

Probing High-Energy Hadronic Interactions with EAS

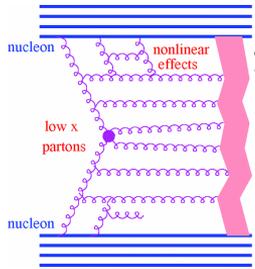
PoS(ICRC2019)005

Lorenzo Cazon

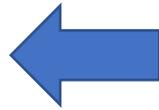
Special thanks to F. Riehn, R. Conceição and H. Dembinski



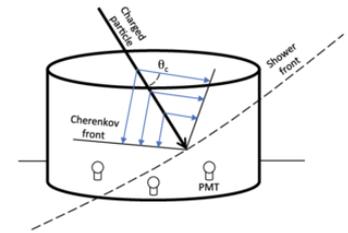
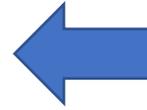
The scope of this talk:



Hadronic
Interactions



Air Shower Physics



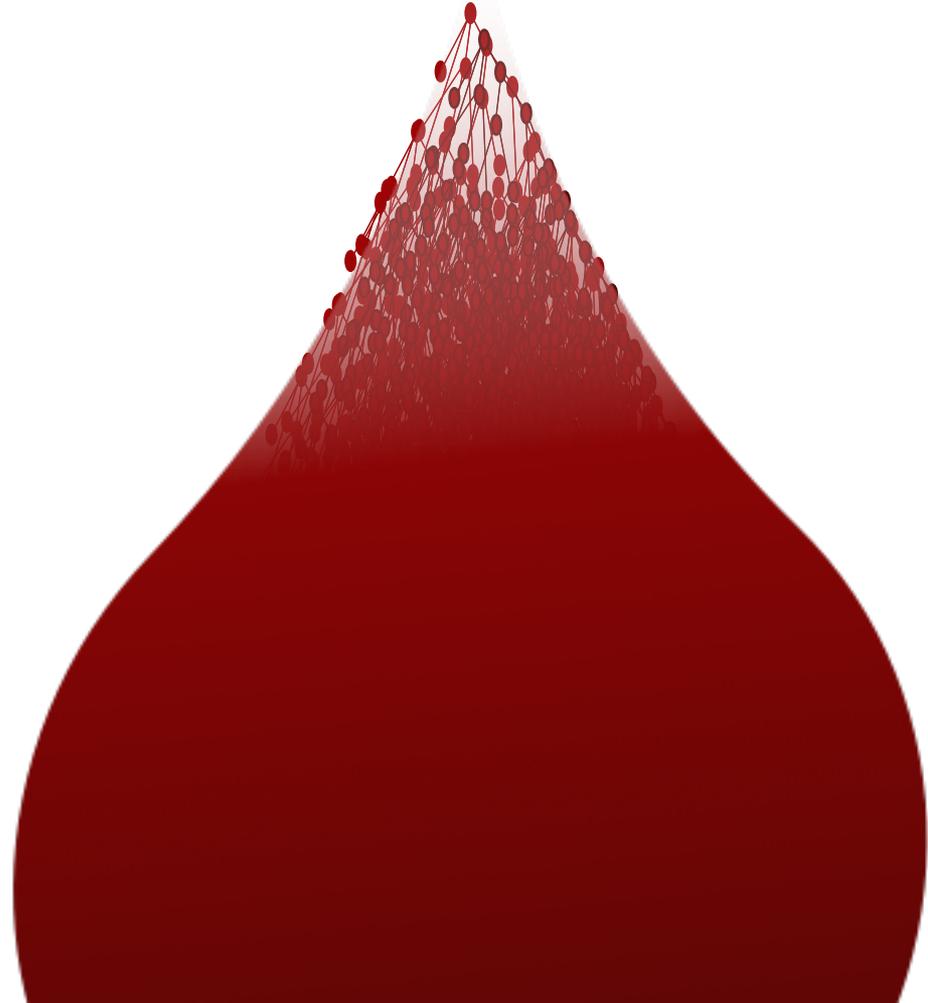
Detection /
Measurements

Extensive Air Showers

Information is degraded.

We go from $\sim \mathcal{O}(10^{12})$ independent variables to $\sim \mathcal{O}(10)$ independent observables.

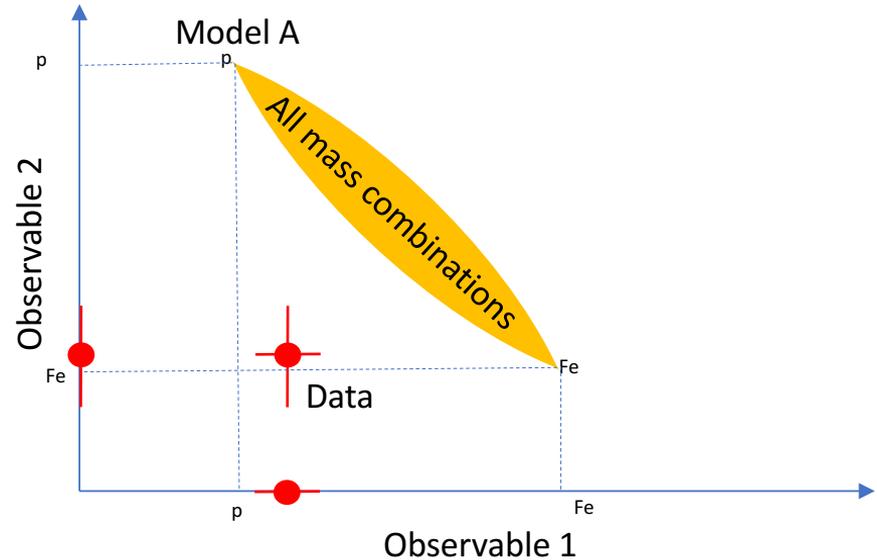
Now much information about the mass of the primary and the interactions is possible to recover?
(In particular from the 1st interaction)



The general strategy

Make troubles for the hadronic models 🐱

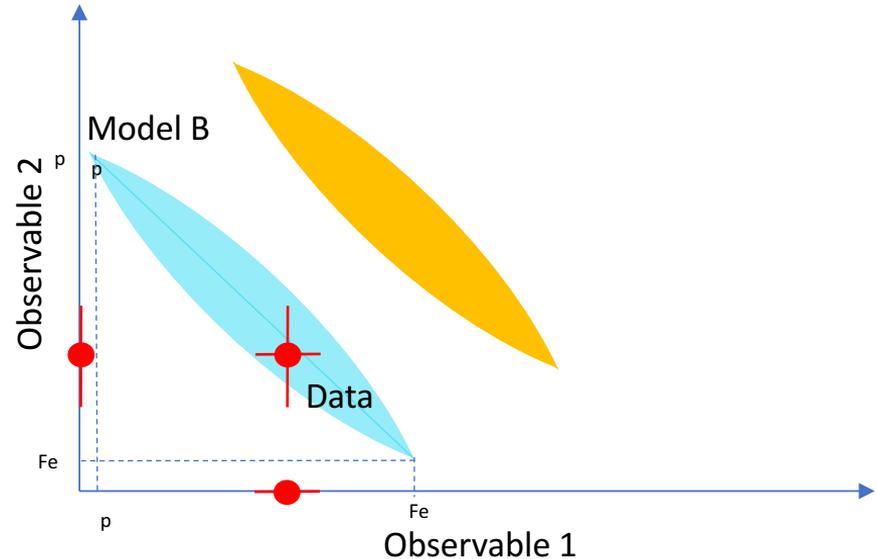
- We check the compatibility of data with the mass phase-space of a given model
- Primary mass and uncertainties in hadronic models share phase-space
- Obs 1 and Obs 2: different mass interpretations for model A



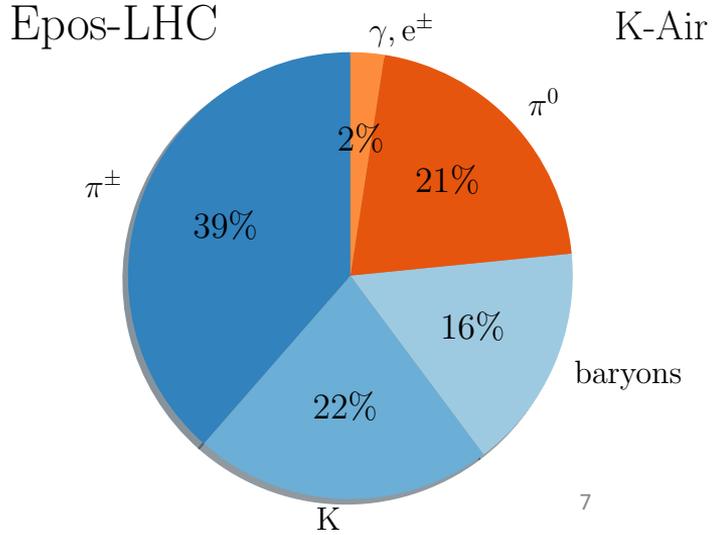
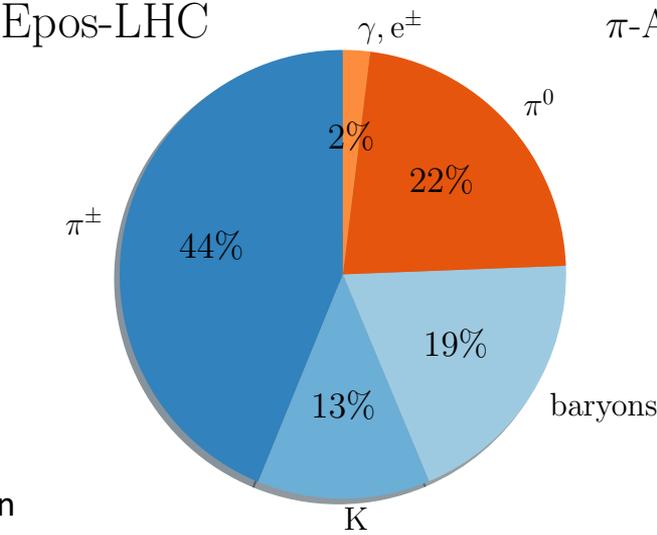
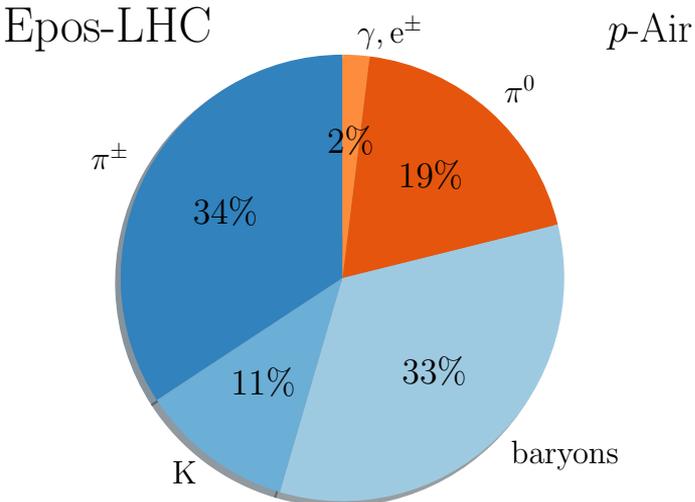
The general strategy

