PINGU

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IceCube Neutrino Observatory

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- threshold energy of $\sim 100$ GeV
- astrophysical $\nu$ flux discovered
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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 $\nu$ oscillation parameters
  (cf. dedicated contribution no. 791)
Atmospheric Neutrinos

- steady $\nu$ flux available over large range of neutrino energies $E_\nu$ and oscillation baselines $L$

- for vertically upgoing $\nu_\mu$, first survival probability minimum at $E_\nu \sim 25$ GeV

- Earth matter effects: characteristic modifications of oscillation probabilities below $\sim 10$ GeV, depending on neutrino mass hierarchy (MH)
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 $\Phi_{\nu}/\Phi_{\bar{\nu}} \sim 1.3$

- $\sigma_{\nu N}/\sigma_{\bar{\nu} N} \sim 2$

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

- massive $O(\text{Mton})$ detectors required for sufficient event statistics
- 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)
  - 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 ⇒ 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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Resolution & Flavour ID Effects

Event Signatures

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

Energy & Zenith Angle Resolutions

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

Neutrino Flavour Identification

- 80% of $\nu_\mu$ CC events correctly ID’d as tracks for $E > 10 \, \text{GeV}$
- low $\nu_{\tau,e}$ CC & $\nu_x$ NC track-ID probability of $5 – 20\%$
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) ⇒ no assumptions about shape
   - shaded region ⇒ 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 $\Delta \chi^2$
Systematic Uncertainties

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

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

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)
- $\nu_e/\nu_\mu \text{ ratio} = \text{nominal $\pm$ 0.03 (Ref. [2])}$
- $\nu/\text{anti-}\nu \text{ ratio} = \text{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]

with all systematics from previous slide included: reach $3\sigma$ 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

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1 M.C. Gonzalez-Garcia et al., *JHEP* 11 052 (2014)
MH Sensitivity & Mixing Angle $\theta_{23}$

- Mass hierarchy sensitivity strongly dependent on octant + value of mixing angle $\theta_{23}$
- Current global best fit $\theta_{23}$ close to sensitivity minimum for both hierarchies

PRELIMINARY
PINGU Oscillation Physics Potential

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

- atmospheric oscillation parameters $\theta_{23}$ & $\Delta m_{31}^2$:
  - expect constraints of precision comparable to that of NO$\nu$A, T2K (projected)

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**Graph:**

- True $\nu_\tau$ normalization
- Livetime (months)
- $\nu_\tau$ norm = 1
- $5\sigma$
- measured $\nu_\tau$

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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, 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)
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- Federal Ministry of Education & Research (BMBF)
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- Deutsches Elektronen–Synchrotron (DESY)
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- 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)
LLR Method

- Greatly improved statistical analysis method since LoI
  - Ability to include many more systematics (from 2 $\rightarrow$ $\sim$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 $\theta_{23}$.

- To test for significance of true hierarchy (TH) / rejection of other hierarchy (OH)
  - pull pseudo data from template of TH, with parameters:
    $\pi^{TH} = (\Delta m_{23}^{TH}, |\theta_{23}|^{TH}, |\theta_{13}|^{TH}, \text{all other params at nominal})$
  - Then following procedure is performed:

  ![Example LLR Distribution for TH=Normal](image)

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

  Repeat Many Times
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  - Run optimizer twice to search for solutions in both octants of $\theta_{23}$.

- To test for significance of true hierarchy (TH)/rejection of other hierarchy (OH)
  - Next: parameters in OH that fit best to TH are found: $\pi^{\text{OH}} = (\Delta m_{31}^{2}, \theta_{23})$
  - Find LLR distribution at these parameters, $\pi^{\text{OH}}$, to find probability of mis-identifying OH as TH.
    - $p$ value then converted to significance of rejecting OH.

![Expected Counts Template, calculated at $\pi^{\text{OH}}$](image1)

![Example pseudo data for OH:](image2)

![Accumulate LLR distribution for OH](image3)

![Calculate LLR](image4)

![Example LLR Distribution for TH=Normal, and OH=Inverted LLR distribution.](image5)
Sensitivity to the Neutrino Mass Hierarchy

- Running: NOvA, T2K
  - $\delta_{cp} = 90^\circ, \theta_{23} = 40^\circ, \text{NH}$
  - $\delta_{cp} = -90^\circ, \theta_{23} = 40^\circ, \text{NH}$
- Atmospheric: MTon Ice/Water Cherenkov
  - $\theta_{23} = 49^\circ, \text{NH}$
  - $\theta_{23} = 51^\circ, \text{NH}$
  - $\theta_{23} = 39^\circ, \text{IH}$
- Atmospheric: Calorimeter
  - $\sigma(E) = 3\%$
  - $\sigma(E) = 3.5\%$
- Reactor
- Future Longbaseline
  - $\delta_{cp} = 90^\circ, 34 \text{ kT}$
  - $\delta_{cp} = -90^\circ, 10 \text{ kT}$

Atmospheric Mixing Parameter Constraints

Inverted Hierarchy

Normal Hierarchy

PRELIMINARY
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 → likely over-counting

- small additional effect compared to existing systematics