Atmospheric Neutrinos

Theory and experimental data of atmospheric neutrino production

Outline

- Historical introduction
- Atmospheric ν beam for particle physics
  - Uncertainties in calculated neutrino fluxes
  - Relation to studies of neutrino oscillations
- Atmospheric ν as foreground for astrophysical neutrinos
  - Extension to very low and very high energy
    - Background for diffuse, relic SNR neutrinos
    - Background for indirect searches for WIMPs
    - Background for neutrino telescopes

Historical context

Detection of atmospheric neutrinos

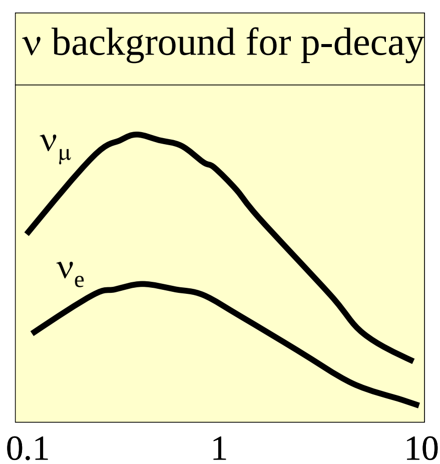
- Markov (1960) suggests Cherenkov light in deep lake or ocean to detect atmospheric ν interactions for neutrino physics
- Greisen (1960) suggests water Cherenkov detector in deep mine as a neutrino telescope for extraterrestrial neutrinos
- First recorded events in deep mines with electronic detectors, 1965: CWI detector (Reines et al.); KGF detector (Menon, Miyake et al.)

Two methods for calculating atmospheric neutrinos:

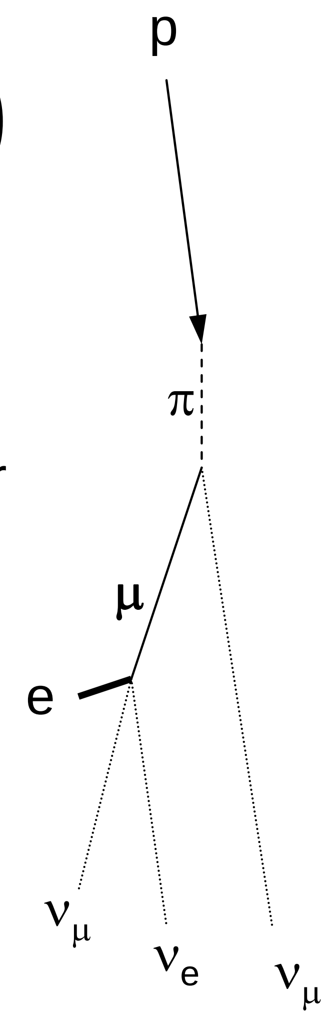
- From muons to parent pions infer neutrinos (Markov & Zheleznykh, 1961; Perkins)
- From primaries to π, K and μ to neutrinos (Cowsik, 1965 and most later calculations)
- Essential features known since 1961: Markov & Zheleznykh, Zatsepin & Kuz'min
- Monte Carlo calculations follow second method

Stability of matter: search for proton decay, 1980's

- IMB & Kamioka -- water Cherenkov detectors
- KGF, NUSEX, Frejus, Soudan -- iron tracking calorimeters
- Principal background is interactions of atmospheric neutrinos
- Need to calculate flux of atmospheric neutrinos



Historical context (cont'd)



Atmospheric neutrino anomaly - 1986, 1988 …

- IMB too few μ decays (from interactions of ν_μ) 1986
- Kamioka μ-like / e-like ratio too small.
- Neutrino oscillations first explicitly suggested in 1988 Kamioka paper
- IMB stopping / through-going consistent with no oscillations (1992)
- Hint of pathlength dependence from Kamioka, Fukuda et al., 1994

Discovery of atmospheric neutrino oscillations by S-K

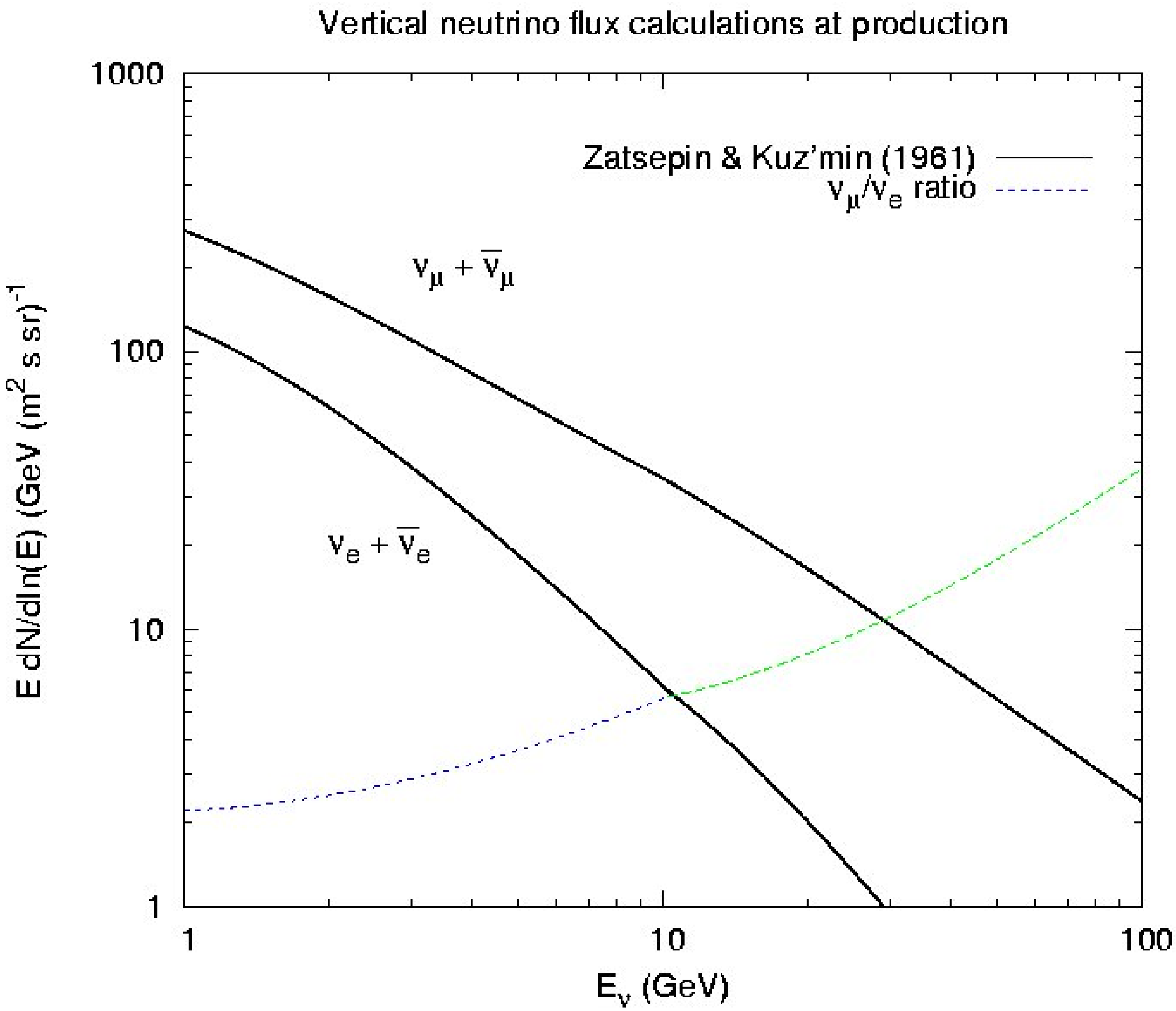
- Super-K: "Evidence for neutrino oscillations" at Neutriino 98
- Subsequent increasingly detailed analyses from Super-K 1998…
- Confirming evidence from MACRO and Soudan
- Analyses based on **ratios** comparing to 1D calculations

Need for precise, complete, accurate, 3D calculations

- $\Theta \sim P_T / E$ is large for sub-GeV neutrinos
- Bending of muons in geomagnetic field important for ν from μ decay
- Complicated angular/energy dependence of primaries (AMS measurement)
- Use improved primary spectrum and hadroproduction information

