1. Introduction to Neutrinos & IceCube

2. A story about Neutrinos & Blazars

3. Particle Physics with IceCube — Neutrino Oscillations
VERY BRIEF HISTORY OF THE NEUTRINO

- In 1914, Chadwick found that the energy spectrum in beta-decays is continuous
- Which led Pauli in 1930 to postulate an additional neutral “neutrino” particle to take part in the interaction
- 1956 Cowan & Reines were able to experimentally detect neutrinos
- 1969 solar neutrinos were observed + “solar neutrino problem”
- 1980s: similar problems in atmospheric neutrino flux ratio
- 1997: Super-K: atmospheric neutrino oscillations observed!
- 2002: SNO solar neutrino oscillation
- 2011-12: reactor neutrino oscillation (Double Chooz, Daya Bay, RENO)
OPEN QUESTIONS

Neutrino Masses
- Ordering?
- Absolute masses?
- Majorana/Dirac – $0\nu\beta\beta$?
- Neutrino sources?
- Cosmic ray origin

Neutrino Mixing
- Generation of masses?
- CP violation?
- Steriles?
- Angles?
- PMNS Unitarity?

Astro physics
- Supernovae
- Coherent scattering
- Glashow resonance?
- Non-standard interactions?

New physics?
- Multimessenger
- Quantum decoherence?
- Dark matter/decay?
- $C\nu B$?
NEUTRINO SOURCES

Glashow resonance

Cross Section ($\langle n_{\nu e} e^{-1} \text{in mb} \rangle$)

Big Bang

Solar

Reactor

Terrestrial

Accelerator

Atmospheric

Cosmic

Neutrino Energy (eV)

arXiv:1401.6077
Charged Current (CC) interaction reveals the flavor from the outgoing charged lepton.

Neutral Current (NC) interactions mediated by Z boson is indistinguishable for the the 3 flavors.

Quasi Elastic (QE) nucleon is left intact, charge changes for CC

Resonant (RES) Delta resonance producing pion

Deep Inelastic (DIS) nucleon breaks up
Many neutrino experiments currently exist or are under construction, just to name a few:

- Super-K & Hyper-K
- T2K, NOvA
- ANTARES/KM3NeT
- Juno
- Dune
- SNO+
- …and many more

What they all have in common is being really huge!
DIGITAL OPTICAL MODULE

- 60 modules per string
- 10” photomultiplier tube
- Contains readout electronics
- Glass pressure housing
DETECTION PRINCIPLE

- A neutrino interaction will usually create a number of charged particles
- When these travel through the ice faster than light, they emit Cherenkov radiation
- This UV/blue light is the same as can be seen in nuclear reactors
- Optically transparent ice allows this light to reach some of the 5160 photosensitive sensors in the ice
CONSTRUCTION

- 5 MW enhanced hot water drill, ca. 48h per hole & 21’000 l jetfuel
The cables of all 86 strings run together in the IceCube Lab.

On-line processing and filtering.

Detector uptime of 99.8% (!)

Data transfer to North:
- High priority data (e.g. alerts) can be sent 24/7 over IRIDIUM connections (very low bandwidth).
- Usually a couple hours per day satellites with higher bandwidth are in reach, can transfer up to ~100 GB/day.
- Rest of data is literally “shipped” out on disk.
EVENTS IN ICECUBE

- Every DOM gets around ~500-800 hits per second, mainly from dark noise
  - Hits from physics events are ~1 order of magnitude fewer

- Most of this is suppressed by trigger conditions

- Per year, we read out roughly:
  - $10^{10}$ events caused by atmospheric muons
  - $10^9$ events caused by noise
  - $100'000$ events from atmospheric neutrinos
  - A **handful** of very high energy events likely to be of astrophysical origin

- Special triggers exist for example looking for supernovae, they monitor the overall hit rate, where a correlated increase could indicate a nearby supernova
We’re around 250 scientists

THE ICECUBE COLLABORATION

FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)

Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)

Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat

The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)
NEUTRINOS & BLAZARS
ICECUBE ALERT IC170922A

- On September 22, 2017 an extremely high energy neutrino interacted in IceCube

- An event with estimated energy of around 290 TeV and high “signalness”
- Location of origin in the sky was narrowed down to roughly 1 degree
- An alert was sent out worldwide after 43 seconds
- 4h later a GCN circular was sent out including a refined reconstruction
- A global follow-up campaign of the event by many different observatories happened over the following weeks…
COINCIDENCE WITH FLARING BLAZAR

- FERMI LAT detected the Blazar TXS 0506-056 in this area to be in a state of high gamma-ray activity (flaring).

