Experimental Constraints to High Energy Hadronic Interaction Models using the Pierre Auger Observatory

Part II

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PIERRE AUGER OBSERVATORY

QCD at Cosmic Energies VII, Chalkida, Greece

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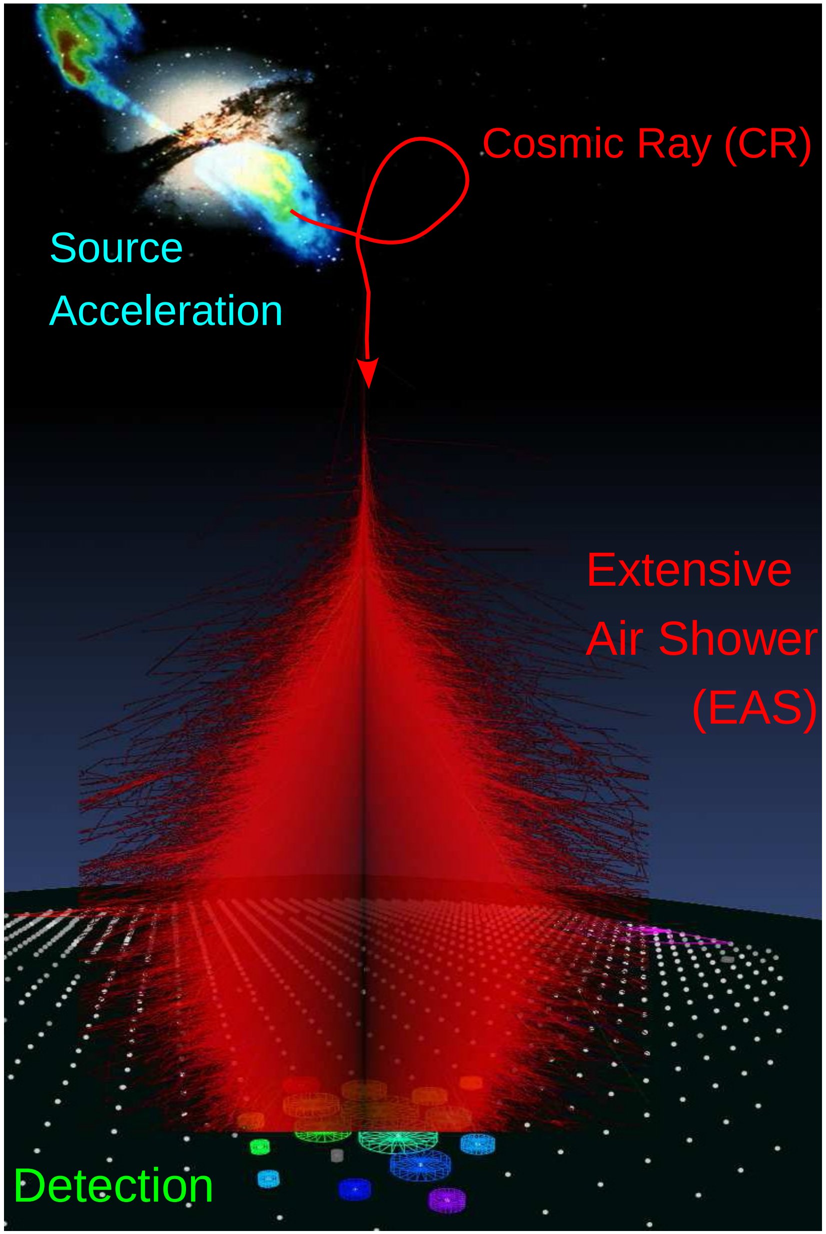
Outline

Hadronic interactions can be tested at ultra-high energy in PAO thanks to the comparison of different observables

➡ No consistent description from models

- **Introduction**
  - ➡ Hadronic Physics in air showers
- **Fluorescence Detector**
  - ➡ Cross section
  - ➡ average shower profile
- **Hybrid analysis**
- **Surface Detector**
  - ➡ Muons in inclined showers
  - ➡ Muon production depth (MPD)

Preamble

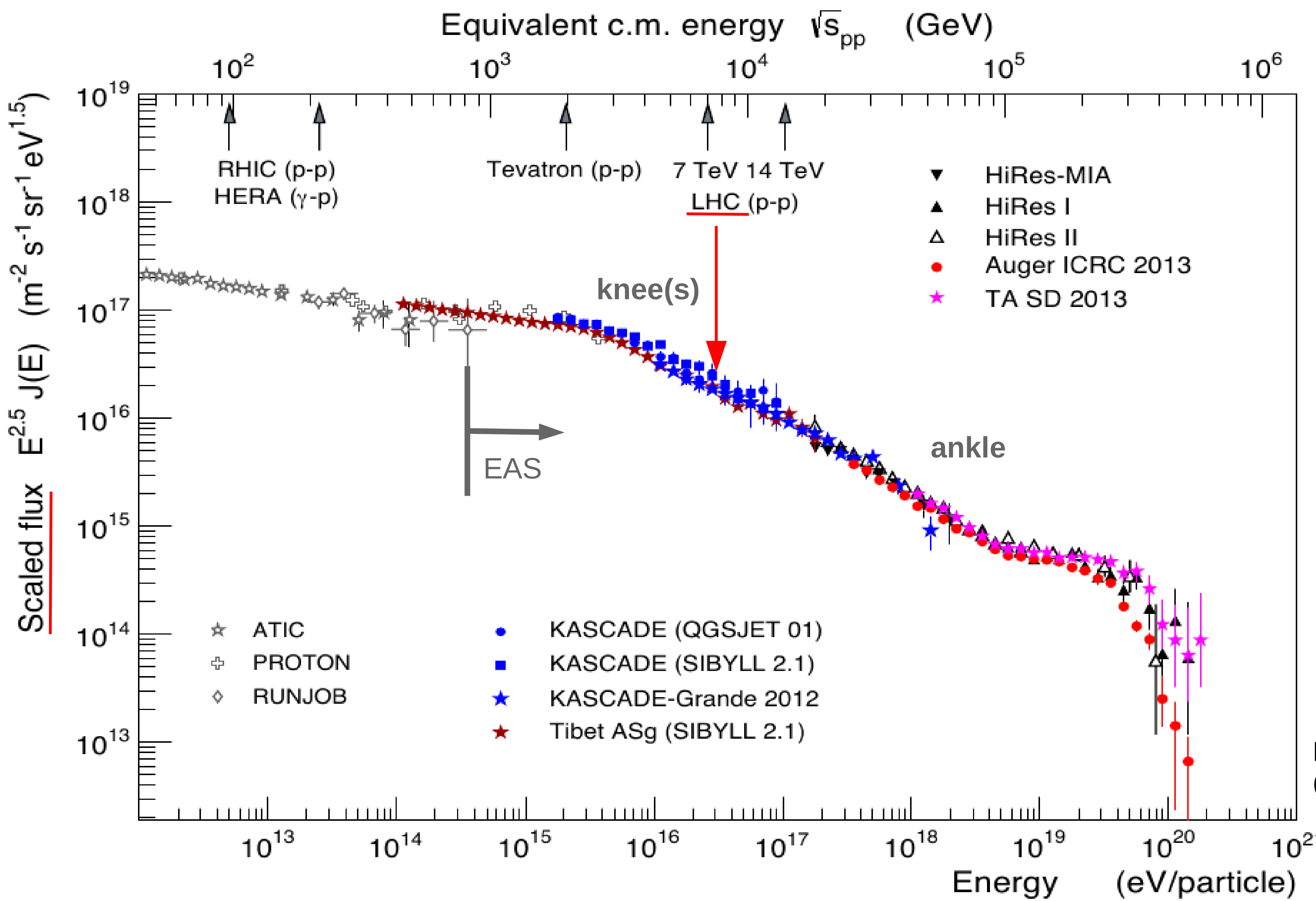


From R. Ulrich (KIT)

- **Goal of Astroparticle Physics :**
  - astronomy with high energy particles
- **How to test hadronic interactions ?**
  - if the source mechanism is well understood we could have a known beam at ultra-high energy (10^{10} GeV and more)
    - unlikely situation
  - reasonable minimum limits from CR abundance :
    - low = hydrogen (proton)
    - high = iron (A=56)
  - test of hadronic interactions in EAS via correlations between observables.

mass measurements should be consistent and lying between proton and iron simulated showers !

Spectrum



R. Engel (KIT)

Extensive Air Shower

- Models for hadronic interactions :
  - ➡ EPOS (Werner et al.)
  - ➡ QGSJETII (Ostapchenko)
  - ➡ Sibyll (Engel et al.)

$A + air \rightarrow$ hadrons
$p + air \rightarrow$ hadrons
$\pi + air \rightarrow$ hadrons

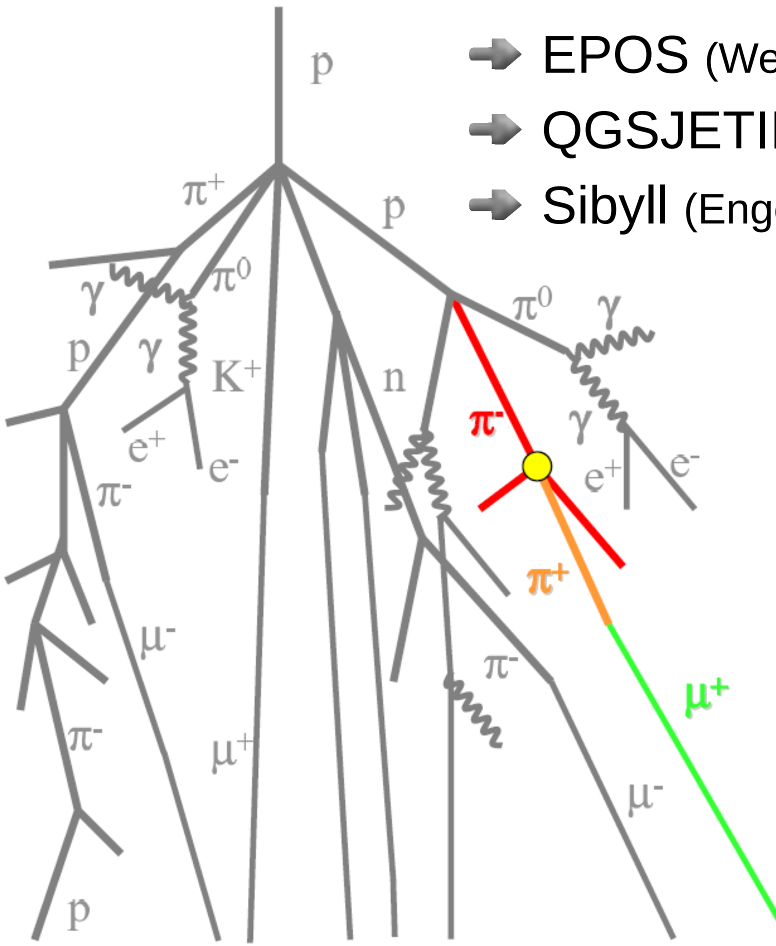
hadronic physics

initial γ from π^0 decay

$e^\pm \rightarrow e^\pm + \gamma$
$\gamma \rightarrow e^+ + e^-$

well known QED

$\pi^\pm \rightarrow \mu^\pm + \nu_\mu/\bar{\nu_\mu}$



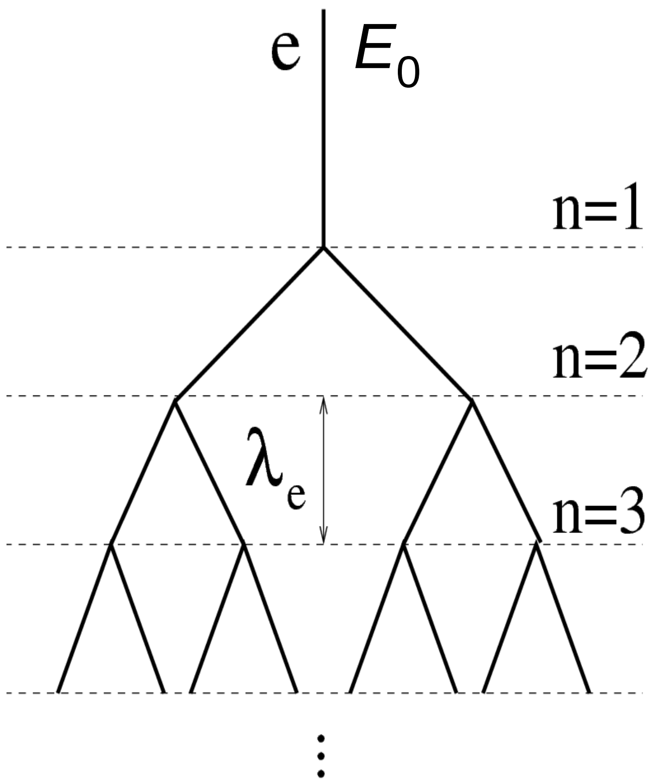
From R. Ulrich (KIT)

- Cascade of particle in Earth's atmosphere

  Number of particles at maximum
  - ➡ 99,88% of electromagnetic (EM) particles
  - ➡ 0.1% of muons
  - ➡ 0.02% hadrons

  Energy
  - ➡ from 100% hadronic to 90% in EM + 10% in muons at ground (vertical)

Toy Model for Electromagnetic Cascade



Primary particle : photon/electron

Heitler toy model :

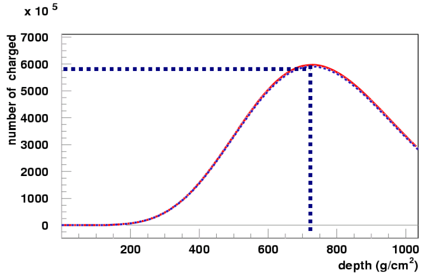
- 2 particles produced with equal energy

2^n particles after *n* interactions

$$n = X/\lambda_e$$

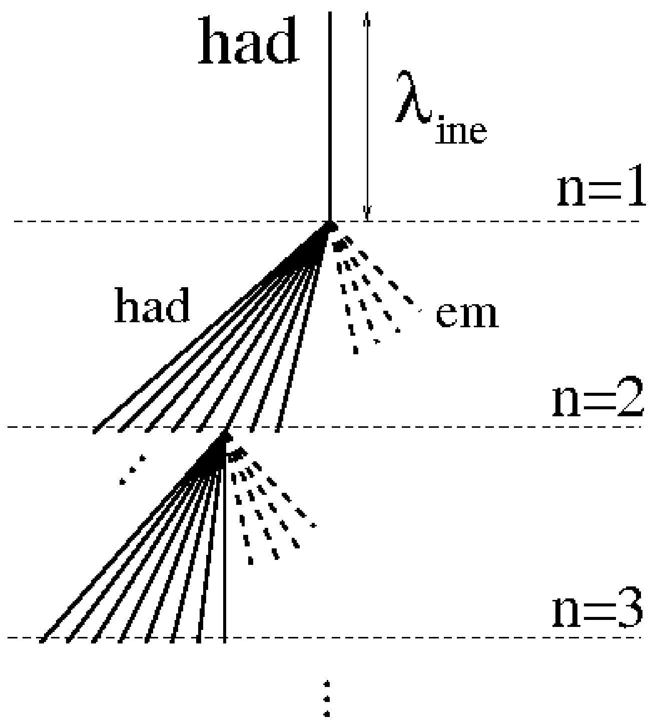
$$N(X) = 2^n = 2^{X/\lambda_e} \qquad E(X) = E_0/2^{X/\lambda_e}$$

Assumption: shower maximum reached if $E(X) = E_c$ (critical energy)



$$N_{max} = E_0/E_c \qquad X_{max} \sim \lambda_e \ln(E_0/E_c)$$

Toy Model for Hadronic Cascade



$$N_{tot} = N_{had} + N_{em}$$

Shower development dominated by first (highest energy $E_0/(2N_{tot})$) produced em particle:

$$X_{max} \sim \lambda_e \ln\left(E_0/(2.N_{tot})/E_c\right) + \lambda_{ine}$$

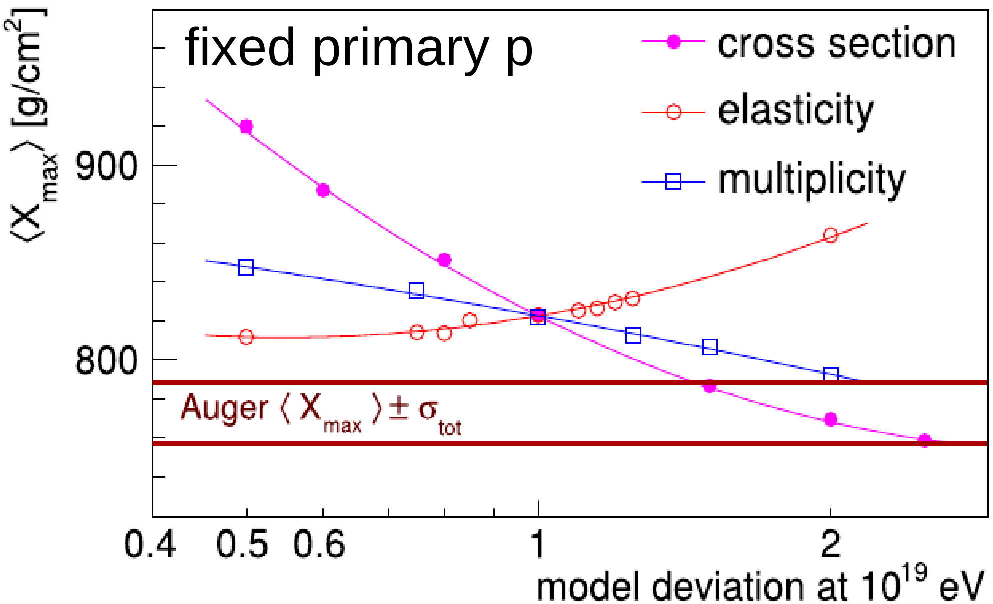
Primary particle : hadron

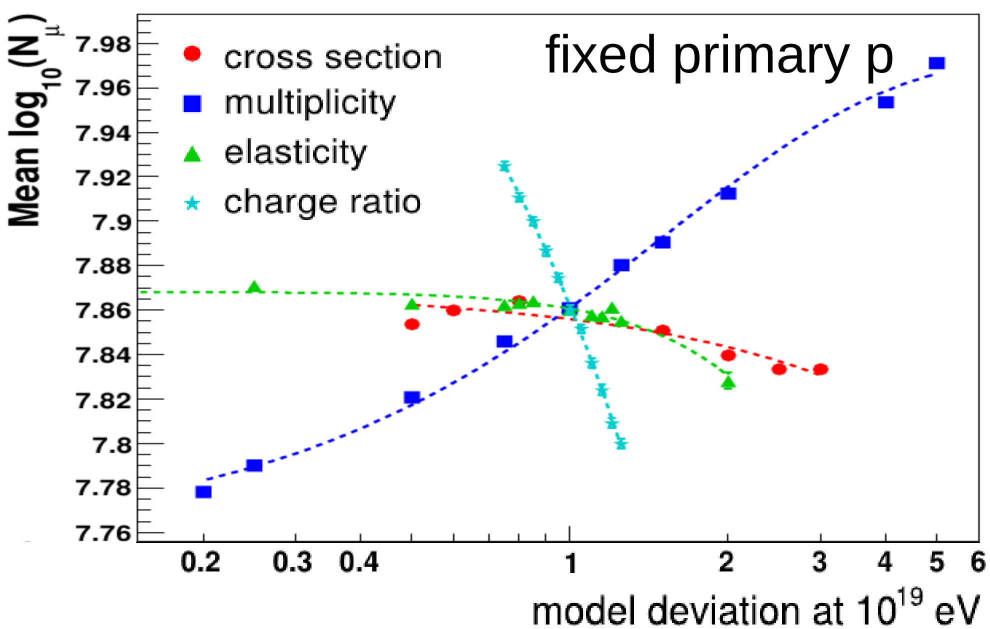
Using a simple generalized Heitler model to understand EAS characteristics :

- fixed interaction length
- equally shared energy
- 2 types of particles :
  - N_{had} continuing hadronic cascade until decay at E_{dec} producing muons (charged pions).
  - N_{em} transferring their energy to electromagnetic shower (neutral pions).

