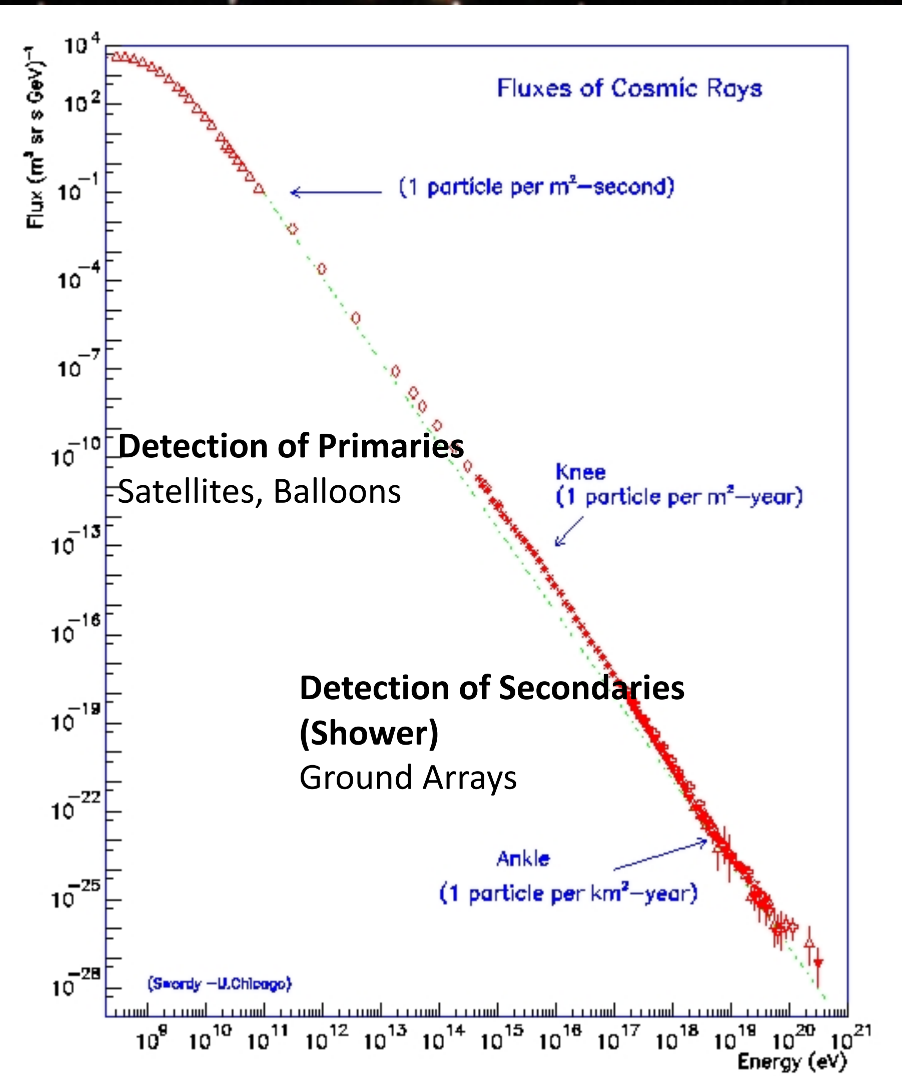
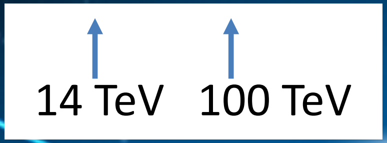
Hadronic Physics with the Pierre Auger Observatory

L. Cazon,

for the Pierre Auger Collaboration

Cosmic Ray Spectrum





- 16 particles above log(E/eV)=18.6 arrive at Earth each second
- The Pierre Auger Observatory collects around 3000 / year.

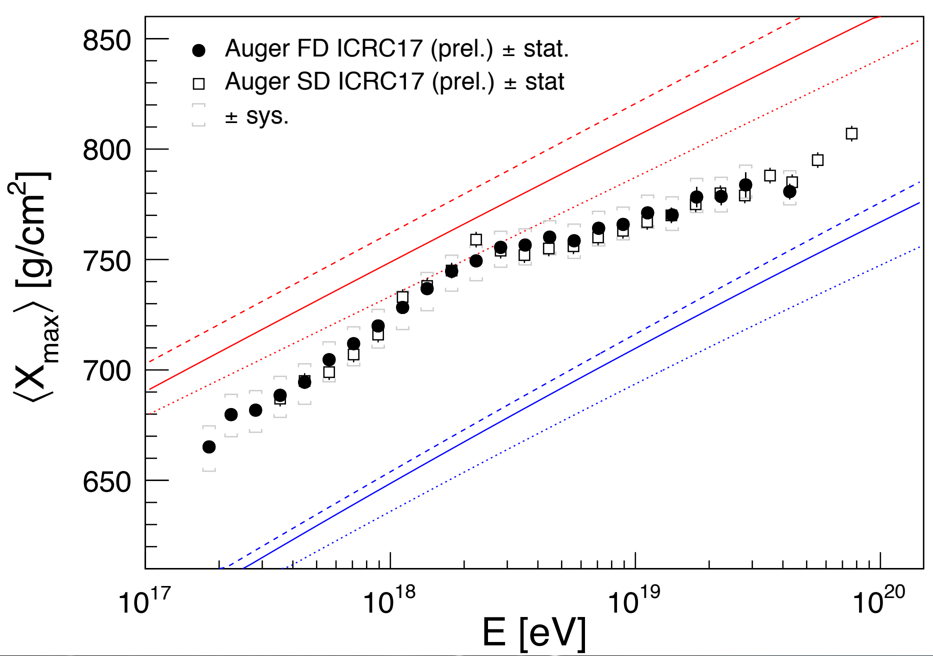
By Johnson Lake in Banff National Park, Canada

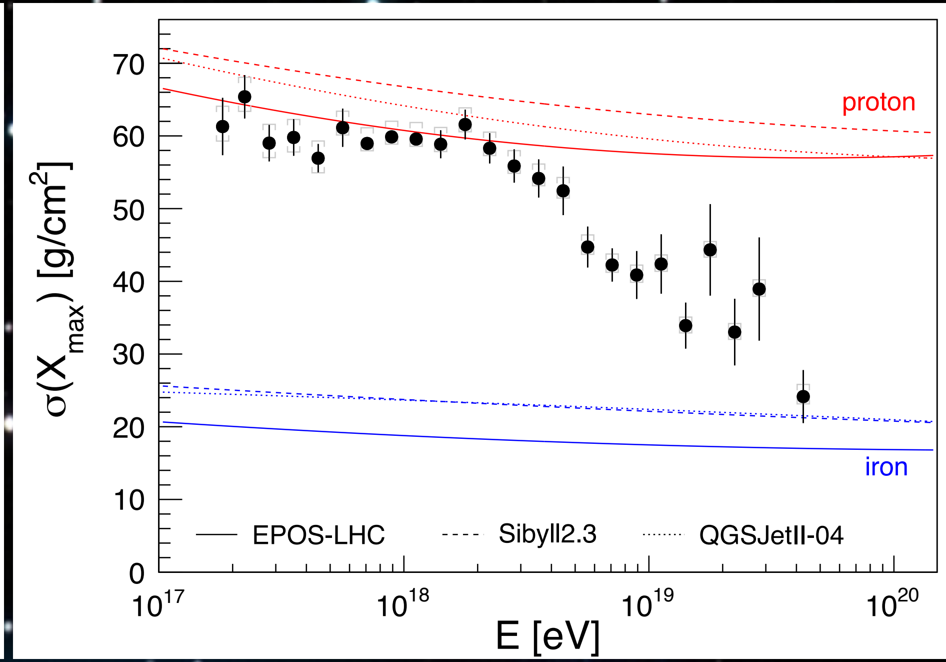
This is a real picture

of a fireball. An Extensive Air Shower would look like that if we could see UV)

Composition

(Depth of EM cascade)

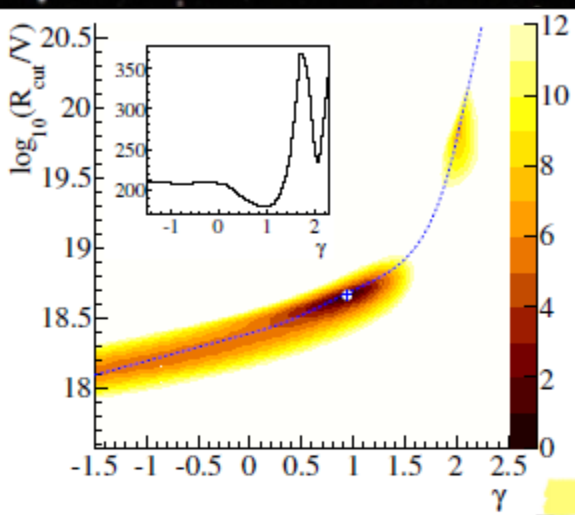


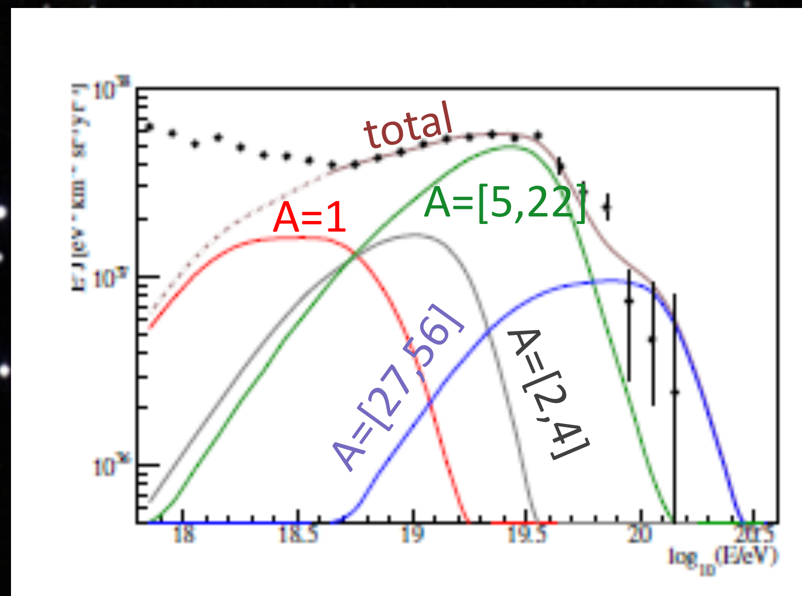


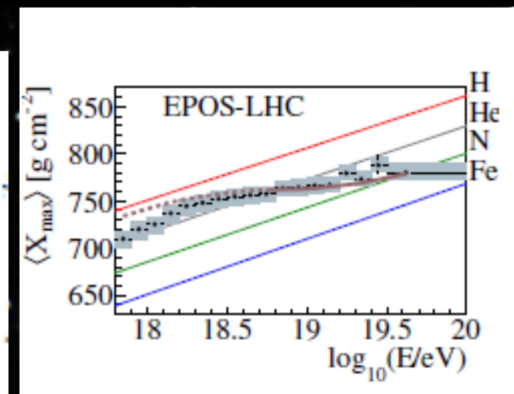
High Metalicity of UHECR (high abundance of A>2 elements)

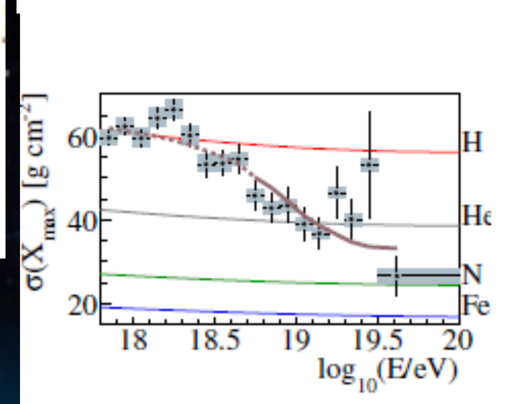
Global fit:

(Simple) Model of UHECR to reproduce the Auger spectrum and Xmax distributions at the same time
Homogeneous distribution of identical sources accelerating p, He, N and Fe nuclei.
Fit parameters: injection flux normalization and spectral index γ, cutoff rigidity R_{cut}, p-He-N-Fe fractions





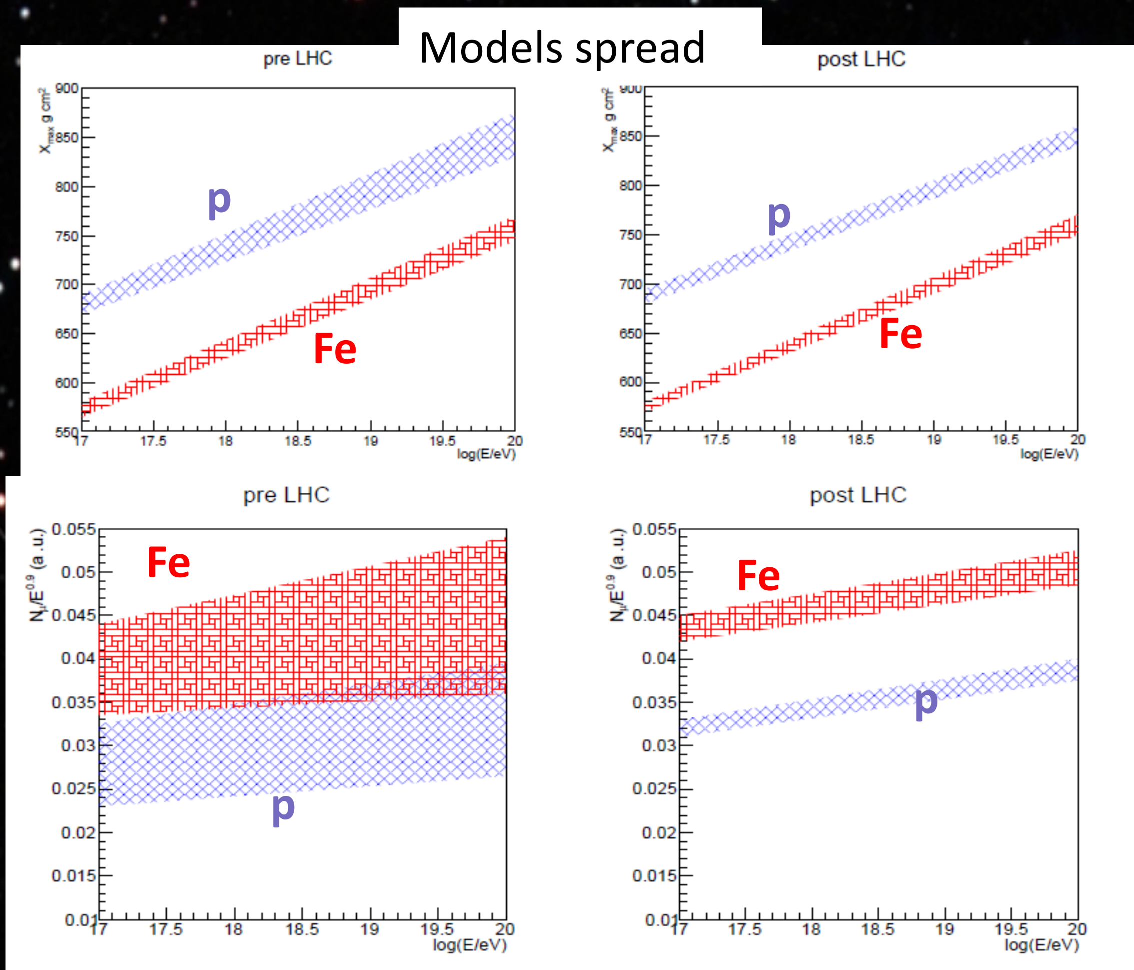




Best fit with very hard injection spectra ($\gamma \leq 1$)