Make troubles for hadronic models 🐱

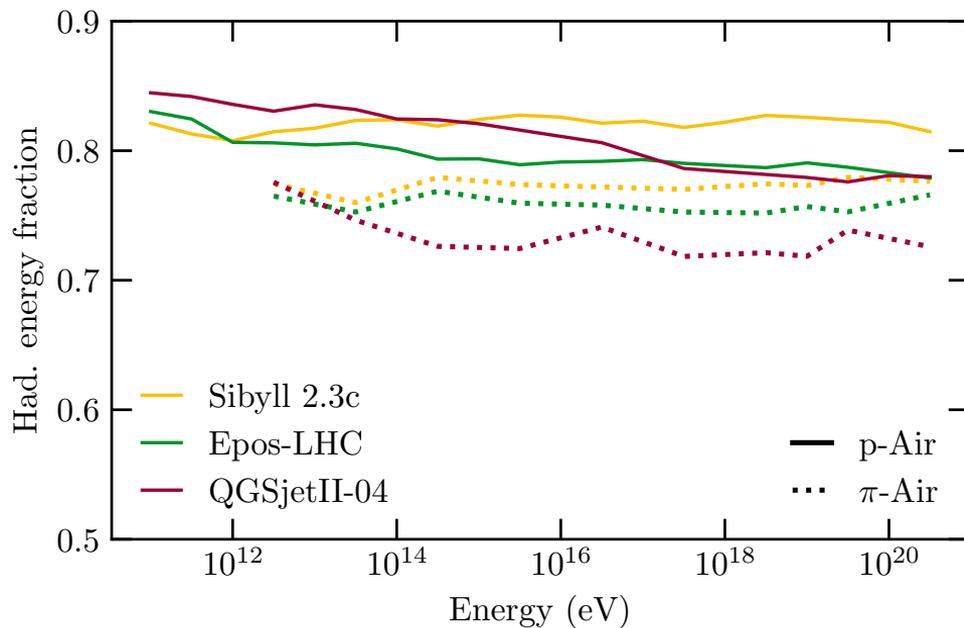
- We check the compatibility of data with the mass phase-space of a given model
- Primary mass and uncertainties in hadronic models share phase-space
- Obs 1 and Obs 2: different mass interpretations for model A.
- **Obs 1 and Obs 2: same mass interpretation for model B**



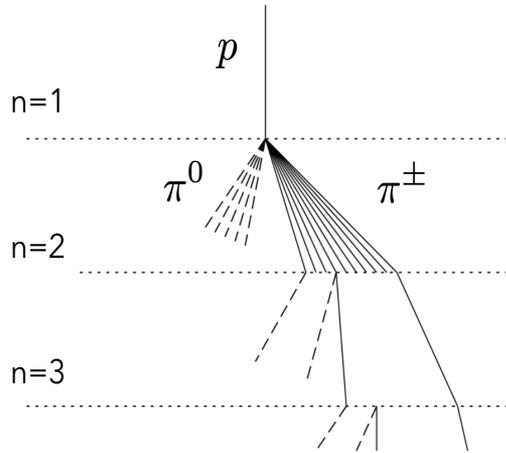
1st interaction energy fraction



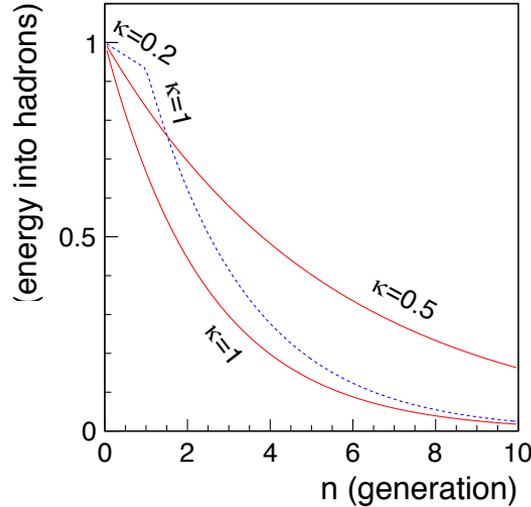
1st interaction energy fraction



Energy Balance of the shower



$$\frac{\sum E_{hadr}}{E_0} = f_1 \cdot f_2 \cdot \dots \cdot f_n = f^n$$



$$1 - \kappa = \frac{E_{\text{leading}}}{E_0}$$

$$f = (1 - \kappa) + \frac{2}{3}\kappa$$

$$f_{\text{EM}} = \frac{1}{3}\kappa$$

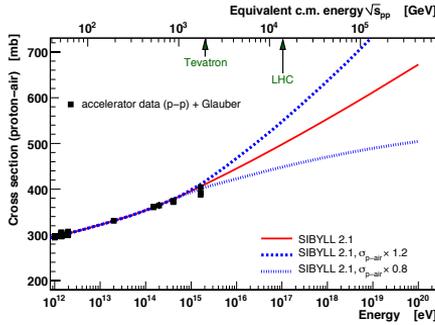
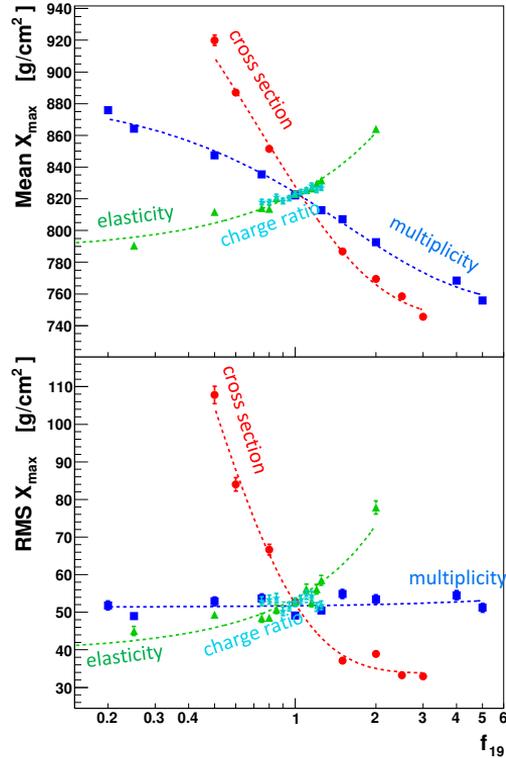
EM cascade takes >50% of its energy from 1st, 2nd and 3rd hadr. generations

Sensitive to High Energy Physics

Hadronic cascade: Keeps developing until critical energy of mesons.

Sensitive to High & Low Energy Physics.

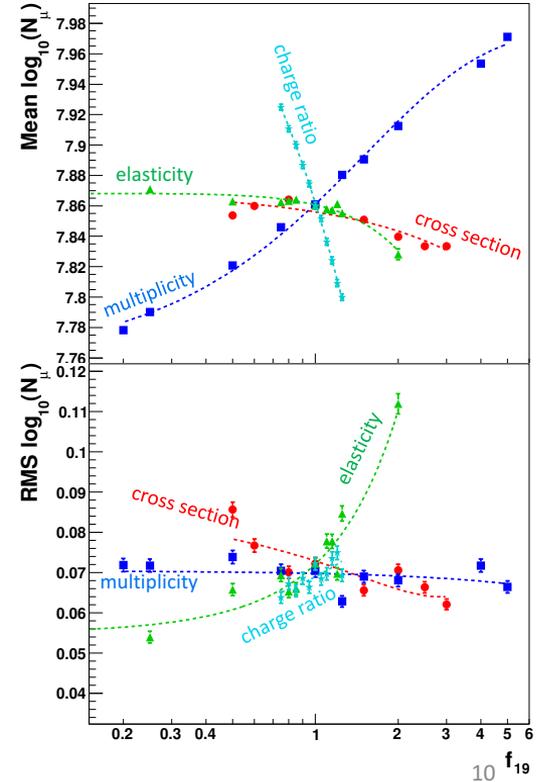
Relevant* hadronic parameters



Smooth parameter modification,
benchmarked at 10^{19} eV, f_{19}

$$\text{charge ratio} = \pi^0 / (\pi^0 + \pi^+ + \pi^-) = f_{EM}$$

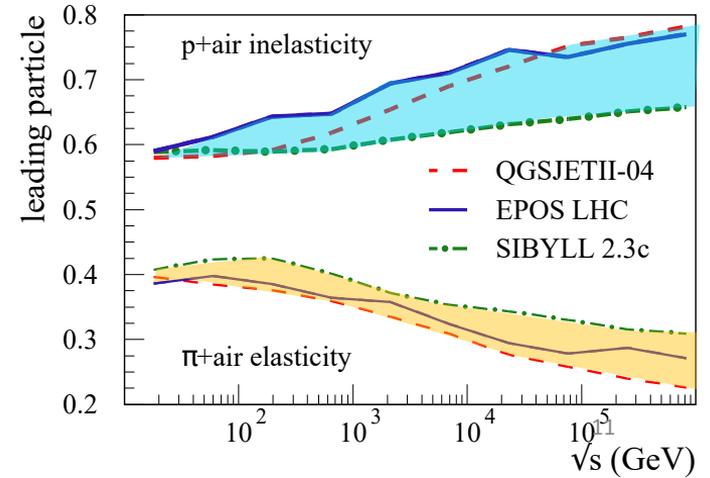
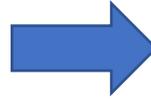
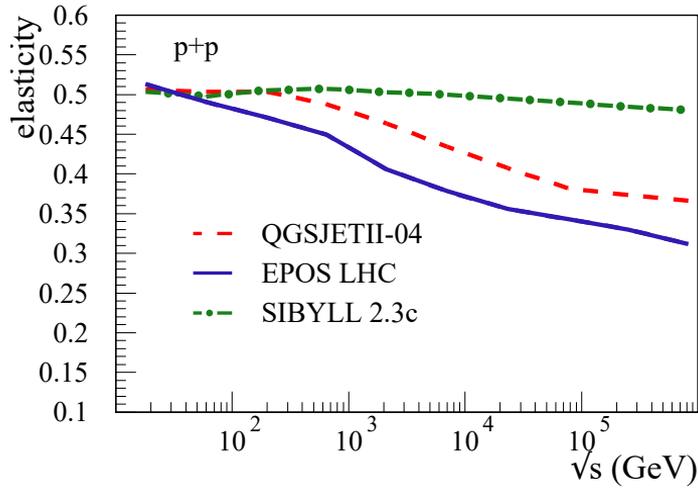
R. Ulrich et al PRD 83 (2011) 054026