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

Sensitivity to Hadronic Interactions





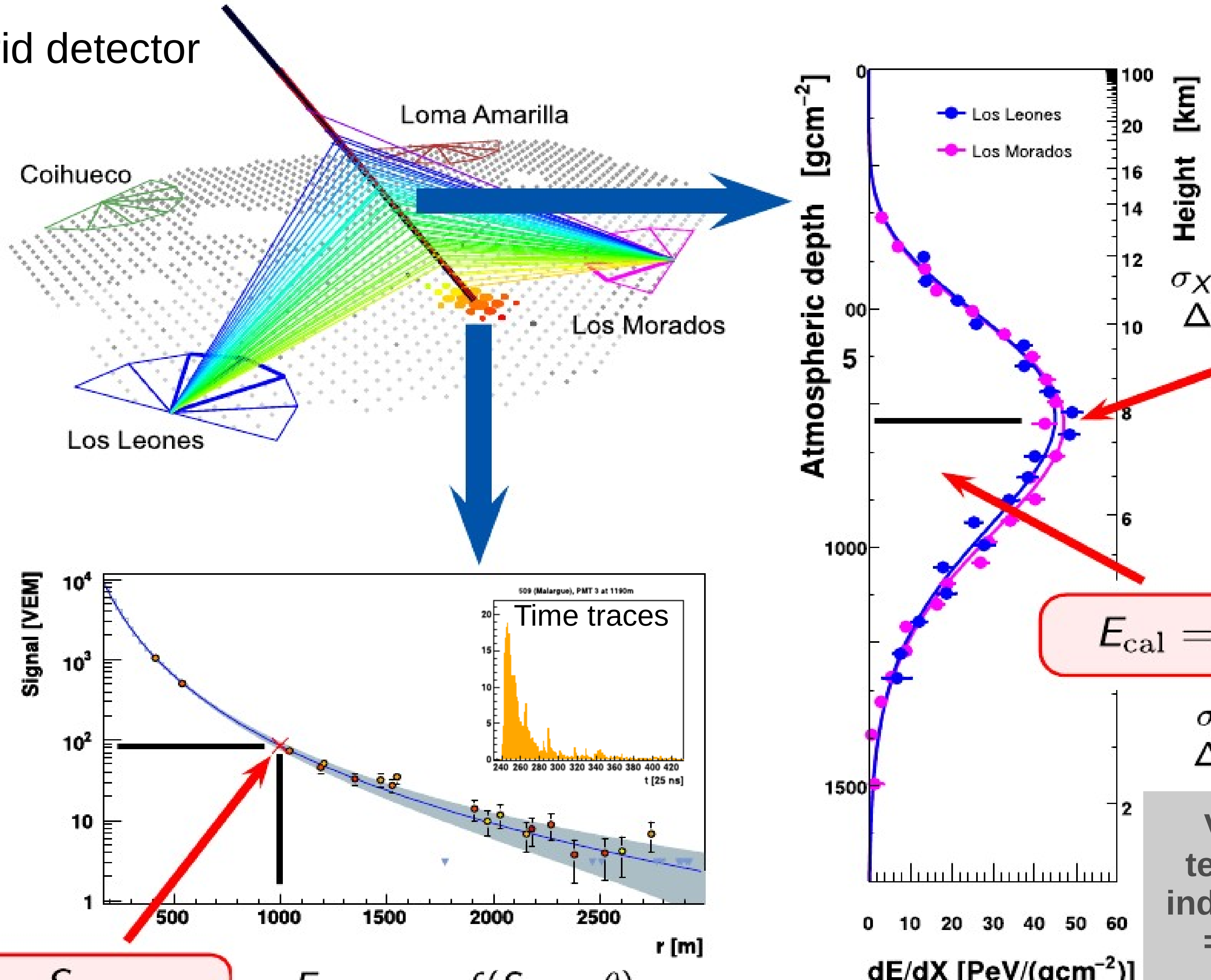
From R. Ulrich (KIT)

- **Air shower development dominated by few parameters**
  - ➜ cross-sections (p-Air and (π-K)-Air)
  - ➜ (in)elasticity
  - ➜ multiplicity
  - ➜ charge ratio and baryon production
- **Change of primary = change of hadronic interaction parameters**
  - ➜ cross-section, elasticity, mult. ...

With unknown mass composition hadronic interactions can only be tested using various observables which should give consistent mass results

Pierre Auger Observatory

Hybrid detector



From R. Ulrich (KIT)

S_{1000}

$E_{\mathrm{surface}} = f(S_{1000}, \theta)$

$\sigma_{X_{\mathrm{max}}} < 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \approx 15\,\mathrm{g/cm^2}$

X_{max}

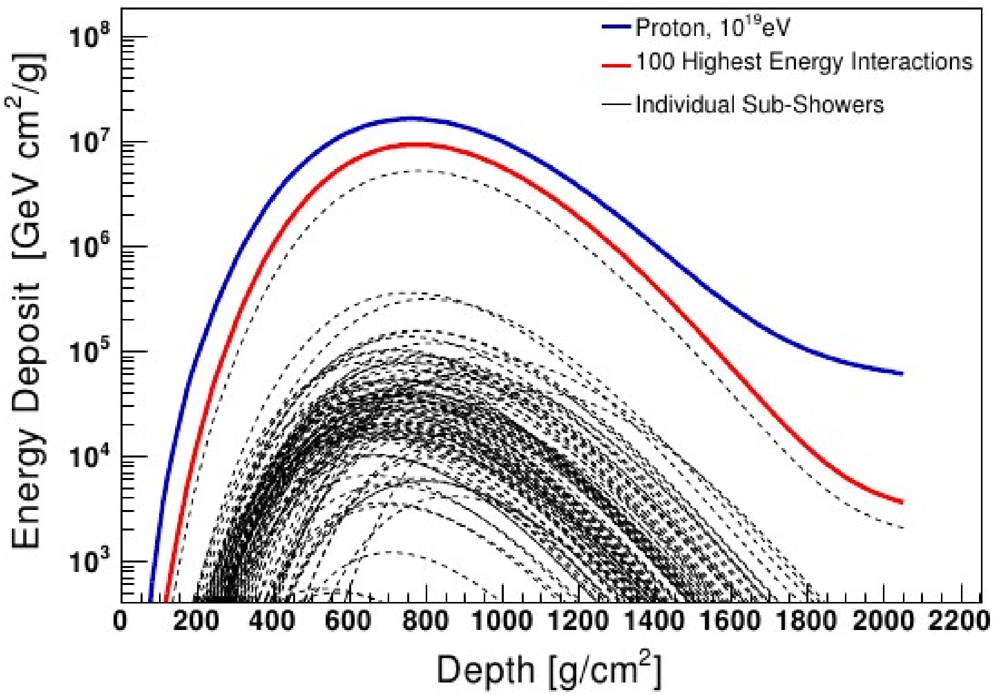
$E_{\mathrm{cal}} = \int \mathrm{d}X \, \frac{\mathrm{d}E}{\mathrm{d}X}$

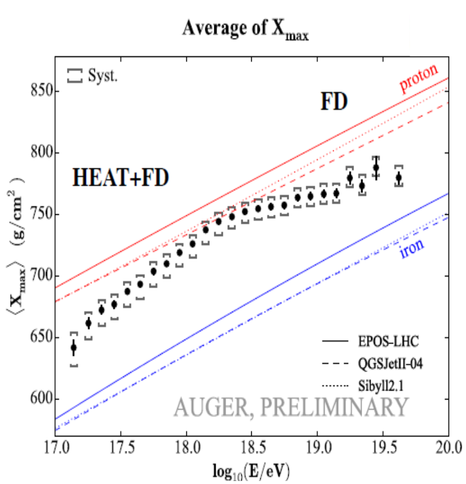
$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 14\,\%$

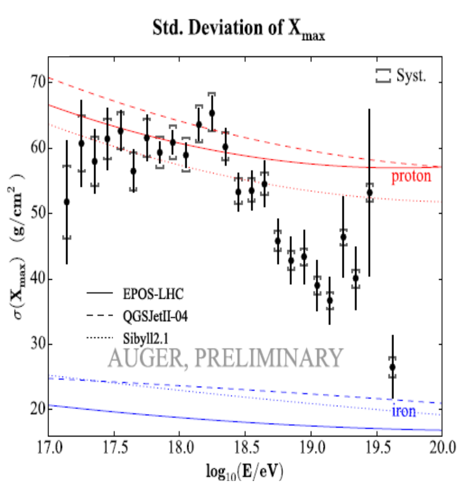
Various detection technique = various independent variables = test of hadronic interactions

Fluorescence Detector

From R. Ulrich (KIT)





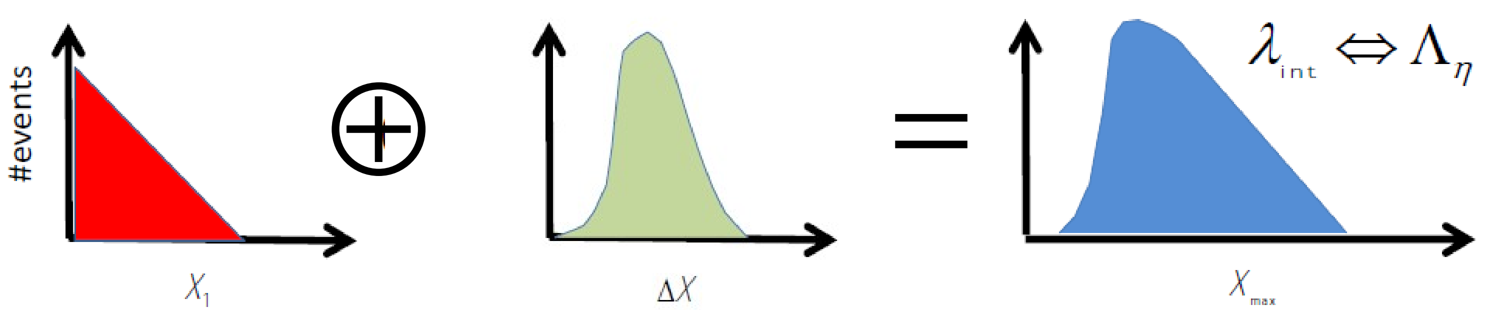


- **Most direct measurement**
  - ➜ dominated by first interaction
- **Reference mass for other analysis (see J. Bellido)**
  - ➜ <lnA> from <X_{max}> and RMS
- **Possibility to use the tail of X_{max} distribution to measure p-Air inelastic cross-section.**
  - ➜ require no contamination from photon induced showers (independent check)
  - ➜ correction to “invisible” cross-section using hadronic models
  - ➜ conversion to p-p cross-section using Glauber model.

Direct Cross-Section Measurement

- **Update of PRL 109, 062002 (2012)**
  - About four times more data: 44218 events
  - Two bins in energy: $10^{17.8} - 10^{18.0} - 10^{18.5}$ eV
  - Updated systematic uncertainties
  - New hadronic interaction models:
    - EPOS-LHC, QGSJetII-04 tuned to LHC data

- **Direct measurement from the tail of X_{max} distribution**
  - X_{max} is a convolution between X_1 (cross-section) and ΔX (shower development from models)



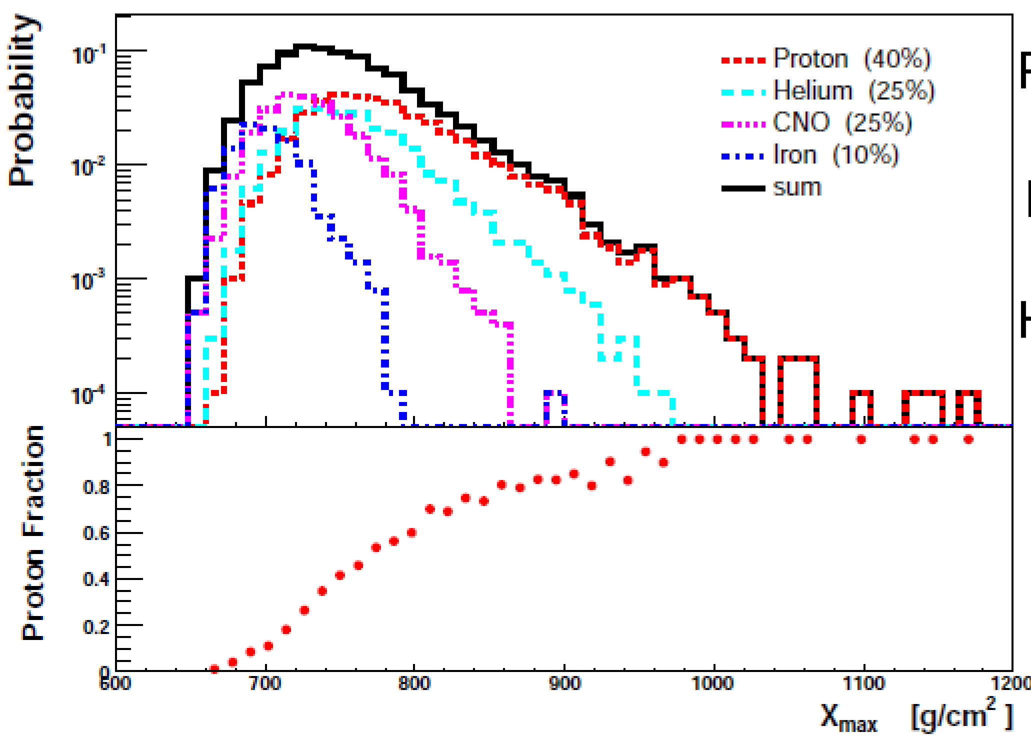
$$\frac{\mathrm{d}p}{\mathrm{d}X_1} = \frac{1}{\lambda_{\mathrm{int}}} \mathrm{e}^{-X_1/\lambda_{\mathrm{int}}}$$

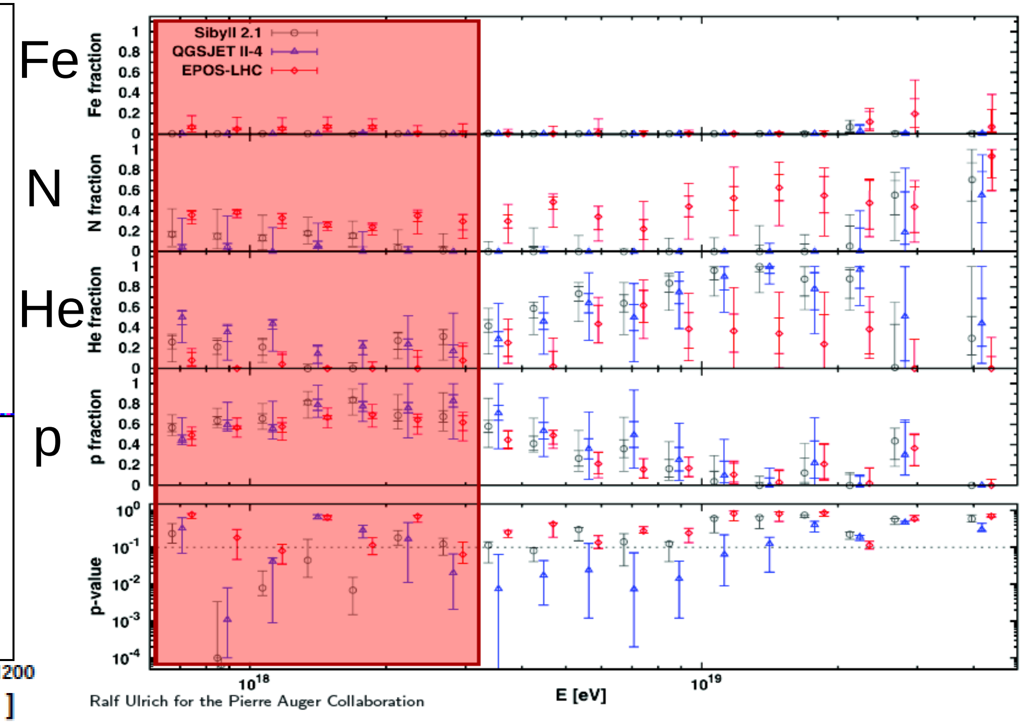
$$\sigma_{\mathrm{int}} = \frac{<m_{\mathrm{air}}>}{\lambda_{\mathrm{int}}}$$

Constraints from Data

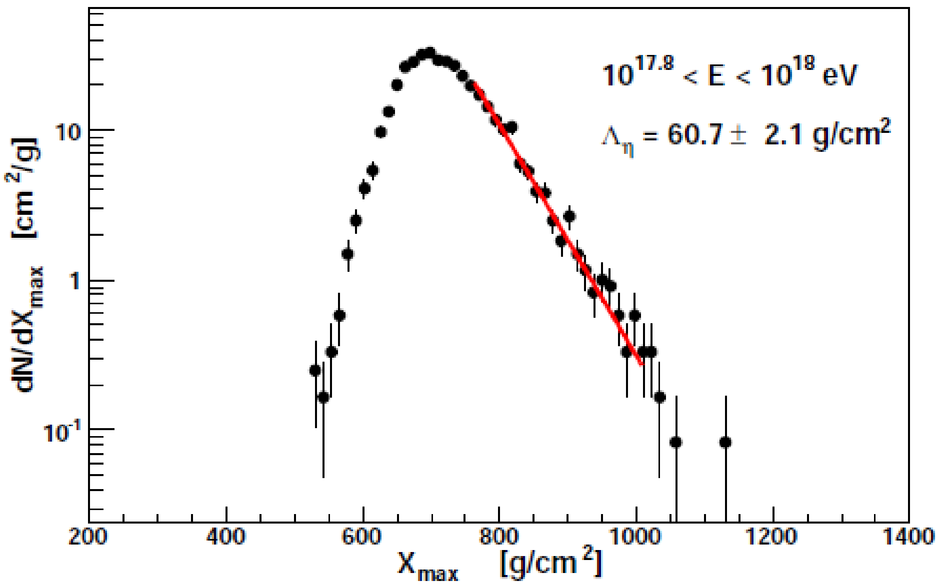
Careful data selection

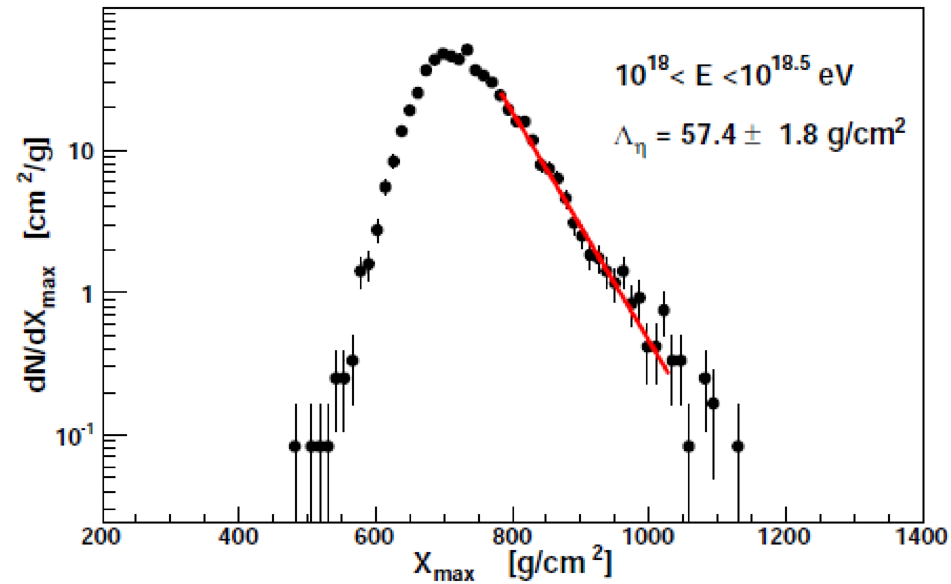
- maximum statistic
- maximum quality (showers completely in field-of-view)
- tail should contain only p-showers (contamination by He is largest uncertainty)
- energy ranged fixed by composition measurement in PAO data (See J. Bellido)





