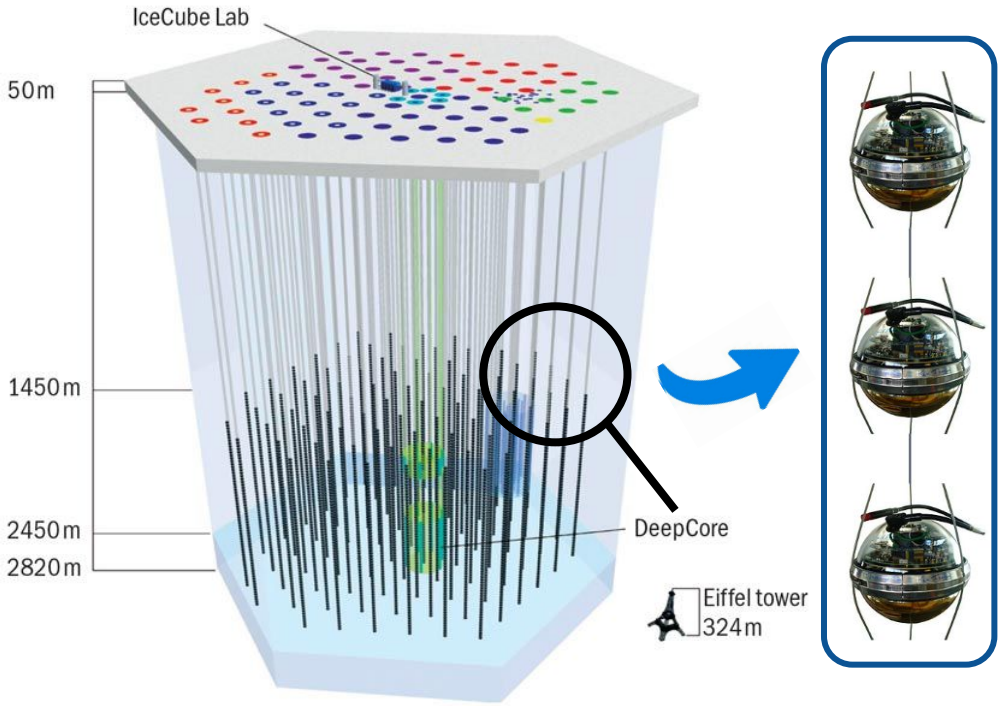
Intrinsic Resolution Limits in Low-Energy Reconstruction with IceCube

Kaustav Dutta

NBI Summer School 2023

July 17, 2023

The IceCube Experiment



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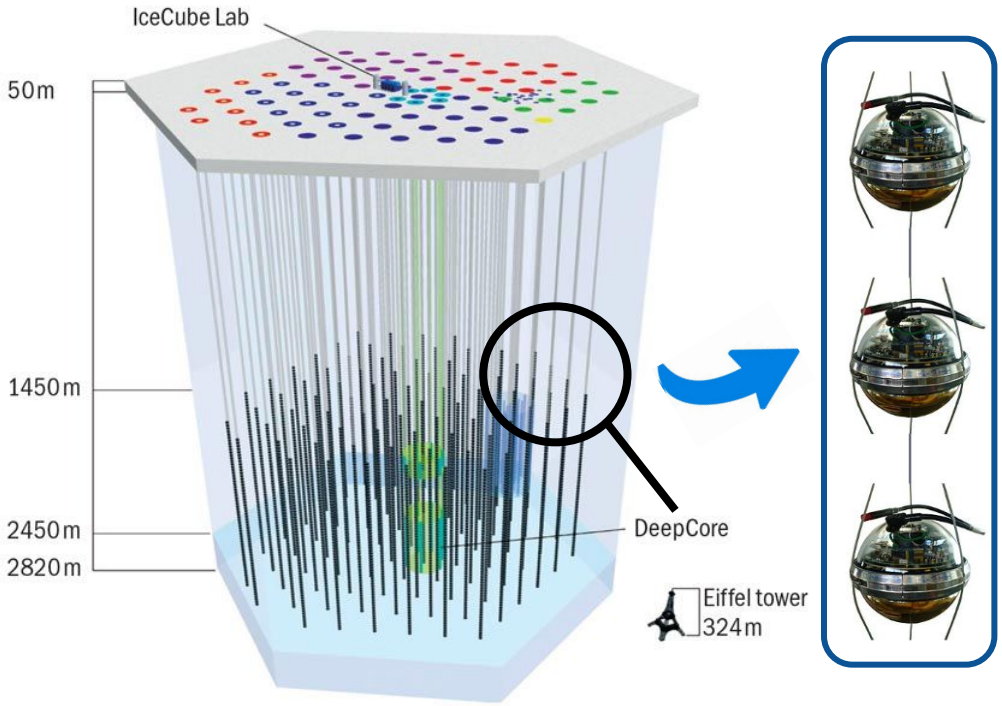
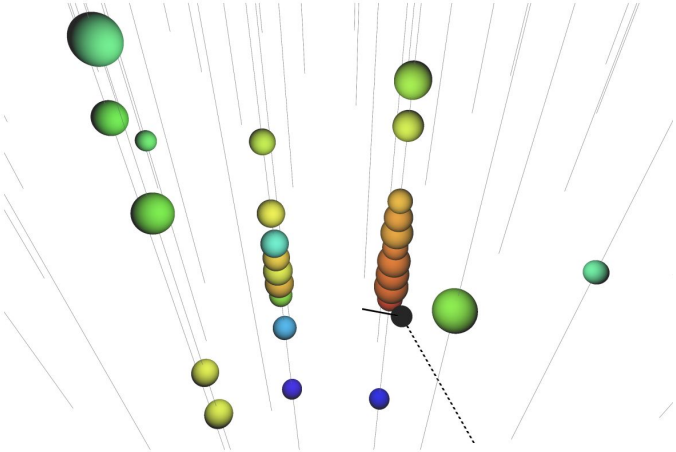


$E_{reco} \sim 25GeV$



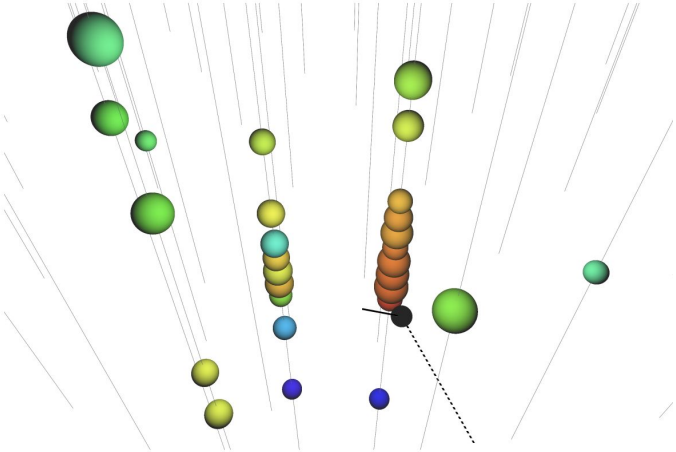
arXiv:2203.02303

Low Energy Reco Challenges & Prospects

Why challenging? fewer cherenkov photons = fewer hits

Why interesting?

1. Neutrino Mass Ordering
2. Oscillation parameters estimation
3. ν_τ identification
4. Sterile Neutrino detection



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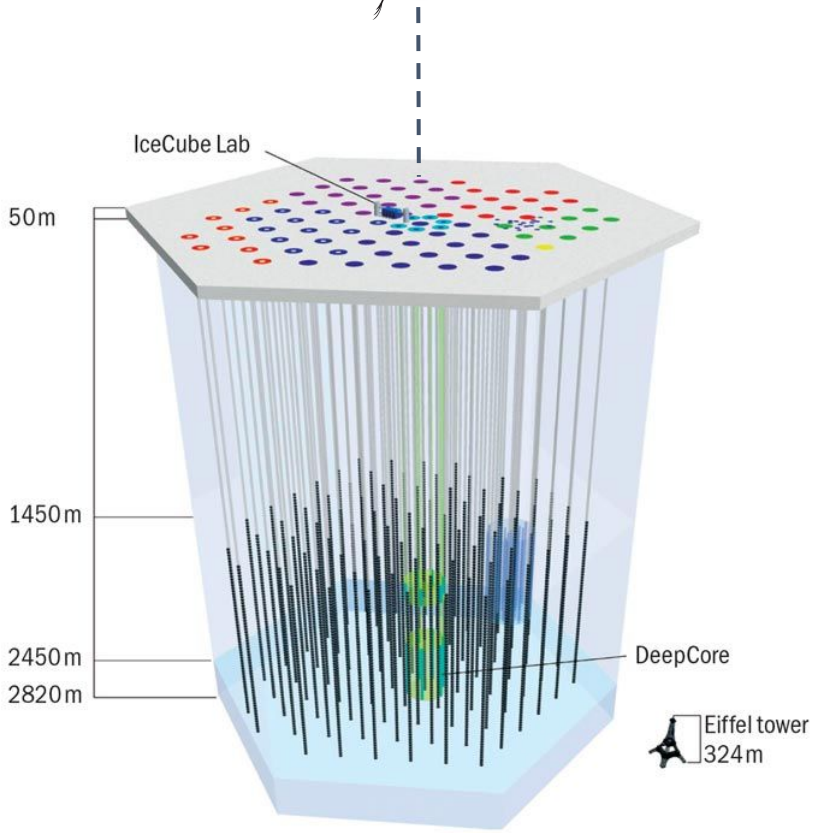
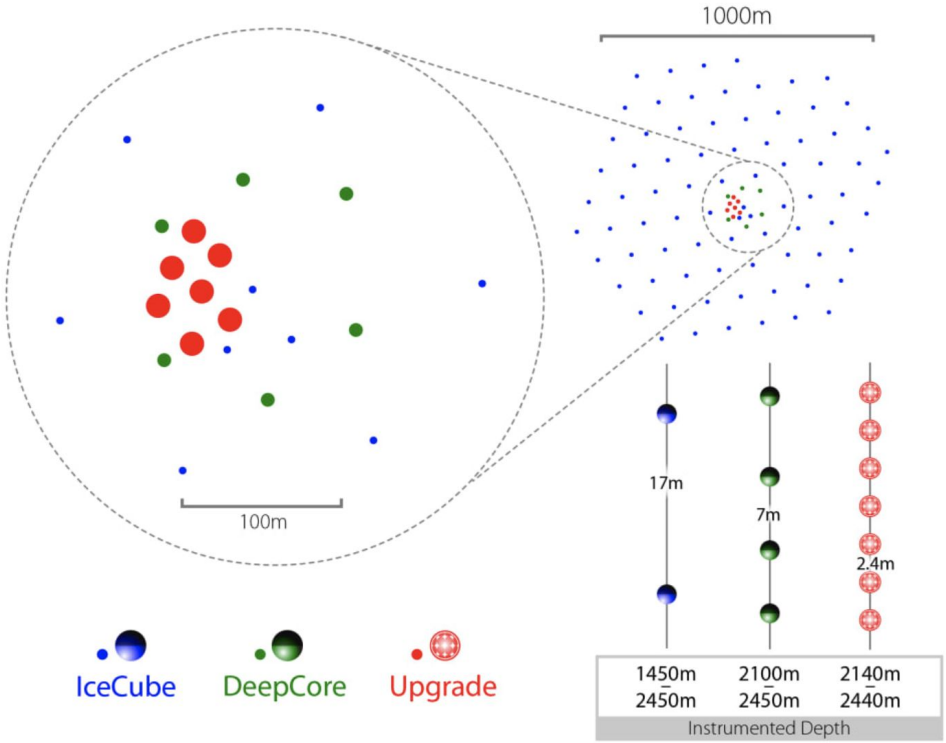
IceCube Low Energy Arrays

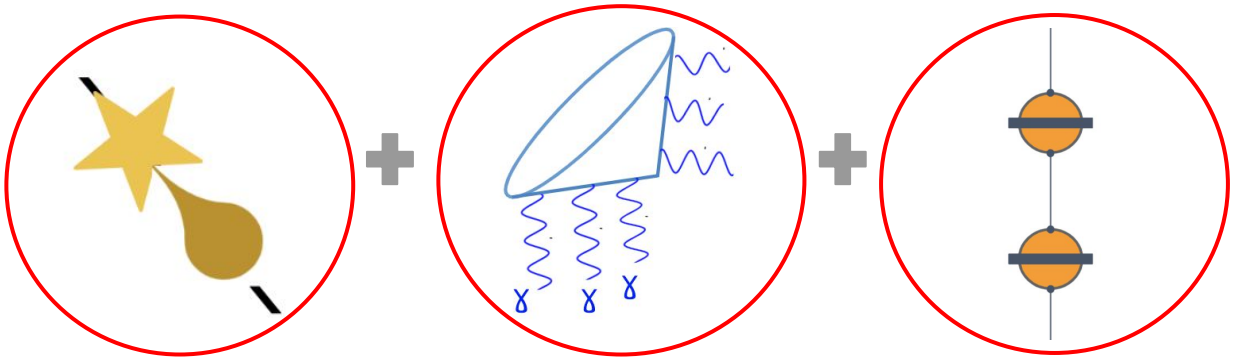




doi.org/10.1016/j.nima.2018.11.109

Towards my work…

- Which aspects are **limiting** the reconstruction performance at low energies?
- Information in events limited by



statistical fluctuations in shower development

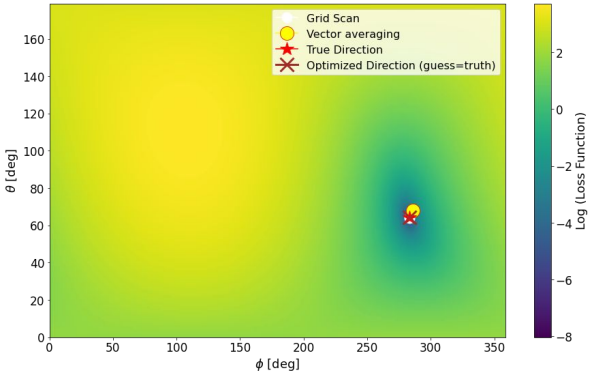
In-ice scattering

Detection efficiencies

- What are the **resolution limits** if we have access to MC truth information**?**

Reconstruction strategies - Loss function

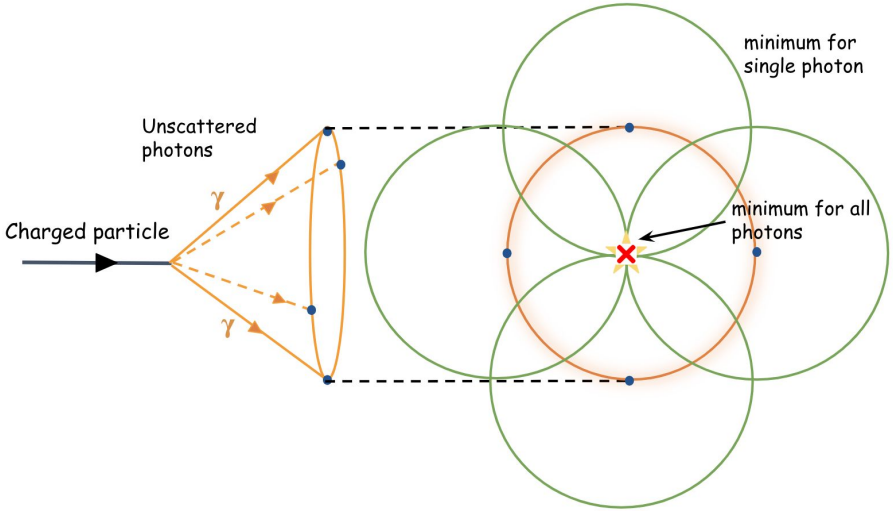
Direction information: $L(\vec{\theta}) = \sum_{i=1}^{N} (\vec{\nu}(\vec{\theta}) \cdot \vec{\gamma}_i - \cos 41^\circ)^2$



No scattering

Hits: 18

Resolution: 0.1^0



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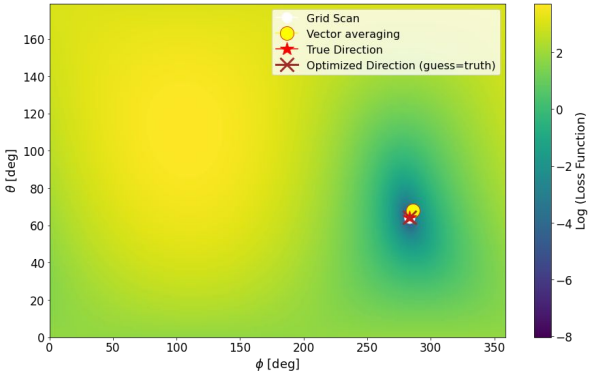

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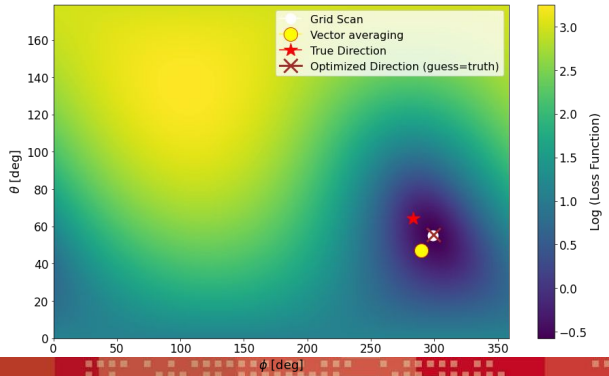
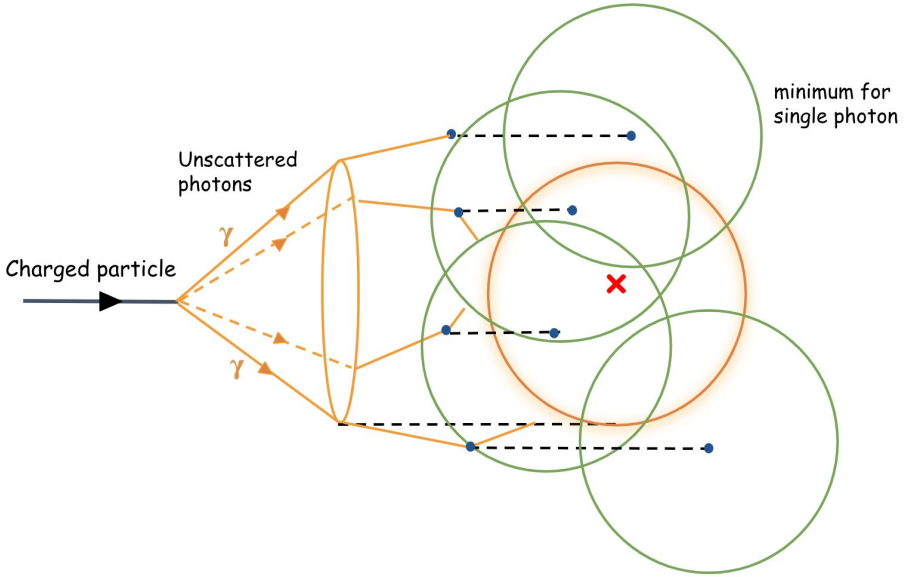


