Atmospheric Neutrinos

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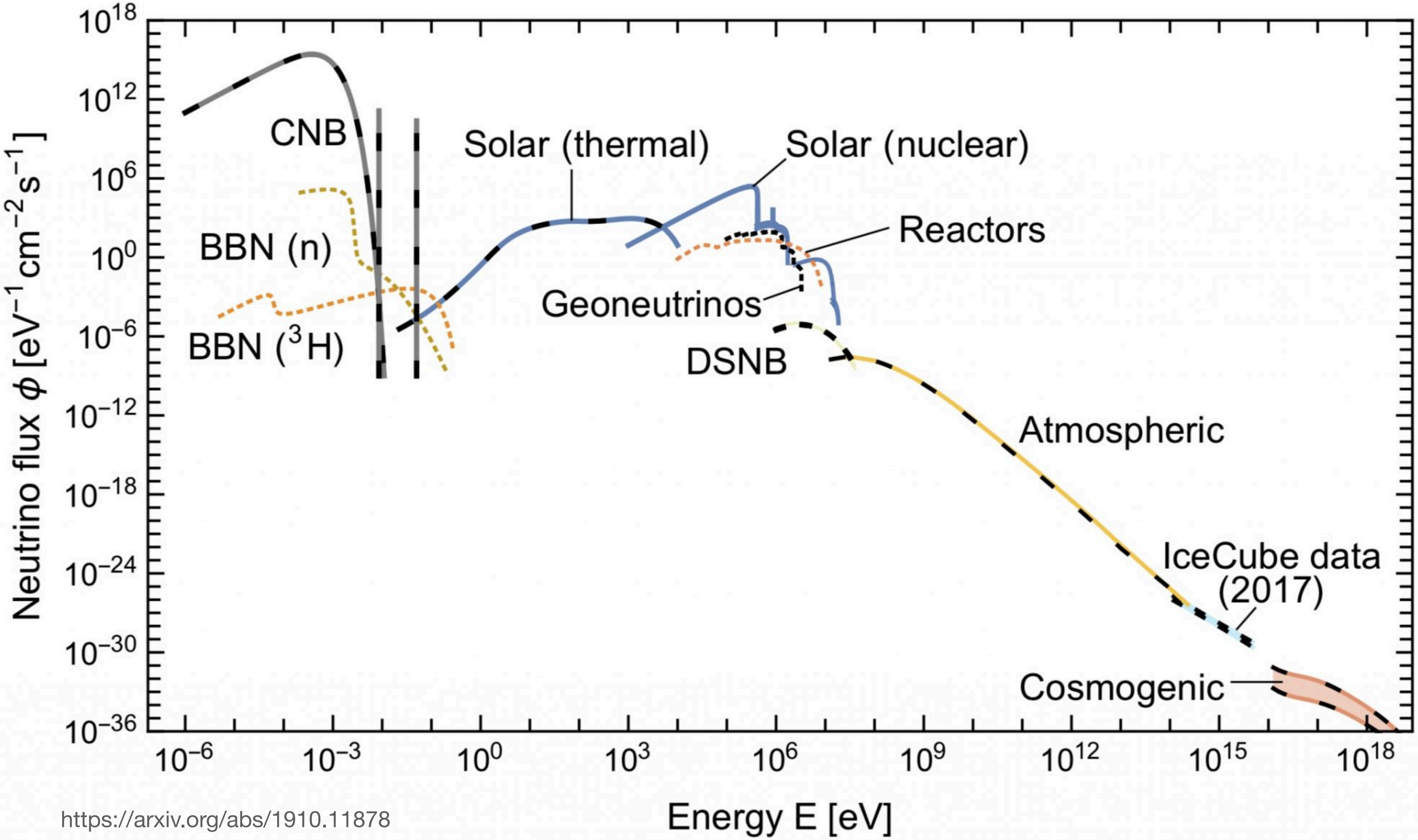
- Course webpage: https://blackboard.cuhk.edu.hk

The Grand Unified Neutrino Spectrum

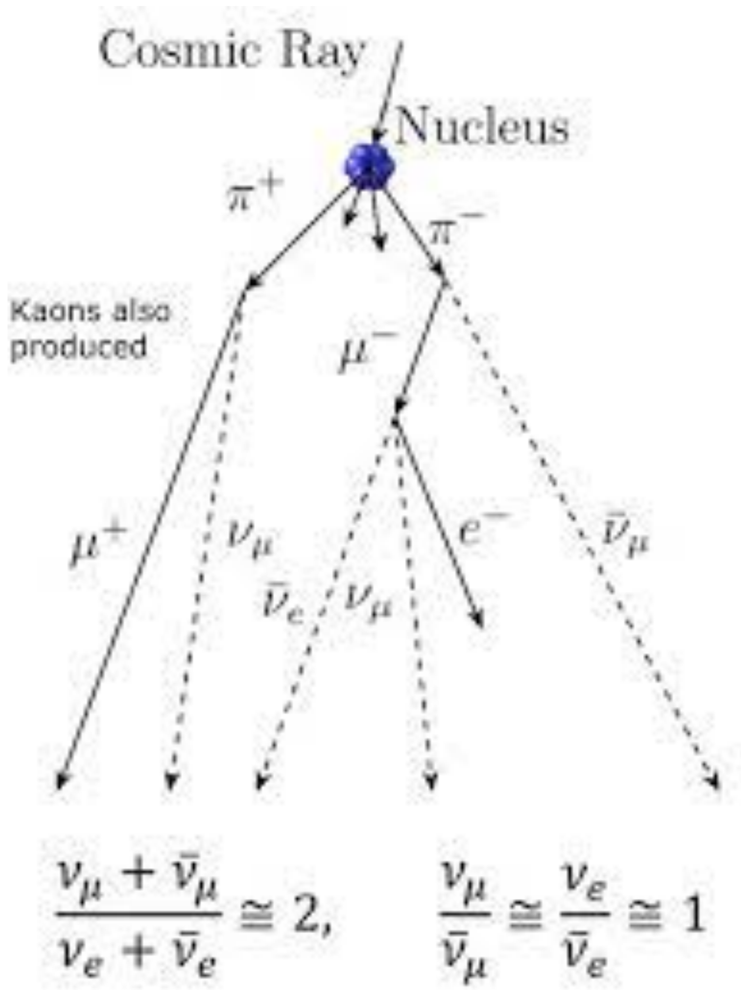


https://arxiv.org/abs/1910.11878

Atmospheric neutrinos

- Cosmic rays are everywhere
- They can hit the Earth atmosphere

- (CR, Proton)+ (Atmosphere, nitrogens, etc)
- Hadronic interactions
  - Pions
  - Charged pions -> Neutrinos
  - If π^+ and π^- are equally produced
  - Then we should roughly expect $\nu_\mu : \nu_e = 2 : 1$
  - Antineutrino: neutrino = 1:1



ATM theory

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Atmospheric neutrino flux calculation using the NRLMSISE00 atmospheric model

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(Dated: May 27, 2015)

$$\begin{aligned} \pi^{\pm} \to\ & \mu^{\pm} + \nu_\mu(\overline{\nu}_\mu) \\ & \searrow \\ & \quad e^{\pm} + \nu_e(\overline{\nu}_e) + \overline{\nu}_\mu(\nu_\mu), \end{aligned}$$

