Testing RG Evolution of Neutrino Mixing with IceCube Double Bang Events

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arXiv:2511.07541, PLB 875 (2026) 140322

In Collaboration with
Carlos A. Argüelles, K.S. Babu, Vedran Brdar

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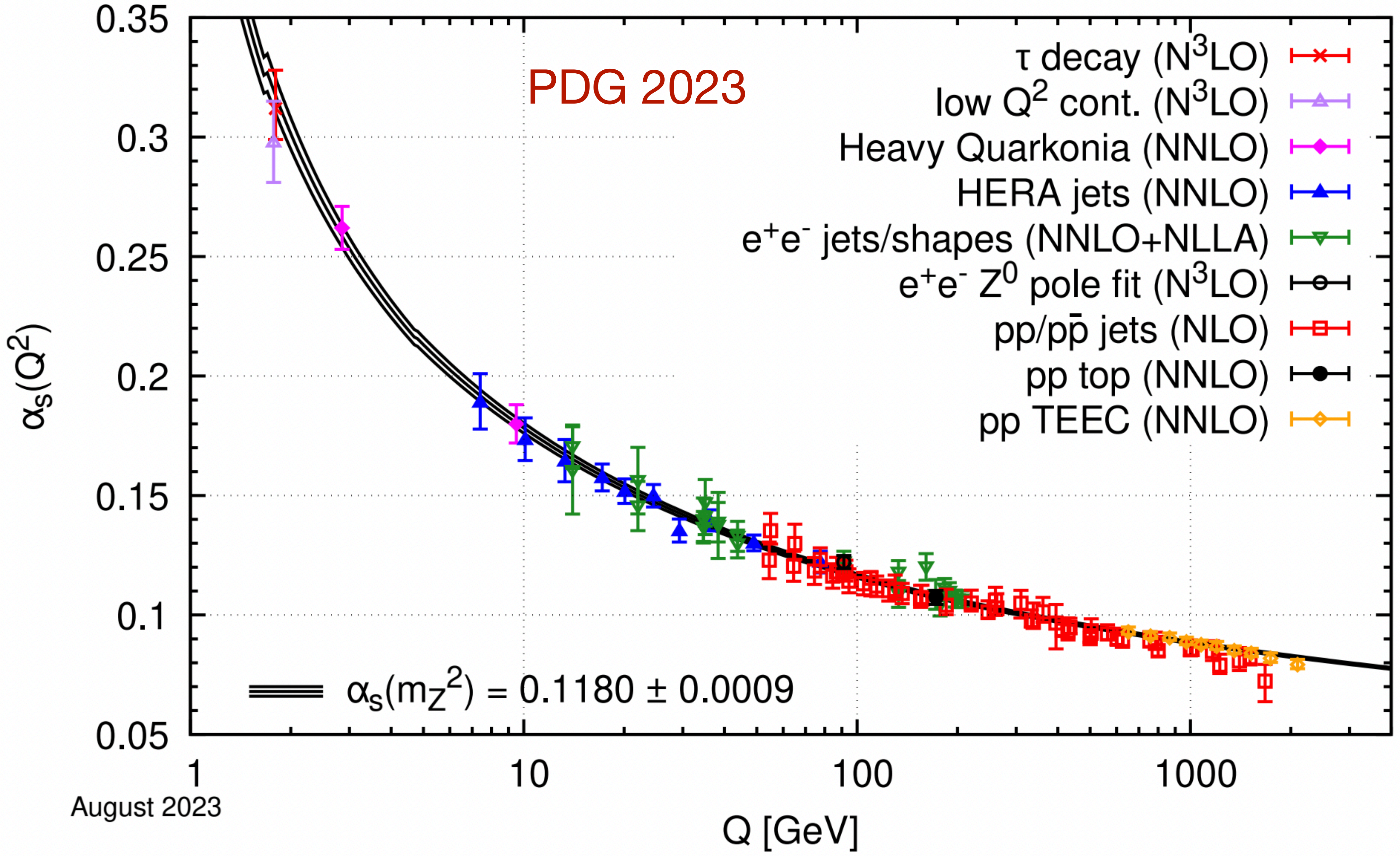
Testing Neutrino Mass Models

- There are many neutrino mass models to explain the origin of neutrino mass Mohapatra, Senjanovic, PRL1980; Zee PLB1980; Babu PLB1988
- The test of any model can be –
  - Unique signature of the new fields
    e.g. single/double charged scalar
  - Direct detection of the new fields e.g. heavy sterile neutrino decaying to SM, detectable particles

The neutrino parameters can be subject to observable Renormalization Group (RG) running in a BSM scenario

Revisiting RG running:
Renormalization Group Evolution (RGE) effects are the changes of quantum field theory parameters with energy.



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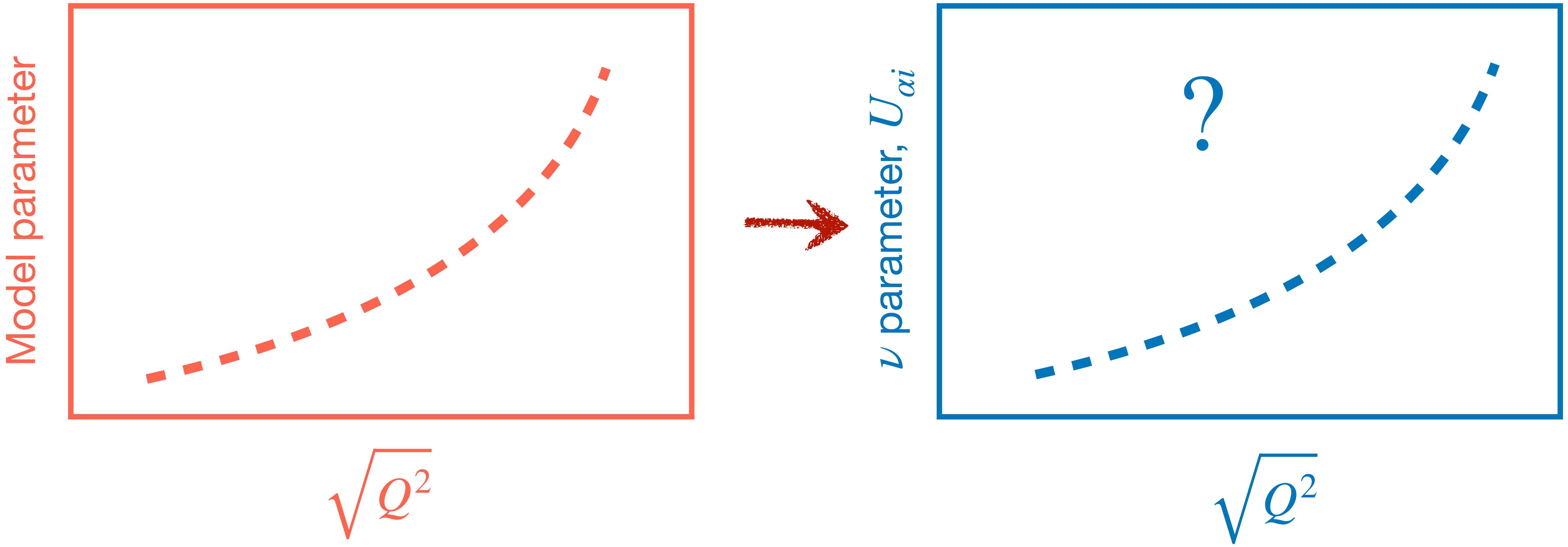
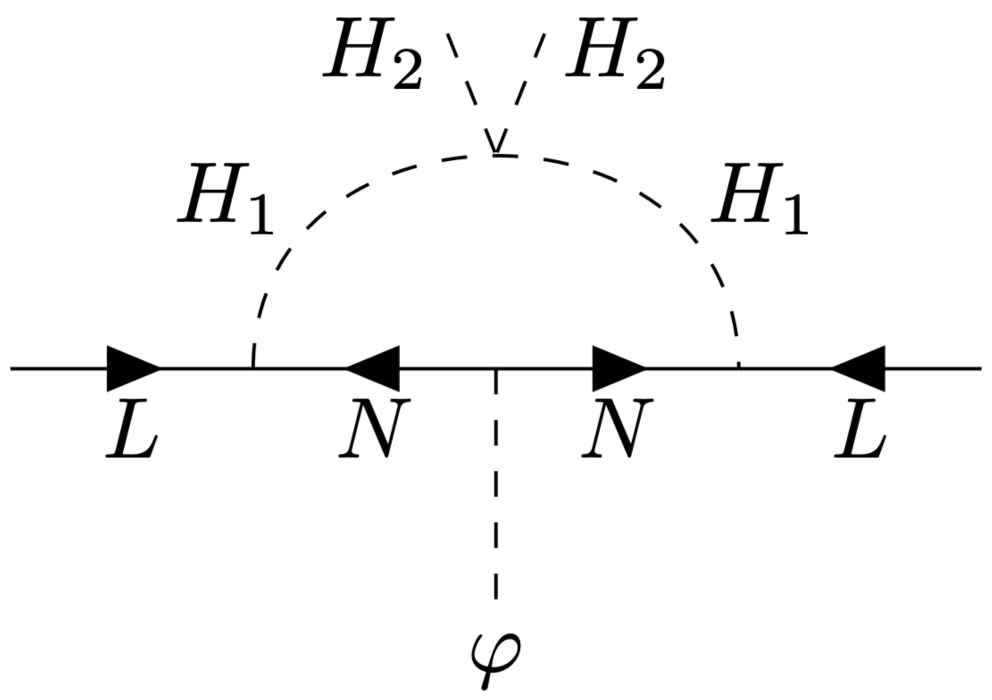


Model Specific Running: from $Y_N(Q^2)$ to $U(Q^2)$

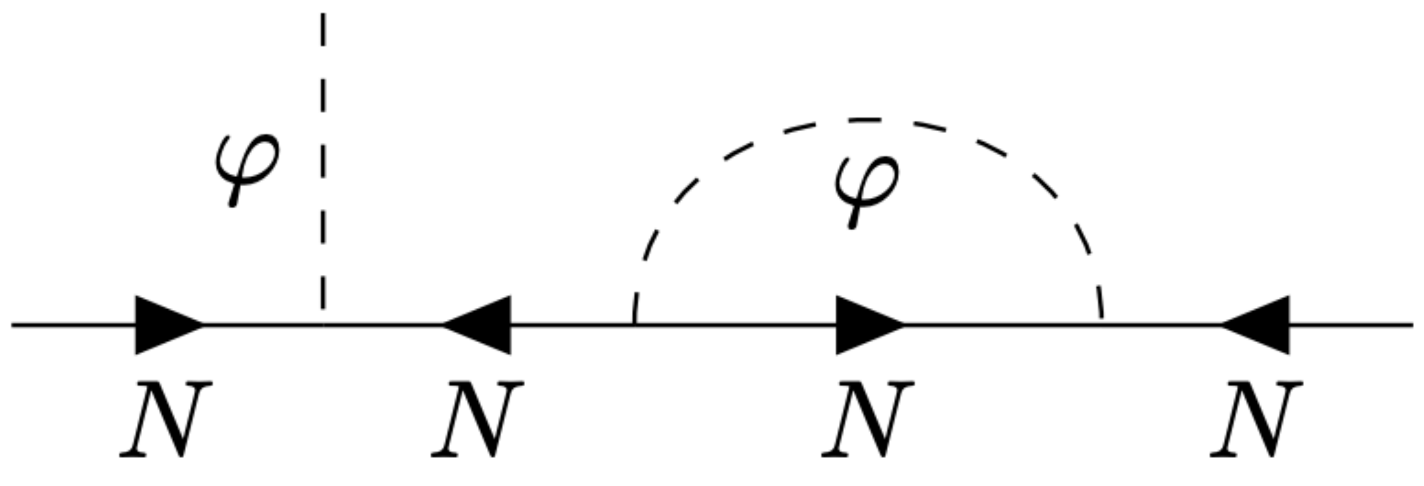
Variation of the scotogenic model

Ma, arXiv:hep-ph/0601225

Babu, Brdar, de Gouvêa, Machado, arXiv:2108.11961

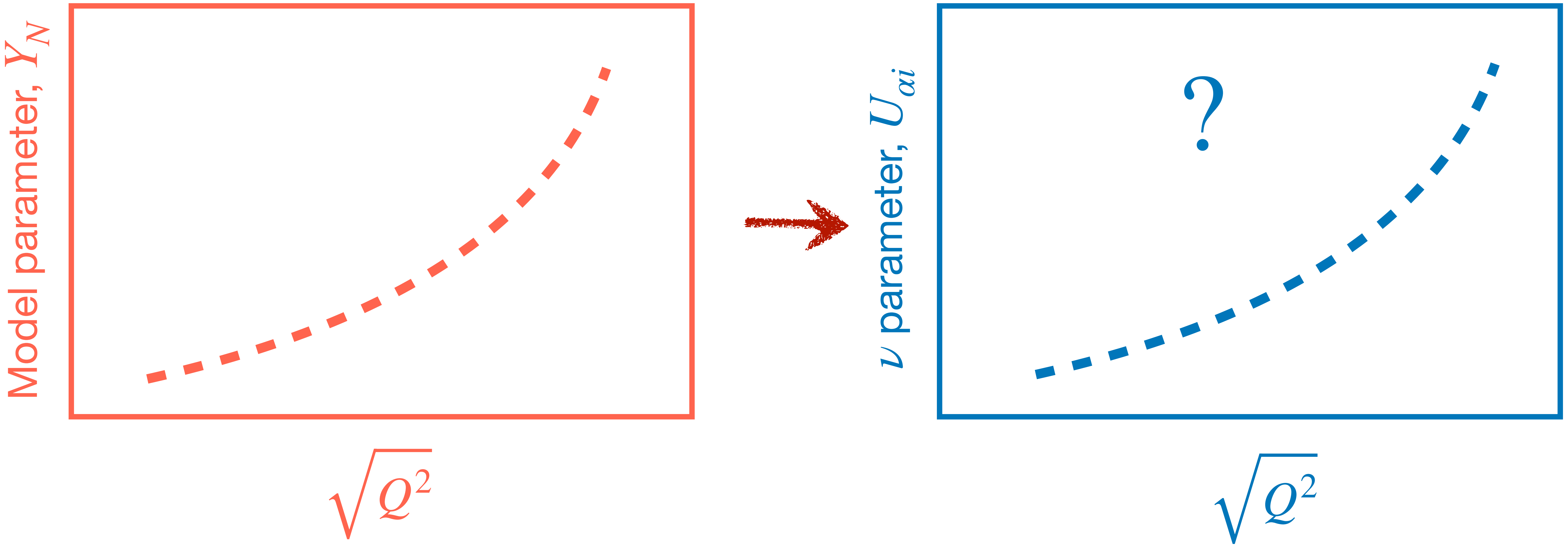


$$-\mathcal{L}_\nu^{(1)} = \overline{L} Y_\nu \tilde{H}_1 N_R + \varphi \overline{N_R^c} Y_N N_R + \text{h.c.}$$



$$16\pi^2 \beta(Y_N) \equiv 16\pi^2 \frac{dY_N}{d\ln|Q|} = 4Y_N \left[Y_N^2 + \frac{1}{2}\mathrm{Tr}(Y_N^2) \right]$$

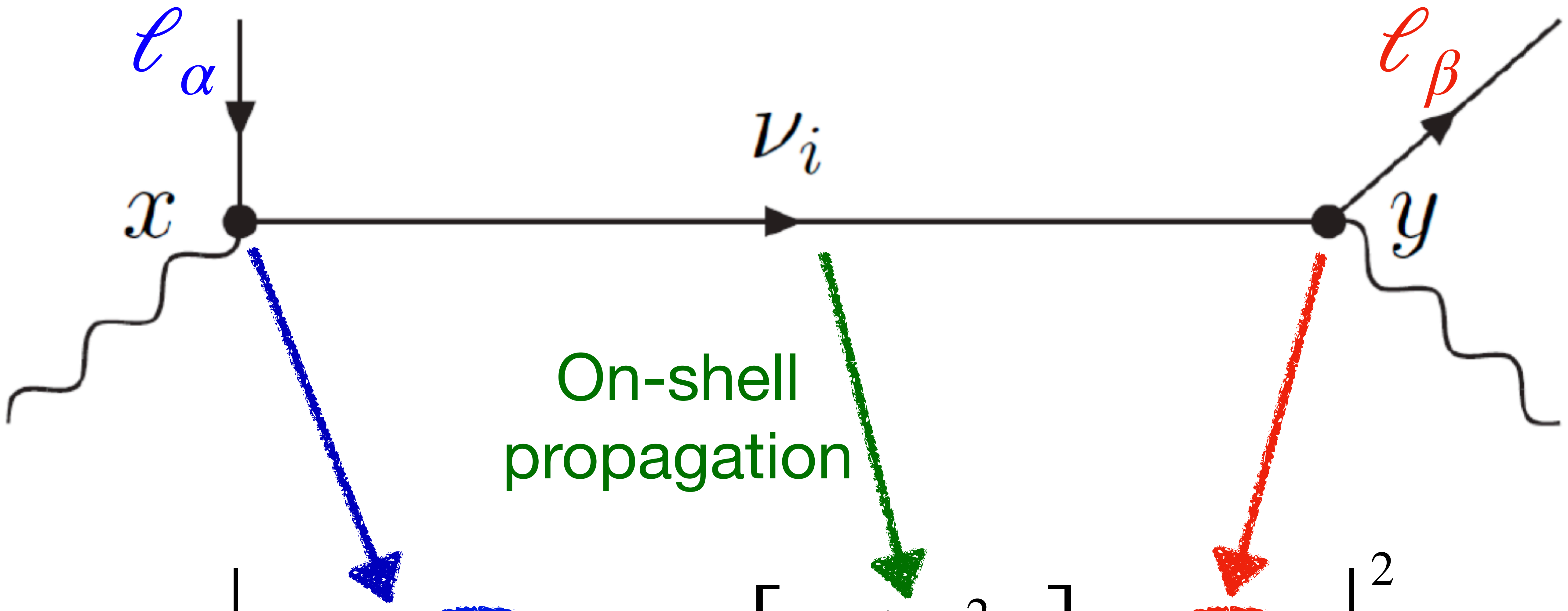
→ PMNS matrix $U(Q^2)$



Oscillation with Mixing Mismatch

Production vertex
at Q_p energy

Q_p is production scale energy



Detection vertex
at Q_d energy

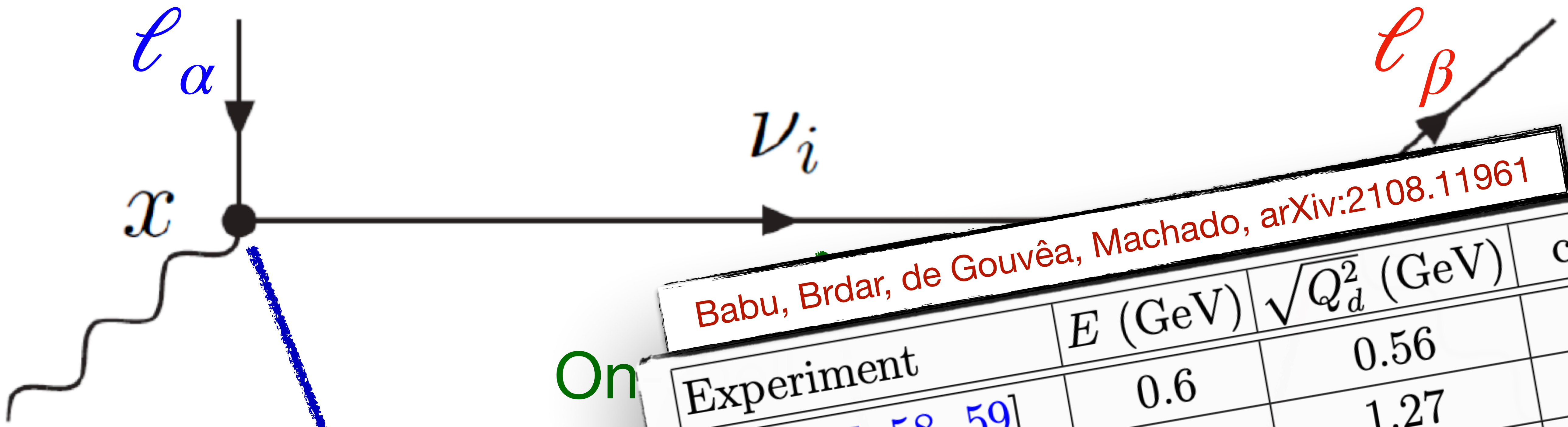
$Q_d \in [0, \sqrt{2 m_N E_\nu}]$

$$P_{\alpha\beta}(L,E) = \left| \sum_i U^*_{\alpha i}(Q_p^2) \exp\left[-i \frac{\Delta m_{i1}^2 L}{2E} \right] U_{\beta i}(Q_d^2) \right|^2$$

$U(Q_p^2) \neq U(Q_d^2)$ affects $P_{\alpha\beta}$.

