

Cosmic Rays

Tanguy Pierog

Karlsruhe Institute of Technology, Institut für Astroteilchenphysik,
Karlsruhe, Germany



Midsummer School in QCD, Saariselkä, Finland

July the 2nd - 3rd 2024

Secondary Cosmic Rays

Tanguy Pierog

Karlsruhe Institute of Technology, Institut für Astroteilchenphysik,
Karlsruhe, Germany



Midsummer School in QCD, Saariselkä, Finland

July the 2nd 2024

Soft QCD and the Production of Secondary Cosmic Rays

Tanguy Pierog

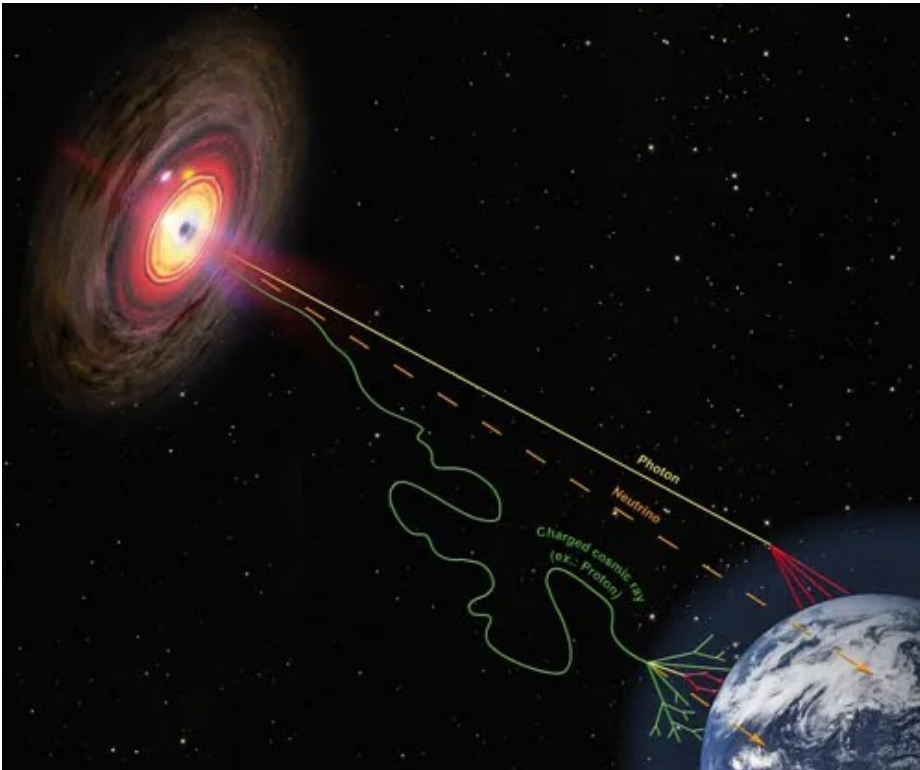
Karlsruhe Institute of Technology, Institut für Astroteilchenphysik,
Karlsruhe, Germany



Midsummer School in QCD, Saariselkä, Finland

July the 2nd 2024

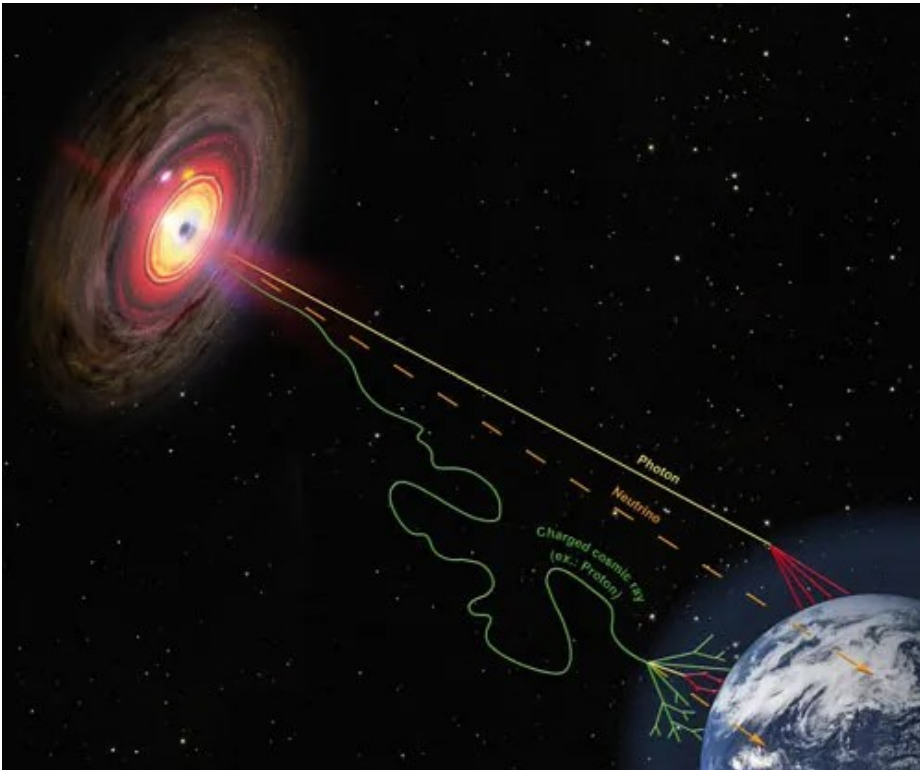
Cosmic Rays (CR)



Cosmic Rays (CR)

Primary CR

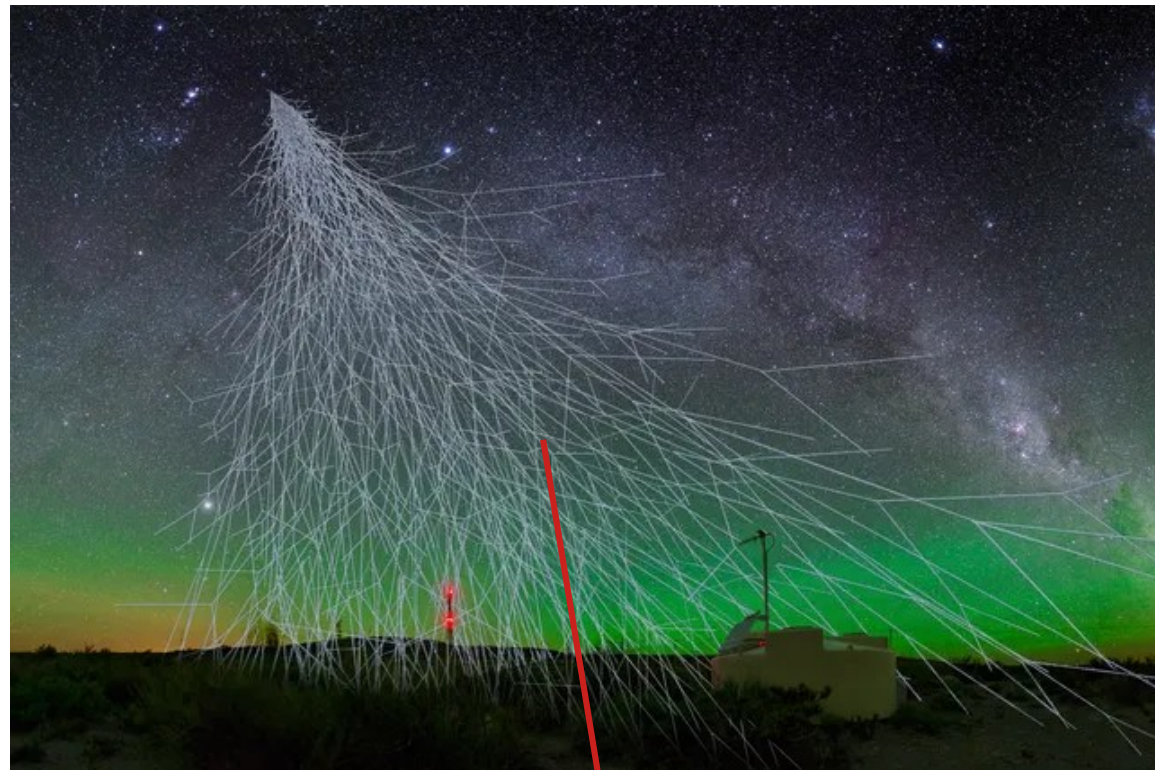
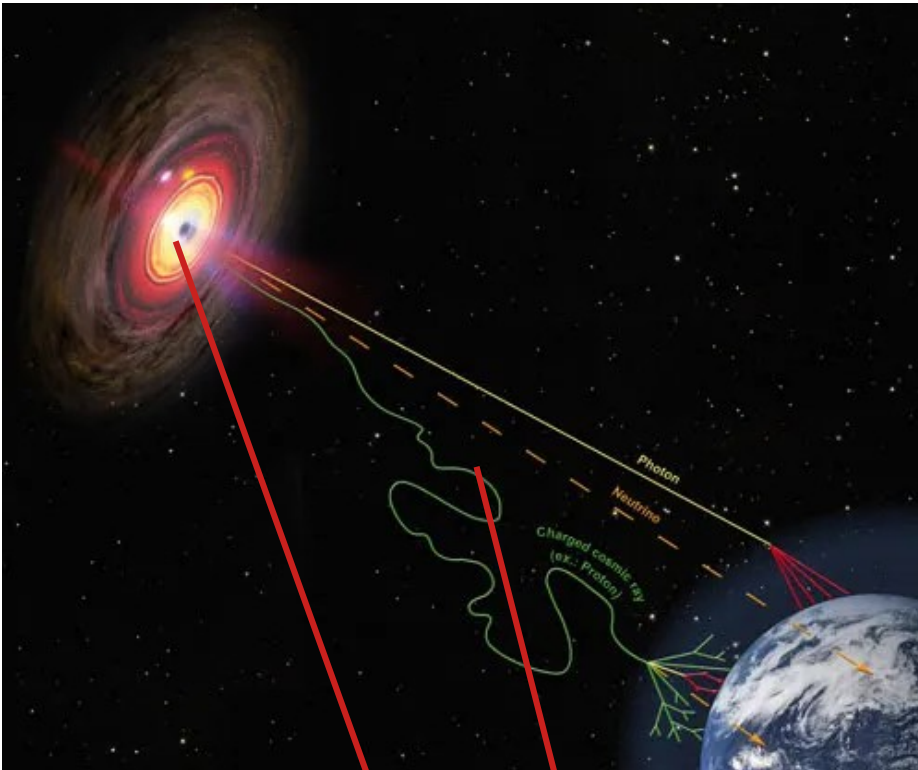
Secondary CR



Cosmic Rays (CR)

Primary CR

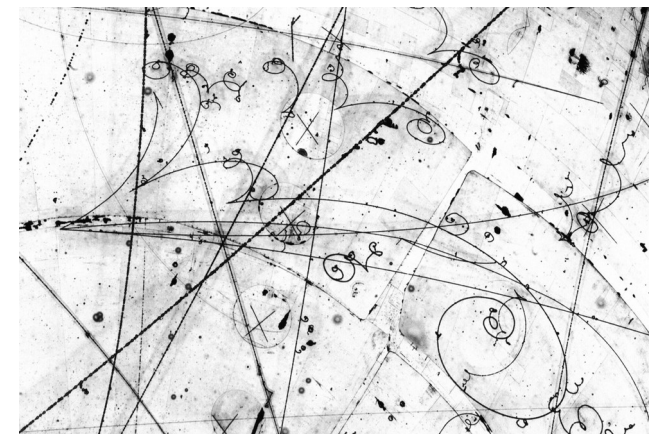
Secondary CR



Soft QCD interactions → “application” of QCD to “real” world

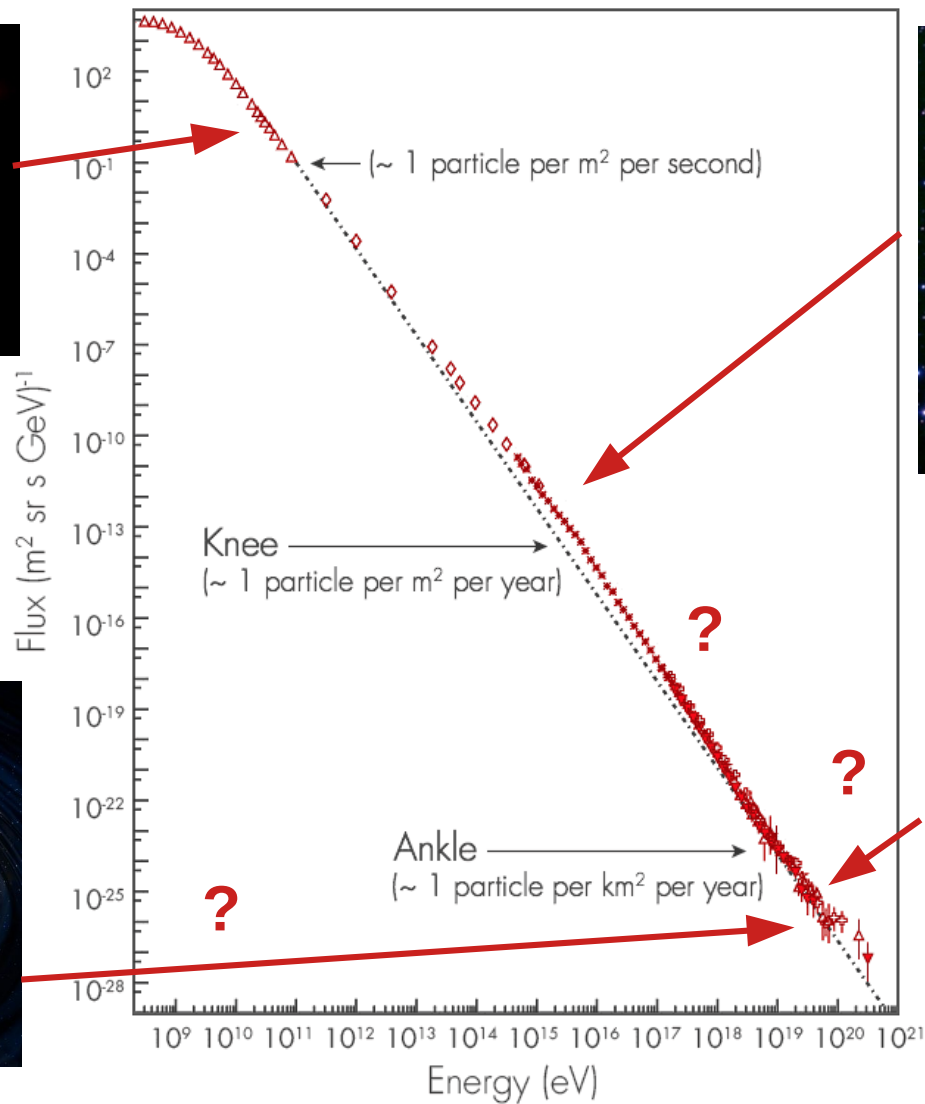
History

- **Victor Hess discovered in 1912 that natural radioactivity was increasing with height**
 - ➔ radiation from space
- **Pierre Auger discovered air showers in 1937**
 - ➔ secondary particles produced by primary cosmic rays
- **until ~1950 particle physics was studied thanks to cosmic rays**
 - ➔ all first unstable particles discovered in cosmic rays
 - **muon, pion, strangeness ...**
 - ➔ cosmic rays could not be used for astrophysics
- **after first start of accelerators, things changed ... until now !**

