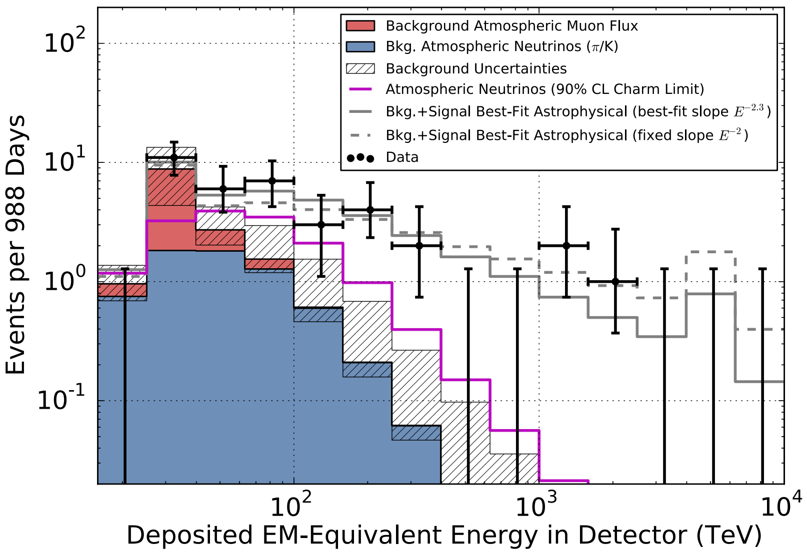
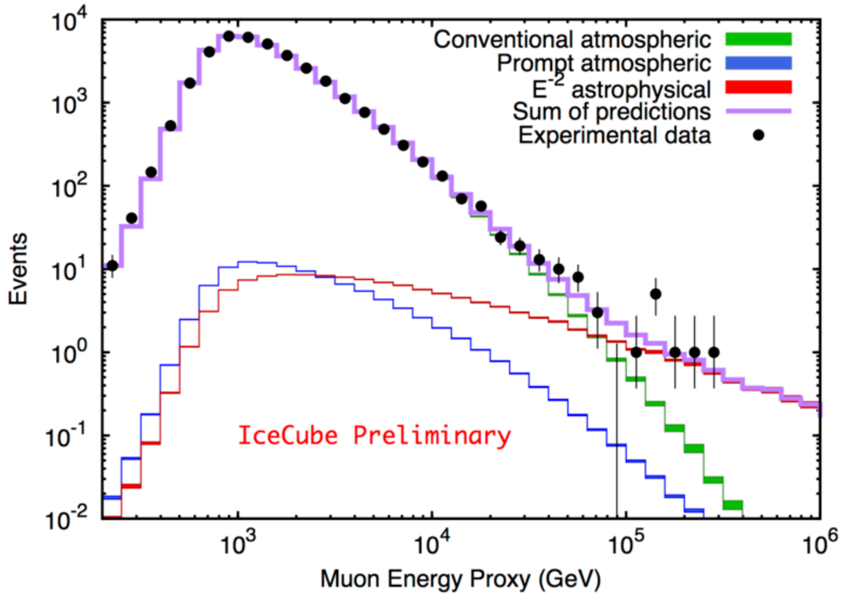
Atmospheric neutrinos

TG with

F. Riehn, A. Fedynitch, R. Engel, T. Stanev, F. Campos-Penha, H. Dembinski

Motivation: to know how the astrophysical flux extends to lower energy





IceCube discovery plot. HESE analysis cuts out low energy. Index of astro flux ~ 2.3, 2.5 ?

PRL 113 (2014) 101101

Upward $\nu_\mu \longrightarrow \mu$

PRL 115 (2015) 081102

Global fit: 1507:03991 (and talk by Lars Mohrmann, in *ν* parallel session)

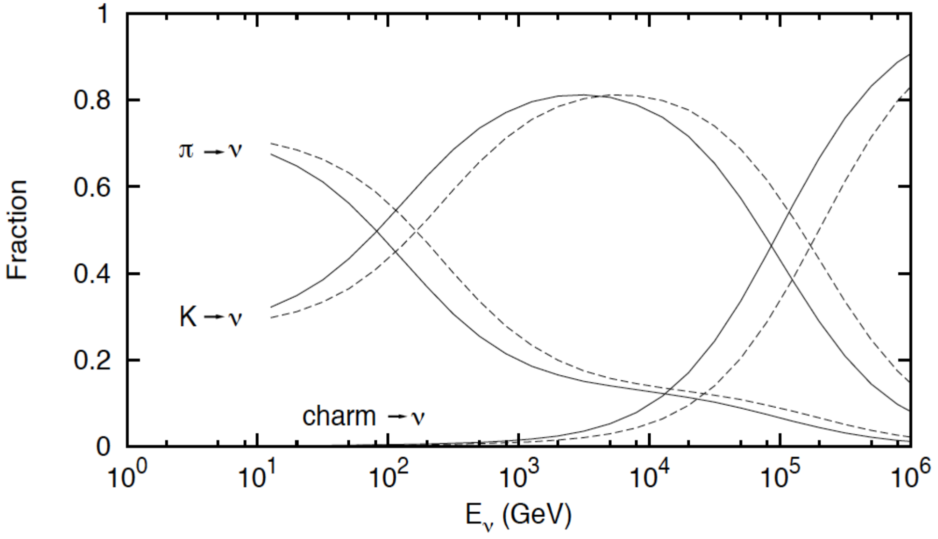
Outline

- Introduction: importance of kaons
  - Muon charge ratio, K/π ratio, $\nu / \bar{\nu}$ ratio
- Primary spectrum
- Atmospheric neutrinos to PeV
  - Must account for knee in cosmic-ray spectrum
  - Prompt neutrinos from decay of charmed hadrons
- Atmospheric neutrino self-veto
- Atmospheric ν backgrounds in IceCube

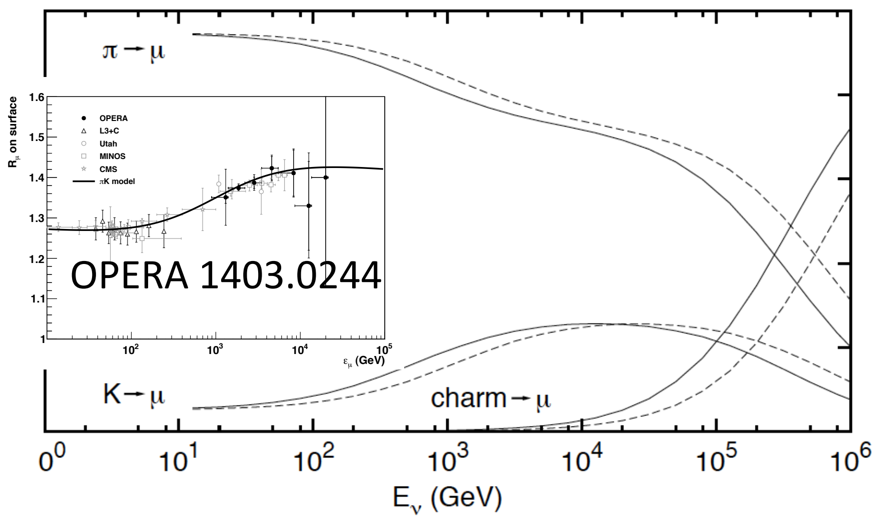
Importance of kaons for neutrinos

- Atmospheric ν_μ mainly from $K^{+/-}$
- TeV atmospheric ν_e from K_{e3} decays of K^0,$K^{+/-}$
- Associated production ($p \rightarrow K^+\Lambda$) favors $K^+ \rightarrow \mu^+/\mu^-$ increase
- Charm → μ, ν : small but potentially important at high E
  - contribution isotropic (compared to secant θ effect for >TeV leptons from decay of π and K)

Neutrinos



Muons

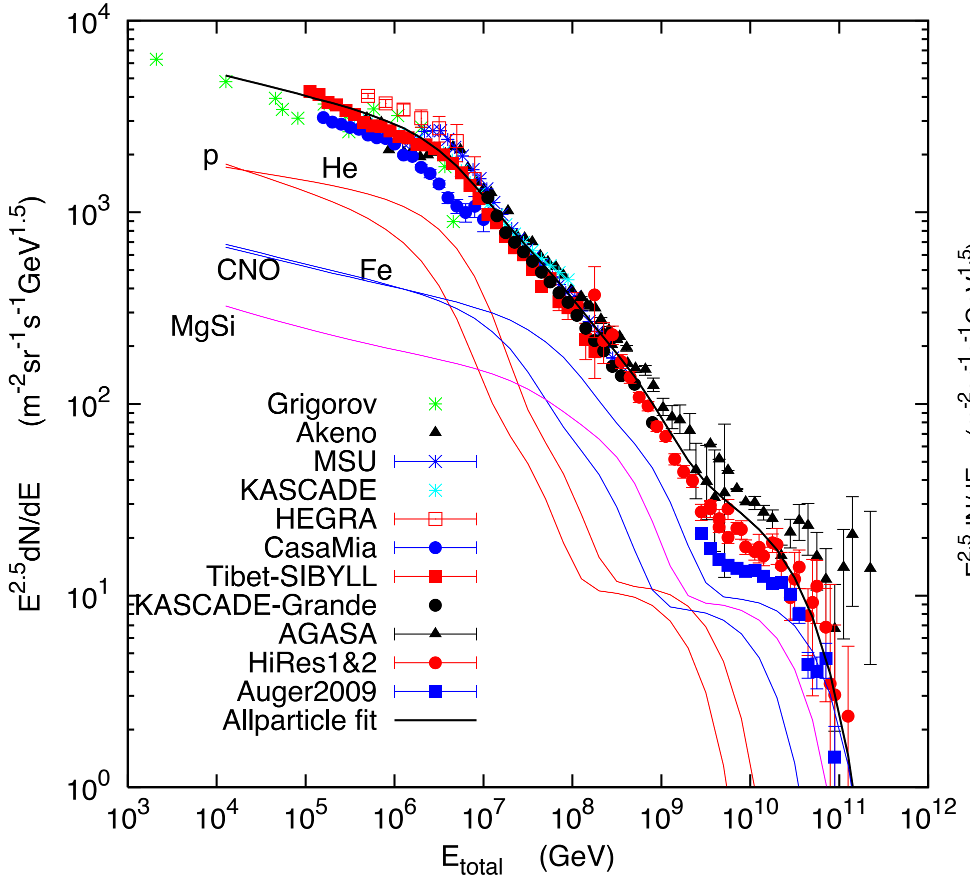


OPERA 1403.0244

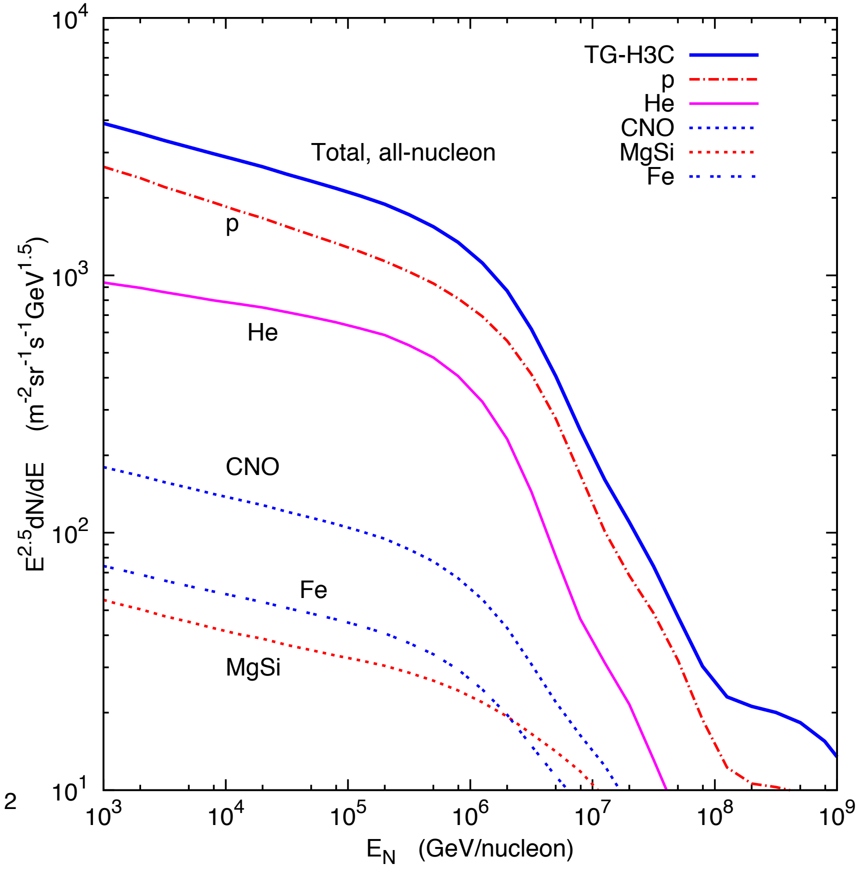
Primary spectrum

- Combine information
  - from direct measurements < 100 TeV
  - with air shower measurements of all-particle spectrum at higher E
- Assumptions:
  - 5 nuclear groups: p, He, CNO, Mg-Si, Fe
  - 3 populations: SNR, Hillas' Galactic component B, extra-galactic
  - All features depend on rigidity, R = Pc / Ze
  - All particle spectrum: $\phi_i(E) \;=\; \Sigma_{j=1}^{3}\, a_{i,j}\, E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right]$
  - Spectrum of nucleons: $\phi_{i,N}(E_N) \;=\; A \times \phi_i(A\, E_N)$
- Requirements
  - Consistency with air shower measurements of the all-particle spectrum
  - Anchor to composition from direct experiments below 100 TeV

