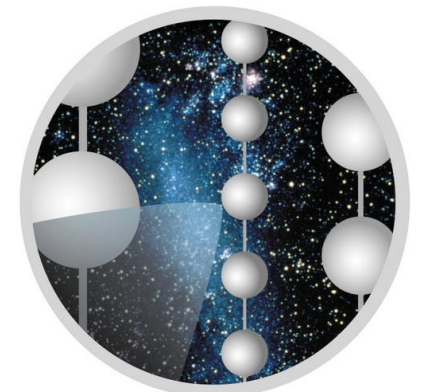




Neutrino Physics Prospects with PINGU

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ICECUBE

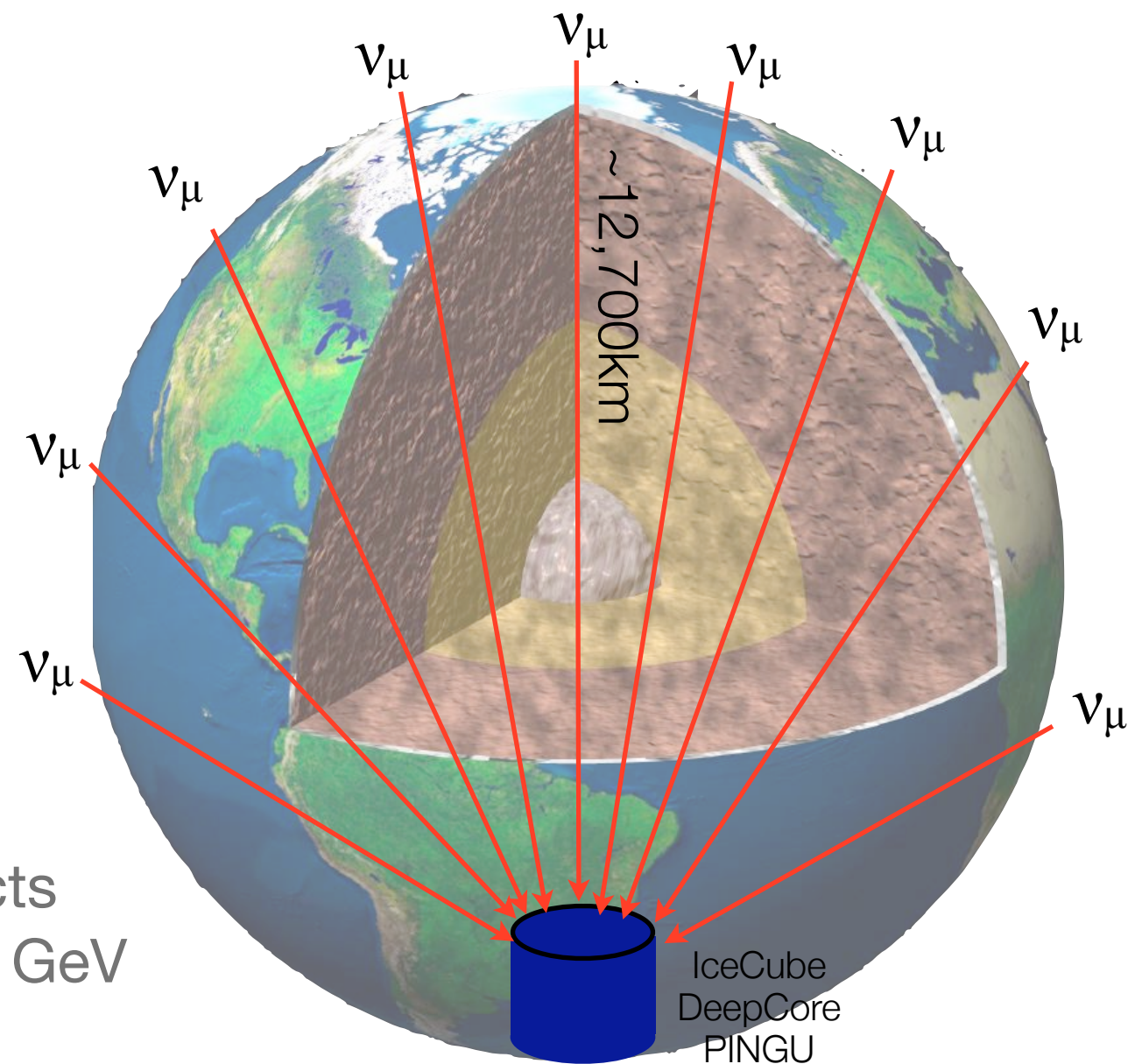
DPF 2015
Ann Arbor, Michigan
August 7, 2015



PRECISION ICECUBE NEXT
GENERATION UPGRADE

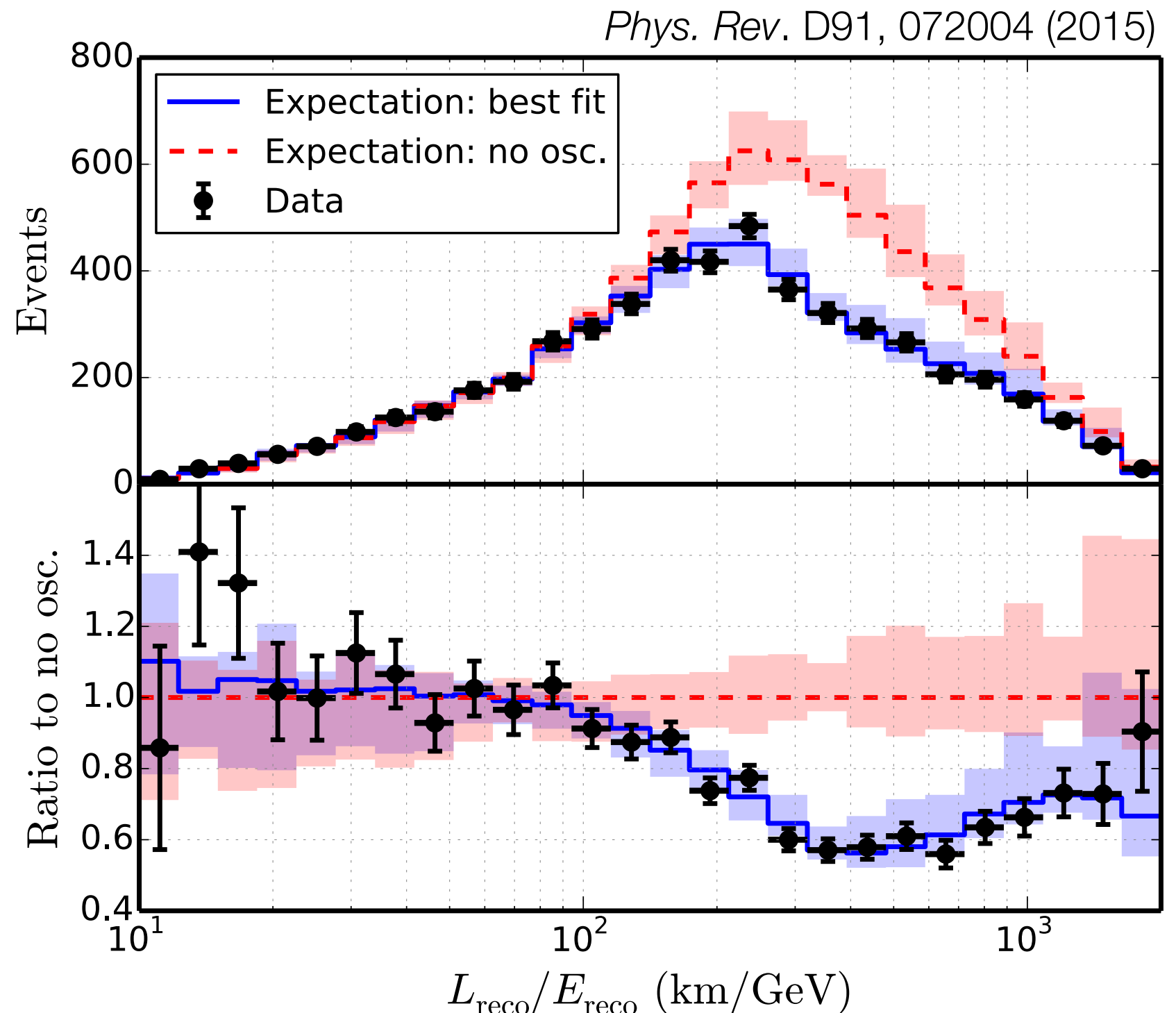
Oscillation Physics with Atmospheric Neutrinos

- 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)

