

Hadronic Interactions at Ultra High Energies with Extensive Air Showers

Lorenzo Cazon



EXCELENCIA
MARÍA
DE MAEZTU



IGFAE
Instituto Galego de Física de Altas Energías

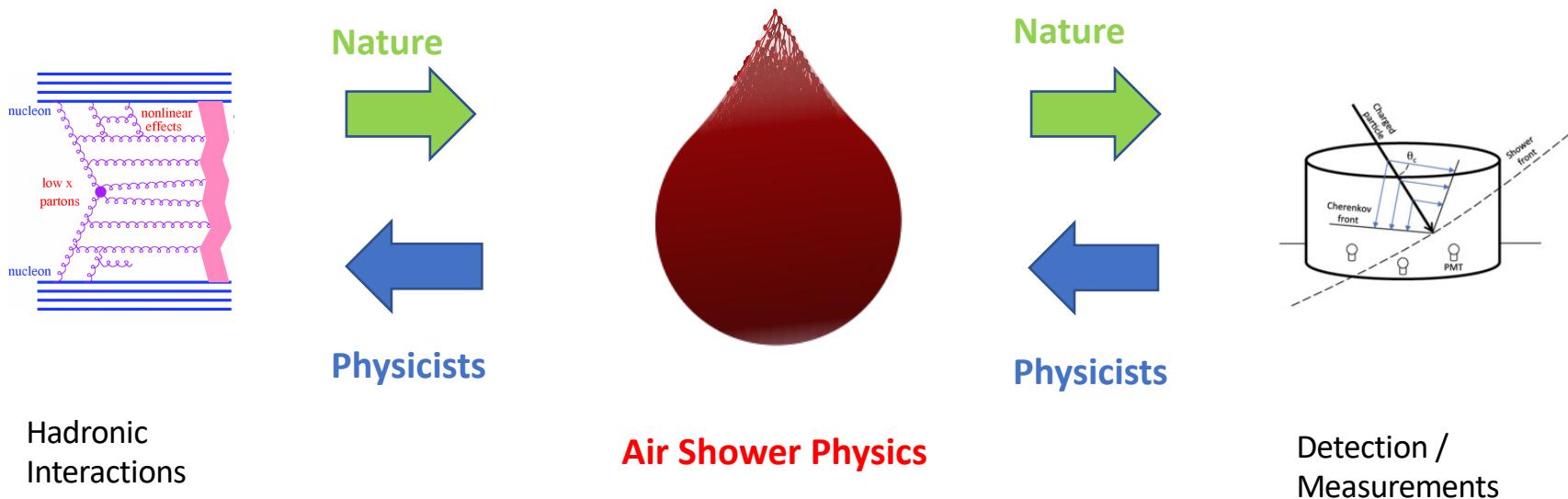


UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA



XUNTA
DE GALICIA

The scope of this talk:



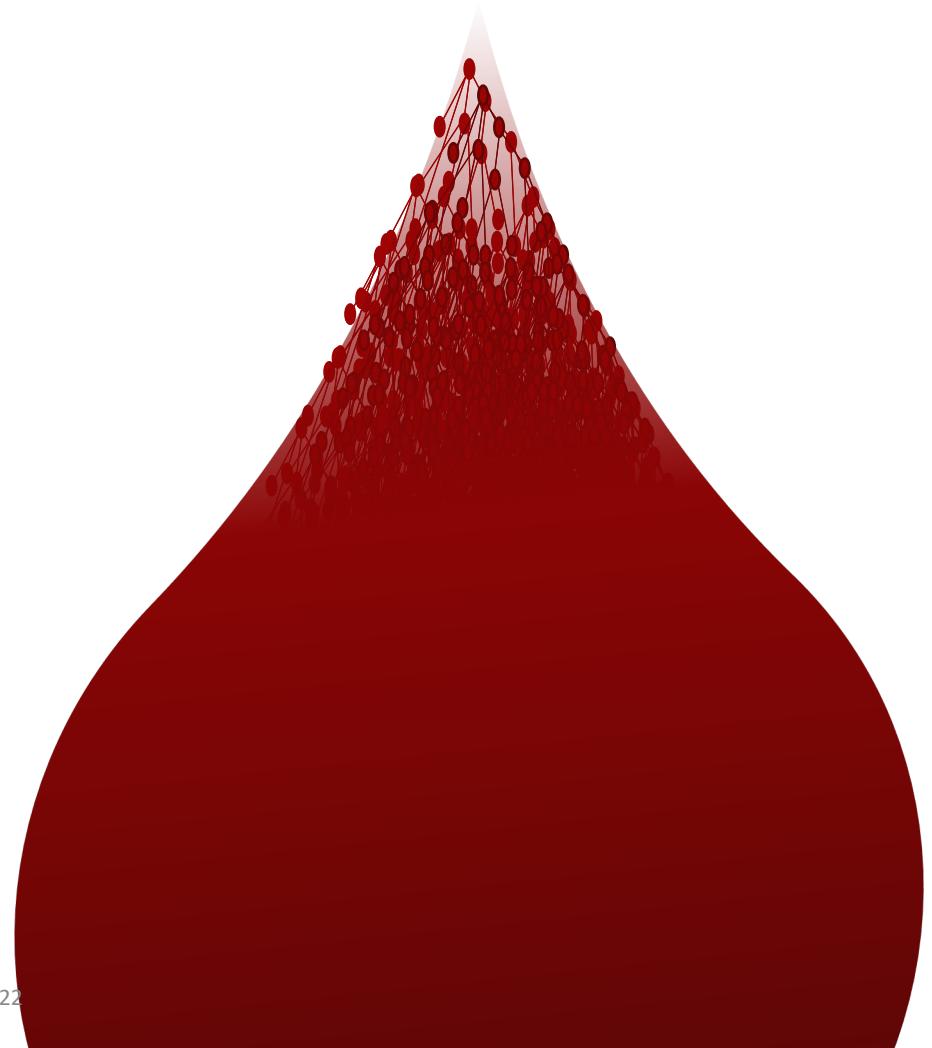
For a complementary review including the connection with the LHC:
Astrophysics and Space Science (2021) arXiv:2105.06148

Extensive Air Showers

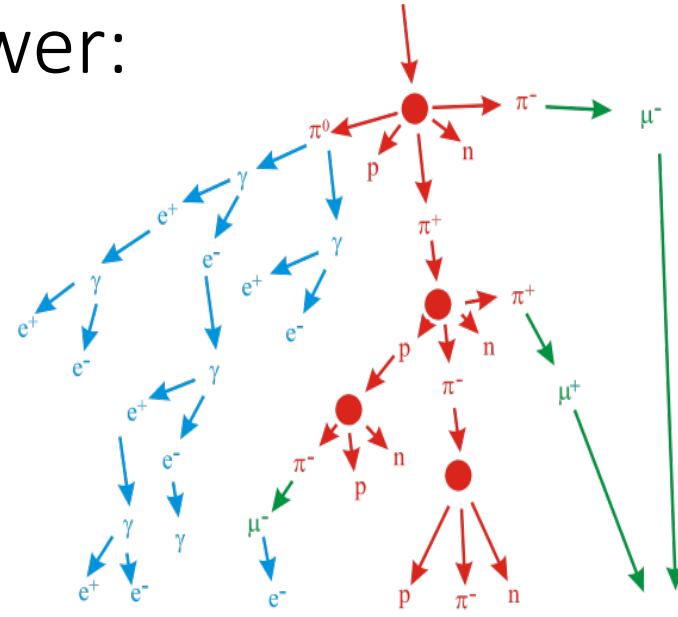
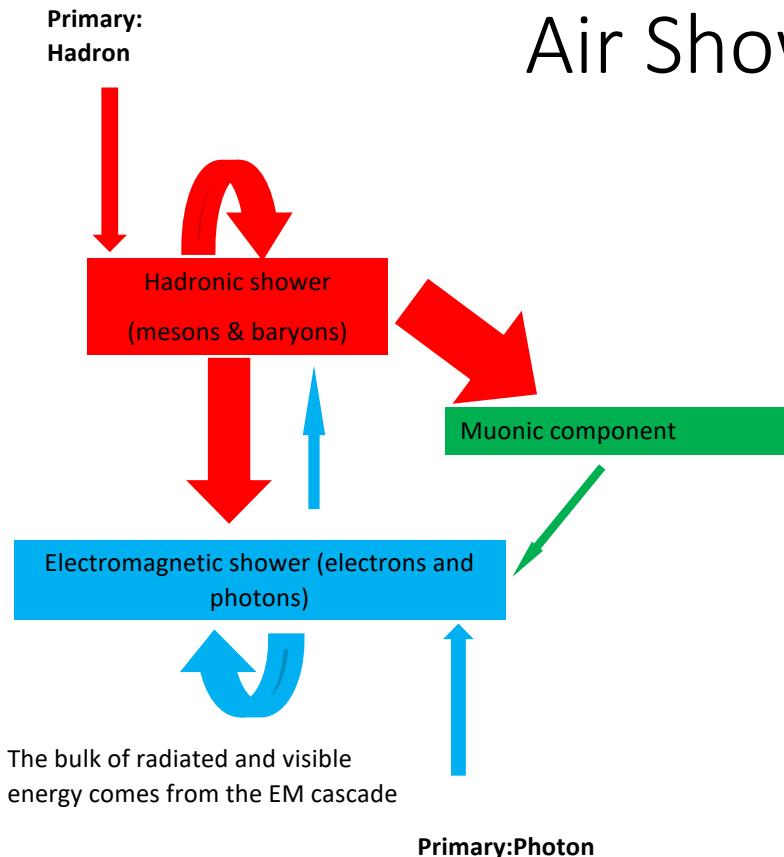
Information is degraded.

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

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

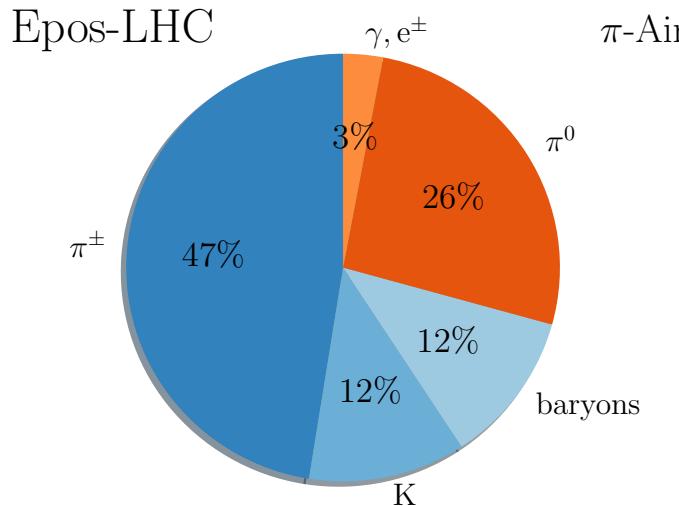
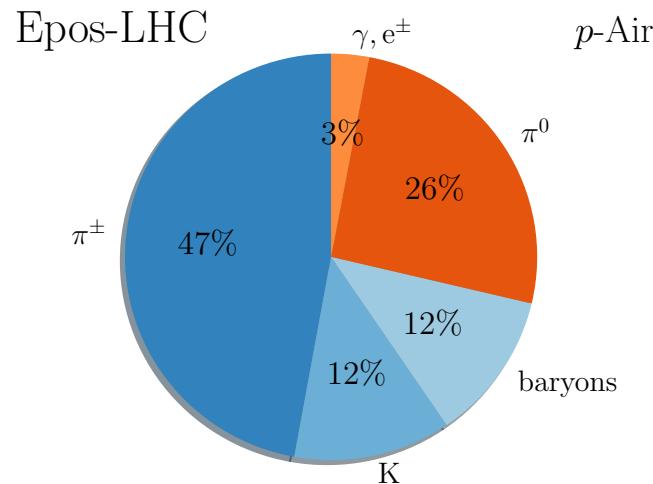


Air Shower:

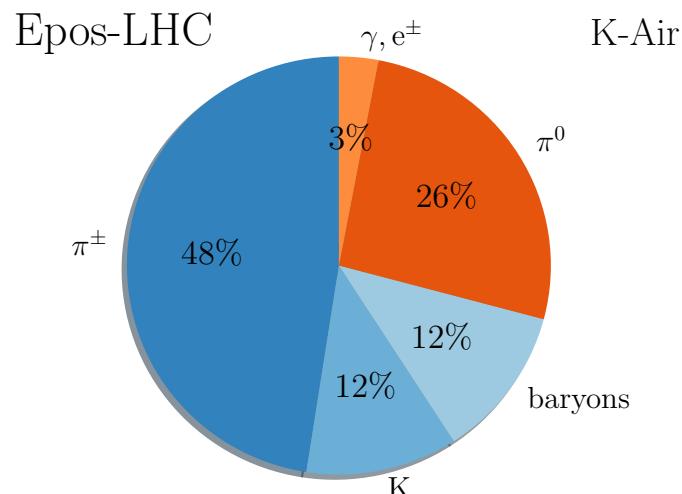


1st interaction multiplicity

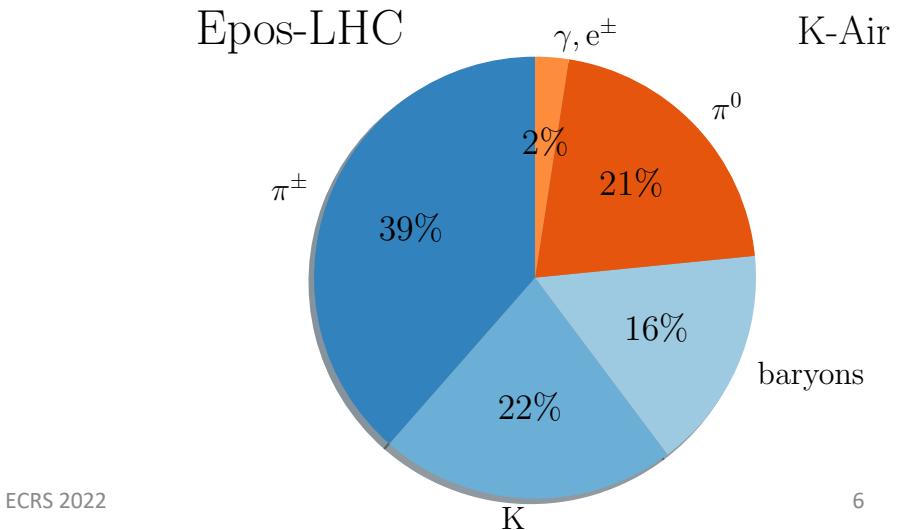
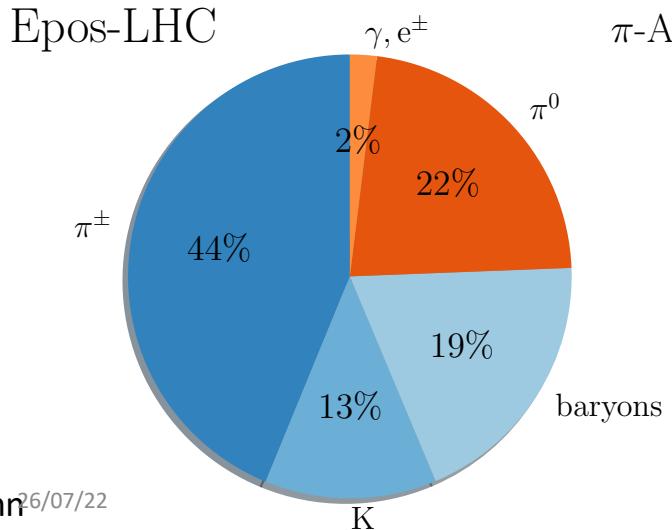
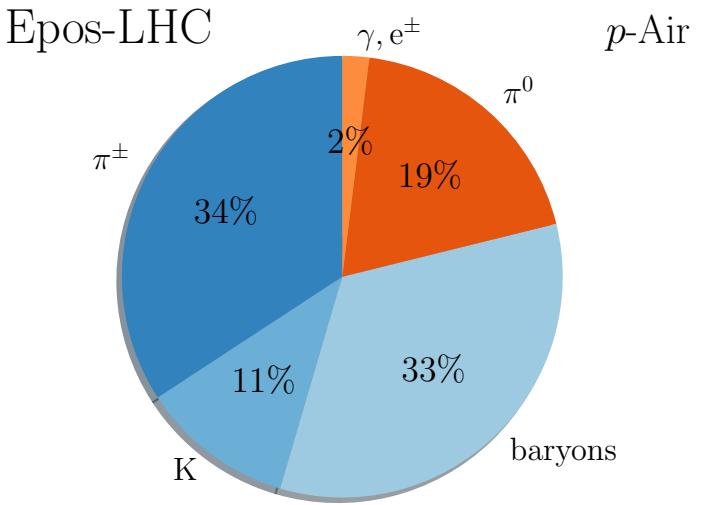
$E=10^{19}$ eV



