Neutrino Physics Prospects with PINGU

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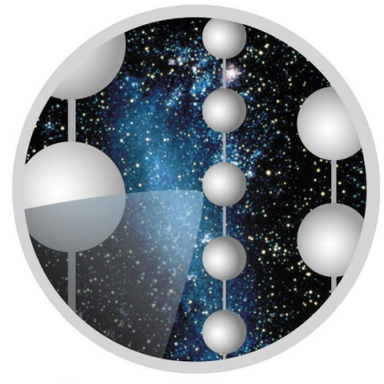
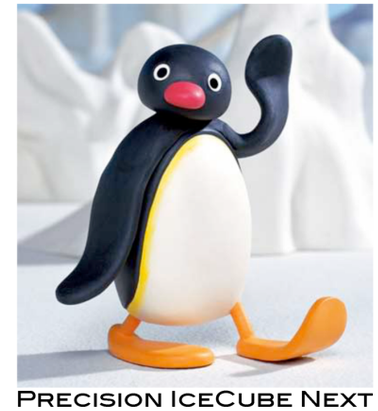
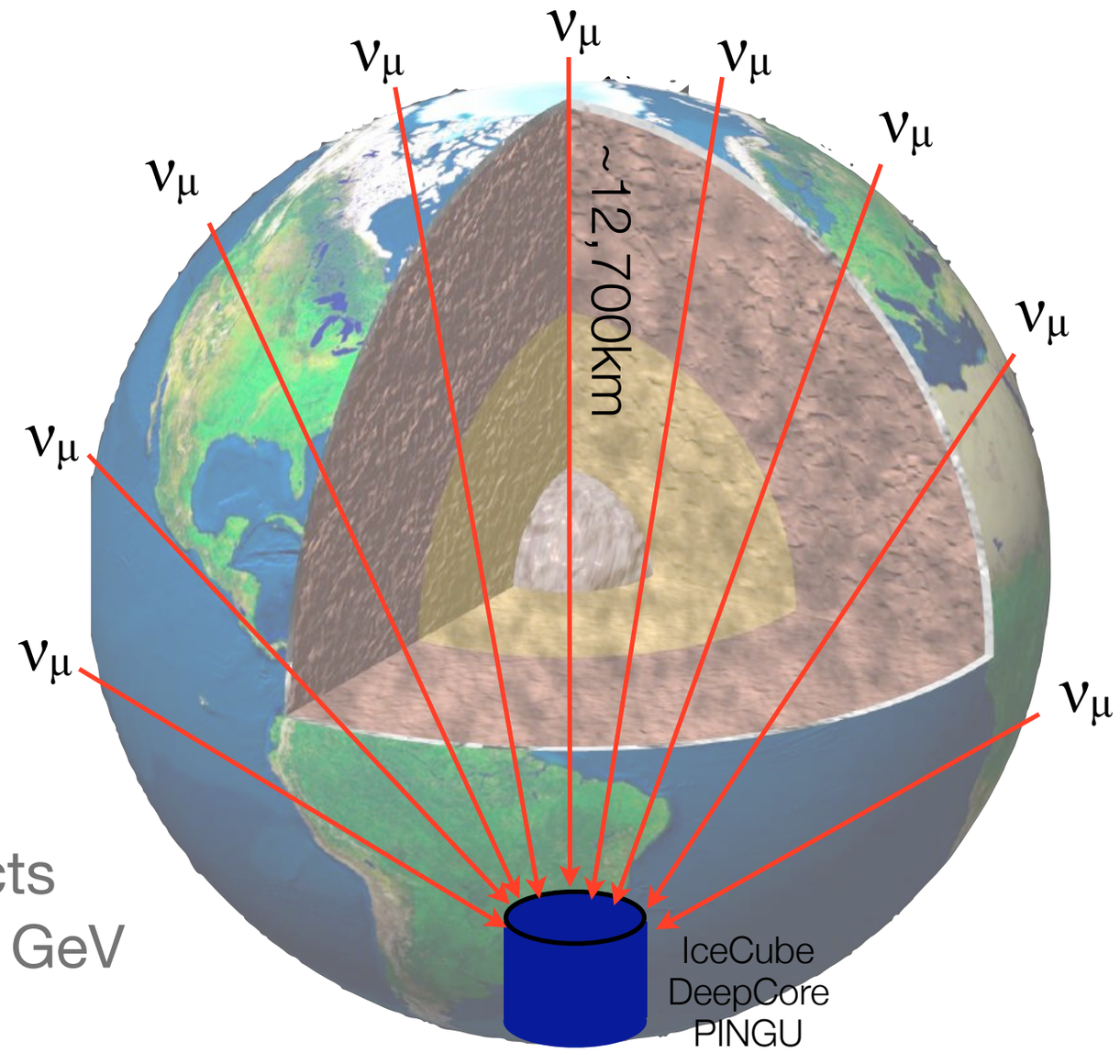




