The Flavour Composition of the IceCube Neutrinos

Aaron Vincent
IPPP Durham

Sergio Palomares-Ruiz,[1] Aaron C. Vincent,[2] and Olga Mena[1] *

[1] *Instituto de Física Corpuscular (IFIC), CSIC-Universitat de València, Apartado de Correos 22085, E-46071 Valencia, Spain*

[2] *Institute for Particle Physics Phenomenology (IPPP), Department of Physics, Durham University, Durham DH1 3LE, UK.*

arXiv:1404.0017 / PhysRevLett.113.091103
arXiv:1411.2998 / proc. ICHEP 2014
arXiv:1502.02649

Sergio Palomares-Ruiz,[1] Aaron C. Vincent,[2] and Olga Mena[1] *

[1] *Instituto de Física Corpuscular (IFIC), CSIC-Universitat de València, Apartado de Correos 22085, E-46071 Valencia, Spain*

[2] *Institute for Particle Physics Phenomenology (IPPP), Department of Physics, Durham University, Durham DH1 3LE, UK.*

arXiv:1404.0017 / PhysRevLett.113.091103
arXiv:1411.2998 / proc. ICHEP 2014
arXiv:1502.02649

*no affiliation with IceCube

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Sergio Palomares-Ruiz,[1] Aaron C. Vincent,[2] and Olga Mena[1] *

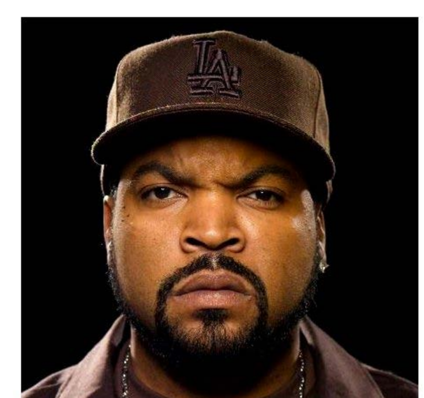
[1] *Instituto de Física Corpuscular (IFIC), CSIC-Universitat de València, Apartado de Correos 22085, E-46071 Valencia, Spain*

[2] *Institute for Particle Physics Phenomenology (IPPP), Department of Physics, Durham University, Durham DH1 3LE, UK.*

arXiv:1404.0017 / PhysRevLett.113.091103
arXiv:1411.2998 / proc. ICHEP 2014
arXiv:1502.02649

*no affiliation with IceCube (or Ice Cube)

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY



Motivation

High energy neutrinos are expected to be produced in astrophysical objects by the decays of charged pions made in cosmic ray interactions with radiation or gas.

-IceCube Collaboration, PRL 113, 101101 (2014)

Everyone agrees… but is this indeed what we have seen?

Most studies so far have tried to identify sources by correlating with poorly-resolved arrival direction. What can we say from the **flavour** & **energy** composition alone?

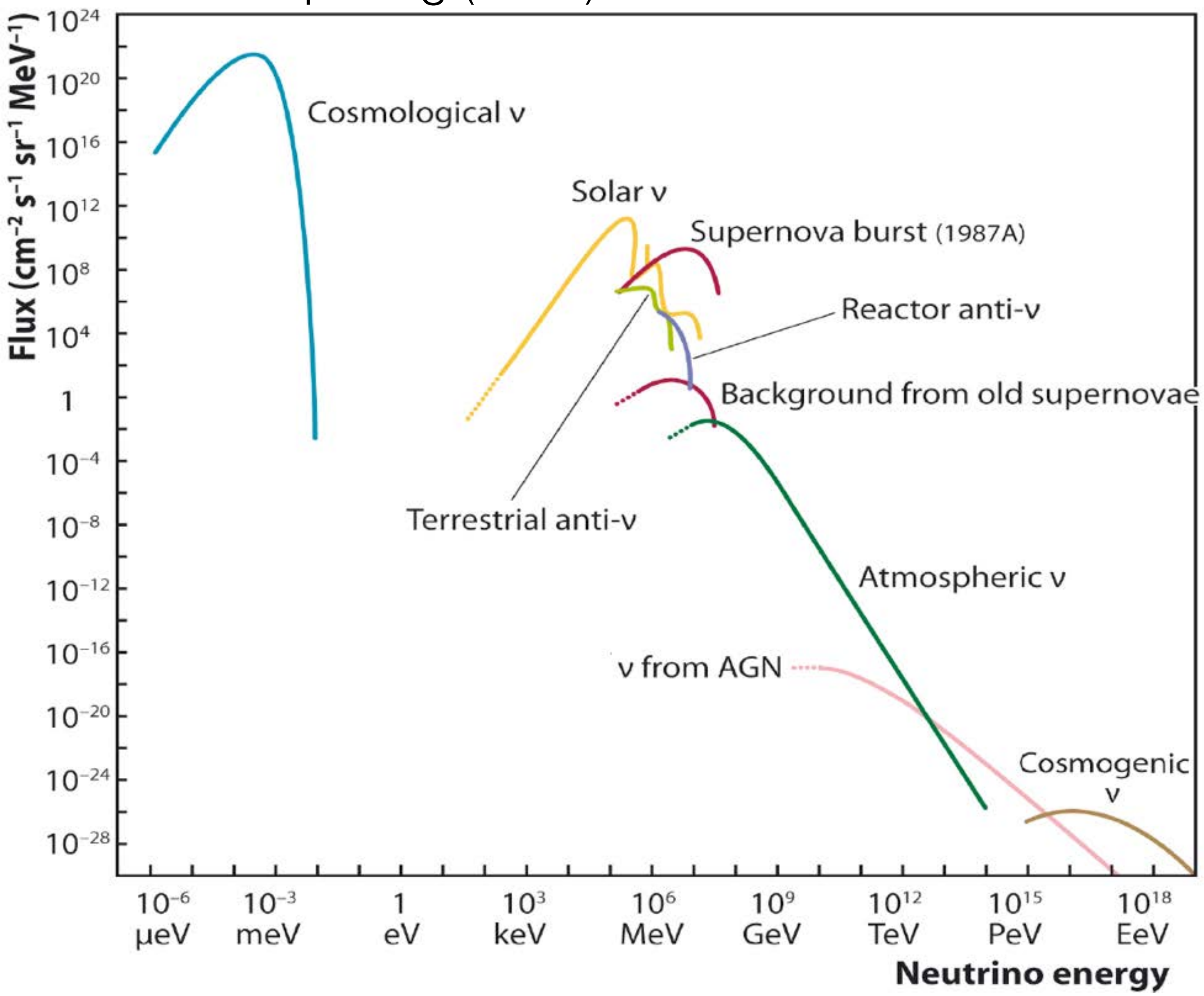
The dawn of neutrino astronomy

Neutrinos are ridiculously weakly interacting, but this can be seen as a feature, rather than a bug:

- They allow us to see *inside* sources (eg. SN 1987A)
- Unlike cosmic rays they point back at their source
- Unlike protons, photons, there is no attenuation in IGM
- Also: quantum number not carried by photons, CRs: *flavour*

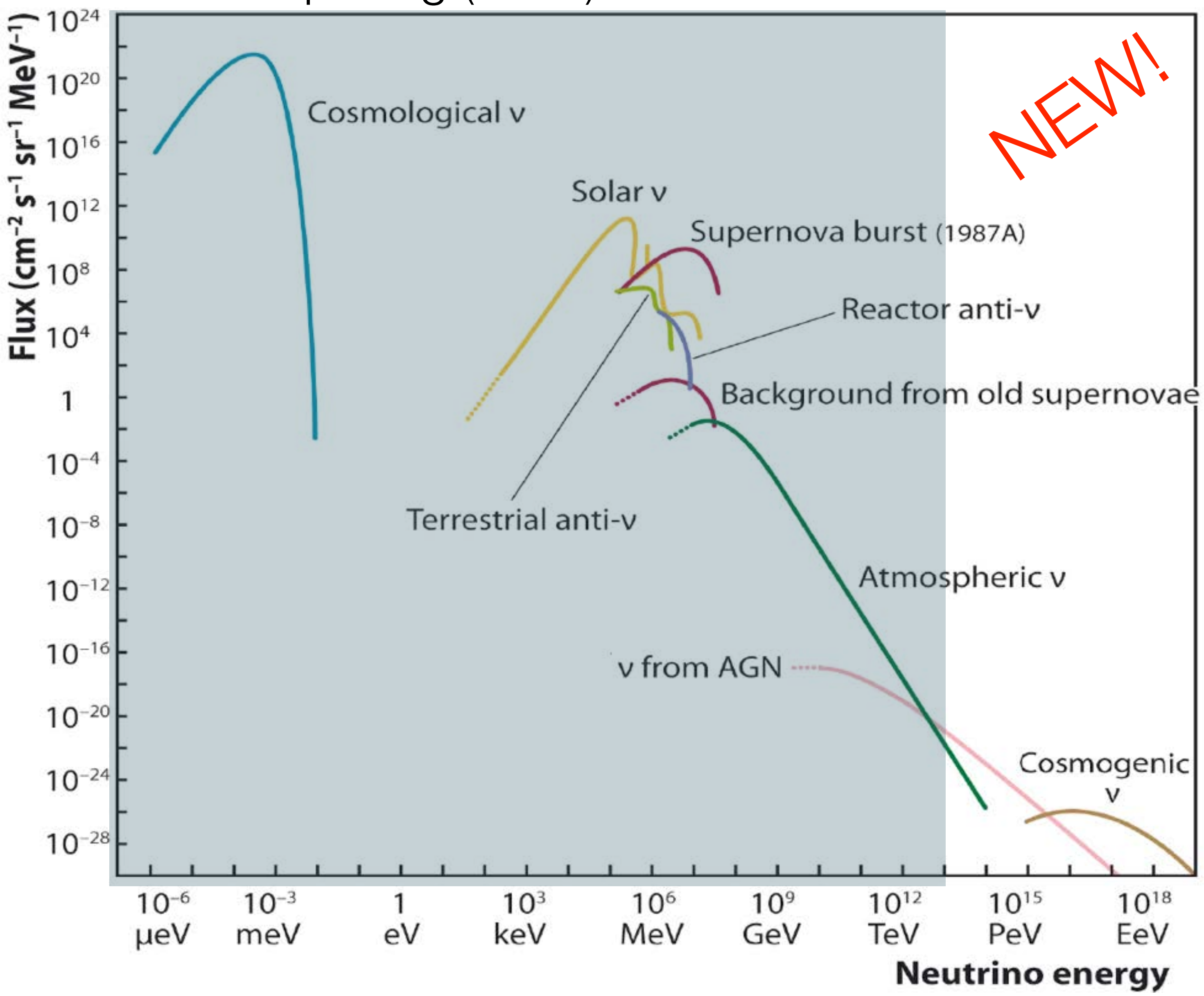
Where do neutrinos come from?

Katz & Spiering (2012)



Where do neutrinos come from?

Katz & Spiering (2012)



Flavour composition in astrophysical sources

(GRBs, AGNs, blazars, pulsars…) $(\alpha_e : \alpha_\mu : \alpha_\tau)$

Pion sources $\pi^+ \to \mu^+ + \nu_\mu$

(c.c. for π^-) $\mu^+ \to e^+ + \nu_\mu + \bar{\nu}_e$

(1 : 2 : 0)

“muon-damped” $\pi^+ \to \cancel{\mu^+} + \nu_\mu$

(c.c. for π^-)

(0 : 1 : 0)

“muon source” $\pi^+ \to \mu^+ + \cancel{\nu_\mu}$

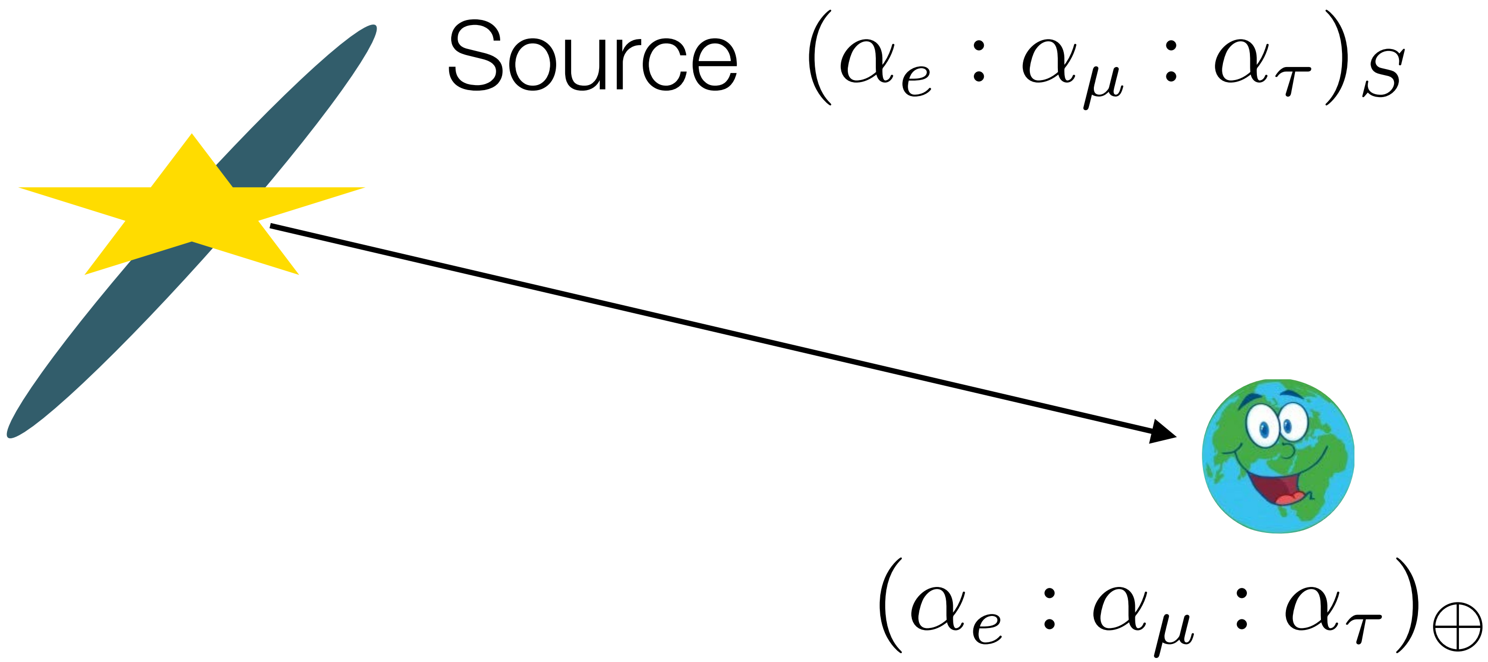
(c.c. for π^-) $\mu^+ \to e^+ + \nu_\mu + \bar{\nu}_e$

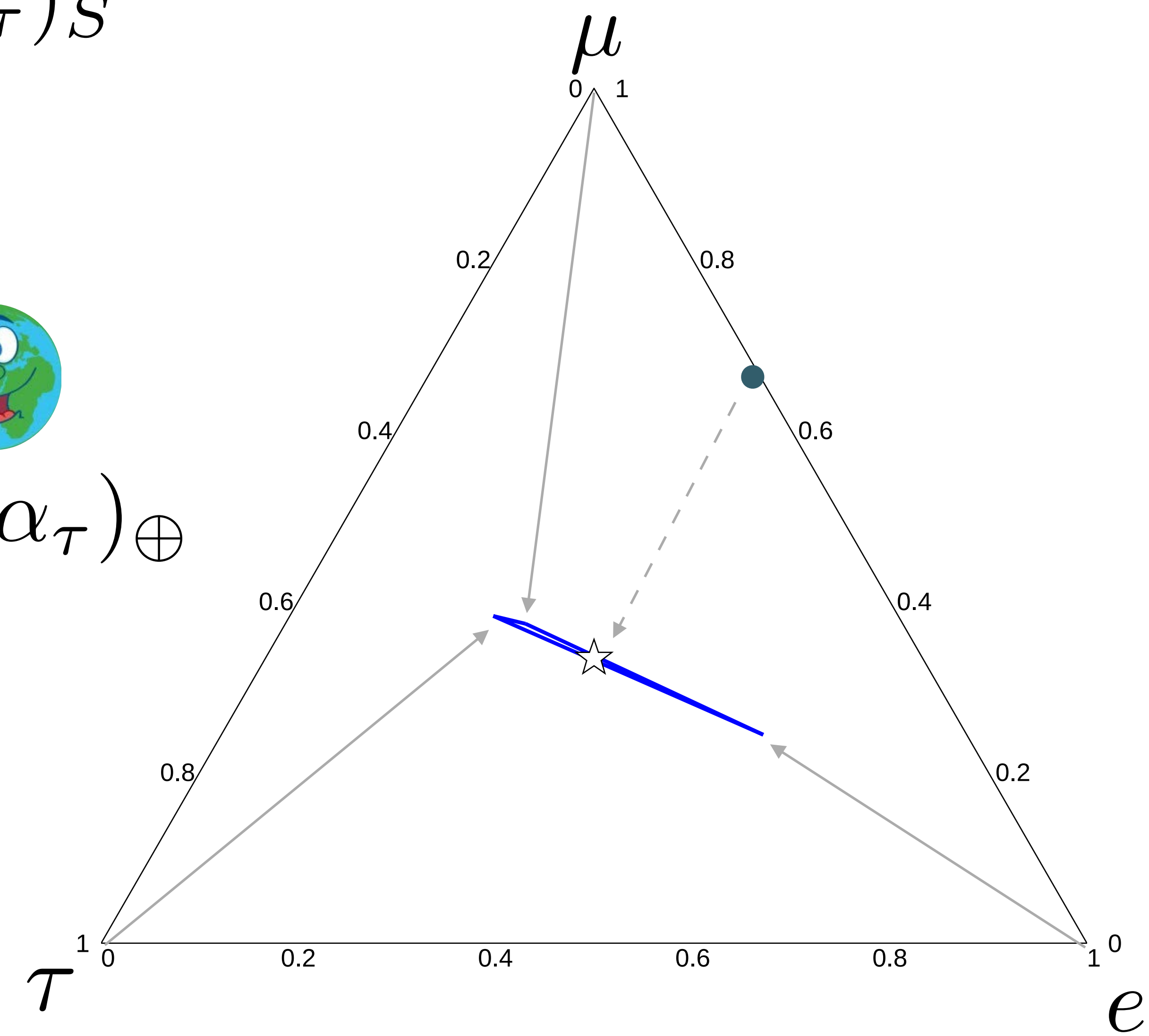
(1 : 1 : 0)

Neutron source $n \to p + e^- + \bar{\nu}_e$

(1 : 0 : 0)

Travel to earth



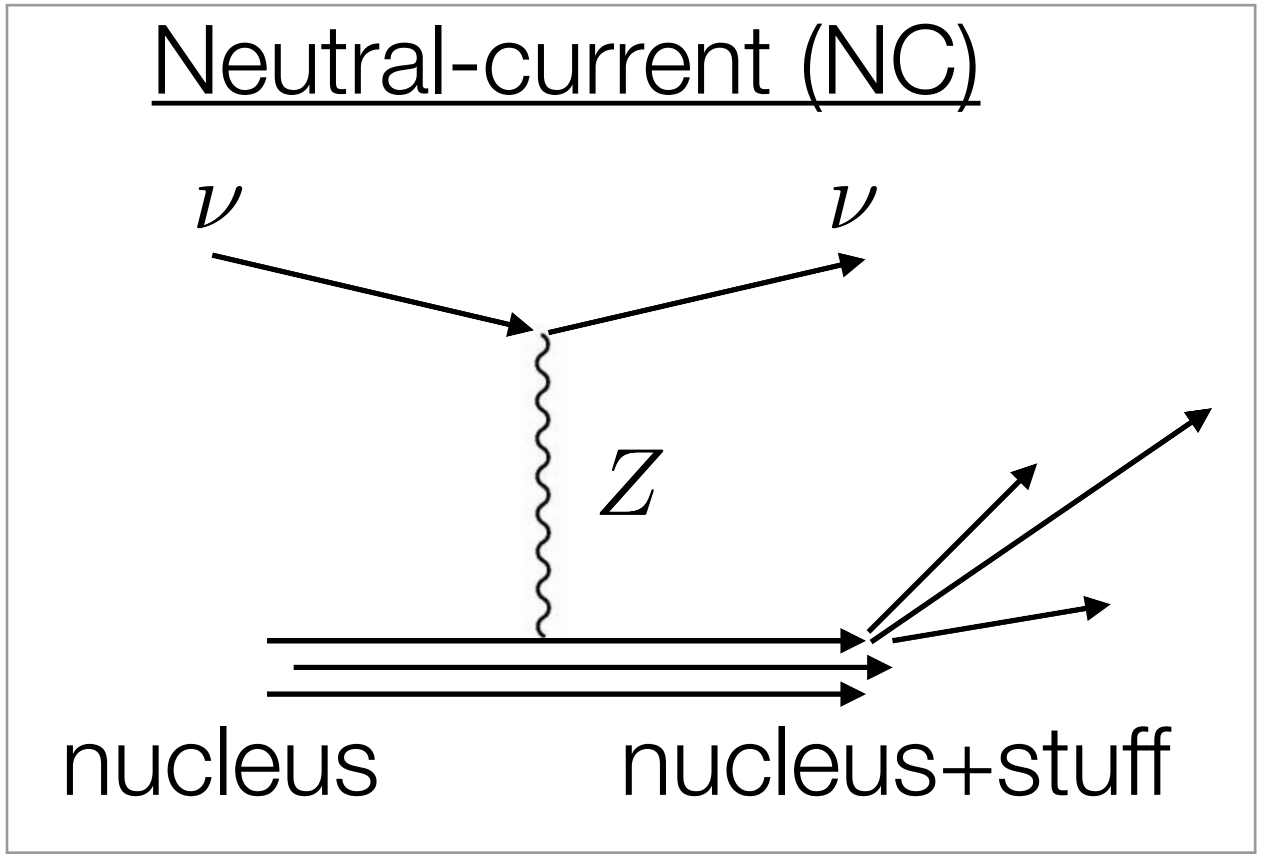


$$\{\alpha_j\}_\oplus = \sum_{k,i} |U_{jk}|^2 |U_{ik}|^2 \{\alpha_j\}_S$$

$$\simeq \frac{1}{18} \begin{pmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{pmatrix}$$

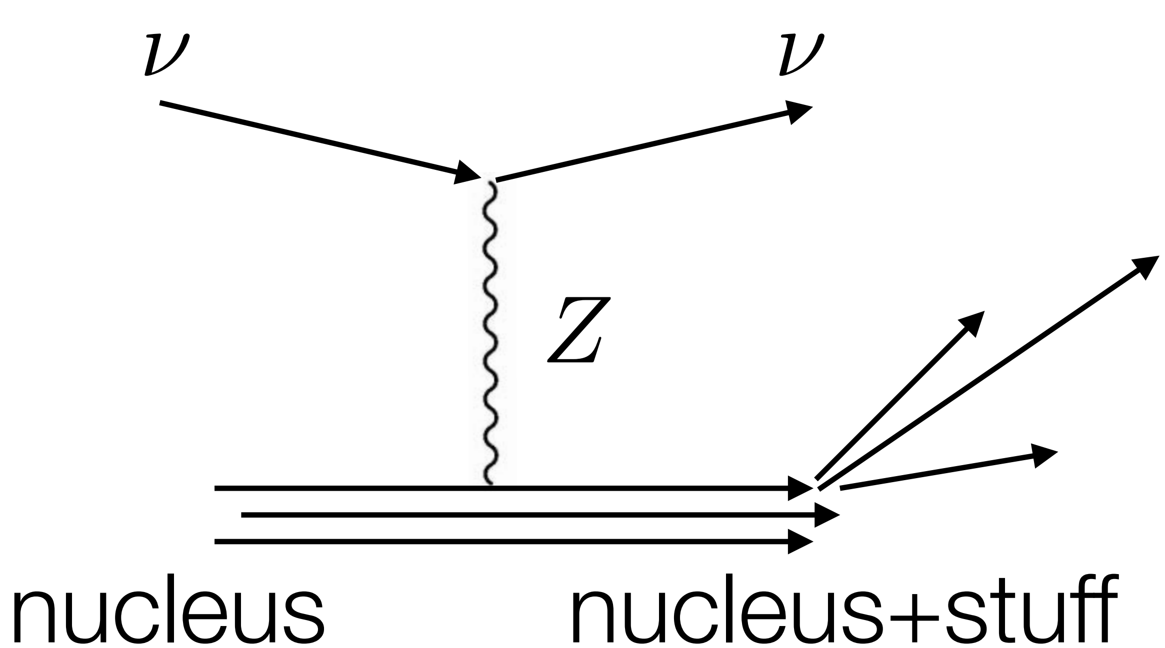
$$(1:2:0) \to (1:1:1)$$
$$(0:1:0) \to (4:7:7)$$
$$(1:0:0) \to (5:2:2)$$

