# Charm and muons in extensive air showers

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1. EASs, atmospheric leptons and *forward* charm
2. Muons in (proton, iron, photon) EASs
3. Muon energy depositions in the air

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• Cosmic rays of energy up to $10^{11}$ GeV enter the atmosphere and produce extensive air showers (EASs), with millions of hadronic collisions and decays. We can see the longitudinal development of the shower (fluorescence detectors) and the particles reaching the ground (surface detectors). The atmosphere is equivalent to 10 m of water (1000 g/cm$^2$) if crossed vertically, twice thicker from $\theta_z = 60^\circ$ and 36 times thicker from the horizon

• The spectrum of the CR flux is very steep ($\propto E^{-2.7}$). The primary flux is dominated by protons and He nuclei up to the CR knee at $\approx 10^{6.5}$ GeV (where the spectral index changes to $-3$). The atmospheric flux of secondary hadrons ($\lambda^{\rm dec} > \lambda^{\rm int}$: $\pi^\pm$ and kaons of $E > 50$ GeV) will inherit the primary spectral index

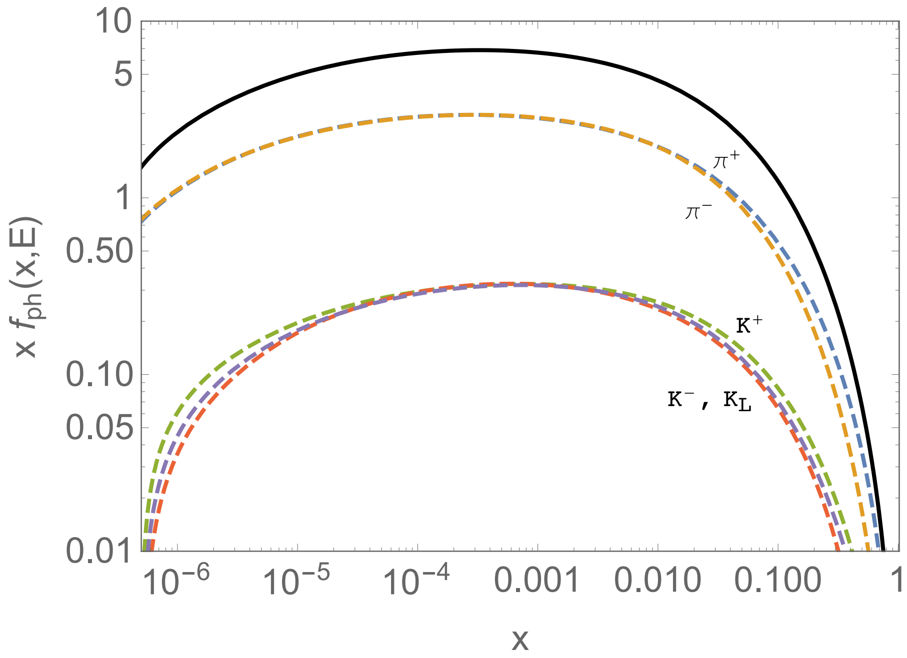



Figure: Yields in $p$–air collisions at $10^6$ GeV ($x = E_h/E$): 52.9 charged pions, 7.9 kaons (EPOS-LHC)

• The decay of charged pions and kaons gives muons and neutrinos

$$\pi^+ \to \mu^+ \nu_\mu \qquad K^+ \to \mu^+ \nu_\mu \qquad K_L \to \pi^- \mu^+ \nu_\mu$$

whereas neutral pions and eta mesons feed the EM component of the EAS

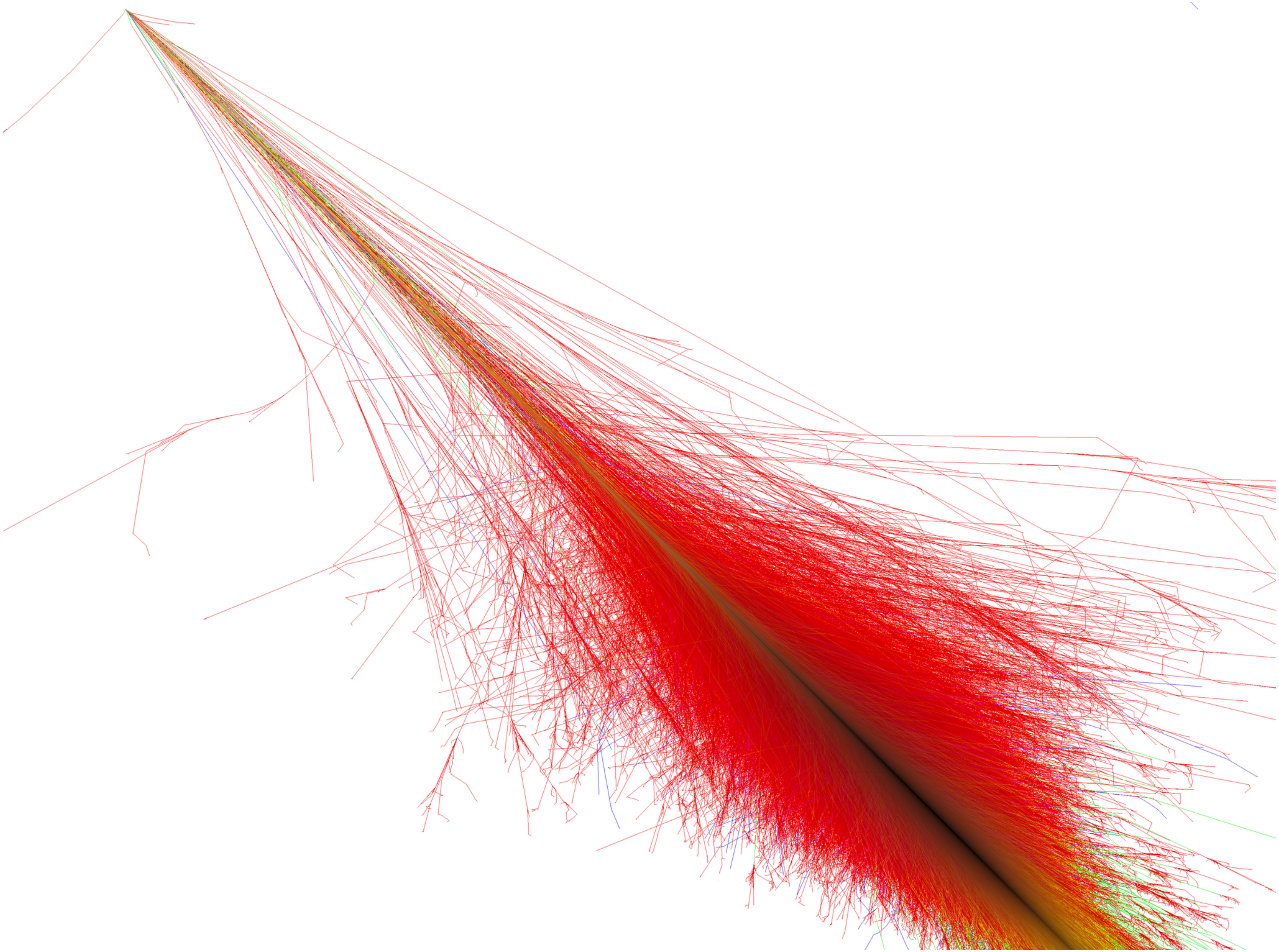
$$\pi^0, \eta \to \gamma\gamma \qquad \gamma Z \to e^+ e^- Z \qquad e Z \to e \gamma Z$$

