High Energy Shower Physics: Air Showers

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ISAPP school "High-Energy Astrophysics: Sources and Detection", Orsay, France

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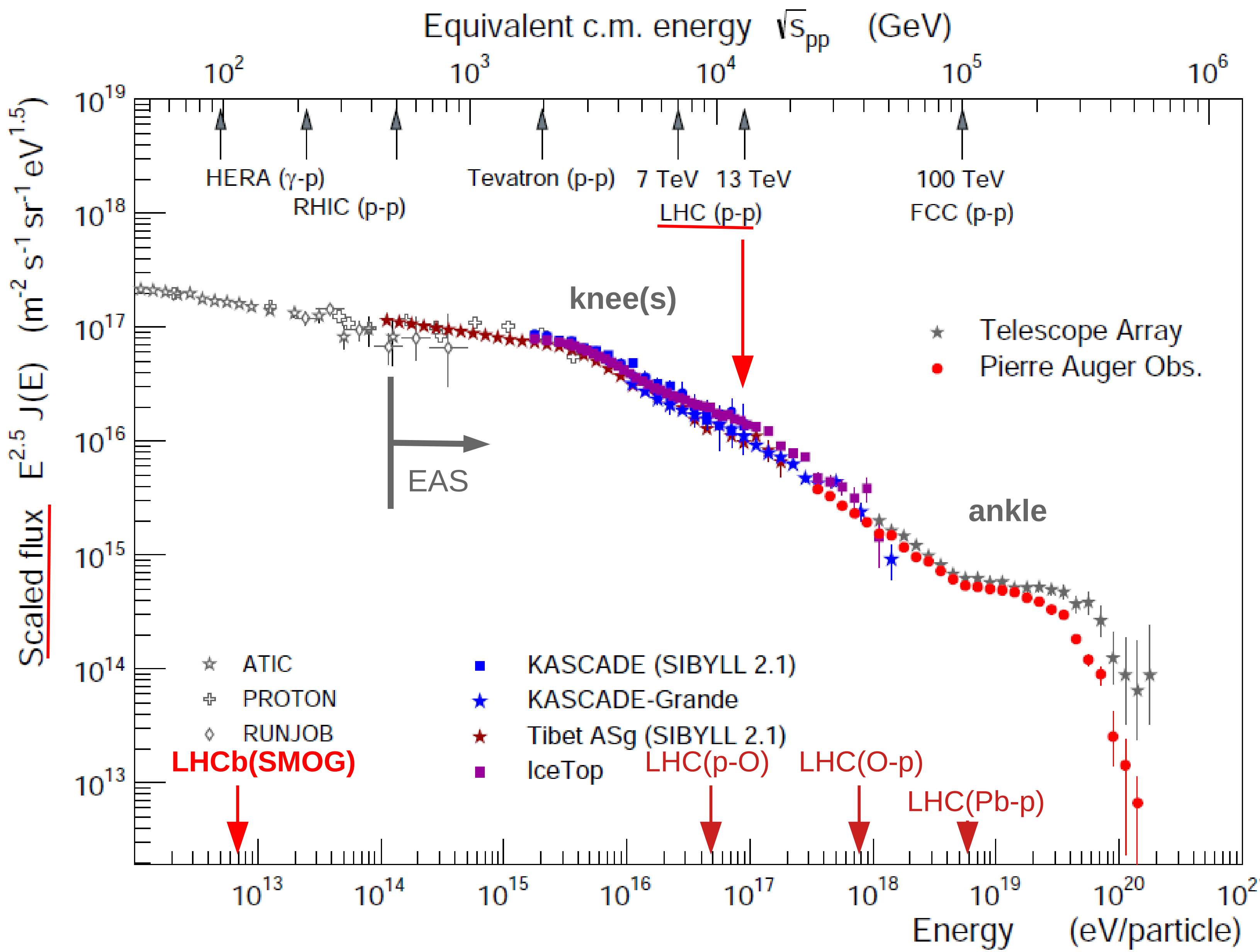
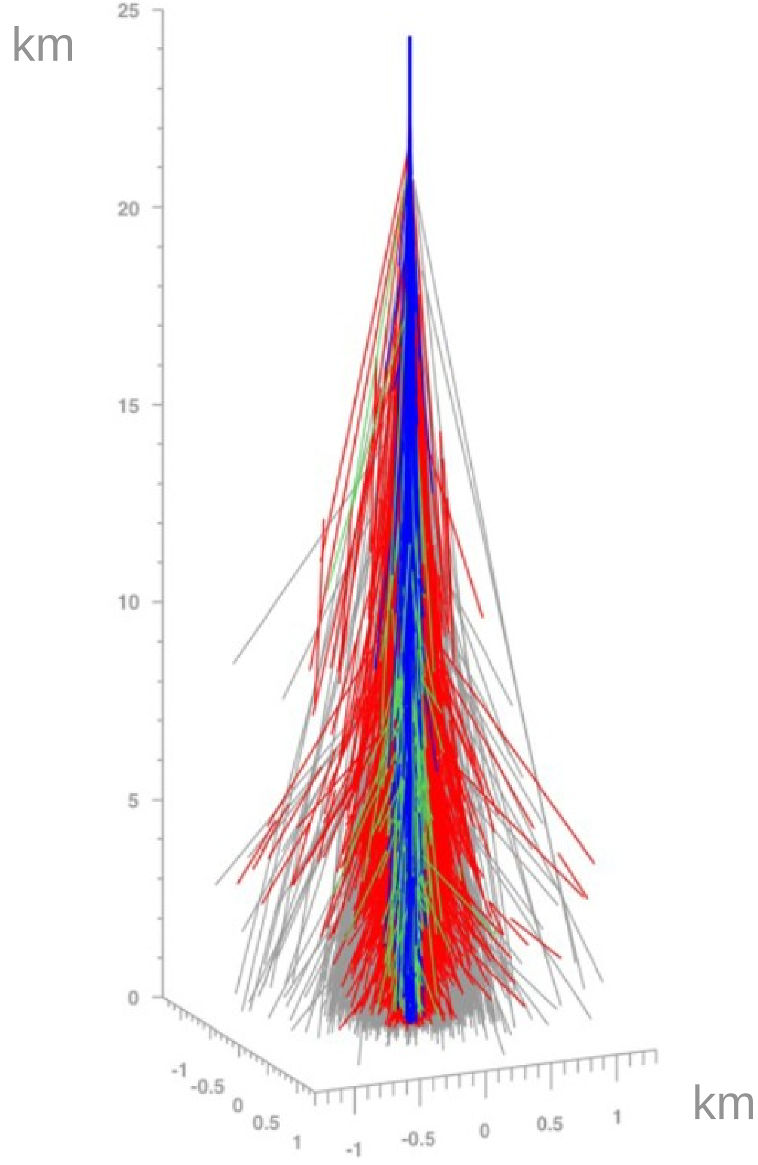
Energy Spectrum

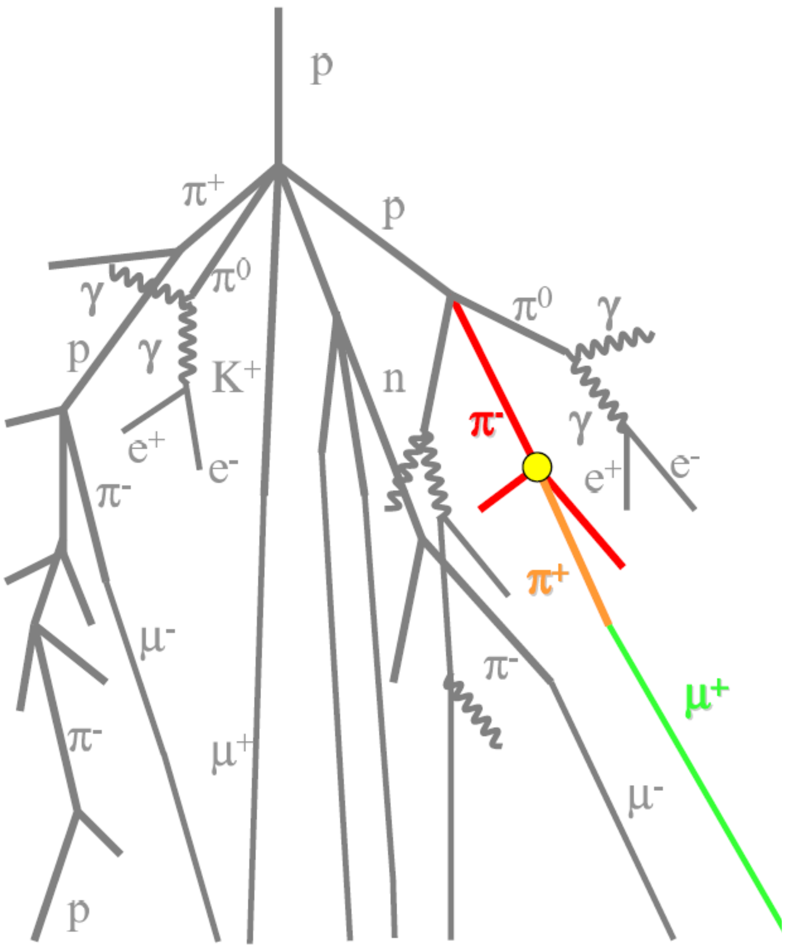


R. Engel (KIT)

(Extensive) Air Showers (EAS)



Extensive Air Shower



From R. Ulrich (KIT)

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

main source of uncertainties

intial γ from π^0 decay

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

well known

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

Cascade of particle in Earth's atmosphere

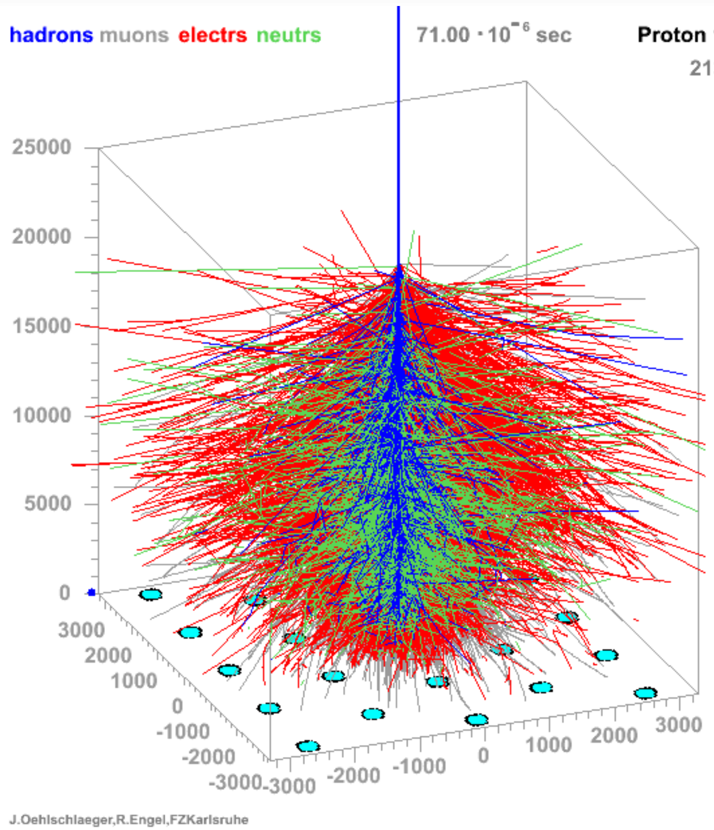
Number of particles at maximum

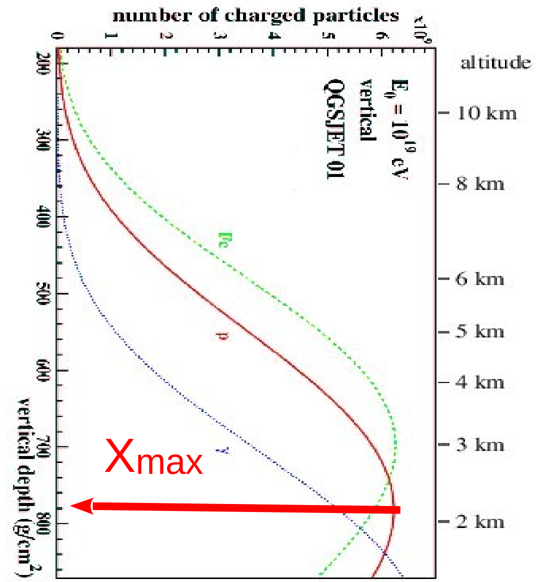
- 99,88% of electromagnetic (e/m) particles
- 0.1% of muons
- 0.02% hadrons

Energy

- from 100% hadronic to 90% in e/m + 10% in muons at ground (vertical)

Extensive Air Shower Observables





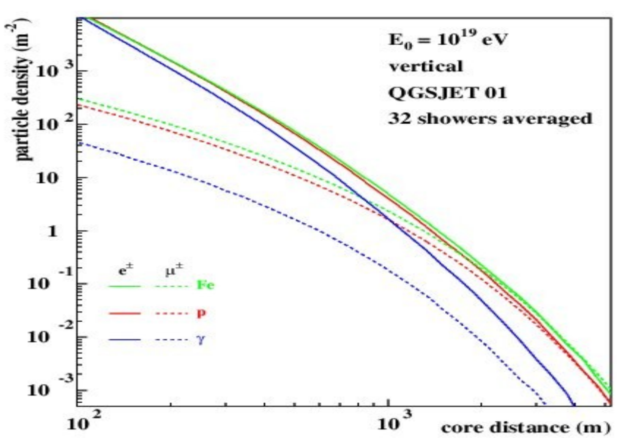
- **Longitudinal Development**
  - number of particles vs depth

