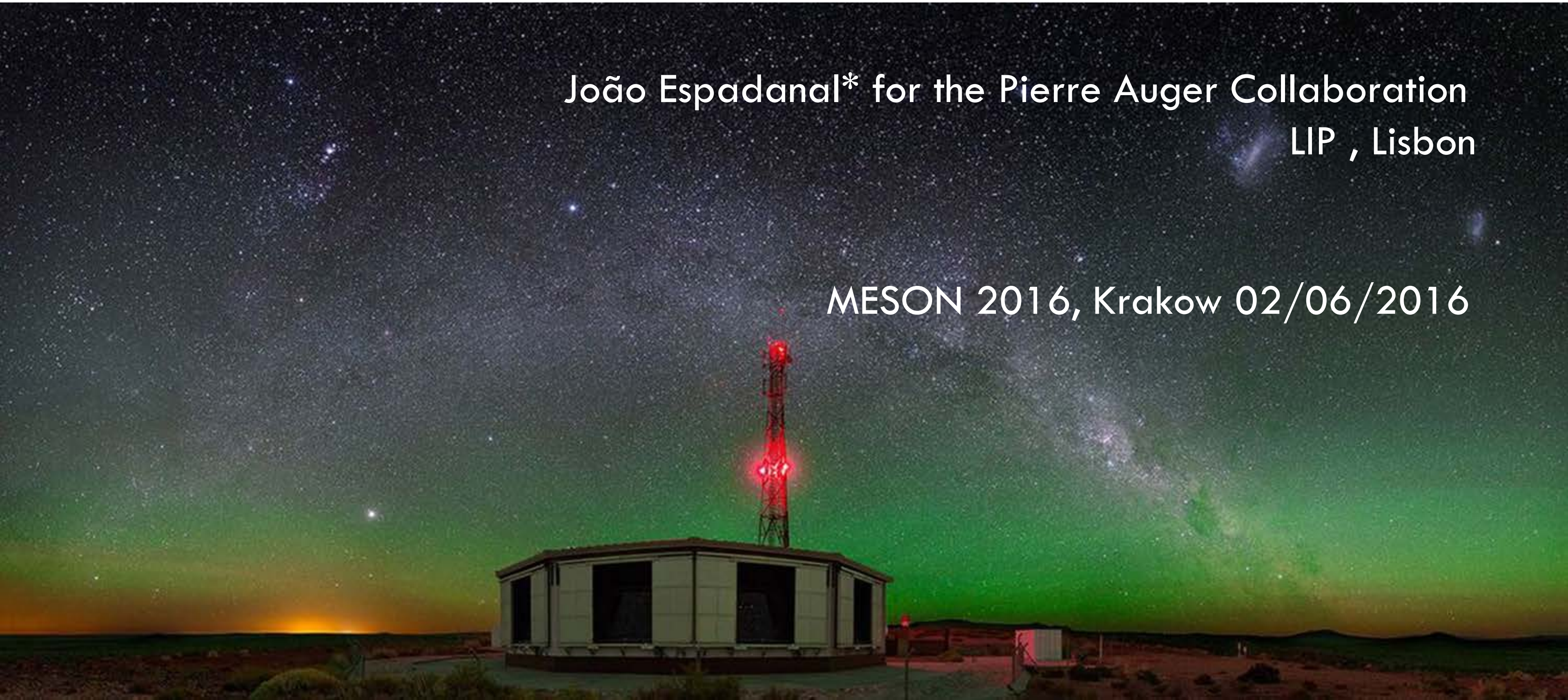
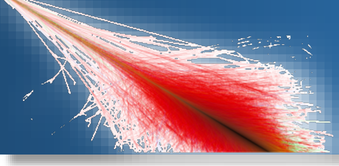
Constraints of hadronic interactions in extensive air showers with the Pierre Auger Observatory

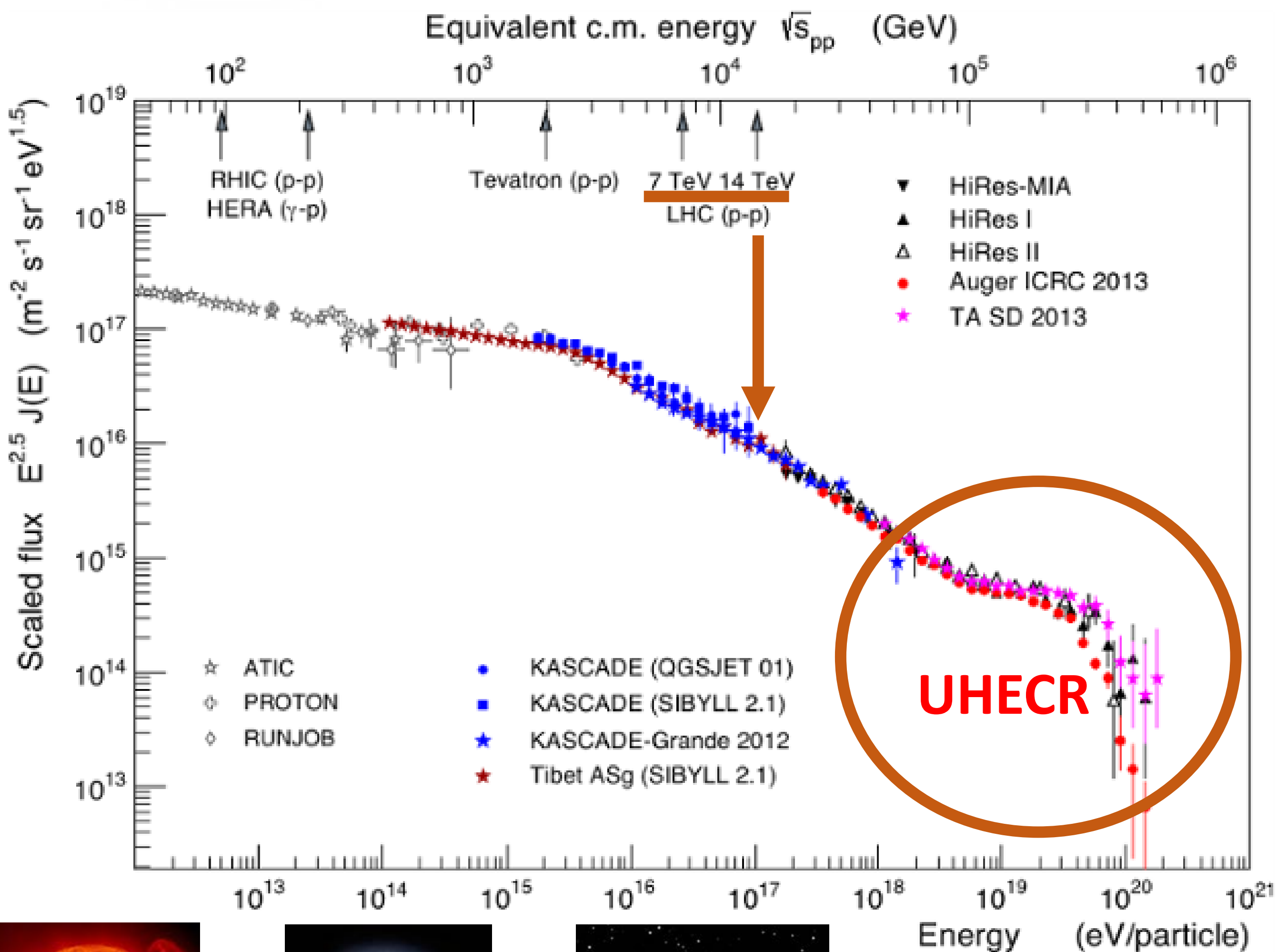


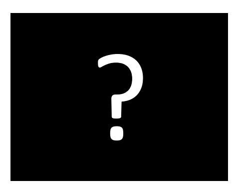
João Espadanal* for the Pierre Auger Collaboration
LIP , Lisbon

MESON 2016, Krakow 02/06/2016



Ultra High Energy Cosmic Rays

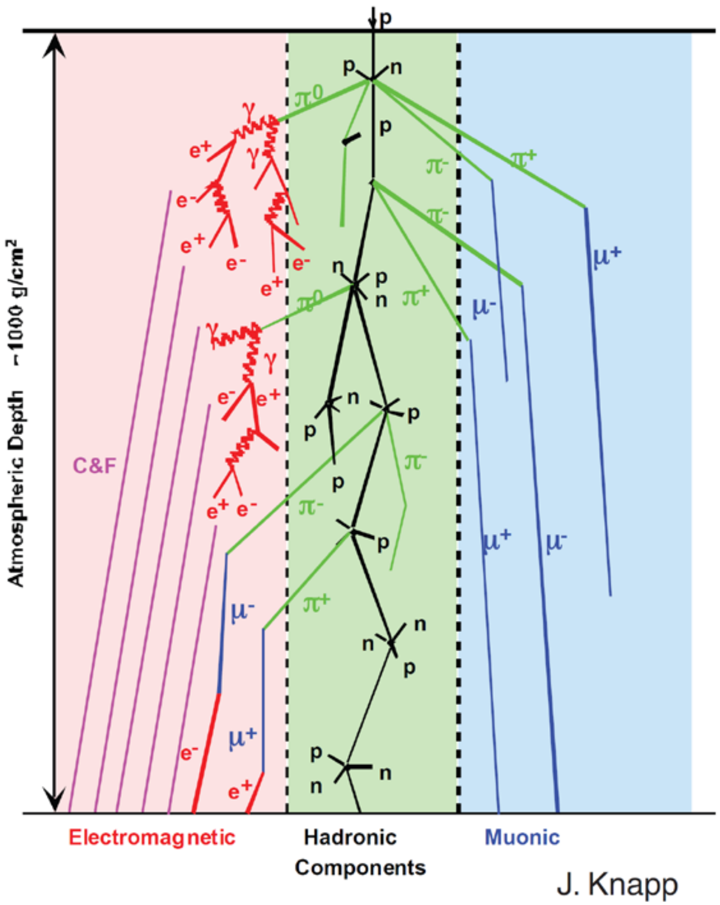




UHECRs

- Opportunity to understand high-energy Universe
  - Production (sources; acceleration mechanisms…)
  - Propagation (Magnetic fields…)
- Opportunity to investigate particle physics at energies above the LHC
  - High-energy interactions
  - Different kinematic regimes

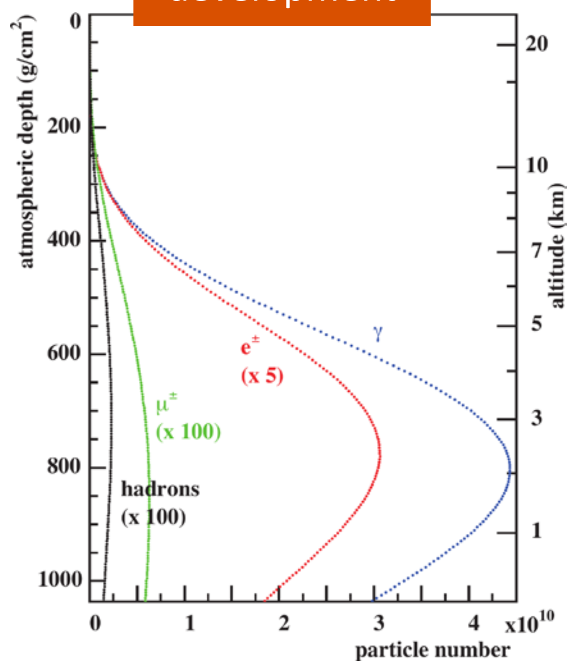
Scheme of an extensive air shower



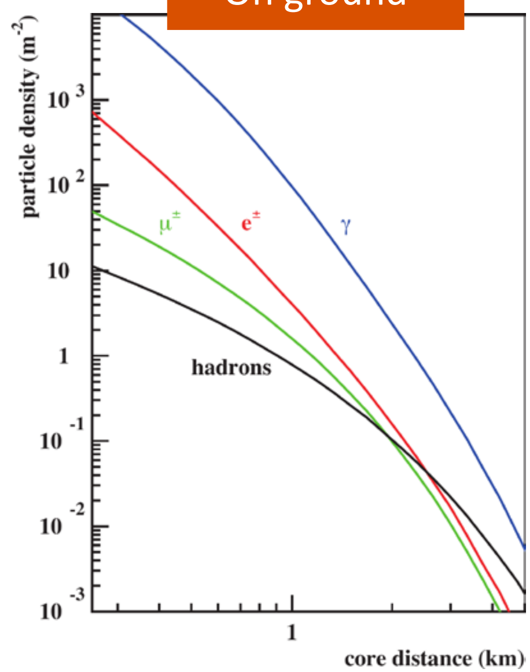
Extensive Air Showers

- For UHECR: billions of particles
  - Secondary hadrons (mostly pions)
  - Electromagnetic cascade (π^0 decay)
  - Muons ($\pi^{\pm}$, K ... decay)

Longitudinal development



Lateral profile On ground



Pierre Auger Observatory

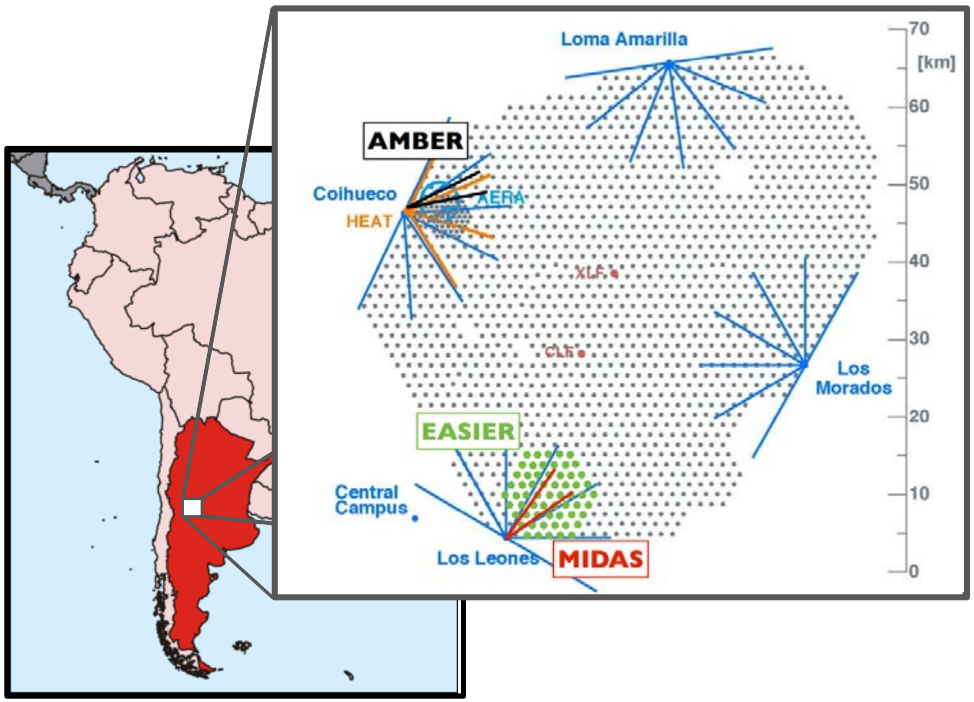
UHECR

flux: $\sim 1 particle\ \mathrm{km}^{-2} century^{-1}$

Located in the Pampa Amarilla,
Mendoza, Argentina
Altitude: 1400 m a.s.l.

Surface detector array

- 1660 water-Cherenkov detectors
- **3000 km2**
- 1500 m spacing , $E > 3 \cdot 10^{18}\mathrm{eV}$



Fluorescence detector FD

- 4 Fluorescence Detectors overlooking the SD array
- 6 x 4 Fluorescence Telescopes

Low energy extension

- Infill - 750m spacing (23.5 km2 area)
  - $E > 3 \cdot 10^{17}\mathrm{eV}$
- HEAT- 3 additional FD telescopes with a high elevation FoV.

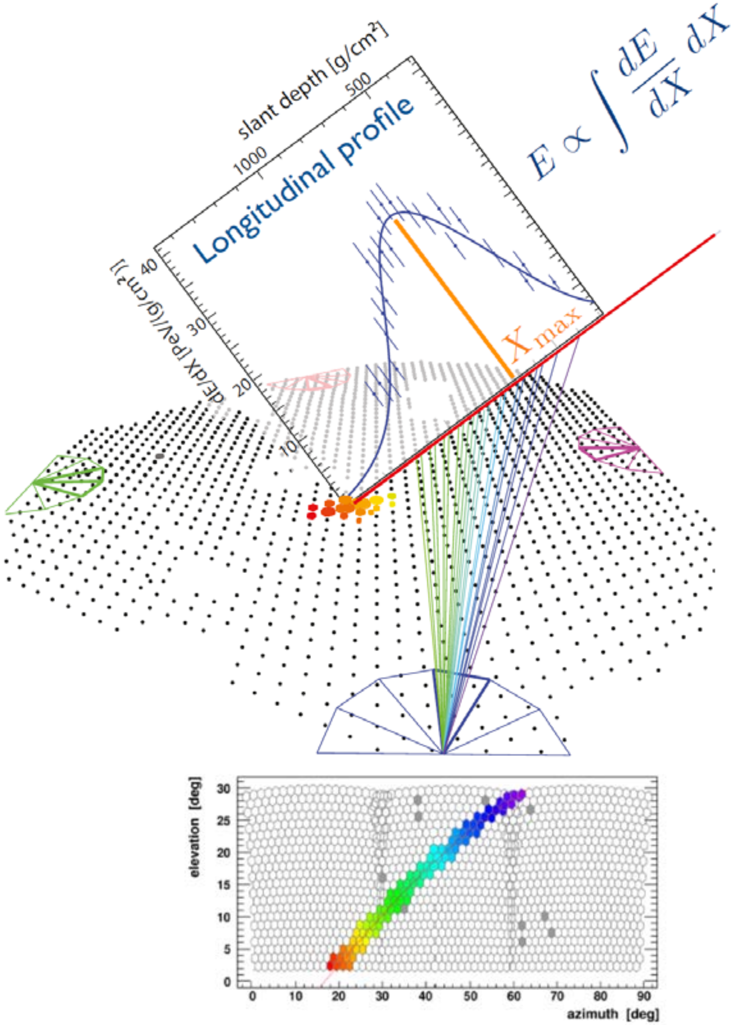
Plus: calibration and monitoring systems…

- Laser, cloud cameras, drones, LIDARS…

What is measured?

longitudinal profile with THE FD

- Direct observation of X_{max} and longitudinal evolution
- average composition from 1st and 2nd moments of the X_{max} distribution abundances of masses from fit of the X_{max} distribution



What is measured?

longitudinal profile with THE FD

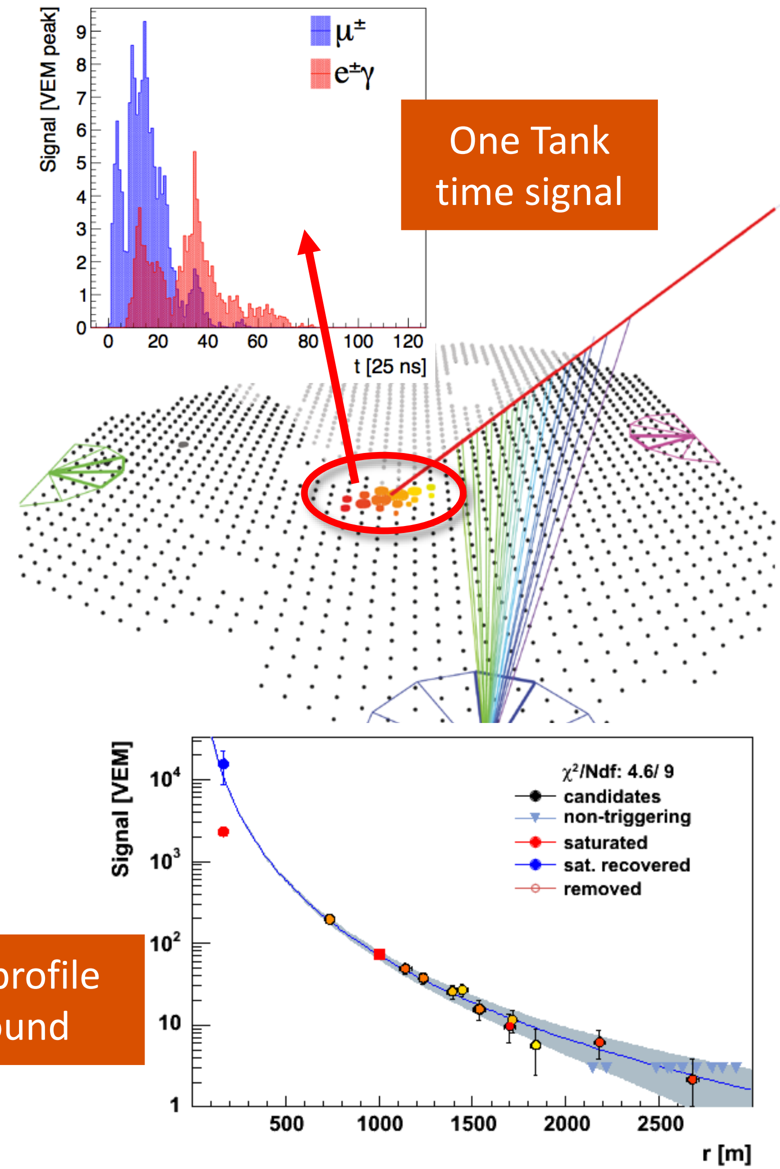
- Direct observation of Xmax and longitudinal evolution

Muon counting with the SD

- It measures both e.m. and muonic particles!
- Muon density at ground
- Temporal structure of SD traces

Complementarity

- Better geometry
- Energy scale of the ground array
- **constrain hadronic interaction models**



Lateral profile on ground

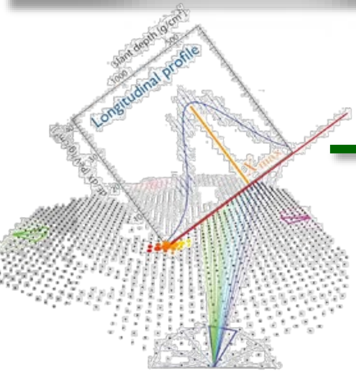
Observing the longitudinal profile with THE FD (telescopes)

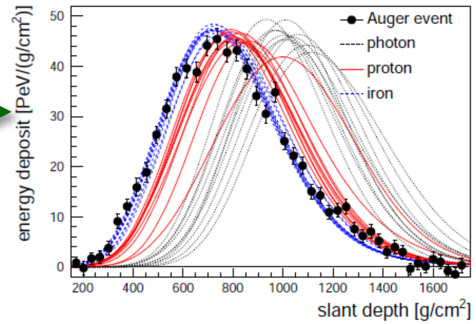
- **X_{max} measurement**
  A. Porcelli for the Pierre Auger Coll., ICRC 2015
  The Pierre Auger Coll., Phys. Rev. D 90, 122005 (2014)

- **Mass composition implications**
  The Pierre Auger Coll., Phys. Rev. D 90, 122006 (2014)

Dominated by the electromagnetic cascade

Depth of shower maximum



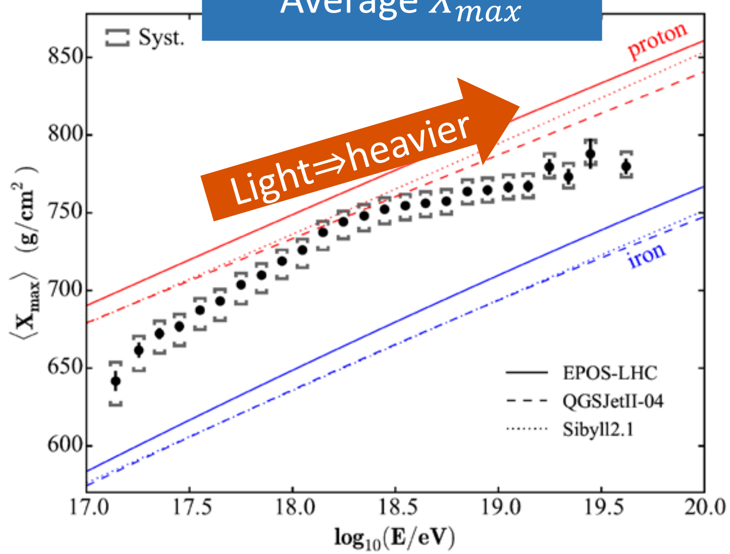


photons protons iron

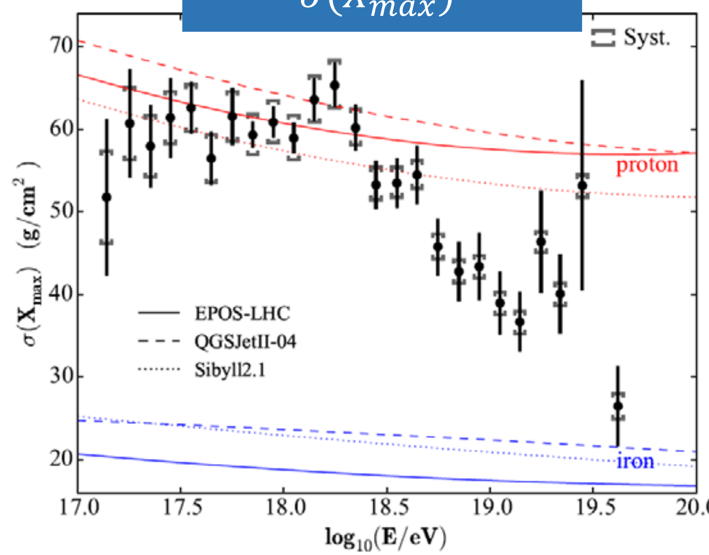
depth of shower

fluctuations

Average X_{max}



$\sigma(X_{max})$



Data better described with a break line than with a linear fit.

