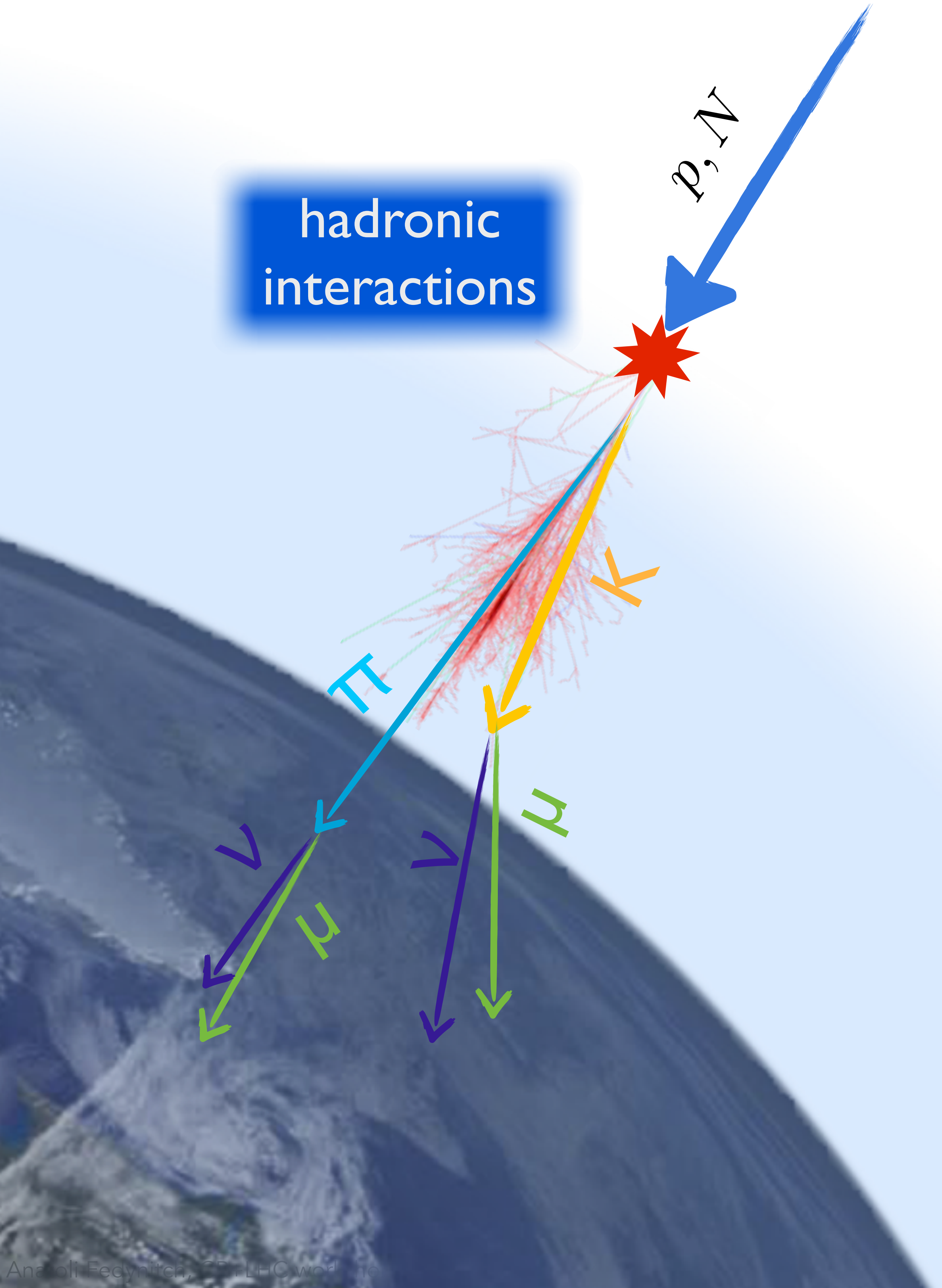
Karlsruhe Institute of Technology

Phenomenology of inclusive leptons in the atmosphere

Anatoli Fedynitch
KIT (IKP) & CERN

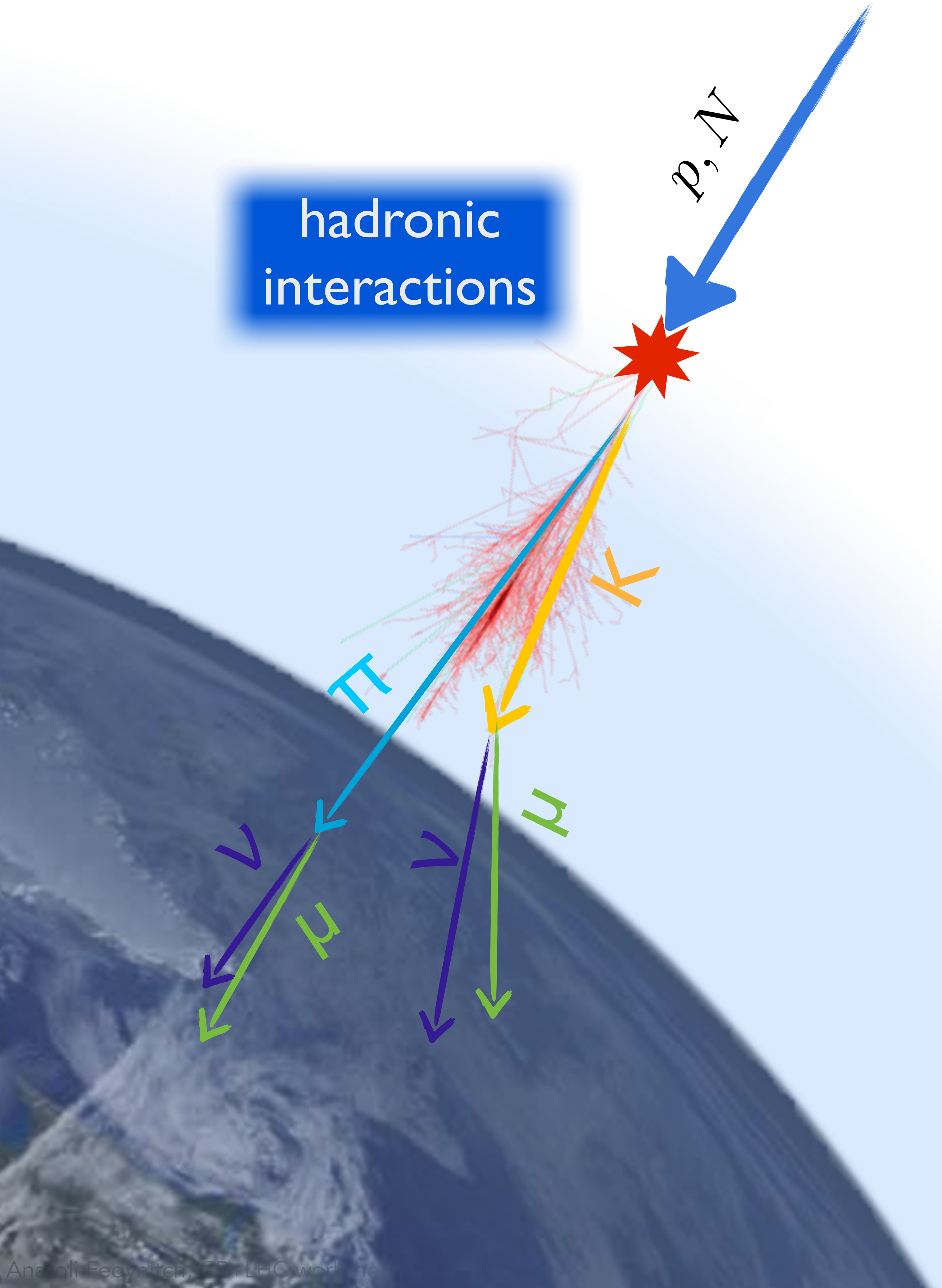
What are inclusive leptons?



- The beam is the flux of CR at the top of the atmosphere
- The target is an average air-nucleus
- The calorimeter is the atmosphere
- Luminosity is under Natures control
- The accessible CMS energy is determined by the effective area and (long) exposure of the detector
- UHE or small cross-sections need ultra sized detectors

Forward particle physics with "organic" accelerators

What are inclusive leptons?