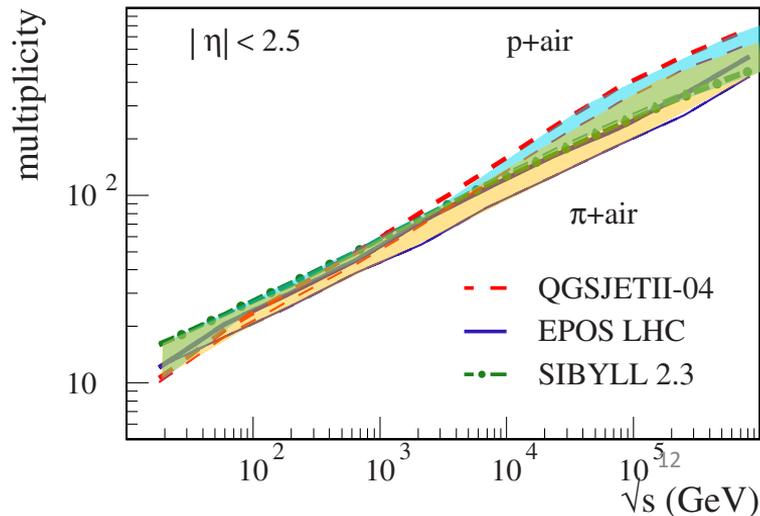
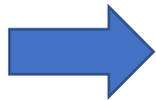
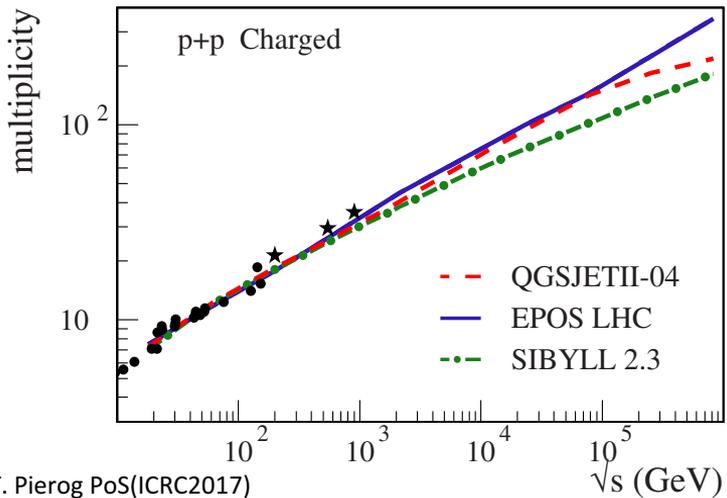
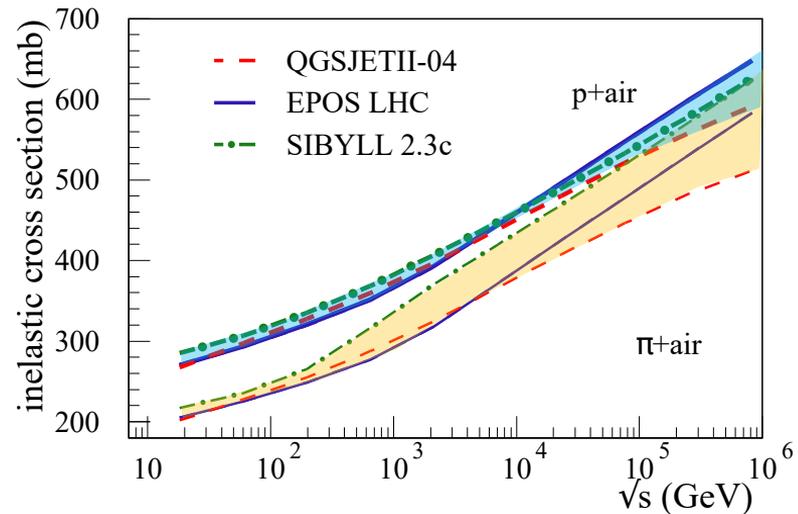
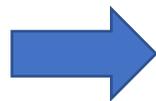
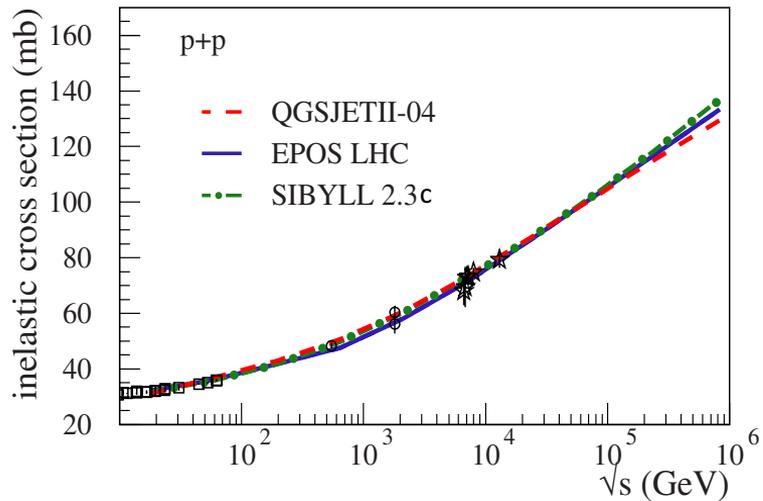


Hadronic Parameters

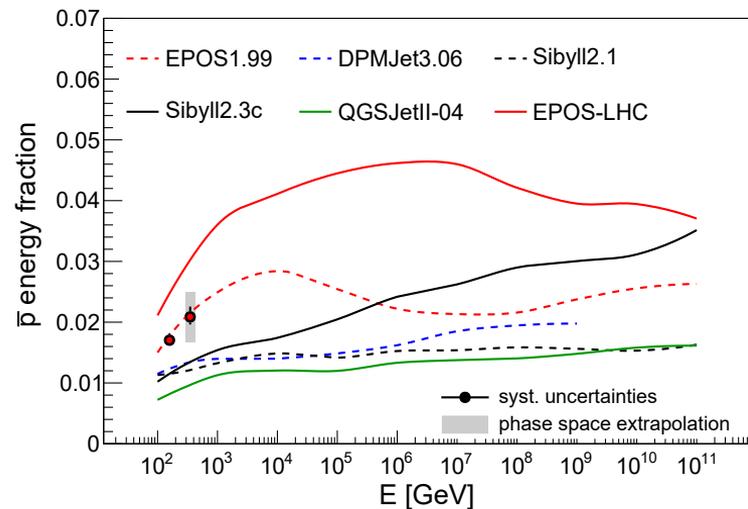
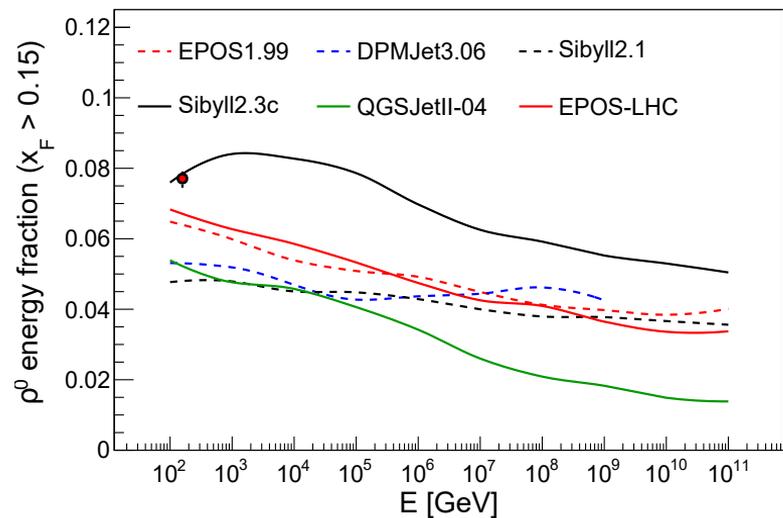
elasticity = $1-k$

inelasticity = k





NA61/SHINE



The shower components

- **EM:** very well understood. X_{\max} has reduced model uncertainty.
 - X_{\max} is used for mass inference

Universality of lateral distribution, energy distribution, angular distribution, and arrival time.

S. Lafebvre *et al.* ,Astropart. Phys. 31 (2009) 243-254

A. Smialkowski and M. Giller, Astrophys. J. 854 (2018) no.1, 48

M. Giller *et al.* ,Astropart. Phys. 60 (2015) 92

F. Nerling *et al.* Astropart. Phys. 24 (2006) 421

M. Giller *et al.* J. Phys. G 30 (2004) 97.

- **Muon:** N_{μ} , X_{\max}^{μ} have large model uncertainties.

Universal distribution at production:

$$\frac{d^3 N}{dX dE_i dcp_t} = \mathcal{N}_{\mu} f(X - \mathcal{X}_{\max}^{\mu}, E_i, cp_t)$$

L. Cazon *et al.* Astropart. Phys. 36 (2012) 211

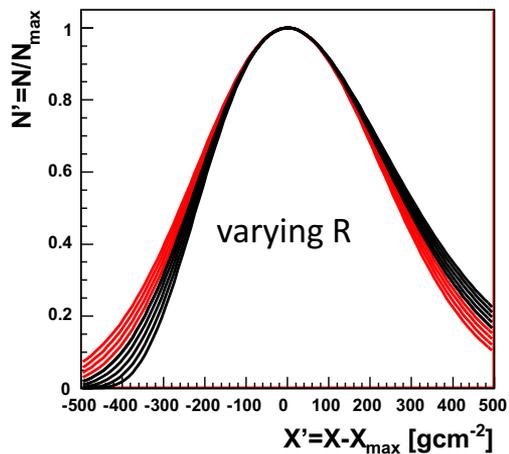
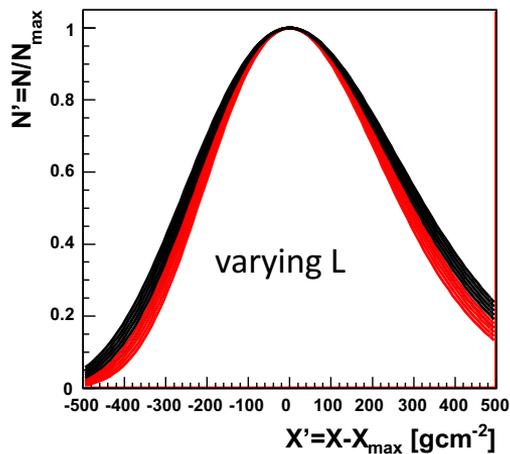
M Ave *et al.* Astropart. Phys. 88 (2017) 46

M Ave *et al.* Astropart. Phys. 87 (2017) 23

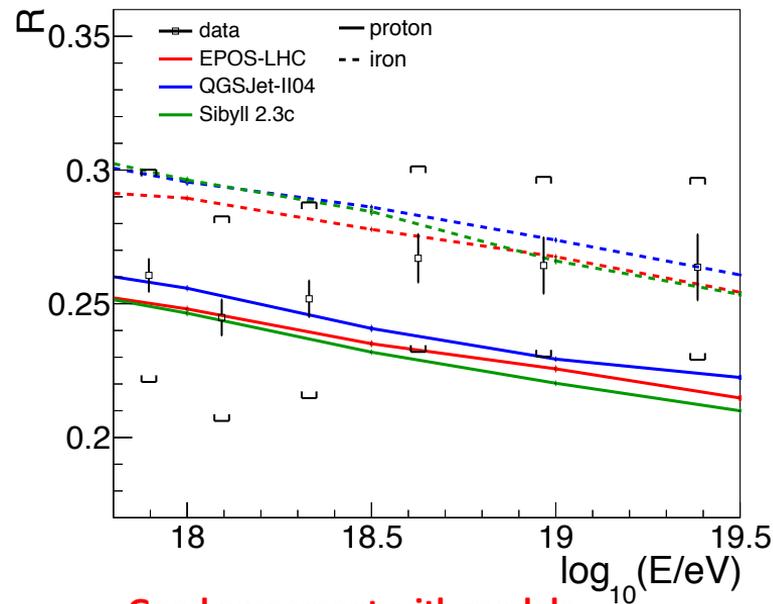
EM average profile

$$R = \sqrt{\lambda/|X'_0|}, \quad L = \sqrt{|X'_0|\lambda} \quad X'_0 = X_0 - X_{\max}$$

$$\frac{dE}{dX} = \left(1 + R \frac{X'}{L}\right) R^{-2} \exp\left(-\frac{X'}{RL}\right)$$