- This blazar is situated in the night sky just off the left shoulder of the constellation Orion and is about 4 billion light years from Earth.

The Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope detected gamma-ray flux from this location of up to 400 GeV.
As we have ~10 years of IceCube data, we wanted to go back and search if there was any clustering of (lower energy) events coming from the same location.

- Found 13 ± 5 events above background clustered around December 13, 2014.
NEUTRINOS AND BLAZARS

- An important piece in the puzzle of understanding the origin of cosmic rays
- A new chapter in multi-messenger astronomy
Neutrino Mixing

- Neutrinos come in three flavours (just like other fermions)
- These eigenstates are what neutrinos are interacting in, mediated via the weak force (Z/W)
- But, one could instead also look at the mass eigenstates
- Where the Hamiltonian becomes diagonal (→ propagation)
- Now these two bases are not the same
- As in the quark sector, matrix to rotate from one basis into the other
- For quarks (CKM) at first order diagonal
- For neutrinos (PMNS) there is no such structure

NEUTRINO OSCILLATIONS

- A consequence of this mismatch of flavor and mass eigenstates is neutrino oscillations.

- Example: simplest 2-flavor, vacuum oscillation probability:

\[ P_{\nu_\mu \rightarrow \nu_e} = \sin^2 2\theta \sin^2 \frac{m_2^2 - m_1^2}{4E_\nu} \frac{L}{E_\nu} \]

- Observing oscillation implies that neutrinos must have non-zero, and different masses.
- Absolute mass scale not accessible.
- Has been established that \( m_2 > m_1 \) ✓
- We don’t know yet whether \( m_3 \) is largest or smallest (NMO) ✗
CURRENT EXPERIMENTAL STATUS

INGREDIENTS

Interaction in Atmosphere
- Primary cosmic ray flux, composition
- Hadronic interaction model
- Shower / Decay

Neutrino-Nucleon Interaction
- Generator
- Parton Distributions (PDFs)
- Parton shower + Hadronization
- Hadron shower / EM cascade / muon propagation / decay

Neutrino Oscillation
- Vacuum Oscillations
- Matter effects

Detector (Sensors / DAQ)
- Cherenkov light propagation
- Optical Acceptance model
- PMT model, Noise, Electronics

 Cosmic ray origin

Earth Model

Magnetic Field Model

Atmosphere Model

Ice Model
SIGNATURES

- Depending on the neutrino interaction & flavour, we expect certain signatures in our detector

**Tracks:** mainly numu CC interactions or atmospheric muons, which both have an extended muon track

**Cascades:** nue and nutau, as well as NC interactions that cause more compact charge deposits

**“Double Bang”:** very high energy taus are boosted enough to travel a sizeable distance before decay (~50m/PeV), creating a second, distinct shower
LOW ENERGY ATMOSPHERIC NEUTRINOS

- For $O(10)$ GeV neutrinos and below, earth diameter provides perfect L/E
- We can look at oscillations in the energy-cos(zenith) ($\propto E-L$) plane

$$P_{\nu_\mu \rightarrow \nu_e} = \sin^2 2\theta \sin^2 \frac{m_2^2 - m_1^2}{4E_\nu} L$$

Matter effects, here: transition to earth’s core

- $\nu_\mu$ disappearance measurement
- $\nu_\tau$ appearance measurement

IceCube

PHILIPP ELLER

NMO measurement
GOING LOWER IN ENERGY

The typical TeV-PeV IceCube event:
• Photons from secondary particles arriving in many strings and modules
• Very clear, extended signature

The typical GeV DeepCore event:
• Photons from secondary particles arriving in few strings, tens of sensors
• Almost impossible to see “by eye” what event it was
ACTUAL SIGNAL

