Cosmic Rays

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July the 2nd 2024

Secondary Cosmic Rays

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Soft QCD and the Production of Secondary Cosmic Rays

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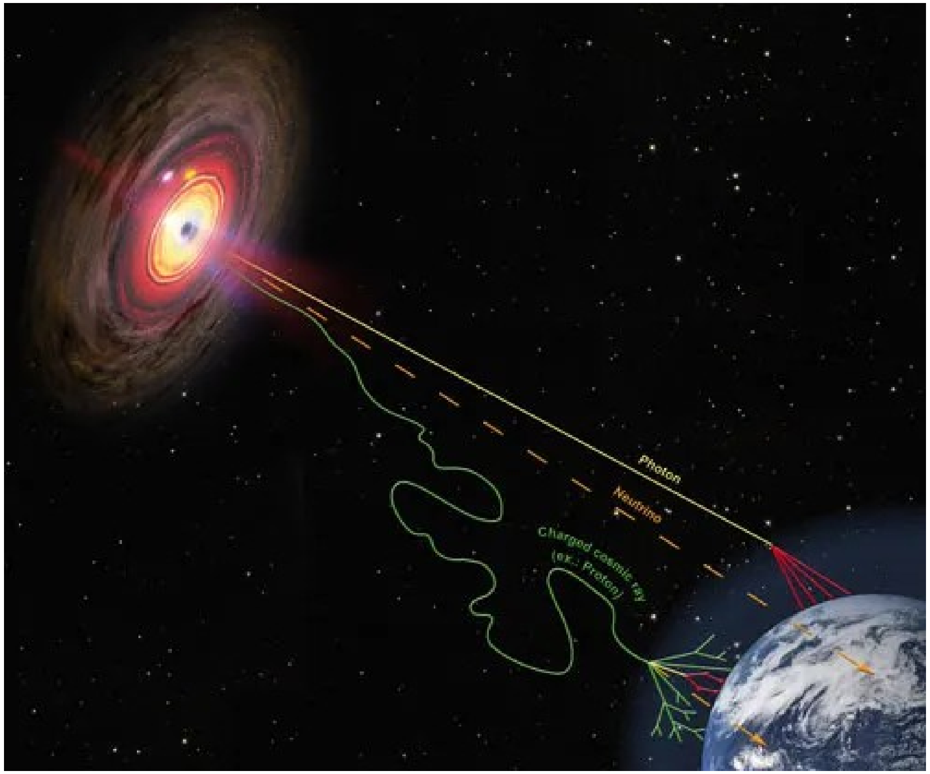
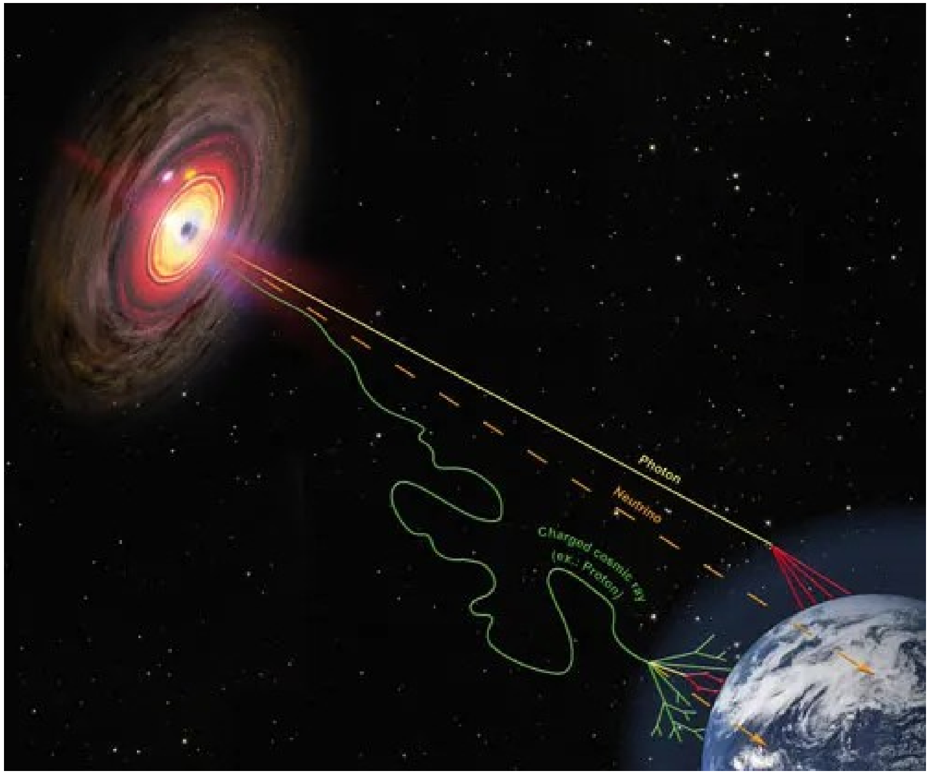
Cosmic Rays (CR)



Cosmic Rays (CR)

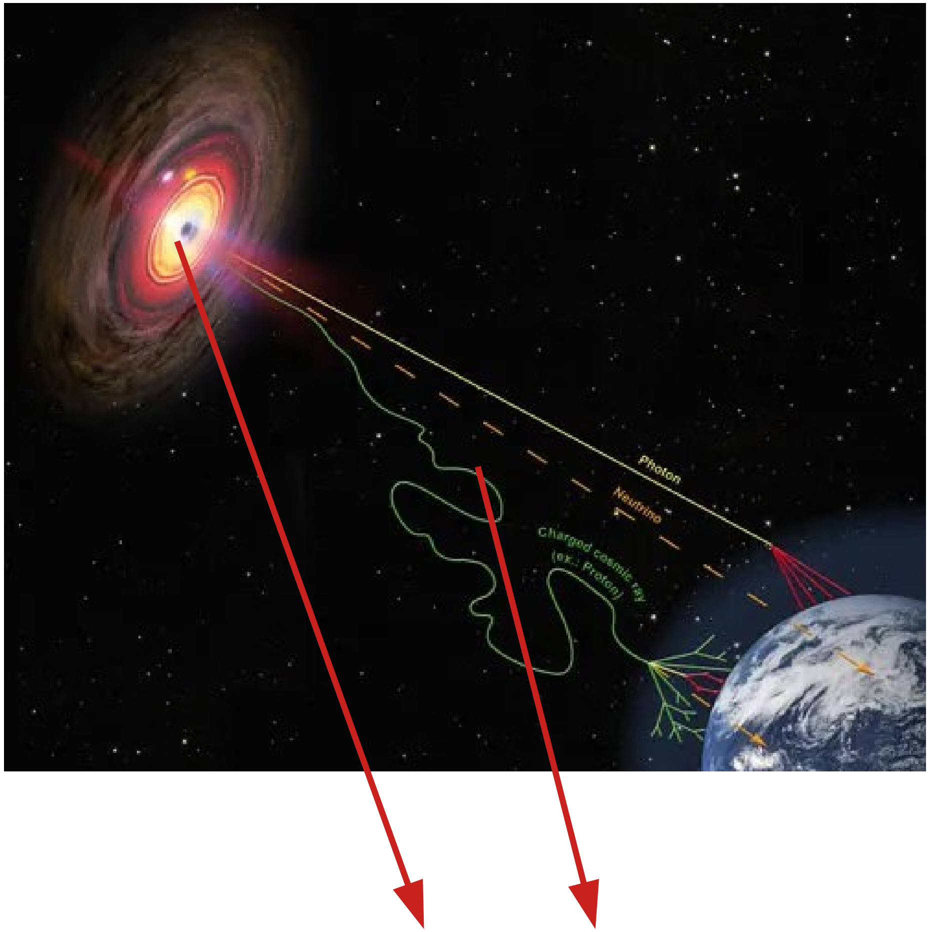
Primary CR



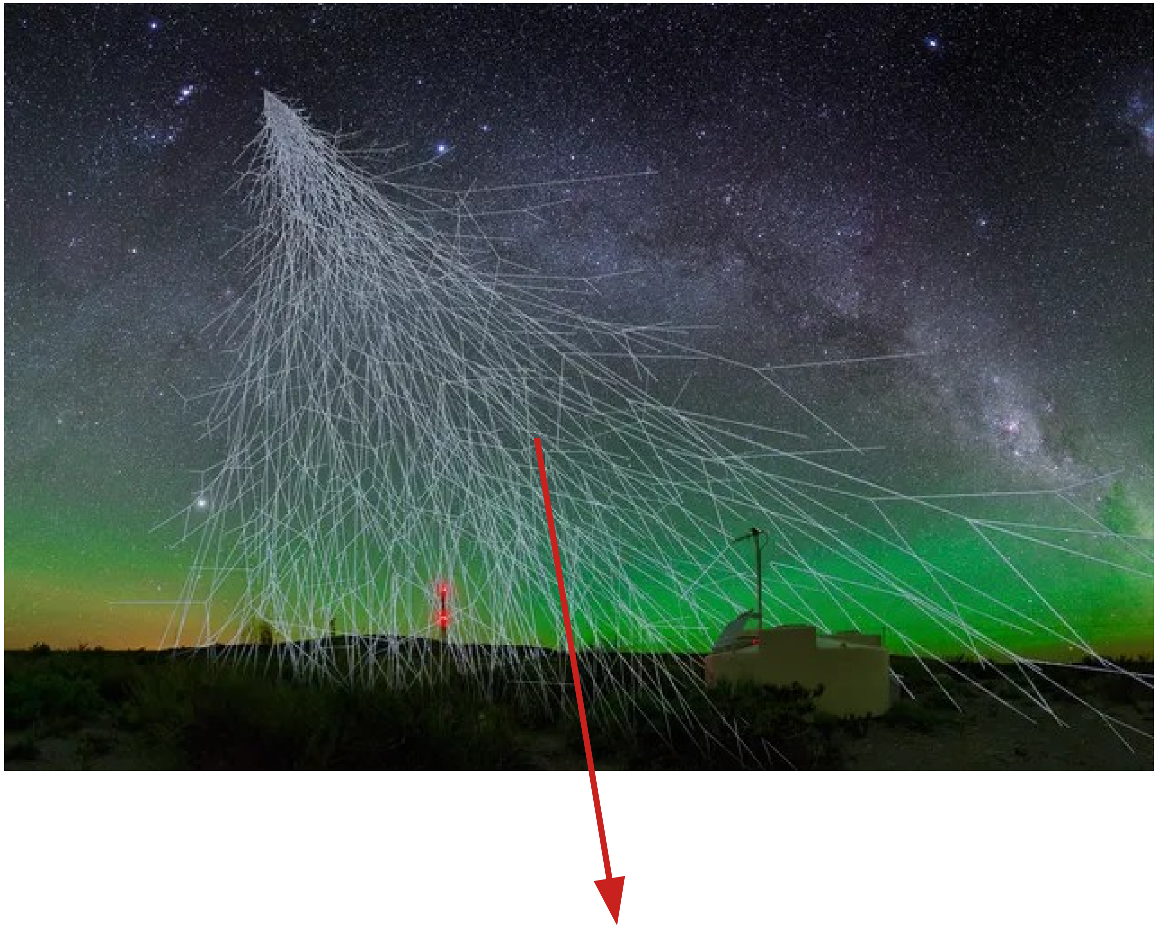
Secondary CR

Cosmic Rays (CR)