Spectrum of nucleons determines fluxes of atmospheric ν and μ

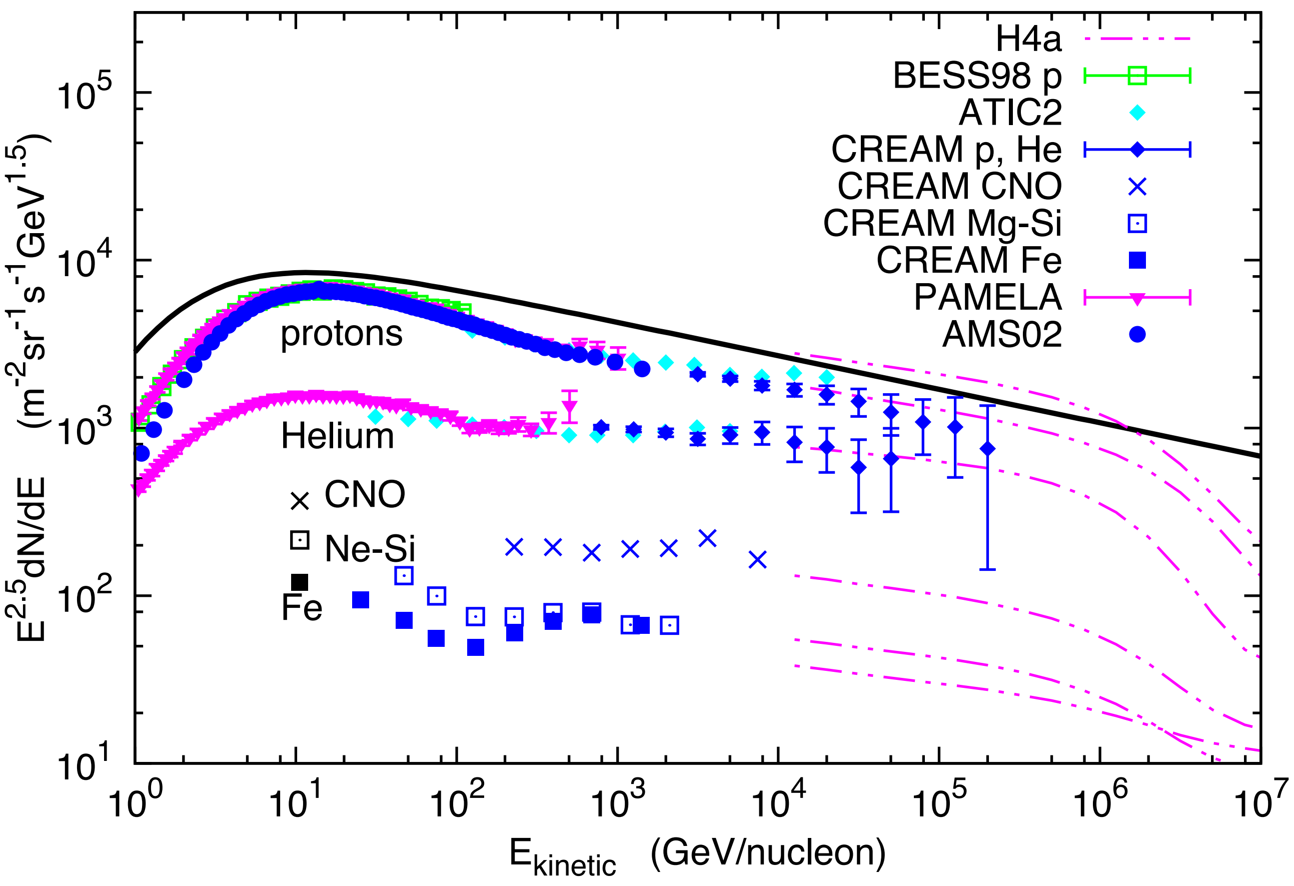


All-particle spectrum

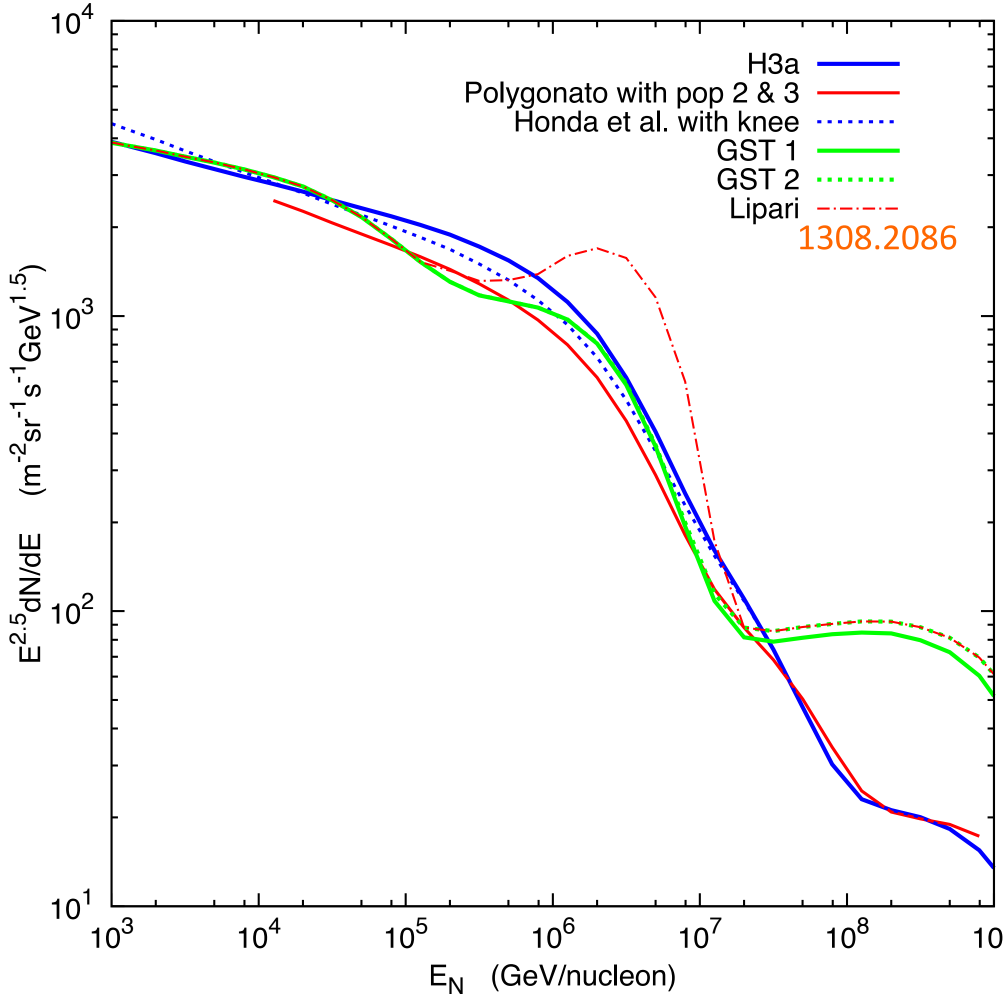


Spectrum of nucleons

Data plotted vs E/nucleon



Models or fits of nucleon spectrum



Challenge:

For the first time, we must account for the knee in the cosmic-ray spectrum to calculate atmospheric neutrinos

Also need to account for non-scaling behavior of meson production over wide energy range

Unified approach to calculating $\phi_\nu(E_\nu)$

- Use simple equations $A_{i\nu} = \frac{Z_{Ni} \times BR_{i\nu} \times Z_{i\nu}}{1 - Z_{NN}}$

$$\phi_\nu(E_\nu) = \phi_N(E_\nu) \times \Sigma_{i=1,3} \left(\frac{A_{i\nu}}{1 + B_{i\nu} \cos^* \theta \, E_\nu / \epsilon_i} \right)$$

- With energy-dependent Z-factors
  - Thunman, Ingelman, Gondolo, Astropart. Phys. 5 (1996) 309-332

$$Z_{i,j}(E) = \int_E^\infty \mathrm{d}E' \, \frac{\phi_N(E')}{\phi_N(E)} \, \frac{\mathrm{d}n_{i,j}(E', E)}{\mathrm{d}E}$$

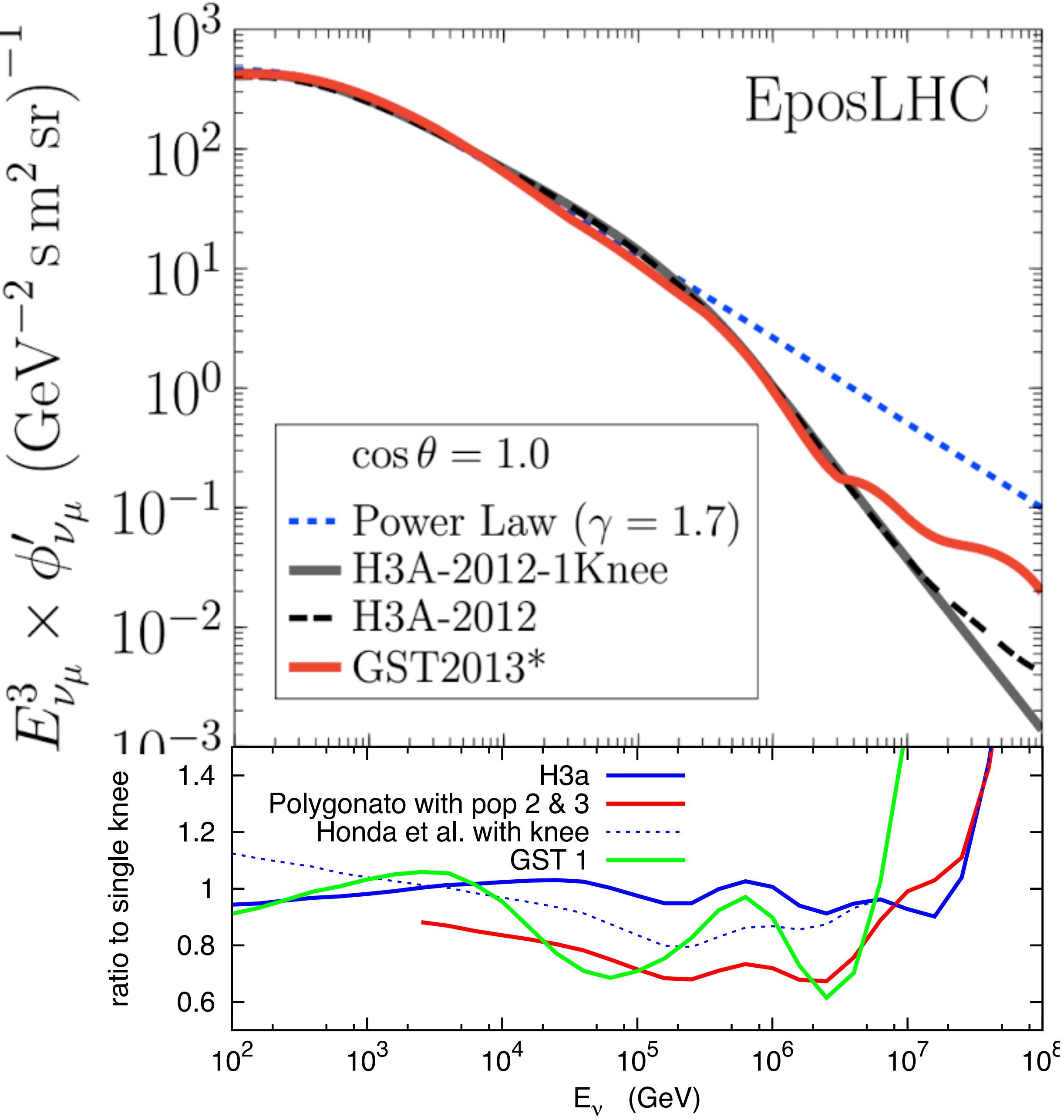
- Allows systematic evaluation of
  - Different primary spectrum/composition models
  - Uncertainties in hadronic interactions
  - TG, ISVHECRI 2014 (arXiv:1412.6424)

$\nu_\mu + \bar{\nu}_\mu$
from K, π

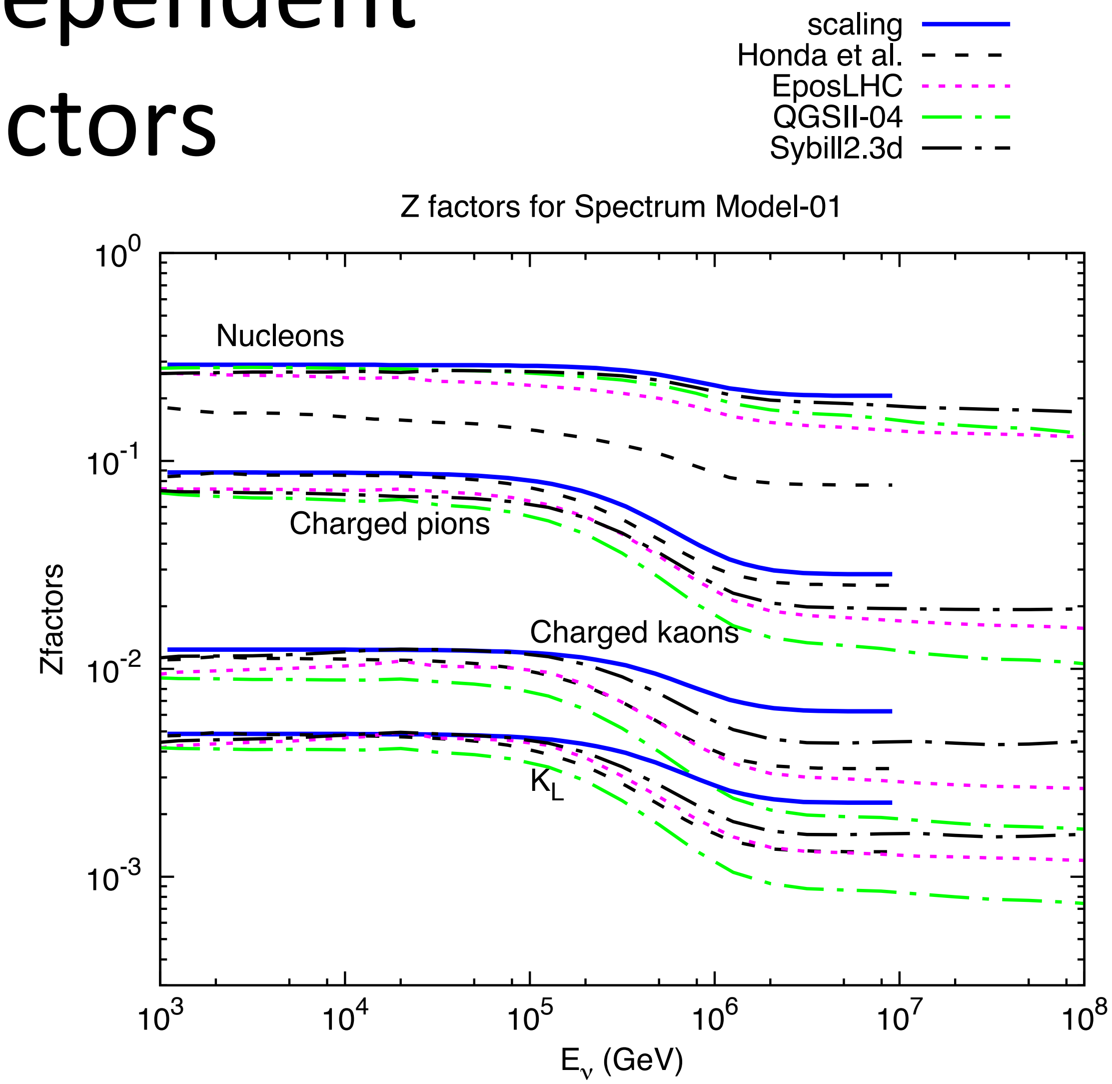
Primary spectrum fits:

