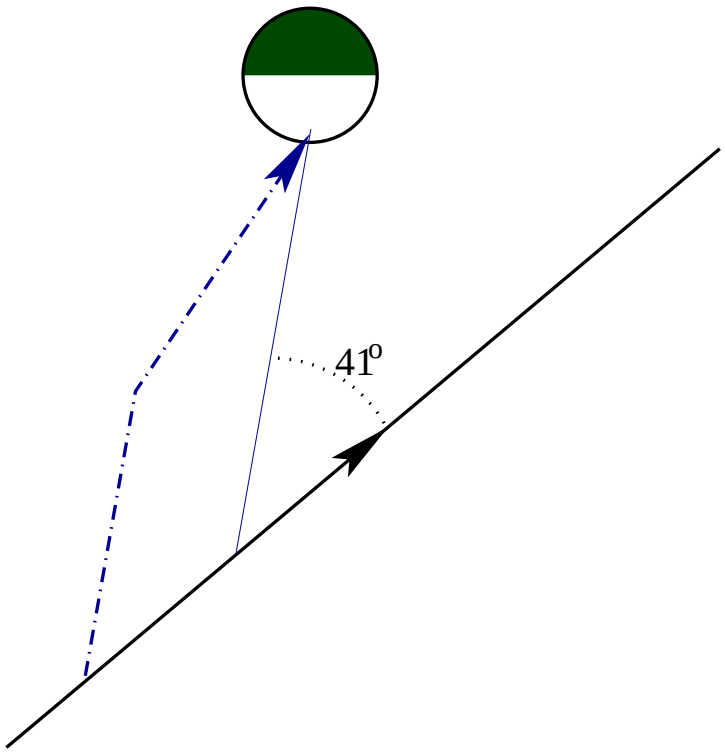

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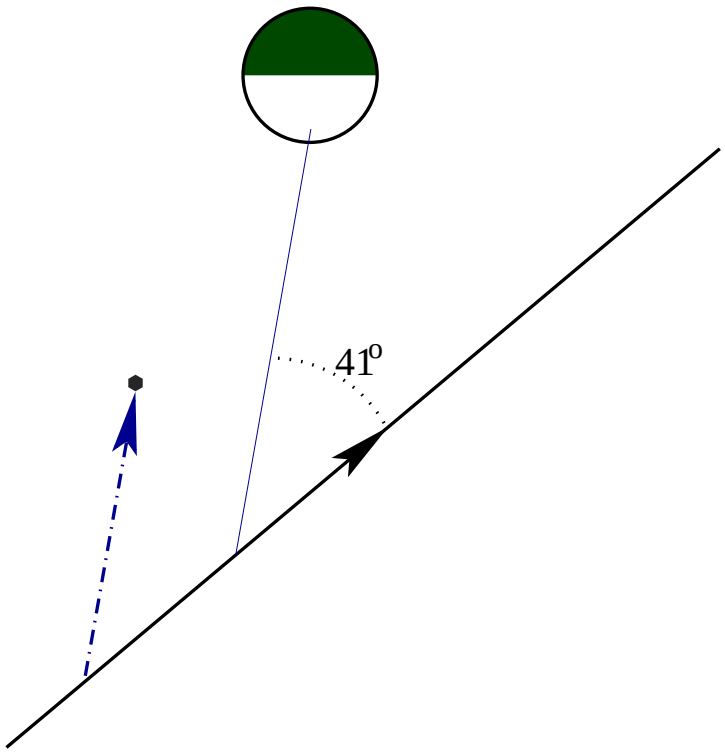