Energy break

$$\lg(E_0 / eV) = 18.27 \pm 0.04(stat.)^{+0.06}_{-0.07}(sys.)$$

Elongation rate

Low energy

$$D_{10} = 86.4 \pm 5.0(stat.)^{+3.8}_{-3.2}(sys.) g / cm^2 / decade$$

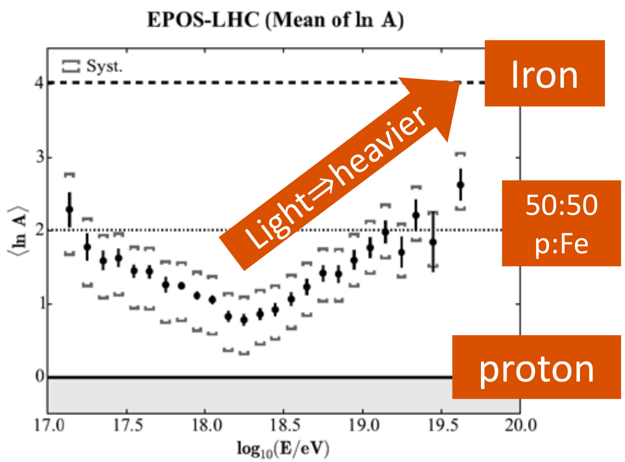
High energy

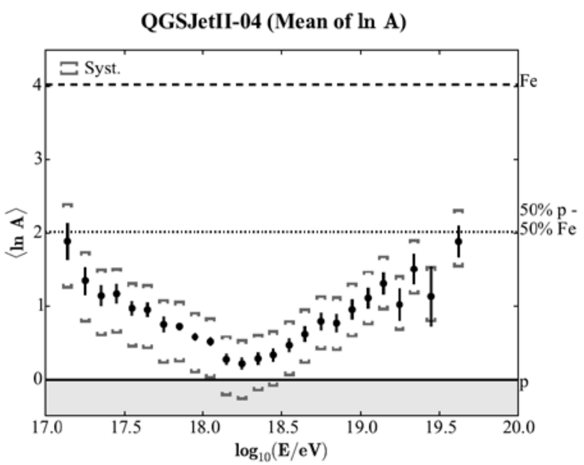
$$D_{10} = 26.4 \pm 2.5(stat.)^{+7.0}_{-1.9}(sys.) g / cm^2 / decade$$

ICRC2015 arXiv:1509.03732

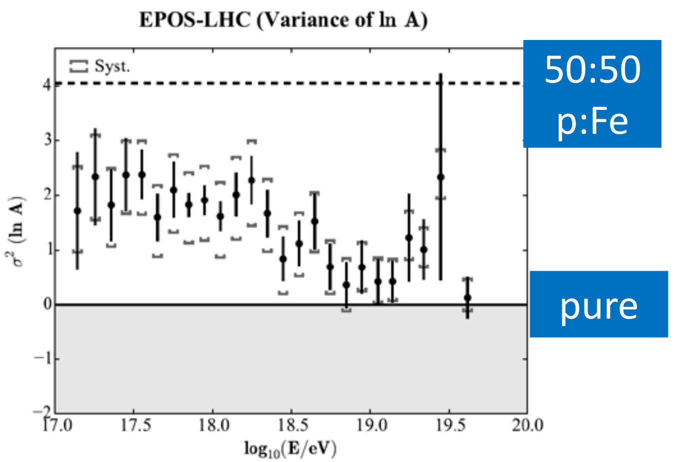
X_{max} interpretation in mass composition

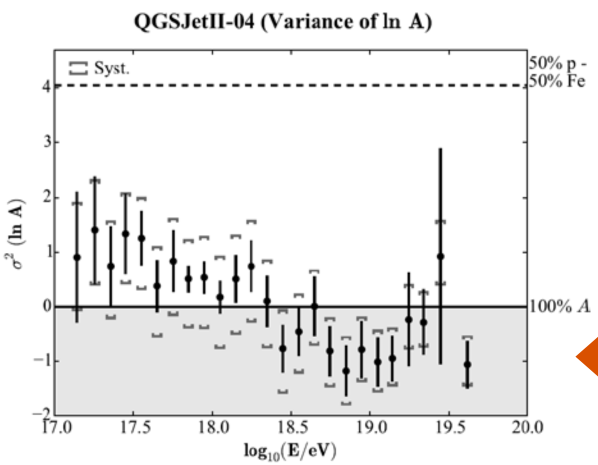
Average composition





Pure or mixed composition?





Unreal values!!!
Not Possible with the model!

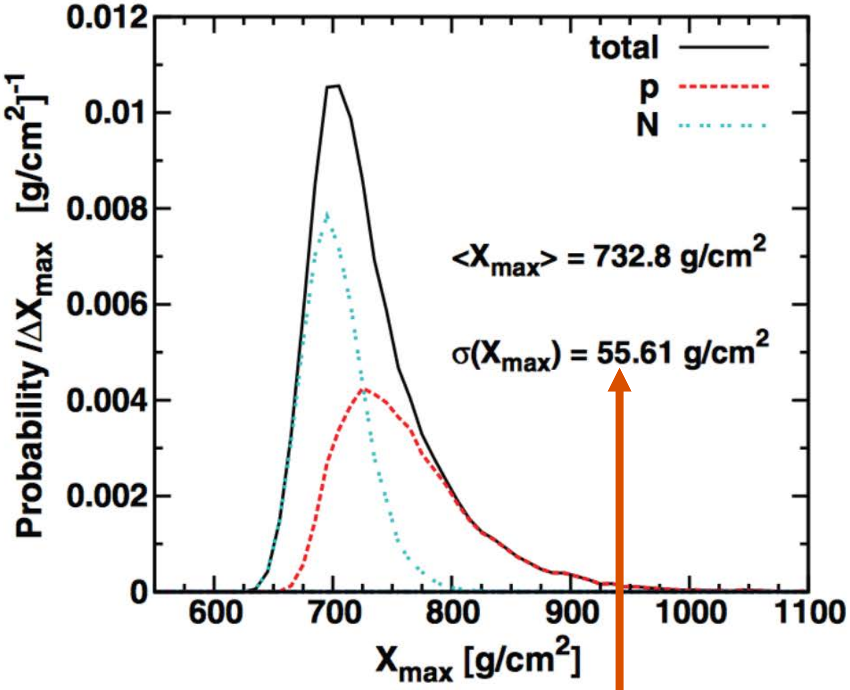
Superposition model

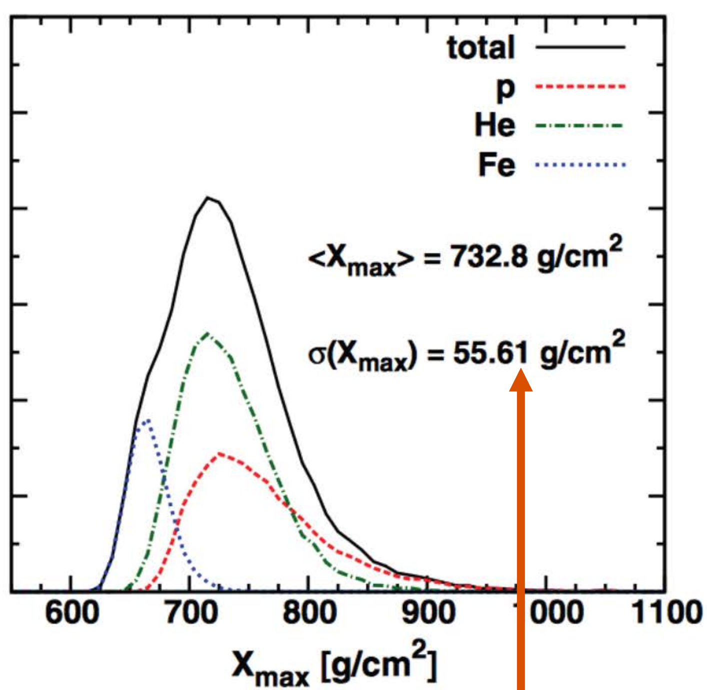
$$\langle X_{max}\rangle \approx \langle X^{p}_{max}\rangle - D_p \langle \ln A\rangle$$

$$\sigma(X_{max})^2 \approx \langle \sigma_i^2\rangle + D_p^2\, \sigma(\ln A)^2$$

V(lnA) measures the purity of the sample

Are the moments of the Xmax distribution enough?

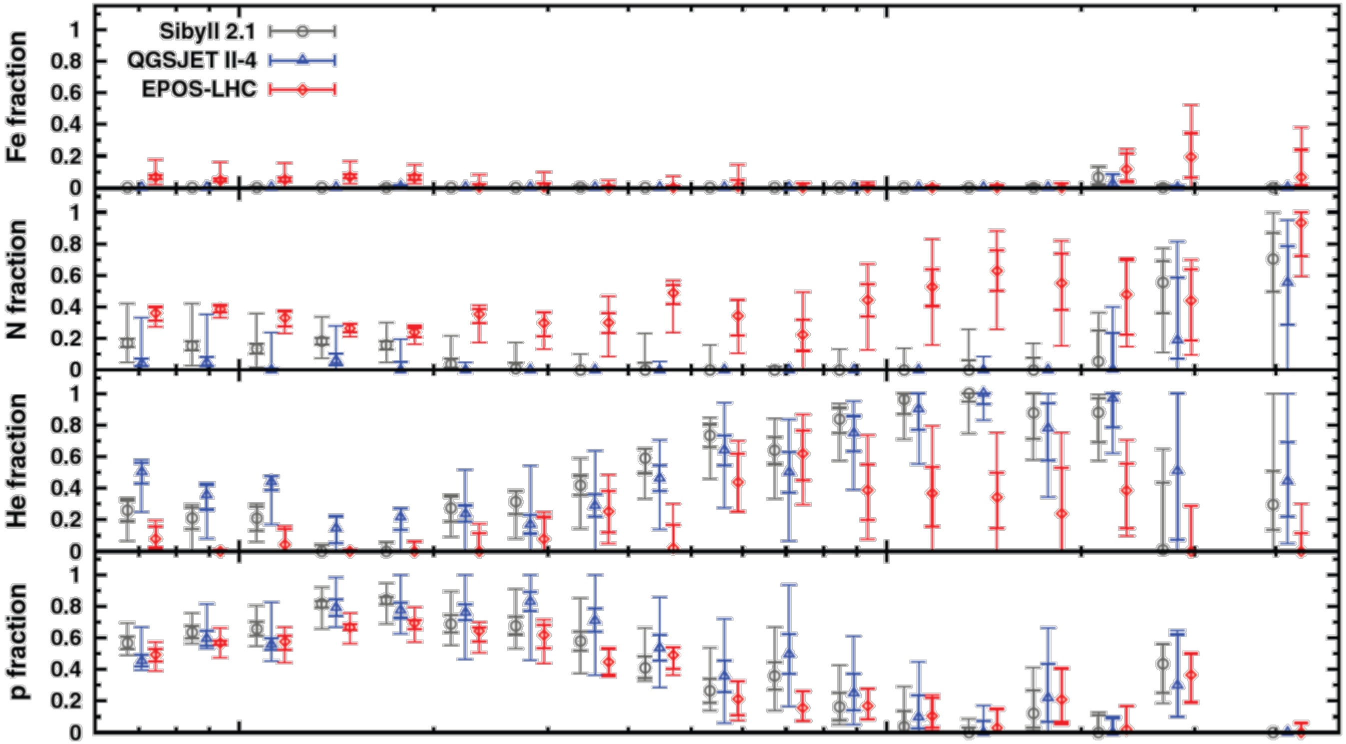




Same X_{max} and $\sigma(X_{max})$ but different mixtures

The X_{max} distribution is compared to MC predictions formed varying nuclear fractions.
A binned maximum-likelihood discriminator is used to choose the best fit fractions.

Interpretation of fitting the X_{max} distributions



Fe

No Iron

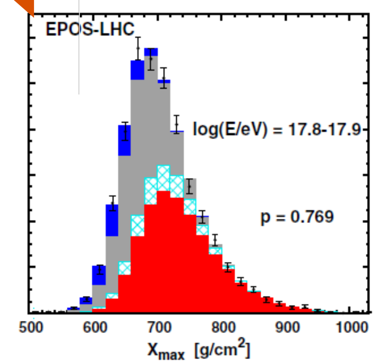
N

Some N with EPOS

He

Transition from p to He !?

p

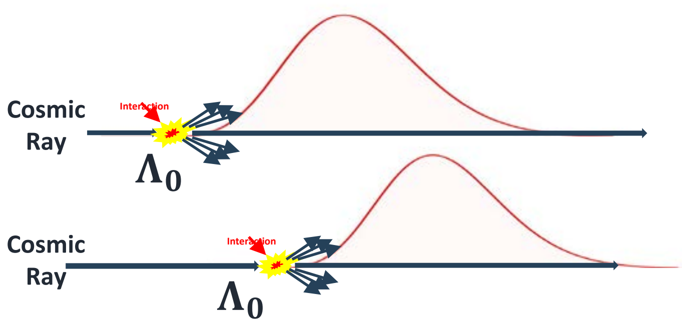


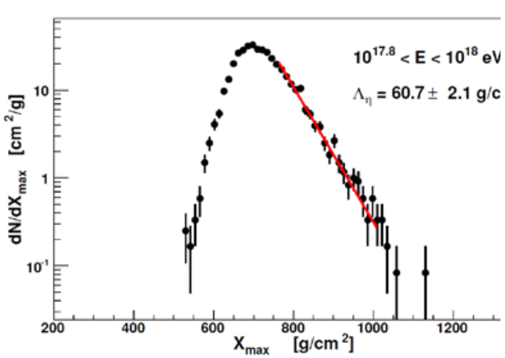
Reasonable agreement with data. EPOS-LHC describes better the data

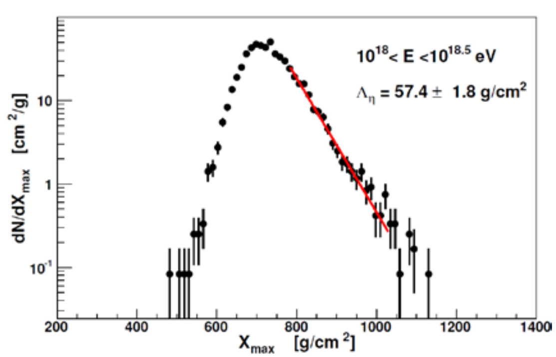
Composition with Pr:Fe and Pr:Fe:N does not reproduce data

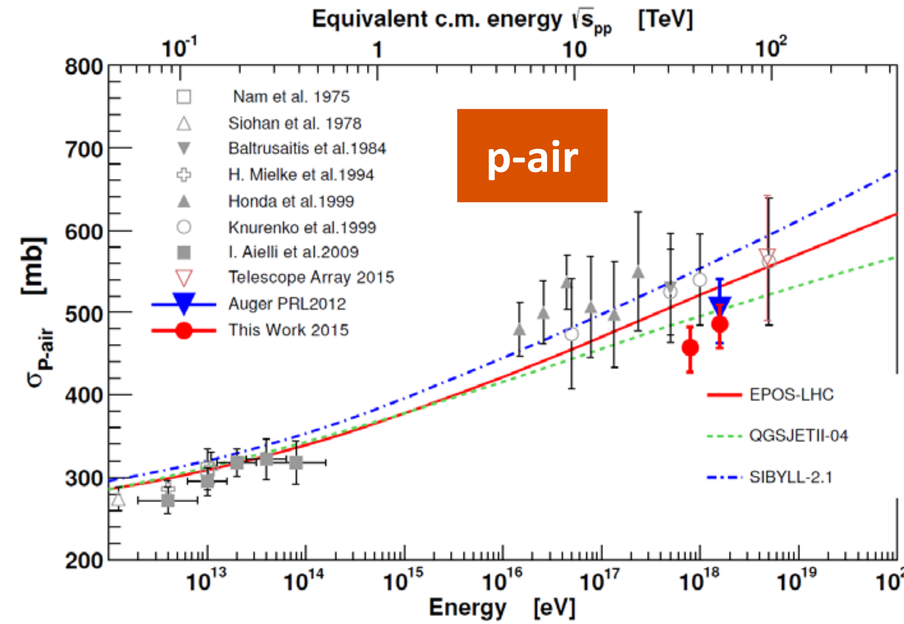
Proton-air Cross-section

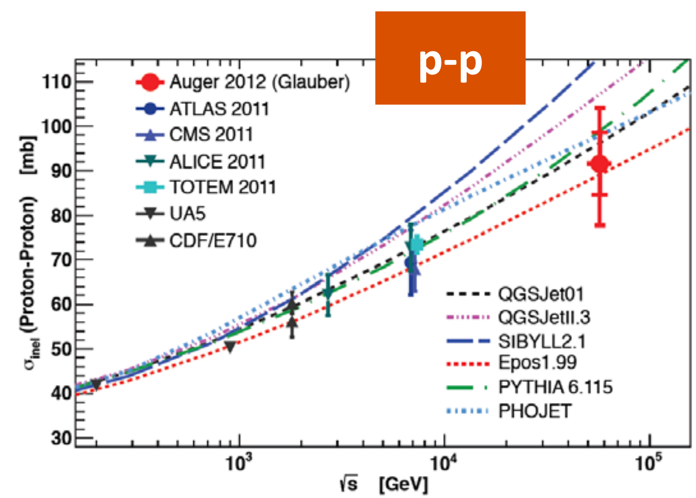
- X_{max} distribution tail is sensitive to the primary cross-section
- If there is enough proton it is possible to measure the p-air cross-section at very high energies
- Using Glauber theory is possible to translate this result into p-p cross-section











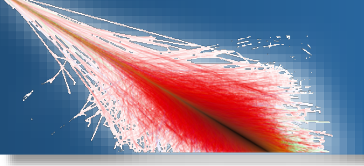
Muon counting with SD

Several indirect measurements:

- **Muon density at ground with horizontal showers (zenith > 60º)**
  L.Collica for the Pierre Auger Coll., ICRC 2015;
  The Pierre Auger Coll., Phys. Rev. D 91, 032003 (2015)

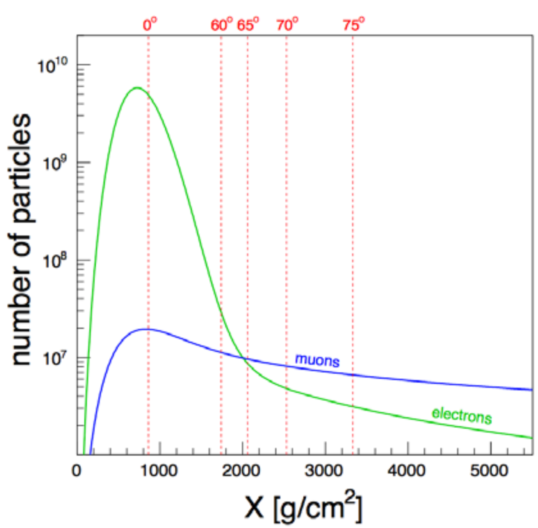
- **Muon Production Depth based on the temporal structure of SD traces**
  L.Collica for the Pierre Auger Coll., ICRC 2015;
  The Pierre Auger Coll., Phys. Rev. D 90, 012012 (2014)

- **Comparison of SD and FD signals in hybrid events (zenith < 60º)**
  L.Collica for the Pierre Auger Coll., ICRC 2015; paper to be published

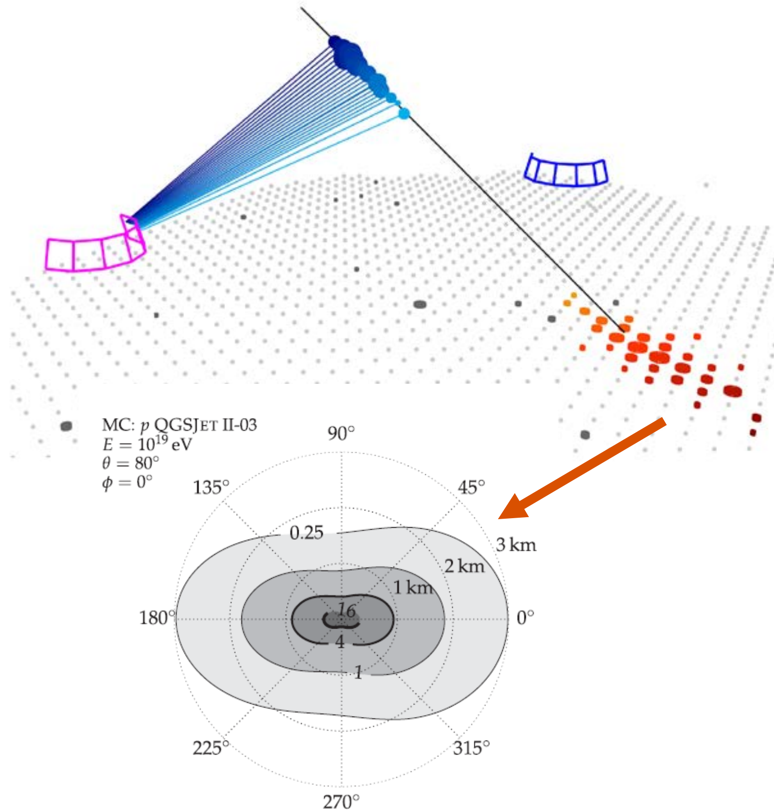


Muon content in air showers

- Muon EAS content is directly related with the hadronic shower component
- Through **inclined showers** is possible to measure directly the muon content (R_{μ}) in the SD
  - Electromagnetic shower component gets attenuated



Inclined hybrid events
($62° < \theta < 80°$ and 4 < E[EeV] < 50)
EM component very suppressed at these angles.
SD signals mainly due to muons.



Reconstruction based on muon density templates

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

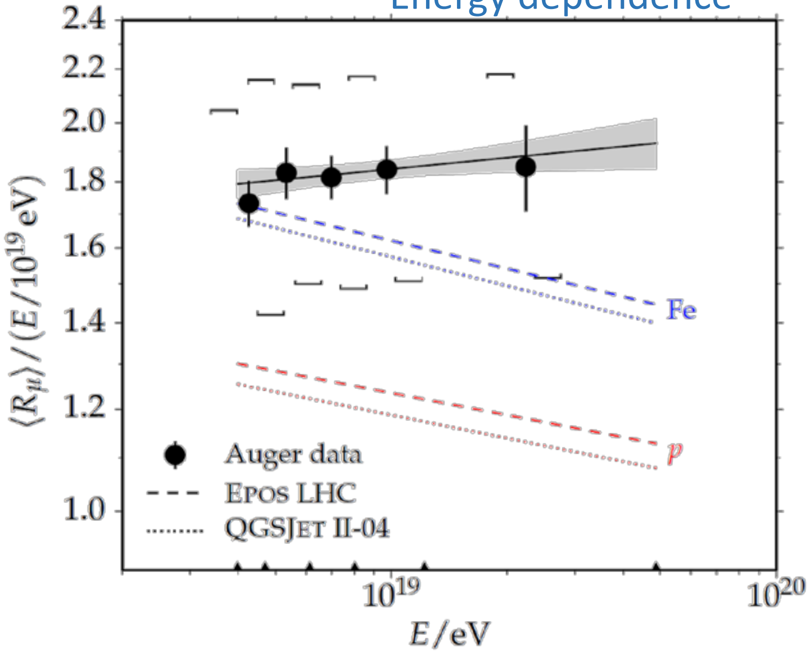
N_{19} muon scale reference value

- Muon EAS content is directly related with the hadronic shower component
- Mean muon number compatible with iron showers within systematic uncertainties

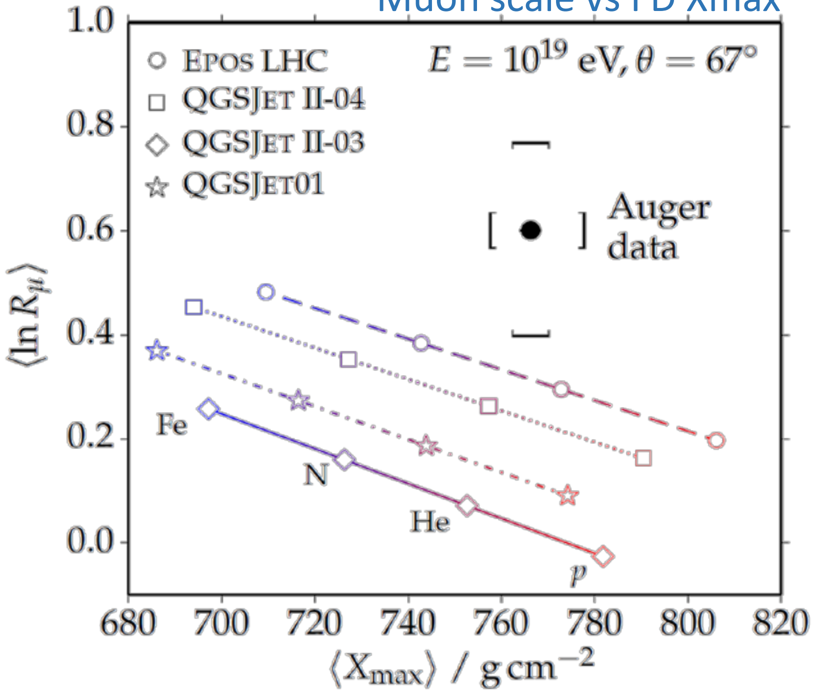
More muons in data than in simulations.
Muon deficit in simulations (from 30% to 80% @ 10^{19} eV depending on models)

Combination of the R_μ with X_{max} shows tension between data and all hadronic interaction models