- $\nu_\mu$ disappearance fit:
  - **Deficit** of events compared to the non-oscillation case
  - mostly visible in the tracks channel
  - For upgoing events, concentrated around the first oscillation maximum of $\sim 25$ GeV

- $\nu_\tau$ appearance fit:
  - **Excess** of events in the cascades channel compared to the non-appearance case
  - Effect $\sim$order of magnitude suppressed compared to disappearance
  - Slightly worse resolution for cascades than for tracks
DATA SAMPLE

- New DeepCore results are based on 3 years of data

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<th>Type</th>
<th>Analysis A Events ±1σ</th>
<th>Analysis B Events ±1σ</th>
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<td>9545 23</td>
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<tr>
<td>$\nu_e + \bar{\nu}_e$ NC</td>
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<td>923 8</td>
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<td>3368 17</td>
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<tr>
<td>observed</td>
<td>62112 249</td>
<td>40902 202</td>
</tr>
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</table>

- Excellent data/MC agreement
- Goodness of fit (p-value) ~20-60%
**EVENT DISTRIBUTIONS**

- Projection of events onto the L/E axis

\[ P_{\nu_\mu \to \nu_e} = \sin^2 2\theta \sin^2 \frac{m_2^2 - m_1^2}{4E_\nu} L \]

- "down-going" events
- "up-going" (Earth crossing) events
- Appearing tau neutrinos
- No oscillation case

No Oscillations

Data

MC Uncertainty
NUMU DISAPPEARANCE RESULTS

- Constraining the atmospheric mixing parameters $\theta_{23}$ and $\Delta m^2_{32}$
- Competitive precision with long baseline experiments

Analysis A best-fit point:

$\sin^2 \theta_{23} = 0.58 + 0.04 - 0.13$

$\Delta m^2_{32} = 2.55 + 0.12 - 0.11 \times 10^{-3} \text{ eV}^2$

Analysis B best-fit point:

$\sin^2 \theta_{23} = 0.51 + 0.07 - 0.09$

$\Delta m^2_{32} = 2.31 + 0.11 - 0.13 \times 10^{-3} \text{ eV}^2$

https://arxiv.org/abs/1707.07081
- Quantifying the appearance of tau neutrinos

- \( \nu_\tau \) normalization:
  - 0 = absence of tau neutrinos
  - 1 = SM expectations

- Similar analyses by OPERA and Super-K

- Difference form 1 could indicated:
  - Non-unitarity of mixing
  - Modification of cross section
WHAT THE FUTURE HOLDS
ICECUBE UPGRADE & PINGU

IceCube Upgrade, Phase 1 (funded)

7 additional strings with different DOMs

full PINGU

26 strings with ~100 DOMs each
THE NEW SENSORS

- New sensor designs with multiple PMTs, here 21 3” PMTs
- 4pi coverage, large photocathode area

- A second design with two large PMTs will also be used
- New calibration devices will be installed
  - Stand-alone Isotropic light sources
  - Integrated LED flashers and
  - Camera systems in every DOM
- Help to understand the optical properties of the ice

POCAM (Precision Optical Calibration Module)

CCD and CMOS prototype boards
TIMELINE

- 7-string upgrade approved by NSF, deployment planned for 2022/23
- Rough timeline (here for “full” PINGU = even more strings)
OSCILLATION CONTOURS

- Able to deliver high precision measurements of atmospheric oscillation parameters
- Better than 10% uncertainty on $\nu_\tau$ normalization (PMNS unitarity)
- $\gg 5$ sigma significance
A WAY TO DETERMINE THE NMO

- For atmospheric neutrinos, the relatively small mixing of $\nu_e \leftrightarrow \nu_\mu$ can be drastically enhanced by matter effects
- For neutrinos under the normal ordering
- For anti-neutrinos under the inverted ordering

- Combined with initial fluxes differences etc., the wrong mass ordering can be excluded