Scattering

Hits: 12

Resolution: 16.4^0



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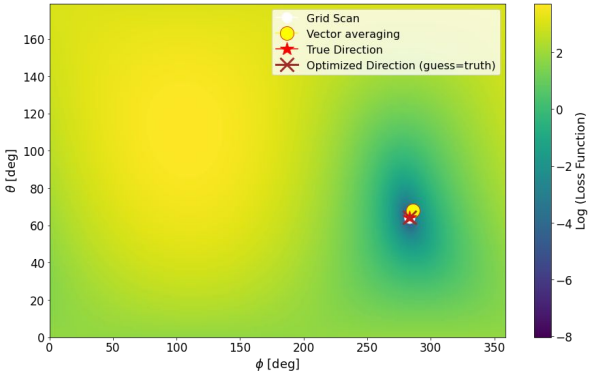
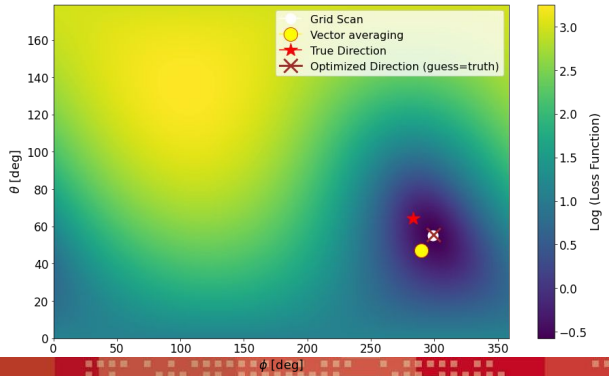


No scattering

Hits: 18

Resolution: 0.123^0



Scattering

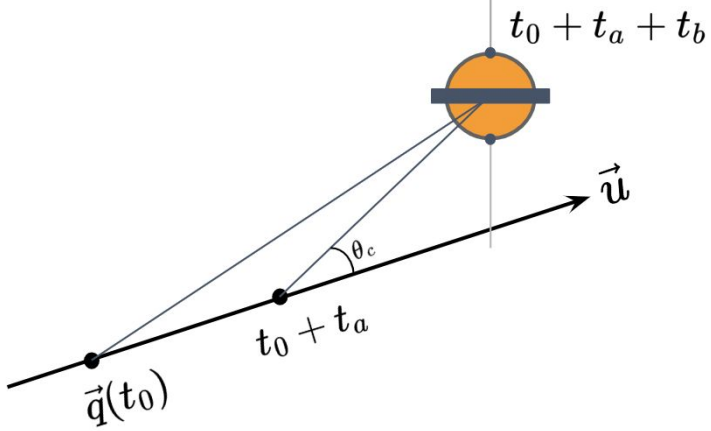
Hits: 12

Resolution: 16.476^0

Timing information: $L(\vec{\theta}) = \sum_{i=1}^{N} (t_{\text{geom},i}(\vec{\theta}) - t_{\text{obs},i})^2$

$$t_{\text{geom}} = t_0 + \frac{1}{c} + \left((\vec{r} - \vec{q}) \cdot \vec{u} + \frac{d_\gamma}{n_{\text{ph}}} (n_{\text{ph}} n_{\text{gr}} - 1) \right)$$

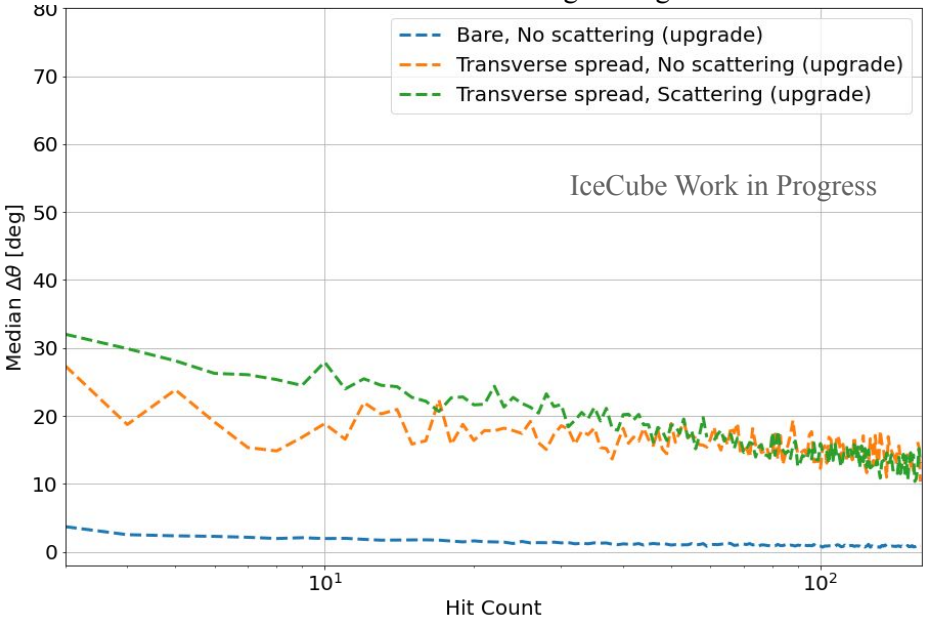
$$d_\gamma = n_{\text{ph}} \sqrt{\frac{1}{n_{\text{ph}}^2 - 1} (\vec{u} \times (\vec{r} - \vec{q}))^2}$$



Overview: Reconstruction using Loss Function

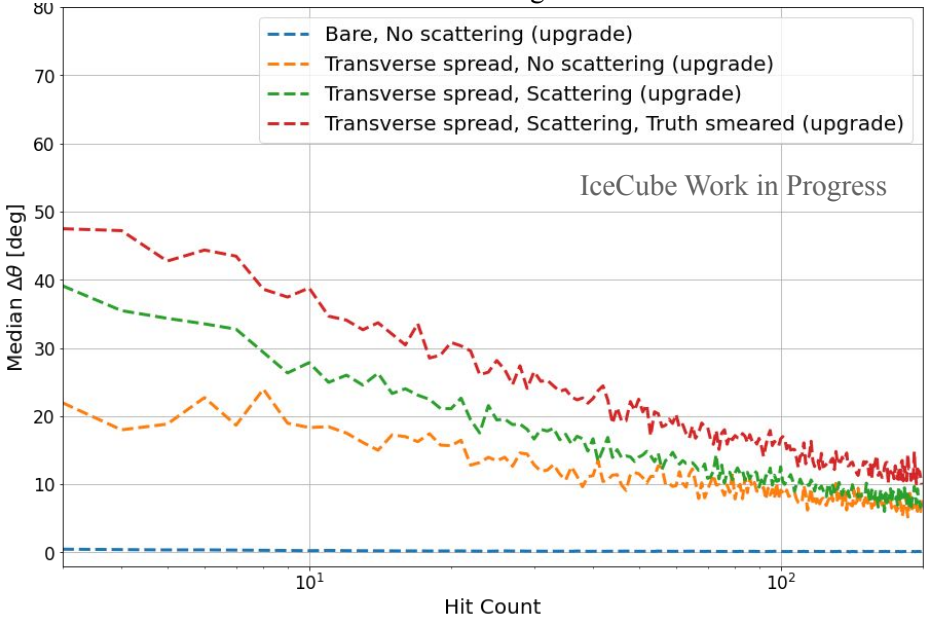
Timing information

Loss function minimisation using Timing information



Direction information

Loss function minimisation using Direction information



Towards a Likelihood approach ….

- Loss function is a good approach and is quite fast (~0.003s/event).
- Not sure if it provides the optimal performance.

Solution?

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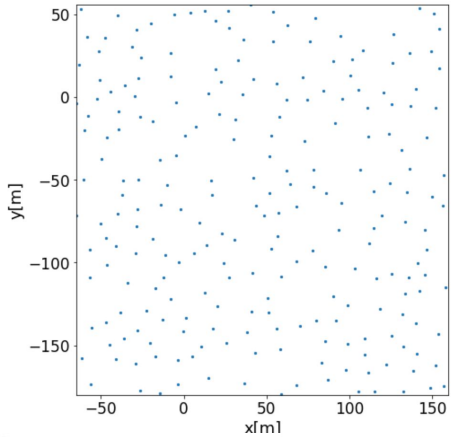
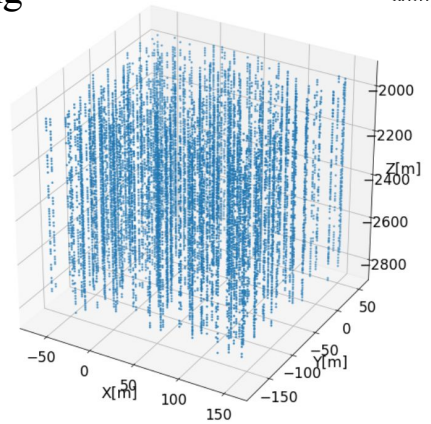
Solution? Use of likelihood approach with the true underlying PDF

Problem… Grid-like structure of arrays, biased photon sampling by sensors, PDF changes with position/direction

Solution? Randomised detector geometry!





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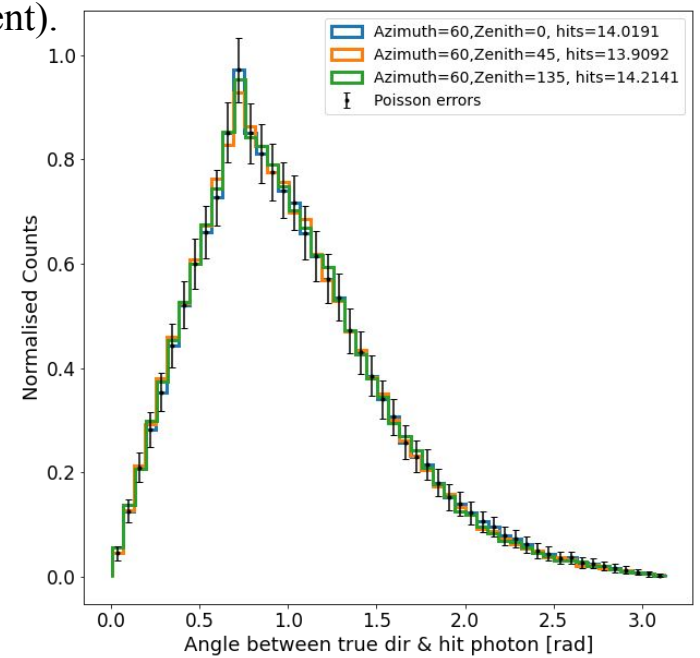
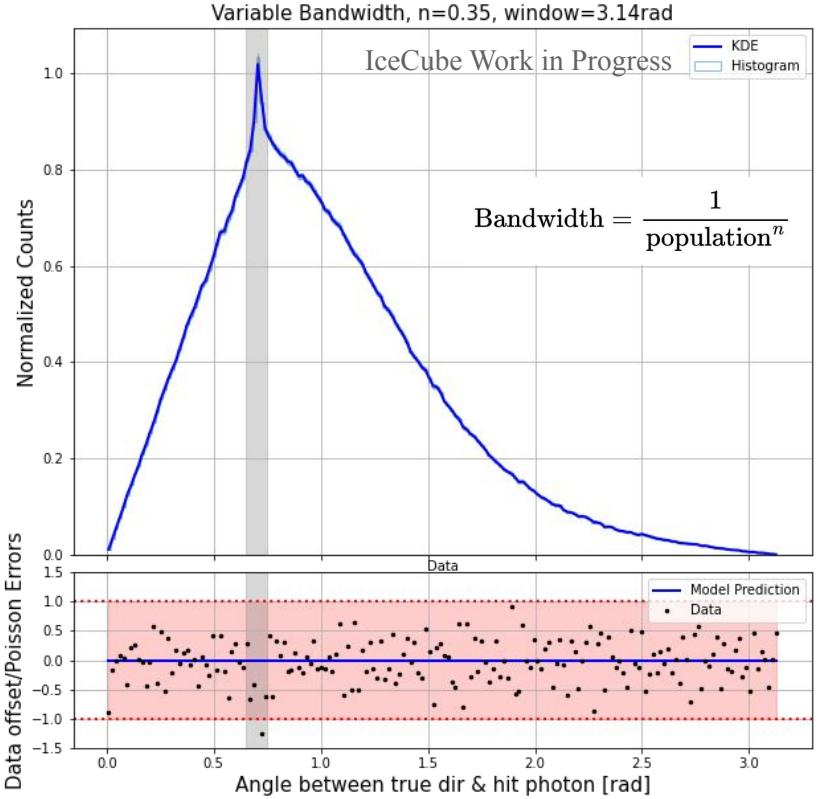
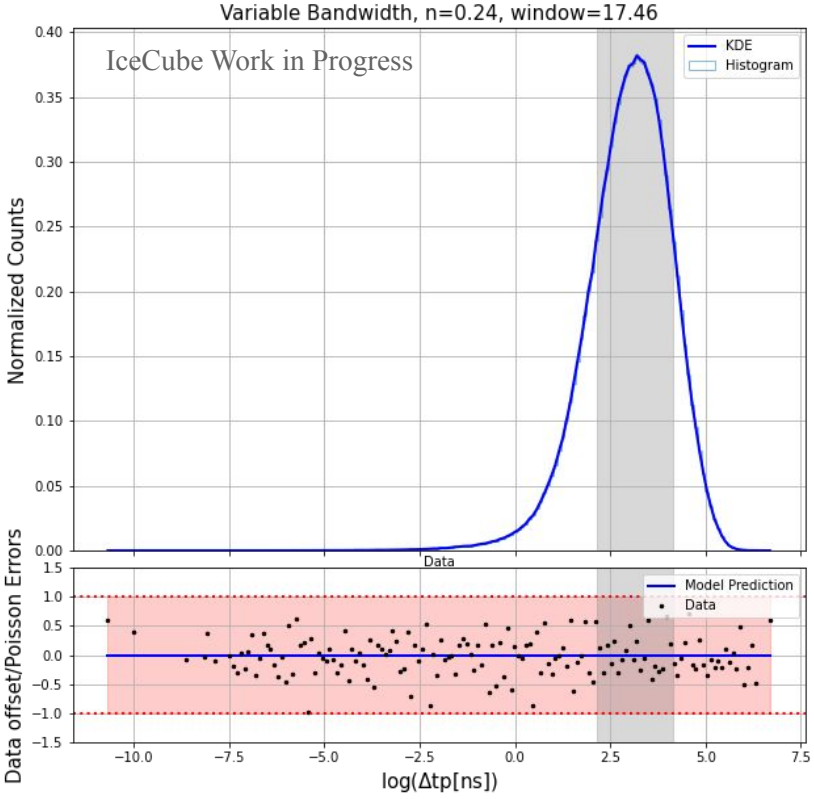


Good agreement between PDFs!

