Hadronic physics with the Pierre Auger Observatory

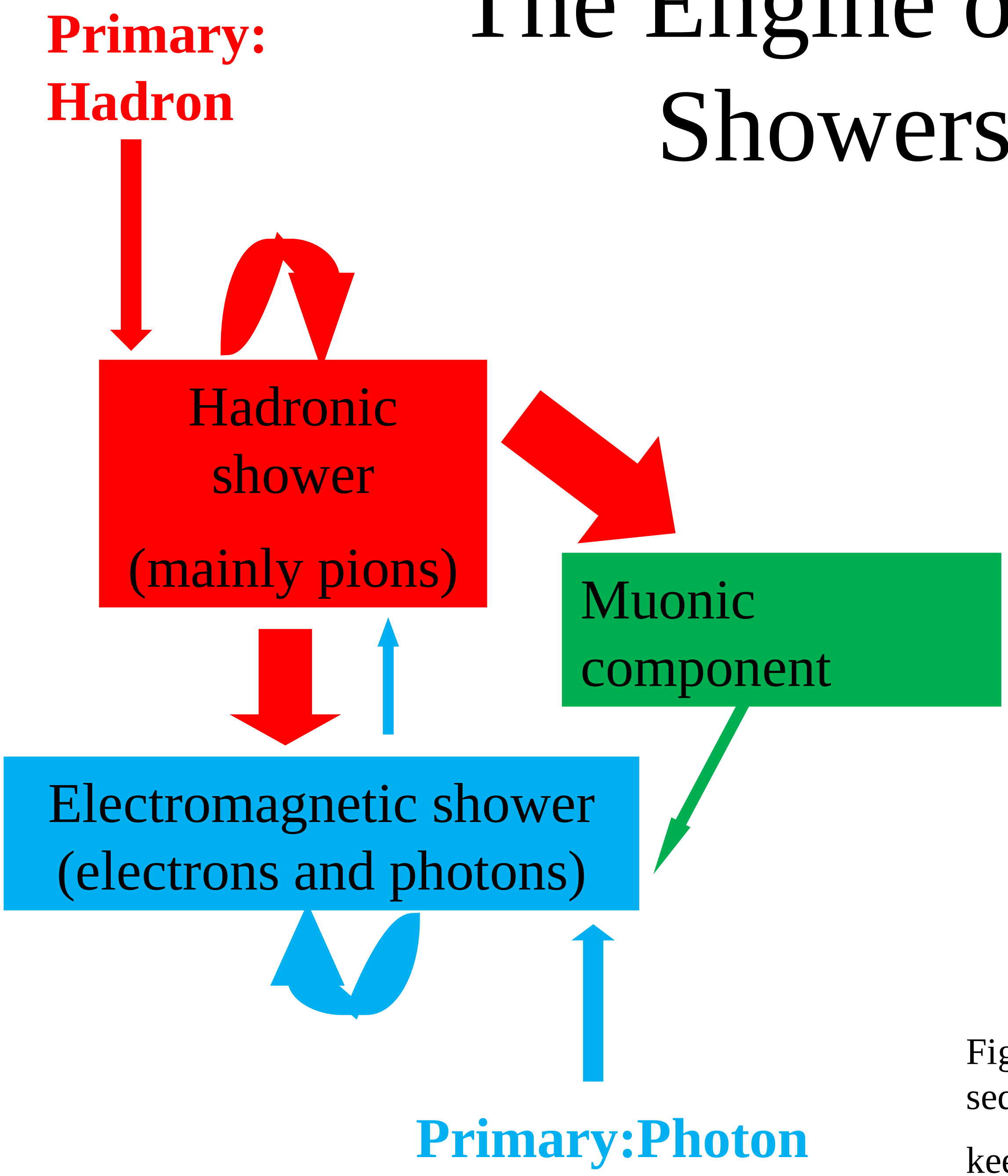
L. Cazon,
for the Pierre Auger Collaboration

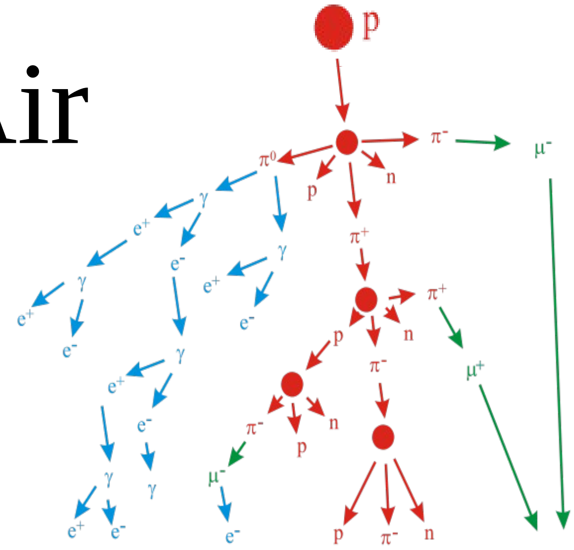
Outline

- The air shower:
  - Main engine and energy balance
  - The shower components and Auger.
- EM longitudinal profile
  - p-air cross section
  - Constraints on models from Xmax momenta
  - EM avg shower profile
- Muon component
  - Muon content
  - Tank simulations validation
  - Muon Production Depth
- Conclusions

The Air Shower

The Engine of Air Showers





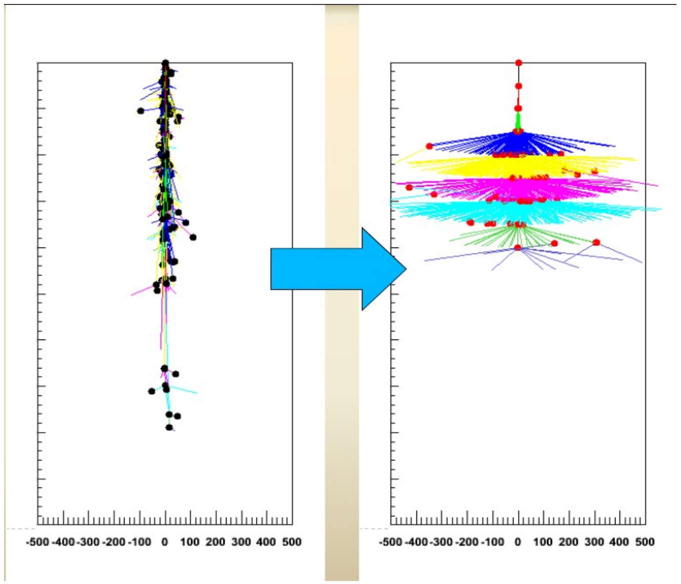
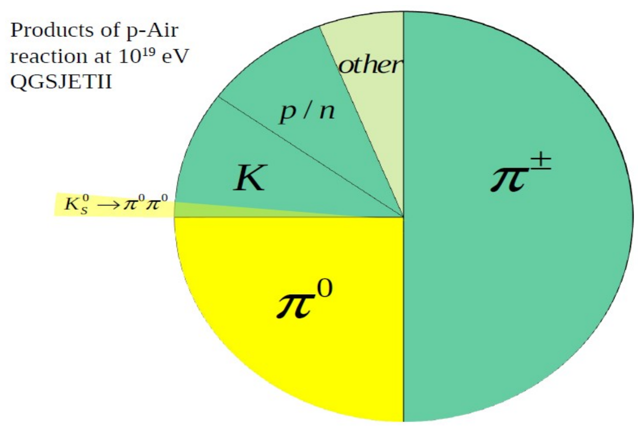


Figure of an hadronic cascade (left) and after sequentially ordering the hadronic generations and keeping keeping real angles of trajectories (right).

EM/Hadronic Energy balance



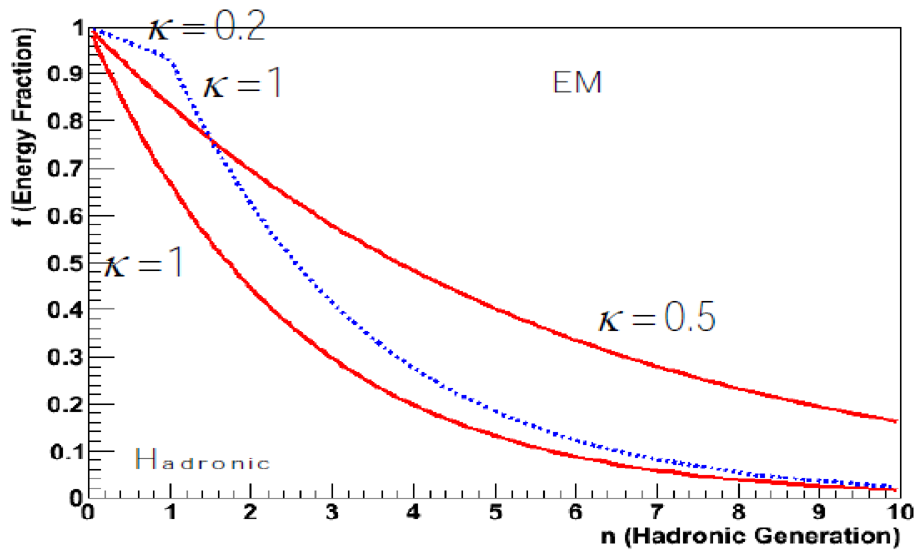
$$\sum E^{\pi} = \left(1 - \frac{1}{3}\kappa\right)^n E_0$$

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

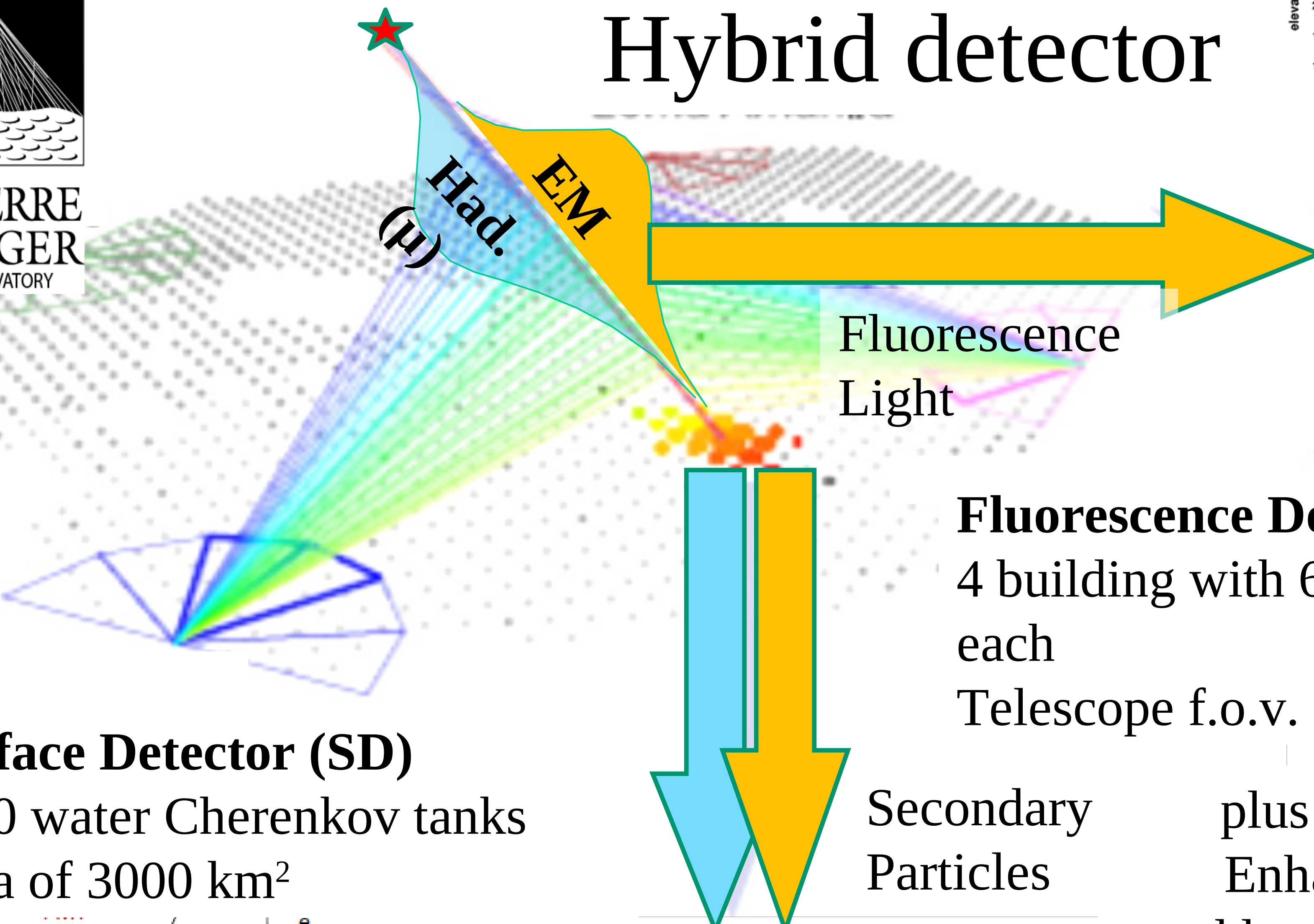
After only 2 generations, most of the energy has been transferred to the EM cascade.

