What Is The Flavor Of The Cosmic Neutrinos Seen By IceCube?

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Outline

- Flavor Ratio of HE cosmic ν
- Expected Track-to-Shower Ratio
- Observed Track-to-Shower in IceCube
- Results for Decaying Neutrinos

G.P., A.Palladino, F. Vissani and F.L.Villante

G. P., A. Palladino, F. Vissani, F.L. Villante: **arXiv:1506.02624**

A.Palladino, G.P., F.L. Villante, F. Vissani, **Phys.Rev.Lett.114 (2015) 17,171101**

F. Vissani, G. P. and F. L. Villante, **JCAP 1309 (2013) 017**

Flavor Ratios of High Energy Neutrinos

The blend of neutrinos (or antineutrinos) at the source $\xi_l^0 \equiv F_l^0 / F_{tot}$ can tell us about the production mechanism

- Pion Decay

$$(\xi_e^0 : \xi_\mu^0 : \xi_\tau^0) = (1/3 : 2/3 : 0)$$

- Charmed mesons decay

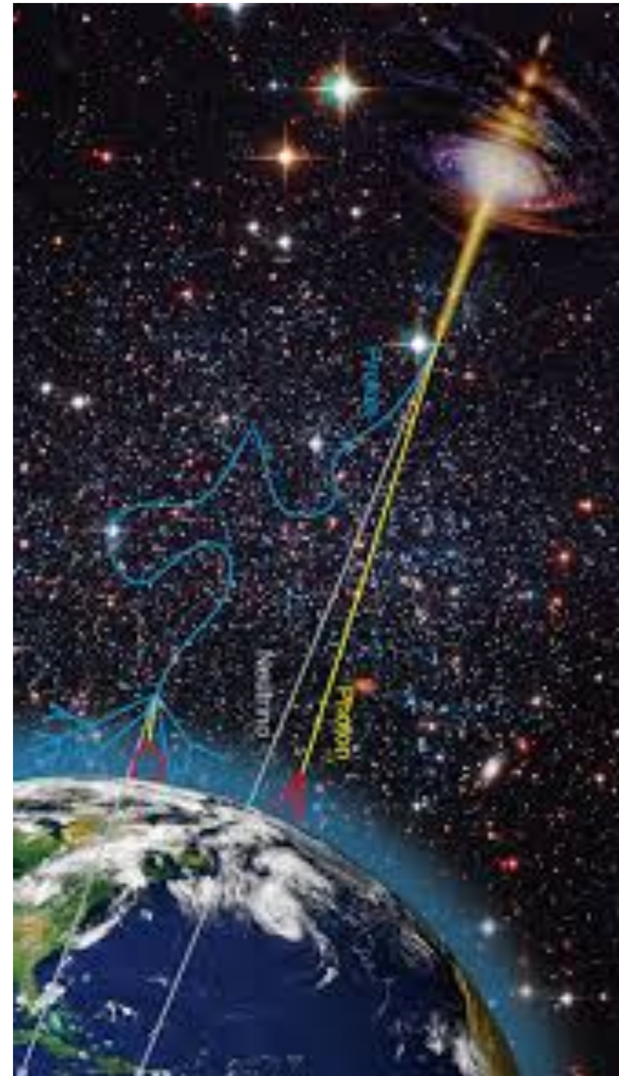
$$(\xi_e^0 : \xi_\mu^0 : \xi_\tau^0) = (1/2 : 1/2 : 0)$$

- Beta decay of neutrons

$$(\xi_e^0 : \xi_\mu^0 : \xi_\tau^0) = (1 : 0 : 0)$$

- Pion decay with damped muons

$$(\xi_e^0 : \xi_\mu^0 : \xi_\tau^0) = (0 : 1 : 0)$$



The Oscillations (10 TeV-10 PeV)

Cosmic Neutrinos

- Vacuum oscillations fully developed

$$\xi_l = \sum_{l'} P_{ll'} \xi_{l'}^0 \quad P_{ll'} = \sum_{i=1,3} \left| U_{li}^2 U_{l'i}^2 \right|$$

Pions: (0.36 : 0.32 : 0.32)
Neutrons: (0.55 : 0.26 : 0.19)
Charms: (0.4 : 0.3 : 0.3)
Damped Muons: (0.26 : 0.36 : 0.38)

