Constraining the flavour of the diffuse astrophysical neutrino flux using starting tracks in IceCube

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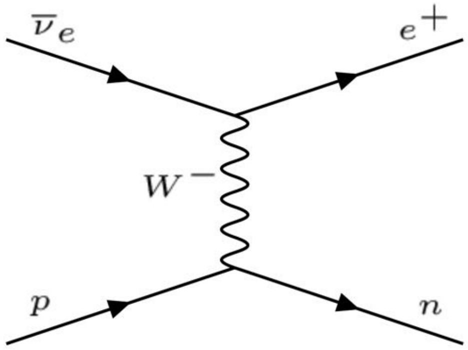
4th March 2025

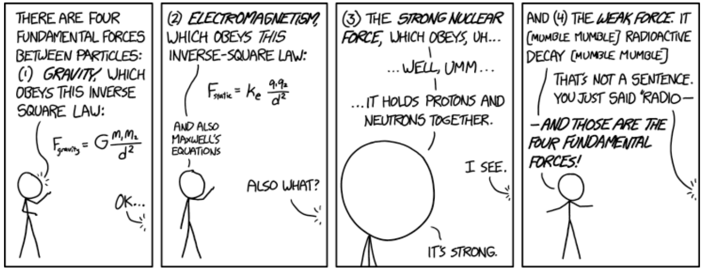
Introduction

- Neutrino physics – the basics
- The IceCube Neutrino Observatory
- Astrophysical neutrino flux
- Sensitivity studies
- What next?

Neutrinos – what are they?

- **Proposed in 1930, detected in 1953**
- **Near-massless (m < 0.8 eV) fermions**
- **Three (known) flavours**
- **Mass states of propagation =! flavour states of production**
- **Only interact through weak force**





Neutrino oscillations

We model mixing between 3 flavour states and 3 mass states with a unitary mixing matrix

- 4 free parameters for mixing, 2 mass differences
- Oscillations are affected by propagation medium

$$\begin{pmatrix} \nu_e(x) \\ \nu_\mu(x) \\ \nu_\tau(x) \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1(x) \\ \nu_2(x) \\ \nu_3(x) \end{pmatrix}$$

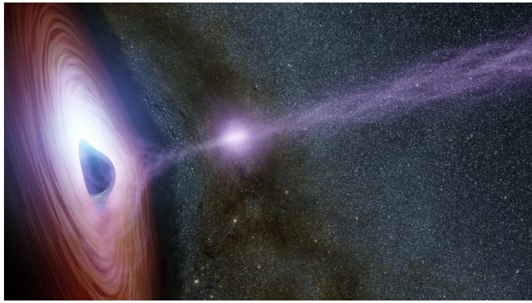
$$\begin{aligned} P_{\alpha\to\beta} = \delta_{\alpha\beta} &- 4 \sum_{j>k} \mathcal{R}_e \left\{ U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \right\} \sin^2\left(\frac{\Delta_{jk} m^2 \, L}{4E} \right) \\ &+ 2 \sum_{j>k} \mathcal{I}_m \left\{ U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \right\} \sin\left(\frac{\Delta_{jk} m^2 \, L}{2E} \right), \end{aligned}$$

What does this mean?

- **Neutrinos produced in X flavour can be detected as Y flavour**
- **Measuring flavour composition of a flux allows us to constrain models**
  - Oscillation parameters (for known production)
  - Production models (from known oscillations)

Neutrino Sources

- Reactor beta decays
- Solar fusion
- Production in accelerators
- Atmospheric Neutrinos
- Astrophysical Neutrinos



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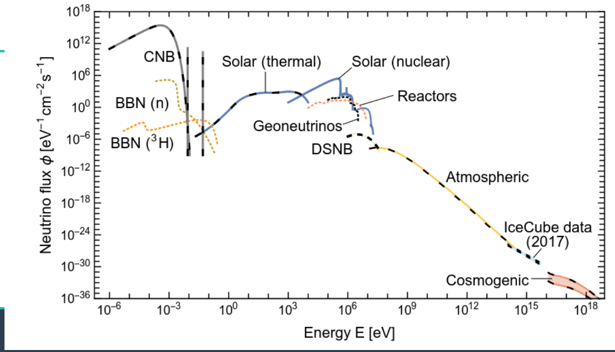
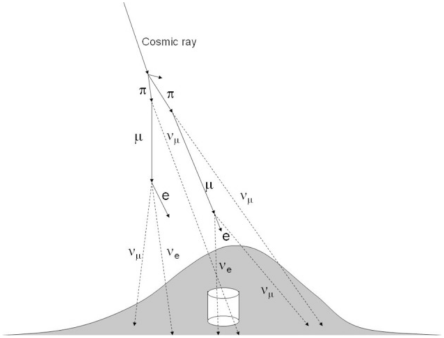
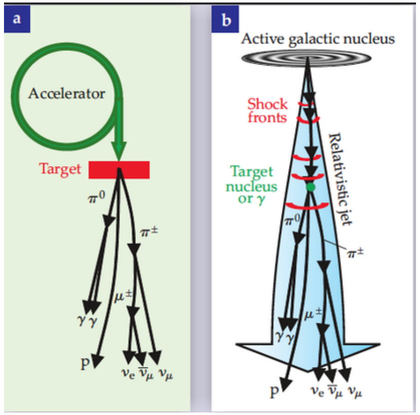
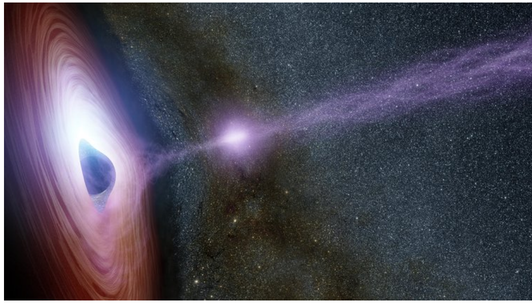


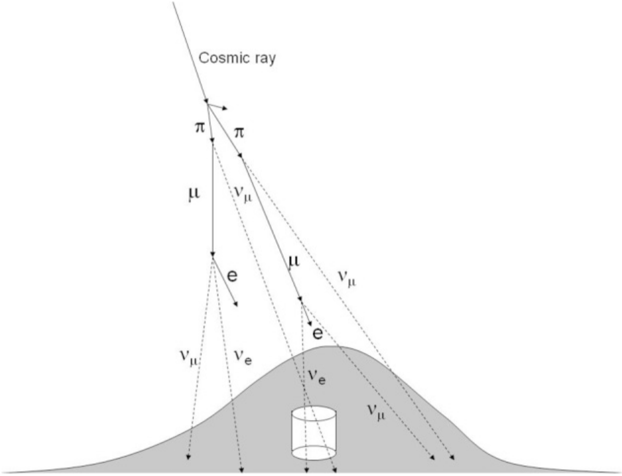






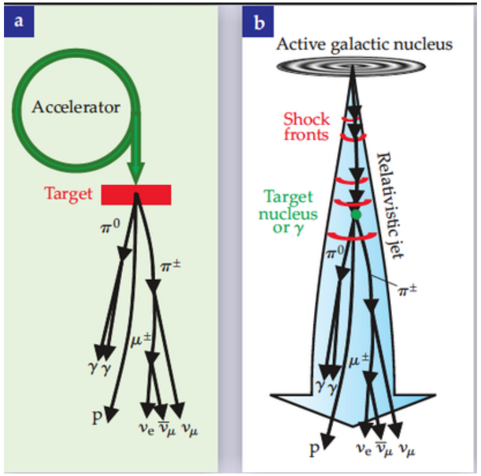
Atmospheric Neutrinos

- Cosmic rays make pions / kaons
- Pions / Kaons decay to muons and neutrinos – CONVENTIONAL FLUX
- Produce small amounts of charmed hadrons – PROMPT FLUX
- Oscillate on length scales from 50km to 12000 km



Astrophysical neutrinos

- **Produced by large cosmic accelerators (AGNs, pulsars, blazars)**
- **Proton accelerated – hits target – produces neutrinos**
  - Exact ratio depends on production mechanism
- **Neutrinos oscillate as they travel intergalactic distances**
- **We should be able to detect all three flavours**

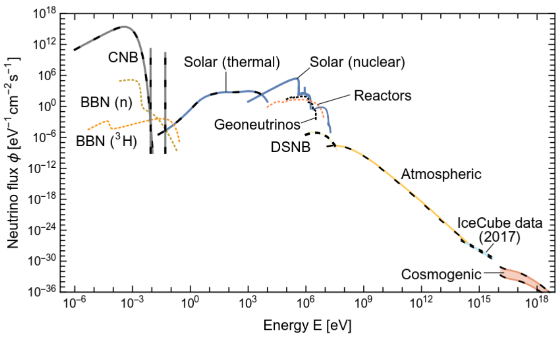


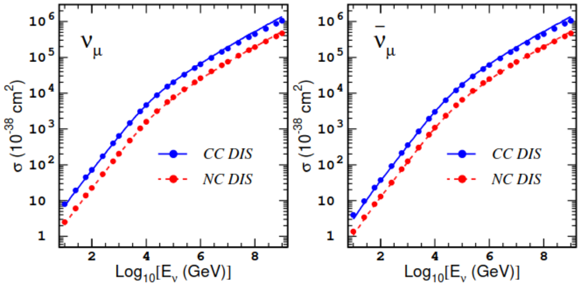
Astrophysical neutrinos

- **Several point sources have been observed**
  - SN1987A, TXS 0506+056, NGC-1068
- **There also exists a diffuse neutrino flux at >TeV energies**
  - No single origin
  - All-sky
  - All-flavour

How do we detect these?