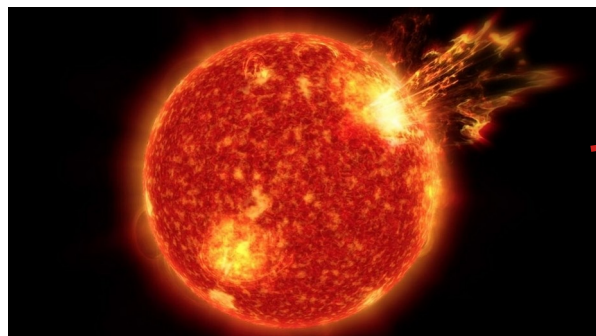


Sources

FLUXES OF COSMIC RAYS



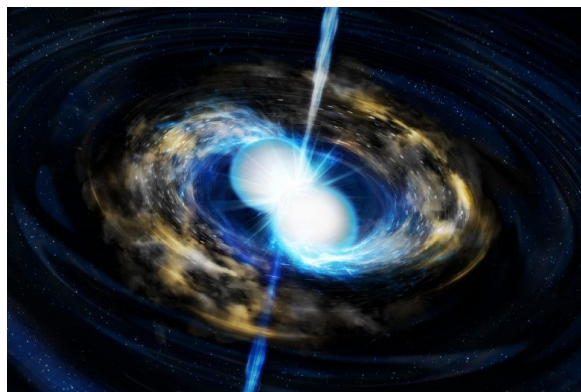
Sun – Corona Mass Ejection



Galactic – Supernovae



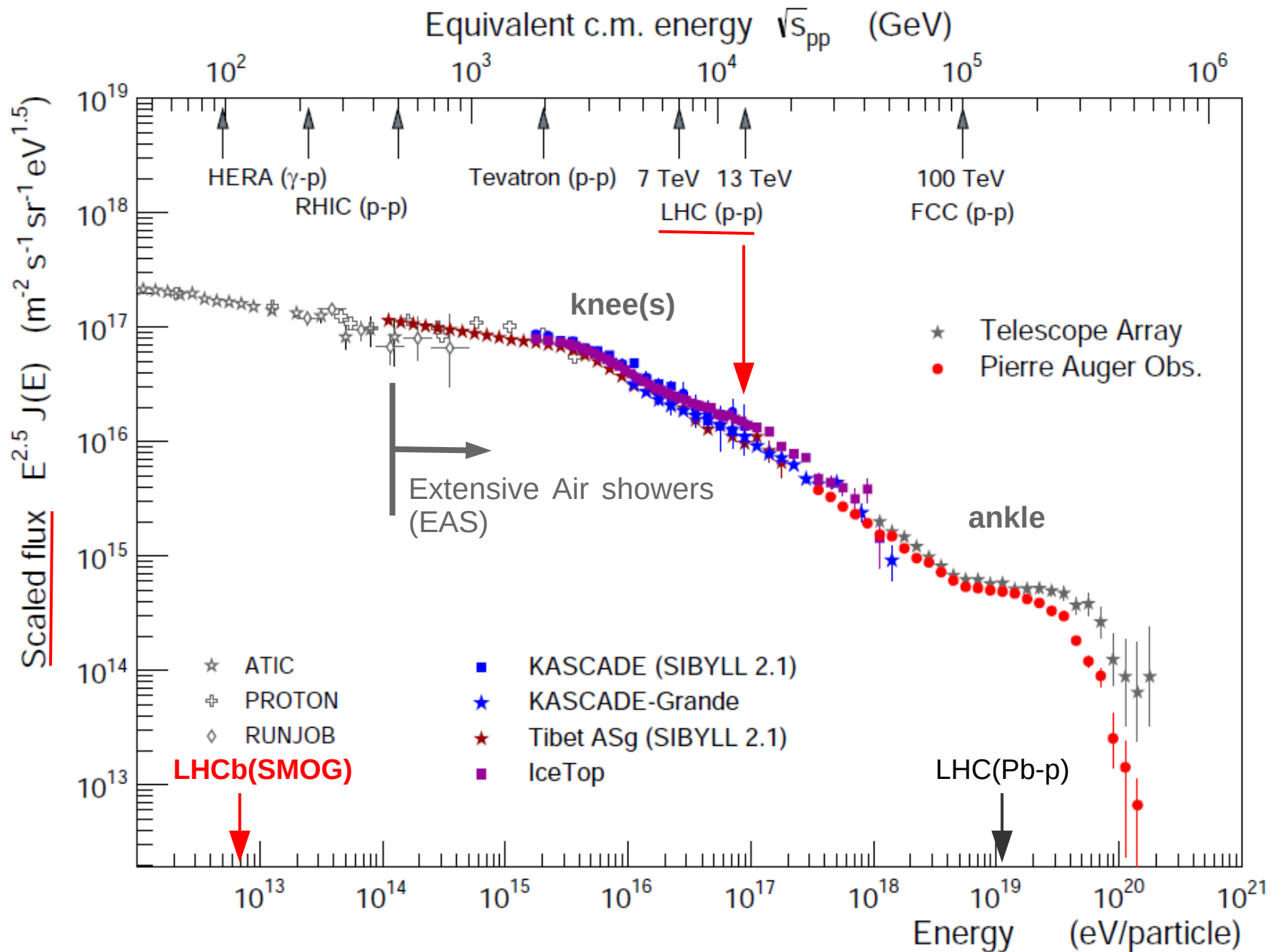
Extragalactic – Transient ?
(neutron star merger)



Extragalactic – constant ?
(Active Galactic Nuclei)



Energy Spectrum

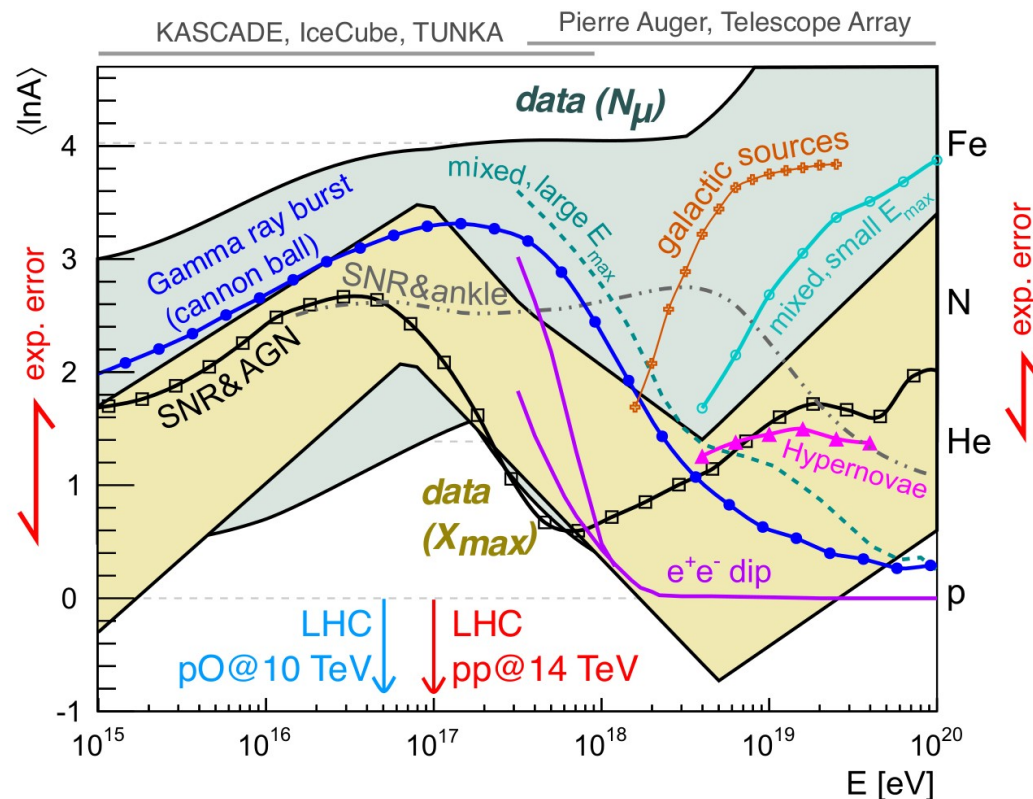


R. Engel (KIT)

UHECR Composition

With muons current CR data are impossible to interpret

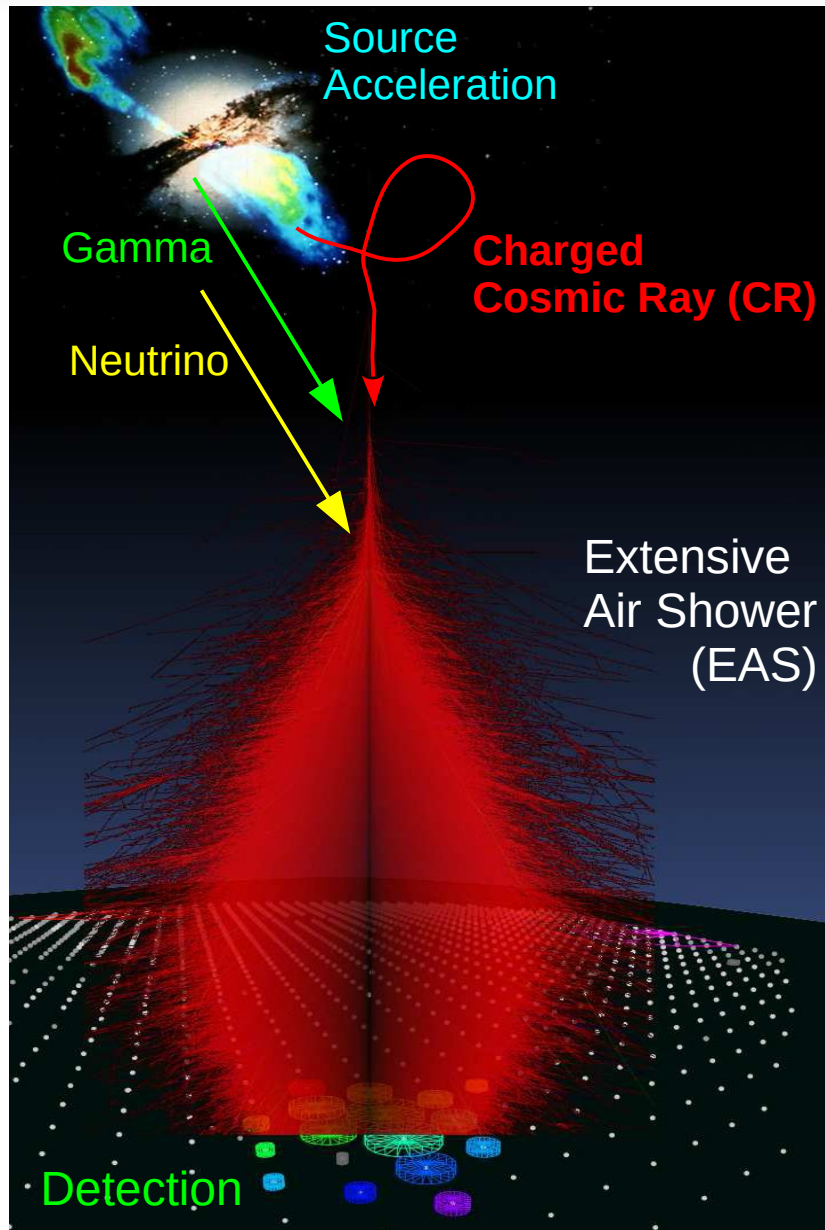
- ➔ Very large uncertainties in model predictions
- ➔ Mass from different element incompatible because of **soft QCD treatment**



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

H. Dembinski UHECR 2018 (WHISP working group)

Astroparticles

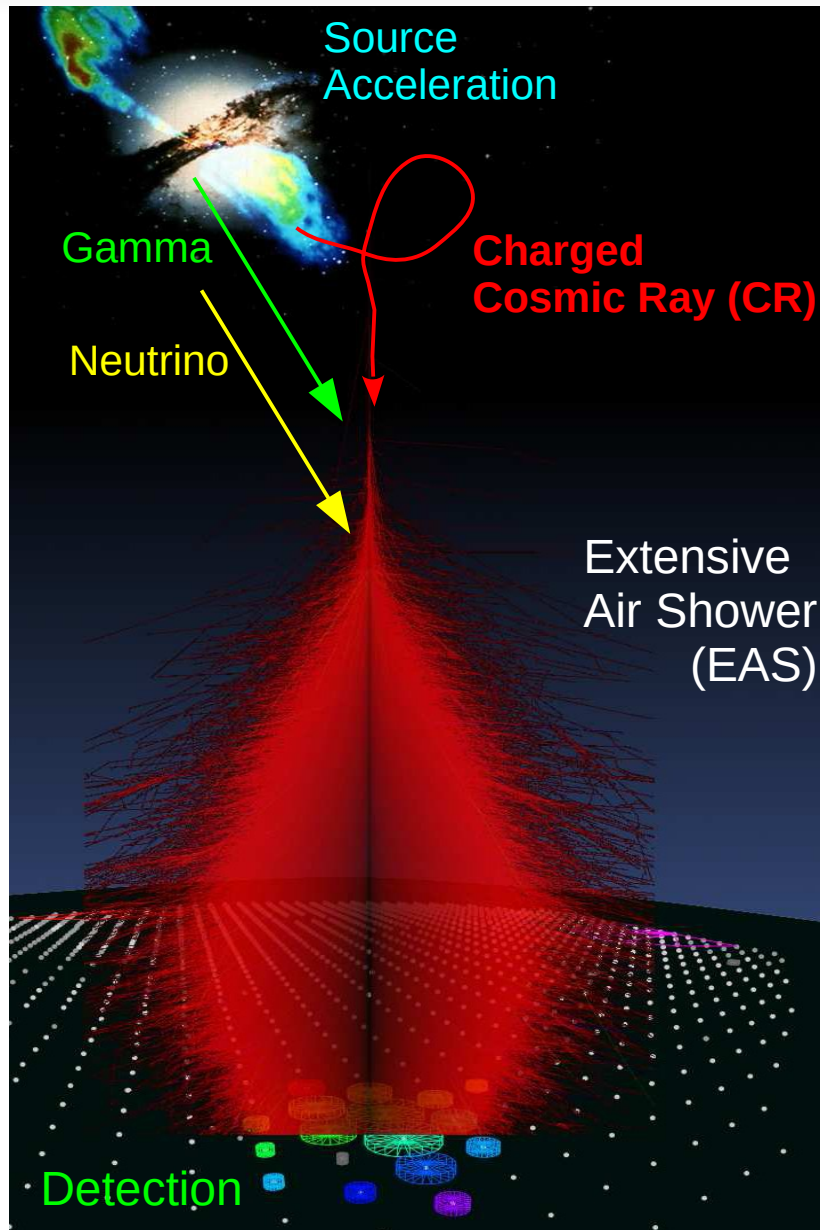


From R. Ulrich (KIT)

- **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

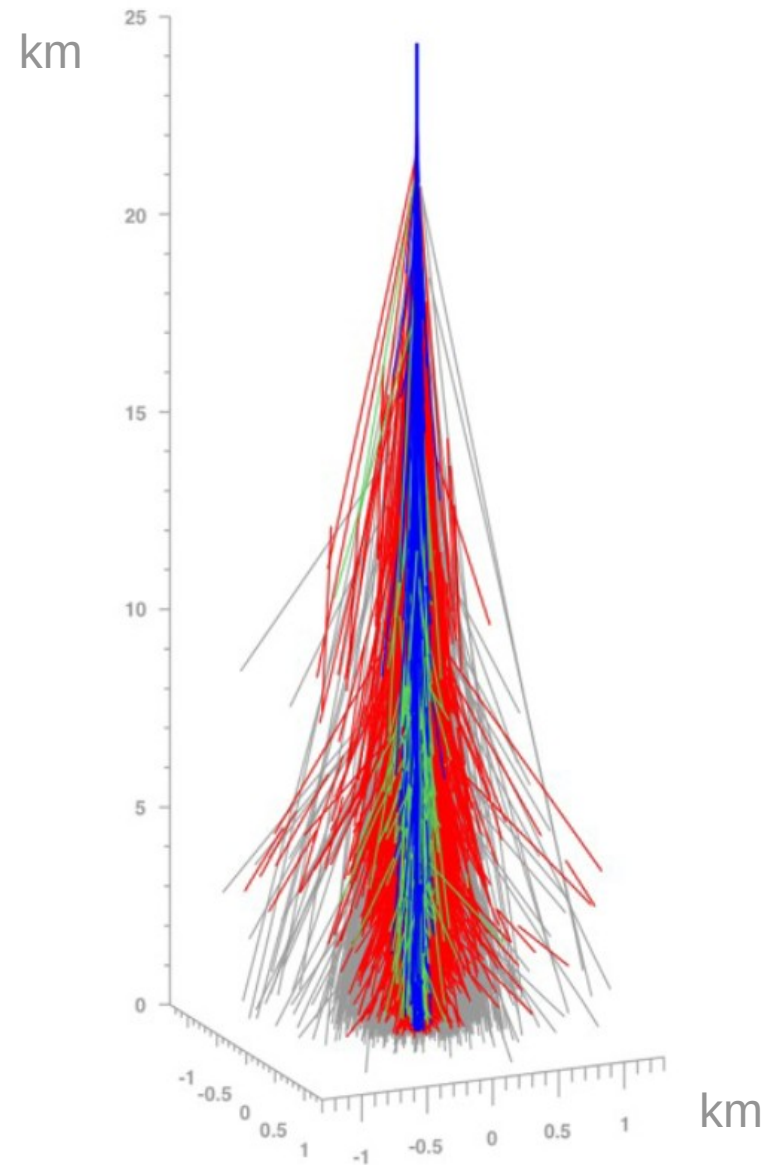
Astroparticles → Multimessenger



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.
- **Gravitational waves**
 - ➔ Source position
 - ➔ Source mass

