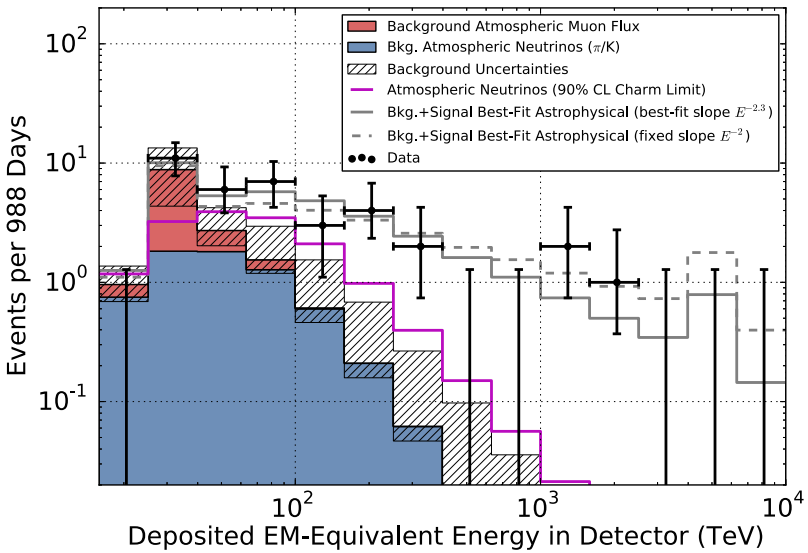
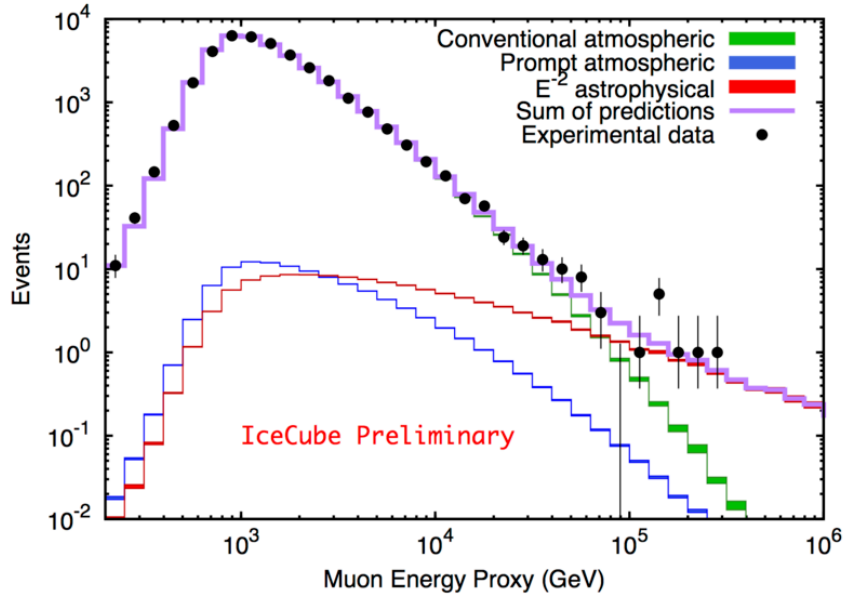
Atmospheric neutrinos

As background for astrophysical neutrinos

Motivation: IceCube discovery is the high-energy tip of an iceberg: What's below the surface?





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

PRL 113, 101101 (2014)

Upward $\nu_\mu \rightarrow \mu$

How does the astro spectrum continue below 100 TeV?

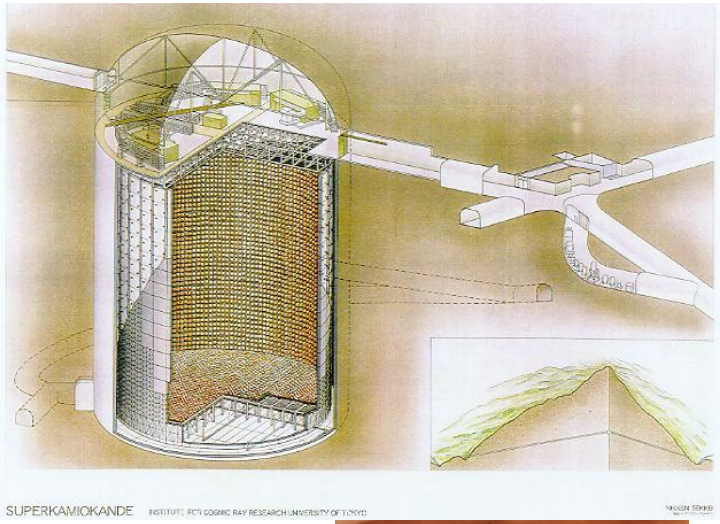
Outline

- Historical introduction
  - Calculating the flux of atmospheric μ and ν
- Muon charge ratio, K/π ratio, $\nu/\bar{\nu}$ ratio
- Atmospheric neutrinos to PeV
  - Energy dependence of hadron production
  - Must account for knee in cosmic-ray spectrum
  - Prompt neutrinos from charm decay
- Atmospheric neutrino self-veto
- Atmospheric ν backgrounds in IceCube

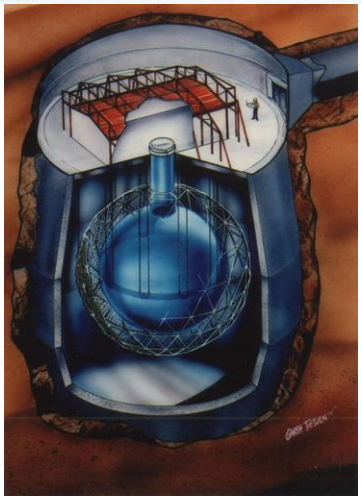
Detecting neutrinos in H_20

Proposed by Greisen, Reines, Markov in 1960

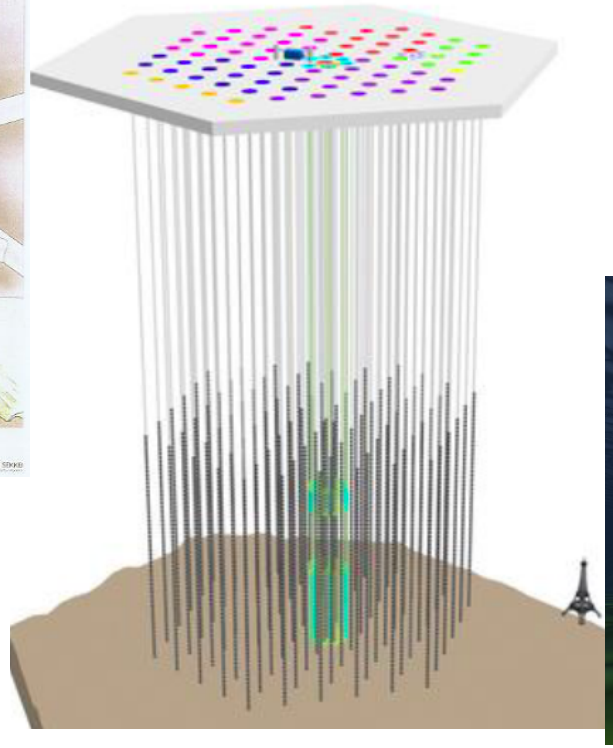
Heritage:
- DUMAND
- IMB
- Kamiokande
- Baikal
- AMANDA



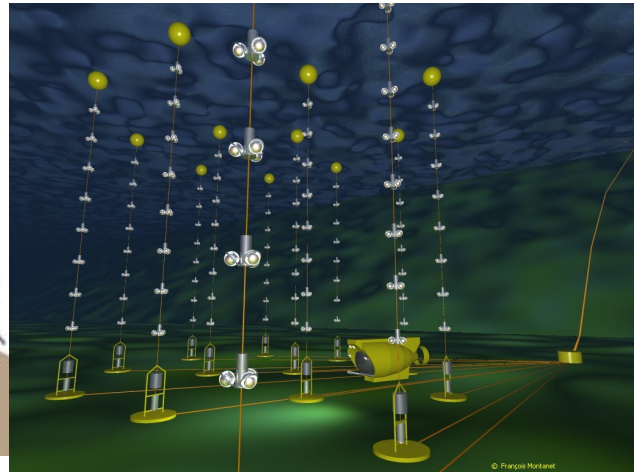
Super-K



SNO



IceCube



ANTARES

Future:
- **KM3NeT**
- **IceCube Gen2**
- **GVD**

1961

SOVIET PHYSICS JETP VOLUME 12, NUMBER 6 JUNE, 1961

ANGULAR DISTRIBUTIONS OF HIGH-ENERGY MUONS IN THE ATMOSPHERE A

THEIR PRODUCTION MECHANISM

G. T. ZATSEPIN and V. A. KUZ'MIN

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor July 10, 1960

J. Exptl. Theoret. Phys. (U.S.S.R.) **39**, 1677-1685 (December, 1960)

The kinetic equation for μ mesons in the atmosphere in which the decay and energy lo are taken into account is solved. The angular distributions of $10^{11} - 10^{14}$ ev μ mesons the atmosphere are computed for two possible production mechanisms: $\pi \rightarrow \mu + \nu$ and $K \rightarrow \mu + \nu$ decays. The results indicate that in the energy range of $10^{11} - 5 \times 10^{12}$ ev the μ-meson angular distributions depend significantly on the mechanism of their production.

K

SOVIET PHYSICS JETP VOLUME 14, NUMBER 6 JUNE,

Z

NEUTRINO PRODUCTION IN THE ATMOSPHERE

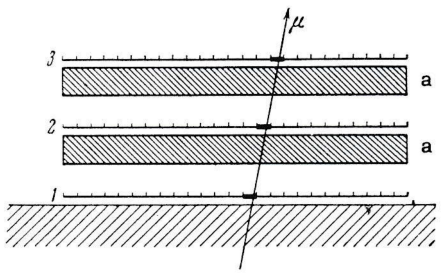
G. T. ZATSEPIN and V. A. KUZ'MIN

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor March 8, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 1818-1827 (December, 1961)

The energy spectra and angular distribution of neutrinos produced in the atmosphere in the $\pi \rightarrow \mu + \nu$ and $\mu \rightarrow e + \nu + \bar{\nu}$ decays are calculated taking the μ-meson energy losses at neutrino energies $\varepsilon = 10^9 - 3 \times 10^{11}$ ev into account. It is shown that the neutrino flux from the $\mu \rightarrow e + \nu + \bar{\nu}$ decay is comparable with that from the $\pi \rightarrow \mu + \nu$ decay. μ-meson energy losses only weakly affect neutrino production. K mesons produce neutrinos more efficiently than do π mesons. An experimental arrangement for detecting high-energy cosmic ray neutrinos is proposed.