(MZhG)ZK

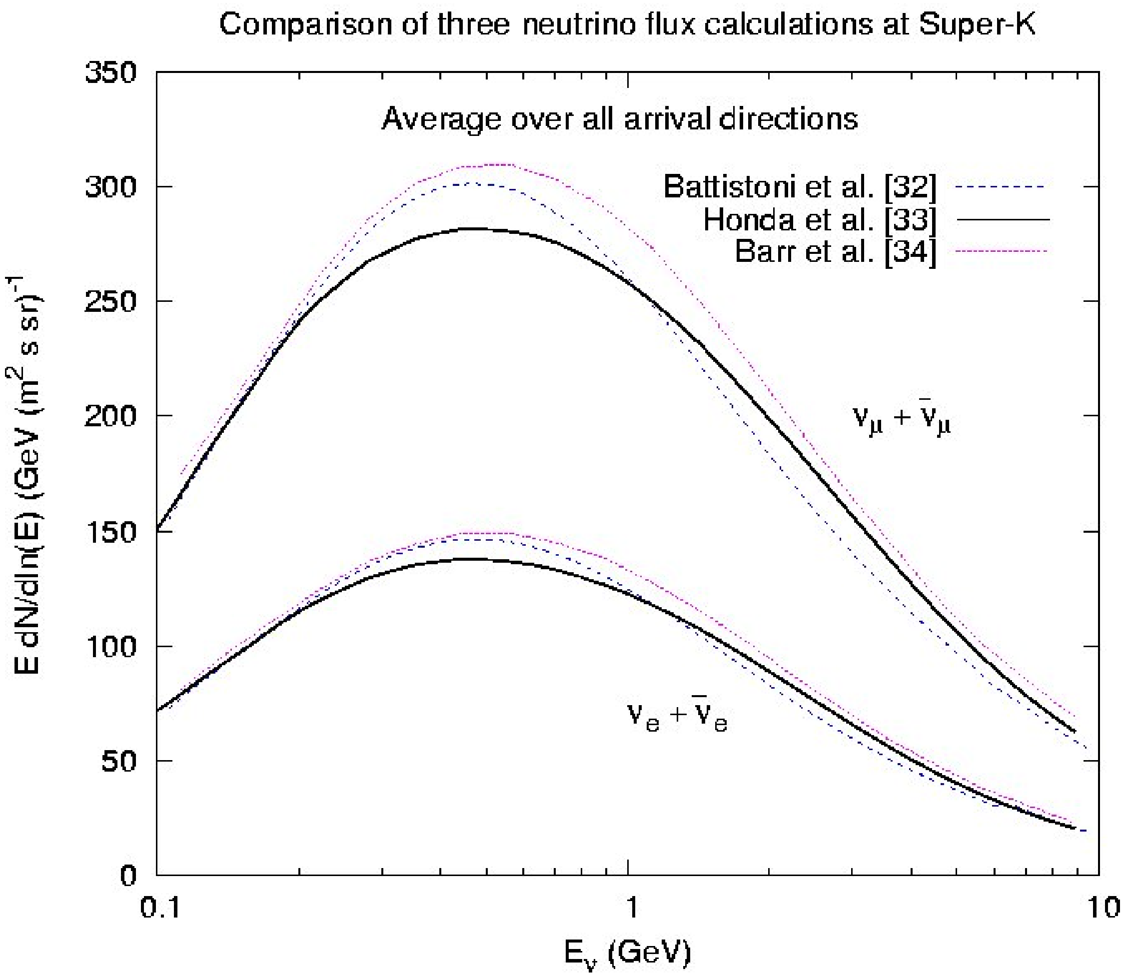
- Basic features of neutrino flux calculated and known since 1961



Summary of Atmospheric Neutrino Calculations

Zatsepin, Kuz'min	SP JETP 14:1294(1961)	Mu		
Many calculations	~ 1965 --- ~1990	1D		
D.H. Perkins	Asp.Phys. 2: 249 (1994)	Mu		
Honda, Kajita, Kasahara, Midorikawa	PRD 52: 4985 (1995)	1D		FRITIOF
Agrawal, Gaisser, Lipari, Stanev	PRD 53: 1314 (1996)	1D		Target
Battistoni et al	Asp.Phys 12:315 (2000) Asp.Phys 19:269 (2003)	3D	B	FLUKA
P. Lipari	Asp.Phys 14:171 (2000)	3D		
V. Plyaskin	PL B516:213 (2001) hep-ph/0303146	3D		GHEISHA
Tserkovnyak et al	Asp.Phys 18:449 (2003)	3D		CALOR-FRITIOF GFLUKA/GHEISHA
Wentz et al	PRD 67 073020 (2003)	3D		Corsika: DPMJET VENUS, UrQMD
Liu, Derome, Buénerd	PRD 67 073022 (2003)	3D		
Favier, Kossalsowski, Vialle	PRD 68 093006 (2003)	3D		GFLUKA
Barr, Gaisser, Lipari, Robbins, Stanev	PRD 70 023006 (2004)	3D	C	Target
Honda, Kajita, Kasahara, Midorikawa	PRD 64 053011 (2001) PRD 70 043008 (2004)	3D	A	DPMJET

Comparison of 3 calculations used by Super-K

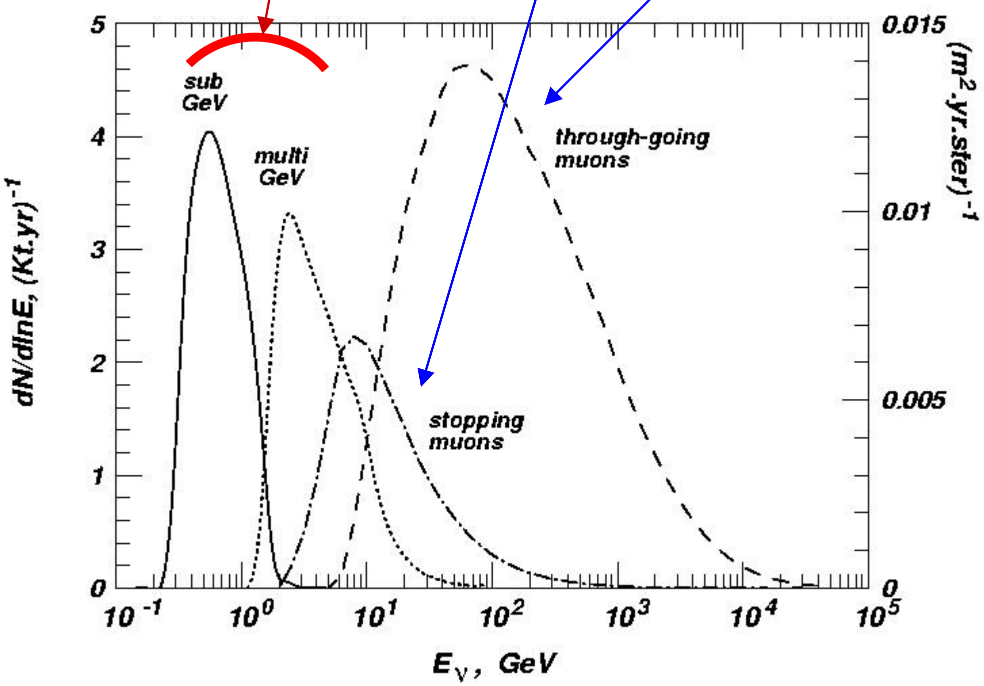


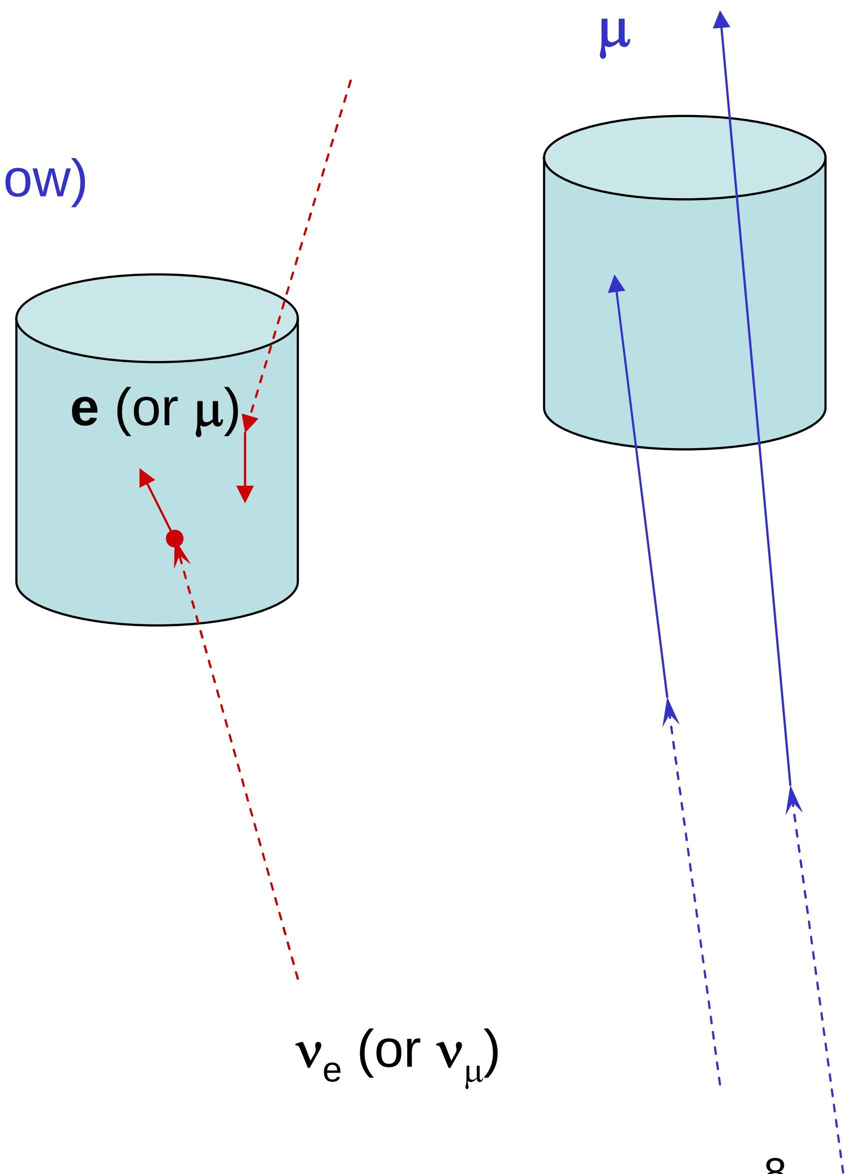
Differences ~ 10%
(using similar primary spectra)

