Improving the muon track reconstruction of IceCube and IceCube-Gen2

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for the IceCube Collaboration

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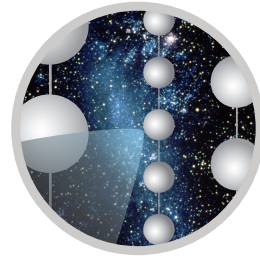
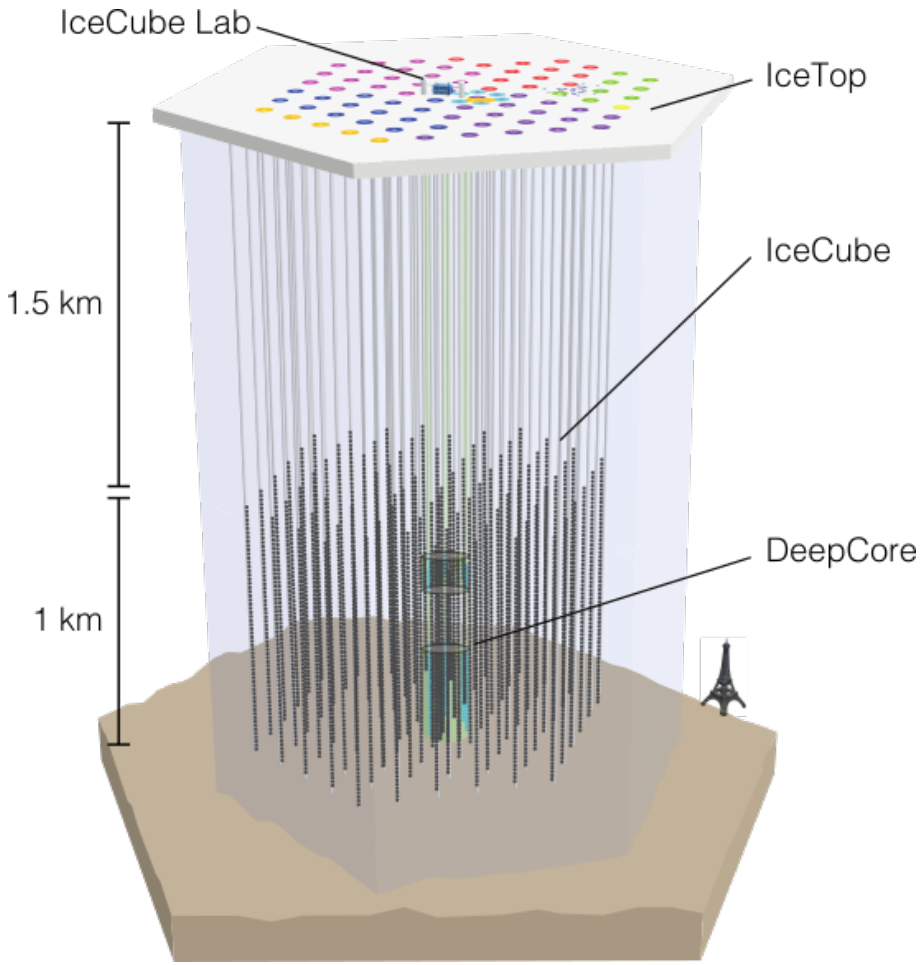


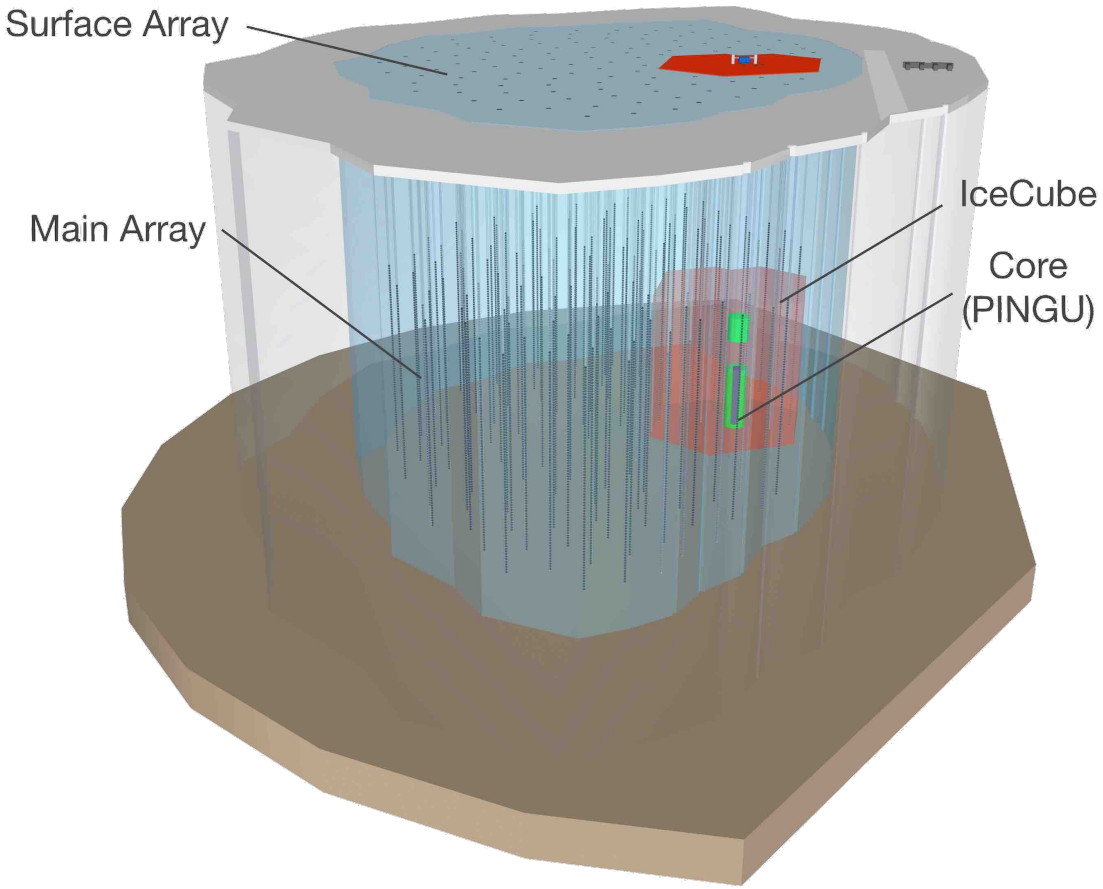
The IceCube Neutrino Observatory



- 1 km^3 volume
- 86 strings
- 60 DOMs per string
- 125 m horizontal spacing
- 17 m vertical spacing

Astrophysical neutrinos observed and evidence for first source

Extending IceCube



IceCube-Gen2 simulation:

- 8 km^3 volume
- 120 new strings
- 80 DOMs per string
- 240 m horizontal spacing

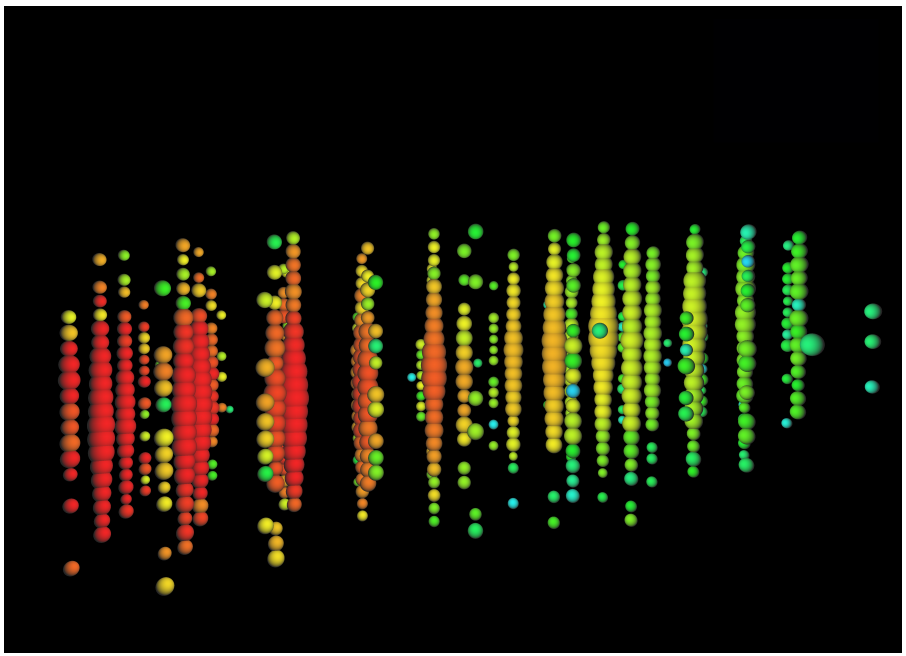
Sensitivity to sources 5 times fainter

Why improving the reconstruction?