Calculating atmospheric lepton fluxes: two approaches

1. Analytic/numerical solutions of the cascade equations

$$\frac{\mathrm{d}N_i(E_i,X)}{\mathrm{d}X} = -\frac{N_i(E_i,X)}{\lambda_i} - \frac{N_i(E_i,X)}{d_i} + \Sigma_{j=i}^{J} \int_E^{\infty} \frac{F_{ji}(E_i,E_j)}{E_i} \frac{N_j(E_j,X)}{\lambda_j} \mathrm{d}E_j$$

2. Convolve primary spectrum with yields per primary

$$\phi_\nu(E_\nu,\theta) = \Sigma_A \int_{E_\nu}^{\infty} \phi_A(E_A) Y_\nu(A,E_\nu,E_A,\theta)\,\mathrm{d}E_A,$$

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
ε_{charm} > 10 PeV

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

$$Z_{pK+} = \frac{1}{\sigma}\int x^\gamma \frac{\mathrm{d}\sigma(x)}{\mathrm{d}x}\mathrm{d}x$$

Spectral index
$\gamma + 1 \approx 2.7$

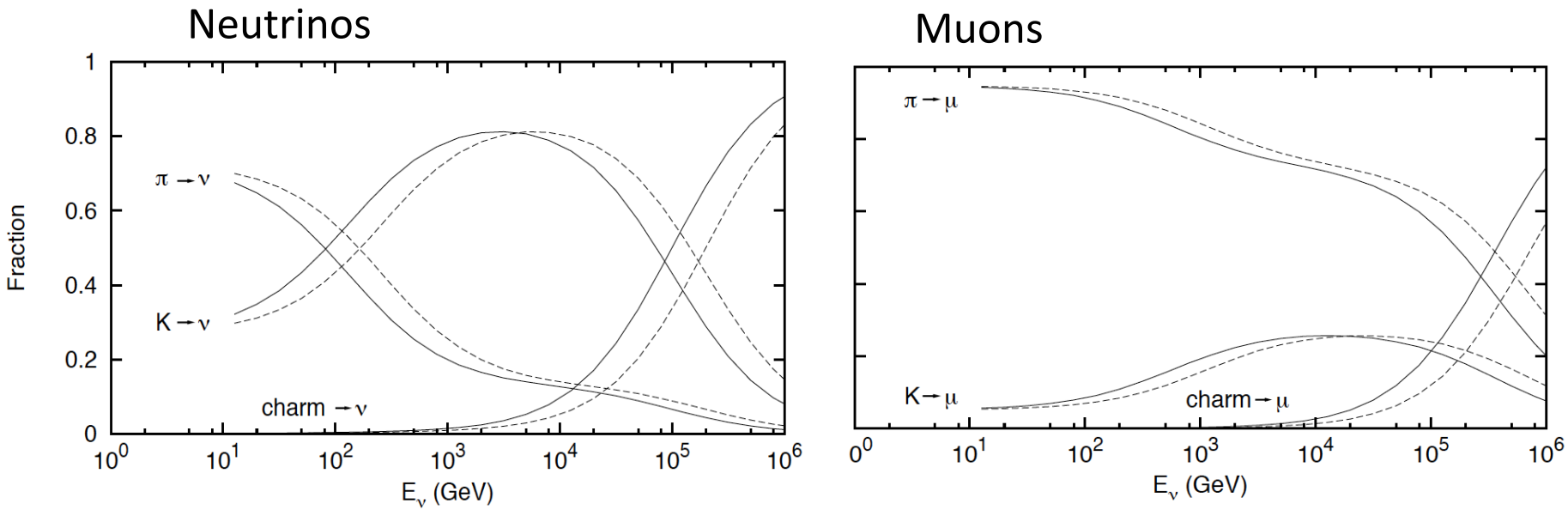
$$Z_{\pi\mu} = \frac{1 - r_\pi^{\gamma+1}}{(\gamma+1)(1-r_\pi)} \quad \text{and} \quad \frac{\epsilon_\pi}{\cos\theta E_\mu}\frac{1 - r_\pi^{\gamma+2}}{(\gamma+2)(1-r_\pi)}$$

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

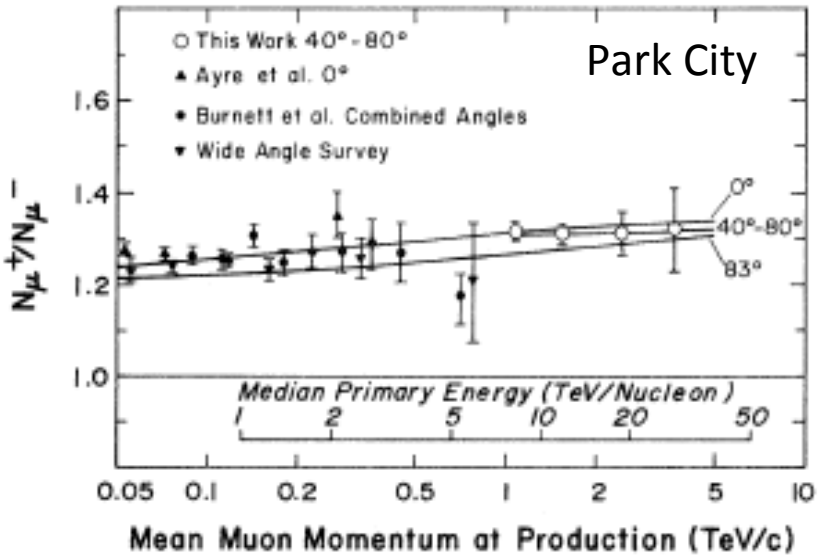
r_π = 0.573 but
r_K = 0.0458

Importance of kaons for neutrinos

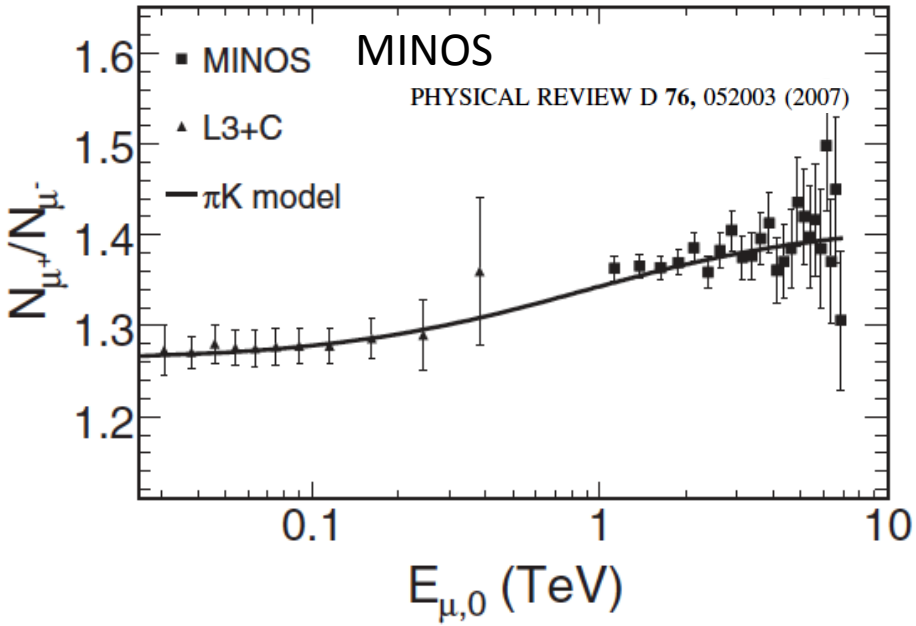
- Atmospheric ν_μ mainly from $K^{+/-}$
- TeV atmospheric ν_e from K_{e3} decays of K^0,$K^{+/-}$
- Associated production ($p \rightarrow K^+\Lambda$) favors K^+
- Charm $\rightarrow \mu, \nu$: small but potentially important at high E
  - contribution isotropic (compared to secant θ effect for >TeV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

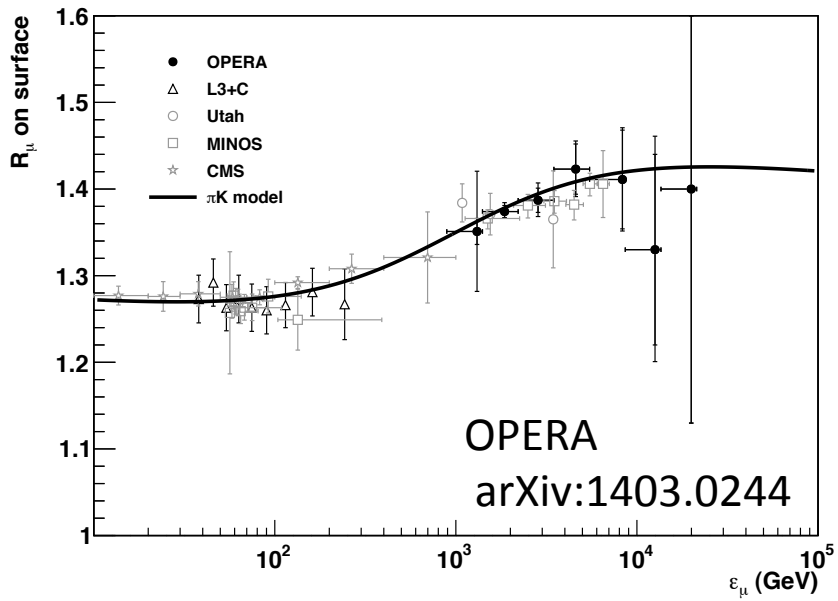


Muon charge ratio



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

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

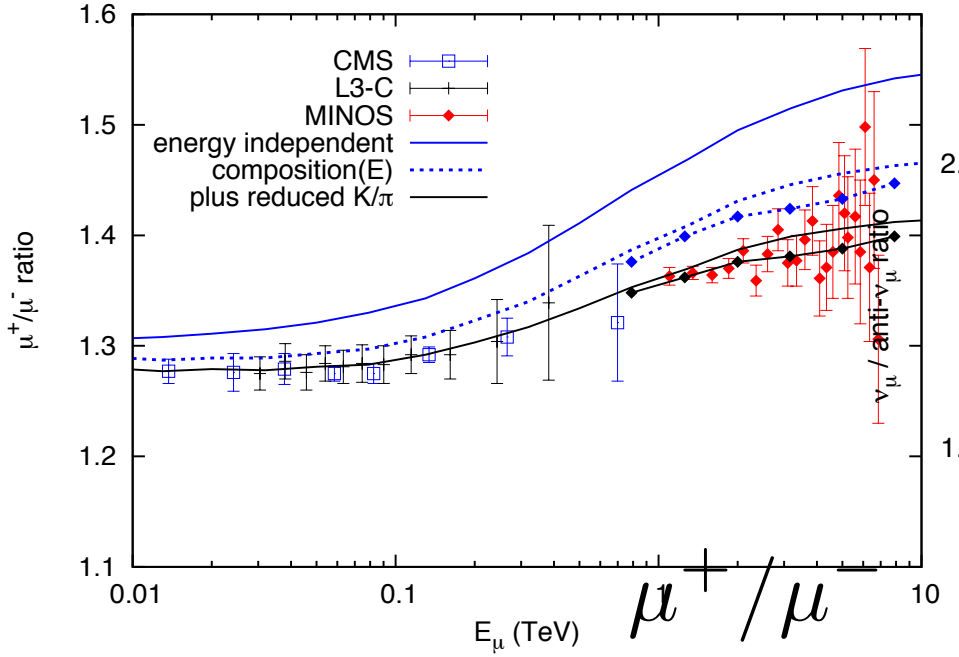
where $\alpha_K = \frac{Z_{pK^+} - Z_{pK^-}}{Z_{pK^+} + Z_{pK^-}}$ TG, Astropart. Phys. 35 (2012) 801

