Neutrino oscillations with IceCube DeepCore

- Recent updates and outlook

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NOW2024, Otranto, Italy

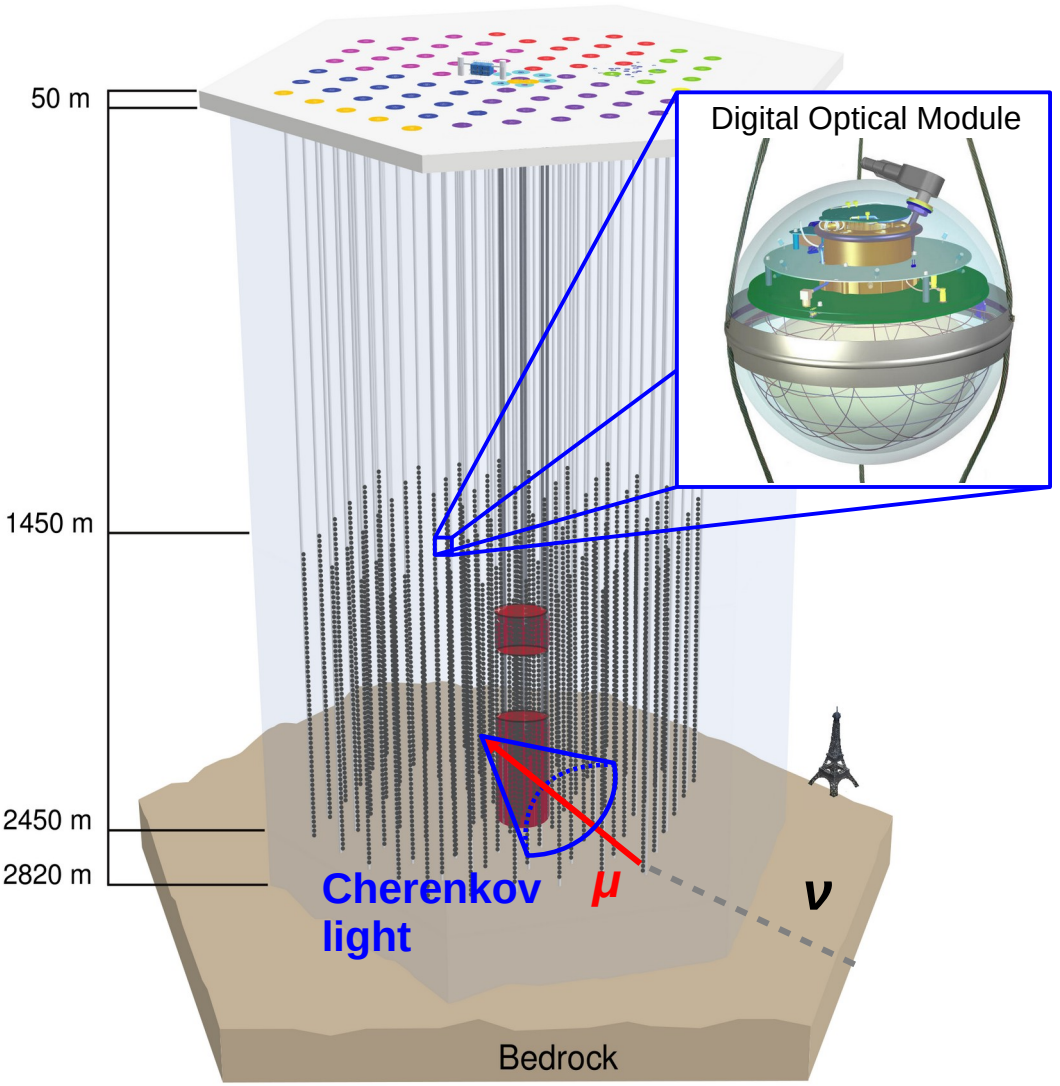
Technical University of Munich

IceCube Neutrino Observatory

IceCube Neutrino Observatory

- IceCube detector:
  - Cherenkov neutrino detector at the South Pole
  - Ice as an optical detection medium
  - 5160 DOMs with 10” PMTs
- DeepCore sub-detector
  - central-bottom part of IceCube
  - the clearest ice
  - denser instrumentation

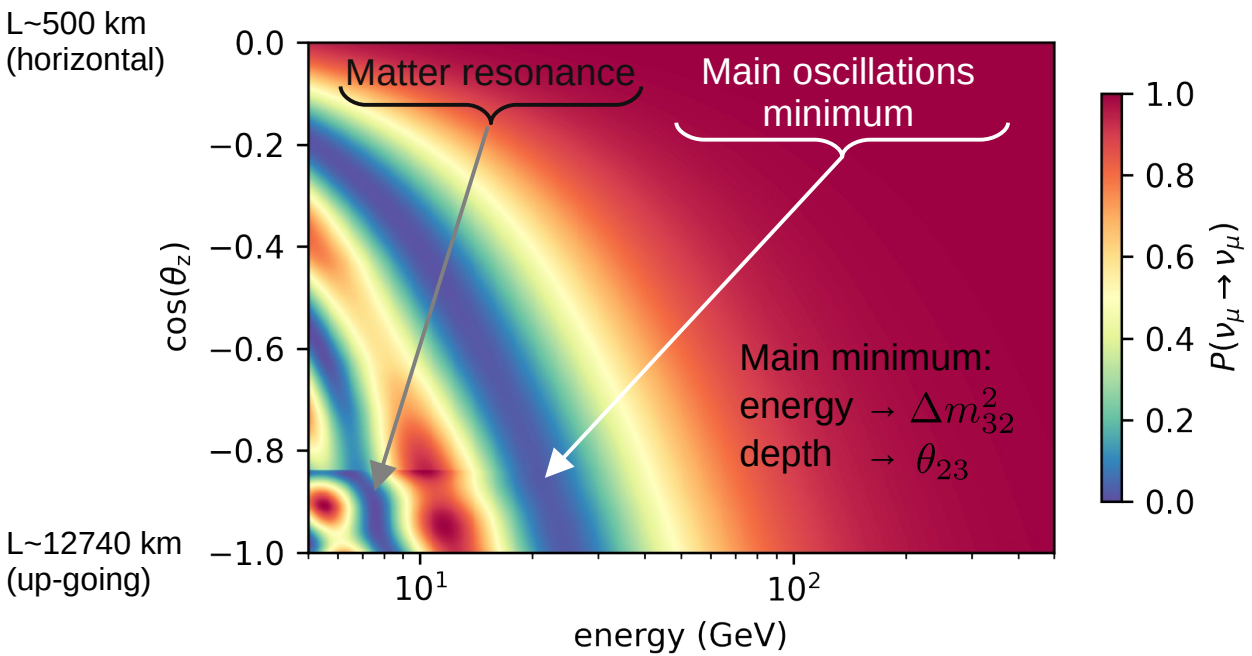
	Hor. [m]	Vert. [m]	Threshold [GeV]
IceCube	125	17	~100 GeV
DeepCore	40-60	7	~5 GeV

