Tau Neutrinos with IceCube

Third-Generation $\nu_\tau$ (and $\tau$) Physics
Spanning over Five Orders of Magnitude in Energy

Doug Cowen
Penn State
Mascot Observations

Penn State’s “Nittany Lion”
Has teeth but does not need to show them.

U. of Louisville’s Cardinal
Anatomically incorrect. Birds don’t have teeth.
IceCube Discovery Timeline

[Timeline Image]

Seven Astrophysical \( \nu_e \) Observed

TXS 0506+056: BL Lac-type blazar, \( z = 0.3365 \)

Nature 591 (2021)

Science 380, 6652 (2023)

Fig. courtesy DESY/Zeuthen

See this talk!
Sources of $\nu_\tau$ in IceCube

We’ll focus here.

The challenge:
• $\sim 10^{12}$ triggers ($\mu_\downarrow$),
• $\sim 10^6 \nu_{\text{atm}}$ and
• $\sim 10^2 \nu_{\text{astro}}$ (per 10 years).
Sources of $\nu_{\tau}$ in IceCube

• Atmospheric neutrinos
  • Created when cosmic rays hit atm.
  • Resulting particle showers make $\nu_{e,\mu}$
    with $E_{\nu} \approx 10^{9-12}$ eV
  • For $(E_{\nu}, L_{\nu}) \sim (20$ GeV, $d_E)$,
    $P(\nu_\mu \rightarrow \nu_\tau) \sim 1$

• Astrophysical high energy neutrinos
  • Created in cosmic accelerators
  • IceCube sees at $E_{\nu} > \sim 50$ TeV
  • Expect $\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$ under
    standard oscillation picture
Sources of $\nu_{\tau}$ in IceCube

- Atmospheric neutrinos
  - Created when cosmic rays hit atm.
  - Resulting particle showers make $\nu_{e,\mu}$ with $E_{\nu} \approx 10^{9-12}$ eV
  - For $(E_{\nu}, L_{\nu}) \sim (20 \text{ GeV}, d_E)$, $P(\nu_\mu \rightarrow \nu_\tau) \sim 1$

- Astrophysical high energy neutrinos
  - Created in cosmic accelerators
  - IceCube sees at $E_\nu > \sim 50$ TeV
  - Expect $\nu_e : \nu_\mu : \nu_\tau \sim 1:1:1$ (std. $\nu$ osc., independent of sources’ $\nu_e : \nu_\mu : \nu_\tau$)

\[ P(\nu_\mu \rightarrow \nu_\tau) \]

\[ L_\nu (\propto \cos \theta_{\text{zen.}}) \]

\[ E^{\text{true}}_{\nu} \text{ (GeV)} \]

\[ \Delta m^2_{32} \]

\[ \delta \]

The IceCube Detector

IceCube Upgrade
- Optimized for
  - GeV neutrinos
  - Calibration

(start: 2026)

IceCube (now)
- Optimized for
  - Diffuse high energy cosmic neutrinos

IceCube-Gen2 (the future)
- Optimized for
  - Cosmic neutrino point sources

Inner fiducial volume 2.2 Mega-ton

IceCube’s instrumentation volume 1 Giga-ton

1.7 km
1 km
3 km
3 km

1450 m 2100 m 2150 m
2650 m 2450 m 2425 m

Instrumented Depth
$\nu_\tau$ Signatures in IceCube

Event morphologies

- $\nu_{\text{atm}}$
- $\nu_{\text{astro}}$

At $\mathcal{O}(10 \text{ GeV})$:
- only $\nu_\tau$ oscillate.

At $\mathcal{O}(100 \text{ TeV})$:
- see both $\nu_{\uparrow,\downarrow}$
- $\lambda_\nu \sim d_{\text{Earth}}$
- $\nu_\tau$ regeneration

$E_{\nu_\tau} \sim \text{PeV}$
($L_\tau = 50 \text{ m/PeV}$)

Simulated 11 GeV $\nu_e$ (DeepCore)
Simulated 13 GeV $\nu_\mu$ (DeepCore)
Simulated 21 GeV $\nu_\tau$ (DeepCore)

~100 m

~1 km

Spheres: DOMs
White: recorded no light
Color: recorded light
Size: light collected
Color shows time information:
Early Late
Signatures in IceCube

Event morphologies

$\nu_{\tau}$ Signatures in IceCube

$\nu_{\tau}$ Signatures in IceCube

With Upgrade ("IC93") expect $\sim$3x more photons for $\nu_{\text{atm}}$.

