Neutrino Properties

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What are neutrinos?

Neutrinos are odd:

Have no electric charge

Have a very small, non-zero mass

They rarely interact - can pass right through you! 65 billion neutrinos go through your thumb every second

Have a flavor

Oscillate between flavors

Only interact via the weak-interaction

Why do we want to study neutrinos?

Neutrinos are one of the least known particles

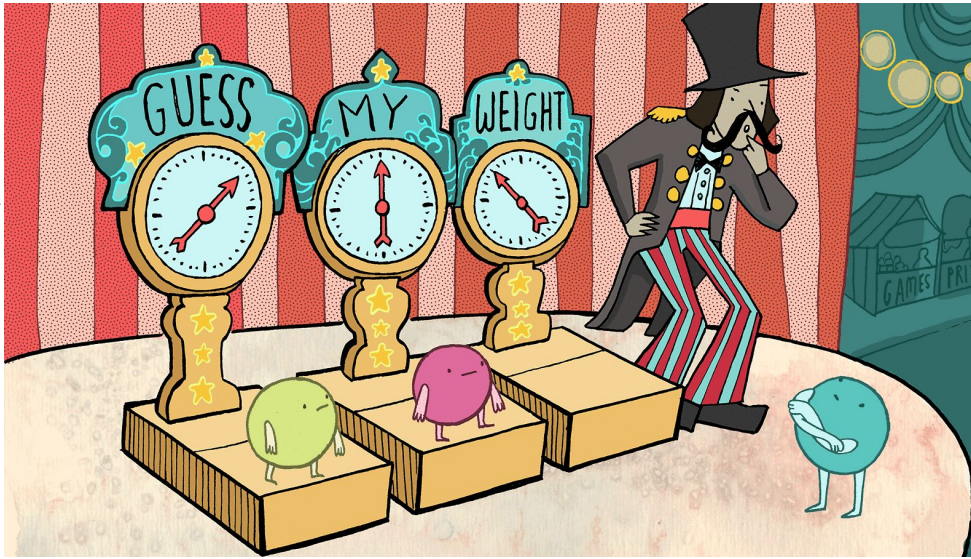
They are difficult to detect - we can only indirectly detect them