- H3A: TG, Astropart. Phys. 35 (2012) 801
- GST: TG, Tilav, Stanev, arXiv:1303.3565
- Polygonato: J. Hörandel, Astropart. Phys. 19 (2003) 193 knee + H3A post-knee
- Honda et al. with knee = spectrum of Engel et al. (ICRC 27, 2001) with knee + H3A post-knee

Composition: ±20%



Energy-dependent Z-factors



From CRMC*
by Hans Dembinski

- EPOS LHC
- QGSJet II-04
- Sib 2.3 (dev)

*CRMC: T. Pierog, C. Baus, R. Ulrich, \url{http://web.ikp.kit.edu/rulrich/crmc.html} (2014)

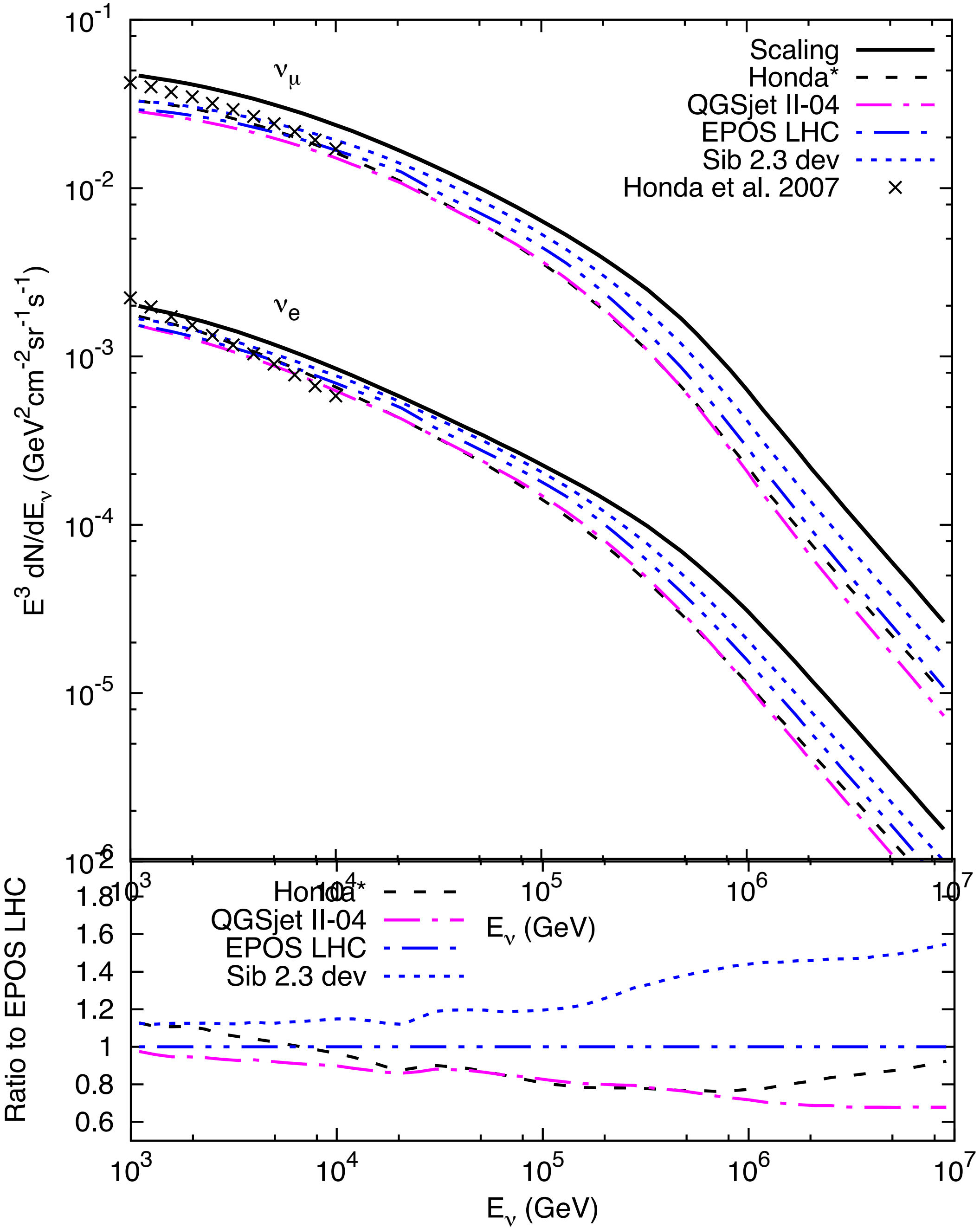
Neutrino spectra (averaged over the sky) $\nu_\mu + \bar{\nu}_\mu$ from K, π

Hadronic interaction models:

- Honda* = Sanuki, Honda et al., PRD 75 (2007) 043005 (Honda, private communication)
- QGSjet II-04, post-LHC version of PRD 83 (2011) 014018
- EPOS LHC T. Pierog et al., 1306.0121
- Sib 2.3 dev, F. Riehn et al., ICRC (2015) and 1502.06353

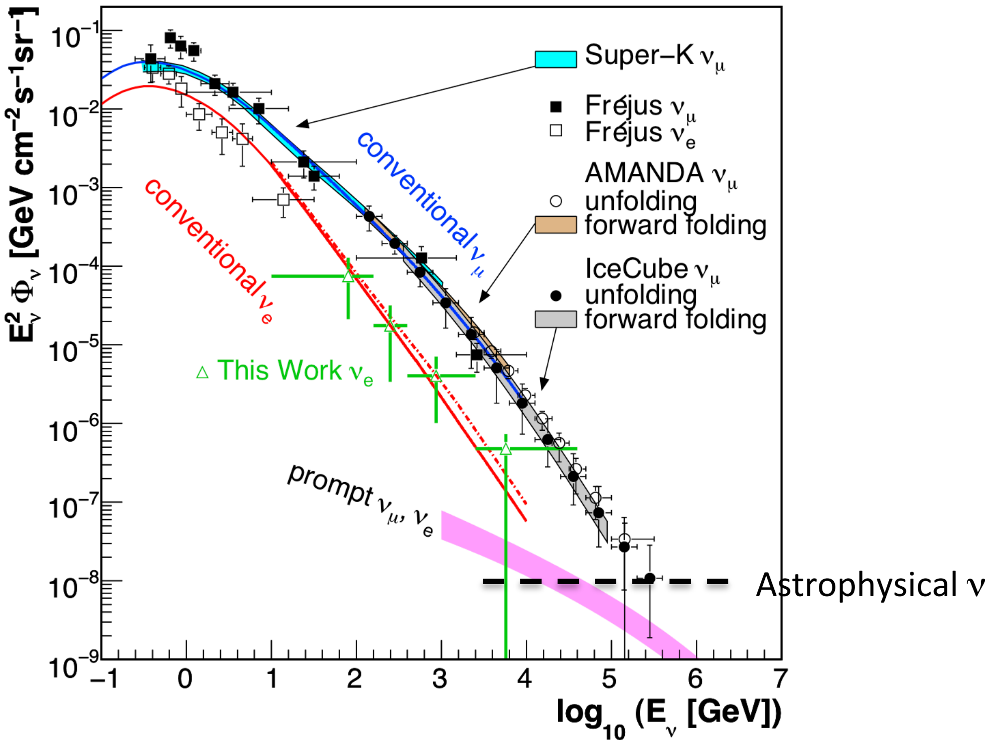
Interaction models:

- ±20% ~ 100 TeV
- ± 30% ~ PeV



What about charm?

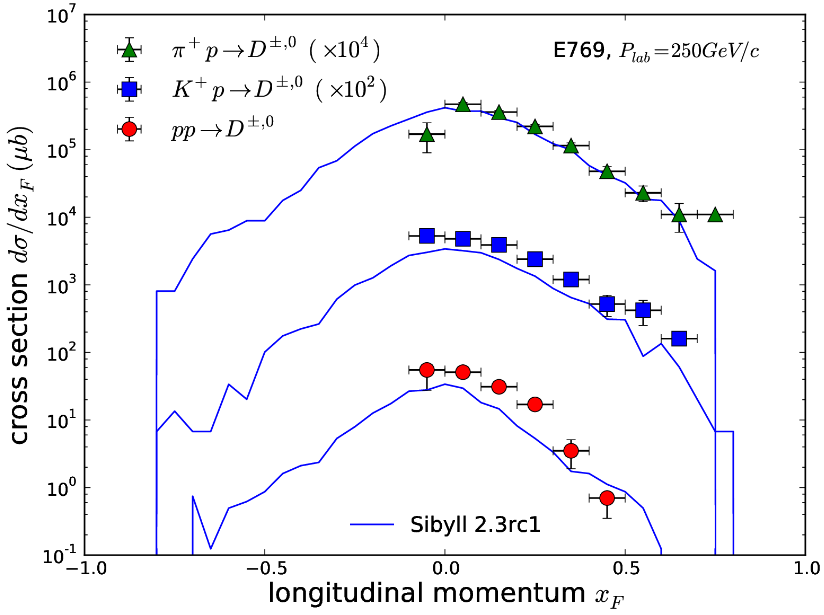
- Critical energy $\varepsilon_{\text{charm}} \approx 10^7$ GeV
- So spectrum of ν from charm follows primary spectrum
- Conventional ν one power steeper
- Crossover of prompt/conventional competes with the transition to astrophysical neutrinos
- A charmed analog of $p \rightarrow K^+\Lambda$ may be important

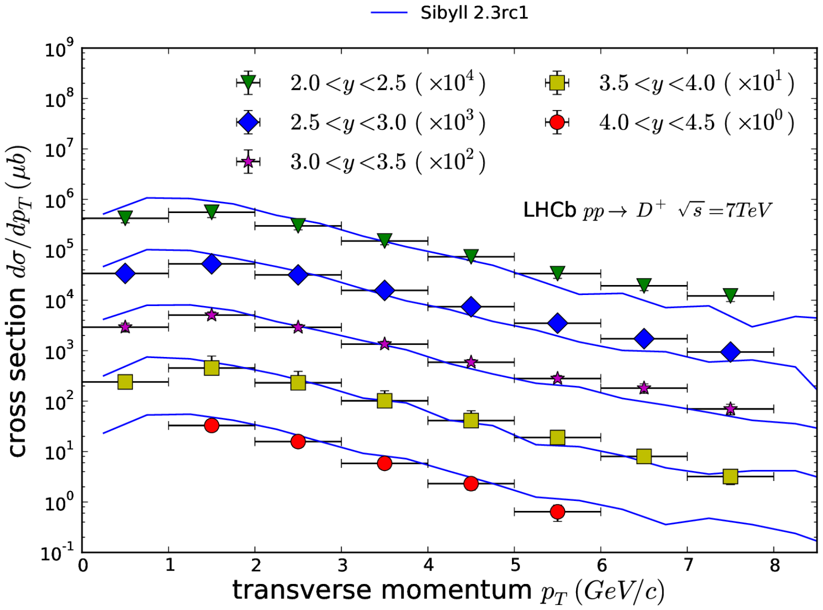


Adding charm to SIBYLL (post-LHC)

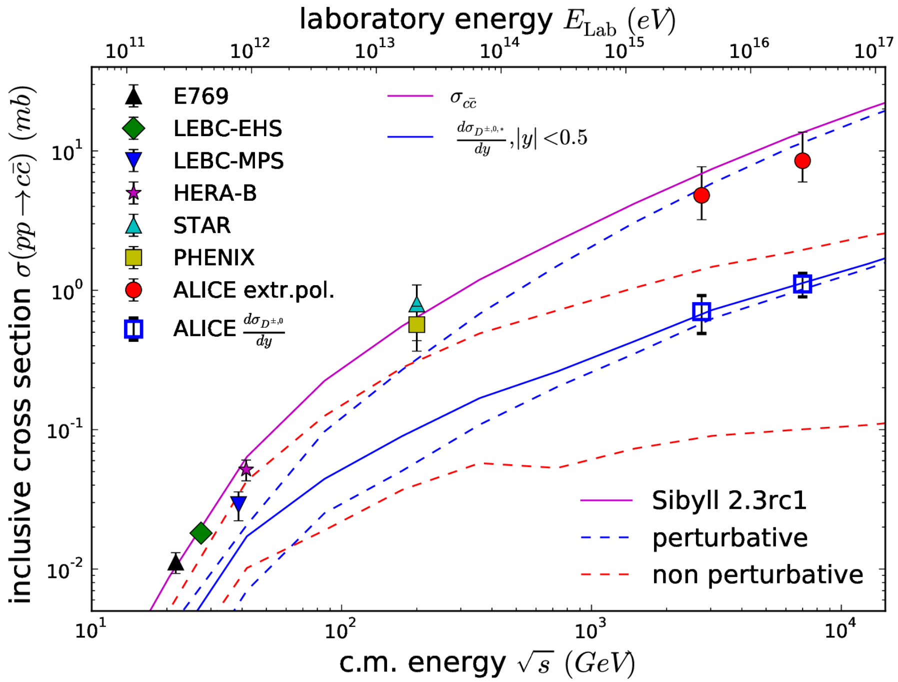
F. Riehn et al., ISVHECRI 2012 (and arXiv: 1502.06353v1)

Strategy: add charm production including a non-perturbative component adjusted to reproduce fixed target measurements in addition to the perturbative QCD contribution





Charm in SIBYLL (cont'd)

