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Addressing the cosmic-ray muon excess by probing a "fireball" state at the Forward Physics Facility

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Recap: Muon Deficit

Mass composition of UHECRs

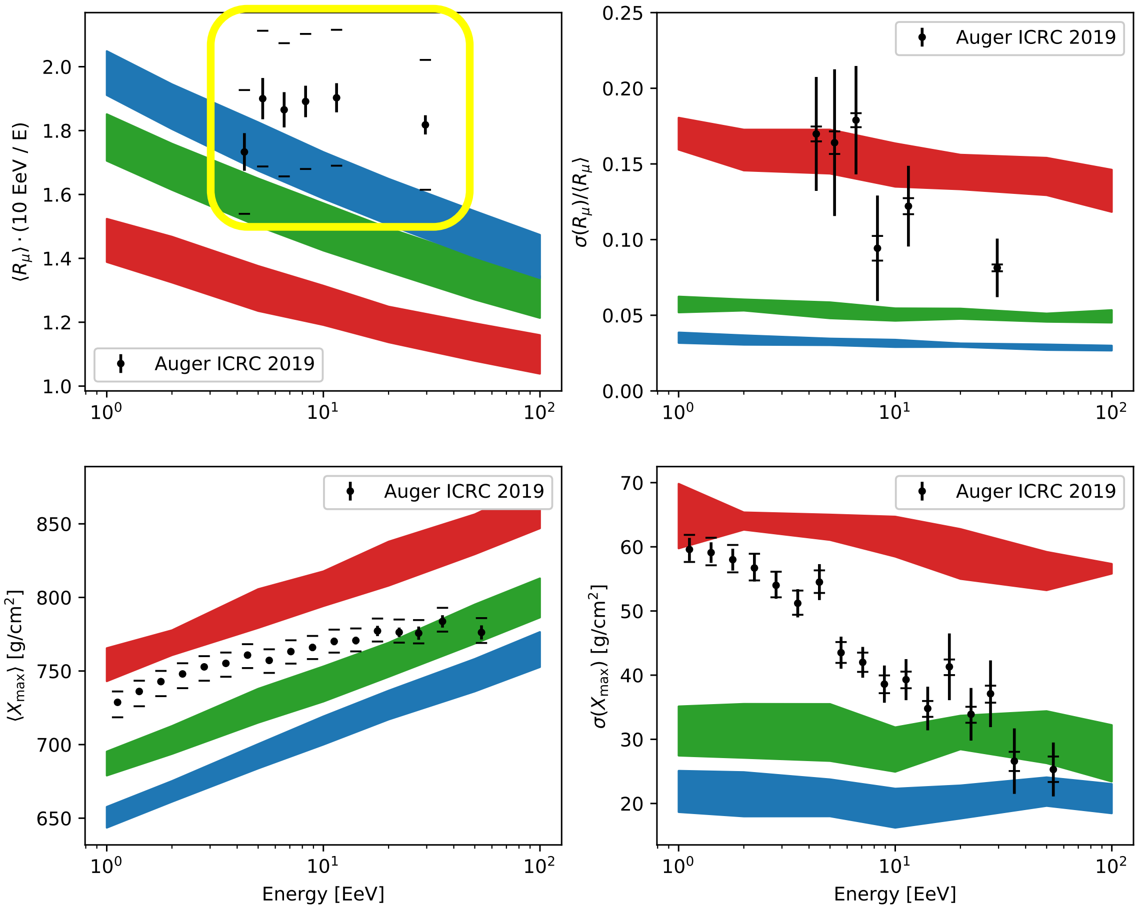
Extensive air shower (EAS) observables
$\boldsymbol{X}_{\mathbf{max}}$ and $\boldsymbol{R}_{\boldsymbol{\mu}}$
(bottom row) (top row)

Obs. distributions quantified through:
- averages $\langle O \rangle$ (left column)
- fluctuations $\sigma(O)$ (right column)

Bands show model predictions
(proton, nitrogen, iron)
(width from differences QGSJetII-04, EPOS-LHC, SIBYLL-2.3c)

Composition interpretation of $\langle R_\mu \rangle$ -data much heavier than of other observables.
Likely a *deficit of muons in simulations*

Somehow increase $\langle R_\mu \rangle$-prediction w/o significantly affecting others



