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Thomas Ehrhardt for the IceCube-PINGU Collaboration

EPS HEP Vienna | July 24th 2015

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JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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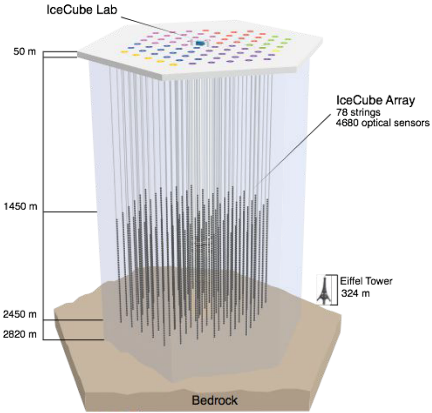
IceCube Neutrino Observatory

IceCube (operational):

- 78 strings: 125m horizontal and 17m vertical spacing
- threshold energy of $\sim$ 100 GeV
- astrophysical ν flux discovered



IceCube Neutrino Observatory

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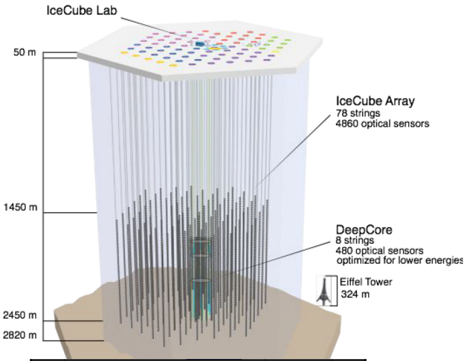
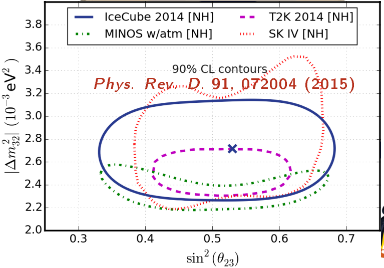
- threshold energy of $\sim$ 100 GeV
- astrophysical ν flux discovered

DeepCore (operational):

- 8 additional, densely instrumented strings: $\sim$ 40-70m / 7m spacing
- covers low-energy range from 10 – 100 GeV
- physics: searches for WIMPs, constraints on atmospheric ν oscillation parameters

  (cf. dedicated contribution no. 791)





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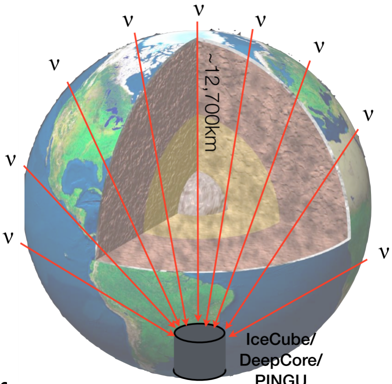
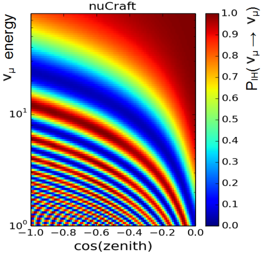
Atmospheric Neutrinos

- steady ν flux available over large range of neutrino energies E_ν and oscillation baselines L
- for vertically upgoing ν_μ, first survival probability minimum at $E_\nu \sim 25$ GeV





- Earth matter effects:
characteristic modifications of oscillation probabilities below ~ 10 GeV, depending on neutrino mass hierarchy (MH)

MH & Atmospheric Neutrino Oscillations

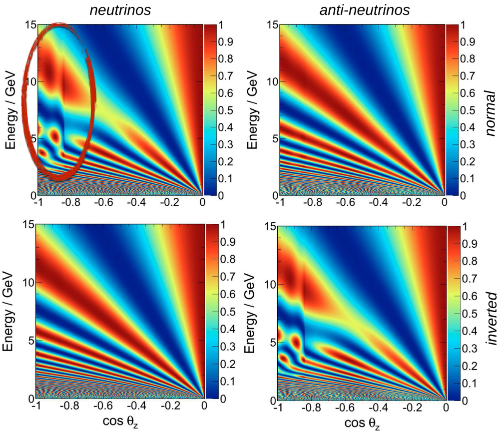
- up to $\sim 50\,\%$ differences in oscillation probabilities, depending on which MH is realised
- effect approximately symmetric under exchange of hierarchy & charge

but:

- atmospheric flux $\Phi_\nu/\Phi_{\bar{\nu}} \sim 1.3$
- x-sections $\sigma_{\nu N}/\sigma_{\bar{\nu}N} \sim 2$

$\Rightarrow$ few percent residuals even without charge discrimination (ν vs. $\bar{\nu}$)

- massive O(Mton) detectors required for sufficient event statistics



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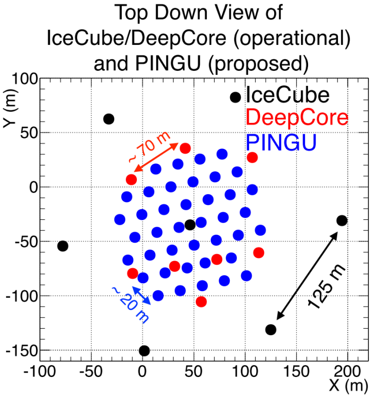
- *initial* baseline detector properties detailed in LOI (arXiv:1401.2046)



- result of geometry optimisation studies:
  - 40 additional strings within lower part of IceCube's DeepCore infill
  - spaced 20 – 22m apart
  - instrumented with 80 – 96 optical modules each (additional DOMs/string marginal added cost)

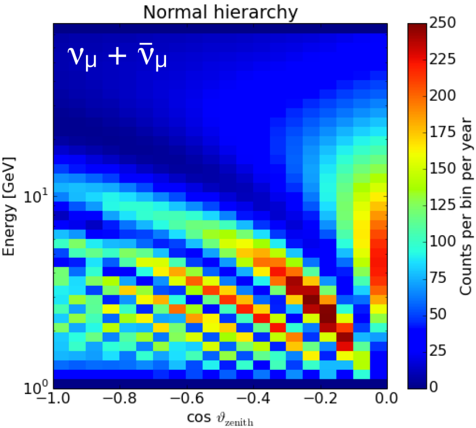
$\Rightarrow$ photocathode density increased by factor of $\sim$ 25 w.r.t. DeepCore

- region of clearest ice

- deployment of additional *dedicated calibration devices* for in situ measurements of detector related systematics

Event Spectra with Ideal PINGU Detector

- neutrino interactions with Earth matter $\Rightarrow$ characteristic modifications of event rates of all flavours
- detected event rates after cuts ($1\,\text{GeV} < E_\nu < 80\,\text{GeV}$):
  - $\sim$ 50k $\nu_\mu + \bar{\nu}_\mu$ per year
  - $\sim$ 38k $\nu_e + \bar{\nu}_e$ per year
- even with 1 year of data: minor yet distinct MH signatures apparent for energies below $\sim 15\,\text{GeV}$
- note: no detector resolutions included here



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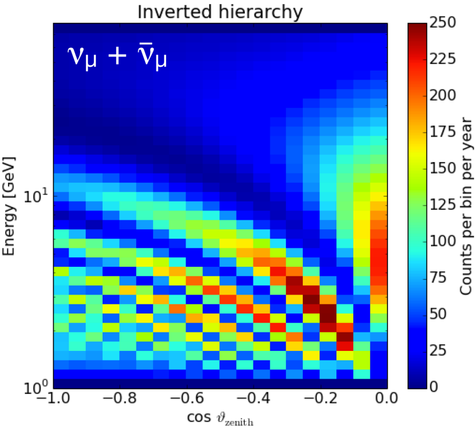

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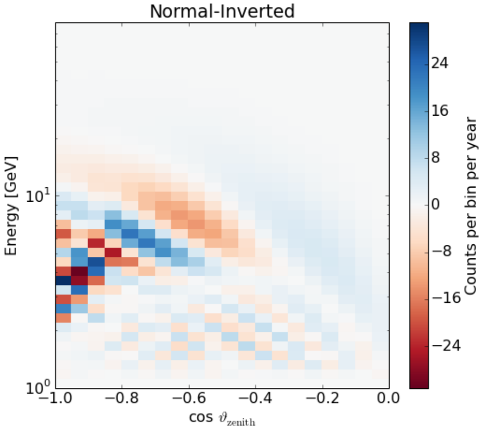