    $X = \int_h^\infty dz\, \rho(z)$ (Air density)

  - Larger number of particles at X_{max}

    For many showers

    - mean : $\langle X_{max} \rangle$
    - fluctuations : RMS X_{max}

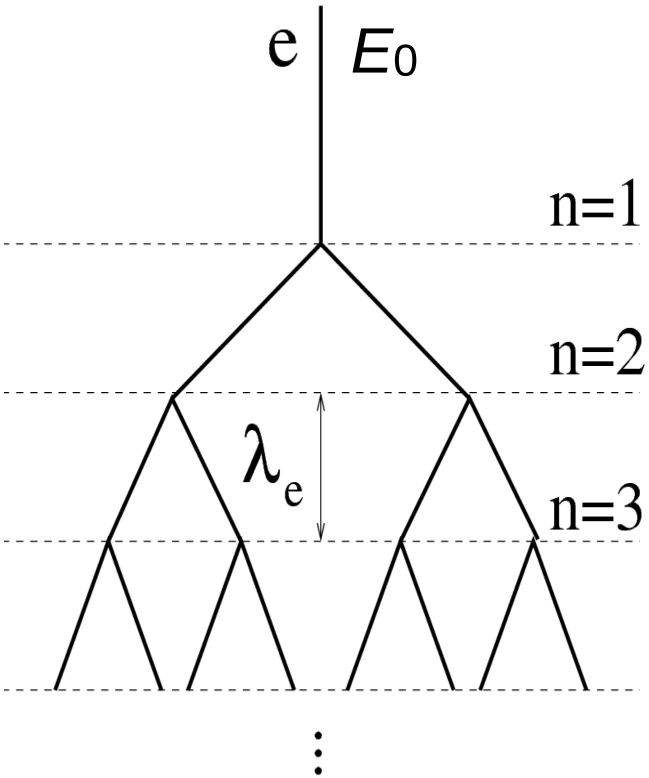


- **Lateral development**
  - particle density at ground vs distance to the impact point (core) = Lateral distribution function (LDF)
  - can be muons or electrons/gammas or a mixture of all.
- **Observables**
  - Particles at ground, fluorescence light, radio emission, cherenkov light ...

Outline

- **EAS : Longitudinal distributions**
  - Heitler model: X_{max}
  - Longitudinal Profile
  - Energy Deposit
- **EAS : Particles at ground**
  - Heitler model: N_{μ}
  - Particles at ground
  - Muon puzzle
  - Muon production depth
- **EAS : Link with hadronic interactions**
  - Hadronic Observables
  - Hadronic interaction models (next lecture)

Toy Model for Electromagnetic Cascade



Primary particle : photon/electron

Heitler toy model :

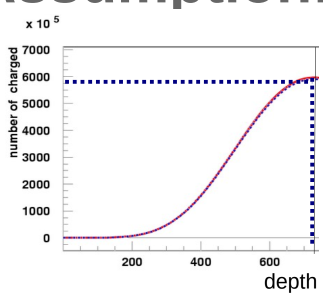
- 2 particles produced with equal energy
- electromagnetic interaction length (37g/cm²) : λ_e

2^n particles after n interactions

$$n = X/\lambda_e$$

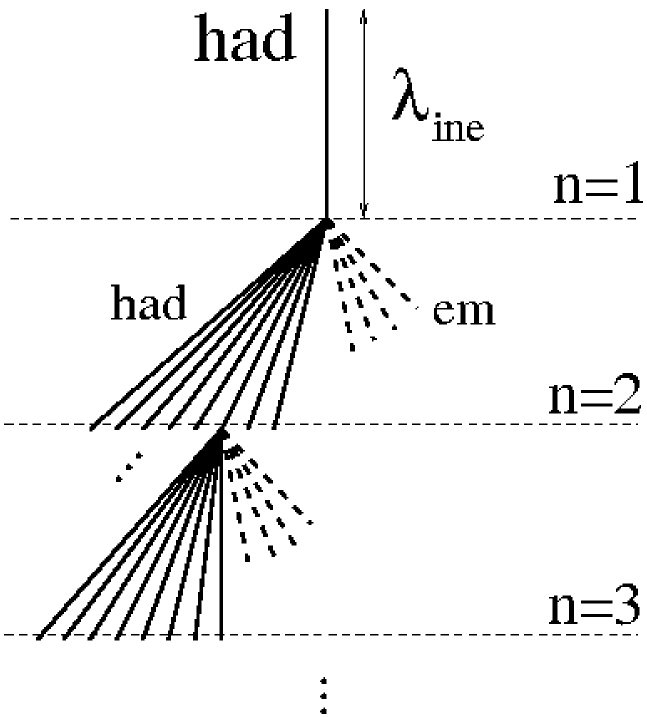
$$N(X) = 2^n = 2^{X/\lambda_e} \qquad E(X) = E_0/2^{X/\lambda_e}$$

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 $\lambda_{ine} = \langle Air \rangle / (A.\sigma_{ine})$
- 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 decaying in 2 photons).

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

Superposition Model

- **Primary nucleus with mass A and energy E**
  - ➡ equivalent to A proton showers with energy E/A

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

- **Theorem: Elongation rate (slope of X_{max}) < radiation length (λ_e) in air for constant primary composition**

$$D = \frac{dX_{max}}{d\ln(E)} \sim \lambda_e \left(1 - B_N - B_\lambda - B_A\right)$$

Multiplicity evolution

$$B_N = \frac{d\ln N_{tot}}{d\ln(E)} \sim cst > 0$$

Cross-section evolution

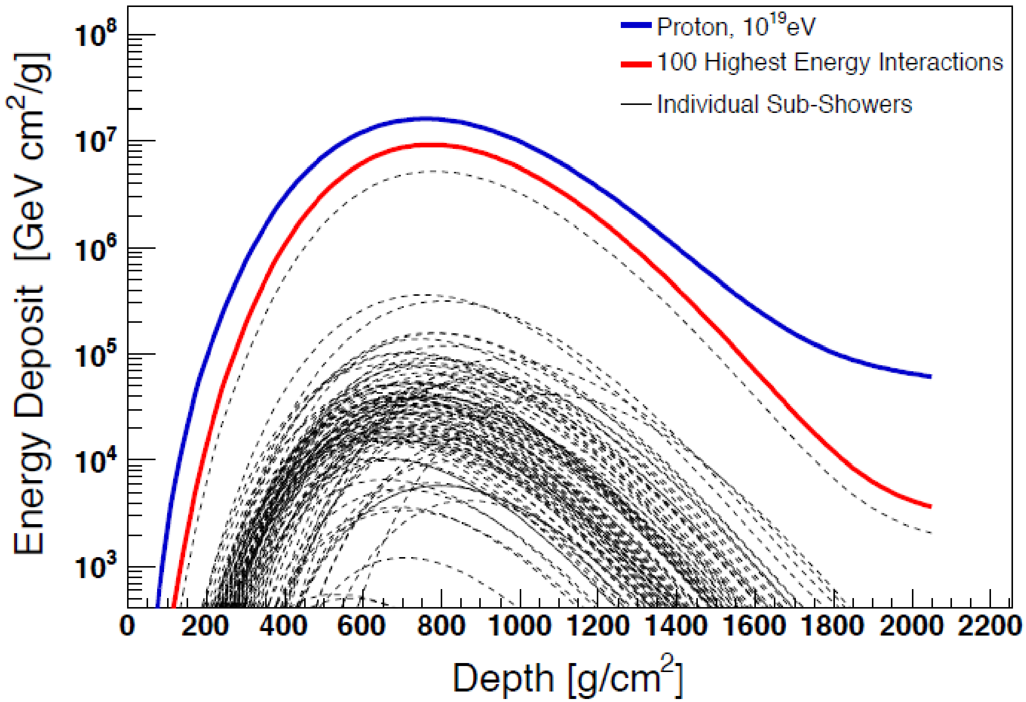
$$B_\lambda = \frac{-\lambda_{ine}}{\lambda_e} \frac{d\ln\lambda_{ine}}{d\ln(E)} \sim cst > 0$$

Mass evolution

$$B_A = \frac{d\ln A}{d\ln(E)}$$

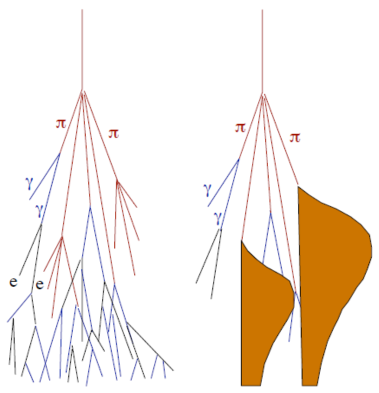
Hadronic Interactions for X_{max}

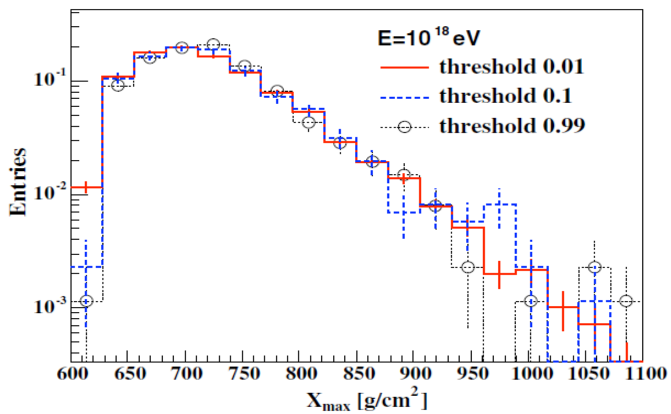
Electrons



Shower particles produced in 100 interactions of highest energy

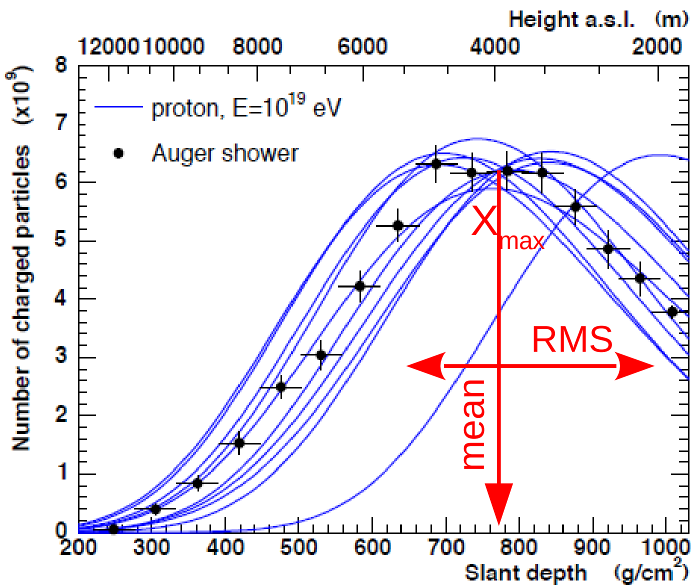
Electrons/photons: high-energy interactions

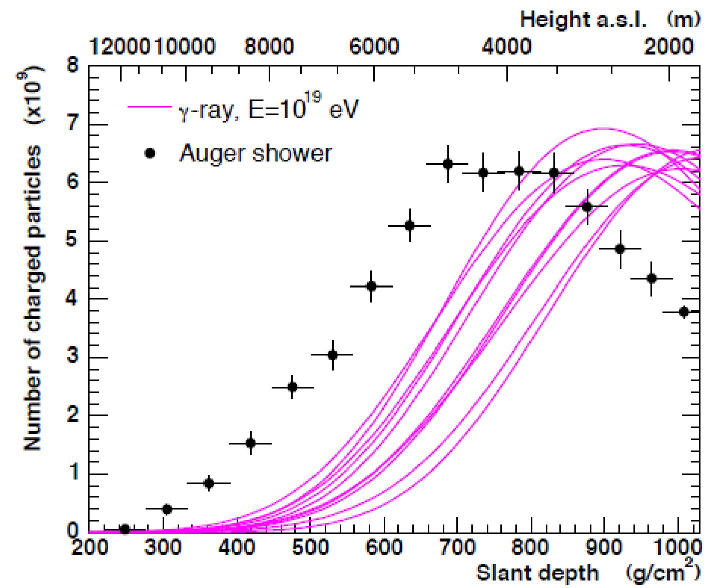


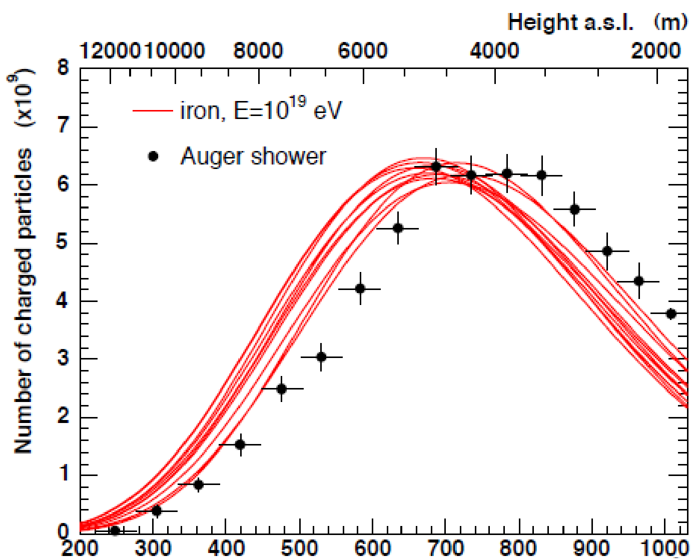


Fluctuations mainly coming from the first hadronic interaction.