Interactions with the charged sector: detection

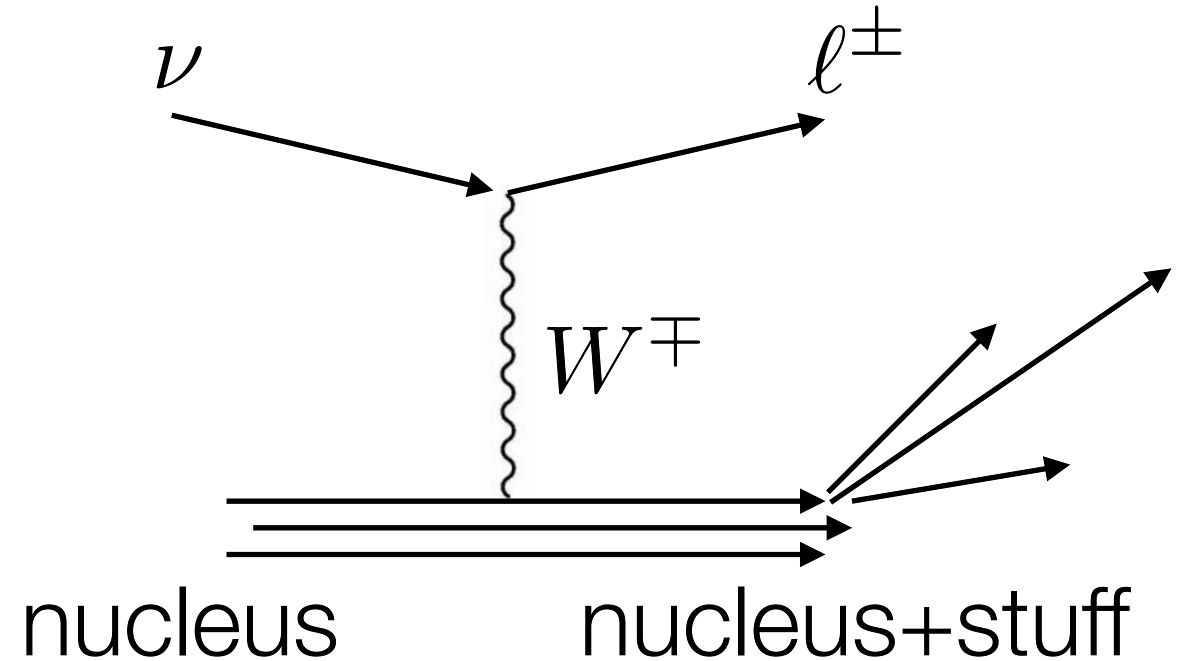


Interactions with the charged sector: detection

Neutral-current (NC)



Charged-current (CC)



Final-state lepton:

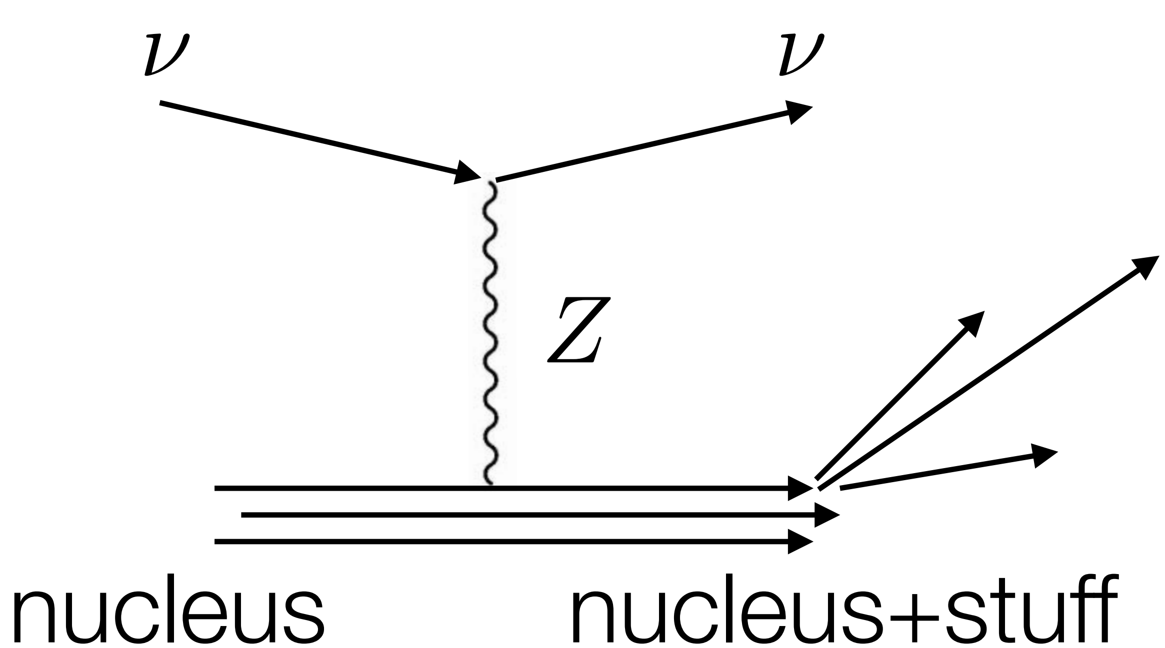
electron: deposits E

muon: can travel ~ km

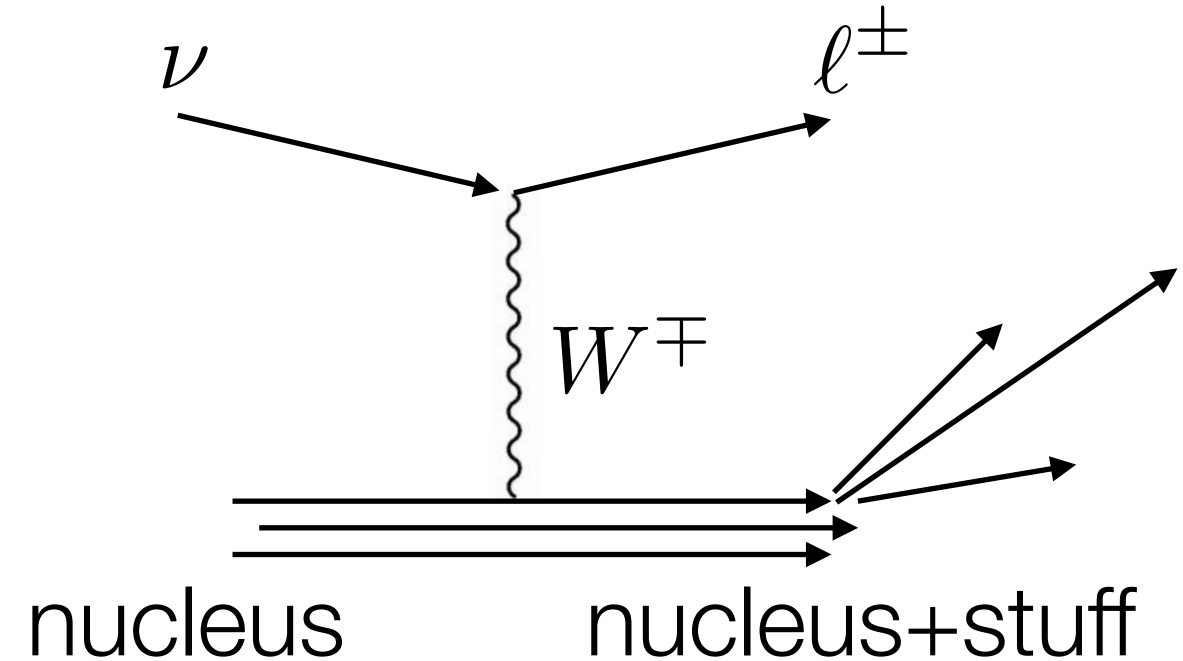
tau : decays to stuff, with 20% b.r. to muon.

Interactions with the charged sector: detection

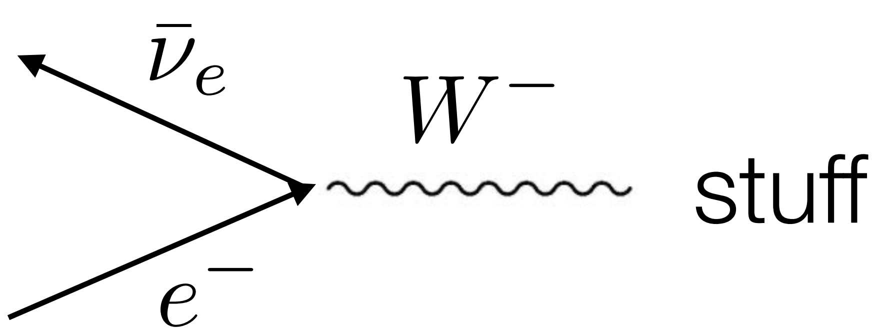
<u>Neutral-current (NC)</u>



<u>Charged-current (CC)</u>



<u>electron</u>



<u>Final-state lepton:</u>

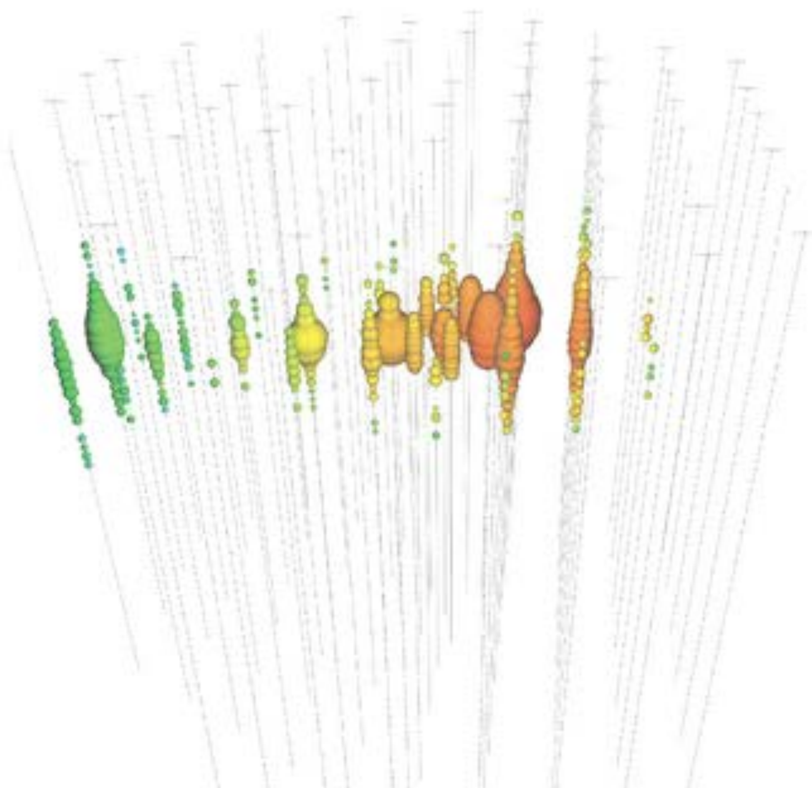
electron: deposits E

muon: can travel ~ km

tau : decays to stuff, with 20% b.r. to muon.

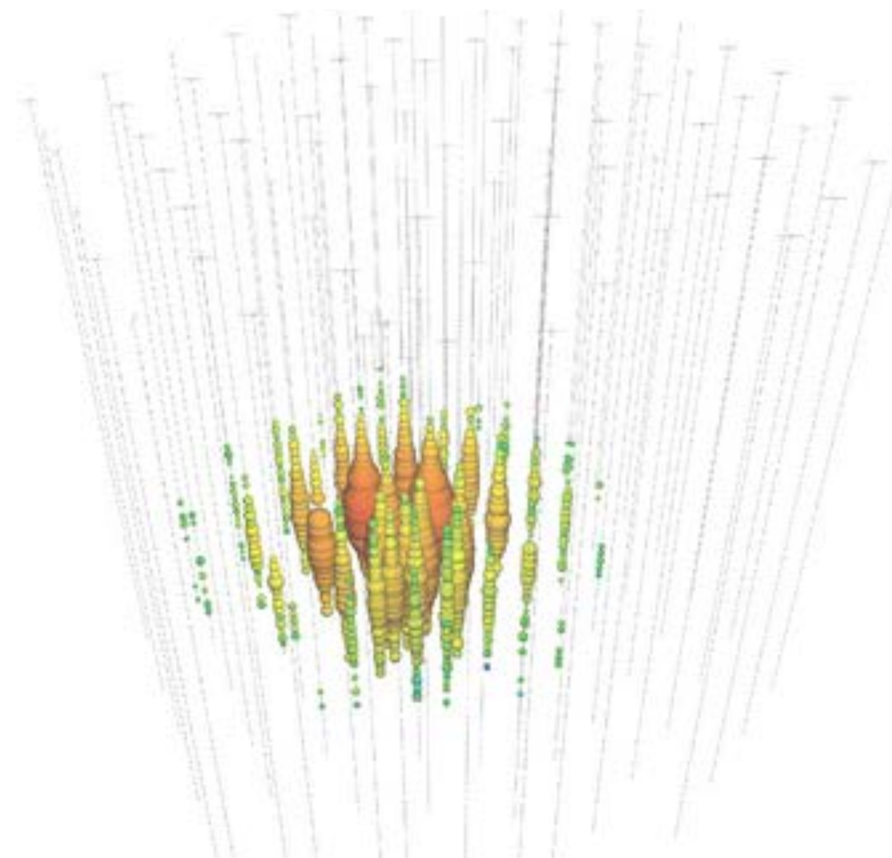
Event topology

Muon track



good angular res. (~ degree)

Shower (cascade)



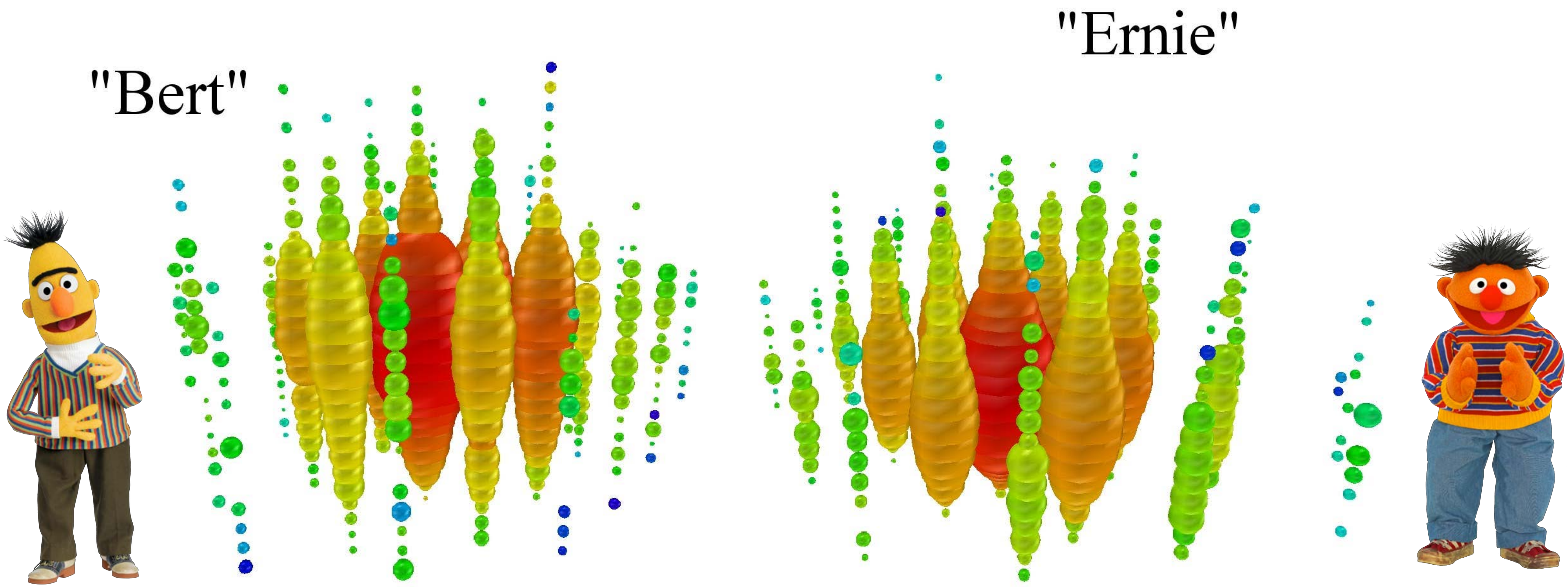
bad angular res. (~ 10 degrees)

Other topologies at even higher energies (when tau lifetime ~ detector resolution):

- Double-bang
- lollipop
- popillol

Images: icecube.wisc.edu

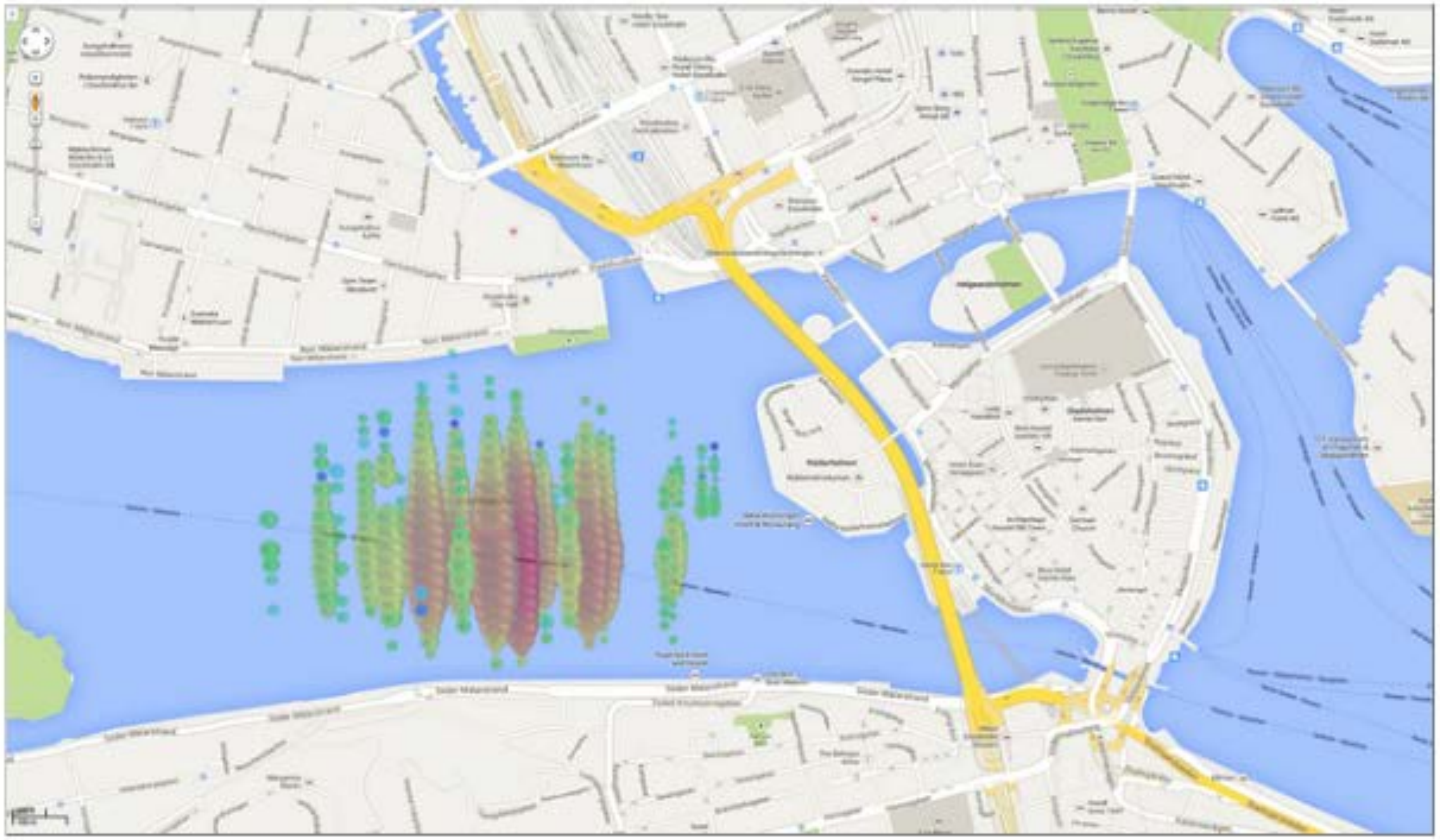
First “light”



August 9, 2011: 1.04 PeV **January 3, 2012: 1.14 PeV**

Images: IceCube/Sesame Workshop

Stockholm for scale



icecube.wisc.edu

New Search Protocol

28 events after 2 years of data

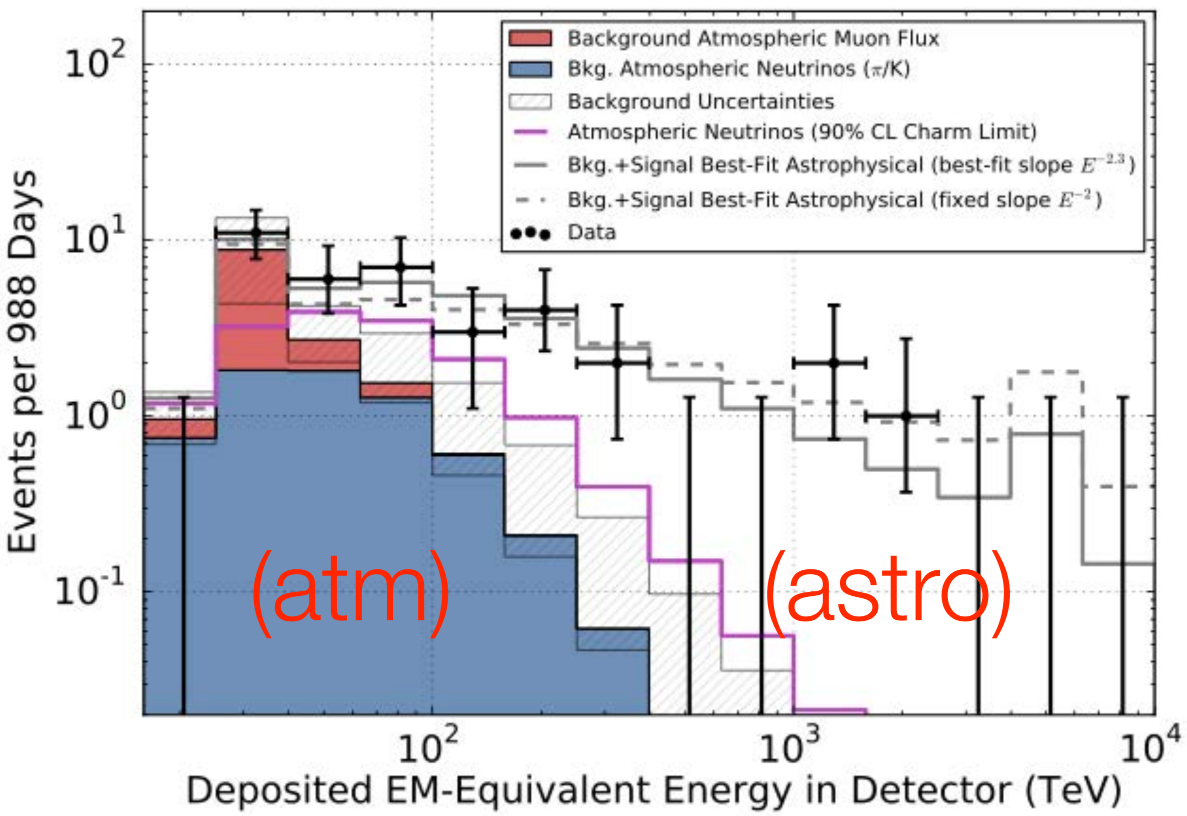
37 events after 3 years of data

(out of 3000 atm. events/s!!!)