- IceCube and IceCube-Gen2 aim to identify sources of astrophysical neutrinos
- Good pointing accuracy is needed
- Muon tracks allow for point-source search with $\sim 1^{\circ}$ resolution
- Improve angular resolution to sub-degree range

Neutrino event signatures

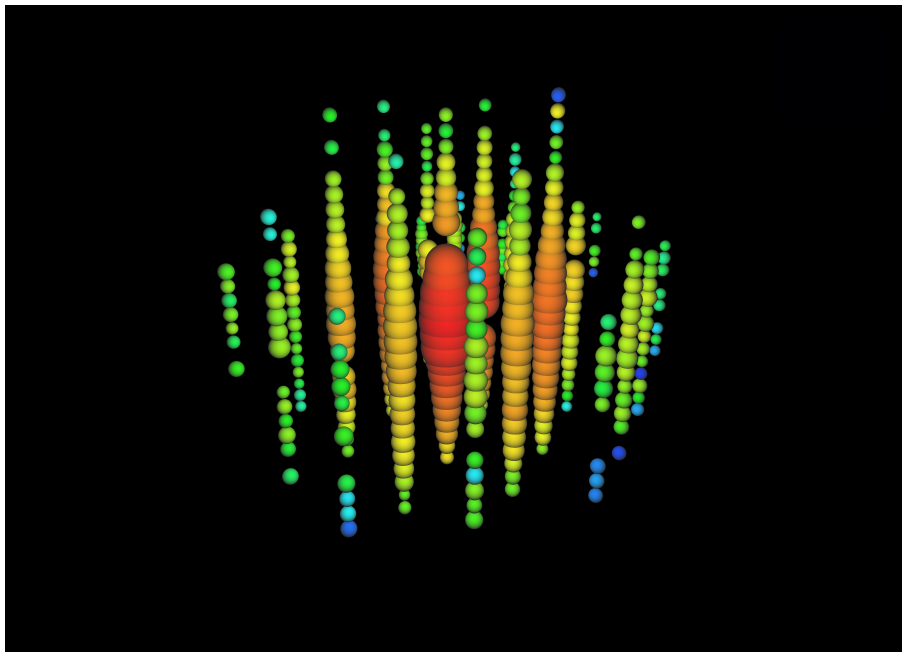
Tracks



$$\nu_\mu + N \rightarrow \mu + X$$

- $\sim 1^\circ$ angular resolution
- Factor of ~ 2 energy resolution

Cascades

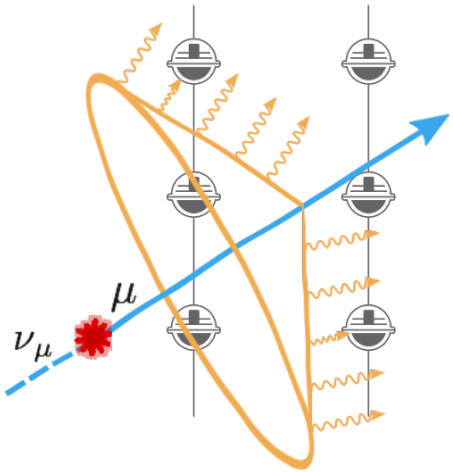


$$\nu_X + N \rightarrow \nu_X + X$$
$$\nu_e + N \rightarrow e + X$$

- $\sim 10^\circ$ angular resolution
- 15% energy resolution

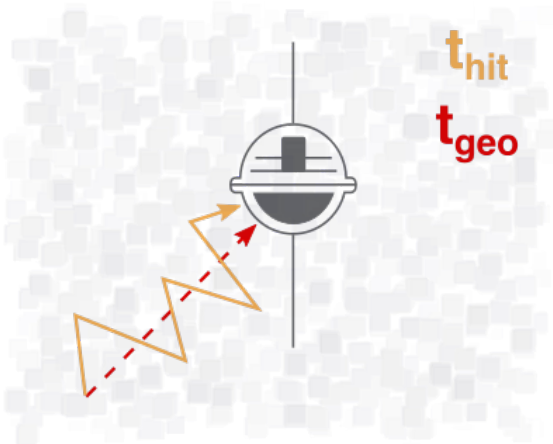
Muon track reconstruction

