Particle physics in cosmic rays

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Outline:
- > Introduction
- > Auger measurement
- > Muon puzzle
- > Summary

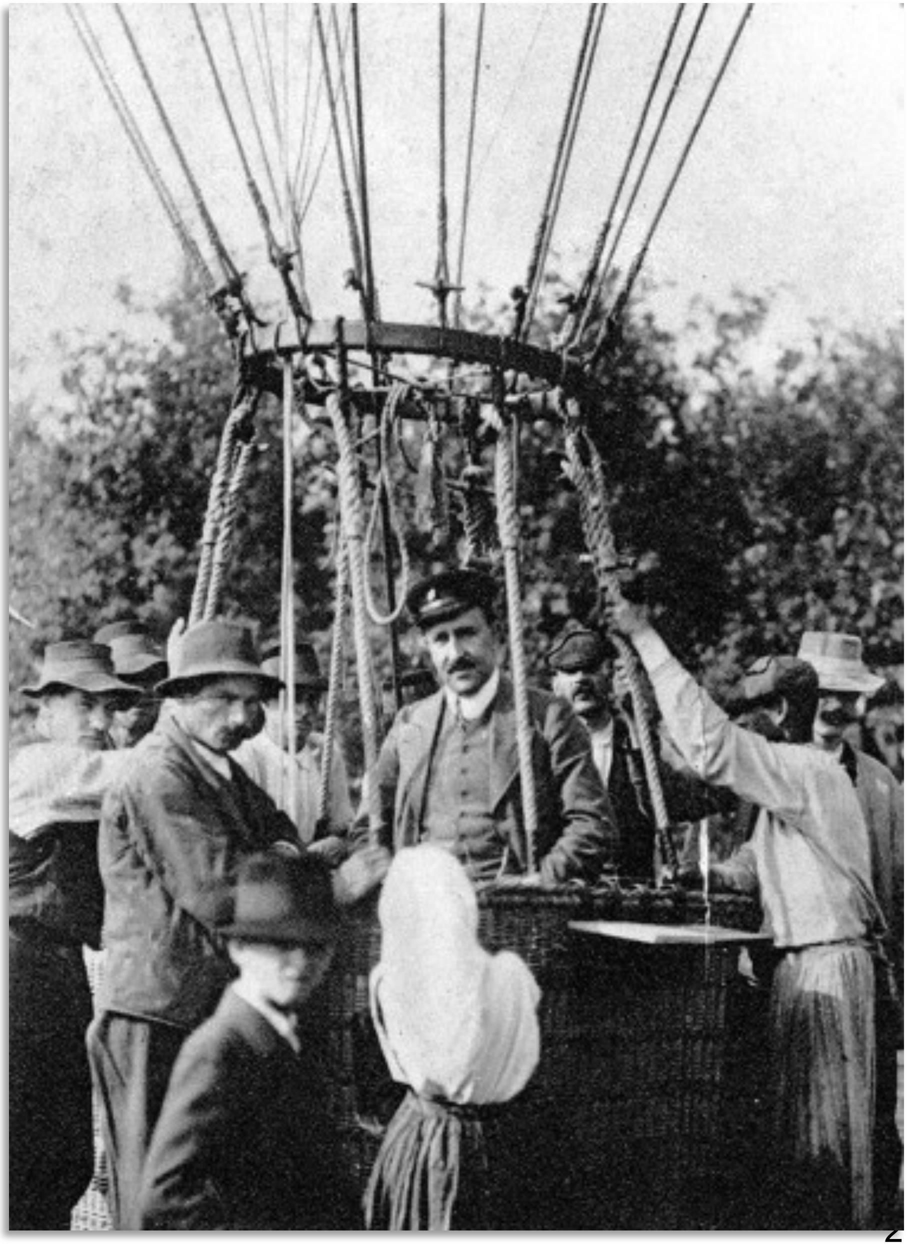
The Ultra-High-Energy Cosmic Rays

1912: Discovery of ionizing radiation of cosmic origin by Victor Hess

> **charged particles (mainly proton)**

> It increases as the balloon gains altitude

The background radiation is of **cosmic origin!**

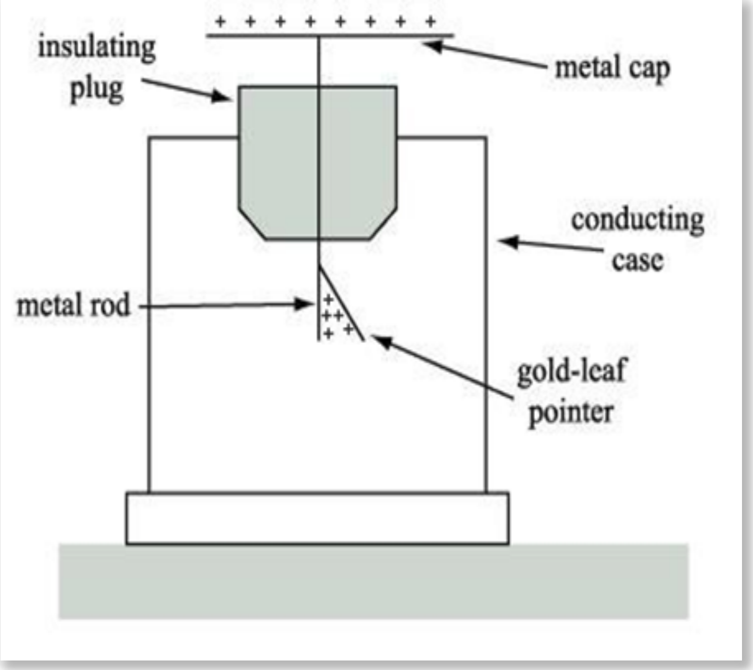


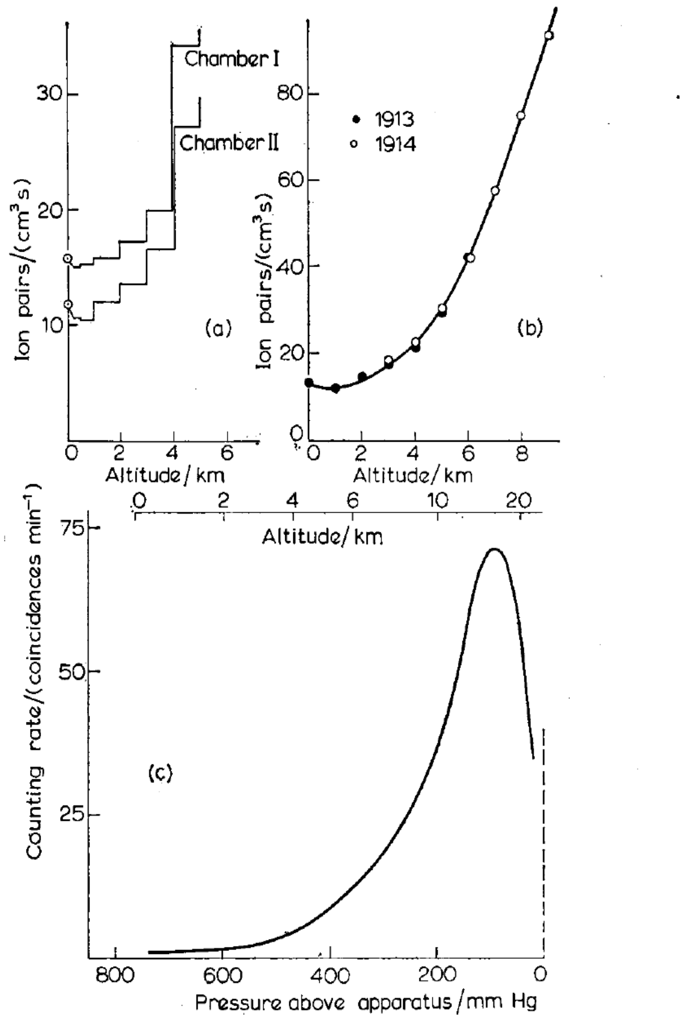
A brief history of cosmic rays

Beginning of the *XXth* century: electroscopes are used to measure the radioactivity of materials.

Discharge of electroscopes in the absence of any ionizing source → **existence of background radiation!**

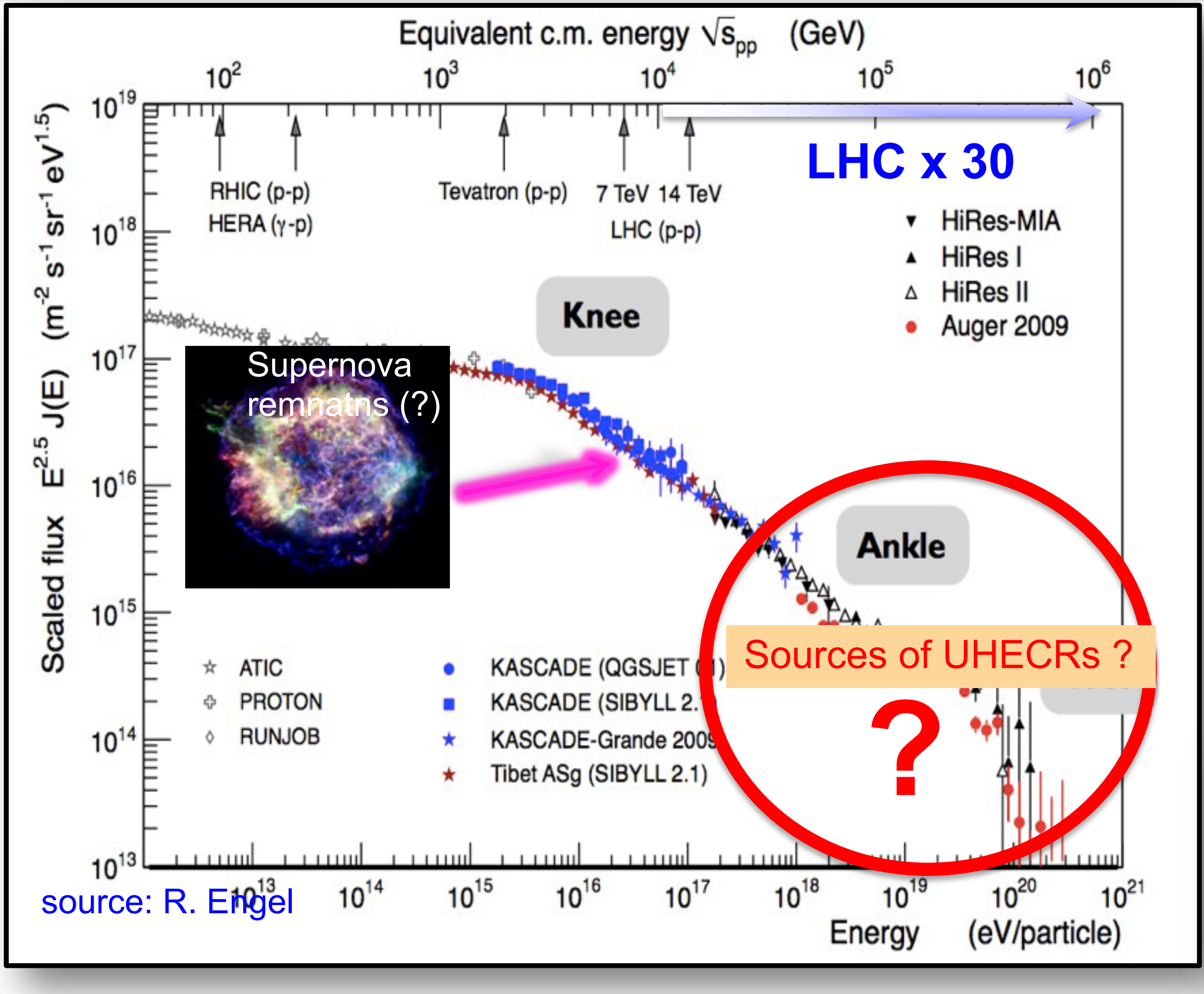
What is its nature ?





!. Altitude variation of ionization. (*a*) Balloon ascent by Hess (1912) carrying two ion chambers. (*b*) Ascents by Kolhörster (1913, 1914) using ion chambers. (*c*) Coincidence counter telescope flown by Pfotzer (1936).

The Ultra-High-Energy Cosmic Ray mystery



source: R. Engel

Particle physics beyond the reach of colliders

> What's their composition?

> Where do they come from?

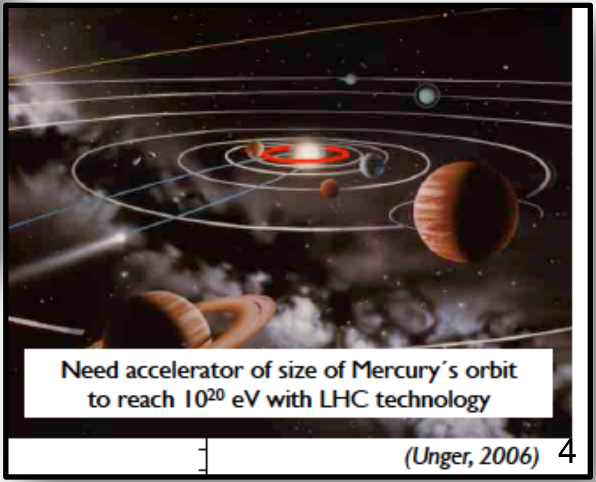
→ *anisotropies weakly correlated to known possible sources: active galactic nuclei, gamma-ray burst,…*

> How do they reach such tremendous energies?

Spectrum suppression:

in the past: *the GZK cut-off*

now: *rather the efficiency limit of particle acceleration by sources*



Need accelerator of size of Mercury's orbit to reach 10^{20} eV with LHC technology

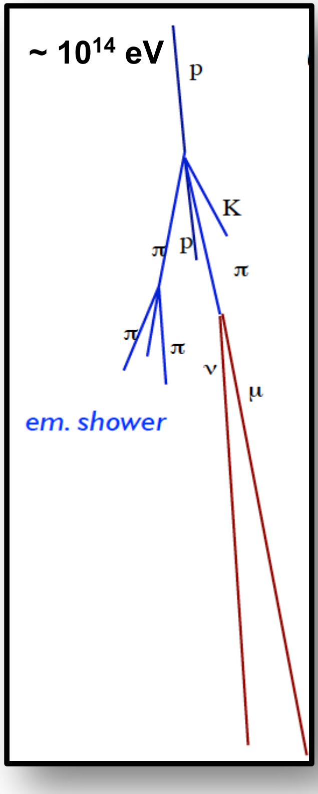
(Unger, 2006)

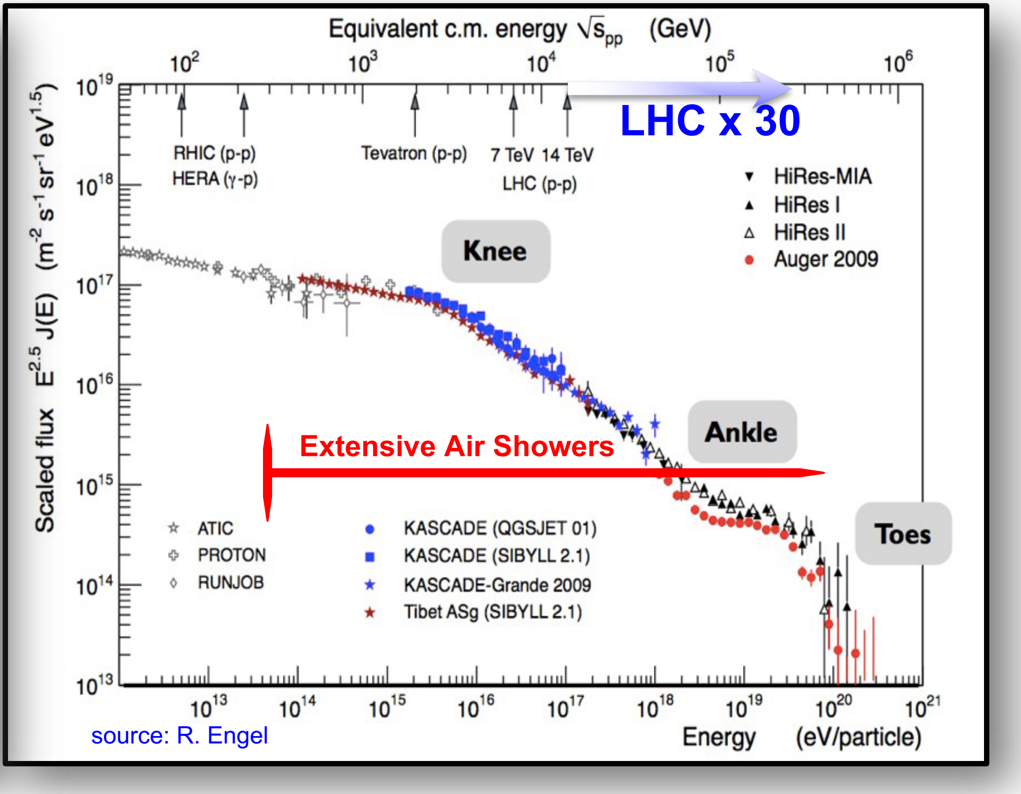
UHECRs: Flux of cosmic rays and interaction energies

Low energy air shower

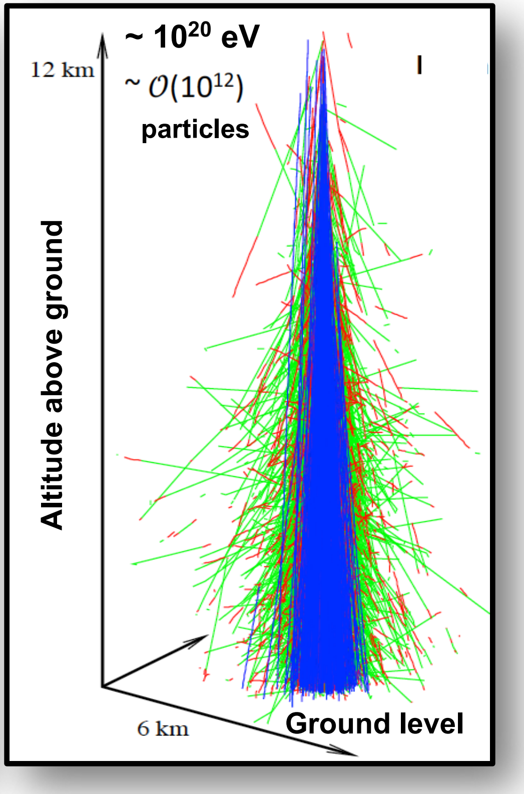
Cosmic rays spectrum

High energy extensive air shower





source: R. Engel

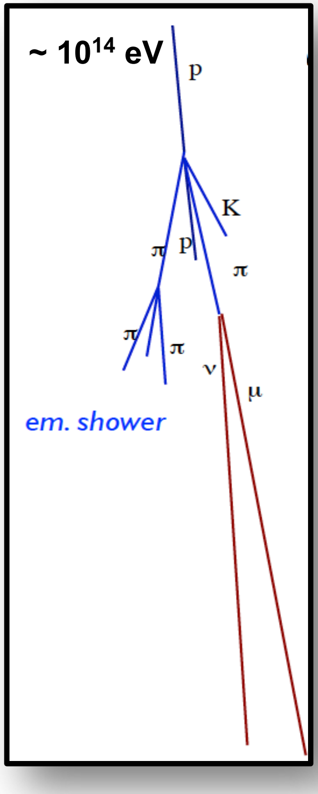


> At ultra-high-energies (> 10^{17} eV) particle physics beyond the reach of colliders

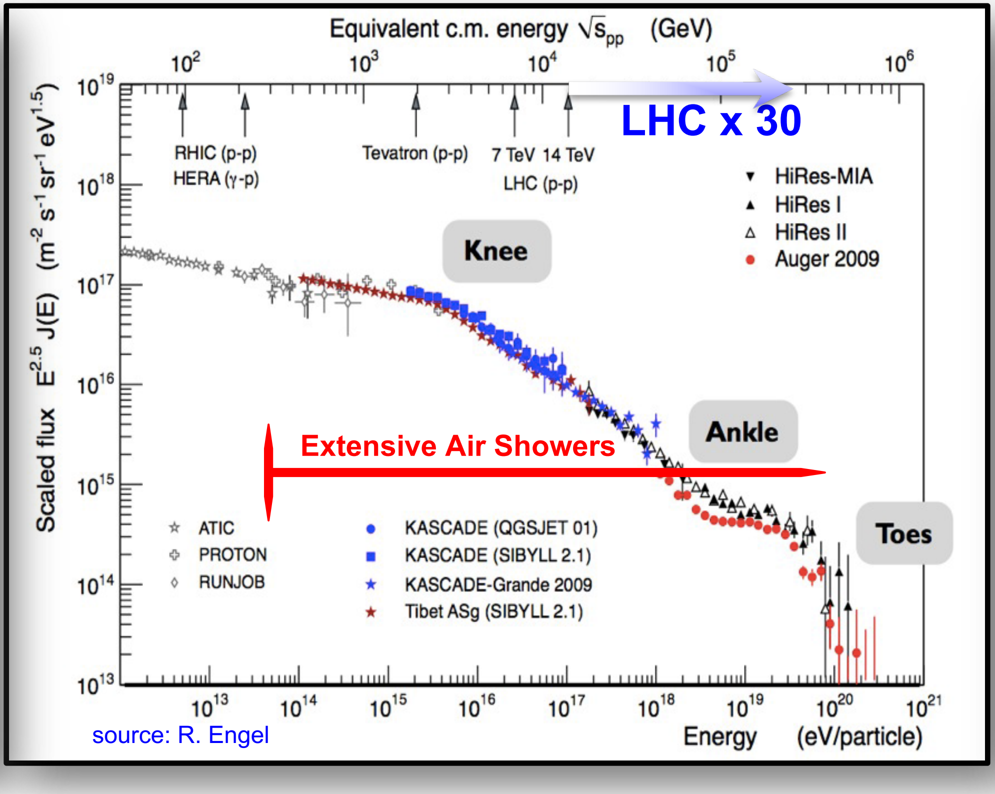
Need accelerator of size of Mercury's orbit to reach 10^{20} eV with LHC technology