Mismatch impacts flavor oscillation.

Oscillation with Mixing Mismatch



Production vertex
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Q_p is production scale energy

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On...
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$E_\nu]$

$$P_{\alpha\beta}(L,E) = \left| \sum_i U^*_{\alpha i}(Q_p^2) \; \text{ex}\ldots \right.$$

$U(Q_p^2) \neq U\ldots$

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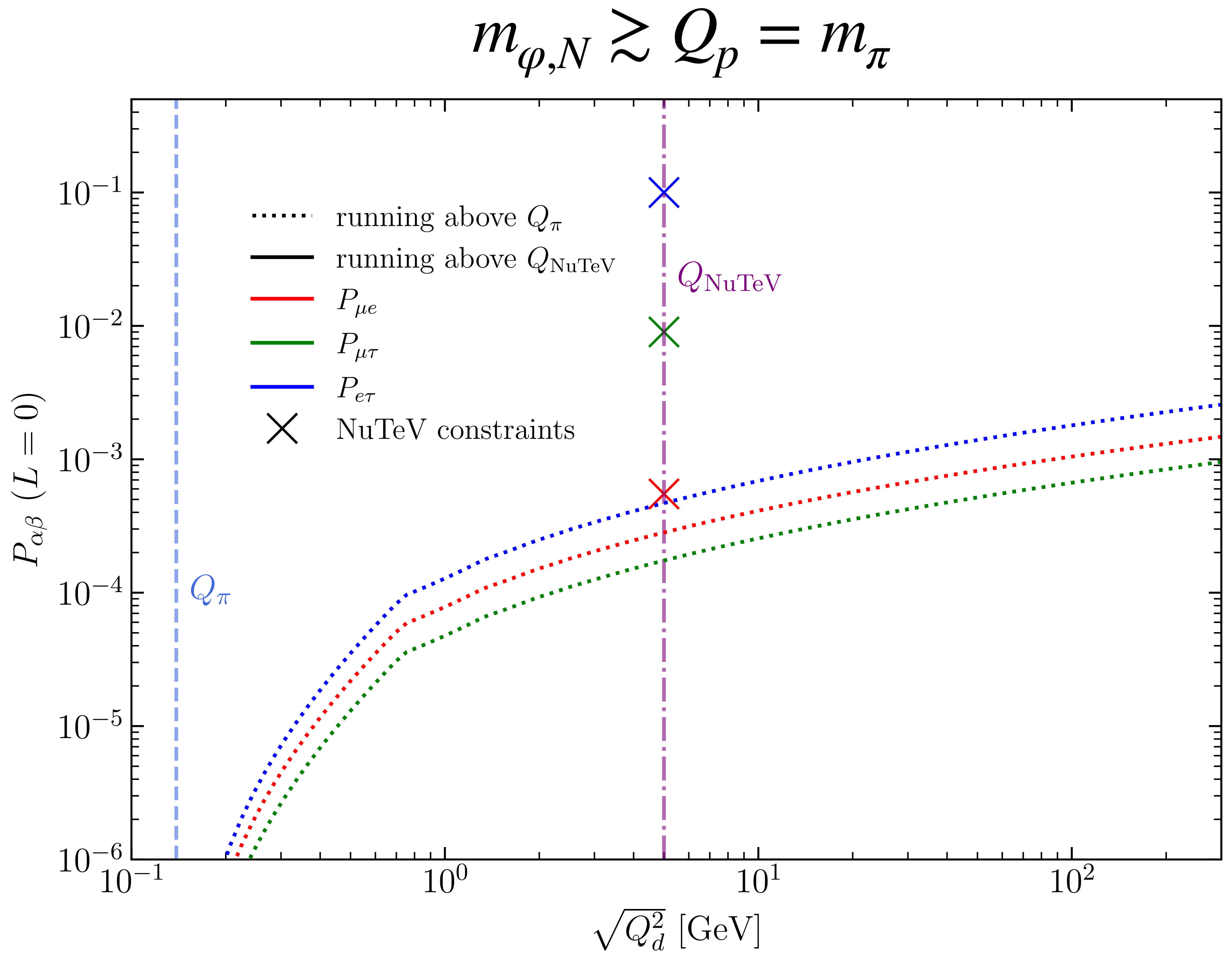
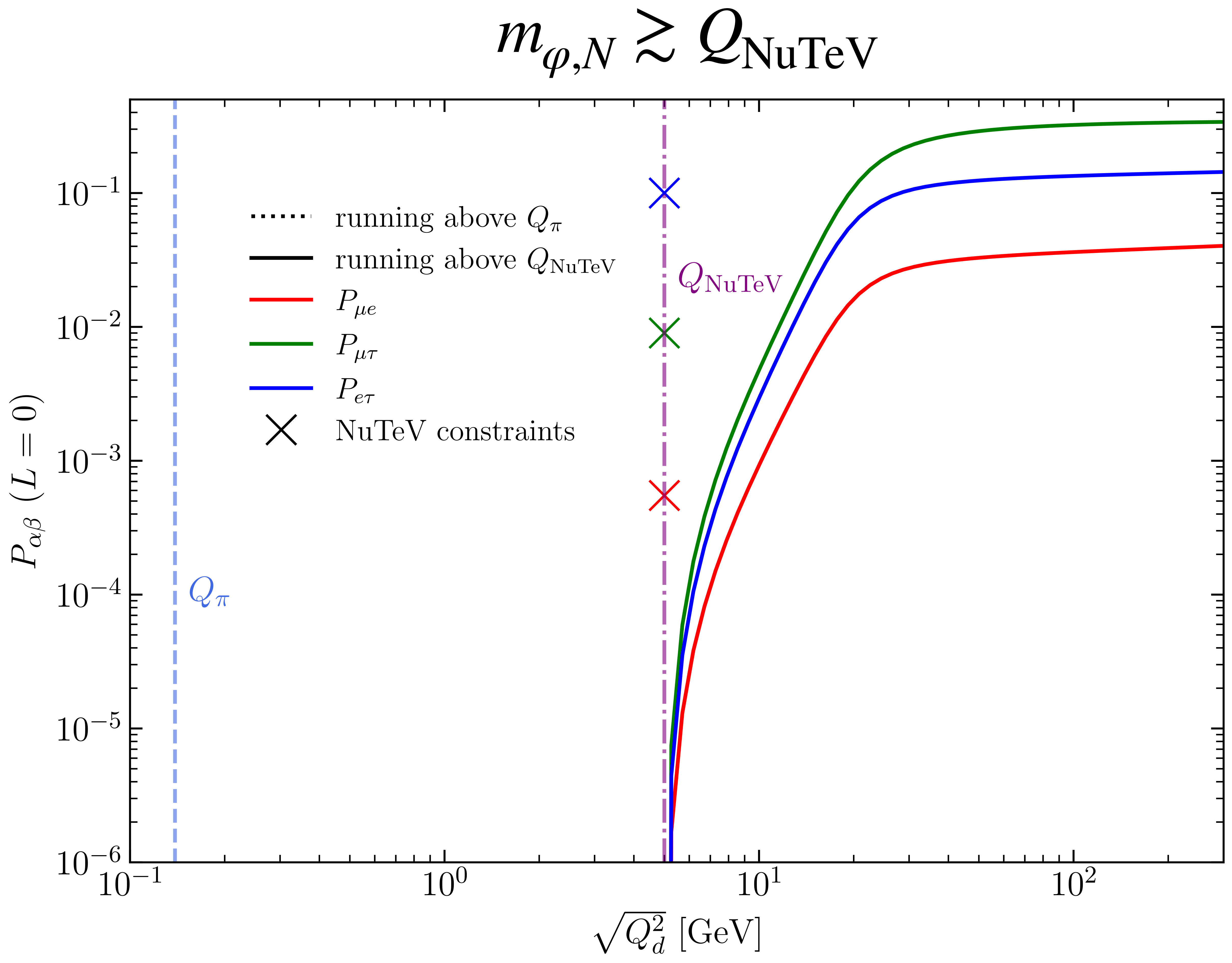
Babu, Brdar, de Gouvêa, Machado, arXiv:2108.11961

Experiment	E (GeV)	$\sqrt{Q_d^2}$ (GeV)	channel	constraint
T2K [47, 58, 59]	0.6	0.56	–	–
NOvA [48, 60, 61]	2.1	1.27	–	–
ICARUS [65]	17	3.94	$\nu_\mu \to \nu_e$	3.4×10^{-3}
CHARM-II [66]	24	4.70	$\nu_\mu \to \nu_e$	2.8×10^{-3}
NOMAD [62–64]	47.5	6.64	$\nu_\mu \to \nu_e$	7.4×10^{-3}
			$\nu_\mu \to \nu_\tau$	1.63×10^{-4}
NuTeV [67, 68]	250	15.30	$\nu_\mu \to \nu_e$	5.5×10^{-4}
			$\nu_e \to \nu_\tau$	0.1
			$\nu_\mu \to \nu_\tau$	9×10^{-3}

Stringent constraints come from short-baseline neutrino experiments, the highest energy constraints from NuTeV

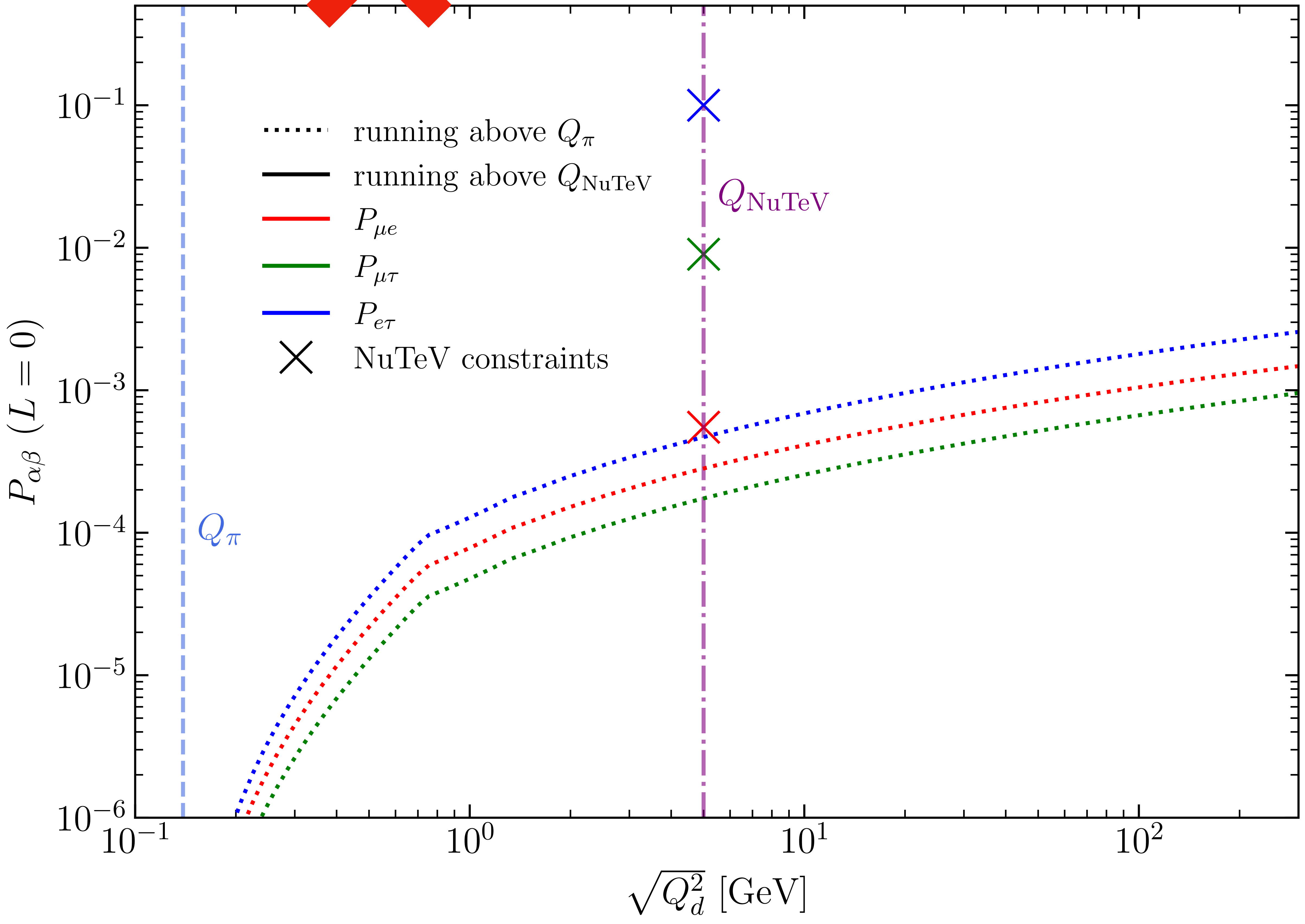
BSM with Large Transition $P_{\alpha\beta}$



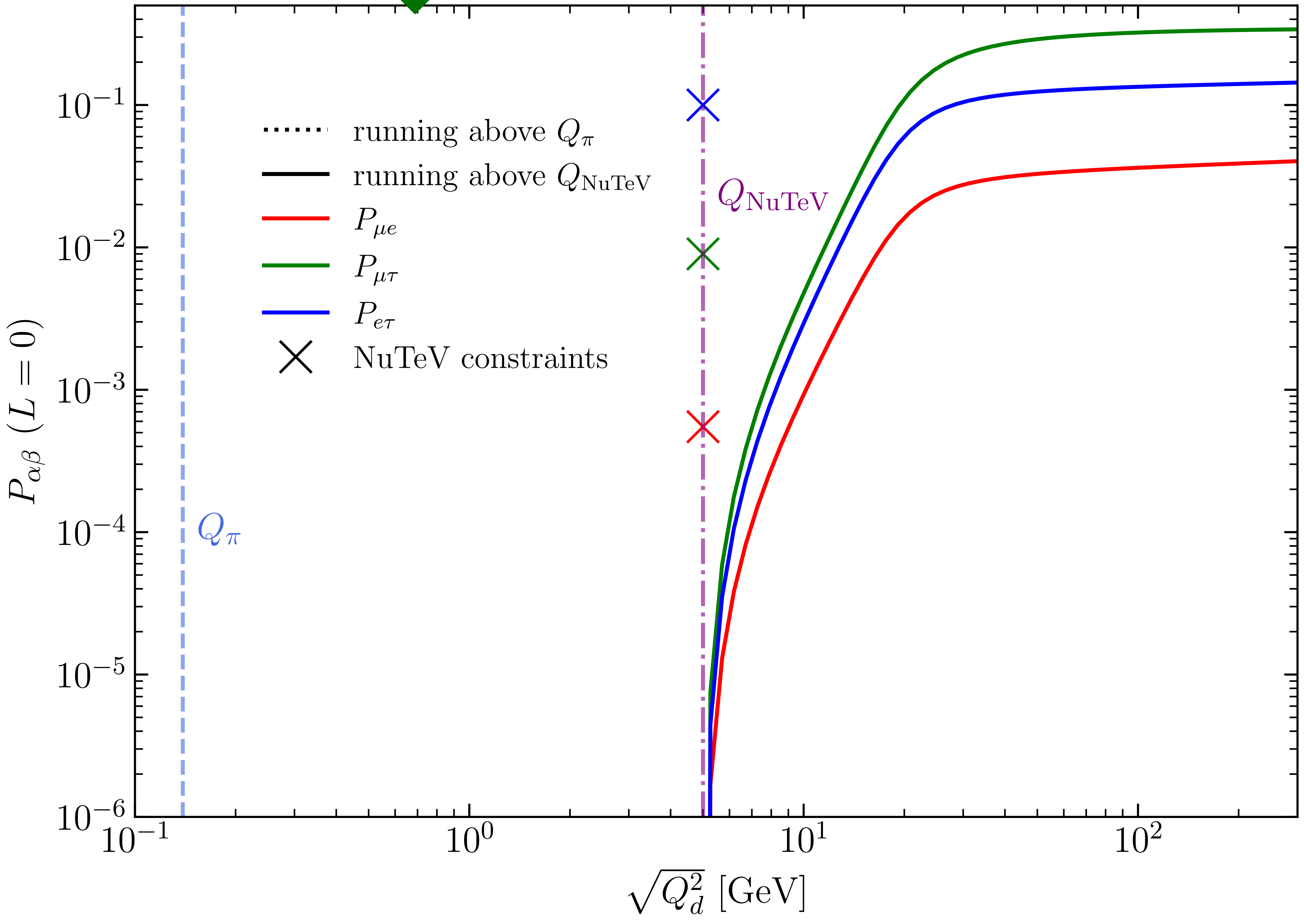


BSM with Large Transition $P_{\alpha\beta}$

✗ $m_{\varphi,N} \gtrsim Q_p = m_\pi$

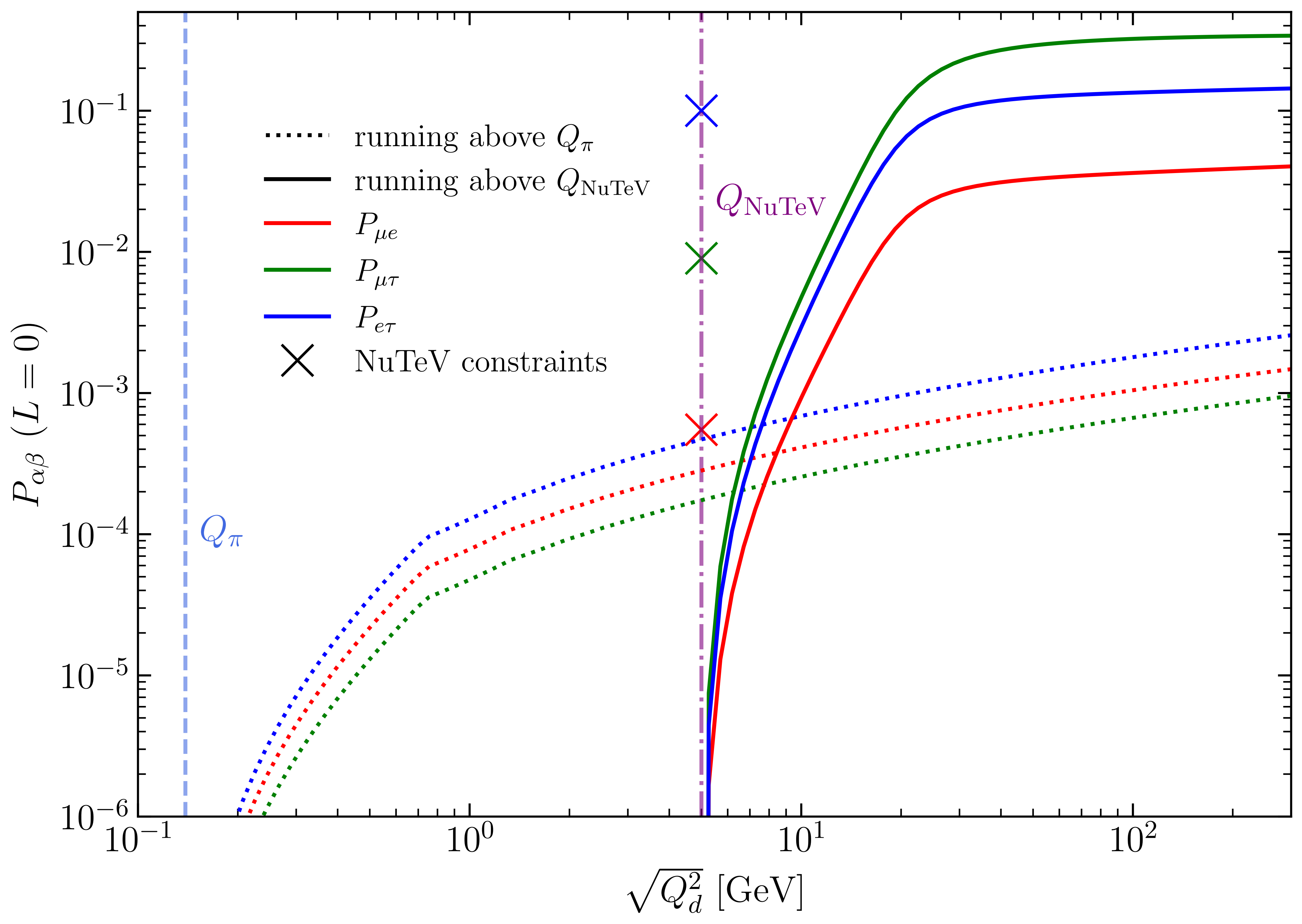


✓ $m_{\varphi,N} \gtrsim Q_{\rm NuTeV}$



Testing RG Running

Which experiment to look at?



