Search for Sphaleron from Ultra-High-Energy Cosmic rays and Neutrinos

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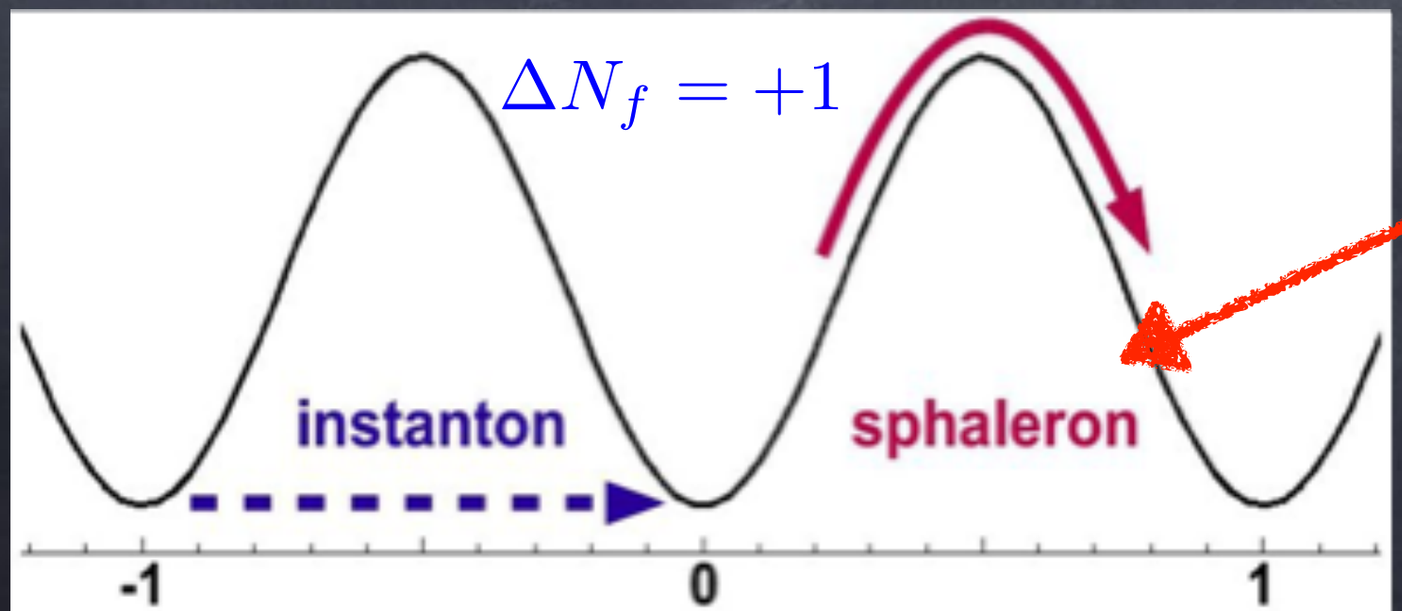
A brief introduction of EW Sphaleron

- Electroweak "theta-vacua"

$$\Delta N_f = \frac{g^2}{16\pi^2}\int d^4x\ \mathrm{Tr}\left[W_{\mu\nu}\tilde{W}^{\mu\nu}\right] = \int d^4x\ \partial_\mu K^\mu$$

generally non-vanishing Chern-Simons Number

$$\pi_3(SU(2)) = \mathbb{Z}$$

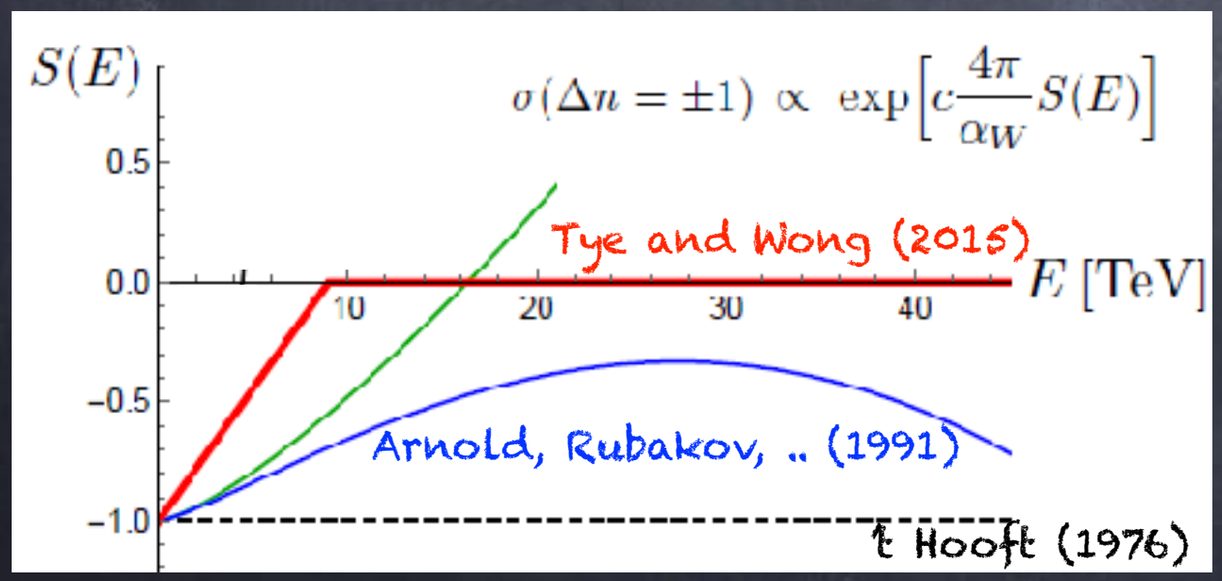


We will focus on sphaleron.

EW Sphaleron Events in High-Energy Cosmic rays

- Cross section of the Sphaleron event

$$\sigma(\Delta N_f = \pm 1) = \frac{p(E_i)}{m_W^2} \sum_{ab} \int dE \frac{d\lambda_{ab}}{dE} \exp\left(\frac{8\pi}{\alpha_W} S(E)\right)$$