Precision IceCube Next Generation Upgrade

Oscillation Physics with Atmospheric Neutrinos

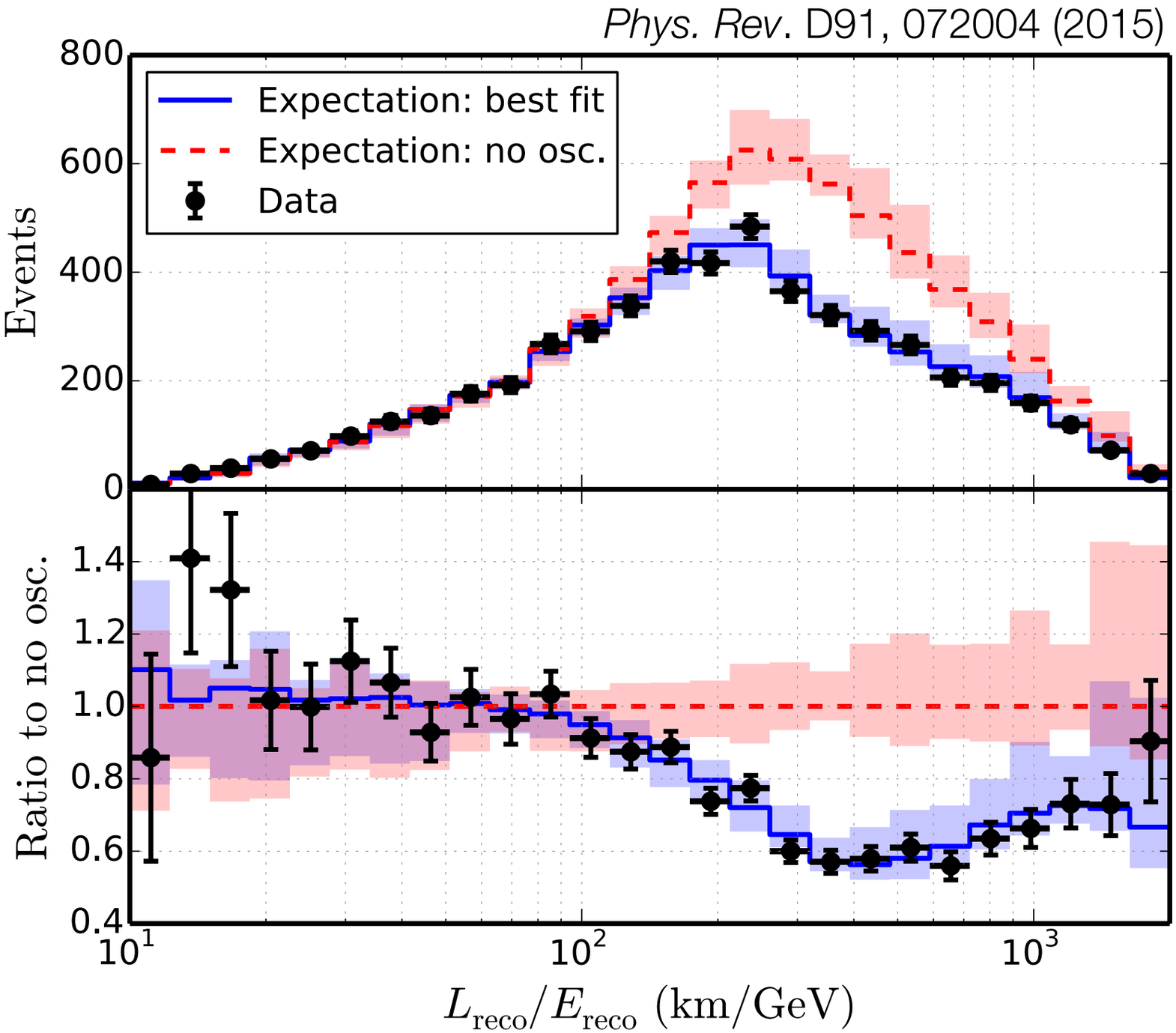
- Neutrinos available over a wide range of energies and baselines
  - Oscillations produce distinctive pattern in energy-angle space
  - Approach: control systematics using events in “side band” regions – trade statistics for constraints on systematics
- Neutrinos oscillating over one Earth diameter have a ν_μ survival minimum at ~25 GeV
  - Hierarchy-dependent matter effects on ν or $\bar{\nu}$ (MSW etc.) below 10-20 GeV



Current IceCube Oscillation Results

- Real analysis is 2D to maximize constraints on systematics
  - Data projected onto reconstructed (L/E_ν) here for illustration
  - Shaded range shows systematic uncertainties allowed by IceCube data
- Details and results in J. Hignight's talk (next)

Phys. Rev. D91, 072004 (2015)