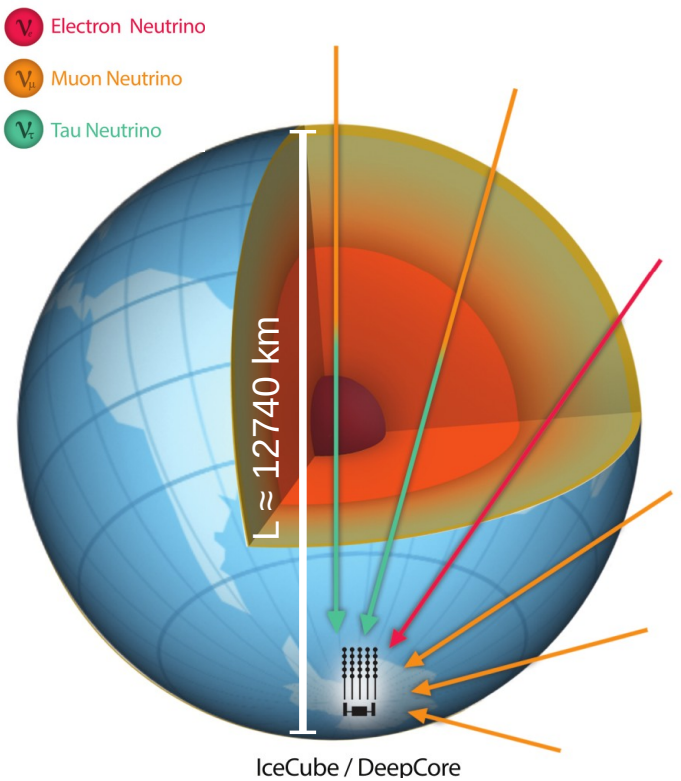


Atmospheric neutrino oscillations

- Leading term – vacuum oscillations

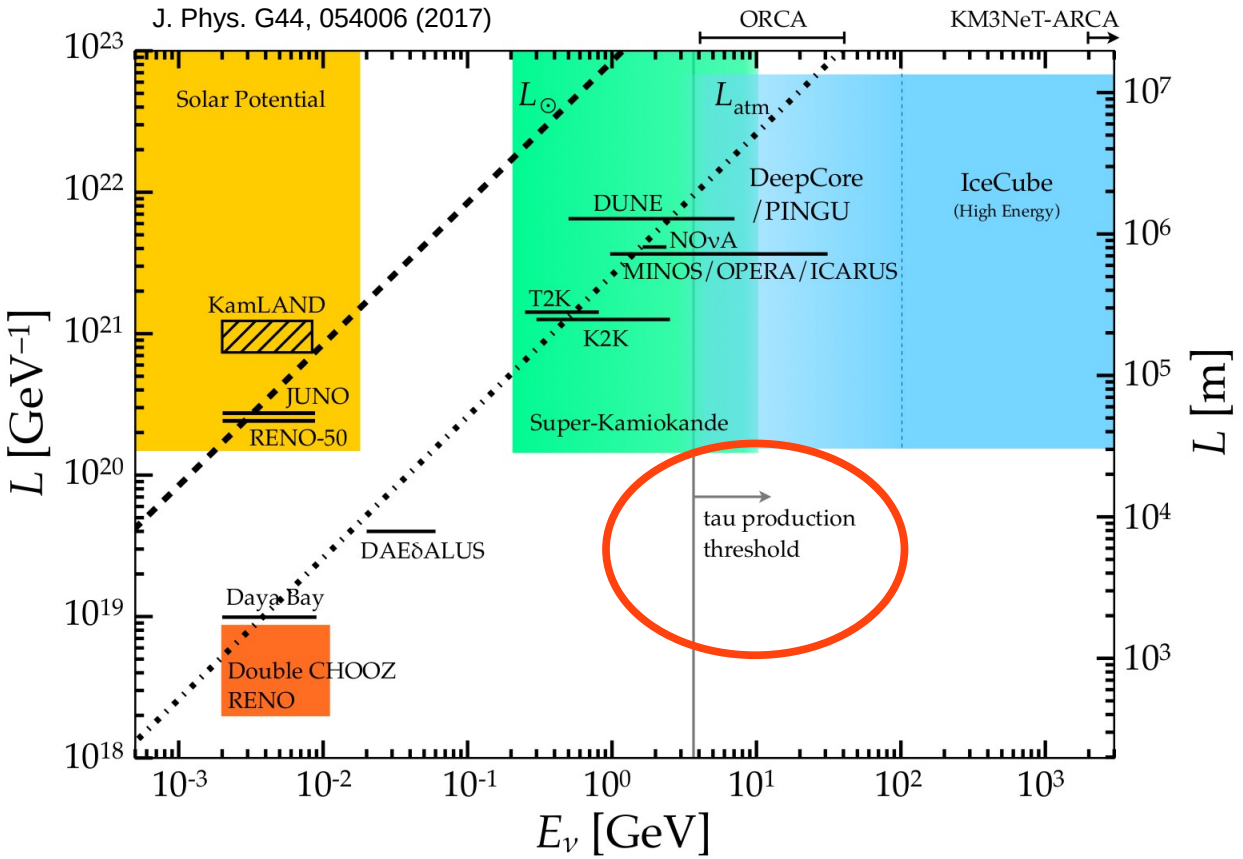
$$P(\nu_\mu \to \nu_\tau) \approx \sin^2(2\theta_{23}) \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right)$$





- Neutrino arrival direction → baseline of 20 – 12740 km

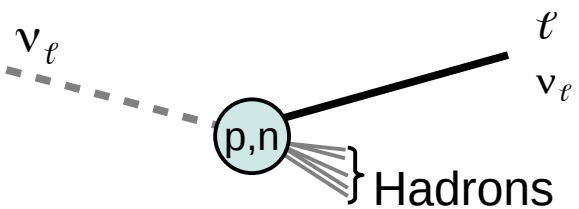
Neutrino telescopes and oscillations

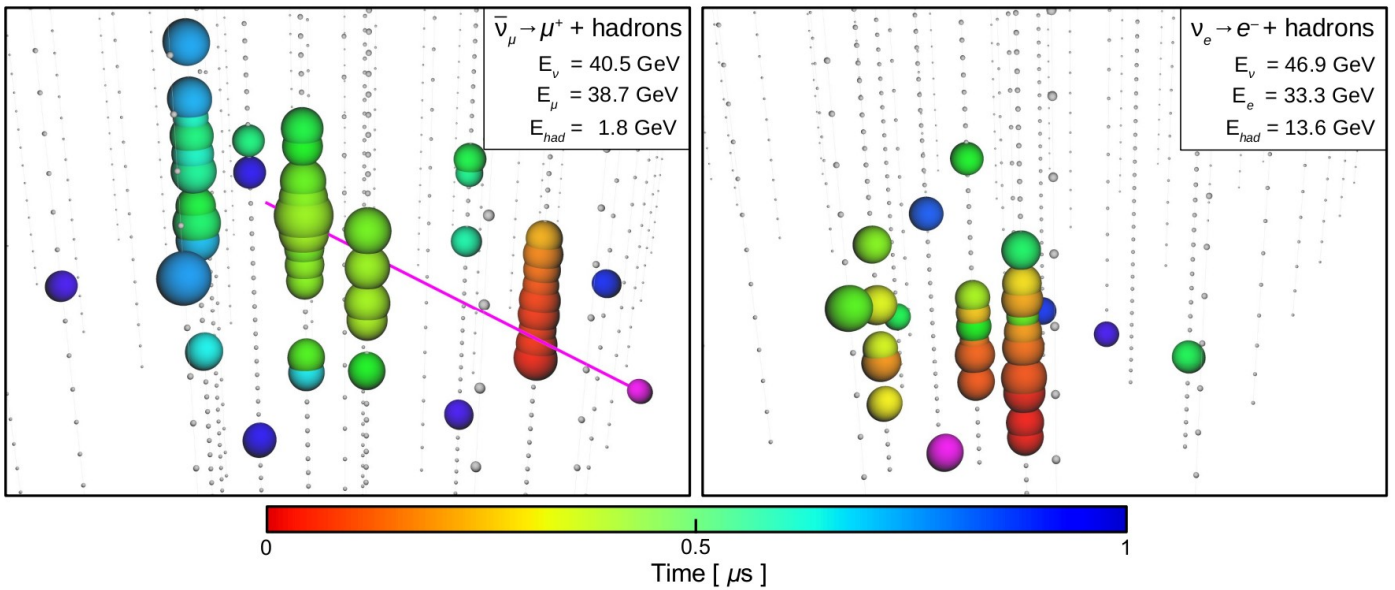


- Measurement of oscillations at the highest possible energies on Earth
- Above tau production threshold → disappearance and appearance studies possible

DeepCore events

Deep Inelastic Scattering



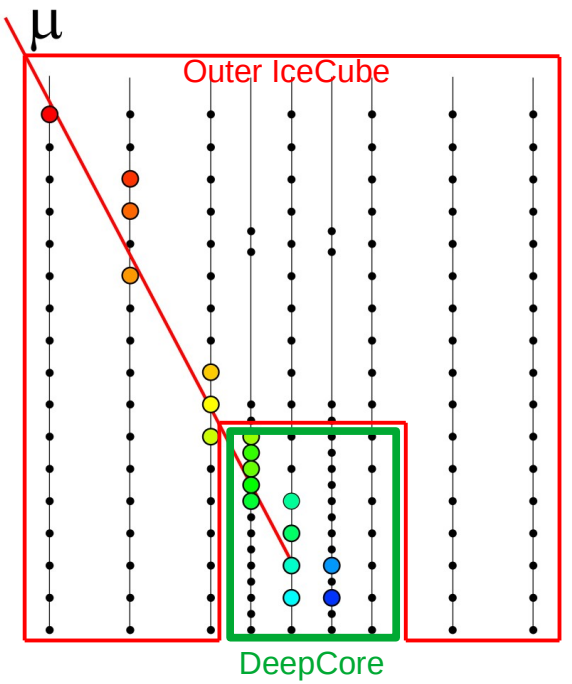


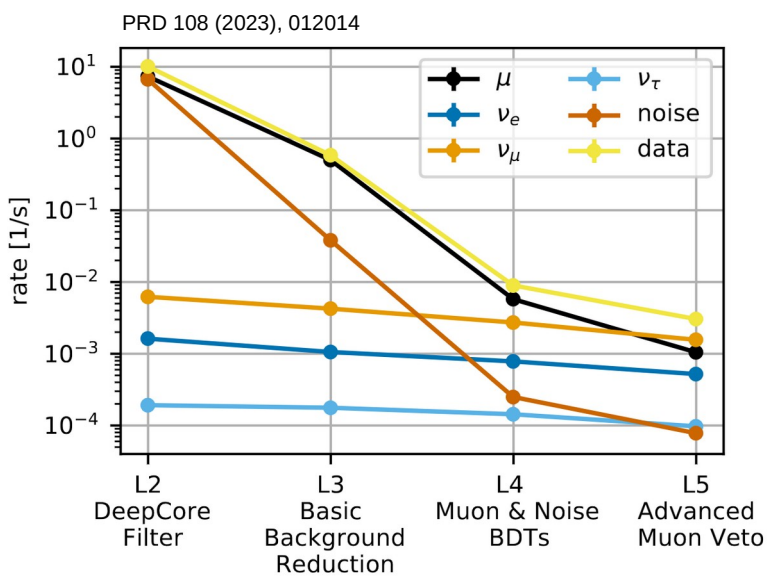
- Event types:
  - Track-like: ν_μ CC
  - Cascade-like: NC, CC of ν_e and ν_τ
- Low energy events (~10-100 GeV)
  - Produce less light
  - Detector systematics are more relevant
  - Harder to select
  - Harder to reconstruct

} makes oscillations studies challenging

Finding needle in a haystack

- Majority of triggered events → background
  - Rejection of atmospheric muons
    - Using Earth as a shield
    - IceCube detector as a veto to find contained events
  - Detector noise / dark counts
    - Temporal and spatial “clustering” of detected light



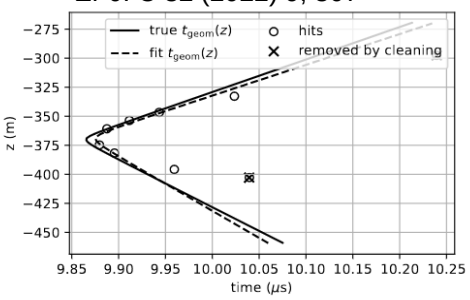


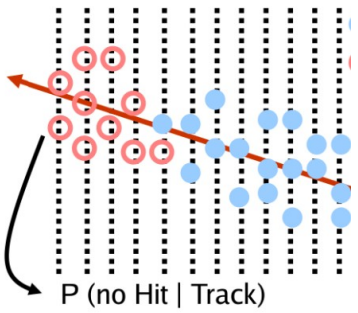
- Updated event selection
  - Improved simulations
  - Most systematically stable variables for “core” selection

