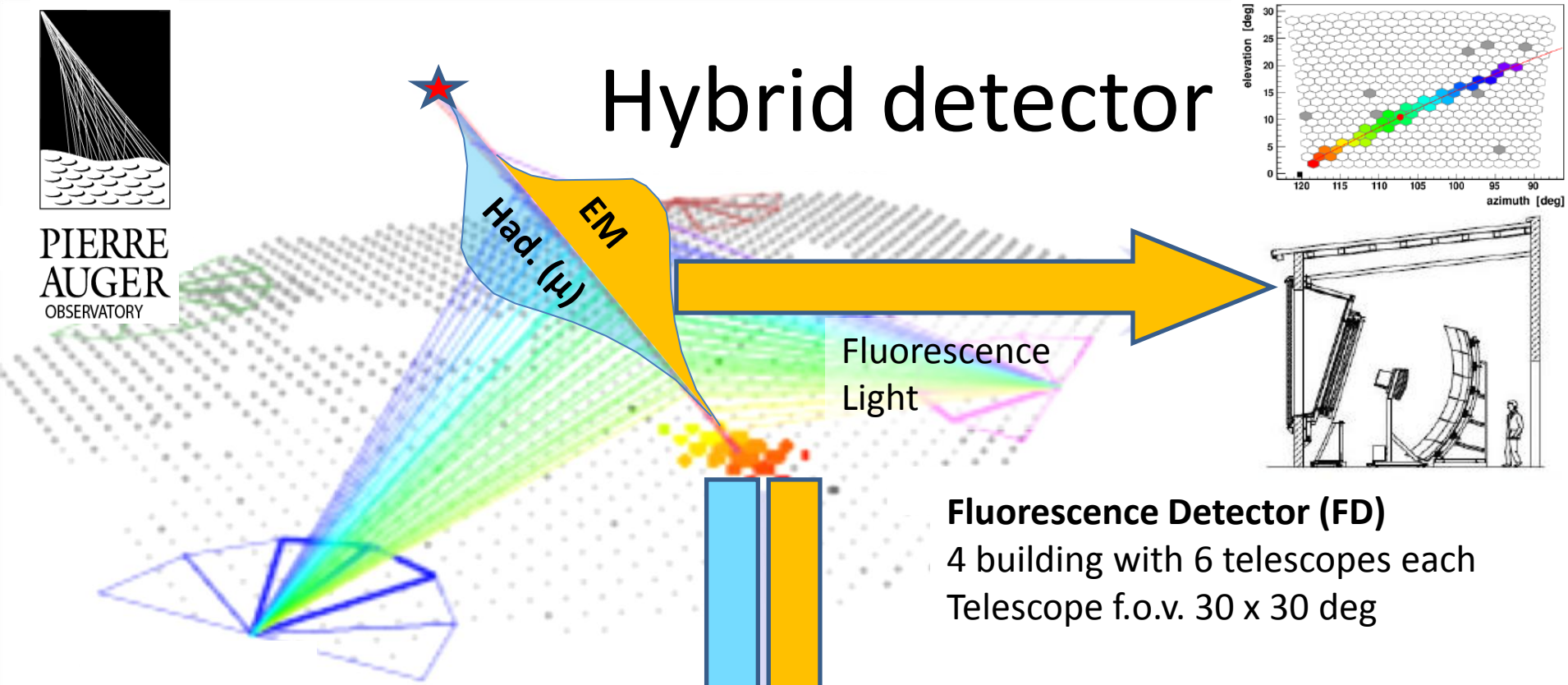
Constraints and measurements of hadronic interactions in extensive air showers with the Pierre Auger Observatory

L. Cazon, for the Auger Collaboration

Hybrid detector

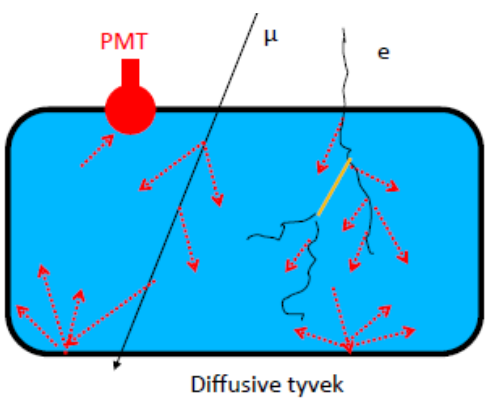


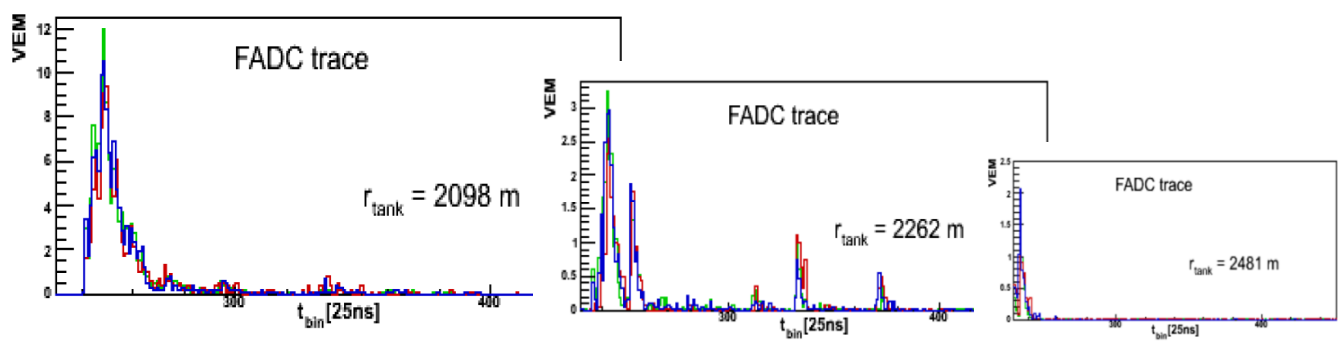
Fluorescence Detector (FD)
4 building with 6 telescopes each
Telescope f.o.v. 30 x 30 deg

