Atmospheric muons and neutrinos at very high energy

José I. Illana

+ Paolo Lipari, Manuel Masip, Davide Meloni

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Motivation

- Atmospheric muons (above a few GeV) and neutrinos reach ground
  - Inform about hadronic interactions and neutrino oscillations
  - Background to astrophysical neutrino sources

- At high energy (above a few TeV) standard sources become *long lived*

- Identify and estimate *all* atmospheric lepton sources

- Revise correlations of muon and neutrino fluxes
  [using the Z-moment method]

Motivation

- Components of atmospheric lepton (μ, ν_e, ν_μ, ν_τ) fluxes according to parent j:

$$\gamma c\tau_j = \lambda_{\rm dec}^{(j)} = h_0 \quad \Rightarrow \quad \boxed{\text{Critical energy}} \quad \varepsilon_j = \frac{m_j c^2}{c\tau_j} h_0 \,, \qquad h_0 = 6.4 \text{ km}$$

Source	j + antipart.		$c\tau_j$	ε_j [GeV]	BR to leptons
✓ Standard	π^+	$\to \mu^+\nu_\mu$	8 m	115	100%
	K_L	$\to \{\mu^\pm\nu_\mu, e^\pm\nu_e\}\pi^\mp$	15 m	210	67%
	K^+	$\to \{\mu^+\nu_\mu, e^\pm\nu_e\}$	4 m	850	69%
✓ Charmed	D^+	$\to \{\mu^+\nu_\mu, e^+\nu_e\}\overline{K}^0$	310 μm	0.38×10^8	18%
	D^0	$\to \{\mu^+\nu_\mu, e^+\nu_e\}K^-$	125 μm	0.96×10^8	7%
	D_s^+	$\to \tau^+\nu_\tau$	150 μm	0.85×10^8	6%
	Λ_c^+	$\to \{\mu^+\nu_\mu, e^+\nu_e\}\Lambda^+$	60 μm	2.40×10^8	4%
! Unflavored	η, η'	$\to \mu^+\mu^-\gamma$	$\lesssim$ Å	—	$\sim 10^{-4}$
	ρ, ω, ϕ	$\to \mu^+\mu^-(\pi^0)$			

Photon conversion to muons negligible

Motivation

- Components of atmospheric lepton (μ, ν_e, ν_μ, ν_τ) fluxes according to parent j:

$$\phi_\ell(E,\theta) = \sum_j \phi_\ell^{(j)}(E,\theta)$$

$$\begin{aligned}\phi_{\nu_\alpha}(E,\theta) &= \phi_{\nu_\alpha}^{\text{stand}}(E,\theta) + \phi_{\nu_\alpha}^{\text{charm}}(E) \\ \phi_\mu(E,\theta) &= \phi_\mu^{\text{stand}}(E,\theta) + \phi_\mu^{\text{charm}}(E) + \phi_\mu^{\text{unflav}}(E) + \phi_\mu^{(\gamma)}(E)\end{aligned}$$

at ground level

The Z-moment method

[T. Gaisser '90, P. Lipari '93]

$$\frac{\partial \phi_j}{\partial t} = \underbrace{-\frac{\phi_j}{\lambda_j} - \frac{\phi_j}{\lambda_{\rm dec}^{(j)}}}_{\text{sink}} + \underbrace{\sum_k \left[S_{k\to j}^{(\rm int)} + S_{k\to j}^{(\rm dec)} \right]}_{\text{source}}$$

$$\lambda_j(E) = \frac{m_{\rm air}}{\sigma_{j-\rm air}(E)} \qquad \lambda_{\rm dec}^{(j)}(E,t,\theta) = \tau_j \frac{E}{m_j}\rho(t,\theta)$$

$$S_{k\to j}^{(\rm int)}(E,t) = \int_E^\infty {\rm d}E_k \, \frac{\phi_k(E_k,t)}{\lambda_k(E_k)} \frac{{\rm d}n_{kj}(E;E_k)}{{\rm d}E}$$

$$S_{k\to j}^{(\rm dec)}(E,t,\theta) = \int_E^\infty {\rm d}E_k \, \frac{\phi_k(E_k,t)}{\lambda_{\rm dec}^{(k)}(E_k,t,\theta)} \frac{{\rm d}n_{kj}(E;E_k)}{{\rm d}E}$$

scaling

1. $\frac{{\rm d}n_{kj}}{{\rm d}E}(E;E_k) \simeq \frac{1}{E_k} F_{kj}(x)\,, \quad x = E/E_k$
2. $\lambda_k = \text{const}$
3. $\phi_k(E,t) = K E_k^{-\alpha} f_k(t)$

$$Z_{kj}(\alpha) = \int_0^1 {\rm d}x \; x^{\alpha-1} \; F_{kj}(x)$$

The Z-moment method

[T. Gaisser '90, P. Lipari '93]

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$$\lambda_j(E) = \frac{m_{\text{air}}}{\sigma_{j-\text{air}}(E)} \qquad \lambda^{(j)}_{\text{dec}}(E,t,\theta) = \tau_j \frac{E}{m_j} \rho(t,\theta)$$

$$S^{(\text{int})}_{k\to j}(E,t) = \int_E^\infty \mathrm{d}E_k \, \frac{\phi_k(E_k,t)}{\lambda_k(E_k)} \frac{\mathrm{d}n_{kj}(E;E_k)}{\mathrm{d}E} \quad \simeq \quad KE^{-\alpha} \, \frac{f_k(t)}{\lambda_k} \, Z_{kj}(\alpha)$$

$$S^{(\text{dec})}_{k\to j}(E,t,\theta) = \int_E^\infty \mathrm{d}E_k \, \frac{\phi_k(E_k,t)}{\lambda^{(k)}_{\text{dec}}(E_k,t,\theta)} \frac{\mathrm{d}n_{kj}(E;E_k)}{\mathrm{d}E}$$

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$$S^{(\rm dec)}_{k\to j}(E,t,\theta) = \int_E^\infty {\rm d}E_k \, \frac{\phi_k(E_k,t)}{\lambda^{(k)}_{\rm dec}(E_k,t,\theta)} \frac{{\rm d}n_{kj}(E;E_k)}{{\rm d}E} \quad \simeq \quad K E^{-(\alpha+1)} \frac{m_k}{\tau_k} \frac{f_k(t)}{\rho(t,\theta)} Z_{kj}(\alpha+1)$$

scaling

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The Z-moment method

- Power law spectrum $[\phi_k(E,t) = KE^{-\alpha} f_k(t)]$ valid if:
  - Primary Nucleon spectrum is a power law

$$\phi_p(E,0) = p_0 KE^{-\alpha}\ , \quad \phi_n(E,0) = n_0 KE^{-\alpha} = (1-p_0)KE^{-\alpha}$$

$$[p_0 \simeq 0.8, \quad \alpha \simeq 2.7 \text{ changes to } \alpha \simeq 3.0 \text{ at } E_{\text{knee}} \simeq 3\times 10^6 \text{ GeV}]$$

  - Decay terms (sink and source) neglected
    e.g. Nucleon fluxes:

$$\frac{\mathrm{d}f_p}{\mathrm{d}t} = -\frac{f_p}{\lambda_p} + \frac{f_p}{\lambda_p}Z_{pp} + \frac{f_n}{\lambda_n}Z_{np}$$
$$\frac{\mathrm{d}f_n}{\mathrm{d}t} = -\frac{f_n}{\lambda_n} + \frac{f_n}{\lambda_n}Z_{nn} + \frac{f_p}{\lambda_p}Z_{pn}$$

$$\Rightarrow f_p(t) \pm f_n(t) = (p_0 \pm n_0)\mathrm{e}^{-t/\Lambda_N^\pm}\ , \quad \Lambda_N^\pm = \frac{\lambda_N}{1 - \underbrace{Z_{pp} \mp Z_{pn}}_{\text{regeneration}}}$$

$$[\lambda_N \equiv \lambda_p = \lambda_n, \quad Z_{pp} = Z_{nn}, \quad Z_{pn} = Z_{np}]$$