Current reconstruction approaches

- Direct photon timing for “verification” sample

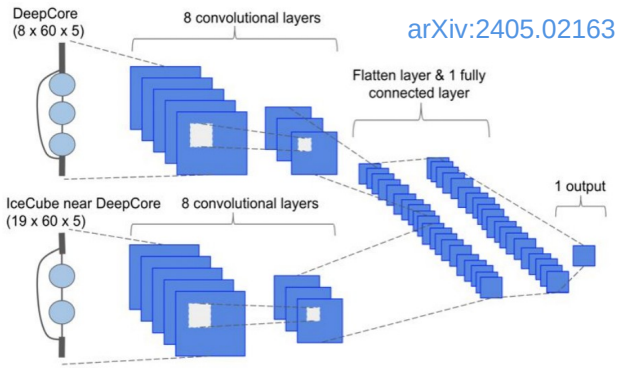
EPJ. C 82 (2022) 9, 807

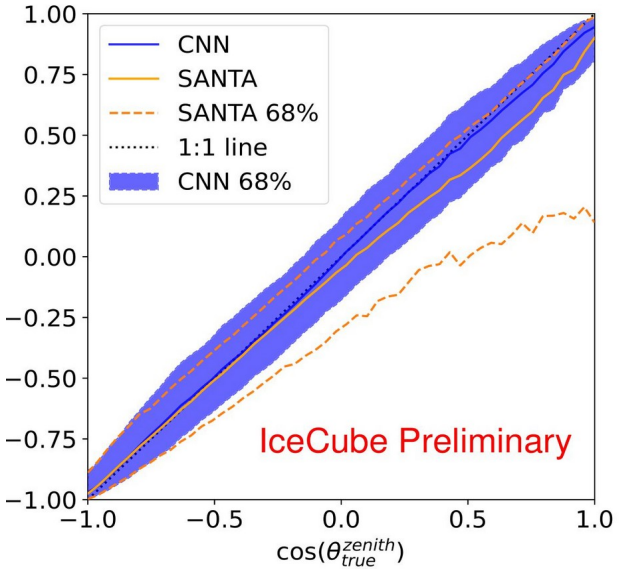


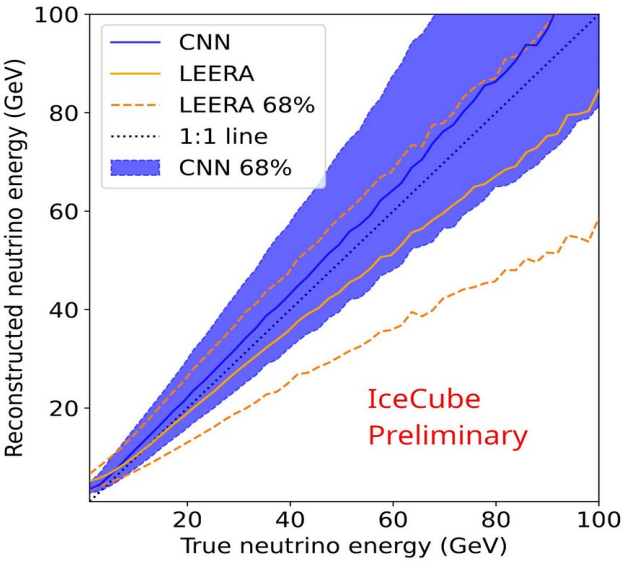


- Full timing/amplitude information in CNN for precision sample

arXiv:2405.02163 [hep-ex]

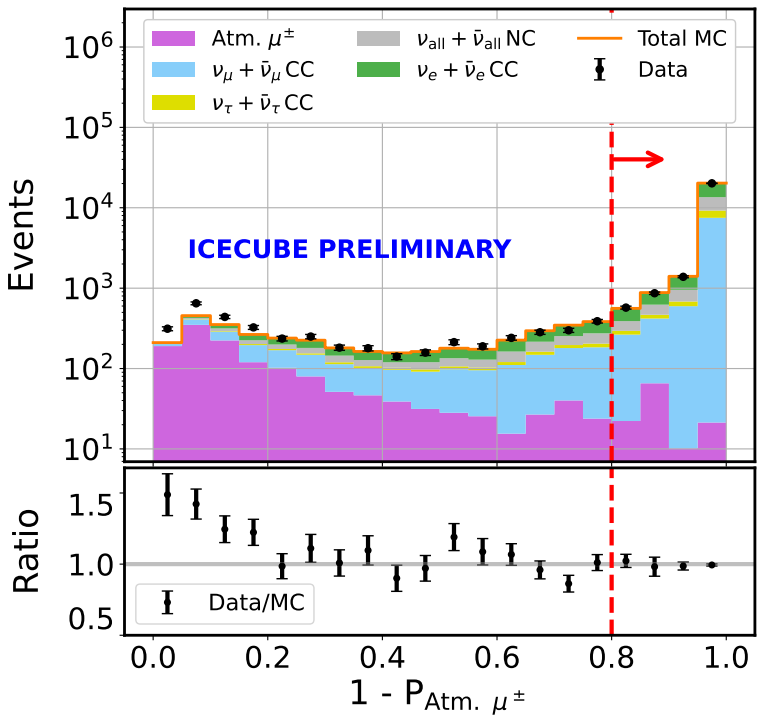




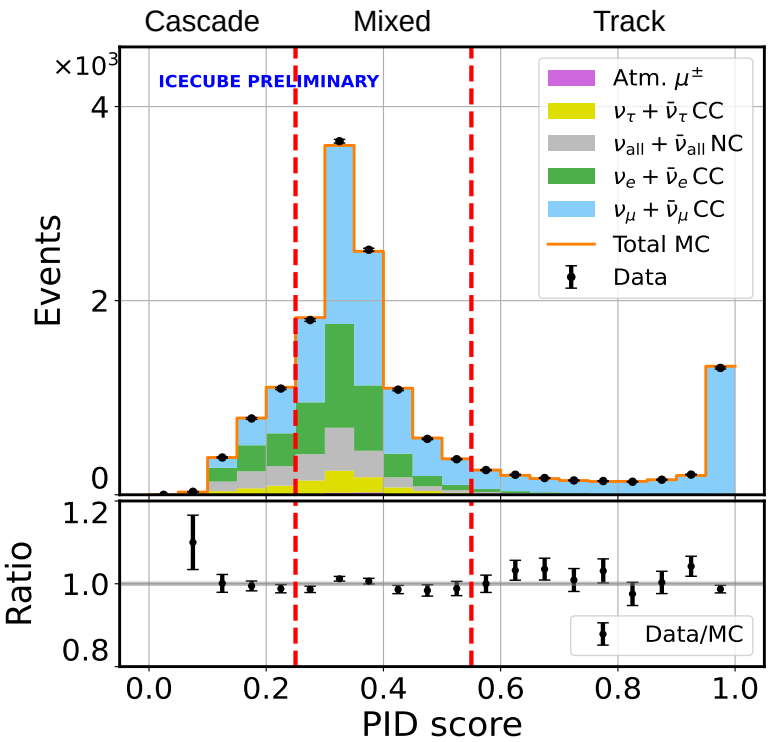


Final selection for high statistics sample

- Rejecting final muons



- Identifying interaction type

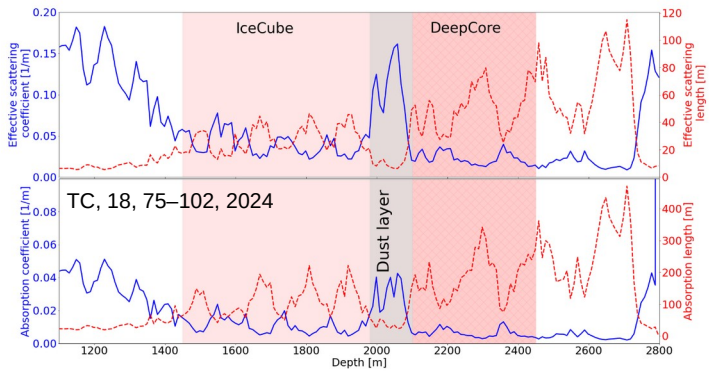


- Less than 1% contamination at final level
- Three bins for tracks, cascades and mixed

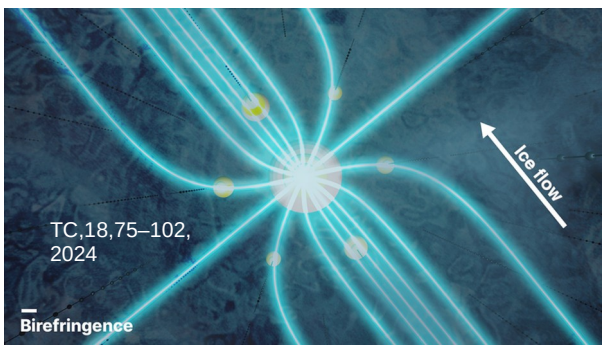
Understanding the detector

- Larger and more precise data sets → larger impact of systematic uncertainties
- Constant refinement of detector knowledge