(Extensive) Air Showers (EAS)



Extensive Air Shower

Hearth atmosphere used as a calorimeter

$A + air \rightarrow$ hadrons

$p + air \rightarrow$ hadrons

$\pi + air \rightarrow$ hadrons

main source of uncertainties

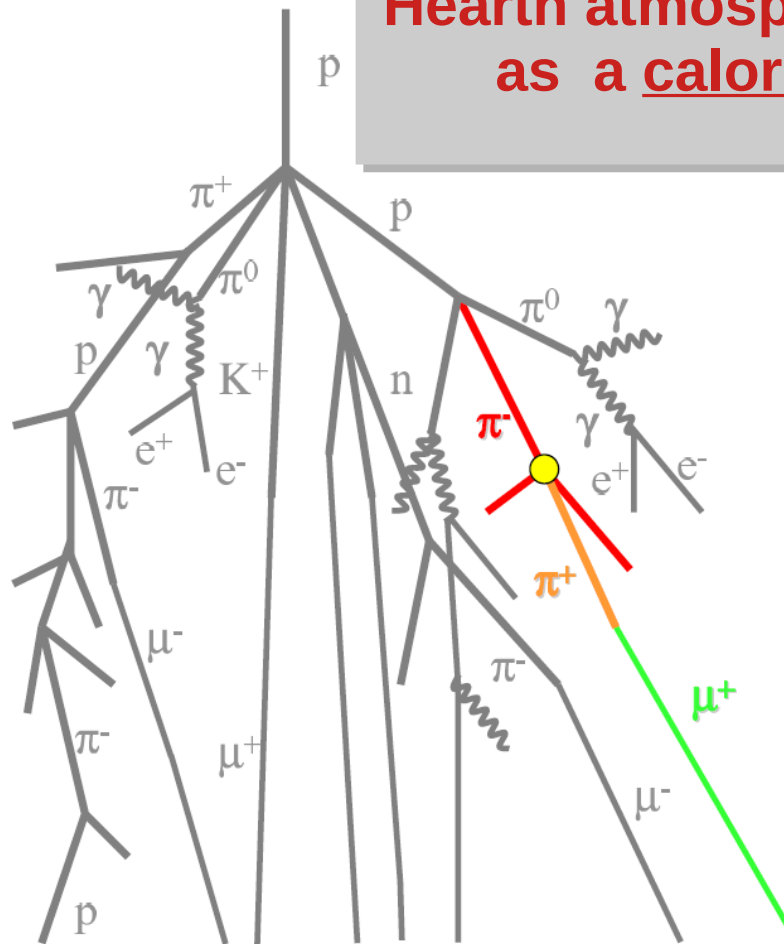
initial γ from π^0 decay

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

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

well known

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



Cascade of particle in Earth's atmosphere

Number of particles at maximum

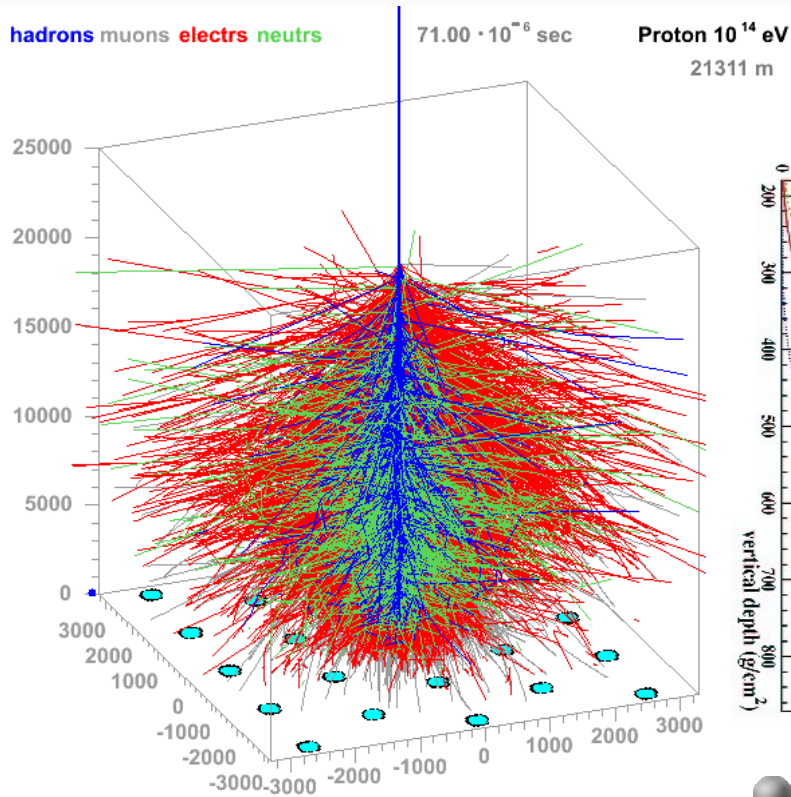
- ➔ 99,88% of electromagnetic (e/m) particles
- ➔ 0.1% of muons
- ➔ 0.02% hadrons

Energy

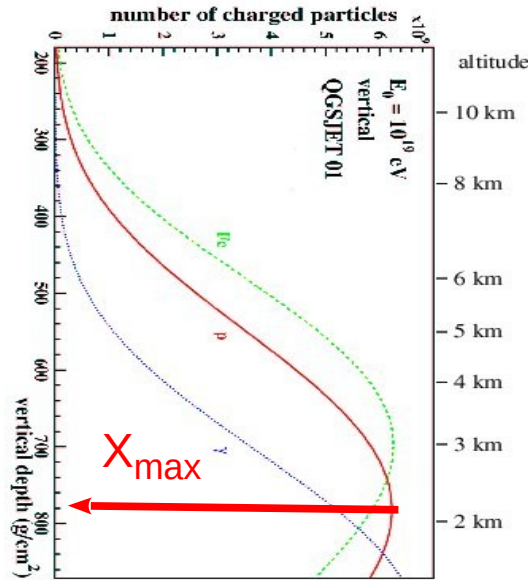
- ➔ from 100% hadronic to 90% in e/m + 10% in muons at ground (vertical)

From R. Ulrich (KIT)

Extensive Air Shower Observables



J.Oehlschlaeger,R.Engel,FZKarlsruhe



● Longitudinal Development

➔ number of particles vs depth

$$X = \int_h^\infty dz \rho(z) \quad (\text{Air density})$$

➔ Larger number of particles at X_{\max}

For many showers

◆ mean : $\langle X_{\max} \rangle$

◆ fluctuations : RMS X_{\max}

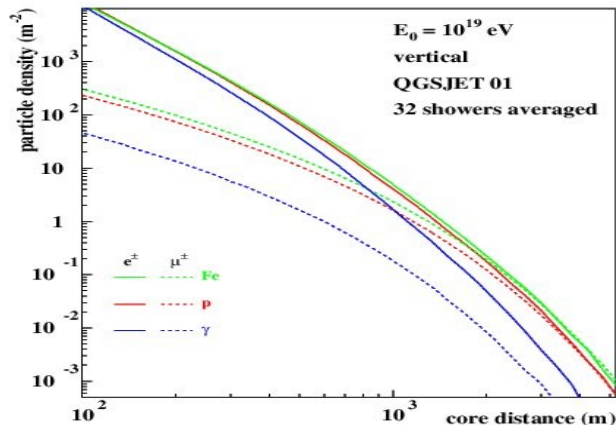
● Lateral development

➔ 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 ...



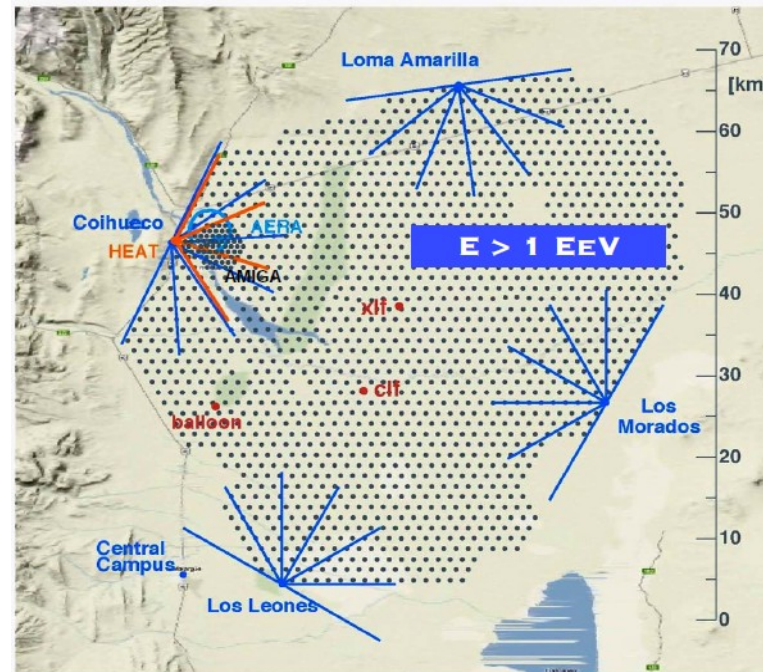
High Energy Measurements

- **Pierre Auger Observatory (PAO)**

- ➔ Mendoza, Argentina
- ➔ Southern Hemisphere
- ➔ 3000 km²: 32000 km²/sr/yr

- **Telescope Array (TA)**

- ➔ Utah, USA
- ➔ Northern Hemisphere
- ➔ 680 km²: 3700 km²/sr/yr



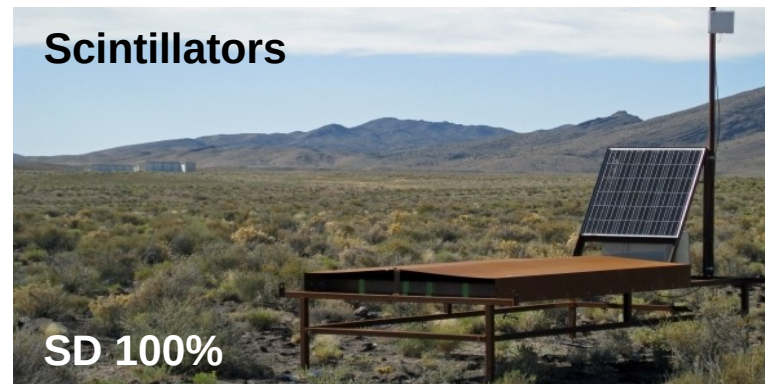
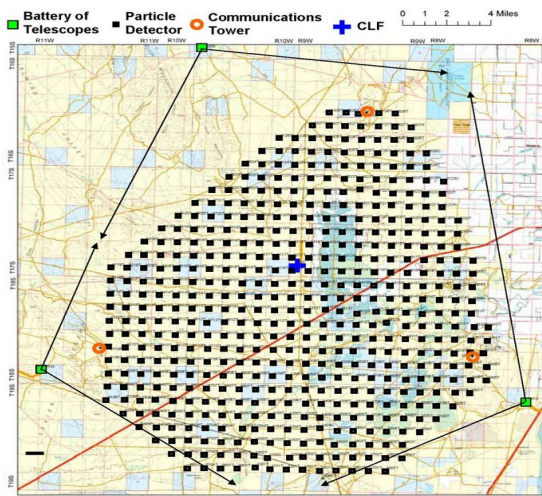
SURFACE DETECTOR ARRAY
 1600 WATER-CHERENKOV STATIONS
 1500 M SPACING
 3000 KM²

100% SD-1500 m

4 FLUORESCENCE DETECTORS
 24 TELESCOPES
 FOV 1-30°

FD 15%

ATMOSPHERIC MONITORING
 LASERS AND LIDARS



Low Energy Measurements (some)

Kascade (Germany)



LHAASO (China)



Grapes 3 (India)

IceTop (above IceCube)



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 for Cosmic Rays

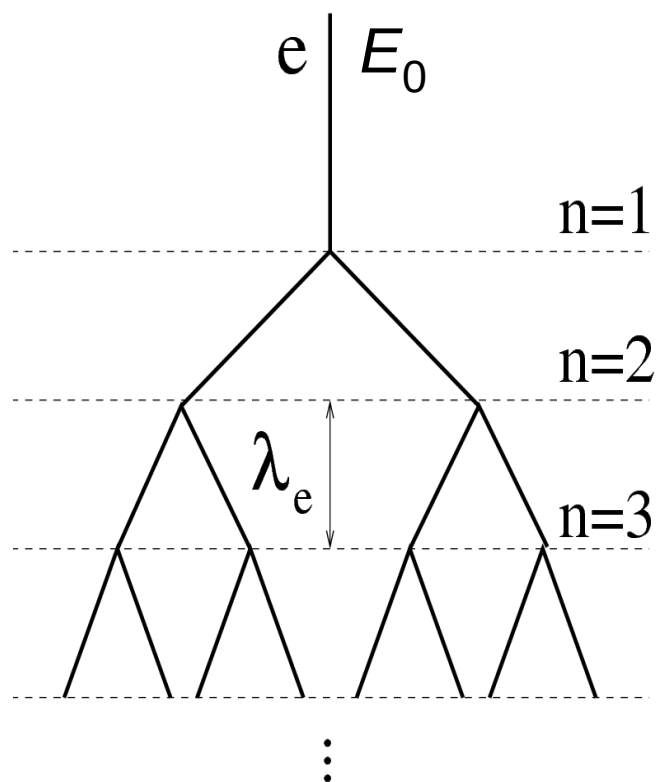
Toy Model for Electromagnetic Cascade

Primary particle :
photon/electron

Heitler toy model :

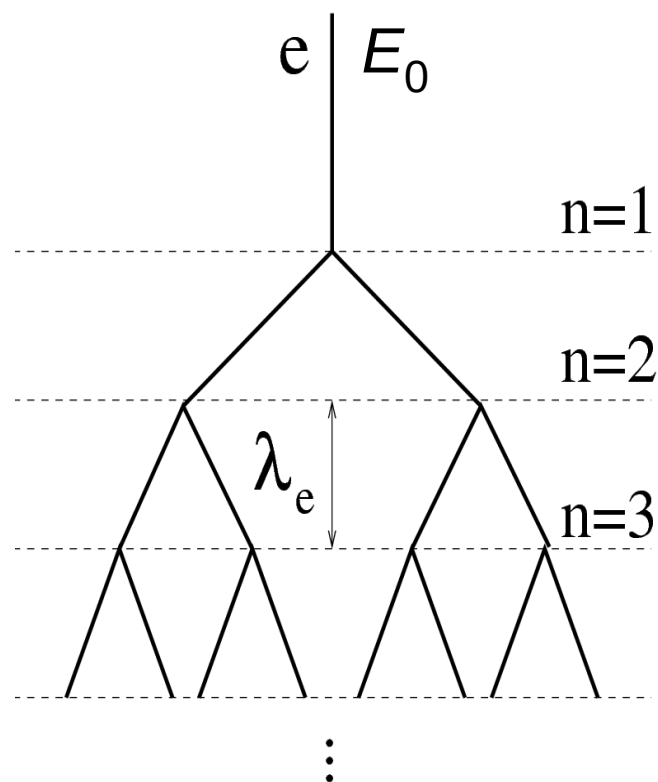
→ 2 particles produced with equal energy

→ electromagnetic interaction length (37g/cm^2) : λ_e



Toy Model for Electromagnetic Cascade

Primary particle :
photon/electron



Heitler toy model :