Atmospheric Neutrinos

- Vacuum oscillations practically absent

Conventional Mechanism

$$(\xi_e : \xi_\mu : \xi_\tau) = (0 : 1 : 0)$$

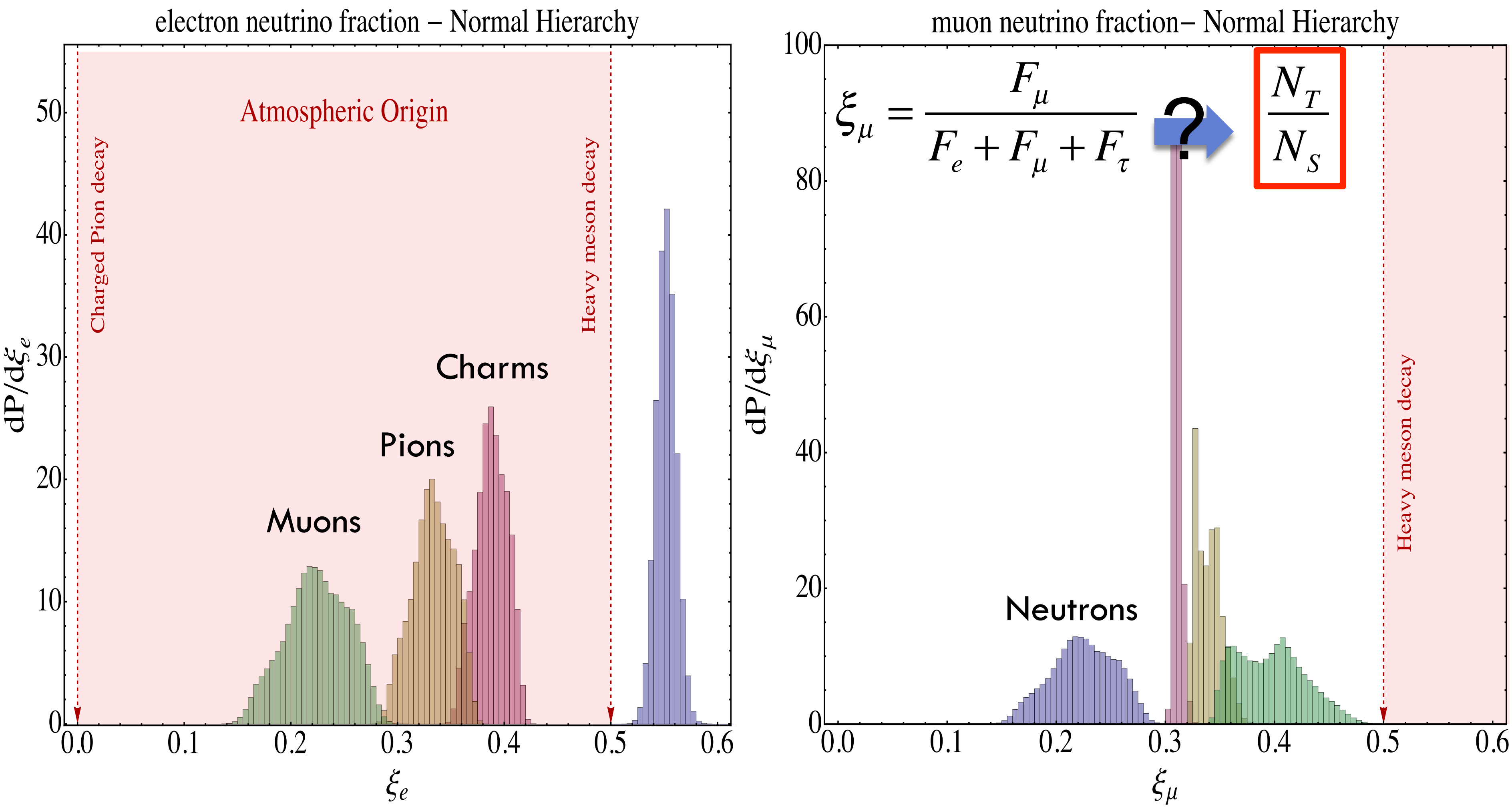
'Prompt' component

$$(\xi_e : \xi_\mu : \xi_\tau) = (1/2 : 1/2 : 0)$$

M. C. Gonzalez-Garcia, M. Maltoni, and T. Schwetz, J. High Energy Phys. 11 (2014) 052

Flavor Content at the Earth

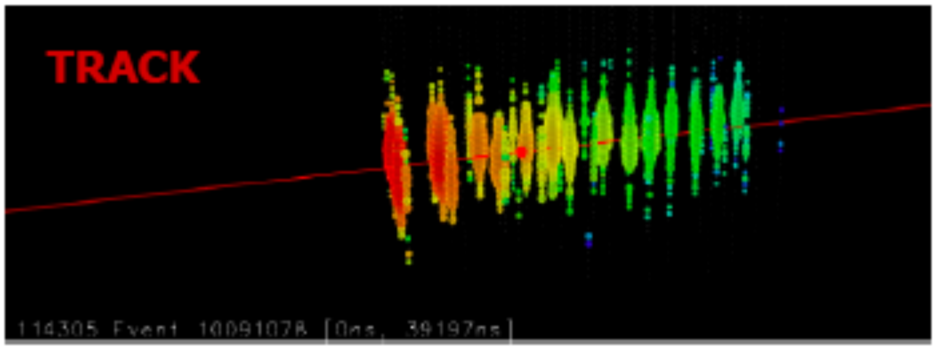
A different blend of neutrinos (and antineutrinos) arrives at the Earth

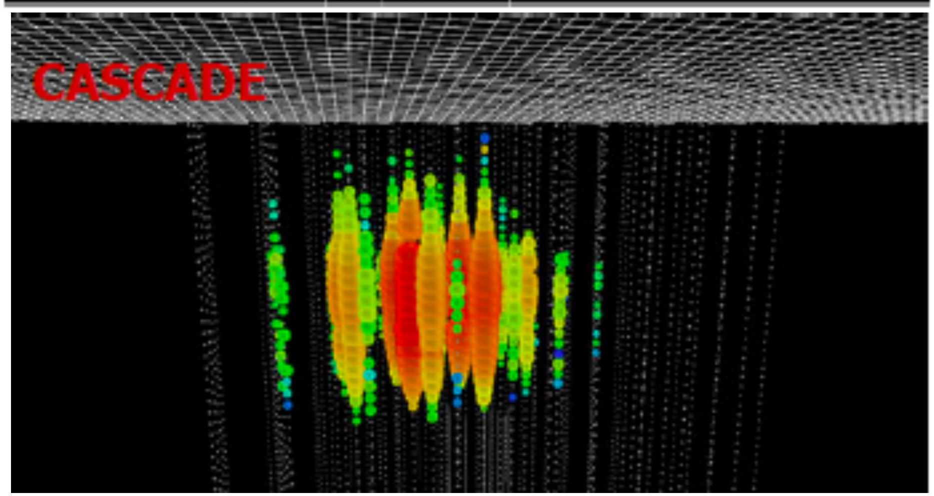


Present uncertainties on oscillation parameters will affect the ratios

IceCube Events Topology

OBSERVED EVENTS TOPOLOGIES





$$\Phi_l(E) = \frac{F_l \cdot 10^{-8}}{cm^2\, sr\, s\, GeV}\left(\frac{GeV}{E}\right)^{\alpha}$$