ECRS 2022

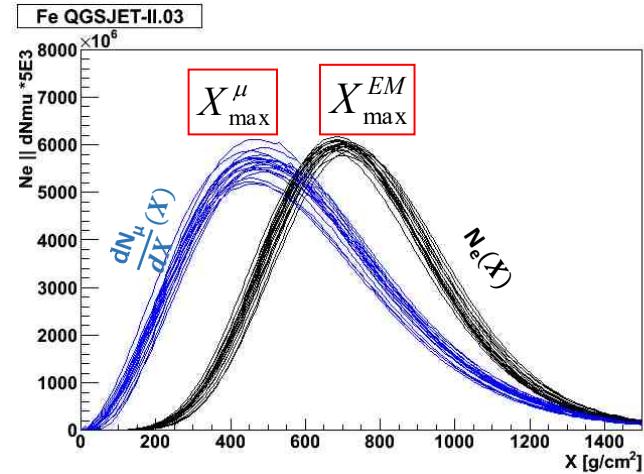
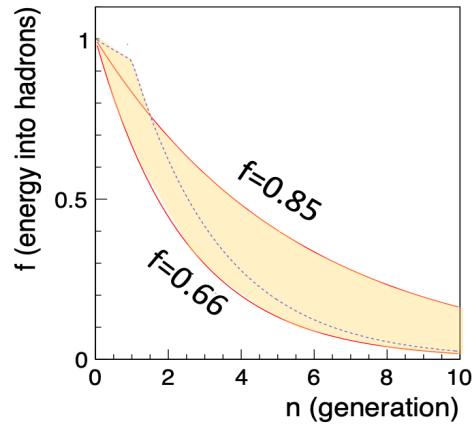
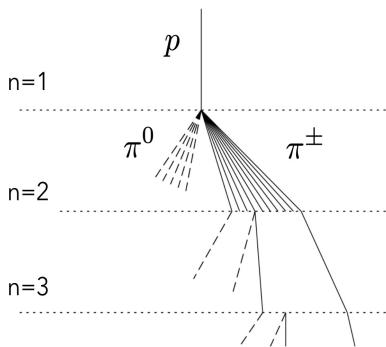


1st interaction energy fraction



Energy Balance of the shower

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

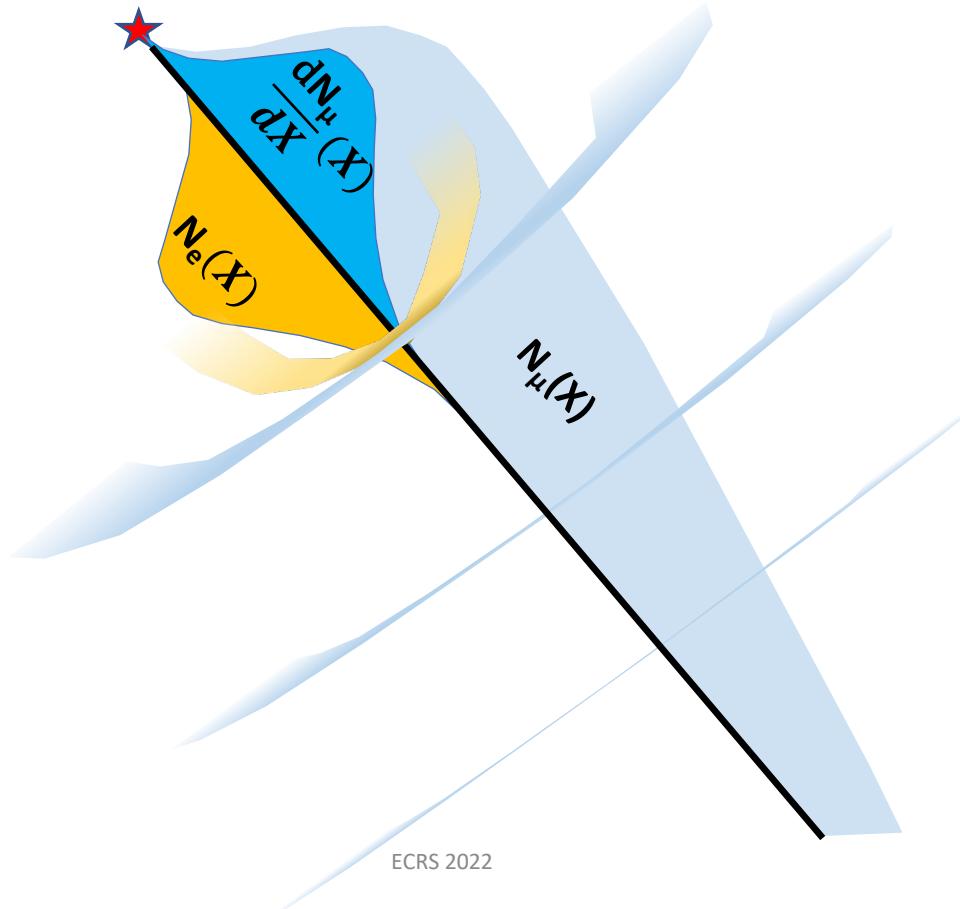


EM cascade takes >50% of its energy from 1st, 2nd and 3rd hadr. generations

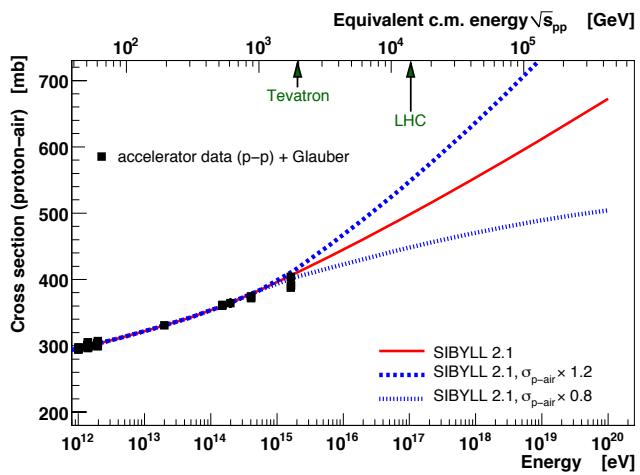
Sensitive to High Energy Physics

Hadronic cascade: Keeps developing until critical energy of mesons.

Sensitive to High & Low Energy Physics.



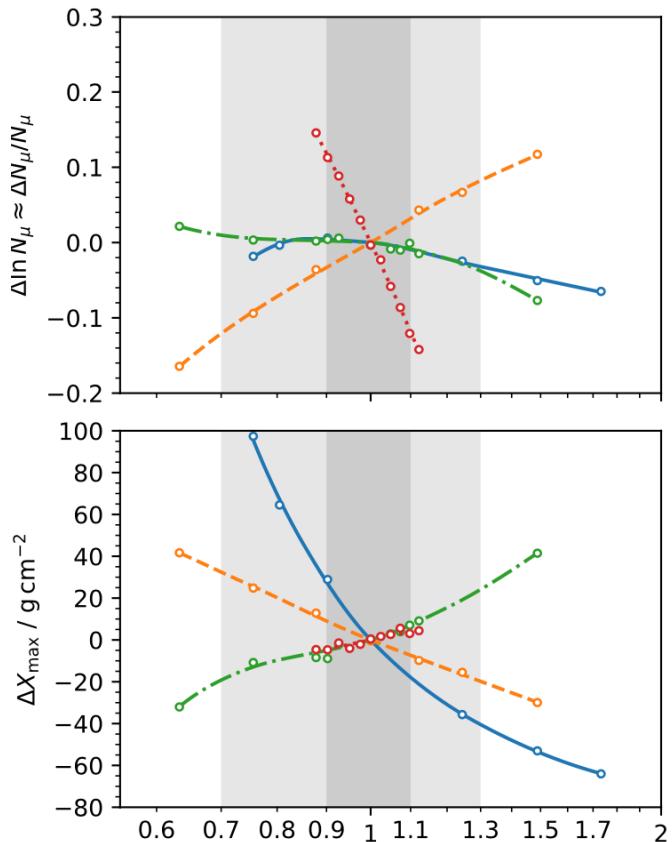
Impact of hadronic parameters



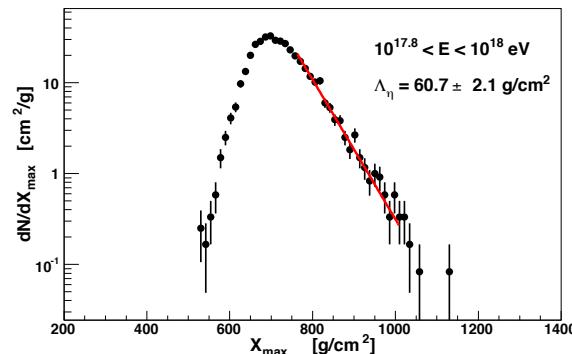
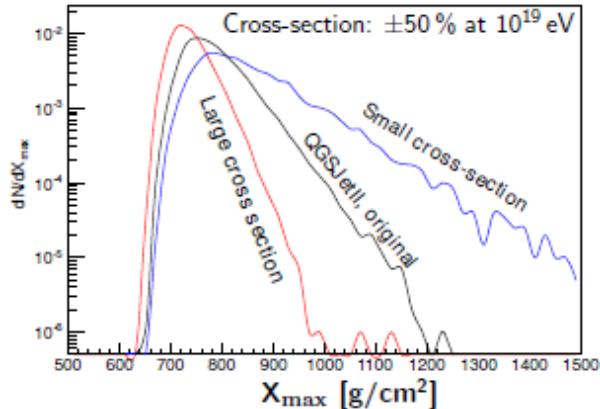
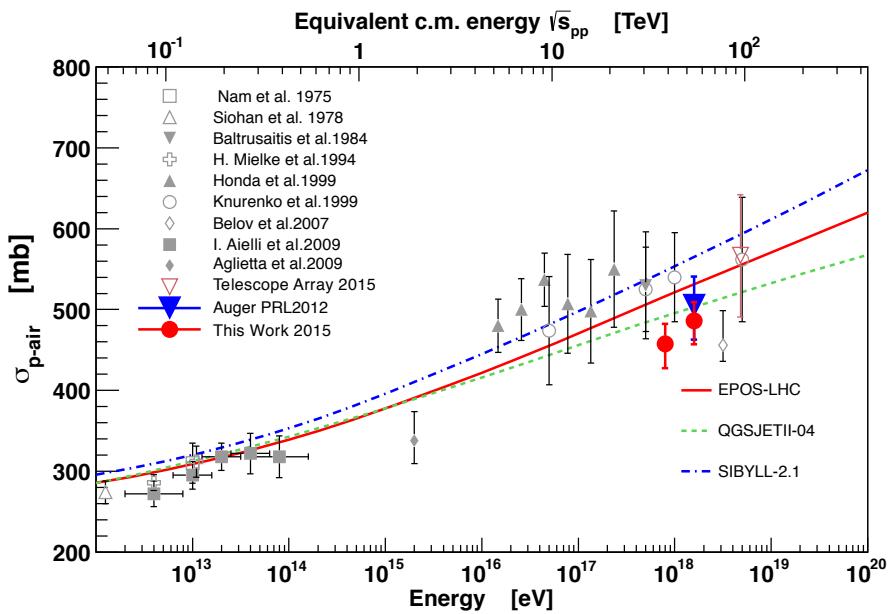
Smooth parameter modification,
benchmarked at 10^{19} eV, f_{19}

CONEX SIBYLL-2.1 p @ $10^{19.5}$ eV

- cross-section
- - - multiplicity
- · - elasticity
- π^0 -fraction

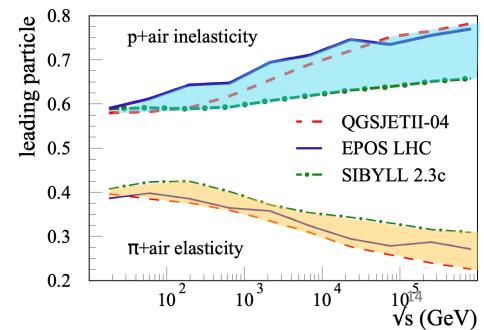
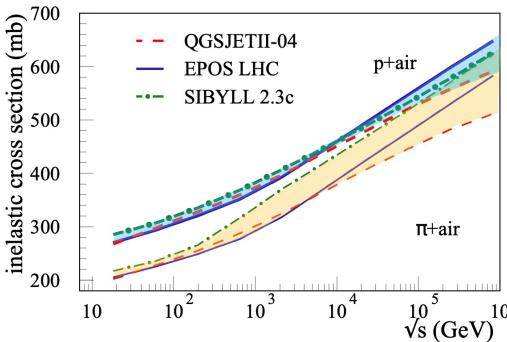
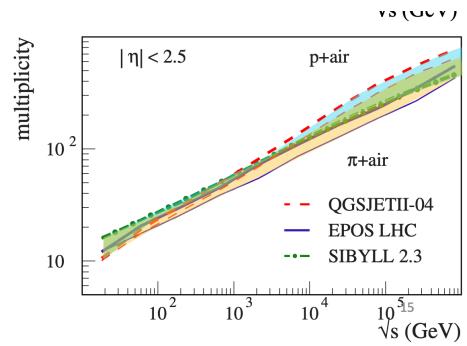
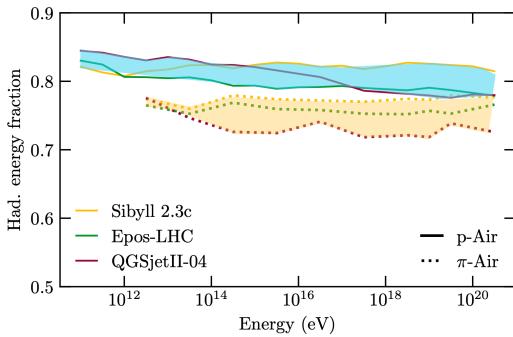


p-Air cross section



Interaction uncertainties

- Model extrapolations beyond LHC phasespace have uncertainties
- It is not guaranteed that actual values are bracketed by those predictions



The shower components

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

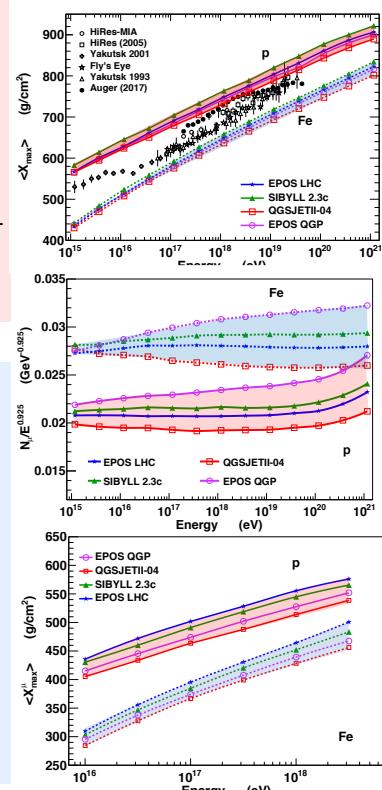
Universality of lateral distribution, energy distribution, angular distribution, and arrival time.

S. Lafebre 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

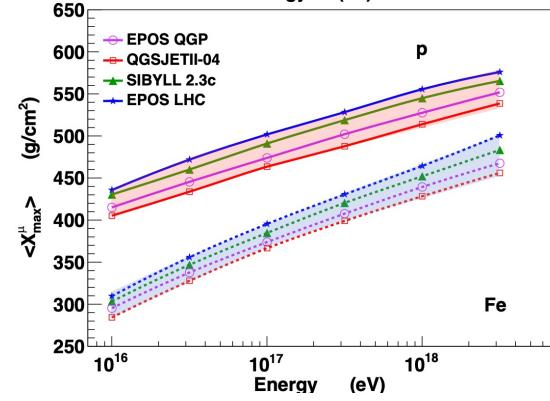
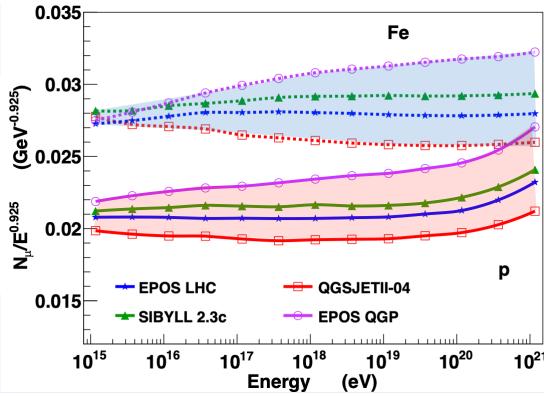
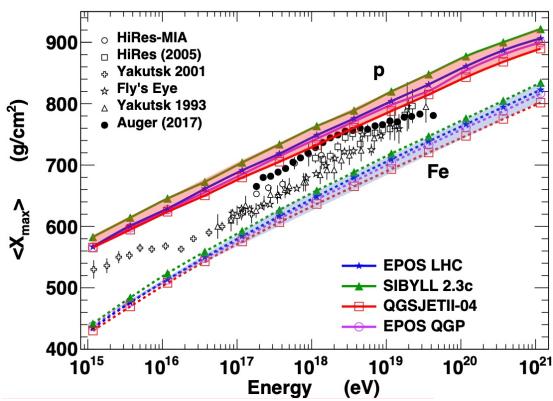
M. Giller et al. J. Phys. G 30 (2004) 97.