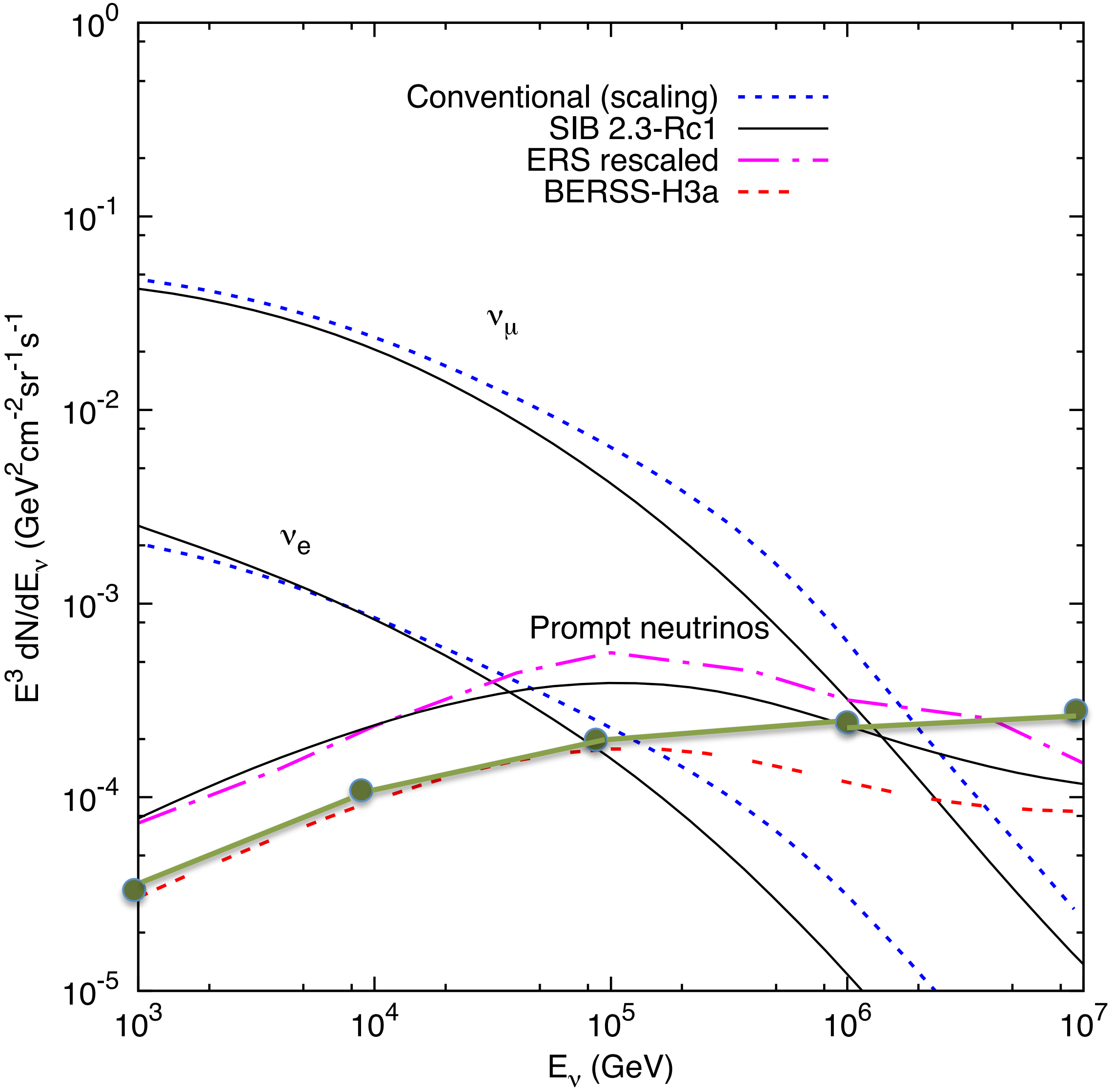


- Normalization depends on treatment of nuclear targets
- Results similar to ERS and MRS
- Fits to IceCube should assume charm at this level as a prior

Prompt ν from charm

Prompt ν calculations:

- SIB 2.3 Rc1: Riehn et al. 1502.06353
- ERS: Enbeg, et al., PR D78 (2008) 043005
- BERSS: Bhattacharya et al., 1502.01076
- Garzelli et al: ●—● 1507.01570 (talk in next ν session)



Contributions to lepton fluxes

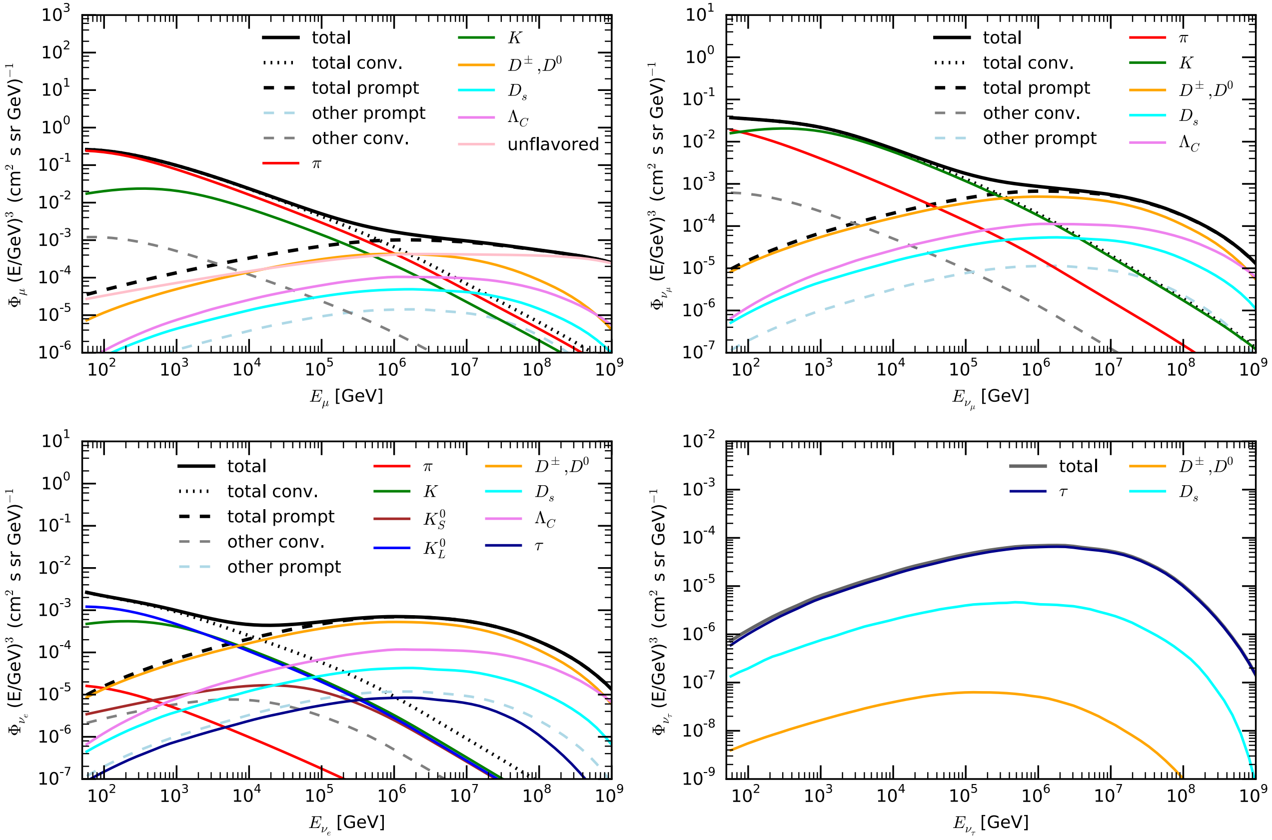
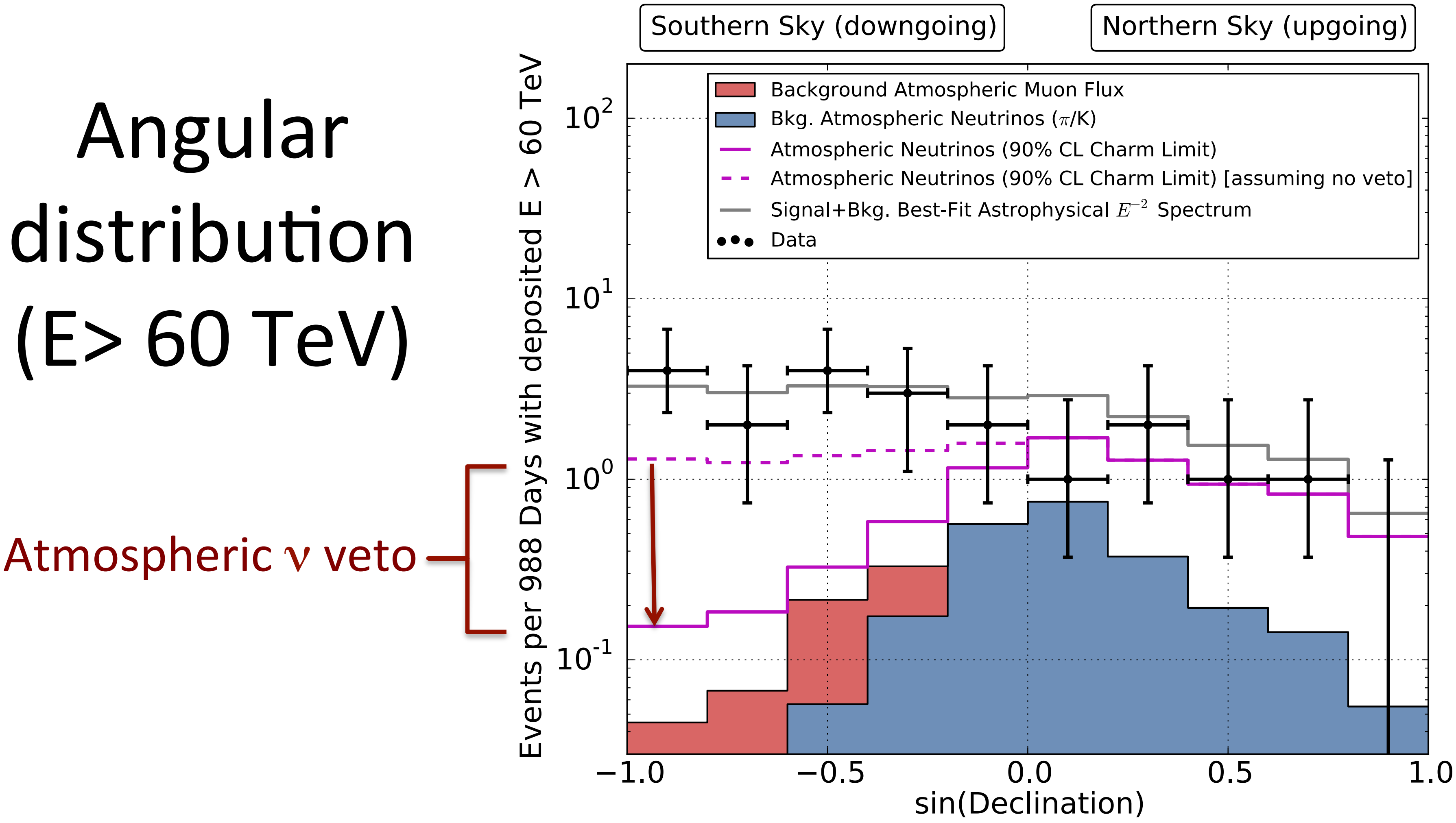


Figure 9. Partial contribution of intermediate particles to the flux of atmospheric muons $\mu^+ + \mu^-$ (top left), muon neutrinos $\nu_\mu + \bar{\nu}_\mu$ (top right), electron neutrinos $\nu_e + \bar{\nu}_e$ (bottom left) and tau neutrinos $\nu_\tau + \bar{\nu}_\tau$ (bottom right). The primary spectrum is TIG and the interaction model is SIBYLL-2.3 RC1.

A. Fedynitch et al., ISVHECRI 2014 (arXiv:1503.00544)

Angular distribution (E> 60 TeV)



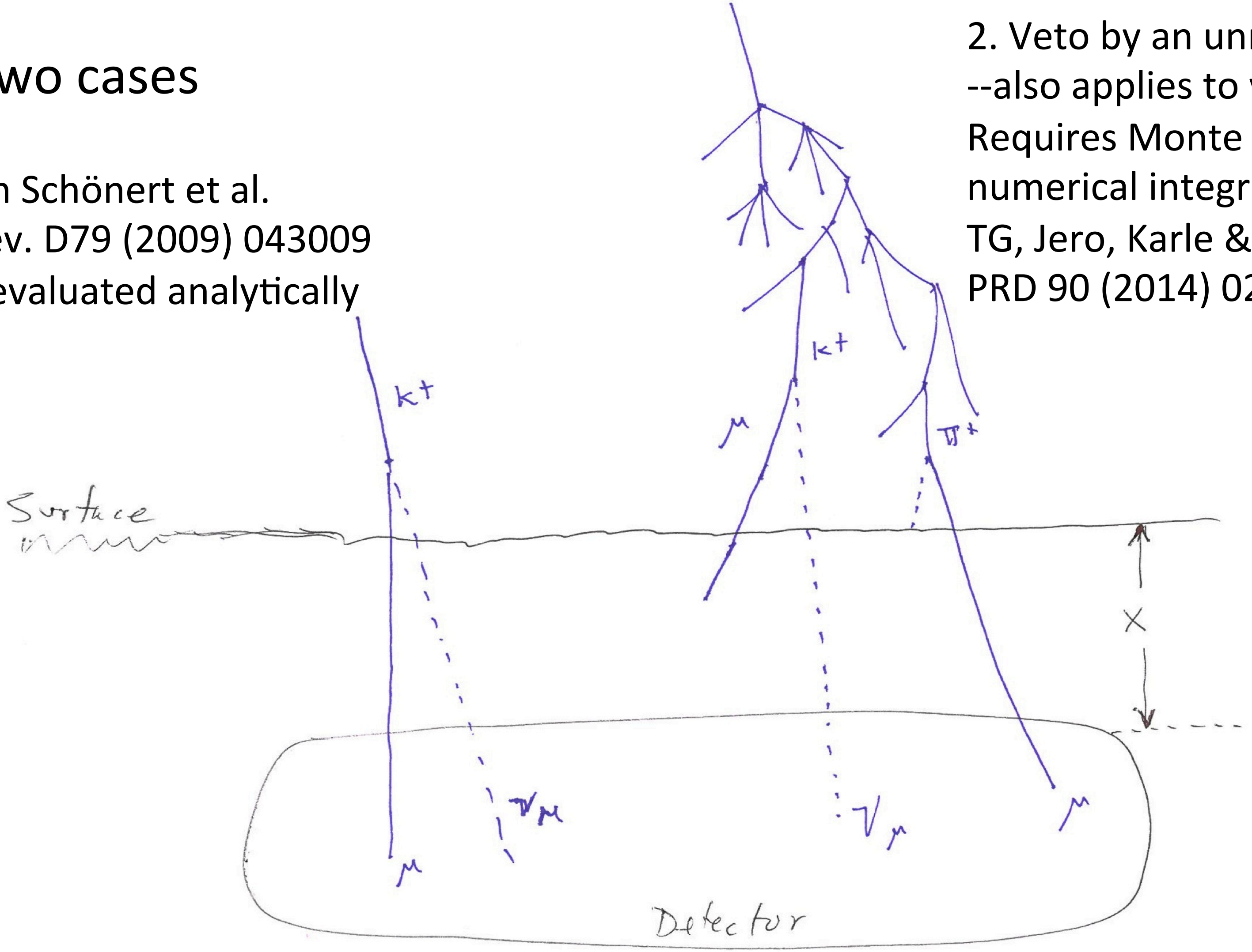
Select E > 60 TeV to get above atmospheric μ background.
Note shape of prompt atmospheric ν background.