$$N_T = 4\pi T \int_0^{\bar{E}} dE \cdot \Phi_\mu(E)\, p_T A_\mu(E)$$

M. G. Aartsen et al. ***PRL 113, 101101 (2013)***

$$p_T \simeq 0.8$$

Probability for a muon neutrino to produce a track event

$$N_S = 4\pi T \int_0^{\bar{E}} dE \cdot \left[\Phi_\mu(E)\left(1 - p_T\right)A_\mu(E) + \Phi_e(E)A_e(E) + \Phi_\tau(E)A_\tau(E)\right]$$

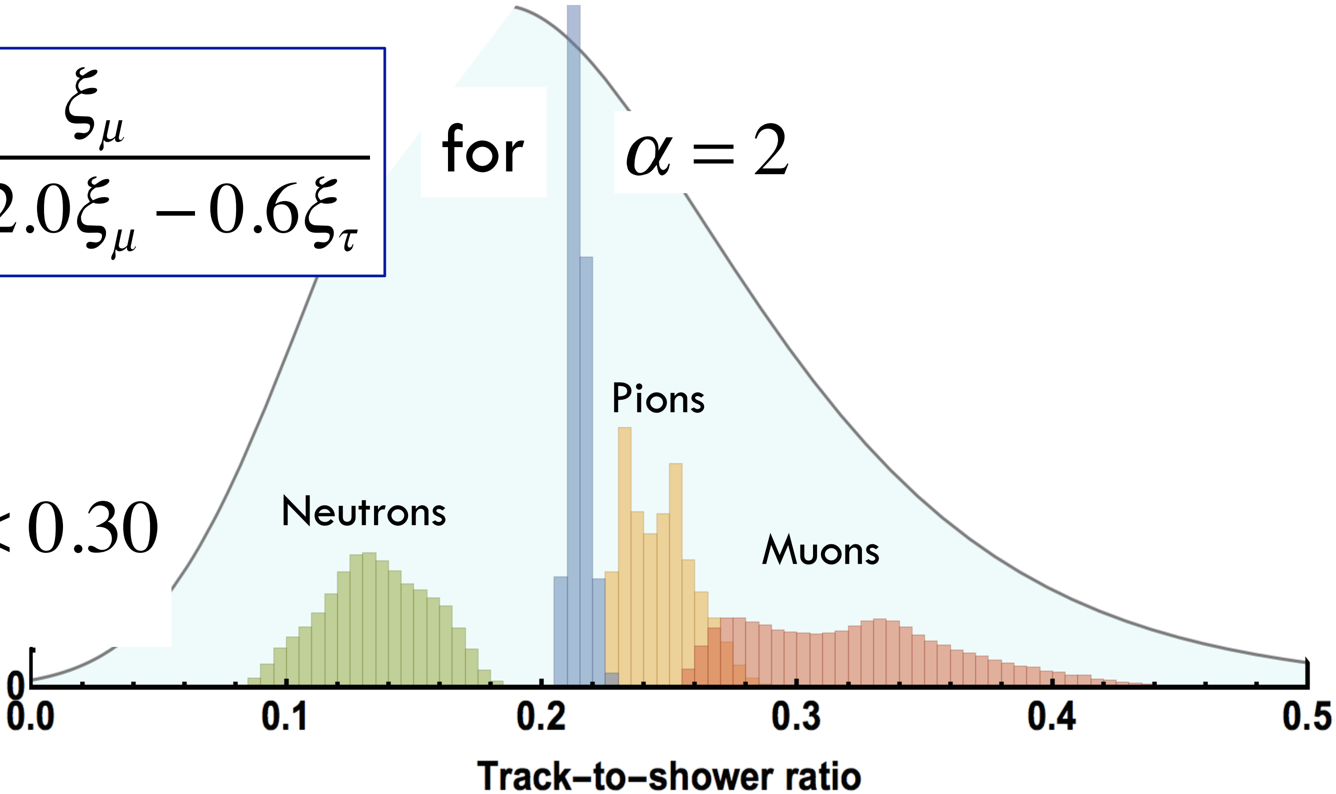
Predicted Track-to-Shower Ratio

- The predicted flavor content at the Earth converted into the observable quantity in IceCube detector, i.e. the track-to-shower ratio is:

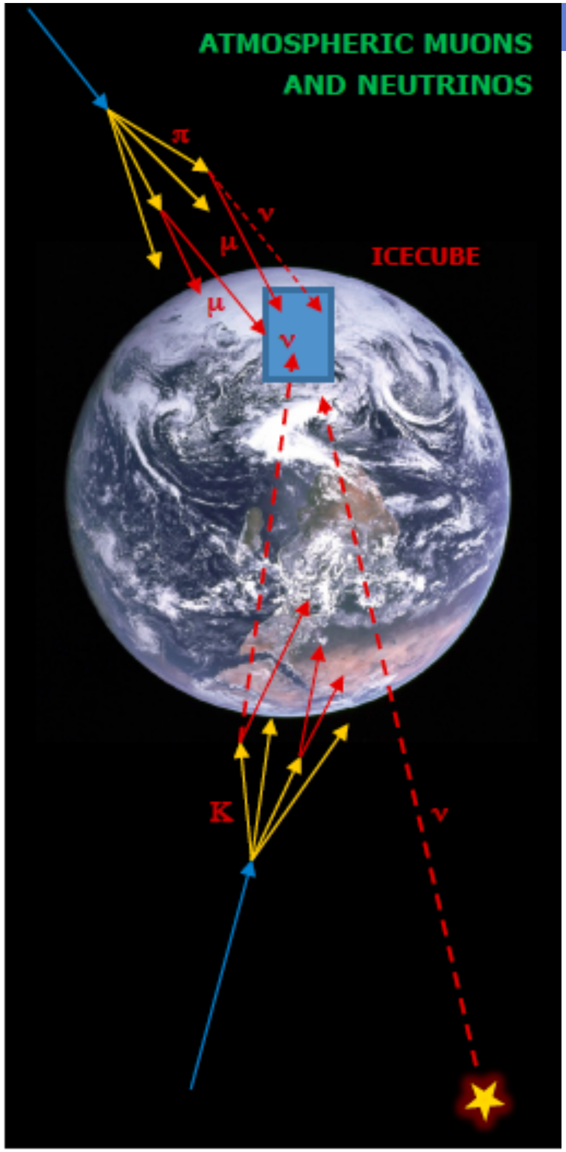
$$\frac{N_T}{N_S} = \frac{\xi_\mu}{2.3 - 2.0\xi_\mu - 0.6\xi_\tau}$$

for $\alpha = 2$

$$0.15 < \frac{N_T}{N_S} < 0.30$$



Observed Track-to-Shower Ratio



HESE data from **PRL 113, 101101 (2013)** with deposited energy >60 TeV

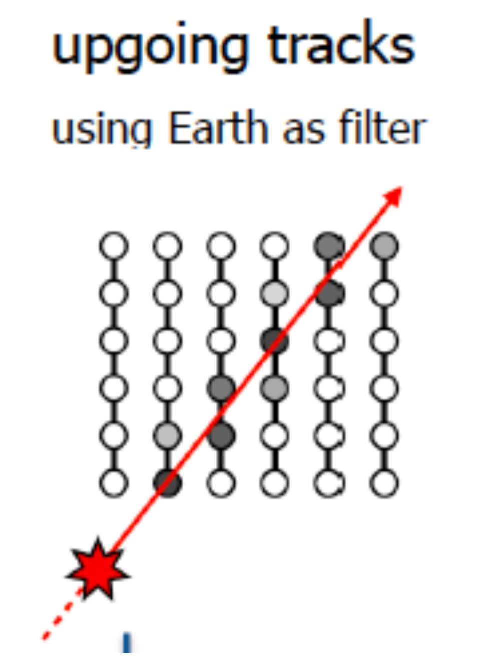
	n_T	n_S
total	4	16
Atm.	1.7	0.7
muons	0.4	0

$$l(N_i) \propto (N_i + b_i)^{n_i} e^{(N_i + b_i)}$$

$$\frac{N_T}{N_S} = 0.11^{+0.23}_{-0.05} \quad \text{HESE}$$

The Constraint from Passing Muons

Passing Muons provide an independent constraint on the normalization of the muonic cosmic component, i,.e on the expected Number of Tracks



$$F_{\mu} = (1.01 \pm 0.35)$$

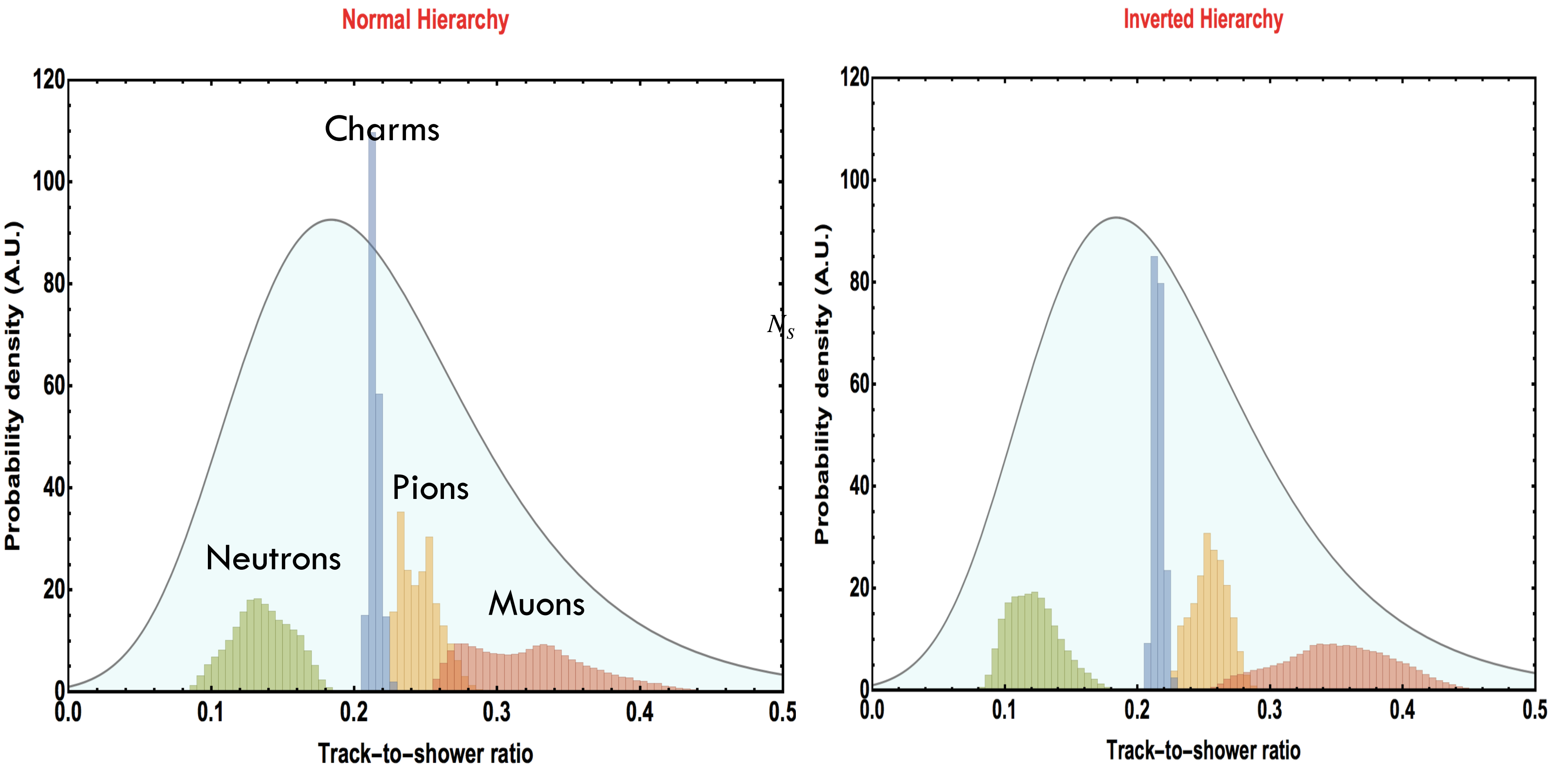
C. Weaver, Spring APS Meeting, Savannah, Georgia 2014