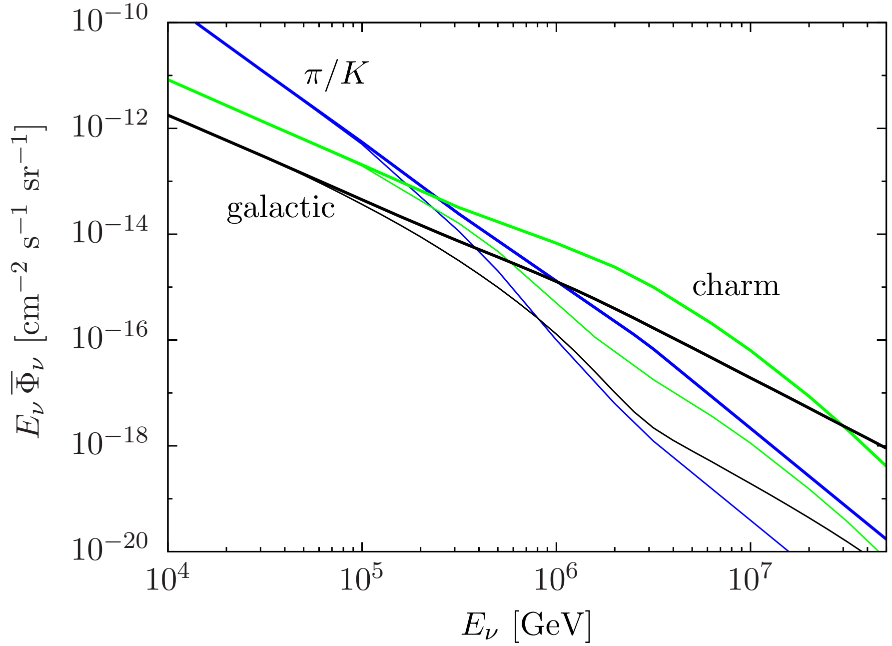
• At $E > 50$ GeV charged pions and kaons tend to collide in the air before they decay: the high-energy lepton flux is very suppressed

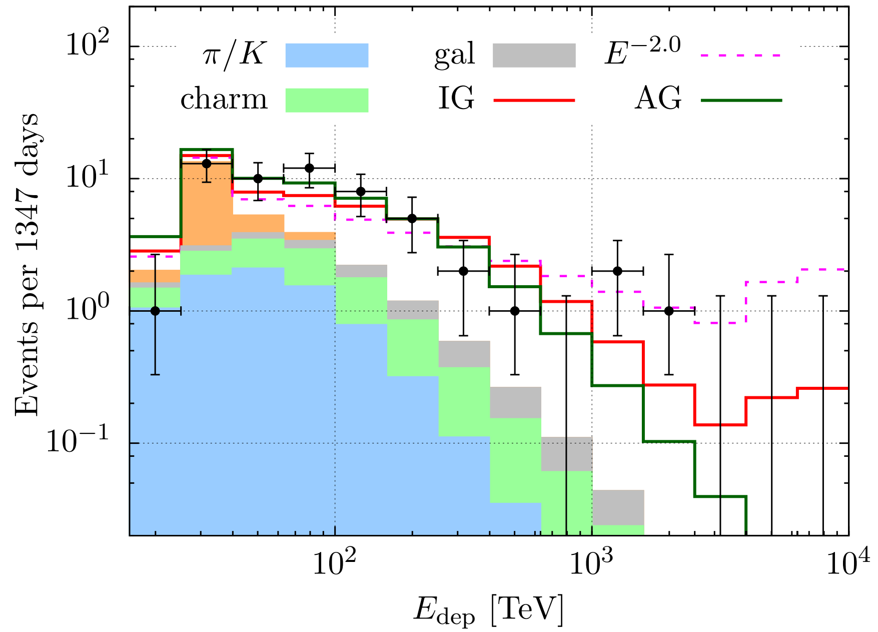
$$\Phi_{\nu,\mu}: \qquad E^{-2.7} \to E^{-3.7}$$

• While neutral pions always give gammas, charged pions tend to collide giving more pions (including $\pi^0$) of lower energy. Most of the energy in the EAS is processed through electrons and photons instead of muons and neutrinos

• High energy muons and neutrinos produced in the EAS reach the ground, photons and electrons double their number each radiation length and define $X_{\max}$. The dispersion $\Delta X_{\max}$ is mostly due to the inelasticity in the first hadronic collisions.