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Light & Photoelectrons

$$t_{residual} = t_{pulse} - t_{direct}$$

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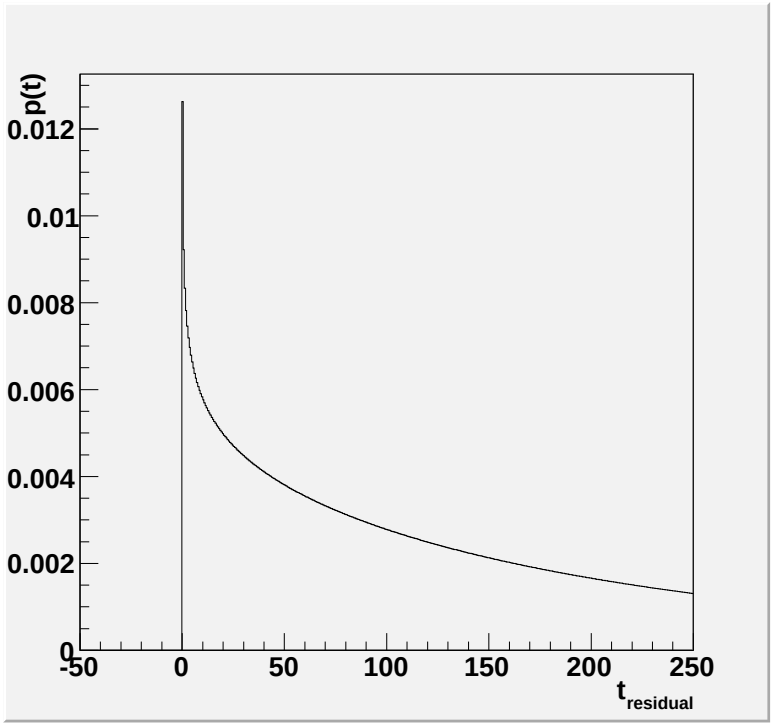

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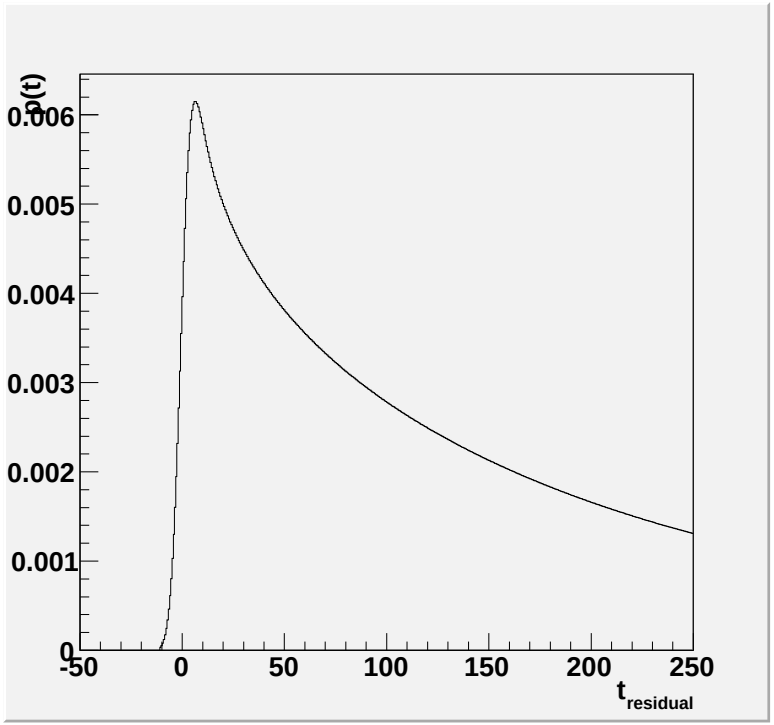

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Light & Photoelectrons

$$p(\xi, \rho, t) = \frac{\rho^{\xi} t^{\xi-1}}{\Gamma(\xi)} e^{-\rho t}$$

$\xi = R/\lambda$

$\rho = \frac{1}{\tau} + \frac{c}{\lambda a}$

$$\mathcal{F}_{\sigma}(\xi, \rho, t) = \int_{-\infty}^{+\infty} p(\xi, \rho, t') g_{\sigma}(t' - t, \sigma) dt'$$

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Light & Photoelectrons

(photonics movie)

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Elements in Event Reconstruction

1. Determine event type(s)
2. Fit variables, parametrization
3. Likelihood L (light emission, propagation)
4. Seeding algorithm
5. Maximize L

- event topology
- which variables are needed to specify the physics
- `I3EventHypothesis`

Elements in Event Reconstruction

1. Determine event type(s)
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- Which physics variables do we want to fit?
- Choose good parametrization (avoid singularities, cyclic variables)
- Stepsizes, bounds, etc.
- `I3ParametrizationBase`

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- light emission (NPE, PDF?)
- data representation (waveforms, pulses?)
- Bayesian terms?
- `I3EventLogLikelihoodBase`