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

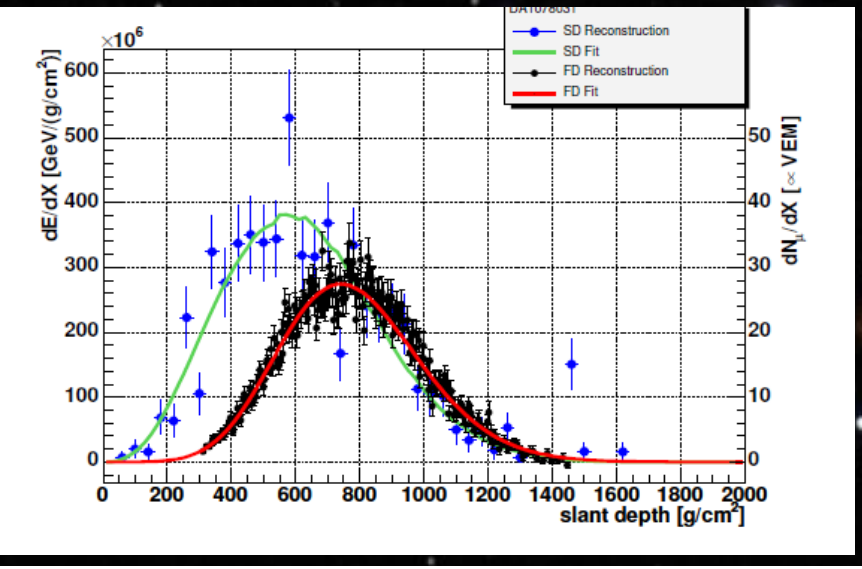
Secondary
Particles

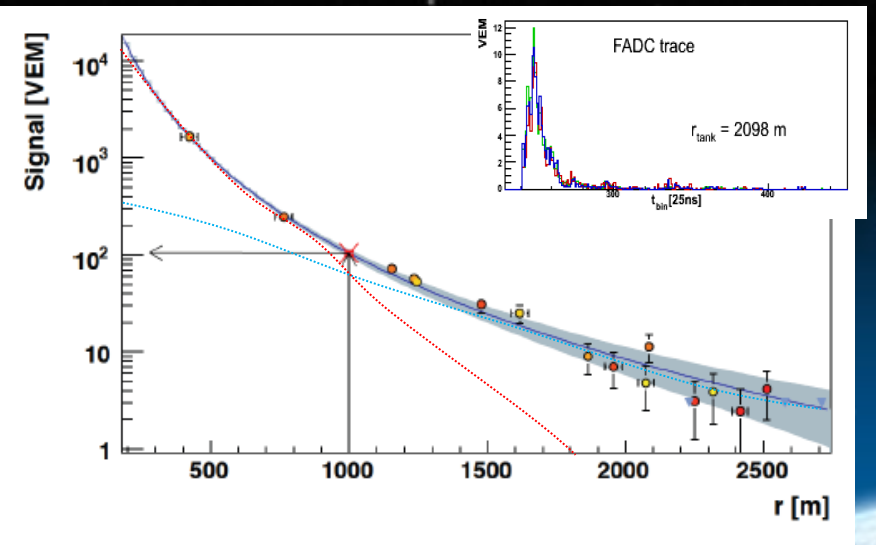
SD & FD
Enhancements





Auger observables at a glance





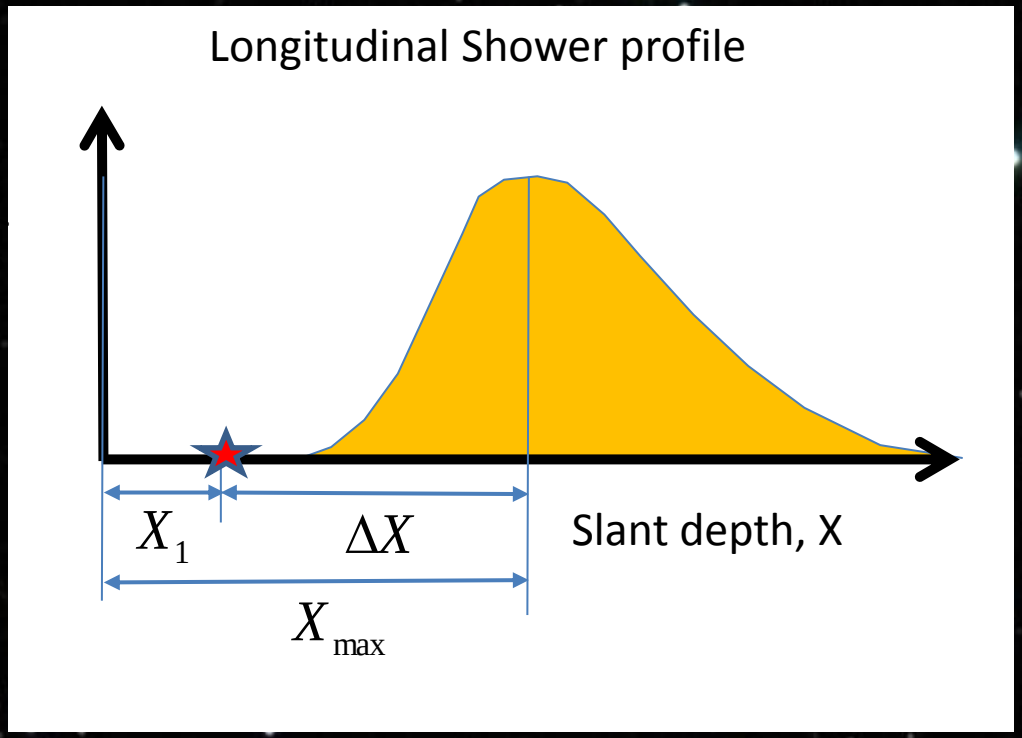
Longitudinal development

- EM profile (FD)
- Muon Production profile (SD)
  - Time structure of muon dominated regions

Lateral ground distribution

- All particles (total signal)
- Pure muonic
  - Inclined showers
- EM/Mu separation
  - Time structure

p-Air cross section

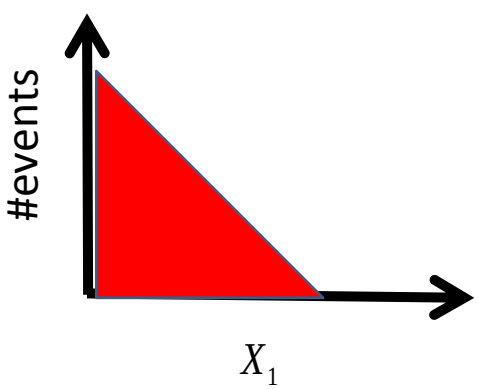


$$\sigma_{\text{int}} = \frac{< m_{air} >}{\lambda_{\text{int}}}$$

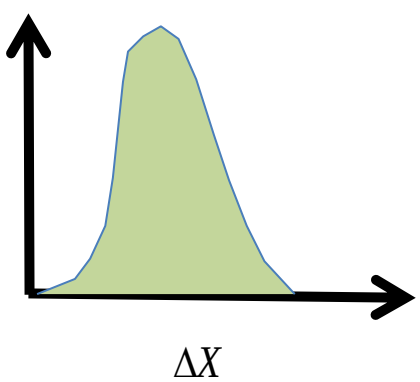
$$\frac{dp}{dX_1} = \frac{1}{\lambda_{\text{int}}} e^{-X_1/\lambda_{\text{int}}}$$

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

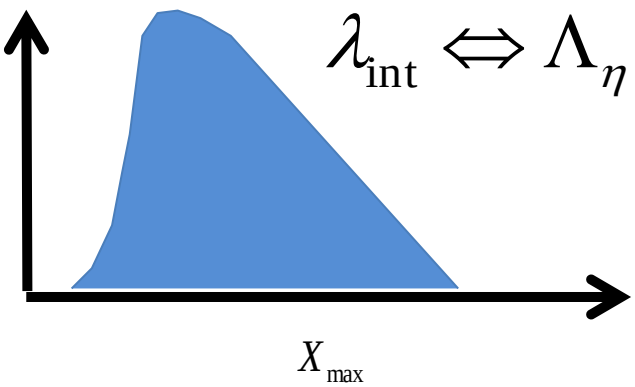
$dN/dX_{max} \propto \exp(-X_{max}/\Lambda_\eta)$

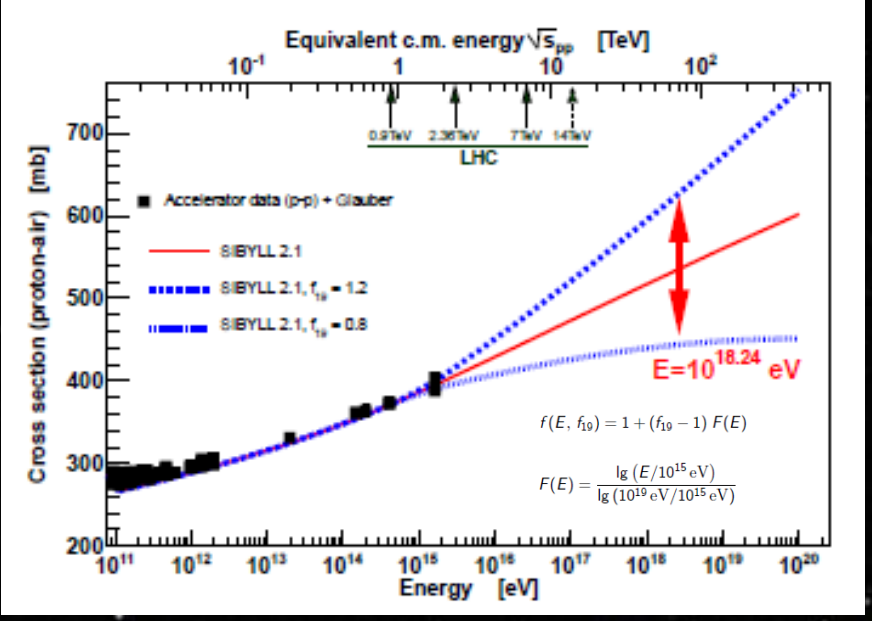


$\oplus$



$=$



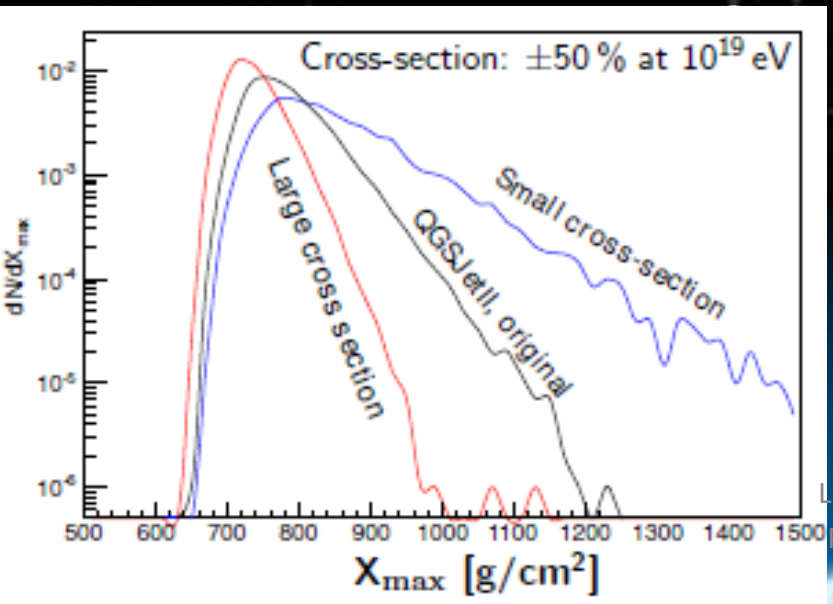


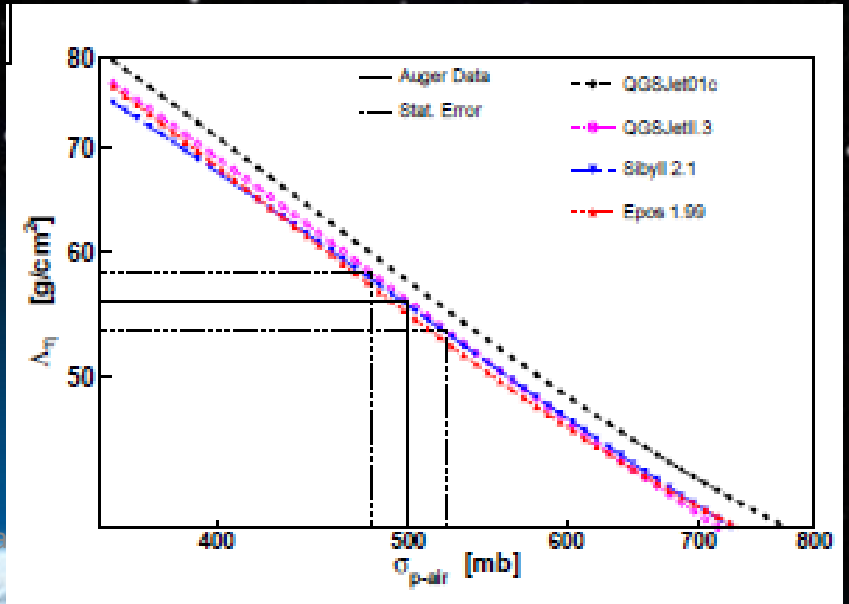
Method

- Continuous reparameterization of cross section in MC

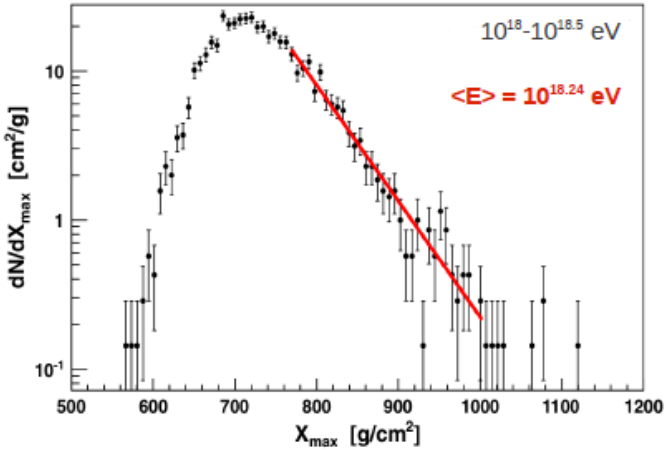
- Simulation of X_{max} distribution
  - different rescalings
  - different models

