Modeling Prompt Atmospheric lepton fluxes with Intrinsic Charm contribution

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Work in progress with L P Das[1], M V Garzelli[2], M H Reno[1], G Sigl[2]
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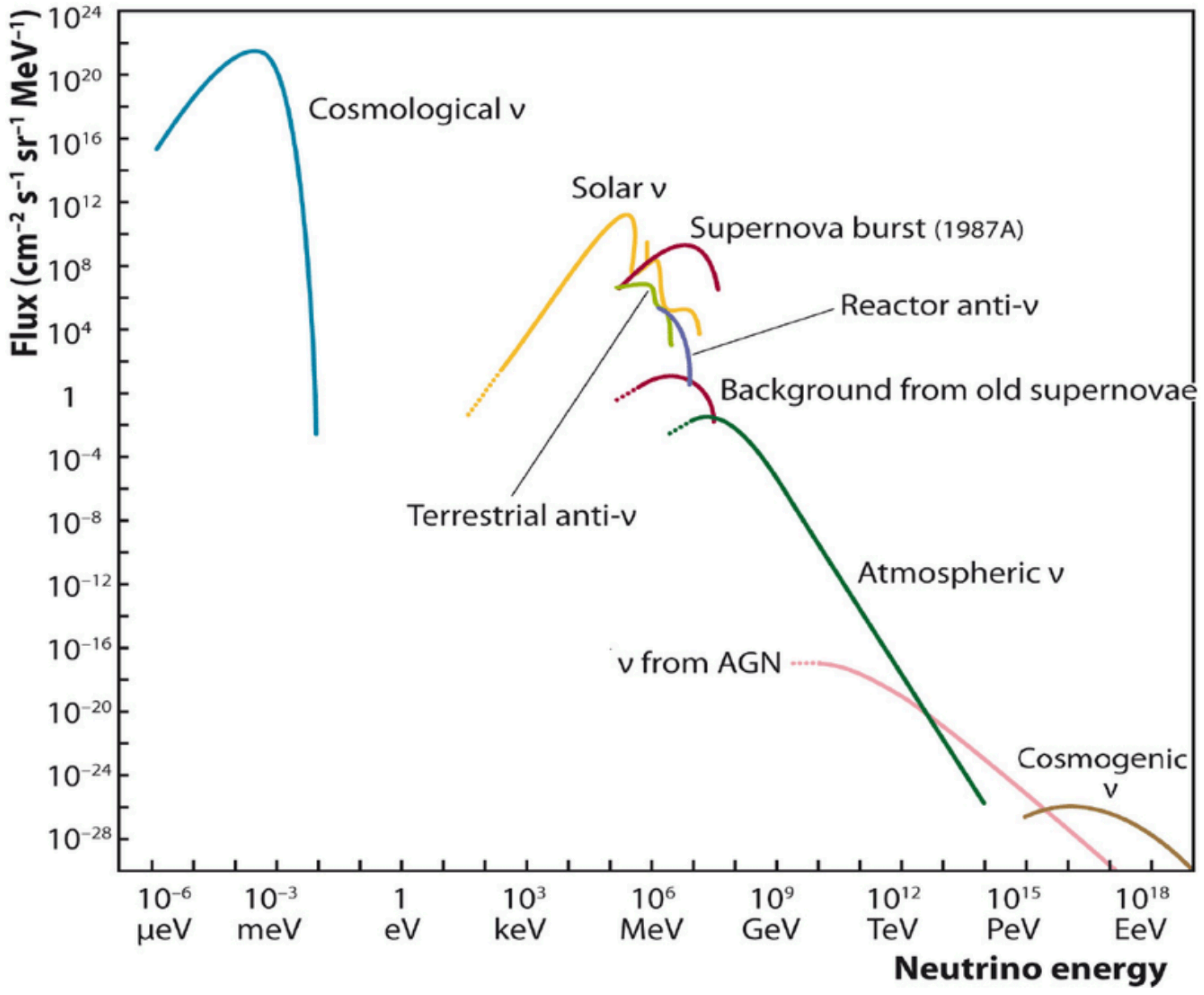
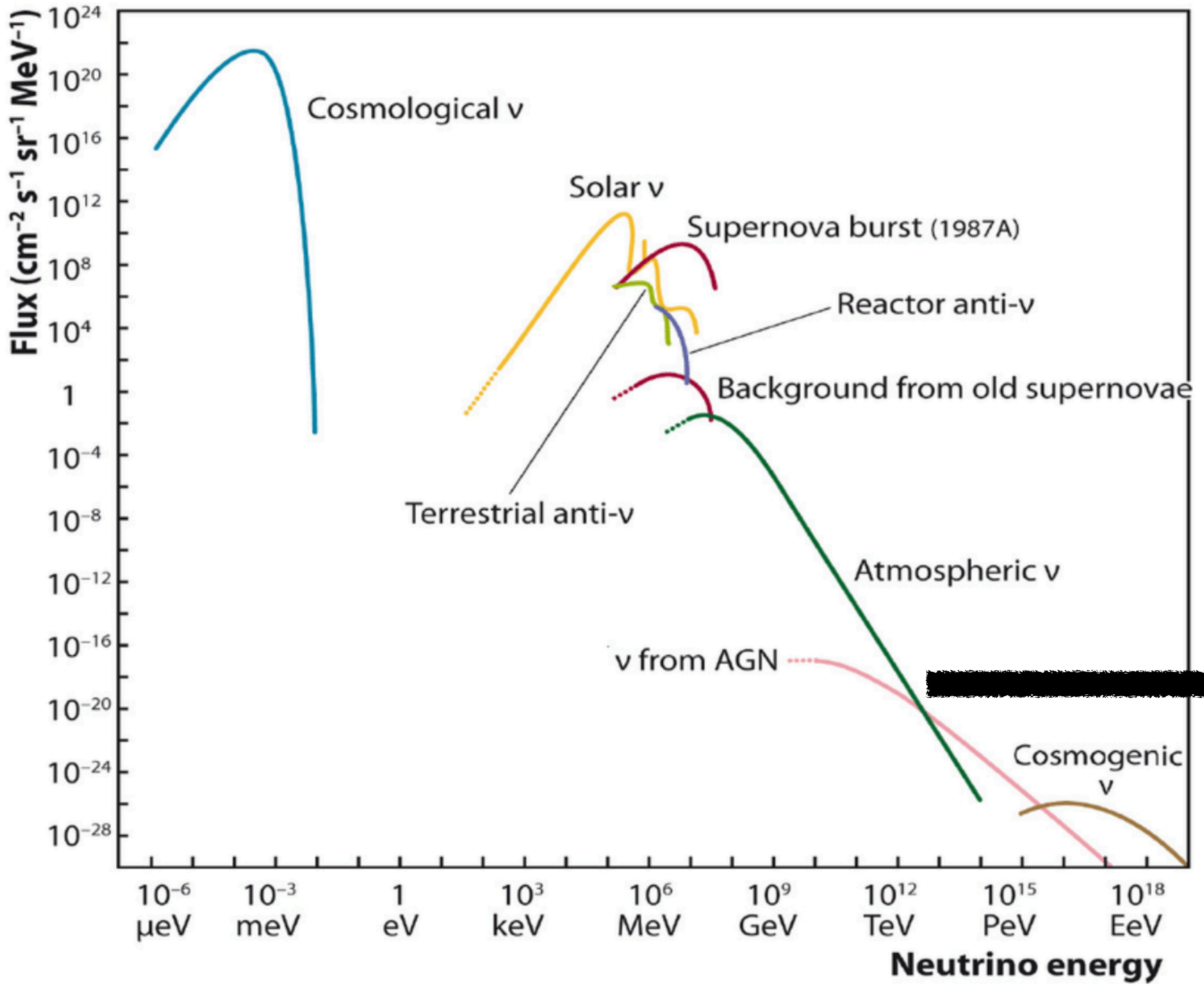
CETUP* Workshop - Neutrino session
July 11, 2025