UHECRs: Flux of cosmic rays and interaction energies

Low energy air shower



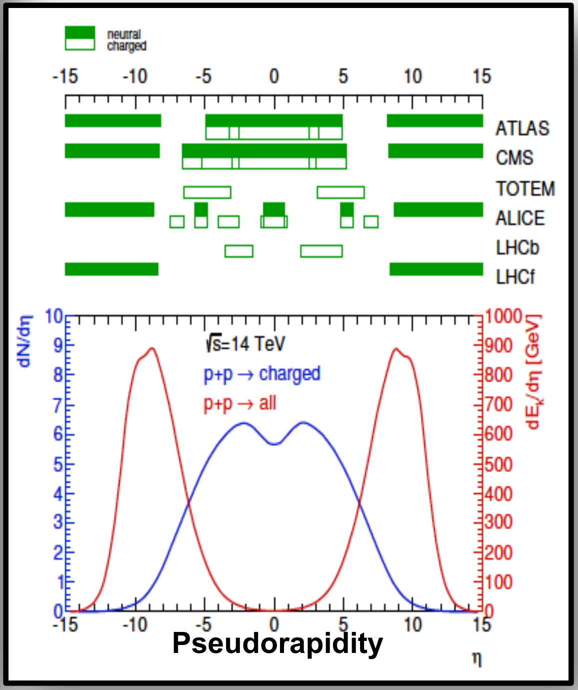
Cosmic rays spectrum



source: R. Engel

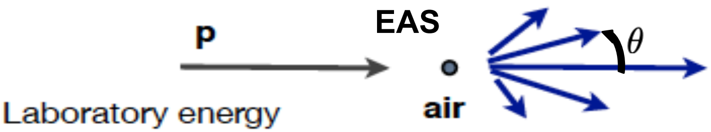
LHC acceptance and phase space

p-p data mainly from “central” detectors $|\eta| < 2.5$



Different phase space for LHC and air showers:

- most of the particles produced at midrapidity - important for models
- EAS: $N_{particle}$ ~ E, most of energy carried by forward (backward) particles - important for air showers
- More LHC data needed in the forward directions and for heavier targets to fill required phase-space for EAS

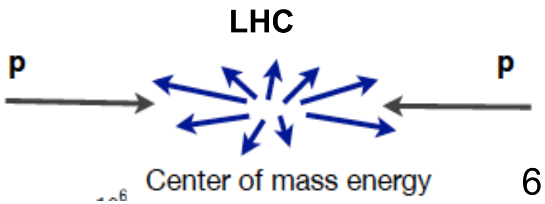


Laboratory energy

$$\eta \equiv -\ln(\tan(\theta/2))$$

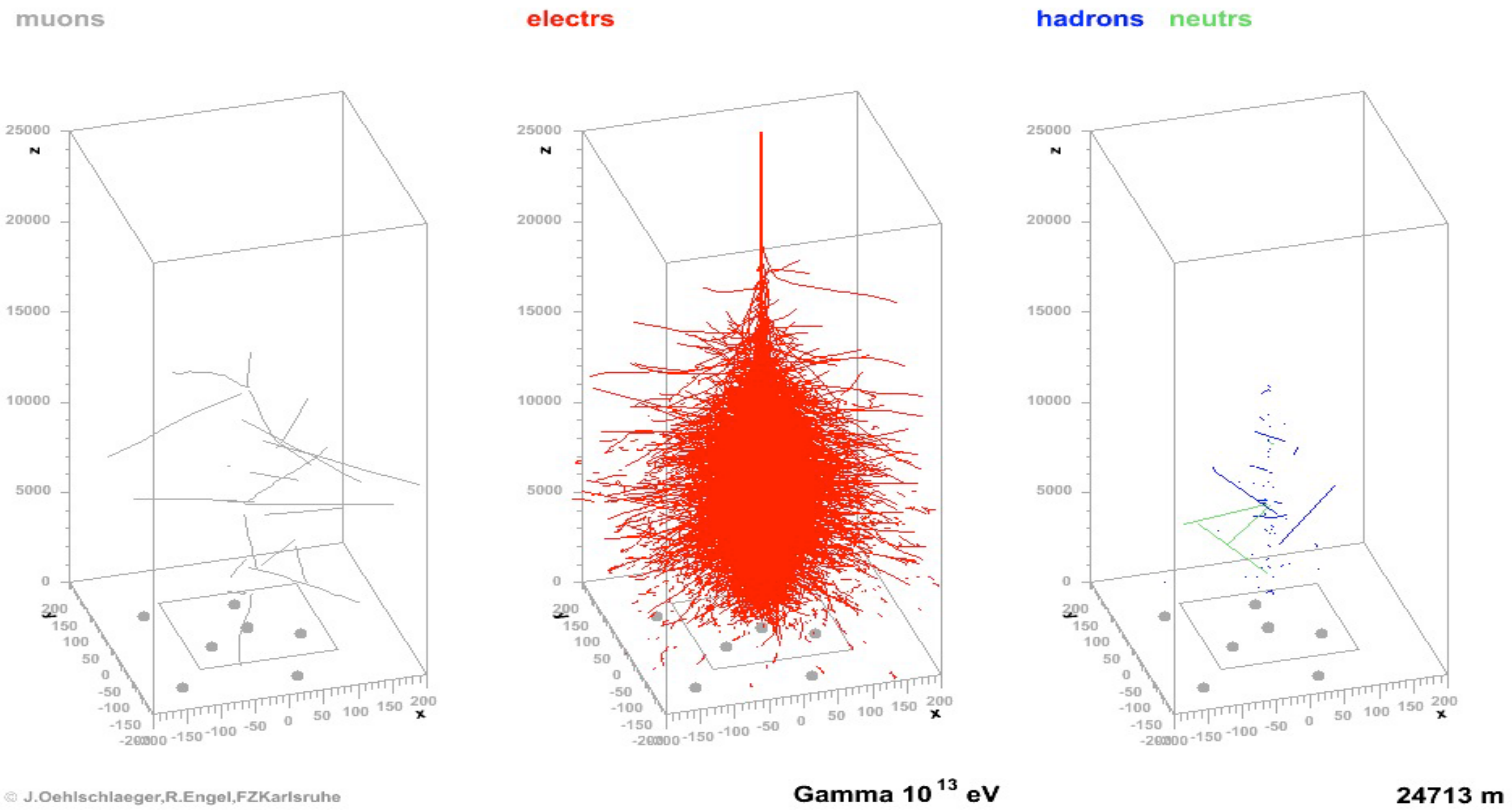
$\eta = 0$ $(\theta = 90)$ is midrapdity

$\eta \gg 1$ is forward $\eta \ll 1$ is backward



Center of mass energy

Particles of a gamma-ray shower



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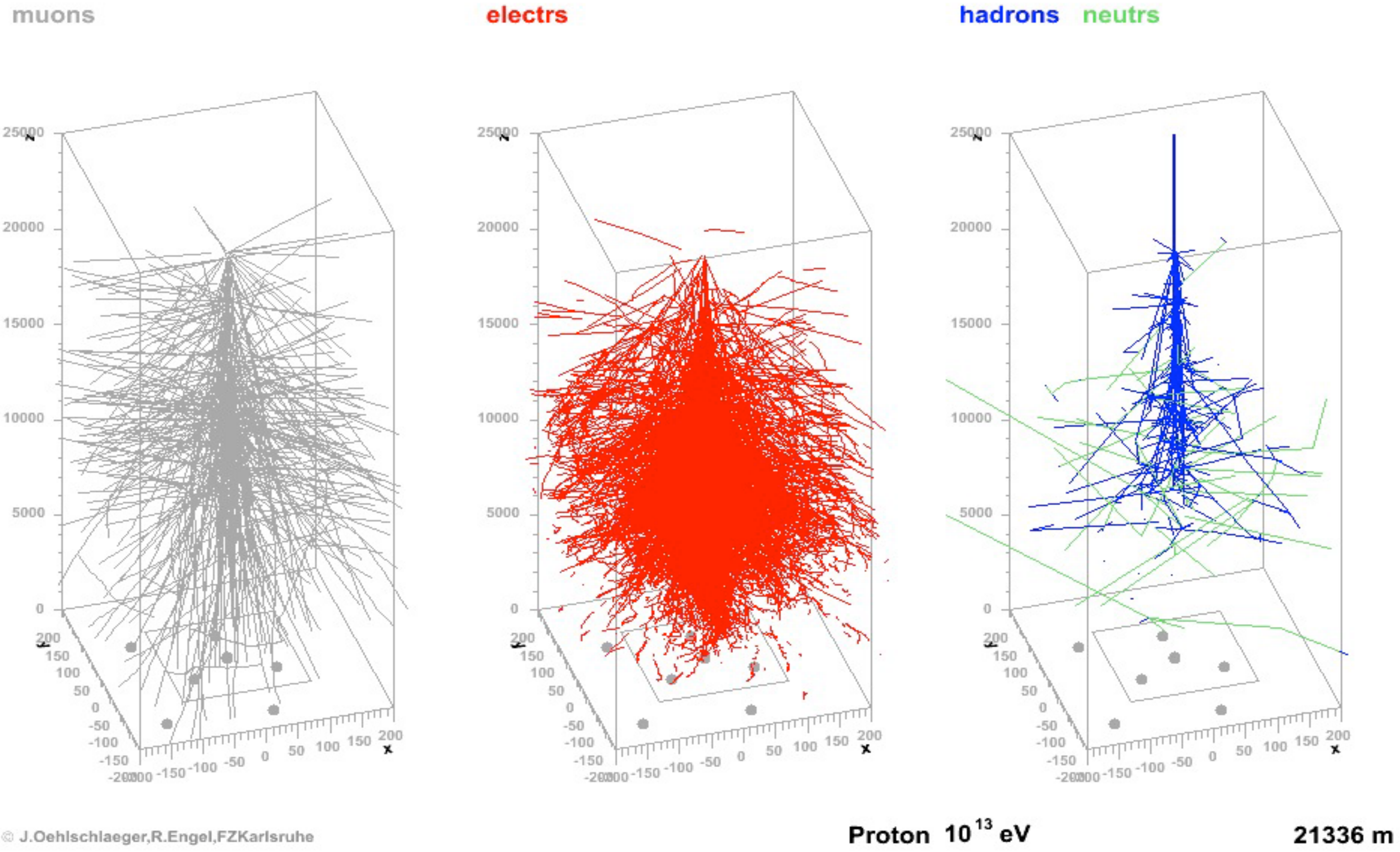
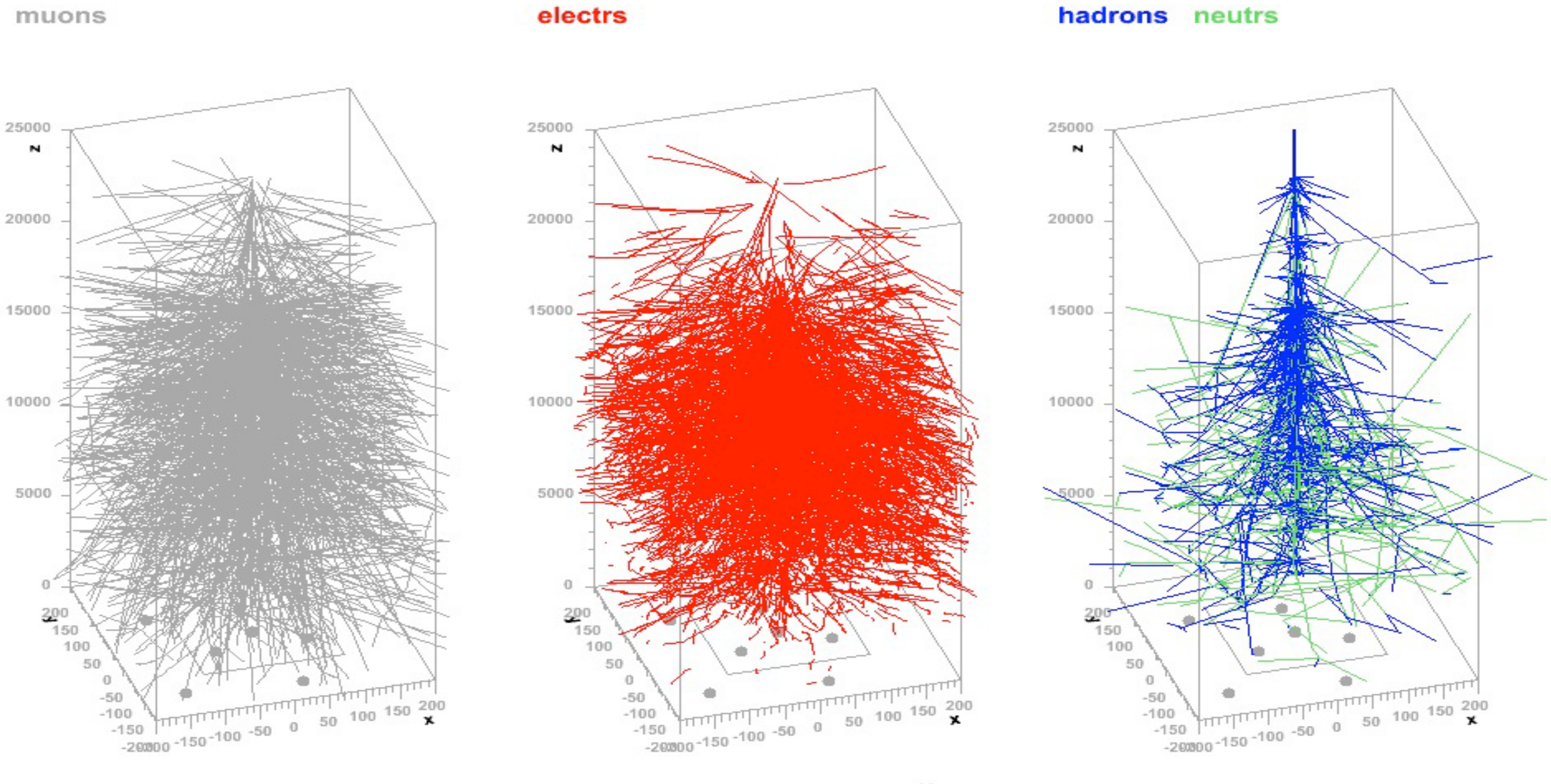
Particles of an proton shower



Particles of an iron shower



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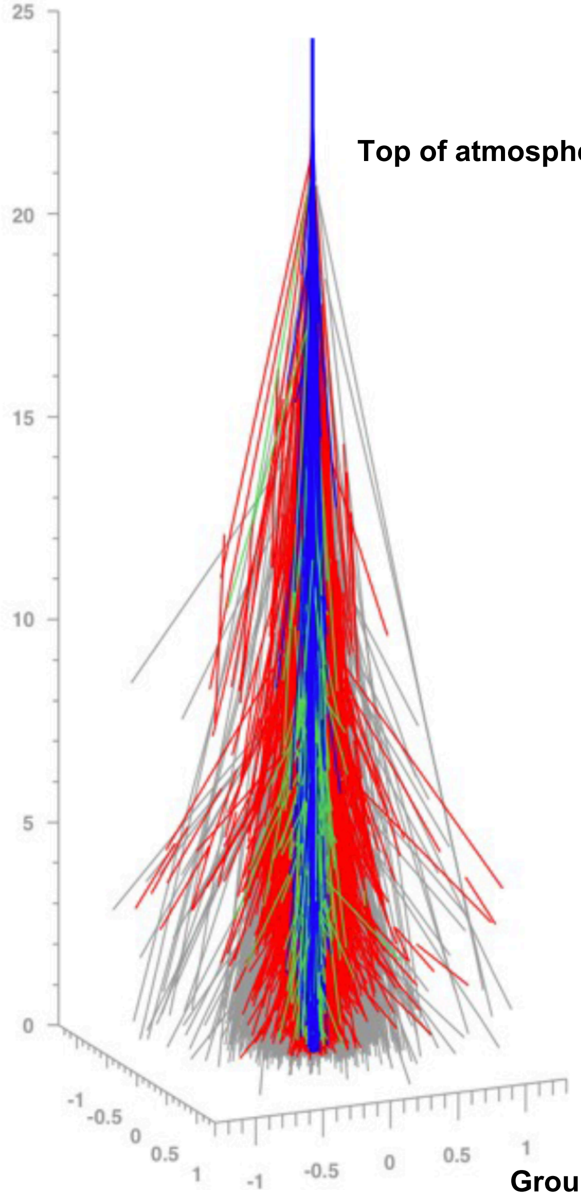
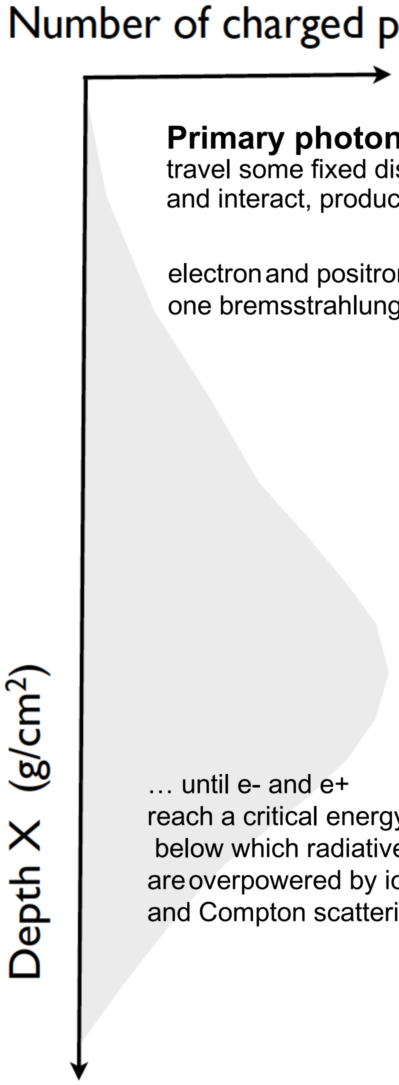
Electromagnetic showers: Heitler model



Top of atmosphere

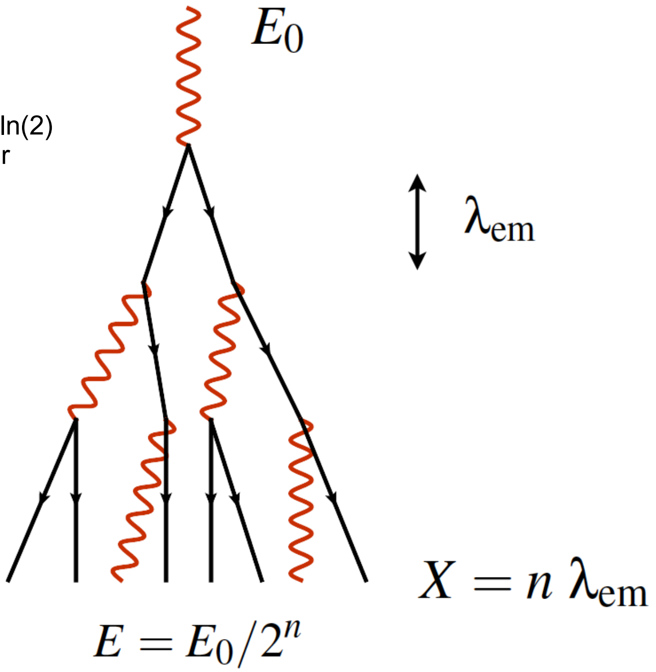
Ground level



Primary photon in air
travel some fixed distance d=$X_0/\ln(2)$
and interact, producing e-/e+ pair

electron and positron radiates
one bremsstrahlung photo

… until e- and e+
reach a critical energy Ec
below which radiative energy losses
are overpowered by ionization
and Compton scattering energy losses



$$X = n\,\lambda_{\text{em}}$$

$$E = E_0/2^n$$

Shower maximum: $E = E_c$

$$N_{\max} = E_0/E_c$$
$$X_{\max} \sim \lambda_{\text{em}} \ln(E_0/E_c)$$

W. Heitler. The Quantum Theory of Radiation, Oxford University Press, London, third edition, 1954. Section 38

Electromagnetic showers: Cascade equations

Energy loss of electron: $$\frac{\mathrm{d}E}{\mathrm{d}X} = -\alpha - \frac{E}{X_0}$$

Critical energy: $E_c = \alpha\, X_0 \sim 85\,\mathrm{MeV}$

Radiation length: $X_0 \sim 36\,\mathrm{g/cm^2}$

Cascade equations

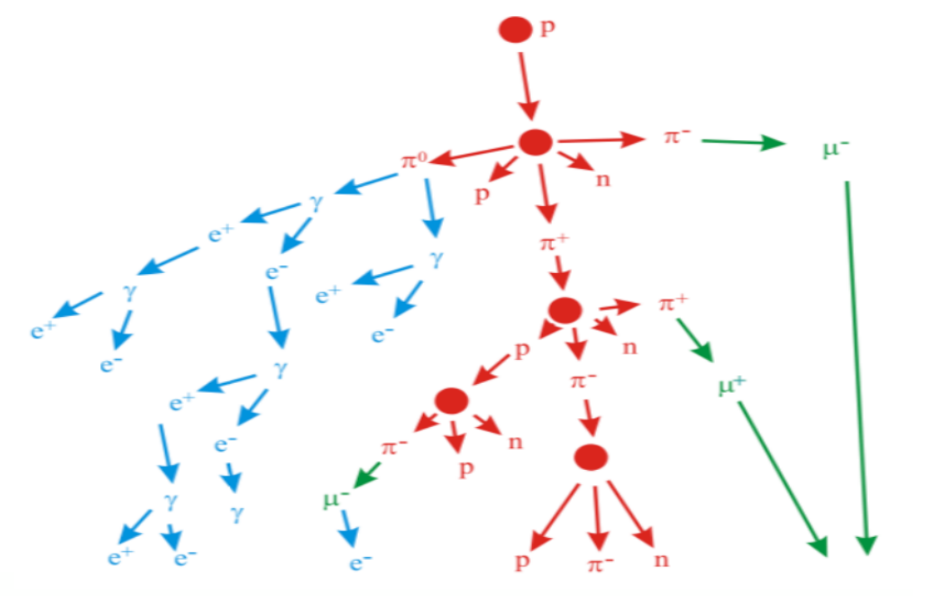
$$\frac{\mathrm{d}\Phi_e(E)}{\mathrm{d}X} = -\frac{\sigma_e}{\langle m_{\mathrm{air}}\rangle}\Phi_e(E) + \int_E^\infty \frac{\sigma_e}{\langle m_{\mathrm{air}}\rangle}\Phi_e(\tilde{E})P_{e\to e}(\tilde{E},E)\mathrm{d}\tilde{E}$$

$$+\int_E^\infty \frac{\sigma_\gamma}{\langle m_{\mathrm{air}}\rangle}\Phi_\gamma(\tilde{E})P_{\gamma\to e}(\tilde{E},E)\mathrm{d}\tilde{E} \;+\; \alpha\frac{\partial\Phi_e(E)}{\partial E}$$

$$X_{\max} \approx X_0 \ln\left(\frac{E_0}{E_c}\right) \qquad N_{\max} \approx \frac{0.31}{\sqrt{\ln(E_0/E_c) - 0.33}}\,\frac{E_0}{E_c}$$