• The $\nu$ flux from the prompt decay of atmospheric charm at $E \geq 10^5$ GeV has not been identified at IceCube, that has found a diffuse flux of unknown origin

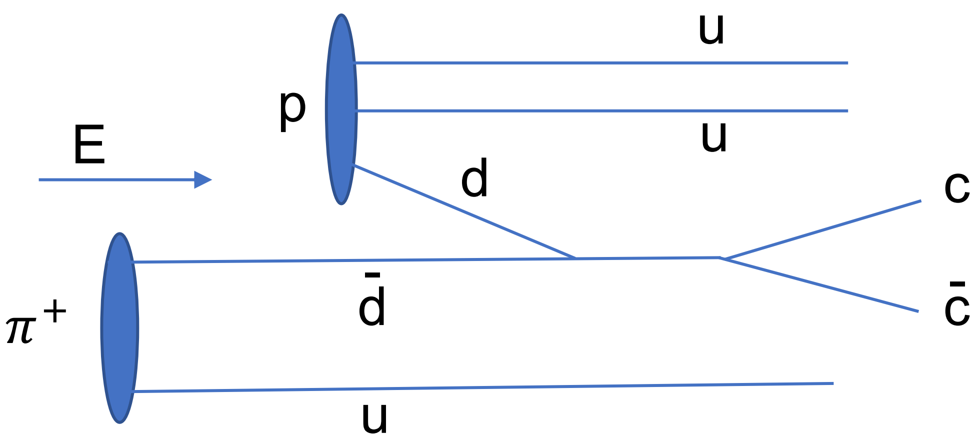
• Why is $\Phi_\nu$ from charm important at high energies and why is it uncertain?

$D$ mesons decay before they interact in the air at $E \leq 10^6$ GeV $\rightarrow$ $\nu$ flux $\sim E^{-2.7}$

Key: fraction $x$ of the collision energy taken by the $D$ and its distribution, $Z_{hD}(1.7)$

h $E \rightarrow D\ xE \rightarrow \nu\ \frac{x}{2}E$: if $D\ x \rightarrow D\ x/3$ then $\Phi_\nu \rightarrow 3^{-1.7}\Phi_\nu = 0.15\ \Phi_\nu$

if $D\ x \rightarrow 3D\ x/3$ then $\Phi_\nu \rightarrow 3^{-0.7}\Phi_\nu = 0.45\ \Phi_\nu$



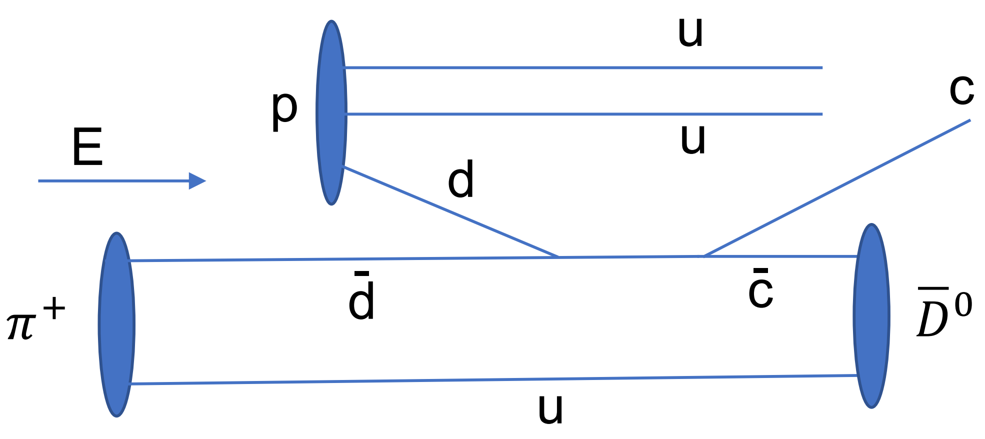

• The factorization theorem in perturbative QCD implies that the charm quarks hadronize through a jet fragmentation function that is independent of the initial state

$$c \to D^0(c\bar{u}) \;\approx\; c \to D^+(c\bar{d}) \qquad\qquad \bar{c} \to \bar{D}^0(\bar{c}u) \;\approx\; \bar{c} \to D^-(\bar{c}d)$$

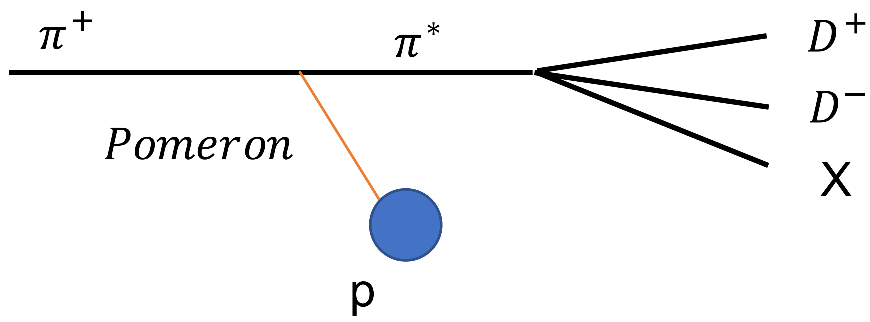
• However, E791 (500 GeV $\pi^+ A$ interactions with carbon and platinum targets) finds more $D^+$ and $\bar{D}^0$ than $D^0$ and $D^-$ in the large $x$ (ultraforward rapidity) region. These *leading* charm hadrons share a valence quark with the incident pion.

• In air shower calculations, small $x$ physics, collective effects or NLO corrections in the perturbative amplitude give a small contribution compared with the uncertainties introduced by the (forward, intrinsic, non-perturbative, leading) charm

- Not included in a perturbative calculation but implemented in MC simulators:



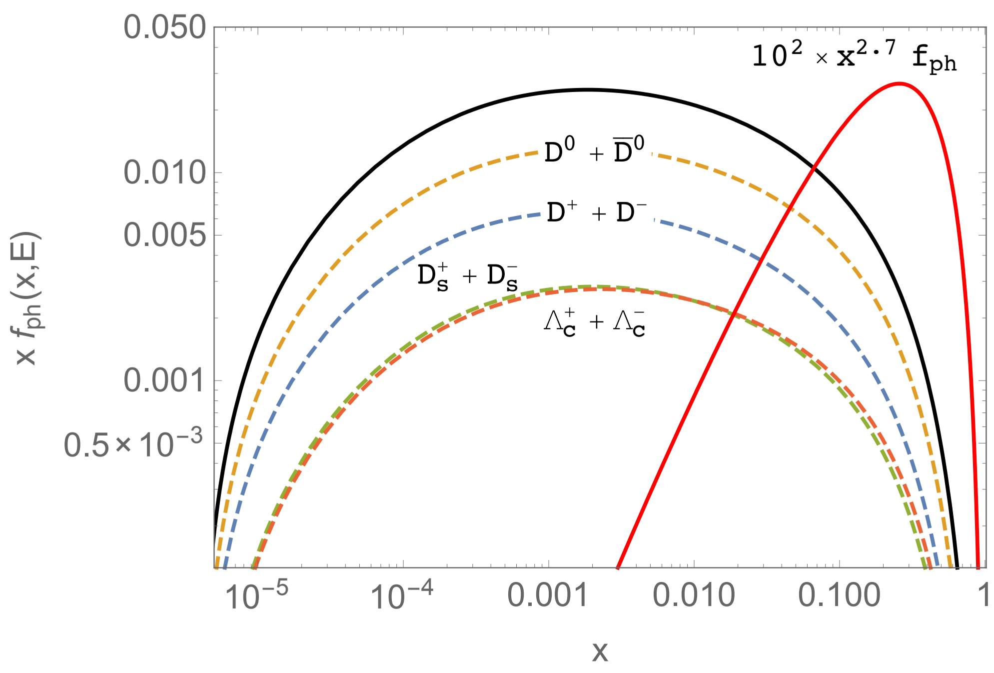

coalescence




Intrinsic charm

Yield of charmed hadrons in proton-air collisions at $10^6$ GeV

(with Sibyll 2.3C)

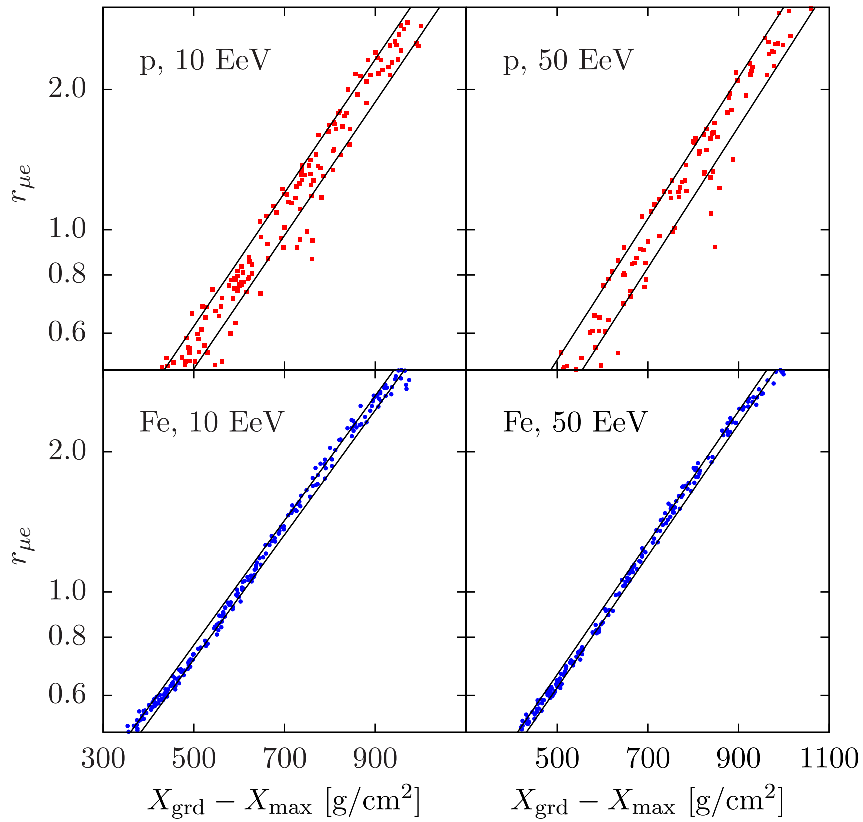


• Atmospheric neutrinos of $E \geq 10^5$ GeV are not the only observable that is sensitive to charm production: also muons; at $E \geq 1$ TeV they can reach a $\nu$ telescope; the slant depth they have crossed (zenith inclination) reveals their minimum energy

• In inclined extended air shower ($\theta_z \geq 60°$) they may experience a *catastrophic* energy deposition near the ground, when most of the shower energy has been absorbed by the atmosphere, introducing anomalies in the surface detectors