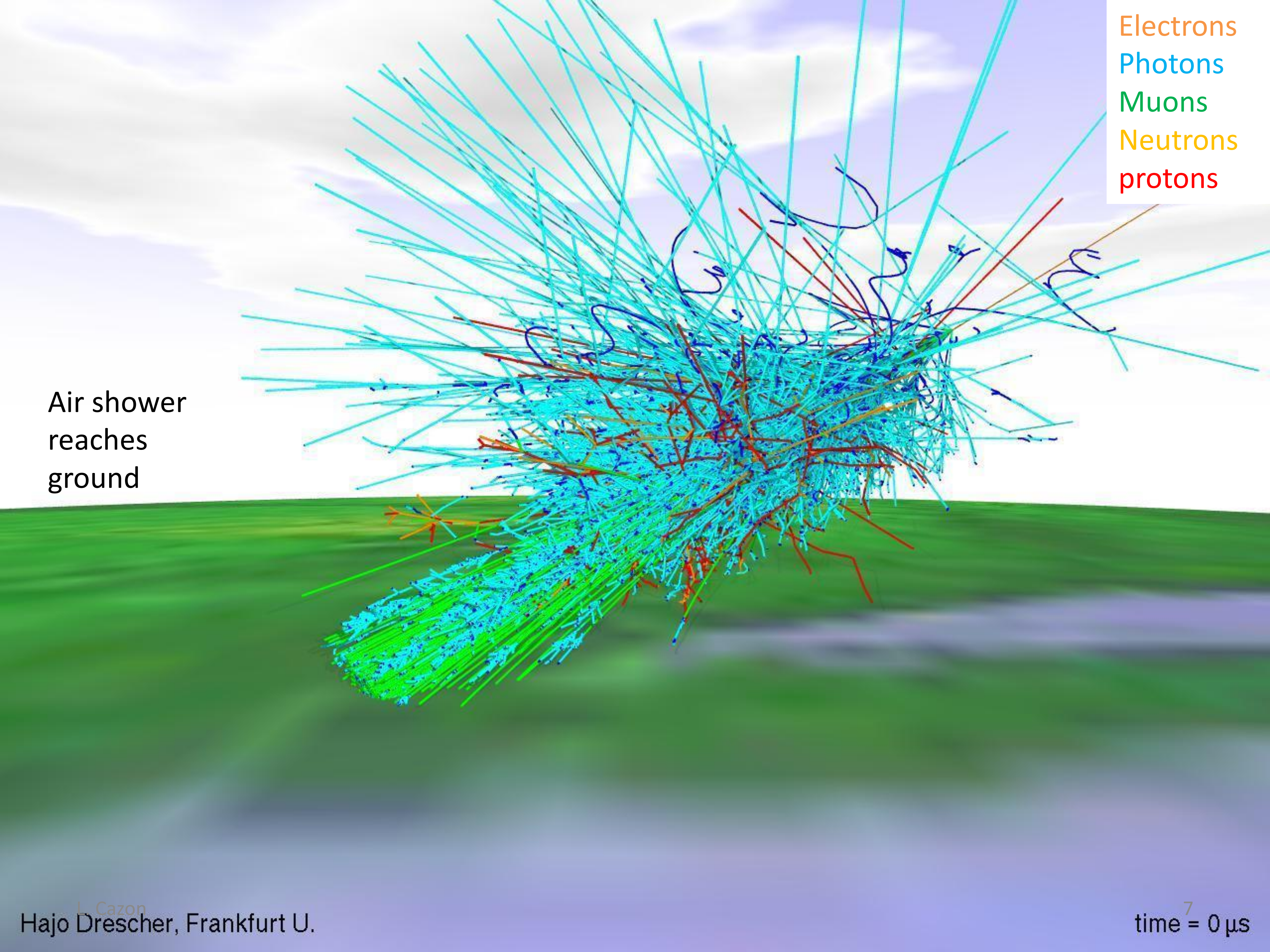
Flux limited by maximum energy at the sources ($R_{cut} \leq 10^{1..7}$ eV

We must use air shower simulations performed with High Energy Hadronic Models extrapolated beyond the LHC to interpret our data.

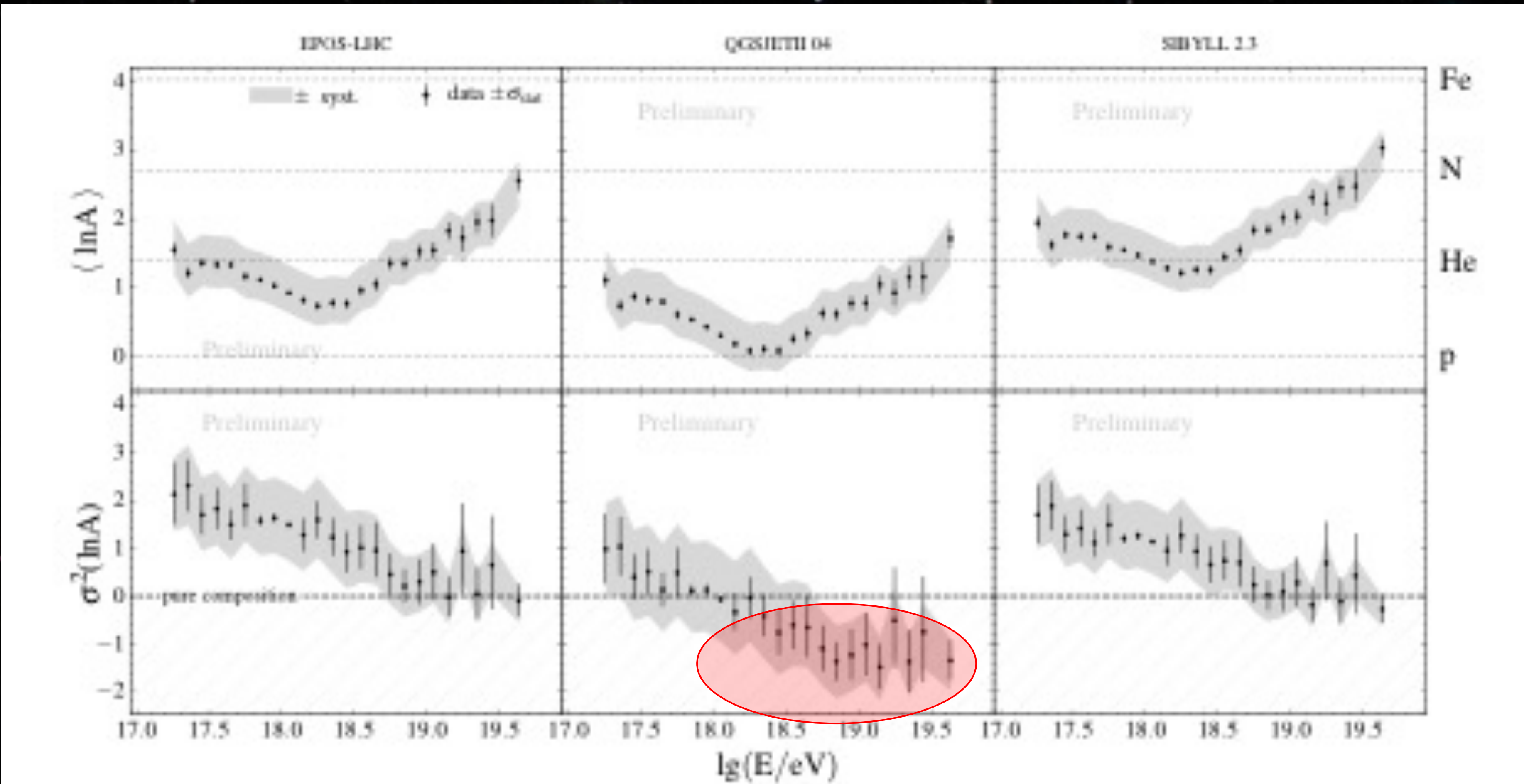


Models spread extrapolations has been reduced after LHC measumrements. There are still differences among models.

Extrapolations venture out orders of magnitude out of the confort zone.

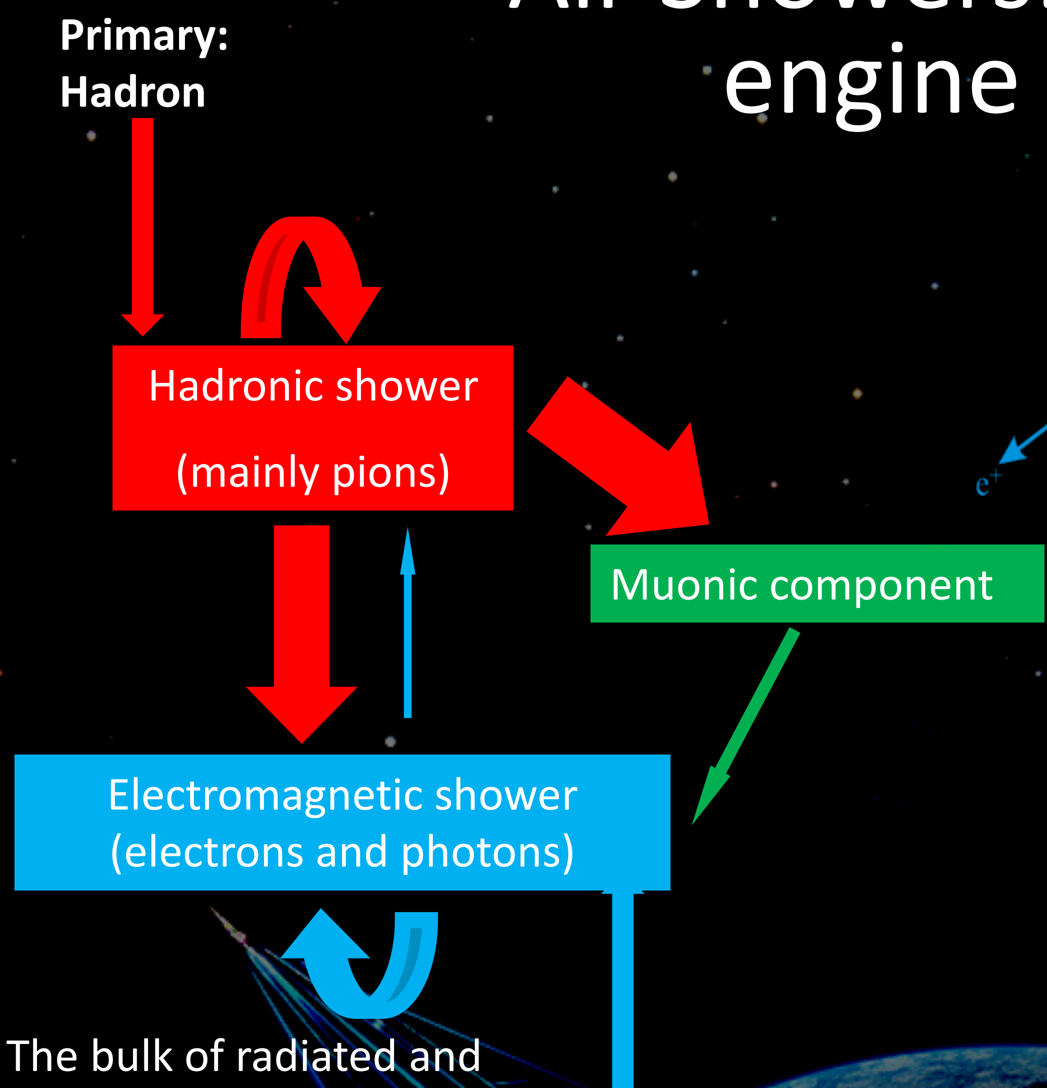

Electrons
Photons
Muons
Neutrons
protons
Air shower
reaches
ground
Hajo Drescher, Frankfurt U.
time = 0 µs

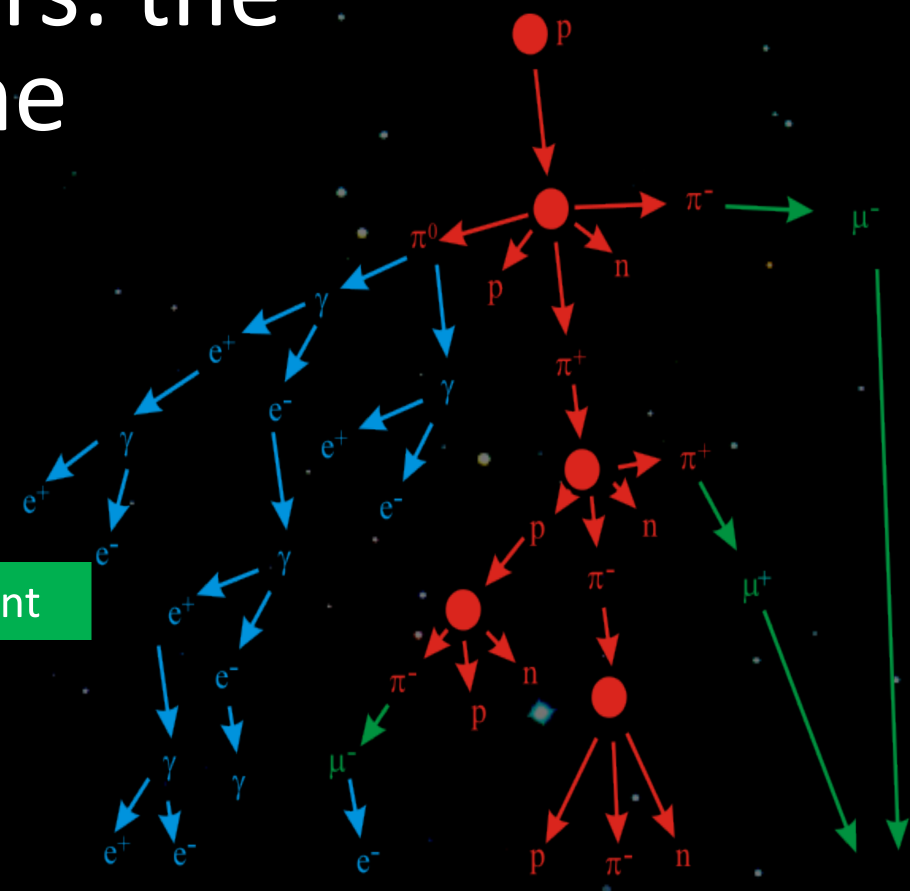
Models show contradictions in the interpretation of Xmax



Xmax distributions are not well predicted by some models.
Leading to unphysical results. (QGSJetII-04)

