Intrinsic Resolution Limits in Low-Energy Cascade Directional Reconstruction with the IceCube Upgrade

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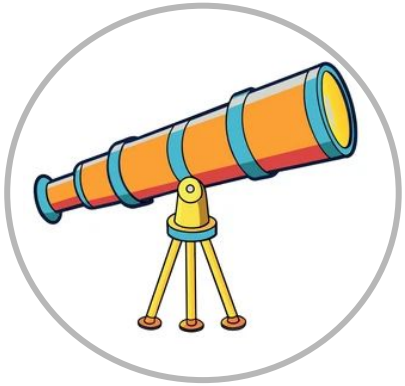
MPA Retreat

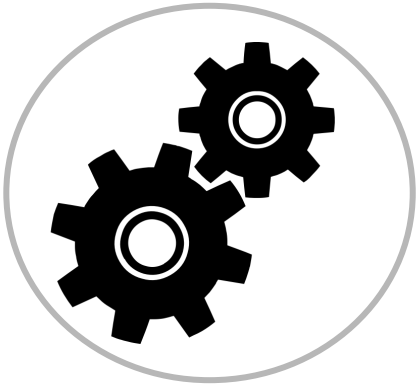
October 01, 2024

Outline



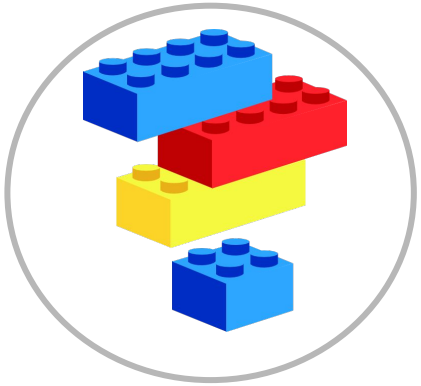
Phase-1: Introduction

What is the IceCube experiment?



Phase-2: Simulations

How are events simulated realistically?



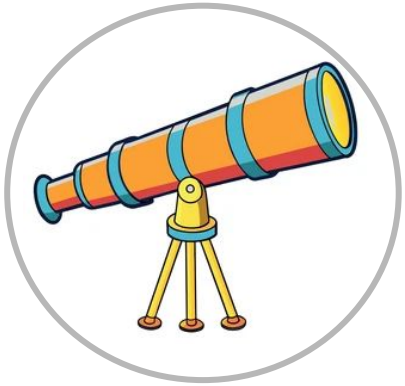
Phase-3: Reconstruction

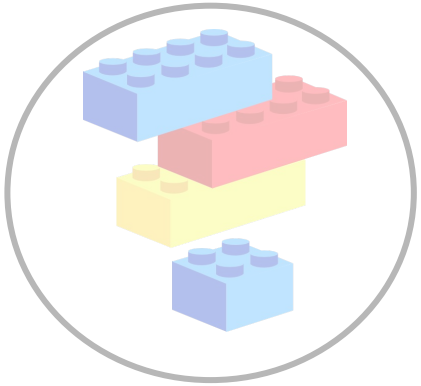
Machinery to estimate event parameters

Phase-4: Results

What do we finally get out of this?

Outline

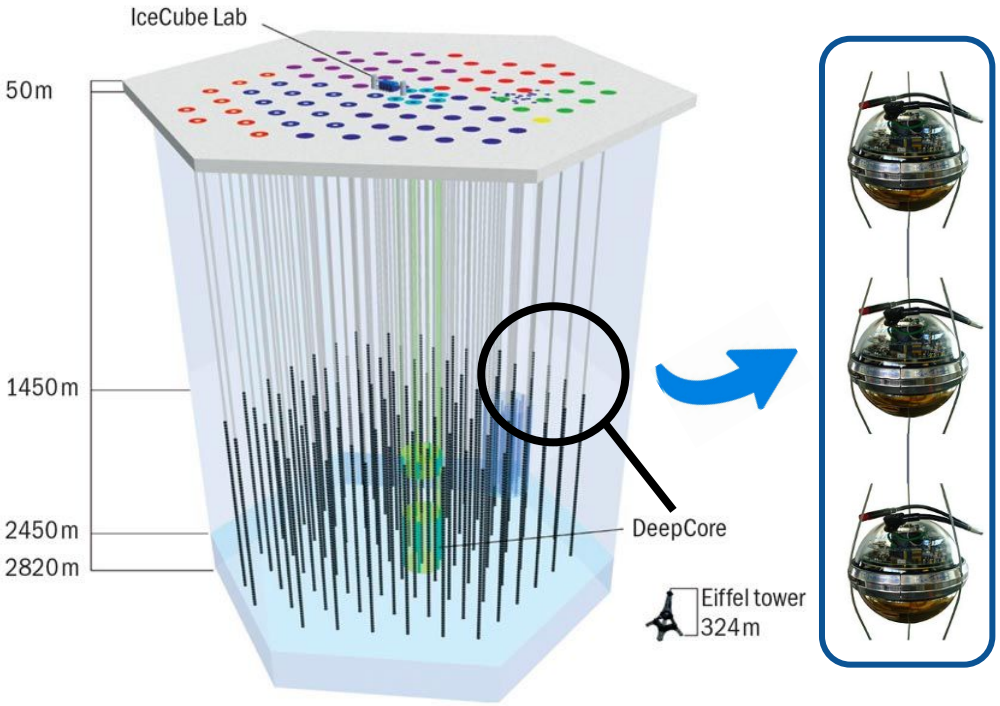


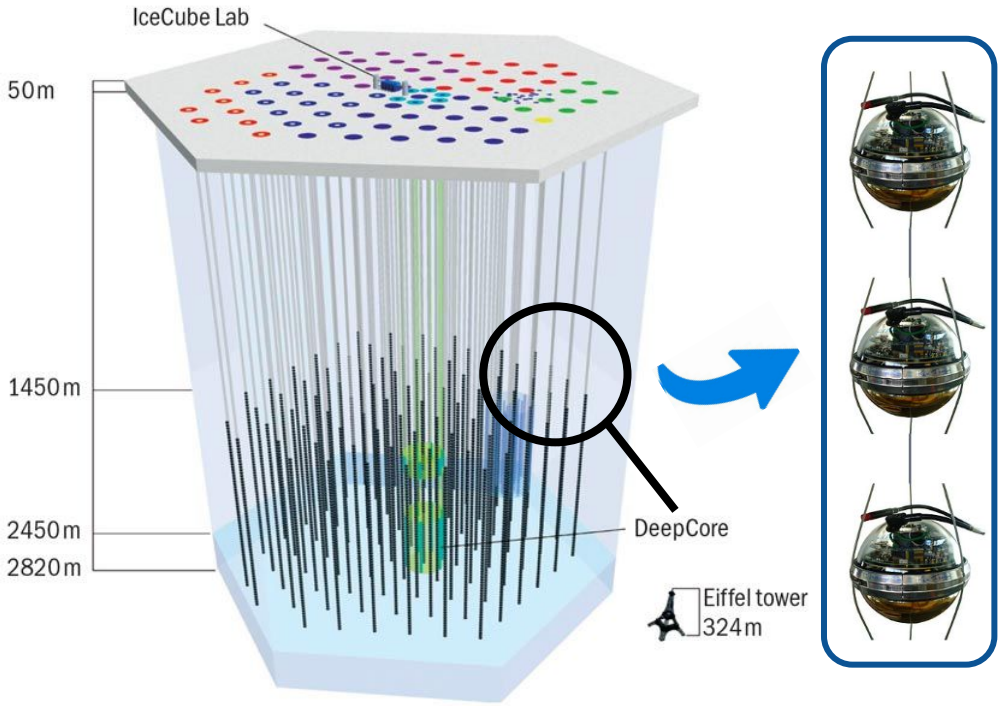


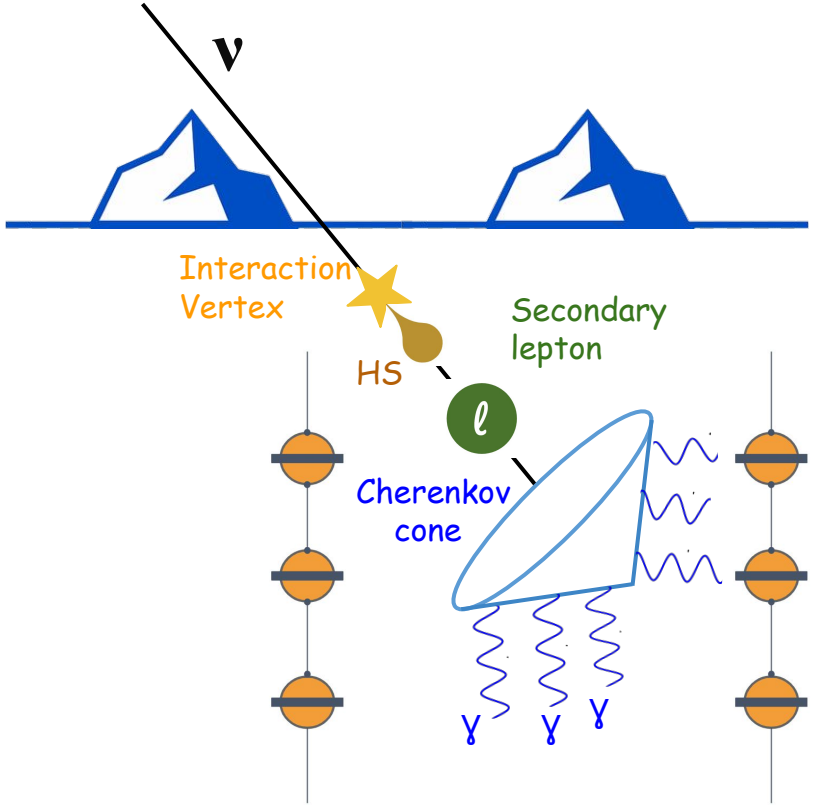
Phase-1: Introduction

What is the IceCube experiment?

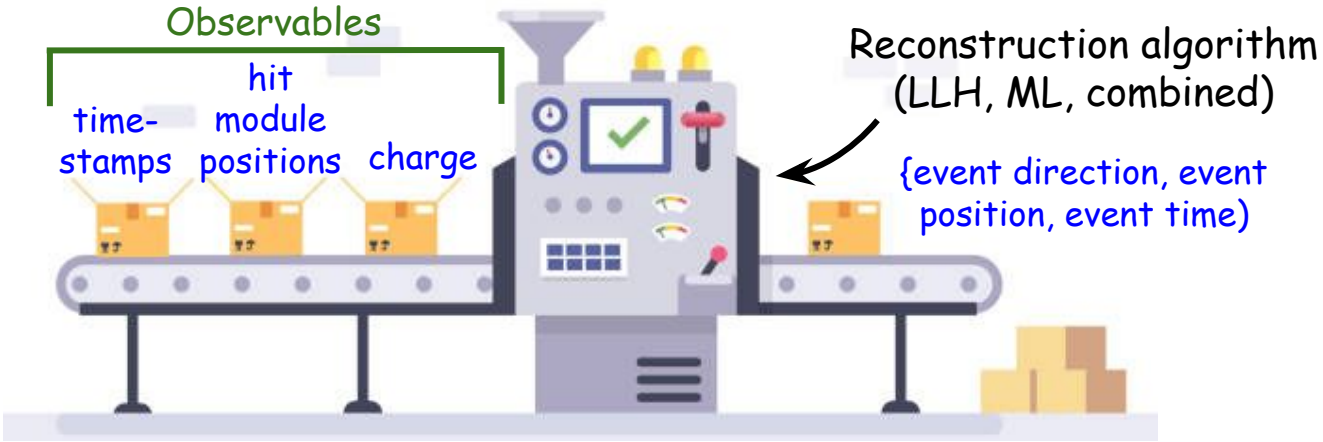
Existing detector / Detection technique



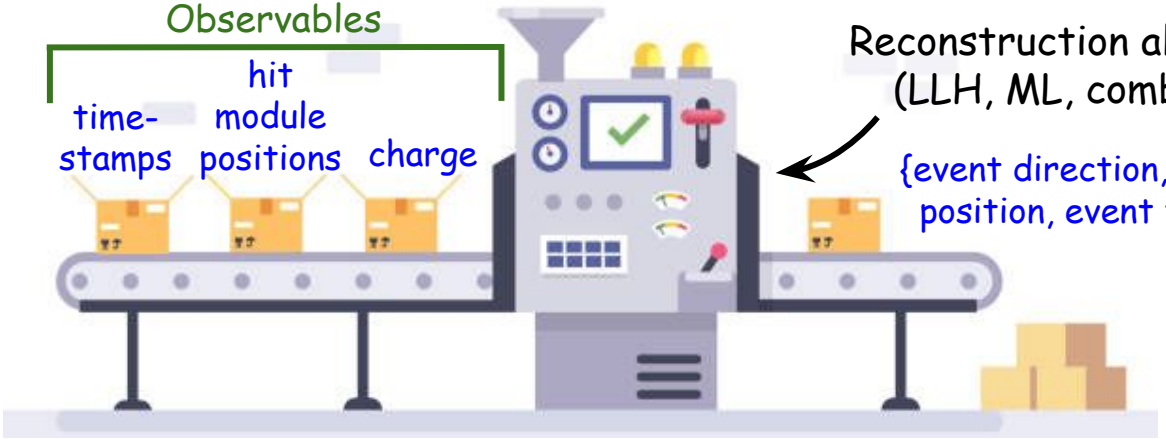

IceCube Lab
50m
1450m
2450m
2820m
DeepCore
Eiffel tower
324m


ν
Interaction
Vertex
Secondary
lepton
HS
ℓ
Cherenkov
cone
γ
γ
γ

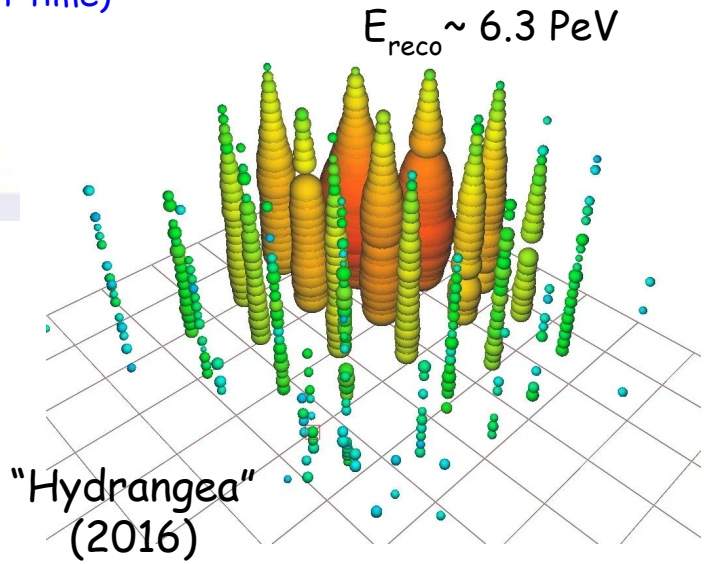
Low Energy Reconstruction & Prospects



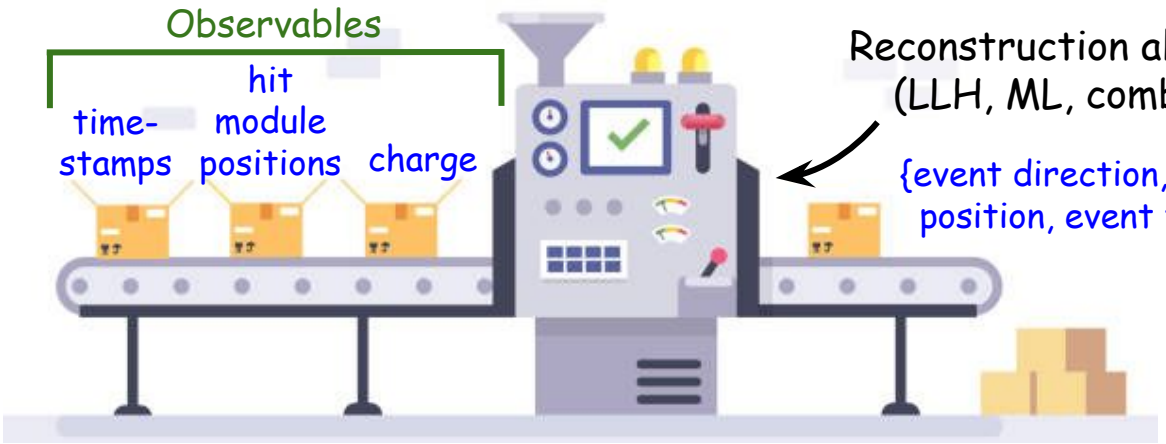
Low Energy Reconstruction & Prospects



Why challenging? fewer photons = fewer hits



Low Energy Reconstruction & Prospects



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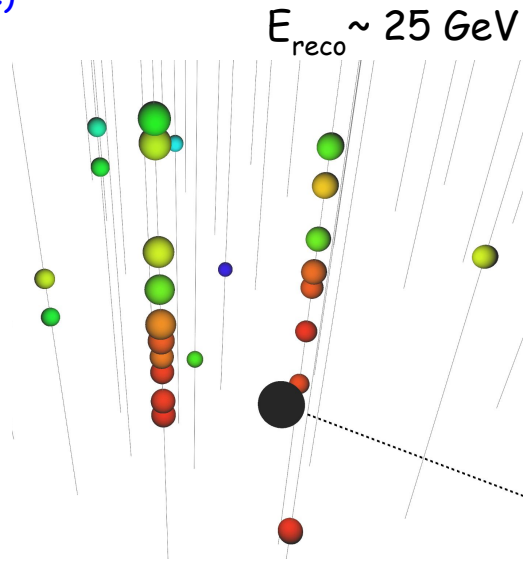
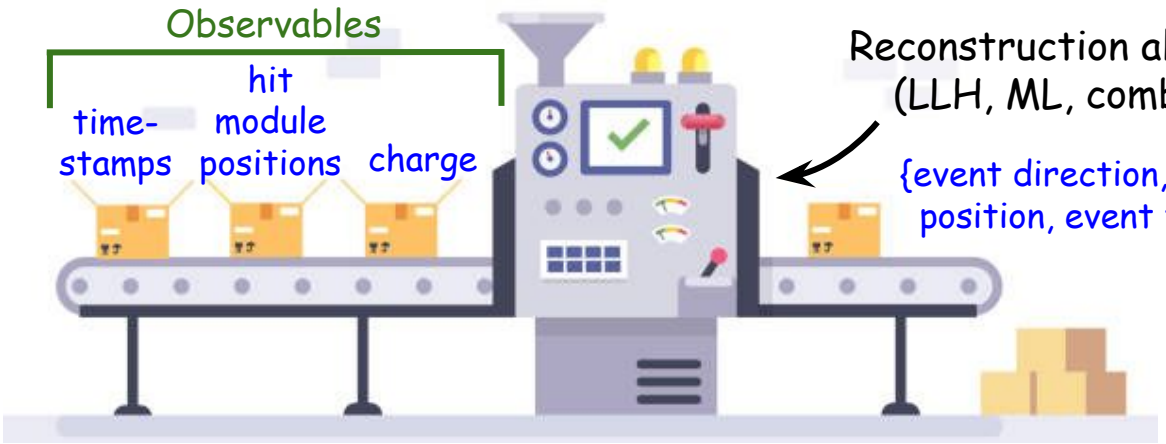
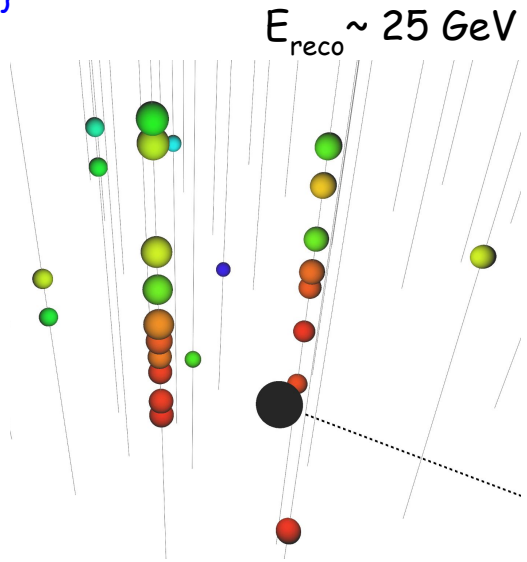