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



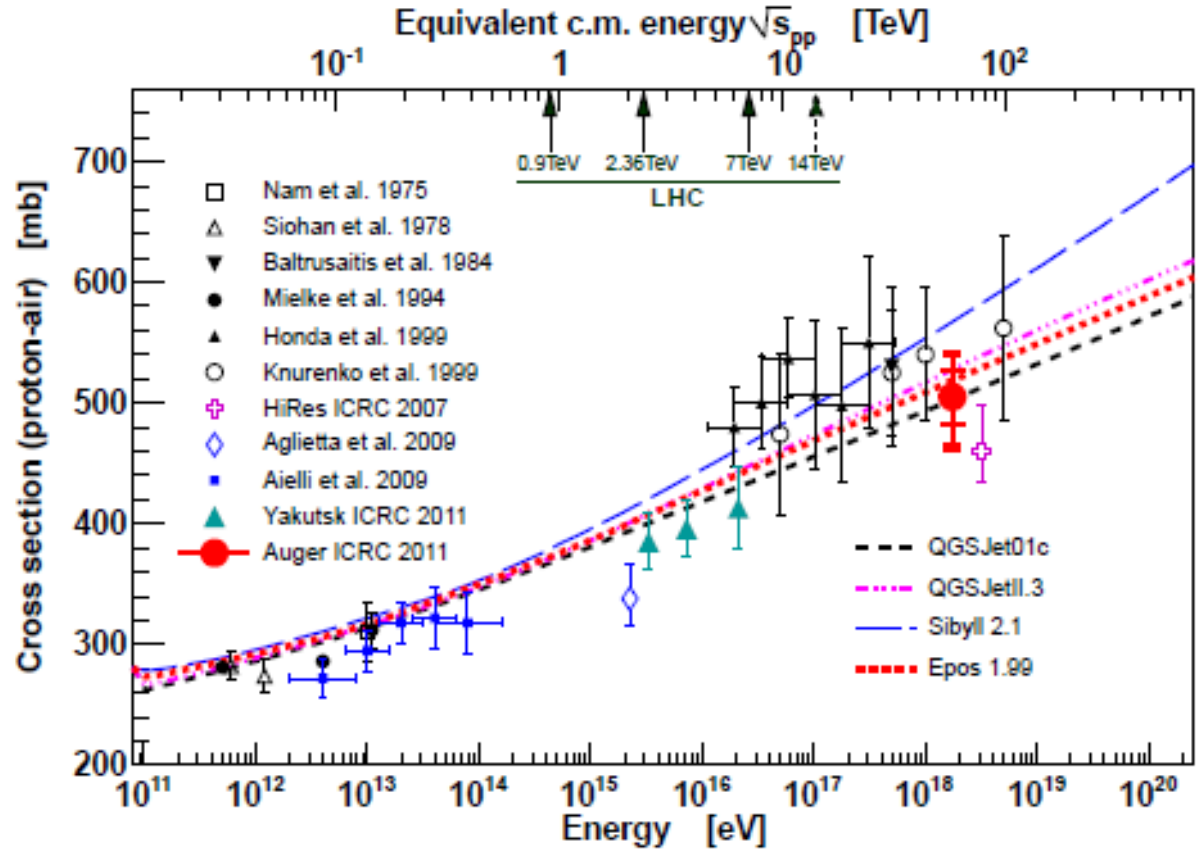


Results



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

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



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

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

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

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

See more details in PRL 2012 and ICRC2011

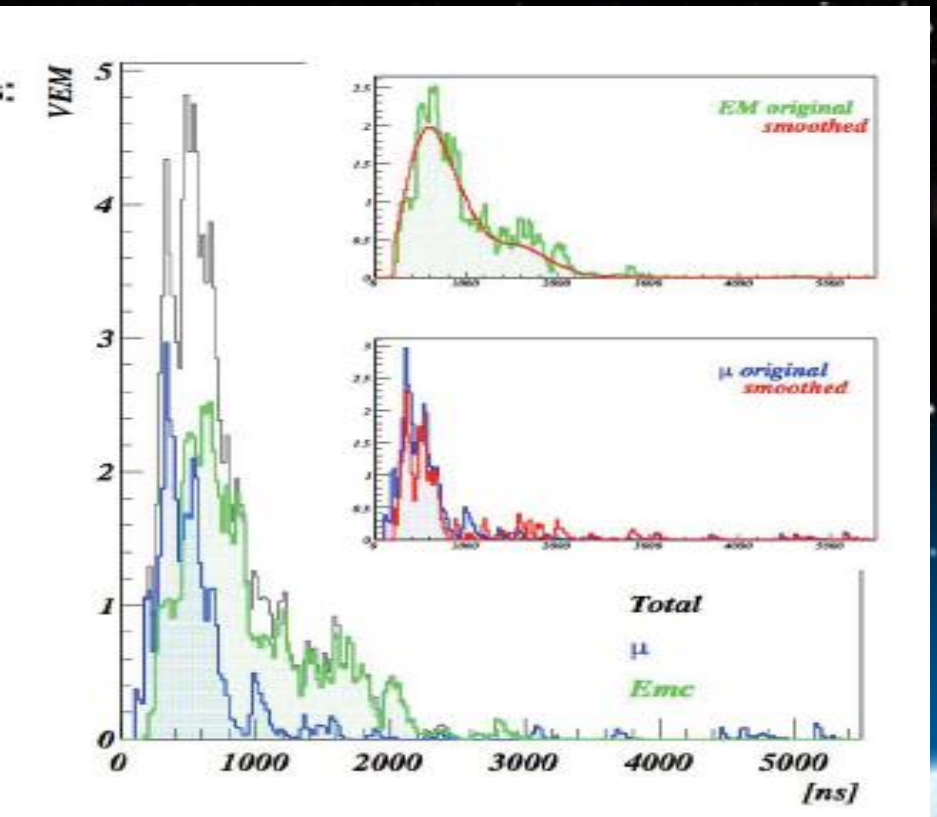
Muon production in air showers

- Analysis of temporal structure of SD signals
- Analysis of signal size of inclined showers
- Analysis of signal size of hybrid events

Temporal structure of SD signals

1. Smoothing

Low pass filter-> EM component
After Substraction of EM-> Muons



2. Multivariate Analysis

Variables sensitive to large relative fluctuations and short signals.

$$f_{0.5}^2 = \frac{\left(\sum x_j (x_j > 0.5)\right)^2}{\left(\sum x_j\right)^2}$$

$$P_0 = \frac{\langle x \rangle^2}{\langle x^2 \rangle}$$

Conversion to muon fraction by:

$$f_\mu = a + b\theta + c\, f_{0.5}^2 + d\theta P_0 + er$$

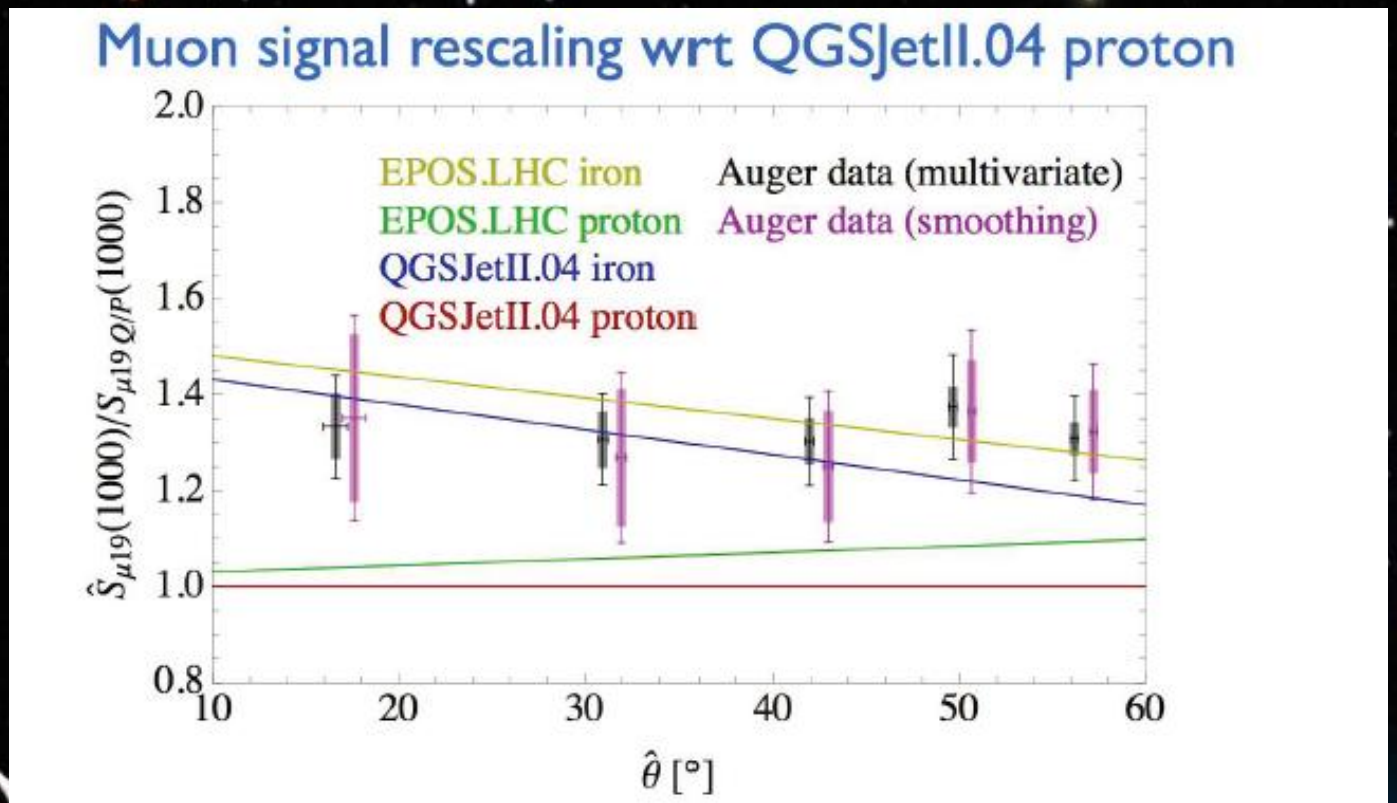
Where *a,b,c,d,e* were calculated using simulations

See more details ICRC2013

Results

$E=[10^{18.98}, 10^{19.02}]$ eV

r=[950,1050] m

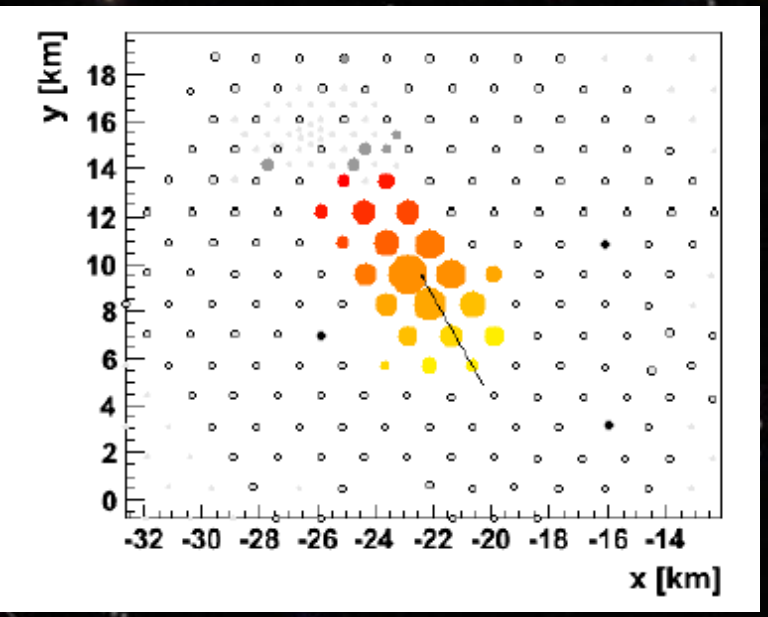


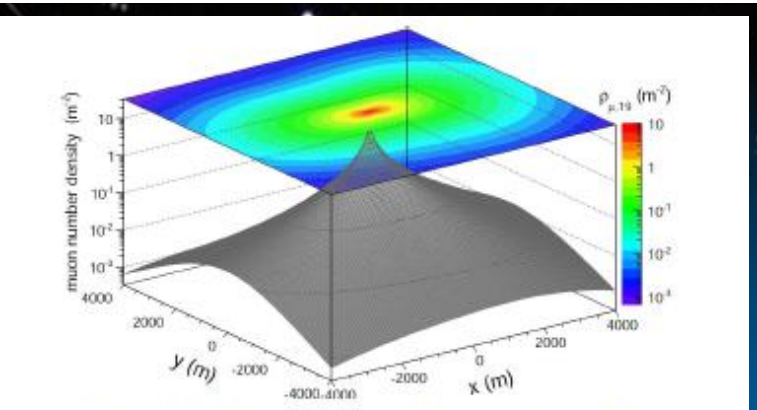
1.33 ± 0.02 (stat.) ± 0.05 (sys.) (multivariate)

1.31 ± 0.02 (stat.) ± 0.09 (sys.) (smoothing)

Inclined hybrid events

62<Θ<80 deg





Example of $\rho_{\mu,19}$ for proton showers at θ=80°, ϕ=0° and core at (x,y) = (0,0)

Fit the muon density in stations

$$\rho_\mu = N_{19}\rho_{\mu,19}(x,y)$$

where N_{19} free parameter
And $\rho_{\mu,19}(x,y)$ is fixed, corresponding to proton QGSJetII-03 at 10^{19} eV

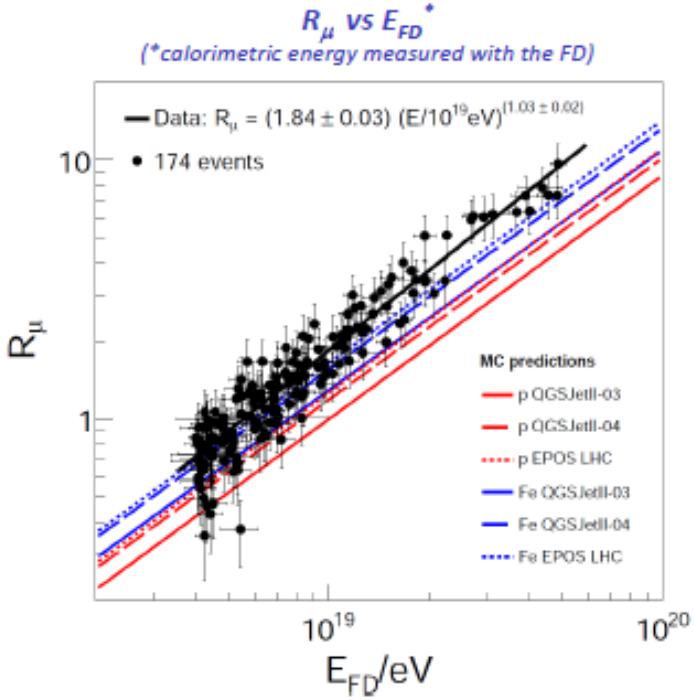
Ratio of the total number of muons N_μ to $N_{\mu,19}$ (proton QGSJetII-03 at 10^{19} eV)

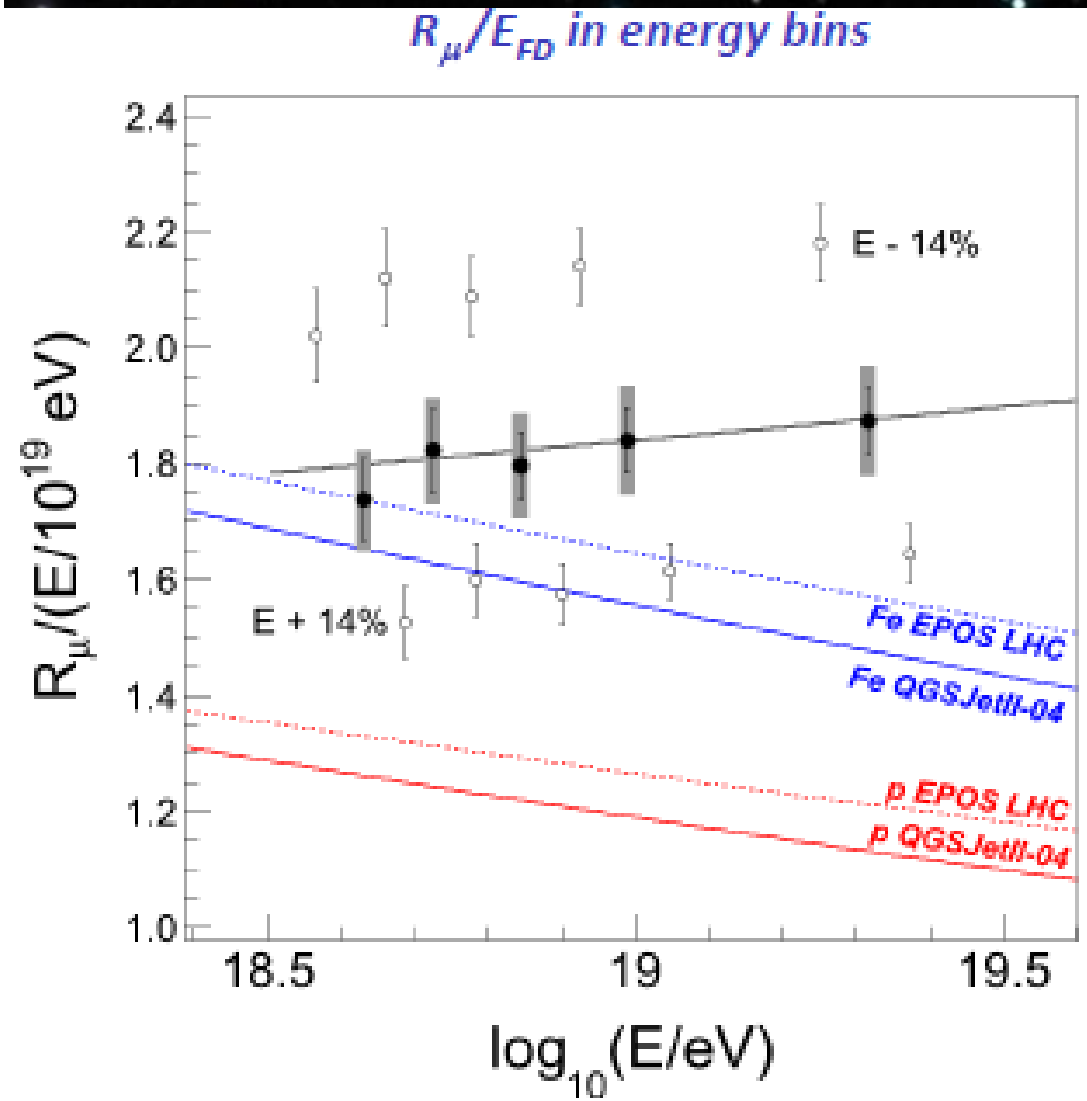
$$R_\mu = N_\mu / N_{\mu,19}$$

Correspondence (<5% bias correction)