Air Showers: the engine

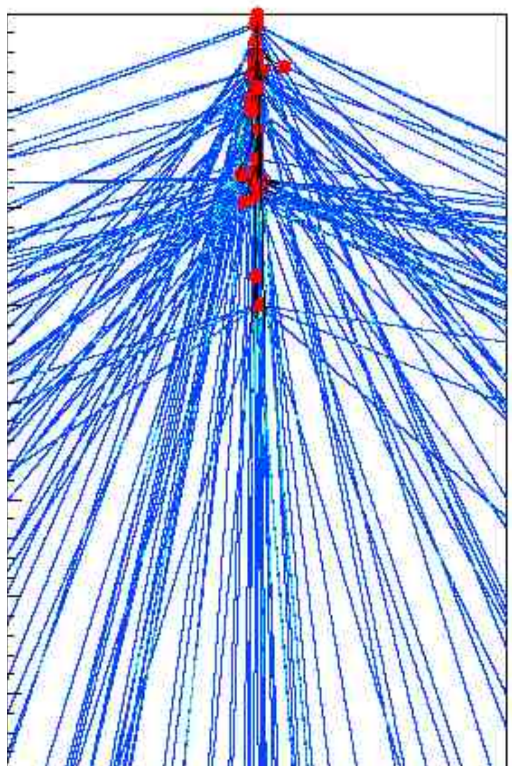
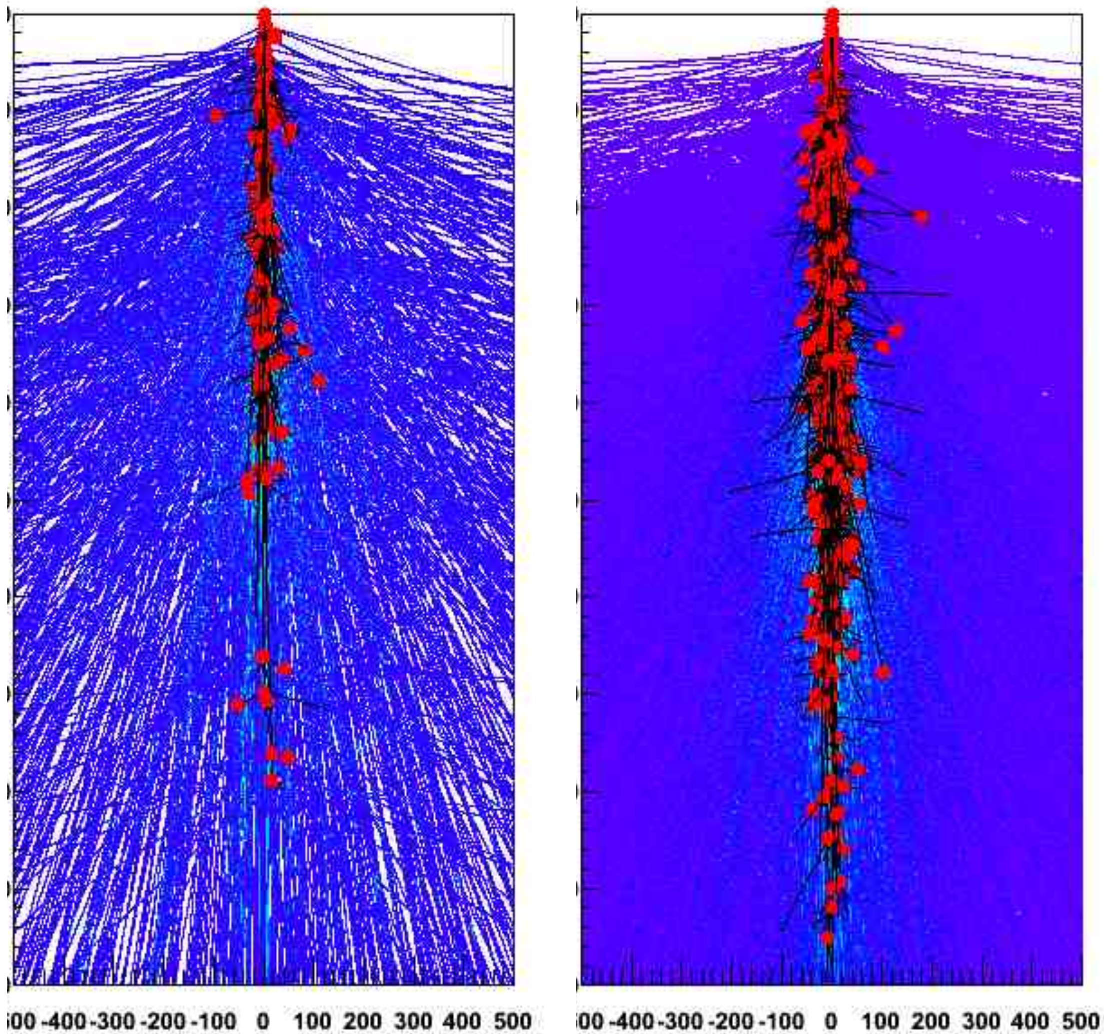




The bulk of radiated and visible energy comes from the EM cascade

Muons are the smoking gun of the hadronic shower which is the real backbone of the whole shower.

π^0 decays are smoking canyons

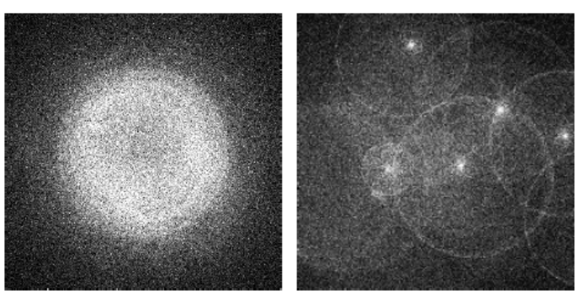
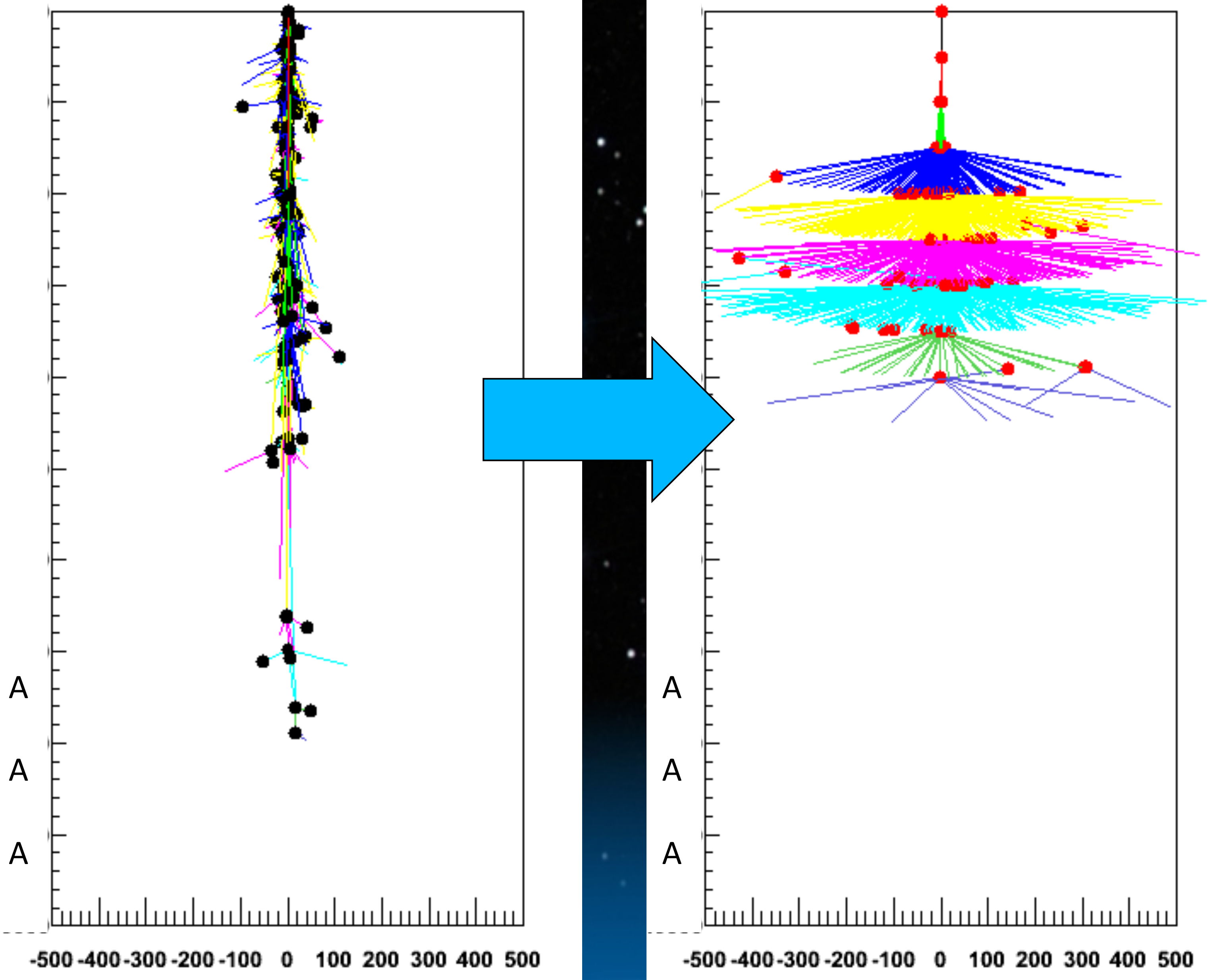
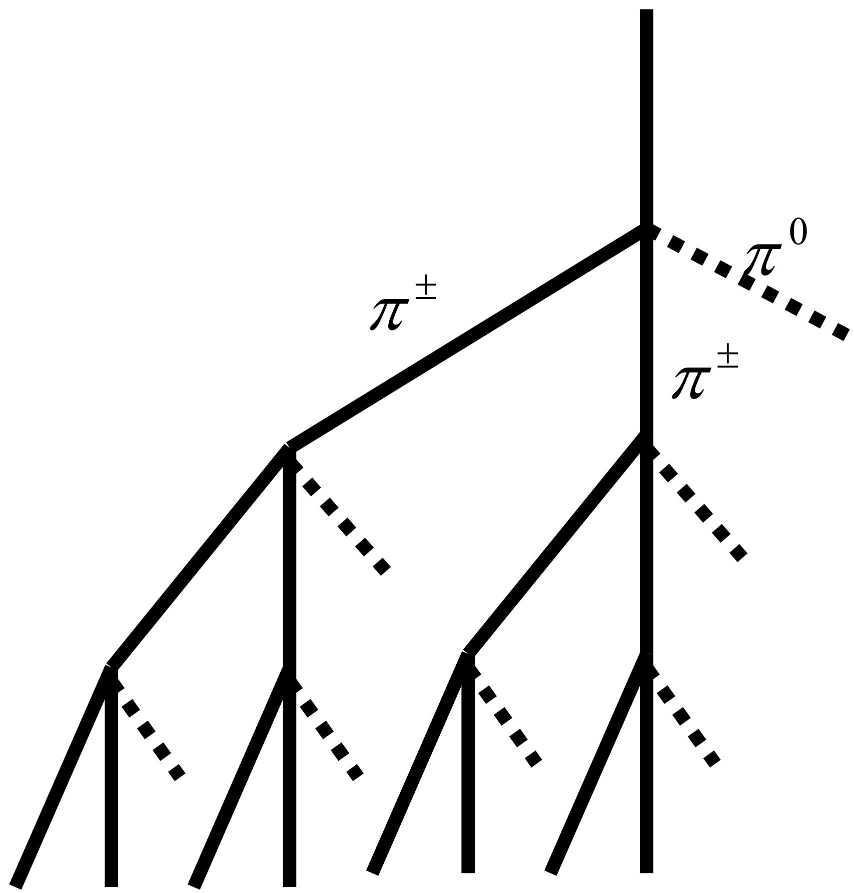


Figure 2.4: Cherenkov light distribution on ground for a 300 GeV γ-ray shower (*left*) and a 1 TeV proton shower (*right*). The side length is 400 m. The pictures are taken from Monte Carlo simulations from [17].


A
A
A
-500 -400 -300 -200 -100 0 100 200 300 400 500
A
A
A
-500 -400 -300 -200 -100 0 100 200 300 400 500

J. Matthews
Astropart.Phys. 22 (2005) 387-397

Hadronic cascade



1 — E_0

N_{ch} — $\dfrac{E_0}{N_{tot}}$

N_{ch}^2 — $\dfrac{E_0}{N_{tot}^2}$

N_{ch}^3 — $\dfrac{E_0}{N_{tot}^3}$

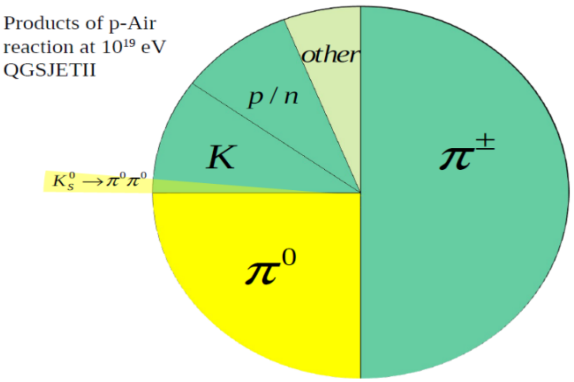
$$N_{tot} = N_{ch} + \frac{1}{2} N_{ch}$$

The hadronic cascade loses energy that goes into the EM cascade

$$\xi_c^{\pi} \approx 20\ GeV$$

$$n_c = \frac{\ln\left(\dfrac{E_0}{\xi_c^{\pi}}\right)}{\ln\left(\dfrac{3}{2} N_{ch}\right)} = 0.85 \log_{10}\left(\frac{E_0}{\xi_c^{\pi}}\right)$$

EM/Hadronic Energy balance



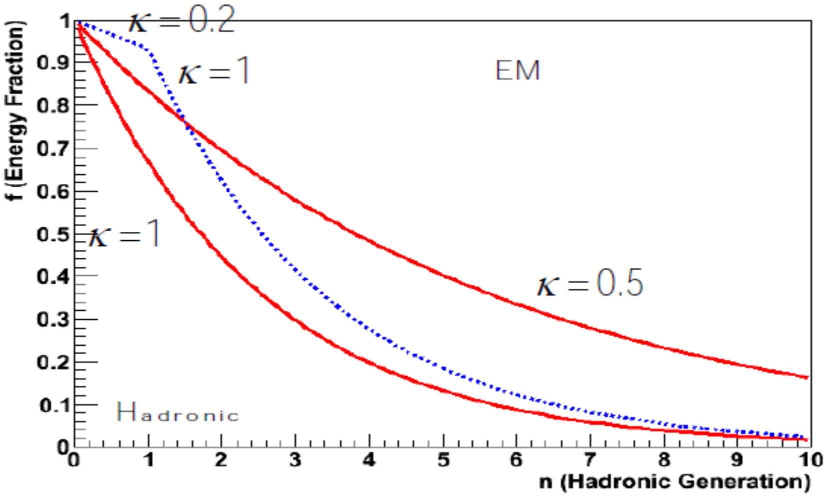
$$\sum E^{\pi} = \left(1 - \frac{1}{3}\kappa\right)^{n} E_0$$

$$\sum E^{EM} = \left[1 - \left(1 - \frac{1}{3}\kappa\right)^{n}\right] E_0$$

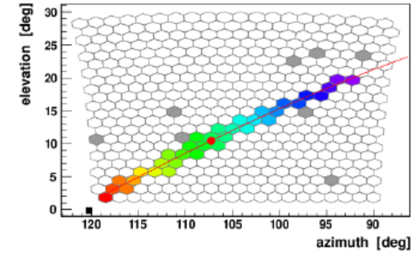
After only 2 generations, most of the energy has been transferred to the EM cascade.