$$r_{\mu e} = \frac{\text{number of } \mu' s}{E_{EM}}$$

strongly correlated with the depth between the ground and $X_{\text{max}}$

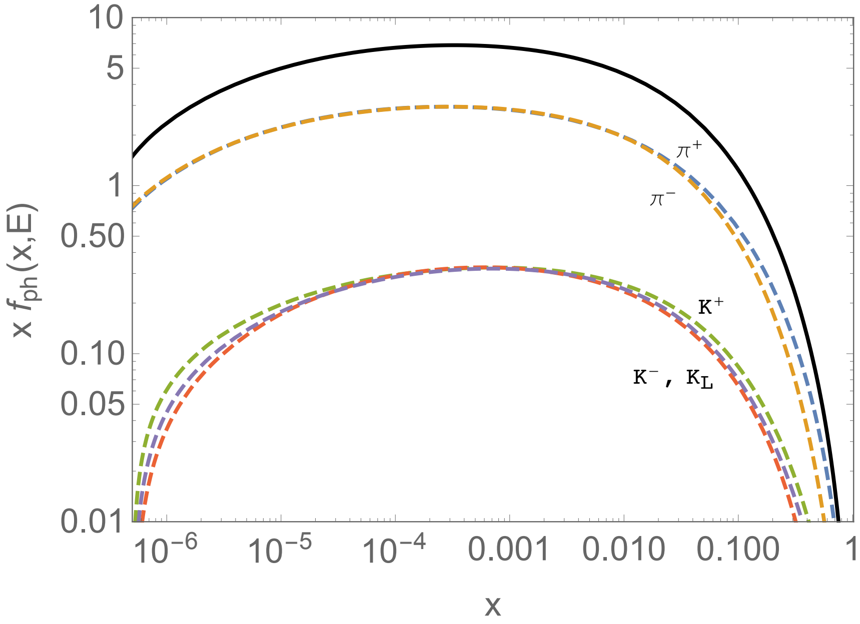


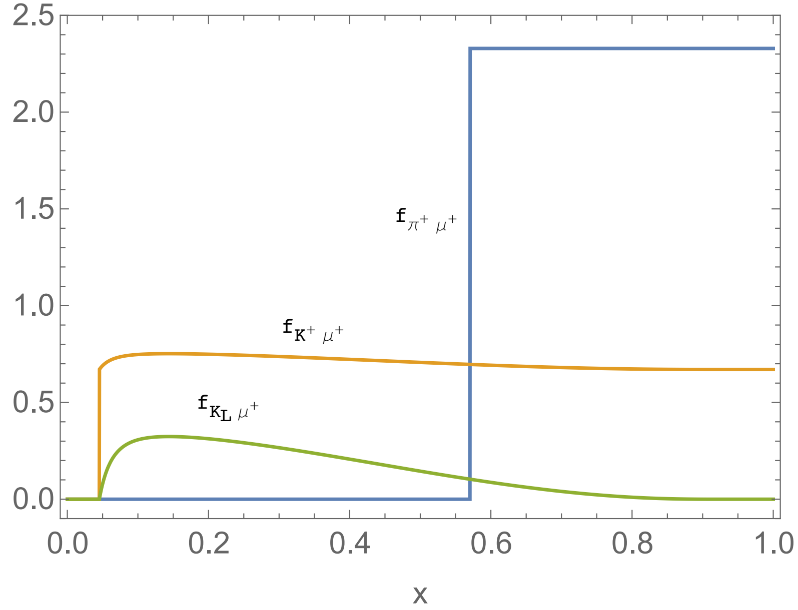
• How many muons of very large energy ($E_\mu / E \approx 0.1\%$) does an EAS contain for different primaries (proton, iron, photon)?

• How frequent are large energy depositions ($E \geq 10^6$ GeV) near the surface in inclined events?

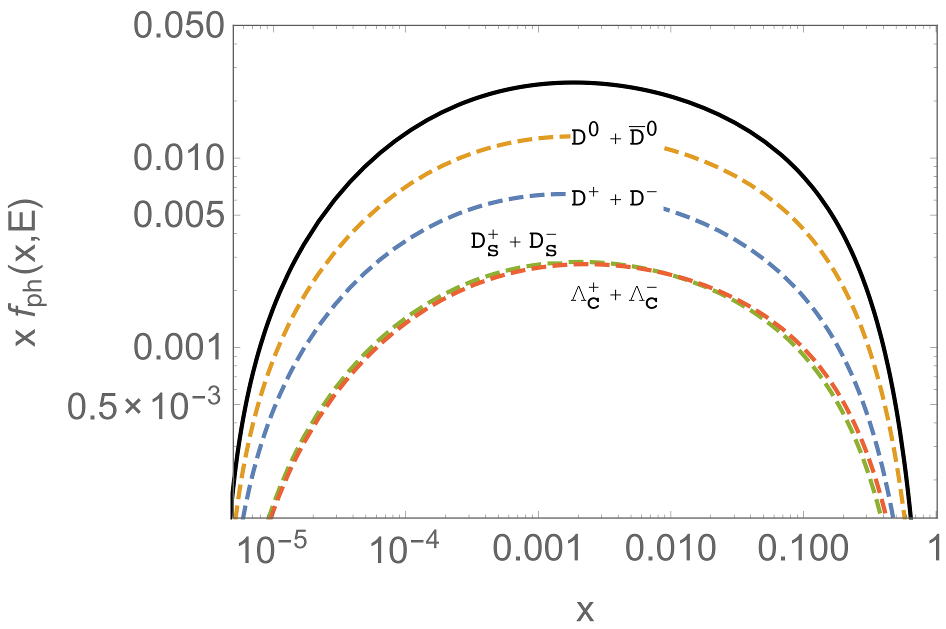
Muons are produced together with neutrinos in the weak decays of hadrons, but they can also appear in EM processes:

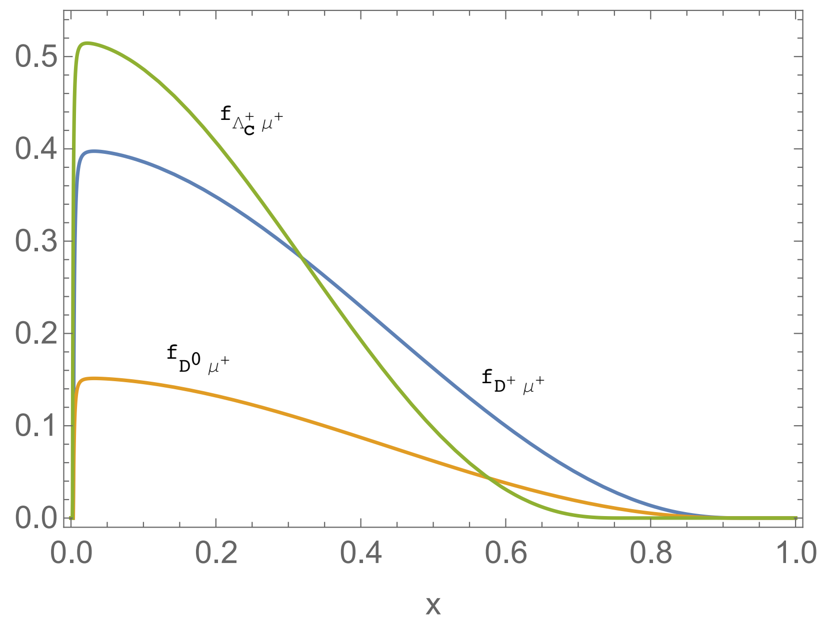
*(i)* Conventional muons from pion and kaon decays