Neutrino Flux



Neutrino Flux



Overlap between atmospheric and astrophysical sources

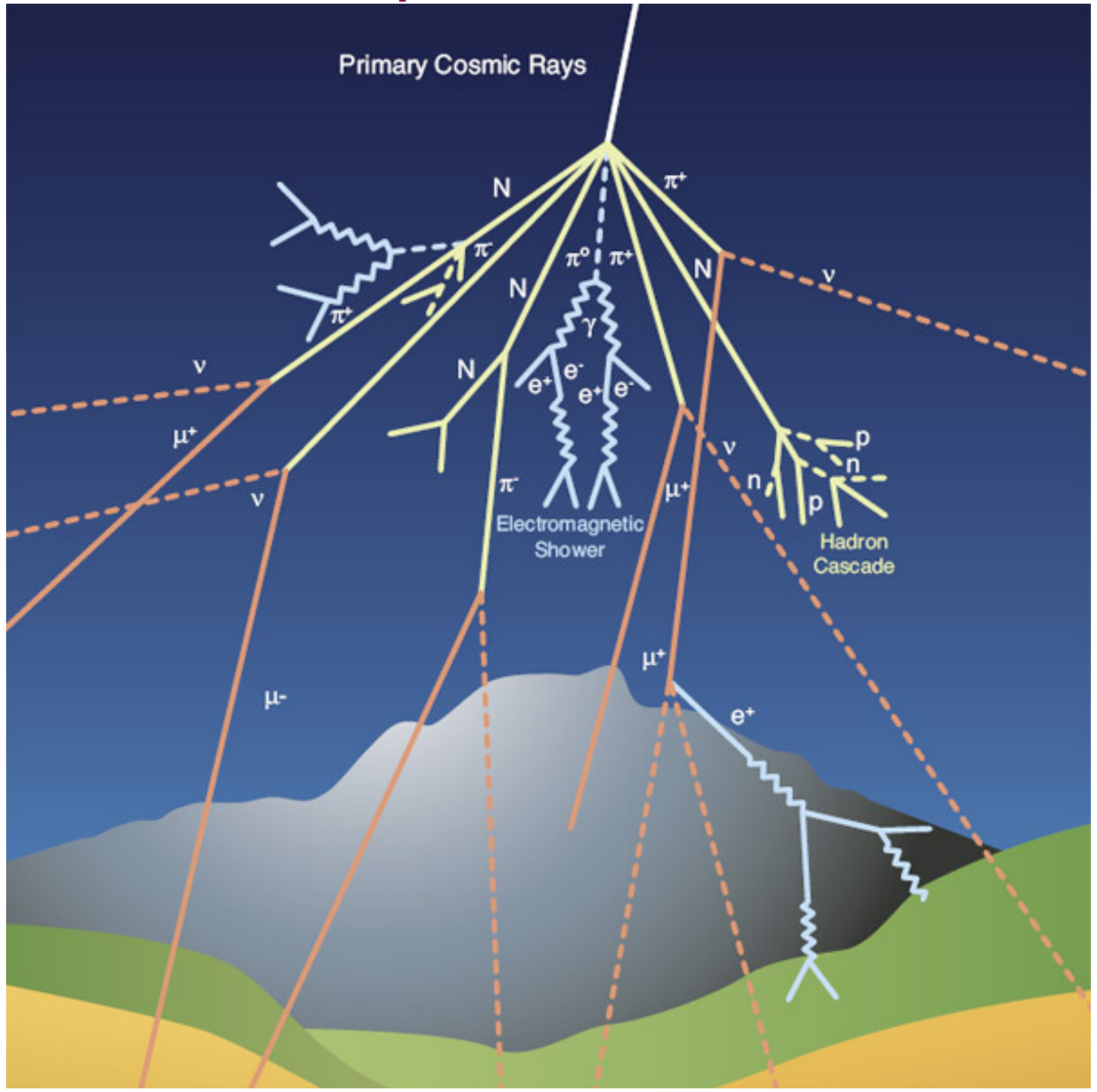
Astrophysical vs Atmospheric Neutrinos

Astrophysical Neutrinos

ν

Distance $\sim \mathcal{O}(\mathrm{Mpc} - \mathrm{Gpc})$

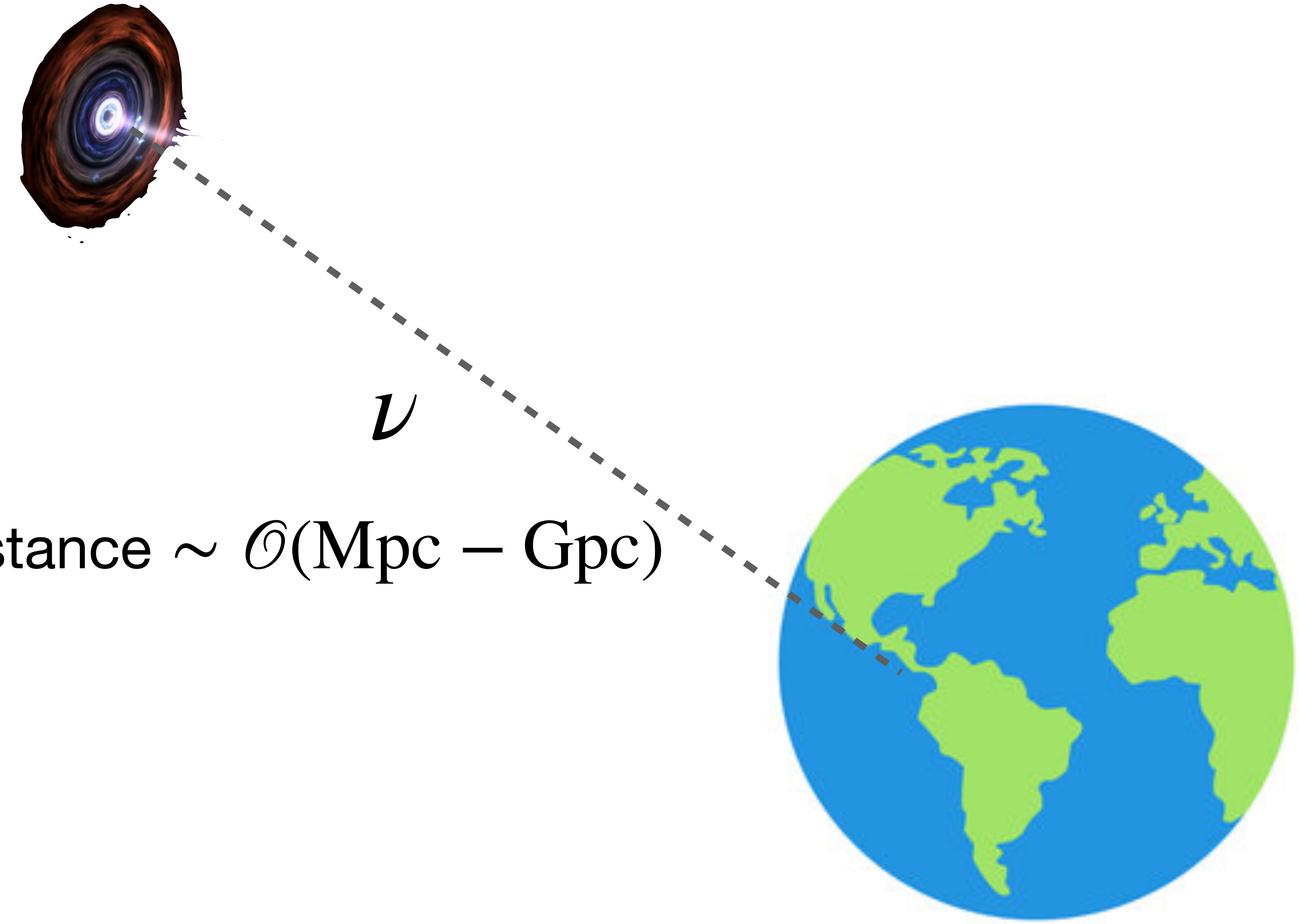
Atmospheric Neutrinos



Src: CERN/Cosmic Rays Particles Outer Space

Astrophysical vs Atmospheric Neutrinos

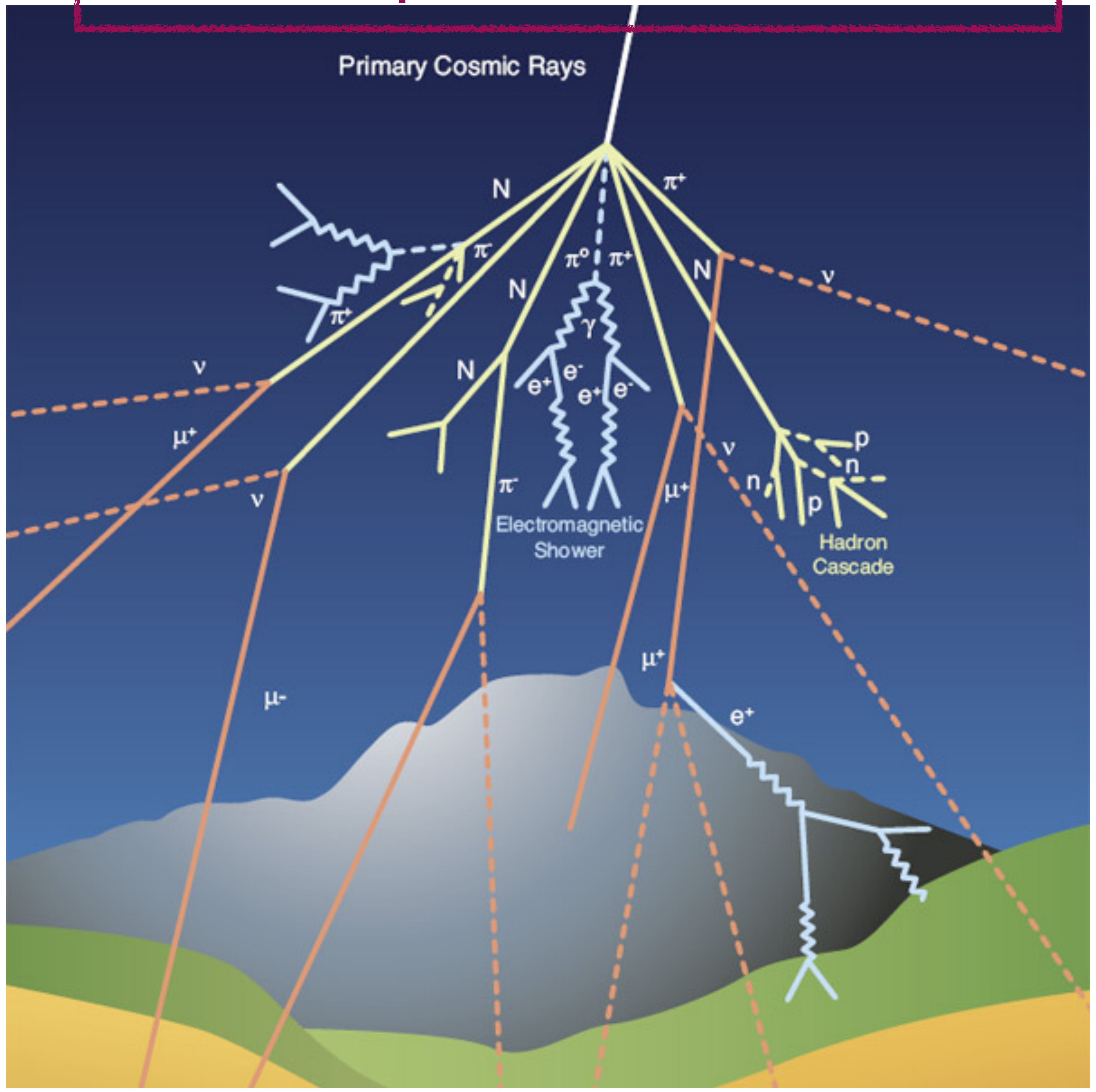
Astrophysical Neutrinos



ν

Distance $\sim \mathcal{O}(\mathrm{Mpc} - \mathrm{Gpc})$

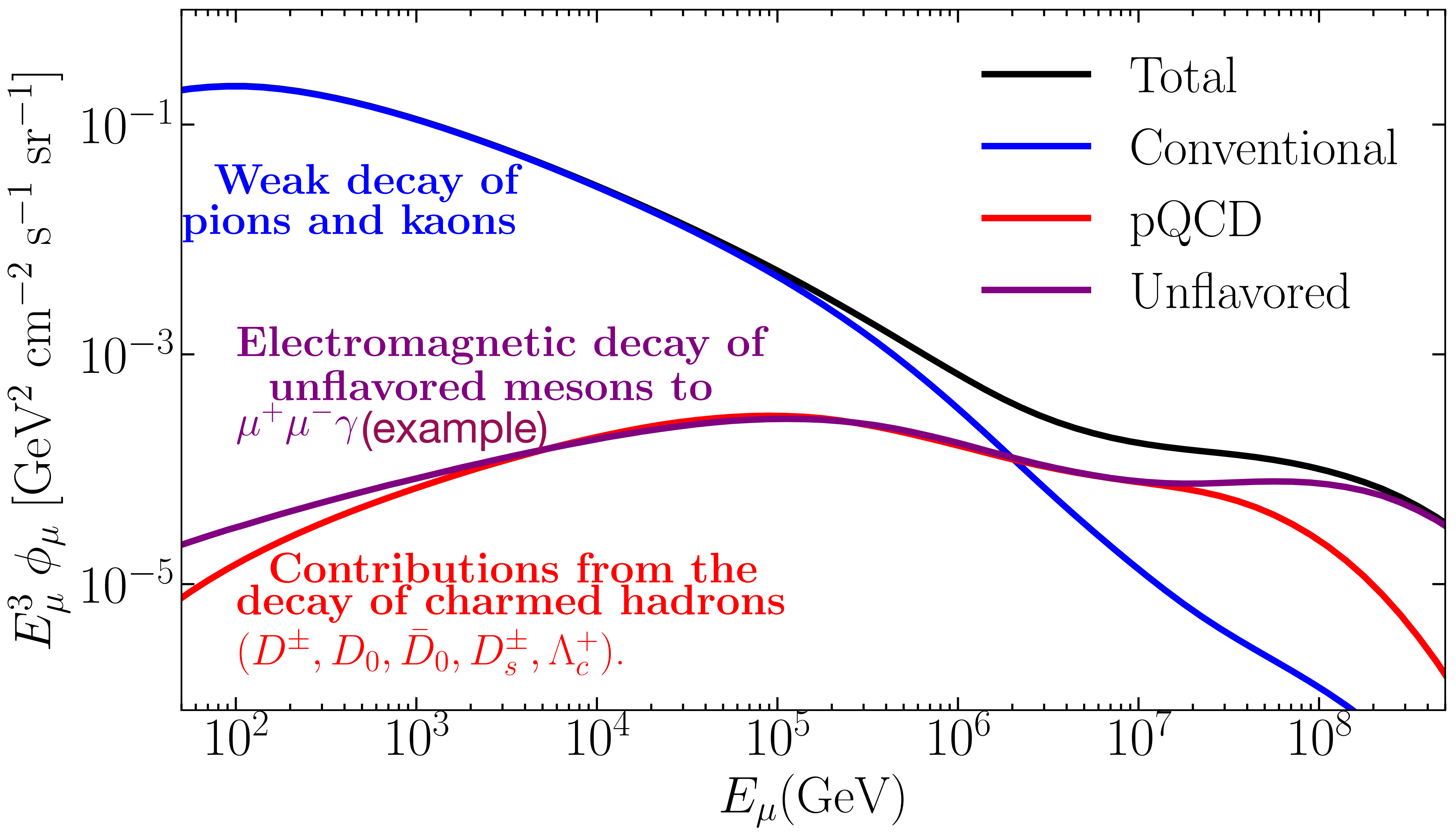
Atmospheric Neutrinos



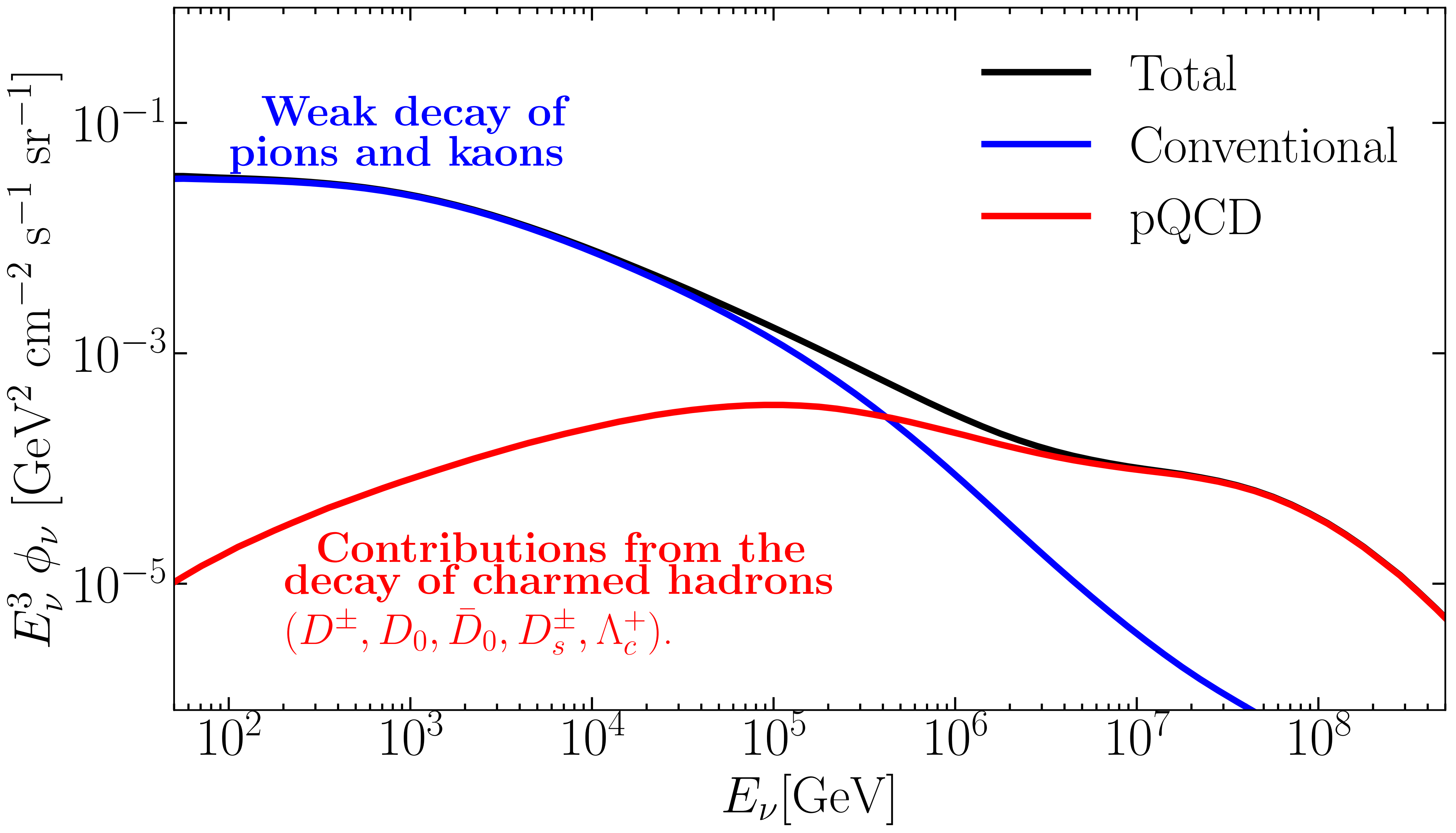
Src: CERN/Cosmic Rays Particles Outer Space

Atmospheric Muons and Neutrinos

Muons



Muon Neutrinos

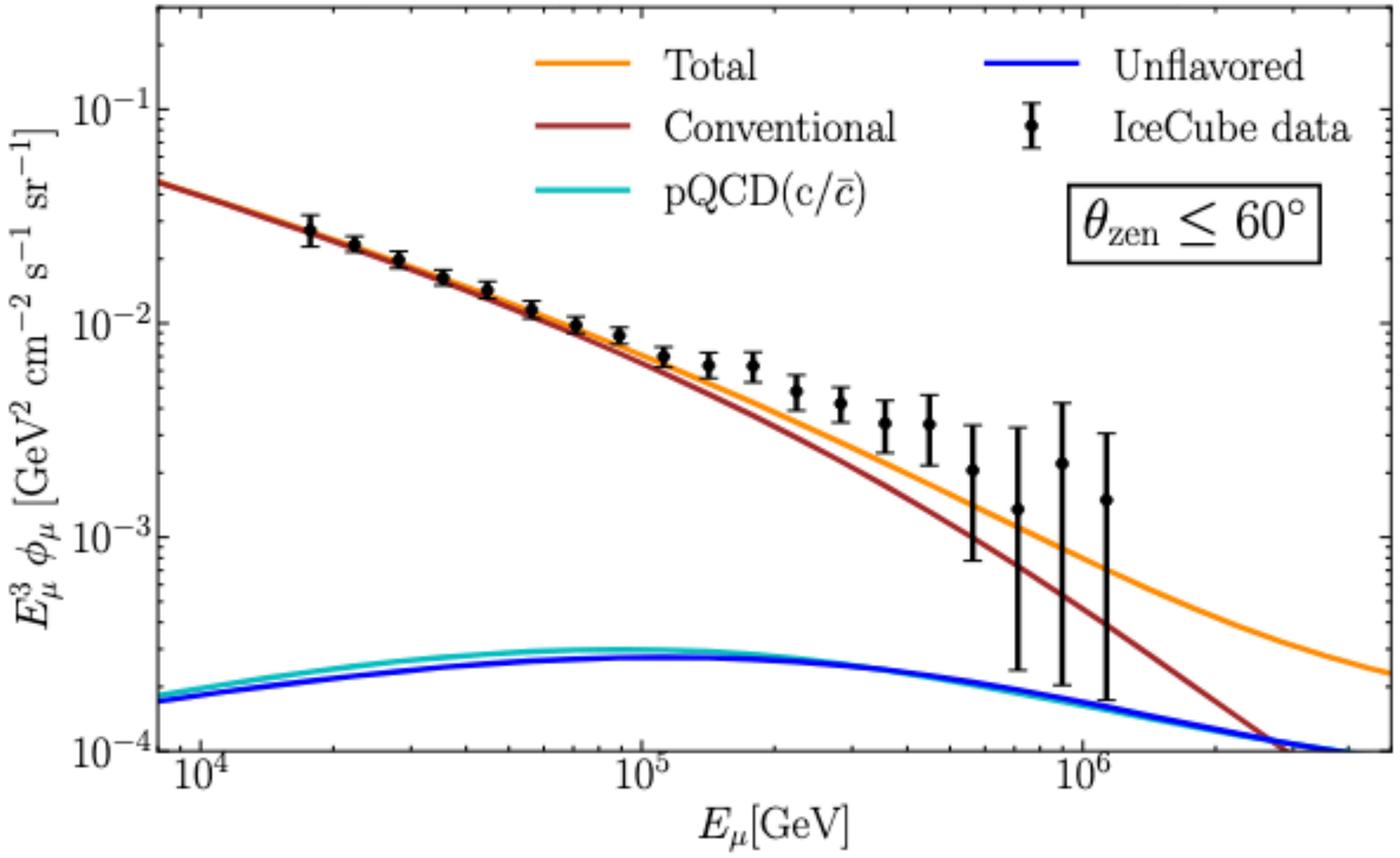


- $\phi_\mu = \phi_\mu^{\text{conv}} + \phi_\mu^{\text{pQCD}} + \phi_\mu^{\text{unfl}}$ prompt
- $\phi_{\nu_\mu} = \phi_{\nu_\mu}^{\text{conv}} + \phi_{\nu_\mu}^{\text{pQCD}}$ prompt
- Unflavored Mesons: $\eta,\ \eta',\ \phi,\ \rho^0,\ \omega,\ J/\psi$