[Graph showing the relationship between $\sin^2 \theta_{23}$ and $\eta_\sigma$ for different scenarios labeled NO (Asimov), NO (LLR), IO (Asimov), and IO (LLR). The graph is labeled PINGU (4y) and indicated as preliminary. The source is https://arxiv.org/abs/1401.2046]
- A longer term future project is a much larger detector
- Volume increased by ~10x
- Also includes surface veto (ground stations, air Cherenkov telescopes)
- Radio Array for ultra high energy events based on the Askaryan effect
The IceCube Gen2 Facility

- Radio Array
- Surface Array
- Main Array
- Core (PINGU)
- IceCube-86, IceTop

≈ 20 km
SUMMARY

- IceCube has a diverse science program
  - Neutrinos over a broad range of energies
  - Recording data since > 10y and still going strong
- Astrophysics using high energy neutrinos
  - Observation of neutrinos in coincidence with flaring blazar
- Particle physics using low energy neutrinos
  - Atmospheric neutrinos can be used for precision oscillation measurements
- Several detector extensions are underway or planned
  - 7-string Upgrade
  - New calibration devices
  - PINGU
  - Gen2
Thank you!
SOUTH POLE LOGISTICS

TRANSPORTING MATERIALS TO THE SOUTH POLE

1. Port Hueneme, CA, USA
2. Vessel travels West through Pacific
3. All materials must fit inside Herc LC-130
4. McMurdo
5. South Pole

- PORT HUENEME, CA, USA
- VESSEL TRAVELS WEST THROUGH PACIFIC
- CHRISTCHURCH, NZ
- ALL MATERIALS MUST FIT INSIDE HERC LC-130
- MCMURDO
- SOUTH POLE

17 days 8,000 miles
7 days 2,400 miles
3 hrs. 900 m.
S. Pole season: 100 days
- Most events in IceCube are created by atmospheric muons and neutrinos

- To reject muons:
  - Look at northern hemisphere -> earth shields from muons
  - Look at starting events / contained vertex -> use outermost layer of strings as veto

- To distinguish from atmospherics?
  - At very high energies (~100 TeV and above) astro flux starts to dominate
    - Like the IC170922A event
  - Or look at correlations in time or location
    - Like the excess of events clustered in time at the TXS location
ASTROPHYSICAL NEUTRINOS

- Discovery of astrophysical neutrino flux

- Independent analysis using thorough-going muon events from the northern hemisphere
FLAVOUR ANALYSIS

- Studying the flavor composition of astrophysical neutrinos
  - Different production mechanisms will produce different ratios
  - For example 1:2:0 (pion decay) or 1:0:0 (neutron decay), etc
  - When detected at IceCube, flavors will have oscillated
  - most scenarios end up close to 1:1:1

Example expectation (arXiv:1506.02043v2)
EARTH ABSORPTION

- Using a sample of 10784 (mostly atmospheric + partially astrophysical) neutrinos between 6.3 – 980 TeV

- Studying charged current muon neutrinos from Earth-crossing (vertical) to almost absorption free (horizontal) trajectories

- Estimated background of < 0.1%

- For a 40 TeV neutrino, the Earth represents roughly one absorption length
CROSS SECTION RESULTS

- Clear attenuation at high energies seen
- Measured cross section 1.3x SM predictions
- Within expectations (+0.21/-0.19 stat., +0.39/-0.43 syst. uncert.)
- No drastic increase with neutrino energy observed (in contrast to some BSM predictions)

Nature volume 551, pages 596–600
**Gamma rays**
They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.

**Neutrinos**
They are weak, neutral particles that point to their sources and carry information from deep within their origins.

**Cosmic rays**
They are charged particles and are deflected by magnetic fields.
- A closer look at one of the most important sources of systematic uncertainty

- The optical efficiency and angular acceptance of our bare sensors modules is well known from lab measurements

- After deployment in the ice and refreezing, zones of enhanced scattering (air bubbles) formed in the ice

- This causes an effective change in detection efficiency and acceptance

- This effect is studied with calibration LEDs and other methods

- Multiple nuisance parameters allow for changes in the acceptance for our measurements
PARAMETERIZATION & UNITARITY

- Standard parameterization for the PMNS matrix, based on 3 angles and one complex phase

\[ U_v = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

- Using this parameterization imposes unitarity
  - Some BSM theories introduce additional neutrinos
  - For example sterile neutrinos
  - As a consequence the 3x3 PMNS matrix is not the complete picture, and will not be unitary
  - We can test for that

\[
\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}
\]