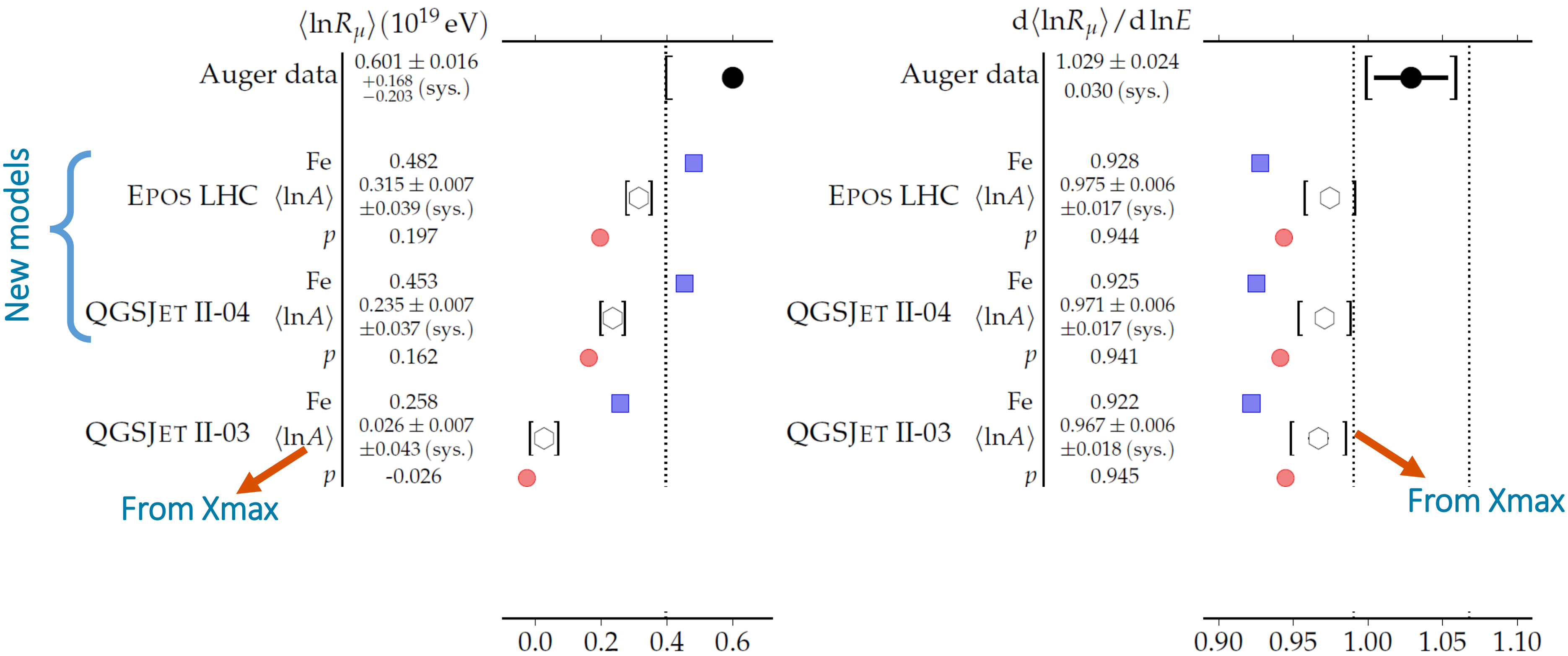
Energy dependence



Muon scale vs FD Xmax



Muon content in air showers



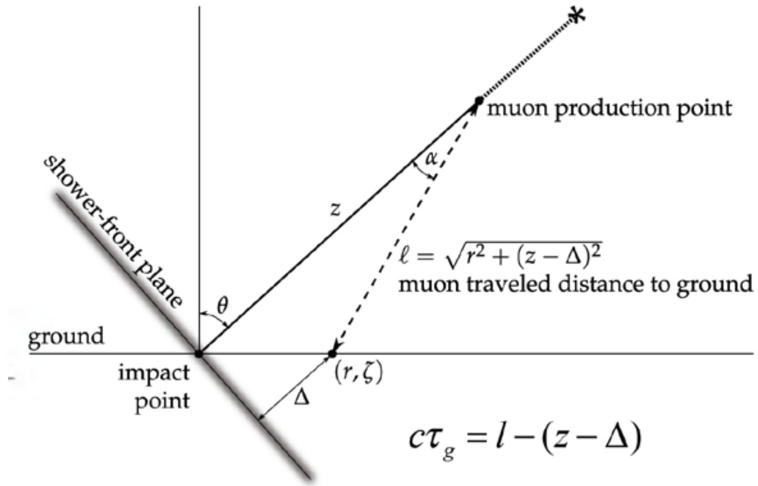
Number of muons not consist with composition coming from longitudinal electromagnetic X_{max}

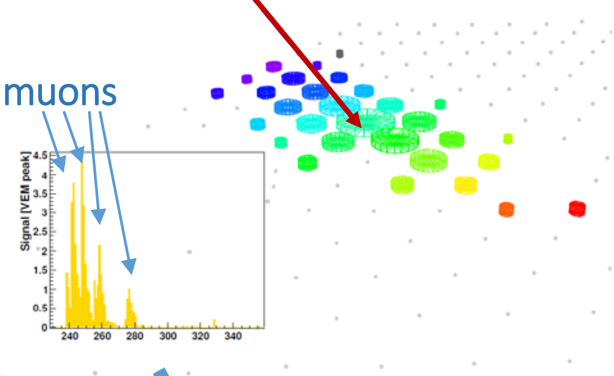
Energy evolution of muons (elongation rate) Not compatible with evolution from electromagnetic X_{max}

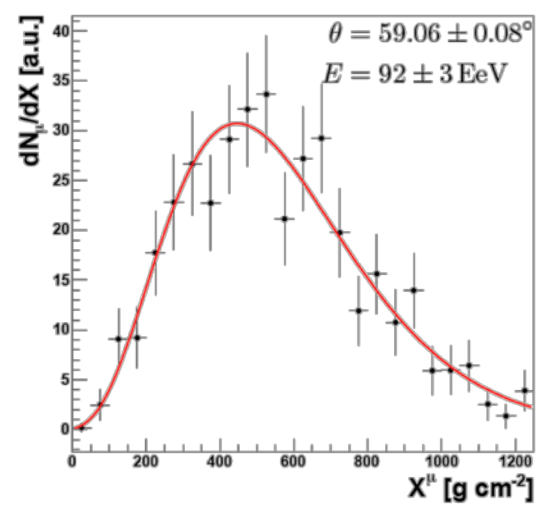
Muon Production Depth (MPD)

Muons at ground carry information about their production point

2 assumptions about muons:
Produced along the shower axis
+ Travel following straight lines at c







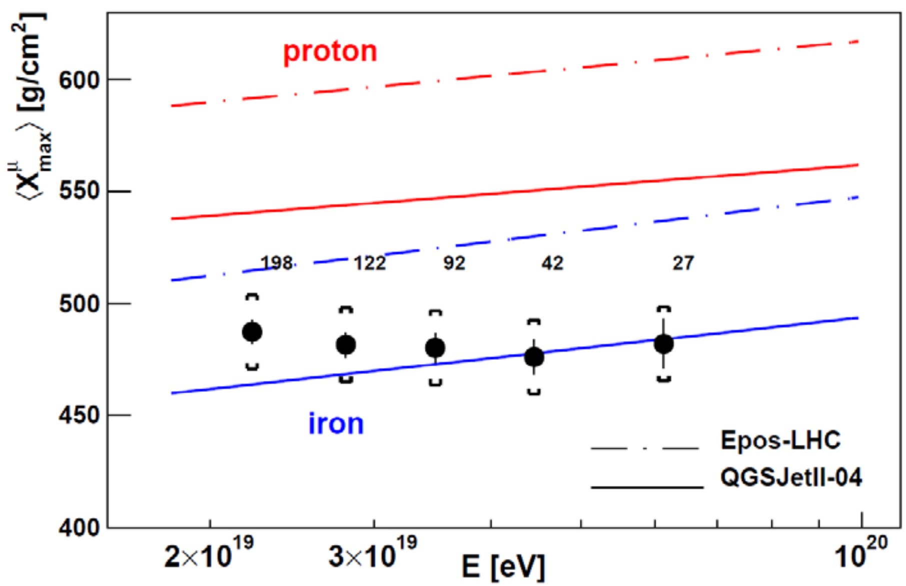
Total time delay measured in SD stations

$\tau[\mathrm{ns}]$ → $z[\mathrm{m}]$ → $X_\mu[\mathrm{g/cm^2}]$

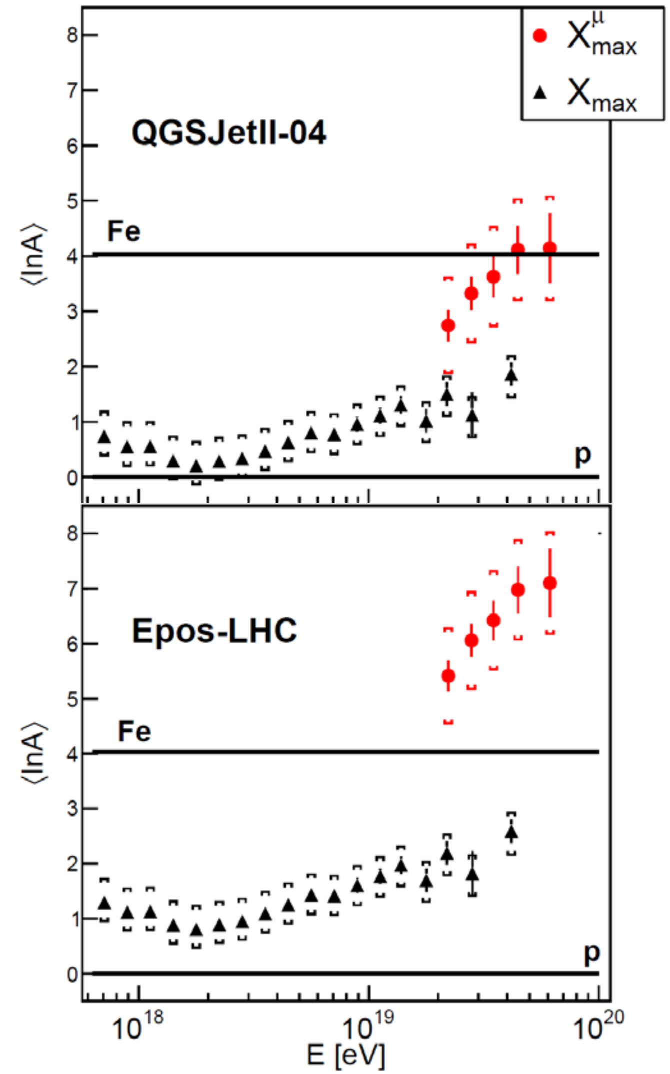
Longitudinal muon production profile!

Muon Production Depth

- Muon production depth is sensitive to composition
- Mean X_{max} and X^{μ}_{max} should give the same average mass composition
- EPOS-LHC fails to provide a consist solution



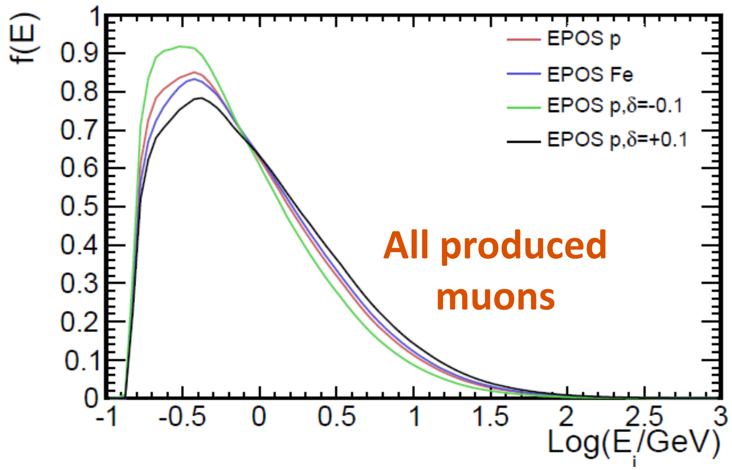
Average composition from muons and e.m.

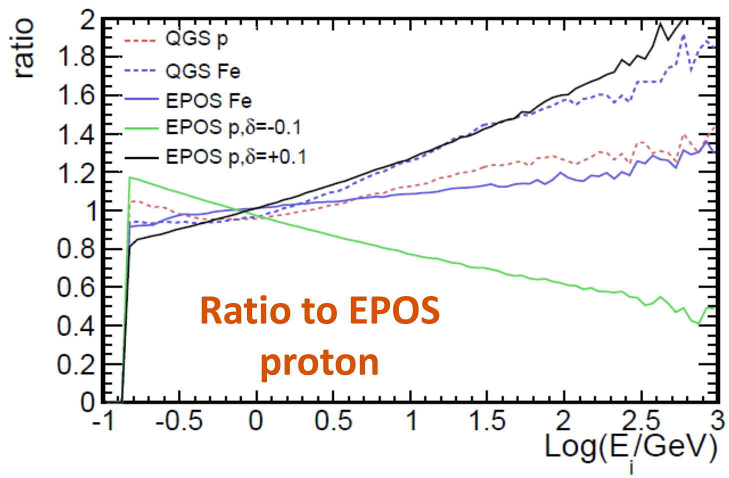


Muon "Grandparents"

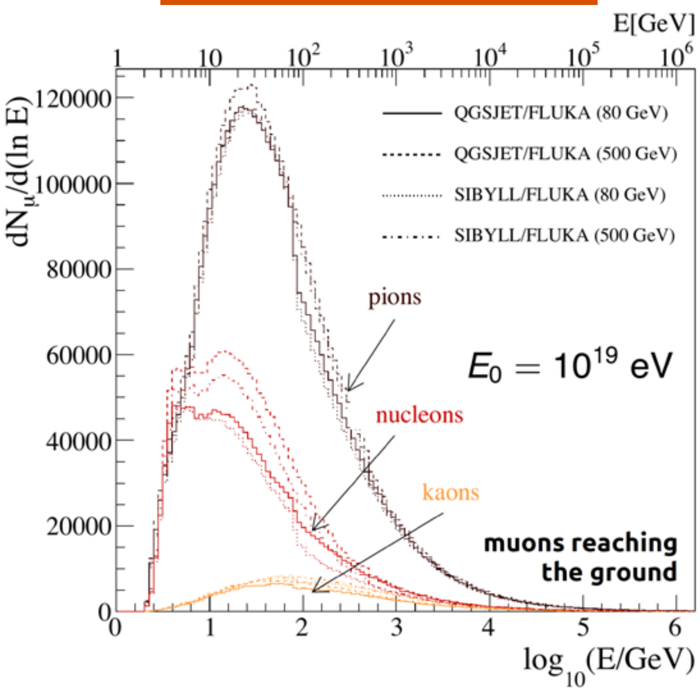
- Muons come mainly from pions
- There are differences on the muon production energy from high and low energy models

Differences in low and high energy models





Origin of the muons

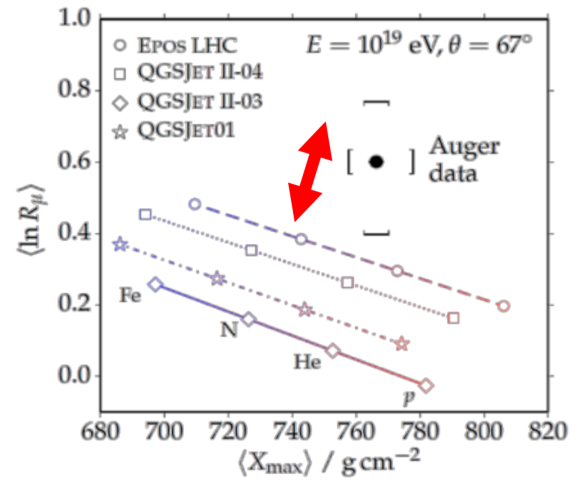


Mariş, ICRC 2009

Summary

Xmax measurement with FD

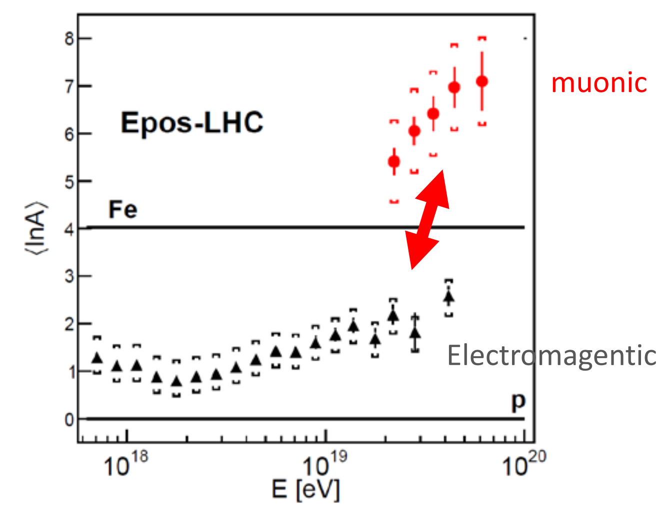
- $\langle X_{max} \rangle$ elongation rate shows a change in the slope from light to heavy composition.
- Data better compatible with Epos-LHC1



Muon content

- <u>Muon deficit</u> in simulations

- <u>Its possible to test EAS models, comparing both contents at the same time</u>
  - Inconsistency between X_{max} and X^{μ}_{max} results
  - Inconsistency in the composition evolution



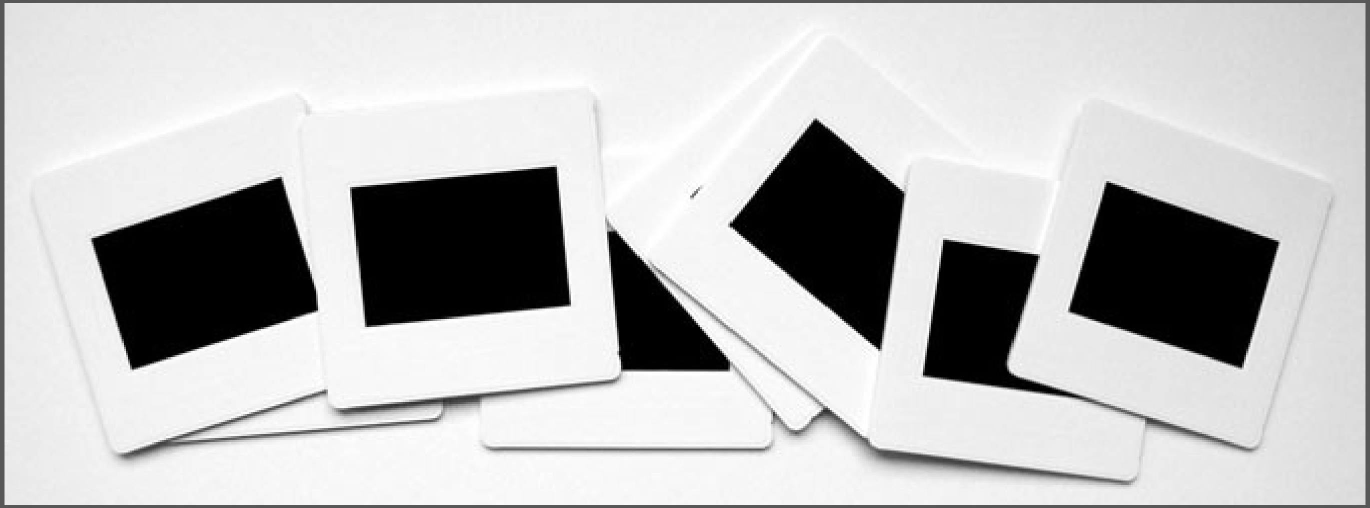
Upgrade: Auger PRIME

- Measure independently the e.m. and muonic component at ground

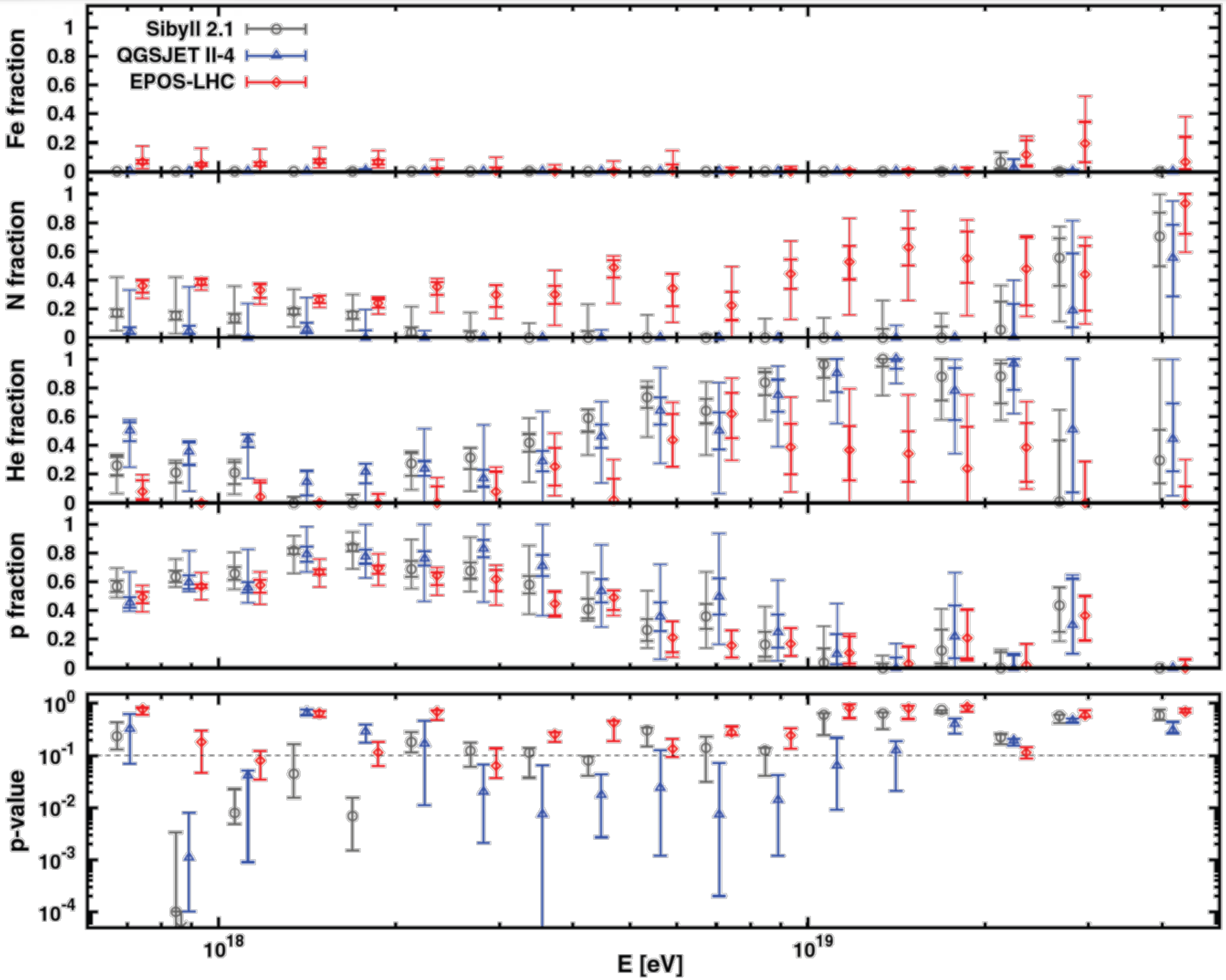
<u>Electromagnetic and muonic development not consistent between data and models</u>

Thank you

Backup slides



Interpretation of fitting the X_{max} distributions

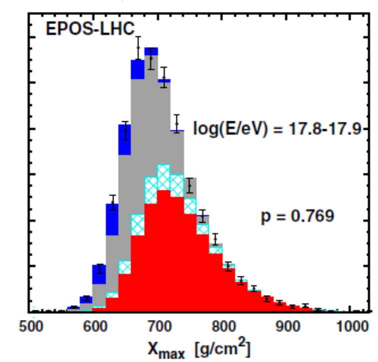


Fe — No Iron

N — Som N with EPOS

He

p — Transition from p to He !?



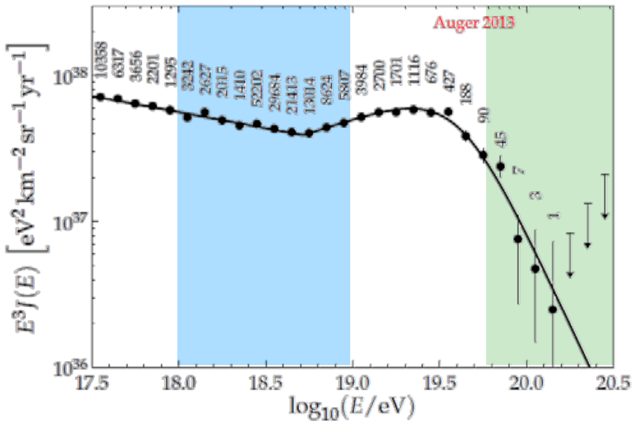
Reasonable agreement with data. EPOS-LHC describes better the data