Low Energy Reconstruction & Prospects



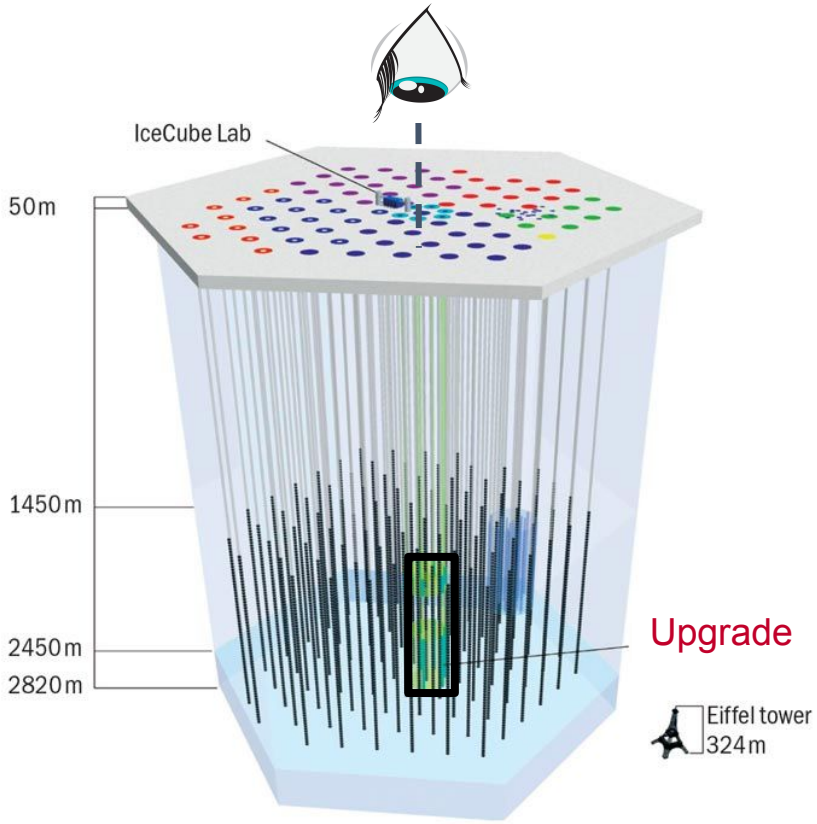


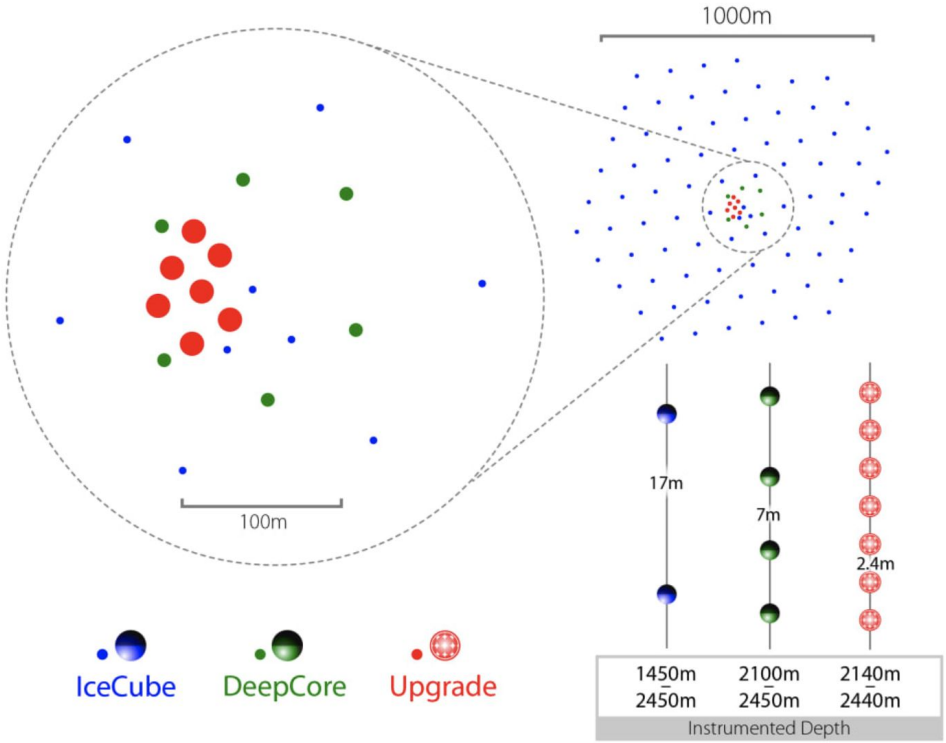
Why challenging? fewer photons = fewer hits

Why interesting?

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

Future IceCube Upgrade

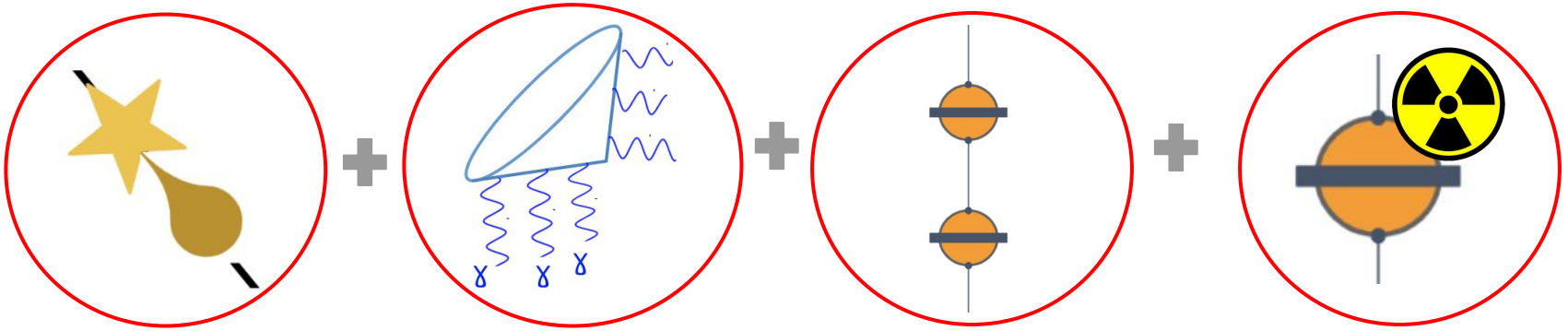




doi.org/10.1016/j.nima.2018.11.109

Study Objectives

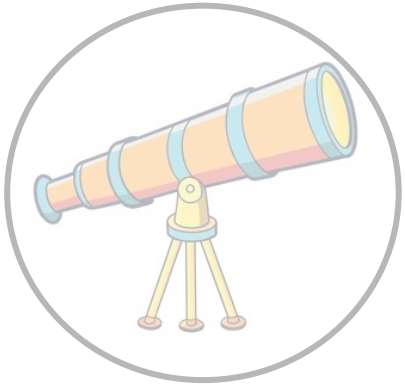
- Contributions from individual **observables** (photon direction, timing, charge, etc.)
- Processes **limiting** the reconstruction performance & their contributions.

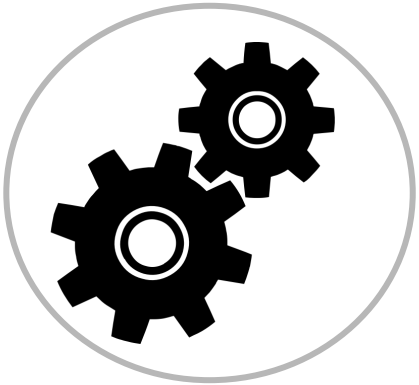


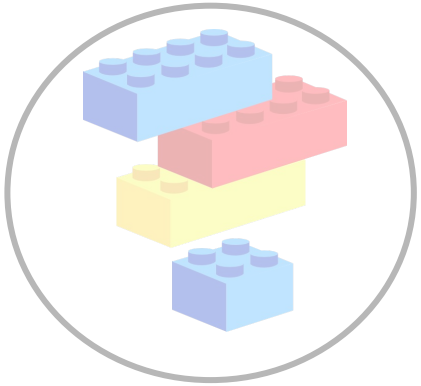
Transverse shower spread | In-ice scattering | Module resolutions | Module noise

- What are the **resolution limits** if all information loss factors are accounted for?

Outline







Phase-2: Simulations

How are events simulated realistically?

Simplifications

- **Detector Medium**

  This study: Homogenous Ice (optical properties depth-independent)
  Usual MC: layer stratifications, birefringence, layer undulations

- **Detector Geometry**

  This study: Constant sensor spacing with only 24-PMT modules.
  Usual MC: Fluctuations in spacings; different types of modules.

- **Module response**

  This study: Idealistic, same angular photon acceptance, no electronics simulation
  Usual MC: Angular acceptance fluctuations; photon-to-charge chain simulated

1-PMT

2-PMT

24-PMT

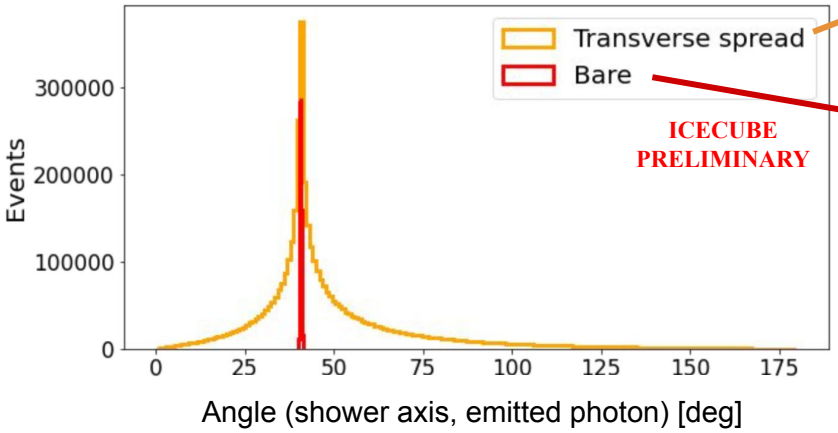
Shower spread

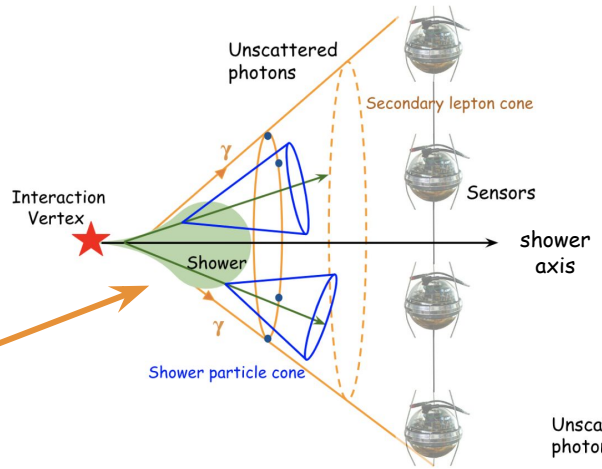
- Sample photons from a known distribution:

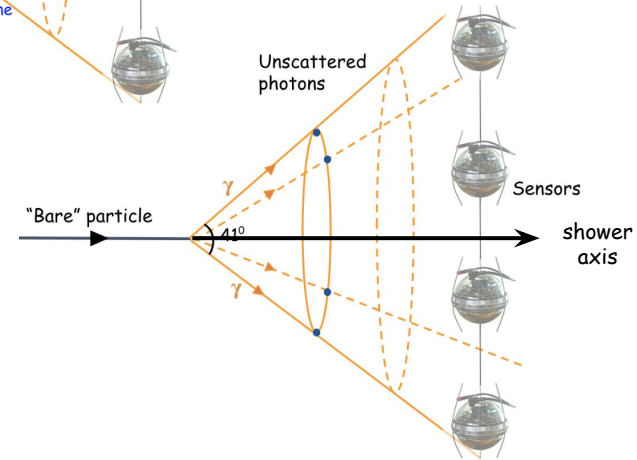
$$\frac{d\ell}{dx} \sim \exp(-bx^a)x^{a-1} \quad \text{with} \quad x = 1 - \cos\theta$$

light-emitting
emitting

a=0.39, b=2.61, fit to 100 GeV cascades







In-ice Scattering

- Sample photons from a known distribution:

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light-emitting
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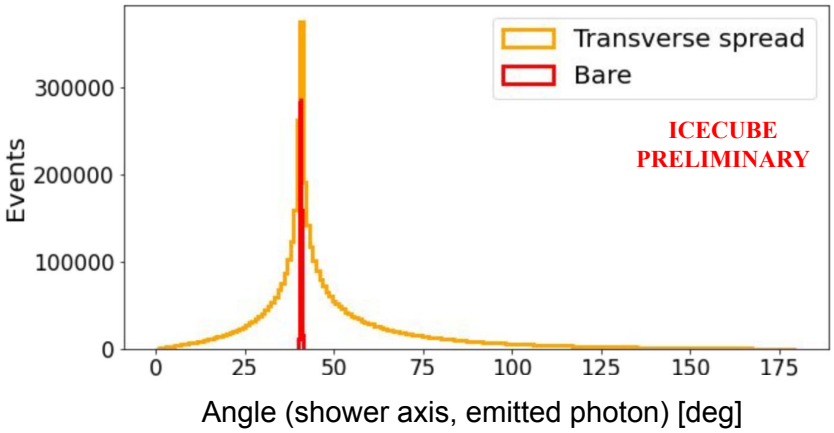
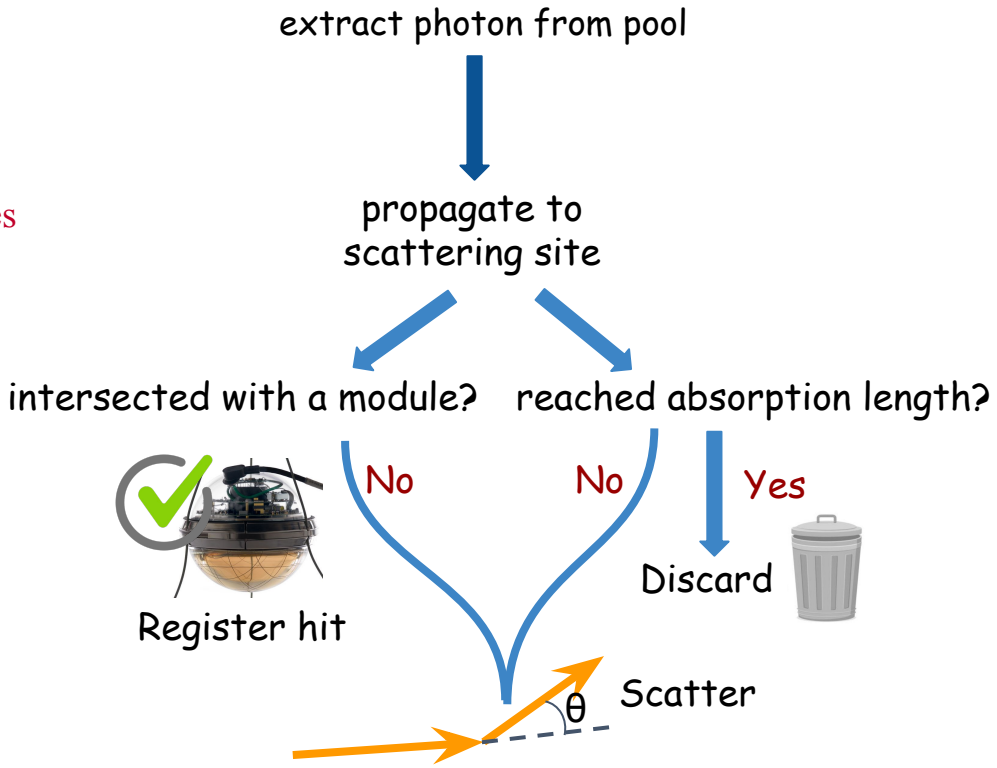
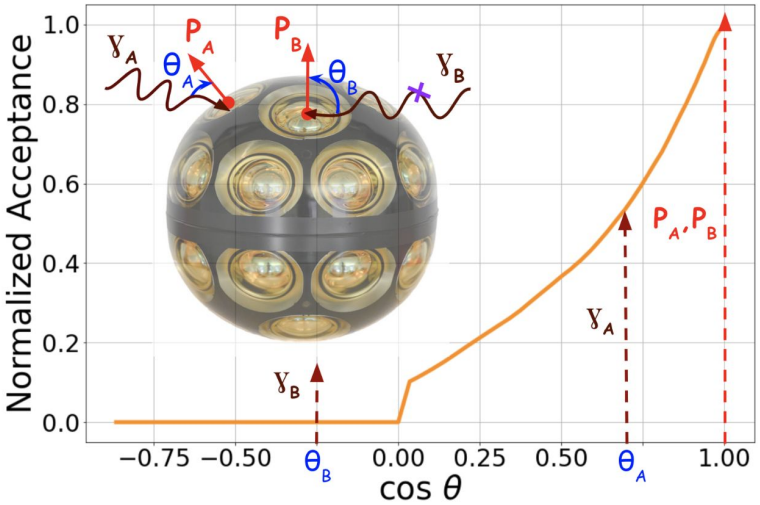