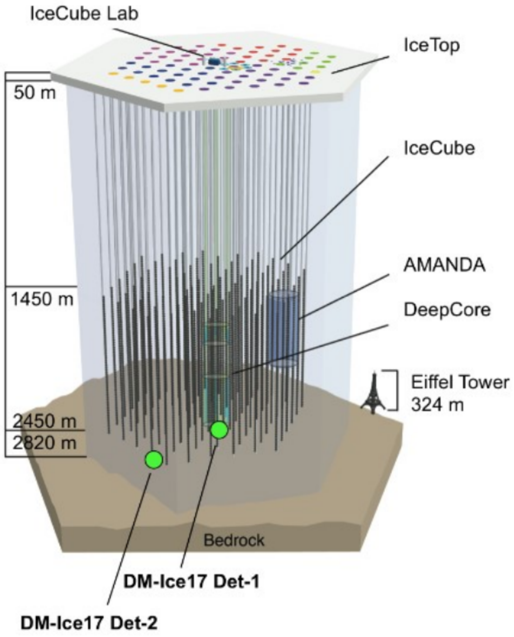
- **Neutrinos have a small ϕ(E) x σ(E)**
- **Measuring energy O(GeV) requires kiloton scale**
- **Astrophysical neutrinos become dominant > O(TeV)**
  - To detect O(1) neutrino a year, we require roughly 1km³ of instrumented volume
  - Motivated to build Gigaton-scale detector





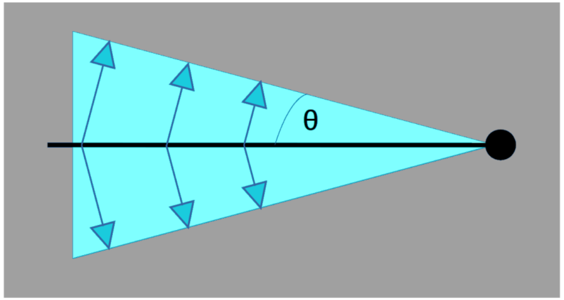
IceCube Neutrino Observatory

- **Located at the South Pole**
- **86 strings of 60 Digital Optical Modules**
  - 78+8 Deep Core
- **IceTop surface array**
  - Cosmic ray observatory and surface veto
- **1450-2450 m water shielding**



The Cherenkov effect

- Neutrino DIS interaction produces charged particles (leptons + hadrons)
- Produce light which transmits through ice
- Light detected in DOM photomultiplier tubes
- TWO main morphologies for how this light is distributed



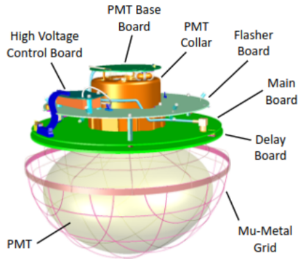
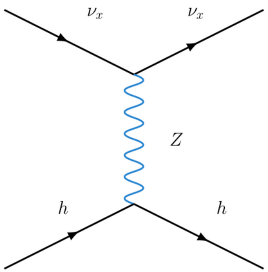
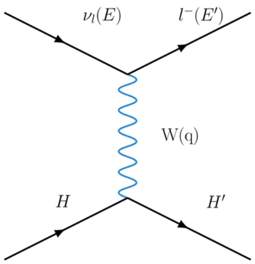


Figure 3.6: Cross-section of an Digital Optical Module, used in IceCube and IceTop arrays. Taken from [69].

Cascades

- **Hadrons + Electrons scattered and attenuated by ice**
- **Cherenkov light forms a cascading bubble around vertex**
- **All Neutral Current + ν_eCC +most ν_τCC**





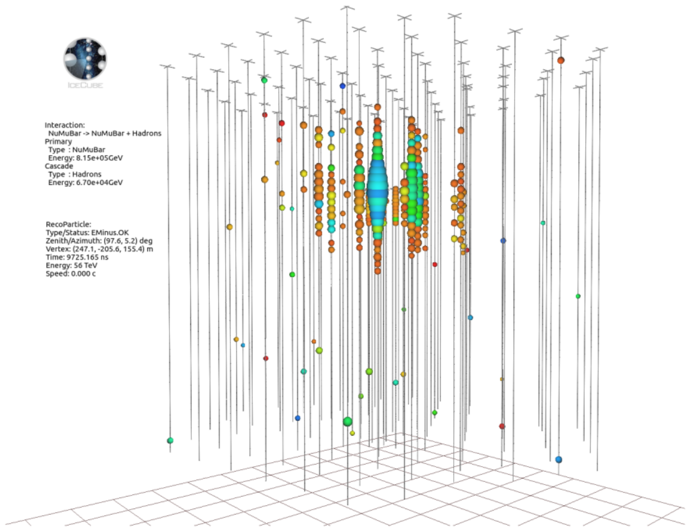
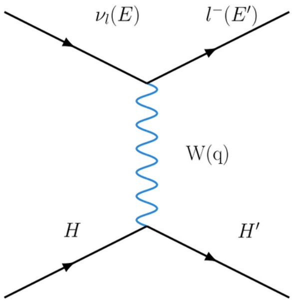


Figure 6.2: A simulated Neutral Current event of a 815 TeV muon neutrino producing a 67 TeV cascade, as visualised in the IceCube event viewer. The final level reconstruction information is also shown - energy = 56 TeV, zenith direction =97.6°, azimuth direction =5.2°. Time progresses red (early) → green → blue (late).

Tracks

- **Muons deeply penetrate the ice**
- **Small initial cascade at vertex, followed by a long track**
- **ν_μCC and some ν_τCC**



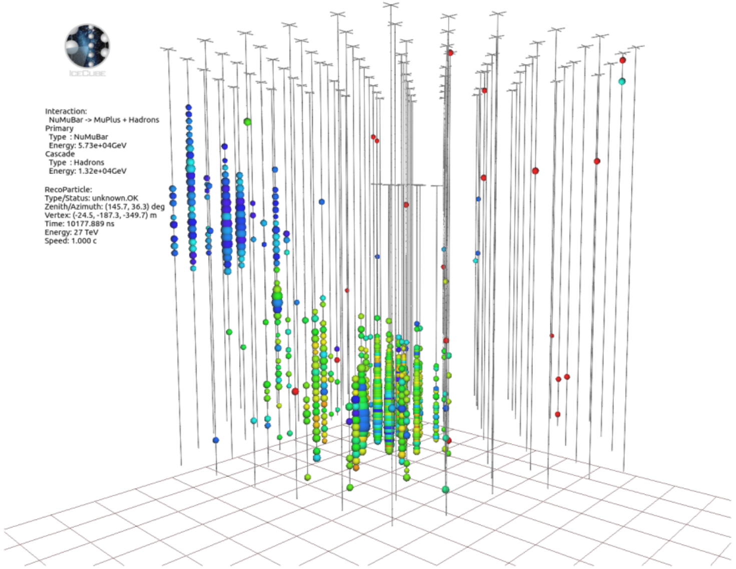
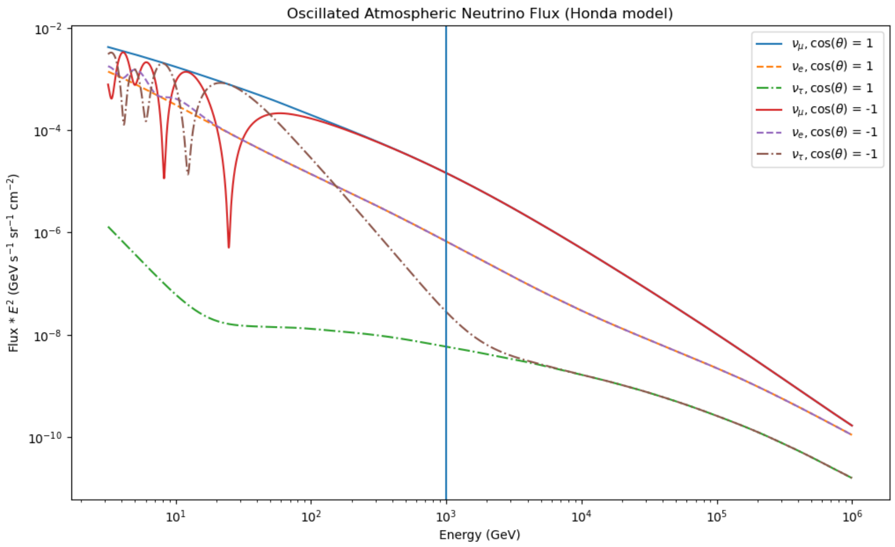


Figure 6.5: A simulated charged current event of an 57.3 TeV muon neutrino producing a 44.1 TeV muon, as visualised in the IceCube event viewer. The true parent information and final level reconstruction are also shown - energy =27 TeV, zenith direction =145.7°, azimuth direction =36.3°. Time progresses red (early) → green → blue (late).