Composition with Pr:Fe and Pr:Fe:N does not reproduce data

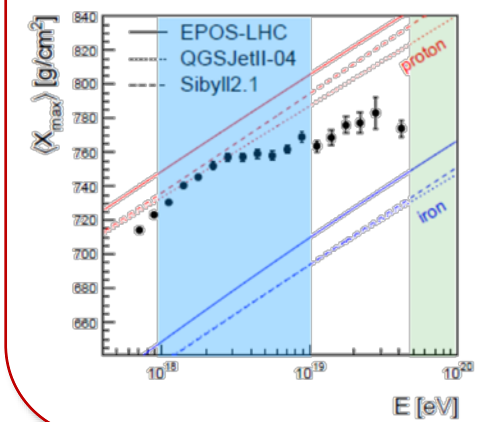
Review

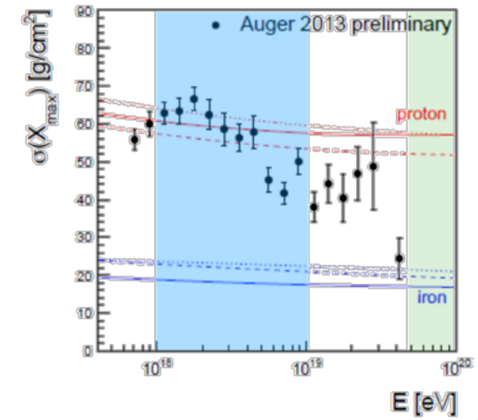
Ankle range
Suppression range

❑ Spectrum

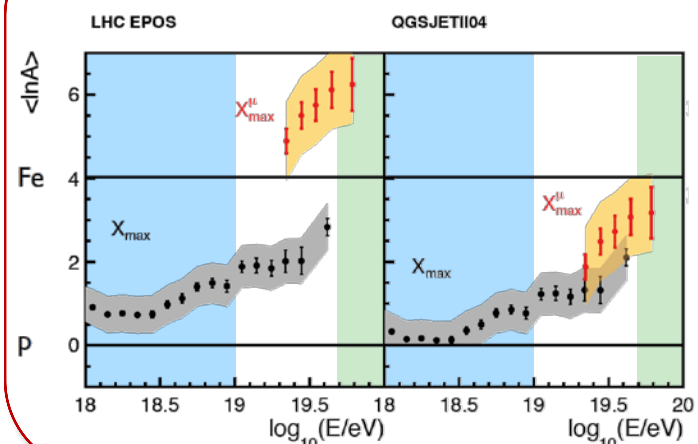


❑ X_{max} and RMS



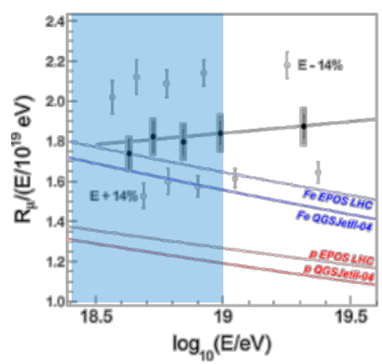


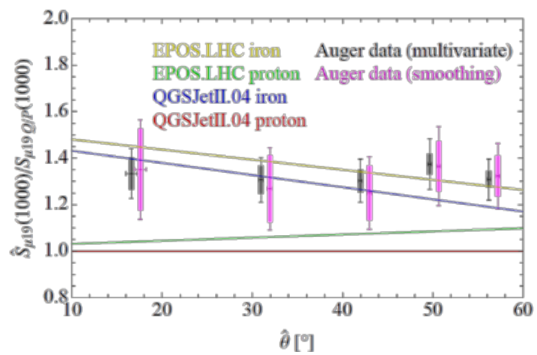
❑ mass composition



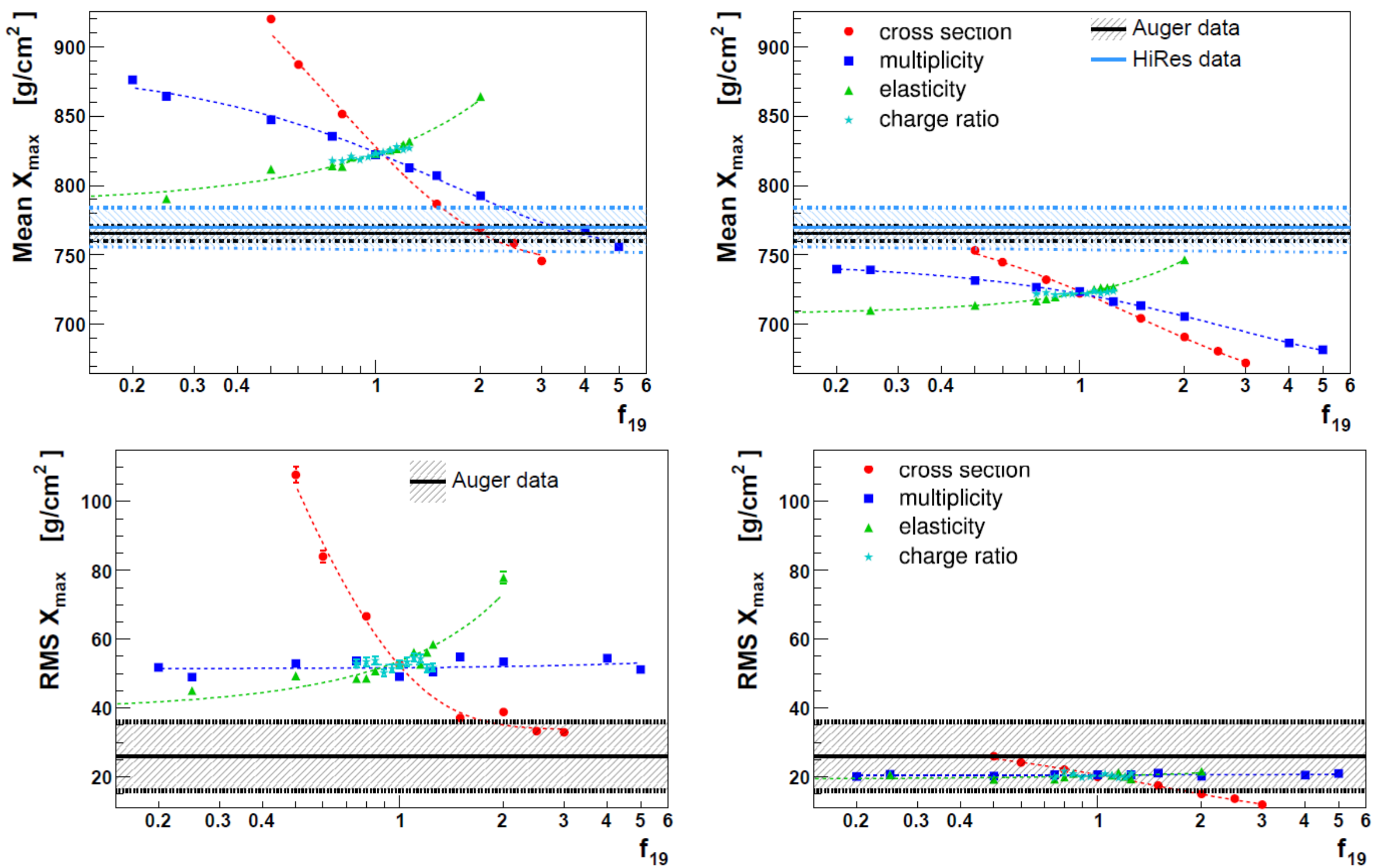
❑ Muon content

10^{19} eV

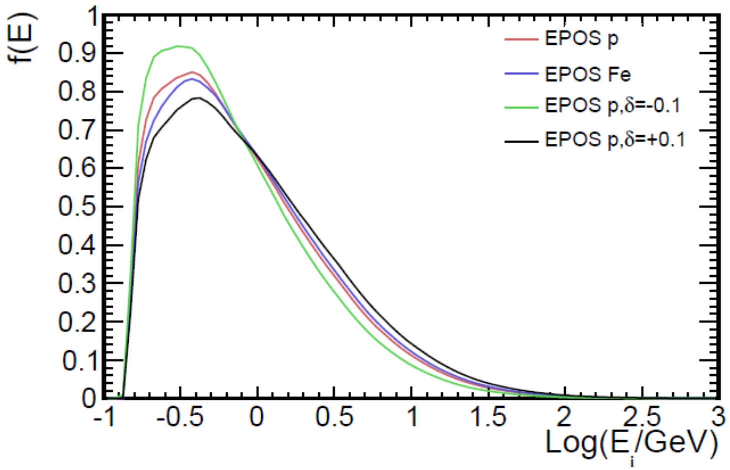


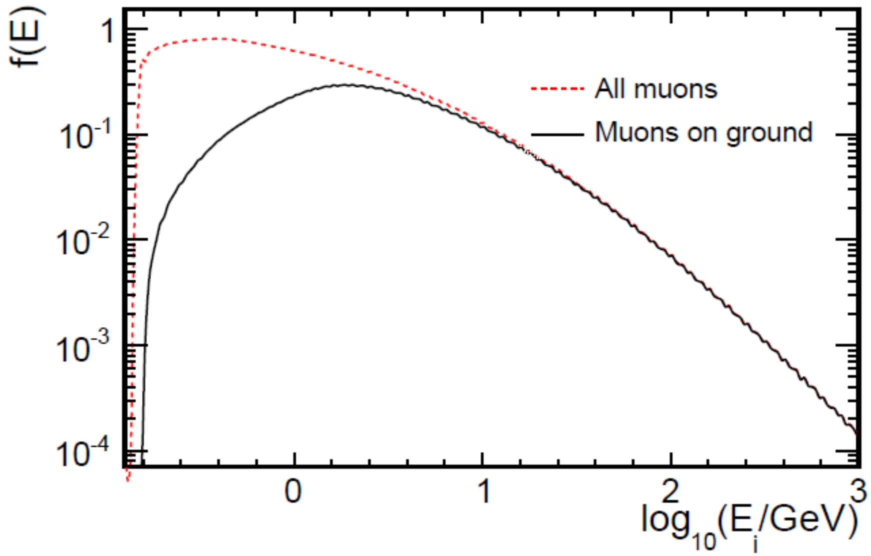


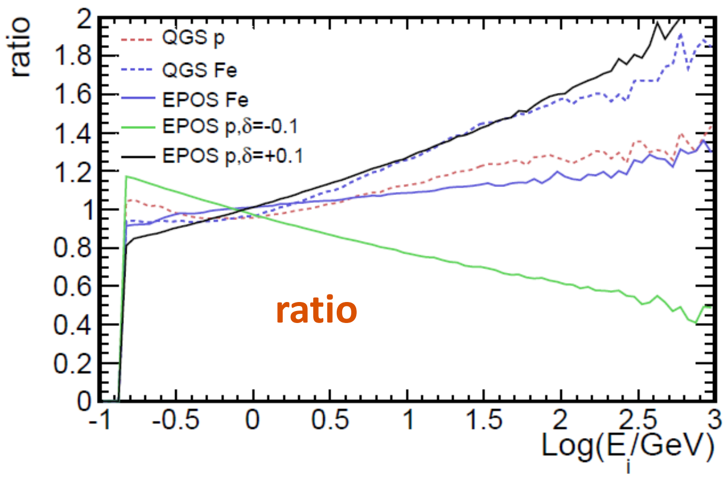
From T. Pierog, Rencontres de Moriond, VHEPU, La Thuille, March 2013;
and doi:10.1088/1742-6596/409/1/012008



R. Ulrich (KIT) with Sibyll model and PAO data @ 1019 eV

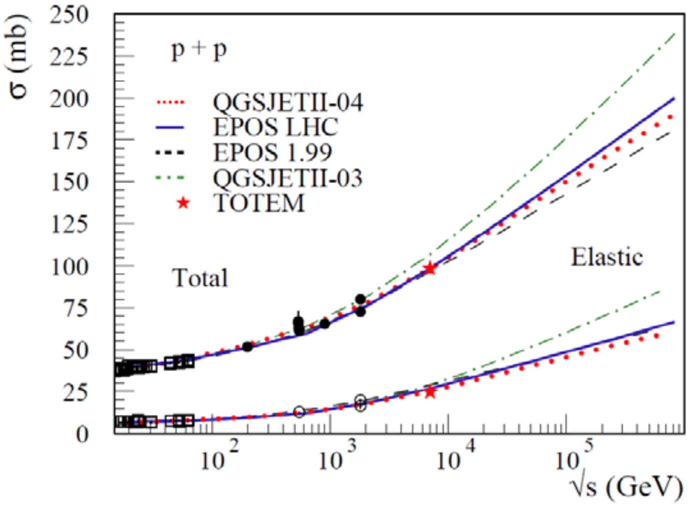


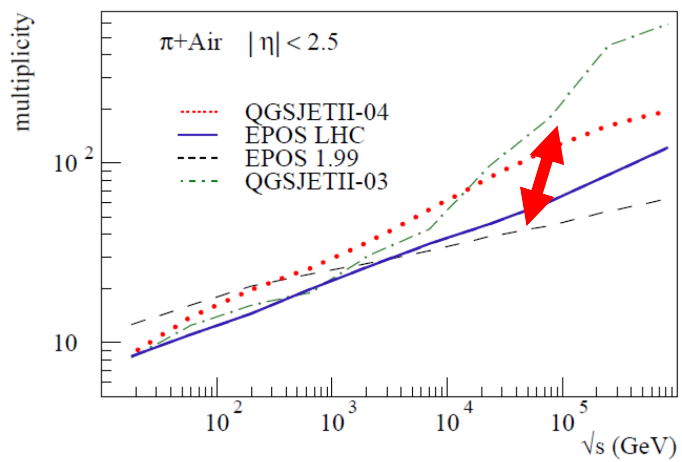




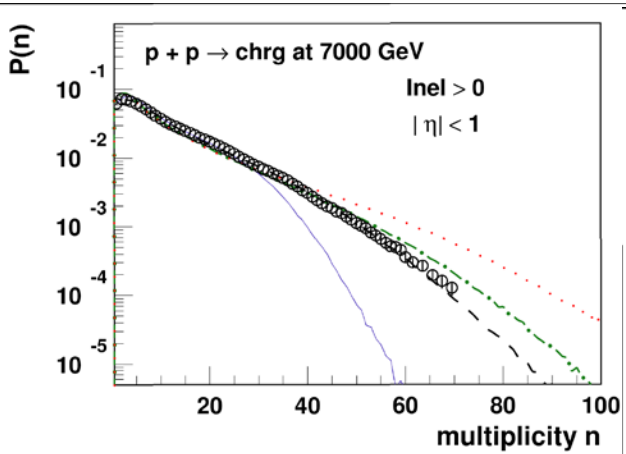
- High uncertainty in the pion+air interactions…

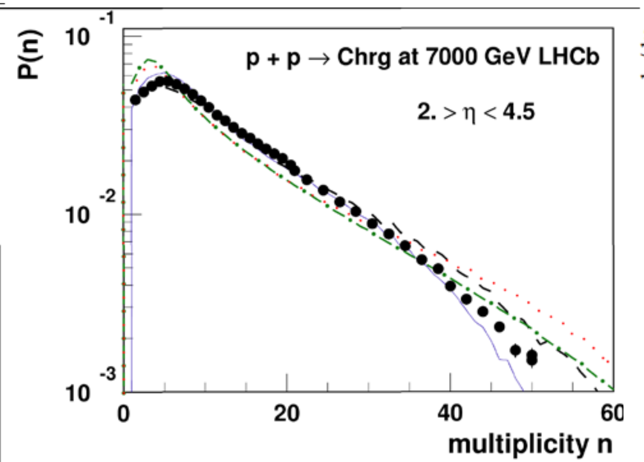
See T. Pierog, Rencontres de Moriond, VHEPU, La Thuille, March 2013; doi:10.1088/1742-6596/409/1/012008

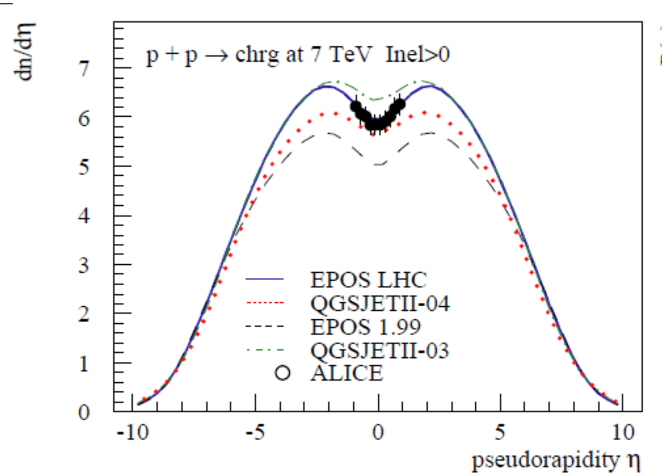


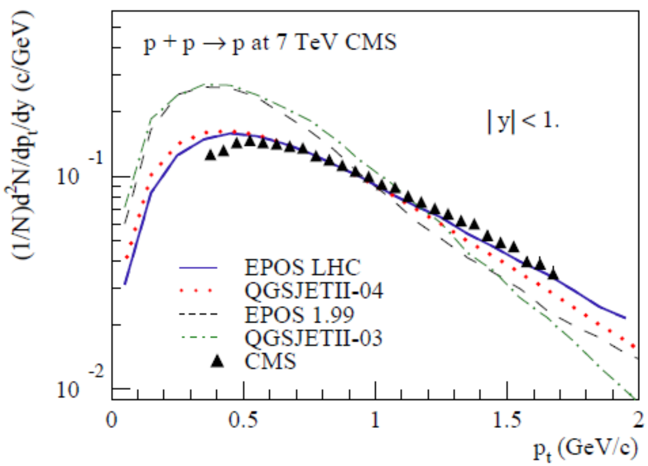


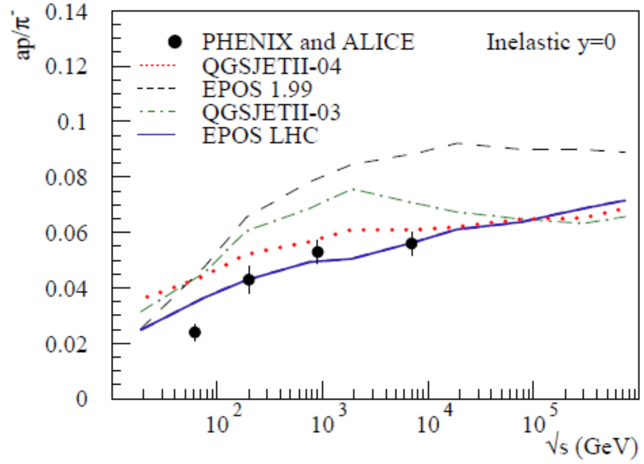
Similar Xmax results for the new models

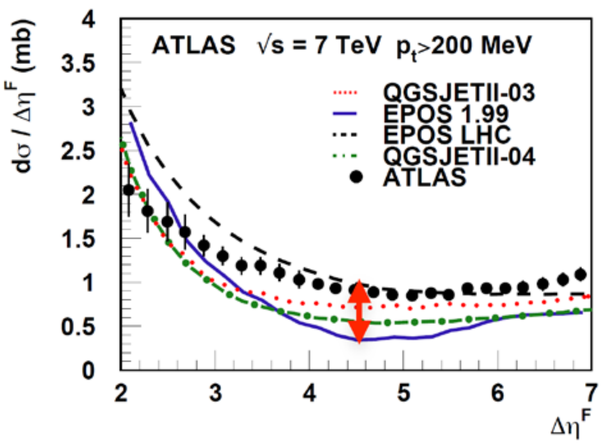




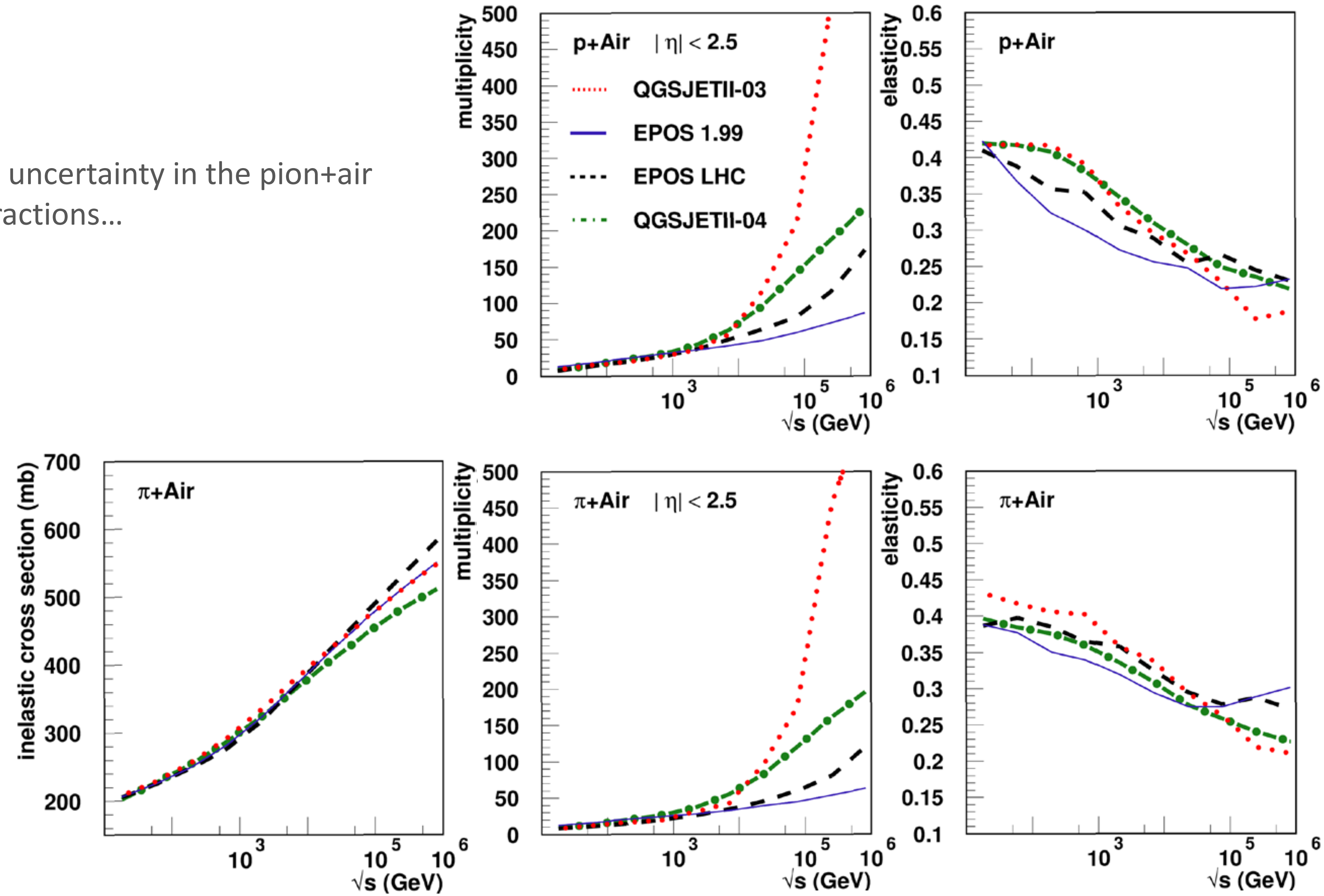



p + p → p at 7 TeV CMS
|y| < 1.
EPOS LHC
QGSJETII-04
EPOS 1.99
QGSJETII-03
CMS
(1/N)d²N/dp_t/dy (c/GeV)
p_t (GeV/c)

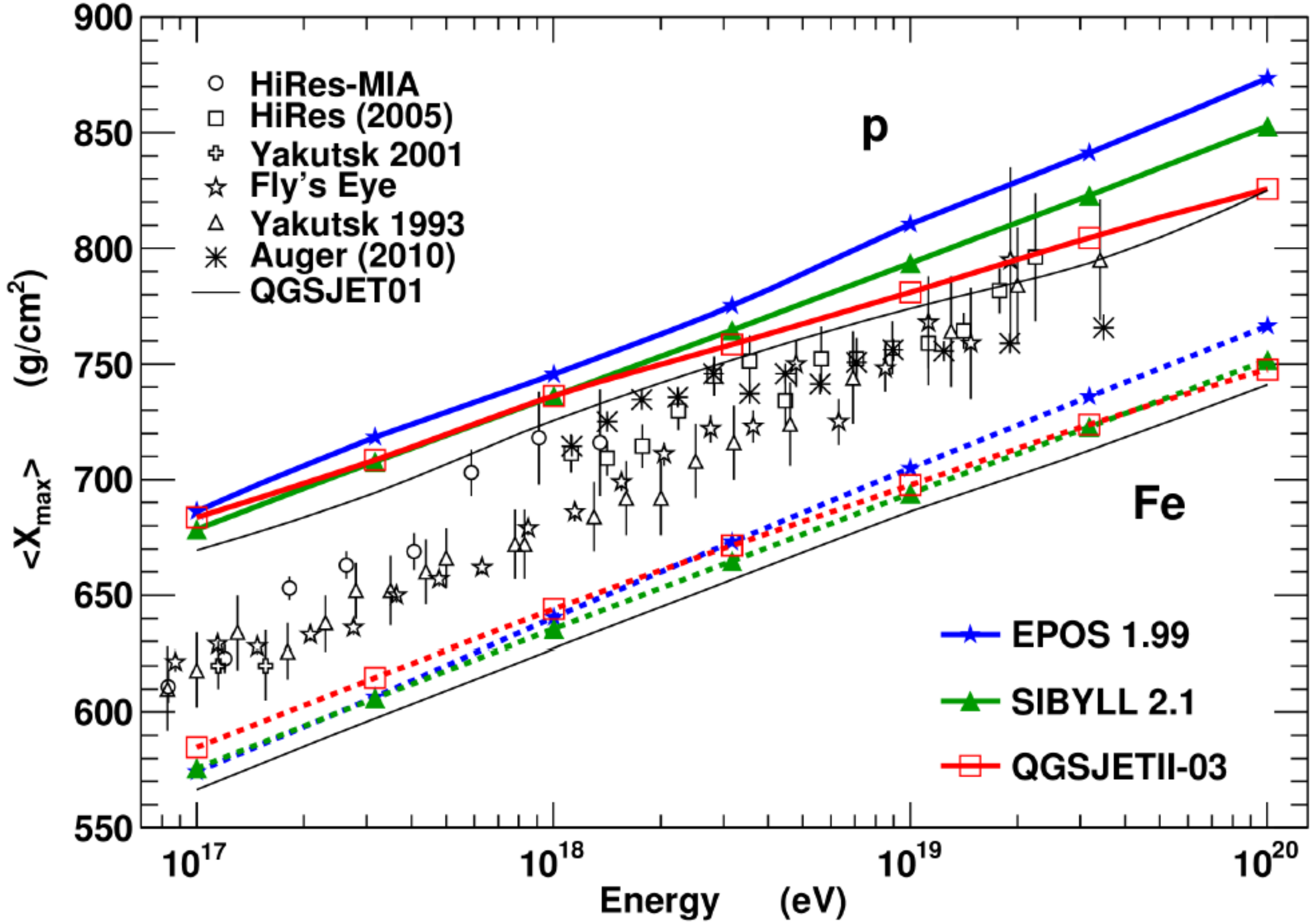

PHENIX and ALICE
Inelastic y=0
QGSJETII-04
EPOS 1.99
QGSJETII-03
EPOS LHC
ap/π⁻
√s (GeV)


ATLAS √s = 7 TeV p_t>200 MeV
QGSJETII-03
EPOS 1.99
EPOS LHC
QGSJETII-04
ATLAS
dσ / Δη^F (mb)
Δη^F

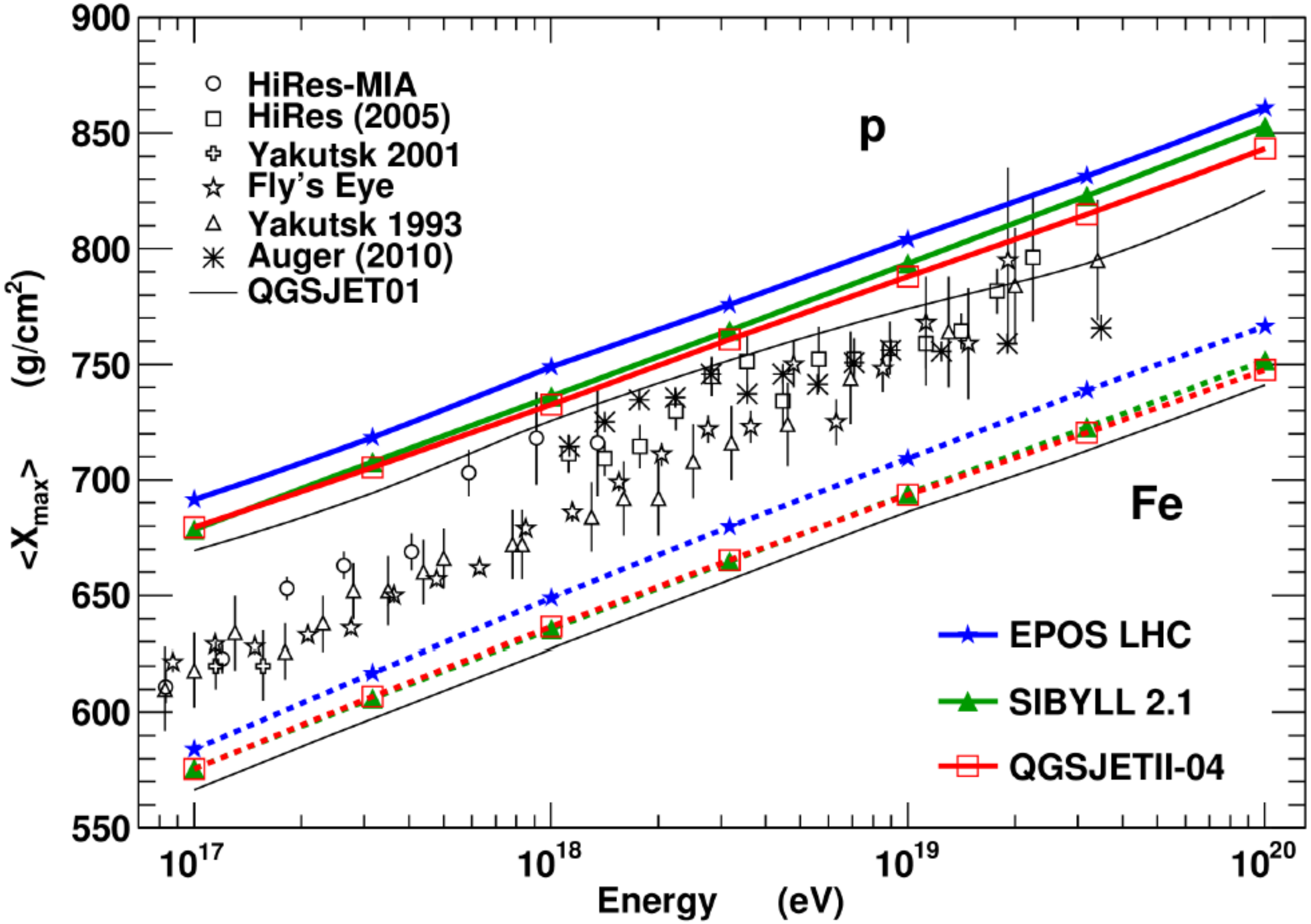
- High uncertainty in the pion+air interactions…



