Probing hadronic interaction models with the hybrid data of the Pierre Auger Observatory

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51st ISMD, Pitlochry, Scottland

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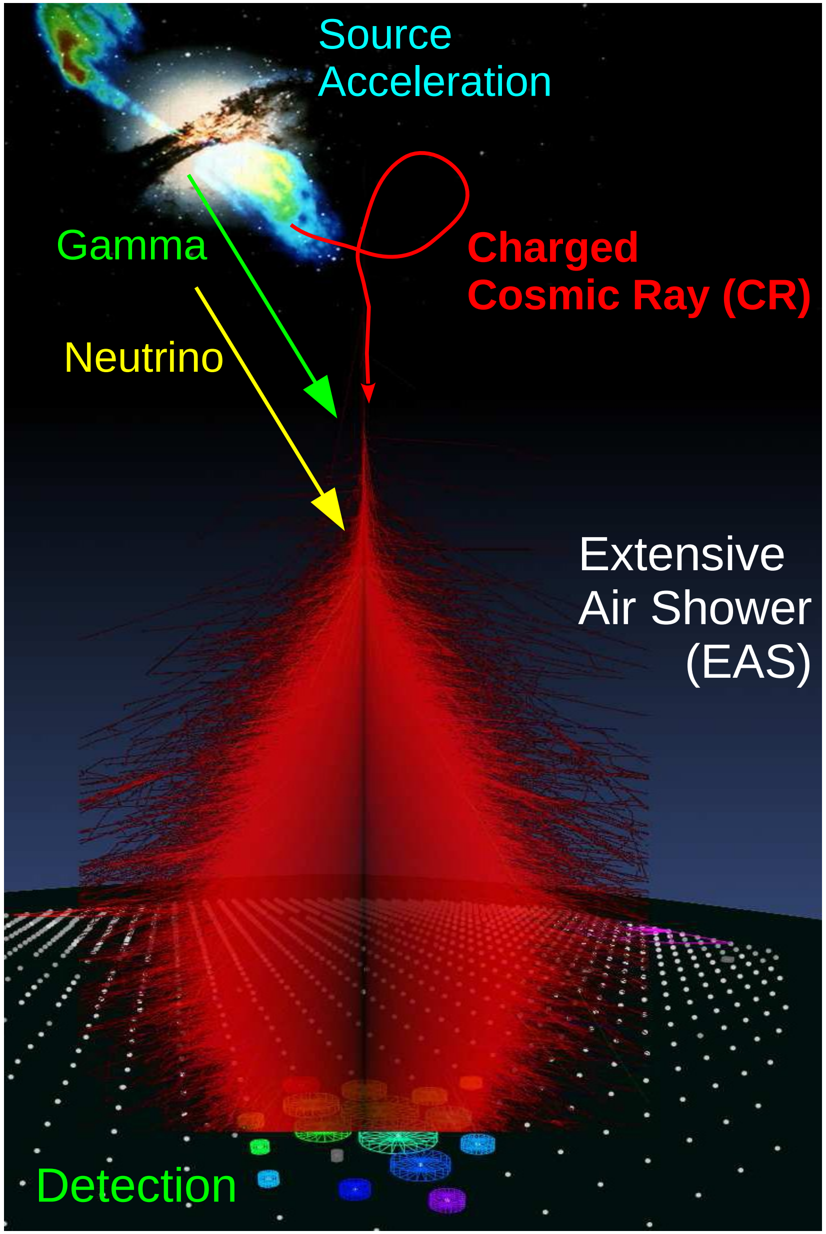
Outline

- Introduction
- Direct Measurement
- Probing hadronic models

The multi-hybrid nature of the Pierre Auger Observatory allows stringent tests of hadronic interactions at energies much beyond LHC.

Astroparticles

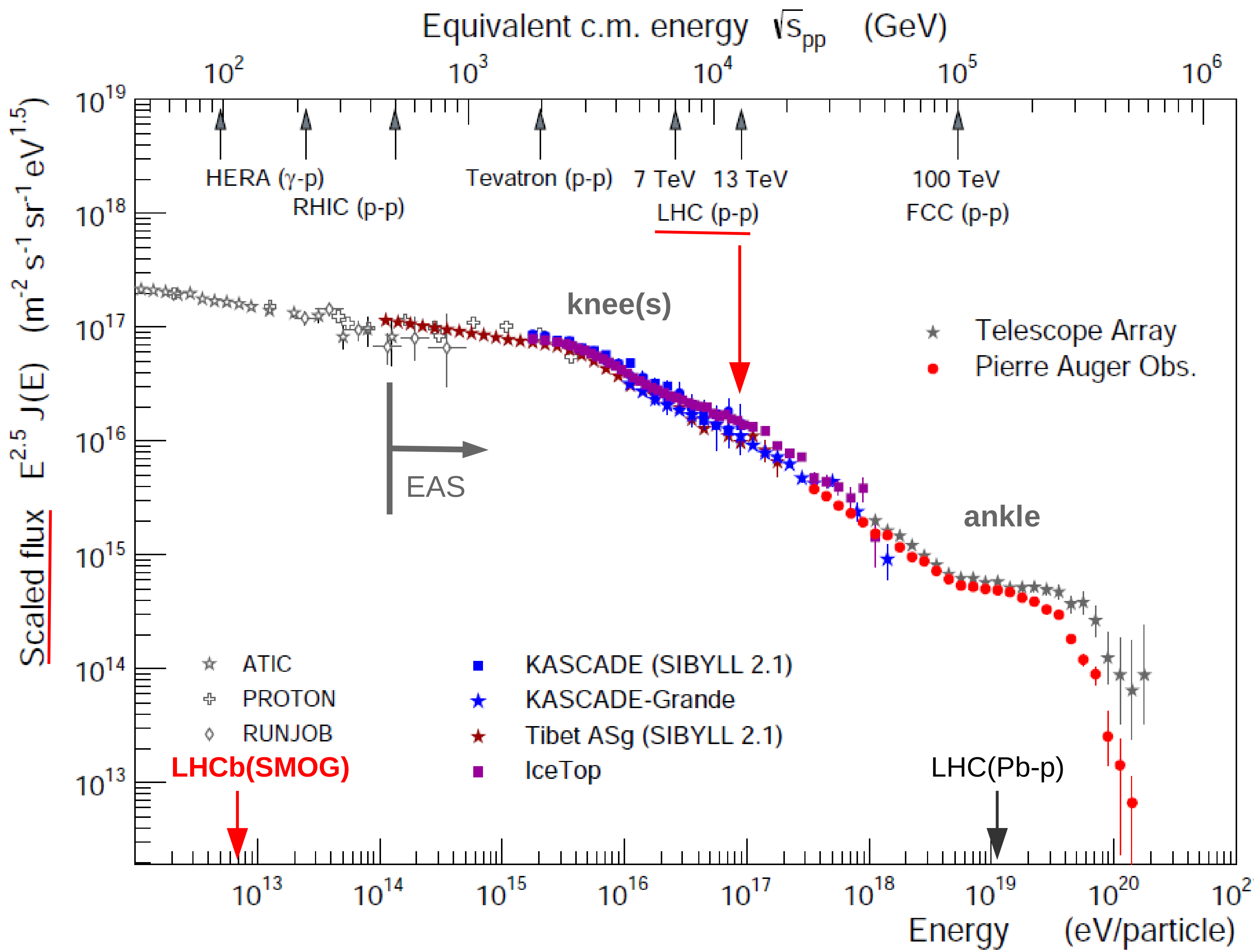


From R. Ulrich (KIT)

- **Astronomy with high energy particles**
  - gamma (straight but limited energy due to absorption during propagation)
  - neutrino (straight but difficult to detect)
  - charged ions (effect of magnetic field)
- **Measurements of charged ions**
  - source position (only for light and high E)
  - energy spectrum (source mechanism)
  - mass composition (source type)
    - light = hydrogen (proton)
    - heavy = iron (A=56)
  - test of hadronic interactions in EAS via correlations between observables.

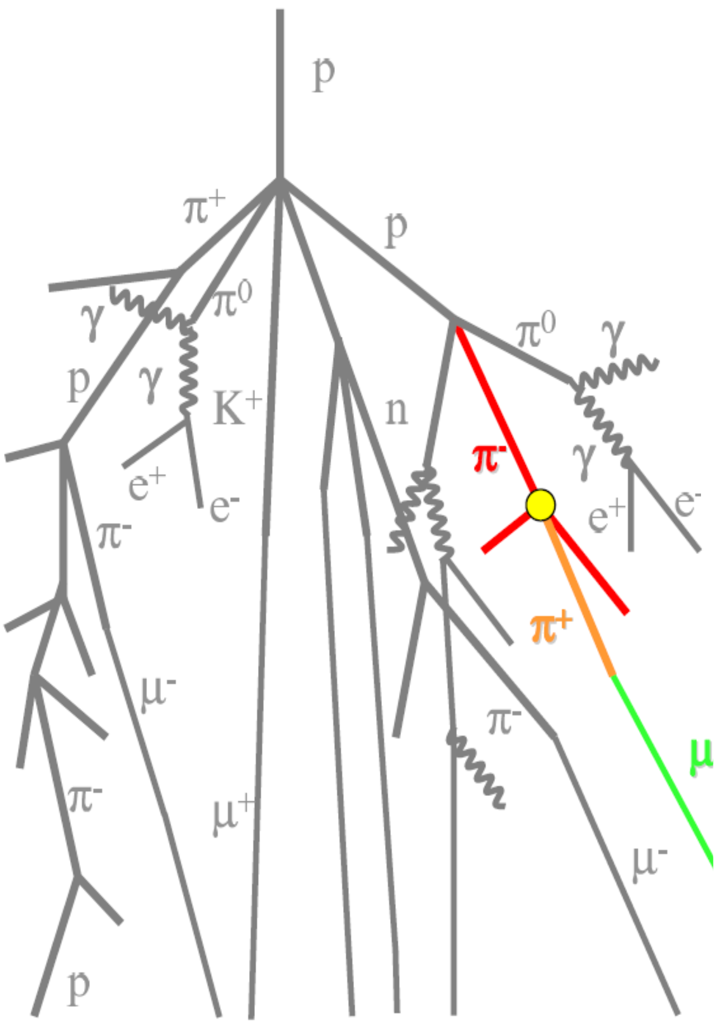
mass measurements should be consistent and lying between proton and iron simulated showers if physics is correct

