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Core-corona approach and the muon deficit

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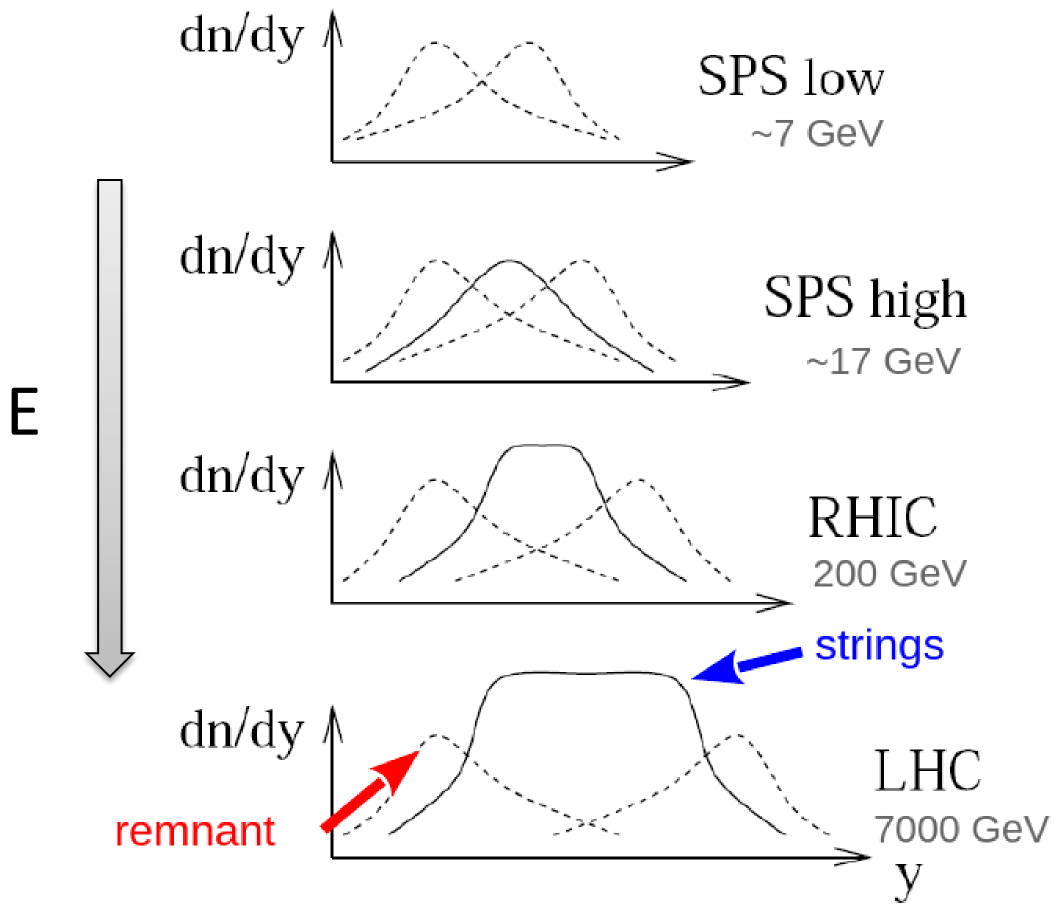
Outline

- Particle production and collective flows
- *Core-Corona* approach
- Particle ratio analysis
- Impact on the number of muons

Particle Production



Only particles from remnants

Strong mixing

Mainly string contribution at mid rapidity with tail of remnants

Only string contribution at mid rapidity

At higher energies it is necessary to modify the **string fragmentation** and/or to take a different approach

Collective flows

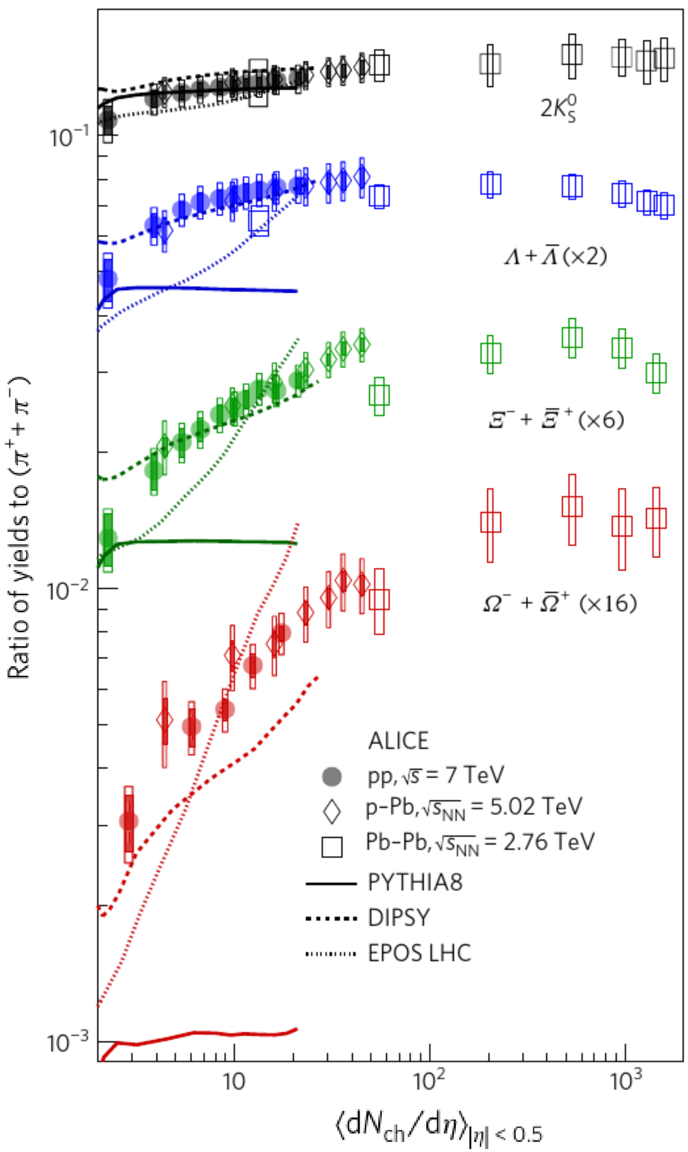
High-energy **A–A interactions**

- High multiplicity of released partons
- **Collective flow** behaviors

The existence of a quark-gluon-plasma (**QGP**) is commonly assumed

- Evolves according to the laws of hydrodynamics
- **Statistical Hadronization**

Even **p-p interactions** at high enough energies can be viewed as collisions of light nuclei with collective flow in the highest multiplicity events.



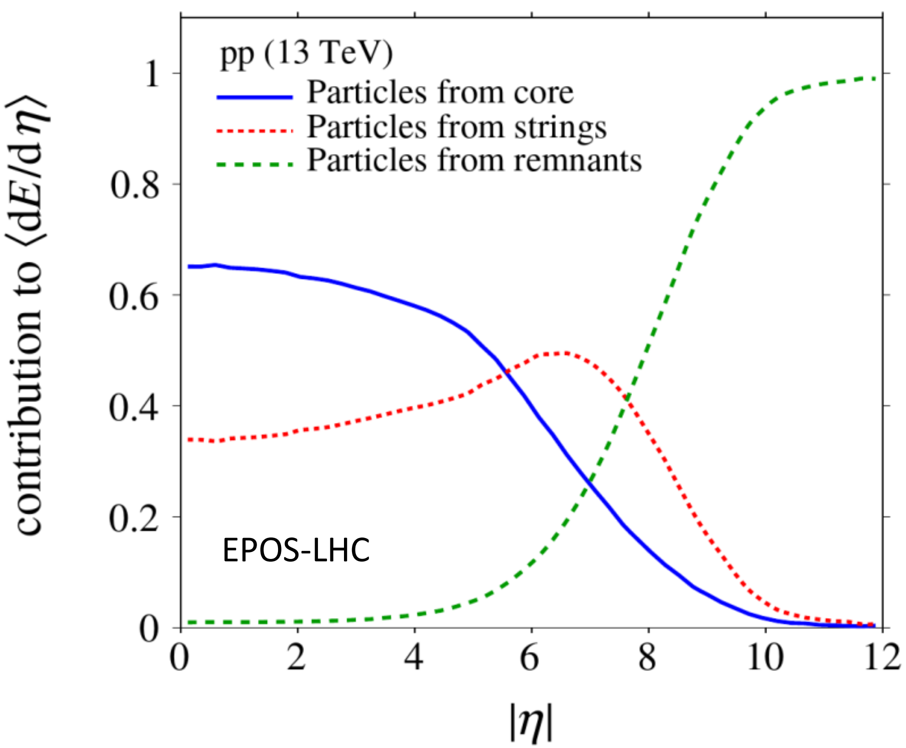
The main goal is to show that collectivity in collisions of hadrons and nuclei can play a so far underestimated role in the understanding of muon production in air showers

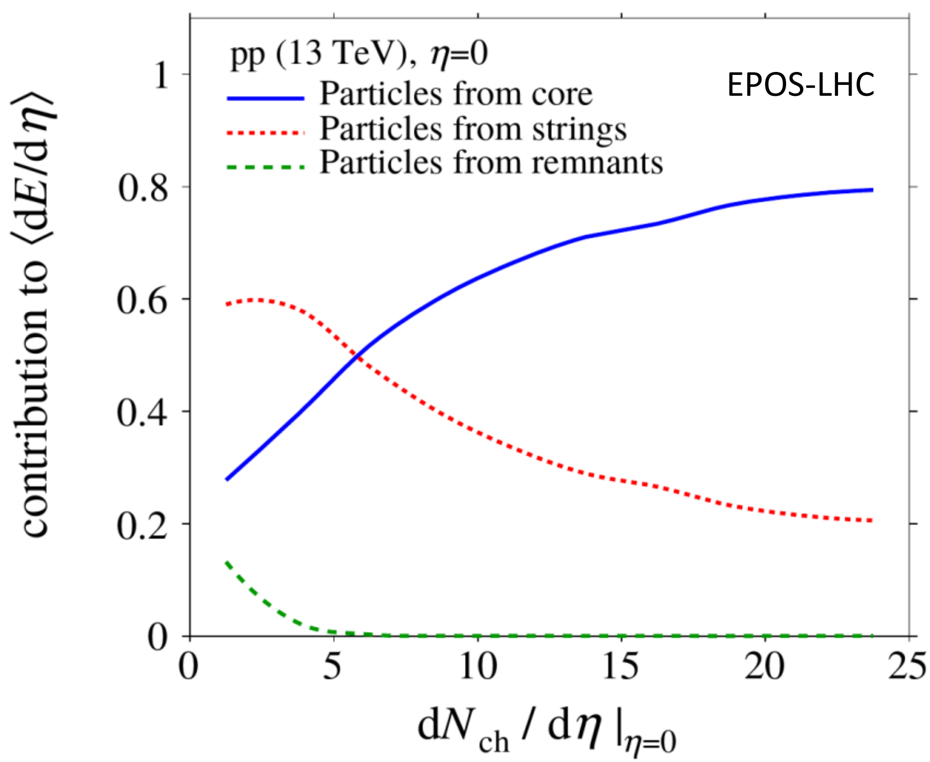
Core-Corona approach

The final state particles originate from three different production mechanisms

- **Core**: High string density ⟶ **Statistical hadronization**
- **Corona**: Low string density ⟶ **Standard string fragmentation (implemented in all HE models)**
- Decay of the beam remnants

Each one gives different particle ratios



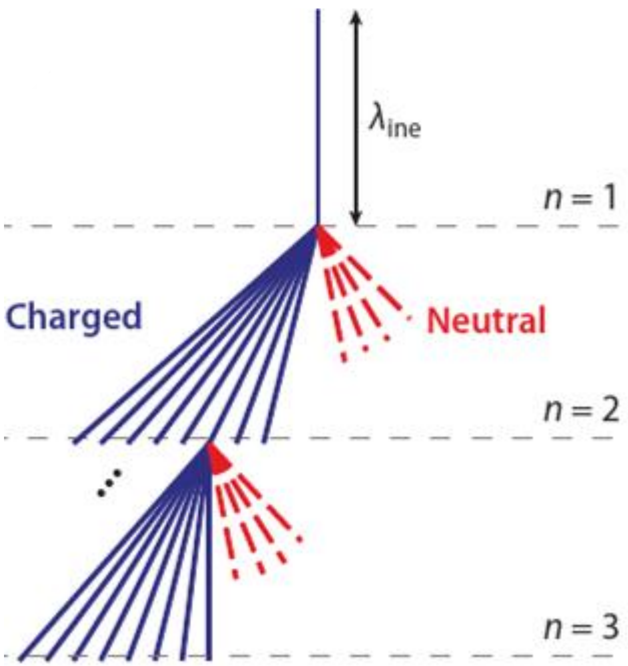


Heitler-Matthews Model

The number of muons depends strongly on the neutral pion and the total particle multiplicities of hadronic interactions.

$$N_\mu = \left(\frac{E_0}{E_{\rm dec}}\right)^\beta \qquad \beta = 1 + \frac{\ln(1-c)}{\ln N_{\rm mult}}$$

$$c = N_{\pi^0}/N_{\rm mult}$$



These multiplicities depend on the hadronization model.