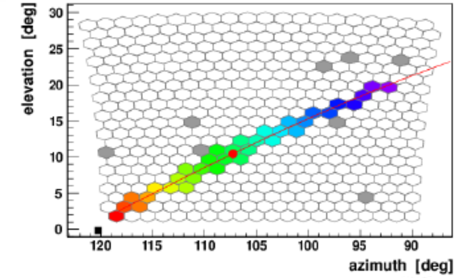
EM and hadronic cascade decouple.

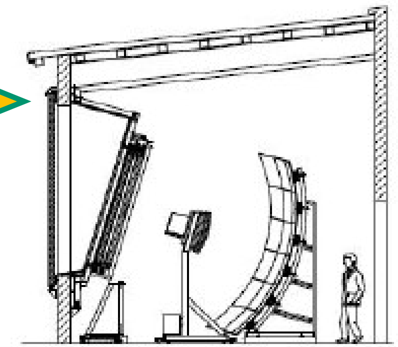
EM cascade is mostly sensitive to high-E hadr, int.
Hadronic cascade is sensitive to high and low E hadr. int.



Hybrid detector



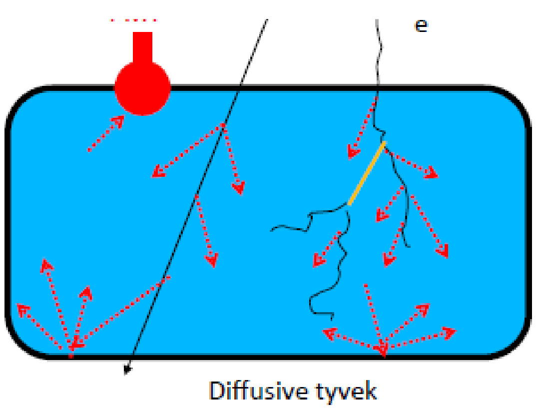


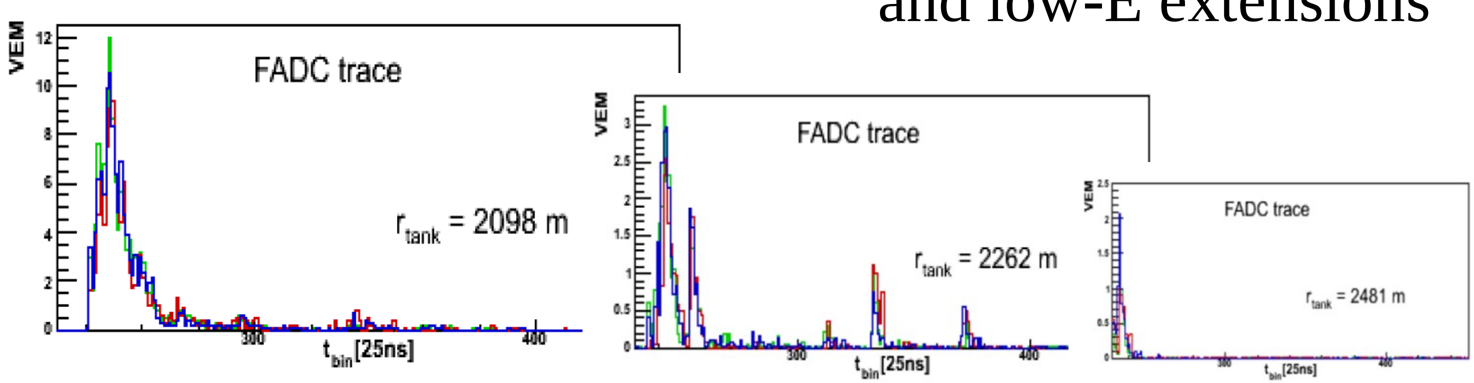


Fluorescence Detector (FD)
4 building with 6 telescopes each
Telescope f.o.v. 30 x 30 deg

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

plus SD & FD Enhancements and low-E extensions





EM longitudinal profile

p-air cross section (update)

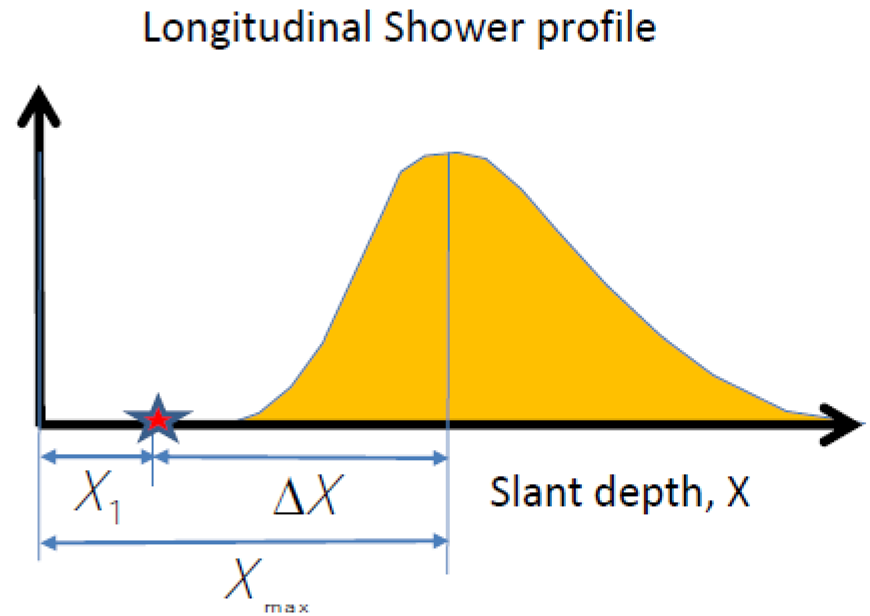
With respect to PRL 109, 062002 (2012)

•About four times more data: 44218 events

•Two bins in energy:
1e17.8 − 1e18.0 − 1e18.5 eV

•Updated systematic uncertainties

•New hadronic interaction models:
EPOS-LHC, QGSJetII.4 tuned to LHC data

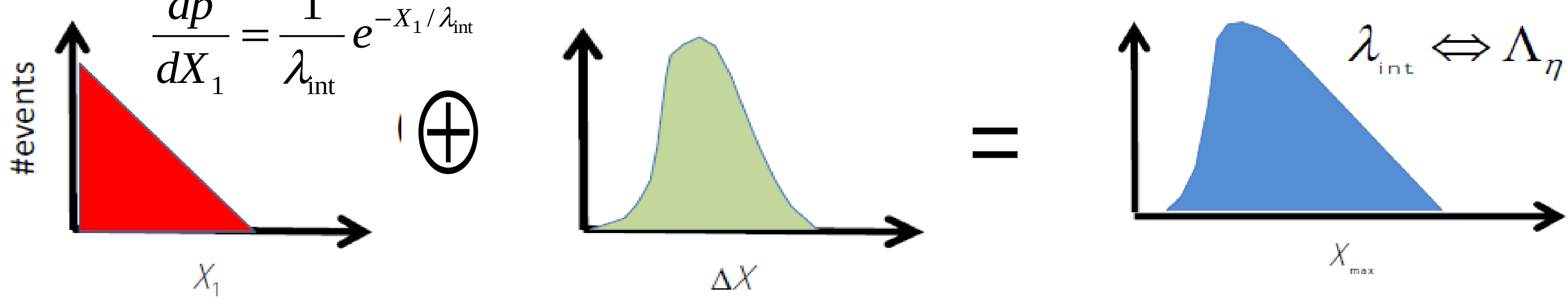


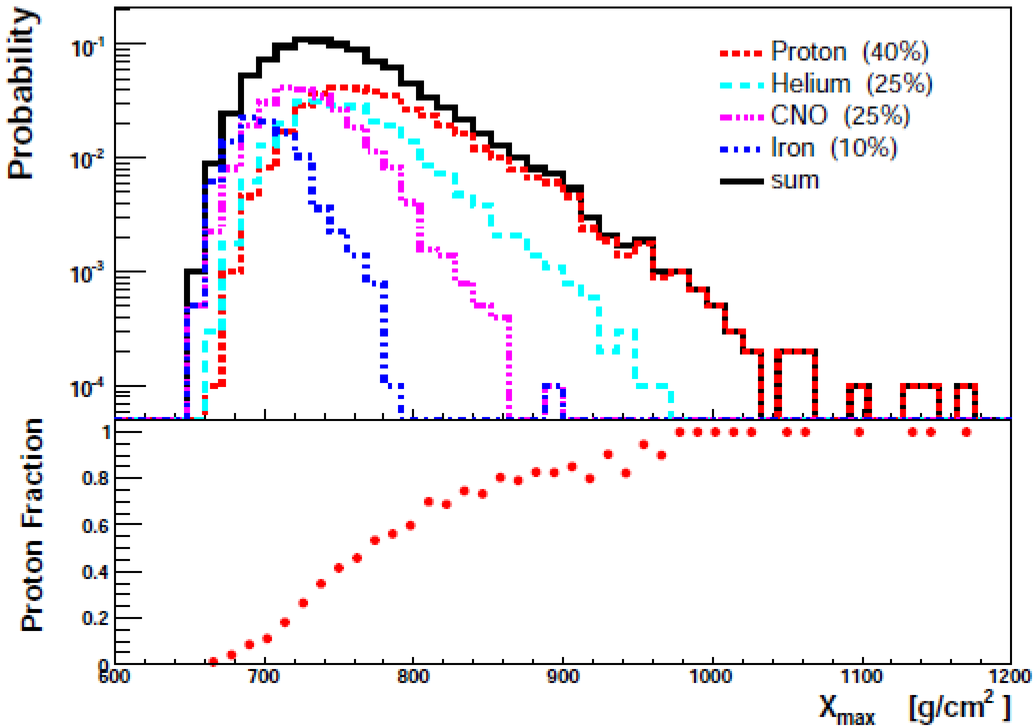
$\Rightarrow$ Tail of X_{max} – Distribution

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

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

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



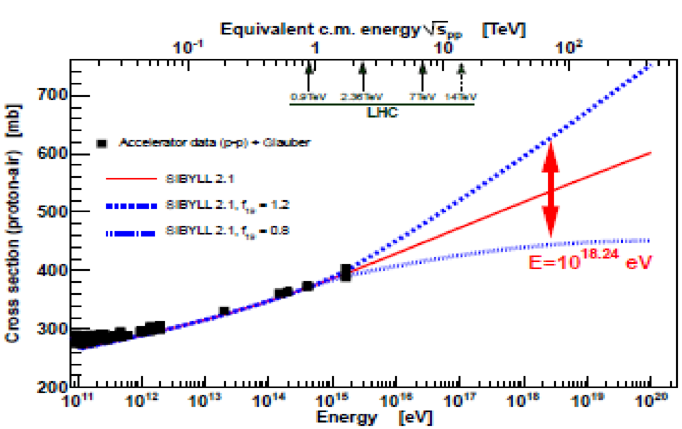


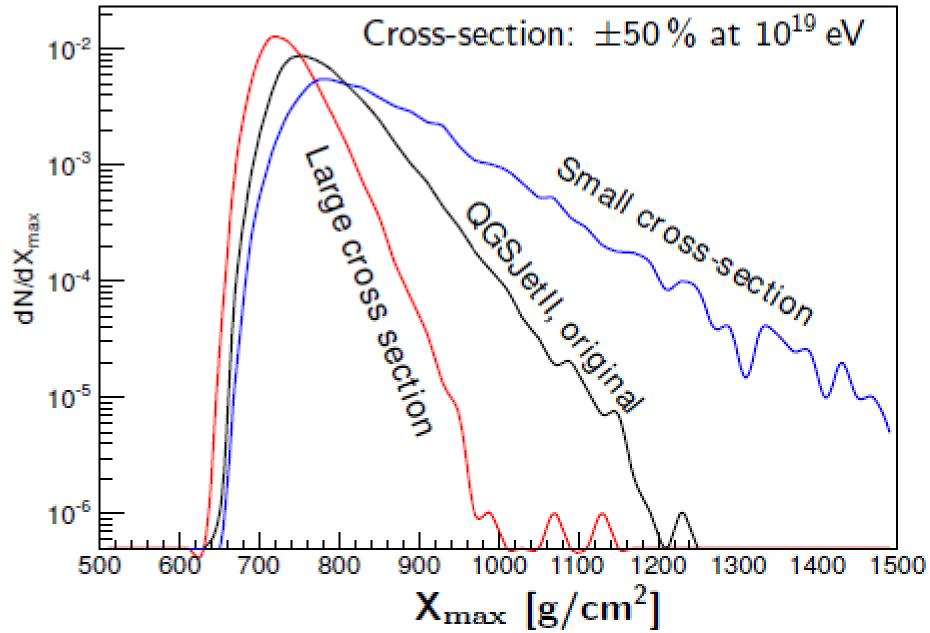
Method

Select deeply penetrating showers to enhanc
proton fraction
(Tail of X-max−Distribution