The Z-moment method

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- Still applicable to our lepton fluxes in two limiting cases:
  - Rapidly decaying sources ($k \xrightarrow{\text{int}} j \xrightarrow{\text{dec}} \ell$) $\Leftarrow$ low energy

$$\frac{\phi_\ell^{(j)}(E)}{(K\, E^{-\alpha})} \simeq \left(\int_0^\infty \mathrm{d}t \sum_k \frac{f_k(t)}{\lambda_k} Z_{kj}(\alpha) \right) Z_{j\ell}(\alpha) = A_j(\alpha)\, Z_{j\ell}(\alpha)$$

e.g. $j =$ *unflavored mesons* and *charmed hadrons below* $\sim 10^7$ GeV

Note: isotropic

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e.g. $j =$ *unflavored mesons* and *charmed hadrons below* $\sim 10^7$ GeV

Note: isotropic

  - Small decay probability (suppressed by $\gamma^{-1} = m_j/E$) $\Leftarrow$ high energy

$$\frac{\phi_\ell^{(j)}(E,\theta)}{(K\,E^{-\alpha})} \simeq \frac{m_j}{\tau_j E}\left(\int_0^\infty \mathrm{d}t\, \frac{f_j(t)}{\rho(t,\theta)}\right) Z_{j\ell}(\alpha+1) \simeq \frac{\varepsilon_j}{E} F_{\text{zenith}}(\theta)\, B_j(\alpha)\, Z_{j\ell}(\alpha+1)$$

since $\rho(t,\theta) \simeq \dfrac{t\cos\theta}{h_0}$ for $\theta \lesssim 60^\circ$ and $F_{\text{zenith}}(\theta) \simeq \dfrac{1}{\cos\theta}$

e.g. $j = \pi/K$ *standard component at high energy*

Note: non-isotropic and steeper

Muons and neutrinos from standard (π/K)

$$\frac{\phi_\ell^{\rm stand}(E,\theta)}{(KE^{-\alpha})} \simeq \frac{\mathbf{E}_\ell(\alpha)}{E\cos\theta} \qquad \mathbf{E}_\ell = \sum_{j\in\{\pi^\pm,K^\pm,K_L\}} \varepsilon_j B_j(\alpha) Z_{j\ell}(\alpha+1) \qquad [E \gtrsim 10\ \text{TeV}]$$

$$[Z_{jN}=0] \qquad \frac{\mathrm{d}f_j}{\mathrm{d}t} = -\frac{f_j}{\lambda_j} + \frac{f_j}{\lambda_j}Z_{jj} + \frac{f_N}{\lambda_N}Z_{Nj} \qquad f_j(t) = p_0 f_{p\to j}(t) + n_0 f_{n\to j}(t)$$

$$B_{pj} \pm B_{nj} = \int_0^\infty \mathrm{d}t\, \frac{f_{p\to j}(t) \pm f_{n\to j}(t)}{t} = \frac{Z_{pj}\pm Z_{nj}}{1-\underbrace{Z_{pp}\mp Z_{pn}}_{\text{regeneration}}} \frac{\Lambda_j}{\Lambda_j - \Lambda_N^\pm} \ln\frac{\Lambda_j}{\Lambda_N^\pm}$$

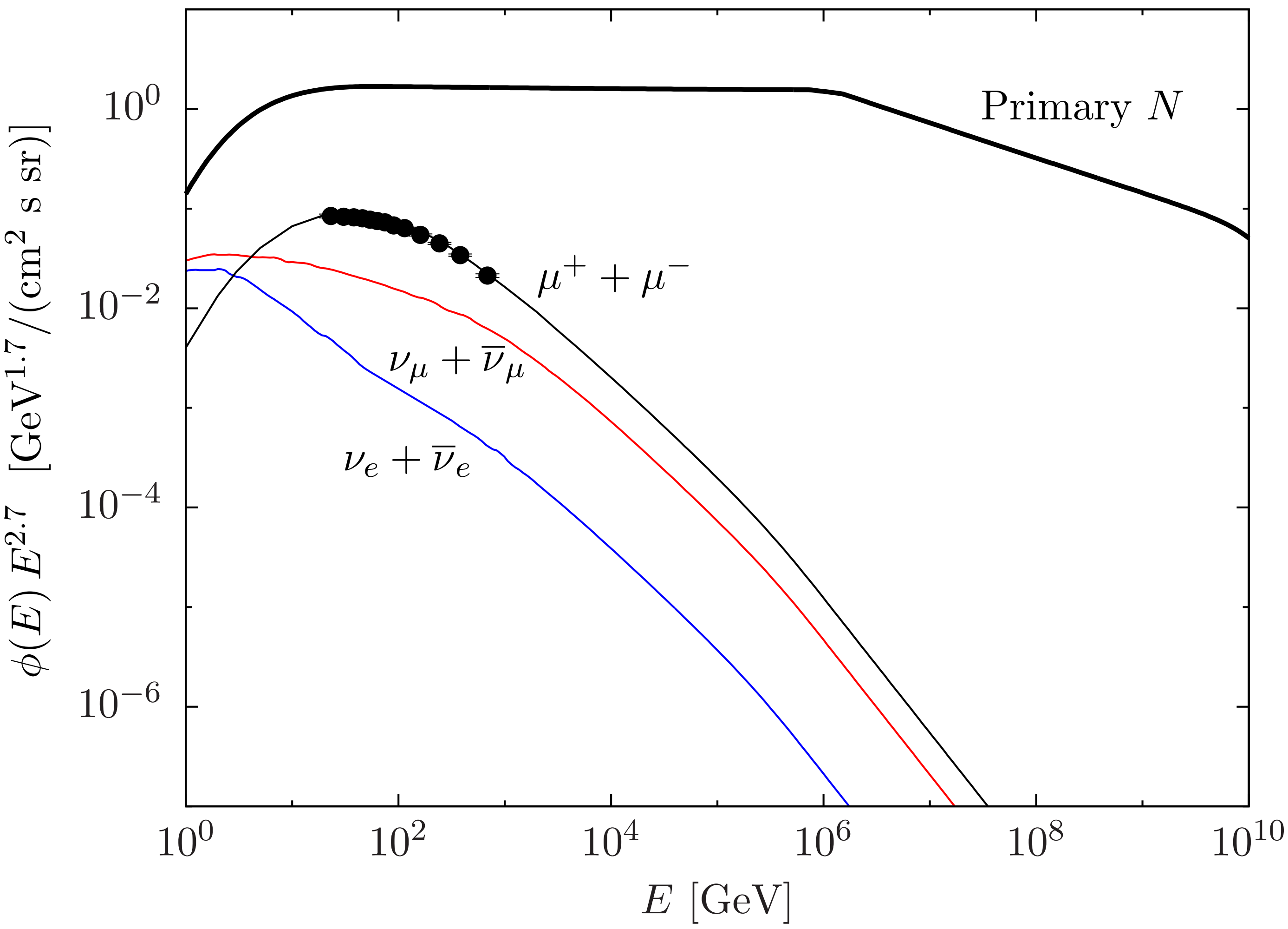
$$\text{e.g. } \Lambda_{\pi^\pm} = \frac{\lambda_\pi}{1-\underbrace{Z_{\pi^+\pi^+}\mp Z_{\pi^+\pi^-}}_{\text{regeneration}}}$$