At $\sim$200 TeV, $\nu_{e,\tau}$ look very similar by eye.
Atmospheric Tau Neutrinos

- Inclusive analysis:
  - Look for excess of cascade-like events: \( \nu_\tau \) appearance

\[
P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 (2\theta_{23}) \sin^2 \left( 1.27 \frac{\Delta m^2_{32} L}{E} \right)
\]
Atmospheric Tau Neutrinos

- Inclusive analysis:
  - Measure
    \[ \nu^\text{norm}_\tau \equiv \frac{\nu^\text{meas.}_\tau}{\nu^\text{pred.}_\tau} \]
  - \( \nu^\text{norm}_\tau \) sensitive to new physics:
    - "non-unitarity"
      \( (\nu_\mu \rightarrow \nu_s) \)
    - unexpected \( \sigma_{\nu_\tau N} \) cross section behavior

All consistent with standard oscillations @30% level.
Atmospheric Tau Neutrinos

• Inclusive analysis:
  • Measure
    \[ \nu_\tau^{\text{norm}} \equiv \frac{\nu_\tau^{\text{meas.}}}{\nu_\tau^{\text{pred.}}} \]
  • \( \nu_\tau^{\text{norm}} \) sensitive to new physics:
    • “non-unitarity” \( (\nu_\mu \rightarrow \nu_s) \)
    • unexpected \( \sigma_{\nu_\tau N} \) cross section behavior

Have data now for \( \sim 10\% \) msmt.; Upgrade \( \rightarrow \sim 5\% \).
Astrophysical Tau Neutrinos

For standard oscillations over astrophysical distances, expect $\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$, and to see some $\nu_\tau$, independent of source's $\nu_e : \nu_\mu : \nu_\tau$ ...

Example: Effect of quantum gravity.

Example:
Effect of quantum gravity.
These Events are Huge

Not easy to identify the neutrino flavor.

~1 km

Assigned Color: relative time of detection of Cherenkov photon(s)
Sphere Size: proportional to number of photons detected

https://youtu.be/vTya9hoKsfM
Astrophysical Tau Neutrinos

• Previous IceCube msmts. looked for $\nu_\tau$ via
  • “Double bang”:

    $\nu_\tau \rightarrow W\tau$
    $W \rightarrow X \bullet$
    $\tau \rightarrow (e, h) \bullet$

$L_\tau \simeq 50m \cdot E_\tau / \text{PeV}$. Severely limited phase space. Not yet seen.

Note: $(\phi^\text{astro.}_\nu \cdot \sigma_{\nu N}) \propto E_\nu^{-1}$, so lowering energy threshold will increase signal level.

• Double cascade:
  Search for $\nu_\tau$-induced waveforms on 1-2 DOMs.
  Candidate $\nu_\tau$ seen, but at low significance.
Astrophysical Tau Neutrinos

• Also inclusively with “HESE” 60-event sample:

  • LLH-based fit classified 41 single cascades, 2 double cascades, & 17 tracks
  • Excluded null hypothesis ($\Phi_{\nu_\tau} = 0$) at 2.8$\sigma$

Candidate $\nu_\tau$: “Double Double”

Measured flavor composition of IceCube HESE events.
★ is best fit point, consistent with presence of all 3 flavors, but $\nu_\tau$ flux only weakly constrained.
Astrophysical Tau Neutrinos

- Current (exclusive) measurement starts with 2-d images, one per string:

- Then it trains CNN (VGG16) to distinguish signal from background.
Astrophysical Tau Neutrinos

• Expected 4–8 $\nu_\tau$ on a bkgd. of $\sim$0.5 with 9.7 years of data; predicted $\sim$50% chance of excluding null hypothesis of $\Phi^{\text{astro}}_{\nu_\tau} = 0$ at $>5\sigma$

• (S,B) levels depend on chosen $\Phi^{\text{astro}}_\nu$; assume 1:1:1 flavor ratio
  - IceCube has 4 $\Phi^{\text{astro}}_\nu$ msmts.; use one w/least-significant exclusion of null hypothesis