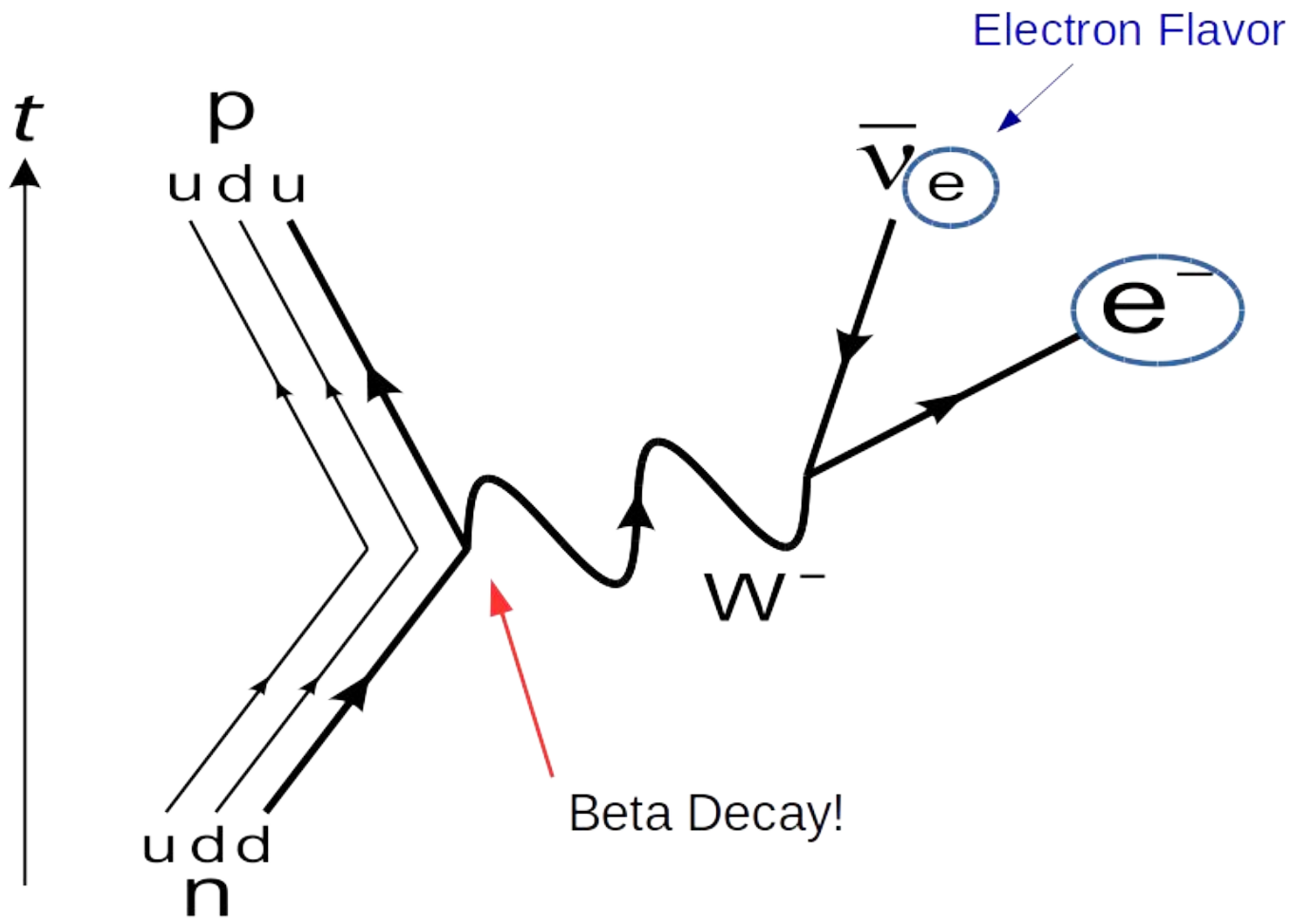
We know they have mass, but we don’t

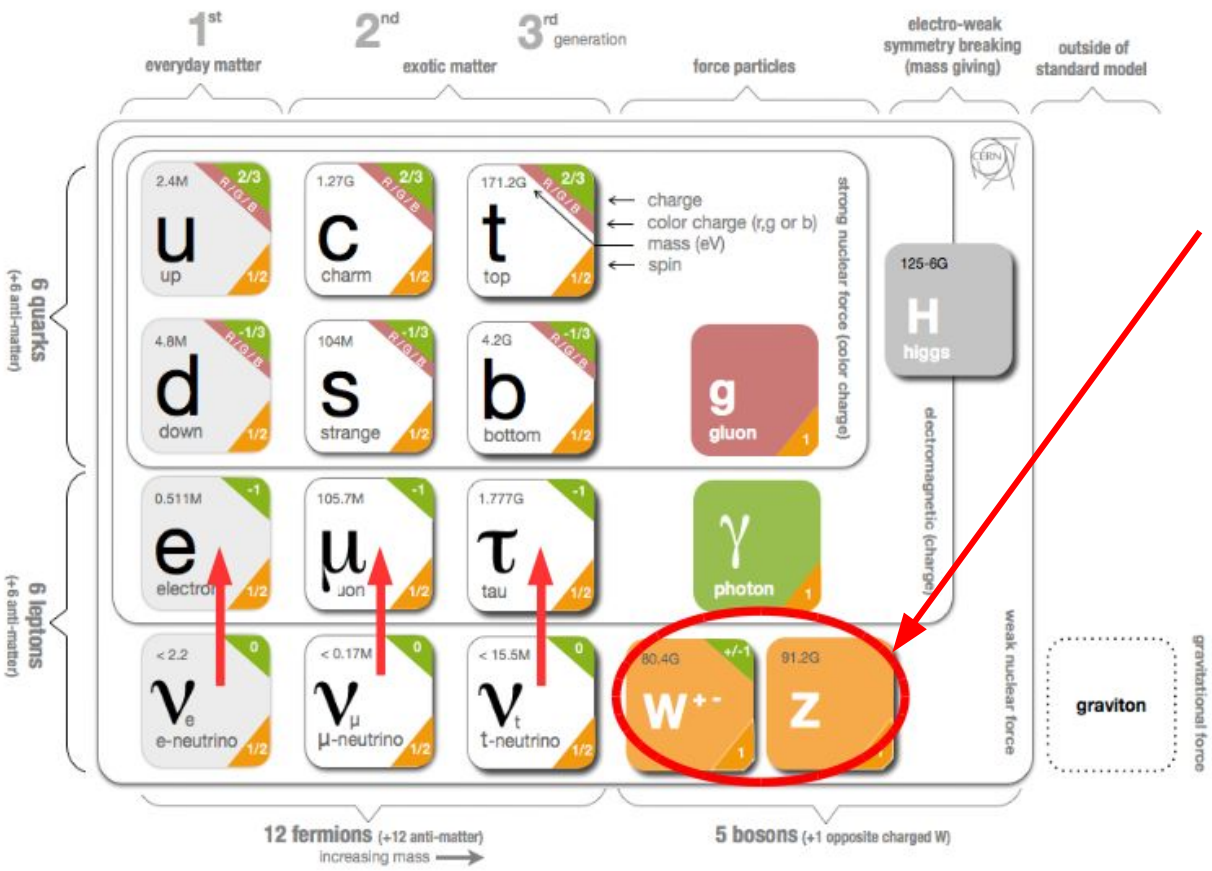
Know where it comes from

We don’t know where the highest energy neutrinos are made in the universe

We can use them to study unknown regions of the universe



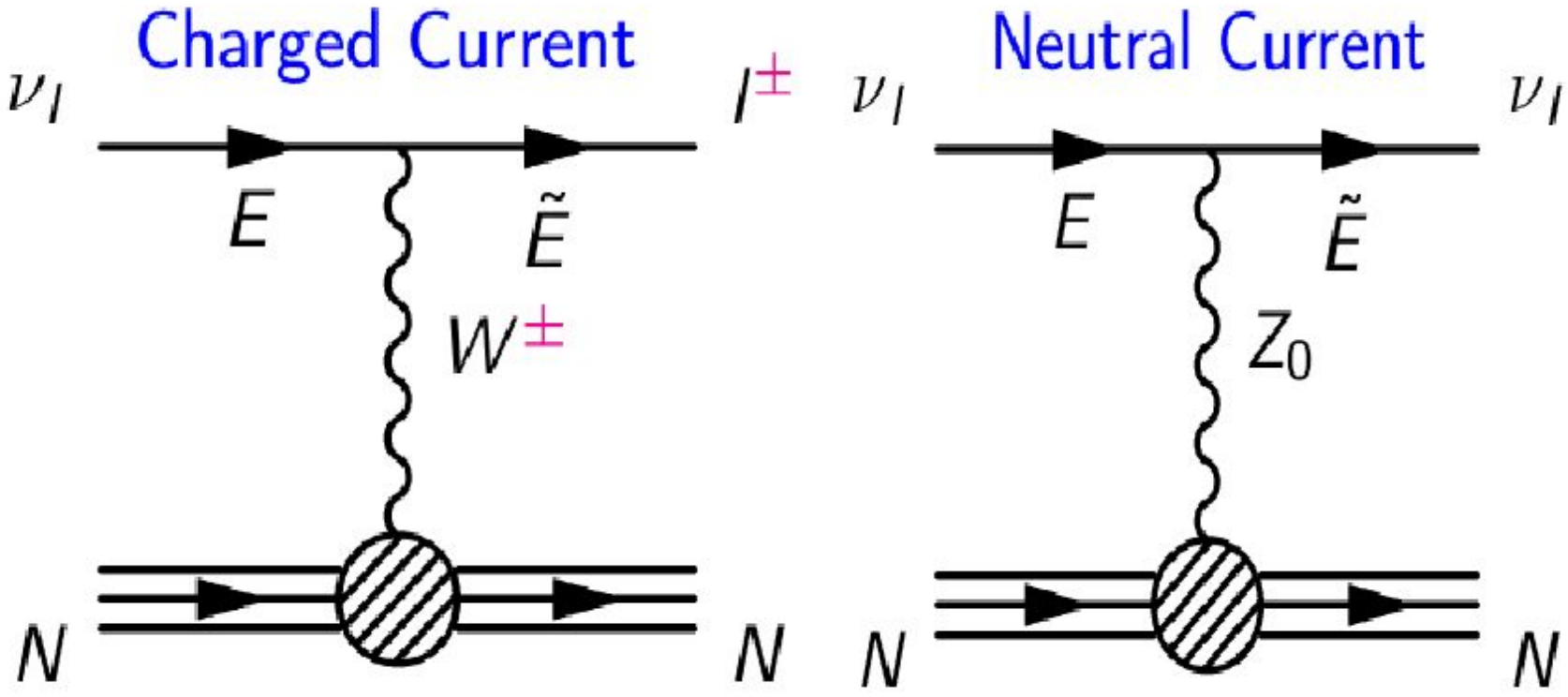

Electron Flavor
t
p
u d u
$\bar{\nu}_e$
e
e^-
W^-
Beta Decay!
u d d
n



Neutrinos only interact via the weak force, which are mediated by the Z and W bosons.