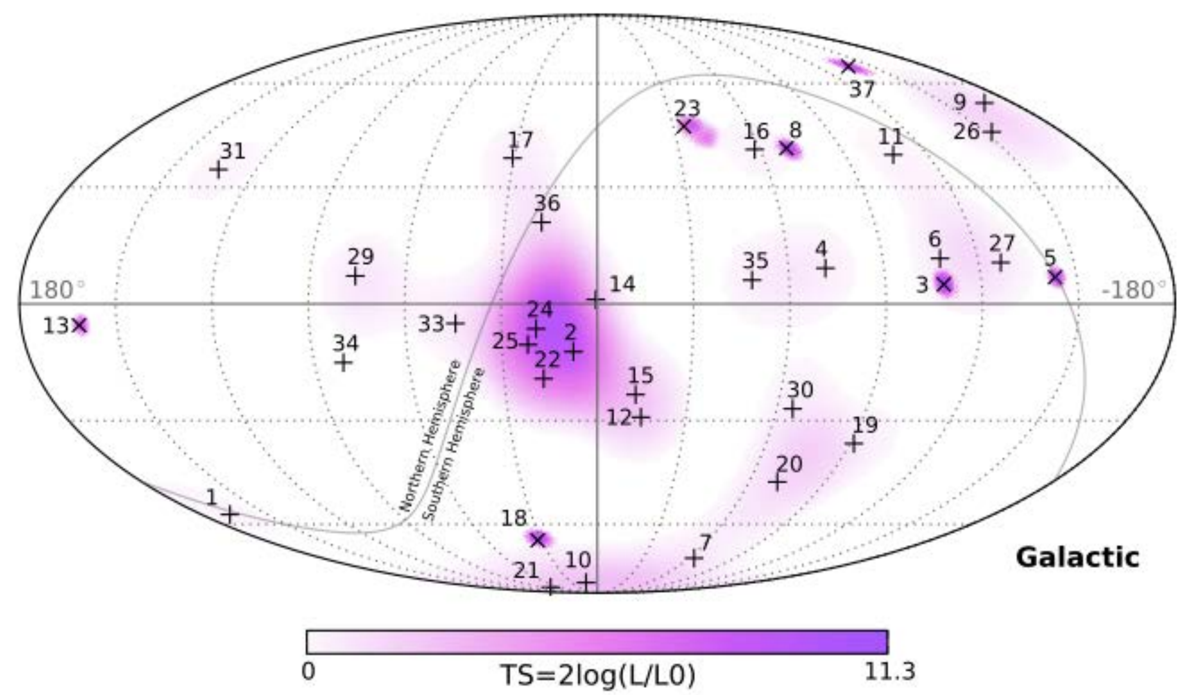
The 36 IceCube events

8 muon tracks, 28 showers

30 TeV < E < 2 PeV



Still consistent with an Isotropic flux



most analyses assume (1:1:1) - let’s examine this hypothesis

IceCube Collaboration, PRL 113, 101101 (2014)

Flavour analysis (arXiv:1404.0017)

Likelihood analysis: tracks vs showers

$$p_{\rm a}^{\rm tr}(\{\alpha_{i,\oplus}\}) = \frac{1}{N_{\rm a}(\{\alpha_{i,\oplus}\})}\left(\alpha_{\mu,\oplus}\,N_{\nu_\mu}^{\rm tr} + \alpha_{\tau,\oplus}\,N_{\nu_\tau}^{\rm tr}\right)$$

$$p_{\rm a}^{\rm sh}(\{\alpha_{i,\oplus}\}) \equiv 1 - p_{\rm a}^{\rm tr}(\{\alpha_{i,\oplus}\})$$

$N_{\nu_i}^{tr/sh}$ depends on

- -spectrum
- -cross section
- -effective mass
- -attenuation
- -fraction of E —> EM energy

$$\mathcal{L}(\{\alpha_{i,\oplus}\}, N_{\rm a}|N_{\rm tr}, N_{\rm sh}) = e^{-(p_{\rm a}^{\rm tr}N_{\rm a}+p_{\mu}^{\rm tr}b_\mu+p_{\nu}^{\rm tr}b_\nu)}\,\frac{(p_{\rm a}^{\rm tr}\,N_{\rm a}+p_{\mu}^{\rm tr}\,b_\mu+p_{\nu}^{\rm tr}\,b_\nu)^{N_{\rm tr}}}{N_{\rm tr}!} \times e^{-(p_{\rm a}^{\rm sh}N_{\rm a}+p_{\mu}^{\rm sh}b_\mu+p_{\nu}^{\rm sh}b_\nu)}\,\frac{(p_{\rm a}^{\rm sh}\,N_{\rm a}+p_{\mu}^{\rm sh}\,b_\mu+p_{\nu}^{\rm sh}\,b_\nu)^{N_{\rm sh}}}{N_{\rm sh}!}$$

$N_{\rm a}$ → (free)

$N_{\rm tr}$ → 8

$N_{\rm sh}$ → 28

Likelihood analysis: tracks vs showers

$$p_{\rm a}^{\rm tr}(\{\alpha_{i,\oplus}\}) = \frac{1}{N_{\rm a}(\{\alpha_{i,\oplus}\})}\left(\alpha_{\mu,\oplus} N_{\nu_\mu}^{\rm tr} + \alpha_{\tau,\oplus} N_{\nu_\tau}^{\rm tr}\right)$$

$$p_{\rm a}^{\rm sh}(\{\alpha_{i,\oplus}\}) \equiv 1 - p_{\rm a}^{\rm tr}(\{\alpha_{i,\oplus}\}).$$

$N_{\nu_i}^{tr/sh}$ depends on

-spectrum

-cross section

-effective mass

-attenuation

-fraction of E —> EM energy

$$\mathcal{L}(\{\alpha_{i,\oplus}\}, N_{\rm a}|N_{\rm tr}, N_{\rm sh}) = e^{-(p_{\rm a}^{\rm tr} N_{\rm a} + p_\mu^{\rm tr} b_\mu + p_\nu^{\rm tr} b_\nu)} \frac{(p_{\rm a}^{\rm tr} N_{\rm a} + p_\mu^{\rm tr} b_\mu + p_\nu^{\rm tr} b_\nu)^{N_{\rm tr}}}{N_{\rm tr}!} \times e^{-(p_{\rm a}^{\rm sh} N_{\rm a} + p_\mu^{\rm sh} b_\mu + p_\nu^{\rm sh} b_\nu)} \frac{(p_{\rm a}^{\rm sh} N_{\rm a} + p_\mu^{\rm sh} b_\mu + p_\nu^{\rm sh} b_\nu)^{N_{\rm sh}}}{N_{\rm sh}!}$$

(free)

8 28

Naively, (1:1:1) gives (track : shower) of (1:4)

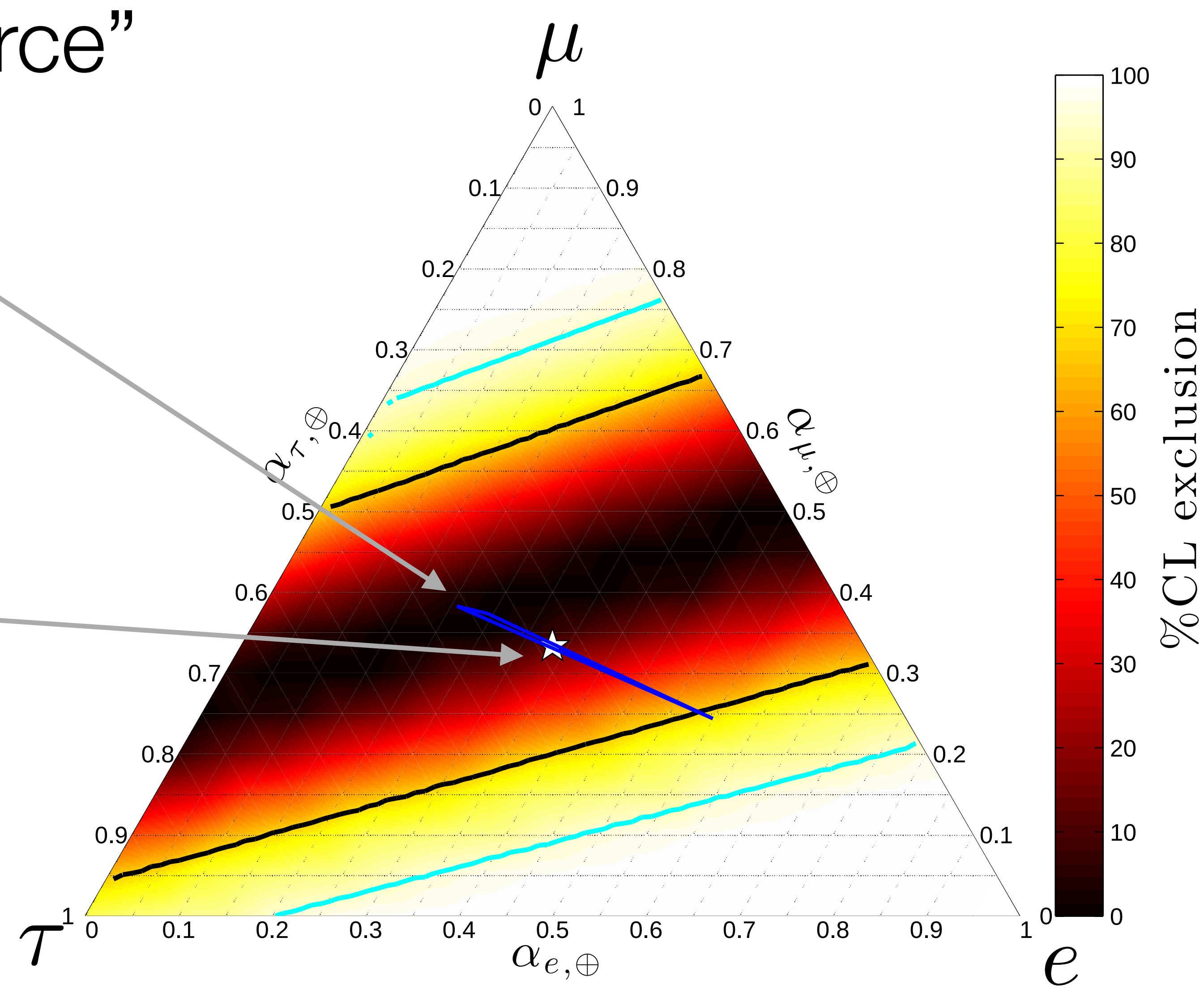
Flavour composition at Earth: no backgrounds

Allowed "source" triangle from oscillation

(1:1:1), from (1:2:0) at source

95% excl.

68% excl.

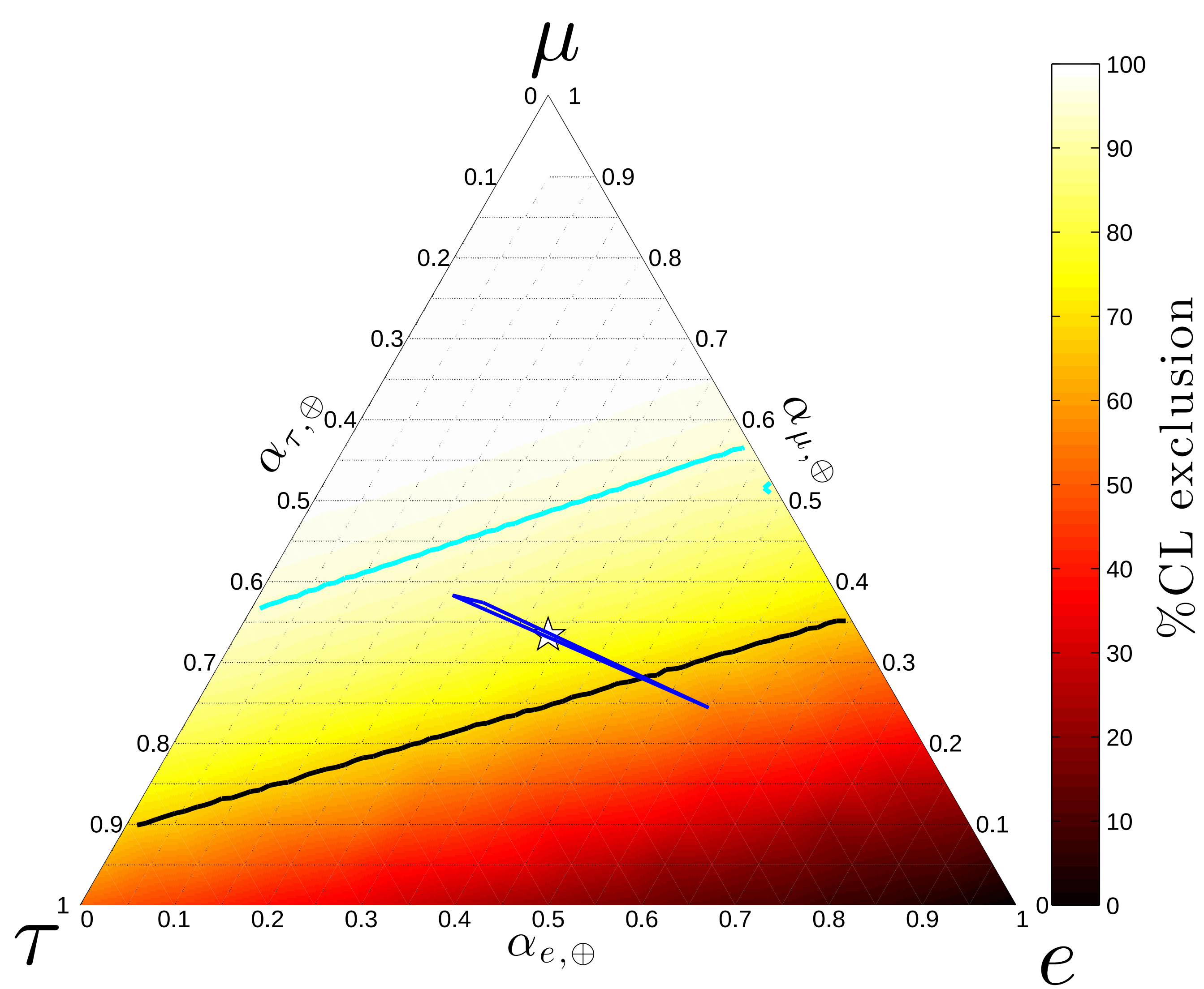


Basis of all analyses by IceCube until 2015: data reflects (1:1:1)

Atmospheric background

- Neutrinos
  - 50%-70% produce tracks
  - **Expect ~ 6.6 in 3yr data**
- Muons
  - ~100% produce tracks
  - **Expect ~ 8.4 in 3yr data**

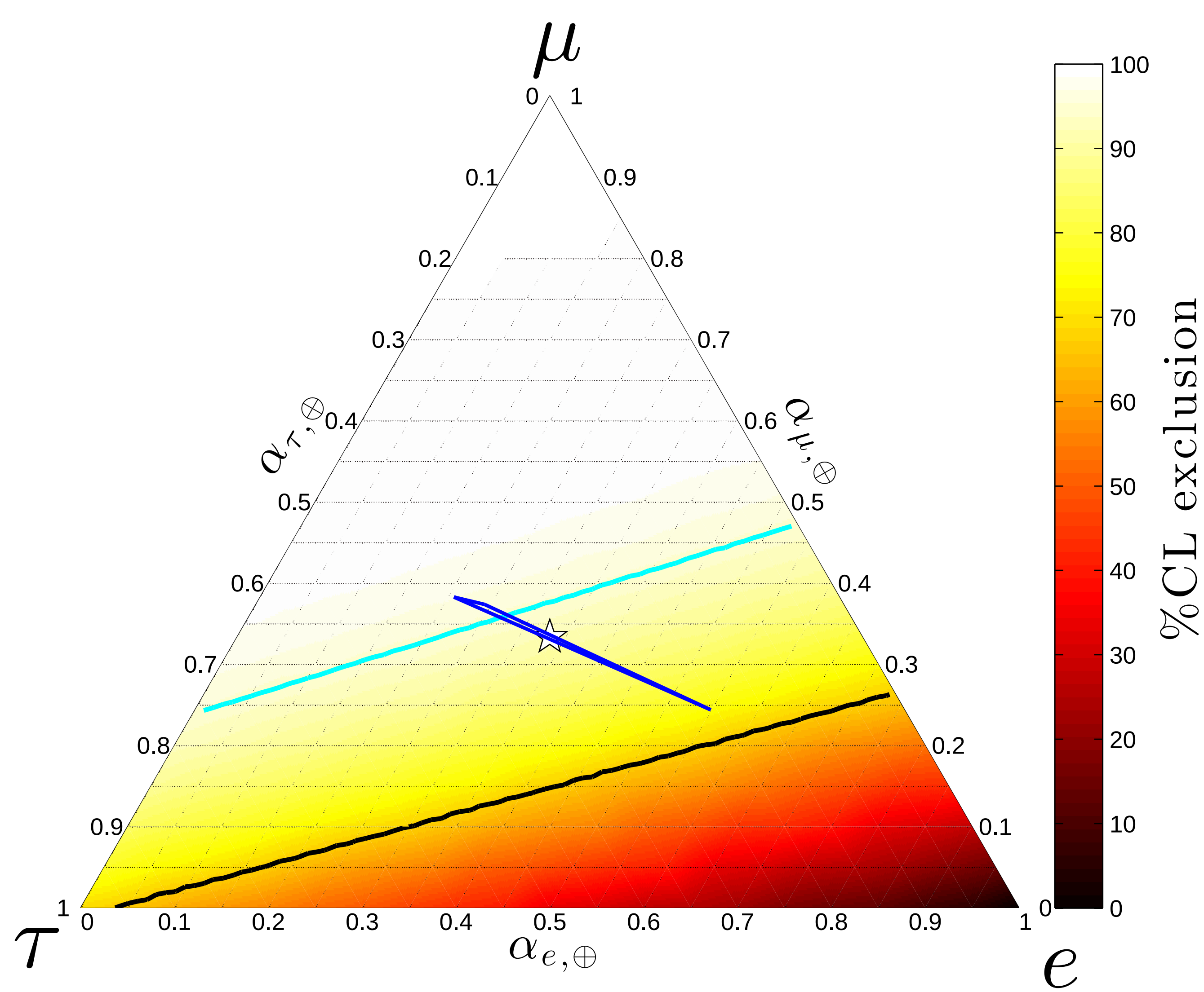
Two-year flavour composition: adding backgrounds



95% excl.

68% excl.

Three-year flavour composition



95% excl.

68% excl.

(1:1:1) excluded at 92% C.L.

Not surprising

From background muons & neutrinos,
~12.1 tracks are expected

Only 8 are observed

Very little room for astrophysical muon neutrinos!

Spectral analysis (arXiv:1502.02649)

New technology

- Include spectral information (and errors) on all the observed neutrino events
- Simultaneously vary all model parameters (spectral index, number of atmospheric bg. neutrinos & muons, flavours and astro flux)
- Slower/stronger/better calculation of the angle-averaged atmospheric fluxes + attenuation & regen.
- Tricky effective mass inversion (function of *deposited* E)
- More accurate computation of the muon track energy deposition

Unbinned analysis

Instead of *N*: $$\frac{dN^c}{dE_{\rm true}} = T\,N_A \int_0^\infty M_{\rm eff}(E_{\rm true})\,Att_{\nu_\ell}(E_\nu)\,\frac{\phi_{\nu_\ell}(E_\nu)}{dE_\nu}\,\frac{d\sigma^c_{\nu_\ell}(E_\nu, E_{\rm true})}{dE_{\rm true}}\,dE_\nu$$

↓

$$\frac{dN^c}{dE_{{\rm dep},i}} = \int_0^\infty \frac{dN^c}{dE_{\rm true}}\,R(E_{\rm true}, E_{{\rm dep},i}, \sigma(E_{\rm true}))\,dE_{\rm true}$$

$$\mathcal{P}^a_i(\{\alpha\},\gamma) = \frac{1}{\sum_{\ell,k}\alpha_\ell \int_{E_{\rm min}}^{E_{\rm max}} dE_{\rm dep}\,\frac{dN^k_{a,\ell}}{dE_{\rm dep}}} \sum_\ell \alpha_\ell \frac{dN^i_{a,\ell}}{dE_{{\rm dep},i}}$$

& likewise for atmospherics

$$\mathcal{L}_{k,i} = N_a\,\mathcal{P}^a_i(\{\alpha\},\gamma) + N_\nu\,\mathcal{P}^\nu_i + N_\mu\,\mathcal{P}^\mu_i + N_p\,\mathcal{P}^p_i$$

$$\mathcal{L} = e^{-N_a - N_\nu - N_\mu - N_p} \prod_{i=1}^{N_{\rm sh,obs}} \mathcal{L}_{{\rm sh},i} \prod_{i=1}^{N_{\rm tr,obs}} \mathcal{L}_{{\rm tr},i}$$

→ throw into MultiNest

Unbinned analysis

Instead of *N*:

$$\frac{dN^c}{dE_{\rm true}} = T\, N_A \int_0^\infty M_{\rm eff}(E_{\rm true})\, Att_{\nu_\ell}(E_\nu)\, \frac{\phi_{\nu_\ell}(E_\nu)}{dE_\nu}\, \frac{d\sigma^c_{\nu_\ell}(E_\nu, E_{\rm true})}{dE_{\rm true}}\, dE_\nu$$

↓

$$\frac{dN^c}{dE_{{\rm dep},i}} = \int_0^\infty \frac{dN^c}{dE_{\rm true}} R(E_{\rm true}, E_{{\rm dep},i}, \sigma(E_{\rm true}))\, dE_{\rm true}$$

$$\mathcal{P}_i^a(\{\alpha\},\gamma) = \frac{1}{\sum_{\ell,k} \alpha_\ell \int_{E_{\rm min}}^{E_{\rm max}} dE_{\rm dep} \frac{dN^k_{a,\ell}}{dE_{\rm dep}}} \sum_\ell \alpha_\ell \frac{dN^i_{a,\ell}}{dE_{{\rm dep},i}}$$

& likewise for atmospherics

$$\mathcal{L}_{k,i} = N_a\, \mathcal{P}_i^a(\{\alpha\},\gamma) + N_\nu\, \mathcal{P}_i^\nu + N_\mu\, \mathcal{P}_i^\mu + N_p\, \mathcal{P}_i^p$$