Instanton Tunneling Probability between neighbor vacua

There are some debates for actual cross section above the threshold E

EW Sphaleron Events in High-Energy Cosmic rays

- Cross section of the Sphaleron event

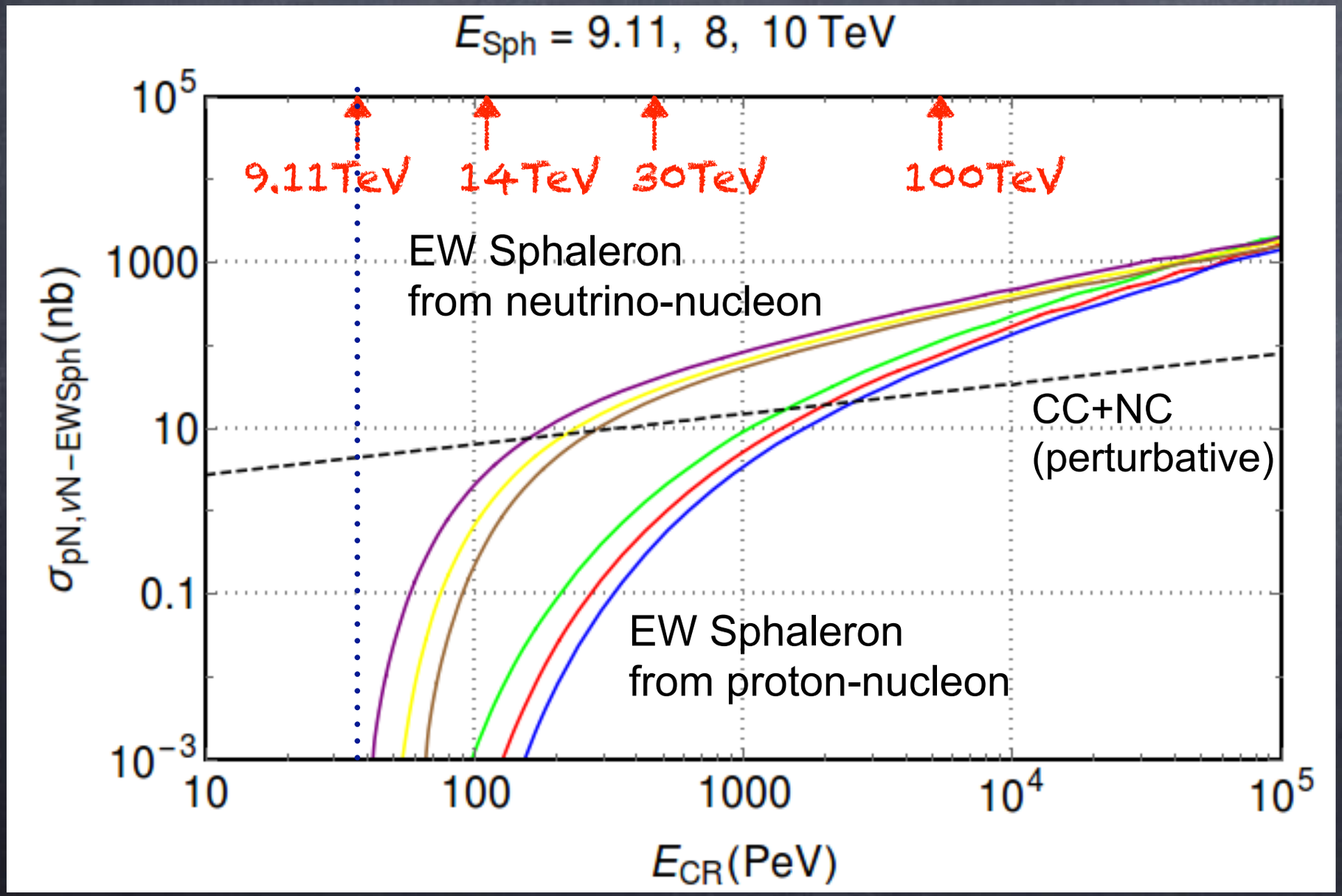
$$\sigma(\Delta N_f = \pm 1) = \frac{p(E_i)}{m_W^2} \sum_{ab} \int dE \frac{d\lambda_{ab}}{dE} \exp\left(\frac{8\pi}{\alpha_W} S(E)\right)$$

Overall factor
(can be tested by experiment)
+
depends on
initial and final state configurations

Energy spectrum with PDF convolution
(Uncertainty at small x and high E region)

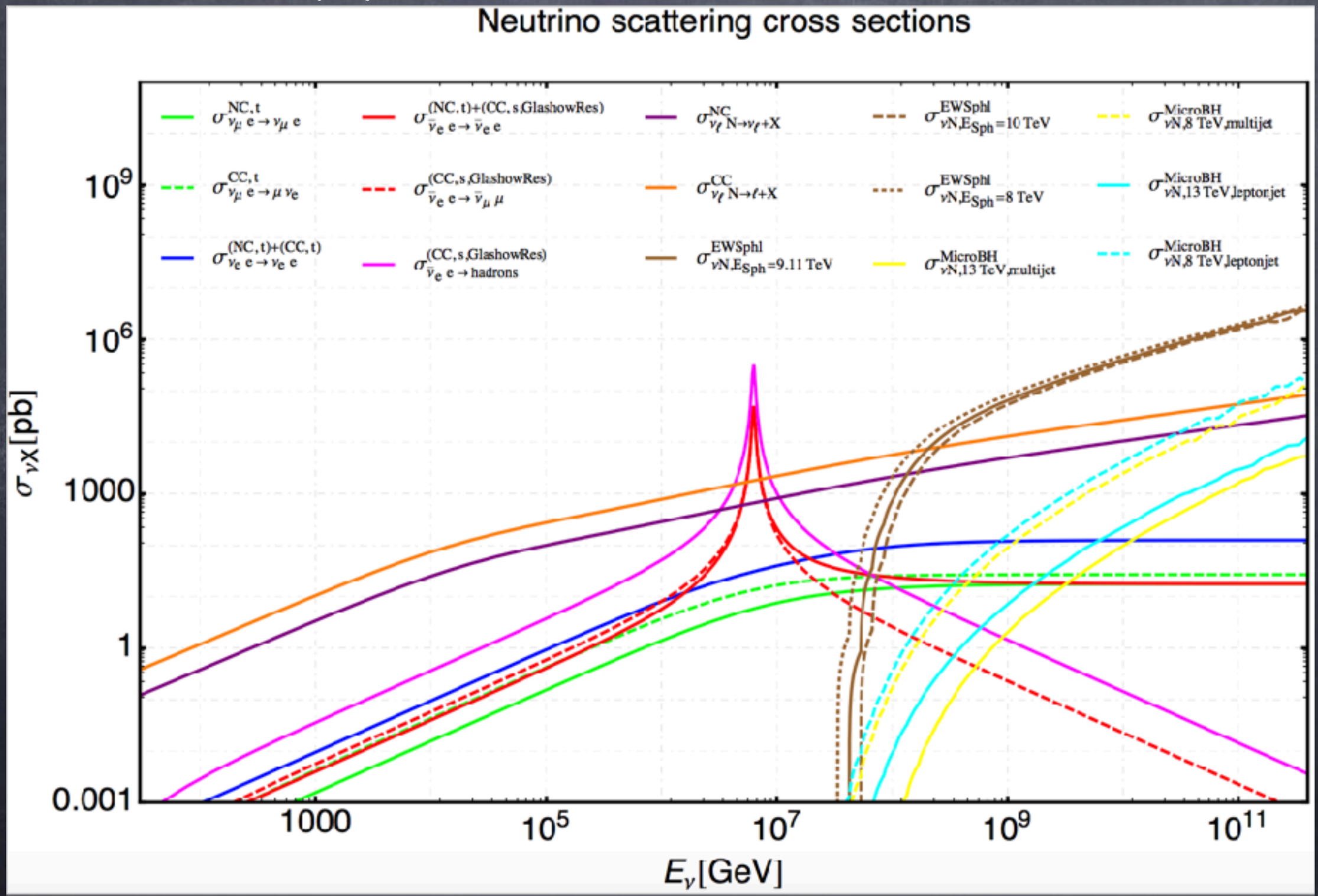
EW Sphaleron Cross section in UHECR

- Cross Section for pp and νN collisions



For Sphaleron, We set p=1 here.

UHE Neutrino Cross sections



New Physics Search with UHE Neutrinos

- Q: Did we reached the sensitivity for observing UHE neutrino event from SM CC+NC or New Physics(such as Microscopic BH, or EW Sphaleron)?