These two bosons are short-lived particles, decaying rapidly to other particles.

Because of these two facts, neutrinos can not be directly observed, but only through secondary particles.


Charged Current
ν_l
$l^{\pm}$
E
$\tilde{E}$
$W^{\pm}$
N
N
Neutral Current
ν_l
ν_l
E
$\tilde{E}$
Z_0
N
N

Charged Current

$$\frac{d^2\sigma}{dxdy} = \frac{2G_F^2 M E_\nu}{\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2\left[xq(x,Q^2)+x\bar{q}(x,Q^2)(1-y)^2\right],$$

PDFs for proton interactions

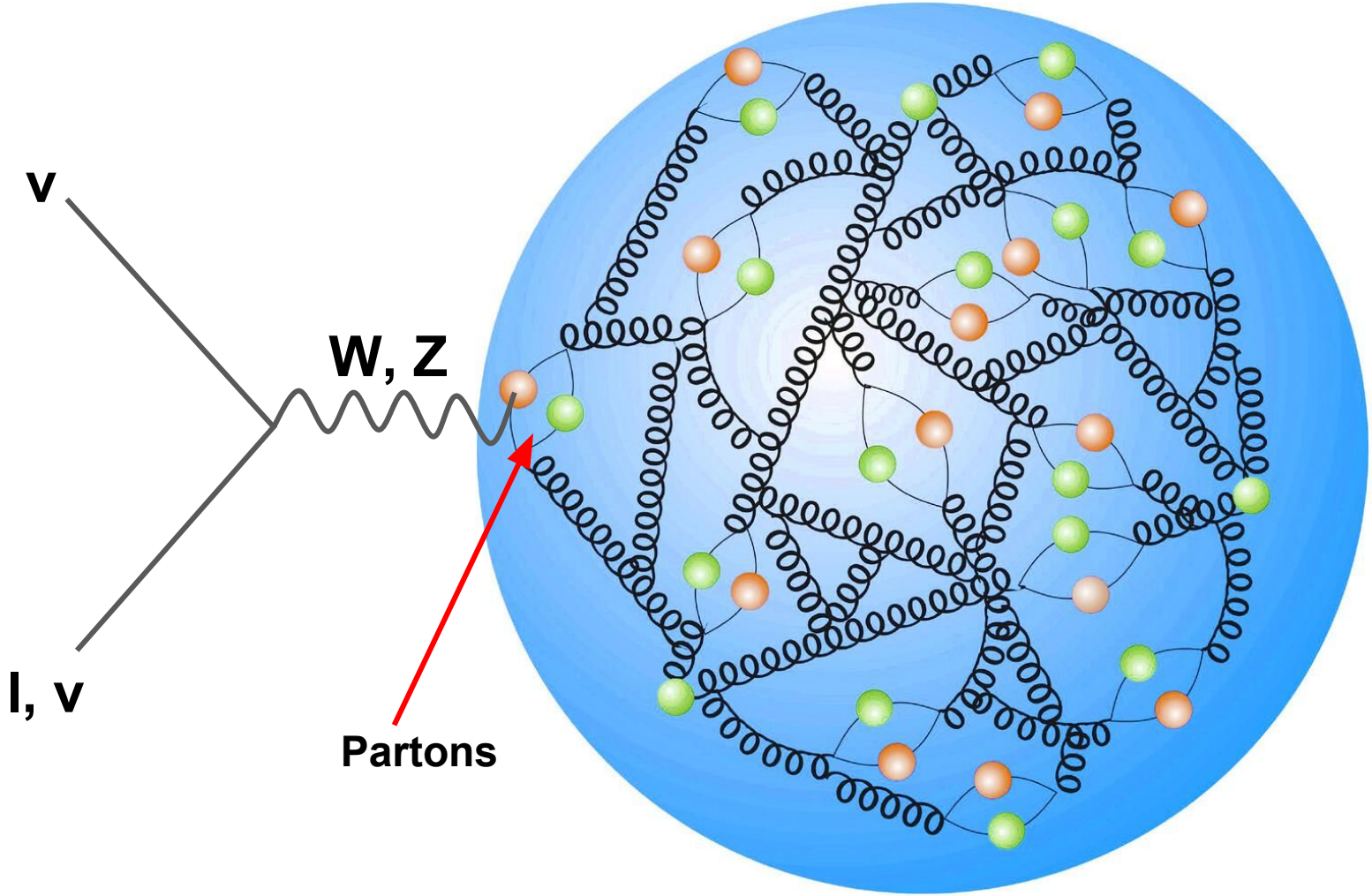
Neutral Current

$$\frac{d^2\sigma}{dxdy} = \frac{G_F^2 M E_\nu}{2\pi}\left(\frac{M_Z^2}{Q^2+M_Z^2}\right)^2\left[xq^0(x,Q^2)+x\bar{q}^0(x,Q^2)(1-y)^2\right],$$

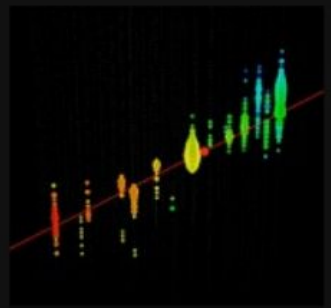
$G_F = 4.541\ 10^{-33}\ cm^2$!!!