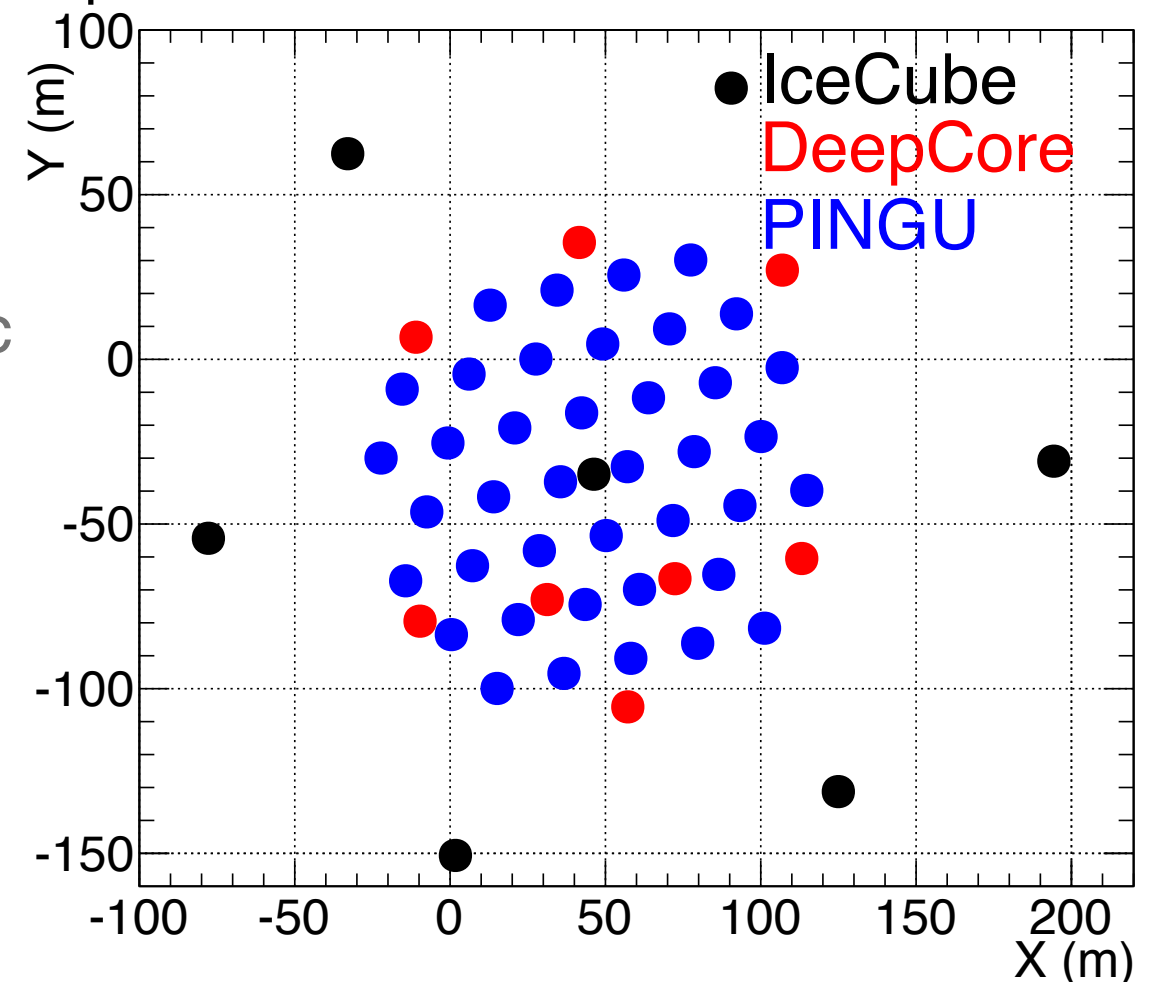


PINGU



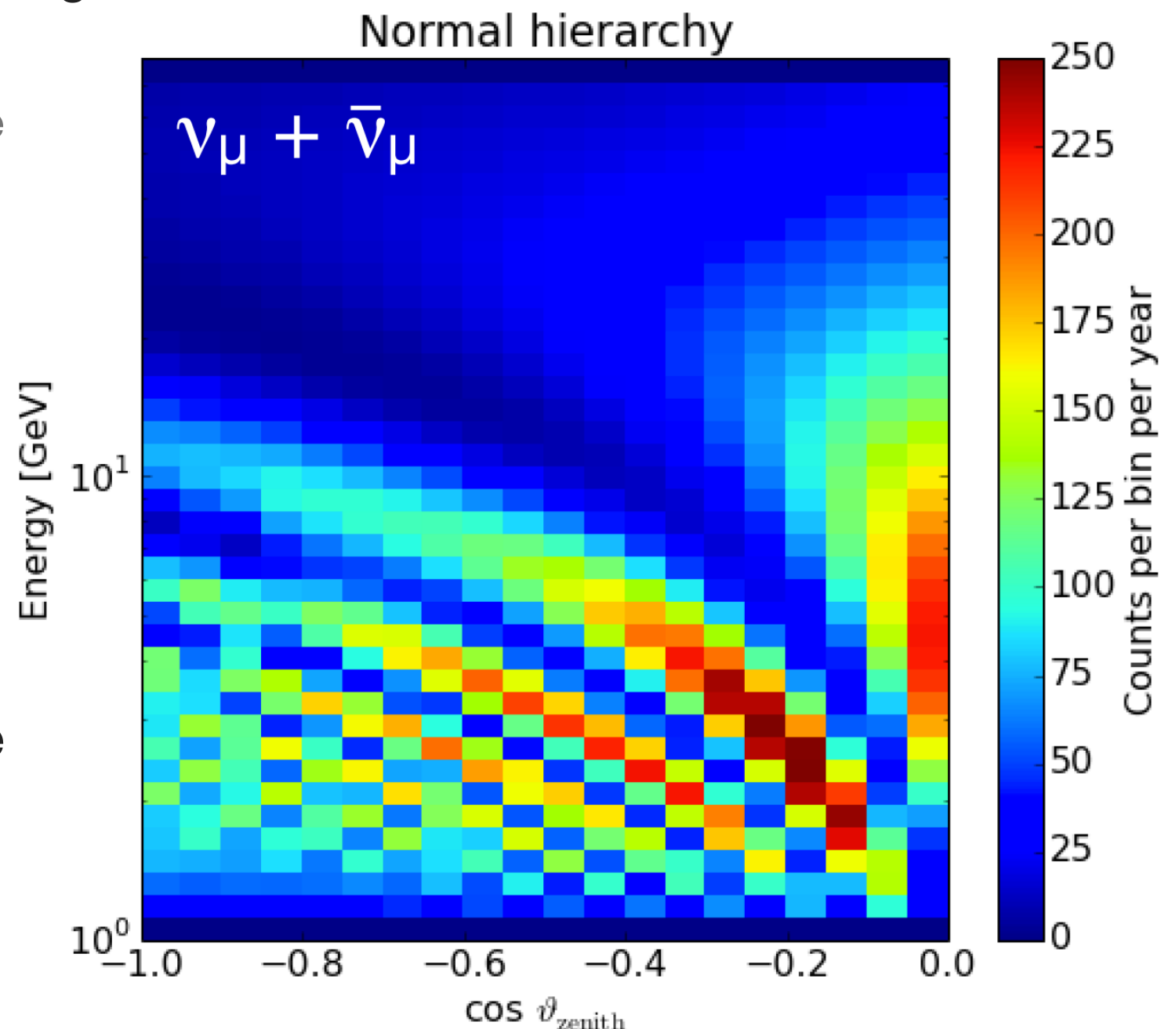
- Baseline 4 MTon detector: 40 additional strings at 22 m spacing, with Digital Optical Modules spaced 3 m vertically, deployed inside IceCube DeepCore
 - Compare to 72 m string spacing and 7 m DOM spacing for DeepCore
 - ~25x higher photocathode density
 - Additional in situ calibration devices will 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



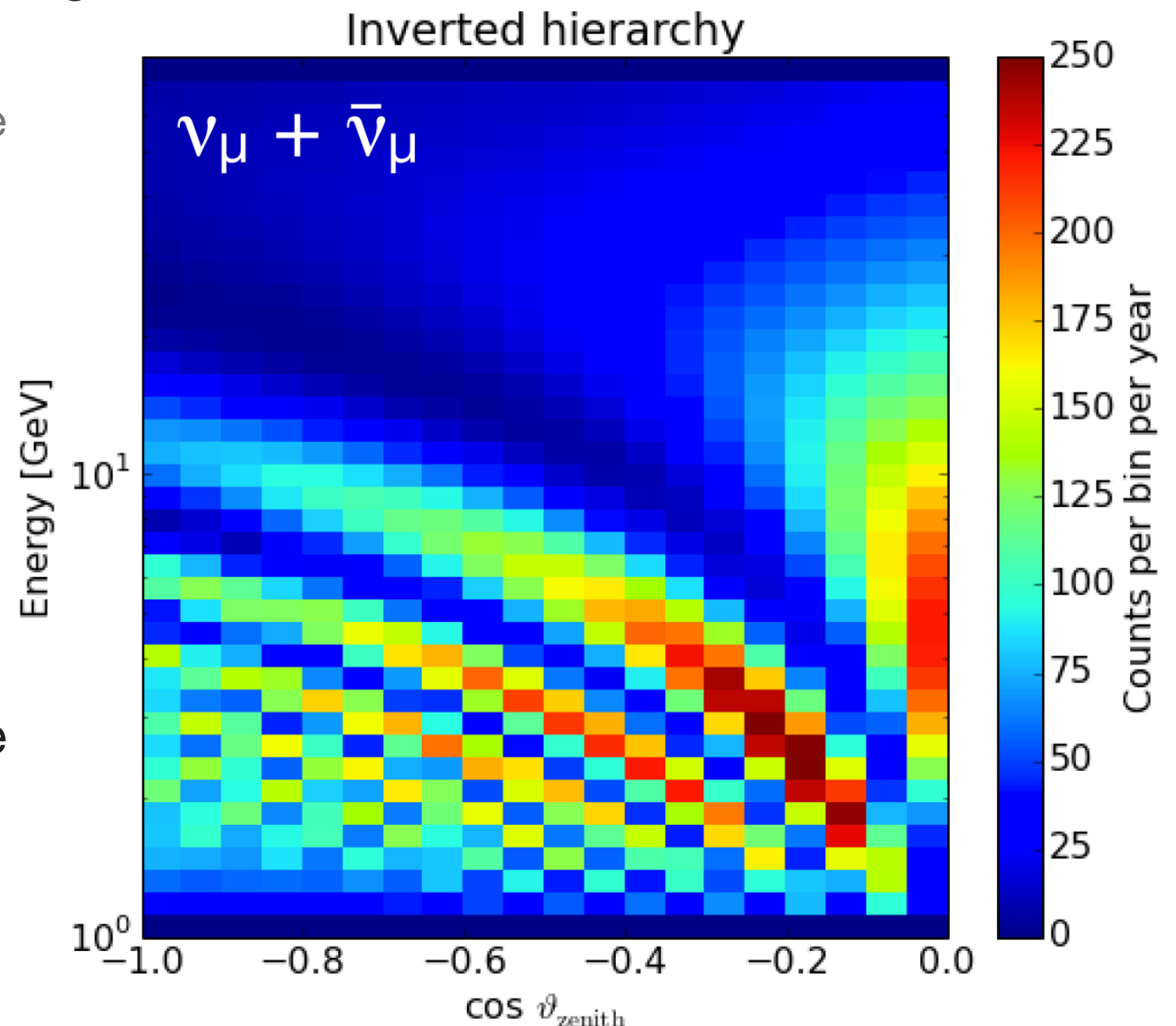
Signatures of the Neutrino Mass Hierarchy

- Matter effects alter oscillation probabilities for ν or $\bar{\nu}$ 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