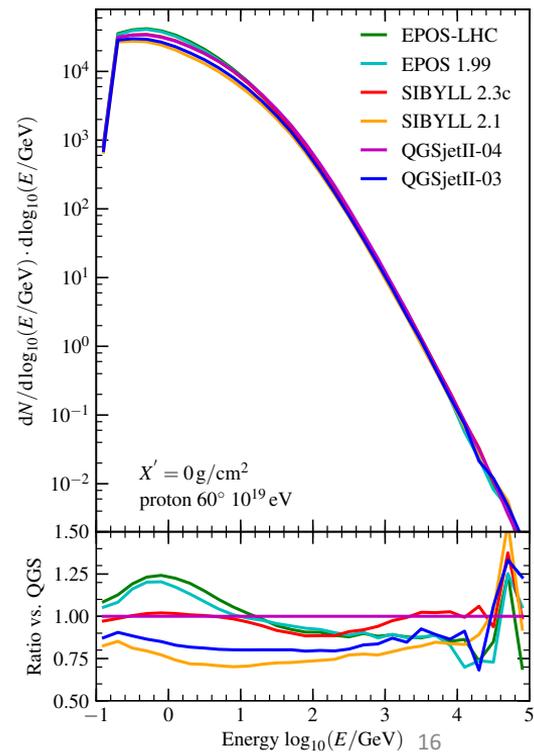
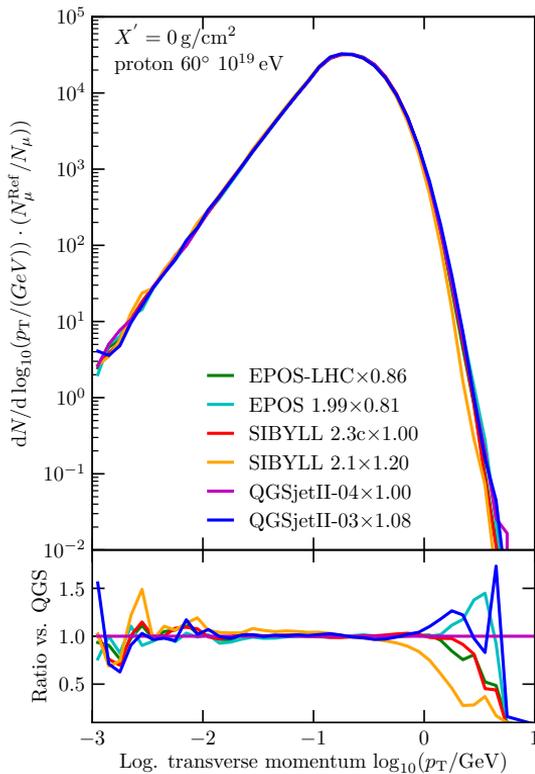
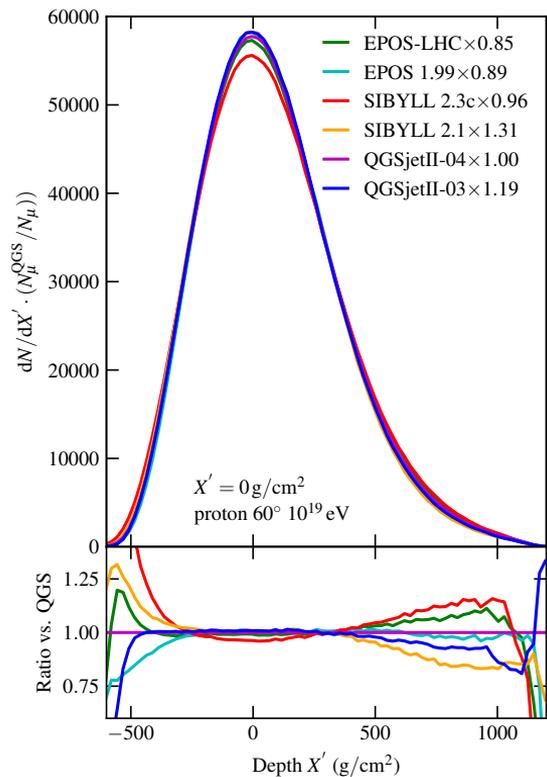
R is sensitive to the injection of **high energy π^0** in the start up of the shower.



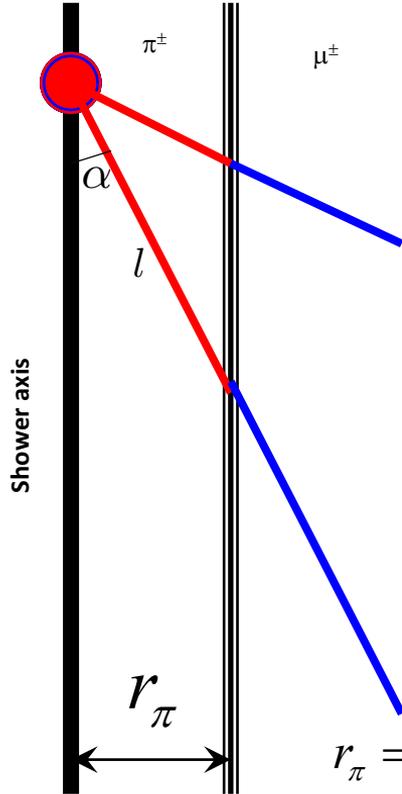
Good agreement with models.

Too large systematics for hadronic physics, for the moment.

Universality Muon Distributions



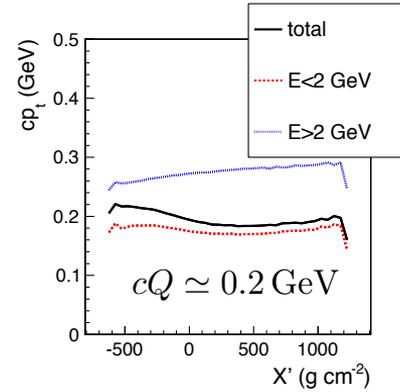
Transverse distance of μ^\pm production / π^\pm decay



$$\sin \alpha = \frac{cp_t}{E}$$

$$l = \frac{E}{m_\pi c^2} c\tau_\pi$$

$$r_\pi = l \sin \alpha = \frac{\tau_\pi p_t}{m_\pi}$$

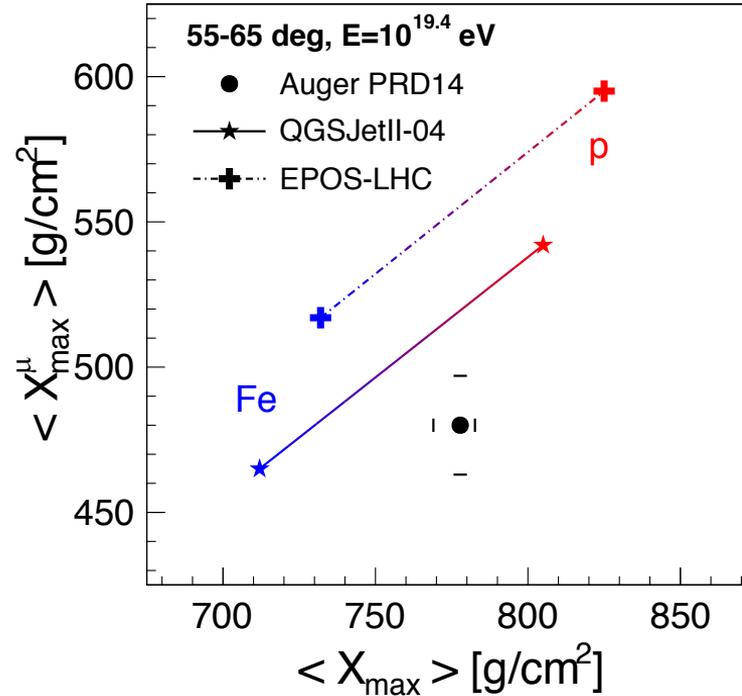


$$\frac{dN}{dp_t} \propto p_t e^{-\frac{p_t}{Q}}$$

59% of pions have $r_\pi < \frac{\tau_\pi 2Q}{m_\pi} = 22 \text{ m}$

Measurements

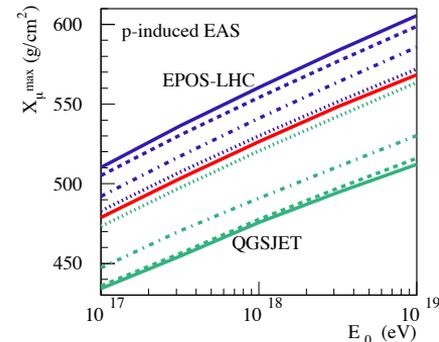
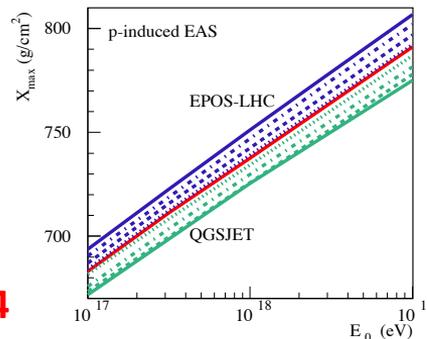
Muon Production Depth : $\langle X_{\max}^{\mu} \rangle$