Atmospheric neutrino self veto

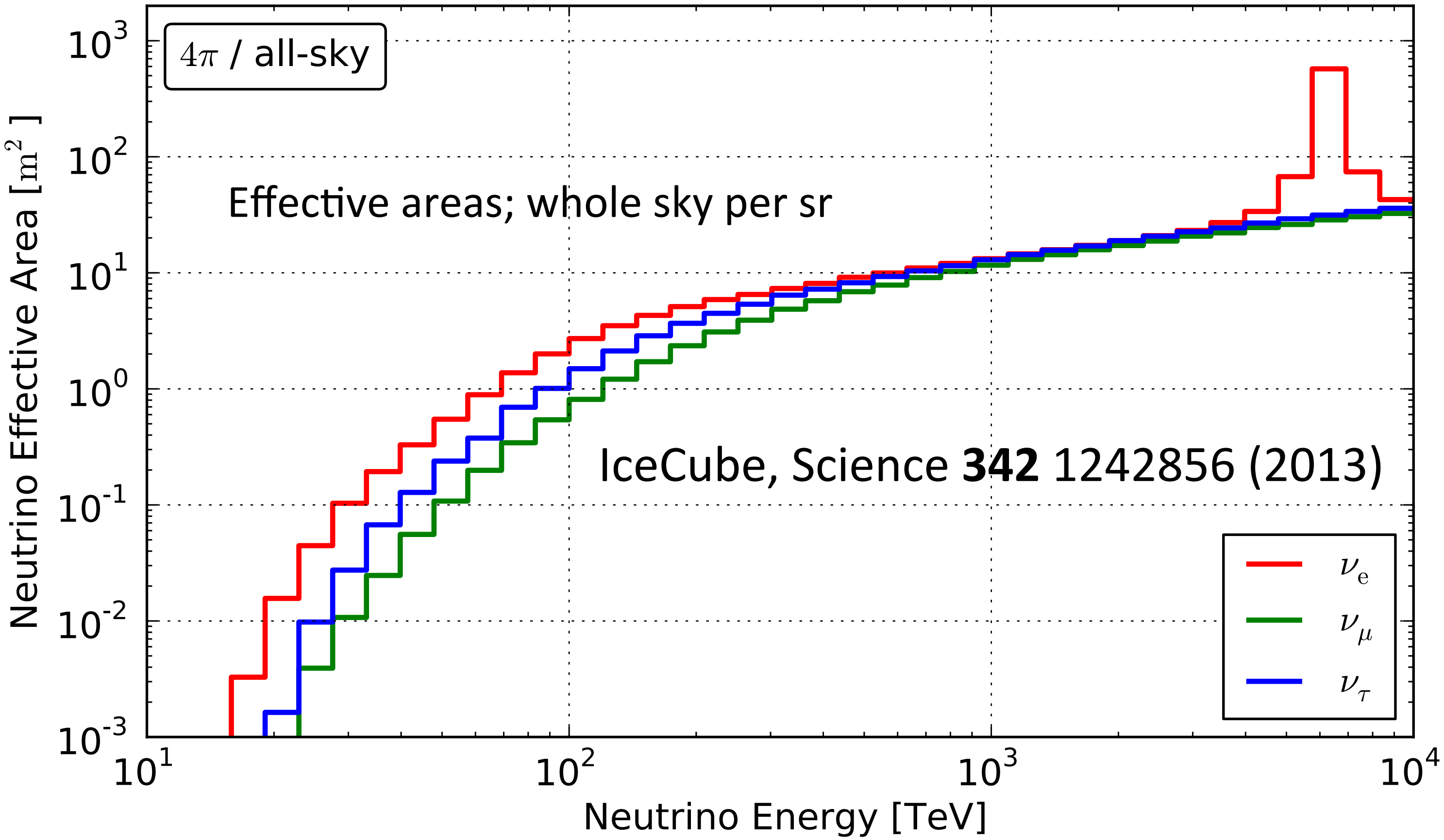
Two cases

1. Stefan Schönert et al.
Phys. Rev. D79 (2009) 043009
Can be evaluated analytically

2. Veto by an unrelated μ
--also applies to ν_e
Requires Monte Carlo or
numerical integration
TG, Jero, Karle & van Santen,
PRD 90 (2014) 023009

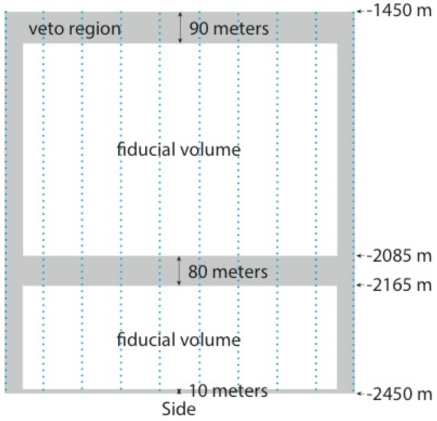


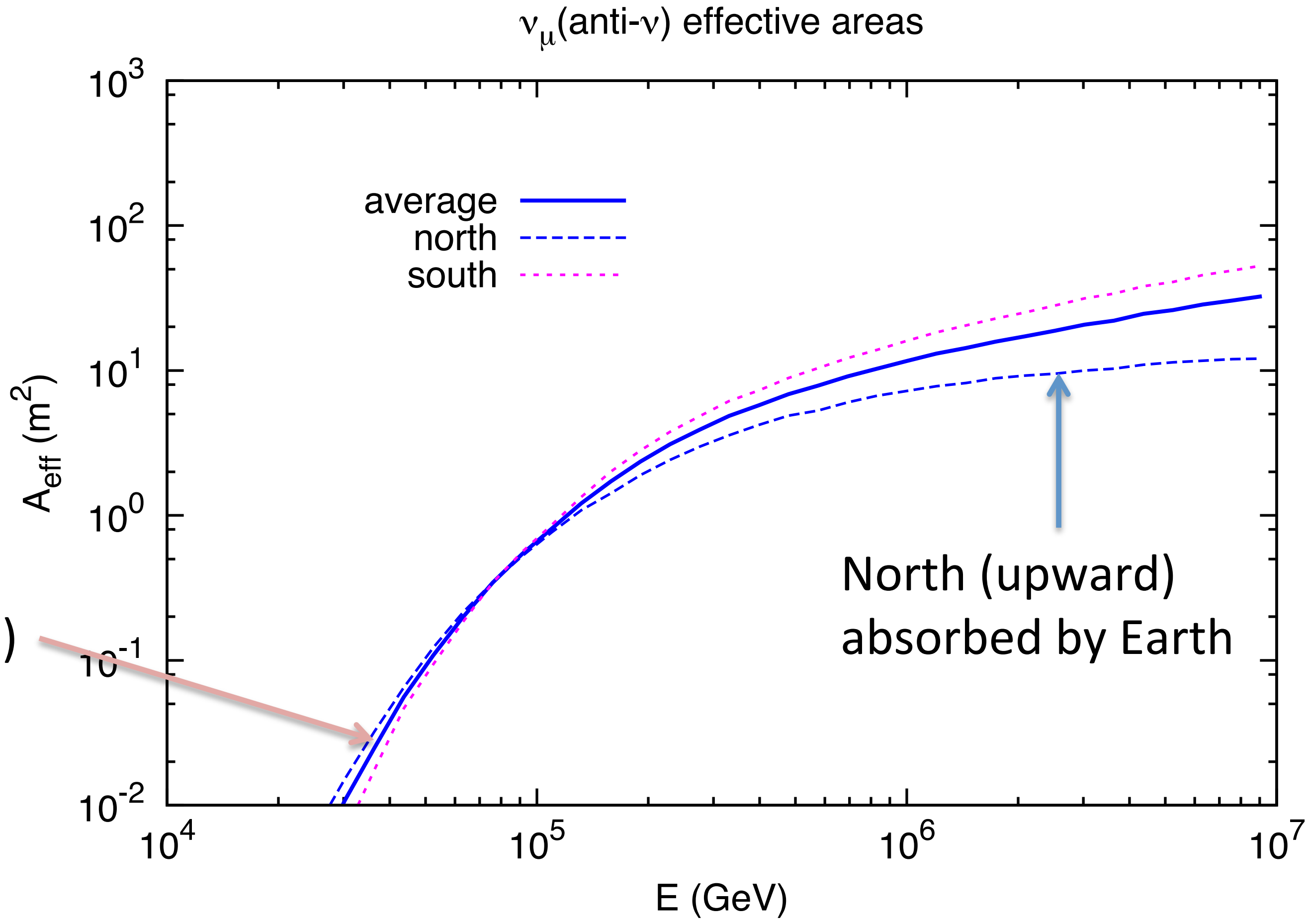
Fold fluxes with IceCube A_{eff} to get rates



Visible energy threshold suppresses ν_τ and ν_μ relative to ν_e

IceCube ν_μ effective areas
separated by hemisphere





Veto tighter for South (downward) than for North

North (upward) absorbed by Earth

Application to IceCube

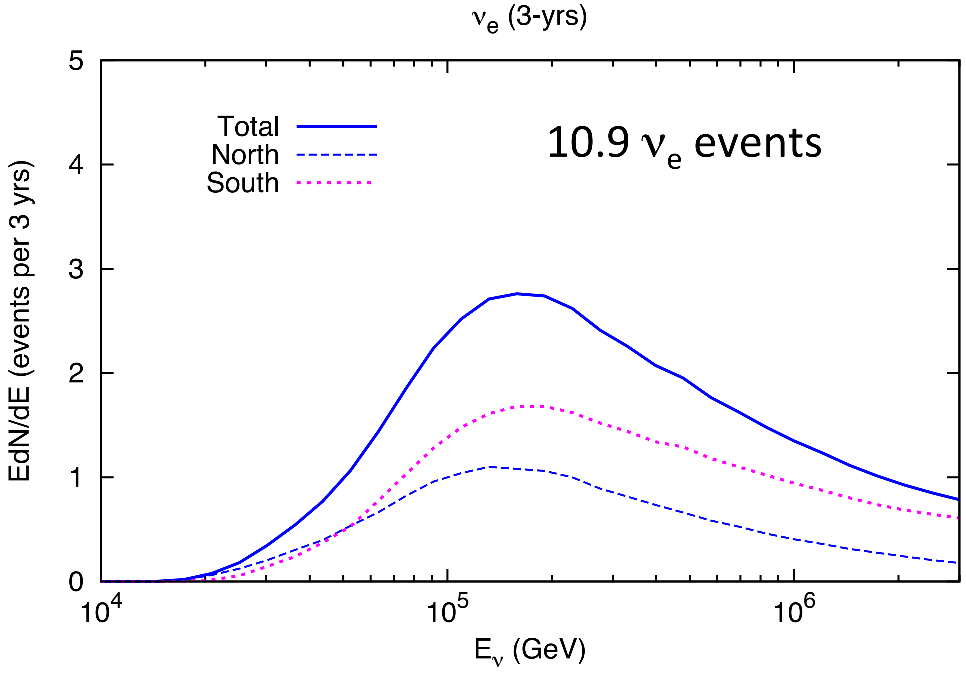
- IceCube 3 yr analysis suggests two fits for astrophysical component up to 3 PeV:

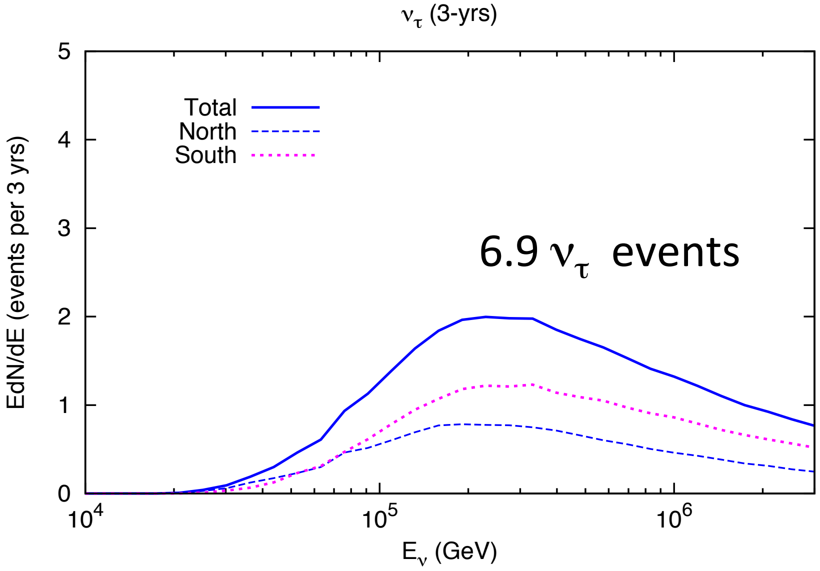
$$E_\nu^2\,\phi_\nu = 0.95\times10^{-8}\,\frac{\mathrm{GeV}}{\mathrm{cm^2 sr\,s}}\ \text{per flavor}$$