The core produces more baryons than the corona, hence *c* decreases and the number of muon increases.

We define a ratio sensitive to the hadronization and closely related to c.

$$R(\eta) = \frac{\langle {\rm d}E_{\rm em}/{\rm d}\eta \rangle}{\langle {\rm d}E_{\rm had}/{\rm d}\eta \rangle}$$

See talk by H. Dembinski

Core-Corona approach

At mid-rapidity the particles come from the core or the corona

$$N_i = \omega_{\rm core}\, N_i^{\rm core} + (1-\omega_{\rm core})\, N_i^{\rm corona}$$

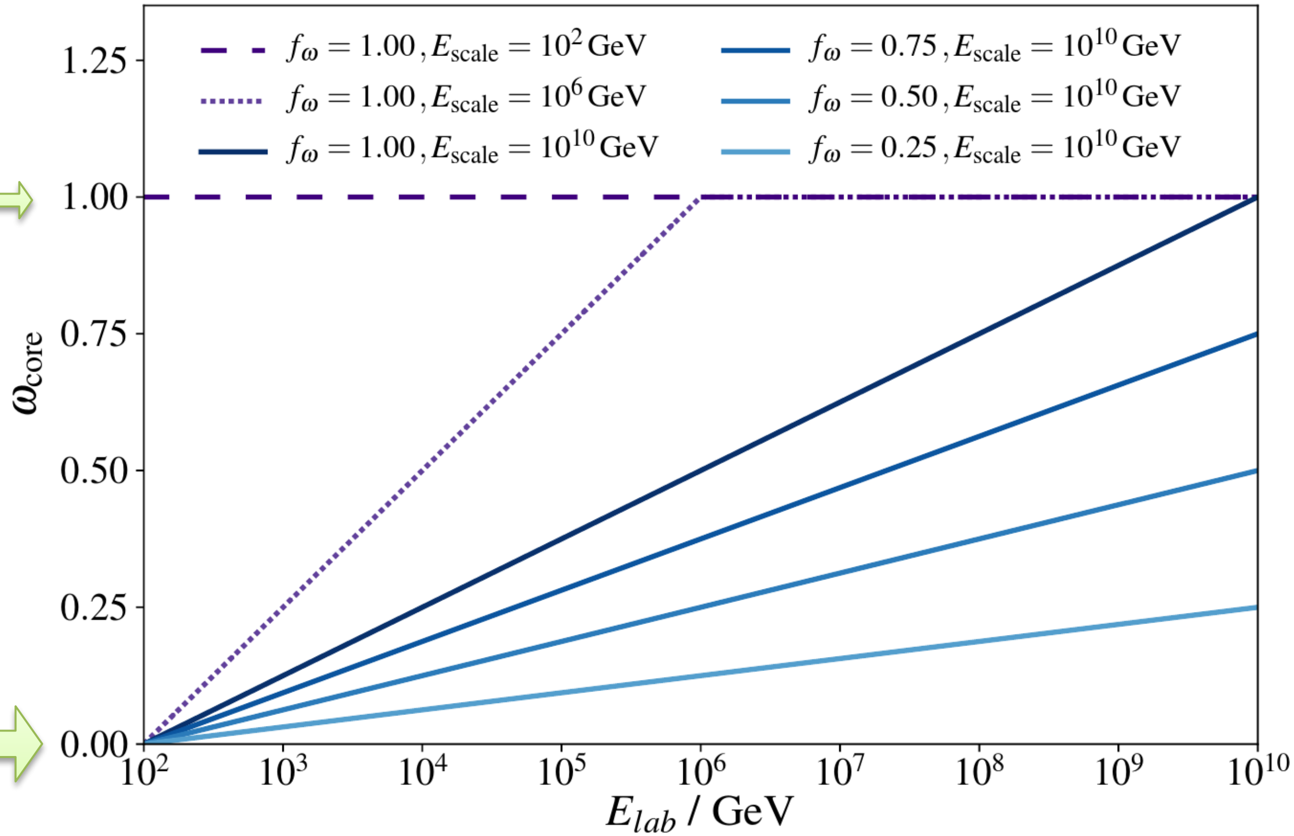
$$\omega_{\rm core}(E_{\rm lab}) = f_\omega\, \underbrace{F(E_{\rm lab}; E_{\rm th}, E_{\rm scale})}_{\frac{\log_{10}(E_{\rm lab}/E_{\rm th})}{\log_{10}(E_{\rm scale}/E_{\rm th})} \text{ for } E_{\rm lab} > E_{\rm th}}$$

$$E_{\rm th} = 100\,{\rm GeV}$$

The particle ratios are modified from the corona to the core taking different values of f_ω and $E_{\rm scale}$

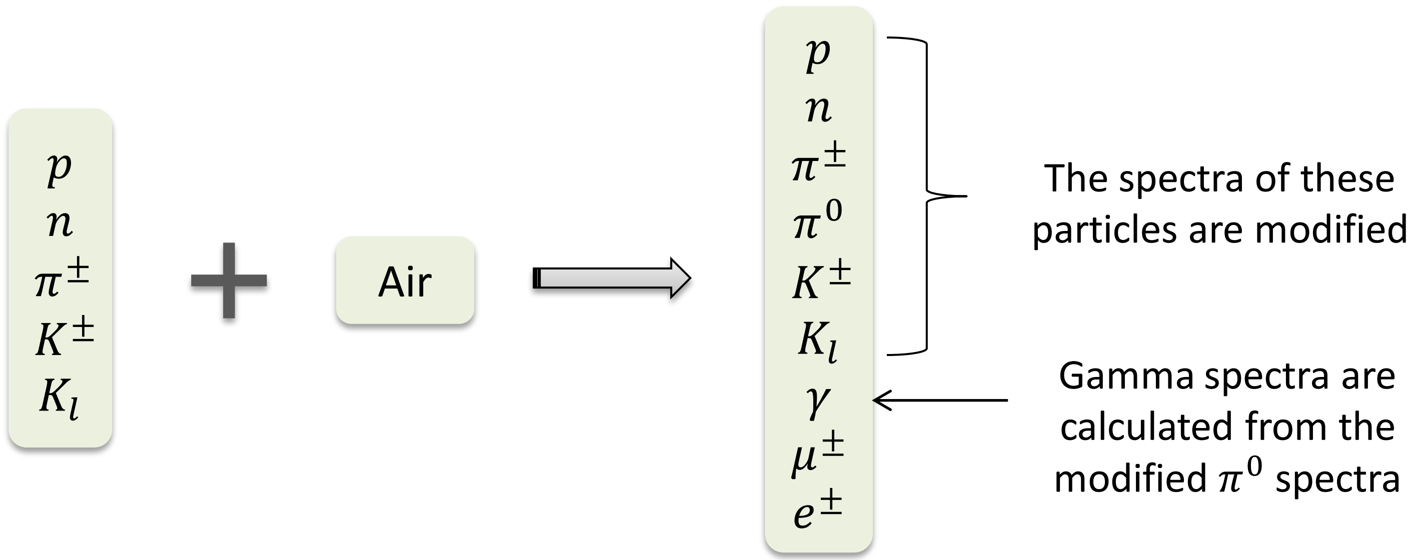
Core ratio

Corona ratio (Unmodified Model)



Energy spectra in CONEX

In order to get the particle ratios given by $\omega_{\rm core}$, we modify the energy spectra used by CONEX in the cascade equation analysis, where just the following interactions are considered



The easiest way to get the particle ratios given by $\omega_{\rm core}$ is modifing the energy spectra by a scale factor.

But remnant contribution must not change and total energy must be conserved.

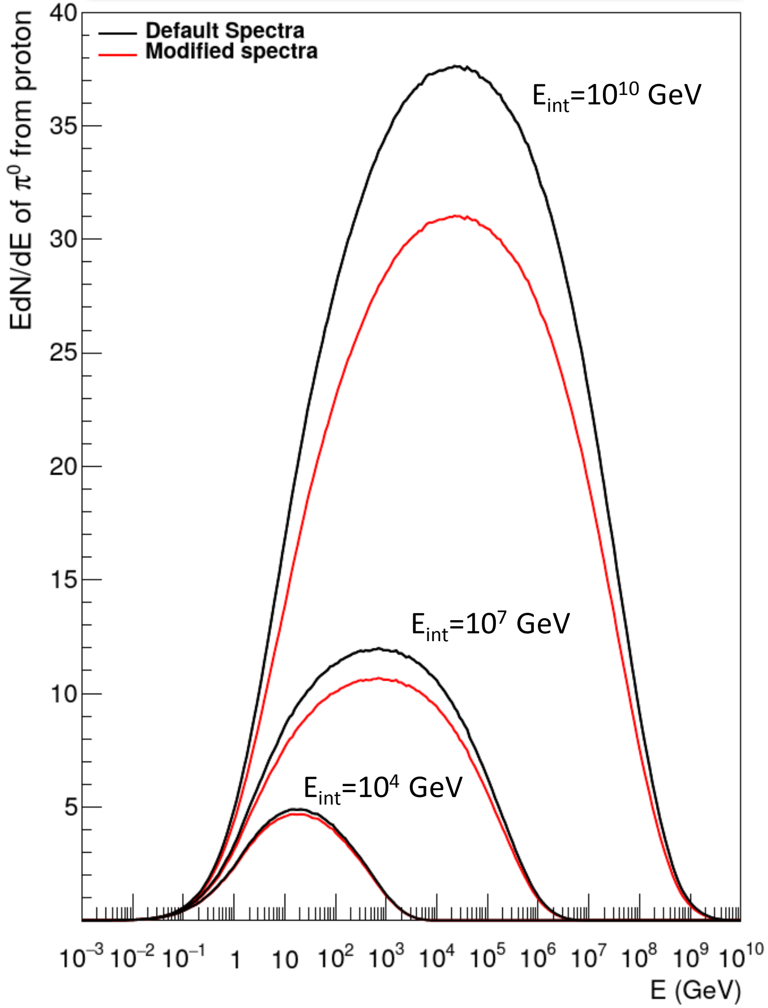
Hence, the spectra of all particles, except the spectra with remnant contribution, are modified by a scale factor. And in the last step, the spectra with remnant contribution change because of energy conservation.