Elements in Event Reconstruction

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5. Maximize L

- first guess
- numerical considerations (e.g. make sure that time residuals are mostly positive)
- `I3SeedServiceBase`

Elements in Event Reconstruction

1. Determine event type(s)
2. Fit variables, parametrization
3. Likelihood L (light emission, propagation)
4. Seeding algorithm
5. Maximize L

- *minimize* -log(L)
- Generic minimizer algorithm
- Typically simplex (brute force, particle swarm, simulated annealing, etc.)
- `I3MinimizerBase`

Likelihood (only charge)

$$
\begin{aligned}
\log(L) &= \sum_{d \epsilon \{\textit{all DOMs}\}} \log(L_d) \\
\log(L_d) &= \log\left(\frac{\mu_d^{N_d} e^{-\mu_d}}{N_d!}\right) \\
&= N_d \log(\mu_d) - \mu_d - \log(N_d!) \\
&= L_{d,\textit{brightness}} + L_{d,\textit{combinatorial}}
\end{aligned}
$$

Here, for every DOM d:

$$
\begin{aligned}
\mu_d &= \text{expected number of photoelectrons} \\
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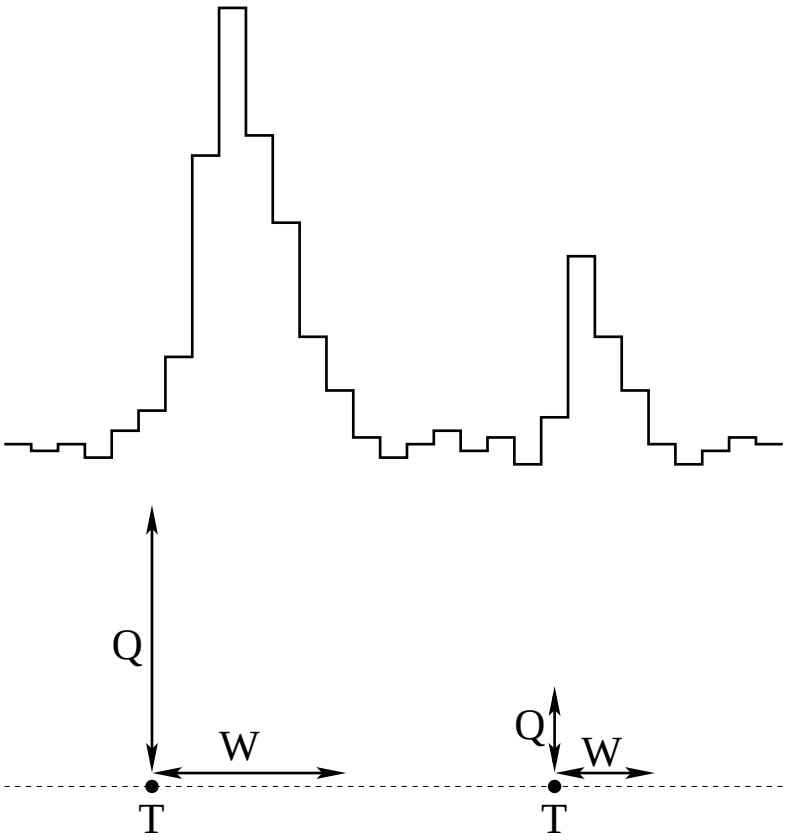
Time information



- Waveforms
  - ATWD (128 $\times$ 3.6ns)
  - FADC (256 $\times$ 25.0ns)
- "Extracted" pulses

Likelihood (charge and time)

$$
\begin{aligned}
\log(L_d) &= \sum_i \log\left(\frac{\mu_{di}^{N_{di}} e^{-\mu_{di}}}{N_{di}!}\right) \\
&= \sum_i N_{di} \log(\mu_{di}/\mu_d) \\
&\quad + N_d \log(\mu_d) - \mu_d \\
&\quad - \sum_i \log(N_{di}!) \\
&= L_{d,timing} + L_{d,brightness} + L_{d,combinatorial}
\end{aligned}
$$

Here, for every DOM d:

μ_{di} = expected number of photoelectrons in time bin i

N_{di} = detected number of photoelectrons in time bin i

μ_d = expected total number of photoelectrons

N_d = detected total number of photoelectrons

Likelihood (charge and time)

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N_d = detected total number of photoelectrons