→ 2 particles produced with equal energy

→ electromagnetic interaction length (37g/cm^2) : λ_e

2^n particles after
 n interactions

$$n = X/\lambda_e$$

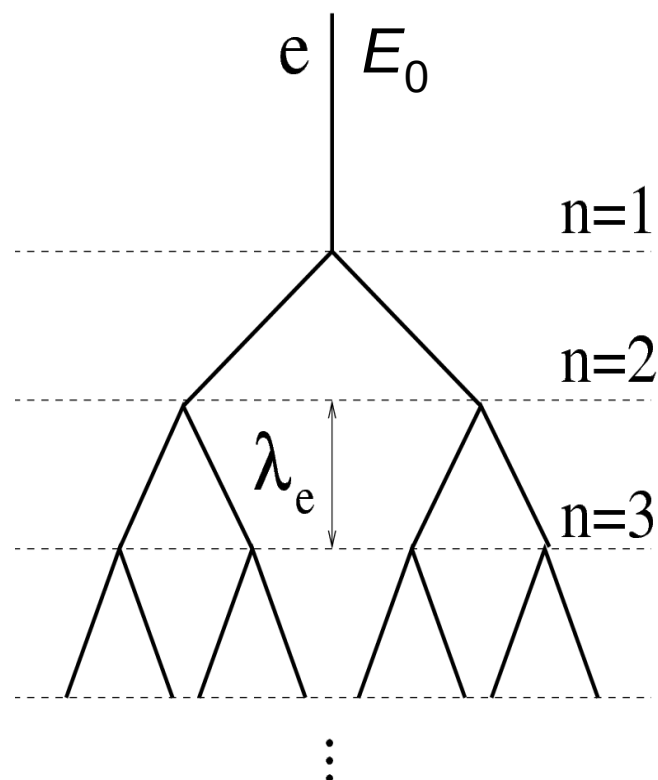
$$N(X) = 2^n = 2^{X/\lambda_e}$$

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

Assumption: shower maximum reached if $E(X) = \underline{E_c}$ (critical energy)

Toy Model for Electromagnetic Cascade

Primary particle :
photon/electron



Heitler toy model :

→ 2 particles produced with equal energy

→ electromagnetic interaction length (37g/cm^2) : λ_e

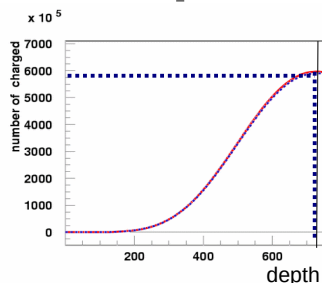
2^n particles after
 n interactions

$$n = X/\lambda_e$$

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

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

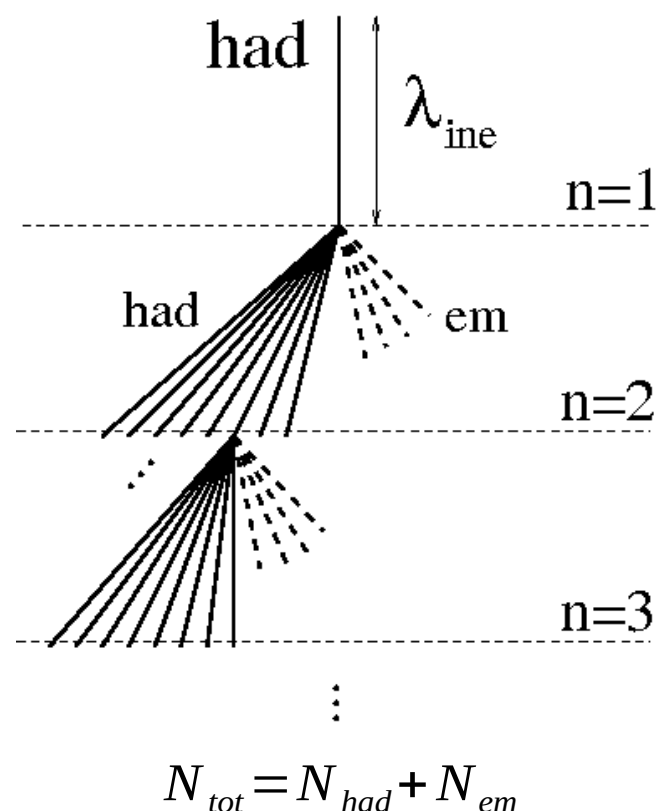
Assumption: shower maximum reached if $E(X) = \underline{E_c}$ (critical energy)



$$N_{\max} = E_0/E_c$$

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

Toy Model for Hadronic Cascade



Primary particle :
hadron

Using a simple generalized Heitler model to understand EAS characteristics :

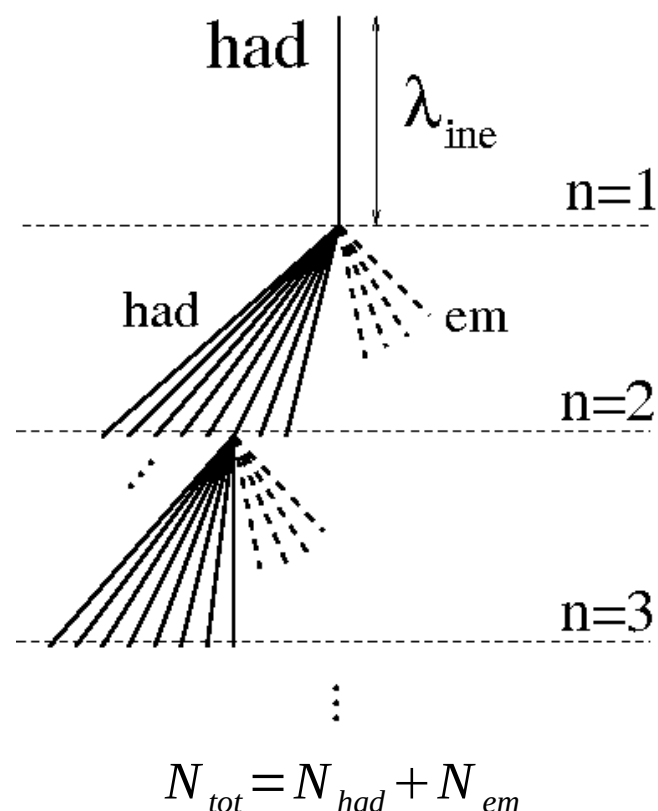
- ➔ fixed interaction length
- ➔ equally shared energy
- ➔ 2 types of particles :

$$\lambda_{ine} = \langle Air \rangle / (A \cdot \sigma_{ine})$$

- 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

Toy Model for Hadronic Cascade



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

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

Primary particle :
hadron

Using a simple generalized Heitler model to understand EAS characteristics :

- ➔ fixed interaction length
- ➔ equally shared energy
- ➔ 2 types of particles :

$$\lambda_{ine} = \langle Air \rangle / (A \cdot \sigma_{ine})$$

- 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

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

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

Superposition Model

- Primary nucleus with mass A and energy E

→ equivalent to A proton showers with energy E/A

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

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

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

Multiplicity evolution

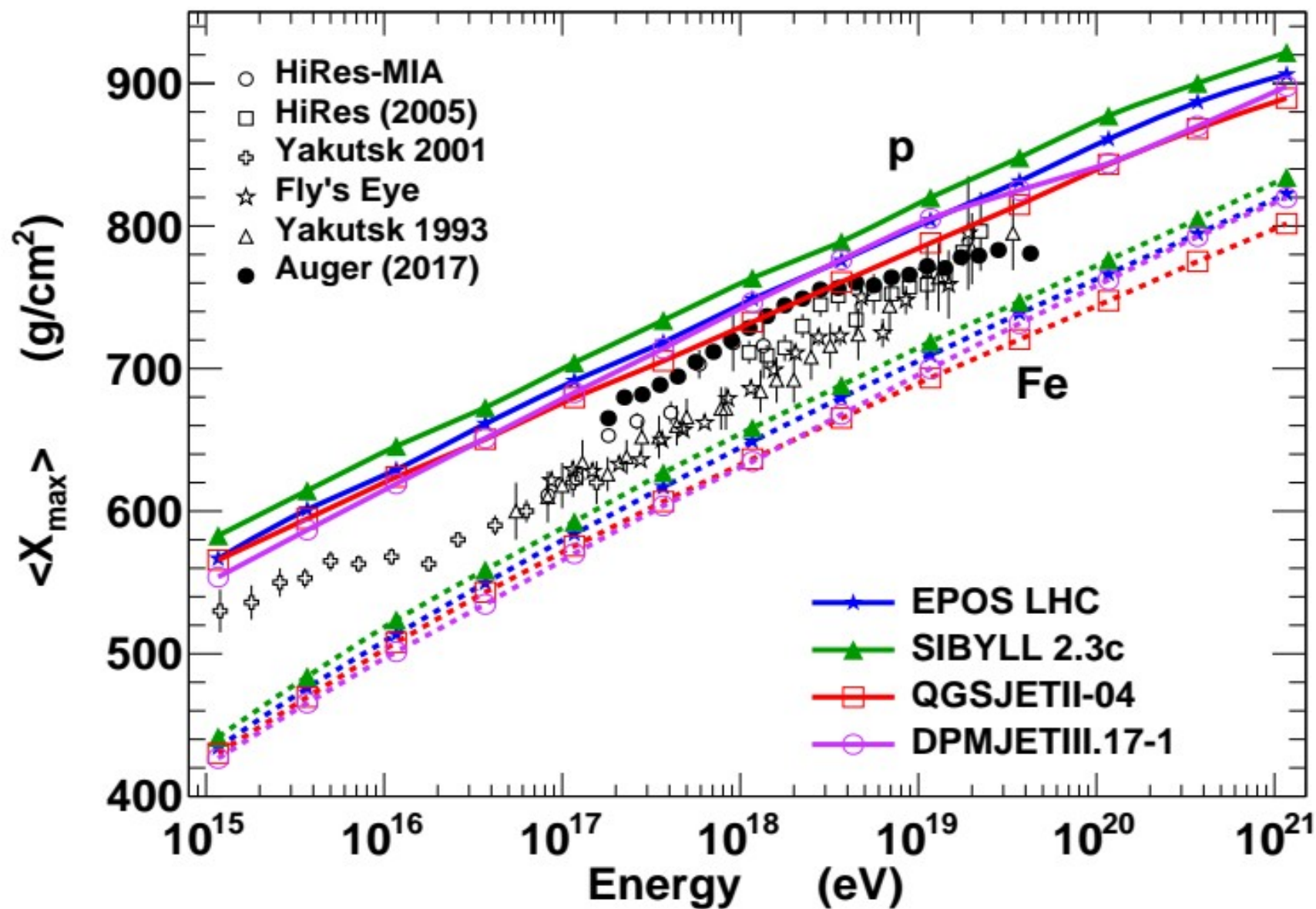
$$B_N = \frac{d \ln N_{\text{tot}}}{d \ln(E)} \sim \text{cst} > 0$$

Cross-section evolution

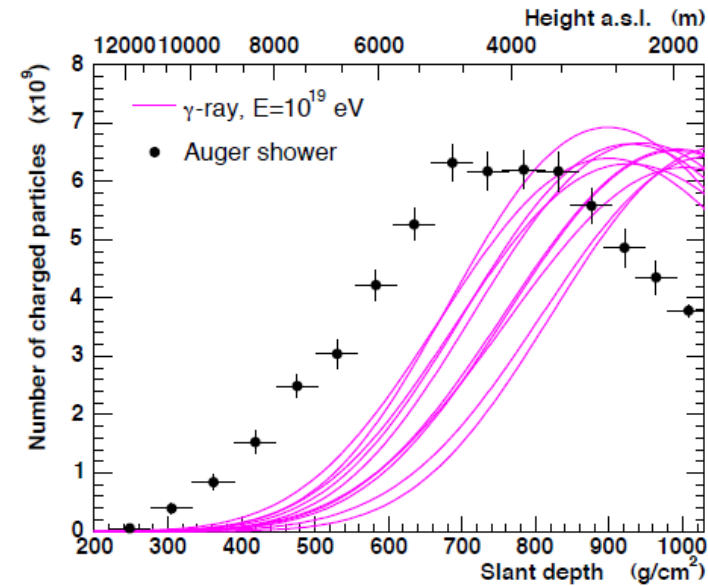
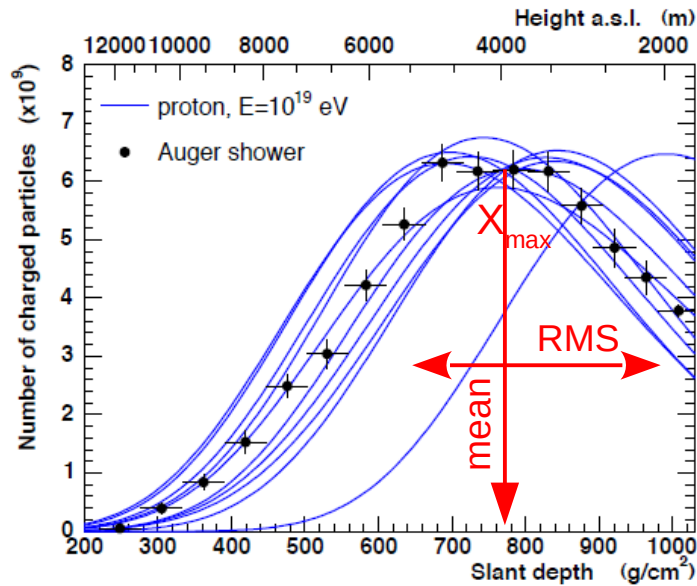
$$B_\lambda = \frac{-\lambda_{\text{ine}}}{\lambda_e} \frac{d \ln \lambda_{\text{ine}}}{d \ln(E)} \sim \text{cst} > 0$$

Mass evolution

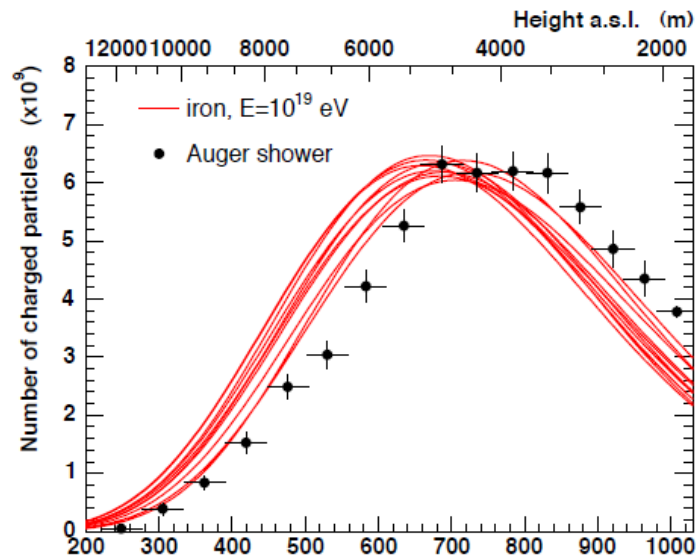
$$B_A = \frac{d \ln A}{d \ln(E)}$$

EAS : $\langle X_{\max} \rangle$ 

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

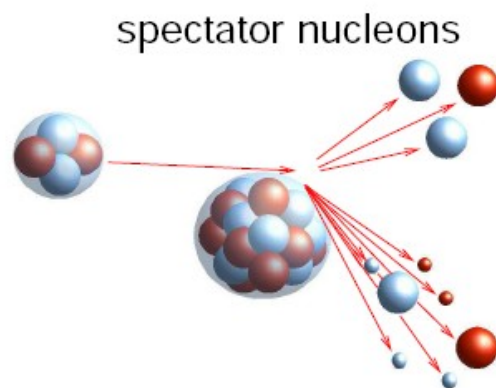
◆ mean:

$$\mu_X(A, E) \approx \mu_X(p, E/A) (!)$$

◆ fluctuations:

$$\sigma_X(A) \gg \frac{1}{\sqrt{A}} \sigma_X(p)$$

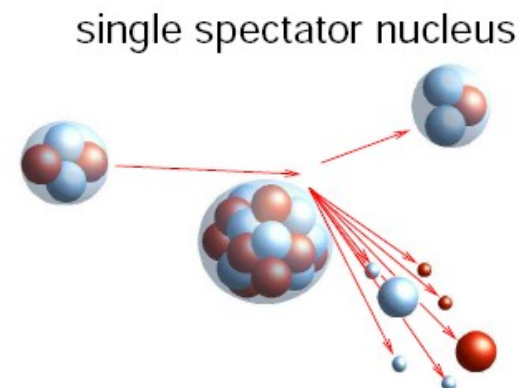
● Extreme cases :