Energy spectra in CONEX

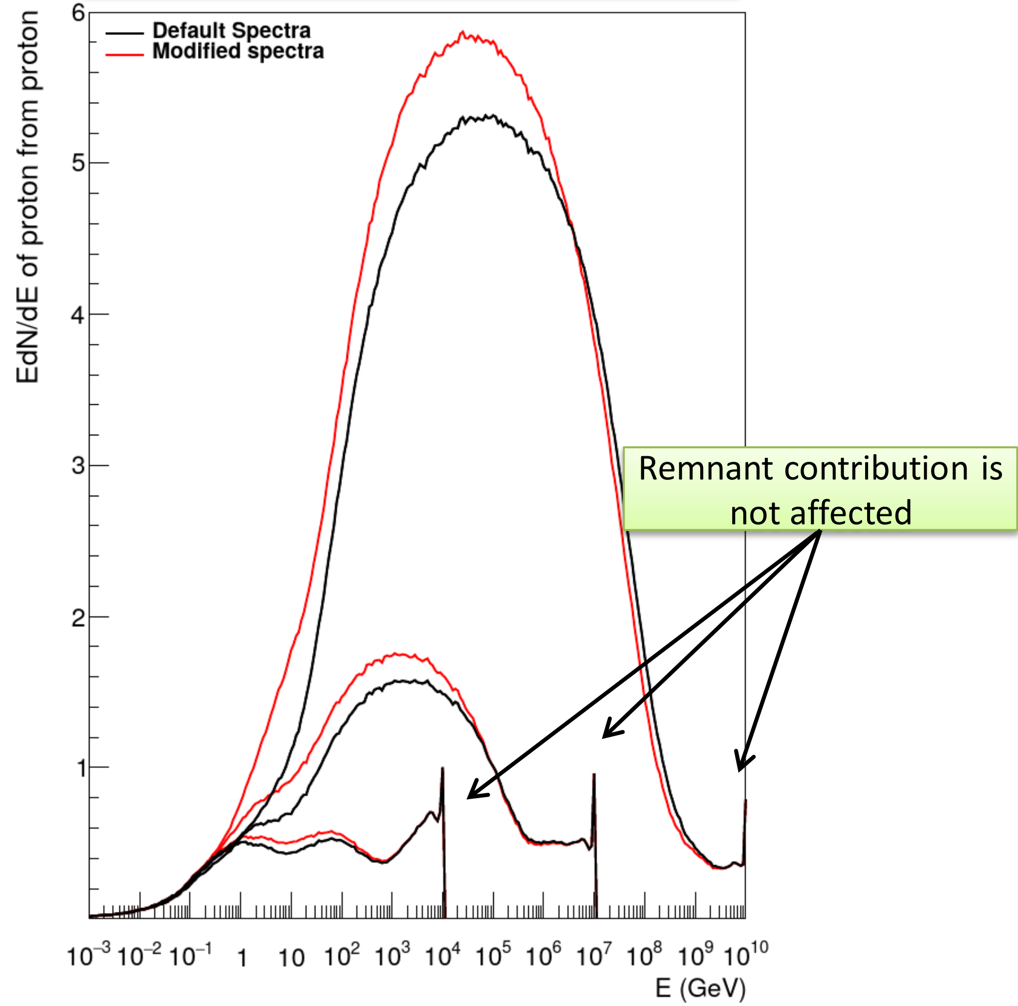
Let's see how the spectra change in proton-air interaction for the case

$$f_\omega = 1.00$$
$$E_{\mathrm{scale}} = 10^{10}\,\mathrm{GeV}$$

Spectra modified by a scale function



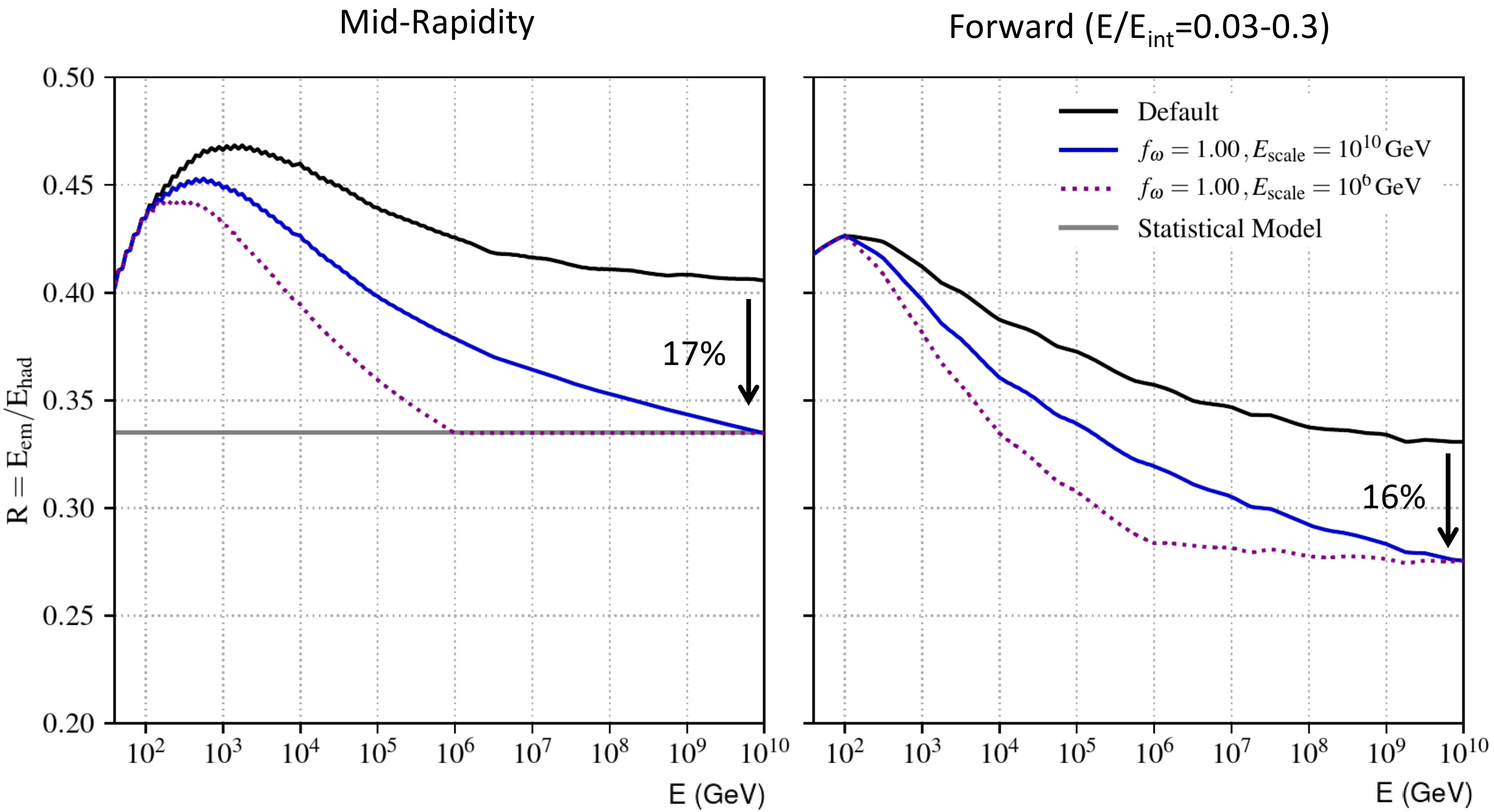
Spectra modified by E conservation



Spectra of neutral pions and protons in p + air interaction at three different proton energies