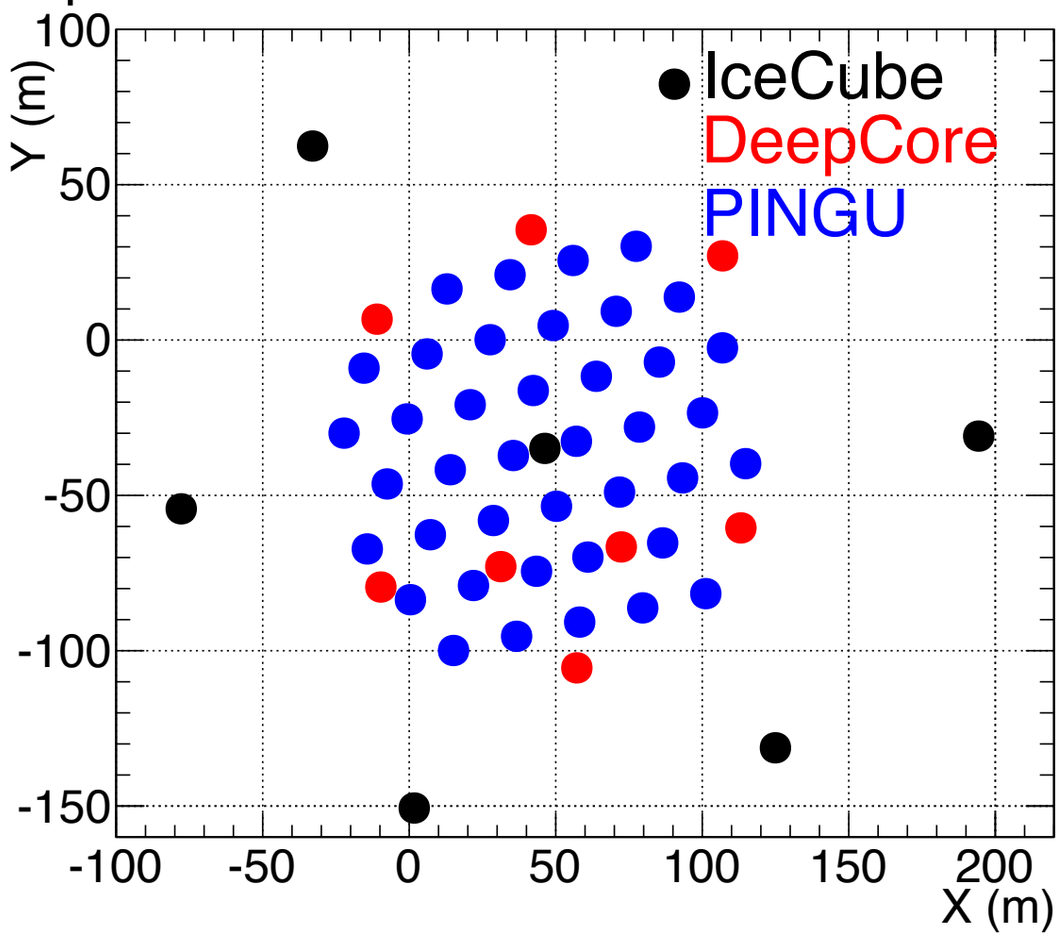


PINGU

Precision IceCube Next Generation Upgrade

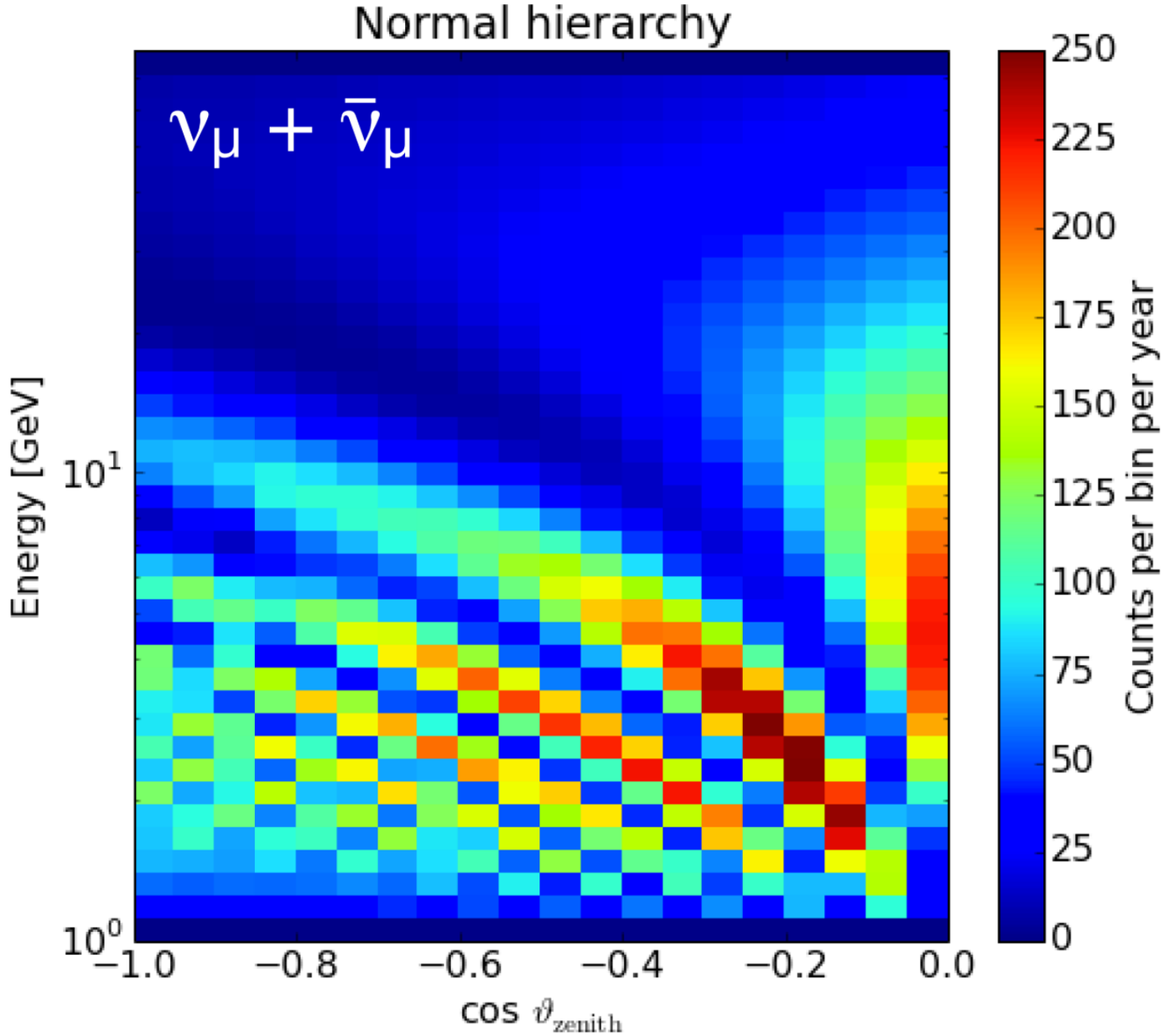
- Baseline 4 MTon detector: 40 additional strings at 22 m spacing, with Digital Optical Modules spaced 3 m vertically, deployed inside IceCube DeepCore
  - Compare to 72 m string spacing and 7 m DOM spacing for DeepCore
  - ~25x higher photocathode density
  - Additional in situ calibration devices will better control detector systematic (not included in projections)
- Achieve few GeV energy threshold
- Engineering and costs are well understood from IceCube

Top view of the PINGU new candidate detector



Signatures of the Neutrino Mass Hierarchy

- Matter effects alter oscillation probabilities for ν or ν̄ traversing the Earth – exploit differences in cross section to distinguish
  - Effects vary with E_ν and L (= zenith angle) due to Earth's density profile
  - Neutrino oscillation probabilities affected if hierarchy is normal, antineutrinos if inverted
  - Rates of all flavors are affected
  - Note: effect of detector resolution not shown here
- Distinct signatures observable in both track (ν_μ CC) and cascade (ν_e and ν_τ CC, ν_x NC) channels
  - At higher energies, ν_μ CC events distinguishable by the presence of a muon track