*(ii)* Muons from charmed-hadron decays



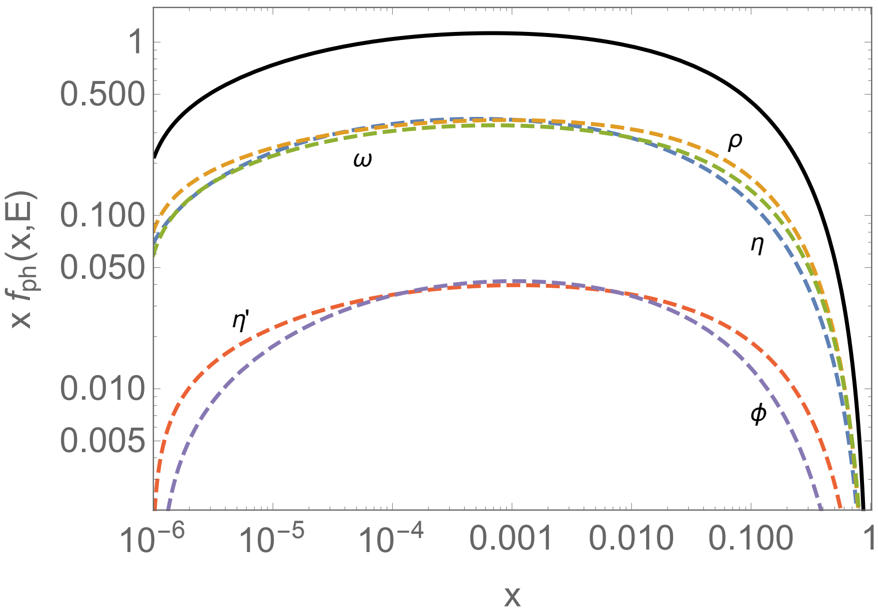



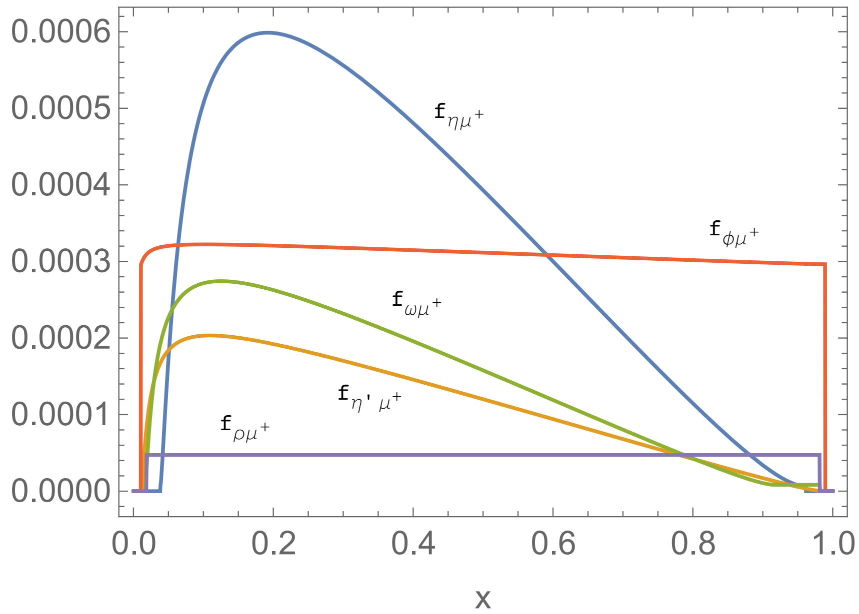

At $E > 10^6$ GeV charmed hadrons tend to collide in the air instead of decaying. Lower inelasticity than in pion collisions ($K_D = 1 - \langle x \rangle \approx 0.44$ versus $K_\pi \approx 0.74$ at $10^6$ GeV)

*(iii)* Muons from the rare decays of unflavored mesons

The unflavored mesons $\eta$, $\rho$, $\omega$, $\eta'$ and $\phi$ –masses between 0.5 and 1 GeV– include decay channels with muon pairs.

$$\mathrm{BR}(\eta \to \mu^+\mu^-\gamma) = 3.1 \times 10^{-4} \qquad \mathrm{BR}(\phi \to \mu^+\mu^-) = 2.9 \times 10^{-4}$$



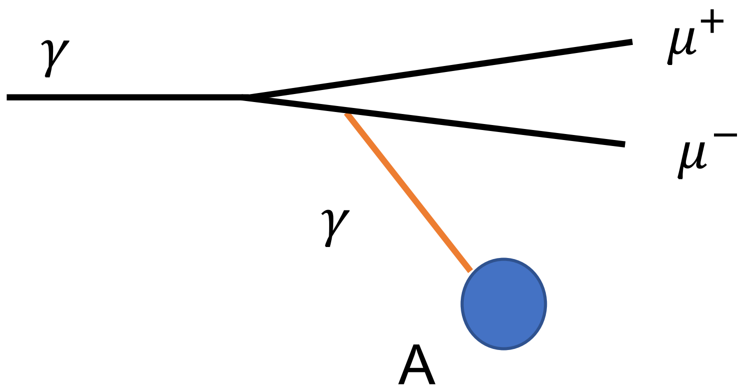



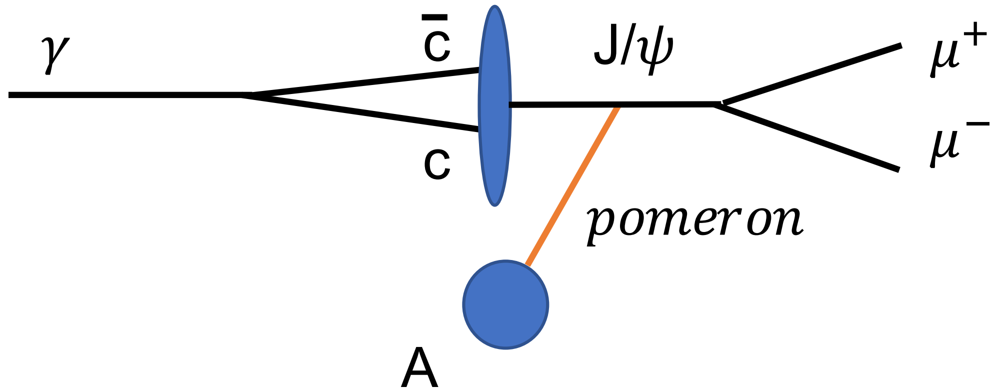

These decays are rare, but always prompt

*(iv)* Photon conversion into a muon pair

Photons (from $\pi^0$ and $\eta$ decays) take 20.6% of the energy in proton-air collisions at $10^6$ GeV –24.4% and 24.1% in pion and kaon collisions, respectively–

$\gamma A \to \mu^+\mu^- A$ suppressed by $m_e^2/m_\mu^2 = 2.4 \times 10^{-5}$ respect to $\gamma A \to e^+e^- A$, but all the photon energy goes into the muons