conventional:

$$p, N + \mathrm{air} \rightarrow \pi^{\pm}, \pi^{0}, \mathrm{K}^{\pm}, \mathrm{K}^{0}_{\mathrm{S,L}}$$

muons and muon neutrinos:

$$\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}(\bar{\nu}_{\mu})$$

electron neutrinos:

$$K^{\pm}, K^{0}_{L} \rightarrow [\pi^{\pm}, \pi^{0}]e^{\pm}\nu_{e}(\bar{\nu}_{e})$$

prompt:

$$p, N + \mathrm{air} \rightarrow \mathrm{D}, \Lambda_{\mathrm{C}}$$

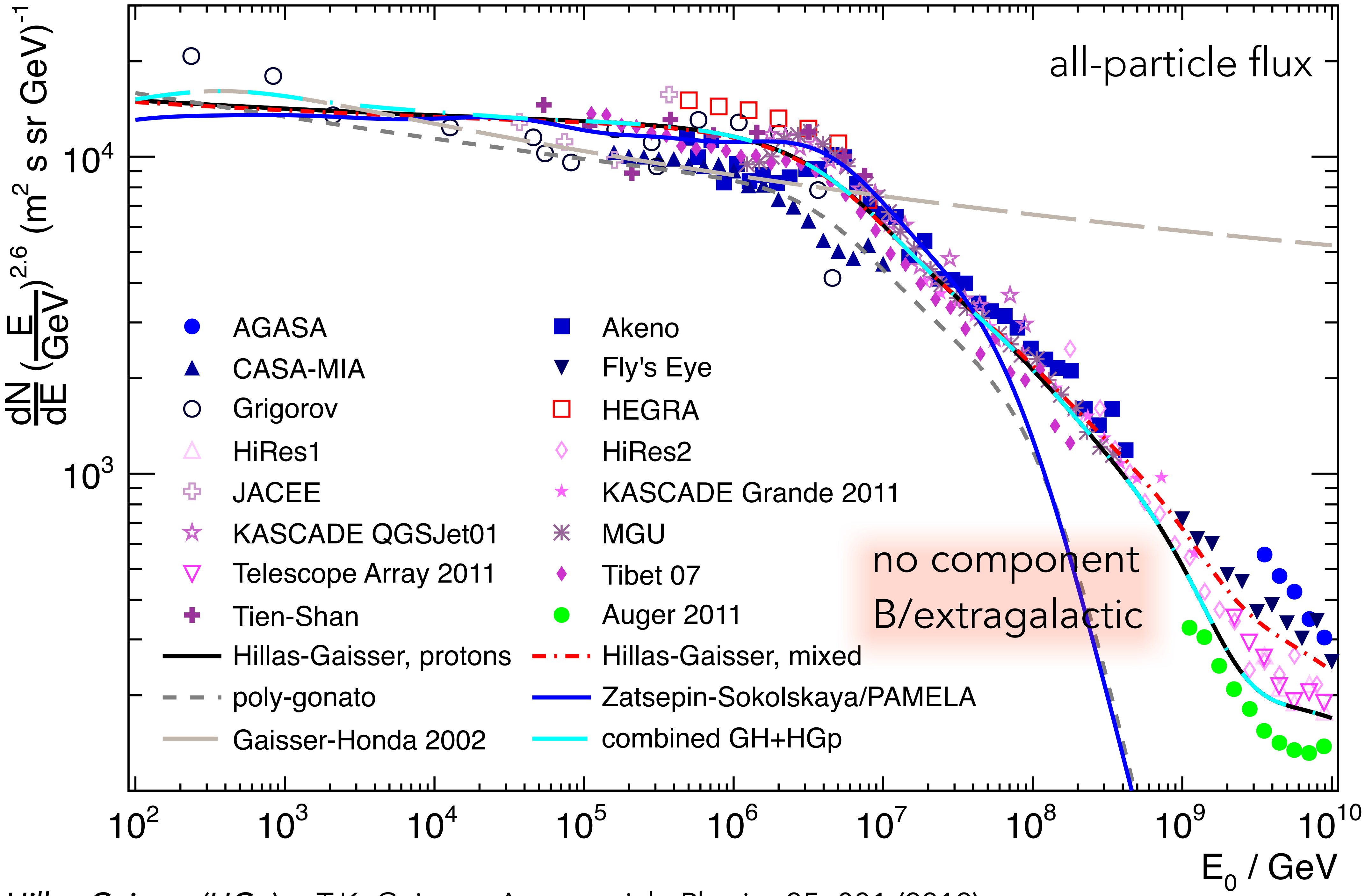
$D'\mathrm{s}, \Lambda_{\mathrm{C}}'\mathrm{s}$ decay with similar branching ratios into μ, ν_{μ}, ν_{e}

Maybe via: η, η', ρ, ϕ

Important criteria: high $x_{\mathrm{Lab}}=E_{\mathrm{lepton}}/E_{\mathrm{nucleon}}$

Anatoli Fedynitch, CR+LHC workshop

Models of the primary spectrum



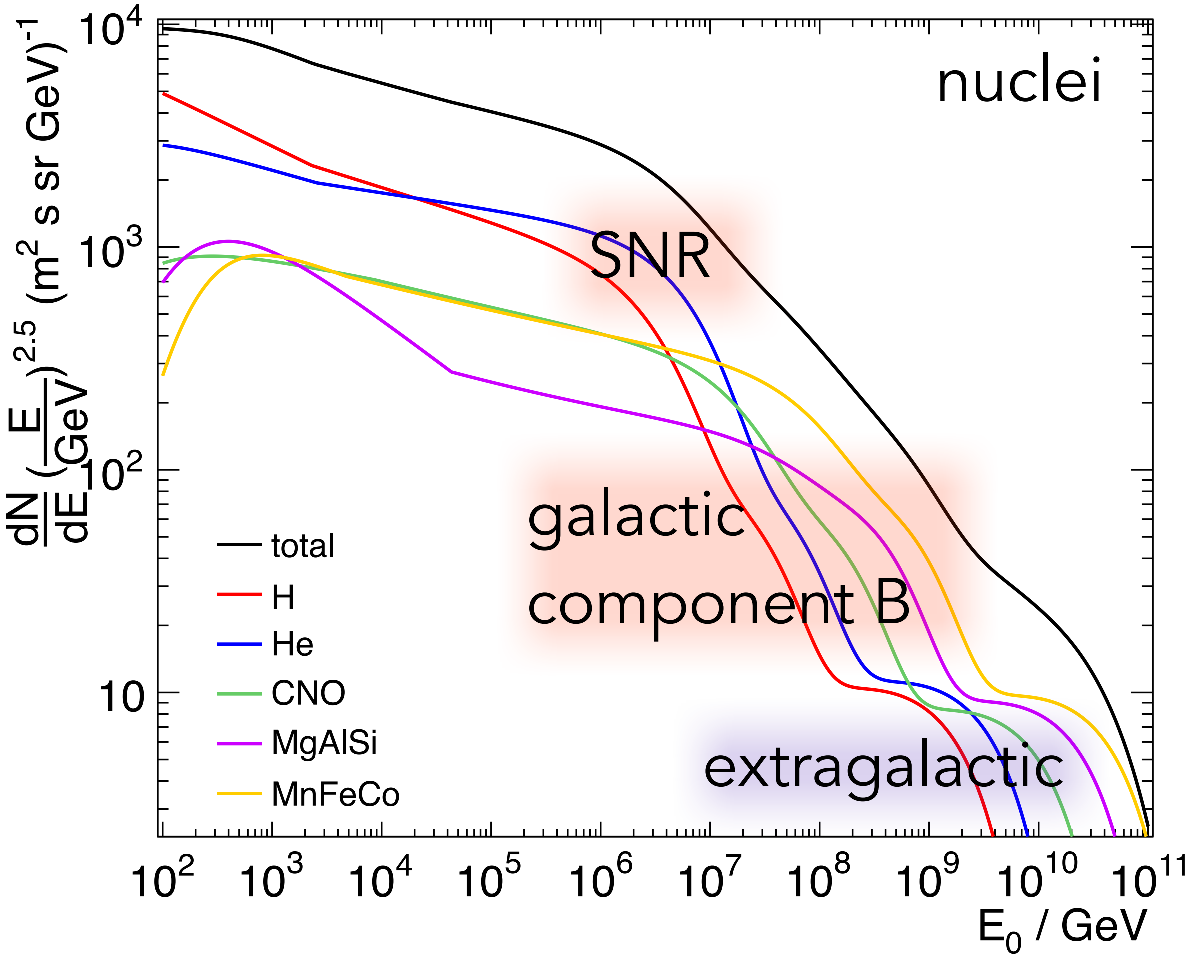
no component B/extragalactic

Hillas-Gaisser (HGx): T.K. Gaisser, Astroparticle Physics 35, 801 (2012).