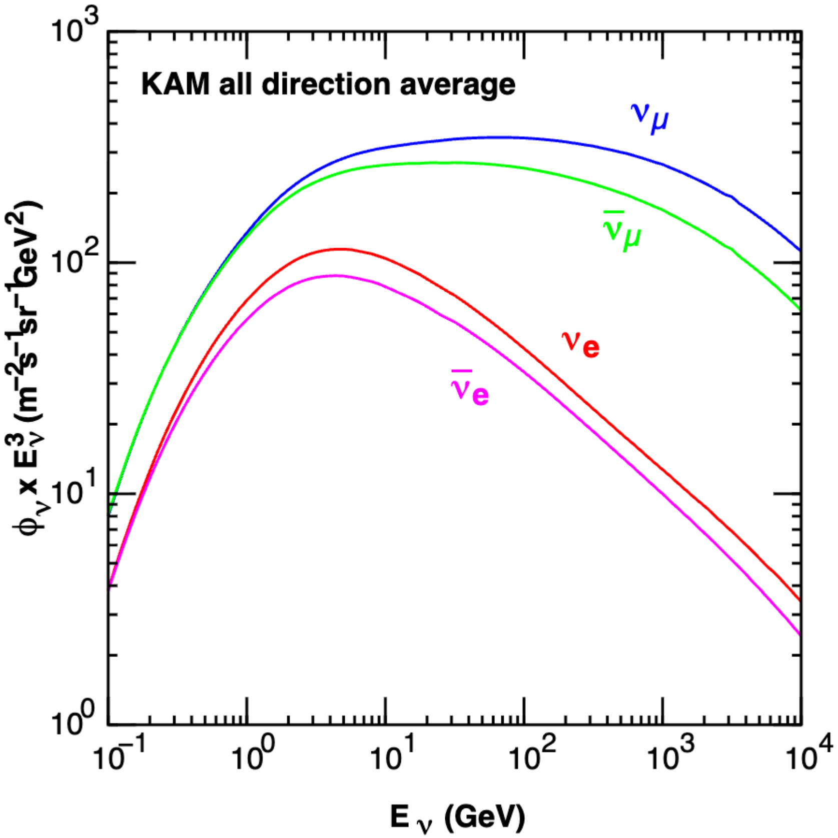
ATM theory

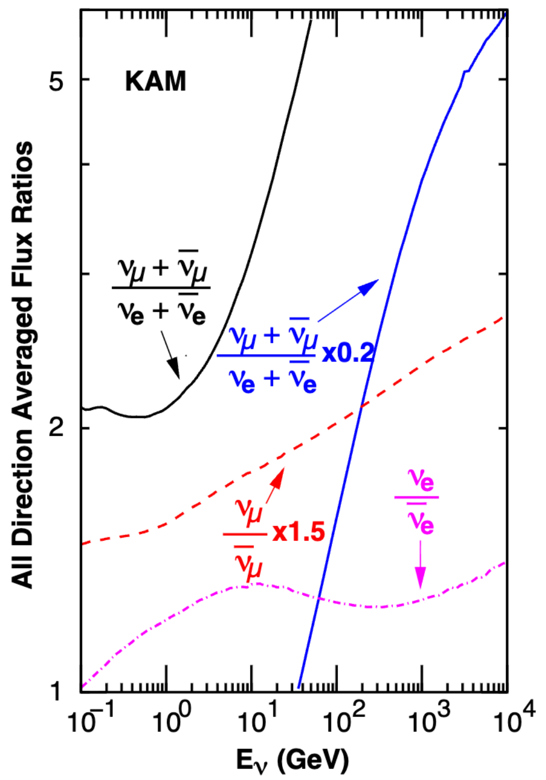
- Actual theory calculation

- $10^0 - 10^2$ GeV, E^{-3} for Mu
neutrinos, then softens

- Electron neutrinos softens even faster

- (Naive expectation would be the primary cosmic-ray spectrum $E^{-2.7}$)
    - Then we should roughly expect $\nu_\mu : \nu_e = 2:1$
    - Antineutrino: neutrino = 1:1





Clearly not what we expect!!!

Side note on pion decay

- Charged pion decay to a muon and muon-neutrino
- It also decays into electron and electron-neutrino but with 0.01% probability.
- To understand this, first remember that only “left-handed” neutrinos participates in the weak interaction

$$\pi^+ \xrightarrow{26\text{ ns}} \mu^+ + \nu_\mu$$

Improved Measurement of the $\pi \to e\nu$ Branching Ratio

PDF

Share

A. Aguilar-Arevalo[1], M. Aoki[2], M. Blecher[3], D. I. Britton[4], D. A. Bryman[5], D. vom Bruch[5], S. Chen[6], J. Comfort[7], M. Ding[6] *et al.*
(PIENU Collaboration)

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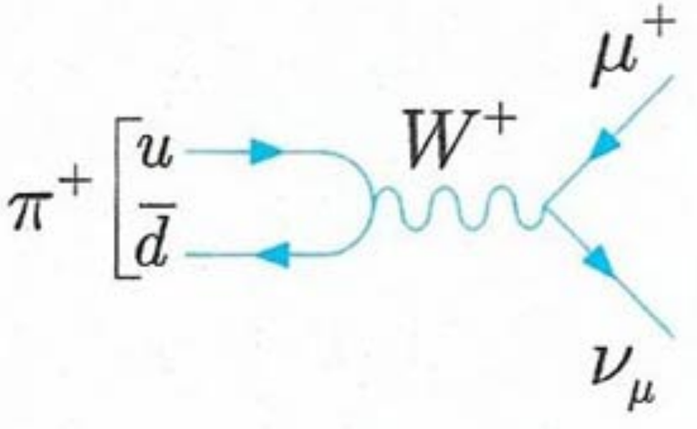
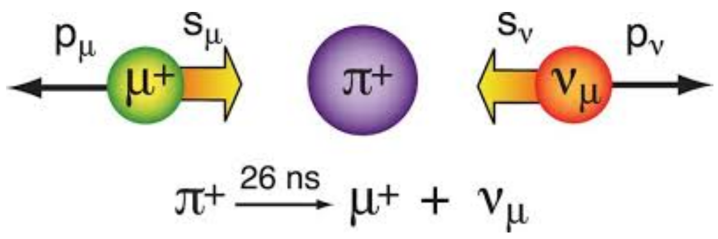
Abstract

A new measurement of the branching ratio $R_{e/\mu} = \Gamma(\pi^+ \to e^+\nu + \pi^+ \to e^+\nu\gamma)/\Gamma(\pi^+ \to \mu^+\nu + \pi^+ \to \mu^+\nu\gamma)$ resulted in $R^{\text{exp}}_{e/\mu} = [1.2344 \pm 0.0023(\text{stat}) \pm 0.0019(\text{syst})] \times 10^{-4}$. This is in agreement with the standard model prediction and improves the test of electron-muon universality to the level of 0.1%.



Side note on pion decay



- To understand this, first remember that only “left-handed” neutrinos participates in the weak interaction

- Introduce a new concept “helicity” which is $\vec{s} \cdot \vec{p}$
    - Turns out helicity = chirality when the particles are massless (Left = -1)
    - Remember this, by observing the helicity is NOT Lorentz invariant in massive case.
        - You can boost to a frame to flip the sign of momentum.
    - Chirality is Lorentz invariant (physics is Lorentz invariant)

- For Pion+ decay (Spin-0) at rest, conservation of angular momentum mean they must have opposite spin, and thus Helicity.
- So, a Negative helicity neutrino (~ left-handed), and a negative helicity anti-muon (~ left-handed)
- Luckily, the anti-muon is only (~ left-handed), so decay is still possible.
    - The larger the mass, the more deviation of Chirality from Helicity, so muon has much higher branching fraction than electrons.
    - The electron channel can also be called helicity suppressed.

$$\frac{\Gamma(\pi^+ \to e^+\nu_\mu)}{\Gamma(\pi^+ \to \mu^+\nu_\mu)} = \left(\frac{m_e^2}{m_\mu^2}\right)\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right) = 1.275 \cdot 10^{-4} \qquad (1.230 \pm 0.004) \cdot 10^{-4}{}_{PDG}$$

ATM theory

- How to calculate ATM neutrinos
- Conceptually, the method is identical to cosmic-ray propagation. Difference are
  - Optical thick regime (cascade/shower)
  - No diffusion
  - Time evolution ($\frac{d}{dt}$) -> distance evolution ($\frac{d}{dx}$)
  - 3D in modern calculations
  -

$$\pi^{\pm} \to \mu^{\pm} + \nu_\mu(\overline{\nu}_\mu)$$
$$\searrow$$
$$e^{\pm} + \nu_e(\overline{\nu}_e) + \overline{\nu}_\mu(\nu_\mu),$$

A. Coupled cascade equations

The equations describe the evolution of the differential flux, defined as the differential of the particle flux ϕ with respect to energy per unit area, unit solid angle, and time