Mean AND Fluctuations







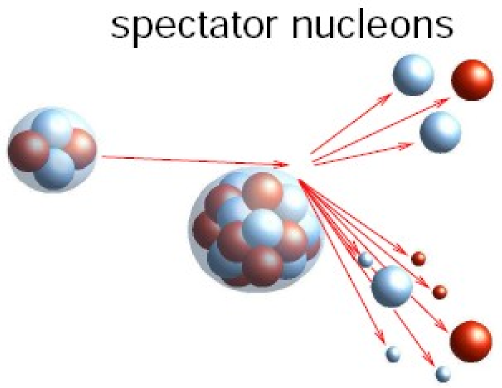
Example: event measured by Auger Collab. (ICRC 2003)

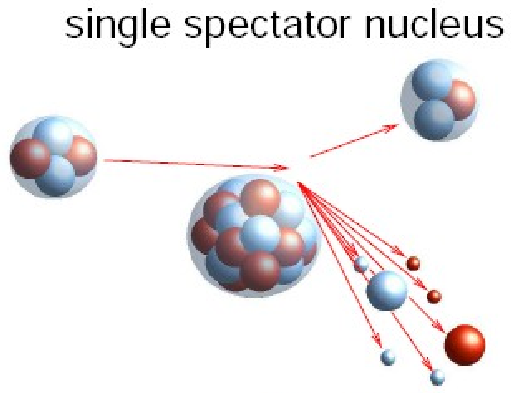
Both mean and fluctuations of X_{max} are important for mass composition measurements

X_{max} fluctuations

- **Basic model predictions :**
  - Superposition model
    - mean: $\mu_X(A,E) = \mu_X(p, E/A)$
    - fluctuations: $\sigma_X(A) = \frac{1}{\sqrt{A}}\sigma_X(p)$
  - Nuclear cross section and fragmentation
    - mean: $\mu_X(A,E) \approx \mu_X(p, E/A)$ (!)
    - fluctuations: $\sigma_X(A) \gg \frac{1}{\sqrt{A}}\sigma_X(p)$

- **Extreme cases :**

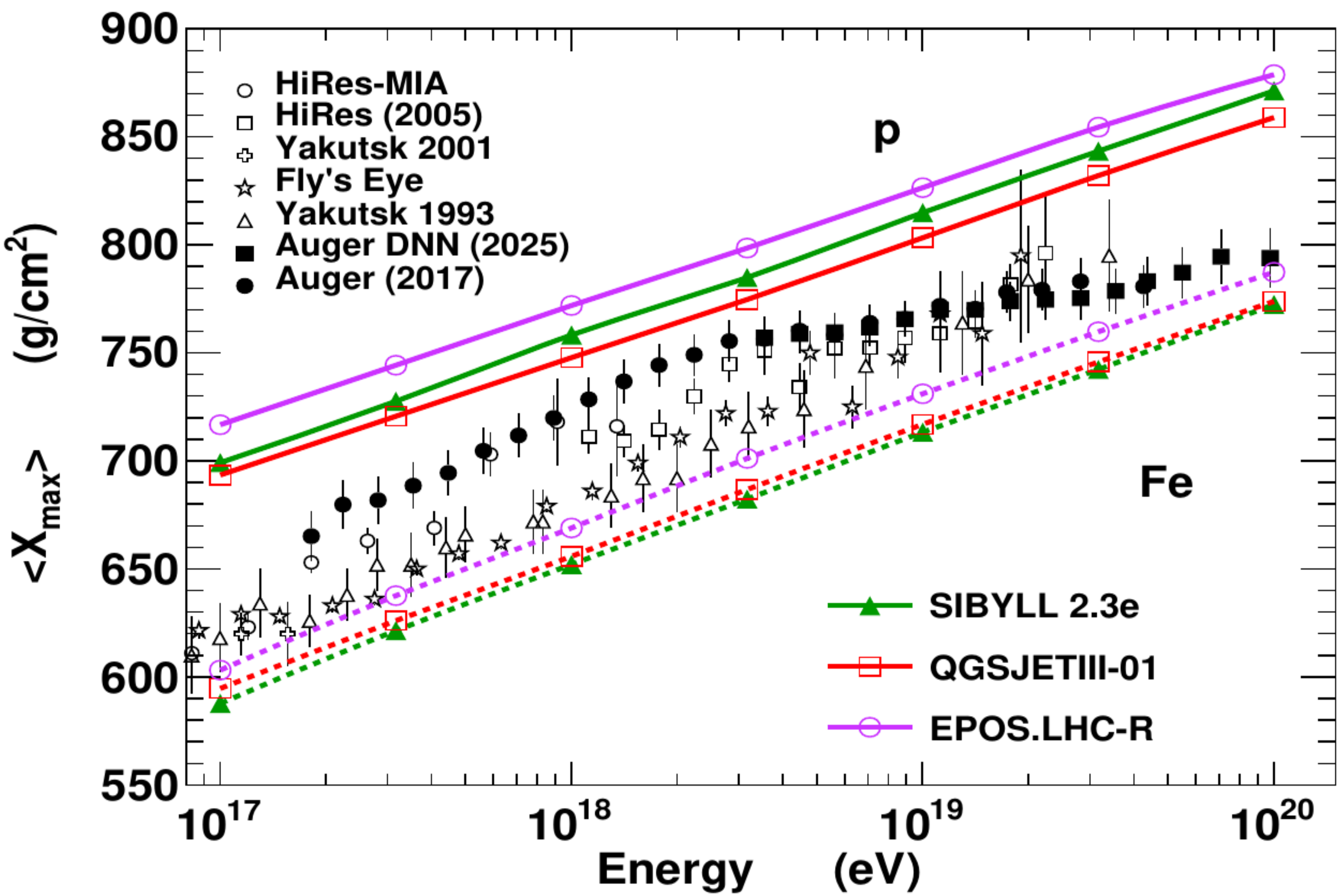




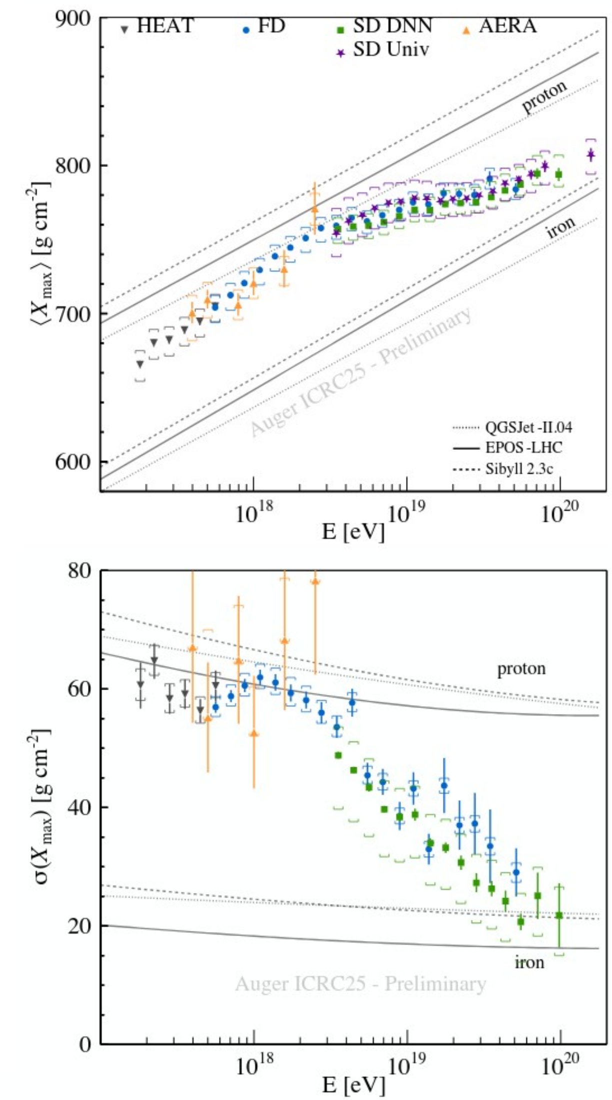
$s_X(A) < \sigma_X(A) < S_X(A)$

Full fragmentation — No fragmentation

X_{max} data



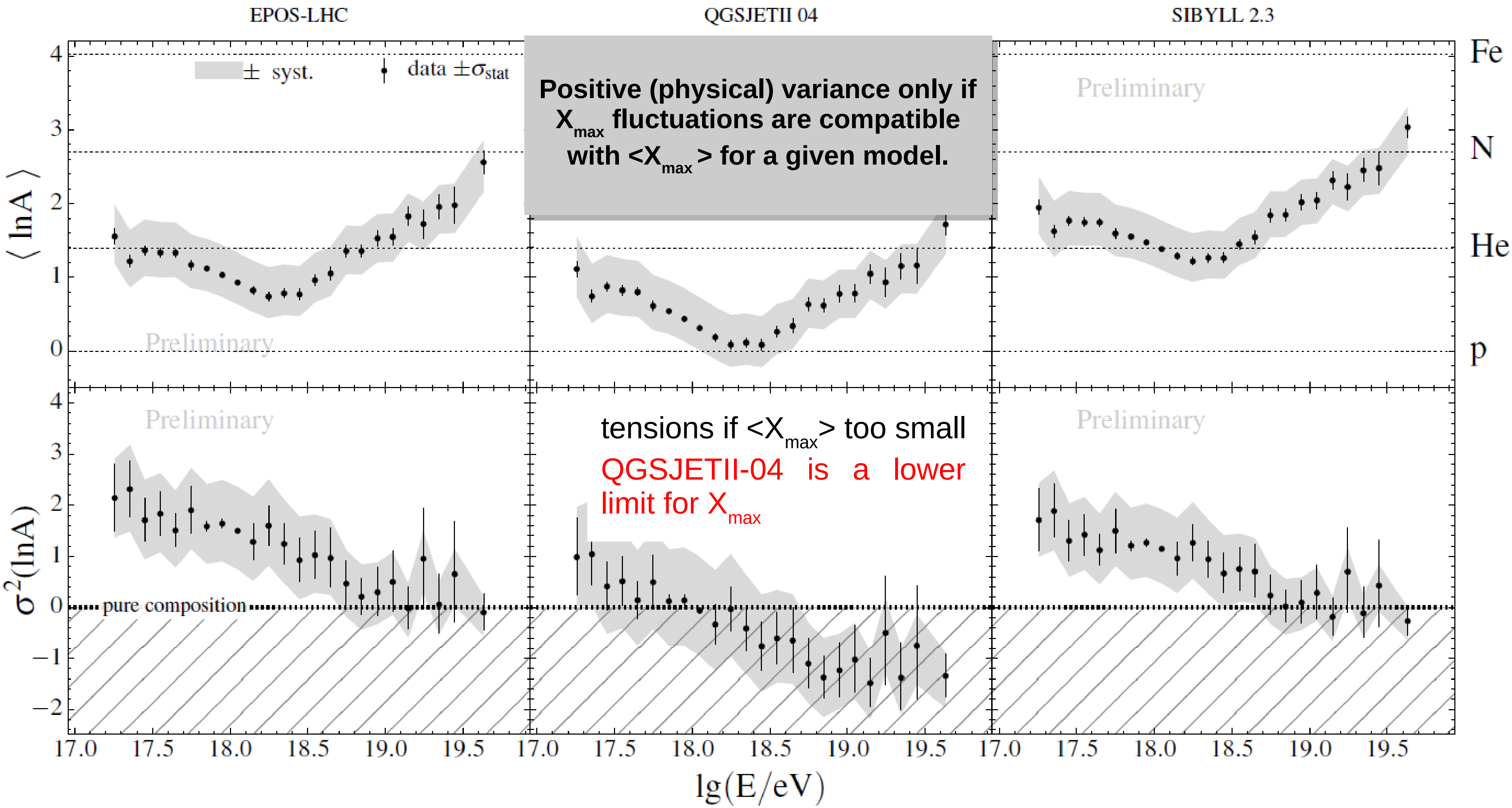
Phys. Rev. D 111 (2025)
Phys. Rev. Lett. 134 (2025)



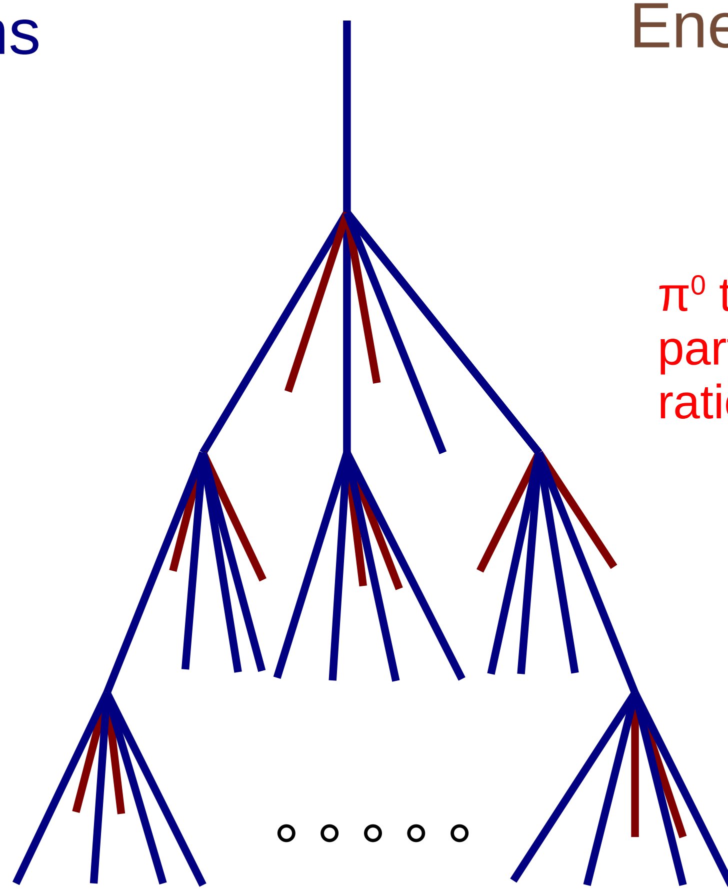
Pierre Auger Observatory (PAO)

Model Consistency using Electromagnetic Component

Study by Pierre Auger Collaboration (ICRC 2017)
➡ std deviation of lnA allows to test model consistency.