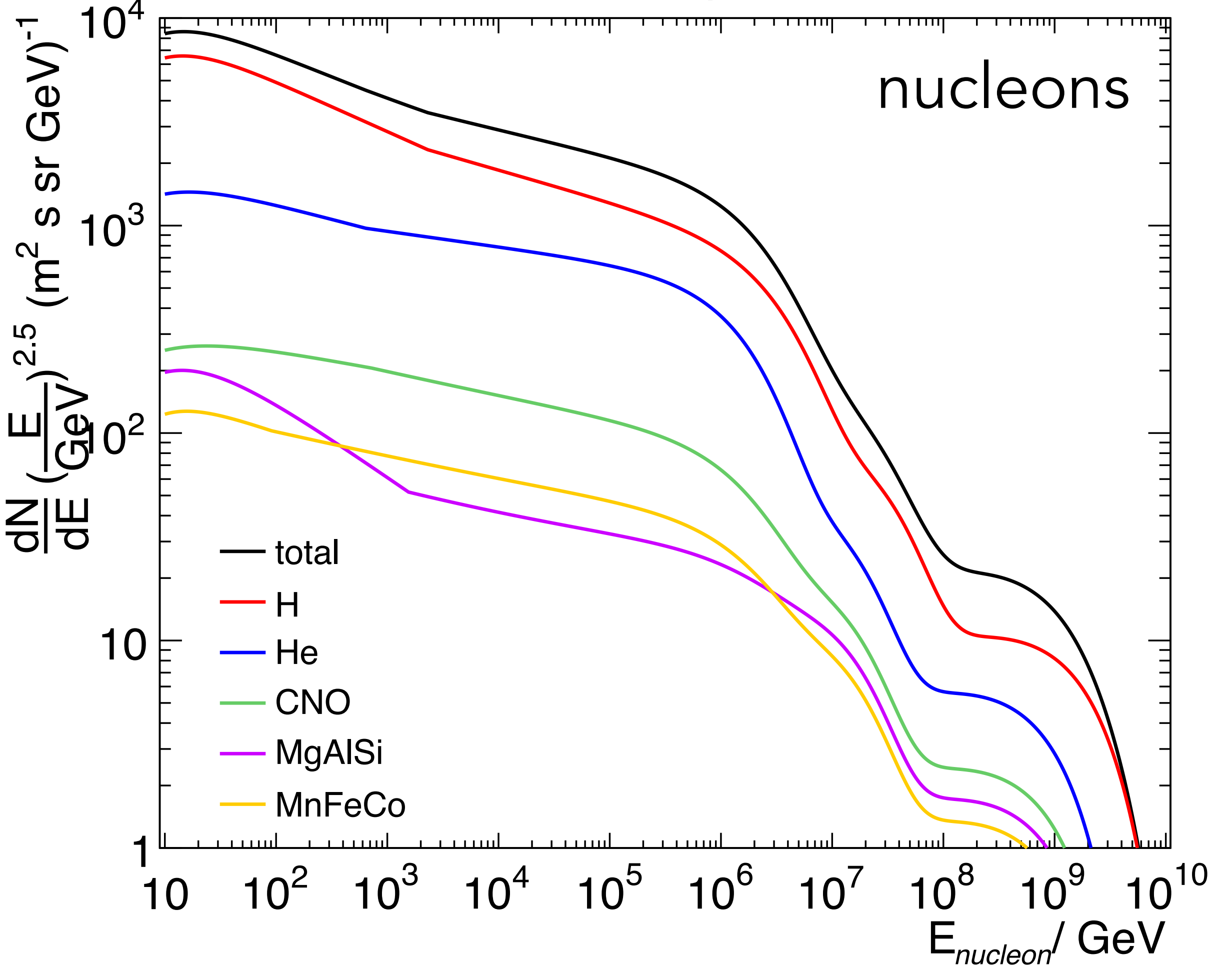
Zatsepin-Sokolskaya/PAMELA: V. I. Zatsepin and N. V. Sokolskaya, A&A 458, 1 (2006). + parameters from O. Adriani et al., Science 332, 69 (2011)

GH: T.K. Gaisser and M. Honda, Annual Review of Nuclear and Particle Science 52, 153 (2002).

Nucleon spectrum



Hillas-Gaisser spectrum (H4a)



- For inclusive spectra the superposition approximation holds
- The average yield of muons originating from a single Fe-initiated EAS can therefore be described by e.g.

$$\frac{\mathrm{dN}_\mu}{\mathrm{dE}_\mu}(E_{Fe}) \approx 26\ \frac{\mathrm{dN}_\mu}{\mathrm{dE}_\mu}(E_p = \frac{E_{Fe}}{52}) + 26\ \frac{\mathrm{dN}_\mu}{\mathrm{dE}_\mu}(E_n = \frac{E_{Fe}}{52})$$

Simple model

- In a first approximation the lepton flux at low energy (~10 - 100 GeV) follows the spectral index of the primary nucleon spectrum

$$\frac{\mathrm{dN}_\mu}{\mathrm{dE}_\mu} \sim E_N^{-2.7}$$

- At higher energy, above the critical energy $\mathcal{E}$, where the probability for interaction is higher compared to the decay probability/length, the spectrum steepens by one power

Decay length (pions)

$$\frac{1}{d_\pi} = \frac{m_\pi c^2 h_0}{E c \tau_\pi X \cos\theta} = \frac{\varepsilon_\pi}{E X \cos\theta}$$

Critical energies for isothermal atmosphere

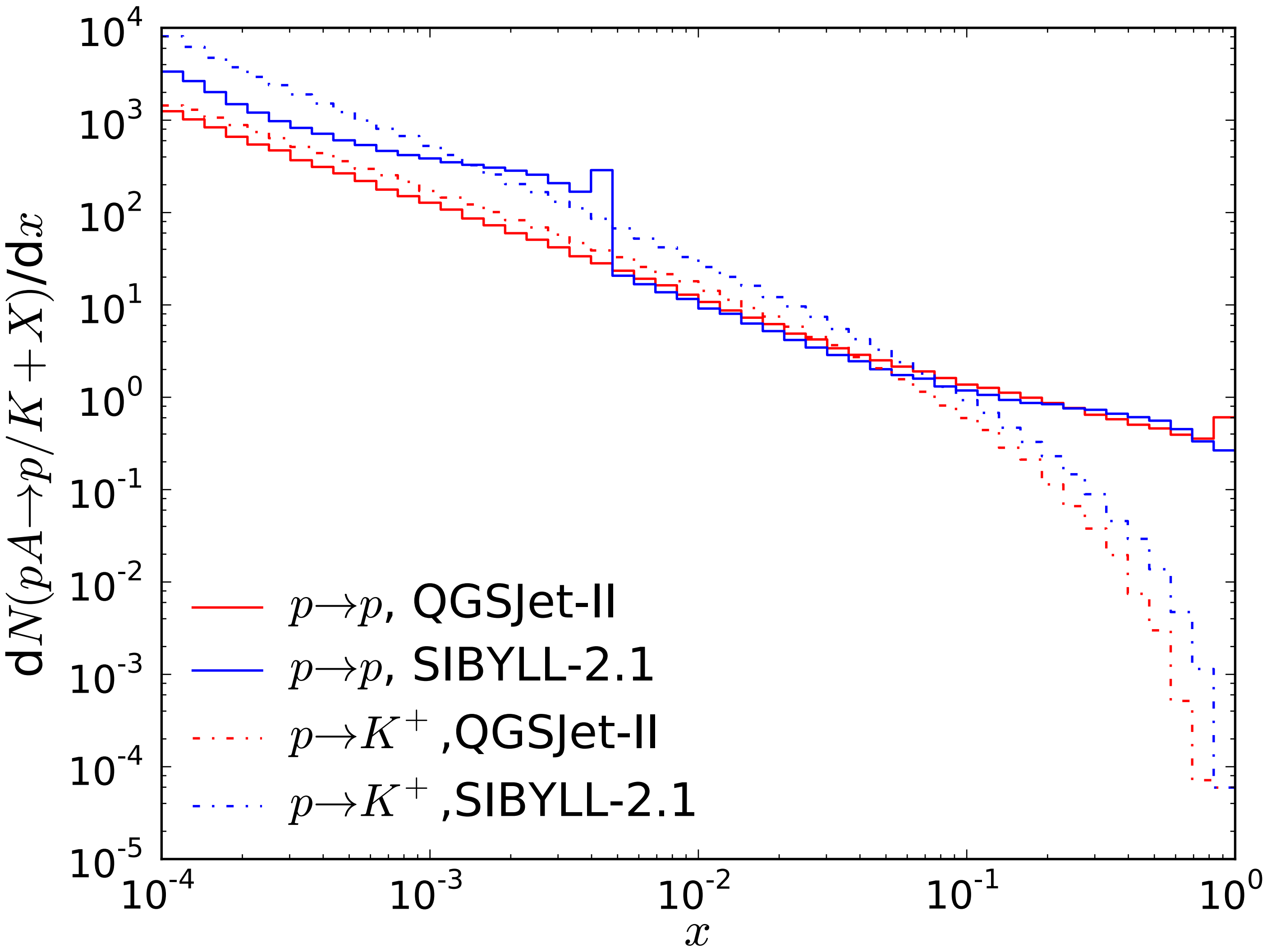
$$\varepsilon_\pi \approx 115 \text{ GeV}$$

$$\varepsilon_K \approx 850 \text{ GeV}$$

$$\frac{\mathrm{dN}_\mu}{\mathrm{dE}_\mu} \sim \frac{E^{-2.7}}{1 - Z_{NN}} \left(\frac{Z_{N\pi} Z_{\pi\to\mu}}{1 + A_\pi E \cos\theta/\varepsilon_\pi} + \frac{Z_{NK} Z_{K\to\mu}}{1 + A_K E \cos\theta/\varepsilon_K} \right)$$

T. K. Gaisser, Cosmic Rays and Particle Physics (Cambridge Univ Pr, 1990).

Simple Z-factors



	SIBYLL	QGSJet	Ratio
Z_{pp}	0.145	0.188	0.77
Z_{pK+}	0.0072	0.0035	2.05

Z-factor

[primary] Spectrum weighted moment

"Approximation A"

1. Ionization energy loss is neglected
2. Inelastic cross-section is constant with energy
3. Inclusive cross-sections obey Feynman scaling

$$Z_{kh} = \int_0^1 dx\ x^{\gamma-1} \frac{dn(kA\to hY)}{dx}$$

Enhanced model

- Due to the knee and ankle of CR, the simple power-law primary spectra do not apply
- Also, the nucleon-air cross-section is not independent of energy
- It is unknown, if Feynman scaling holds at all energies