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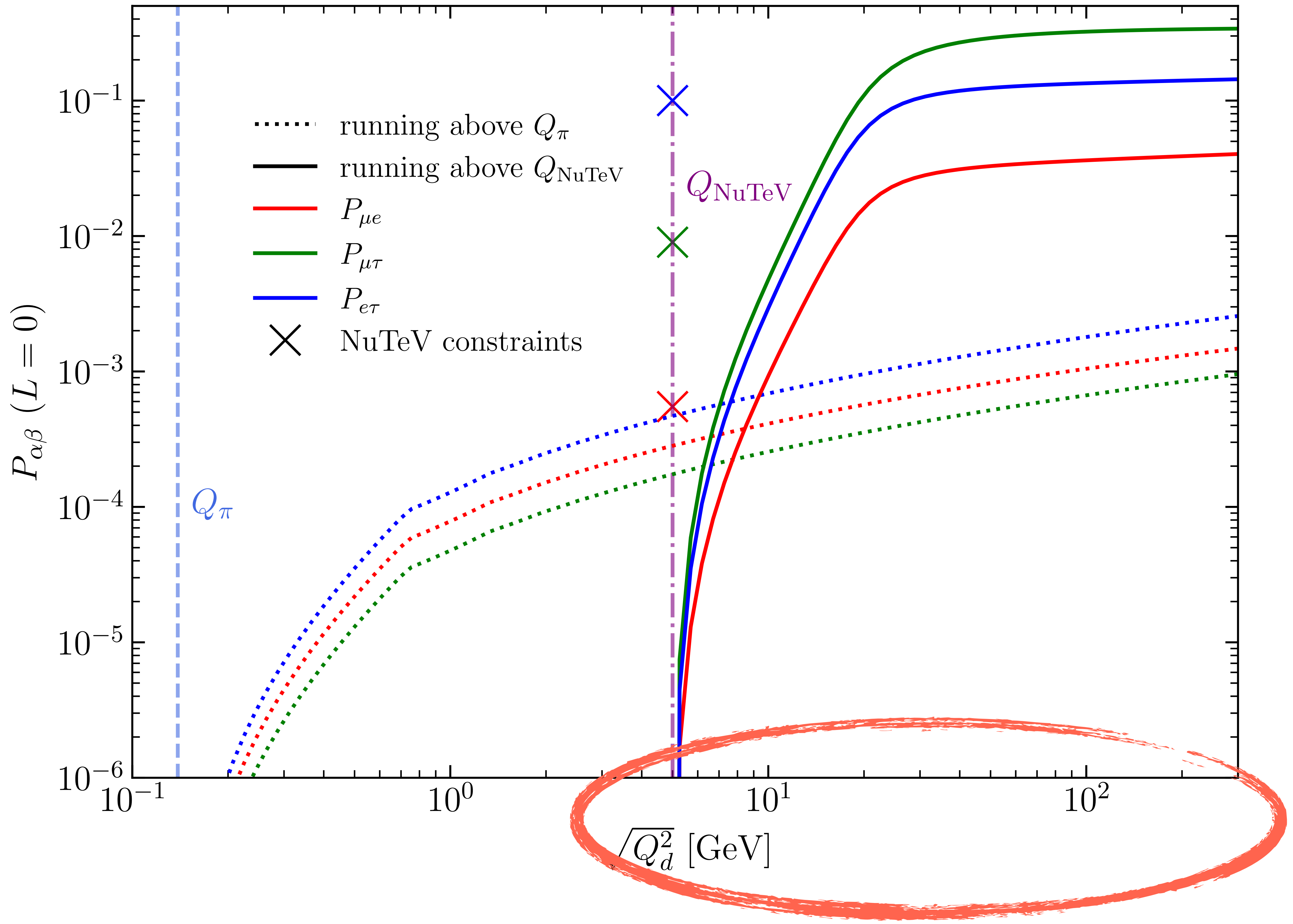
Access to high-energy neutrinos



Testing RG Running

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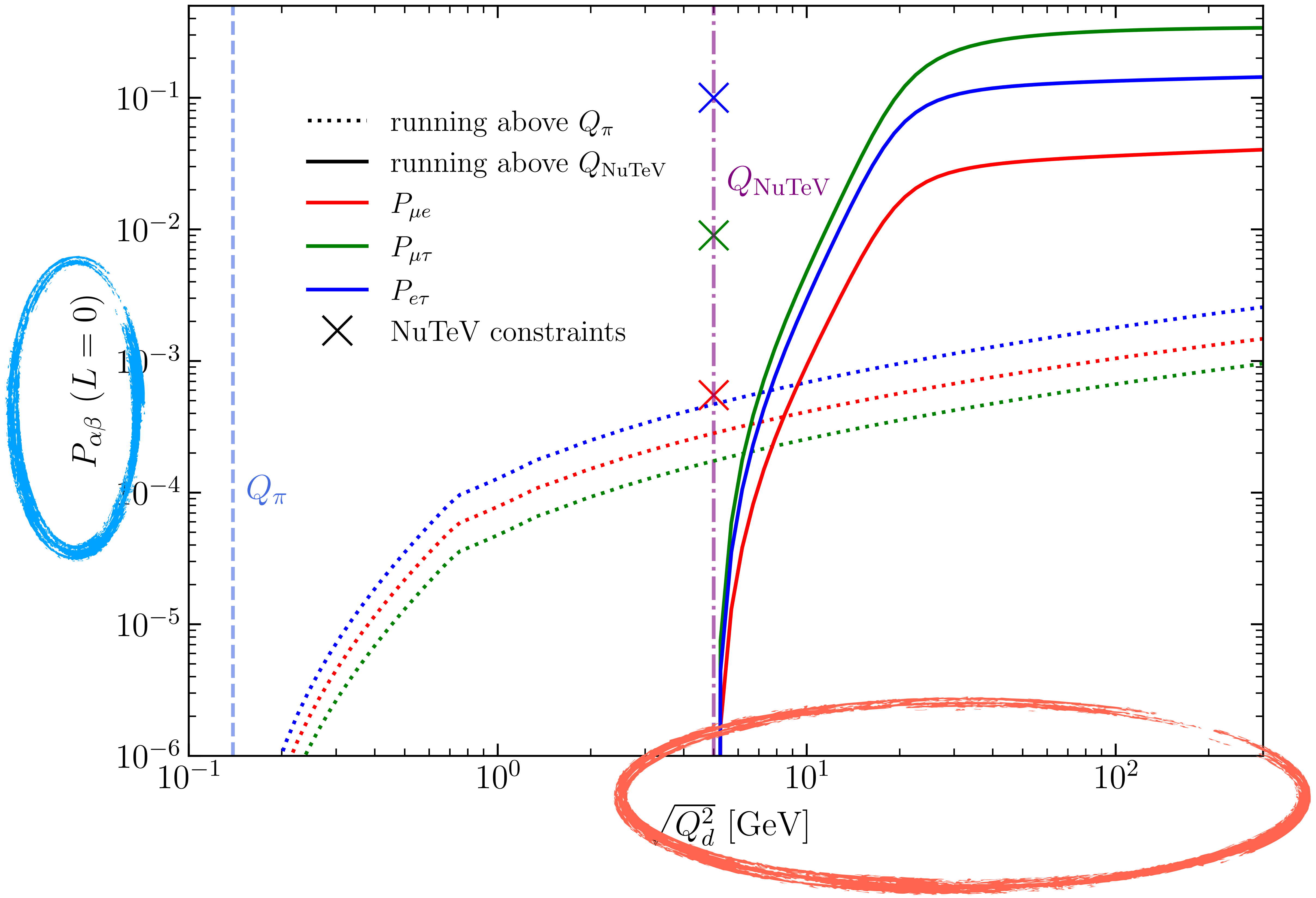
Access to high-energy neutrinos

Sensitive to flavor oscillation $P_{\alpha\beta}$



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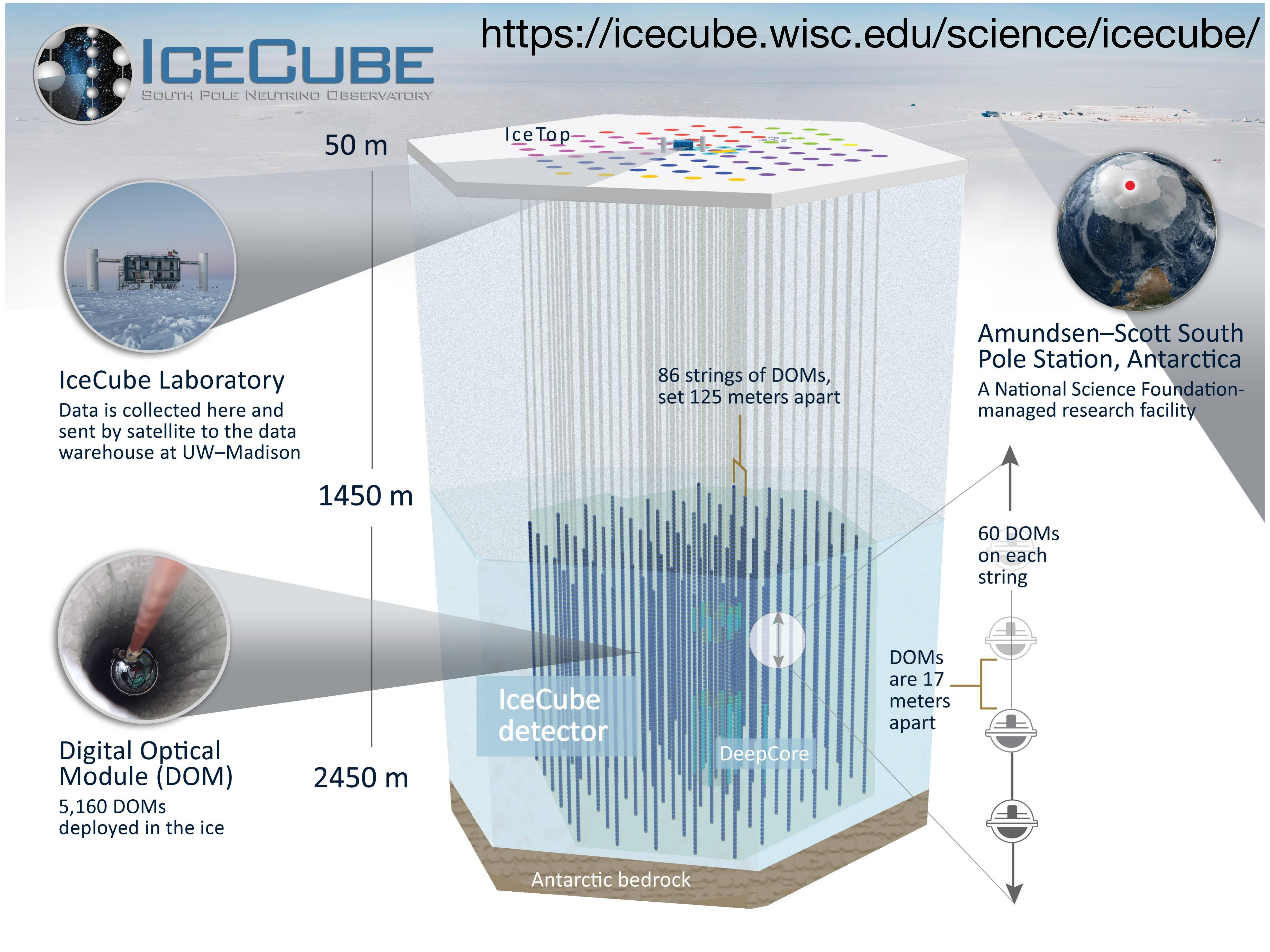
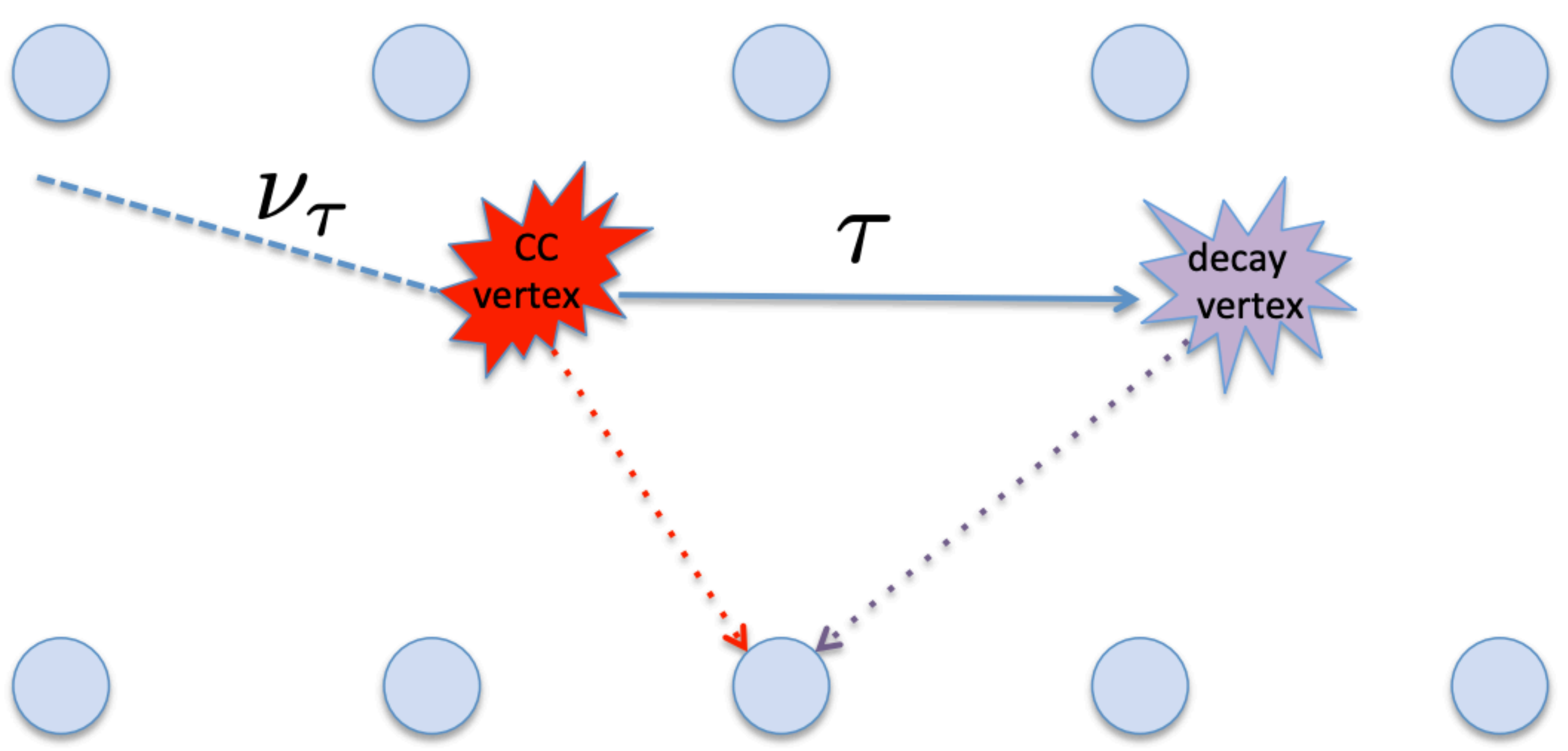


Tau Neutrino Detection at IceCube

- **double bangs** morphology at high-energy:
  Learned and Pakvasa, arXiv:hep-ph/9405296
  - ☑ Tau producing vertex — first shower
  - ☑ Tau decaying vertex — second shower
- $50\,\mathrm{m/PeV}$ separation
- High-energy starting events (HESE) data in 7.5 years data [IceCube Collaboration, arXiv:2011.03545]
  - Total 102 events (ν_e, ν_μ, ν_τ) → Only 4 ν_τ-candidates
  - 4 ν_τ-candidates → 2 ν_τ-events with high likelihood of being ν_τ [IceCube Collaboration, arXiv:2011.03561]

IceCube Collaboration, arXiv:1509.06212



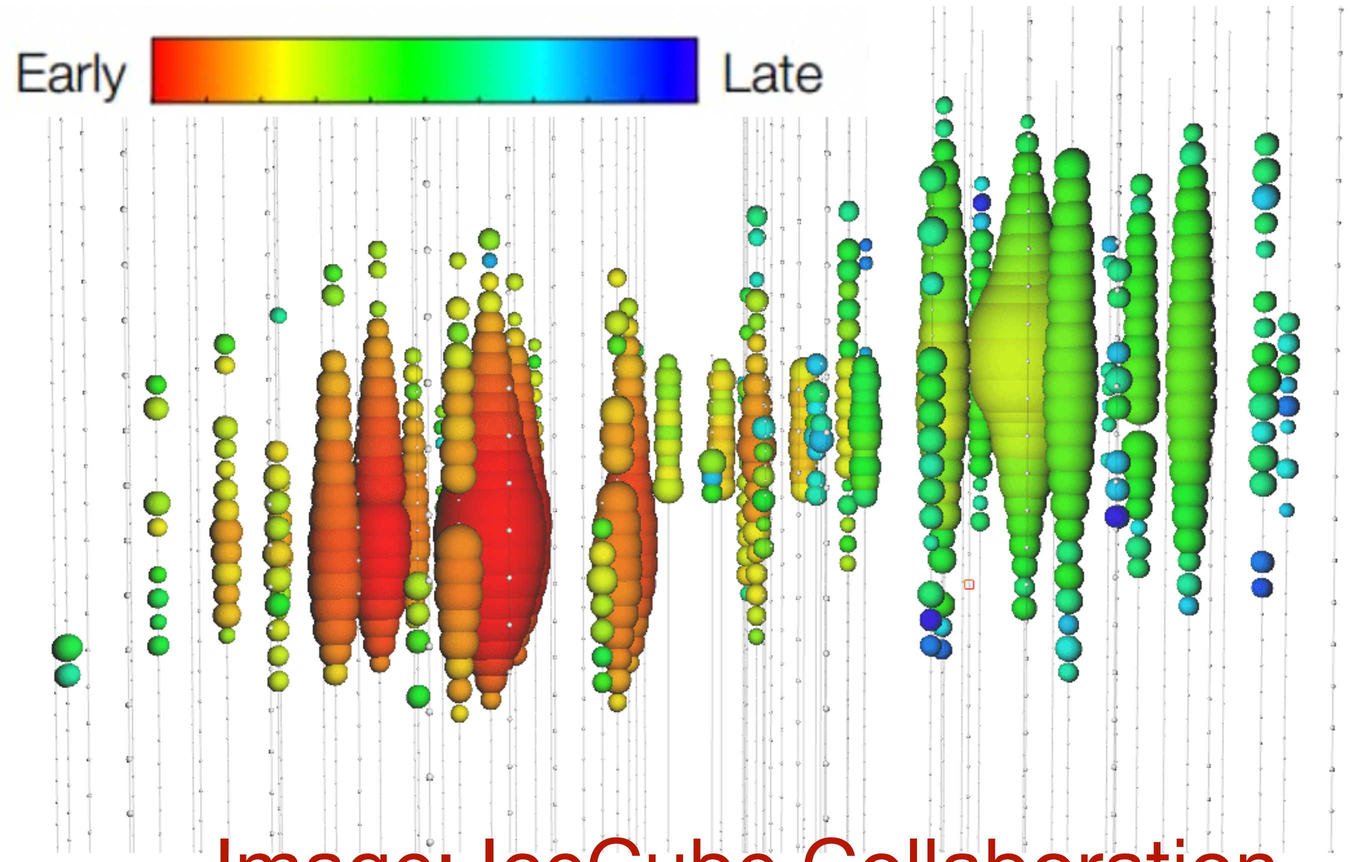


Image: IceCube Collaboration

BSM weight and Number of Events N_β

Number of ν_β neutrino events,

$$N_\beta = T \int dE_\nu \, w^{\rm BSM}_{\alpha\to\beta}(E_\nu)\, \epsilon_\beta(E_\nu)\, \Phi_{\nu_\alpha}(E_\nu)\, \sigma_{\nu N}(E_\nu)$$