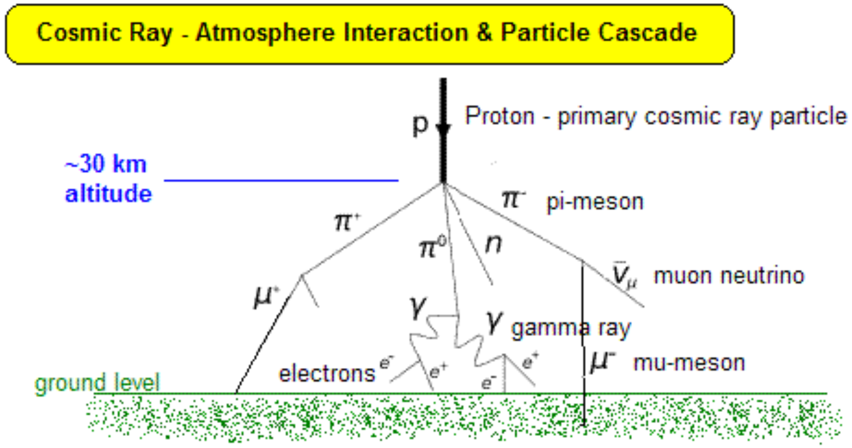
$$\Phi = \frac{\mathrm{d}\phi}{\mathrm{d}E} = \frac{\mathrm{d}N}{\mathrm{d}E\,\mathrm{d}A\,\mathrm{d}\Omega\,\mathrm{d}t}. \tag{2}$$

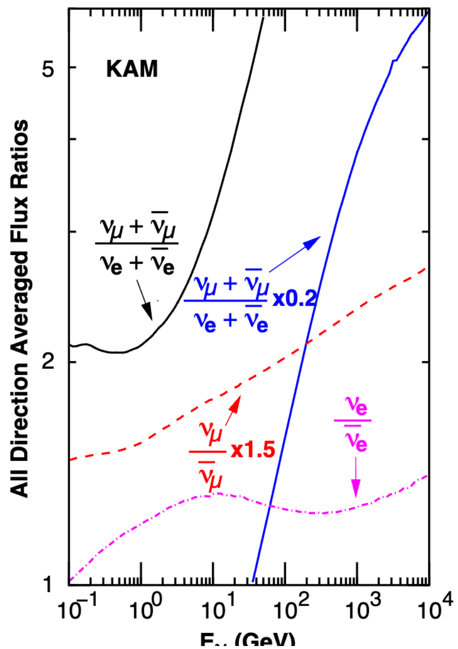
The coupled cascade equations

$$\begin{aligned}\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = &-\frac{\Phi_h(E,X)}{\lambda_{\mathrm{int},h}(E)} - \frac{\Phi_h(E,X)}{\lambda_{\mathrm{dec},h}(E,X)} \\ &- \frac{\partial}{\partial E}(\mu(E)\Phi_h(E,X)) \\ &+ \sum_\ell \int_E^\infty \mathrm{d}E_\ell \frac{\mathrm{d}N_{\ell(E_\ell)\to h(E)}}{\mathrm{d}E} \frac{\Phi_\ell(E_\ell,X)}{\lambda_{\mathrm{int},l}(E_\ell)} \\ &+ \sum_\ell \int_E^\infty \mathrm{d}E_\ell \frac{\mathrm{d}N^{\mathrm{dec}}_{\ell(E_\ell)\to h(E)}}{\mathrm{d}E} \frac{\Phi_\ell(E_\ell,X)}{\lambda_{\mathrm{dec},l}(E_\ell,X)},\end{aligned} \tag{3}$$

ATM theory

- All are known physics
- So, given the cosmic-ray flux at the top of the atmosphere, we should understand everything that goes on with atm flux.
- 1) Why electron neutrino flux are more suppressed.
- Muon decay life time = 2.2 micro second.
- $c\tau =$ 660m
- If the typical interaction altitude is about 30km
- Then a muon of γ factor about 50, would hit the ground before decaying
- γm ~ 5 GeV.





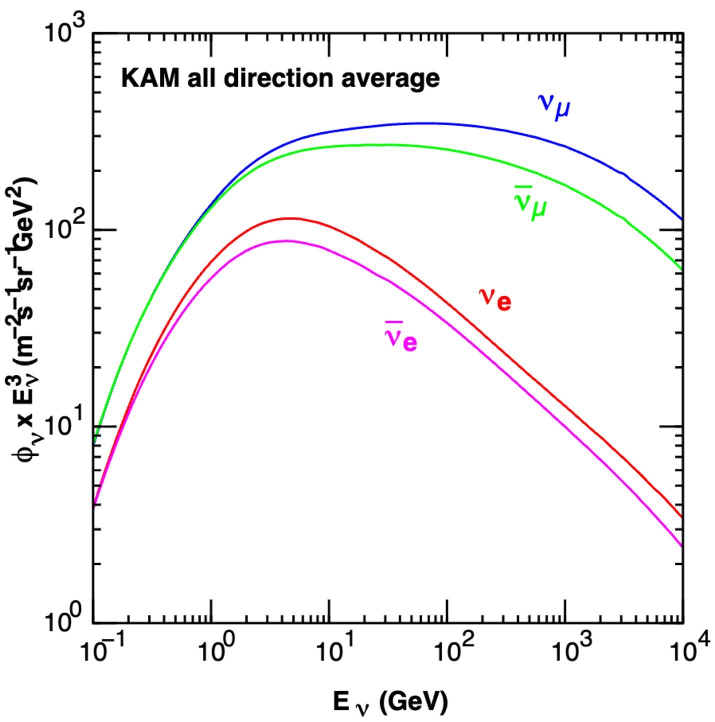
ATM theory

Properties of kaons

Particle name	Particle symbol	Antiparticle symbol	Quark content	Rest mass [MeV/c^2]	I^G	J^{PC}	S	C	B'	Mean lifetime [s]	Commonly decays to (> 5% of decays)
Kaon[1]	K^+	K^-	$u\bar{s}$	493.677 ± 0.016	$\frac{1}{2}$	0^-	1	0	0	$(1.2380 \pm 0.0020) \times 10^{-8}$	$\mu^+ + \nu_\mu$ or $\pi^+ + \pi^0$ or $\pi^+ + \pi^+ + \pi^-$ or $\pi^0 + e^+ + \nu_e$
K-short[3]	K^0_S	self	$\frac{d\bar{s} - s\bar{d}}{\sqrt{2}}$ [†][4][5]	497.611 ± 0.013[‡]	$\frac{1}{2}$	0^-	[*]	0	0	$(8.954 \pm 0.004) \times 10^{-11}$	$\pi^+ + \pi^-$ or $\pi^0 + \pi^0$
K-long[6]	K^0_L	self	$\frac{d\bar{s} + s\bar{d}}{\sqrt{2}}$ [†][4][5]	497.611 ± 0.013[‡]	$\frac{1}{2}$	0^-	[*]	0	0	$(5.116 \pm 0.021) \times 10^{-8}$	$\pi^\pm + e^\mp + \nu_e$ or $\pi^\pm + \mu^\mp + \nu_\mu$ or $\pi^0 + \pi^0 + \pi^0$ or $\pi^+ + \pi^0 + \pi^-$

- The contribution of Kaons
- Meson that contains a strange quark
- Critical energy, above that interaction > decay
  - Pions: 115 GeV
  - Kaons: 850 GeV
- Above ~ 850 GeV, mesons re-interact more than decay

- This is why the nu-mu spectrum softens again above TeV



ATM theory

- Angular distribution of atmospheric neutrinos
- Two extremely cases
  - a) Isotropic emitter in the shell
    - A collection of stars
  - b) blackbody emitter in the shell $\dfrac{dL}{dA} \propto \cos\theta_e$
    - The case of a cavity, isotropic at the observer