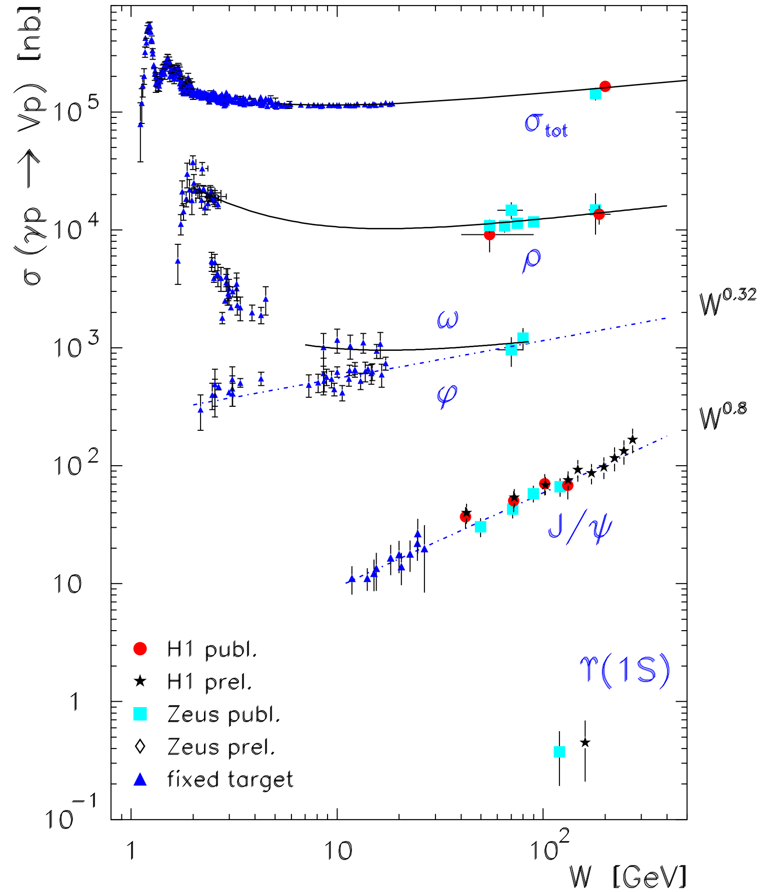

*(v)* Photon conversion into a vector meson decaying into muons

The conversion is less likely due to the larger mass of the $J/\psi$

pomeron-mediated

$W_{\gamma p} \leq 300$ GeV $\rightarrow W_{\gamma p} \leq 300$ TeV

$\mathrm{BR}(J/\psi \rightarrow \mu^+\mu^-) = 6\%$



- Cascade equations

$$\frac{\mathrm{d}\Phi_i(E,t)}{\mathrm{d}t} = -\frac{\Phi_i(E,t)}{\lambda_i^{\mathrm{int}}(E)} - \frac{\Phi_i(E,t)}{\lambda_i^{\mathrm{dec}}(E,t)} + \sum_{j=h,\gamma,e} \int_0^1 \mathrm{d}x \, \frac{f_{ji}(x,E/x)}{x} \, \frac{\Phi_j(E/x,t)}{\lambda_j^{\mathrm{int}}(E/x)} + \sum_{k=h} \int_0^1 \mathrm{d}x \, \frac{f_{ki}^{\mathrm{dec}}(x,E/x)}{x} \, \frac{\Phi_k(E/x,t)}{\lambda_j^{\mathrm{dec}}(E/x,t)}$$

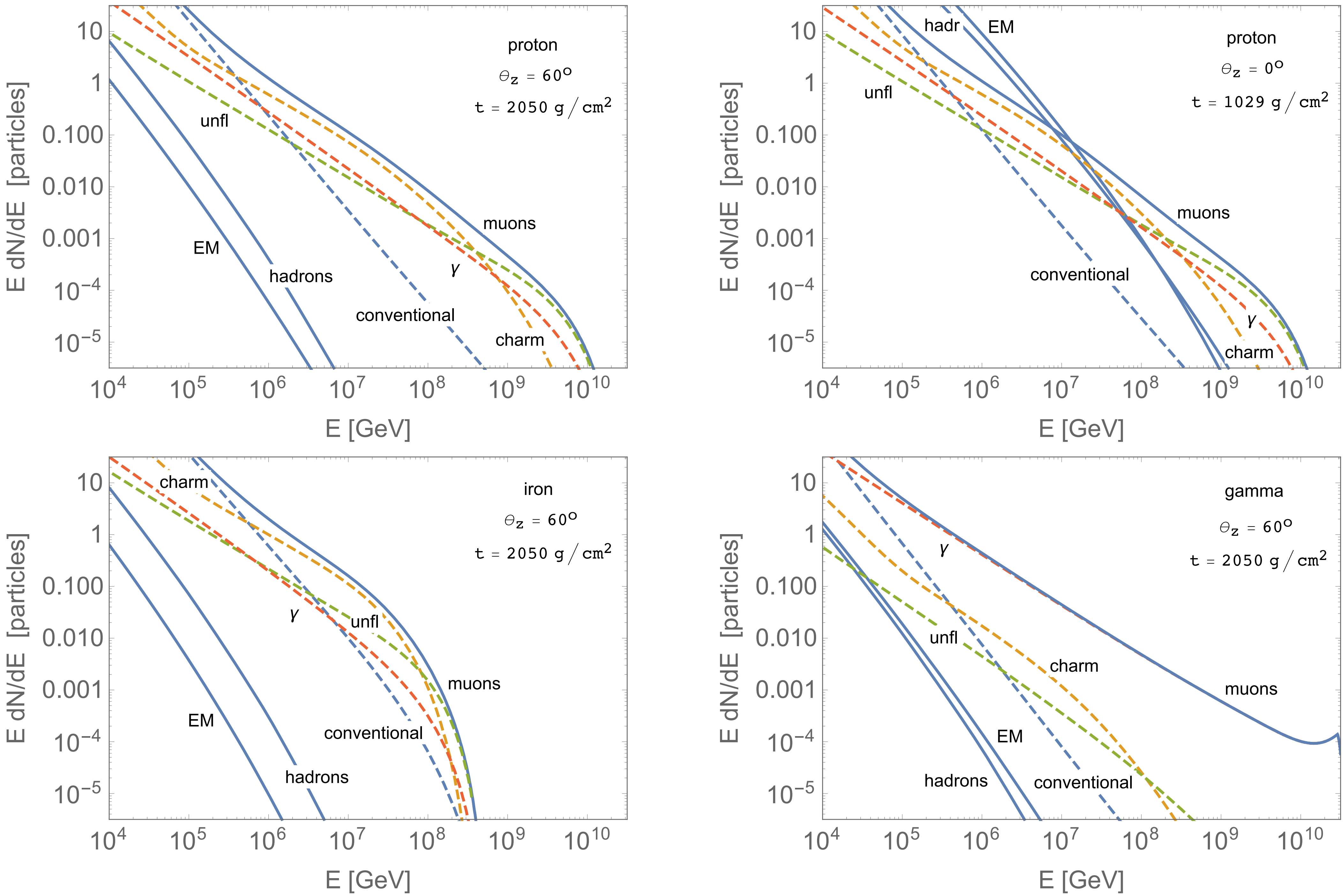
- Air density

$$\rho(h) = \begin{cases} 1.210 \times 10^{-10} \, (44.33 - h)^{4.253} \, , & h < 11 \text{ km}; \\ \\ 2.053 \times 10^{-3} \exp\left(-\frac{h}{6.344 \text{ km}}\right) , & h > 11 \text{ km} \, . \end{cases}$$