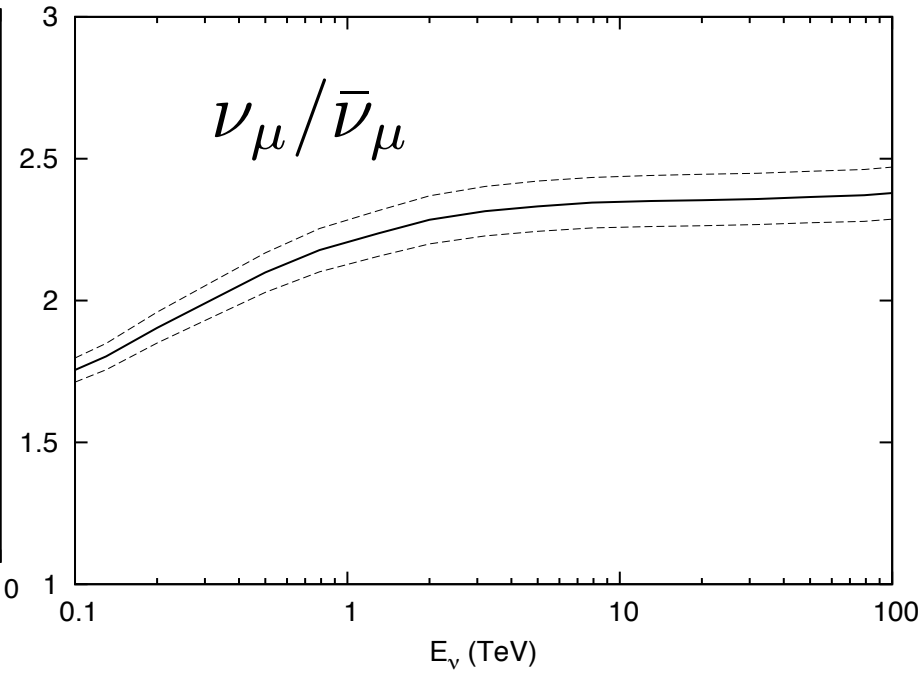
OPERA fit data as a function of cosθ and E with two free parameters.

They find $Z_{pK^+} = 0.0086 \pm 0.0004$ and $\delta_0 = 0.61$ at ~ 20 TeV/nucleon

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

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



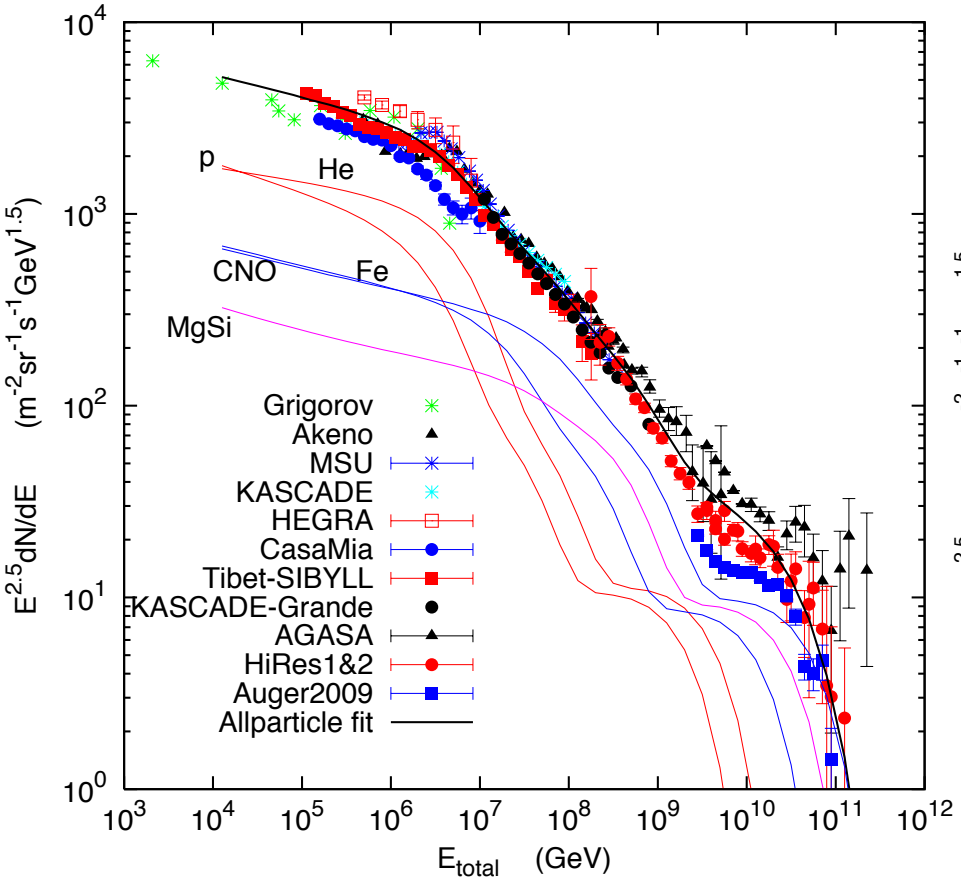


Important because $\sigma_\nu \neq \sigma_{\bar{\nu}}$

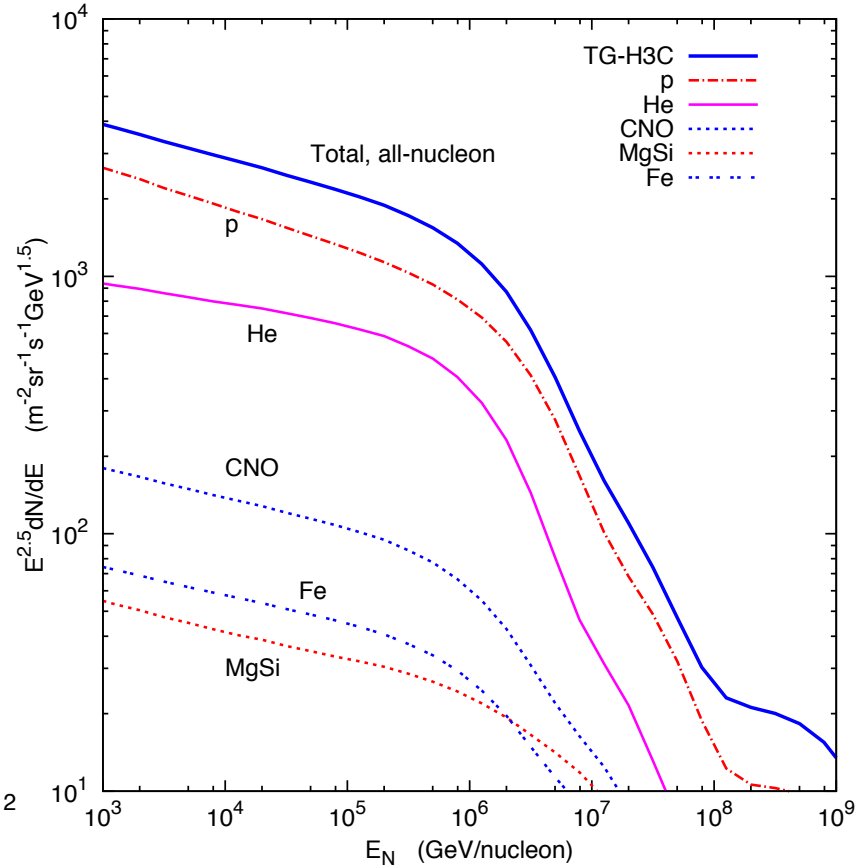
Primary spectrum

- 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

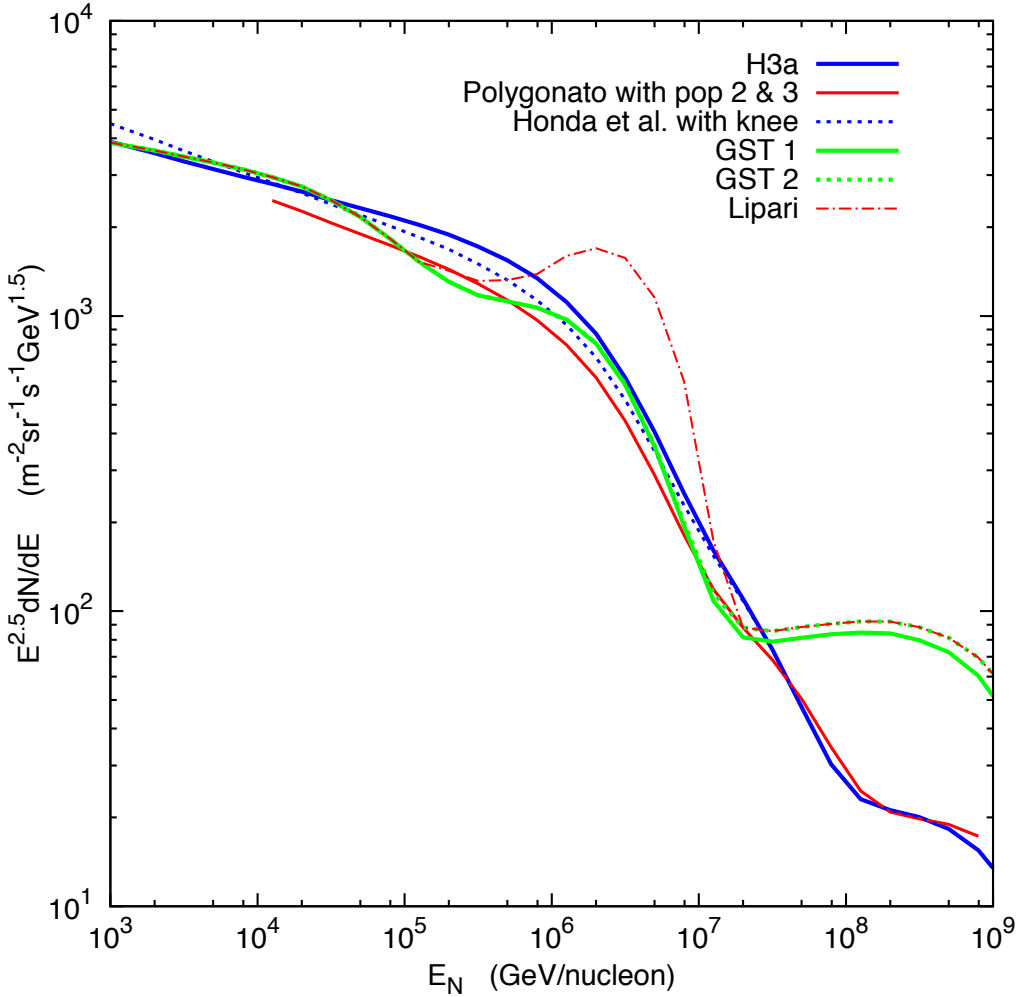


All-particle spectrum



Spectrum of nucleons

Spectrum of nucleons



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

Atmospheric neutrinos to PeV

- Bartol fluxes, Honda et al.
  - G. Barr et al. PRD 70, 023006; Honda et al., PRD 75 (2007) 043006
  - Full Monte Carlo gives yields for a grid of primary energies and masses
  - Convolve with primary spectrum
  - Produce tables of neutrino fluxes to 10 TeV
- Full Monte Carlo calculations
  - are awkward at high energy because
  - mesons almost always interact rather than decay
- Use numerical method:
  - Thunman, Ingelman, Gondolo, Astropart. Phys. 5 (1996) 309