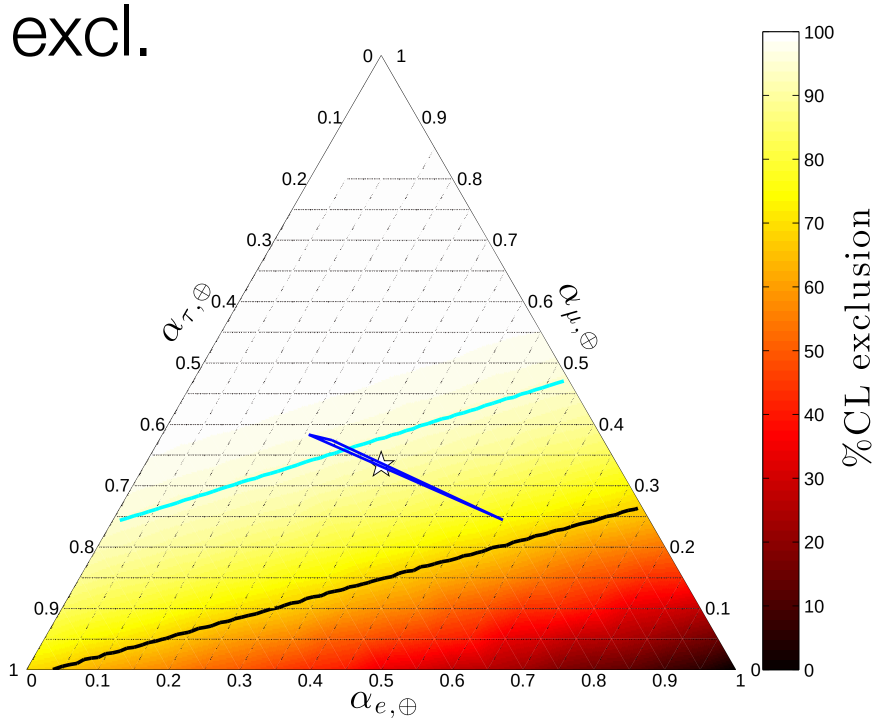
$$\mathcal{L} = e^{-N_a - N_\nu - N_\mu - N_p} \prod_{i=1}^{N_{\rm sh,obs}} \mathcal{L}_{{\rm sh},i} \prod_{i=1}^{N_{\rm tr,obs}} \mathcal{L}_{{\rm tr},i}$$

→ throw into MultiNest

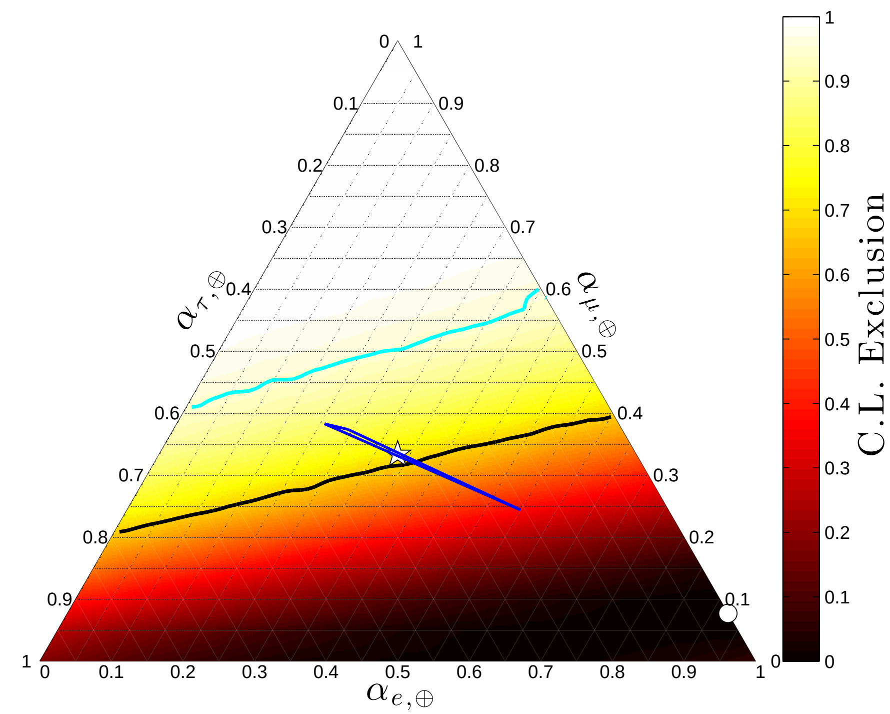
Including spectral information (28 TeV - 3 PeV)

95% excl.

68% excl.



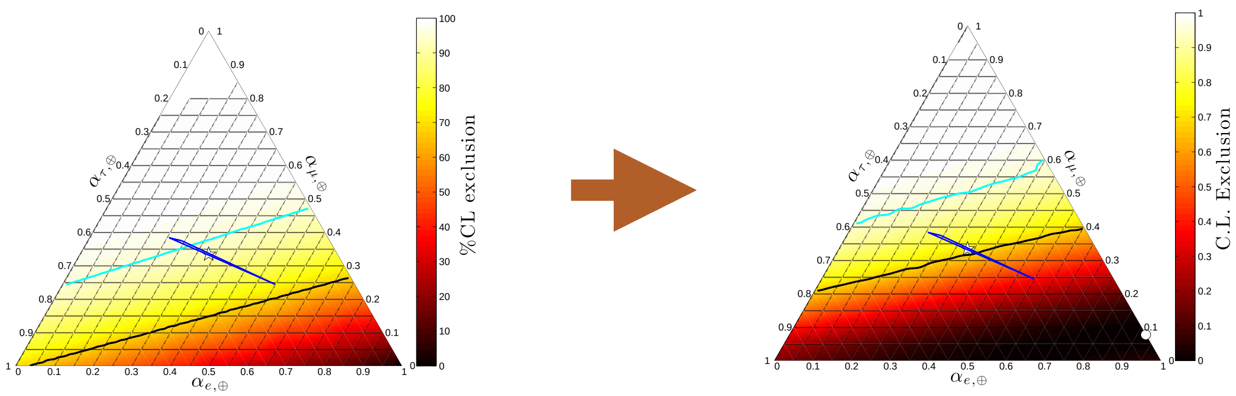
only topology

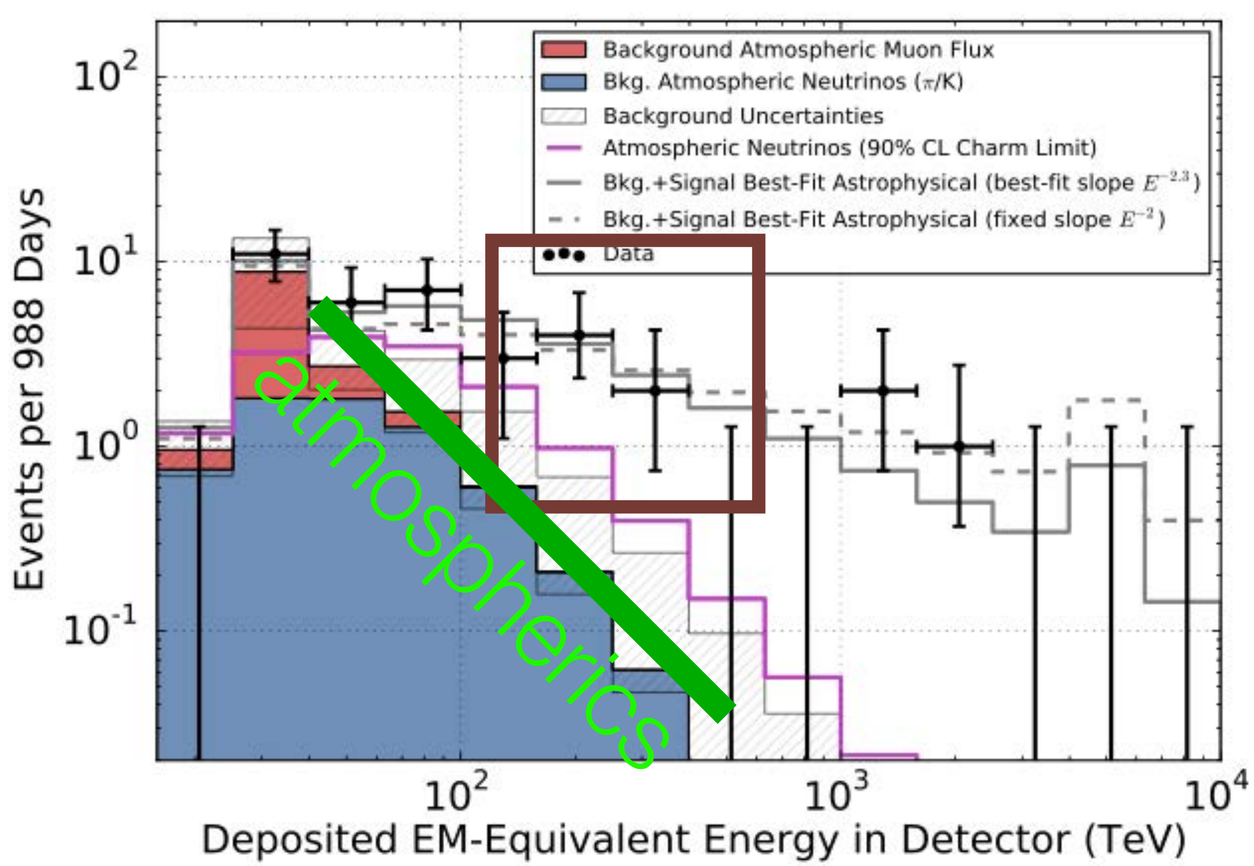


topology + event energies

(+ a few other bells & whilstles)

Including spectral information (28 TeV - 3 PeV)

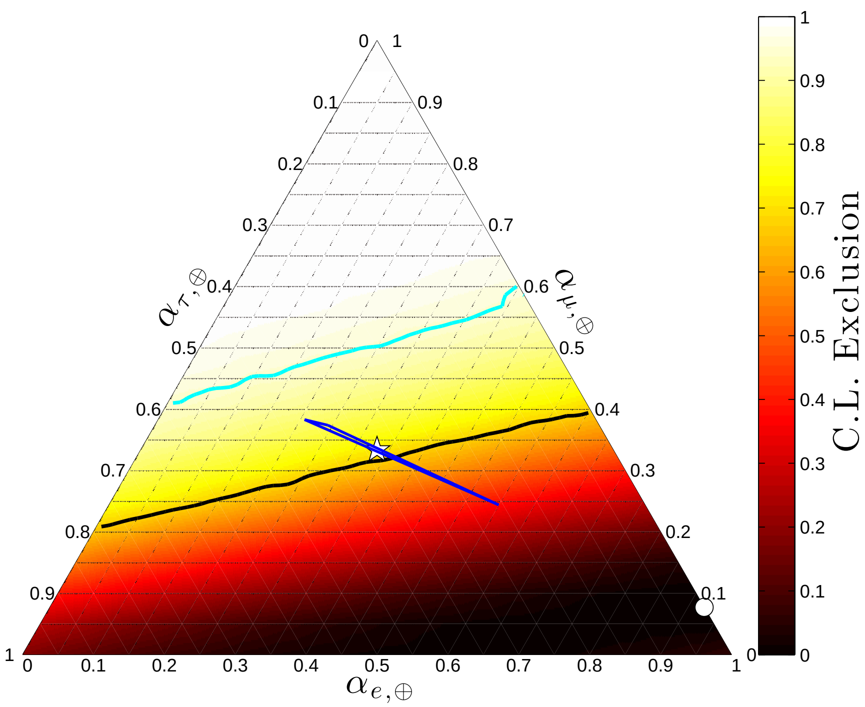


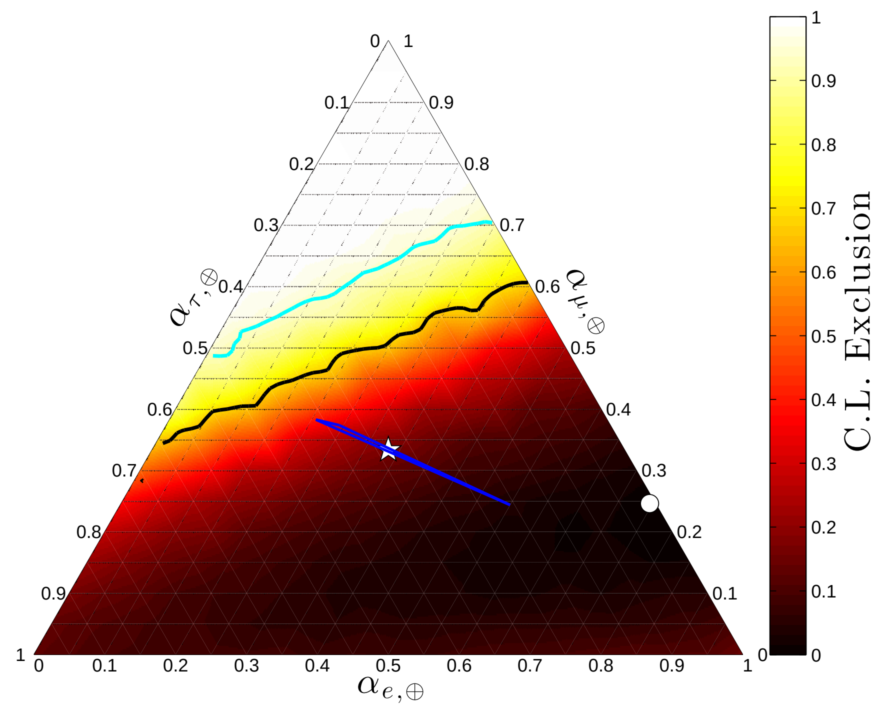


While the number of muon tracks is not quite consistent with an astro explanation, their spectrum is not necessarily consistent with an atmospheric origin

Freeing spectrum, atmospheric background

$$\frac{dN_{\nu,astro}}{dE_\nu} \propto E_\nu^{-\gamma}$$



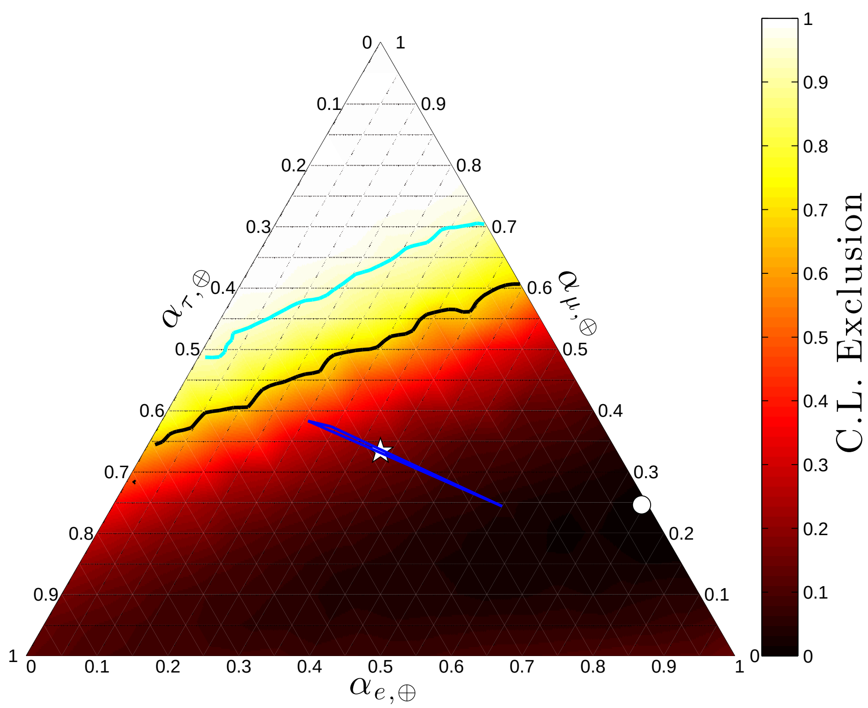


Fixed γ, N_ν, N_μ

Free γ, N_ν, N_μ

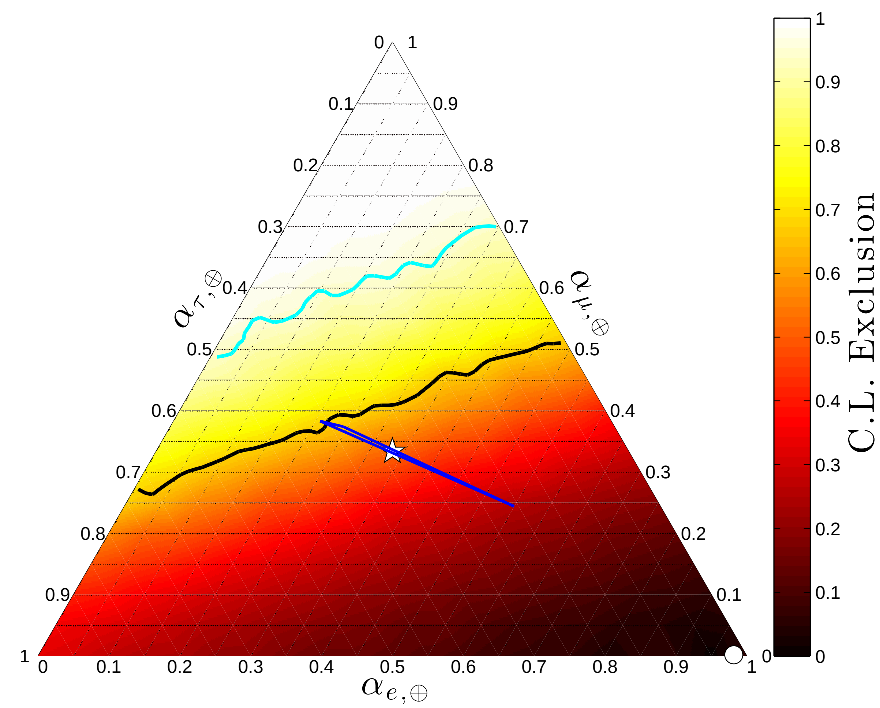
	$(\alpha_e : \alpha_\mu : \alpha_\tau)_\oplus$	γ	N_a	N_ν	N_μ	$p(1:1:1)_\oplus$
Fixed	(0.92 : 0.08 : 0.00)	*2.3*	$20.6^{+6.6}_{-4.8}$ (22.2 ± 5.0)	*6.6*	*8.4*	0.29
Free	(0.75 : 0.25 : 0.00)	$2.96\ ^{+0.34}_{-0.37}$ (2.86 ± 0.28)	$26.2\ ^{+8.8}_{-8.9}$ (25.3 ± 5.7)	$4.8\ ^{+9.1}_{-4.4}$ (7.9 ± 4.7)	$4.7\ ^{+4.4}_{-3.7}$ (6.0 ± 3.1)	0.84

Cut events below 60 TeV: removing atm. muons



28 TeV < E < 3 PeV

(36 events)

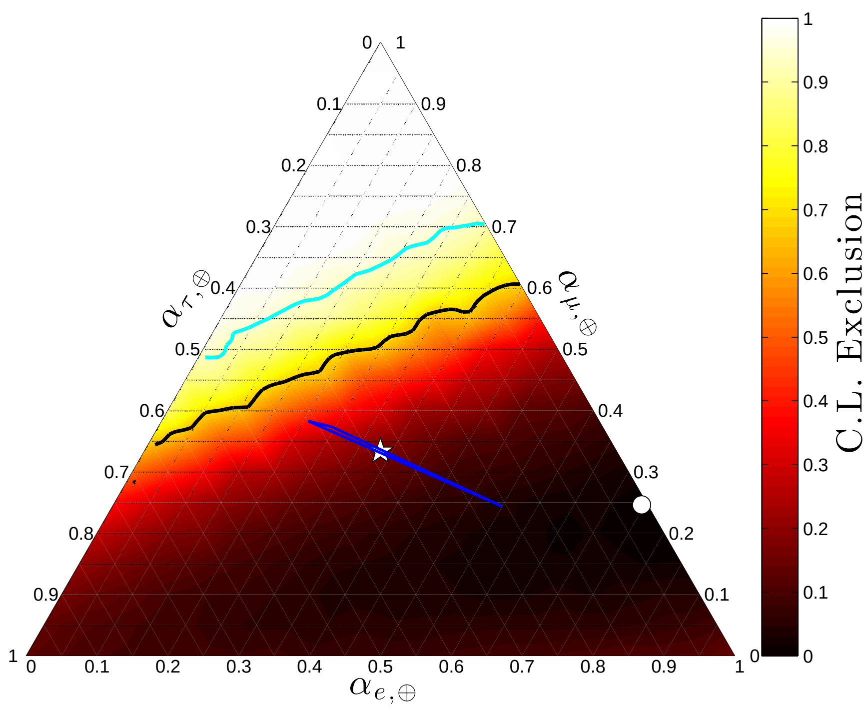


60 TeV < E < 3 PeV

(20 events)

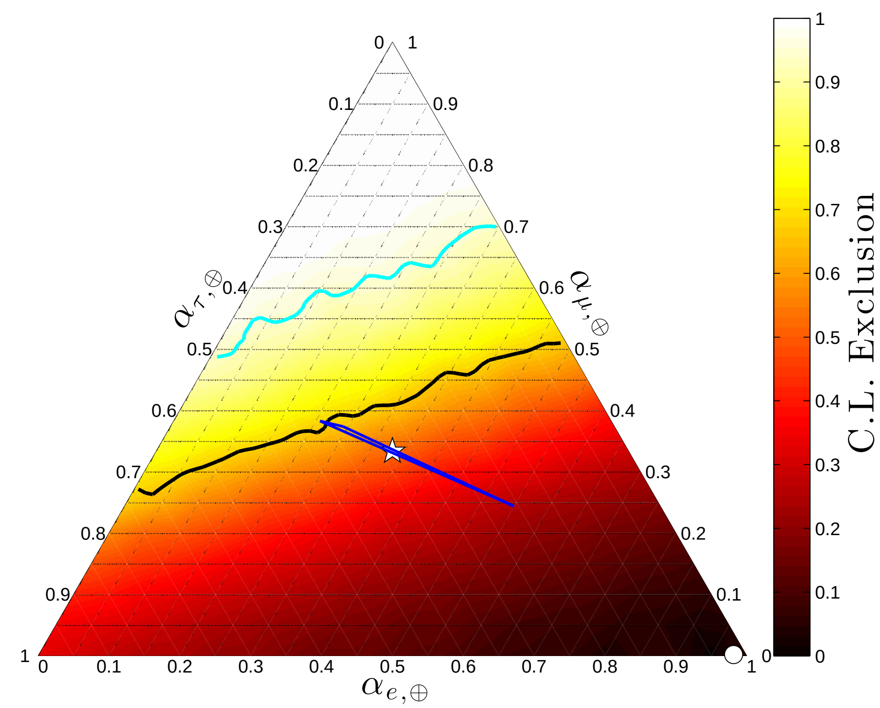
	$(\alpha_e : \alpha_\mu : \alpha_\tau)_\oplus$	γ	N_a	N_ν	N_μ	$p(1:1:1)_\oplus$
> 28 TeV	$(0.75 : 0.25 : 0.00)$	$2.96\ ^{+0.34}_{-0.37}\ (2.86 \pm 0.28)$	$26.2\ ^{+8.8}_{-8.9}\ (25.3 \pm 5.7)$	$4.8\ ^{+9.1}_{-4.4}\ (7.9 \pm 4.7)$	$4.7\ ^{+4.4}_{-3.7}\ (6.0 \pm 3.1)$	0.84
> 60 TeV	$(0.98 : 0.00 : 0.02)$	$2.34\ ^{+0.39}_{-0.31}\ (2.40 \pm 0.29)$	$13.7\ ^{+7.2}_{-4.2}\ (16.0 \pm 4.0)$	$6.5\ ^{+4.1}_{-5.5}\ (4.6 \pm 3.1)$	$0.06\ ^{+4.8}_{-0.0}\ (3.0 \pm 2.0)$	0.50

Cut events below 60 TeV: removing atm. muons



28 TeV < E < 3 PeV

(36 events)