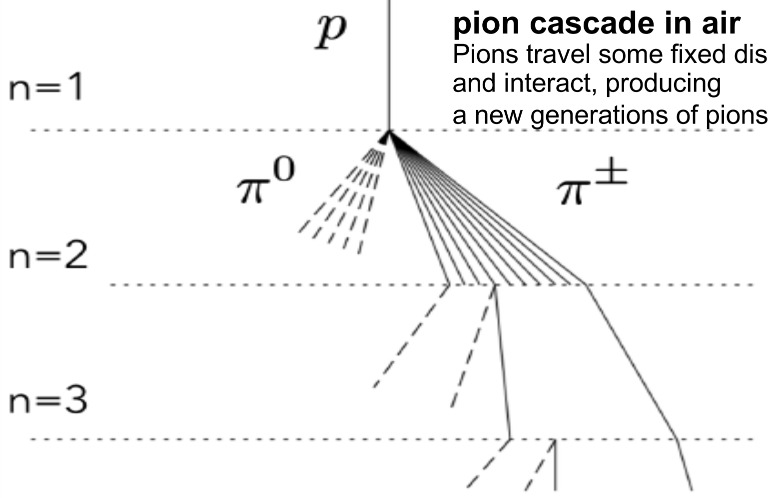
(Rossi & Greisen, Rev. Mod. Phys. 13 (1940) 240)

Air shower and its connetions to hadronic interactions



Hadronic Heitler model

J. Matthews, Astropart. Phys. 22 (2005) 387



pion cascade in air
Pions travel some fixed distance
and interact, producing
a new generations of pions

Electromagnetic part (EM):

well understood

EM cascade takes **> 50%** of energy from **1st, 2nd and 3rd** hadronic generations

$$\pi^0 \to \gamma\gamma$$

Sensitive to High Energy Physics

Hadronic cascade:

Keeps developing until critical energy of mesons $\xi_c^{\pi^\pm}$

$$\pi^\pm \to \mu\nu_\mu$$

Sensitive to High & Low Energy Physics

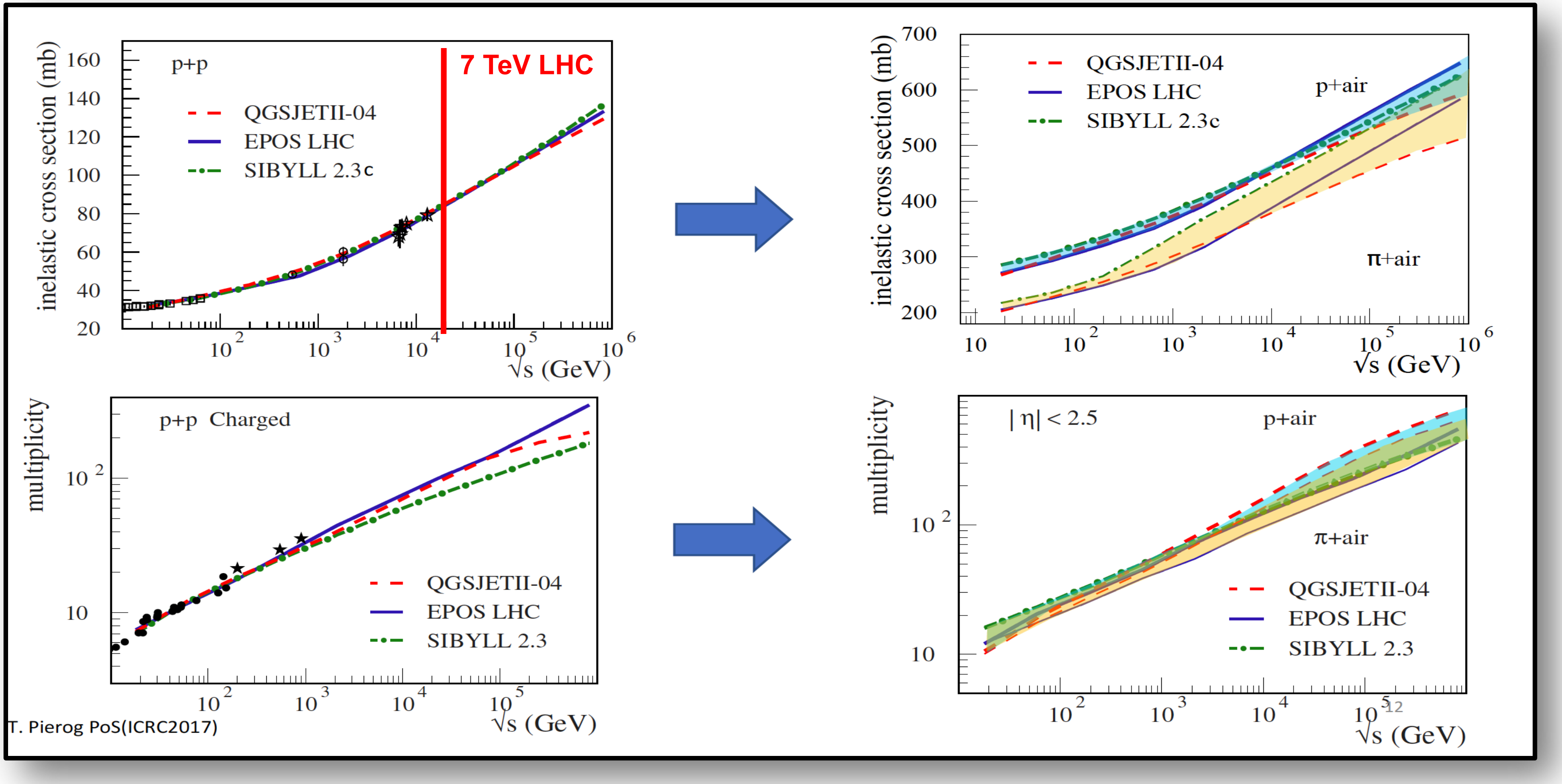
Muon part: have large model uncertainties
measured observables:

Muon number	Muon production depth and its error
$\mathbf{N}_\mu \propto \mathbf{A}\mathbf{E}^\beta/(\mathbf{A}\xi_\mathbf{c}^{\pi^\pm})^\beta$	X_μ, $RMS_{X\mu}$

> Muon number via parameter β depends on multiplicity, pion charge-ratio, and (in)elasticity,
- connection between air shower physics and hadronic interaction models

Hadronic interactions models

> Hadronic interaction models commonly used to simulate EAS were updated to take into account LHC data at 7 TeV: QGSJETII-04 **Phys. Rev. D 83, 014018**, EPOS-LHC **Phys. Rev. C 92, 034906**, and SIBYLL-2.3c **Phys. Rev. D 80, 094003**



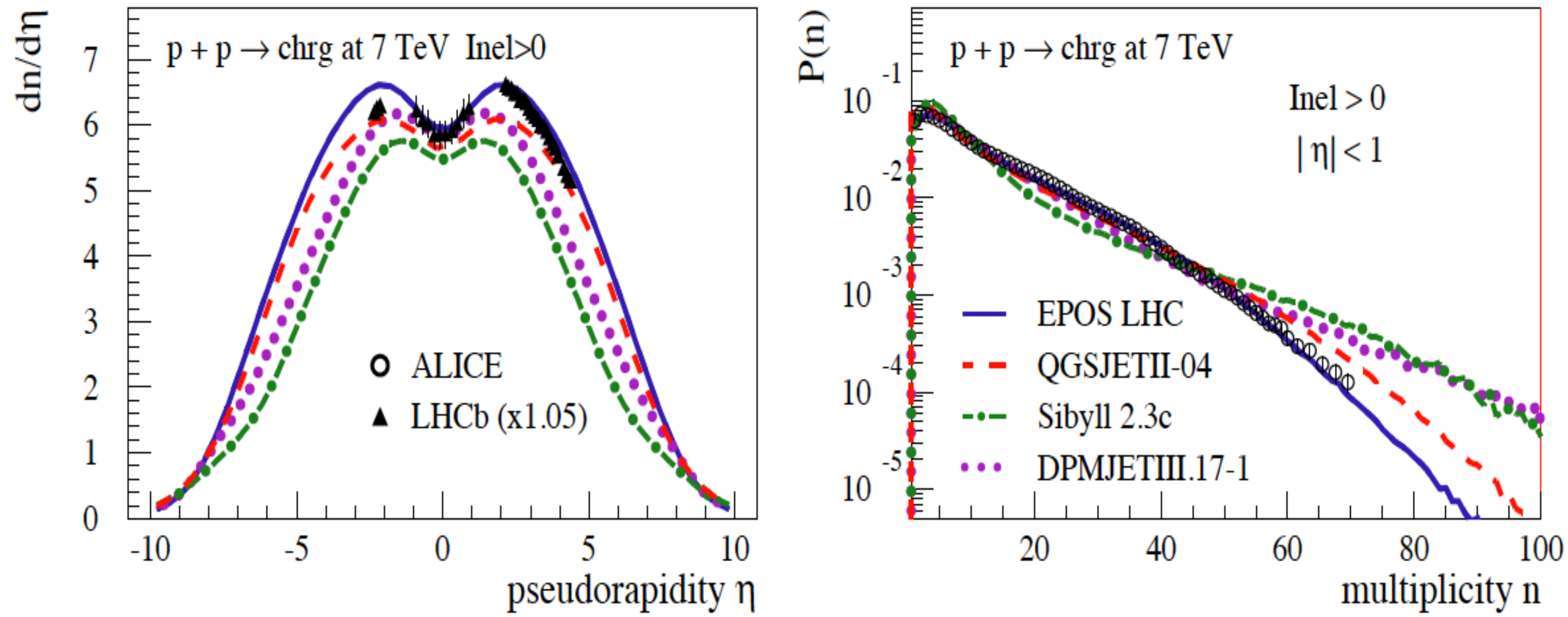
T. Pierog PoS(ICRC2017)

> The p-p cross section is very well described up to the LHC energy (extrapolation up to the highest energies is very similar between models).
… but differences in the extrapolations of the p-air and π-air inelastic cross-sections

> More LHC data needed in the forward directions and for heavier targets.

Hadronic interactions models

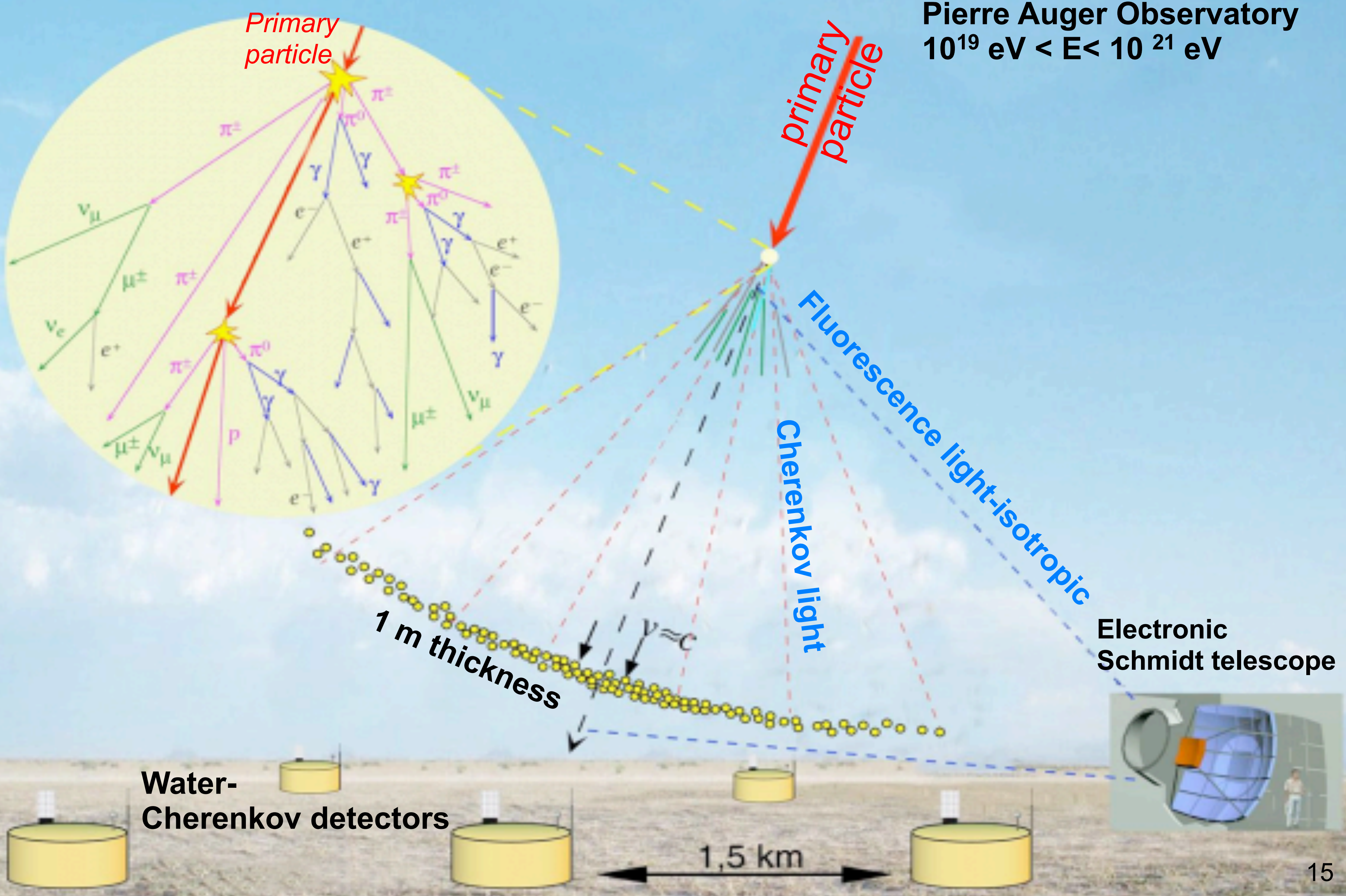
> Only small differences in p-p model predictions - main difference in high multiplicity tail



T. Pierog, PoS ICRC2017 (2018) 1100

> The extrapolations of p-p data to highest energies have large uncertainties

Extended air showers



Pierre Auger Observatory
10^{19} eV < E< 10^{21} eV

primary particle

Fluorescence light-isotropic

Cherenkov light

1 m thickness

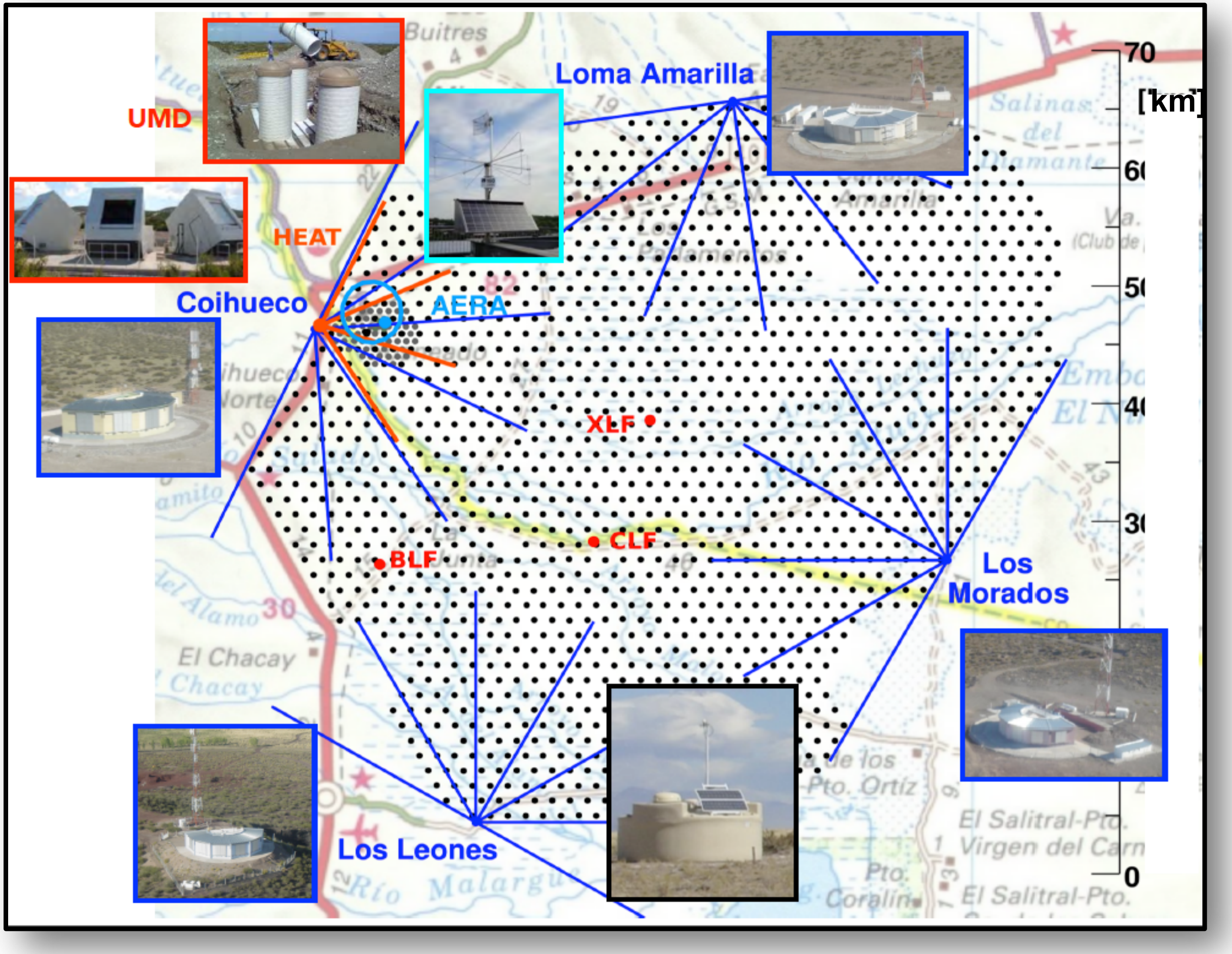
Electronic Schmidt telescope

Water-Cherenkov detectors

Pierre Auger Observatory - the largest UHECRs observatory

> **Water-Cherenkov stations**
➡SD1500 : 1600, 1.5 km grid, 3000 km^2
➡SD750 : 61, 0.75 km grid, 25 km^2

> **Fluorescence Sites:**
➡ 4 sites, 24 telescopes, 1-30deg FoV
HEAT: ➡ 3 high elevation FD, 30-60 deg FOV



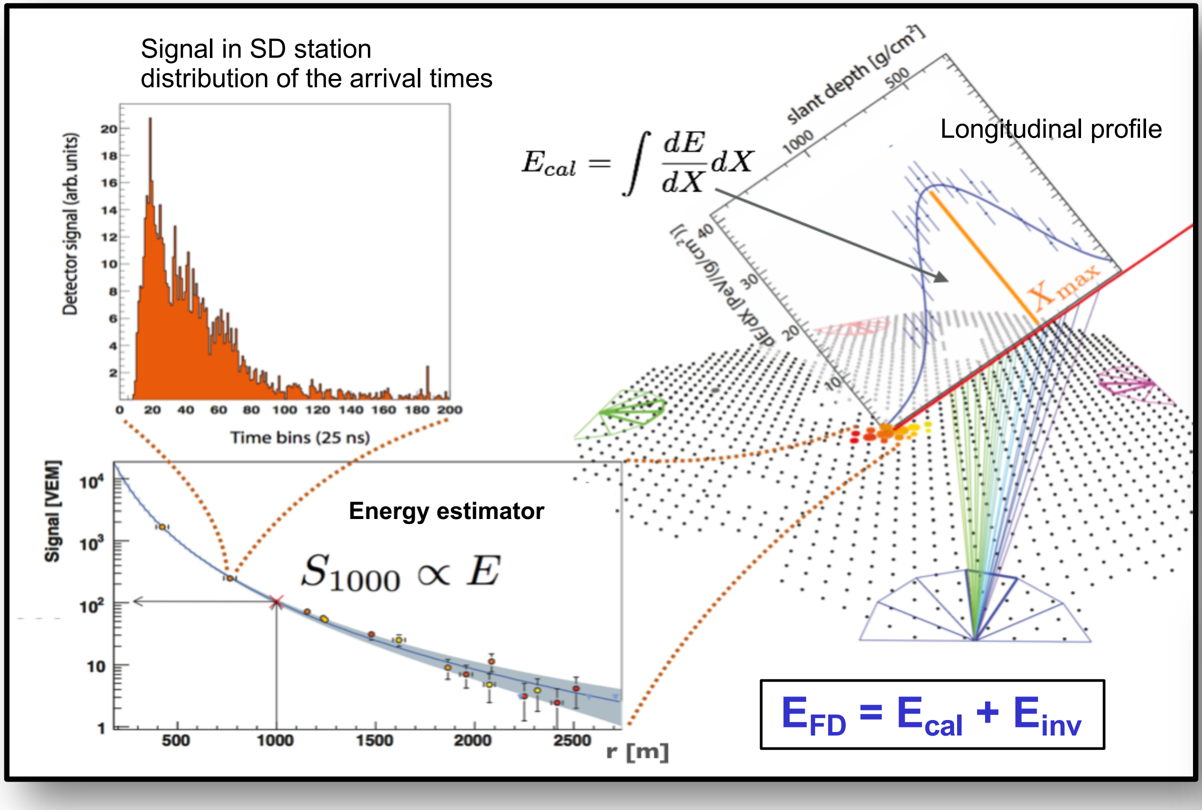
Underground Muon Detectors:
➡ 7 in engineering array phase -61 aside the Infill stations

AERA radio antennas
➡ 153 graded 17 km2

+**Atmospheric monitoring**
devices CLF, XLF, Lidars, …

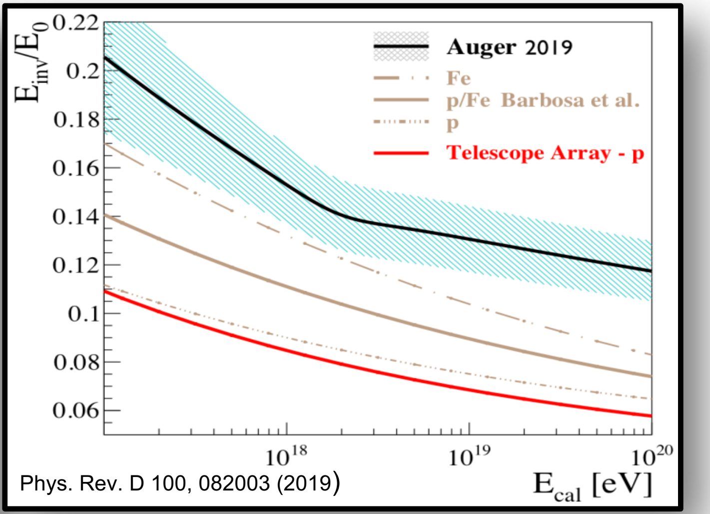
Hybrid reconstruction

> Detection of air shower



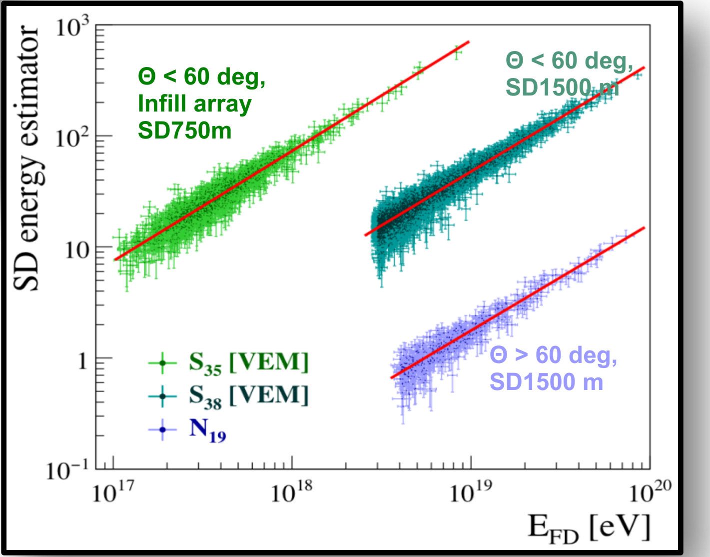
$$E_{FD} = E_{cal} + E_{inv}$$

Invisible energy fraction



Phys. Rev. D 100, 082003 (2019)

Hybrid Energy Calibration (model indepen.)