MPD discussion

Cocktail models

- EPOS-LHC
- EPOS-LHC.04
- QPOS-LHC.04
- QGOS-LHet.04
- EPOS-JetII.04
- EGSJetII.04
- QGSJetII.04



S. Ostapchenko EPS Web Conf. 210 (2019) 02001

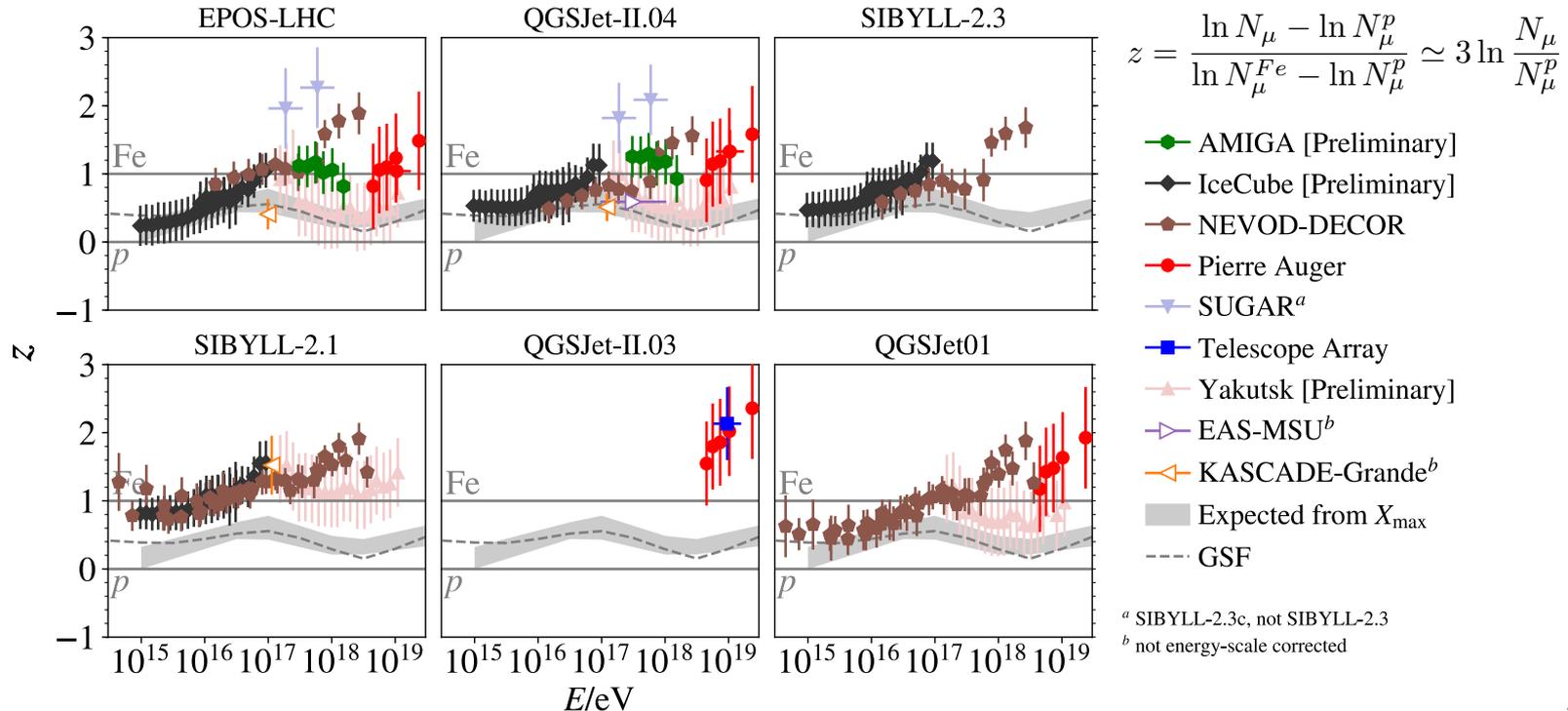
- $\langle X_{\max}^{\mu} \rangle$ is very sensitive to
 - **baryon production:**
 - baryons have smaller critical energy. They reach deeper and do not produce muons
 - **π -Air diffraction:**
 - slows down multiplicative process
 - **K & π energy spectrum:**
 - bulk of mesons closer to critical energy

Change in $\langle X_{\max}^{\mu} \rangle \sim 50 \text{ g cm}^{-2}$
corresponds to
change in $\langle X_{\max} \rangle \sim 15 \text{ g cm}^{-2}$

$\langle X_{\max}^{\mu} \rangle$ can be used to improve
 $\langle X_{\max} \rangle$ model uncertainty

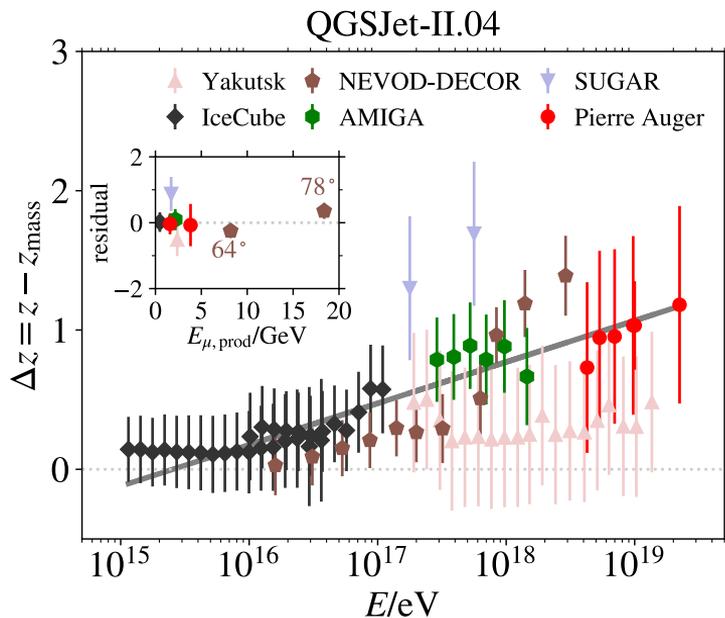
WHISP results on **muon deficit**

(aka muon excess in data)

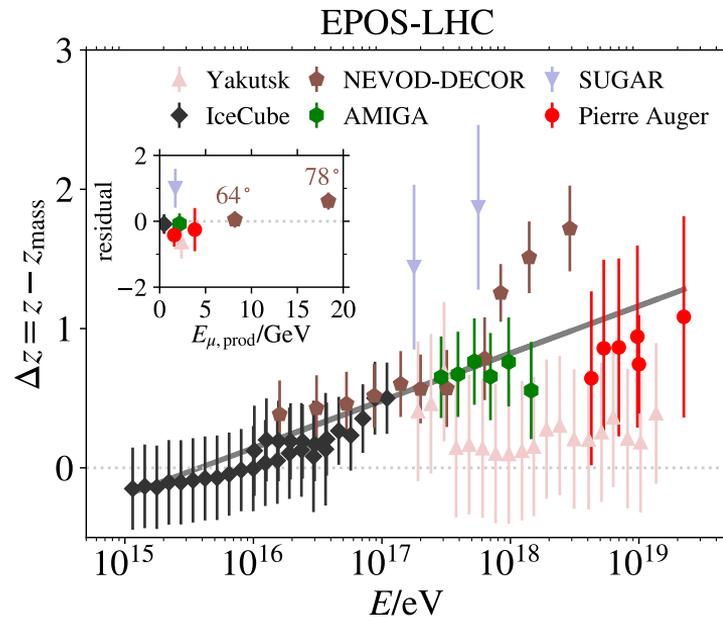


$$\Delta z = z - z_{\text{mass}} \simeq 3 \ln \frac{N_{\mu}}{N_{\mu}^{\text{mass}}}$$

$$\Delta z_{\text{fit}} = a + b \log_{10}(E/10^{16} \text{eV})$$



$$b = 0.30 \pm 0.03$$



$$b = 0.34 \pm 0.04$$

8 σ significance

E-spectrum

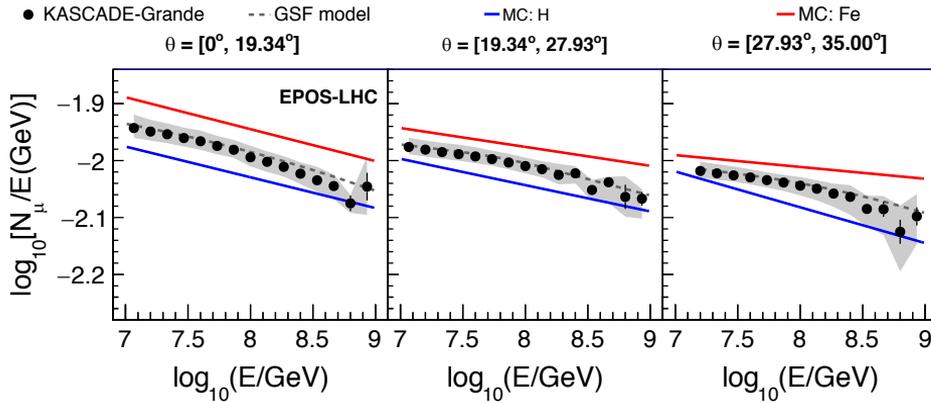
$$E_{\mu \text{ prod}}(\theta) \simeq X_v \sec \theta \frac{dE}{dX}$$

scanning zenith angles = scanning
different energies at production

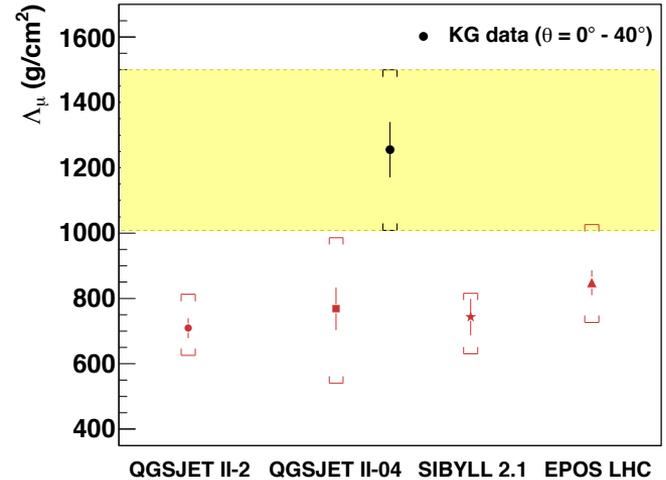
If muon excess increases as a
function of zenith angle, indication
of a harder E-spectrum wrt model

Experiment	$E_{\text{data}}/E_{\text{ref}}$	sec θ	$E_{\mu \text{ prod}}/\text{GeV}$
EAS-MSU	-	1.1	11.9
IceCube Neutrino Observatory	1.19	1.0	0.7
KASCADE-Grande	-	1.0 , 1.3	1.5 , 2.1
NEVOD-DECOR	1.08	2.3 , 4.8	8.4 , 18.6
Pierre Auger Observatory	0.948	1.3 , 2.4	1.8 , 4.0
AMIGA	0.948	1.2	2.4
SUGAR	0.948	1.0	1.9
Telescope Array	1.052	1.3	1.4
Yakutsk EAS Array	1.24	1.1	2.6

KASCADE-Grande



J. C. Arteaga PoS(ICRC2019)177



KASCADE-Grande Astropart. Phys. 95 (2017) 25

KASCADE-Grande observes a **larger attenuation length** for muons -> harder muon spectrum

Reasons for different muon E-spectrum

- Different of **meson production E-spectrum**
- Differences in the **π/K ratio** in the cascade
 - change in the effective average critical energy of mesons

$$\xi_{crit}^{\pi^\pm} \sim \mathcal{O}(100 \text{ GeV})$$

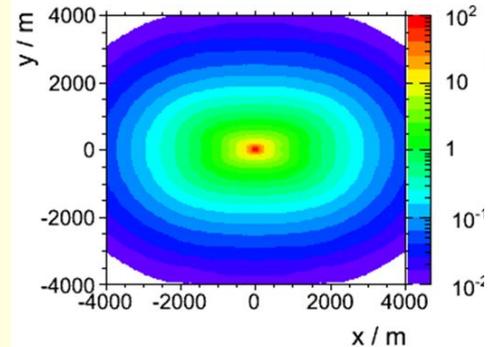
$$\xi_{crit}^{K^\pm} \sim \mathcal{O}(1000 \text{ GeV})$$

$$\xi_{crit}^{K_L^0} \sim \mathcal{O}(200 \text{ GeV})$$

$$\xi_{crit}^{K_S^0} \sim \mathcal{O}(30 \text{ TeV})$$

Other methods to study the muon E-spectrum:

- **Muon deflections by Geomagnetic Field** in inclined showers
- **Arrival Time distributions close to the core**
 - Parallel trajectories, delays are due to subluminal velocities and multiple scattering
- **Time-track complementarity**
 - Effective measurement of multiple scattering