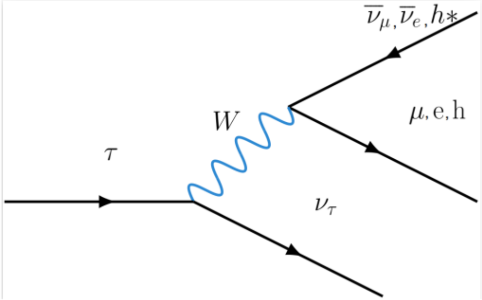
Tau Neutrinos

- **At high energies, we expect very few taus from atmospherics**
- **Tau flux is strong indicator of astrophysical signal**
- **Complex to detect due to tau decay**
  - $c\gamma\tau_\tau$ = 50 m/PeV



How to look for Taus?

- **87% in CC channel – could search for Double Cascades**
  - Initial tau interaction + tau decay to hadron / electron
- **Requires VHE taus to see the separation**
- **See arXiv:2108.05504**
- **for details**



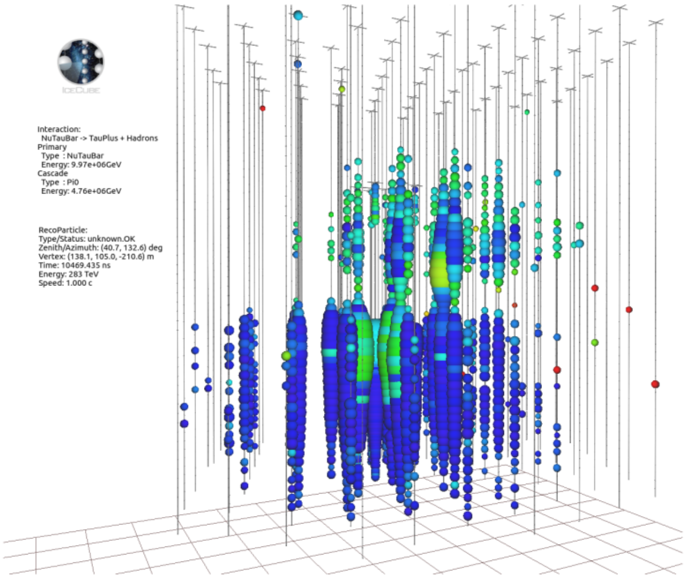
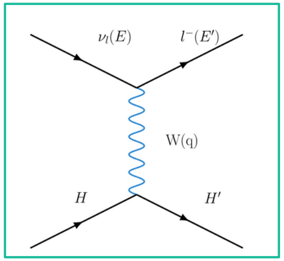
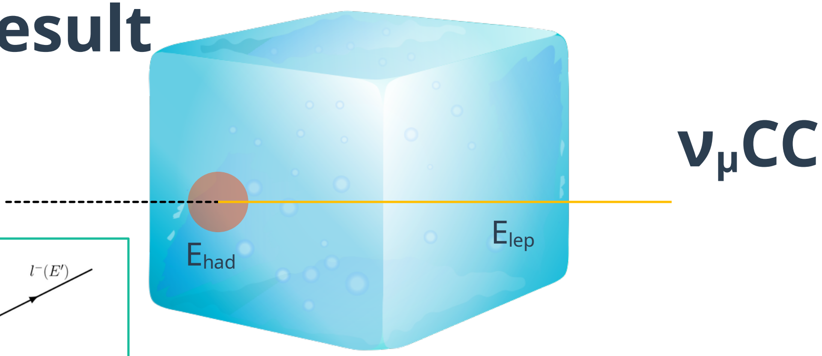


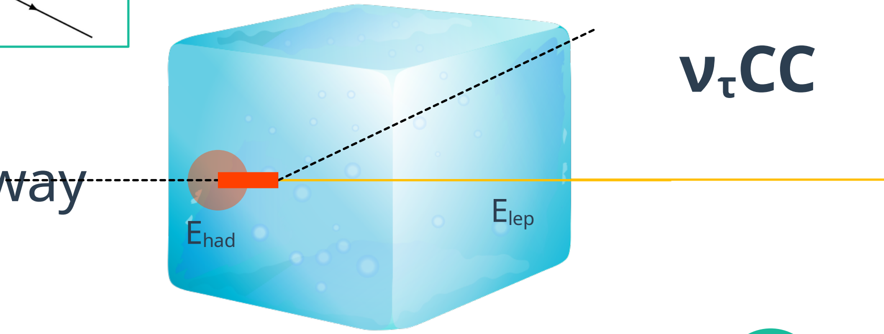
Figure 6.7: A simulated charged current event of an 9.97 PeV tau neutrino producing a 5.21 PeV tau, as well as a 4.76 PeV π^0 which produces the upper cascade. The tau then undergoes a secondary decay to a pair of hadrons, which produces the lower cascade, as visualised in the IceCube event viewer. The true parent information and final level reconstruction are also shown - energy =283 TeV, zenith direction =40.7°, azimuth direction =132.6°. Time progresses red (early) → green → blue (late).

What about the tracks?

- **We expect ~17% of ν_τCC events to result in a muon track**
- **What differences in physics can we exploit?**
  - Tau track change in direction?
  - Tau loses energy slower than muon?
  - Tau decay to ν_τ carries visible energy away from track…

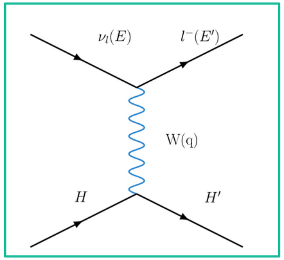


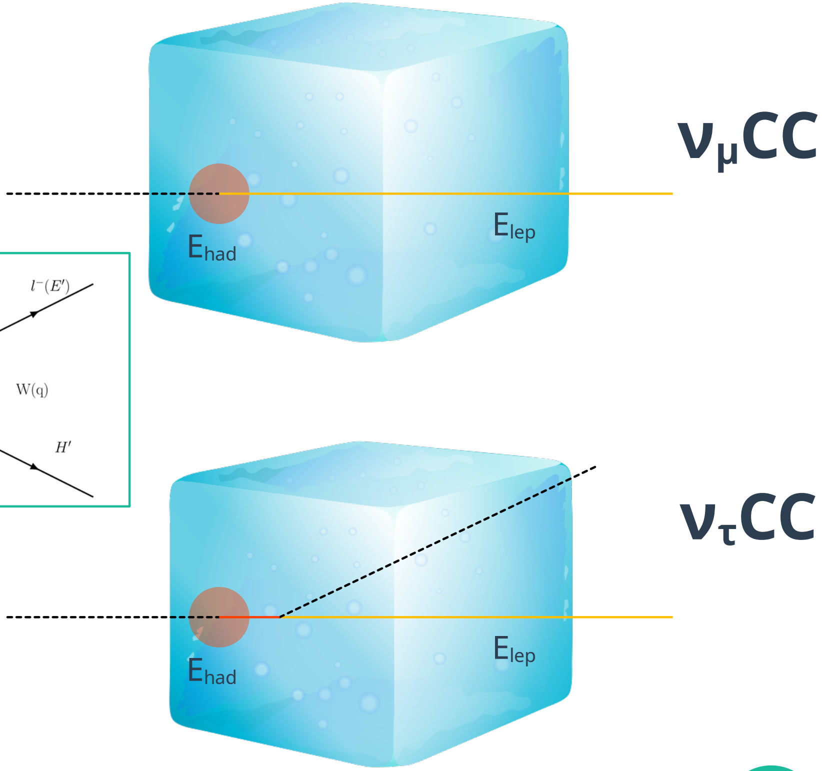




What about the tracks?

- **At E_{nu} >> m_{tau}, we expect equivalent vertex interactions for mu vs tau**
  - Same E_{had} distributions
- **In tau tracks, E_{lep} is stepped down compared to the mu track due to nu emission**





What about the tracks?

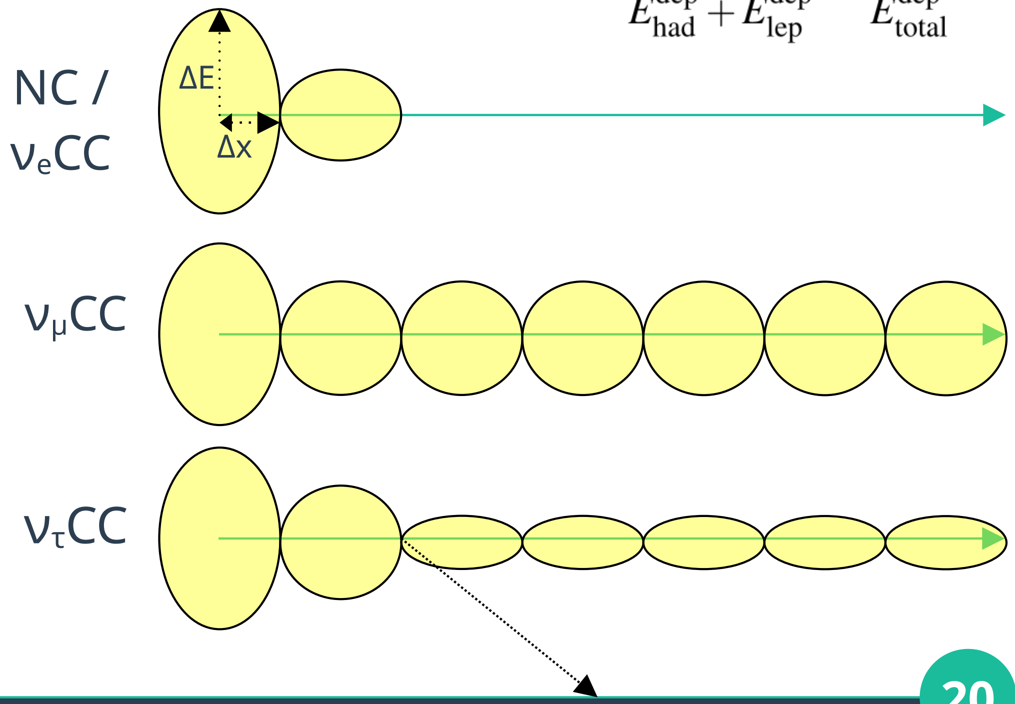
Define new reconstructed variable

y_{eff}

For tau tracks, y_{eff} has a higher average than for the muon tracks

Fitting the y_{eff} distribution to overall data allows us to put constraints on the flavour composition of the sample