$$x = Q^2/2M\nu \quad y = \nu/E_\nu$$

Ref: R. Ghandi et al. hep-ph/9807264

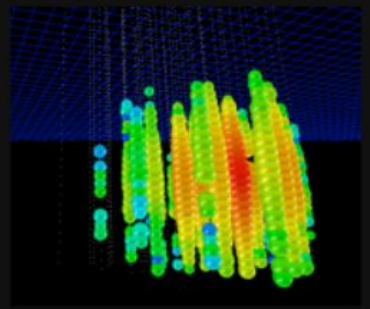

ν
W, Z
l, ν
Partons

CC Muon Neutrino



$$\nu_\mu + N \rightarrow \mu + X$$

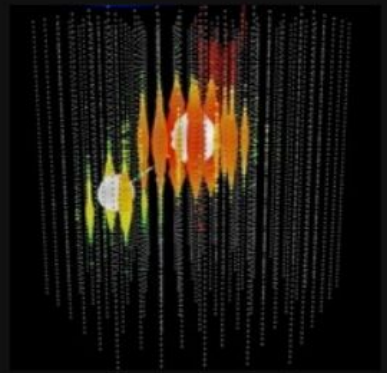
Neutral Current / Electron Neutrino



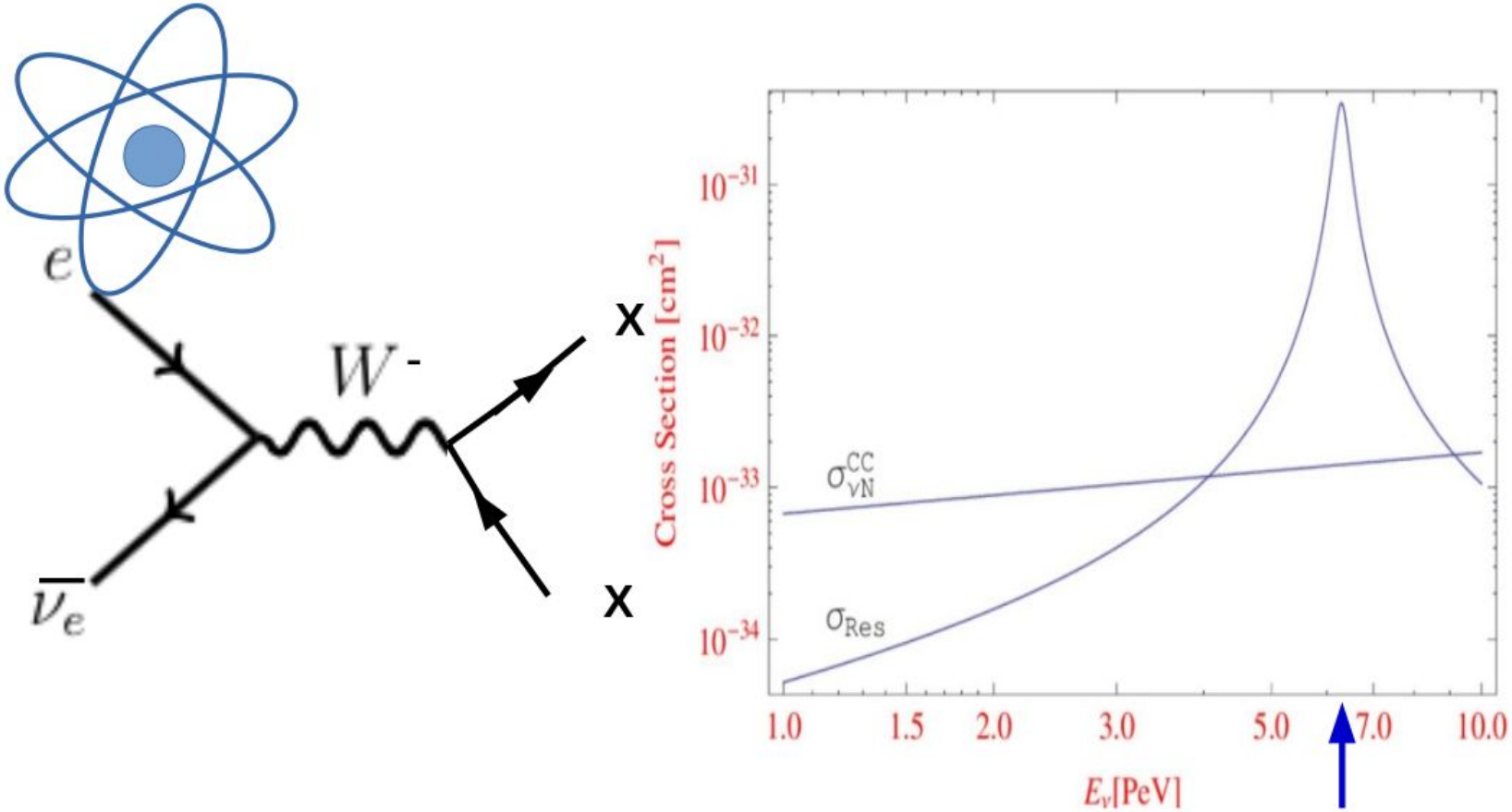
$$\nu_\mathrm{e} + N \rightarrow \mathrm{e} + X$$