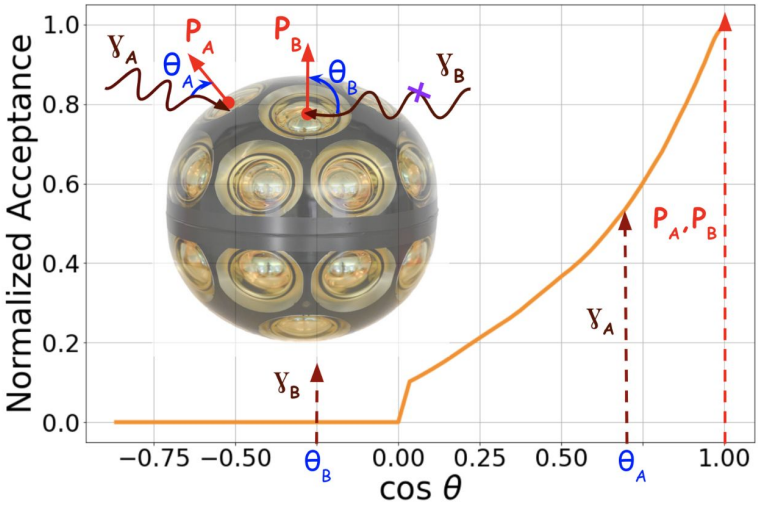
Module resolutions

- Select the PMT closest to the point of photon impact.
- Include acceptance curve information.
- Project photon direction onto the PMT axis.

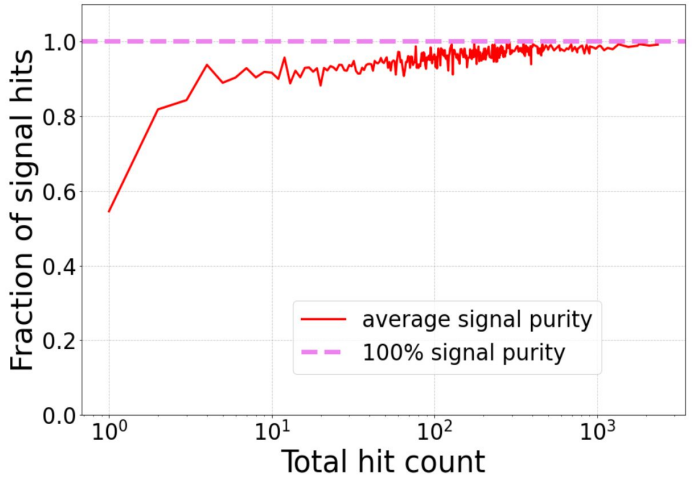


Module noise

- Select the PMT closest to the point of photon impact.
- Include acceptance curve information.
- Project photon direction onto the PMT axis.



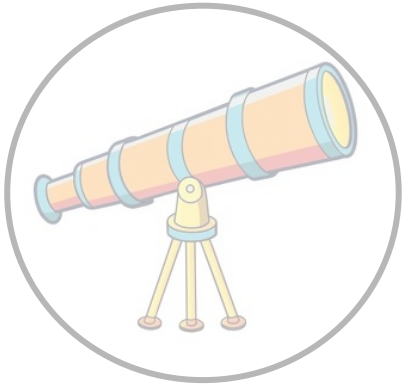
HOW MANY?

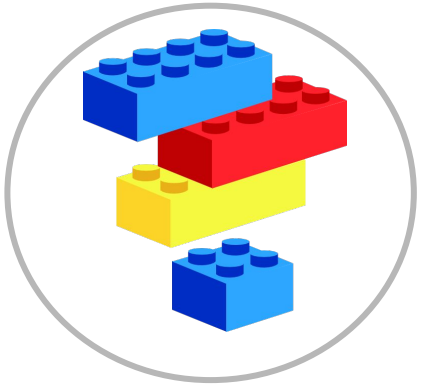


WHERE?

- **Spatially:** trigger a random PMT on one of the hit modules with physics hits.
- **Temporally:** sample from a uniform distribution within the event time window of physics hits.

Outline

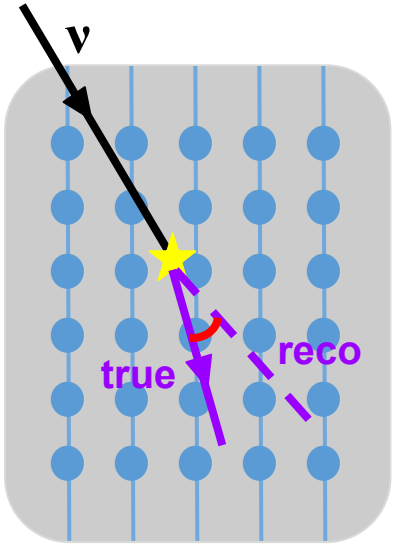


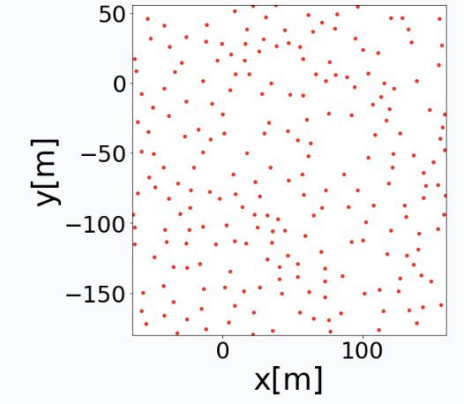


Phase-3: Reconstruction

Machinery to estimate event parameters

- **Event type:** Point-like cascades with anisotropic light emission
- **Energy range:** 1-20 GeV
- **Observables:** hit PMT position on 24-PMT modules, timestamps
- **Reconstruction method:** Maximum Likelihood Estimation
- **Reconstructed parameters:** direction, position, timing of event (7 parameters)
- **Parameter of interest:** Zenith
- **Reconstruction metric:** $|\cos(\theta_{\text{reco}}) - \cos(\theta_{\text{true}})|$

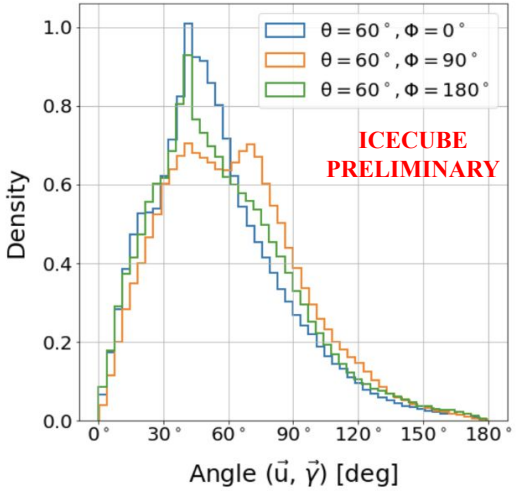


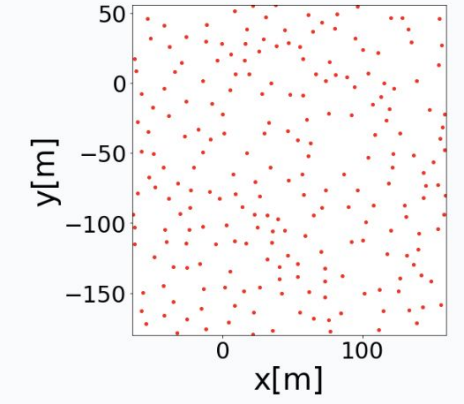


1

Fixed detector geometry creates a **photon sampling bias**

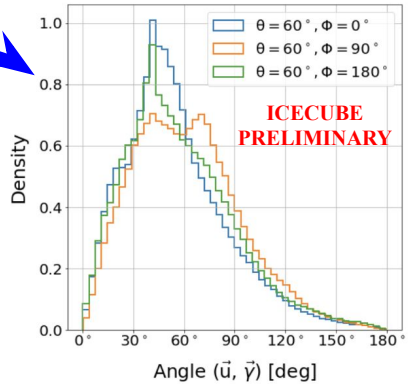
Randomized geometry generated by positioning strings and modules within a string randomly with spacing thresholds to avoid clustering.

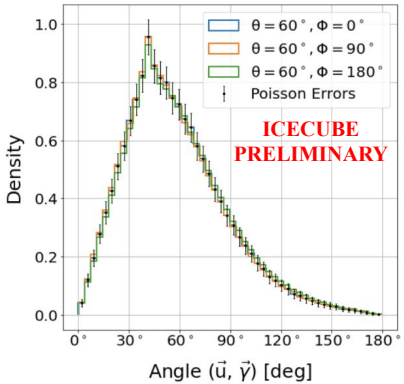




1

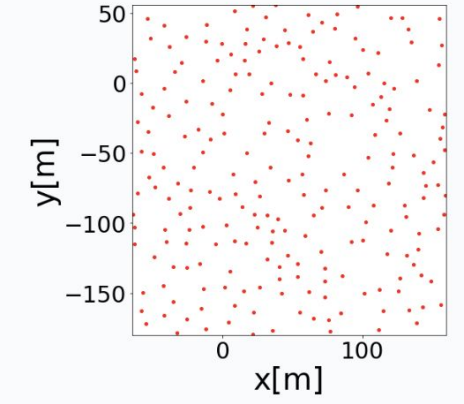
Randomised geometry





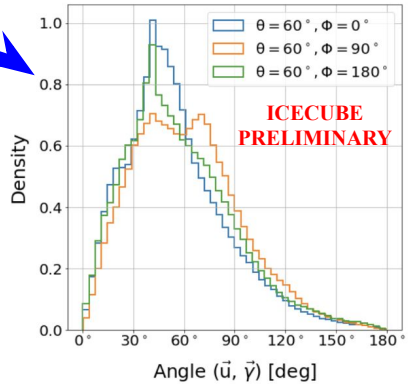
2

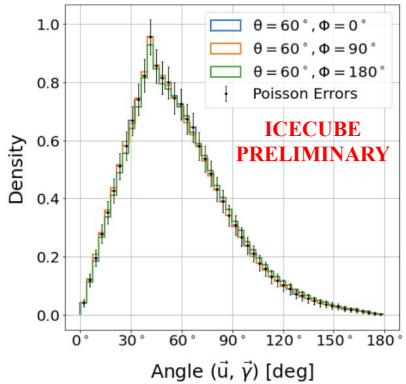
Vertex-averaged photon distributions with uniformly distributed events in a randomized geometry are direction-independent!



1

Randomised geometry



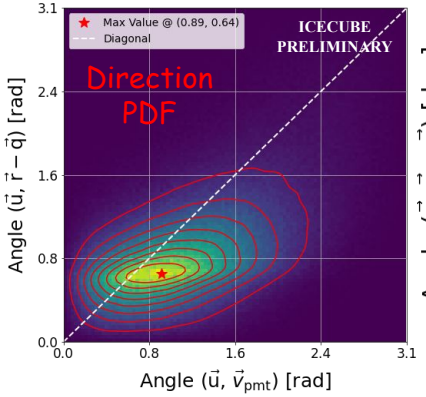


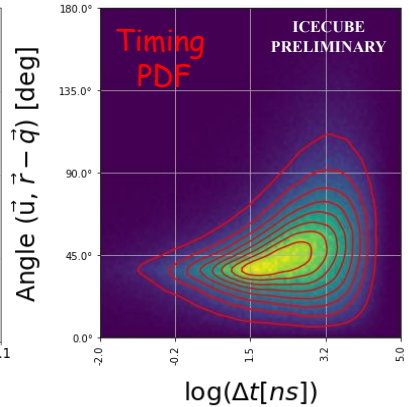
2

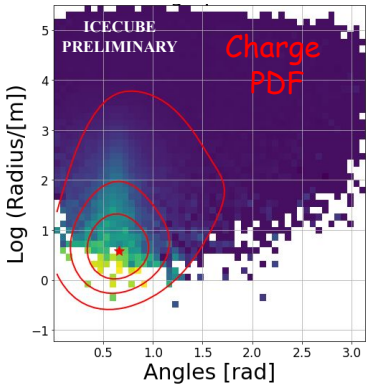
Vertex-averaged photon distributions

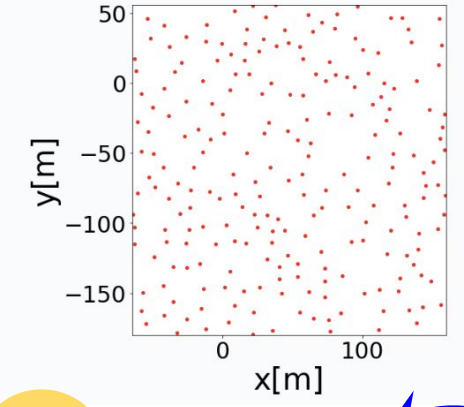
3

Expected photon distributions, with a fitted VBW KDE.









1

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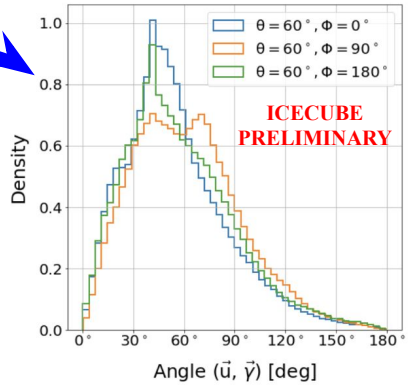
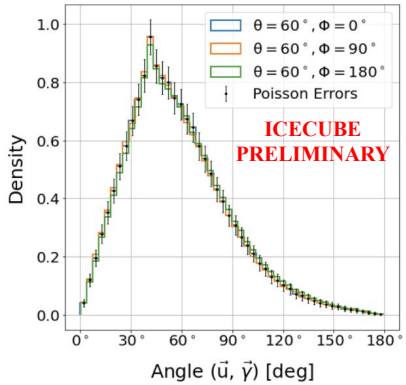




2

Vertex-averaged photon distributions

4

Maximum Likelihood Reconstruction

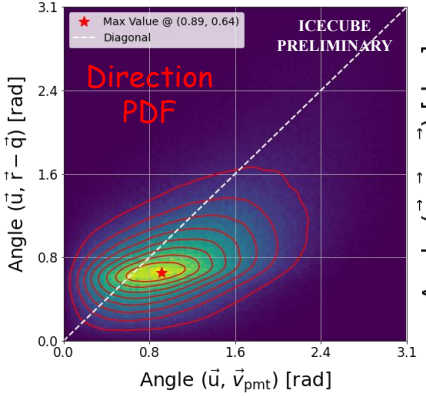
3

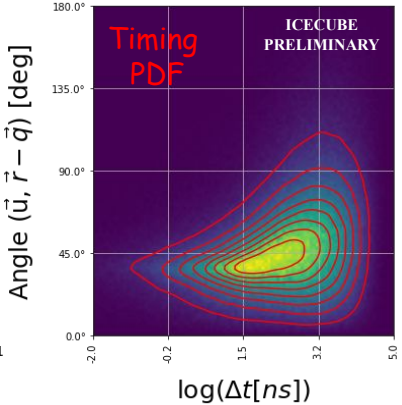
PDFs

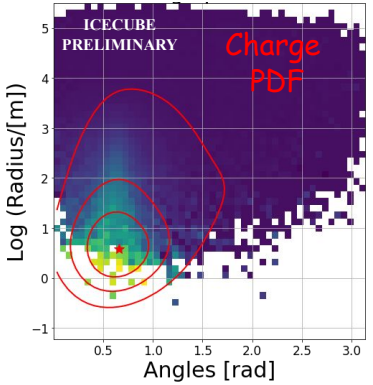
$$\mathcal{L}(\theta \mid \mathbf{x}) = \prod_{s=1}^{N_{\text{sens}}} \left[\prod_{i=1}^{N_s} p_s(\mathbf{x}_{i,s} \mid \theta) \right] P_s(N_s \mid \theta)$$

Photon info

Charge info







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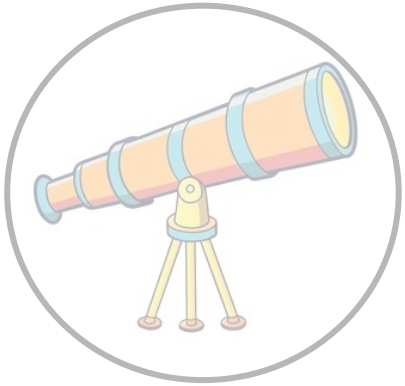
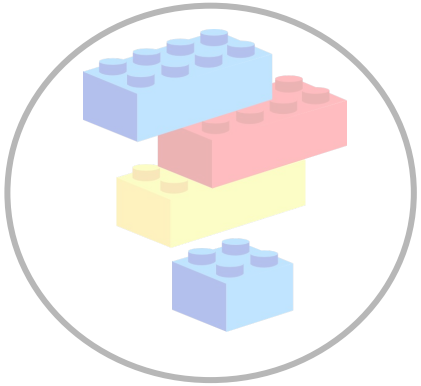
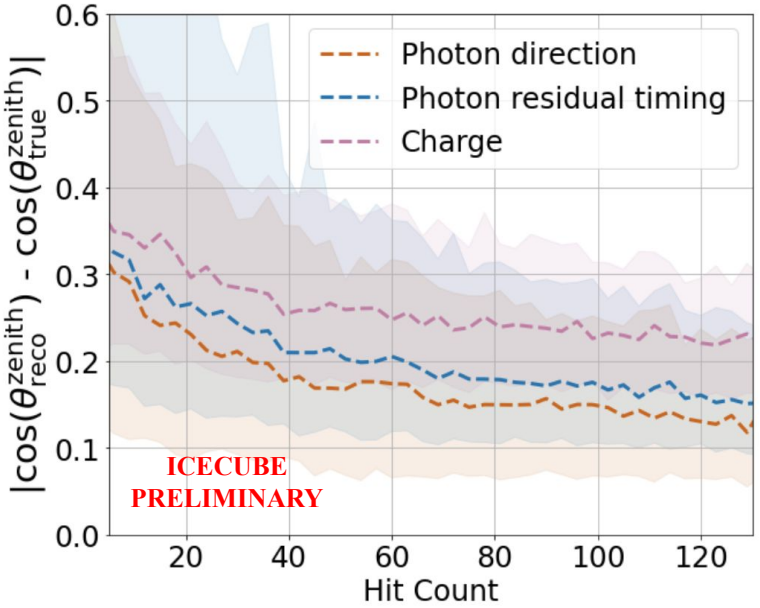


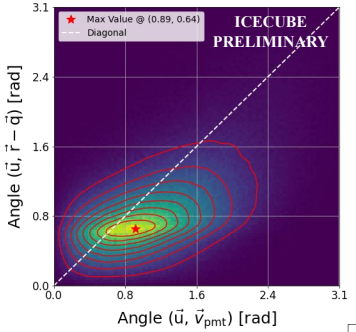


Phase-4: Results

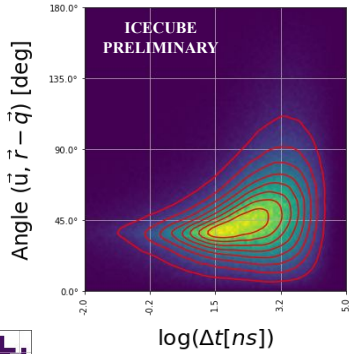
What do we finally get out of this?