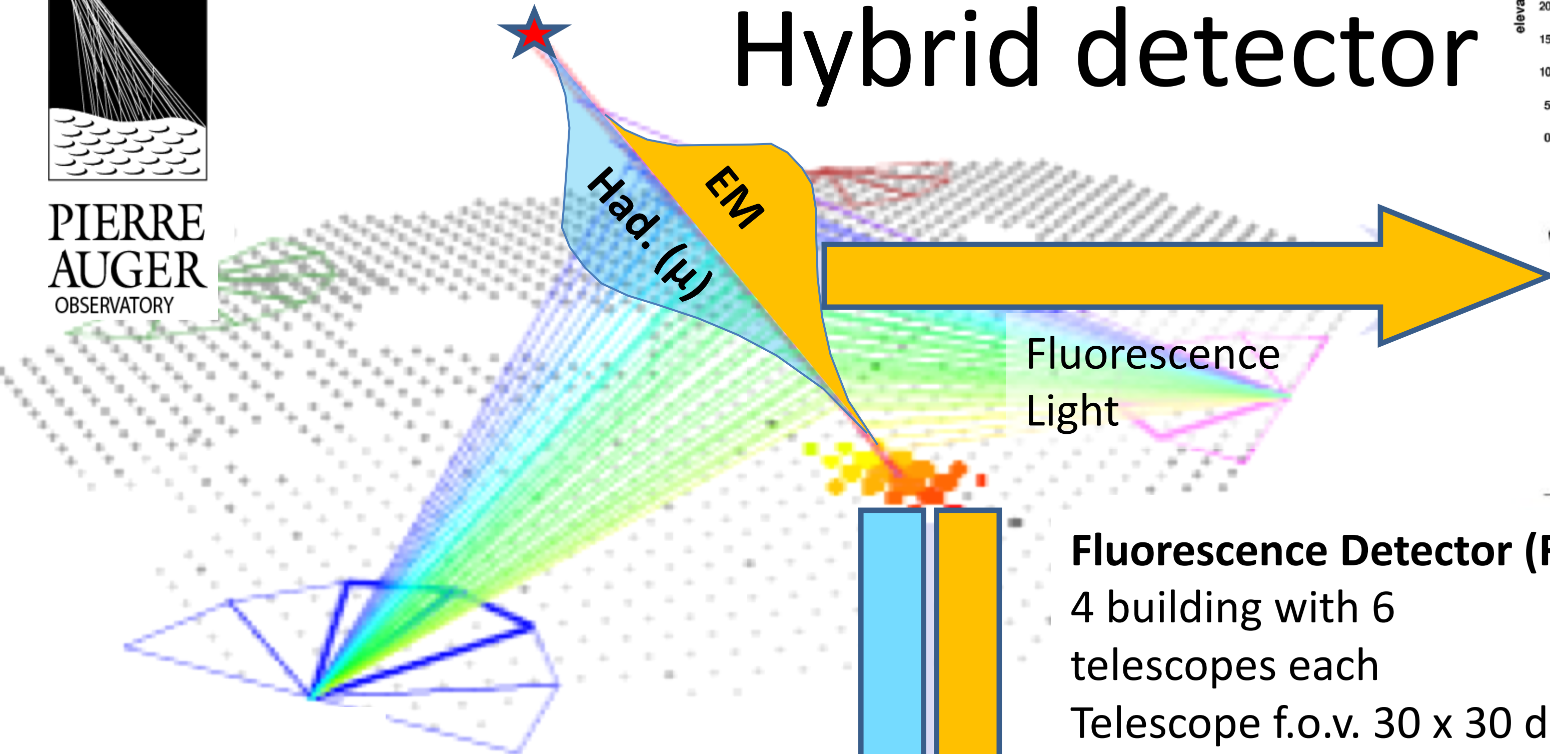
EM and hadronic cascade decouple.

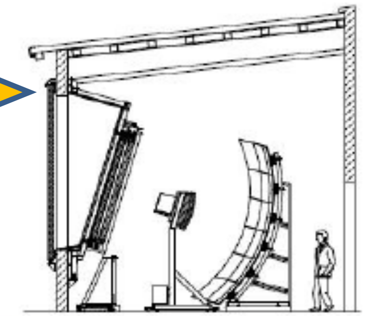
EM cascade is mostly sensitive to high-E hadr, int.
Hadronic cascade is sensitive to high and low E hadr. int.

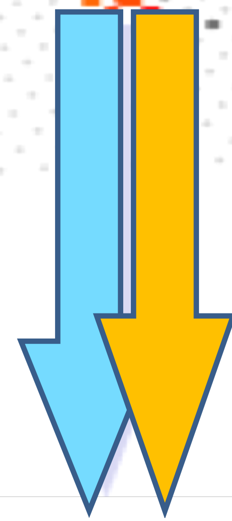


Hybrid detector

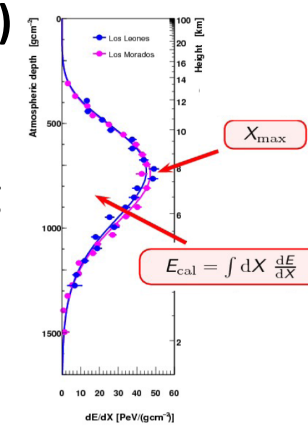




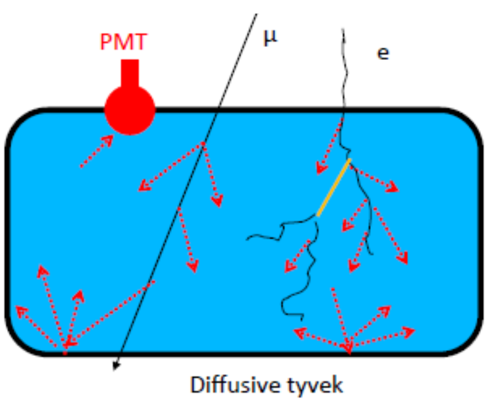


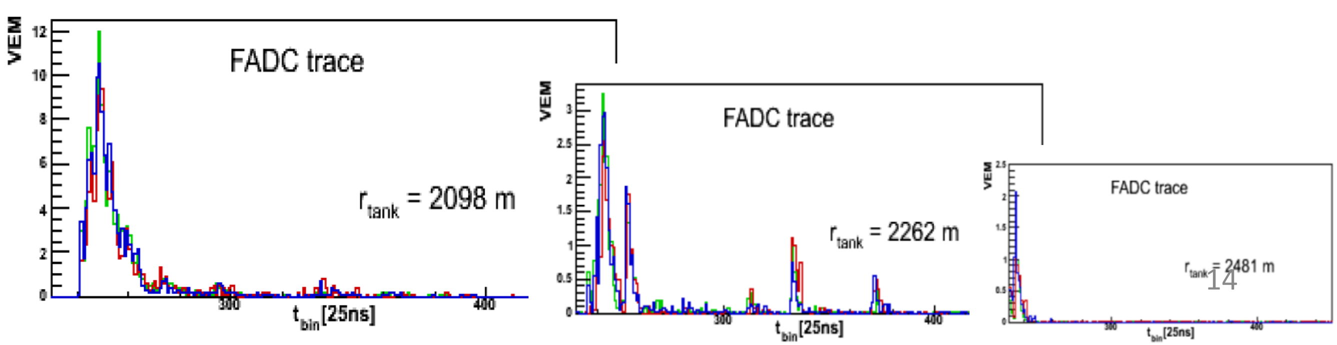


Fluorescence Detector (FD)
4 building with 6 telescopes each
Telescope f.o.v. 30 x 30 deg

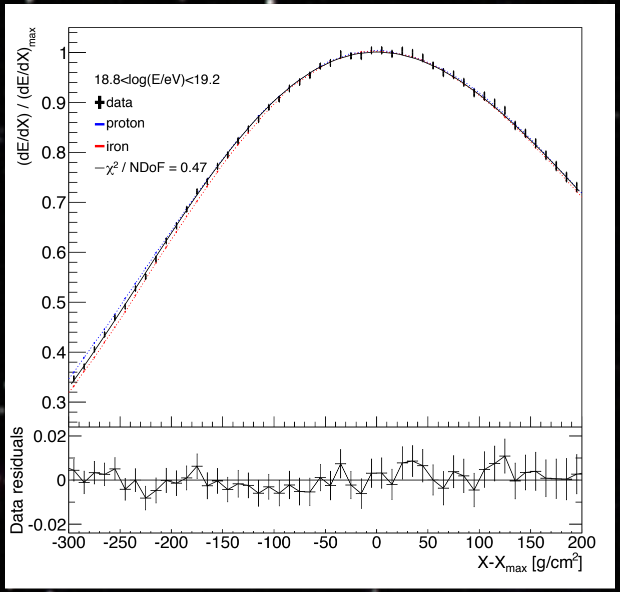


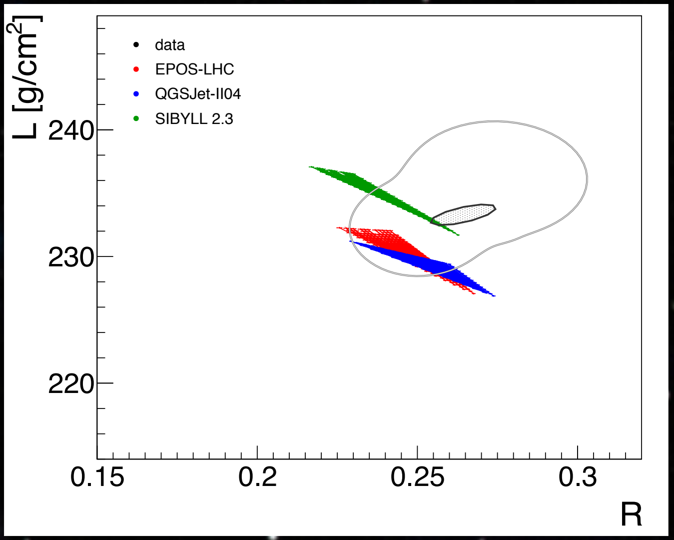
Surface Detector (SD)
1600 water Cherenkov tanks
Area of 3000 km^2

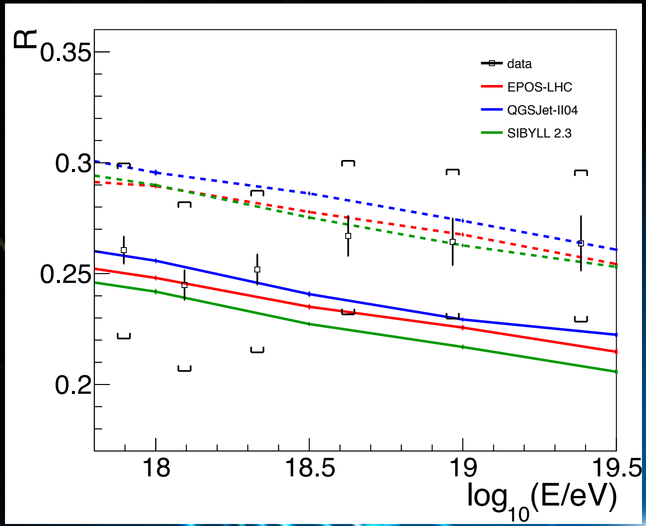


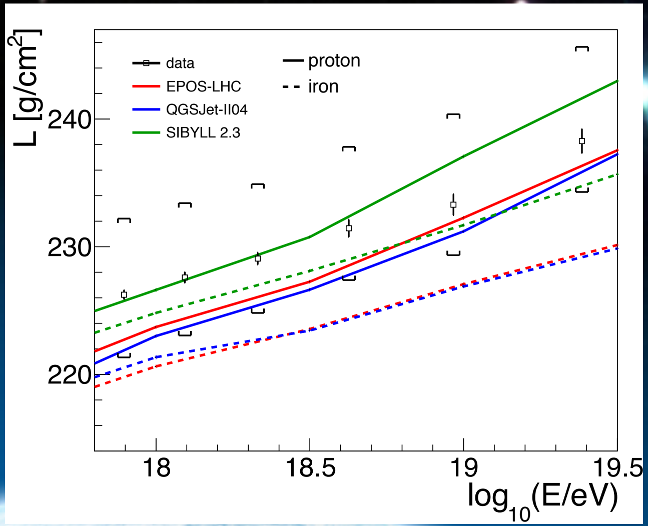


Average EM profile









F.Diogo, S. Andringa, R. Conceição

Muon production depth

Muon Production Depth profile can be estimated from the muon arrival times distributions

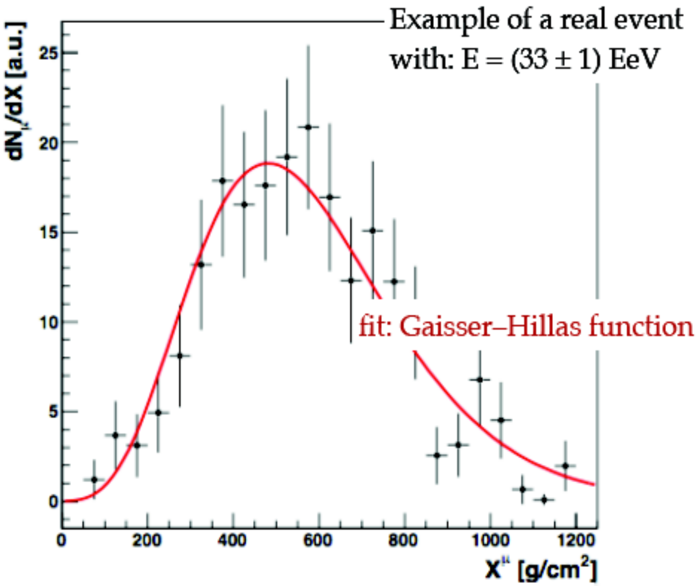
Two assumptions:

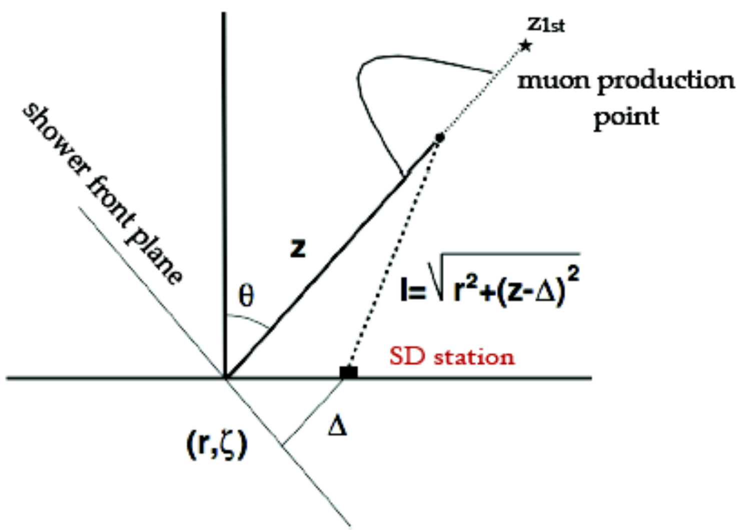
♦ Muons are produced in the shower axis

♦ Muons travel following straight lines

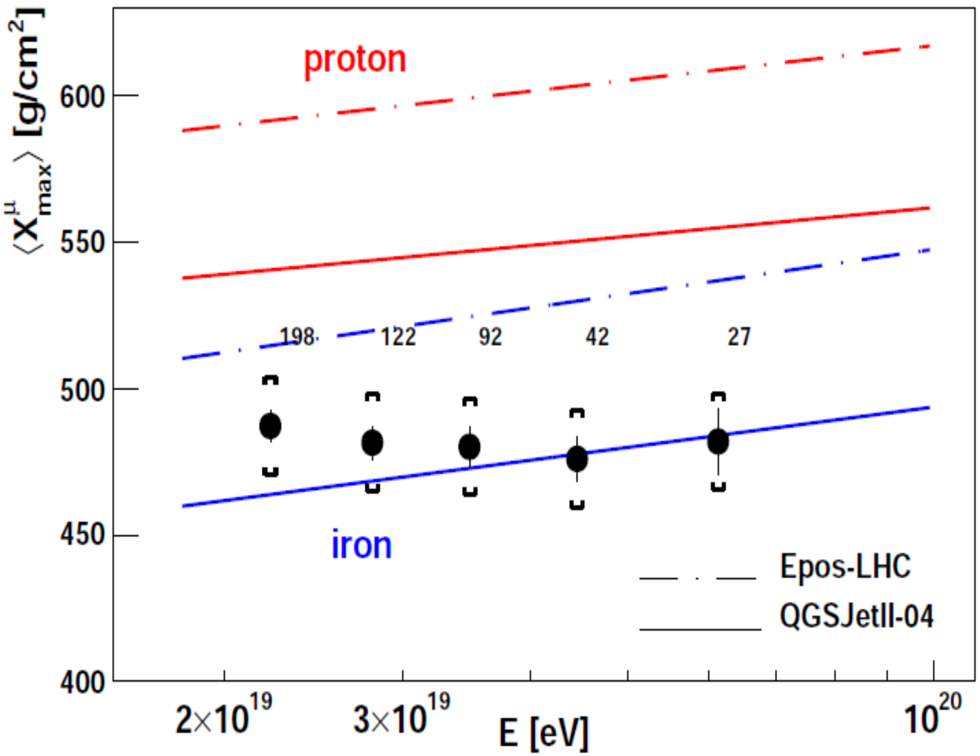
Map from t to z muon by muon

$$z \simeq \frac{1}{2}\left(\frac{r^2}{c(t-\langle t_\epsilon\rangle)} - c(t-\langle t_\epsilon\rangle\right) + \Delta$$





Muon Production Depth vs. energy



data set: 01/2004 – 12/2012

E > 1e19.3 eV

zenith angles [55°,65°]

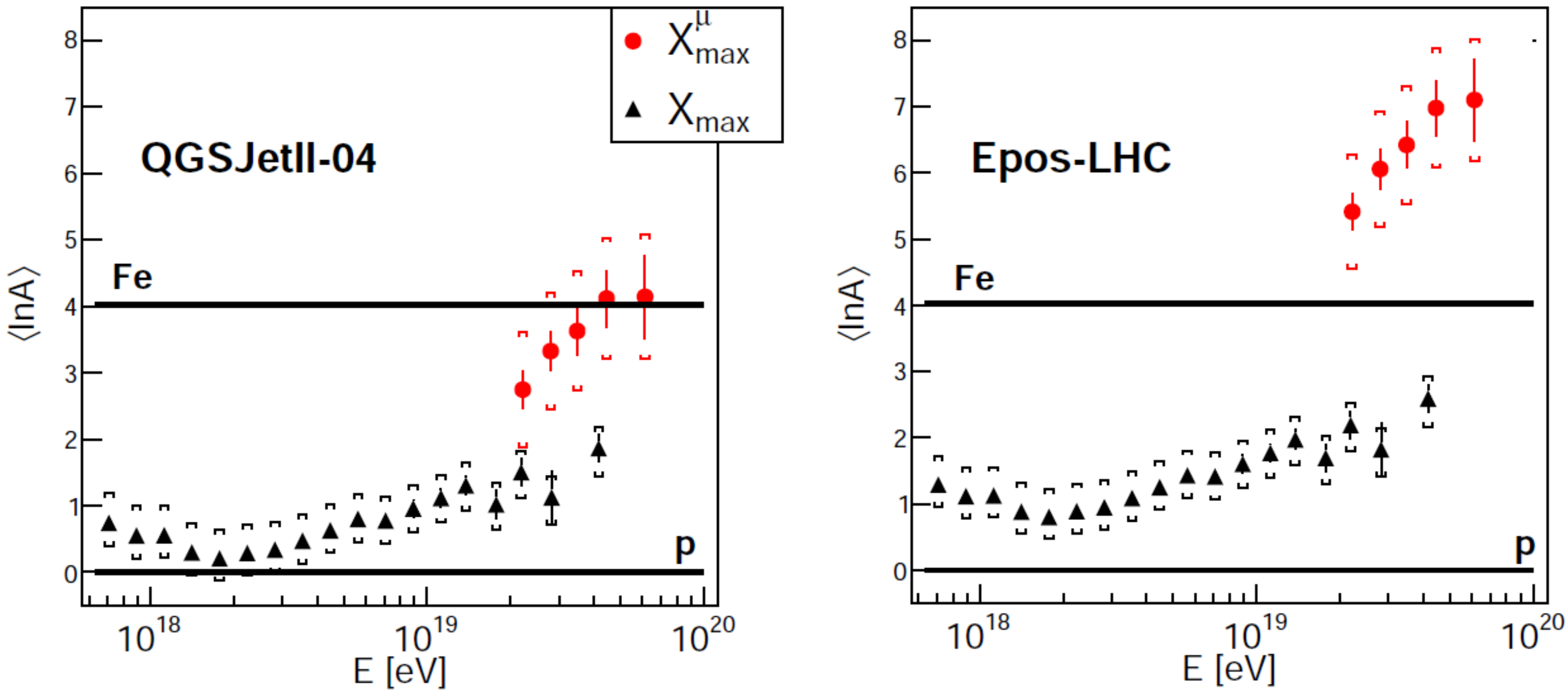
Core distances [1700 m, 4000 m]
(more muons/event)

481 events after quality cuts

syst: 17 g/cm2
Event by event resolution:
100 (80) g/cm2 at 1e19.3 eV for p (Fe)
50 g/cm2 at 1e20 eV

- QGSJetII-04: data bracketed by predictions
- EPOS-LHC: predictions above data

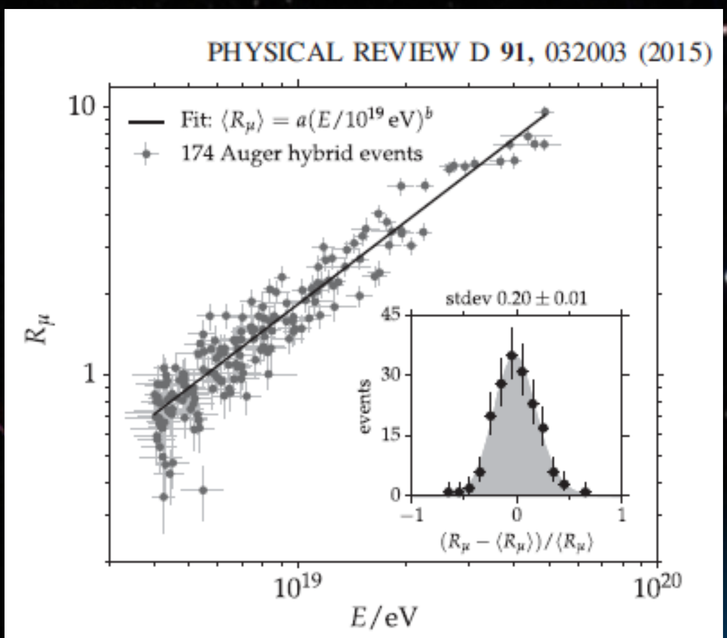
Compatibility between Xmax and Xμmax



- QGSJetII-04: compatible values within 1.5 σ
- EPOS-LHC: incompatibility at a level of at least 6 σ

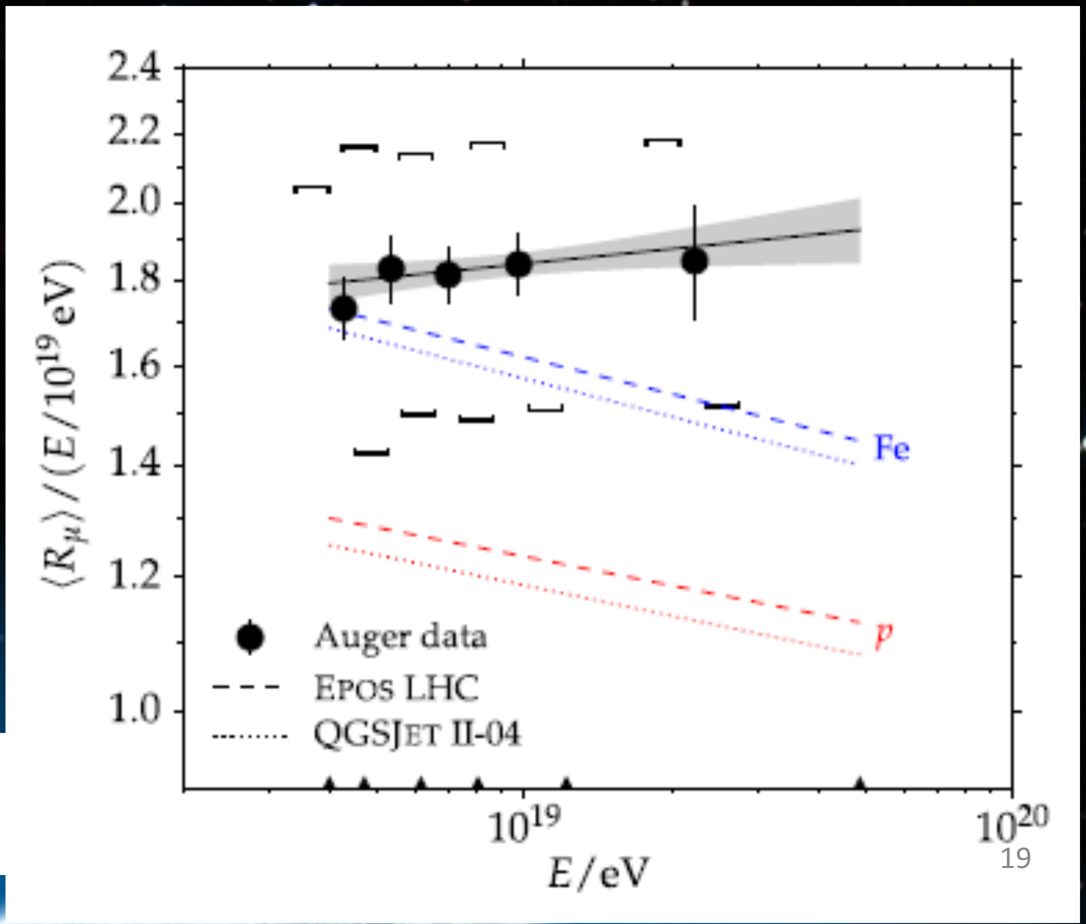
Rmu in horizontal showers

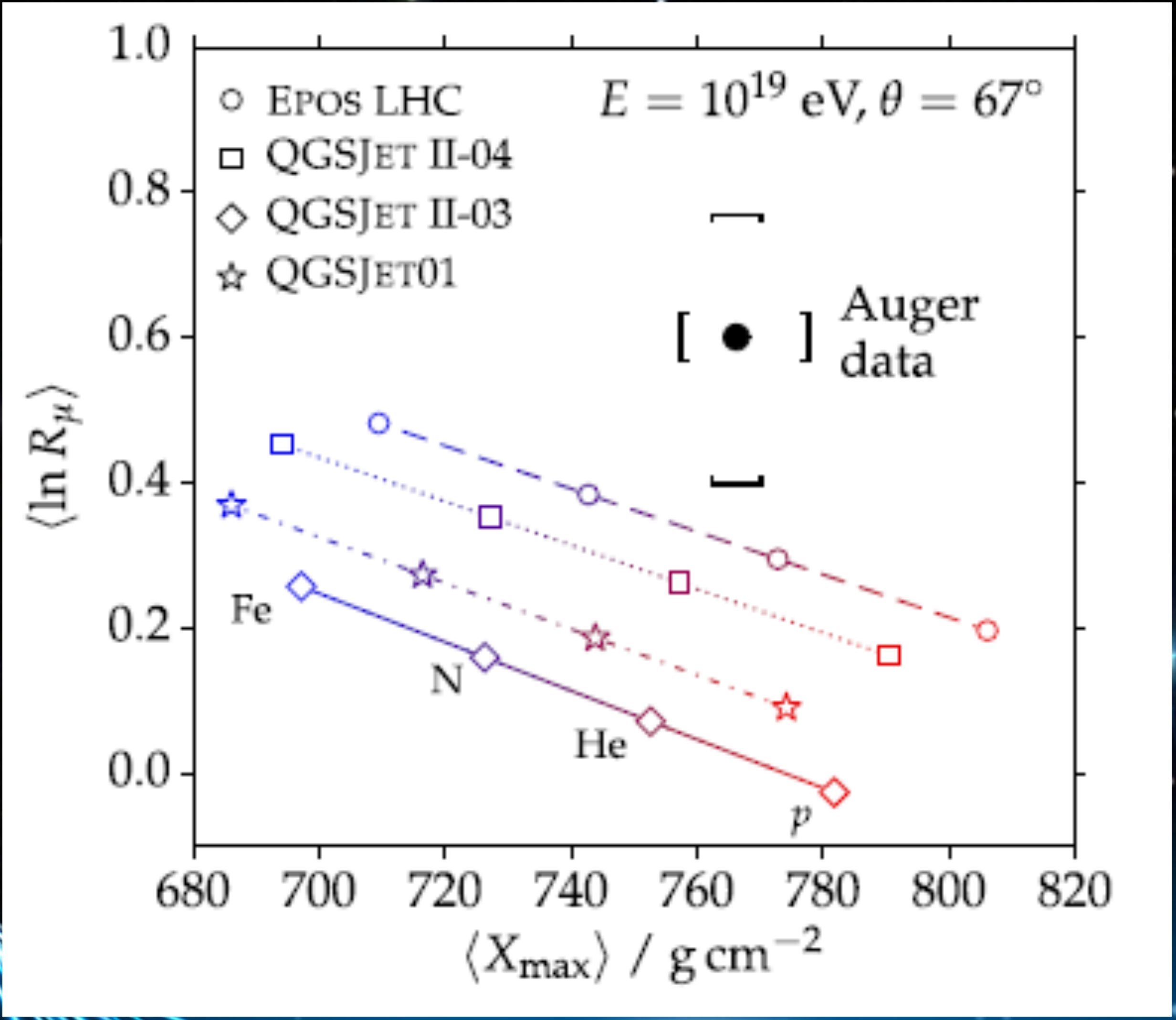
$$N_\mu = A\left(\frac{E/A}{\xi_c}\right)^\beta,$$



$$a = \langle R_\mu \rangle(10^{19}\ \mathrm{eV}) = (1.841 \pm 0.029 \pm 0.324(\mathrm{sys})),$$