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

Simulation for proton showers
with different cross sections
(contiunous parametrization)
Very good sensitivity of tail of
distribution





Composition and energy range

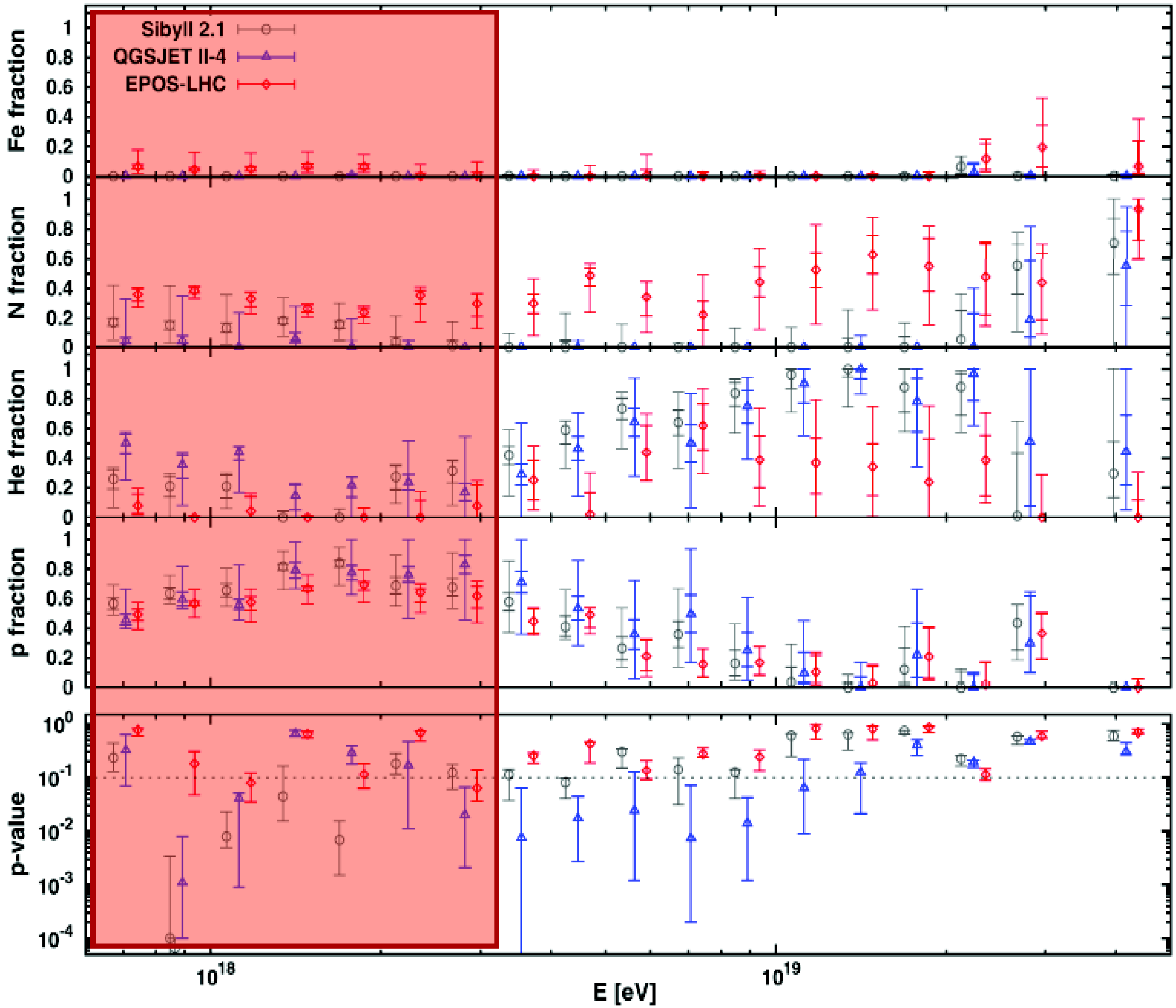
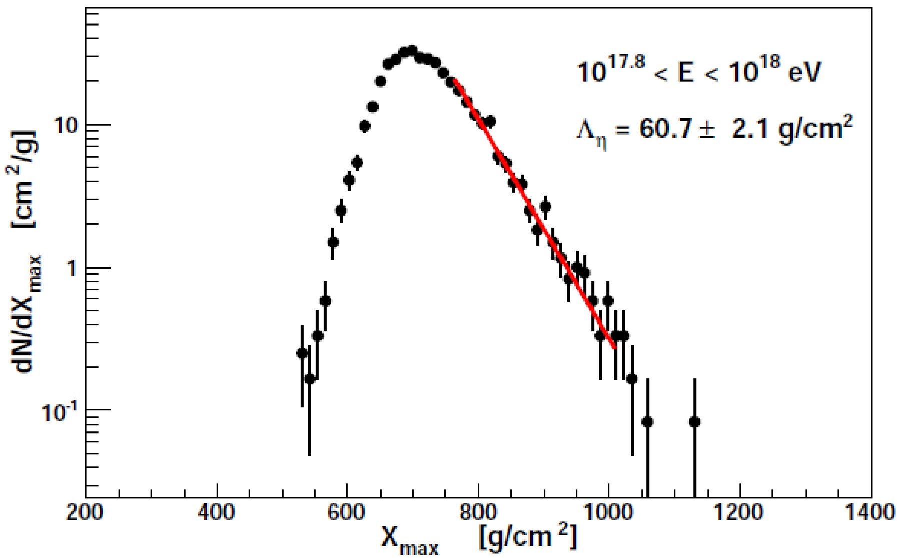


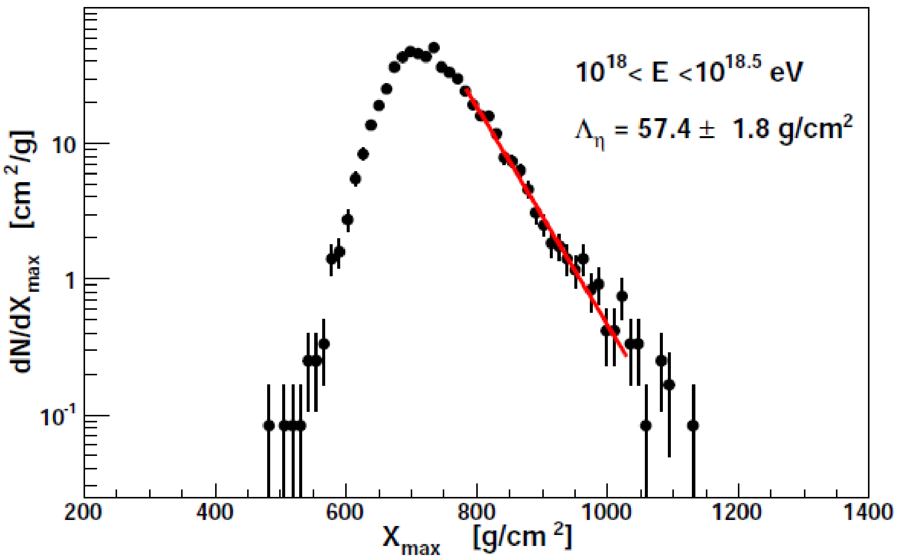
Figure from:
PRD 90, 122006 (2014)
Red area:
1e17.8 – 1e18.0 – 1e18.5 eV

- Most compatible with high proton fraction
- Helium fraction smallest

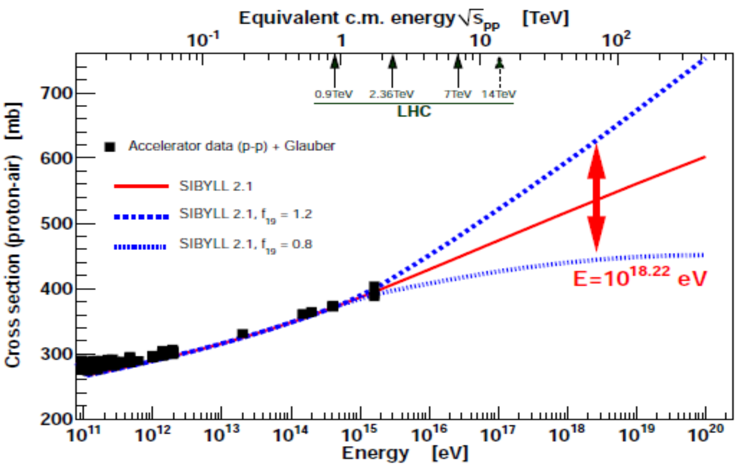
- at higher energies: proton decreases, helium increases