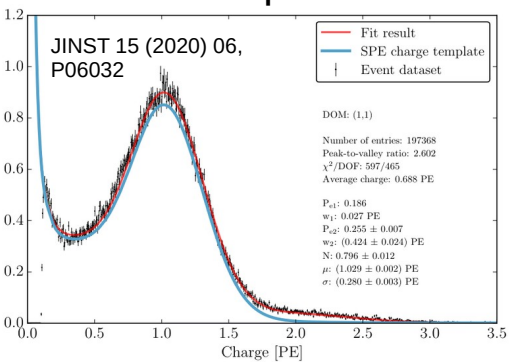
Bulk ice properties



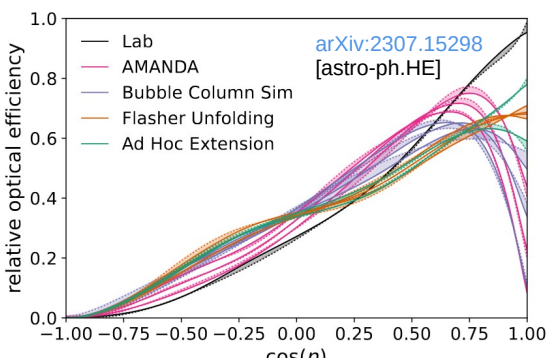
Light propagation

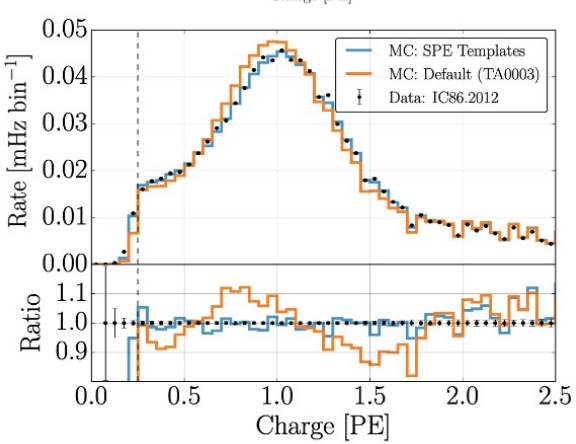


DOM response



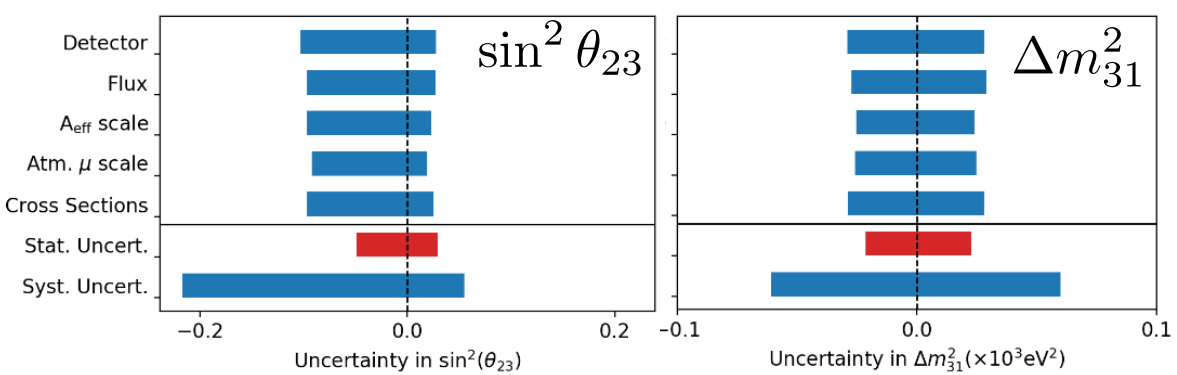
Refrozen “hole” ice properties



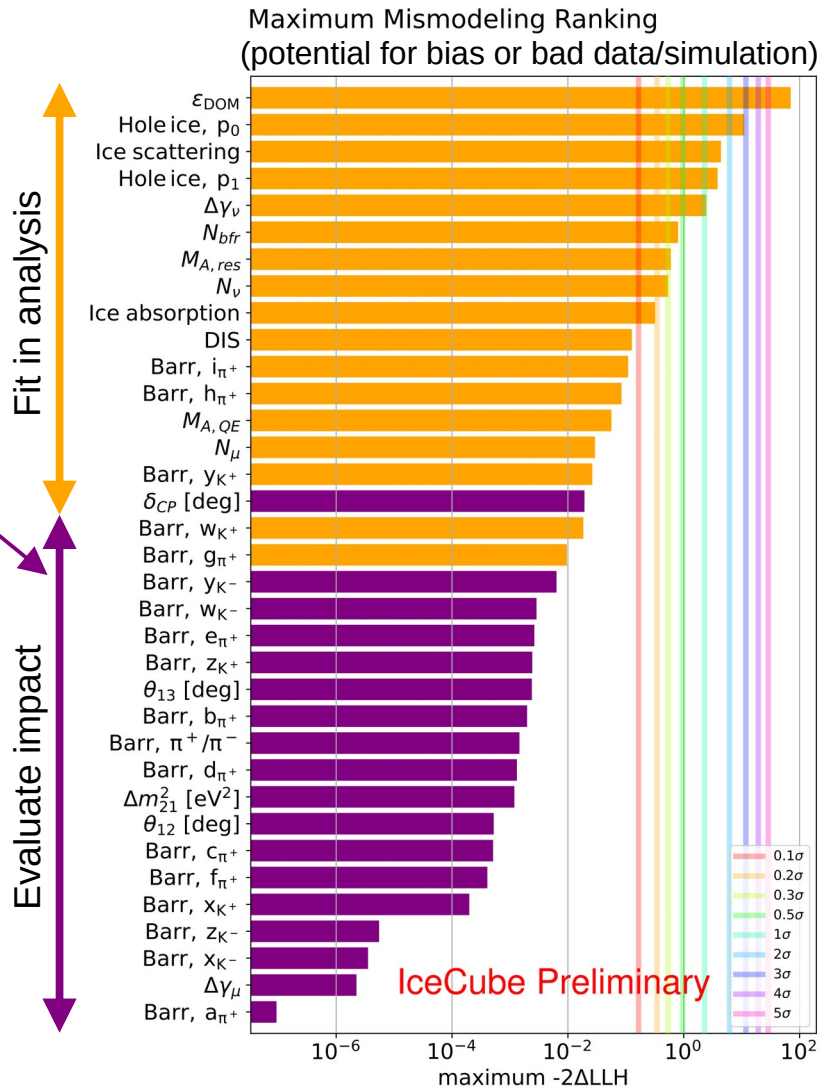


Accounting for systematics

- Example of deciding which parameters to treat
  - If high impact – fit in analysis
  - For low impact – investigate potential biases
- Impact of systematic parameters



- Detector uncertainties play a crucial role!

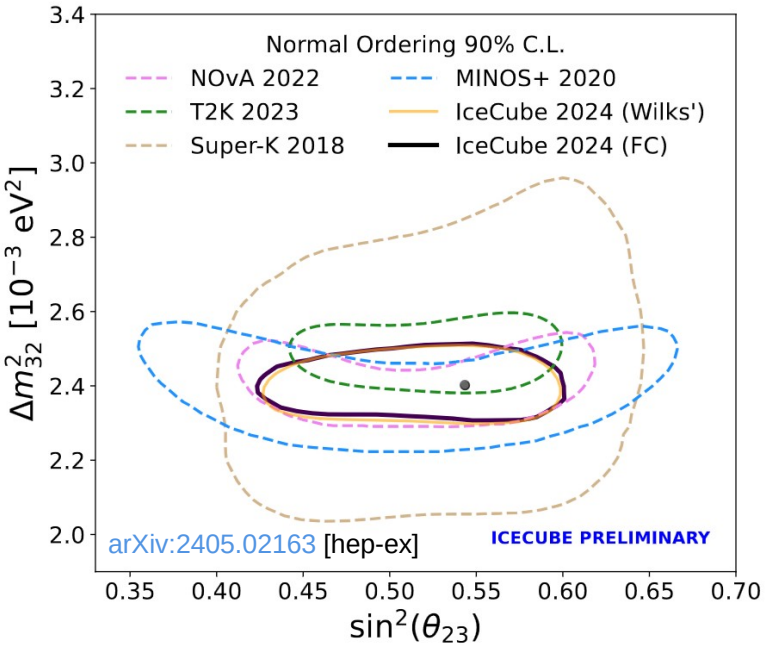


Present: current three-neutrino studies

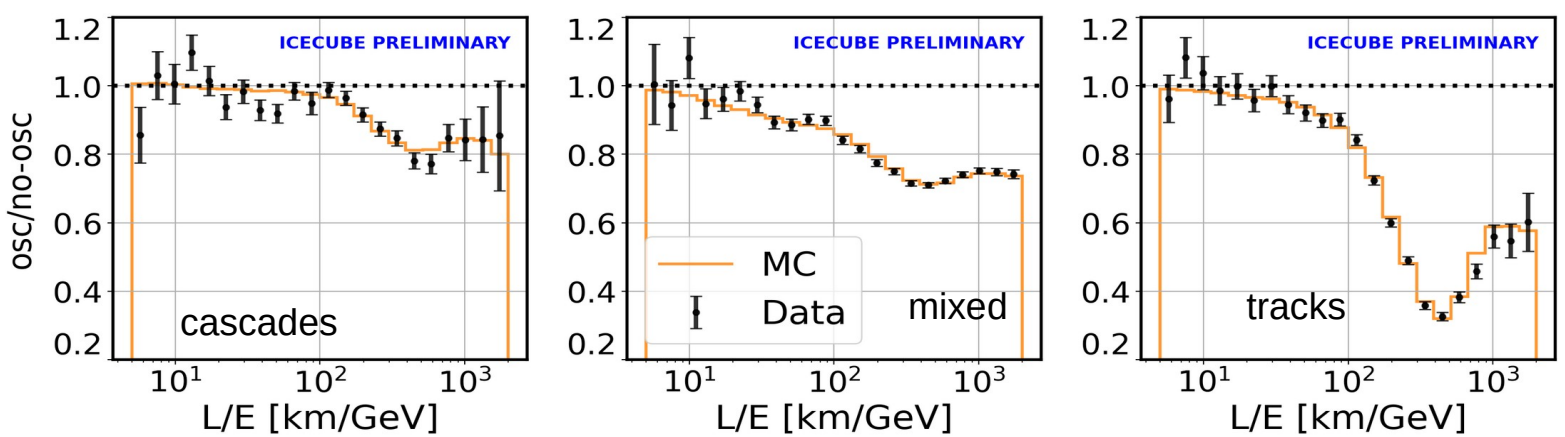
- 150k events in 9.3 years of IceCube data
- Measured oscillations parameters (68% C.L.)

$$\Delta m^2_{32} = 2.40^{+0.05}_{-0.04} \cdot 10^{-3} eV^2$$
$$\sin^2\theta_{23} = 0.54^{+0.04}_{-0.03}$$

- Public release of result likelihoods:
  - https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/U20MMB