Transverse Momentum - No results

- **No demonstrated deviations** *wrt* universal expectations.
 - Some studies find deviations in the muon LDFs
 - They can be attributed to other factors: mass, E-spectrum*, X_{\max}^{μ}

* J. Espadanal et al. Astropart. Phys. 86 (2017) 32

From Heitler model to Energy model

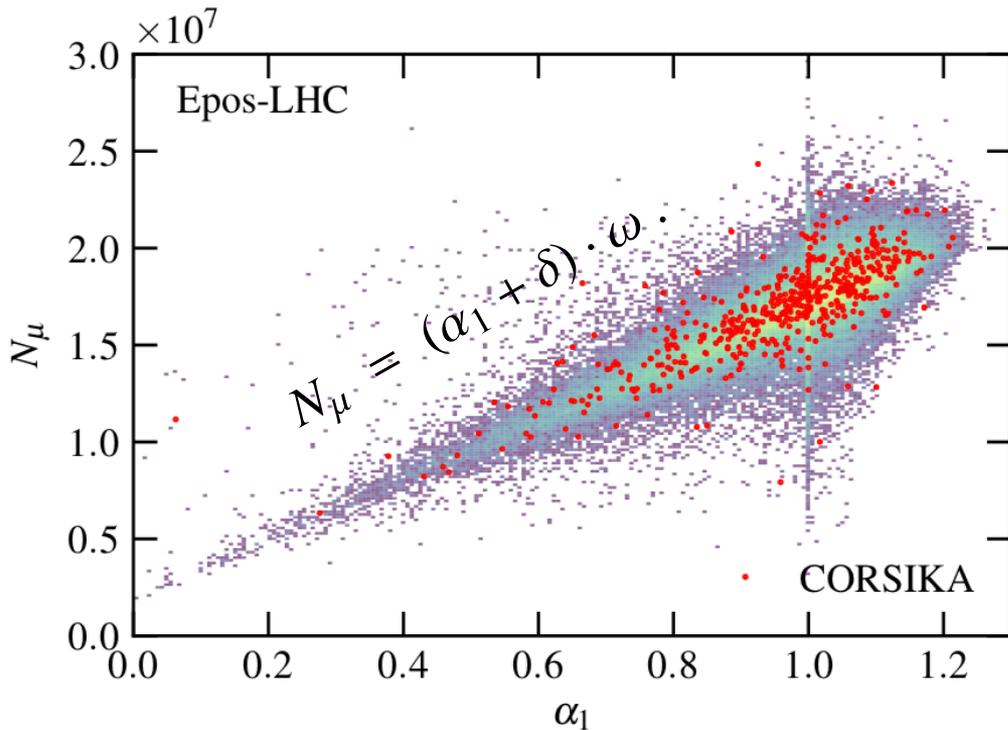
hadr. multiplicity $N_\mu = m_1 \cdot m_2 \cdot \dots \cdot m_c \quad \beta \rightarrow 0$

$$\alpha = \sum_{i \in \text{hadr}}^m \left(\frac{E_i}{E_0} \right)^\beta \quad N_\mu \propto \alpha_1 \cdot \alpha_2 \cdot \dots \cdot \alpha_c \quad \beta = 0.93$$

hadr. energy fraction $N_\mu = f_1 \cdot f_2 \cdot \dots \cdot f_c \cdot \frac{E_0}{\xi_c} \quad \beta \rightarrow 1$

In most practical cases $\alpha \simeq f$

Correlation with the 1st interaction (shower to shower)



	EPOS-LHC	SIBYLL 2.3c	QGSJET II-04
α_1	0.79 (0.82)	0.76 (0.78)	0.75 (0.78)
E_{had}/E	0.67 (0.66)	0.67 (0.66)	0.53 (0.52)
m_1	0.15 (0.21)	0.17 (0.22)	0.22 (0.27)
κ_{inel}	-0.15 (-0.08)	-0.11 (-0.07)	-0.04 (0.00)
m_1/m_{tot}	0.16 (0.18)	0.12 (0.13)	0.19 (0.18)
X_0	0.23 (0.12)	0.21 (0.12)	0.28 (0.19)
ϵ^*	-0.01 (-0.08)	-0.12 (-0.17)	-0.09 (-0.14)

Phys.Lett. B784 (2018) 68-76

N_μ Fluctuations

$$\left(\frac{\sigma(N_\mu)}{N_\mu}\right)^2 \simeq \left(\frac{\sigma(\alpha_1)}{\alpha_1}\right)^2 + \left(\frac{\sigma(\alpha_2)}{\alpha_2}\right)^2 + \dots + \left(\frac{\sigma(\alpha_c)}{\alpha_c}\right)^2$$



carries 70% of the fluctuations for protons!!!

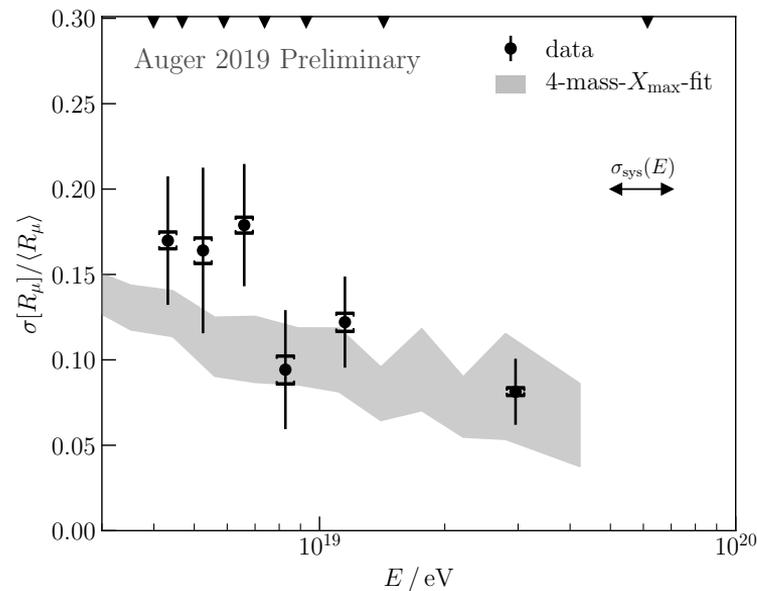
The PMT analogy

$$\sigma(\alpha_i) \propto \frac{1}{\sqrt{m_1 \cdot m_2 \cdot \dots \cdot m_{i-1}}}$$
$$\sigma(\alpha_1) \propto \frac{1}{\sqrt{A}}$$

- An **exotic model** that saturates $\langle f_1 \rangle \rightarrow 1$
 - for instance no π^0 decay, or no π^0 production
- **Would result in** $\sigma(\alpha_1) \rightarrow 0$
 - muon fluctuations will be suppressed and dominated by 2nd 3rd interactions ($\sim 4\%$, 5%)

$\sigma(N_\mu)/\langle N_\mu \rangle$ first experimental results

Fluctuations of partition of energy in the **1st interaction** are **well described** by models.
Large deviations of $\langle f_1 \rangle$ are disfavored.

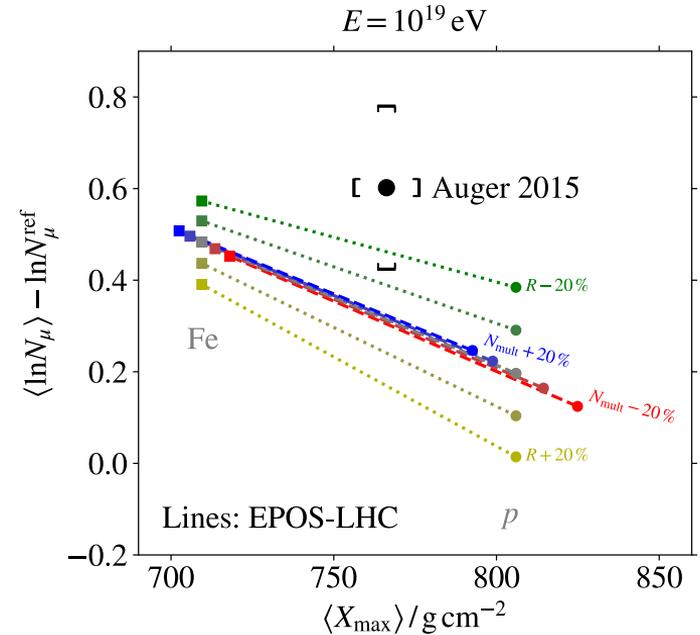


Discussion

$$N_{\mu} \propto (f + \delta f)^c$$

$$(1 + 0.05)^6 \simeq 1.30$$

- The **muon deficit** can be fixed by a smooth increment of hadronic fraction (f) over several generations



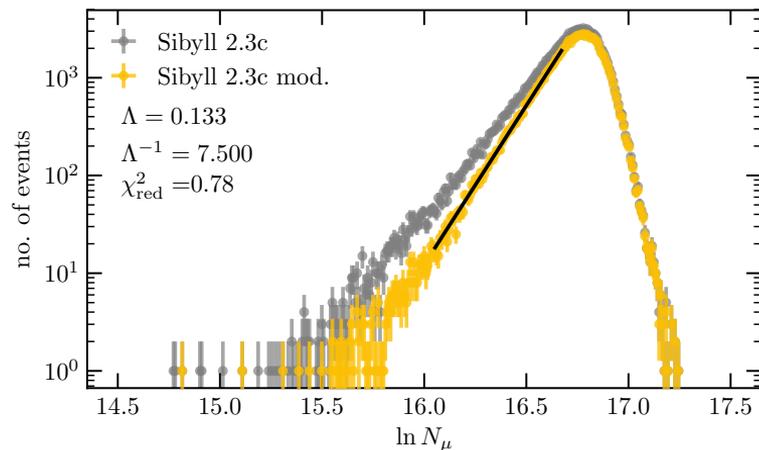
S. Baur et al. arXiv: 1902.09265

T. Pierog et al. PoS(ICRC2019)387

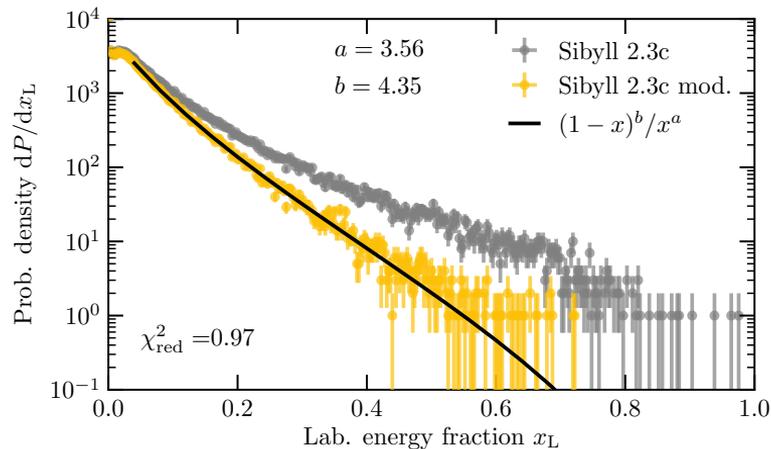
H. Dembinski et al. PoS(ICRC2019)235

π^0 production spectrum in p-Air

Low N_μ tail is a direct consequence of inclusive π^0 production cross section at large x_L