Simplified likelihood

Reconstruct only track geometry

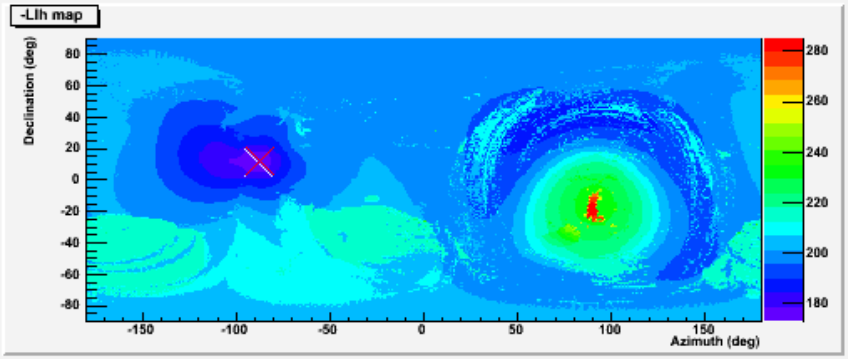
- "SPE" likelihood: ignore pulse charges

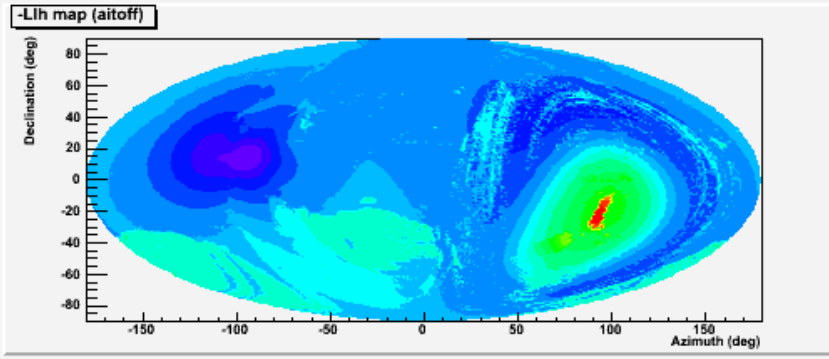
$$\log(L_d) = \sum_i \log\left(\frac{\mu_{di}}{\mu_d}\right) = \sum_i \log(p(t_i))$$

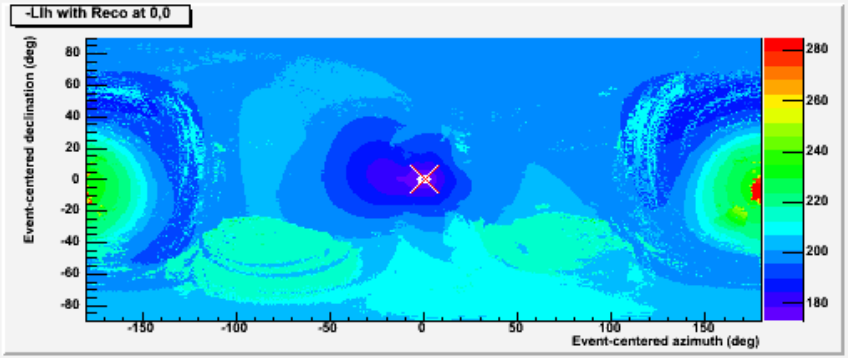
  - "SPEAll": use all pulses
  - "SPE1st": use only first pulse every DOM
- "MPE" likelihood: use total charge and time of first hit:

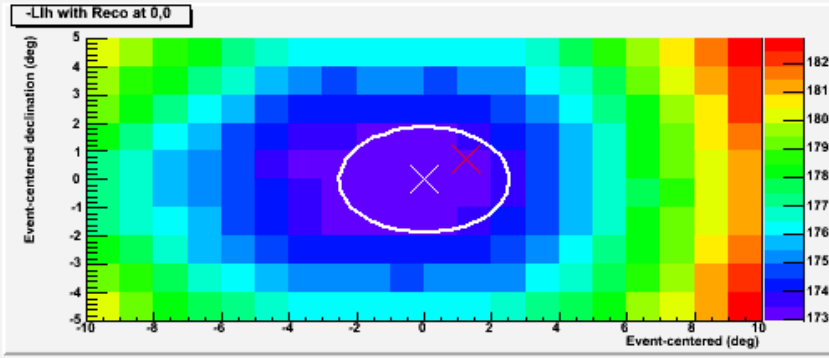
$$L_d = N_d p(t_0) \left[\int_{t_0}^{\infty} p(t)dt\right]^{N_d-1}$$