$$\nu_\mathrm{x} + N \rightarrow \nu_\mathrm{x} + X$$

CC Tau Neutrino



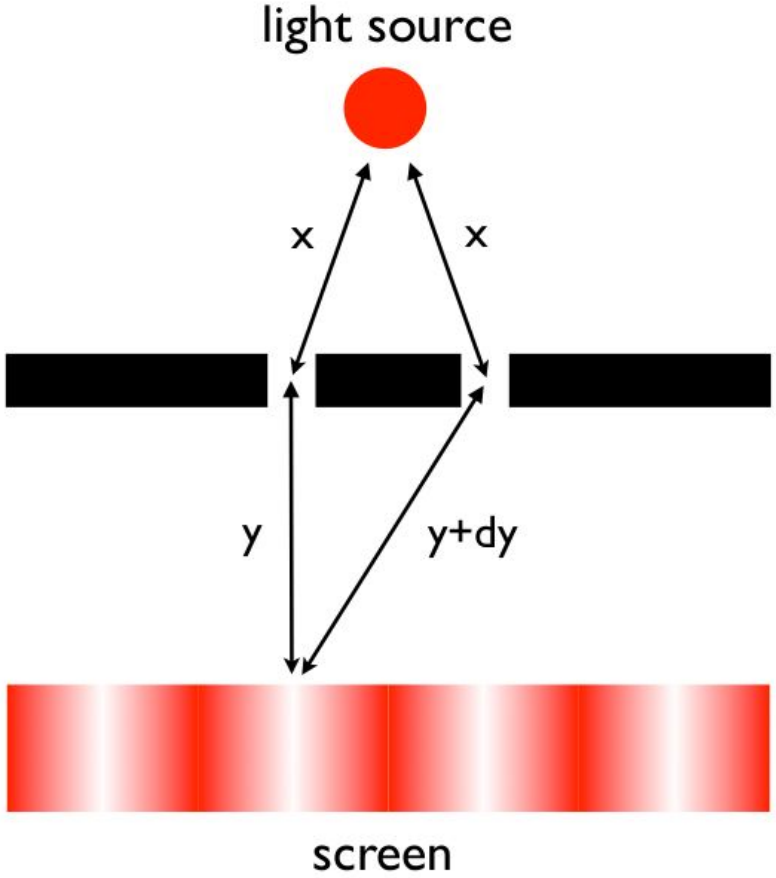
$$\nu_\tau + N \rightarrow \tau + X$$

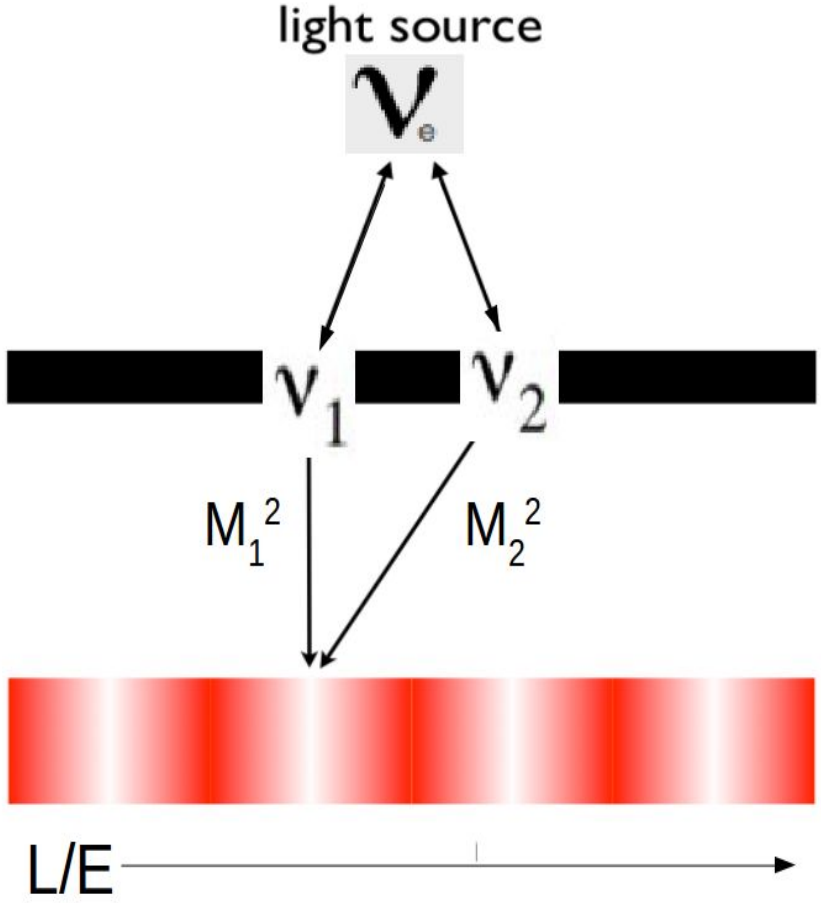


[Barger et. al. 1407.3255]