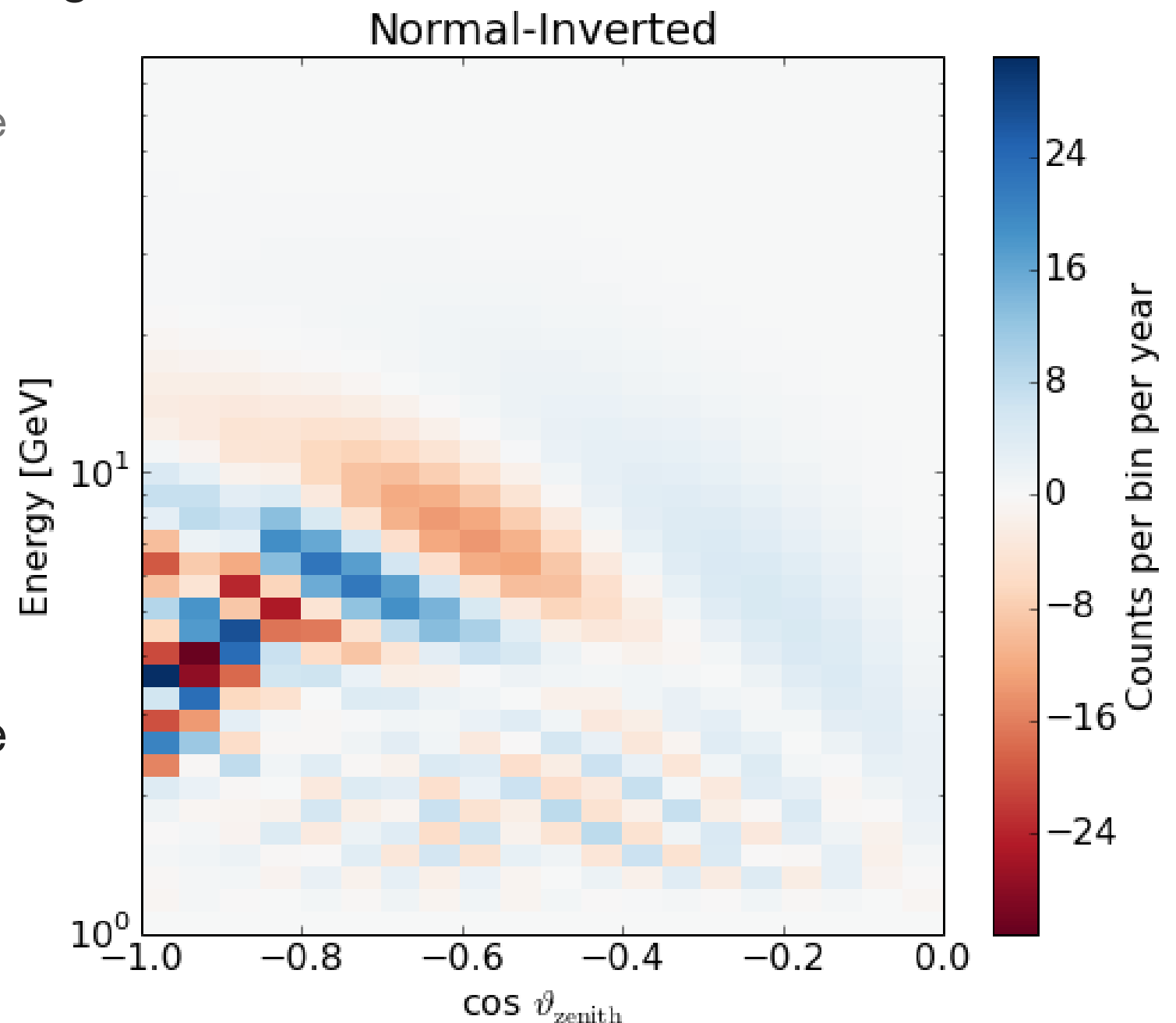
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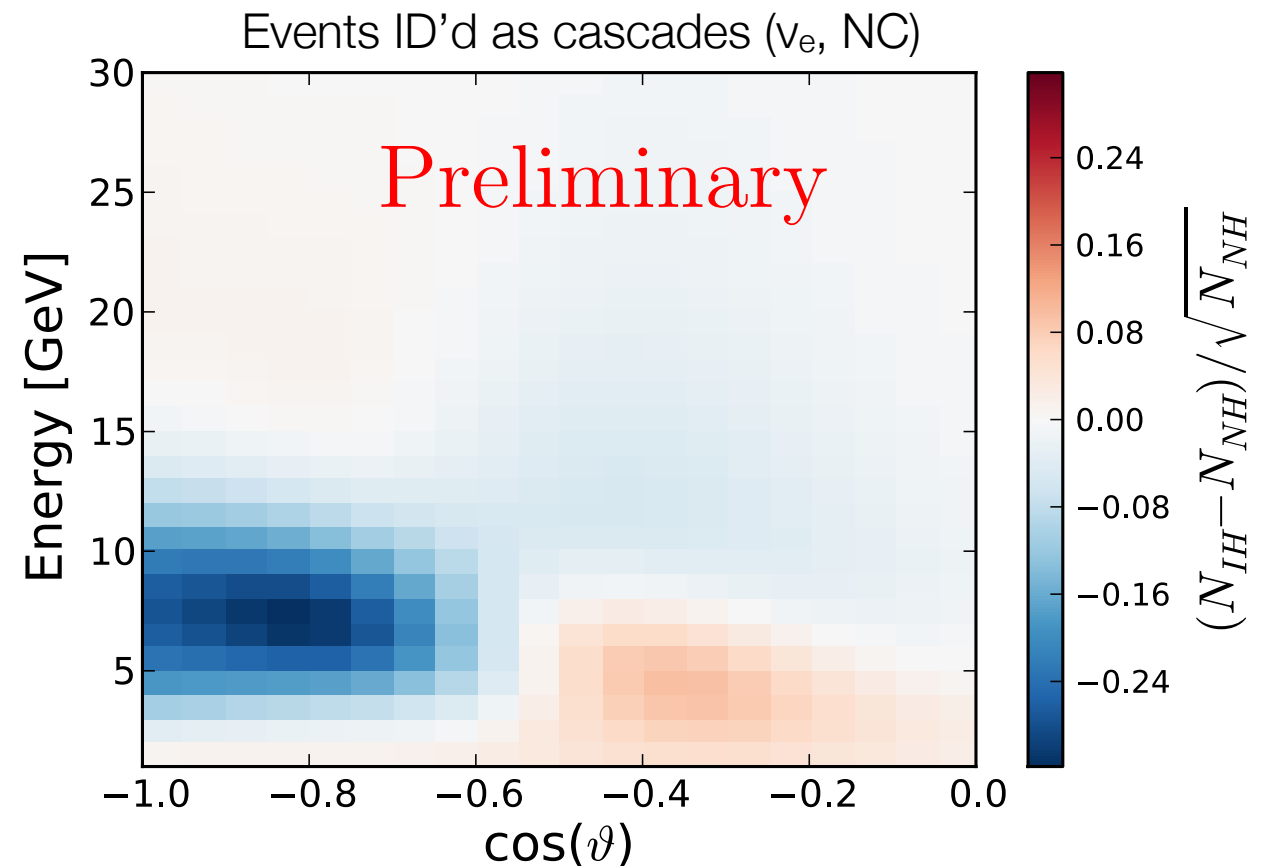
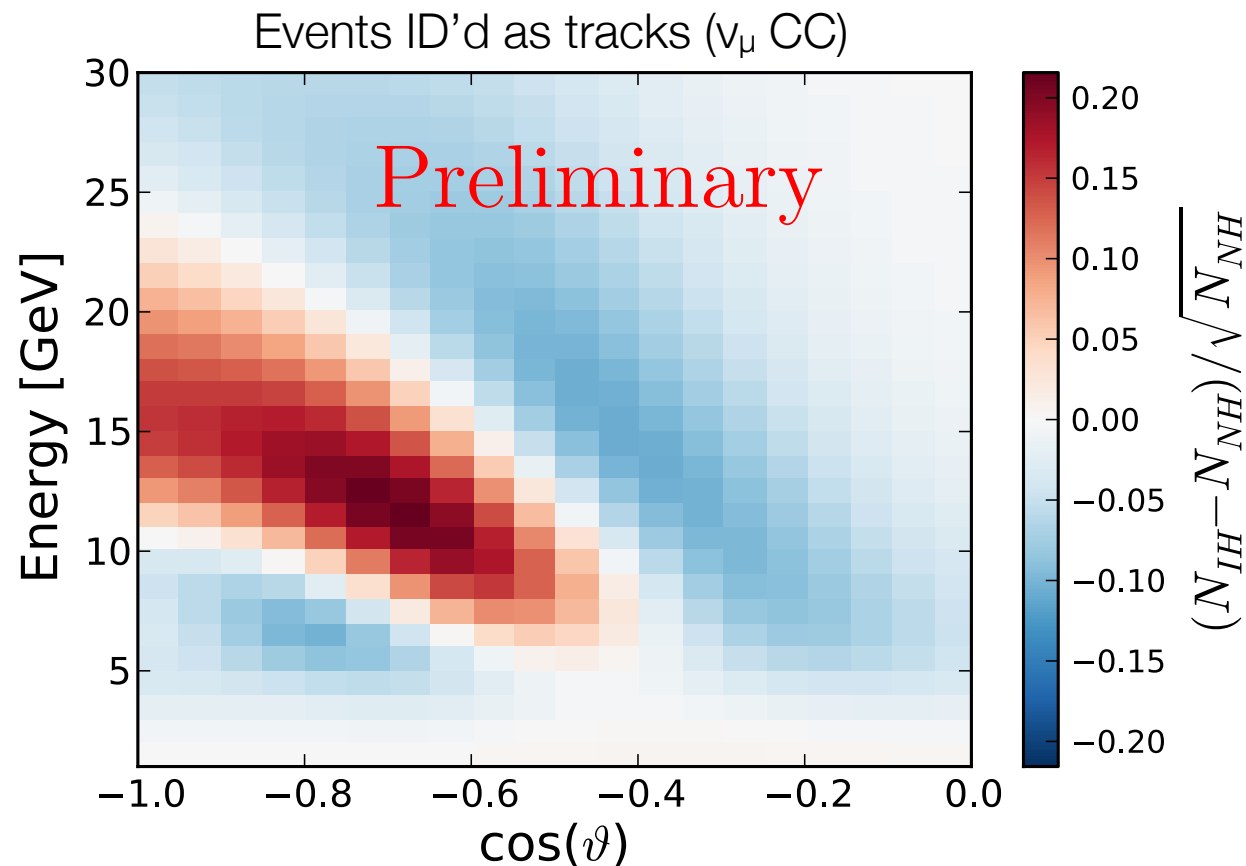
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Hierarchy Signature: Observables