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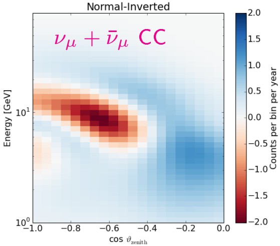
Resolution & Flavour ID Effects

Event Signatures

- NC all + ν_e CC: *cascade* with extent of O(m)
- + minimum ionising *track* with $\Delta E/\Delta x \approx -200\,\mathrm{MeV\,m^{-1}}$ in case of CC ν_μ interaction

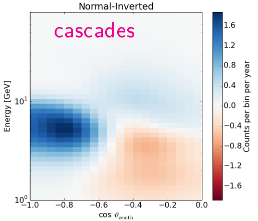
Energy & Zenith Angle Resolutions

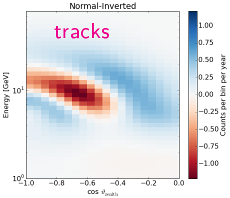
- $\sigma_E/E \approx 20\,\%$ for $E > 10\,\mathrm{GeV}$
- $\sigma_{\cos\theta} \approx 0.15$ for $E = 10\,\mathrm{GeV}$ & improving with increasing E



Neutrino Flavour Identification

- 80 % of ν_μ CC events correctly ID'd as tracks for $E > 10\,\mathrm{GeV}$
- low $\nu_{\tau,e}$ CC & ν_x NC track-ID probability of $5-20\%$





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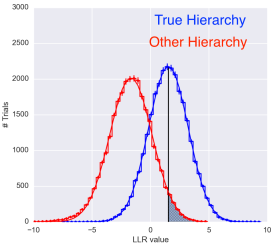
Constraining MH & Physics Parameters

- different methods available to determine PINGU's MH discrimination power & parameter uncertainties

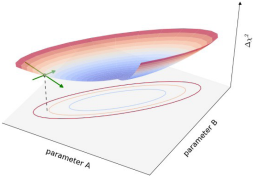
1. log-likelihood ratio

- makes use of large ensemble of MC pseudo-data sets in order to build up distribution of test statistic (TS) $\Rightarrow$ no assumptions about shape
- shaded region $\Rightarrow$ probability of misidentifying hierarchy in the median experiment



2. $\Delta\chi^2$ (pull) method

- relatively fast: scan of nonlinear parameter(s), linear error propagation for linear parameters
- analytic minimisation of TS $\Delta\chi^2$



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Systematic Uncertainties

Physics parameters (oscillations, from nu-fit.org [1]):

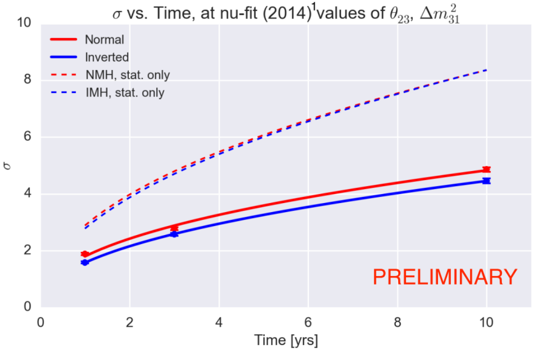
- Δm^2_{31} (NH/IH) = 2.46/-2.37$\times 10^{-3}$ eV^2 (without a prior)
- θ_{23} (NH/IH) = 42.3°/49.5° (w/o prior)
- $\theta_{13} = 8.5° \pm 0.2°$

Detector/flux/cross section related systematics:

- **event rate** (effective area, flux normalisation) = nominal (w/o prior)
- **energy scale** = nominal $\pm$ 0.10 (based on recent calibration data)
- ν_e/ν_μ **ratio** = nominal $\pm$ 0.03 (Ref. [2])
- ν/**anti-**ν **ratio** = nominal $\pm$ 0.10 (Refs. [2] & [3])
- **atmospheric spectral index** = nominal $\pm$ 0.05 (Ref. [2])
- studied in addition:
  - detailed cross section systematics based on GENIE [3] parameters
  - detailed atmospheric flux uncertainties, based on Ref. [2]