EAS with old CR Models : X_{max}



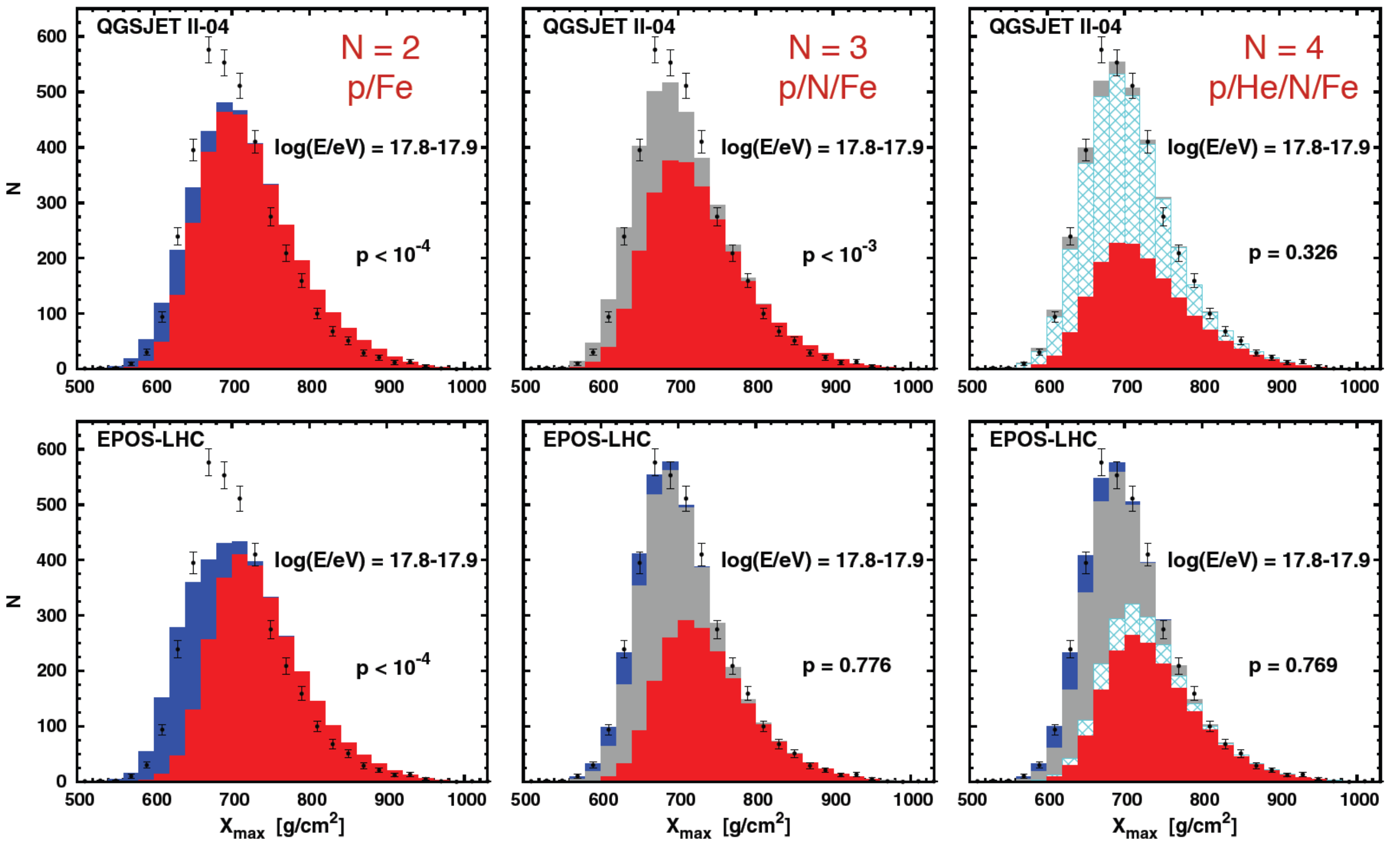
EAS with Re-tuned CR Models : X_{max}



fit the X_{max} distribution with a ***N-components model***

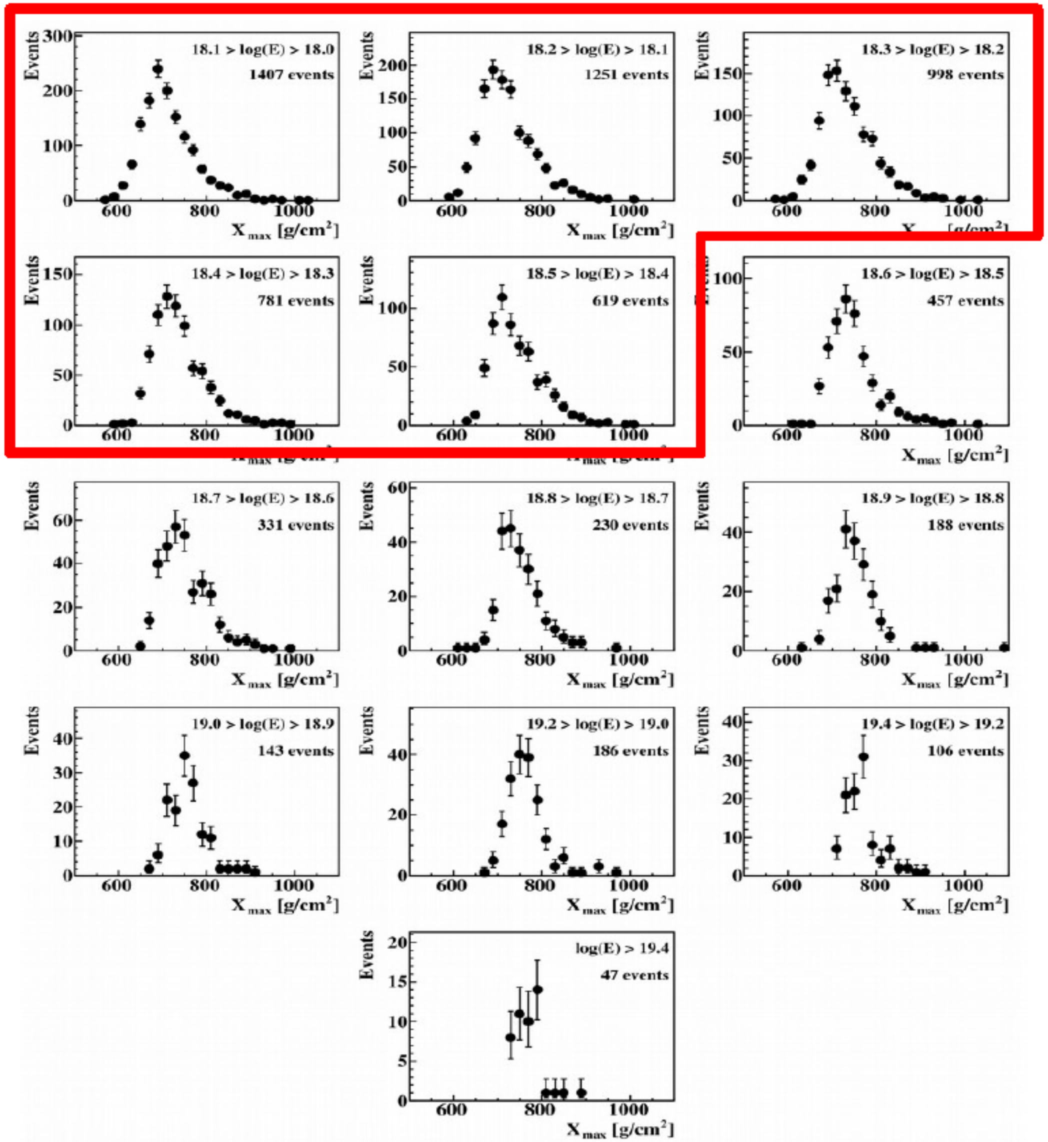
$$C_j = \frac{N_{\rm data}}{N} \sum_s f_s X^{\rm m}_{s,j},$$

fraction of the specie *s*

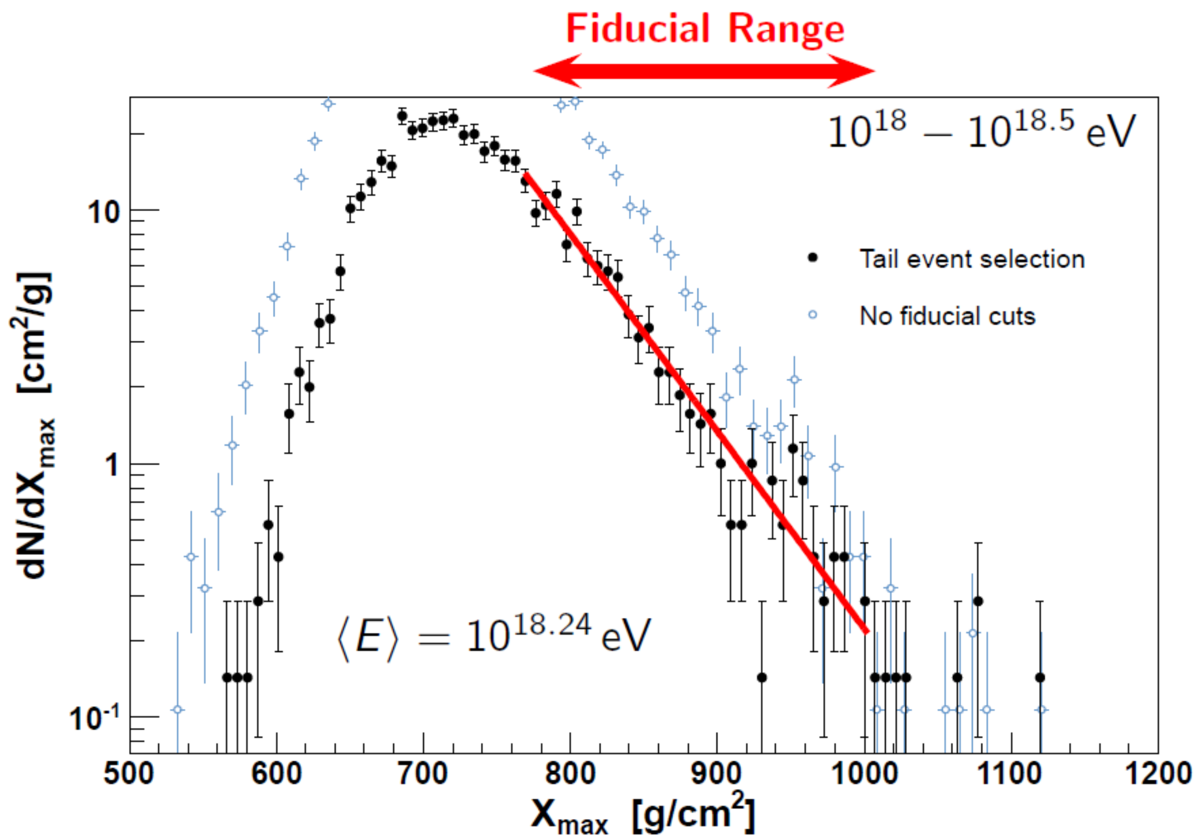


18.0 → 18.5

3082 events

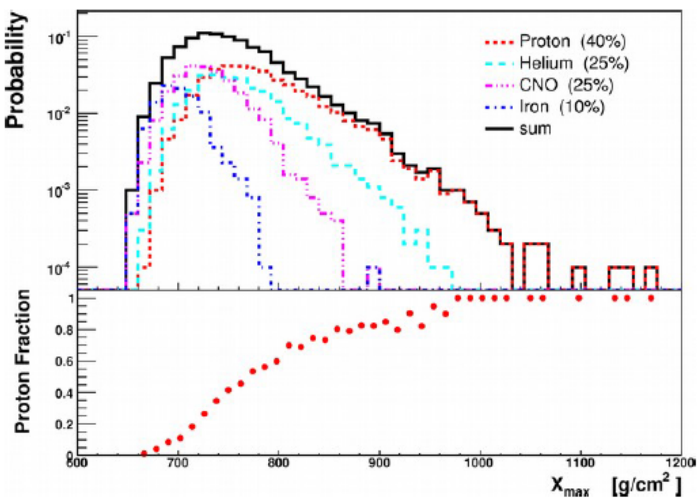


Pedro Facal ICRC2011 arXiv:1107.4804v1

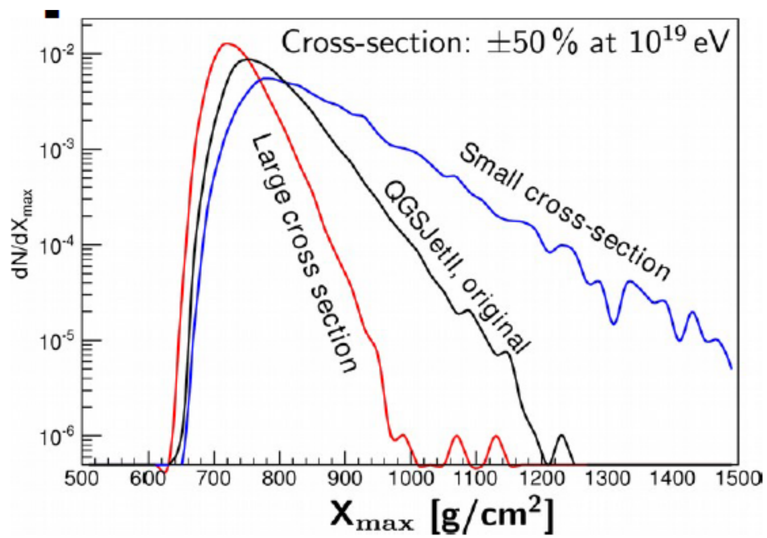


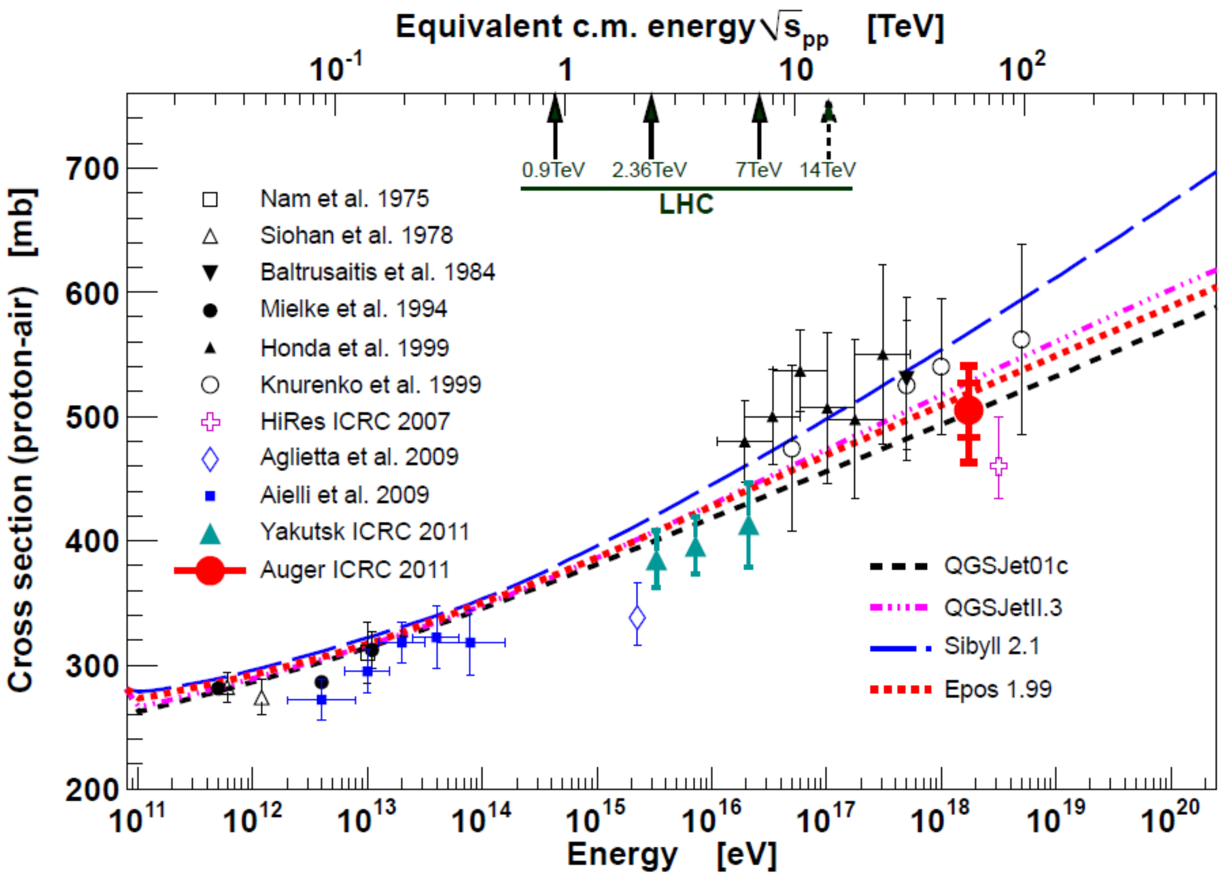
$$\Lambda_\eta = [55.8 \pm 2.3_{\mathrm{stat}} \pm 1.6_{\mathrm{sys}}]\,\mathrm{g/cm^2}$$

Pierre Auger Collaboration arXiv:1208.1520v2 ; Ralf Ulrich ICRC2011 arXiv:1107.4804v1



mixed composition: tail *p* dominated



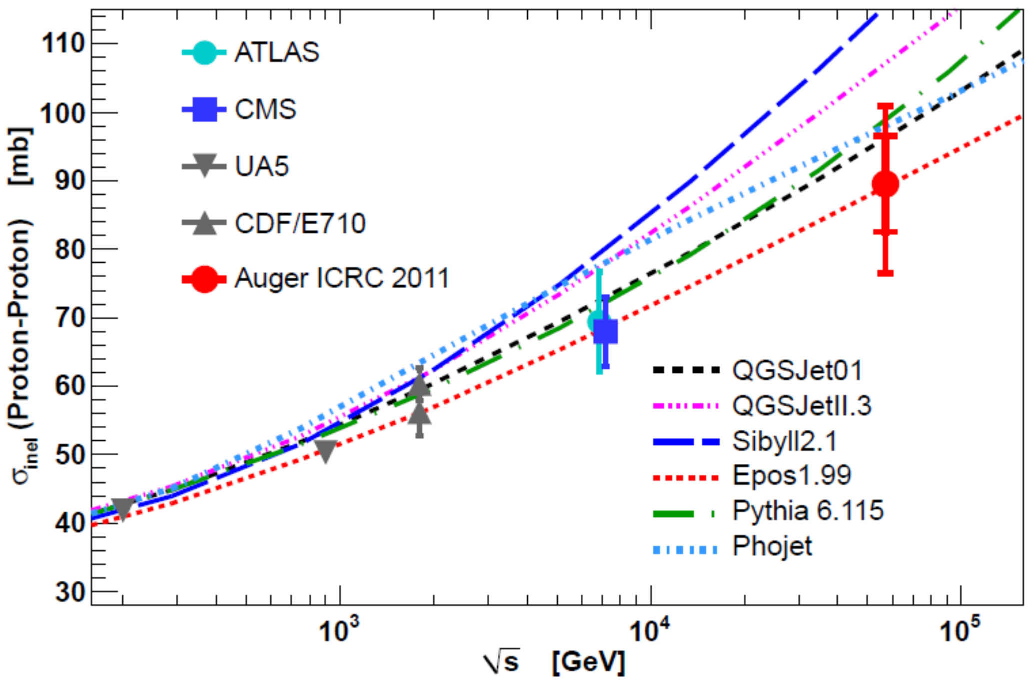


At 57 TeV

$$\sigma_{p-air} = 505 \pm 22(stat)^{+28}_{-36}(syst)mb$$

$$\sigma^{inel}_{p-p} = 92 \pm 7(stat)^{+9}_{-11}(syst) \pm 7(Glauber)mb$$

Pierre Auger Collaboration arXiv:1208.1520v2 ; Ralf Ulrich ICRC2011 arXiv:1107.4804v1



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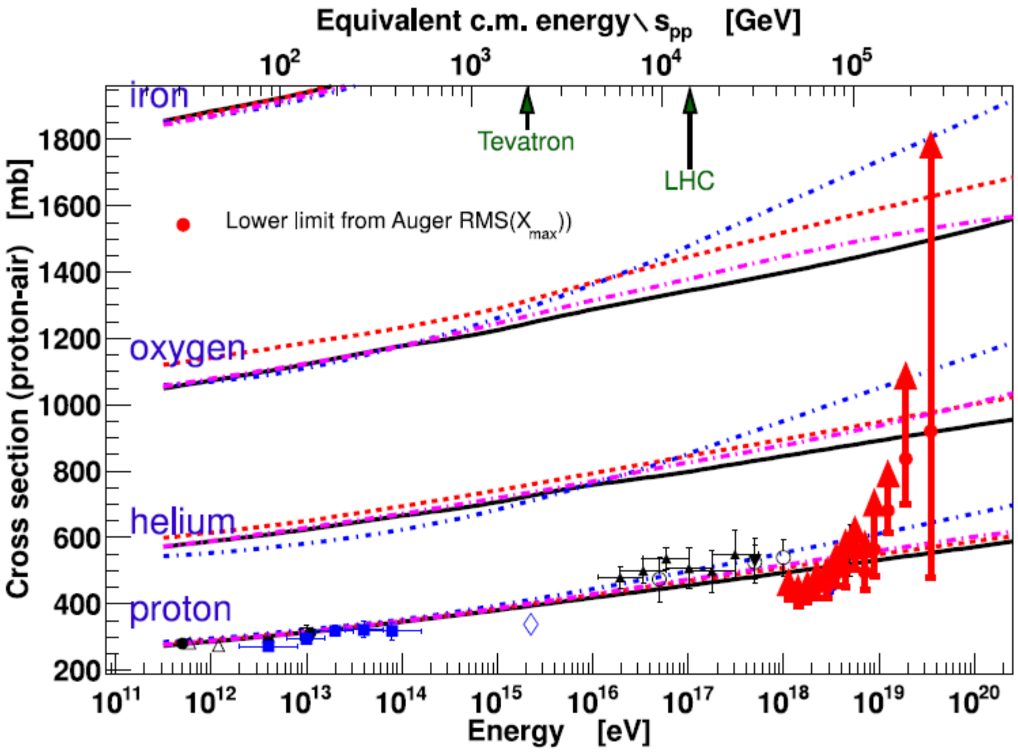
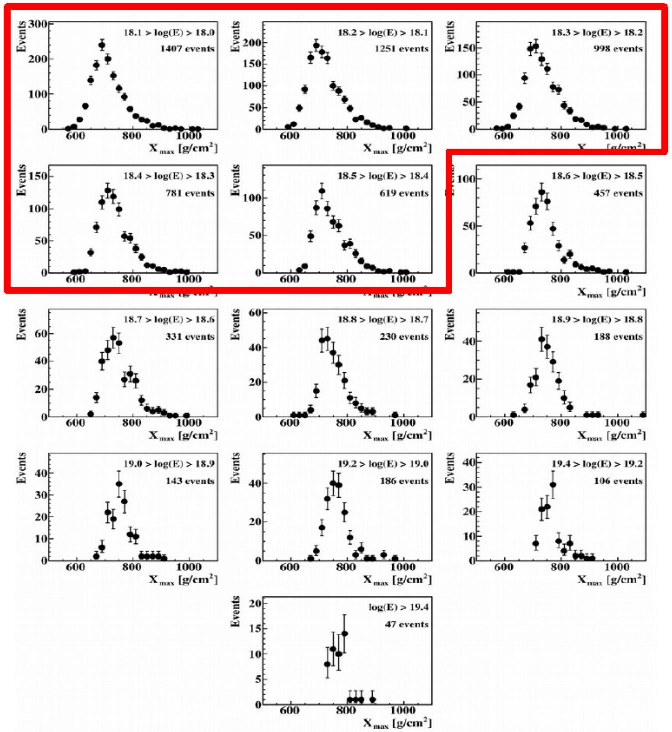
Pierre Auger Collaboration arXiv:1208.1520v2 ; Ralf Ulrich ICRC2011 arXiv:1107.4804v1

$$RMS(X_1) = \lambda_{\text{int}} = \sqrt{RMS(X_{\max})^2 - RMS(\Delta X)^2} < RMS(X_{\max})$$

