A Vision for Neutrino and Particle Physics at the South Pole

João Pedro Athayde Marcondes de André for the IceCube-Gen2 Collaboration

17 March 2017
Neutrino oscillations with atmospheric neutrinos

- Several baselines available
  - L/E dependency on oscillation
- IceCube-DeepCore:
  - See clear $\nu_\mu$ disappearance
  - Harder measurement of $\nu_\tau$ appearance (on-going)
    - low $\nu_\tau$ x-sec
    - missing energy from $\tau$-decay
- Need next generation of experiments for:
  - Precision measurements of $\nu_\tau$ appearance
  - Neutrino mass ordering
\( \nu_\tau \) appearance: testing unitarity of the mixing matrix \( U \)

- If we don’t assume unitarity of mixing matrix → 9 parameters to be measured

\[
U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\]

\( \leftrightarrow \) \( \nu_e \) appearance and disappearance

\( \leftrightarrow \) \( \nu_\mu \) disappearance and \( \nu_e \) or \( \nu_\tau \) appearance

- \( \nu \) disappearance: sensitive to the absolute values of 1 row
- \( \nu \) appearance: sensitive to products between 2 rows

Probing the \( \tau \)-row: \( \nu_\tau \) appearance!

- OPERA and SK measured that
- in both cases saw too many \( \nu_\tau \)
  - not statistically significant
  - \Rightarrow need precision measurements

\begin{figure}
\centering
\includegraphics[width=\textwidth]{nu-tau-appearance}
\caption{Phys. Rev. D 93, 113009}
\end{figure}
- Instrument 1 Gton of ice
- Optimized for TeV-PeV neutrinos
  - Astrophysical $\nu$ discovered!
- At its center: DeepCore
  - $\sim$10 Mton region with denser instrumentation
  - lower E threshold
  - study neutrino oscillations
  - Surrounding detector used as active veto against atmospheric $\mu$
IceCube-DeepCore

25 GeV $\nu_\mu$ CC

- color $\rightarrow$ hit time
- size $\rightarrow$ hit charge

IceCube DOM

10" PMT
IceCube-DeepCore: $\nu_\mu$ disappearance measurement

- Brand new results (first shown at Feb 2017) with improved analysis on 3 year sample
- Fitting done in 3D space ($E, \cos \theta_z, \text{PID}$) → projected in L/E for illustration
- Consistent & competitive results to accelerator based measurements
  - Different $E$ range (and baselines) than for accelerator based studies

![Graph showing track-like events and numbers of events over log10(E_recoil/E_over)](Image)

![Diagram showing $\Delta m^2$ vs. $\sin^2(\theta_{23})$ and $\Delta \chi^2$)](Image)

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International Workshop on Neutrino Telescopes 2017

17 March 2017
IceCube-Gen2 Phase1

25 GeV $\nu_\mu$ CC

color $\rightarrow$ hit time
size $\rightarrow$ hit charge

mDOM

24 $\times$ 3” PMTs
IceCube Gen2 Phase1 analysis goals

- $\nu_\tau$ appearance analysis
- Sensitivity to $\theta_{23}$ and $\Delta m^2_{31}$
  complementary to dedicated LBL experiments
- Octant/Maximal mixing
  ($3\sigma$ in 3 years for NO$\nu$A best fit $\theta_{23}$)
- Neutrino mass ordering
  (1.5-2$\sigma$ in 3 years)
- Improvements on eV sterile $\nu$ searches, solar WIMP searches, ... 
- New calibration devices will also be installed
  ⇒ Better ice description and calibration
  ⇒ Improvements in reconstruction resolutions
  ⇒ Improvement to neutrino astronomy

Proposal submitted to NSF
Signal for $\nu_\tau$ appearance in IceCube-Gen2 Phase1

- Appearing $\nu_\tau$ events usually classified as cascades
  - There is no clear $\mu$ track
- Our signal: $\nu_\tau$ events at specific $L/E$ region in cascade channel
  - Measurement done in 3D: $\cos \theta_z \times E \times PID$ space
  - 1D projection of $\cos \theta_z$ shown below for simplicity

![Graph showing signal for $\nu_\tau$ appearance](image_url)
Signal for $\nu_\tau$ appearance in IceCube-Gen2 Phase1

- Appearing $\nu_\tau$ events usually classified as cascades
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![Graph showing ratio to standard oscillations and appearance of $\nu_\tau$ events in cascade sample](image)