$$N_{19} \Leftrightarrow R_\mu$$

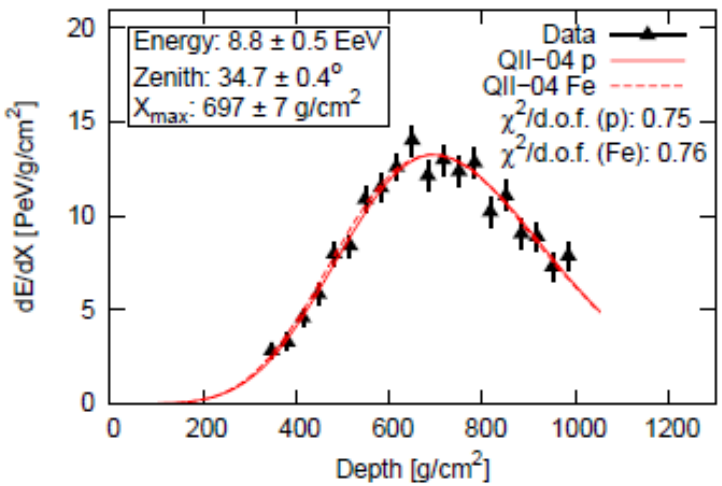
Results

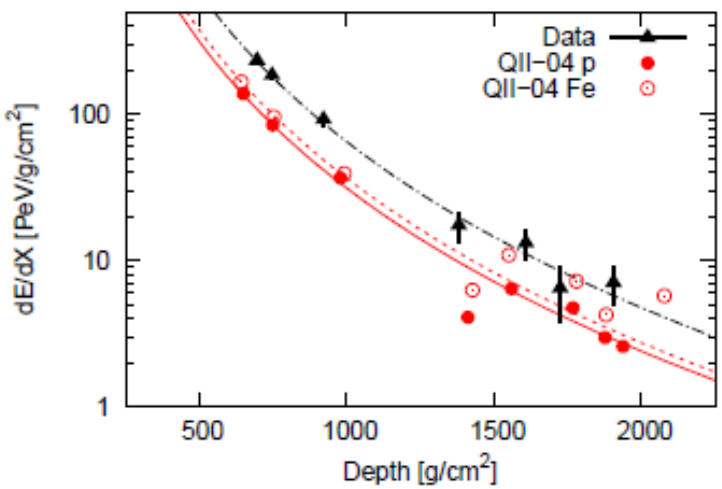

R_μ vs E_{FD}*
(*calorimetric energy measured with the FD)
Data: $R_\mu = (1.84 \pm 0.03)\ (E/10^{19}\text{eV})^{(1.03 \pm 0.02)}$
174 events
MC predictions
p QGSJetII-03
p QGSJetII-04
p EPOS LHC
Fe QGSJetII-03
Fe QGSJetII-04
Fe EPOS LHC
R_μ
E_{FD}/eV
10^{19}
10^{20}
10
1


R_μ/E_{FD} in energy bins
E - 14%
E + 14%
Fe EPOS LHC
Fe QGSJetII-04
p EPOS LHC
p QGSJetII-04
$R_\mu/(E/10^{19}\ \text{eV})$
$\log_{10}(E/\text{eV})$
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
18.5
19
19.5

See more details in ICRC2013
L. Cazon

Hybrid events

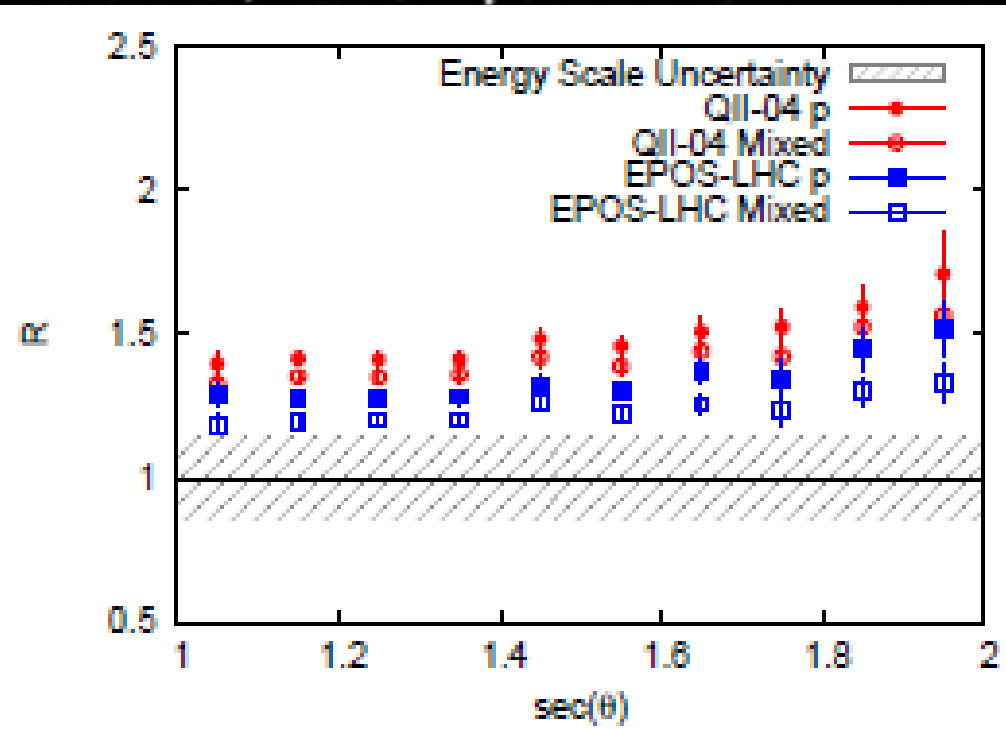




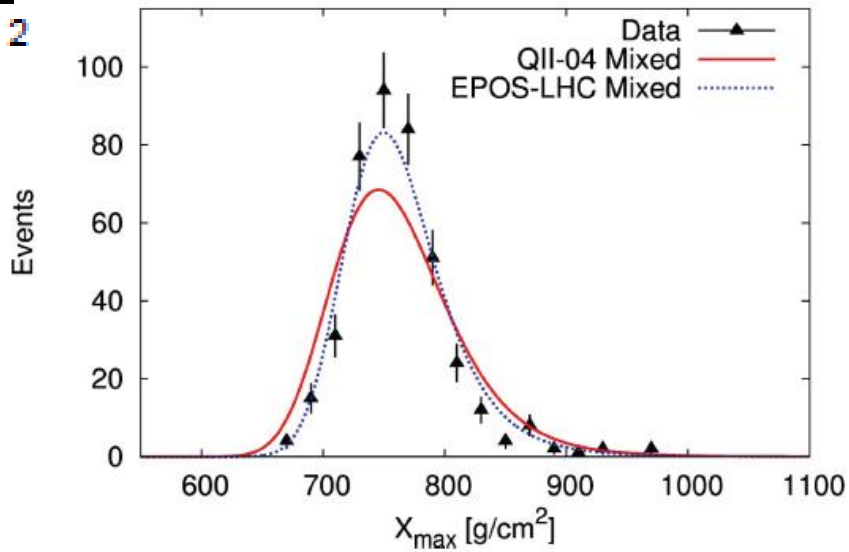
$E=[10^{18.8}, 10^{19.2}]$ eV

- Find simulations which match FD profile, **for each event**
- Compare SD signals for simulations and data
- Rescale muon content until simulated SD best match data