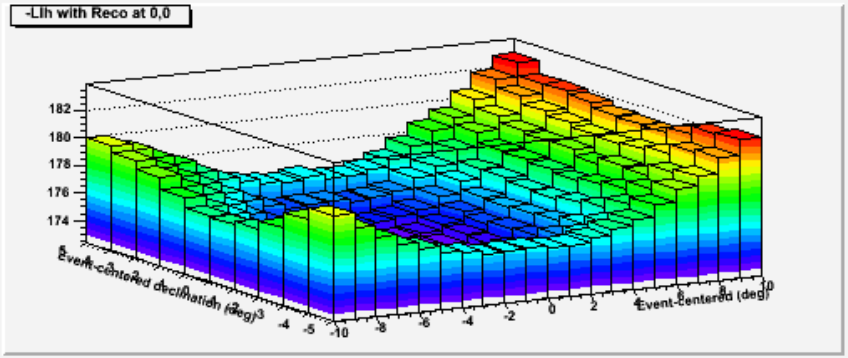
-log(L) map (good neutino event, IC22)











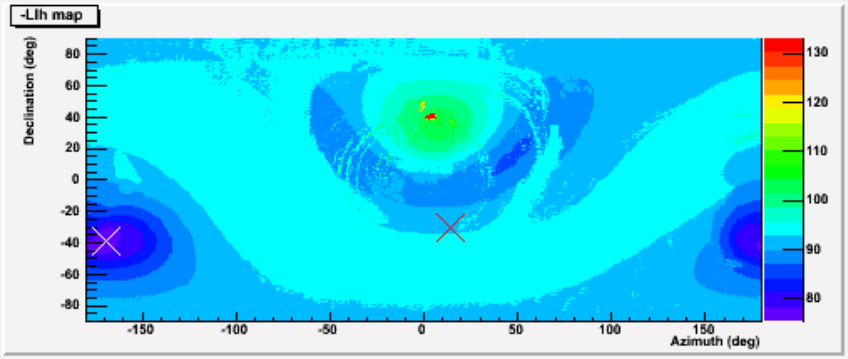
RunID = 1, SubRunID= 0, EventID = 1134, nSamples = 82506

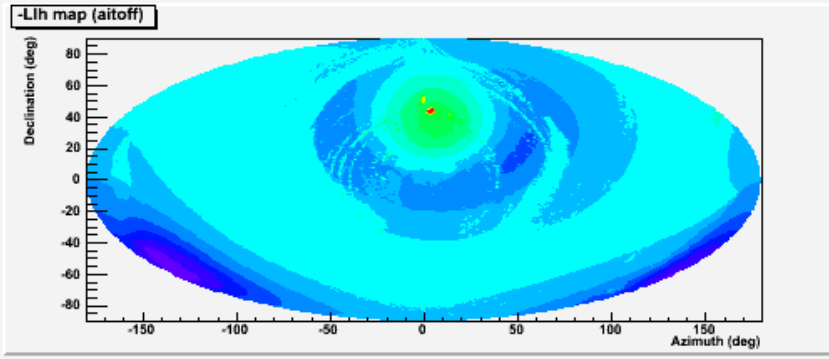
True Zen= 102.2, True Azi = -86.9, Reco Zen = 101.5, Reco Azi = -88.2 (all in deg)

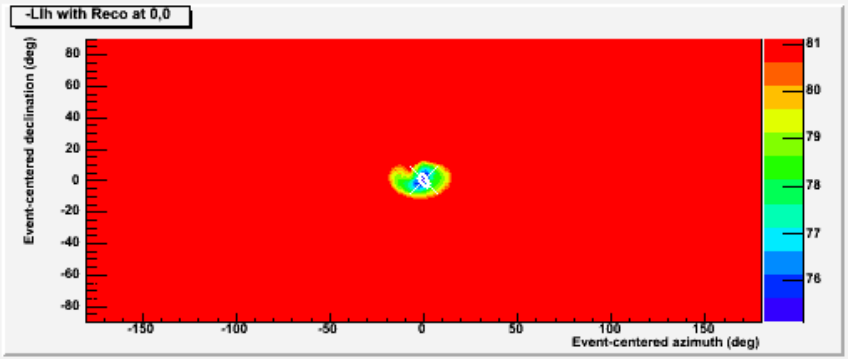
Nchan = 28, Nstring = 5, Ndir = 11, Ldir = 209.3 m