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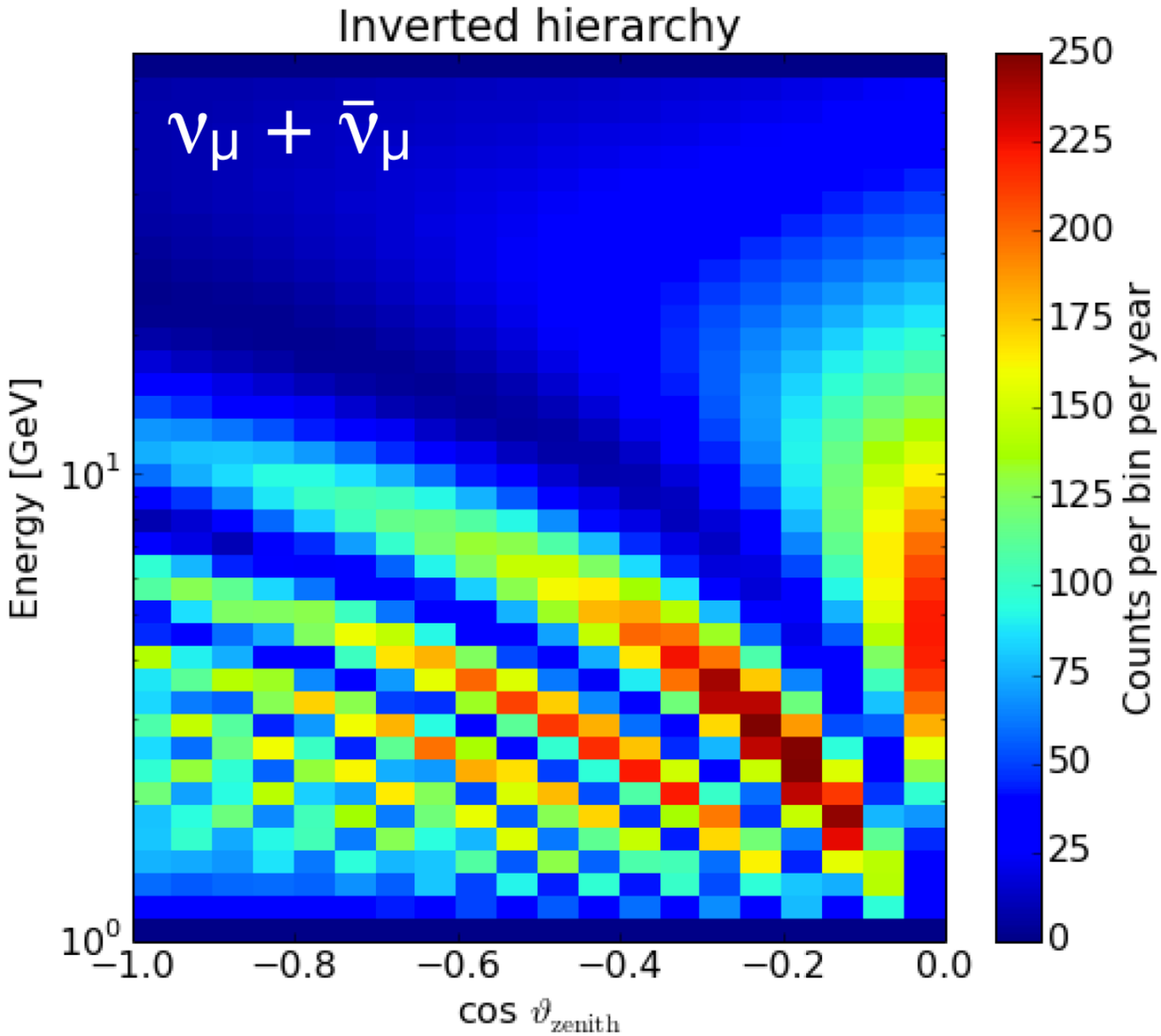