$$y_{\mathrm{eff}} = \frac{E_{\mathrm{had}}^{\mathrm{dep}}}{E_{\mathrm{had}}^{\mathrm{dep}} + E_{\mathrm{lep}}^{\mathrm{dep}}} = \frac{E_{\mathrm{had}}^{\mathrm{dep}}}{E_{\mathrm{total}}^{\mathrm{dep}}}$$

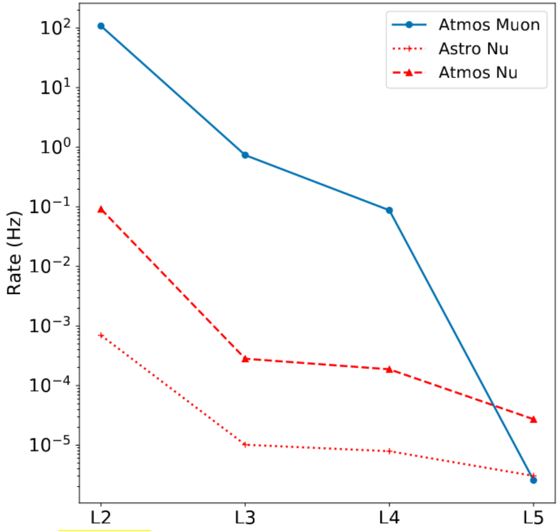


How can we exploit this?

- **We need a set of neutrino events that satisfies**
  - **High energy sample (> TeV)** to see the astrophysical spectrum
  - **Contained starting events** to measure energy of initial vertex
  - **Large number of events** to best leverage the fit templates

Medium Energy Starting Events

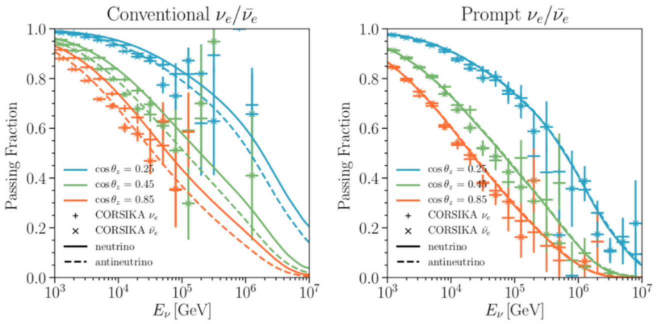
- **All-sky sample optimised for > 1 TeV**
- **Events classified into tracks vs cascades using Deep Neural Network (DNN)**
- **11.35 years of data**
- **Full MC simulation**
  - Including background muons
- **See arXiv:2402.18026**



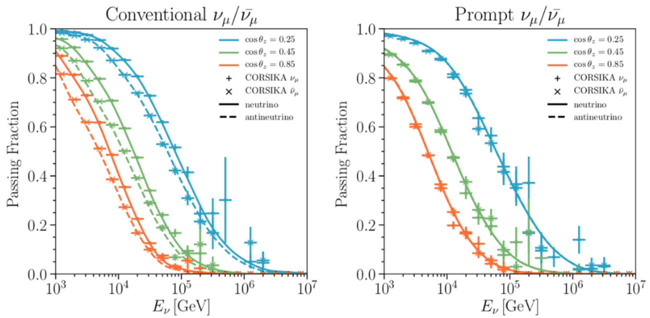
CASCADE	Atmos ν	Prompt ν	Astro ν		Total
ν_e	1277	60	392		1730
ν_μ	2216	8	60		2284
ν_τ	0	13	279		293
Atmospheric μ				275	
Total	3493	81	732	275	4581
TRACK					
ν_e	19	1	13		33
ν_μ	3597	15	105		3717
ν_τ	0	1	24		186
Atmospheric μ				186	
Total	3616	17	142	186	3961

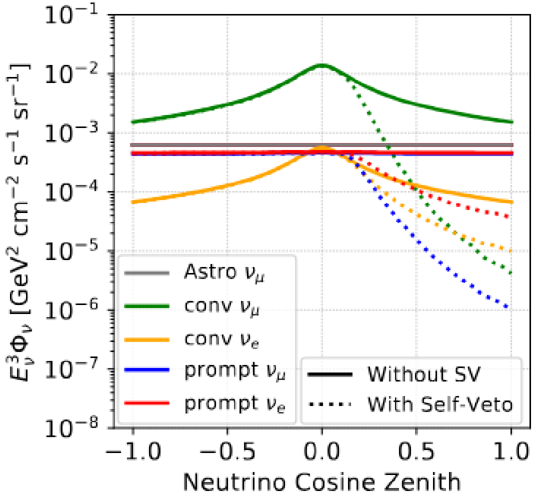
Atmospheric Self-Veto

- **Simulate neutrino and muon events separately**
- **We will remove neutrino events which are coincident with muons**
  - Reweight them based on likelihood of removal



[165] C. A. Argüelles, A. Schneider, and T. Yuan. "A binned likelihood for stochastic models". In: *Journal of High Energy Physics* 2019.6 (June 2019). ISSN: 1029-8479. DOI: 10.1007/jhep06(2019)030. URL: http://dx.doi.org/10.1007/JHEP06(2019)030.

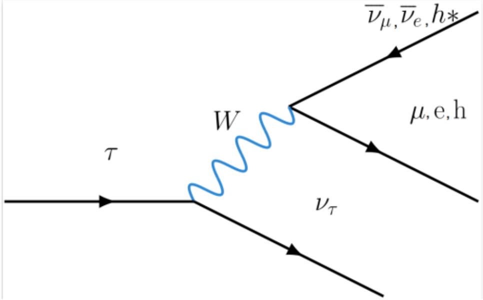


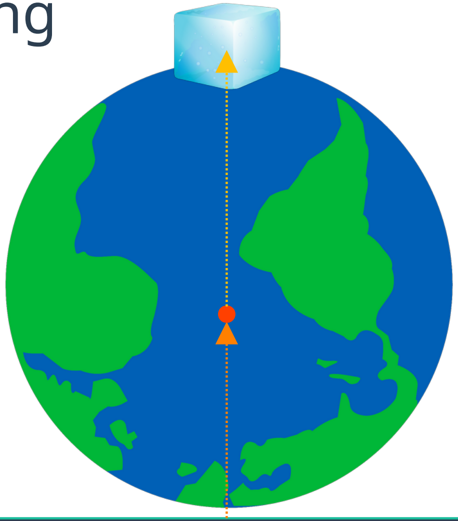


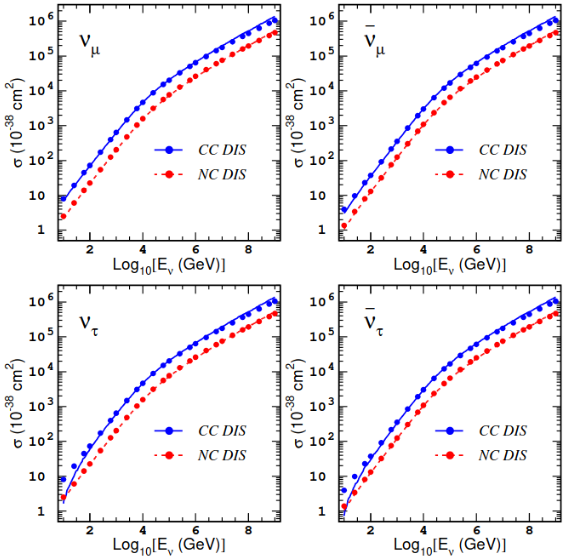
"Characterization of the astrophysical diffuse neutrino flux using starting track events in IceCube", Abbasi, R. and others

Tau Regeneration

- **Neutrino cross-section increases with energy**
  - High energy upgoing neutrinos will be absorbed before interacting
- **HE neutrinos propagate through tau decay “regenerating” the neutrino flux**