Results



Mixed composition reproduces X_{max}-distribution of data



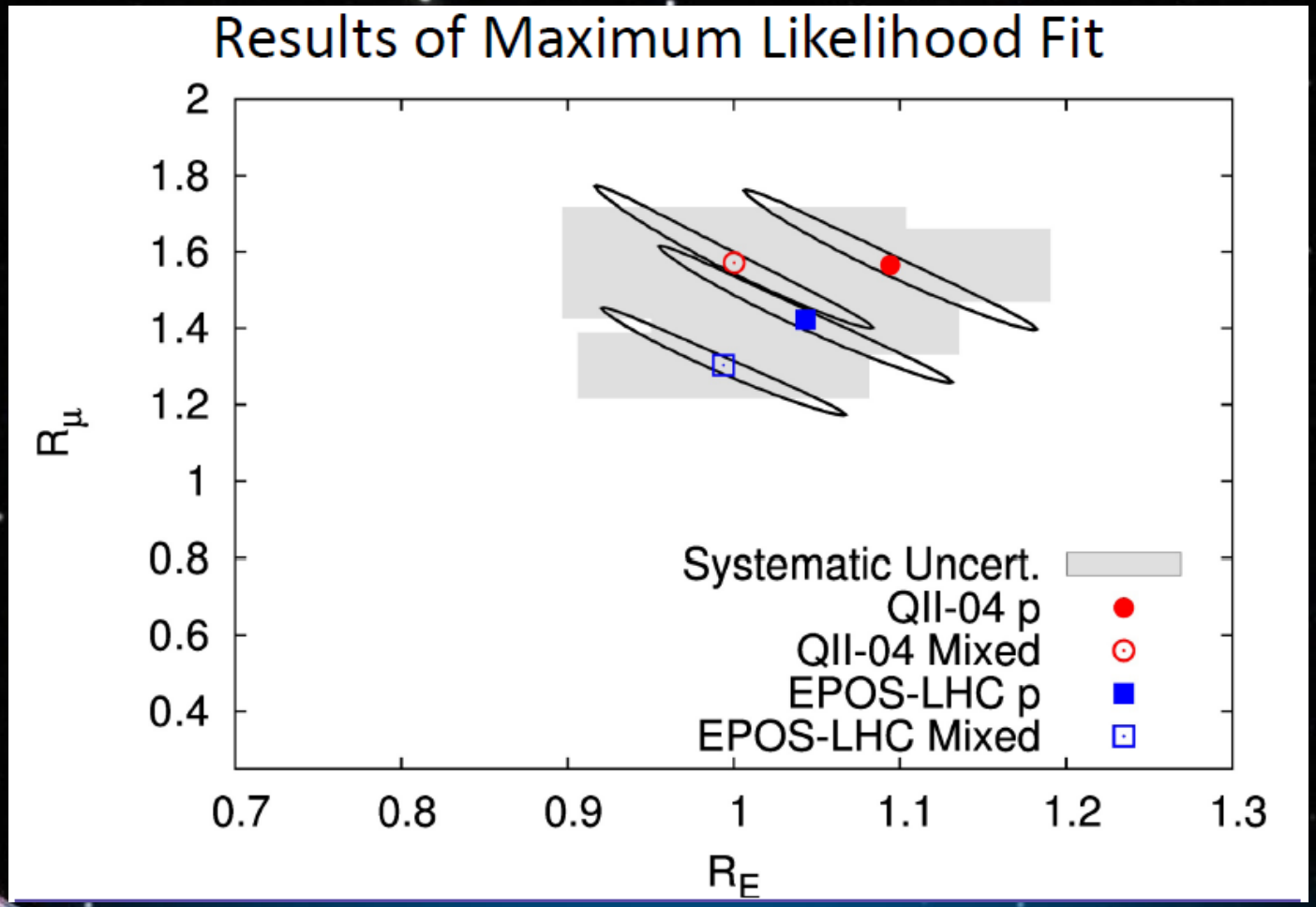
Indentifying the discrepancy

- R_E: Energy rescaling. Rescales EM and muonic components
- R_μ: Muonic rescaling.
- Find R_E & R_μ for best overall fit

$$S_{resc}(R_E, R_\mu)_{i,j} \equiv R_E S_{EM,i,j} + R_E^\alpha R_\mu S_{\mu,i,j}$$

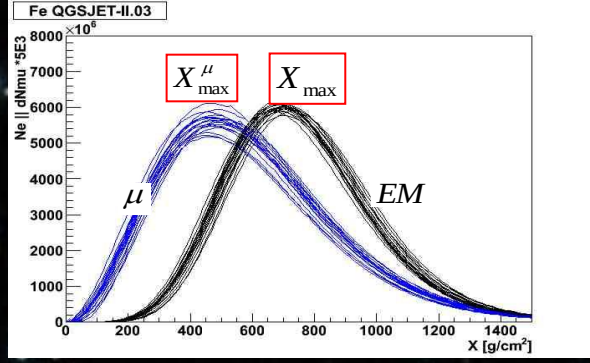
$$Likelihood = \prod_i \sum_j p_j(X_{\max,i})\, Gaus\left(S_{resc}(R_E, R_\mu)_{i,j} - S_{1000,i}\right)$$

Results



See more details in ICRC2013

EM profile
vs
Muon Production profile



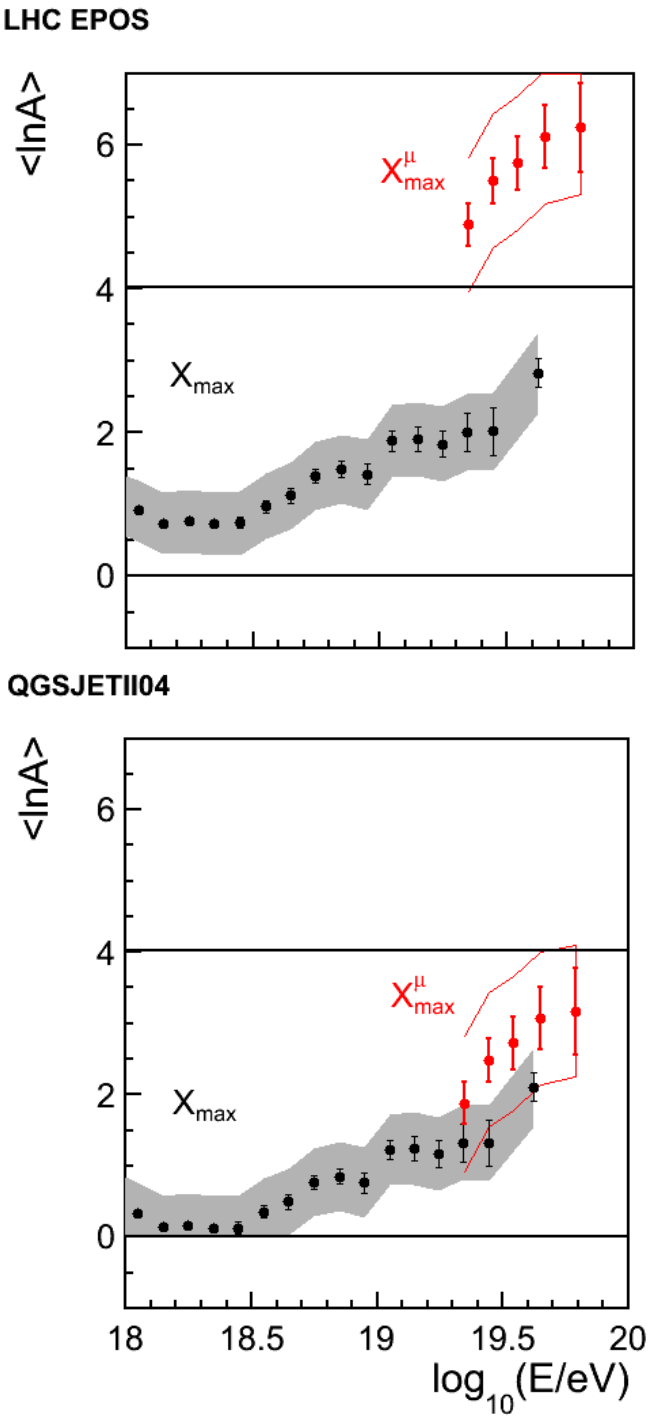
- ~1-2 hadr. generations after the 1st interaction
  - >90% energy is in the EM channel,
  - EM cascade practically decoupled from the hadronic cascade
- MPD profile: reflects development of the hadronic cascade
  - All hadr. generations contribute
- ΔX^{μ} & ΔX test different hadronic properties

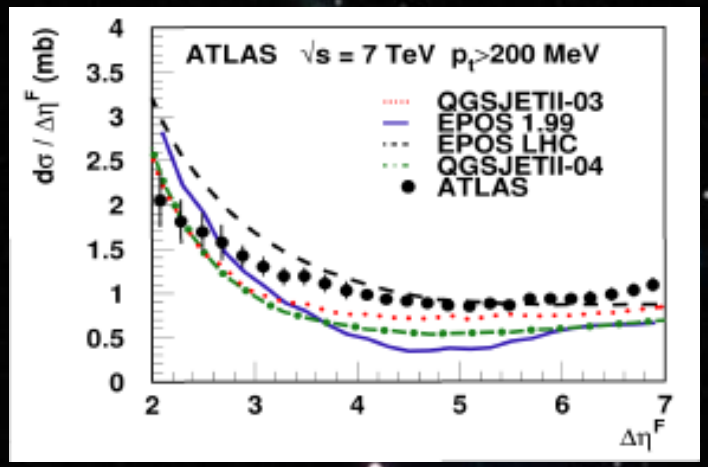
$$X_{max} = X_1 + \Delta X$$

$$X^{\mu}_{max} = X_1 + \Delta X^{\mu}$$

lnA compatibility

Conversion of X^{μ}_{max} & X_{max} into *lnA* using the models unveals problems (opportunities!) for the models.





A difference between the models, LHC-EPOS makes a better treatement of diffraction rapidity gaps.