T = Detector livetime

ϵ_α = Detector efficiency

Φ_{ν_α} = Incoming atmospheric and astrophysical flux

$\sigma_{\nu N}$ = Deep inelastic cross section

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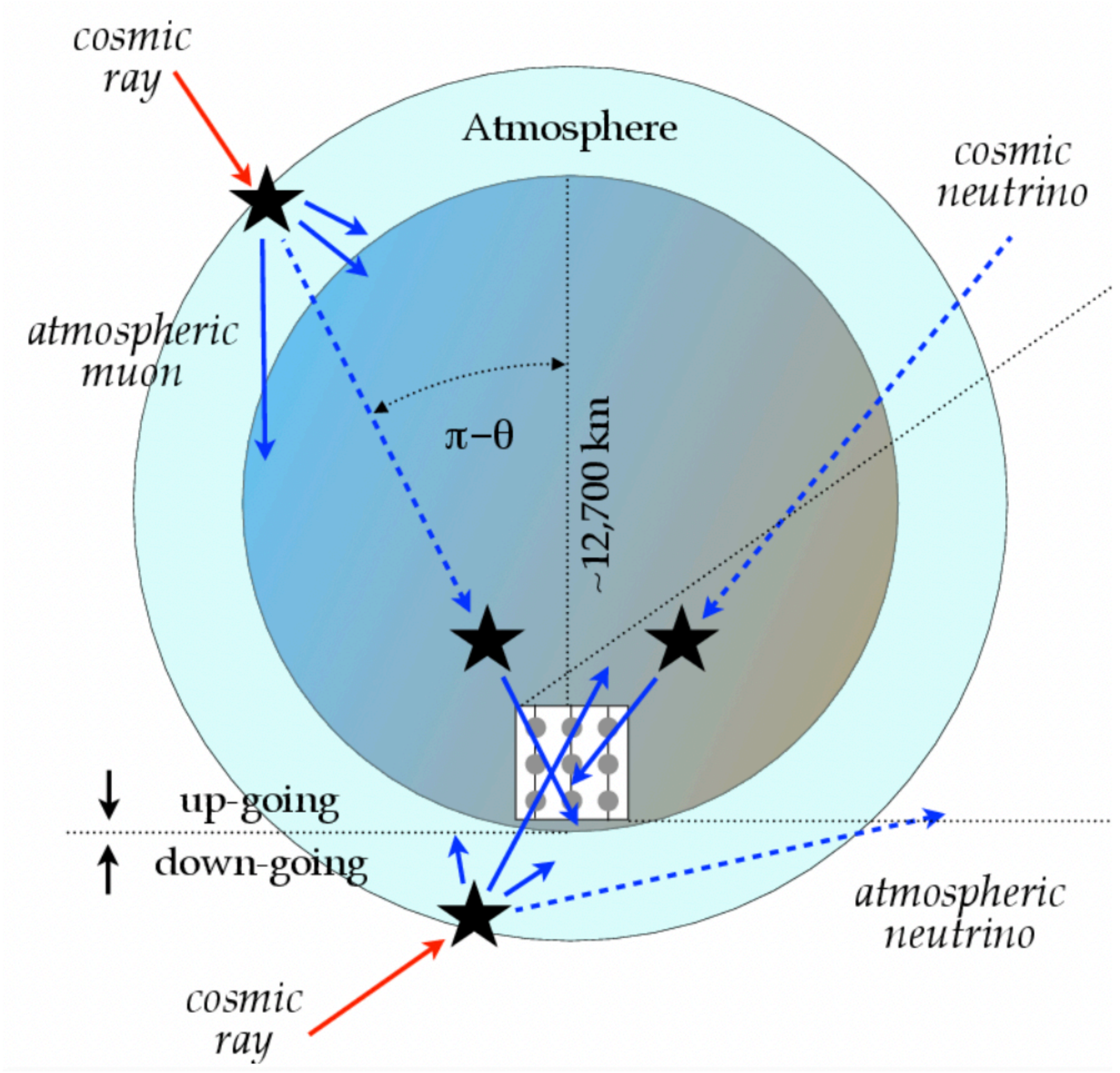
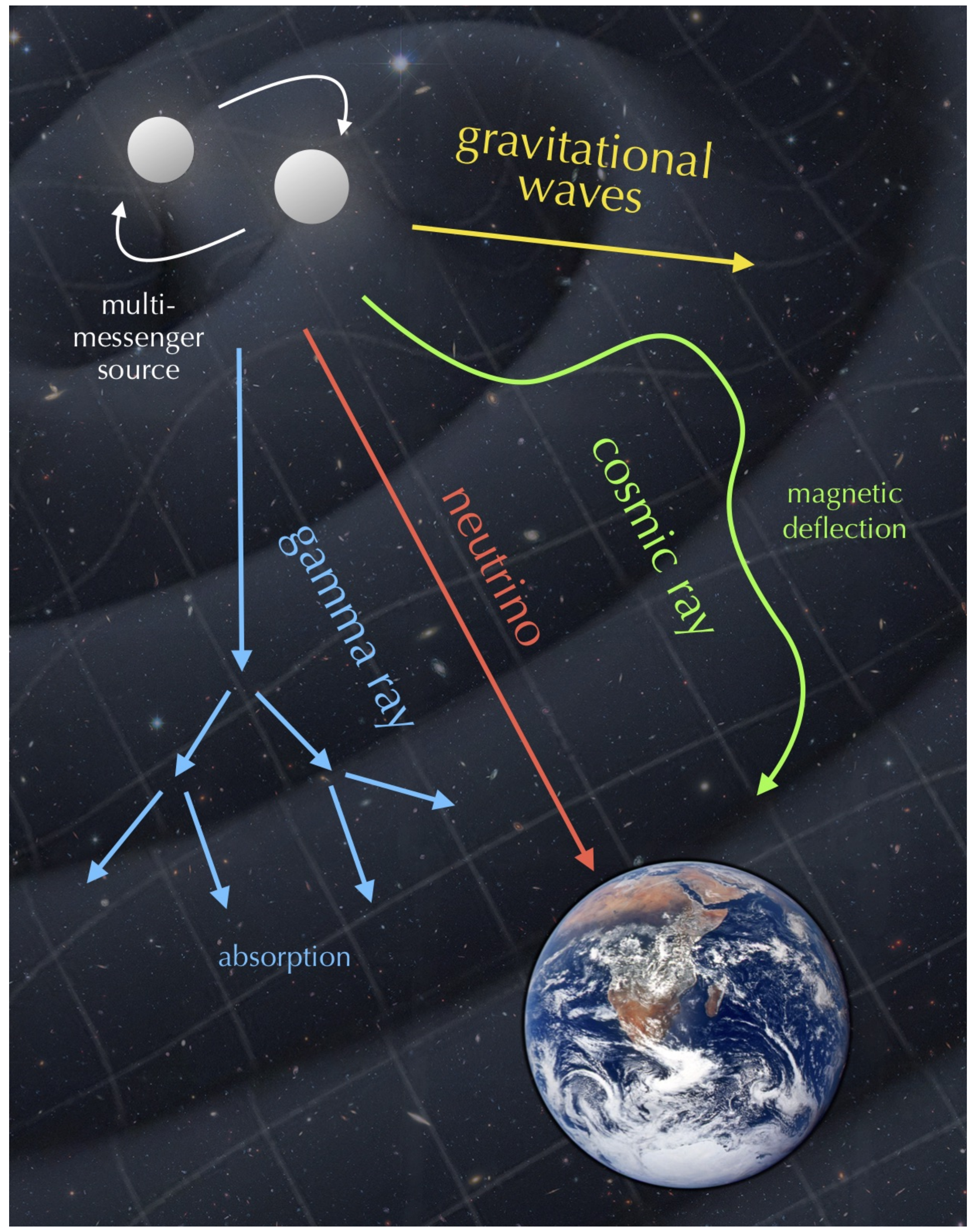
BSM weight from the deep inelastic scattering cross section weighted by $P_{\alpha\beta}(E_\nu, Q^2)$,

$$w^{\rm BSM}_{\alpha\to\beta}(E_\nu) = \frac{\int_\nu P_{\alpha\beta}(E_\nu, Q^2) + \int_{\bar\nu} P_{\bar\alpha\bar\beta}(E_\nu, Q^2)}{\int_\nu \; + \; \int_{\bar\nu}},$$

$$\int_{\nu/\bar\nu} = \int dx\, dQ^2 \, \frac{d^2\sigma_{\nu/\bar\nu}}{dx\, dQ^2}$$

$P_{\alpha\beta}$ for Neutrino Fluxes





Atmospheric neutrinos: $L \ll L_{osc}$

$$P_{\alpha\beta} = P_{\alpha\beta}(L=0) = \left| \sum_i U^*_{\alpha i}(Q_p^2)\; U_{\beta i}(Q_d^2) \right|^2$$

Astrophysical neutrinos: $L \gg L_{osc}$

$$P_{\alpha\beta}(L \gg L_{osc}) = \sum_i \left| U_{\alpha i}(Q_p^2) \right|^2 \left| U_{\beta i}(Q_d^2) \right|^2$$

Tau Neutrino Appearance at IceCube

Difference in the number of events,

$$\Delta N_\alpha = (N_{\text{running}} - N_{\text{no running}})_\alpha$$

Standard oscillation: $\Delta N_\mu = \Delta N_\tau = 0$

$N_\tau^{\text{no running}} = 2\text{-}3$ events

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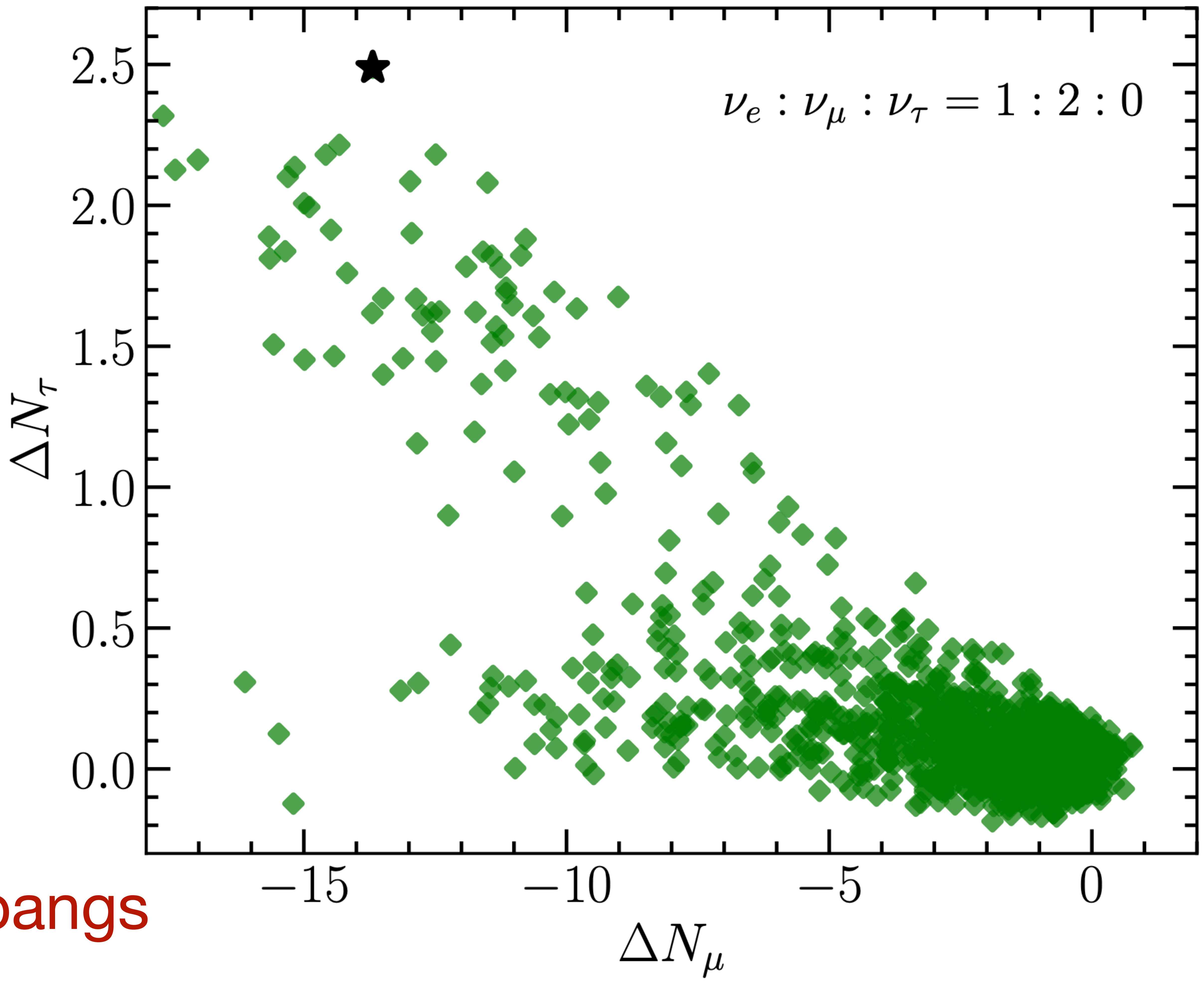
★ benchmark:

maximal number of BSM-induced double bangs



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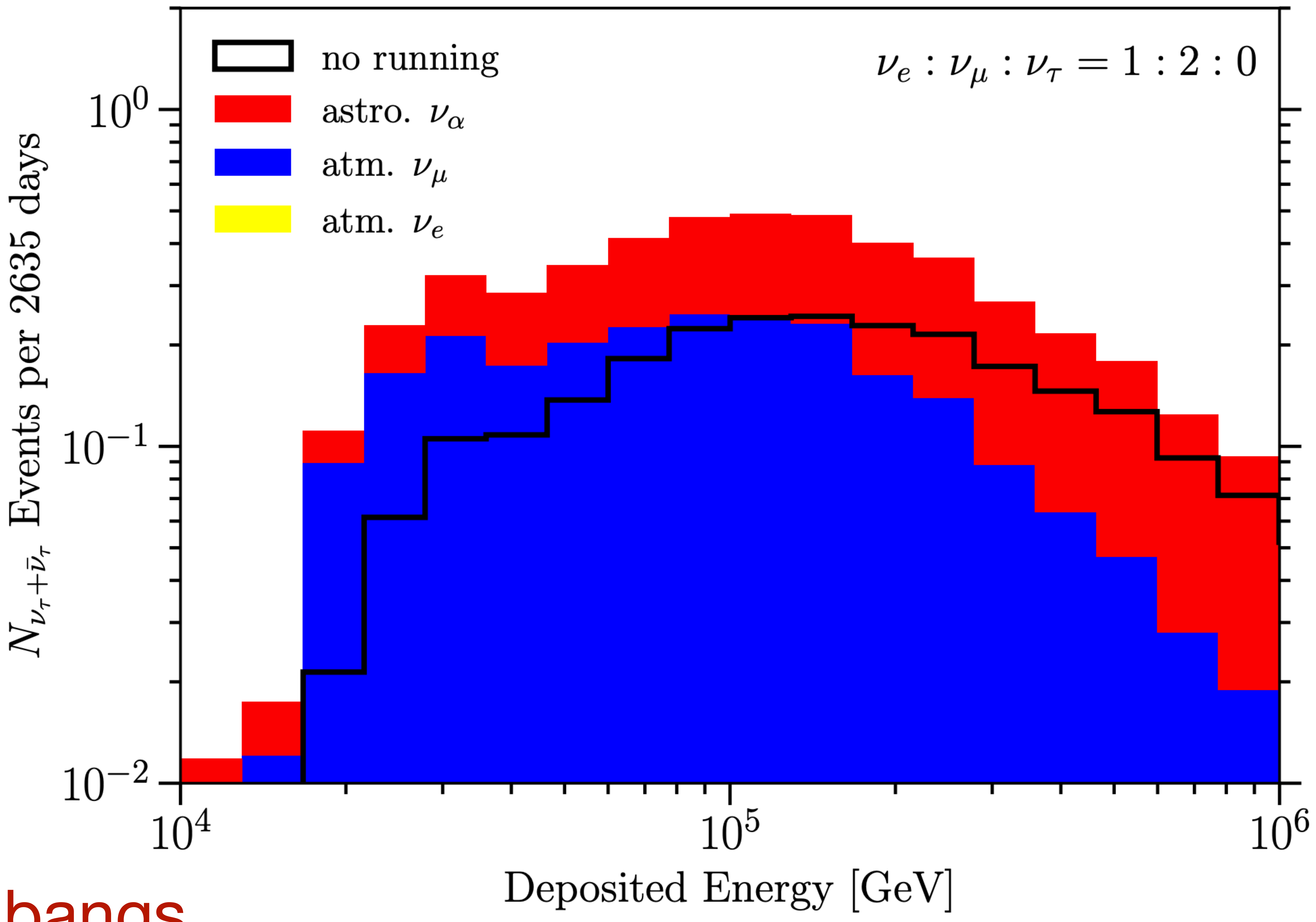
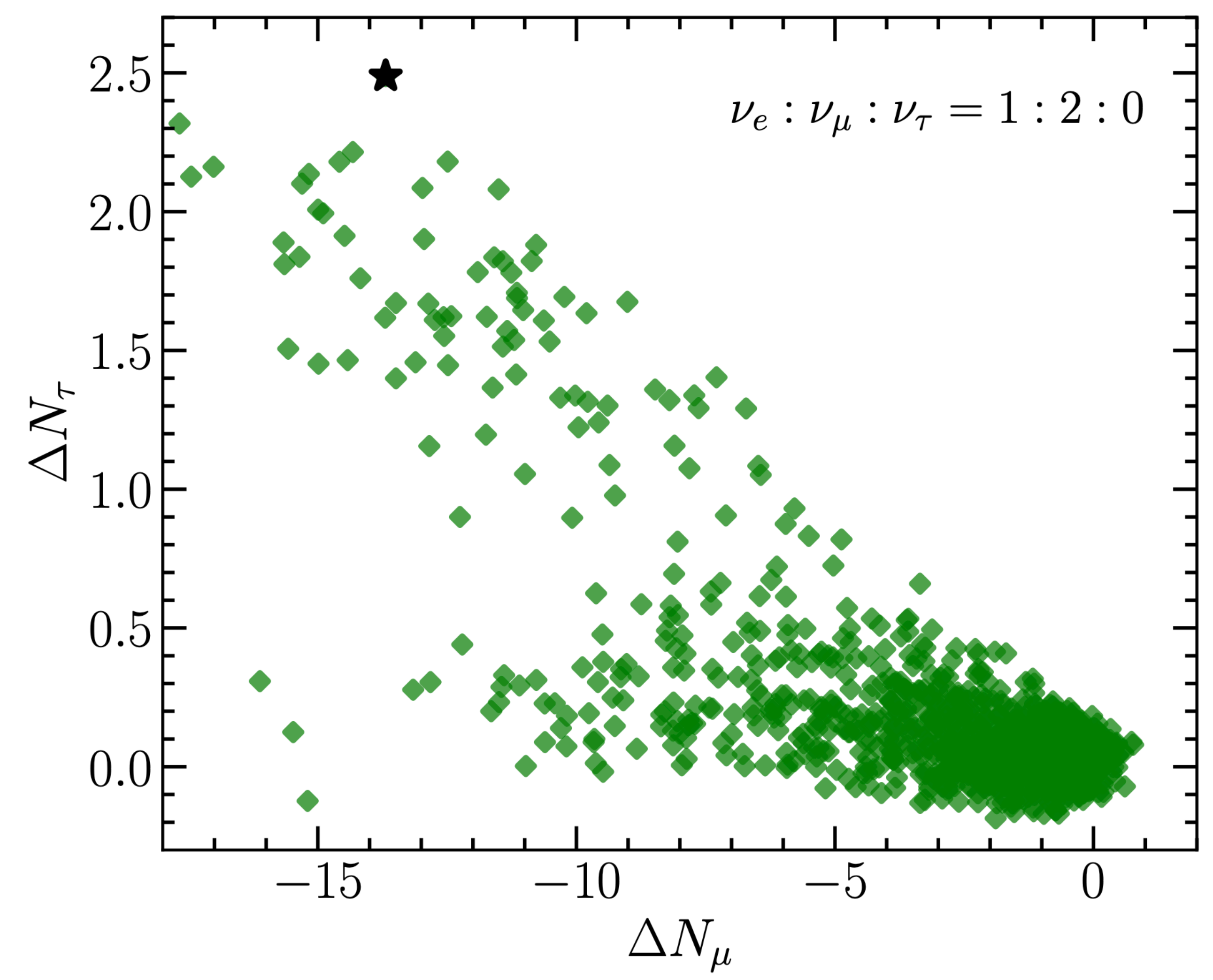
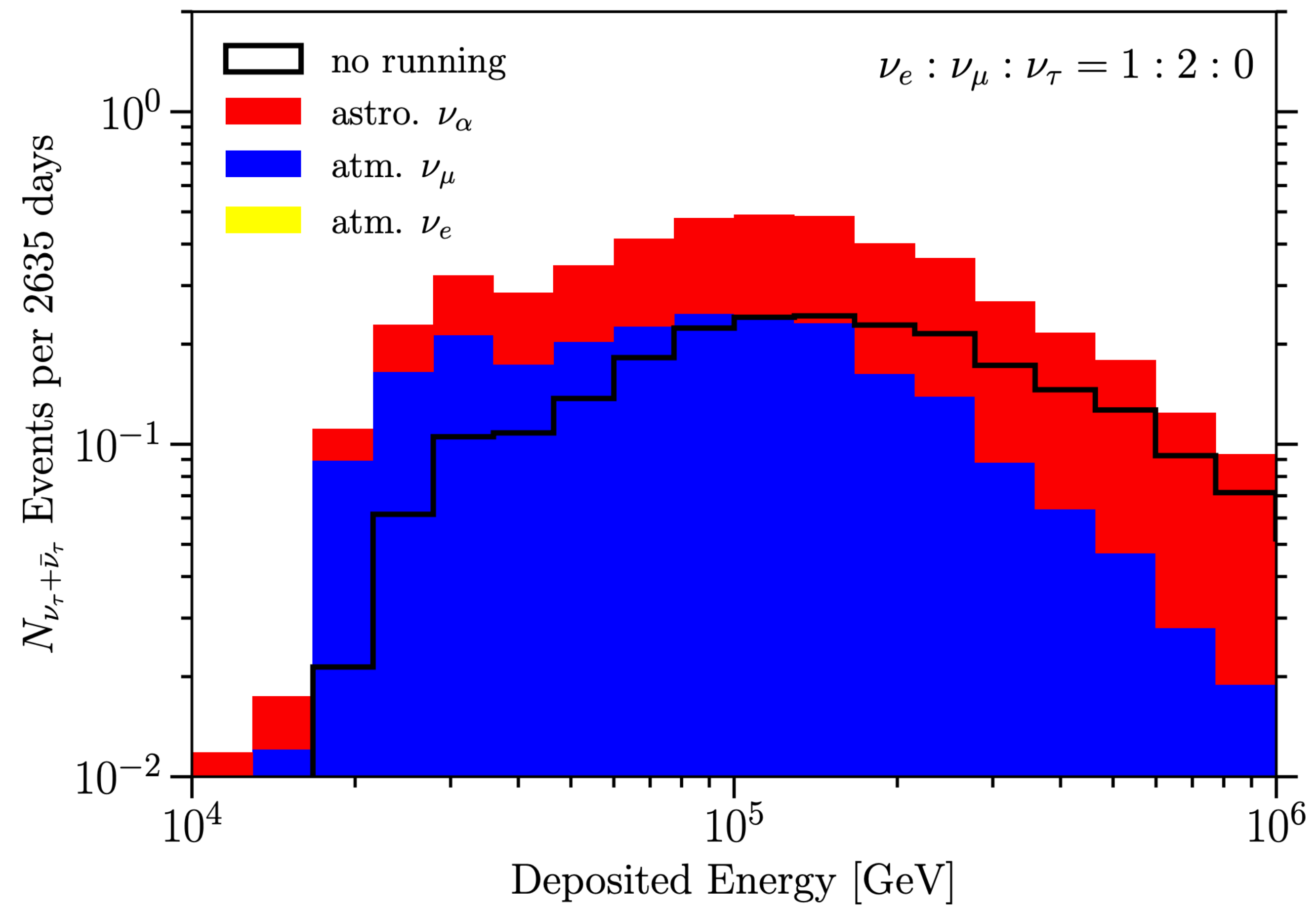


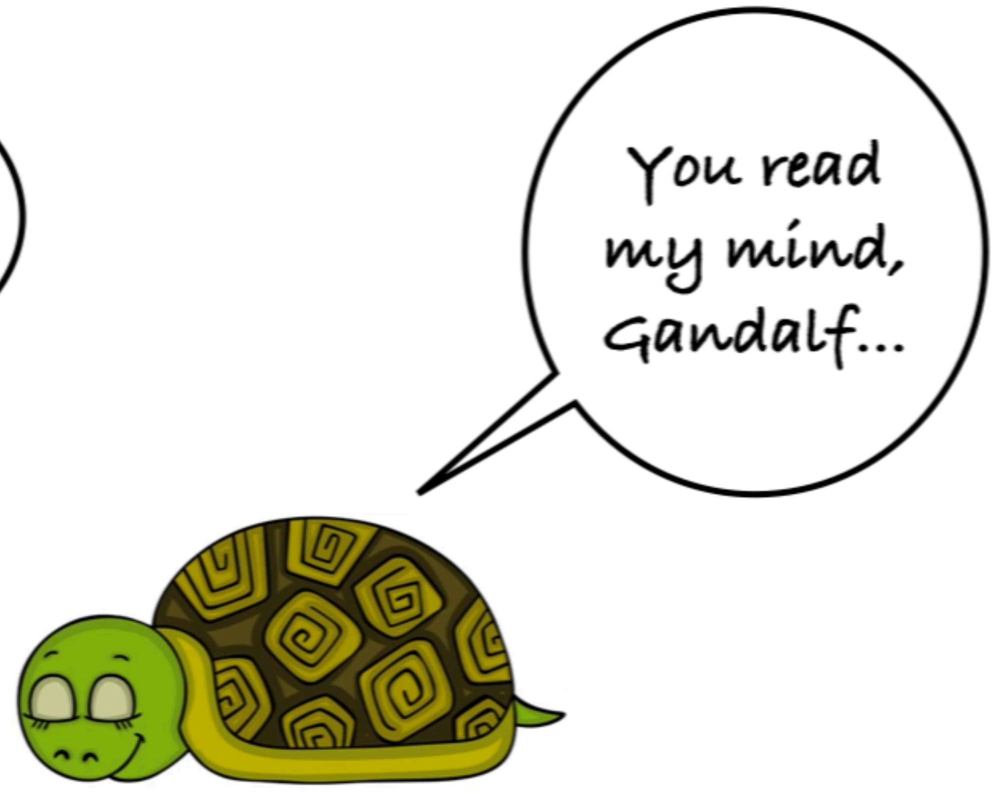
Summary

- BSM exhibiting RG running of the neutrino mixing below the electroweak scale
- Excess in double bang events at IceCube
- Substantial contribution from atmospheric ν_μ
- $\sim$6x larger statistics at IceCube-Gen2 than IceCube, reducing fluctuations

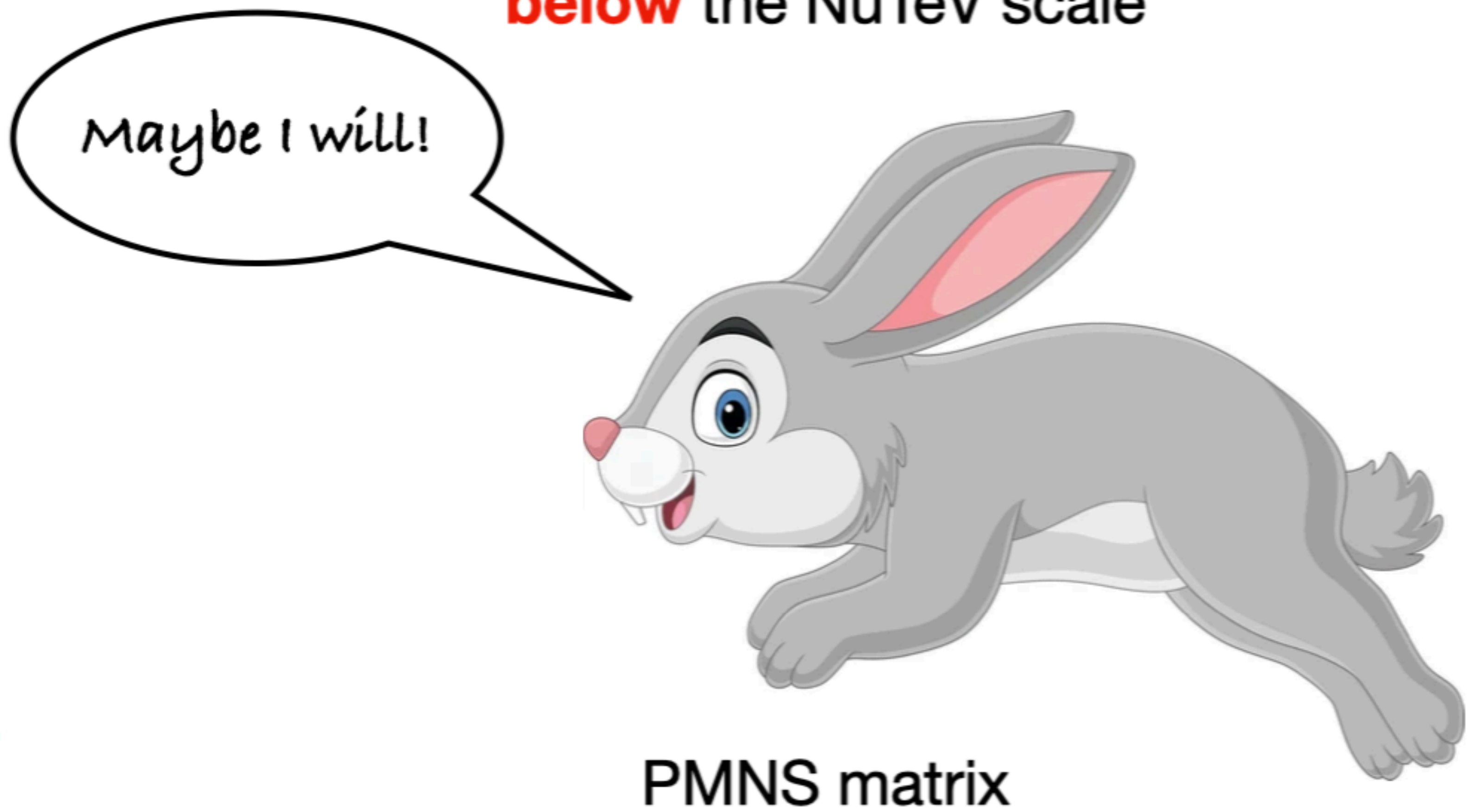




Short Baseline Gandalf



PMNS matrix
below the NuTeV scale

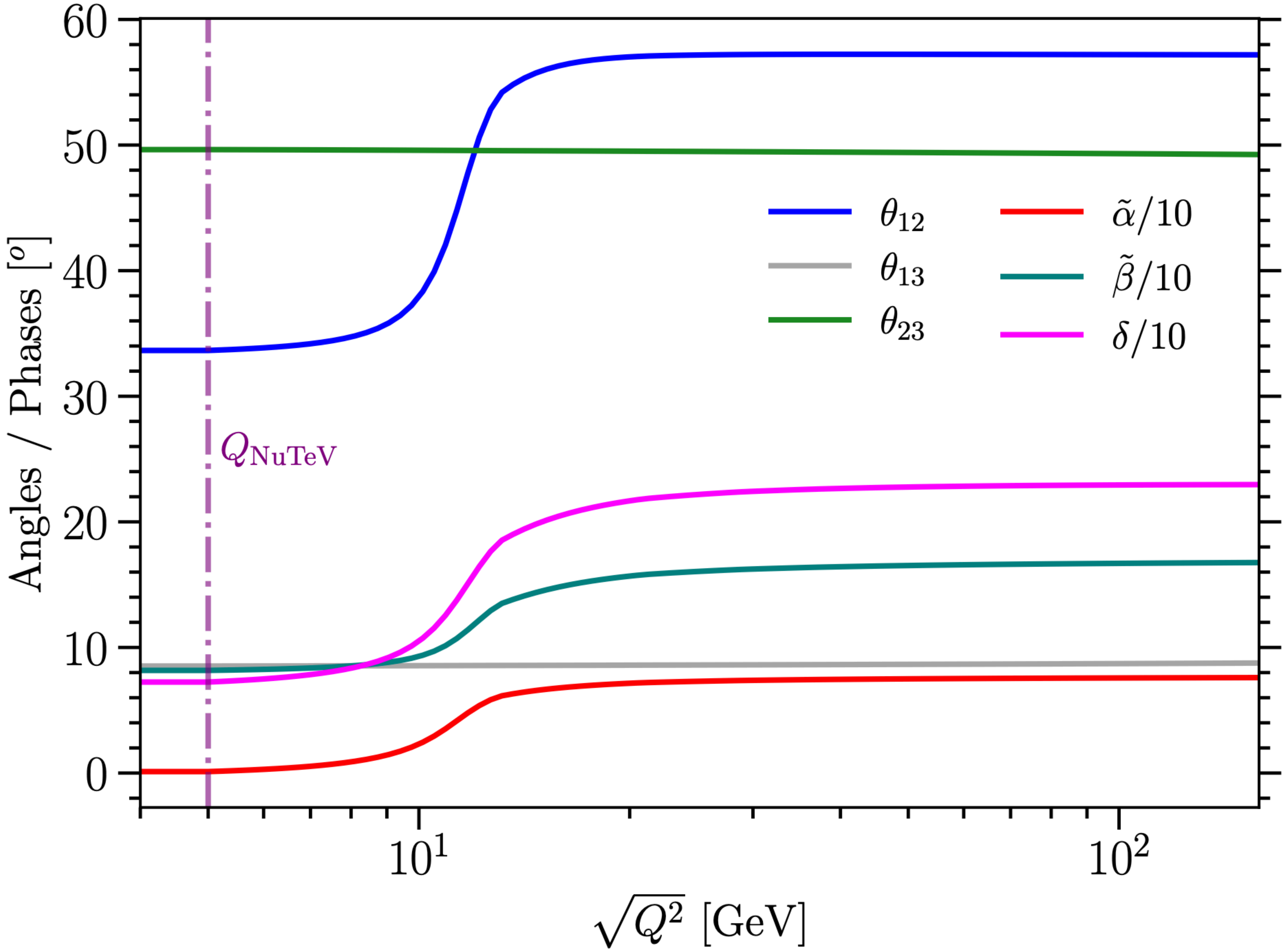


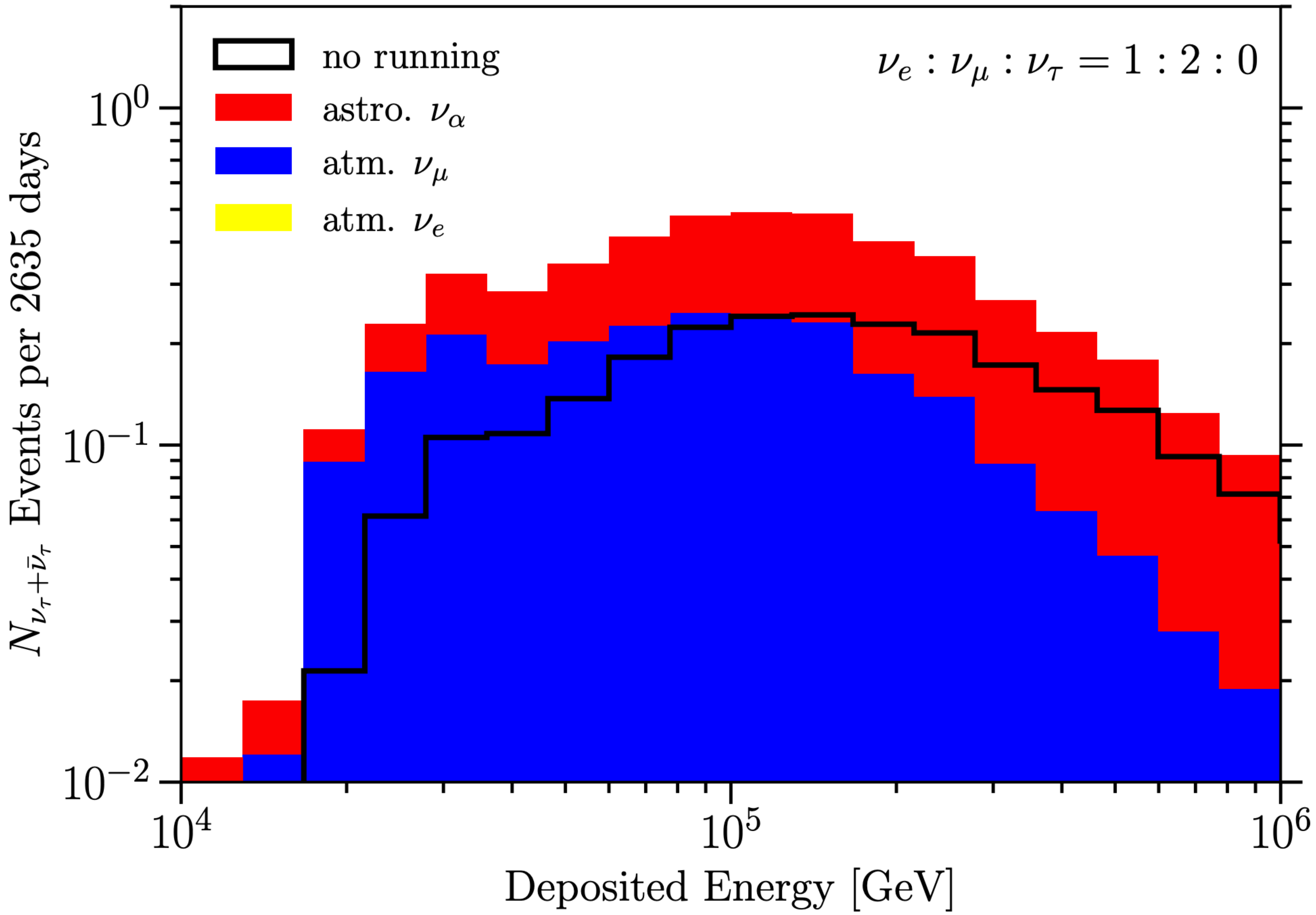
PMNS matrix
above the NuTeV scale

Backup

★ Benchmark at IceCube

- 100% excess in double bangs
- Dominant contribution from atm. $\nu_\mu \to \nu_\tau$