$$s_X(A)$$

Full fragmentation

$$< \sigma_X(A) <$$



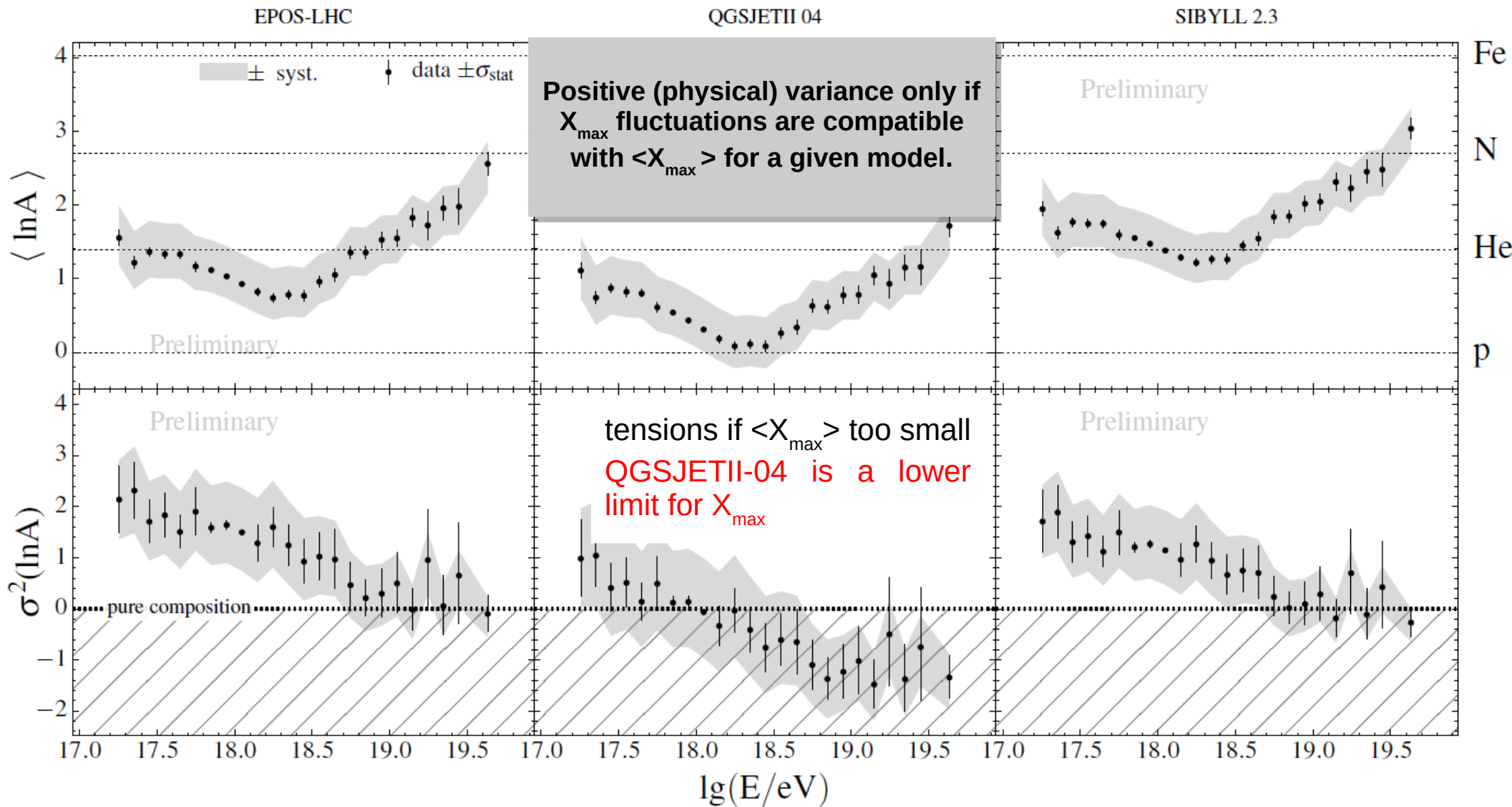
$$S_X(A)$$

No fragmentation

Model Consistency using Electromagnetic Component

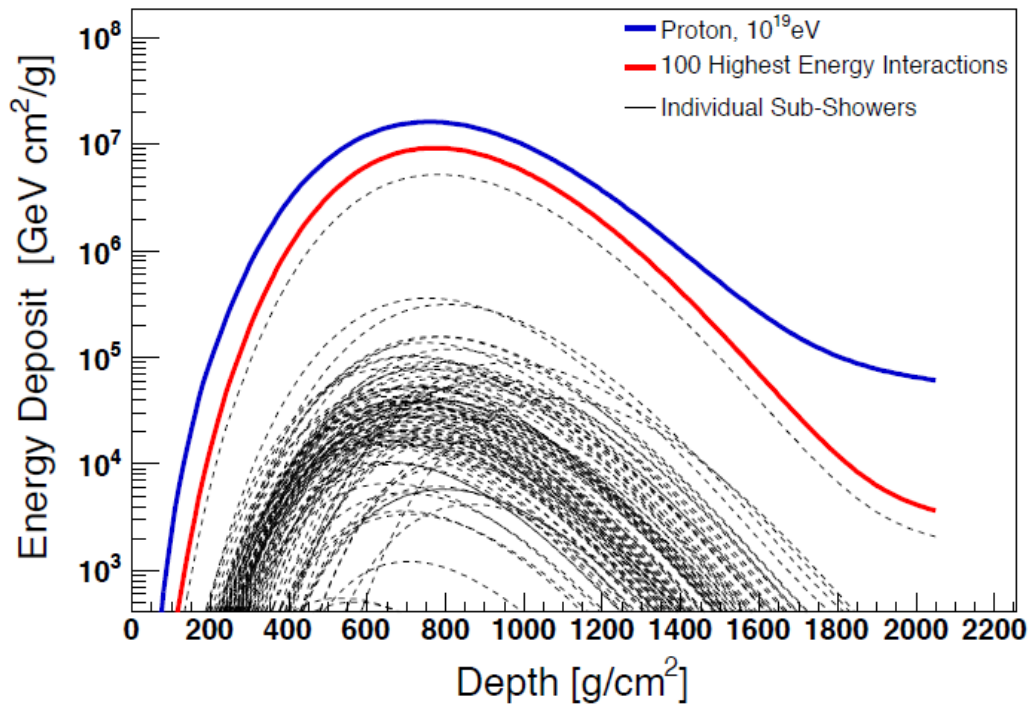
Study by Pierre Auger Collaboration (ICRC 2017)

➔ std deviation of $\ln A$ allows to test model consistency.



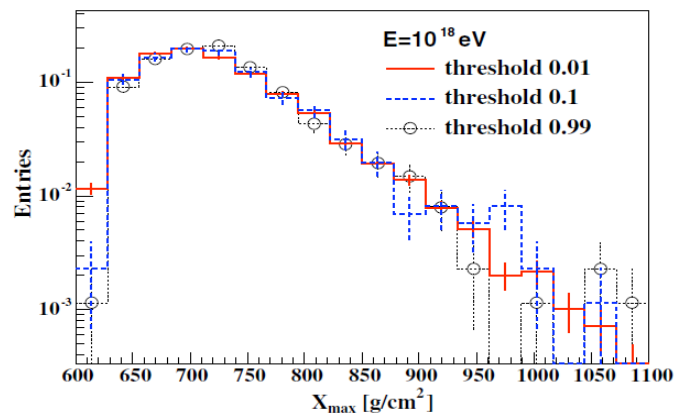
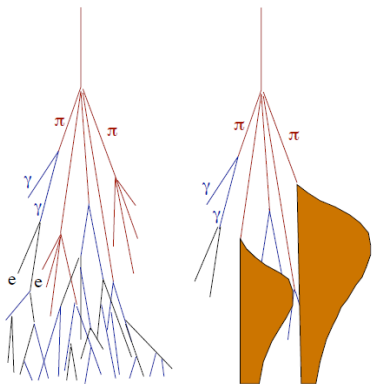
Energy of hadronic interactions for X_{\max}

Electrons



Shower particles produced in 100 interactions of highest energy

Electrons/photons:
high-energy interactions



Fluctuations mainly coming from the first hadronic interaction.

Energy Transfer : Energy Deposit

Energy of all hadrons

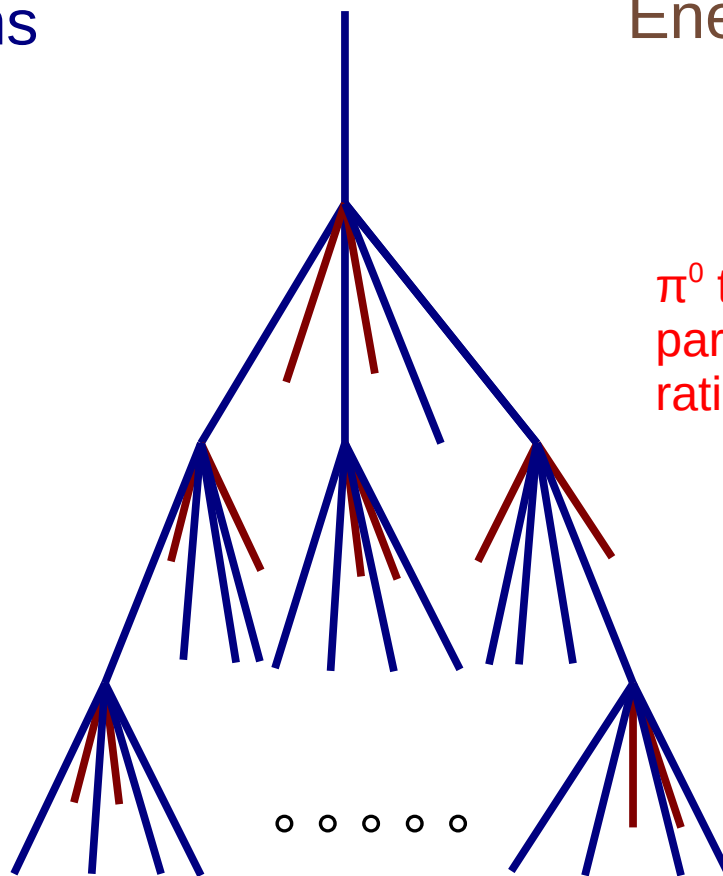
$$E_0$$

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

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

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 $\rightarrow \frac{1}{3} E_0$

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

Energy in em. $\sim 90\%$

($n=5$, $E_{had} \sim 12\%$
 $n=6$, $E_{had} \sim 8\%$)

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

Real Energy Deposit

● Ionization process :

➔ all charged particles : all energy loss converted to energy deposit

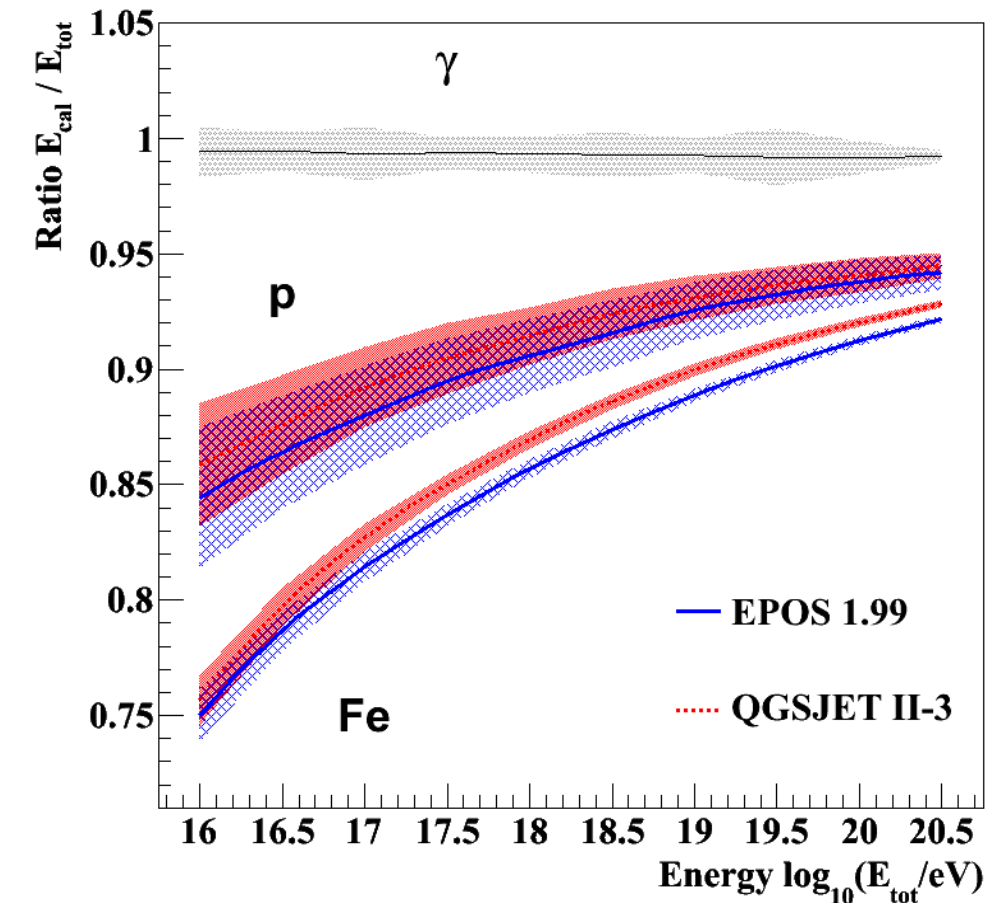
➔ Energy deposit proportional to total number of charged particles

● Particle below threshold

➔ all particles (but neutrinos) : part of particle energy converted to energy deposit

- for EM particles : all energy is deposited
- for muons : part of the energy is deposited (neutrino)
- 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

Energy Deposit



● Average value used

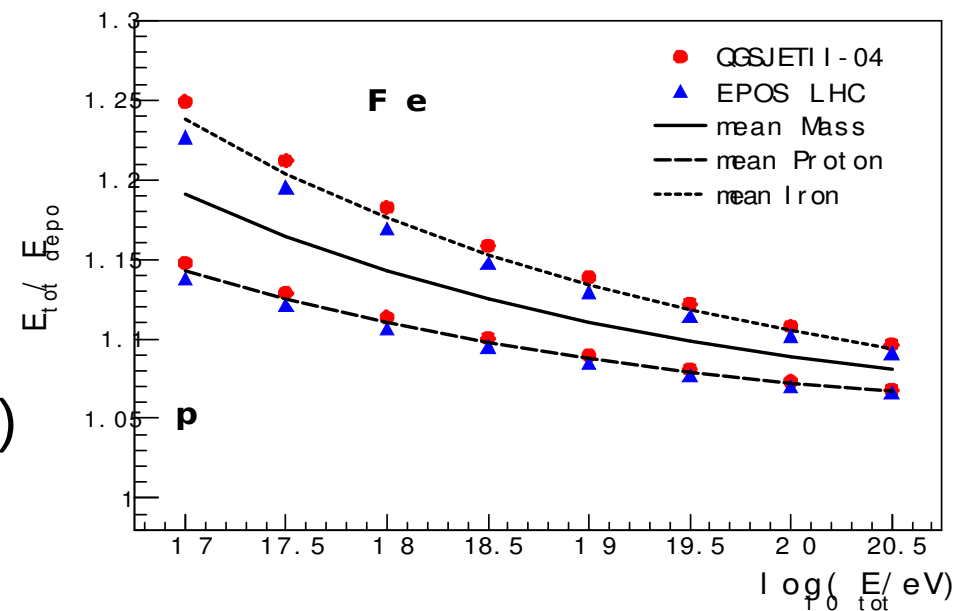
- ➔ Small error due to models (~1-2%)
- ➔ Main uncertainty from unknown mass (~5-2%)

● From Heitler model

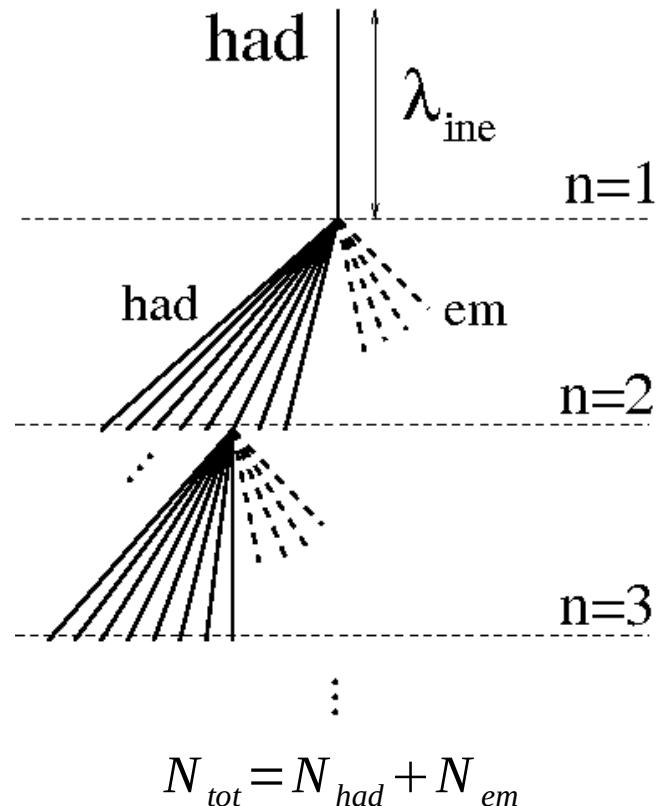
$$E_{em} = \left[1 - \left(\frac{N_{em}}{N_{tot}} \right)^{n(A)} \right] E_0$$