$$\boxed{\phi_\mu^{\text{pQCD}} \approx \phi_{\nu_\mu}^{\text{pQCD}}}$$

IceCube Experiment - Data and Limit

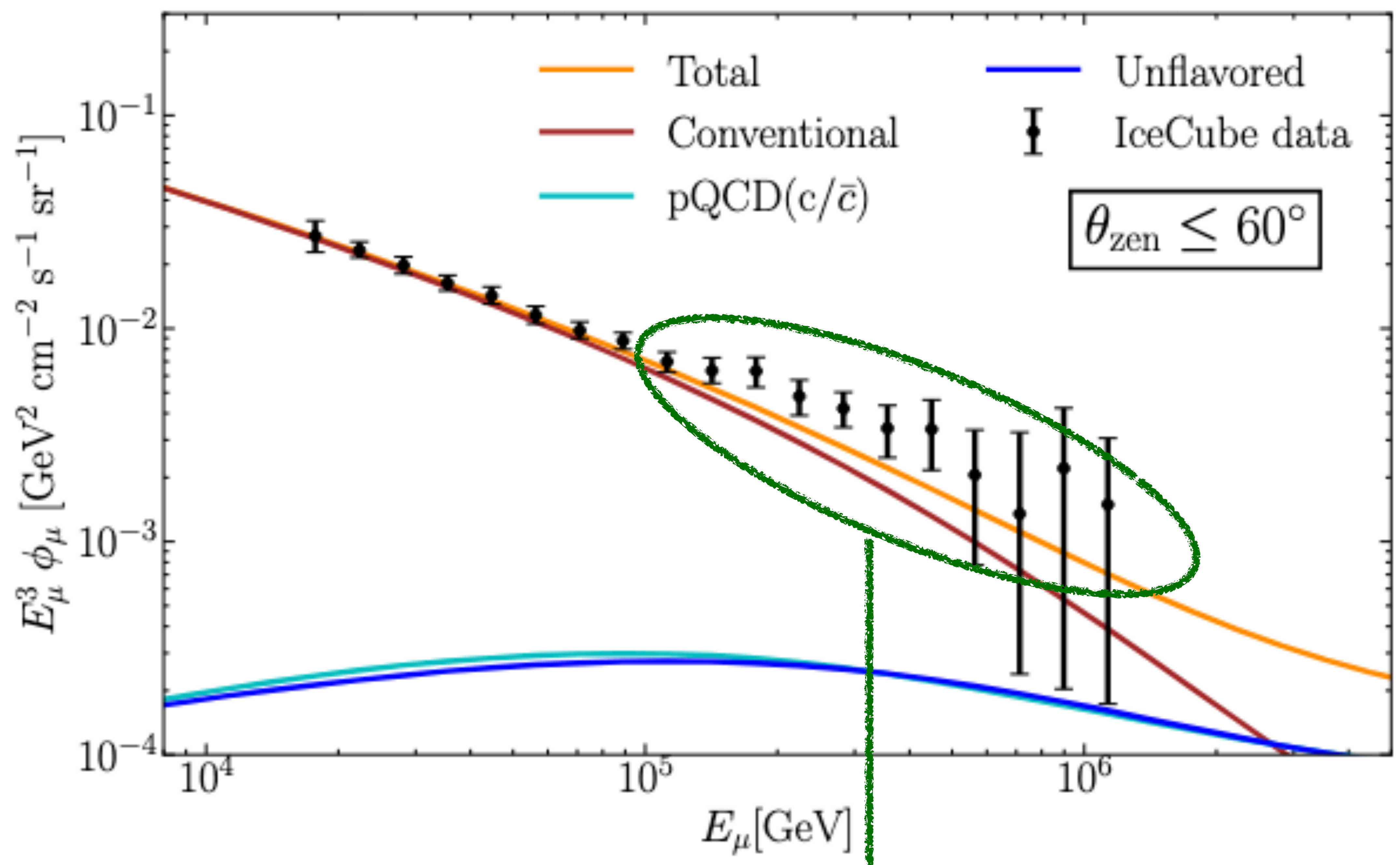
Muons



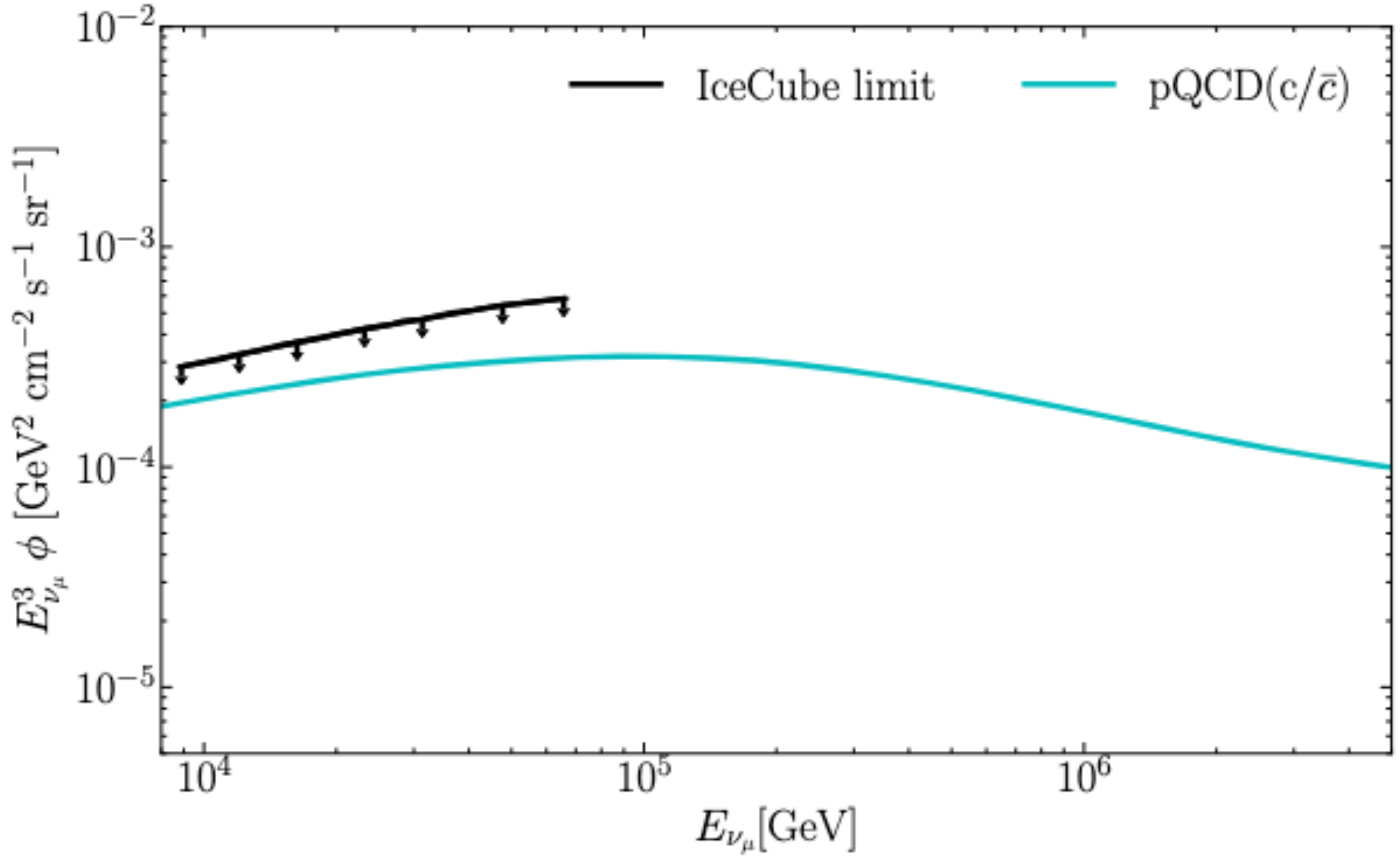
Muon data: MG Aartsen et al., Astropart.Phys. 78 (2016) 1-27

IceCube Experiment - Data and Limit

Muons



Muon Neutrinos



Main motivation: Add a new contribution to produce missing muon flux

Neutrino limit: MG Aartsen et al., Astrophys.J. 833 (2016)

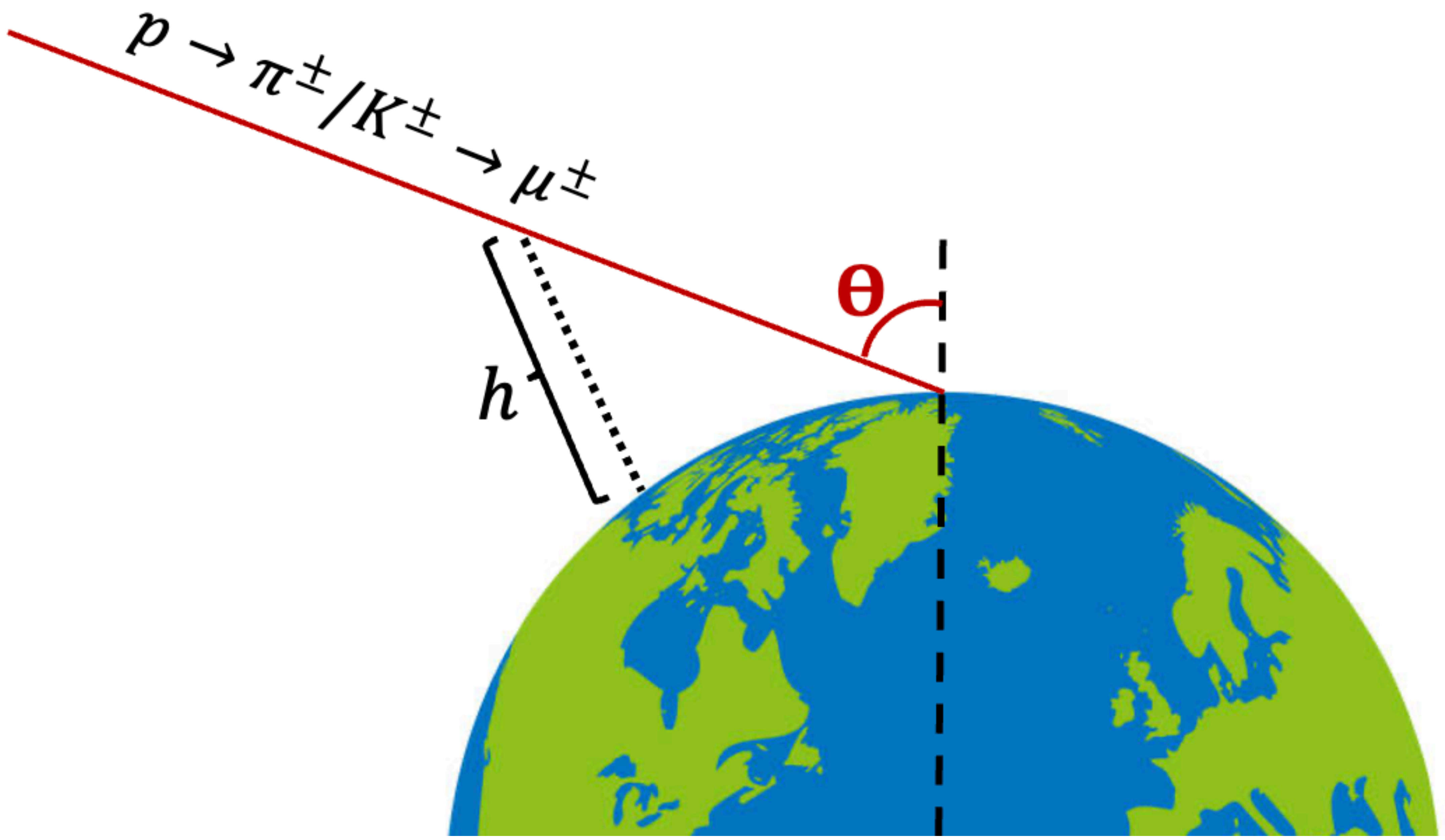
Matrix Cascade Equations (MCEq) package

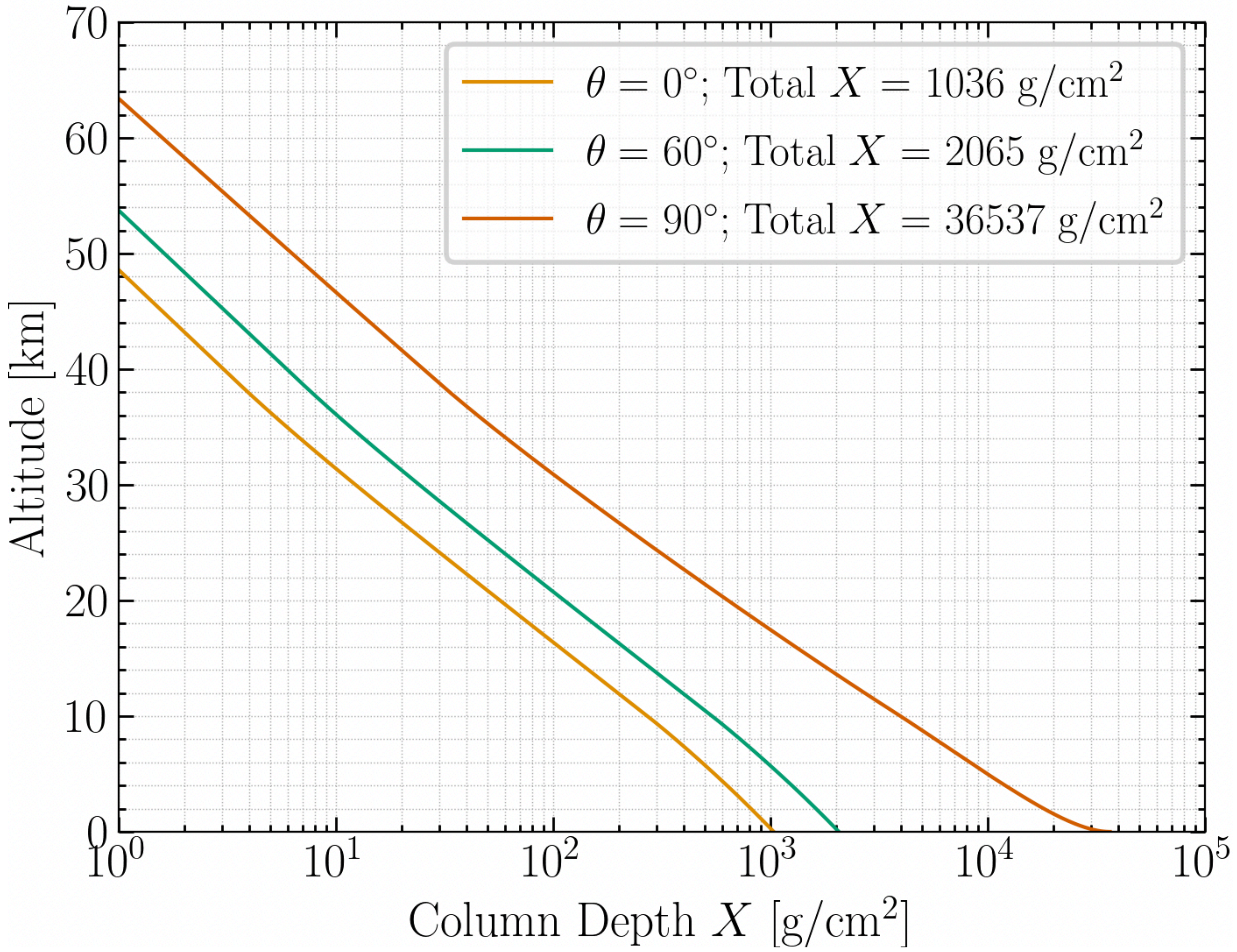
https://github.com/mceq-project/MCEq

- US Standard Earth atmosphere[1]
- Cosmic ray flux - Gaisser Hillas model H3a[2]
- Hadronic interaction model - *SIBYLL2.3c*[3]
- Continuous energy loss for particles considered.
- No Earth's magnetic field considered.

[1]: D. Heck et al., Tech. Rep. FZKA 6019, Karsruhe (1998)
[2]: Gaisser, T.K., Astroparticle Physics 35, 801 (2012)
[3]: F. Riehn et al., PoS ICRC2017

Altitude vs Column Depth





Column Depth: $X(l, \alpha) = \int_l^\infty dl' \rho(h(l', \alpha))$

Cascade equations

To evaluate the flux of muons, we step through the column depth of the atmosphere with steps ΔX:

- Muon flux:

$$\phi_\mu(E, X+\Delta X) = \left[\underbrace{\phi_\mu(E', X)}_{\text{Muon flux at previous X step}} \left(1 - \overbrace{\frac{\Delta X}{\lambda_\mu^{\text{dec}}}}^{\text{Loss from decay}} \right) + \sum_{j=\pi,K,..} \underbrace{Z_{j\to\mu}}_{\text{Source term}} \phi_j(E', X) \frac{\Delta X}{\lambda_j^{\text{dec}}} \right] \exp(b\Delta X)$$

$$\boxed{E' > E}$$

Intrinsic Charm

- Non-perturbative fluctuations of proton and neutron.
  - $|uudc\bar{c}\rangle$ and $|uddc\bar{c}\rangle$
  - $pA \rightarrow \bar{D}^0\Lambda_c^+X$ and $nA \rightarrow D^-\Lambda_c^+X$
- $\bar{D}^0 \rightarrow \mu^- + \bar{\nu}_\mu + X$
- $D^- \rightarrow \mu^- + \bar{\nu}_\mu + X$
- $\Lambda_c \rightarrow \mu^+ + \nu_\mu + X$

Intrinsic Charm production models

$$\boxed{\frac{d\sigma^{(\mathrm{intr})}_{p+\mathrm{air}\to\mathrm{h_c}}(E, x_{h_c})}{dx_{h_c}} = w^{c}_{\mathrm{intr}}\sigma_{p-\mathrm{air}}(E) f^{(\mathrm{intr})}_{h_c}(x_{h_c})} \quad \text{where} \quad x_{h_c} = \frac{E_{h_c}}{E_p}$$

- Regge fragmentation functions [1]:

$$f^{\mathrm{intr}}_{h_c}(x) = N_{\mathrm{intr}}\, x^{-a_\psi}(1-x)^{-a_\psi+2(1-a_N)}$$

$$N_{\mathrm{intr}} = \frac{\Gamma(-2a_\psi + 4 - 2a_N)}{\Gamma(-a_\psi + 1)\Gamma(-a_\psi + 3 - 2a_N)}$$

[1]: A.B. Kaidalov et al., Z.Phys. C 30 (1986) 145

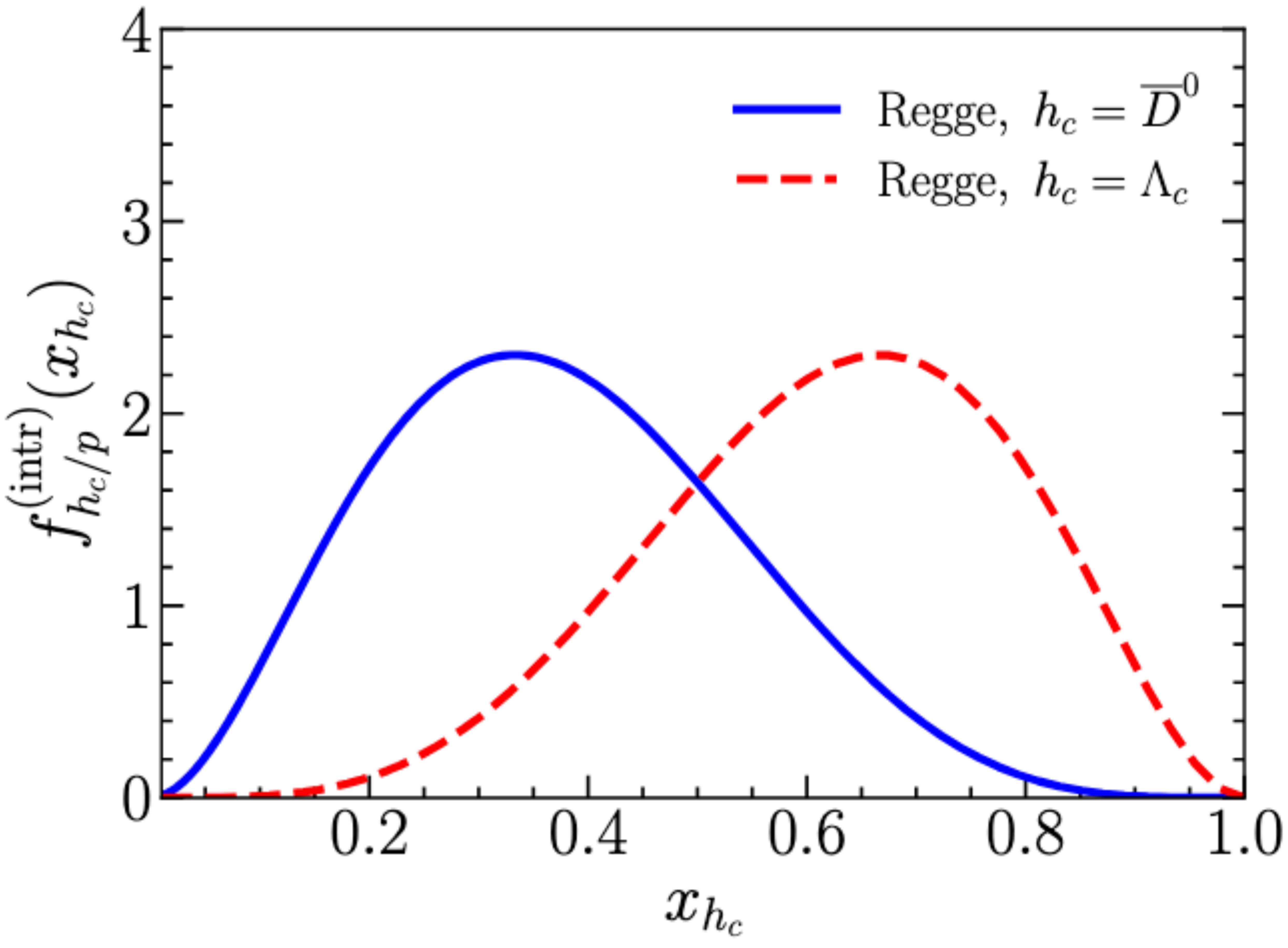
Intrinsic Charm production models

Regge formulation with $a_\psi = -2$ and $\mathrm{a_N} = -0.5$

- For Regge Model:

$$f^{(\mathrm{intr})}_{D^-}(x_D) = f^{(\mathrm{intr})}_{\overline{D}^0}(x_D)$$

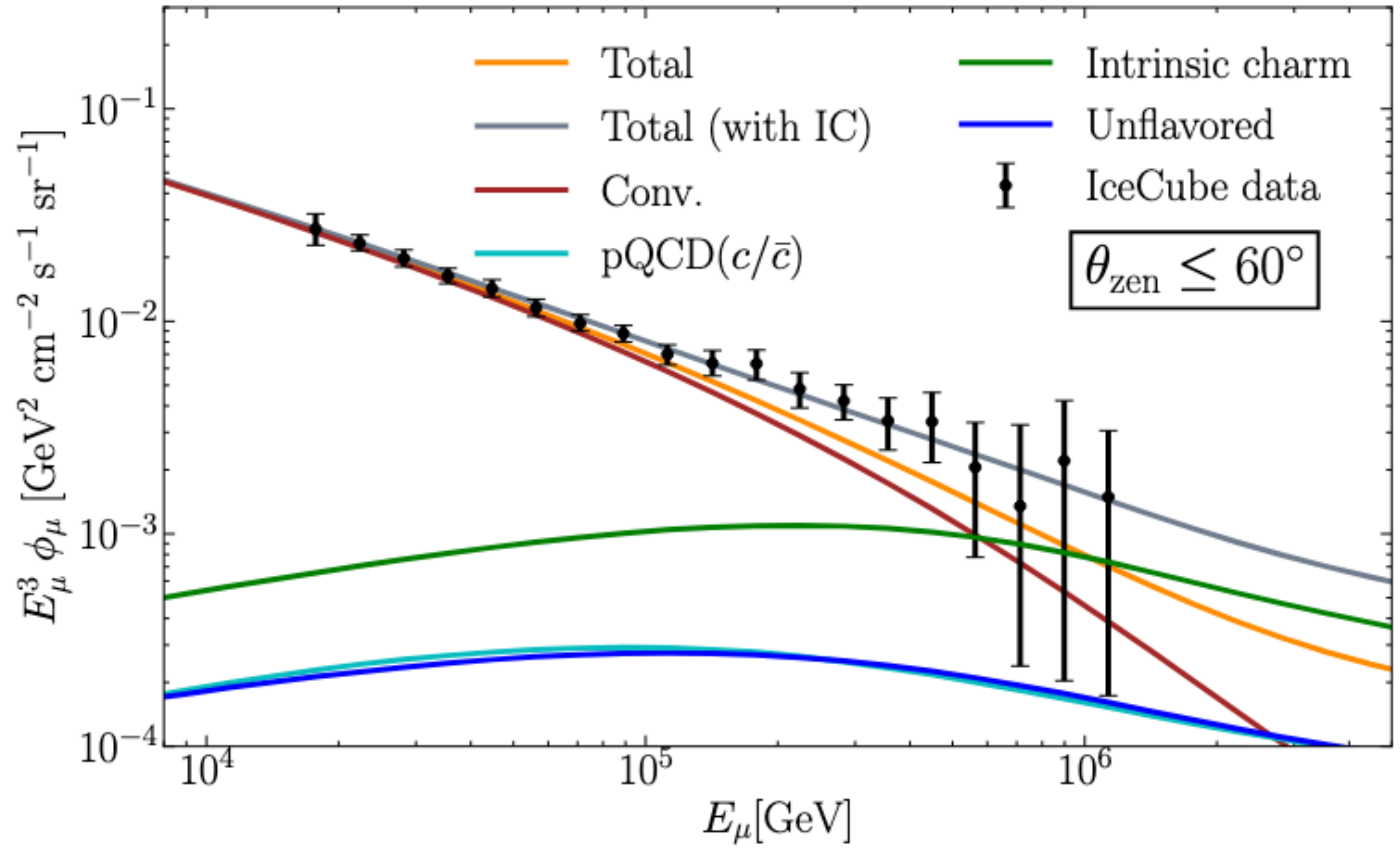
$$f^{(\mathrm{intr})}_{\Lambda_c}(x_\Lambda) = f^{(\mathrm{intr})}_{\overline{D}^0}(1 - x_\Lambda)$$



Muon flux with Intrinsic Charm

Regge formulation with $a_\psi = -2$ and $\mathrm{a_N} = -0.5$

$$\boxed{w_c^{intr} = 3.91 \times 10^{-3}}$$



Muon flux with Intrinsic Charm

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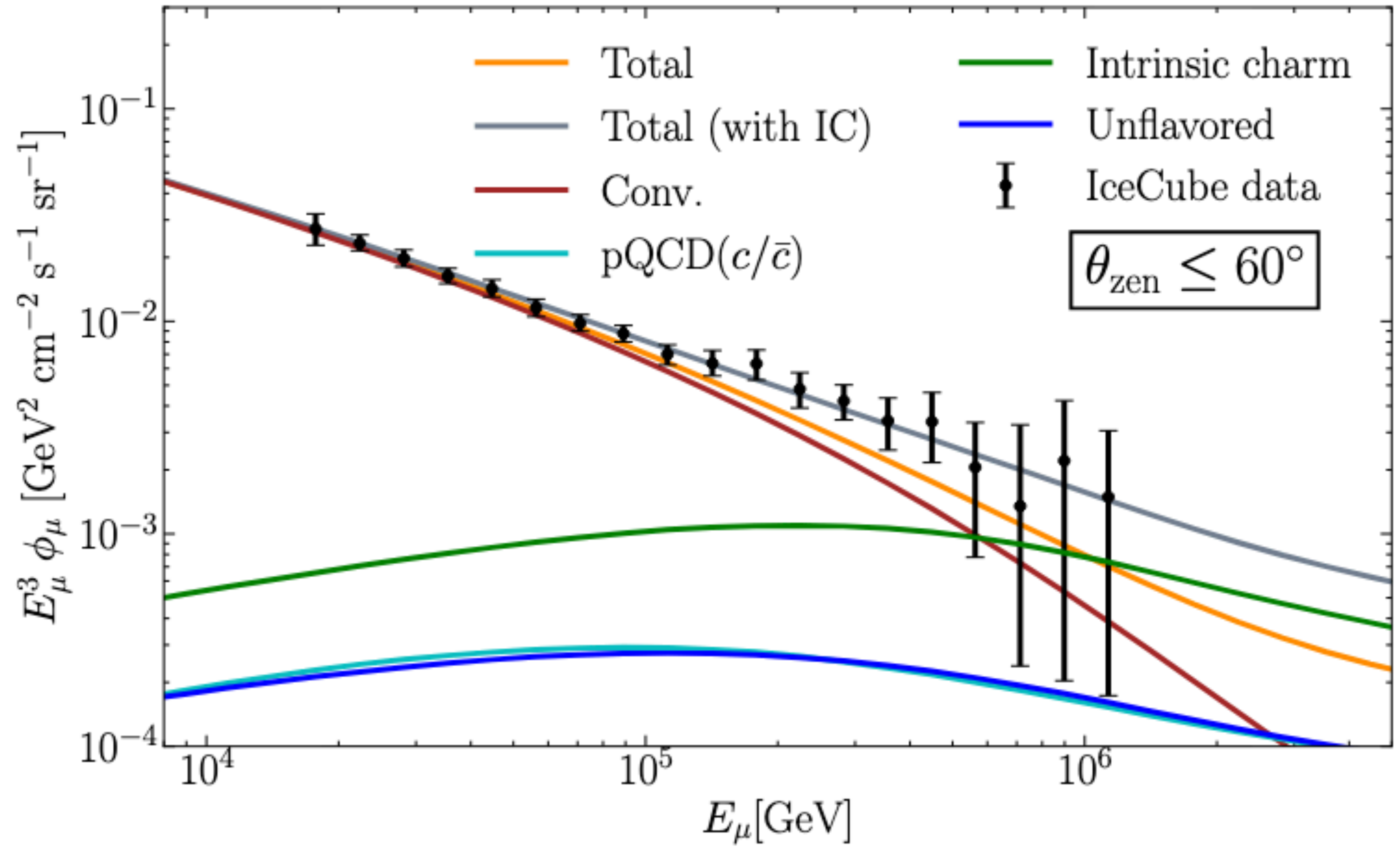
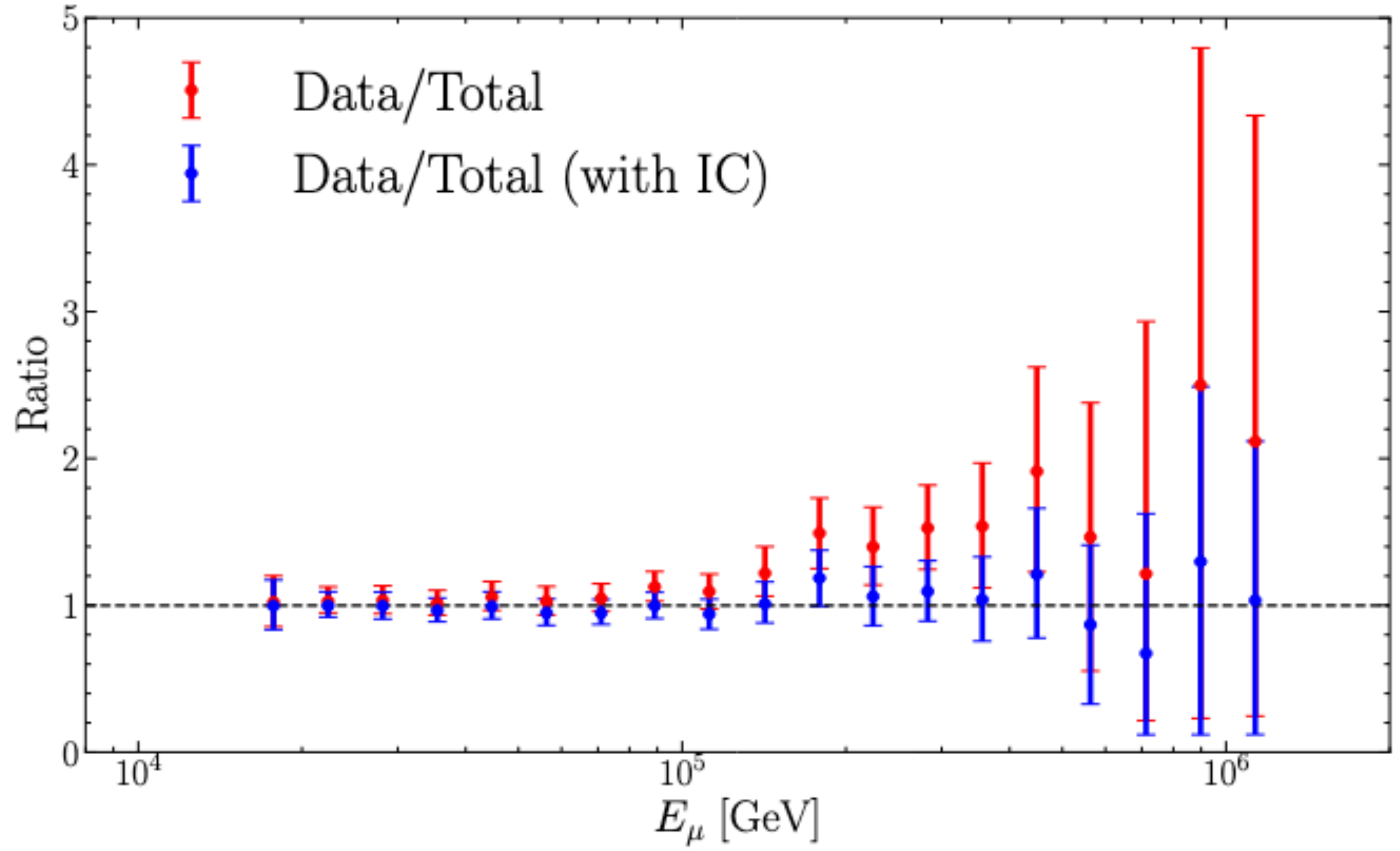
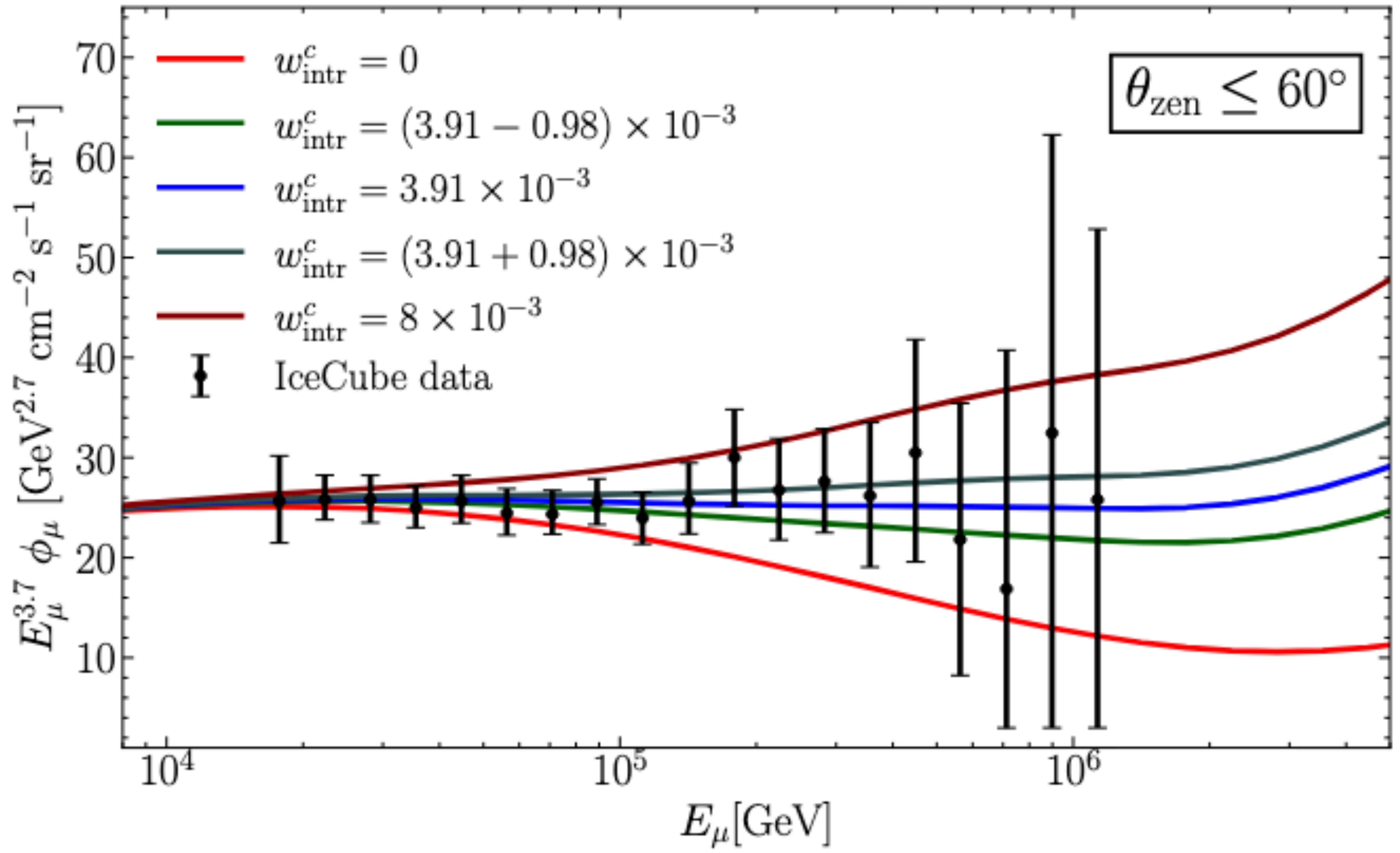