Getting PDFs by VBW KDEs

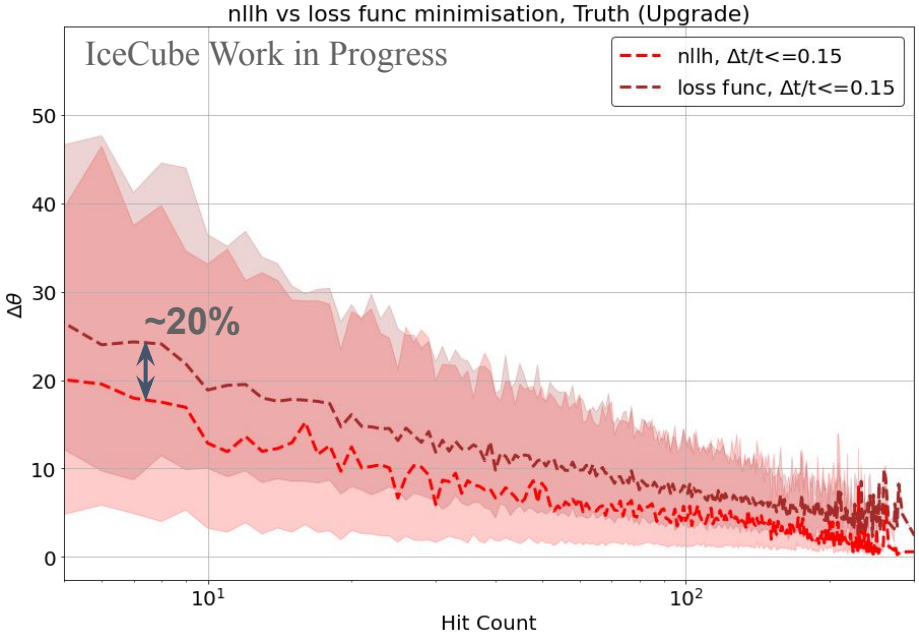


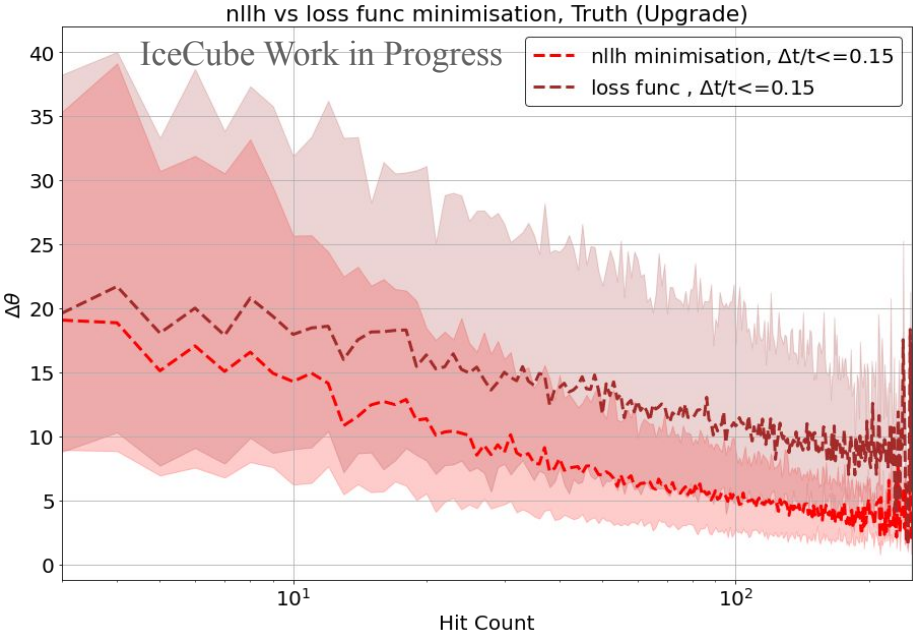


Improvement over Loss Function approach

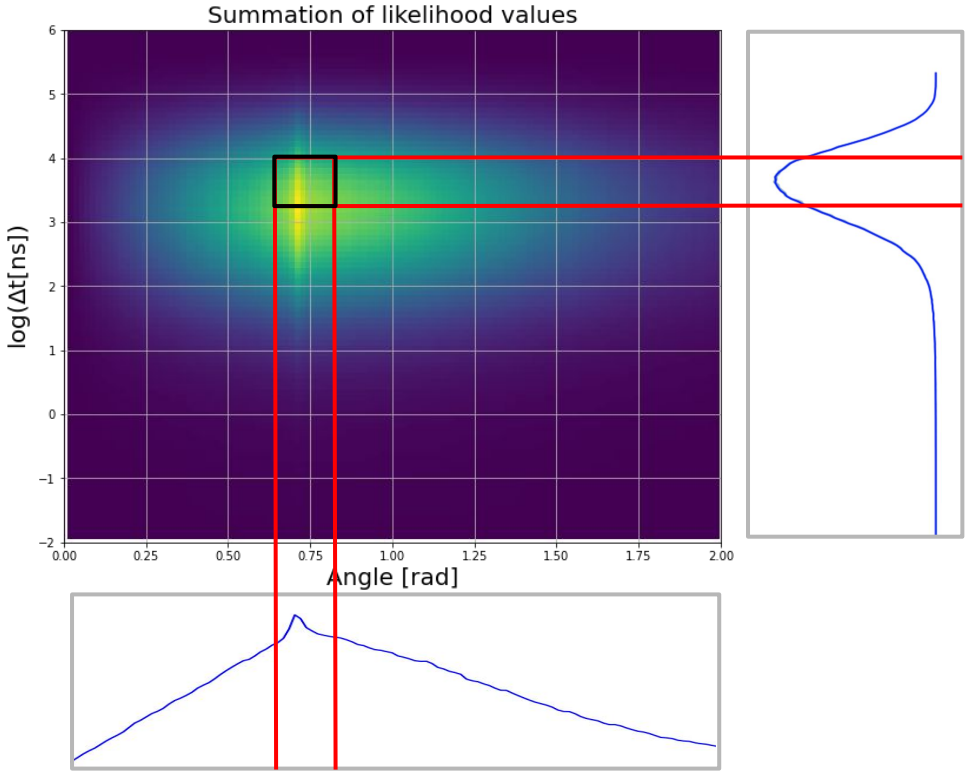
Direction information: $\hat{\theta}_{\text{opt}} = \arg\max\left[\mathcal{L}(\gamma \cdot \mathbf{u}|\boldsymbol{\theta})\right]$

Timing information: $\hat{\theta}_{\text{opt}} = \arg\max\left[\mathcal{L}(\Delta t|\boldsymbol{\theta})\right]$



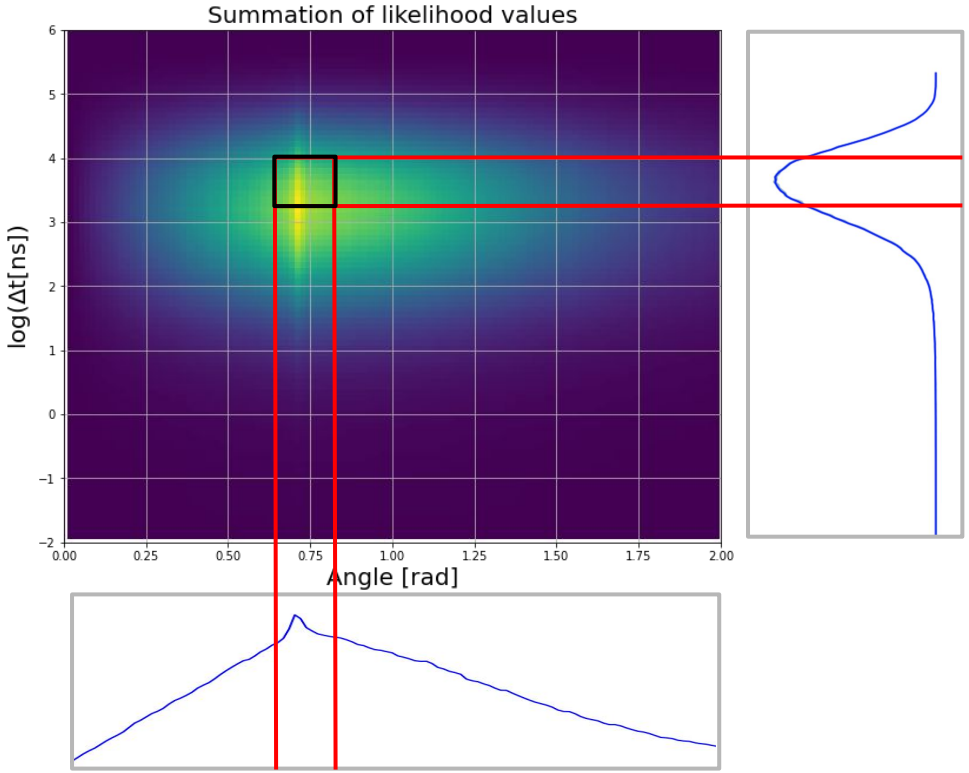


Combined Analysis using Synergic Information



$$\log \mathcal{L}_{\text{joint}} = \log \mathcal{L}_{\text{direction}}(\gamma \cdot \mathbf{u}|\theta) + \log \mathcal{L}_{\text{timing}}(\Delta t|\theta)$$

Combined Analysis using Synergic Information



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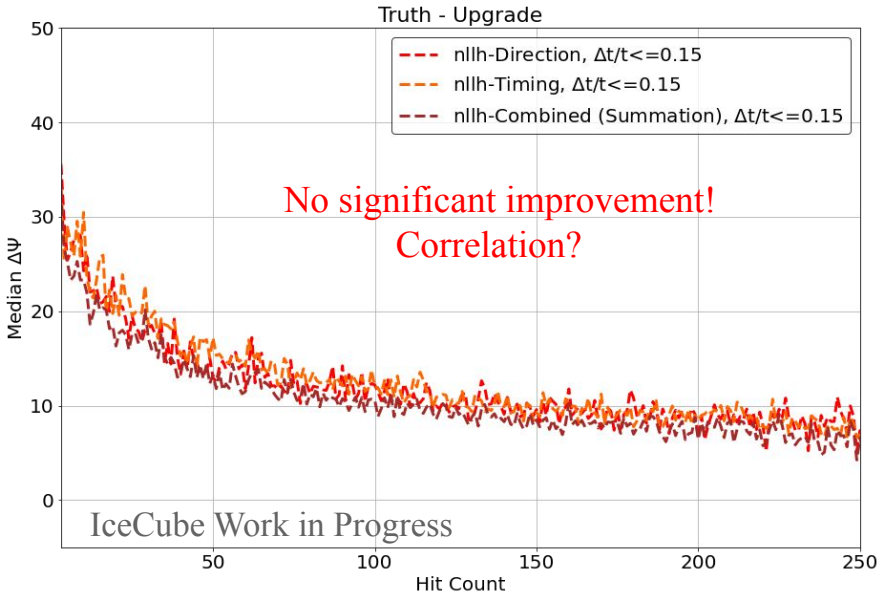

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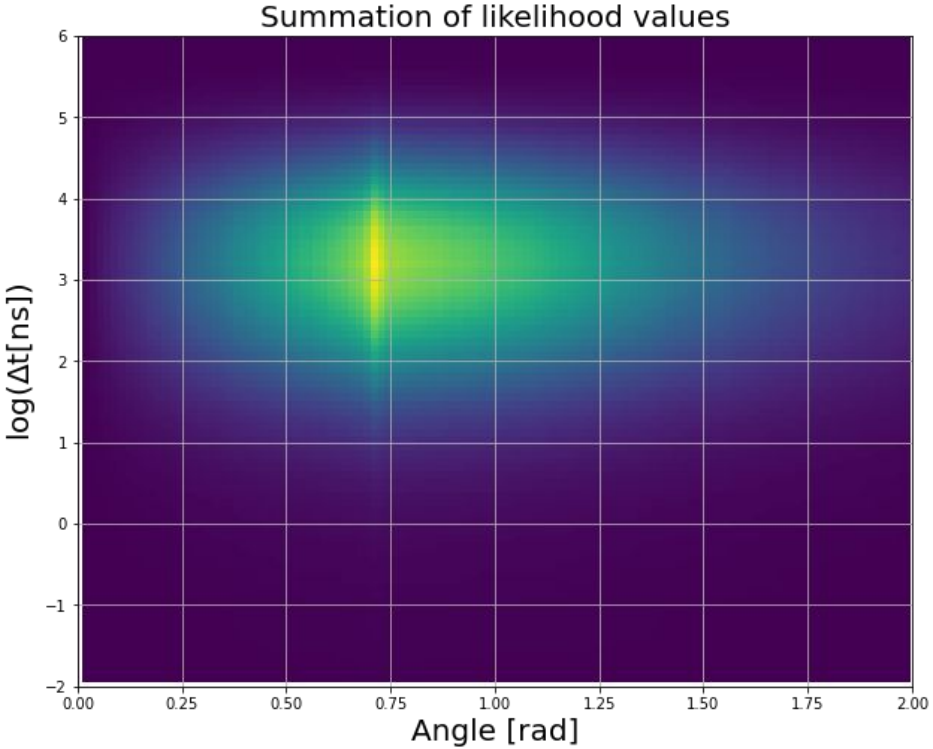

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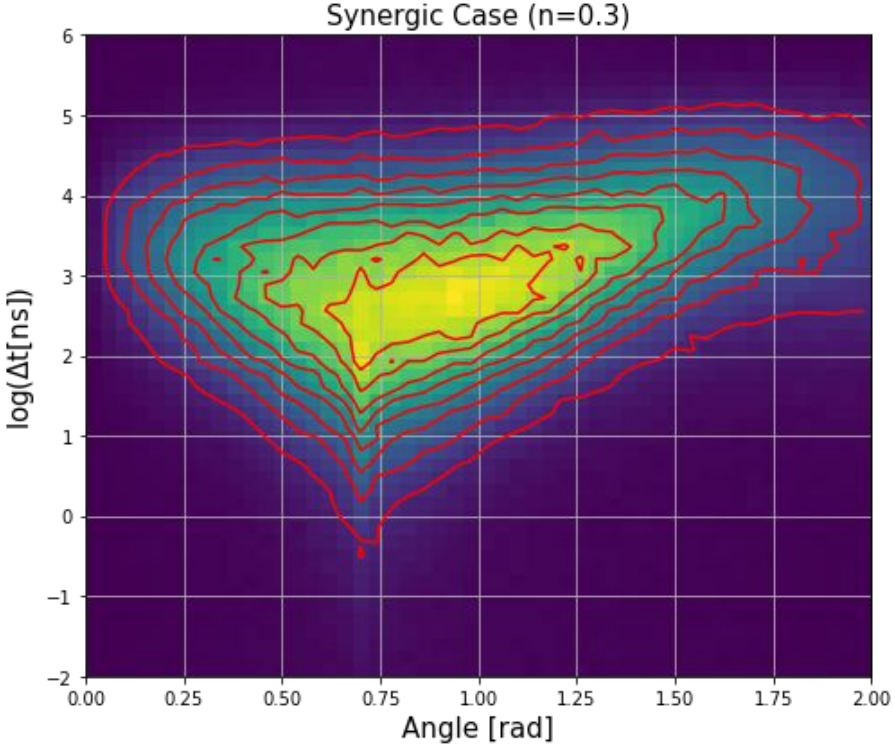
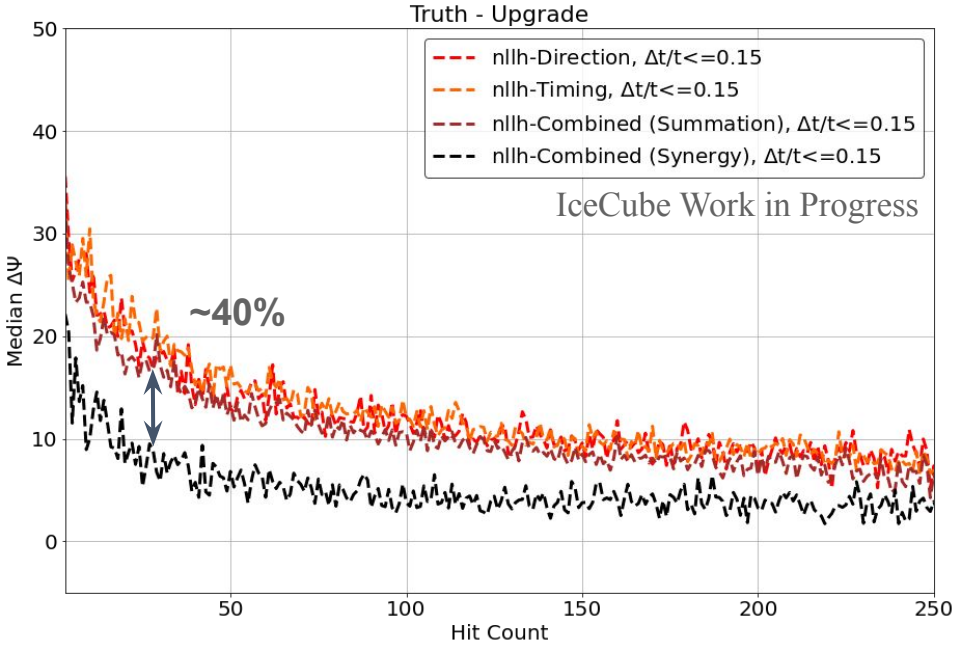
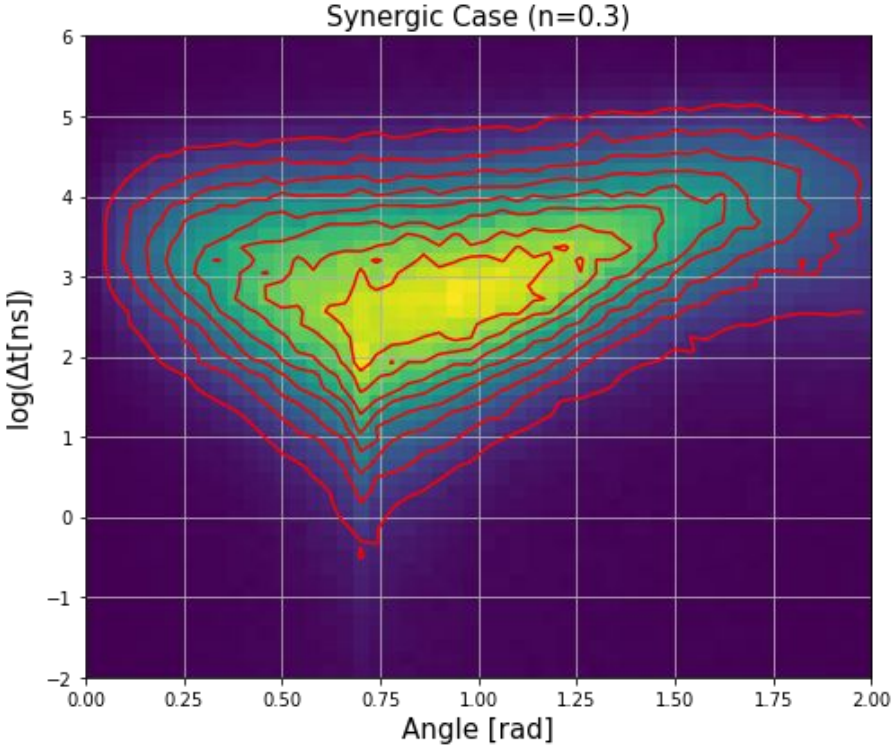


$$\log L(\gamma \cdot \mathbf{u}, \Delta t|\theta)$$

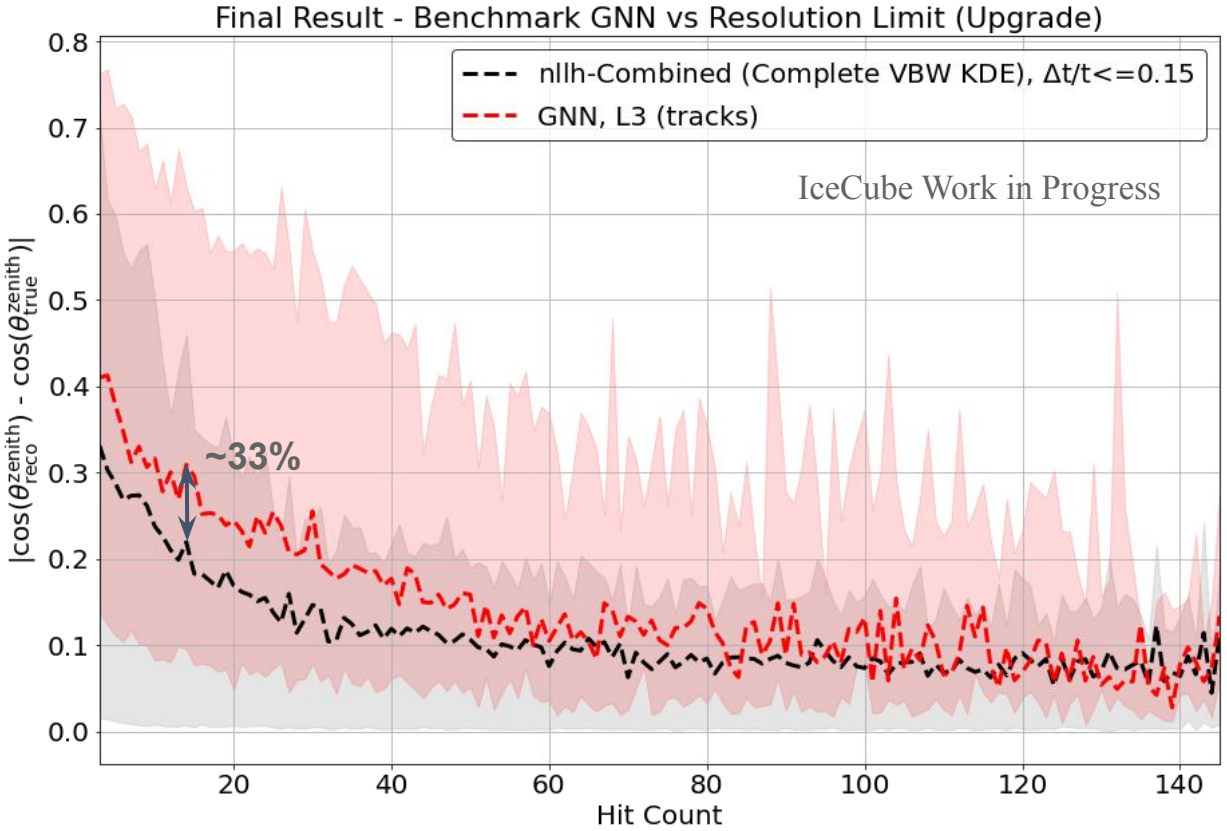
Combined Analysis using Synergic Information