Auger “design concept”. Twofold benefit:

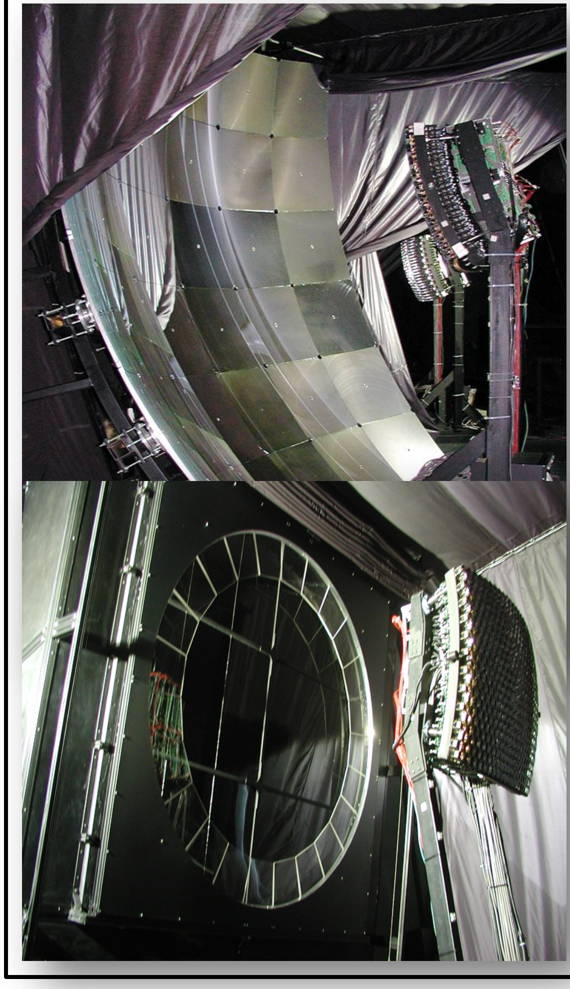
- > Hybrid events fewer (DC ≈ 15%) but superior (better geometry, energy and mass determination)
- > Hybrid events calibrate SD events (DC ≈100%)

Energy scale set by Fluorescence Detector
$\sigma(E_{FD})/E_{FD} \sim 8\%$
Systematic uncertainty ~14%

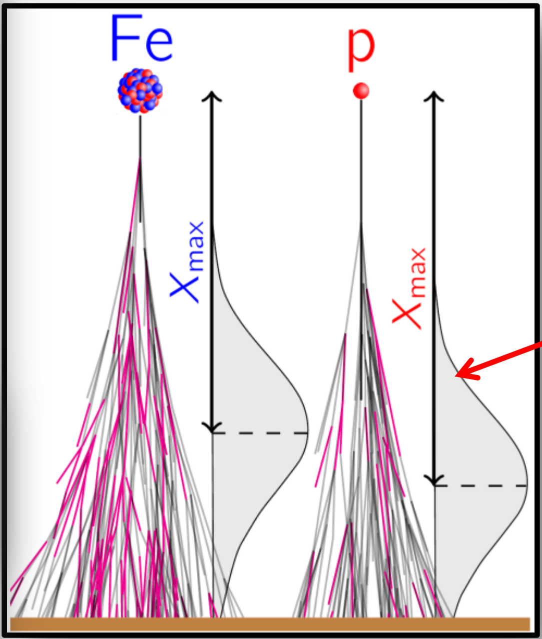
Mass composition with FD

> **Depth of shower maximum X_{max}** is an observable sensitive to the mass composition

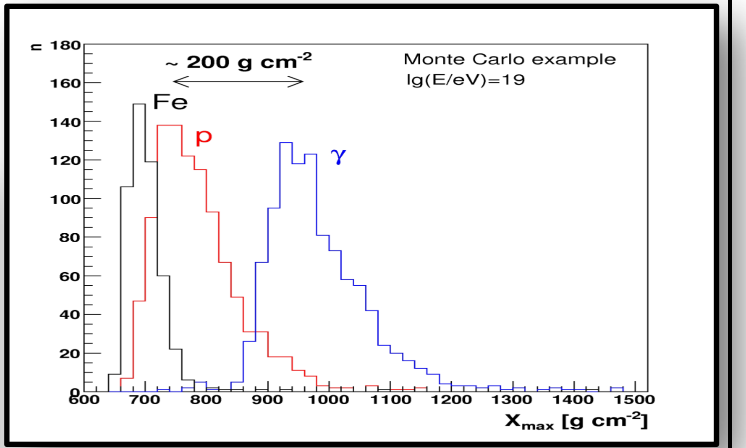
> **… from fluorescence detector:**



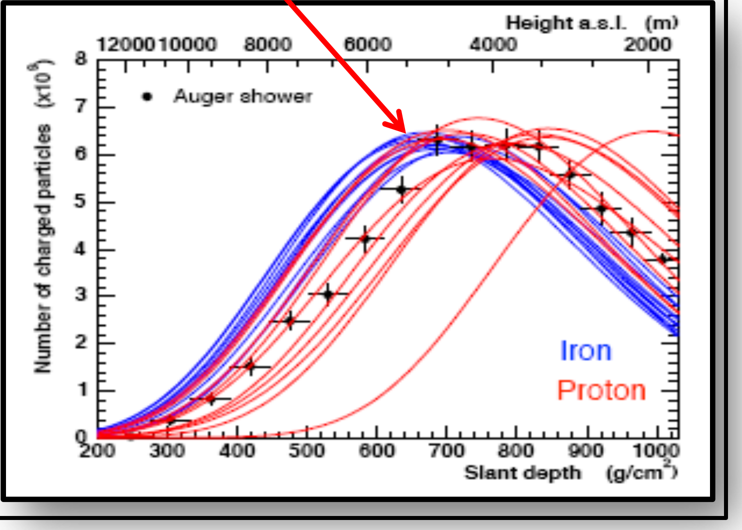
Top of atmosphere



Detector level



Longitudinal Profile



$X_{max}(Fe) < X_{max}(p) < X_{max}(\gamma)$ $RMS[X_{max}(Fe)] < RMS[X_{max}(p)]$

Longitudinal profile

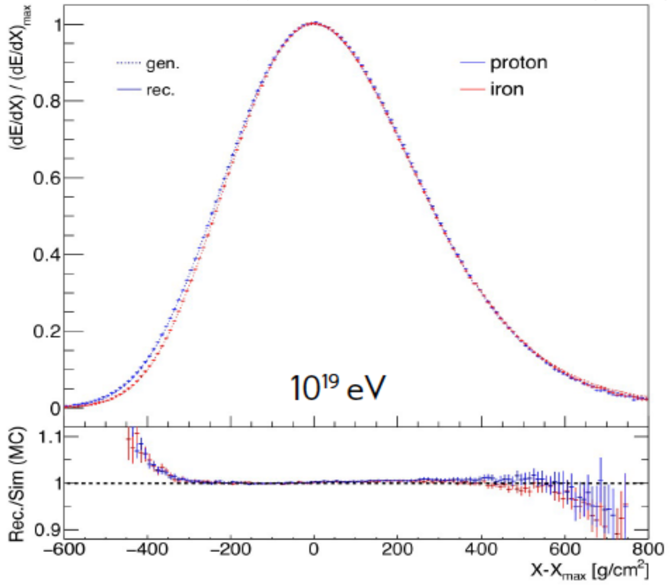
> Gaisser-Hillas function describes shape of longitudinal profile well (within measurement uncertainties)

$$(\mathrm{d}E/\mathrm{d}X)' = \left(1 + R\,\frac{X'}{L}\right)^{R^{-2}} \exp\left(-\frac{X'}{RL}\right)$$

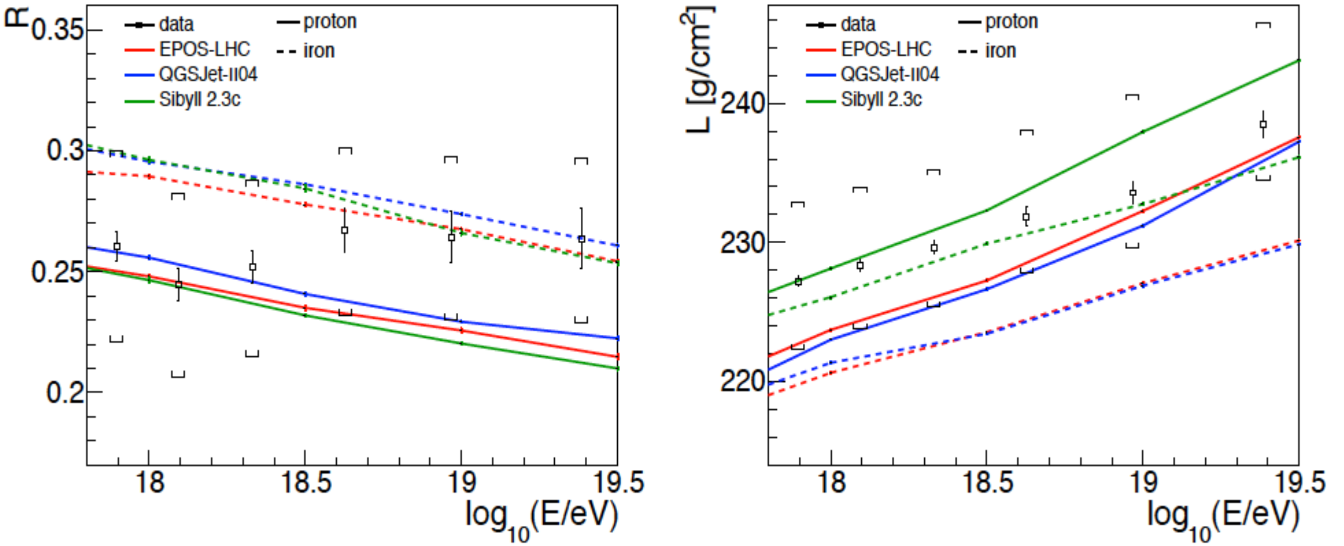
width parameter

$$R = \sqrt{\lambda/|X_0'|},\ L = \sqrt{|X_0'|\lambda} \text{ and } X_0' \equiv X_0 - X_{\max}$$

asymetry parameter



The Pierre Auger Collaboration, JCAP03(2019)018



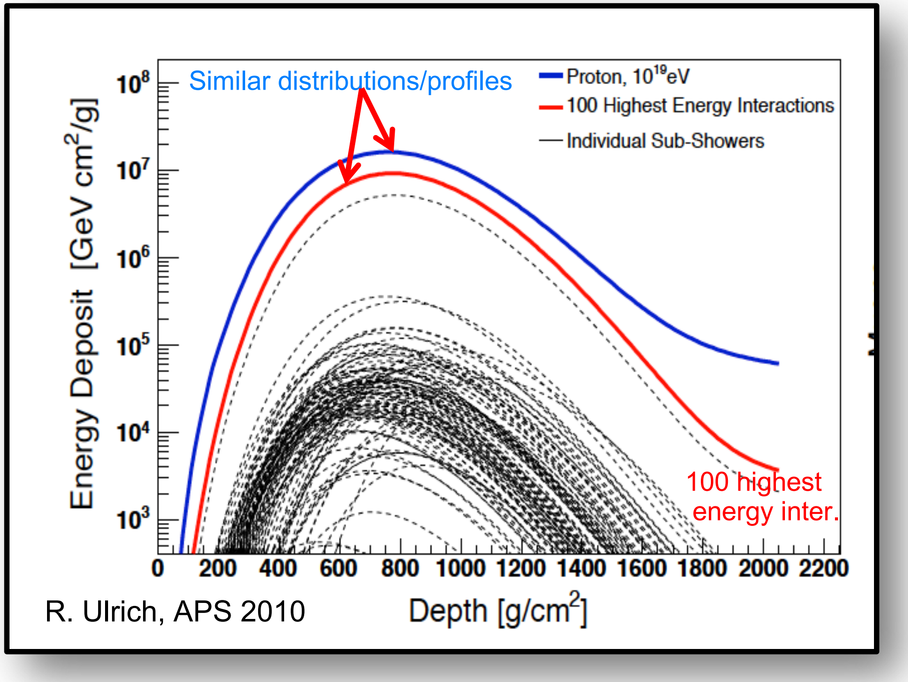
The Pierre Auger Collaboration, JCAP03(2019)018

> The asymmetry, R, and the width, L, in data agree well with the predicted values for all models

Influence of hadronic models parameters

X_{max} and its RMS sensitive to

- inelastic cross-section (very sensitive)
  High-precision measurements from LHC, see e.g.
  LHCb collab. JHEP 1806 (2018) 100 and refs. therein
- hadron multiplicity

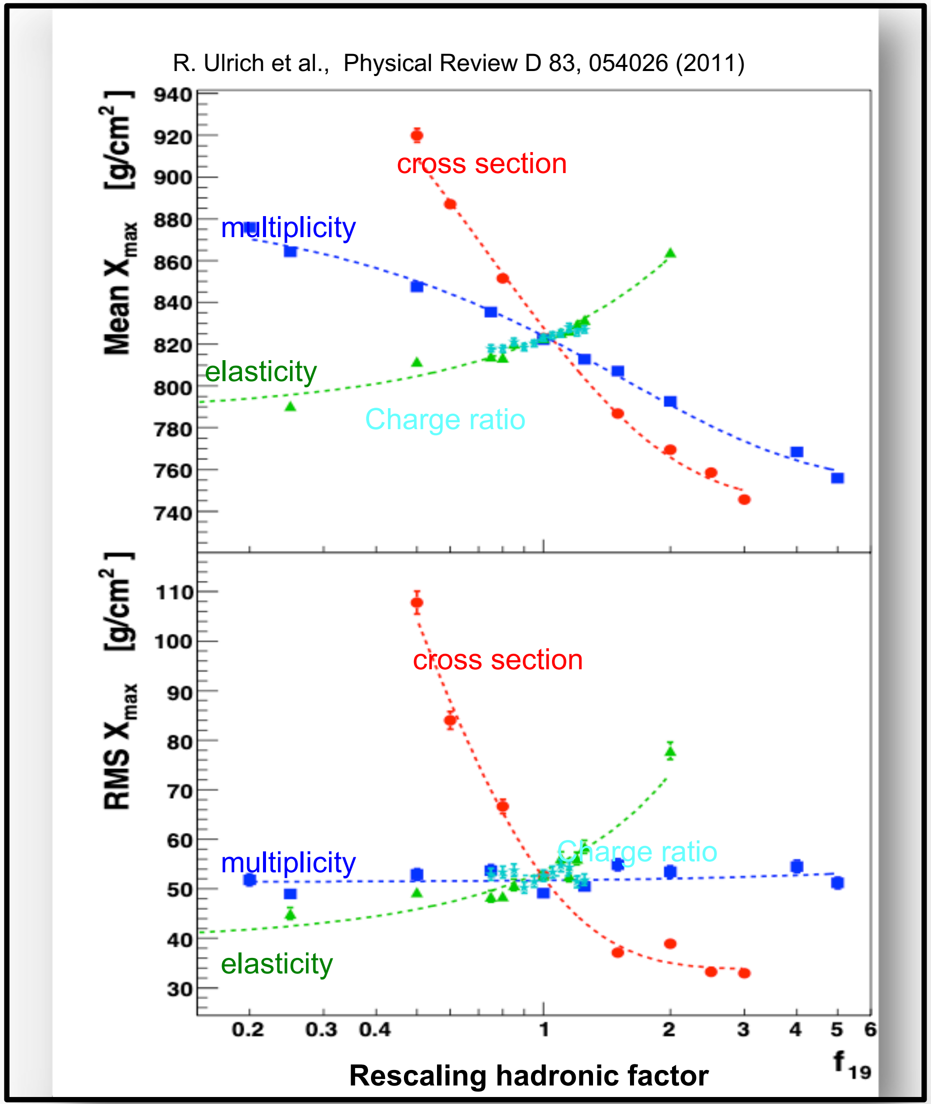


R. Ulrich, APS 2010

X_{max} is dominanted by first interactions and related mostly to electromagnetic component of EAS

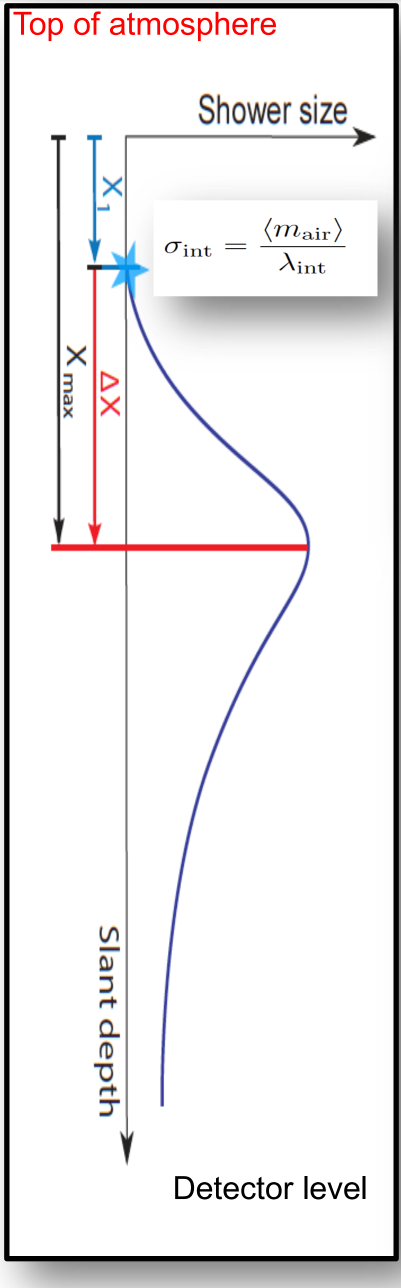
The average shape of profile is well reproduced by the Gaisser-Hillas parametrization and agree well with predictions from hadronic interaction models, The Pierre Auger Collaboration, JCAP03(2019)018

Impact of hadronic interaction features on the shower maximum



R. Ulrich et al., Physical Review D 83, 054026 (2011)

p-Air cross-section method



$$\sigma_{\rm int} = \frac{\langle m_{\rm air} \rangle}{\lambda_{\rm int}}$$

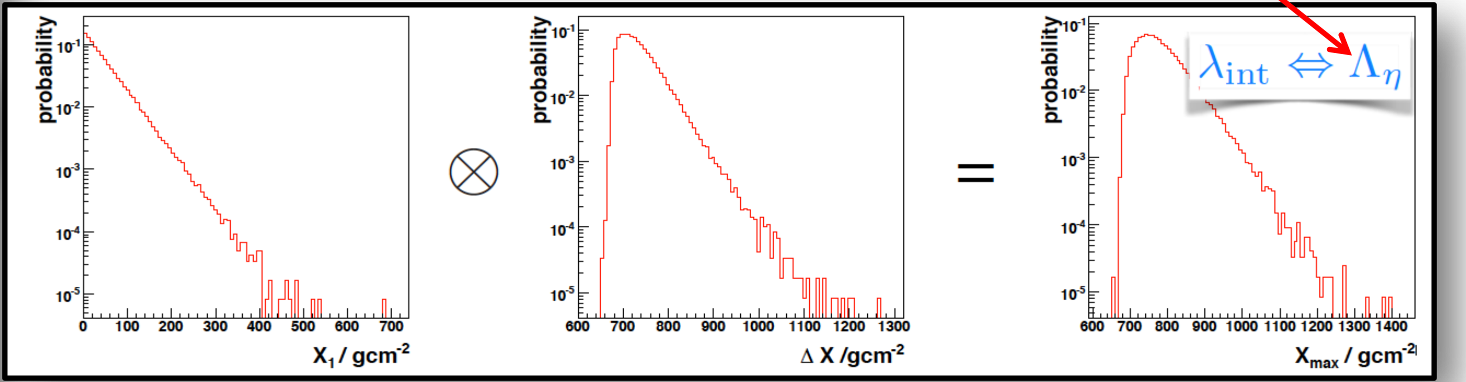
$$\frac{\mathrm{d}\,p}{\mathrm{d}\,X_1} = \frac{1}{\lambda_{\rm int}} e^{-\frac{X_1}{\lambda_{\rm int}}}$$