- Q: Can we identifying New Physics UHE neutrino Event from ordinary CC+NC UHE neutrino event?

UHE neutrino Event rate

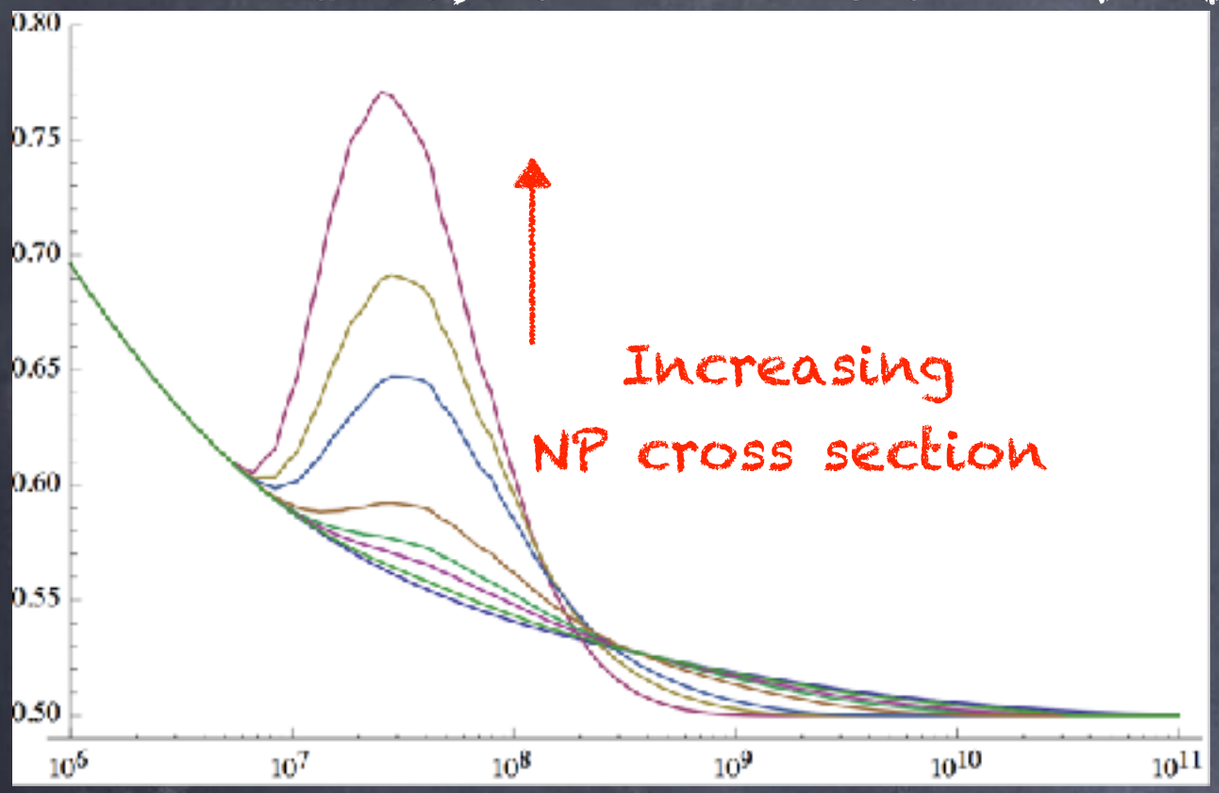
$$\frac{dN}{dt} = N_A \int_0^1 dy \int_0^\infty dE_\nu \, Att^f_\nu(E_\nu) \frac{d\phi^f_\nu(E_\nu)}{dE_\nu} M_{eff}(E_\nu) \frac{d\sigma^f_{int}(E_\nu, y)}{dy}$$

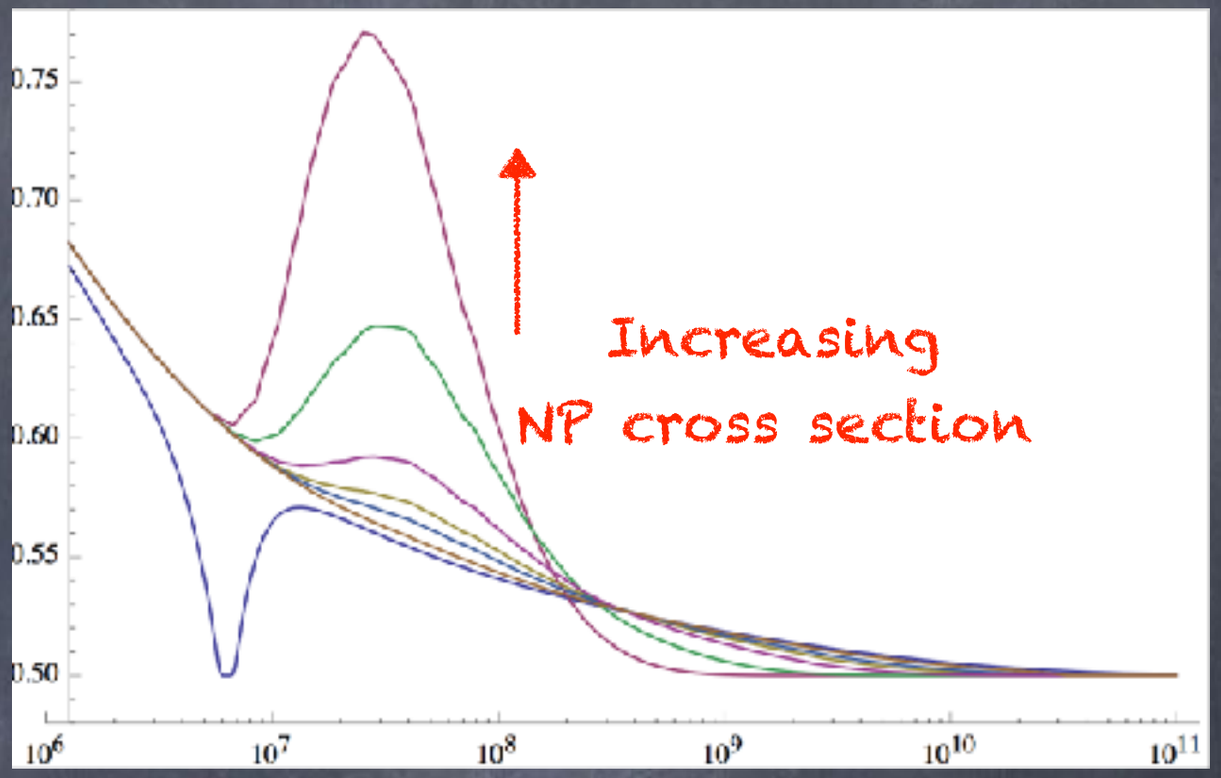
Neutrino Attenuation and Regeneration while going through the Earth