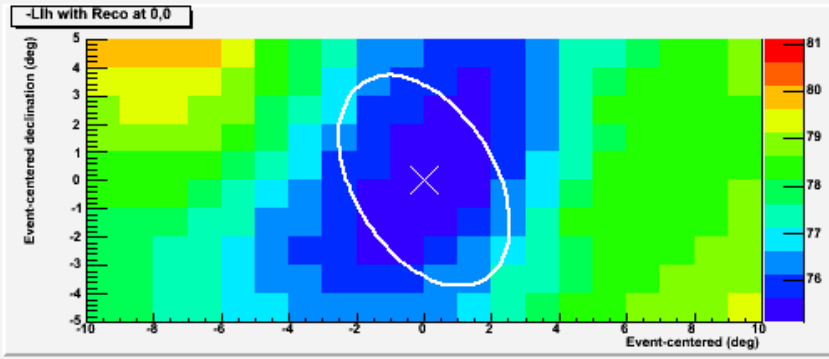
Sigma = 2.21, err_1 = 2.51, err_2 = 1.85, alpha = -89.89 (all in deg)

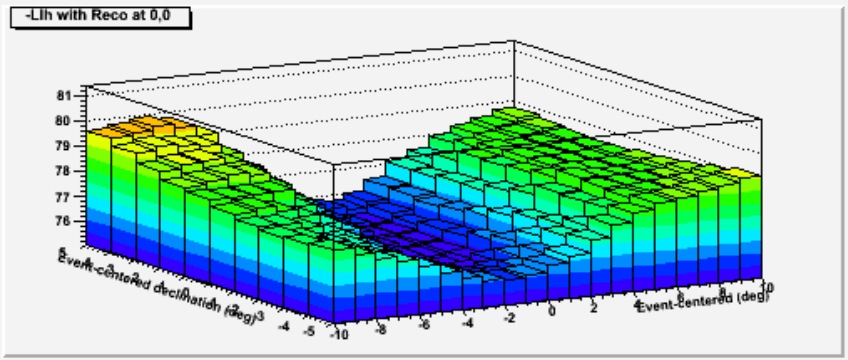
-log(L) map (coincident muons, IC22)











RunID = 1, SubRunID= -1, EventID = 27, nSamples = 82506

MC Zen= 59.8, MC Azi = 14.4 (deg), MC E = 1676.7, # muons = 2

Reco Zen = 50.7, Reco Azi = -168.9 (deg)

Nchan = 13, Nstring = 3, Ndir = 7, Ldir = 327.6 m

Sigma = 3.18, err_1 = 3.94, err_2 = 2.17, alpha = 23.25 (all in deg)

Quality Parameters

(To do: a cartoon illustrating what direct hits are)

- Direct hits: N_{dir}, L_{dir}
- Likelihood ratios
- Likelihood width ("paraboloid sigma")

Quality Parameters

(To do: a cartoon illustrating what direct length is)

- Direct hits: N_{dir}, L_{dir}
- Likelihood ratios
- Likelihood width ("paraboloid sigma")

Quality Parameters

(To do: a cartoon illustrating the use of likelihood ratios)