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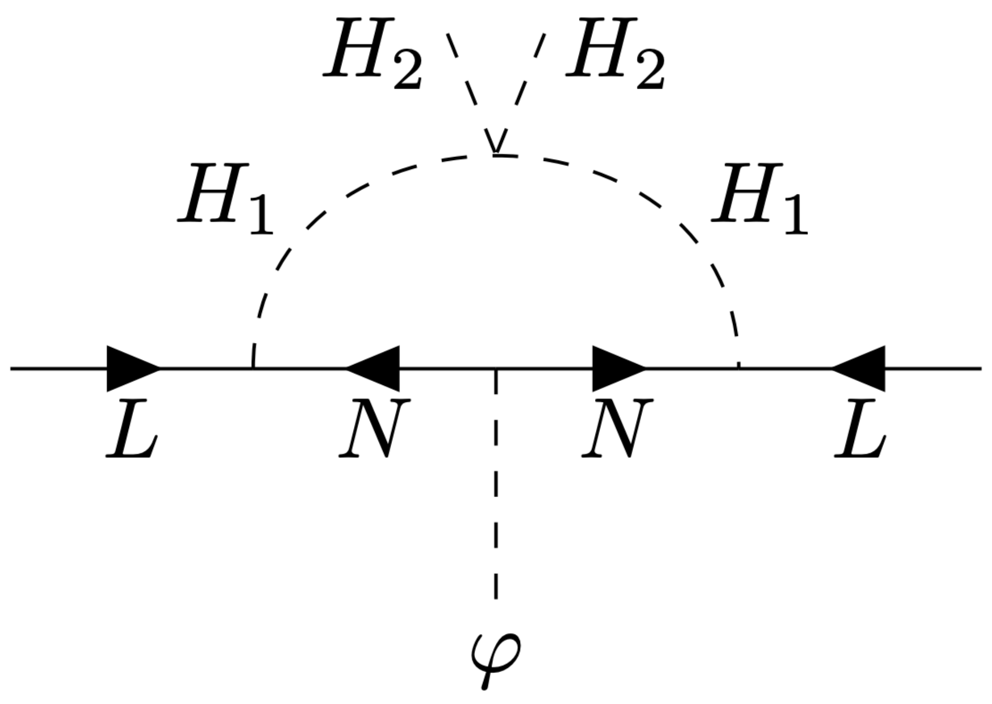

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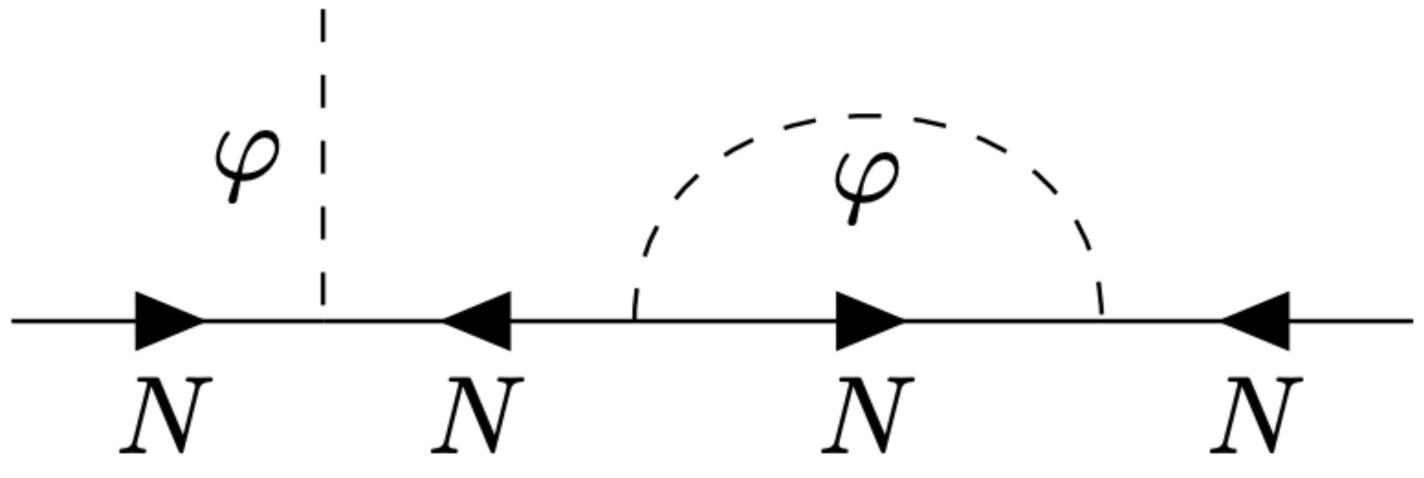

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↓

Neutrino mass matrix, $M_\nu \simeq \frac{\lambda v_\varphi}{16\sqrt{2}\pi^2} \ln\left(\frac{M_H^2}{M_A^2}\right) Y_\nu Y_N(Q^2) Y_\nu^T$

↓

PMNS matrix $U(Q^2)$ diagonalizes

$M_\nu \to U^T M_\nu U = \text{diag}(m_1, m_2, m_3)$

Oscillation with 2 Flavors

$$U(Q^2) = \begin{pmatrix} \cos\theta(Q^2) & \sin\theta(Q^2) \\ -\sin\theta(Q^2) & \cos\theta(Q^2) \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & e^{i\tilde{\beta}(Q^2)} \end{pmatrix}$$

$$\theta(Q_p^2) \equiv \theta_p, \qquad \theta(Q_d^2) \equiv \theta_d, \qquad \tilde{\beta}(Q_d^2) - \tilde{\beta}(Q_p^2) \equiv \beta$$

$\tilde{\beta}$ = CP-violating phase

$$P_{e\mu} = P_{\mu e} = \sin^2(\theta_p - \theta_d) + \sin 2\theta_p \sin 2\theta_d \sin^2\left(\frac{\Delta m^2 L}{4E} + \frac{\beta}{2}\right),$$

$$P_{ee} = P_{\mu\mu} = \cos^2(\theta_p - \theta_d) - \sin 2\theta_p \sin 2\theta_d \sin^2\left(\frac{\Delta m^2 L}{4E} + \frac{\beta}{2}\right).$$

At zero baseline $L = 0$ with $\theta_p \approx \theta_d$:

$$P_{\alpha\beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E} + \frac{\beta}{2}\right)$$

$$= \sin^2 2\theta \sin^2\left(\frac{\beta}{2}\right) \neq 0$$

$\beta = 0$ in the absence of running.

$\beta \neq 0$ gives oscillation contribution at zero baseline $L = 0$.

Tau Neutrino Detection at IceCube

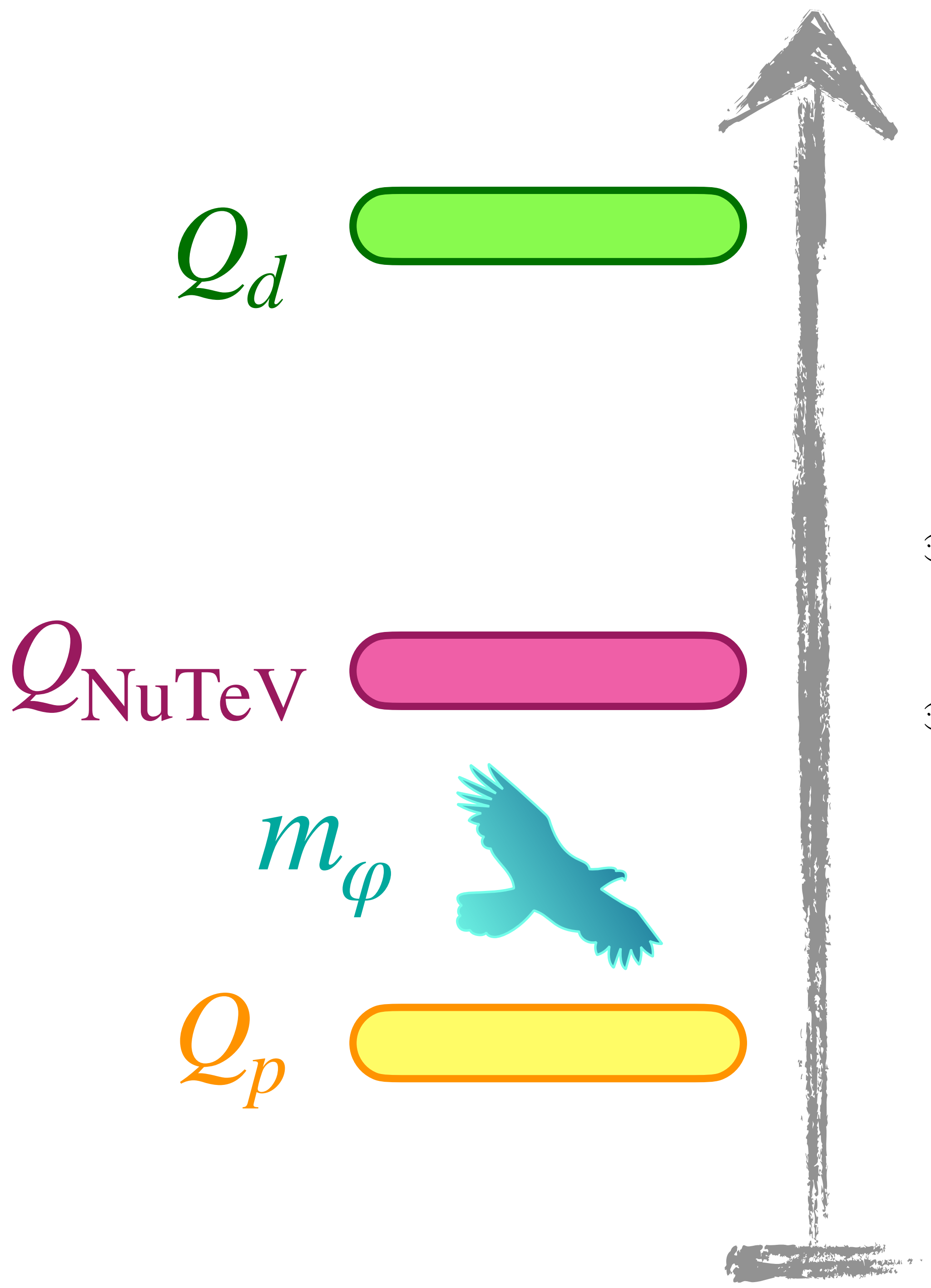
- 4 tau-neutrino-candidate events reported out of 102 high-energy starting events (HESE) sample in 7.5 years data [arXiv:2011.03545]
  - Two event has the high likelihood of being tau neutrino [arXiv:2011.03561]

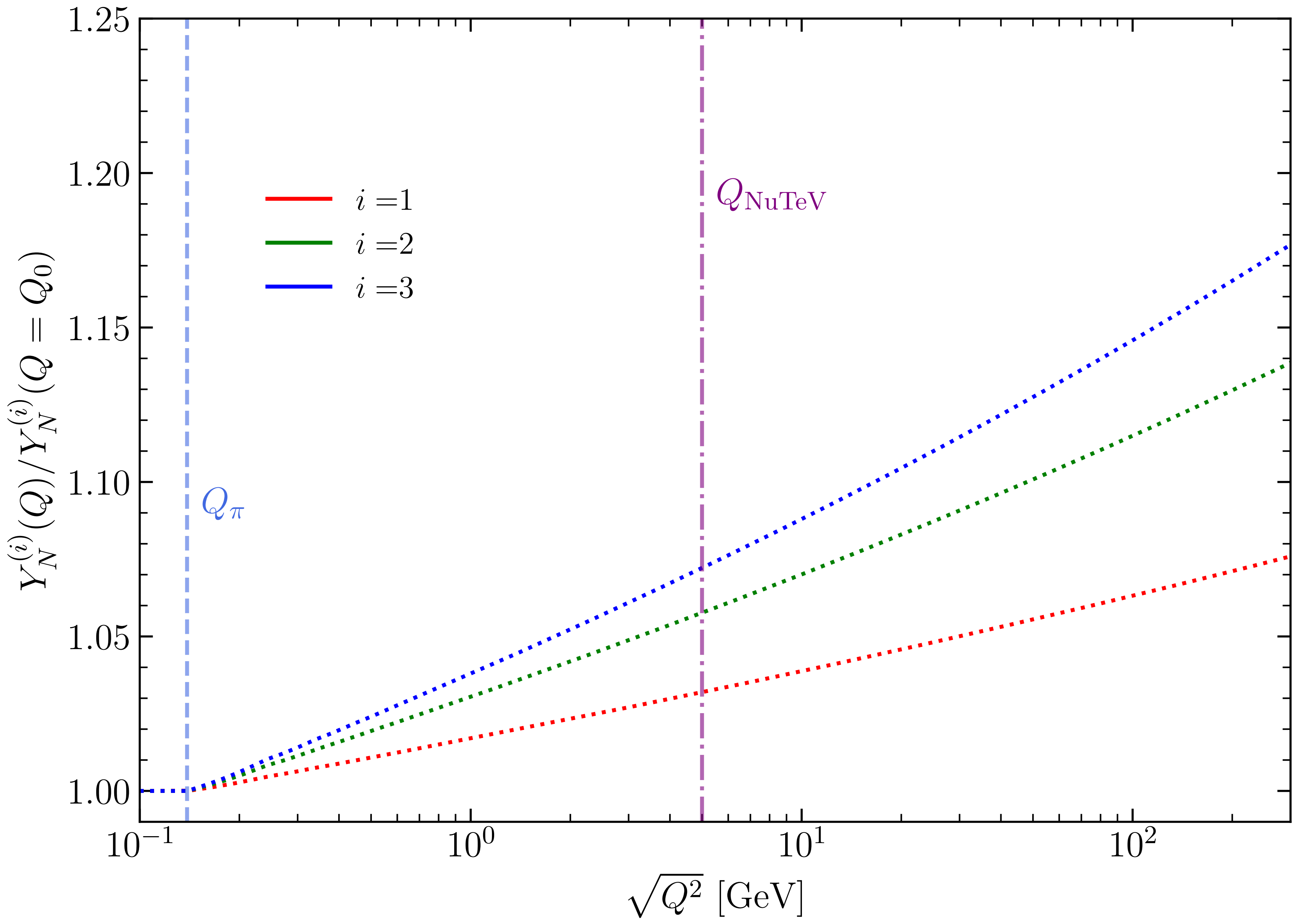
Category	$E < 60\,\text{TeV}$	$E > 60\,\text{TeV}$	Total
Total Events	42	60	102
Up	19	21	40
Down	23	39	62
Cascade	30	41	71
Track	10	17	27
Double Cascade	2	2	4

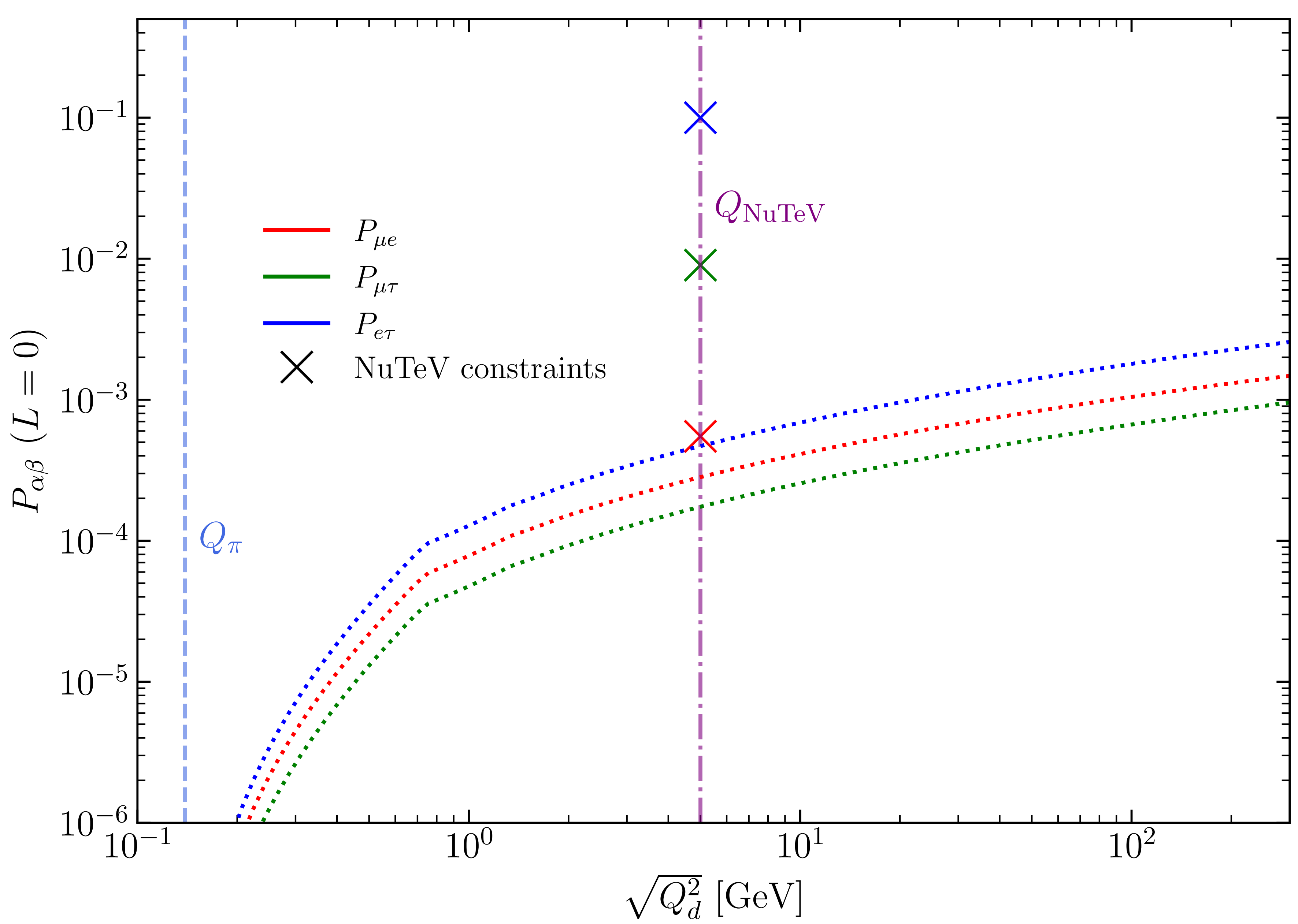
- Tauness of two events, $P_\tau^{DD} = 97.5\,\%$, $P_\tau^{BB} = 76\,\%$

RG Running

Case 1: $m_{\varphi,N} \sim Q_p = Q_\pi = m_\pi$ (pion decay production)