• Main contributors to the $\sim$0.5 background events
  - $\nu^{\text{astro}}_{\text{other}}$: Dependent on chosen $\Phi^{\text{astro}}_\nu$ (IceCube msmts.)
  - $\nu^{\text{atm}}$: Conventional flux (Honda et al.; IceCube msmts.);
    Possible prompt* flux (Bhattacharyya et al.; IceCube exclusion)
  - $\mu_\downarrow$: Only conventional (prompt* not yet seen)
  - Other: Charm in $\nu^{\text{astro}}$ interactions; on-shell W; Earth-crossing $\nu_e, \nu_\mu \rightarrow \nu_\tau$

<table>
<thead>
<tr>
<th>Signal</th>
<th>Backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu^{\text{astro}}<em>{\nu</em>\tau,CC}$</td>
<td>$\nu^{\text{astro}}_{\text{other}}$</td>
</tr>
<tr>
<td>initial</td>
<td>160 $\pm$ 0.2 (190 $\pm$ 0.3)</td>
</tr>
<tr>
<td>final</td>
<td>6.4 $\pm$ 0.02 (4.0 $\pm$ 0.02)</td>
</tr>
</tbody>
</table>

IceCube’s GlobalFit flux assumed (HESE flux in parentheses).

*From charm decays.
Opening the box, we saw 7 events.

4 events are brand new.
3 events are old; 1 of which had been identified as a $\nu_\tau$ candidate.

Tau-ness: $P_\tau(i) = n_s(i)/(n_s(i) + n_b(i)) \rightarrow (0.90 - 0.92, 0.94 - 0.95)$
Post-Unblinding Checks

- Apply single-pulse reco. to
  - simulated $\nu_\tau$
  - candidate $\nu_\tau$
- Good data–MC agreement...
  - ...but take numbers with a grain of salt
- Event vertices (see backup)
  - Over-clustered but consistent with stat. fluctuation
- Loosening $C_1$ score
  - admits 12 total events without visible clustering
  - retains high significance level

(IceCube’s “GlobalFit” flux assumed above.)
Conclusions: Exclusion of Null Hypothesis

- For IceCube’s GlobalFit flux, exclude $\phi(\nu^\text{astro}_\tau) = 0$ at $5.1\sigma$
  - Other fluxes: $5.2\sigma, 5.2\sigma, 5.5\sigma$ (Inelasticity, Diffuse, HESE)
  - Measured $\phi(\nu^\text{astro}_\tau)$ is consistent with all four $\phi(\nu^\text{astro})$
- Alternatively, this is a 40%-level confirmation of the standard oscillation picture: $7 \pm \sqrt{7}$ events.
- Also, since $\nu^\text{atm}_\tau$ negligible at these $E_\nu$
  - Detection of energetic $\nu_\tau$ powerfully confirms IceCube’s earlier $\nu^\text{astro}$ discovery.
\( \nu^{\text{astro}}_{\tau} \): What’s Next?

- Used just 3 (of 86) strings. Using more strings would:
  - Improve bkgd rejection, allowing for relaxation of cuts→more signal
  - Improve \( \phi(\nu^{\text{astro}}_{\tau}) \) measurement
  - Update “triangle plot” with \( \nu_{\tau} \) information
    - Search for new physics (e.g., quantum gravity)
    - Identify likely astrophysical-source acceleration scenarios; maybe exclude some
- Apply a dedicated \( \nu_{\tau} \) reconstruction for direction, E,…
  - Study parameters of highest-energy \( \nu_{\tau} \) and \( \tau \) ever detected
    - \( L_{\tau} \), energy asymmetry, ...
  - Use high-astrophysical-purity \( \nu_{\tau} \) to look for point sources
Conclusions

• IceCube has world-leading sensitivity to atmospheric $\nu_\mu \rightarrow \nu_\tau$ oscillations
  • Current $\sim$30% measurement with 3 yrs DeepCore
  • Future measurements will have sensitivity to new physics
    • $\sim$10% measurement with $\sim$decade of DeepCore: already have these data
    • $\sim$5% measurement with $\sim$3 years Upgrade: deployment in 2025/26

• IceCube has world’s only sample of astrophysical $\nu_\tau$
  • New analysis yielded considerable sensitivity boost: 5$\sigma$-level achieved!
  • Future analyses will further increase sample and exploit physics content
    • Enhance sensitivity to astrophysical source acceleration environment
    • Study the most energetic $\tau$ leptons available
    • Search for new 3rd-generation physics
Thank you!