Mostly GZK neutrino from the interaction between UHE Cosmic rays and CMB photon

SM or NP

Neutrino Attenuation in the Earth with NP contribution

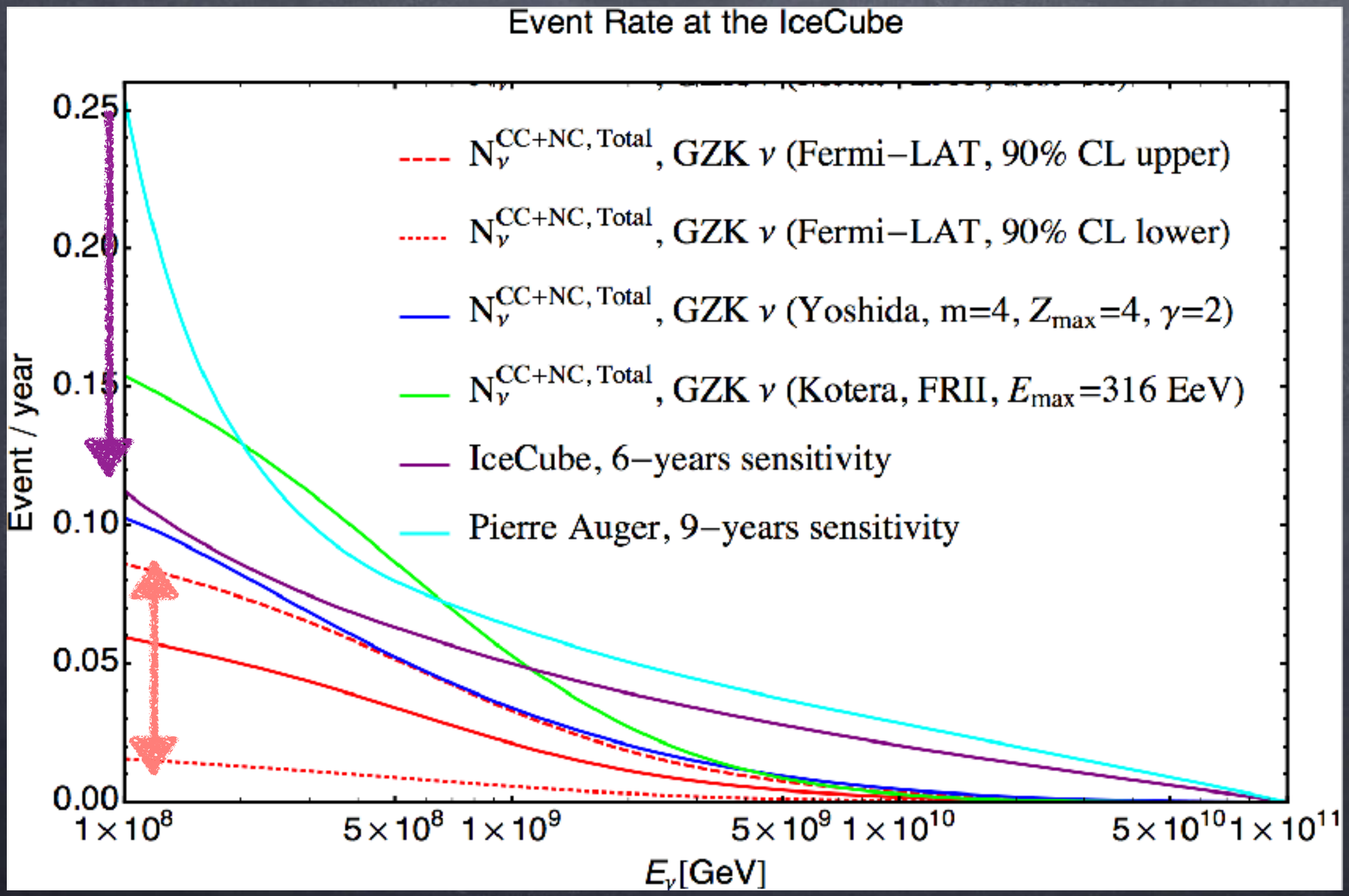




$$\frac{\partial}{\partial X}\left(\frac{d\phi^f_{\nu_\ell}(E_\nu,X)}{dE_\nu}\right) = -N_A\left(\sigma^{\rm NC}_{\nu_\ell}(E_\nu)+\sigma^{\rm CC}_{\nu_\ell}(E_\nu)\right)\frac{d\phi^f_{\nu_\ell}(E_\nu,X)}{dE_\nu}$$
$$+N_A\int_0^1\frac{dy}{1-y}\frac{d\sigma^{\rm NC}_{\nu_\ell}(E_\nu/(1-y),y)}{dy}\frac{d\phi^f_{\nu_\ell}(E_\nu/(1-y),X)}{dE_\nu}$$

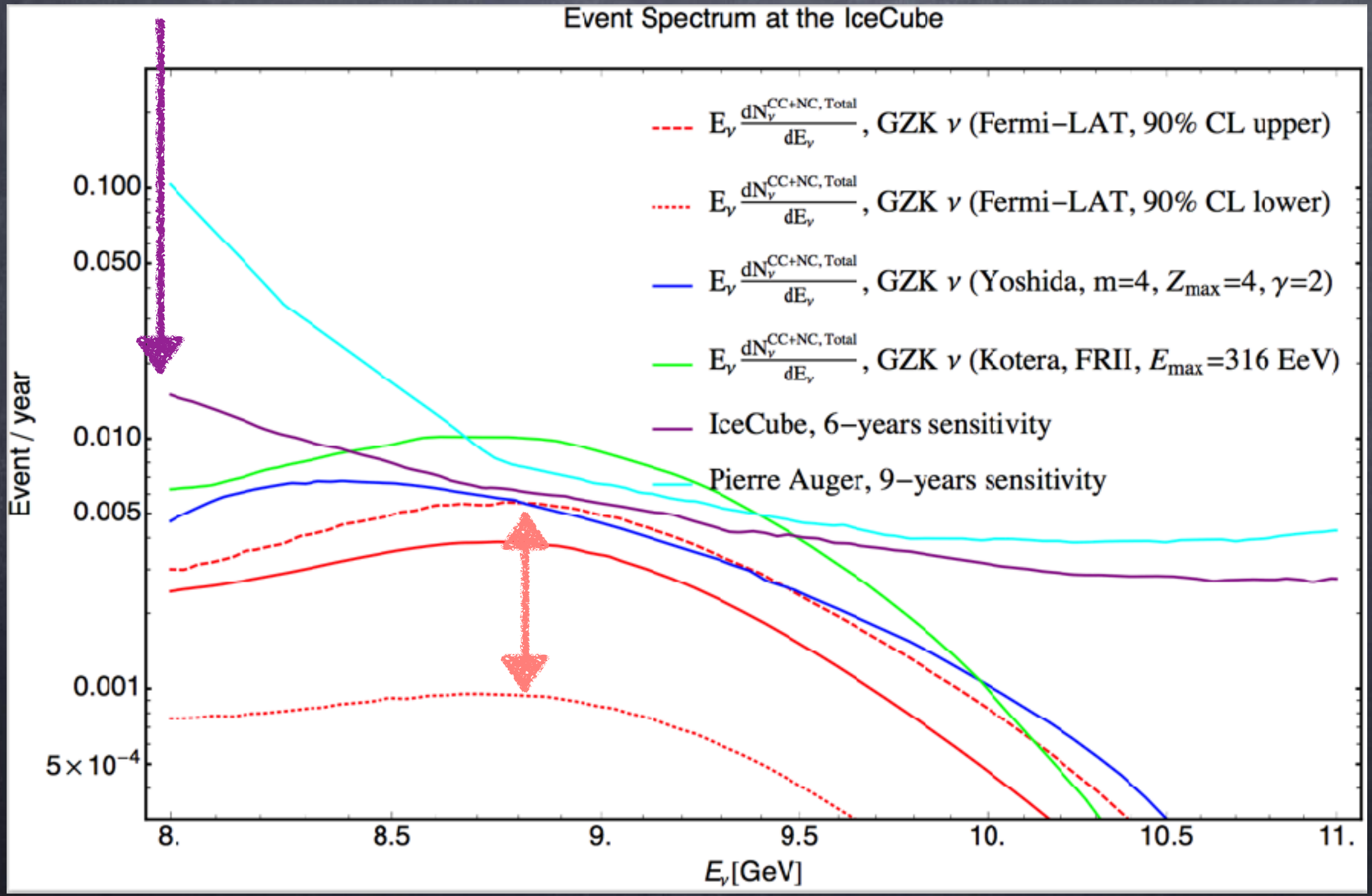
- Attenuation at High E only contribute O(1) correction
- But Earth-Skimming region it can be important.