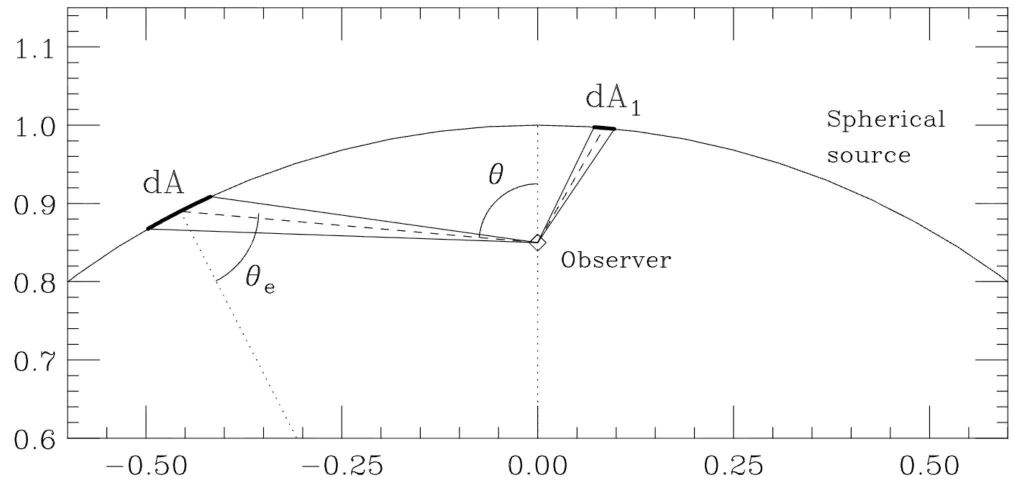
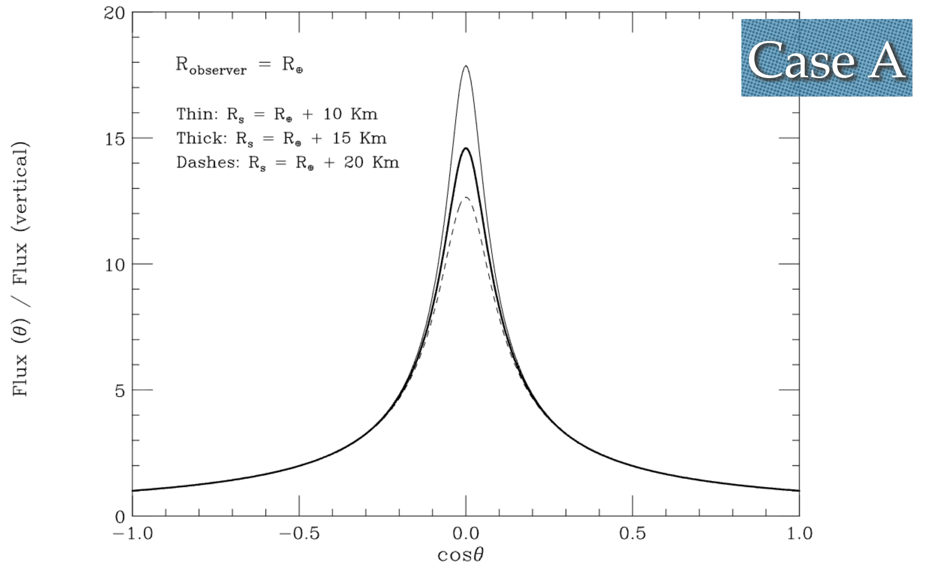


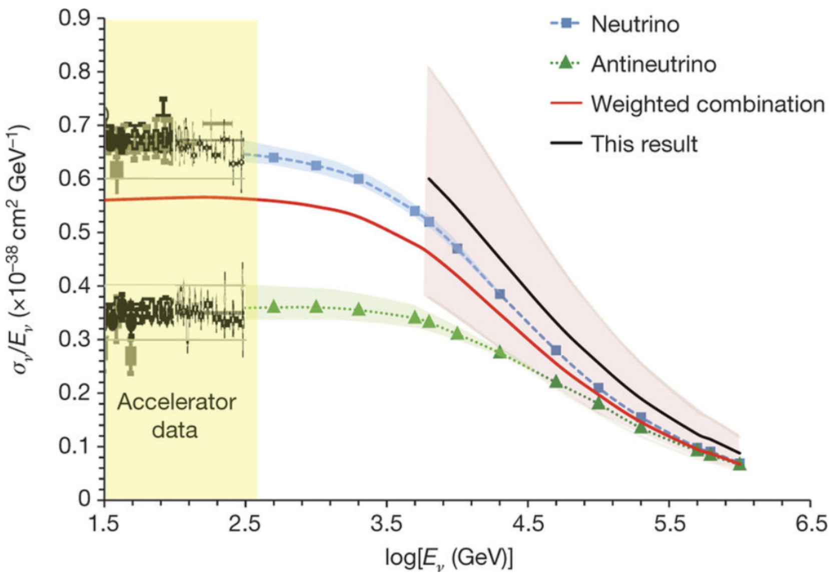
Figure 2: Geometry of the emission from a thin spherical shell with the observer located inside the shell.

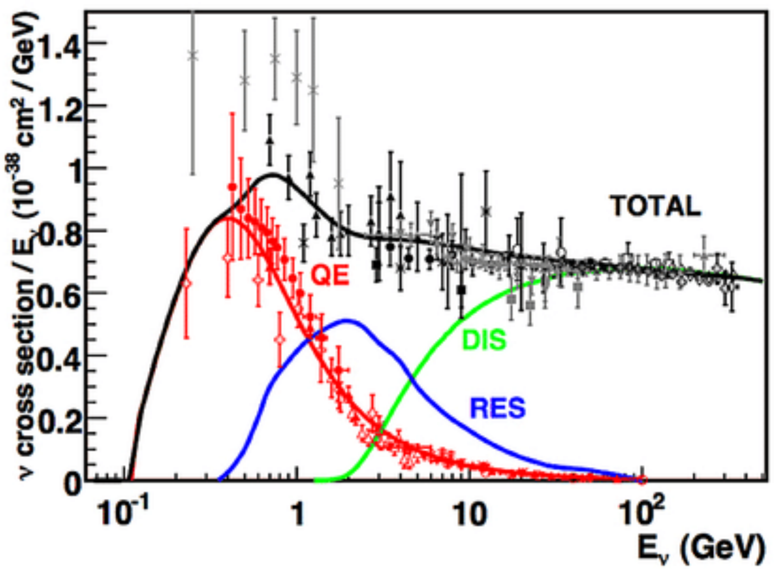


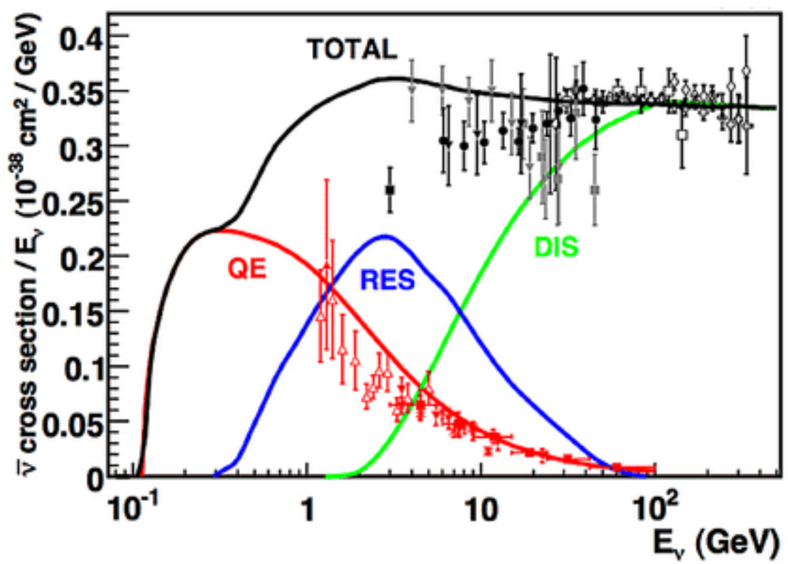
Atmospheric neutrinos are in-between the two cases
But they are always symmetric wrt horizon!

ATM theory

- Atmospheric neutrino interactions
- Quasielastic scattering
- Resonant scattering
- Deep Inelastic scattering