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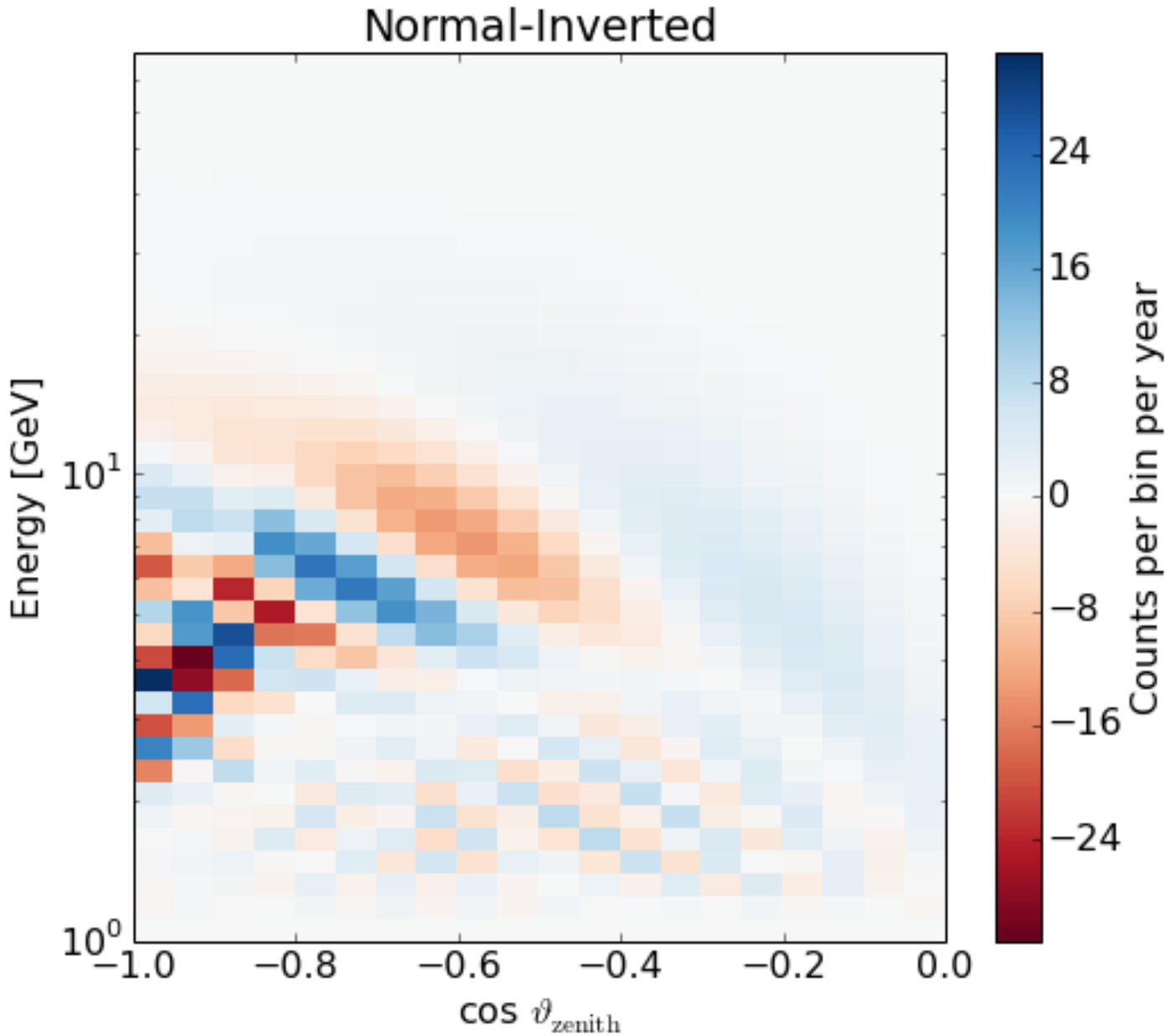
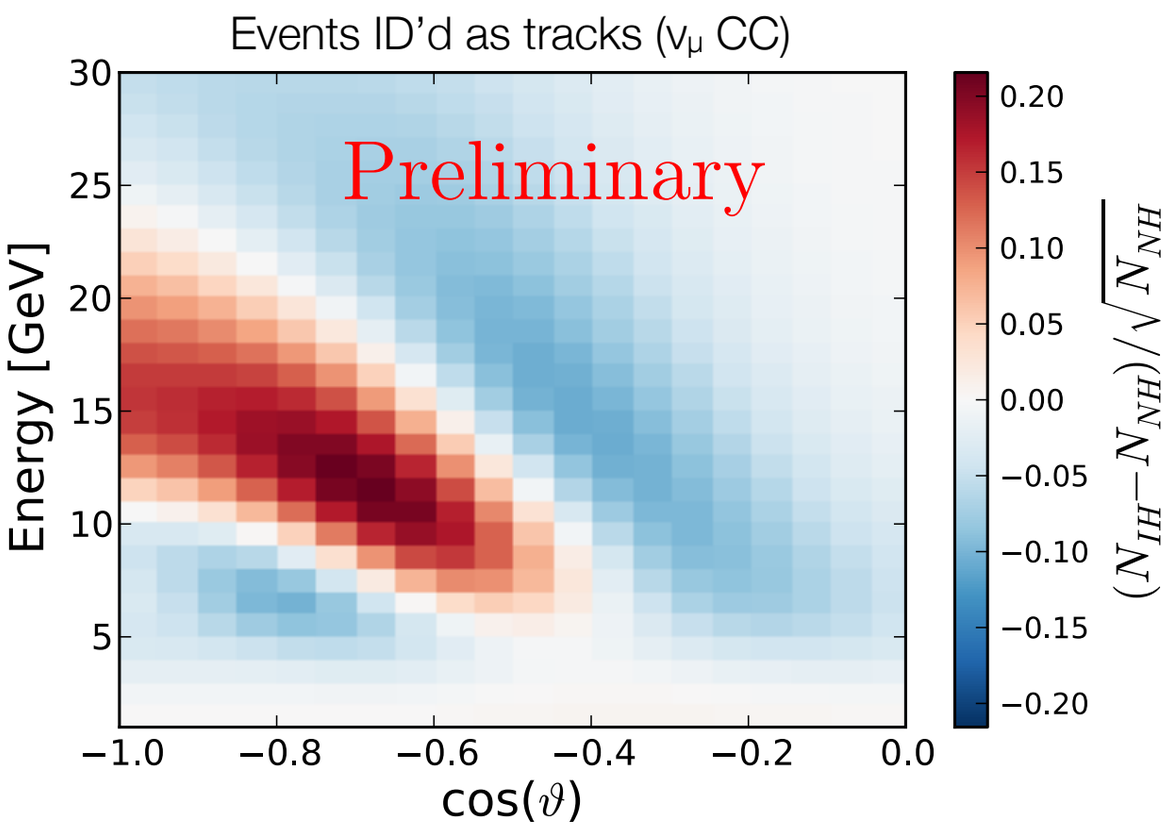
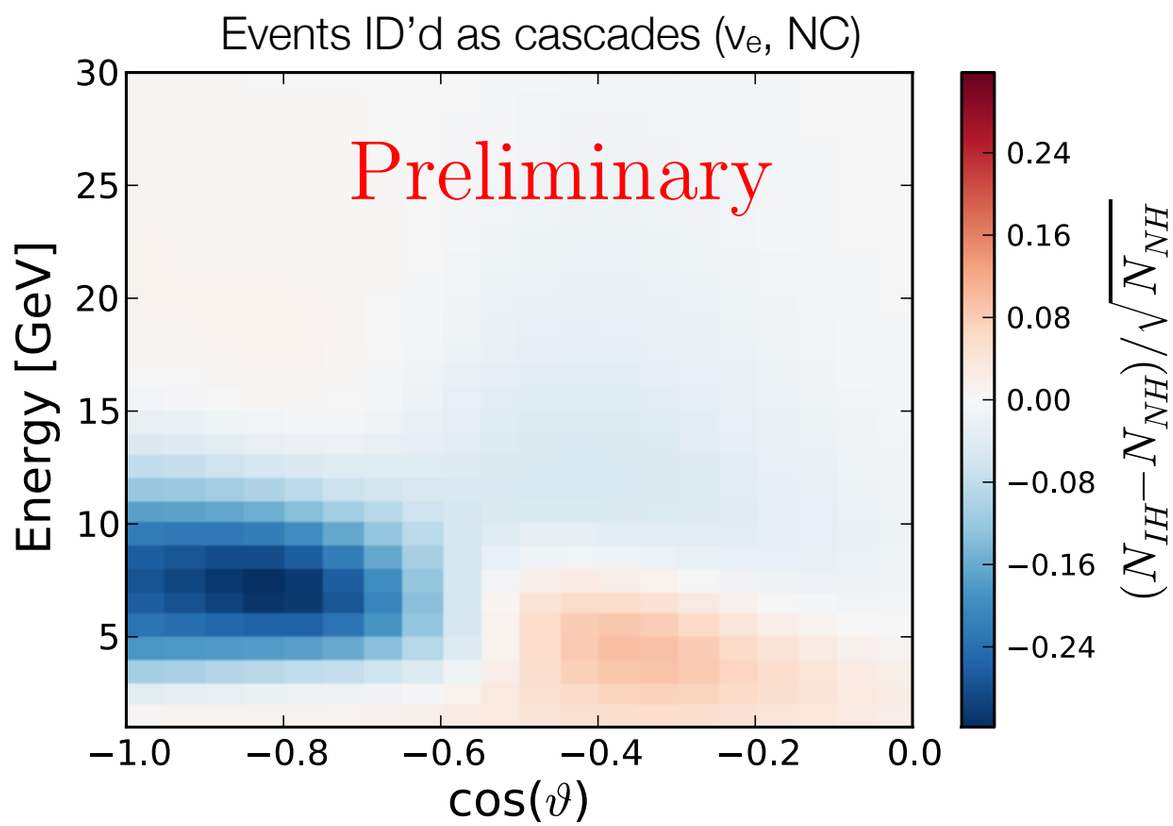


Hierarchy Signature: Observables

arXiv:1401.2046





- Simple visualization of statistical signal, with full detector response included
- Distinctive (and quite different) hierarchy-dependent signatures visible in both the track and cascade channels
  - Parametrized rates, detector resolutions and efficiencies from full detector Monte Carlo used to eliminate statistical fluctuations – statistical distributions checked with MC