1. Cherenkov light detected by PMTs



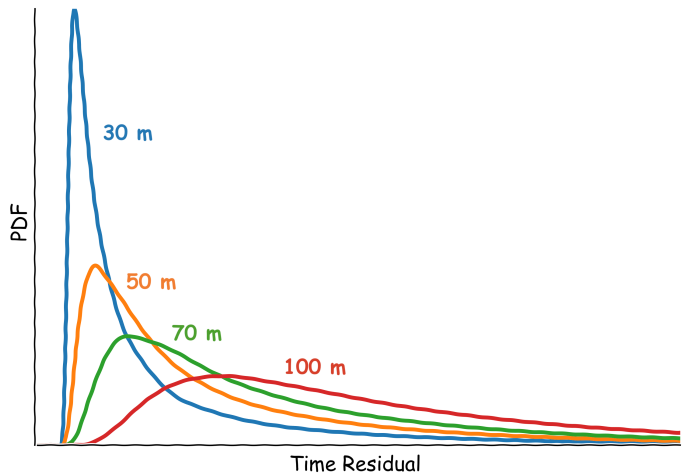
t_{hit}, N_{PE}

2. Scattering in the ice causes delays



$$t_{\mathrm{res}} = t_{\mathrm{hit}} - t_{\mathrm{geo}}$$

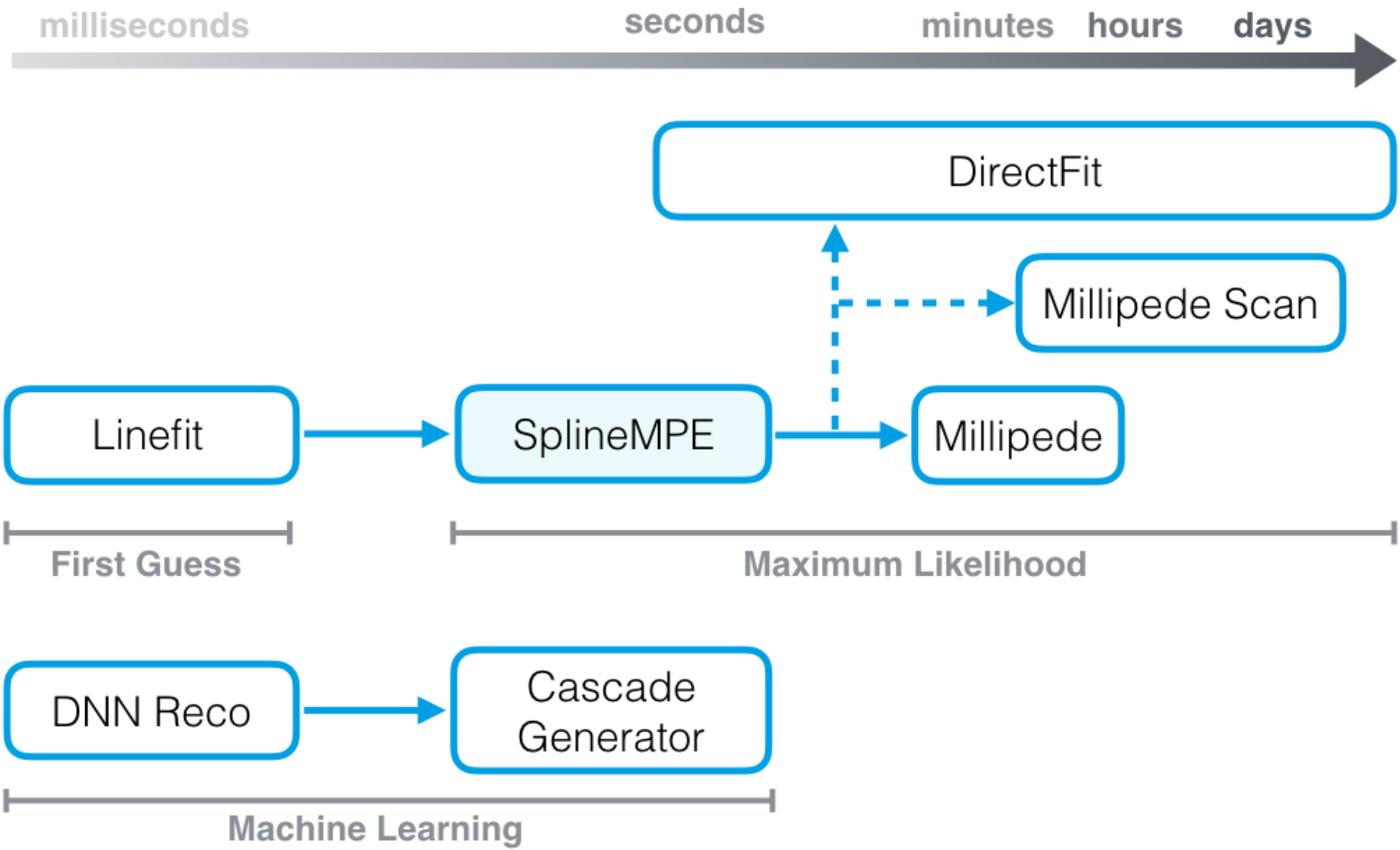
3. PDF of photon arrival time



4. Maximum likelihood algorithm

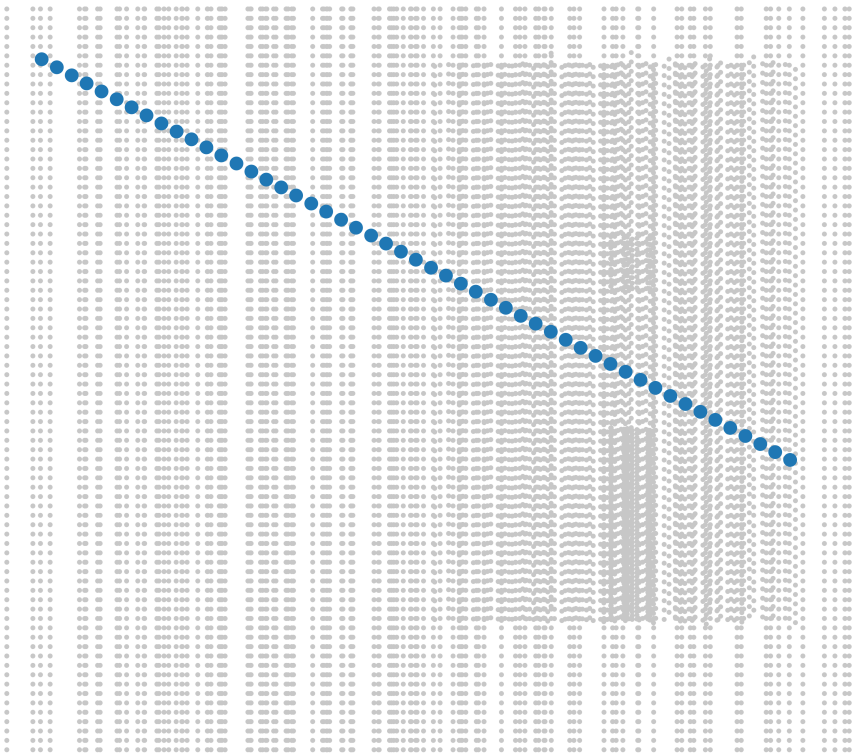
$$\mathcal{L} = \prod_{i \in \mathrm{DOM}} p(t_{\mathrm{res}})$$

Track reconstruction methods



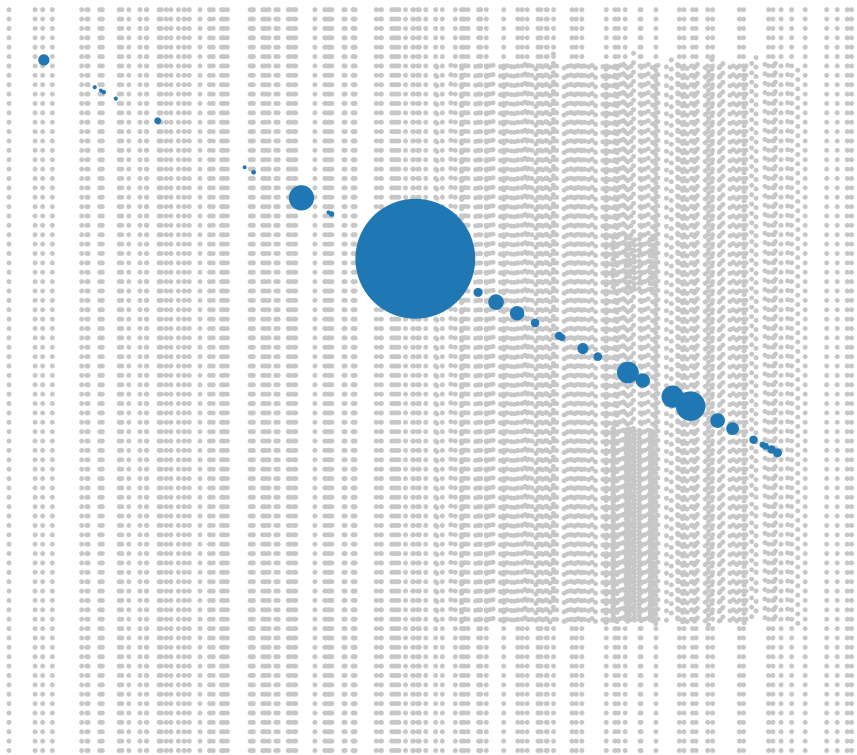
Are we reconstructing the truth?

Expectation



Continues Energy Losses

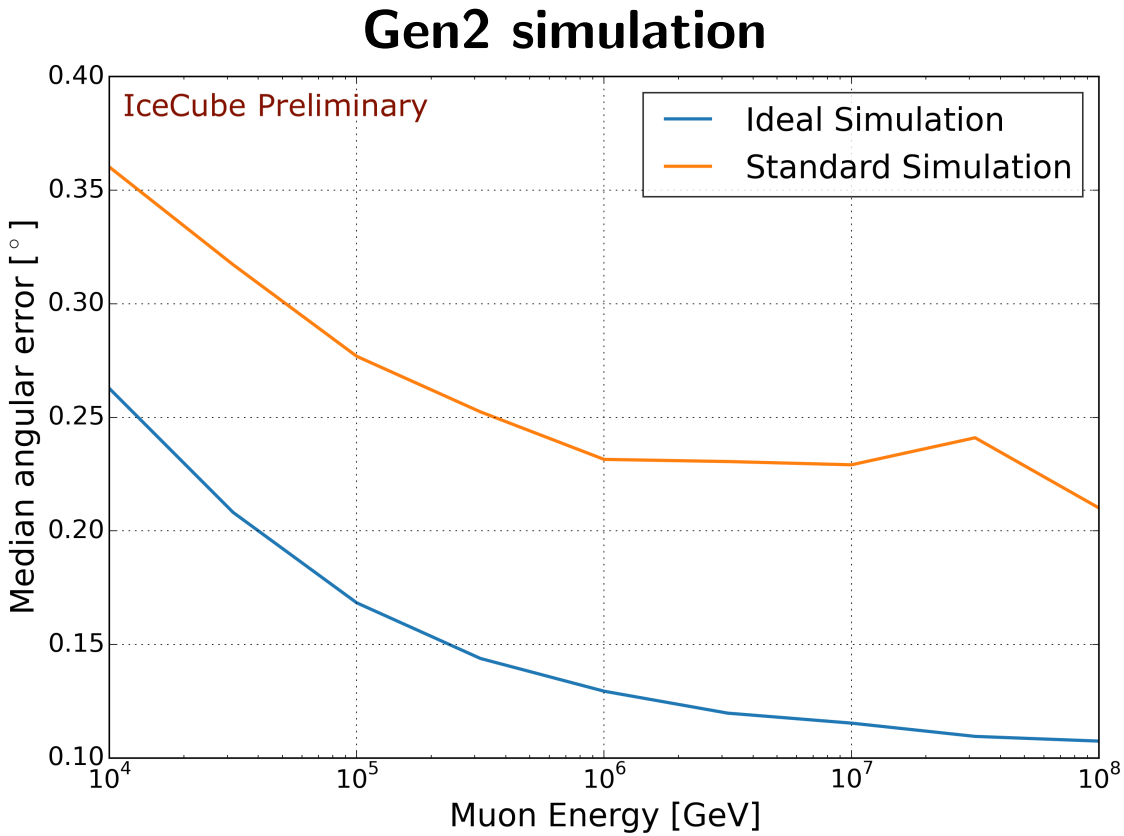
Reality



Stochastic Energy Losses

What is the best resolution we could achieve?