UHE neutrino Event With SM CC+NC interactions

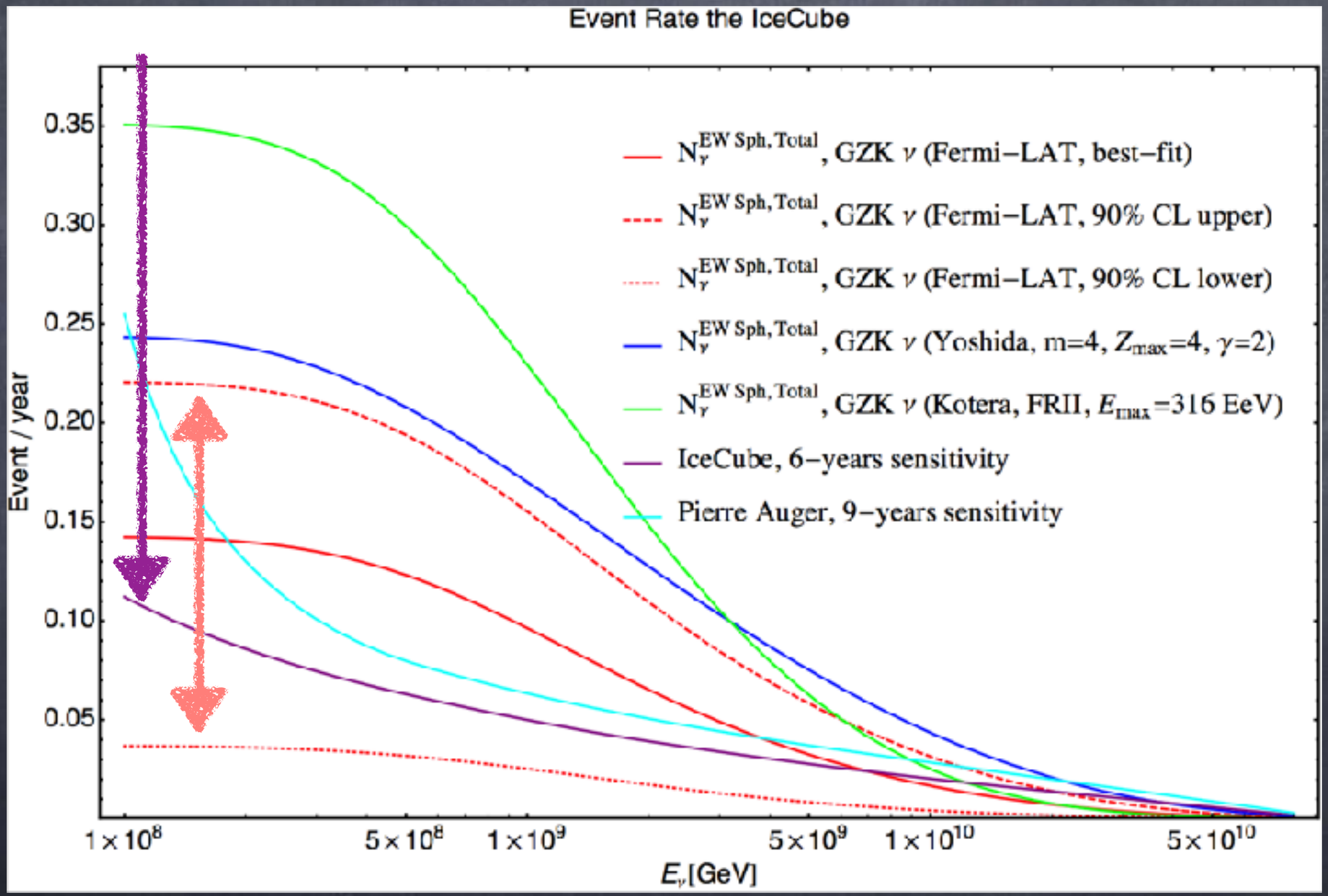


- We've reached the floor (for SM CC+NC interaction case.)