Classes of atmospheric ν events

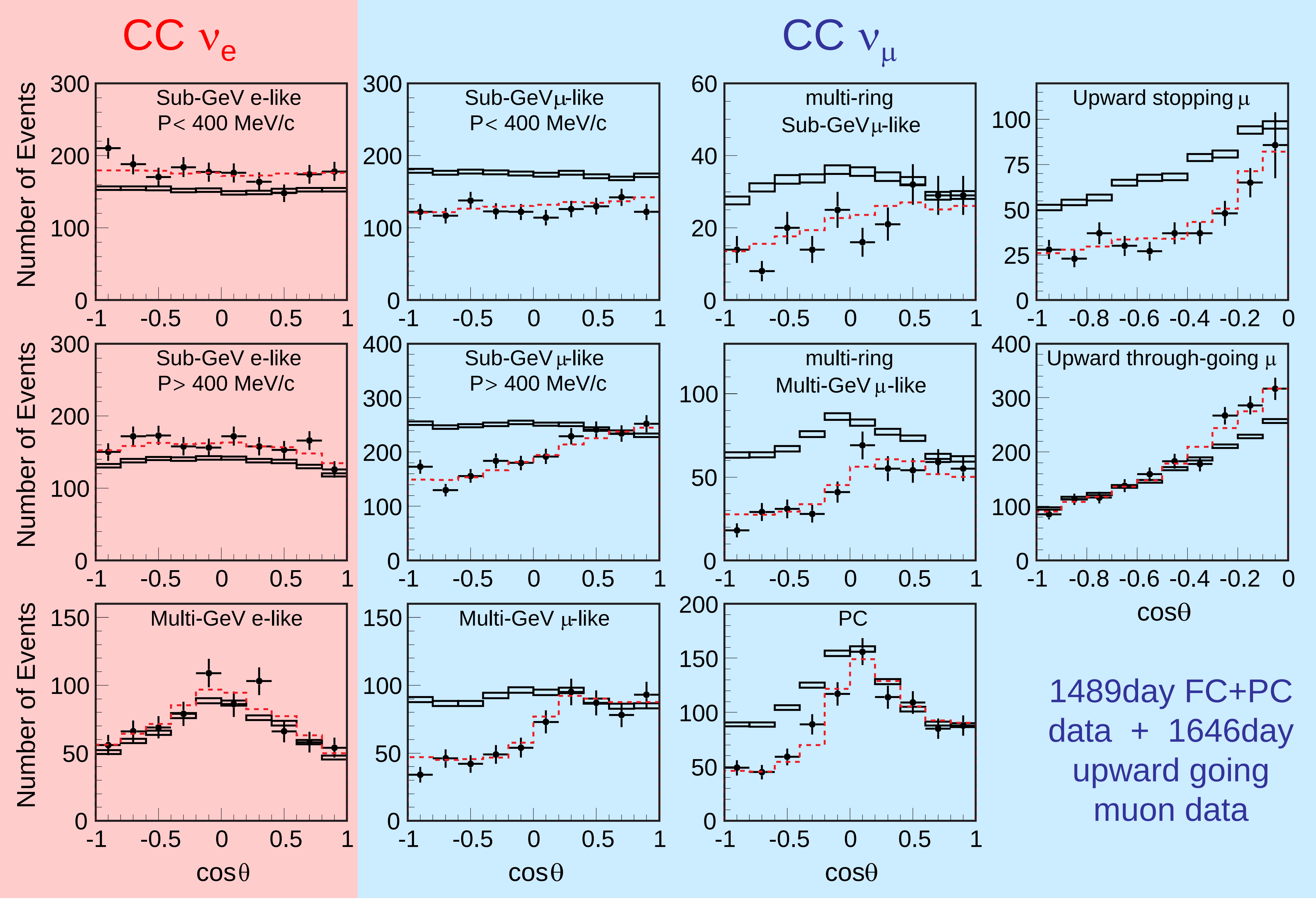
Contained (any direction)

ν-induced μ (from below)