- Muon: N_μ , X_{\max}^μ have larger model uncertainties.

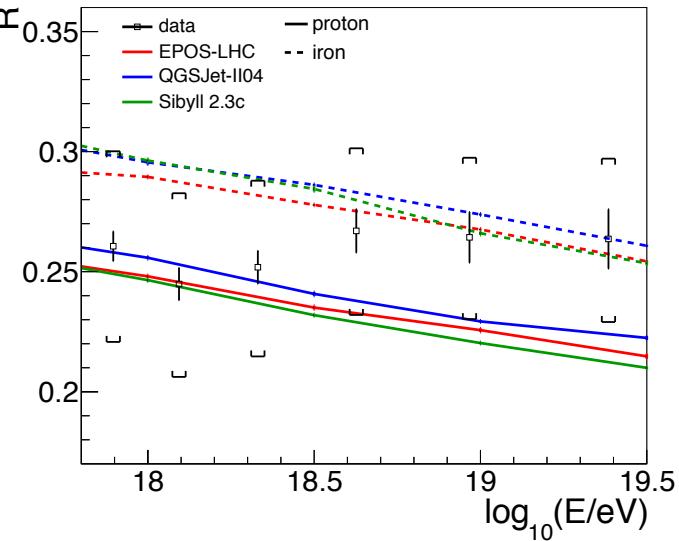
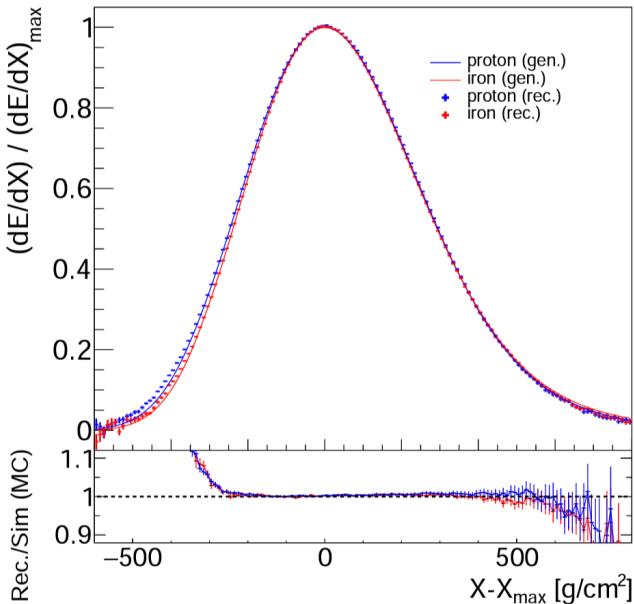
Universal distribution at production:

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



EM average profile

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



$$L = \sqrt{|X'_0| \lambda}$$

$$X'_0 = X_0 - X_{\max}$$

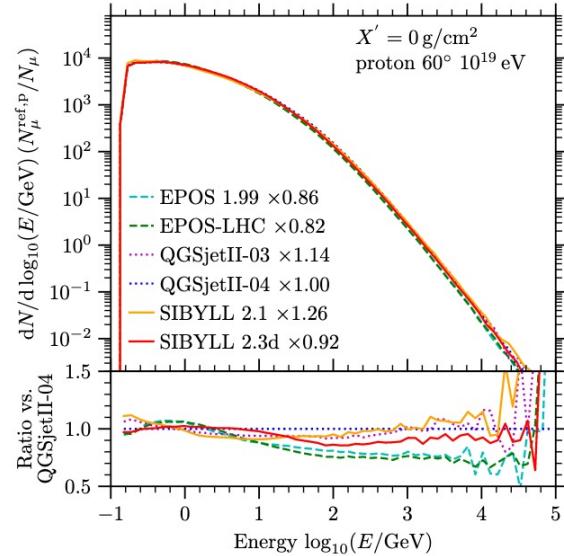
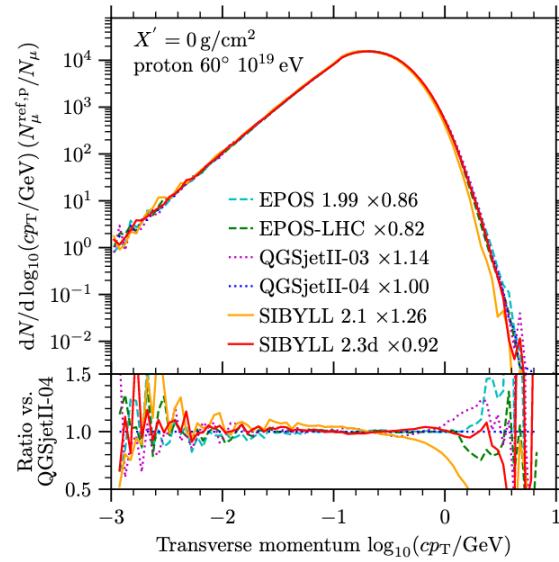
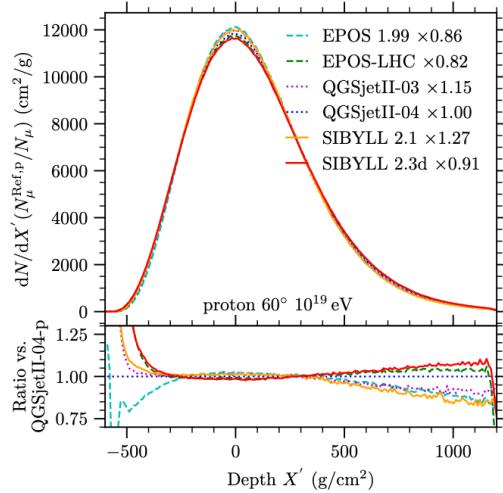
$$R = \sqrt{\lambda / |X'_0|},$$

Good agreement with models.

Too large systematics for hadronic physics, for the moment.

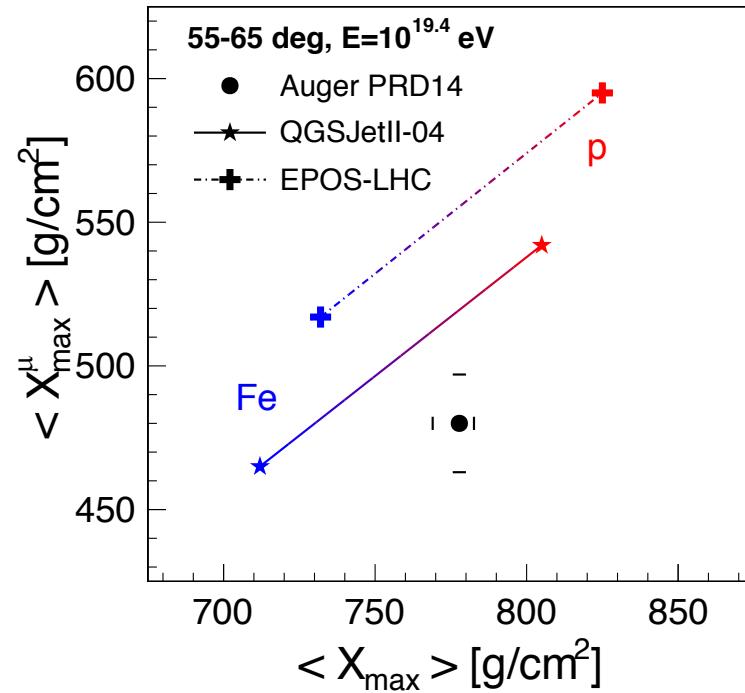
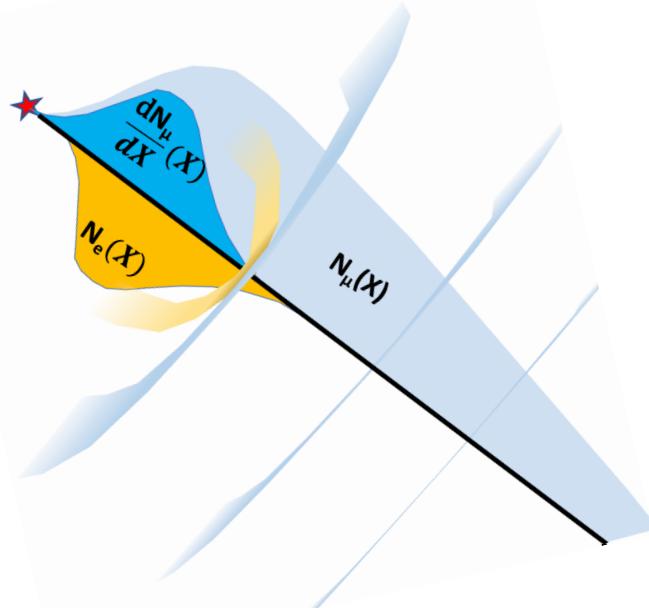
R is sensitive to the injection of **high energy π^0** in the start up of the shower.

Universality of the Muon Production Distributions



Measurements

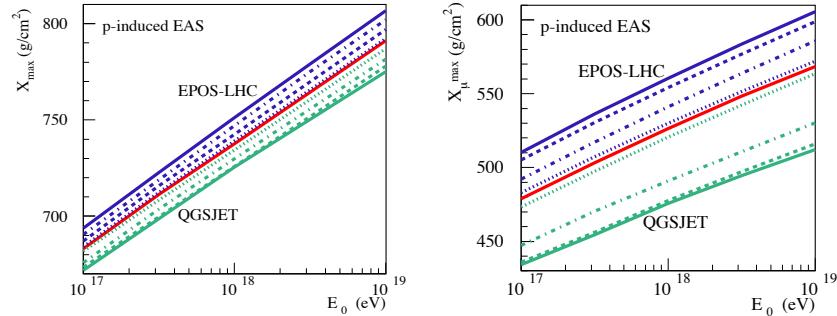
Muon Production Depth : $\langle X_{\max}^{\mu} \rangle$



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:
 - 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

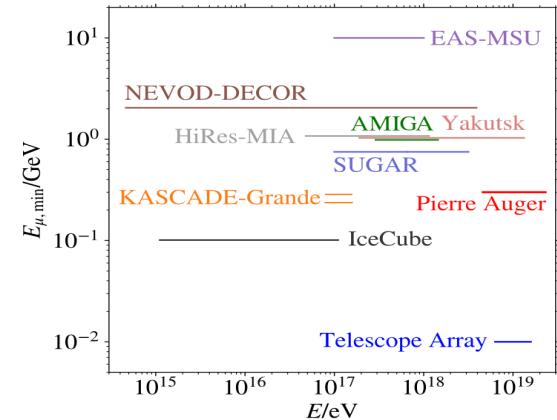
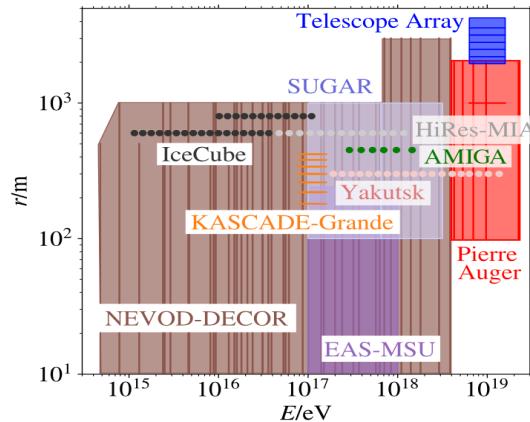
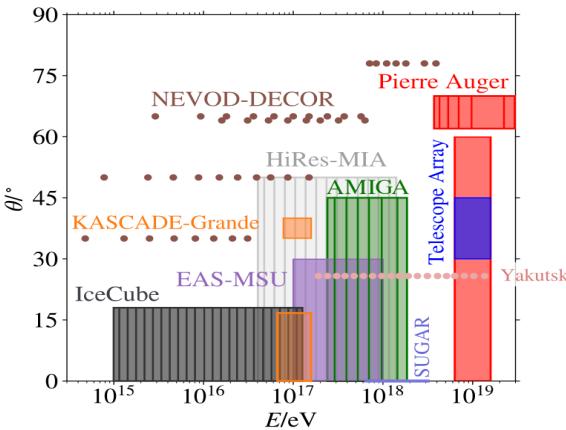
Change in $\langle X_{\max}^{\mu} \rangle \sim 50 \text{ g cm}^{-2}$
corresponds to
change in $\langle X_{\max} \rangle \sim 15 \text{ g cm}^{-2}$

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

Working group on Hadronic Interactions and Shower Physics

- Meta-analyses of **muon surface densities** at ground of 9 experiments
- Very different experimental conditions
- A new variable to make the comparisons: z
- z depends on the HM

$$z = \frac{\ln N_\mu - \ln N_\mu^p}{\ln N_\mu^{Fe} - \ln N_\mu^p}$$



Experiments Typology

Shower energy
(optical) and
muon density
(SD)

- AUGER
- AMIGA
- TA
- Yakutsk*

Shower energy
(SD) and muon
density (SD)

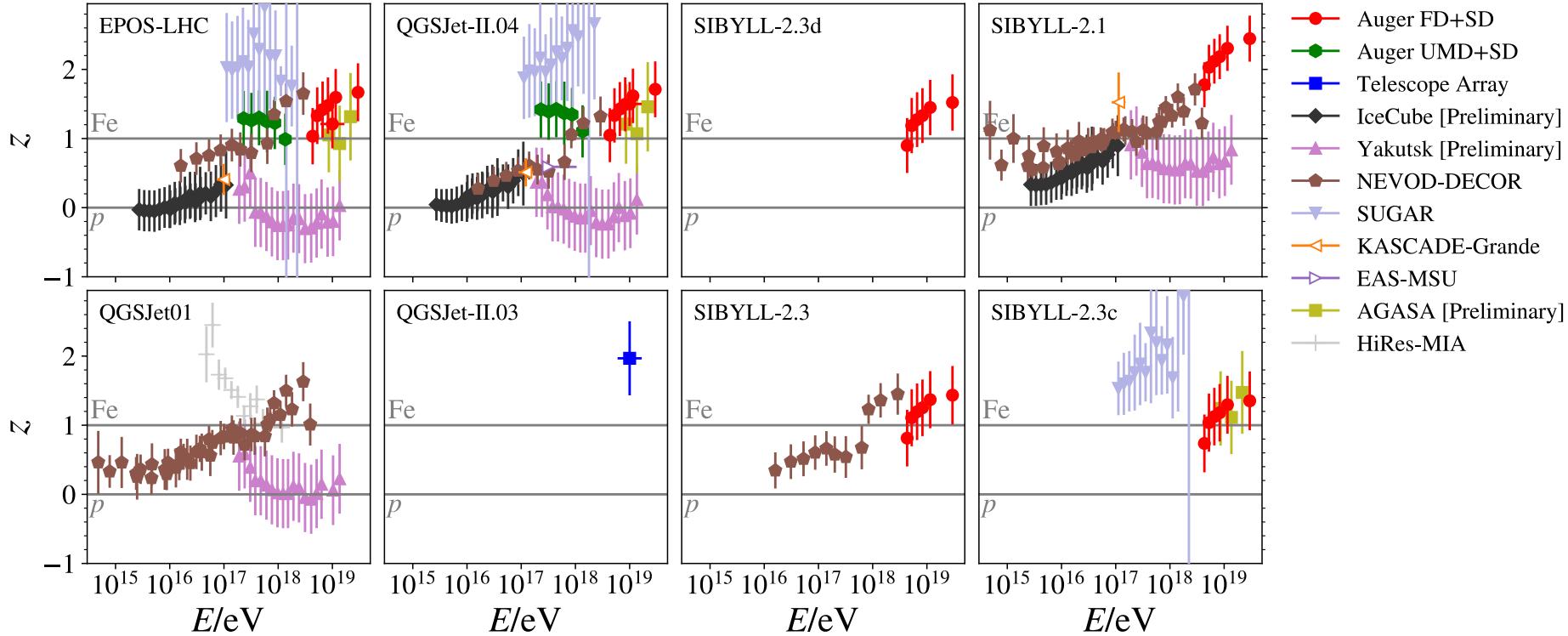
- IceCube
- AGASA

Electron
density (SD)
and muon
density (SD)