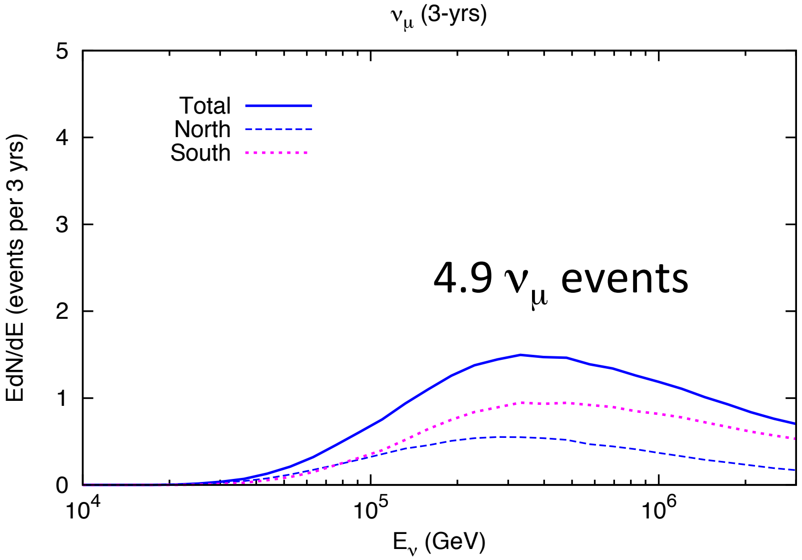
$$E_\nu^2\,\phi_\nu = 1.5\times10^{-8}\left(\frac{E}{100\mathrm{TeV}}\right)^{-0.3}\,\frac{\mathrm{GeV}}{\mathrm{cm^2 sr\,s}}\ \text{per flavor}$$

Astrophysical events for $E^{-2.3}$ fit

(Convolve astro spectrum with Aeff)

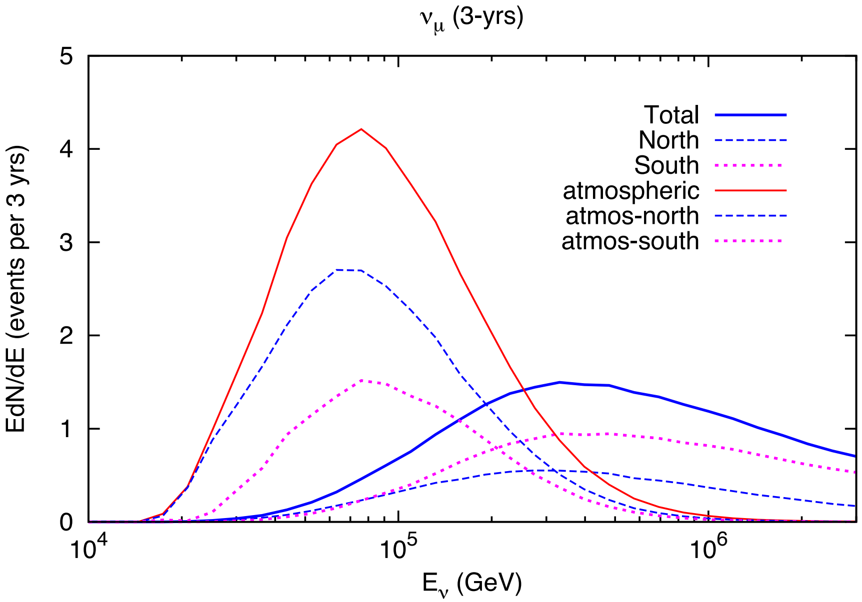


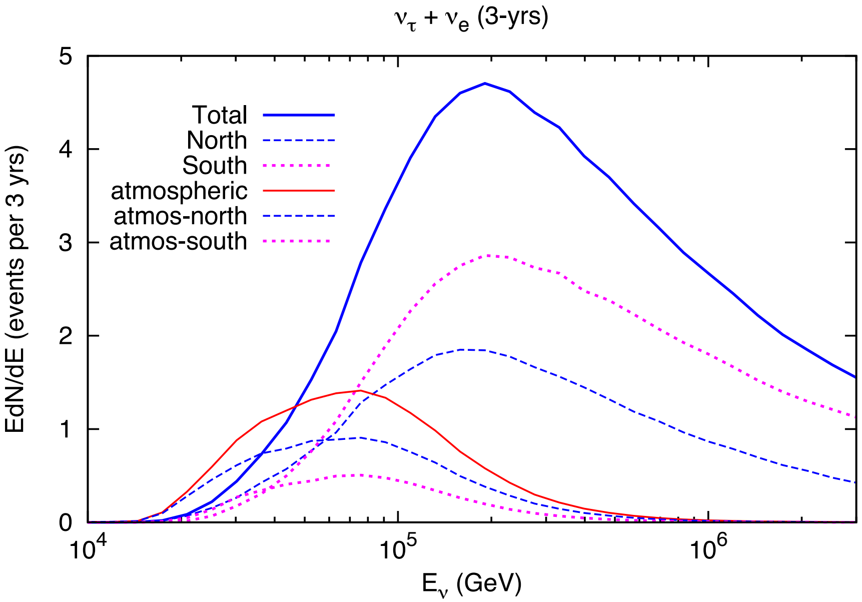




Note: Plots are vs ν energy (not E_{vis}) assuming $\phi_\nu \sim (E_\nu)^{-2}$

Signal/background





Note: plots are vs true neutrino energy, not $E_{visible}$

The distortion is biggest for ν_μ

37 events assuming $E^{-2.3}$ spectrum

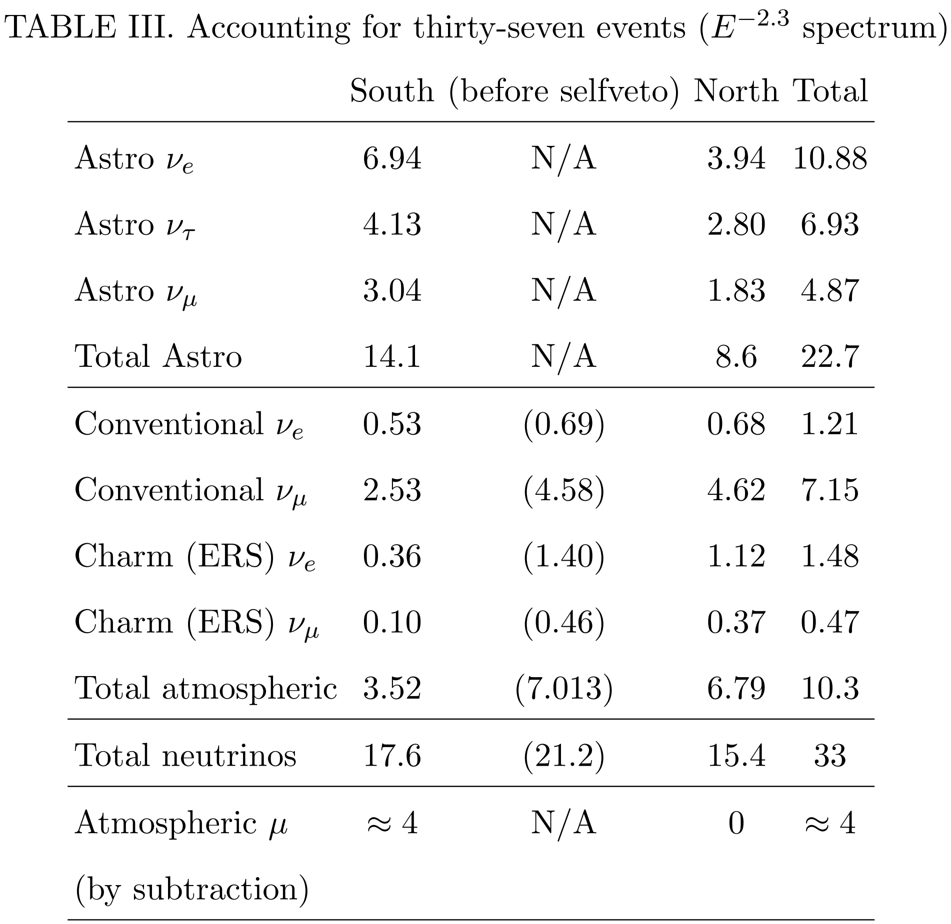


TABLE III. Accounting for thirty-seven events ($E^{-2.3}$ spectrum)

	South	(before selfveto)	North	Total
Astro ν_e	6.94	N/A	3.94	10.88
Astro ν_τ	4.13	N/A	2.80	6.93
Astro ν_μ	3.04	N/A	1.83	4.87
Total Astro	14.1	N/A	8.6	22.7
Conventional ν_e	0.53	(0.69)	0.68	1.21
Conventional ν_μ	2.53	(4.58)	4.62	7.15
Charm (ERS) ν_e	0.36	(1.40)	1.12	1.48
Charm (ERS) ν_μ	0.10	(0.46)	0.37	0.47
Total atmospheric	3.52	(7.013)	6.79	10.3
Total neutrinos	17.6	(21.2)	15.4	33
Atmospheric μ (by subtraction)	≈ 4	N/A	0	≈ 4

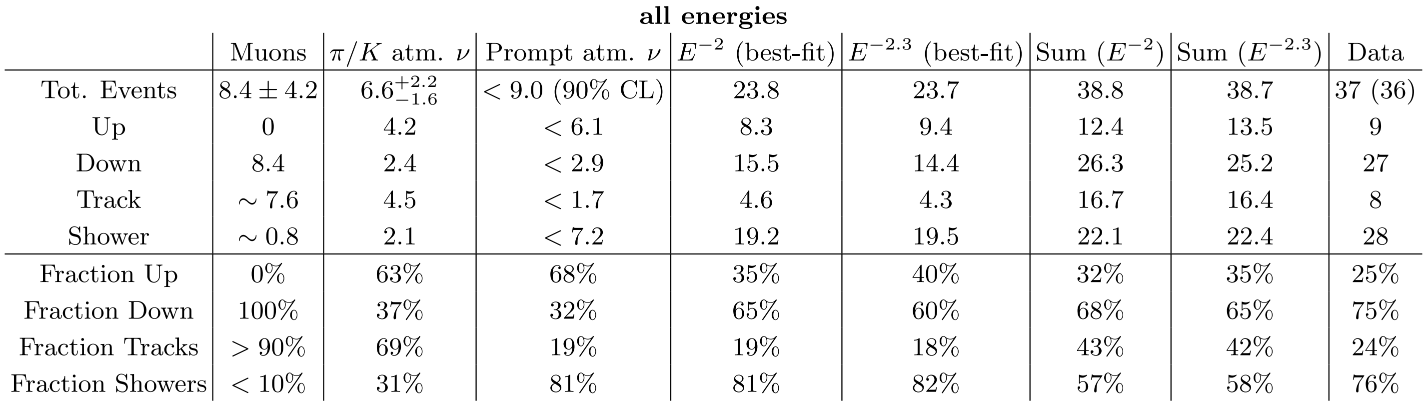
	Cascades	Tracks
	18	5
	4	6
		4?
	----------------	----------------
	22	15
Data:	28	9

Summary comments

- Analytic/numerical evaluation of ν fluxes
  - Account for non-scaling, and knee of spectrum
  - Useful for exploring uncertainties in atmospheric ν flux
- Kaon channel dominates atmospheric ν
  - Increase of μ^+/μ^- sets level of kaon production
  - Implications for $\nu / \bar{\nu}$ ratio and rate of atmospheric background
- Level of charm production is still uncertain
  - Hidden in IceCube ν by astrophysical component
  - ν self-veto reduces downward background atmospheric ν
  - Also gives handle to set limits on charm
- Cascade/track ratio:
  - more data needed to get flavor ratio
  - Lars Mohrmann's talk in ν session

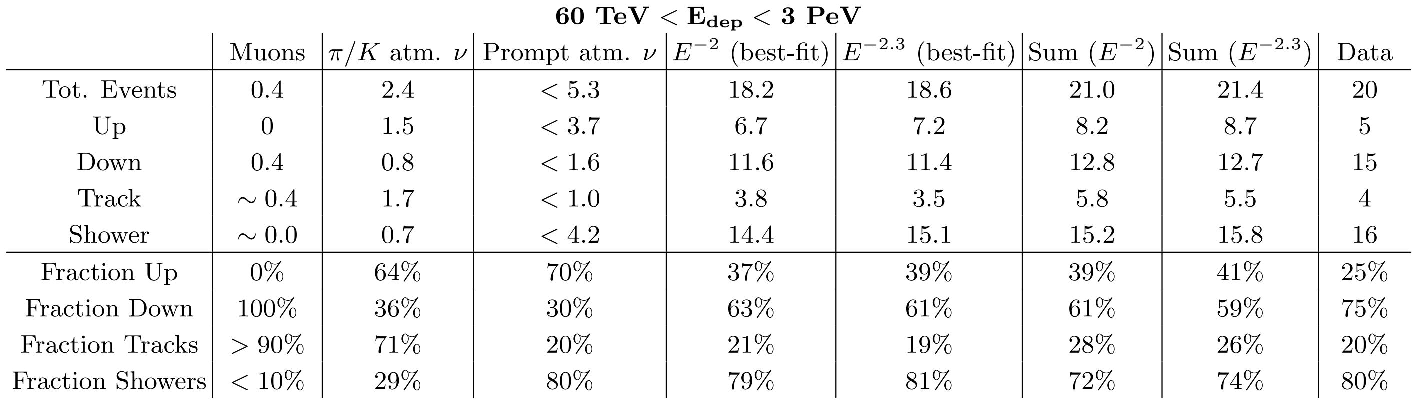
Back up slides

From HESE 3 yr paper appendix*



all energies

	Muons	π/K atm. ν	Prompt atm. ν	E^{-2} (best-fit)	$E^{-2.3}$ (best-fit)	Sum (E^{-2})	Sum ($E^{-2.3}$)	Data
Tot. Events	8.4 ± 4.2	$6.6^{+2.2}_{-1.6}$	< 9.0 (90% CL)	23.8	23.7	38.8	38.7	37 (36)
Up	0	4.2	< 6.1	8.3	9.4	12.4	13.5	9
Down	8.4	2.4	< 2.9	15.5	14.4	26.3	25.2	27
Track	~ 7.6	4.5	< 1.7	4.6	4.3	16.7	16.4	8
Shower	~ 0.8	2.1	< 7.2	19.2	19.5	22.1	22.4	28
Fraction Up	0%	63%	68%	35%	40%	32%	35%	25%
Fraction Down	100%	37%	32%	65%	60%	68%	65%	75%
Fraction Tracks	$> 90\%$	69%	19%	19%	18%	43%	42%	24%
Fraction Showers	$< 10\%$	31%	81%	81%	82%	57%	58%	76%