Energy Spectrum

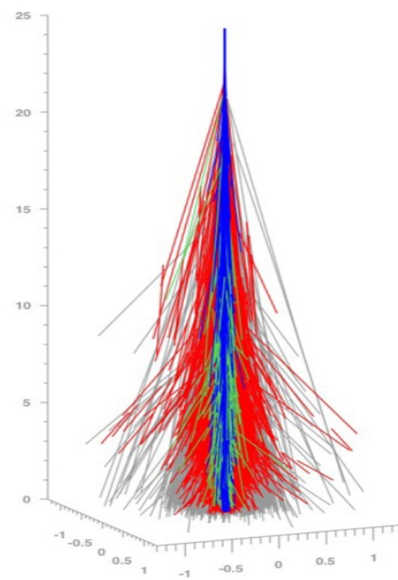


R. Engel (KIT)

Extensive Air Shower



From R. Ulrich (KIT)



$A + air \rightarrow \text{hadrons}$

$p + air \rightarrow \text{hadrons}$

$\pi + air \rightarrow \text{hadrons}$

hadronic physics

initial γ from π^0 decay

$e^{\pm} \rightarrow e^{\pm} + \gamma$

$\gamma \rightarrow e^{+} + e^{-}$

well known QED

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

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)

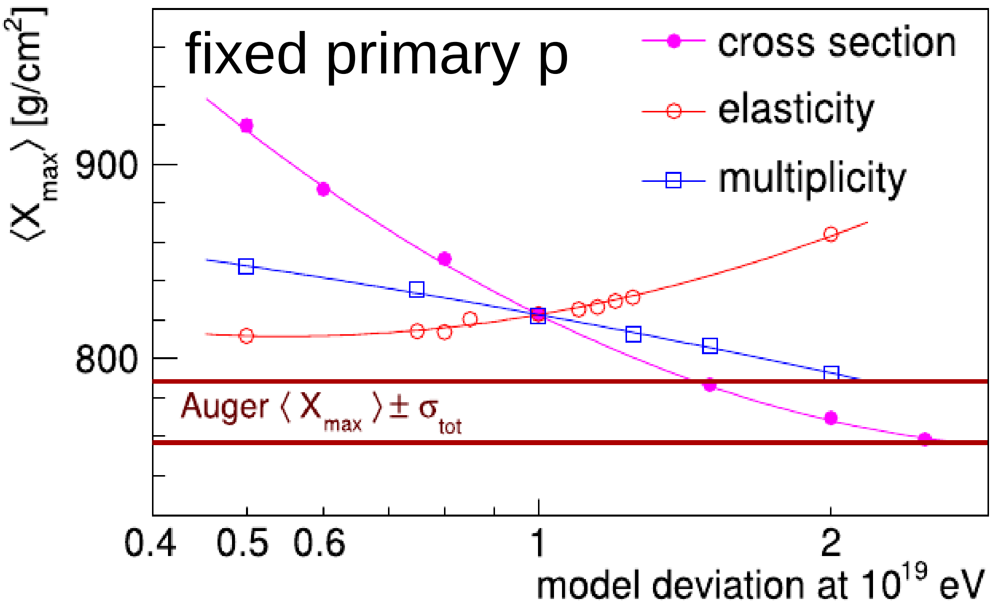
Air Shower Simulation

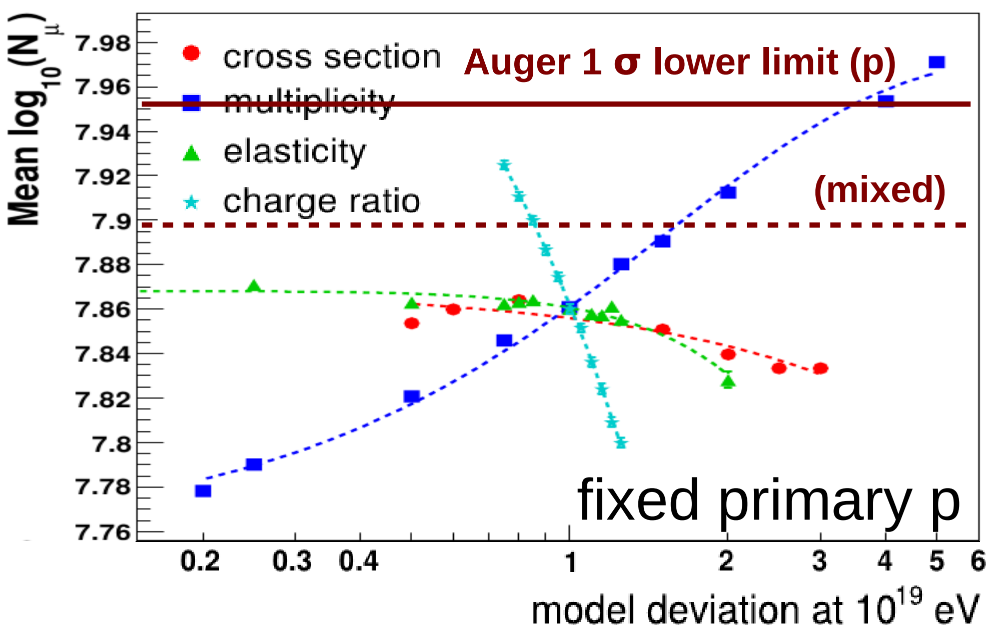
- **EAS simulations necessary to study high energy cosmic rays**
  - ➡ complex problem: identification of the primary particle from the secondaries

- **Hadronic models are the key ingredient !**
  - ➡ follow the standard model (QCD)
    - ➡ but mostly non-perturbative regime (phenomenology needed)
  - ➡ main source of uncertainties

- **Which model for CR ?** **(alphabetical order)**
  - ➡ **DPMJETIII.17-1** by S. Roesler, A. Fedynitch, R. Engel and J. Ranft
  - ➡ **EPOS (1.99/LHC/3/4)** (from VENUS/NEXUS before) by H.J. Drescher, F. Liu, T. Pierog and K.Werner.
  - ➡ **QGSJET** (01/II-03/II-04/III) by S. Ostapchenko (starting with N. Kalmykov)
  - ➡ **Sibyll (2.1/(2.3c/)2.3d)** by E-J Ahn, R. Engel, R.S. Fletcher, T.K. Gaisser, P. Lipari, F. Riehn, T. Stanev

Sensitivity to Hadronic Interactions





From R. Ulrich (KIT)

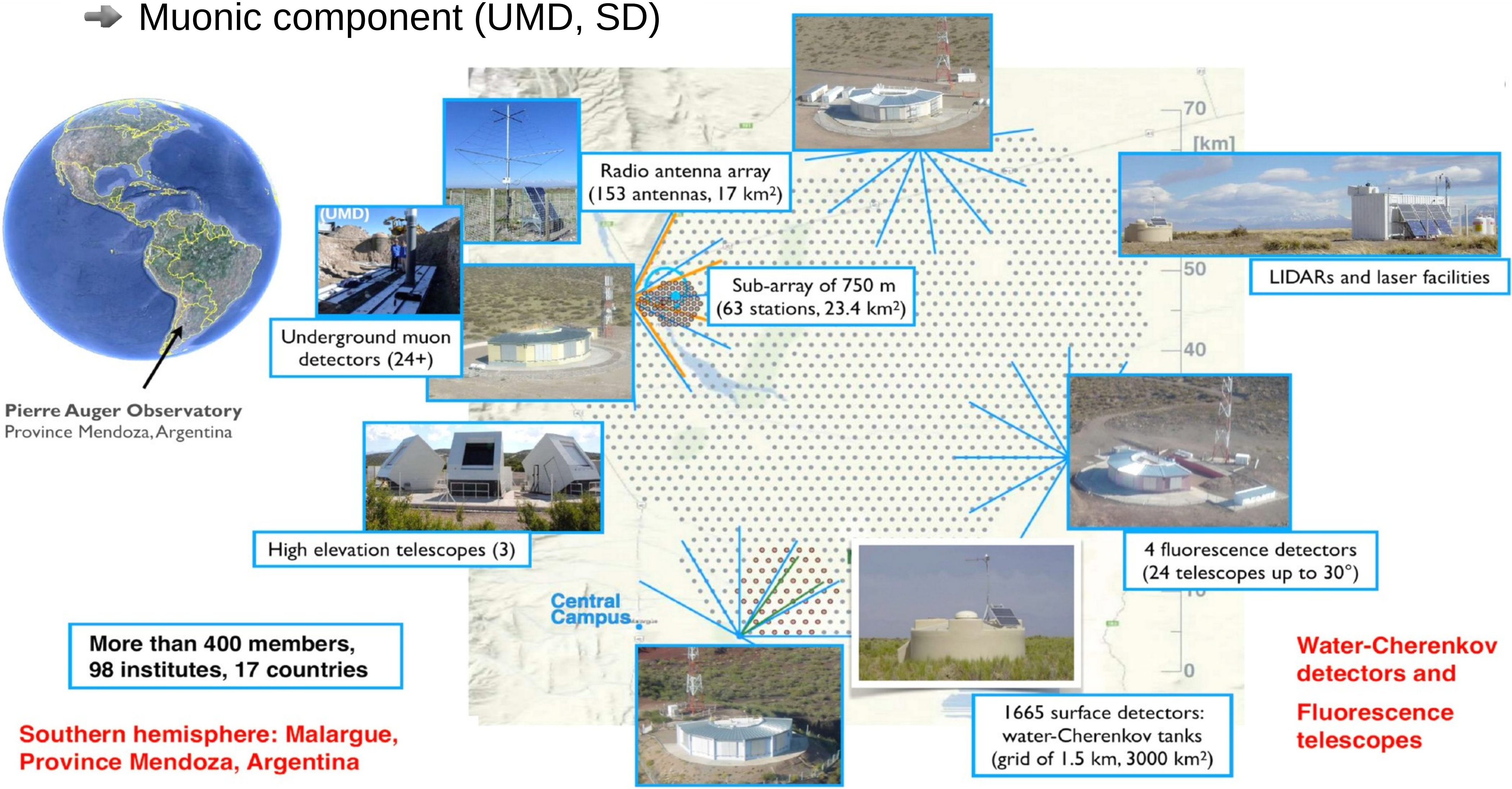
- **Air shower development dominated by few parameters**
  - ➔ mass and energy of primary CR
  - ➔ cross-sections (p-Air and (π-K)-Air)
  - ➔ (in)elasticity
  - ➔ multiplicity
  - ➔ charge ratio and baryon production
- **Change of primary = change of hadronic interaction parameters**
  - ➔ cross-section,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