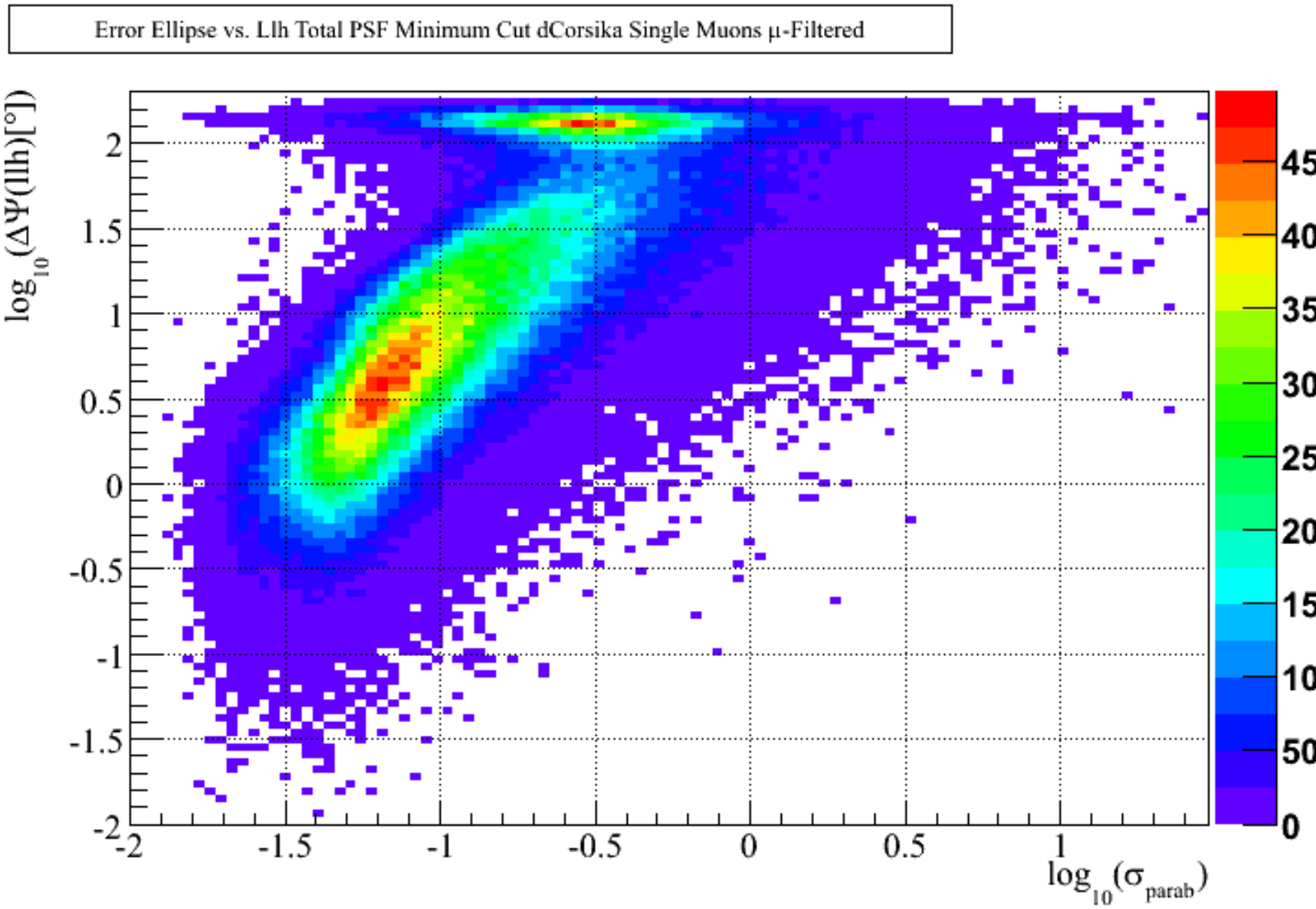
- Direct hits: N_{dir}, L_{dir}
- Likelihood ratios
- Likelihood width ("paraboloid sigma")