60 TeV $< \mathbf{E_{dep}} <$ 3 PeV

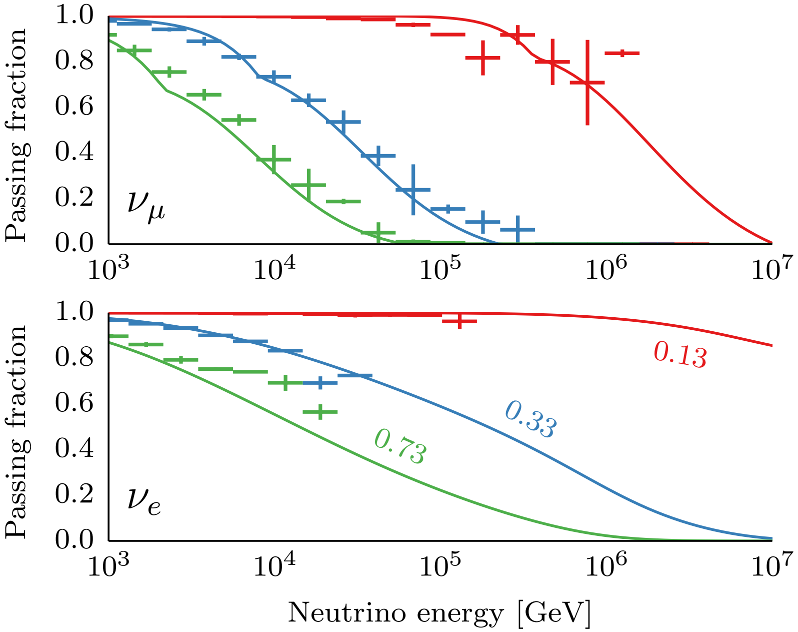
	Muons	π/K atm. ν	Prompt atm. ν	E^{-2} (best-fit)	$E^{-2.3}$ (best-fit)	Sum (E^{-2})	Sum ($E^{-2.3}$)	Data
Tot. Events	0.4	2.4	< 5.3	18.2	18.6	21.0	21.4	20
Up	0	1.5	< 3.7	6.7	7.2	8.2	8.7	5
Down	0.4	0.8	< 1.6	11.6	11.4	12.8	12.7	15
Track	~ 0.4	1.7	< 1.0	3.8	3.5	5.8	5.5	4
Shower	~ 0.0	0.7	< 4.2	14.4	15.1	15.2	15.8	16
Fraction Up	0%	64%	70%	37%	39%	39%	41%	25%
Fraction Down	100%	36%	30%	63%	61%	61%	59%	75%
Fraction Tracks	$> 90\%$	71%	20%	21%	19%	28%	26%	20%
Fraction Showers	$< 10\%$	29%	80%	79%	81%	72%	74%	80%

*IceCube Collaboration, arXiv:1405.5303v2

Generalized ν self-veto

$$P_\nu(E_\nu,\theta) = \frac{\int \mathrm{d}E_N \phi_N(E_N) Y_\nu(E_\nu, E_N, \theta) \exp^{-N_\mu(E_N, E_{\mu,\min}(\theta))}}{\phi_\nu(E_\nu,\theta)}$$

P = Passing fraction

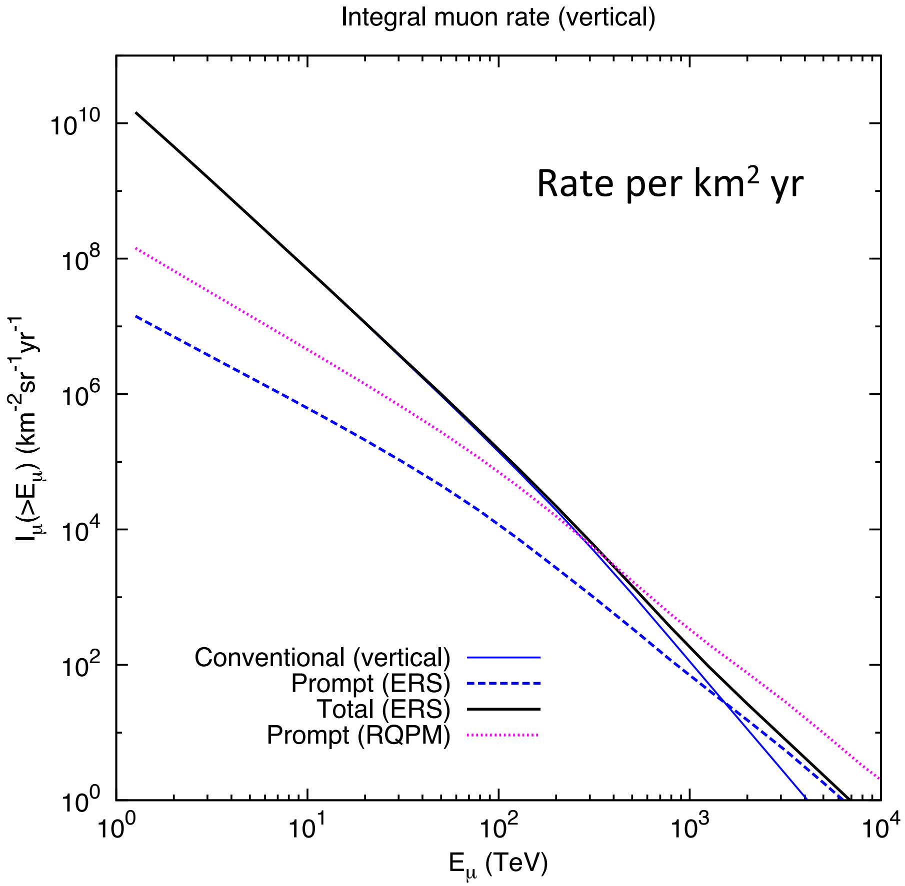


- New parameterizations of yields of ν_μ, ν_e, and μ
- $E_{\mu,\min}(\theta)$ = energy for μ at θ to reach depth of detector
- Compare to full MC

TG, Jero, Karle & van Santen, PRD 90 (2014) 023009

Can we identify prompt component with atmospheric muons?

- Advantages:
  - No astro component
  - High rate
  - Angular dependence
    - Isotropic for prompt
    - sec(θ) for conventional
  - Seasonal variation*
    - Strong for conventional
    - Absent for prompt
- Problems in practice
  - Crossover at high energy
  - Uncertain contribution of unflavored mesons not present for neutrinos



*P. Desiati & TG, PRL 105 (2010) 121102

Scaling/power-law solutions for ν

$$\phi_\nu(E_\nu) = \phi_N(E_\nu) \times \left\{ \frac{A_{\pi\nu}}{1 + B_{\pi\nu}\cos(\theta)E_\nu/\epsilon_\pi} + \frac{A_{K\nu}}{1 + B_{K\nu}\cos(\theta)E_\nu/\epsilon_K} + \frac{A_{\mathrm{charm}\,\nu}}{1 + B_{\mathrm{charm}\,\nu}\cos(\theta)E_\nu/\epsilon_{\mathrm{charm}}} \right\},$$

Same form for μ;
Different kinematics
→ μ, ν differences

ε_π = 115 GeV
ε_K = 850 GeV
$\varepsilon_{\mathrm{charm}}$ > 10 PeV

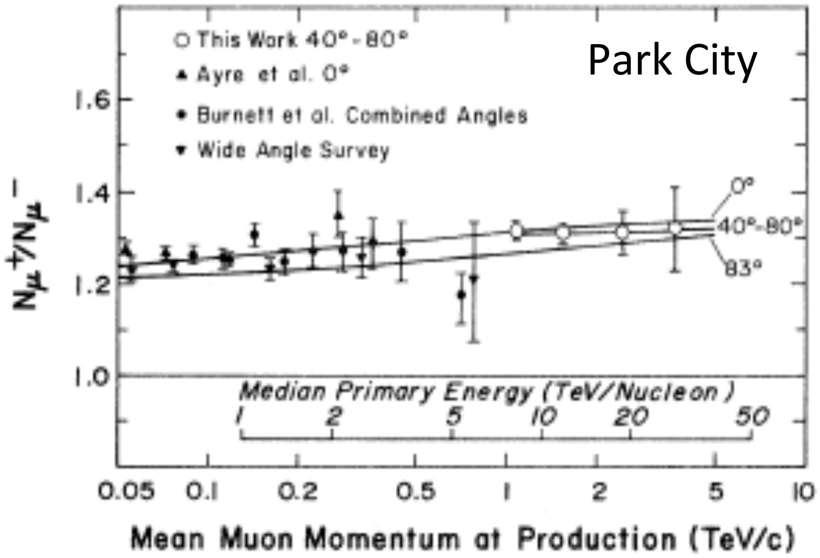
$$A_{i\nu} = \frac{Z_{Ni} \times BR_{i\nu} \times Z_{i\nu}}{1 - Z_{NN}} \qquad Z_{pK^+} = \frac{1}{\sigma}\int x^\gamma \frac{\mathrm{d}\sigma(x)}{\mathrm{d}x}\mathrm{d}x$$

$$Z_{\pi\mu} = \frac{1 - r_\pi^{\gamma+1}}{(\gamma+1)(1 - r_\pi)} \text{ and } \frac{\epsilon_\pi}{\cos\theta E_\mu}\frac{1 - r_\pi^{\gamma+2}}{(\gamma+2)(1 - r_\pi)}$$

$$Z_{\pi\nu} = \frac{(1 - r_\pi)^\gamma}{(\gamma+1)} \text{ and } \frac{\epsilon_\pi}{\cos\theta E_\mu}\frac{(1 - r_\pi)^{(\gamma+1)}}{(\gamma+2)}$$

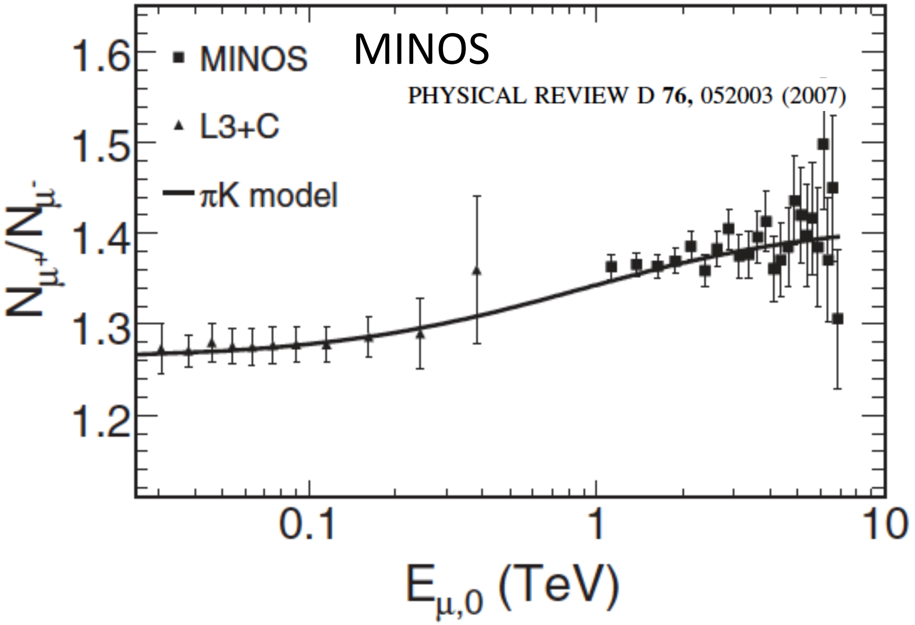
r_π = 0.573 but
r_K = 0.0458

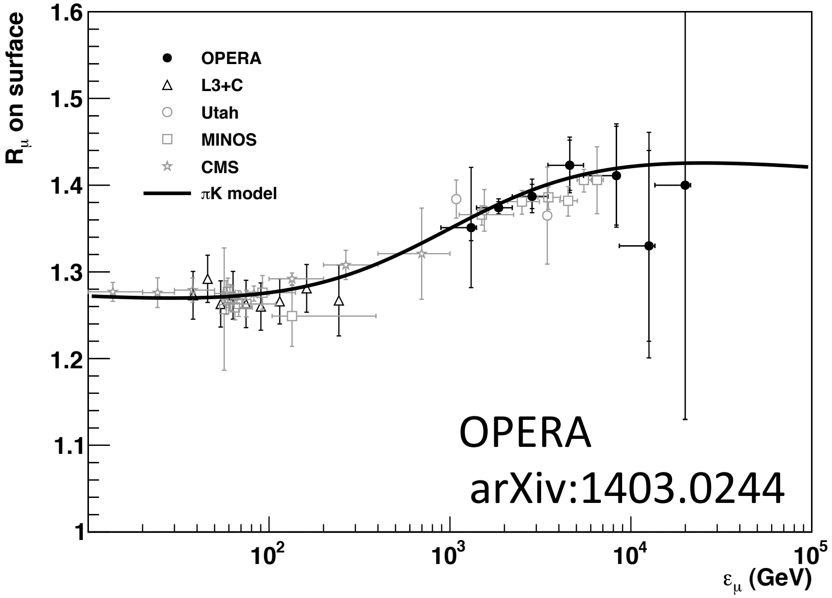
Muon charge ratio



Ashley, Elbert, Keuffel, Larsen, Morrison, PRL 31(1973) 1091

- Ratio due to excess of p over n in primary CR + steep spectrum which favors p→ π^+ over p→ π^-
- Rise at TeV due to increased importance of Kaons (especially K^+)