Energy Transfer : Energy Deposit



Energy of all hadrons

$$E_0$$

$$\frac{2}{3}E_0$$

$$\frac{2}{3}\left(\frac{2}{3}E_0\right)$$

After *n* generations

$$E_{had}=\left(\frac{2}{3}\right)^n E_0$$

Energy of all em. particles

$$0$$

π^0 to all particles ratio → $\frac{1}{3}E_0$

$$\frac{1}{3}E_0+\frac{1}{3}\left(\frac{2}{3}E_0\right)$$

$$E_{em}=\left[1-\left(\frac{2}{3}\right)^n\right]E_0$$

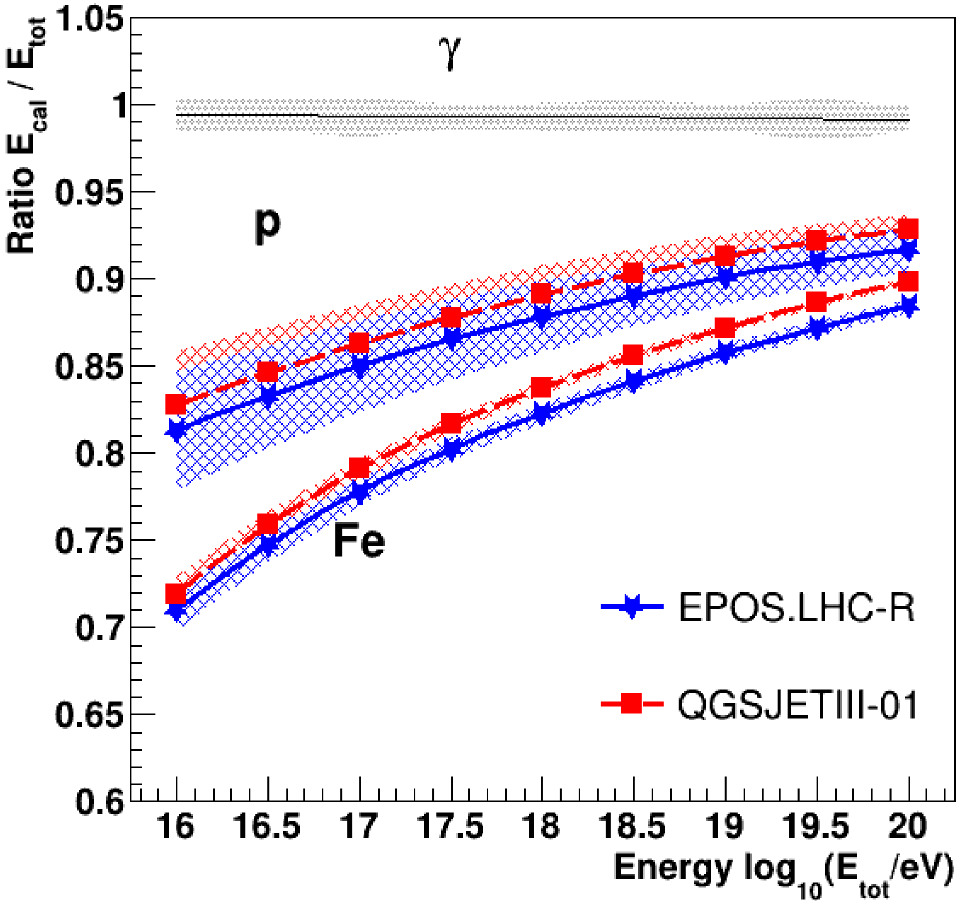
Energy in em. ~ 90 %

(n=5, E_{had}~12%
n=6, E_{had}~8%)

Real Energy Deposit

- **Ionization process :**
  - ➔ all charged particles : all energy loss converted to energy deposit
    - ➔ Energy deposit proportional to total number of charged particles
- **Particle below threshold**
  - ➔ all particles (but neutrinos) : only part of particle energy converted to energy deposit
    - for EM particles : all energy is deposited
    - for muons : all energy is deposited
    - for charged mesons : 25% of E_k in energy deposit
    - for neutral kaons : 50% of E_k in energy deposit
    - for other hadrons : 100% of E_k in energy deposit

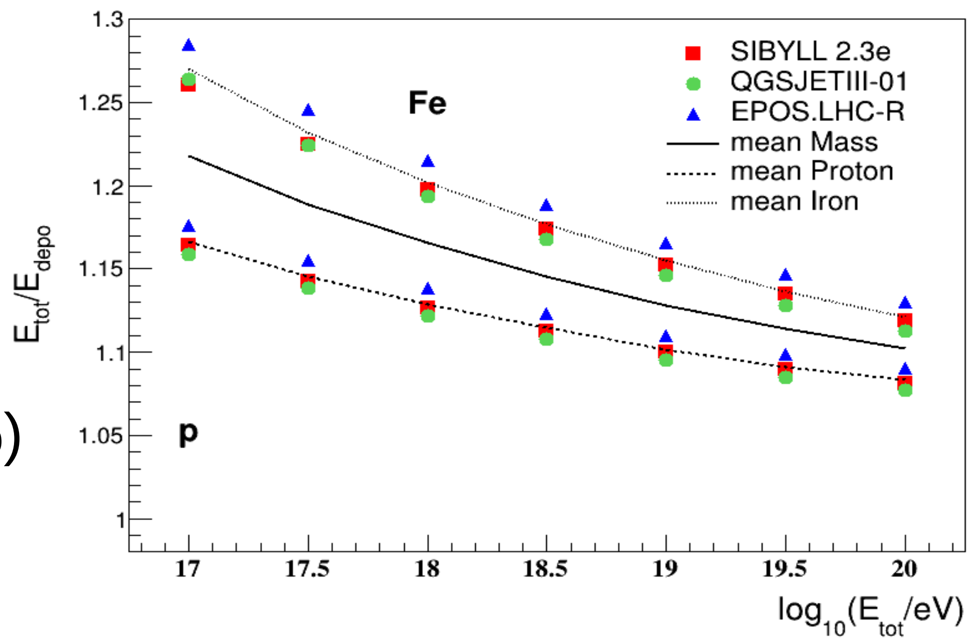
Calorimetric Energy



- **From Heitler model**

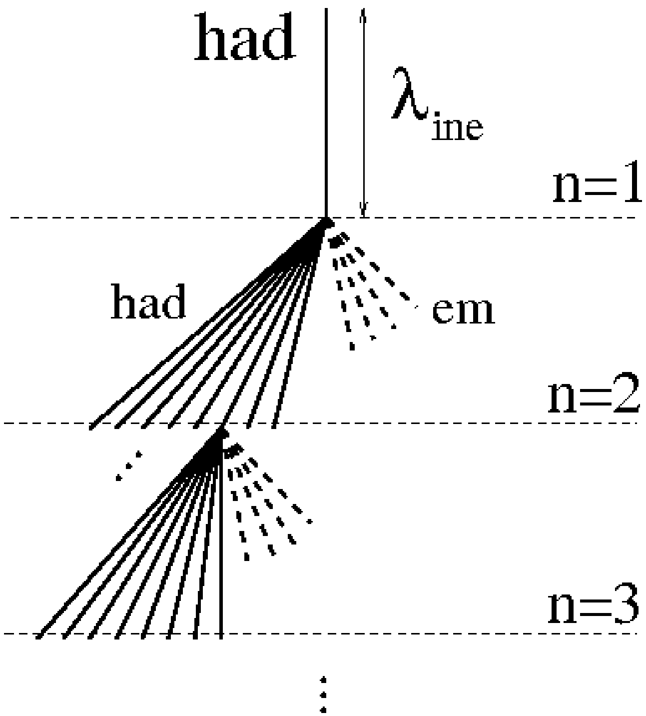
$$E_{em} = \left[1 - \left(\frac{N_{em}}{N_{tot}}\right)^{n(A)}\right] E_0$$

- **Energy deposit depends on total number of muons**
  - ➡ Primary mass dependent
  - ➡ Hadronic model dependent



- **Average value used**
  - ➡ Small error due to models (~1-2%)
  - ➡ Main uncertainty from unknown mass (~5-2%)

Toy Model for Hadronic Cascade



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

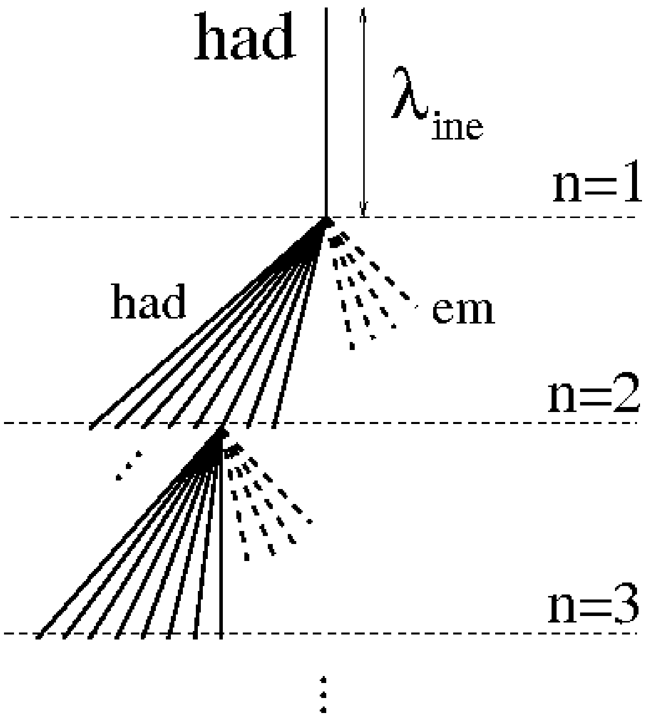
J. Matthews, Astropart.Phys. 22 (2005) 387-397

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).