λ_j from PDG

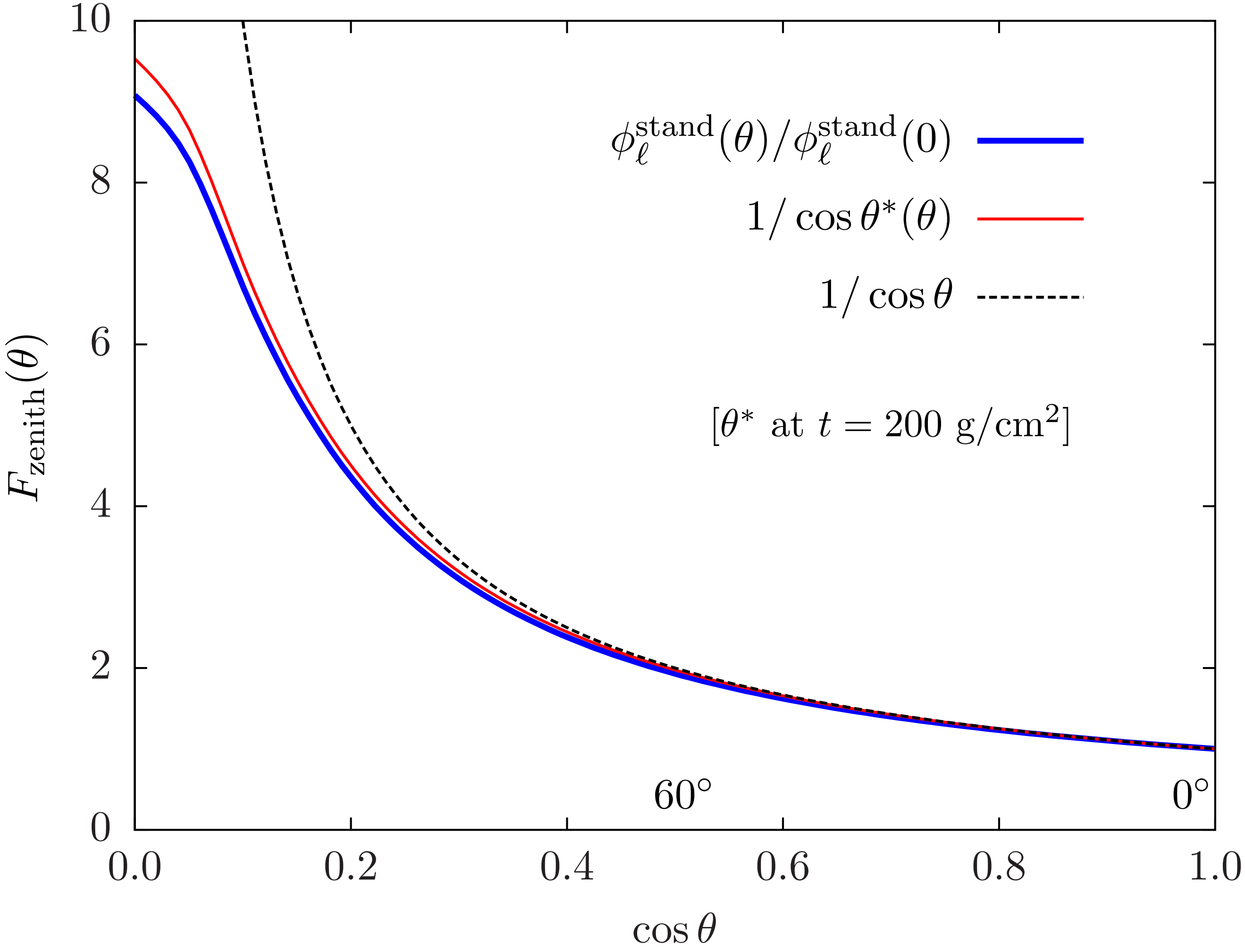
Z-factors using Glauber with `Sibyll`

$\mathbf{E}_\ell(\alpha)$/GeV	μ^+	μ^-	$(\mu^+ + \mu^-)$	ν_μ	$\bar\nu_\mu$	$(\nu_\mu + \bar\nu_\mu)$	ν_e	$\bar\nu_e$	$(\nu_e + \bar\nu_e)$
$\alpha = 2.7$	5.2	4.1	9.3	2.2	1.2	3.4	0.10	0.07	0.17
$\alpha = 3.0$	2.8	2.1	4.9	1.1	0.6	1.7	0.06	0.04	0.10
			1	$\div$		0.35	$\div$		0.02

Muons and neutrinos from standard vertical flux



Muons and neutrinos | from standard | zenith angle distribution



Muons from unflavored $(\eta,\eta',\rho,\omega,\phi)$

Very fast electromagnetic decays into $\mu^+\mu^-(\gamma,\pi^0)$ with $\mathcal{B}\sim 10^{-4}$, high multiplicities

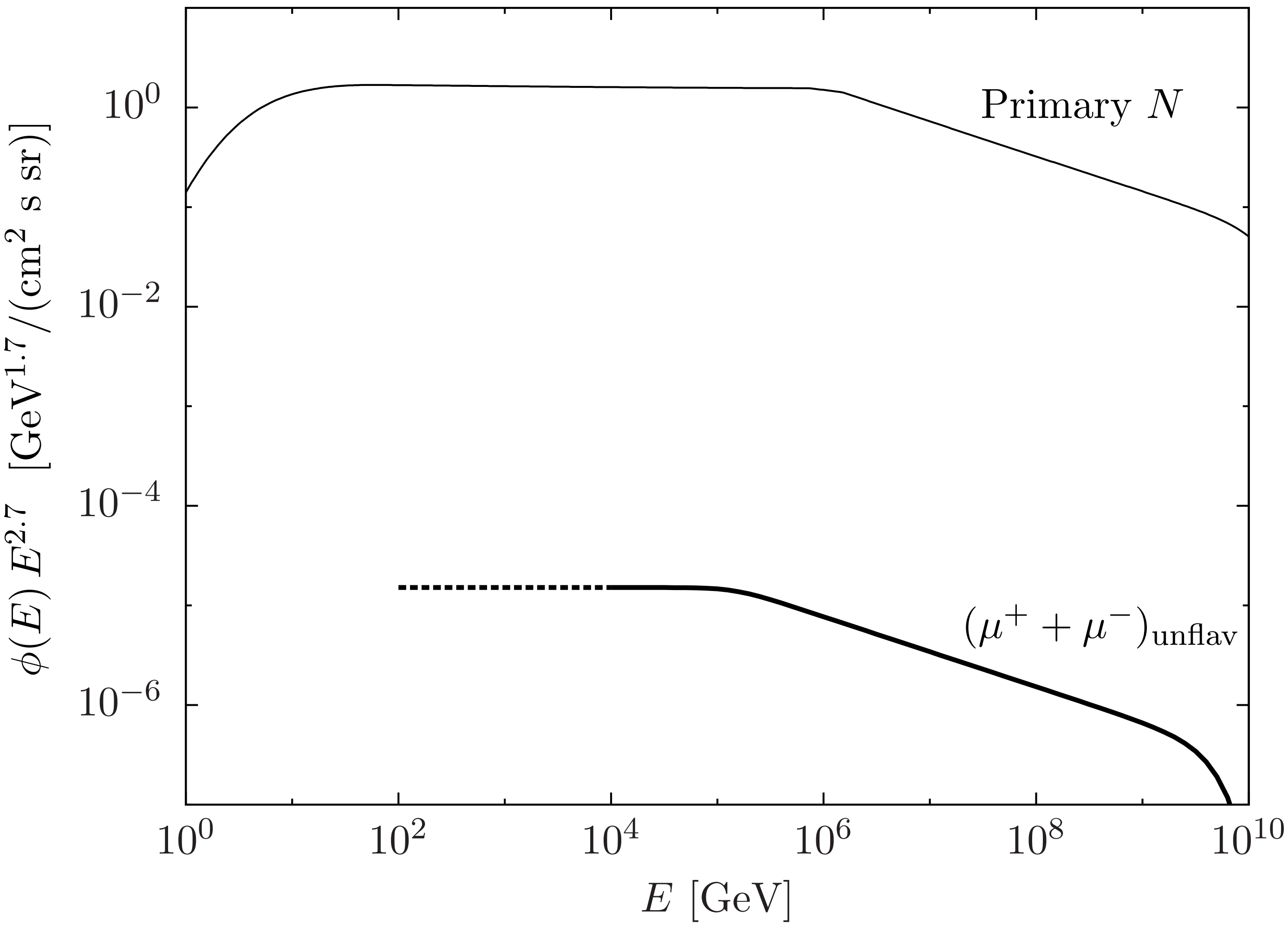
$$\boxed{\frac{\phi_\mu^{\rm unflav}(E)}{(KE^{-\alpha})}=C_\mu^{\rm unflav}(\alpha)}=\sum_{j\in\{\eta,\eta',\rho,\omega,\phi\}}A_j(\alpha)Z_{j\ell}(\alpha)$$

$$\text{e.g. } A_\eta(\alpha)=\underbrace{\frac{Z_{N\eta}(\alpha)}{1-Z_{NN}(\alpha)}}_{\text{nucleon int with reg}}+\underbrace{\frac{Z_{N\pi}(\alpha)Z_{\pi\eta}(\alpha)}{[1-Z_{NN}(\alpha)][1-Z_{\pi\pi}(\alpha)]}}_{\text{pion int with reg}}$$