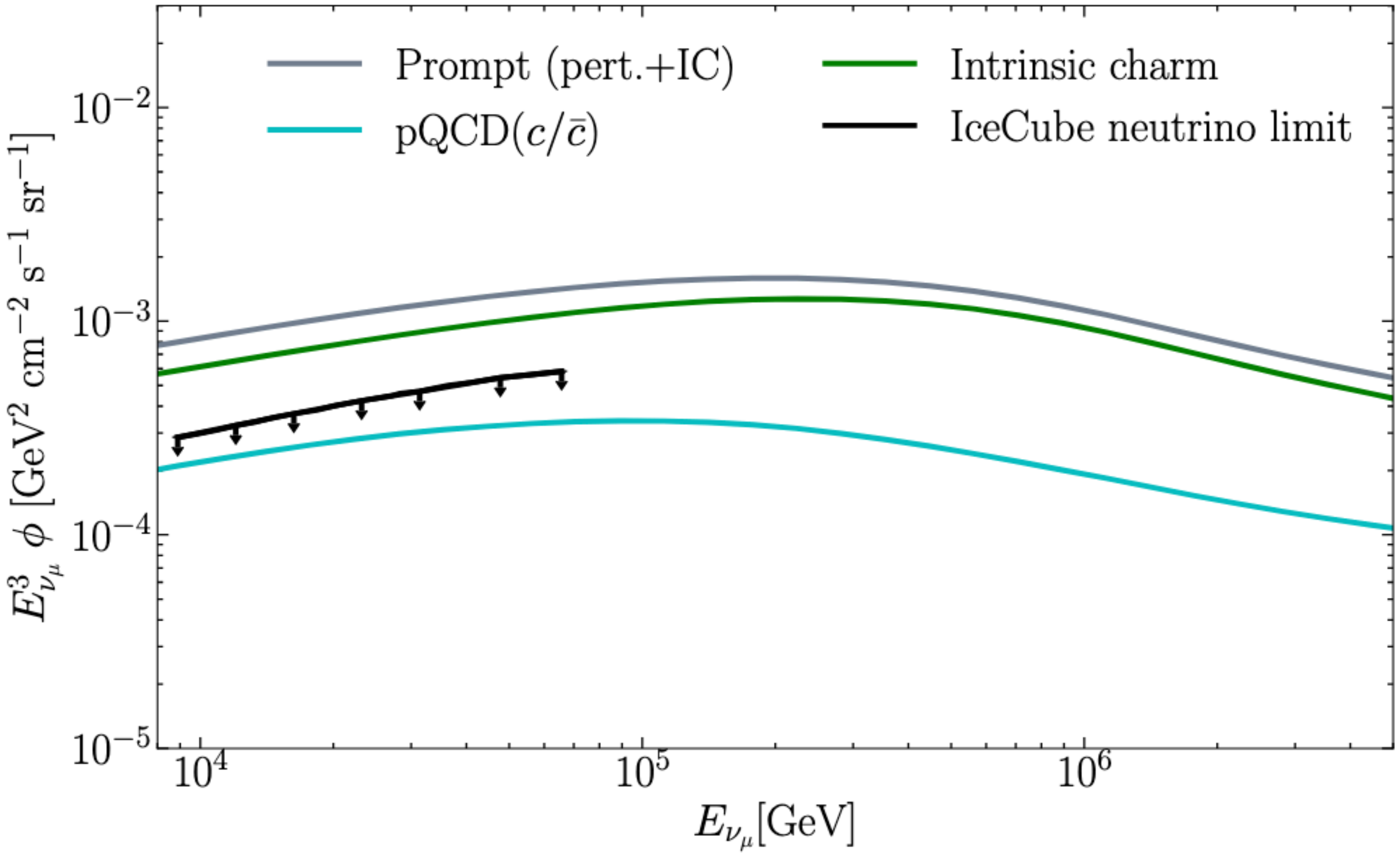




Muon Neutrino flux

Regge formulation with $a_\psi = -2$ and $\mathrm{a_N} = -0.5$

$$\boxed{w_c^{intr} = 3.91 \times 10^{-3}}$$



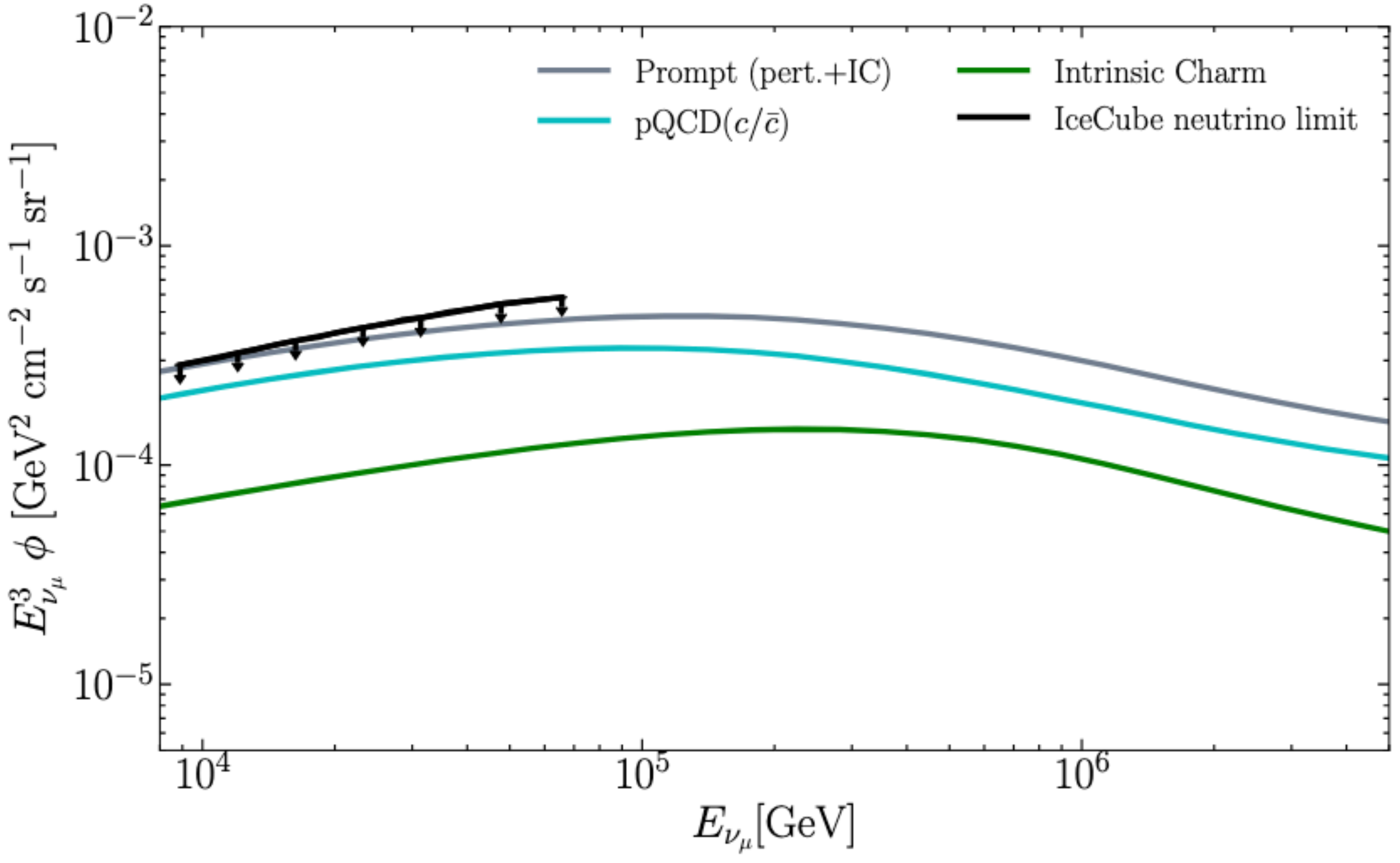
Overshoots the upper bound!

Fitting Muon Neutrino flux limit first

Regge formulation with $a_\psi = -2$ and $\mathrm{a_N} = -0.5$

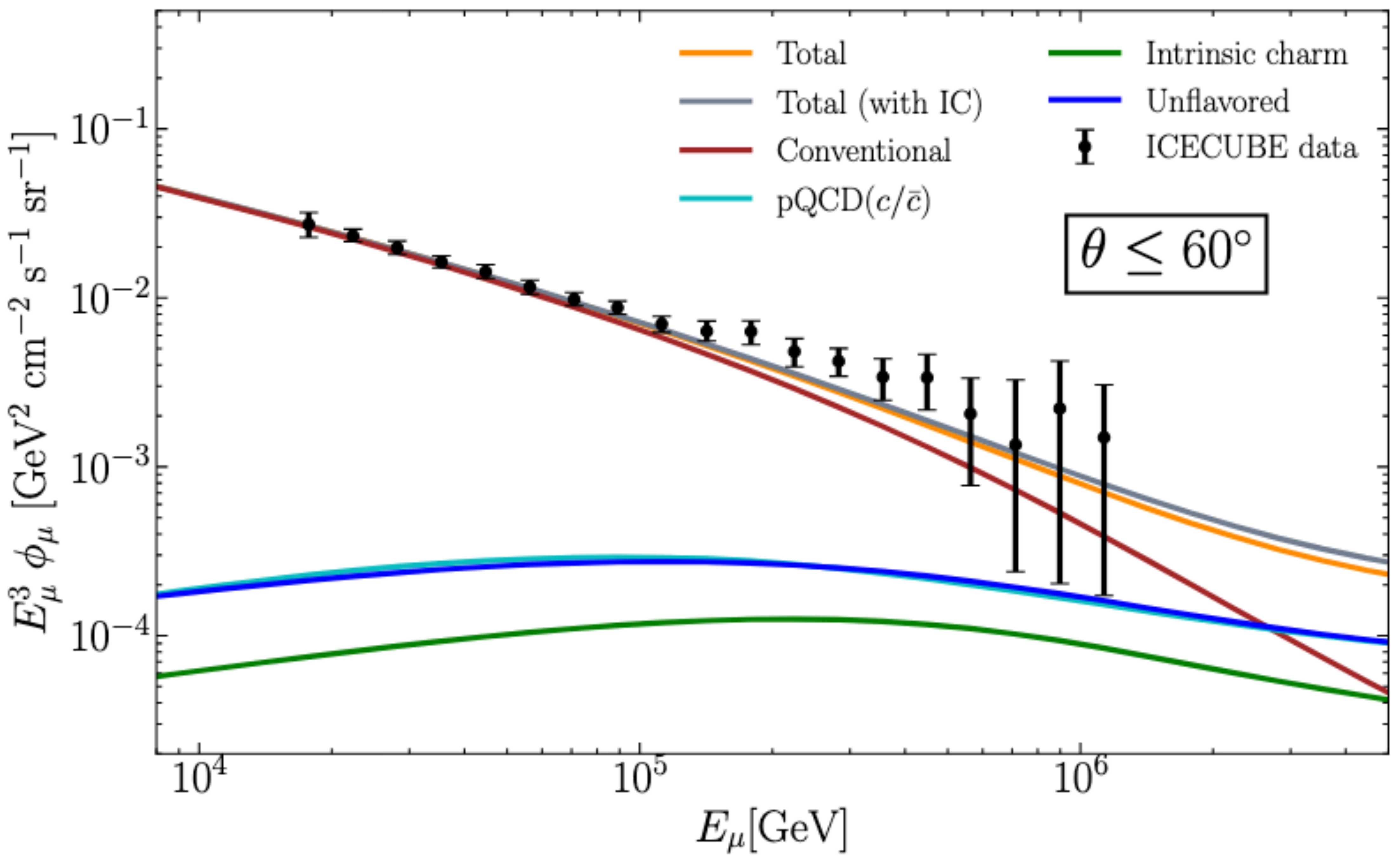
Undershoots the data!