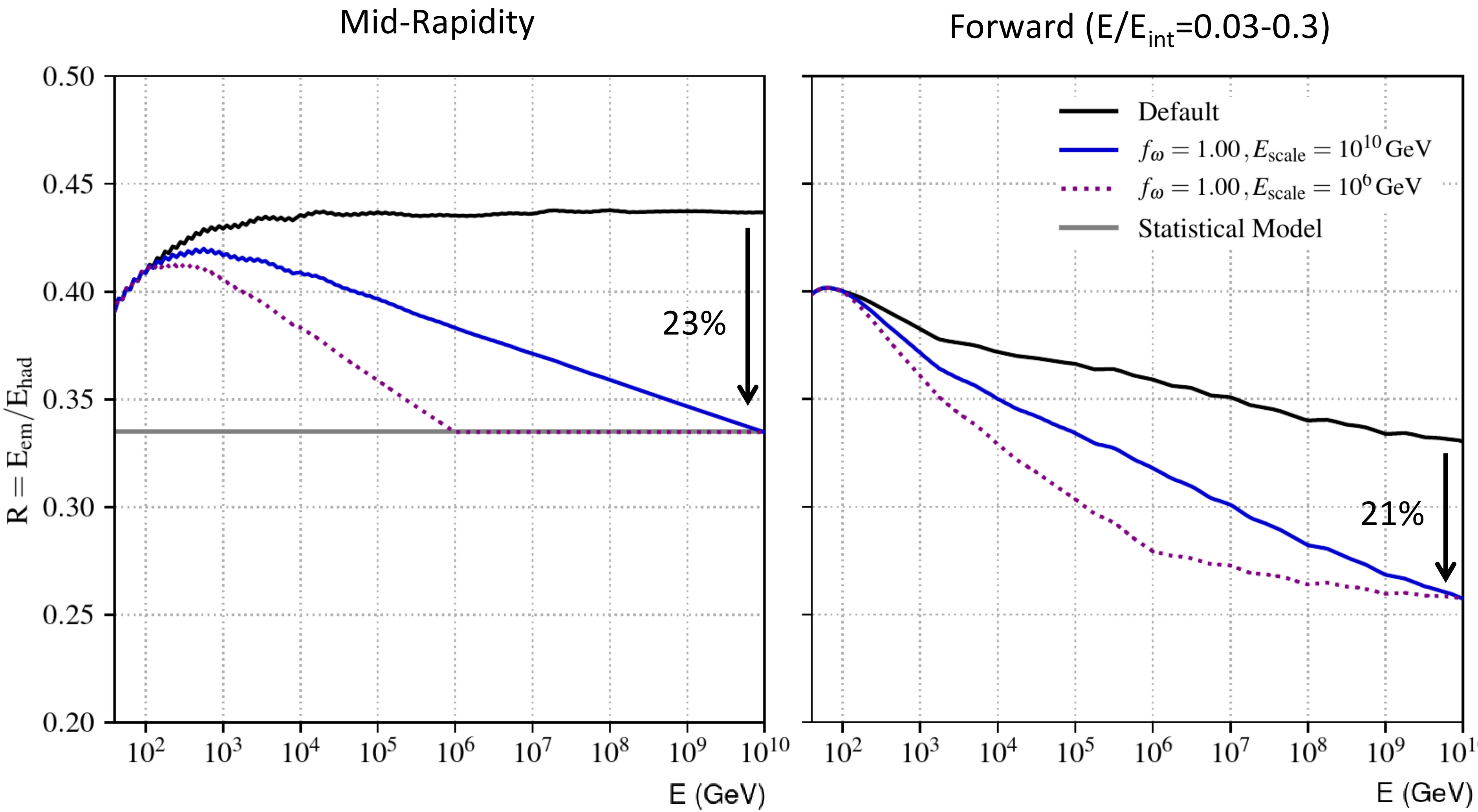
Ratio R

EPOS-LHC



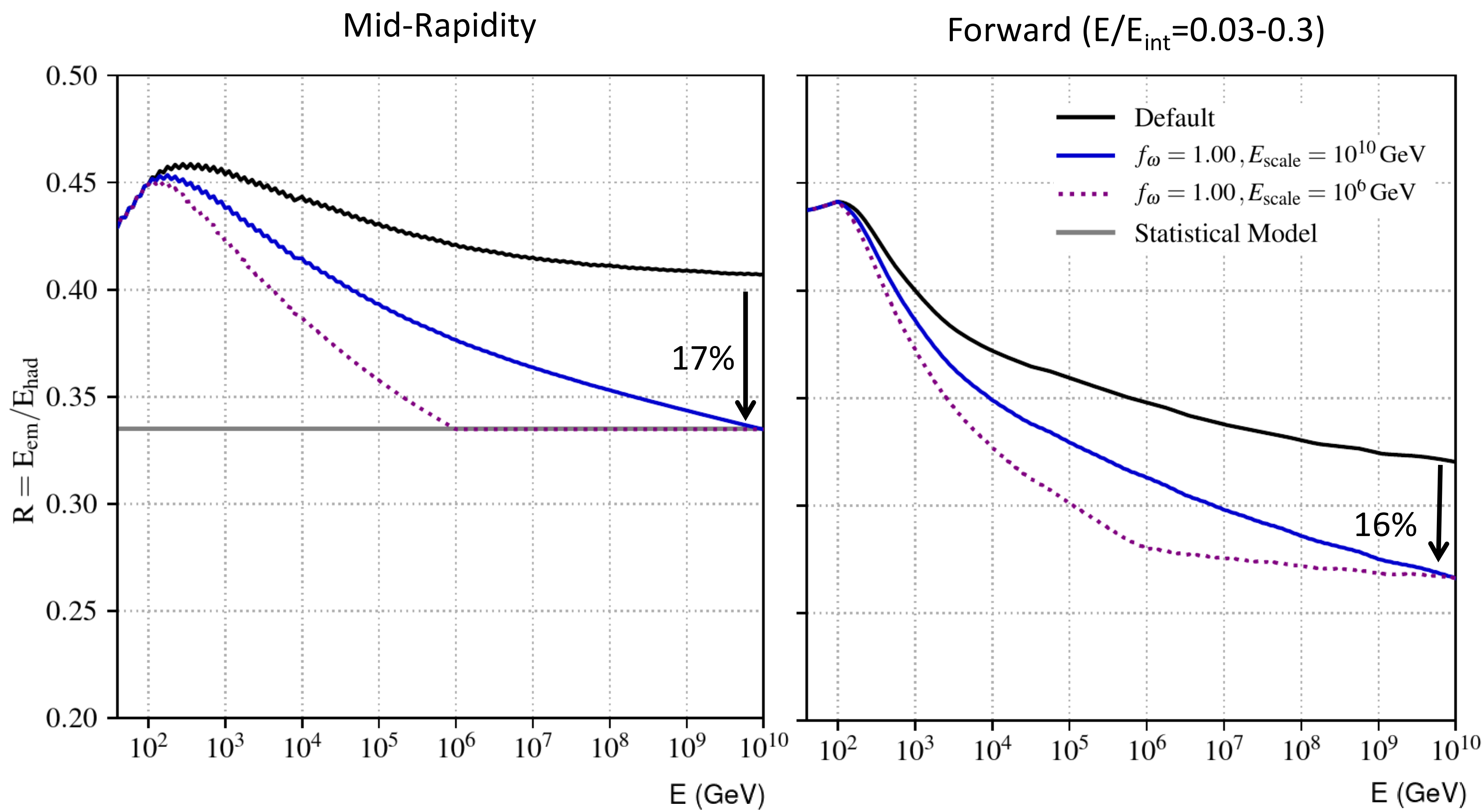
Ratio R

QGSJet-II.04

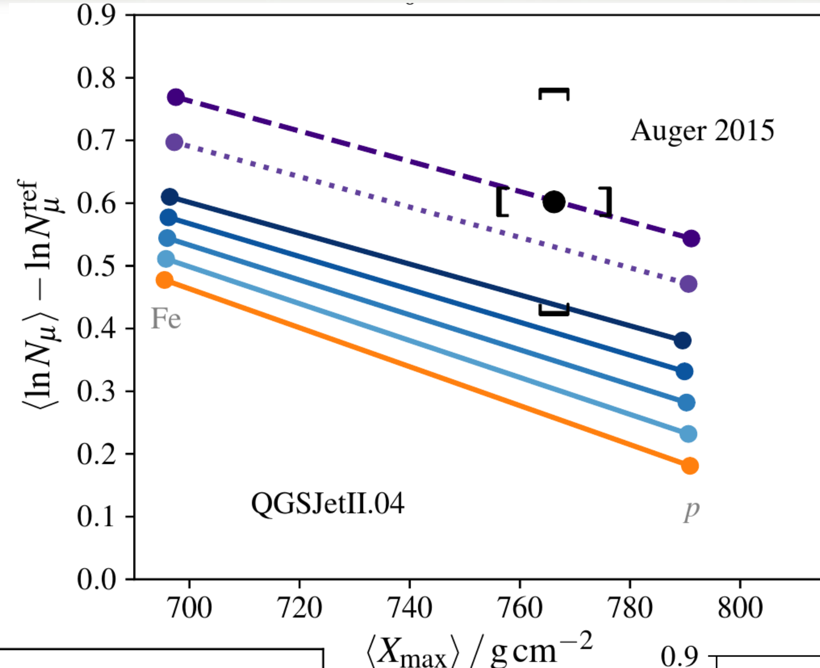


Ratio R

SIBYLL 2.3d



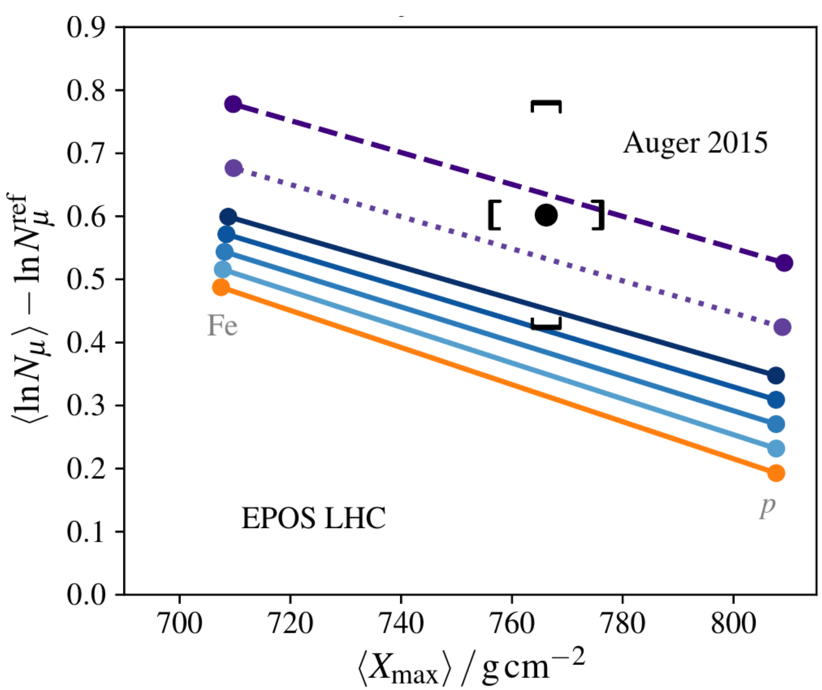
Number of muons vs X_{max}

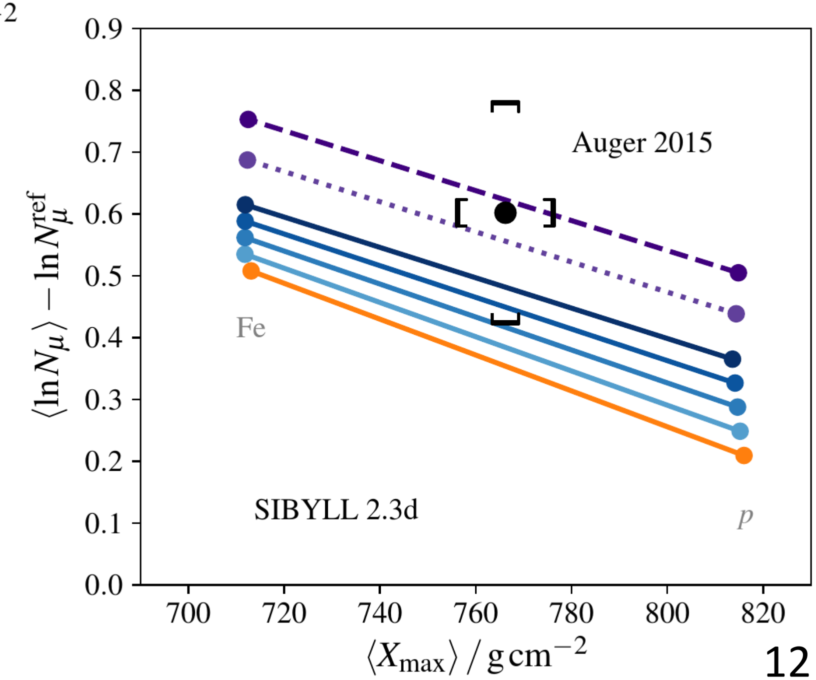


Full cascade equation showers

$E = 10^{19}$ eV

- $f_\omega = 1.00\,, E_{scale} = 10^2$ GeV
- $f_\omega = 1.00\,, E_{scale} = 10^6$ GeV
- $f_\omega = 1.00\,, E_{scale} = 10^{10}$ GeV
- $f_\omega = 0.75\,, E_{scale} = 10^{10}$ GeV
- $f_\omega = 0.50\,, E_{scale} = 10^{10}$ GeV
- $f_\omega = 0.25\,, E_{scale} = 10^{10}$ GeV
- $f_\omega = 0$ (Default model)