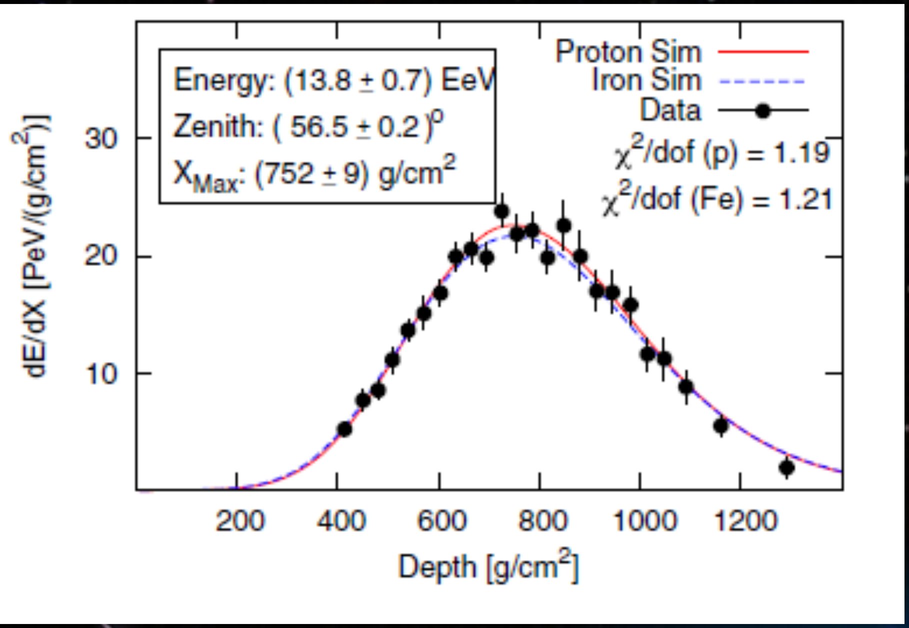
$$b = \mathrm{d}\langle \ln R_\mu \rangle / \mathrm{d} \ln E = (1.029 \pm 0.024 \pm 0.030(\mathrm{sys})),$$

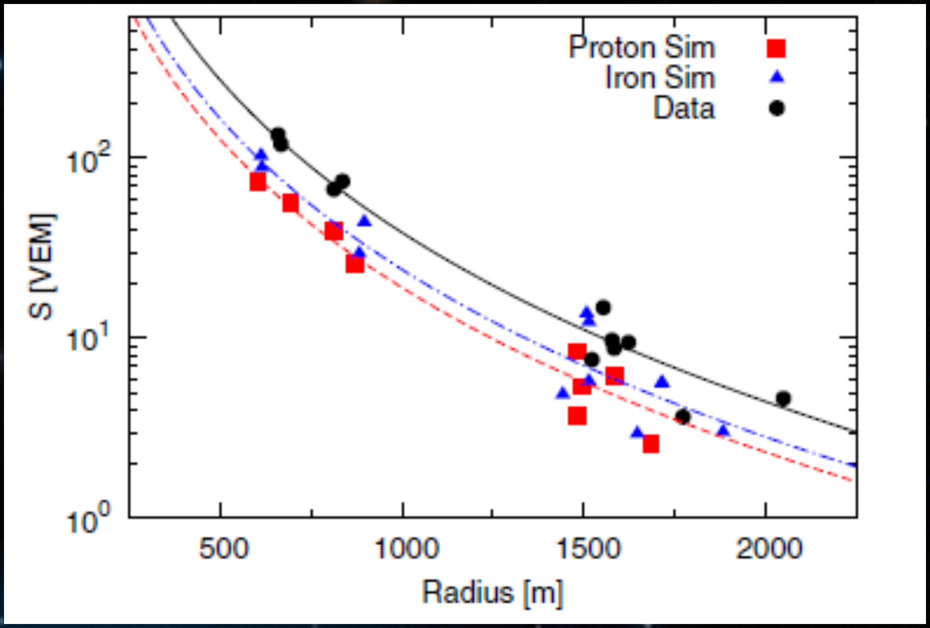




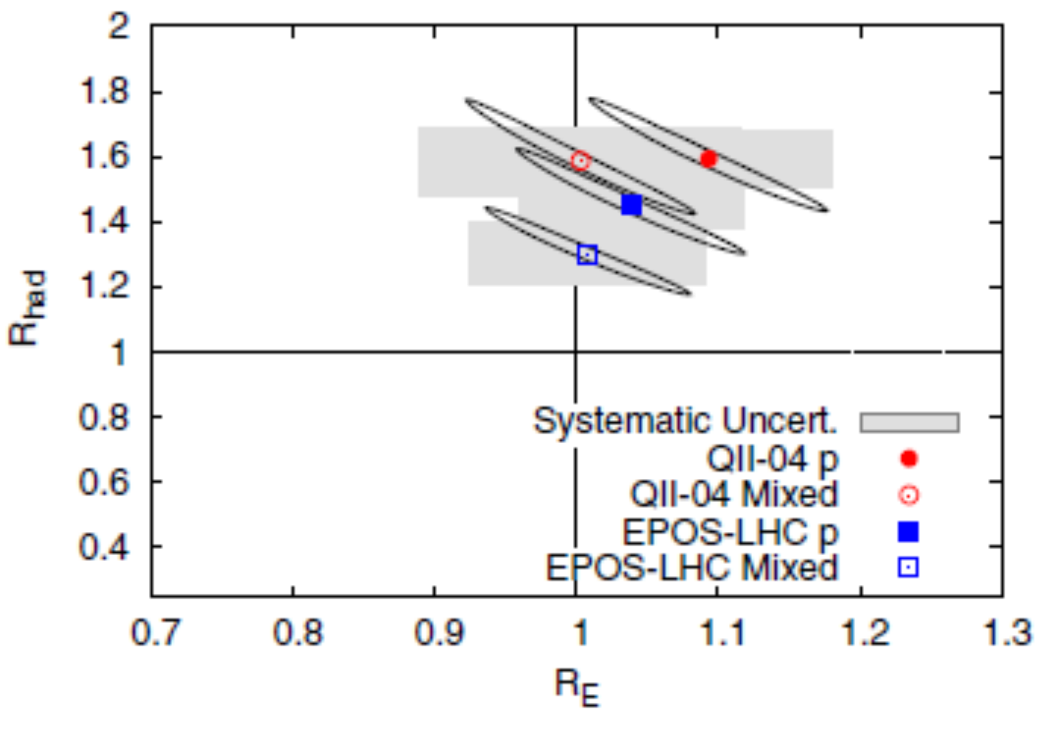
1.0
0.8
0.6
0.4
0.2
0.0
EPOS LHC
QGSJET II-04
QGSJET II-03
QGSJET01
$E = 10^{19}$ eV, $\theta = 67°$
Auger data
Fe
N
He
p
$\langle \ln R_\mu \rangle$
680
700
720
740
760
780
800
820
$\langle X_{max} \rangle$ / g cm^{-2}

Independent confirmation with vertical hybrids





Results



- **No energy rescaling is needed**

- The observed muon signal is a factor 1.3 to 1.6 larger than predicted by models

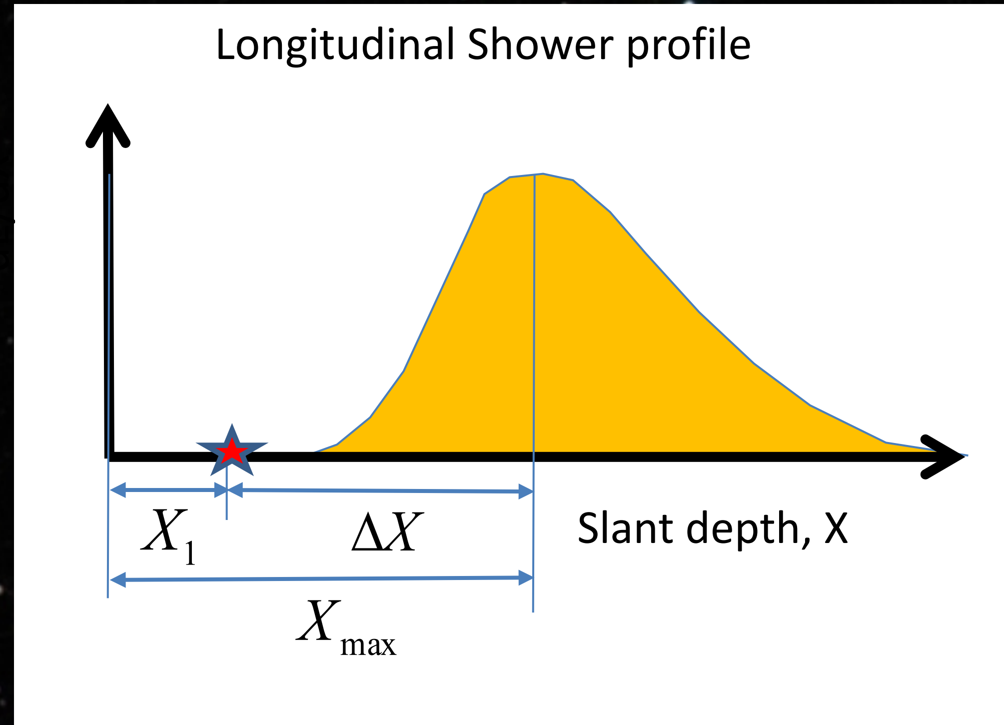
- Smallest discrepancy for EPOS-LHC with mixed composition, at the level of 1.9 σ

Model	R_E	R_{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	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

Conclusions so far

- QGSJetII.04 Xmax distributions produce unphysical mass results
- Number of muons higher than expected
  - 80% higher than QGSJetII.04
  - 30% higher than EPOS-LHC
  - **Data does not favour a change in the energy scale that would reduce the significance of the number of muons**.
  - Existence of new phenomena?
  - Just fine tunning?
- Muon production depth is too shallow for EPOS-LHC
- NO SATISFACTORY MODEL

p-Air cross section

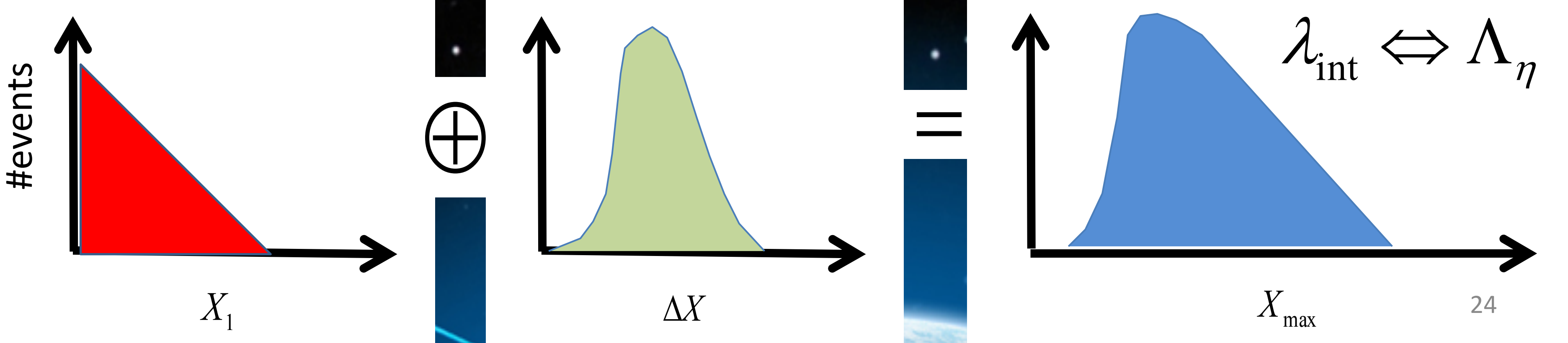


$$\sigma_{\text{int}} = \frac{< m_{air} >}{\lambda_{\text{int}}}$$

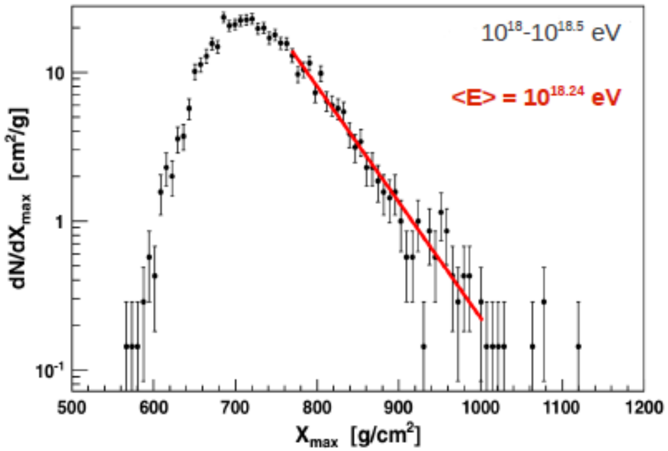
$$\frac{dp}{dX_1} = \frac{1}{\lambda_{\text{int}}} e^{-X_1/\lambda_{\text{int}}}$$