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

The Pierre Auger Observatory

Multicomponent (hybrid) detector

- Electromagnetic component (FD, RD, SD)
- Muonic component (UMD, SD)



More than 400 members, 98 institutes, 17 countries

Southern hemisphere: Malargue, Province Mendoza, Argentina

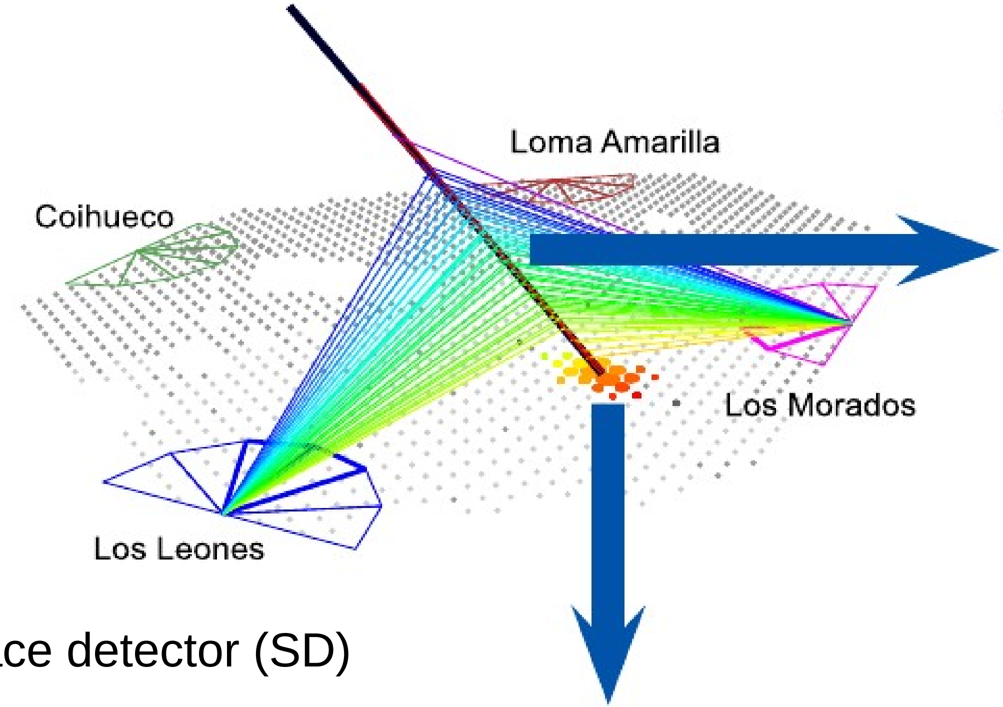
Water-Cherenkov detectors and

Fluorescence telescopes

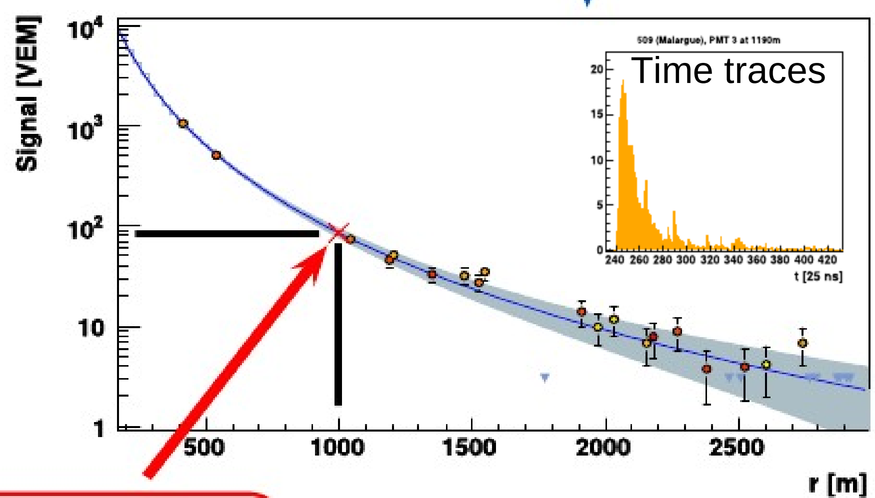
The Pierre Auger Observatory

Multicomponent (hybrid) detector

Pierre Auger Observatory Data



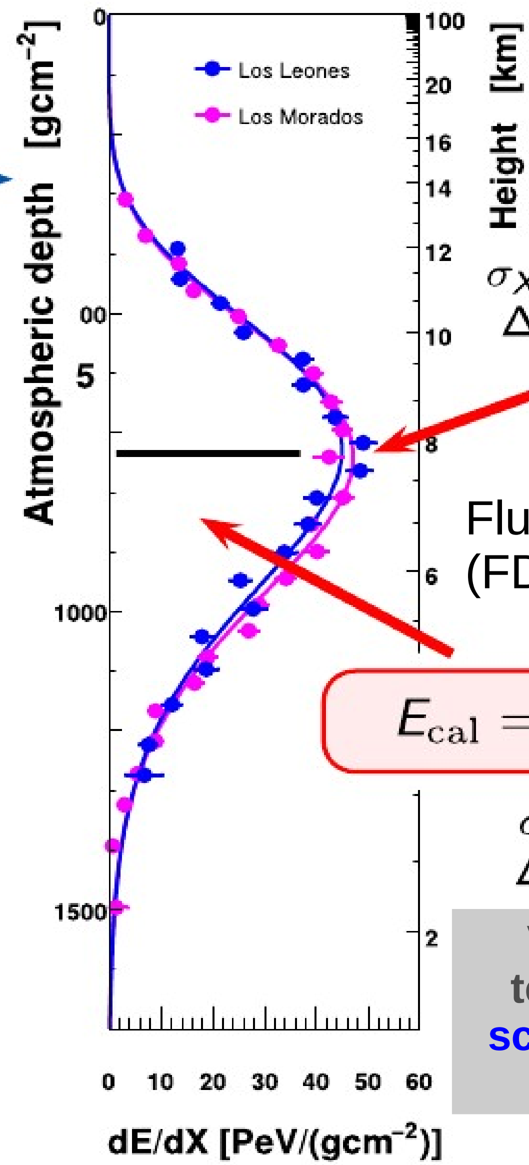
Surface detector (SD)



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}

Fluorescence detector (FD)

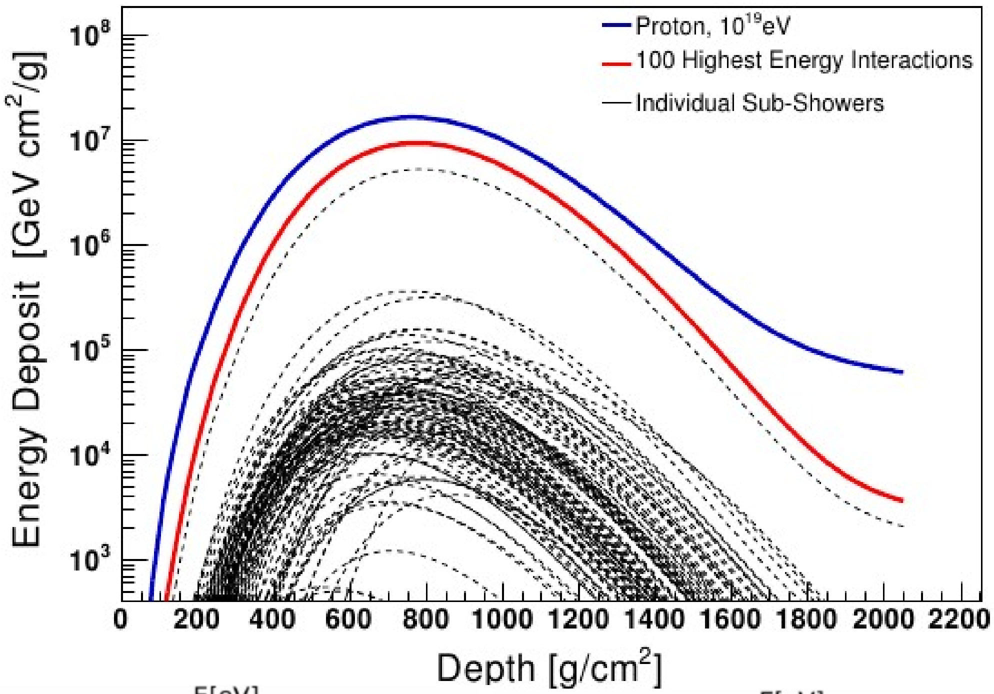
$E_{\mathrm{cal}} = \int \mathrm{d}X\, \frac{\mathrm{d}E}{\mathrm{d}X}$