Muon Neutrino



$$w_c^{intr} = 4.46 \times 10^{-4}$$

Muon

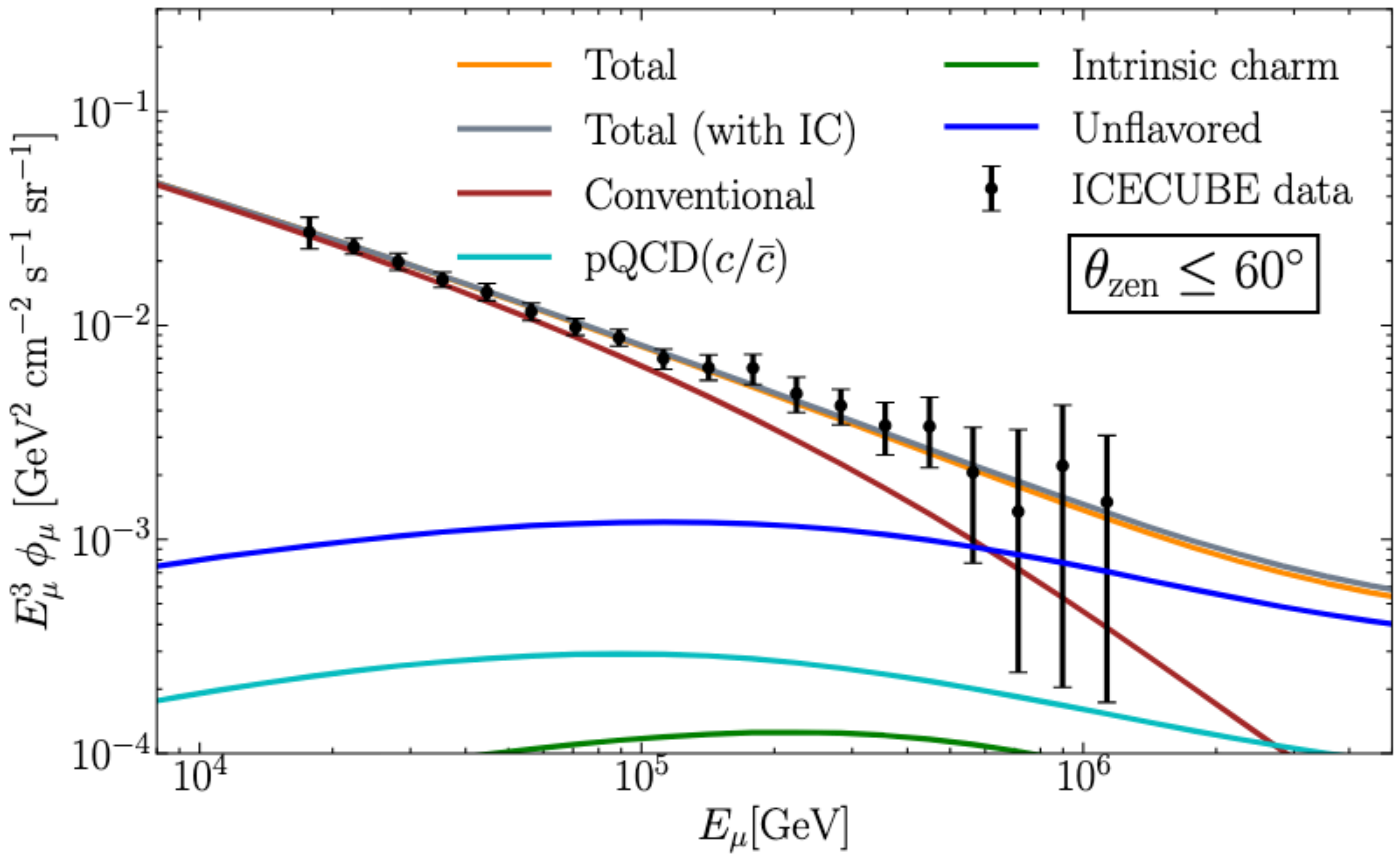


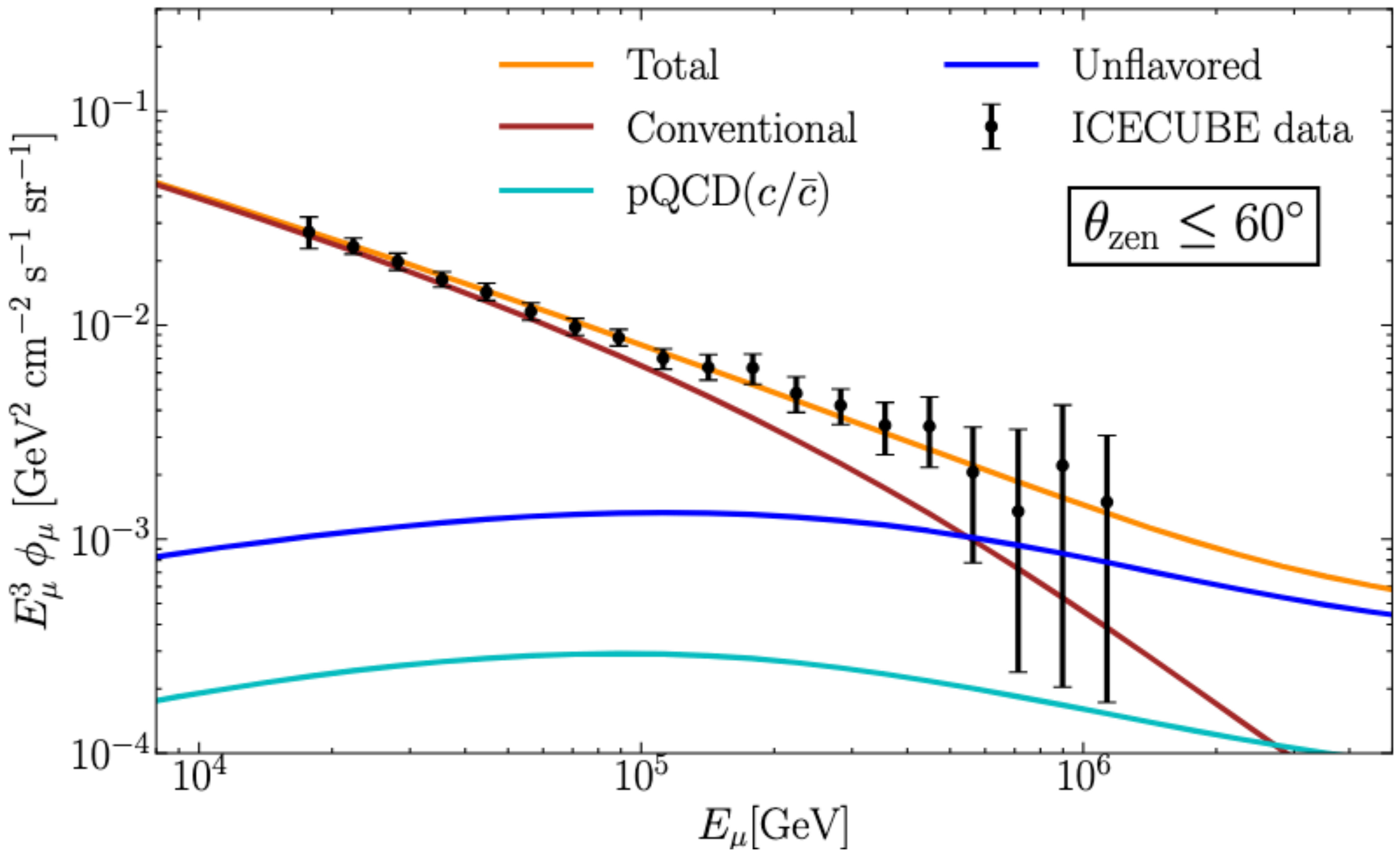
$$w_c^{intr} = 4.46 \times 10^{-4}$$

Unflavored mesons

For muon flux

Regge formulation with $a_\psi = -2$ and $\mathrm{a_N} = -0.5$





$w_c^{intr} = 4.46 \times 10^{-4}$ and $\alpha_{\rm unfl} = 4.39$

$w_c^{intr} = 0$ and $\alpha_{\rm unfl} = 4.84$

Uncertainties in Prompt flux

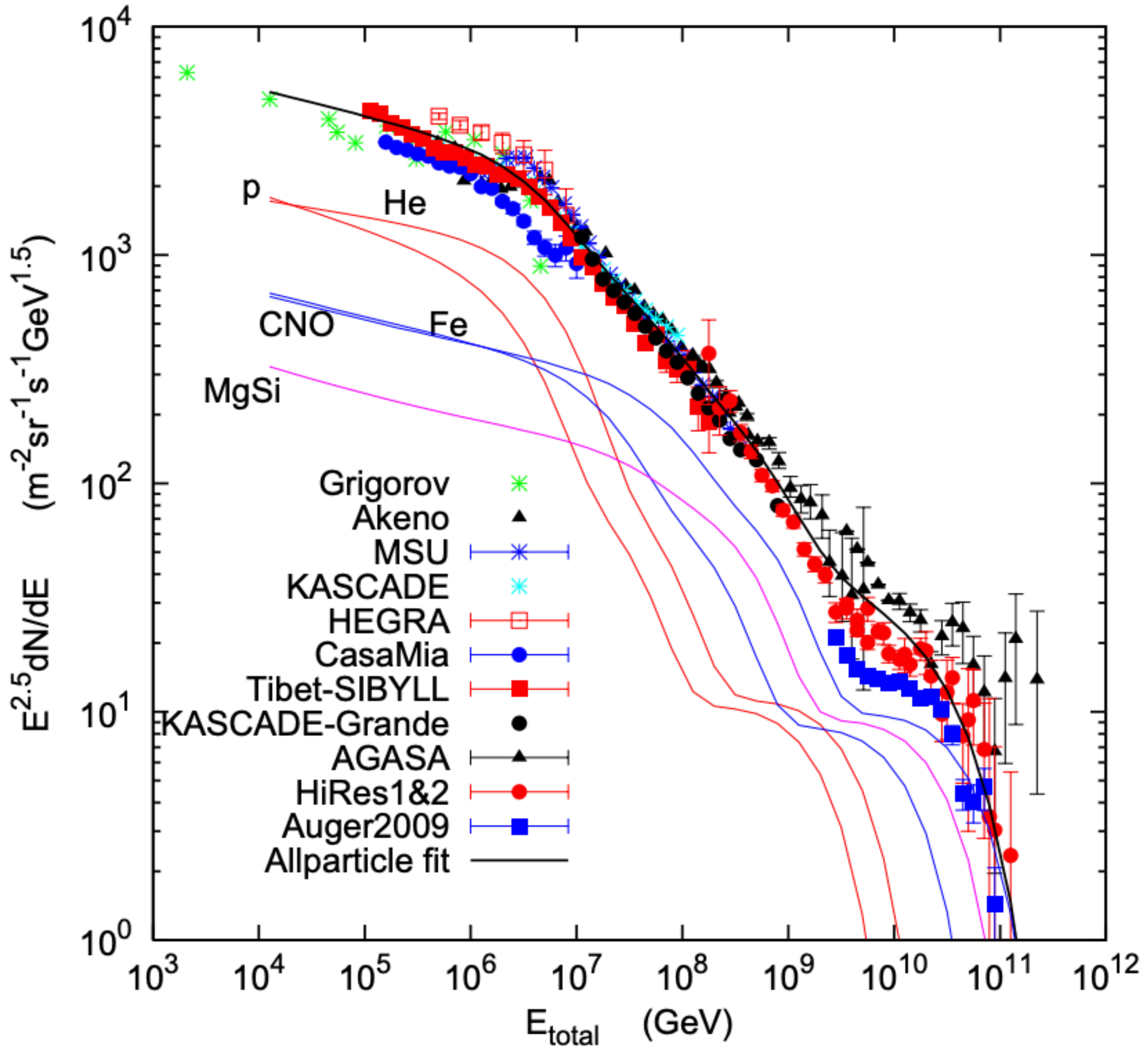
1. Since, $\phi_{\nu_\mu,\mathrm{pQCD}} \simeq \phi_{\mu,\mathrm{pQCD}}$, to reach neutrino upper bound: $\sim 1.4\phi_{\mu,\mathrm{pQCD}}$.
   - From unflavored meson decays $\sim 4.4\phi_{\mu,\mathrm{unfl}}$
   - Large enhancement of forward unflavored meson production in *p-air* collisions at high energies required in modeling to make up this gap.
2. Neutrino upper limit: can be relaxed.
3. Other hadronic interaction models for unflavored meson contributions to $\mu^+\mu^-$:
   - comparable *DPMJET-III* and *EPOSLHC* to *SIBYLL2.3c*.
   - lower *QGSJET-II* and *QGSJET-III* than *SIBYLL2.3c*.

Summary

- IceCube data exists for atmospheric muons and upper bound on prompt muon neutrino.
- With $w_c^{\text{intr}} = 3.91 \times 10^{-3}$: best fit for Muon IceCube data but overshoot the prompt muon neutrino upper limit.
- With $w_c^{\text{intr}} = 4.46 \times 10^{-4}$: best fit for Muon neutrino upper bound but fall short for muon data.
- Another possibility is changing unflavored contribution to atmospheric muons $\alpha^{\text{unfl}} = 4.4 - 4.8$.
- Neutrino upper limit can be relaxed based on uncertainties in the prompt production.

Backup slides

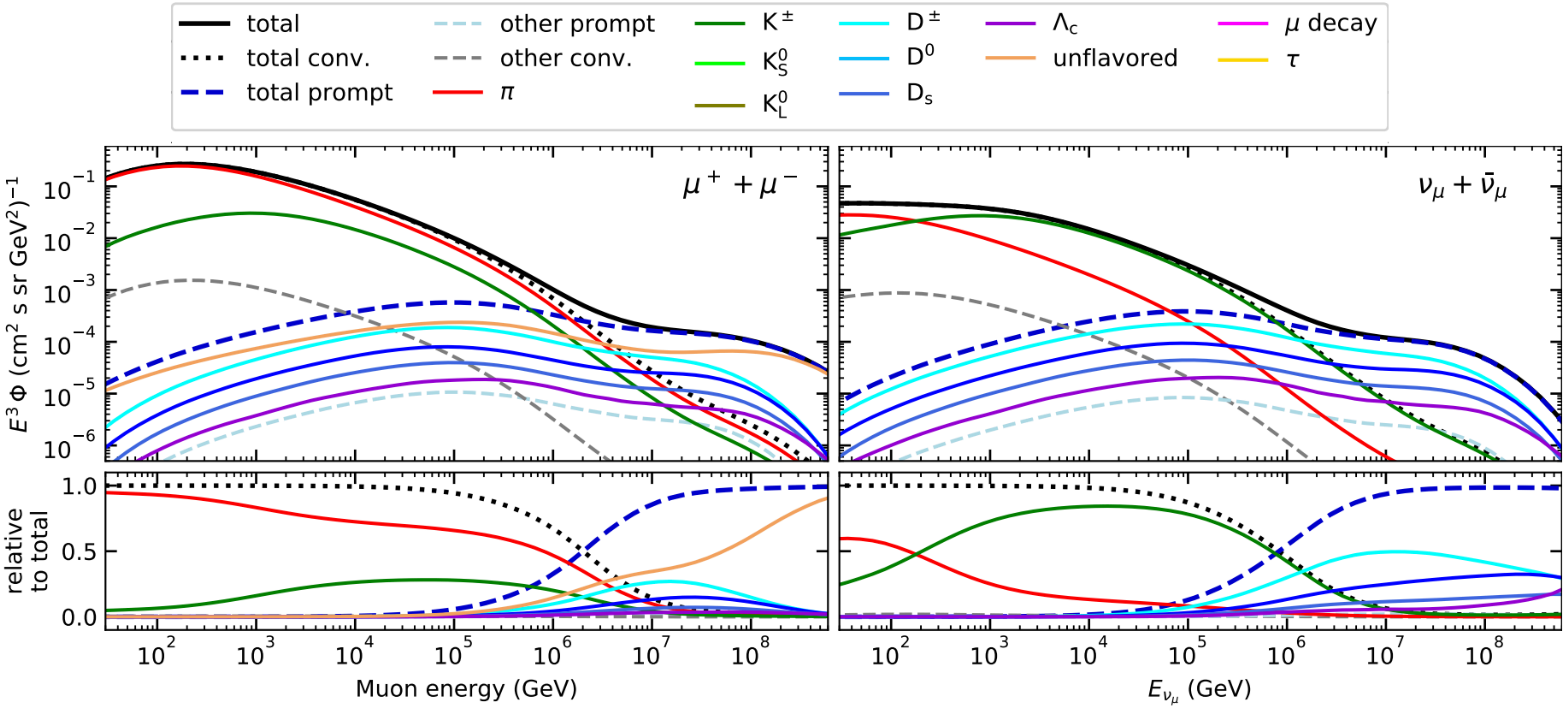
CR flux - H3a



10^4
10^3
10^2
10^1
10^0
$E^{2.5}dN/dE \quad (m^{-2}sr^{-1}s^{-1}GeV^{1.5})$
p
He
CNO
Fe
MgSi
Grigorov
Akeno
MSU
KASCADE
HEGRA
CasaMia
Tibet-SIBYLL
KASCADE-Grande
AGASA
HiRes1&2
Auger2009
Allparticle fit
10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12}
$E_{total} \quad (GeV)$

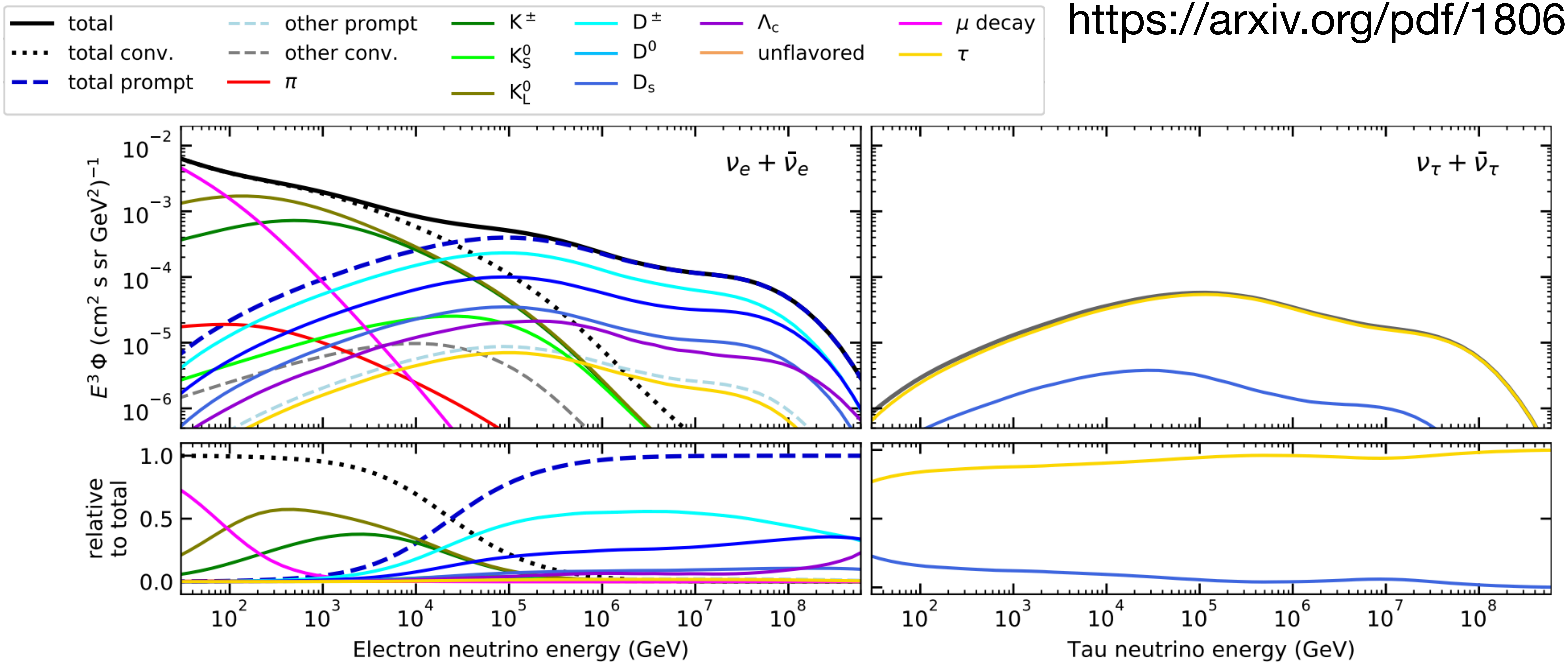
MCEq Flux - Muons and Muon neutrinos

https://arxiv.org/pdf/1806.04140



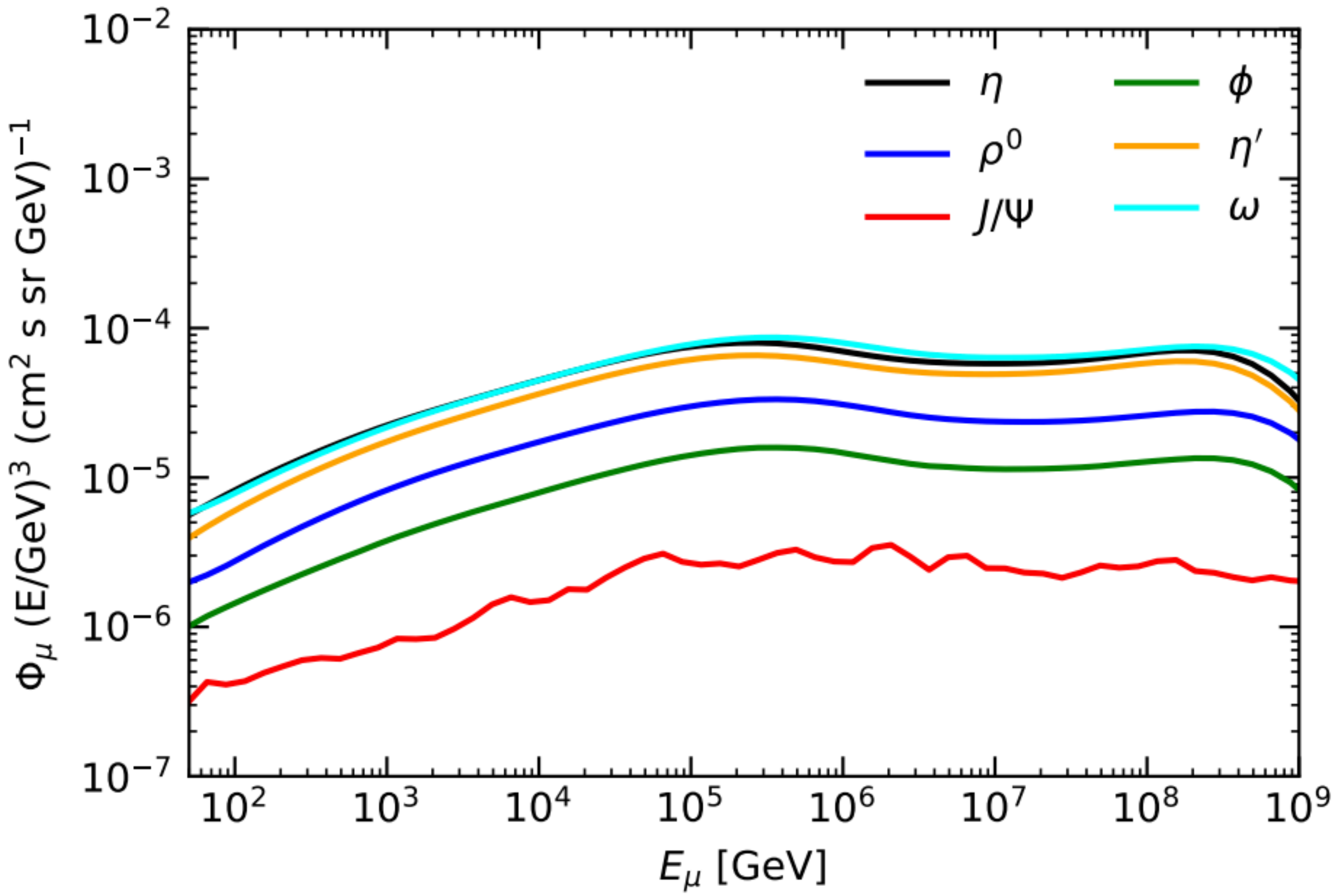
MCEq Flux - Electron and Tau neutrinos

https://arxiv.org/pdf/1806.04140



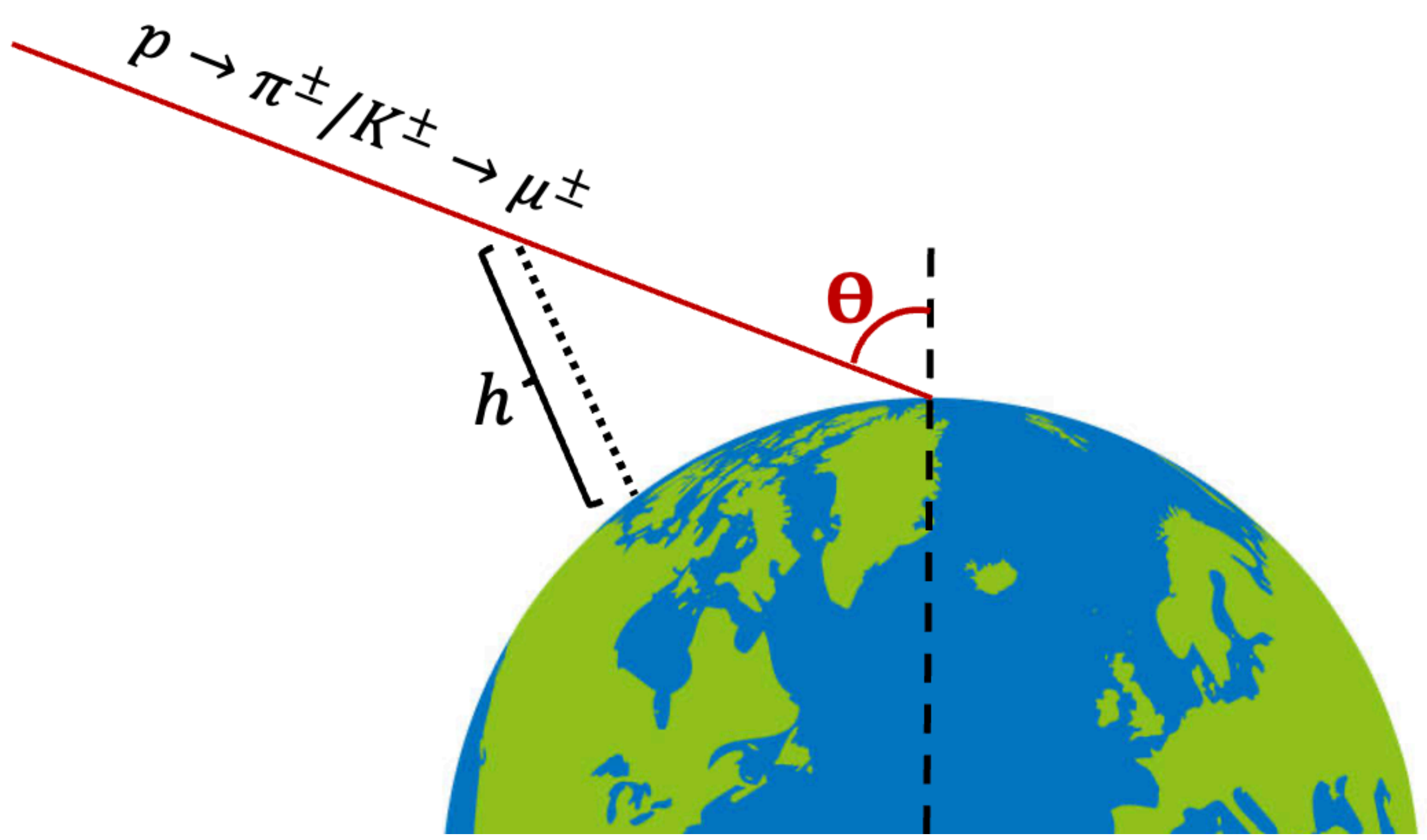
MCEq - Unflavored Mesons

https://arxiv.org/pdf/1806.04140



Cascade equations

To evaluate the flux of muons, we step through the column depth of the atmosphere with steps ΔX:



- Muon flux:

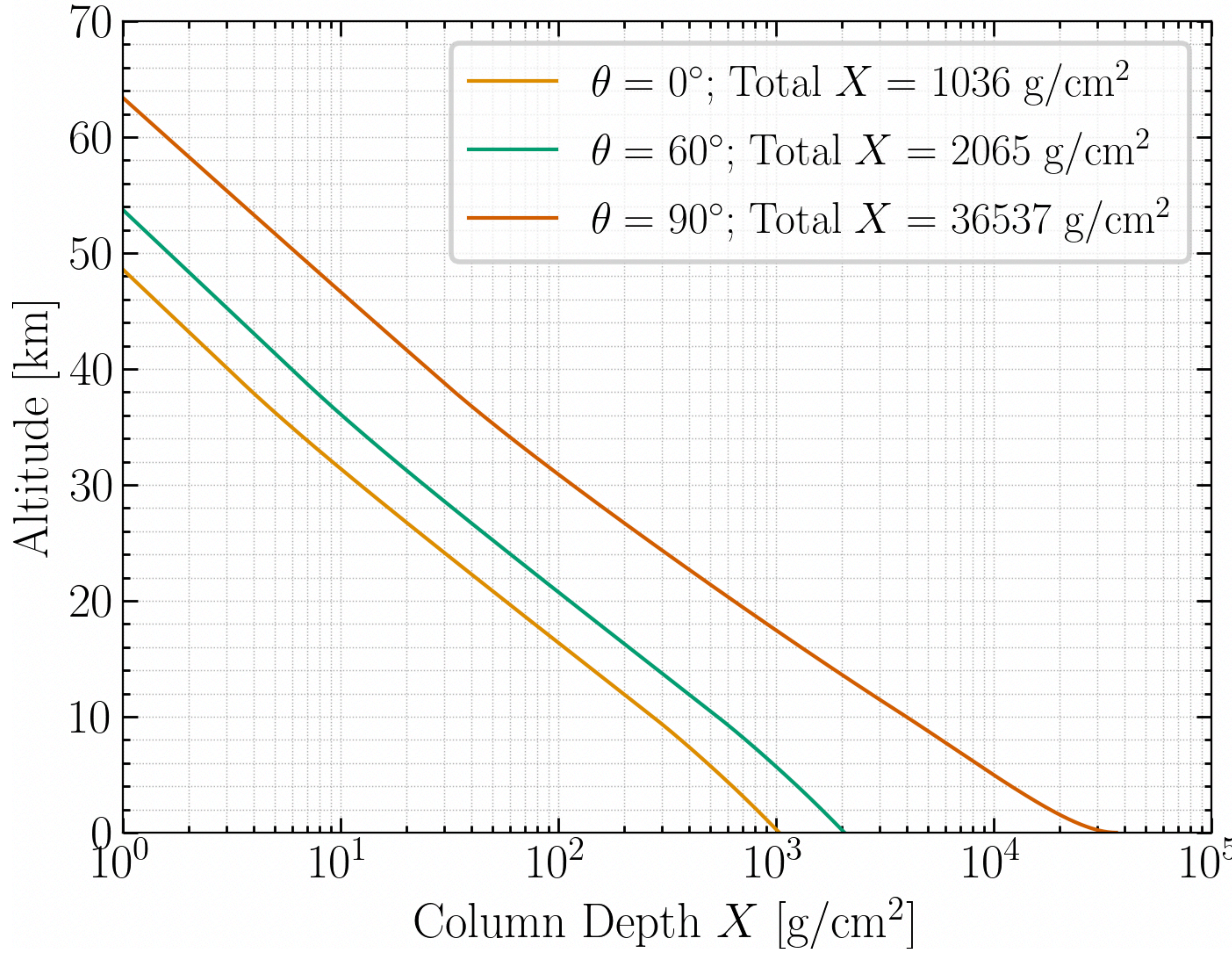
$$\phi_\mu(E, X+\Delta X) = \left[\phi_\mu(E', X)\left(1 - \frac{\Delta X}{\lambda_\mu^{\mathrm{dec}}}\right) + Z^{dec}_{\pi/K\to\mu}\phi_{\pi/K}(E', X)\frac{\Delta X}{\lambda^{\mathrm{dec}}_{\pi/K}}\right]\exp(b\Delta X)$$

- Meson flux like Pion and Kaon:

$$\phi_{\pi/K}(E, X+\Delta X) = \phi_{\pi/K}(E, X)\left(1 - \frac{\Delta X}{\lambda^{\mathrm{dec}}_{\pi/K}}\right) + Z_{CR\to\pi/K}\phi_{CR}(E, X)\frac{\Delta X}{\lambda_{CR}}$$

- Cosmic ray flux:

$$\phi_{CR}(E, X+\Delta X) = \phi_{CR}(E, X)\left(1 - \frac{\Delta X}{\Lambda_{CR}}\right)$$



Z-moments

$$Z(k \to j) = \left[\int_E^\infty dE' \frac{\phi_k(E', X)}{\phi_k(E, X)} \frac{\lambda_k(E)}{\lambda_k(E')} \frac{dn(k \to j; E', E)}{dE} \right] \frac{\phi_k(E, X)}{\lambda_k(E)}$$

$$Z(CR \to IC) = w^c_{intr} \left[\int_0^1 \frac{dx}{x} \frac{\phi_{CR}(E_{CR}, X)}{\phi_{CR}(E_{IC}, X)} \frac{\lambda_{CR}(E_{IC})}{\lambda_{CR}(E_{CR})} \frac{dn(CR \to IC; E_{CR}, E_{IC})}{dx} \right] \frac{\phi_{CR}(E_{IC}, X)}{\lambda_{CR}(E_{IC})}$$

$$Z(h \to \mu) = \left[\int_{E_\mu}^\infty dE_h \frac{\phi_h(E_h, X)}{\phi_h(E_\mu, X)} \frac{\lambda_h^{dec}(E_\mu)}{\lambda_h^{dec}(E_h)} \frac{dn(h \to \mu; E_h, E_\mu)}{dE_\mu} \right] \frac{\phi_h(E_\mu, X)}{\lambda_h(E_\mu)}$$

Branching ratio and Fragmentation functions

Charmed hadrons

- $\bar{D}^0 \to \mu^- + \bar{\nu}_\mu + X$ BR = 7%
- $D^- \to \mu^- + \bar{\nu}_\mu + X$ BR = 17.6%
- $\Lambda_c \to \mu^+ + \nu_\mu + X$ BR = 4.5%

Particle	N	B_c	ϵ
D^0	0.577	0.606	0.101
D^+	0.238	0.244	0.104
D_s^+	0.0327	0.081	0.0322
Λ_c^+	0.0067	0.061	0.00418

D0 (c ubar)

D+ (c dbar)

Lambda_c (udc)

Splitting functions for HLM model

- Splitting functions for charmed baryon-meson states (HLM [2])

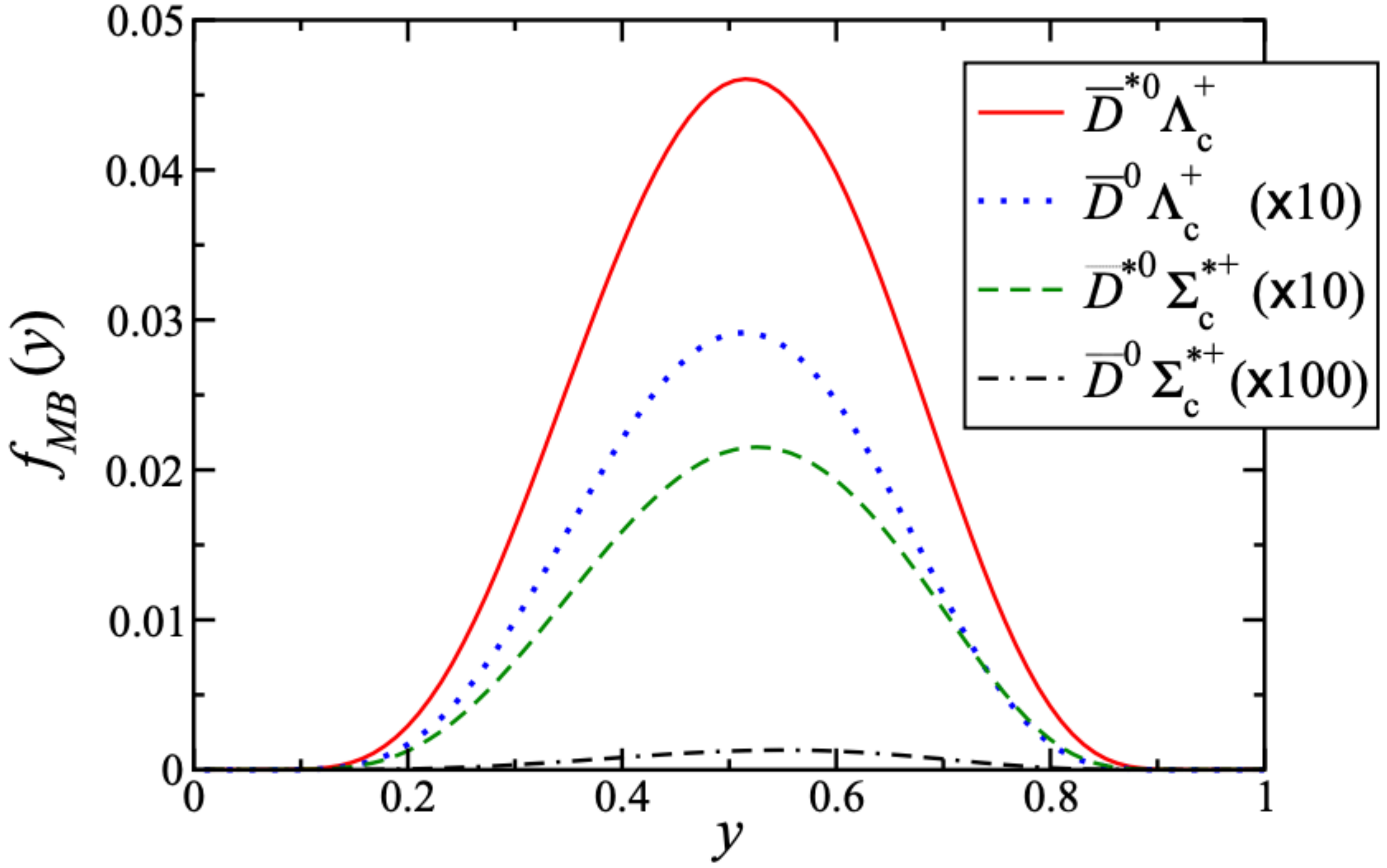
$$f_{D^*B}(y) = T_B \frac{1}{16\pi^2} \int \frac{dk_\perp^2}{y(1-y)} \frac{|F(s)|^2}{(s-M^2)^2} \times \left[g^2 G_v(y,k_\perp^2) + \frac{gf}{M} G_{vt}(y,k_\perp^2) + \frac{f^2}{M^2} G_t(y,k_\perp^2) \right], \quad (19)$$

where

$$G_v(y,k_\perp) = -6MM_B + \frac{4(P\cdot k)(p\cdot k)}{m_D^2} + 2P\cdot p, \quad (20a)$$

$$G_{vt}(y,k_\perp) = 4(M+M_B)(P\cdot p - MM_B) - \frac{2}{m_D^2}\left[M_B(P\cdot k)^2 - (M+M_B)(P\cdot k)(p\cdot k) + M(p\cdot k)^2\right], \quad (20b)$$

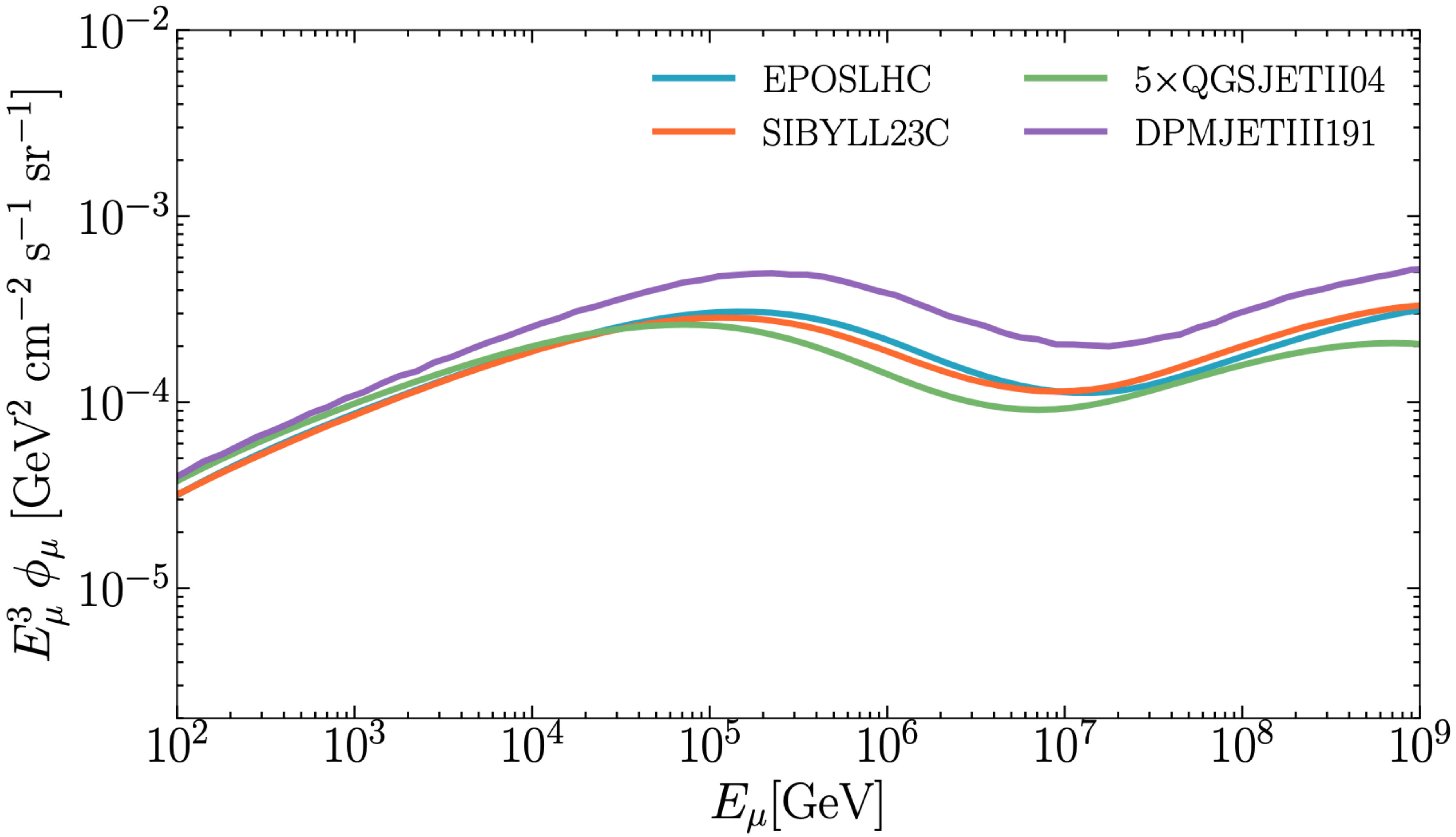
$$G_t(y,k_\perp) = -(P\cdot p)^2 + (M+M_B)^2 P\cdot p - MM_B(M^2+M_B^2+MM_B) + \frac{1}{2m_D^2}\Big[(P\cdot p - MM_B)[(P-p)\cdot k]^2 - 2(M_B^2 P\cdot k - M^2 p\cdot k)[(P-p)\cdot k] + 2(P\cdot k)(p\cdot k)(2P\cdot k - M_B^2 - M^2)\Big], \quad (20c)$$