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*

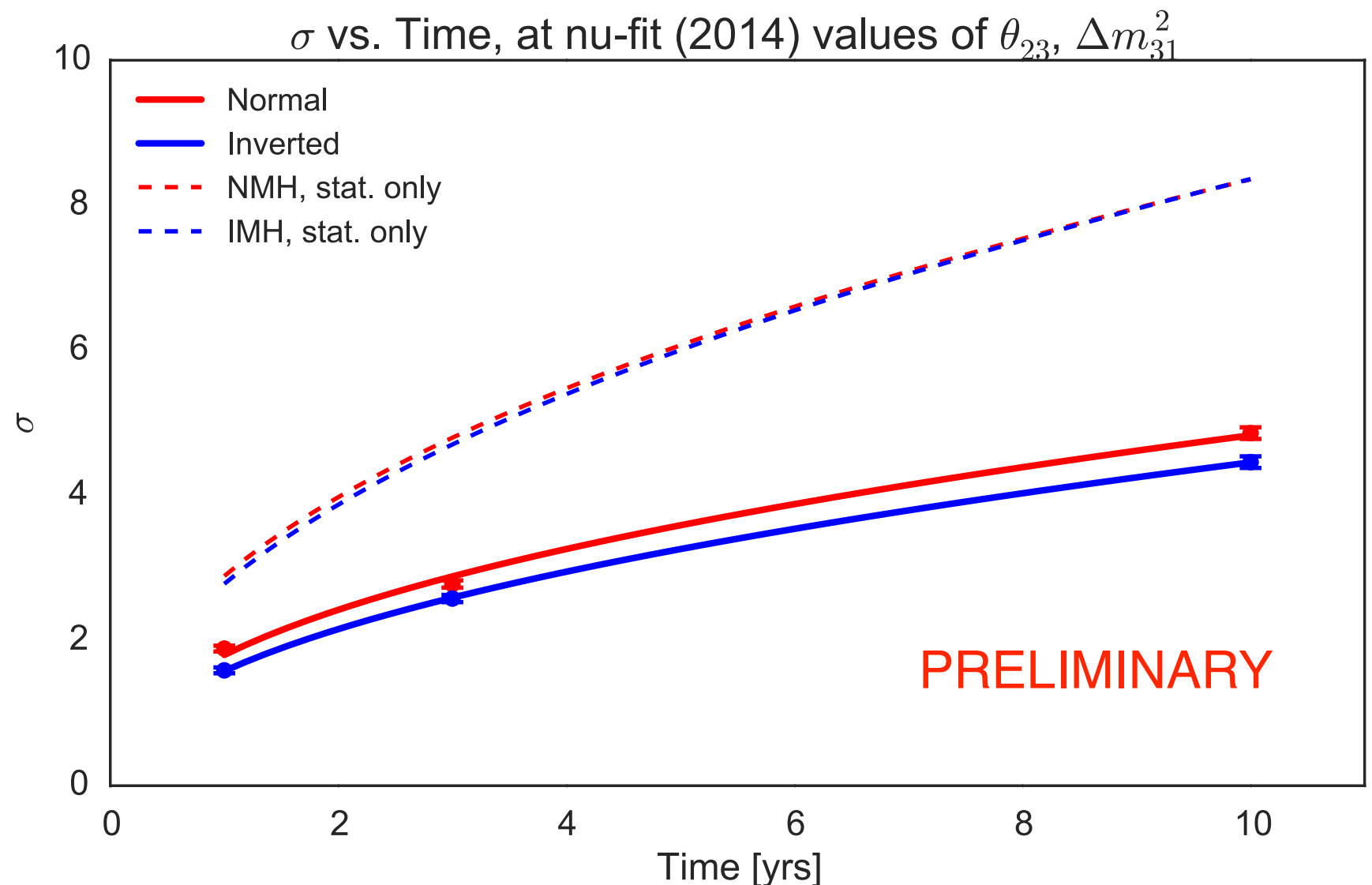
Type	3y σ (NH)	3 y σ (IH)
stat only	4.84	4.82
flux only	4.55	4.56
det only	4.06	3.99
θ_{23} only	3.52	3.26
osc only	2.96	2.53
All	2.90	2.51

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



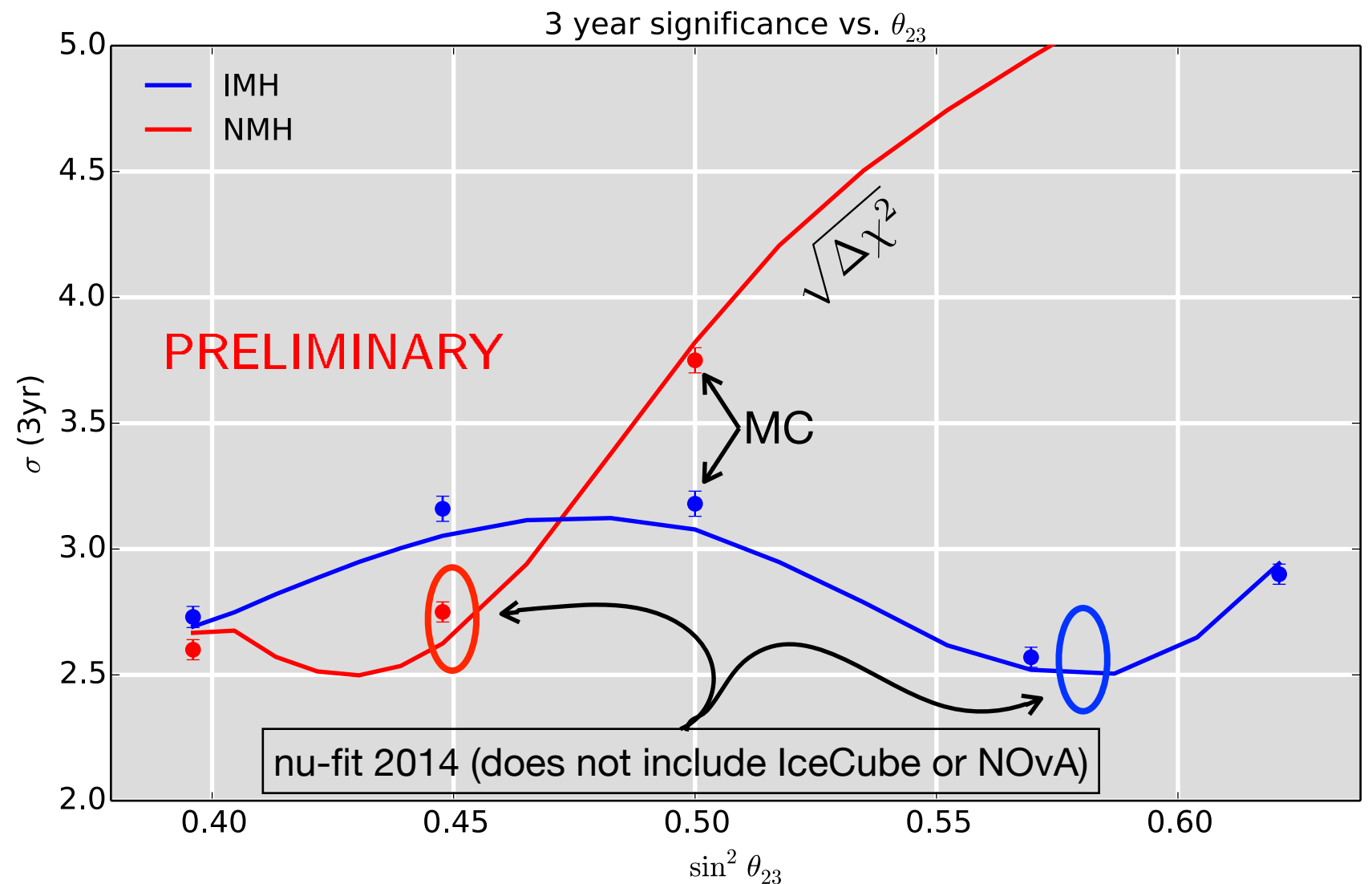
Significance vs. Time

- 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
- Mass ordering measured at $\geq 3\sigma$ in 3-4 years over full $\pm 2\sigma$ range of global fit

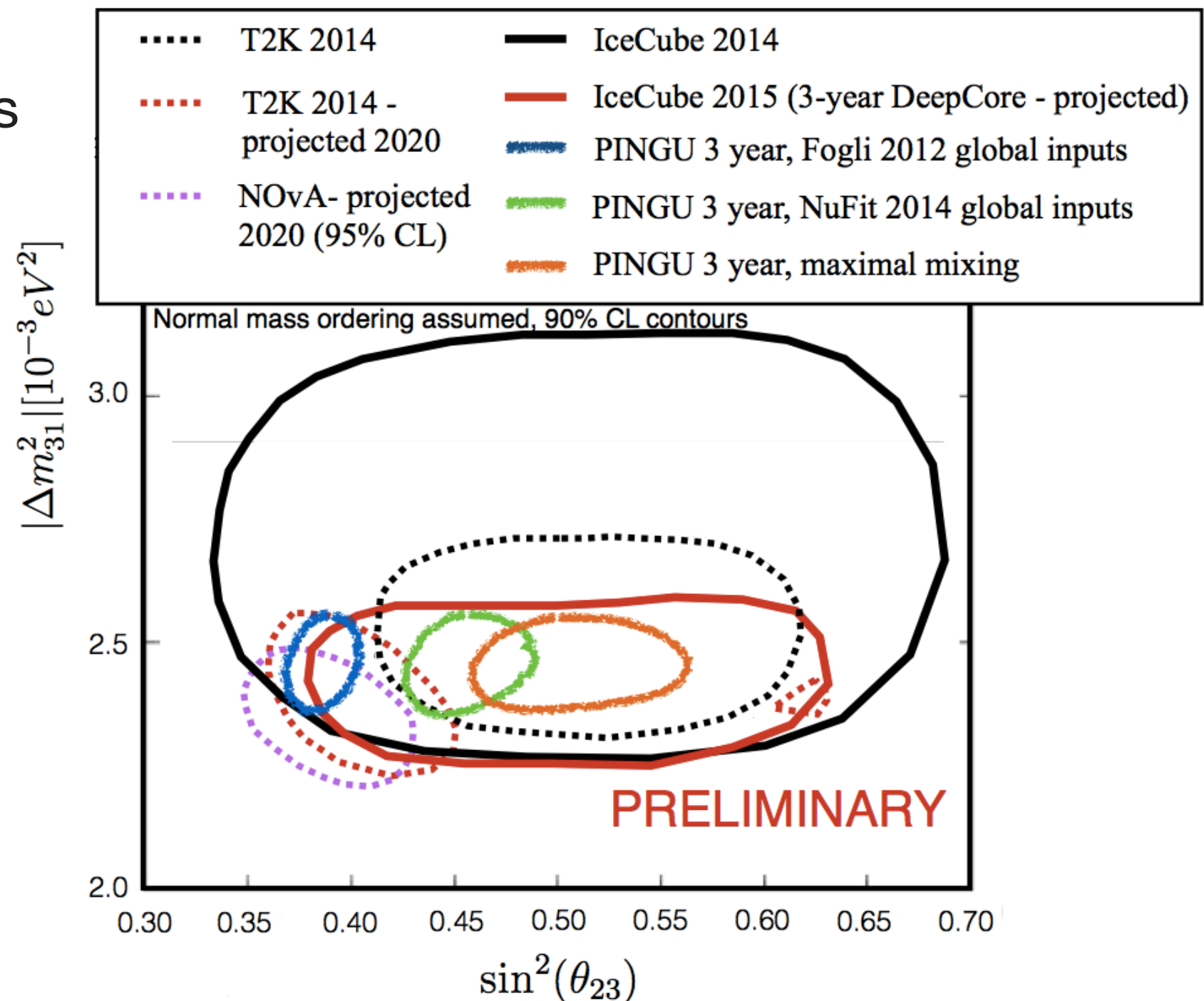


M.C. Gonzalez-Garcia et al. *JHEP* 11, 052 (2014)