- Kascade-
Grande
- EAS-MSU

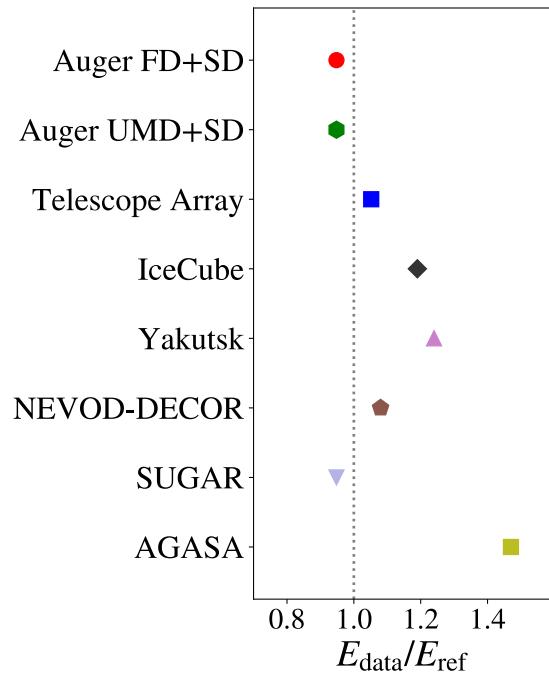
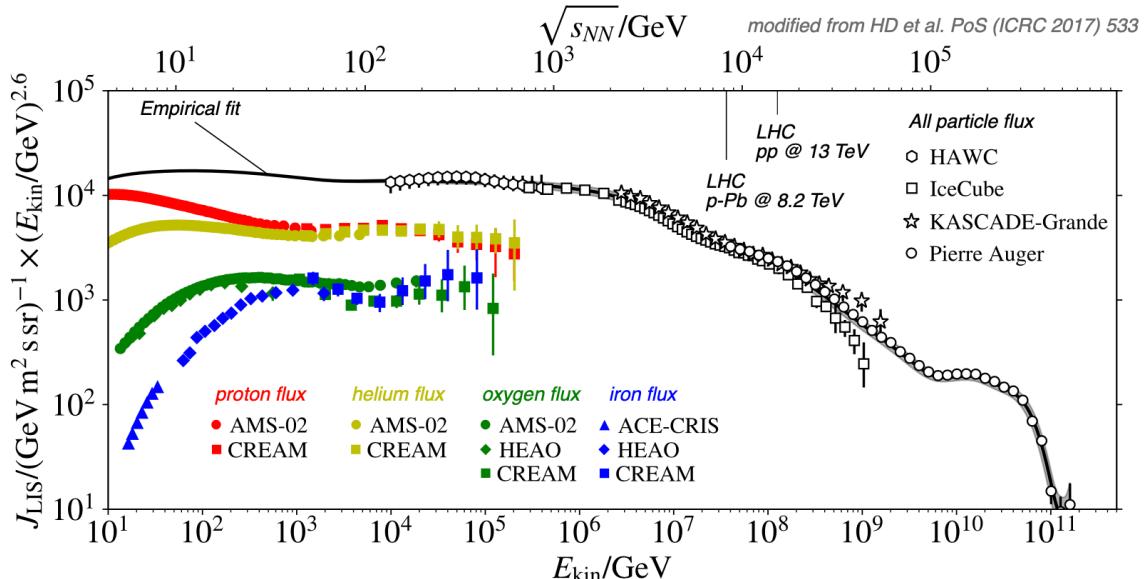
Muon density
(SD)

- NEVOD-
DECOR
- SUGAR



Energy rescaling to match spectra

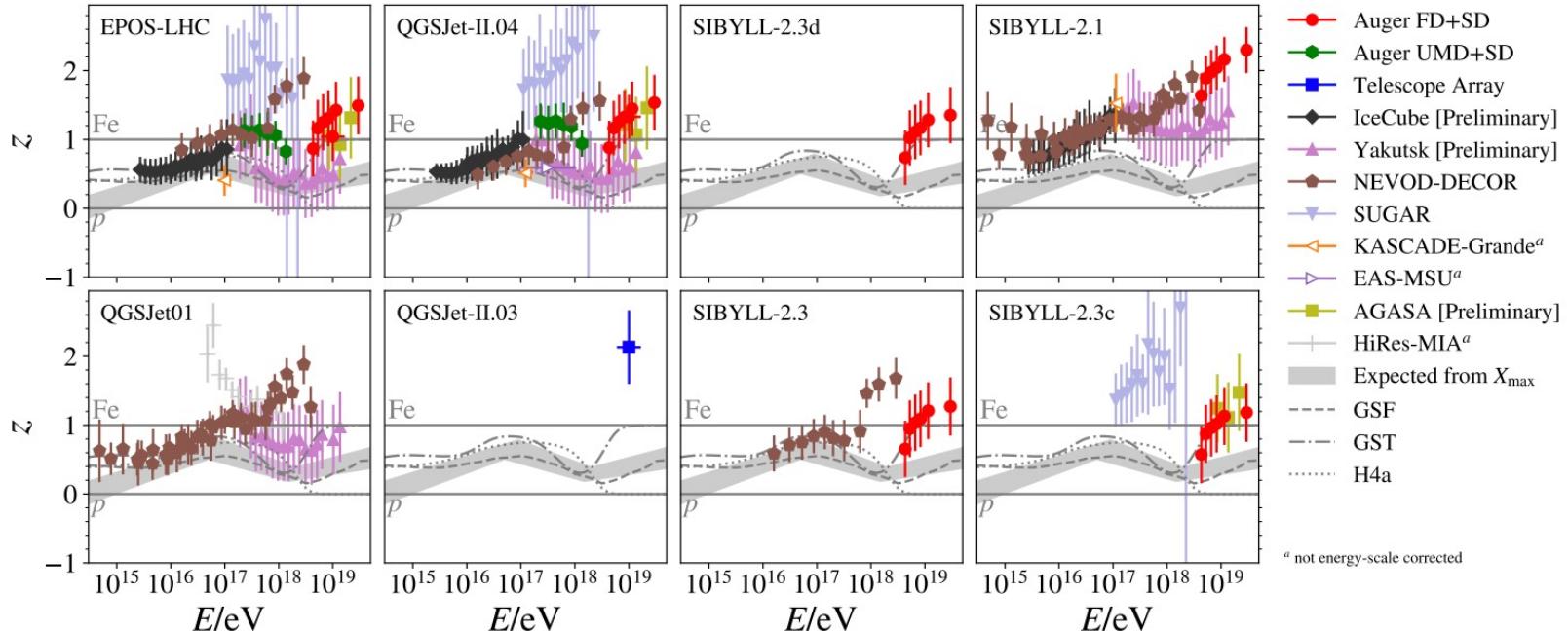
$$N_\mu \propto E^{0.93}$$



WHISP results on muon deficit

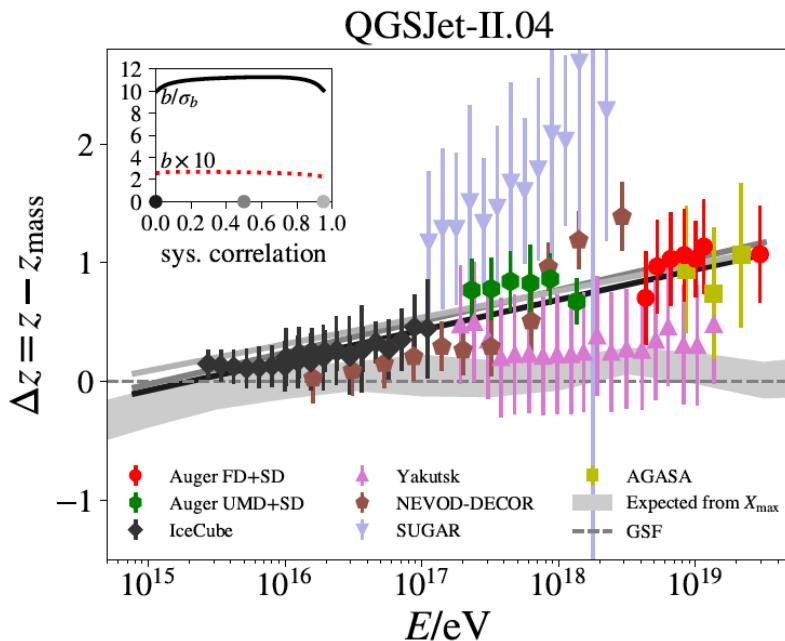
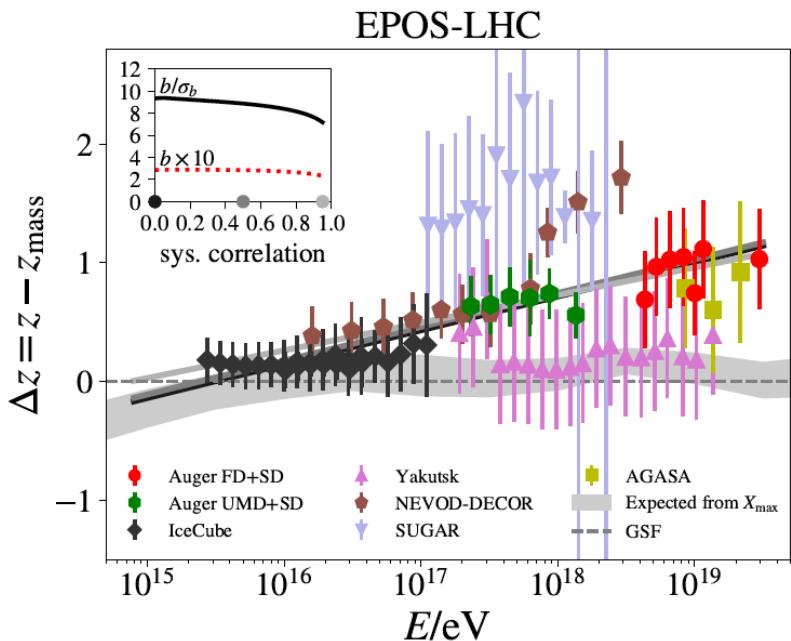
(aka muon excess in data)

$$z = \frac{\ln N_\mu - \ln N_\mu^p}{\ln N_\mu^{Fe} - \ln N_\mu^p} \simeq 3 \ln \frac{N_\mu}{N_\mu^p}$$



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

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



Significance $>> 8 \sigma$

Muon E-spectrum

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

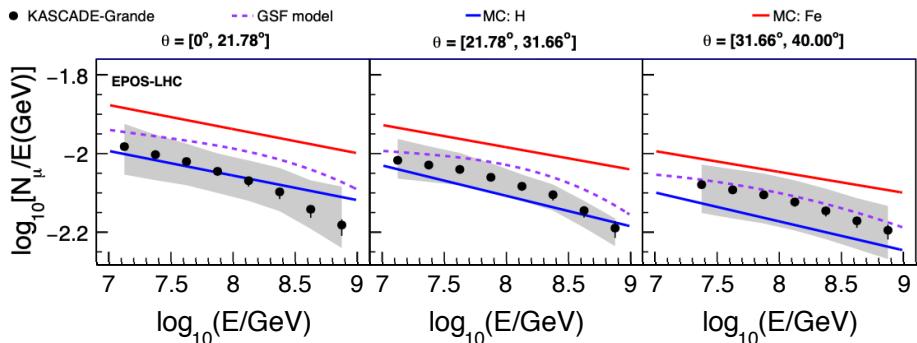
NO EVIDENCE OF A CHANGE (BY WHISP)

scanning zenith angles = scanning different energies at production

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

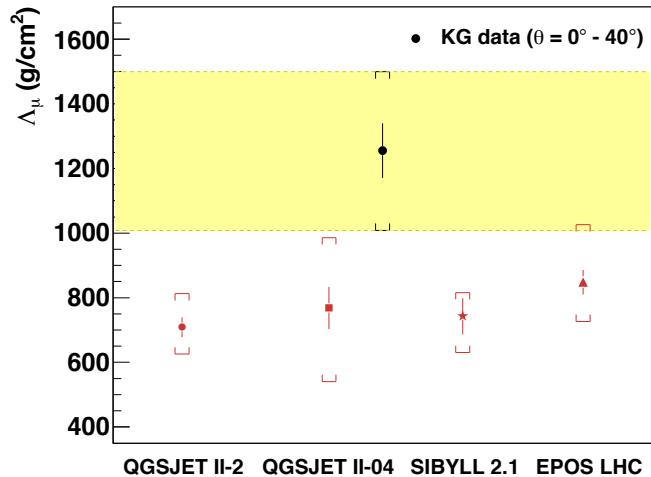
Experiment	$E_{\text{data}}/E_{\text{ref}}$	$\sec \theta$	$E_{\mu \text{ prod}}/\text{GeV}$
EAS-MSU	-	1.1	11.9
IceCube Neutrino Observatory	1.19	1.0	0.7
KASCADE-Grande	-	1.0 , 1.3	1.5 , 2.1
NEVOD-DECOR	1.08	2.3 , 4.8	8.4 , 18.6
Pierre Auger Observatory	0.948	1.3 , 2.4	1.8 , 4.0
AMIGA	0.948	1.2	2.4
SUGAR	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(ICRC2021)376

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



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

Reasons for different muon E-spectrum

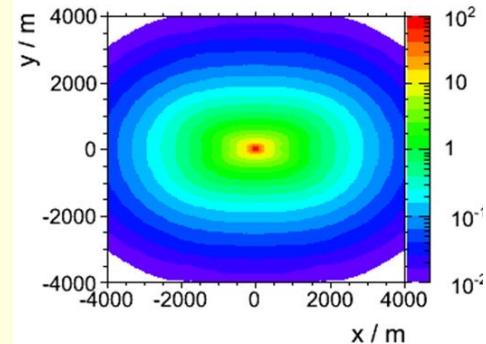
$$\xi_{crit}^{\pi^\pm} \sim \mathcal{O}(100 \text{ GeV})$$
$$\xi_{crit}^{K^\pm} \sim \mathcal{O}(1000 \text{ GeV})$$
$$\xi_{crit}^{K_L^0} \sim \mathcal{O}(200 \text{ GeV})$$

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

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

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



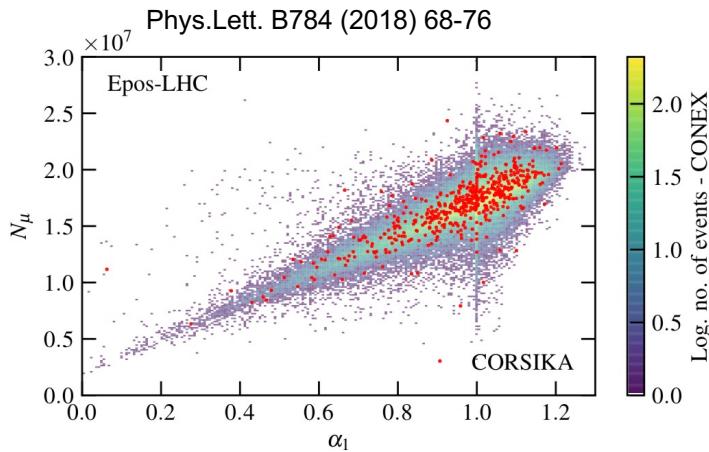
Transverse Momentum Distribution ($\text{pt} < 2 \text{ GeV}$) - No results

- **No demonstrated deviations** wrt universal expectations at the bulk of EAS muons ($\text{pt} < 2 \text{ GeV}$)
 - 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

See [Astrophysics and Space Science \(2021\)](#)
[arXiv:2105.06148](#) for a comprehensive list of results on
 $\text{pt} > 2 \text{ GeV}$ and other muon atmospheric fluxes

Shower-to-Shower correlation of N_μ with 1st interaction variables



hadr. multiplicity

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

$$\frac{N_\mu (N_\mu^{\text{prod}})}{\alpha_1} \quad 0.79 (0.82)$$

$$\alpha = \sum_{i \in \text{hadr}}^m \left(\frac{E_i}{E_0} \right)^\beta$$

$$N_\mu \propto \alpha_1 \cdot \alpha_2 \cdot \dots \cdot \alpha_c \quad \beta = 0.93$$

$$E_{\text{had}}/E \quad 0.67 (0.66)$$

hadr. energy fraction

$$N_\mu = f_1 \cdot f_2 \cdot \dots \cdot f_c \cdot \frac{E_o}{\xi_c} \quad \beta \rightarrow 1$$

$$\kappa_{\text{inel}} \quad -0.15 (-0.08)$$

$$\begin{aligned} m_1/m_{\text{tot}} & 0.16 (0.18) \\ X_0 & 0.23 (0.12) \end{aligned}$$

In most practical cases $\alpha \simeq f$

$$\epsilon^* \quad -0.01 (-0.08)$$

N_μ Fluctuations

$$N_\mu = f_1 \cdot f_2 \cdot \dots \cdot f_c \cdot \frac{E_o}{\xi_c}$$

carries 70% of the fluctuations for protons!!!