$\Rightarrow$ Tail of $X_{\max}$ − Distribution

$$dN/dX_{\max} \propto \exp(-X_{\max}/\Lambda_\eta)$$

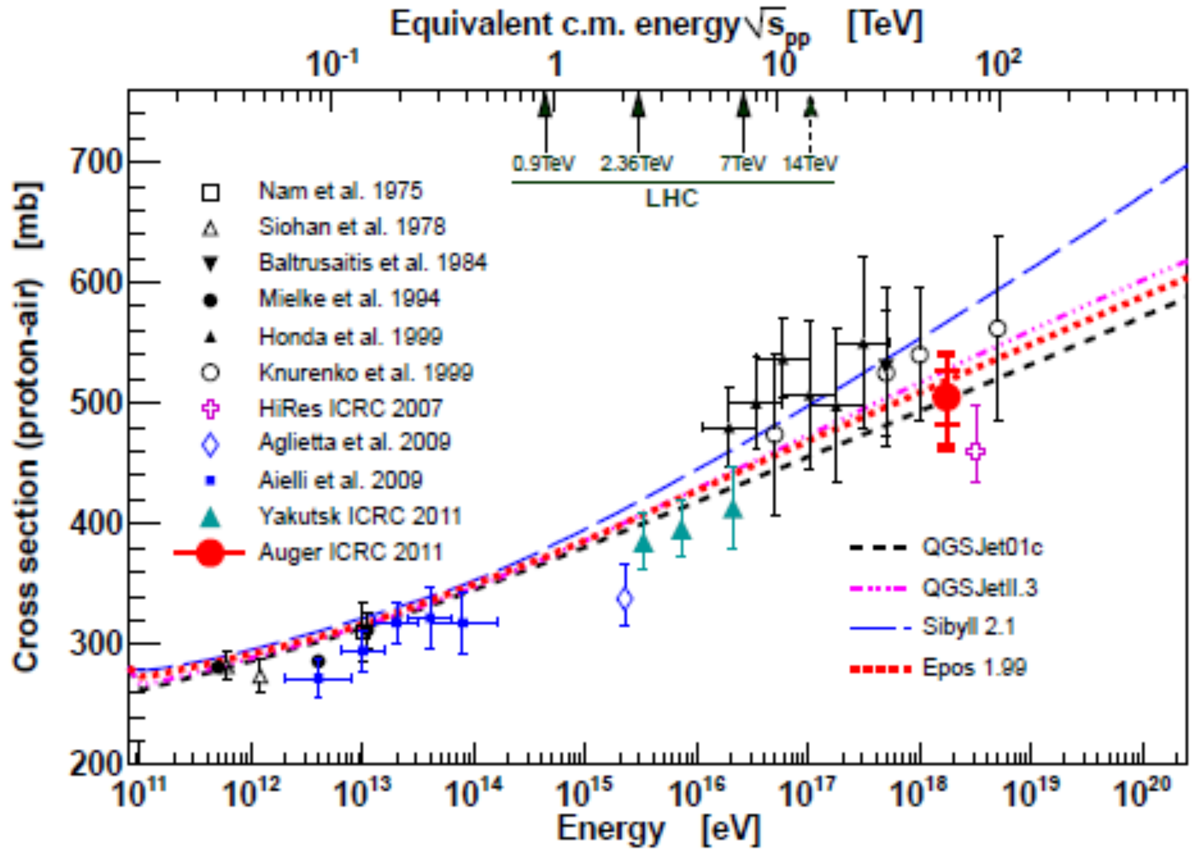


Results



$\Lambda_\eta = [55.8 \pm 2.3_{stat} \pm 1.6_{sys}]\, g/cm^2$

Description	Impact on $\sigma_{p\text{-air}}$
Λ_η systematics	± 15 mb
Hadronic interaction models	$^{+19}_{-8}$ mb
Energy scale	± 7 mb
Conversion of Λ_η to $\sigma^{prod}_{p\text{-air}}$	± 7 mb
Photons, <0.5 %	< +10 mb
Helium, 10 %	−12 mb
Helium, 25 %	−30 mb
Helium, 50 %	−80 mb
Total (25 % helium)	−36 mb, +28 mb



Possible He contamination is the main source of systematic uncertainty. 25% He maximum contamination assumed for sys. uncertainties

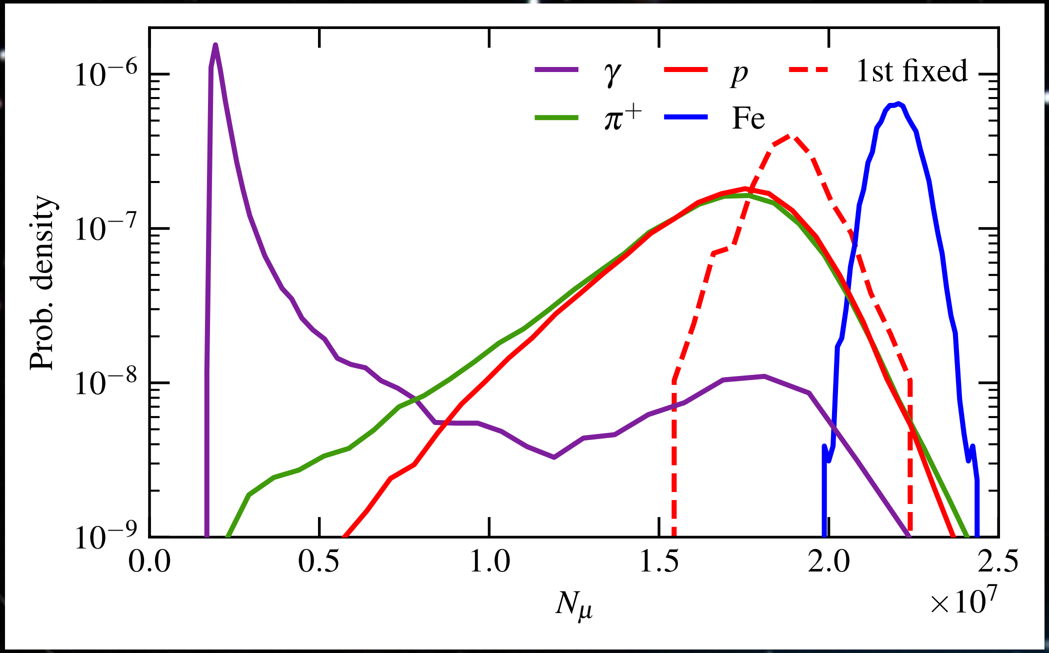
$$\sigma_{p\text{-air}} = \left[505 \pm 22_{stat} \left(^{+28}_{-36}\right)_{sys}\right] \text{ mb}$$

$$\sigma^{inel}_{pp} = [90 \pm 7_{stat} \left(^{+9}_{-11}\right)_{sys} \pm 1.5_{Glauber}] \text{ mb}$$

$$\sqrt{s_{pp}} = [57 \pm 6] \text{ TeV}$$

See more details in PRL 2012 and ICRC2011

The shower-to-shower fluctuations of the muon content



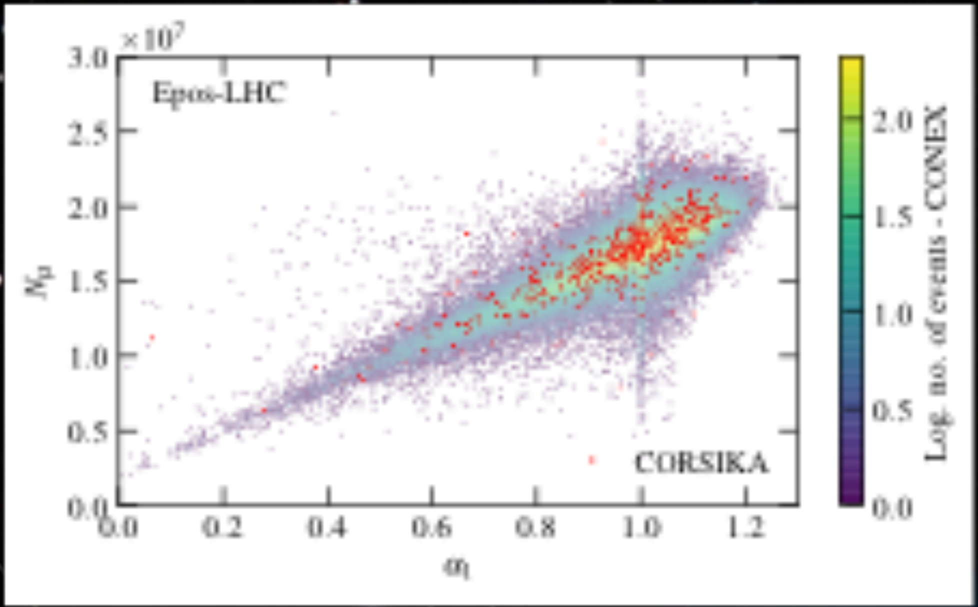
Fluctuations are of the order of 14%.

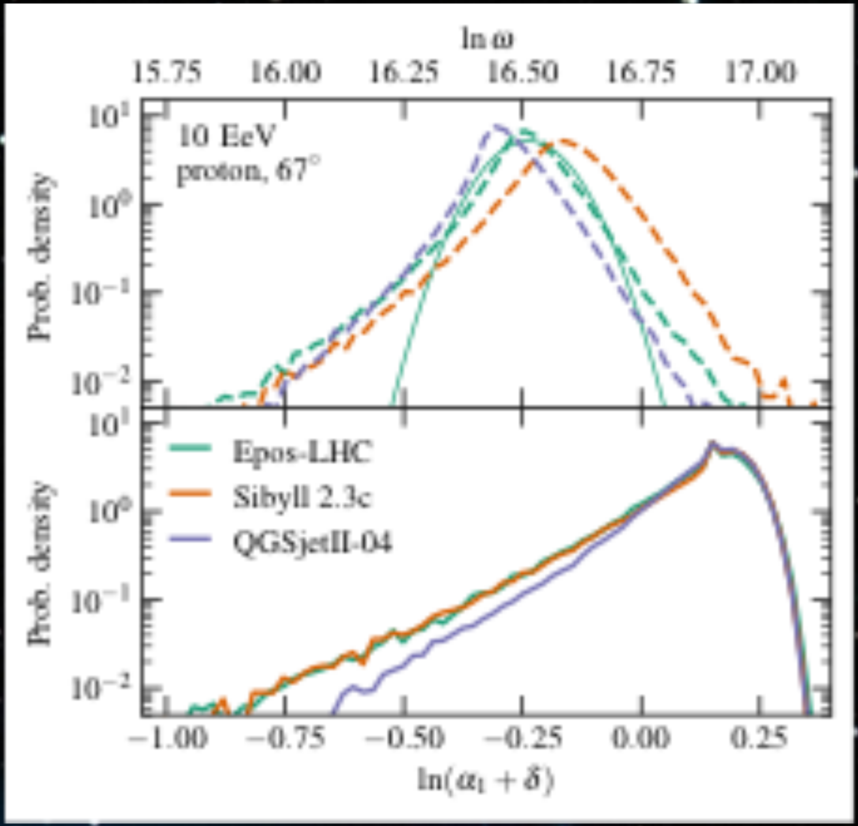
This is compatible with ~50 independent participants.

(showrs contain 1E7 muons)

L. Cazon, R. Conceição, F. Riehn,to be published

p-Air



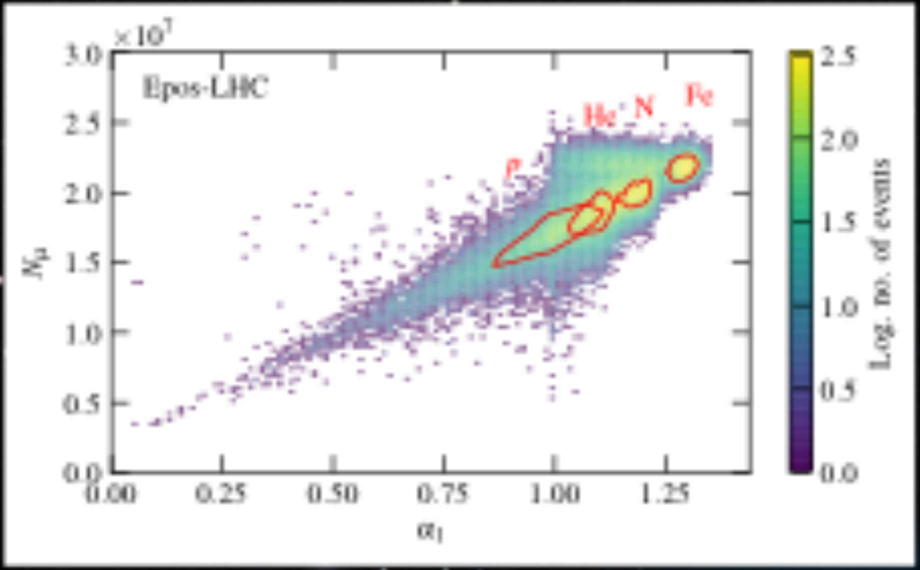


The shower-to-shower distribution of muon content reflects the distribution of hadronic energy fraction of the first interaction.

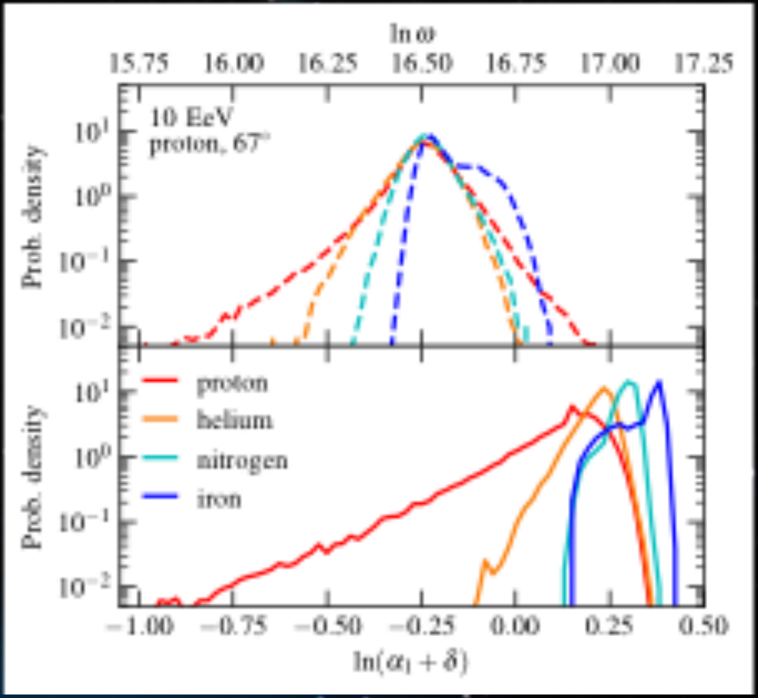
$$N_\mu \;=\; \alpha_1 \cdot \omega \,.$$

$$\alpha_1 \equiv \sum_{j=1}^{m_1} x_j^\beta \,,$$

nucleus-Air



Epos-LHC
p
He
N
Fe
N_μ
$\times 10^7$
α_1
Log. no. of events



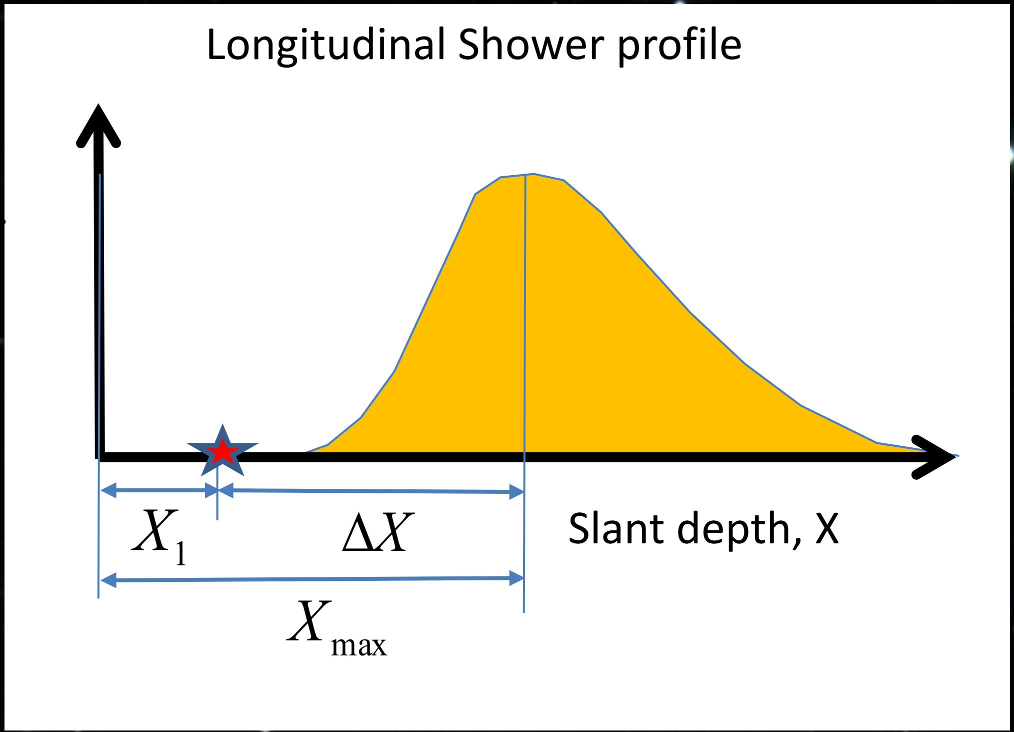
ln ω
10 EeV
proton, 67°
Prob. density
proton
helium
nitrogen
iron
$\ln(\alpha_1 + \delta)$