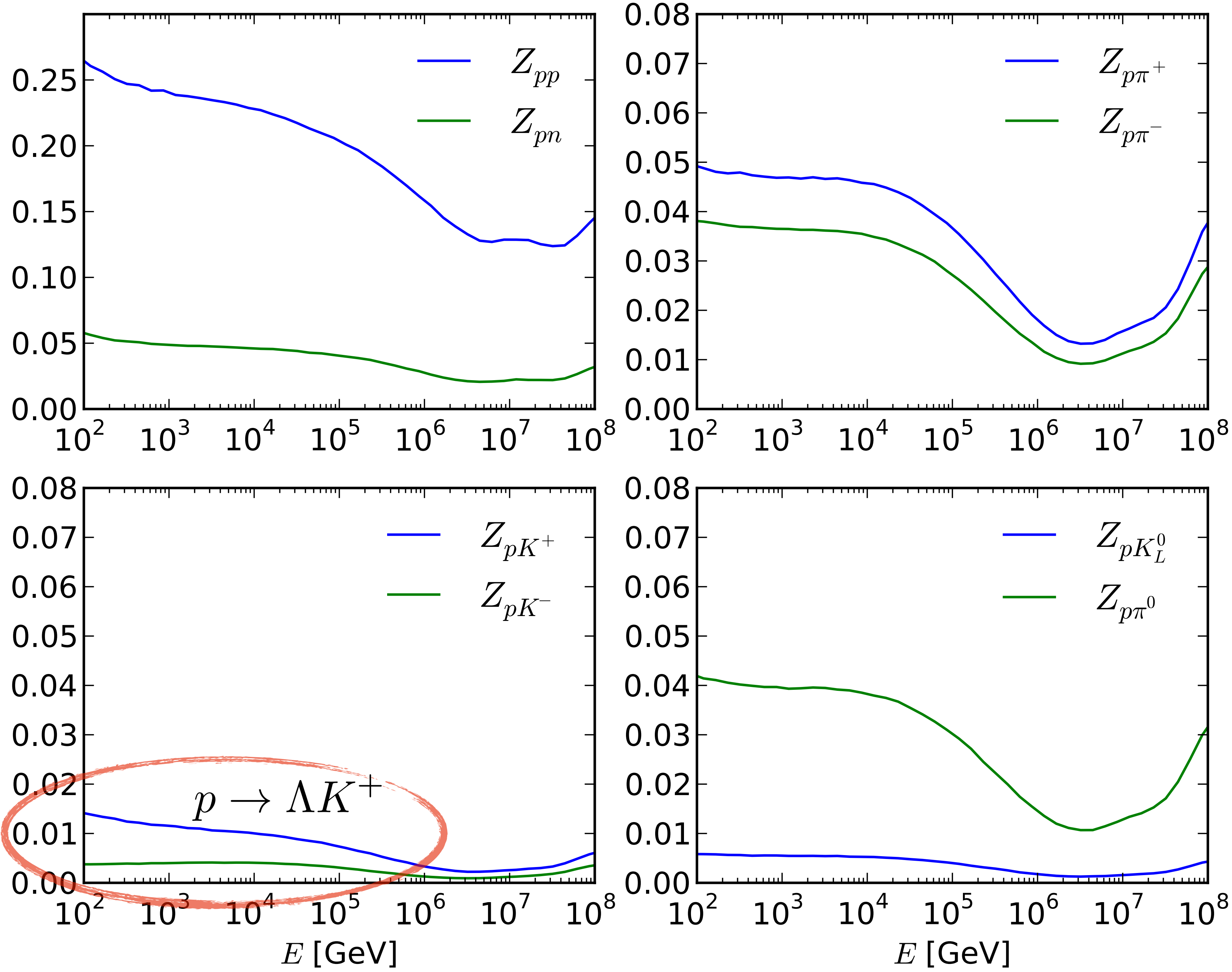
Energy dependent Z-factor (M. Thunman et al., Astropart. Phys. 5, 309 (1996))

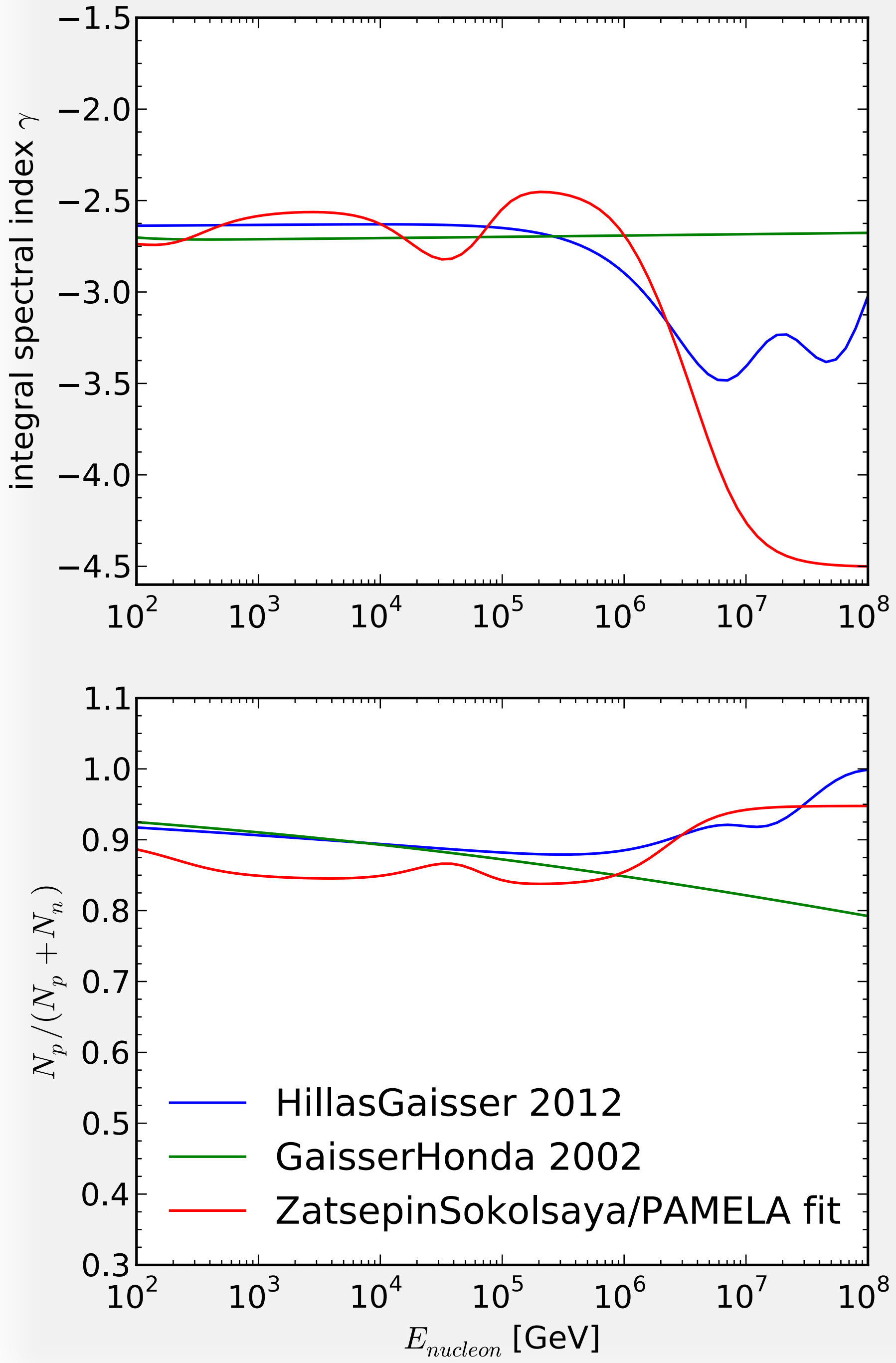
$$Z_{kh}(E) = \int_E^\infty dE' \; \frac{d\Phi_N(E',\theta)}{d\Phi_N(E,\theta)} \frac{\sigma_{kA}(E')}{\sigma_{kA}(E)} \frac{dn(kA \to hY; E', E)}{dE}$$

Spect. index dependent decay Z-factor P. Lipari, Astropart. Phys. 1, 195 (1993).

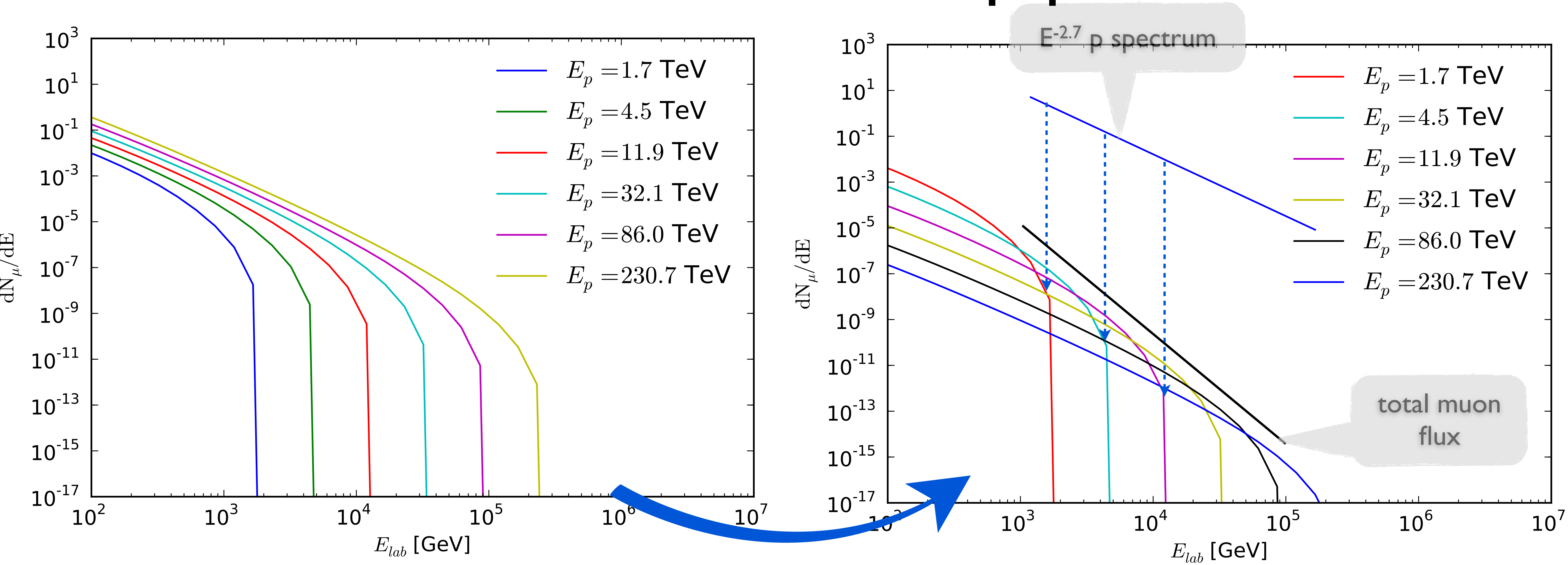
$$Z_{M\to l,\gamma(E_N)} = \int_0^1 dx \; x^{\gamma(E_N)-1} F(M \to l)$$