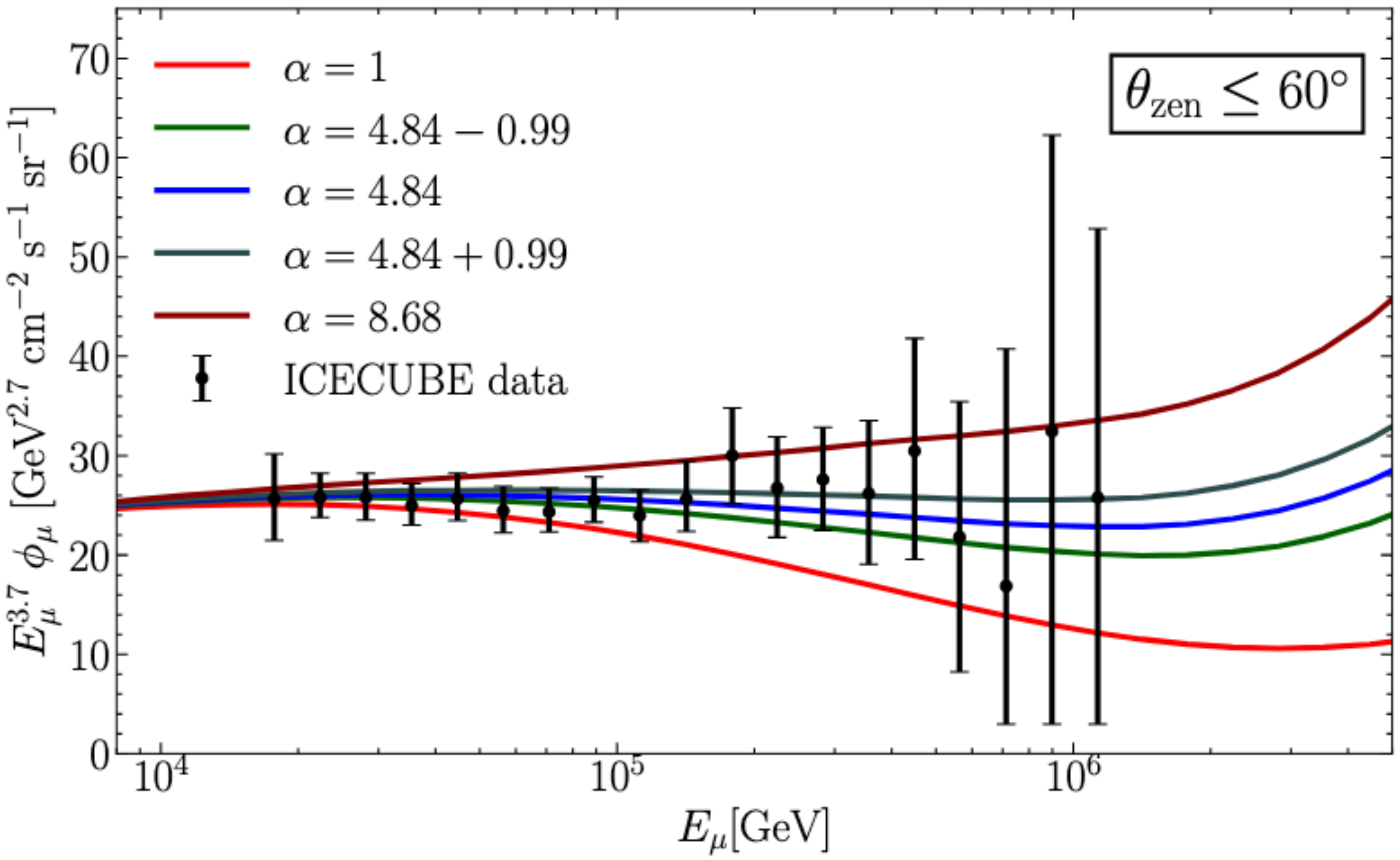
- For HLM Model:
  - $pA \to \bar{D}^{*0}\Lambda_c^+$ dominates.
  - $\bar{D}^{*0} \to \bar{D}^0\gamma$ (first approx)
  - $x_{\Lambda_c} = 1 - x_{\bar{D}^{*0}}$

Unflavored contribution

To muon flux from different MCEq models



Sibyll2.3c



$$\boxed{w_c^{\rm intr} = 0 \text{ and } \alpha_{\rm unfl} = 4.84}$$

$$\begin{aligned}\phi_{\mu,\mathrm{prompt}} &= \phi_{\mu,\mathrm{pQCD}} + \phi_{\mu,\mathrm{unfl}} \\ &\sim \phi_{\mu,\mathrm{pQCD}} + 4.8\phi_{\mu,\mathrm{unfl}} \\ &\simeq 5.8 f_{\mu,\mathrm{prompt}} \ \text{as}\ \phi_{\mu,\mathrm{pQCD}} \simeq \phi_{\mu,\mathrm{unfl}} = \mathrm{f}_{\mu,\mathrm{prompt}}\end{aligned}$$

Fit values

Table 1: Best fit values of w^c_{intr} for model-dependent fit to angle averaged muon energy spectrum along with the $1\,\sigma$ interval.

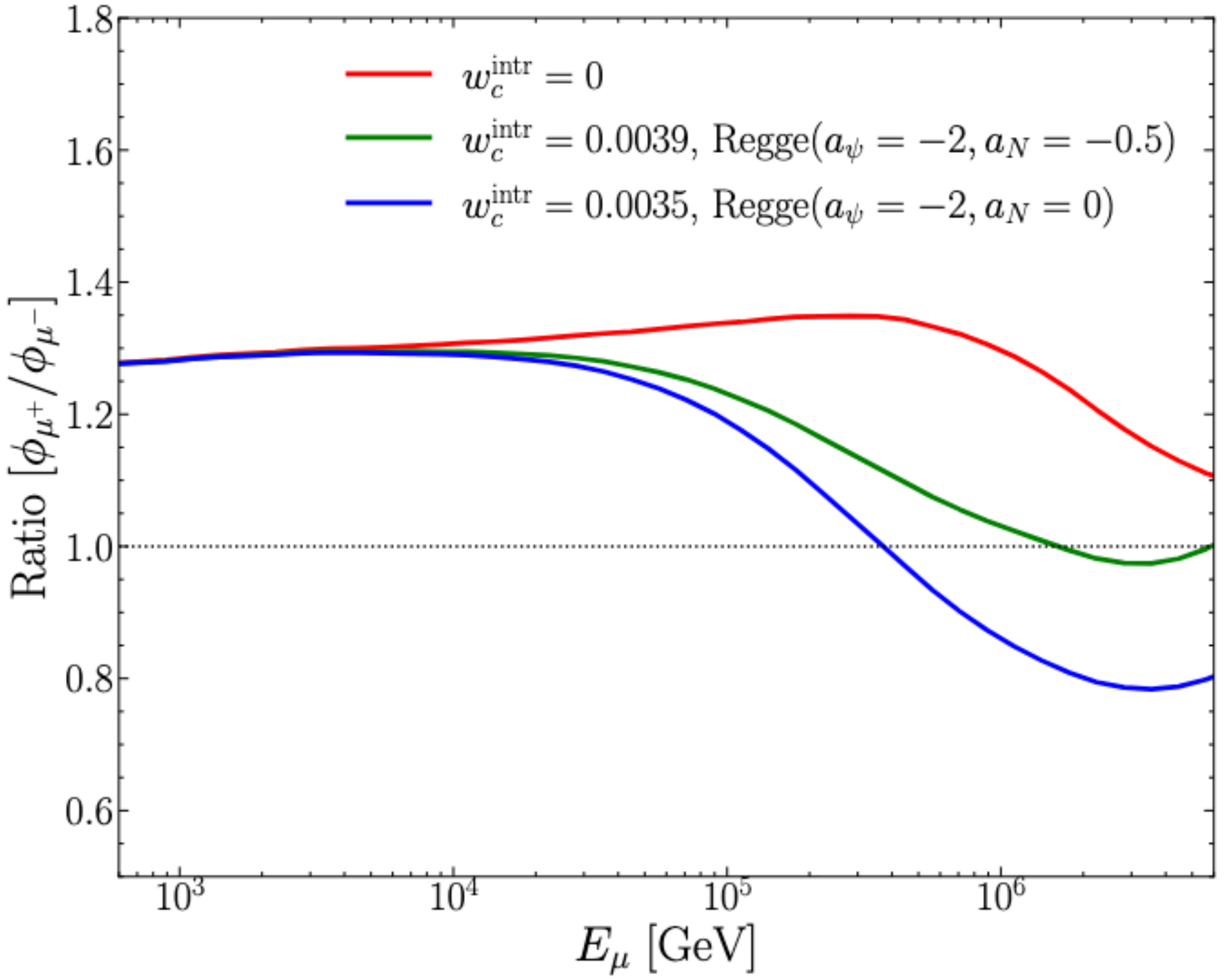
Model	Best fit $\mathbf{w}^{\mathbf{c}}_{\text{intr}}(\times\mathbf{10^{-3}})$	$\mathbf{1\sigma}$ interval $(\times\mathbf{10^{-3}})$
Regge $1(a_\psi = -2, a_N = -0.5)$	3.91	$2.93 - 4.89$
Regge $2(a_\psi = -2, a_N = 0)$	3.53	$2.65 - 4.42$
HLM	3.02	$2.26 - 3.77$

Overshoots neutrino upper limit

Table 2: Best fit values for the scaling factor of the unflavored flux if we use w_c^{intr} needed to meet the neutrino upper limit, along with the 1σ interval. For no intrinsic charm, we have $\alpha_{\text{unfl}} = 4.84$ and 1σ interval is $3.85 - 5.83$

Model	$\mathbf{w}^{\mathbf{c}}_{\text{intr}} \times \mathbf{10^{-4}}$	Best fit α_{unfl}	$\mathbf{1\sigma}$ interval
Regge $1(a_\psi = -2, a_n = -0.5)$	4.46	4.39	3.40 - 5.38
Regge $2(a_\psi = -2, a_n = 0)$	4.15	4.38	3.39 - 5.37
HLM	3.69	4.36	3.37 - 5.35

Unflavored is increased to match with muon data and still within neutrino upper bound



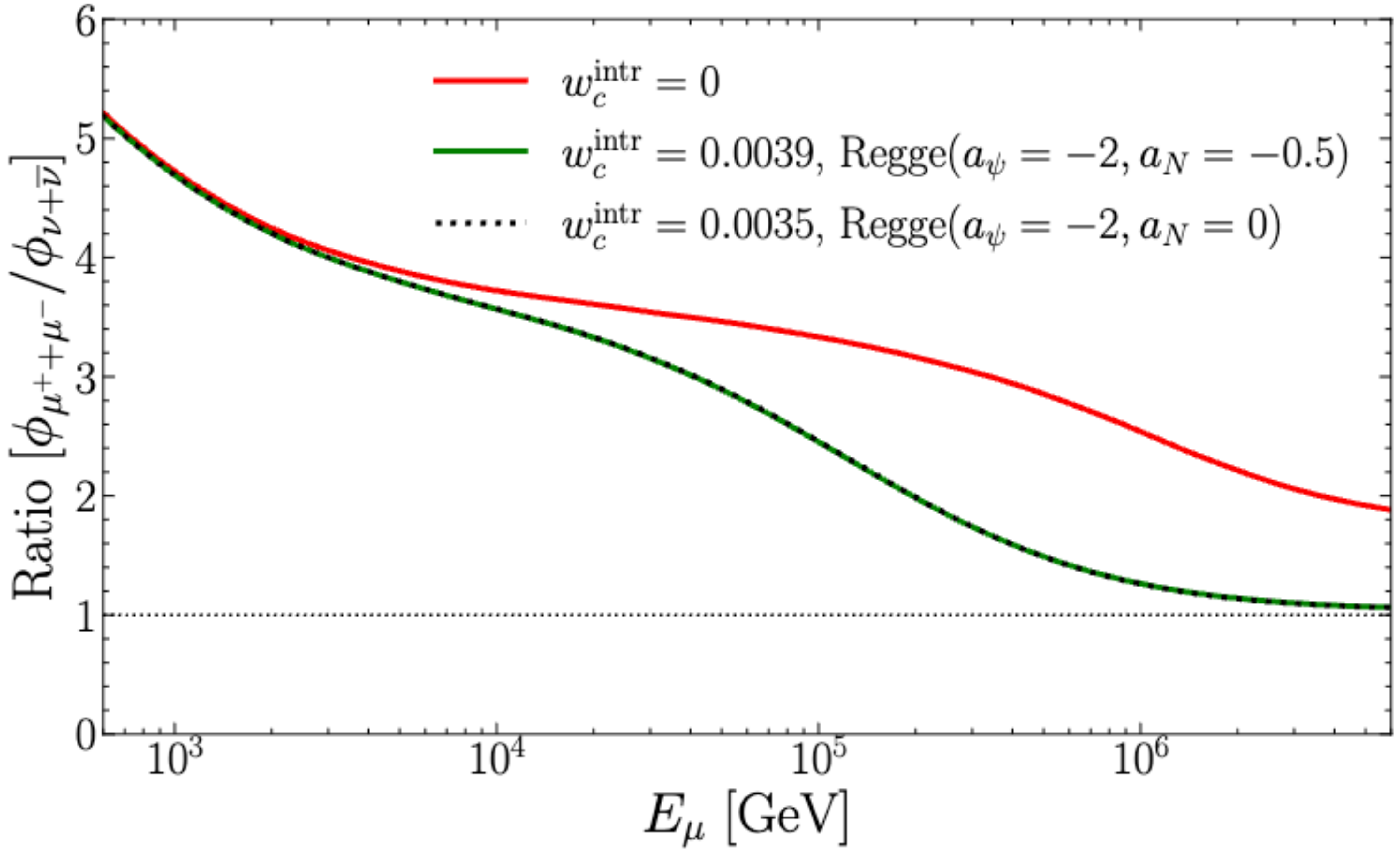


Figure 10. Ratio of muon flux to muon neutrino flux with and without intrinsic charm. For intrinsic charm, two Regge models are used. The $w_c^{\rm intr}$ for the two models are the best fit values we get in order to fit the model to the muon data. Here, $\alpha_{\rm unfl} = 1$.

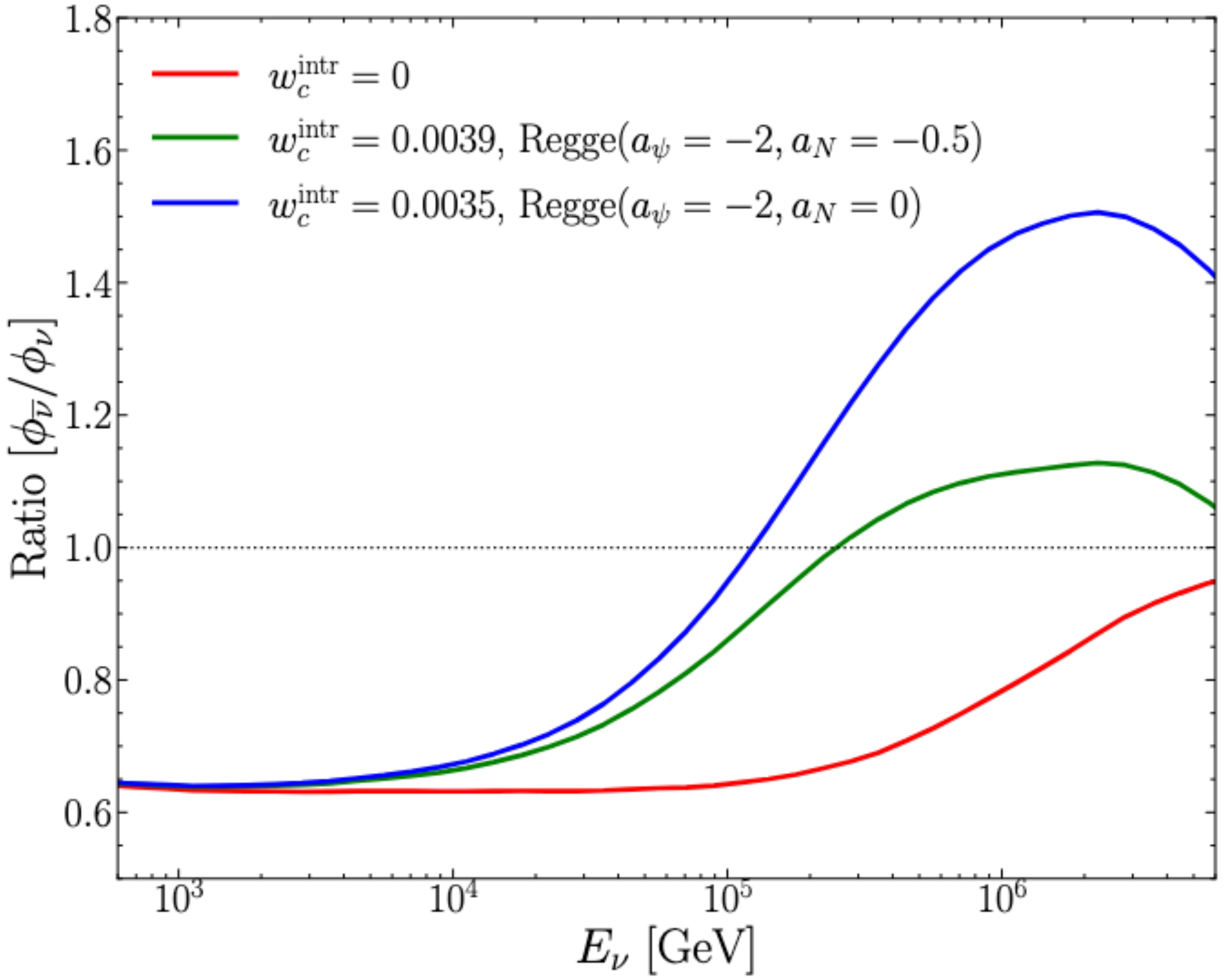


Figure 9. Left: Muon charge ratio without any intrinsic charm and with intrinsic charm. Right: Anti-neutrino to neutrino flux ratio without and with intrinsic charm. Ratios are of fluxes angle averaged for $\theta < 60^\circ$ and $\alpha_{\rm unfl} = 1$.