- Clear signatures of neutrino “disappearance“

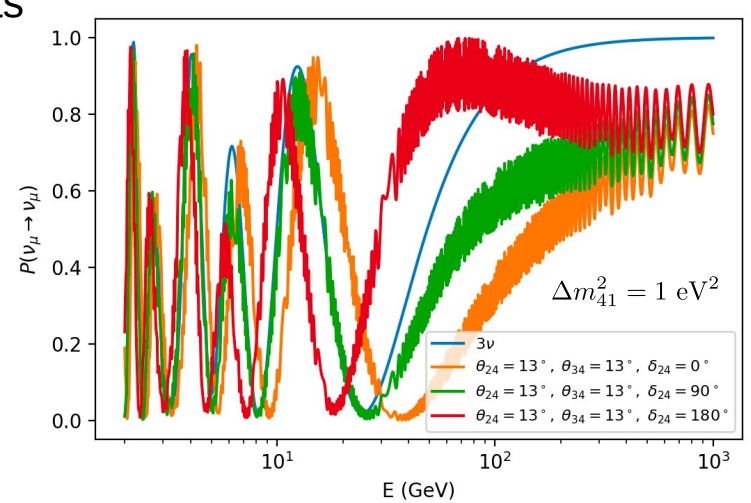


Look beyond three neutrinos

- 3+1 model

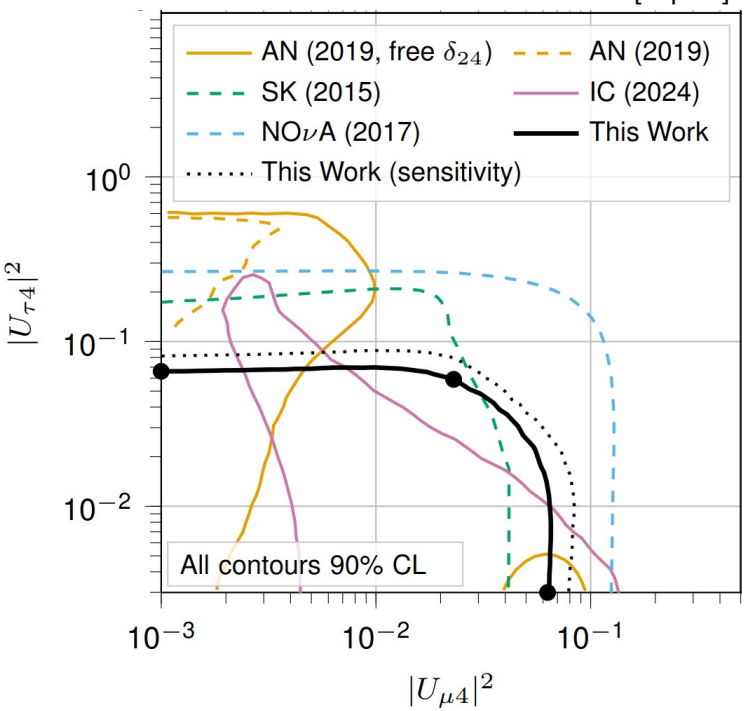
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

- Impacts standard atmospheric oscillations via matter effects



- Study is done with 7.5 years of “golden sample” with approx 22 k events

arXiv:2407.01314 [hep-ex]



- Limits at 90 % C.L.

$$|U_{\mu 4}|^2 < 0.0534$$

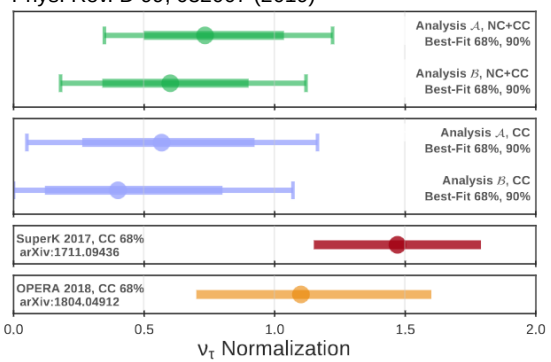
$$|U_{\tau 4}|^2 < 0.0574$$

And there is much more

- and so little time to cover here..

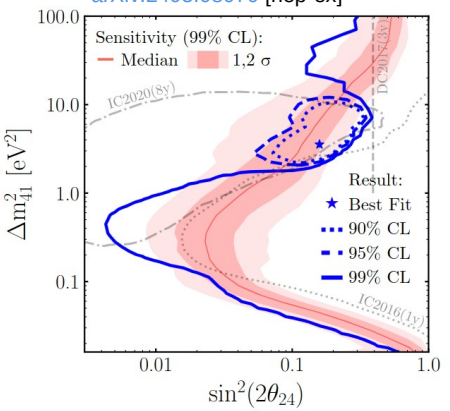
- Tau neutrino appearance

Phys. Rev. D 99, 032007 (2019)

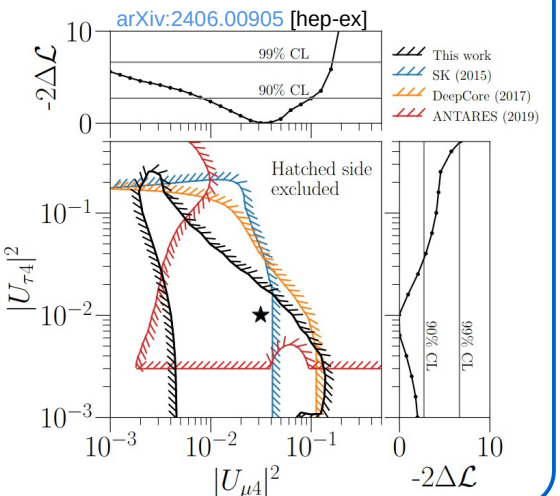


- Searches of sterile neutrinos at ~TeV energies

arXiv:2405.08070 [hep-ex]

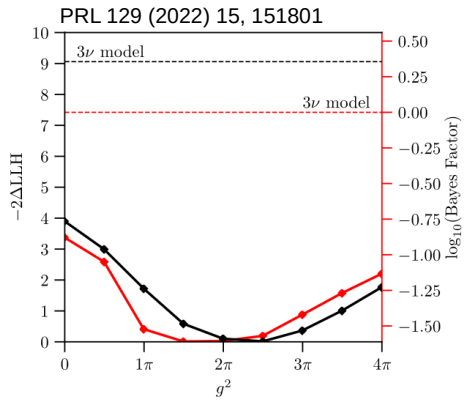


arXiv:2406.00905 [hep-ex]



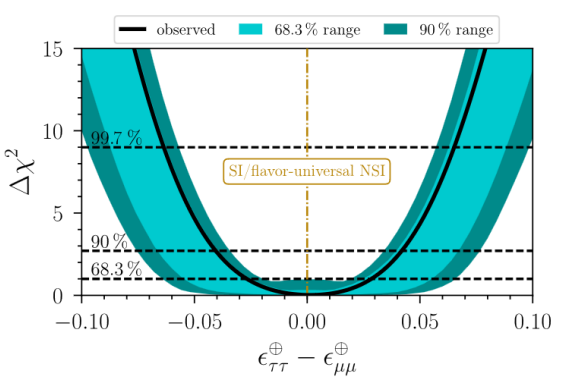
- Unstable sterile neutrino

PRL 129 (2022) 15, 151801



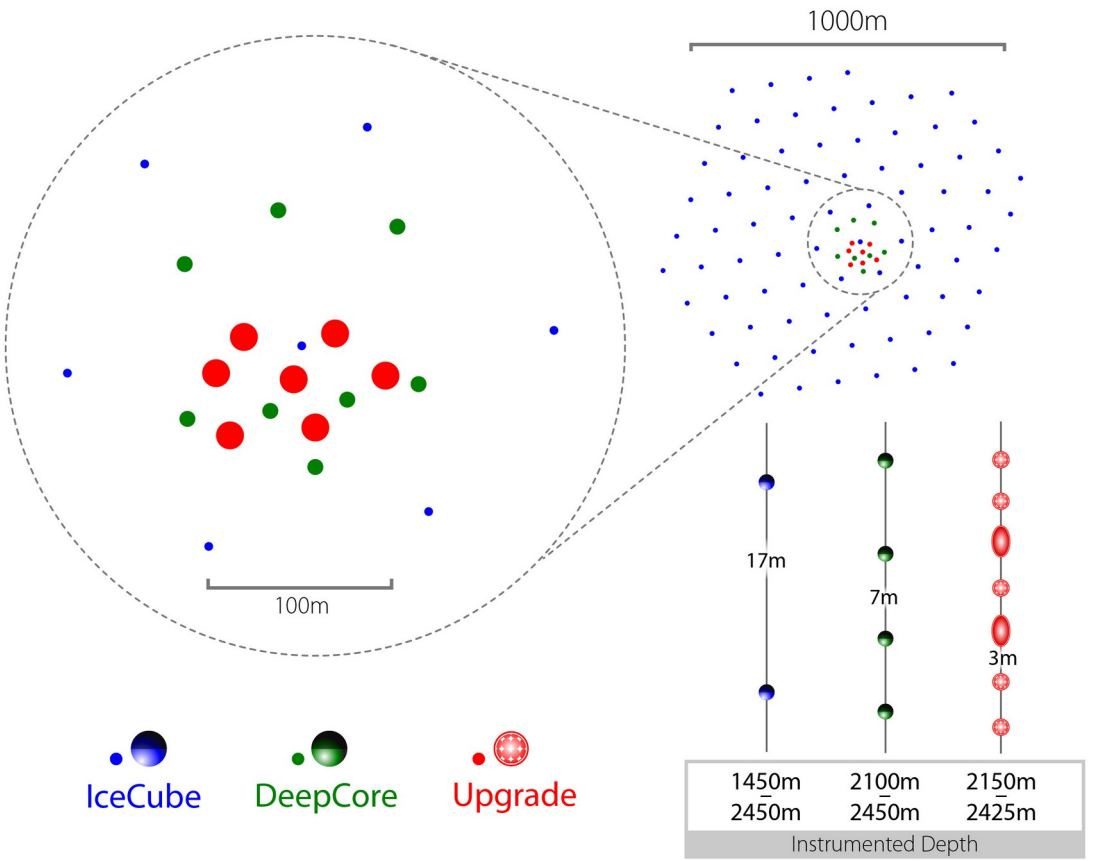
- Non-standard neutrino interactions

PRD 104(2021) 072006



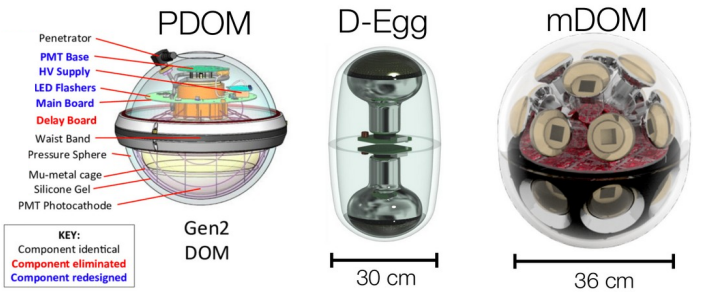
- And more….