UHE neutrino Event Spectrum With SM CC+NC interactions

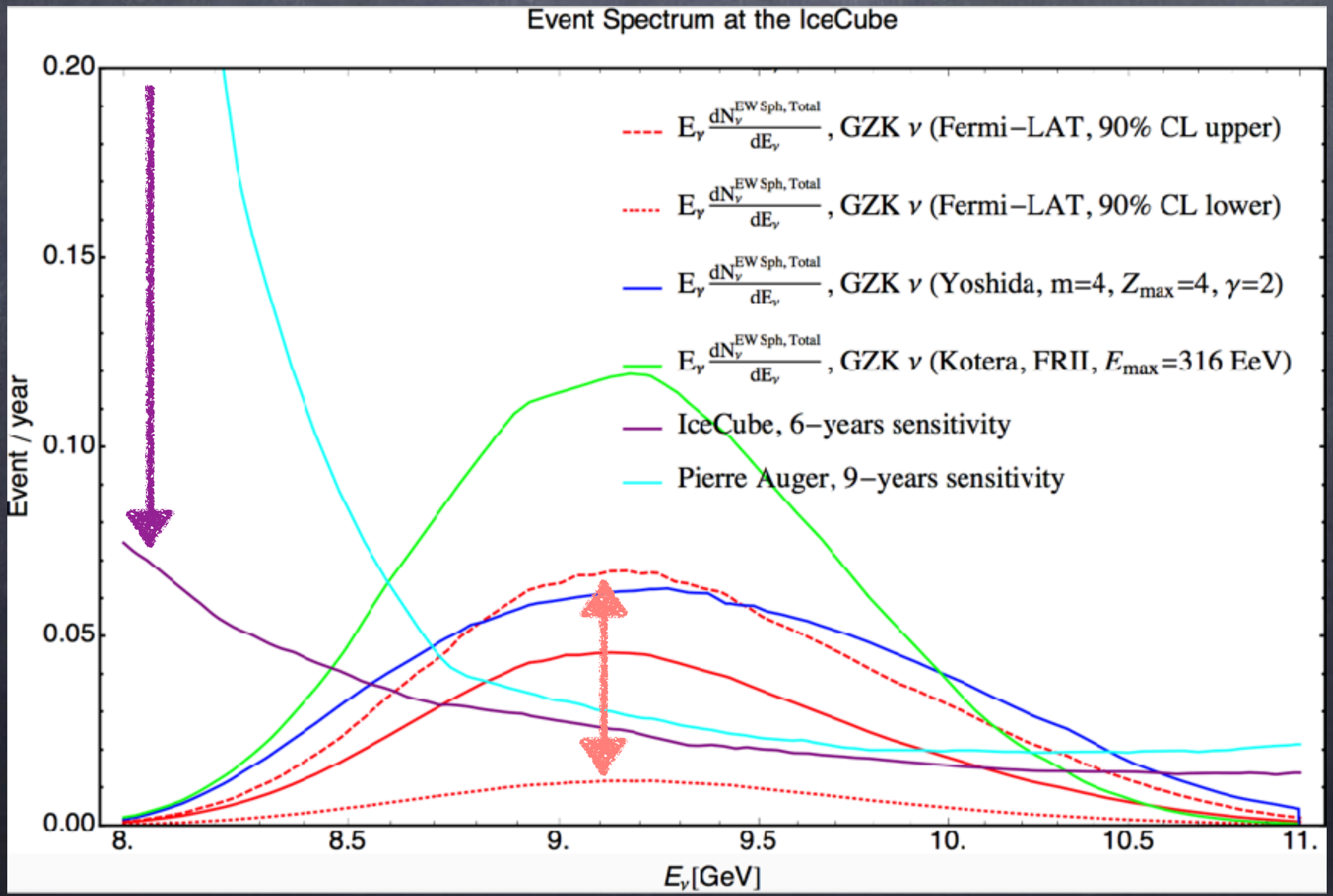


UHE neutrino Event With NP interactions



- Many parameter space of New Physics are still within GZK neutrino flux uncertainty band

UHE neutrino Event Spectrum With NP interactions



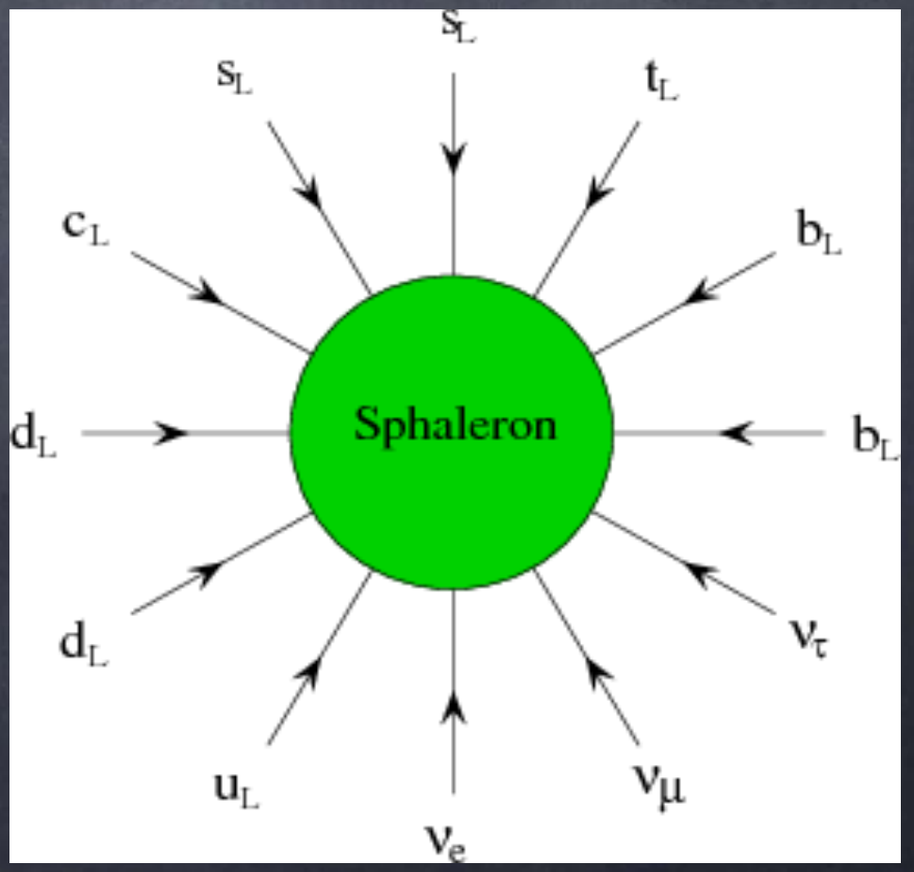
How to identify NP-induced process?

- Actually, any arbitrary initial and final state is possible if Total Charge conserved (or equivalently, if Total Isospin conserved)

- 12 LH fermion numbers should have same difference

$$L_1 = L_2 = L_3$$
$$= \Delta q_1 = \Delta q_1 = \Delta q_1$$
$$= \Delta q_2 = \Delta q_2 = \Delta q_2$$
$$= \Delta q_3 = \Delta q_3 = \Delta q_3 = N = \int d^4x \, \partial_\mu K^\mu$$