- S_{12} = \sin(\theta_{12}) - “solar” angle
- S_{13} = \sin(\theta_{13}) - “reactor” angle
- S_{23} = \sin(\theta_{23}) - “atmospheric” angle
- \( \delta \) - CP violating phase
DEEPCORE

- **High energy** - whole IceCube
  - 1 km$^3$ of instrumented Ice
  - $>5000$ DOMs (digital optical modules)
  - TeV - PeV energy range

- **Low energy** - DeepCore
  - Additional 8 strings with densely spaced high efficiency DOMs
  - In clearest part of ice (below dust layer)
  - Surrounded by IceCube strings (used as atm. muon veto)
  - Neutrino energies down to $\sim 5$ GeV
- Unitarity of mixing matrix can be tested for
- Precision tests are done for the quark mixing for many years
- The typical precision on CKM elements: $\sim 0.1\% - 0.01\%$

http://ckmfitter.in2p3.fr/
UNITARITY

- For the neutrino sector we’re far from drawing triangles...

\[
\begin{pmatrix}
0.76 \rightarrow 0.85 & 0.50 \rightarrow 0.60 & 0.13 \rightarrow 0.16 \\
0.79 \rightarrow 0.85 & 0.50 \rightarrow 0.59 & 0.14 \rightarrow 0.16 \\
0.21 \rightarrow 0.54 & 0.42 \rightarrow 0.70 & 0.61 \rightarrow 0.79 \\
0.22 \rightarrow 0.52 & 0.43 \rightarrow 0.70 & 0.62 \rightarrow 0.79 \\
0.18 \rightarrow 0.58 & 0.38 \rightarrow 0.72 & 0.40 \rightarrow 0.78 \\
0.24 \rightarrow 0.54 & 0.47 \rightarrow 0.72 & 0.60 \rightarrow 0.77
\end{pmatrix}
\]

Typical precision ~10%

- Experimental constraints in \(\tau\)-sector ~order of magnitude worse than for \(e\) and \(\mu\) sectors -> need to improve precision

All these contain one or more \(\tau\)-elements
EVENT SELECTION

- Two different event selections for oscillation analyses:
  - **Analysis A**: primary goal nutau measurement, larger sample / more cascade events
  - **Analysis B**: primary goal: numu disappearance measurement, high purity sample

- Main challenge reducing ~5 orders of magnitude of background
  - Atmospheric muons
  - Accidental triggers due to noise

- Using 3y of detector data, resulting in:
  - ~62k events for Analysis A
  - ~41k events for Analysis B
cosmic rays

atmospheric muon neutrinos

\[ \nu_\mu \]

tau neutrino

IceCube

South Pole Neutrino Observatory
**ICECUBE EVENT SIGNATURES**

- Reconstructed using a hybrid Cascade + Track hypothesis
  - position, direction, energy and PID (= whether event is track- or cascade-like)

---

**Track-like**

- Typical $\nu_\mu$ event:
  - Energy deposited in
    - Extended muon track ($E \sim$ length)
    - Hadron shower from e.g. DIS

**Cascade-like**

- Typical $\nu_{e/\tau}$ event:
  - All energy deposited in form of showers
    (hadronic and electromagnetic)
  - Spatially more compact (no track)
PRELIMINARY NMO RESULT

- These are the very first IceCube/DeepCore results on NMO
- Based on same 3y dataset as the presented disappearance/appearance analyses
- Results not significant, more a proof-of-concept exercise
PERFORMANCE

- Similar performance of ORCA and full PINGU

- Some key differences:
  - Seawater homogeneous, absorption dominated medium
  - Ice heterogeneous, scattering dominated medium
  - PINGU contained inside DeepCore/IceCube, ORCA stand alone

IMPROVED RECONSTRUCTION

- For the past year we developed an improved IceCube reconstruction at PSU
- Optical properties of the ice eminent for reco
- receiver based tables for describing photon propagation in ice
- Finely sampled hypothesis from cascades and tracks
- Fast fitting process
- Allowing to significantly improve oscillations results
NEUTRINO OSCILLATION LANDSCAPE