Primary CR



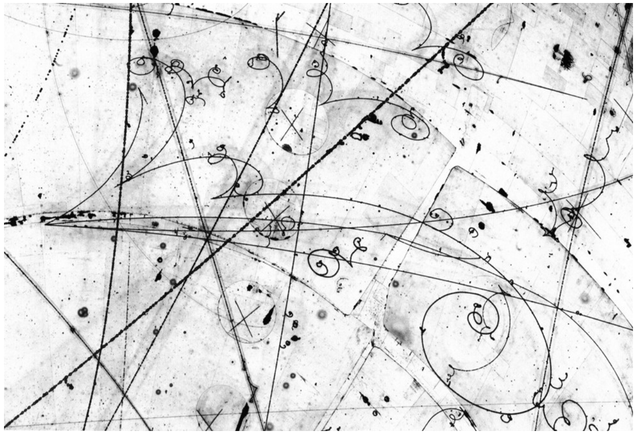
Secondary CR



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

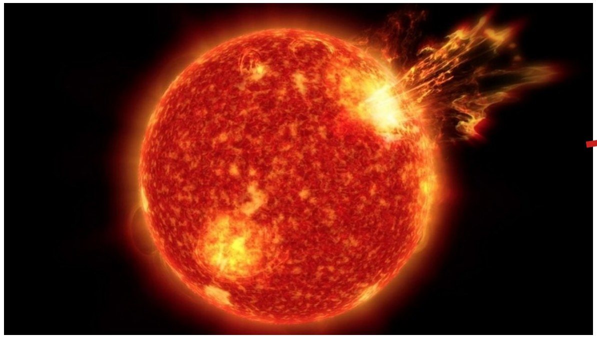
History

- **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 !**

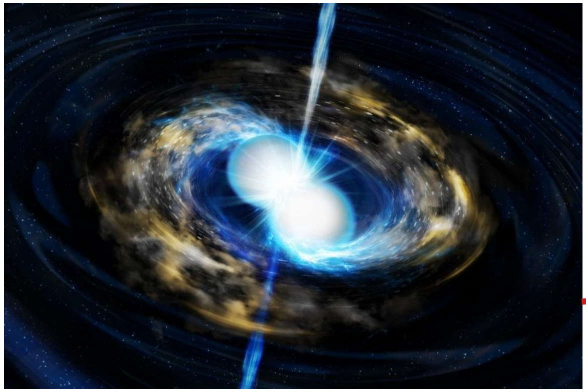


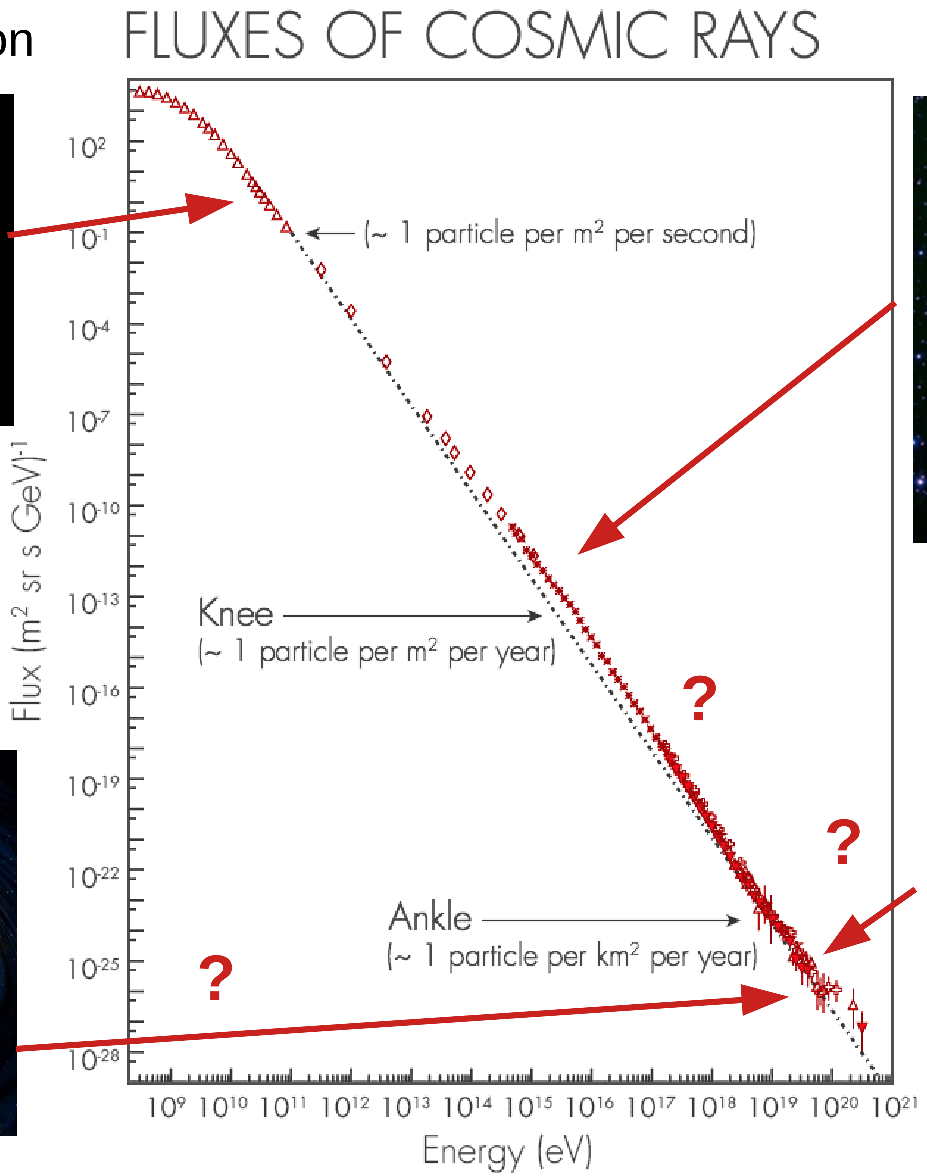
Sources

Sun – Corona Mass Ejection



Extragalactic – Transient ?
(neutron strar merger)

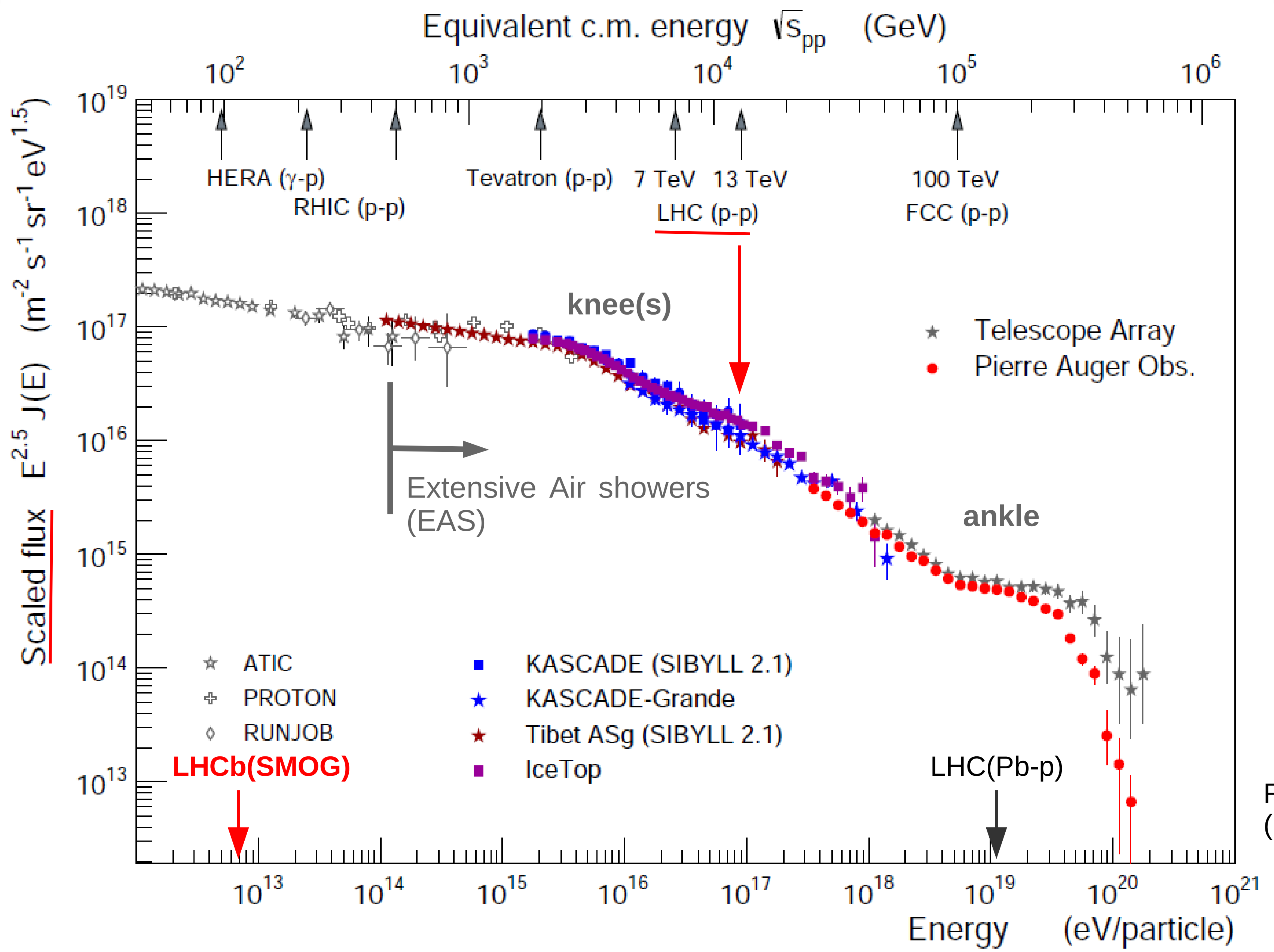




Galactic – Supernovae

Extragalactic – constant ?
(Active Galactic Nuclei)

Energy Spectrum

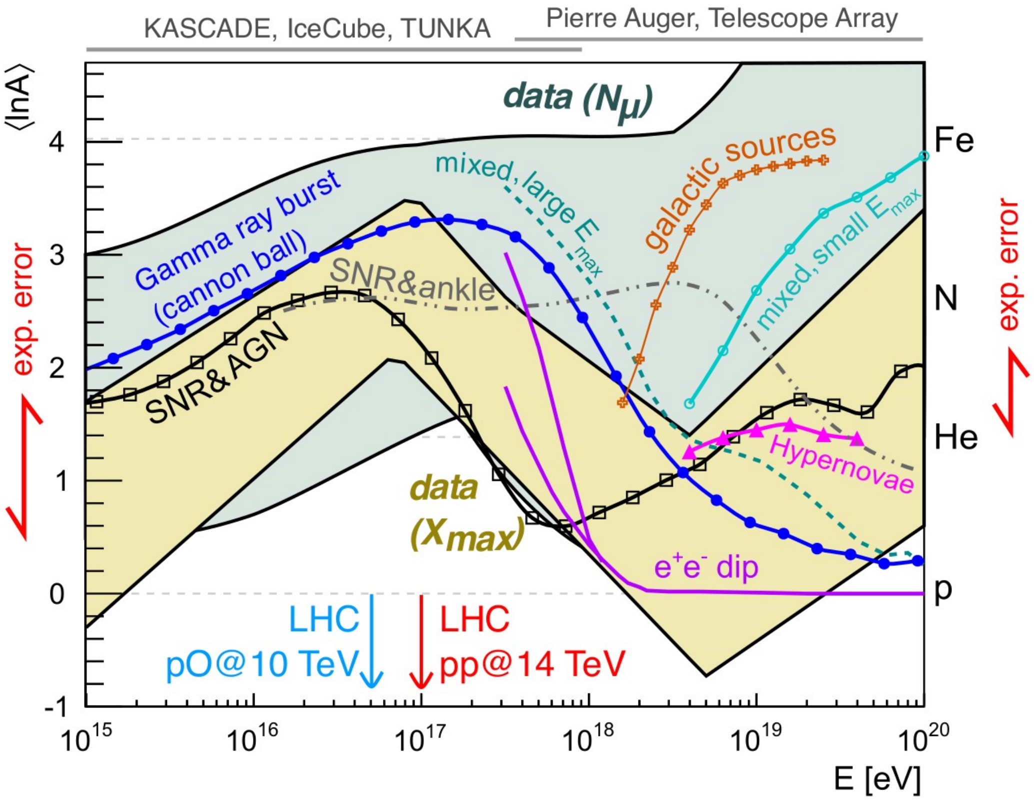


R. Engel (KIT)

UHECR Composition

With muons current CR data are impossible to interpret

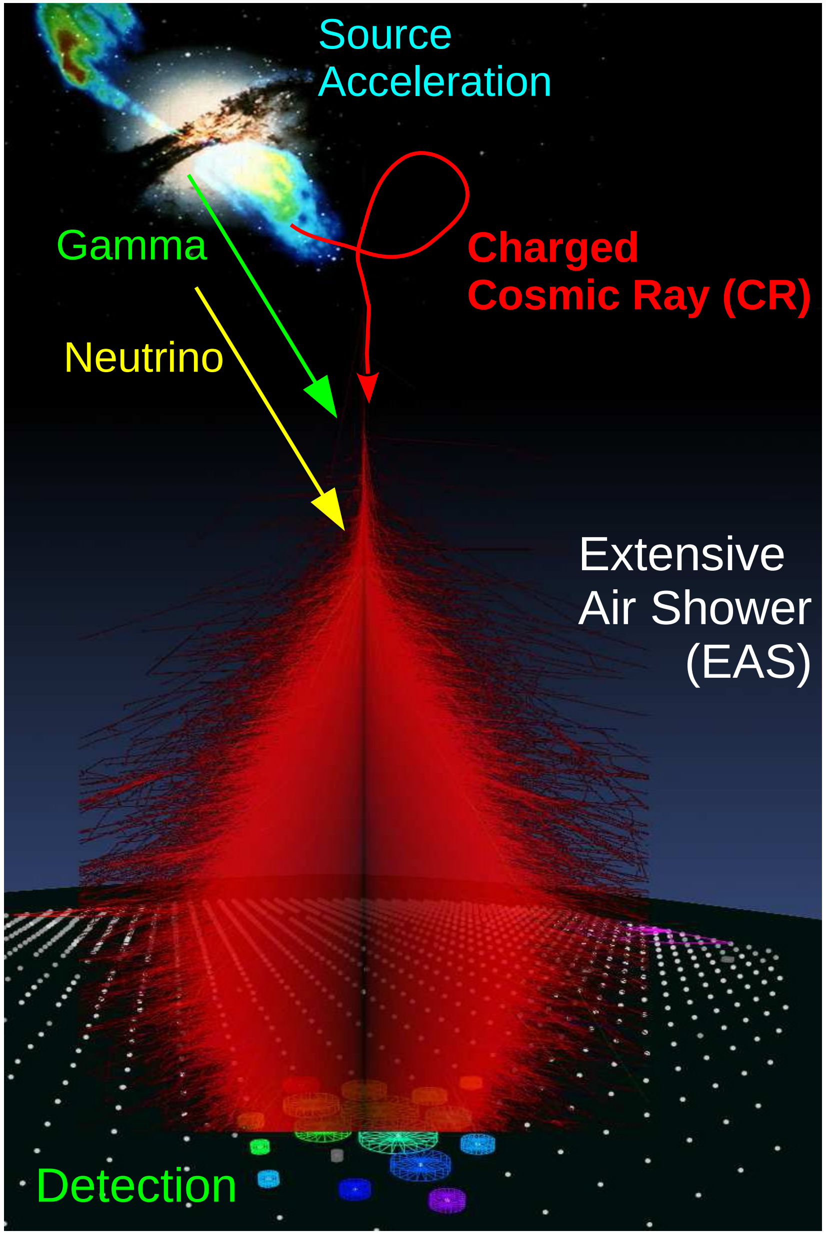
- Very large uncertainties in model predictions
- Mass from different element incompatible because of soft QCD treatment