Attenuation Length





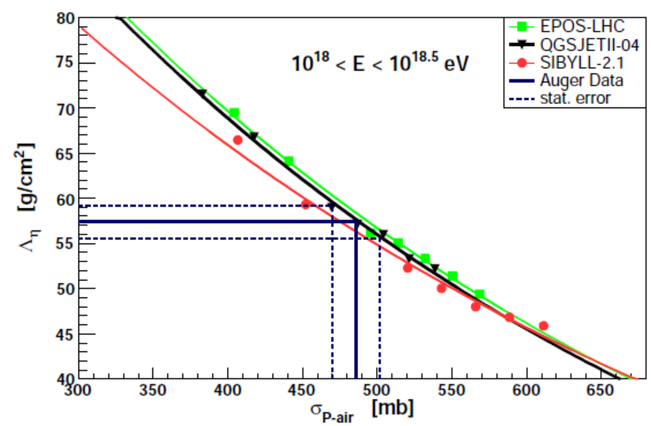
$$\langle E \rangle = 10^{17.90}\,\mathrm{eV}$$

$$\Lambda_\eta = 60.7 \pm 2.1(\mathrm{stat}) \pm 1.6(\mathrm{syst})\,\mathrm{g/cm^2}$$

$$\langle E \rangle = 10^{18.22}\,\mathrm{eV}$$

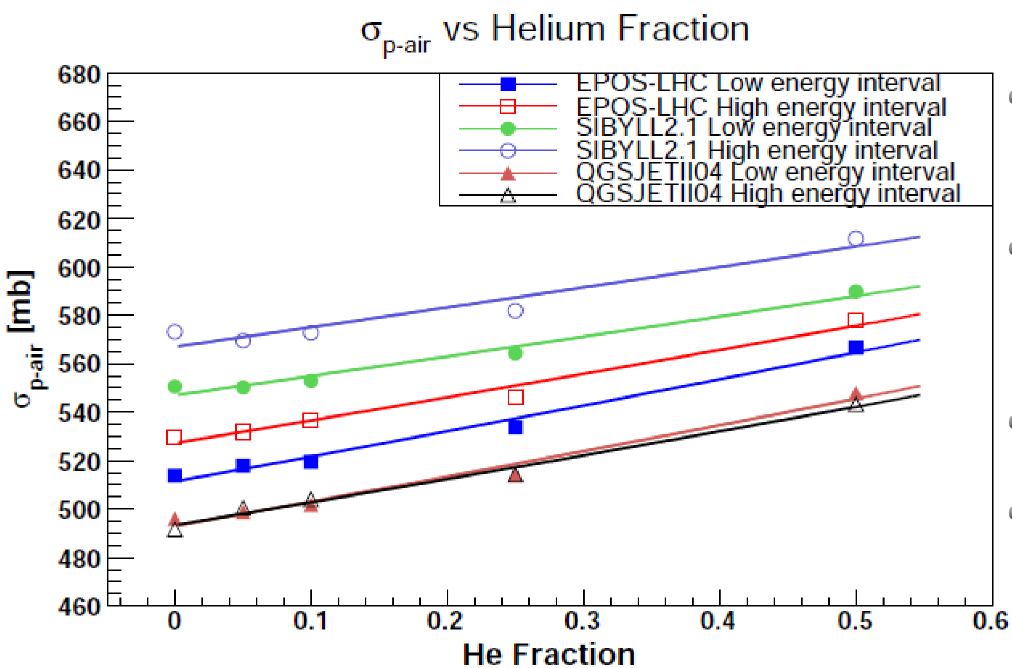
$$\Lambda_\eta = 57.4 \pm 1.8(\mathrm{stat}) \pm 1.6(\mathrm{syst})\,\mathrm{g/cm^2}$$

- η= fraction of event from highest energy
- deconvolution from Λ_η to σ using hadronic models to take into account diffraction (syst. uncertainties, dominated by Sibyll 2.1)
- not enough sensitivity (yet) to slope of energy or event fraction dependence.



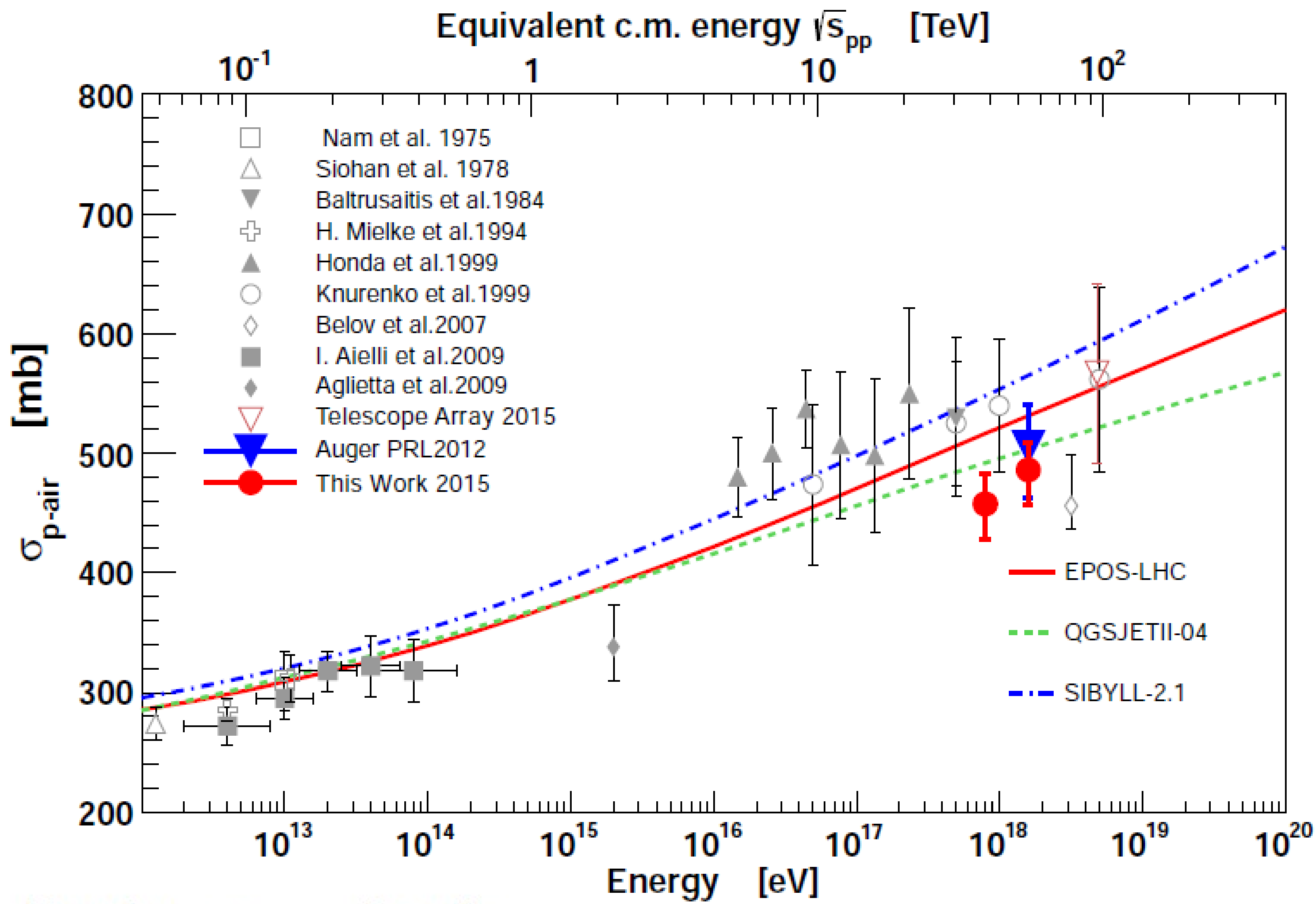
Sytematic Uncertainties

	$10^{17.8} - 10^{18}$ 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



- 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

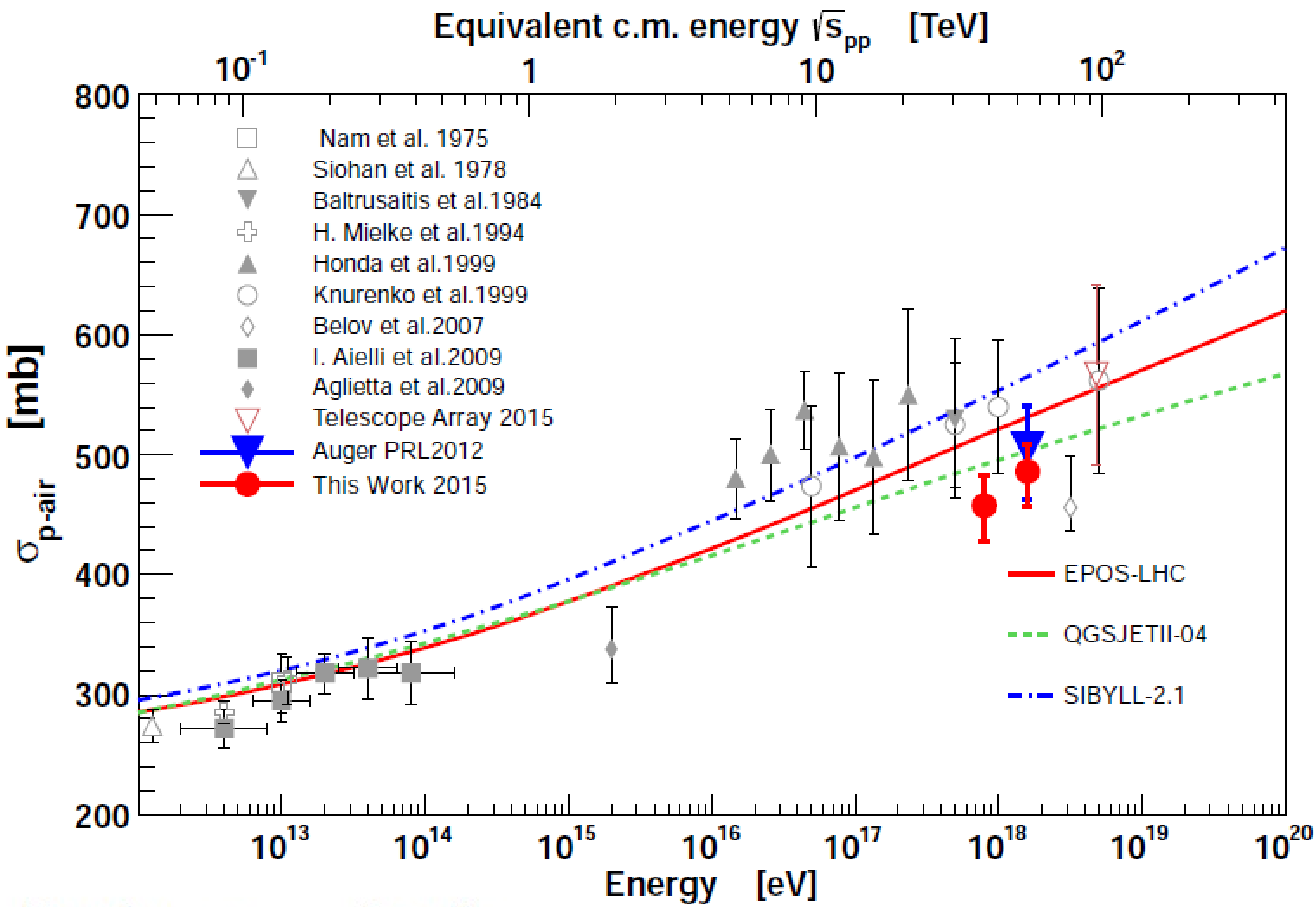
p-Air Production Cross Section @ 57 TeV



Results, σ_{p-air} in mb

Lower energy point	Higher energy point
457.5±17.8(stat)+19/-25(syst)	485.8±15.8(stat)+19/-25(syst)

p-Air Production Cross Section @ 39 and 55 TeV

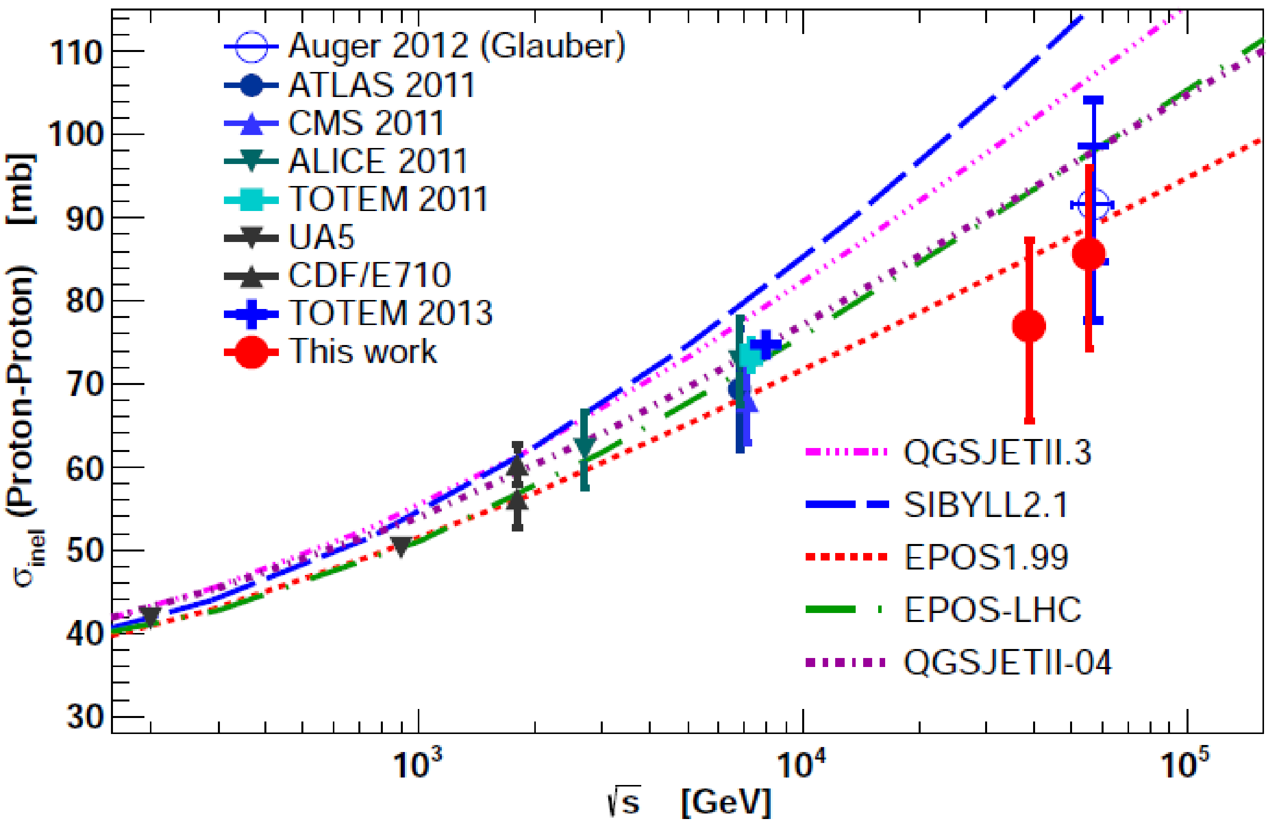


Higher cross-section in models:

QGSJETII-04 : ~OK ; EPOS LHC +1σ ; Sibyll 2.1 +3.5σ

p-p Inelastic Cross Section @ 39 and 55 TeV

Conversion using Glauber model: $\mathrm{Glauber}(\sigma_{pp}^{\mathrm{tot}},\ B_{\mathrm{el}},\ \lambda,\ \ldots) \rightarrow \sigma_{\mathrm{p-air}}$



- Extended Glauber conversion with inelastic screening
- propagation of modeling uncertainties
- Model uncertainties may be underestimated, since there are other theoretical models available for the conversion

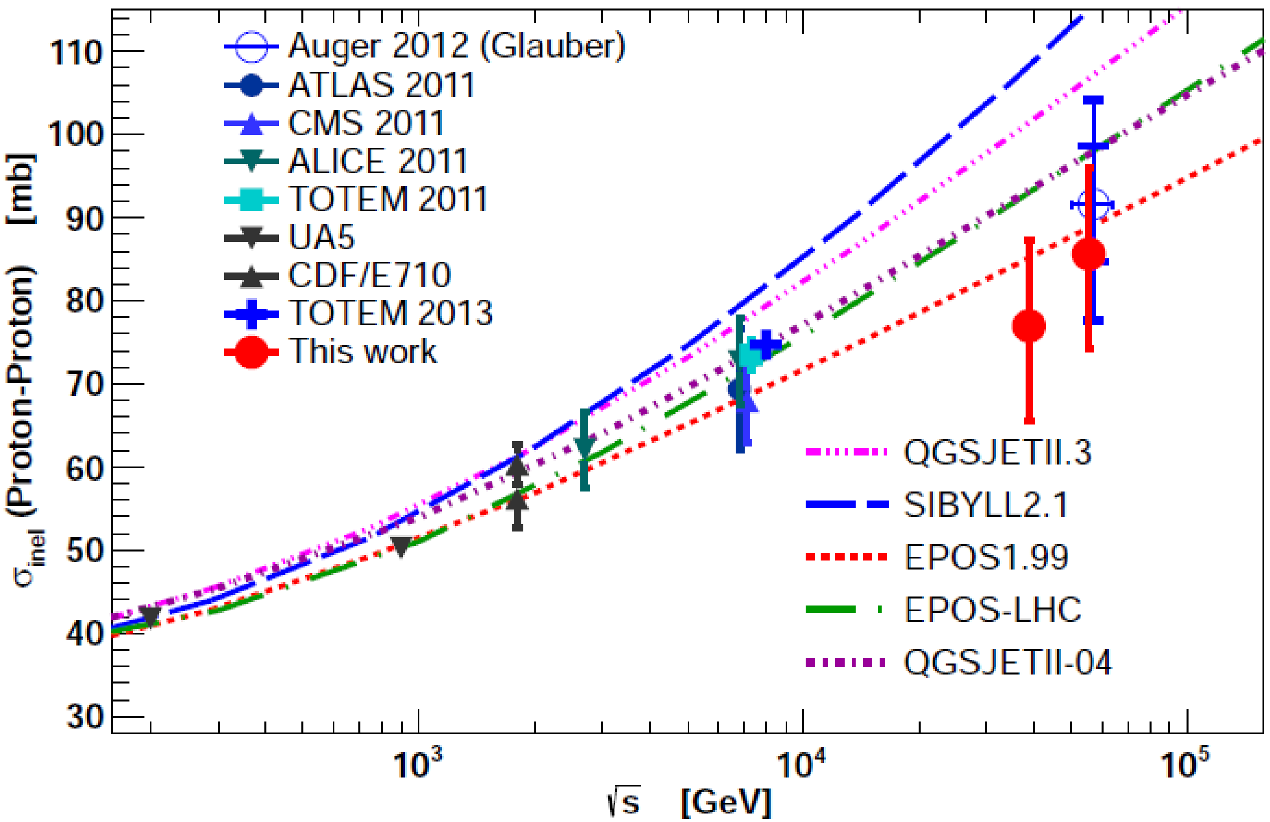
Results, $\sigma_{\mathrm{pp}}^{\mathrm{inel}}$ in mb