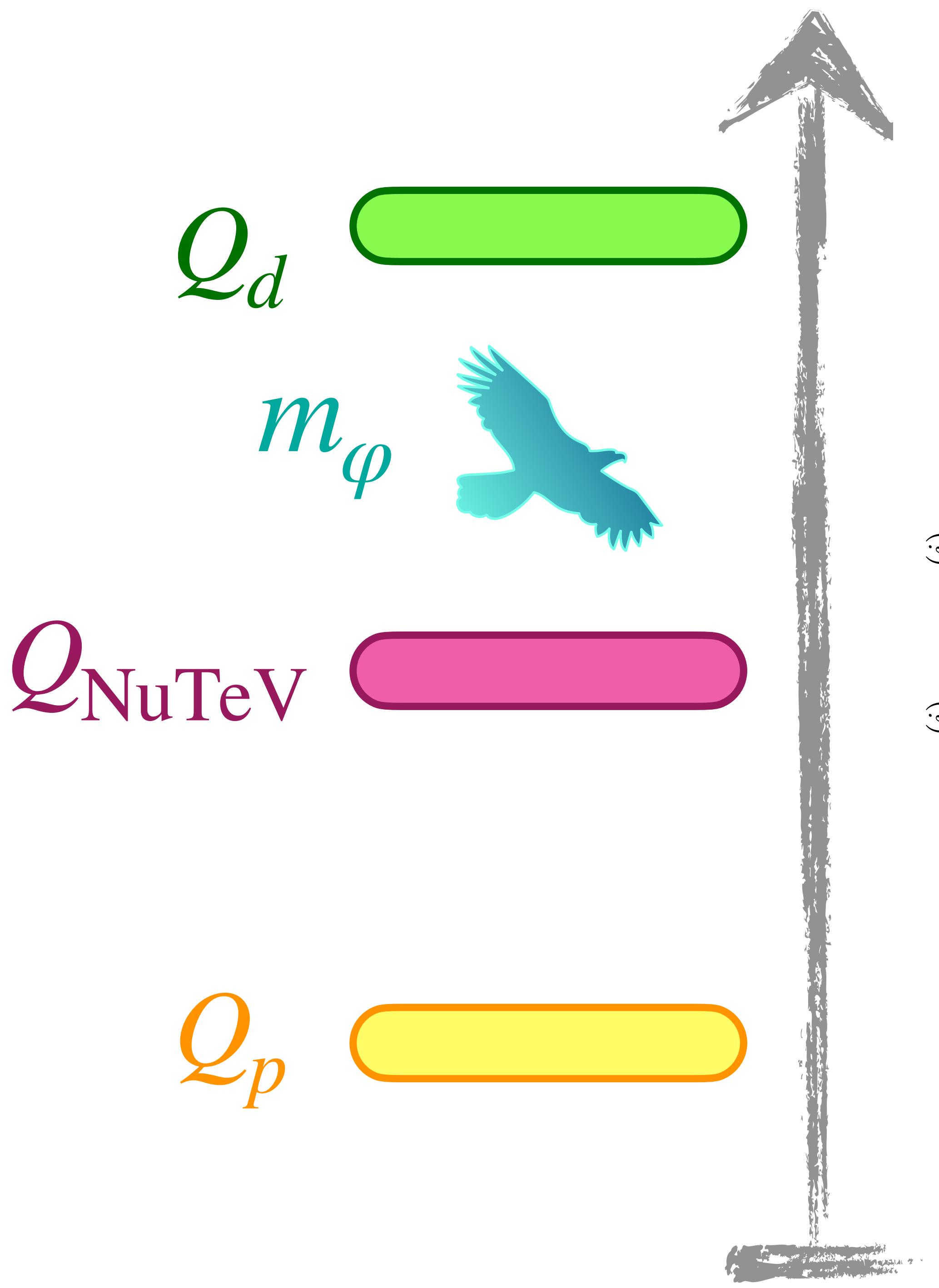


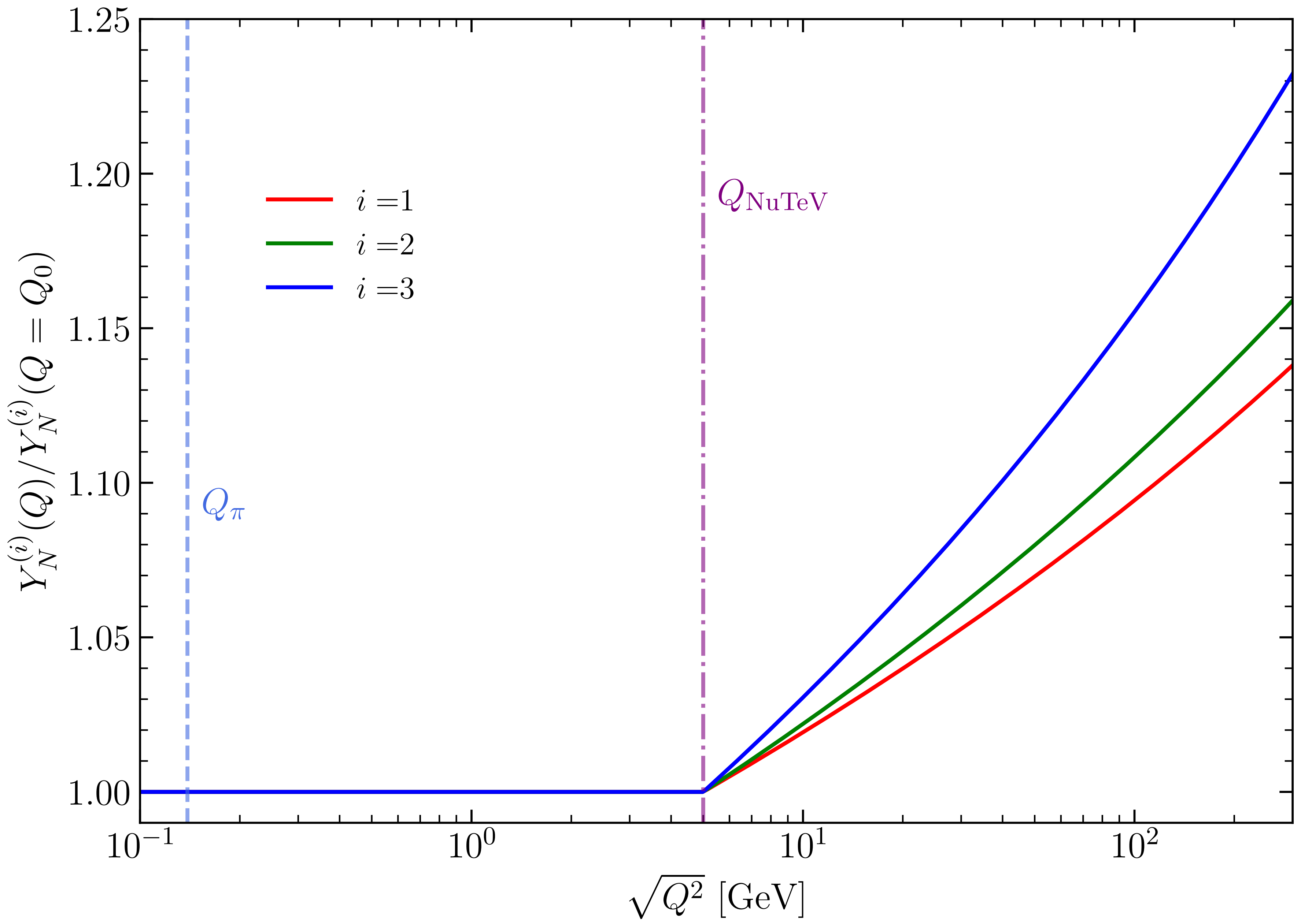


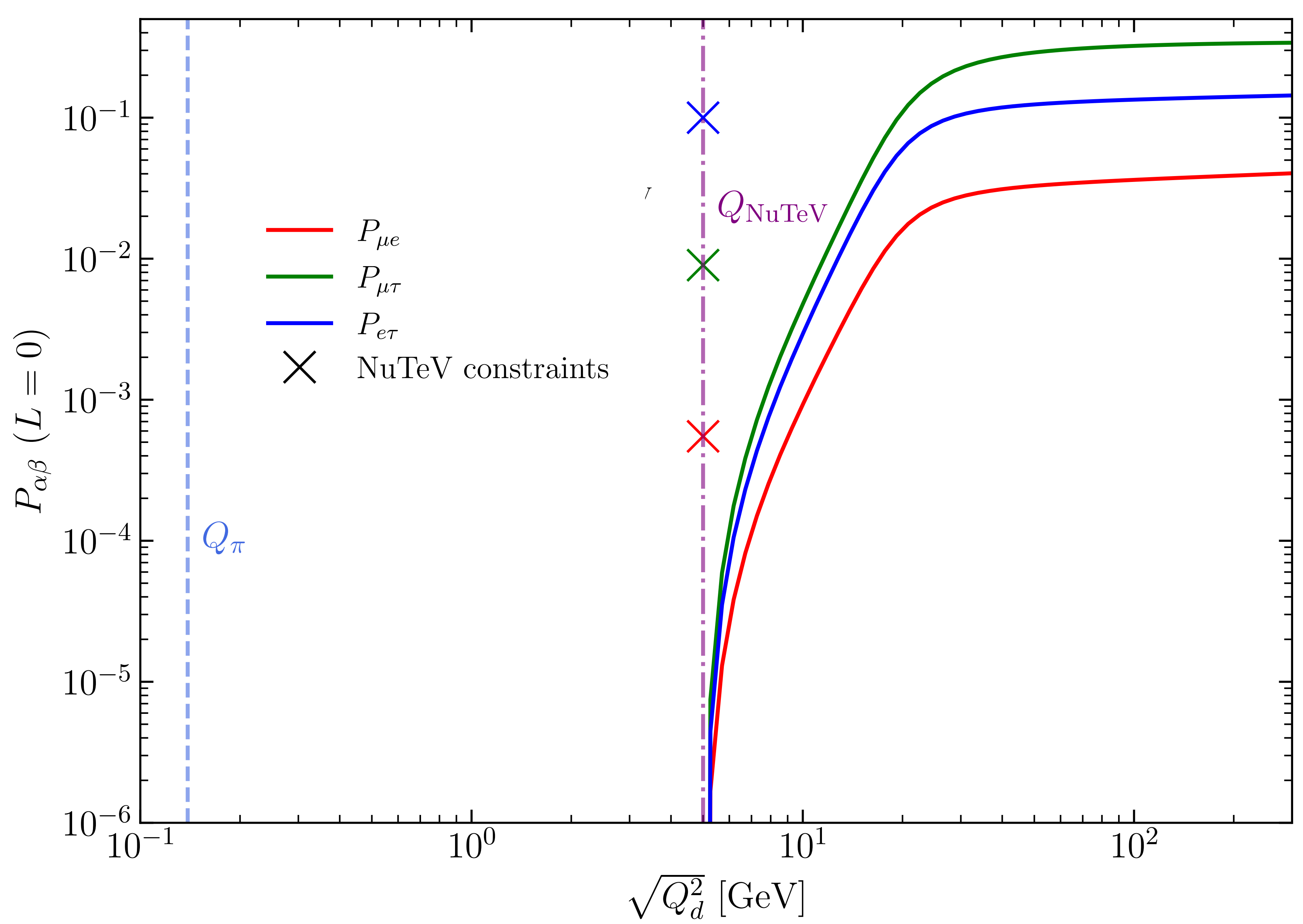
Y_N running → Oscillation at zero baseline