● Energy deposit depends on total number of muons

- ➔ Primary mass dependent
- ➔ Hadronic model dependent



Toy Model for Hadronic Cascade



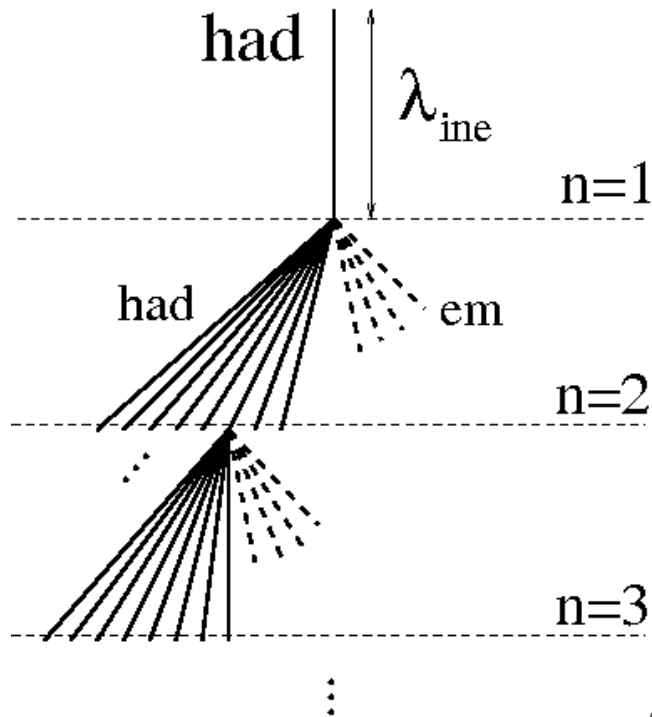
J. Matthews, *Astropart.Phys.*
22 (2005) 387-397

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

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

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

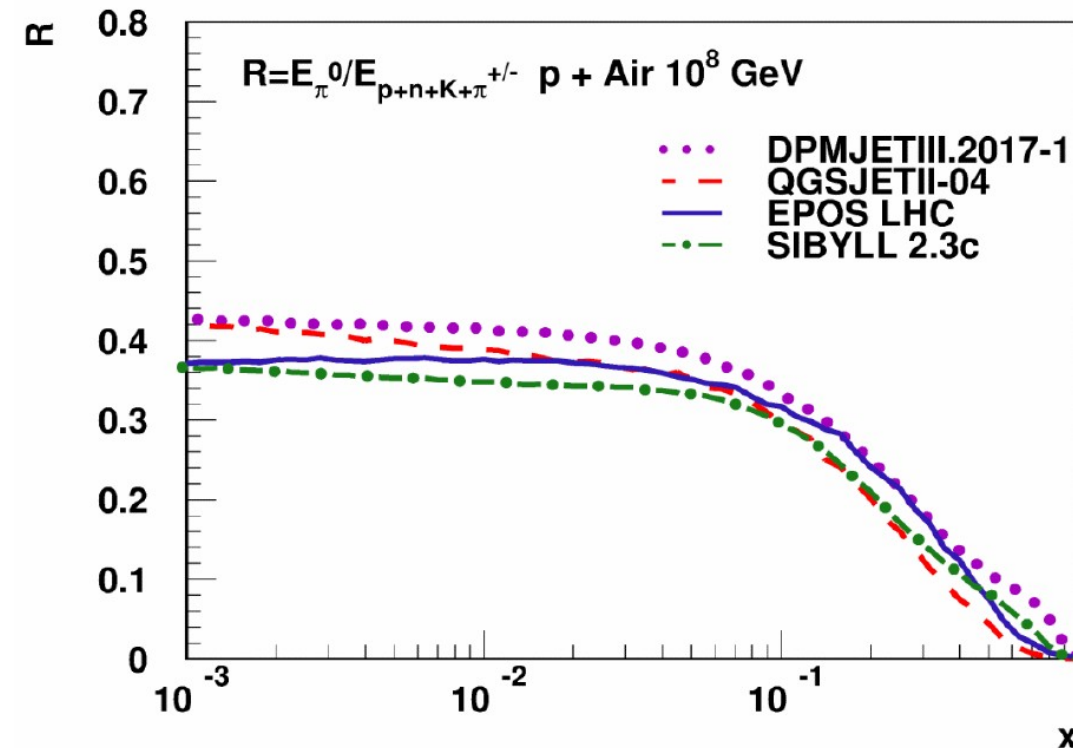
$$\ln(N_{\mu}) = \ln(N(n_{max})) = n_{max} \ln(N_{had})$$

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 less ...)



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

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

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

Very important :

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

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

Superposition Model

- Primary nucleus with mass A and energy E

→ equivalent to A proton showers with energy E/A

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

- More muons from primary nucleus

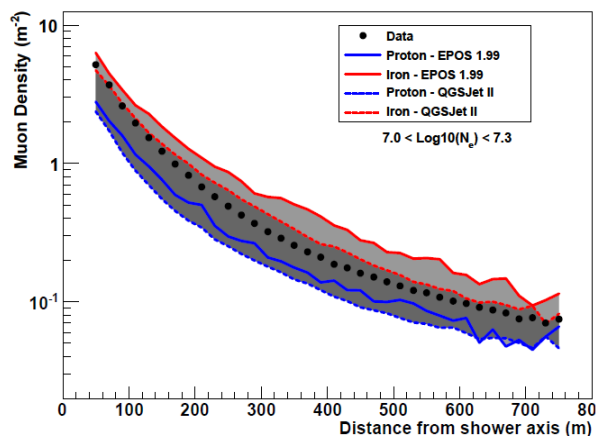
$$N_{\mu}(A) = N_{\mu}(p) A^{1-\beta}$$

Particles at Ground

● 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
- ➔ Muons suffer little attenuation and less fluctuations.

➔ Only muons at large distances and for very inclined showers



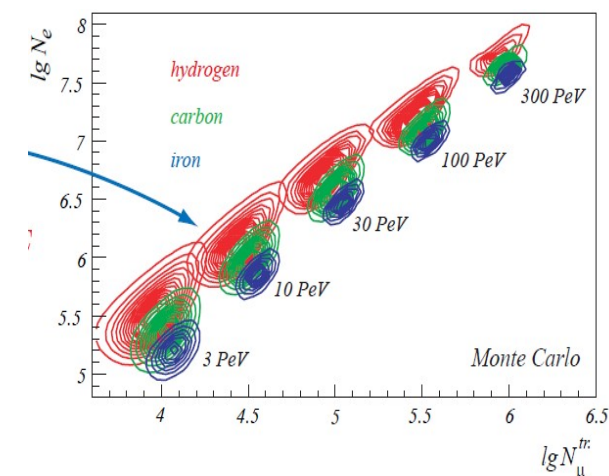
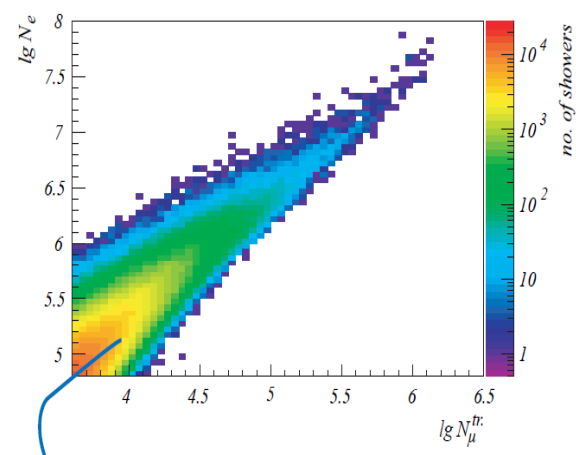
● LDF different for different particles and primary masses

- ➔ different production height and attenuation

KASCADE-GRANDE

● Utilize correlations between N_e and N_{μ} to determine the mass spectra

- ➔ Correlations increase discrimination power

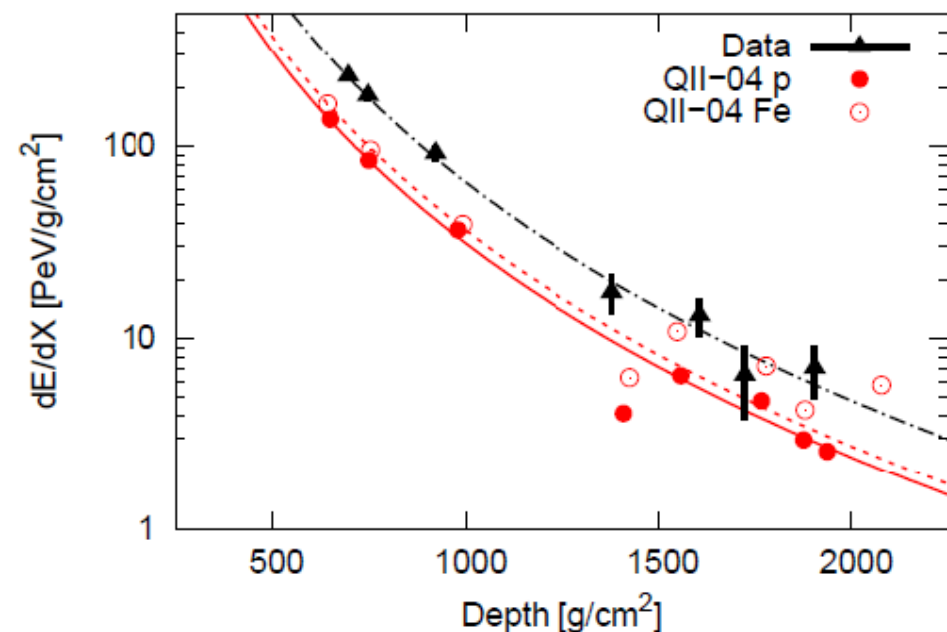
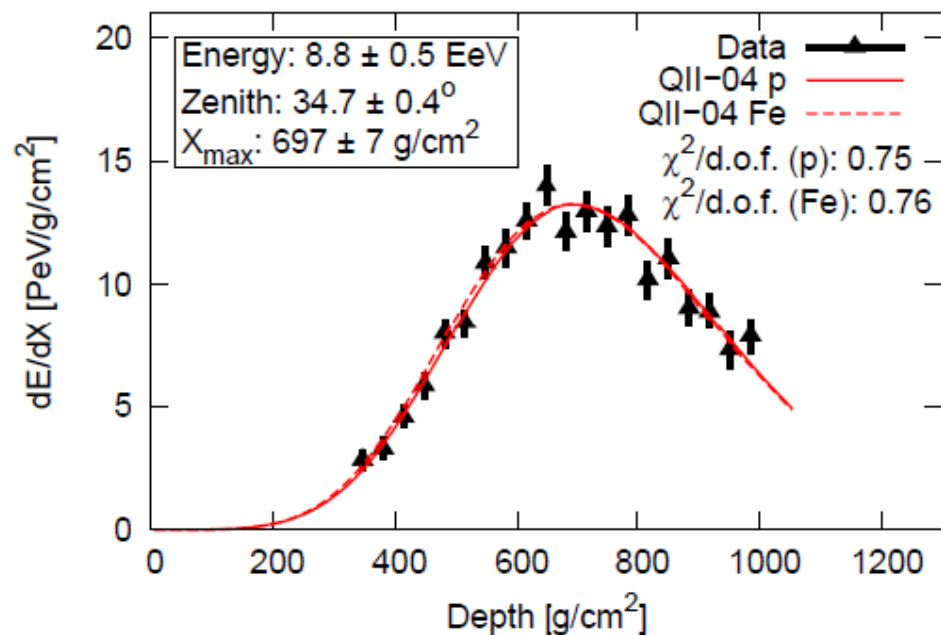


Auger Event-by-Event $E \sim 10^{19}$ eV

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 !



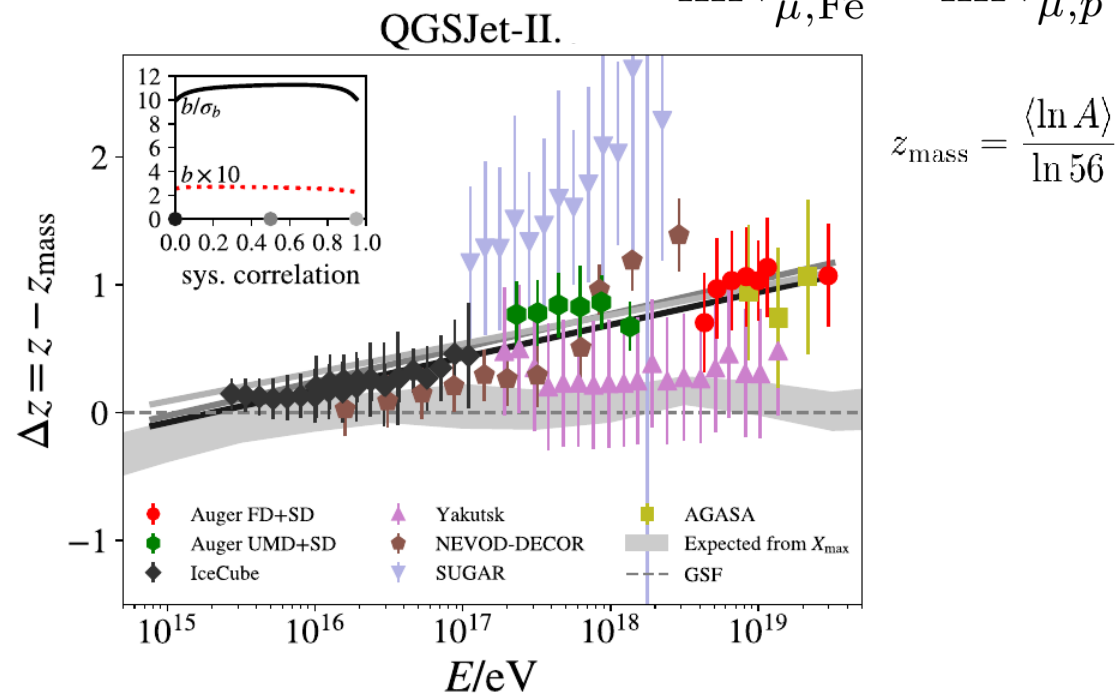
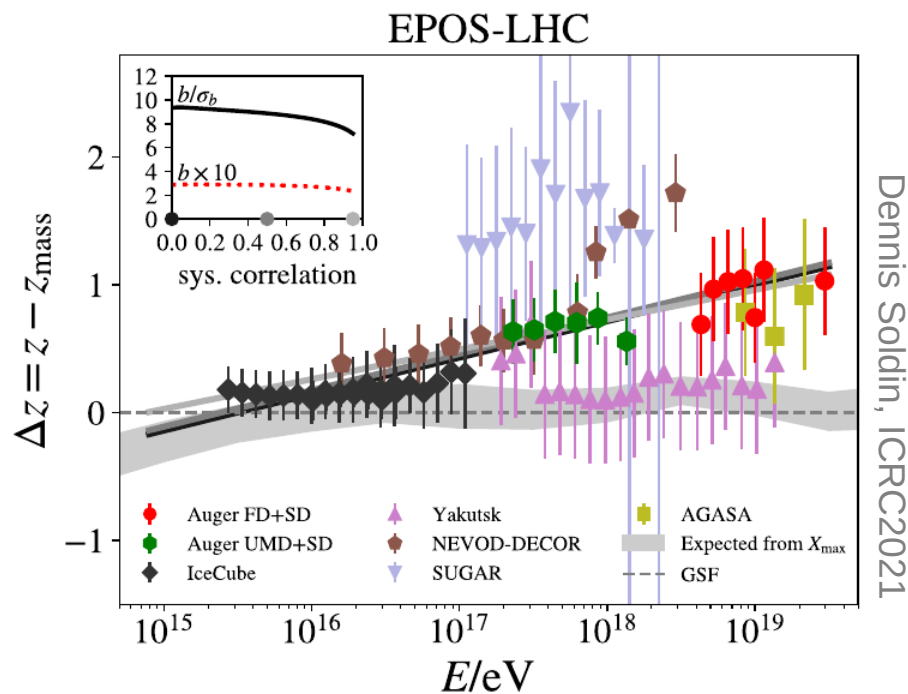
Muon "Puzzle"