Lower energy point
76.95±5.4(stat)+5.2/-7.2(syst)±7(glauber)
at $\sqrt{s_{\mathrm{pp}}} = 38.7 \pm 2.5$ TeV

Higher energy point
85.62±5(stat)+5.5/-7.4(syst)±7.1(glauber)
at $\sqrt{s_{\mathrm{pp}}} = 55.5 \pm 3.6$ TeV

p-p Inelastic Cross Section @ 39 and 55 TeV

Conversion using Glauber model: $\text{Glauber}(\sigma_{pp}^{\text{tot}}, B_{\text{el}}, \lambda, \ldots) \rightarrow \sigma_{\text{p-air}}$



- Extended Glauber conversion with inelastic screening
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Results, $\sigma_{\text{pp}}^{\text{inel}}$ in mb

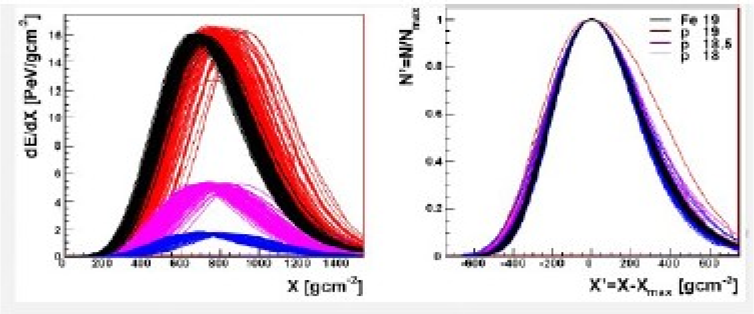
Relatively low cross-section compared to TOTEM:

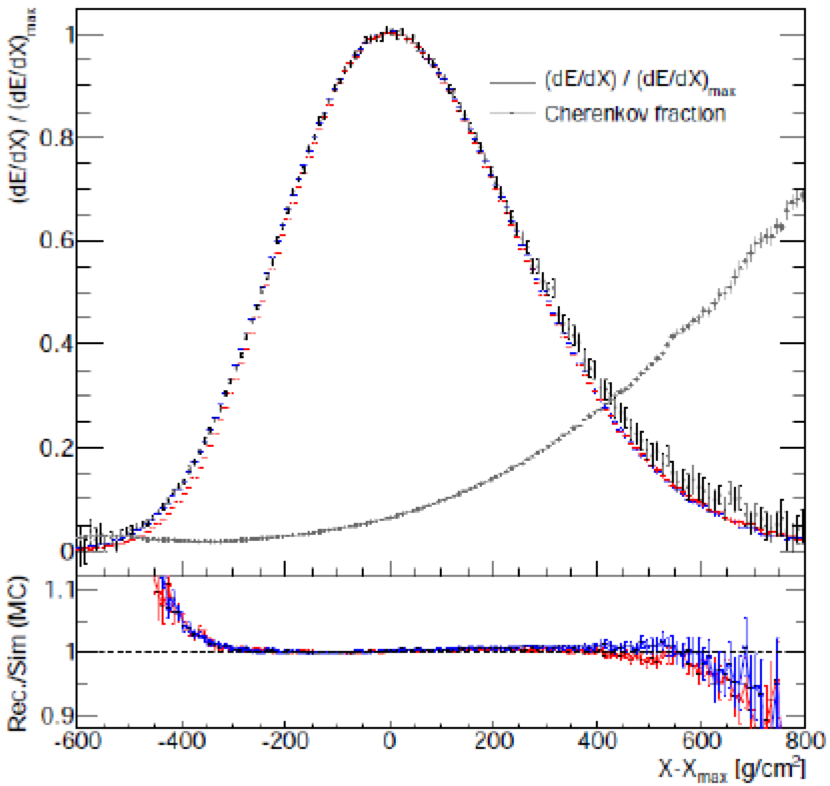
Limitations due to Glauber approach ? uncertainties to low ?

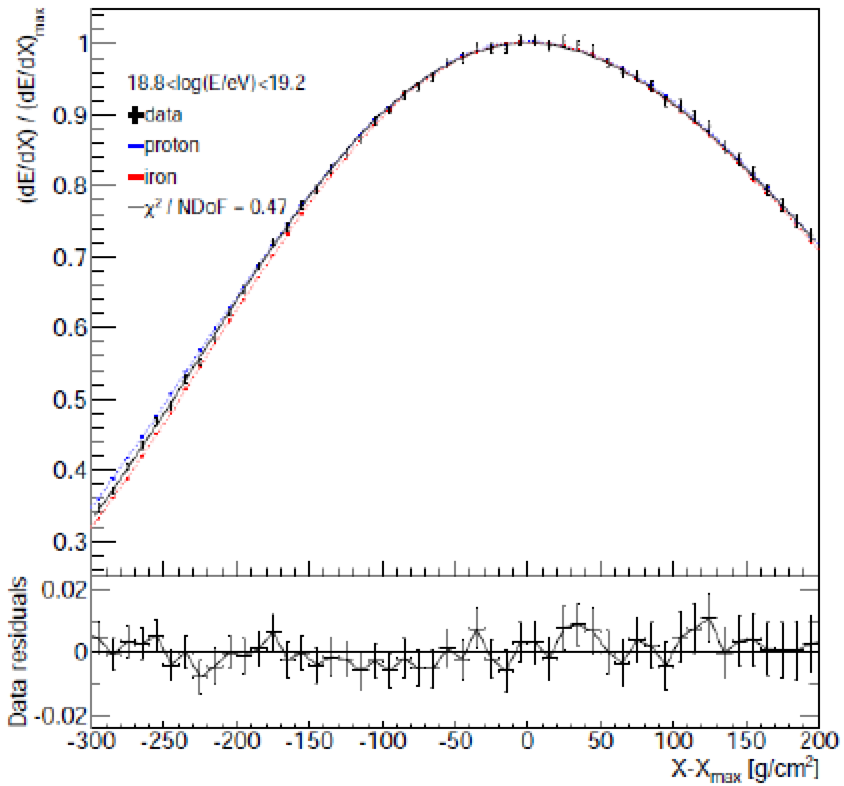
Mean Longitudinal Profile

Average of all FD measurements rescaled and centered at $X' = X - X_{max}$:

- Extract 2 parameters from mean shower shape
  - L from rising before maximum
  - R from fall after maximum
- Sensitivity to mass composition and hadronic interactions







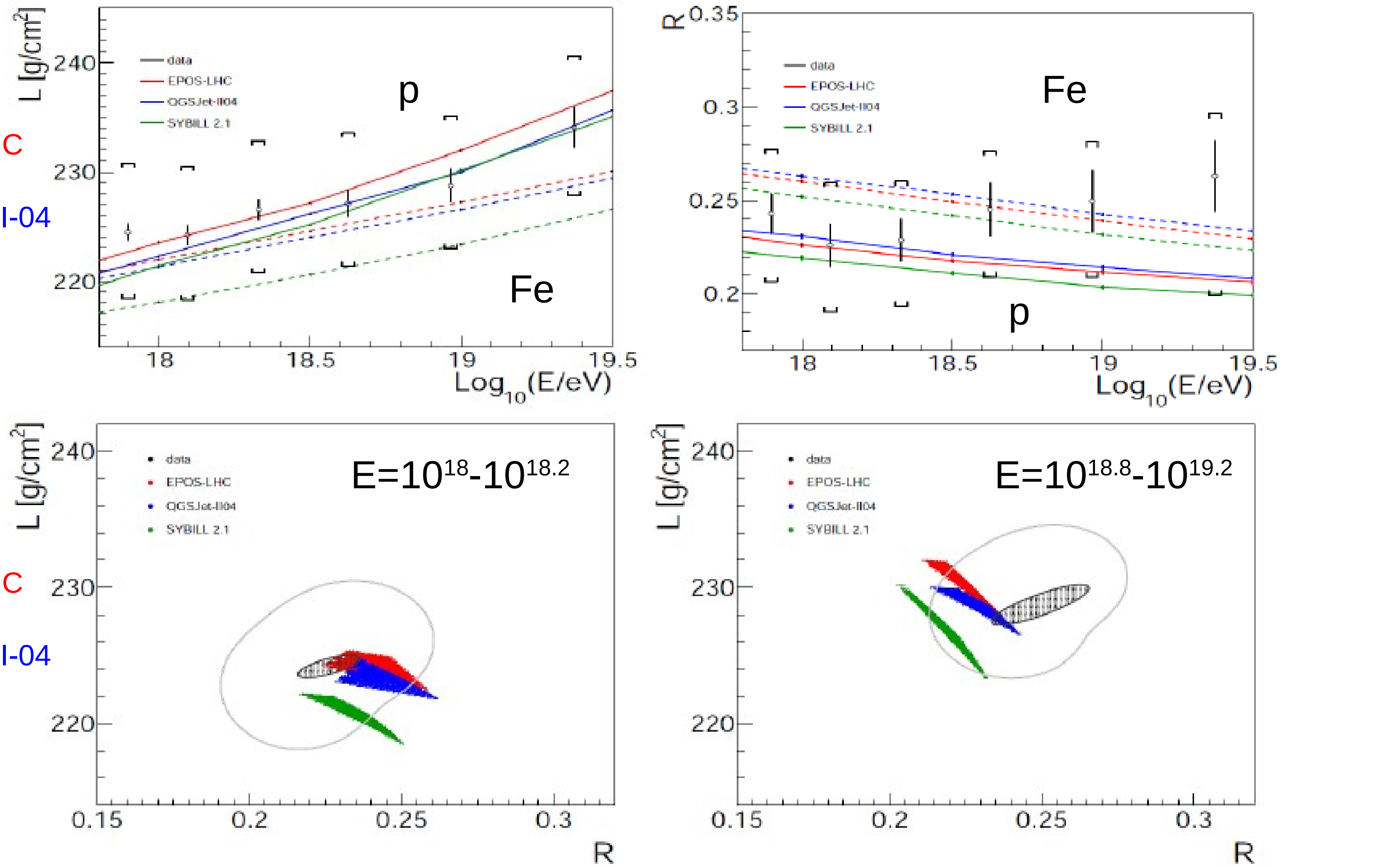
Shape Parameters vs Energy

➡ Large uncertainties but similar results between models and compatible with data

EPOS LHC

QGSJETII-04

Sibyll 2.1



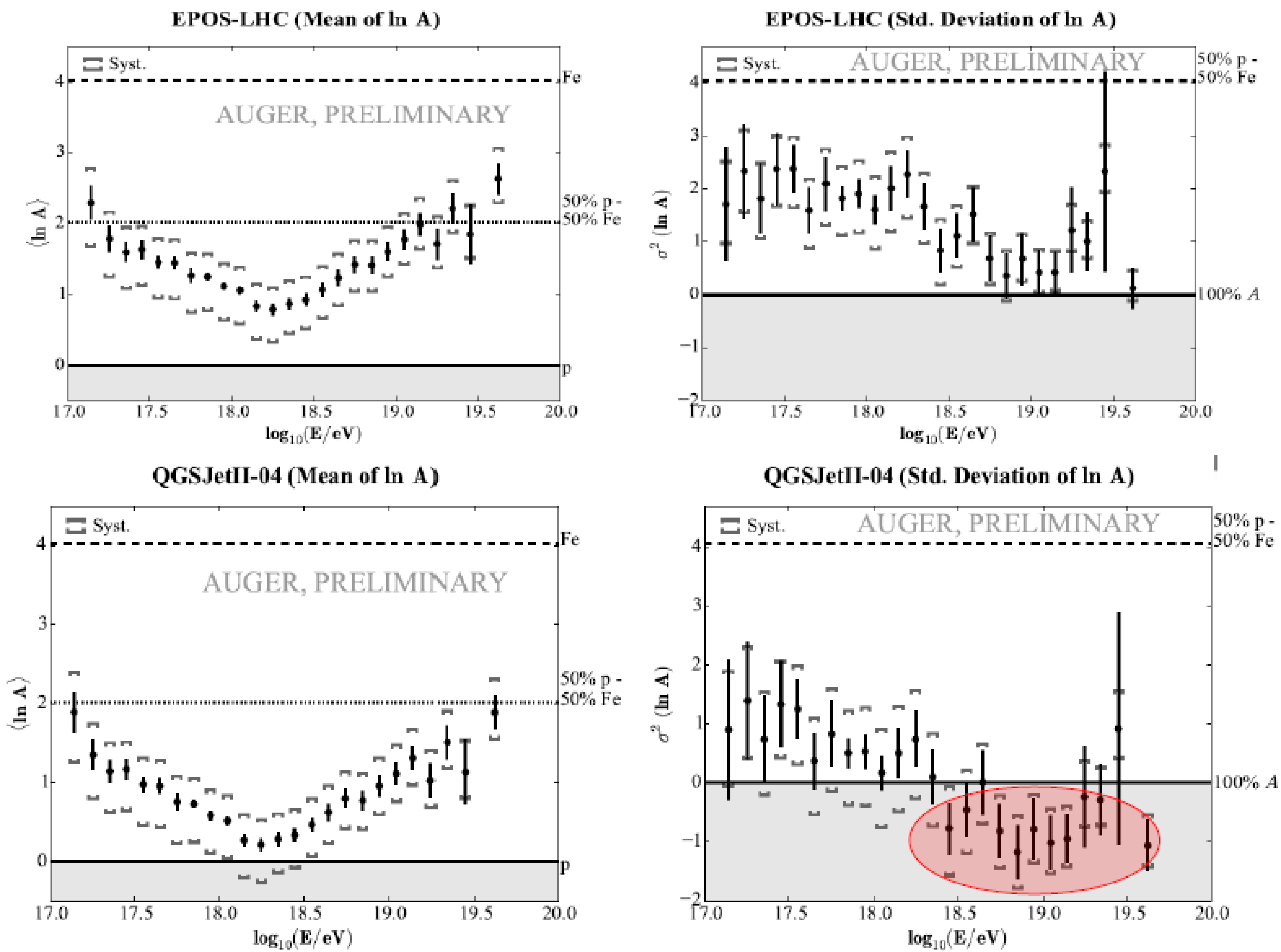
EPOS LHC

QGSJETII-04

Sibyll 2.1

Model Consistency using FD

- Shown by J. Bellido : std deviation of lnA allows to test model consistency.



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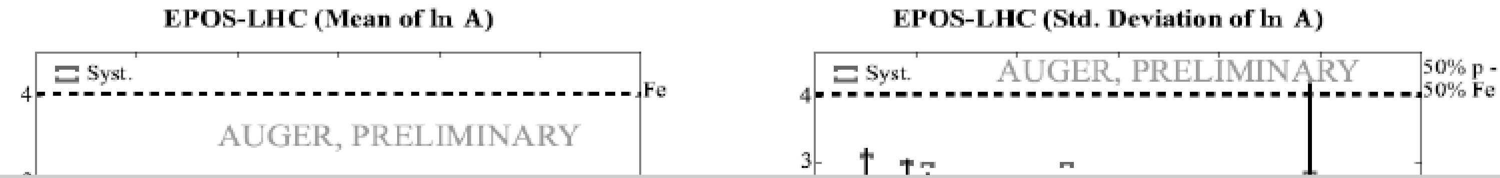
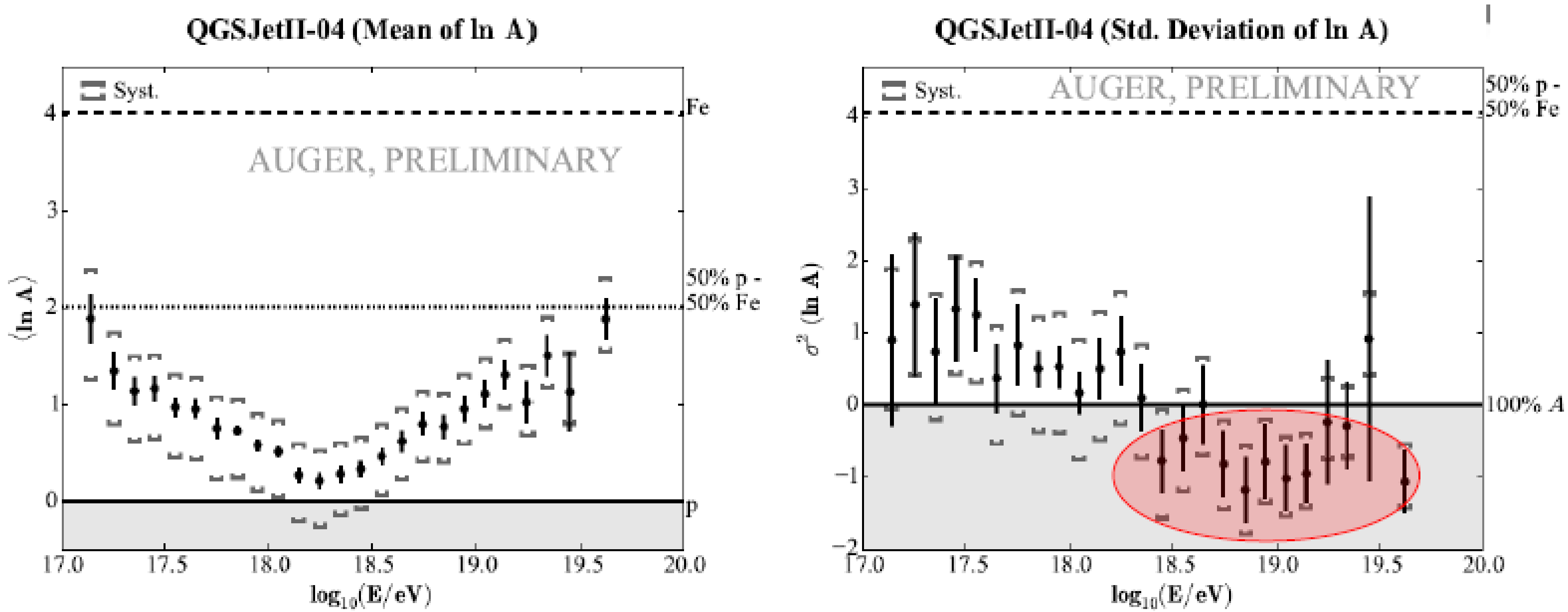


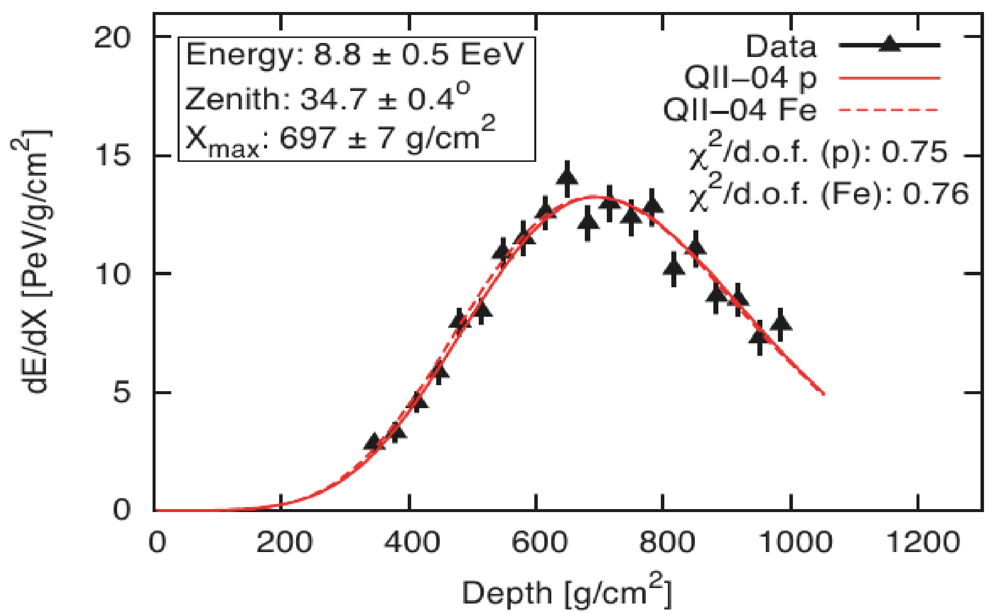
Tests using FD only:

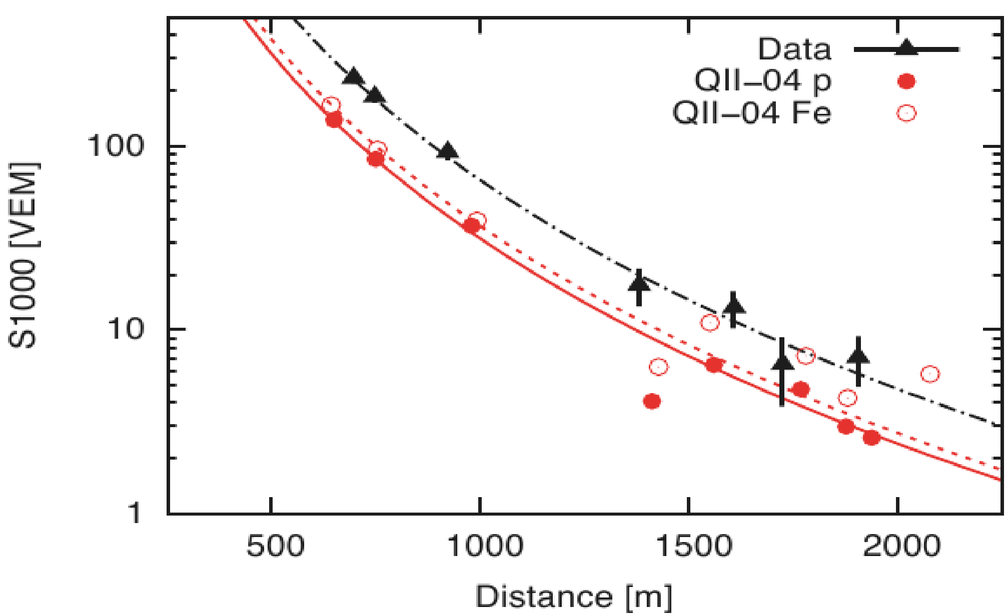
Post-LHC models (QGSJETII-04 and EPOS LHC) reproduce air shower longitudinal profile consistently

(up to 1 sigma deviation)



Hybrid Analysis





- **Analysis based on 411 Golden Hybrid Events**
  - find simulated showers reproducing each FD profile for all possible models and primary masses (p, He, N, Fe),
  - decompose ground signal into pure electromagnetic (S_{EM}) and muon dependent signal (S_μ),
  - rescale both component separately (R_E and R_μ to reproduce SD signal for each showers,

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

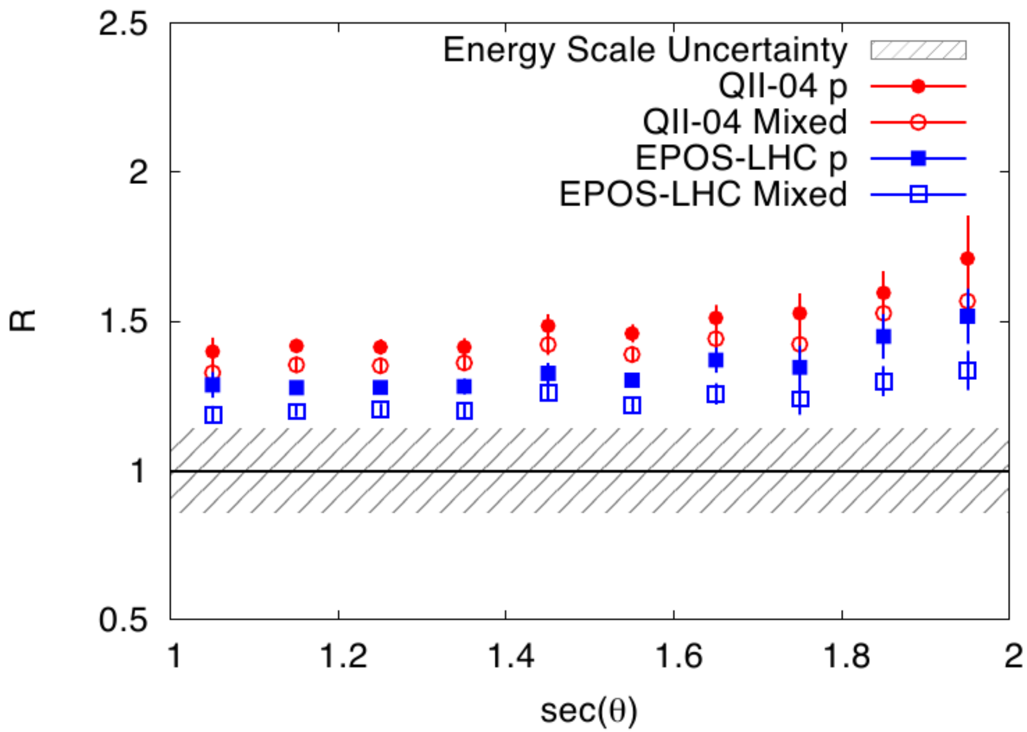
  - for mixed composition, give weight according to X_{max} distribution.

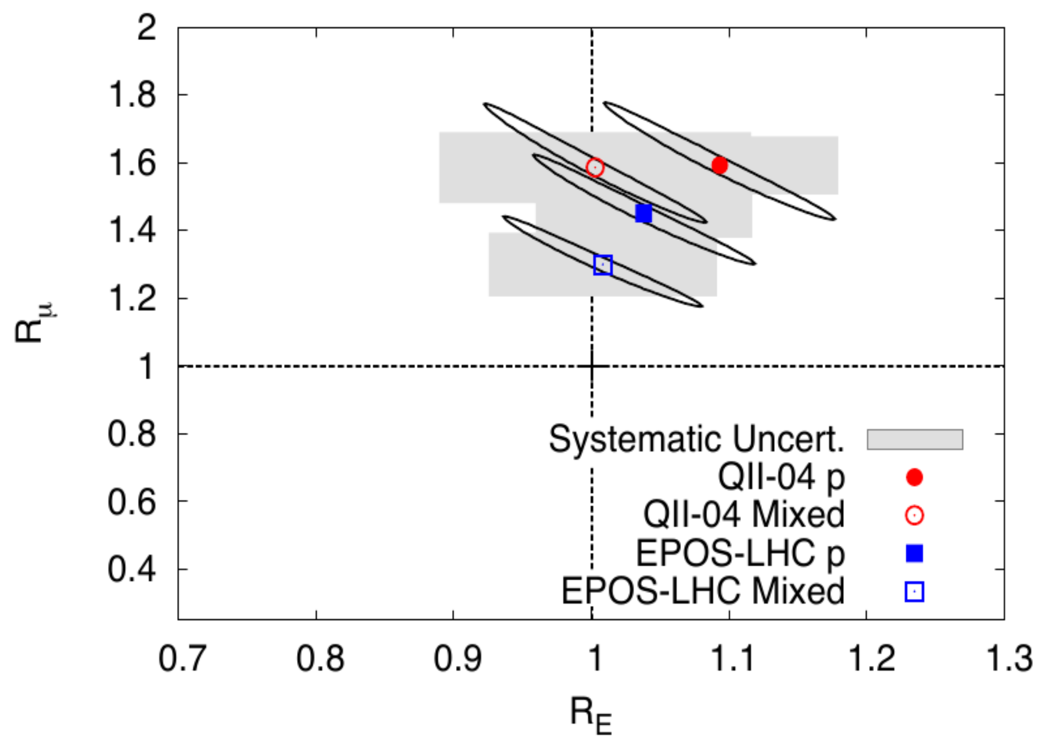
Muon Rescaling

- Simulations don't reproduce FD and SD signal consistently
  - ➡ $R=S_{1000}^{observed}/S_{1000}^{predicted}$ increase with zenith angle
  - ➡ EPOS-LHC Iron could be (almost) compatible with data, but X_{max} data are NOT pure Iron (but mixed).

- To reproduce data simulations have to be rescaled
  - ➡ for mixed composition, only muon component has to be changed

    ➡ correct energy scale
  - ➡ 30% muon deficit for EPOS-LHC and 59% for QGSJETII-04.



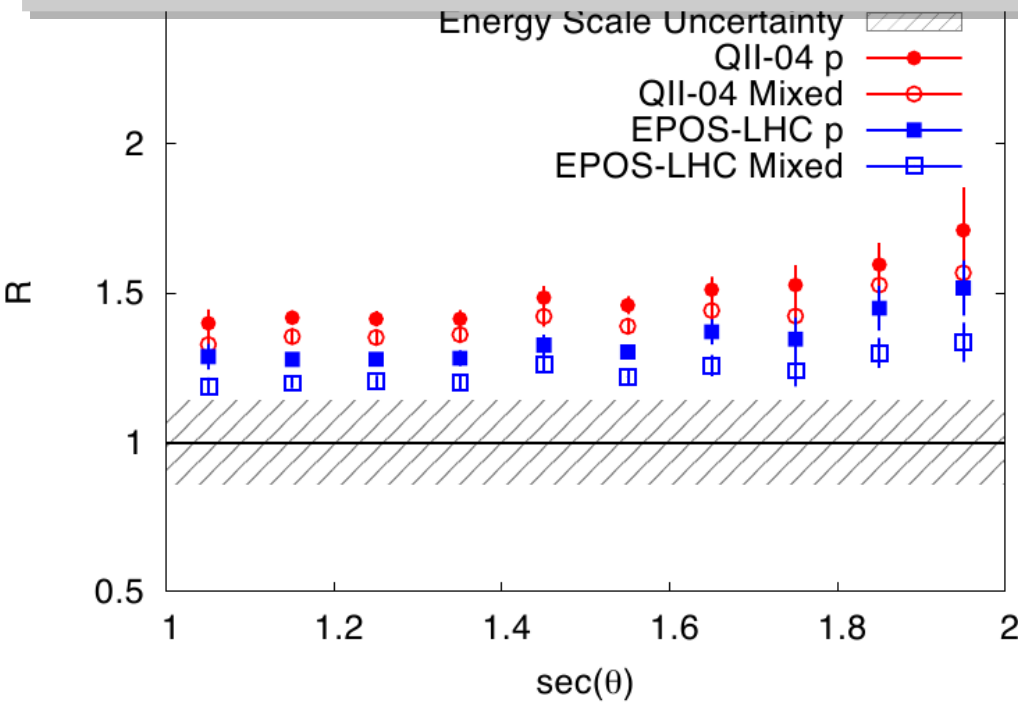


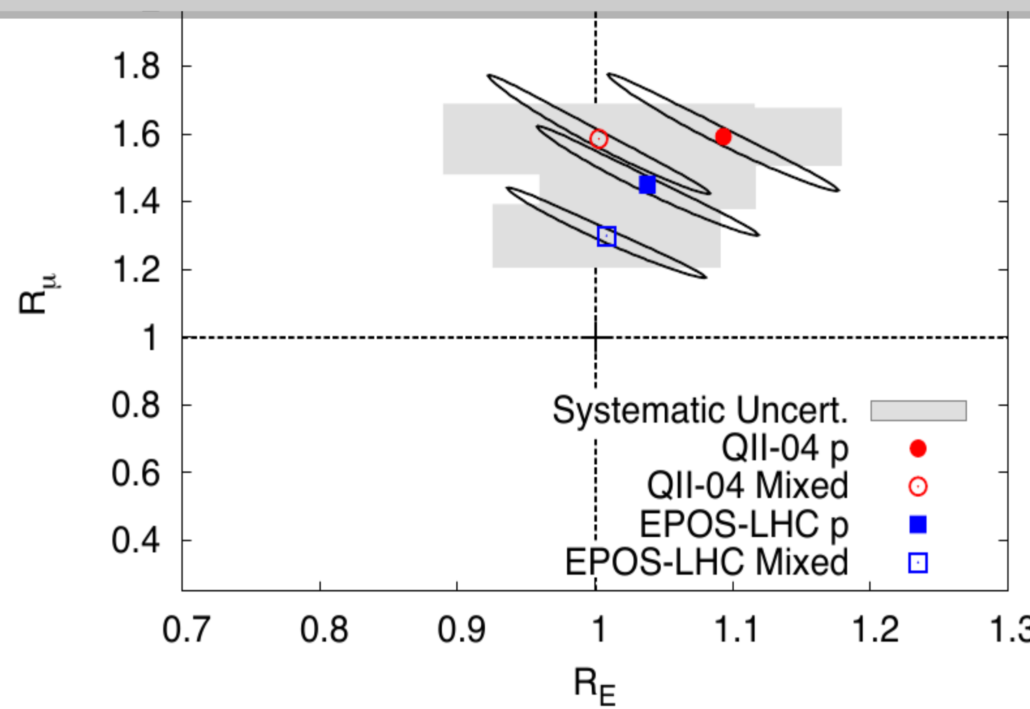
Muon Rescaling

- **Simulations don't reproduce FD and SD signal consistently**
  - ➡ $R=S_{1000}^{observed}/S_{1000}^{predicted}$ increase with zenith angle
- **To reproduce data simulations have to be rescaled**
  - ➡ for mixed composition, only muon component has to be changed

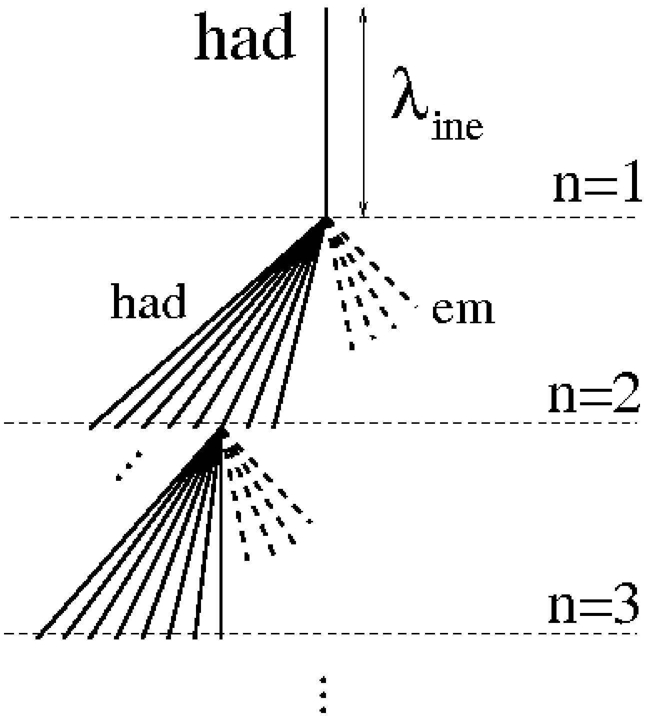
To get FD and SD data consistently reproduced, muon signal has to be increased in simulations :

Check it by direct muon measurement !





Toy Model for Hadronic Cascade



$$N_{tot} = N_{had} + N_{em}$$

Primary particle : hadron

Muons produced after many had. generations

$N_{had}{}^{n}$ particles can produce muons after *n* interactions

$$N(n) = N_{had}^{n}$$

$N_{tot}{}^{n}$ particles share E_0 after *n* interactions

$$E(n) = E_0 / N_{tot}^{n}$$

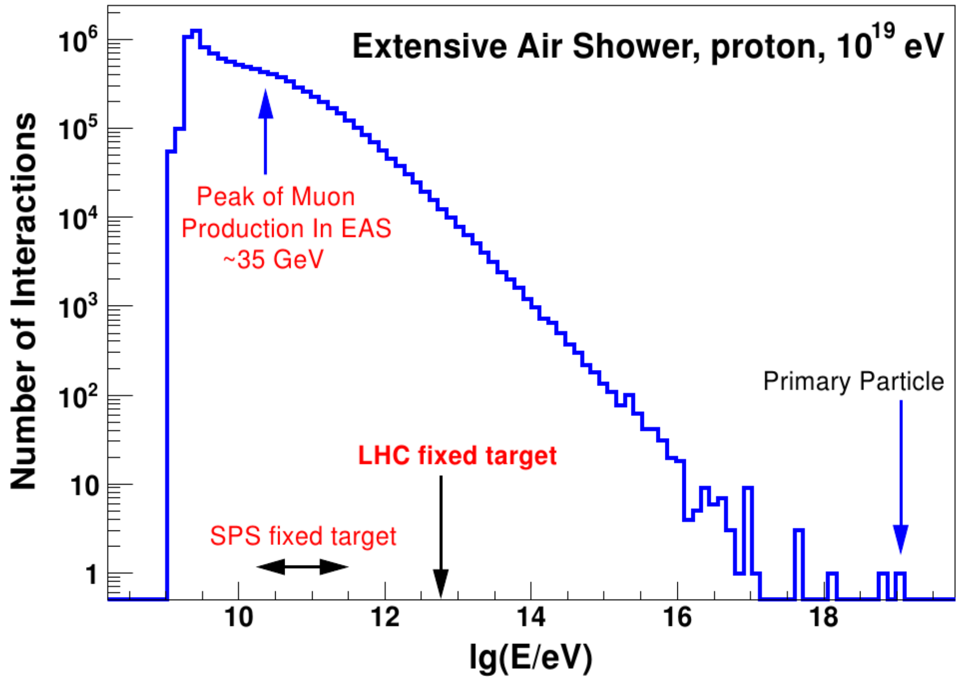
Assumption: particle decay to muon when *E* = E_{dec} (critical energy) after n_{max} generations