Spring 2022 Collaboration Meeting, Brussels, Belgium
Backup
Searching for Astrophysical $\nu_\tau$

- Initial $\nu_\tau$ DP selection criteria
  - Require $\geq 2000$ p.e. on highest-charge string and $\geq 10$ p.e. on two neighbors
  - Require cascade topology

- After initial criteria, have $\sim 300x$ more background than signal

```
$R_{\text{exp}} / \text{Hz}$

$Q_{\text{st}}^{\text{max}} / \text{p.e.}$

```

"selected" = post CNN
Searching for Astrophysical $\nu_\tau$

- Trained 3 independent CNNs
  - $C_1$: DP vs. SP ($\nu^{CC}_{\tau}$ vs. $\nu^{CC}_e$, $\nu^{NC}_{\bar{x}}$)
  - $C_2$: DP vs track ($\nu^{CC}_{\tau}$ vs. $\mu_\downarrow$)
  - $C_3$: DP vs Track ($\nu^{CC}_{\tau}$ vs. $\nu^{CC}_{\mu}$)
- $C_1 \geq 0.99$, $C_2 \geq 0.98$, $C_3 \geq 0.85$
- Gives S/N $\sim$ 14.

- Backgrounds
  - Dominant: $\nu_{\text{astro.}}$ and $\nu_{\text{atm.}}$
  - Sub-dominant: $\mu_\downarrow$

- 3 separate CNNs worked better than 1 all-purpose CNN

- Off-signal region Data-MC agreement is good for $C_{1,2,3}$

Cumulative rate; signal region excluded

$C_1$, $C_2$, $C_3$, $C_{1,2,3}$ score

$N_{\text{evt}}$, $C_{1,2,3}$
Searching for Astrophysical $\nu_\tau$

- $E_{\nu_\tau}$ spectrum:
  - After final (CNN) cuts, peaks at $\sim 200$ TeV
  - Lower $E_{\nu_\tau}$ threshold translates to higher $N_{\nu_\tau}$
  - Peak signal efficiency at several PeV, but flux there is very low
Searching for Astrophysical $\nu_\tau$

- Backgrounds/Systematics in more detail: Charm
  - Charm: $\nu_e^{\text{astro}} \rightarrow eW; W \rightarrow cs$ (and $\nu_{\text{NC}}^{\text{astro}}; Z \rightarrow c\bar{c}$)
    - $\lambda_{\text{charm}} \sim \mathcal{O}(m), \quad E_{\text{dep.}} \sim 10^{12-14} \text{ eV}$
    - Double pulse from first shower of $e$ and second shower due to large ($\lambda_{\text{charm}}, E_{\text{dep.}}$)
  - Full charm MC: $\sim 20\%$ increase in $\nu^{\text{astro}}$ bkgd.
    - Small correction to account for MC’s older PDFs
    - Added to estimated background after unblinding
      - (Future improvement: Charm event morphology may be sufficiently different from $\nu_\tau$ that new CNN could reject.)
Searching for Astrophysical $\nu_\tau$

- **Backgrounds/Systematics, cont’d:**
  - $\mu_\downarrow, \mu_{\text{DIS}} (\mu + X \rightarrow \nu_\mu + X')$: considerably smaller than $\nu^\text{astro}$
  - Impact of detector-related systematics all found to be small. Uncertainties in the following items were modeled via randomly fluctuating non-$\nu_\tau$ fluxes within their expected range:
    - bulk ice scattering & absorption
    - hole ice scattering & absorption
    - DOM efficiencies
  - Other physics processes determined to be sub-dominant:
    - On-shell $W$ production ($\nu_e \rightarrow eW; ~ W \rightarrow \tau \nu_\tau; ~ \tau \rightarrow (e, h)$)*
    - High-energy Earth-crossing $\nu_e, \nu_\mu \rightarrow \nu_\tau$**

**A. G. Soto et al., PRL 128, 171101 (2022)
Searching for Astrophysical $\nu_\tau$

- Confidence intervals calculation (Feldman & Cousins)

- Test statistic $\text{TS}(\lambda_\tau) = \ln L(\hat{\lambda}_\tau) - \ln L(\lambda_\tau)$

- where $\lambda_\tau = \frac{\phi_{\nu_\tau, \text{astro.}}}{\phi_{\nu_\tau, \text{nominal}}}$ and $\hat{\lambda}_\tau$ maximizes Poisson-based LLH across 16 bins in $(C_3, C_1)$ space.
CNN Robustness: Saliency Maps

Saliency maps “rank the pixels in an image based on their contribution to the final score from a CNN.” Saliency = gradient of CNN score vs. pixel content.