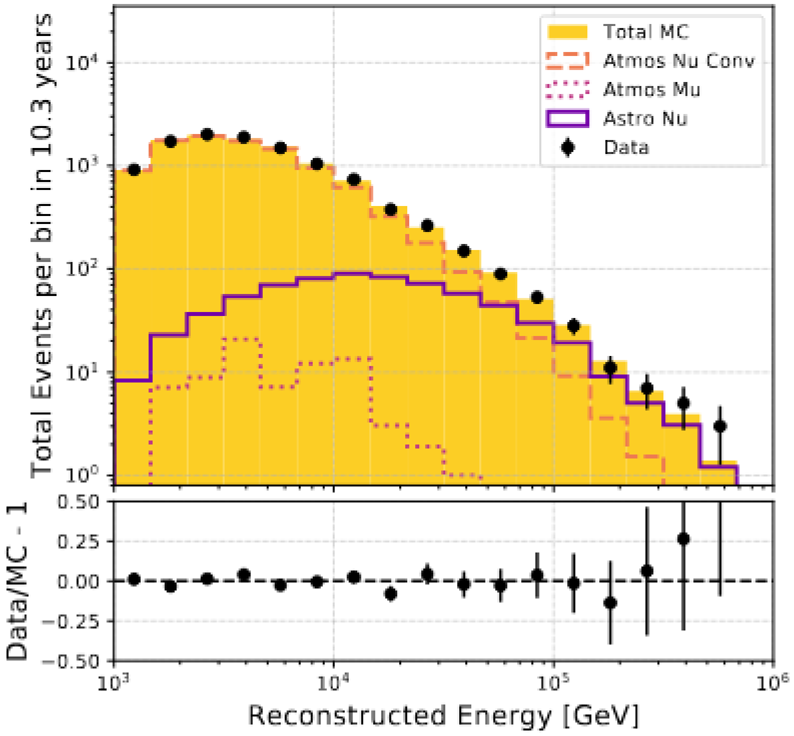


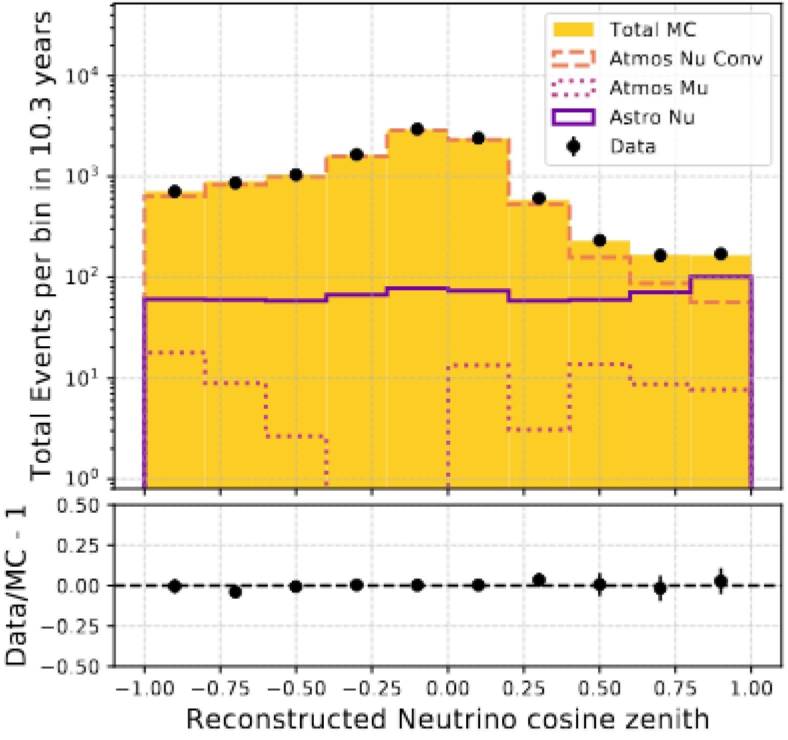




[57] E Bugaev. “Propagation of tau-neutrinos and tau-leptons through the Earth and their detection in underwater/ice neutrino telescopes”. In: *Astroparticle*

MC / Data evaluation for MESE

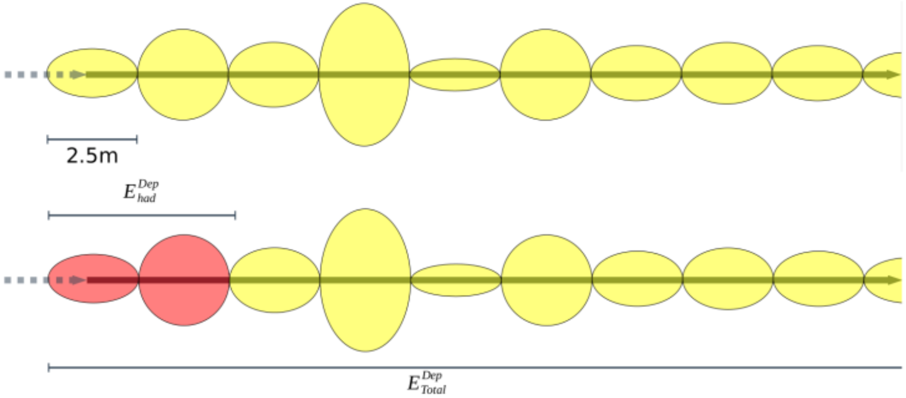




Effective inelasticity

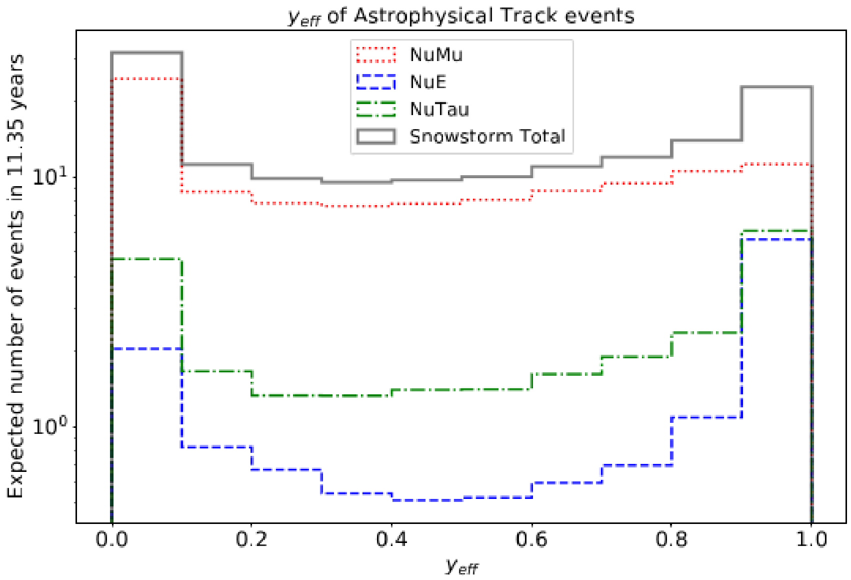
- **Constructed using Millipede segmented fit**
- **Number of segments to contain initial cascade scales with E_{total}**

$$y_{eff} = \frac{\sum_i E_{had,i}^{Dep}}{E_{Total}^{Dep}}$$



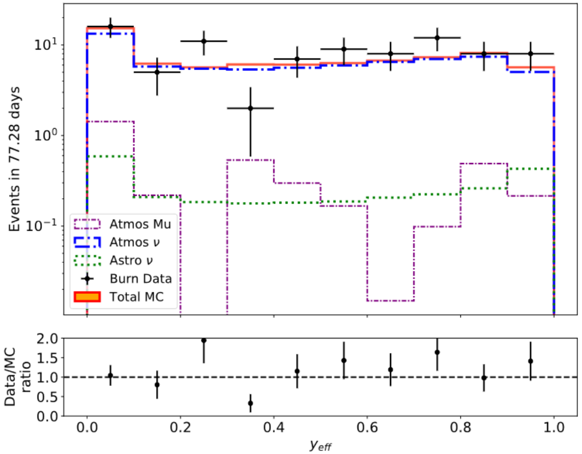
Bubbles show stochastic energy losses along track
Include red energy losses in E_{had}

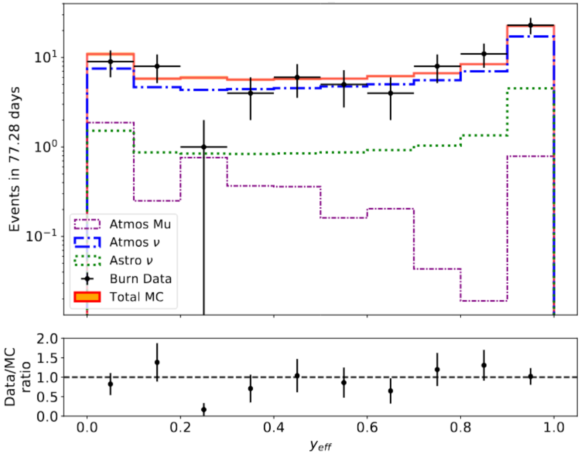
MC / Data evaluation for MESE



Distribution of MC events weighted with MESE best-fit spectrum

Data-MC agreement for 77 days of burn data





Measuring flavour ratio

- **Perform a forward-folding binned likelihood fit to data by reweighting MC events**
  - Cascade events binned in 2D (Energy + Zenith)
  - Track events binned in 3D (Energy + Zenith + y_{eff})
- **Maximise effective likelihood for low statistics (resolves to poisson form at high statistics)**

$$\mathscr{L}(\mu_j) = \Pi_j \mathscr{L}^j(\mu_j; d_j)$$

$$w_i = \frac{w_i(\vec{\theta})}{w_{sim}}$$

$$\mu_j = \sum_{i \text{ in bin } j} w_i$$

	Cascades	Tracks
Reco Energy	[3, 7, 24, logarithmic]	[3, 7, 14, logarithmic]
Reco Zenith	[-1, 1, 11, cosine]	[-1, 1, 11, cosine]
y_{eff}	-	[0, 1, 11, linear]

What parameters do we include?