Conclusions

- Hadronic Physics with UHECR has been traditionally made by “brute force” comparison with full air shower simulations/High Energy Hadronic models.
  - we have made important contributions. Models have been including improvements after Auger results (muon number, MPD)
- We have been working to change the paradigm
  - in shower phenomenology to undestand how information of first interaction is trasmited/degraded.
  - e.g: Possible to access hadronic energy fraction of first interaction
    - we are exploring the physics of this distribution
      - low alpha tail
    - An auger publication on real data is being prepared.
- Expertise in cosmic ray muon -> *applied field* -> Muon Tomography

back-up slides

p-Air cross section

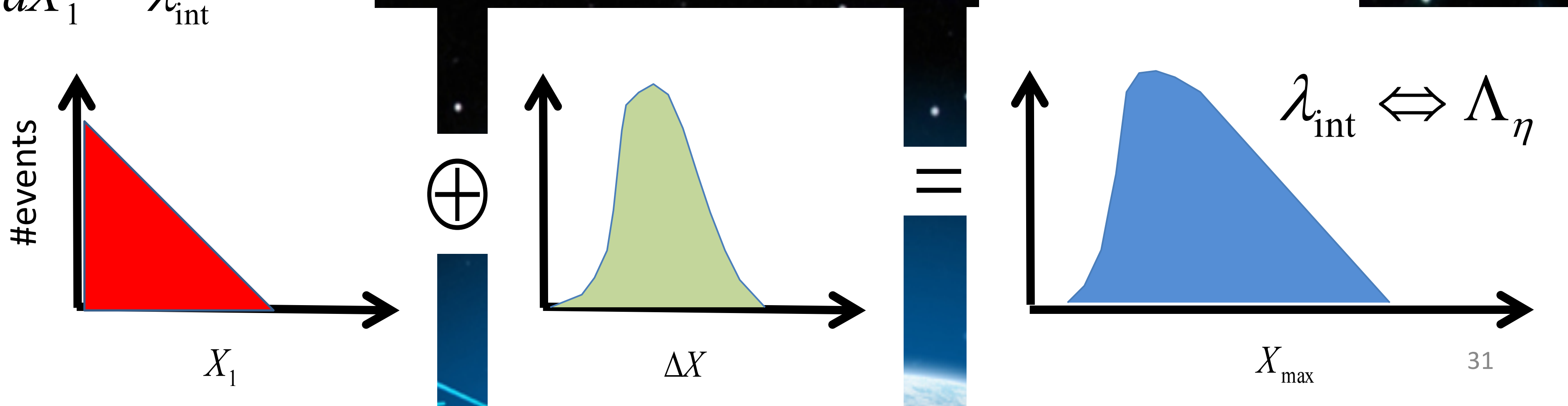


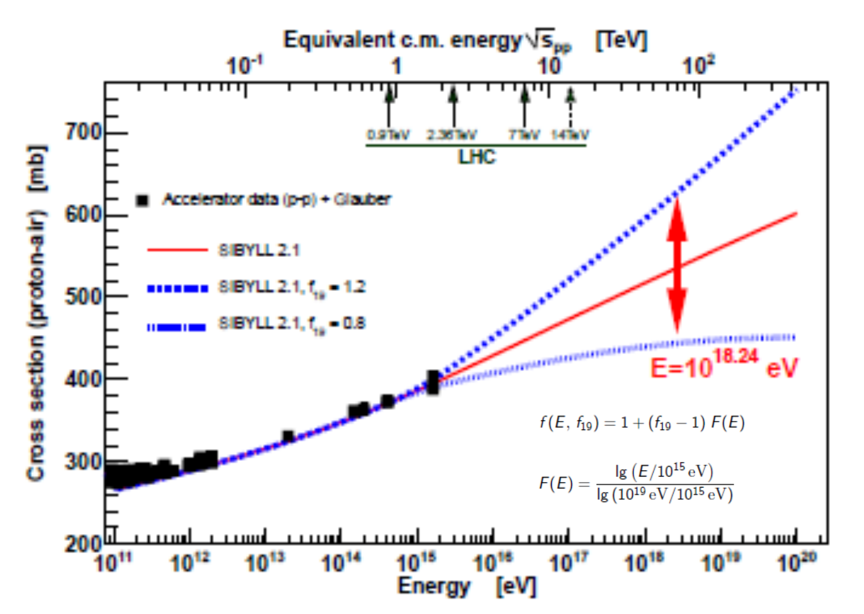
$$\sigma_{\text{int}} = \frac{< m_{air} >}{\lambda_{\text{int}}}$$

$$\frac{dp}{dX_1} = \frac{1}{\lambda_{\text{int}}} e^{-X_1/\lambda_{\text{int}}}$$

$\Rightarrow$ Tail of X_{max} −Distribution

$dN/dX_{max} \propto \exp(-X_{max}/\Lambda_\eta)$



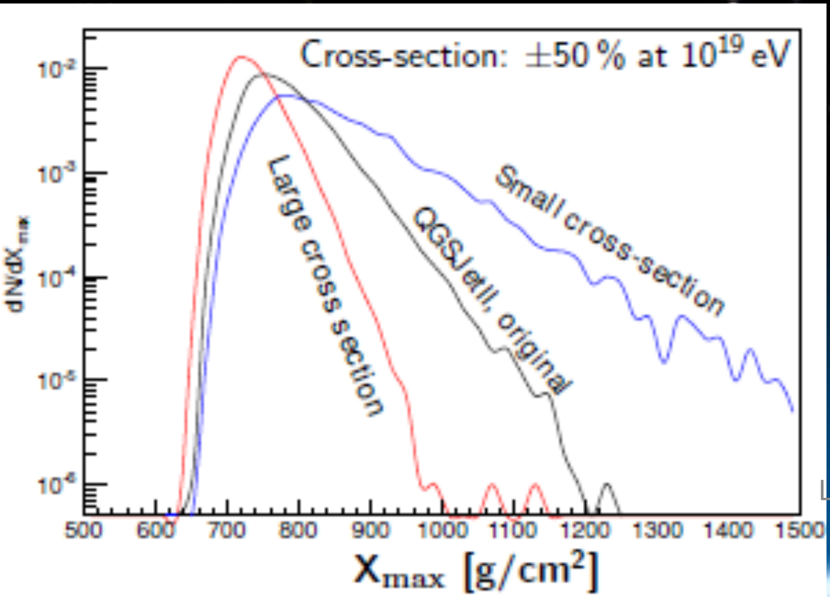


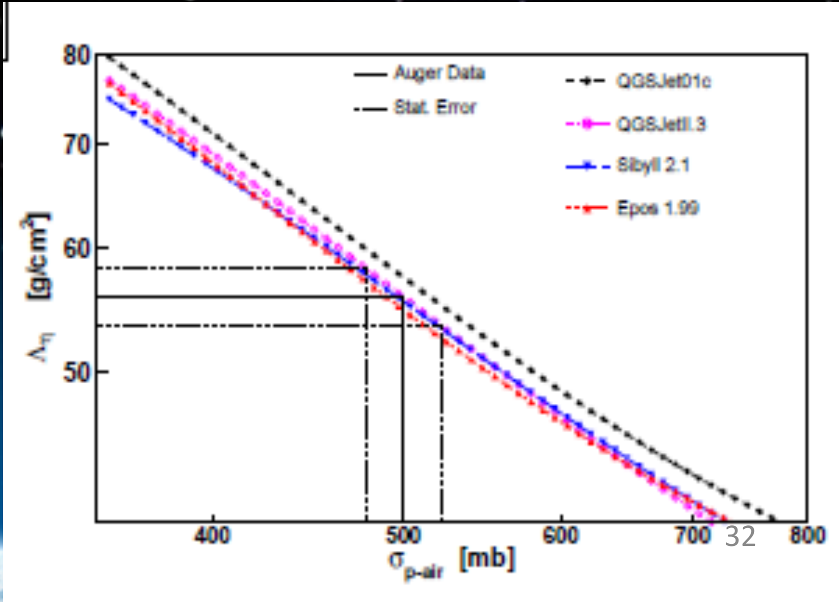
Method

- Continuous reparameterization of cross section in MC

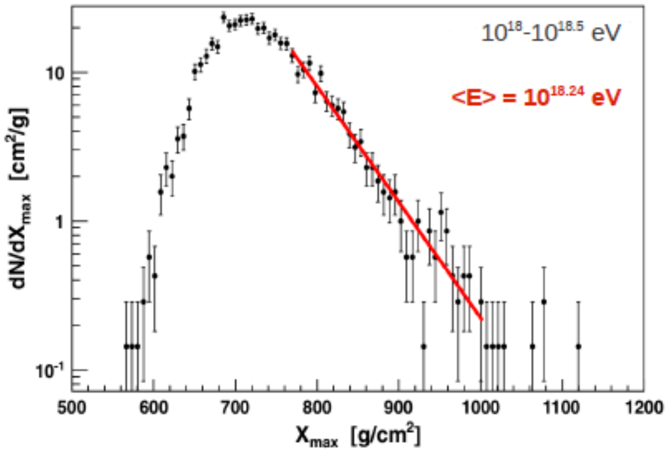
- Simulation of X_{max} distribution
  - different rescalings
  - different models

- $\Lambda_\eta \leftrightarrow \sigma_{p\text{-}Air}$ conversion





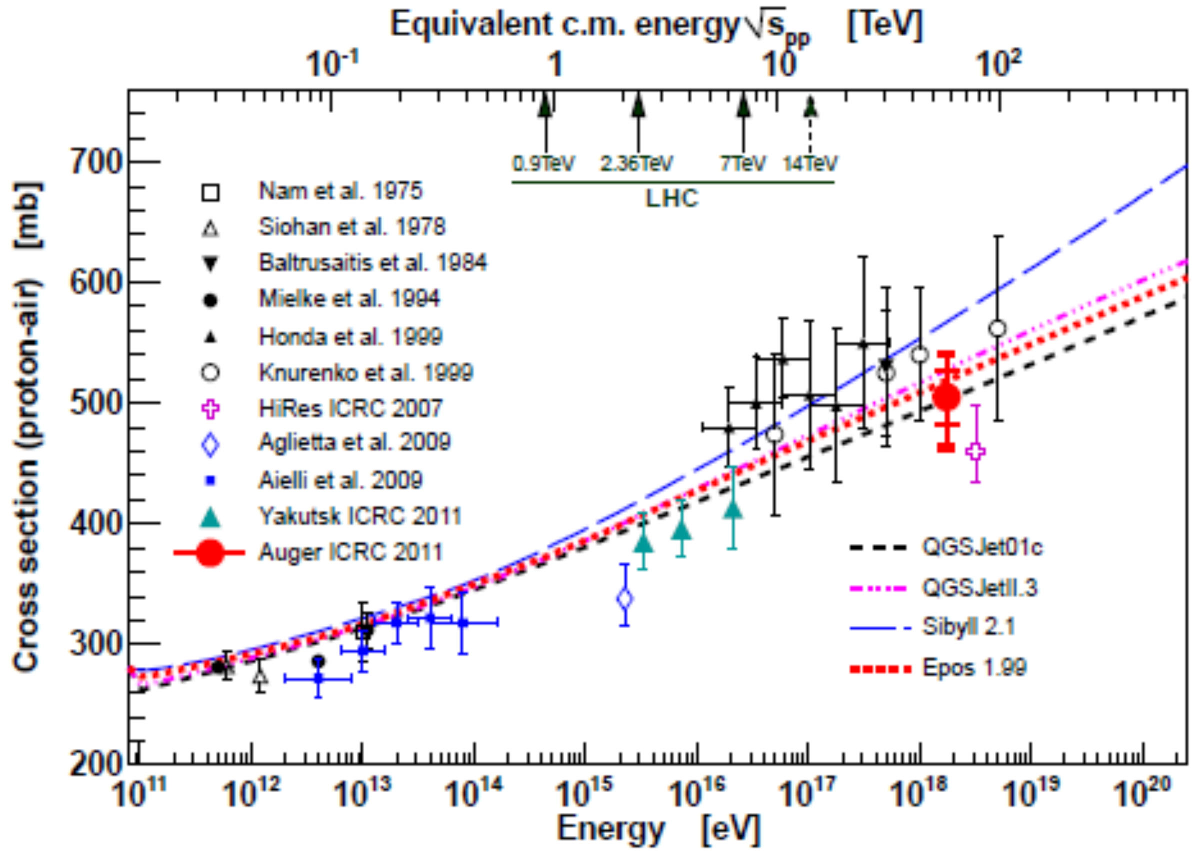
Results



$$\Lambda_\eta = [55.8 \pm 2.3_{stat} \pm 1.6_{sys}]\ g/cm^2$$

Description	Impact on $\sigma_{p\text{-air}}$
Λ_η systematics	± 15 mb
Hadronic interaction models	$^{+19}_{-8}$ mb
Energy scale	± 7 mb
Conversion of Λ_η to $\sigma^{\text{prod}}_{p\text{-air}}$	± 7 mb
Photons, $<0.5\,\%$	$< +10$ mb
Helium, $10\,\%$	-12 mb
Helium, $25\,\%$	-30 mb
Helium, $50\,\%$	-80 mb
Total ($25\,\%$ helium)	-36 mb, $+28$ mb

Possible He contamination is the main source of systematic uncertainty. 25% He maximum contamination assumed for sys. uncertainties



$$\sigma_{p\text{-air}} = \left[505\ \pm 22_{stat}\ \left(^{+28}_{-36}\right)_{sys}\right]\ \text{mb}$$

$$\sigma^{\text{inel}}_{pp} = \left[90\ \pm 7_{stat}\ \left(^{+9}_{-11}\right)_{sys}\ \pm 1.5_{\text{Glauber}}\right]\ \text{mb}$$

$$\sqrt{s_{pp}} = [57\ \pm 6]\ \text{TeV}$$

See more details in PRL 2012 and ICRC2011