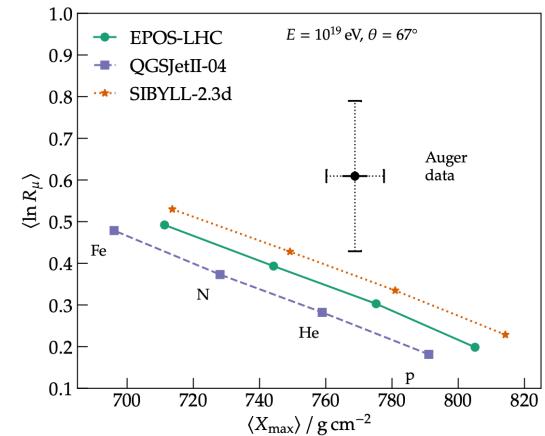
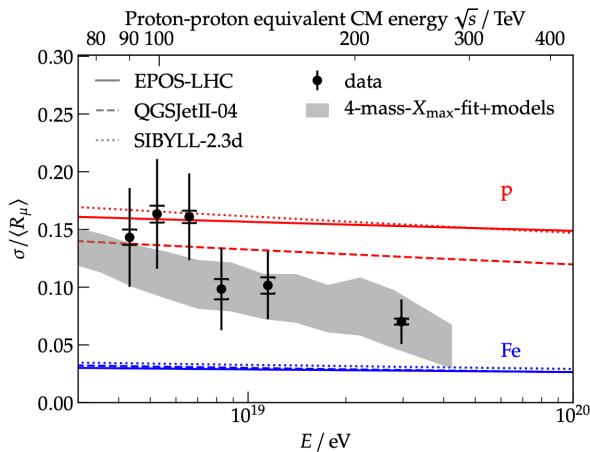
$$\sigma(f_n) = \frac{\sigma(f)}{\sqrt{m_1 m_2 \dots m_n}}$$

$$\left(\frac{\sigma(N_\mu)}{N_\mu}\right)^2 = \left(\frac{\sigma(f_1)}{f_1}\right)^2 + \left(\frac{\sigma(f_2)}{f_2}\right)^2 + \dots + \left(\frac{\sigma(f_c)}{f_c}\right)^2$$

- 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** $\sigma(f_n) \rightarrow 0$
 - 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 energy share in the **1st interaction** are **well described** by models.
Large deviations of expectations in 1st interaction are disfavored.



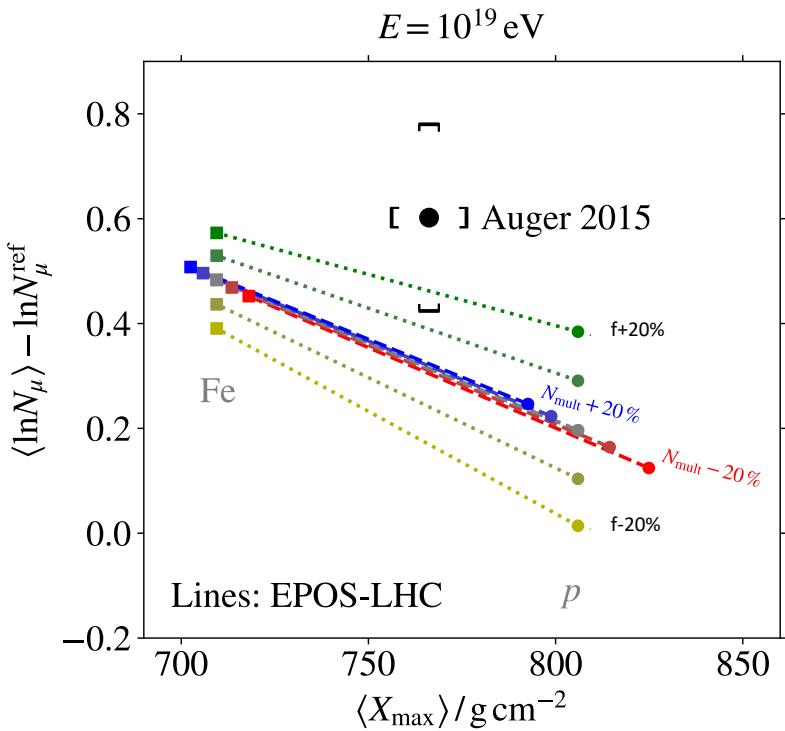
Auger Collab. *PRL* 126 (2021) 15, 152002

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

Solving the muon puzzle by increasing f :

String percolation

Strange Fireball

Chiral Symmetry Restoration

Core-Corona(QGP)

Lorentz Invariance Violation

astro-ph:1209.6474

PRD 95(2017) 06005

EPJ Web Conf. 53(2013) 07007

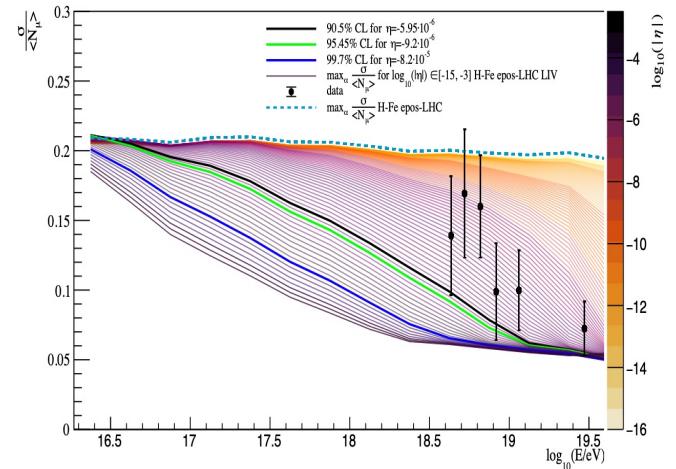
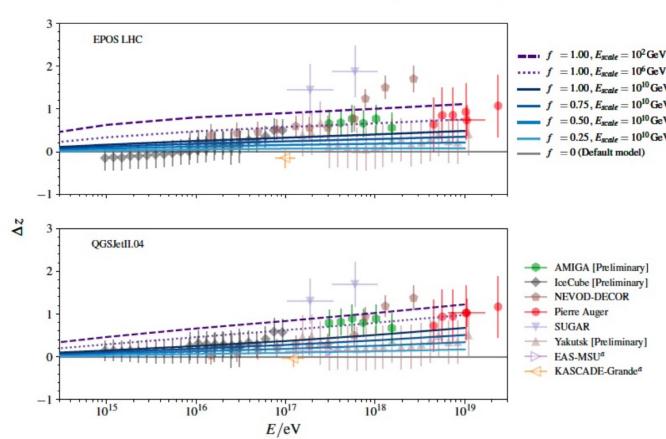
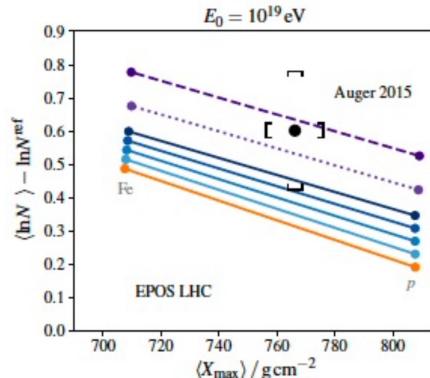
PoS(ICRC2021)469

PoS ICRC2021 (2021) 340

They must keep compatibility with the other variables

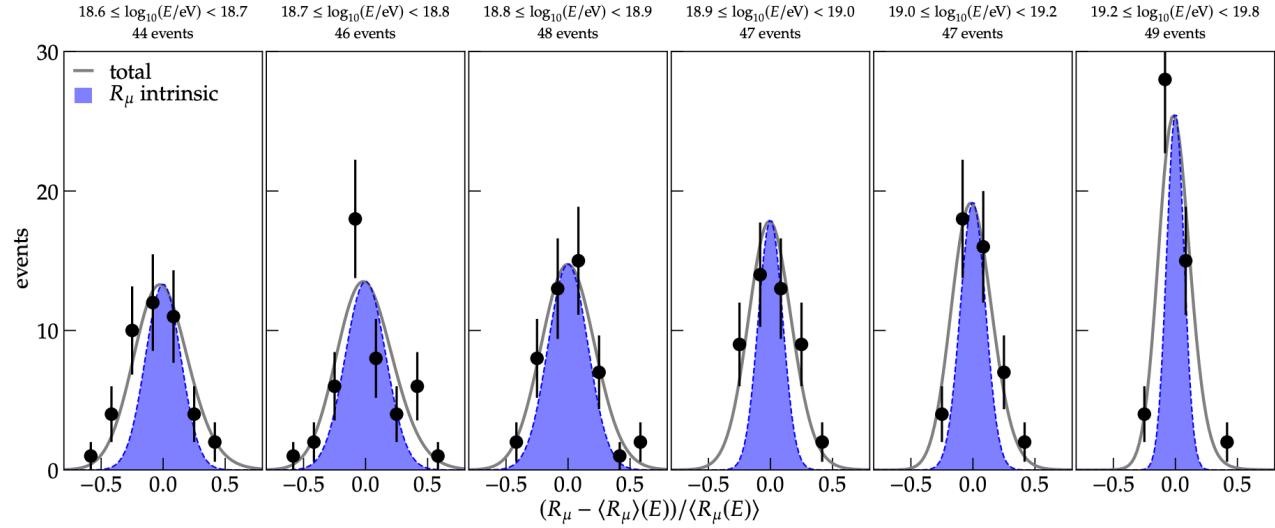
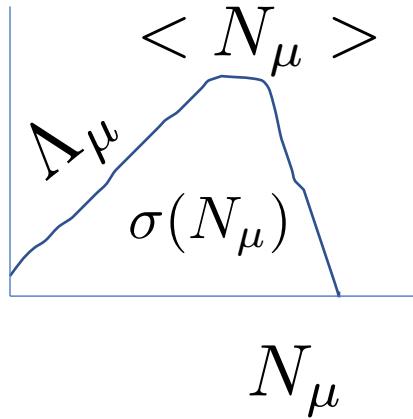
LIV violation saturates f ($f=1$) reducing the muon fluctuations \rightarrow limits on LIV

S. Baur, HD, M. Perlin, T. Pierog, R. Ulrich, K. Werner, arXiv:1902.09265



- Toy model with statistical hadronization (core) in addition to string/remnant fragmentation (corona)
 - Statistical hadronization needed to describe strangeness enhancement seen by ALICE
 - Can close muon number gap number in air showers and matches faster increase with energy

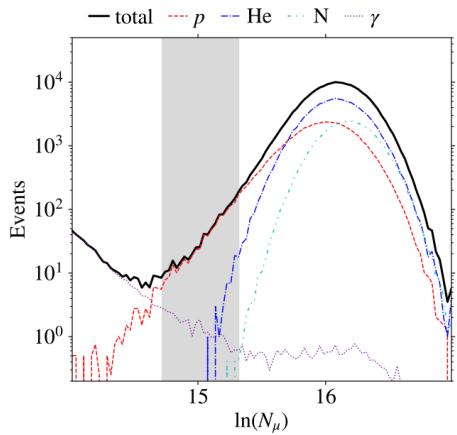
Towards the full N_μ distribution



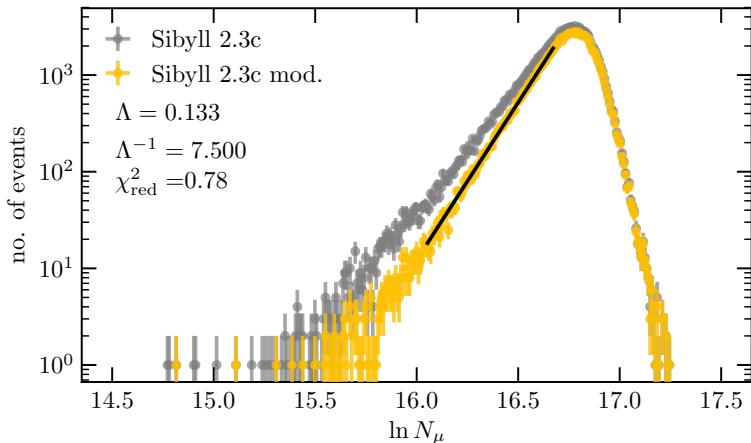
Auger Collab. *PRL* 126 (2021) 15, 152002

To attain maximum physics output, we need to measure all other moments, or the full distribution:

$$\begin{aligned} & \langle N_\mu \rangle, \quad \sigma(N_\mu), \quad \Lambda(N_\mu), \\ & \langle X_{\max} \rangle, \quad \sigma(X_{\max}), \quad \Lambda(X_{\max}) \\ & \langle X_{\max}^\mu \rangle, \quad \sigma(X_{\max}^\mu), \quad \Lambda(X_{\max}^\mu) \end{aligned}$$

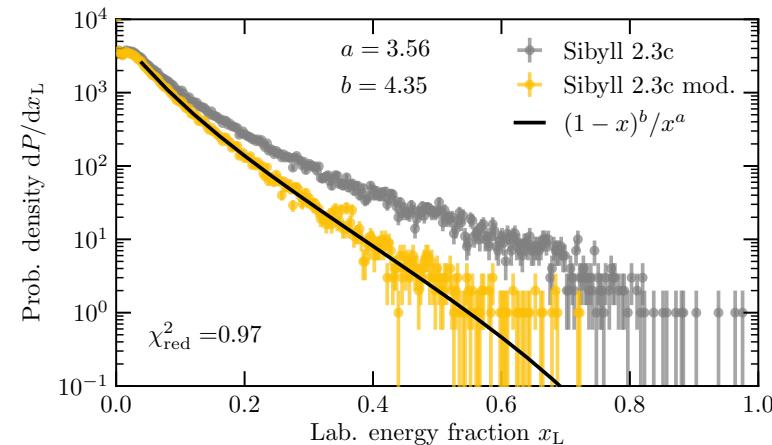


Low N_μ tail is a direct consequence of inclusive π^0 production cross section at large x_L

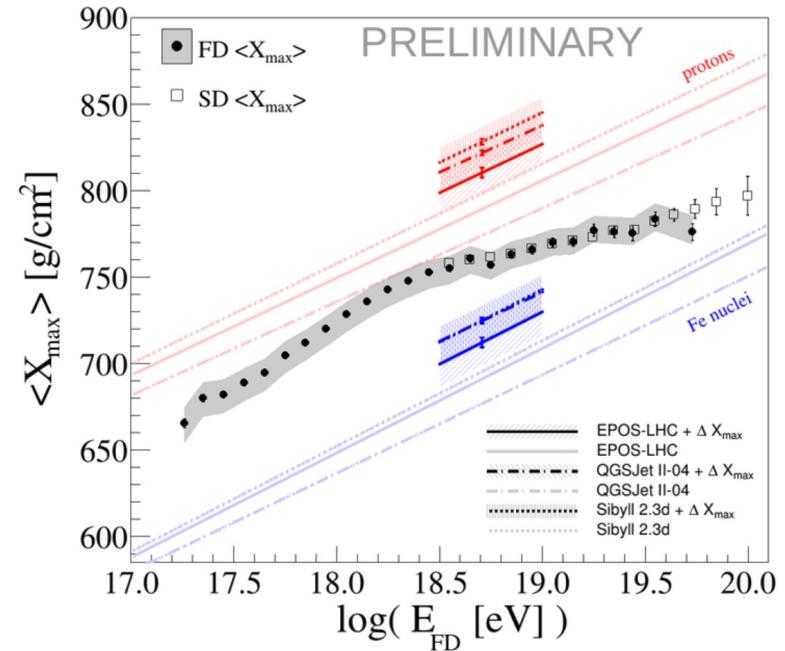


π^0 production spectrum in p-Air

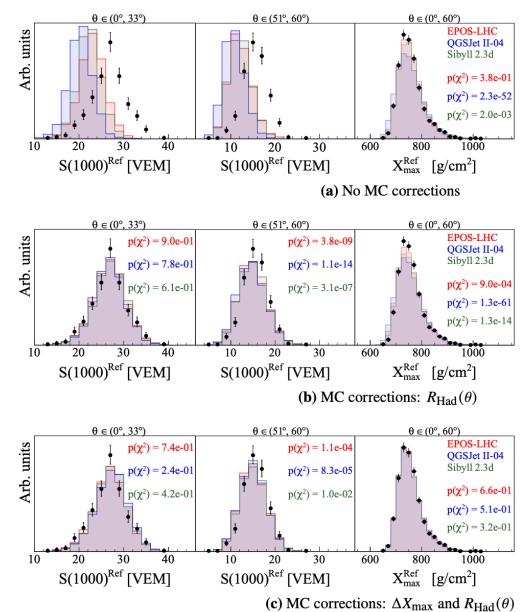
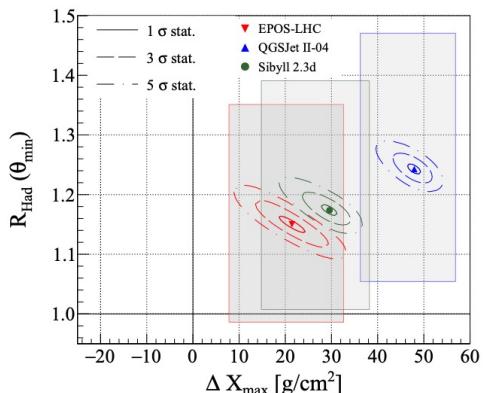
The technique resembles the other direct measurement on the 1st interaction: p-Air cross section



A tantalizing strange unexpected interesting possibility



It is shown that a **shift in X_{\max} predictions** actually improves the fits of X_{\max} and ground signal and reduces the muon problem, (through a change of composition going to heavier)



Conclusions

- Important differences in model extrapolations to p-Air and π -Air
 - p-O in next LHC phase
- X_{\max} is less model dependent.
 - Used to measure p-Air cross section
 - Reference observable for mass compositionBUT new results by P. Auger might shake this picture
- X_{\max}^{μ} is sensitive to the *cascading velocity*
 - π -Air diffraction, baryon production, meson E-spectrum.
- Indications of harder muon E-spectrum
- $\langle N_{\mu} \rangle$ mismatch slope confirmed with $>8\sigma$ by WHISP analysis of 9 experiments
 - Muon puzzle starts at 10^{16} eV
 - Cumulative effect of hadronic energy fraction starting at 10^{16} eV ?
- 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} -distribution $\langle N_{\mu} \rangle$, $\sigma(N_{\mu})$, and $\Lambda(N_{\mu})$.