ATM theory

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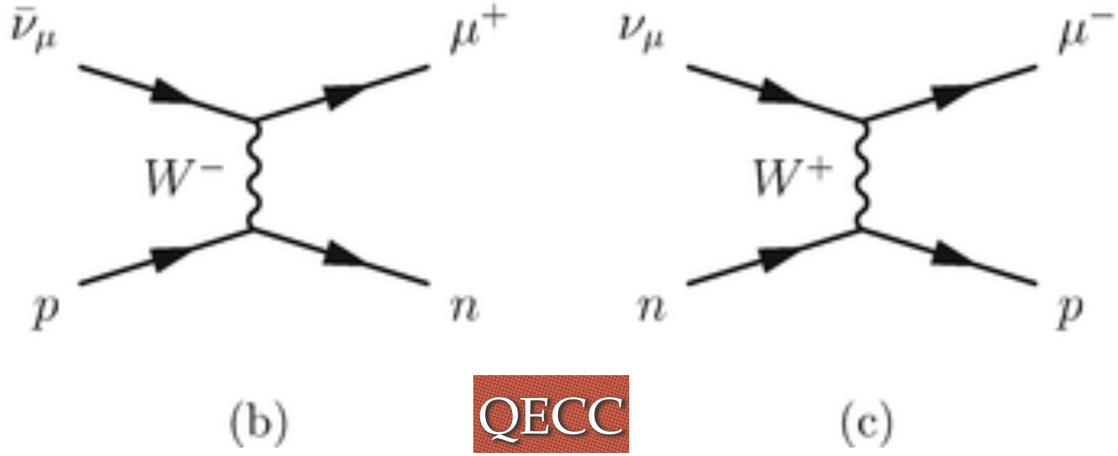
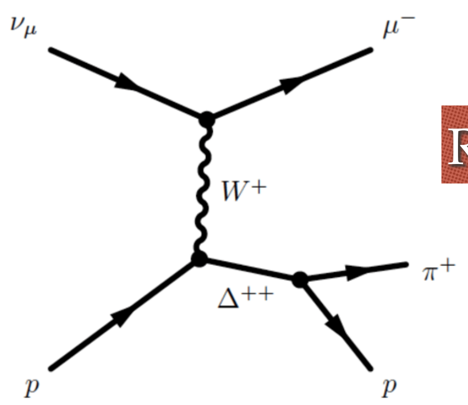


QECC

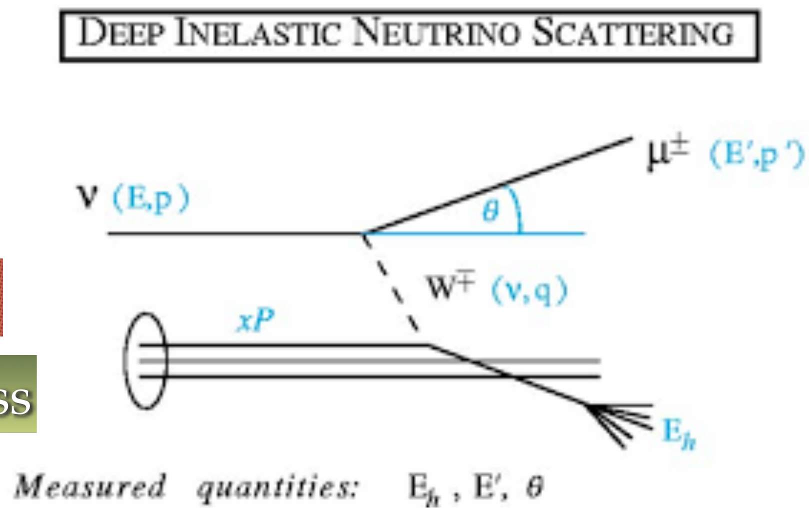


Resonant production

Producing pions, etc

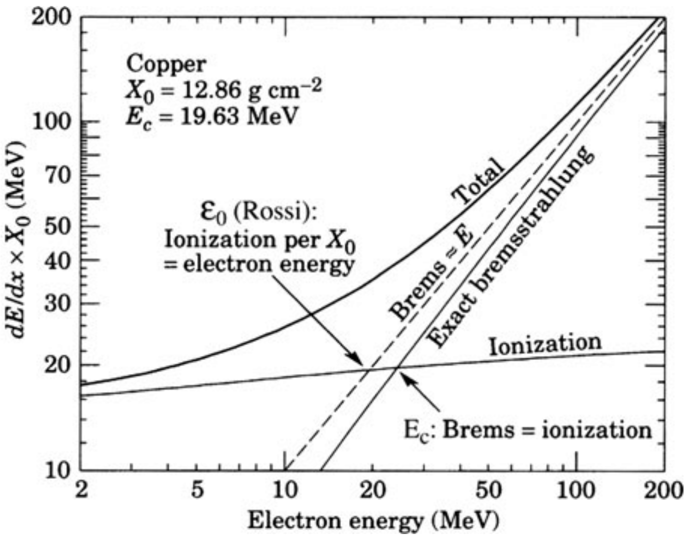
Deep Inelastic

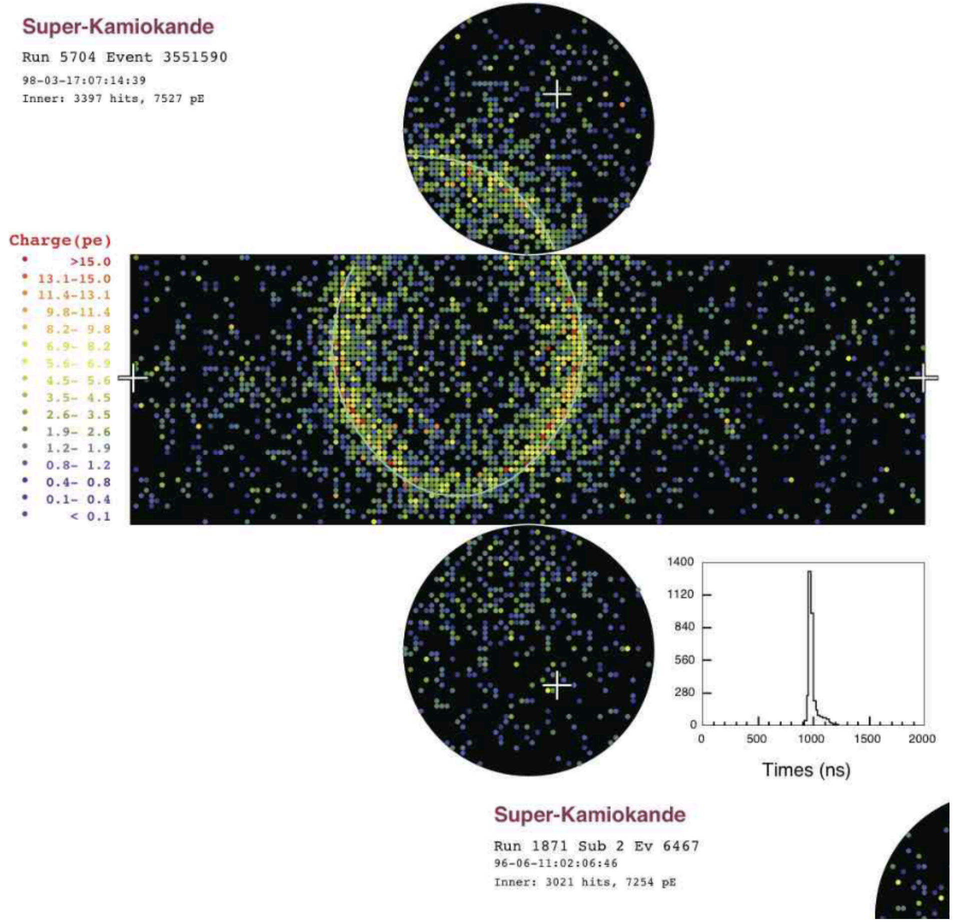
Producing a mess



ATM observation
Electron and muon like events

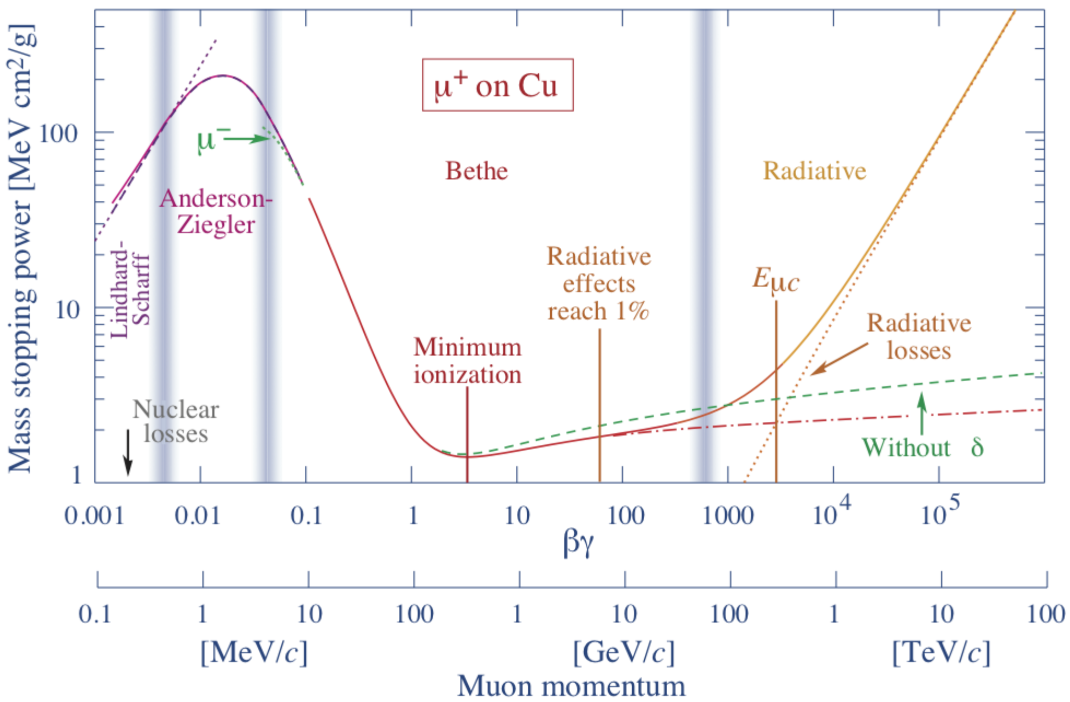
- Election like events, **fuzzy rings.**
  - Due to electromagnetic shower initiated by the electron
    - More than 1 electrons