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

H. Dembinski UHECR 2018 (WHISP working group)

Astroparticles

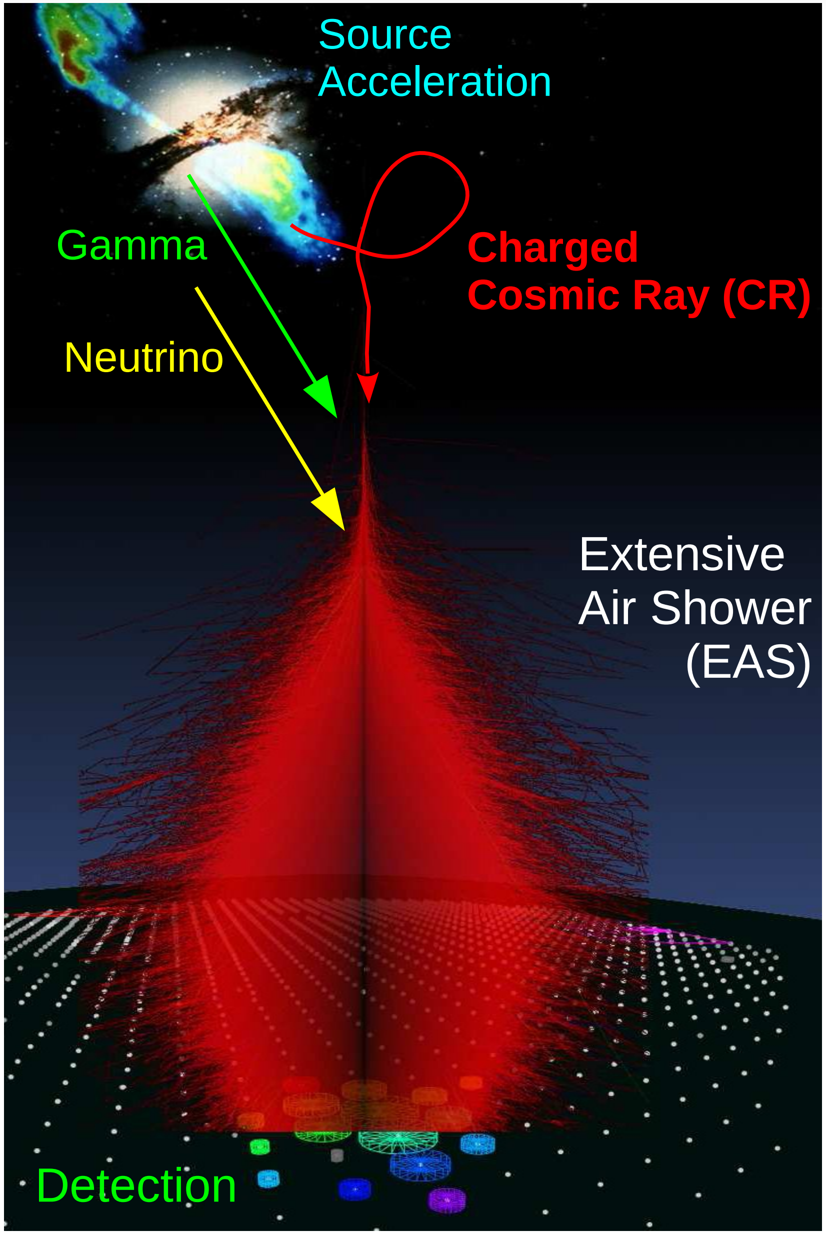


From R. Ulrich (KIT)

- **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



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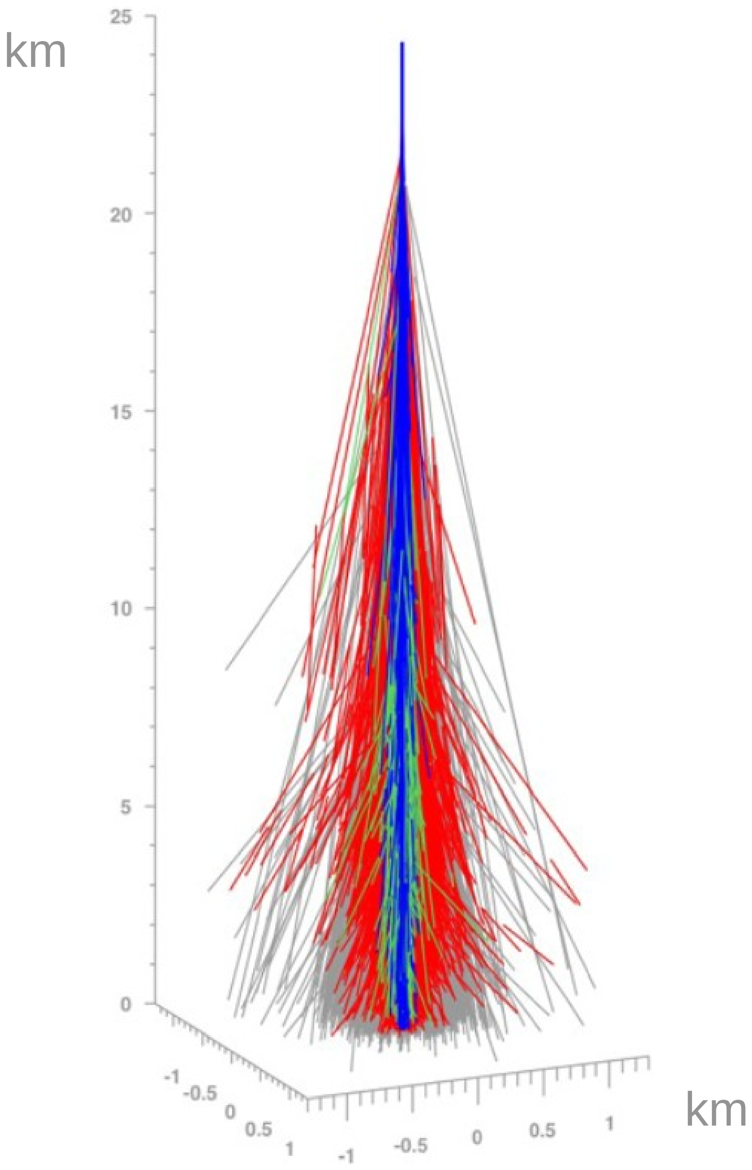
  - test of hadronic interactions in EAS via correlations between observables.
- **Gravitationnal waves**
  - Source position
  - Source mass

(Extensive) Air Showers (EAS)



Extensive Air Shower

Hearth atmosphere used as a calorimeter

$$A + air \to \text{hadrons}$$
$$p + air \to \text{hadrons}$$
$$\pi + air \to \text{hadrons}$$

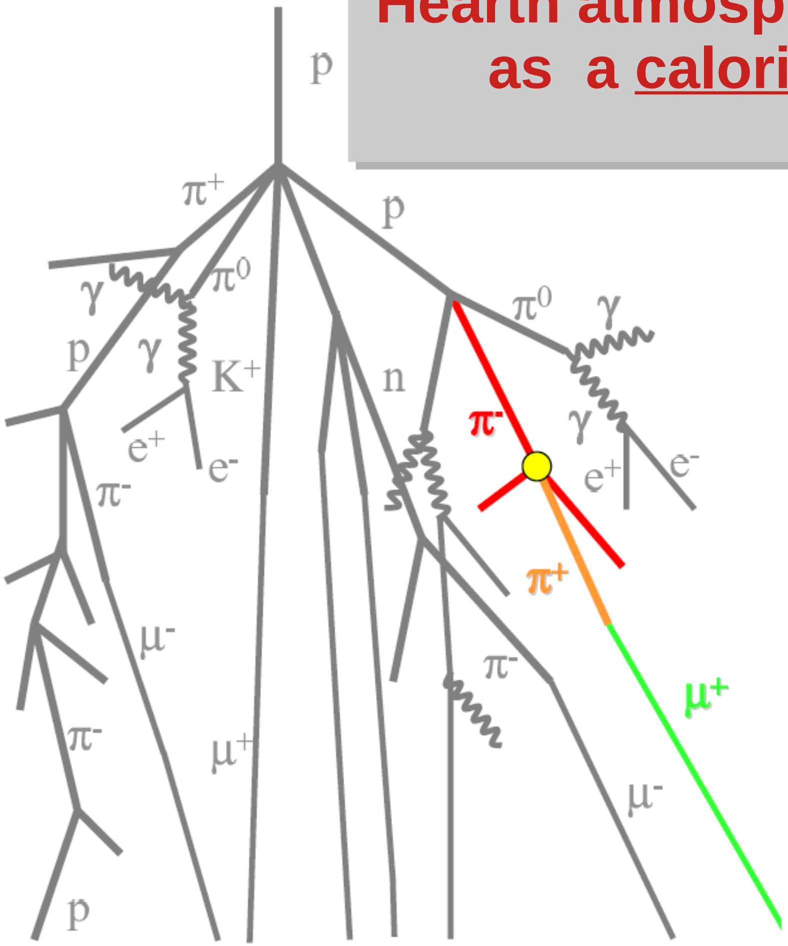
main source of uncertainties

intial γ from π^0 decay

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

well known

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



From R. Ulrich (KIT)