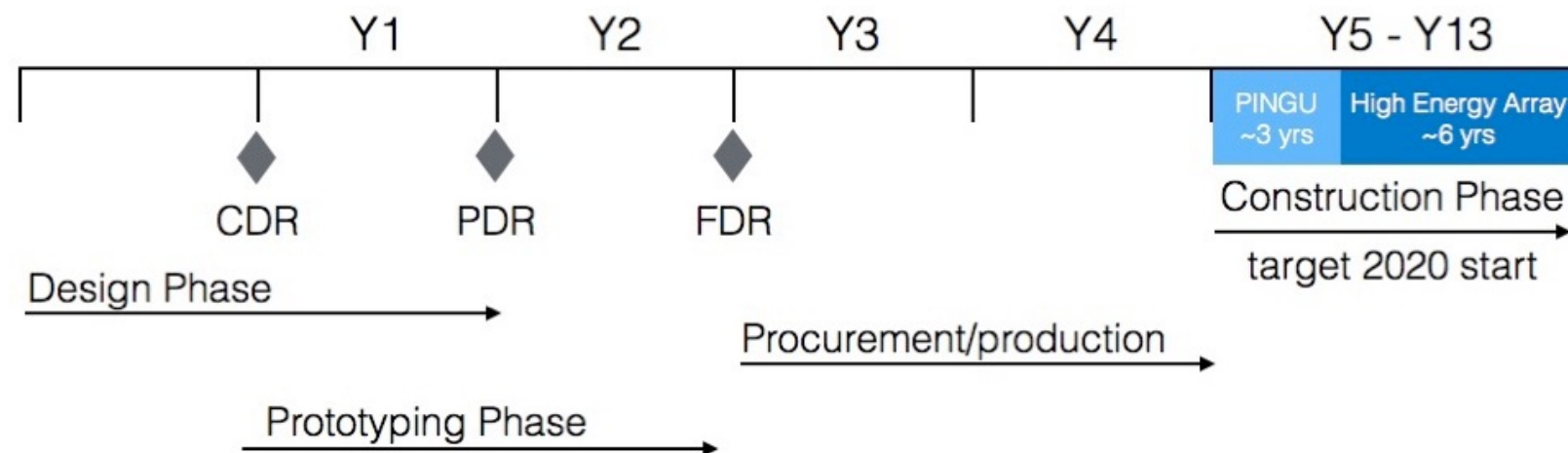
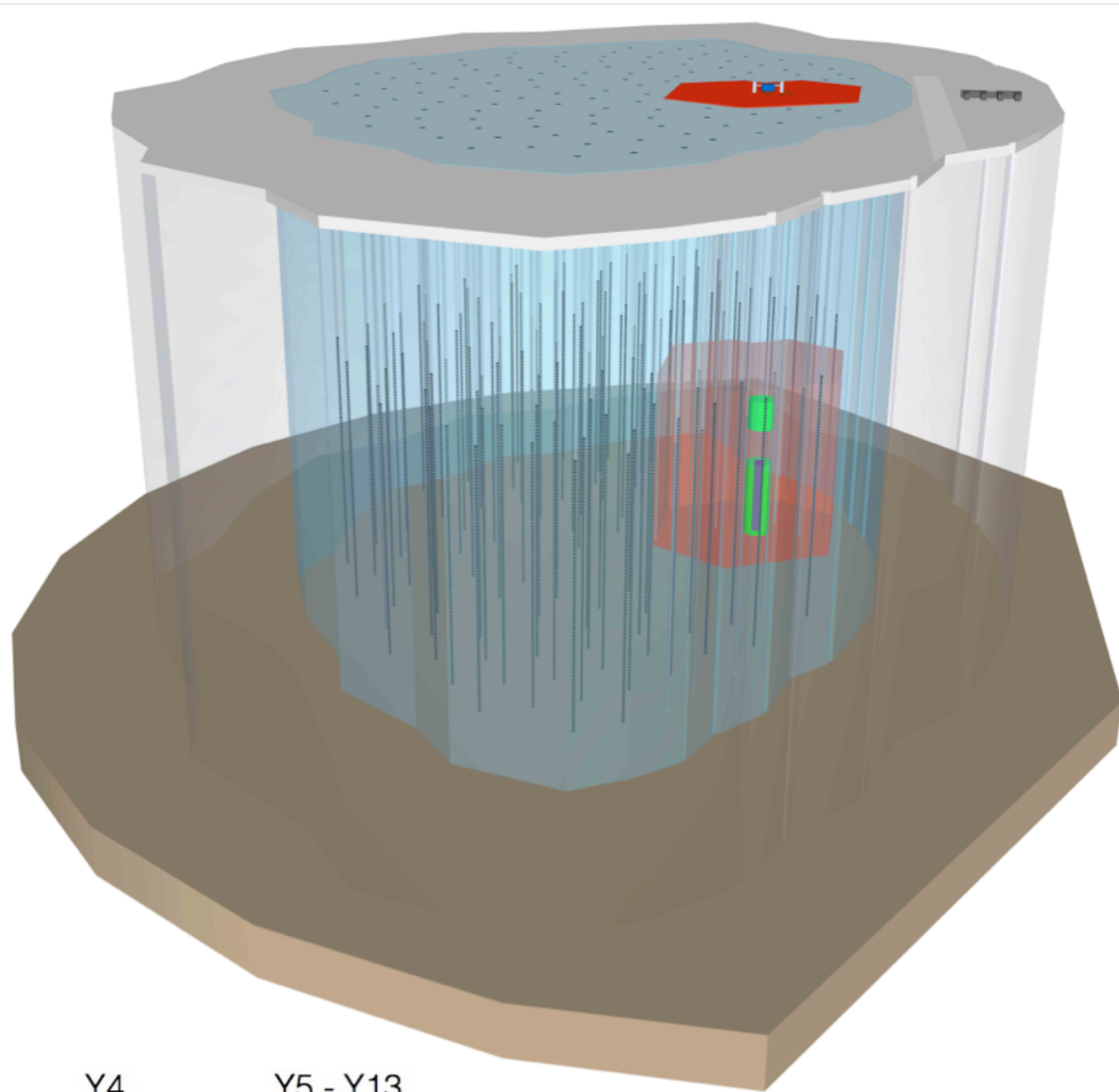
Oscillation Parameters with PINGU

- 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](https://arxiv.org/abs/1412.5106) – more details and PINGU update later this year
- PINGU will be one component of IceCube-Gen2



Outlook

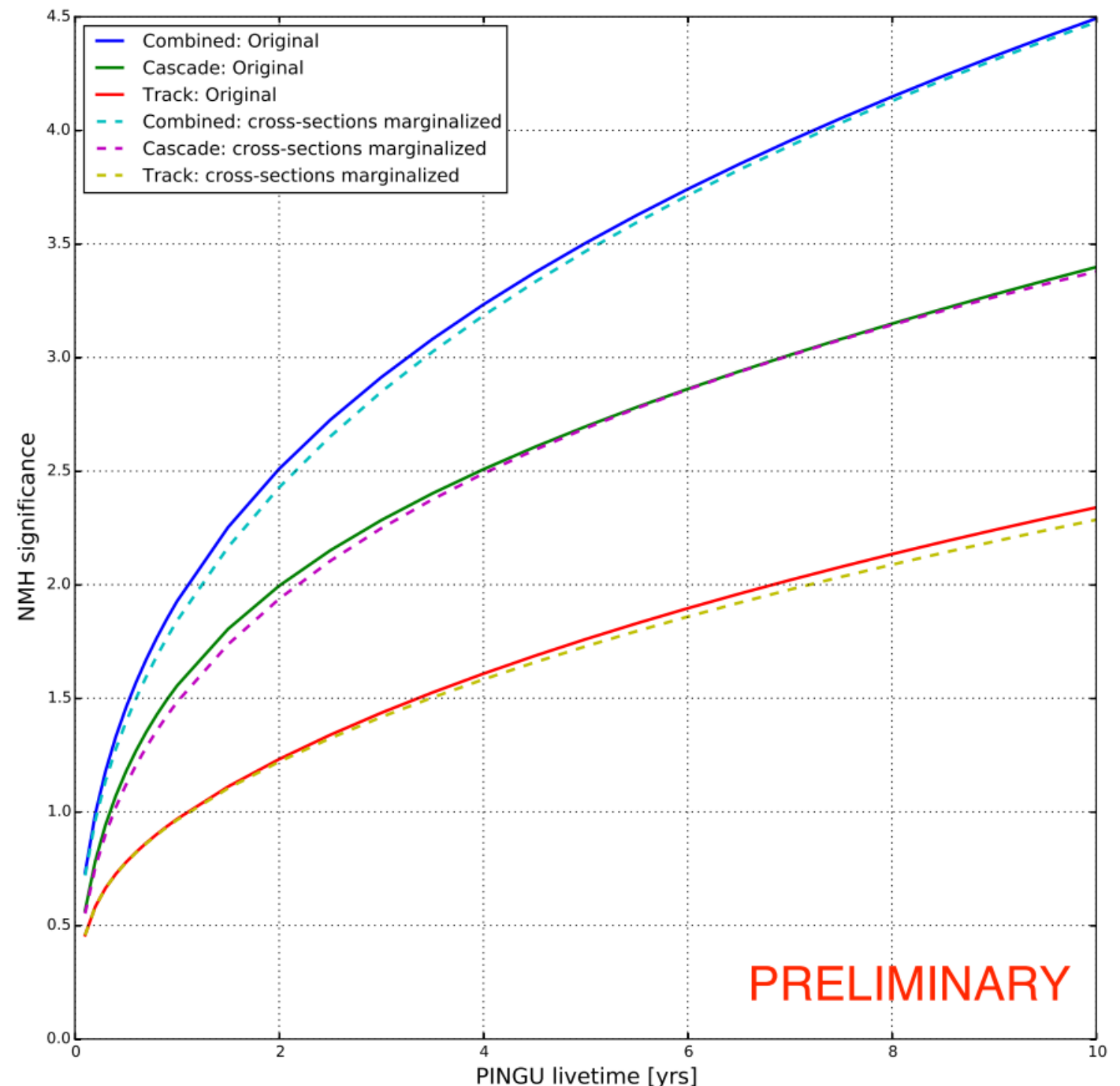
- PINGU has a unique place in the world-wide neutrino program
 - Measurements at a range of higher energies/longer baselines, with high statistics
- Opportunity to discover new physics is greatly enhanced by PINGU's complementarity with other experiments
- PINGU will be a natural part of the IceCube-Gen2 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