Result 1: Contributions from individual observables

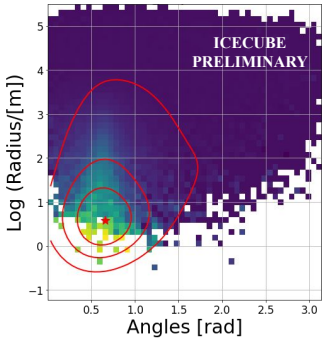




PHOTON DIRECTION



PHOTON RESIDUAL TIMING



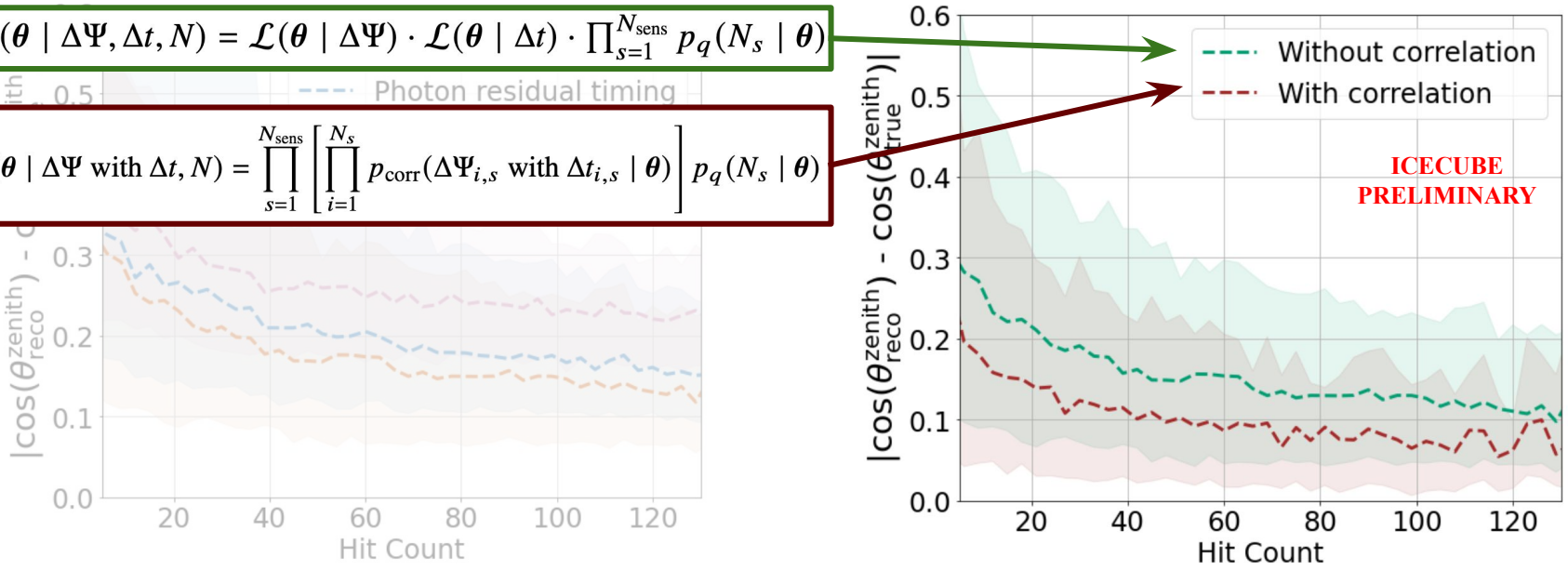
CHARGE

- Simulations include **all** information loss processes.

Result 1: Contributions from individual observables

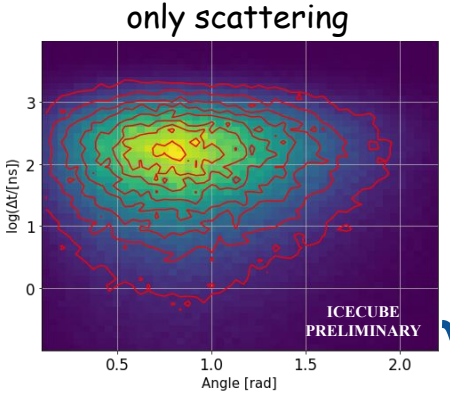
$$\mathcal{L}(\boldsymbol{\theta} \mid \Delta\Psi, \Delta t, N) = \mathcal{L}(\boldsymbol{\theta} \mid \Delta\Psi) \cdot \mathcal{L}(\boldsymbol{\theta} \mid \Delta t) \cdot \prod_{s=1}^{N_{\text{sens}}} p_q(N_s \mid \boldsymbol{\theta})$$

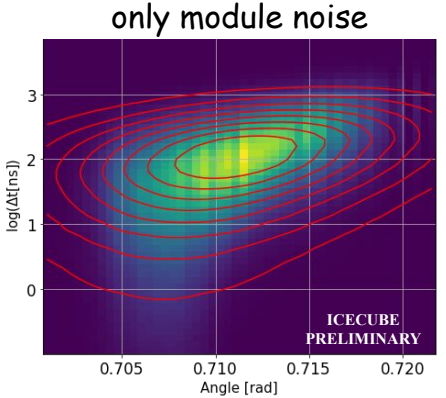
$$\mathcal{L}(\boldsymbol{\theta} \mid \Delta\Psi \text{ with } \Delta t, N) = \prod_{s=1}^{N_{\text{sens}}} \left[\prod_{i=1}^{N_s} p_{\text{corr}}(\Delta\Psi_{i,s} \text{ with } \Delta t_{i,s} \mid \boldsymbol{\theta}) \right] p_q(N_s \mid \boldsymbol{\theta})$$

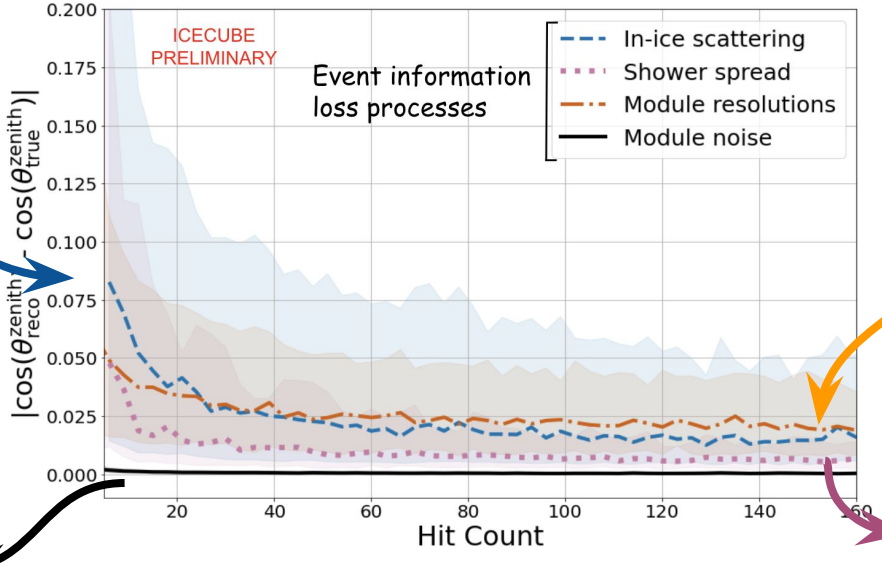


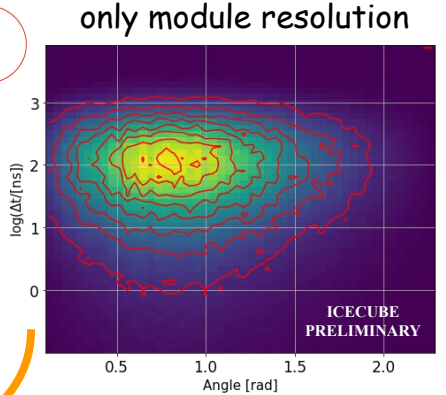
- Simulations include **all** information loss processes.
- Brown line is the approximate resolution limit.

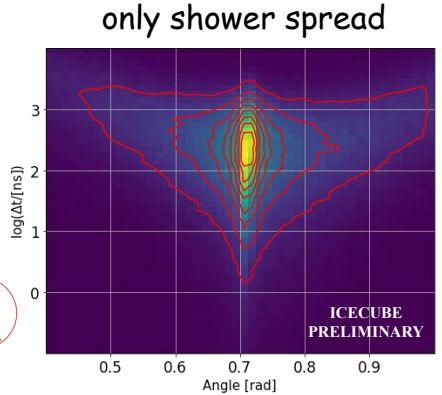
Result 2: Contributions from information limiting processes



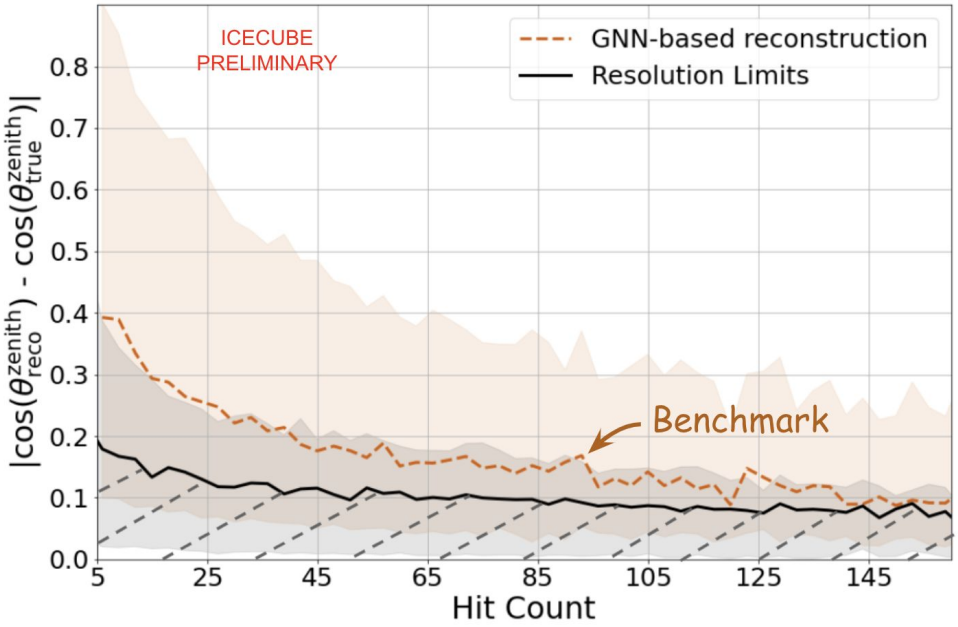






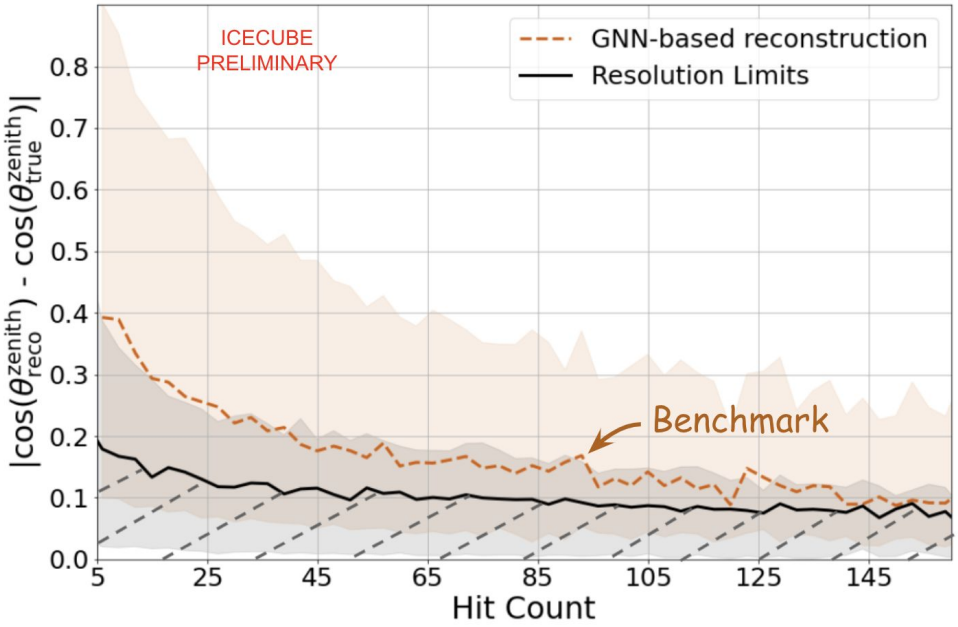


Result 3: Comparison with the benchmark



- Benchmark reconstruction uses Graph Neural networks (GNNs) on full-detector simulations.
  ice and detector systematics
- GNN trained on all simulated Upgrade events - tracks/cascades, reconstruction only on ν_e NC events.
- Scope for resolution improvement at low hit counts, however **current benchmark approaches limits at high hit counts.**

Result 3: Comparison with the benchmark



Why is this a conservative estimate of the intrinsic resolution limit ?

- **Homogeneous ice** prevents systematic errors from intricate ice modelling.
- **Photon direction**, **timing**, and **per-module charge information** provides optimal input to the reconstruction.
- Averaged PDFs are **good approximations of truth PDFs**; near-ideal likelihood descriptions for a given hypothesis.

Key Takeaways

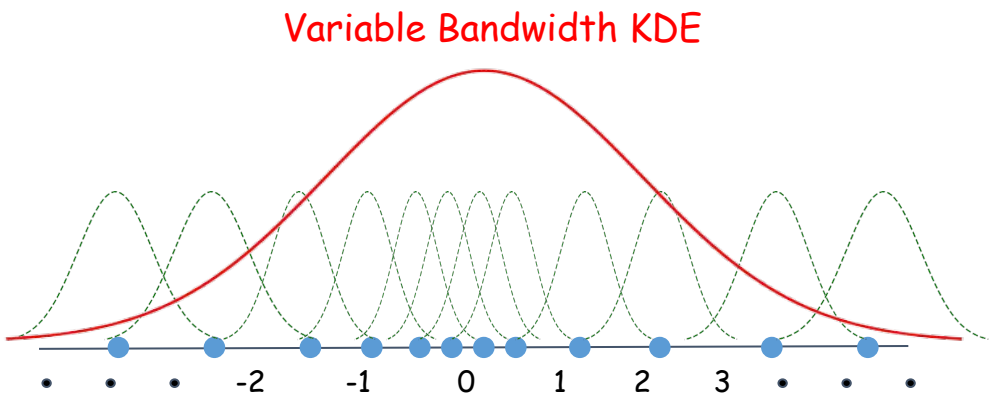
- **Vertex-averaged PDFs** generated within a randomized geometry in homogeneous ice offer **near-ideal likelihood description**.
- Boost in reconstruction by the using the **correlation** of photon direction and timing.
- **Photon scattering** in ice and **module resolutions** are the **dominant contributors** to limiting physics information in IceCube events.
- Reconstruction performance of the benchmark using GNN **approaches resolution limits** at high photon hit counts.