Enhanced Z-factors


Z-factors for proton primary, SIBYLL-2.1


Primary spectrum: nucleon index and proton fraction

Yield (EAS-MC) approach



$E^{-2.7}$ p spectrum

total muon flux

apply weight

The flux at the surface is the convolution of the yields with a primary spectrum

$$\Phi_\mu(E_\mu) = \sum_{Z_p} \sum_{E_{p,i}} w(E_{p,i}, Z_p) \times \frac{\mathrm{dN}_\mu}{\mathrm{dE}_\mu}(E_\mu, E_{p,i}, \theta, Z_p)$$

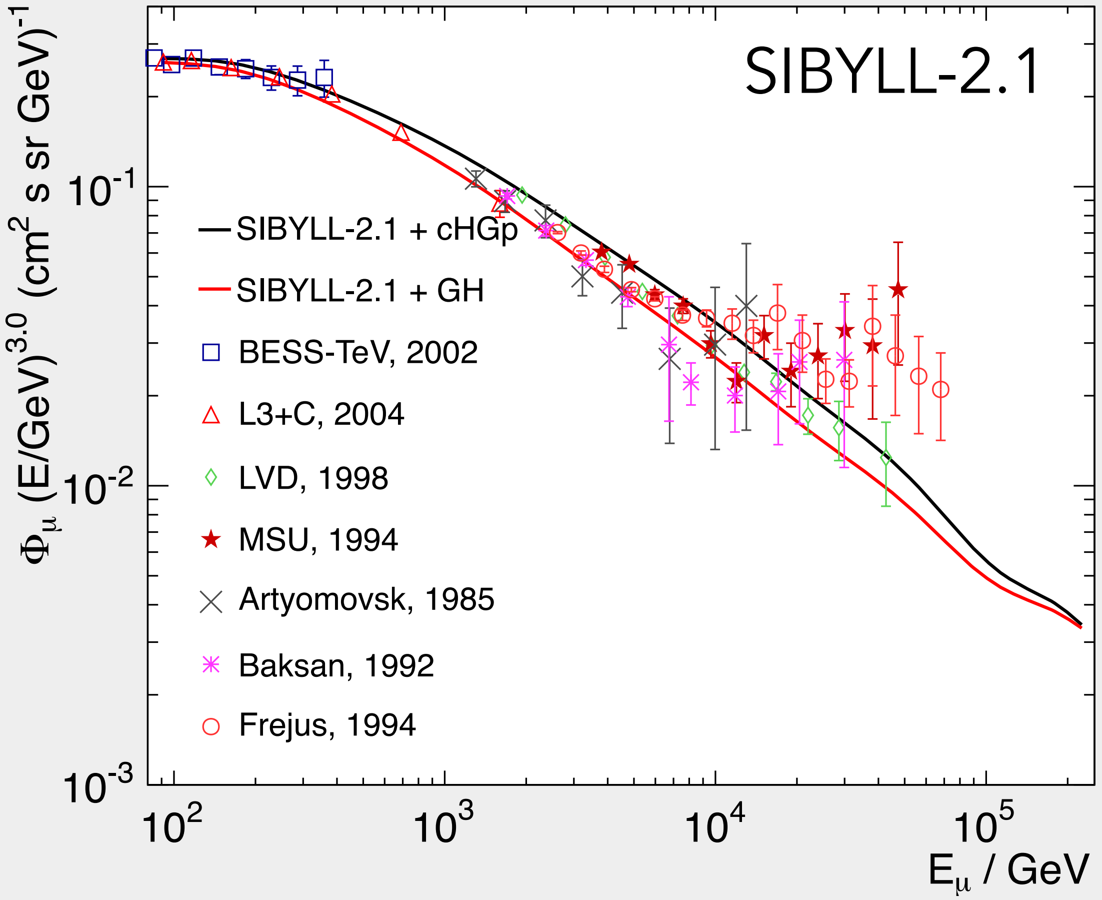
nuclei

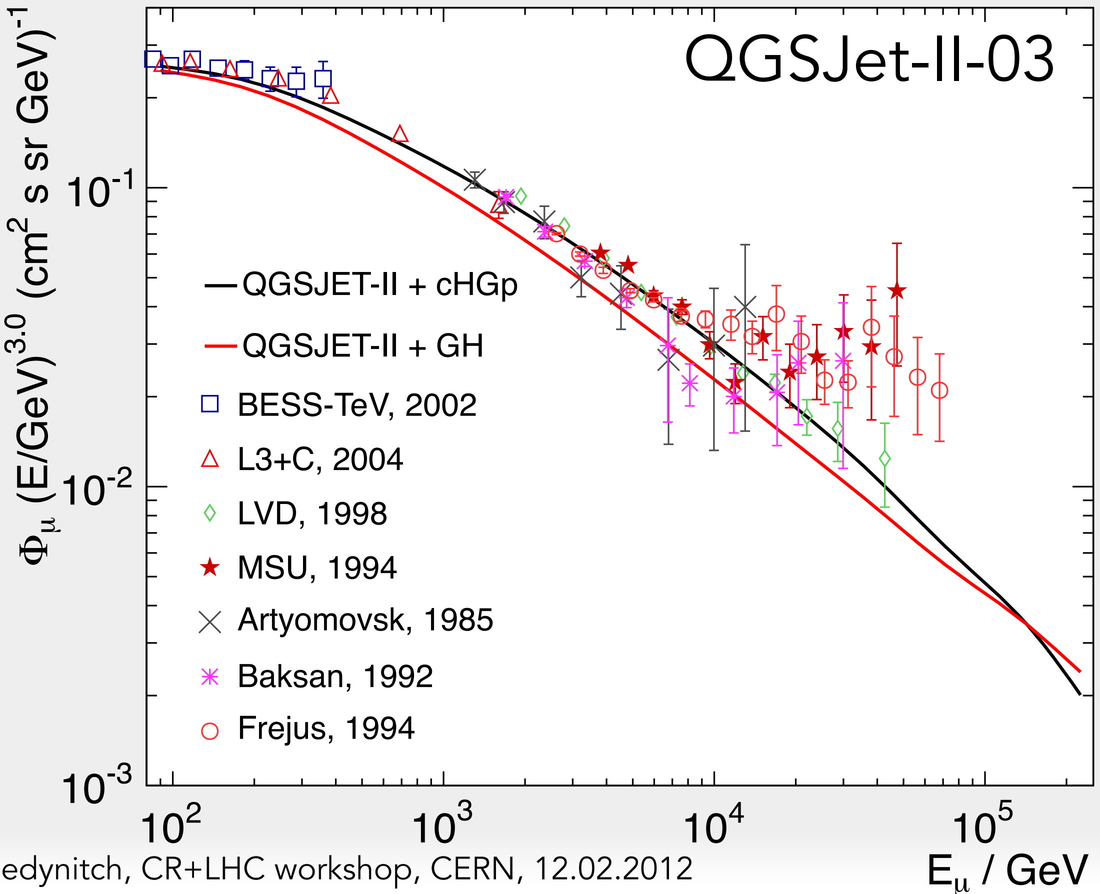