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

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

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

- With energy-dependent Z-factors

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

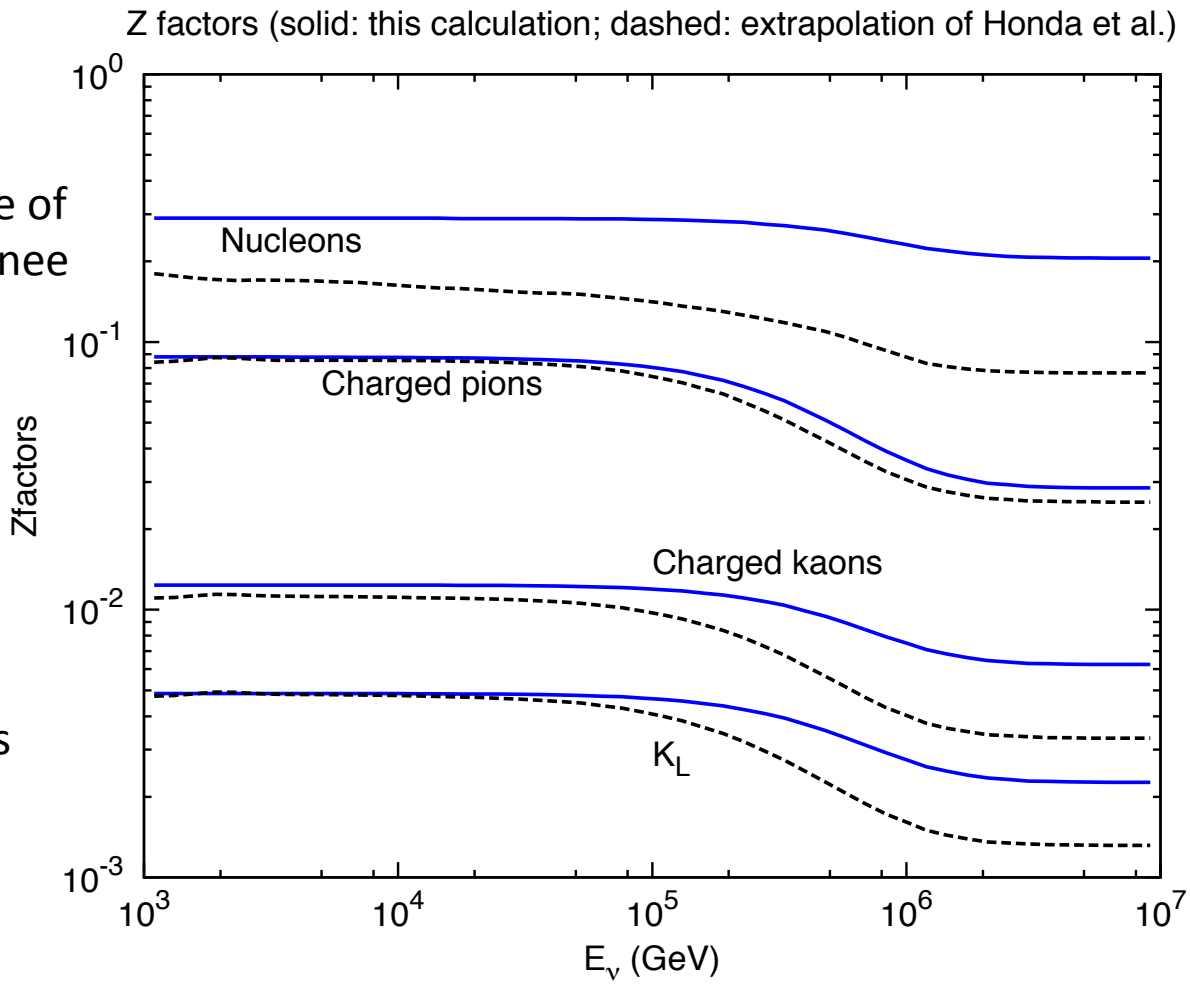
- Allows systematic evaluation of
  - Different primary spectrum/composition models
  - Uncertainties in hadronic interactions
  - Non-scaling, non-power-law energy dependence

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

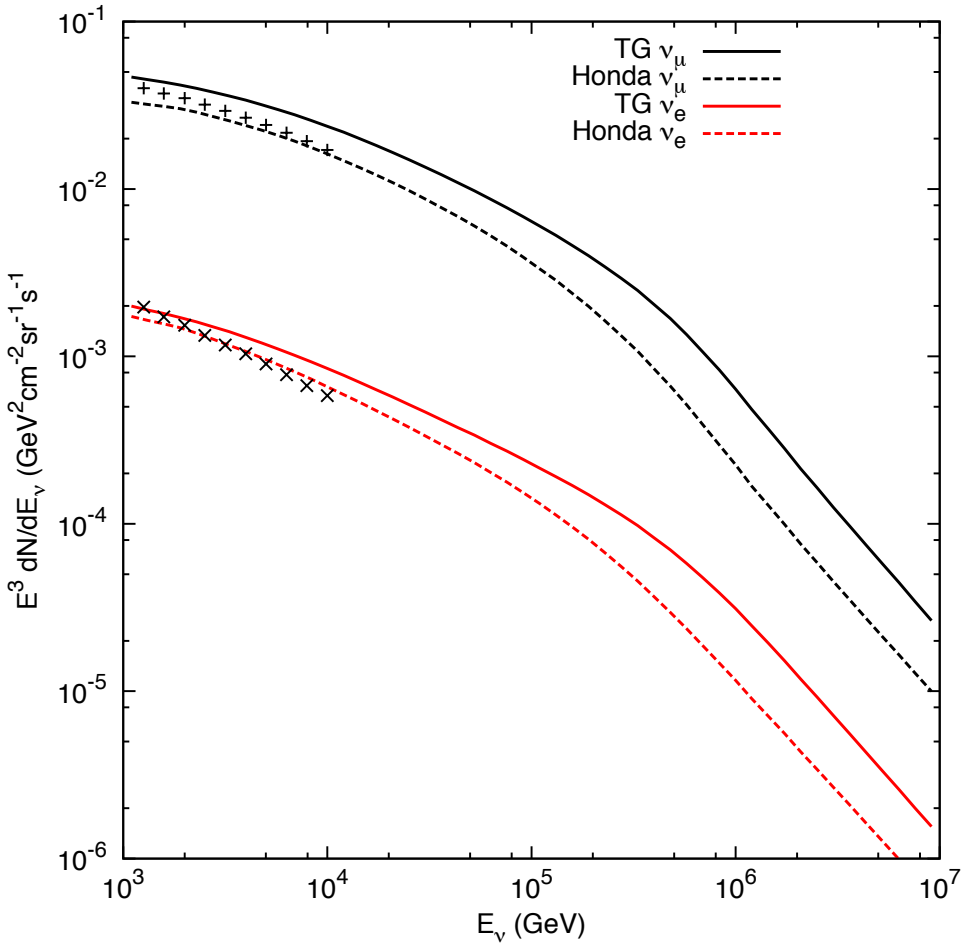


Compare with extrapolated Honda

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

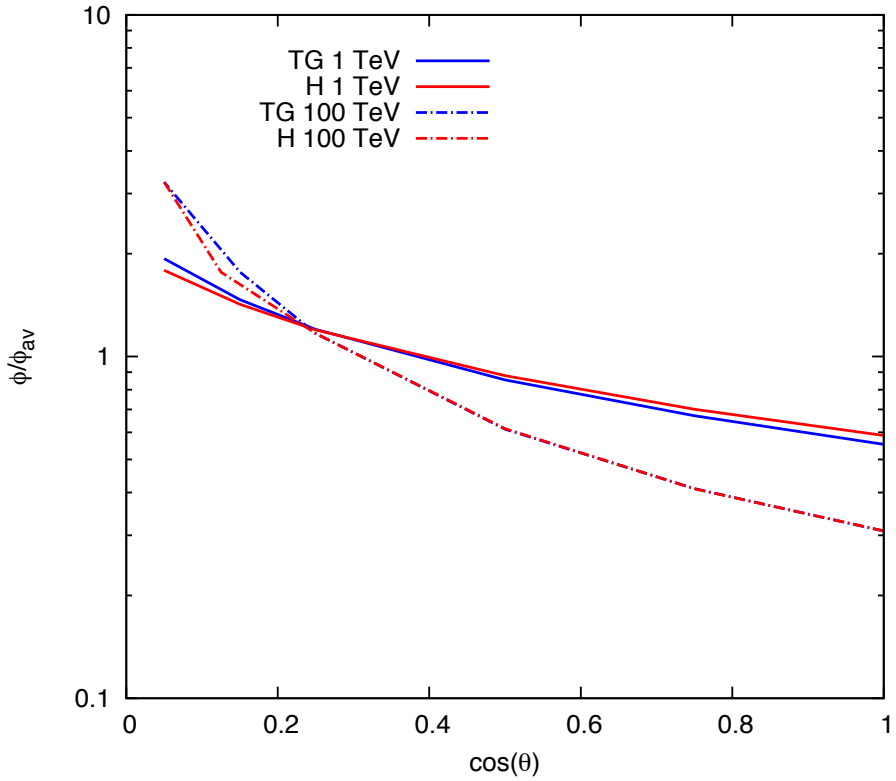
Data points from Honda et al. Monte Carlo calculation, which is steeper at low energy due to neutrinos from muon decay. Also, it has a slightly different primary spectrum.