Toy Model for Hadronic Cascade



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

Primary particle : hadron

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

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

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

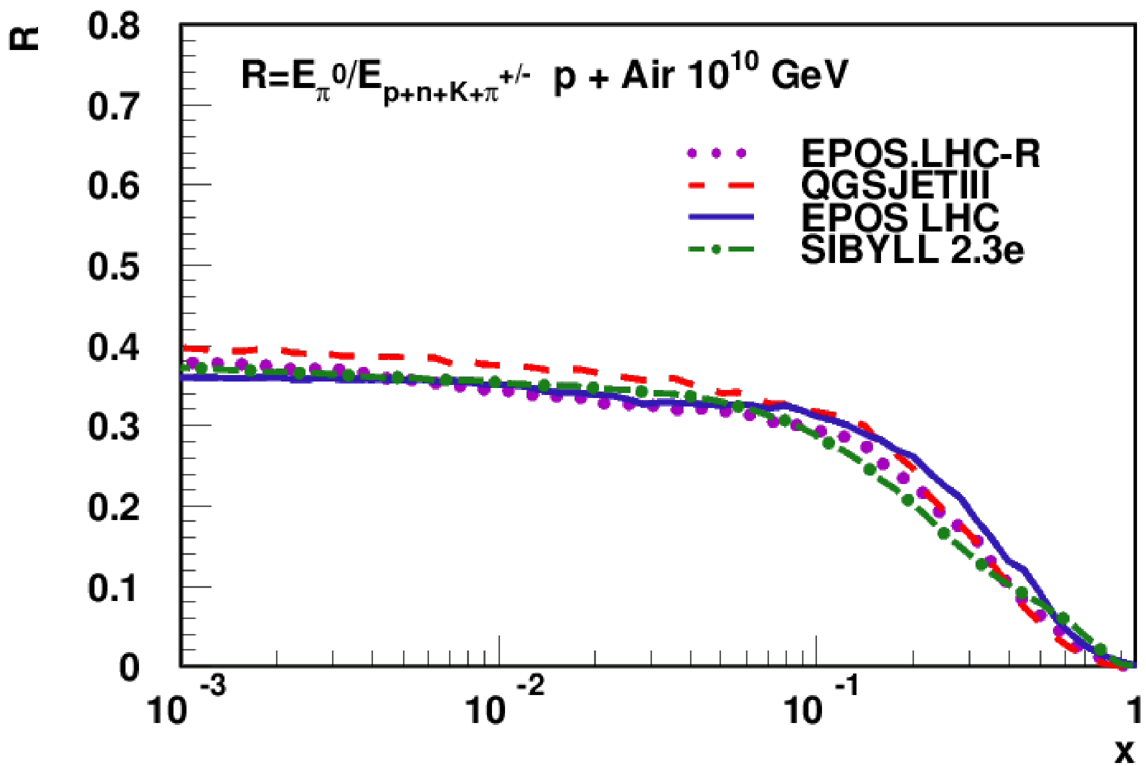
$$\ln(N_\mu) = \ln(N(n_{max})) = n_{max} \ln(N_{had})$$

Muon Number

- **From Heitler**

$$N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\beta, \quad \beta = \frac{\ln N_{had}}{\ln(N_{had}+N_{em})}$$

➡ In real shower, not only pions : resonances, Kaons and (anti)Baryons (but fewer ...)



$$\beta = \frac{\ln(N_{tot}-N_{em})}{\ln(N_{tot})} = 1 + \frac{\ln(1-c)}{\ln(N_{tot})}$$

$$c = \frac{N_{em}}{N_{tot}} \approx \frac{N_{\pi^0}}{N_{\pi^{ch}}+N_{other}+N_{\pi^0}} < 1$$

$$R = \frac{E_{em}}{E_{had}} \approx \frac{c}{1-c}$$

Very important :
R depends on the hadronization scheme (not given by 1st principles)

Less neutral pions or larger N_{tot} = $\beta \to 1$ = more muons

Superposition Model

- **Primary nucleus with mass A and energy E**
  - ➡ equivalent to A proton showers with energy E/A

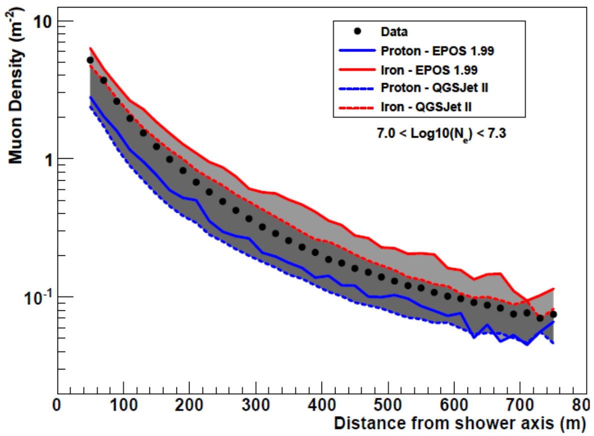
$$N_\mu(A) = A\left(\frac{E_0/A}{E_{dec}}\right)^\beta \qquad \beta \sim 0.925$$

- **More muons from primary nucleus**

$$N_\mu(A) = N_\mu(p)\,A^{1-\beta}$$

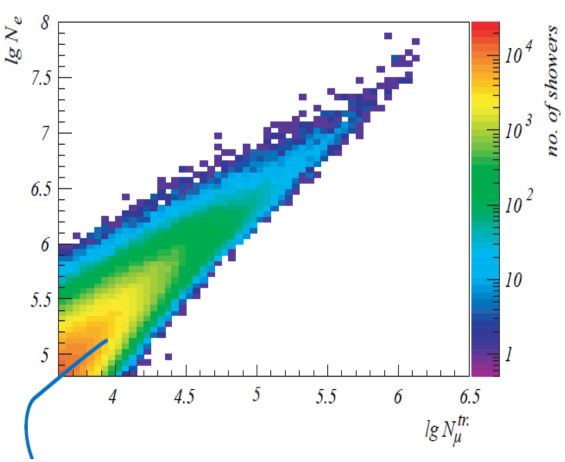
Ratio between proton and iron showers ?

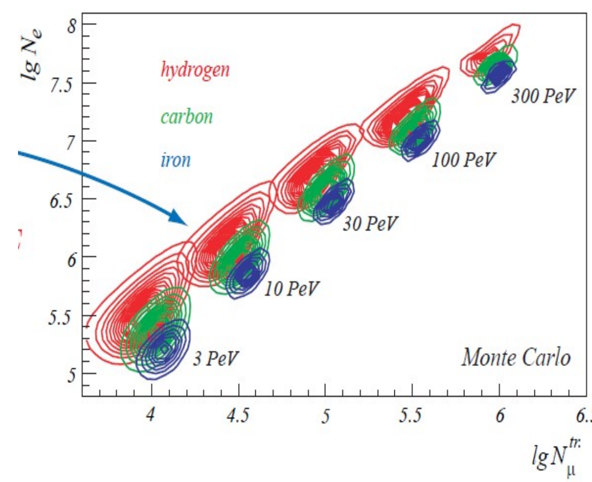
Particles at Ground



KASCADE-GRANDE

- **Particles at ground of various types**
  - Electron and photons directly linked to the longitudinal profile (X_{max} fluctuations) and strongly attenuated by the atmosphere
  - Hadrons are rare (but was measured by KASCADE)
  - Muons suffer little attenuation and less fluctuations.
    - "Pure" muon signal at large distances and for very inclined showers
- **LDF different for different particles and primary masses**
  - different production height and attenuation
- **Utilize correlations between N_e and N_{mu} to determine the mass spectra**
  - Correlations increase discrimination power



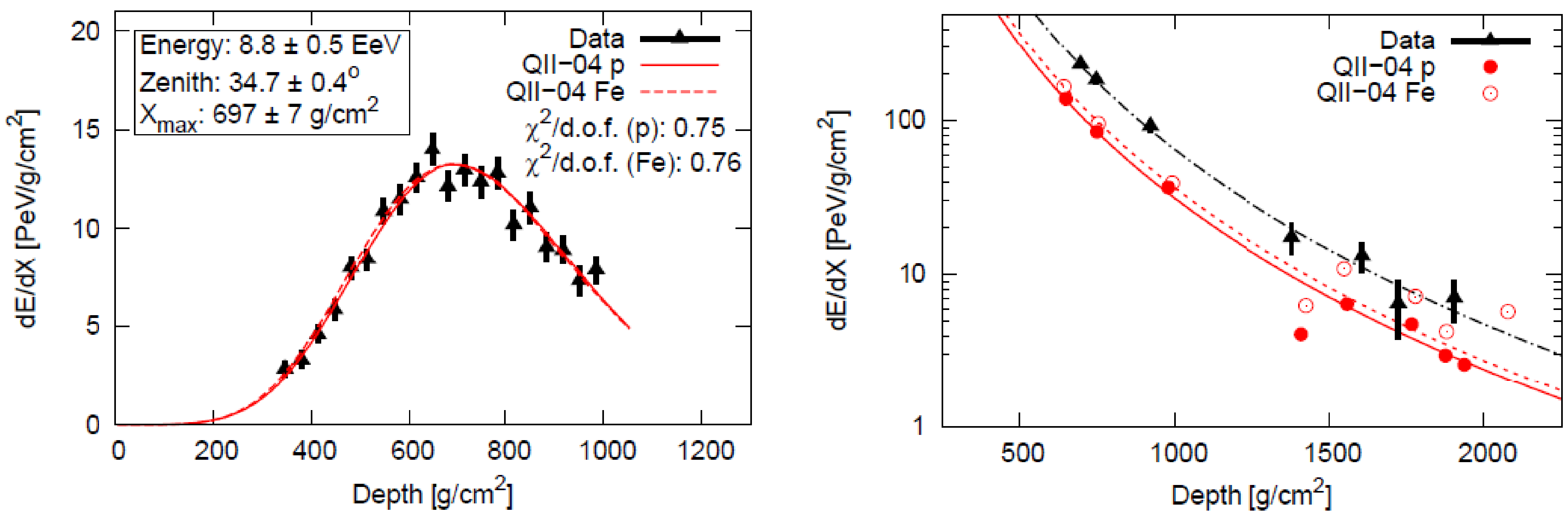


Auger Event-by-Event E~10^{19} eV

Top-down reconstruction

- Measure longitudinal profile and LDF at the same time
- Direct comparison between data and simulation (fixed energy and X_{max})

→ A problem appear : not enough signal at ground in simu : missing muons !

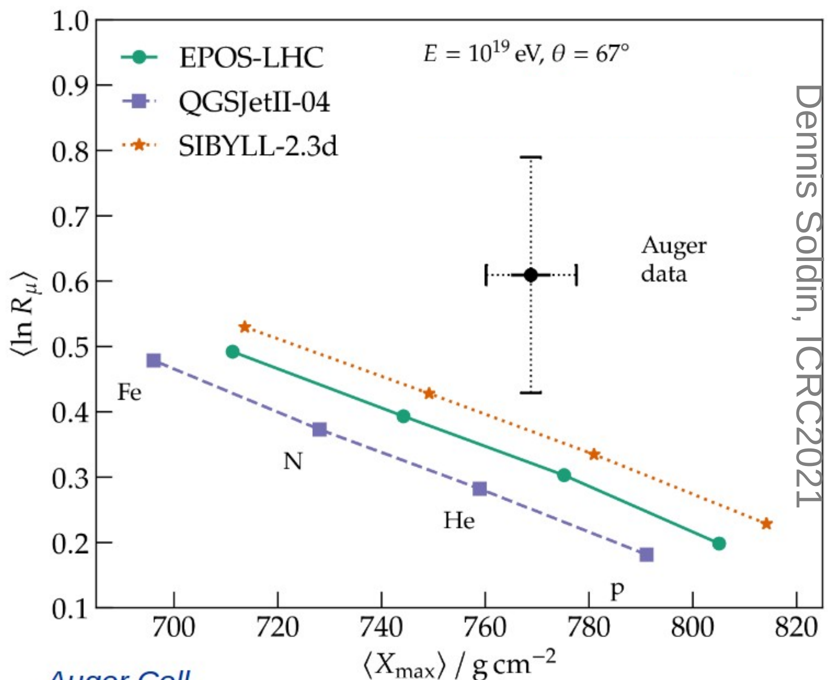


Muon "Puzzle"

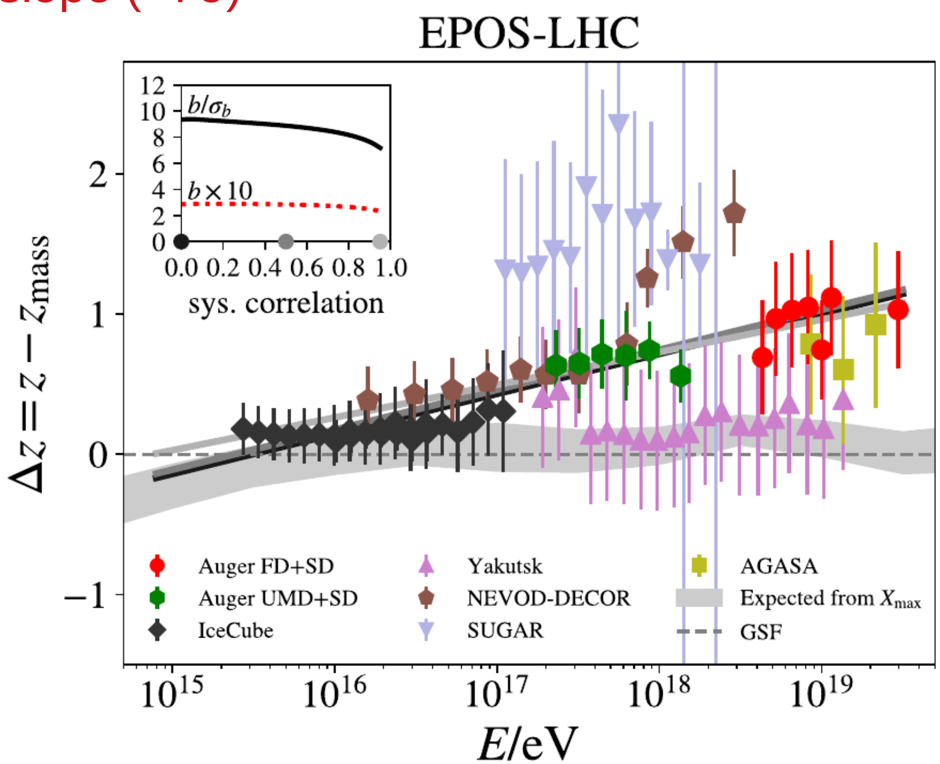
- **Clear muon excess in data compared to simulation**
  - PAO: inconsistent number of muons for a given X_{max}
  - Global: different energy evolution between data and simulations
  - Significant non-zero slope (>7σ)

$$z = \frac{\ln N_\mu^{det} - \ln N_{\mu,p}^{det}}{\ln N_{\mu,Fe}^{det} - \ln N_{\mu,p}^{det}}$$

$$z_{mass} = \frac{\langle \ln A \rangle}{\ln 56}$$



Auger Coll., Phys. Rev. Lett. 2021



Dennis Soldin, ICRC2021

- **Different energy or mass scale cannot change the slope**
  - Different property of hadronic interactions at least above 10^{16} eV