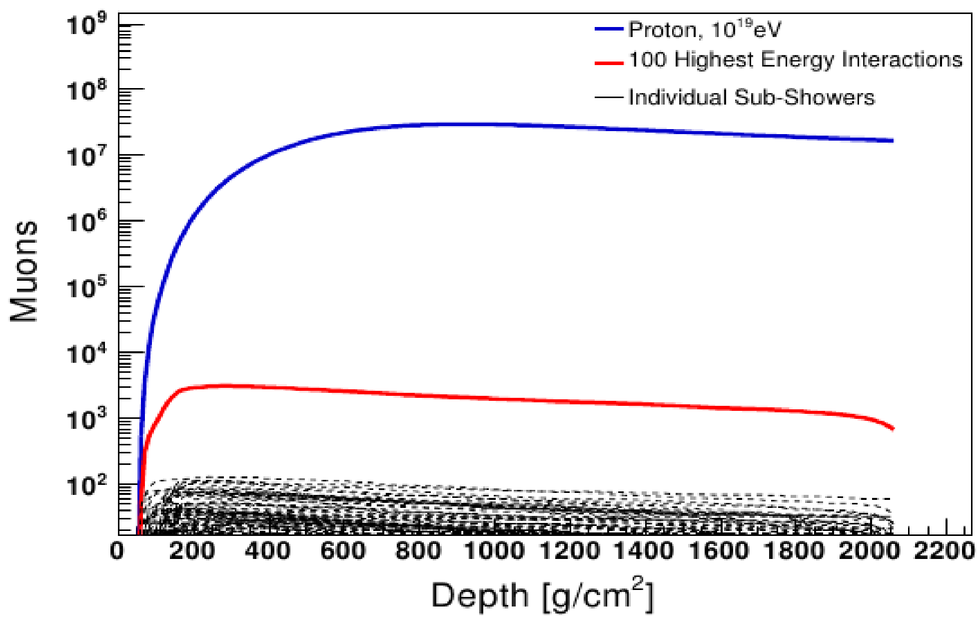
$$E_{dec} = E_0 / N_{tot}^{n_{max}}$$

$$n_{max} = \frac{\ln(E_0/E_{dec})}{\ln(N_{tot})}$$

$$\ln(N_{\mu}) = \ln(N(n_{max})) = n_{max} \ln(N_{had})$$

Surface Detector

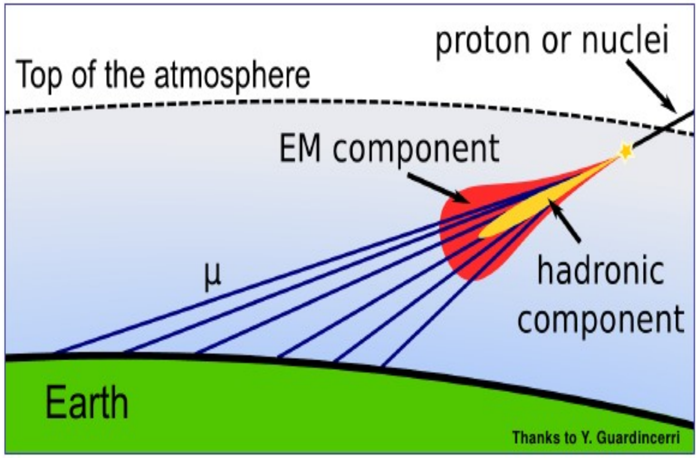


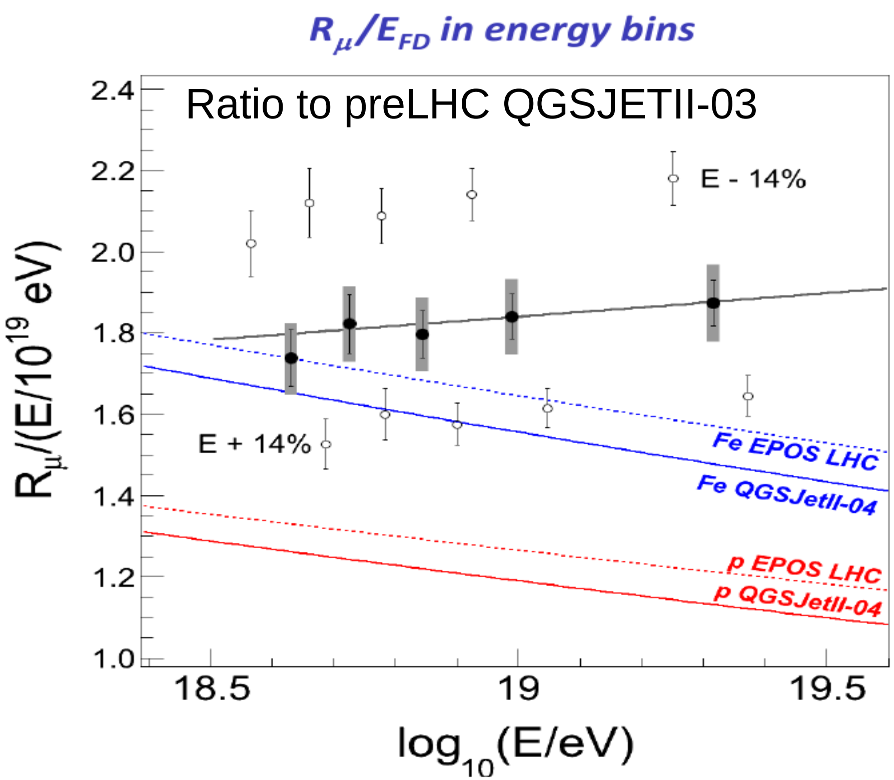


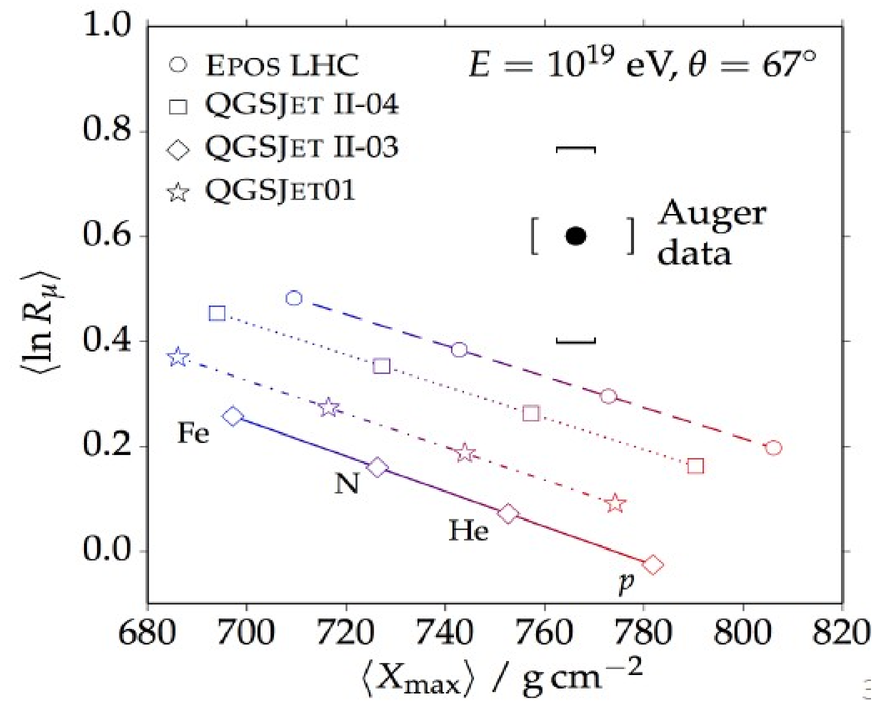
- **SD detector sensitive to**
  - electromagnetic particles (EM)
  - muons
- **Particles at ground produced after many generations of hadronic interactions**
  - most of EM particles from pure EM (universal) shower (depend on high (first) energy hadronic interactions)
  - muons produced at the end of hadronic cascade (depend on low energy hadronic interactions)
  - small fraction of EM (at large r) produced by last hadronic generation
- **EM and muons give different signal in Cherenkov detector.**
  - property of time traces

Direct Muon Measurement

- **Old showers contain only muon component**
  - ➡ direct muon counting with very inclined showers (>60°) by comparing to simulated muon maps (geometry and geomagnetic field effects)
  - ➡ EM halo accounted for
  - ➡ correction between true muon number and reconstructed one from map by MC (<5%)

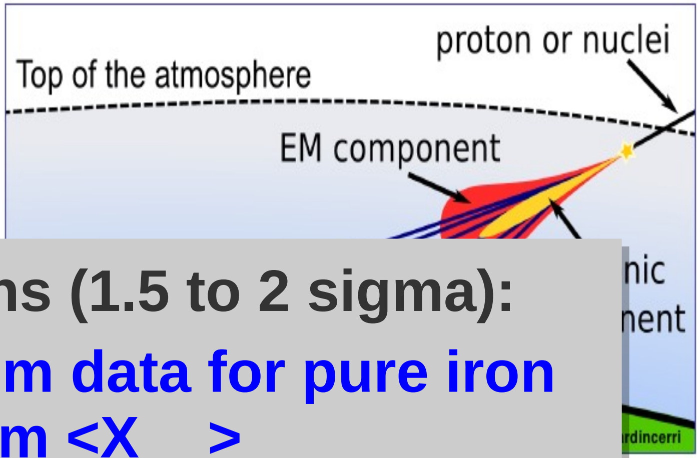






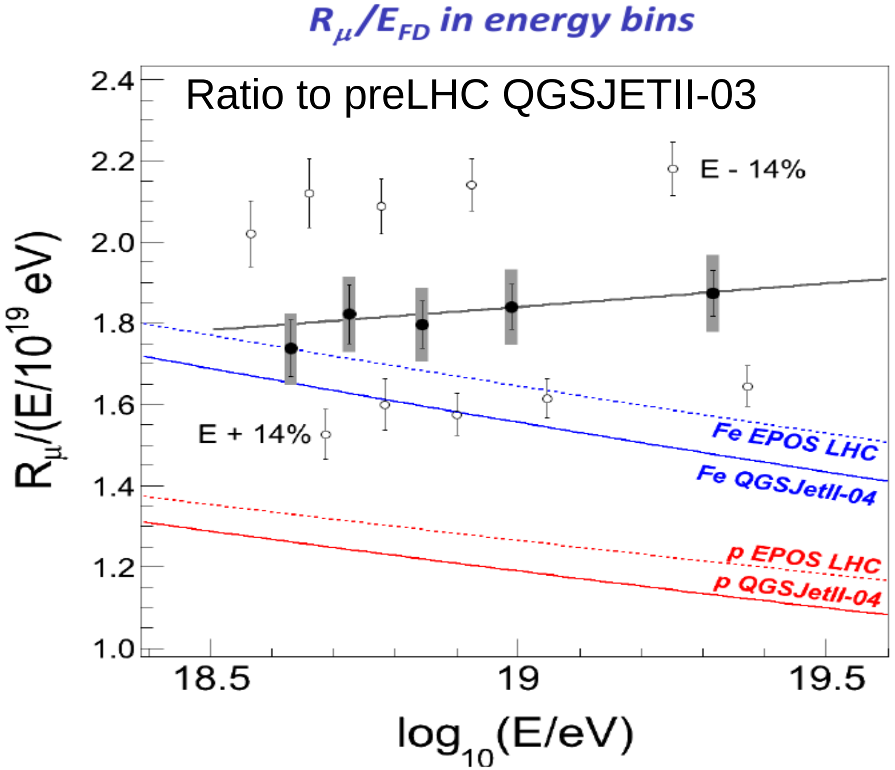
Direct Muon Measurement

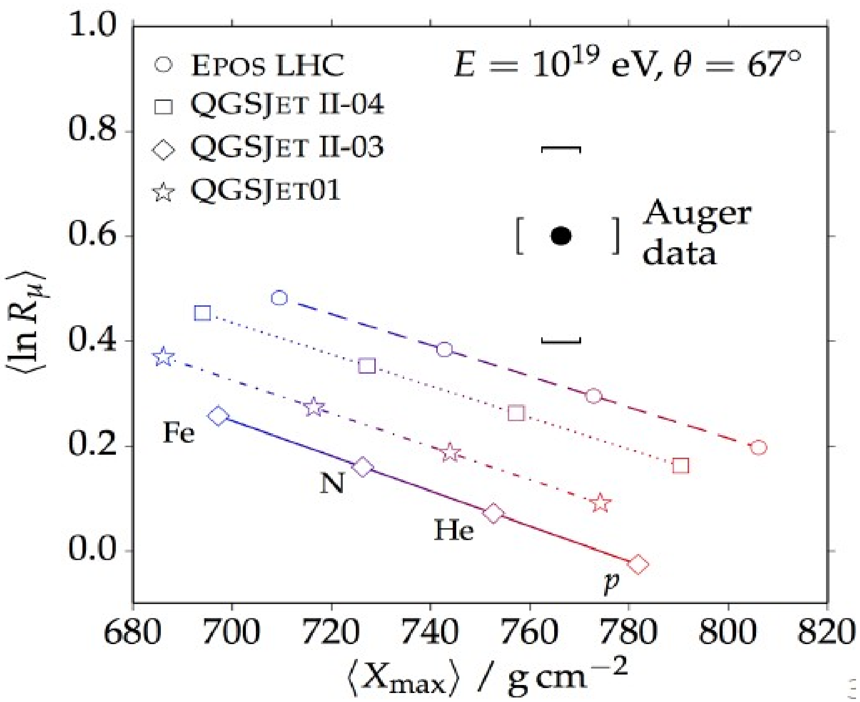
- **Old showers contain only muon component**
  - direct muon counting with very inclined showers (>60°) by comparing to simulated muon maps (geometry and geomagnetic field effects)



Clear muon deficit in air shower simulations (1.5 to 2 sigma):

Models could be compatible with muons from data for pure iron but not consistent with mass from $<X_{max}>$





Muon Production Depth

- **Independent SD mass composition measurement**
  - ➡ geometric delay of arriving muons

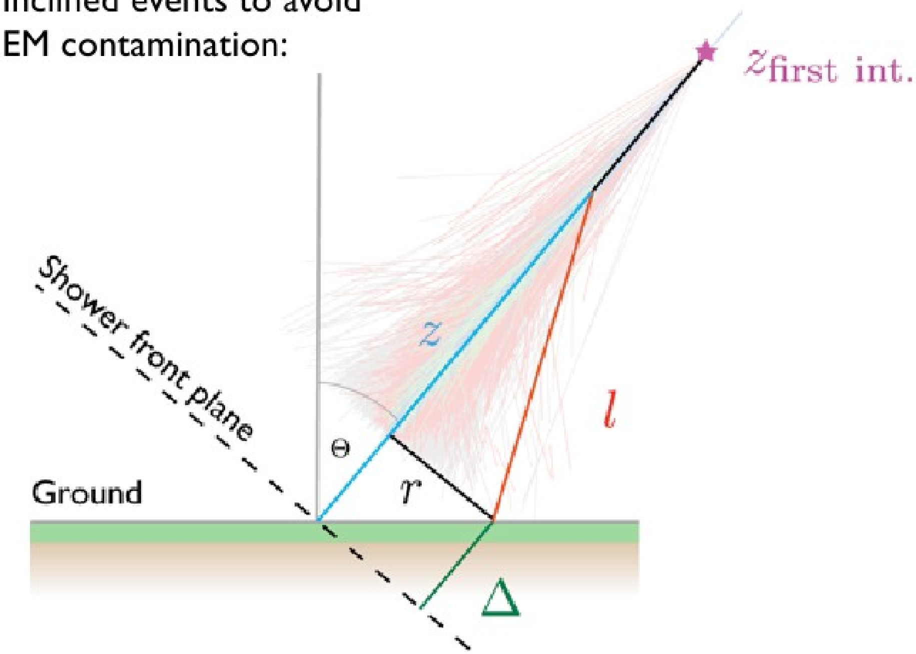
$$c \cdot t_{\mathrm{g}} = l - (z - \Delta)$$
$$= \sqrt{r^2 + (z-\Delta)^2} - (z - \Delta)$$

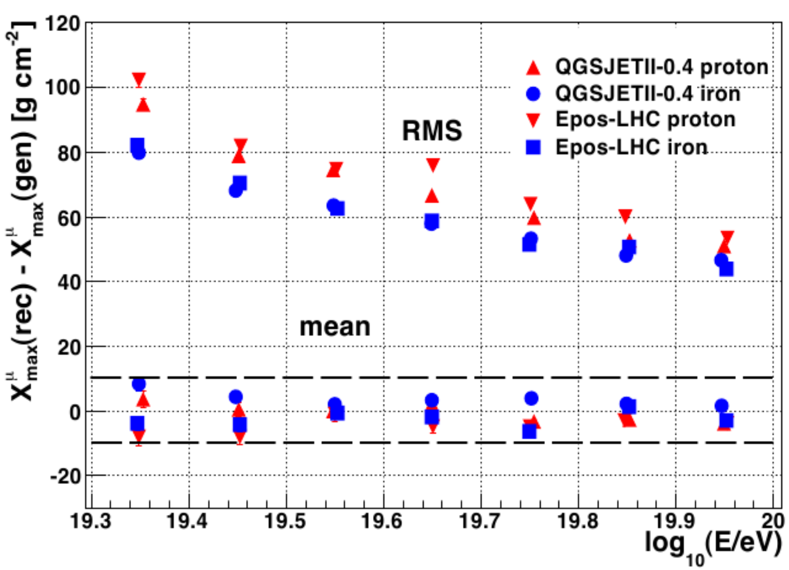
  - ➡ mapped to muon production distance

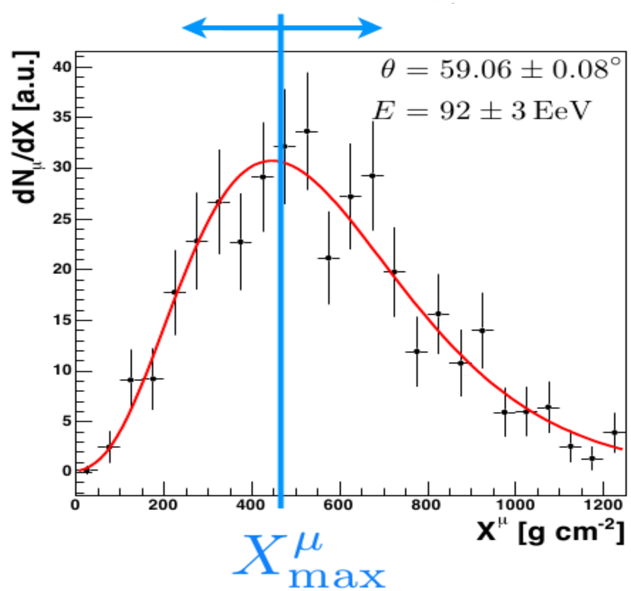
$$z = \frac{1}{2}\left(\frac{r^2}{ct_{\mathrm{g}}} - ct_{\mathrm{g}}\right) + \Delta$$

  - ➡ decent resolution and no bias

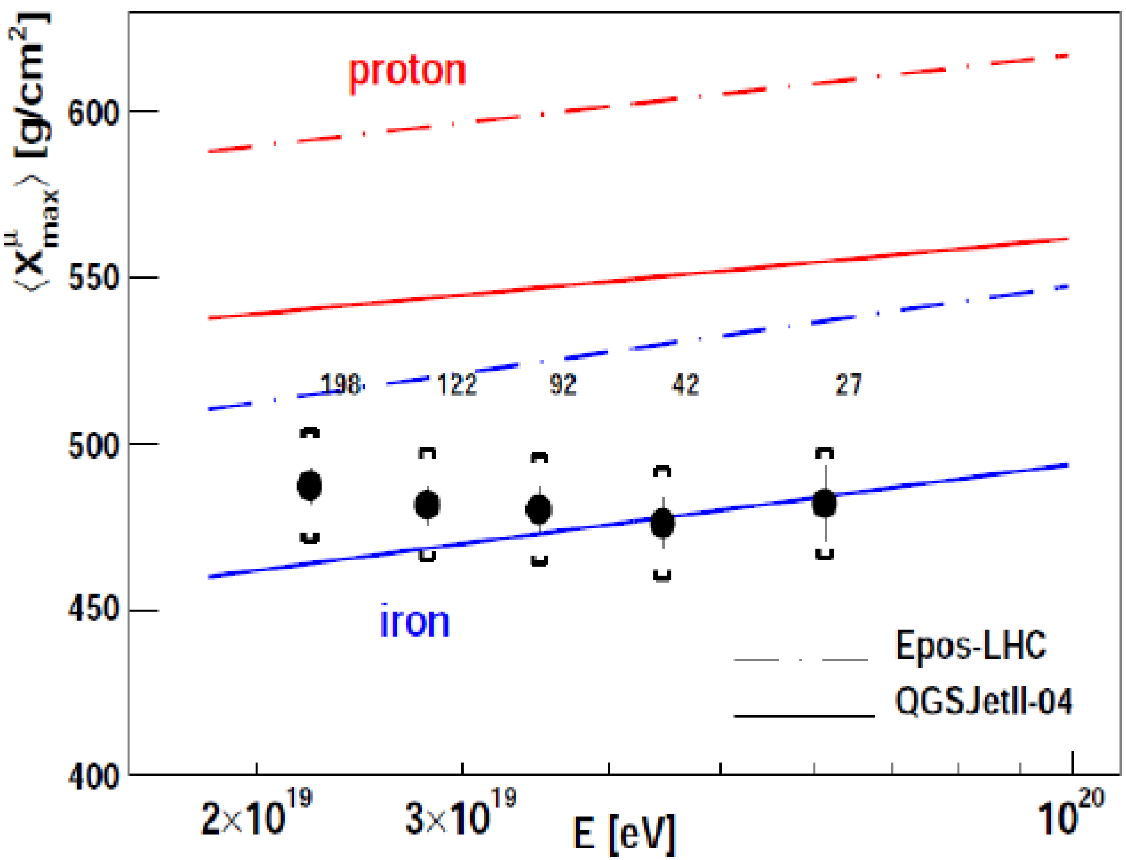
Inclined events to avoid EM contamination:







MPD and Models



- 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 $10^{19.3}$ eV for p (Fe)
  - 50 g/cm2 at 10^{20} eV

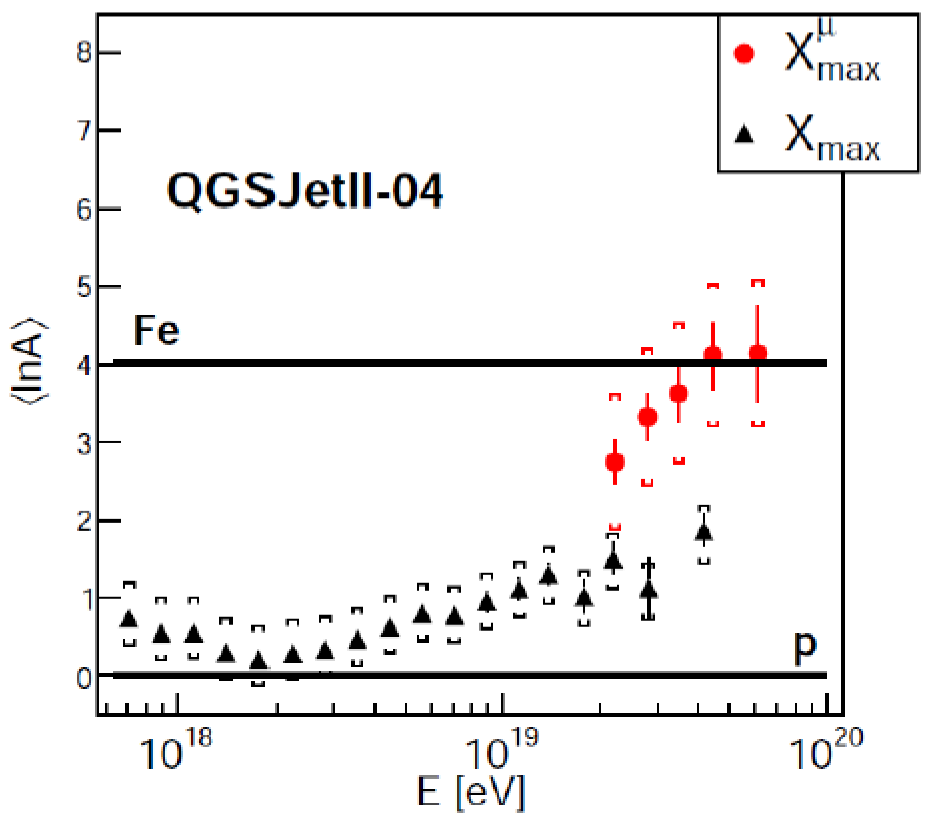
Large discrepancies between models :

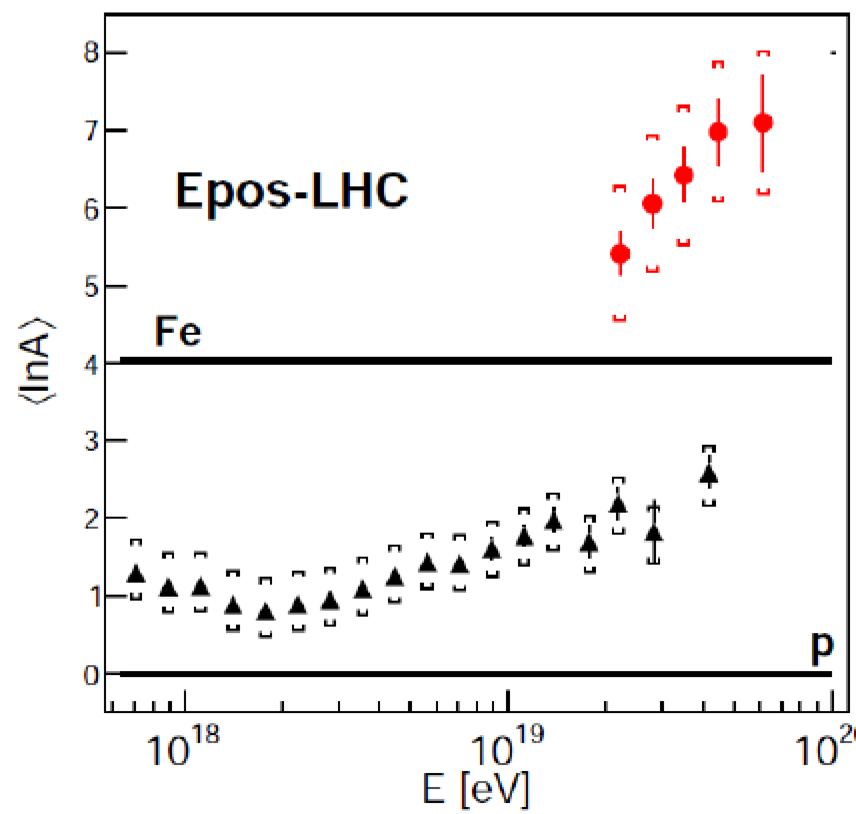
EPOS LHC predictions for MPD excluded by data (outside p-Fe range)

High sensitivity of MPD to some details of hadronic interactions

MPD and Models

- **2 independent mass composition measurements**
  - ➡ both results should be between p and Fe
  - ➡ both results should give the same mean logarithmic mass for the same model
  - ➡ problem with EPOS appears after corrections motivated by LHC data (low mass diffraction) and model consistency (forward baryon production at high energy : see S.Ostapchenko's talk): direct constraint on hadronic interactions.





Summary

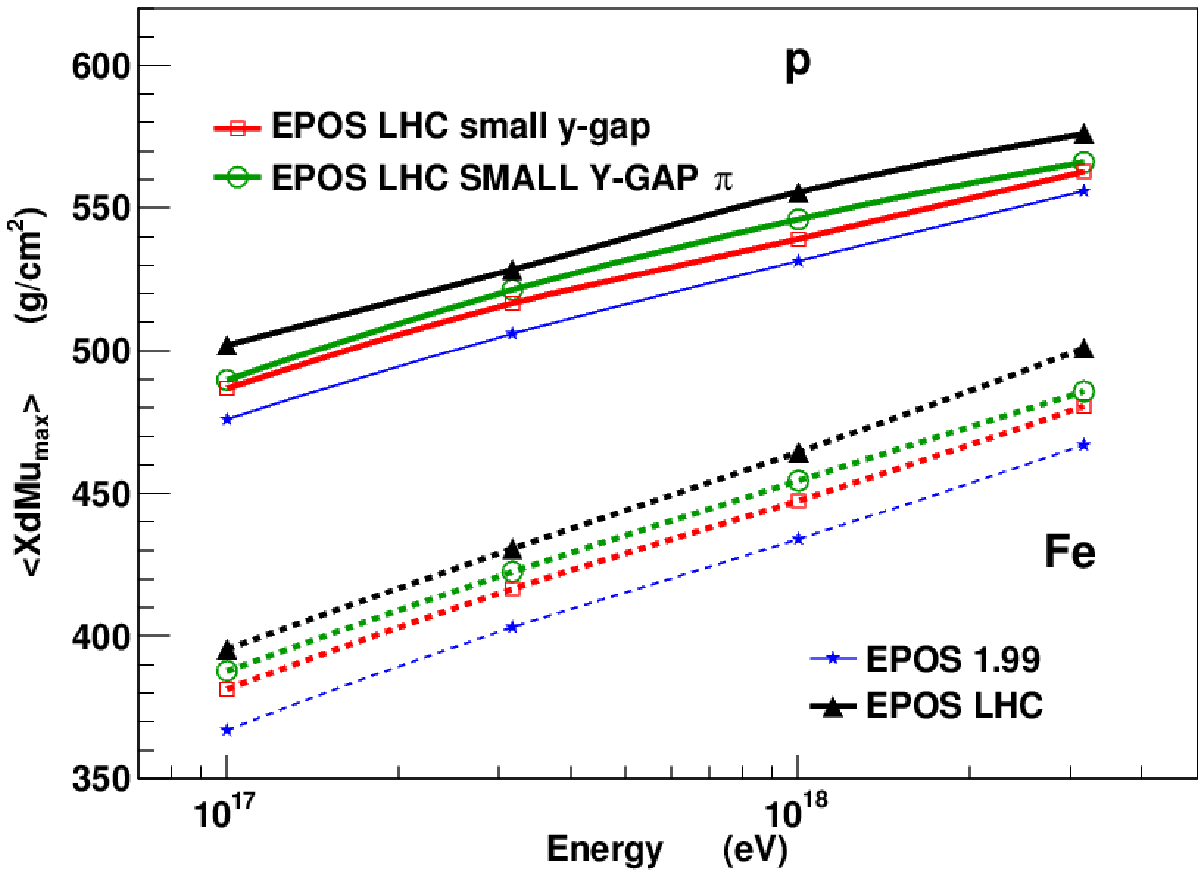
- **Measurements of the EM content in showers:**
  - ➜ relatively well reproduce by models
- **Measurements of the muon content in showers:**
  - ➜ direct results comparable with Fe-like predictions from post-LHC models
  - ➜ observed X_{max} distribution (EM component) not compatible with Fe-dominated composition: discrepancy between data and hadronic interaction models.
- **Comparison of <lnA> from X_{max} from FD and X^{μ}_{max} from SD allows direct test of hadronic interaction models (and Physics behind !)**
  - ➜ test small effects amplified by cascade effect
  - ➜ test energy, phase space (forward) and projectile (mesons) difficult to reach with accelerators

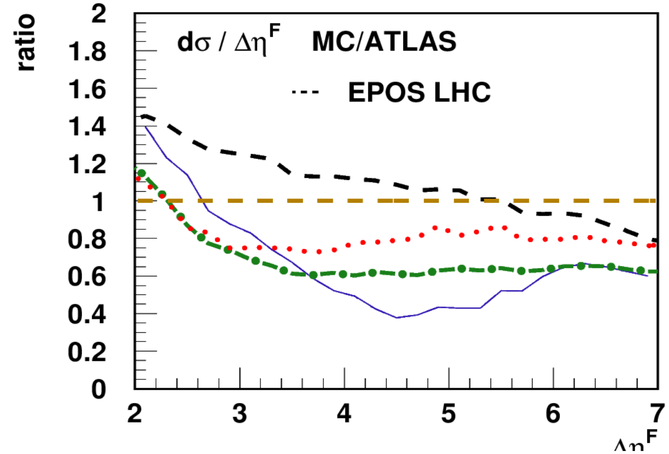
Hadronic interactions can be tested at ultra-high energy in PAO thanks to the comparison of different observables

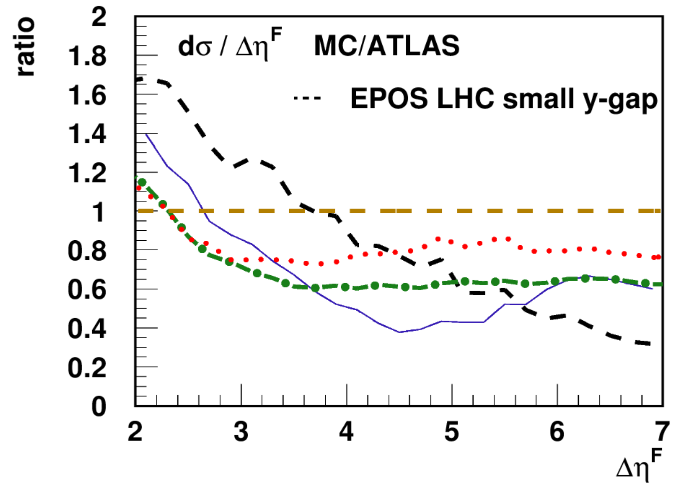
➜ No consistent description from models

Small Rapidity Gaps

- **Effect of remnant mass distribution in EPOS**
  - small y-gap or EPOS 1.99 : diffractive mass distribution 1/M for p and π
  - small y-gap π : diffractive mass distribution $1/M^2$ for p and 1/M for π
  - EPOS LHC : diffractive mass distribution $1/M^2$ for p and π







Small Rapidity Gaps

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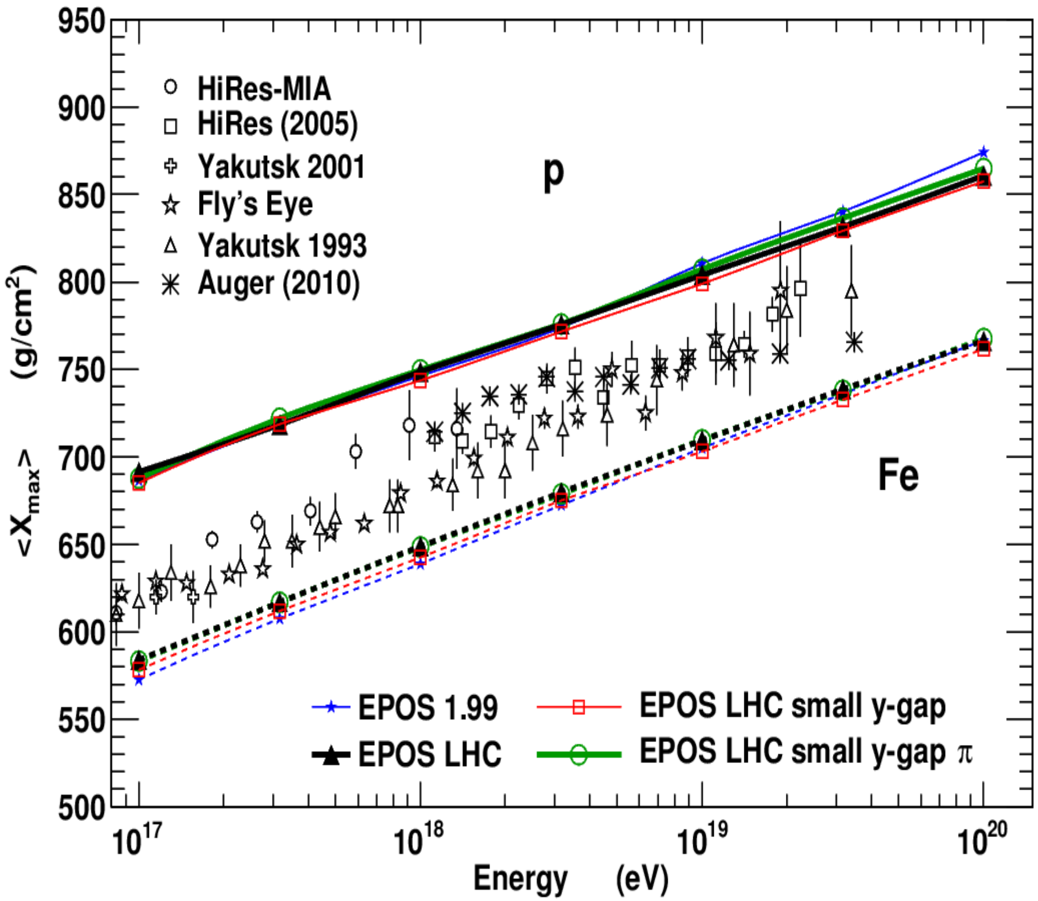
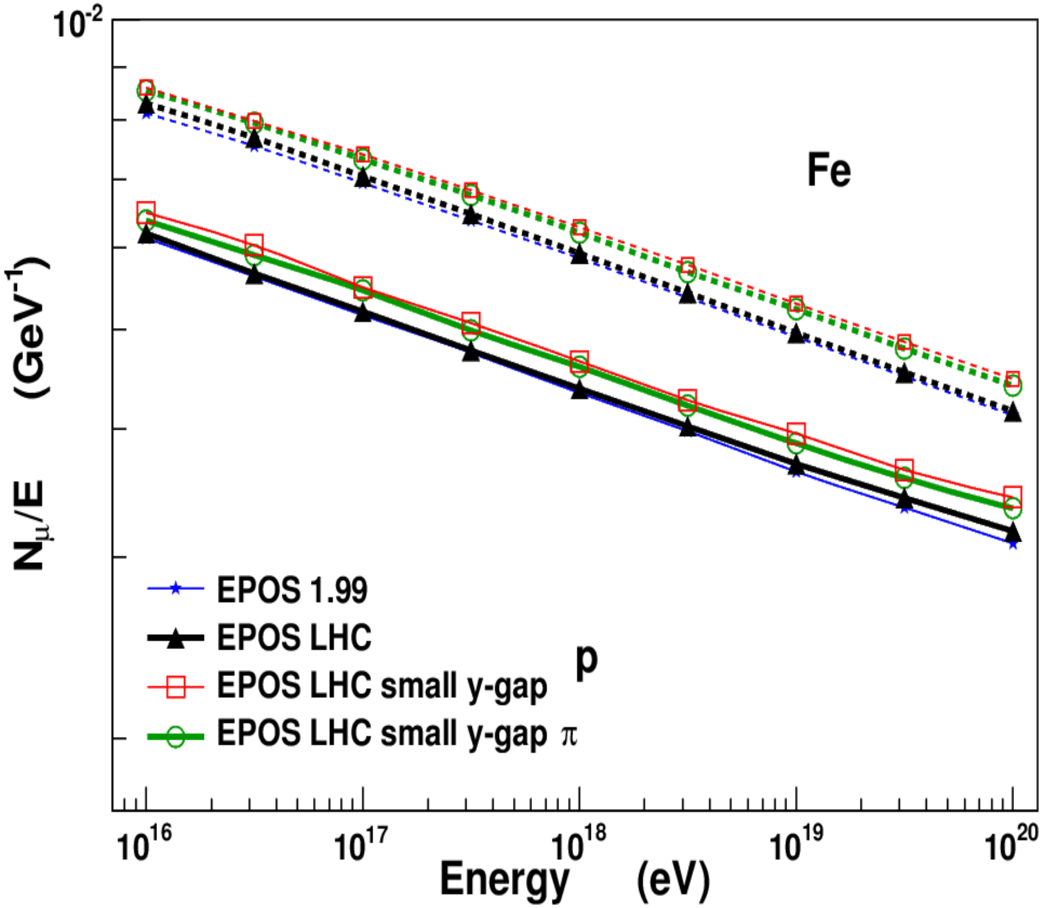
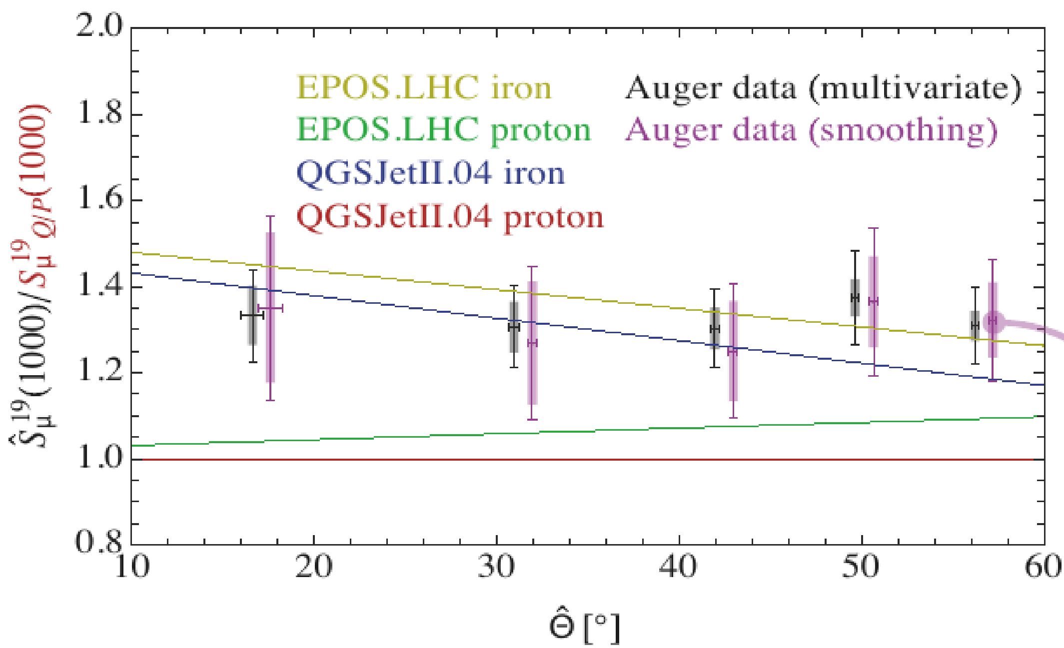