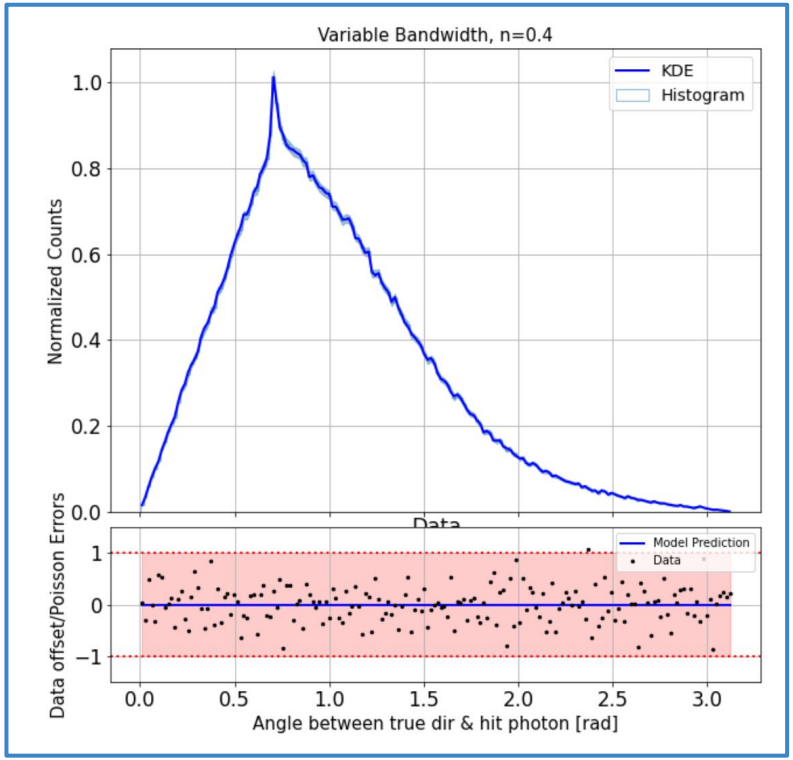
Thank you!

Questions?

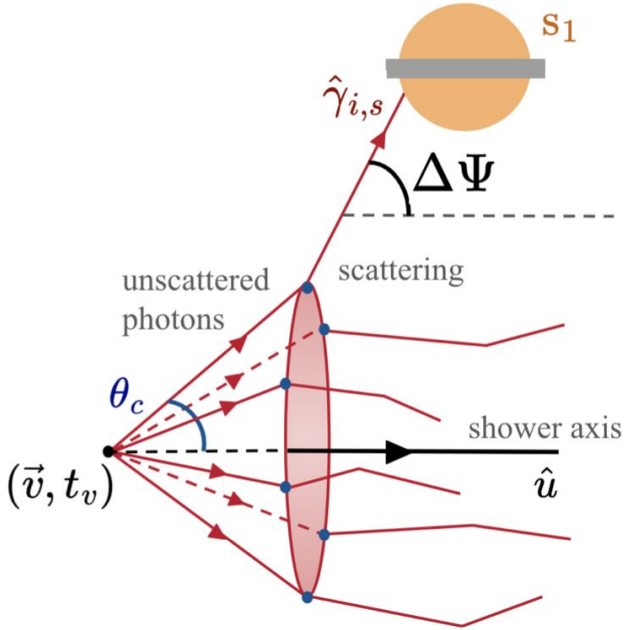
Backups

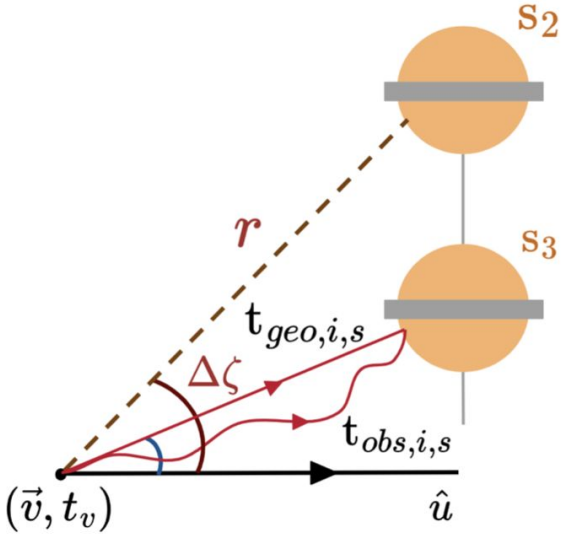
Variable Bandwidth KDE



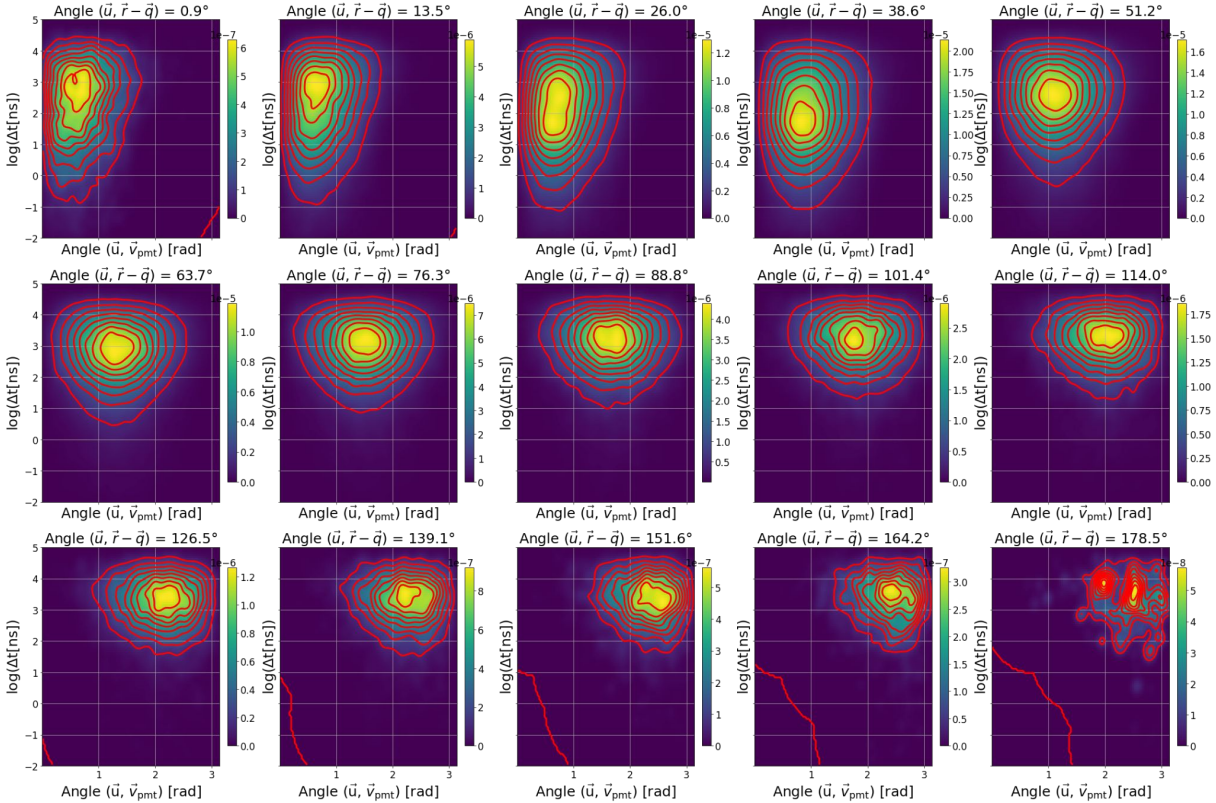


Observables



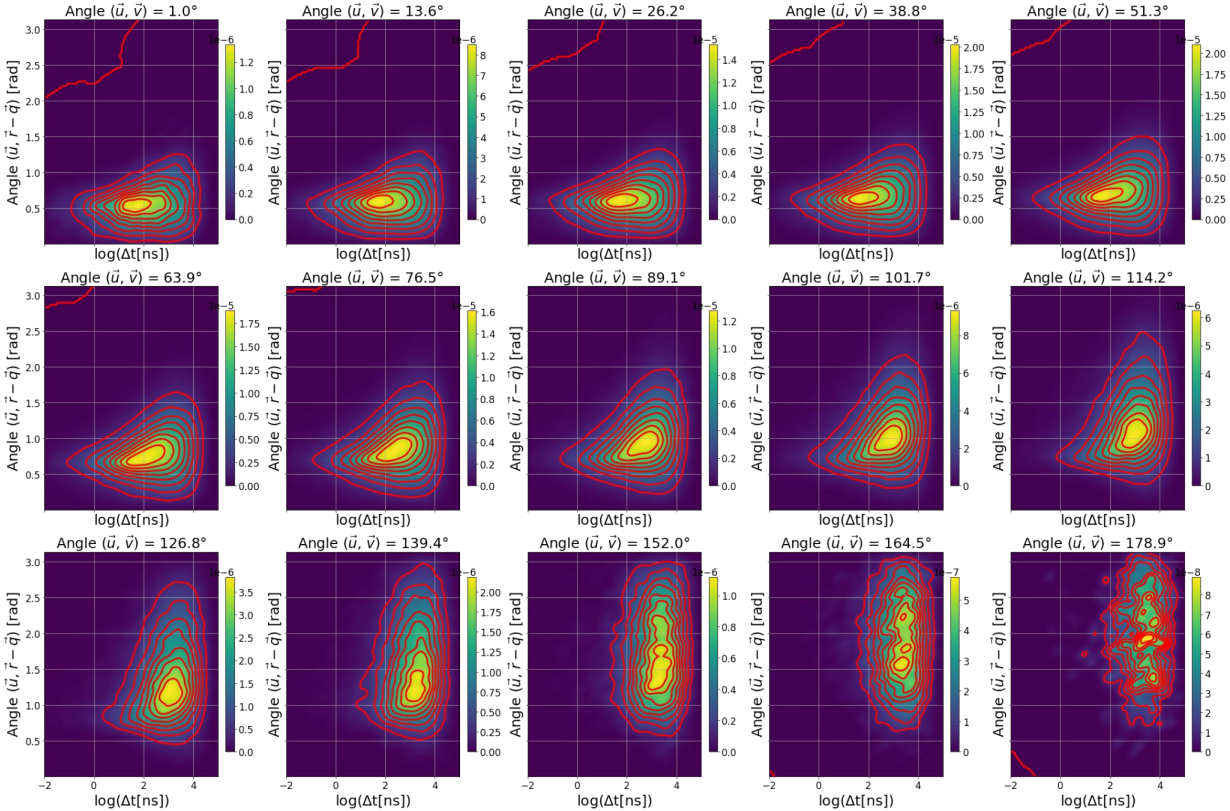


3D correlation PDF slices



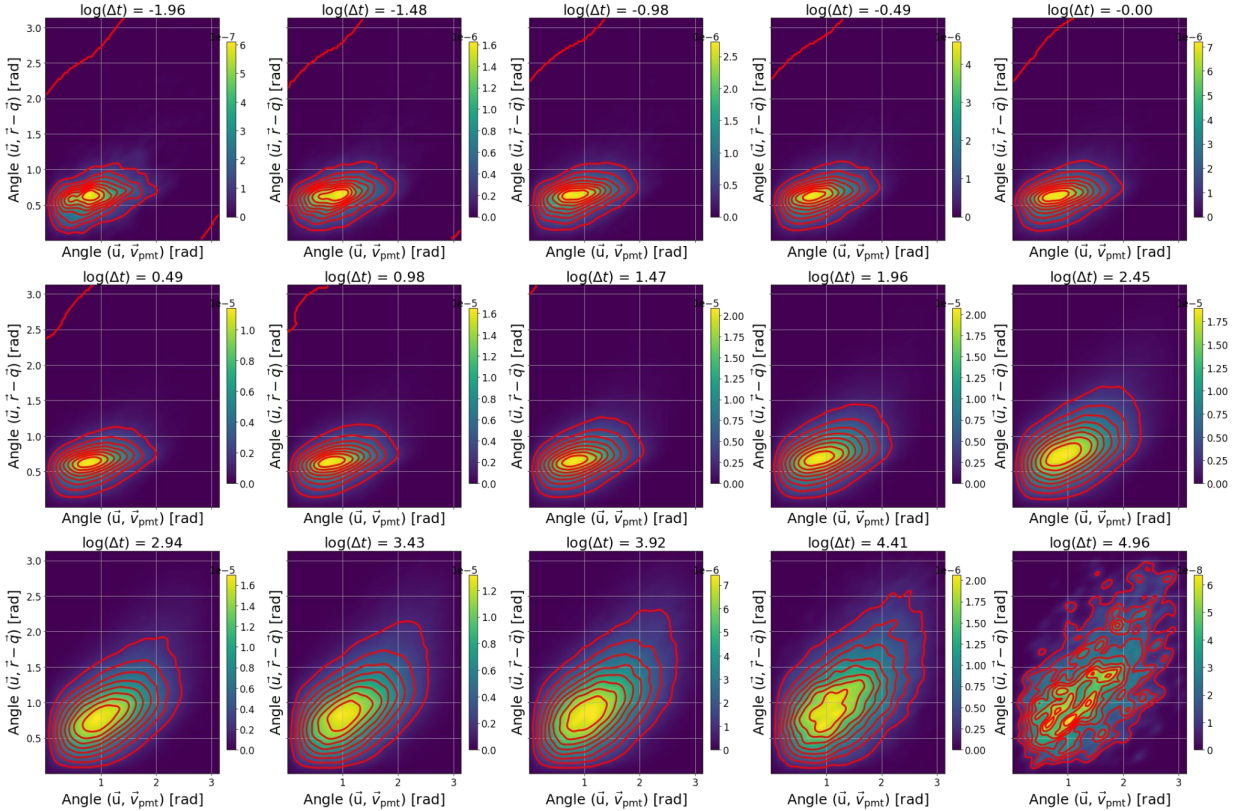
- **Slices of constant opening angle (shower axis, radius vector).**
- VBW KDE fitting takes almost 2 hours for 10^6 photons (entries).
- Using the KDE values directly from the fit during LLH minimisation for 20,000 events between 1-20 GeV takes around **1 day**.
- Therefore, using a **RegularGridInterpolator** in **cubic mode** with 100 bins in each dimension, now takes **10 hours.**

3D correlation PDF slices



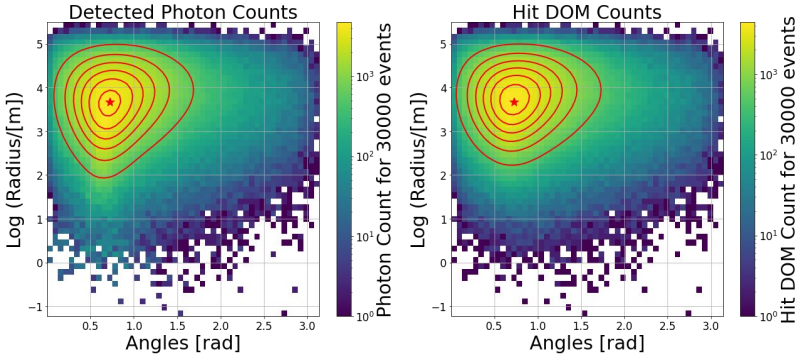
- **Slices of constant opening angle (shower axis, hit PMT vector).**
- VBW KDE fitting takes almost 2 hours for 10^6 photons (entries).
- Using the KDE values directly from the fit during LLH minimisation for 20,000 events between 1-20 GeV takes around **1 day**.
- Therefore, using a **RegularGridInterpolator** in **cubic mode** with 100 bins in each dimension, now takes **10 hours.**

3D correlation PDF slices

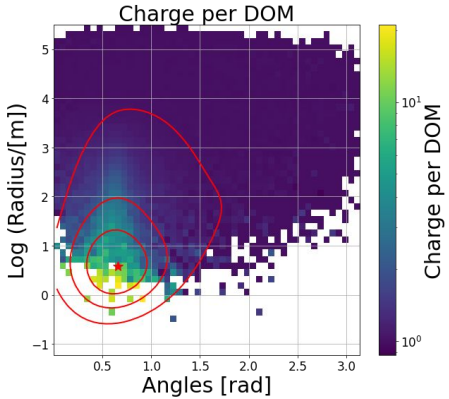


- **Slices of constant residual timings.**
- VBW KDE fitting takes almost 2 hours for 10^6 photons (entries).
- Using the KDE values directly from the fit during LLH minimisation for 20,000 events between 1-20 GeV takes around **1 day**.
- Therefore, using a **RegularGridInterpolator** in **cubic mode** with 100 bins in each dimension, now takes **10 hours.**