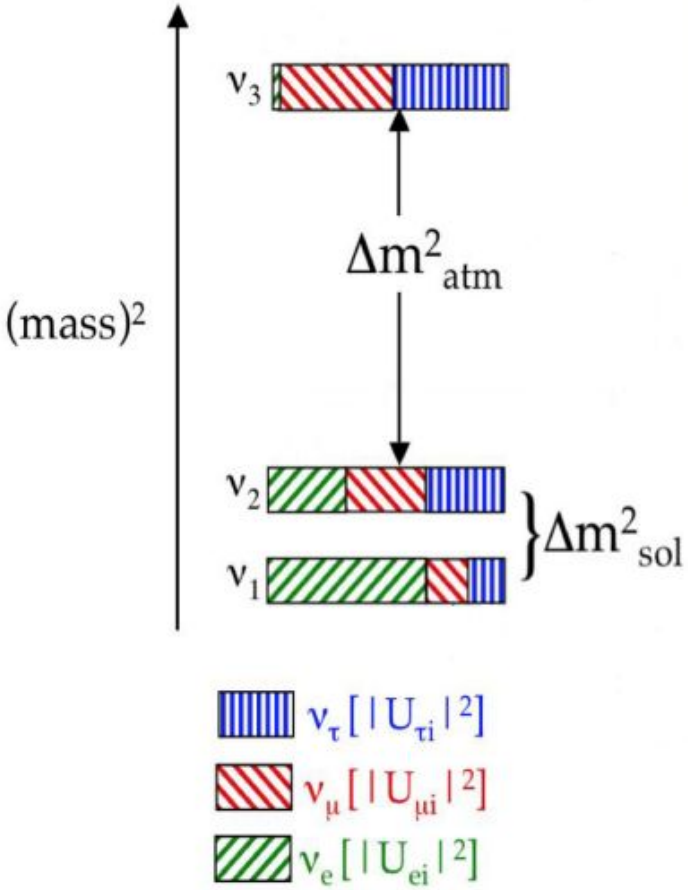
6.3 PeV

Oscillations




light source
ν_e
ν_1
ν_2
M_1^2
M_2^2
L/E

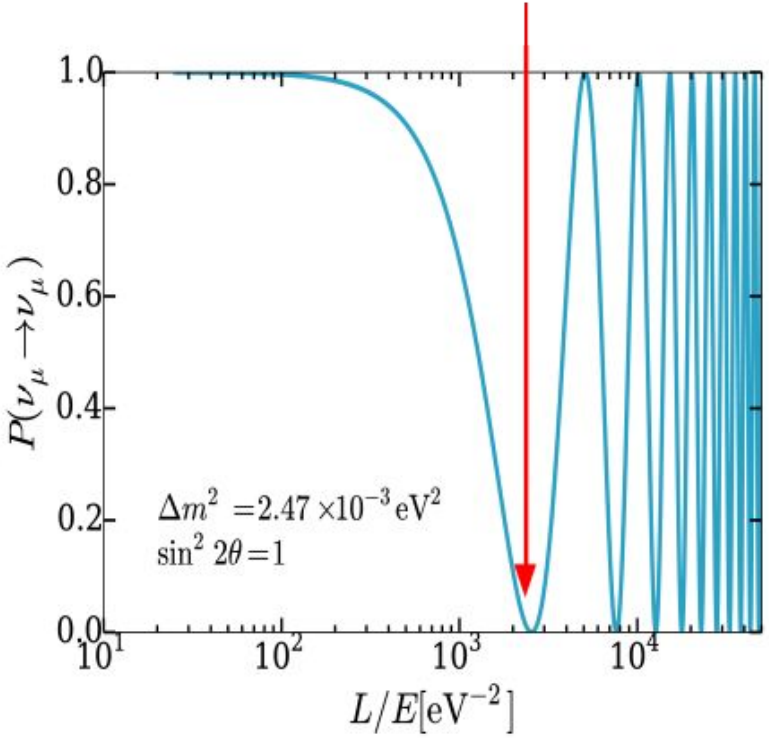
$$\Delta m^2_{\rm sol} = 7.5 \times 10^{-5} {\rm eV}^2$$
$$|\Delta m^2_{\rm atm}| = 2.4 \times 10^{-3} {\rm eV}^2$$

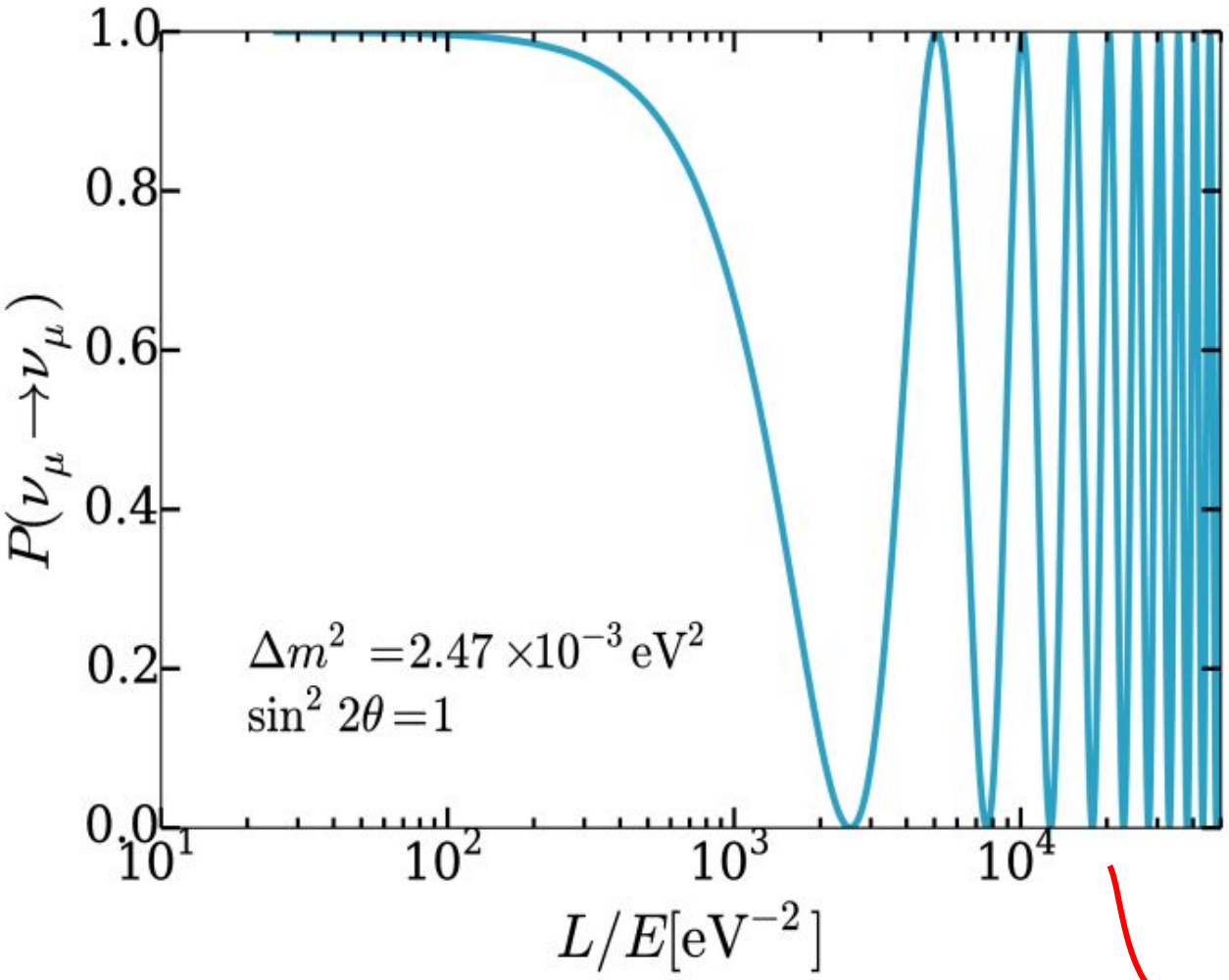


[B. Kayser, hep-ph/0506165 (2004)]