Hadronic interaction parameters

Ulrich et al. (2011), arXiv:1010.4310

Ad-hoc model adjusting hadronic interaction parameters
by factor *f(E)*:

$$f(E) = 1 + (f_{19} - 1) \cdot \begin{cases} 0 & E < 1\,\mathrm{PeV} \\ \frac{\log_{10}\left(\frac{E}{1\,\mathrm{PeV}}\right)}{\log_{10}\left(\frac{10\,\mathrm{EeV}}{1\,\mathrm{PeV}}\right)} & E \geq 1\,\mathrm{PeV} \end{cases}$$

E = energy of projectile in target rest-frame

π⁰-fraction and multiplicity significantly affect average muon number

Changes in multiplicity constrained by X_{max}: introduces tension between $\langle X_{\max} \rangle$ and $\sigma(X_{\max})$

π⁰-fraction is key to resolving muon deficit

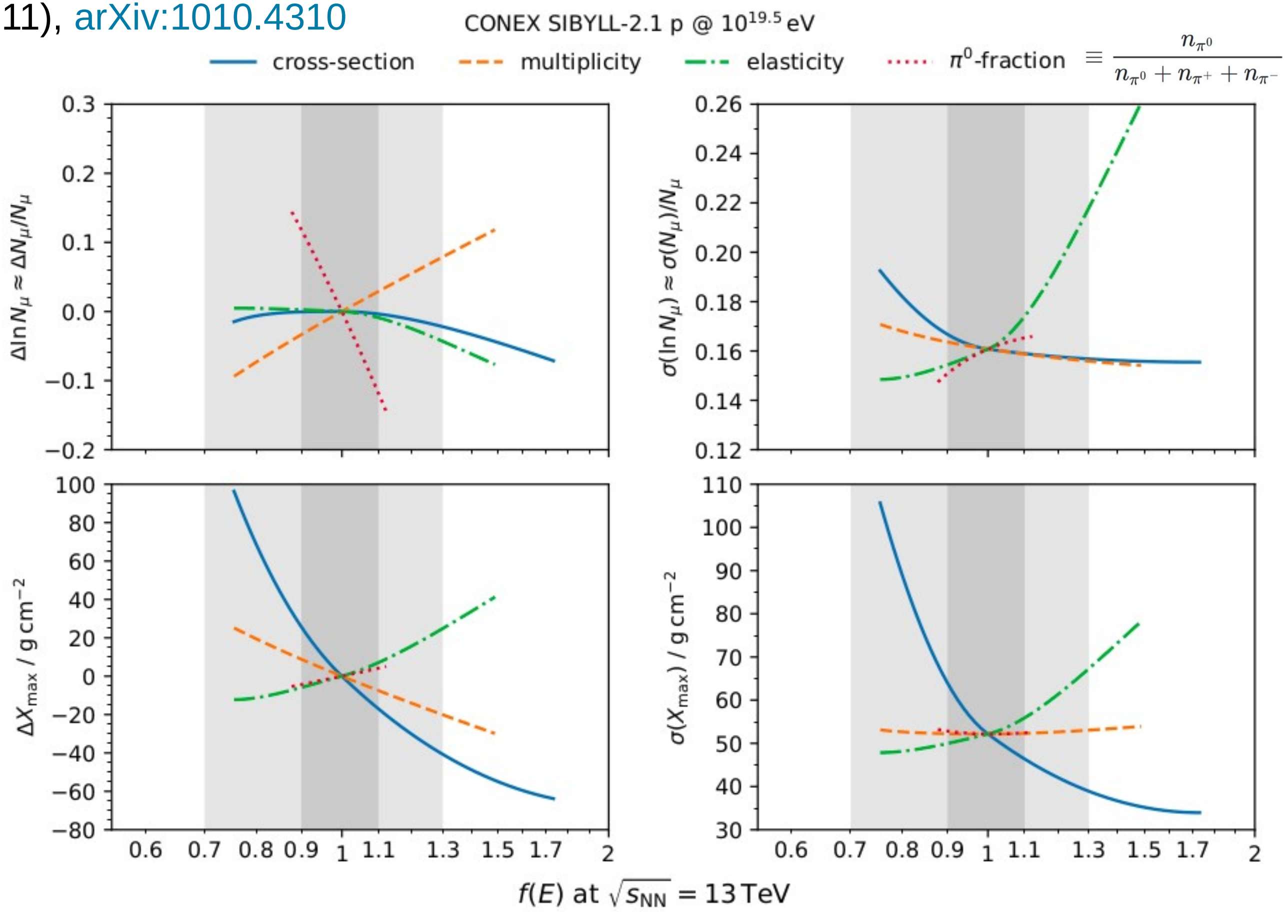


Figure from Albrecht et al. 2021, arXiv:2105.06148

Heitler-Matthews Model

Effect on muon number can be understood within Heitler-Matthews model

Muon number is trade off between:

- increasing shower size at each generation n_{mult} (multiplicity)
- energy lost to electromagnetic component *1-r* (~ π^0-fraction)

$r \equiv E_{had} / E_{proj}$: hadronic energy fraction; *(target rest frame)*
fraction of energy kept in hadronic component after interaction

→ production of rn_{mult} hadrons per interaction

Matthews (2005), DOI

$$N_\mu = (rn_{\mathrm{mult}})^{k_c} = \left(\frac{E_0}{E_c}\right)^{\beta}$$

where: $\beta \equiv \log(rn_{\mathrm{mult}})/\log(n_{\mathrm{mult}})$ ~ 0.9

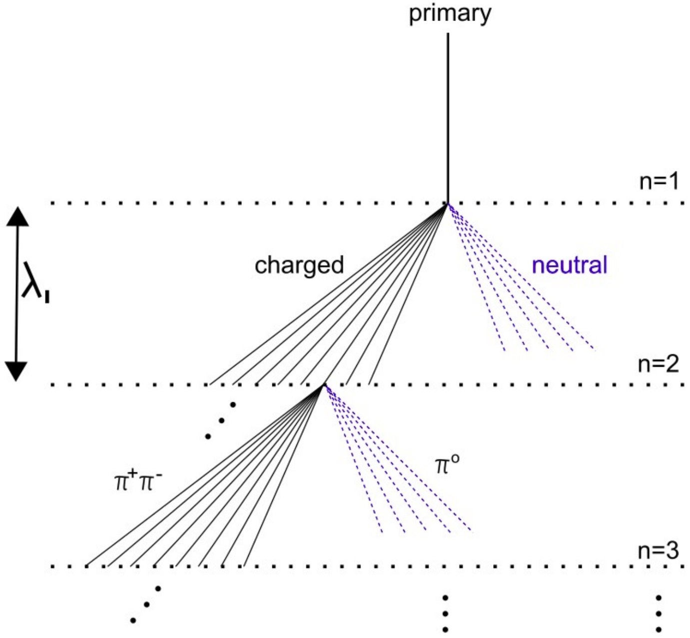


Figure from Ulrich et al. (2011)
arXiv:1010.4310

Fireball Model

Anchordoqui et al. (2017), arXiv:1612.07328

Production of deconfined quark matter state (= *fireball*)
that enhances strange particle production

→ indirect suppression of π^0 production → more energy available for muons

Currently lacks detailed model

Soriano et al. (2018), arXiv:1811.07728 :

Mimic fireball by producing expected secondaries: ***swap pions and kaons***

→ π^0-fraction is given by the smaller K^0-fraction

Strangeness enhancements at mid-rapidities observed at LHC

ALICE (2017),
arXiv:1606.07424

Hints for similar effects in forward regions

Extension to Heitler-Matthews Model

Fireball in Heitler model: <u>some interactions have increased r-value</u>

→ An effective r-value for collisions with (projectile) energy *E*:

$$r_{\text{eff}}(E) \equiv [1 - p(E)]\, r_{\text{SM}} + p(E)\, r_{\text{fb}}$$

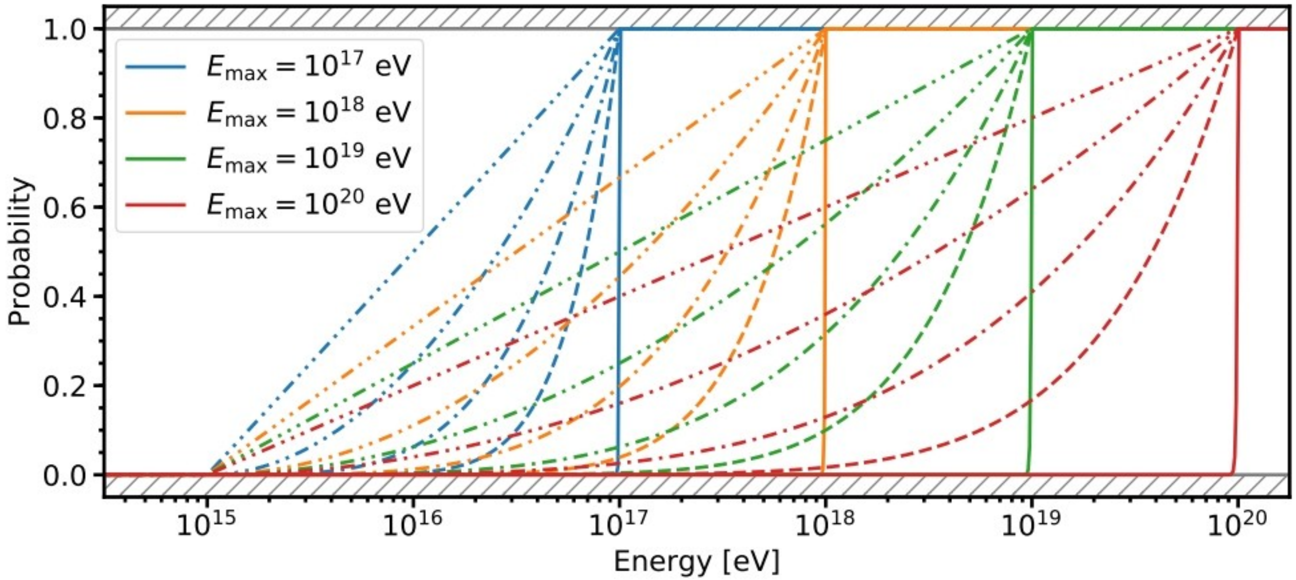
r_{SM} ~ 0.75-0.8,
r_{fb} ~ 0.9-0.95 (from π ↔ K)

with *p(E)* the probability of producing a fireball at energy *E* (due to energy density, impact parameter, ...)

p(E) not known a priori

↓

treat as phenomenological model parameter



Parametrization:

E_{min} : energy below which no fireballs

E_{max} : energy above which only fireballs

n : rate at which fireball becomes more likely

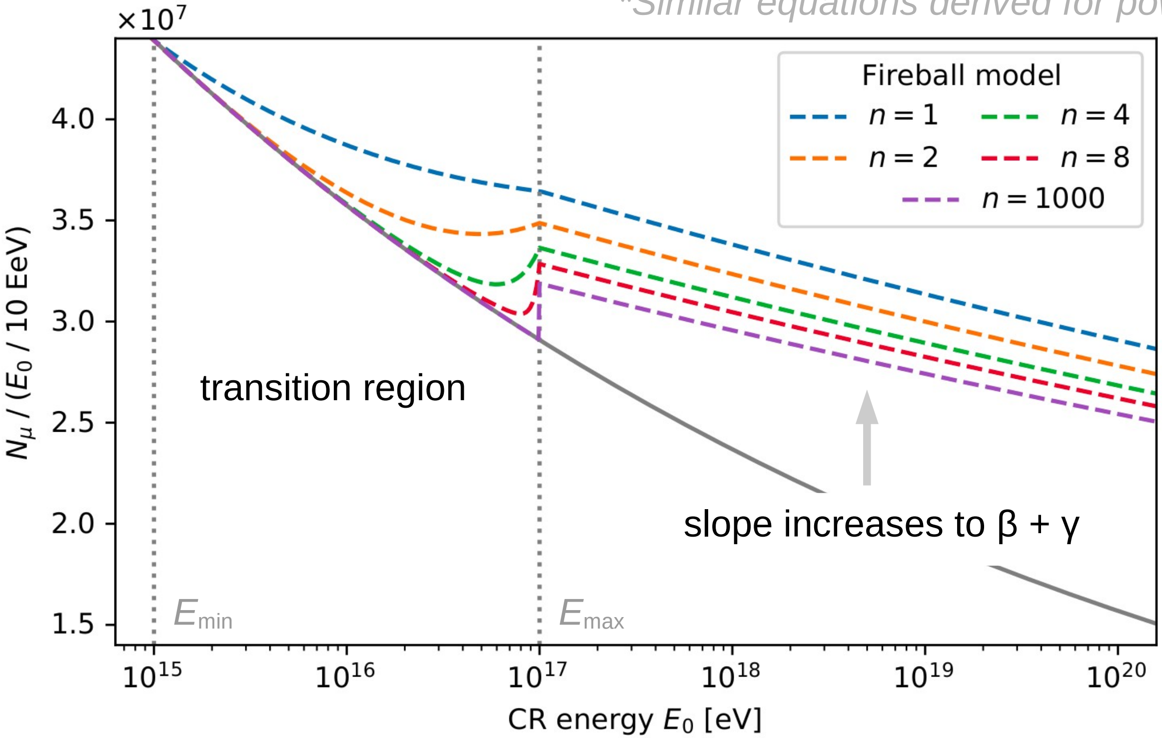
Is there a *p(E)* that reproduces Auger data?