primary energies

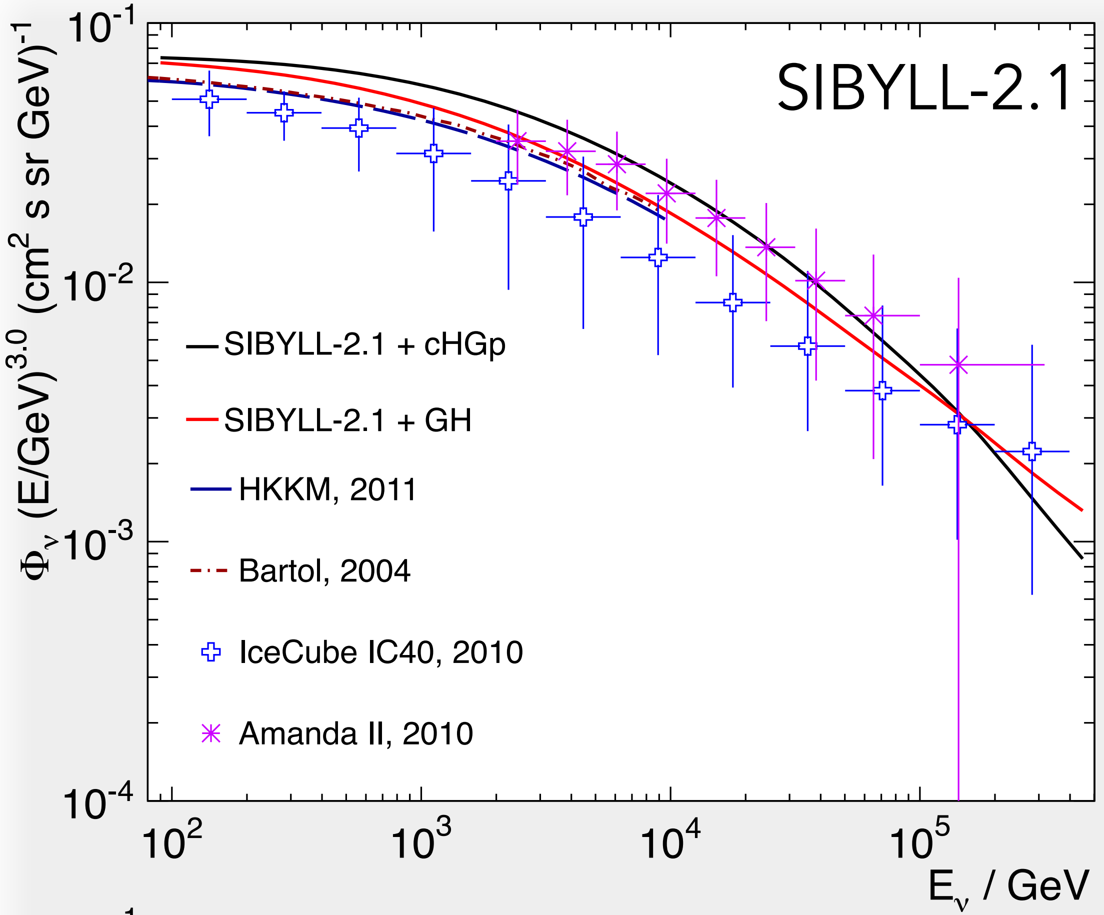
AF, Tjus, Desiati arXiv:1206.6710

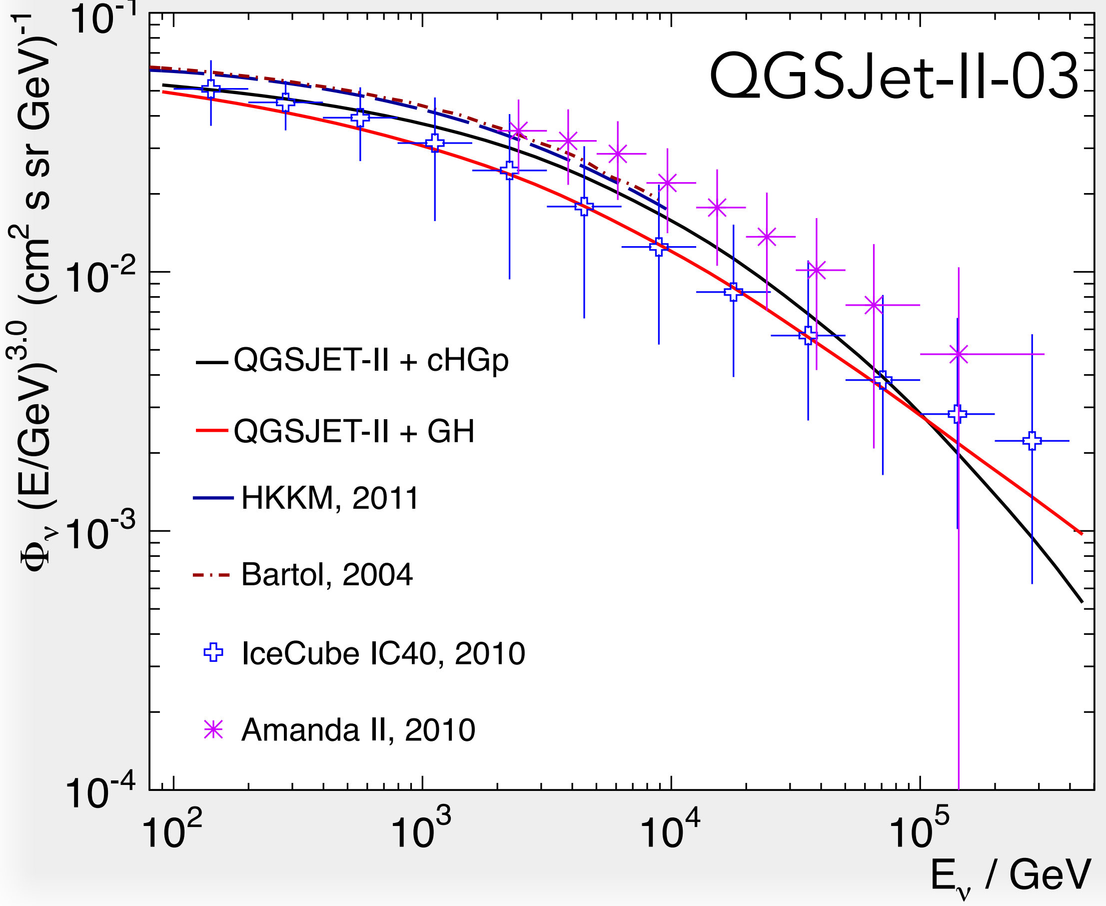
Inclusive spectra

atmospheric muons



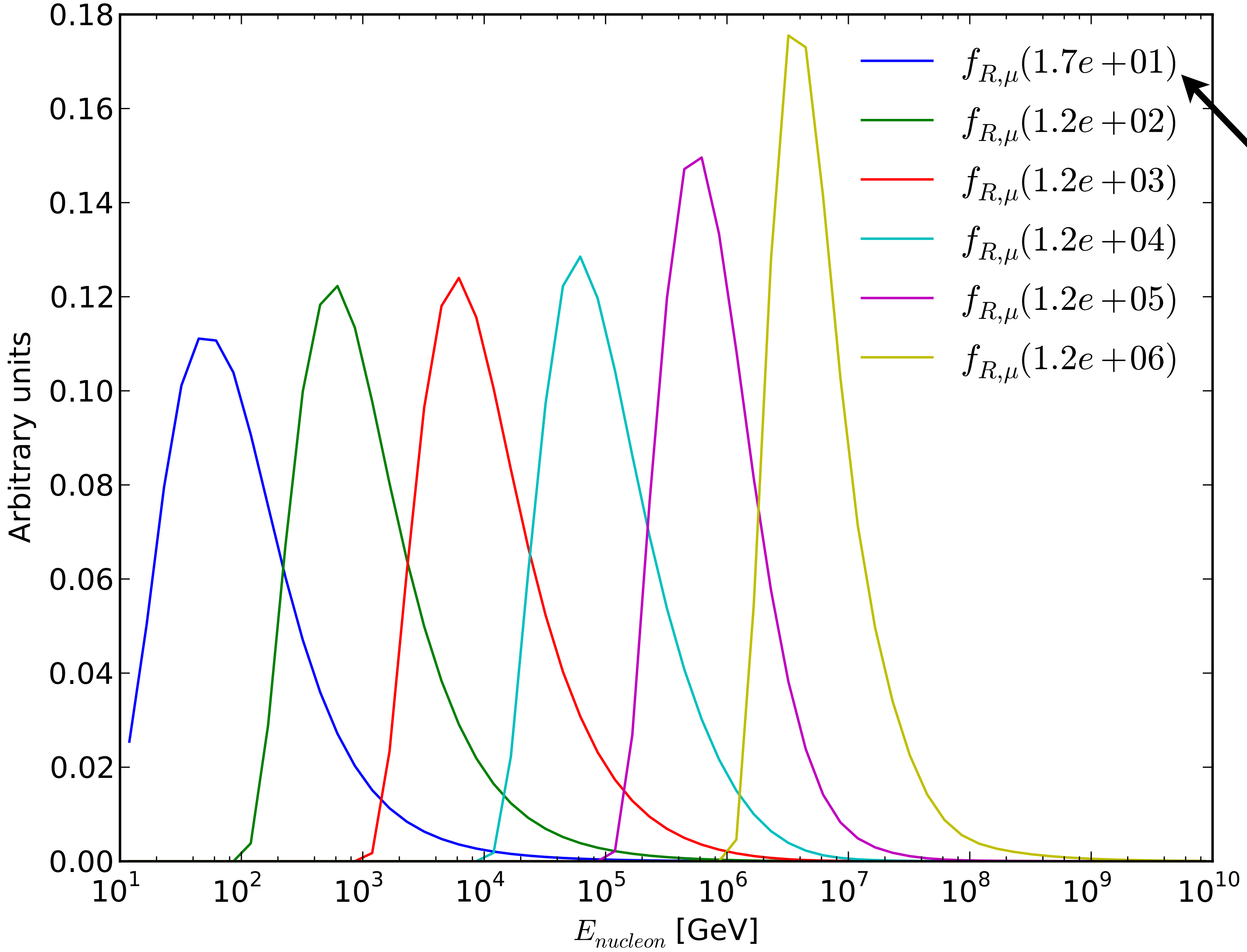






atmospheric muon neutrinos

Relation to primary energy



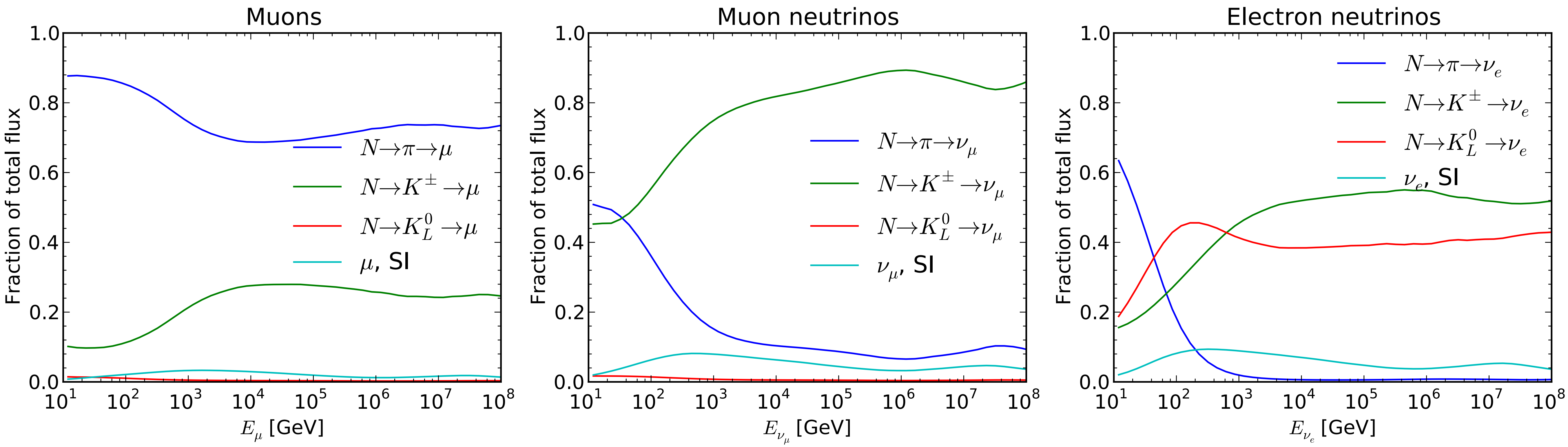
Fixed muon energy in GeV

The response function, the inverse of the yield, is the distribution of primary nucleon energies responsible for the generation of muons with energy E_μ.