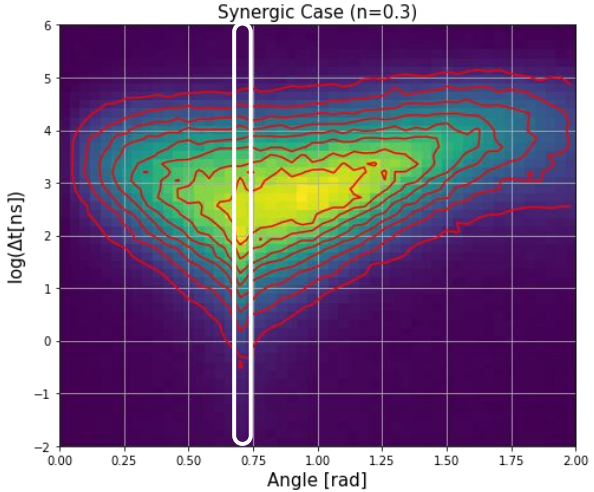
$$\log L(\boldsymbol{\gamma} \cdot \mathbf{u}, \Delta t | \theta)$$

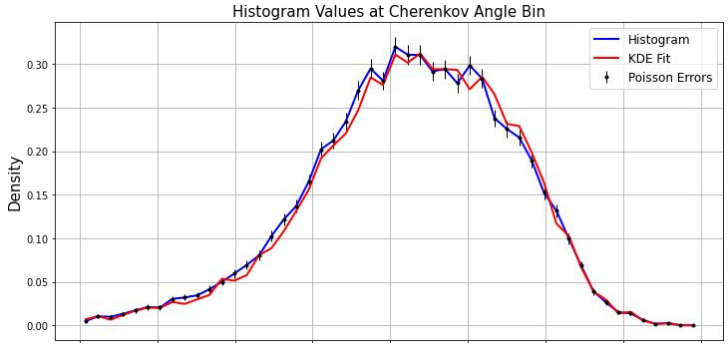
Comparison with benchmark algorithm



Ongoing & Future Work

- Extend the likelihood analysis to the DeepCore-like geometry.
- Try to improve the modelling of the PDF (more statistics).



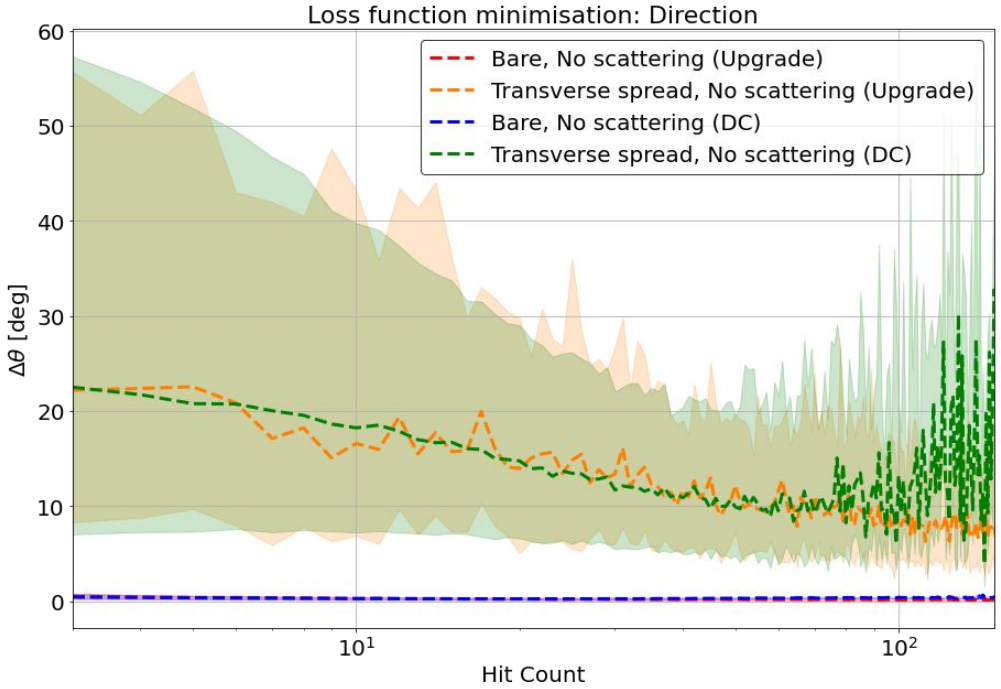


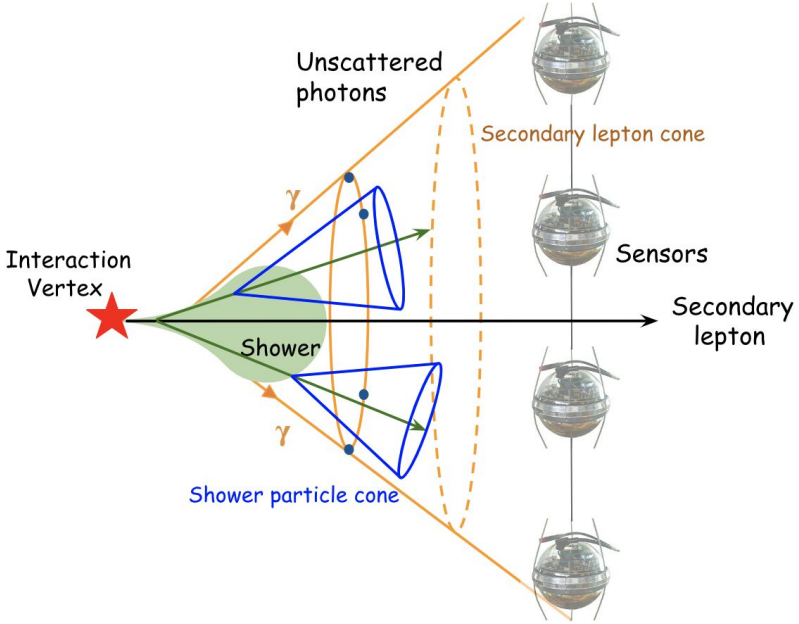
Thank you!

Questions?

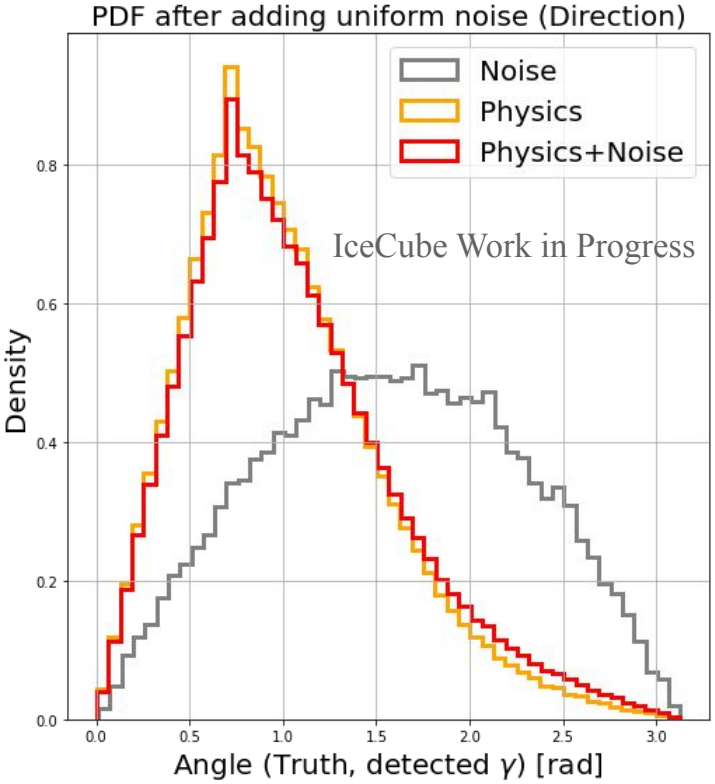
Backup Slides

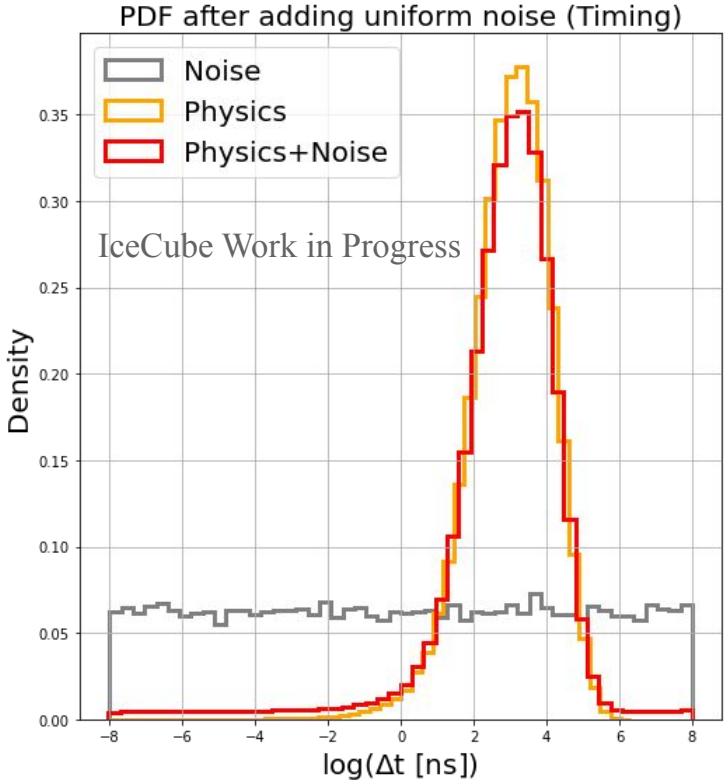
Effect of Shower Spread



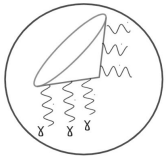


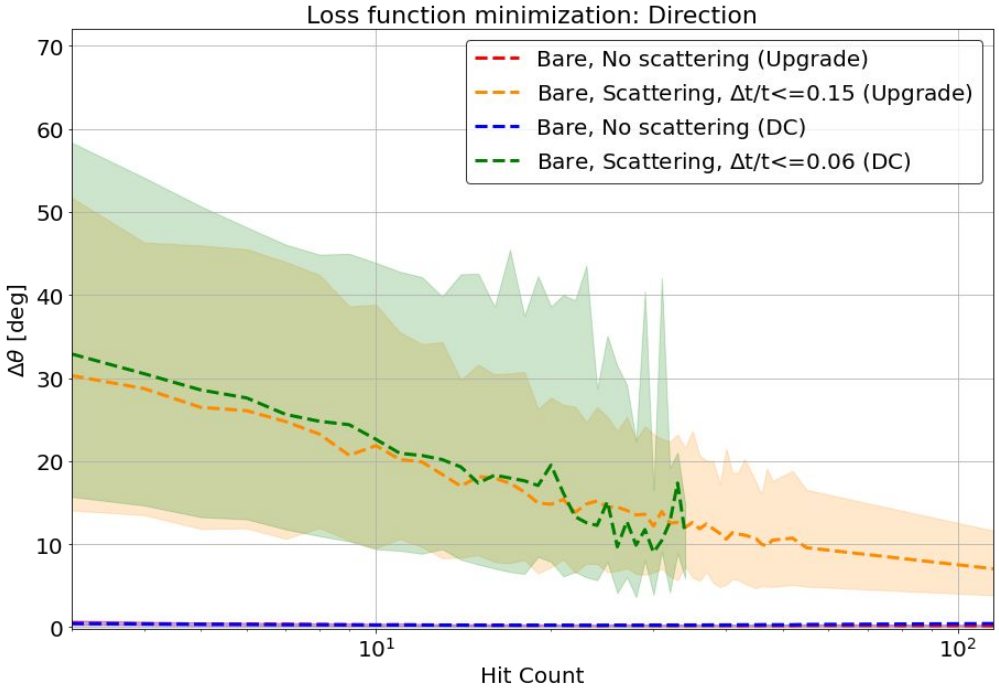
Finally adding noise

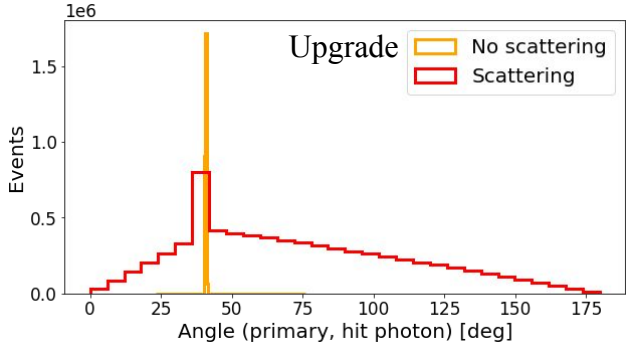


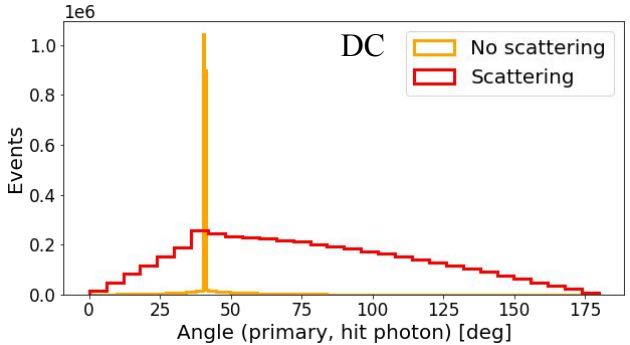


Effect of Scattering



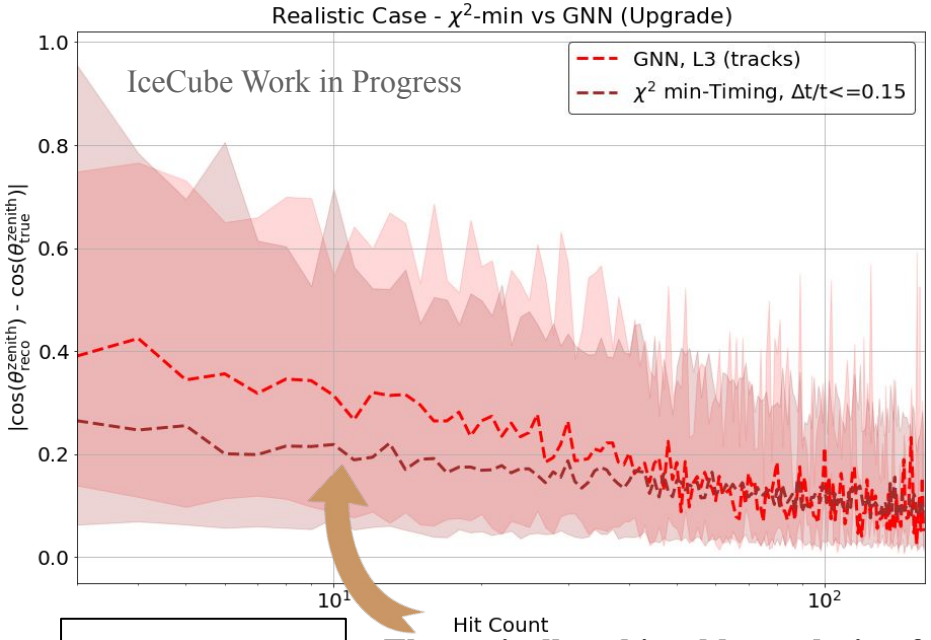






Comparison with benchmark algorithm (April, 2023)

Timing information



E ∈ [1GeV, 20GeV]
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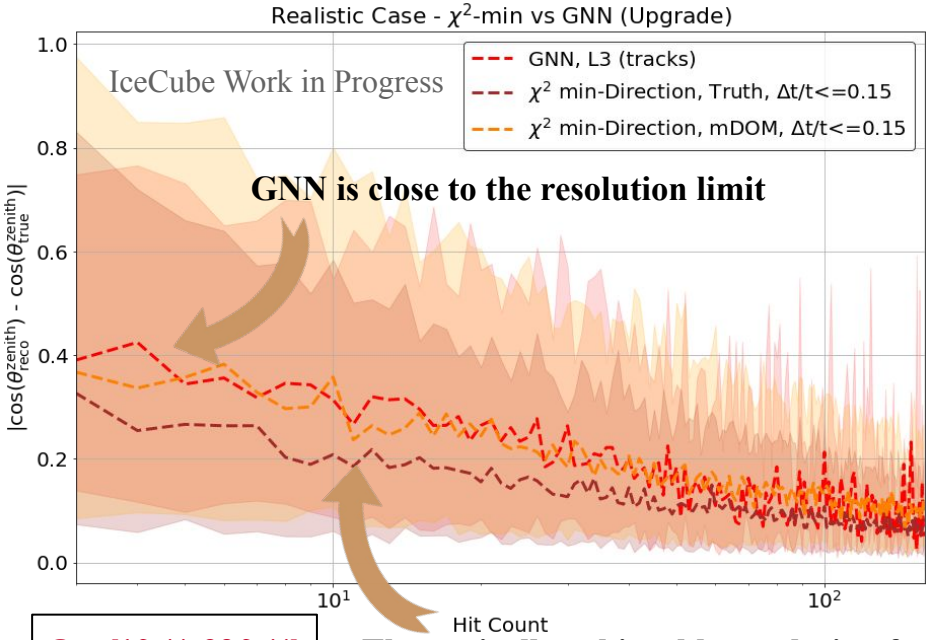
Theoretically achievable resolution for the detector geometry (using timing information)