Future: the IceCube Upgrade



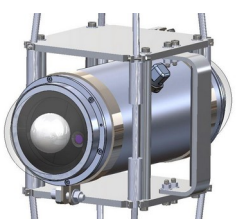
- Fully funded and to be deployed in 2025/26 season

- Over 800 new modules
  - New multi-PMT detection modules



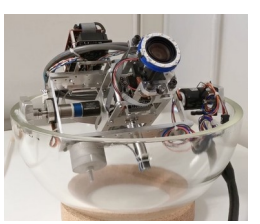
  - New dedicated calibration modules

POCAM (isotropic light)



Pencil Beam (collimated light)

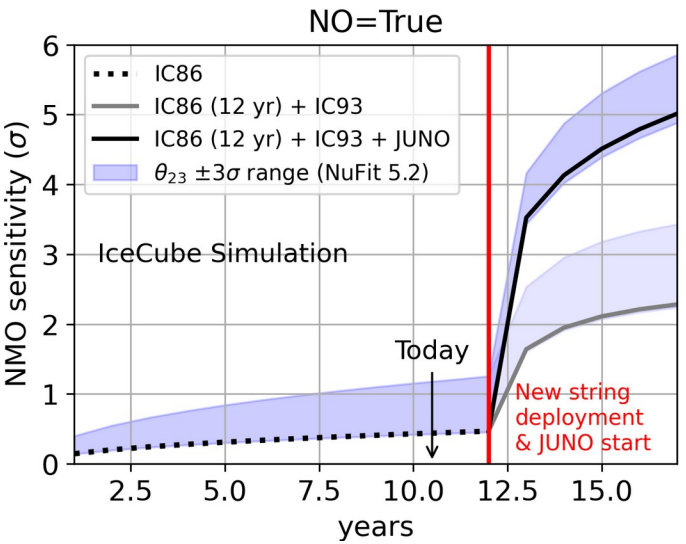
Swedish Camera (camera system)



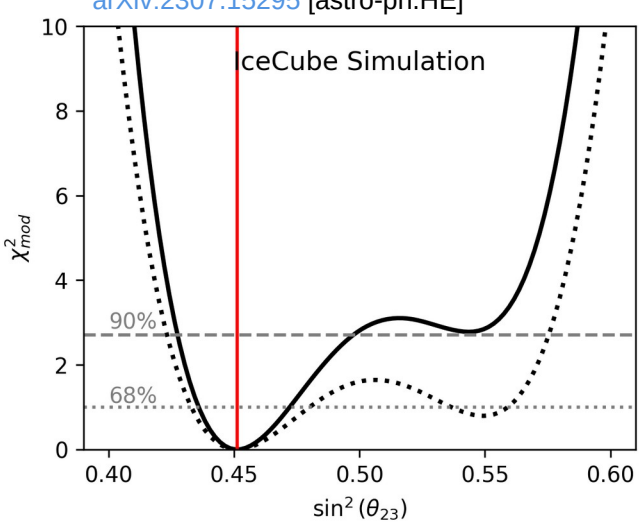
  - flashers and cameras in detection modules
  - and more special devices
- R&D platform for future IceCube-Gen2

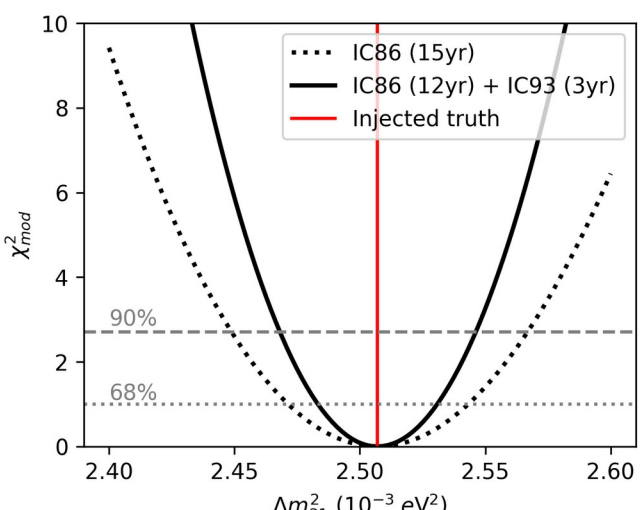
Future: oscillations with IC Upgrade

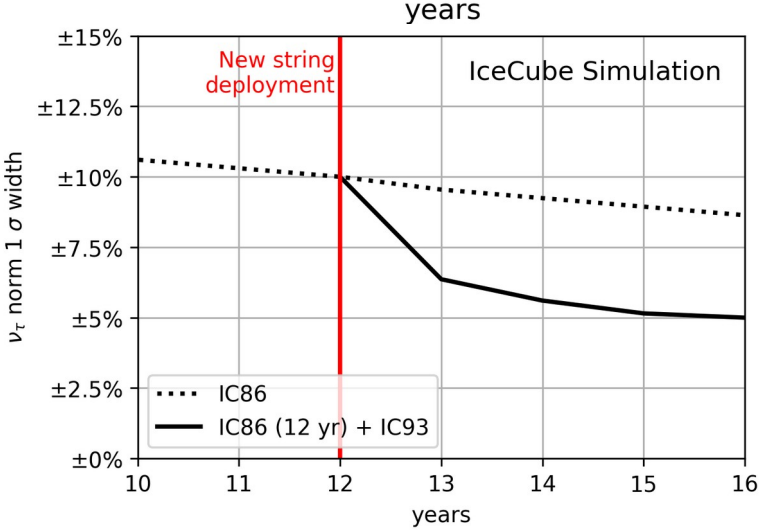
- Improved sensitivity to θ_{23} and Δm^2_{32}
- Up to 3σ sensitivity to neutrino mass ordering (5σ with JUNO)
- 5% sensitivity to tau appearance to test PMNS unitarity
- And more:
  - BSM physics, Dark Matter, calibration, improved reconstruction for high energy neutrinos …



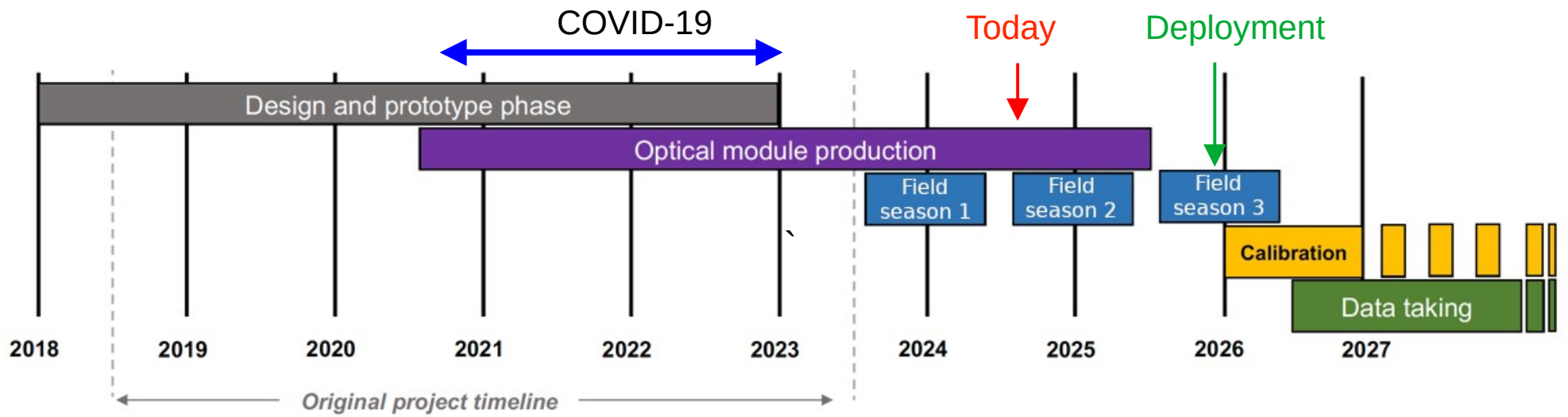
arXiv:2307.15295 [astro-ph.HE]