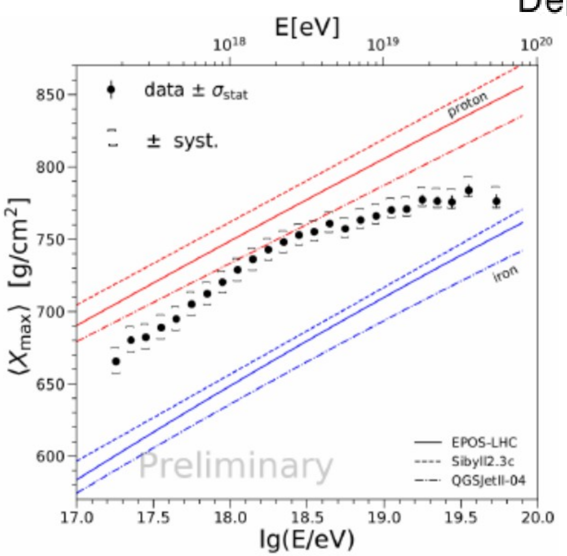
$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 14\,\%$

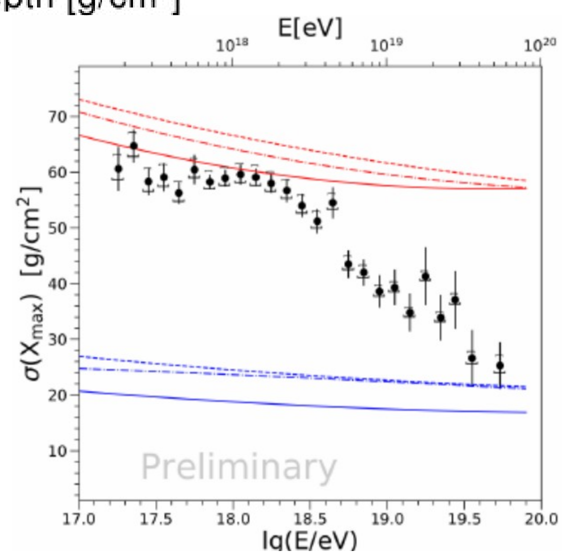
Various detection technique = energy scale independent of EAS simulations

Fluorescence Detector

From R. Ulrich (KIT)

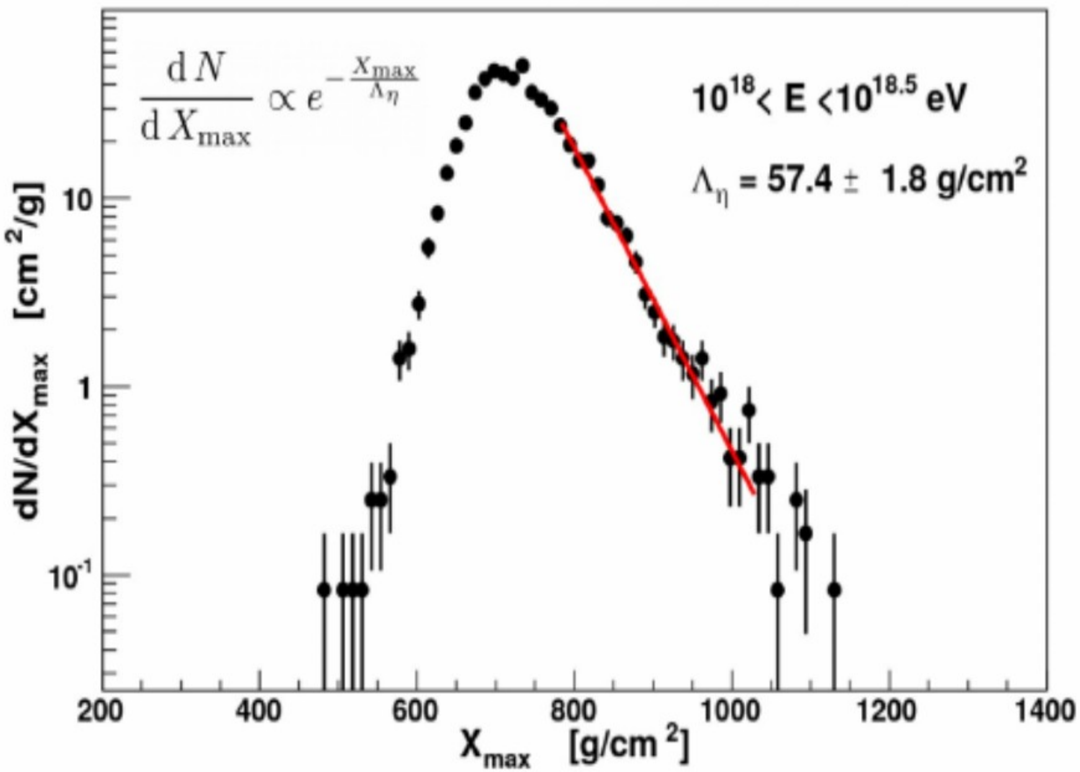






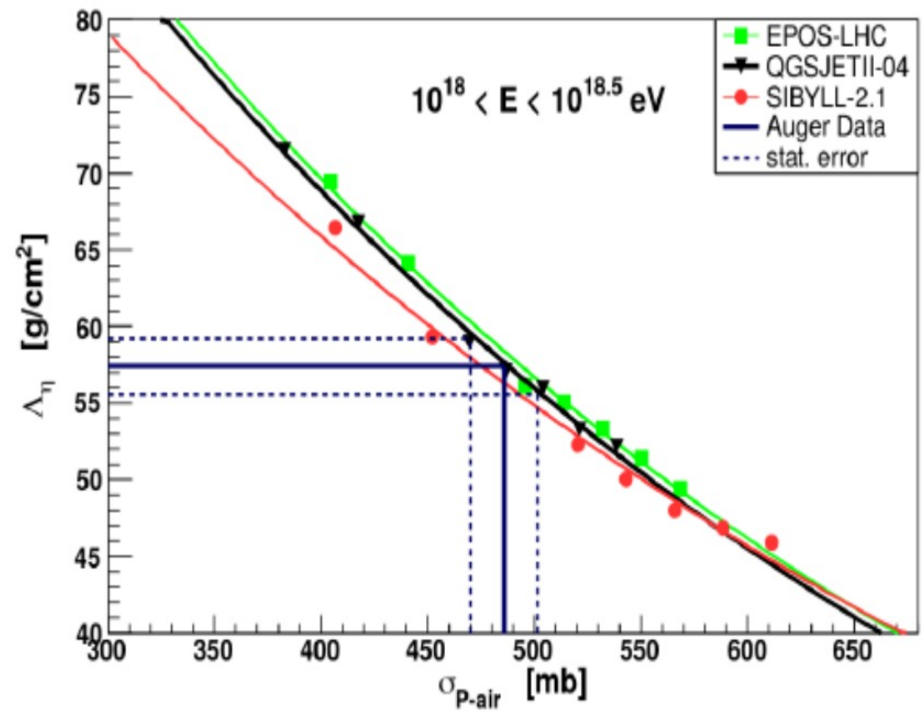
- **Most direct measurement**
  - ➔ dominated by first interaction
- **Reference mass for other analysis**
  - ➔ <lnA> from <X_{max}> and RMS
- **Possibility to use the tail of X_{max} distribution to measure p-Air inelastic cross-section.**
  - ➔ require no contamination from photon induced showers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

Attenuation Length



Careful data selection

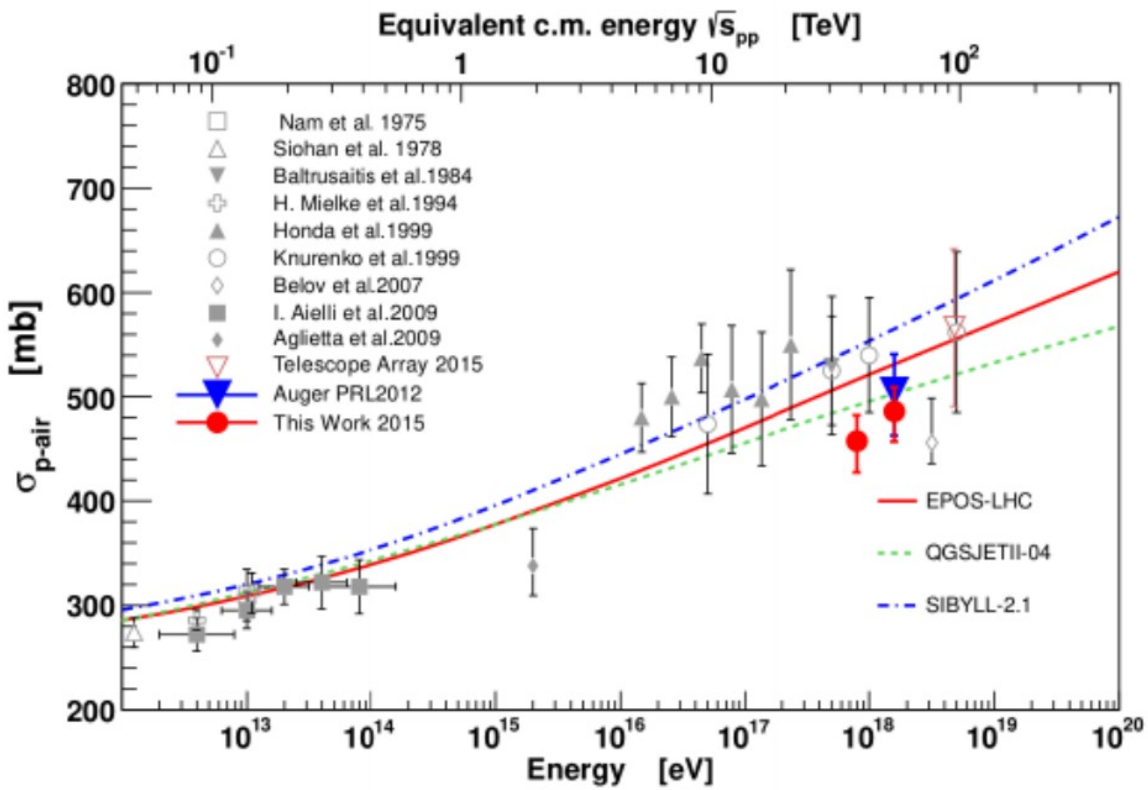
- maximum statistic
- maximum quality (showers completely in fov)
- tail should contain only p-showers (contamination by He is largest uncertainty)