Measurement of Λ_η





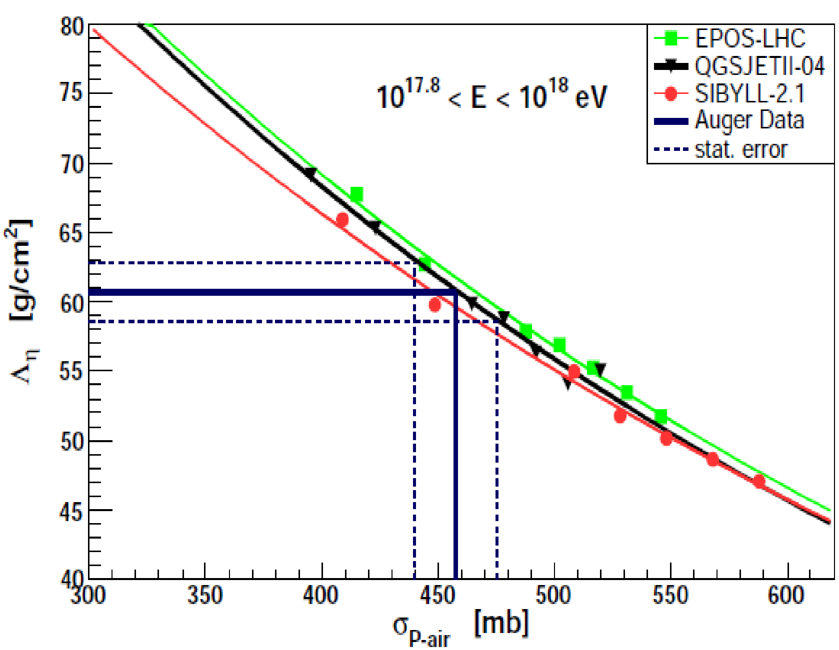
Conversion

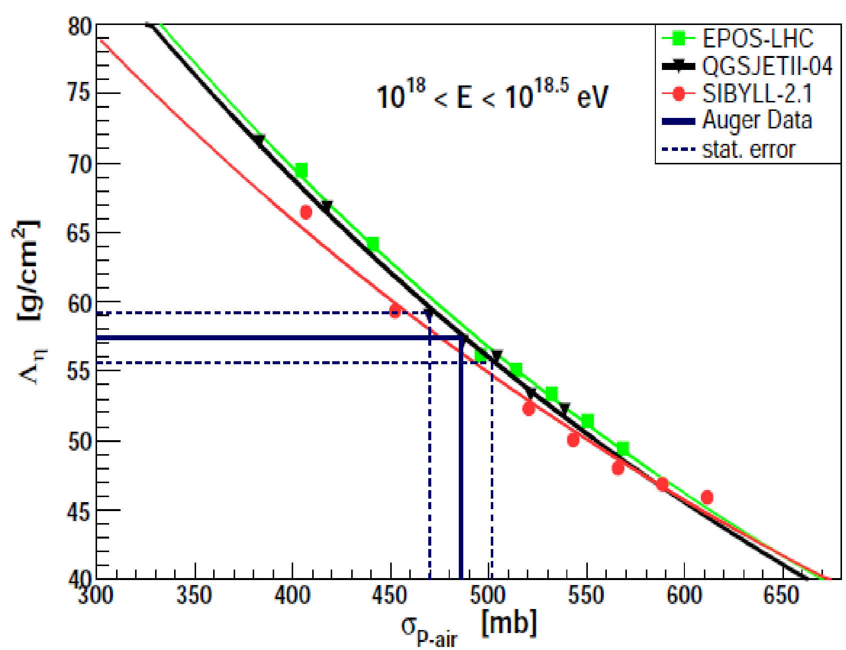


$$f(E,\ f_{19}) = 1 + (f_{19} - 1)\ F(E)$$

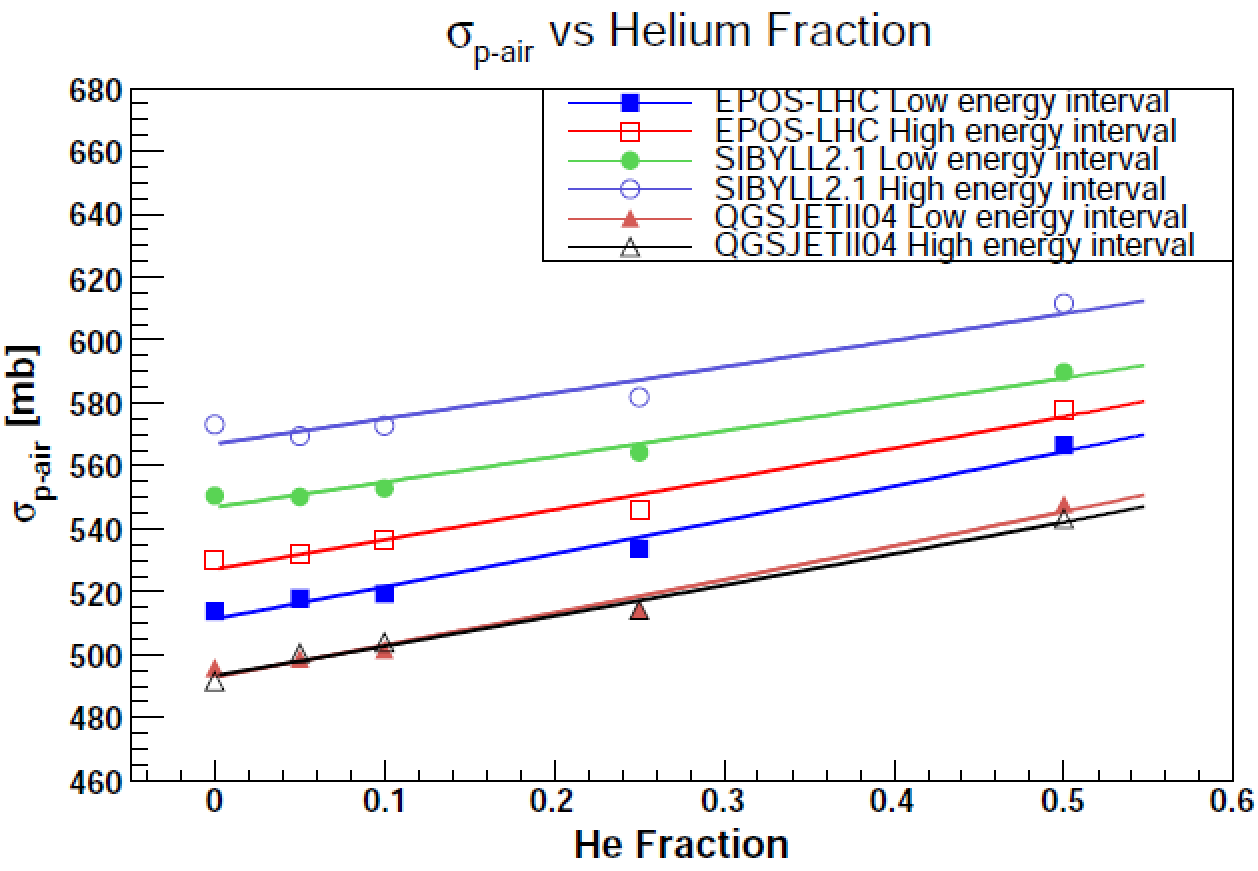
$$F(E) = \frac{\lg\left(E/10^{15}\,\mathrm{eV}\right)}{\lg\left(10^{19}\,\mathrm{eV}/10^{15}\,\mathrm{eV}\right)}$$

Simulations with f19:
Consistent description of cross-section
No discontinuities in cross-sect
predictions





Mass composition



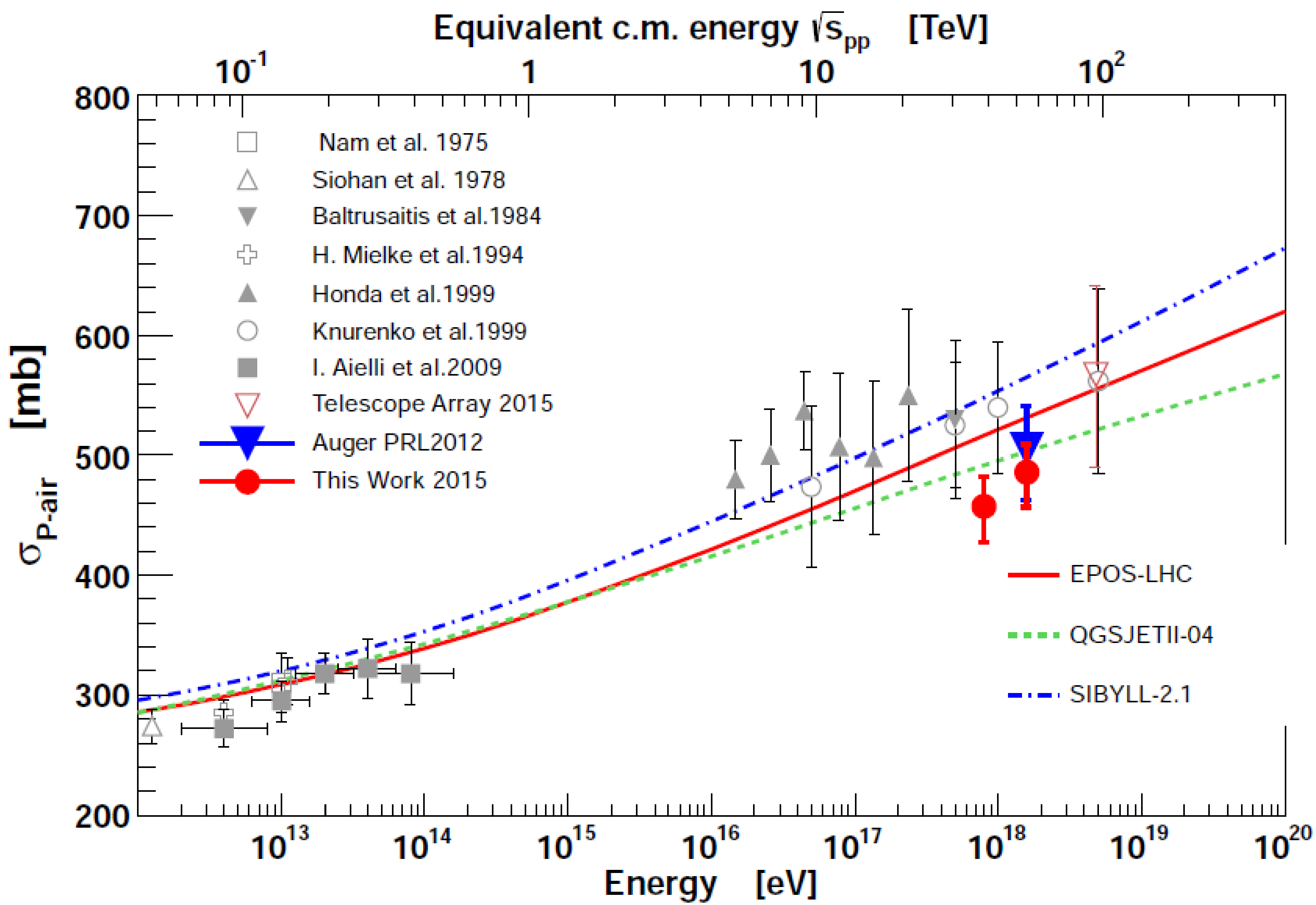
•Helium fraction does not exceed 25% in mass composition fits published by Auger
•Up to 25% Helium: induced bias < 20mb
•CNO induces no bias up to 50% of CNO.
•Up to 0.5% of Photons: induced bias < 10mb

Systematics

	$10^{17.8} - 10^{18}$ eV	$10^{18} - 10^{18.5}$ eV
Λ_η, systematic uncertainties (mb)	13.5	14.1
Hadronic interaction models (mb)	10	10
Energy scale uncertainty, $\Delta E/E = 14\%$ (mb)	2.1	1.3
Conversion of Λ_η to $\sigma_{\mathrm{p-air}}$ (mb)	7	7
Photons (mb)	+4.7	+4.2
Helium, 25% (mb)	-17.2	-15.8
Total systematic uncertainty on $\sigma_{\mathrm{p-air}}$ (mb)	+19/-25	+19/-25

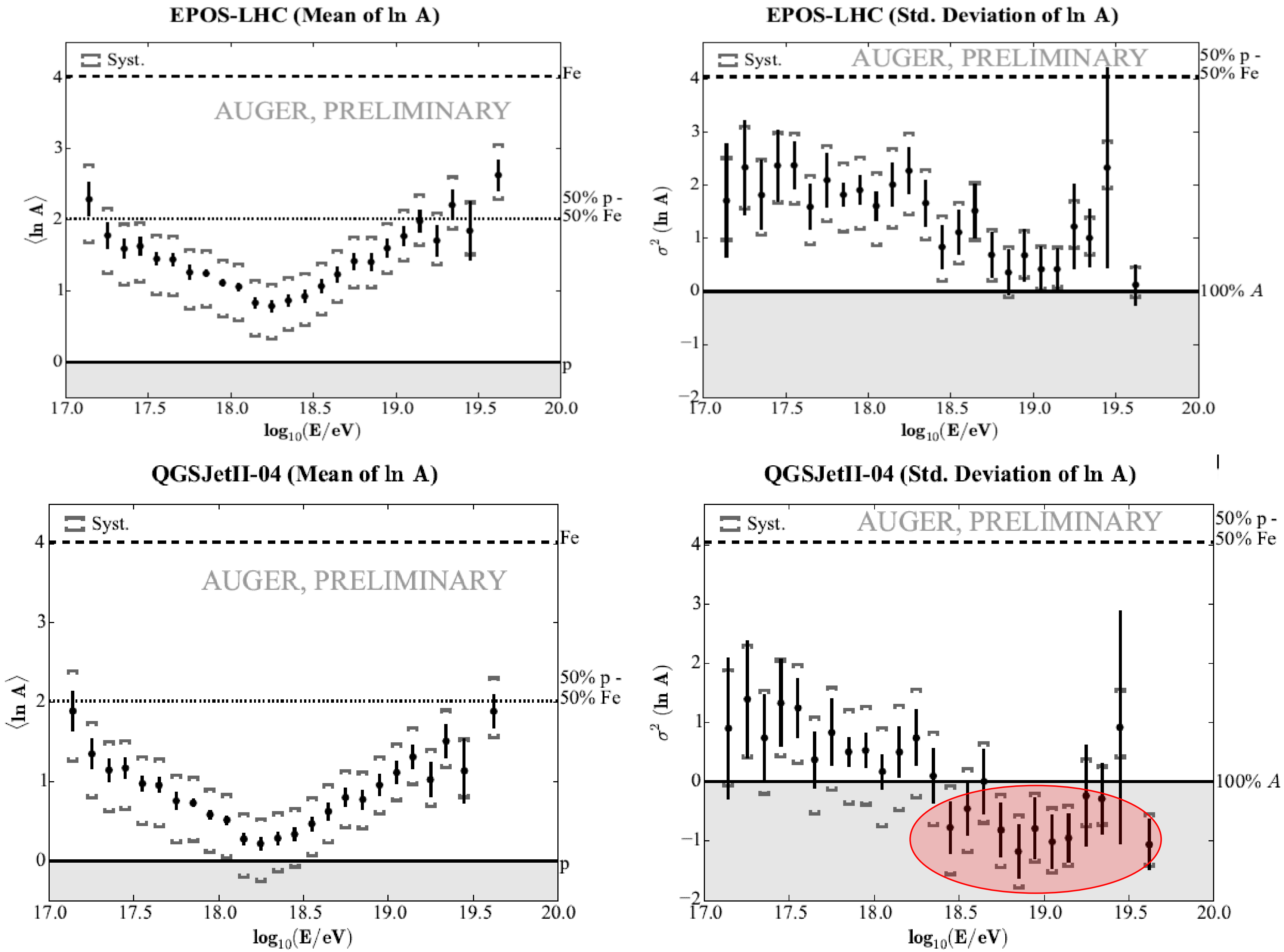
- Extensive cut-variation, sub-sample and parameter-scan analysis
- Helium bias most important
- Analysis design: Systematic uncertainties (!helium) on same level as statistical precision