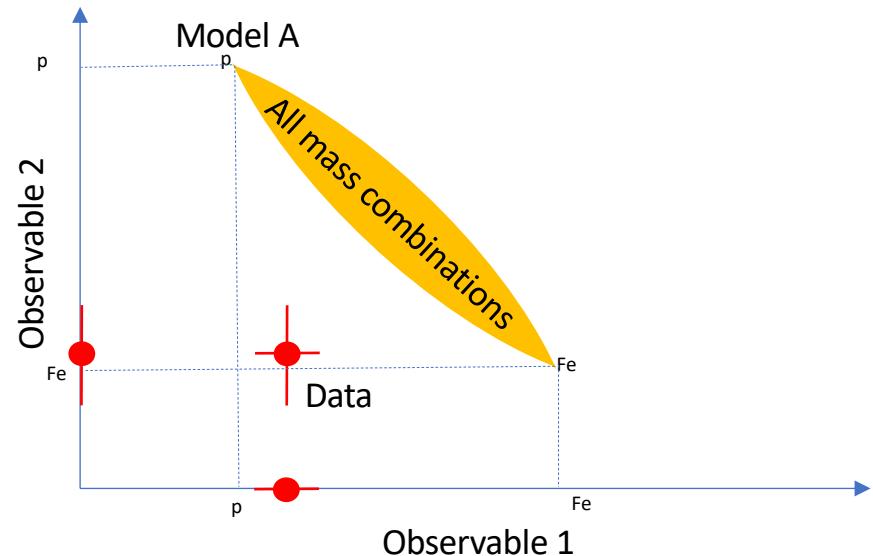
Thanks!

The general strategy

Direct measurement on variables of the 1st interaction (end of this talk)

Constrain the hadronic models

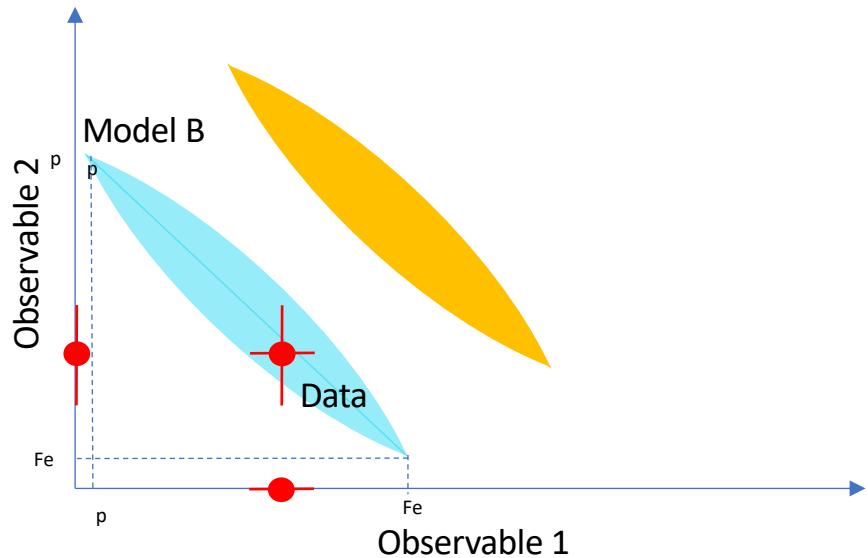
- We do not know the composition of the CR beam. We simulate all possibilities.
- We check the compatibility of data with the mass phase-space of a given model A
- Obs 1 and Obs 2: different mass interpretations for model A



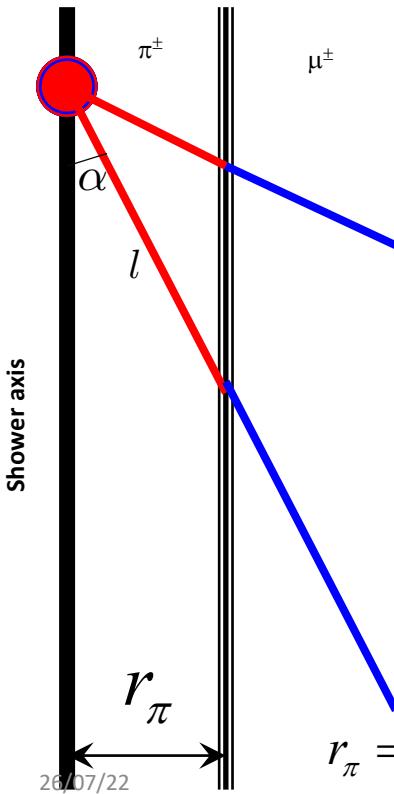
The general strategy

Constrain the hadronic models

- We check the compatibility of data with the mass phase-space of another model, B
- 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**



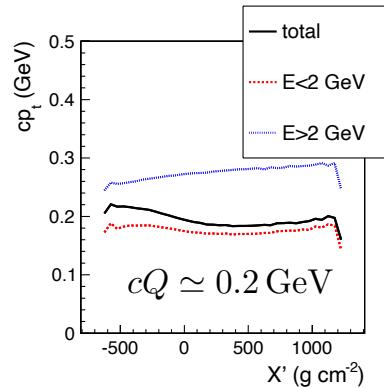
Transverse distance of μ^\pm production / π^\pm decay



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

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

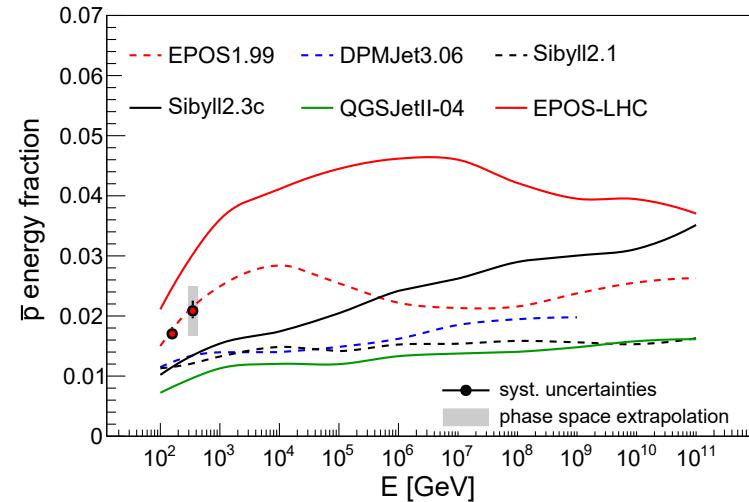
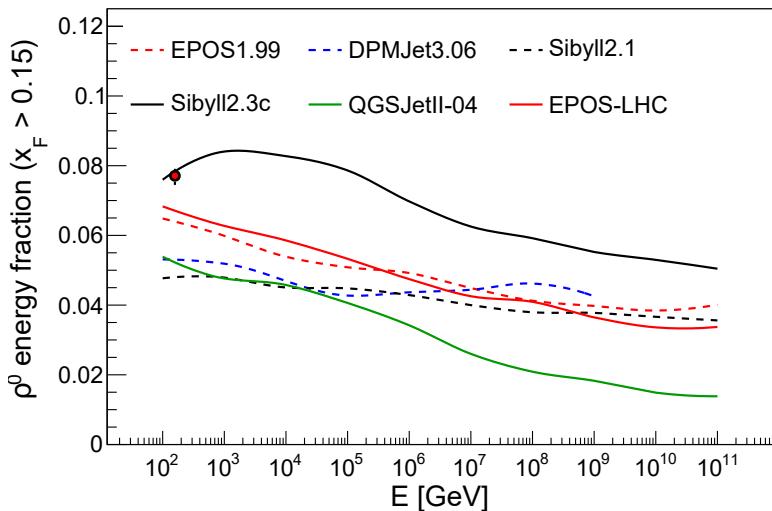
$$r_\pi = l \sin \alpha = \frac{\tau_\pi p_t}{m_\pi}$$



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

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

NA61/SHINE



Importance of forward acceptance

arXiv:2105.06148

EPOS-LHC: pO 10 TeV

„Muon production weight“
how many muon would be produced in shower
by secondaries in this collision

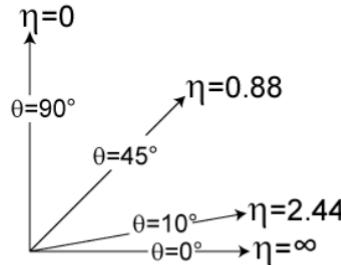
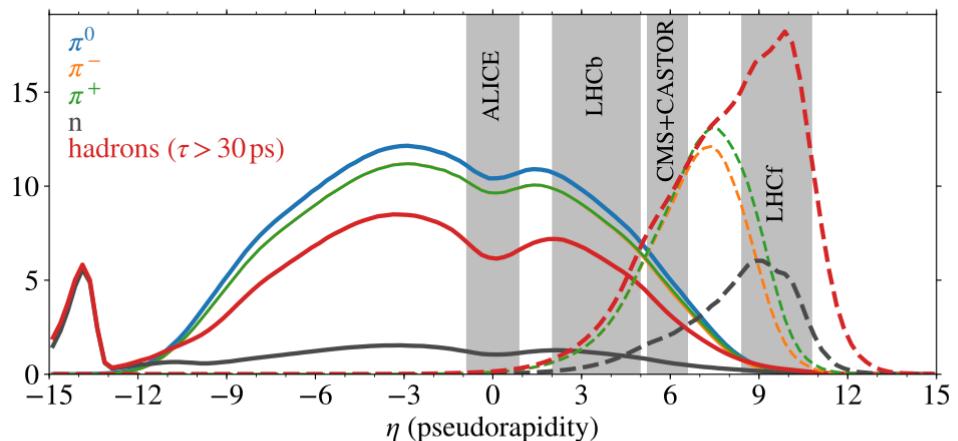
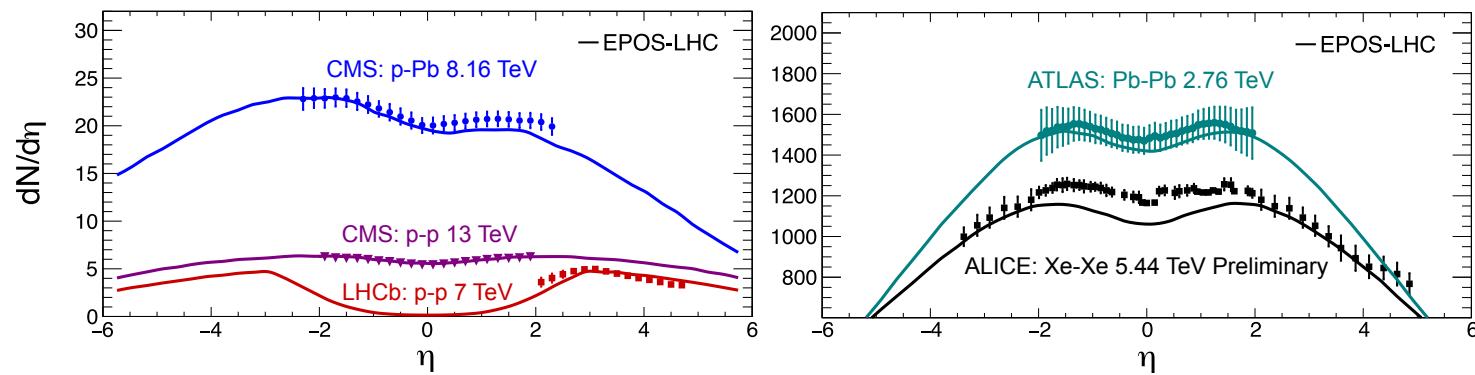
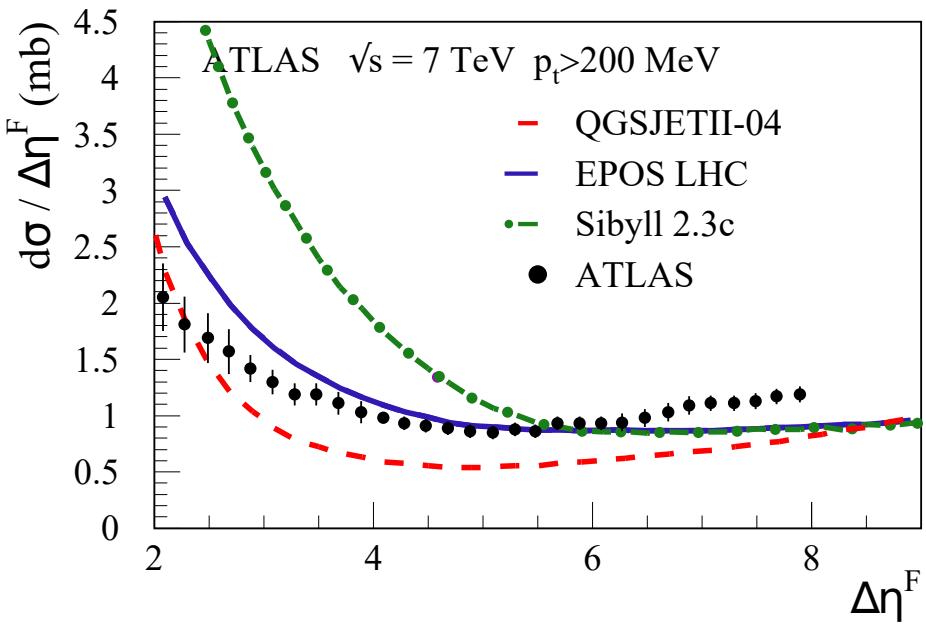


Image credit:
JabberWok - Wikipedia CC BY-SA 3.0

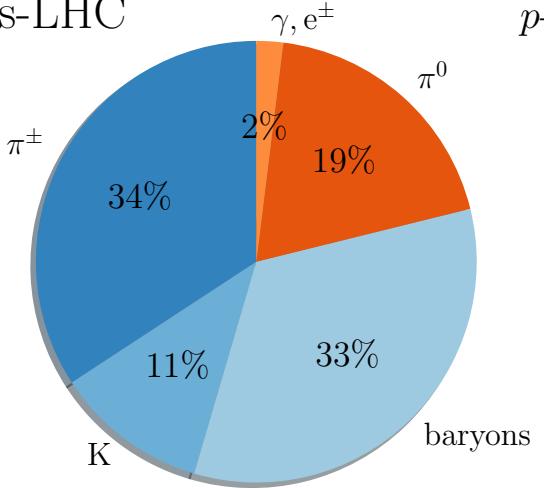
See PoS(ICRC2021)463 for full simulation of "muon production weight" with CORSIKA 8