Constraints from Correlated Change

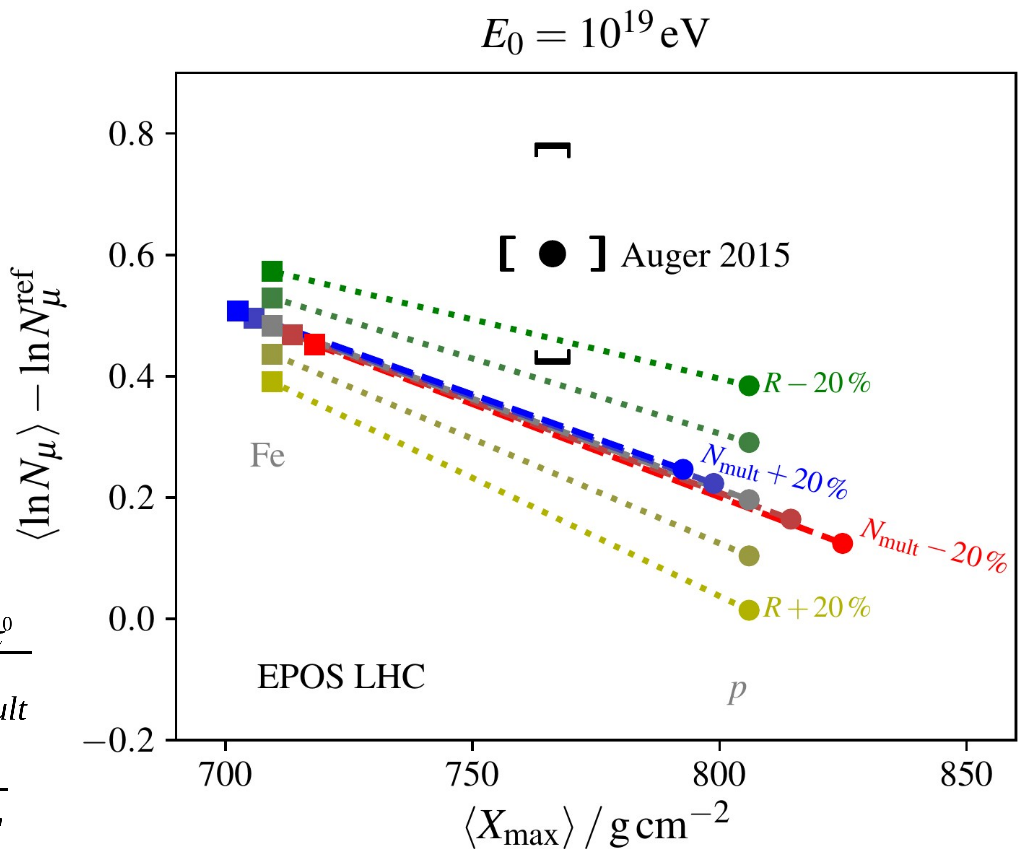
- One needs to change energy dependence of muon production by ~+4%

$$N_\mu = A^{1-\beta}\left(\frac{E}{E_0}\right)^\beta$$

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

- To reduce muon discrepancy β has to be change
  - X_{max} alone (composition) will not change the energy evolution
  - β changes the muon energy evolution but not X_{max}

- $$\beta = \frac{\ln(N_{mult} - N_{\pi^0})}{\ln(N_{mult})} = 1 + \frac{\ln(1-c)}{\ln(N_{mult})}$$
  - +4% for β ➤ -30% for $c = \frac{N_{\pi^0}}{N_{mult}}$
  - Measure@LHC : $R = \frac{E_{e/m}}{E_{had}} \approx \frac{c}{1-c}$



ArXiv 1902.09265

Muon Production Depth

Independent SD mass composition measurement

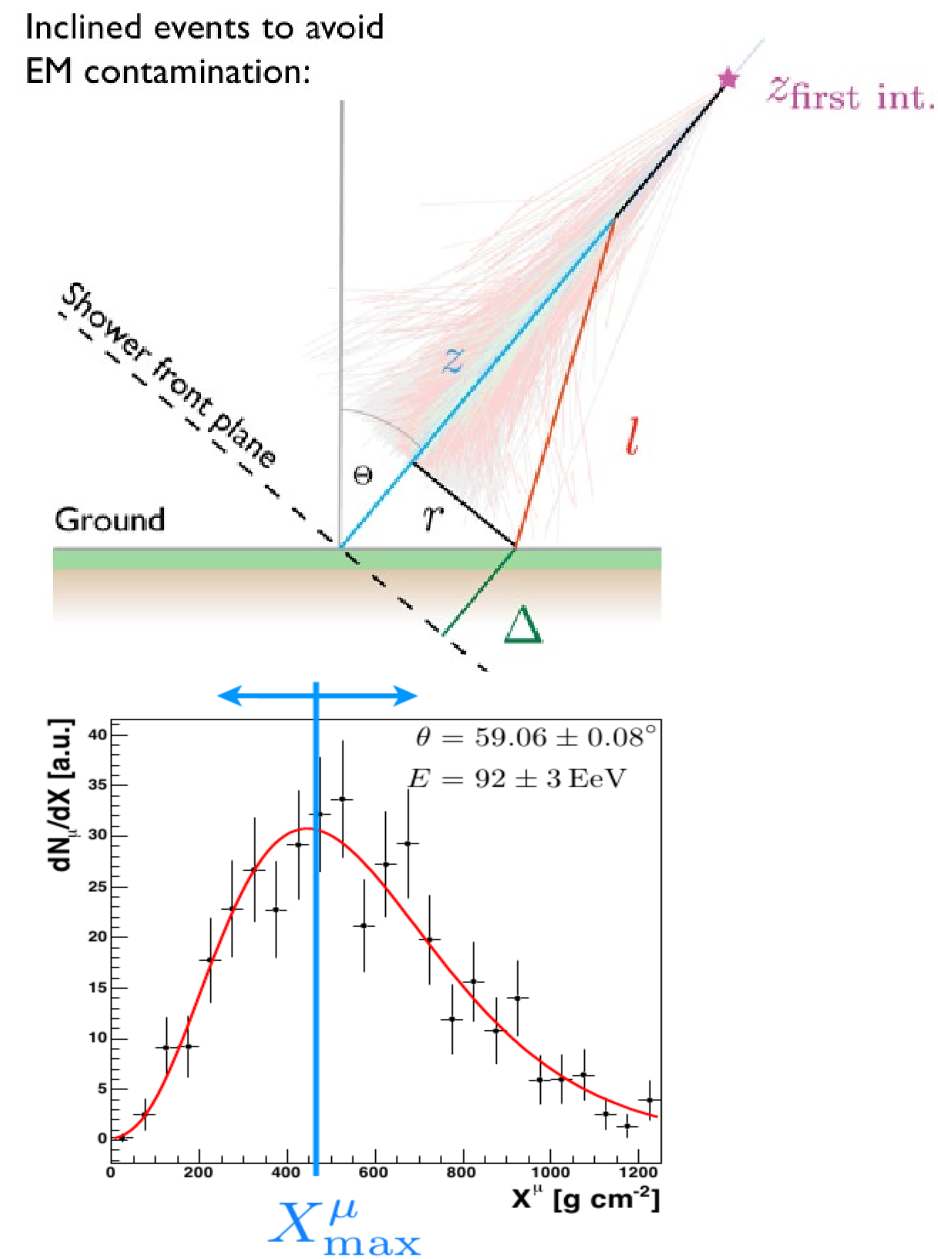
- Use time distribution of muons at ground
- geometric delay of arriving muons

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

- mapped to muon production distance

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

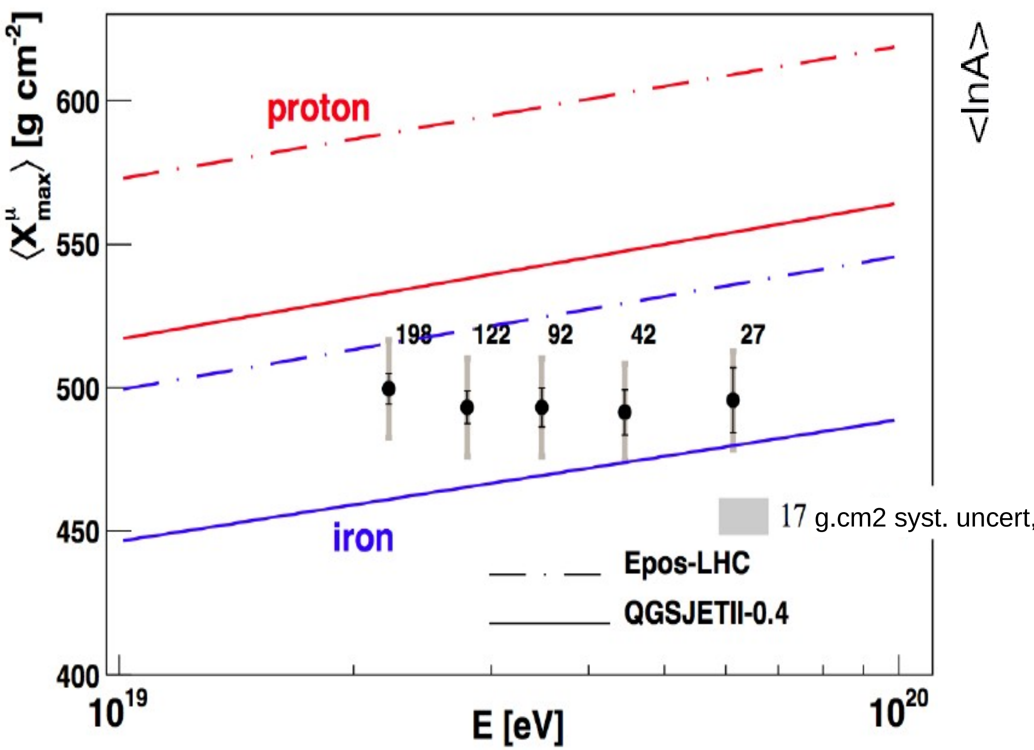
- Position of the maximum production depends on primary mass
  - Different than Xmax (do not depend only on the first interactions)
  - Very sensitive to hadronic interactions (all generations)