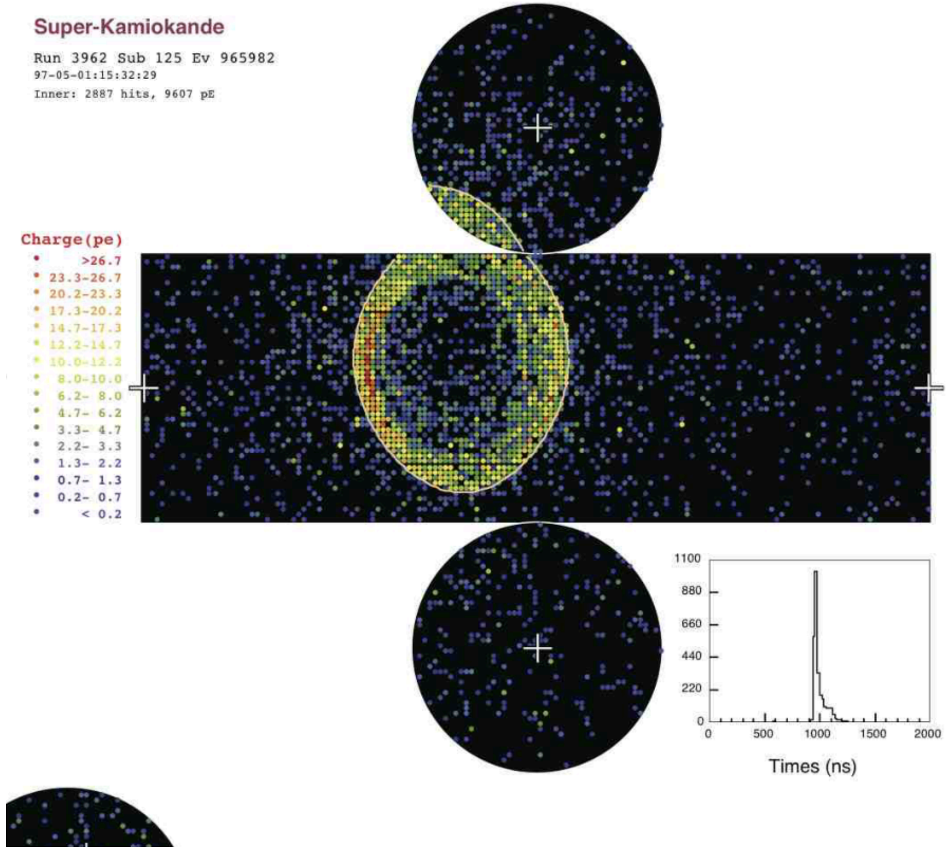




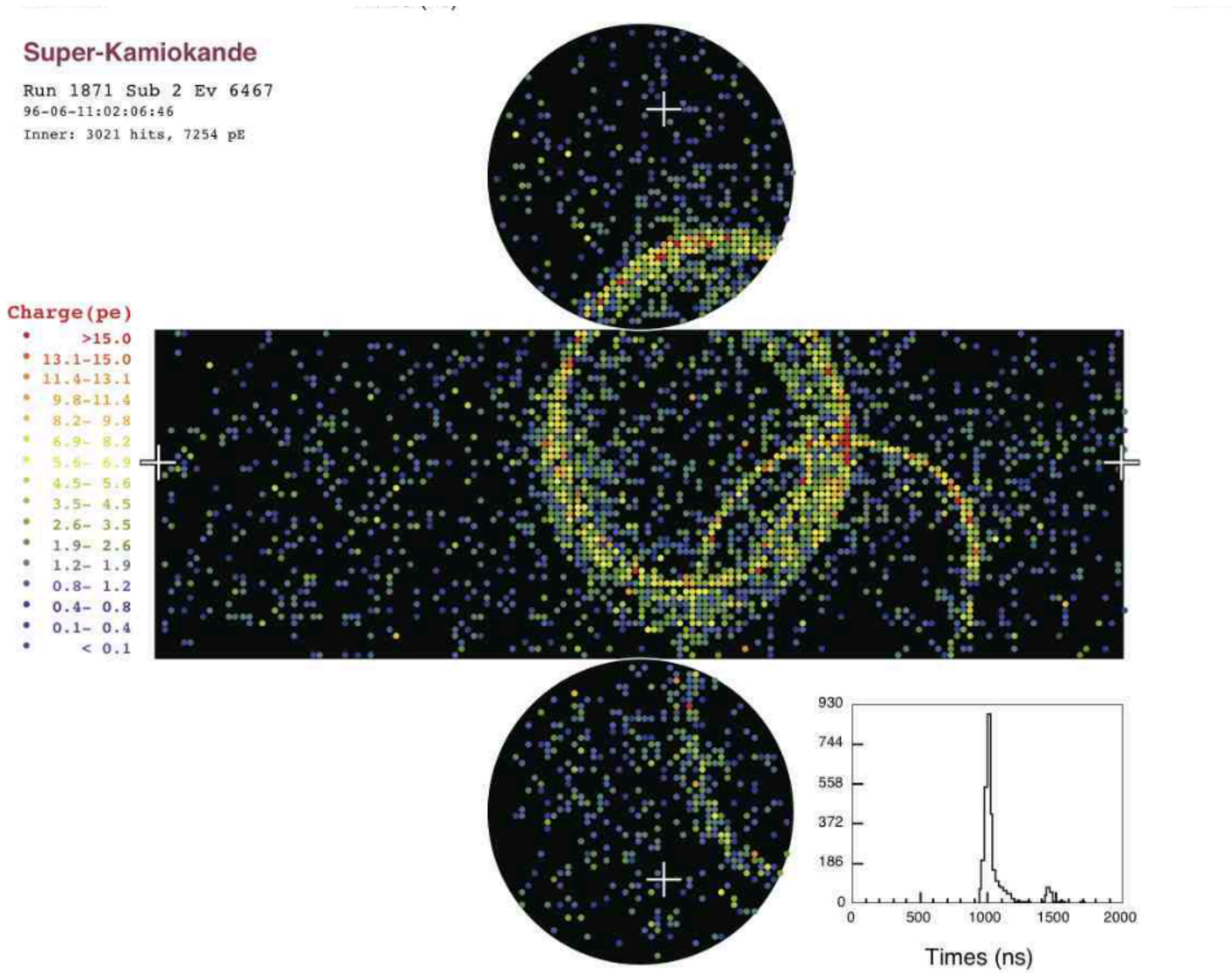
ATM observation
Electron and muon like events