[1] M.C. Gonzalez-Garcia et al., *JHEP* 11 052 (2014)
[2] G.D. Barr, T.K. Gaisser et al., *Phys.Rev. D* 74 094009 (2006)
[3] C.Andreopoulos et al., *Nucl.Instrum.Meth. A* 614:87-104 (2010)

MH Sensitivity & Systematics Impact



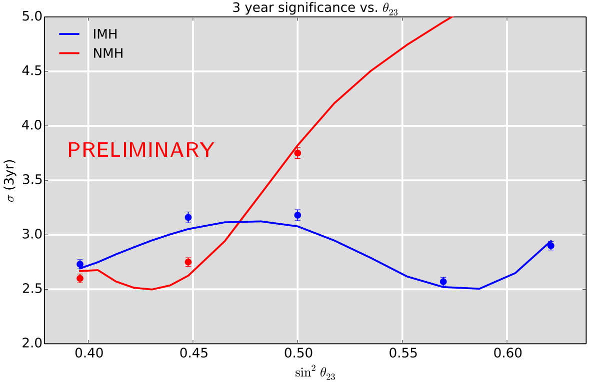
Type	3yr σ (NMH)	3yr σ (IMH)
stat. only	4.84	4.82
flux only	4.55	4.56
det. only	4.06	3.99
θ_{23} only	3.52	3.26
osc. only	2.96	2.53
All	2.90	2.51

PRELIMINARY

- with all systematics from previous slide included: reach 3σ after $\sim 3-4$ years of livetime (w/o data from DeepCore or the partially deployed detector)
- sensitivity most strongly impacted by atmospheric oscillation parameters, then detector systematics

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

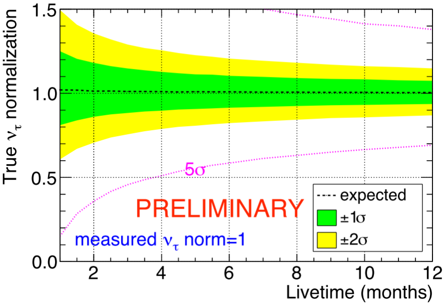
MH Sensitivity & Mixing Angle θ_{23}



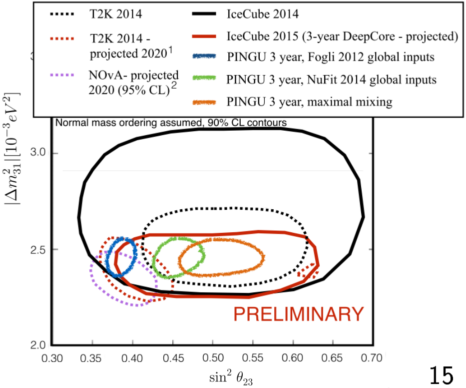
- mass hierarchy sensitivity strongly dependent on octant + value of mixing angle θ_{23}
- current global best fit θ_{23} close to sensitivity minimum for both hierarchies

PINGU Oscillation Physics Potential

- detection of $\sim 3\text{k}\ \nu_\tau/\text{yr}$
- sensitivity to ν_τ appearance:
  - expect $\sim 5\sigma$ exclusion of no ν_τ appearance within 1 month of livetime
  - precision measurement of standard 3-flavour oscillation prediction $\rightarrow$ verify unitarity of neutrino mixing matrix



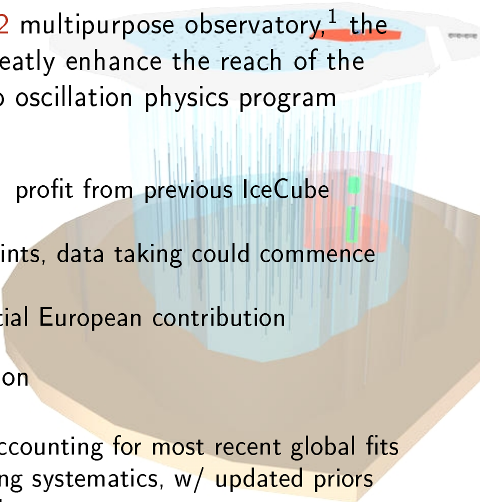
- atmospheric oscillation parameters θ_{23} & Δm^2_{31}:
  - expect constraints of precision comparable to that of NOνA, T2K (projected)