- X_{max} is a convolution between X_{first} (cross-section) and ΔX (shower development from models)
- deconvolution from Λ_η to σ using hadronic models (syst. uncertainties)

p-p Inelastic Cross Section @ 55.5 and 57 TeV

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



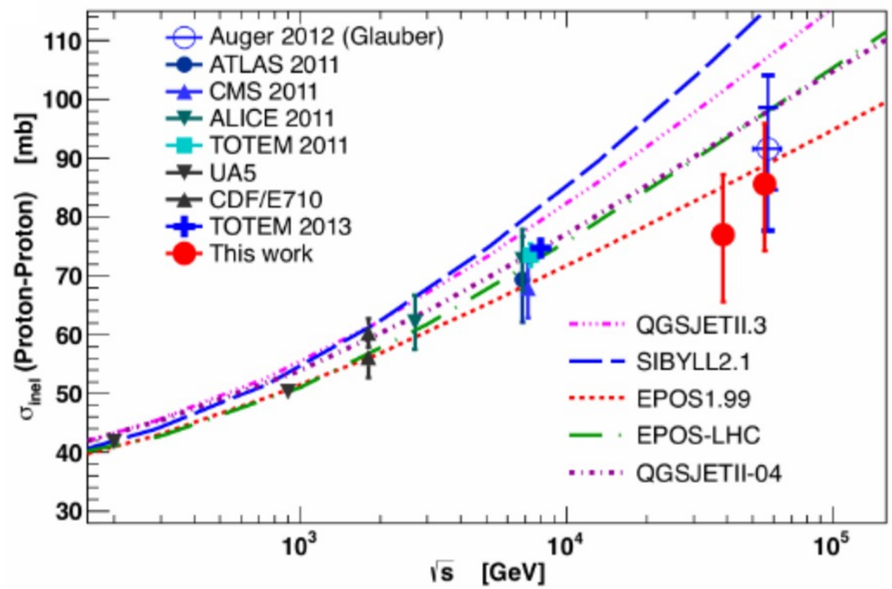
Phys. Rev. Lett. 109, 062002 (2012), PoS(ICRC2015)401

Systematic uncertainties

- effect of diffraction

$$\Gamma_{pp\rightarrow pX}(s,\vec{b}) = \lambda(s)\Gamma_{pp\rightarrow pp}(s,\vec{b})$$

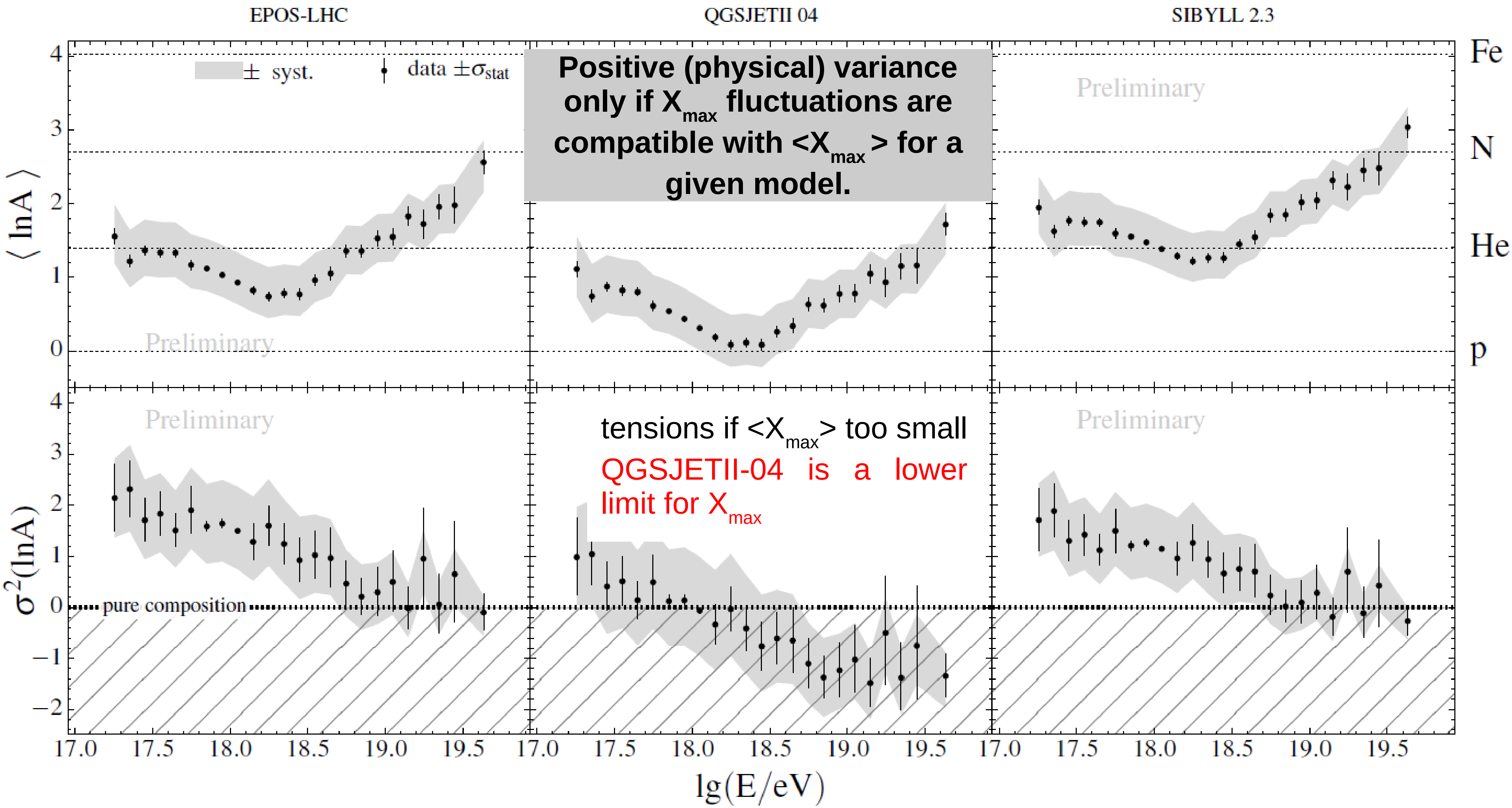
- effect of elastic slope



Model Consistency using Electromagnetic Component

Study by Pierre Auger Collaboration (ICRC 2017)

➡ std deviation of lnA allows to test model consistency.