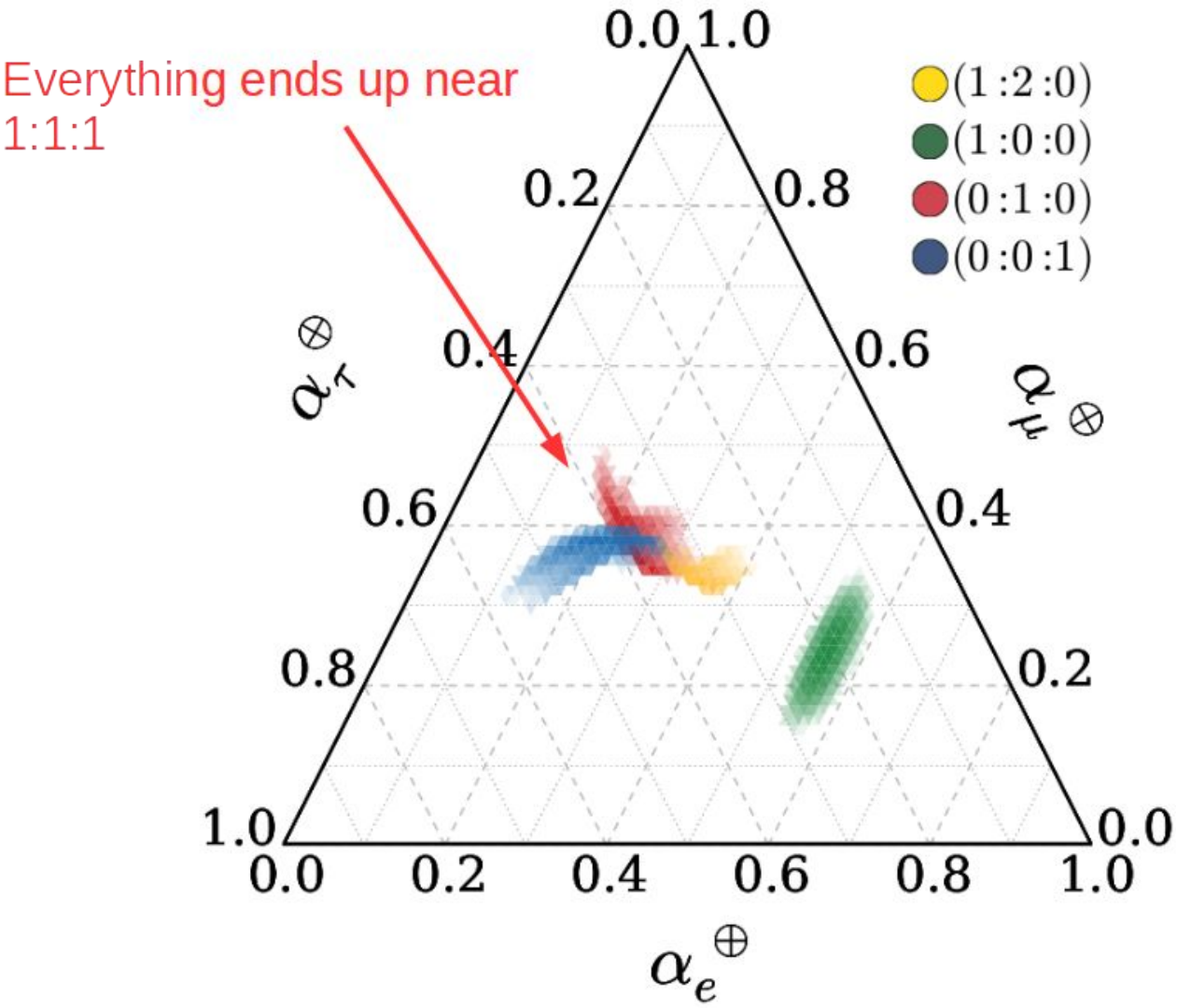
[C. Gonzalez-Garcia et al., JHEP 12 (2012)]

Disappearance of muon neutrinos!





Oscillations become rapid compared to distance over long distances


Everything ends up near
1:1:1
(1 :2 :0)
(1 :0 :0)
(0 :1 :0)
(0 :0 :1)
0.0
0.2
0.4
0.6
0.8
1.0
$\alpha_\tau^\oplus$
$\alpha_\mu^\oplus$
$\alpha_e^\oplus$

$$p + p \rightarrow \pi^+ + X$$

$$\hookrightarrow \mu^+ + \nu_\mu$$

$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Cosmic Rays at source

$$p + \gamma \rightarrow \pi^+ + X$$

$$\hookrightarrow \mu^+ + \nu_\mu$$

$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

GZK or CR+Gamma Ray

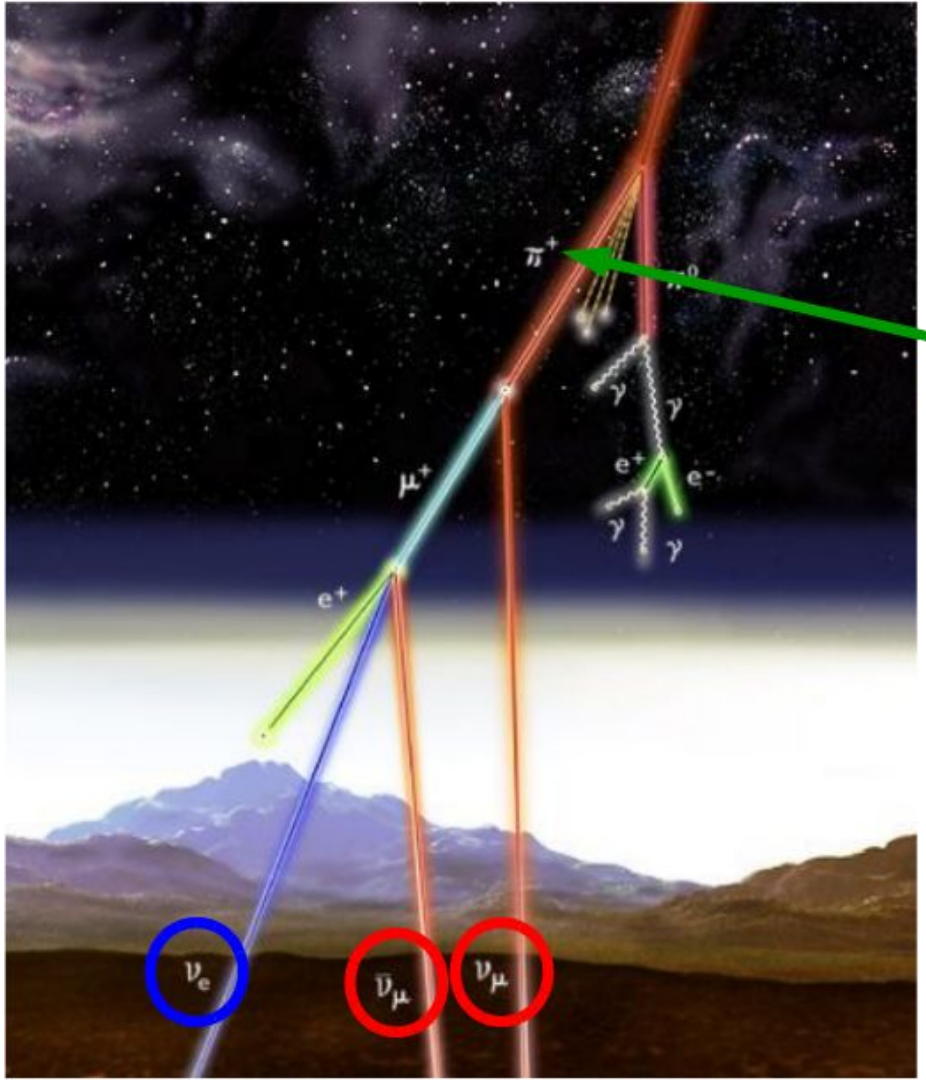
$$p + \gamma \rightarrow \Delta^+(1232) \rightarrow \pi^+ + n$$