Cascade of particle in Earth's atmosphere

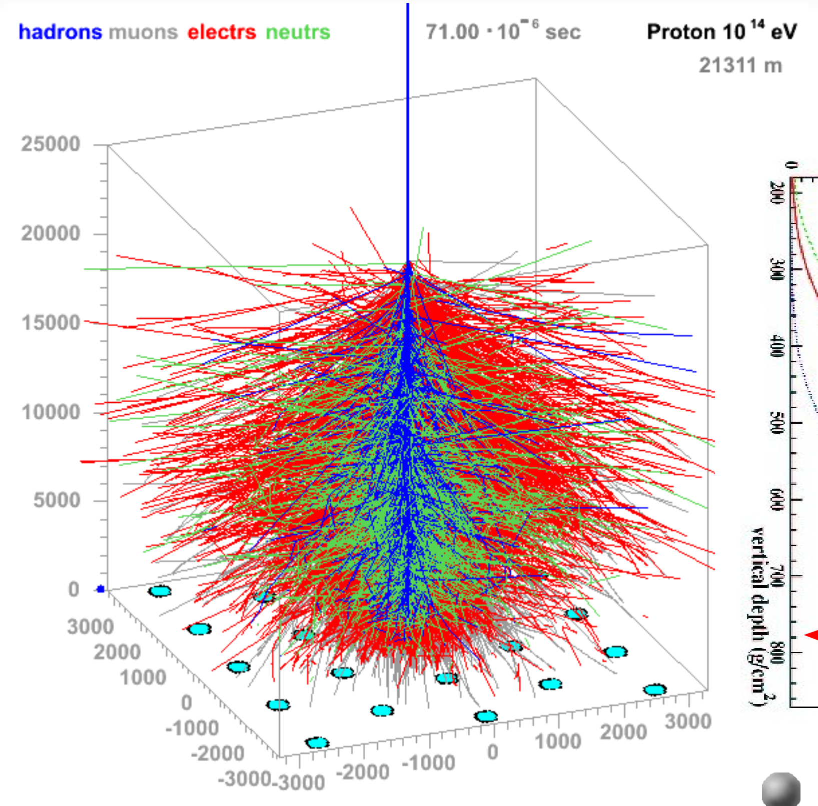
Number of particles at maximum

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

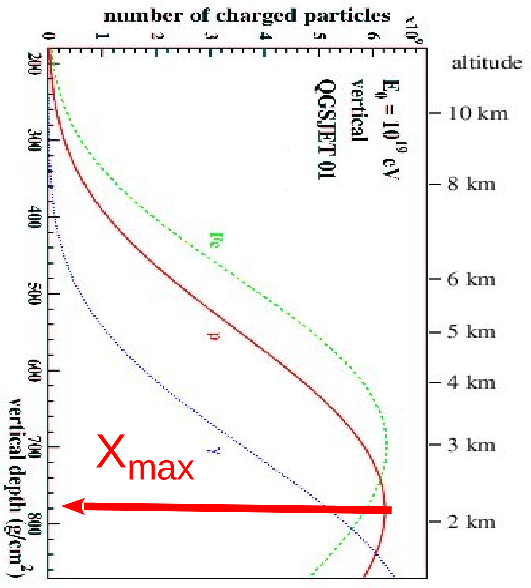
Energy

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

Extensive Air Shower Observables



J.Oehlschlaeger,R.Engel,FZKarlsruhe

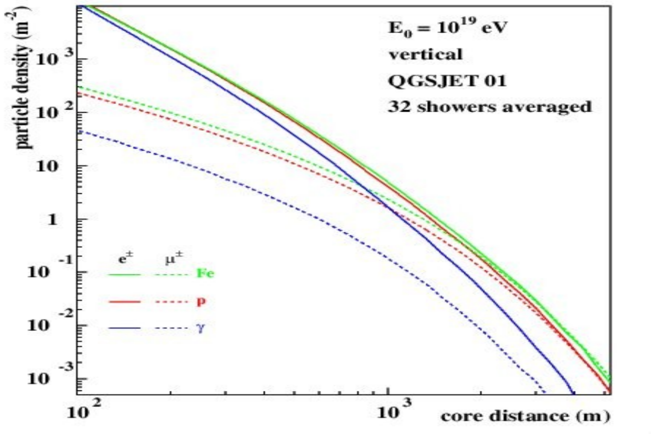


- **Longitudinal Development**
  - ➨ number of particles vs depth

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

  - ➨ Larger number of particles at X_{max}

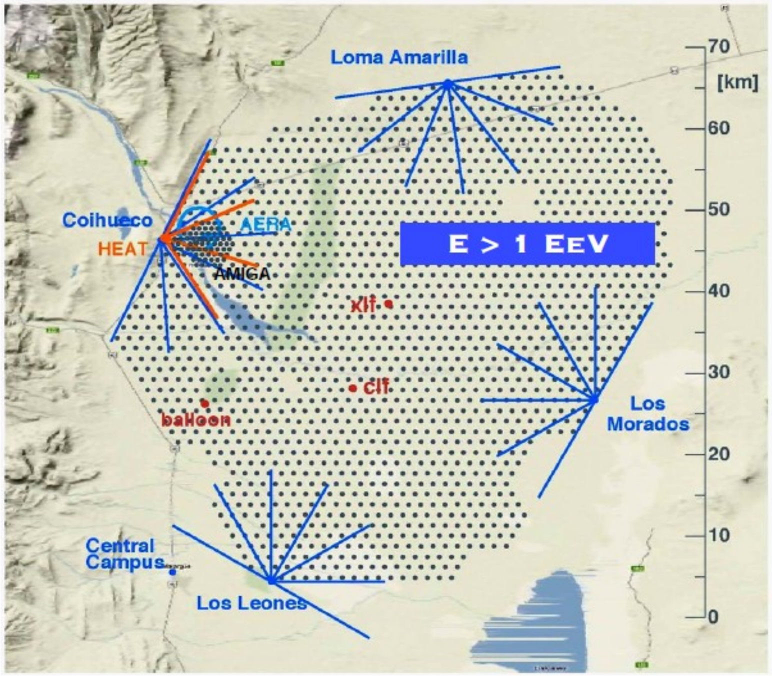
    For many showers
    - mean : $<X_{max}>$
    - fluctuations : RMS X_{max}

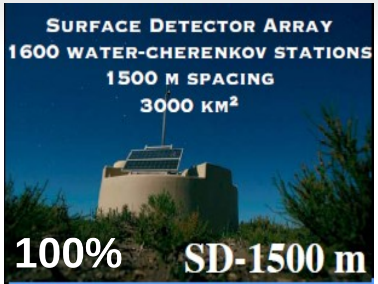


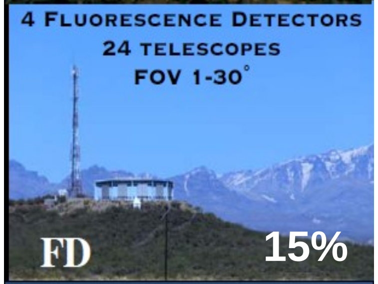
- **Lateral development**
  - ➨ particle density at ground vs distance to the impact point (core) = Lateral distribution function (LDF)
  - ➨ can be muons or electrons/gammas or a mixture of all.
- **Observables**
  - ➨ Particles at ground, fluorescence light, radio emission, cherenkov light ...

High Energy Measurements

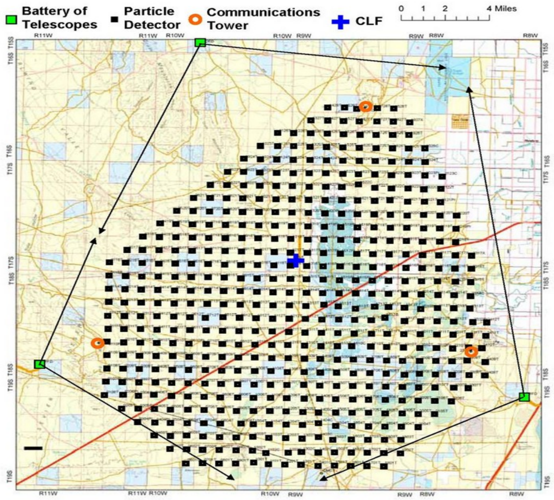
- **Pierre Auger Observatory (PAO)**
  - Mendoza, Argentina
  - Southern Hemisphere
  - 3000 km^2: 32000 km^2/sr/yr







- **Telescope Array (TA)**
  - Utah, USA
  - Northern Hemisphere
  - 680 km^2: 3700 km^2/sr/yr



Low Energy Measurements (some)

Kascade (Germany)

Grapes 3 (India)

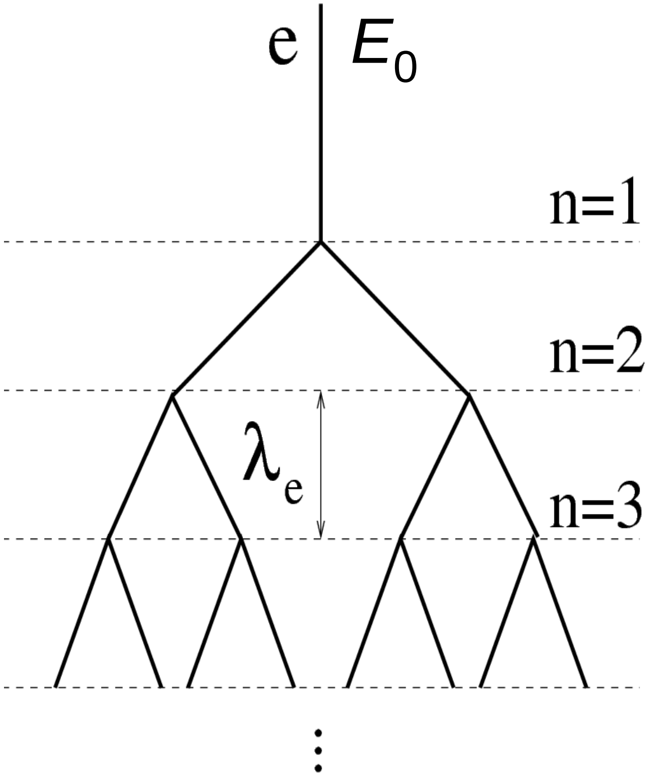
LHAASO (China)

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

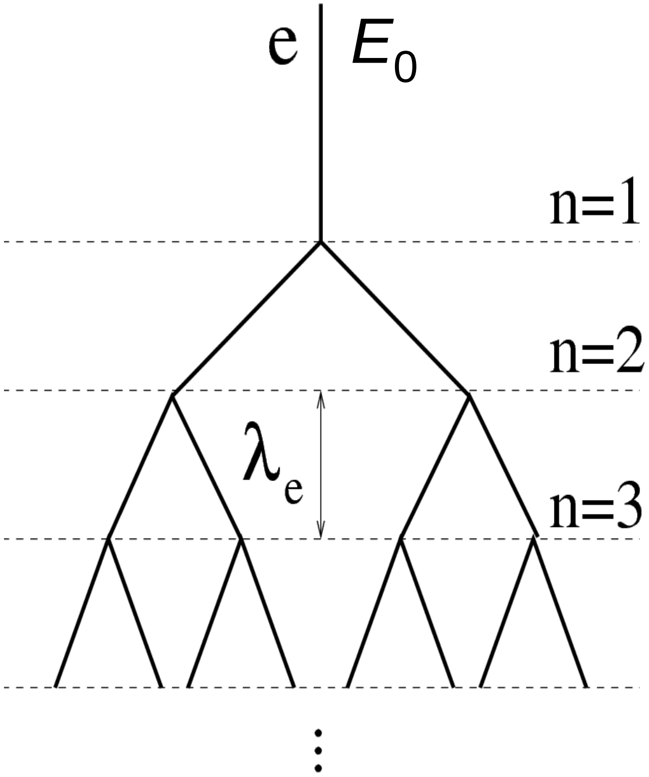


Primary particle : photon/electron

Heitler toy model :

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

Toy Model for Electromagnetic Cascade



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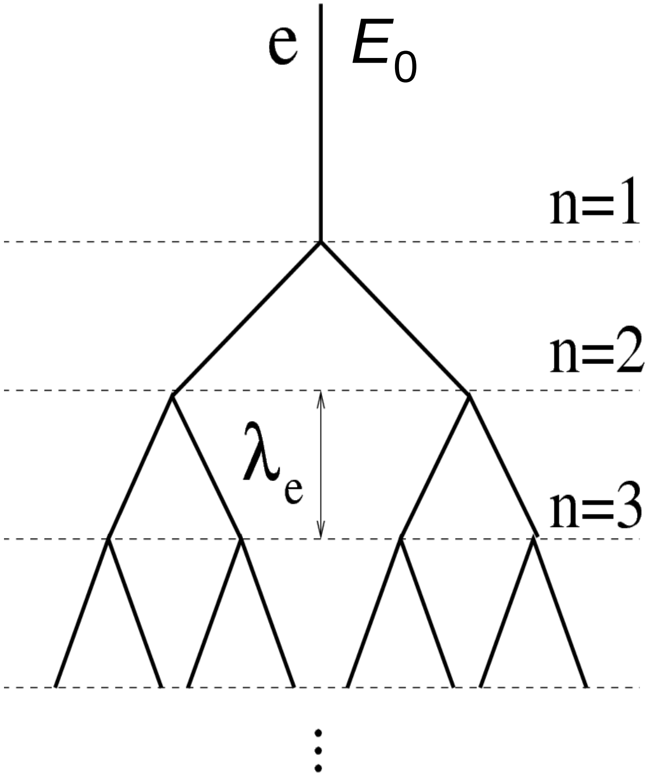
2ⁿ particles after *n* interactions

$$n = X/\lambda_e$$

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

Assumption: shower maximum reached if *E(X)* = $\underline{E_c}$ <u>(critical energy)</u>

Toy Model for Electromagnetic Cascade



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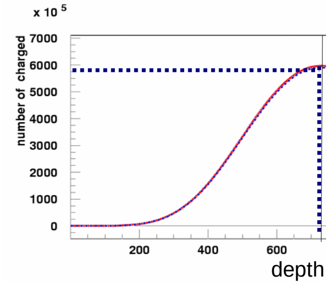
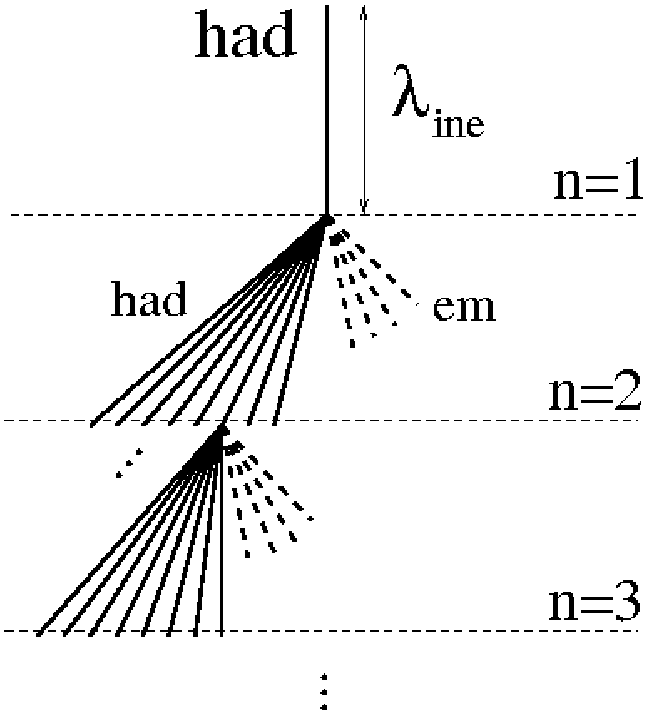


$$N_{max} = E_0/E_c \qquad X_{max} \sim \lambda_e \ln(E_0/E_c)$$

Toy Model for Hadronic Cascade



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

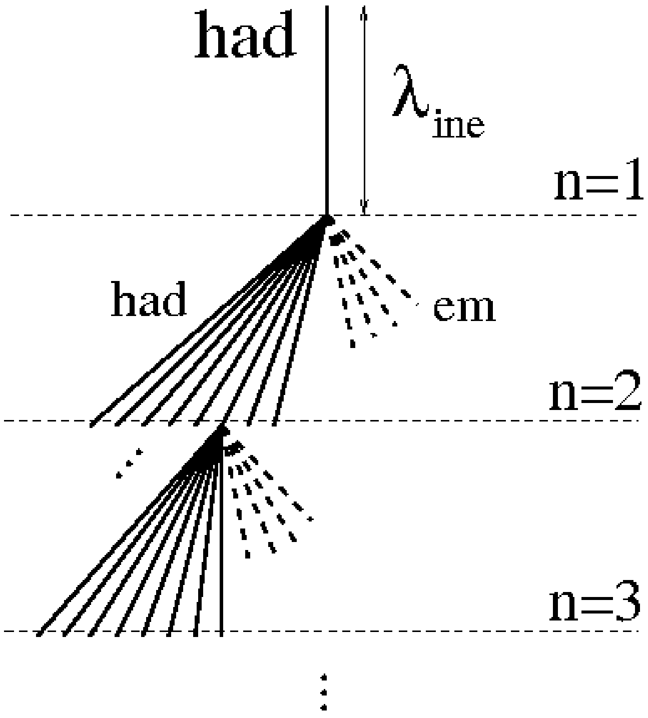
Primary particle : hadron

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

Toy Model for Hadronic Cascade



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- 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).