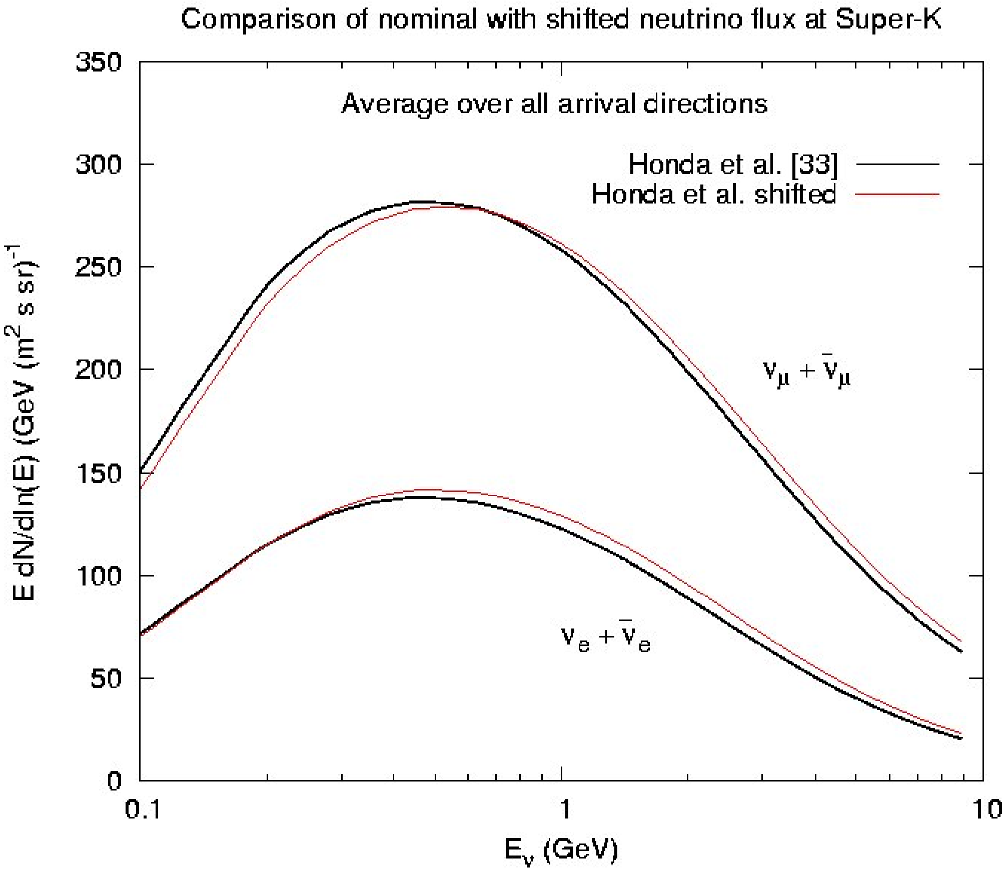




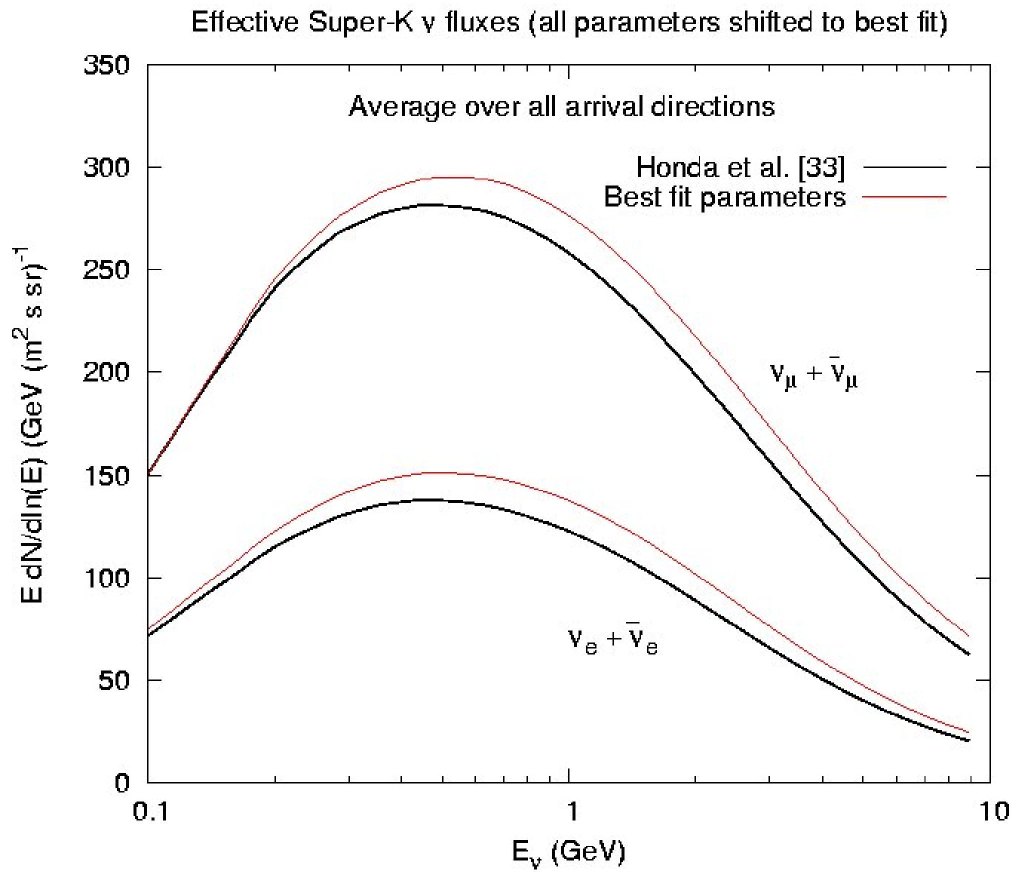
Super-K atmospheric neutrino data (hep-ex/0501064)



Super-K adjust atmospheric ν parameters in their fit



Atmospheric parameters only

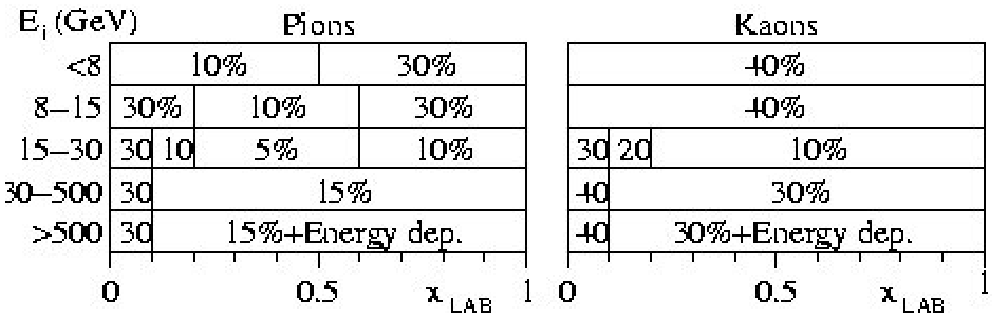


Effective flux including shifts in neutrino cross sections, etc.

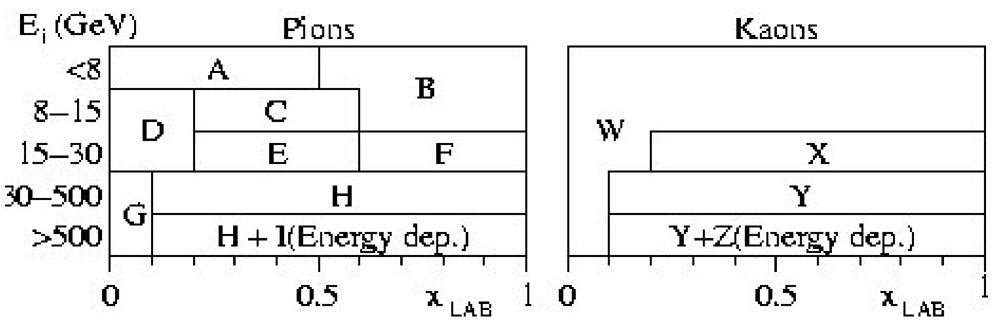
A priori analysis of uncertainties

Giles Barr et al., 2006

Uncertainties in
p + A → π (K) + X

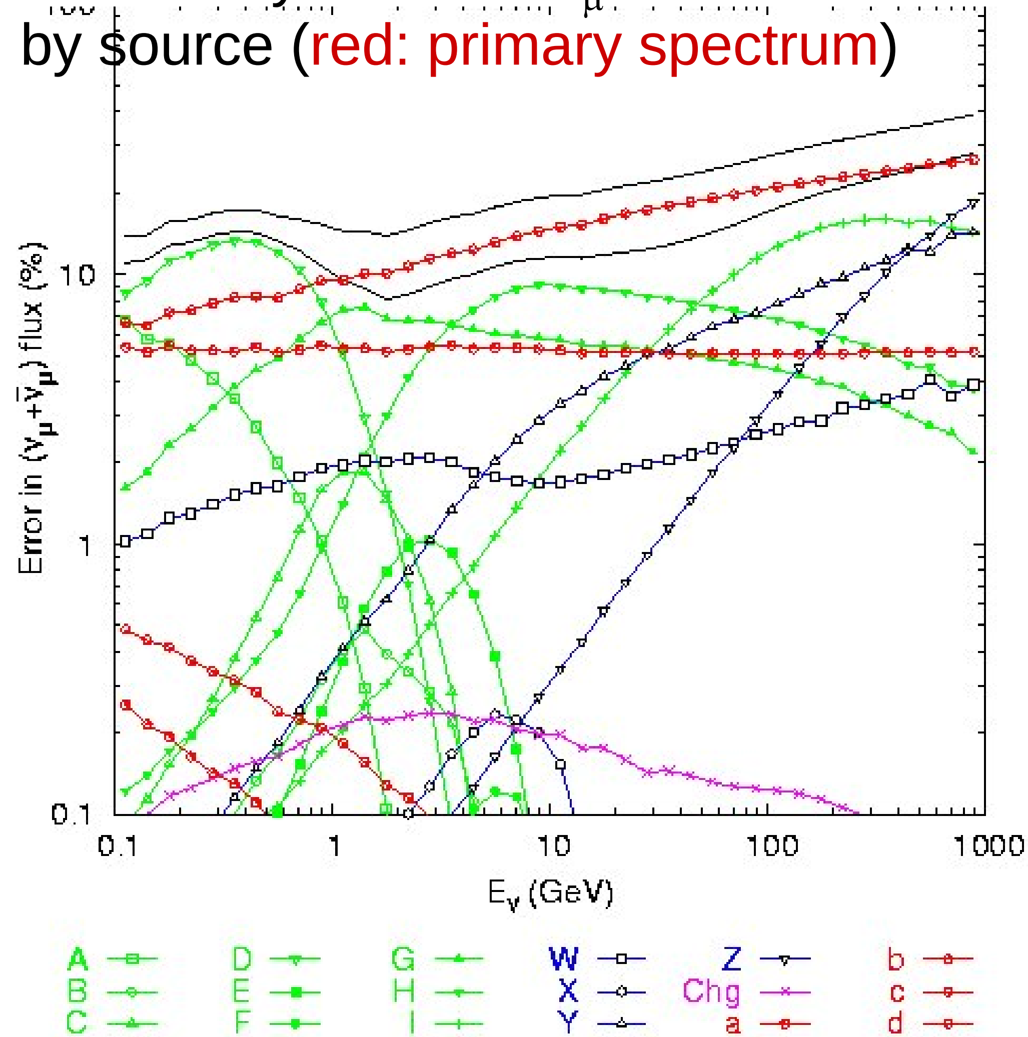


Assumed uncertainties in phase space



Assume 9 (π) + 4(K) independent regior

Uncertainty in flux of ν_μ broken down by source (red: primary spectrum)