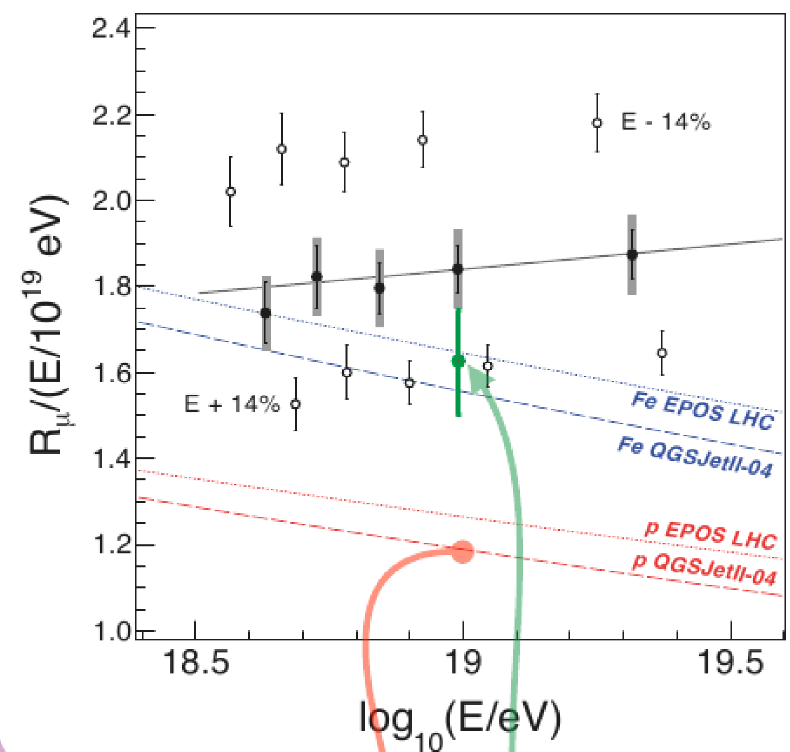
Muon Counting

From *vertical* events i.e. Θ in [0,60°]
analysing FADC traces @ 10^{19} eV



1.33 ± 0.02 (stat.) ± 0.05 (sys.) (multivariate)
1.31 ± 0.02 (stat.) ± 0.09 (sys.) (smoothing)

From *inclined* showers:
Θ > 62° (i.e. muon dominated)



1.35 x 1.2 = 1.6

Reference model: QGSJet II.04 (proton)

Reference model: QGSJet II.03 (proton)

The Smoothing Method

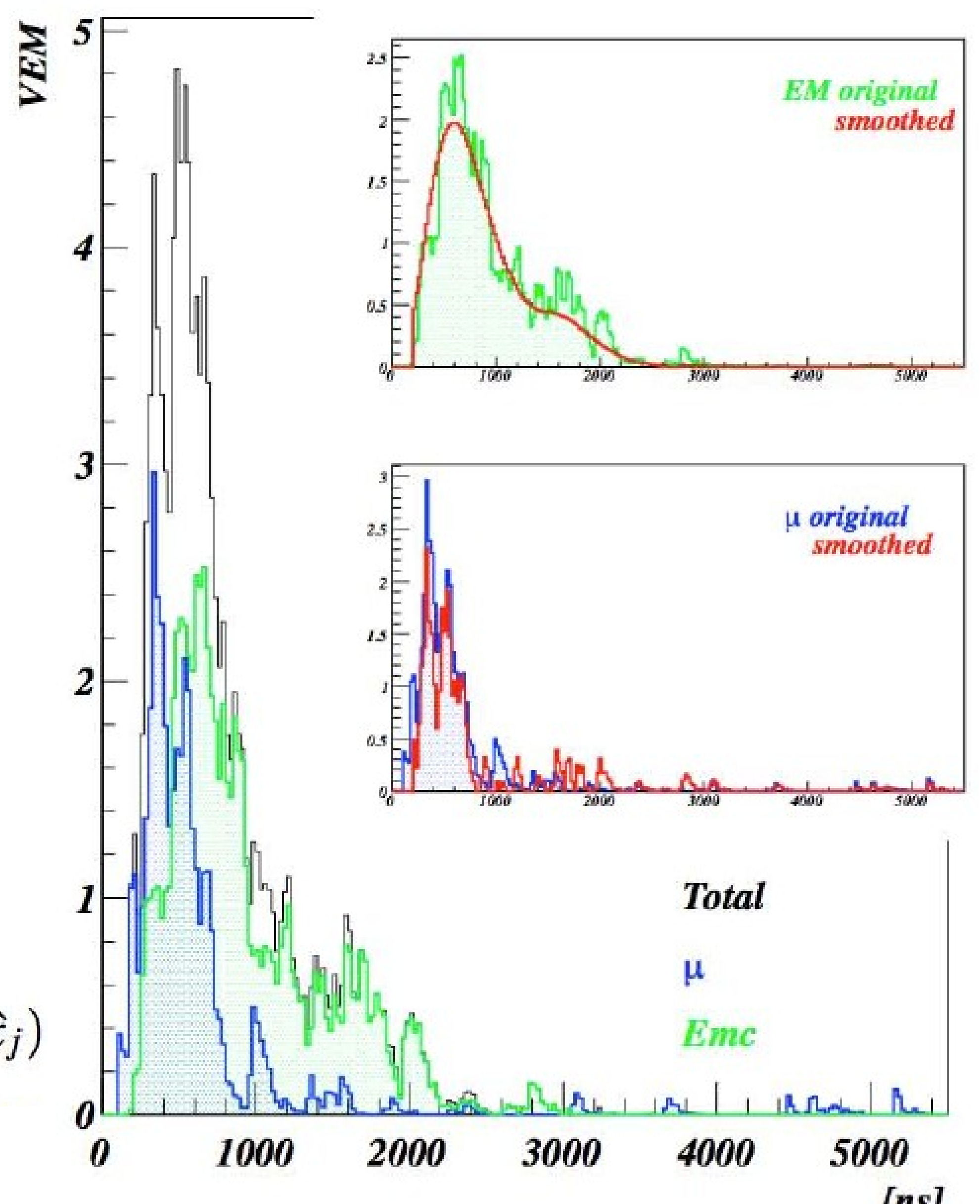
- **Time traces analysis**
  - amplitude distribution of the particle responses:
    - muon signal is peaky
    - EM signal is smooth
  - arrival time distributions:
    - muonic signal is short and high
    - EM signal is low and elongated
- **Method**
  - smooth the signal with a low-pass rectangular filter:

$$\hat{x}_j = \sum_{i=1}^{N} x_i p_{ij}$$

  - assign any positive difference to the muon signal

$$S_\mu = \sum_{j=1}^{N} \mathbb{I}\{x_j > \hat{x}_j\}(x_j - \hat{x}_j)$$

  - repeat the procedure on the smooth component until convergence to get muon fraction



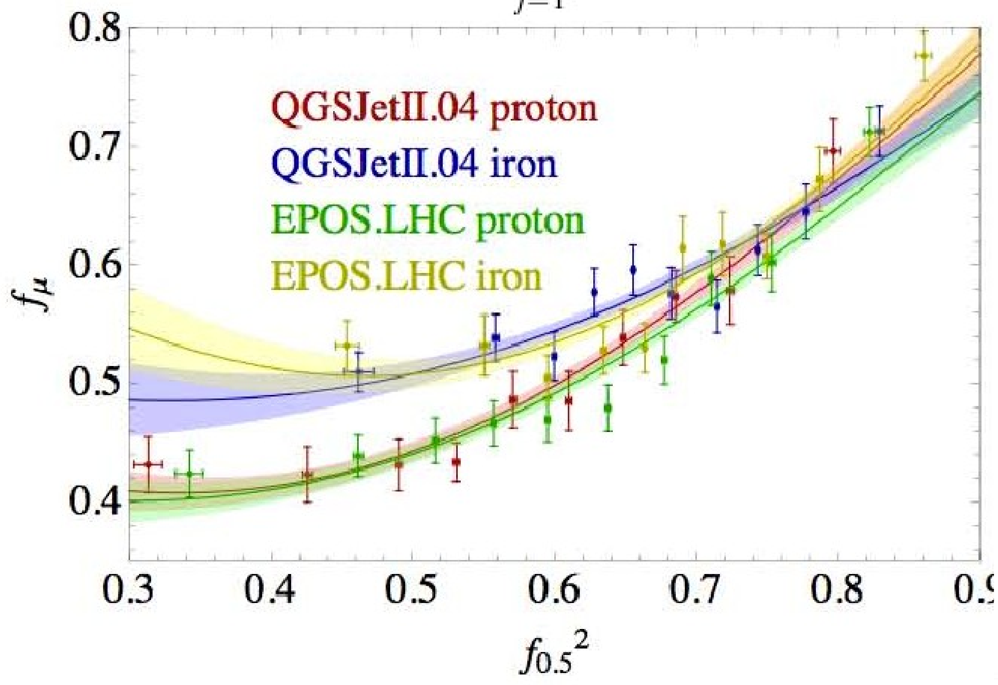
Systematic uncertainty of 5% due to hadronic models and primaries. Average resolution of 0.08

The Multivariate Method

- **Time traces analysis**
  - muon fraction measured by combining muon-content characteristics of the FADC signal : $\hat{f}_\mu = a + b\,\hat{\theta} + c\,f_{0.5}^2 + d\,\hat{\theta}\,P_0 + e\,\hat{r}$
  - $f_{0.5}$ and P_0 sensitive to large relative fluctuations and short signals as those when muons are signal dominant
  - fit parameters (a, b, c, d, e) estimated using MC simulations

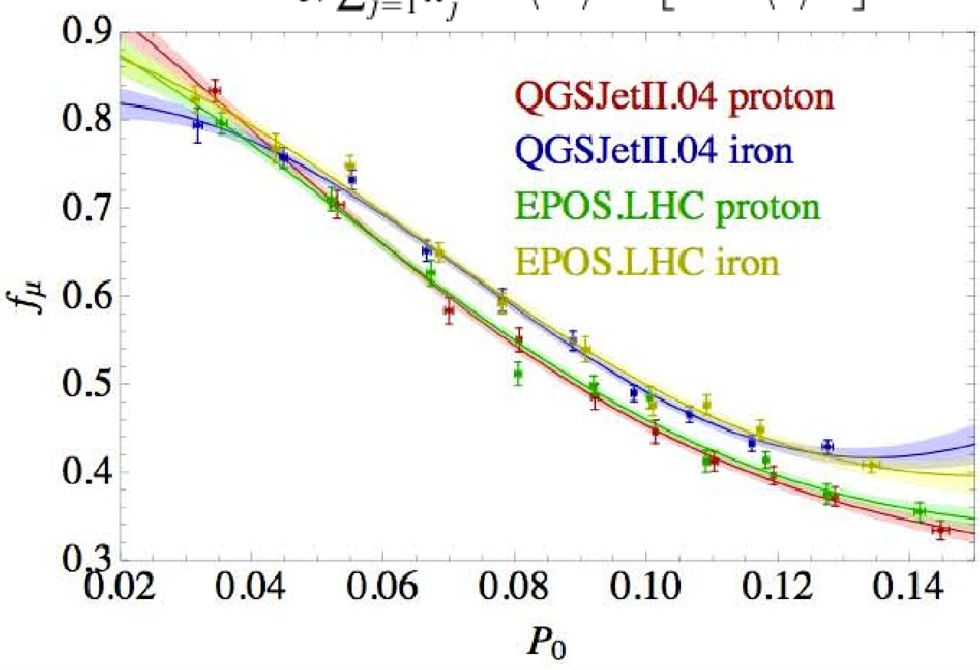
Squared thresholded normalized total signal

$$f_{0.5} = \frac{1}{S}\sum_{j=1}^{N} x_j \mathbb{I}\{x_j > 0.5\}$$



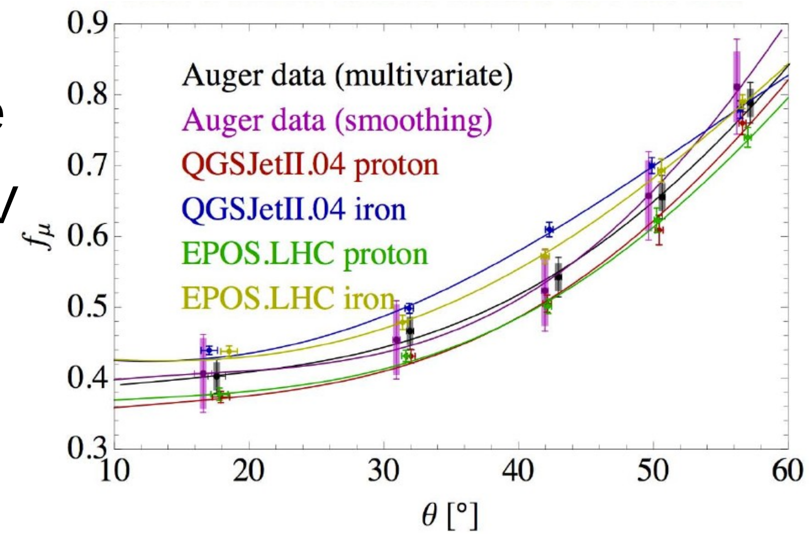
Normalized spectral power of the constant component

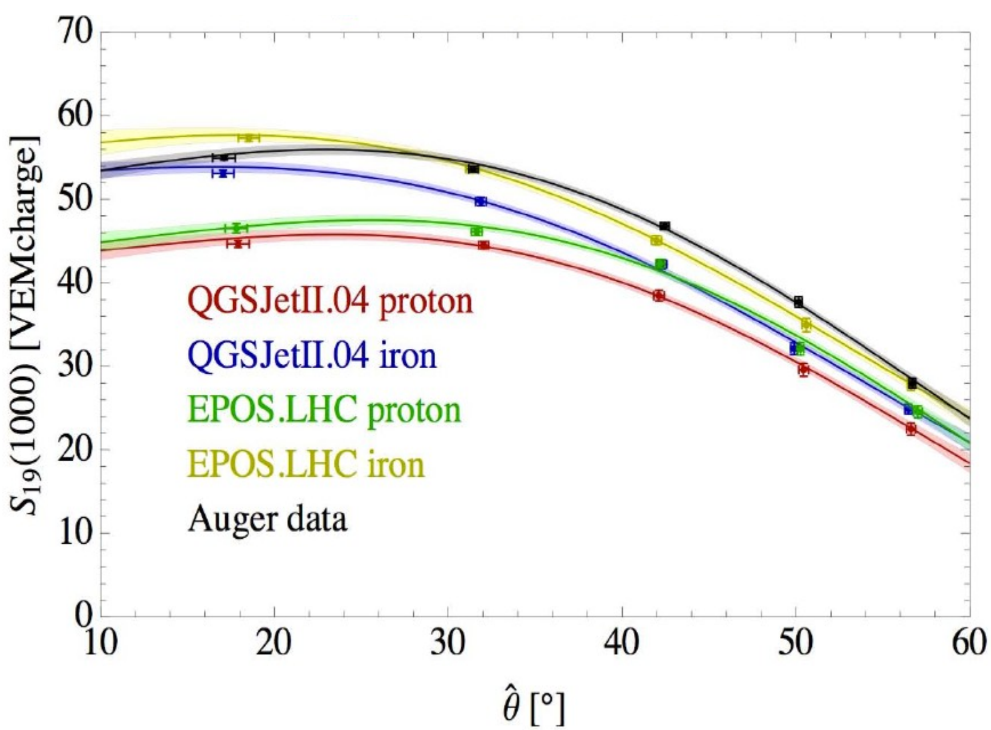
$$P_0 = \frac{S^2}{N\sum_{j=1}^{N} x_j^2} = \frac{\langle \mathbf{x}\rangle^2}{\langle \mathbf{x}^2\rangle} = \left[1 + \frac{\sigma^2(\mathbf{x})}{\langle \mathbf{x}\rangle^2}\right]^{-1}$$

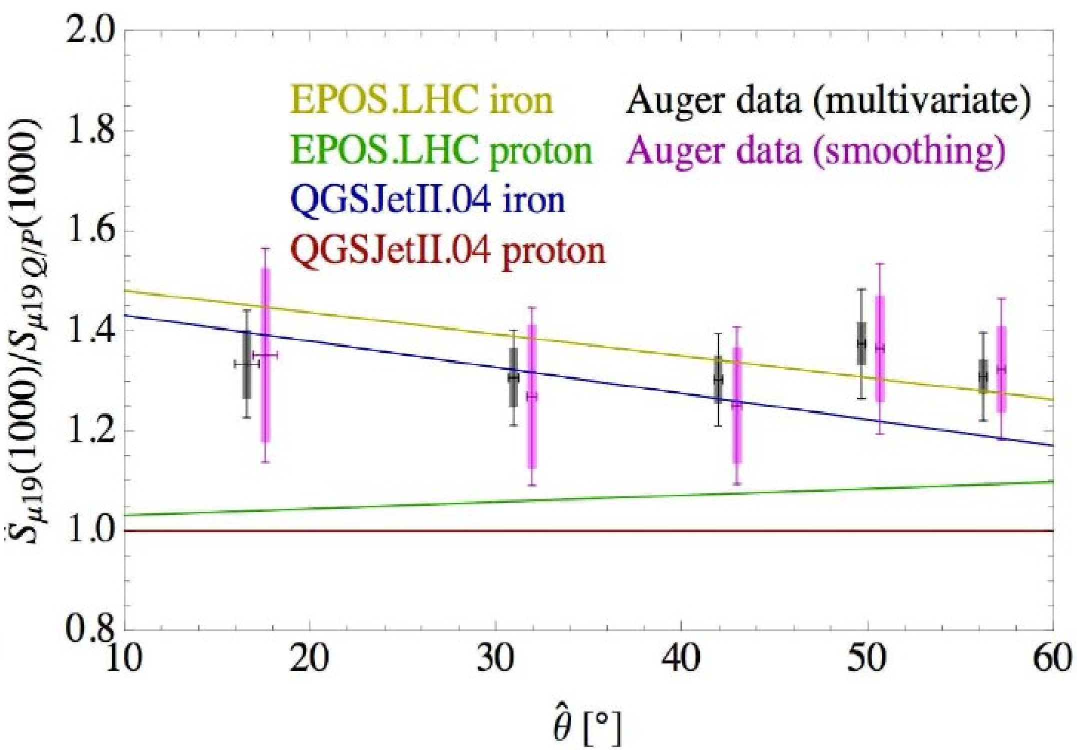


Muon Signal from Time Traces

- **Time traces analysis**
  - ➡ from FADC traces at 1000 m from shower core
  - ➡ SD events with θ < 60°, E_{recon}: $10^{18.98} – 10^{19.02}$ eV
  - ➡ normalized to QGSJETII-04 proton:
    - Multivariate: 1.33 ± 0.02 (stat) ± 0.05 (sys)
    - Smoothing: 1.31 ± 0.02 (stat) ± 0.09 (sys)







MPD and Diffraction

- **Inelasticity linked to diffraction (cross-section and mass distribution)**
  - weak influence on EM X_{max} since only 1st interaction really matters
  - cumulative effect for X^{μ}_{max} since muons produced at the end of hadr. subcasc.
  - rapidity-gap in p-p @ LHC not compatible with measured MPD
  - harder mass spectrum for pions reduce X^{μ}_{max} and increase muon number !

probably different diffractive mass distribution for mesons and baryons