$$\sigma_{\text{int}} > \langle m_{\text{air}} \rangle / RMS(X_{\max})$$





At 57 TeV

$$\sigma_{p-air} = 505 \pm 22(stat)^{+28}_{-36}(syst)mb$$

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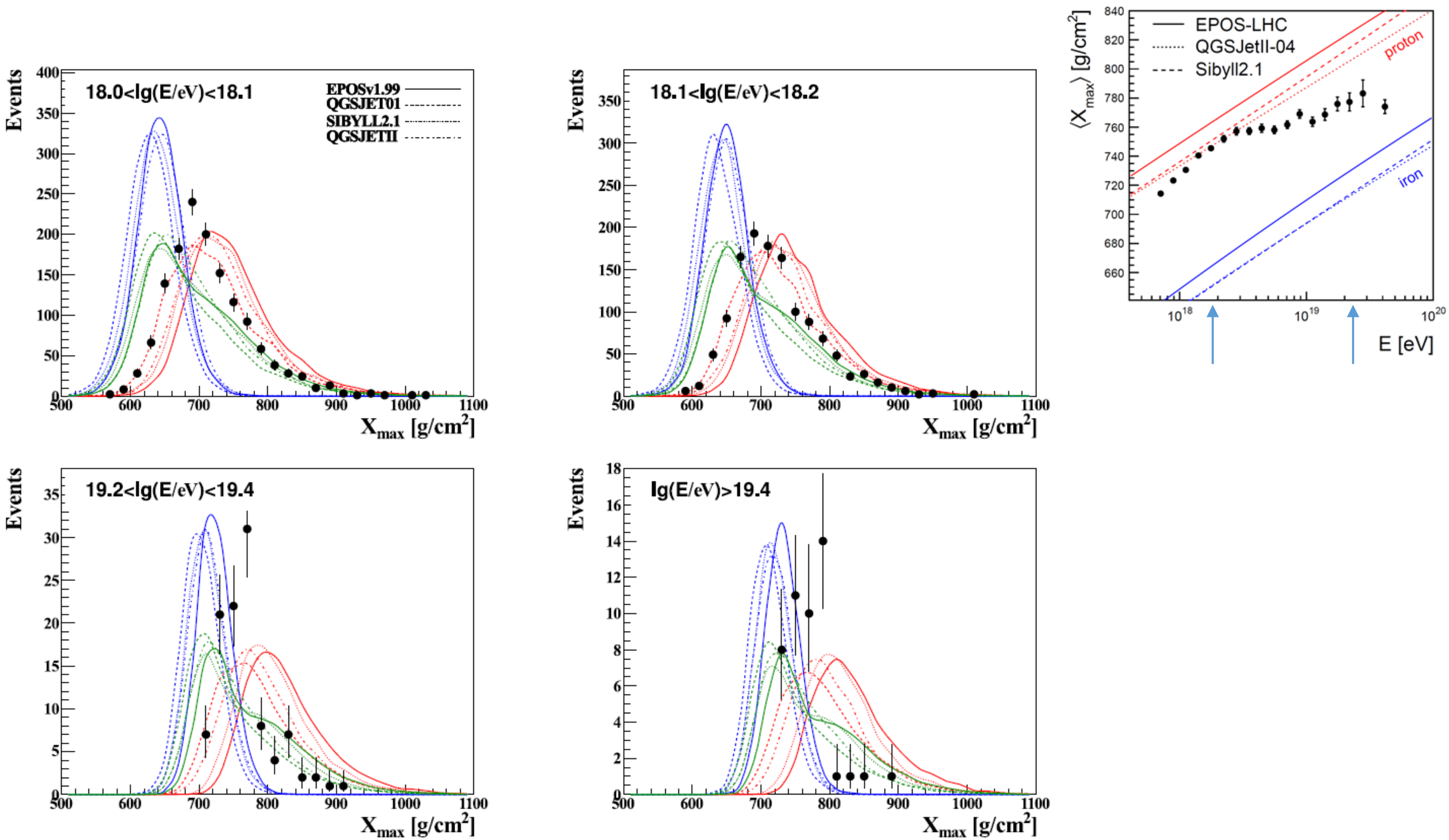
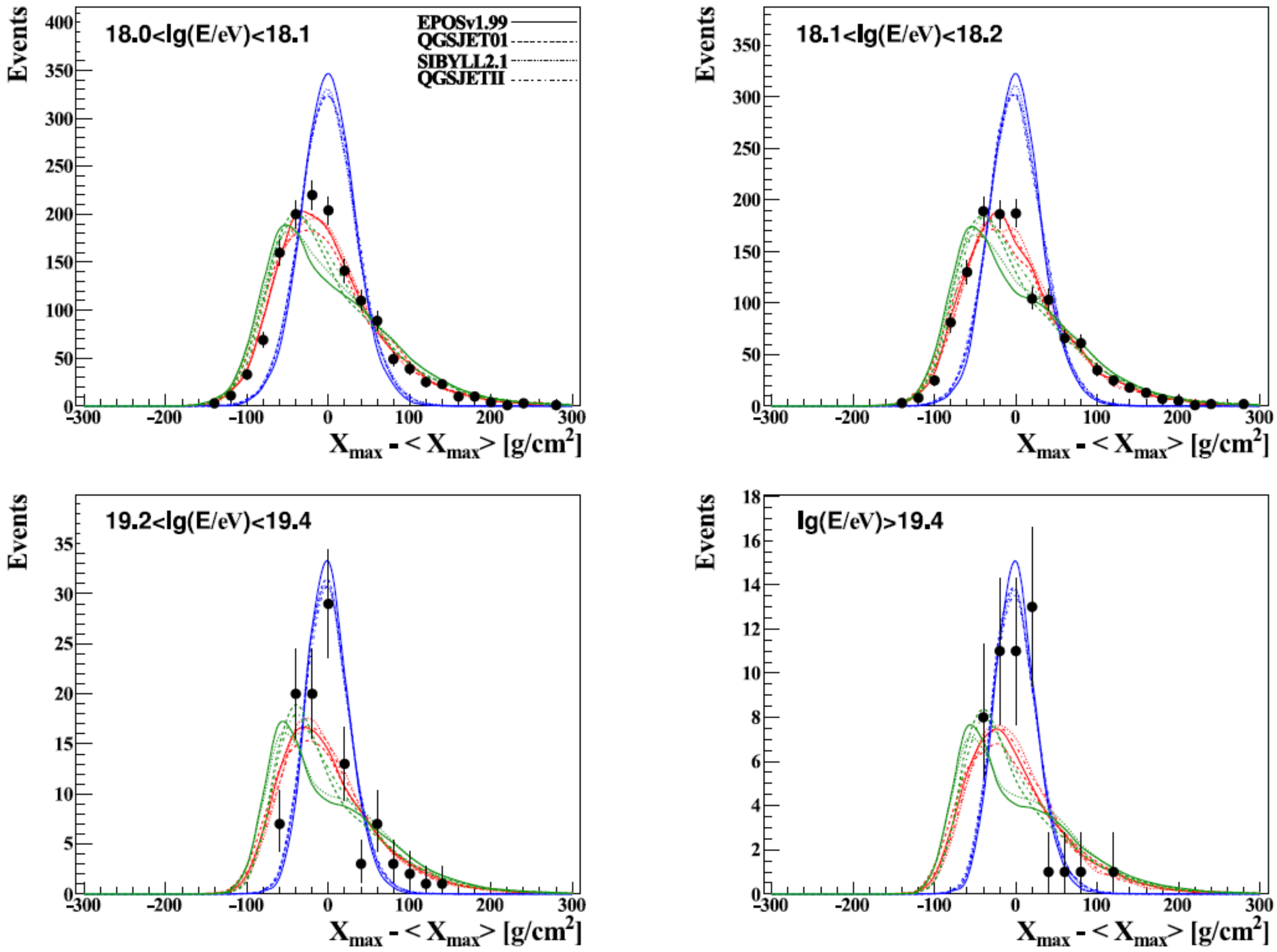
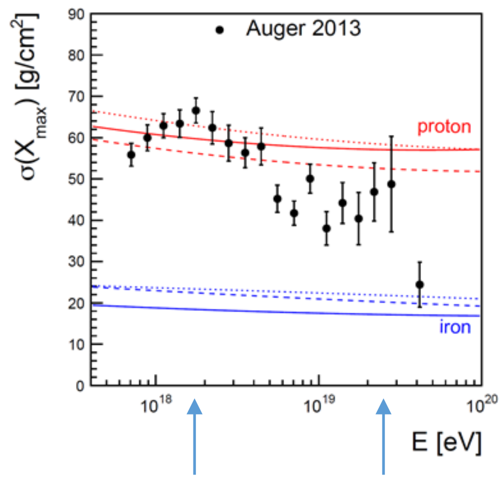
Distribution of Xmax



Pedro Facal ICRC2011 arXiv:1107.4804v1

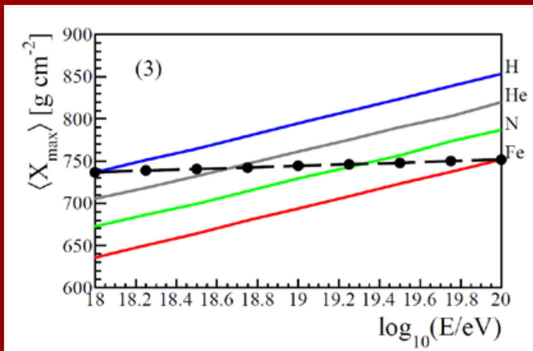
Shape of Xmax

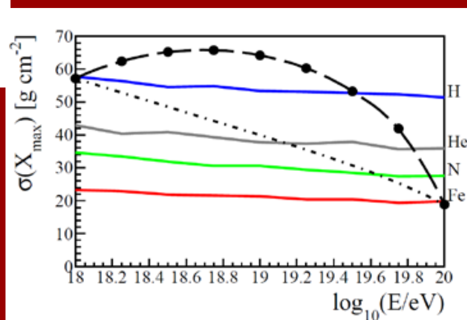


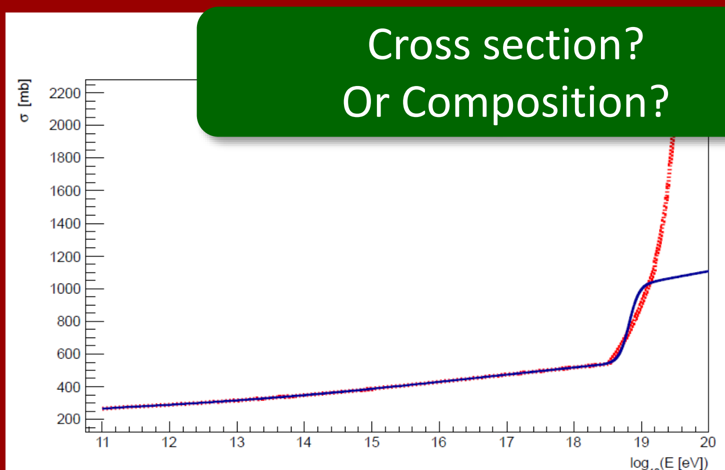


Pedro Facal ICRC2011 arXiv:1107.4804v1

Xmax

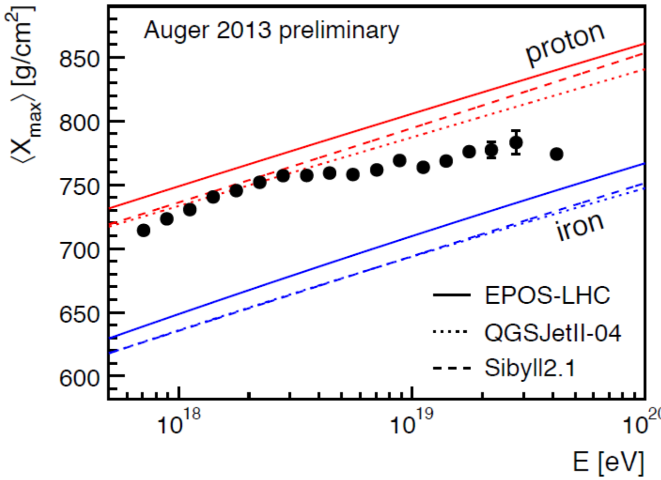


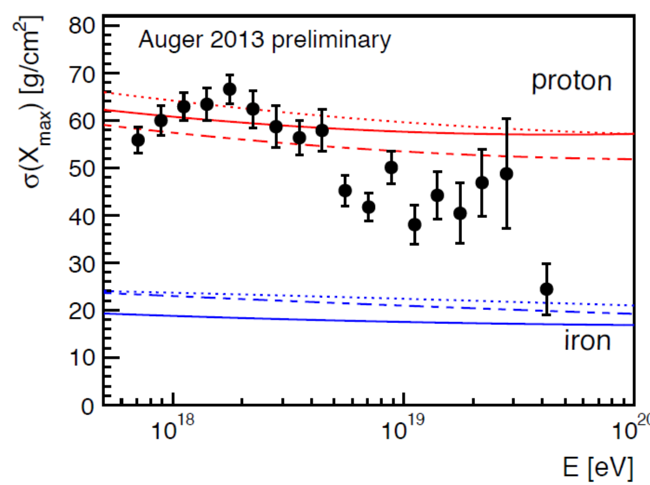




Cross section?
Or Composition?

- Recent Xmax results:





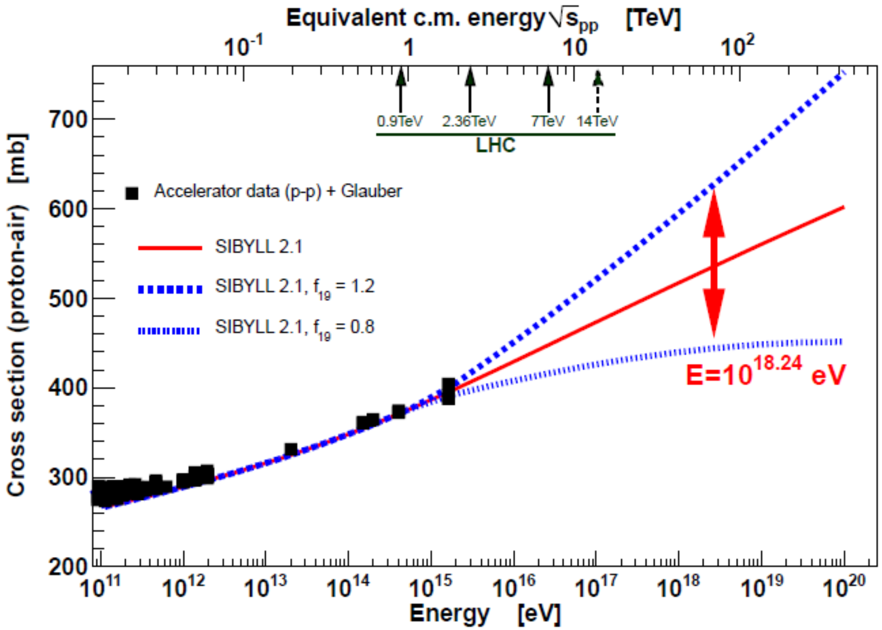
ICRC 2013, arXiv:1307.5059v1

Description	**Impact on $\sigma_{\text{p-air}}$**
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

- Extensive cut-variation, sub-sample and parameter-scan analysis
- Helium bias potentially most important

Total systematics includes +10 mb for photon-contribution and -30 mb for helium contribution in the following.

Pierre Auger Collaboration arXiv:1208.1520v2 ; Ralf Ulrich ICRC2011 arXiv:1107.4804v1

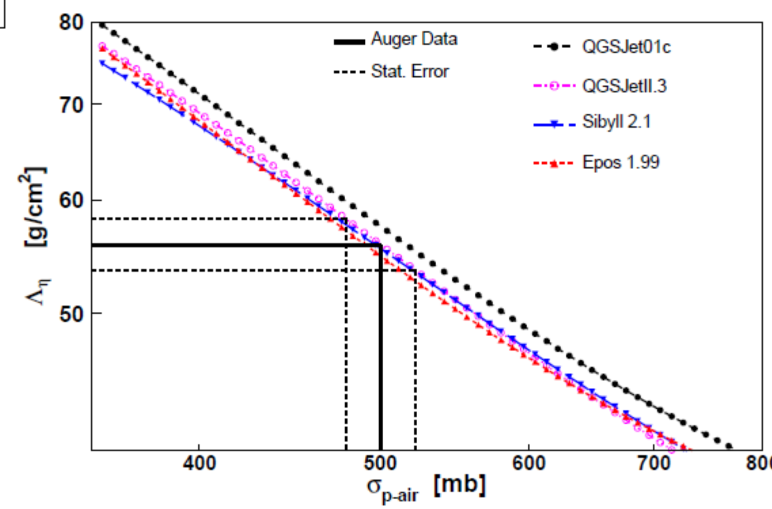


$$f(E,\, f_{19}) = 1 + (f_{19} - 1)\, F(E)$$

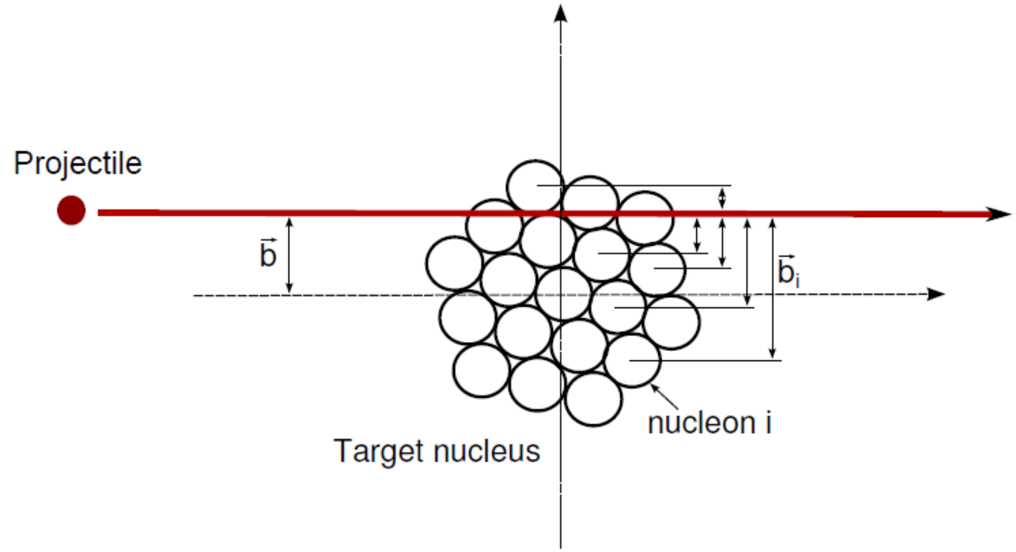
$$F(E) = \frac{\lg\left(E/10^{15}\,\mathrm{eV}\right)}{\lg\left(10^{19}\,\mathrm{eV}/10^{15}\,\mathrm{eV}\right)}$$

Simulations with f_{19}:

- Consistent description of cross-section
- No discontinuities in cross-section predictions



Pierre Auger Collaboration arXiv:1208.1520v2 ; Ralf Ulrich ICRC2011 arXiv:1107.4804v1



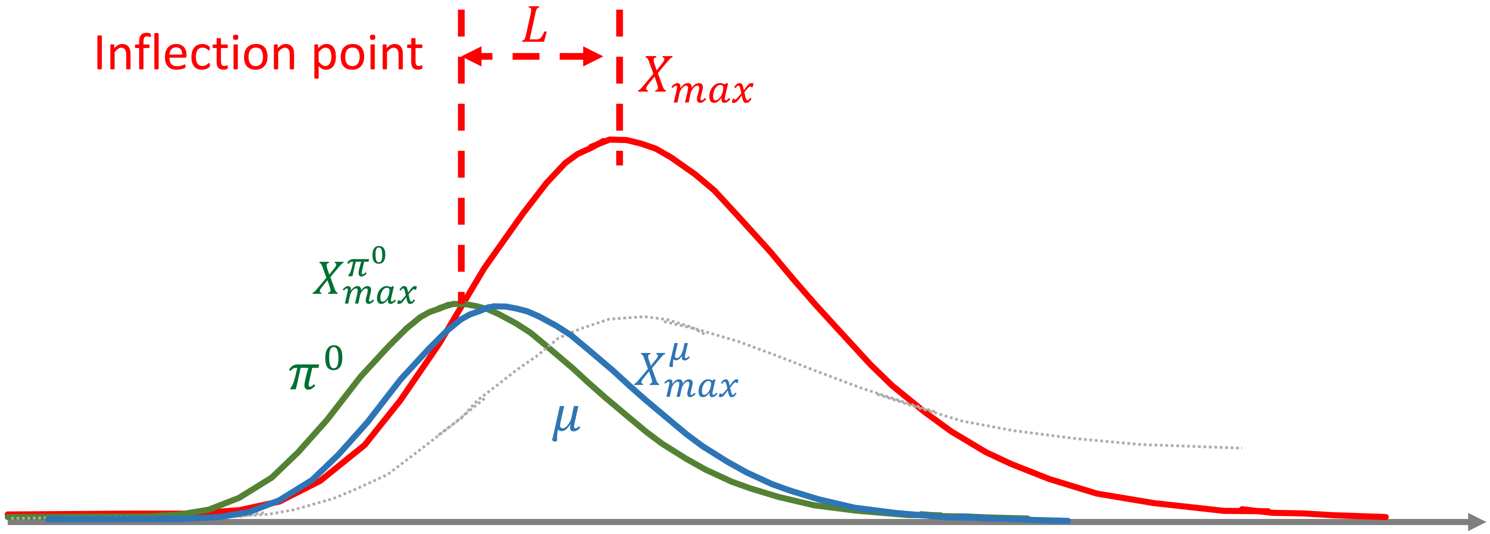
$$\sigma_{hA}^{\mathrm{tot}} = 2\Re e \int \Gamma_{hA}(\vec{b}) d^2 b$$

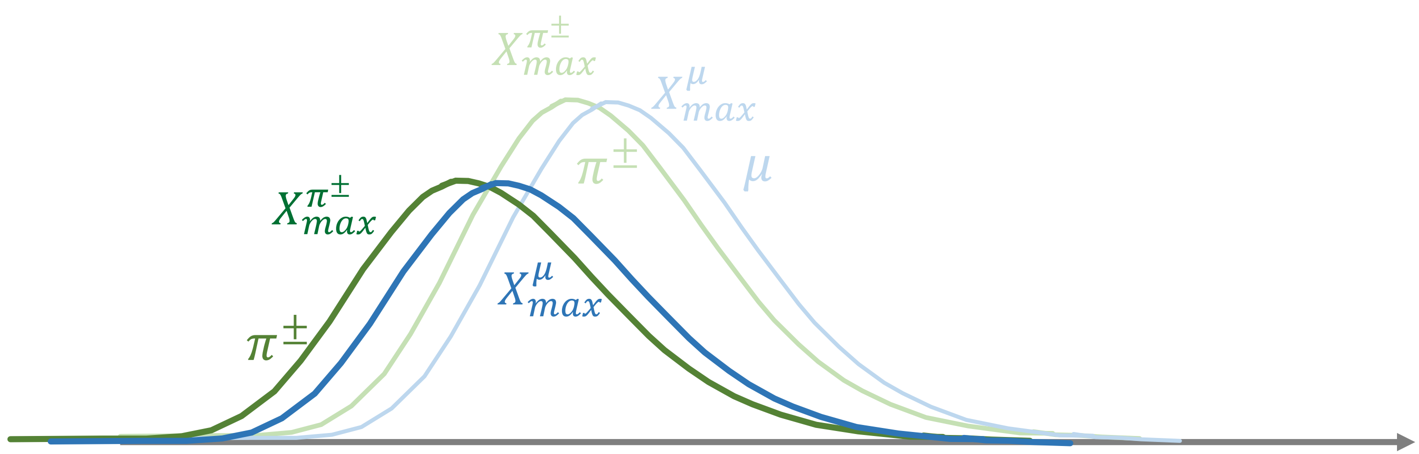
$$\Gamma_{hN}(\vec{b}) = (1 - i\rho_{hN}) \frac{\sigma_{hN}^{\mathrm{tot}}}{4\pi B_{hN}^{\mathrm{el}}} \exp\left\{ -\frac{\vec{b}^2}{2B_{hN}^{\mathrm{el}}} \right\}$$

R. Glauber, Phys. Rev. **100**, 242 (1955).

R. Glauber and G. Matthiae, Nucl. Phys. B **21**, 135 (1970).

X_{max} and X_{max}^{μ}



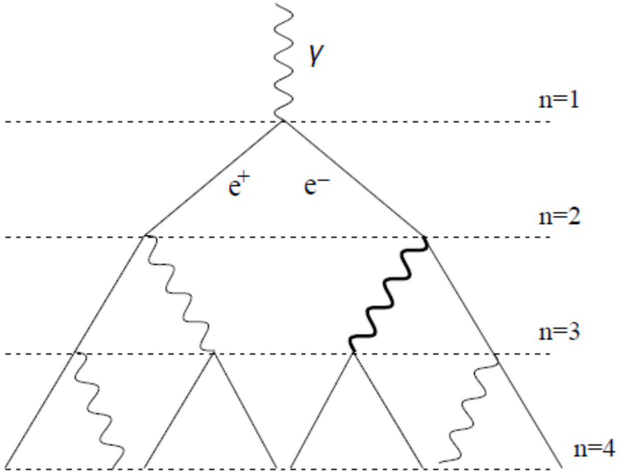


μ with higher energy

Heitler model

Electromagnetic part

$$\lambda_r = 13.8\ \mathrm{g\,cm^{-2}},\ \xi_c = \frac{710\mathrm{MeV}}{Z_{eff}+0.92} \approx 86\mathrm{MeV}$$



The number of particles at the shower maximum

$$E_0 = \xi_c^e \cdot N_{max}$$

$$N_{max} = E_0/\xi_c^e\ .$$

The depth of maximum shower development (X_{max})

$$N_{max} = 2^{n_{max}}$$

$$n_{max} = \ln(E_0/\xi_c^e)/\ln 2$$

$$X_{max} = \lambda_r \ln 2 \cdot n_{max} = \lambda_r \cdot \ln(E_0/\xi_c^e)$$

The elongation rate is the evolution of X_{max} with energy

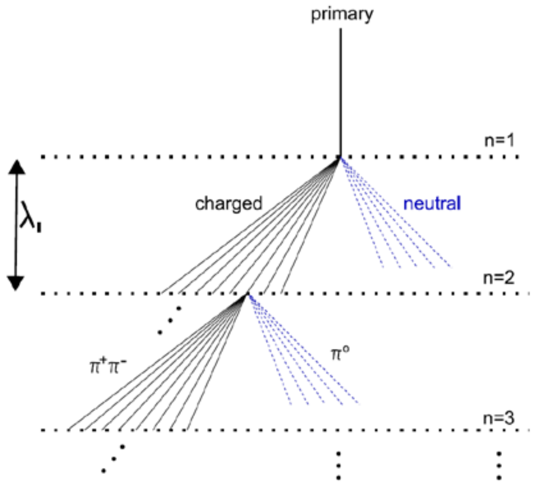
$$\Lambda_{10} \equiv \frac{dX_{max}}{d\log_{10} E_0} = 2.3\lambda_r \simeq 85\mathrm{g/cm}^2$$

Modied Heitler model

Pion part

$\xi_c^\pi = 20$ GeV
pions in air, $\lambda_I \approx 120\ \mathrm{g\,cm^{-2}}$

$\xi_c^\pi = 30$ GeV at $E_\circ = 10^{14}$ eV
$\xi_c^\pi = 10$ GeV at $E_\circ = 10^{17}$ eV



$$N_{\pi^\pm} = \left(N_{mult,\pi^\pm}\right)^n$$
$$E_\pi = (2/3)^n E_0/\left(N_{mult,\pi^\pm}\right)^n = E_0/\left(3/2N_{mult,\pi^\pm}\right)^n$$
$$n_c = \frac{\ln(E_0/\xi_c^\pi)}{\ln 3/2N_{mult,\pi^\pm}}$$