Backup Slides

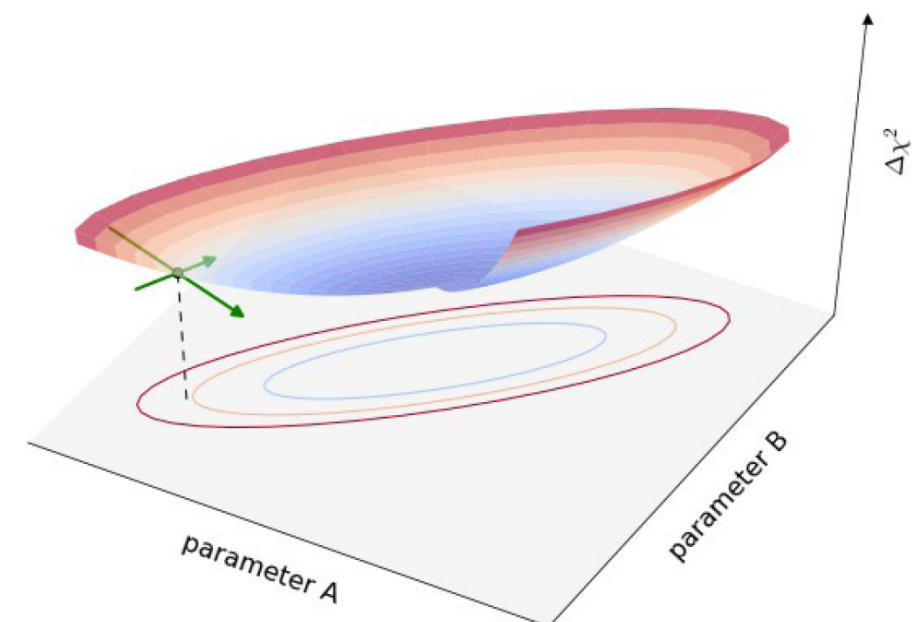
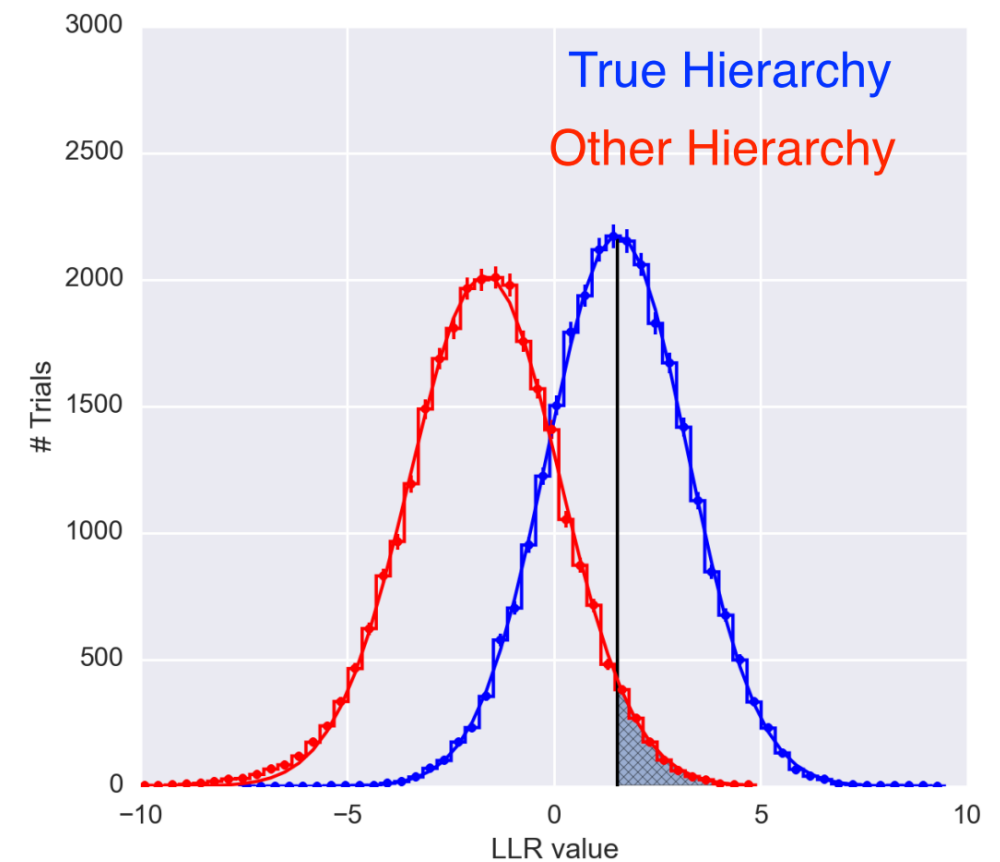
Neutrino-Nucleon Interaction Uncertainties

- Comparison of impact of GENIE uncertainties to original ad hoc treatment
- Net impact of full treatment is negligible – oscillation uncertainties dominate
 - Largest impacts from m_A in CCQE and resonance interactions, higher twist parameters in Bodek-Yang DIS model

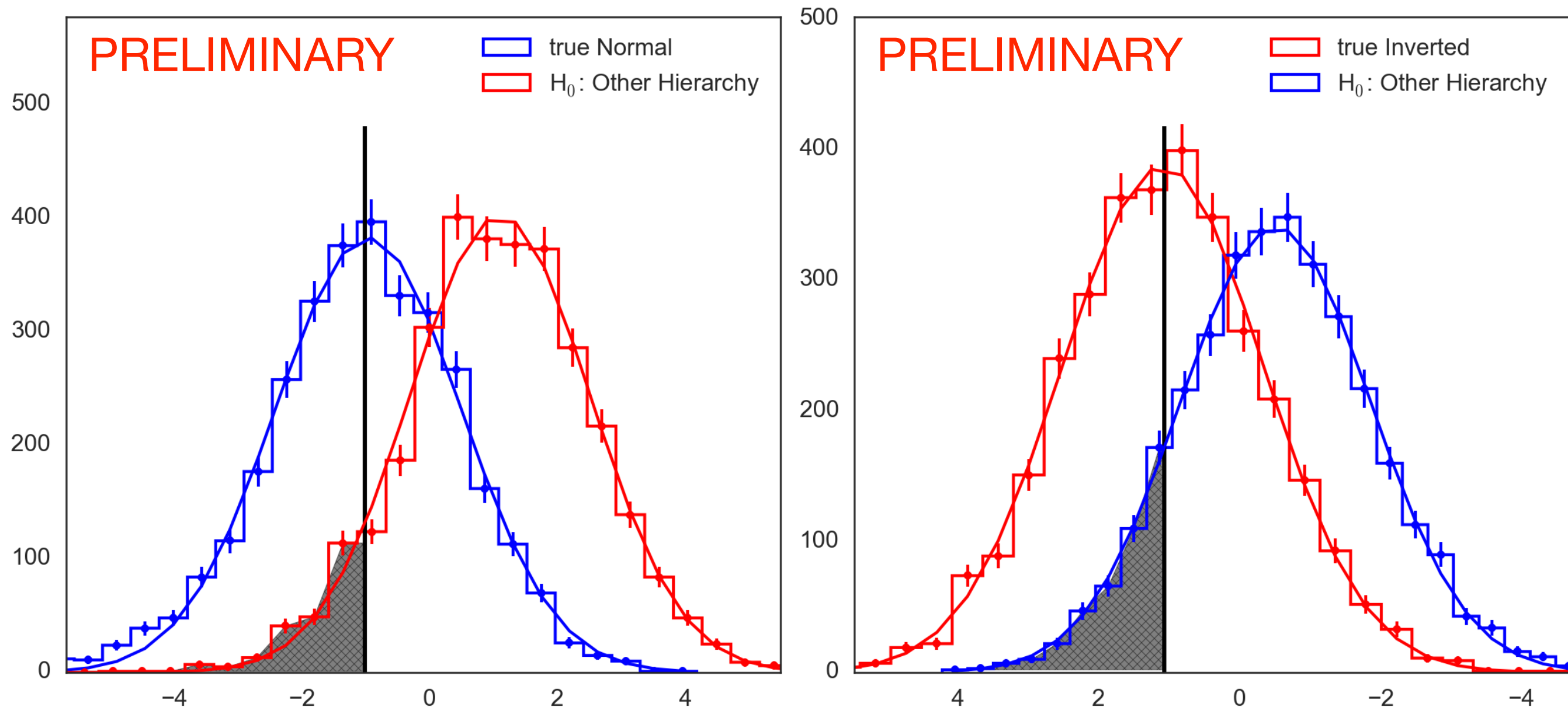


Estimating Sensitivity to the Mass Hierarchy

- Comparison of two methods of calculating expected significance
- Log-likelihood ratio method
 - Large ensemble of pseudo-data sets, best-fit physics and nuisance parameters determined numerically
 - Build up distribution of test statistic and integrate tail for expected significance
- Penalized $\Delta\chi^2$ (pull) method
 - Asimov data set rather than ensemble
 - Linear error propagation for linear parameters, scan over nonlinear ones
 - Fast: analytic minimization of $\Delta\chi^2$