1 arXiv:1409.7469
2 http://www-nova.fnal.gov/plots_and_figures/plot_and_figures.html

Outlook

- as integral part of the IceCube-Gen2 multipurpose observatory,[1] the low-energy extension PINGU will greatly enhance the reach of the existing IceCube/DeepCore neutrino oscillation physics program
- Deployment & Cost
  - first component of IceCube-Gen2: profit from previous IceCube deployment experience
  - depending on engineering constraints, data taking could commence $4-5$ years after approval
  - cost effective, aiming for substantial European contribution
- improved version of LoI available soon
  - optimised detector geometry
  - updated oscillation parameters, accounting for most recent global fits
  - detailed studies of new and existing systematics, w/ updated priors
  - refined statistical analysis methods



[1] cf. white paper: arXiv:1412.5106

The IceCube–PINGU Collaboration

International Funding Agencies

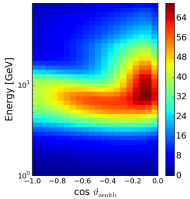
Fonds de la Recherche Scientifique (FRS–FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen–Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF–Office of Polar Programs
NSF–Physics Division
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

BACKUP

LLR Method

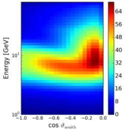
- Greatly improved statistical analysis method since LoI
  - Ability to include many more systematics (from 2 → ~10) by using a minimizer to find optimal LLH fit rather than grid scan
  - Run optimizer twice to search for solutions in both octants of θ_{23}.
- To test for significance of true hierarchy (TH)/rejection of other hierarchy (OH)
  - pull pseudo data from template of TH, with parameters:
    $\pi^{TH} = (\Delta m^2_{31}|^{TH}, \theta_{23}|^{TH}, \theta_{13}|^{TH}$, *all other params at nominal*)
  - Then following procedure is performed:

Expected Counts Template, calculated at π^{TH}



Poisson Fluctuations

Example pseudo data for TH:

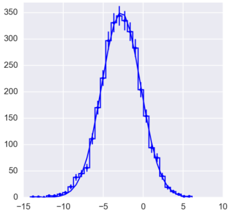


Accumulate LLR distribution for TH

$$\text{Calculate LLR} = \frac{\text{max LLH(Inverted hypothesis, fit } \pi)}{\text{max LLH(Normal hypothesis, fit } \pi)}$$