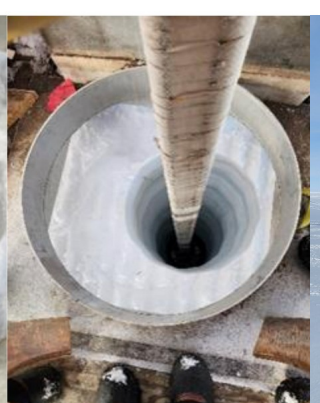


IceCube Upgrade timeline



- Successful first field season to prepare for deployment

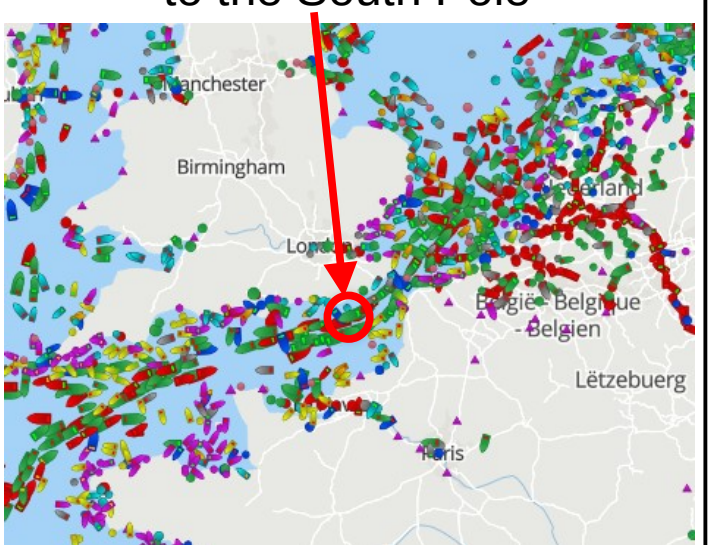




Summary

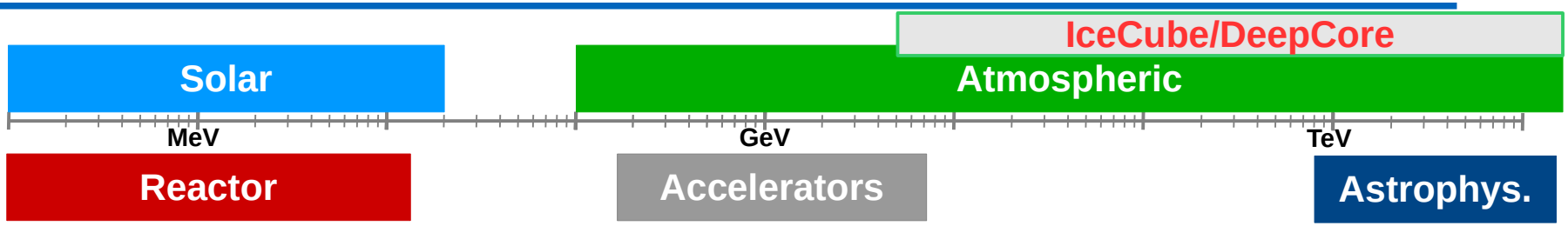
- Decade of neutrino oscillations measurement with IceCube DeepCore
  - improvements in reconstruction, selection, calibration and more
  - competitive measurement of atmospheric neutrino mixing
  - stringent limits beyond 3 neutrinos model
- Bright outlook to the future:
  - IceCube Upgrade to be deployed in 2025/26 season
  - Lower energy detection threshold
  - Improved detector calibration
  - transition towards precision era with IceCube
- More from IceCube at NOW2024
  - Beyond Standard Model physics → Leander Fischer, Fri, 6 Sep 2024
  - High energy neutrino astronomy → Colton Hill, Sat, 7 Sep 2024
- Stay tuned for future updates from IceCube!

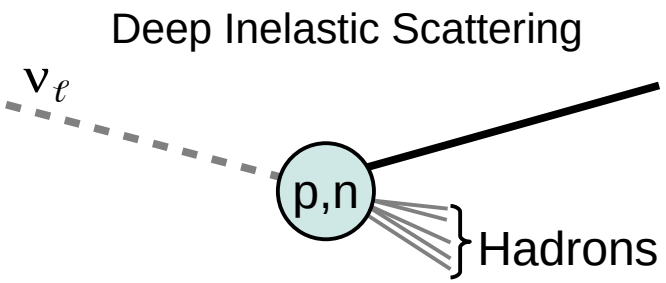
First “European” IceCube Upgrade modules en route to the South Pole