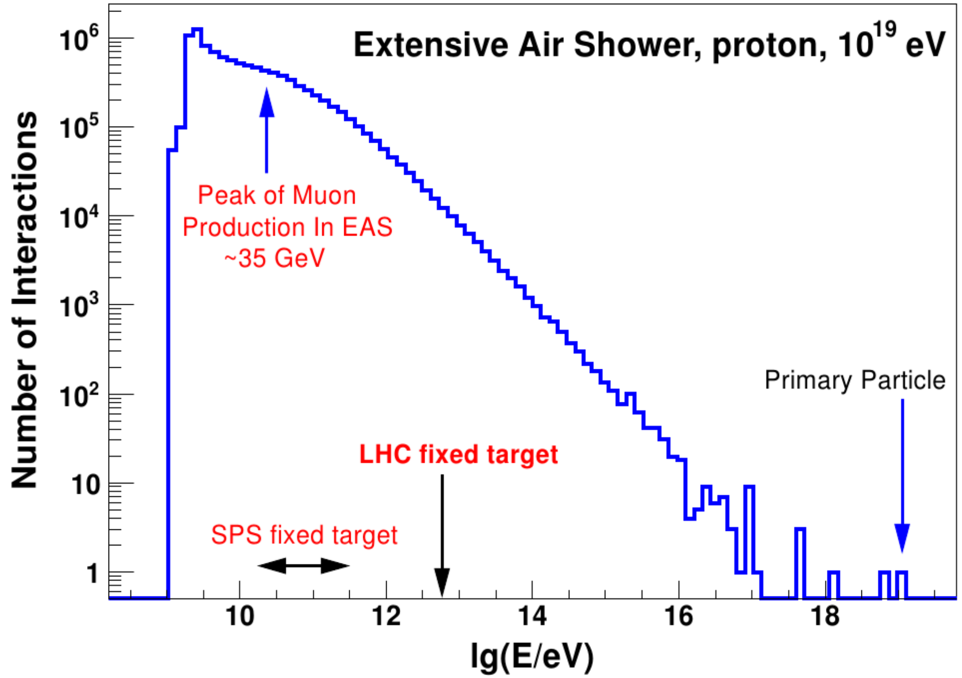


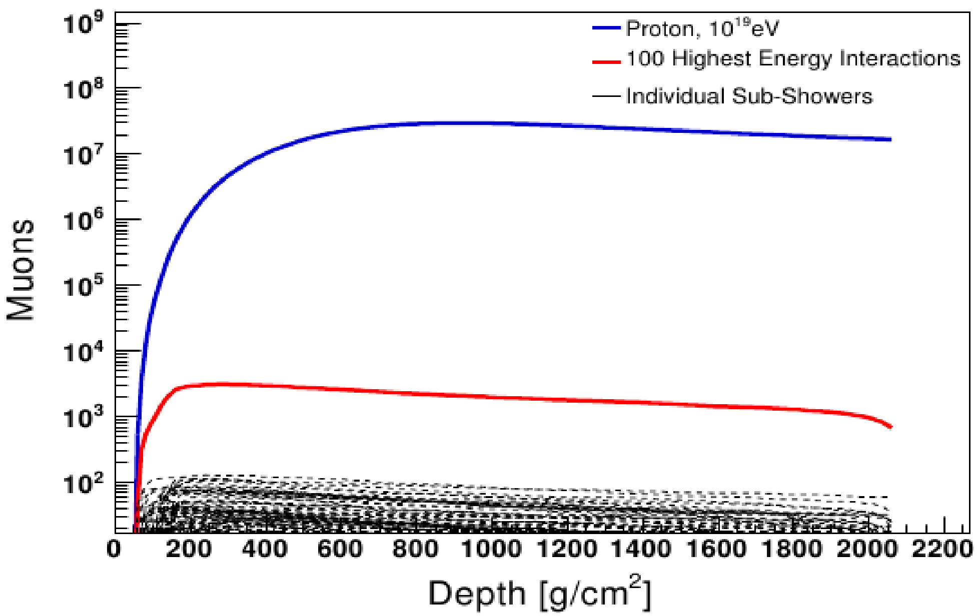
Positive (physical) variance only if X_{max} fluctuations are compatible with $<X_{max}>$ for a given model.

tensions if $<X_{max}>$ too small

QGSJETII-04 is a lower limit for X_{max}

Surface Detector

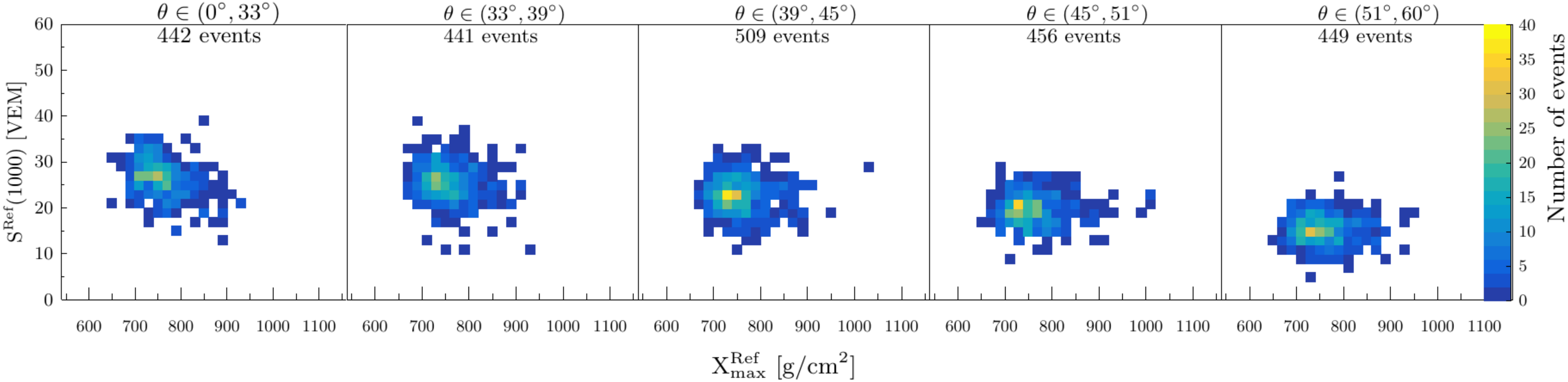




- **SD detector sensitive to**
  - ➔ electromagnetic particles (EM)
  - ➔ muons
- **Particles at ground produced after many generations of hadronic interactions**
  - ➔ most of EM particles from pure EM (universal) shower (depend on high (first) energy hadronic interactions)
  - ➔ muons produced at the 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

X_{max}-S(1000) correlation

Hybrid measurements allows to test model consistency in more details

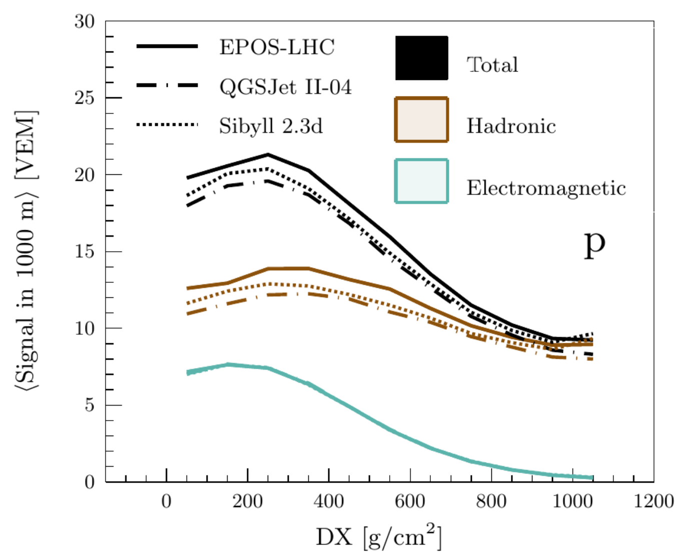


$$X^{\rm Ref}_{\rm max} \equiv \widehat{X^{\rm Ref}_{\rm max}} + \Delta X_{\rm max},$$
$$S^{\rm Ref}(1000) \equiv \widehat{S^{\rm Ref}(1000)} \cdot f_{\rm SD}(\theta)$$

Parameters:
$\Delta X_{max}, R_{Had}, R_{em}, \xi_1, \xi_2, \xi_3$

Describe the 4 mass fractions

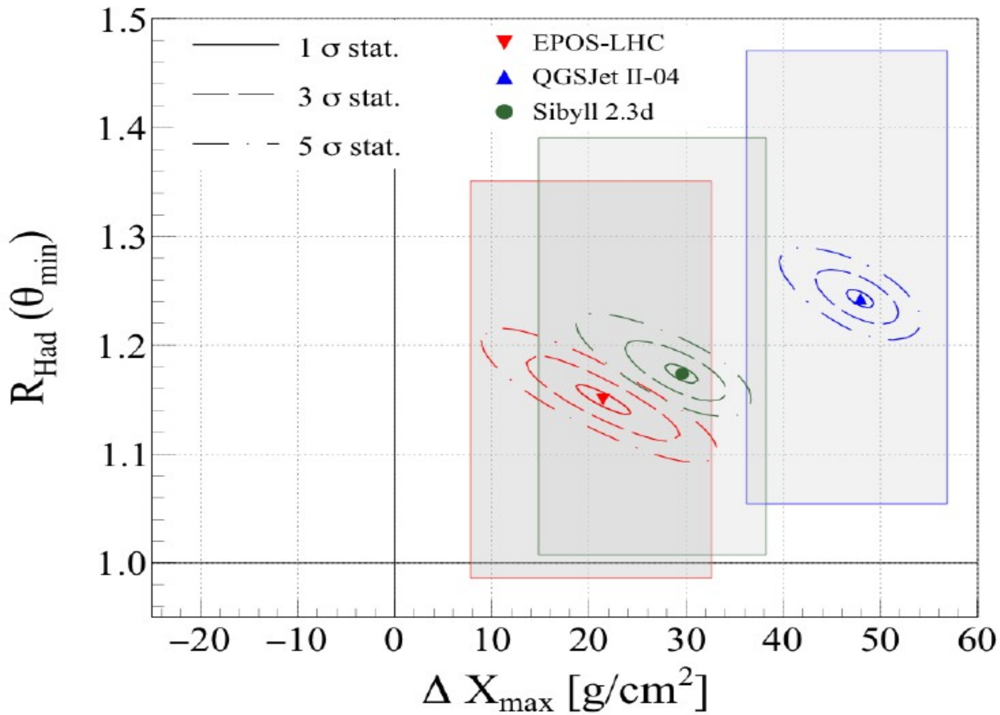
$$\phi = c \cdot f_{Gumbel}\left(X^{Ref}_{max}\right) \cdot f_{Gauss}\left(X^{Ref}_{max}, S^{Ref}(1000)\right)$$

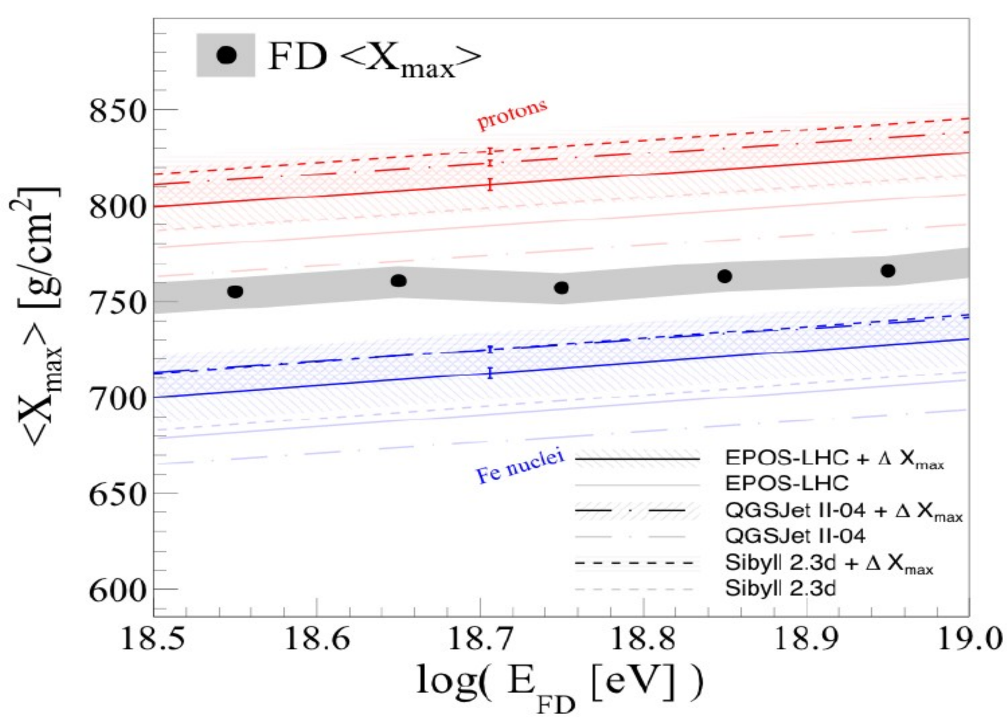


The final MC templates are a sum of templates of the form of Φ of individual primary species weighted by their relative fractions.