● Clear muon excess in data compared to simulation

➔ Different energy evolution between data and simulations

➔ Significant non-zero slope ($>7\sigma$)

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



● 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 $\sim +4\%$

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

- To reduce muon discrepancy β has to be change

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

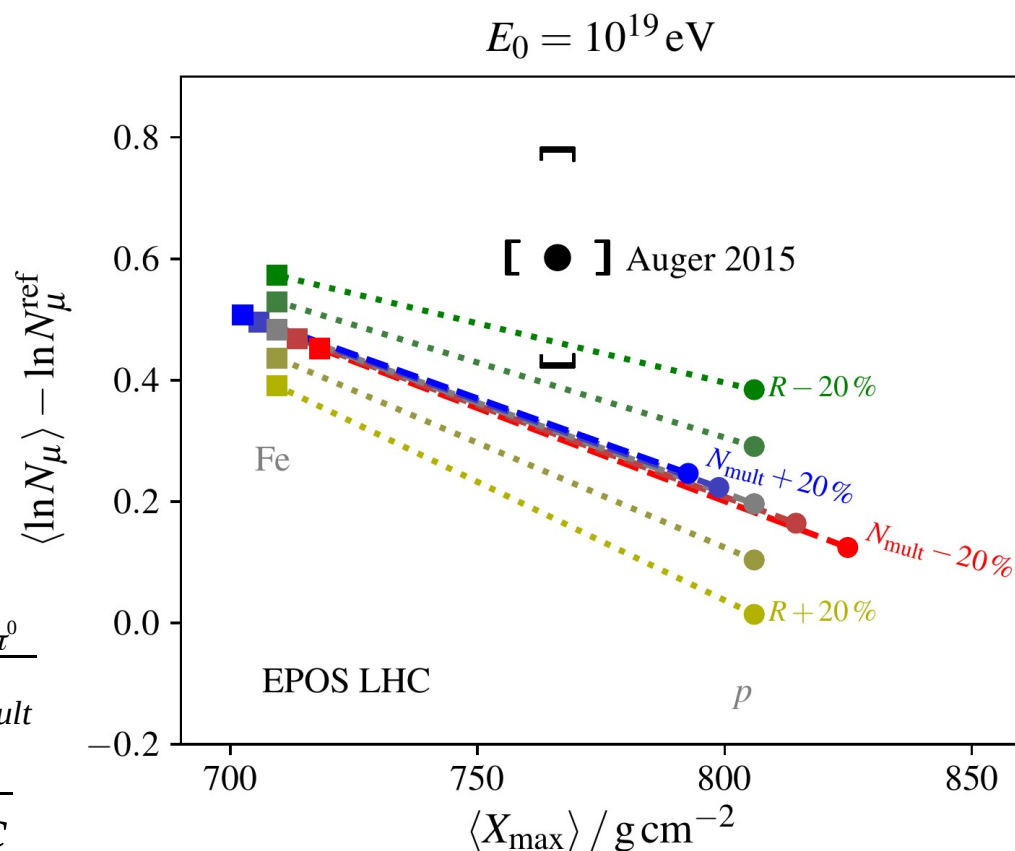
→ X_{\max} alone (composition) will not change the energy evolution

→ β changes the muon energy evolution but not X_{\max}

$$\beta = \frac{\ln(N_{\text{mult}} - N_{\pi^0})}{\ln(N_{\text{mult}})} = 1 + \frac{\ln(1-c)}{\ln(N_{\text{mult}})}$$

→ $+4\%$ for β → -30% for $c = \frac{N_{\pi^0}}{N_{\text{mult}}}$

→ Measure@LHC: $R = \frac{E_{e/m}}{E_{\text{had}}} \approx \frac{c}{1-c}$



Muon Production Depth

Independent SD mass composition measurement

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

$$c \cdot t_g = l - (z - \Delta)$$

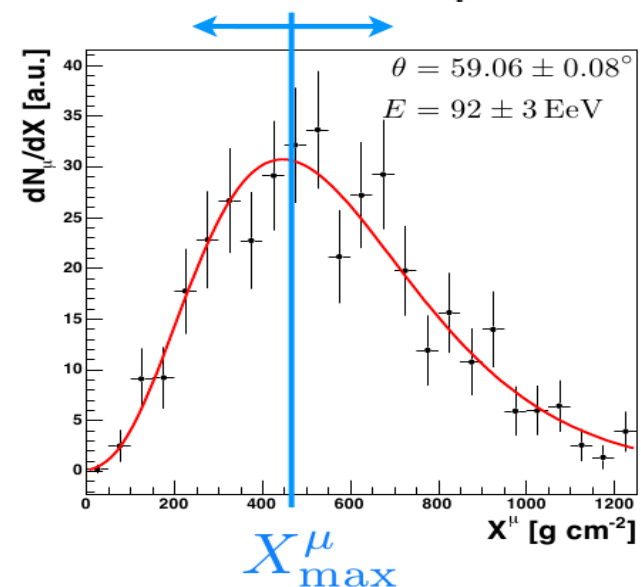
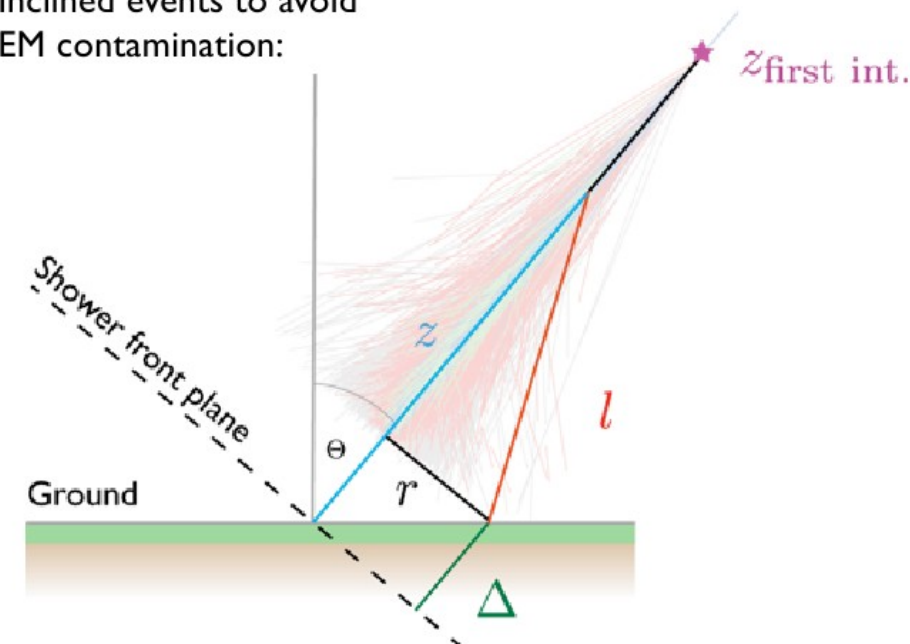
$$= \sqrt{r^2 + (z - \Delta)^2} - (z - \Delta)$$

- ➔ 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 X_{\max} (do not depend only on the first interactions)
 - Very sensitive to hadronic interactions (all generations)

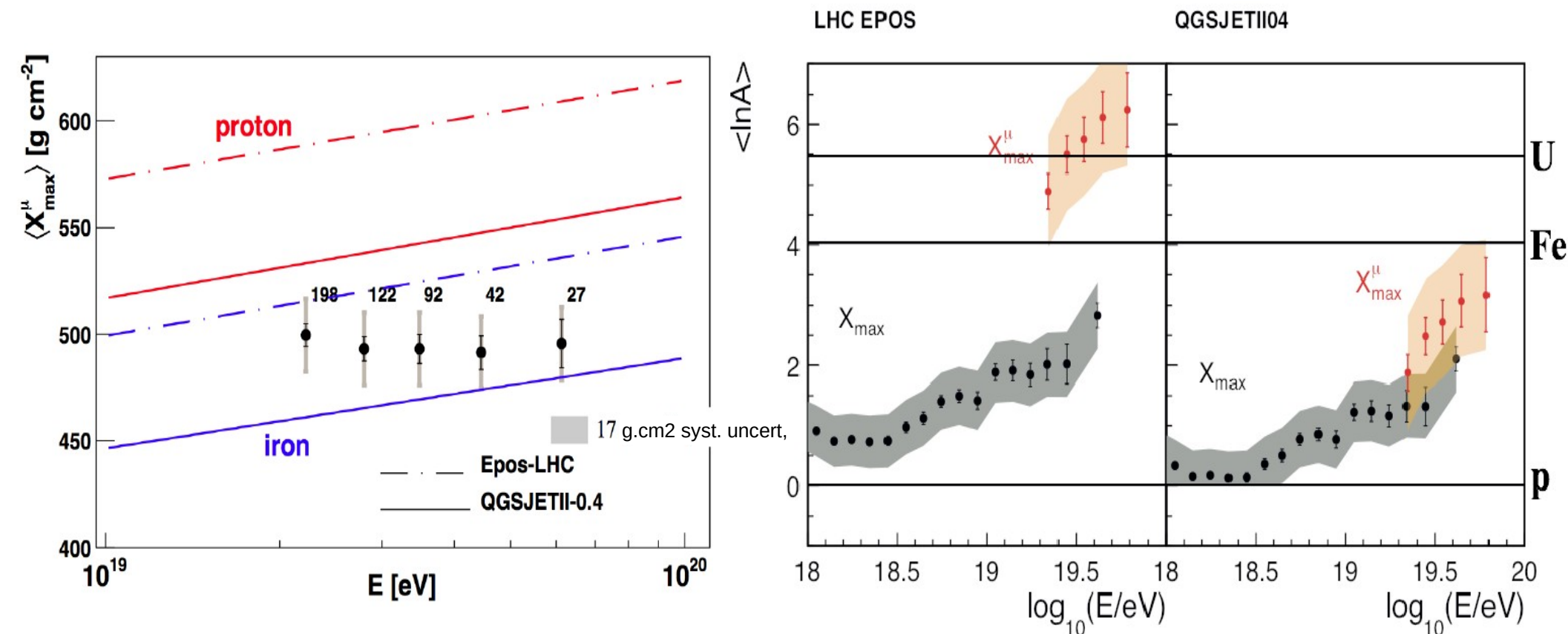
Inclined events to avoid EM contamination:



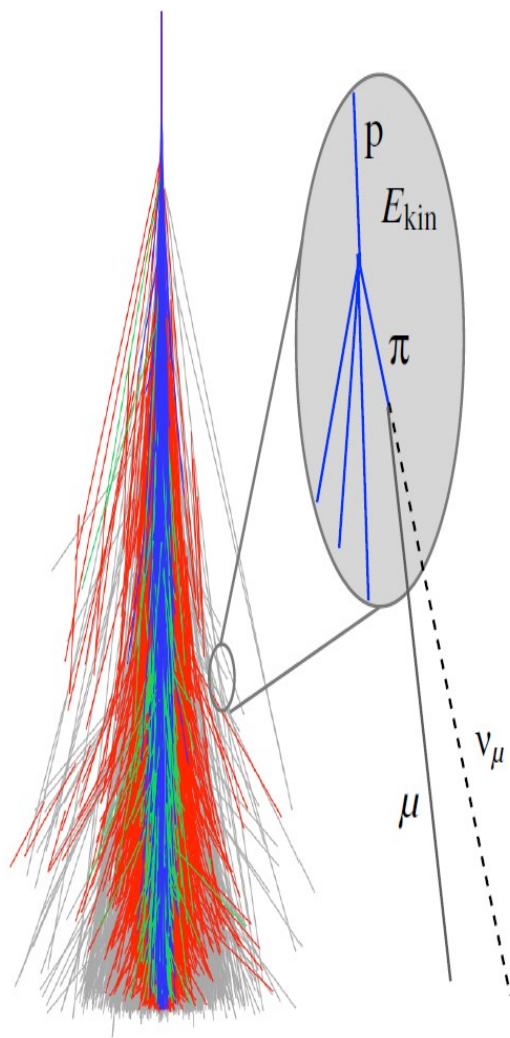
Muon Production Depth and Models

2 independent mass composition measurements

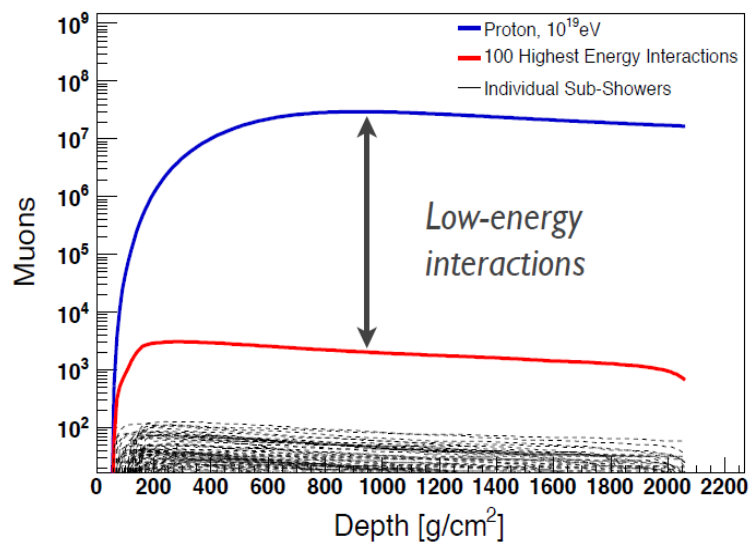
- ➔ both results should be between p and Fe
- ➔ both results should give the same mean logarithmic mass for the same model
- ➔ problem with EPOS appears after corrections motivated by LHC data



Muon production by low energy interactions

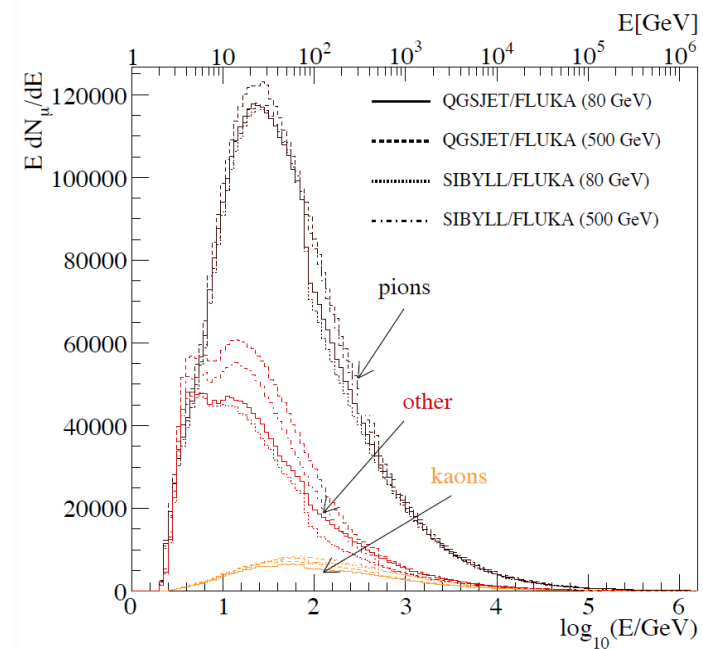
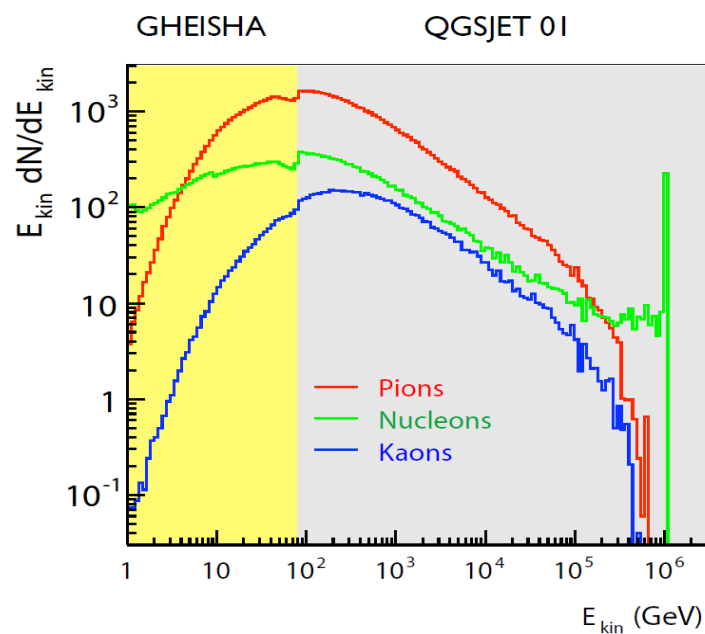