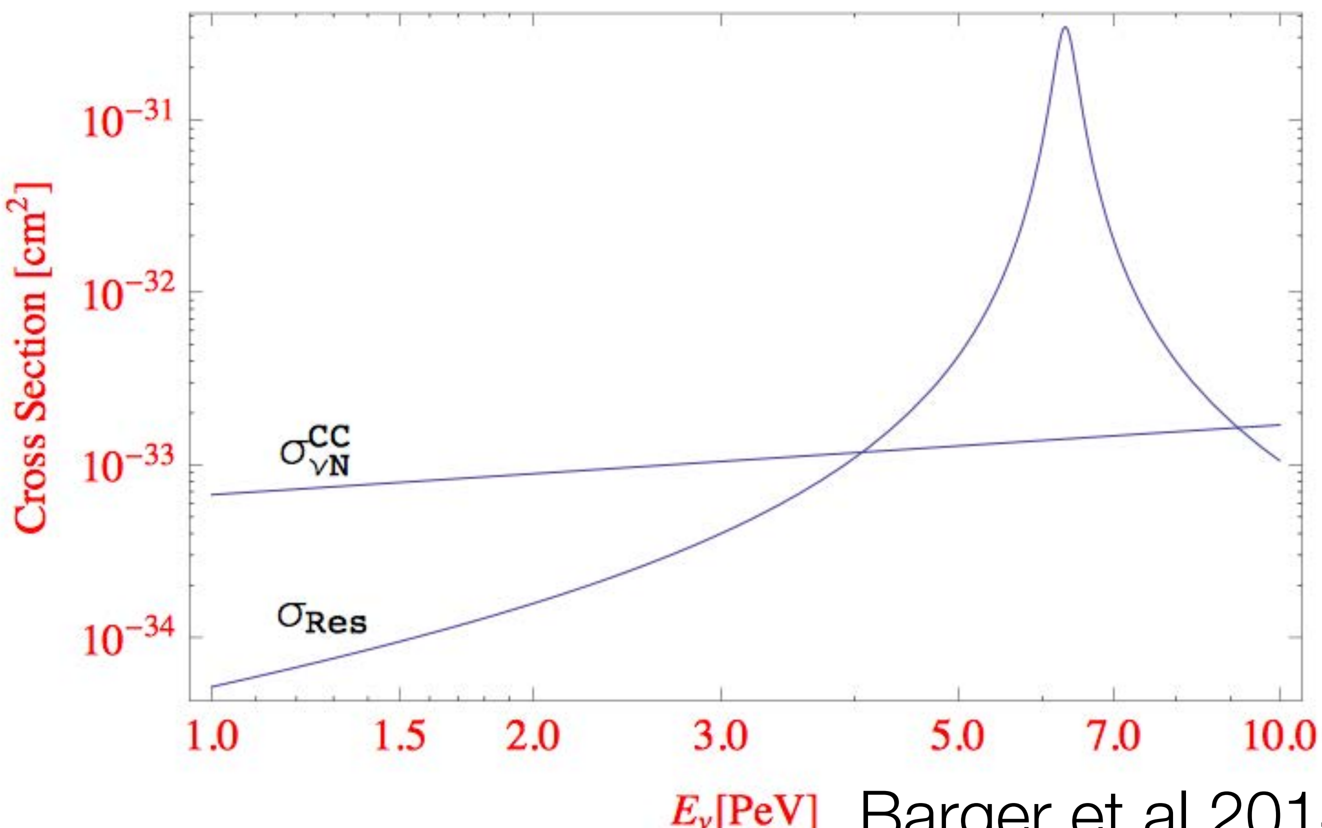
60 TeV < E < 3 PeV

(20 events)

	$(\alpha_e : \alpha_\mu : \alpha_\tau)_\oplus$	γ	N_a	N_ν	N_μ	$p(1:1:1)_\oplus$
> 28 TeV	$(0.75 : 0.25 : 0.00)$	$2.96\ ^{+0.34}_{-0.37}\ (2.86 \pm 0.28)$	$26.2\ ^{+8.8}_{-8.9}\ (25.3 \pm 5.7)$	$4.8\ ^{+9.1}_{-4.4}\ (7.9 \pm 4.7)$	$4.7\ ^{+4.4}_{-3.7}\ (6.0 \pm 3.1)$	0.84
> 60 TeV	$(0.98 : 0.00 : 0.02)$	$2.34\ ^{+0.39}_{-0.31}\ (2.40 \pm 0.29)$	$13.7\ ^{+7.2}_{-4.2}\ (16.0 \pm 4.0)$	$6.5\ ^{+4.1}_{-5.5}\ (4.6 \pm 3.1)$	$0.06\ ^{+4.8}_{-0.0}\ (3.0 \pm 2.0)$	0.50
(fixed	$(0.82 : 0.18 : 0.00)$	*2.3*	$16.2\ ^{+5.5}_{-4.2}\ (17.4 \pm 4.2)$	*2.4*	*0.4*	0.60)

Extending the analysis to higher energies

There is no a priori reason to cut the analysis at 3 TeV. In fact, at E ~ 6.3 PeV, Glashow resonance from production of on-shell W by electron antineutrino

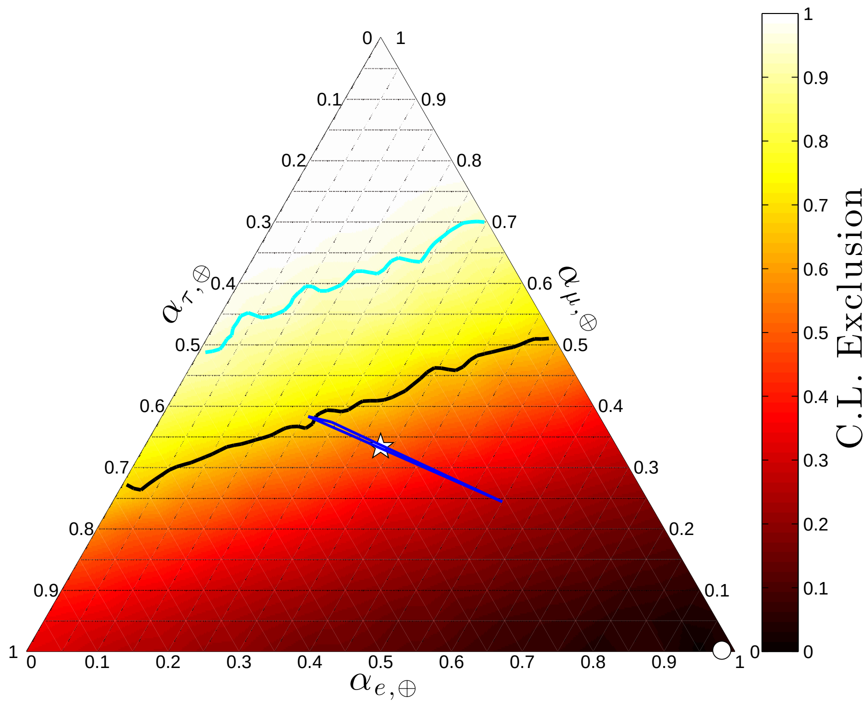


Barger et al 2014

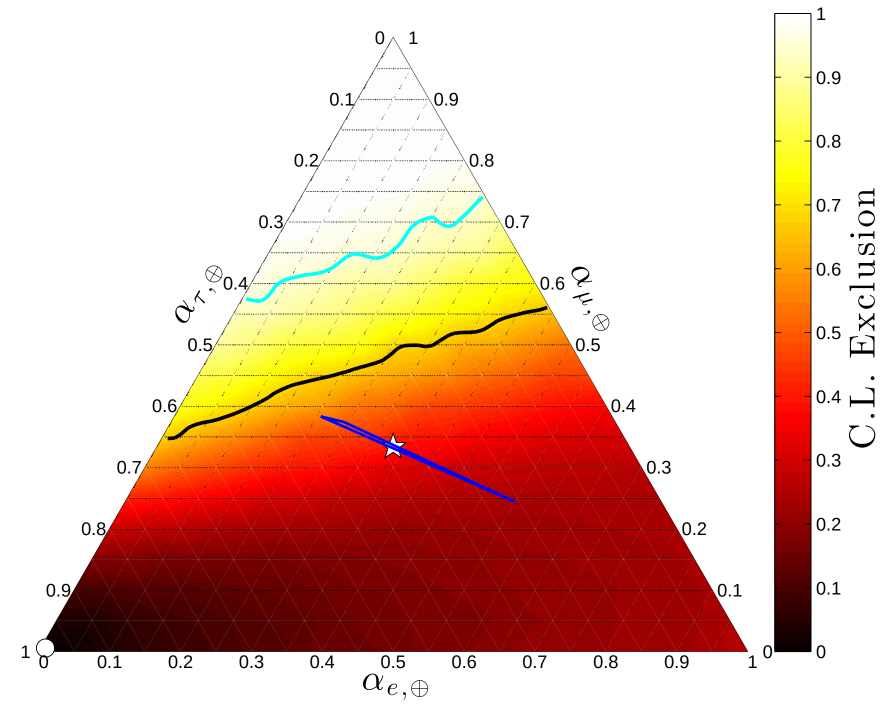
$$E_{CM} = \sqrt{2E_{\bar{\nu}_e} m_e} = M_W$$

$$E_{\bar{\nu}_e} = 6.3 \text{ PeV}$$

Above 3 PeV: the Glashow resonance?



60 TeV < E < 3 PeV



60 TeV < E < 10 PeV

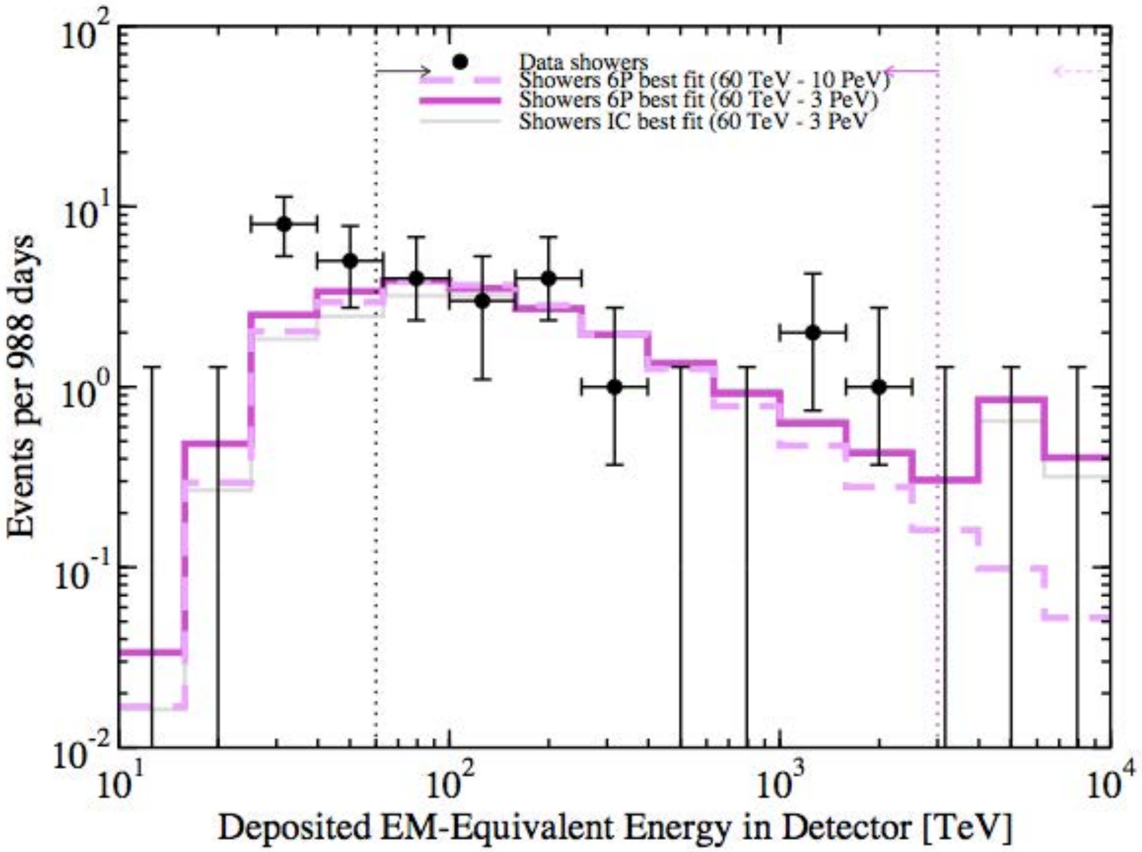
Not enough tracks —> no muon neutrinos
No Glashow peak —> no electron neutrinos

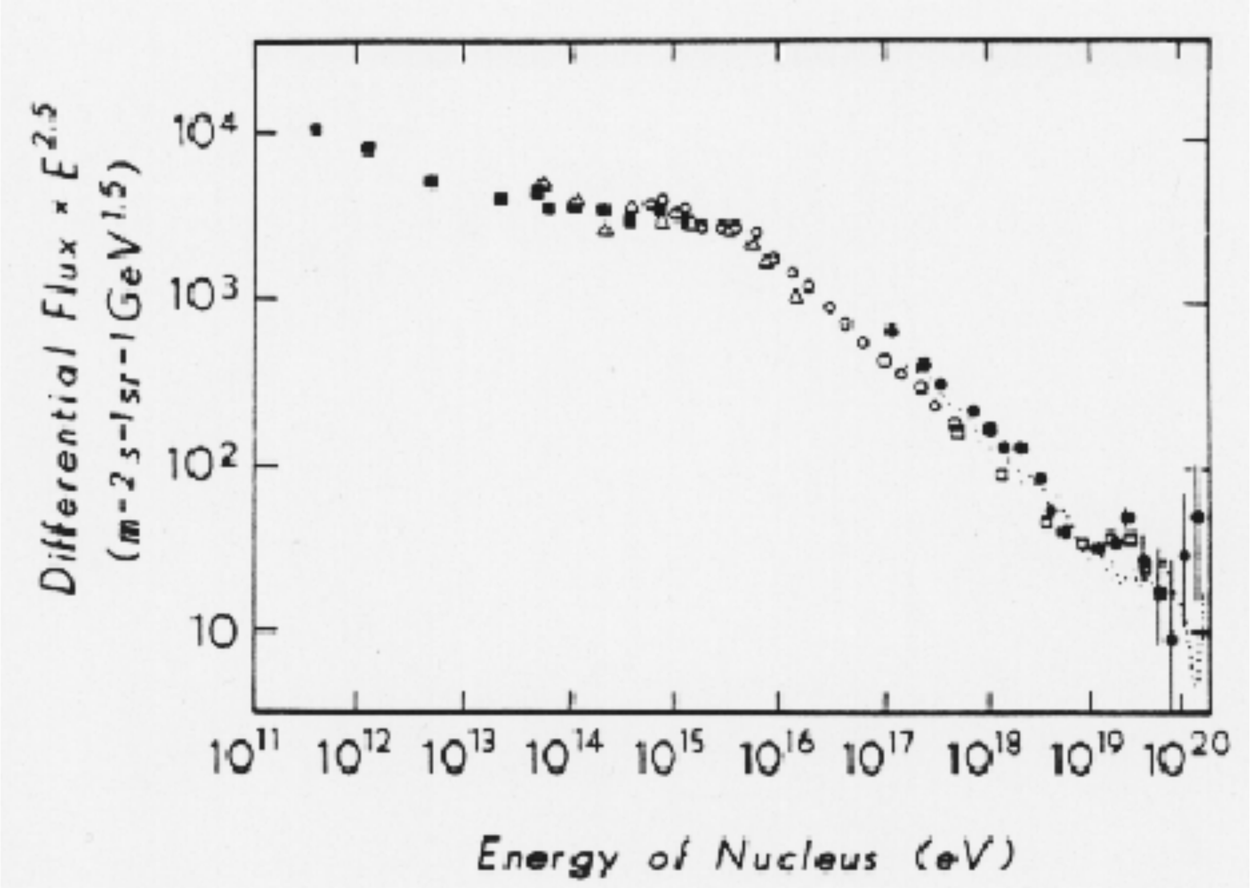
→ all taus???

	$(\alpha_e : \alpha_\mu : \alpha_\tau)_\oplus$	γ	N_a	N_ν	N_μ	$p(1:1:1)_\oplus$
< 3 PeV	$(0.98 : 0.00 : 0.02)$	$2.34\ ^{+0.39}_{-0.31}\ (2.40 \pm 0.29)$	$13.7\ ^{+7.2}_{-4.2}\ (16.0 \pm 4.0)$	$6.5\ ^{+4.1}_{-5.5}\ (4.6 \pm 3.1)$	$0.06\ ^{+4.8}_{-0.0}\ (3.0 \pm 2.0)$	0.50
	$(0.01 : 0.01 : 0.98)$	$2.48\ ^{+0.33}_{-0.34}\ (2.58 \pm 0.25)$	$16.6\ ^{+4.9}_{-6.1}\ (16.4 \pm 4.0)$	$1.5\ ^{+7.0}_{-1.1}\ (4.3 \pm 3.0)$	$2.2\ ^{+2.8}_{-2.2}\ (2.9 \pm 2.0)$	0.61

Glashow resonance

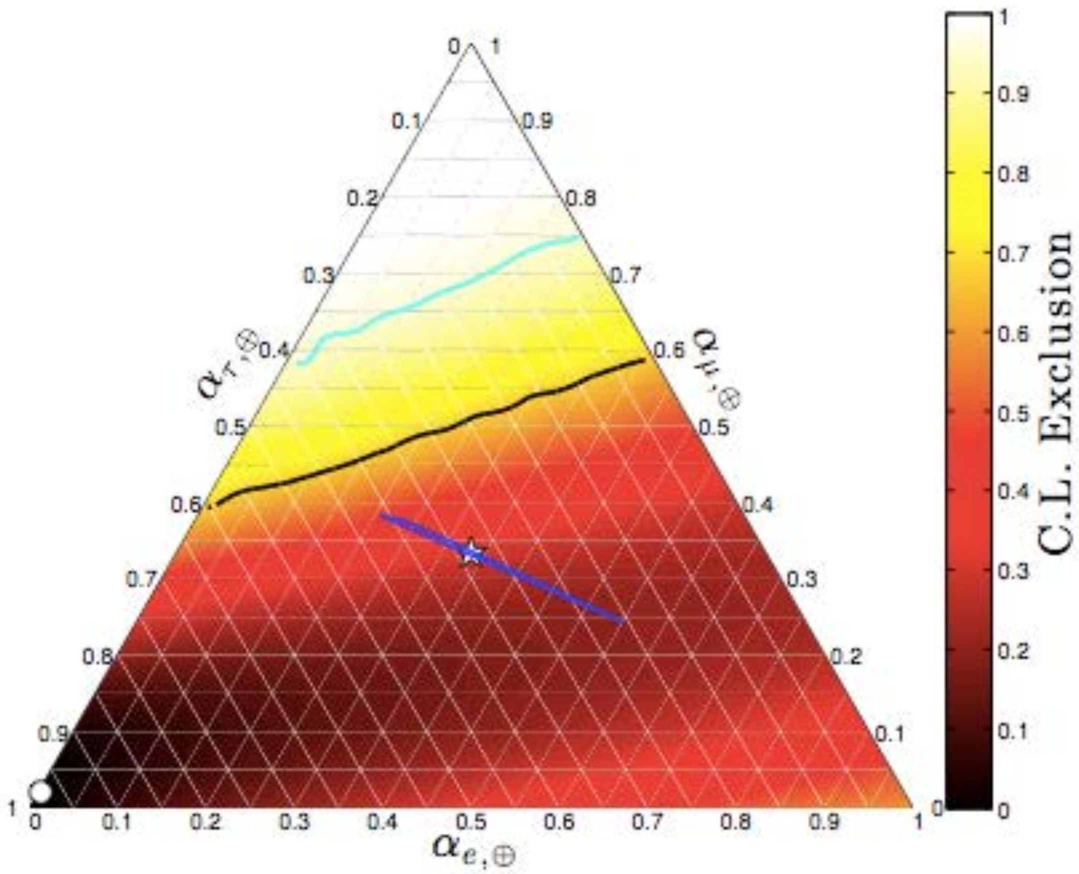
Relation to the cosmic ray spectrum?



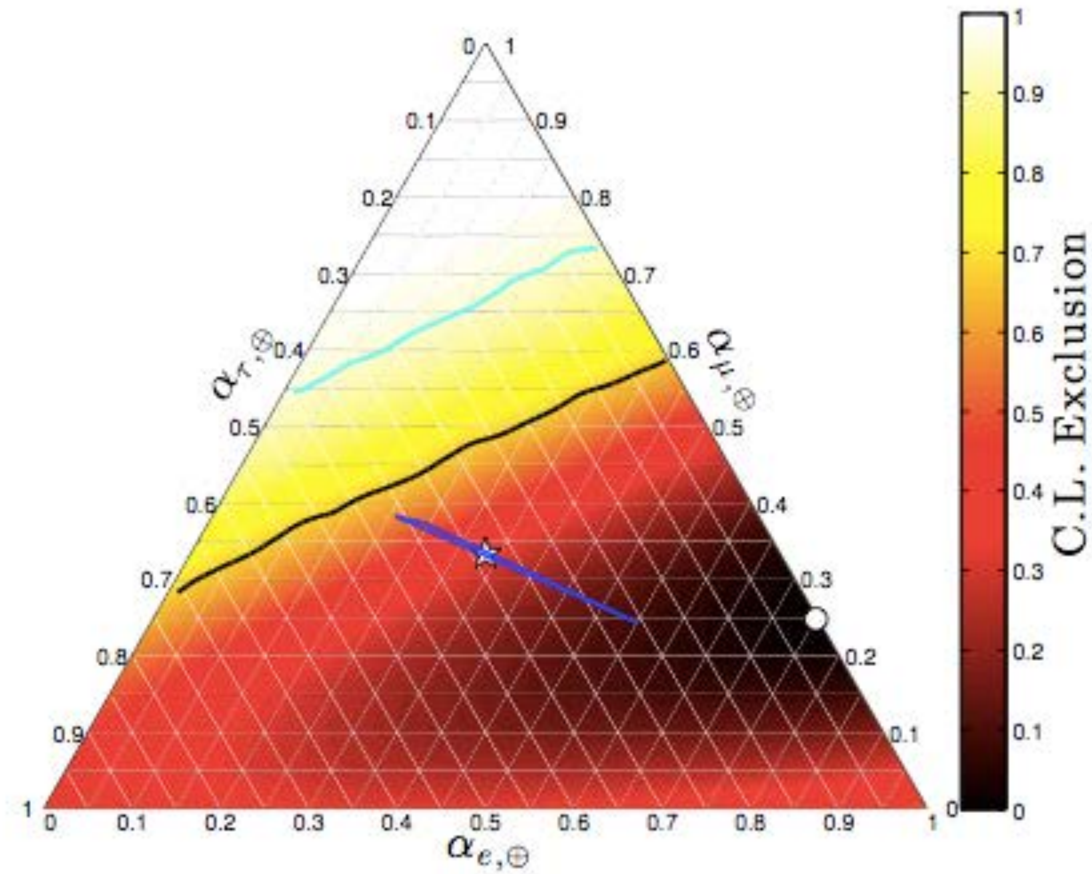


nasa.gov

Break in the spectral index



No break



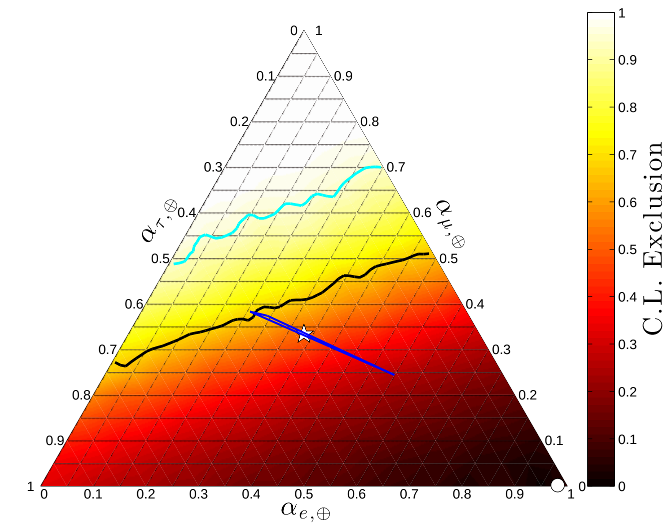
Unit break at 1 PeV

Two potential puzzles

- Is there a deficit in astrophysical muon neutrinos?
- Is there a deficit in electron antineutrinos > 3 PeV?