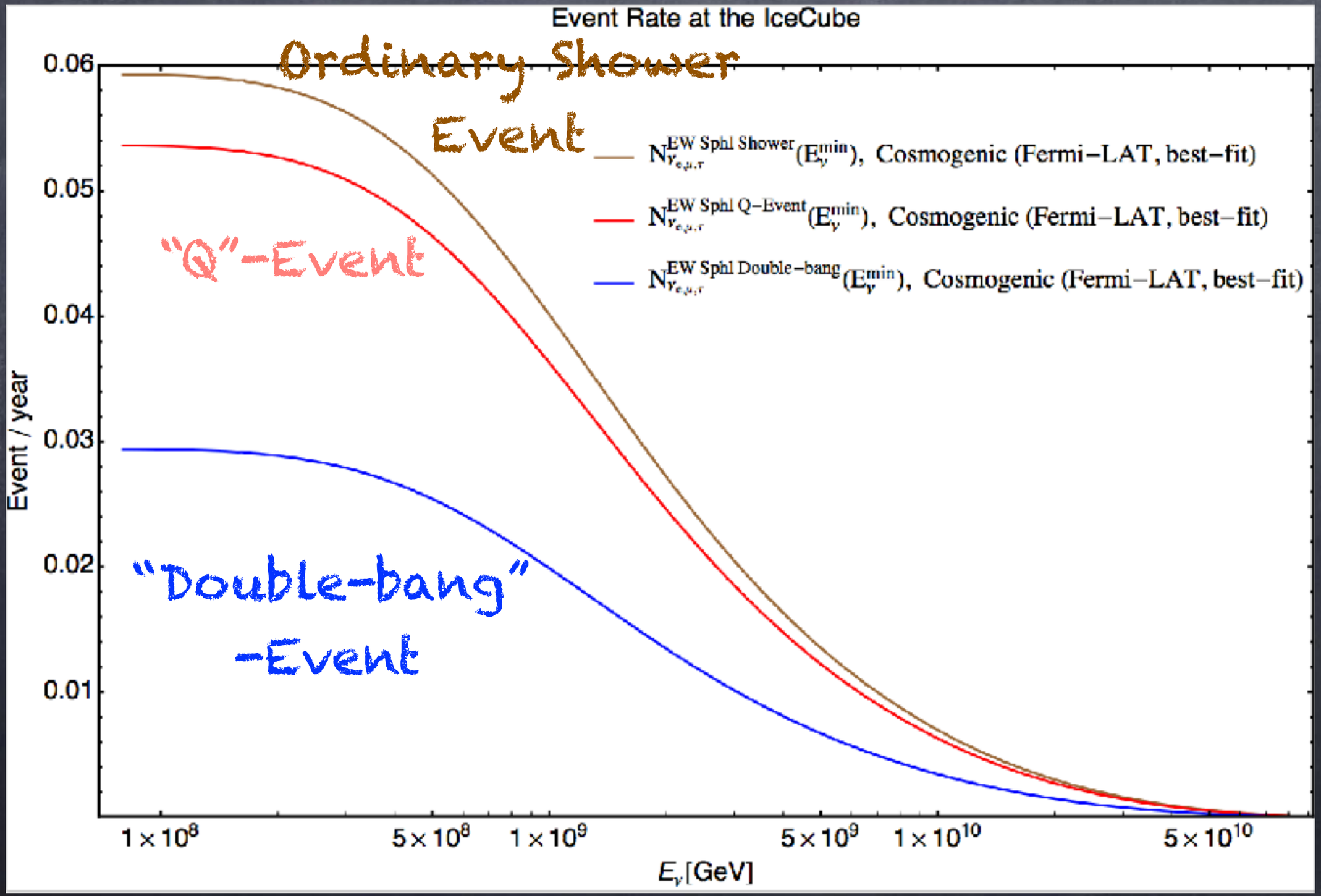
Every LH Doublets should be included



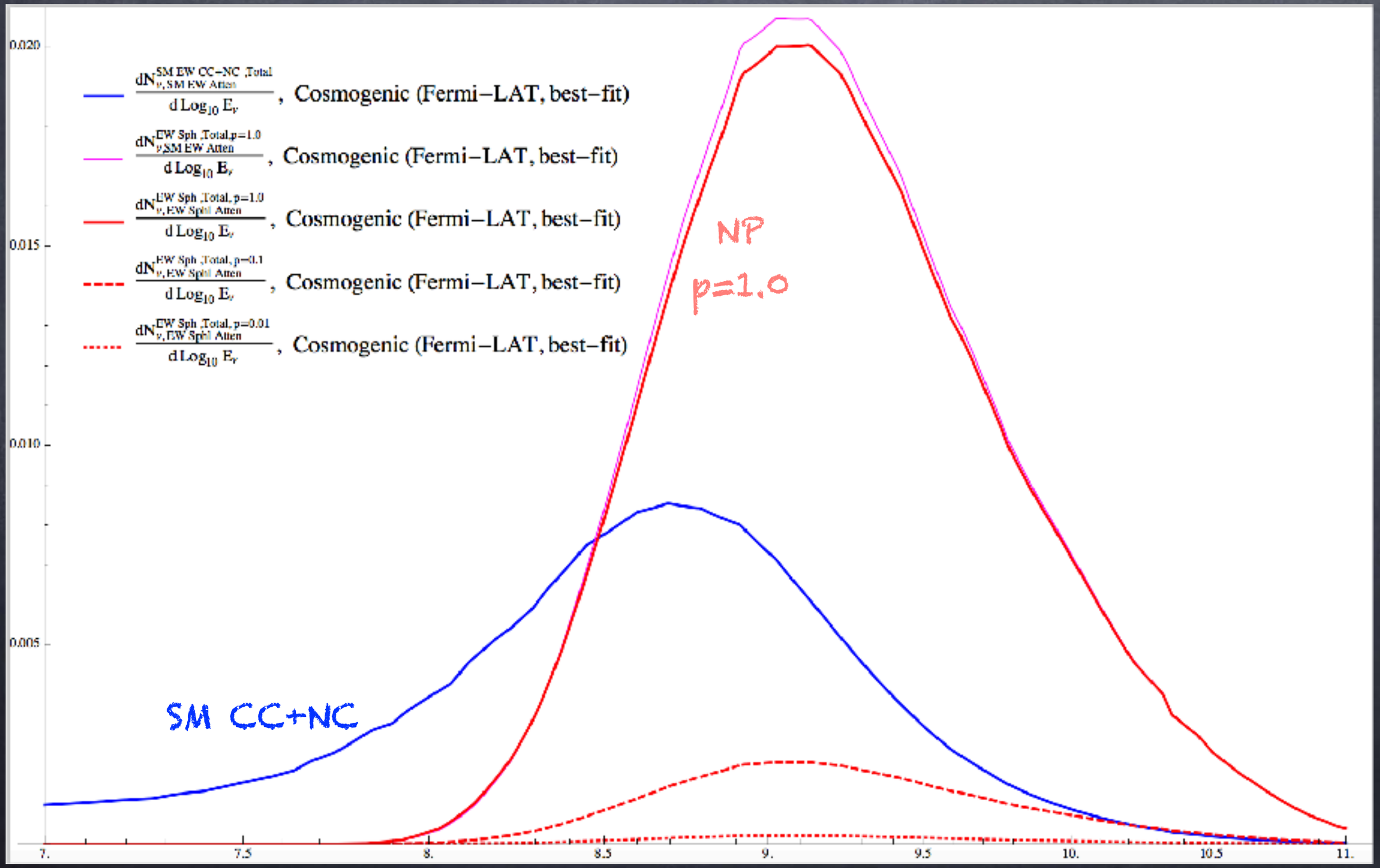
Event Topologies

- Shower (8 jets + 2 neutrinos , or electron)
- "Q"-Event = Shower + Muon Track (for 8~9 jets + 1 muon + 1 neutrinos)
- "Double-bang" Event = Shower + Tau decay (for 8~9 jets + 1 tau + 1 neutrinos)

NP Event Rate for each cases



Event Spectrum SM CC+NC vs. NP



Extensive Air Shower Event Analysis

Extensive Air Shower

- Longitudinal Development

Atmospheric Interaction Depth $X = \int_{x_0}^{x_f} \rho(x)\ dx$

$$N(X) = N_{max}\left(\frac{X - X_0}{X_{max} - X_0}\right)^{\frac{X_{max}-X_0}{\lambda}} \exp\left(\frac{X_{max} - X}{\lambda}\right)$$