Repeat Many Times

Example LLR Distribution for TH=Normal



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LLR Method

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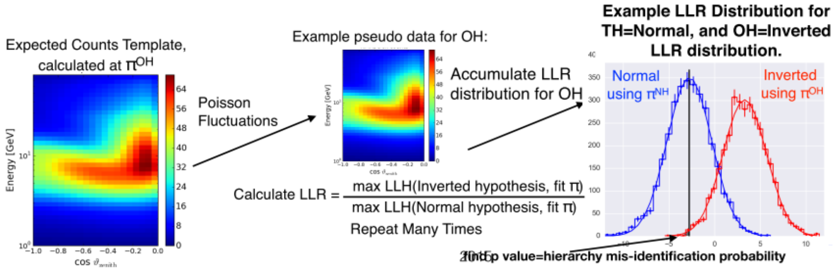
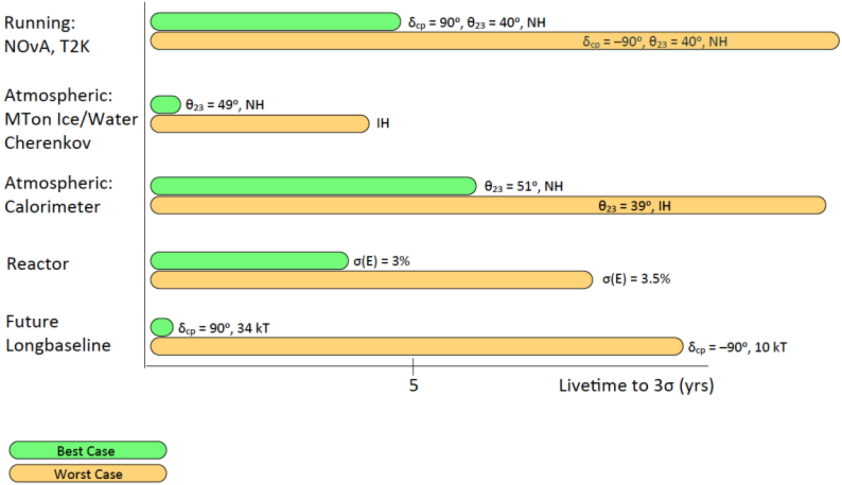
  - Ability to include many more systematics (from 2 → ~10) by using a minimizer to find optimal LLH fit rather than grid scan
  - Run optimizer twice to search for solutions in both octants of θ_{23}.
- To test for significance of true hierarchy (TH)/rejection of other hierarchy (OH)
  - Next: parameters in OH that fit best to TH are found: $\pi^{OH} = (\Delta m^2_{31}|^{OH}, \theta_{23}|^{OH})$
  - Find LLR distribution at these parameters, π^{OH}, to find probability of mis-identifying OH as TH.
    - p value then converted to significance of rejecting OH.



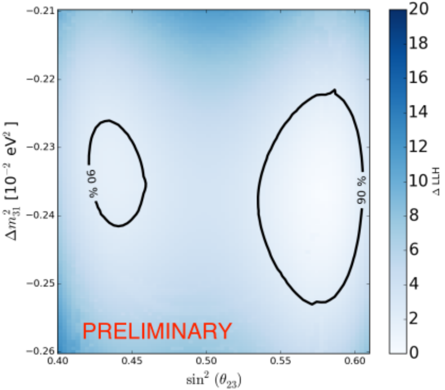
Sensitivity to the Neutrino Mass Hierarchy



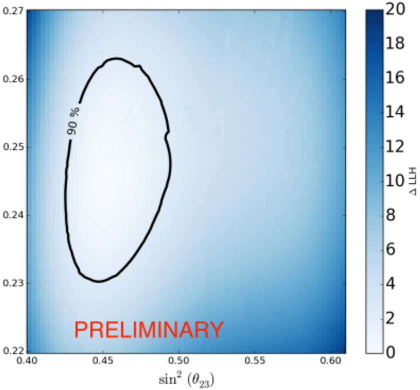
Sources: arXiv:1311.1822, arXiv:1401.2046v1, arXiv:1406.3689v1, Neutrino 2014, LBNE-doc-8087-v10

Atmospheric Mixing Parameter Constraints

Inverted Hierarchy



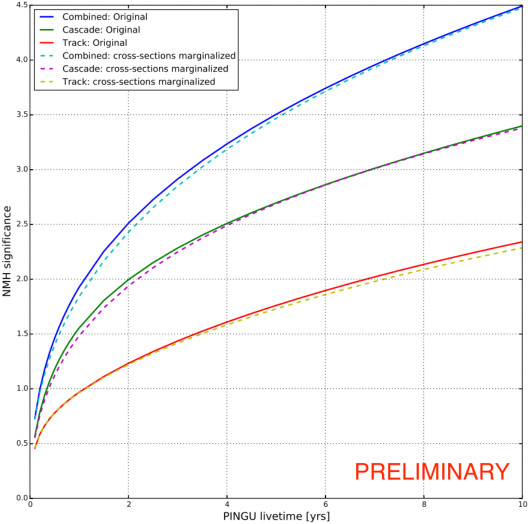
Normal Hierarchy



Neutrino Interaction Uncertainties

GENIE parameters

- strongest impact from:
  - axial mass parameters for CCQE and hadron resonance production
  - Bodek-Yang higher twist parameters (DIS)
- effective ad hoc scalings still included and correlations not accounted for $\rightarrow$ likely over-counting
- small additional effect compared to existing systematics



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