Charge distribution modeling

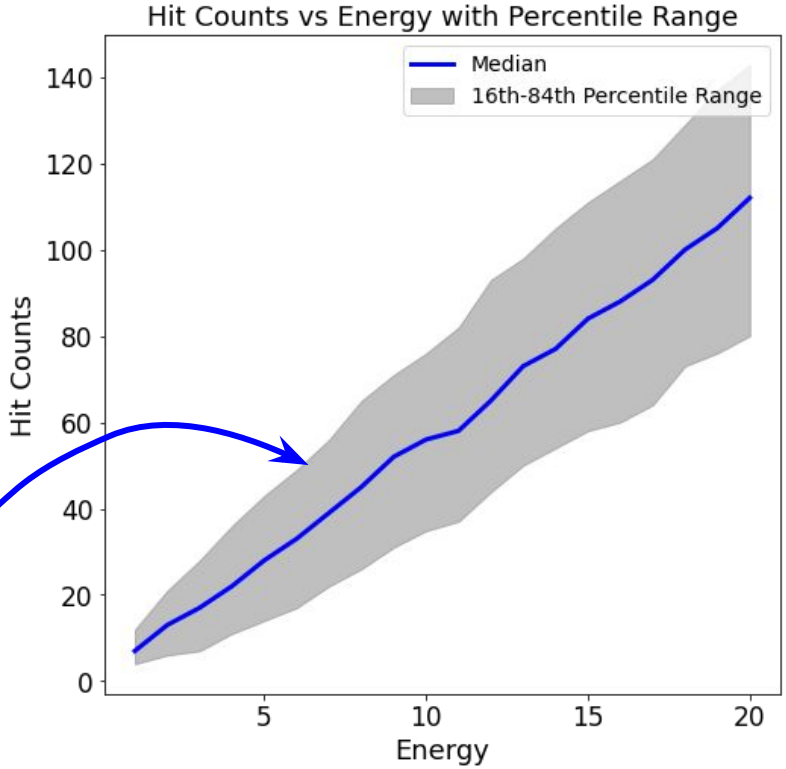


5 GeV

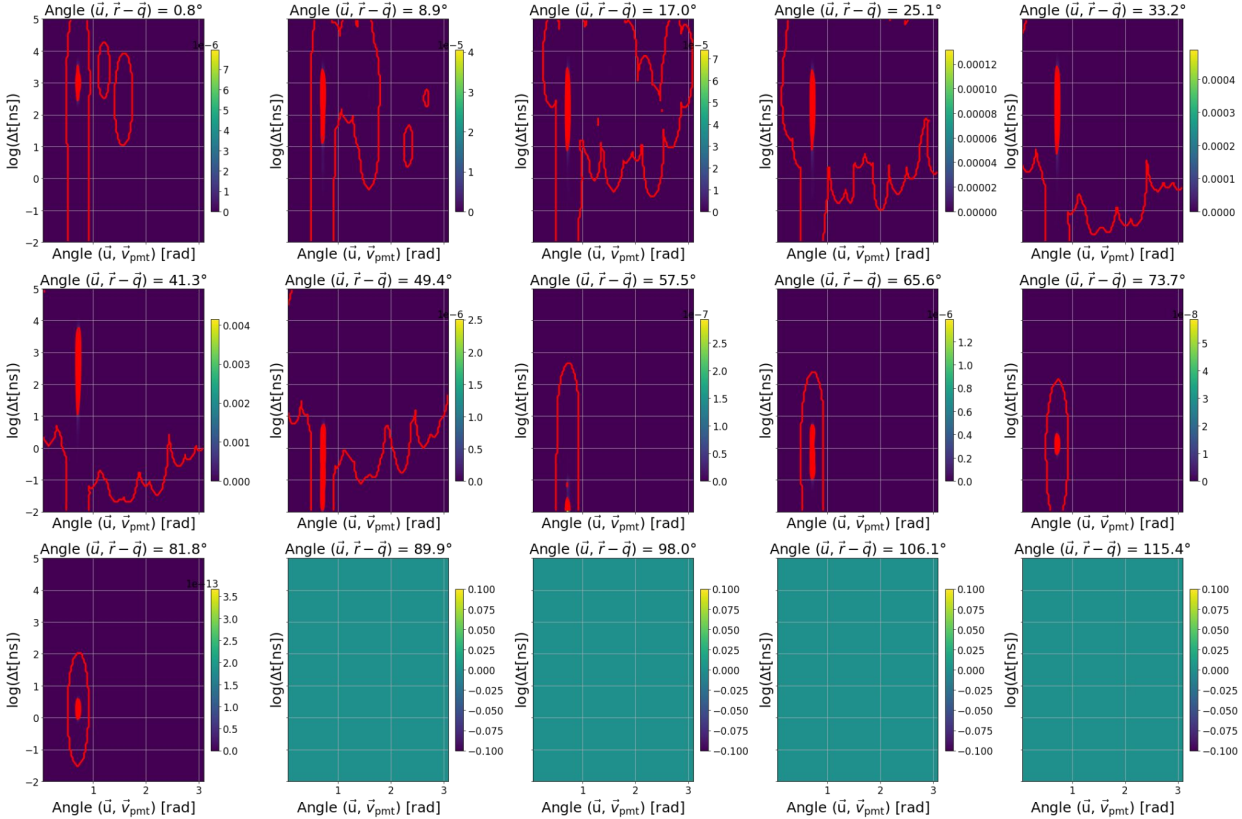


Expected total hit count for a given energy.

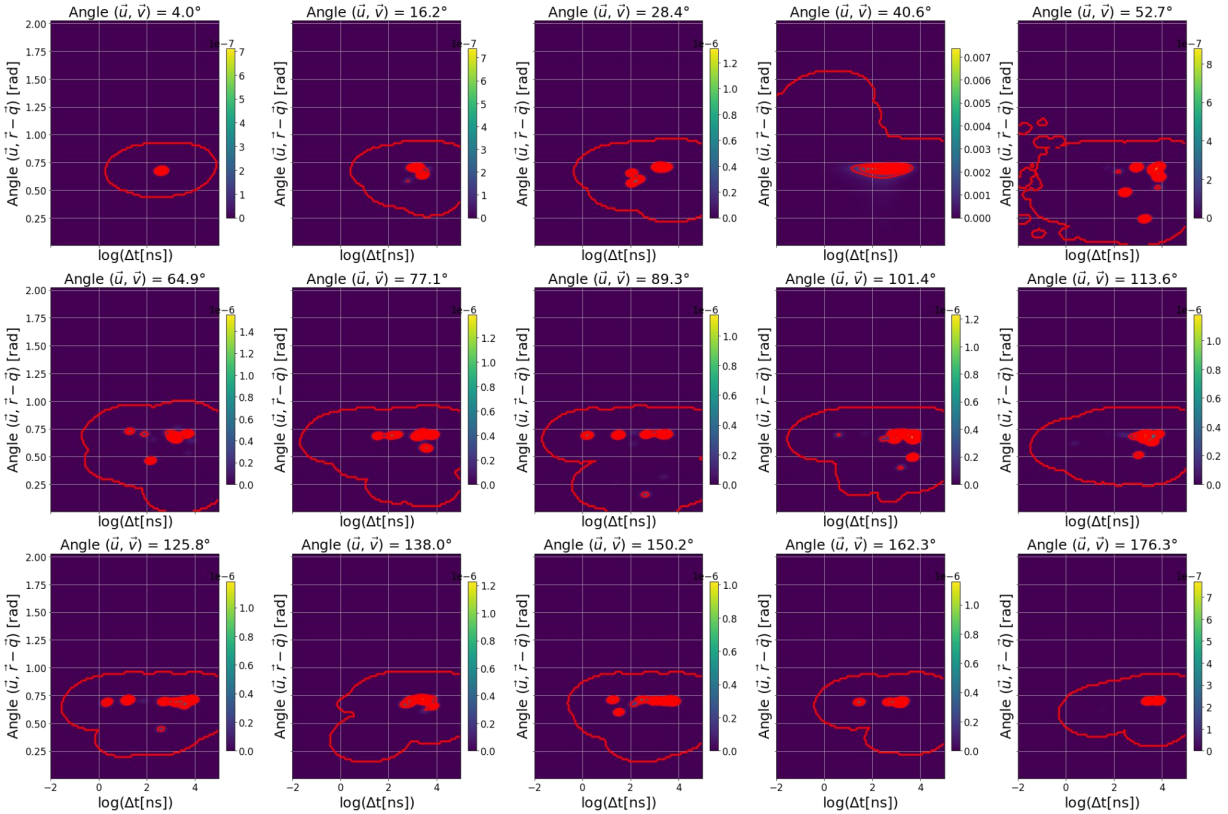
Charge distribution remains same and is simply scaled up.