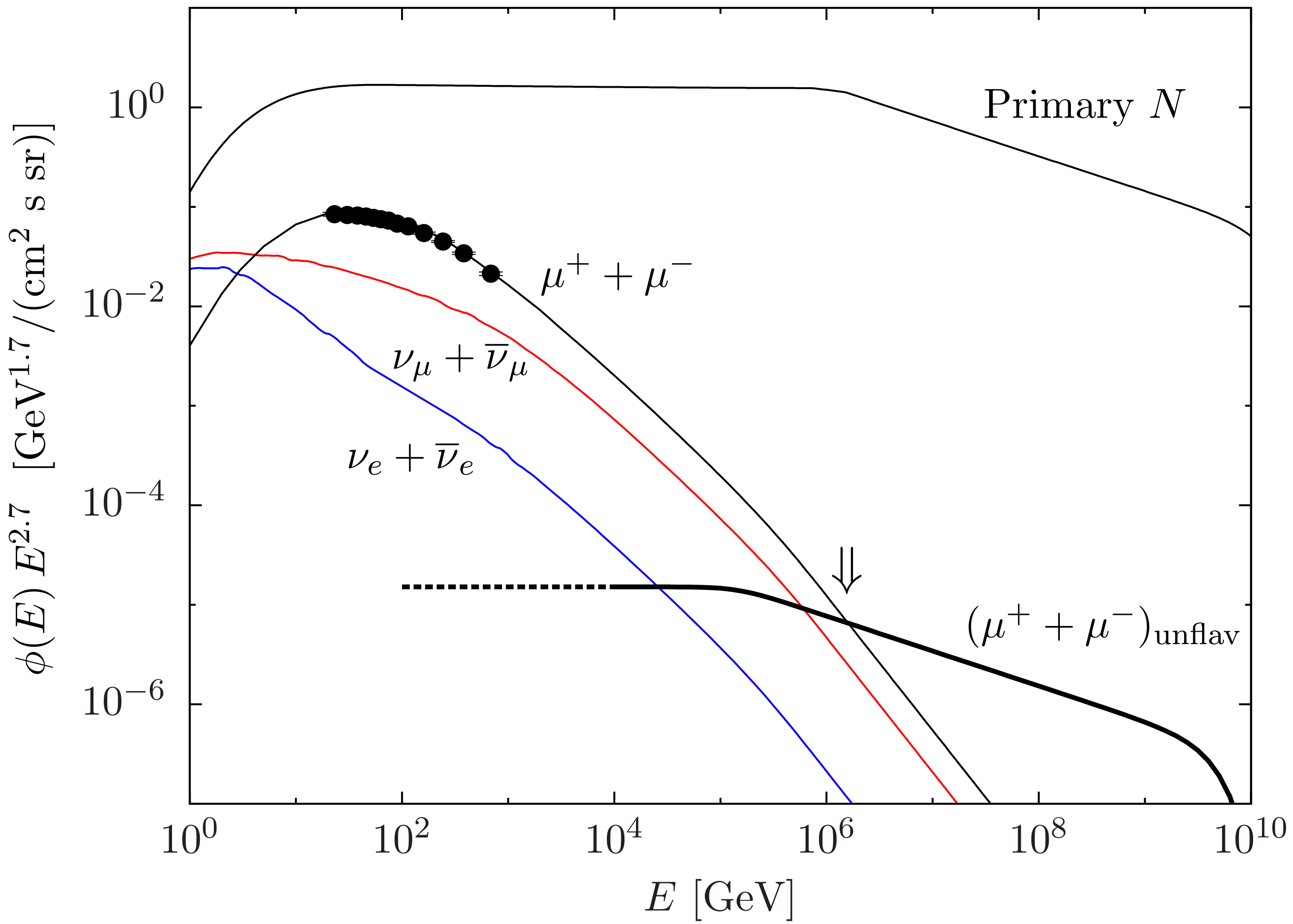
j	η	η'	ρ	ω	ϕ
$Z_{Nj}(2.7)$	0.014	0.013	0.013	0.010	0.00038
$Z_{Nj}(3.0)$	0.0087	0.0086	0.0082	0.0066	0.00022
$Z_{\pi j}(2.7)$	0.029	0.027	0.026	0.021	0.00047
$Z_{\pi j}(3.0)$	0.021	0.020	0.019	0.016	0.00019
$Z_{j\mu}(2.7)/10^{-4}$	1.37	0.43	0.33	1.00	2.15
$Z_{j\mu}(3.0)/10^{-4}$	1.12	0.35	0.30	0.86	1.93

$C_\mu^{\rm unflav}(\alpha)$	$\mu^+ + \mu^-$
$\alpha = 2.7$	6.2×10^{-6}
$\alpha = 3.0$	3.1×10^{-6}

Muons from unflavored flux



Muons from unflavored flux



$$\left.\frac{\mathbf{E}_\mu(\alpha)}{E\cos\theta}\right|_{\text{stand},\ \theta=0^\circ} = C_\mu^{\text{unflav}}(\alpha) \quad \Rightarrow \quad \boxed{E_\times \simeq 1.5\times 10^6\ \text{GeV}}$$

Muons from unflavored modelling

- Understanding unflavored-meson production

$$Z_{Nj}(\alpha) = \int_0^1 \mathrm{d}x\, x^{\alpha-1} F_{Nj}(x)\,, \quad \langle x_j \rangle = Z_{Nj}(2)$$

$$F_{Nj}(x) = \frac{\langle x \rangle}{x}(1+n_j)(1-x)^{n_j}\,, \quad 3 \lesssim n_j \lesssim 4$$

$$\langle x_j \rangle = \frac{\langle E_j \rangle}{E_0} \simeq 0.6 \frac{\langle E_j \rangle}{E_{q\bar{q}}}\,, \quad E_0 \simeq E_{qqq} + E_{\bar{q}\bar{q}\bar{q}} + \underbrace{E_{q\bar{q}}}$$

inputs: $E_{q\bar{q}}/E_0 \simeq 0.6\,, \quad P_{\text{scalar}} \simeq 0.5\,, \quad P_s \simeq 0.13$

$$0^- \left[\begin{array}{lcl} \pi^0 & = & \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \\ \eta & = & \frac{1}{2}(u\bar{u} + d\bar{d}) - \frac{1}{\sqrt{2}} s\bar{s} \\ \eta' & = & \frac{1}{2}(u\bar{u} + d\bar{d}) + \frac{1}{\sqrt{2}} s\bar{s} \end{array} \right. \quad 1^- \left[\begin{array}{lcl} \rho & = & \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \\ \omega & = & \frac{1}{2}(u\bar{u} + d\bar{d}) \\ \phi & = & s\bar{s} \end{array} \right\}$$

$$\frac{\langle E_\eta \rangle}{\langle E_{q\bar{q}} \rangle} \simeq \frac{\langle E_{\eta'} \rangle}{E_{q\bar{q}}} \simeq P_{\text{scalar}} \left[\frac{(1-P_s)^2}{8} + \frac{P_s^2}{2} \right]$$