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

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

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**

Superposition Model

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- **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

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

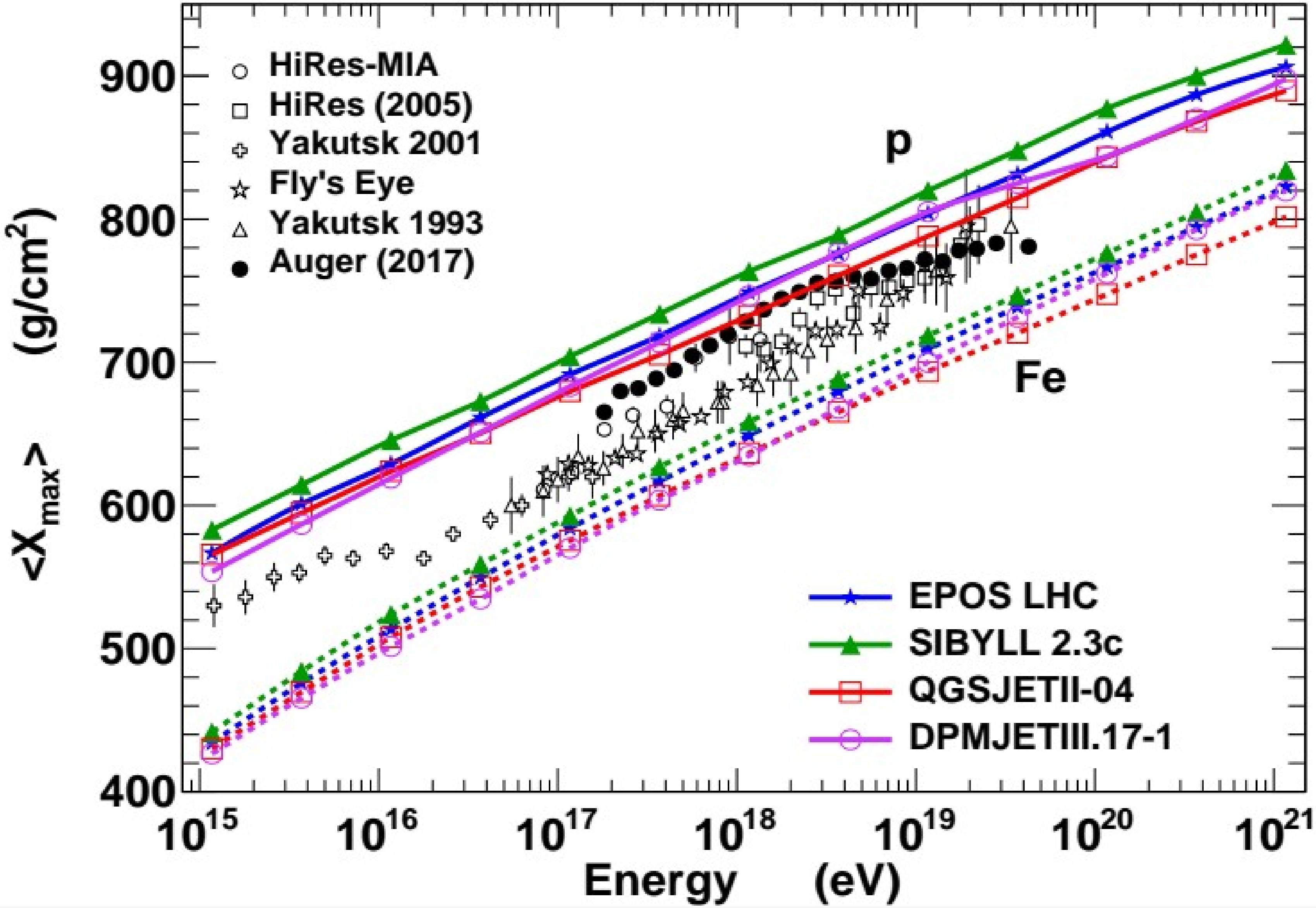
Cross-section evolution

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

Mass evolution

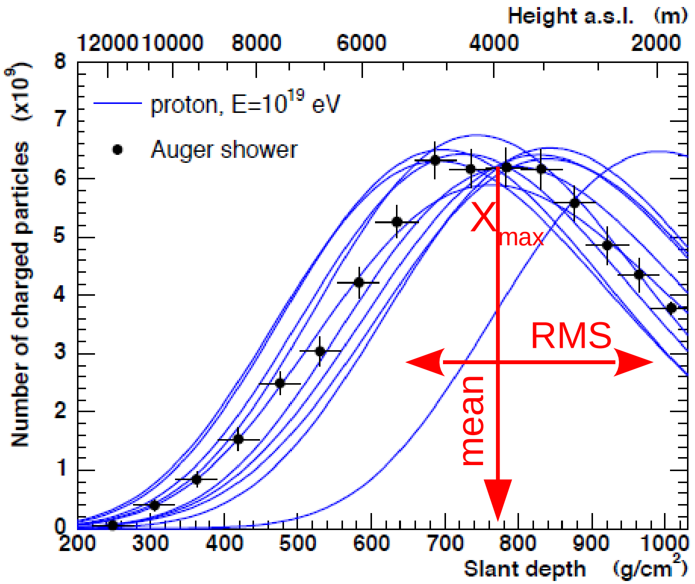
$$B_A = \frac{d\ln A}{d\ln(E)}$$

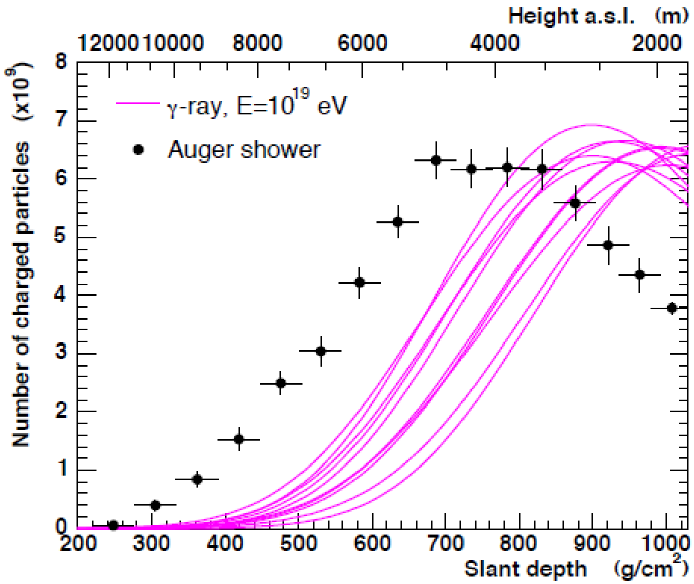
EAS : $<X_{max}>$

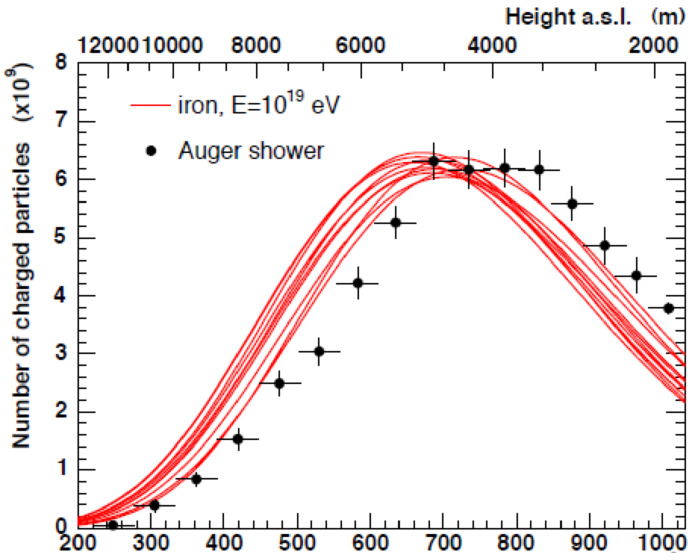


$<X_{max}>$ (g/cm^2)
900
800
700
600
500
400
○ HiRes-MIA
□ HiRes (2005)
✚ Yakutsk 2001
☆ Fly's Eye
△ Yakutsk 1993
● Auger (2017)
p
Fe
EPOS LHC
SIBYLL 2.3c
QGSJETII-04
DPMJETIII.17-1
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
Energy (eV)

Mean AND Fluctuations







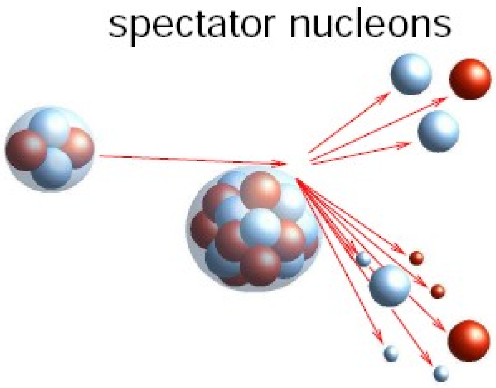
Example: event measured by Auger Collab. (ICRC 2003)

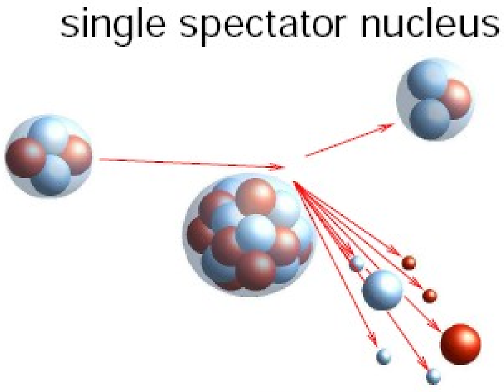
Both mean and fluctuations of X_{max} are important for mass composition measurements

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 :**





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

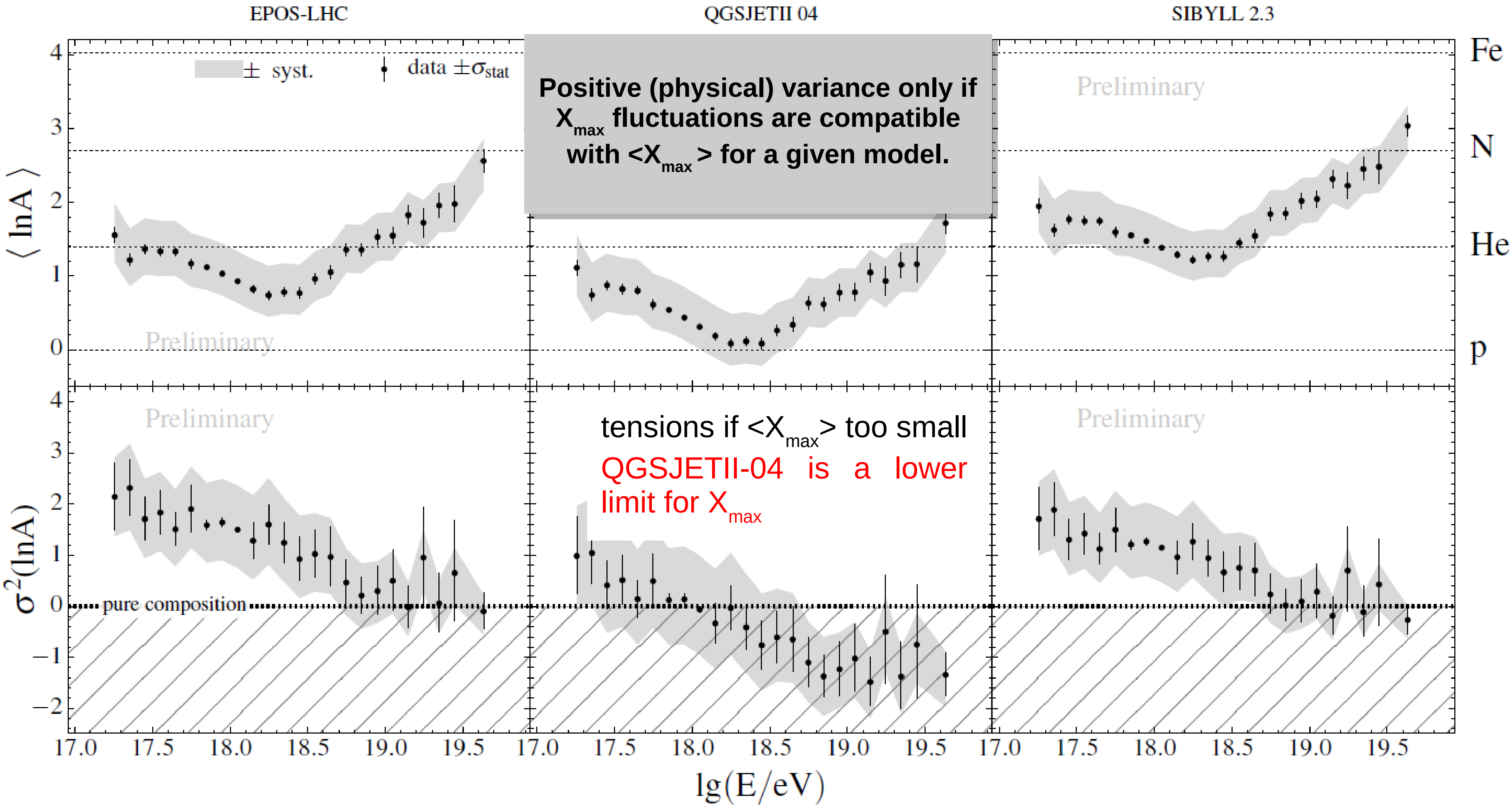
Full fragmentation

No fragmentation

(by M. Unger)