QGSJetII.04 could be missing additional and relevant effects that compensate X^{μ}_{max}

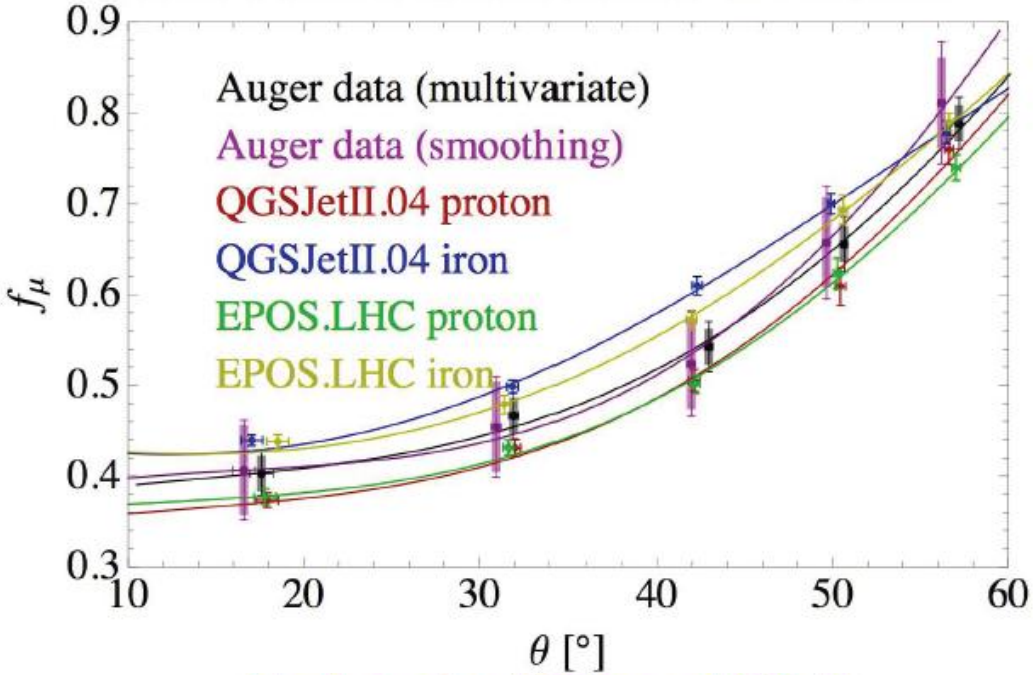
Conclusions

- $\sigma_{p\text{-}Air}$ for particle production measured at $\sqrt{s}$=57 TeV
  - Compatible with most models.
  - Systematics: up to 25% He contamination.
- Updated measurements of muon production

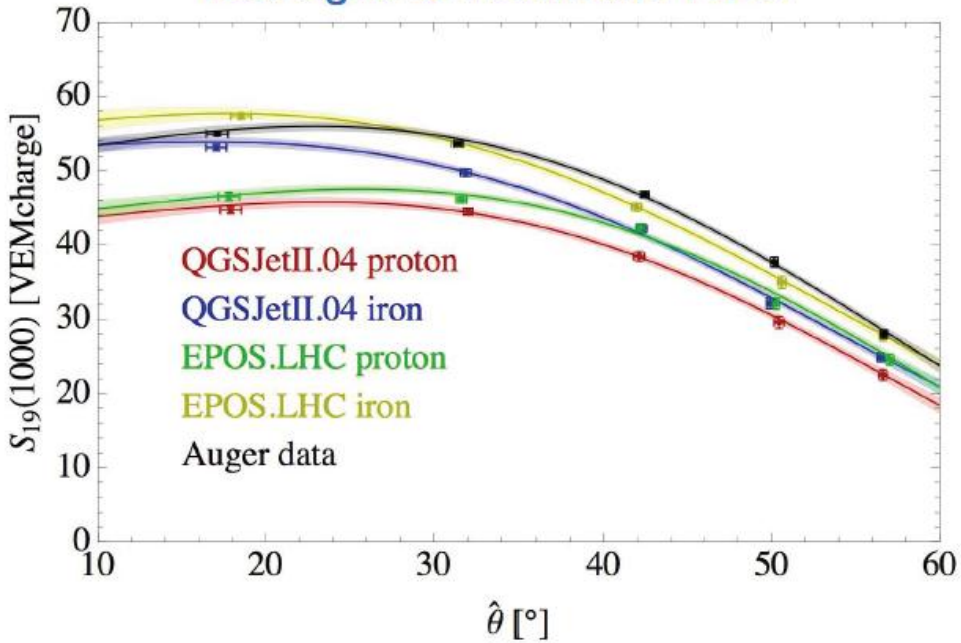
  new E scale, method's improvements and new hadronic models, **20% more muons**.
  - X_{max} incompatible with iron dominated up to $2x10^{19}$ eV -> muon content is too large
  - Absolute value similar to iron predicions, but angular dependence close to proton at 10^{19} eV
  - Muon rescaling factor 1.3-1.6
  - No need for E rescaling
- Muon Production Depth provides new constraints in hadronic models