- Use the same hypothesis of the reconstruction: photon arrival time distribution according to PDFs



In Gen2 there is room for $\sim$ 30% improvement

How do we improve the angular resolution?

Better description of the arrival time distribution of photons

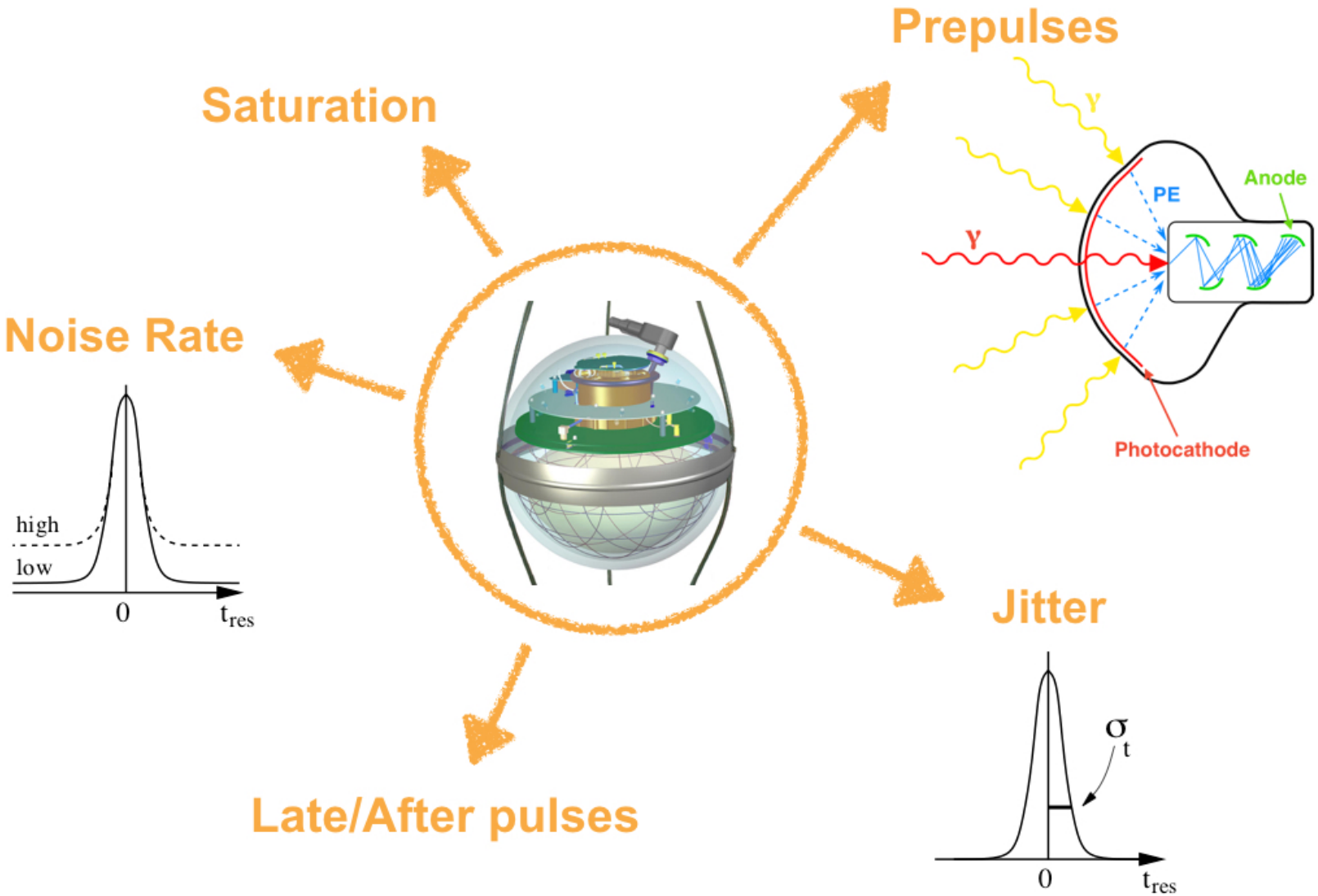
Current reconstruction:

- No photomultiplier related effects (e.g. prepulses, afterpulses)
- Continuous energy losses along the muon track

Improvements:

- Parametrization of photomultiplier related effects
- Parametrization of stochastic energy losses along the muon track

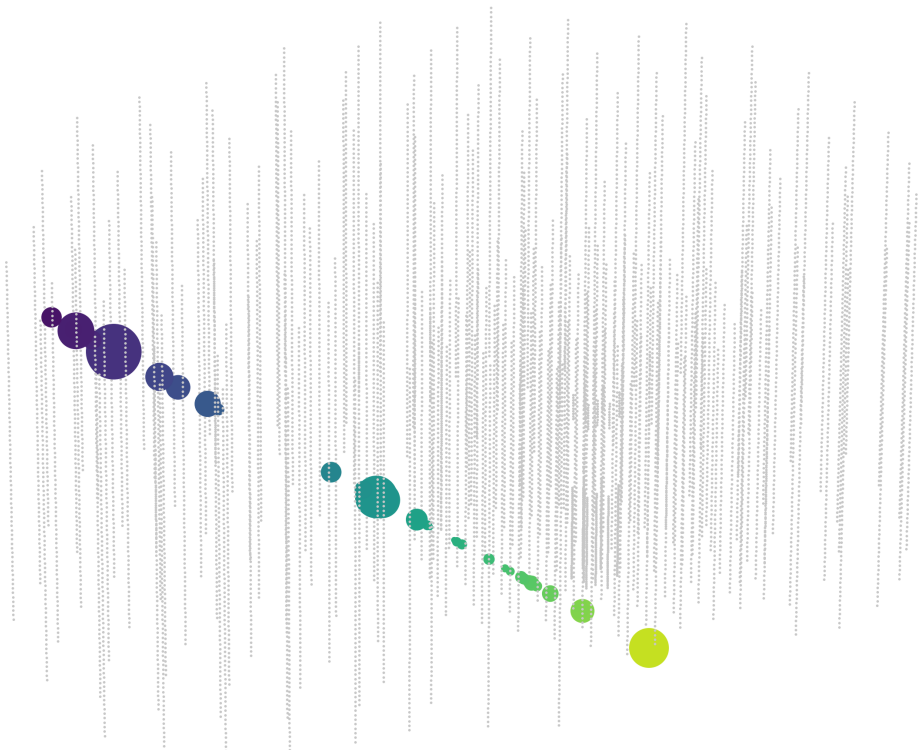
Which photomultiplier effects?



These are not the major limiting factors of the angular resolution

What are stochastic energy losses?

- Cherenkov light is not the only contribution above 1 TeV
- Secondary contributions: bremsstrahlung radiation, pair production and nuclear interactions
- Cascades of different brightness randomly added along the muon track
- Slightly broader average PDF



How to include stochastic energy losses?