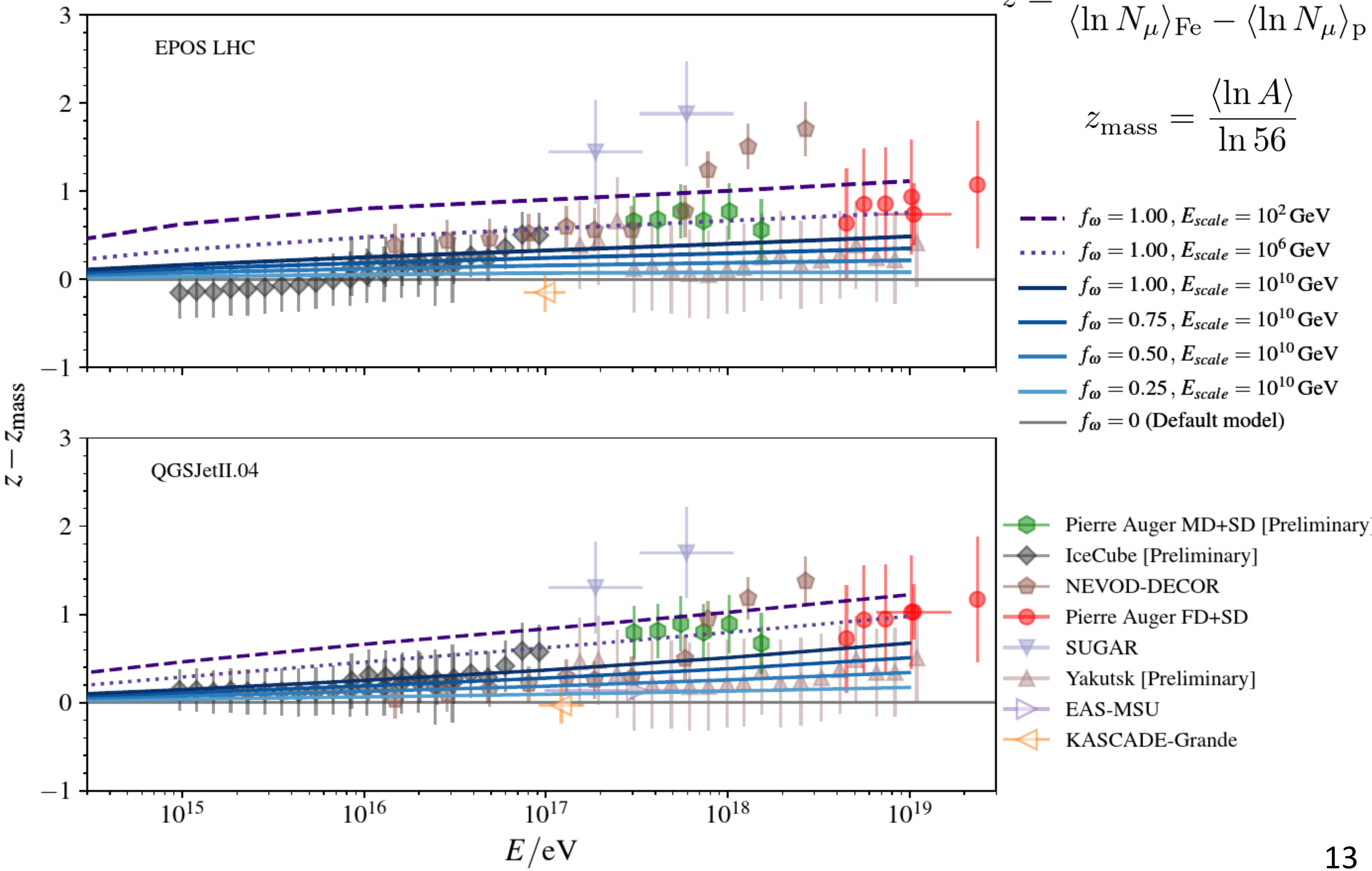




Z factor

$$z = \frac{\langle \ln N_\mu \rangle - \langle \ln N_\mu \rangle_p}{\langle \ln N_\mu \rangle_{Fe} - \langle \ln N_\mu \rangle_p}$$

$$z_{mass} = \frac{\langle \ln A \rangle}{\ln 56}$$



Summary

- We have shown that the muon production significantly depends on the ratio $R = E_{em} / E_{had}$, which depends on the hadronization mechanism.

- A core-corona approach has been implemented successfully in CONEX for cascade equation analysis.

- The core was modeled through realistic values from the statistical hadronization increasing the changes logarithmically with energy.

- Conservative core-corona scenarios can reproduce the muon measurements for most experiments.

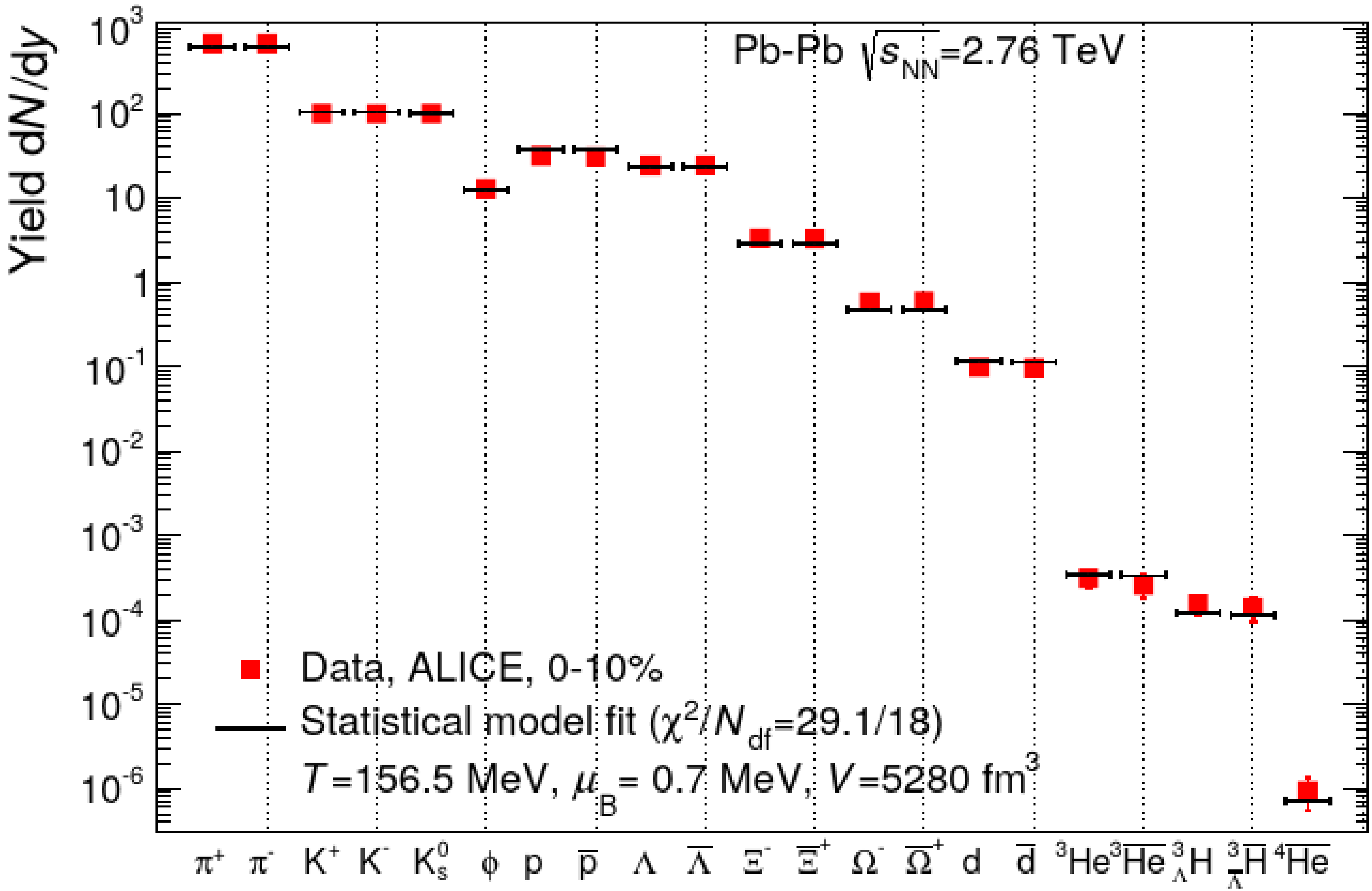
Thanks for
your attention

BACK-UP SLIDES

Statistical Hadronization Model (SHM)

Hadron yields, the chemical freeze-out and the QCD phase diagram

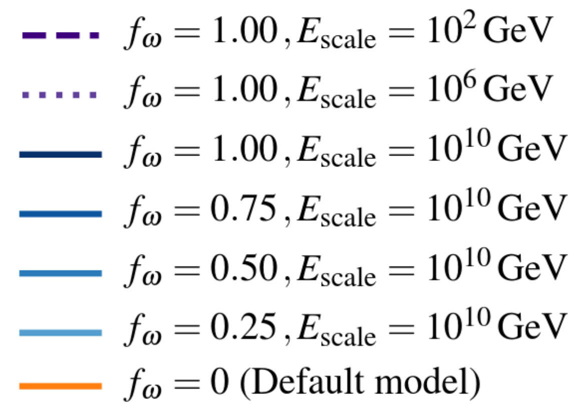
To cite this article: A Andronic *et al* 2017 *J. Phys.: Conf. Ser.* **779** 012012

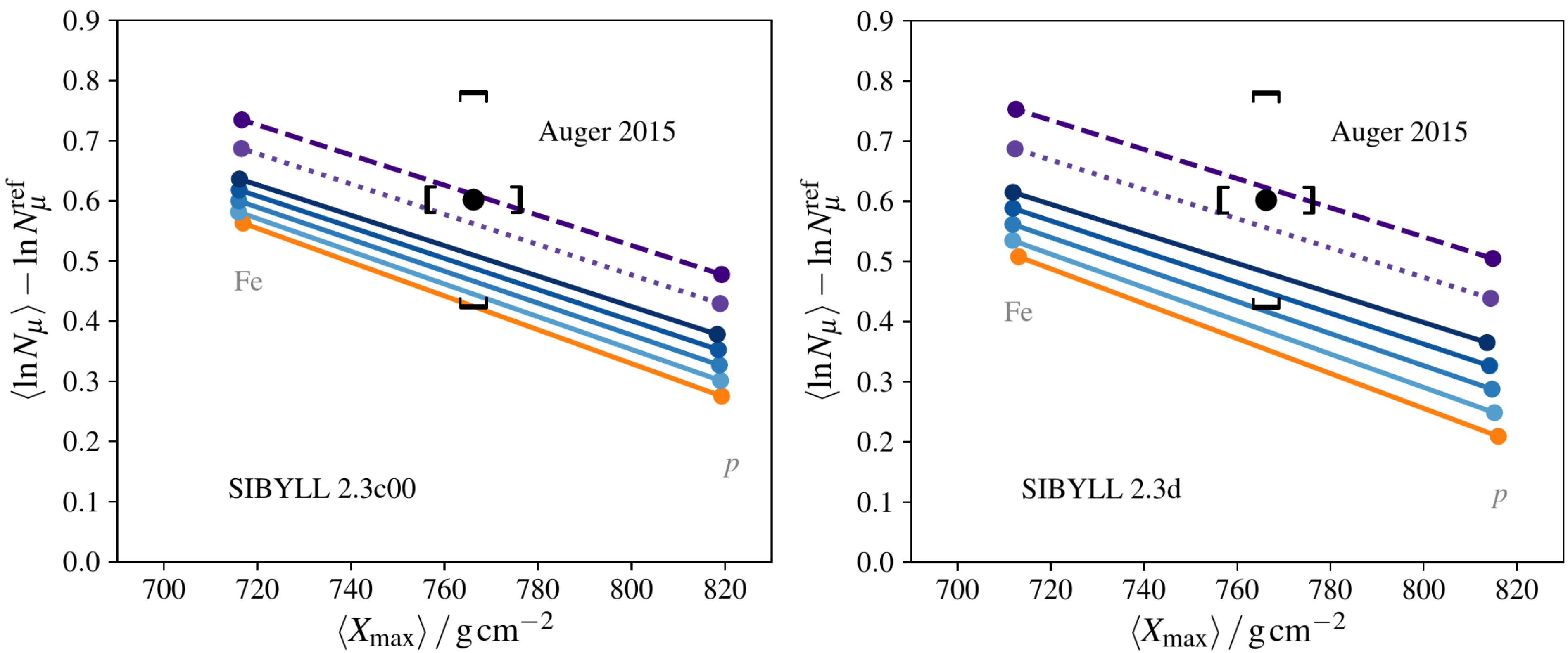


Number of muons vs X_{max}

Full cascade equation showers

$E = 10^{19}$ eV





Gamma spectra from π^0 spectra

If neutral pion spectra are modified it is necessary calculate the new gamma spectra

