Approximate Intrinsic Resolution Limits for Low-Energy Cascade Events with the IceCube Upgrade

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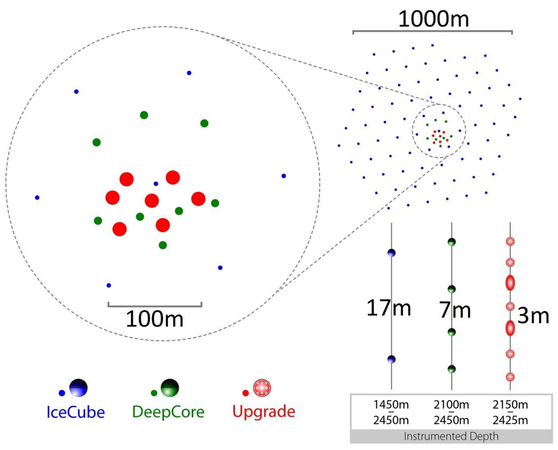
The IceCube Upgrade

The IceCube Upgrade [1] is the upcoming **low-energy** extension to the existing IceCube detector. Some of its features:

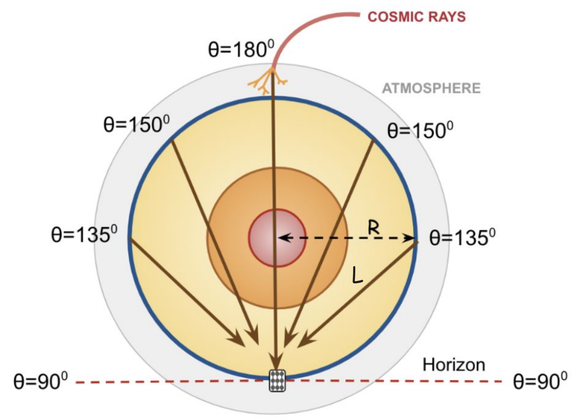
- **Seven** new strings within the DeepCore volume.
- Novel **multi-PMT** optical modules & calibration devices.
- Denser instrumentation, with horizontal & vertical inter-module spacings at ~30 m and 3 m respectively.



Introduction

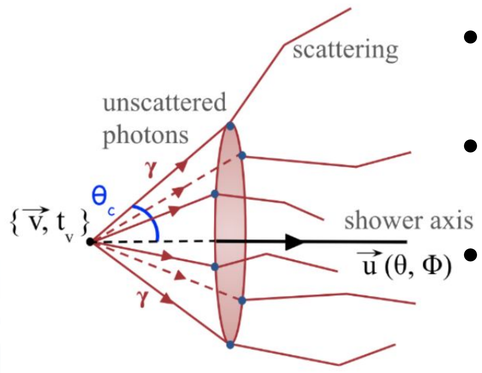
Scientific Motivation

- Zenith angle θ of a neutrino translates to the **baseline** L propagated within the Earth, as L ≅ 2R cosθ.
- Reconstruction accuracy relevant for oscillation physics analyses such as sensitivity towards **atmospheric oscillation parameters** [2] & **NMO** [3].

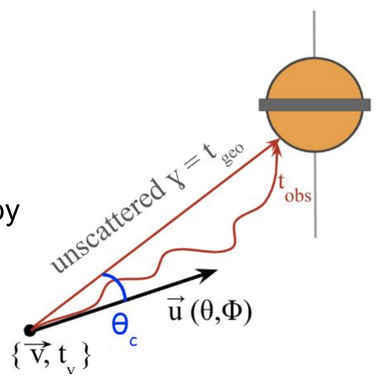


- A 5%, 10%, and 15% zenith resolution improvement **enhances NMO sensitivity** by 3%, 10%, and 15% [4].

Event Information



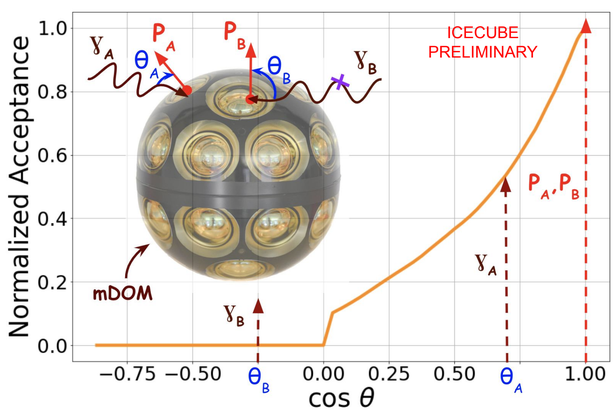
- An IceCube event is a collection of detected **Cherenkov photons**.
- PMTs in modules record **charge** and **timing** values of detected photons.
- Pointing resolution of multi-PMT modules provide additional **directional** information.
- The **angular** and **temporal distribution** of individual photons along with the **per-module charge** utilized in reconstruction.
- Directional information limited by **shower spread**, in-ice **photon scattering**, **finite PMTs** in modules (module resolutions) and **background noise**.