Muon charge ratio including kaons

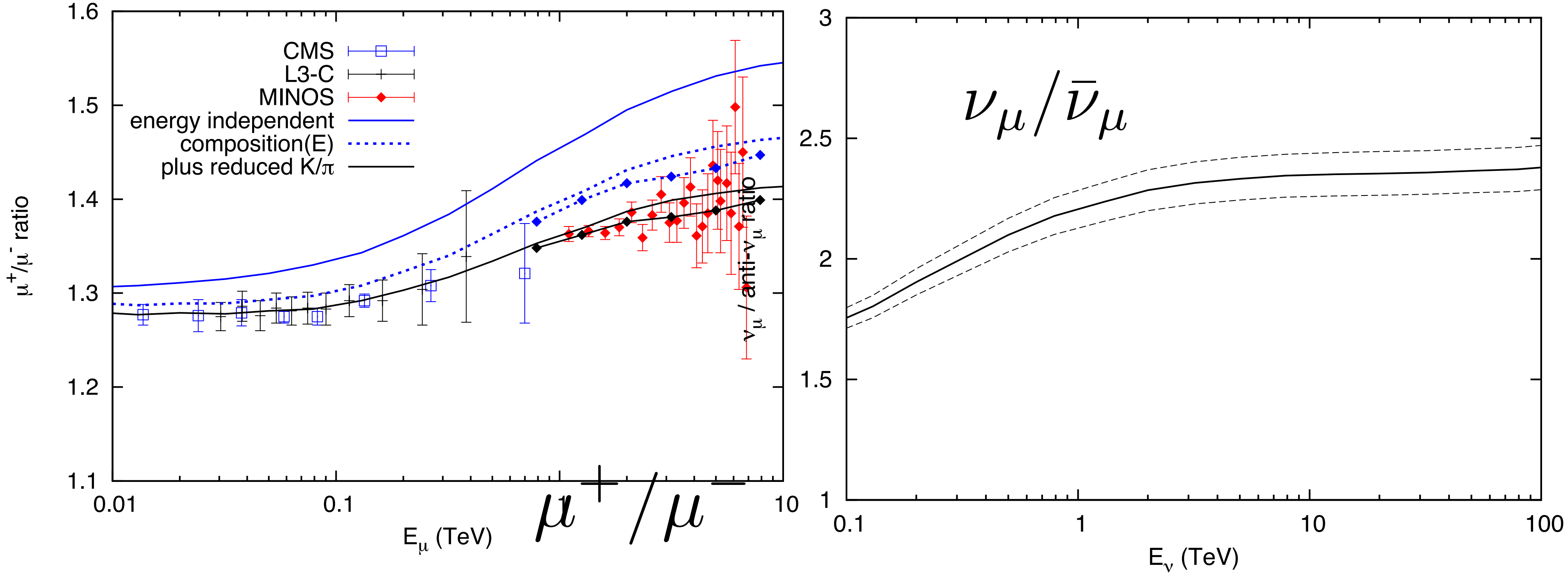
$$\frac{\mu^+}{\mu^-} = \left[\frac{f_{\pi^+}}{1 + B_{\pi\mu}\cos(\theta)E_\mu/\epsilon_\pi} + \frac{\frac{1}{2}(1+\alpha_K\beta\delta_0)\,A_{K\mu}/A_{\pi\mu}}{1 + B^+_{K\mu}\cos(\theta)E_\mu/\epsilon_K}\right] \times \left[\frac{(1-f_{\pi^+})}{1 + B_{\pi\mu}\cos(\theta)E_\mu/\epsilon_\pi} + \frac{(Z_{NK^-}/Z_{NK})\,A_{K\mu}/A_{\pi\mu}}{1 + B_{K\mu}\cos(\theta)E_\mu/\epsilon_K}\right]^{-1}$$

where $\alpha_K = \frac{Z_{pK^+} - Z_{pK^-}}{Z_{pK^+} + Z_{pK^-}}$ TG, Astropart. Phys. 35 (2012) 801

OPERA fit data as a function of cosθ and E with two free parameters. They find Z_{pK}+ = 0.0086 ± 0.0004 and δ_0 = 0.61 at ~ 20 TeV/nucleon (compared to 0.0079 and ~0.63 in Astropart. Phys. 35 (2012) 801)

Results for $Z_{pK^+} = 0.086 \pm 0.04$

p → Λ K^+ is relatively more important for $\nu/\bar{\nu}$



Important because $\sigma_\nu \neq \sigma_{\bar{\nu}}$

Details

$$Z_{ij}(\gamma) = \int_0^1 x^\gamma \frac{\mathrm{d}n_{ij}}{\mathrm{d}x}\,\mathrm{d}x \qquad \frac{\mathrm{d}n_{ij}}{\mathrm{d}x} = c_{ij}\frac{(1-x)^{p_{ij}}}{x}, \;\; x = \frac{E_j}{E_i}$$

Procedure:

1) start with a table of Z-factors as a function of E_{nucleon} from accelerator measurement and/or from an event generator
2) Find values of c and p for each channel by evaluating Z(1), Z(2)
3) Use simple forms for dn/dx to evaluate Z(E) for a non-power-law primary spectrum from

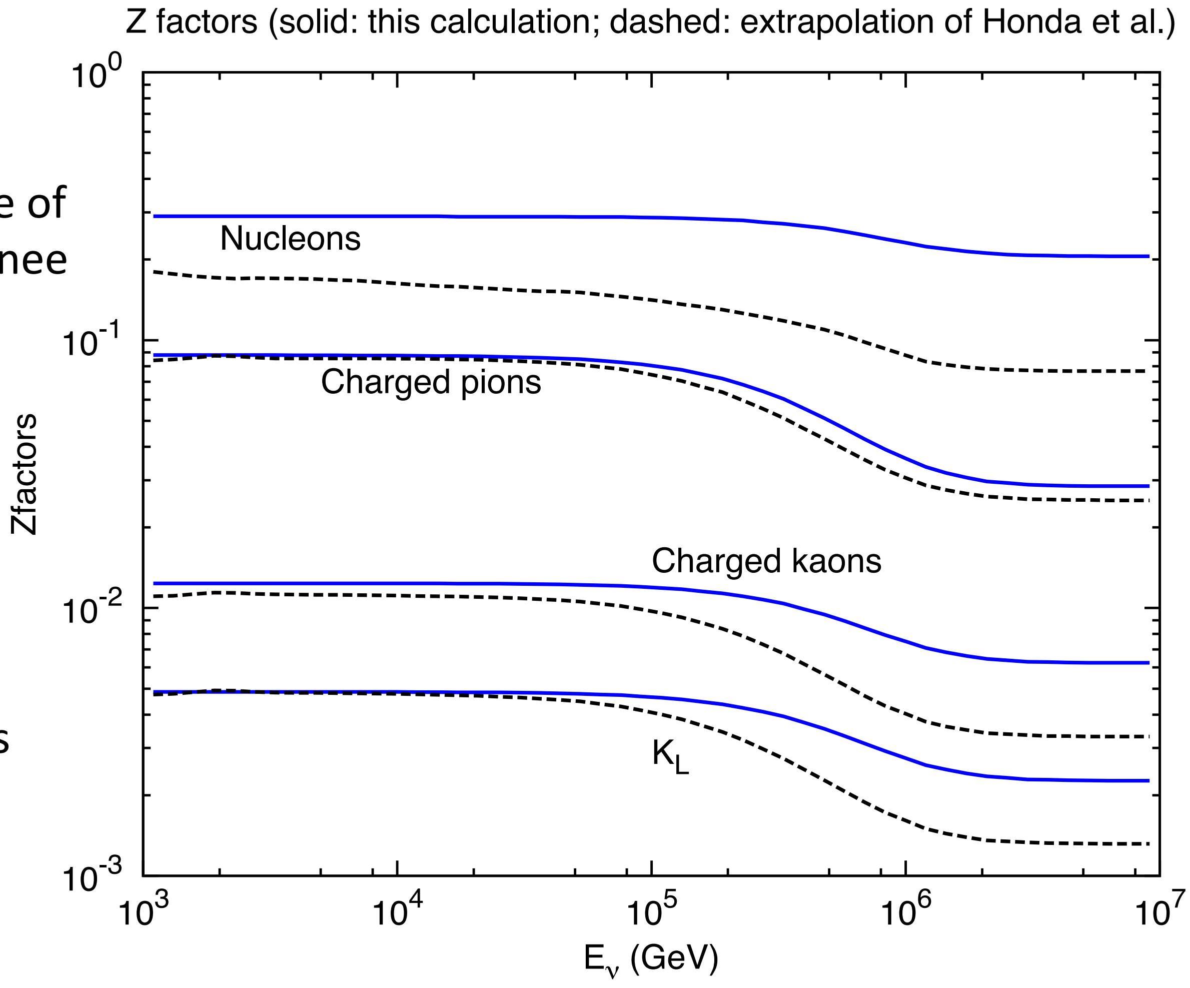
$$Z_{ij}(E) = \int_0^1 \frac{\mathrm{d}x}{x}\frac{\phi_N(E/x)}{\phi_N(E)}\frac{\mathrm{d}n_{ij}(E/x,E)}{\mathrm{d}x}$$

Energy-dependent Z-factors

Solid lines:
Energy-independent interactions; only source of energy dependence is knee

Dotted lines:
thanks to M. Honda for providing extended table of Z-factors from PRD 75 (2007) 043006

Monte Carlo calculations of atmospheric ν extend only to 10 TeV (also for "Bartol" fluxes, 2004:
G. Barr et al. PRD 70, 023006

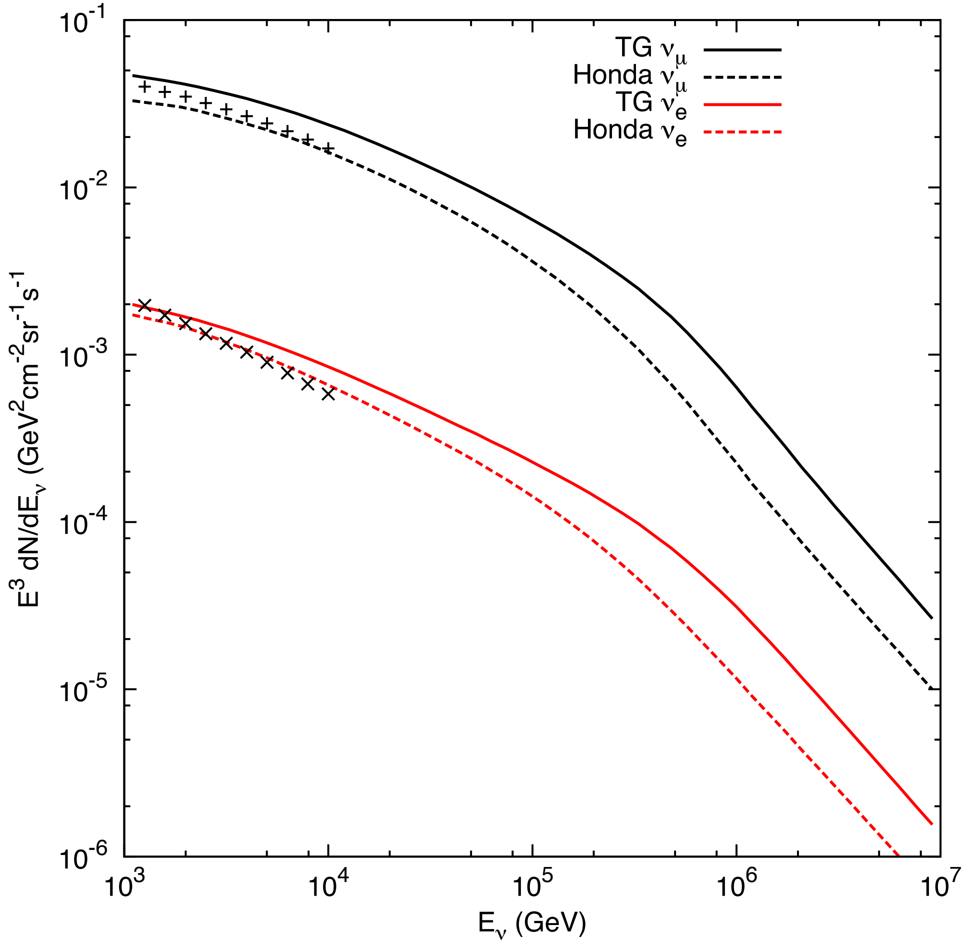


Compare with extrapolated Honda

Solid lines: energy-independent hadronic interactions.
Dotted lines: Honda et al with same primary spectrum

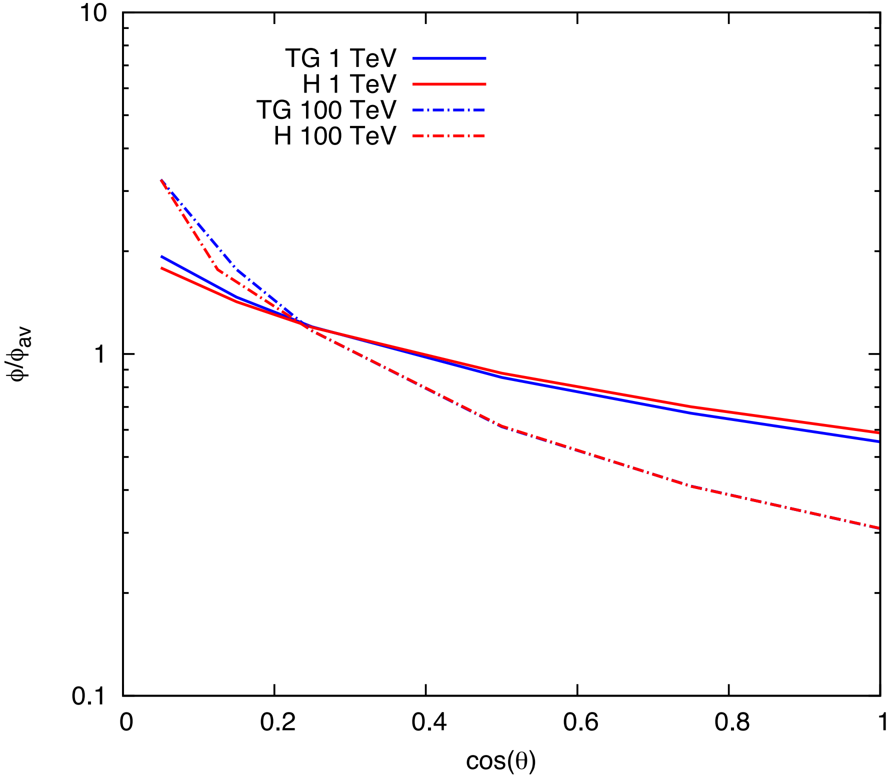
Data points from Honda et al. Monte Carlo calculation, which is steeper at low energy due to neutrinos from muon decay. Also, it has a slightly different primary sepctrum.

Note: ν_e are from Ke3 decays, including $7 \cdot 10^{-4}$ K_S , which becomes significant only for Energy ~ $\varepsilon_{critical}$ ≈ 120 TeV.
TG & S. Klein, arXiv:1409.4924



Angular distributions

angular-numu



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