These saliency maps show what parts of the photos the CNN finds most useful for identifying the dog in the dog photo, and the cat in the cat photo. (Evidently, the training sample had many of its cats sitting on tables.)

https://usmanr149.github.io/urmlblog/cnn/2020/05/01/Salincy-Maps.html
Event Pics w/Saliency Maps

“BarnOwl,” with log $Q_{str}$ and saliency maps:

Measured light levels in each of 3 strings.

Saliency:

$$S(C_1) = \frac{\partial(C_1)}{\partial(\text{pixel})}.$$

- light↑, $C_1$↑
- light↓, $C_1$↑

Contours: where light level $\to 0$.

Large $S(C_1)$ show where & when light-level change most effectively changes $C_1$.

Bright pixels with small $S(C_1)$ show where $C_1$ is less sensitive to light-level changes.

Generally, $S(C_1)$ shows $C_1$ sensitive to overall event shape.
Event Pics w/Saliency Maps

DoubleDouble, with $\log Q_{\text{str}}$ and saliency maps:

![Graphs showing $Q_{\text{str}}$ and saliency maps.](image)

DOM number (α depth)

DOM number

time/ns

(Gratifying to see this event again.)

All event pics in backup.
CNN Robustness

• Data-driven tests

• Randomly scale pre-CNN data events’ light levels within known uncertainties

  • Use patterns to mimic detector systematics (module efficiency, ice properties) with ~6M pseudo-data events

  • Estimated signal $\rightarrow$ background migration probability: $< 0.3\% \pm 0.08 \%$ in all cases ($< 0.02$ signal events)

  • Estimated background $\rightarrow$ signal: $< 0.002\% \pm 0.0002 \%$ (<0.2 background events)

    • Adding in 0.2 background events modestly reduces significance

    • Analysis already includes these systematics, estimated from MC; replacing one estimate with the other would not impact the final result.
CNN Robustness

• For 7 candidate signal events:
  • Manually merged double pulse waveforms, manually shifted light arrival times: CNN response unchanged
  • “Adversarial Attack” (DeepFool): Find closest decision boundary and compute perturbation required to cross it
    • Only with pixel variations outside uncertainties could one event could be forced to migrate
  • With random ±10% pixel variations, $10^4$ trials/event, one candidate event had $(2.1 \pm 0.14)\%$ migration probability

• For background events:
  • Attacks did not reveal any exceptionally susceptible region; changes required to get $B \to S$ migration outside uncertainties
  • Attacked 634 simulated $\nu_e$, allowing pixels to change ±10%, and only 1 $\nu_e \to \nu_\tau$
Data-Driven Systematic Checks

- Starting point: 8,188 events
  - Use 8,175 at slight distance signal box edge
- Vary waveforms to estimate migration probability
  - Procedure:
    - Apply variation randomly to each event,
    - evaluate CNN scores,
    - calculate migration probabilities.
  - Repeat 750 times/event. ~6M trials for bkgd; ~5k for signal.
Data-Driven Systematic Checks

• Variations studied:
  • DOMEff: scale waveforms \( \sigma = \pm 10\% \)
  • Ice absorption and scattering: scale in groupings in \( z \): every 3, 4, 5 DOMs (every 51m, 68m, 85m) \( \sigma = \pm 20\% \)
  • Ice scattering: shift times in groups of 4 DOMs with \( \sigma = \pm 10\text{ ns} \)
  • Ice birefringence: scale all 120 DOMs in 2nd and 3rd strings with central value dependent on azimuth \( \sigma = \pm 20\% \)
  • Note: scaling inverted from expectation: MC did not have full birefringence but data does
Data-Driven Systematic Checks

• Outcomes:
  • Migration out of signal box:
    • Very unlikely: < 0.3% ± 0.08% in all cases (< 0.02 signal events)
  • Migration into signal box:
    • Also very unlikely: < 0.002% ± 0.0002% (<0.2 background events)
      • Adding in 0.2 background events would modestly reduce our significance.
      • Current analysis already includes these systematics, estimated from MC
        • Replacing one estimate with the other (so as not to double count) would not impact the final result.
Post-Unblinding Checks