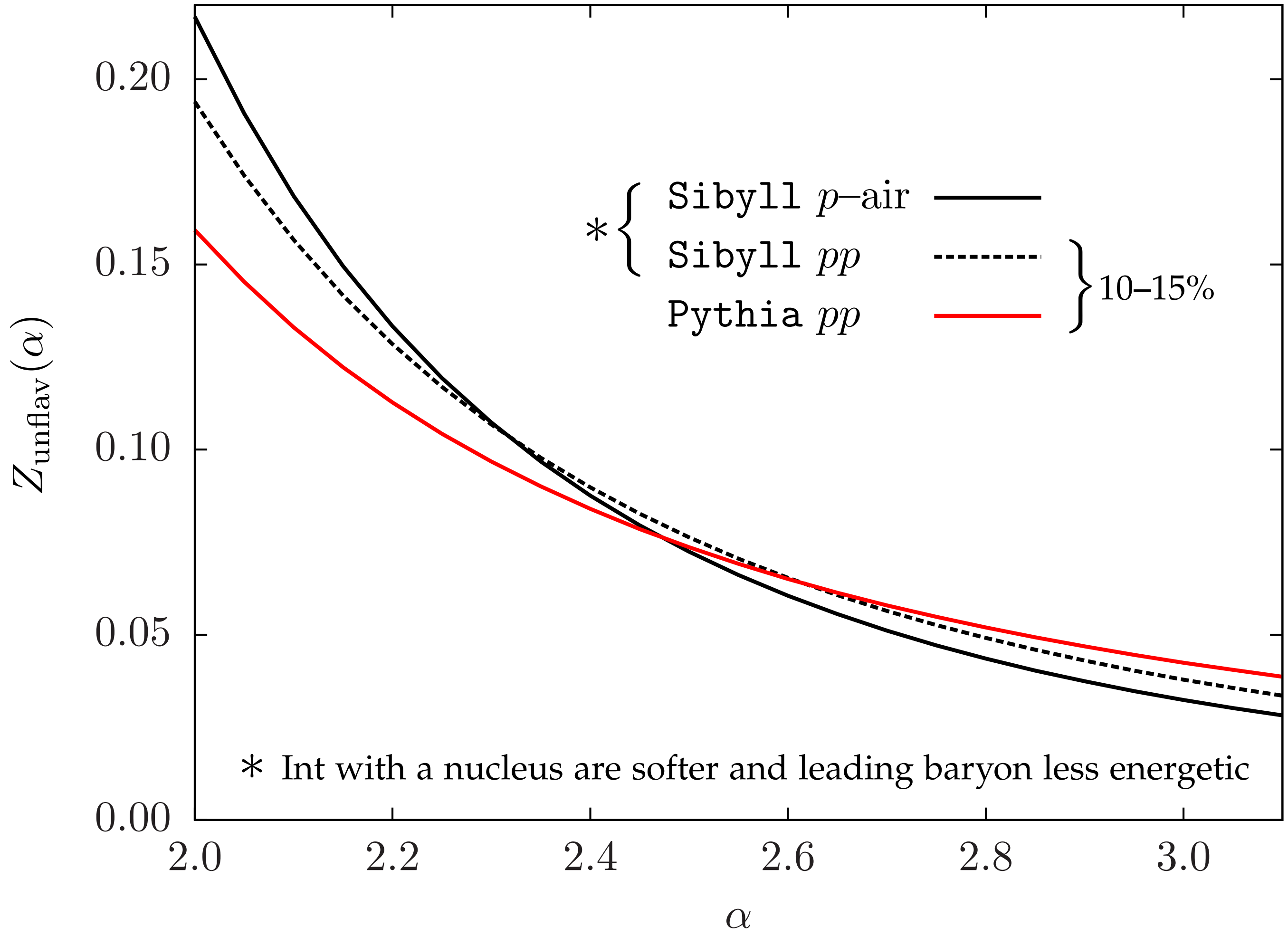
$$\frac{\langle E_\rho \rangle}{\langle E_{q\bar{q}} \rangle} \simeq \frac{\langle E_\omega \rangle}{E_{q\bar{q}}} \simeq (1-P_{\text{scalar}}) \frac{(1-P_s)^2}{4}$$

$$\frac{\langle E_\phi \rangle}{\langle E_{q\bar{q}} \rangle} \simeq (1-P_{\text{scalar}}) P_s^2$$

(agrees well with `Sibyll`)

Muons | from unflavored | comparison

$$Z_{\rm unflav}(\alpha) = \sum_{j\in\{\eta,\eta',\rho,\omega,\phi\}} Z_{Nj}(\alpha)$$



Muons and neutrinos from charmed $(D^\pm, D^0/\overline{D}^0, D_s^\pm, \Lambda_c^\pm)$

Decays like $D^0 \to \{\mu^+\nu_\mu, e^+\nu_e\}K^-$ or $D_s^+ \to \tau^+\nu_\tau$ with $\mathcal{B} \sim 10\%$ but suppressed prod.

$$\frac{\phi_\ell^{\rm charm}(E)}{(KE^{-\alpha})} = C_\ell^{\rm charm}(\alpha, E) = \sum_{j\in\{D^\pm,D^0/\overline{D}^0,D_s^\pm,\Lambda_c^\pm\}} A_j(\alpha,E)Z_{j\ell}(\alpha) \qquad [E \lesssim 10^7 \text{ GeV}]$$

$$[\text{scaling violation}] \quad A_j(\alpha,E) \simeq \frac{Z_{Nj}(\alpha,E)}{1-Z_{NN}(\alpha)} + \underbrace{\frac{Z_{N\pi}(\alpha)Z_{\pi j}(\alpha,E)}{[1-Z_{NN}(\alpha)][1-Z_{\pi\pi}(\alpha)]}}_{\sim 20-30\%}$$

$$Z_{Nj}(\alpha,E) = \int_0^1 \mathrm{d}x\, x^{\alpha-1} F_{Nj}(x,E)\,, \quad F_{Nj}(x,E) \simeq \frac{\sigma_{c\bar{c}}^{pA}(E_0)}{\sigma_{\rm inel}^{pA}(E_0)} p_j c_j (1-x)^{n_j}/x^{3/2}\,, \quad \sum_j p_j = 1$$

$$\sigma_{c\bar{c}}^{pA} \simeq A\sigma_{c\bar{c}}^{pp}\,, \quad \sigma_{c\bar{c}}^{pp} \simeq \sigma_{D\overline{D}}^{pp} + \sigma_{\Lambda_c\overline{D}}^{pp}$$

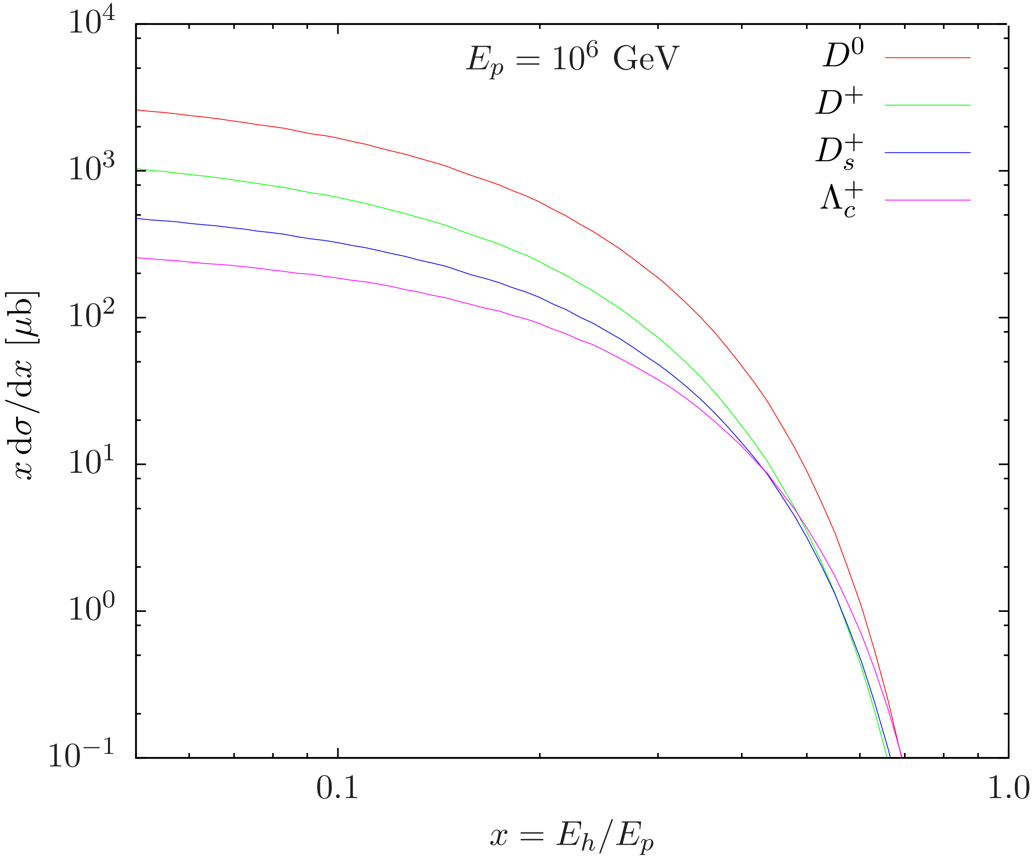
$[E_p = 10^6 \text{ GeV}]$
$[n_D \simeq 5,\ n_{\Lambda_c} \simeq 1]$ $\quad C_\mu^{\rm charm}(3) \simeq 1.2\times10^{-6}\left[\frac{\sigma_{D\overline{D}}^{pp}}{4\text{ mb}}\right] + 1.5\times10^{-6}\left[\frac{\sigma_{\Lambda_c\overline{D}}^{pp}}{4\text{ mb}}\right] \lesssim C_\mu^{\rm unflav}(3)$!!