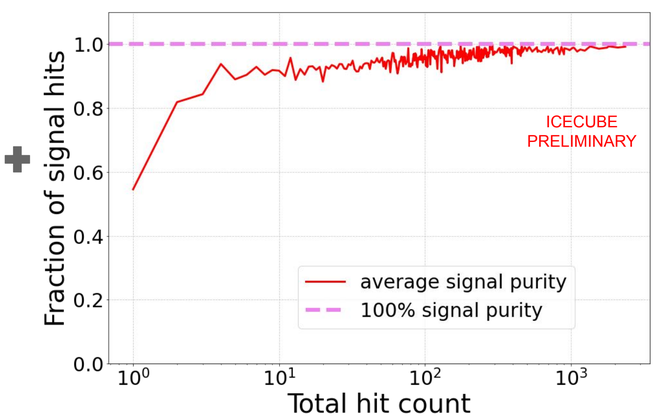


Procedure

Event Simulation

- **Photon emission profile** and **propagation** simulated on the PPC [5].
- PPC output: detected photon directions, recorded time, hit string and module index, etc.
- Idealisations in contrast to full-fledged MC chain:
  - **Homogeneous ice** simplifies photon propagation and circumvents complex ice modelling.
  - Event triggering, filtering, and PMT readout bypassed.

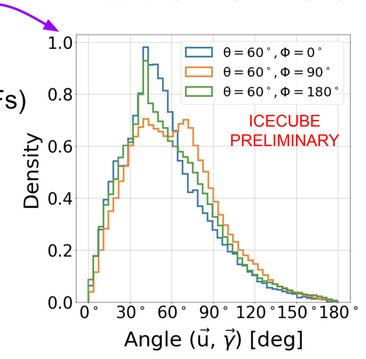


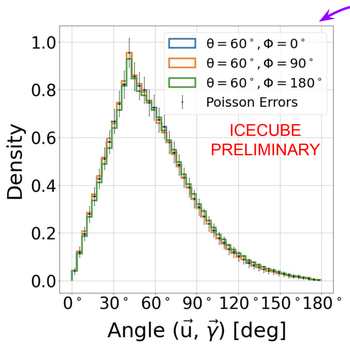


- **Module resolutions** simulated by projecting incident photon directions onto the nearest PMT axis, resulting in a realistic response.
- **Poissonian noise** simulated by rejection sampling on the signal purity curve obtained from Upgrade simulations.

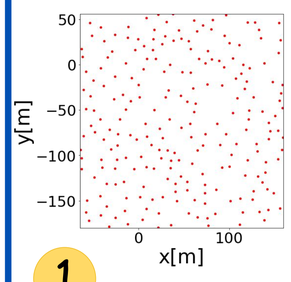
Event Reconstruction

PDFs in the actual geometry (truth PDFs) change with event direction.





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



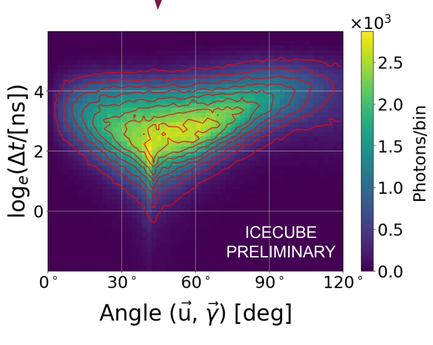
1 **Randomized geometry** generated by positioning strings and modules within a string randomly with spacing thresholds to avoid clustering.