![Graph showing the neutrino oscillation landscape with various experiments and parameters.]
SYSTEMATIC UNCERTAINTIES

- Incorporating a large variety of nuisance parameters in the measurements

- Covering uncertainties of:
  - Initial atmospheric neutrino flux
  - Interaction (cross sections)
  - Oscillation parameters
  - Detector uncertainties (efficiencies of optical modules and ice uncertainties)
  - Atmospheric muon background

- More systematic uncertainties were evaluated and deemed unimportant or fully correlated

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<th>Parameter Type</th>
<th>Fit Parameter</th>
<th>Analysis A</th>
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ATMOSPHERIC + JUNO

- An interesting way to arrive at a decisive NMO measurement very fast is combining JUNO + atmospheric
- The constraints on $\Delta m_{31}^2$ are very different
- They align for the true mass splitting, but are shifted for the wrong sign
- Leading to a better significance to exclude the wrong ordering
  - Here $\sqrt{\text{chi}^2} = 8.2$ for joint analysis, 5.2 for naïve combination
NEUTRINO FLUX AND UNCERTAINTIES

Nominal flux, Honda et. al. 2015

Relative uncertainty, Barr et. al. 2006
- Our ability to distinguish track and cascade-like events mainly depends on neutrino energy
  - Higher energy = longer muon tracks

- Analysis B: Separation based on an additional reconstruction using cascade only (no track)
  - Difference in likelihood to the standard reconstruction used as classifier

- Analysis A is based on a simpler approach using track length (muon energy) as discriminator
Both analyses follow a different strategy to model the background of atmospheric muons.

- Muons are inherently difficult to produce in simulation with high enough statistics.
- Since our selections are extremely efficient at removing those.

**Analysis A:**
- Simulation using a muon gun targeted at regions where we actually expect contamination.
- Needs to take into account simulation uncertainties.

**Analysis B:**
- Data driven method.
- Use a sideband to estimate the shape of the muons in the signal region.
- Extrapolation uncertainty.
COMPARISON TO OTHER PROJECTIONS

- With 3y of IceCube Upgrade data we project to achieve:
  - Better than 10% nutau normalization
  - Disappearance contours at the level of the NOvA 6y and T2K 2021 projected precision
NEW NOVA RESULT

- This January, a seminar talk at Fermilab showed updated NOvA results

- Joint analysis of different samples
- New reconstruction (using CVN)
- Events sorted by resolution
- Some refined systematics
- Better data/MC agreement
- 50% more data

- Contours changed drastically
- Before in tension with maximal mixing, now in favour of
TAU NEUTRINO DISTRIBUTIONS

- Visible energies distributed around ~15 GeV (analysis range 5.6 – 56 GeV)
- This is a higher energy regime than the Super-K nutau analysis

- $\nu_\tau$ events appear in upgoing region (-1,0) (= earth crossing trajectories)

- Mostly classified as cascade-like events

background subtracted data from Analysis B overlaid with best-fit $\nu_\tau$ expectations

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ATMOSPHERIC NEUTRINOS

- Need to understand the primary flux
  - Composition / Spectral shape

- hadronic interaction model
  - E.g.: DPMJET-III or Sibyll 2.3c

- model for decay, Atmosphere, magnetic field
  - Rely on external calculation: e.g. Honda et. al
  - Or use directly a tool like MCeq

Figure: S. Blot

Dembinski 2017

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MEASUREMENT PARAMETERS

- The numu disappearance measurement:
  - Extracting two parameters:
    - $\theta_{23}$: magnitude of disappearance
    - $\Delta m^2_{31}$: location of disappearance in terms of L/E
  
  $$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m^2_{31} L}{4E} \right)$$

- Nutau appearance measurement:
  - same as disappearance, plus an additional scale factor for tau neutrinos
    - $\nu_\tau$ norm = 0: no tau neutrinos at all
    - $\nu_\tau$ norm = 1: standard oscillation expectation
  
  - Scale factor can be applied to:
    - All tau neutrinos (referred to as “CC+NC”)
    - Only tau neutrinos interacting via charged current (CC) (same as OPERA, Super-K)
    - We present results for both
NUTAU CHANNELS