Model Consistency using Electromagnetic Component

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



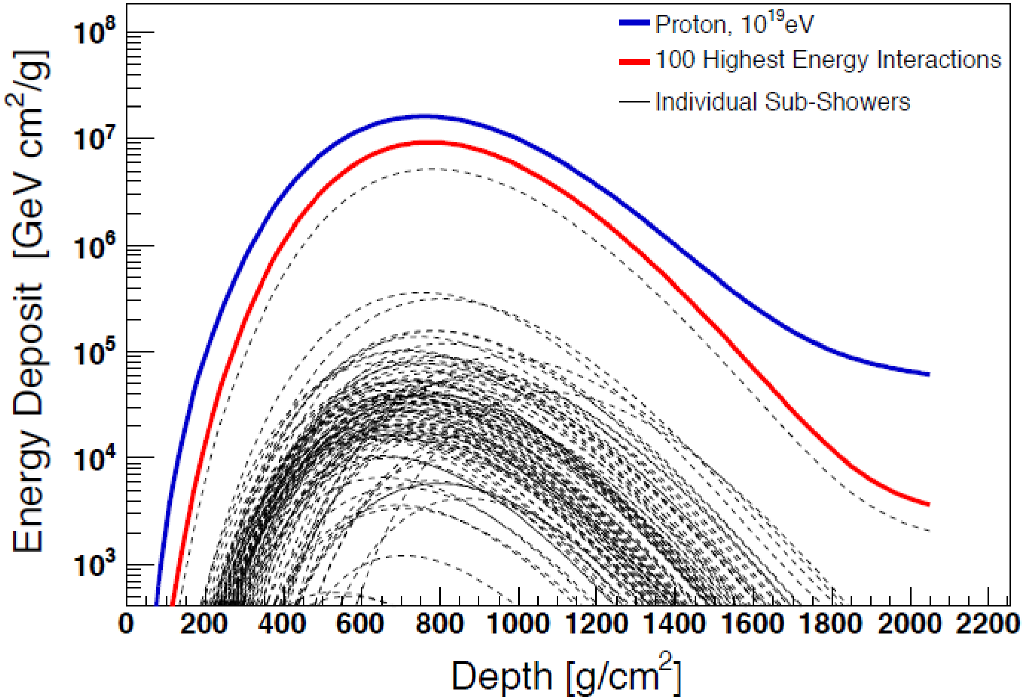
Positive (physical) variance only if X_{max} fluctuations are compatible with $<X_{max}>$ for a given model.

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

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

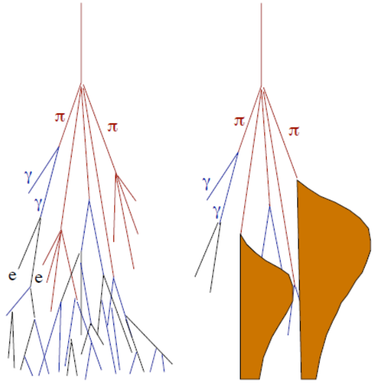
Energy of hadronic interactions for X_{max}

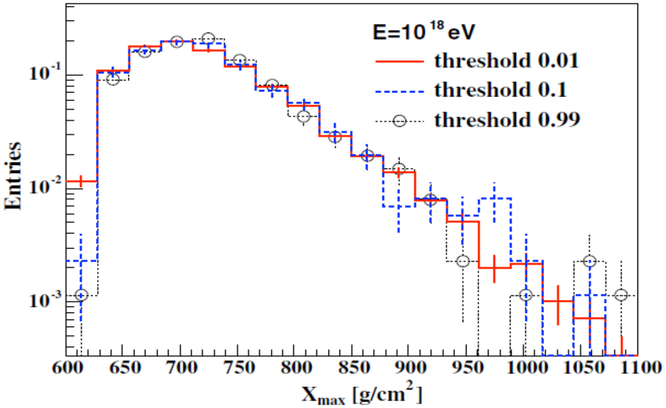
Electrons



Shower particles produced in 100 interactions of highest energy

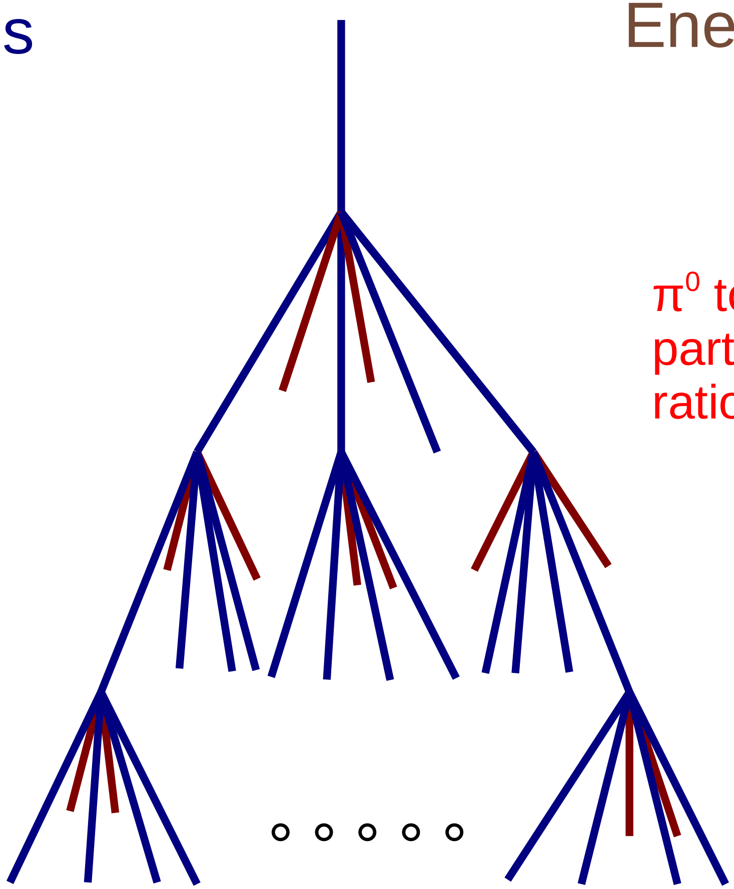
Electrons/photons:
high-energy interactions





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 → $\frac{1}{3}E_0$

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

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

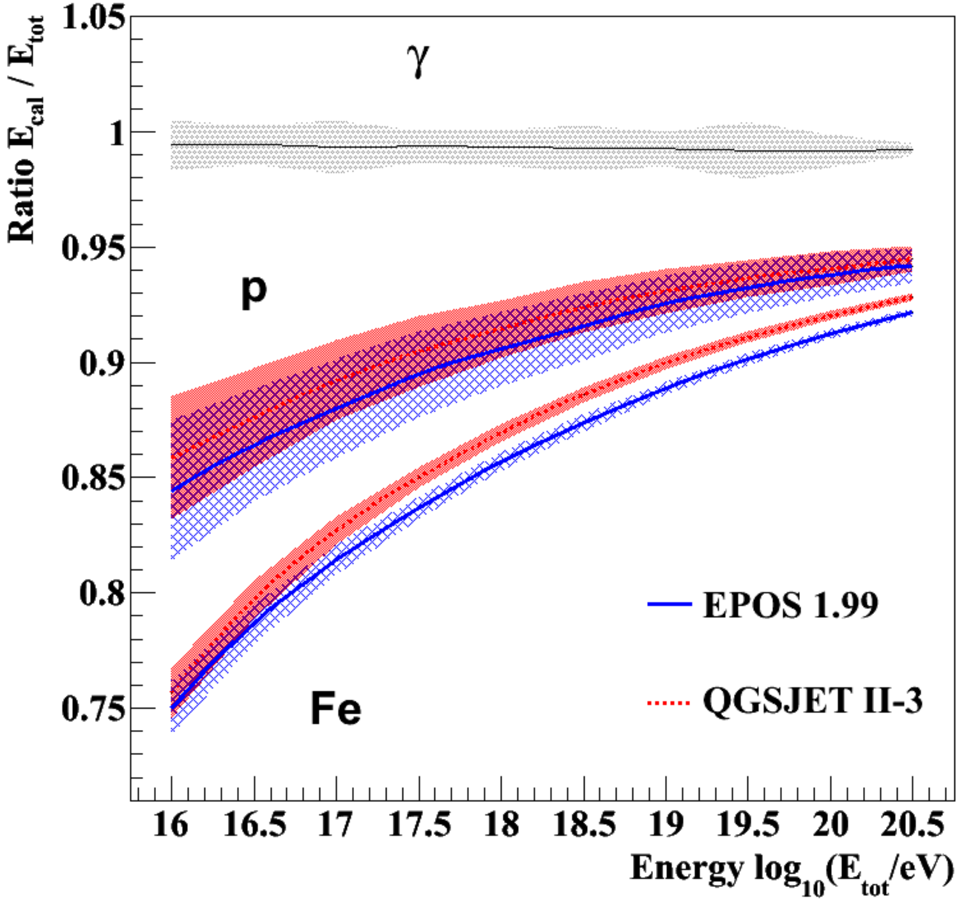
Energy in em. ~ 90 %

(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) : 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

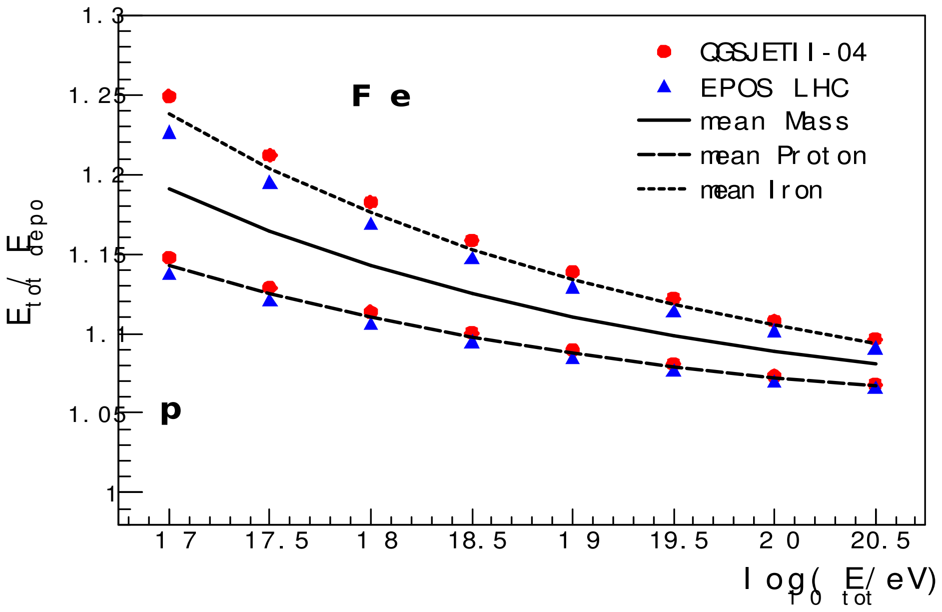
Energy Deposit



- **From Heitler model**

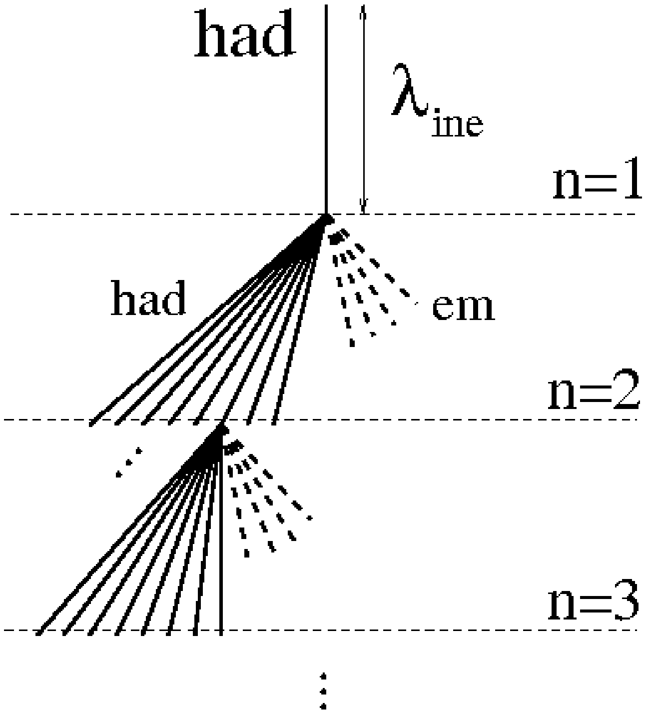
$$E_{em} = \left[1 - \left(\frac{N_{em}}{N_{tot}}\right)^{n(A)}\right] E_0$$

- **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



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

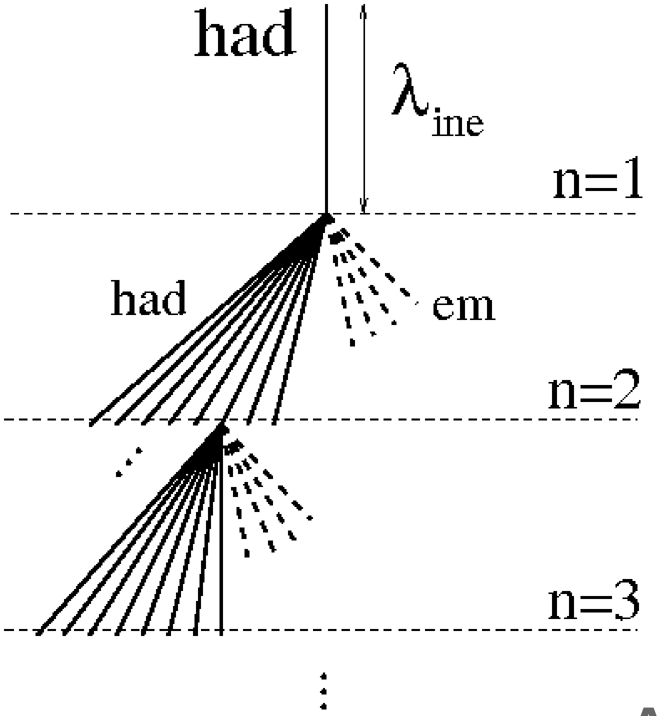
J. Matthews, Astropart.Phys. 22 (2005) 387-397