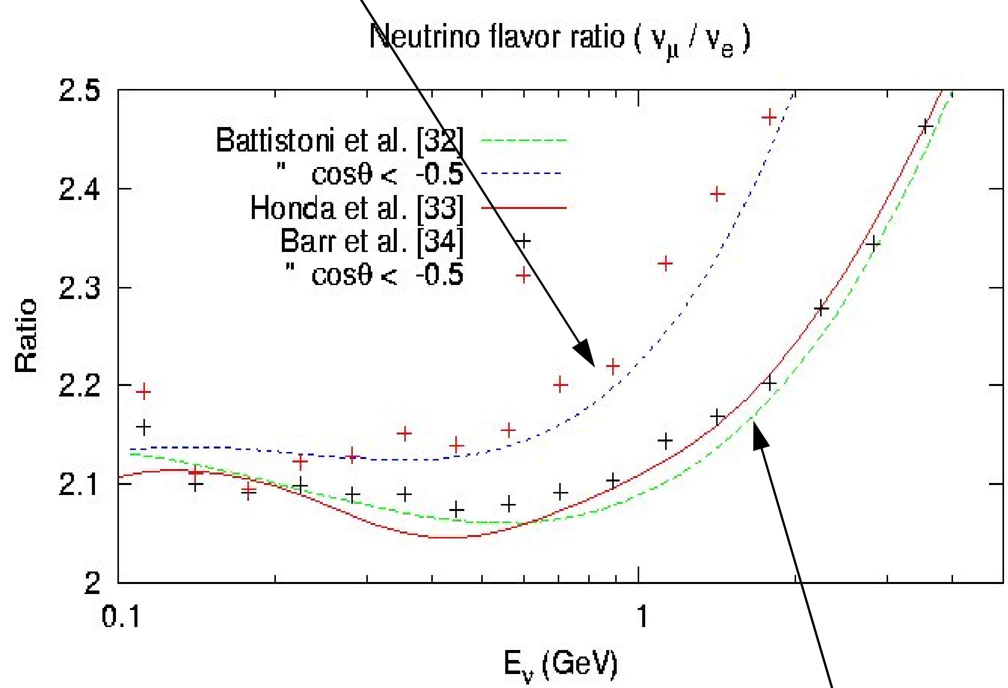


Flavor ratio at production

- uncertainties ~cancel in ratios (e.g. ν_μ/ν_e differences < 1.5 %)
- $r = \nu_\mu/\nu_e$ at production sets background for search for effects of solar & s_{13} mixing and the octant of θ_{23} e.g.,
- $N_e/N_e^{(0)} - 1 = P_2(r \cos^2\theta_{23} - 1)$

  Peres & Smirnov, 2004
- → 0 for r = 2, θ_{23}=45°
- $r_{sub\text{-}GeV}$ ~2.04 – 2.1
- r larger for vertically upward

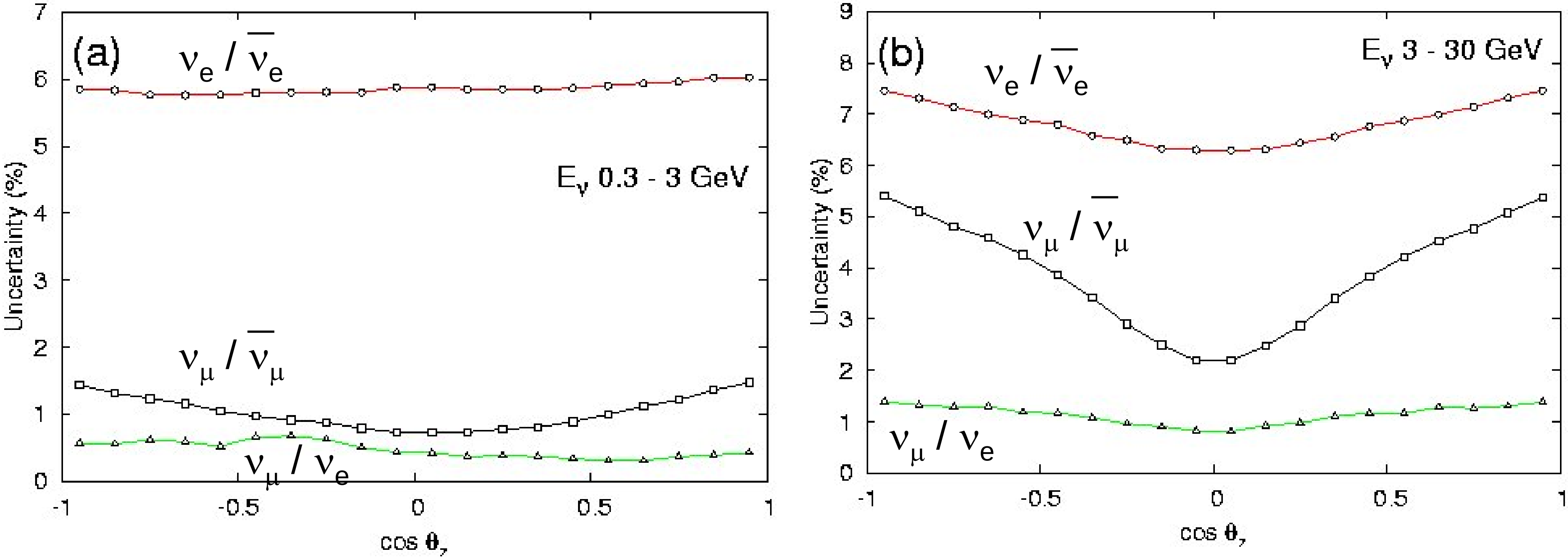
Near vertically up (cosθ < - 0.5)



All directions

Analysis of uncertainties in ratios

Barr et al.



New measurements in progress

HARP
E910
NA49
MIPP

For example:
New results from NA49
p C → $\pi^{+/-}$ X at 158 GeV/c
hep-ex/0606028