The muon number at the shower maximum

$$N_\mu = N_{\pi^\pm} = \left(\frac{3}{2}N_{mult,\pi^\pm}\right)^{n_c} = \left(\frac{E_0}{\xi_c^\pi}\right)^\beta$$

$$\beta = \frac{\ln(N_{mult,\pi^\pm})}{\ln\left(\frac{3}{2}N_{mult,\pi^\pm}\right)}$$

The depth of maximum shower development

$$X_{max}^p = X_0^p + \lambda_r \ln\left(\frac{E_0/\xi_0^e}{3N_{mult,\pi^\pm}}\right) = X_{max}^\gamma + X_0^p - \lambda_r \ln(3N_{mult,\pi^\pm})$$

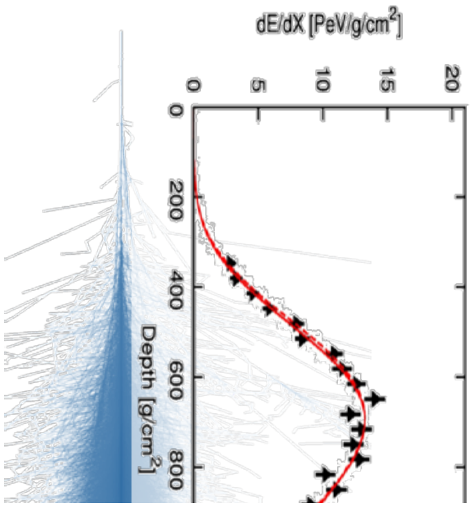
$$X_{max}^I = X_0^I + \lambda_r \ln\left(\frac{E_0/\xi_0^e A}{3N_{mult,\pi^\pm}}\right) \propto \ln\left(\frac{E_0}{A}\right) \sim X_{max}^p - \lambda_r \ln A$$

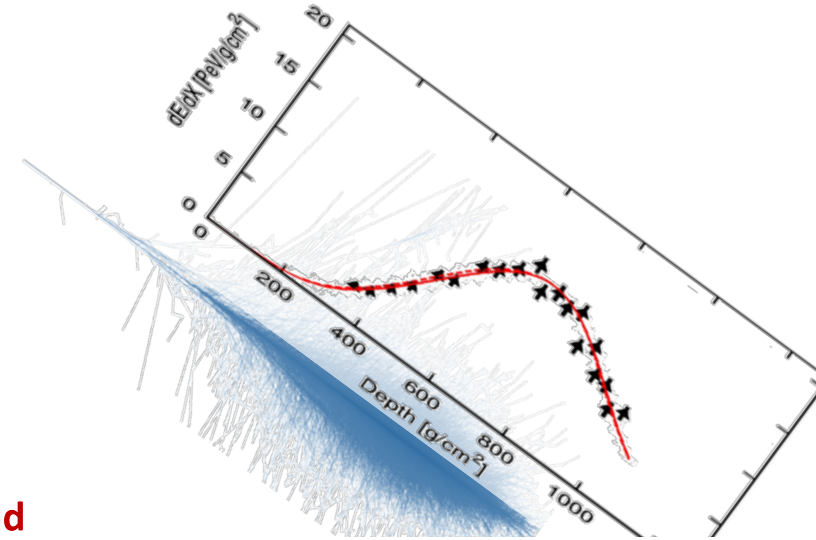
The elongation rate

$$\Lambda^p = \Lambda^\gamma + \frac{d}{d\log_{10} E_0}\left[X_0^p - \lambda_r\left(3N_{mult,\pi^\pm}\right)\right] \simeq 58\ \mathrm{g/cm^2}\ \text{per decade}$$

Direct Measurement of muons

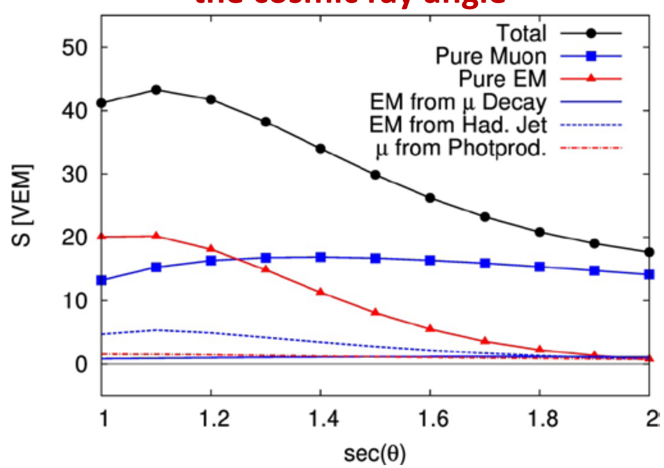
- Vertical Showers
- Inclined Showers





Ground

Ground signal as function of the cosmic ray angle



Vertical events: Have a big EM component

Very inclined events: Almost all particles are muons

We don't have the expected signal on the ground (LDF-Lateral distribution Function)

From hybrid events:

Longitudinal Profile ($\sim Calorimetry$)

Lateral Profile (LDF)

Choose an Energy bin $10^{18.8} < E < 10^{19.2}\ eV$

$E_{lab} = 10EeV \quad \rightarrow \quad E_{CM} = 137\ TeV$

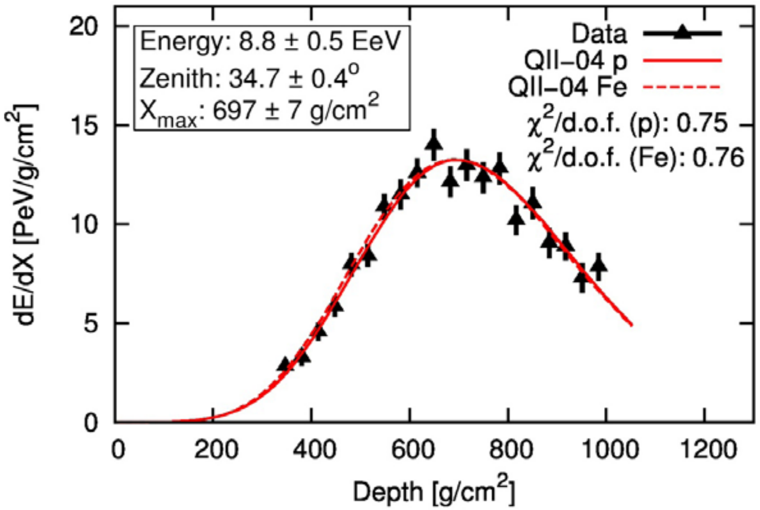
Cosmic ray inclination $0° < \theta < 60°$

Idea: Re-simulate measured hybrid events(FD+SD)

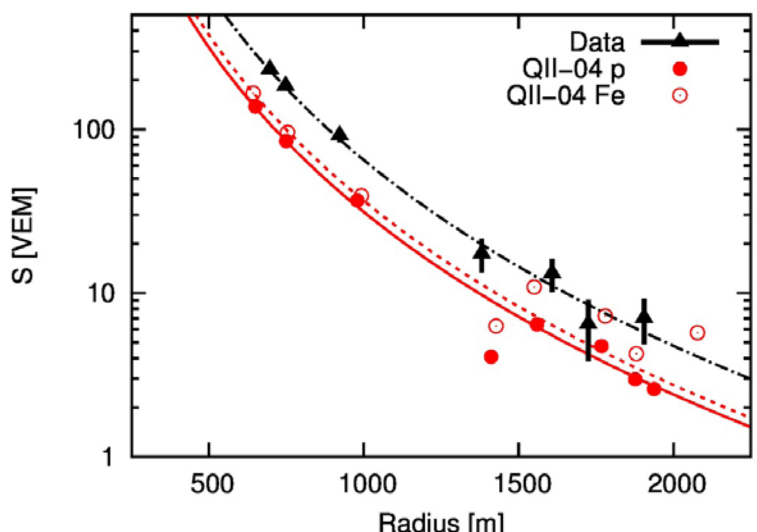
- Match longitudinal FD light profile
- Rescale ground signal to match SD data
- Contributions of EM and muon component vary with zenith angle

$$S_{resc} = R_E S_{EM} + R_E^{\alpha} R_{\mu} S_{\mu}$$

- Atmosphere -> FD -> Longitudinal Profile

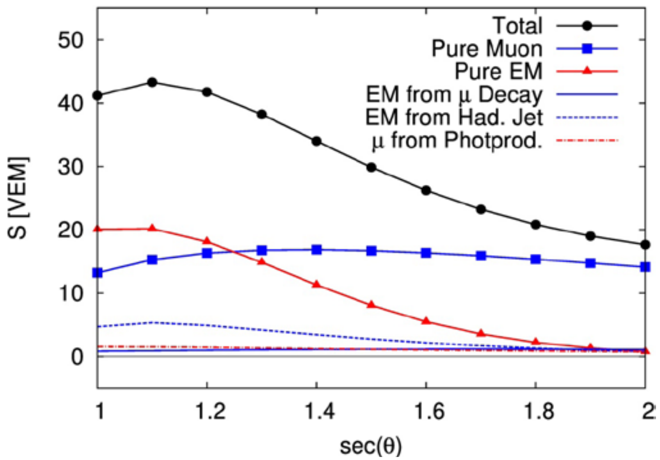


- Ground -> SD ->LDF (Lateral distribution Function)

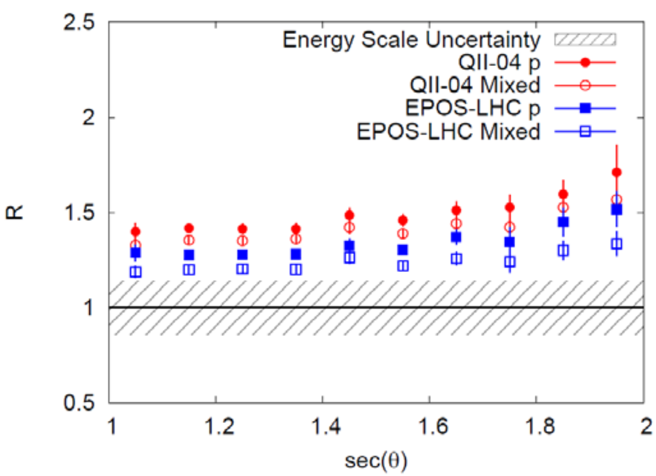


G. Farrar ICRC2013 arXiv:1307.5059v1

- Ground Signal from MC
  have different EM/muon component

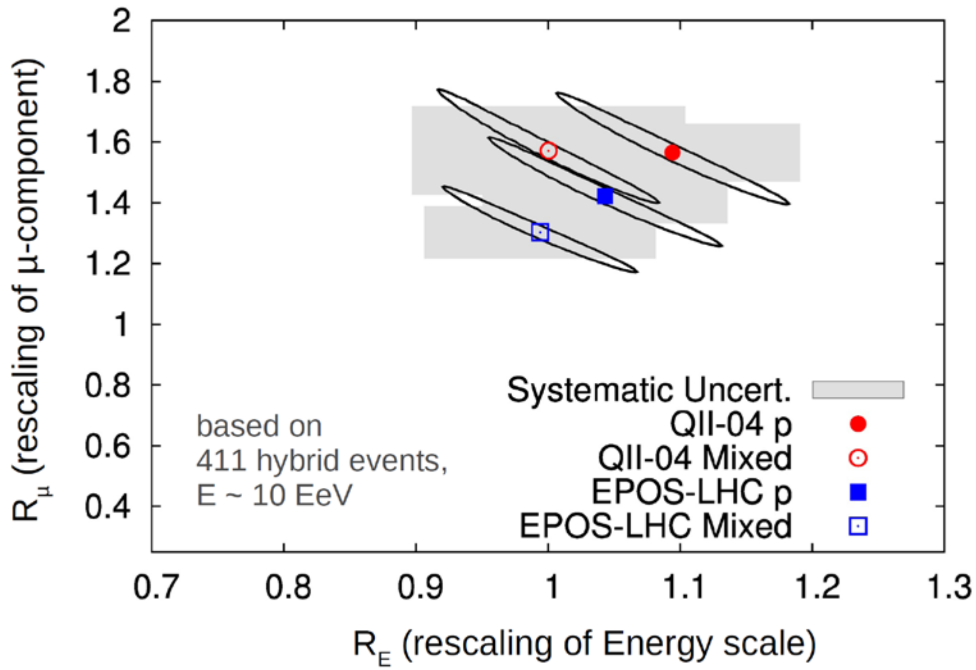


- Energy Rescaling ⇔ EM rescaling:

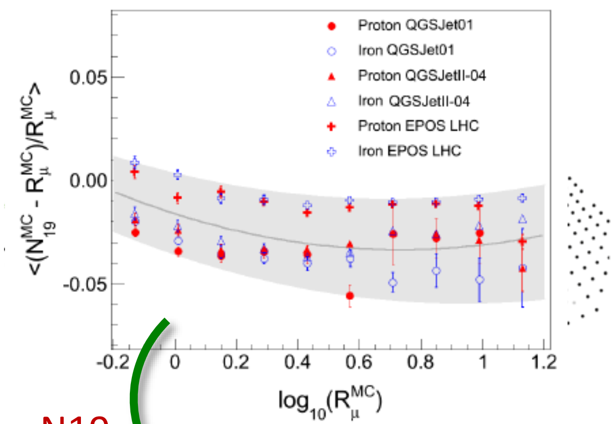


$$S_{resc} = R_E S_{EM} + R_E^{\alpha} R_{\mu} S_{\mu}$$

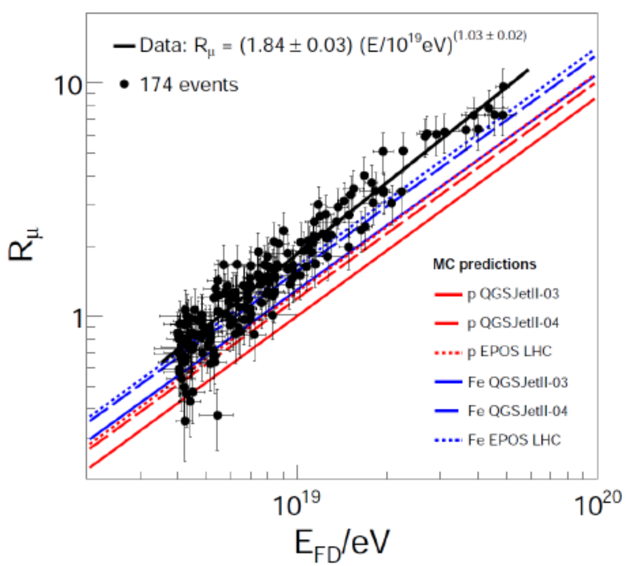
Muon number in simulations is too low by at least a factor of 1.3
Beware: Fixing models with two factors is probably not the end of story



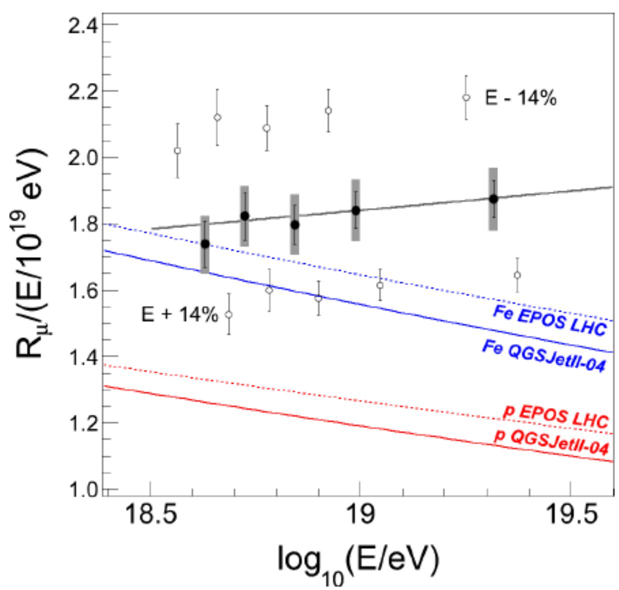
G. Farrar ICRC2013 arXiv:1307.5059v1



N19



Rμ = Nμ(event) / (E/10^19)

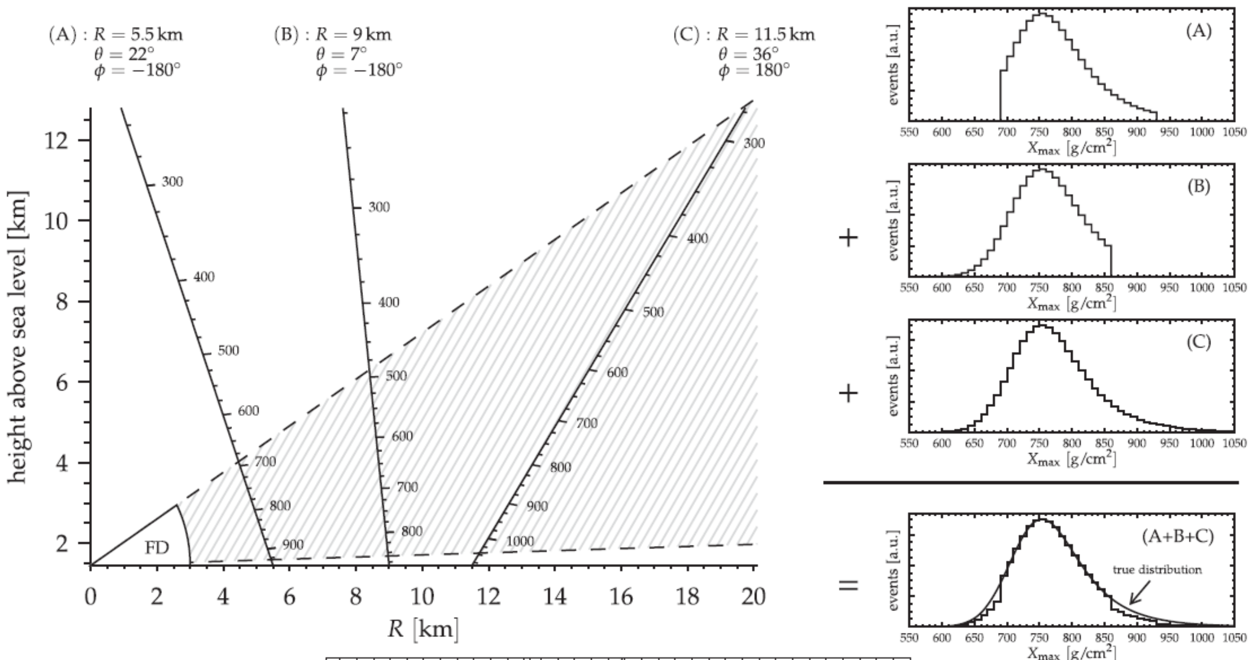


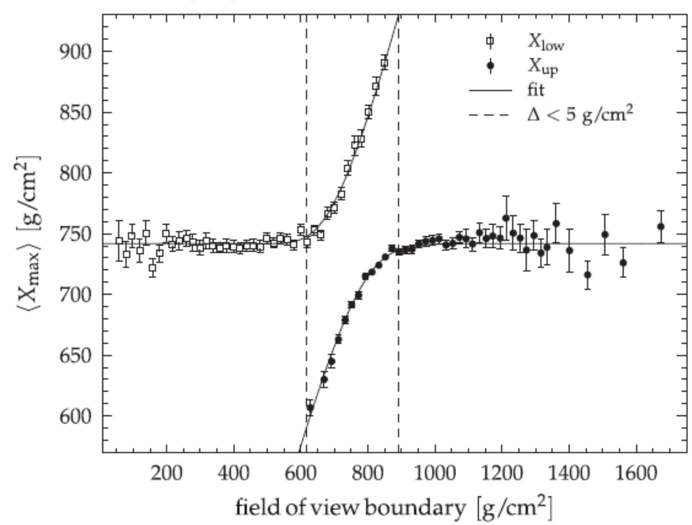
Very inclined air showers

- Long distance to ground, only muons survive
- First and most direct measurement of muon scale

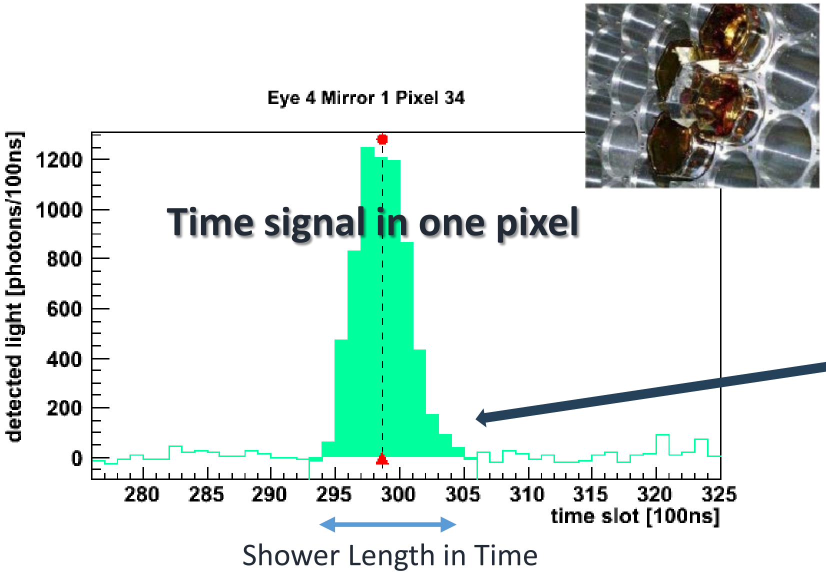
I. Valino ICRC2013 arXiv:1307.5059v1

Cut	Events	ε [%]
Pre-selection:		
Air-shower candidates	2573713	...
Hardware status	1920584	74.6
Aerosols	1569645	81.7
Hybrid geometry	564324	35.9
Profile reconstruction	539960	95.6
Clouds	432312	80.1
$E > 10^{17.8}$ eV	111194	25.7
Quality and fiducial selection:		
P(hybrid)	105749	95.1
X_{max} observed	73361	69.4
Quality cuts	58305	79.5
Fiducial field of view	21125	36.2
Profile cuts	19947	94.4

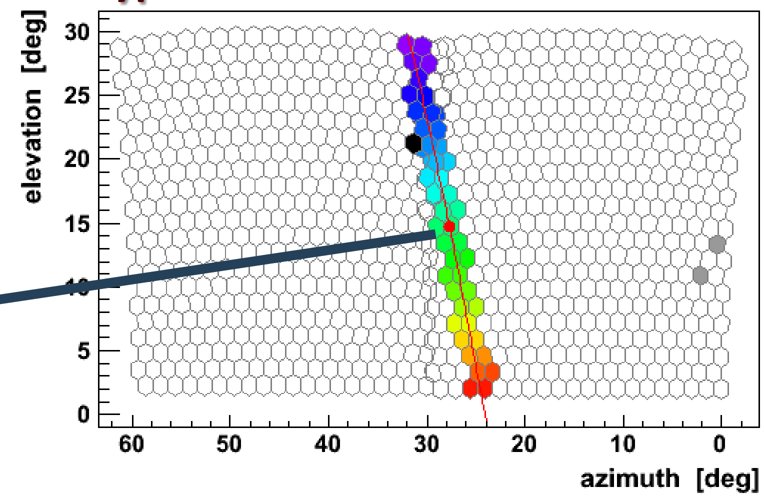

(A) : R = 5.5 km
θ = 22°
φ = −180°
(B) : R = 9 km
θ = 7°
φ = −180°
(C) : R = 11.5 km
θ = 36°
φ = 180°
height above sea level [km]
R [km]
FD
events [a.u.]
Xmax [g/cm²]
(A)
(B)
(C)
(A+B+C)
true distribution
+
+
=


⟨Xmax⟩ [g/cm²]
field of view boundary [g/cm²]
Xlow
Xup
fit
Δ < 5 g/cm²

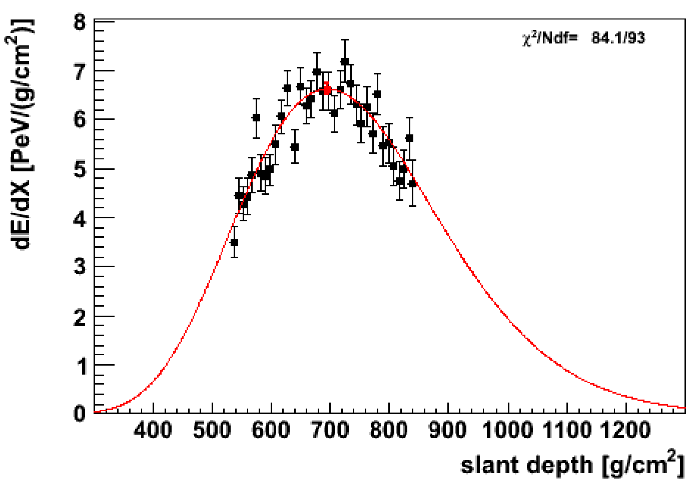
Light Detected in the Telescope



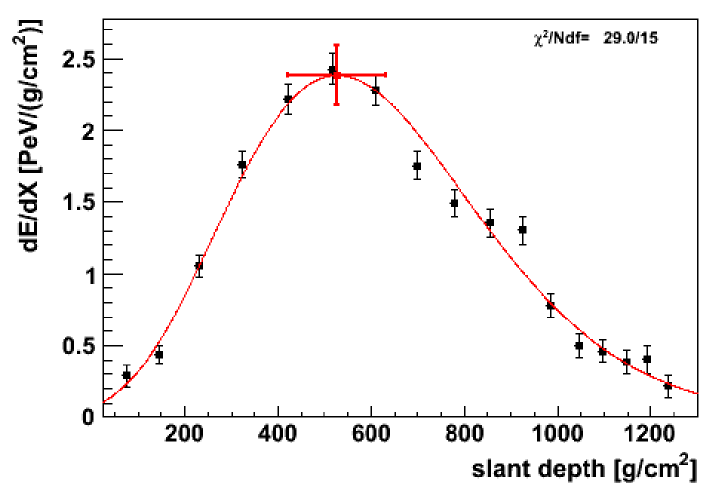
One typical event:



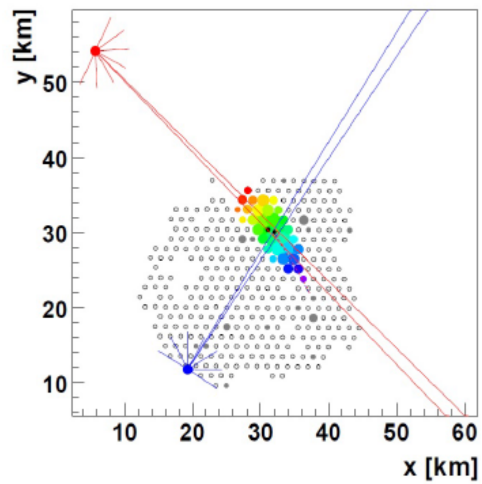
❑ Fluorescence rich event



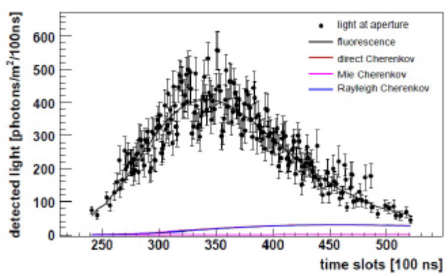
❑ Cherenkov rich event



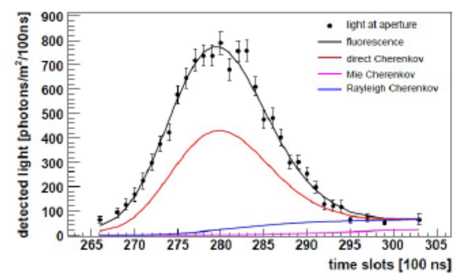
FD event



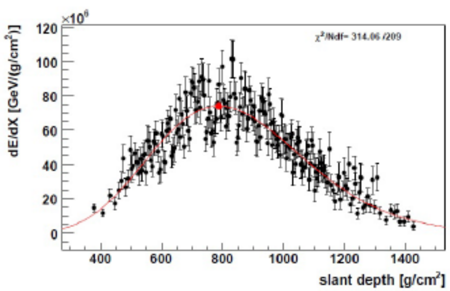
(a) *Top view. Tank colors range from early (cold) to late (hot) arrival times*



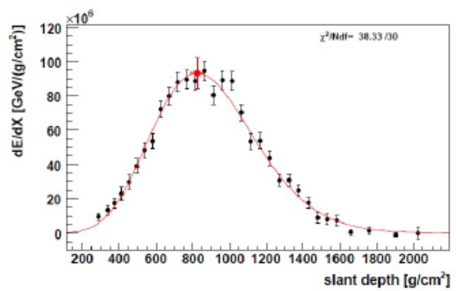
(b) *Light flux at Los Leones.*



(c) *Light flux at Coihueco.*



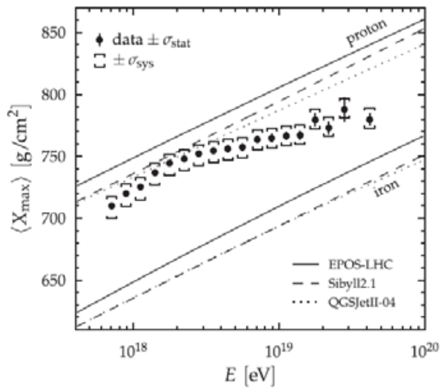
(d) *Energy deposit at Los Leones.*



(e) *Energy deposit at Coihueco.*

➢SD calibration with electromagnetic signal

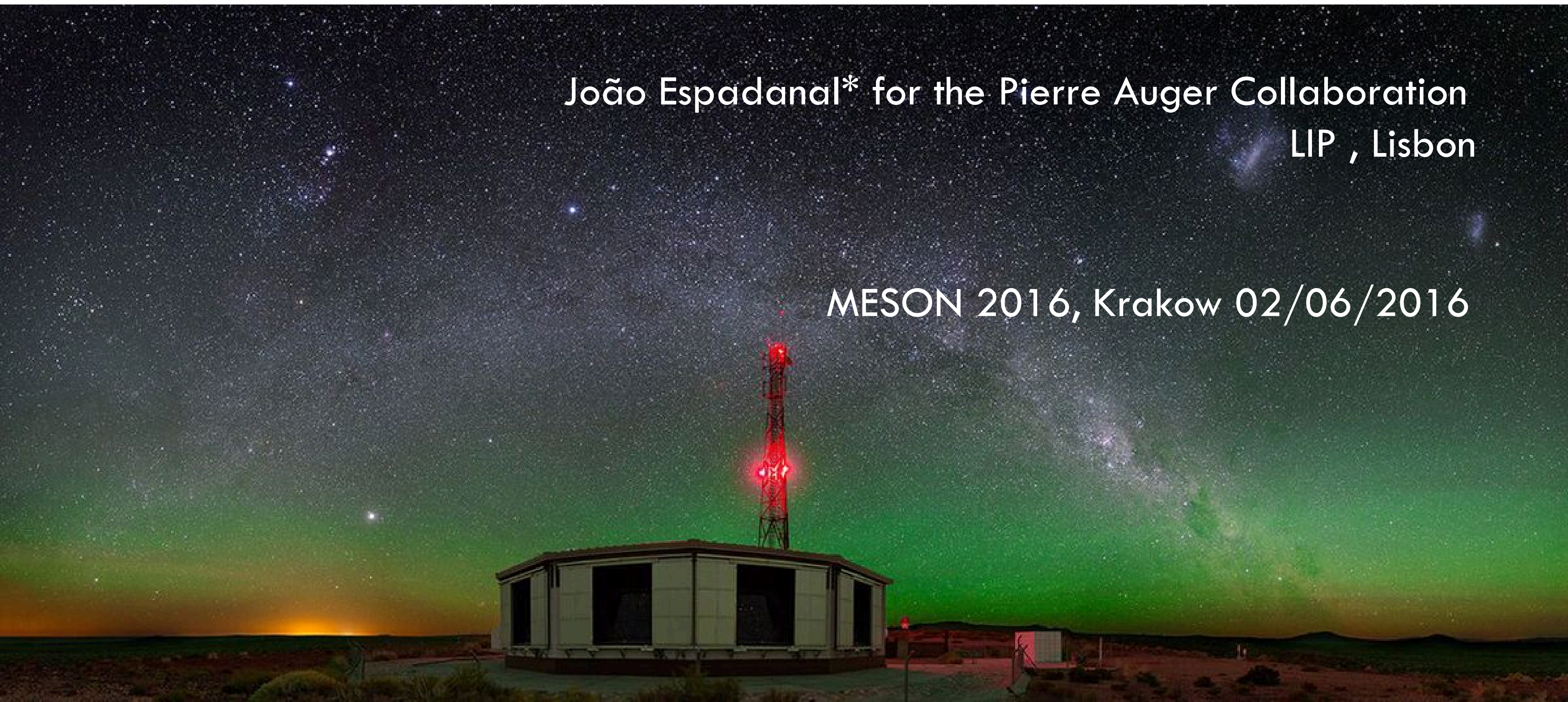
- ➢ FD energy directly correlated with the electromagnetic signal
- ➢ Better resolution in the energy estimator (with the electromagnetic component.
- ➢ Energy evolution independent from muons
- ➢ Recover Xmax from $\frac{S_{1000,EM}}{S_{1000,MU}}$ with resolution ~43g/cm^2
- ➢ Mixture of 50% proton/iron
  - Total signal: energy-> proton underestimated by ~9%
    iron overestimated by ~9%
  - EM signal -> proton underestimated by ~2%
    iron overestimated by ~3%
  - It increases the separation in the Xmax,
    increase the measure RMS
    but reduce the separation in the Nmu



➢Muon detector

- ➢ Distinguish the muonic and electromagnetic component
- ➢ Reduce the invisible energy
  (currently 1.5% for SD and 3% in FD)
- ➢ Used the muons to test the hadronic models
  - Composition estimators
  - …
- ➢ Test the electromagnetic and muonic sectors

Constraints of hadronic interactions in extensive air showers with the Pierre Auger Observatory



João Espadanal* for the Pierre Auger Collaboration
LIP , Lisbon

MESON 2016, Krakow 02/06/2016

Constraints of hadronic interactions in extensive air showers with the Pierre Auger Observatory

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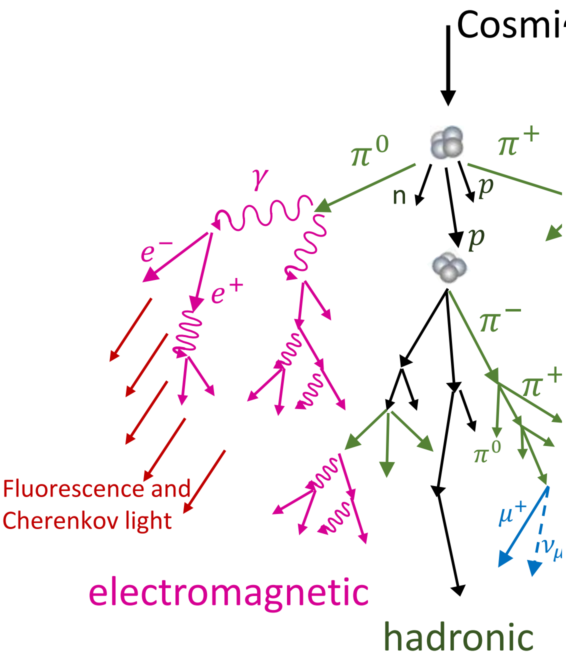
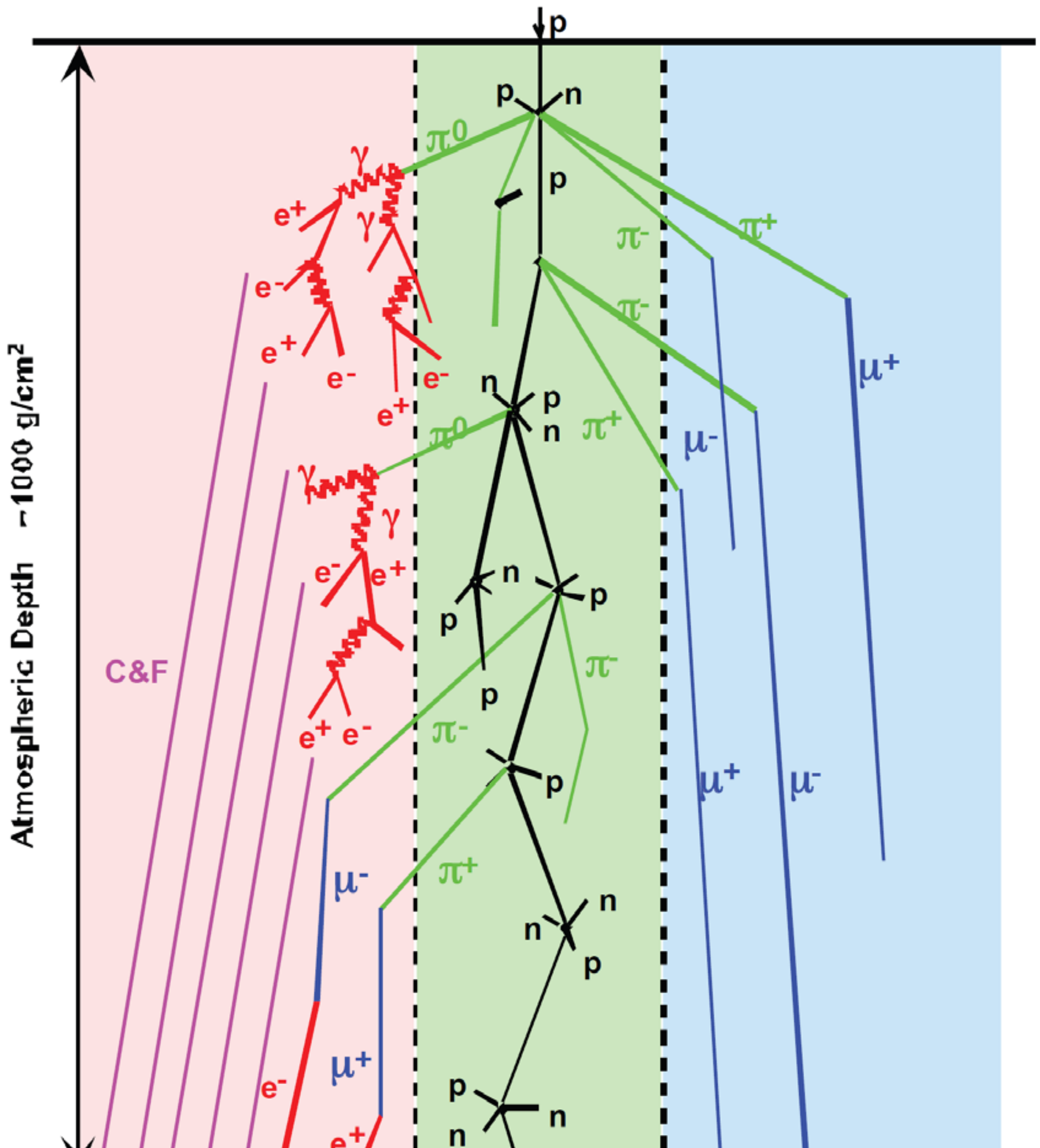
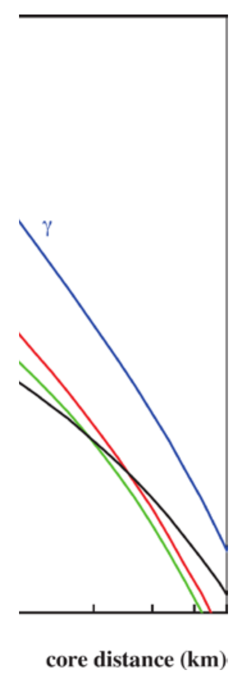
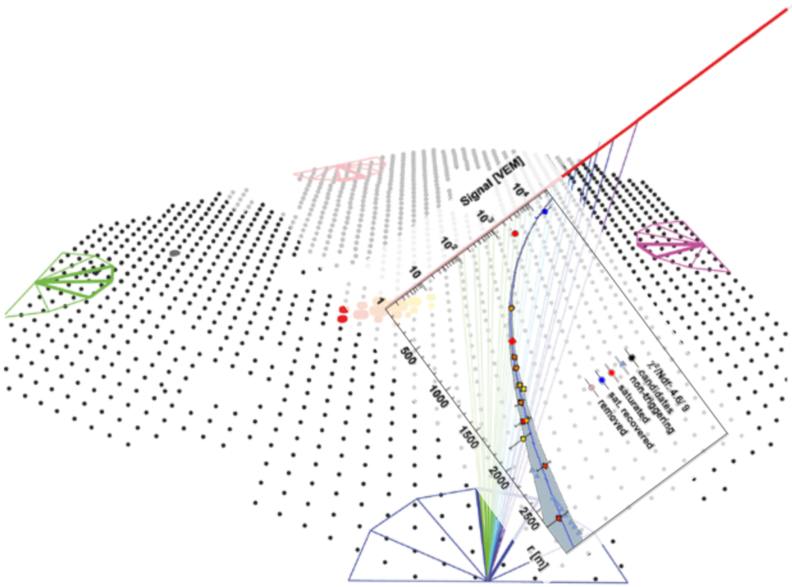
Extensive Air Showers

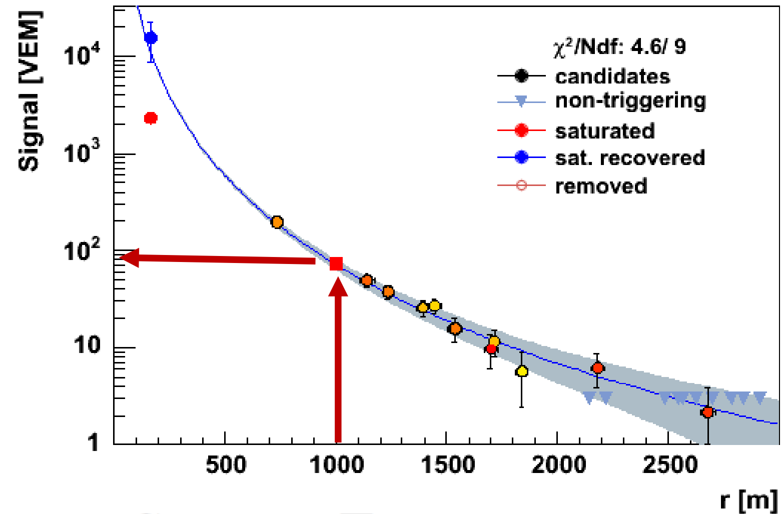




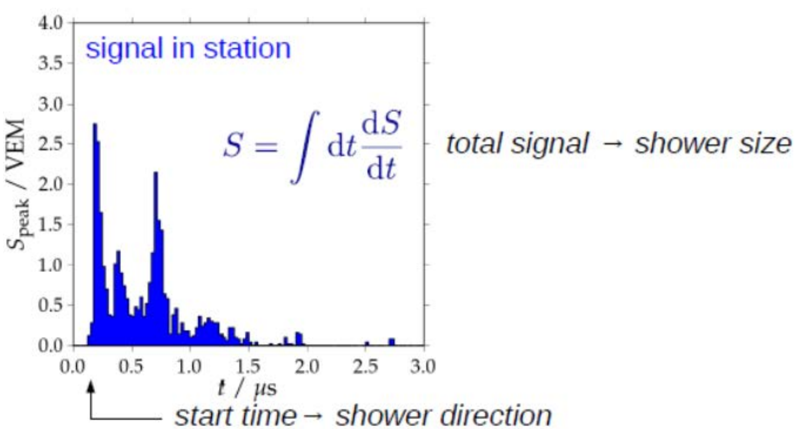


Air shower observables: Surface Detector Array





$$S_{1000} \propto E$$

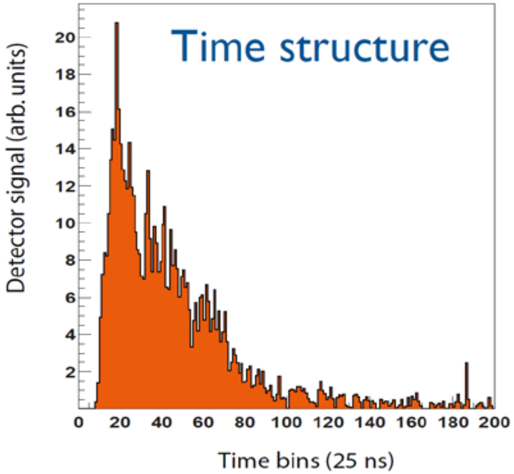


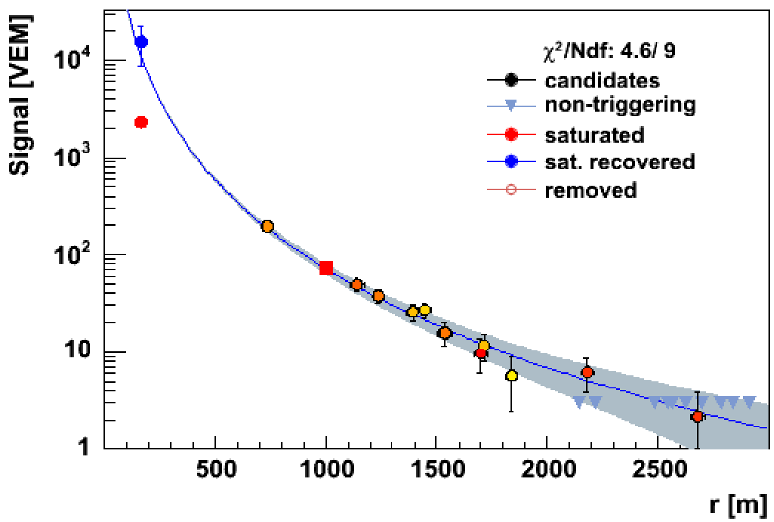
$S(r_{opt})$ Shower size estimator from LDF

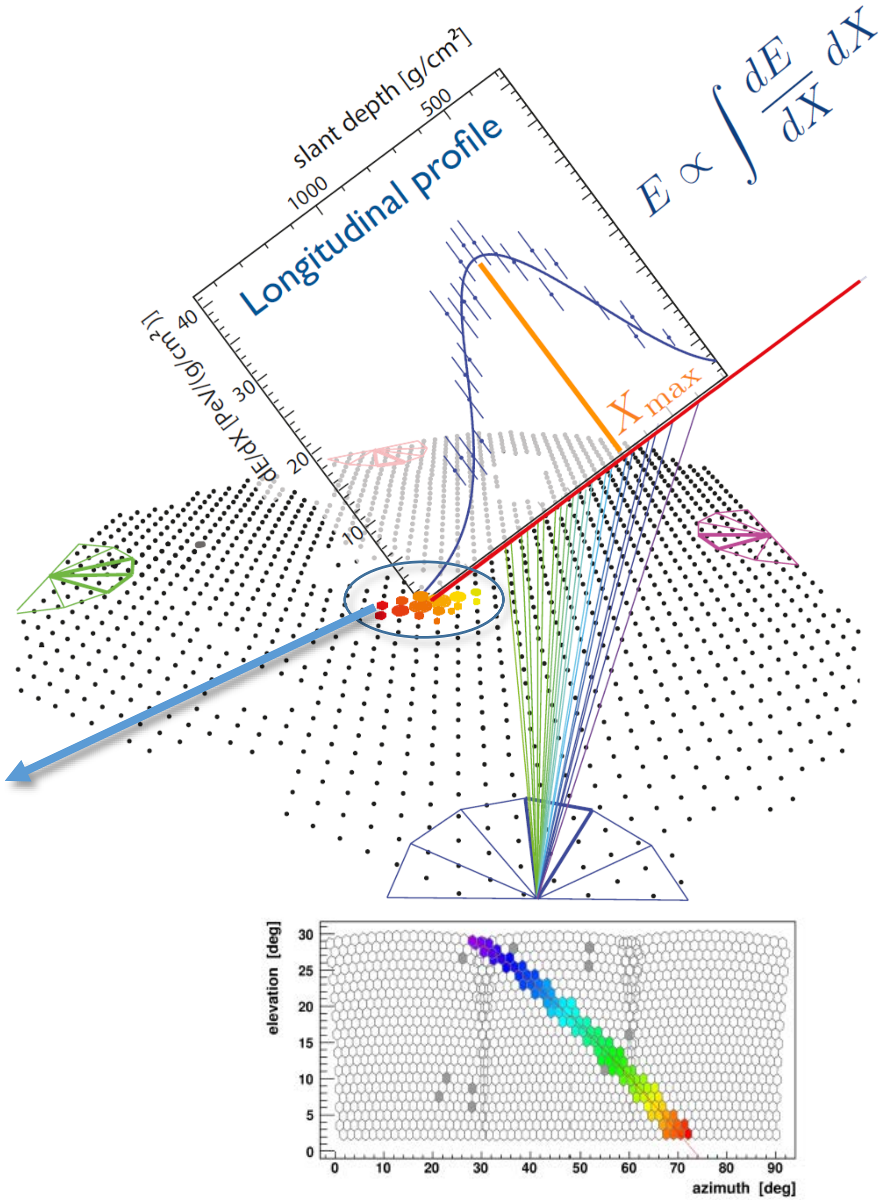
1500m grid: $r_{opt} = 1000m$

750m grid: $r_{opt} = 450m$

Model, data-based


Time structure
Detector signal (arb.units)
Time bins (25 ns)


χ^2/Ndf: 4.6/ 9
candidates
non-triggering
saturated
sat. recovered
removed
Signal [VEM]
r [m]

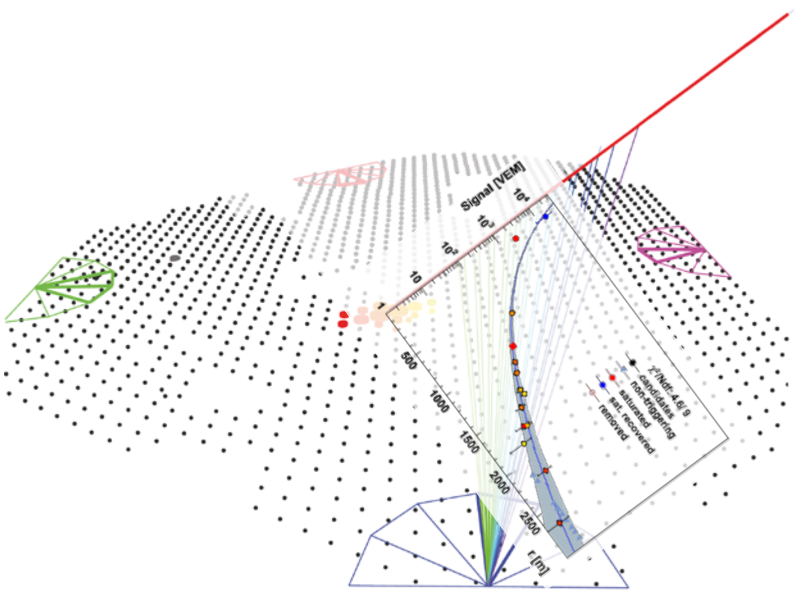

slant depth [g/cm^2]
Longitudinal profile
dE/dX [PeV/(g/cm^2)]
X_{max}
$E \propto \int \frac{dE}{dX}\, dX$
elevation [deg]
azimuth [deg]

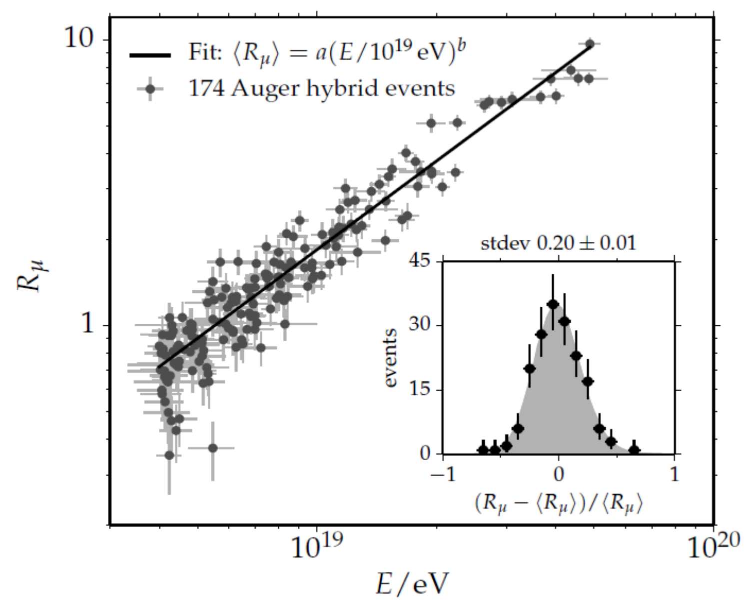
Muon content in air showers

- Muon EAS content is directly related with the hadronic shower component
- Through inclined showers is possible to measure directly the muon content (Rμ) in the SD
  - Electromagnetic shower component gets attenuated
- Mean muon number compatible with iron showers within systematic uncertainties

Inclined hybrid events
(62º < θ < 80º and 4 < E[EeV] < 50)
EM component very suppressed at these angles.
SD signals mainly due to muons.

$$R_\mu = N_\mu / N_{\mu,19}$$





Muon content in air showers

- Muon EAS content is directly related with the hadronic shower component
- Through inclined showers is possible to measure directly the muon content (Rμ) in the SD
  - Electromagnetic shower component gets attenuated
- Mean muon number compatible with iron showers within systematic uncertainties
- **Combination of the Rμ with Xmax shows tension between data and all hadronic interaction models**

More muons in data than in simulations.

Strong interaction test at energy scales larger than LHC