Preliminary events with $E_\nu < 10$ GeV - only events with $E_\nu > 10$ GeV, cascade sample

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### Systematic errors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Priors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric $\nu$ flux parameters</td>
<td></td>
</tr>
<tr>
<td>$\Delta \gamma$ (spectral index)</td>
<td>0.00±0.10</td>
</tr>
<tr>
<td>$\nu_e$ normalization</td>
<td>1.00±0.20</td>
</tr>
<tr>
<td>$\nu$ NC normalization</td>
<td>1.00±0.20</td>
</tr>
<tr>
<td>$\Delta(\nu/\bar{\nu})$, energy dependent‡</td>
<td>0 ± 1 $\sigma$</td>
</tr>
<tr>
<td>$\Delta(\nu/\bar{\nu})$, zenith dependent‡</td>
<td>0 ± 1 $\sigma$</td>
</tr>
<tr>
<td>Cross section parameters (from GENIE)</td>
<td></td>
</tr>
<tr>
<td>$M_A$ (resonance) [GeV]</td>
<td>1.12±0.22</td>
</tr>
<tr>
<td>$M_A$ (quasi-elastic) [GeV]</td>
<td>0.99$^{+0.25}_{-0.15}$</td>
</tr>
</tbody>
</table>

‡: Following Barr, et al., PRD 74, 094009.

- In general same systematics used for IceCube-DeepCore analysis
  - $\theta_{13}$, DIS x-sec uncertainties tested and observed to be irrelevant
- Impact of systematics limited in result due to different $L \times E$ dependency to signal
- New calibration devices with IceCube-Gen2 Phase1 ⇒ improve detector systematics
- Leading systematics for $\nu_\tau$ appearance: $\Delta(\nu/\bar{\nu})$, zenith dependent

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Priors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2_{32}$</td>
<td>no prior</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>no prior</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Detector parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole ice scattering* from calibration</td>
<td></td>
</tr>
<tr>
<td>DOM efficiency* [%]</td>
<td>100±10</td>
</tr>
</tbody>
</table>

*: Systematic change studied for IceCube-DeepCore used here.
Sensitivity to $\nu_\tau$ appearance in IceCube-Gen2 Phase1

- < 7% precision in the $\nu_\tau$ normalization after 3 years of data
- Not many experiments can do this measurement!

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Projected DeepCore sensitivity using same sample as in pg 6.
IceCube-Gen2 PINGU

12 GeV $\nu_\mu$ CC

color $\rightarrow$ hit time
size $\rightarrow$ hit charge

IceCube DOM mDOM

in LoI
plan to use

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IceCube Gen2 PINGU analysis goals

- Improves on IceCube-Gen2 Phase1 sensitivities across the board
- $\nu_{\tau}$ appearance analysis:
  - in 6 months reach 10% precision
- Improved sensitivity to $\theta_{23}$ and $\Delta m^2_{31}$ →
- Neutrino mass ordering
- ...
Neutrino oscillations in matter

\[ \Delta m_{32}^2 = 2.32 \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2(2\theta_{23}) = \frac{\pi}{4} \]

\[ \cos \theta_z = -0.84 \]

Increasing density

Outer core

Neutrinos
Normal hierarchy

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Neutrino Mass Ordering effect observable on PINGU

PINGU cannot differentiate $\nu$ and $\bar{\nu}$: rely on difference in flux and cross-section
  ▶ Large statistical samples: $\sim 33k \nu_\mu + \bar{\nu}_\mu$ CC per year, $\sim 25k \nu_e + \bar{\nu}_e$ CC per year

Distinct ordering dependent signatures for tracks (mostly $\nu_\mu$ CC) and cascades
  ▶ Intensity is statistical significance of each bin with 1 year data
  ▶ Particular expected “distortion pattern” helps mitigate impact of systematics
Sensitivities calculated with 2 different methods (LLR and $\Delta \chi^2$) in agreement

NMO sensitivity strongly depends on true $\theta_{23}$
  - $\theta_{23}$ uncertainty also has large effect in precision: synergy with other efforts!