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

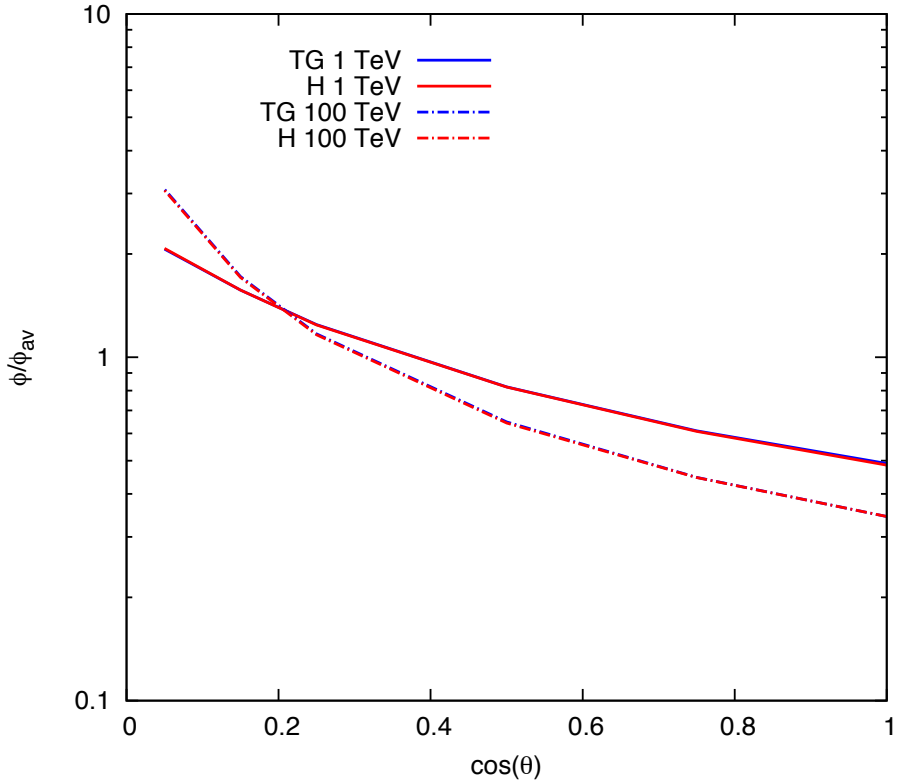


Angular distributions

angular-numu

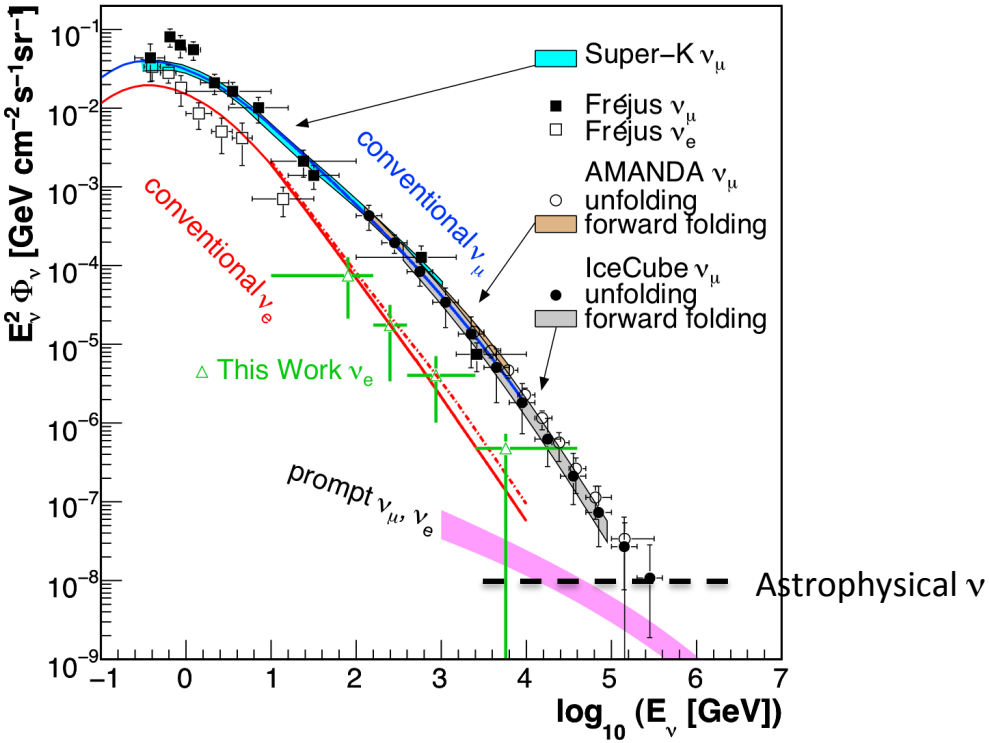


angular-nue



Importance of charm

- Critical energy $\varepsilon_{charm} \approx 10^7$ 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

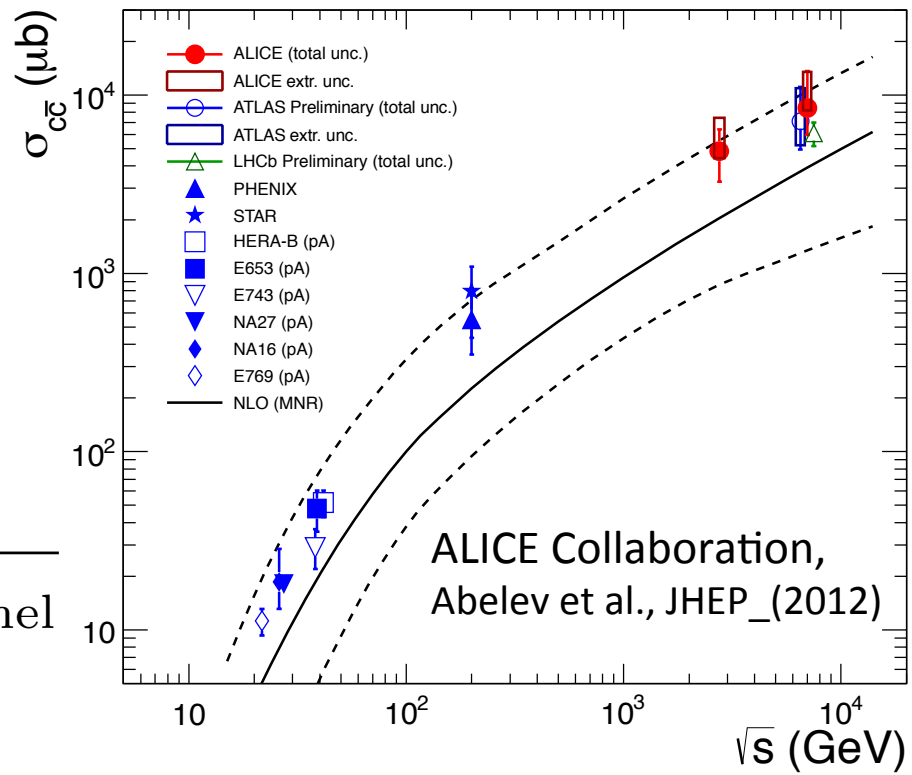


Estimate prompt ν from charm:

- Scale inclusive cross sections from plot
  - Limited phase space:
  - Use FONLL to get total σ_{charm}
  - Compare inclusive σ_π:

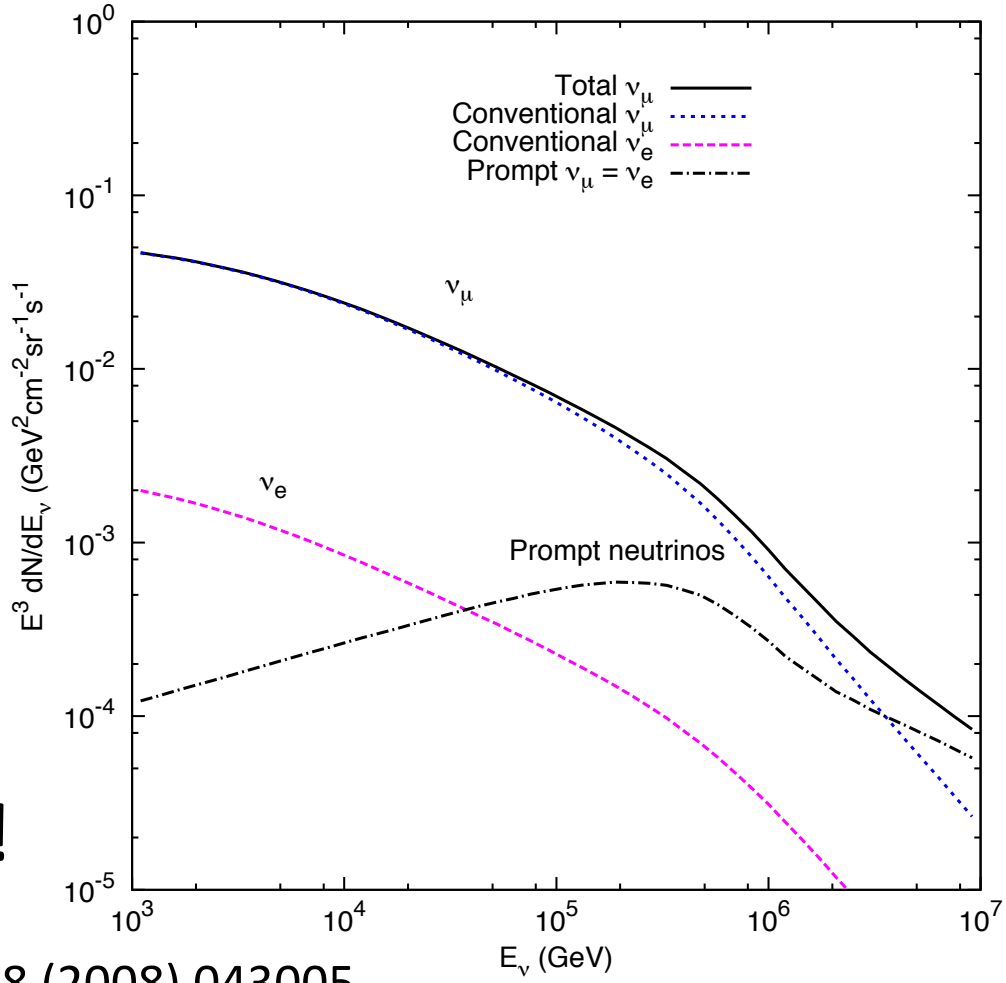
$$Z_{N\,\mathrm{charm}} \sim Z_{N\pi} \frac{\sigma_{\mathrm{charm}}}{< n_\pi > \sigma_{\mathrm{inel}}}$$

  - Add charm decay kinematics and nuclear target effect



Prompt vs conventional neutrinos

- Estimate ≈ ERS*
- For conventional ν (for E > TeV) $\phi(\nu_e) \approx \phi(\nu_\mu)/20$
- Prompt crossover earlier for ν_e
- Prompt component cannot be nelected!