Results



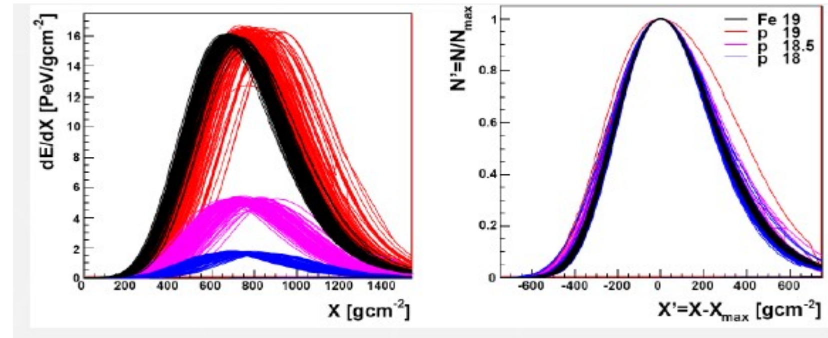
Equivalent c.m. energy $\sqrt{s}_{pp}$ [TeV]
10^-1
1
10
10^2
800
700
600
500
400
300
200
$\sigma_{P\text{-}air}$ [mb]
Nam et al. 1975
Siohan et al. 1978
Baltrusaitis et al.1984
H. Mielke et al.1994
Honda et al.1999
Knurenko et al.1999
I. Aielli et al.2009
Telescope Array 2015
Auger PRL2012
This Work 2015
EPOS-LHC
QGSJETII-04
SIBYLL-2.1
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
Energy [eV]

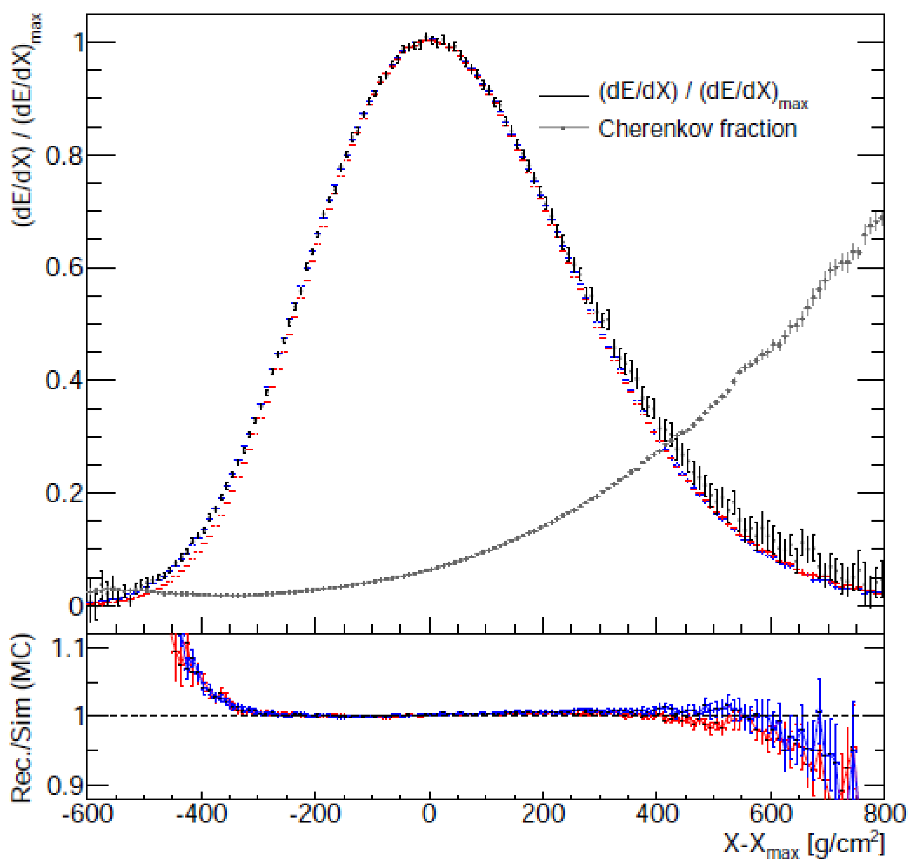
Mean and std. dev. of lnA

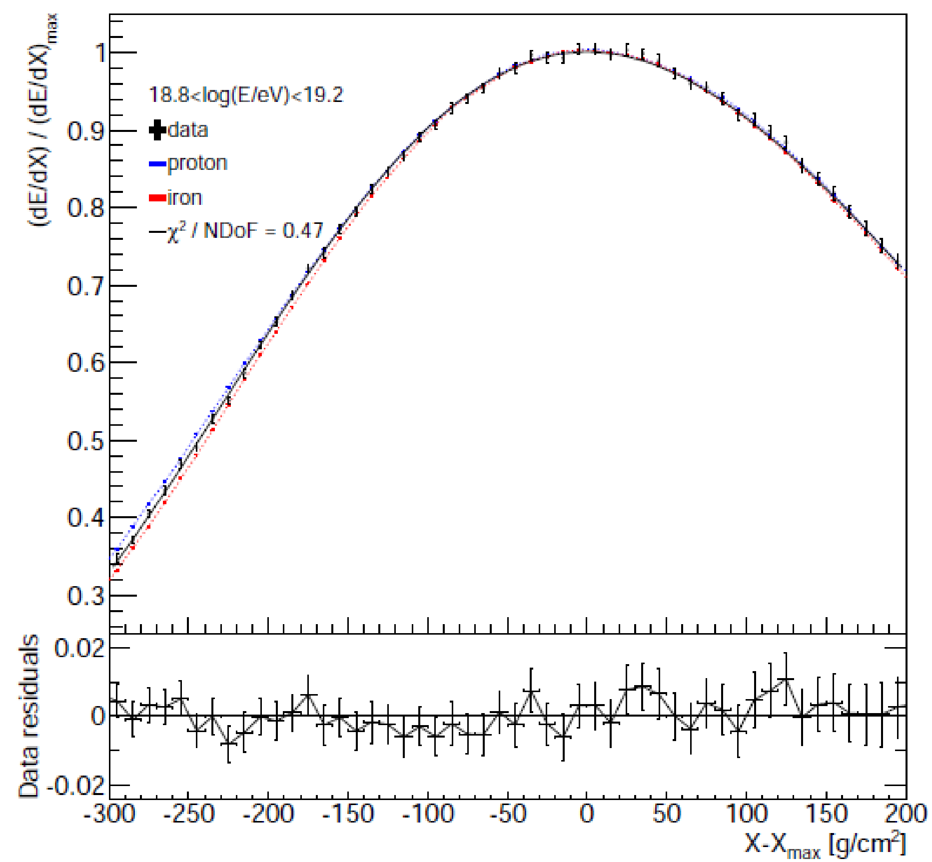


Average longitudinal profiles

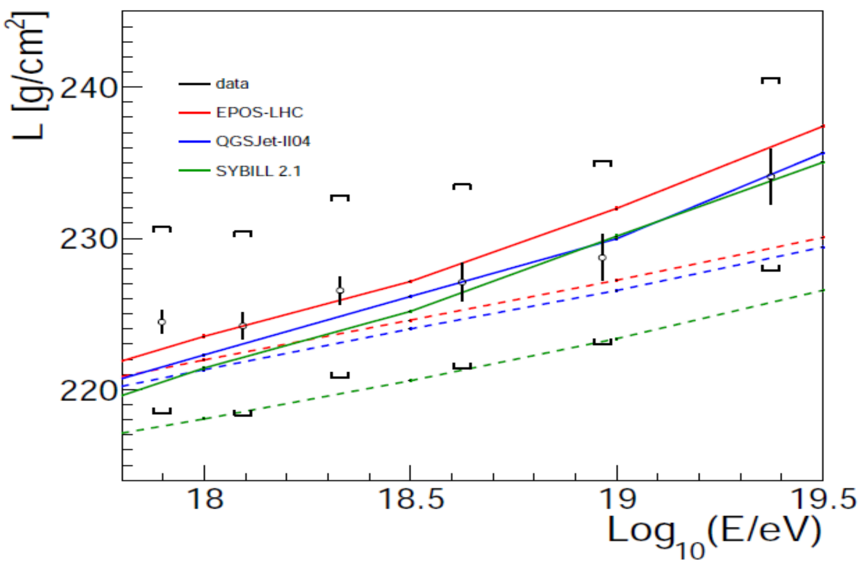
Profiles, when centered (X'=X-Xmax), normazized