Combine track reco (SplineMPE) with stochastic energy losses reco (Millipede):

SegmentedSplineMPE

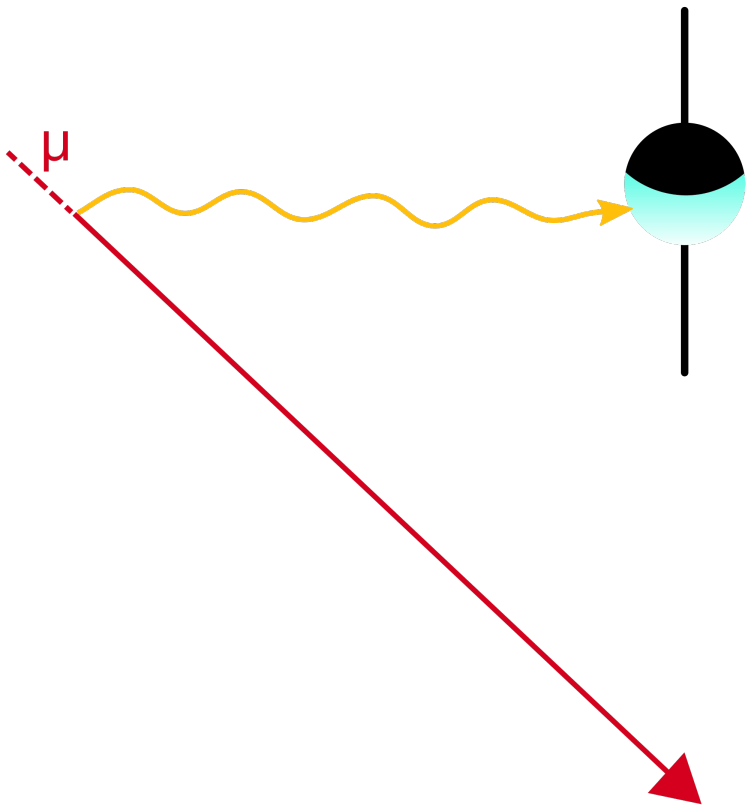
- Reconstruction based on SplineMPE
- Hypotesis: cascade-segmented track
- Likelihood:
  - MPE likelihood:

$$\mathcal{L}_{\mathrm{MPE}} = \prod_{DOMs\ i} N \cdot p_1(t_{res,i})(1 - P_1(t_{res,i}))^{(N-1)}$$

  - $p_1(t_{res,i})$ and $P_1(t_{res,i})$ calculated for each cascade and weighted with their energy:

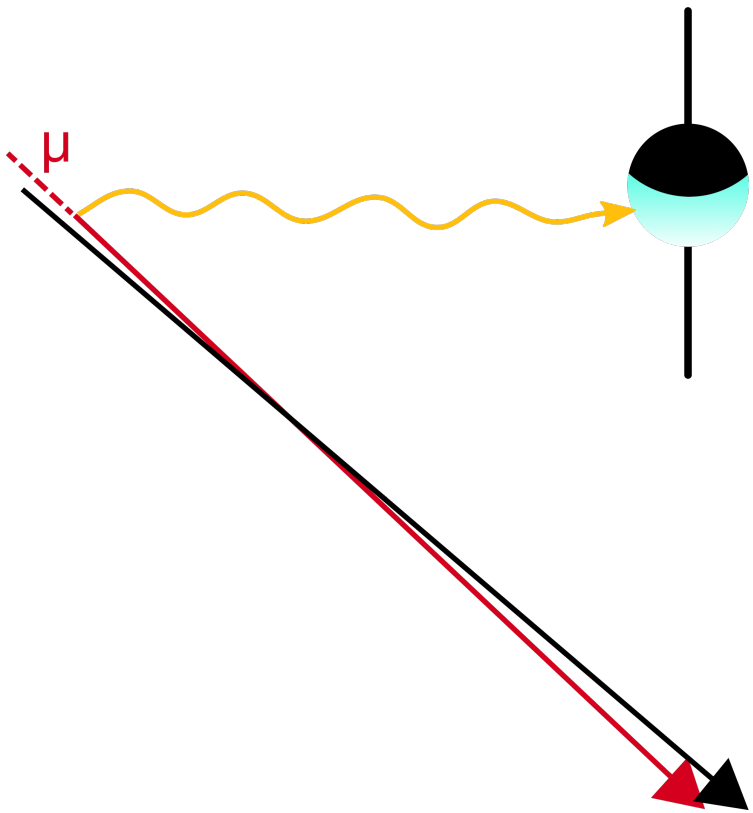
$$p_1(t_{res,i}) = \sum_{sources\ j} w_j p_{1,j}(t_{res,i})$$

SegmentedSplineMPE in a nutshell

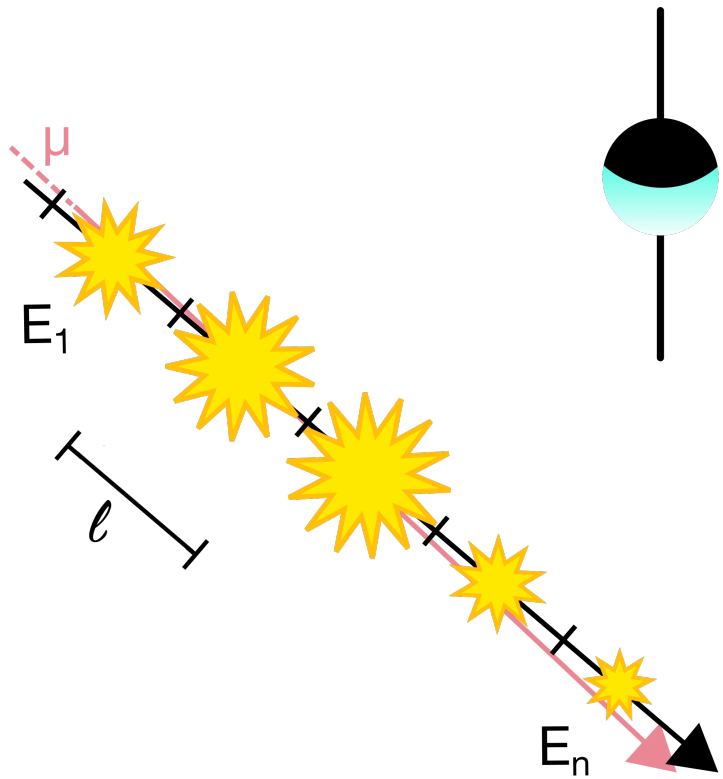


SegmentedSplineMPE in a nutshell

Track reconstruction
(SplineMPE)



SegmentedSplineMPE in a nutshell

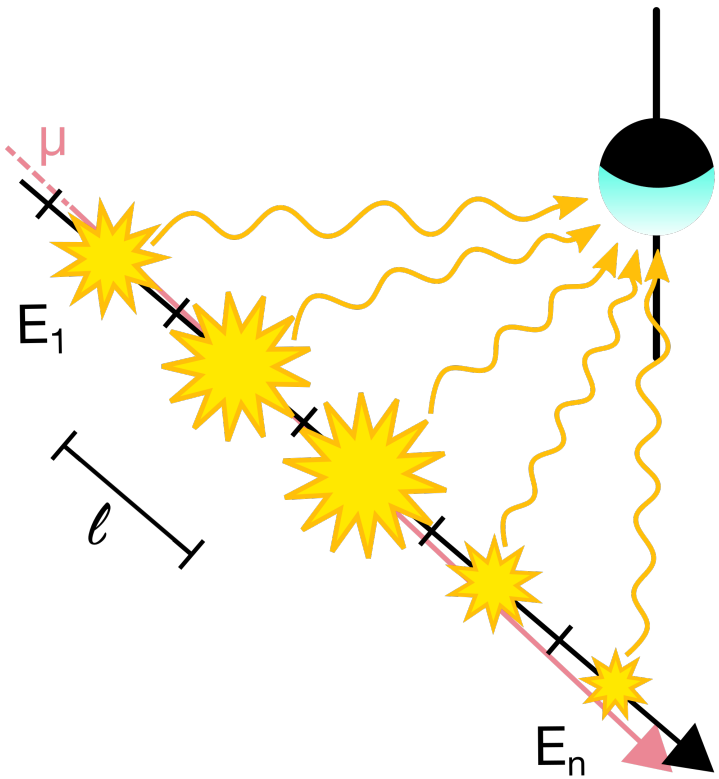


Track reconstruction
(SplineMPE)

seed

Energy loss reconstruction
(Millipede)