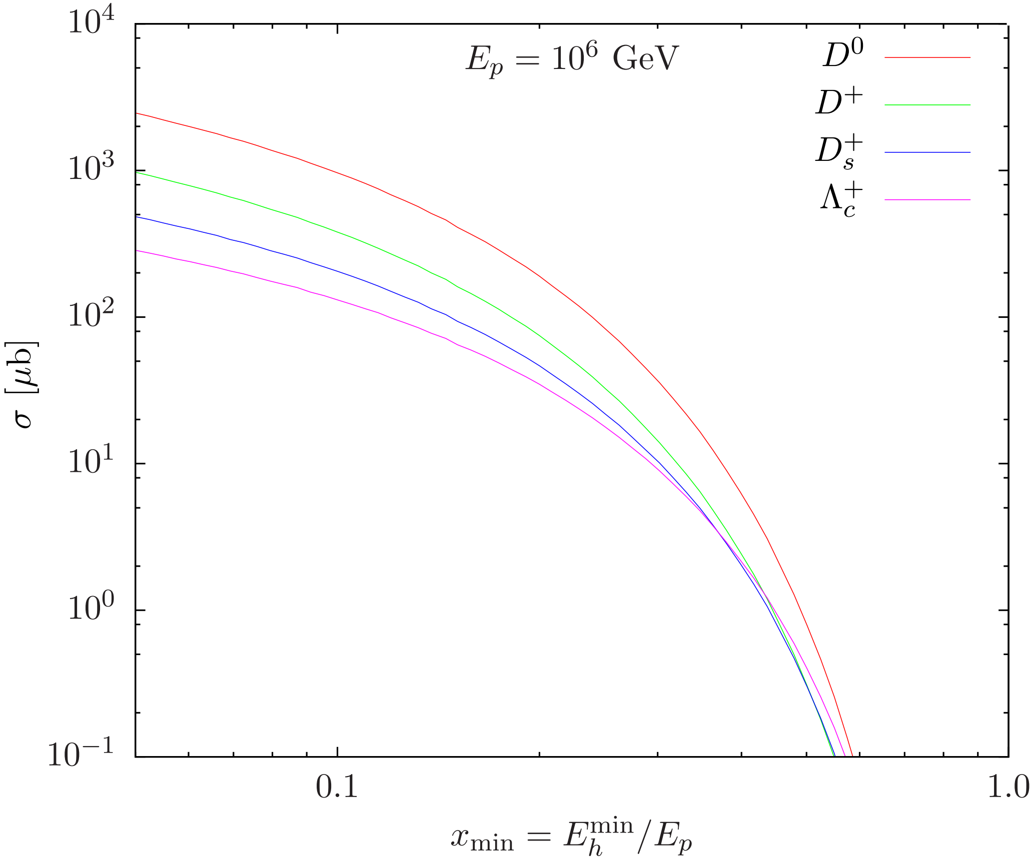
$$Z_{D\nu_\mu}(3) \simeq Z_{D\nu_e}(3) \simeq 1.25\, Z_{D_\mu}(3)$$
$$Z_{\Lambda_c\nu_\mu}(3) \simeq Z_{\Lambda_c\nu_e}(3) \simeq 1.16\, Z_{D_\mu}(3)$$

$\Rightarrow$ ν_e and ν_μ fluxes 20% higher than μ (robust)
(ν_τ flux 30 times smaller than ν_e or ν_μ)

Cross-sections for charm production

Consistent with [Gonçalves, Machado '07; Enberg, Reno, Sarcevic '08]