Inserted in the analysis as a Gaussian prior for the expected number of tracks

$$\frac{N_T}{N_S} = 0.18^{+0.13}_{-0.05} \quad \text{HESE+muons}$$

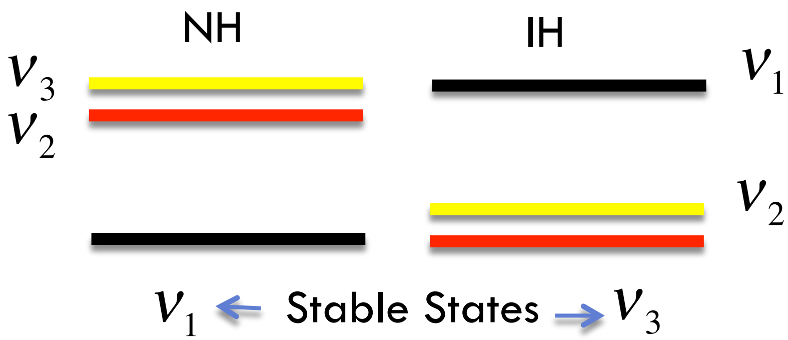
Results with 3 years data

A. Palladino et al., **Phys.Rev.Lett.114 (2015) 17,171101**



3 years data-set (HESE+Muons) is compatible with a cosmic origin of HEN, yet not enough statistic to discriminate the production mechanism.

Testing Unstable Neutrinos



Beacom et al., Phys. Rev. Lett. 90 (2013) 181301

"Non radiative Neutrino decay can be tested using flavor ratios of cosmic HEN"