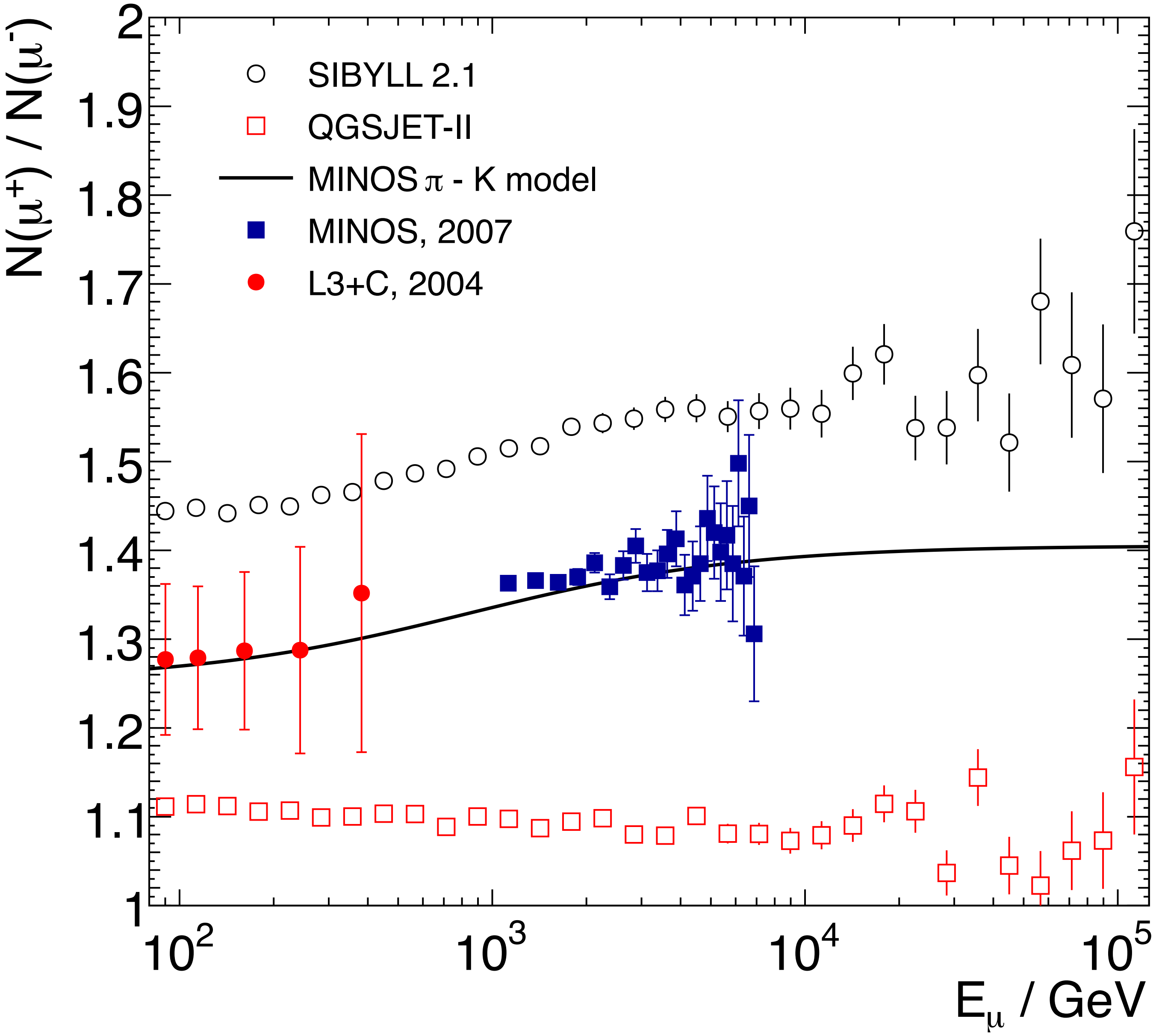
Mesonic origin

- The combination of meson abundance, their decay length, the density of the atmospheric profile,the branching ratios and the decay kinematics results in different meson origin of the observed lepton species

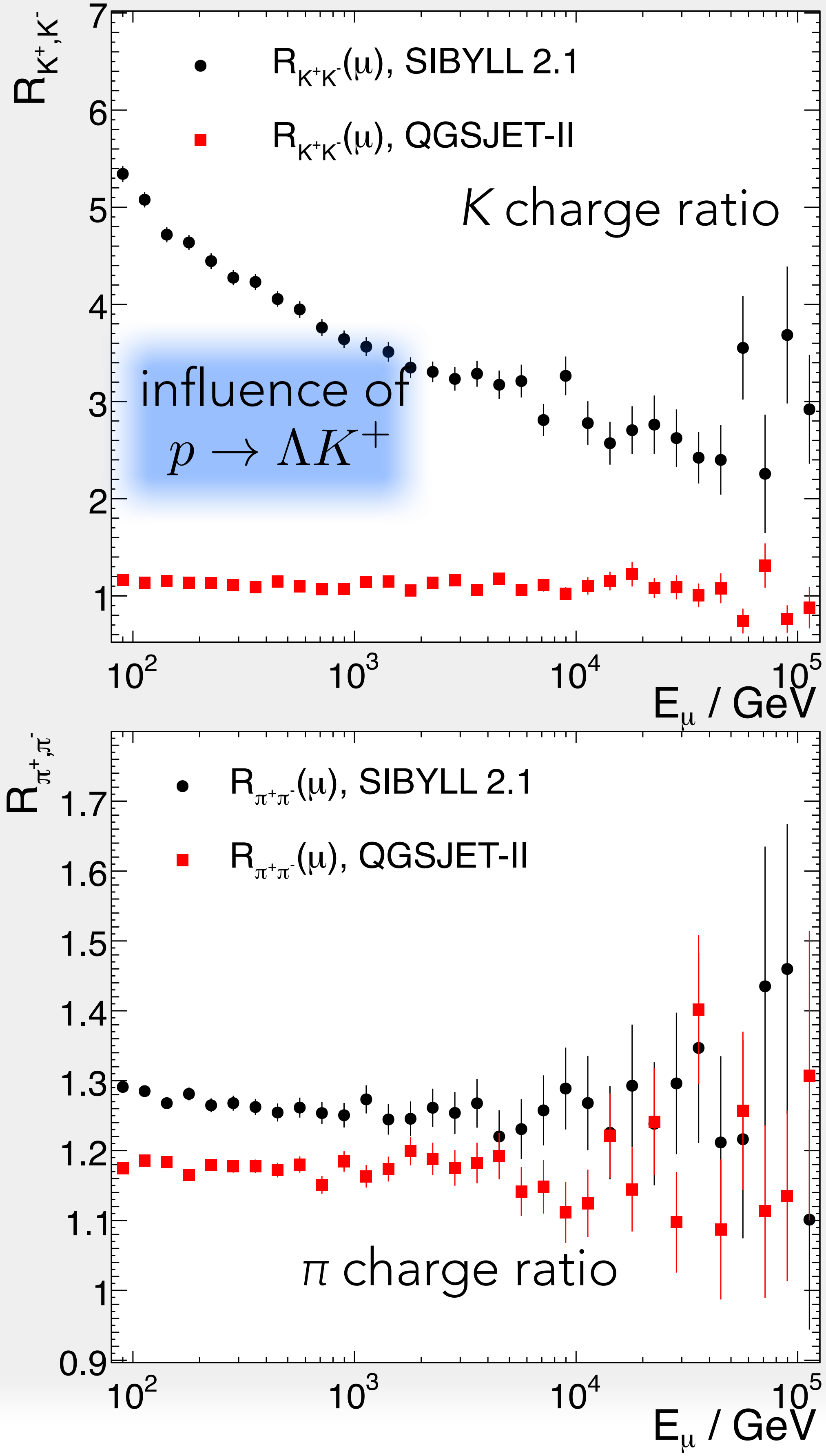
- The steepness of the primary spectrum suppresses the contribution of secondary interactions (SI) of the form $N \to K \to \pi \to \mu$ or $N \to \pi \to \pi \to \mu$