Interaction length

Tail of X_{max} distributions:

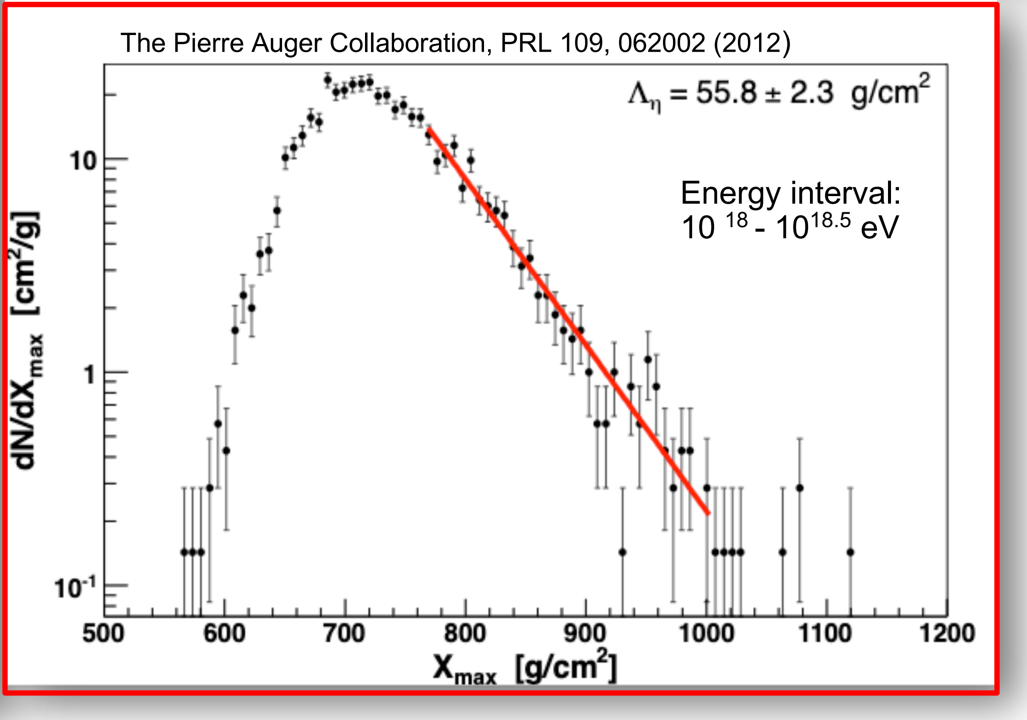
$$\frac{\mathrm{d}\,N}{\mathrm{d}\,X_{\rm max}} \propto e^{-\frac{X_{\rm max}}{\Lambda_\eta}}$$

Fitting parameter



$$\lambda_{\rm int} \Leftrightarrow \Lambda_\eta$$

The Pierre Auger Collaboration, PRL 109, 062002 (2012)



$\Lambda_\eta = 55.8 \pm 2.3$ g/cm^2

Energy interval:
10^{18} - $10^{18.5}$ eV

Difficulties

- mass composition

  Possible He contamination main source of systematic uncertainty. $\eta = 25\%$ He maximum contamination assumed

- fluctuations in shower development

  (model needed for correction)

- experimental resolution

  ~20 g/cm^2

p-p/p-Air cross-section

> Conversion from p-air to p-p by Glauber theory to get inelastic p-p cross-section

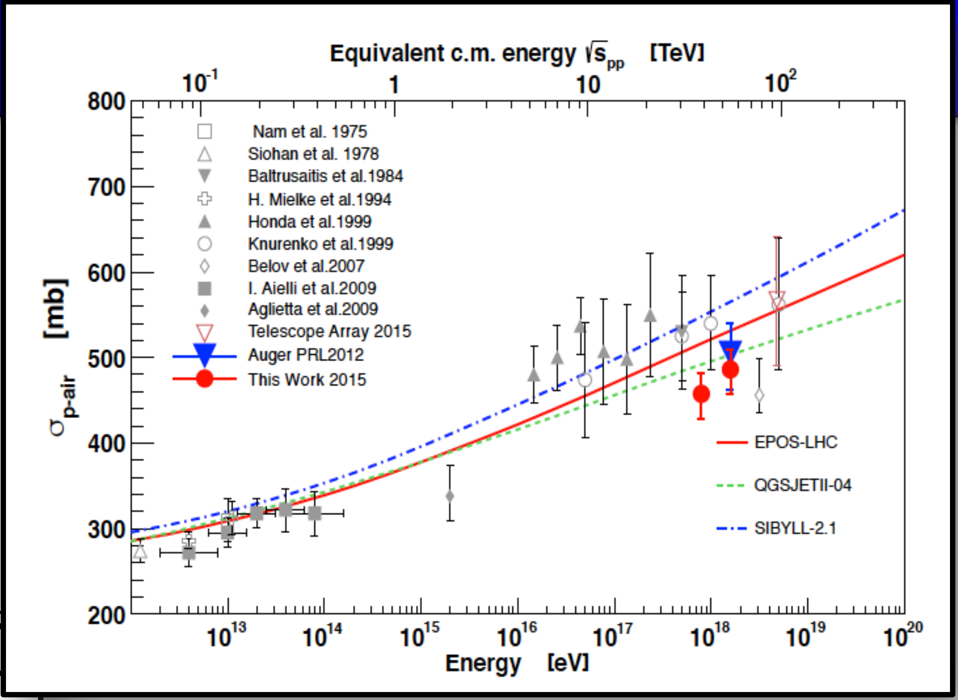
lower energy point in mb

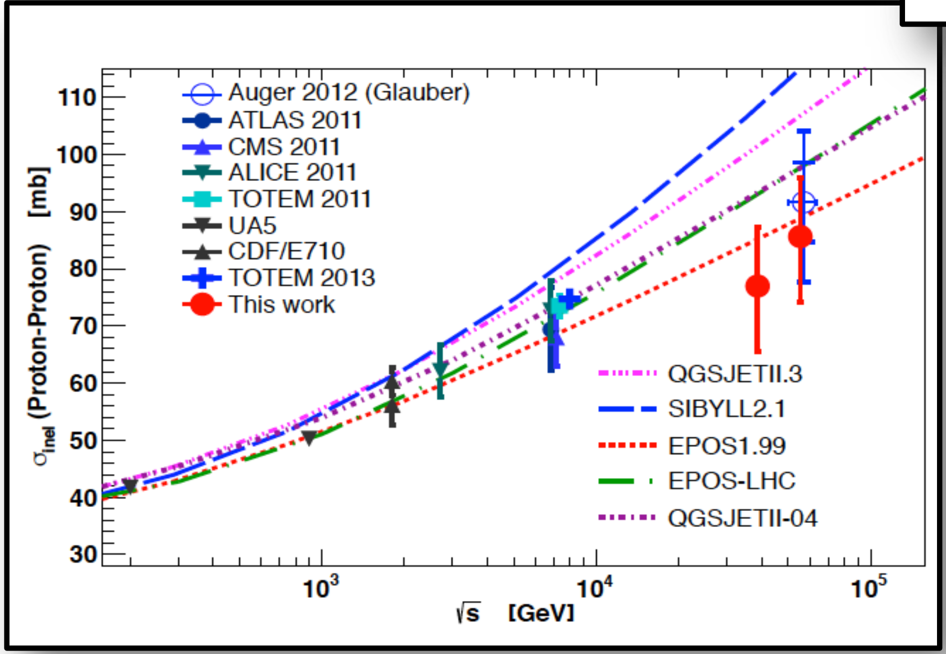
$$457.5 \pm 17.8(\mathrm{stat}) +^{+19}_{-25}\,(\mathrm{sys})$$

higher energy point in mb

$$485.8 \pm 15.8(\mathrm{stat}) +^{+19}_{-25}\,(\mathrm{sys})$$

The Pierre Auger Collaboration Phys. Rev. Lett. 109, 062002 (2012);
R. Ulrich for the Pierre Auger Collaboration, ICRC2015





p-p cross-section in mb:

$$85.62 \pm 5(\mathrm{stat}) +^{+5.5}_{-7.4}\,(\mathrm{sys}) \pm 7.1(\mathrm{Glauber})$$

$$\text{at } \sqrt{s_{pp}} = 55.5 \pm 3.6 \text{ TeV}$$

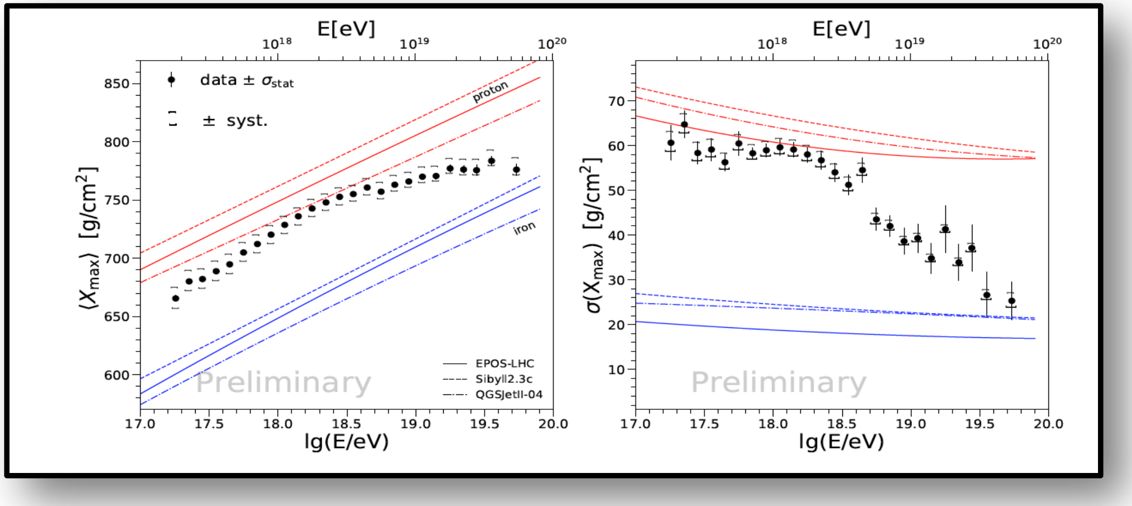
$$76.95 \pm 5.4(\mathrm{stat}) +^{+5.2}_{-7.2}\,(\mathrm{sys}) \pm 7.1(\mathrm{Glauber})$$

$$\text{at } \sqrt{s_{pp}} = 38.7 \pm 2.5 \text{ TeV}$$

> The data agree with an extrapolation from LHC energies to 57 TeV for a limited set of models.

Models show contradictions in the interpretation of X_{max}

> Above E= 2 EeV both X_{max} moments become compatible to MC predictions for heavier nuclei



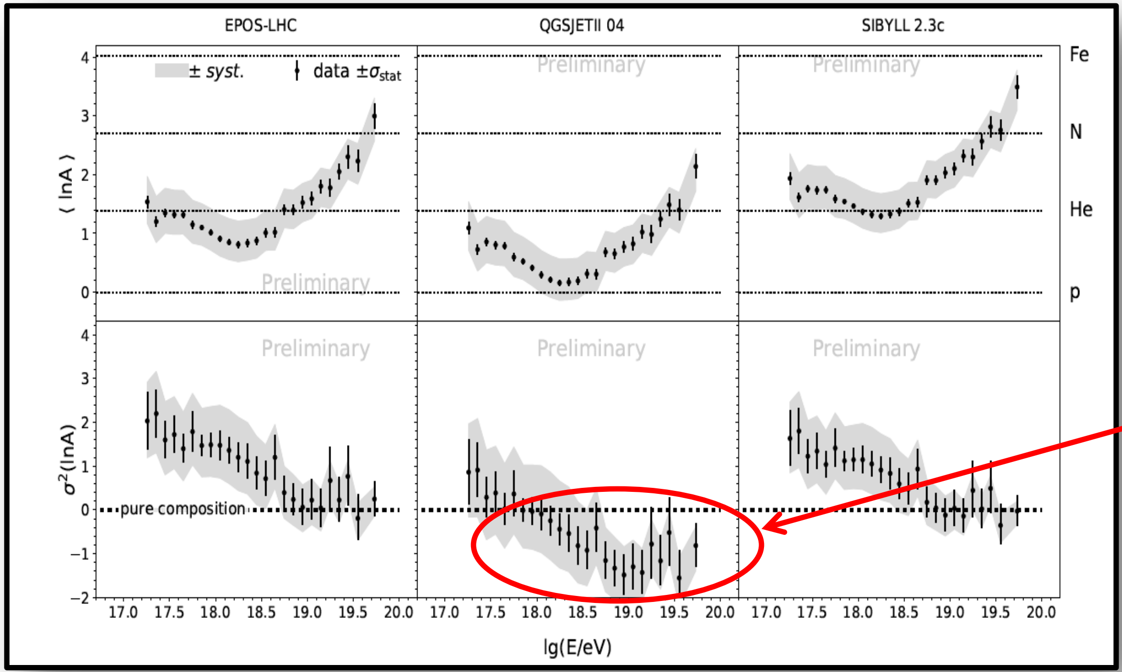
Method to interpret X_{max} and $\sigma^2(X_{max})$:

The Pierre Auger Collaboration, JCAP 02 (2013) 026

$$\langle X_{max} \rangle = \langle X_{max} \rangle_p + f_E \langle \ln A \rangle$$

$$\sigma^2(X_{max}) = \langle \sigma^2_{sh} \rangle + f_E^2 \, \sigma^2(\ln A)$$

A.Yushkov for the Pierre Auger Collaboration, ICRC 2019

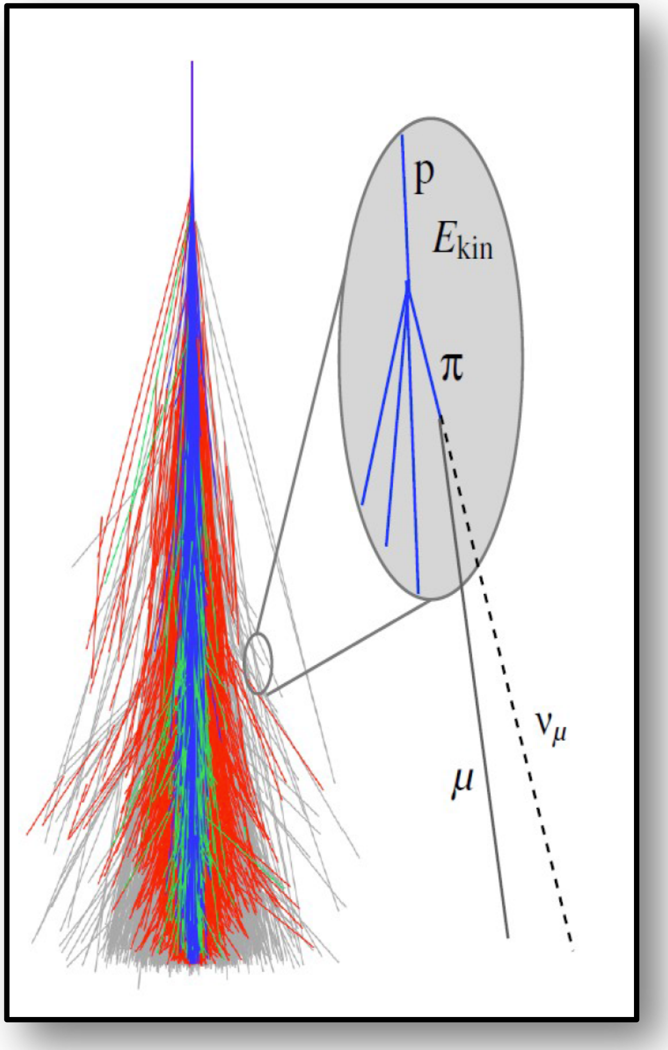


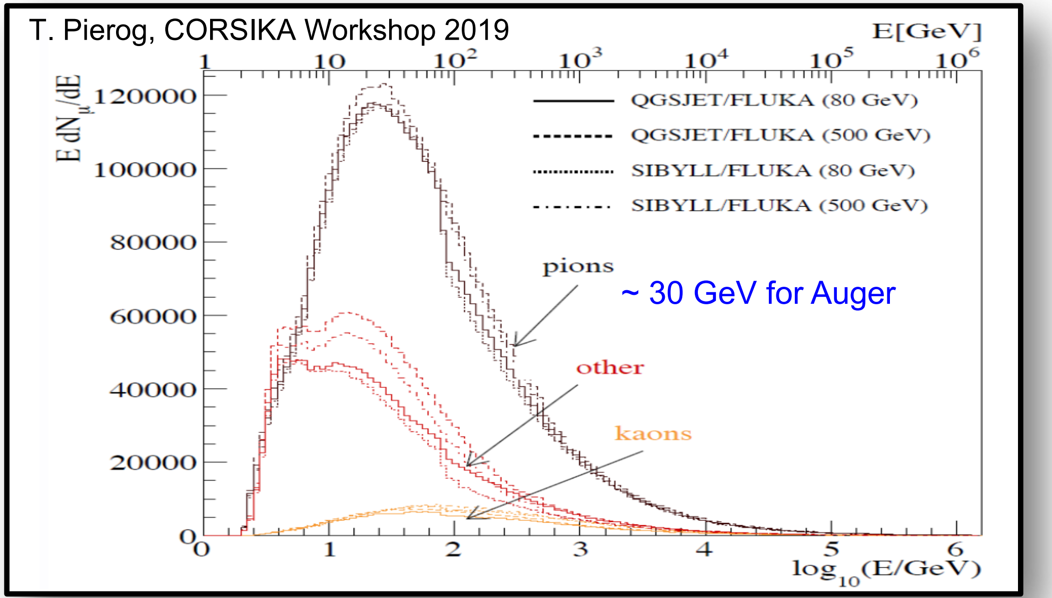
> <ln A> and σ^2(ln A) vary depending on hadronic interaction models

> Trend is similar, but not in absolute value

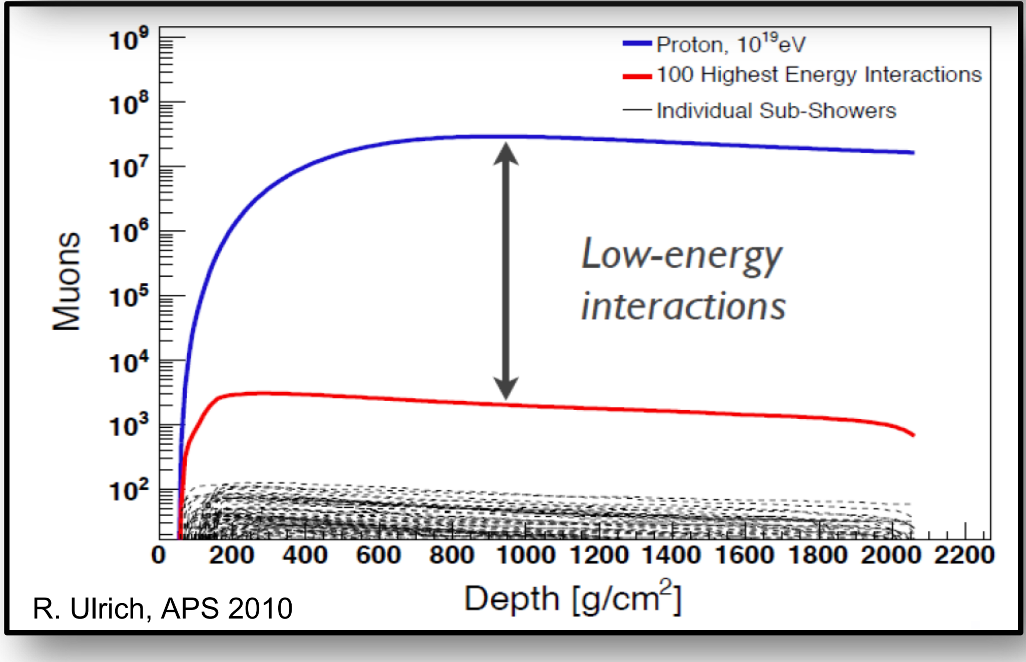
> QGSJET-II.04 predicts shower-to-shower fluctuations larger than mass range considered. X_{max} distributions not well predicted, leading to unphysical results. .