RG Running

Case 2: $m_{\varphi,N} \gtrsim Q_{\rm NuTeV}$

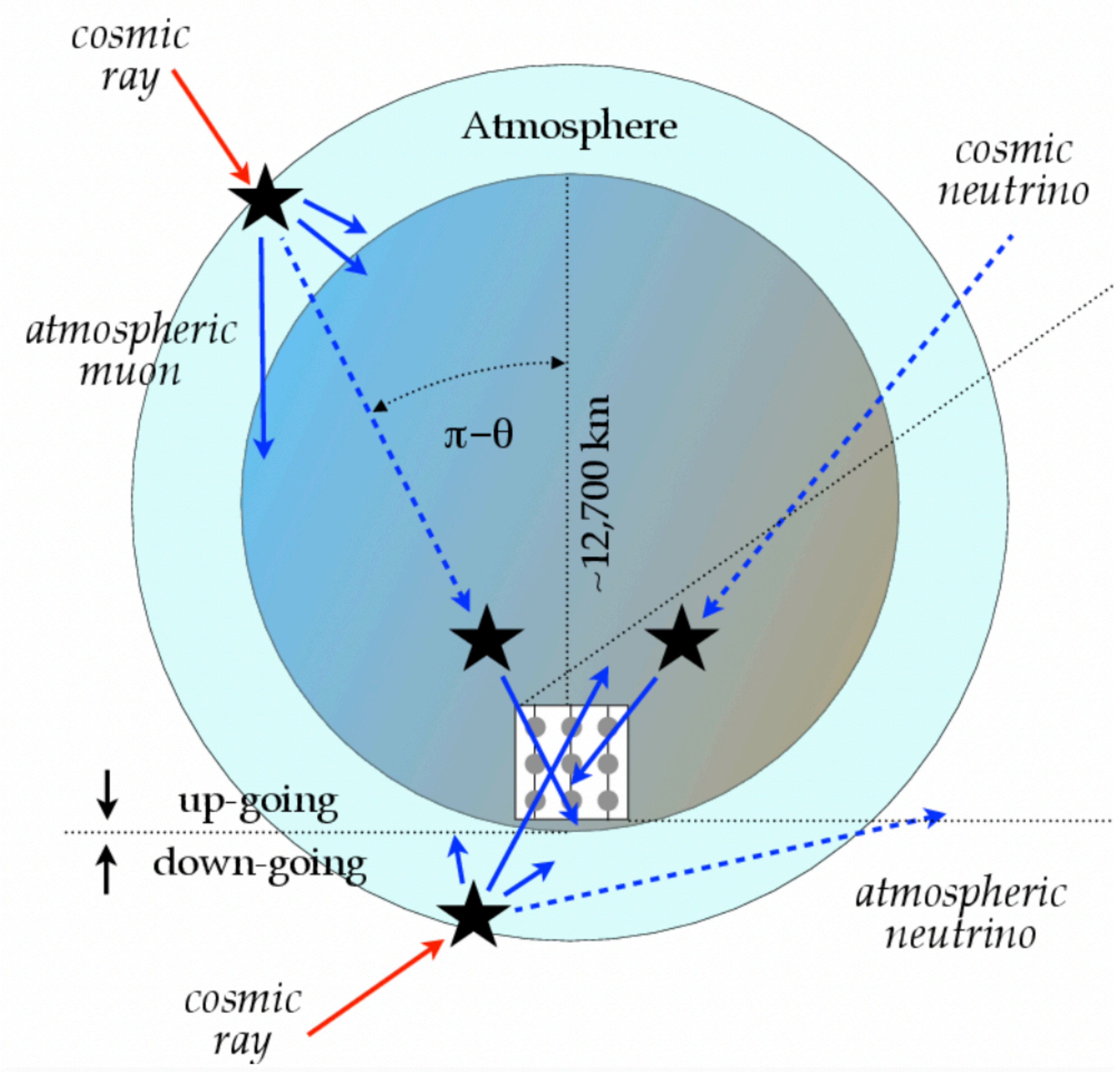


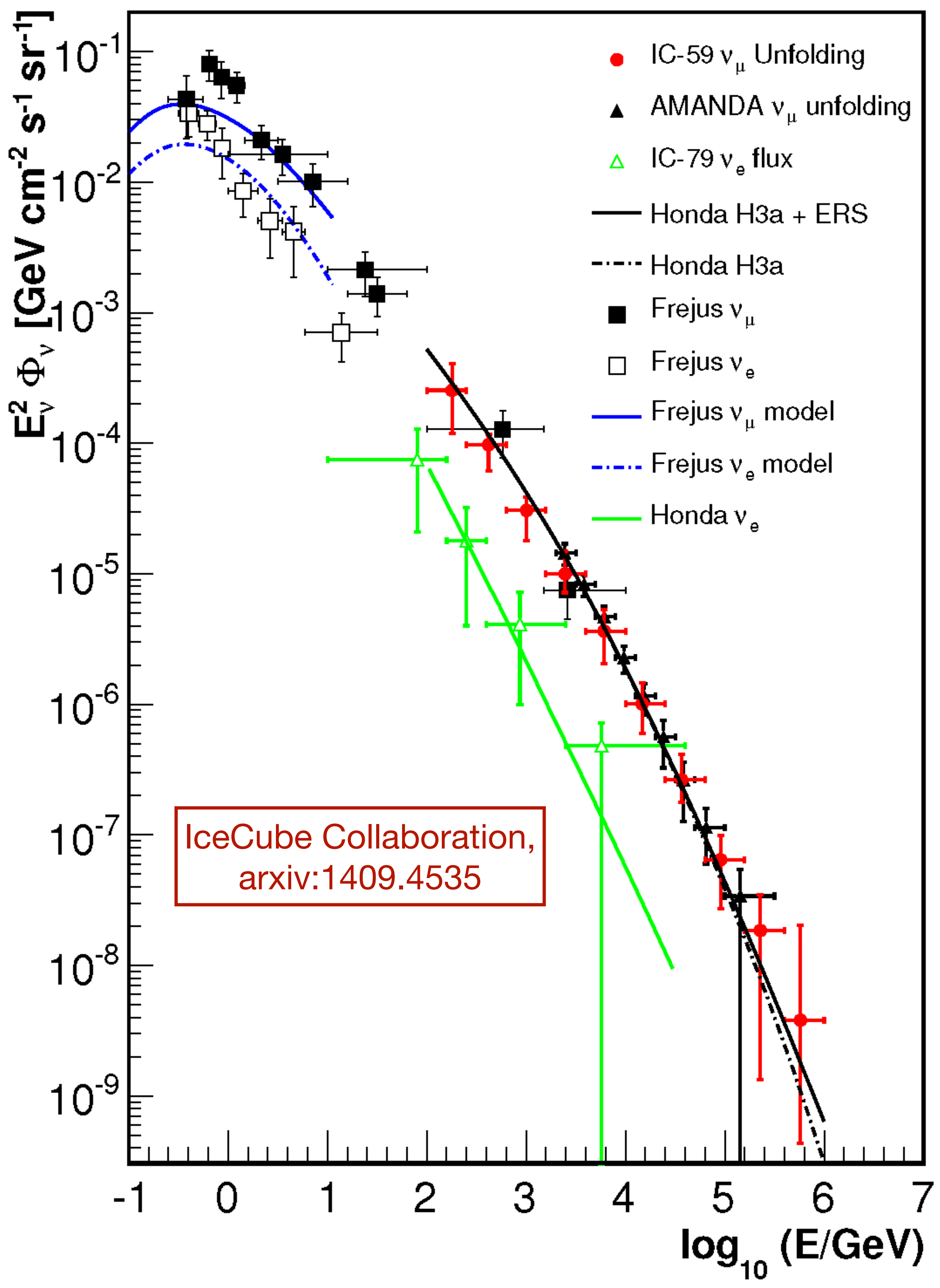




Y_N running → Oscillation at zero baseline

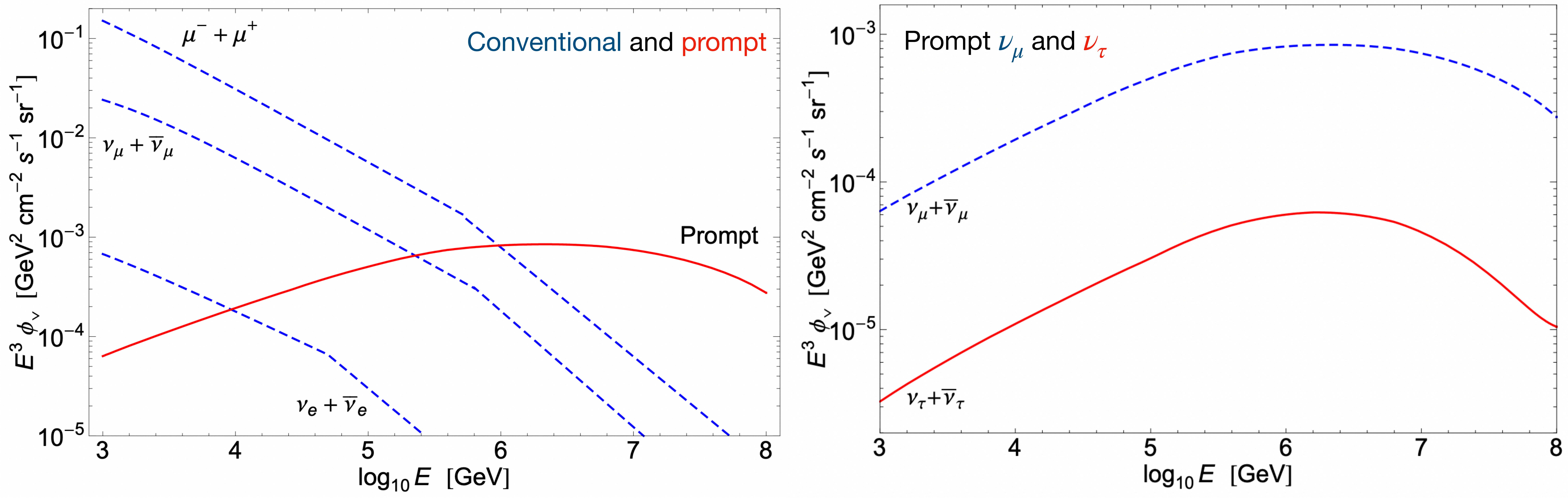
Atmospheric Muon Neutrinos at IceCube



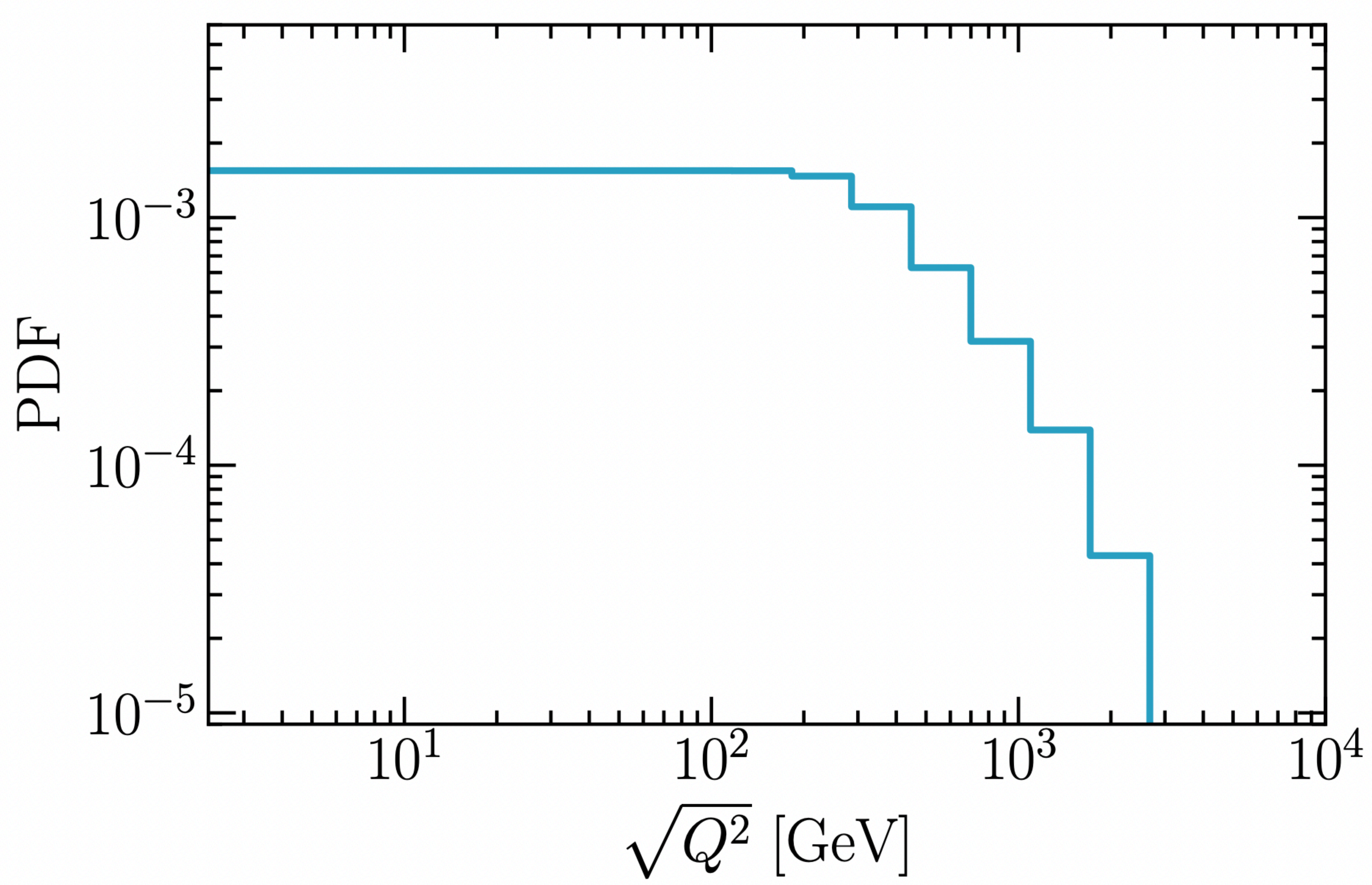


Atmospheric Neutrinos

Enberg, Reno, Sarcevic, arXiv:0806.0418



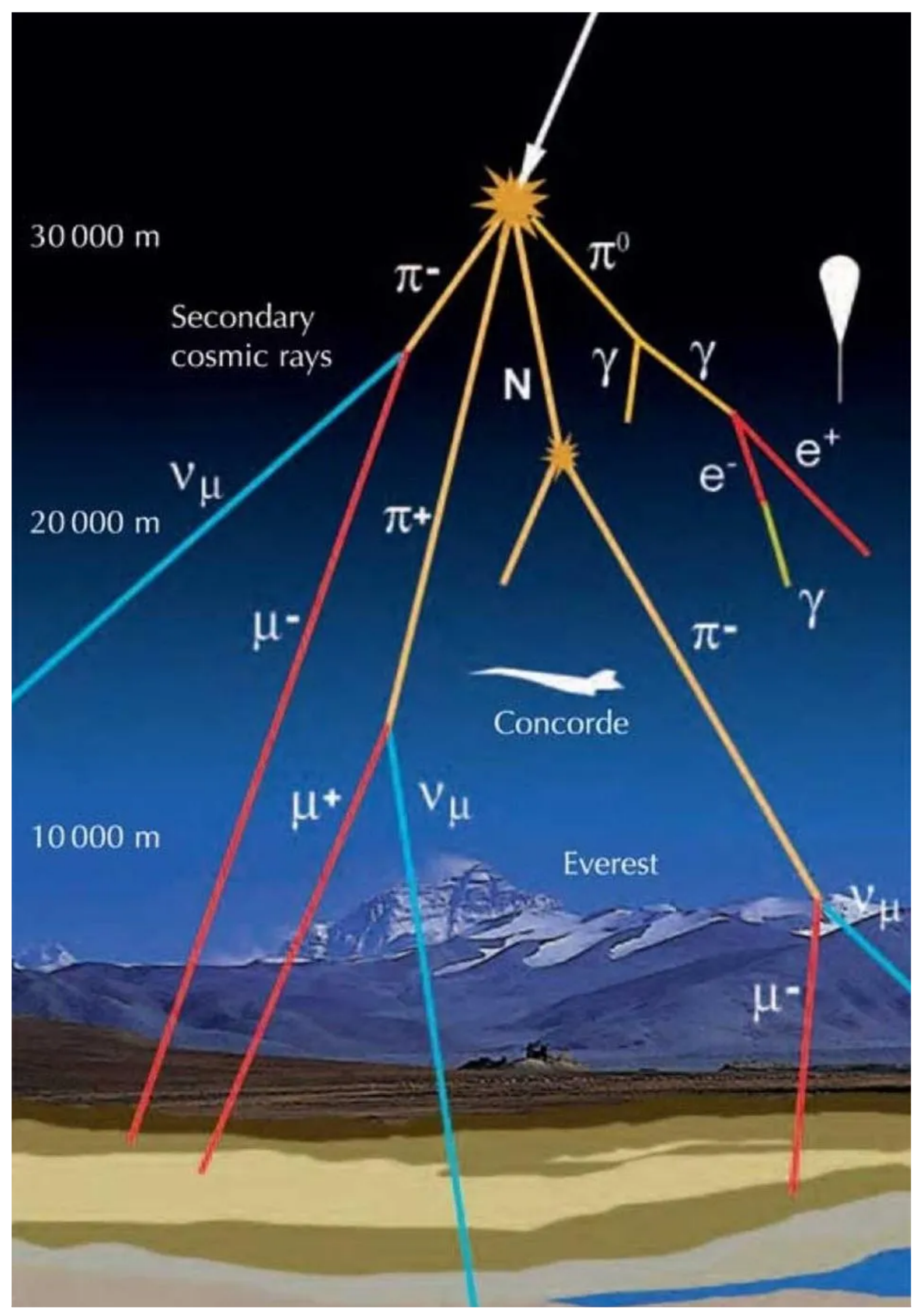
$\sqrt{Q^2}$ Distribution at HESE Sample

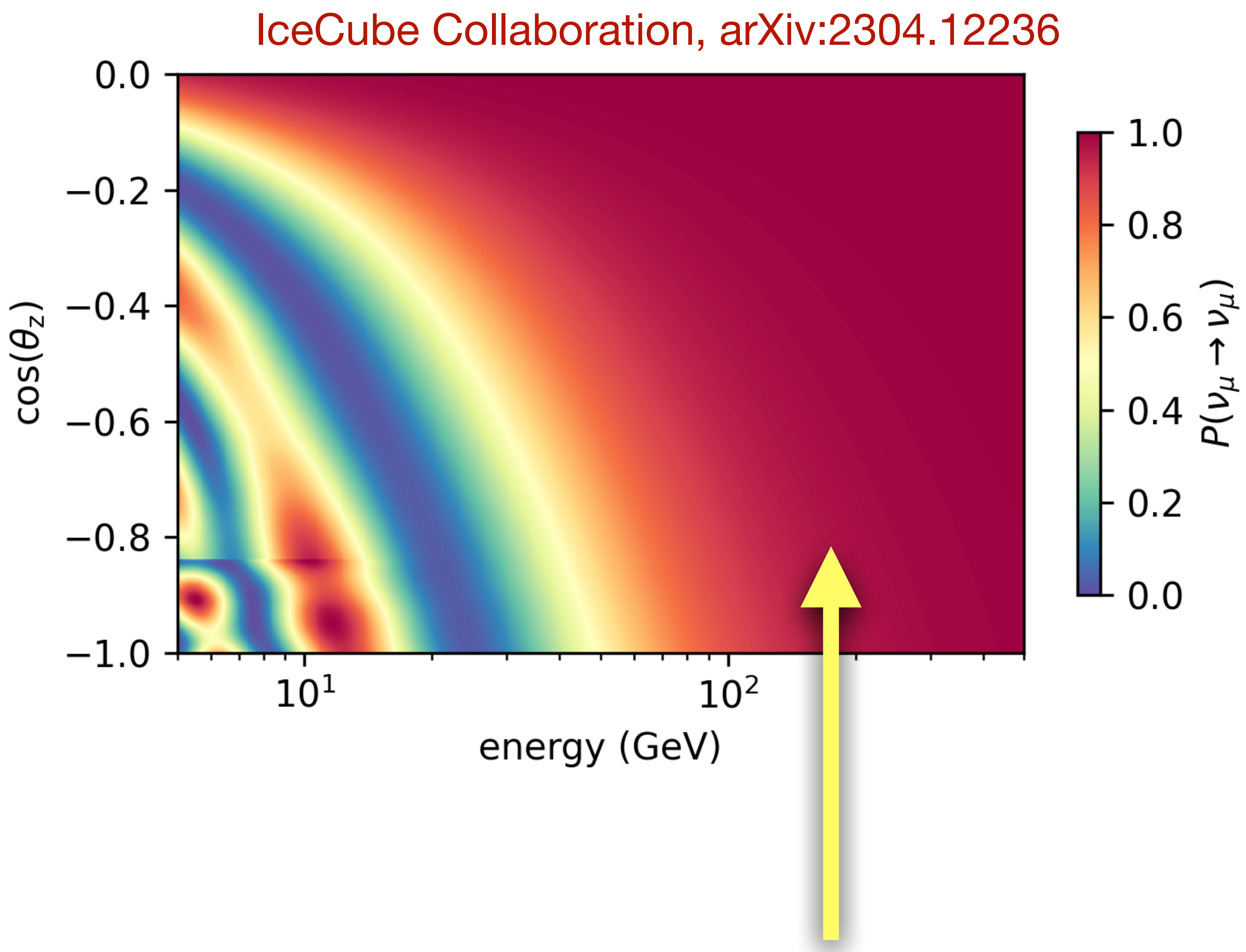


Atmospheric Neutrinos at IceCube

- Atmospheric neutrinos:
  CR + atm. $\to \pi, K, \ldots \to \nu + \ell^{\pm}$
- ~99% ν are muon neutrinos
- 'atmosphere to IceCube'
  baseline $L \sim 10$ km to 10000 km
- $E_\nu = 100$ GeV, $L_{osc} = 10^5$ km

  where transition probability $P \propto \sin^2\left(\frac{L}{L_{\rm osc}}\right)$
- Baseline is not long enough to oscillate
  at high energy $E_\nu > 100$ GeV
- RG running may allow atmospheric $\nu_{e,\mu} \to \nu_\tau$





Standard oscillation → no flavor transition
BSM running →flavor transition leading to tau neutrino appearance

Tau Neutrino Appearance at IceCube: Astrophysical Neutrinos

- Flavor conversion, $P_{\alpha\beta}(L \gg L_{osc}) = \sum_i \left| U_{\alpha i}(Q_p^2) \right|^2 \left| U_{\beta i}(Q_d^2) \right|^2$

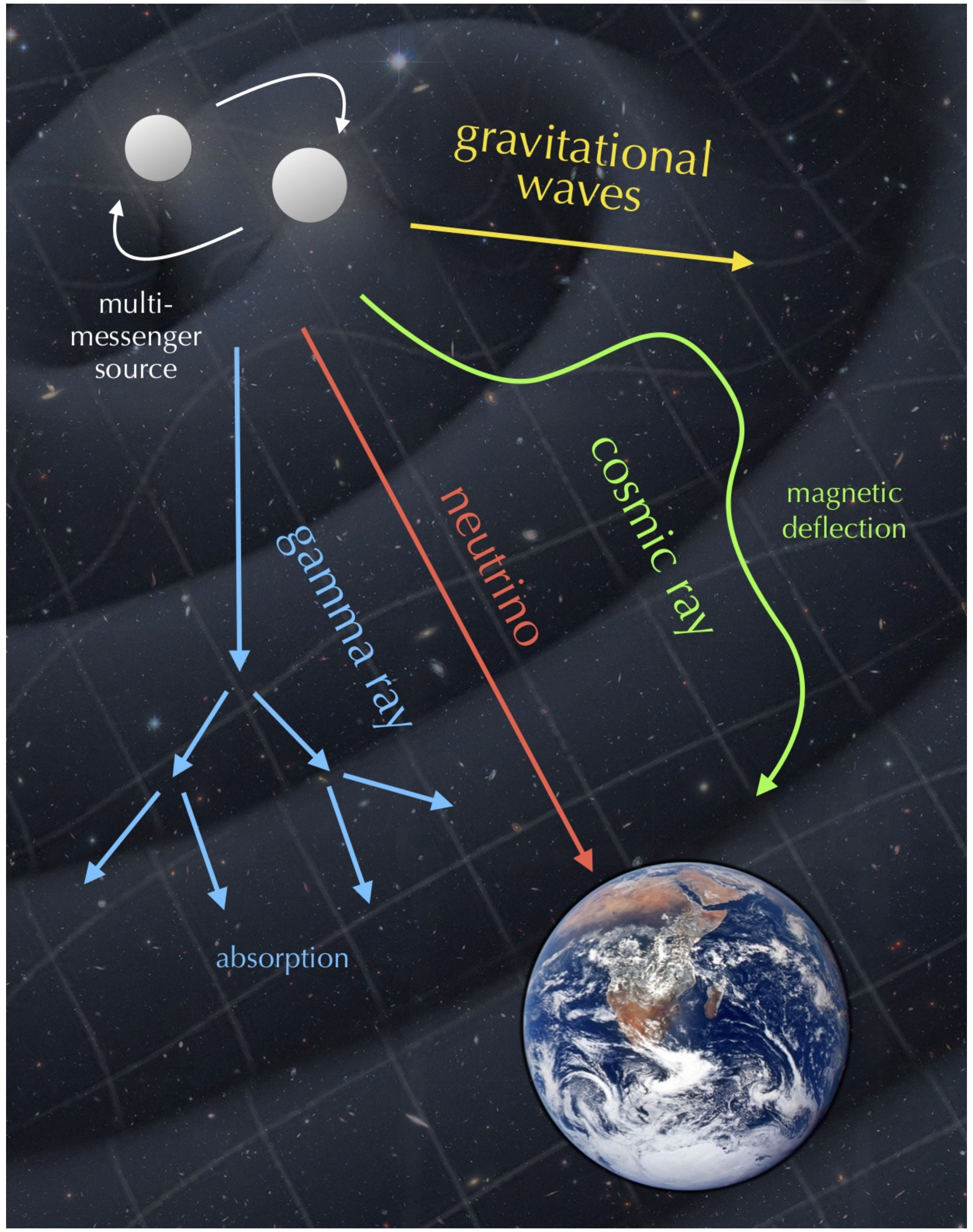
- This $P_{\alpha\beta}(L \gg L_{osc})$ enters the BSM weight,

$$w^{\text{BSM}}_{\alpha\to\beta}(E_\nu) = \frac{\int_\nu P_{\alpha\beta}(E_\nu, Q^2) + \int_{\bar\nu} P_{\bar\alpha\to\bar\beta}(E_\nu, Q^2)}{\int_\nu \quad + \quad \int_{\bar\nu}}$$

- Flavor ratio on earth, $X^{\text{earth}}_\beta = P_{\alpha\beta} X^{\text{prod}}_\alpha$
  where X^{prod}_α = astrophysical flavor ratio at the source

* Pion decay: $(f_e : f_\mu : f_\tau)_S = 1 : 2 : 0$
* Muon damped: $(f_e : f_\mu : f_\tau)_S = 0 : 1 : 0$
* Neutron decay: $(f_e : f_\mu : f_\tau)_S = 1 : 0 : 0$

$$N^{\text{astro}}_\tau = T \int dE_\nu \; \epsilon_\tau(E_\nu) \, \Phi^{\text{astro}}_{1\nu}(E_\nu) \, \sigma_{\nu N}(E_\nu) \sum_{\alpha=e,\mu,\tau} w^{\text{BSM}}_{\alpha\to\tau}(E_\nu) X^{\text{prod}}_\alpha$$



IceCube Gen-2 and Fluctuation

https://icecube-gen2.wisc.edu/science/publications/tdr/

Table 5: Rate of upgoing tracks in the IceCube-Gen2 optical array [yr^{-1}]

Deposited energy	astrophysical-ν IceCube	astrophysical-ν IceCube-Gen2	atmospheric-ν IceCube	atmospheric-ν IceCube-Gen2
>1 TeV	1.2×10^2	4.0×10^2	2.9×10^5	3.4×10^5
>10 TeV	16	59	2.4×10^2	5.3×10^2
>100 TeV	1.4	3.8	0.67	0.99

Table 6: Rate of astrophysical neutrinos of various event categories (optical array only) [yr^{-1}]

Deposited energy	shower-type events IceCube	shower-type events IC-Gen2	double cascades IceCube	double cascades IC-Gen2	starting tracks IceCube	starting tracks IC-Gen2
> 10 TeV	6.0	50	0.36	2.4	1.4	21
> 100 TeV	3.6	32	0.3	1.9	0.81	13

Expected number of events n	Poisson probability of observing 2n events
2	0.090
5	0.018
10	0.002