1. **Uncertainties in the ice model**
2. **Uncertainties in atmospheric neutrino + muon flux**
    1. Both conventional and prompt
3. **Uncertainty in passing fraction effective veto**
4. **Uncertainty in neutrino cross-section**
5. **Flux parameters for astrophysical model**

Choice of astrophysical model

- **Simple Power Law**
  - Two variable parameters
  - Normalisation + Spectral Index

$$\Phi_{\nu+\bar{\nu}} = \Phi_{100\mathrm{TeV}} \left(\frac{E}{100\,\mathrm{TeV}} \right)^{-\gamma}$$

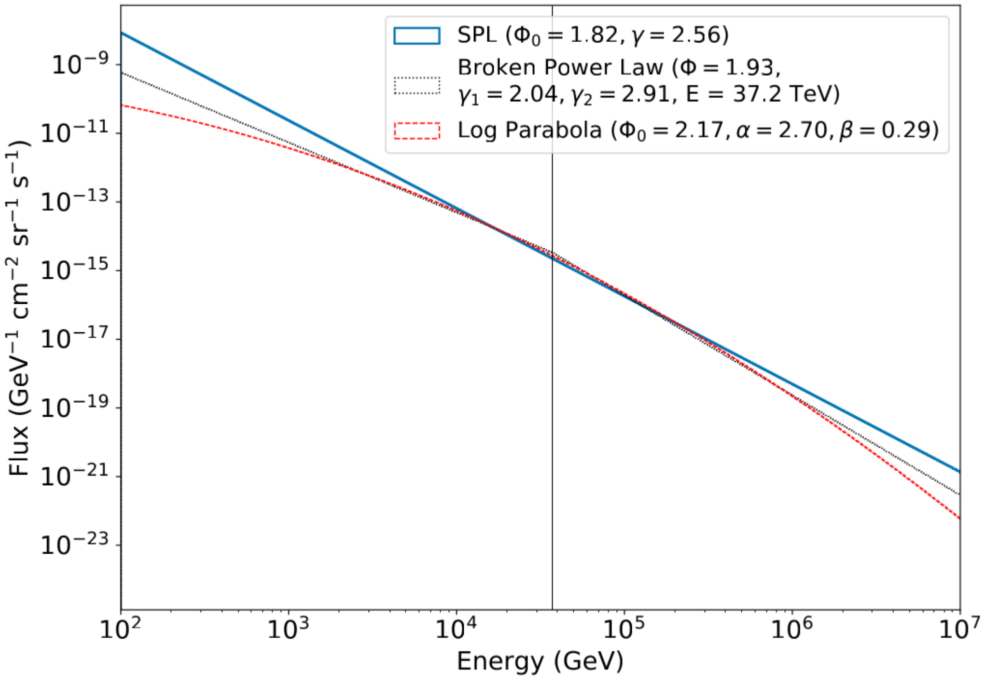
- **Broken Power Law**
  - Four variable parameters
  - Normalisation, 2 x spectral index, E_{break}

$$\Phi_{\nu+\bar{\nu}} = \Phi_{100\mathrm{TeV}} \left(\frac{E_{break}}{100\,\mathrm{TeV}} \right)^{-\gamma_2} \begin{cases} \left(\frac{E}{E_{break}} \right)^{-\gamma_1} & E < E_{break} \\ \left(\frac{E}{E_{break}} \right)^{-\gamma_2} & E \geq E_{break} \end{cases}$$

- **Log Parabolic Law**
  - Three variable parameters
  - Normalisation, spectral index, parabolic index

$$\Phi_{\nu+\bar{\nu}} = \Phi_{100\mathrm{TeV}} \left(\frac{E}{100\,\mathrm{TeV}} \right)^{-\alpha - \beta \log\left(\frac{E}{100\,\mathrm{TeV}} \right)}$$

Choice of astrophysical model



CASCADE	Single Power Law	Broken Power Law	Log Parabola
ν_e	573	392	401
ν_μ	71	60	61
ν_τ	346	279	285
Total	990	732	747
TRACK			
ν_e	16	13	13
ν_μ	129	105	108
ν_τ	28	24	24
Total	173	142	145

Parameters taken from arXiv:2307.15183

Sensitivity Studies

- **Before looking at data, probe the sensitivity of the analysis using an Asimov dataset.**
- **Generated based on the default values for the fit parameters θ_0**

$$\tilde{d}_j = \langle \frac{e^{-\mu_j(\vec{\theta}_0)} \mu_j(\vec{\theta}_0)^k}{k!} \rangle = \mu_j(\vec{\theta}_0)$$

- **All flavour fits shown use no data**

Fitting flavour

- **Introduce fit parameters s_{tau} and s_e**

$$\Phi_{\nu+\bar{\nu}} = \Phi_{100\mathrm{TeV}} \times (1 + s_e + s_\tau) \times f^{\mathrm{model}}(E)$$

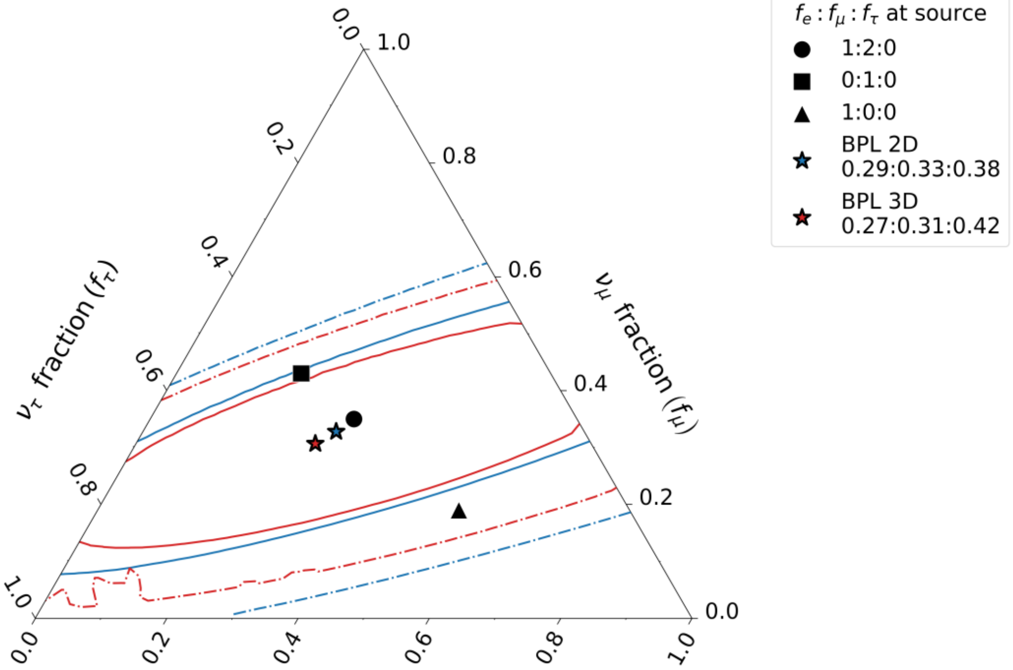
- **Subsequent flavour ratio f_e:f_{mu}:f_{tau} derived at best fit point**
- **For contours, fix s_{tau} and s_e and calculate best fit likelihood**

$$f_e = \frac{s_e}{1 + s_e + s_\tau}$$

$$f_\mu = \frac{1}{1 + s_e + s_\tau}$$

$$f_\tau = \frac{s_\tau}{1 + s_e + s_\tau}$$

Sensitivity – Broken Power Law



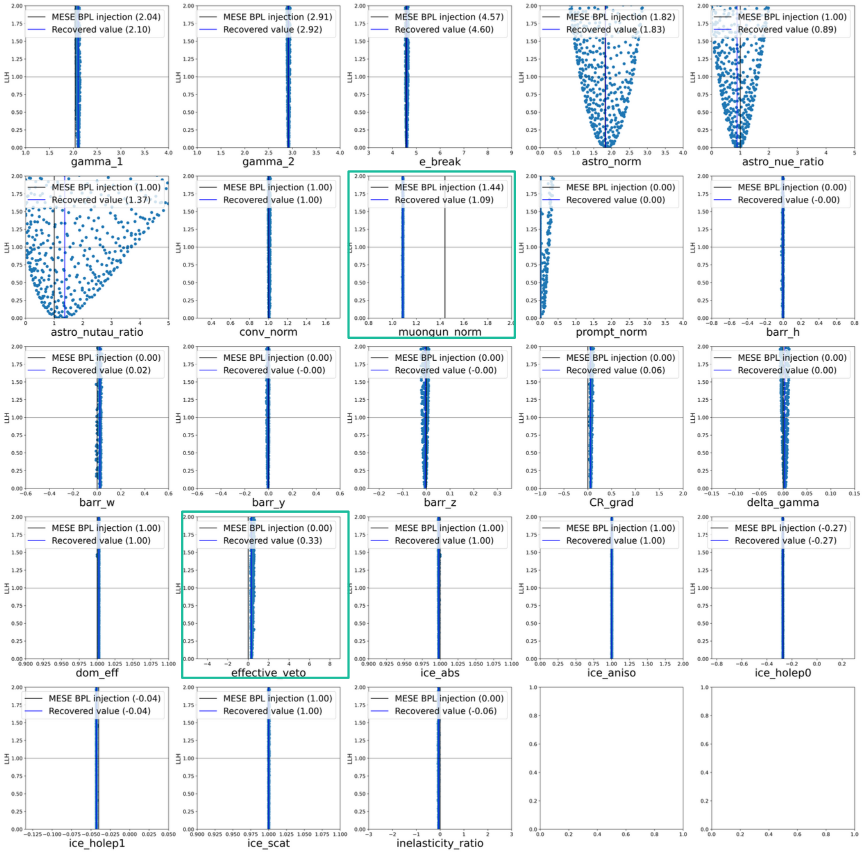
Blue = 2D binning (No y_{eff})
Red = 3D binning (incl y_{eff})