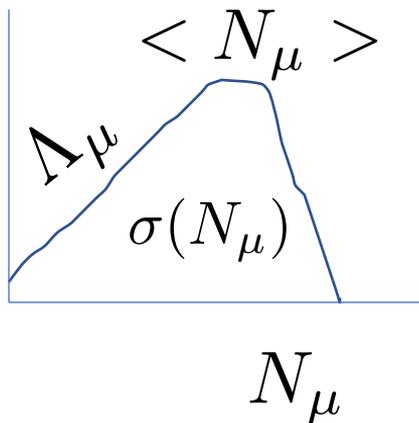
The technique resembles the other direct measurement on the 1st interaction: p-Air cross section



Models to solve the *muon puzzle*:

String percolation
 Strange Fireball
 Chiral Symmetry Restoration
 Quark Gluon Plasma
 Lorentz Invariance Violation

astro.ph:1209.6474
 PRD 95(2017) 06005
 EPJ Web Conf. 53(2013) 07007
 PoS(ICRC2017)387
 Phys. Rev. D 59, 116008 (1999)

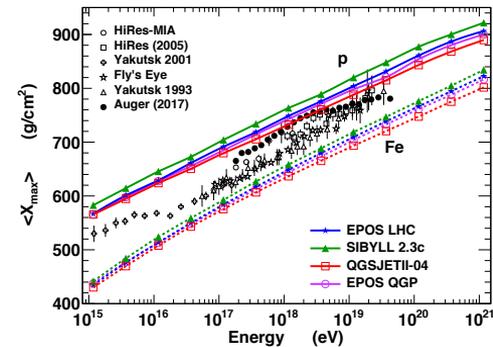
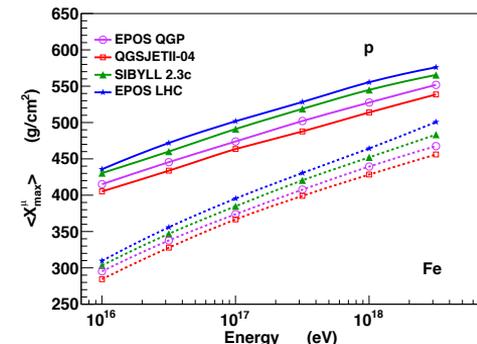
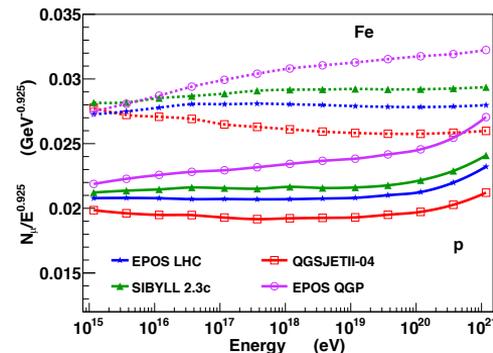


Apart from $\langle N_\mu \rangle$, need to be compatible with the other moments:

$$\langle N_\mu \rangle, \quad \sigma(N_\mu), \quad \Delta(N_\mu),$$

$$\langle X_{\max} \rangle, \quad \sigma(X_{\max}), \quad \Delta(X_{\max})$$

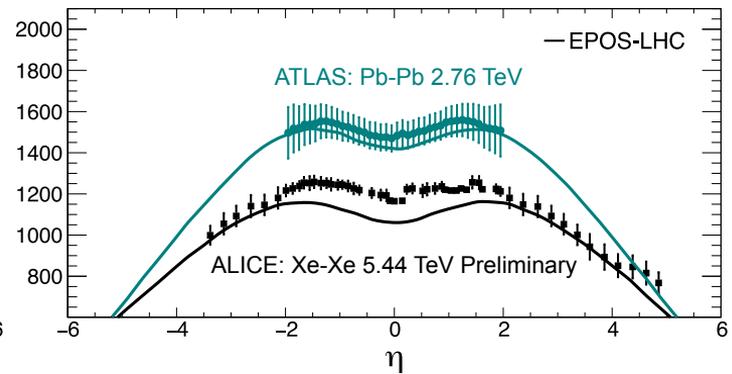
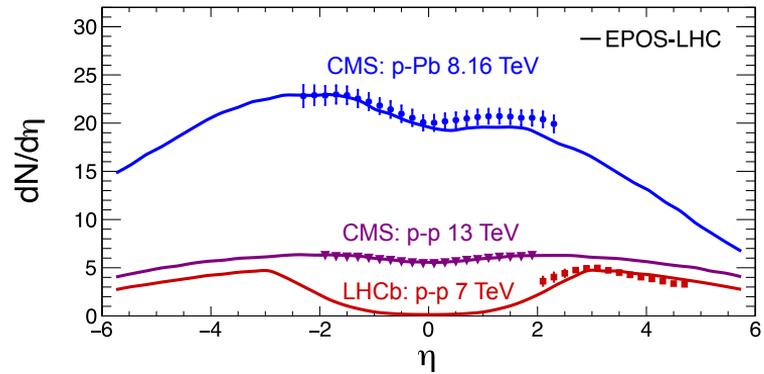
$$\langle X_{\max}^\mu \rangle, \quad \sigma(X_{\max}^\mu), \quad \Delta(X_{\max}^\mu)$$

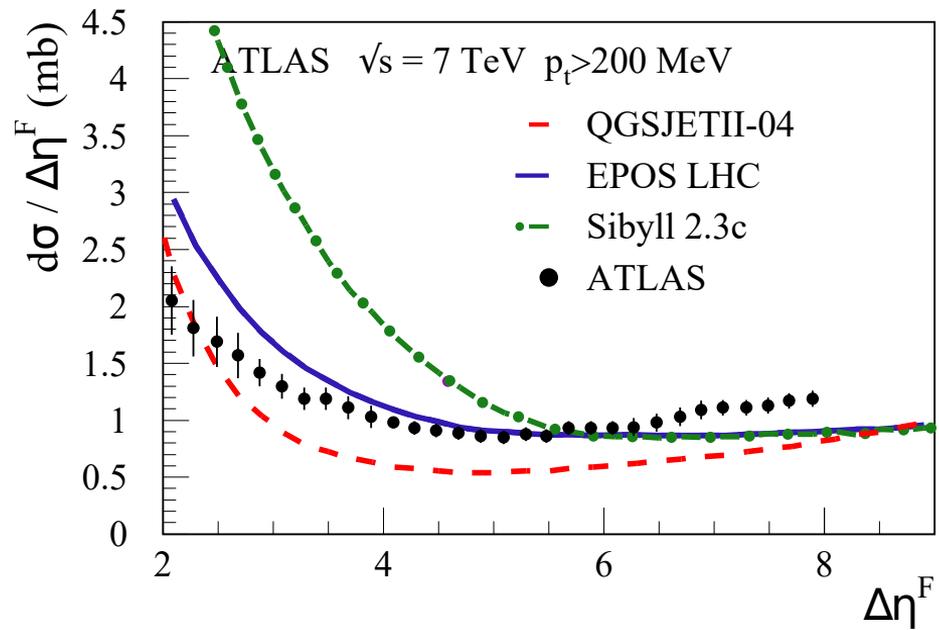


Conclusions

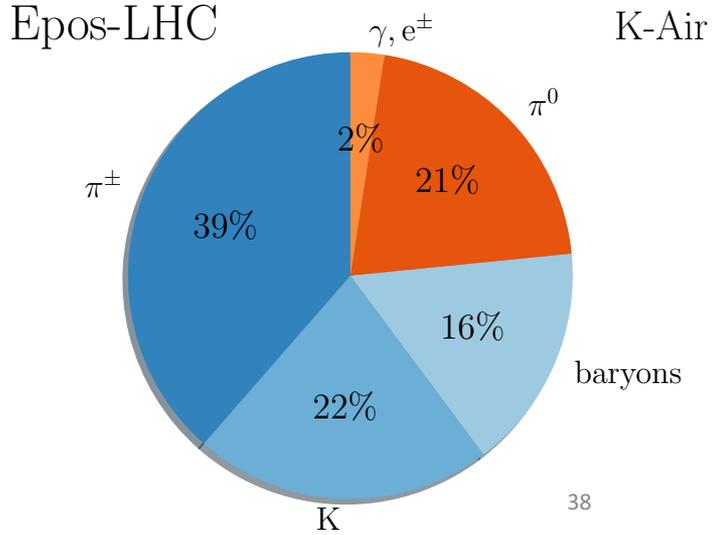
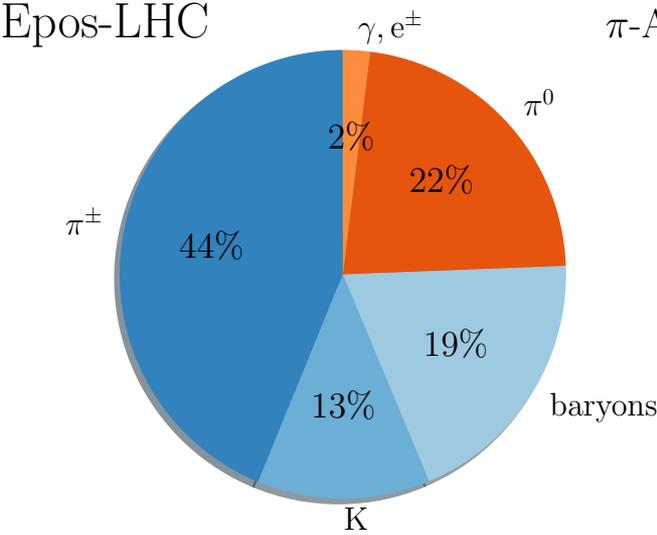
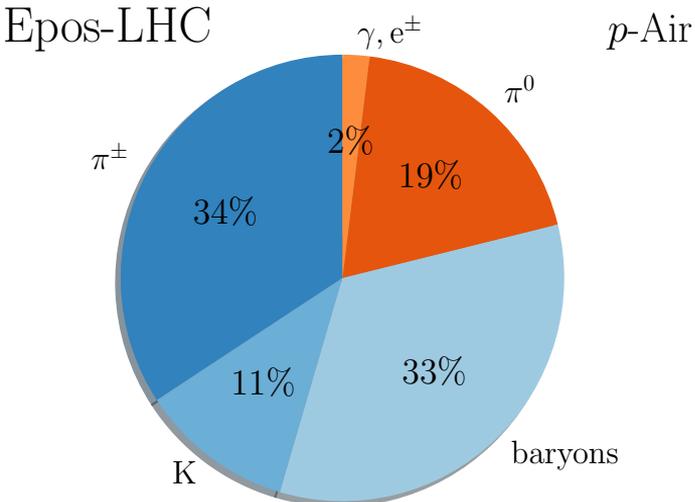
- Important **differences in model extrapolations** from LHC p-p collisions to **p-Air and π -Air**
 - p-O is being proposed for next LHC phase
- X_{\max}^{μ} is sensitive to the *cascading velocity*
 - **π -Air diffraction**, baryon production, meson E-spectrum.
 - N_{μ} is sensitive to *cascade gain/growth*
- **Large departure** from expectations **on UHECR-Air interactions are disfavored** by $\sigma(N_{\mu})$ measurement.
 - $\langle N_{\mu} \rangle$ mismatch likely explained by **small cumulative deviations** of fraction of energy into hadrons $f + \delta f$.
- There are new opportunities for **direct measurements** on the 1st p-Air interactions through low- N_{μ} tail **$\Lambda(N_{\mu})$** .