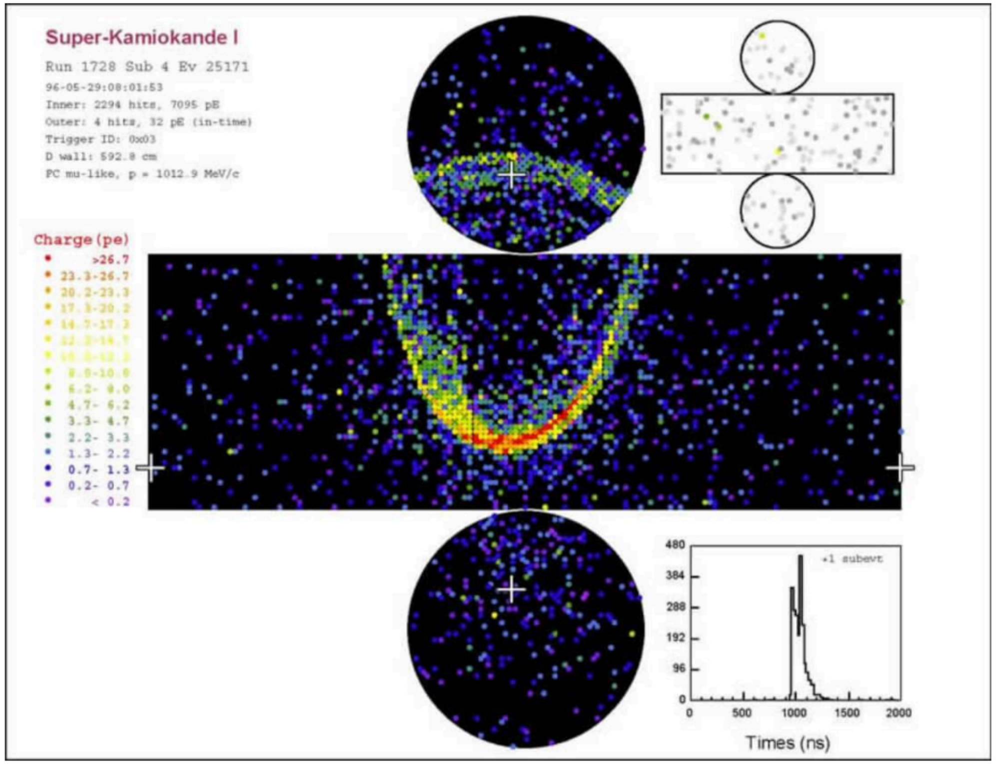
- Muon like events, **clean rings**
  - Muon energy loss is dominated by ionisation

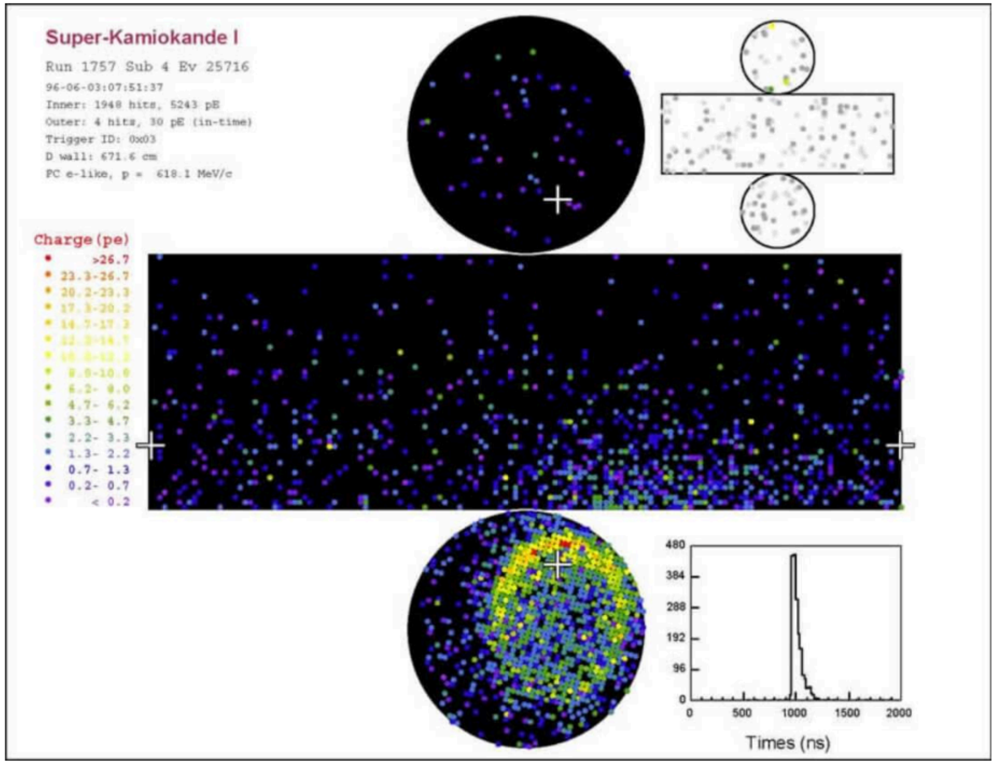




Multiple muon rings




Super-Kamiokande I
Run 1728 Sub 4 Ev 25171
96-05-29:08:01:53
Inner: 2294 hits, 7095 pE
Outer: 4 hits, 32 pE (in-time)
Trigger ID: 0x03
D wall: 592.8 cm
PC mu-like, p = 1012.9 MeV/c
Charge (pe)
>26.7
23.3-26.7
20.2-23.3
17.3-20.2
14.7-17.3
12.2-14.7
10.0-12.2
8.0-10.0
6.2- 8.0
4.7- 6.2
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2
+1 subevt
480
384
288
192
96
0
0
500
1000
1500
2000
Times (ns)


Super-Kamiokande I
Run 1757 Sub 4 Ev 25716
96-06-03:07:51:37
Inner: 1948 hits, 5243 pE
Outer: 4 hits, 30 pE (in-time)
Trigger ID: 0x03
D wall: 671.6 cm
PC e-like, p = 618.1 MeV/c
Charge (pe)
>26.7
23.3-26.7
20.2-23.3
17.3-20.2
14.7-17.3
12.2-14.7
10.0-12.2
8.0-10.0
6.2- 8.0
4.7- 6.2
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2
480
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Times (ns)

ATM observation
Angular distribution

VOLUME 81, NUMBER 8 PHYSICAL REVIEW LETTERS 24 AUGUST 1998

Evidence for Oscillation of Atmospheric Neutrinos

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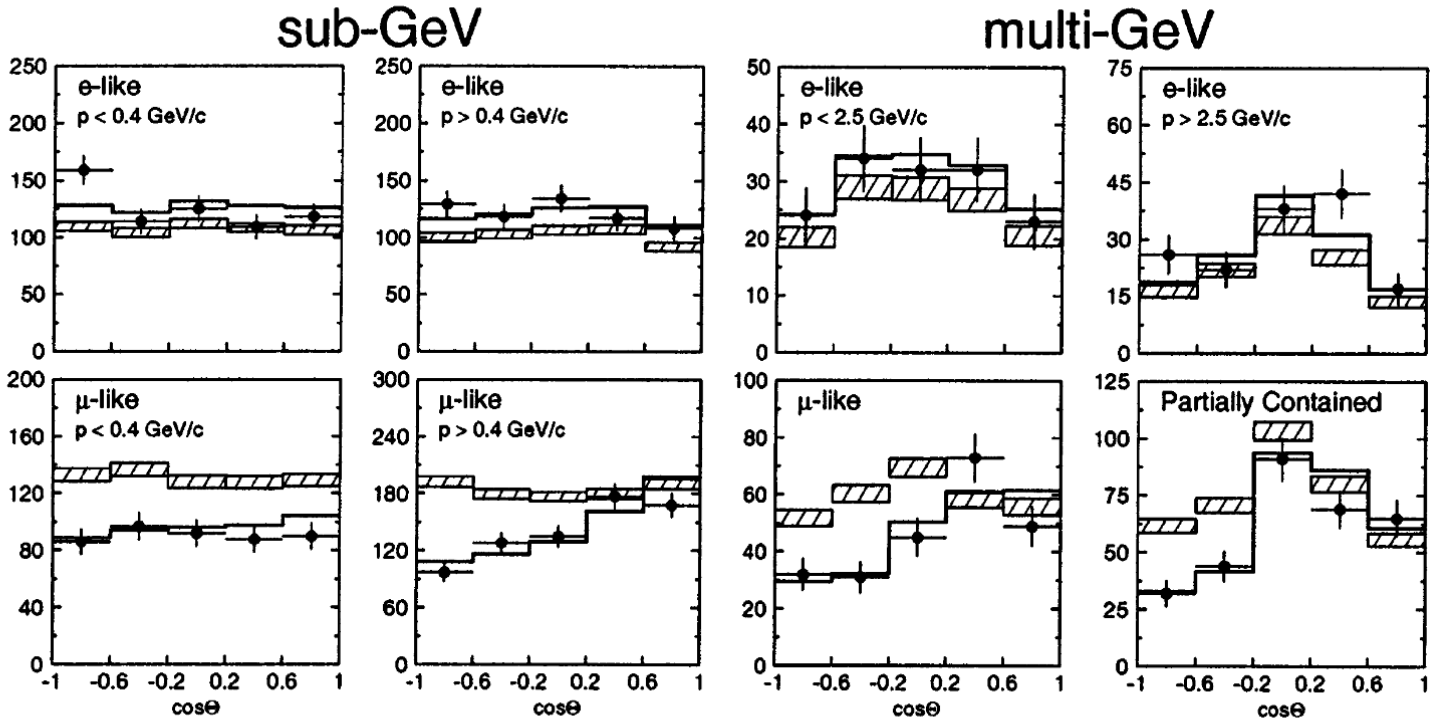
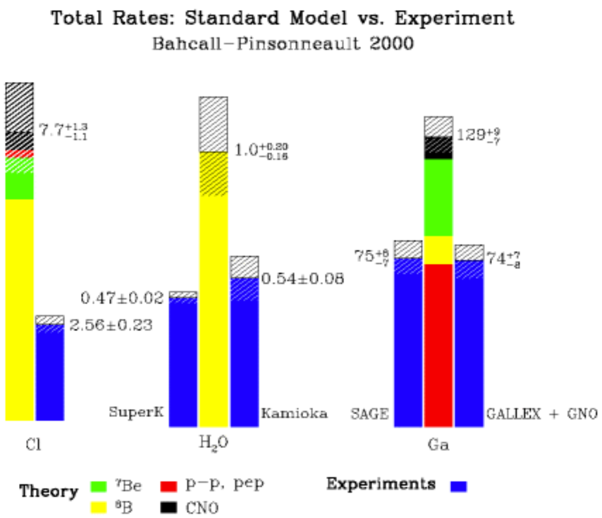
(Super-Kamiokande Collaboration)