Best fit not at 1:1:1 injection due to difference between poisson (Asimov dataset) and SAY-LLH (fit likelihood)

Including y_{eff} parameter improves contours, but we lack the power to claim tau flux

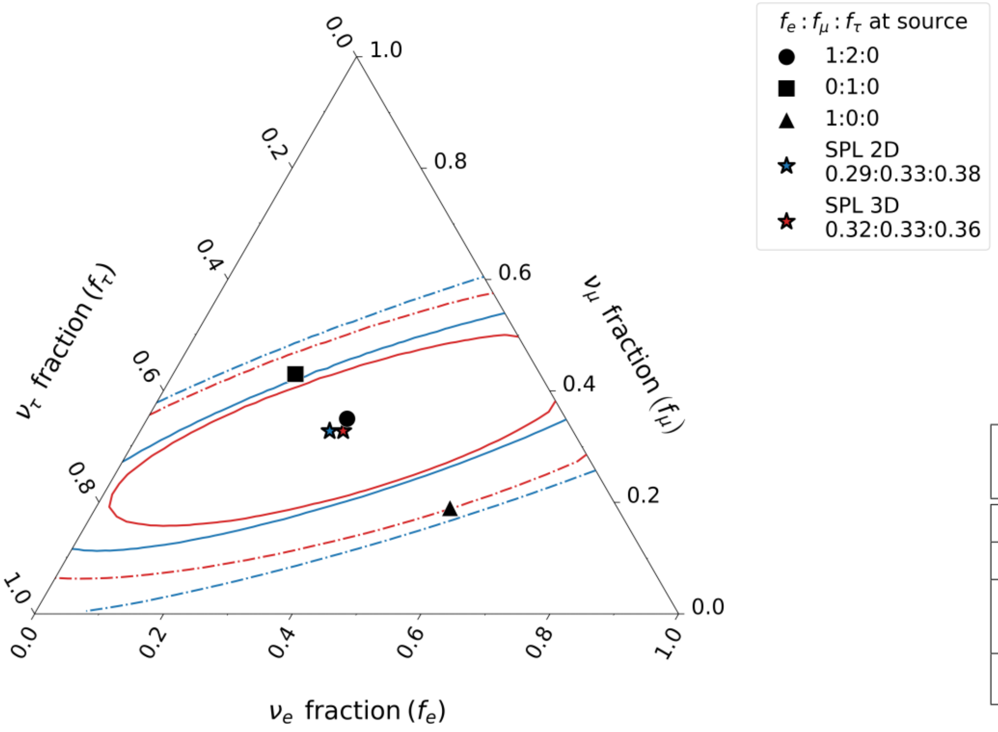
	Best fit 2D	Exclusion Limit (2D)	Best Fit 3D	Exclusion Limit (3D)
Free fit	0.29:0.33:0.38	-	0.27:0.31:0.42	-
No ν_e (0:x:1-x)	0:0.21:0.79	0.53 σ (0.60)	0:0.21:0.79	0.75 σ (0.45)
No ν_μ (x:0:1-x)	0.06:0:0.94	1.60 σ (0.11)	0.09:0:0.91	2.20 σ (0.027)
No ν_τ (x:1-x:0)	0.55:0.45:0	0.27 σ (0.79)	0.56:0.44:0	0.59σ (0.56)

Is the fit any good?



- Plot shows systematic and astrophysical parameters varying during the fit
- Mostly fine with two of some interest
  - Muon normalisation consistently lower than expected
  - Effective veto recovering higher than expected
- Could be due to 3D binning resulting in many bins with 0 events, pulling down the overall best fit flux

Sensitivity – Single Power Law

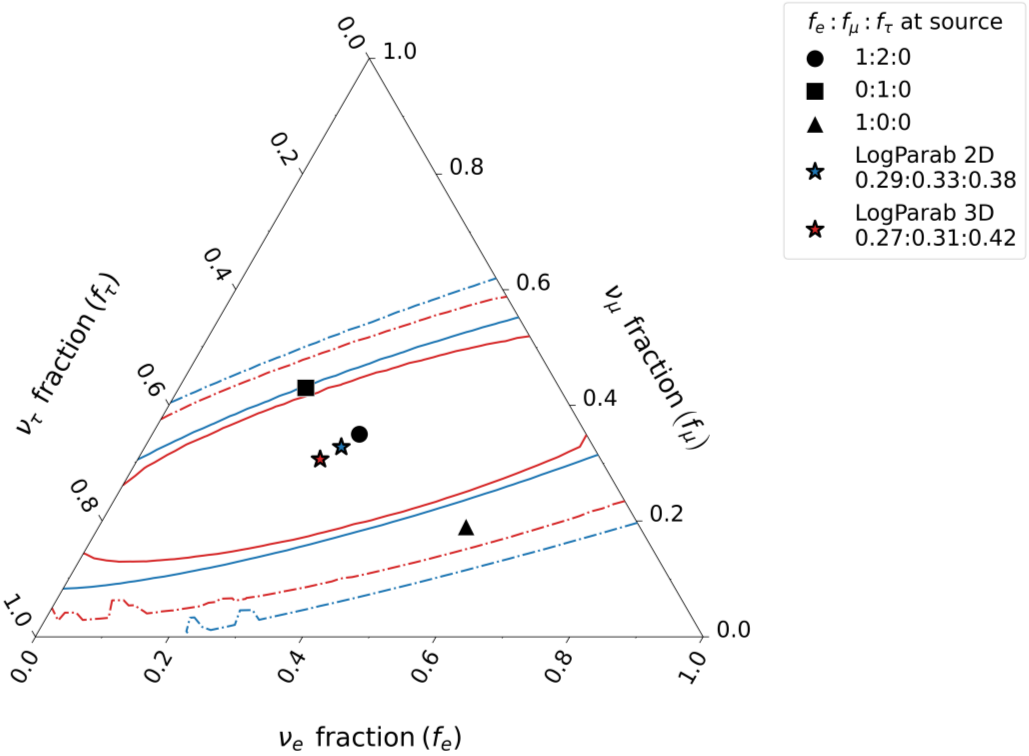


Blue = 2D binning (No y_{eff})
Red = 3D binning (incl y_{eff})

Tighter contours due to higher neutrino flux at higher energies in Asimov dataset

	Best fit 2D	Exclusion limit (2D)	Best Fit 3D	Exclusion Limit (3D)
Free fit	0.29:0.33:0.38		0.32:0.33:0.36	
No ν_e	0:0.20:0.80	0.75 σ (0.45)	0.21:0.79:0	1.08σ (0.28)
No ν_μ	0:0:1	1.87 σ (0.06)	0:0:1	2.69 σ (7.1×10^{-3})
No ν_τ	0.55:0.45:0	0.38 σ (0.70)	0.55:0.45:0	0.75σ (0.45)