What if the BF continues to lie away from (1:1:1)?

Some non-standard dominant source, e.g. neutron decay



Matter effects in the source (Mena et al. 2006)

Interactions in the source (e.g. muon energy loss before decay)

Strange new source properties (black hole firewall?) (Afshordi & Yazdi 2015)

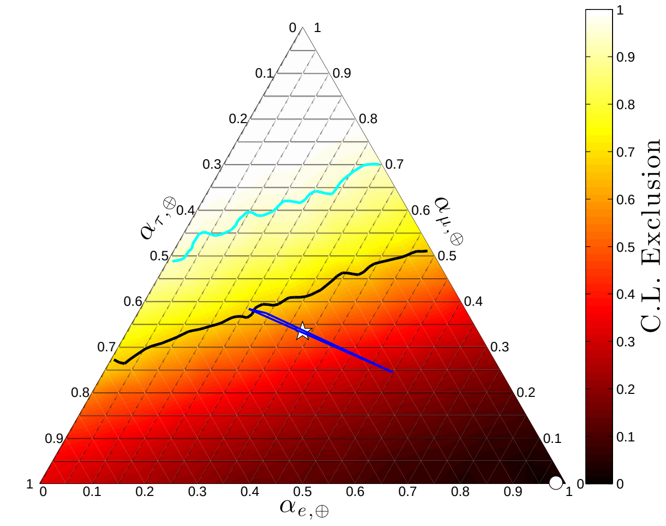
Gamma-ray limits can constrain all of these

(e.g. Anchordoqui et al. 2014)

What if the BF continues to lie outside the “source” triangle?

Exotic new physics?

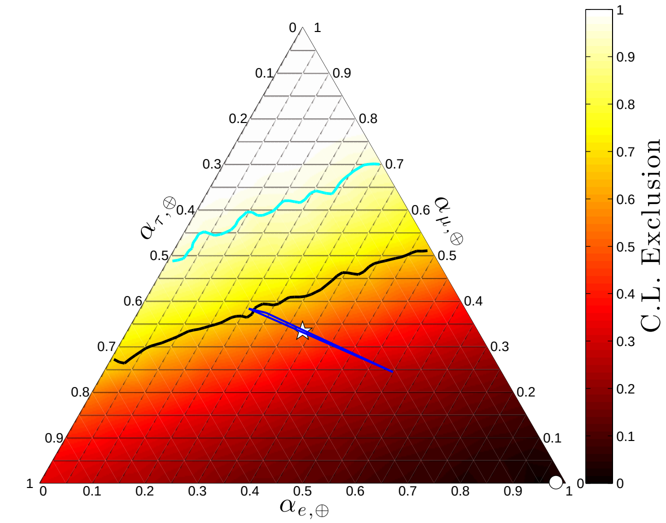
- Neutrino decay (Beacom et al 2003)
- CPT violation (Barenboim & Quigg 2003)
- Pseudo-Dirac (Crocker et al. 2002, Beacom et al. 2004)
- New effects during propagation



What if the BF continues to lie outside the “source” triangle?

Exotic new physics?

- Neutrino decay (Beacom et al 2003)
- CPT violation (Barenboim & Quigg 2003)
- Pseudo-Dirac (Crocker et al. 2002, Beacom et al. 2004)
- New effects during propagation

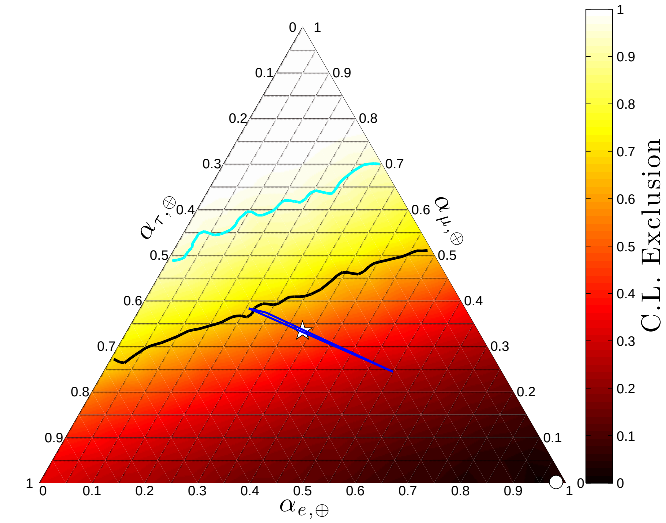


Something more banal: misidentification of tracks?

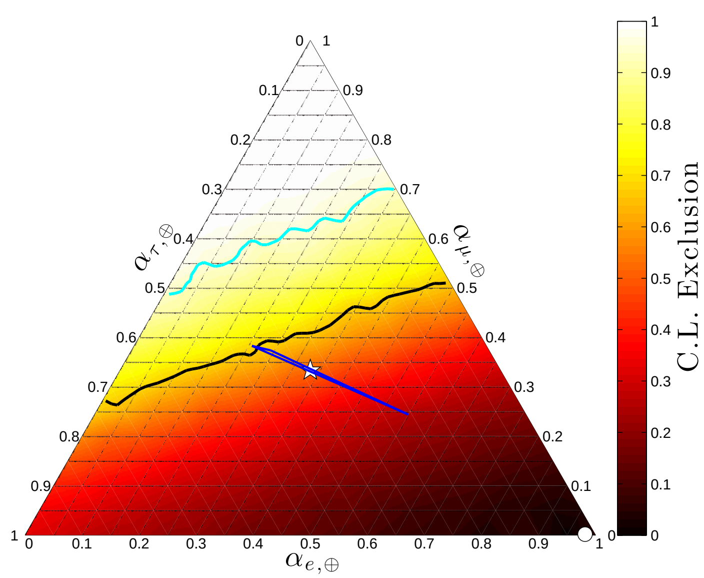
What if the BF continues to lie outside the “source” triangle?

Exotic new physics?

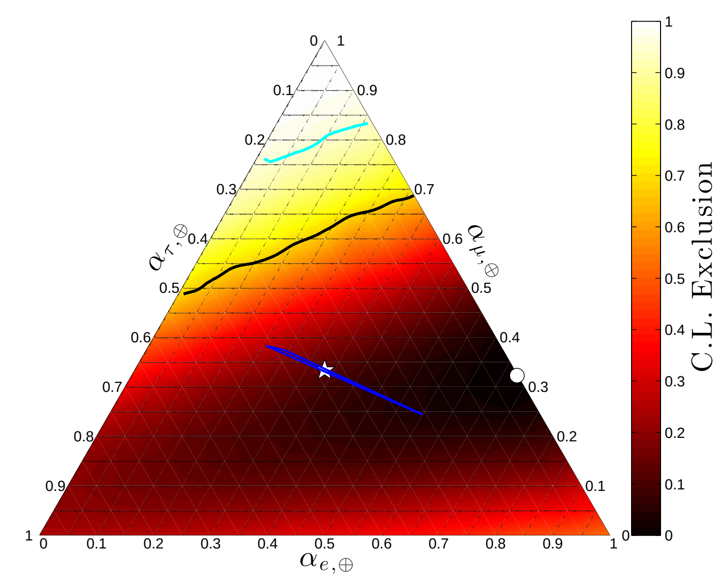
- Neutrino decay (Beacom et al 2003)
- CPT violation (Barenboim & Quigg 2003)
- Pseudo-Dirac (Crocker et al. 2002, Beacom et al. 2004)
- New effects during propagation



Something more banal: misidentification of tracks?



20%
track mis-ID



Flavor Ratio of Astrophysical Neutrinos above 35 TeV in IceCube

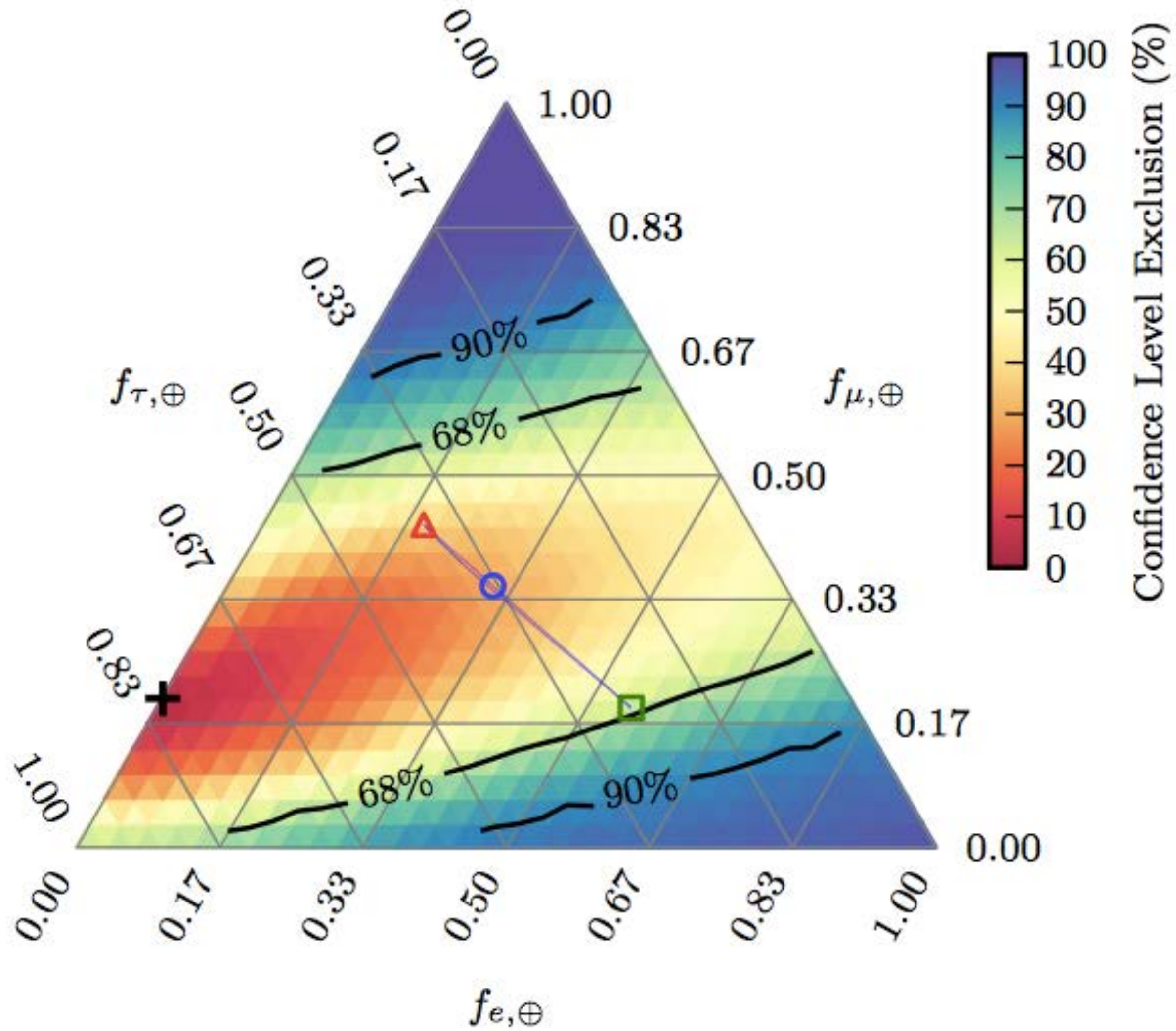
IceCube Collaboration: M. G. Aartsen, M. Ackermann, J. Adams, J. A. Aguilar, M. Ahlers, M. Ahrens, D. Altmann, T. Anderson, C. Arguelles, T. C. Arlen, J. Auffenberg, X. Bai, S. W. Barwick, V. Baum, R. Bay, J. J. Beatty, J. Becker Tjus, K.-H. Becker, S. BenZvi, P. Berghaus, D. Berley, E. Bernardini, A. Bernhard, D. Z. Besson, G. Binder, D. Bindig, M. Bissok, E. Blaufuss, J. Blumenthal, D. J. Boersma, C. Bohm, F. Bos, D. Bose, S. Böser, O. Botner, L. Brayeur, H.-P. Bretz, A. M. Brown, N. Buzinsky, J. Casey, M. Casier, E. Cheung, D. Chirkin, A. Christov, B. Christy, K. Clark, L. Classen, F. Clevermann, S. Coenders, D. F. Cowen, A. H. Cruz Silva, J. Daughhetee, J. C. Davis, M. Day, J. P. A. M. de André, C. De Clercq, H. Dembinski, S. De Ridder, P. Desiati, K. D. de Vries, M. de With, et al. (241 additional authors not shown)

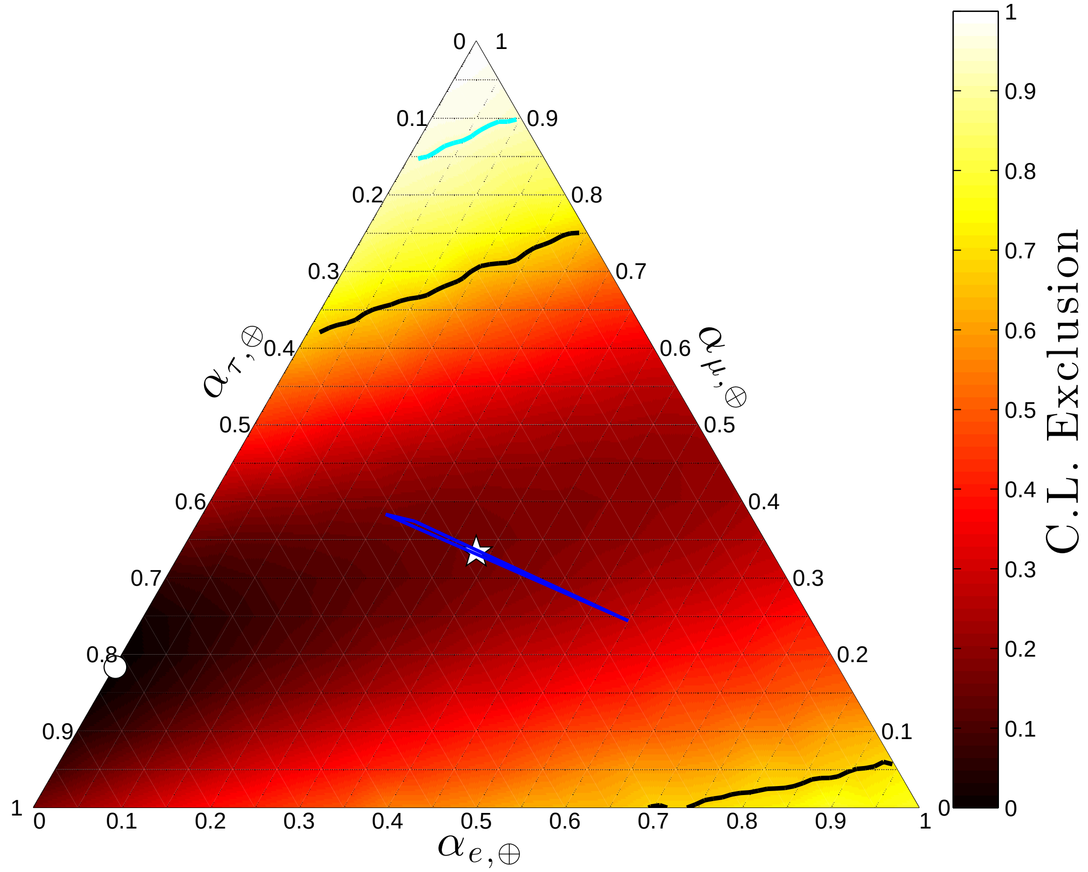
(Submitted on 11 Feb 2015)

A diffuse flux of astrophysical neutrinos above $100\,\mathrm{TeV}$ has been observed at the IceCube Neutrino Observatory. Here we extend this analysis to probe the astrophysical flux down to $35\,\mathrm{TeV}$ and analyze its flavor composition by classifying events as showers or tracks. Taking advantage of lower atmospheric backgrounds for shower-like events, we obtain a shower-biased sample containing 129 showers and 8 tracks collected in three years from 2010 to 2013. We demonstrate consistency with the $(f_e : f_\mu : f_\tau)_\oplus \approx (1:1:1)_\oplus$ flavor ratio at Earth commonly expected from the averaged oscillations of neutrinos produced by pion decay in distant astrophysical sources. Limits are placed on non-standard flavor compositions that cannot be produced by averaged neutrino oscillations but could arise in exotic physics scenarios. A maximally track-like composition of $(0:1:0)_\oplus$ is excluded at 3.3σ, and a purely shower-like composition of $(1:0:0)_\oplus$ is excluded at 2.3σ.

Comments: 8 pages, 3 figures. Submitted to PRL
Subjects: **High Energy Astrophysical Phenomena (astro-ph.HE)**; High Energy Physics - Experiment (hep-ex)
Cite as: arXiv:1502.03376 **[astro-ph.HE]**
(or arXiv:1502.03376v1 **[astro-ph.HE]** for this version)

30% track mis-ID, energies up to 10 PeV





- Different methods (e.g. binned vs unbinned)
- Some angular info (4 bins)
- Inclusion of 101 more low-E showers

IceCube Feb. 11 2015

These results contrast with an earlier analysis of IceCube's 3-year data, which found a preference for $(1:0:0)_\oplus$ over $(1:1:1)_\oplus$ at 92% confidence level [68]. We attribute this discrepancy mainly to two unaccounted for effects — partial classification of ν_μ CC events as showers and systematic uncertainty on muon background. Repeating their analysis but accounting for the $\sim 30\%$ of ν_μ CC events classified as showers and using a profile likelihood incorporating the 50% uncertainty in muon background, a $(1:0:0)_\oplus$ best-fit is still obtained but neither $(1:1:1)_\oplus$ or our best-fit of $(0:0.2:0.8)_\oplus$ are excluded at $> 68\%$ confidence level. Since only shower and track counts were analyzed, the tighter constraints reported here result from the use of energy and directional information in addition to the lower energy data.

(also different spectra)

IceCube Feb. 11 2015

These results contrast with an earlier analysis of IceCube's 3-year data, which found a preference for $(1:0:0)_\oplus$ over $(1:1:1)_\oplus$ at 92% confidence level [68]. We attribute this discrepancy mainly to two unaccounted for effects — partial classification of ν_μ CC events as showers and systematic uncertainty on muon background. Repeating their analysis but accounting for the $\sim 30\%$ of ν_μ CC events classified as showers and using a profile likelihood incorporating the 50% uncertainty in muon background, a $(1:0:0)_\oplus$ best-fit is still obtained but neither $(1:1:1)_\oplus$ or our best-fit of $(0:0.2:0.8)_\oplus$ are excluded at $> 68\%$ confidence level. Since only shower and track counts were analyzed, the tighter constraints reported here result from the use of energy and directional information in addition to the lower energy data.

(also different spectra)

best-fit is obtained for $(1:0:0)_\oplus$ at Earth, which cannot be achieved from any flavor ratio at sources with averaged oscillations during propagation. If confirmed, this result would suggest either a misunderstanding of the expected background events, or a misidentification of tracks as showers, or even more compellingly, some exotic physics which deviates from the standard scenario.

Us, April 2014

IceCube Feb. 11 2015

These results contrast with an earlier analysis of IceCube's 3-year data, which found a preference for $(1:0:0)_\oplus$ over $(1:1:1)_\oplus$ at 92% confidence level [68]. We attribute this discrepancy mainly to two unaccounted for effects — partial classification of ν_μ CC events as showers and systematic uncertainty on muon background. Repeating their analysis but accounting for the $\sim 30\%$ of ν_μ CC events classified as showers and using a profile likelihood incorporating the 50% uncertainty in muon background, a $(1:0:0)_\oplus$ best-fit is still obtained but neither $(1:1:1)_\oplus$ or our best-fit of $(0:0.2:0.8)_\oplus$ are excluded at $> 68\%$ confidence level. Since only shower and track counts were analyzed, the tighter constraints reported here result from the use of energy and directional information in addition to the lower energy data.

best-fit is obtained for $(1:0:0)_\oplus$ at Earth, which cannot be achieved from any flavor ratio at sources with averaged oscillations during propagation. If confirmed, this result would suggest either a misunderstanding of the expected background events, or a misidentification of tracks as showers, or even more compellingly, some exotic physics which deviates from the standard scenario.

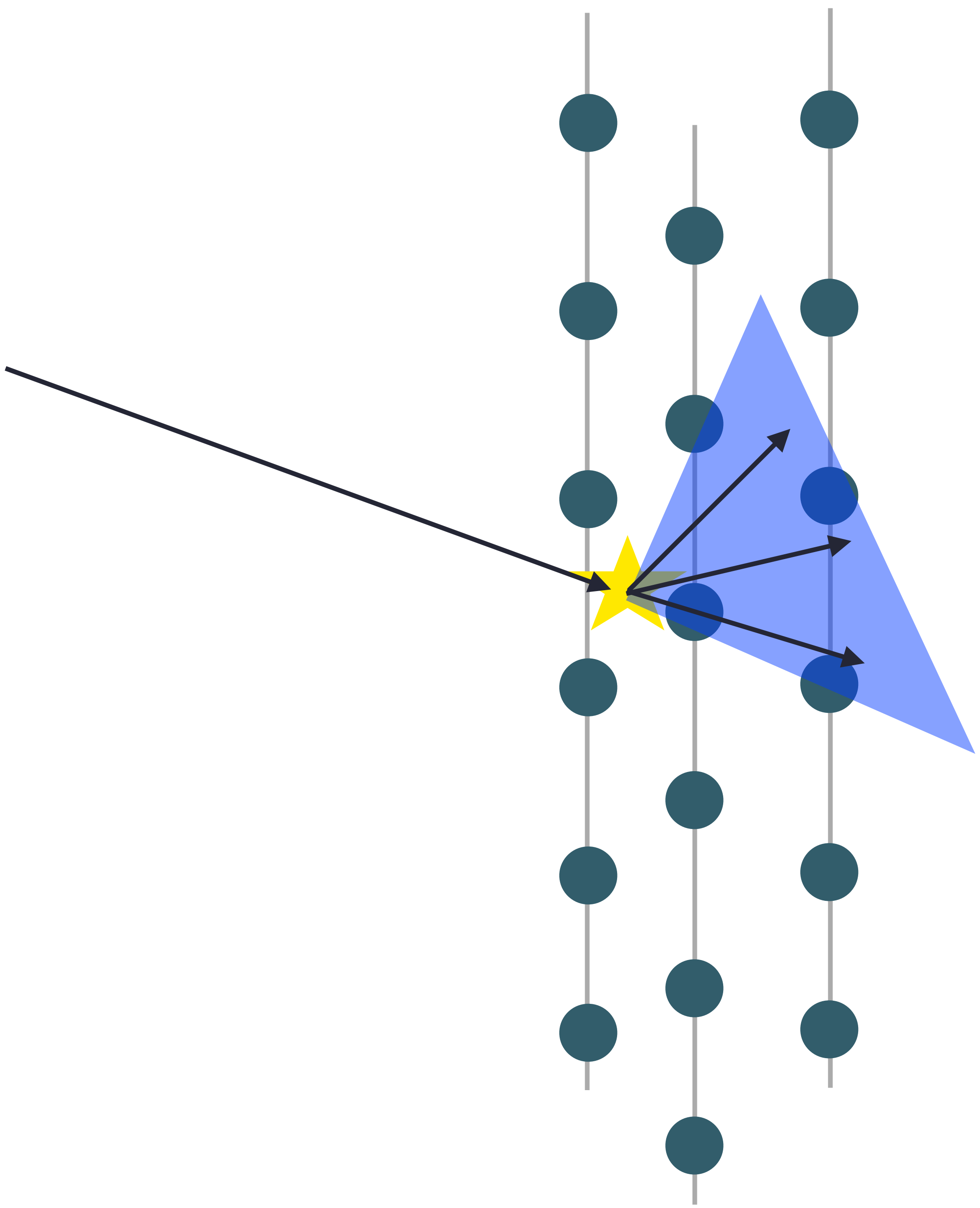
Us, April 2014

Conclusions

- Amazing results from IceCube
- “First light” in high-energy neutrino astronomy has given us a lot to think about, including some interesting puzzles
- 17 more events this year …
- Including angular information will help
- Need more data… KM3NeT, Gen-2 IceCube?