$\pi^0 \longrightarrow \gamma\gamma$ is isotropic in the rest frame, so $$\frac{dN}{d\cos\theta^*} = \frac{1}{2}$$

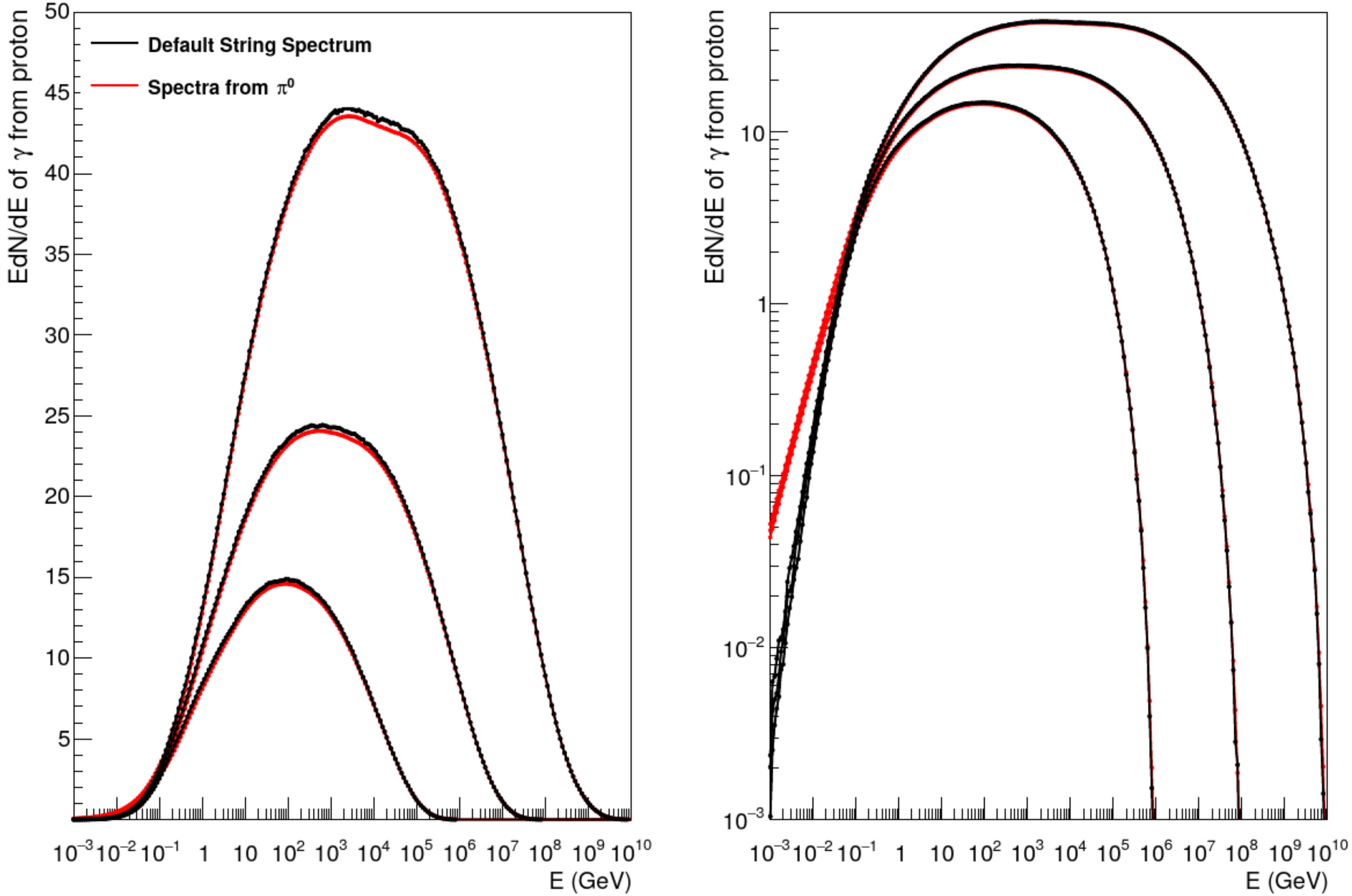
The energy distribution of gammas from neutral pions with momentum *p* is

$$\frac{dN}{dE_\gamma} = \frac{2}{p_\pi}$$

So the number of gammas is

$$N_\gamma(E_\gamma) = \int_{E_\gamma}^{\infty} \frac{2}{p_\pi} dp_\pi \approx \sum_{j=i}^{j_{max}} \frac{2}{E_j} \Delta E_i \, N_\pi(E_j)$$