Effects of Systematics

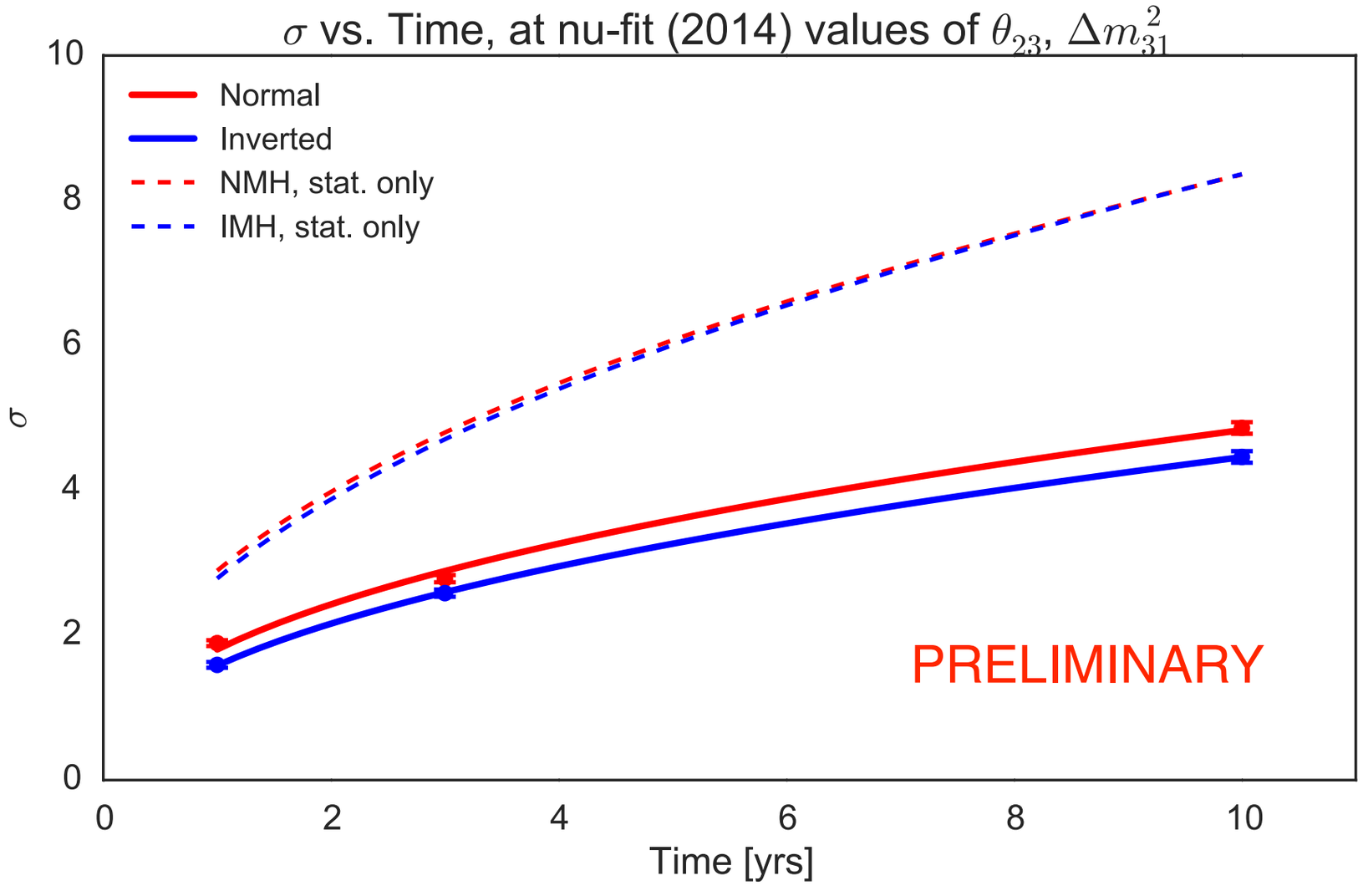
- Oscillation physics produces distinctive patterns unlike those of other effects
- Uncertainties in oscillation parameters (mainly θ_{23}) dominate systematics
  - No prior placed on θ_{23} or Δm^2_{atm} – fit jointly with NMH
  - θ_{13} fit with prior, solar parameters and δ_{CP} (=0) held fixed
- Flux: ν_e/ν_μ ratio (3%), $\nu/\bar{\nu}$ ratio (10%), spectral index (5%), detailed flux uncertainties from Barr et al. 2006*
- Detector: rate/normalization (free), energy scale (10%), detailed cross-section systematics from GENIE*

Type	3y σ (NH)	3 y σ (IH)
stat only	4.84	4.82
flux only	4.55	4.56
det only	4.06	3.99
θ_{23} only	3.52	3.26
osc only	2.96	2.53
All	2.90	2.51