Median sensitivity of $\sim 3\sigma$ with 4 years of data for current best-fit values
  - Current global best fit close to sensitivity minimum for both orderings
IceCube-DeepCore detector: good performance to measure neutrino oscillations
  ▶ Latest $\theta_{23}$ and $\Delta m^2_{32}$ measurement of similar precision to those from accelerators

IceCube-Gen2 Phase1: proposal submitted to NSF
  ▶ First step towards full IceCube-Gen2 program
  ▶ Very good sensitivity to $\nu_\tau$ appearance: expected precision better than 7% after 3 years
  ▶ Improvements in wide range of measurements expected
    * including improvements to neutrino astronomy via improvement in calibrations!

IceCube-Gen2 PINGU: going beyond IceCube-Gen2 Phase1
  ▶ Potential low-energy extension within IceCube-Gen2
  ▶ Essential to measure Neutrino Mass Ordering
  ▶ Other improvements in broad physics program ($\nu$ oscillation, WIMPs, SNs, ...)

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Backup slides
## IceCube-DeepCore $\nu_\mu$ disappearance result systematics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Priors</th>
<th>Best fit NH</th>
<th>Best fit IH</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard neutrino mixing parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta m^2_{32}$ [$10^{-3}$ eV$^2$/c$^4$]</td>
<td>no prior</td>
<td>$2.31^{+0.12}_{-0.14}$</td>
<td>$-2.32^{+0.12}_{-0.13}$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>no prior</td>
<td>$0.51^{+0.08}_{-0.08}$</td>
<td>$0.51^{+0.08}_{-0.07}$</td>
</tr>
<tr>
<td><strong>Atmospheric neutrino flux parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta \gamma$ (spectral index)</td>
<td>$0.00 \pm 0.10$</td>
<td>-0.02</td>
<td>-0.02</td>
</tr>
<tr>
<td>$\nu_e$ normalization</td>
<td>$1.00 \pm 0.20$</td>
<td>1.24</td>
<td>1.24</td>
</tr>
<tr>
<td>$\nu$ NC normalization</td>
<td>$1.00 \pm 0.20$</td>
<td>1.05</td>
<td>1.05</td>
</tr>
<tr>
<td>$\Delta (\nu/\bar{\nu})$, energy dependent</td>
<td>‡</td>
<td>-0.56σ</td>
<td>-0.60σ</td>
</tr>
<tr>
<td>$\Delta (\nu/\bar{\nu})$, zenith dependent</td>
<td>‡</td>
<td>-0.53σ</td>
<td>-0.55σ</td>
</tr>
<tr>
<td><strong>Cross section parameters (from GENIE)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_A$ (resonance) [GeV]</td>
<td>$1.12 \pm 0.22$</td>
<td>0.91</td>
<td>0.92</td>
</tr>
<tr>
<td><strong>Detector parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DOM lateral sensitivity (hole ice)</td>
<td>$0.020 \pm 0.010$</td>
<td>0.022</td>
<td>0.022</td>
</tr>
<tr>
<td>DOM forward sensitivity (hole ice)</td>
<td>no prior</td>
<td>-0.76</td>
<td>-0.70</td>
</tr>
<tr>
<td>DOM efficiency [% of nominal]</td>
<td>$100 \pm 10$</td>
<td>103</td>
<td>103</td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atm. $\mu$ contamination [%]</td>
<td>no prior</td>
<td>5.2</td>
<td>5.2</td>
</tr>
</tbody>
</table>

‡: Following Barr, et al., PRD74, 094009.
IceCube-Gen2 Phase1 L/E

Preliminary

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IceCube-Gen2 Phase1 impact in neutrino astronomy

- Better understanding of ice and calibration ⇒ improve reconstruction resolutions/PID
- Use better reconstructions to re-analyse existing IceCube data
IceCube-Gen2 Phase 1 timescale

- Proposals for Gen2 Phase I submitted to NSF and foreign partners
  - Seven strings of new instrumentation in the center of IceCube – tau physics and improved calibration to enable reanalysis with improved sensitivity
Measurement strategy

- Main background is atmospheric $\mu$
  - Use IC as veto to reject atm $\mu$ events
- Reconstruct $\nu$ energy and direction
  - oscillation distance (L) given by zenith
- Do oscillation measurement!
- Same concept from DeepCore works on Gen2 Phase1
Atmospheric neutrinos

- 2:1 ratio between $\nu_\mu : \nu_e$
- similar rate of $\nu$ and $\bar{\nu}$
  - however, x-sec for $\bar{\nu}$ half of $\nu$