Direction information



E ∈ [1GeV, 20GeV]
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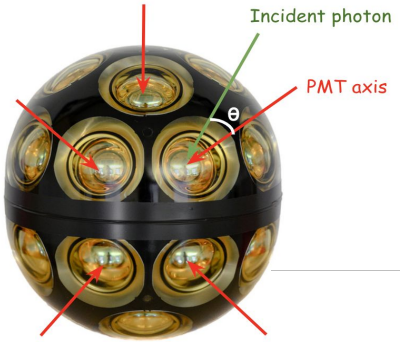
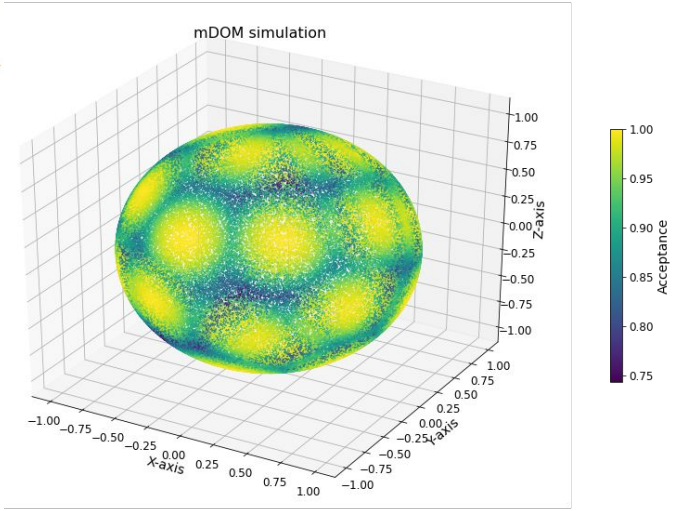
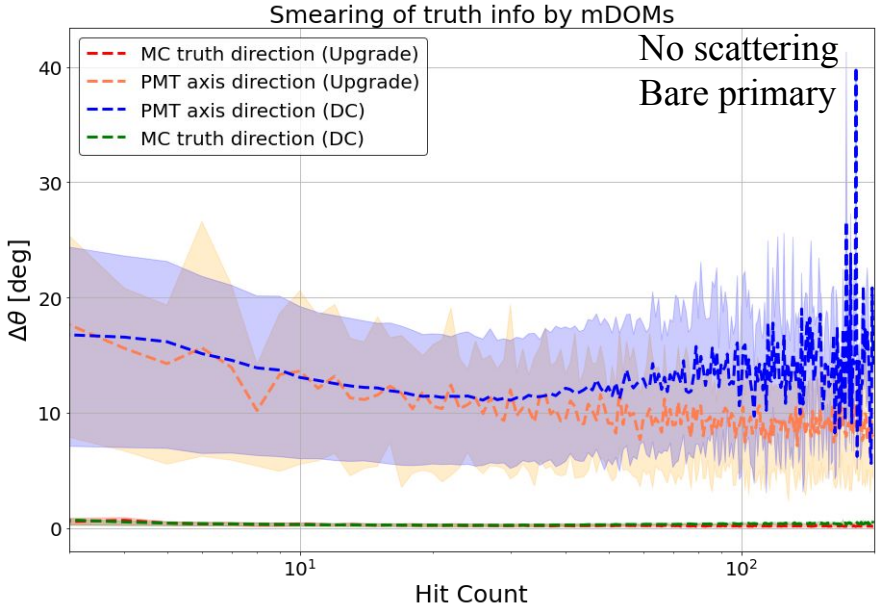
Theoretically achievable resolution for the detector geometry (using direction information)

Effect of Sensor Efficiencies



- Select the PMT in terms of **spatial proximity** to the point of photon impact.
- Include acceptance curve information.
- Assume that photon arrives along the PMT axis : Truth information smeared.

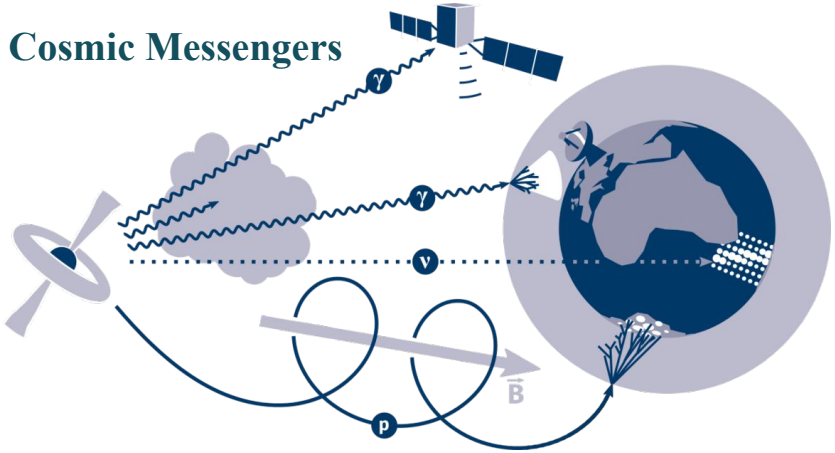


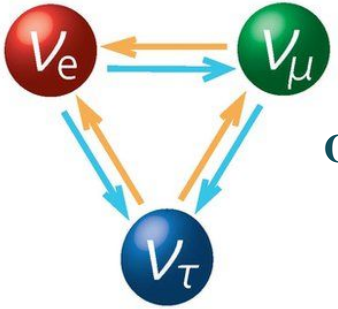


Neutrinos in the Standard Model

mass →	≈2.3 MeV/c²	≈1.275 GeV/c²	≈173.07 GeV/c²	0	≈126 GeV/c²
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
QUARKS	u up	c charm	t top	g gluon	H Higgs boson
	≈4.8 MeV/c²	≈95 MeV/c²	≈4.18 GeV/c²	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	d down	s strange	b bottom	γ photon	
	0.511 MeV/c²	105.7 MeV/c²	1.777 GeV/c²	91.2 GeV/c²	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS	<2.2 eV/c²	<0.17 MeV/c²	<15.5 MeV/c²	80.4 GeV/c²	GAUGE BOSONS
	0	0	0	±1	
	1/2	1/2	1/2	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

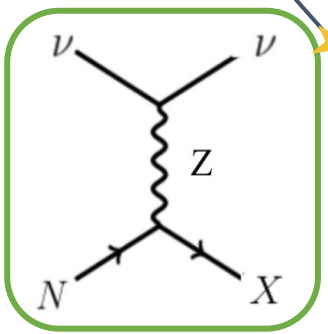
Cosmic Messengers



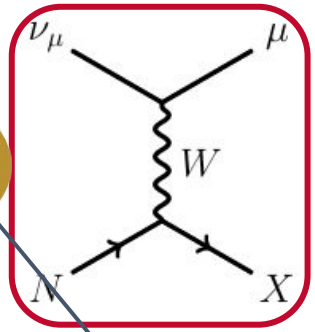


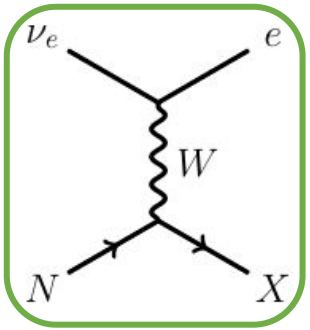
Oscillations (BSM Physics)

Neutrino-Nucleon Interactions

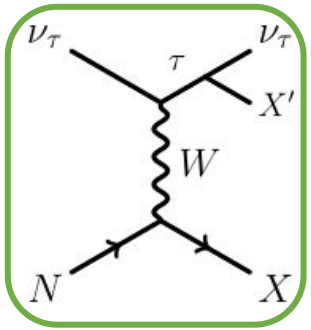


Neutral Current





Charged Current



HS

Track

μ^-

17m

HS

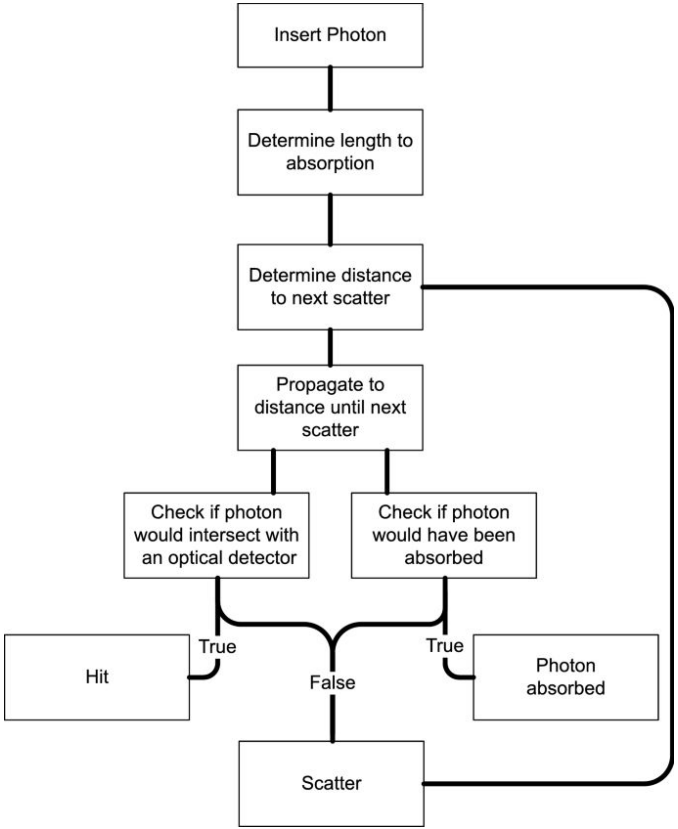
ES

HS

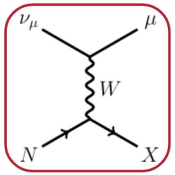
HS

ES/HS

Photon Propagation Code



IceCube Event Signatures



Muon track signal

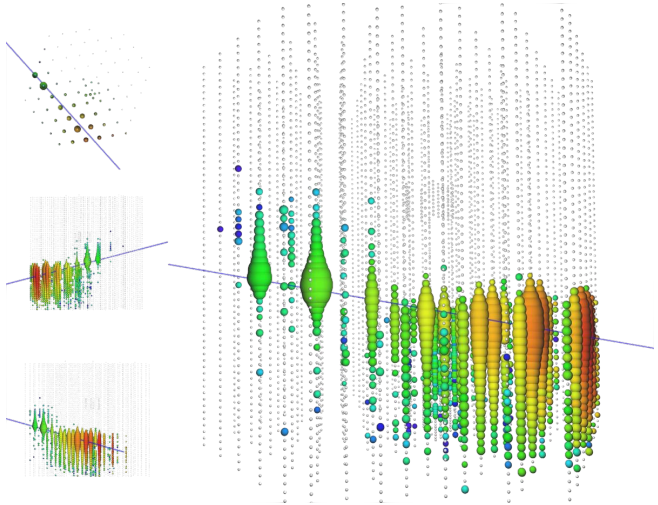
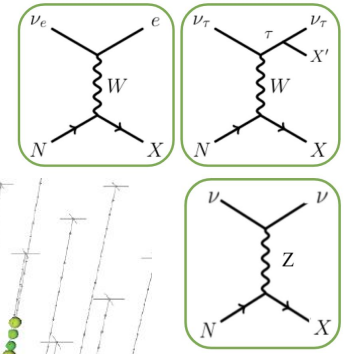


Image: J. Phys, Conf. Ser. 888 012007

Good angular resolution: **Neutrino astronomy**

- **~0.6^0 at 10 TeV**
- Vertex can be outside the detector: **Increased effective volume**



Cascade signal

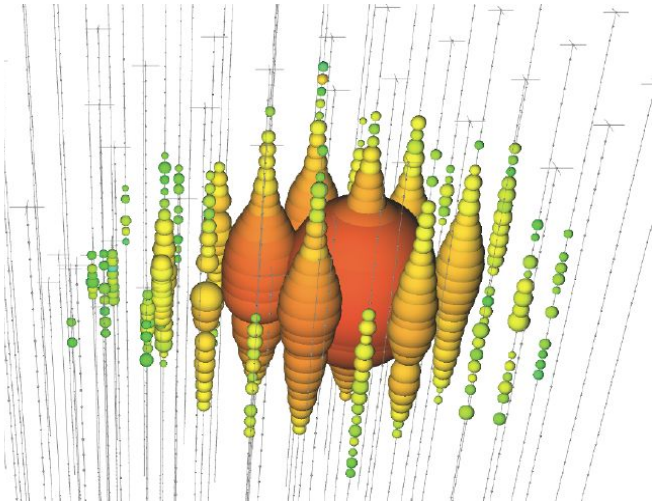
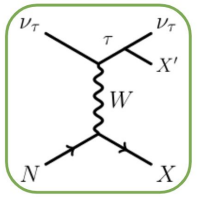


Image: J. Phys, Conf. Ser. 888 012007

ν_e, ν_τ and all-flavor neutral current

Fully active calorimeter: **High energy resolution**
Angular reconstruction above ~50 TeV



Tau Neutrino Signature

"Double-Bang" signature

$\nu_\tau \rightarrow \tau^-$

$\tau^- \rightarrow \mu^-$

Green=late arriving photons

τ lifetime=0.29ps

Red=early arriving photons

BR=18% for leptons
(τ− →μ−+νμ+ντ , e−+νe+ντ)
BR=64% for hadrons
(τ− → ντ + mesons)

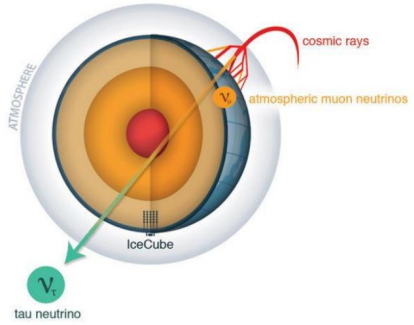
SIMULATION!

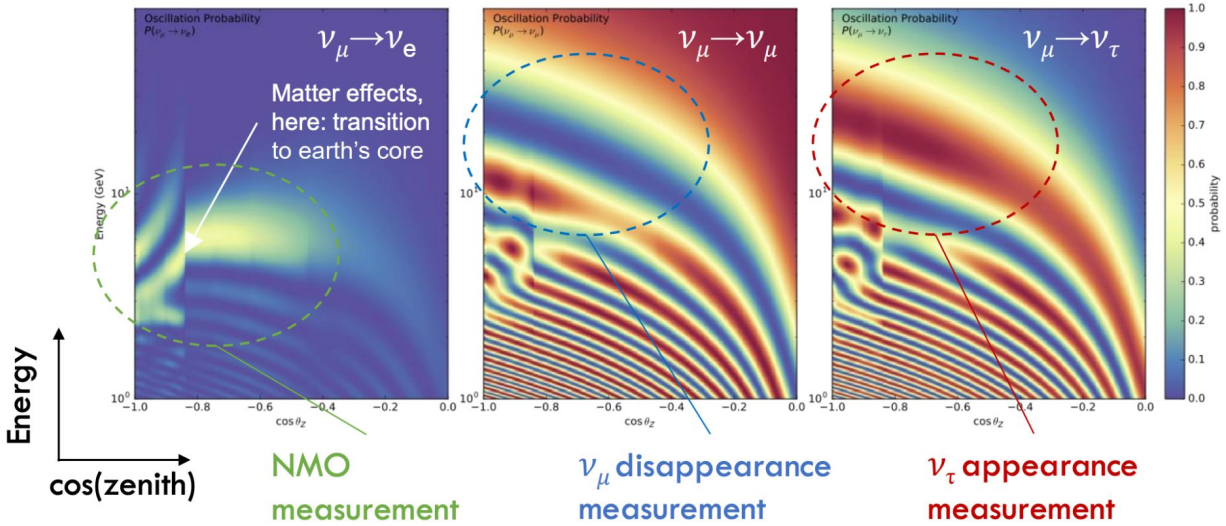
Image: J. Phys. Conf. Ser. 888 012007

IceCube & Oscillations

- For O(10) GeV neutrinos and below, earth diameter provides perfect L/E
- We can look at oscillations in the energy vs. cos(zenith) ($\propto$L) plane

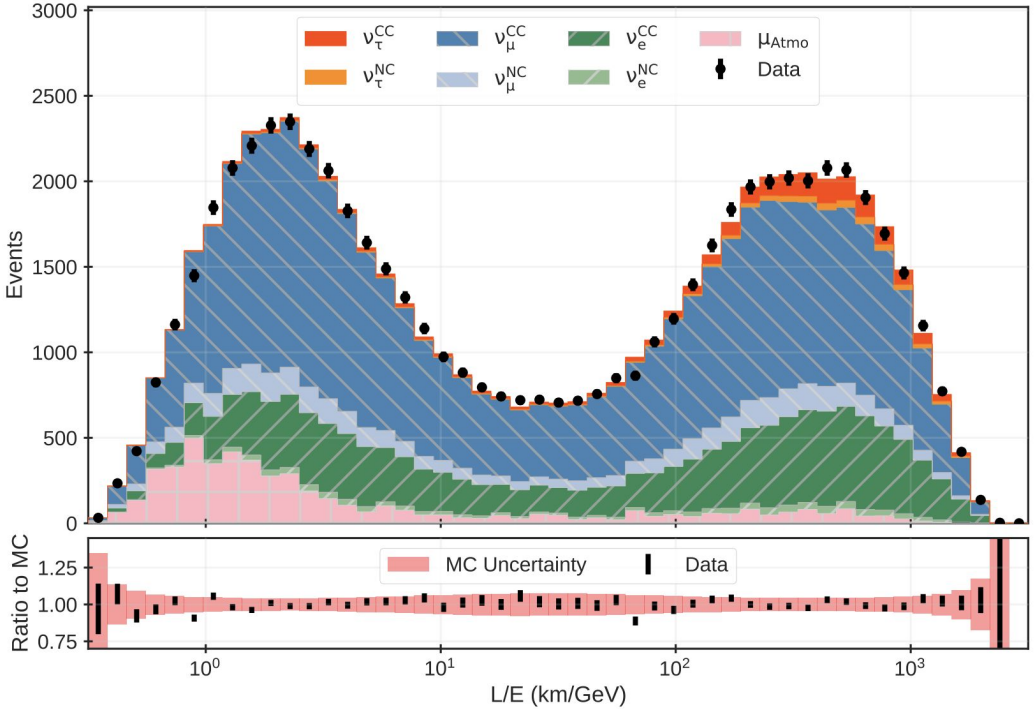
$$P_{\nu_\mu \to \nu_e} = \sin^2 2\theta \sin^2 \frac{m_2^2 - m_1^2}{4E_\nu} L$$