Muons



~ 100 GeV for KASCADE
~ 30 GeV for Auger

Muons/hadrons:
low-energy interactions



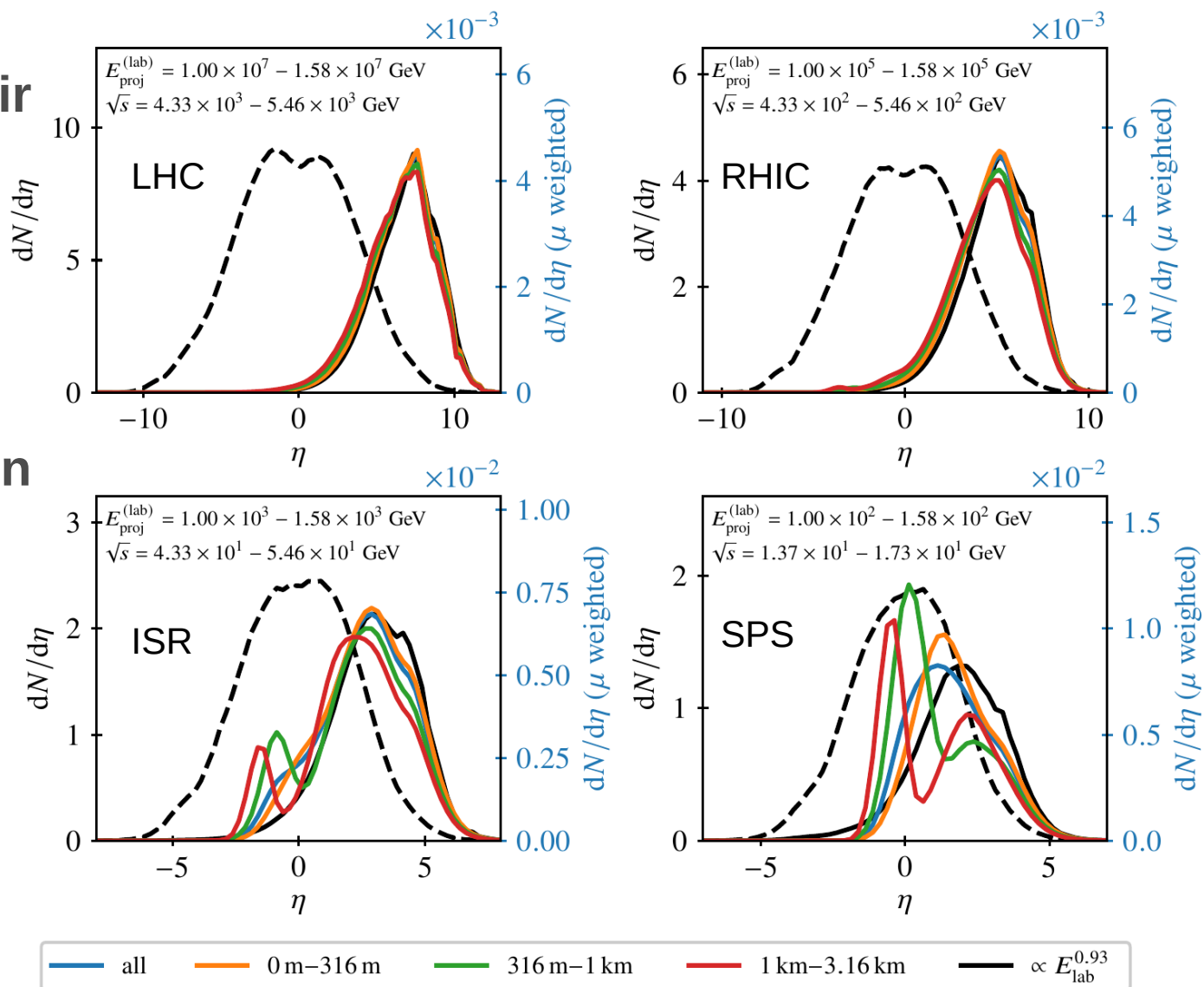
Relevant Phase Space in Air Showers

- Muon production in air showers dominated by forward produced particles

➔ True at high energy

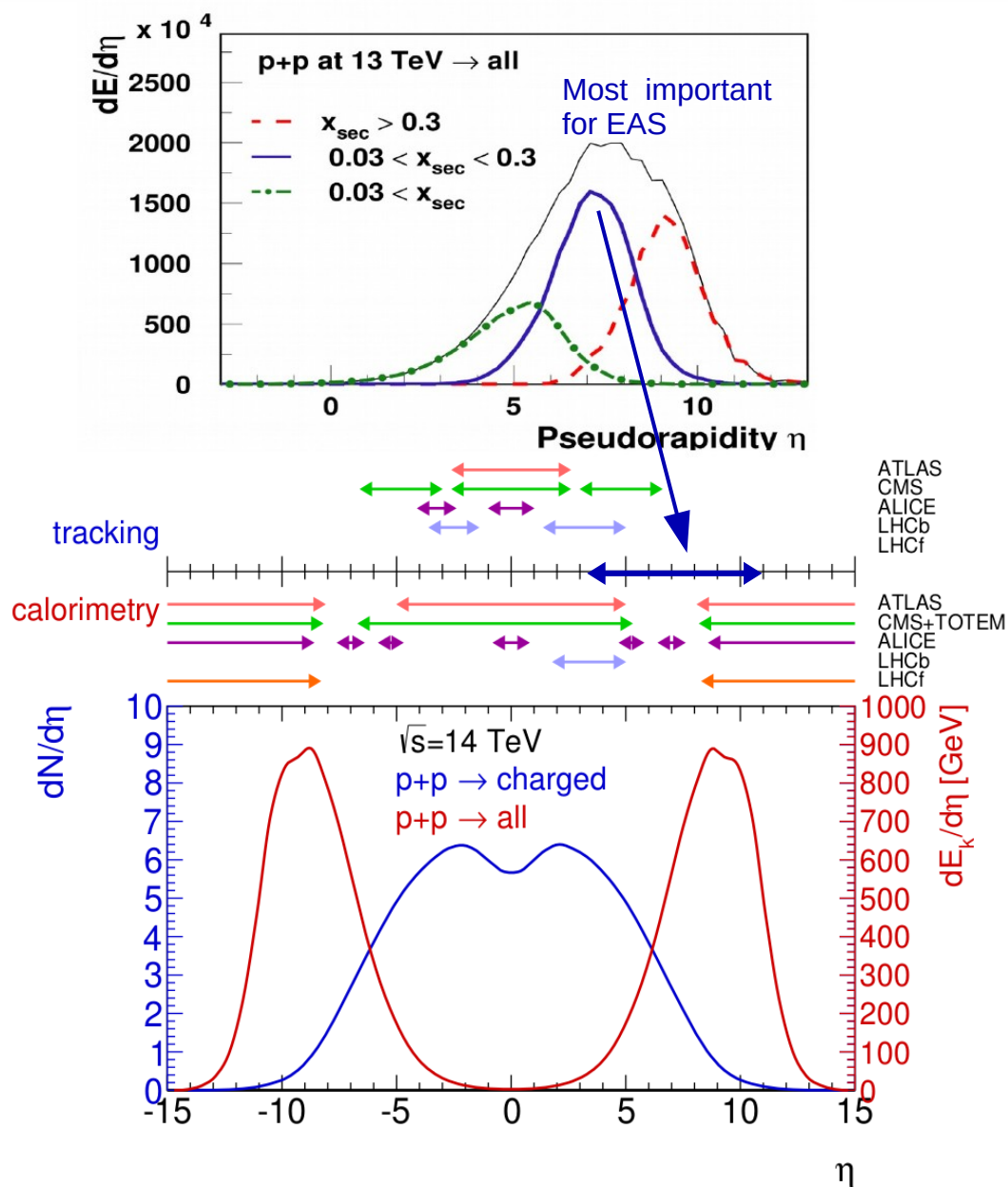
- Midrapidity production important in the last generations and for muon at large distances from the shower core

➔ 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
- ➔ $\theta \gg 1$ is forward
- ➔ $\theta \ll 1$ 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**

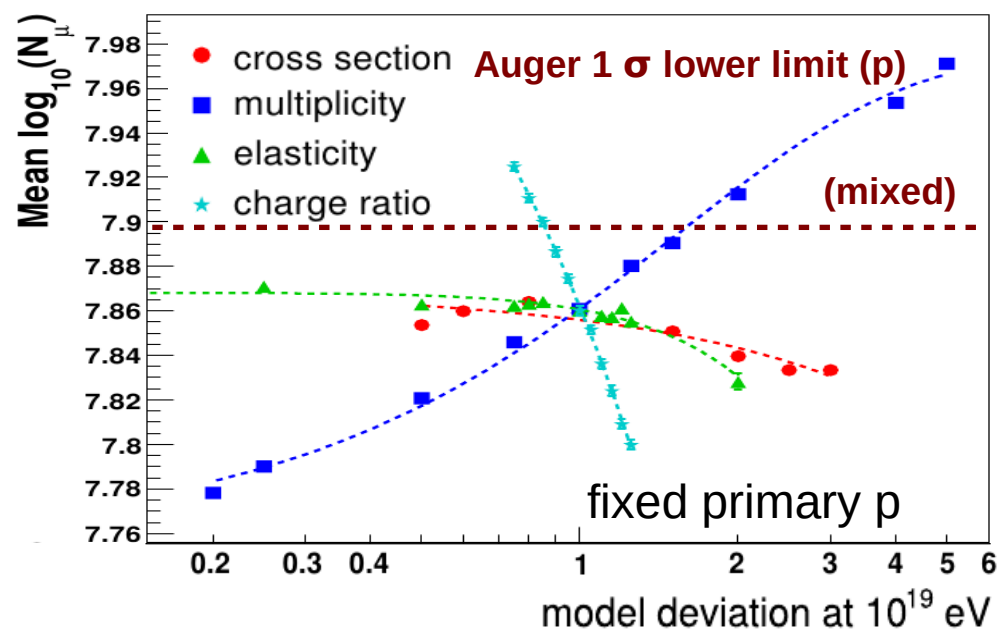
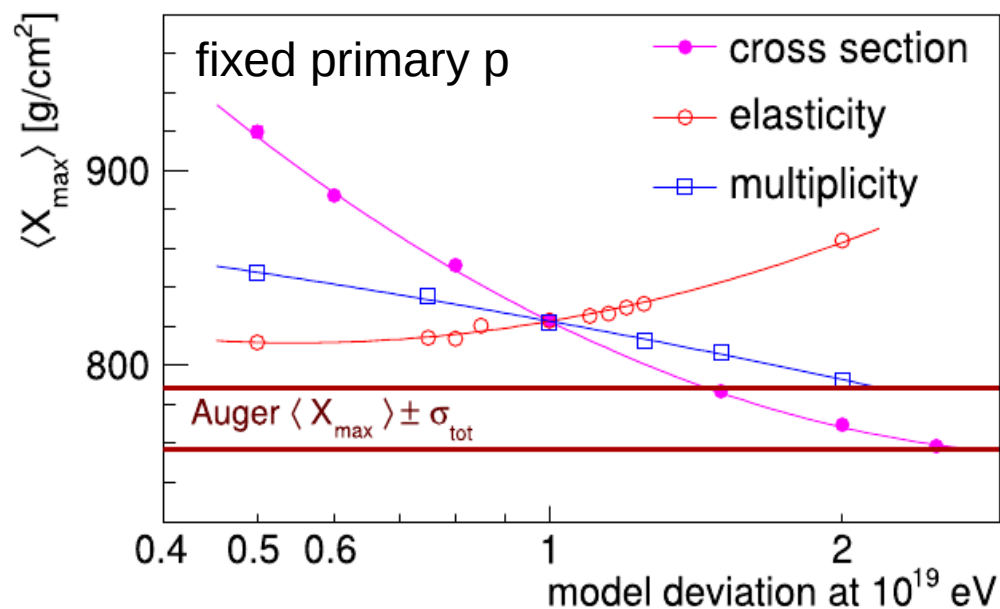
Lessons From Heitler Model

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



● Air shower development dominated by few parameters

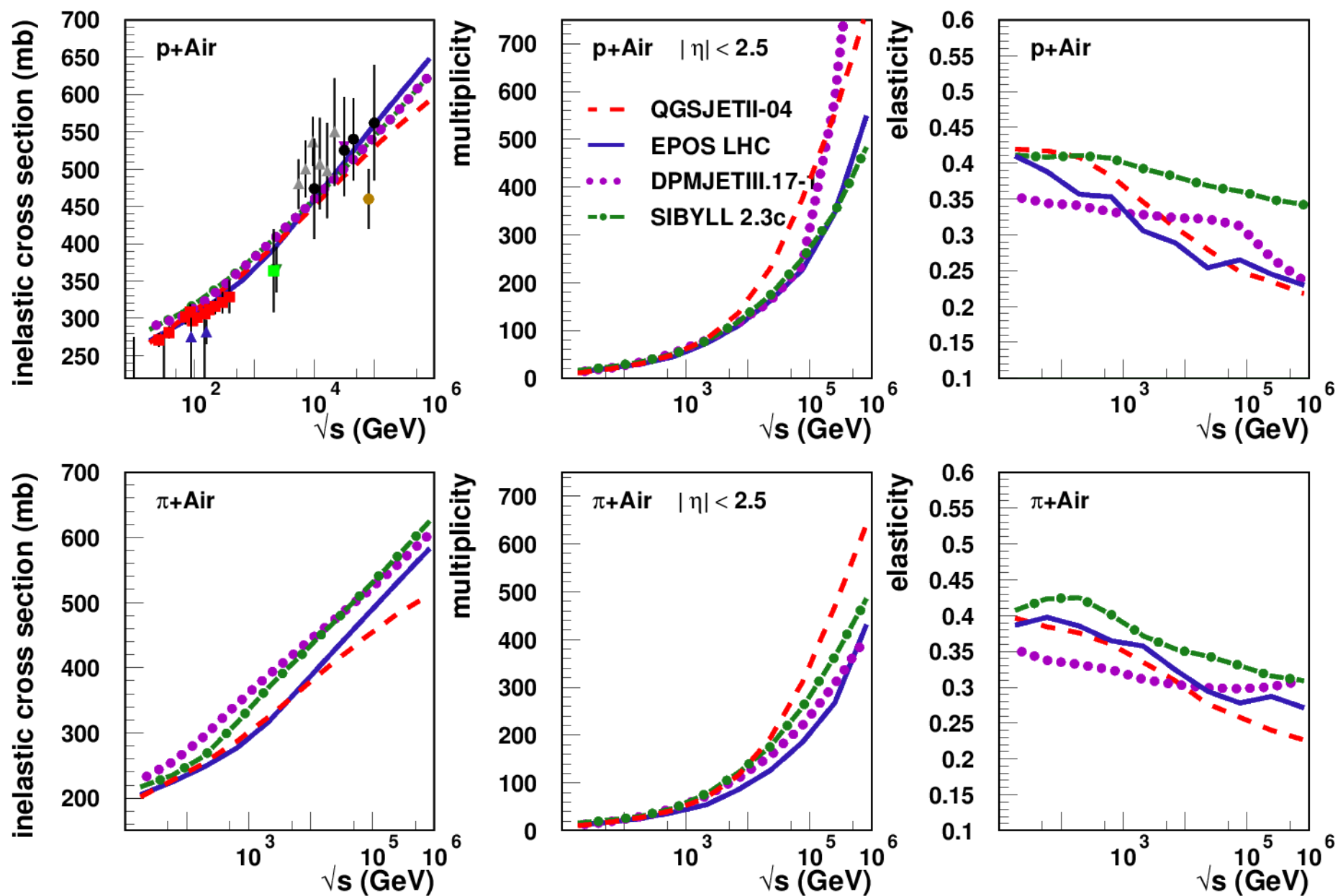
- ➔ mass and energy of primary CR
- ➔ cross-sections (p-Air and (π-K)-Air)
- ➔ (in)elasticity
- ➔ multiplicity
- ➔ charge ratio and baryon production

● 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



Questions on air showers ?