- various baselines available
Atmospheric neutrinos

- $\nu$ energy over several orders of magnitude
- Various baselines available

$\Rightarrow$ wide range of $L/E$ available
Atmospheric neutrinos oscillations

Largest baseline (L=12760 km, \(\cos \theta_Z = -1\)) has:
- First oscillation maxima at \(\sim 25\) GeV
- Matter effects below \(\sim 12\) GeV
- Potential for \(\nu_e\) appearance at 8 GeV
Atmospheric neutrinos oscillations

- Largest baseline (L=12760 km, $\cos \theta_z = -1$) has:
  - First oscillation maxima at $\sim 25$ GeV
  - $\delta_{CP}$ below $\sim 12$ GeV
    - but matter effects dominate that region
  - Potential for $\nu_e$ appearance at 8 GeV

\[ \Delta m_{21}^2 = 7.59 \times 10^{-5} \text{ eV}^2 \]
\[ \Delta m_{32}^2 = 2.42 \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2(2\theta_{12}) = 0.861 \]
\[ \sin^2(2\theta_{13}) = 0.098 \]
\[ \sin^2(2\theta_{23}) = 0.490 \]

Bands: $\delta_{CP} \in [0, 2\pi]$
Matter Effects

- MSW effect alter oscillation probabilities of $\nu$ (NH) or $\bar{\nu}$ (IH)
  - Sharp changes in density between zones produce visible effects in oscillation probabilities
- Different paths “see” different mass patterns $\Rightarrow$ can be probed by measuring the zenith of the neutrino
Neutrino oscillations in vacuum

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta) \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \]

\[ \Delta m_{32}^2 = 2.32 \times 10^{-3} \text{eV}^2 \]
\[ \sin^2(2\theta_{23}) = \frac{\pi}{4} \]
Estimating sensitivity to the NMO: Log Likelihood Ratio

1. Generate pseudo-data trial in analysis binning
   - True physics and systematics kept fixed for generation
2. Fit assuming NO and IO
3. Calculate log likelihood ratio between IO and NO

Advantages of the method:
- Can account for any systematic given
- Does not pre-suppose shape of $\Delta$LLH distribution

Disadvantages of the method:
- The significance “limited” by number of trials
  - If Gaussian can provide approximate significances
- Since each trial is a full fit (and given lots of trials needed) having large number of systematics can became prohibitively time consuming
Median sensitivity

- For quantifying significance to measure ordering usually use median sensitivity
  - Widely used in literature
- “Median sensitivity” will mean that 50% of the time we can do better and 50% of the time we can do worse
- “Median sensitivity” calculated by integrating shade region under wrong ordering assumption
  - If distribution fits well Gaussian, integrate area under Gaussian curve instead of trial distribution
Excluding an ordering

- To say we measure the true ordering (TO) at a given CL we want to be able to exclude the wrong ordering (WO) for any value of the oscillation parameters

\[ \Delta m^2_{23} \quad \text{sin}^2 \theta_{23} \]

- Testing every point of the WO parameter space too costly
  - WO best-fit gives parameters of “maximum confusion”
    (used to get WO trial distribution)
Estimating sensitivity to the NMO: $\Delta \chi^2$ method

1. Get expected number of events in analysis binning
   ▶ True physics and systematics kept fixed as in LLR method
   ▶ But, no Poisson fluctuations applied

2. Calculate minimal $\Delta \chi^2$ for the WO
   ▶ $\Delta \chi^2 = \min_{p \in \text{WO}} \sum_i \left( \frac{\mu_{i,\text{TO}}(p_0) - \mu_{i,\text{WO}}(p)}{\sigma_i} \right)^2$
   ▶ $\Delta \chi^2$ is Gaussian distributed with mean $\pm \Delta \chi^2$ and sigma $2\sqrt{\Delta \chi^2}$

3. Evaluate distribution of $\Delta \chi^2$ for NO and IO
   ⇒ correspond to the LLR trial distribution

- Advantages of the method:
  ▶ Linear systematics are extremely fast to be computed
  ▶ Even with non-linear systematics still much faster than LLR

- Disadvantage of the method:
  ▶ Intrinsic assumption of gaussianity of final distribution
  ▶ Not possible to include non-centered priors
    ★ cannot include prior on $\theta_{23}$ due to “maximum confusion” method
Comparing Test Statistic of LLR and $\Delta \chi^2$

- Good agreement between TS
  ⇒ sensitivities in agreement
    - lines from $\Delta \chi^2$
    - points from LLR