Muon charge ratio



Mother particle charge ratios



K charge ratio

influence of $p \to \Lambda K^+$

π charge ratio

$\varepsilon_\pi \approx 115\text{GeV}$ $\varepsilon_K \approx 850\text{GeV}$ $\varepsilon_{D^\pm} > 10^7\text{GeV}$

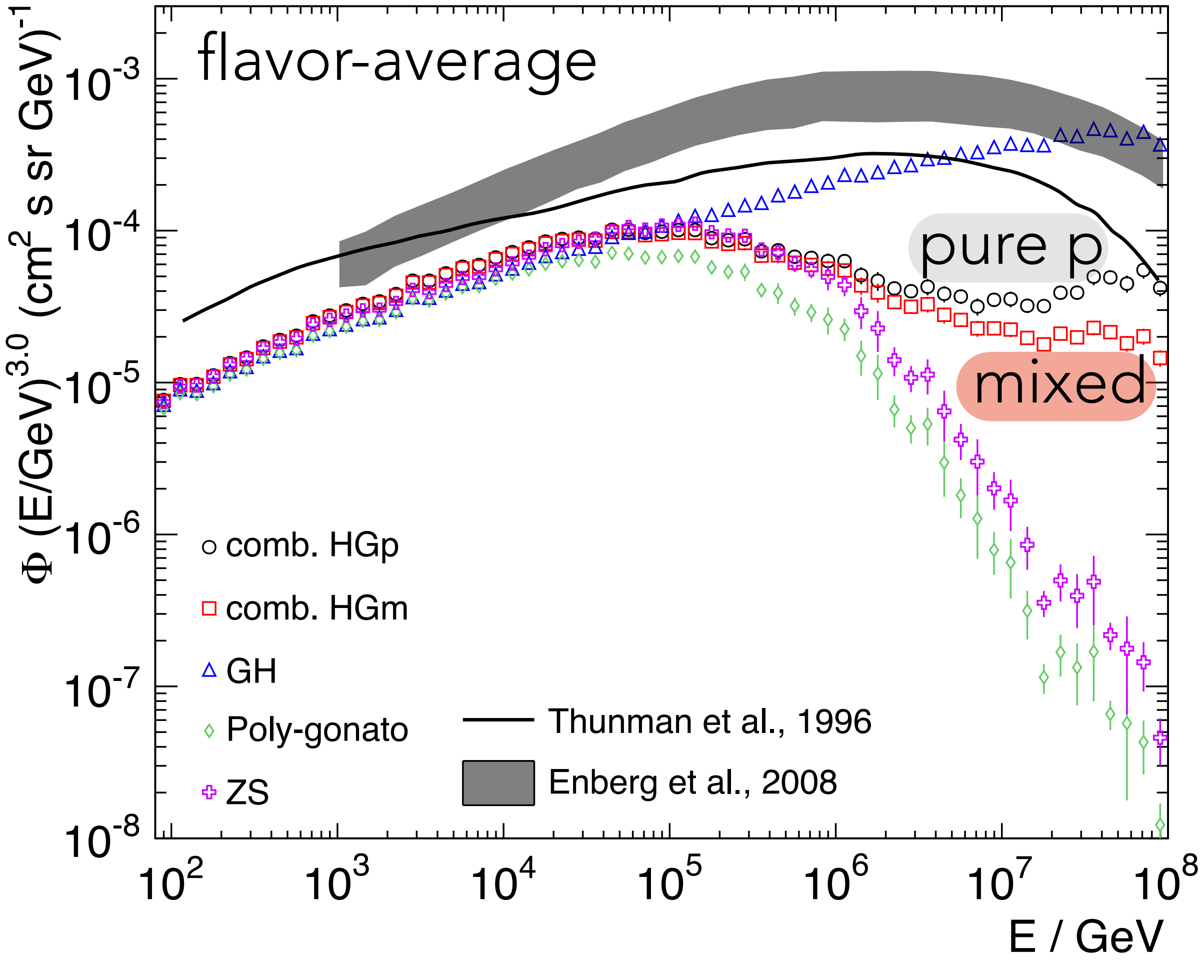
π dominated *K* dominated charm?

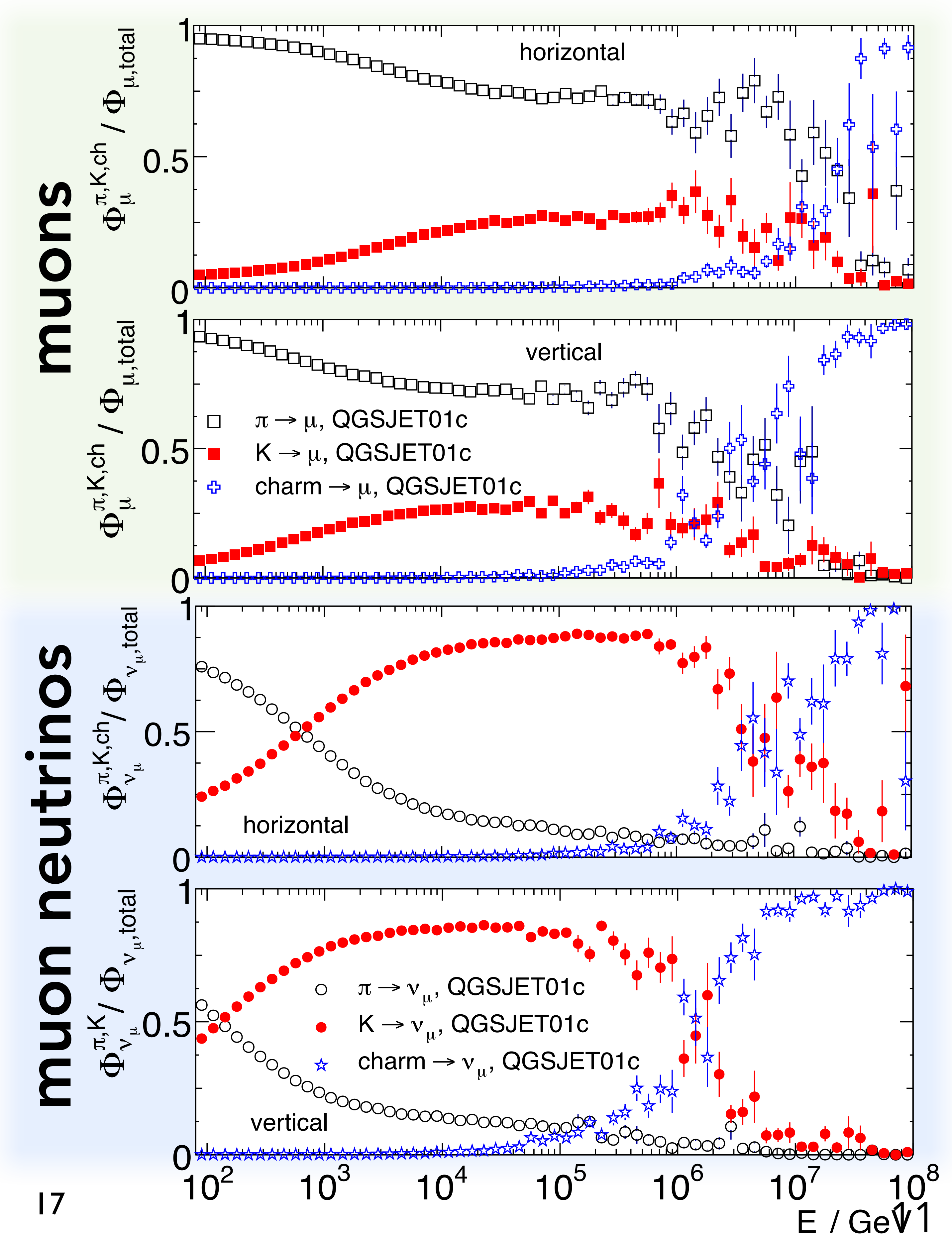
Conclusion

- The spectrum of inclusive leptons results from the convolution of the primary spectrum and hadronic interactions
- It is mostly dominated by the behavior of the very first interaction
- Calculations using Tevatron-era hadronic interaction models and modern models of the primary flux bracket the available experimental data
- The muon charge ratio provides sensitivity to the ratio of high energy kaons and pions
- A better knowledge of primary flux, hadronic interactions, muon flux and charge ratio would allow to precisely predict the atmospheric neutrino background

Backup

Charm in QGSJet01





- Calculation of the prompt component is very sensitive to the primary spectrum above the knee

- Composition of CR above the ankle introduces flux variation up to 40%

Muon charge ratio

T. K. Gaisser, Astropart. Phys. 35, 801 (2012).