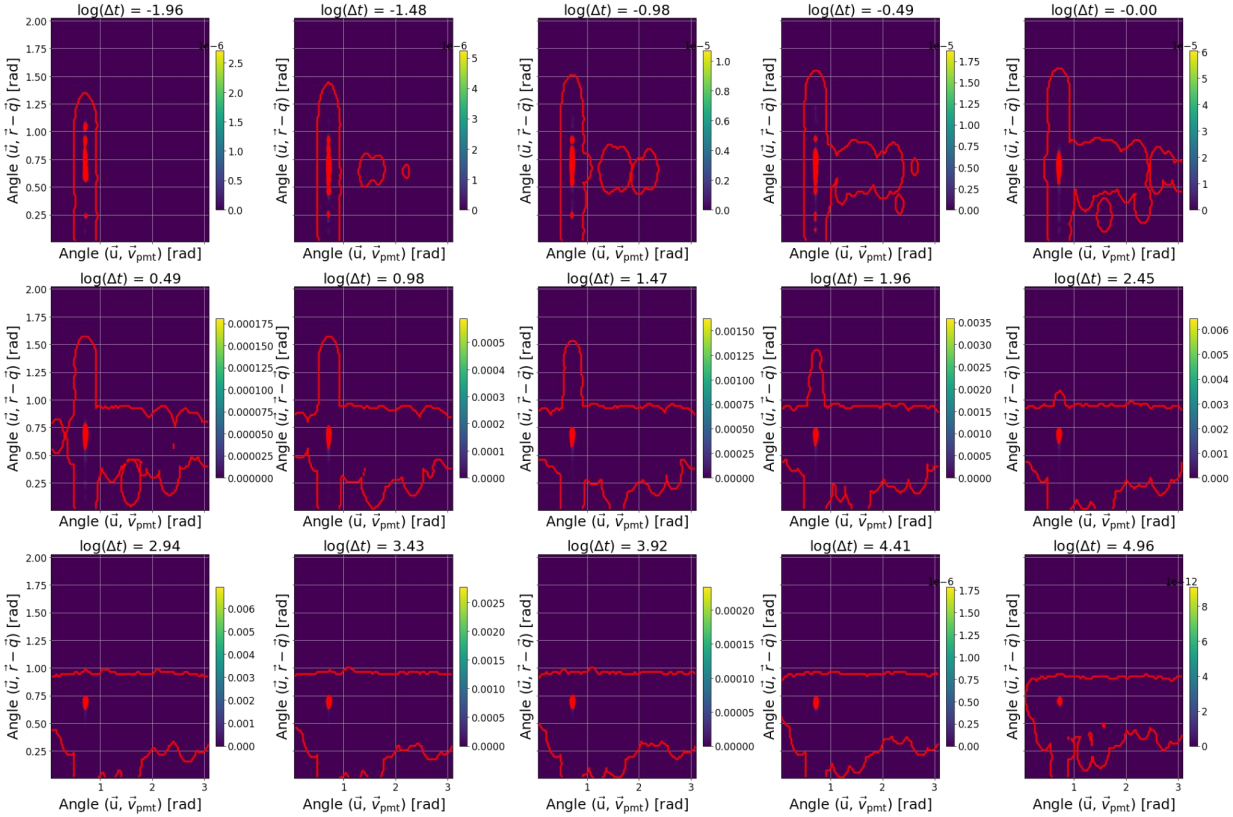
3D PDF from module noise



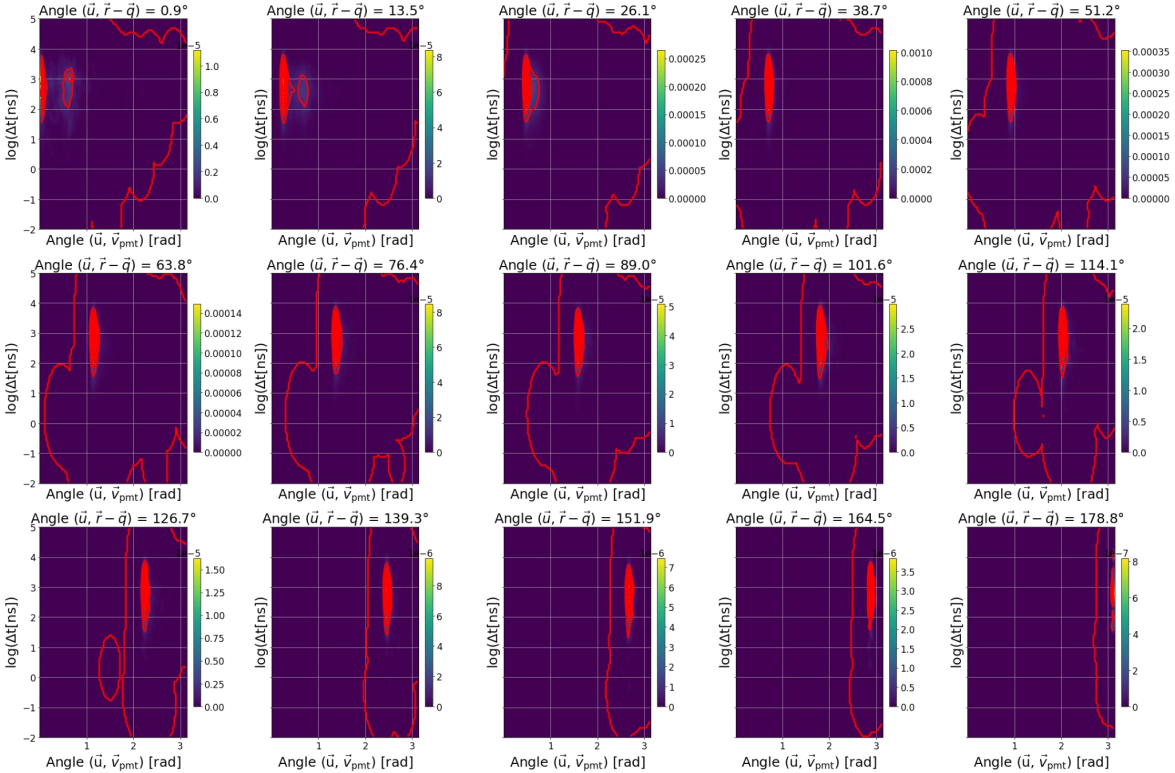
3D PDF from module noise



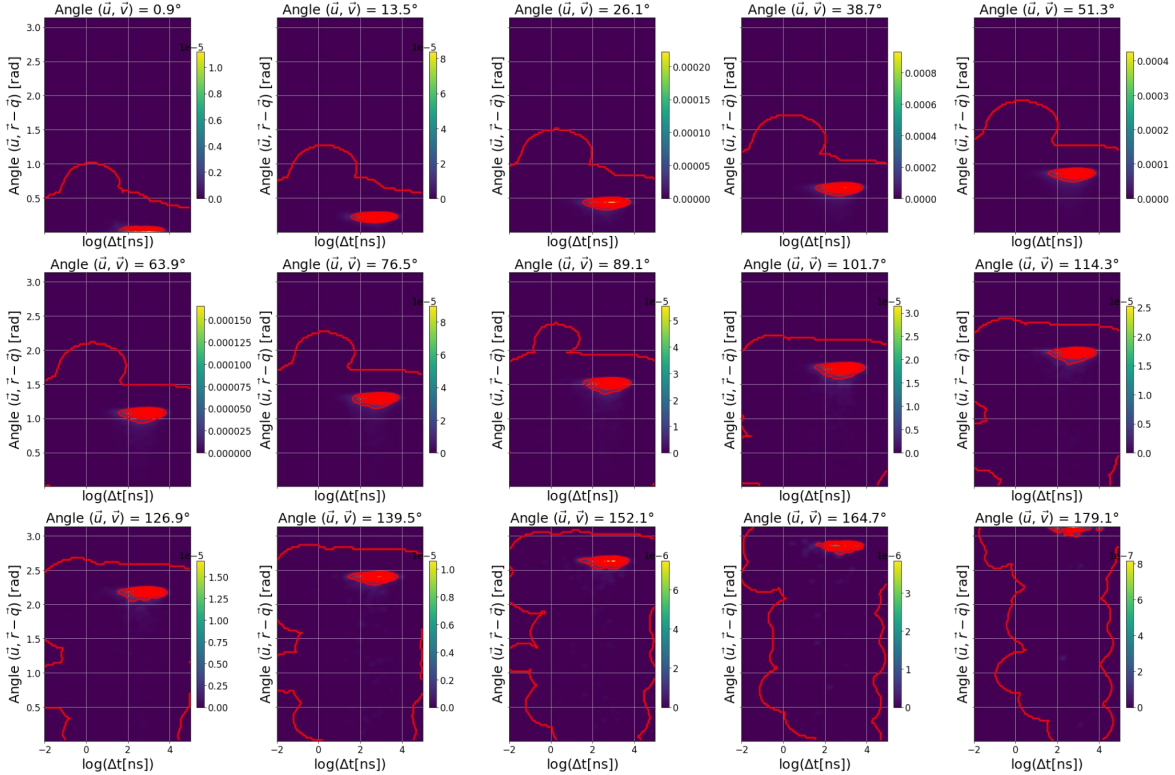
3D PDF from module noise



3D PDF from shower spread



3D PDF from shower spread



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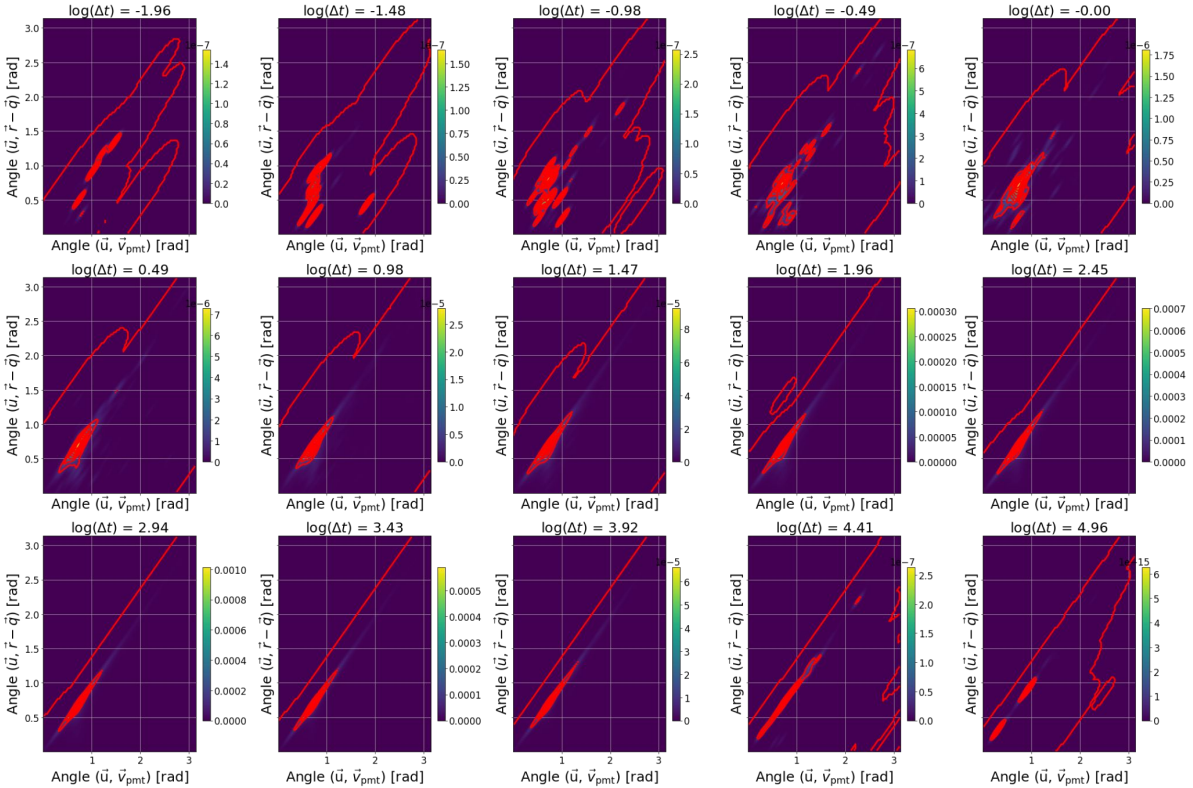
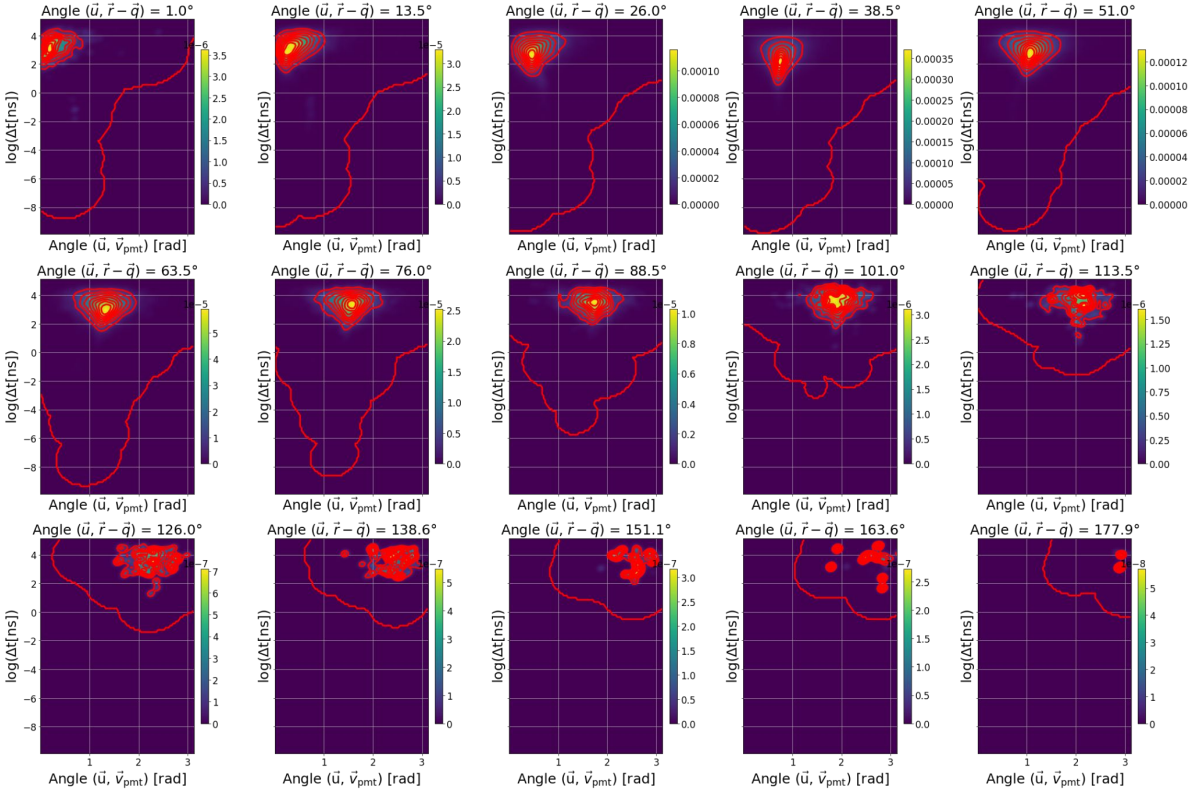


3D PDF from scattering



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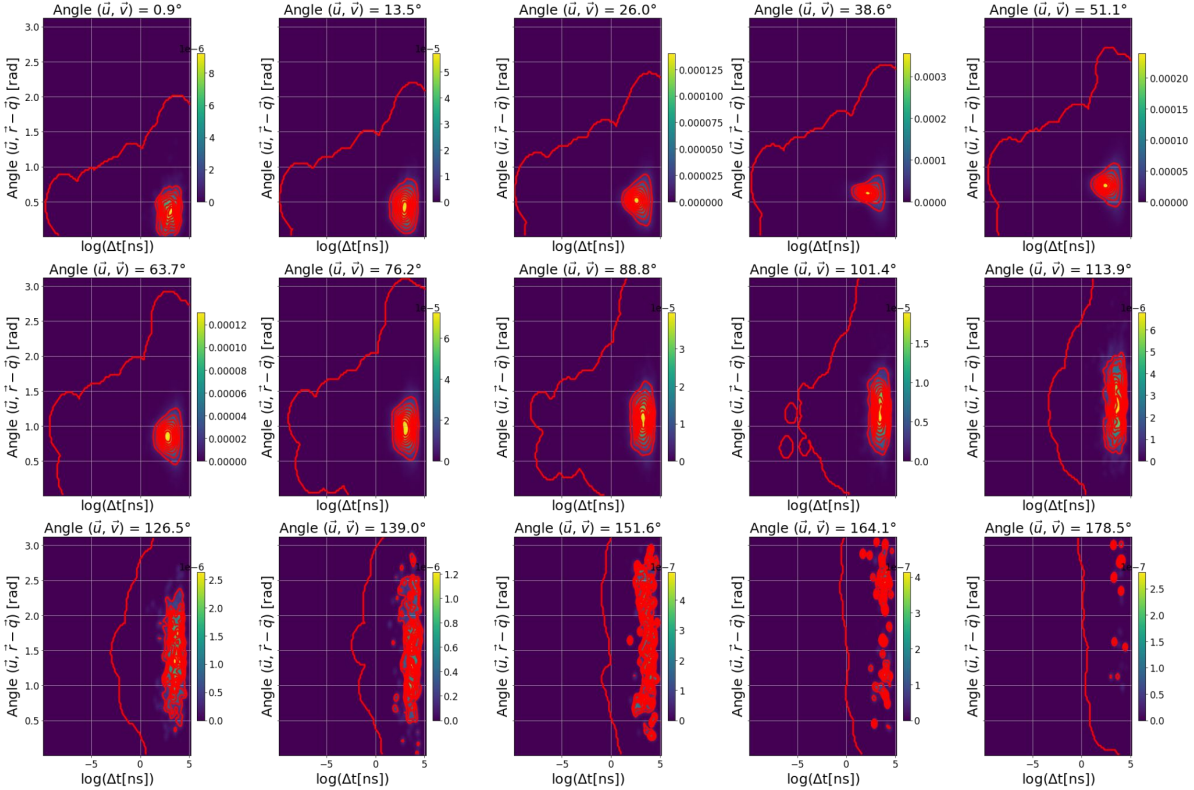
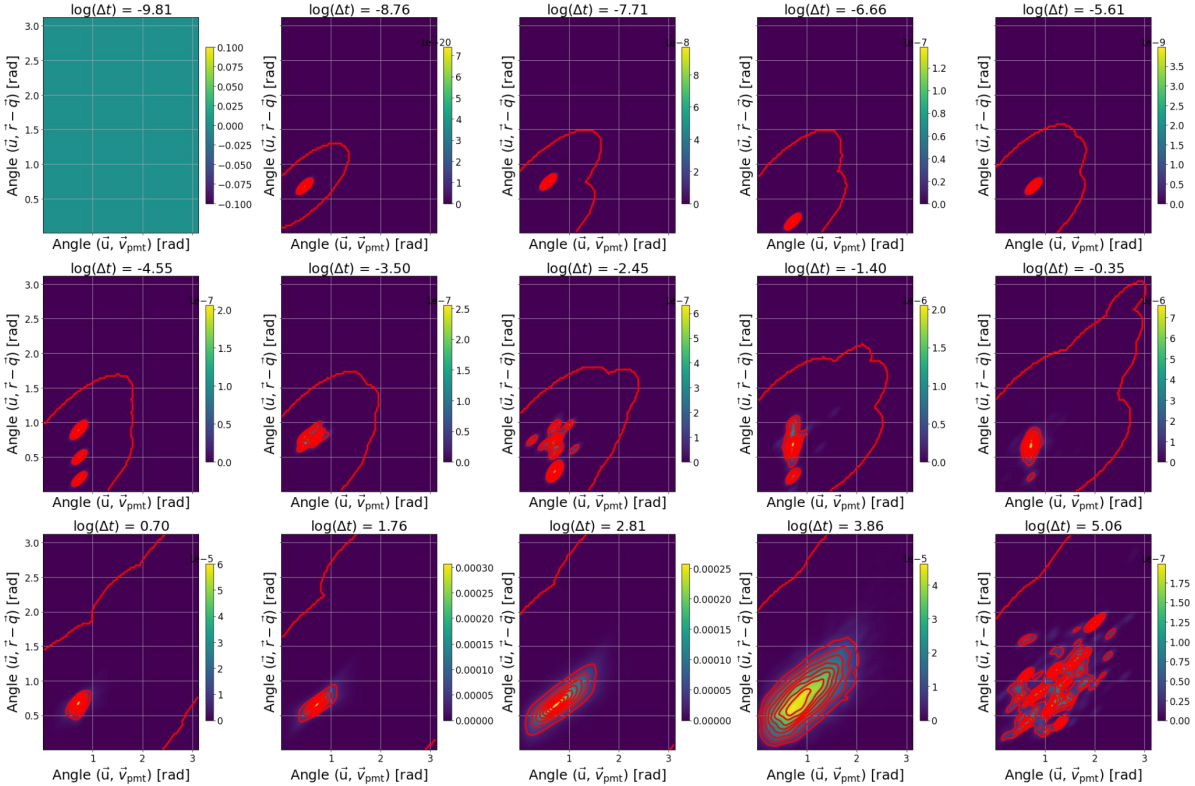
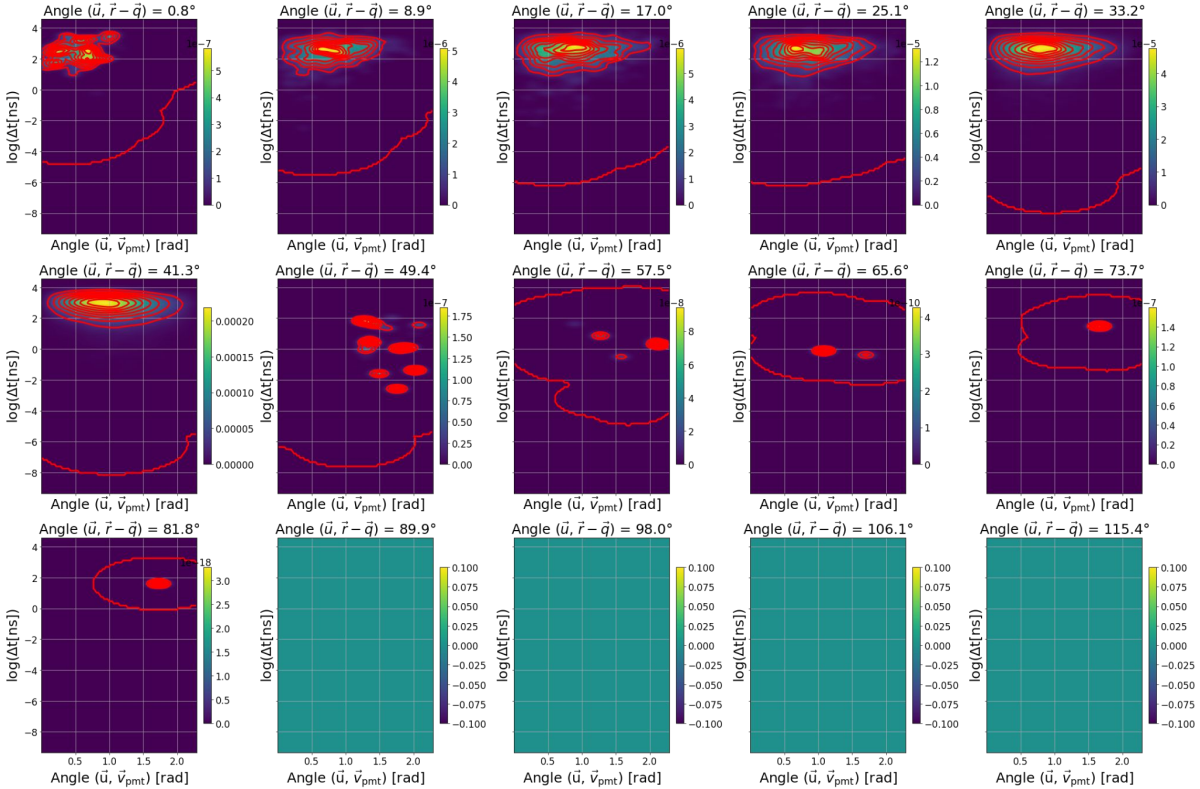