SegmentedSplineMPE in a nutshell



Track reconstruction
(SplineMPE)

seed

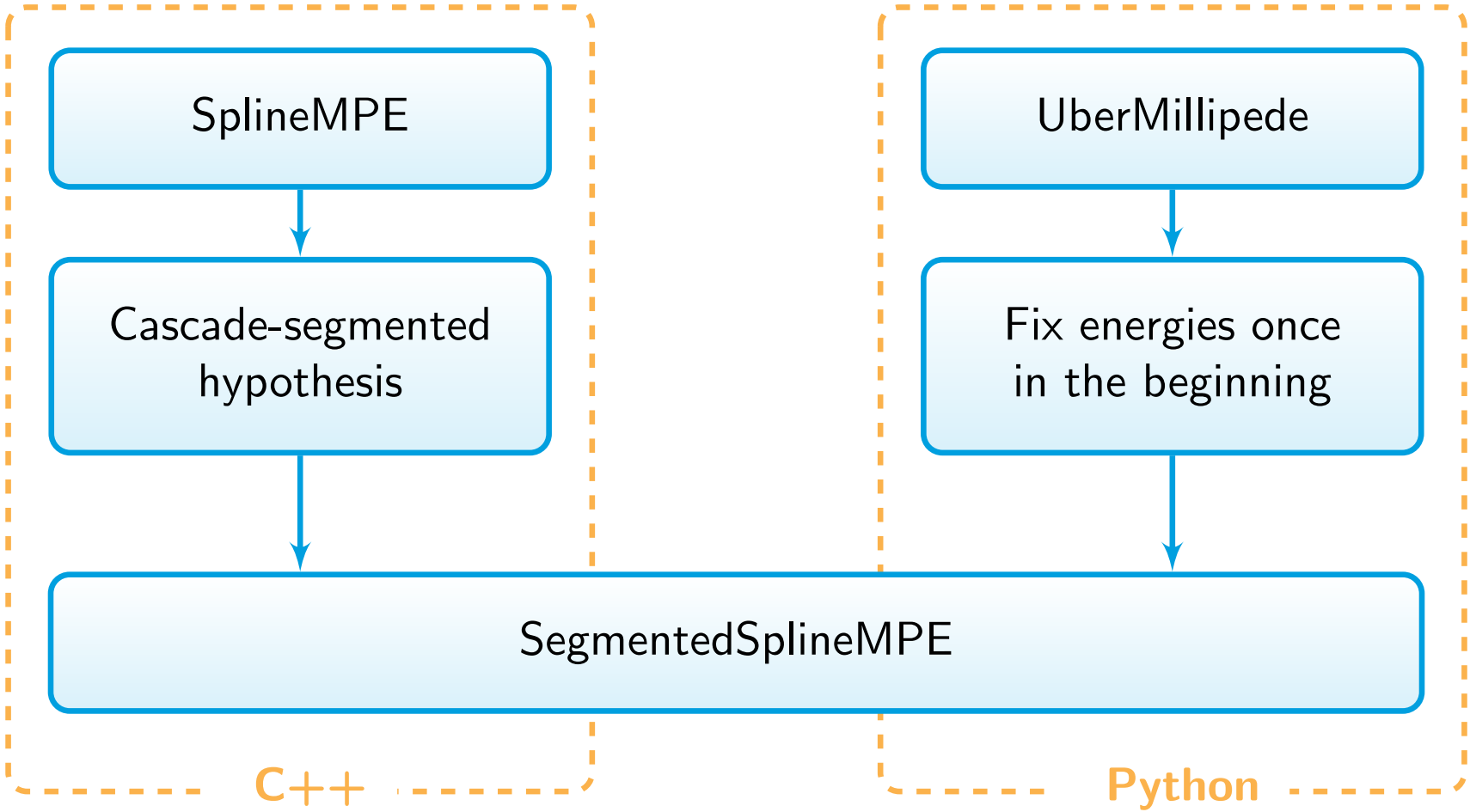
Energy loss reconstruction
(Millipede)

weights

$$p(t_{\mathrm{res}}) = \sum_{i=1}^{n} w_i p_i(t_{\mathrm{res}})$$

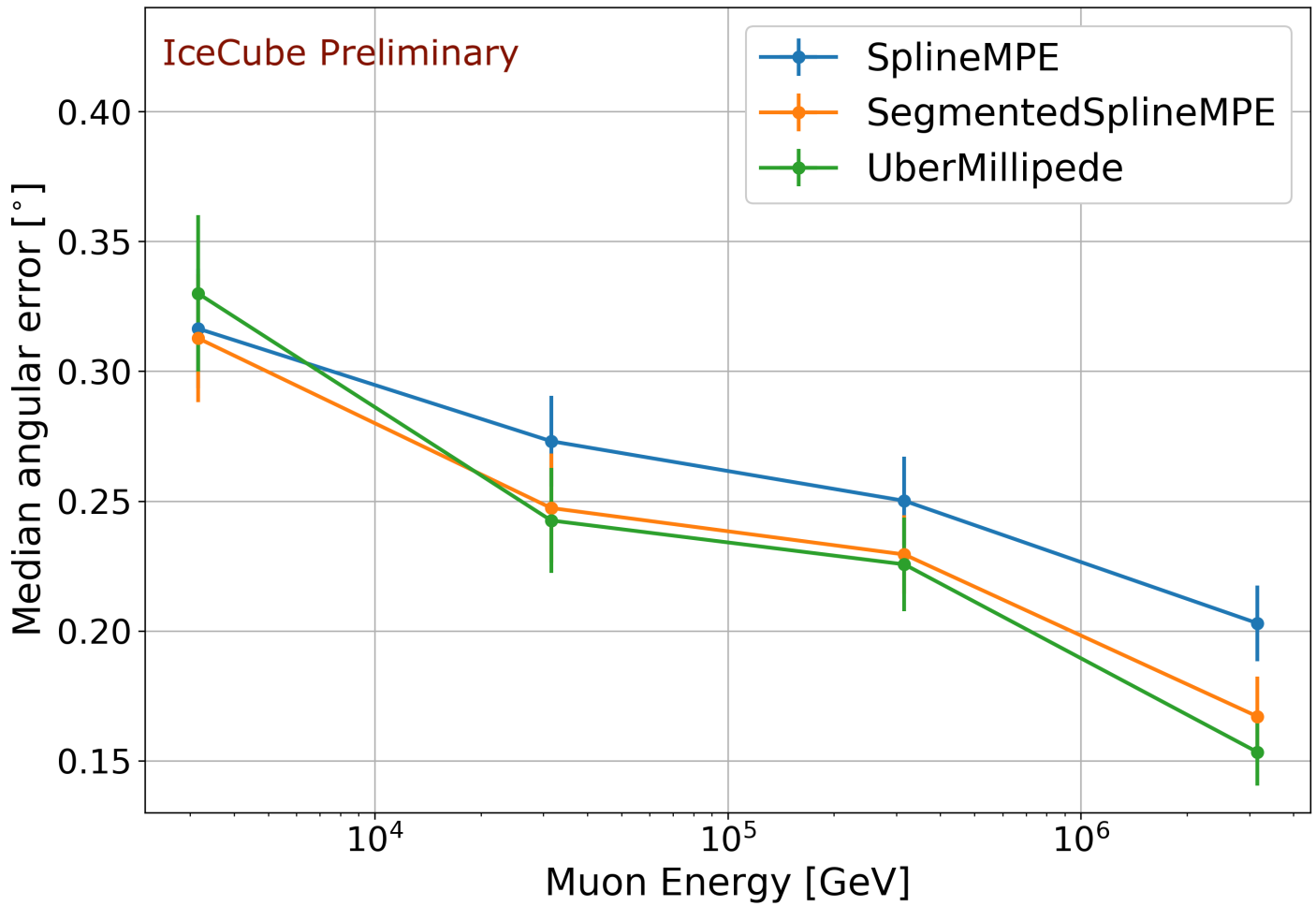
$$\forall\ \mathrm{DOM},\ \ \mathrm{w_i} = \mathrm{E_i} / \sum_{i=1}^{n} \mathrm{E_i}$$