Muon production by low energy interactions




T. Pierog, CORSIKA Workshop 2019

~ 30 GeV for Auger

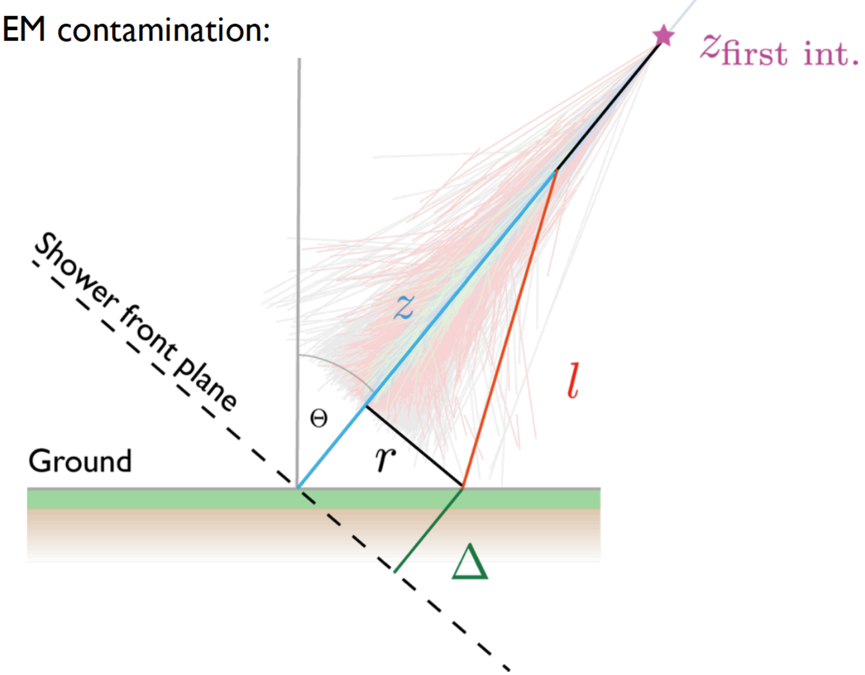


R. Ulrich, APS 2010

> Muons are produced late in shower cascade, amplified sensitivity to hadronic interactions

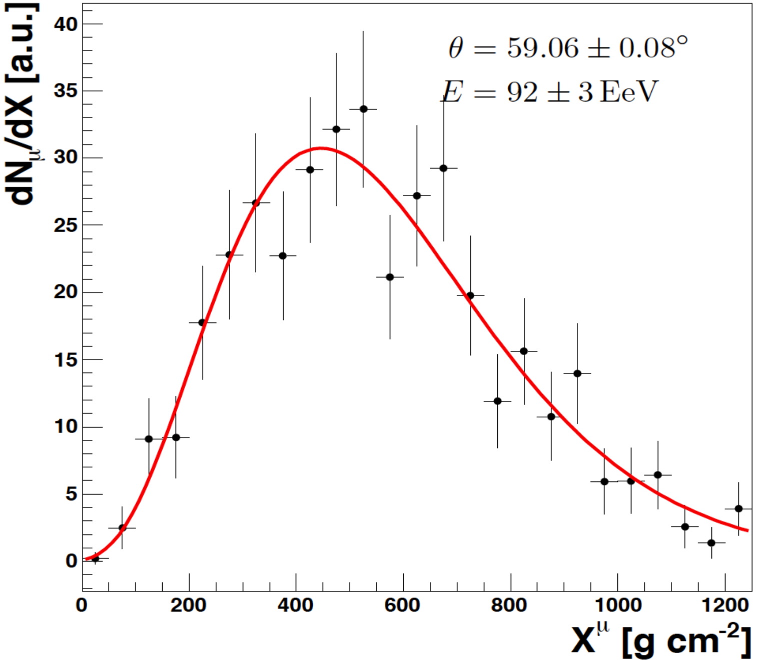
Muon production depth

Inclined events to avoid EM contamination:



Geometric time delay of arriving muons:

$$c \cdot t_{\text{g}} = l - (z - \Delta)$$
$$= \sqrt{r^2 + (z-\Delta)^2} - (z - \Delta)$$



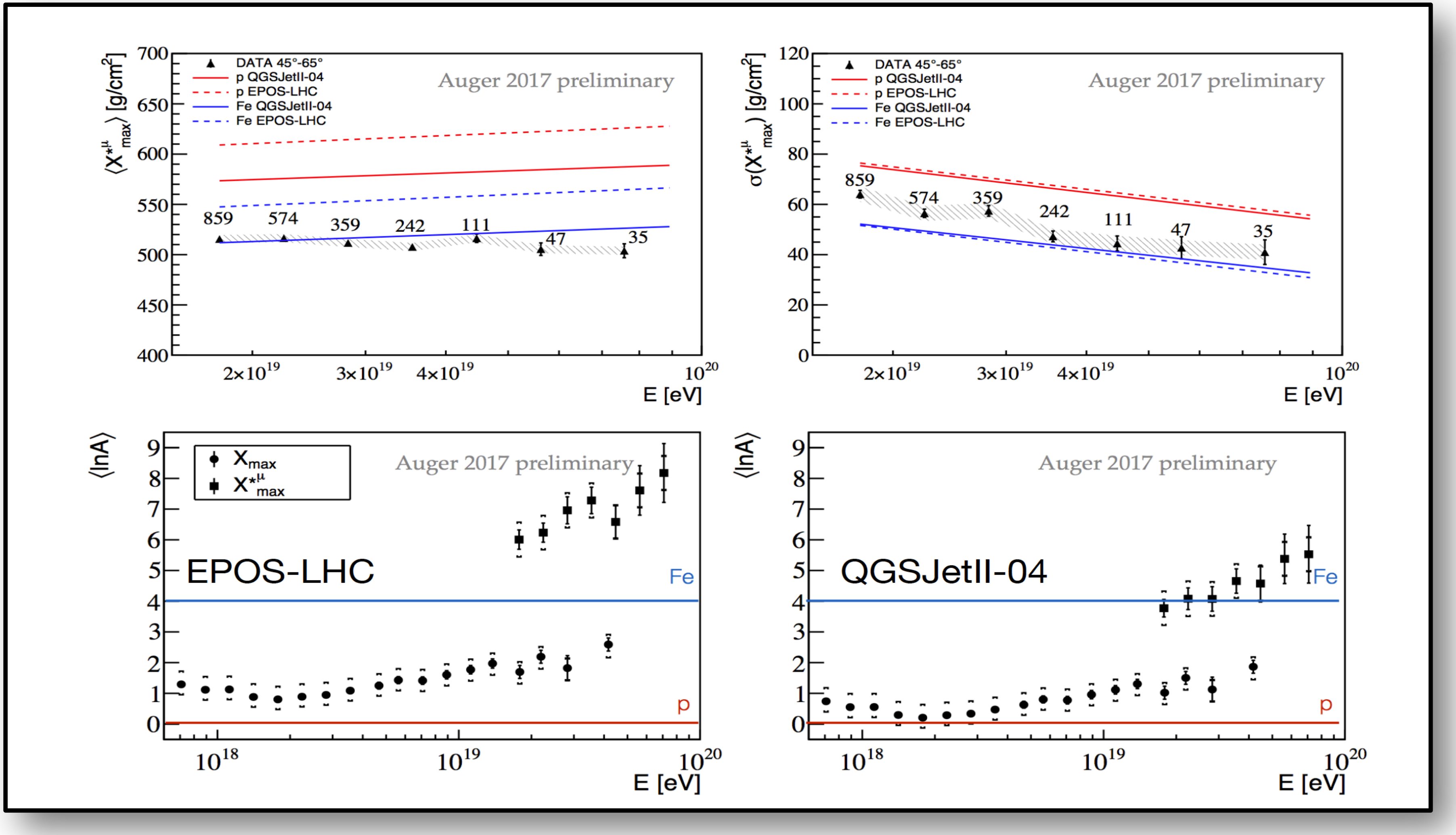
Mapped to muon production depth:

$$z = \frac{1}{2}\left(\frac{r^2}{ct_{\text{g}}} - ct_{\text{g}}\right) + \Delta$$

> Two assumptions:
- muons are produced in the shower axis
- muons travel following straight lines

Muon production depth X^{μ}_{max} and X_{max}

Pierre Auger Collaboration, Phys. Rev. D 90, 012012 (2014); M. Mallamaci for the Pierre Auger Collaboration, ICRC 2017



> two independent mass composition measurements, both results should be between p and Fe

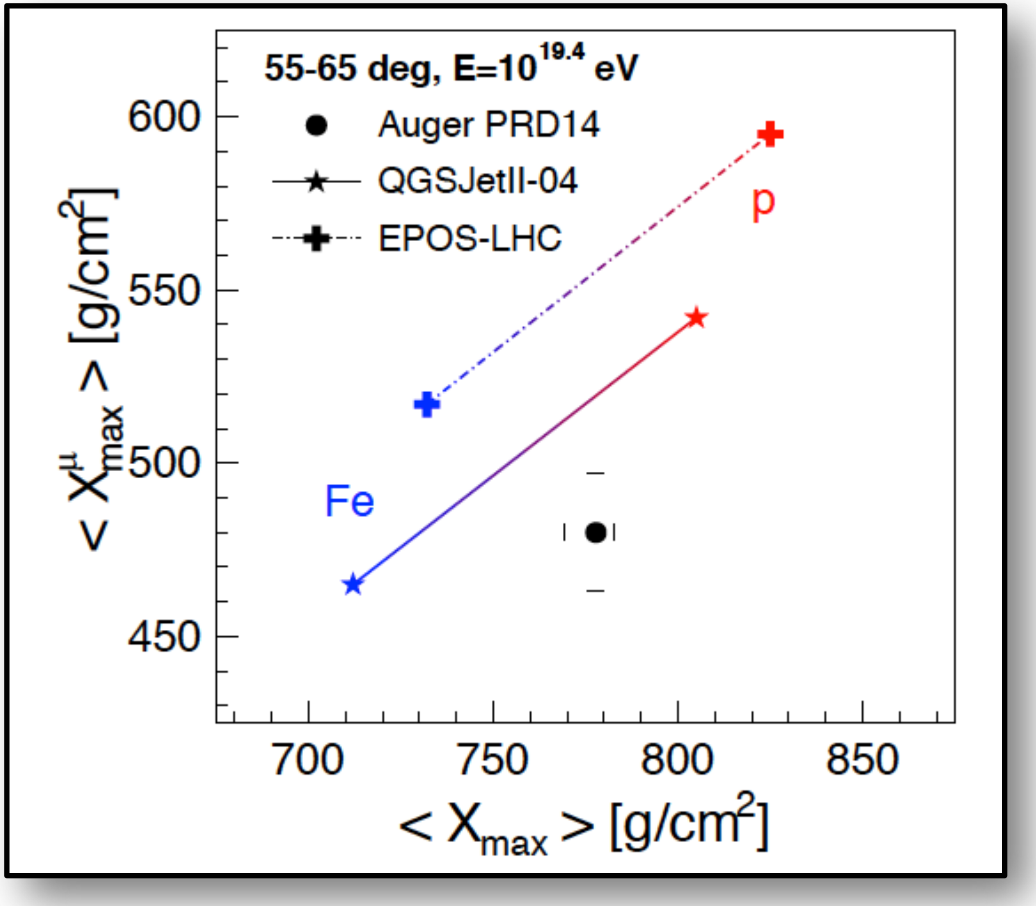
> both results should give the same mean logarithmic mass for the same model

> … as we can see results from X^{μ}_{max} are incompatible with the one from X_{max}

Muon production depth X^{μ}_{max} : discussion

> Data from the Pierre Auger Observatory can be used to constrain diffraction in pion interactions to get consistent results between the mean logarithmic mass extracted from X^{μ}_{max} and the one deduced from X_{max}

The Pierre Auger Collaboration, Phys. Rev. D 90, 012012 (2014)



$< X^{\mu}_{max} >$ is very sensitive to:

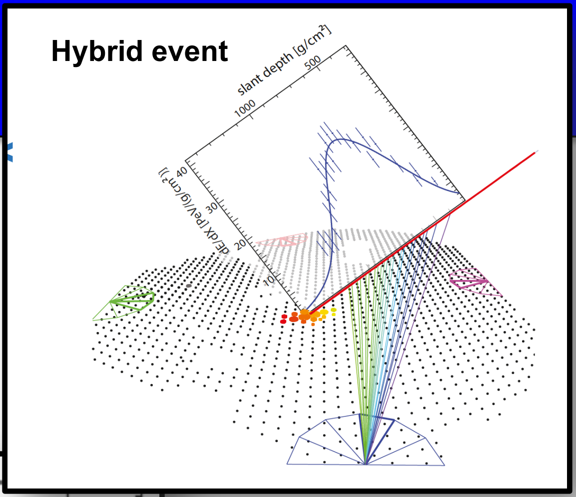
- baryon production:
  baryons have smaller critical energy.
  They reach deeper and do not produce muons

- π-Air diffraction:
  slows down multiplicative process

- K & π energy spectrum:
  bulk of mesons closer to critical energy

See for example: S. Ostapchenko and M. Bleicher, *Constraining pion interactions at very high energies by cosmic ray data* , Phys. Rev. D93 (2016) 051501, [1601.06567], also EPS Web Conf. 210 (2019)02001

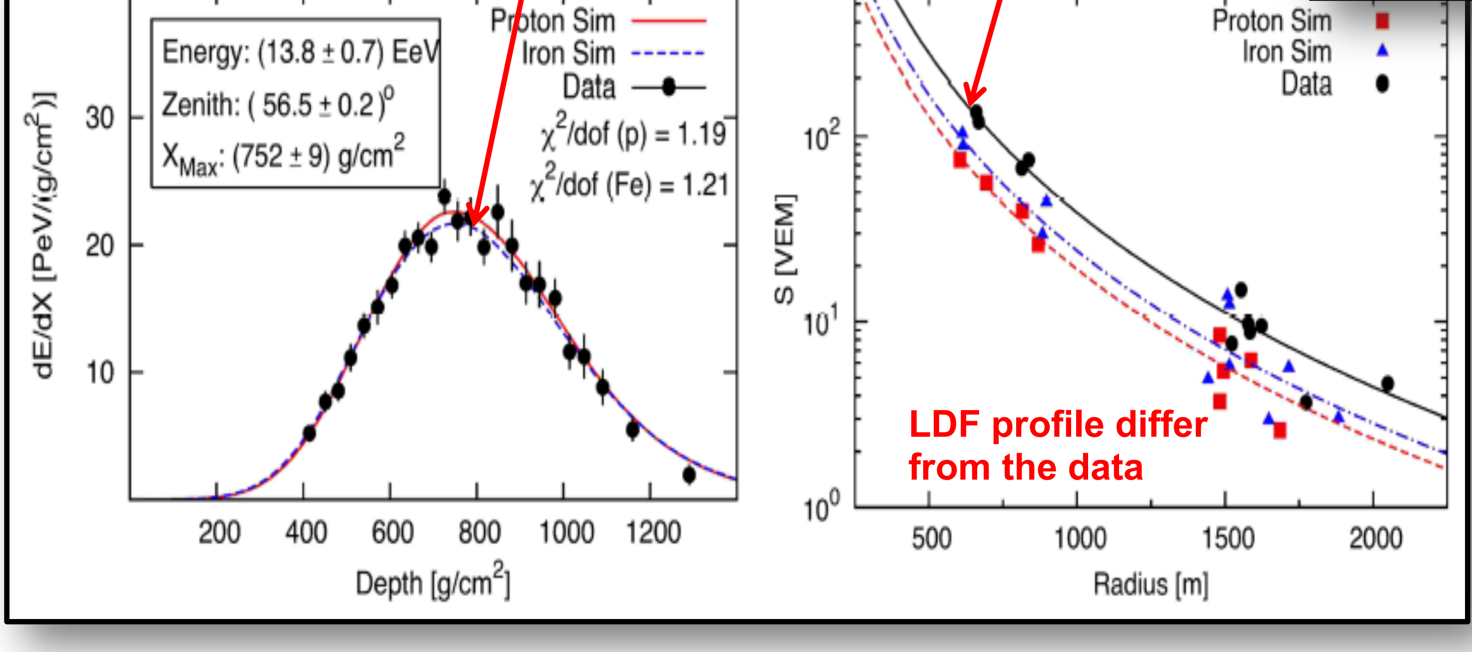
Muon studies with hybrid events (<60°)



> We observe more muons than we simulate, Monte Carlo correctly reproduces Longitudinal Profile (LP)

but has too low SD signal (LDF)

The Pierre Auger Collaboration, Phys. Rev. Lett. 117, 0192001 (2016)



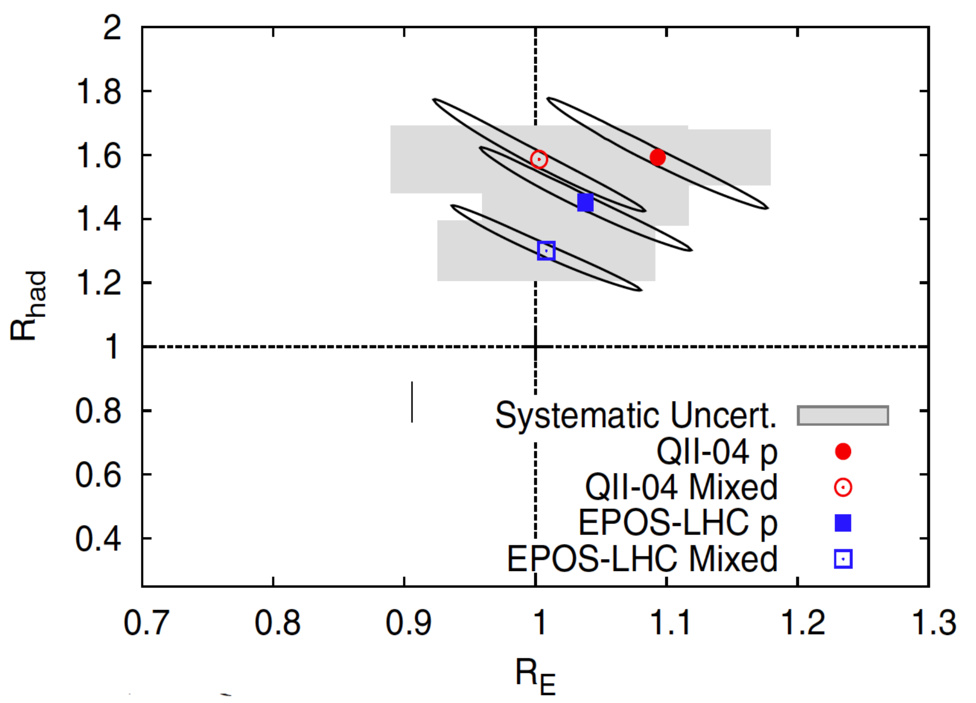
LDF profile differ from the data

- E = $10^{18.8}$ - $10^{19.2}$ eV
- zenith angles [0°, 60°]
- 411 hybrid events after quality cuts

> Idea: compare hybrid data with simulated showers
  - – match longitudinal FD light profile data with best simulation profile (p, He, N, Fe)
  - – extract S_{EM} and S_{had} from simulation
  - – rescale simulated SD signal to match data (extract R_E and R_{had})

Muon studies with hybrid events (<60°)

The Pierre Auger Collaboration, Phys. Rev. Lett. 117, 0192001 (2016)



Model	R_E	$R_{\rm had}$
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

> Fit adjusting EM and muonic contribution to signal at 1000 m ($S_{\rm resc}$)

R_E and **$R_{\rm had}$** rescaling factors to match the SD and FD signals (hybrid data)

$$S_{\rm resc} = R_E\, S_{\rm EM} + R_{\rm had}\, R_E^{\alpha}\, S_{\rm had}$$

$$\alpha \simeq 0.9$$

$$R_\mu \approx 0.93\, R_E^{0.9}\, R_{\rm had} + 0.07\, R_E$$

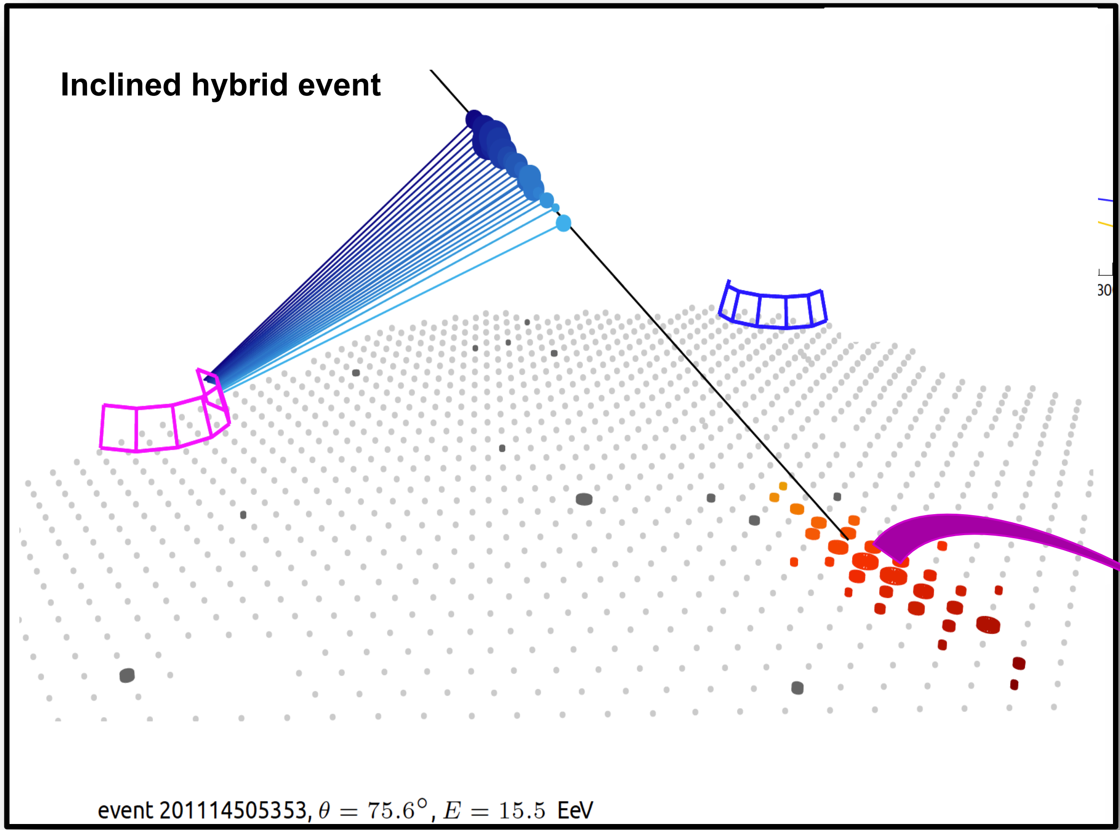
> Smallest dicrepancy for EPOS-LHC with mixed composition at level of 1.9σ

Systematic uncertainties on R_E and $R_{\rm had}$ ~10 %

> The observed muon signal is a factor 1.33 (EPOS-LHC) to 1.61 (QGSJET-II.04) larger than predicted by models

Muon studies with inclined hybrid events (60° -80°)

> Inclined showers: only the muon components survive to the ground.