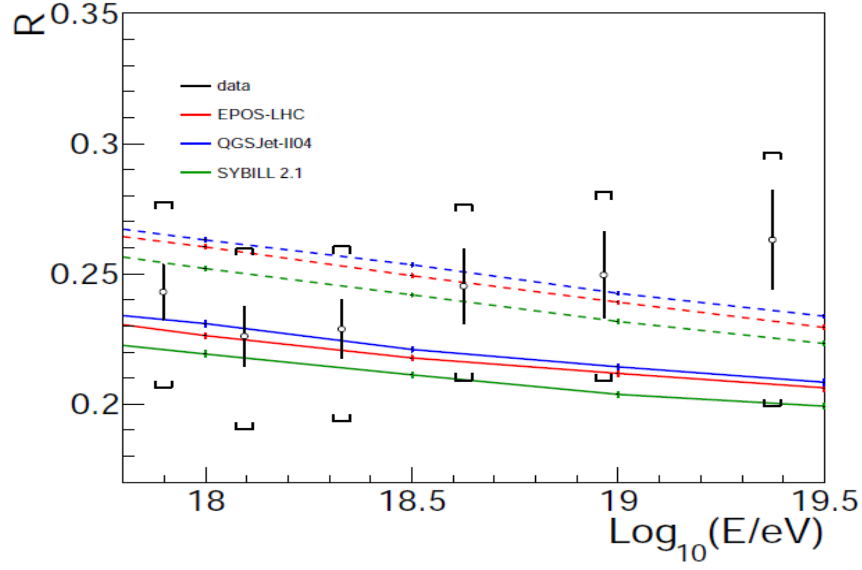


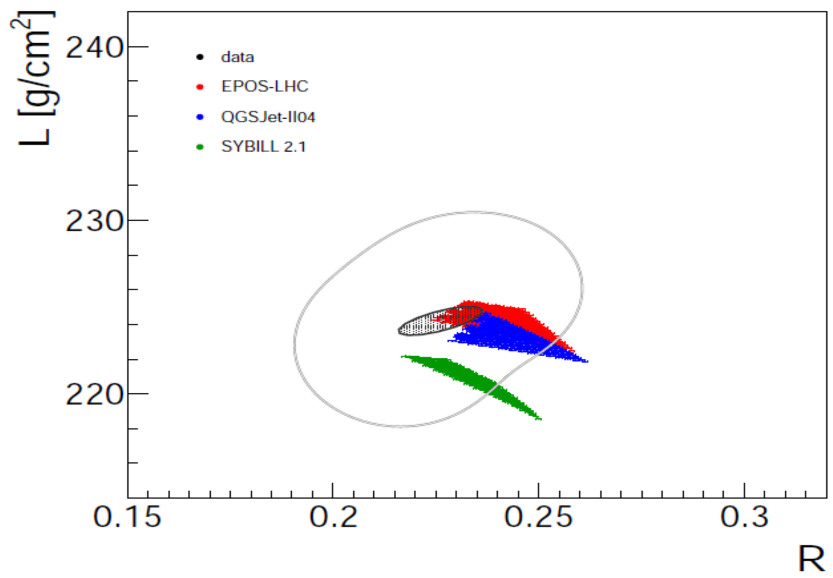


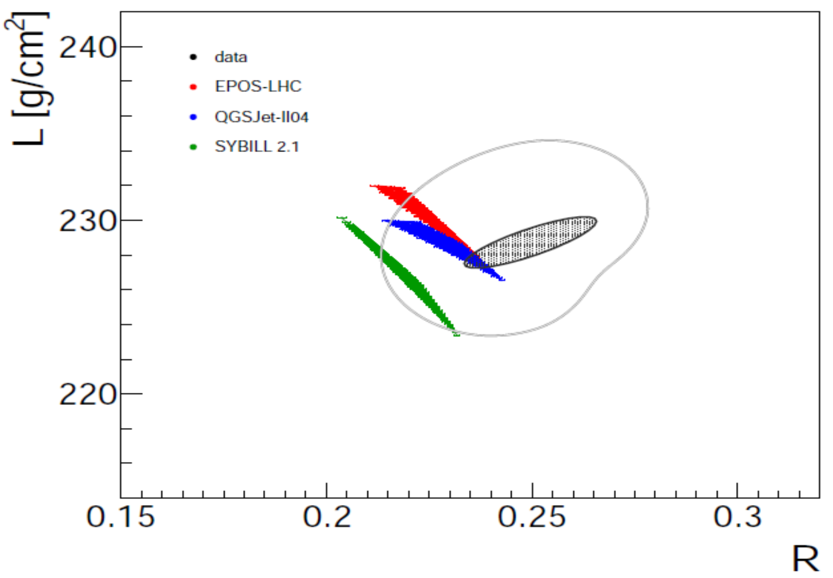


Shape parameters evolution with energy







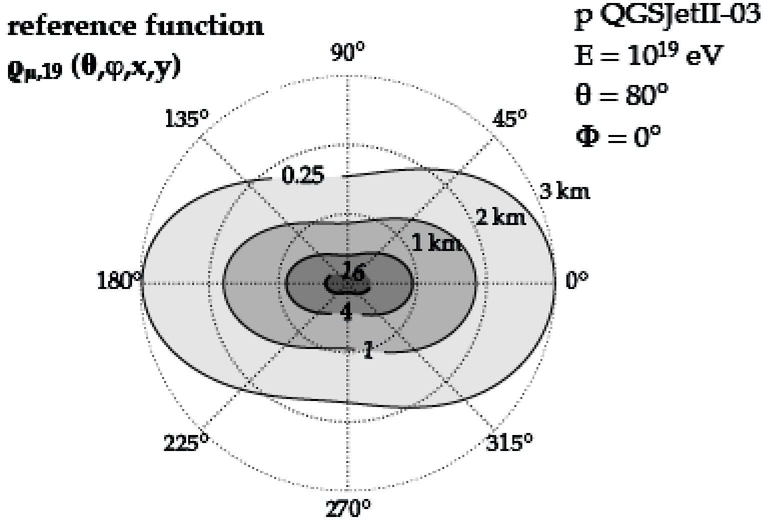


Muon Component

Muon content in inclined showers

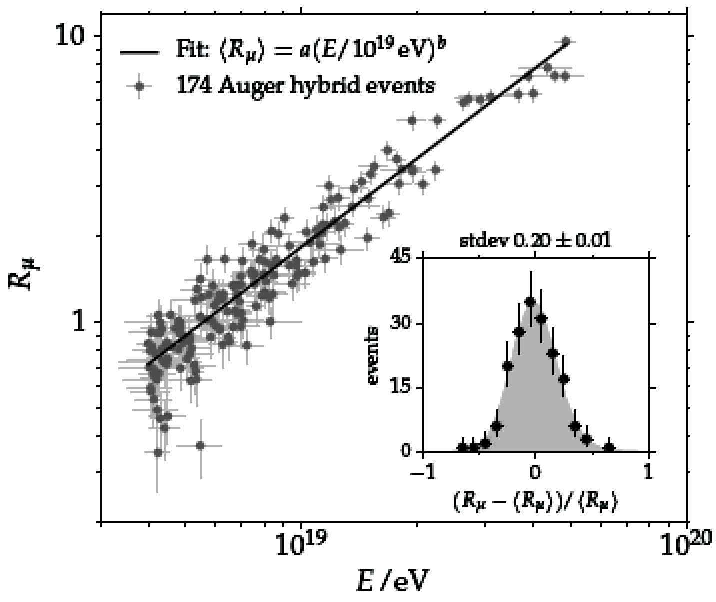
The number of muons per unit area at the ground level has a shape which is almost independent of energy, composition or hadronic model

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



The measured muon scale factor N19 with respect to muon reference density profiles is converted to

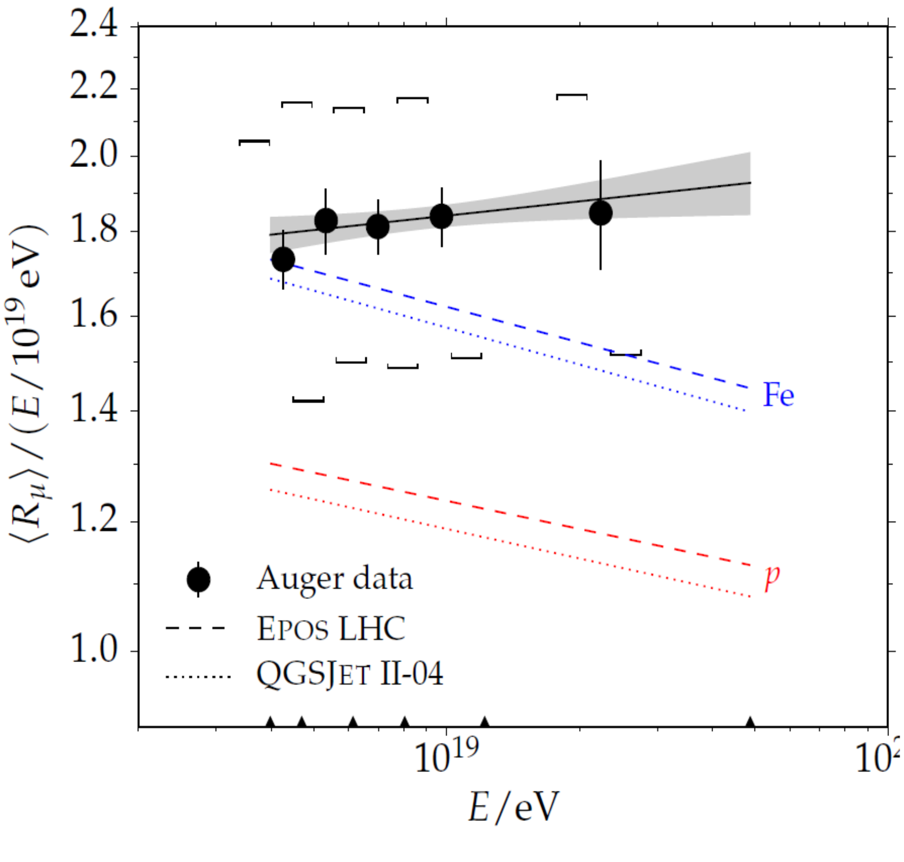
$$R_\mu = \frac{N_\mu^{data}}{N_{\mu,19}^{MC}}$$

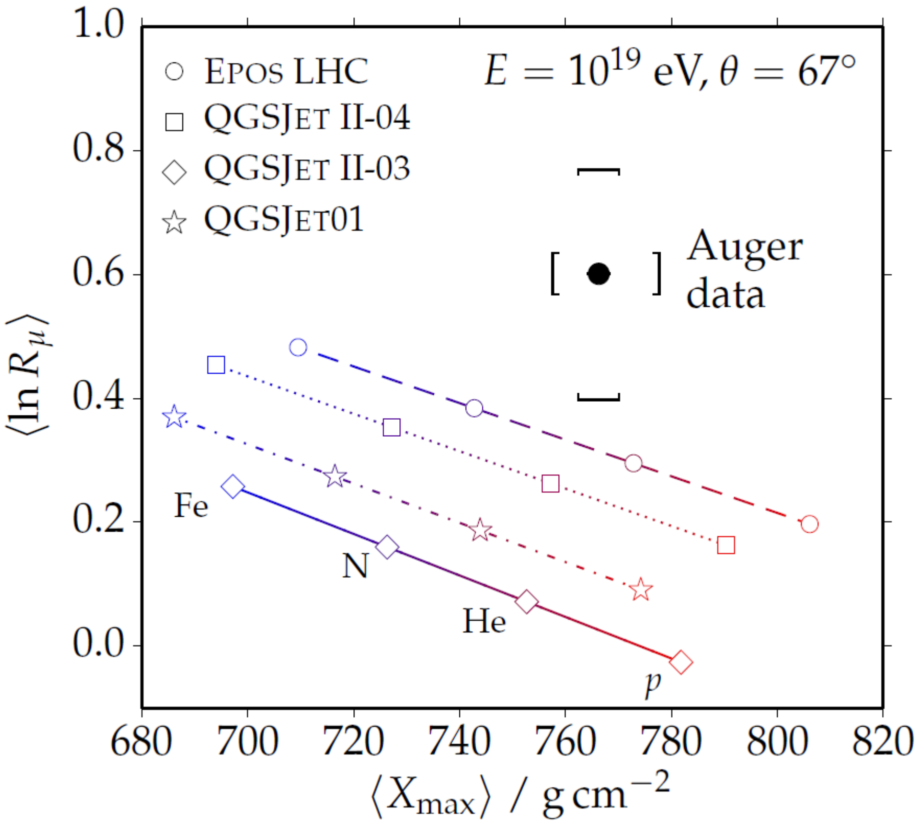


Analysis details:

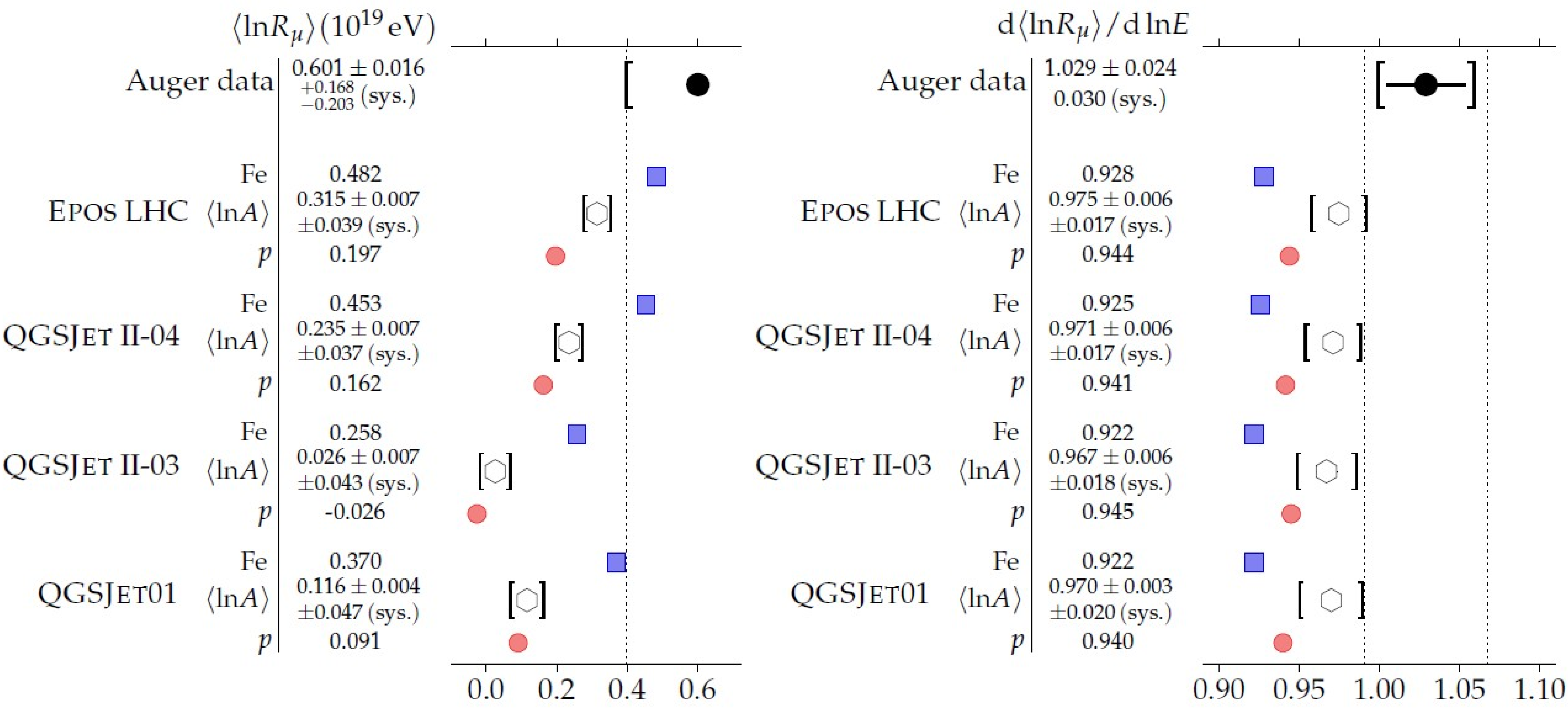
➤ data set: 01/2004 - 12/2013
➤ E > 4 x 1e18 eV (100% SD trigger)
➤ zenith angles [62°, 80°] (low EM contamination)
➤ 174 hybrid events after quality cuts
➤ systematic uncertainty on Rμ: 11%