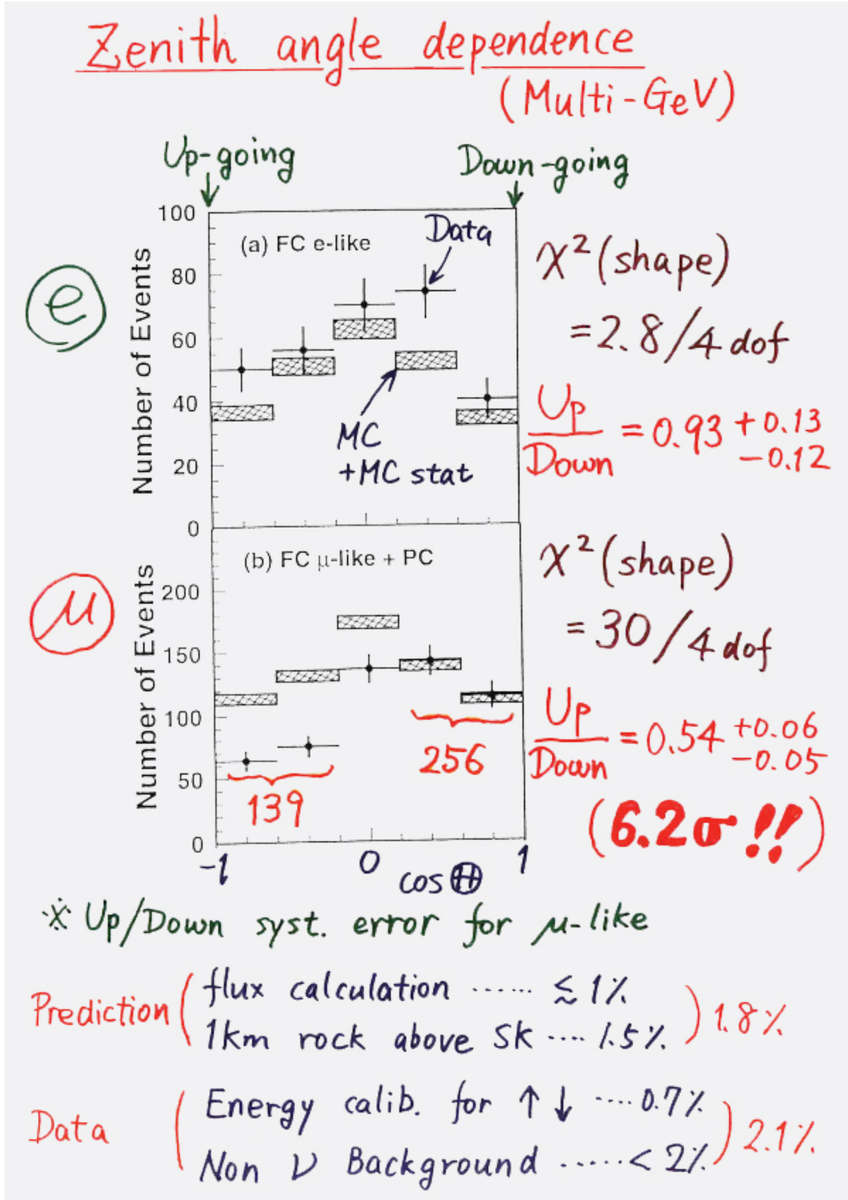
- Nothing was going on for electron type neutrinos
- < 0.4GeV muon neutrinos
  - Overall suppression
- > 0.4 GeV muon neutrinos
  - Location dependent suppressions (disappearing)



ATM observation
Angular distribution

- Prof. Kajita's presentation at Neutrino 1998
- The disappearance of solar neutrinos is not "astrophysics"
- Neutrino particle physics need to be modified!





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VOLUME 81, NUMBER 8 PHYSICAL REVIEW LETTERS 24 AUGUST 1998

Evidence for Oscillation of Atmospheric Neutrinos

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We present an analysis of atmospheric neutrino data from a 33.0 kton yr (535-day) exposure of the Super-Kamiokande detector. The data exhibit a zenith angle dependent deficit of muon neutrinos which is inconsistent with expectations based on calculations of the atmospheric neutrino flux. Experimental biases and uncertainties in the prediction of neutrino fluxes and cross sections are unable to explain our observation. The data are consistent, however, with two-flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with $\sin^2 2\theta > 0.82$ and $5 \times 10^{-4} < \Delta m^2 < 6 \times 10^{-3}$ eV^2 at 90% confidence level. [S0031-9007(98)06975-0]

$$P_{a\to b} = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right),$$

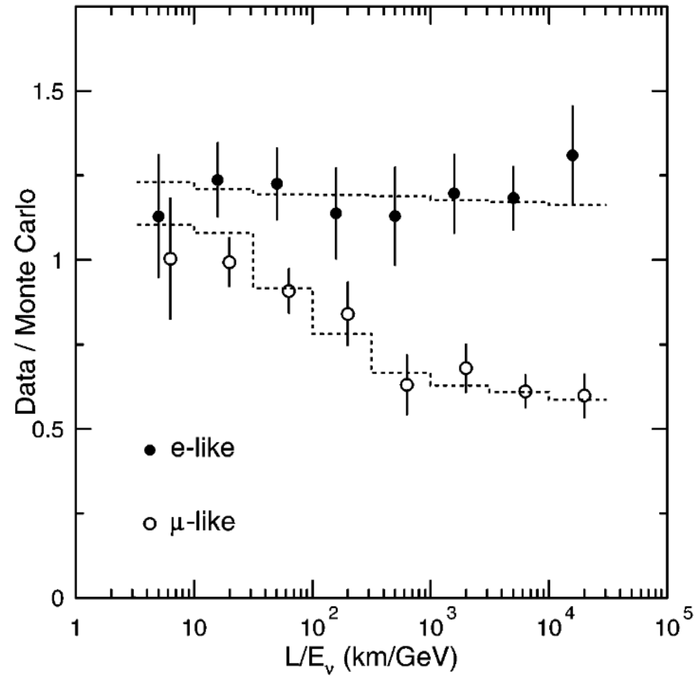

FIG. 4. The ratio of the number of FC data events to FC Monte Carlo events versus reconstructed L/E_ν. The points show the ratio of observed data to MC expectation in the absence of oscillations. The dashed lines show the expected shape for $\nu_\mu \leftrightarrow \nu_\tau$ at $\Delta m^2 = 2.2 \times 10^{-3}$ eV^2 and $\sin^2 2\theta = 1$. The slight L/E_ν dependence for e-like events is due to contamination (2–7%) of ν_μ CC interactions.