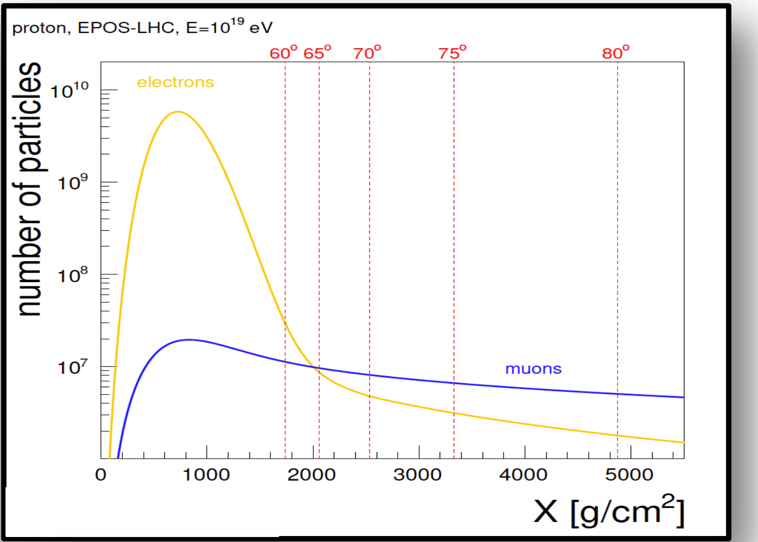
Muon density from fit of **the normalization factor of reference model**

Reference muon profile

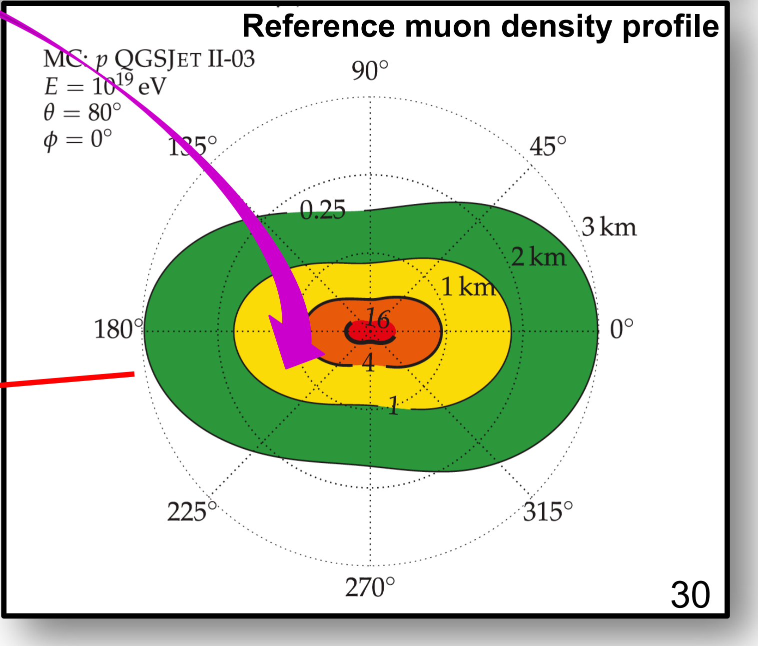
$$\rho_\mu(\mathrm{data}) = N_{19}\cdot\rho_\mu(\mathrm{QGSJETII03},\ p, E = 10^{19}\ eV,\ \theta)$$

$$R_\mu = \frac{N_\mu^{data}}{N_{\mu,19}^{MC}}$$

Total numbers of muons at the ground relative to the average number of muons in a shower with energy 10^{19} eV.

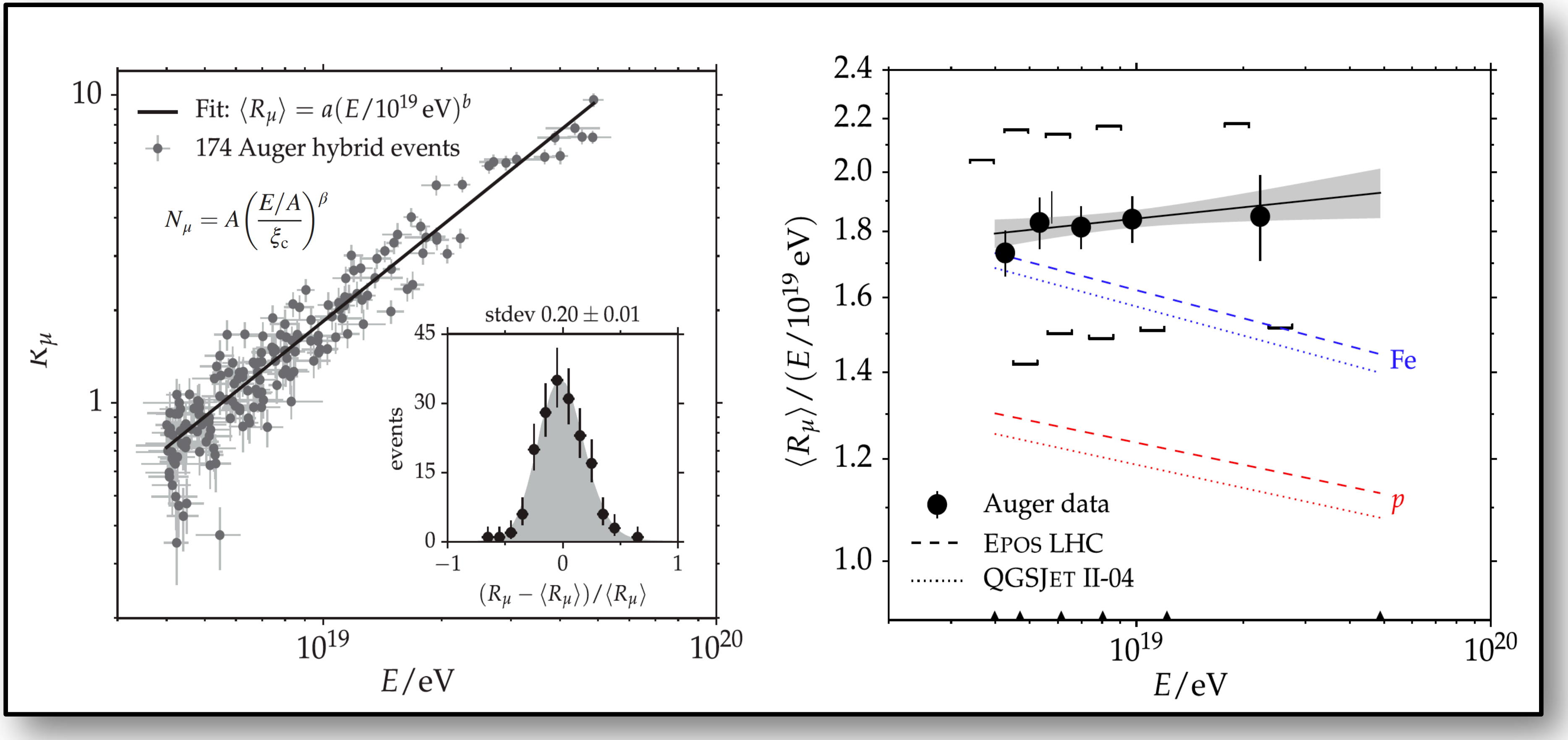


Reference muon density profile



Muon studies with inclined hybrid events (60° -80°)

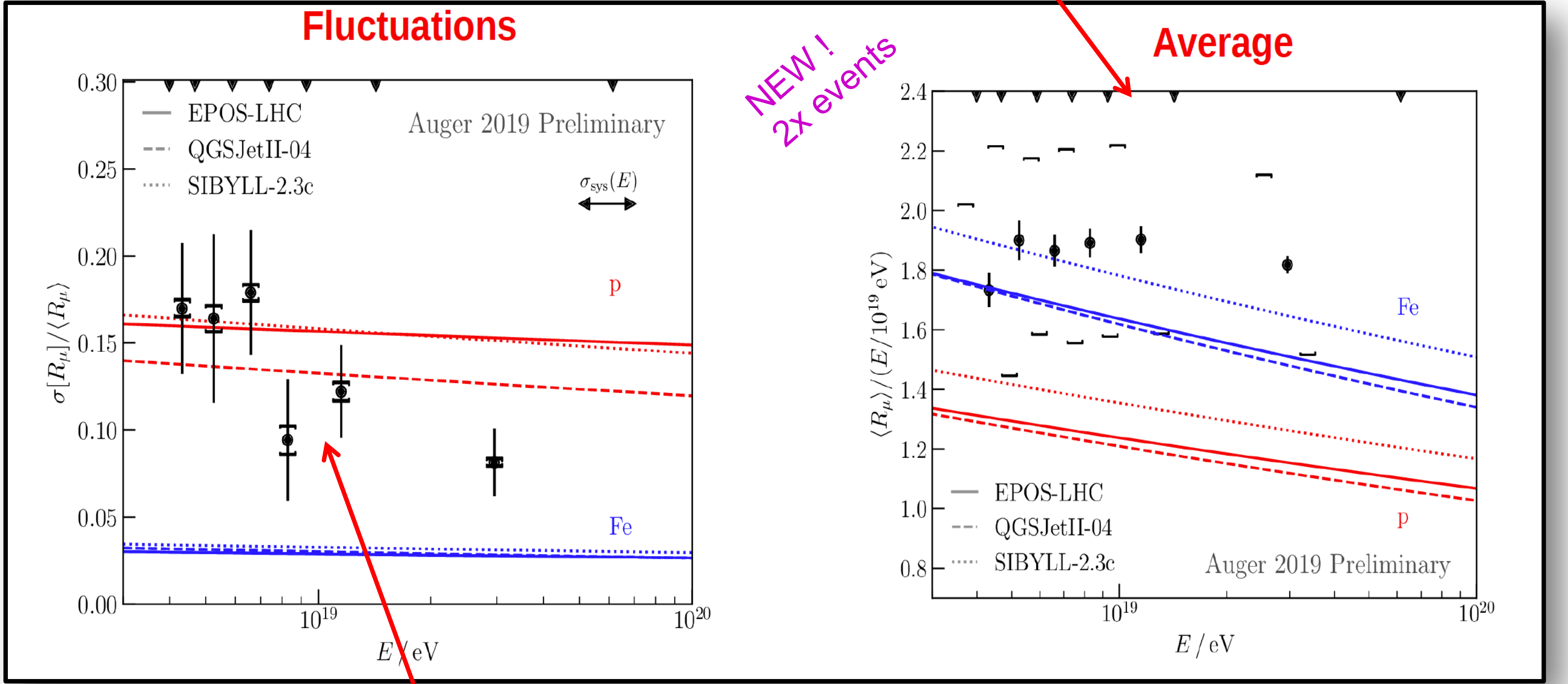
The Pierre Auger Collaboration, PRD D91 (2015) 3, 032003



> Hadronic models underestimate the number of muons produced in showers.

Update ICRC 2019: Muon studies with inclined hybrid events (60° -80°)

> Hadronic models underestimate the number of muons produced in showers.



Fluctuations

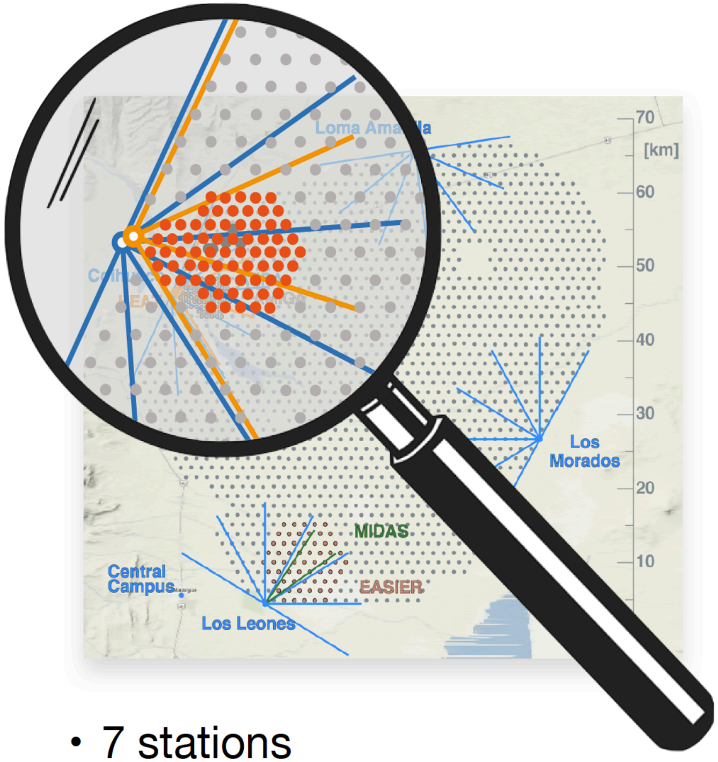
Average

NEW !
2x events

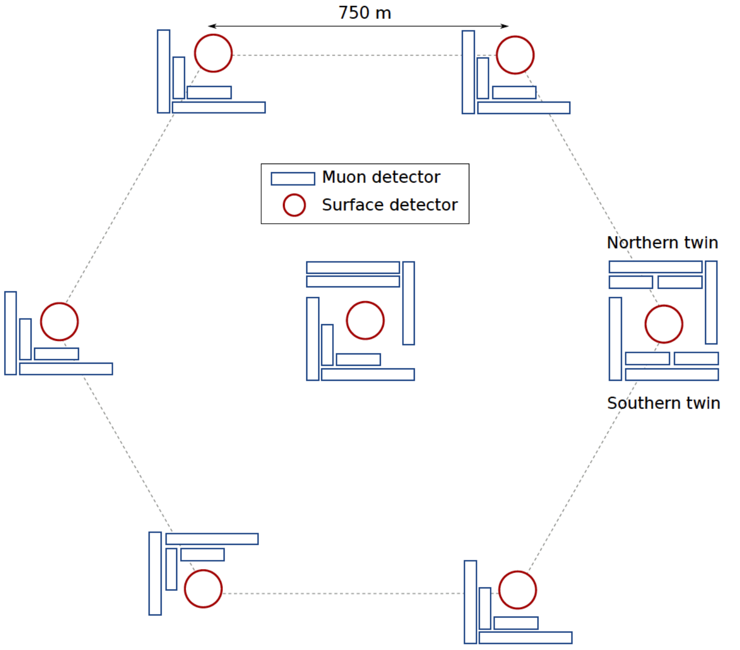
> Muon fluctuations however appears to fit expectation.

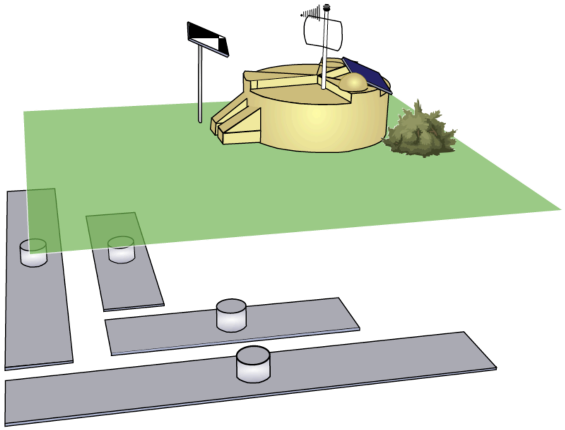
Could be an indication that first interaction may not be responsible for the muon deficit in models.
Small difference that accumulates over particle generations?

Direct muon measurement with AMIGA



- 7 stations
- 30 (60) m^2 scintillator modules
- 2.3 m below ground (~530 gcm^{-2} to shield E.M. component of EAS)
- 1 GeV/cosθ
- AMIGA in slave mode wrt SD station
- 1 full year of data with PMTs
- PMTs to be replaced by SiPMs





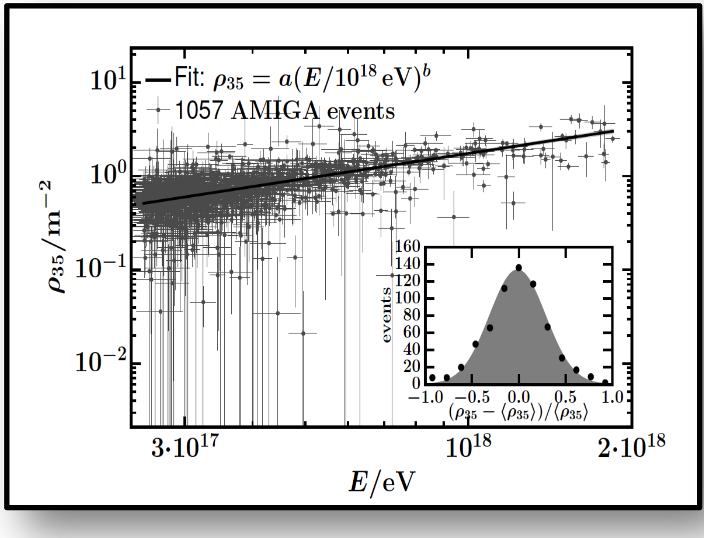
Direct muon measurement with AMIGA

> First direct measurement of the muon densities at energies $10^{17.3}$ eV < E < $10^{18.3}$ eV

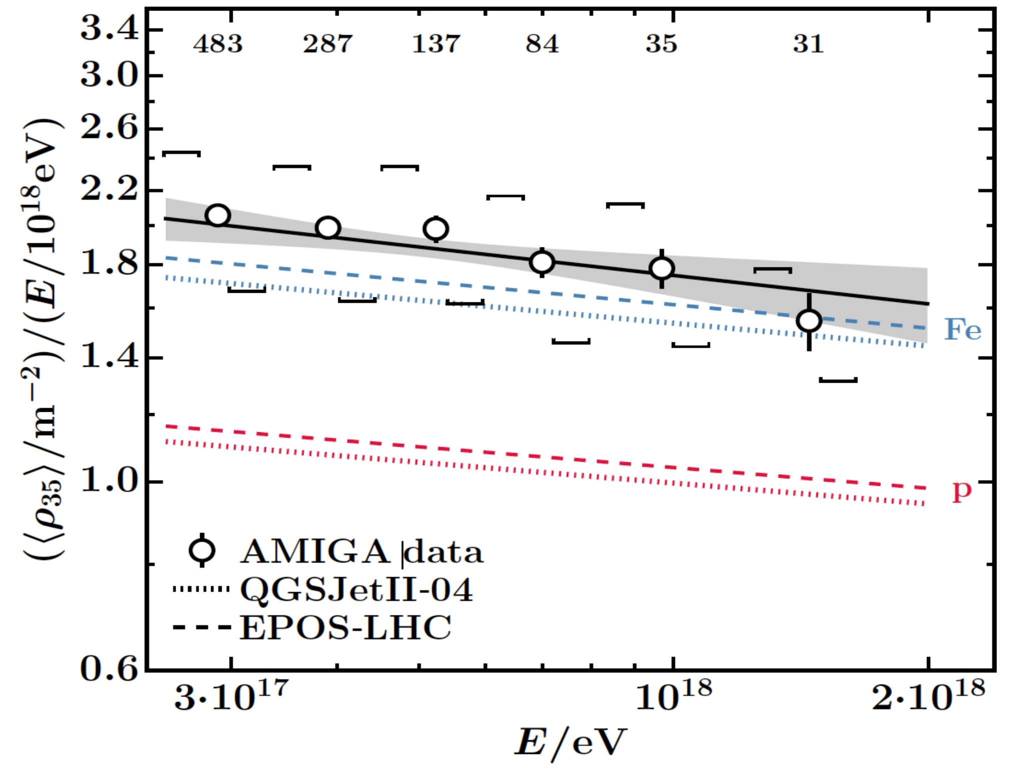
The attenuation curve f_{att} is used to determine an attenuation-free muon density

$$\boxed{\rho_{35} = \rho(450)/f_{\text{att}}(\theta)}$$

Muon density at 450 m



F. Sánchez for the Pierre Auger Collaboration, ICRC 2019



> Hint to muon deficit in simulations at lower energies (from X_{max} dominated by light elements!)

@$10^{17.5}$ eV	**EPOS**	**38%**
	QGSJet	**50%**

@$10^{18.0}$ eV	**EPOS**	**38%**
	QGSJet	**53%**

Comparison with other Auger measurements

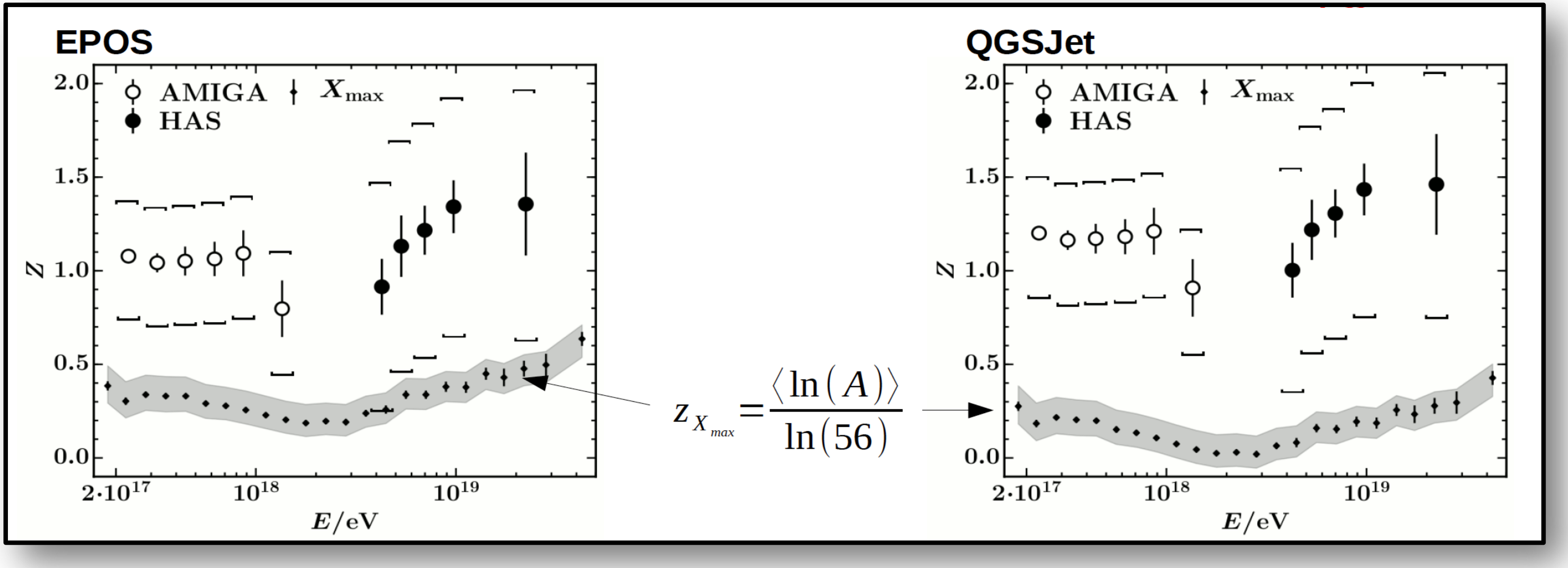
Muon number estimator

$$z_\alpha = \frac{\langle \ln(\alpha) \rangle - \langle \ln(\alpha) \rangle_p}{\langle \ln(\alpha) \rangle_{Fe} - \langle \ln(\alpha) \rangle_p}$$

one composition-sensitive from various measurement

SD → R_μ
FD → X_{max}
UMD → ρ_{35}

F. Sánchez for the Pierre Auger Collaboration, ICRC 2019



$$z_{X_{max}} = \frac{\langle \ln(A) \rangle}{\ln(56)}$$

> Within the statistical and systematic uncertainties, the z-factors derived by the two muon studies seem to be in agreement at the intermediate energies between their distinct energy ranges