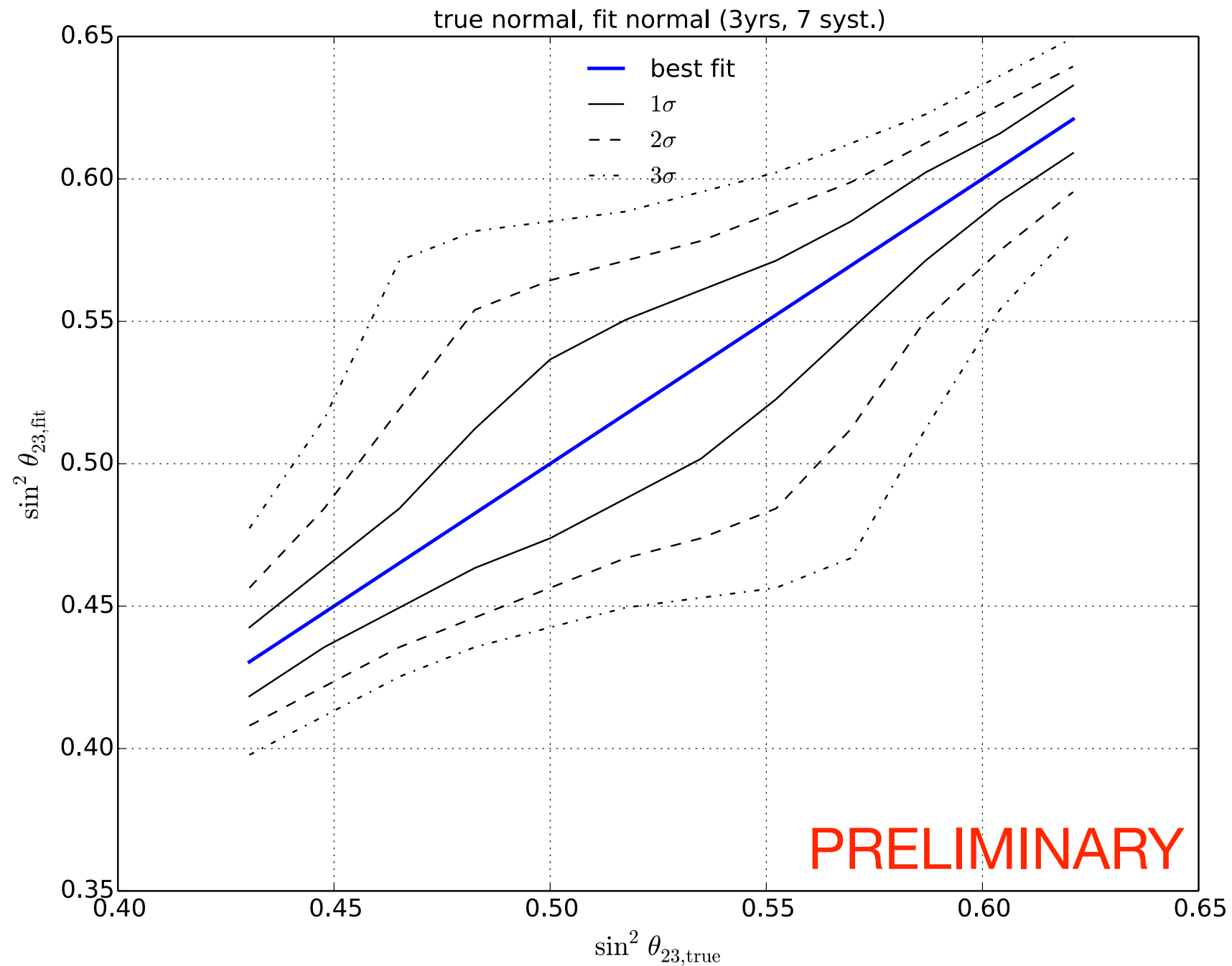
- example: LLR distributions for PINGU for True NH and True IH
 - ✦ 1 year significance: 1.83 (NH) and 1.55 (IH) for the NuFit¹ values of oscillation parameters