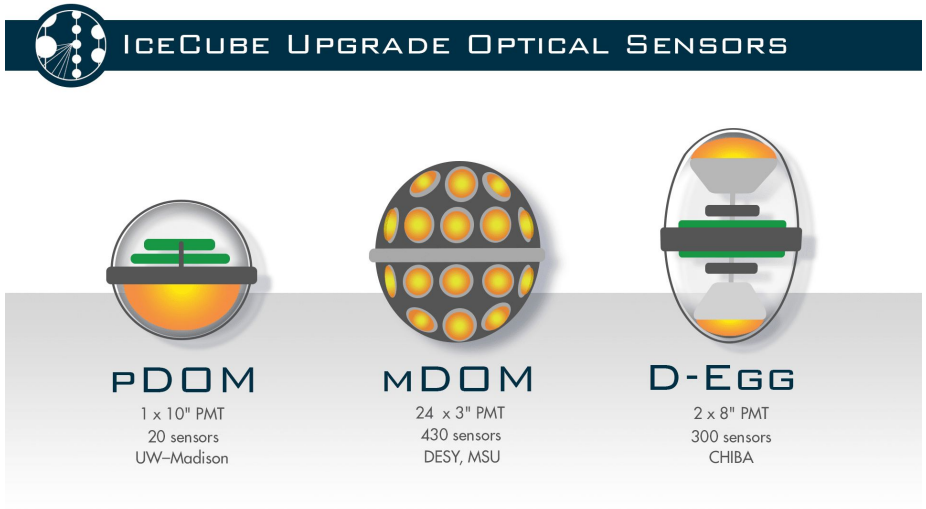


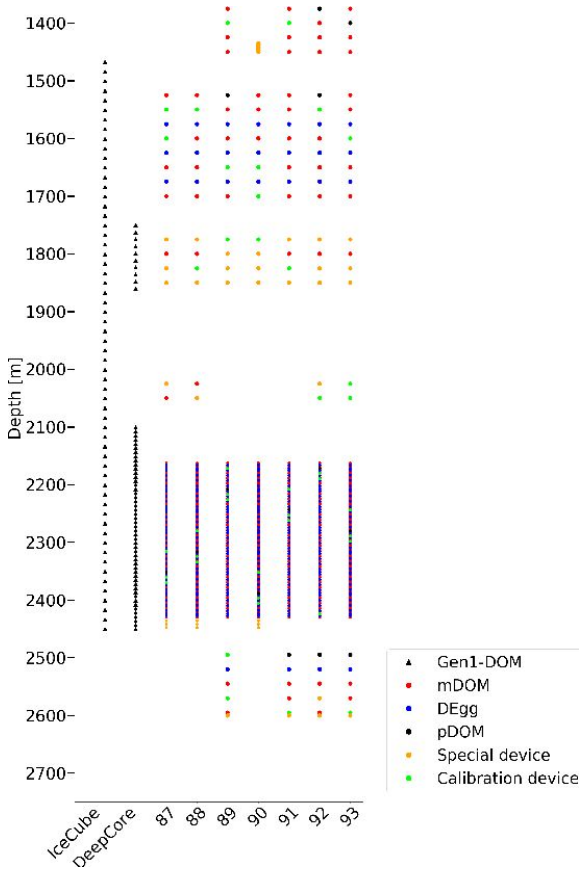
Slide taken from Phillip Eller (TU Munich)

Tau Neutrino Appearance



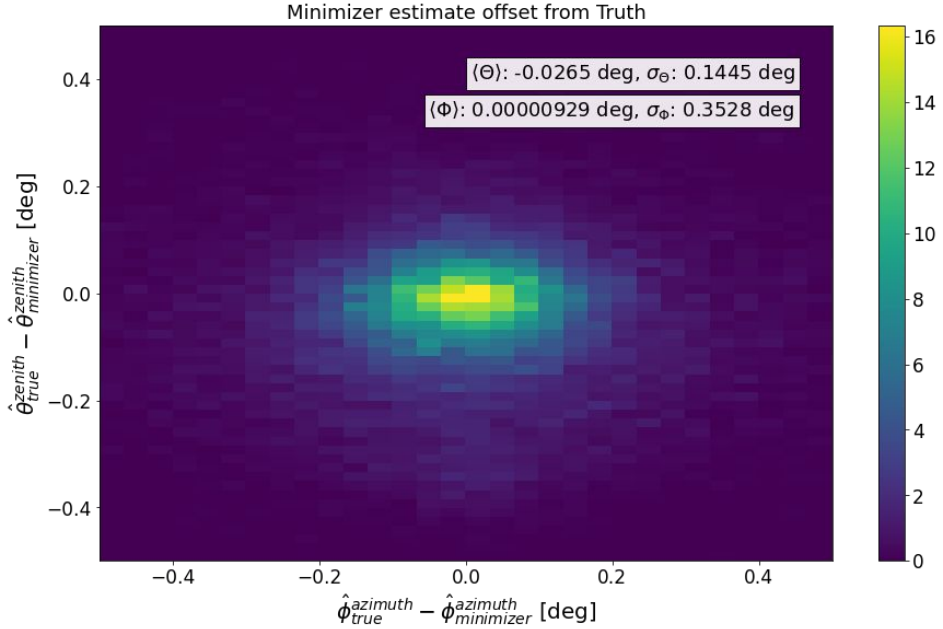
IceCube Upgrade modules

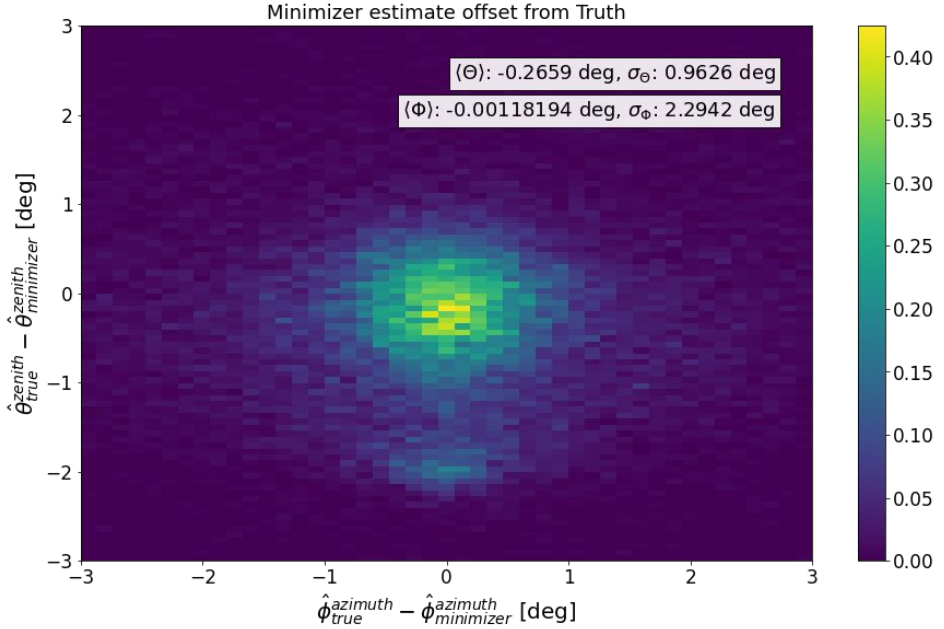




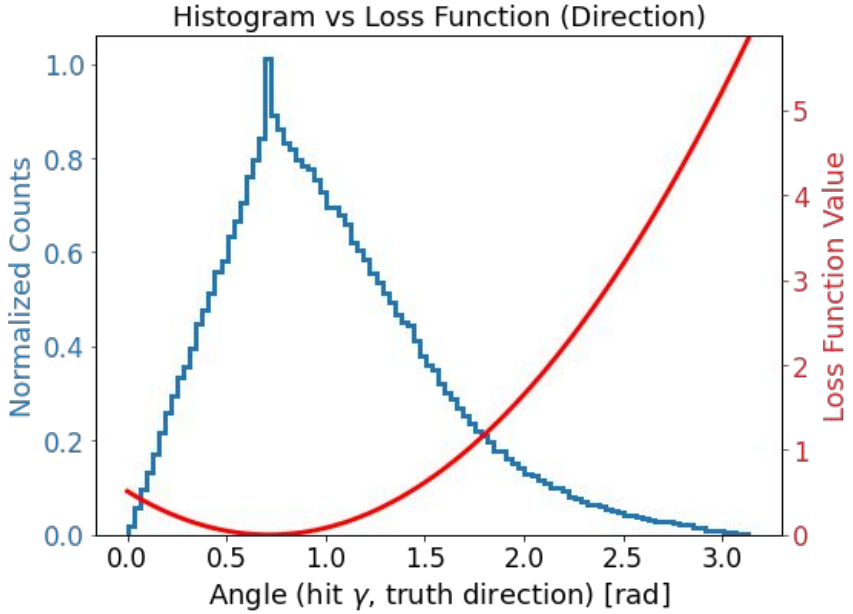
Minimizer Performance

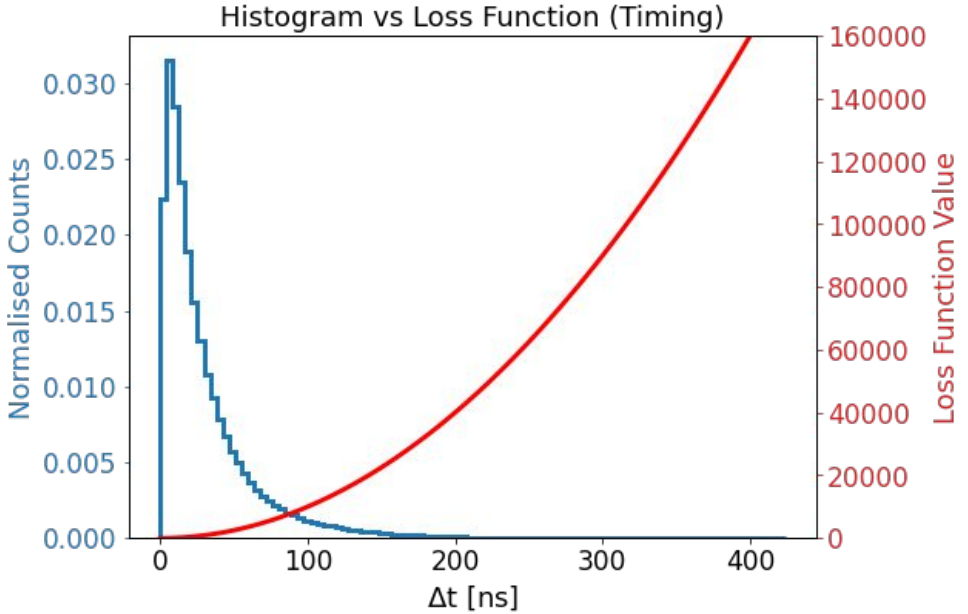
- 2D parameter space: zenith, azimuth
- scipy.minimize (seed=truth)





Limitations of loss function approach

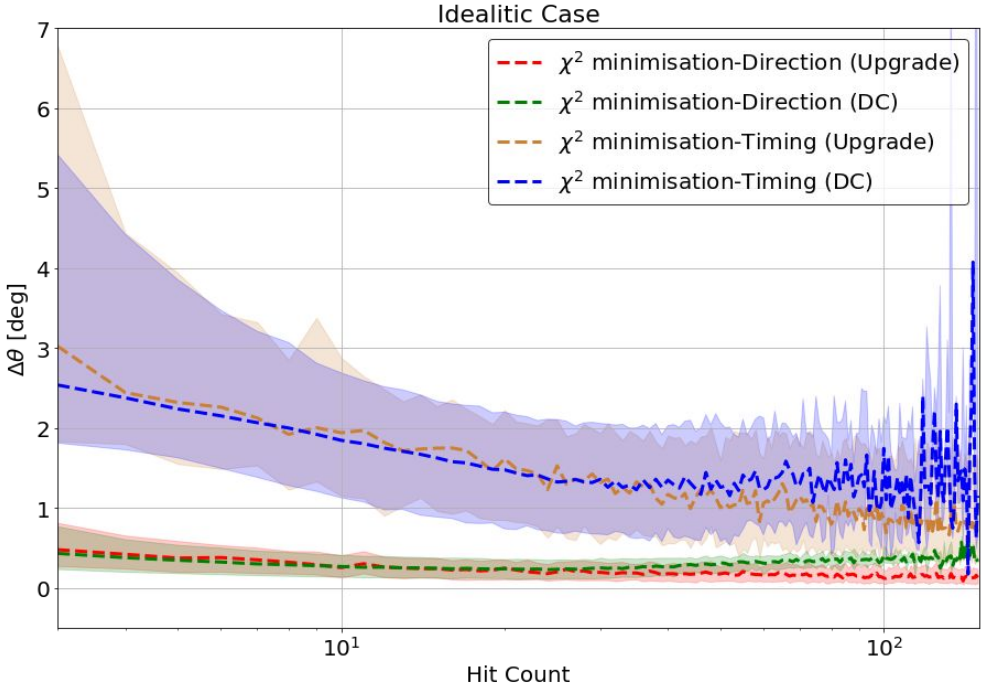


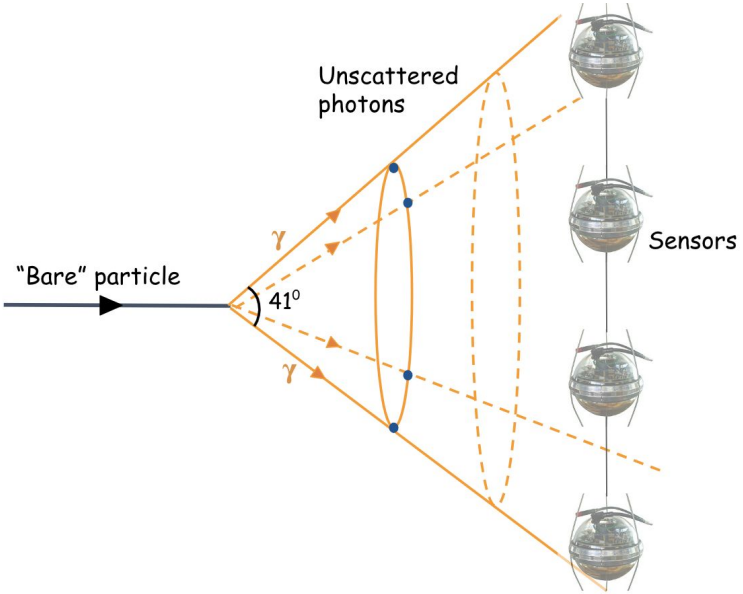


$$L(\vec{\theta}) = \sum_{i=1}^{N} (\vec{\nu}(\vec{\theta}) \cdot \vec{\gamma}_i - \cos 41^\circ)^2$$

$$L(\vec{\theta}) = \sum_{i=1}^{N} (t_{\text{geom},i}(\vec{\theta}) - t_{\text{obs},i})^2$$