$$\hookrightarrow \mu^+ + \nu_\mu$$

$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

CR CMB

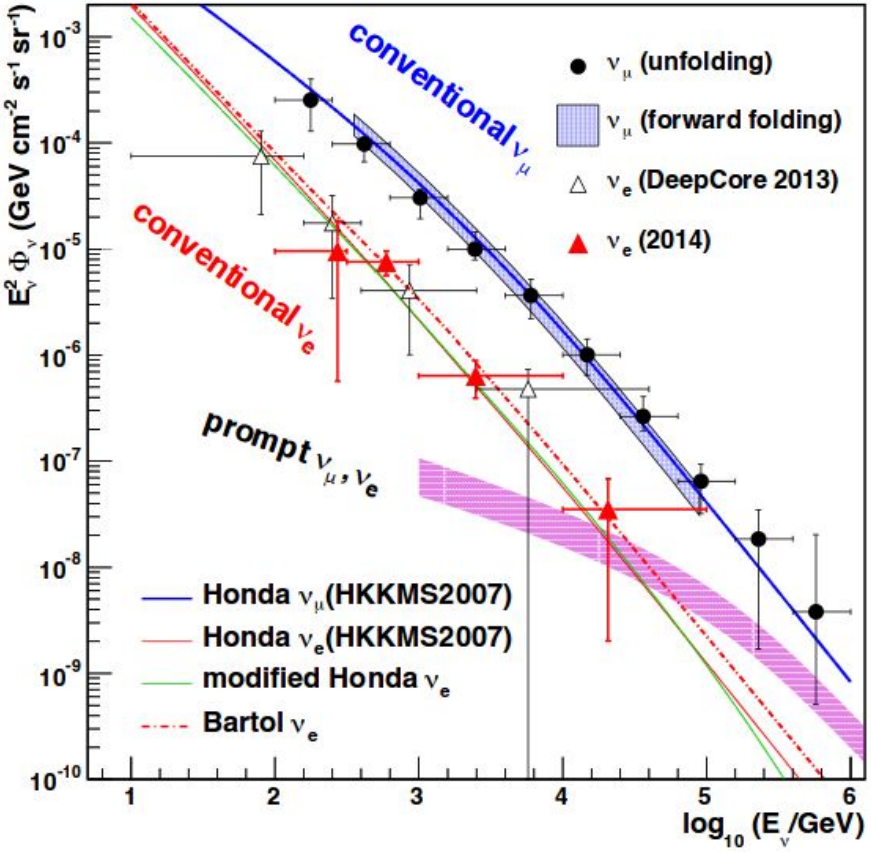
GZK

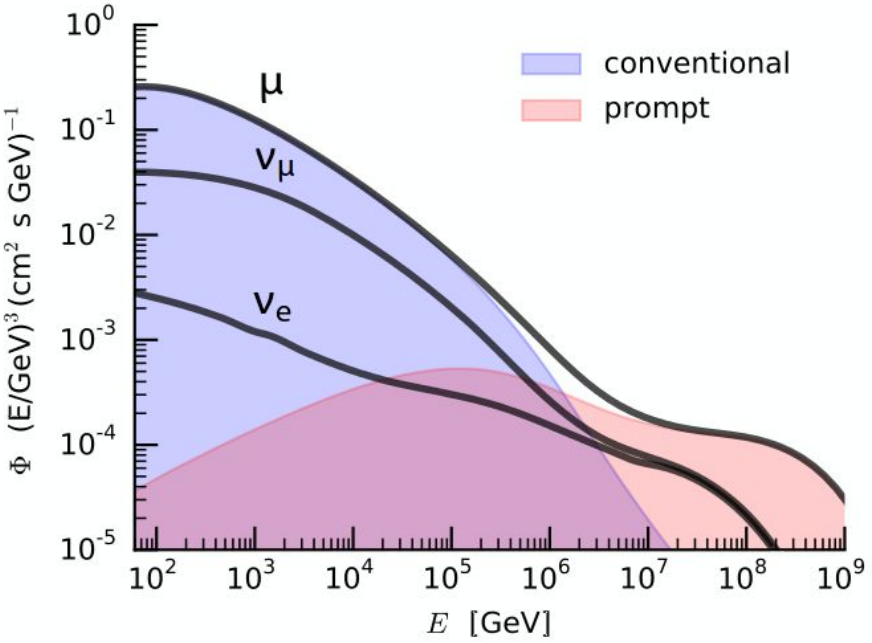


Could be a Kaon

[Enberg VLVnT 2013]
[INFN-Notizie No.1 June 1999]

Atmospheric neutrinos





Neutrinos are weird and fascinating

They are one of the hardest particles to detect but there are billions of them all around you

We don’t have a full particle theory describing them, this shows that the Standard Model is incomplete and there is more physics to be discovered

They have quantum behaviors that no other particle has, they can change from one flavor to another and back again

Lets study some neutrinos!