- The event vertex distribution did not look as uniform as expected
  - Several events’ highest charge string was near detector’s edge
  - More clustered in z above and below the “dust band”
    - A ~3σ-ish effect, depending on assumptions
Event Vertex Distribution

- **Geometry:** There’s a lot of physical volume near the edge.
- **Loosening CNN scores** $C_{2,3}$ ($\nu_\tau^{CC}$ vs. $(\nu_\mu^{CC}, \mu)$) adds new events mostly at top of detector.
  - Very unlikely all 4 edge events are $\mu$:
    $$p_{KS}(C_3 > 0.75) = 0.1$$
    $$[p_{KS}(C_3 > 0.85) = 0.004]$$
  - One of the four events reconstructs as outward-going.
  - Likely $\nu$: absence of light on $\sim 0.5$ km path toward vertex.
Event Vertex Distribution

- Loosening $C_1$ score ($\nu^\text{CC}_\tau$ vs. $(\nu^\text{CC}_e, \nu^\text{NC}_x)$)
  - Expected $9.4 \nu_\tau$ and $2.9$ bkgd events
  - Saw $12$ (see figure)
- New events more evenly distributed in $(\rho, z)$
- Note: The $12$ events would also exclude null hypothesis of $\phi(\nu_\tau^\text{astro}) = 0$ at high significance.

Conclusions: The $7$ candidates’ vertex distribution is an unfortunate statistical fluctuation, and the edge events are inconsistent with cosmic ray muons.
Conclusions: Fitted $\nu_\tau$ Fluxes

$\phi = \phi_0 E^{-\gamma}$; fix $\gamma$, fit for $\phi_0$:

Excellent agreement with all four IceCube (non-$\nu_\tau$) measured fluxes.
Event Pics w/Saliency Maps

ScarletMacaw, with log $Q_{str}$ and saliency maps:

![Graph showing log $Q_{str}$ and saliency maps over time/ns and DOM number (α depth).]
Event Pics w/Saliency Maps

Atlantic Puffin, with \( \log Q_{\text{str}} \) and saliency maps:

- \( Q_{\text{str}} = 4.0 \times 10^3 \) p.e.
- \( Q_{\text{str}} = 1.5 \times 10^3 \) p.e.
- \( Q_{\text{str}} = 1.1 \times 10^3 \) p.e.

DOM number (\( \alpha \) depth)

time/\(3.3\) ns

d Doug Cowen/Penn State/dfc13@psu.edu
Event Pics w/Saliency Maps

Estragon, with log $Q_{str}$ and saliency maps:

- $Q_{str} = 6.2e3$ p.e.
- $Q_{str} = 1.7e3$ p.e.
- $Q_{str} = 1.0e3$ p.e.

DOM number ($\alpha$ depth)

time/ns
Event Pics w/Saliency Maps

MacaroniPenguin, with \( \log Q_{str} \) and saliency maps:

time/ns
Event Pics w/Saliency Maps

Ernie, with $\log Q_{\text{str}}$ and saliency maps:

time/ns
$L_{\tau}$ vs. $E_{\tau}$

Analysis prefers events with $\tau$’s with above-average lifetimes:
CNN Scores vs. Charge

- High charge is neither sufficient nor necessary
$C_3$ vs. $C_1$ ($Q_{str} > 2000$ p.e.)
Searching for Astrophysical $\nu_\tau$

- Trained 3 independent CNNs
  - $C_1$: DP vs. SP ($\nu_\tau^{CC}$ vs. $\nu_e^{CC}$, $\nu_x^{NC}$)
  - $C_2$: DP vs track ($\nu_\tau^{CC}$ vs. $\mu$)
  - $C_3$: DP vs Track ($\nu_\tau^{CC}$ vs. $\nu_\mu^{CC}$)
- $C_1 \geq 0.99$, $C_2 \geq 0.98$, $C_3 \geq 0.85$
  - Gives $S/N \sim 14$.