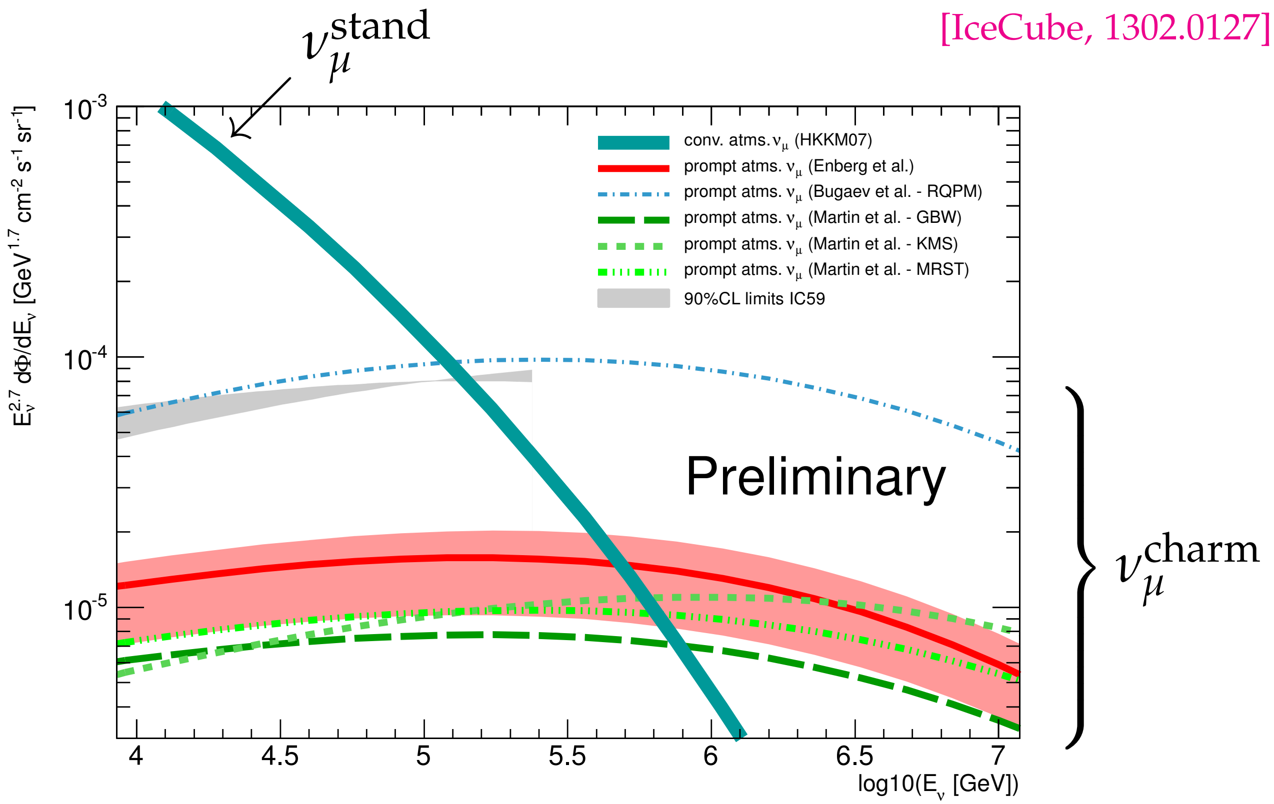


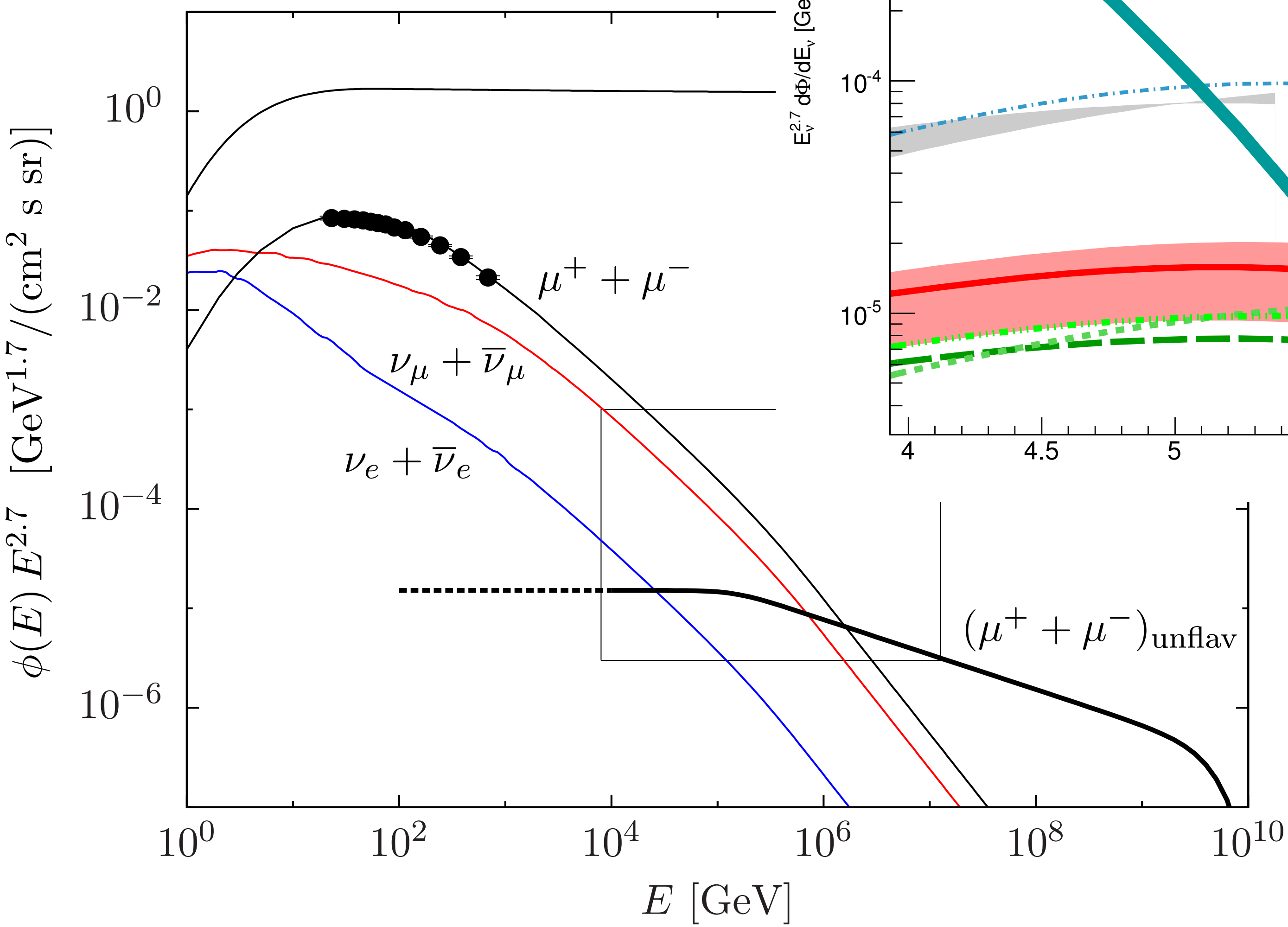
Muons and neutrinos | from charmed | models and limits

$$C_\mu^{\text{charm}} \lesssim C_\mu^{\text{unflav}}$$

$$\mu \div \nu_\mu \div \nu_e \div \nu_\tau \simeq 1 \div 1.2 \div 1.2 \div 0.04$$

[IceCube, 1302.0127]





- Bugaev et al
- Enberg et al
- Martin et al
- 95% CL upper limit IC59

($E \lesssim 10^{5.4}$ GeV $= 250$ TeV)

Muons | from photon conversion

$$\boxed{\gamma + \text{nucleus} \to \mu^+\mu^- + \text{nucleus}}$$

$$\frac{d\sigma_{\gamma\to\mu^+\mu^-}}{du} \simeq \underbrace{\left(\frac{m_e}{m_\mu}\right)^2}_{2\times10^{-5}} \frac{d\sigma_{\gamma\to e^+e^-}}{du}\,, \qquad u = E/E_\gamma$$

$$\boxed{\frac{\phi_\mu^{(\gamma)}}{(KE^{-\alpha})} = C_\mu^{(\gamma)}(\alpha)} \quad \Rightarrow \quad C_\mu^{(\gamma)}(2.7) = 1.0\times10^{-6} \qquad C_\mu^{(\gamma)}(3.0) = 0.39\times10^{-6}$$

$$C_\mu^{(\gamma)}(\alpha) \sim 0.15 \times C_\mu^{\text{unflav}}(\alpha) \ \Rightarrow \ \text{negligible}$$

Conclusions

- Atmospheric lepton fluxes:
  - Standard: steeper than primary nucleon flux $\propto 1/\cos\theta$ ($\theta \lesssim 60^\circ$)

    $\boxed{\mu \div \nu_\mu \div \nu_e \div \nu_\tau \simeq 1 \div 0.35 \div 0.02 \div 0.00}$ $\left\langle \Phi_\mu^{\text{stand}} \right\rangle \simeq 400 \left[\frac{10^6\ \text{GeV}}{E_{\min}}\right]^{-3} (\text{km}^2\,\text{yr}\,\text{sr})^{-1}$

  - Unflavored: follows nucleon flux isotropic dominant μ @ $E \gtrsim 1.5 \times 10^6$ GeV

    $\boxed{1 \div 0.00 \div 0.00 \div 0.00}$ $\left\langle \Phi_\mu^{\text{unflav}} \right\rangle \simeq 90 \left[\frac{10^6\ \text{GeV}}{E_{\min}}\right]^{-2} (\text{km}^2\,\text{yr}\,\text{sr})^{-1}$

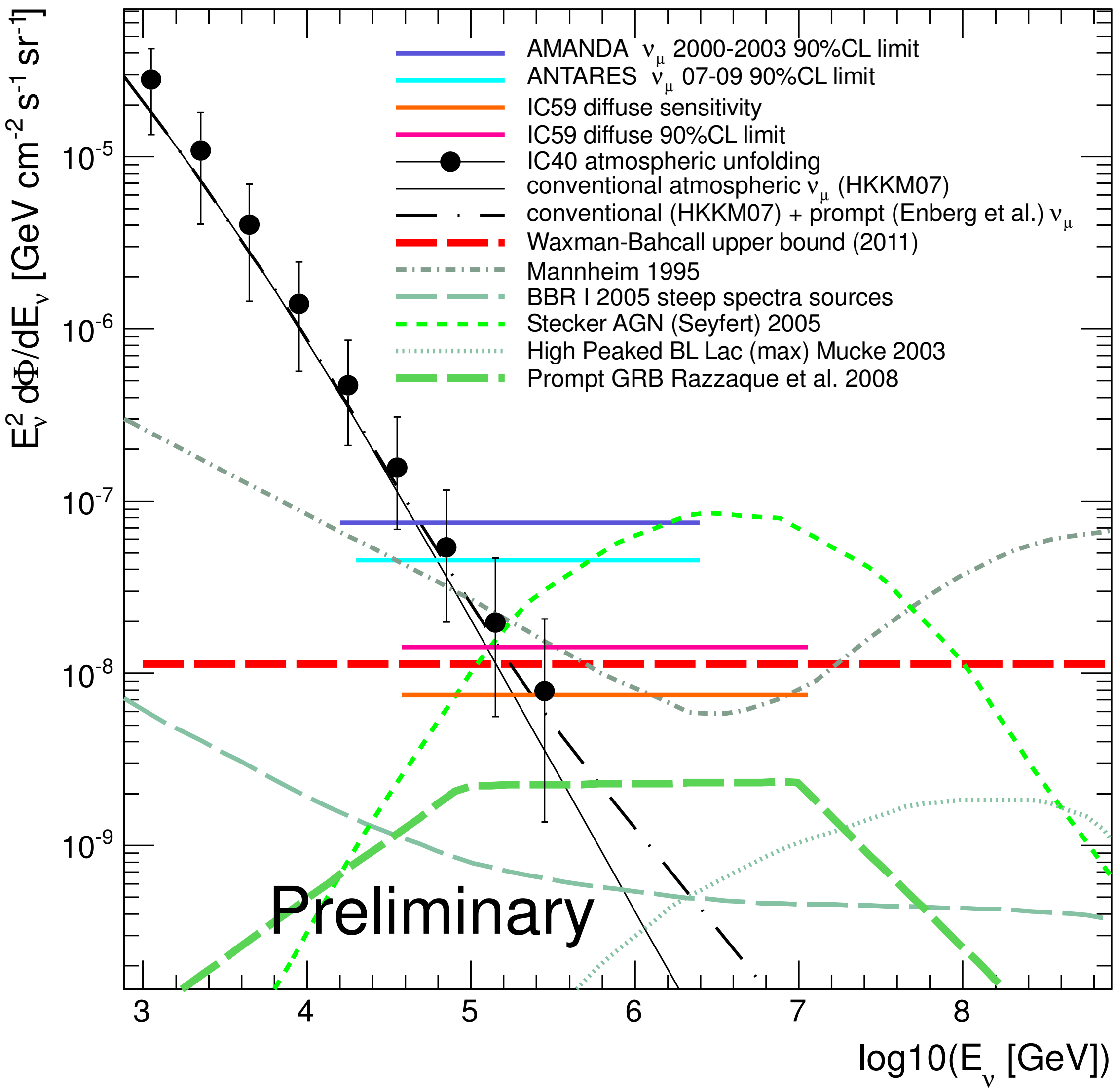
  - Charmed: isotropic below 10^7 GeV *large uncertainties*