Muon Scale results





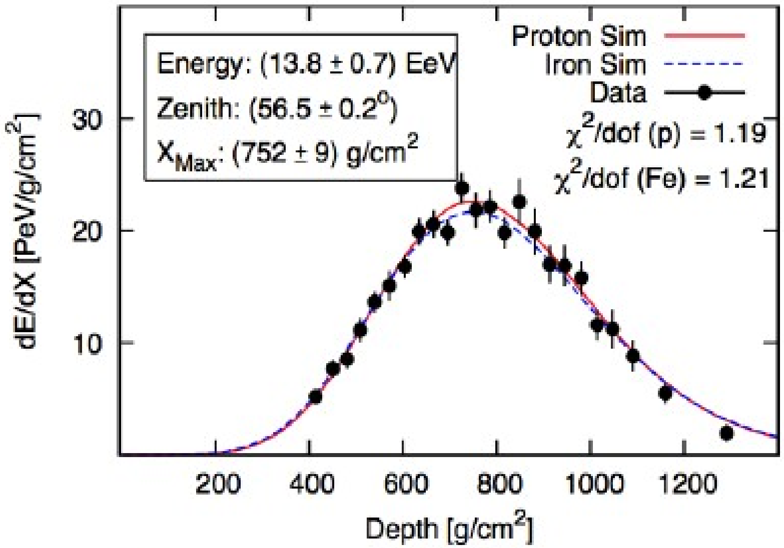
Average muon content and its derivative with energy

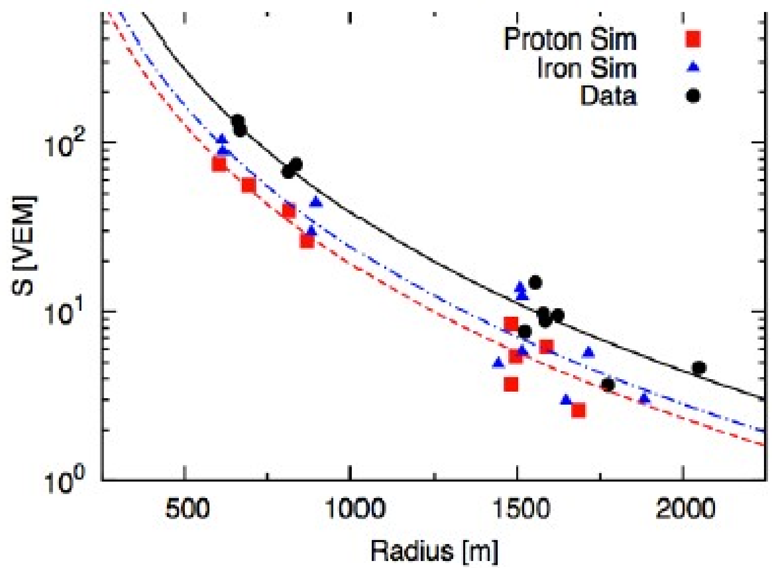


Muon deficit from 30% to 80% at 1e19 eV depending on the model:
Best case for EPOS-LHC

Deviations from a constant proton (iron) at the level of 2.2 (2.6) σ

Hadronic & EM scaling in vertical showers





MC simulations selected to match Xmax data (LP)

Then, ground signal components are rescaled to fit data (LDF)

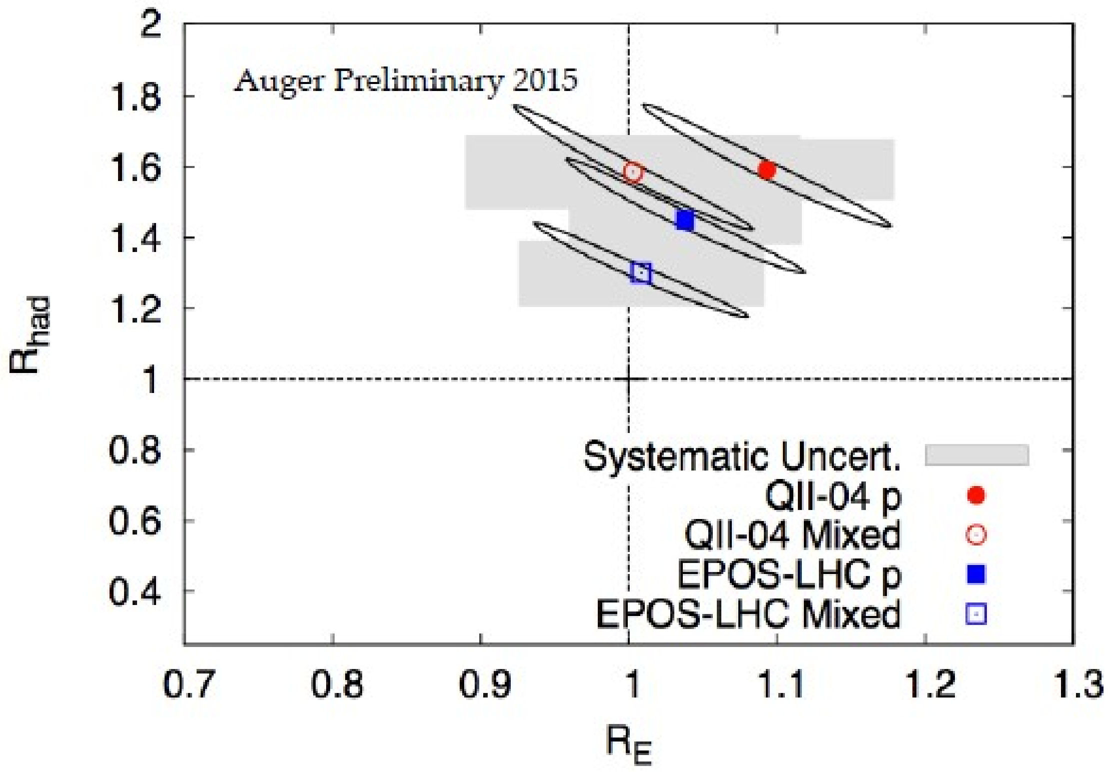
Rescaling factors:

R_E Signal from EM shower origin.

R_{had} Signal from hadonic shower origin.

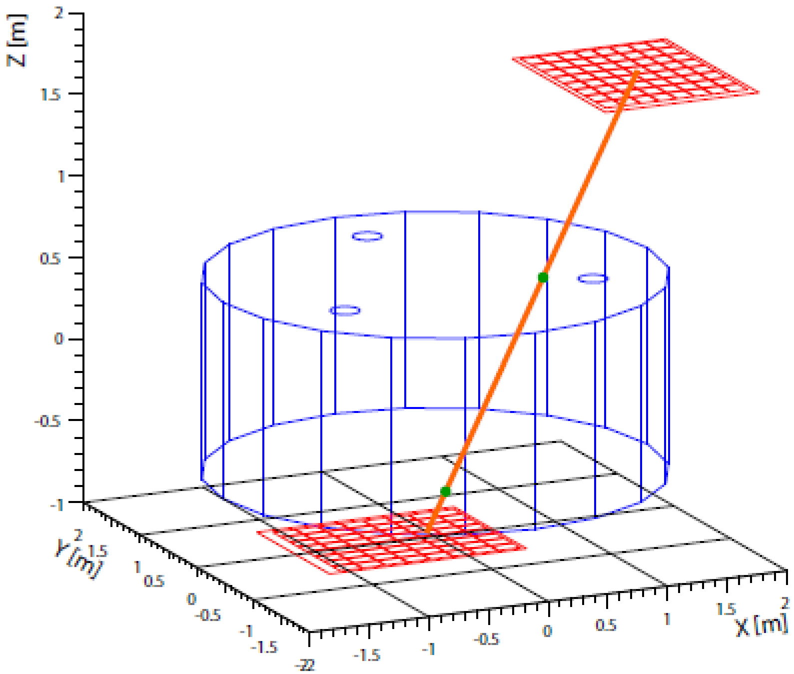
Data details:
- Data set 01/2012 – 12/2014
- log(E/eV)=[18.8,19.2]
- Zenith angle 0- 60 deg
- 411 hybrid events after cuts

Results on the R_{had}-R_E plane

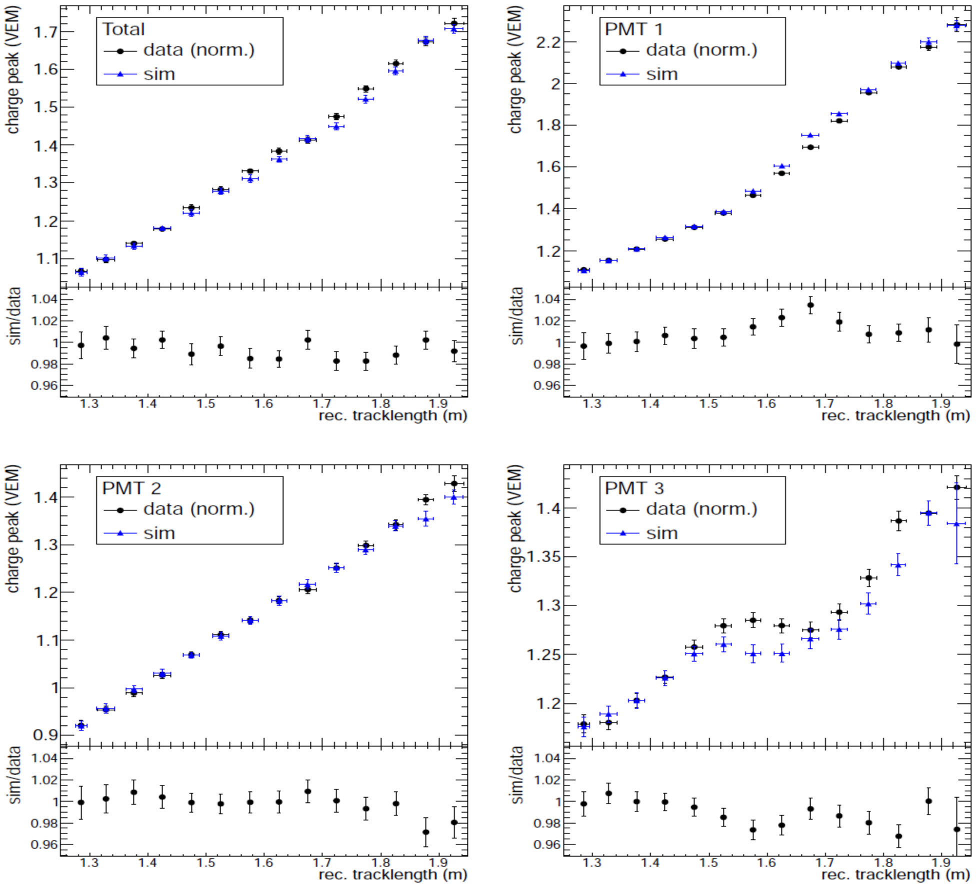


- No energy rescaling is needed
- The observed muon signal is a factor 1.3 to 1.6 larger than predicted by models
- Smallest discrepancy for EPOS-LHC with mixed composition, at the level of 1.9 σ

Validation of tank simulations with a Muon Telescope



Reconstruction of a track



Two segmented RPCs above and beneath the Gianni-Navarra tank reveal a good match between tank simulations and measurents (signal vs tracklengh)

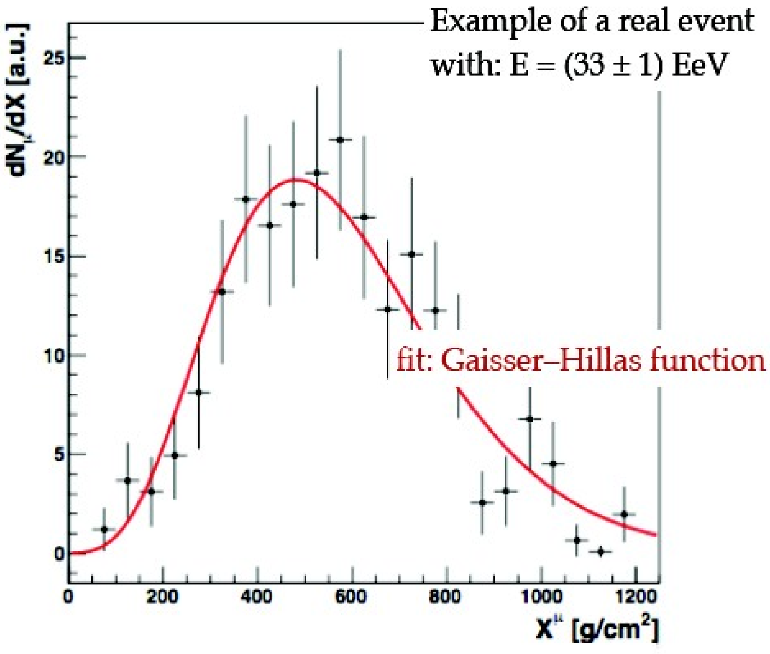
Muon production depth

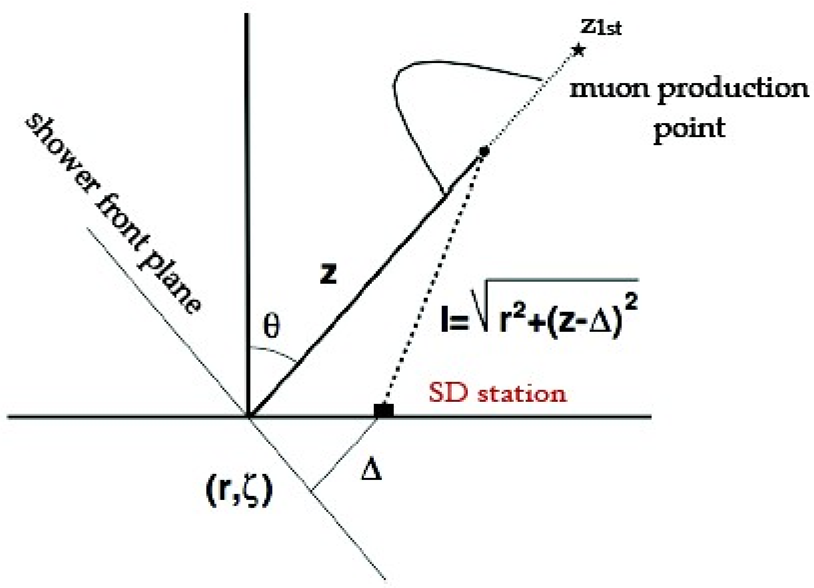
Muon Production Depth profile can be estimated from the muon arrival times distributions