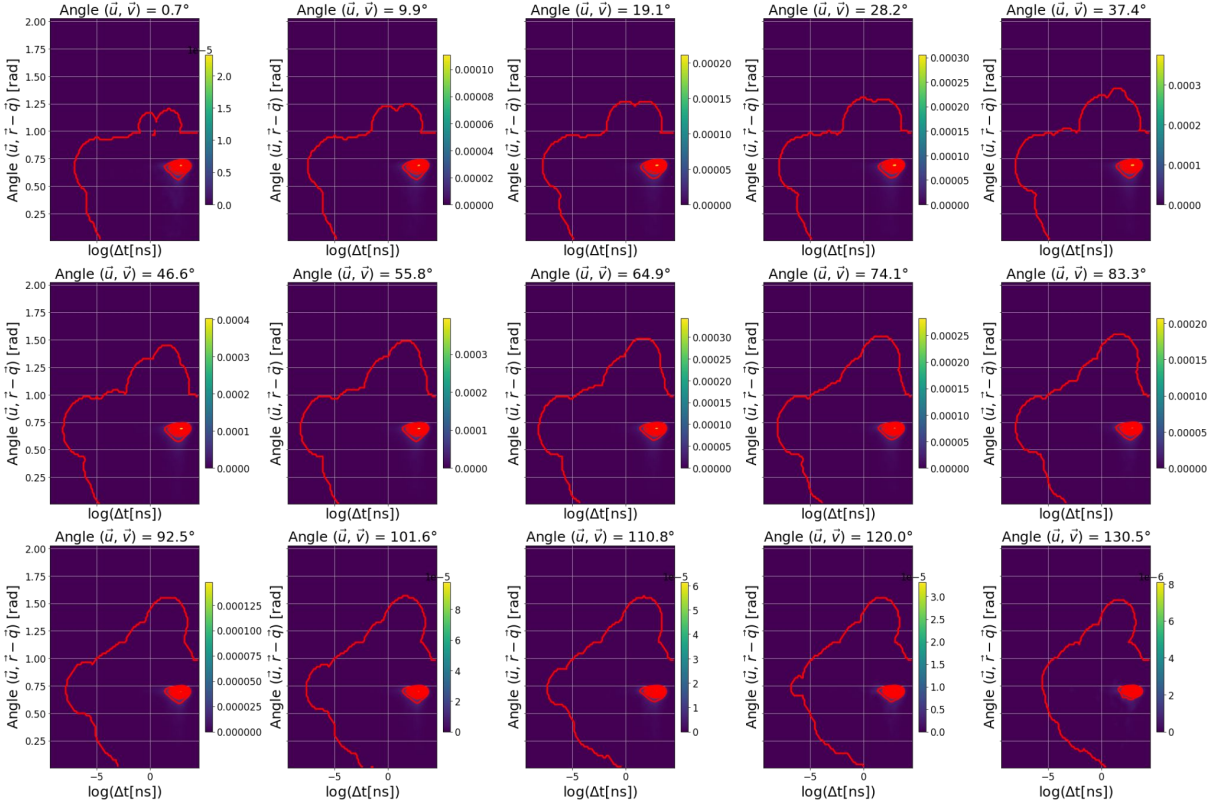
3D PDF from scattering



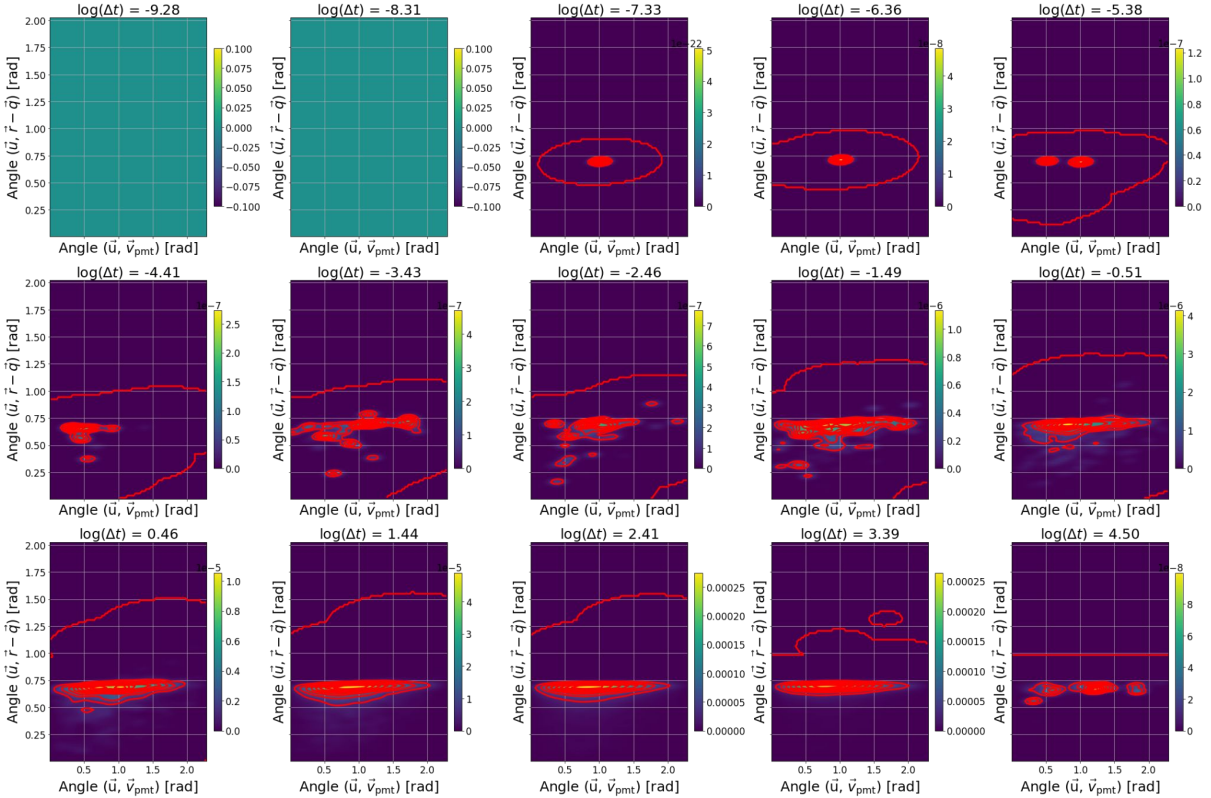
3D PDF from module resolutions



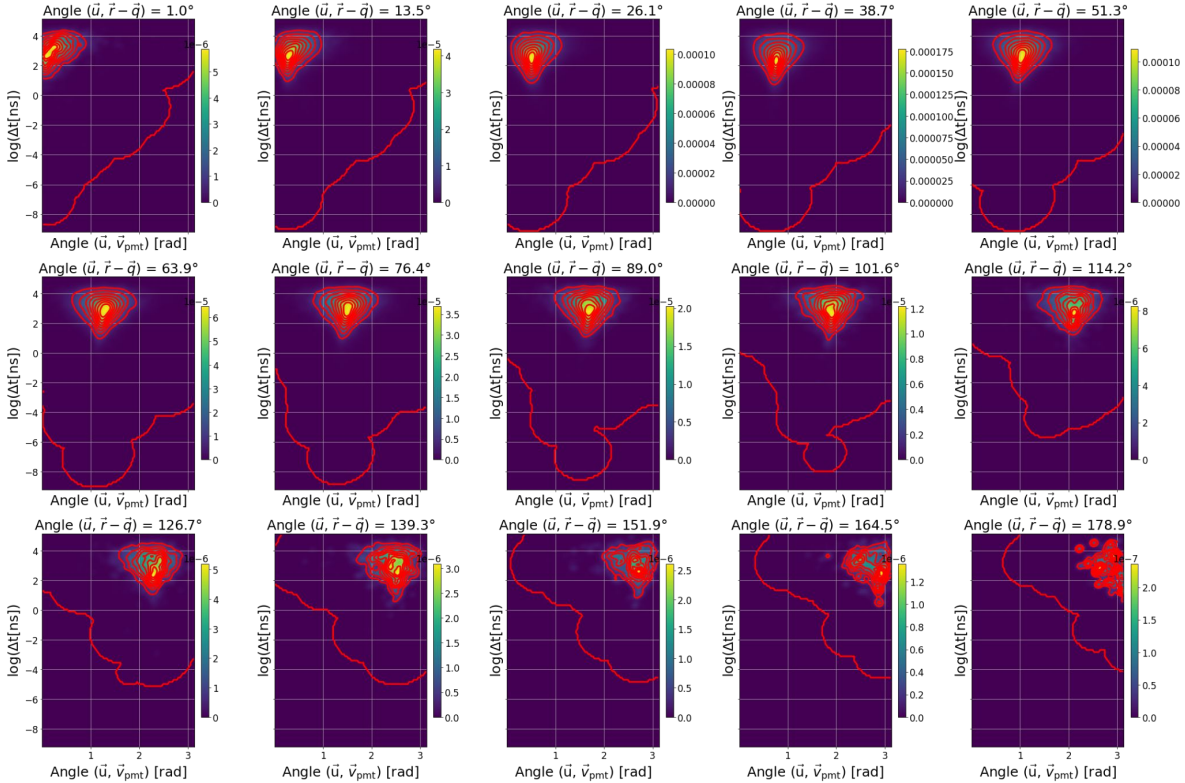
3D PDF from module resolutions



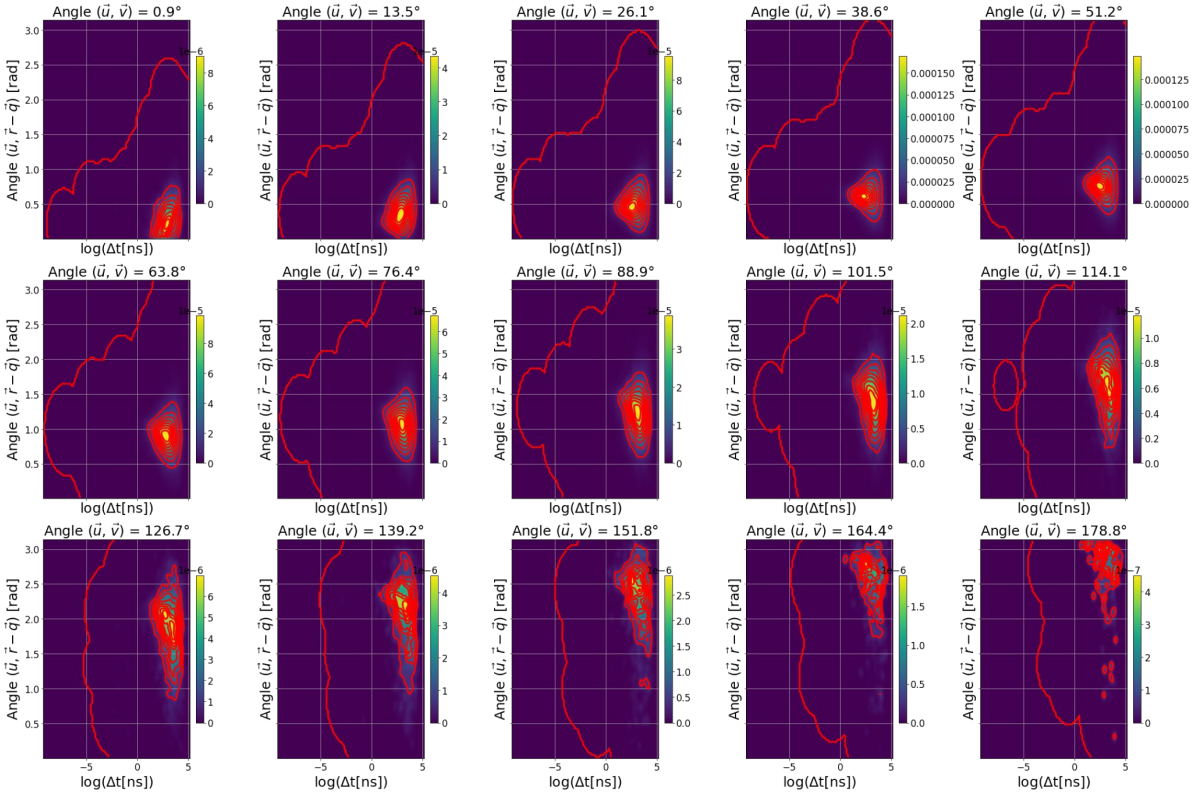
3D PDF from module resolutions



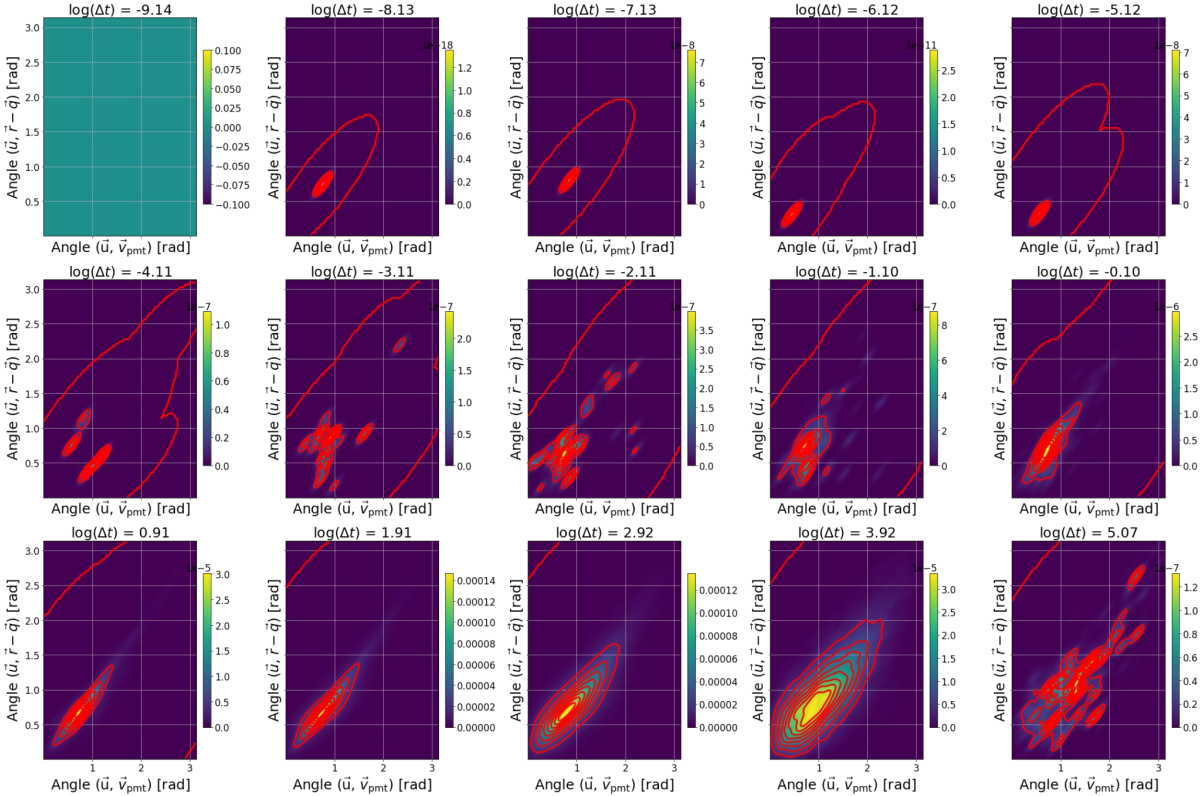
3D PDF ignoring module resolutions



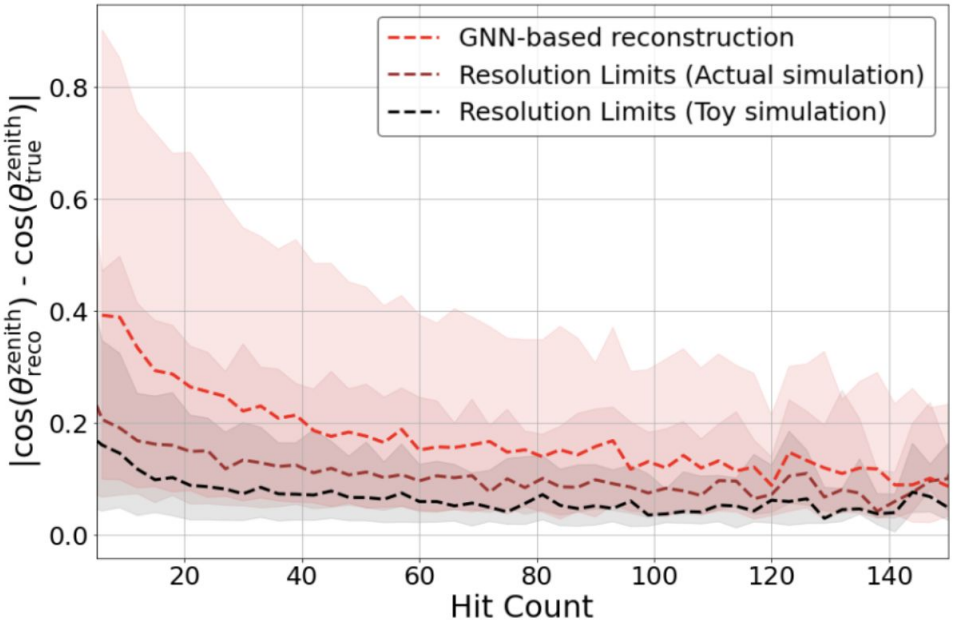
3D PDF ignoring module resolutions



3D PDF ignoring module resolutions



Accounting for PDF modelling errors: Toy MC



- **GNN plot** remains the same as v4 of the paper.
- **Resolution limit plot** updated with 3D averaged PDFs+charge PDF.
- For the **Toy simulation**:

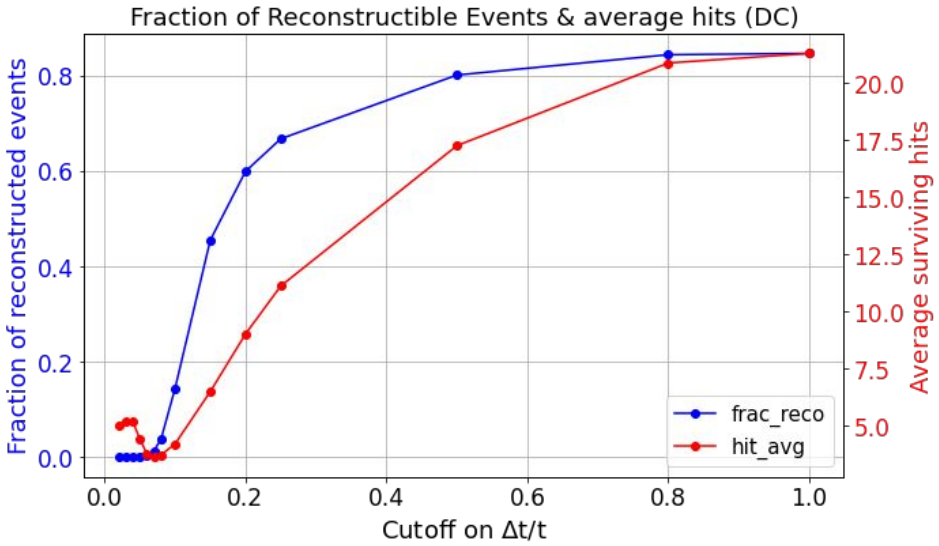
  (a) Timestamps and photon directions constructed by sampling Δt and $\Delta\Psi$ (hit PMT, event) from the averaged PDFs.

  (b) Charge distribution not changed; only the observed values for each photon from PPC replaced with the PDF sampled values.

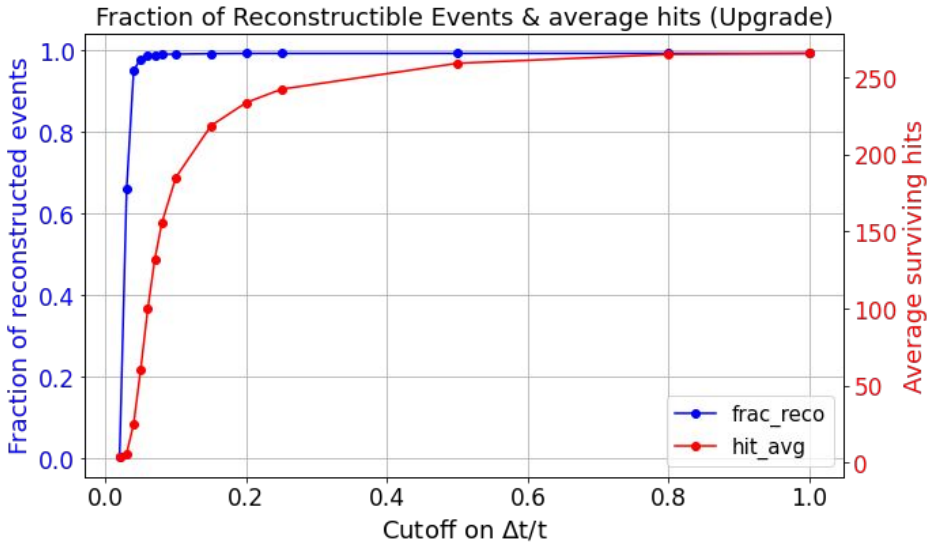
Each module has identical PDFs = averaged integrated PDF ➡ No PDF mismodeling errors.

Surviving hit fraction vs delay time cutoff

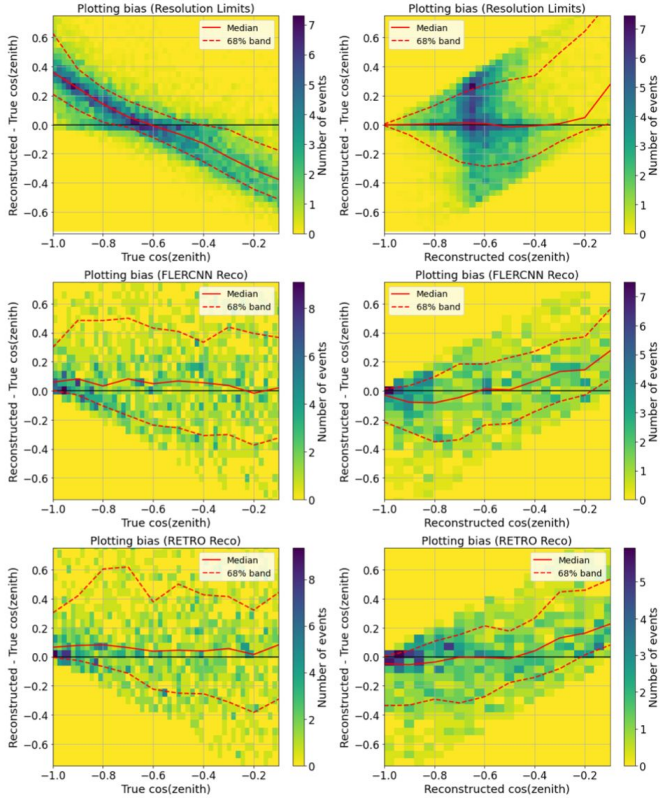
DeepCore



Upgrade



Reconstruction errors for DeepCore



Impact of adding noise on PDFs