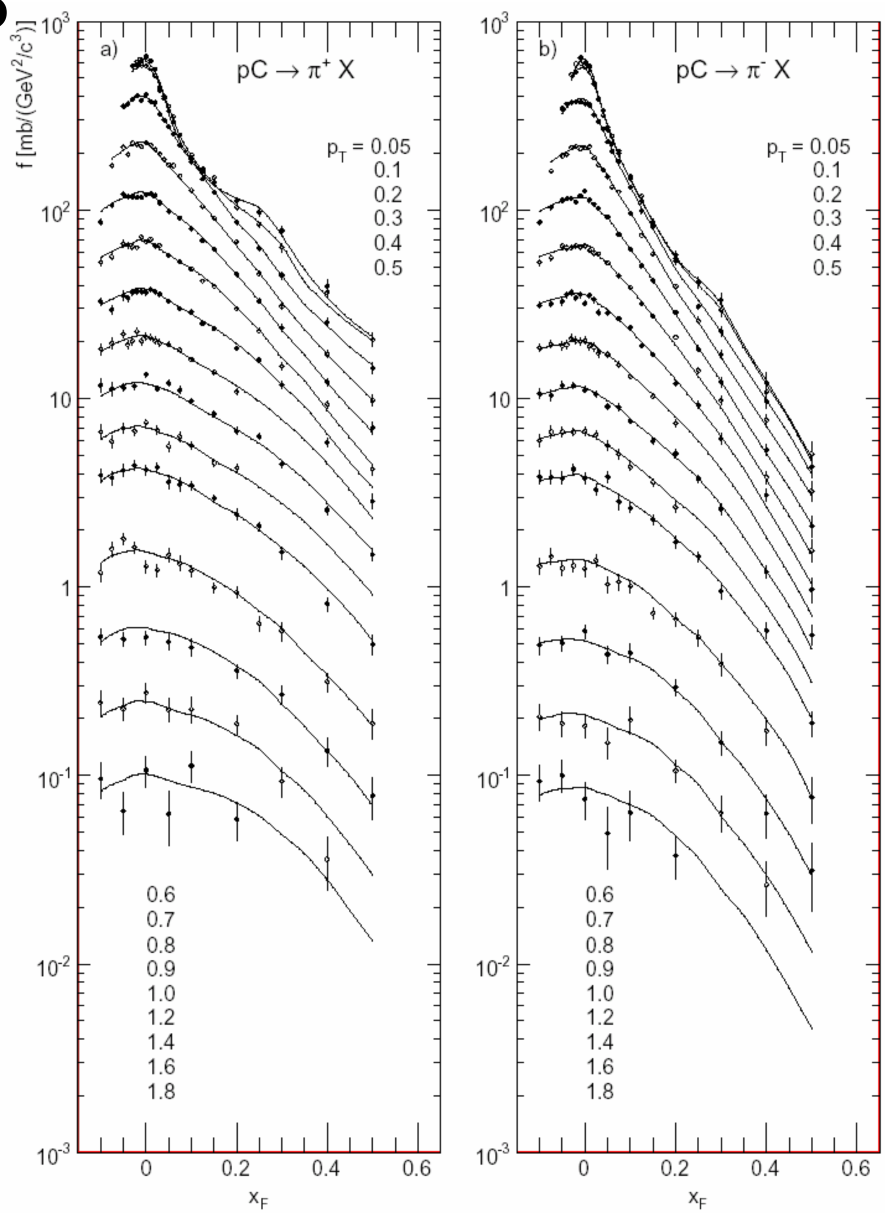


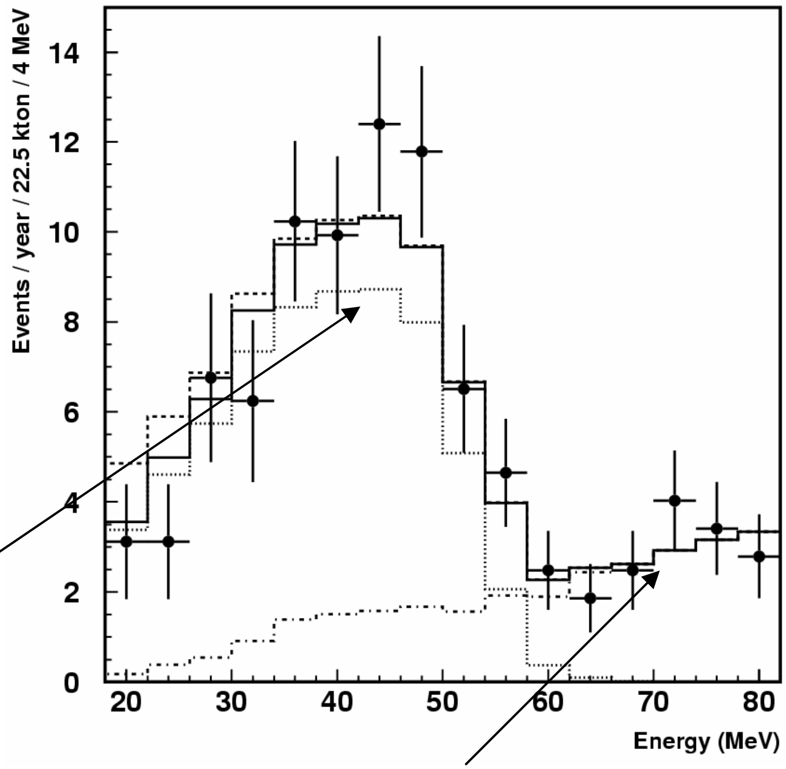
Figure 18: Invariant cross section as a function of x_F at fixed p_T for a) π^+ and b) π^- produced in p+C collisions at 158 GeV/c

Atmospheric neutrinos as background for astrophysical neutinos

- Some examples
  - Diffuse neutrinos from relic supernovae
    - anti-ν_e, 20-50 MeV
  - Neutrinos from WIMP annihilation
    - 10 -1000 GeV
    - directional source (e.g. Sun) above atmospheric background
  - High energy neutrinos
    - Talk of Gary Hill Monday

Diffuse, relic supernova neutrinos

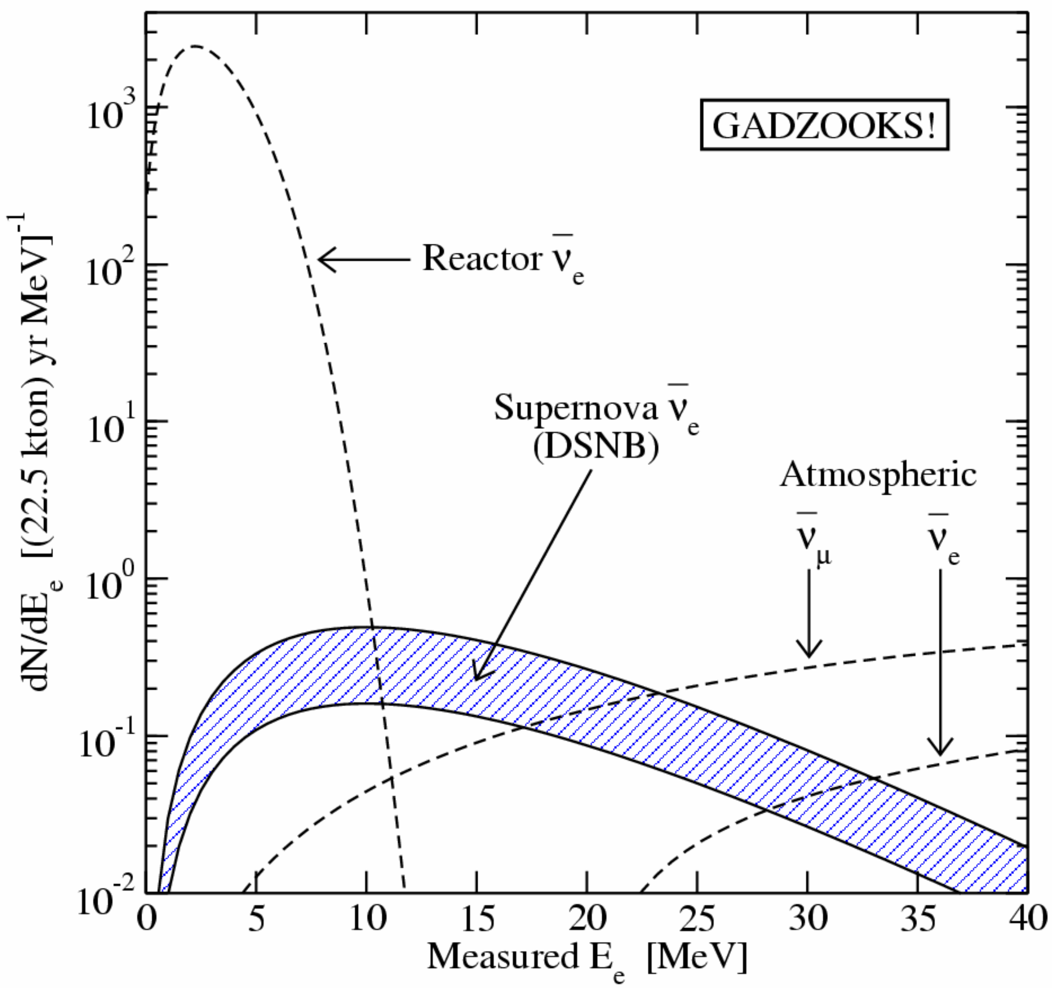
- Super-K limit is from $\bar{\nu}_e + p \rightarrow n + e^+$
- Neutron not detected in current Super-K
- Backgrounds:
  - atmospheric ν_e and $\bar{\nu}_e$
  - solar ν_e and reactor $\bar{\nu}_e$
  - atmospheric $\nu_\mu \rightarrow \mu$ (E_μ < 50 MeV)