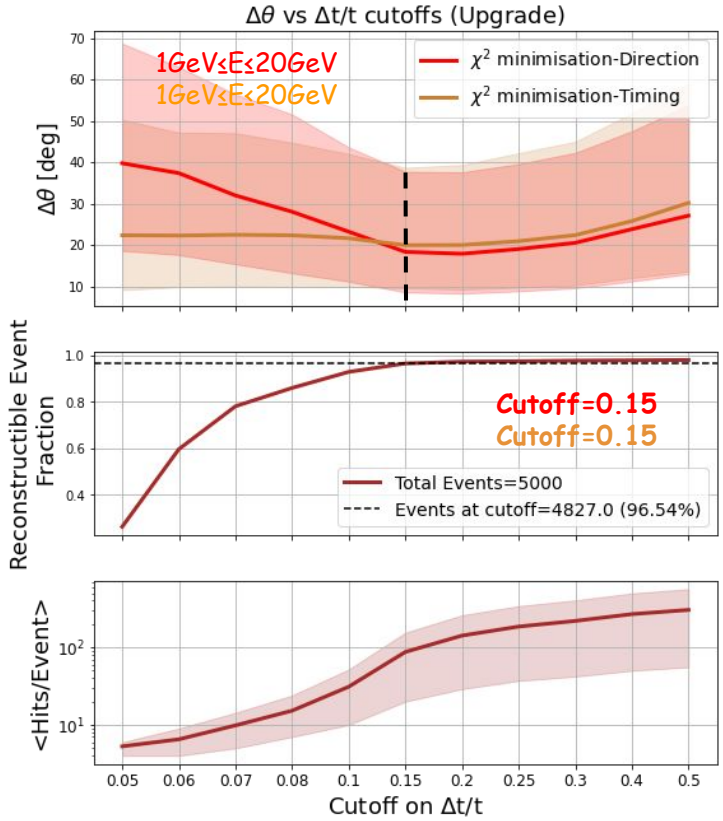
Idealistic Case



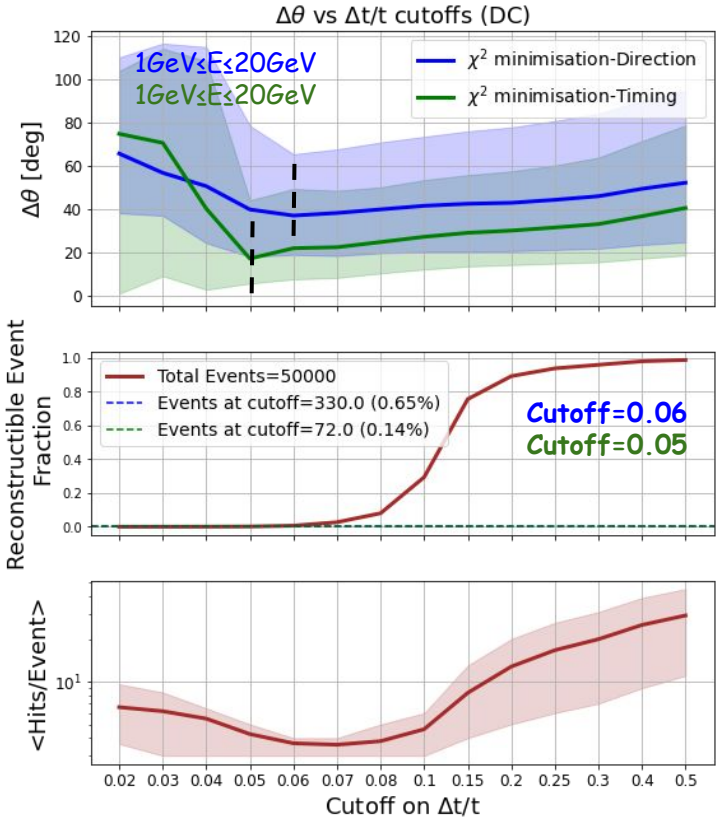


- No transverse shower spread
- No scattering
- Hit photon MC truth direction

Cutoff Optimization



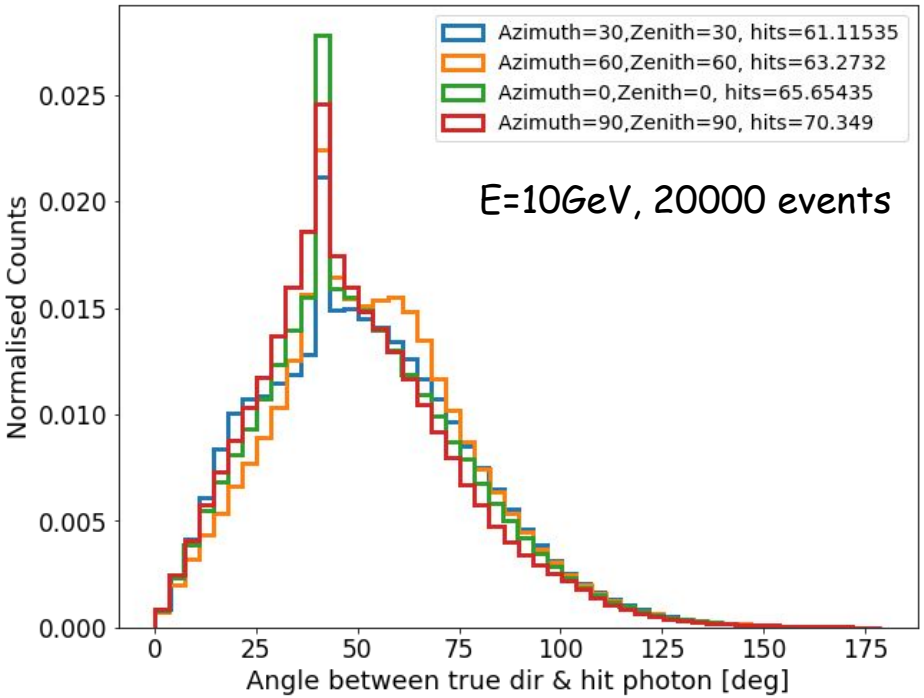
hits>=3



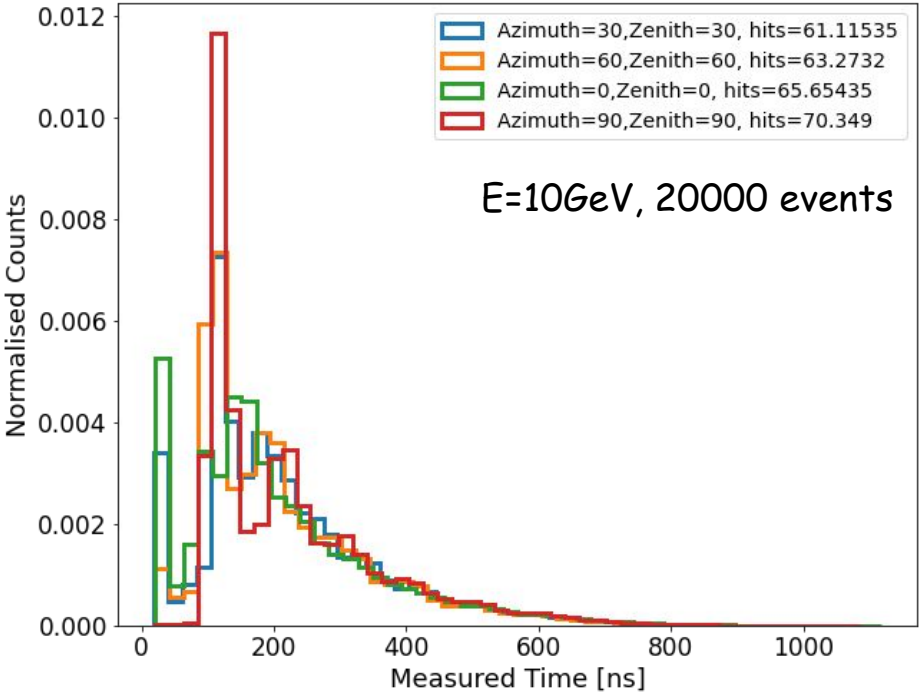
hits>=3

PDF dependence on vertex/direction

Fixed Vertex

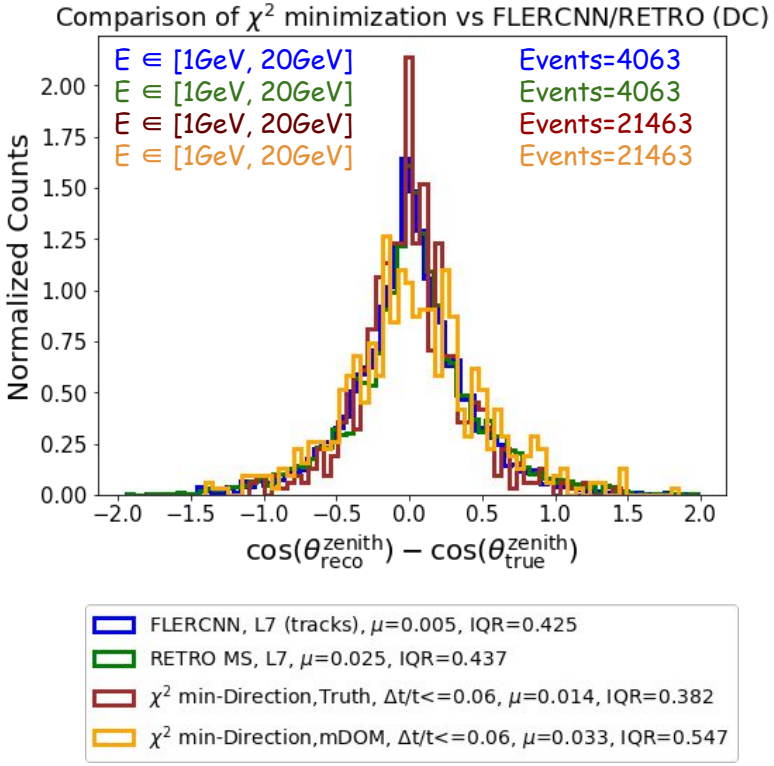


Fixed Vertex

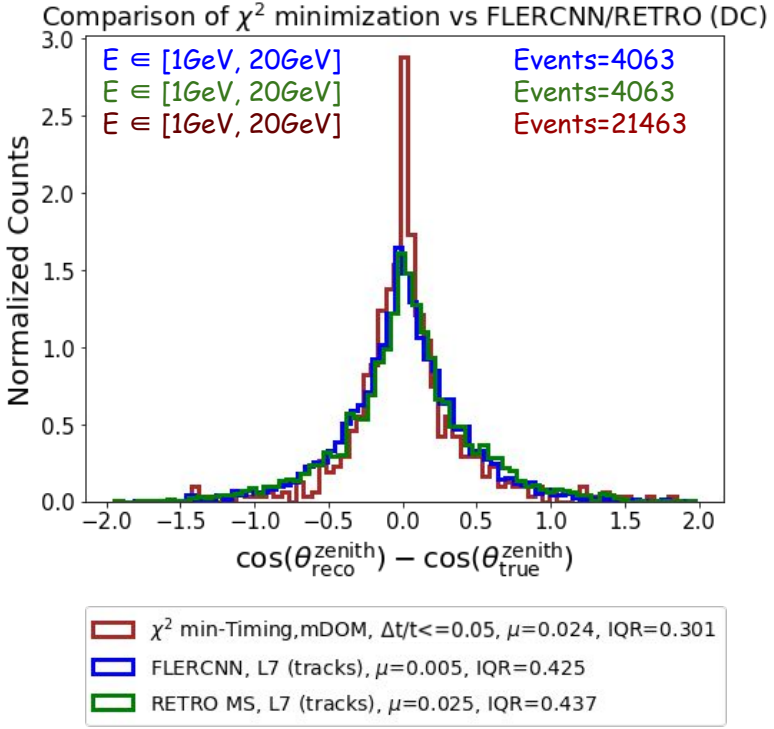


Comparison with benchmark algo (DC)

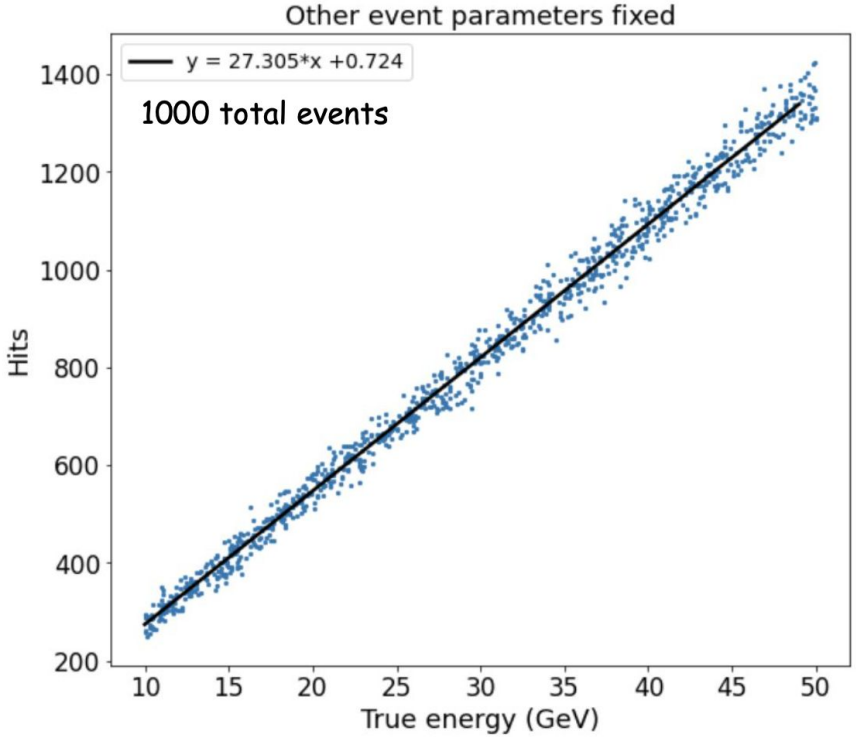
Direction information



Timing information

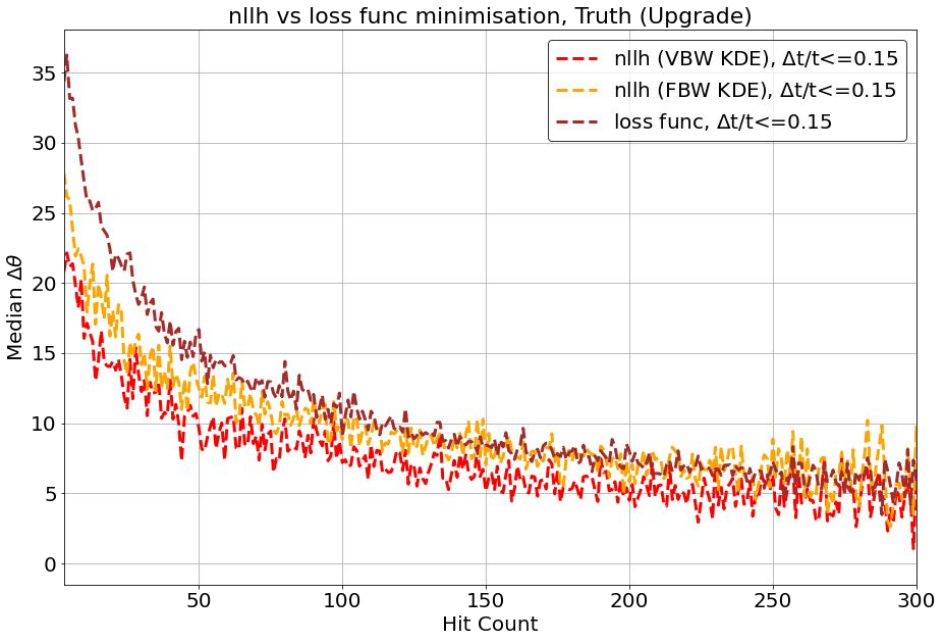


Energies & Hits

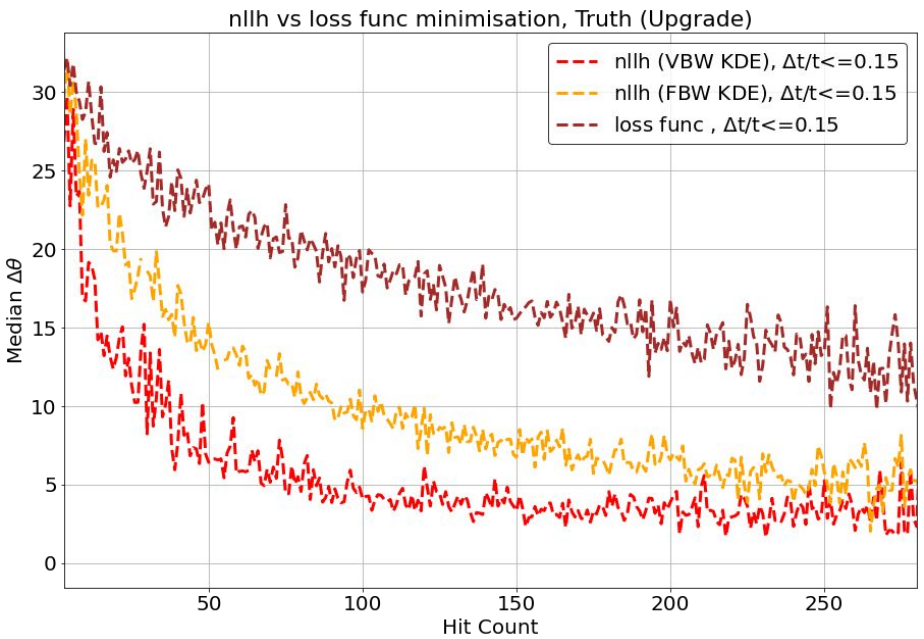


Variable Bandwidth Estimation

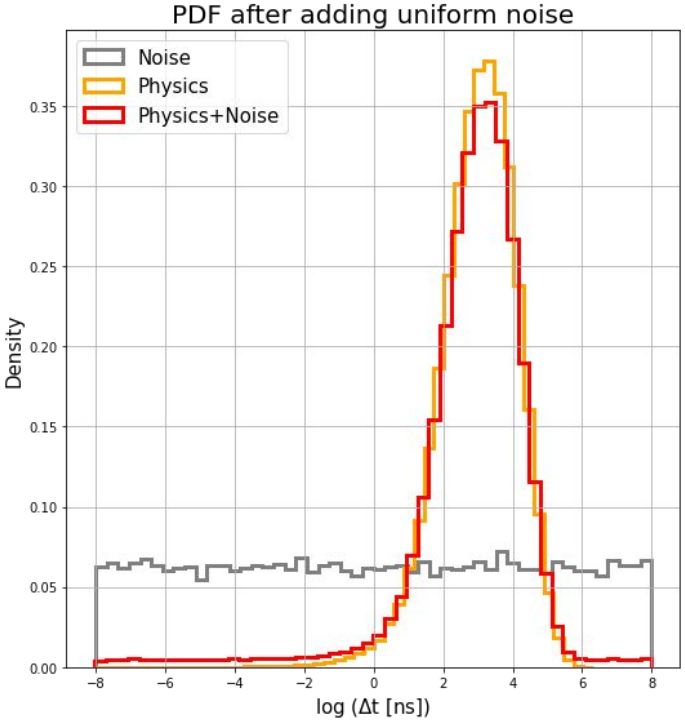
Direction information: $\hat{\theta}_{\text{opt}} = \arg\max\left[\mathcal{L}(\gamma \cdot \mathbf{u}|\boldsymbol{\theta})\right]$



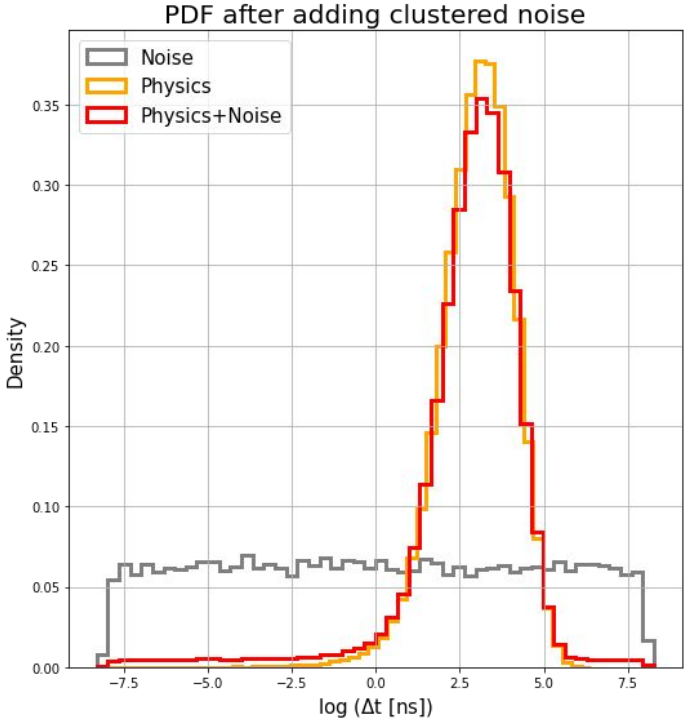
Timing information: $\hat{\theta}_{\text{opt}} = \arg\max\left[\mathcal{L}(\Delta t|\boldsymbol{\theta})\right]$