Thanks!

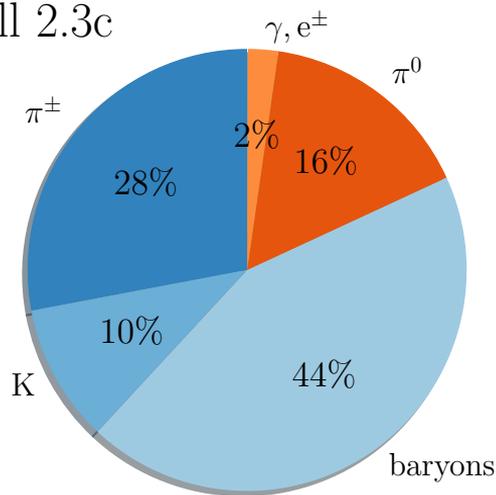




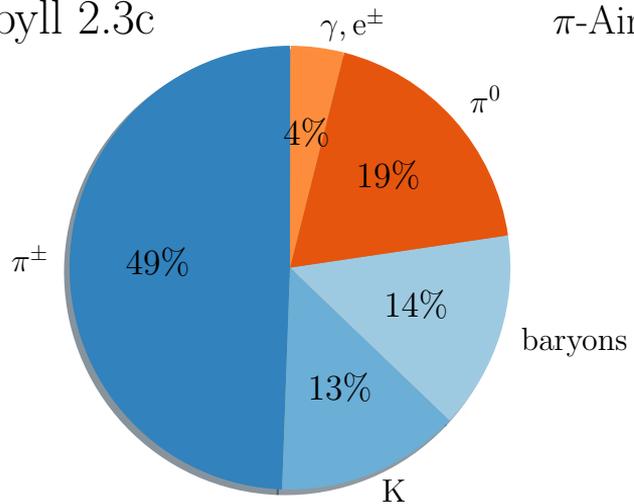
1st interaction energy fraction



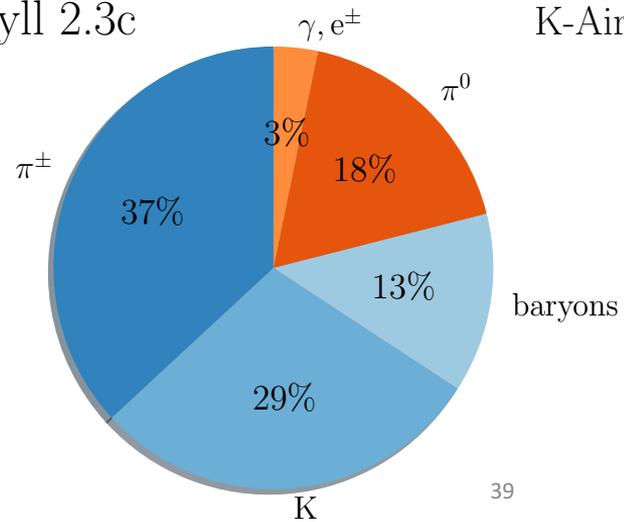
Sibyll 2.3c

 p -Air

Sibyll 2.3c

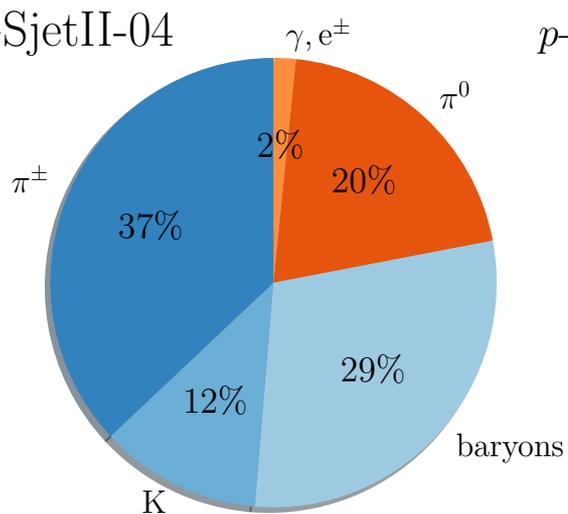
 π -Air

Sibyll 2.3c

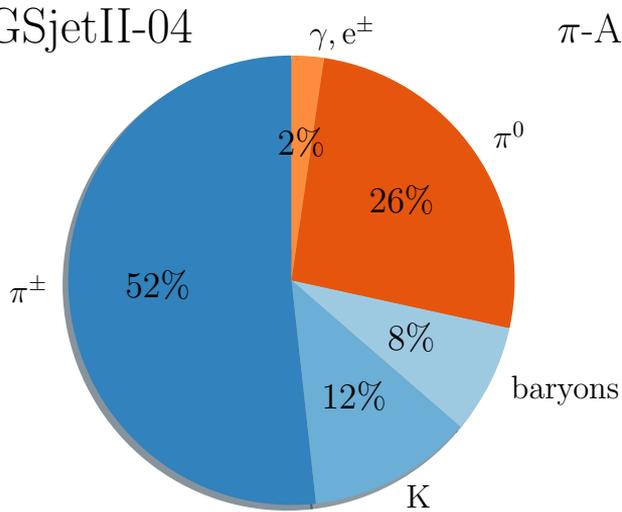


K-Air

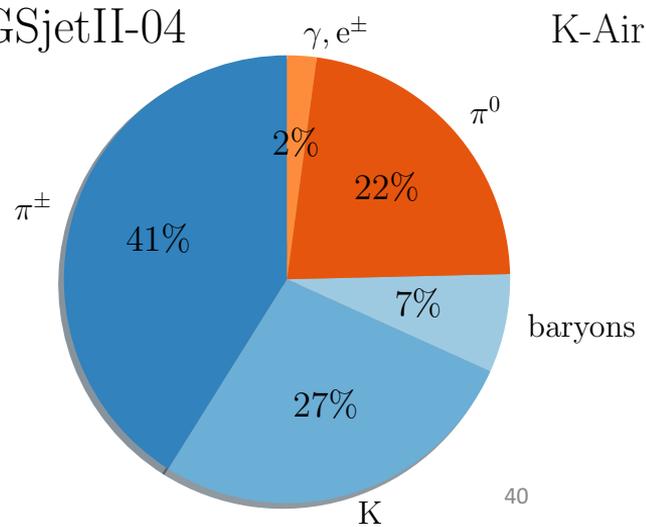
QGSjetII-04



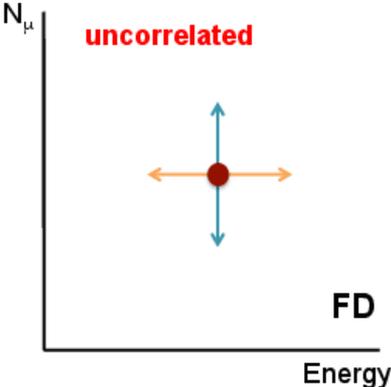
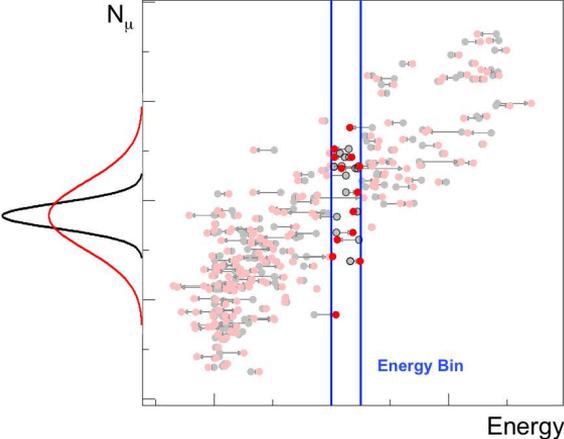
QGSjetII-04

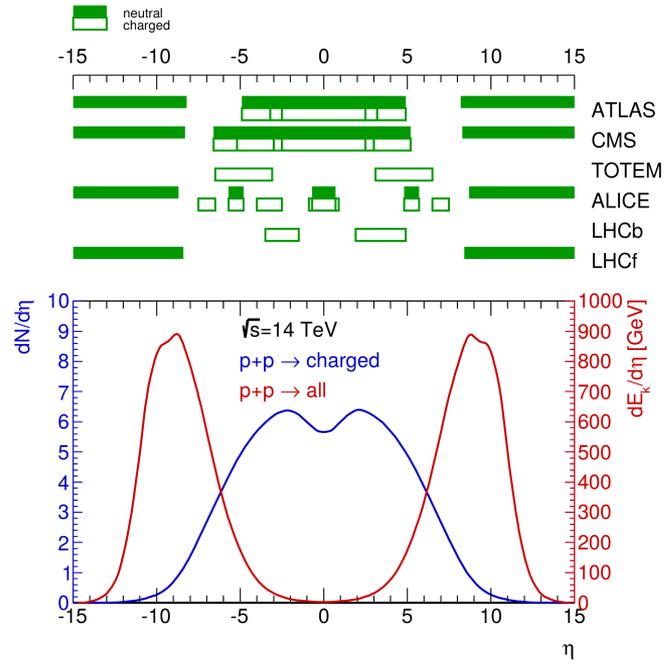


QGSjetII-04



Quick list of experiments





$$\frac{d \ln N_{\mu}}{d \ln E} = \beta$$

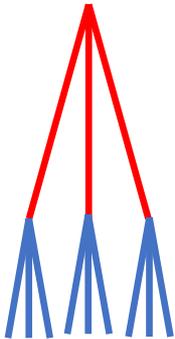
$$\beta = \frac{\ln m}{\ln m_{\text{tot}}}$$

$$\frac{d \ln N_{\mu}}{d \ln E} = \frac{d \ln f_1}{d \ln E} + \beta$$

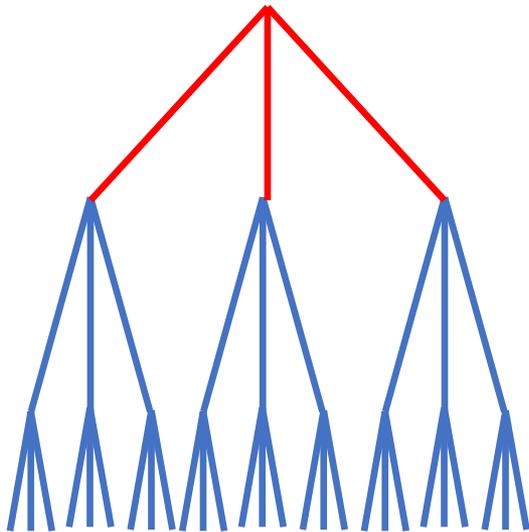
$$\log N_{\mu} = \underline{\log f_i}$$



$$\log N_\mu = \log f_{i-1} + \log f_i$$



$$\log N_\mu = \log f_{i-2} + \log f_{i-1} + \log f_i$$



$$\log N_\mu = \log f_{i-3} + \log f_{i-2} + \log f_{i-1} + \log f_i$$