    $\boxed{1 \div 1.20 \div 1.20 \div 0.04}$ $C_\mu^{\text{charm}} \lesssim C_\mu^{\text{unflav}}$

  - Photon conversion: isotropic negligible
- Bkgd for astrophysical neutrino sources (isotropic, equal fluxes of all neutrino flavors)

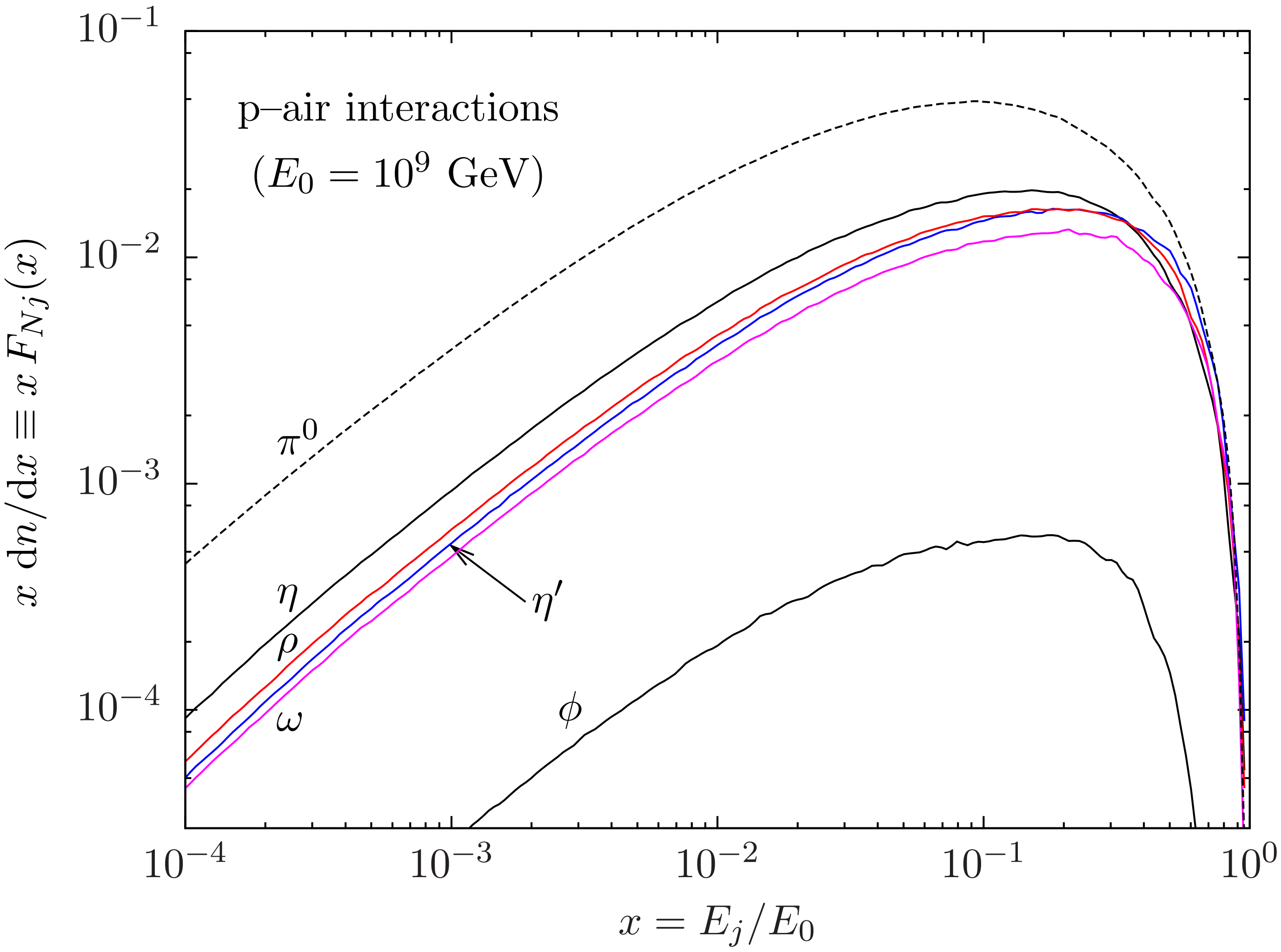
Limit on an extragalactic diffuse neutrino flux

[IceCube, 1302.0127]

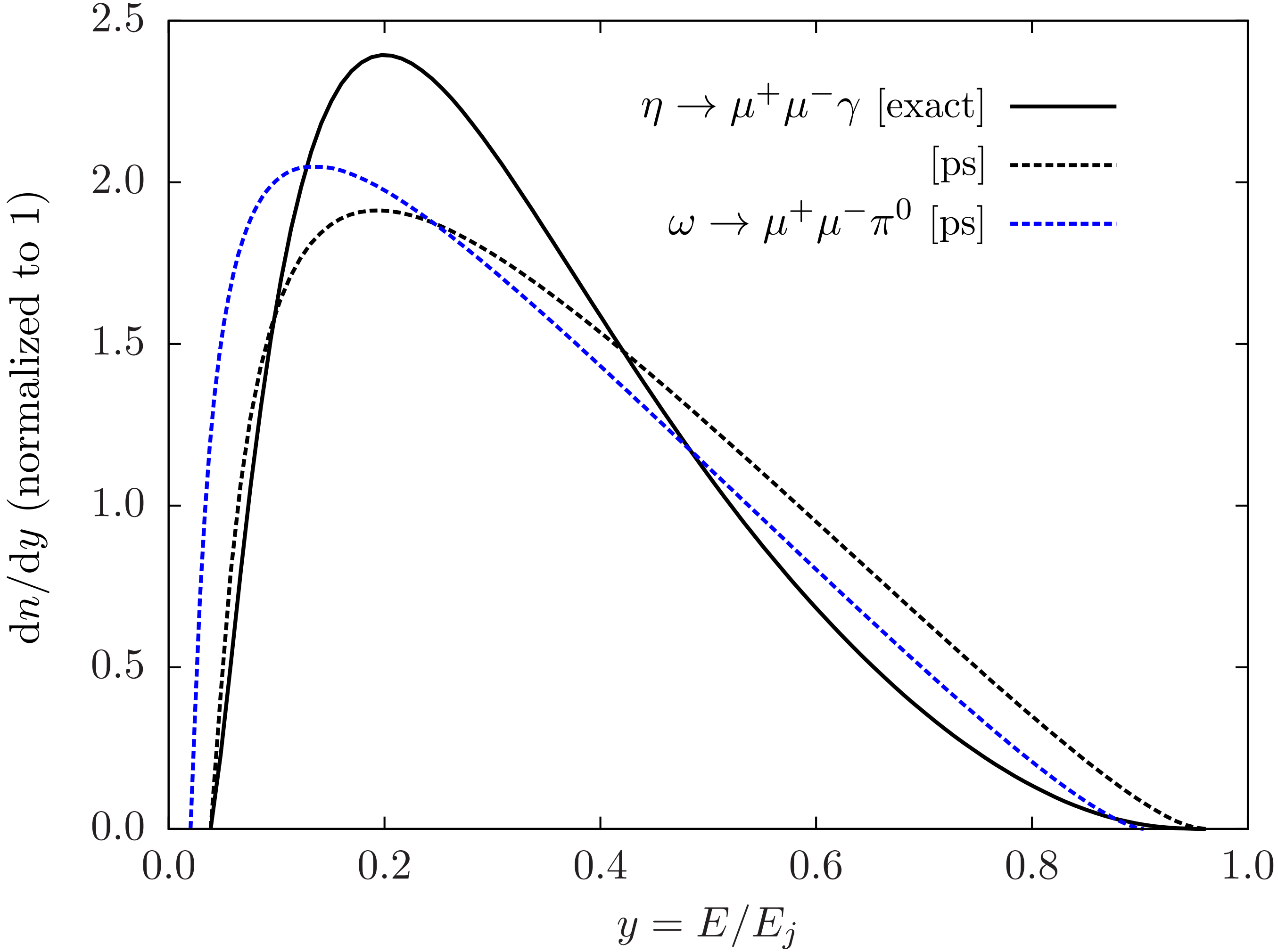


BACKUP

Muons from unflavored meson spectra



Muons from unflavored muon spectra



Muons and neutrinos from charm lepton spectra