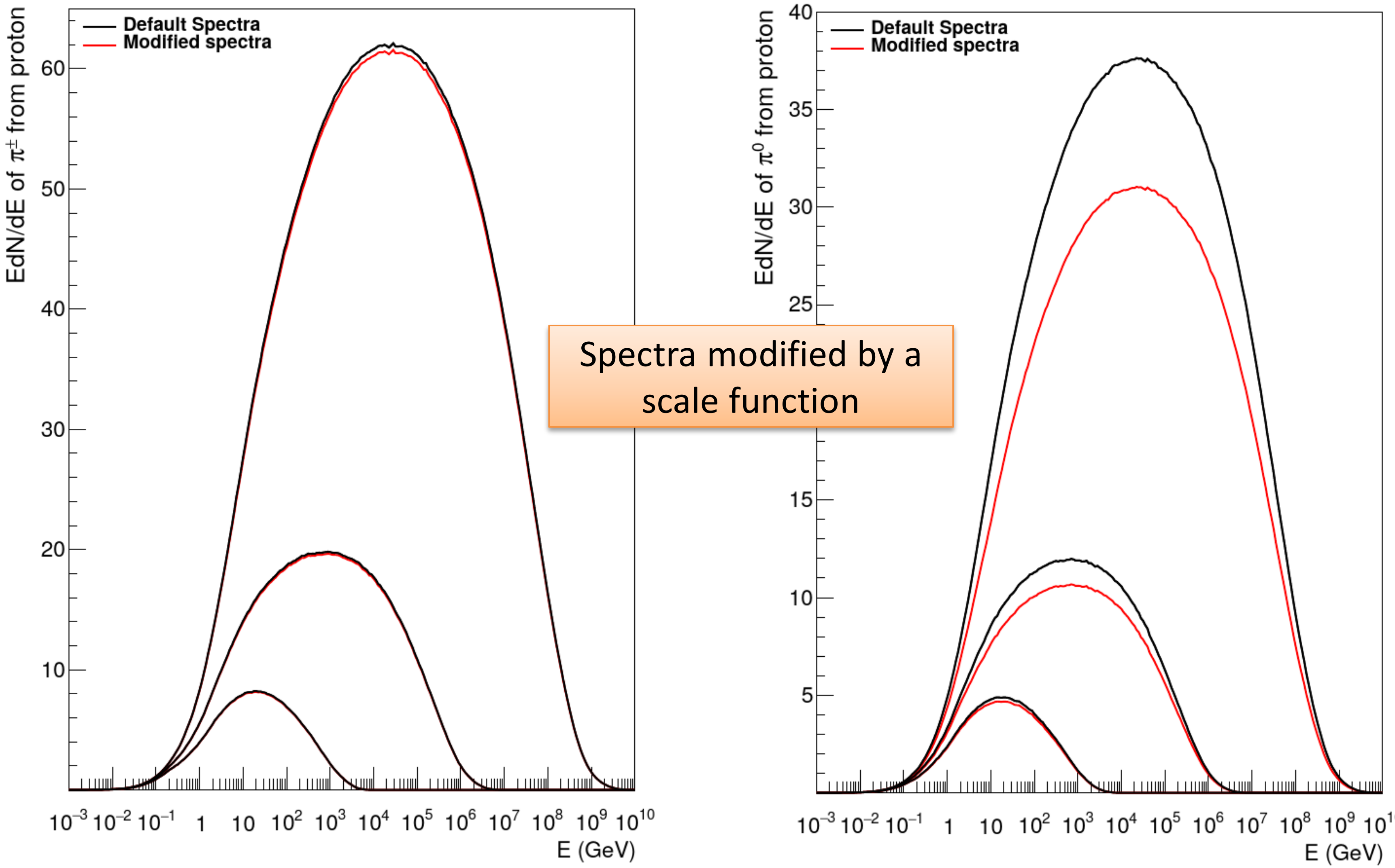
Gamma spectra from π^0 spectra



Energy spectra

Let's see how the spectra change in proton-air interaction for the case

$$f_\omega = 1.00$$
$$E_{\rm scale} = 10^{10}\,{\rm GeV}$$

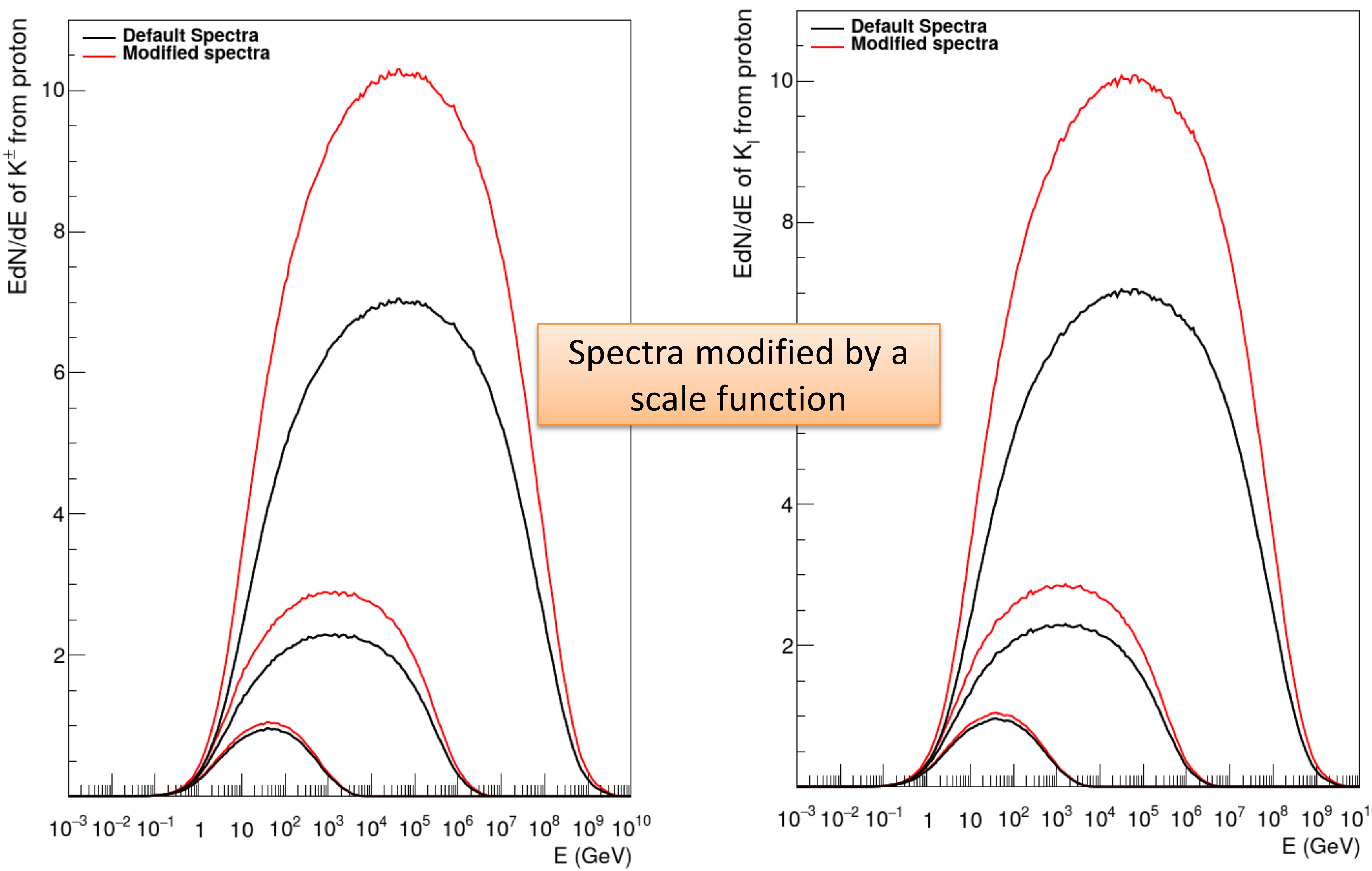


Spectra of pions in p + air interaction at three different proton energies

Energy spectra

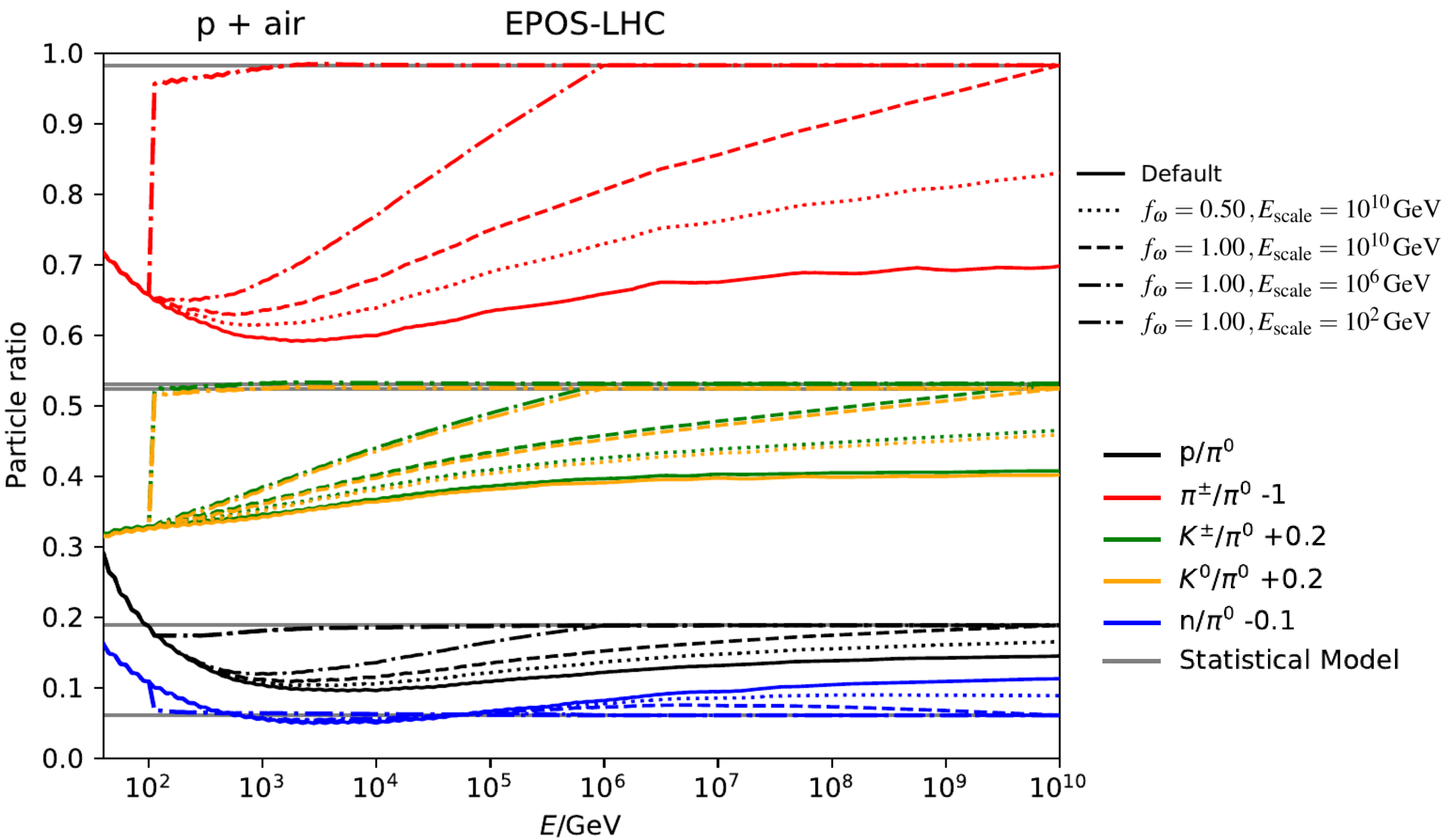
Let's see how the spectra change in proton-air interaction for the case