- What oscillation experiments can be done to measure tau sector?
  - \( e \rightarrow \tau \):
    - Small mixing \( \times \)
    - \( \nu_e \) from atmosphere \( \checkmark \)
    - \( e/\tau \) signatures in many detectors hard to distinguish \( \times \)
  
  - \( \mu \rightarrow \tau \):
    - Large mixing \( \checkmark \)
    - \( \nu_\mu \) from accelerators \( \checkmark \)
      - OPERA: CNGS beam
    - \( \nu_\mu \) from atmosphere \( \checkmark \)
      - Super-K and IceCube/DeepCore
  
  - \( \tau \rightarrow \tau \):
    - Large mixing \( \checkmark \)
    - Tau production in atmosphere negligible \( \times \)
    - Currently impossible to have a suitable beam \( \times \)
- **https://arxiv.org/abs/1711.09436**
- Atmospheric neutrinos
- Evidence with a significance of 4.6 sigma
- Based on 15 years of data
- Best constraint on $\nu_\tau$ normalization with $1.47 \pm 0.32$ (68% C.L.)
- Energies around $\sim 5$ GeV
  - Dominated by QE and resonance events

- Using a neural network classifier output $x \cos(\text{zenith})$ distributions for fit
- CNGS ~17 GeV muon neutrinos / 732 km baseline
- Observation of $\nu_\tau$ appearance with 6.1 sigma significance
- Total of 10 individually identified $\nu_\tau$ candidates
- Low background (estimated 2 total background events)
- Only weak constraints on $\nu_\tau$ normalization: 1.1 $-$0.4 $+$0.5 (68% C.L.)

- Example event display:
OTHER ATMOSPHERIC NEUTRINO RESULTS

- Non-standard interactions:
  
  https://arxiv.org/abs/1709.07079

- Sterile neutrinos using high energy events:
  

- Sterile neutrinos using low energy events:
  
  https://arxiv.org/abs/1702.05160
SYSTEMATICS IMPACT

- On Analysis A (nutau)
Science 342, 6161 (2013)
DEEPCORE RESOLUTIONS
ATM. NEUTRINOS: INGREDIENTS

Interaction in Atmosphere
- Primary cosmic ray flux, composition
  - Experimental data
- Hadronic interaction model
  - DPMJET, SIBYLL, ...
- Shower / Decay
  - MCEq, calculations by Honda et al., ...

Neutrino-Nucleon Interaction
- Generator (quasi-elastic, resonant, deep inelastic)
  - GENIE, NUGEN, ...
- Parton Distributions (PDFs)
  - so many choices...
- Parton shower + Hadronization
  - Pythia (or Herwig, Sherpa, ...)
- Hadron shower / EM cascade / muon propagation / decay
  - GEANT4, parameterizations

Neutrino Oscillation
- Vacuum Oscillations
- Matter effects (MSW)
- Non-standard interactions (?)
  - Prob3, NuSQUIDs, ...

Detector (Sensors / DAQ)
- Cherenkov light propagation
  - CLsim, PPC
- Optical Acceptance model
  - Local ice properties, glass, wavelength and angular acceptance, ...
- PMT model, Noise, Electronics

Cosmic ray origin

Ice Model
- South Pole Ice (SPIce)
DARK MATTER

- Several searches for WIMPs to neutrinos

Solar WIMP annihilation (spin-dependent)

Galactic Halo WIMP search

IceCube Preliminary

NFW
$\chi \chi \rightarrow \tau^+ \tau^-$

Natural scale

Fermi / MAGIC
Dwarfs
HESS GC/Eni

IceCube (2011-2014)
Super-K (1996-2012)
Antares (2007-2012)

PICO-3L (2013-2019)
PICO-60 (2015)

$\sigma_{SD}^{SD} \chi \chi \rightarrow \ell^+ \ell^-$
$W^+ W^-$
$\tau^+ \tau^-$

$\langle \sigma v \rangle \chi \chi \rightarrow \ell^+ \ell^-$
STERILES

- High-energy resonance of eV scale (3+1) model sterile neutrino