Back-up slides

Events in IceCube

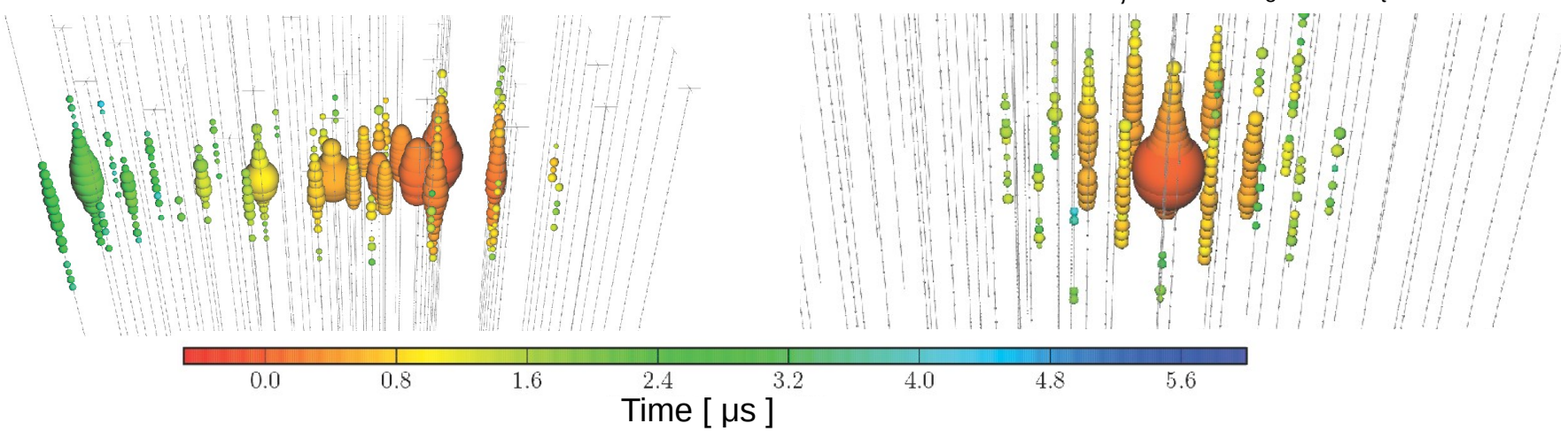




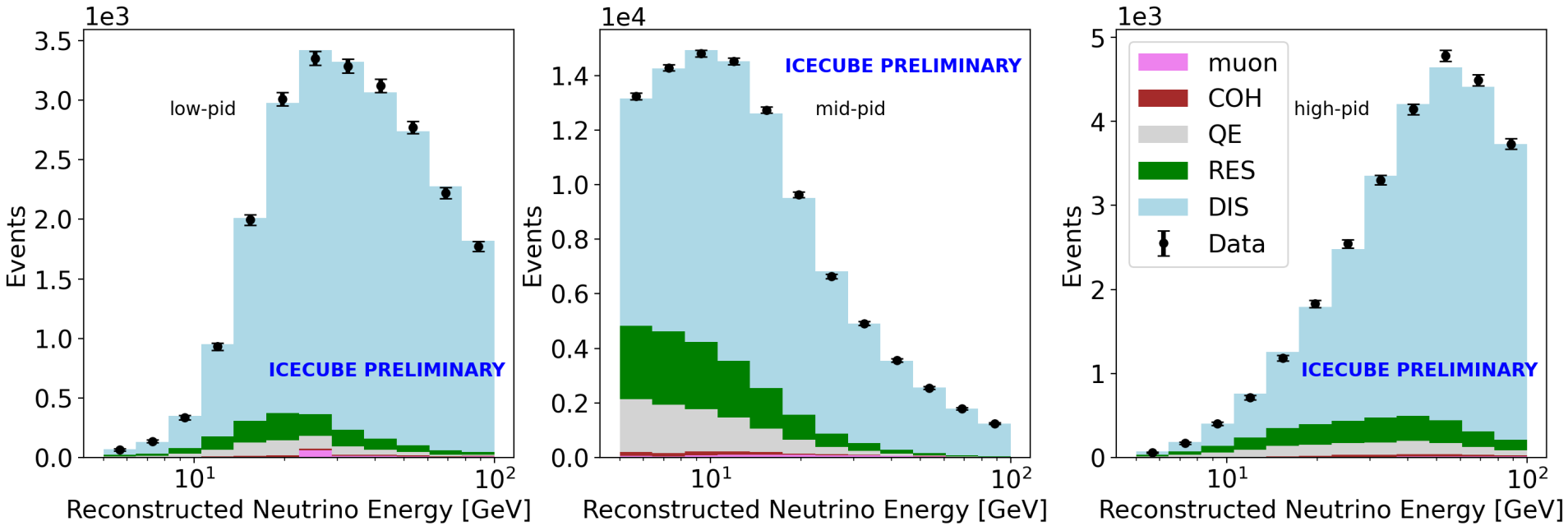
ℓ – charged current (CC) interaction

ν_ℓ – neutral current (NC) interaction

- Track-like: ν_μ CC
- Cascade-like: NC, CC of ν_e and ν_τ

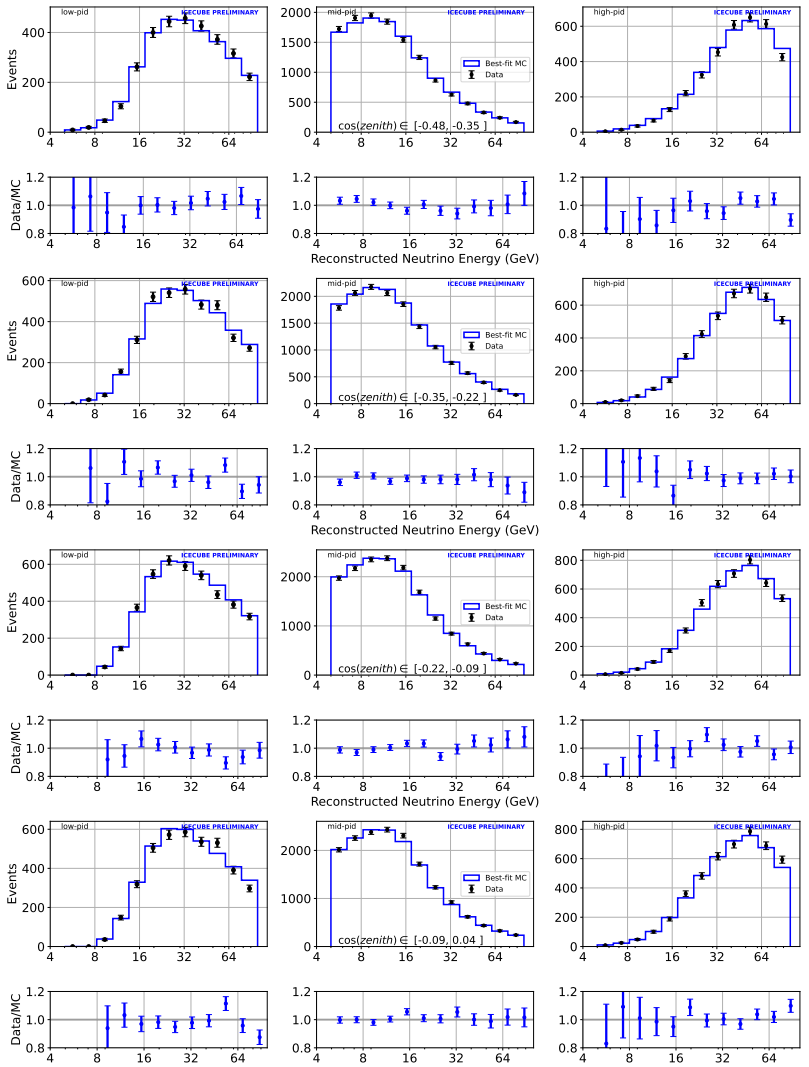


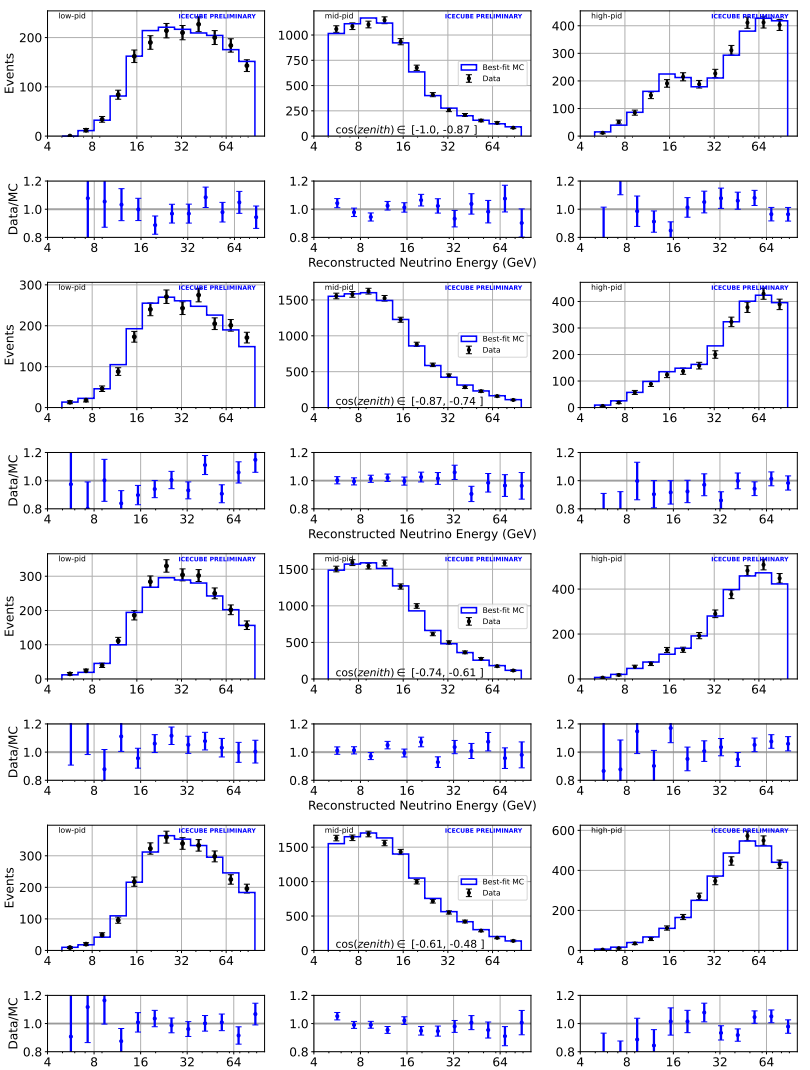
Backup: interactions in the sample



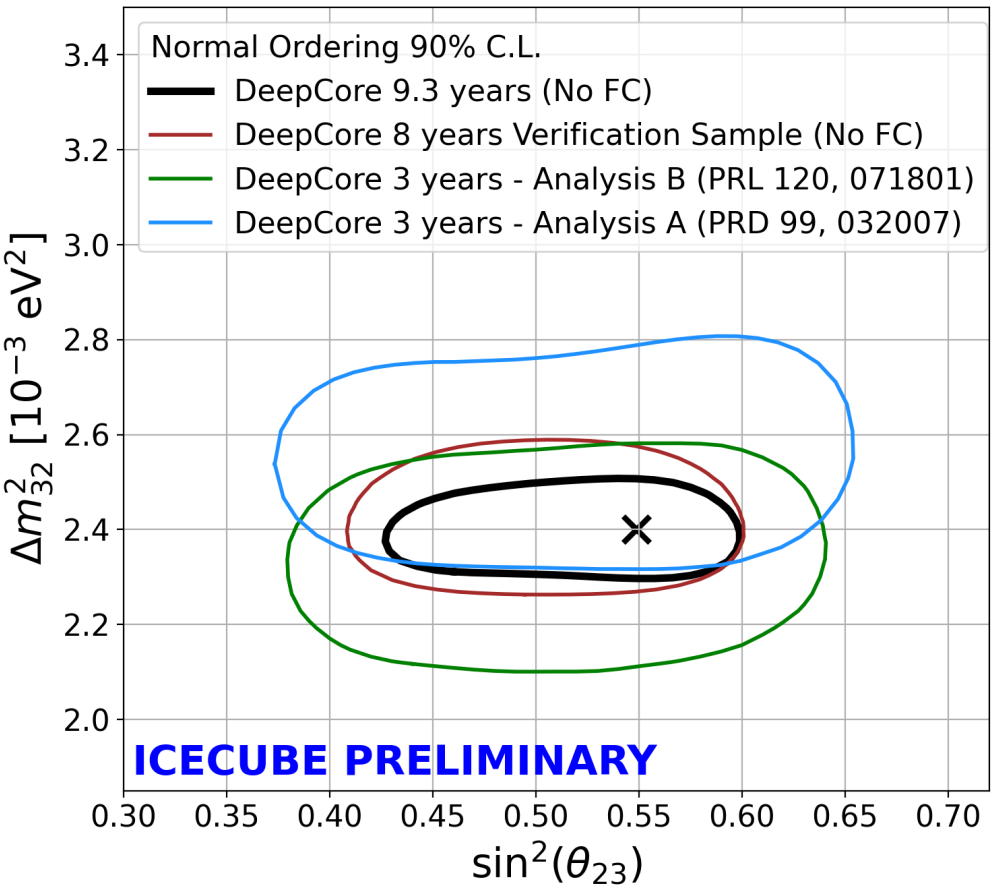
- Most of the events are Deep Inelastic Scattering
- Some contribution of resonant and quasi-elastic interactions at lower energies

Backup: data / MC in bins



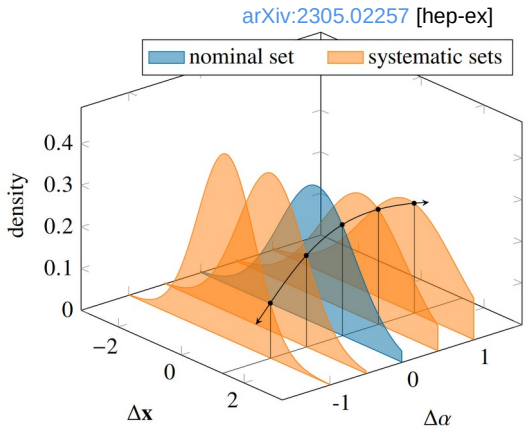


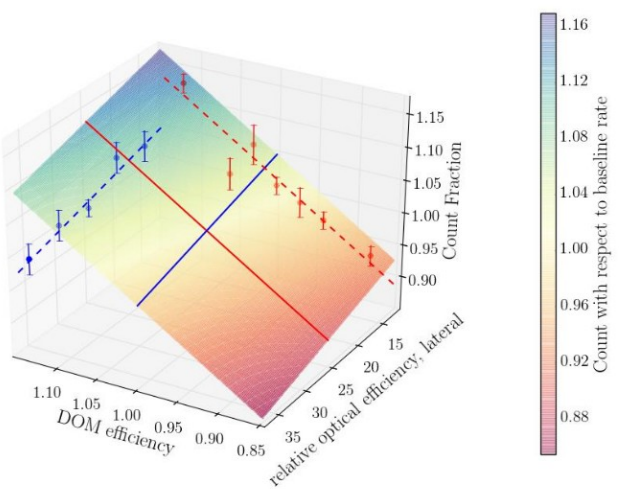
Backup: results for different samples



Backup: treatment of detector systmatics

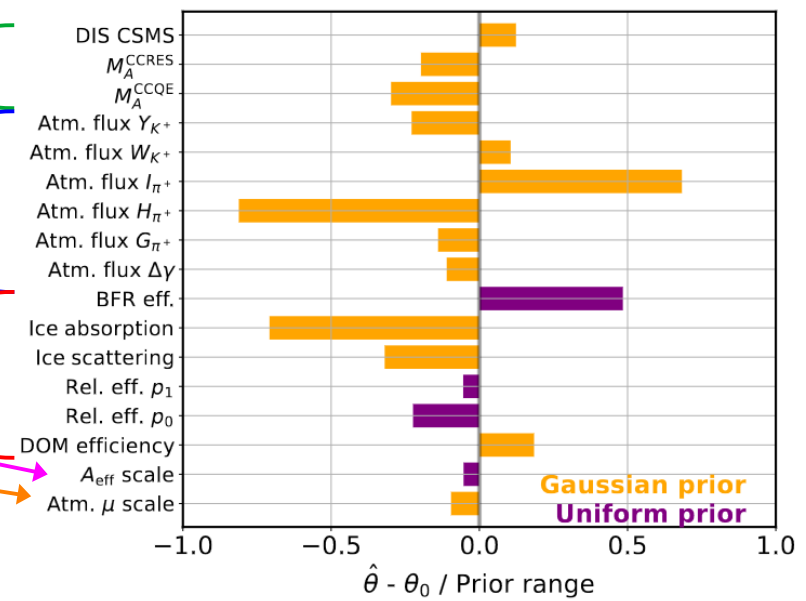
- Treatment of discrete detector systematics
  - Based on discrete systematic sets
  - Computes event-by-event or bin-by-bin correction as multidimensional surface for smooth variation
  - Used in final likelihood or chi2 as nuisance parameter





Systematic parameter pulls

- Wide range of nuisance parameters
  - Cross-section
  - Neutrino flux
  - Detector-related uncertainties
  - General normalization
  - Background contamination



Composition of the sample

arXiv:2405.02163 [hep-ex]