¹ M.C. Gonzalez-Garcia, et al. *JHEP* **11** 052, 2014

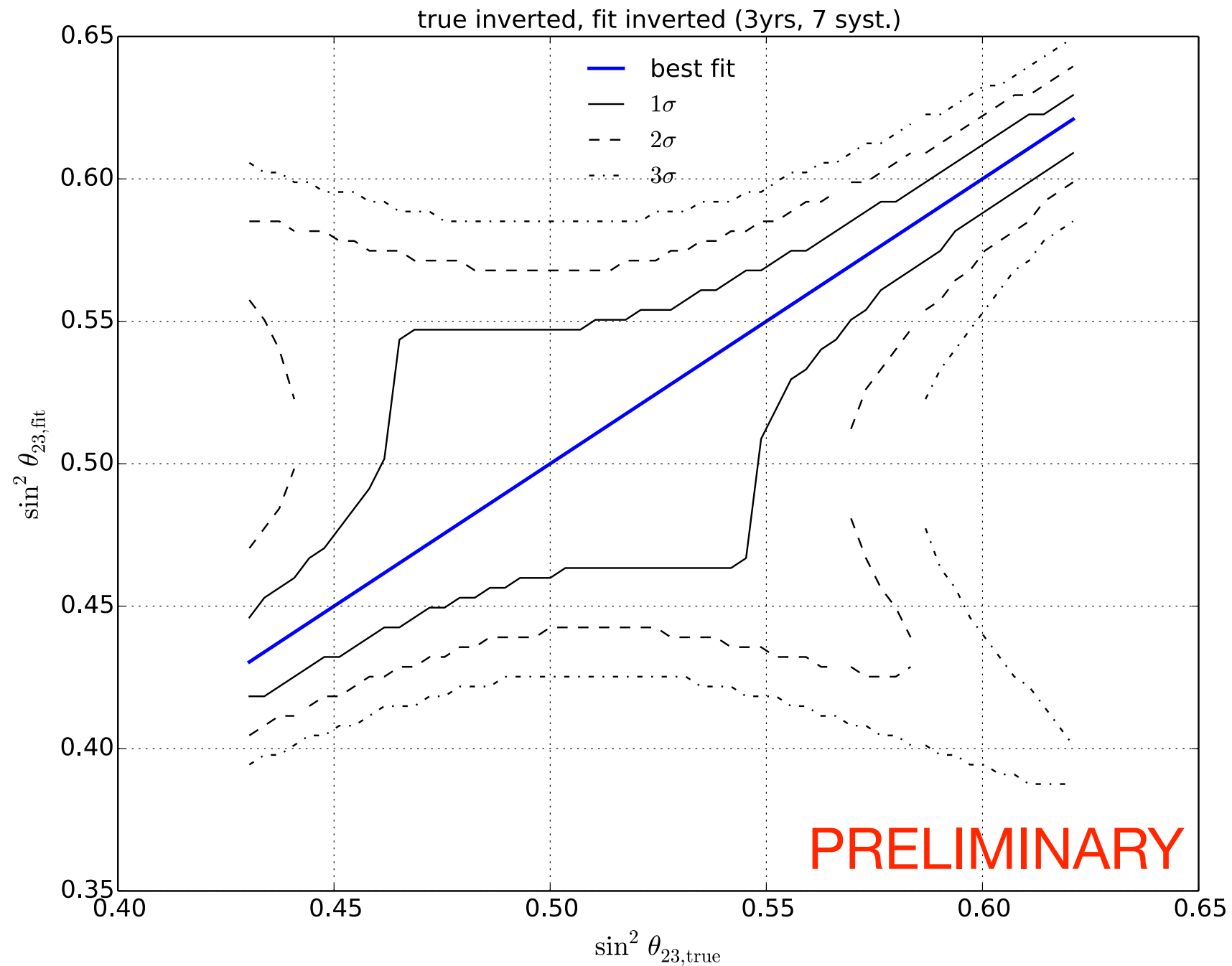
Oscillation Parameters with PINGU

after 3 years of livetime, with **normal hierarchy correctly identified**



Oscillation Parameters with PINGU

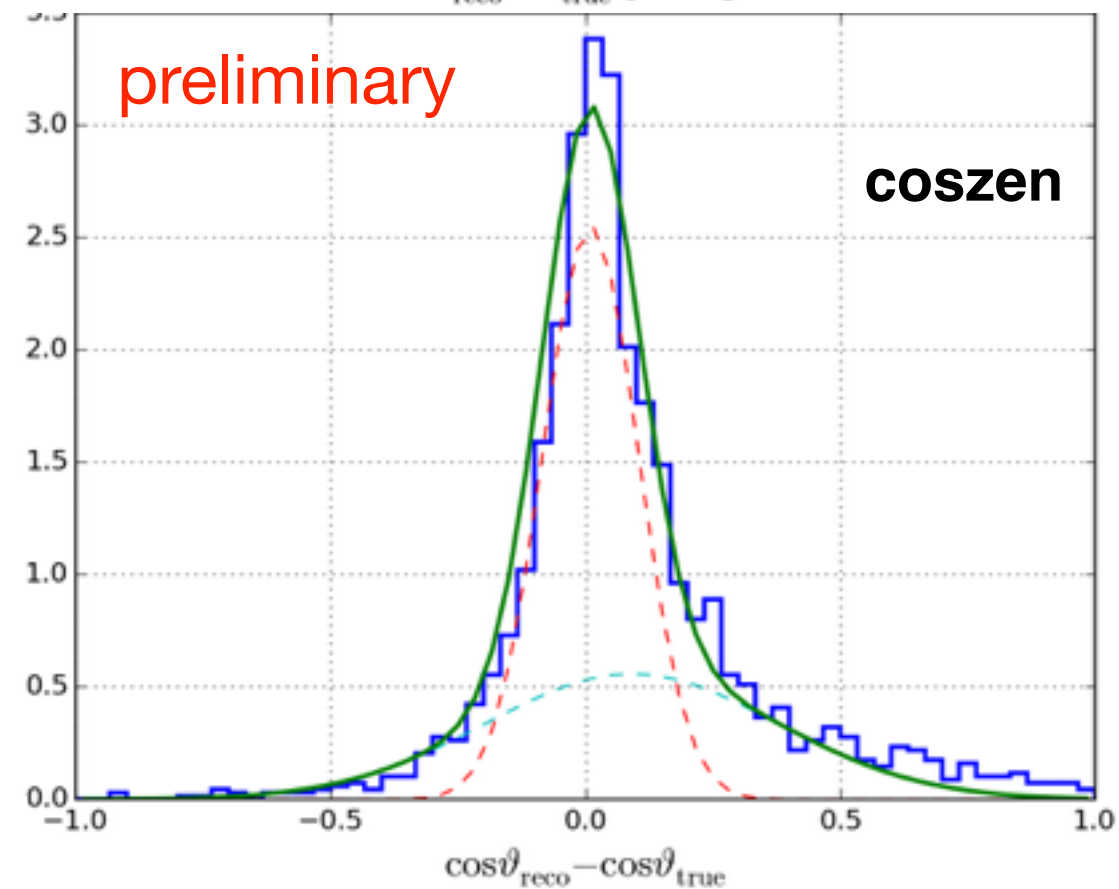
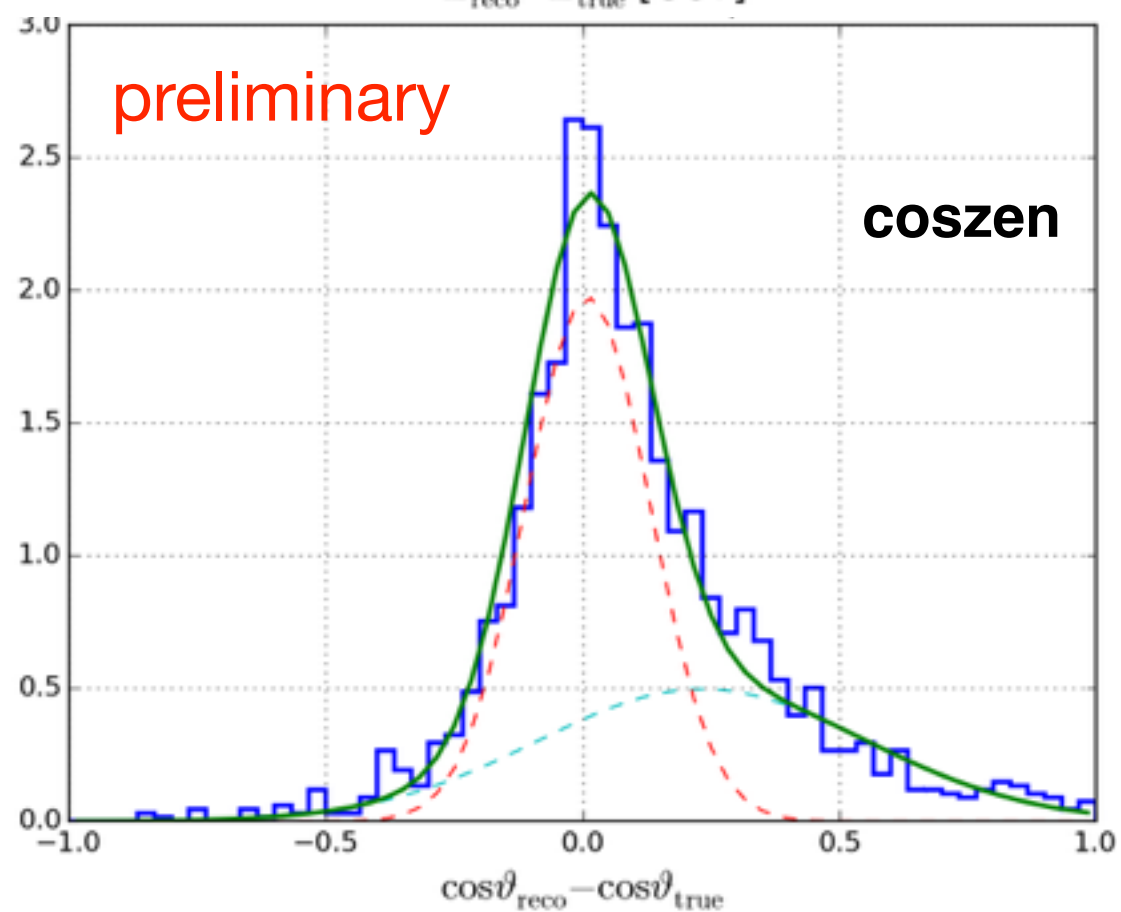
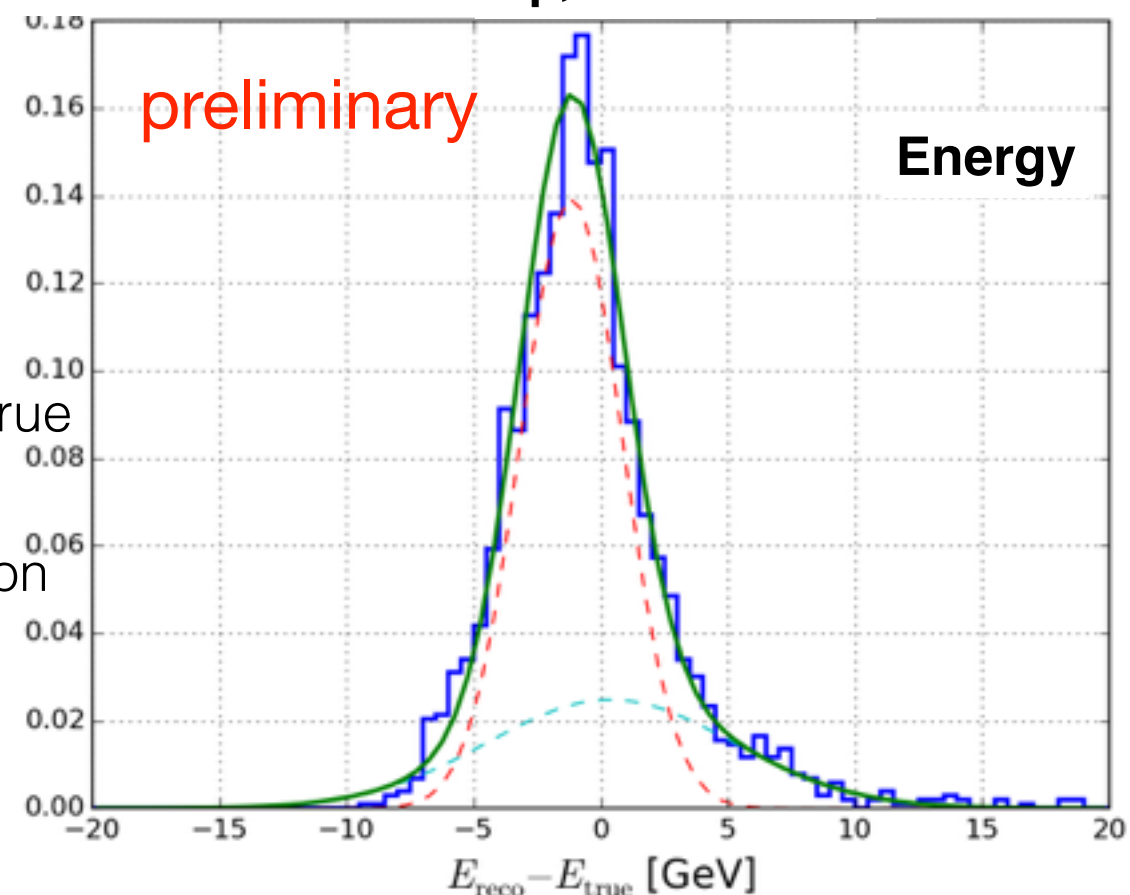
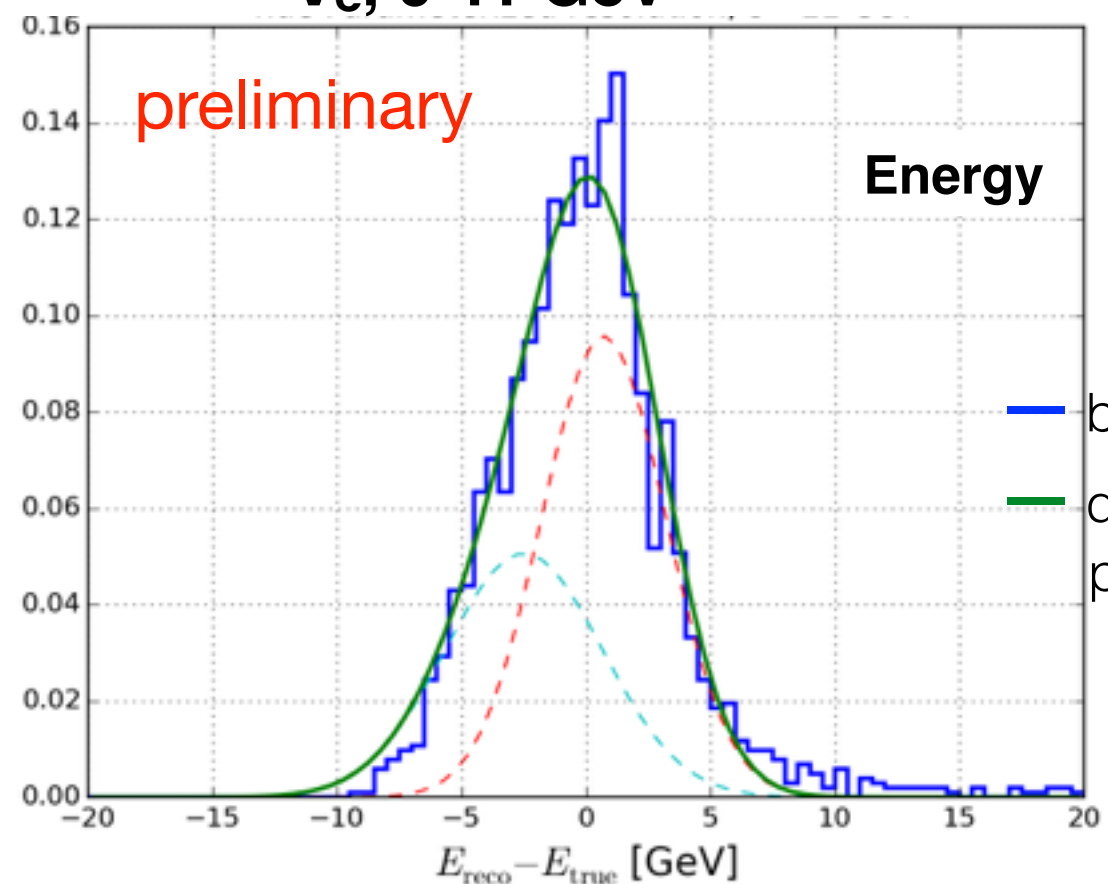
after 3 years of livetime, with **inverted hierarchy correctly identified**



Resolutions

ν_e , 9-11 GeV

ν_μ , 9-11 GeV



Cost and Schedule

- Primary US funding source for IceCube-Gen2 would be NSF
 - Total cost comparable to IceCube
 - Many items common to PINGU and other elements (drill, engineering, etc.)
 - Marginal cost of PINGU within larger IceCube-Gen2 is \$88M, with anticipated non-US contributions of \$25M
- Gen2 conceptual design document and PINGU performance update to be released later this year

Cost for PINGU Component

Hardware	\$48M
Logistics	\$23M
Contingency	\$16M
<hr/>	
Expected non-US contributions	\$25M
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Total US Cost	\$63M

(elements do not sum to total due to rounding)