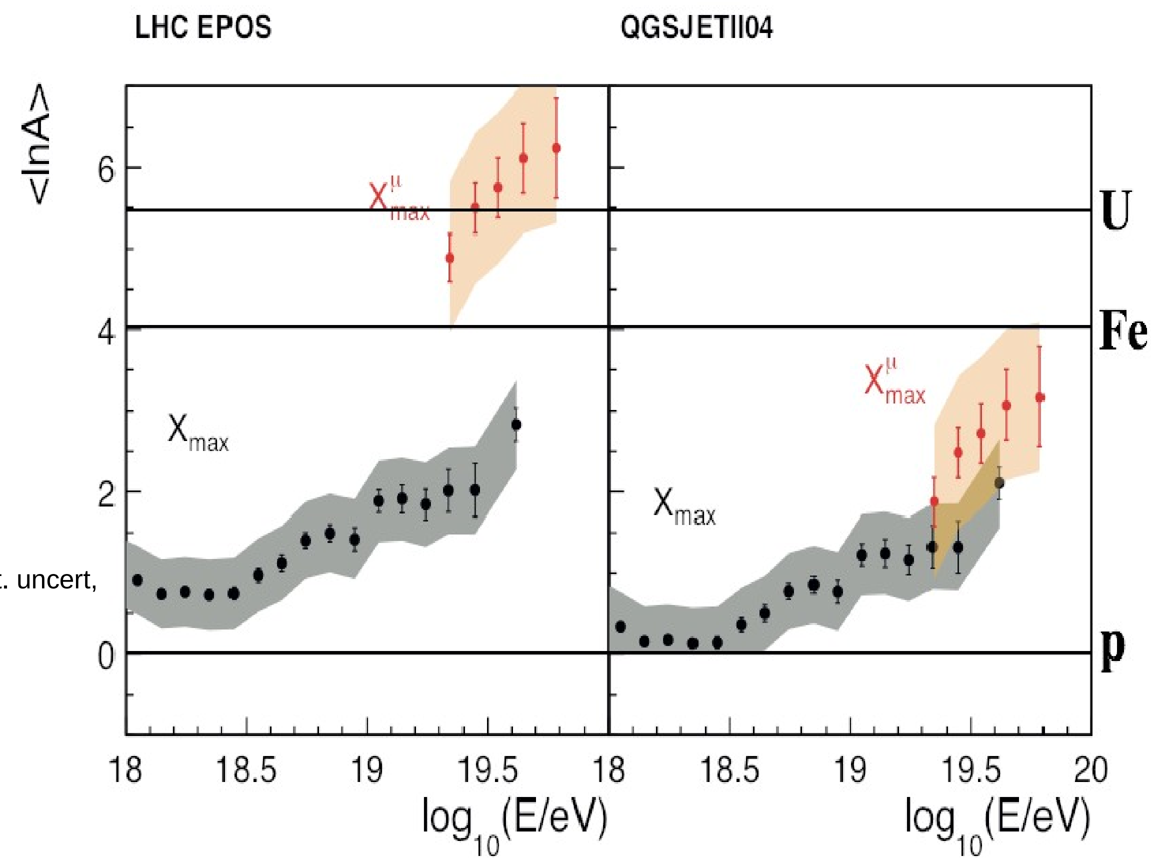


Muon Production Depth and Models

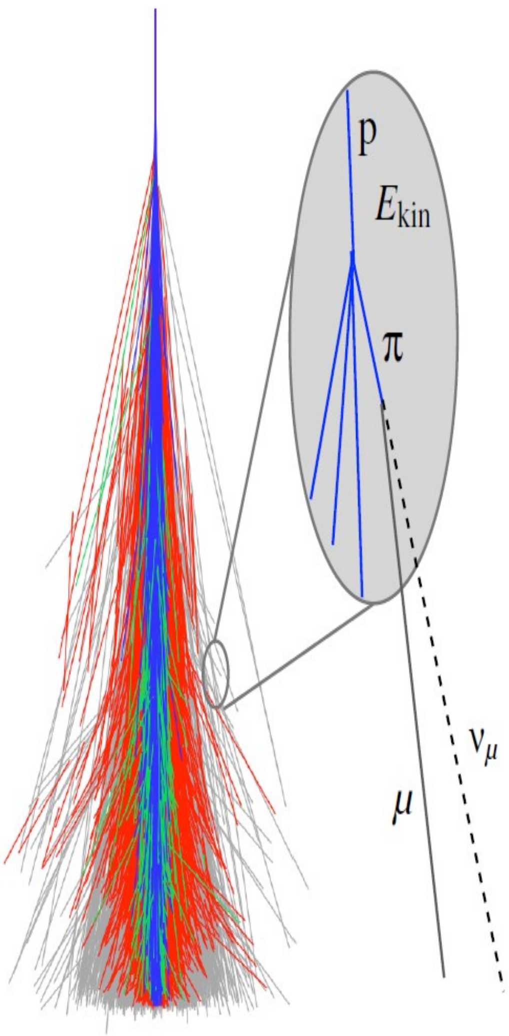
2 independent mass composition measurements

- 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

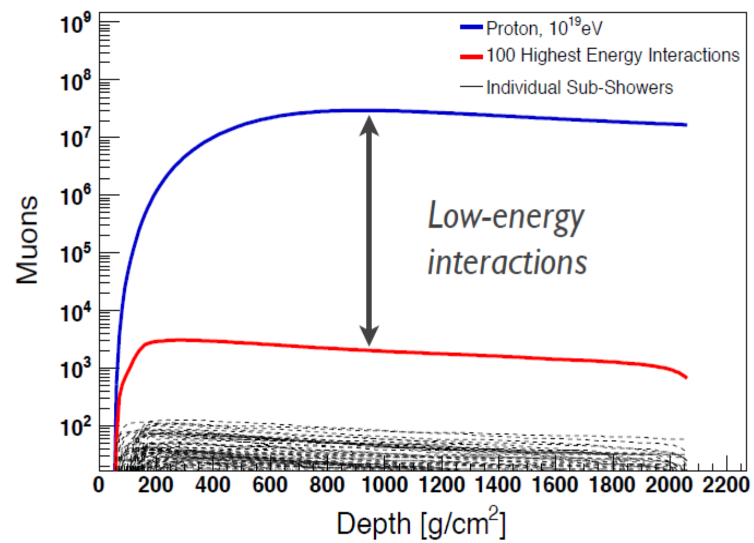




Muon production by low energy interactions

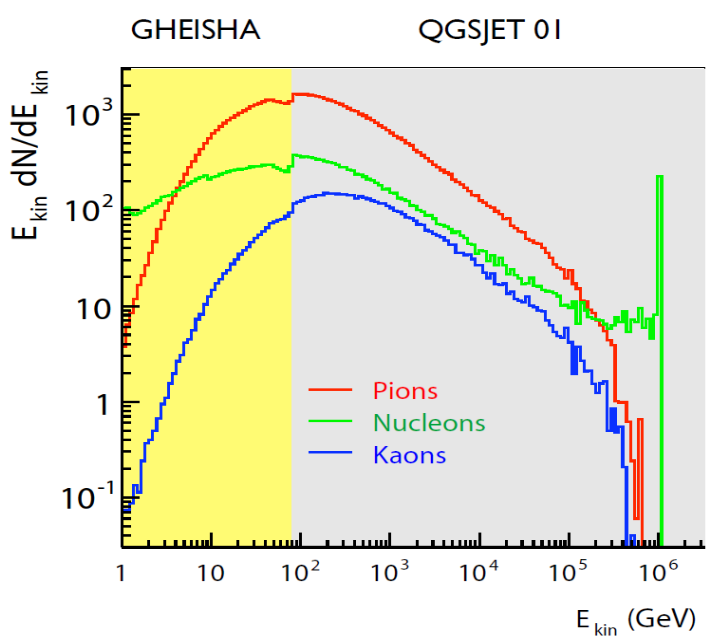


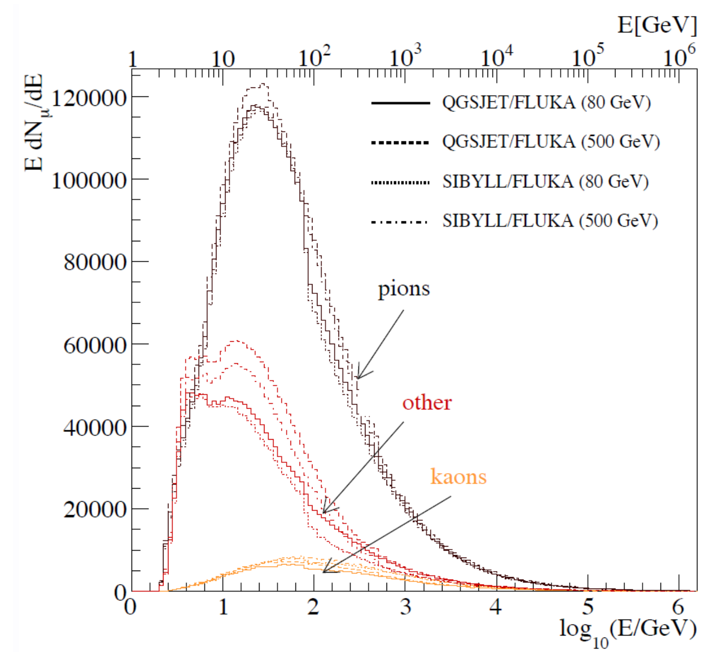
Muons



~ 100 GeV for KASCADE
~ 30 GeV for Auger

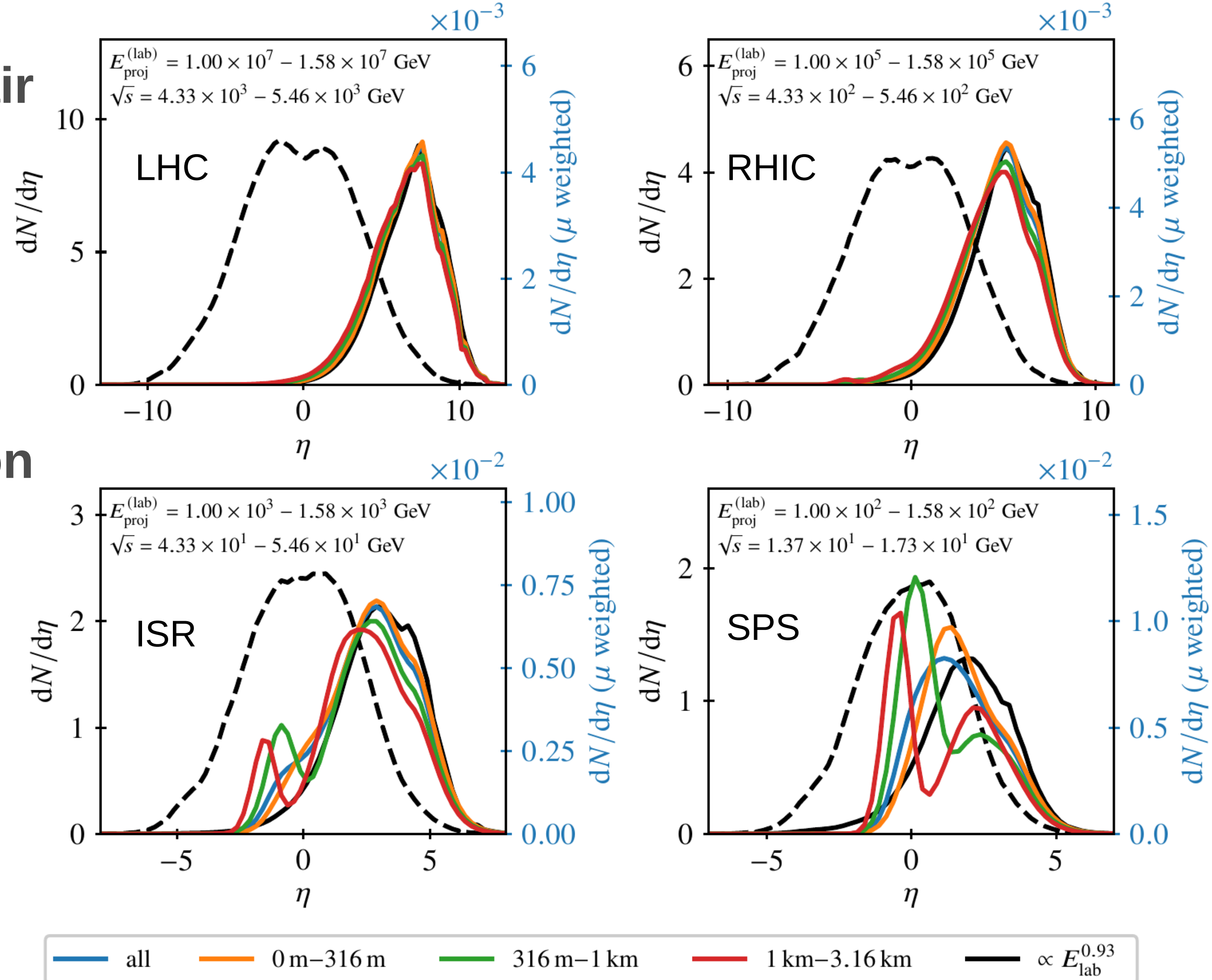
Muons/hadrons:
low-energy interactions





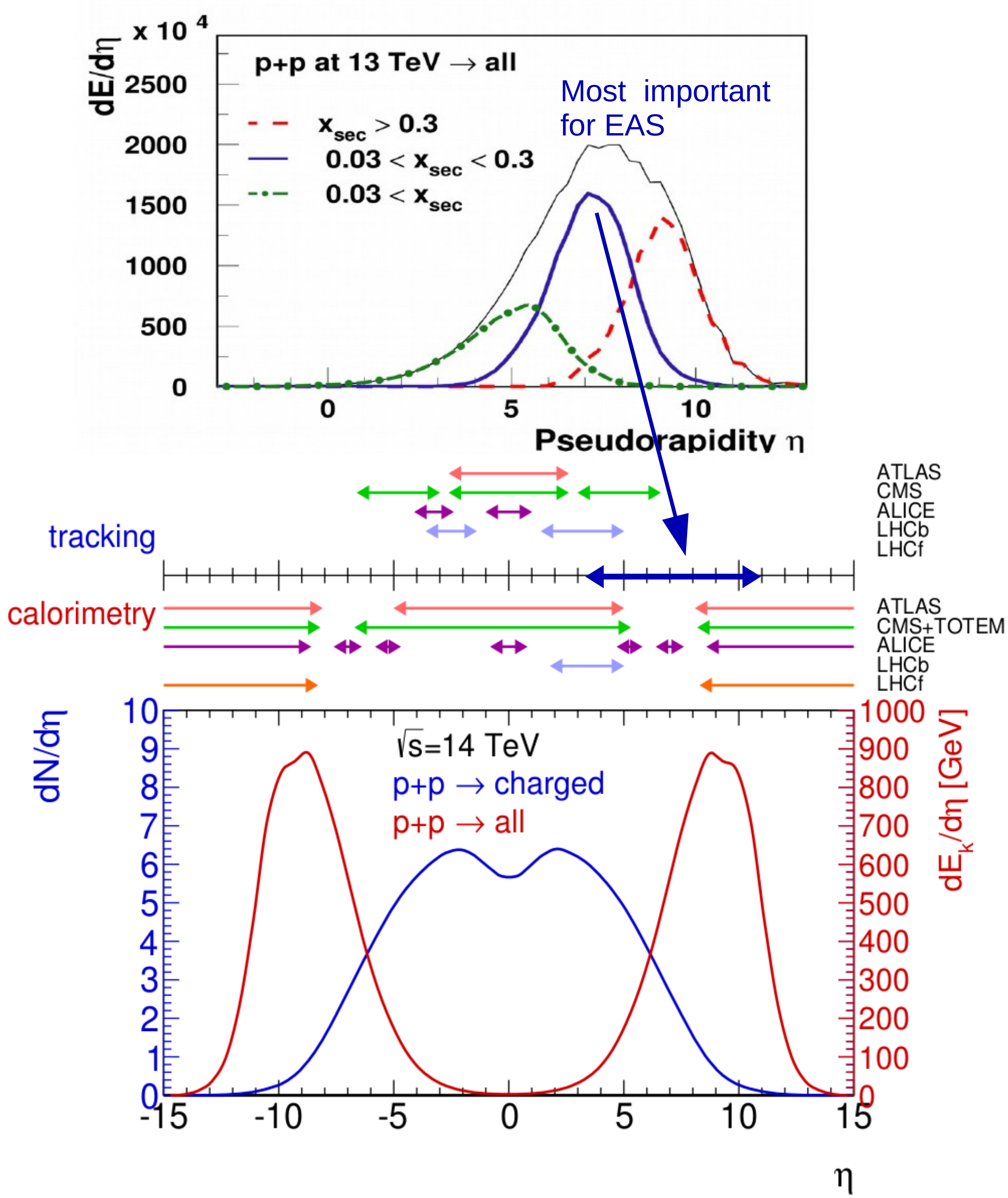
Relevant Phase Space in Air Showers

- **Muon production in air showers dominated by forward produced particles**
  - ➡ True at high energy
- **Midrapidity production important in the last generations and for muon at large distances from the shower core**
  - ➡ Low energy data as important than high energy data