4 **Extended unbinned likelihood reconstruction**

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

Photon info — Charge info

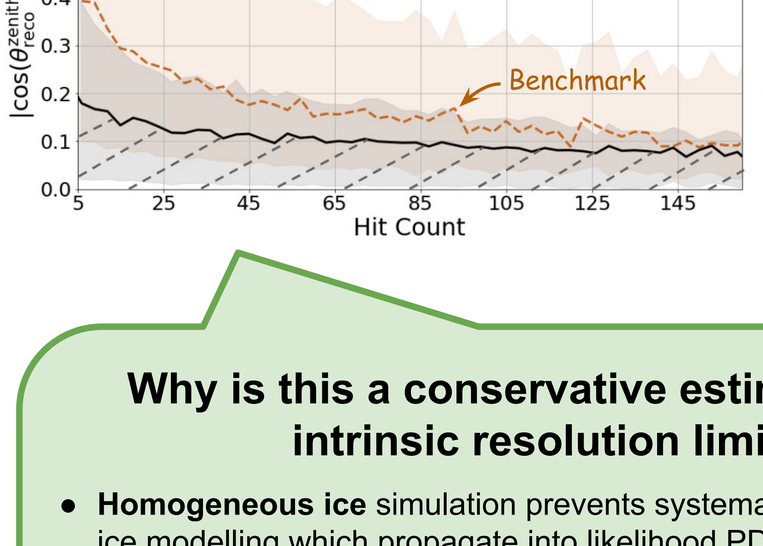
θ = parameter set to reconstruct
x = simulated data
p_s,P_s = vertex-averaged PDFs
N_s = hits within a sensor
N_{sens} = Total number of sensors



3 **2D Variable Bandwidth KDEs** use the correlation between the angular and temporal distributions of detected photons.

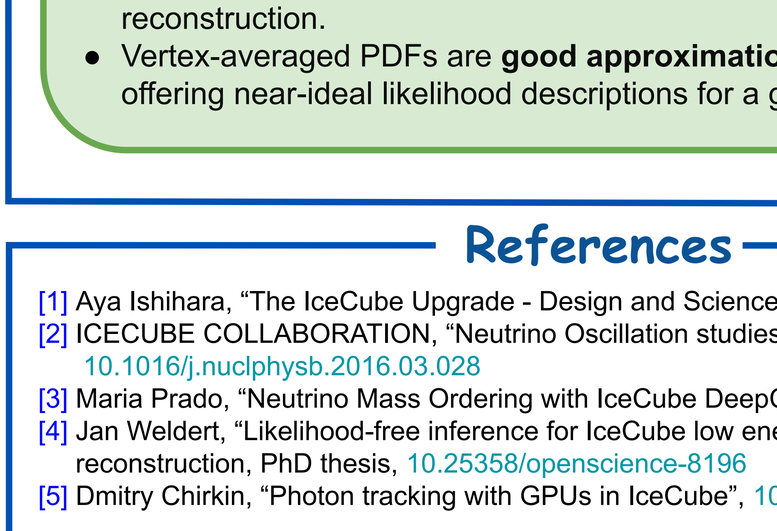
Results

Contributions towards resolution degradation



- Event simulation and likelihood PDFs include a specific information loss process.
- Poissonian **module noise** has a **minimum** impact on resolution degradation, followed by shower spread.
- **Photon scattering** and **module resolutions** are the dominant contributors!

Approximate intrinsic directional resolution limits



- Benchmark reconstruction on simulated Upgrade events uses Graph Neural Network (GNN).
- GNN trained on all simulated Upgrade events, reconstruction only on ν_e NC events.
- Scope for resolution improvement at low hit counts, however **current benchmark approaches limits at high hit counts.**

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

- **Homogeneous ice** simulation prevents systematic errors from intricate ice modelling which propagate into likelihood PDFs and finally into reconstructions.
- The likelihood reconstruction utilizes **photon direction**, **timing**, and **per-module charge information**, providing optimal input to the reconstruction.
- Vertex-averaged PDFs are **good approximations of truth PDFs**, offering near-ideal likelihood descriptions for a given hypothesis.

Conclusions

- **Vertex-averaged PDFs** generated within a randomized geometry in homogeneous ice offer **near-ideal likelihood description** for a given hypothesis.
- **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.

References

[1] Aya Ishihara, “The IceCube Upgrade - Design and Science Goals”, 10.22323/1.358.1031
[2] ICECUBE COLLABORATION, “Neutrino Oscillation studies with IceCube-DeepCore”, 10.1016/j.nuclphysb.2016.03.028
[3] Maria Prado, “Neutrino Mass Ordering with IceCube DeepCore”, 10.3390/psf2023008007
[4] Jan Weldert, “Likelihood-free inference for IceCube low energy reconstruction, PhD thesis, 10.25358/openscience-8196
[5] Dmitry Chirkin, “Photon tracking with GPUs in IceCube”, 10.1016/j.nima.2012.11.170