$$f_\omega = 1.00$$
$$E_{\text{scale}} = 10^{10}\,\text{GeV}$$

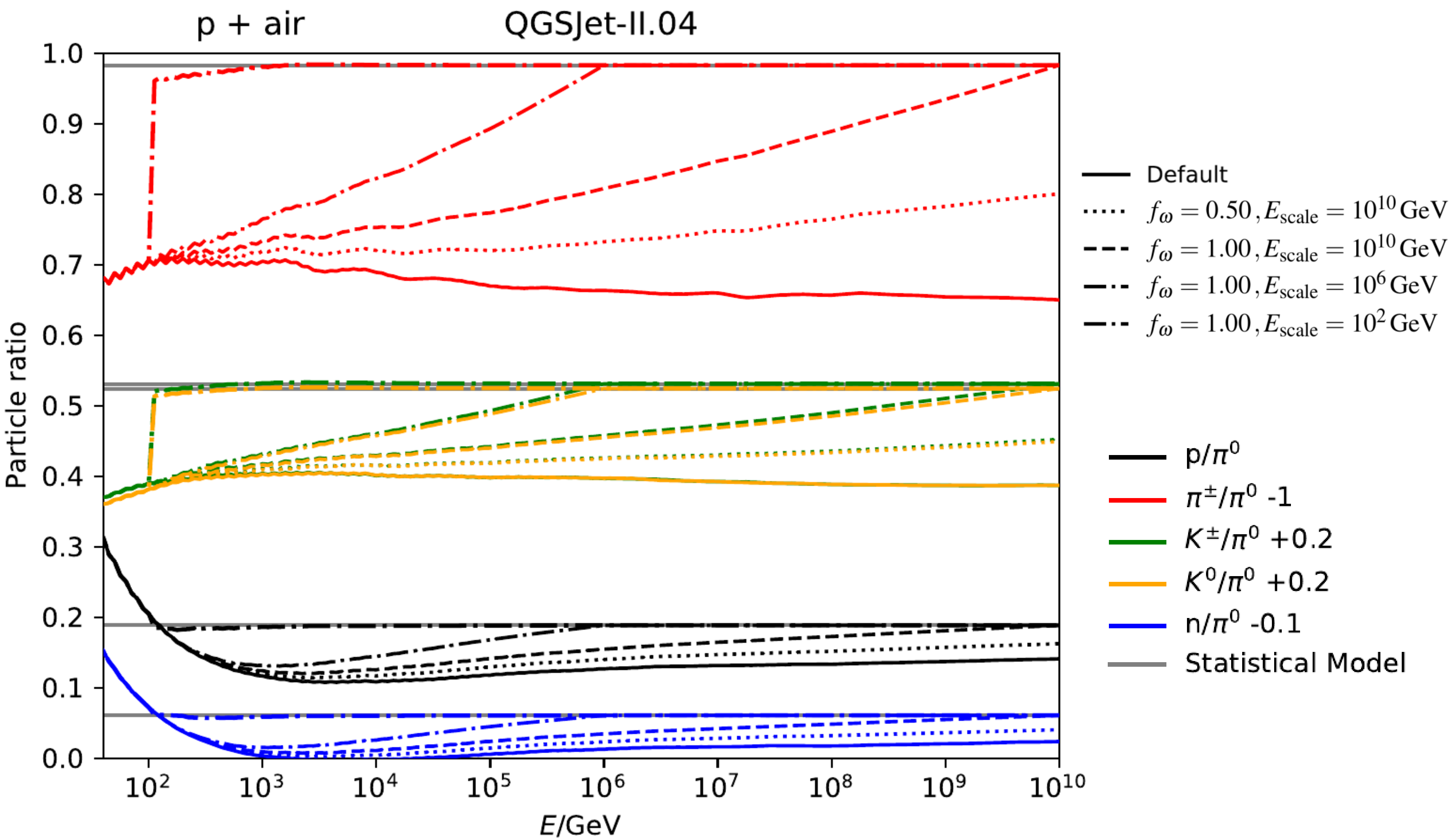


Spectra of kaons in $p +$ air interaction at three different proton energies

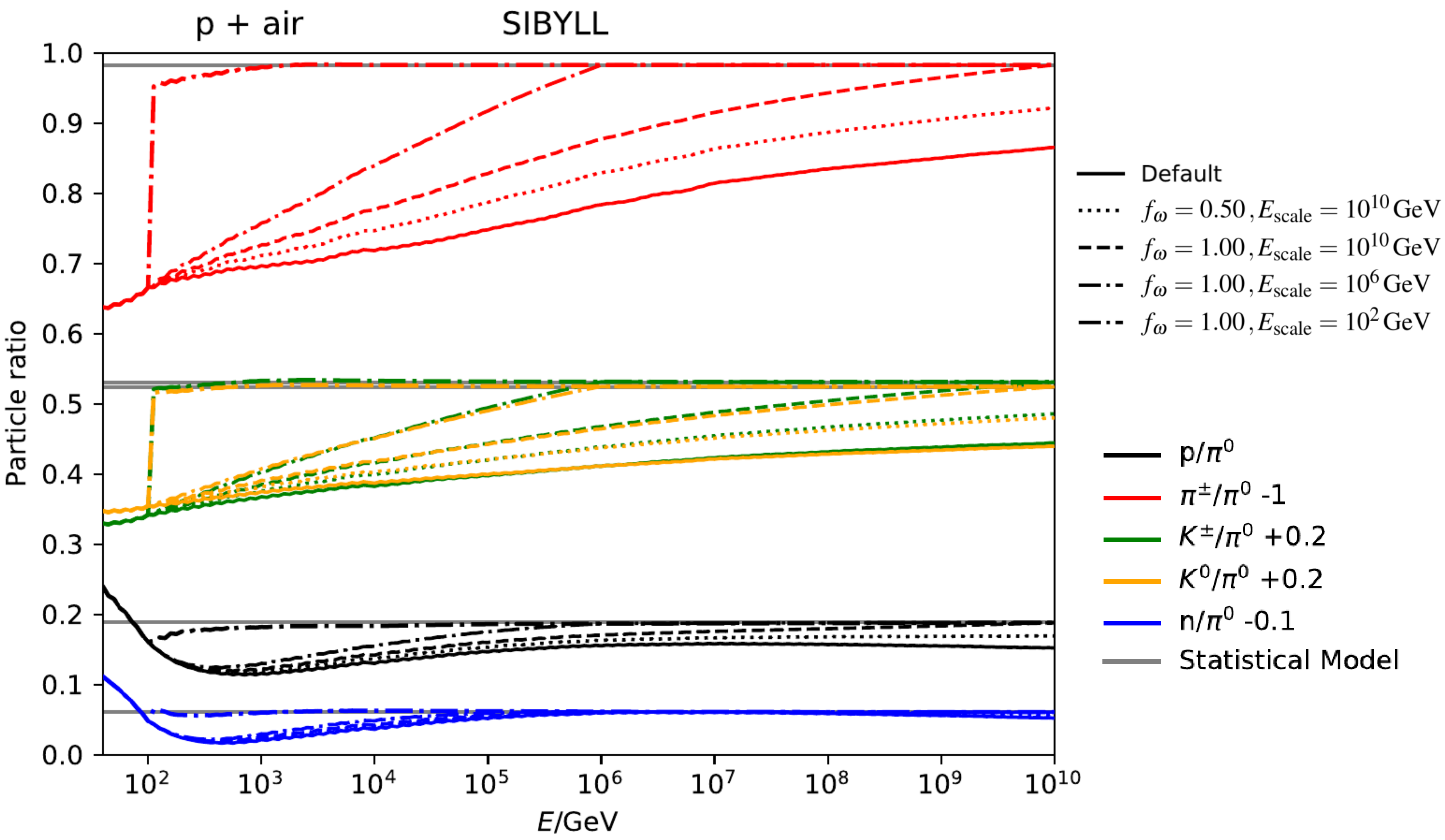
Particle ratio at mid rapidity



Particle ratio at mid rapidity

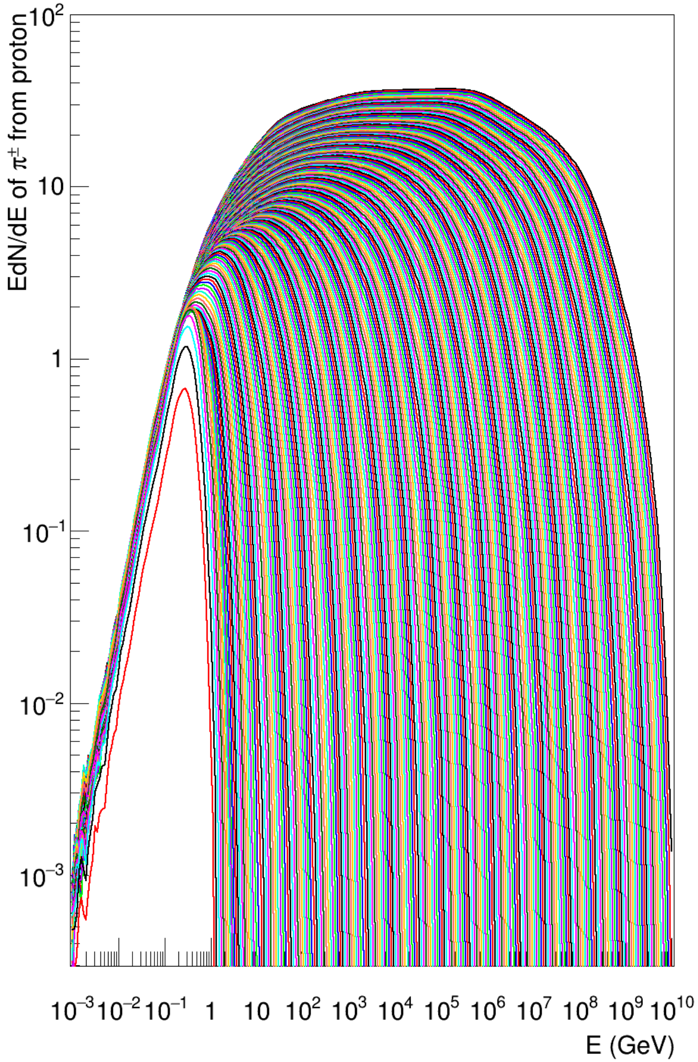


Particle ratio at mid rapidity

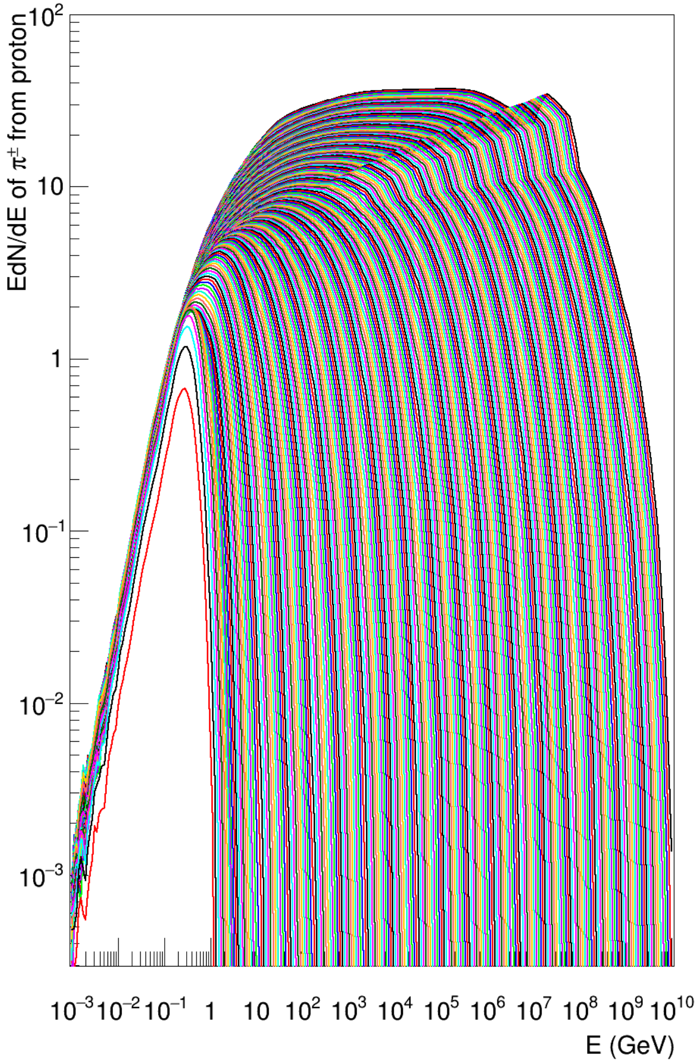


Energy spectra

Spectra of $\pi^{\pm}$ in p+air interaction for all proton energies



Spectra shape change linearly with logE.

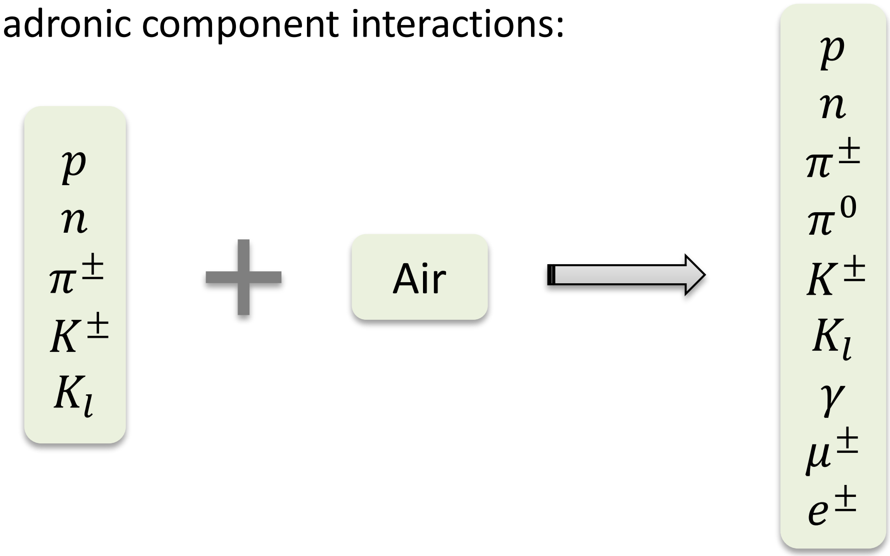


CONEX

CONEX program

Describe average EAS development numerically based on cascade equations.

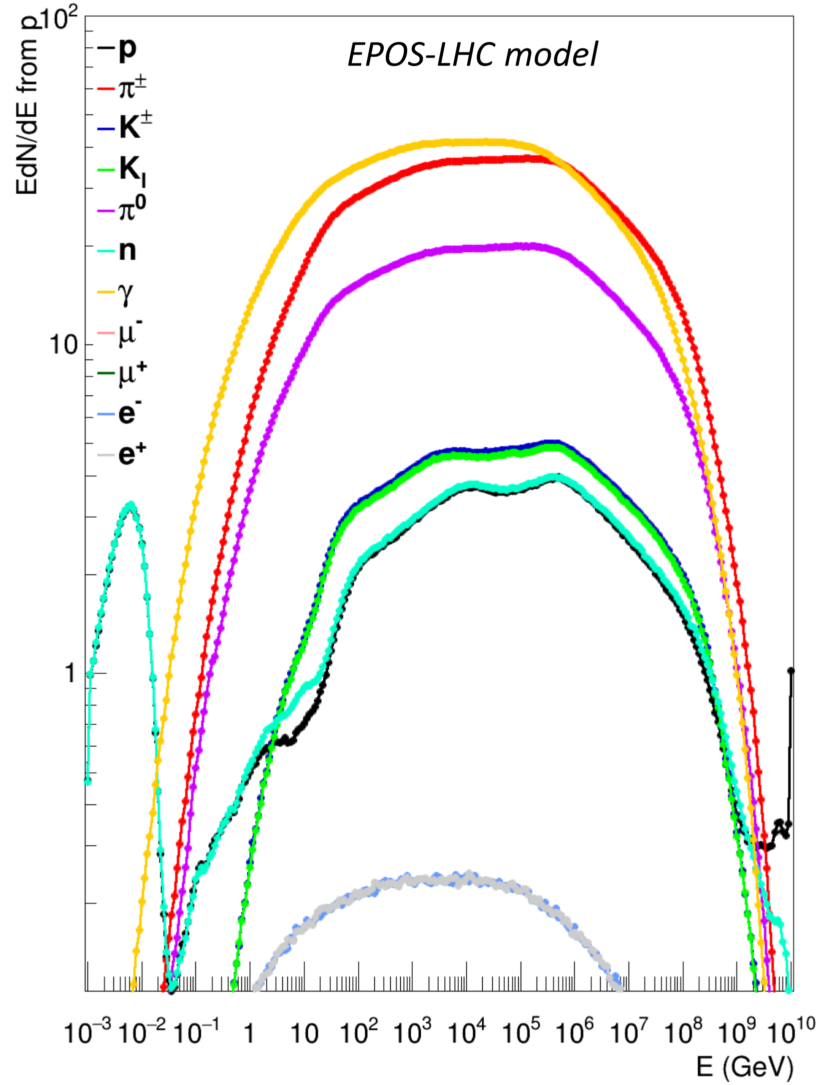
Hadronic component interactions:



All other types of hadrons produced are assumed to decay immediately

Each hadronic model is used to pre-calculate secondary particle spectra for later use it in the hadronic CE

Spectra of secondary particles in p + air interaction at 10^{19} eV



Statistical Hadronization Model (SHM)

It is mainly applied to heavy ion collision.
This model has given strikingly good results in elementary collisions as well.

The physical picture of a high energy collision is:
Underlying non-perturbative strong-interaction dynamics eventually giving rise to the formation of colourless extended massive objects → Clusters or fireballs

Clusters decay coherently into multihadronic states in a purely statistical fashion
Hadronization occurs at some critical energy density of a number of clusters.

The single cluster's decay rate into any channel would be determined only by its phase space with no special dynamical weight → Phase space dominance

SHM lies in two assumptions

- In the late stage of a high energy collision, clusters are produced which decay into hadrons at a critical value of energy density or some other relevant parameter
- All multihadronic states within the cluster compatible with its quantum numbers are equally likely