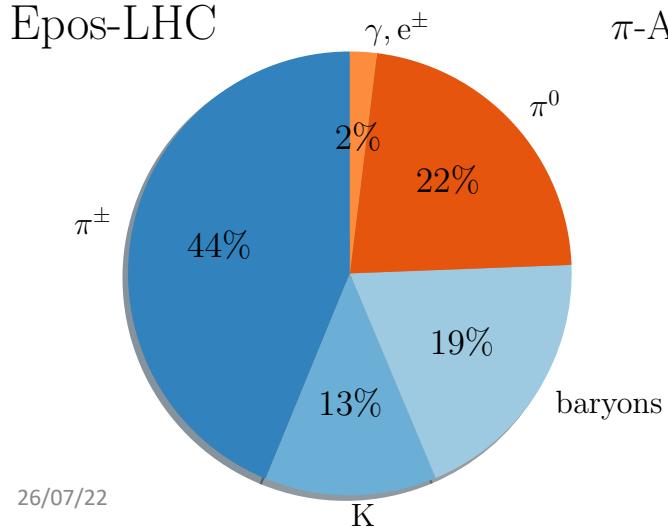


1st interaction energy fraction

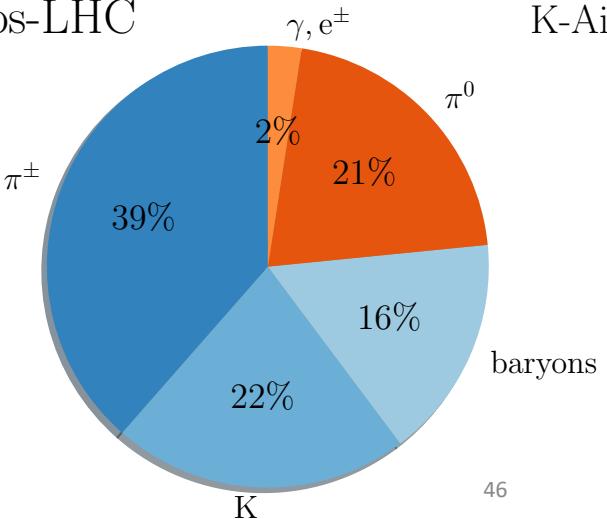
Epos-LHC p -Air



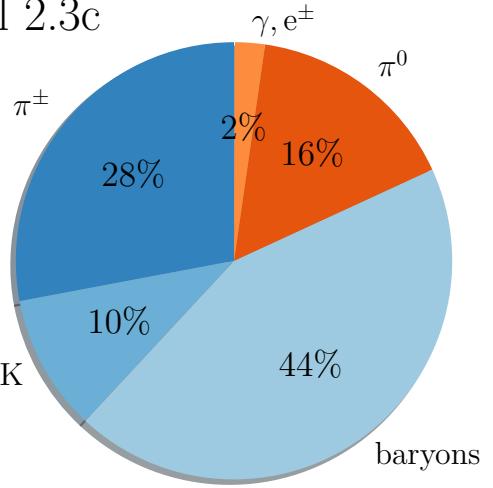
Epos-LHC π -Air



Epos-LHC K-Air

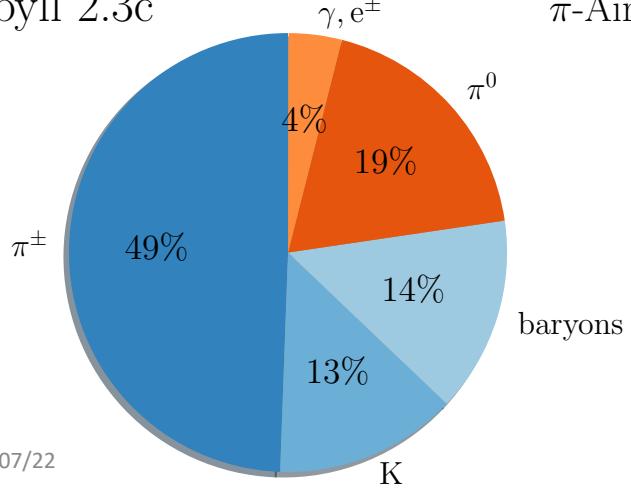


Sibyll 2.3c



p-Air

Sibyll 2.3c



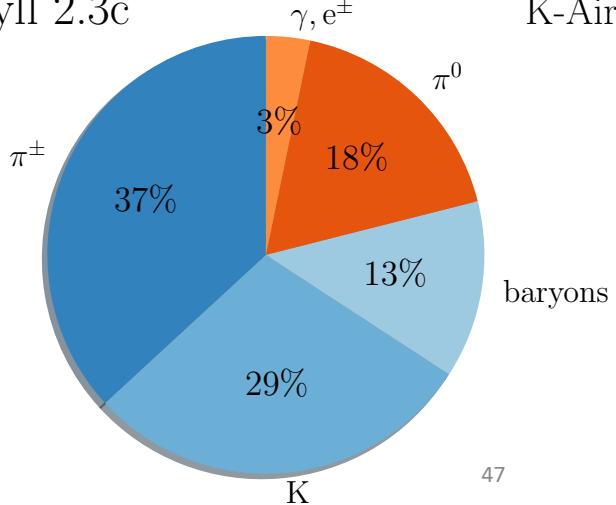
π -Air

26/07/22

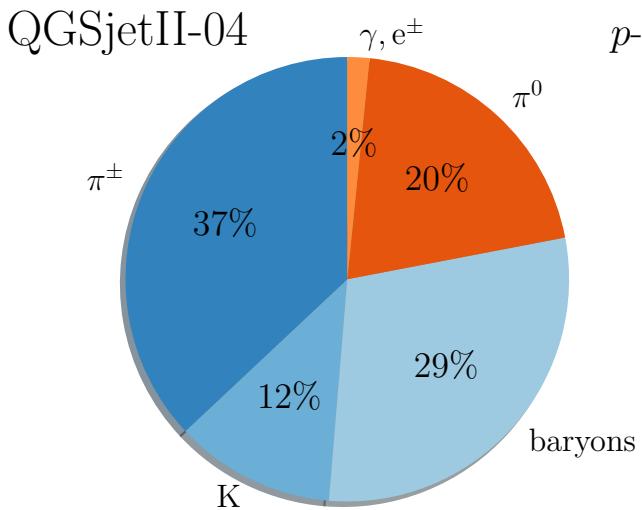
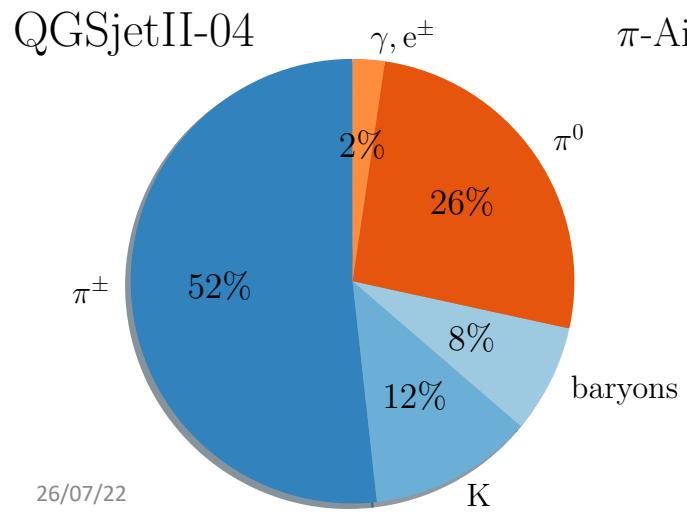
ECRS 2022

47

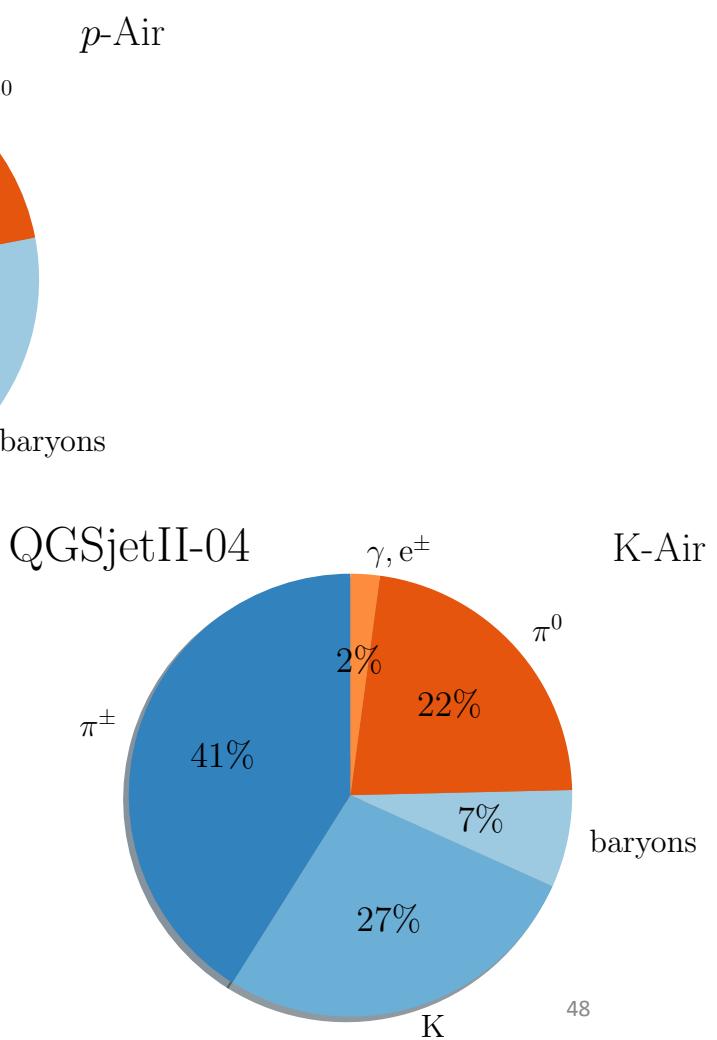
Sibyll 2.3c



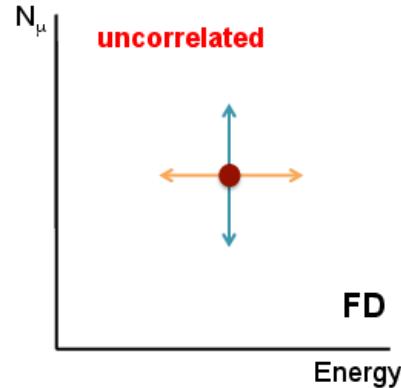
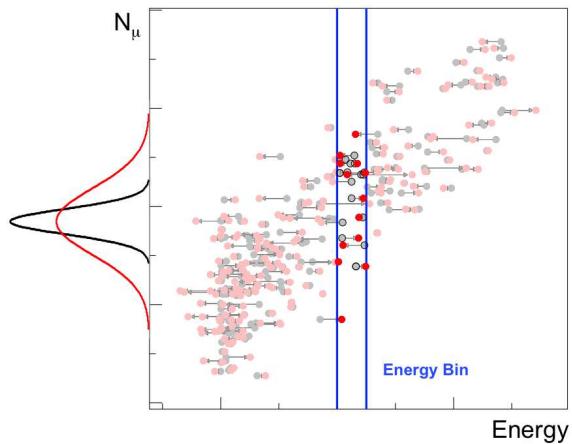
K-Air

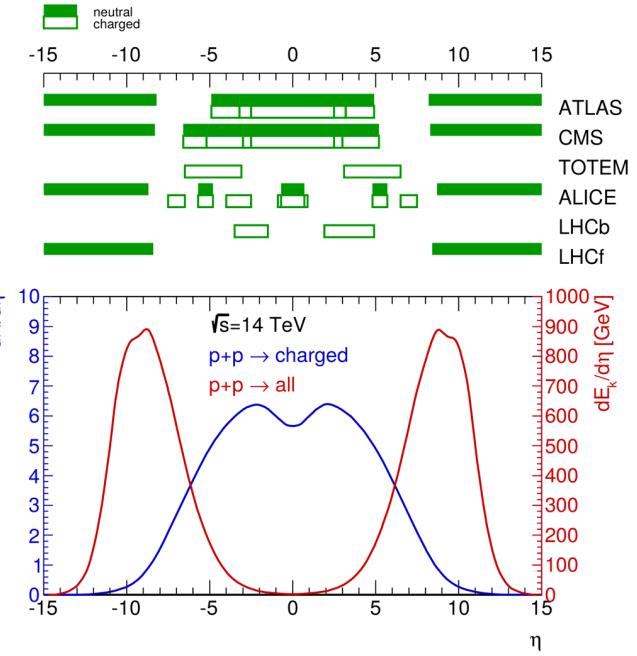


ECRS 2022



Quick list of experiments





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

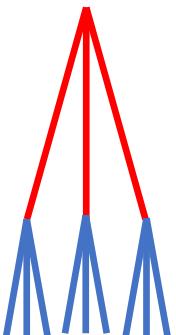
$$\beta = \frac{\ln m}{\ln m_{\text{tot}}}$$

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

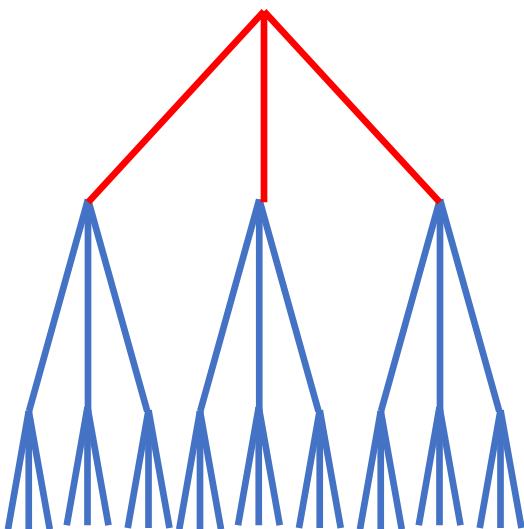
$$\log N_\mu = \underline{\log f_i}$$



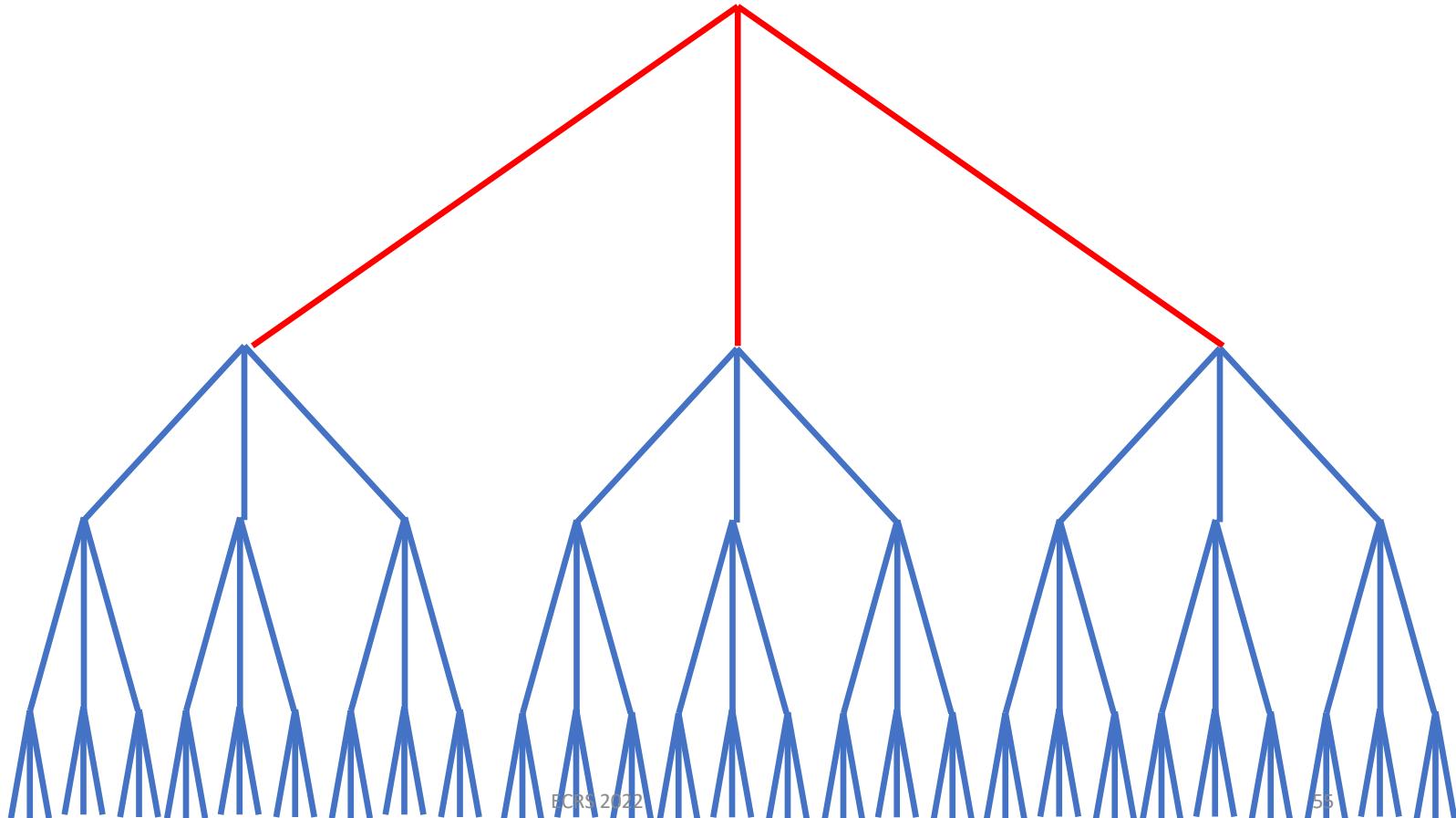
$$\log N_\mu = \underline{\log f_{i-1}} + \log f_i$$