*only with $\Delta\chi^2$ method

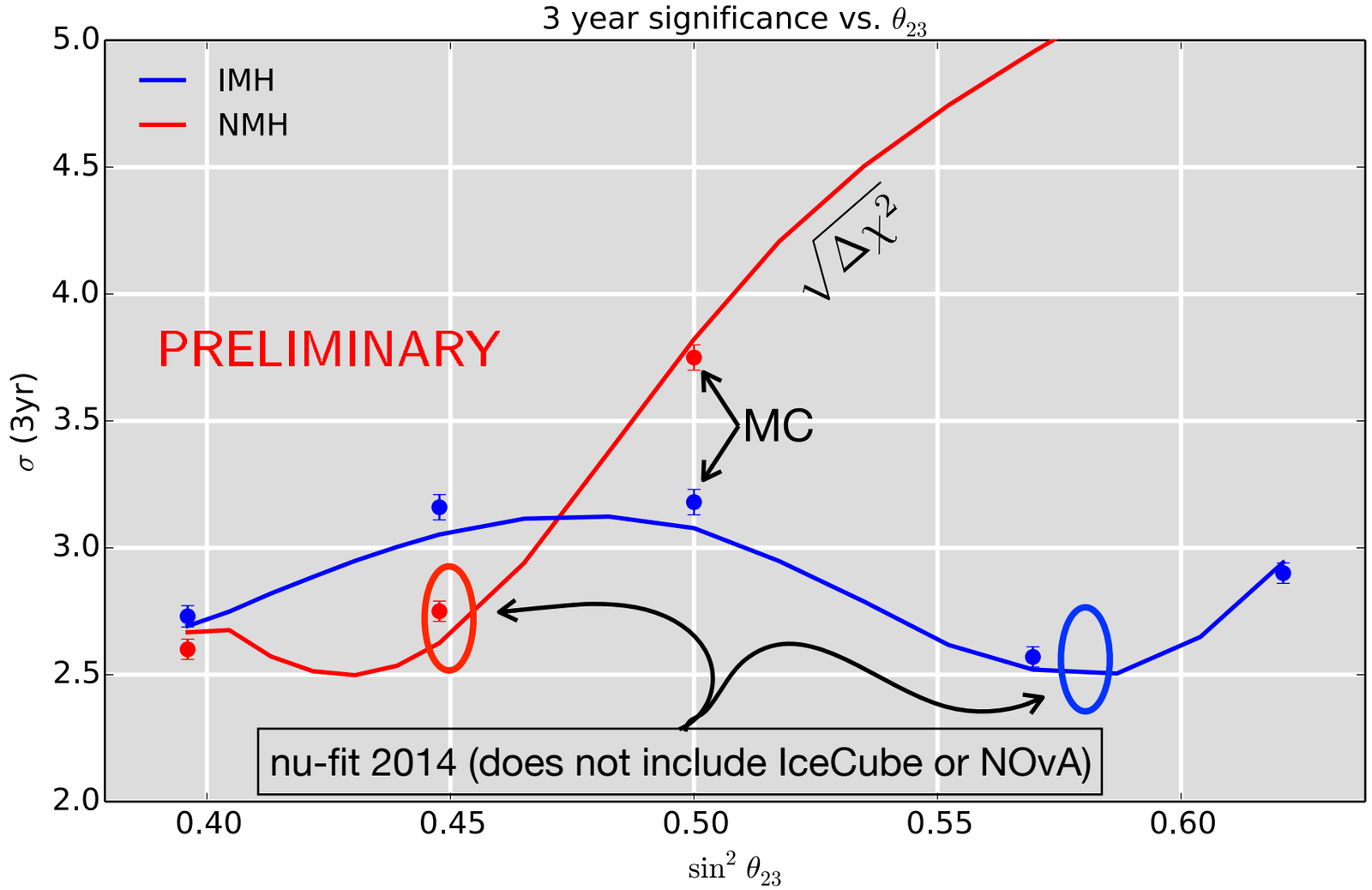
Significance vs. Time

- Measurement strongly affected by systematics, but continues to improve with time
- Systematics are constrained by same data set
  - Increased statistics means gradually better control of systematics



Dependence on Mixing Angle

- Most values of θ_{23} would give higher significance for mass ordering
  - Drift toward maximal mixing since PINGU LoI has increased both matter effects and degeneracies

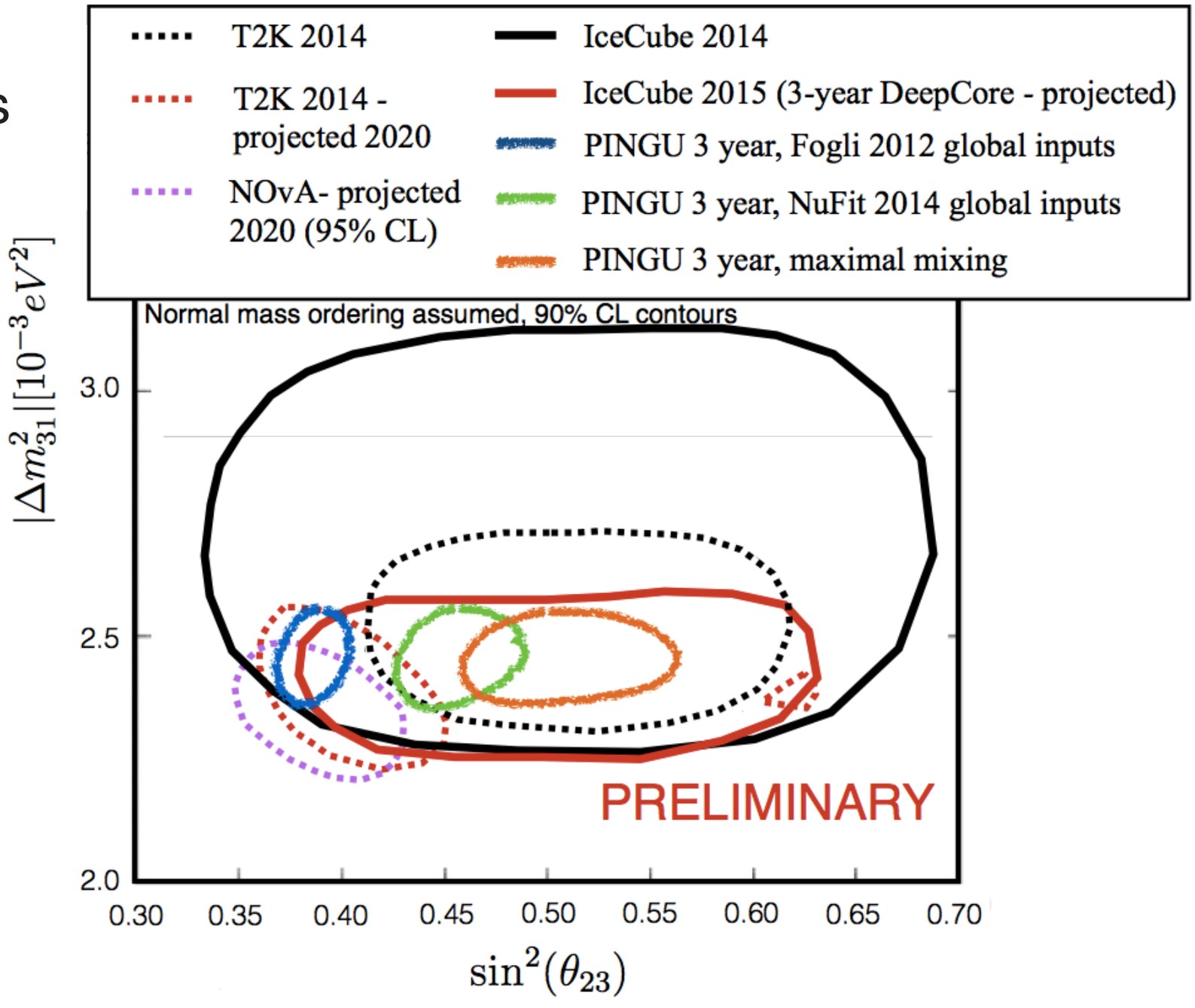


M.C. Gonzalez-Garcia et al. *JHEP* 11, 052 (2014)