Sensitivity – Log Parabolic Law



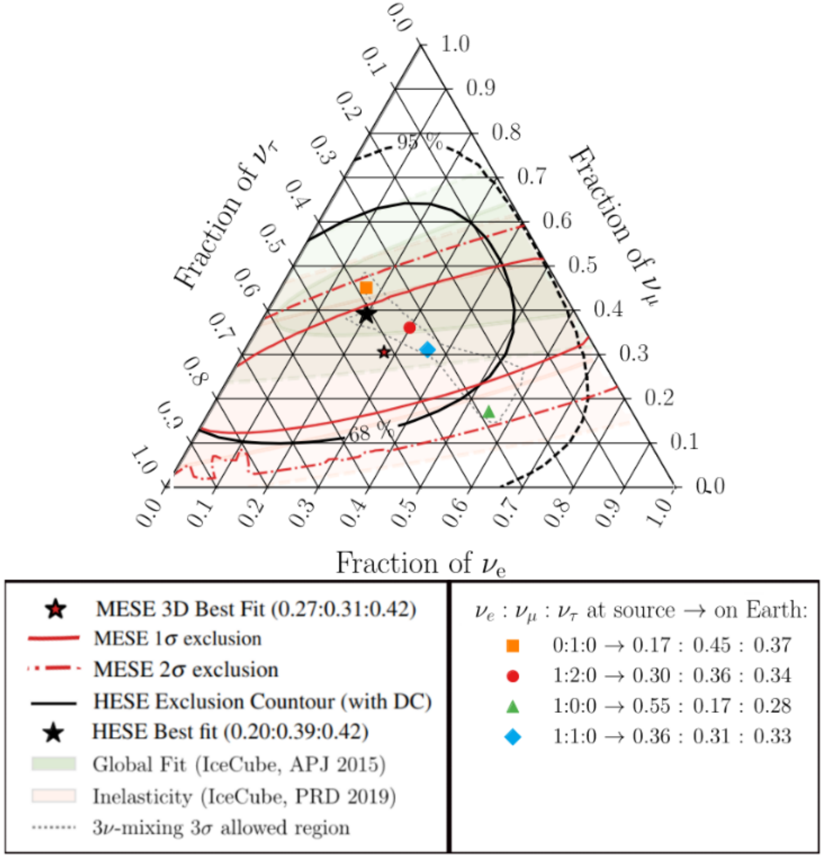
Blue = 2D binning (No y_{eff})

Red = 3D binning (incl y_{eff})

Similar constraints to BPL arising from similar drop in flux

	Best fit 2D	Exclusion limit (2D)	Best Fit 3D	Exclusion Limit (3D)
Free fit	0.29:0.33:0.38		0.27:0.31:0.42	
No ν_e	0:0.21:0.79	0.54 σ (0.59)	0:0.24:0.76	0.9 σ (0.37)
No ν_μ	0.04:0:0.96	1.66 σ (0.10)	0.09:0:0.91	2.34 σ (0.019)
No ν_τ	0.55:0.45:0	0.28 σ (0.78)	0.56:0.44:0	0.49 (0.62) σ

Global Picture



- **HESE fit using Double Cascades can exclude no nuTau**
- **But MESE using y_{eff} parameter constrains in the perpendicular phase space**
- **Overlap between NuE and NuTau makes excluding taus directly hard, but can enable fixing non-NuMu flux**

Future Outlook

- **Currently, no joint fit for DC tau search and y_{eff} tau fit**
- **Combining has the best of both worlds**
  - Use both track and cascade events
  - Constrain different parts of the flavour space

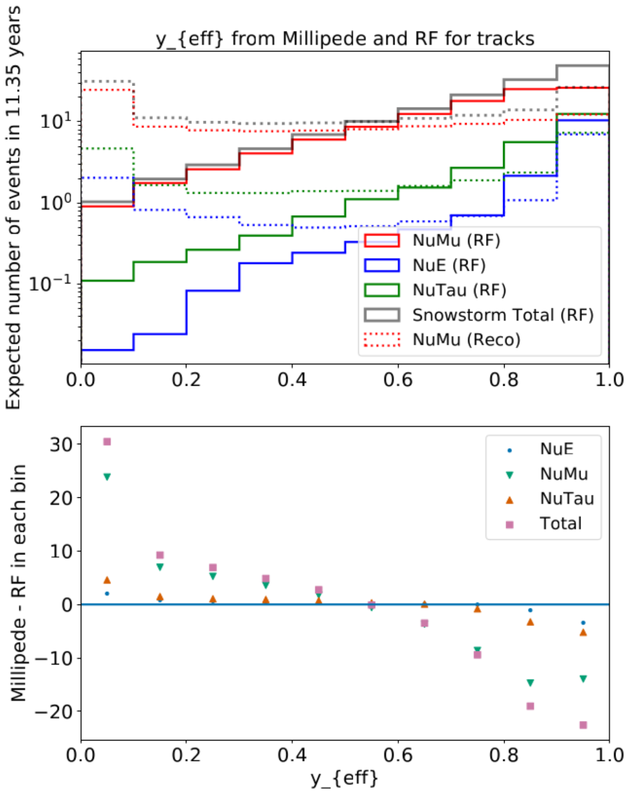
Conclusion

- We have shown the feasibility of using y_{eff} for constraining flavour in tracks with current IceCube software and data
- We demonstrated the improvement over baseline flavour fits but show we still lack exclusion of no ν_τ flux scenario
- We illustrated how our results are affected by choice of astrophysical model and compare to other results using different methods

Backup slides

What next?

- **Improve y_{eff} calculation method**
  - Neural network was trialled with no good results
- **Combined with using y_{eff} and Double Cascades**
- **The more data you take, the more leverage you have on the tau flux**



What could you do next?

- **Improve y_{eff} calculation method**
  - Neural network was trialled with no good results
- **Combined with using y_{eff} and Double Cascades**
- **The more data you take, the more leverage you have on the tau flux**

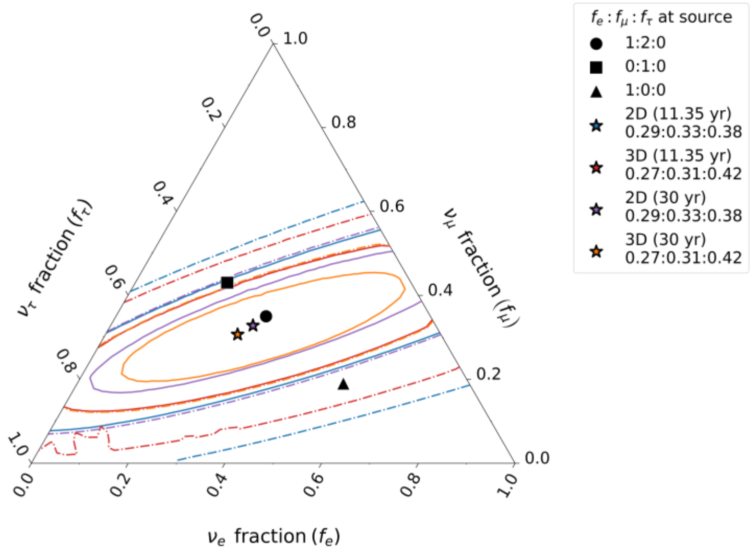


Figure 10.2: Comparison between MESE 11.35 year flavour fit, and MESE-Gen2 5 year flavour fit, both with (3D) and without (2D) the effective inelasticity parameter. Blue = MESE 2D, Orange = MESE 3D, Purple = MESE-Gen2 2D, Orange = MESE-Gen2 3D.

Correlation matrix for parameters

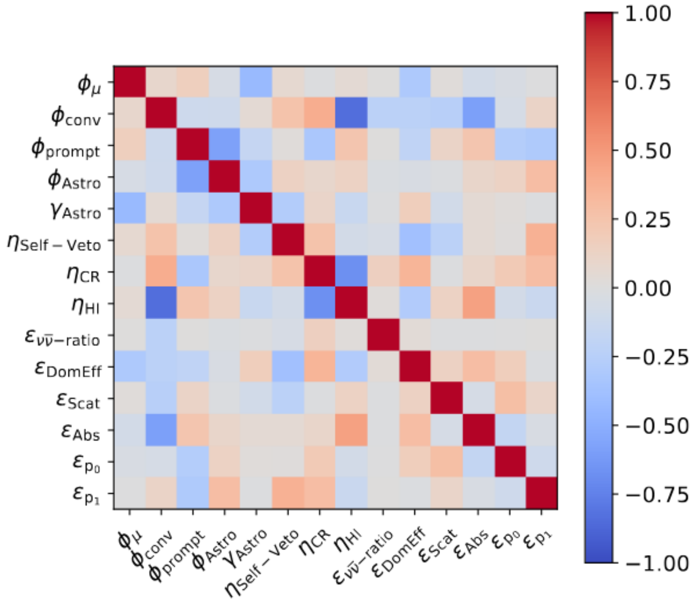


FIG. 16. Correlation matrix for the single power law flux measurement for all parameters used in the likelihood fit. The correlations are computed using the Hessian matrix.

Pulls on each bin (2D)

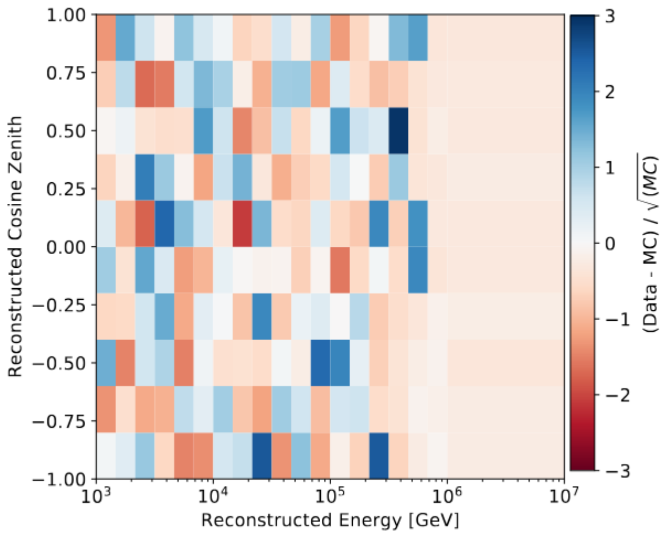


FIG. 15. The pulls on each energy/zenith bin for the data and Monte Carlo. No unexpected effects are observed.