Improvement with tagged neutron

Beacom & Vagins,
PRL 93 (2004) 171101

Prescribe gadolinium additive
to detect neutrons
and select anti-ν_e only

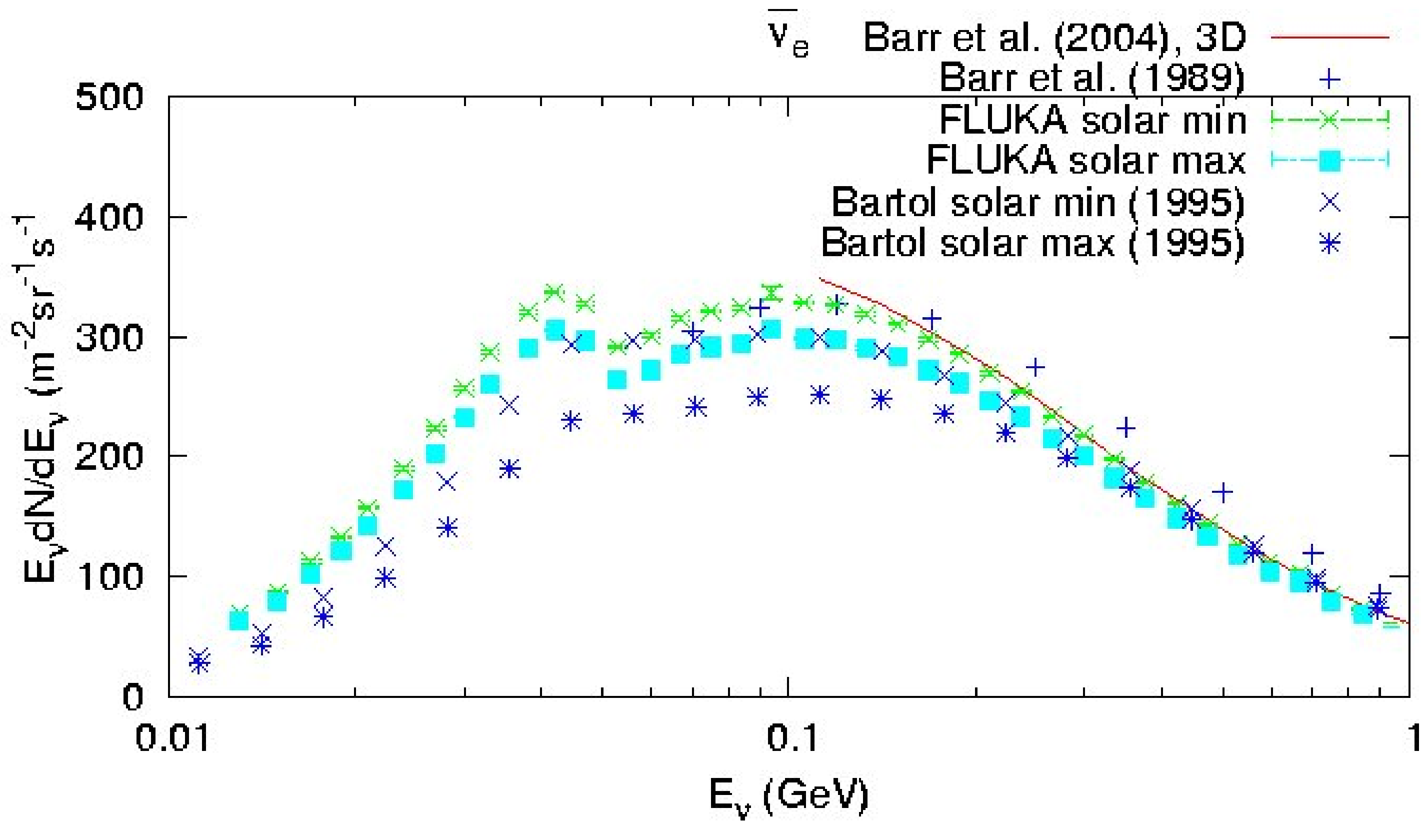


Calculations of anti-ν_e background 10-100 MeV

Note dependence on phase of solar cycle:

• 10 – 20% variation a signature of back-ground, not of signal

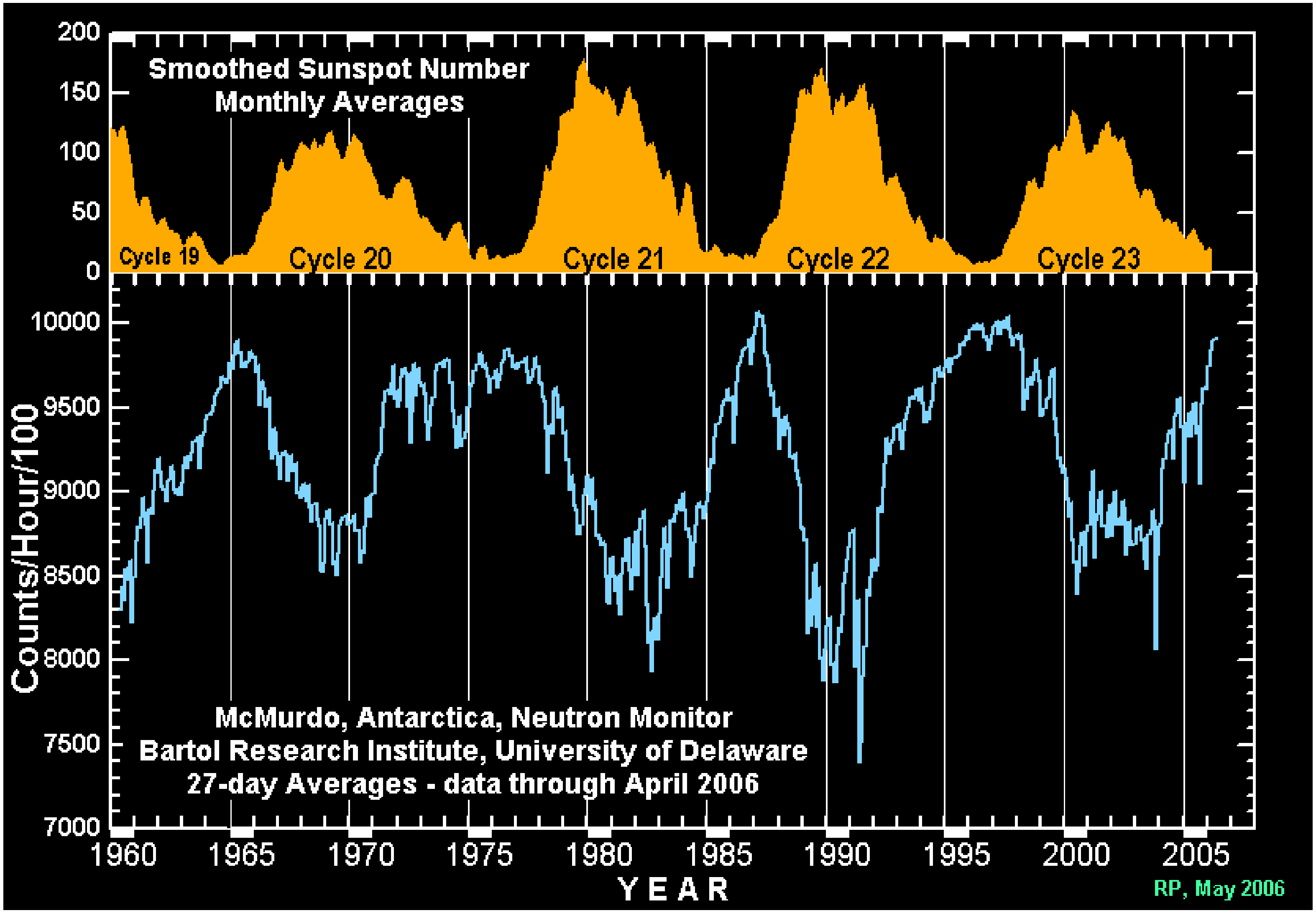
• similar to response of neutron monitors



FLUKA 10-100 MeV

Battistoni et al.(2004): http://www.mi.infn.it/~battist/neutrino.html

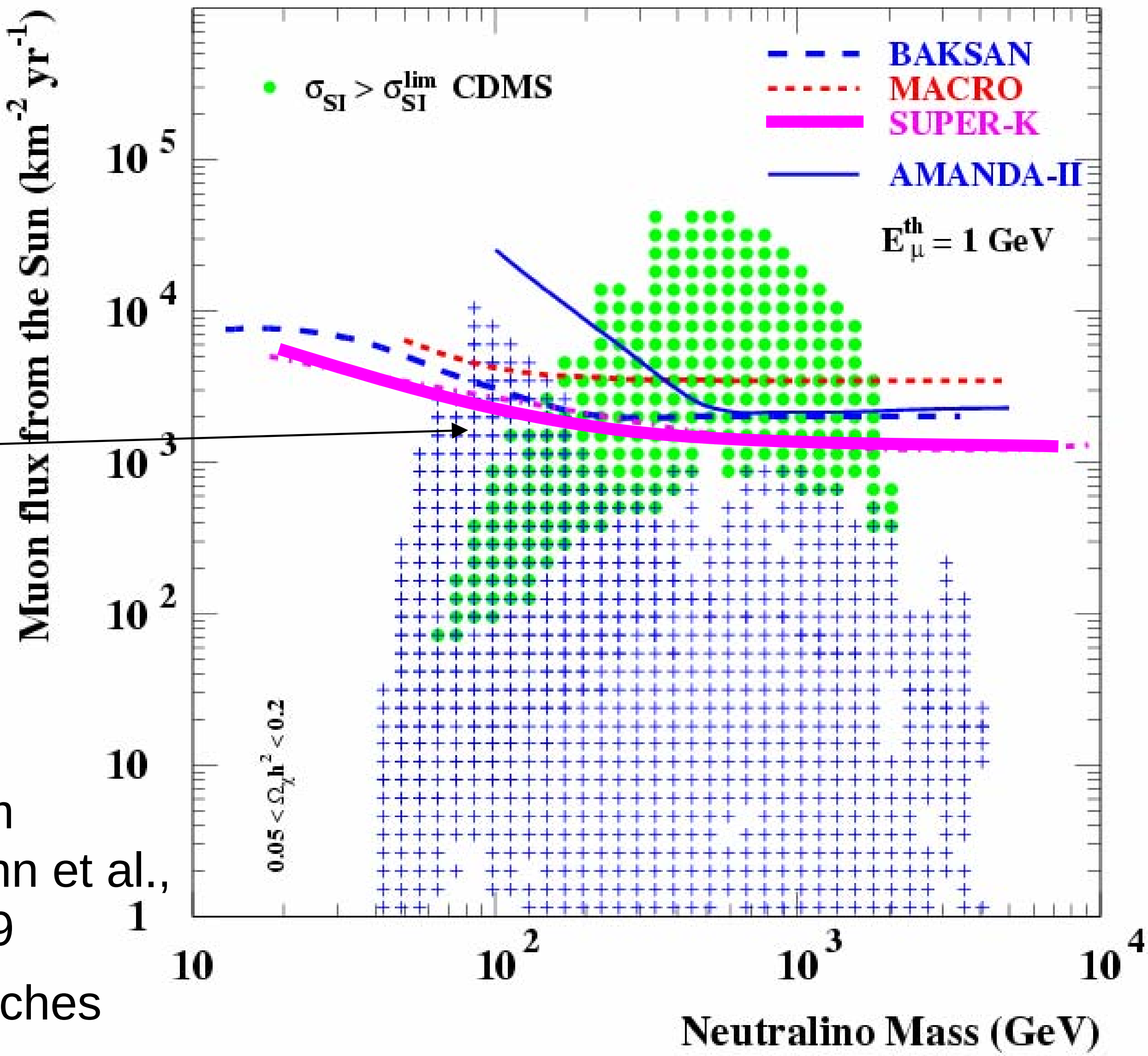
Variation with solar cycle



Indirect limits on WIMPs in Sun

From ν_μ-induced upward muons

~ 5 x 10^{-15} cm^{-2}s^{-1}



Summary of current limits from AMANDA paper, M. Ackermann et al., Astropart. Phys. 24 (2006) 459