- Mass ordering measured at ≥3σ in 3-4 years over full ±2σ range of global fit

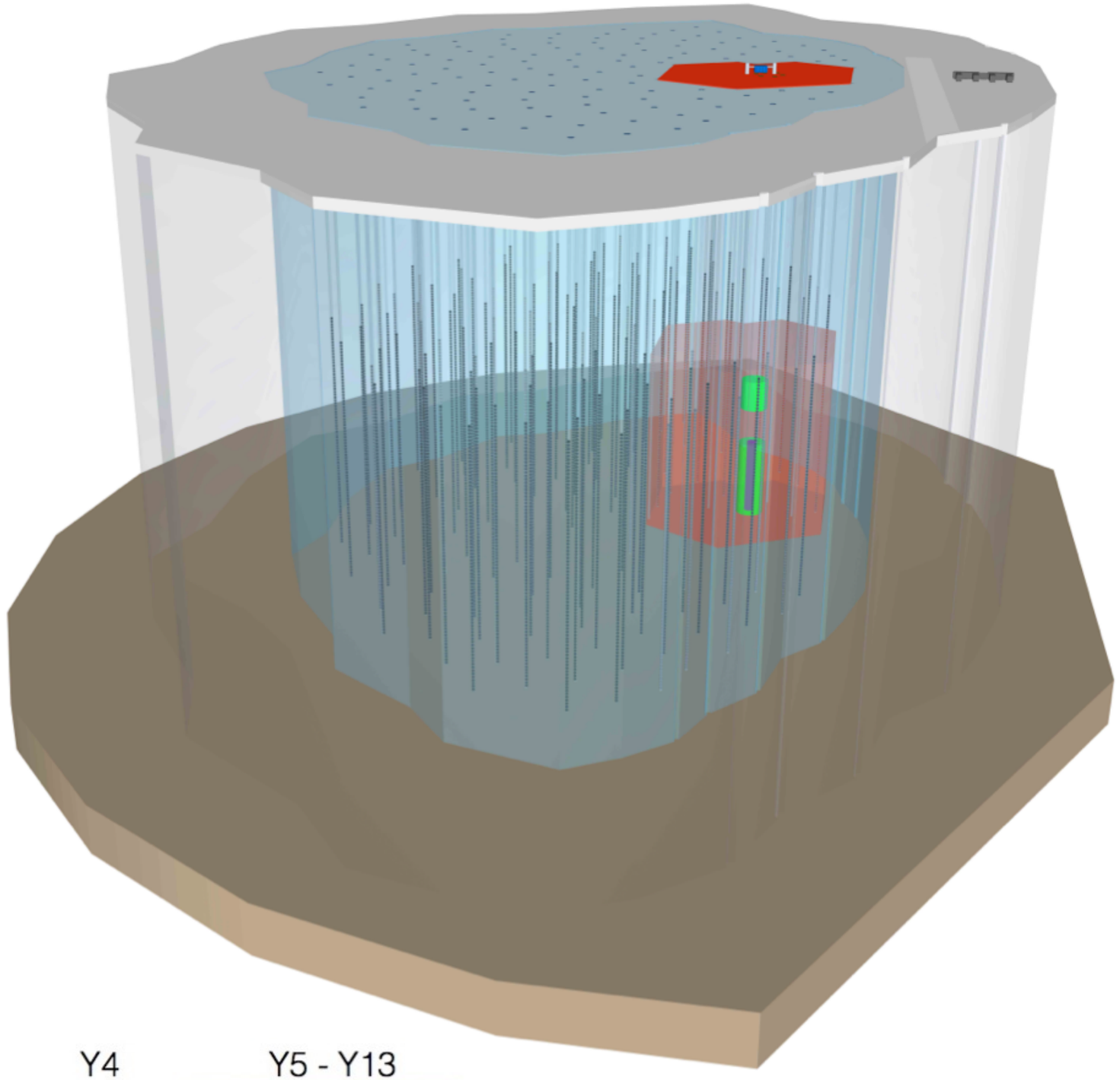
Oscillation Parameters with PINGU

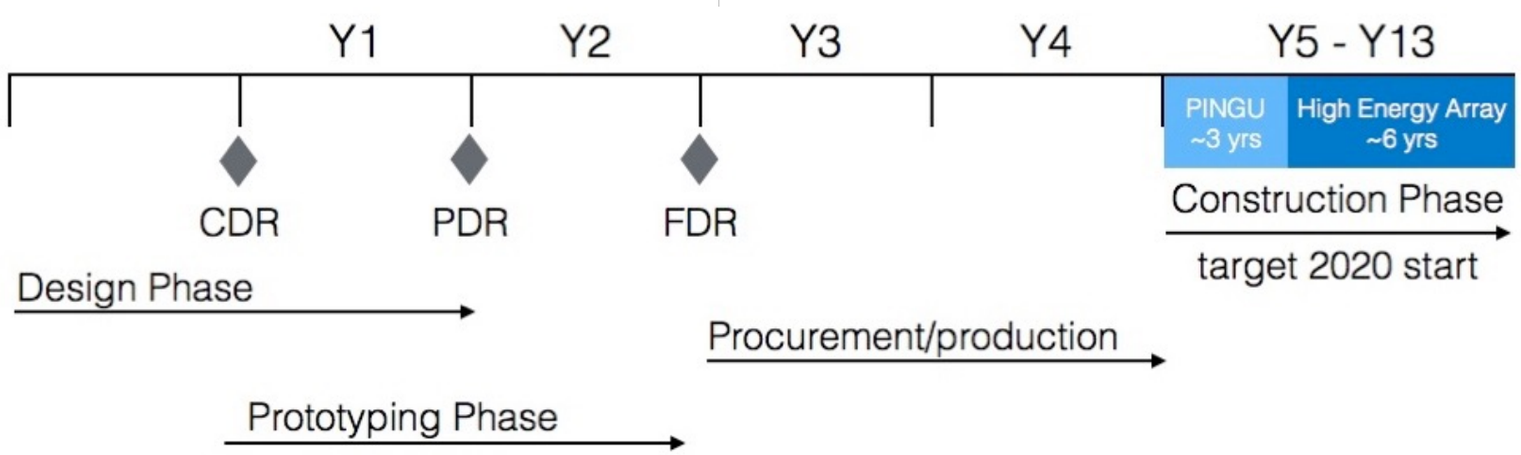
- Significantly improve IceCube measurements of θ_{23} and Δm^2_{atm}
- Comparable precision to NOvA, T2K
- Complementary to other measurements – interesting tests of standard oscillations
  - Higher energies, joint disappearance-tau appearance measurement



IceCube-Gen2

- Planning underway for a multipurpose facility leveraging the experience and investment in IceCube
  - White paper at arXiv:1412.5106 – more details and PINGU update later this year
- PINGU will be one component of IceCube-Gen2





Outlook

- PINGU has a unique place in the world-wide neutrino program
  - Measurements at a range of higher energies/longer baselines, with high statistics
- Opportunity to discover new physics is greatly enhanced by PINGU's complementarity with other experiments
- PINGU will be a natural part of the IceCube-Gen2 Observatory
  - Closely based on IceCube technology – low technical and cost risk
  - PINGU will use the same hardware as high energy extensions of IceCube – common design gives flexibility to optimize based on progress of the field
- Focused here on neutrino physics, but also interesting potential in searches for low mass dark matter and other exotica