Maximilian Reininghaus, ICRC2021

LHC acceptance



- **p-p data mainly from "central" detectors**
  - pseudorapidity $\eta=-\ln(\tan(\theta/2))$
  - $\theta=0$ is midrapidity
  - $\theta>>1$ is forward
  - $\theta<<1$ is backward
- **Different phase space for LHC and air showers**
  - most of the particles produced at midrapidity
    - important for models
  - most of the energy carried by forward (backward) particles
    - important for air showers

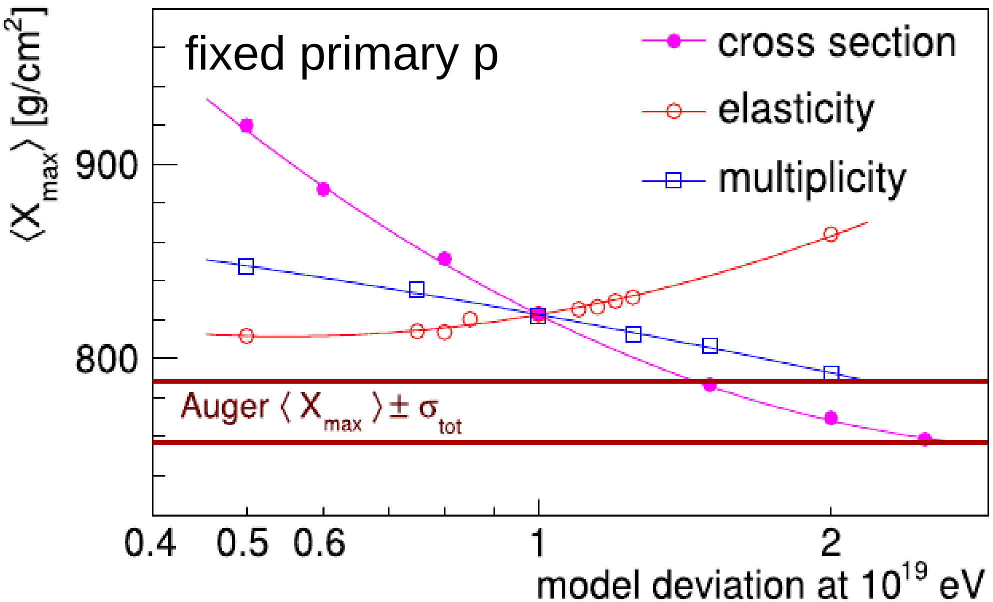
Lessons From Heitler Model

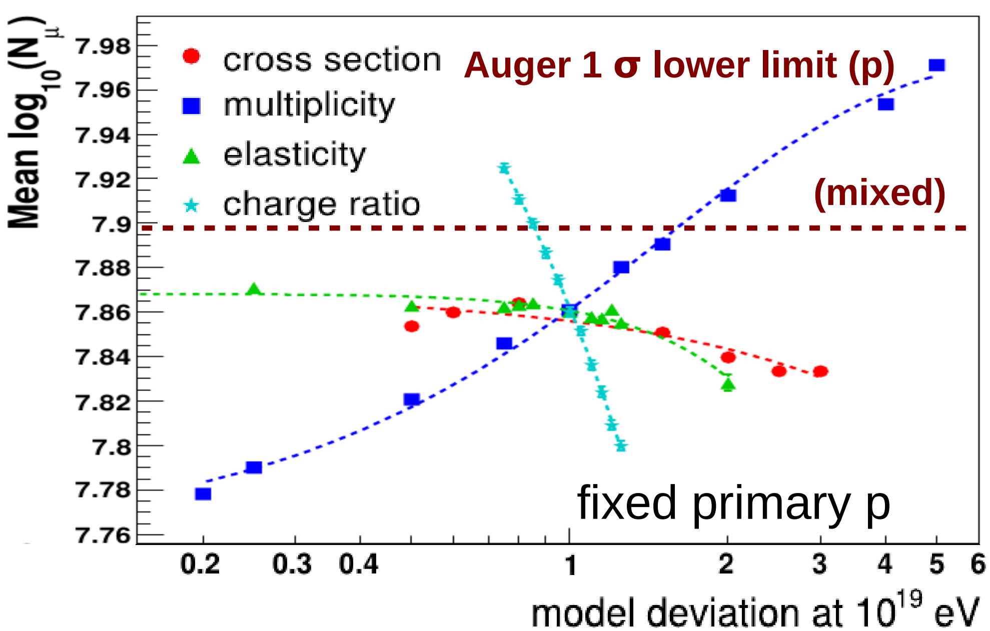
Important hadronic interaction parameters :

- **For X_{max} :**
  - ➔ Cross section
  - ➔ Multiplicity
  - ➔ (Elasticity: fraction of energy kept in leading hadronic particle)
- **For Energy deposit :**
  - ➔ Elasticity
  - ➔ π^0 to all particles ratio
- **For the number of muons :**
  - ➔ Multiplicity
  - ➔ π^0 to all particles ratio and baryons

Cross check using modified realistic simulations.

Sensitivity to Hadronic Interactions



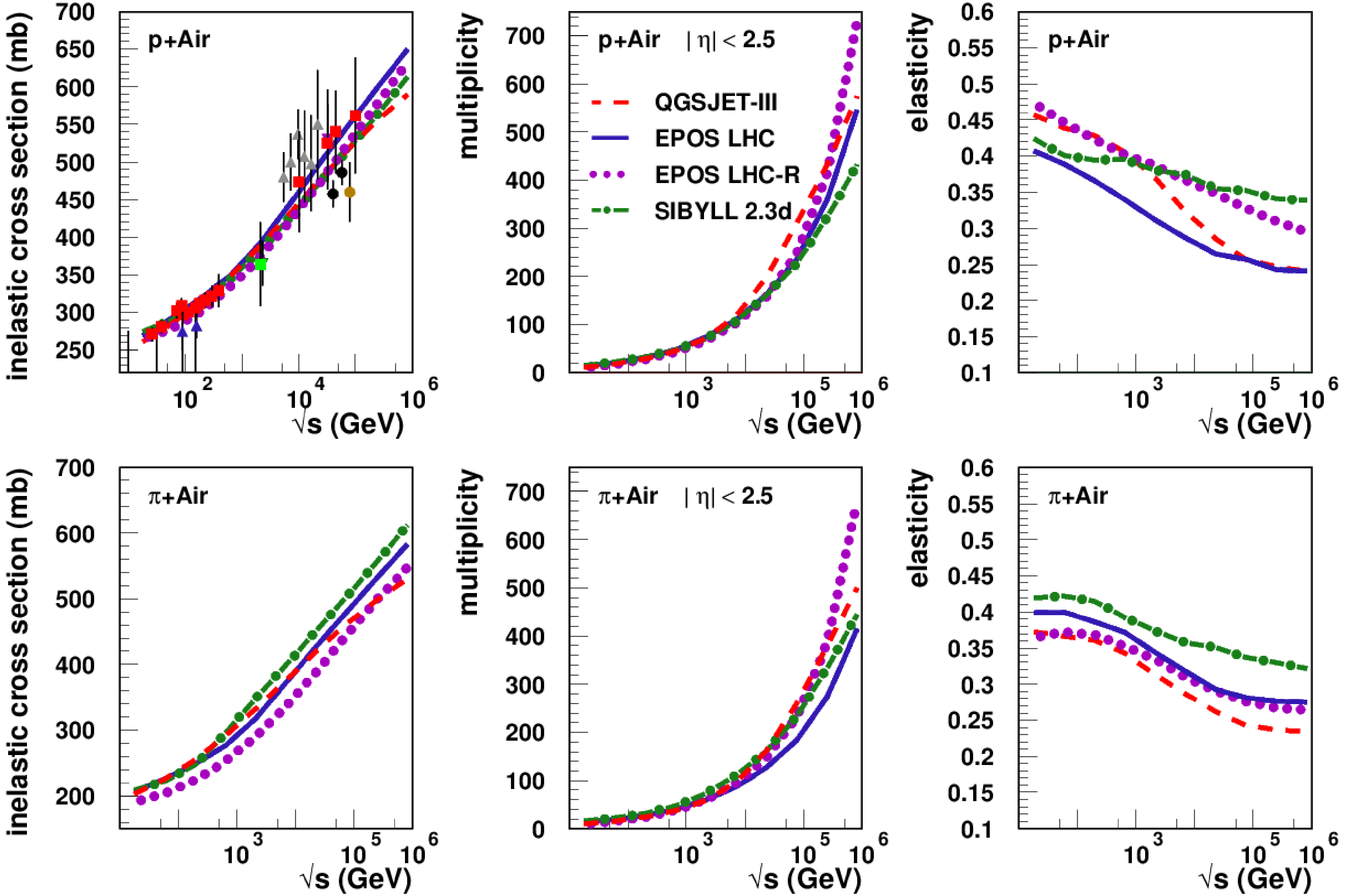


From R. Ulrich (KIT)

- **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

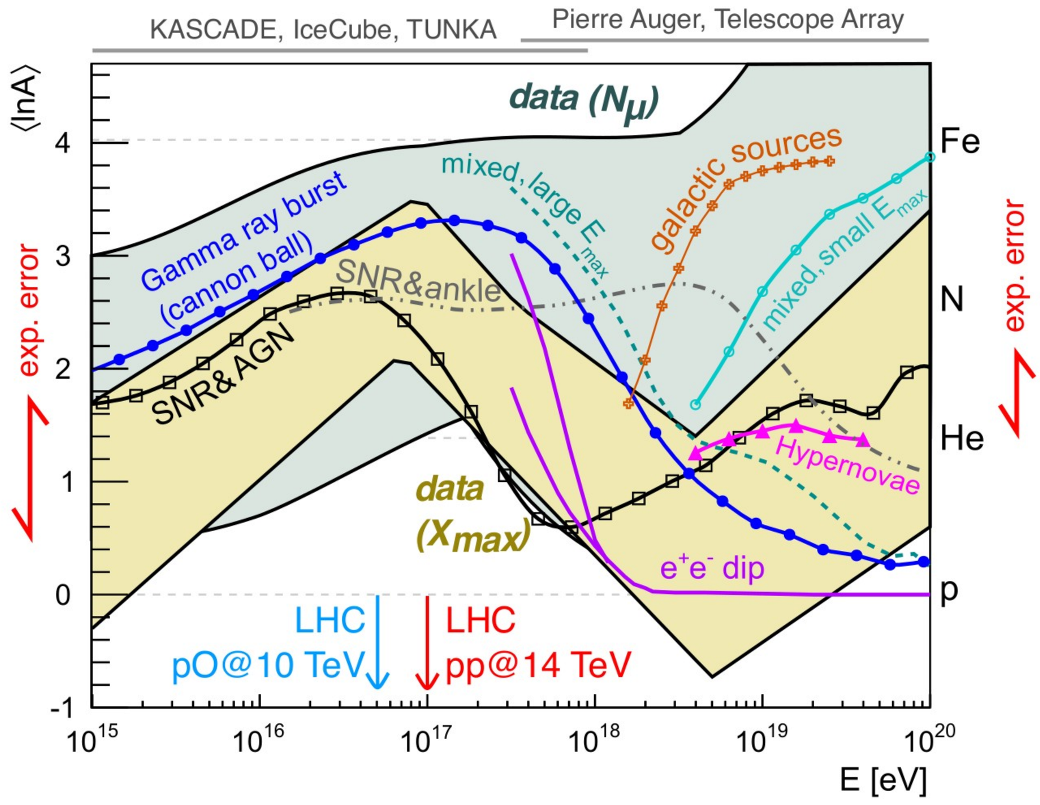
Ultra-High Energy Hadronic Model Predictions



UHECR Composition

With muons current CR data are impossible to interpret

- Very large uncertainties in model predictions
- Mass from muon data incompatible with mass fro X_{max}



Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

H. Dembinski UHECR 2018 (WHISP working group)