Thank you

Neutrino-ice interactions



Cherenkov Light yield: ~ total electron track length

EM Cascade: ~ 100% energy deposition

Hadron Cascade: inefficient, due to higher Cherenkov threshold of hadrons; binding energies

$$F_h(E_X) = 1 - (1 - f_0)\left(\frac{E_X}{E_0}\right)^{-m}$$

$f_0 = 0.467$, $E_0 = 0.399$ GeV and $m = 0.130$

Muon track: muons travel ~ km in ice. Average muon deposited energy (via electrons created in scattering) is about 12%

Measured energies are always “EM-equivalent”

Showers: neutral current

$$N_{\nu_i}^{\mathrm{sh,NC}} = T\,N_A \int_{E_{\min}}^{\infty} dE_\nu\, M^{\mathrm{NC}}(E_\nu)\, Att_{\nu_i}(E_\nu)\, \frac{d\phi_{\nu_i}(E_\nu)}{dE_\nu} \times \int_{y_{\min}}^{y_{\max}} dy\, \frac{d\sigma^{\mathrm{NC}}(E_\nu, y)}{dy}$$

Cross-section

Incoming neutrino spectrum

Attenuation (passage through earth)

Effective detector mass

Exposure time

Showers: charged current

$$N_{\nu_e}^{\mathrm{sh,CC}} = T\,N_A \int_{E_{\mathrm{min}}}^{\infty} dE_\nu\, M_{\nu_e}^{\mathrm{CC}}(E_\nu)\, Att_{\nu_e}(E_\nu)\, \frac{d\phi_{\nu_e}(E_\nu)}{dE_\nu} \times \int_0^1 dy\, \frac{d\sigma_{\nu_e}^{\mathrm{CC}}(E_\nu, y)}{dy} \times \Theta\left(E_{\mathrm{max}} - E_\nu\right)$$

$$N_{\nu_\tau}^{\mathrm{sh,CC-had}} = T\,N_A \int_{E_{\mathrm{min}}}^{\infty} dE_\nu\, M_{\nu_\tau}^{\mathrm{CC}}(E_\nu)\, Att_{\nu_\tau}(E_\nu)\, \frac{d\phi_{\nu_\tau}(E_\nu)}{dE_\nu} \int_0^1 dy\, \frac{d\sigma_{\nu_\tau}^{\mathrm{CC}}(E_\nu, y)}{dy} \int_0^1 dz\, \frac{dn(\tau \to \mathrm{had})}{dz}$$
$$\times \Theta\left(E_\nu(y + (1-y)(1-z)) - E_{\mathrm{min}}\right) \times \Theta\left(E_{\mathrm{max}} - E_\nu(y + (1-y)(1-z))\right) \;,$$

$$N_{\nu_\tau}^{\mathrm{sh,CC-em}} = T\,N_A \int_{E_{\mathrm{min}}}^{\infty} dE_\nu\, M_{\nu_\tau}^{\mathrm{CC}}(E_\nu)\, Att_{\nu_\tau}(E_\nu)\, \frac{d\phi_{\nu_\tau}(E_\nu)}{dE_\nu} \int_0^1 dy\, \frac{d\sigma_{\nu_\tau}^{\mathrm{CC}}(E_\nu, y)}{dy} \int_0^1 dz_e\, \frac{dn(\tau \to \mathrm{e})}{dz_e}$$
$$\times \Theta\left(E_\nu(y + (1-y)z_e) - E_{\mathrm{min}}\right) \times \Theta\left(E_{\mathrm{max}} - E_\nu(y + (1-y)z_e)\right) \;,$$

Showers: charged current

$$N_{\nu_e}^{\mathrm{sh,CC}} = T\, N_A \int_{E_{\min}}^{\infty} dE_\nu\, M_{\nu_e}^{\mathrm{CC}}(E_\nu)\, Att_{\nu_e}(E_\nu)\, \frac{d\phi_{\nu_e}(E_\nu)}{dE_\nu} \times \int_0^1 dy\, \frac{d\sigma_{\nu_e}^{\mathrm{CC}}(E_\nu, y)}{dy} \times \Theta\left(E_{\max} - E_\nu\right)$$

$$N_{\nu_\tau}^{\mathrm{sh,CC-had}} = T\, N_A \int_{E_{\min}}^{\infty} dE_\nu\, M_{\nu_\tau}^{\mathrm{CC}}(E_\nu)\, Att_{\nu_\tau}(E_\nu)\, \frac{d\phi_{\nu_\tau}(E_\nu)}{dE_\nu} \int_0^1 dy\, \frac{d\sigma_{\nu_\tau}^{\mathrm{CC}}(E_\nu, y)}{dy} \int_0^1 dz\, \frac{dn(\tau \to \mathrm{had})}{dz}$$
$$\times \Theta\left(E_\nu(y + (1-y)(1-z)) - E_{\min}\right) \times \Theta\left(E_{\max} - E_\nu(y + (1-y)(1-z))\right) ,$$

$$N_{\nu_\tau}^{\mathrm{sh,CC-em}} = T\, N_A \int_{E_{\min}}^{\infty} dE_\nu\, M_{\nu_\tau}^{\mathrm{CC}}(E_\nu)\, Att_{\nu_\tau}(E_\nu)\, \frac{d\phi_{\nu_\tau}(E_\nu)}{dE_\nu} \int_0^1 dy\, \frac{d\sigma_{\nu_\tau}^{\mathrm{CC}}(E_\nu, y)}{dy} \int_0^1 dz_e\, \frac{dn(\tau \to \mathrm{e})}{dz_e}$$
$$\times \Theta\left(E_\nu(y + (1-y)z_e) - E_{\min}\right) \times \Theta\left(E_{\max} - E_\nu(y + (1-y)z_e)\right) ,$$

[box] As in NC case

(outside box): counting final states giving EM deposition

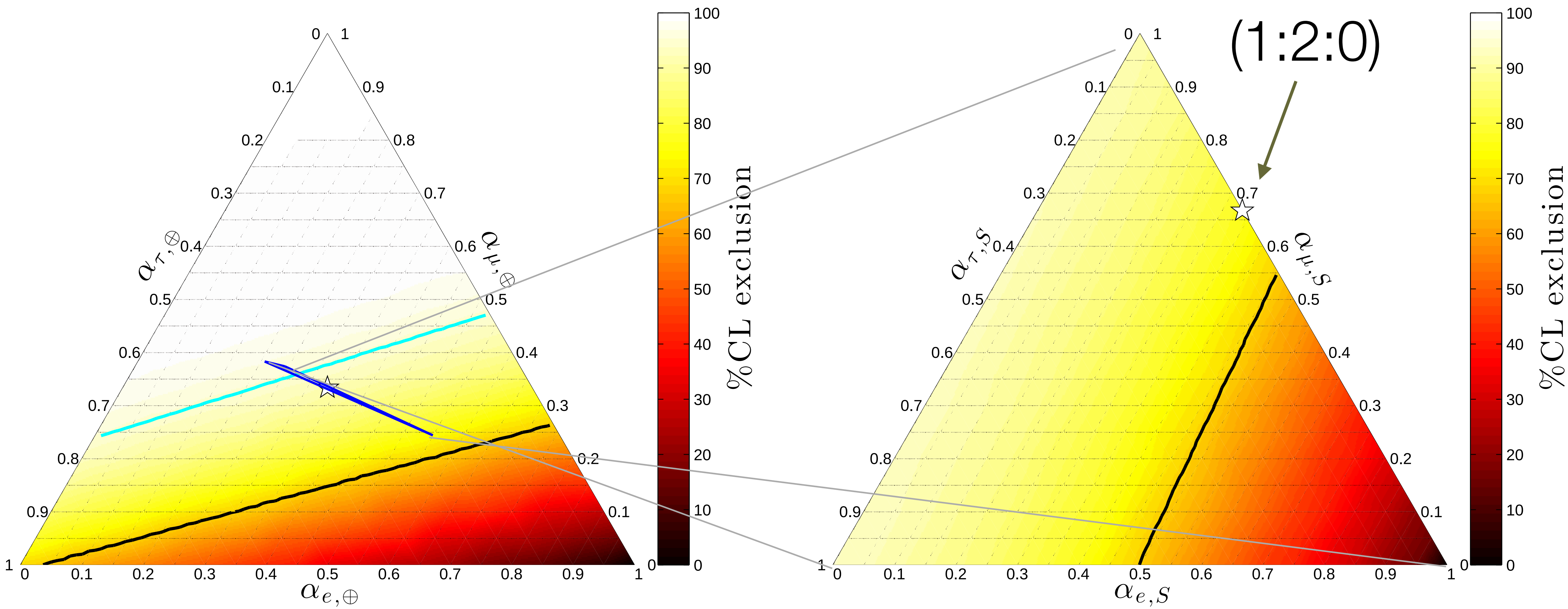
Tracks in IceCube

$$N_{\nu_\mu}^{\rm tr} = T\, N_A \int_{E_{\rm min}}^{\infty} dE_\nu\, M_{\nu_\mu}^{\rm CC}(E_\nu)\, Att_{\nu_\mu}(E_\nu)\, \frac{d\phi_{\nu_\mu}(E_\nu)}{dE_\nu} \int_{y_{\rm min}}^{y_{\rm max}} dy\, \frac{d\sigma_{\nu_\mu}^{\rm CC}(E_\nu, y)}{dy}$$

$$N_{\nu_\tau}^{\rm tr} = T\, N_A \int_{E_{\rm min}}^{\infty} dE_\nu\, M_{\nu_\tau}^{\rm CC}(E_\nu)\, Att_{\nu_\tau}(E_\nu)\, \frac{d\phi_{\nu_\tau}(E_\nu)}{dE_\nu} \int_{y_{\rm min}}^{y_{\rm max}} dy\, \frac{d\sigma_{\nu_\tau}^{\rm CC}(E_\nu, y)}{dy}\, Br(\tau \to \mu)$$

Flavour ratio at source? E_ν^{-2}

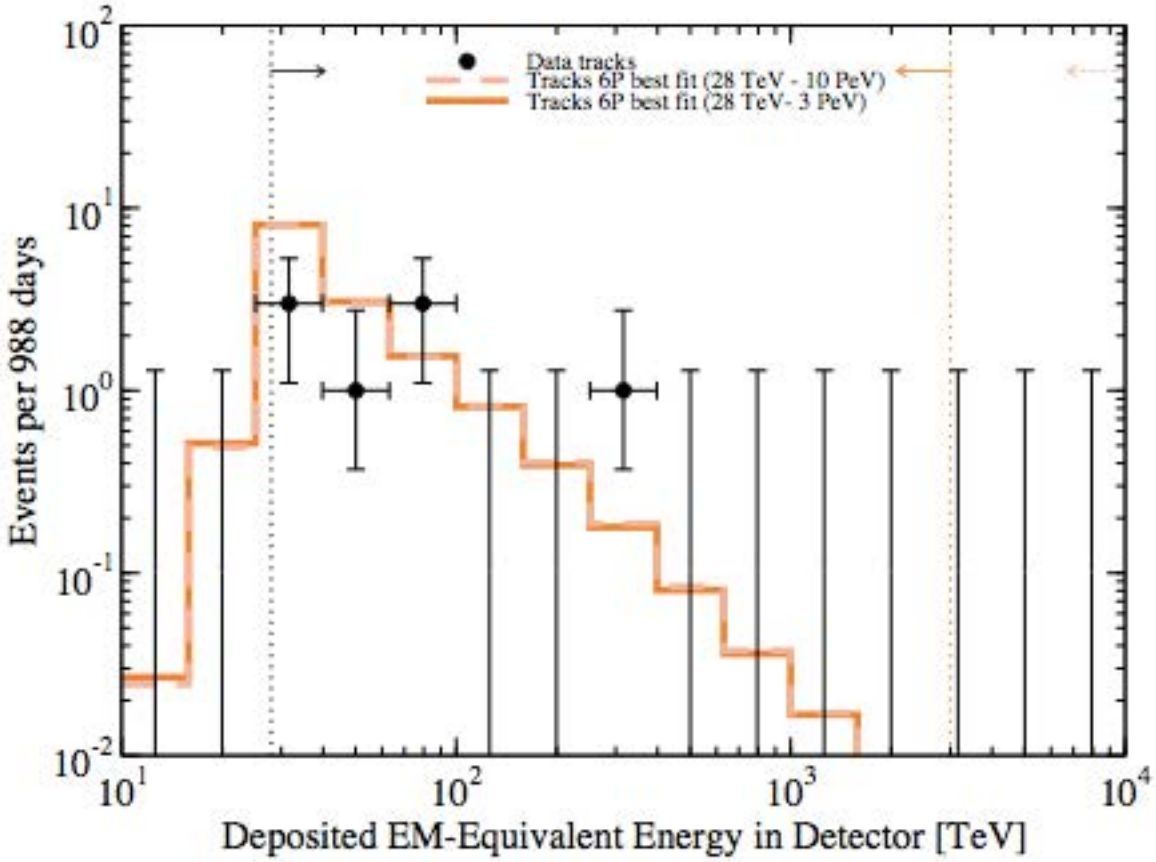
Restrict the flavour ratios to those available by averaging via propagation