> The combined muon measurements match the trend of z derived from X_{max} measurements as a function of the energy

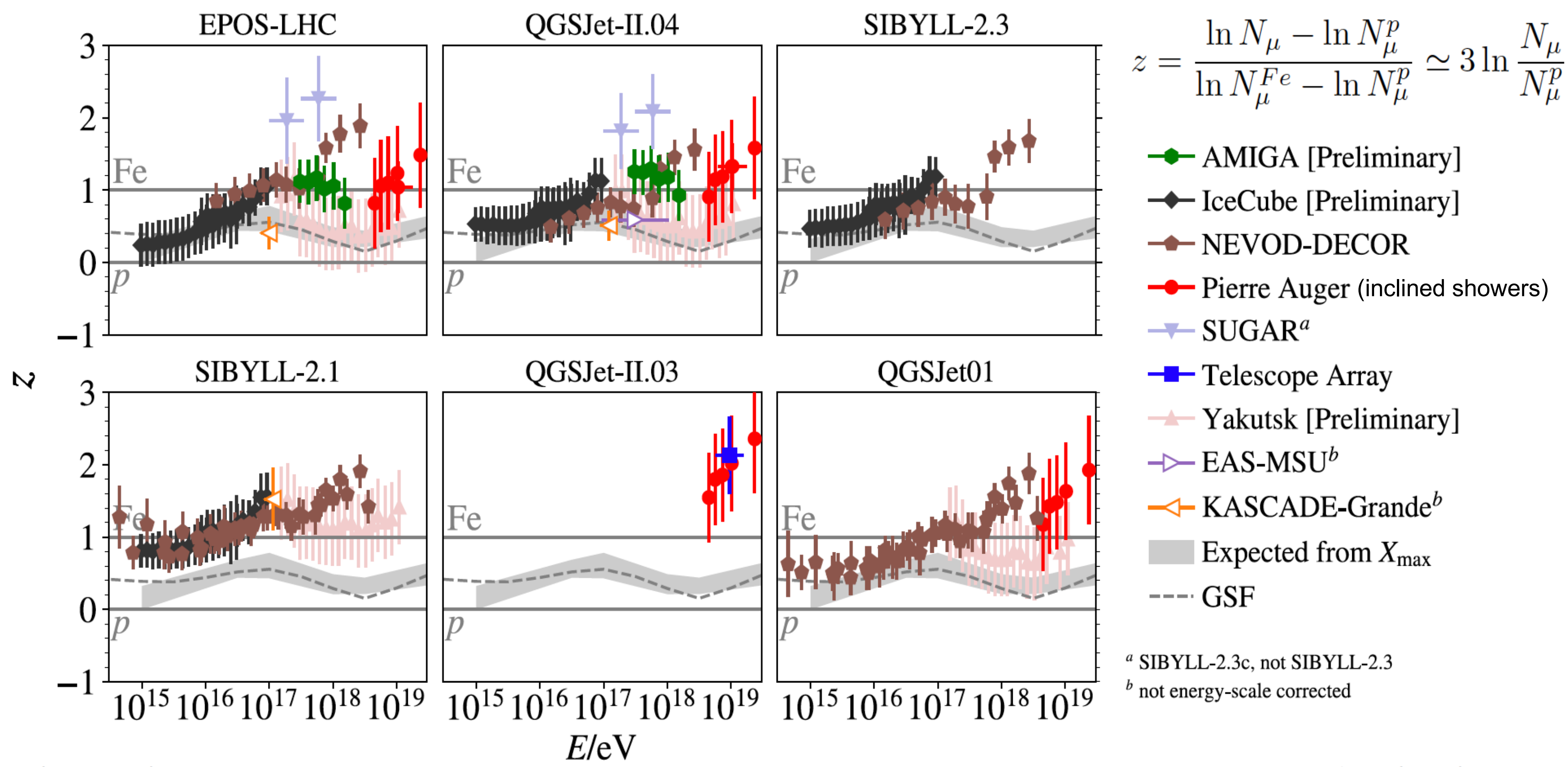
Muon deficit in simulations (*aka* muon excess in data)

Muon number estimator

$$z_\alpha = \frac{\langle \ln(\alpha)\rangle - \langle \ln(\alpha)\rangle_p}{\langle \ln(\alpha)\rangle_{Fe} - \langle \ln(\alpha)\rangle_p} \Rightarrow$$

one composition-sensitive from various measurement

$$\begin{cases} \text{SD} \longrightarrow R_\mu \\ \text{FD} \longrightarrow X_{max} \\ \text{UMD} \longrightarrow \rho_{35} \end{cases}$$



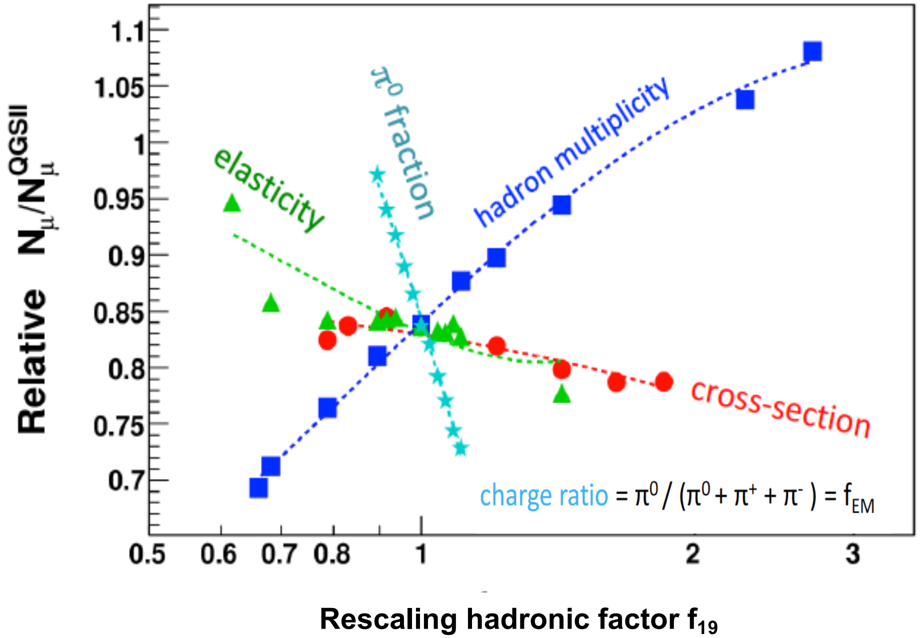
Cazon PoS(ICRC2019)214

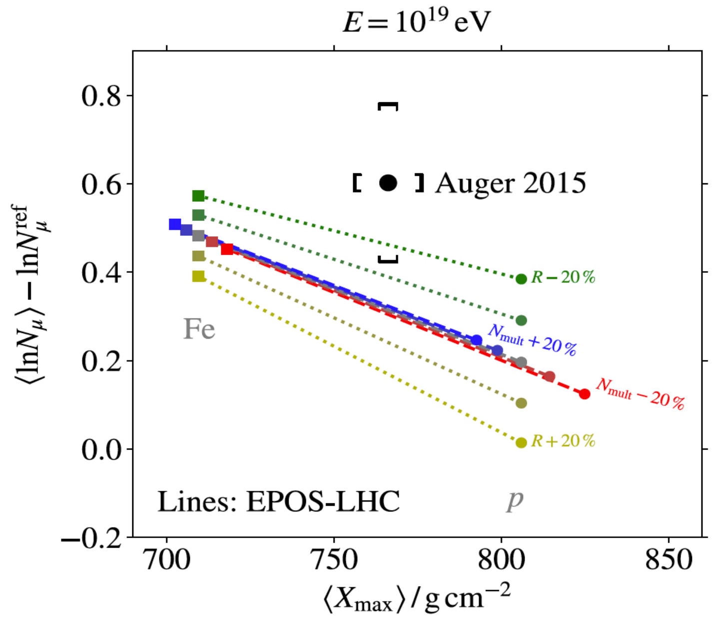
H. Dembinski et al. EPJ Web Conf 210 (2019) 02004

> Muon deficit seen also in other experiments

Muon deficit: Possible solutions

R. Ulrich et al., Physical Review D 83, 054026 (2011)





S. Baur et al. arXiv: 1902.09265
T. Pierog et al. PoS(ICRC2019)387
H. Dembinski et al. PoS(ICRC2019)235

> The muon deficit can be fixed by a smooth increment of hadronic fraction **($f=E_{had}/E_0$)** over several generations
For example in Heitler model:

$$N_\mu \propto (f+\delta f)^c \qquad (1+0.05)^6 \simeq 1.30$$

R- energy ratio of electomagnetic particles to hadronic one

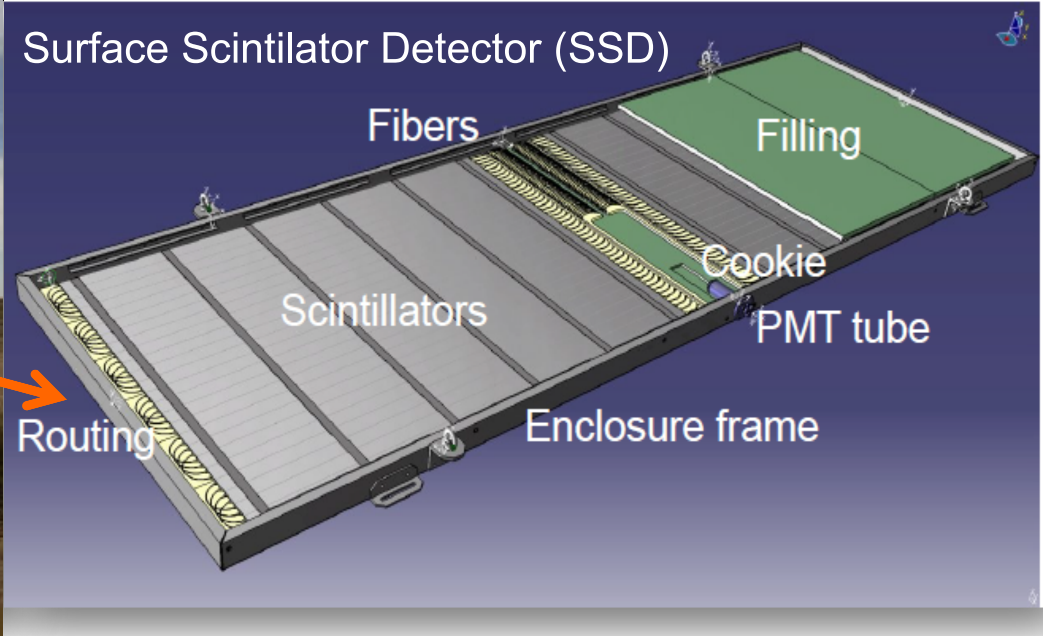
> Models to solve the muon deficit:

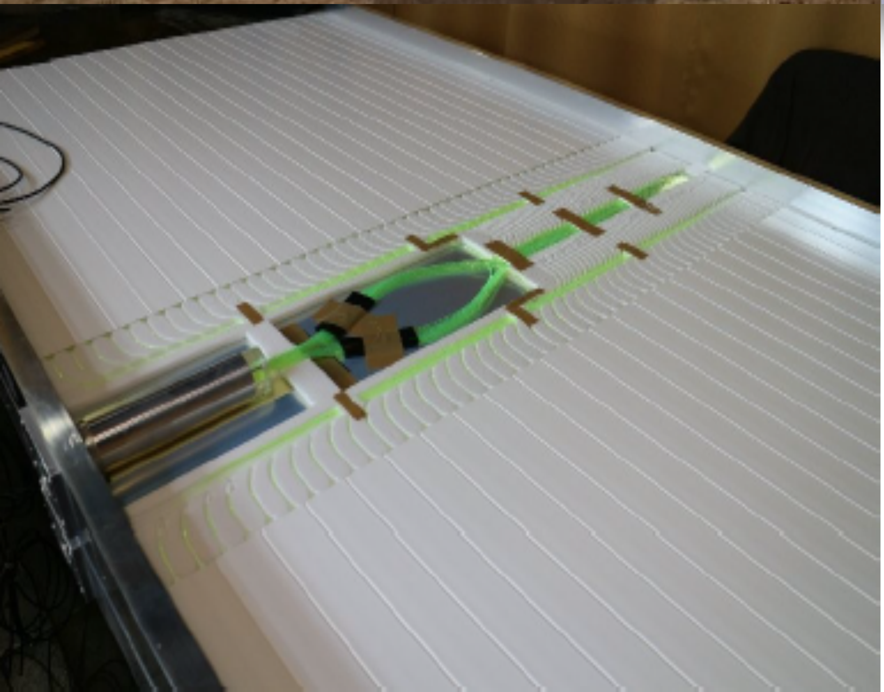
String percolation	astro.ph:1209.6474
Strange Fireball	PRD 95(2017) 06005
Chiral Symmetry Restoration	EPJ Web Conf. 53(2013) 07007
Quark Gluon Plasma	PoS(ICRC2019)387
Lorentz Invariance Violation	Phys. Rev. D 59, 116008 (1999)

... but still unsolved

Auger prime

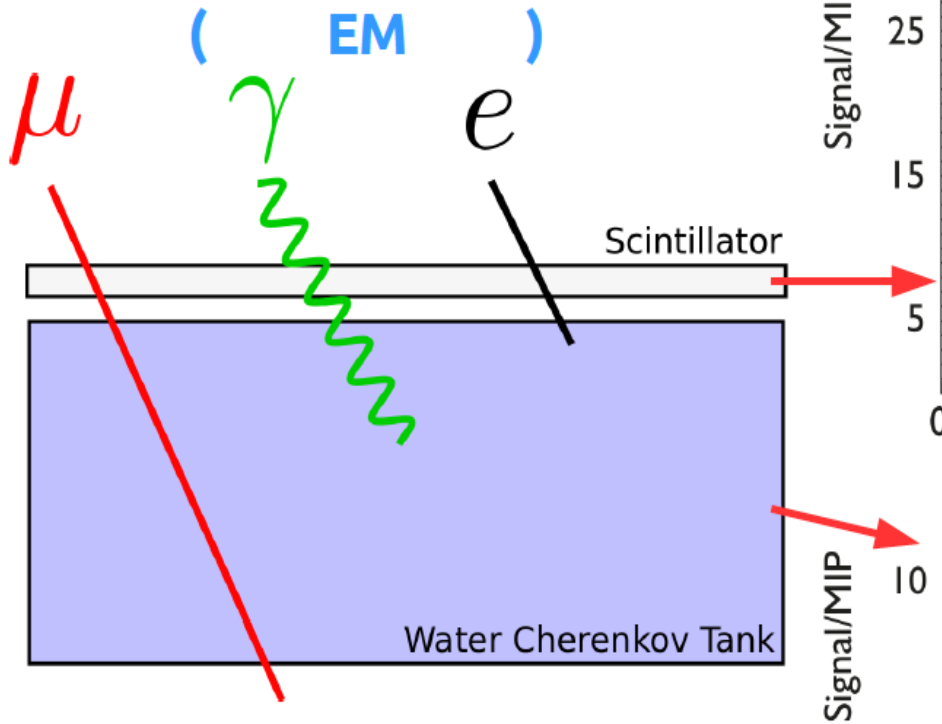
Detector Upgrades for AugerPrime

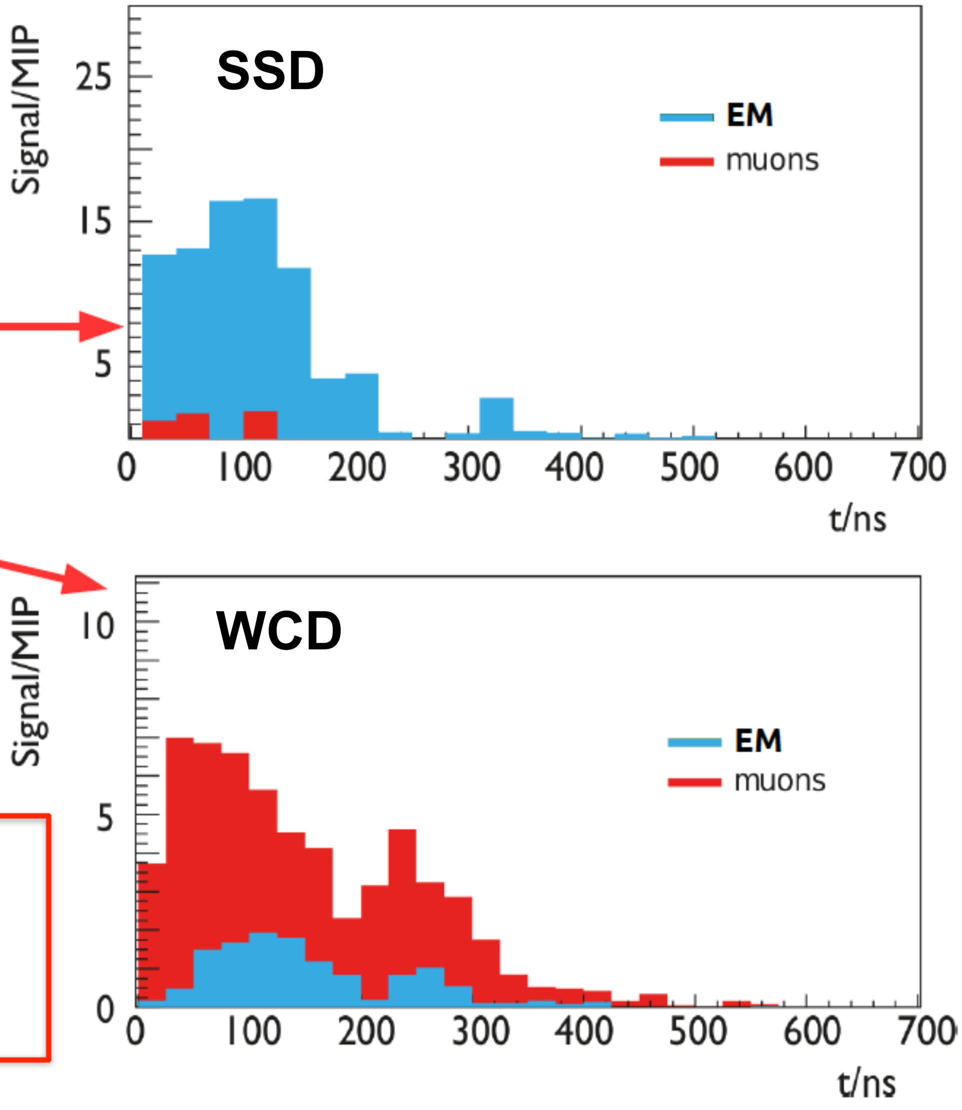




- 3.8 m^2 scintilators (SSD)
  on each 1500-m array station
- Upgrade of station electronics
- Additional small PMT to increse dynamic range
- Buried muon counters in 750-m array (AMIGA)
- Increasded FD uptime

Complementary response





$$S_{\mu,\mathrm{WCD}} = a\,S_{\mathrm{WCD}} + b\,S_{\mathrm{SSD}}$$

$$S_{\mathrm{em,WCD}} = c\,S_{\mathrm{WCD}} + d\,S_{\mathrm{SSD}}$$

Summary

> Auger measurements:

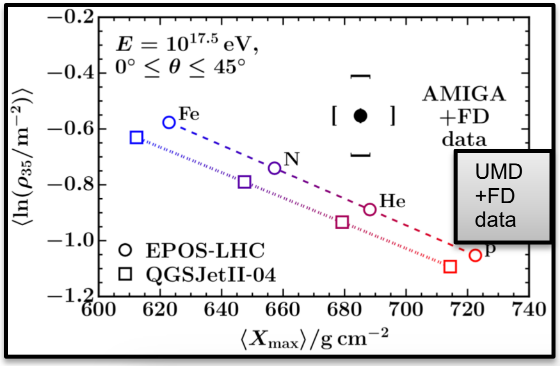
- FD: EM shower is fairly well described by models, our best mass estimator is X_{max}

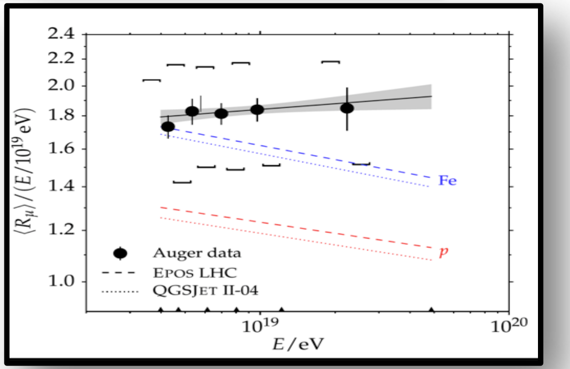
- FD+SD: Measurements of muon content;
  - no need for energy rescaling, thus muon problem
  - Muon rescaling factor 1.3-1.6

- SD: R_{μ} in inclined showers
  Increasing MC deficit with increasing energy

- SD: Muon Production Depth mismatch provides
  further constraints in hadronic models

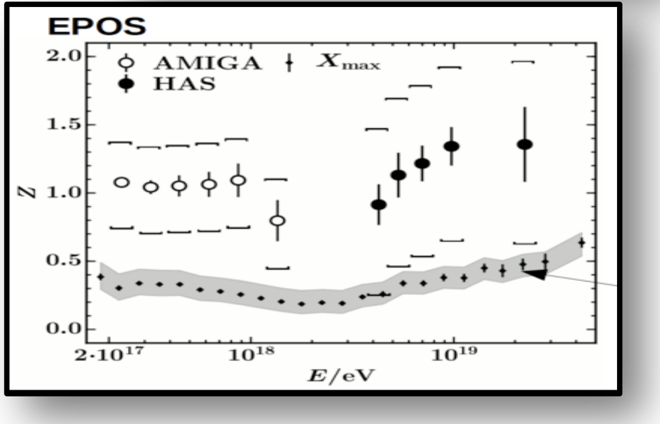
- AMIGA (new): extending down to 3×10^{17} eV





> Muon Puzzle

Experimentally established at 8σ
- statement by eight leading air shower experiments
- problem not in the data, theory has to change



> Future:

Key measurements to be done at the LHC
- energy ratio R of π^0 to other hadrons at forward rapidity
- nuclear modification in forward hadron production
- Proton+oxygen collisions planned about ~2023

Auger Prime: Increased accuracy of muon measurements