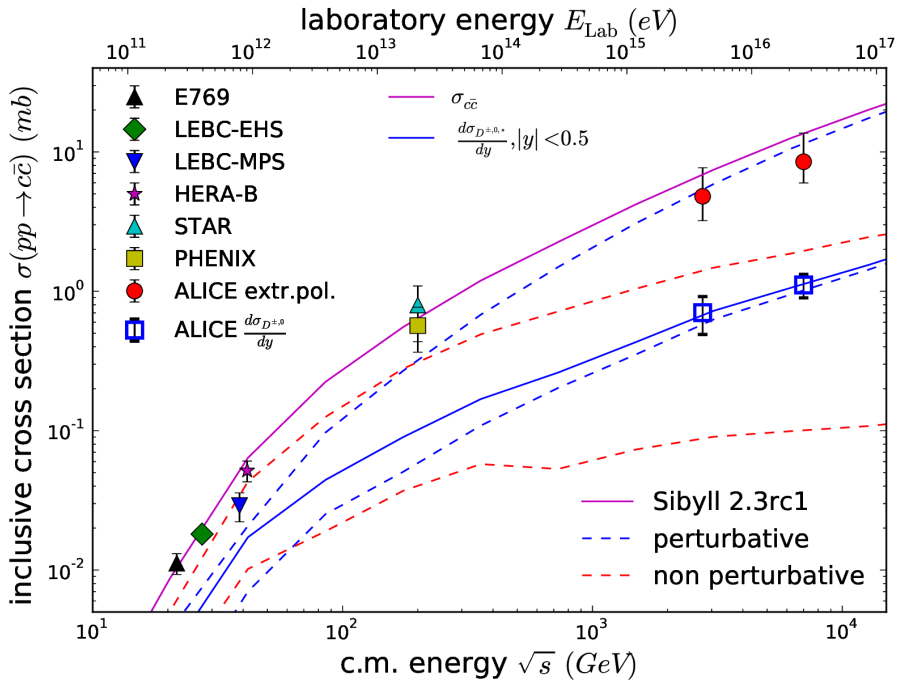


*ERS = Enberg, Reno, Sarcevic, PRD 78 (2008) 043005

Adding charm to SIBYLL (post-LHC)

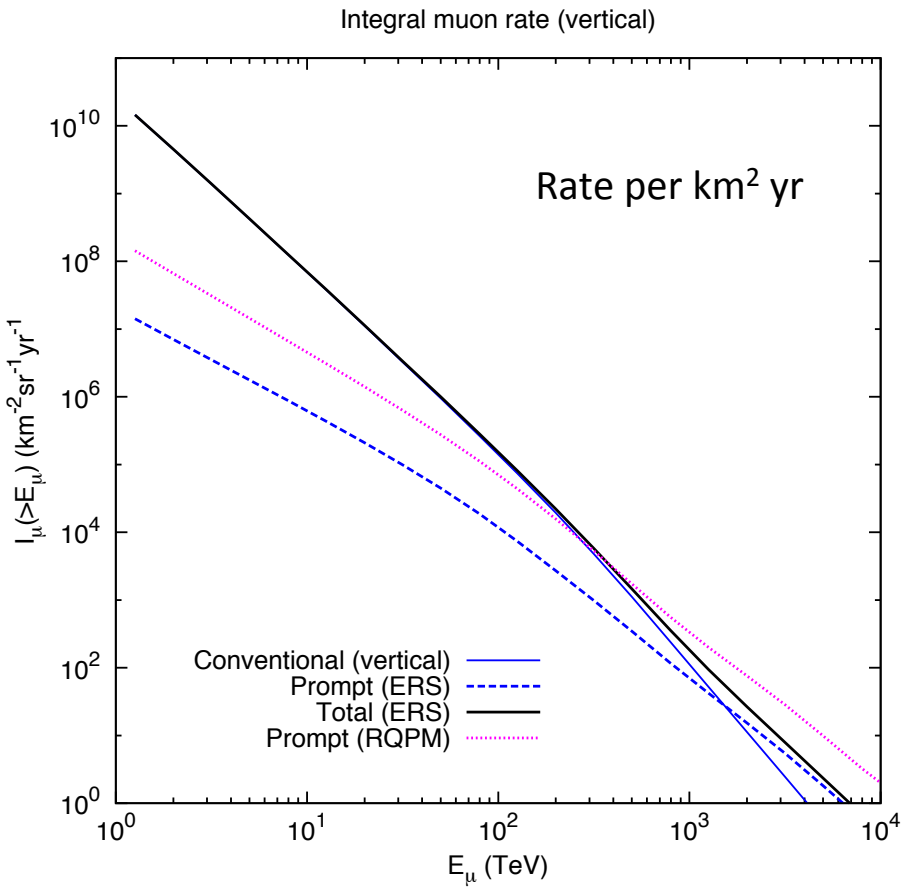
Felix Riehn, ISVHECRI 2014

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



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
  - Energy resolution



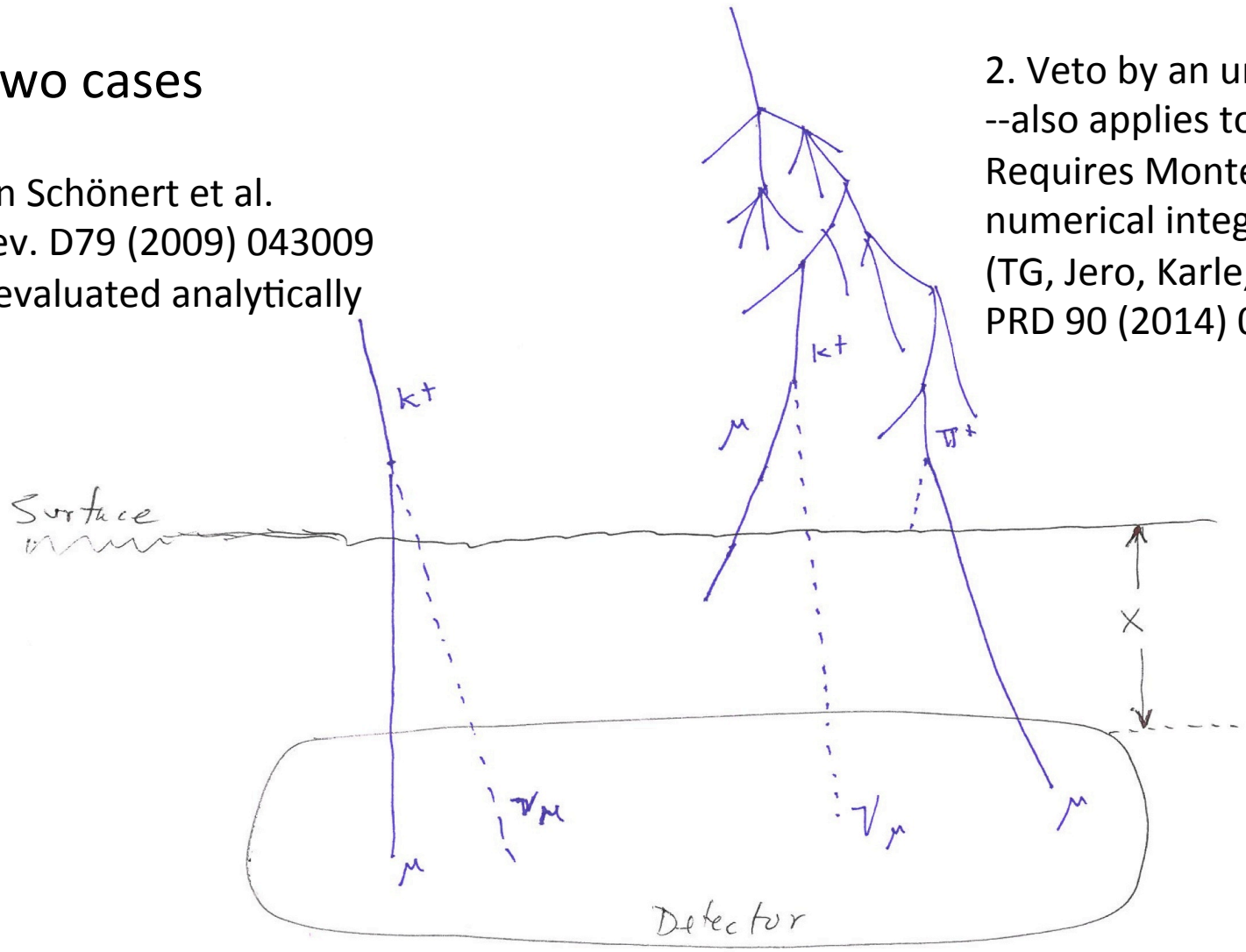
*P. Desiati & TG, PRL 105 (2010) 121102

Atmospheric neutrino self veto

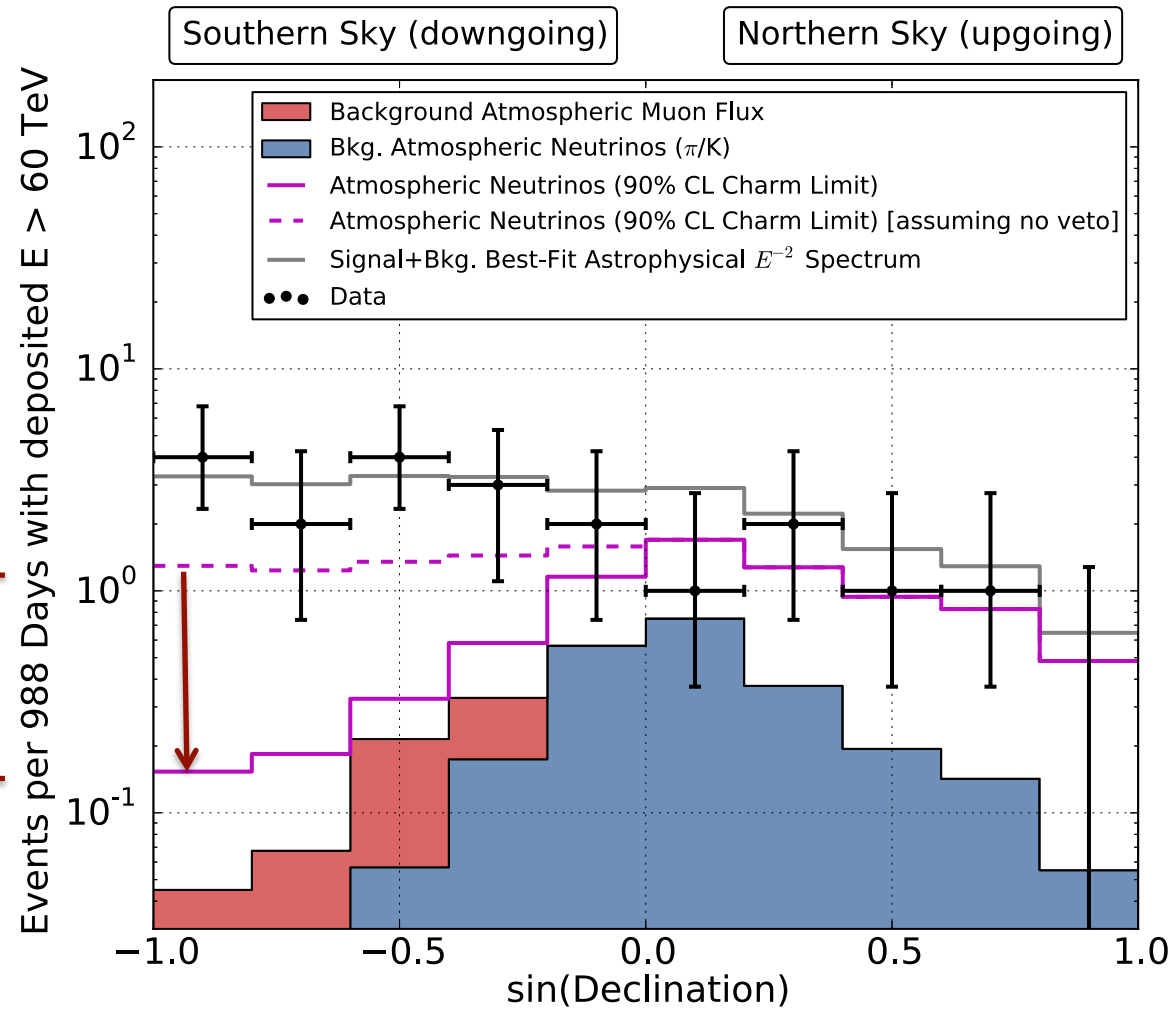
Two cases

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)