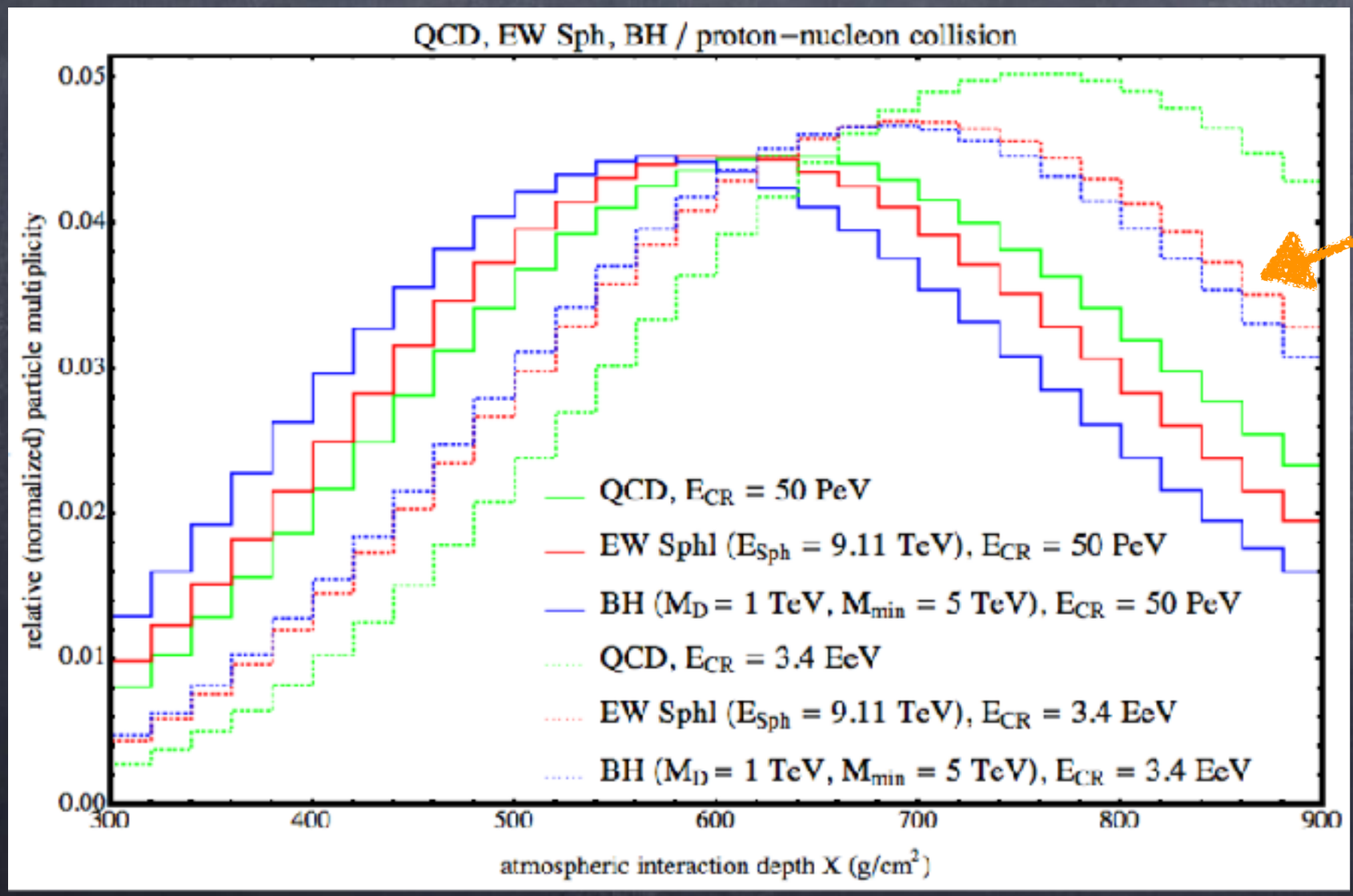
We use Gaisser-Hillas function
as a generic fitting for EAS

we use

- our own MC generator for Parton Level Event generator
- PYTHIA8 for primary hadronization
- AIRES 2.8.4 package for cascade simultion in Air Shower
  - SYBILL 2.1 for hadronic interaction

Extensive Air Shower

- Longitudinal Development



Similar to Heavy Nuclei case

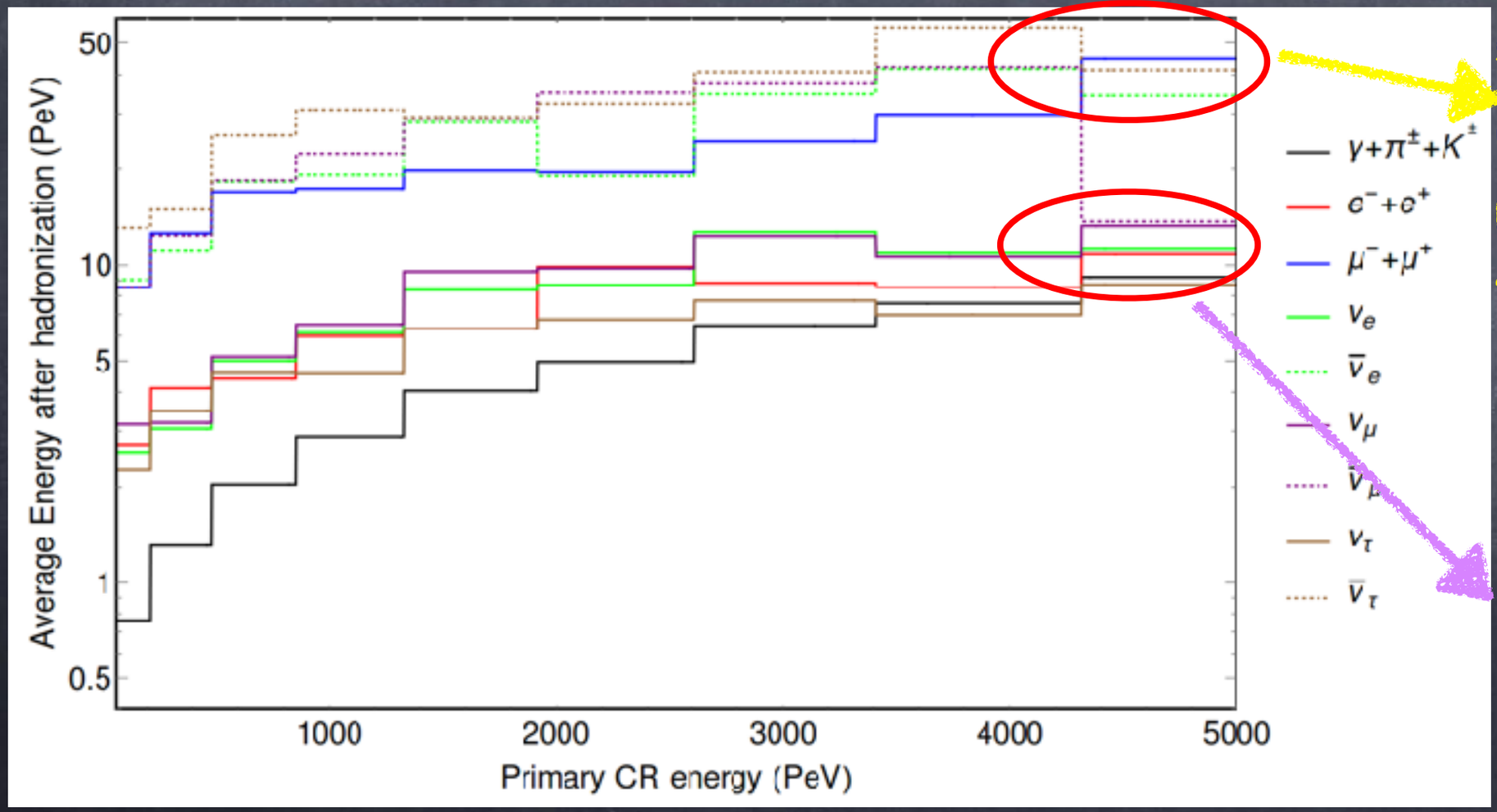
(smaller Xmax values)

High Altitude

Low Altitude

Extensive Air Shower

- Average Energies after primary harmonization



Energetic muons and neutrinos from Sphaleron Hard-process

Pions and photons from ordinary QCD Shower

Conclusion

- Non-Resonance type New Physics above O(100) PeV neutrinos energies can be tested in large volume neutrino telescopes.
- Uncertainty of UHE neutrino flux is quite large, and new physics contribution still can hide in them. Future Experiments, They can be tested further.
- Exotic event topologies might be helpful to identify NP event in the neutrino detector and ground CR detector array.

Thank you