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

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

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

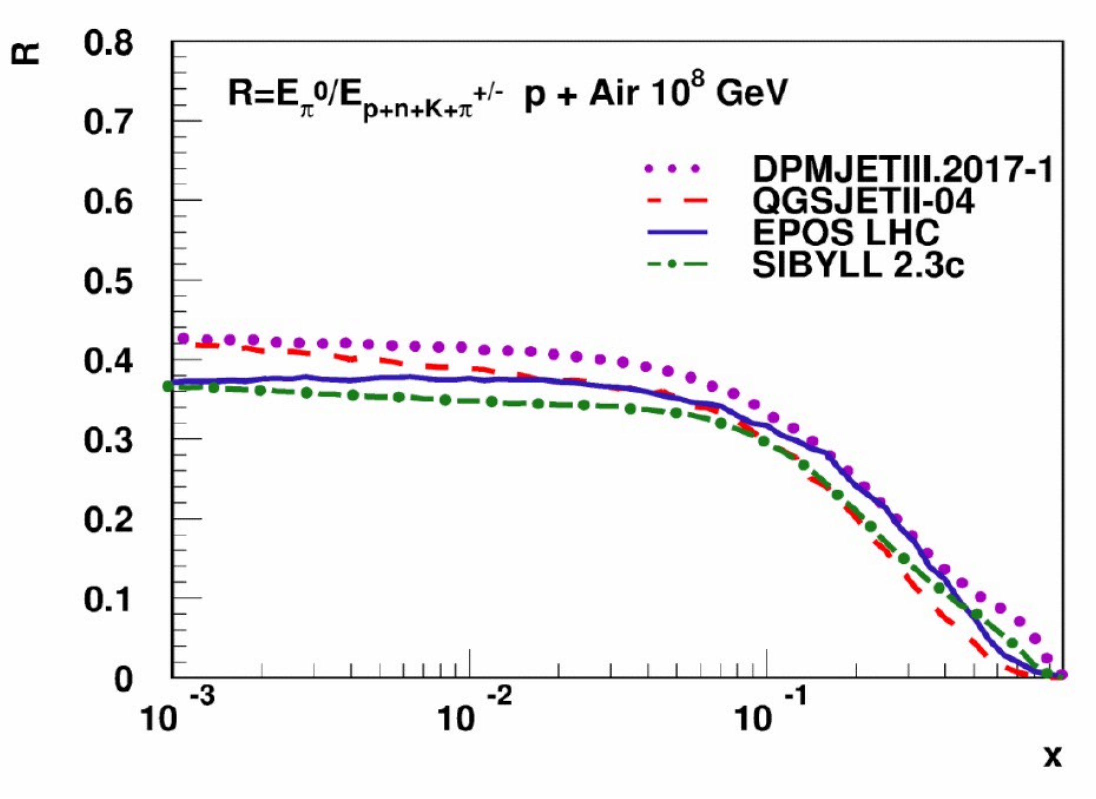
$$\ln(N_{\mu}) = \ln(N(n_{max})) = n_{max} \ln(N_{had})$$

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 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**

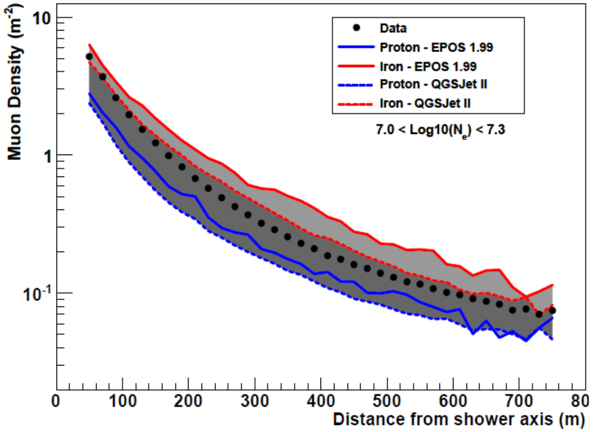
  ➜ equivalent to A proton showers with energy E/A

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

- **More muons from primary nucleus**

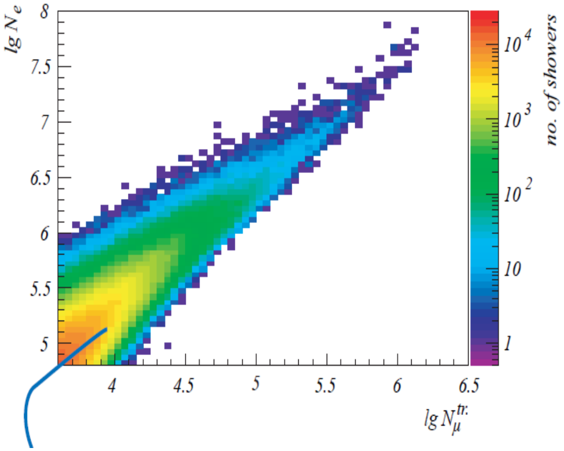
$$\boxed{N_\mu(A) = N_\mu(p)\,A^{1-\beta}}$$

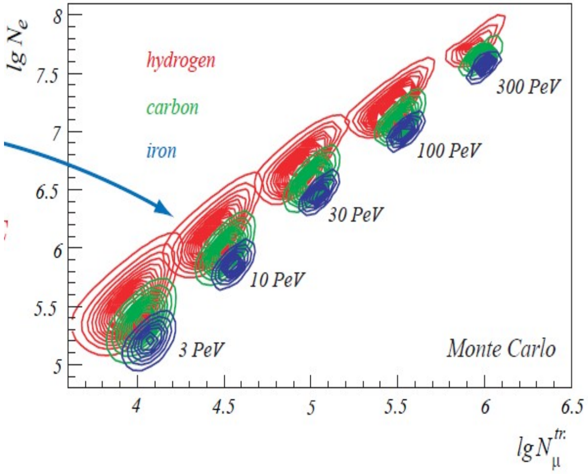
Particles at Ground



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
  - 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
- **Utilize correlations between Ne and N_{mu} to determine the mass spectra**
  - Correlations increase discrimination power



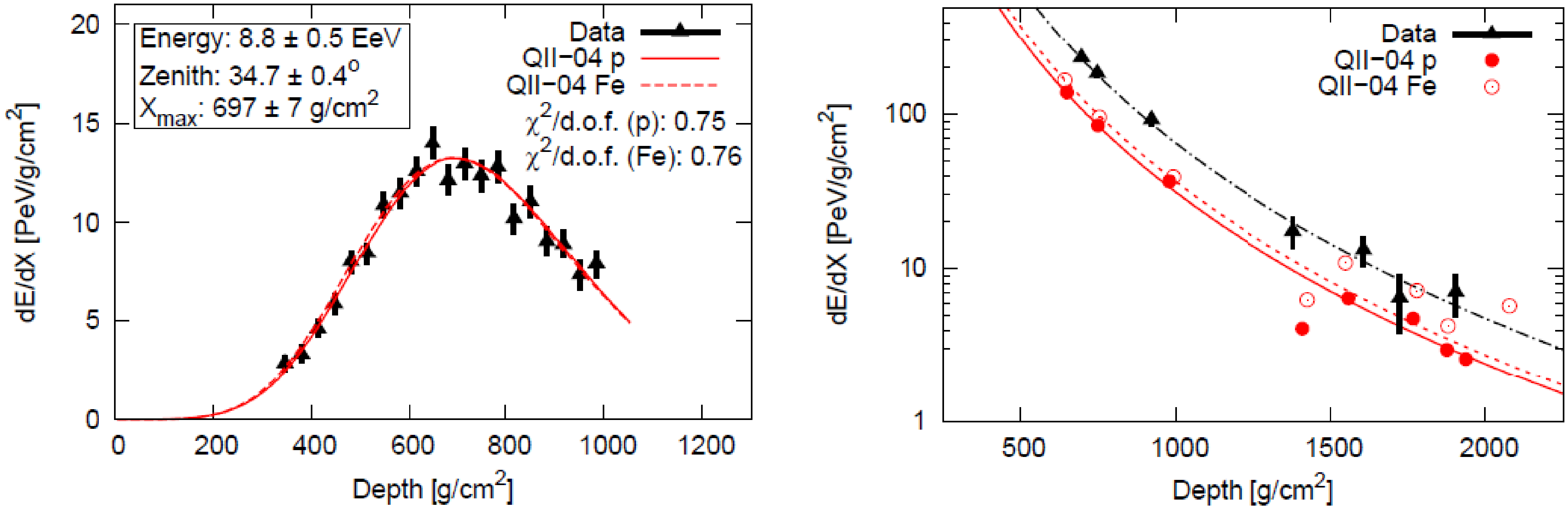


Auger Event-by-Event E~10^{19} eV

Top-down reconstruction

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

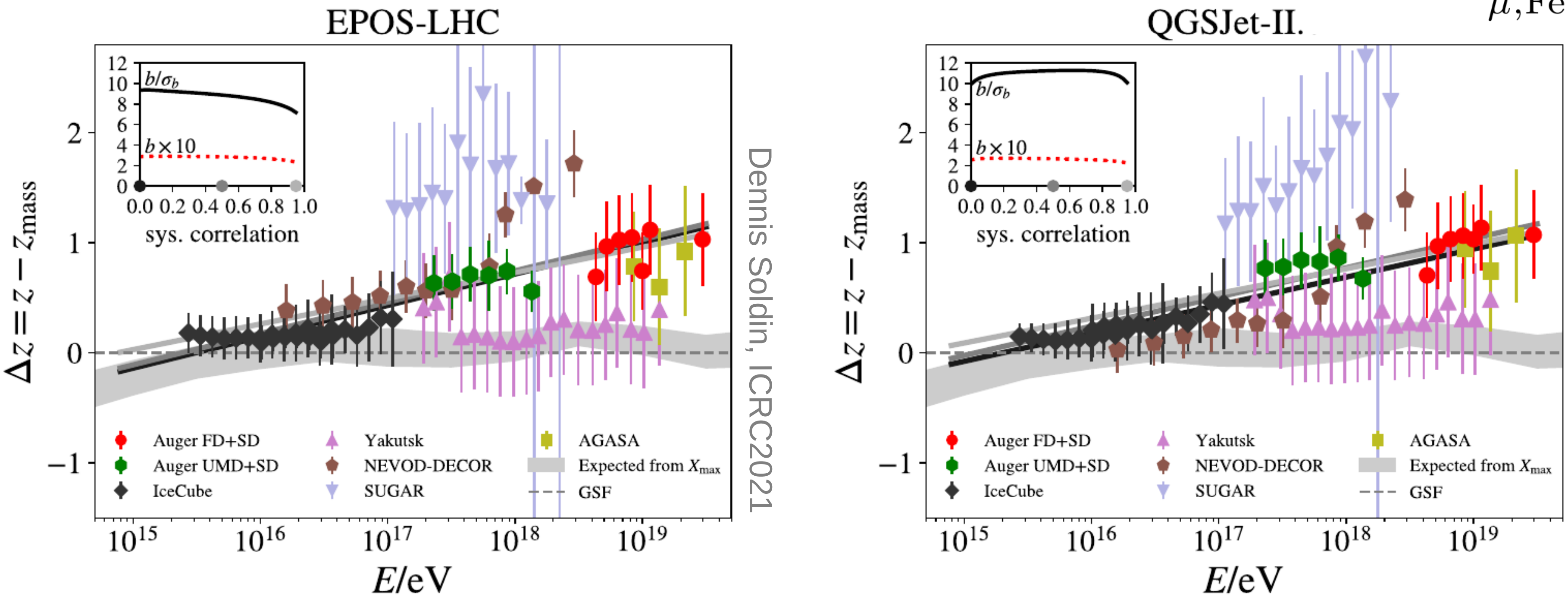
A problem appear : not enough signal at ground in simu : missing muons !