SegmentedSplineMPE: two approaches



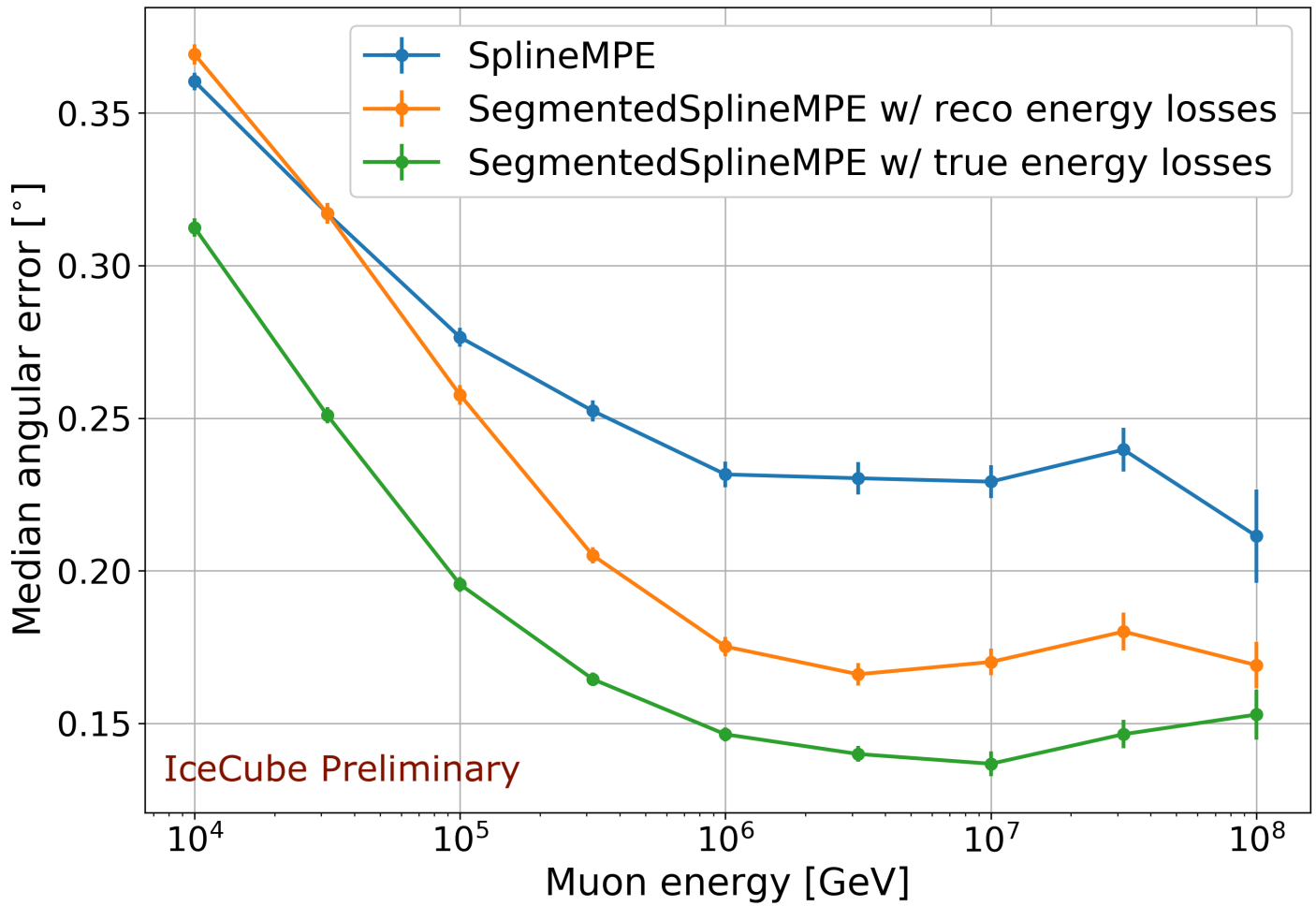
SegmentedSplineMPE results for IceCube

- **Track Seed:** SplineMPE
- **Cascades Seed:** UberMillipede (cascade length = 10 m)



SegmentedSplineMPE results for Gen2

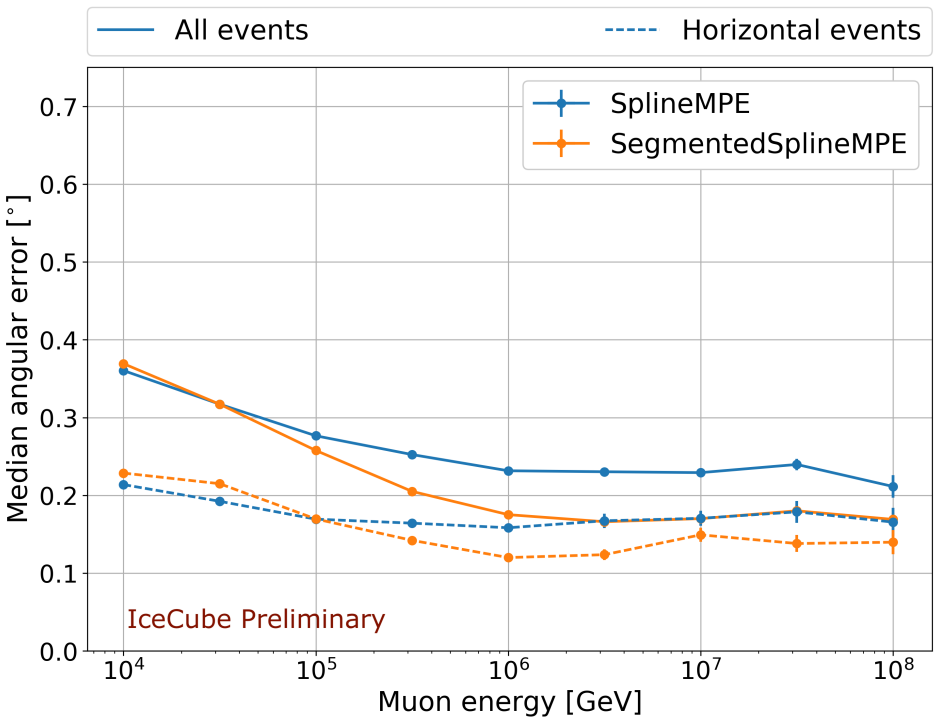
- **Track Seed:** SplineMPE
- **Cascades Seed:** Millipede (cascade length = 10 m)



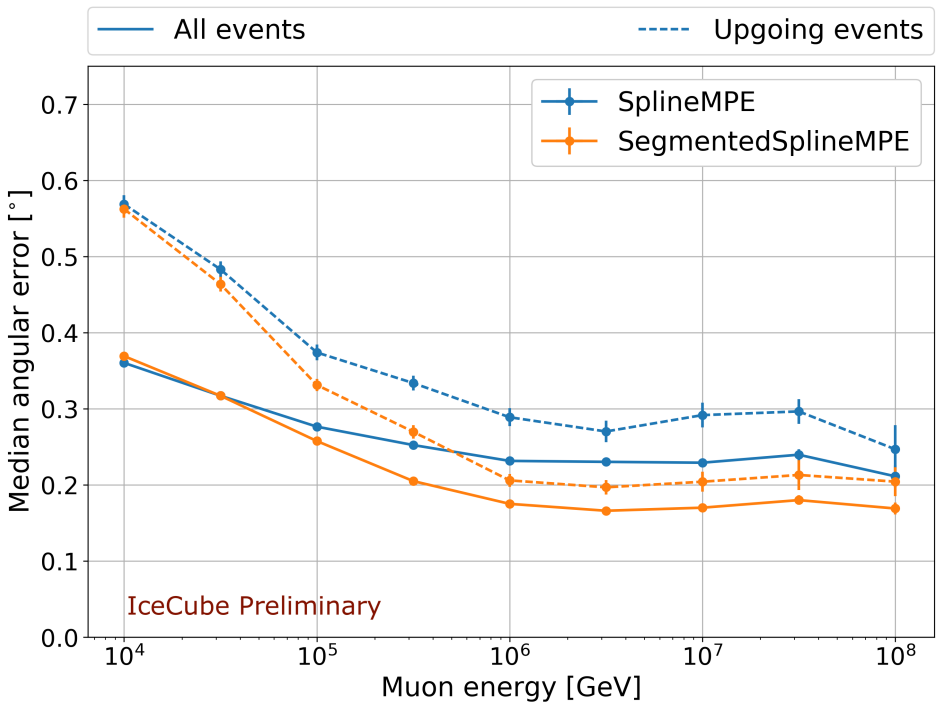
Horizontal vs Vertical Events

- Horizontal events: $90° < \text{Zenith} < 120°$
- Upgoing events: $130° < \text{Zenith} < 180°$
- Larger improvements for upgoing tracks