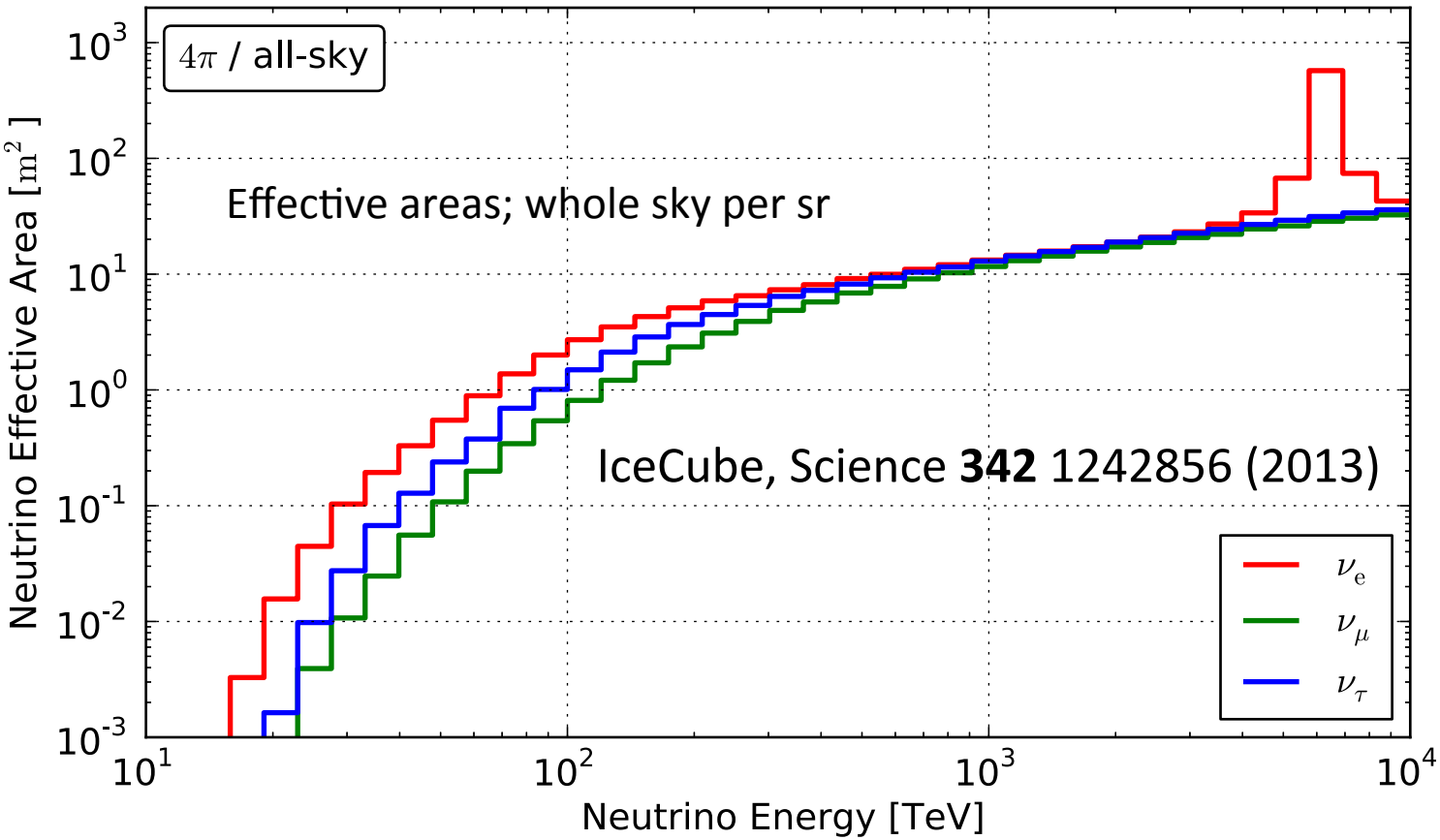
Angular distribution (E> 60 TeV)



Atmospheric ν veto

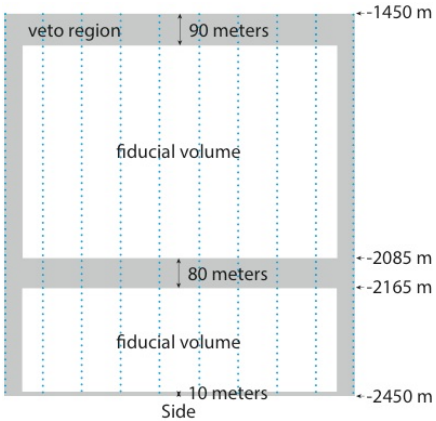
Note shape of prompt atmospheric ν background:
Veto does not have to be complete to be useful

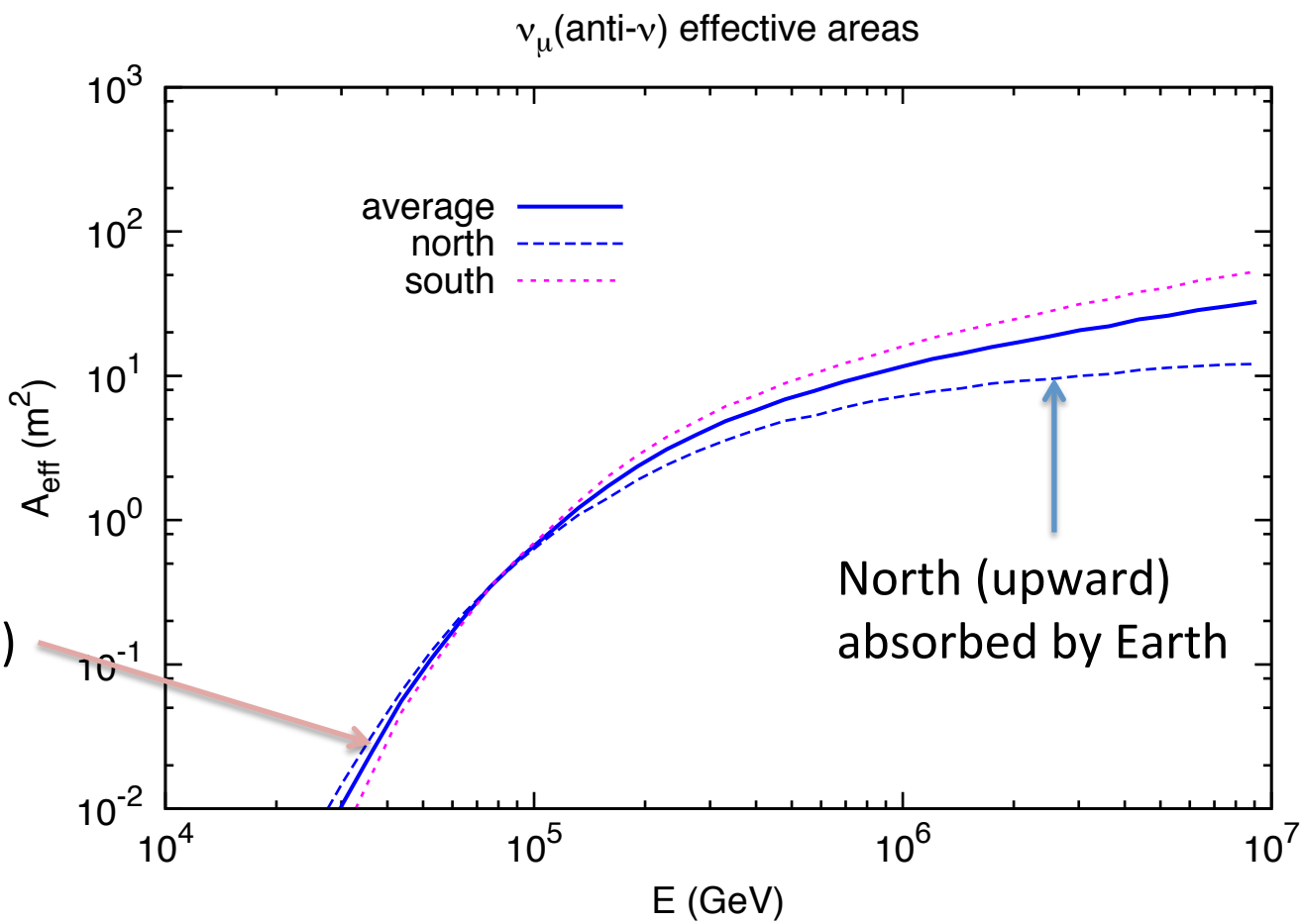
Fold fluxes with IceCube A_{eff} to get rates



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

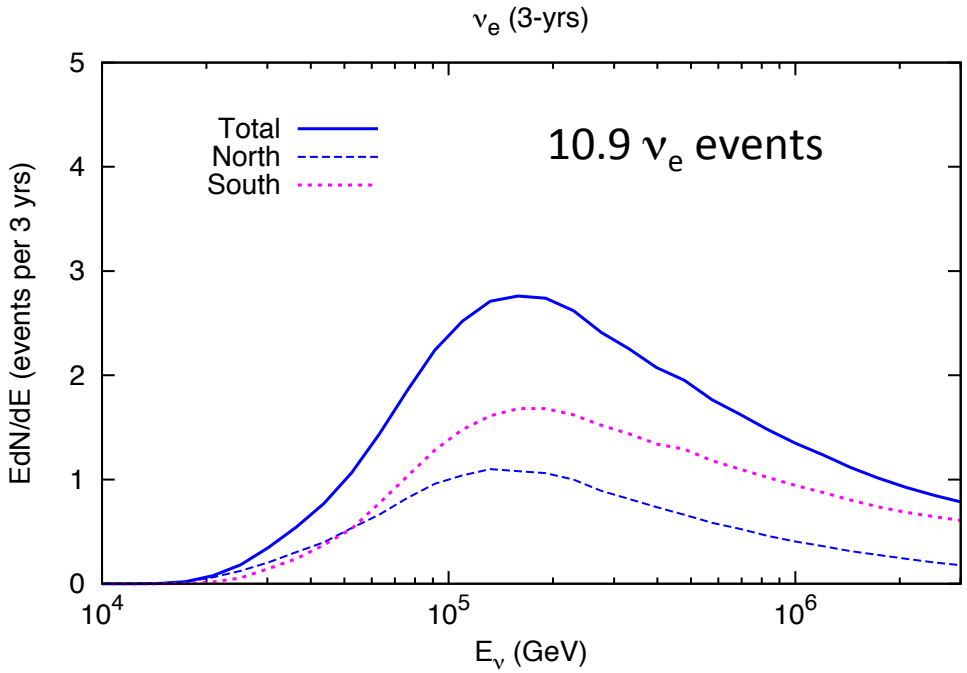
- IceCube 3 yr analysis suggests two fits for astrophysical component up to 3 PeV:

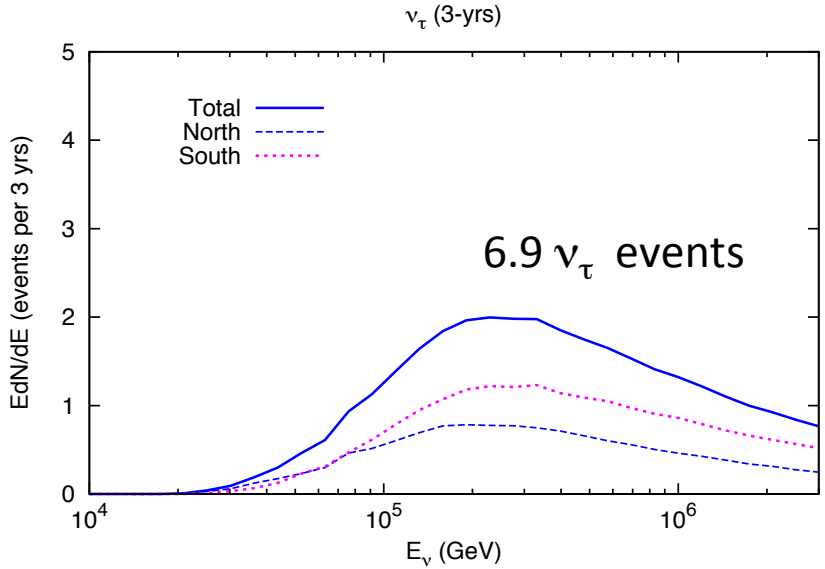
$$E_\nu^2\,\phi_\nu = 0.95 \times 10^{-8}\,\frac{\mathrm{GeV}}{\mathrm{cm^2 sr\,s}}\ \mathrm{per\,flavor}$$

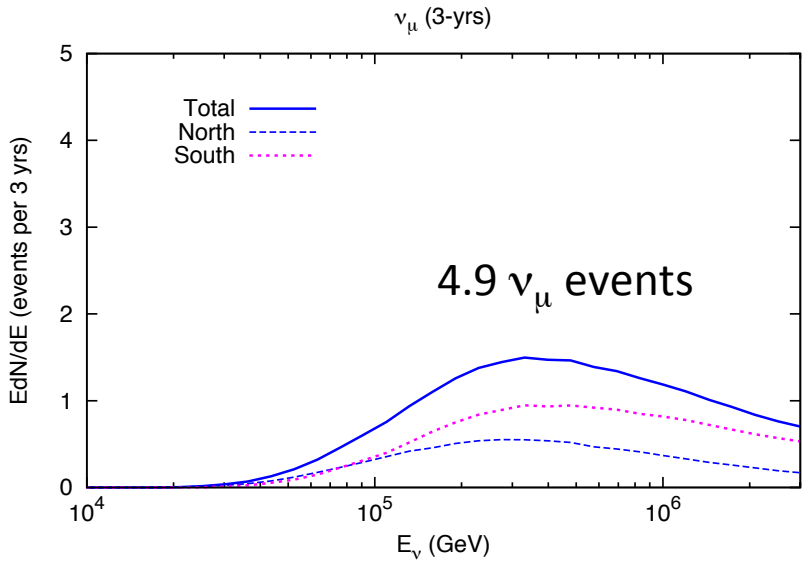
$$E_\nu^2\,\phi_\nu = 1.5 \times 10^{-8}\left(\frac{E}{100\mathrm{TeV}}\right)^{-0.3}\,\frac{\mathrm{GeV}}{\mathrm{cm^2 sr\,s}}\ \mathrm{per\,flavor}$$

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

(Convolve astro spectrum with Aeff)

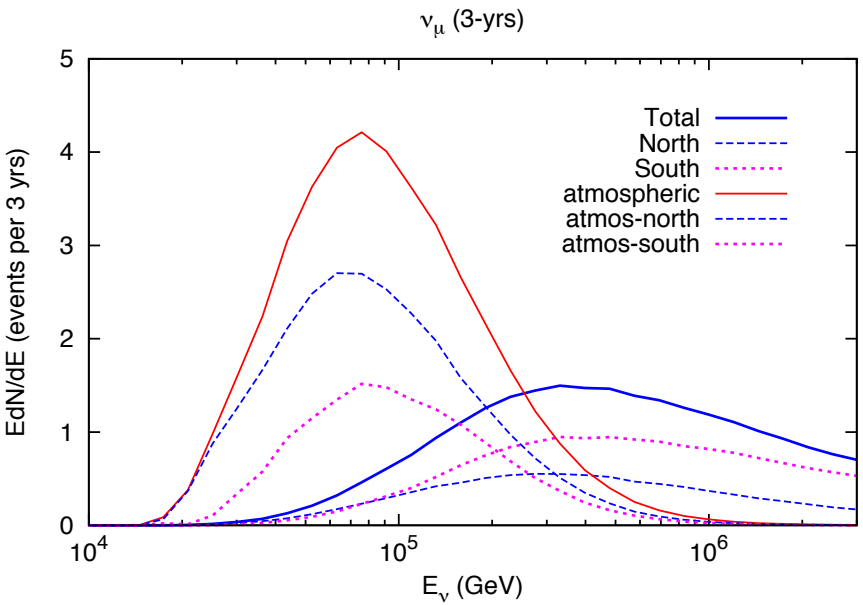


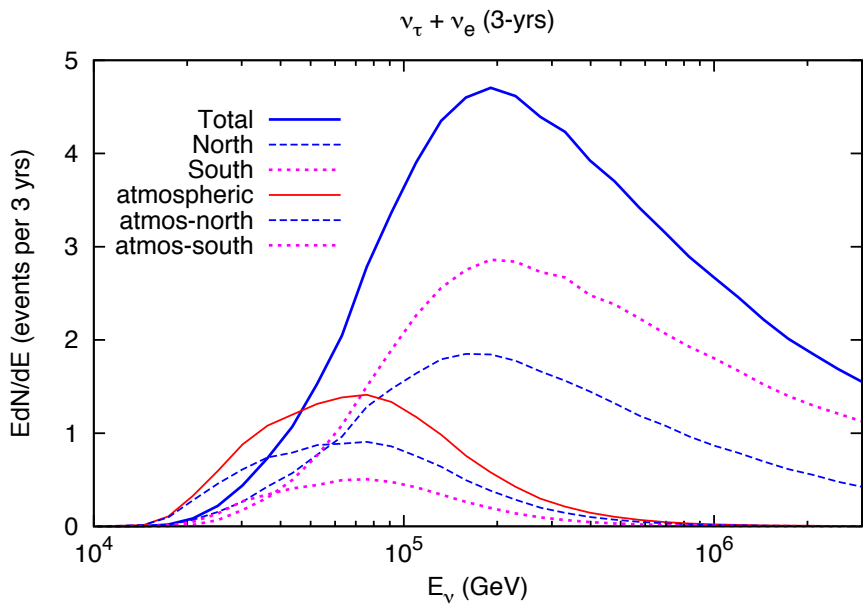




Note: Plots are vs ν energy (not E_{vis}) assuming $\phi_\nu \sim (E_\nu)^{-2}$

Signal/background



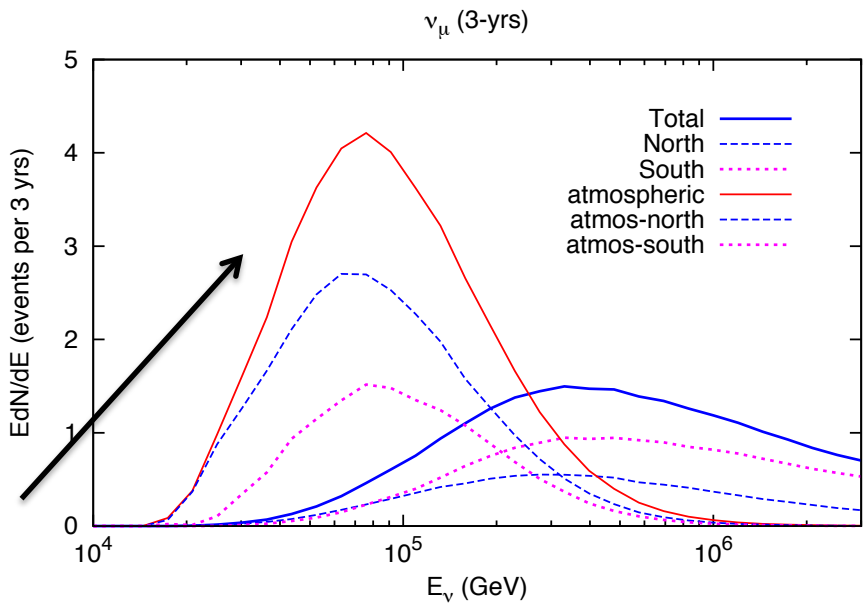


Note: plots are vs true neutrino energy, not $E_{visible}$

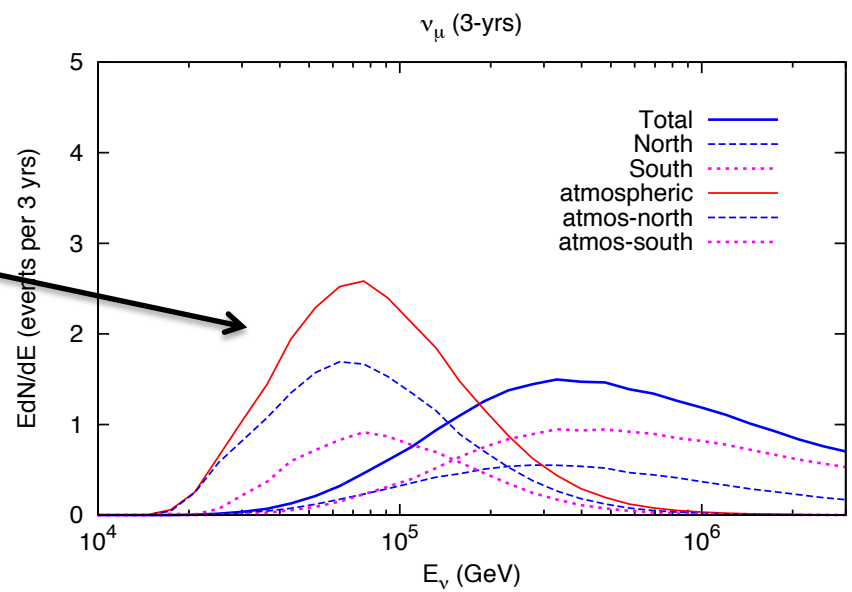
The distortion is biggest for ν_μ

Uncertainty in background limits inference on flavor ratio at Earth

Scaling extrapolation with knee: expect 7 atmospheric ν_μ in 3 yrs IceCube HESE analysis



Extrapolation of Honda flux (with knee):
Expect ≈ 4 atmospheric 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
  - Selex expt suggests some intrinsic charm
  - Hidden in IceCube ν by astrophysical component
  - Sibyll with charm should be ready soon
- ν self-veto reduces downward background atmospheric ν
- Cascade/track and flavor ratio:
  - more data + better understanding of background needed

Discussion

- Physics motivation:
  - Background for astrophysical neutrinos
  - Beam for high-energy physics (charm, neutrino properties)
- Experimental status (5 yrs)
  - Beginnings of KM3NeT
  - IceCube Gen2 (PINGU + HEX) proposal & start?
- Opportunities
  - Determine the level of charm and prompt ν
  - Mine accelerator data for hadronic interactions (recall Sanford & Wang, BNL, AGS internal report, 1967)
  - Determine flavor ratio of astrophysical ν at Earth
- Longer term
  - Operations of next generation detectors

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 $< E_{dep} <$ 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