Two assumptions:
♦ Muons are produced in the shower axis
♦ Muons travel following straight lines

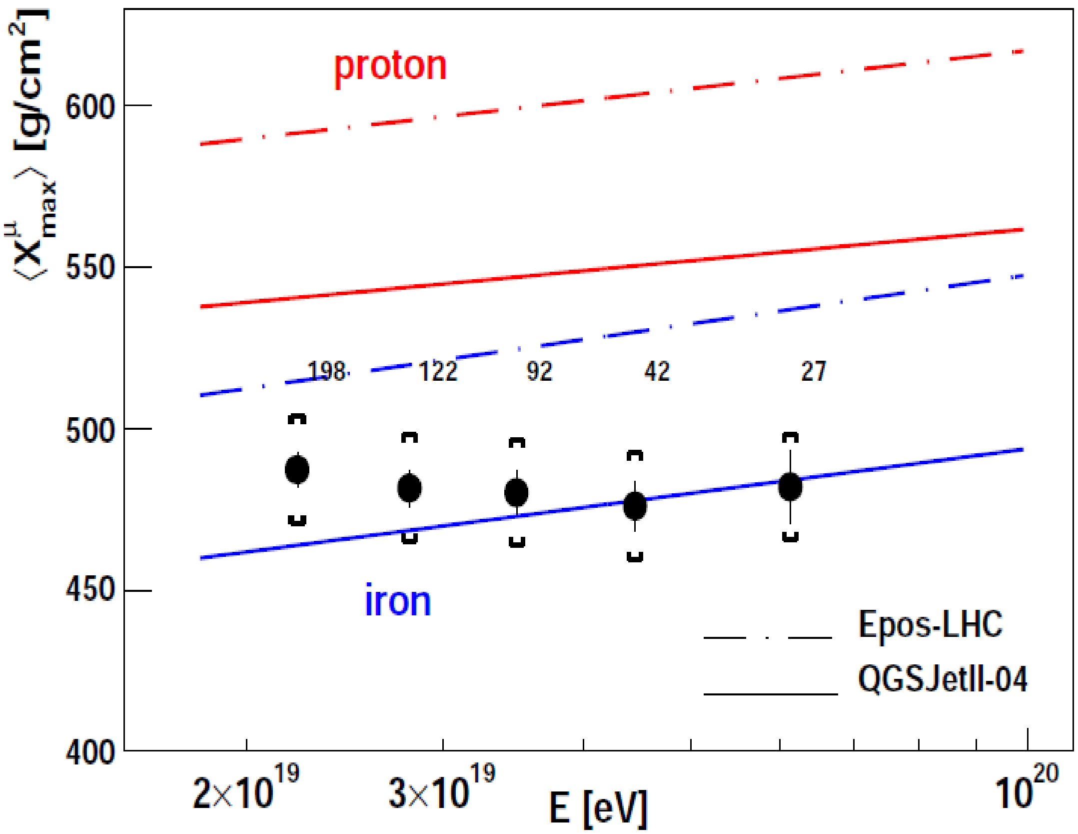
Map from t to z muon by muon

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





Xμmax vs. energy



data set: 01/2004 – 12/2012

E > 1e19.3 eV

zenith angles [55°,65°]

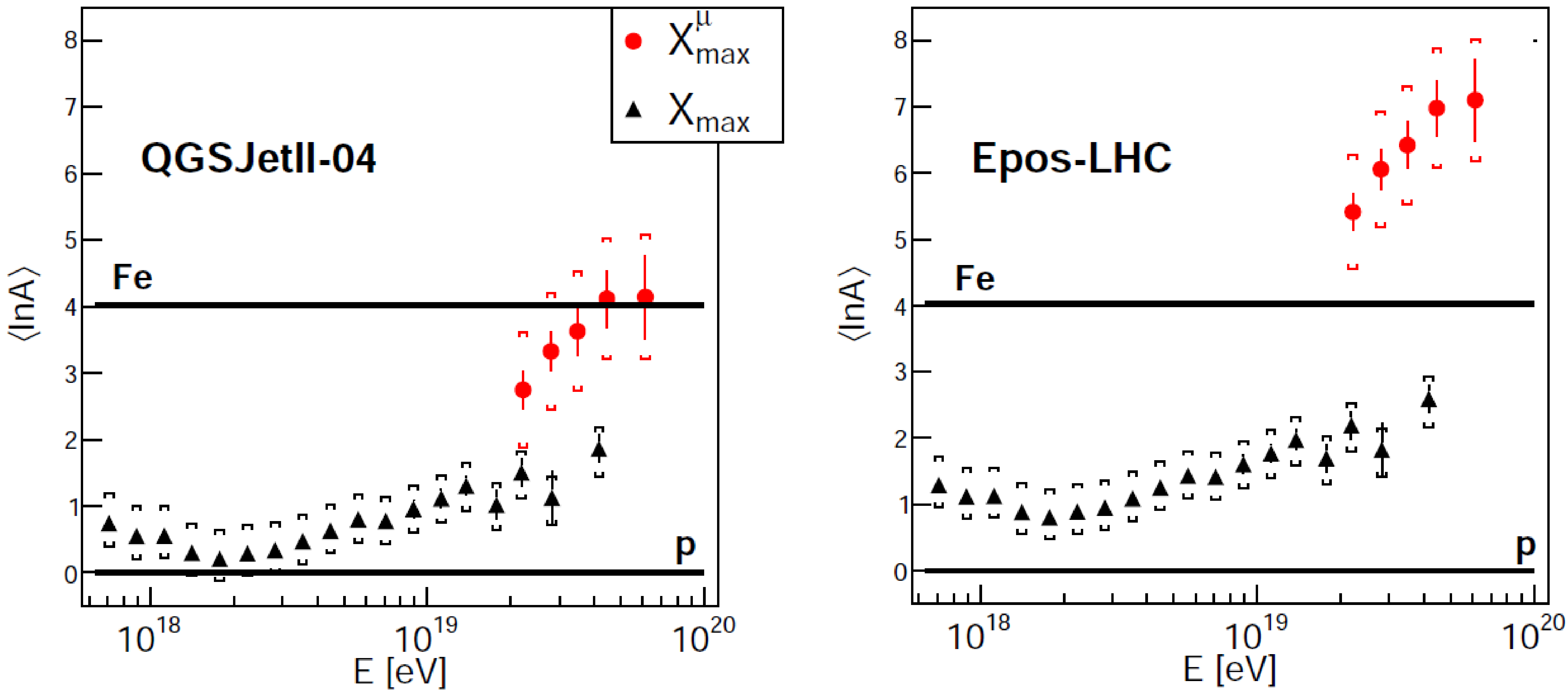
Core distances [1700 m, 4000 m]
(more muons/event)

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

Conclusions I

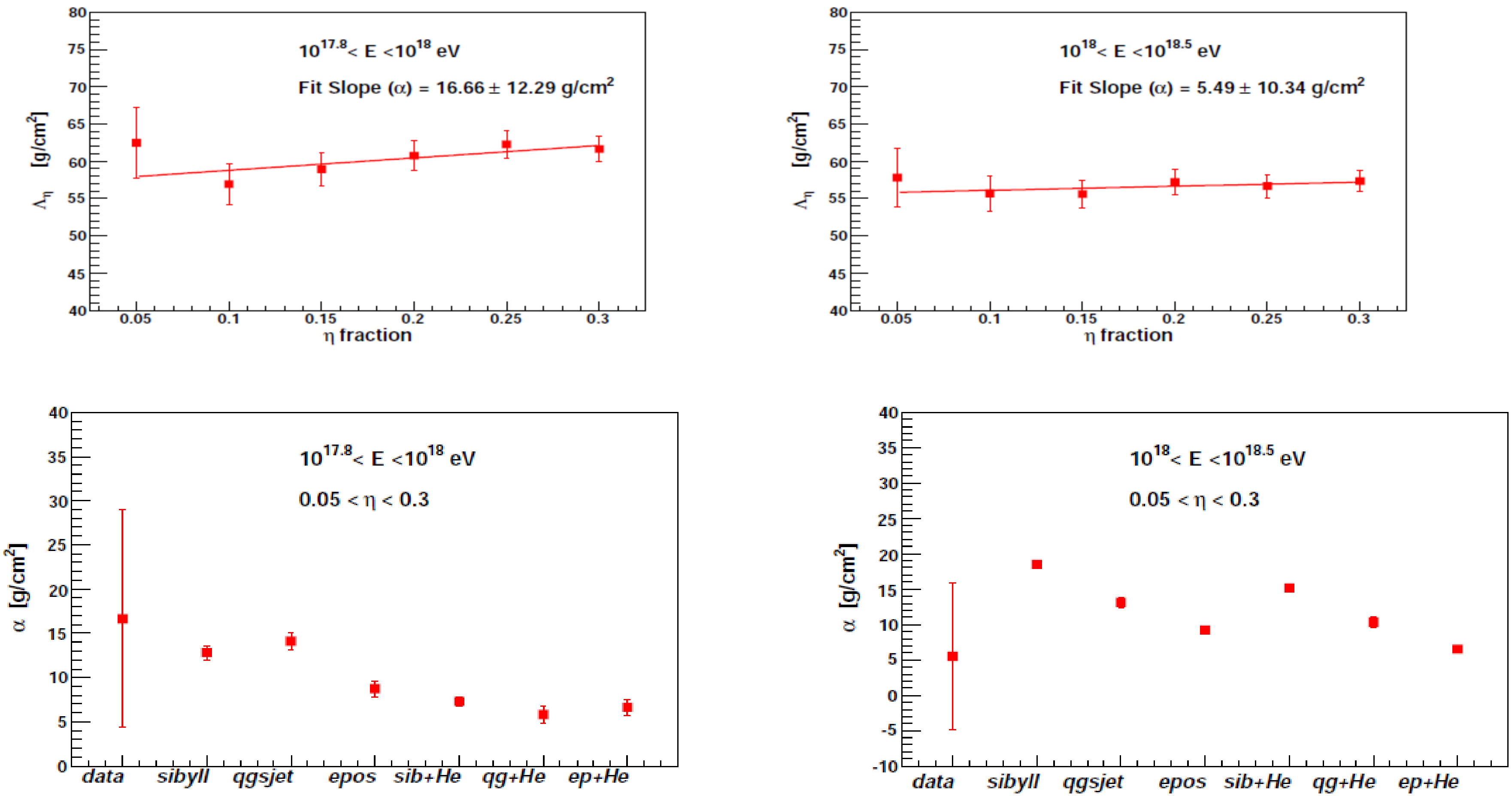
- Xmax momenta:
  - tension with V(lnA) from QGSJetII.04
- p-Air cross section:
  - Update with more statistics
  - Two energy bins well above LHC energies
  - Improved study of systematics. Helium dominated
  - Monte Carlo systematics smaller after LHC tuning
- Average EM Longitudinal Shape:
  - Data and models match within systematics.

Conclusions II

- We observe a muon deficit in the simulation (vertical and inclined)
- No need for EM rescaling
- Best model in muon content (EPOS-LHC) fails to describe the MPD
  - A small change in pion-air inelasticity can induce cumulative effect on MPD, and likely on the total number of muons (T.Pierog ICRC2015)
- Air shower data are constraining the post LHC hadronic models


Thanks!

Stability of Λ_η



•Slope in data and different simulation scenarios do not indicate any discrepancy incompatible with the assumptions of the analysis

•This can change with the choice of air shower energies, e.g. because of a changing mass composition

p-p cross section