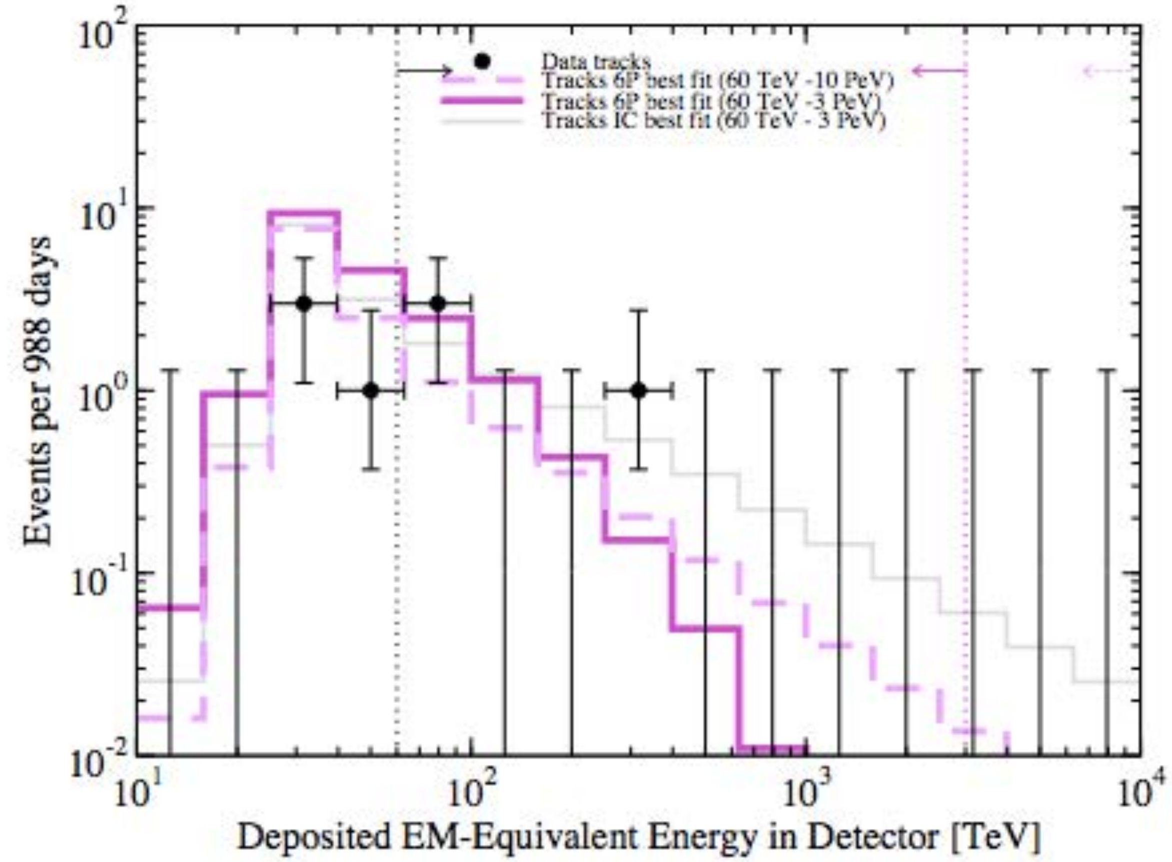


Earth faraway source

Still not enough statistics to discriminate

Tracks only

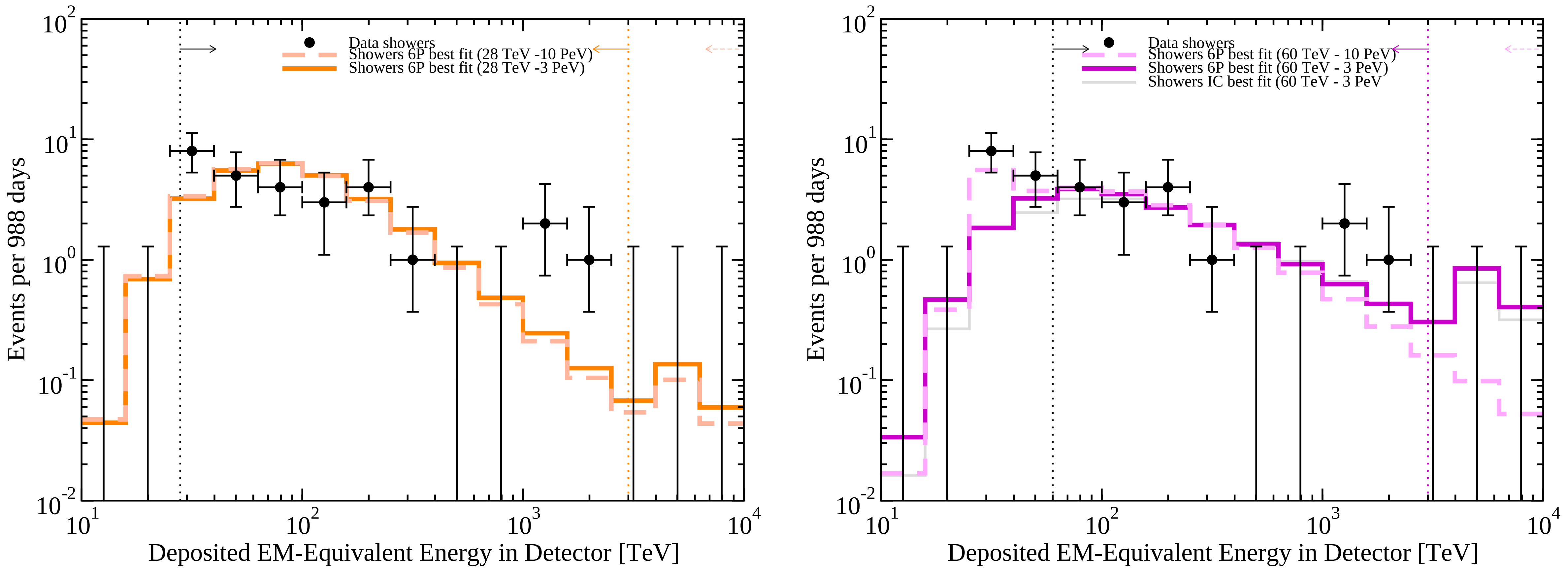




IceCube fit

our fits

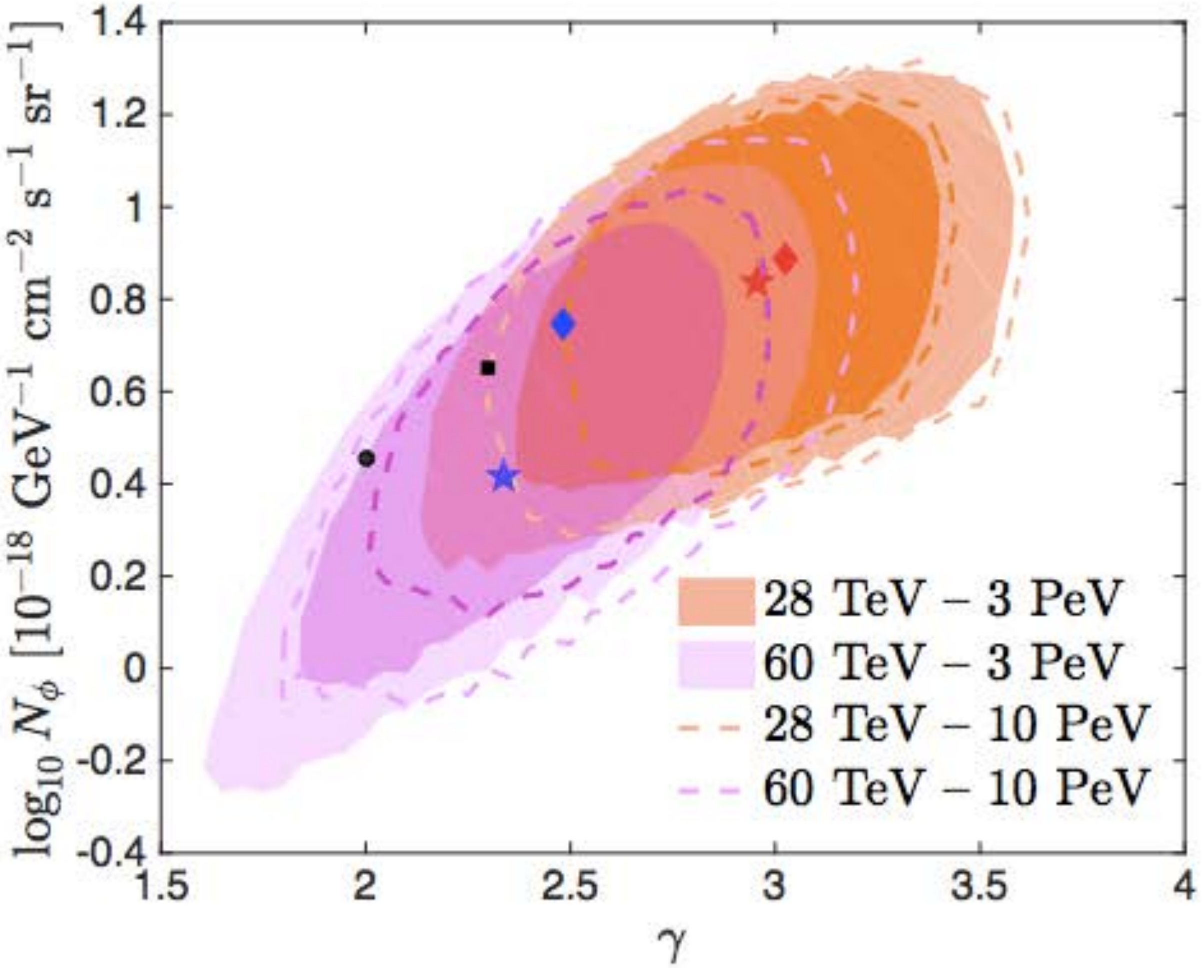
Showers only

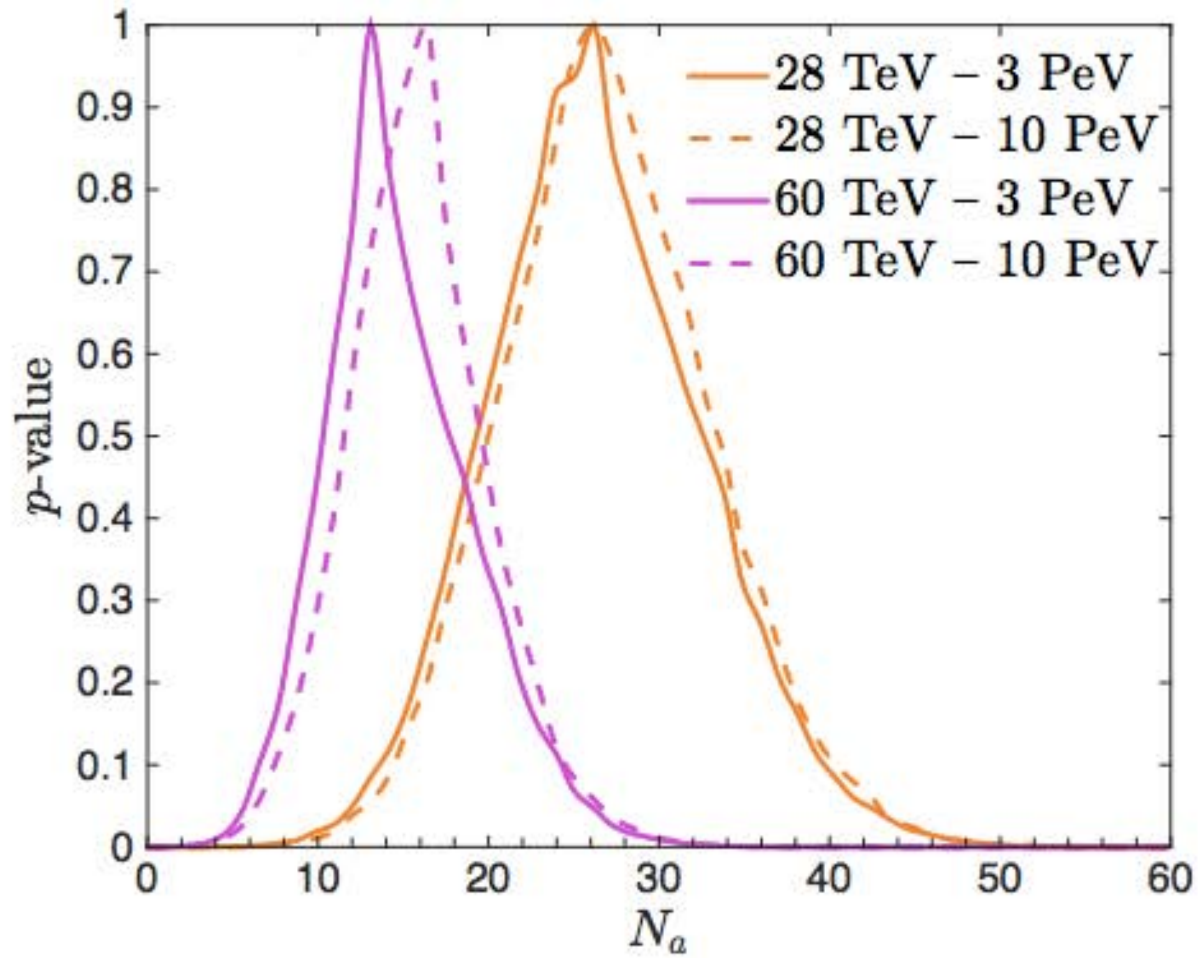


IceCube fit

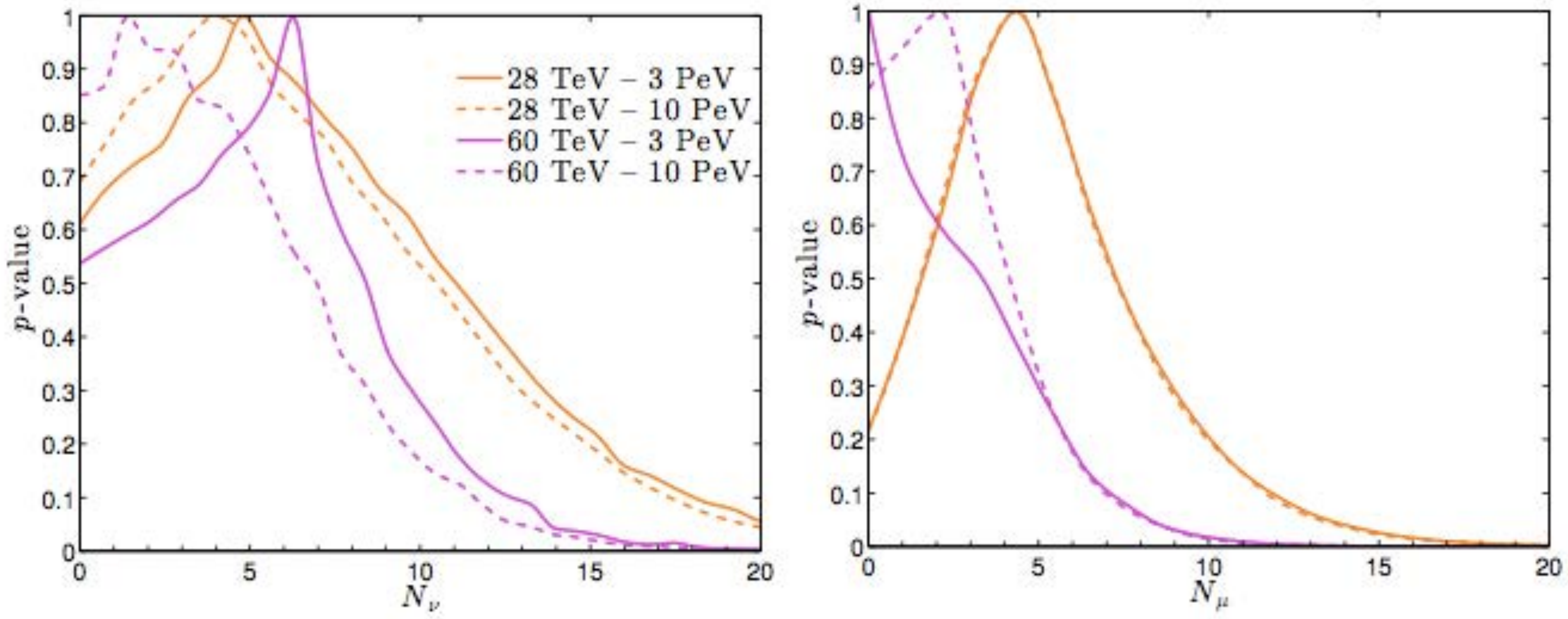
our fits

Flux normalisations





Atmospherics



Prompt charm component

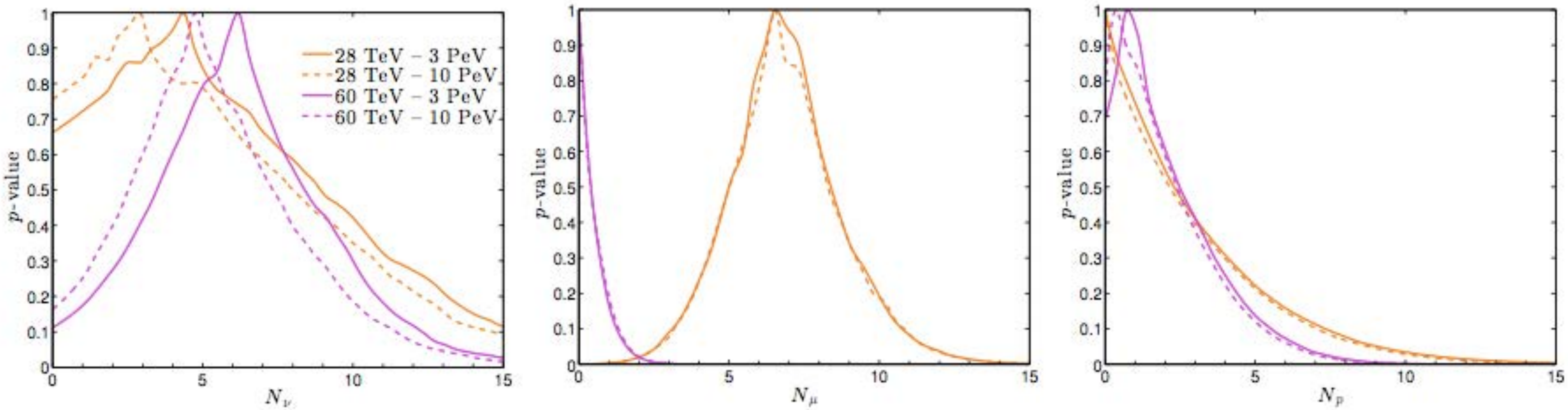


TABLE II. Same as Table I but with the 7P parameter set, *i.e.*, including the number of prompt atmospheric neutrinos N_p associated with charmed meson decays, as well as a prior on the N_p and N_μ, as explained after Eq. (69).

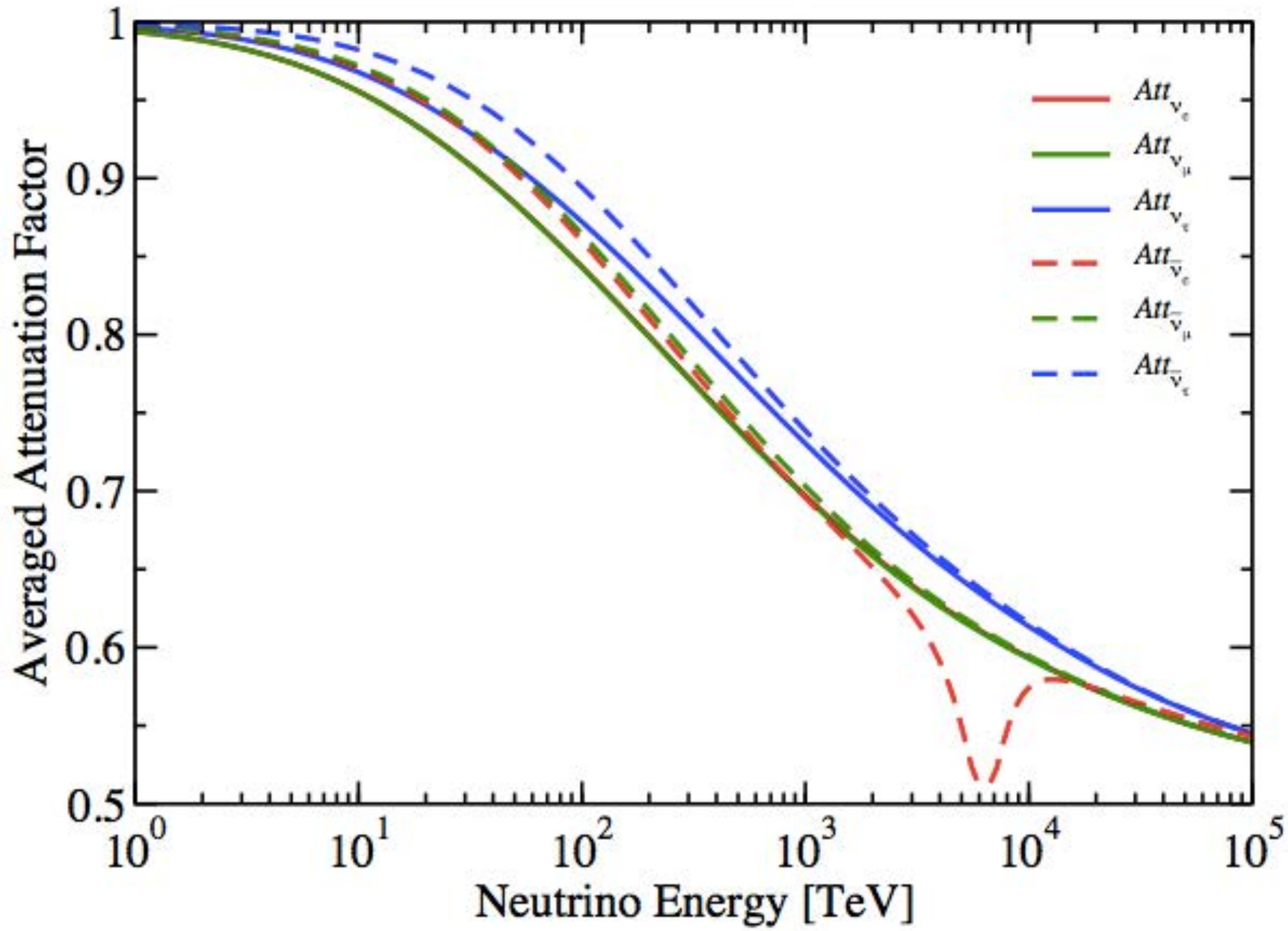
Energy range	$(\alpha_e : \alpha_\mu : \alpha_\tau)_\oplus$	γ	N_a	N_ν	N_μ	N_p	$p(1:1:1)_\oplus$
28 TeV – 3 PeV	$(0.75 : 0.25 : 0.00)$	$2.93\ ^{+0.32}_{-0.39}\ (2.80 \pm 0.40)$	$24.6\ ^{+10.0}_{-7.2}\ (20.7 \pm 6.4)$	$4.3\ ^{+6.9}_{-4.0}\ (6.8 \pm 3.9)$	$6.6\ ^{+2.6}_{-2.2}\ (7.1 \pm 2.0)$	$0.2\ ^{+3.9}_{-0.2}\ (4.7 \pm 3.1)$	0.80
28 TeV– 10 PeV	$(0.61 : 0.30 : 0.09)$	$2.97\ ^{+0.31}_{-0.35}\ (2.91 \pm 0.33)$	$26.5\ ^{+8.3}_{-8.3}\ (21.6 \pm 6.2)$	$2.9\ ^{+7.4}_{-2.9}\ (6.3 \pm 3.8)$	$6.8\ ^{+2.6}_{-2.2}\ (7.0 \pm 2.0)$	$0.2\ ^{+3.8}_{-0.2}\ (4.5 \pm 3.0)$	0.89
60 TeV – 3 PeV	$(0.99 : 0.00 : 0.01)$	$2.23\ ^{+0.44}_{-0.31}\ (2.24 \pm 0.36)$	$11.9\ ^{+7.3}_{-3.5}\ (12.4 \pm 4.2)$	$6.8\ ^{+3.4}_{-4.2}\ (5.3 \pm 2.9)$	$0.1\ ^{+0.7}_{-0.1}\ (0.8 \pm 0.6)$	$0.7\ ^{+3.2}_{-0.4}\ (3.4 \pm 1.8)$	0.43
60 TeV – 10 PeV	$(0.01 : 0.01 : 0.98)$	$2.39\ ^{+0.40}_{-0.28}\ (2.47 \pm 0.31)$	$14.3\ ^{+4.9}_{-5.7}\ (12.9 \pm 4.1)$	$4.5\ ^{+4.2}_{-2.8}\ (4.9 \pm 2.8)$	$0.1\ ^{+0.7}_{-0.1}\ (0.8 \pm 0.6)$	$1.0\ ^{+2.6}_{-0.7}\ (3.2 \pm 1.8)$	0.55

Energy range	Params.	$(\alpha_e : \alpha_\mu : \alpha_\tau)_\oplus$	γ	N_a	N_ν	N_μ	$p(1:1:1)_\oplus$
28 TeV – 3 PeV	6P	(0.75 : 0.25 : 0.00)	$2.96\ ^{+0.34}_{-0.37}$ (2.86 ± 0.28)	$26.2\ ^{+8.8}_{-8.9}$ (25.3 ± 5.7)	$4.8\ ^{+9.1}_{-4.4}$ (7.9 ± 4.7)	$4.7\ ^{+4.4}_{-3.7}$ (6.0 ± 3.1)	0.84
	4P	(0.86 : 0.14 : 0.00)	$2.82\ ^{+0.31}_{-0.31}$ (2.85 ± 0.26)	$23.6\ ^{+6.3}_{-5.7}$ (24.8 ± 5.2)	*6.6*	*8.4*	0.42
	3P	(0.92 : 0.08 : 0.00)	*2.3*	$20.6^{+6.6}_{-4.8}$ (22.2 ± 5.0)	*6.6*	*8.4*	0.29
20% mis-ID	4P	(0.77 : 0.23 : 0.00)	$2.76\ ^{+0.31}_{-0.33}$ (2.78 ± 0.27)	$22.4\ ^{+6.7}_{-5.3}$ (23.8 ± 5.2)	*6.6*	*8.4*	0.71
28 TeV – 10 PeV	6P	(0.63 : 0.27 : 0.10)	$3.02\ ^{+0.38}_{-0.35}$ (2.95 ± 0.25)	$26.9\ ^{+9.5}_{-9.8}$ (25.9 ± 5.6)	$4.1\ ^{+9.5}_{-9.8}$ (7.5 ± 4.5)	$4.9\ ^{+9.5}_{-9.8}$ (5.9 ± 3.0)	0.89
	4P	(0.85 : 0.14 : 0.01)	$2.90\ ^{+0.32}_{-0.31}$ (2.92 ± 0.24)	$23.7\ ^{+6.7}_{-5.5}$ (25.1 ± 5.2)	*6.6*	*8.4*	0.48
	3P	(0.00 : 0.00 : 1.00)	*2.3*	$21.1\ ^{+5.9}_{-5.4}$ (21.9 ± 4.8)	*6.6*	*8.4*	0.16
20% mis-ID	4P	(0.75 : 0.25 : 0.00)	$2.87\ ^{+0.27}_{-0.41}$ (2.86 ± 0.25)	$23.2\ ^{+6.0}_{-6.3}$ (24.1 ± 5.1)	*6.6*	*8.4*	0.79
60 TeV – 3 PeV	6P	(0.98 : 0.00 : 0.02)	$2.34\ ^{+0.39}_{-0.31}$ (2.40 ± 0.29)	$13.7\ ^{+7.2}_{-4.2}$ (16.0 ± 4.0)	$6.5\ ^{+4.1}_{-5.5}$ (4.6 ± 3.1)	$0.1\ ^{+4.8}_{-0.0}$ (3.0 ± 2.0)	0.50
	4P	(0.77 : 0.23 : 0.00)	$2.48\ ^{+0.31}_{-0.33}$ (2.52 ± 0.27)	$16.6\ ^{+4.8}_{-4.9}$ (17.6 ± 4.1)	*2.4*	*0.4*	0.69
	4P+br	(0.76 : 0.24 : 0.00)	$2.35\ ^{+0.36}_{-0.34}$ (2.37 ± 0.31)	$16.5\ ^{+4.7}_{-4.9}$ (17.6 ± 4.1)	*2.4*	*0.4*	0.58
	3P	(0.82 : 0.18 : 0.00)	*2.3*	$16.2\ ^{+5.5}_{-4.2}$ (17.4 ± 4.2)	*2.4*	*0.4*	0.60
20% mis-ID	4P	(0.68 : 0.32 : 0.00)	$2.48\ ^{+0.30}_{-0.34}$ (2.49 ± 0.28)	$16.4\ ^{+4.7}_{-5.0}$ (17.4 ± 4.1)	*2.4*	*0.4*	0.88
60 TeV – 10 PeV	6P	(0.01 : 0.01 : 0.98)	$2.48\ ^{+0.33}_{-0.34}$ (2.58 ± 0.25)	$16.6\ ^{+4.9}_{-6.1}$ (16.4 ± 4.0)	$1.5\ ^{+7.0}_{-1.1}$ (4.3 ± 3.0)	$2.2\ ^{+2.8}_{-2.2}$ (2.9 ± 2.0)	0.61
	4P	(0.00 : 0.02 : 0.98)	$2.50\ ^{+0.36}_{-0.28}$ (2.65 ± 0.25)	$16.4\ ^{+4.8}_{-4.8}$ (17.8 ± 4.1)	*2.4*	*0.4*	0.69
	4P+br	(0.75 : 0.25 : 0.00)	$2.43\ ^{+0.31}_{-0.34}$ (2.44 ± 0.29)	$16.5\ ^{+4.8}_{-4.8}$ (17.6 ± 4.1)	*2.4*	*0.4*	0.65
	3P	(0.00 : 0.00 : 1.00)	*2.3*	$16.2\ ^{+5.5}_{-4.0}$ (17.3 ± 4.1)	*2.4*	*0.4*	0.33
20% mis-ID	4P	(0.00 : 0.11 : 0.89)	$2.50\ ^{+0.35}_{-0.29}$ (2.62 ± 0.25)	$16.7\ ^{+4.8}_{-4.9}$ (17.5 ± 4.1)	*2.4*	*0.4*	0.82
30% mis-ID	4P	(0.00 : 0.18 : 0.82)	$2.49\ ^{+0.35}_{-0.30}$ (2.61 ± 0.25)	$16.3\ ^{+5.8}_{-3.9}$ (17.4 ± 4.1)	*2.4*	*0.4*	0.84

TABLE II. ***Same as Tab. I but for the 7P analyses***, *i.e.*, including the number of prompt atmospheric neutrinos N_p associated with charmed meson decays, as well as a prior on the N_p and N_μ, as explained after Eq. (69).

Energy range	$(\alpha_e : \alpha_\mu : \alpha_\tau)_\ominus$	γ	N_a	N_ν	N_μ	N_p	$p(1:1:1)_\ominus$
28 TeV – 3 PeV	(0.75 : 0.25 : 0.00)	$2.93\ ^{+0.32}_{-0.39}$ (2.80 ± 0.40)	$24.6\ ^{+10.0}_{-7.2}$ (20.7 ± 6.4)	$4.3\ ^{+6.9}_{-4.0}$ (6.8 ± 3.9)	$6.6\ ^{+2.6}_{-2.2}$ (7.1 ± 2.0)	$0.2\ ^{+3.9}_{-0.2}$ (4.7 ± 3.1)	0.80
28 TeV– 10 PeV	(0.61 : 0.30 : 0.09)	$2.97\ ^{+0.31}_{-0.35}$ (2.91 ± 0.33)	$26.5\ ^{+8.3}_{-8.3}$ (21.6 ± 6.2)	$2.9\ ^{+7.4}_{-2.9}$ (6.3 ± 3.8)	$6.8\ ^{+2.6}_{-2.2}$ (7.0 ± 2.0)	$0.2\ ^{+3.8}_{-0.2}$ (4.5 ± 3.0)	0.89
60 TeV – 3 PeV	(0.99 : 0.00 : 0.01)	$2.23\ ^{+0.44}_{-0.31}$ (2.24 ± 0.36)	$11.9\ ^{+7.3}_{-3.5}$ (12.4 ± 4.2)	$6.8\ ^{+3.4}_{-4.2}$ (5.3 ± 2.9)	$0.1\ ^{+0.7}_{-0.1}$ (0.8 ± 0.6)	$0.7\ ^{+3.2}_{-0.4}$ (3.4 ± 1.8)	0.43
60 TeV – 10 PeV	(0.01 : 0.01 : 0.98)	$2.39\ ^{+0.40}_{-0.28}$ (2.47 ± 0.31)	$14.3\ ^{+4.9}_{-5.7}$ (12.9 ± 4.1)	$4.5\ ^{+4.2}_{-2.8}$ (4.9 ± 2.8)	$0.1\ ^{+0.7}_{-0.1}$ (0.8 ± 0.6)	$1.0\ ^{+2.6}_{-0.7}$ (3.2 ± 1.8)	0.55

(angle-averaged) Attenuation/regeneration



Effective mass