- Backgrounds
  - Dominant: $\nu_{\text{astro}}$ and $\nu_{\text{atm}}$.
  - Sub-dominant: $\mu$

- 3 separate CNNs worked better than 1 all-purpose CNN

(Events not weighted.)
IceCube Fluxes

https://arxiv.org/pdf/2203.08096
Searching for Astrophysical $\nu_\tau$

- Backgrounds, cont’d:
  - $\mu_\downarrow$: sub-dominant but presented low-hanging background fruit
    - “Corner-clippers” could look like $\nu_\tau$ DP, only 1/200 yrs., but nevertheless:
      - Add requirement $C_3 \geq 0.95$ if highest-charge string at outer edge.
      - Reduced background to 1/2,000 yrs, at a cost of 15% of the expected signal.
    - Saw excess edge events in pre-defined bkgd region
      - Would have failed CNN criteria, but had highly asymmetric light deposition pattern
      - Asymmetry cut reduced this excess by 10x, at cost of 3% of signal

“Corner-clipper” background. Intrinsically rare; made 10x rarer.
Searching for Astrophysical $\nu_\tau$

• Backgrounds, cont’d:

• $\mu_{\text{DIS}}$: $\mu + X \rightarrow \nu_\mu + X'$
  • Initial $\mu$ deposits light, followed by light from hadronic shower
  • Not directly simulated

• At $E > 100$ TeV expect $N_{\mu}^{\text{atm.}} \approx N_{\nu_\mu}^{\text{atm.}}$, but $\mu$ will lose energy traveling through atmosphere and ice
  • Conservatively doubled estimated background from $\nu^{\text{CC}}_\mu, \text{atm.}$
CNN Scores ($Q_{str} > 2000$ p.e.)

- $C_1$: Cascade vs. $\nu_\tau$
- $C_2$: $\mu_\downarrow$ vs. $\nu_\tau$
- $C_3$: $\nu_\mu$ vs. $\nu_\tau$
Cumulative $C_{1,2,3}$ ($\phi_{\text{HESE}}$ assumed)

- $C_1$: Cascade vs. $\nu_\tau$
- $C_2$: $\mu_\downarrow$ vs. $\nu_\tau$
- $C_3$: $\nu_\mu$ vs. $\nu_\tau$
Cumulative $C_{1,2,3}$ ($\phi_{\text{HESE}}$ assumed)

$C_1$: Cascade vs. $\nu_\tau$

Roughly equal numbers of astrophys. $\nu^{\text{CC}}_\tau$ & $(\nu^{\text{CC}}_e, \nu^{\text{NC}}_\chi)$
Cumulative $C_{1,2,3}$ ($\phi_{\text{HESE}}$ assumed)

$C_2$: $\mu_{\downarrow}$ vs. $\nu_\tau$

Roughly equal numbers of $\mu_{\downarrow}$, $\nu^{\text{bkgd}}_{\astro}$
Cumulative $C_{1,2,3}$ ($\phi_{\text{HESE}}$ assumed)

$C_3$: $\nu_\mu$ vs. $\nu_\tau$

Mostly astrophysical $\nu_\tau$ but not in signal region
Signal $\nu_{\tau}$ mostly downgoing
Importance of Flavor ID for $\nu^{\text{astro}}$

Status quo:

Measured flavor composition of IceCube HESE events. ★ is best fit point, consistent with presence of all 3 flavors, but $\nu_\tau$ flux only weakly constrained.

Better identification of $\nu_\tau$ would help to shrink the contour and maybe signpost new physics.

Also:
- Study $\nu_\tau$ (and \tau) behavior at ultrahigh energies;
- Leverage their very high astrophysical purity;
- Get bragging rights with the largest exclusive sample of $\nu_\tau$. 

Here’s “Double Double,” an old event & prior $\nu_\tau$ candidate:

Gratifying to find this event again.
A Less Obvious Event Pic

Here’s “Barn Owl,” another new event:

No clear double pulse waveform. What makes it a $\nu^\text{astro}_\tau$ candidate? To better understand CNN, use saliency maps.
Ice Optical Properties: Birefringence

- Light intensity ratio Data/MC
- Azimuth angle from emitter towards receiver
- Tilt axis
- Flow axis
Here’s “Scarlet Macaw,” a new event:

Clear double pulse structure. Detected in 2019 (too recent for previous analyses to have seen).
The IceCube Upgrade

• 7 new strings with new modules

DeepCore: Simulated 3.8 GeV $\nu_\mu \rightarrow \mu$
The IceCube Upgrade

• 7 new strings with new modules

Upgrade: Simulated 3.8 GeV $\nu_\mu \rightarrow \mu$