Quality Parameters

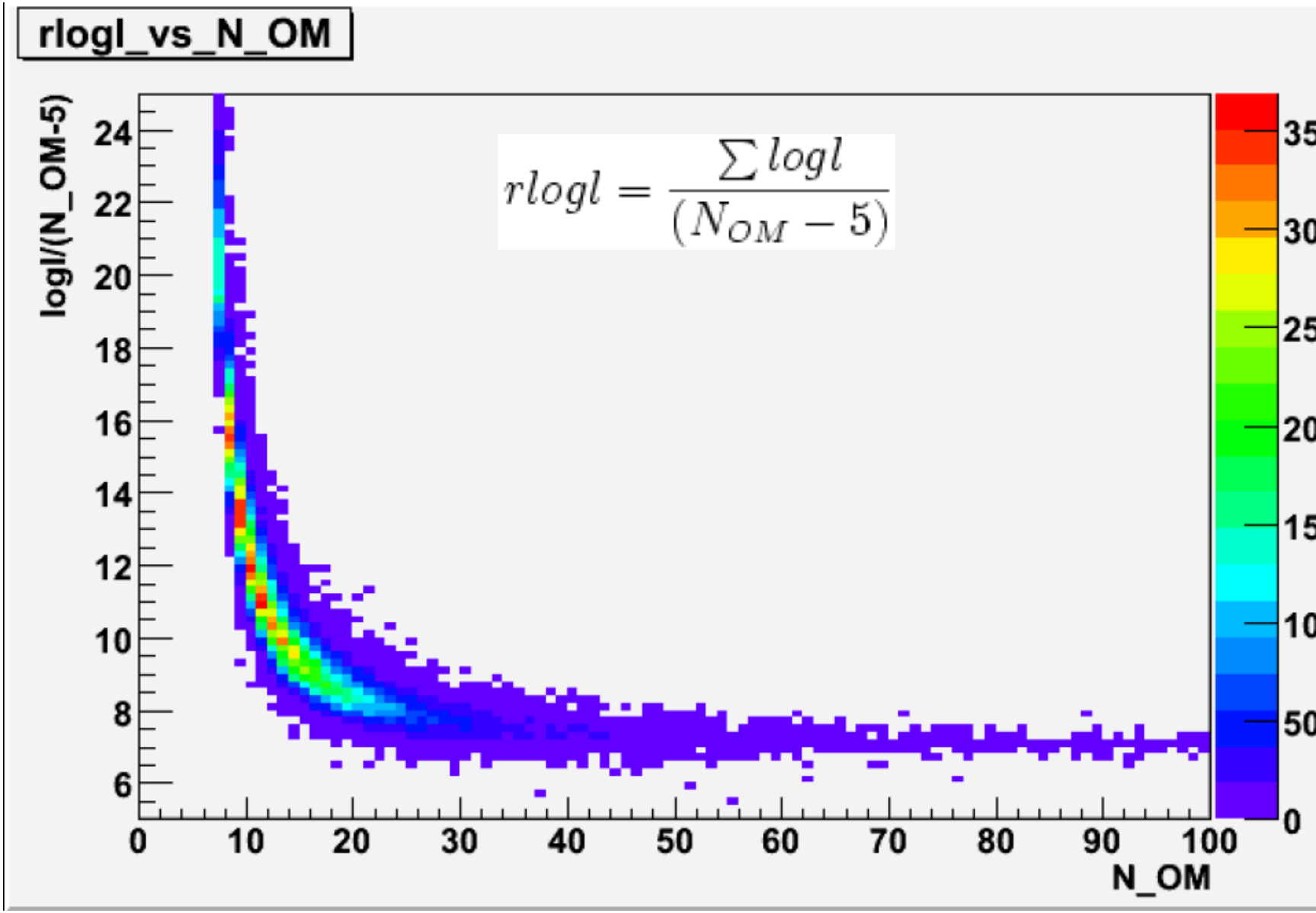
(To do: a cartoon illustrating what a paraboloid error ellips)

- Direct hits: N_{dir}, L_{dir}
- Likelihood ratios
- Likelihood width ("paraboloid sigma")

Paraboloid


Error Ellipse vs. Llh Total PSF Minimum Cut dCorsika Single Muons μ-Filtered
log10(ΔΨ(llh)[°])
log10(σparab)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
45
40
35
30
25
20
15
10
50
0

Reduced log-likelihood



Some reference material

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- arXiv:astro-ph/0407044: J. Ahrens *et al.*, *Muon Track Reconstruction and Data Selection Techniques in AMANDA*, Nucl. Instrum. Meth. **A524** (2004) 169
- arXiv:astro-ph/0506136: George Japaridze and Mathieu Ribordy, *Realistic arrival time distribution from an isotropic light source*
- arXiv:astro-ph/0611604: M. Ribordy, *Reconstruction of Composite Events in Neutrino Telescopes*
- arXiv:astro-ph/0702108: J. Lundberg *et al.*, *Light tracking through ice and water – Scattering and absorption in heterogeneous media with Photonics*, Nucl. Instrum. Meth. **A581** (2007) 619-631
- arXiv:0704.1706: N. van Eijndhoven, O. Fadiran, G. Japaridze, *Implementation of a Gauss convoluted Pandel PDF for track reconstruction in Neutrino Telescopes*, Astropart. Phys. **28** (2007) 456-462
- wikipedia: Cramér-Rao bound
- *Reconstruction of high energy muons in IceCube*: paper in preparation