$$\nu_i \rightarrow \nu_j + X$$

Only 1 stable mass eigenstate survives

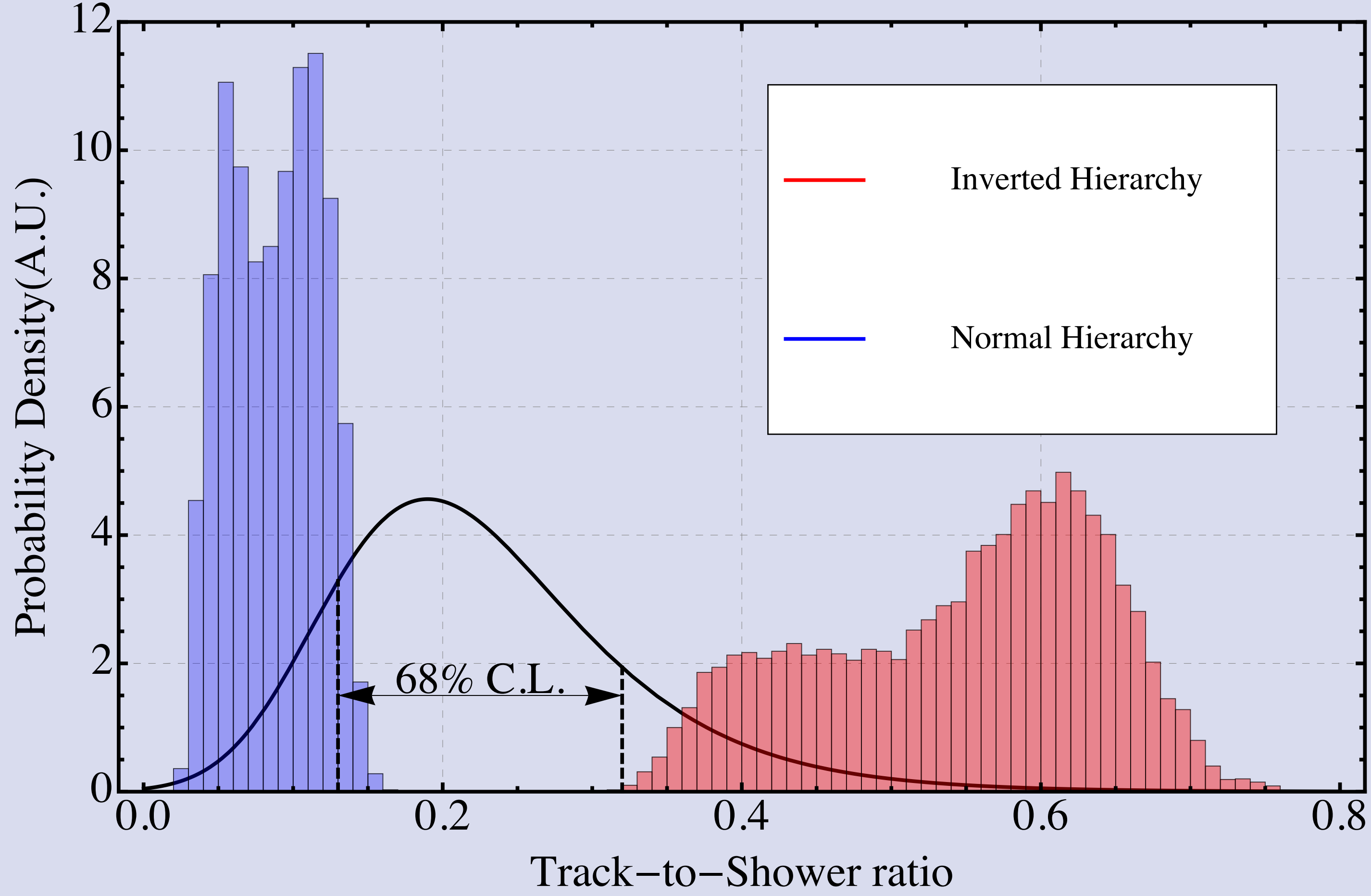
$$\xi_l = |U_{lj}|^2$$

Complete Decay Scenario

$$\frac{N_T}{N_S} = \frac{|U_{\mu j}|^2}{2.3 - 2.0|U_{\mu j}|^2 - 0.6|U_{\tau j}|^2}$$

$$\left(\frac{N_T}{N_S}\right)_{NH}^{BF} = 0.12$$

$$\left(\frac{N_T}{N_S}\right)_{IH}^{BF} = 0.62$$



Non-Radiative Neutrino Decay

3 years data-set (HESE+Muons) already disagrees with the decay hypothesis for both the mass hierarchies

G. P., A. Palladino, F. Vissani, F.L. Villante: **arXiv:1506.02624**

Conclusions

- Informations provided by the Flavor Ratio of HEN are transferred to the observable Track-To-Shower Ratio;
- Different Production Mechanisms of Cosmic neutrinos are distinguishable despite oscillations uncertainties;
- Passing muons provide an important piece of information;
- In scenarios with only one stable neutrino, the track-to-shower ratio is different from that predicted in the case of stable neutrinos, even taking into account the uncertainty in the neutrino production mechanisms;
- The data are compatible with Cosmic origin and already disfavor the possibility of neutrinos decay for both normal and inverted mass hierarchy.

Comparison with IceCube fits

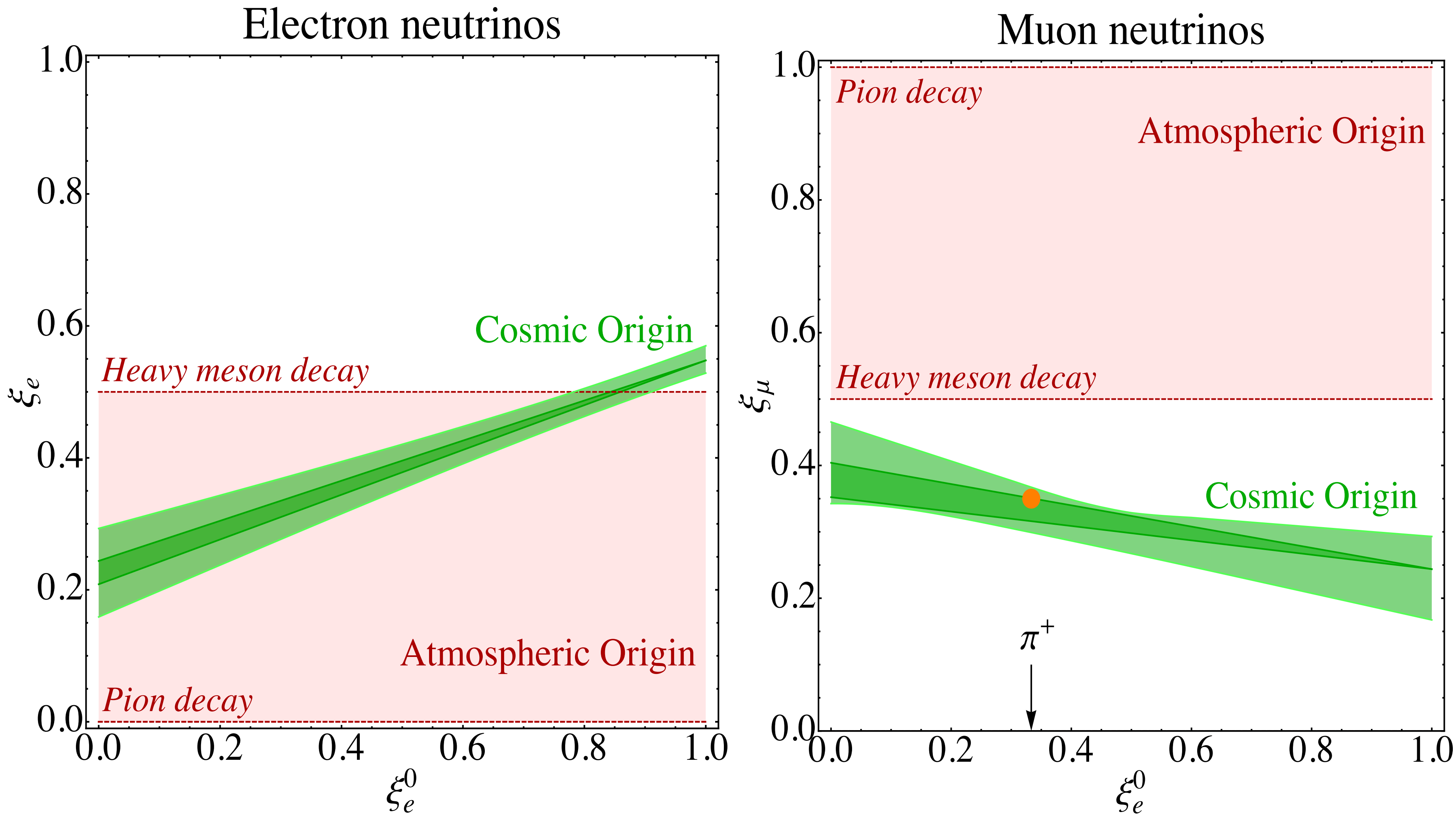
IceCube fit provided in Table IV of **PRL 113, 101101 (2013)**:

60 TeV < E_{dep} < 3 PeV	Muons	π/K atm. ν	Prompt atm. ν	E^{-2} (best-fit)	Sum (central)	Data
Tot. Events	0.4	2.4	< 5.3	18.2	21.0	20
Up	0	1.4	< 3.5	6.5	8.0	5
Down	0.4	0.9	< 1.8	11.7	13.0	15
Track	~ 0.4	1.7	< 1.0	3.8	5.9	4
Shower	~ 0.0	0.7	< 4.2	14.4	15.2	16

Results from our procedure:

$$N_T = 3.6 \quad N_S = 14.8$$

Flavor Ratio

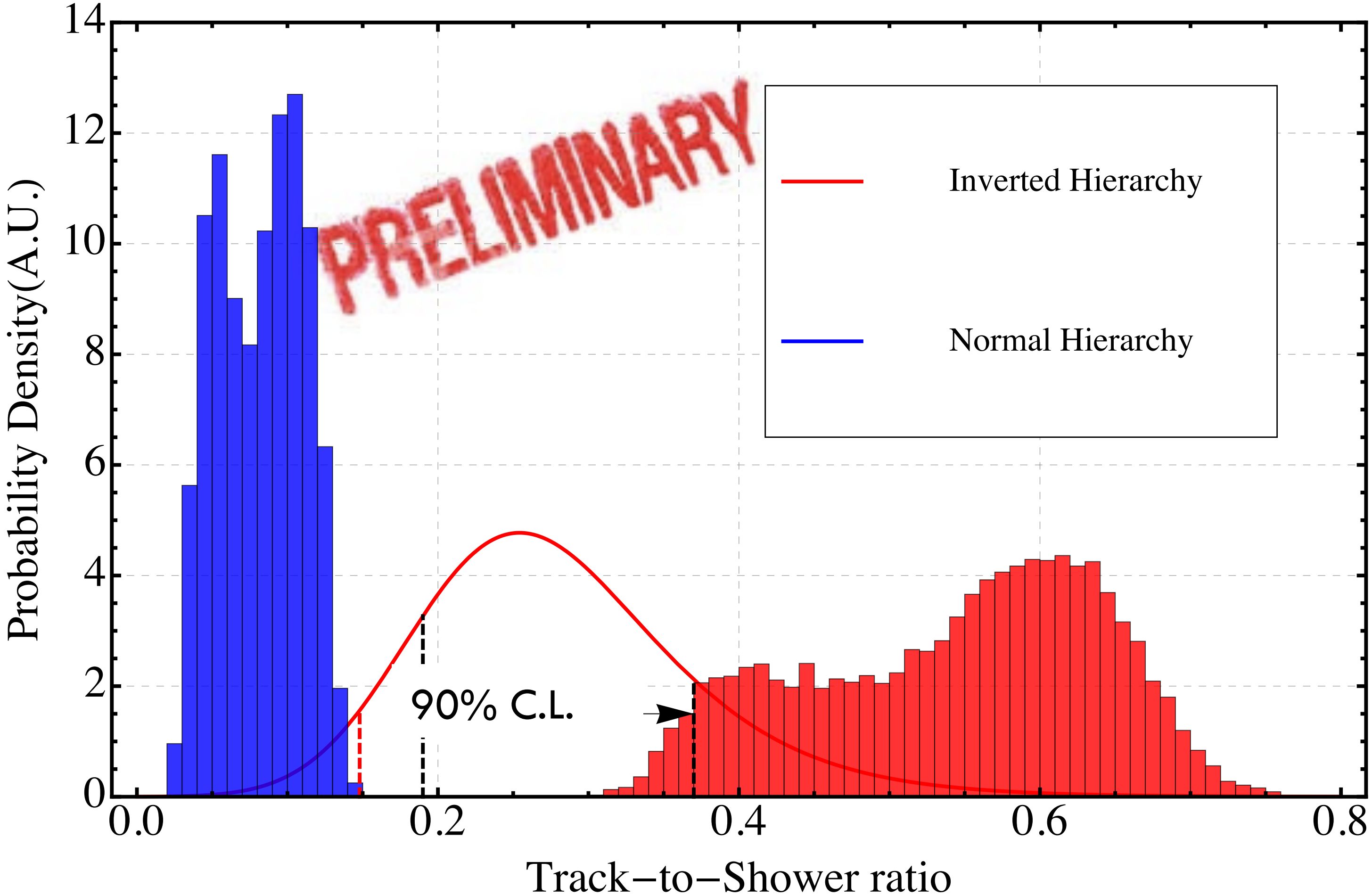


F. Vissani, G. P. and F. L. Villante, **JCAP 1309 (2013) 017**

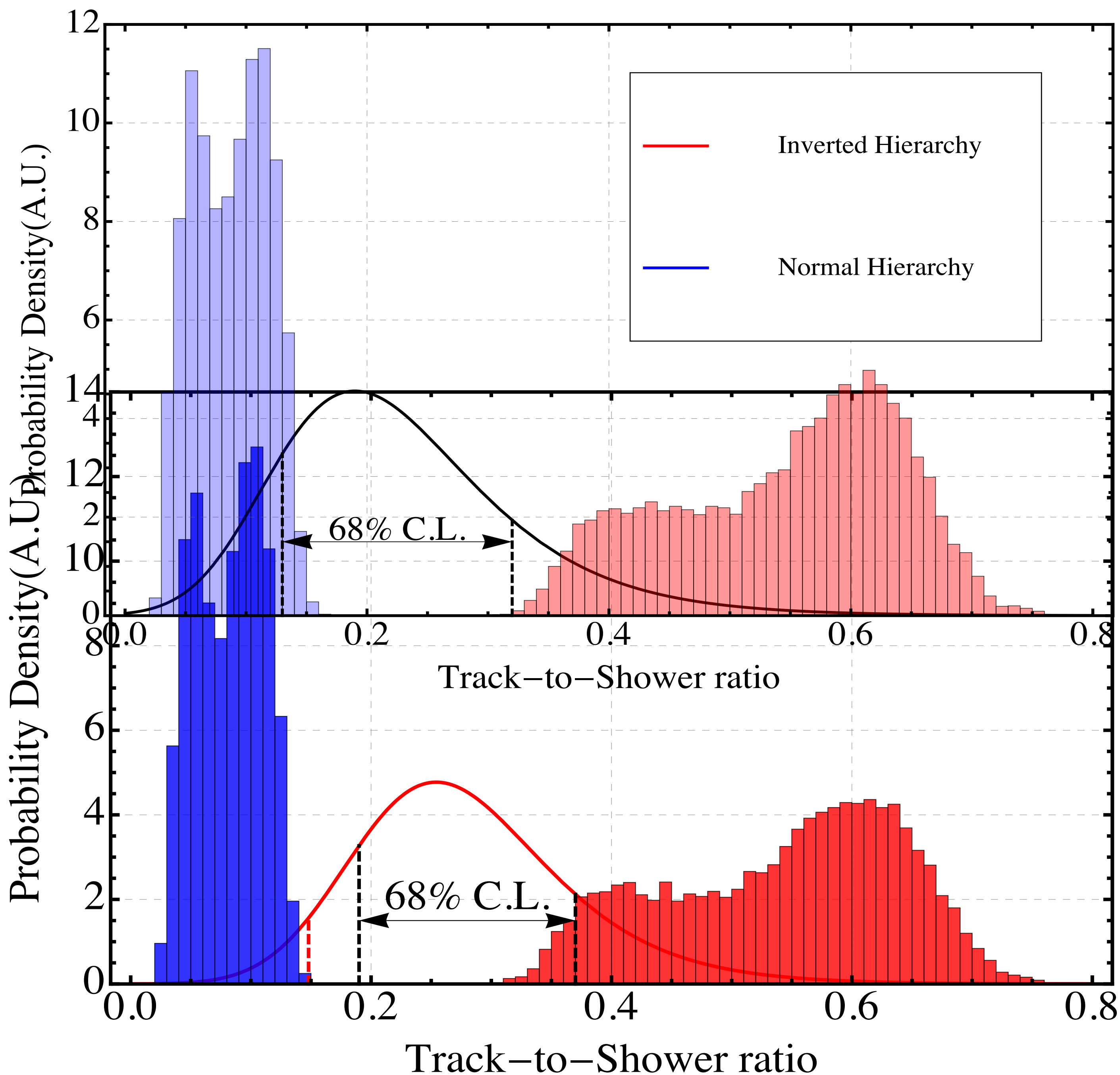
For a Different Spectral Index

Alpha = 2	Alpha = 2.2
Expectation for 988 days of exposure	Expectation for 988 days of exposure
$N_T = 3.6 F_\mu$	$N_T = 0.27 F_\mu$
$N_S = 8.4 F_e + 0.9 F_\mu + 6.3 F_\tau$	$N_S = 0.67 F_e + 0.07 F_\mu + 0.48 F_\tau$
$\frac{N_T}{N_S} = \frac{\xi_\mu}{2.3 - 2.0\xi_\mu - 0.6\xi_\tau}$	$\frac{N_T}{N_S} = \frac{\xi_\mu}{2.4 - 2.2\xi_\mu - 0.7\xi_\tau}$

Spectral Index 2.2 and 4 years



IceCube 4 years data + new results for Passing Muons


Inverted Hierarchy
Normal Hierarchy
68% C.L.
68% C.L.
Probability Density(A.U.)
Probability Density(A.U.)
Track−to−Shower ratio
Track−to−Shower ratio
0.0
0.2
0.4
0.6
0.8
0
2
4
6
8
10
12
14

New Data above 60 TeV

Prof. O.Botner contribution at IPA 2015

Data	988 days	1460 days
Shower	16	25
Track	4	8

Passing muons results from IceCube in arXiv:1507.04005v1

F_mu (10^-8)	alpha
0.99±0.35	=2
17.0±7.0	2.2±0.2

The Probability pT(E)

CC interaction cross section

effective detector mass
For CC interaction of ν_μ

$$p_T(E) = \frac{\sigma_{CC}(E)\cdot M_\mu^{CC}(E)}{\sigma_{NC}(E)\cdot M^{NC}(E) + \sigma_{CC}(E)\cdot M_\mu^{CC}(E)}$$

effective detector mass
For NC interaction of ν_μ

NC interaction cross section

M. G. Aartsen et al., Science 342,1242856 (2013)

R. Gandhi et al. , Phys. Rev. D 58, 093009 (1998)