Noise (Uniform & Clustered)

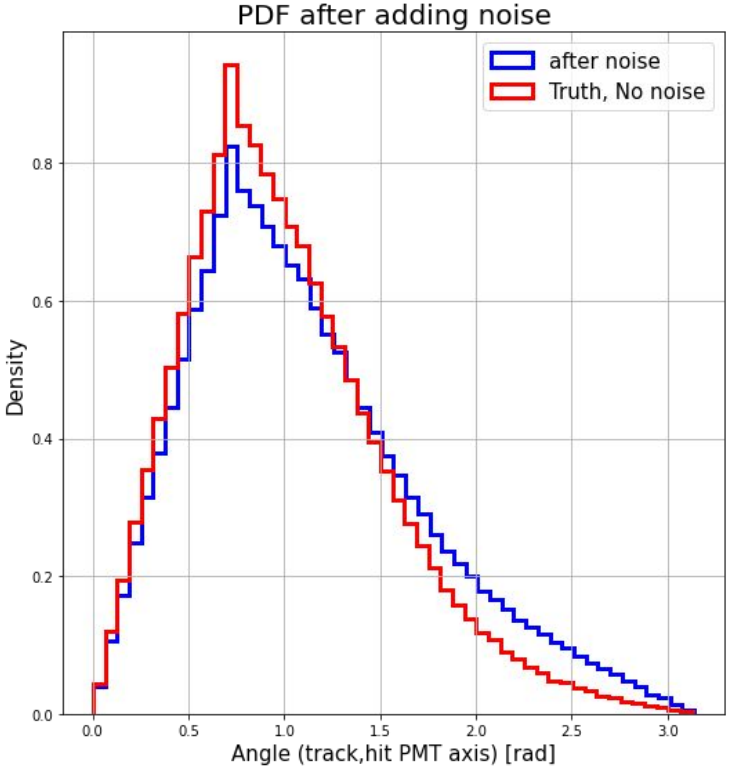


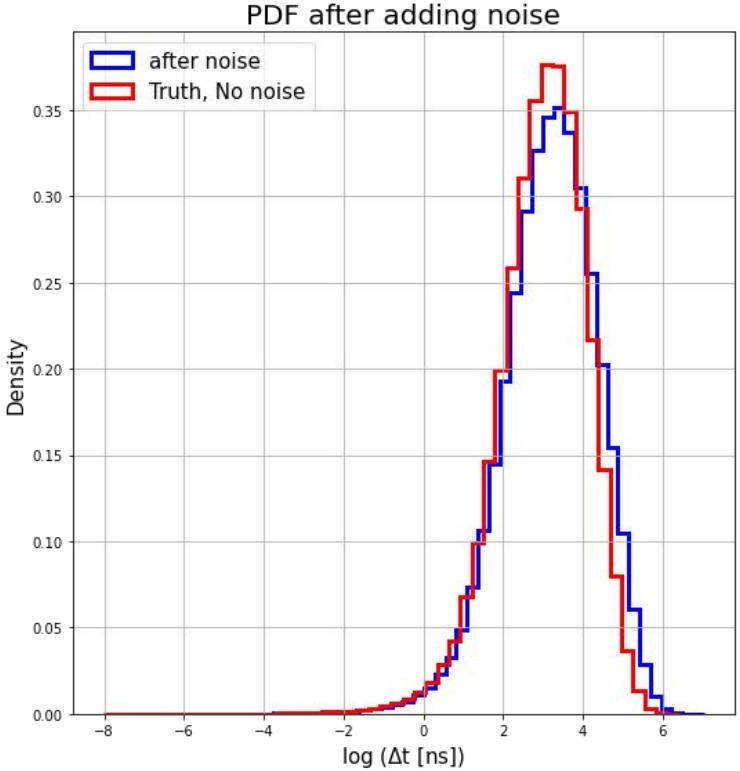
Noise uniformly distributed



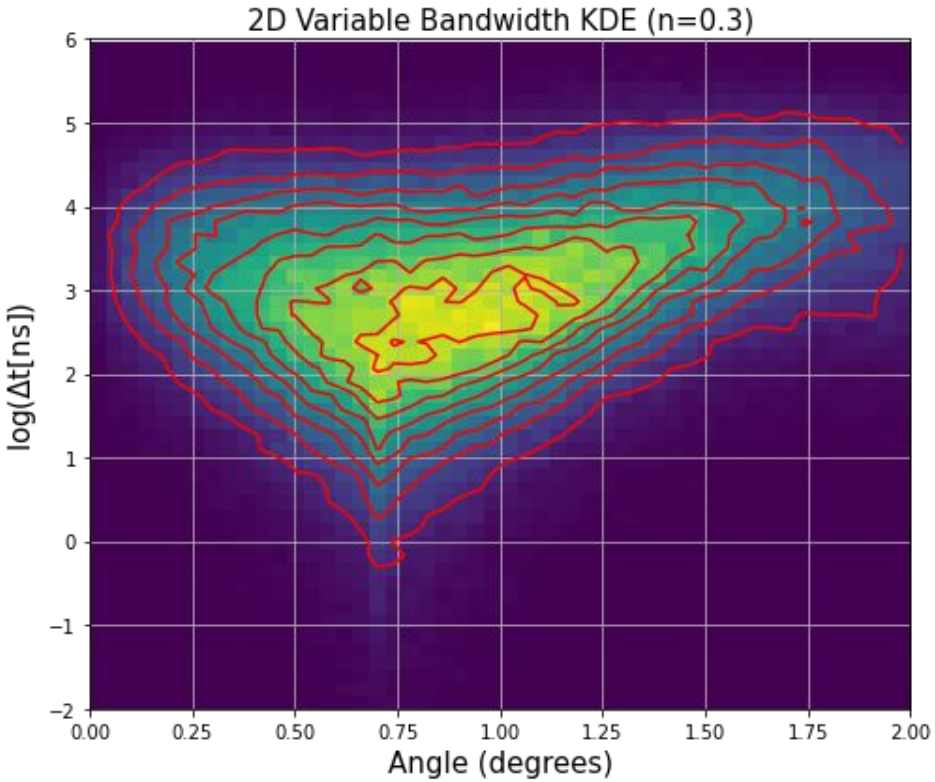
Noise clustered around a specific Δt each event.

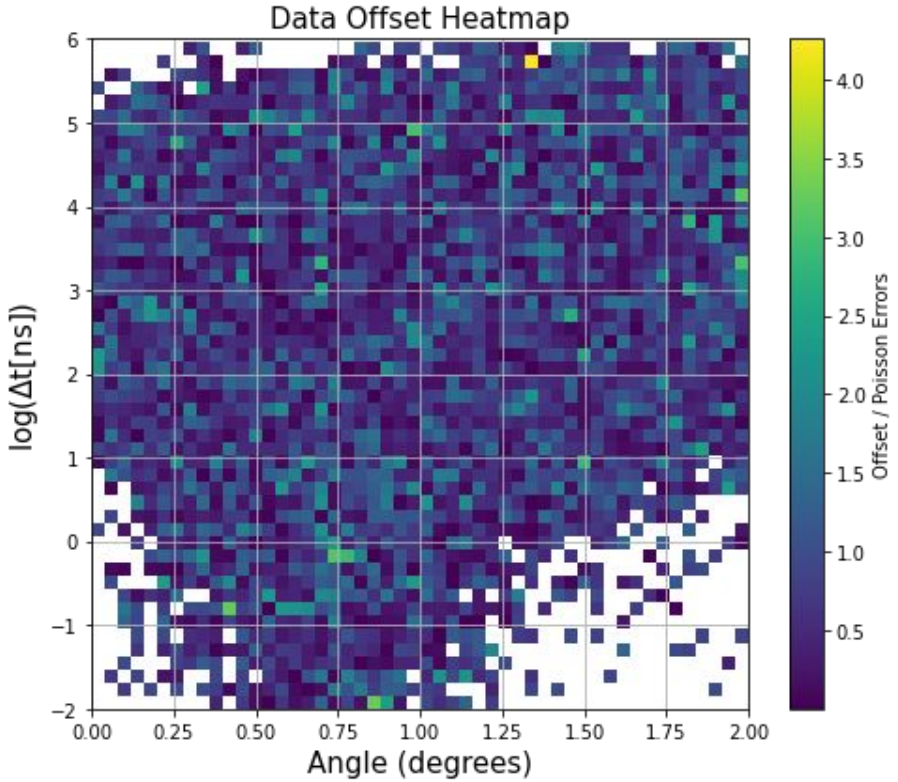
Noise (Uniform & Clustered)



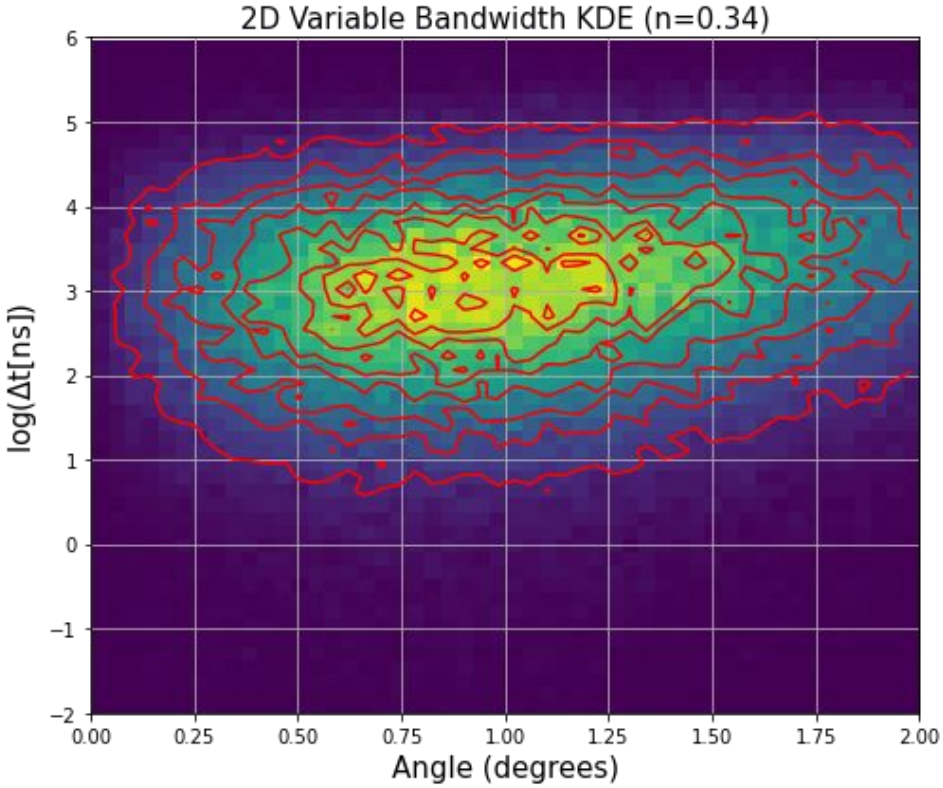


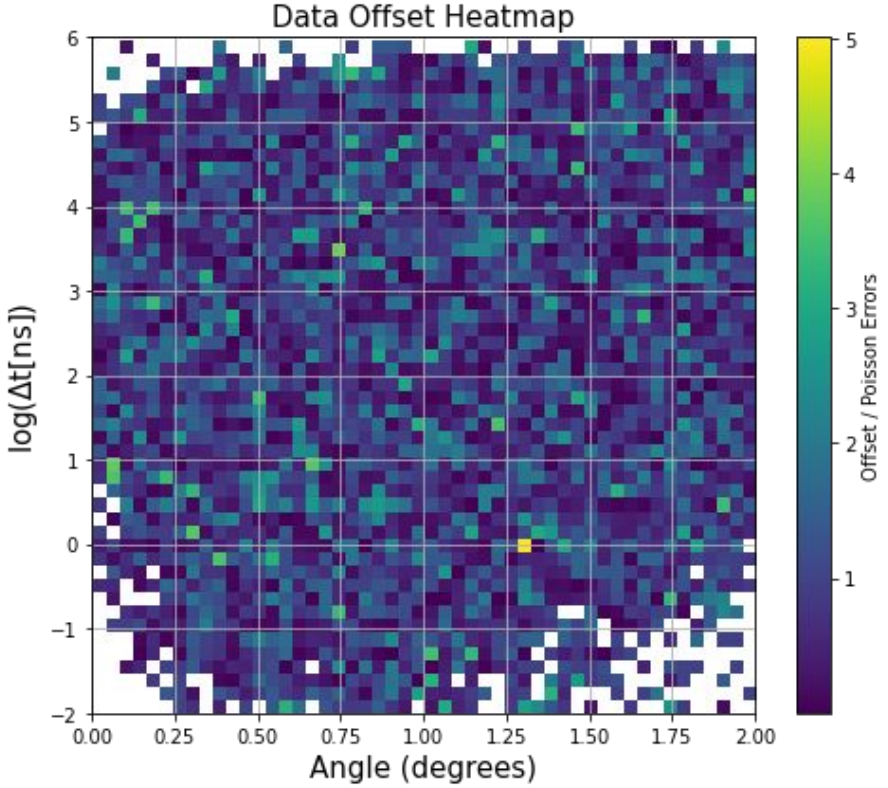
Combined PDF (Truth)



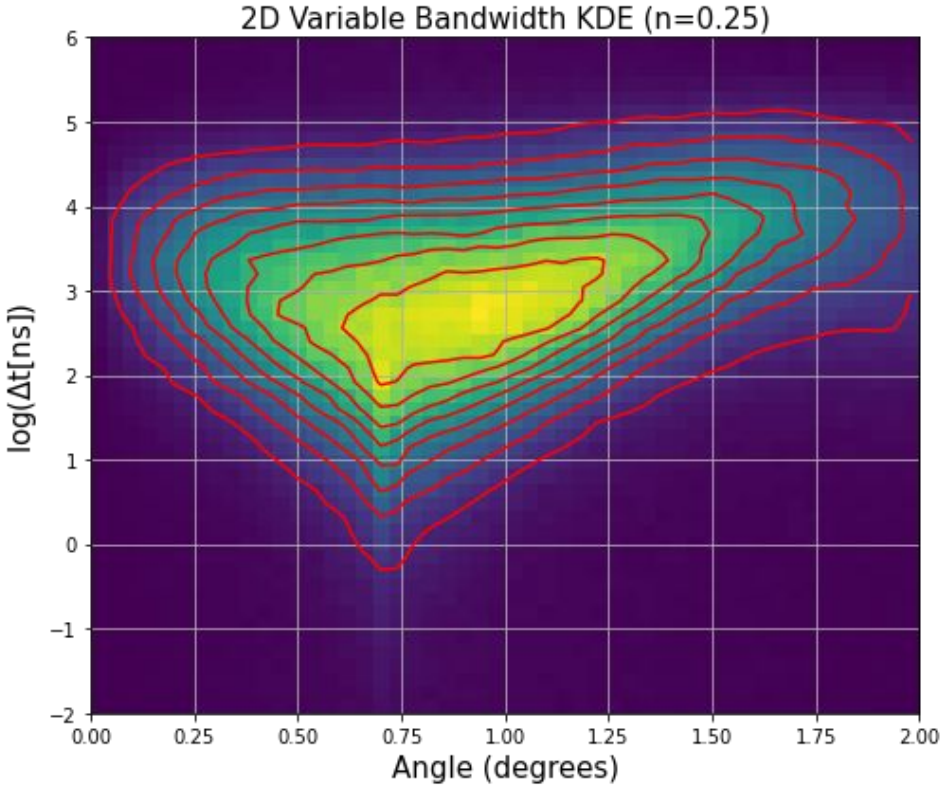


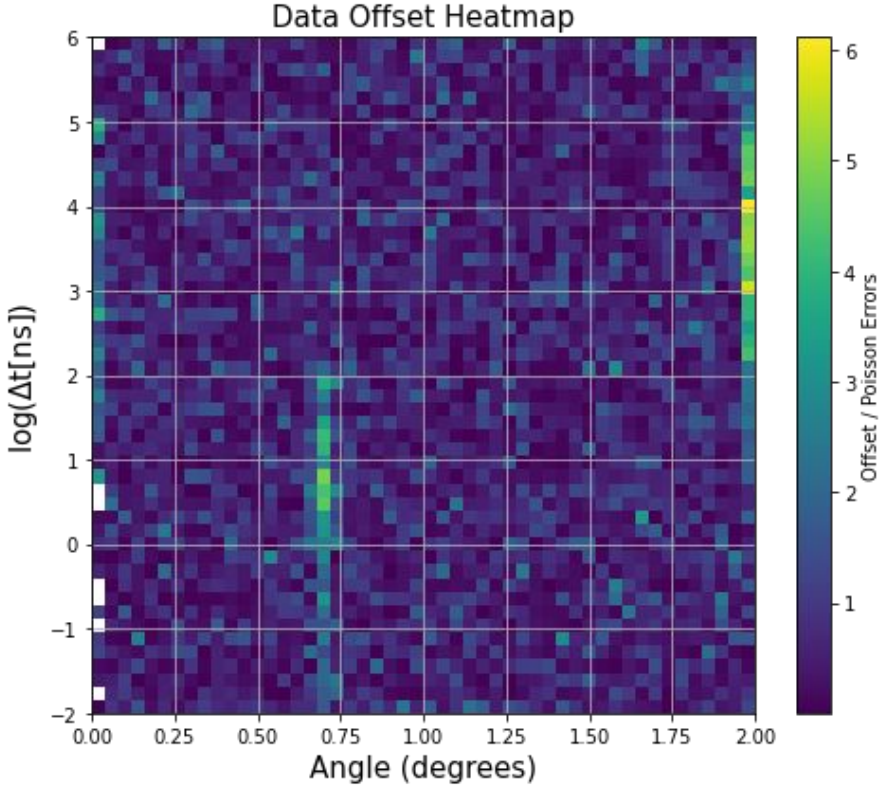
Combined PDF (PMT smeared)





Combined PDF (Noise)





Signal Purity in GNN reco