- Numerical solution for a $10^{10.5}$ GeV shower

200 logarithmic bins of energy

2500 linear bins of altitude, $h_0 = 70$ km


proton
$\theta_z$ = 60°
t = 2050 g/cm²
unfl
muons
EM
hadrons
γ
conventional
charm
E dN/dE [particles]
E [GeV]
proton
$\theta_z$ = 0°
t = 1029 g/cm²
hadr
EM
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muons
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γ
charm
E dN/dE [particles]
E [GeV]
iron
$\theta_z$ = 60°
t = 2050 g/cm²
charm
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hadrons
E dN/dE [particles]
E [GeV]
gamma
$\theta_z$ = 60°
t = 2050 g/cm²
γ
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muons
EM
hadrons
conventional
E dN/dE [particles]
E [GeV]

$E = 10^{10.5}$ GeV

- 1 in 35 inclined proton showers include a muon of $E_\mu \geq 10^{7.5}$ GeV ($x \geq 0.001$).
1 in 150 with $E_\mu \geq 10^8$ GeV

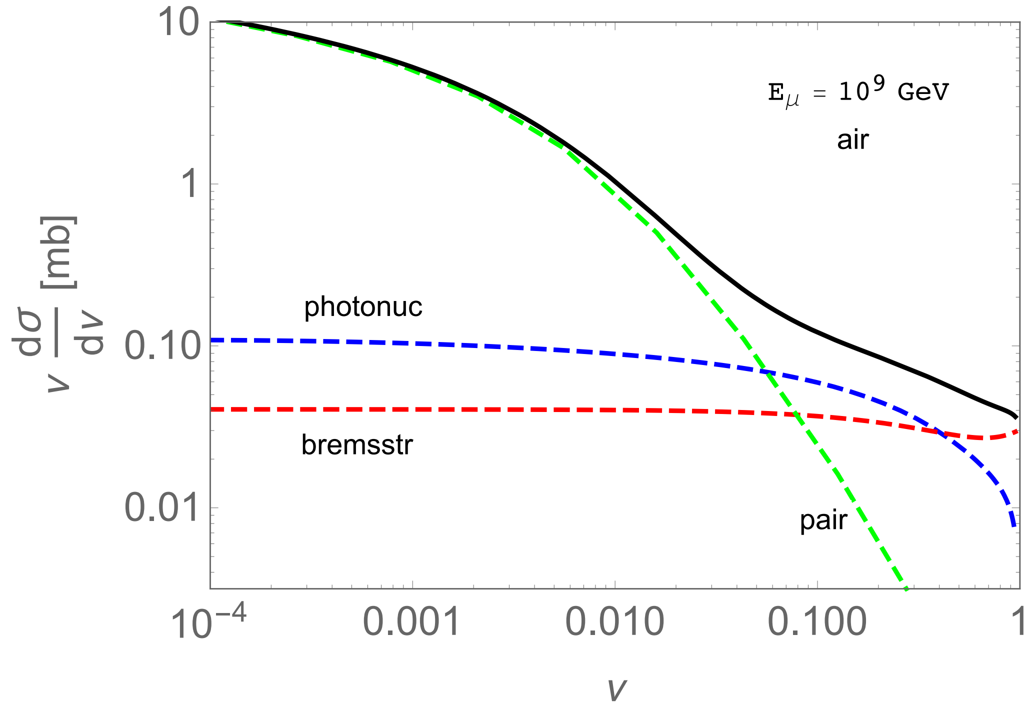
- 1 in 43 vertical proton showers include a muon of $E_\mu \geq 10^{7.5}$ GeV ($x \geq 0.001$).
1 in 190 with $E_\mu \geq 10^8$ GeV

- 1 in 60 inclined iron showers include a muon of $E_\mu \geq 10^{7.5}$ GeV ($x \geq 0.001$).
1 in 1000 with $E_\mu \geq 10^8$ GeV

- 1 in 62 inclined photon showers include a muon of $E_\mu \geq 10^{7.5}$ GeV ($x \geq 0.001$).
1 in 190 with $E_\mu \geq 10^8$ GeV

How frequent
large energy depositions ($E > 10^6$ GeV) near the ground (within 500 g/cm$^2$) are?

Bremsstrahlung, pair production and photonuclear collisions in the air




- 1 in 6 inclined proton showers include a radiative deposition of $E \geq 10^6$ GeV

1 in 330 of $E \geq 10^7$ GeV

- 1 in 92 inclined iron showers include a radiative deposition of $E \geq 10^6$ GeV

1 in 7000 of $E \geq 10^7$ GeV

# Conclusions

• Atmospheric high energy neutrinos and muons are a probe for the production of forward charm in hadronic collisions. Muons also probe the production of unflavored meson production (30% contribution) as well as gamma conversions into muon pairs (17%) and $J/\psi$ mesons (6%)

• These muons can be observed at neutrino telescopes. In inclined EASs catastrophic energy depositions deep in the atmosphere may introduce anomalies in the muon to electromagnetic signal at the surface detectors

• The production of high energy muons is very different in proton, iron or gamma showers. 1 in 6 inclined proton showers of energy $10^{10.5}$ GeV include a radiative deposition of $E \geq 10^6$ GeV within 500 g/cm$^2$, but only 1 in 92 iron showers. After the upgrade in the surface detectors at AUGER, they may be useful in composition analysis.

• In photon showers the conversions $\gamma \to \mu^+\mu^-, J/\psi$ are the dominant source of muons (over pions from photonuclear collisions) at $E_\mu \geq 10^4$ GeV