Modifications of X_{max} and signal at ground

- **Best fit of data require multiple changes in hadronic models**
  - Rescaling (increase) of muons (hadronic component → confirmed)
  - Shift in X_{max} toward higher mass (electromagnetic component → new)
- **Might imply a change in mass composition**
  - Importance of LHC data to improve models (pO data to reduce X_{max} and muon (core-corona ?) uncertainties)





Summary

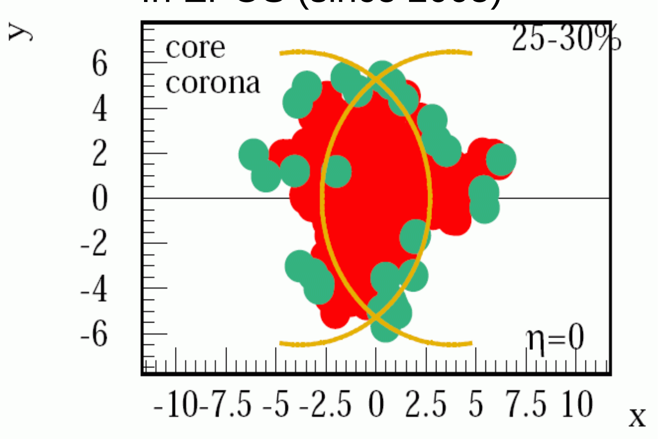
- **The Pierre Auger Observatory is the largest cosmic ray detector measuring hadronic interactions at energies beyond 100 TeV.**
- **Hybrid nature of the detector allows direct test of hadronic interaction models (and Physics behind !)**
  - ➡ test small effects amplified by cascade effect
  - ➡ test energy, phase space (forward) and projectile (mesons) difficult to reach with accelerators
  - ➡ complex multi-variate problems: correlations are very important
- **Both X_{max} and muons (next talk) seems in tension with exp. data**
  - ➡ More LHC data to constrain first interaction parameters
  - ➡ More LHC data to constrain electromagnetic to hadronic energy ratio

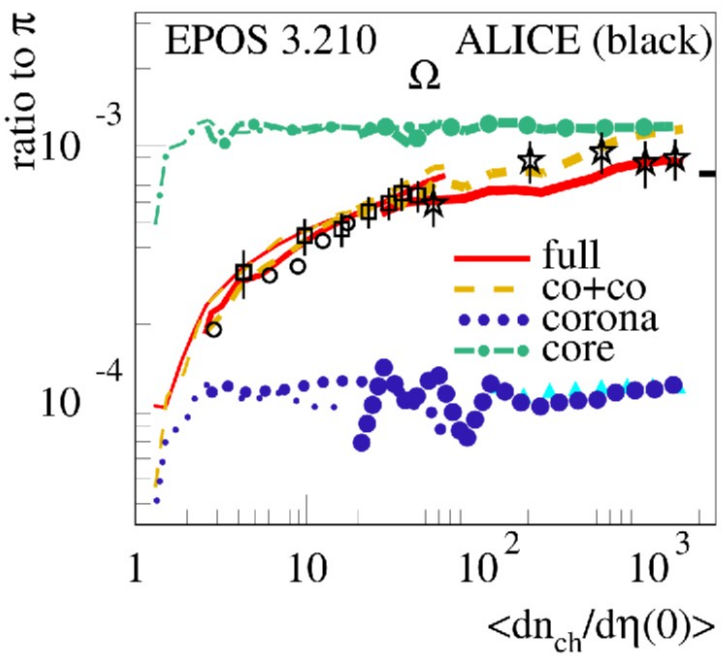
The multi-hybrid nature of the Pierre Auger Observatory allows stringent tests of hadronic interactions at energies much beyond LHC.

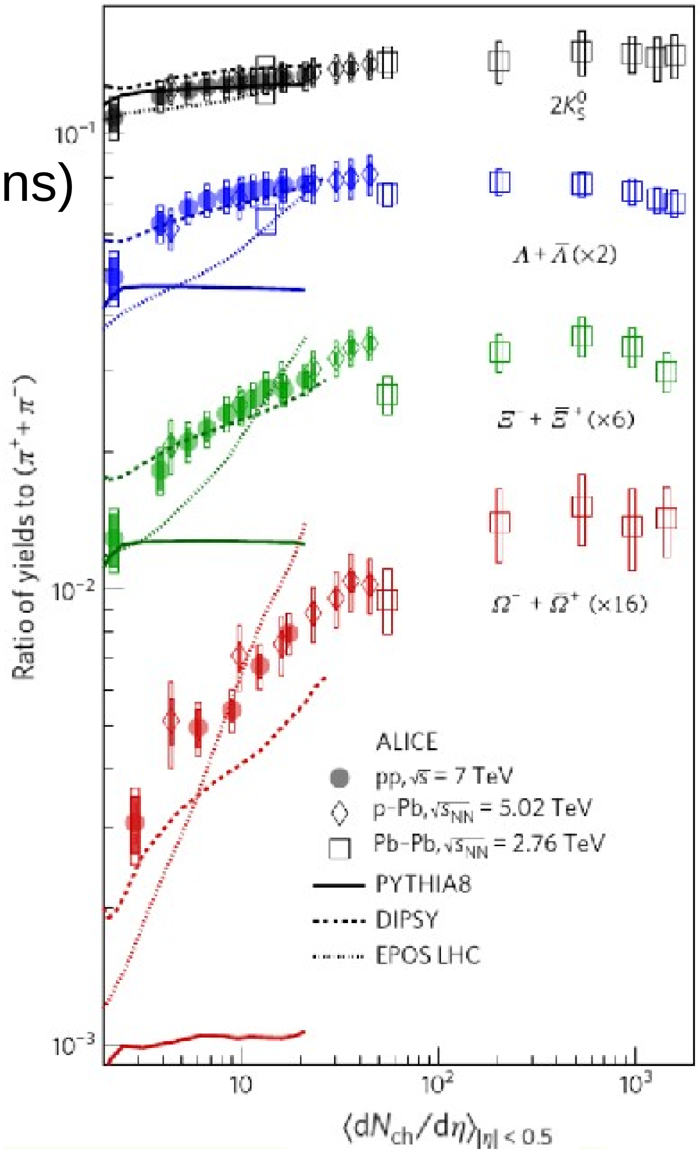
Core-Corona Approach

- **Mixing of core and corona hadronization needed to achieve detailed description of p-p data (EPOS)**
  - Evolution of particle ratios from pp to PbPb
  - Particle correlations (ridge, Bose Einstein correlations)
  - Pt evolution, …
- **Both hadronizations are universal but the fraction of each change with particle density**
- **2 simultanous source of particles**

In EPOS (since 2005)