Extension to Heitler-Matthews Model

<u>Implementing hybrid-*r* approach into Heitler model</u>

with my *p(E)*-parametrization and a constant multiplicity*:

**Similar equations derived for power-law multiplicity*



$$N_\mu = \left(\frac{E_0}{E_c}\right)^{\beta} \times \begin{cases} 1, & \text{if } E_0 \leq E_{\min}, \\ \left(\frac{E_0}{E_{\min}}\right)^{\delta(E_0)}, & \text{if } E_{\min} \leq E_0 \leq E_{\max}, \\ \left(\frac{E_{\max}}{E_{\min}}\right)^{\delta(E_{\max})} \left(\frac{E_0}{E_{\max}}\right)^{\gamma} & \text{if } E_0 \geq E_{\max}, \end{cases}$$

where:

$$\beta = \frac{\log(r_{\mathrm{SM}} n_{\mathrm{mult}})}{\log(n_{\mathrm{mult}})}$$

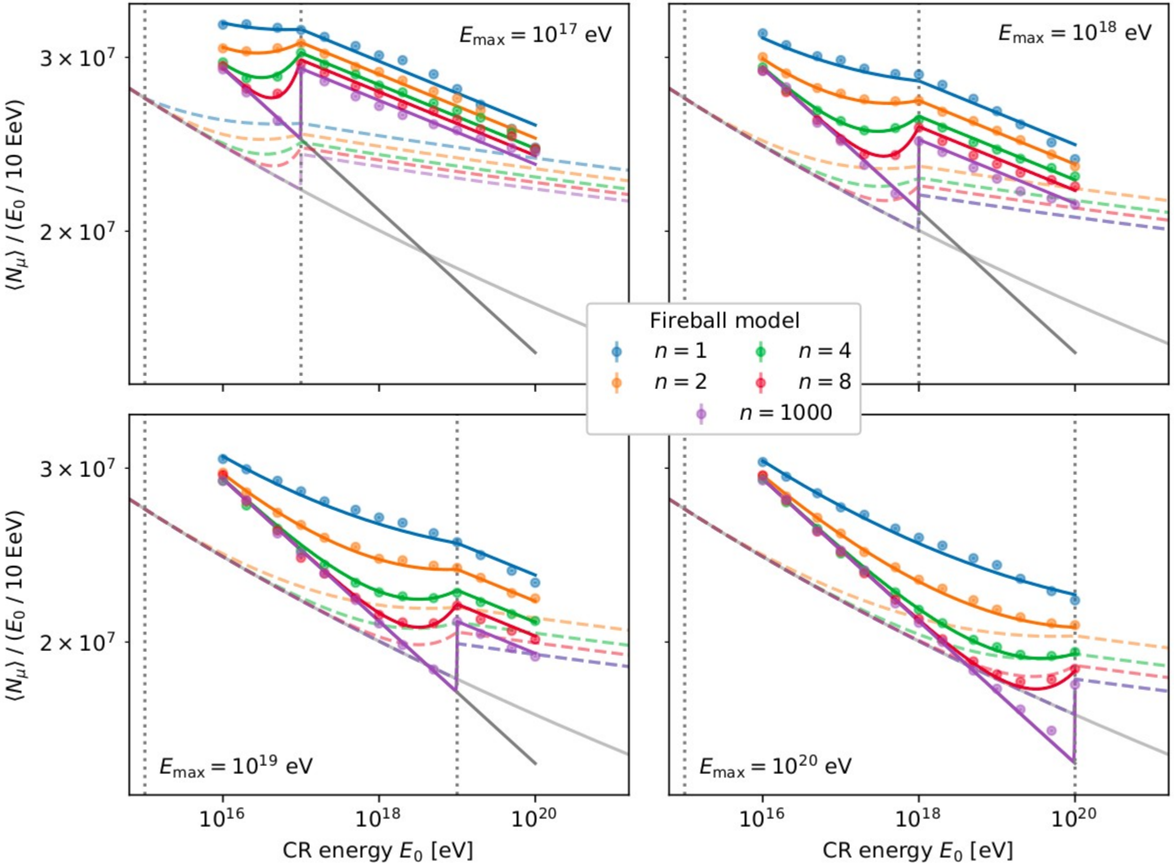
$$\beta + \gamma = \frac{\log(r_{\mathrm{fb}} n_{\mathrm{mult}})}{\log(n_{\mathrm{mult}})}$$