• disfavored out by direct searches

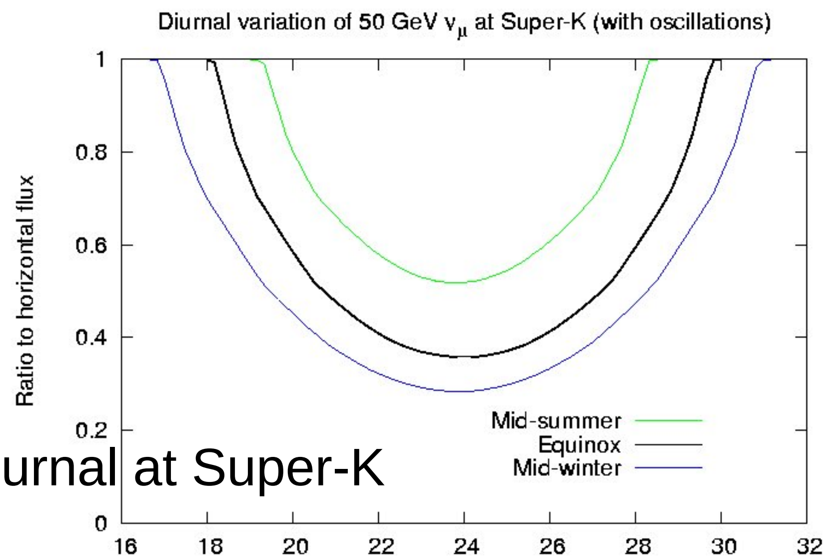
Time signature of background

Flux of atmospheric ν_μ

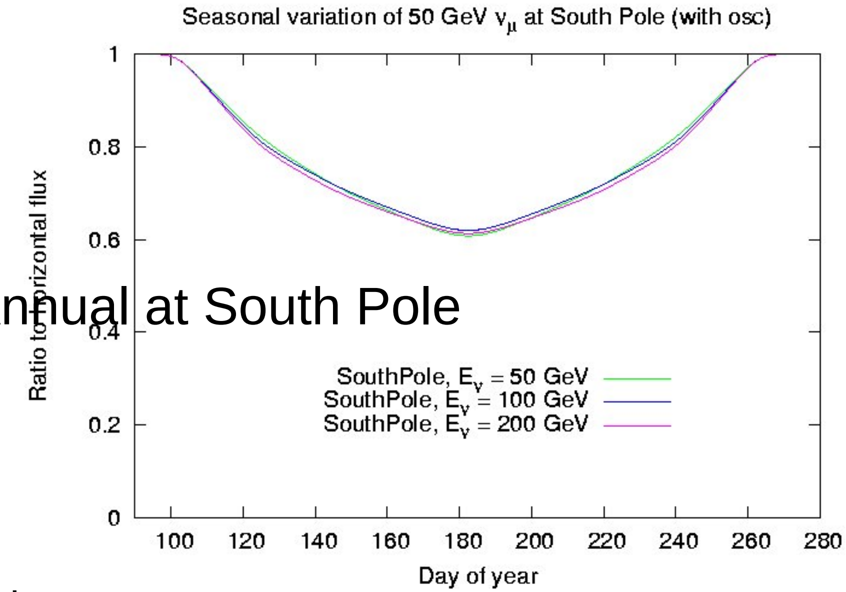
- higher from near horizon
- lower from near vertical
- parent mesons more likely to decay in less dense atmosphere

→Lowest from direction of sun at local midnight

→Possible signature to enhance sensitivity of search for WIMPs

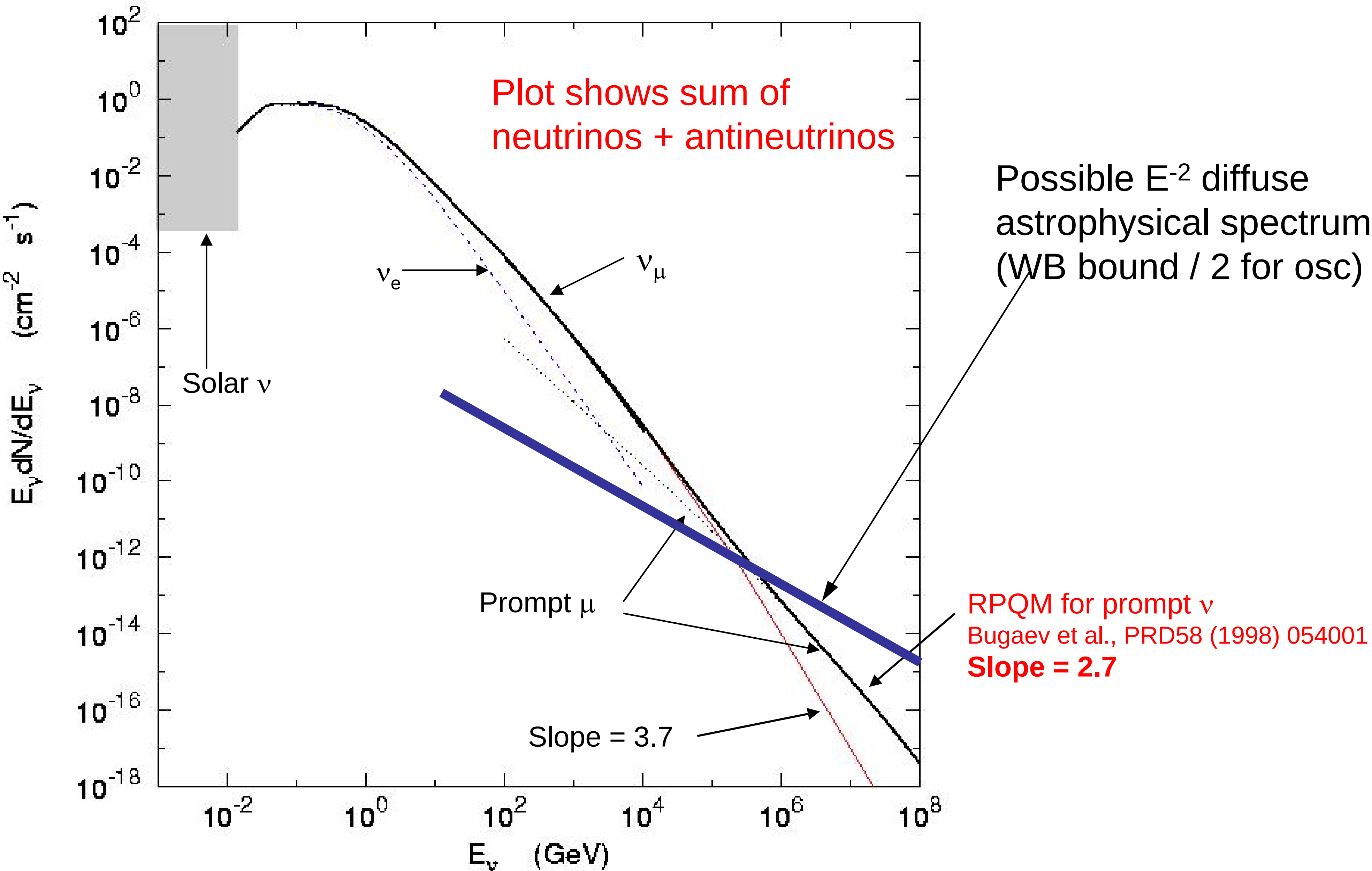


Diurnal at Super-K



Annual at South Pole

Global view of atmospheric ν spectrum



Concluding comments

- Uncertainty in calculated ν fluxes at production ($0.1 < E_\nu < 10$ GeV)
  - Calculations differ by ~10%
  - $\nu_\mu/\nu_e \sim 2.1$ for sub-GeV; differences < 2%
  - a priori estimate: uncertainty in $\nu_\mu/\nu_e \sim 1\%$
  - HARP, E910, NA49, MIPP → further reductions?
- Properties of atmospheric ν distinguish signal from background:
  - Known secular and directional variations
  - Low content of > TeV ν_e, ν_τ compared to
    - Astrophysical $\nu_\mu:\nu_e:\nu_\tau \sim 1:1:1$