Horizontal Events

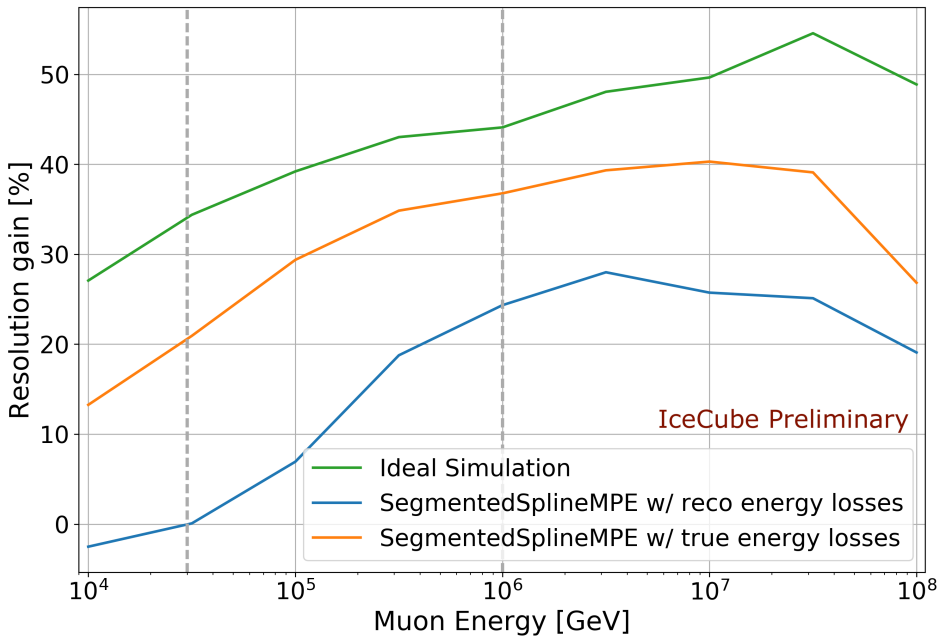


Upgoing Events



Which improvements for Gen2?

- Improvements w.r.t. SplineMPE (standard track reconstruction)



15 years projection for horizontal events

	Reconstruction	5σ Discovery Flux	90% Upper Flux Limit
IceCube	SplineMPE	$0.575 \times 10^{-12} \cdot \mathrm{E}^2$ cm^{-2} s^{-1}	$12.723 \times 10^{-12} \cdot \mathrm{E}^2$ cm^{-2} s^{-1}
$\phi_{\mathrm{IceCube}}/\phi_{\mathrm{Gen2}}$	SplineMPE	3.54	1.25
$\phi_{\mathrm{IceCube}}/\phi_{\mathrm{Gen2}}$	SegmentedSplineMPE	3.69	1.30

Summary

- Current muon reconstruction assumes continuous energy loss along the muon track, and does not take into account PMT-related effects
- A correct description of the expected arrival time distribution of photons would increase the resolution by $\sim 40\%$ at 100 TeV and $\sim 45\%$ at 1 PeV
- PMT-related effects are not the major limiting factor of the angular resolution
- A new direction reconstruction has been developed that includes stochastic energy losses in the likelihood model
- Parameterization of stochastic energy losses improves the angular resolution by 10% at 100 TeV and 25% at 1 PeV

Backup slides

How to improve reconstruction at lower energies?

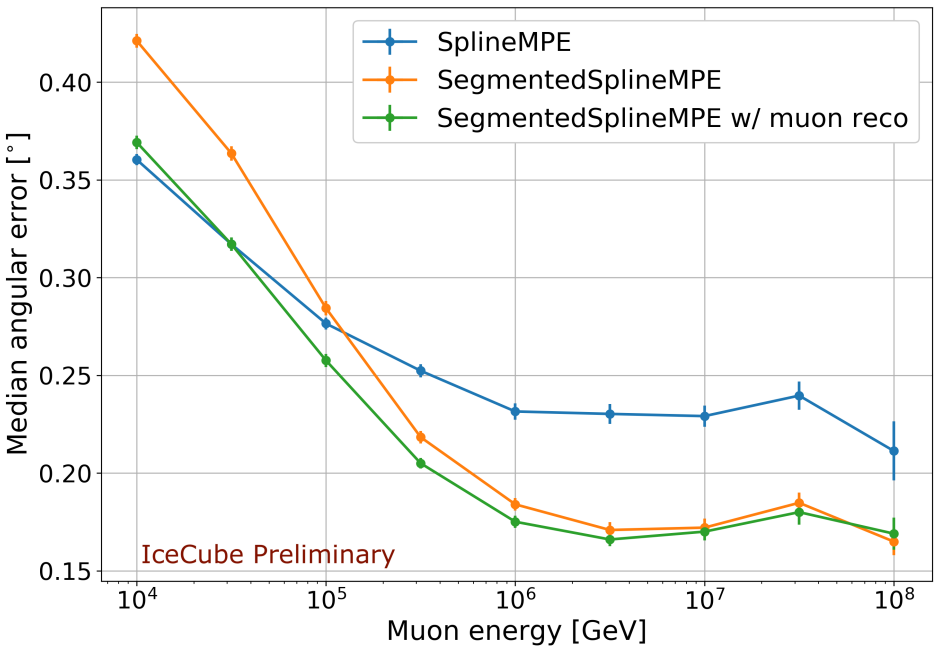
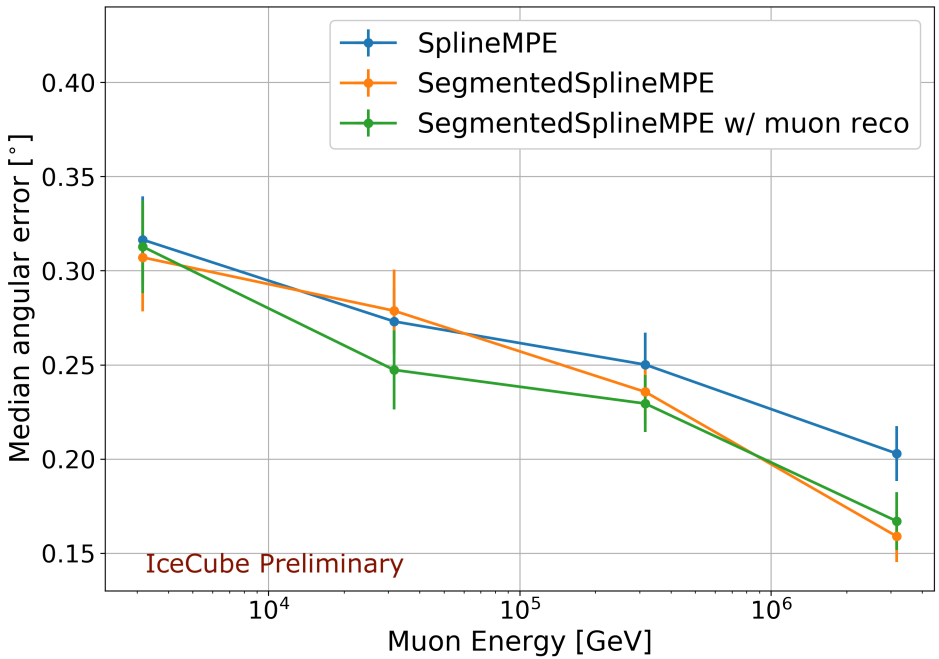
- Stochastic energy losses reconstruction can give a wrong description at low energies
- Muon track PDF considers only continuous energy losses and goes like $\sim \log E$
- It can help to give a better description at lower energies
- For each DOM, the PDF is:

$$p(t_{res}) = \frac{A \cdot p_{\mathrm{muon}}(t_{res}) + B \cdot p_{\mathrm{cascades}}(t_{res}) + C \cdot p_{\mathrm{noise}}}{A + B + C}$$

where A, B and C are amplitudes of each term

How to improve reconstruction at lower energies?

Gen2



IceCube