Provides physical insight on effect of *p(E)*-parameters E_{min}, E_{max}, and *n*

Extension to Heitler-Matthews Model

EPOS-LHC

Fits well to fireball-implemented Conex simulations



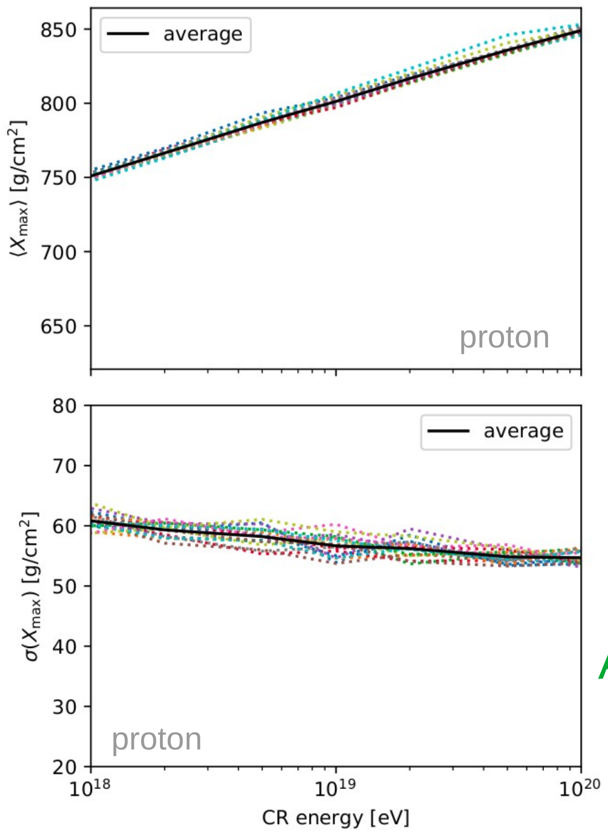
Single set of 5 parameters for each hadronic interaction model:
r_{fb}, r_{SM}, n_{scale}, b, E_c
(simultaneously fits 260 MC points)

Heitler extension gives interpolation of shower Monte Carlos to any E_{min}, E_{max}, n and E_0

Enables direct interpretation of Auger data

Interpretation of Auger Data

EPOS-LHC



<u>Need to take into account CR mass composition</u>

X_{max} is unaffected → composition same for all fireball models

Current efforts:

- Simulate showers for different masses (so far all proton)
- Find *p(E)* that allows consistent composition interpretation from $\langle X_{\max} \rangle$ and $\langle R_\mu \rangle$

Any *p(E)* will be constrained by muon fluctuations

Likely excludes first interaction only

↓

An effect should be visible at lower energies:

$E_{proj} \sim 10^{16}$ eV ↔ $\sqrt{s_{NN}} \sim O$(few TeV)

→ promising for FPF

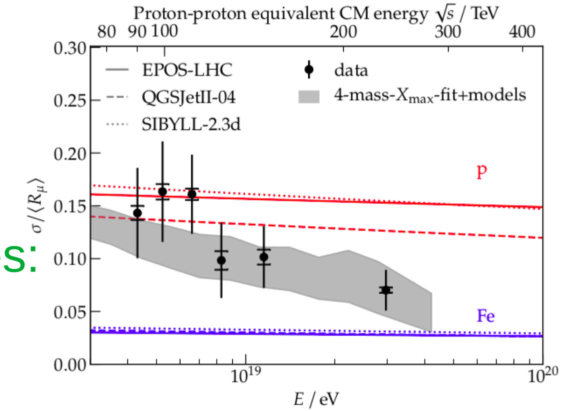


Figure from Auger (2021), arXiv:2102.07797

Outlook: Potential Role of FPF

FPF neutrinos to constrain pion-to-kaon ratio in very forward interactions

→ experimental access to ‘*r*’-value

Air shower data strongly indicate deviation from SM extrapolation

Phenomenological fireball-extended Heitler model can provide predictions for
1) *relevant energies* and 2) *size of deviation*

FPF in ideal position to follow-up and solve muon deficit

Enables much better composition inferrence, invaluable to quest for UHECR origin