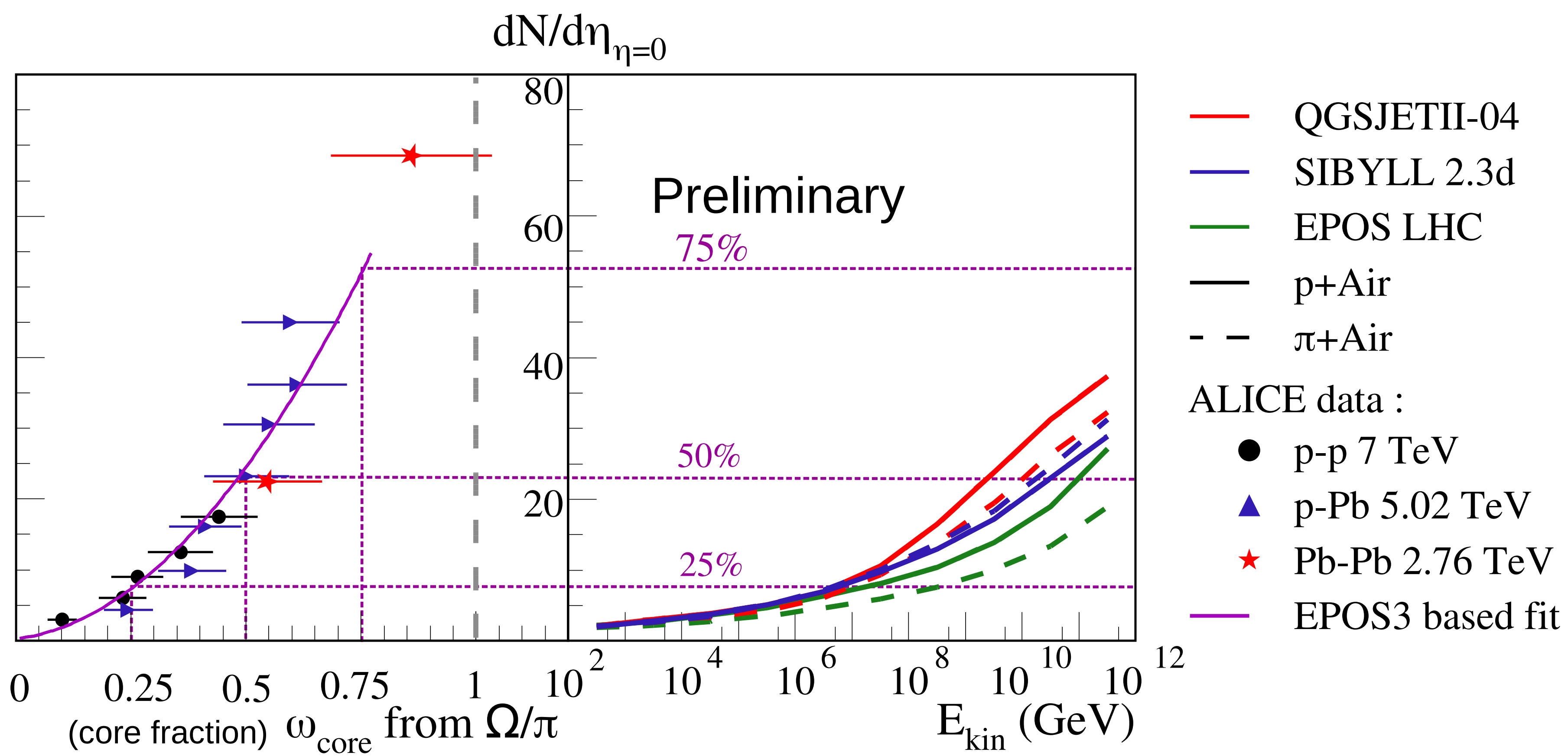




Particle Densities in Air Showers

Is particle density in air shower high enough to expect core formation ?

- Core formation start quite early according to ALICE data
- Cosmic ray primary interaction likely to have 50% core at mid-rapidity !



Core-Corona appoach and CR

To test if a QGP like hadronization can account for the missing muon production in EAS simulations a core-corona approach can be artificially apply to any model

- Particle ratios from statistical model are known (tuned to PbPb) and fixed : core
- Initial particle ratios given by individual hadronic interaction models : corona
- Using CONEX, EAS can be simulated mixing corona hadronization with an arbitrary fraction ω_{core} of core hadronization: $N_i = \omega_{\text{core}}\, N_i^{\text{core}} + (1-\omega_{\text{core}})\, N_i^{\text{corona}}$

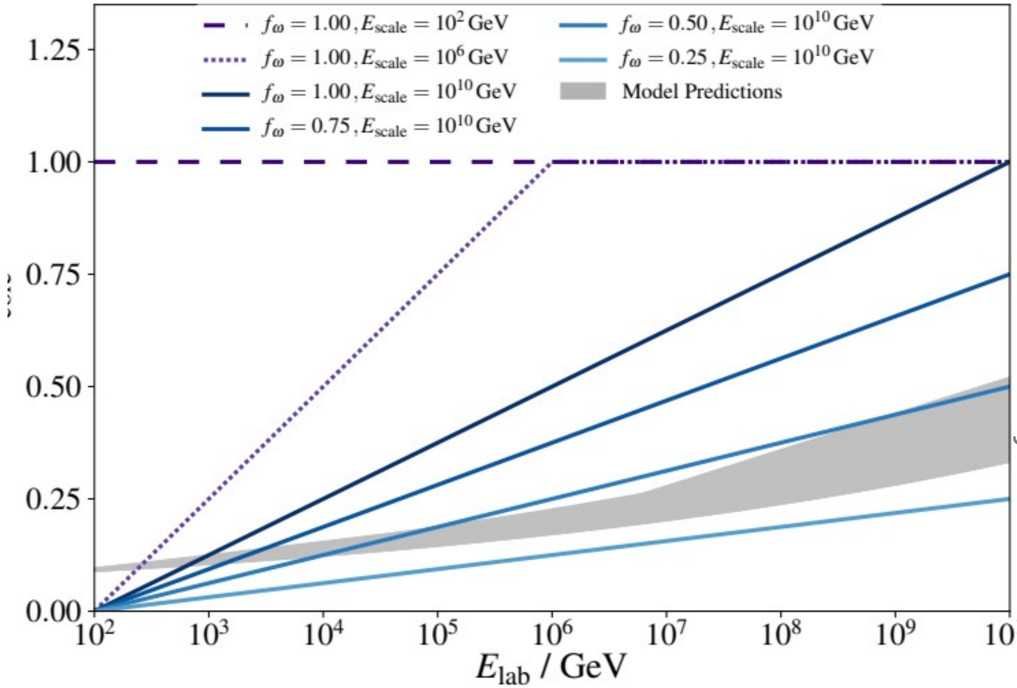
$$\omega_{\text{core}}(E_{\text{lab}}) = f_\omega\, \underbrace{F(E_{\text{lab}}; E_{\text{th}}, E_{\text{scale}})}_{\frac{\log_{10}(E_{\text{lab}}/E_{\text{th}})}{\log_{10}(E_{\text{scale}}/E_{\text{th}})} \text{ for } E_{\text{lab}} > E_{\text{th}}}$$

$$E_{\text{th}} = 100\,\text{GeV}$$

Different scenarii can be studied playing with f_ω and E_{scale}.

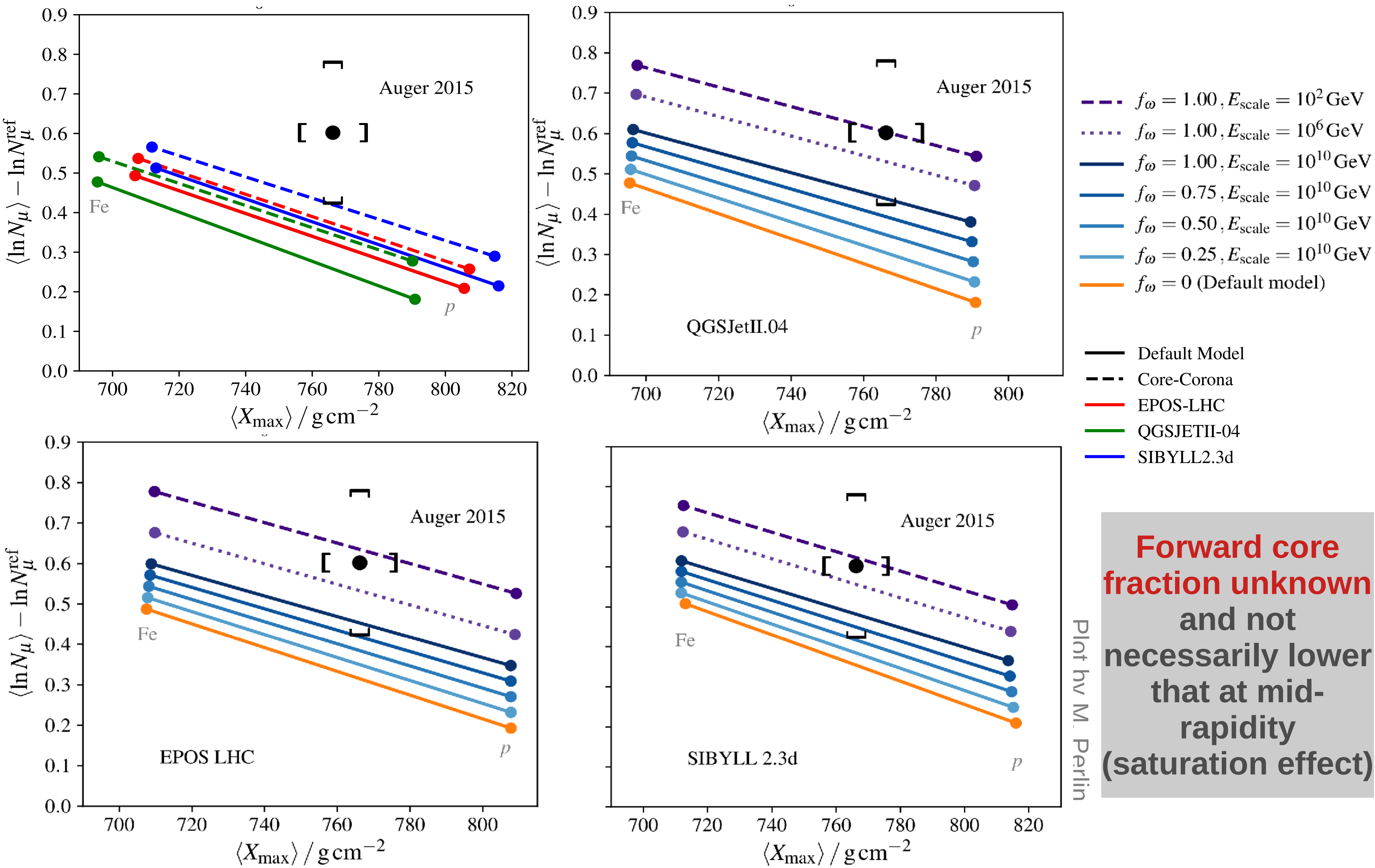
Note : the leading particle is NOT modified (projectile remnant)

Baur et al., arXiv:1902.09265



Plot by M. Perlin

Results for X_{max}-N_{mu} correlation



Plot by M. Perlin

Forward core fraction unknown and not necessarily lower that at mid-rapidity (saturation effect)