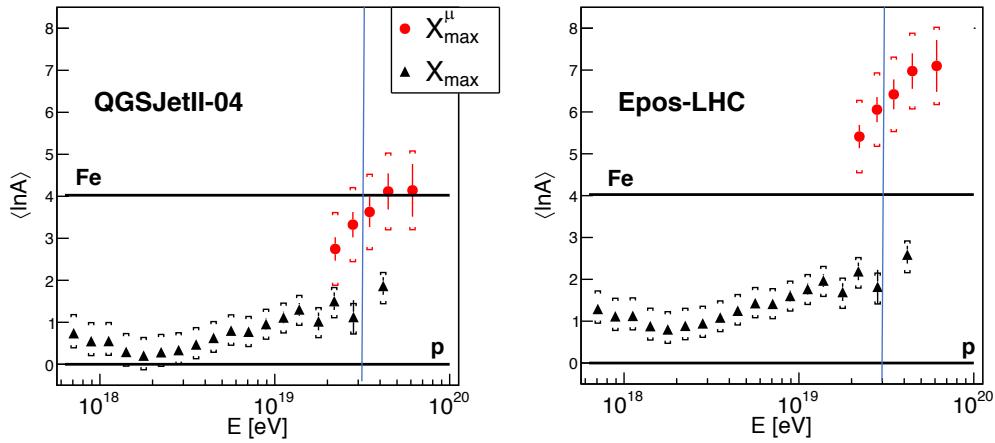


$$\log N_\mu = \underline{\log f_{i-2}} + \log f_{i-1} + \log f_i$$

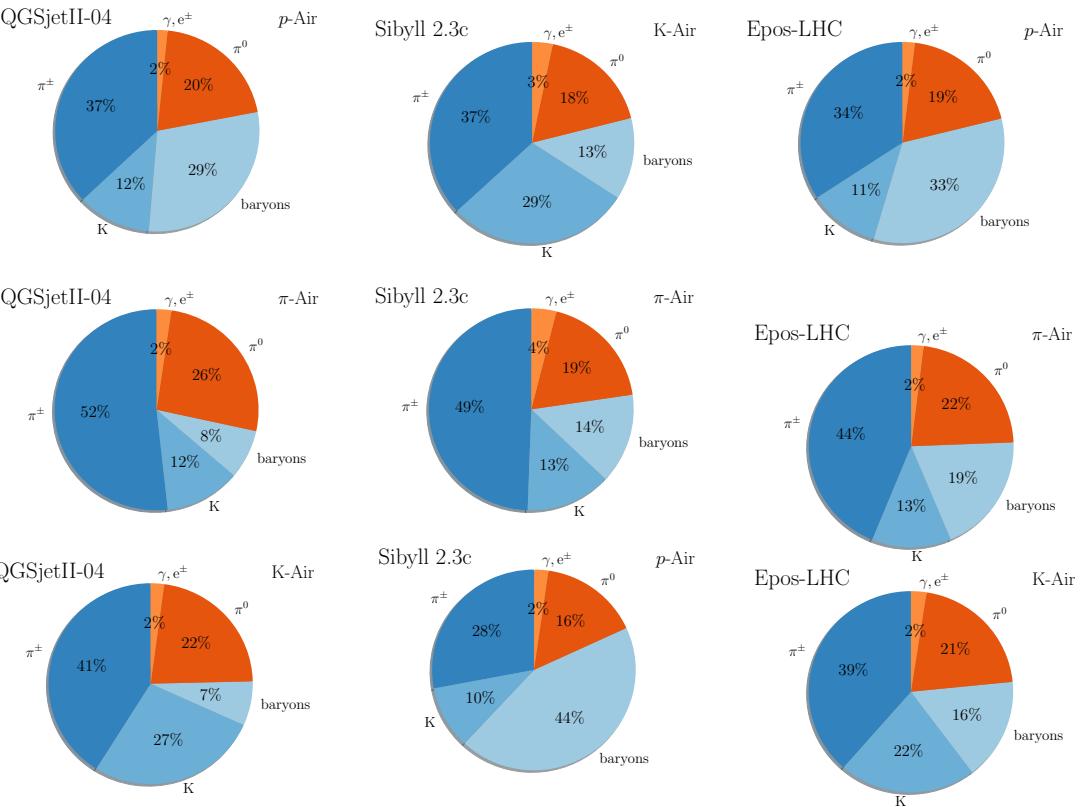


$$\log N_\mu = \underline{\log f_{i-3}} + \log f_{i-2} + \log f_{i-1} + \log f_i$$

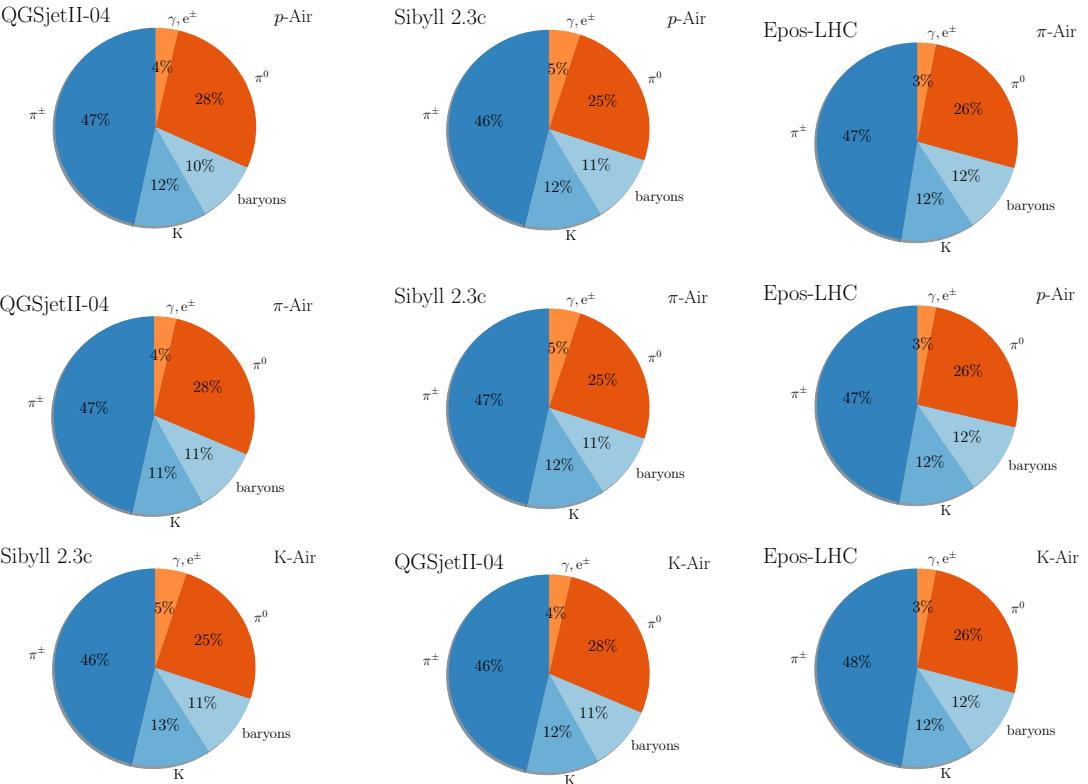




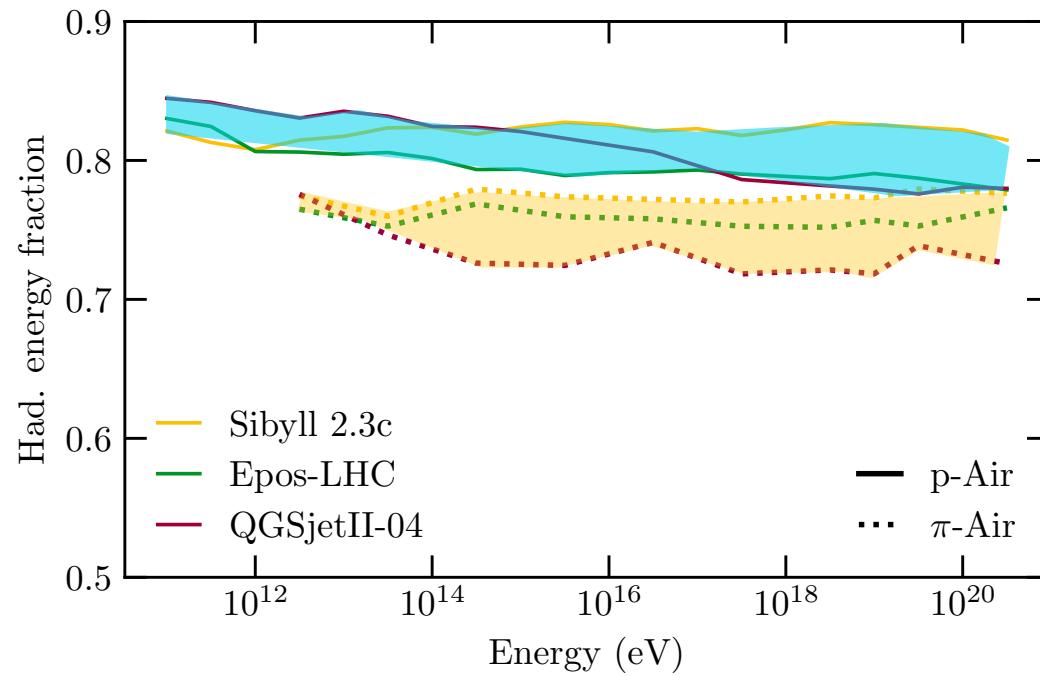
Energy share



Multiplicities



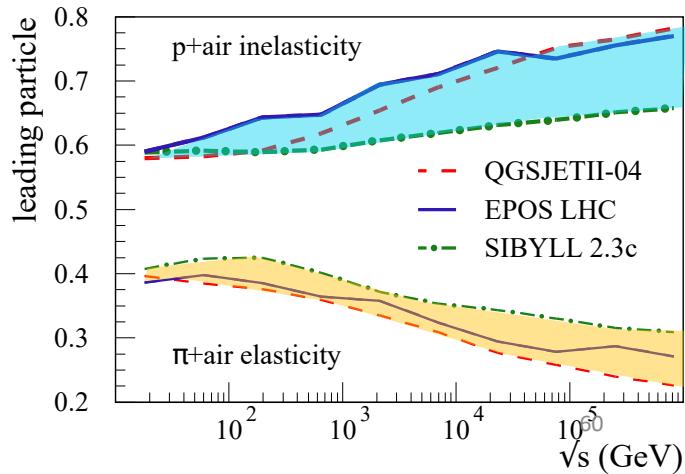
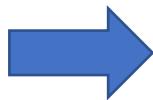
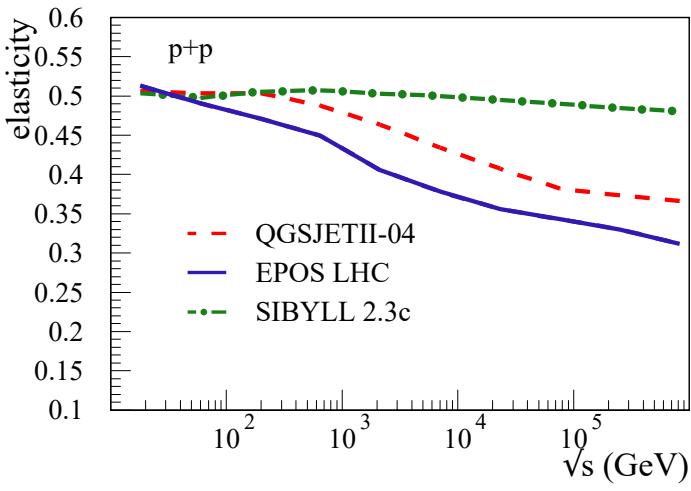
1st interaction energy fraction

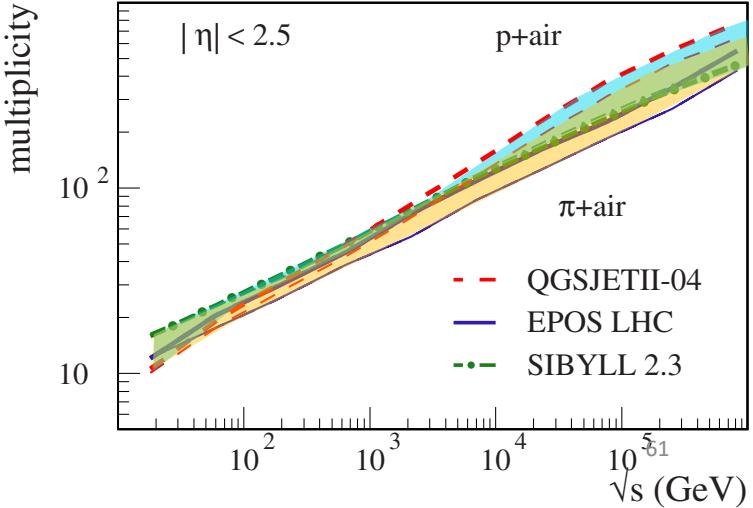
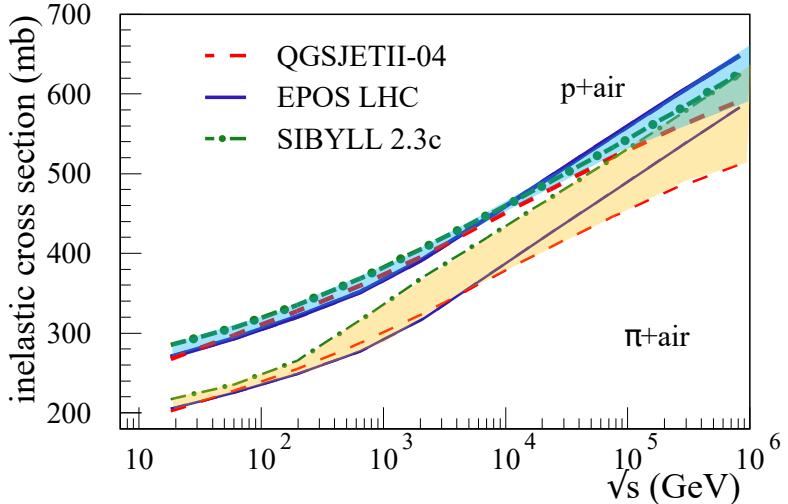
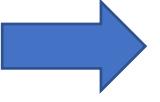
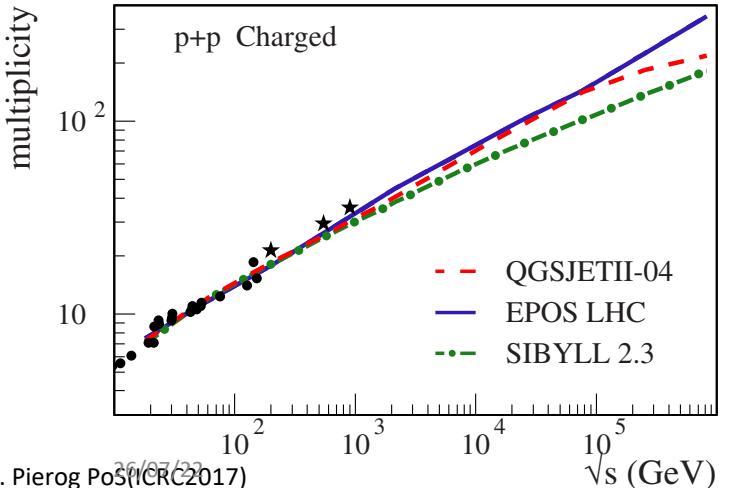
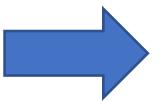
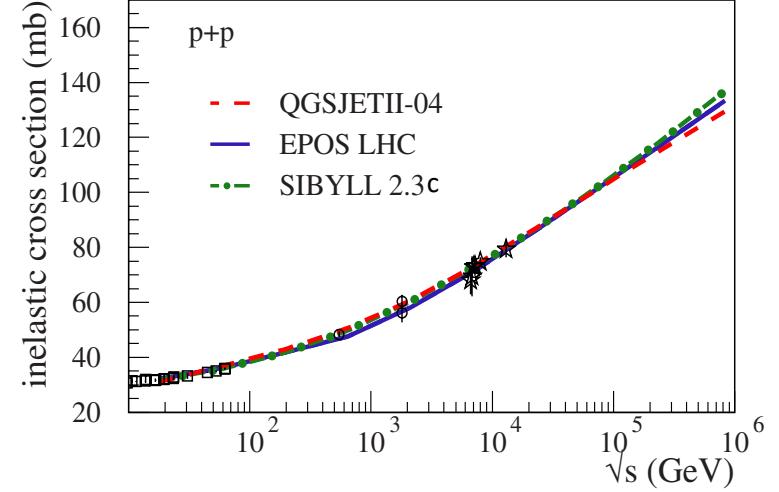


Hadronic Parameters

elasticity = $1-k$

inelasticity = k





ECRS 2022

From Heitler model to Energy model

hadr. multiplicity

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

$$\alpha = \sum_{i \in hadr}^m \left(\frac{E_i}{E_0} \right)^\beta$$

$$N_\mu \propto \alpha_1 \cdot \alpha_2 \cdot \dots \cdot \alpha_c \quad \beta = 0.93$$

hadr. energy fraction

$$N_\mu = f_1 \cdot f_2 \cdot \dots \cdot f_c \cdot \frac{E_o}{\xi_c} \quad \beta \rightarrow 1$$

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

↓

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 ($\sim 4\% - 5\%$)