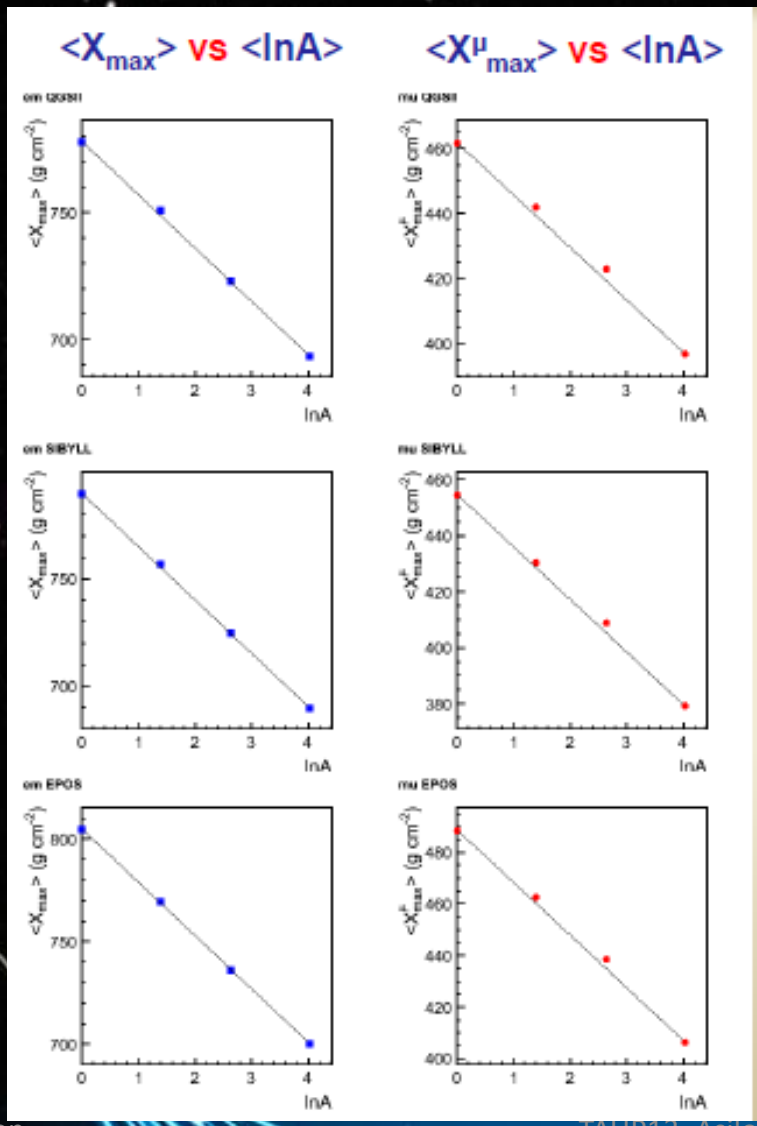
BACK UP SLIDES

Muon fraction measurements and models



Total signal at 1000m and 10EeV





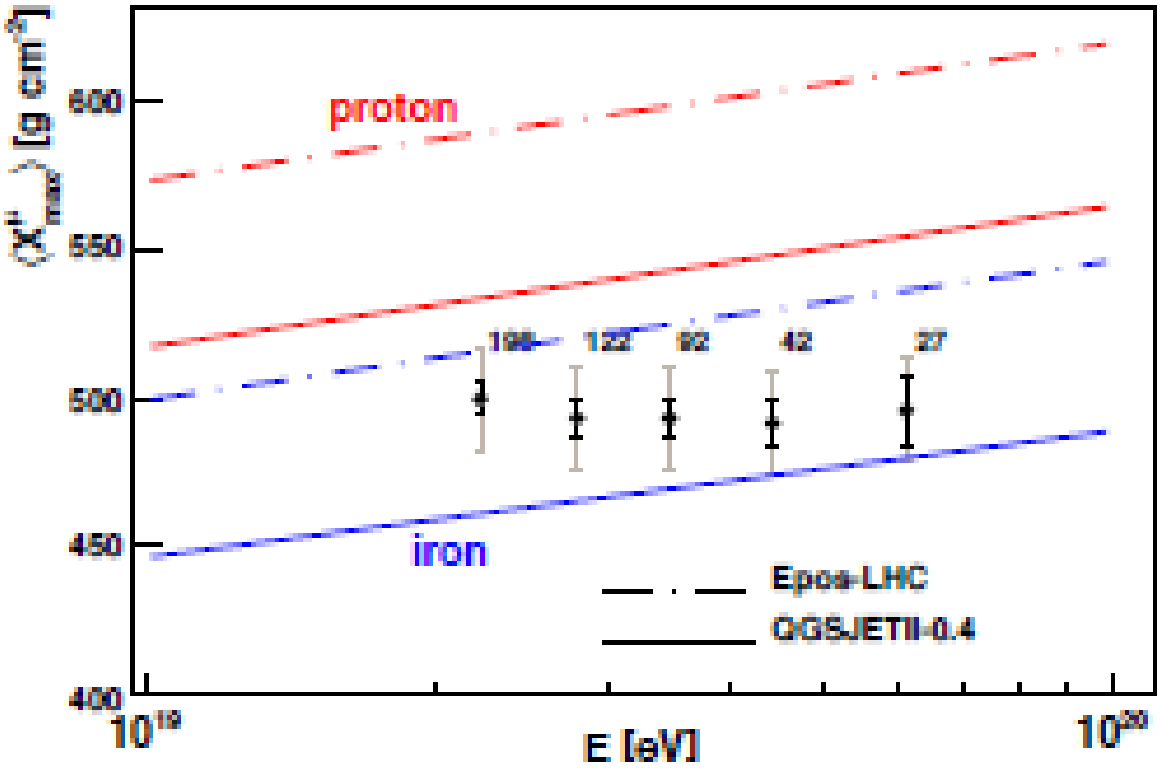
Linearity check*

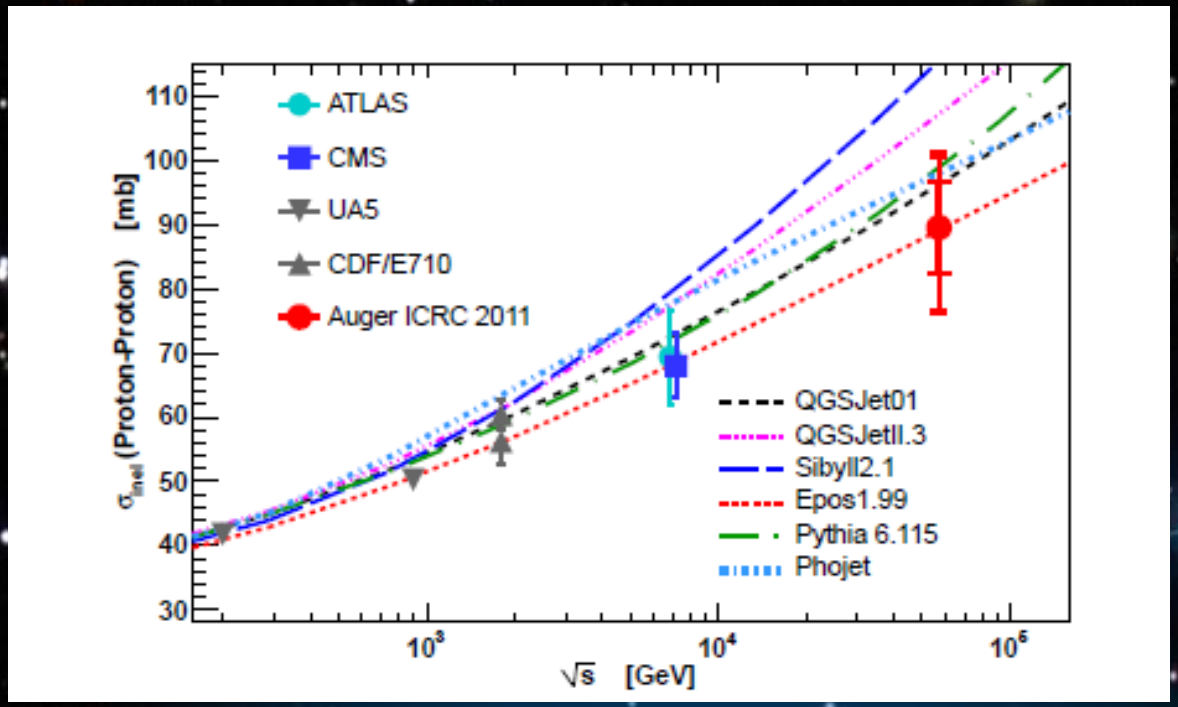
$$\langle \ln A \rangle^{EM} = \ln 56 \, \frac{\langle X_{max} \rangle_p - \langle X_{max} \rangle}{\langle X_{max} \rangle_p - \langle X_{max} \rangle_{Fe}}$$

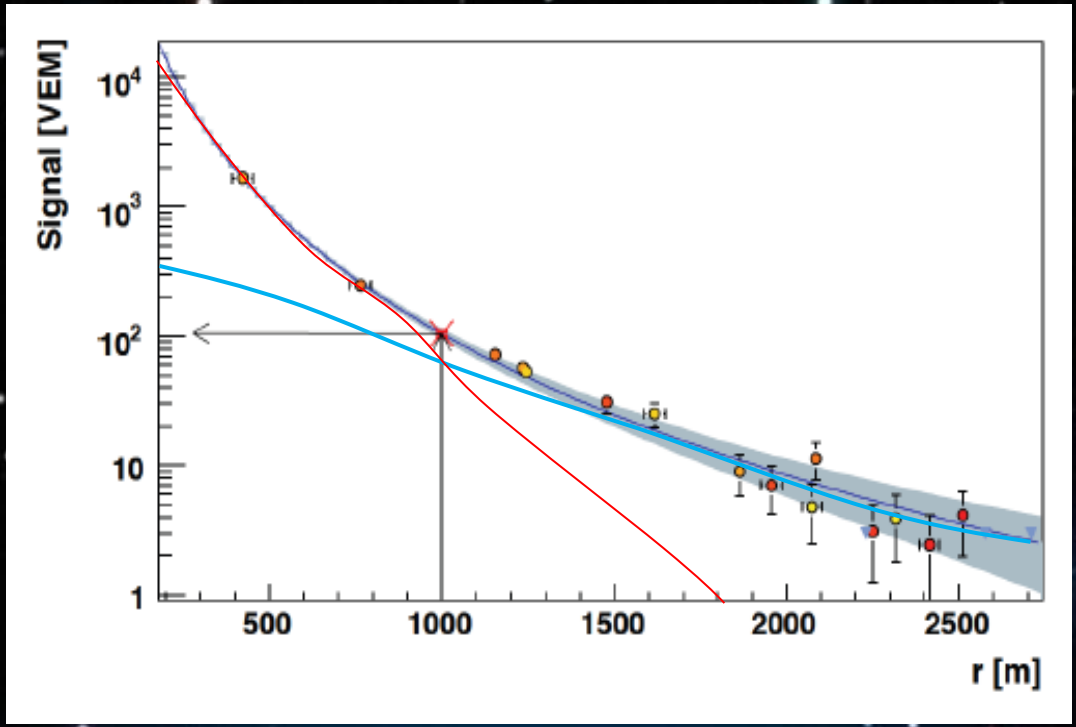
$$\langle \ln A \rangle^{\mu} = \ln 56 \, \frac{\langle X^{\mu}_{max} \rangle_p - \langle X^{\mu}_{max} \rangle}{\langle X^{\mu}_{max} \rangle_p - \langle X^{\mu}_{max} \rangle_{Fe}}$$

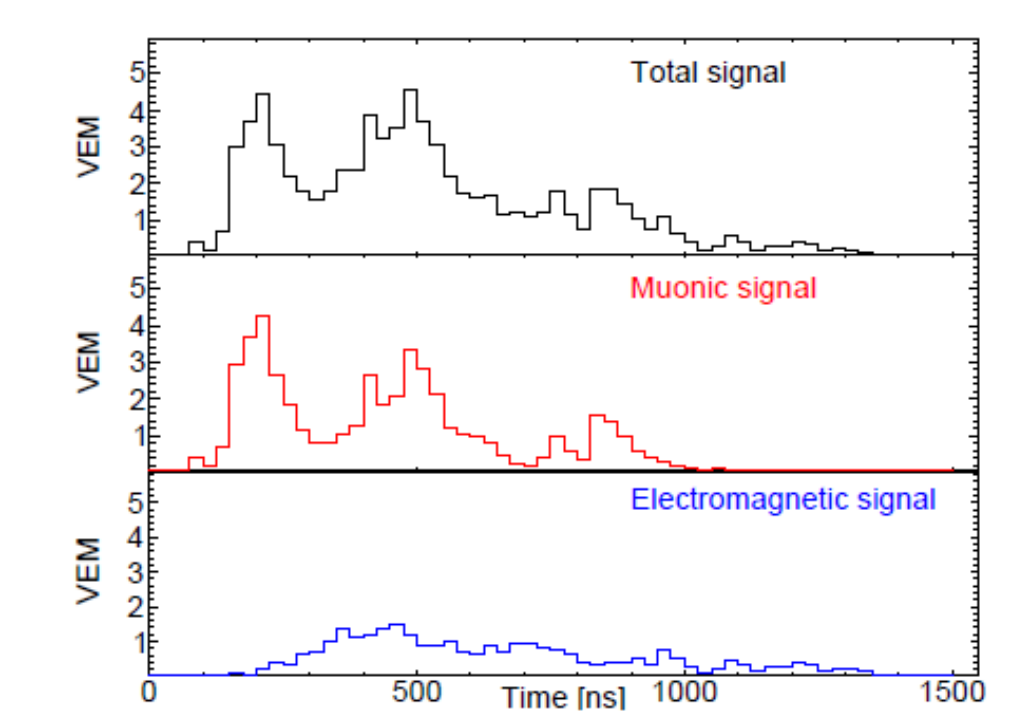
*Apparent MPD Indirectly Inferred using CONEX in conbination with CORSIKA

4


$\langle X'_{max} \rangle$ [g cm^{-2}]
600
550
500
450
400
proton
iron
198
122
92
42
27
Epos-LHC
QGSJETII-0.4
10^{19}
10^{20}
E [eV]


ATLAS
CMS
UA5
CDF/E710
Auger ICRC 2011
QGSJet01
QGSJetII.3
Sibyll2.1
Epos1.99
Pythia 6.115
Phojet
σ_{inel} (Proton-Proton) [mb]
$\sqrt{s}$ [GeV]
110
100
90
80
70
60
50
40
30
10^3
10^4
10^5


Signal [VEM]
10^4
10^3
10^2
10
1
500
1000
1500
2000
2500
r [m]


Total signal
Muonic signal
Electromagnetic signal
VEM
VEM
VEM
5
4
3
2
1
0
500
1000
1500
Time [ns]