Muon “Puzzle”

- **Clear muon excess in data compared to simulation**
  - ➡ Different energy evolution between data and simulations
    - ➡ Significant non-zero slope (>7σ)

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



Dennis Soldin, ICRC2021

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

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

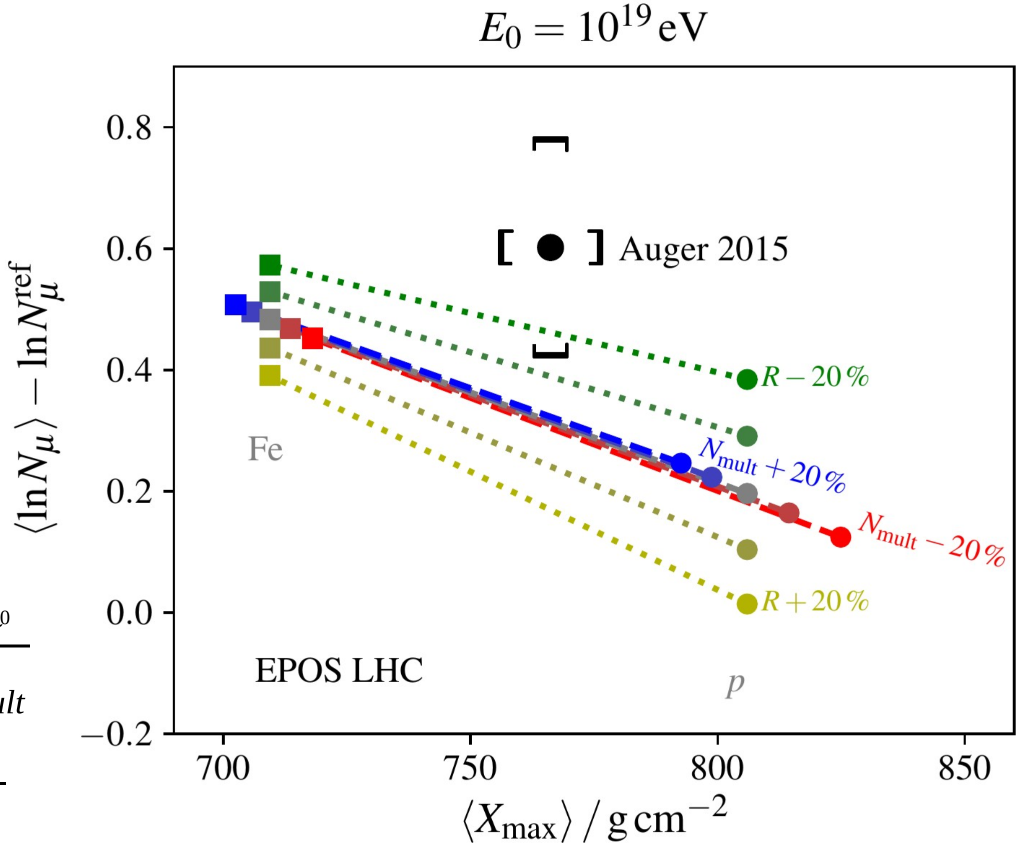
Constraints from Correlated Change

- **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

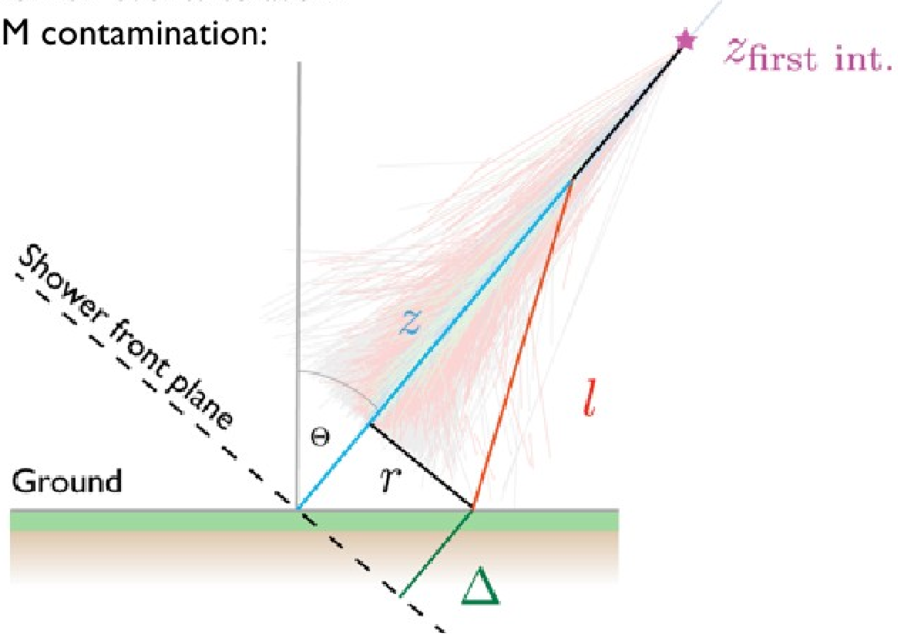
$$\begin{aligned} c \cdot t_g &= l - (z - \Delta) \\ &= \sqrt{r^2 + (z-\Delta)^2} - (z - \Delta) \end{aligned}$$

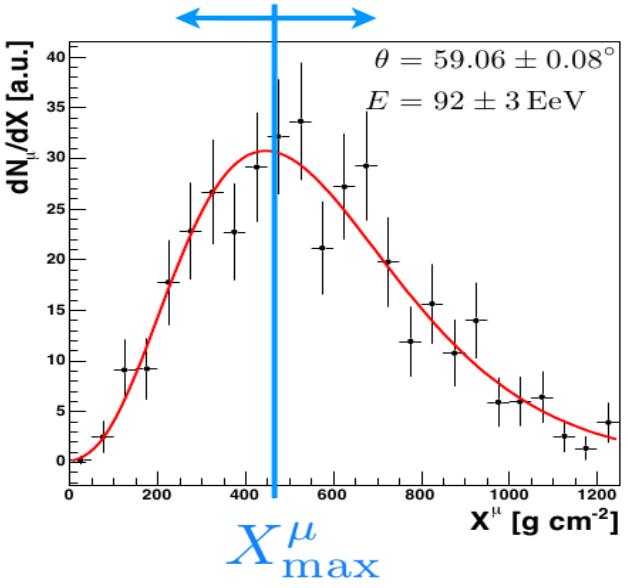
- mapped to muon production distance

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

- 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)

Inclined events to avoid EM contamination:

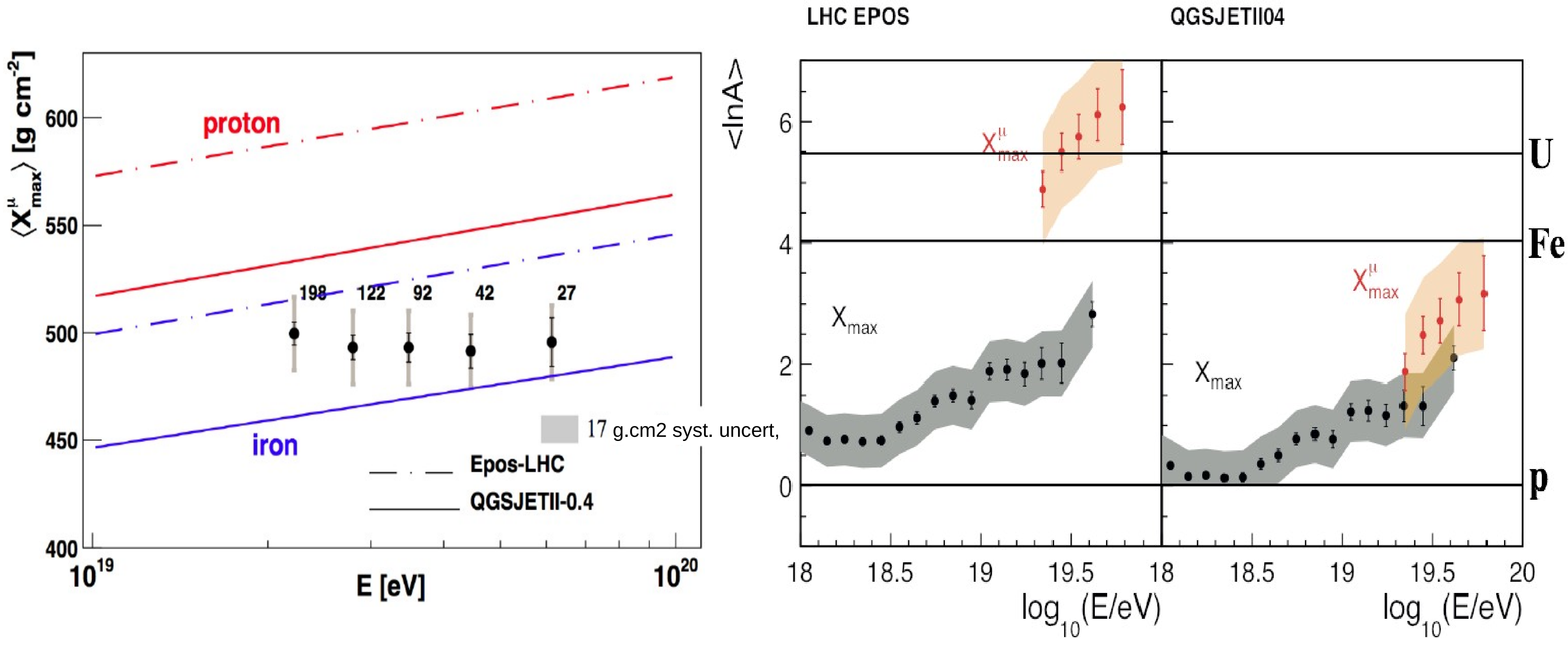




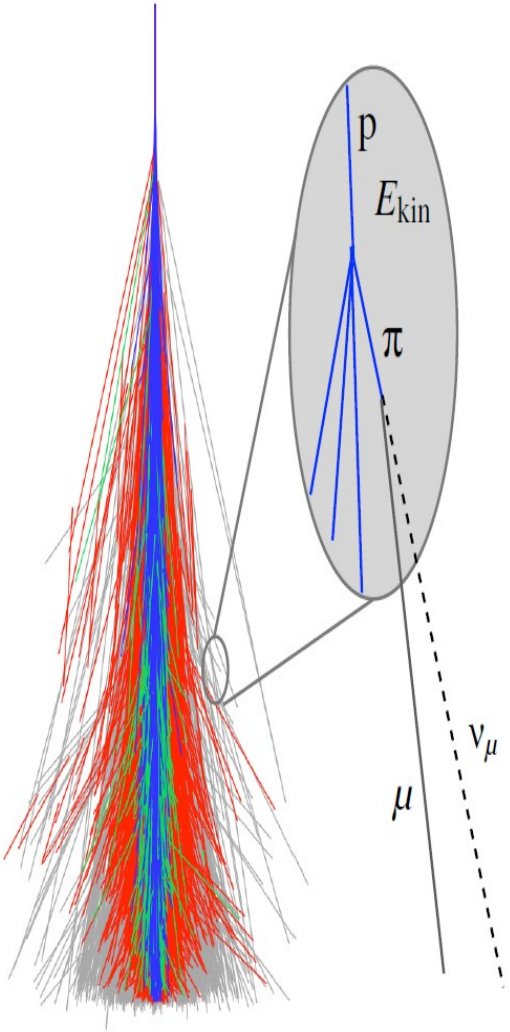
Muon Production Depth and Models

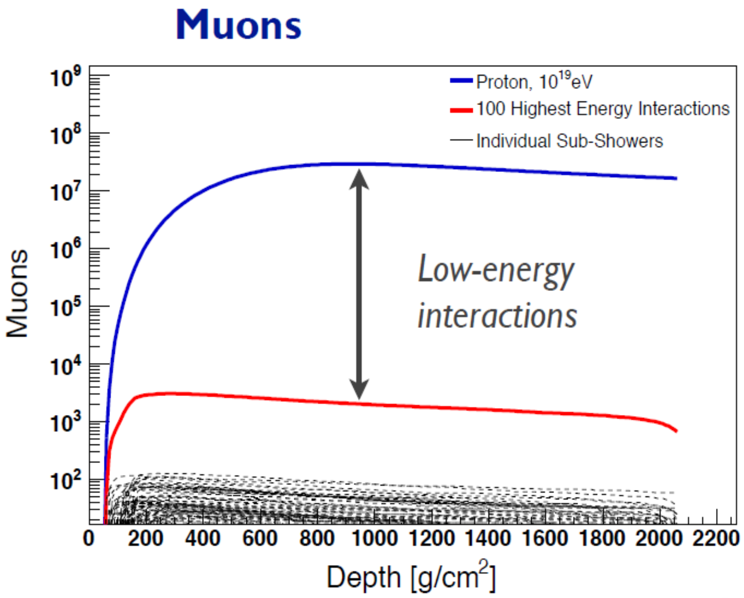
2 independent mass composition measurements

- ➡ 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



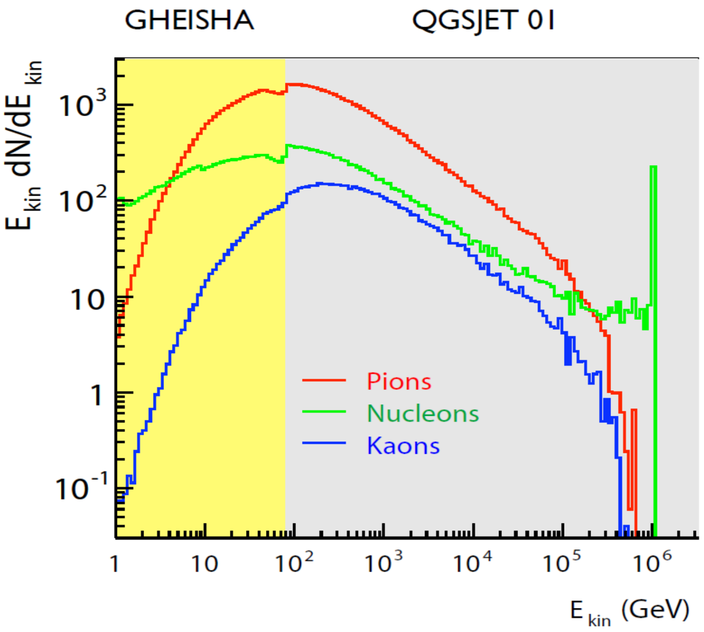
Muon production by low energy interactions

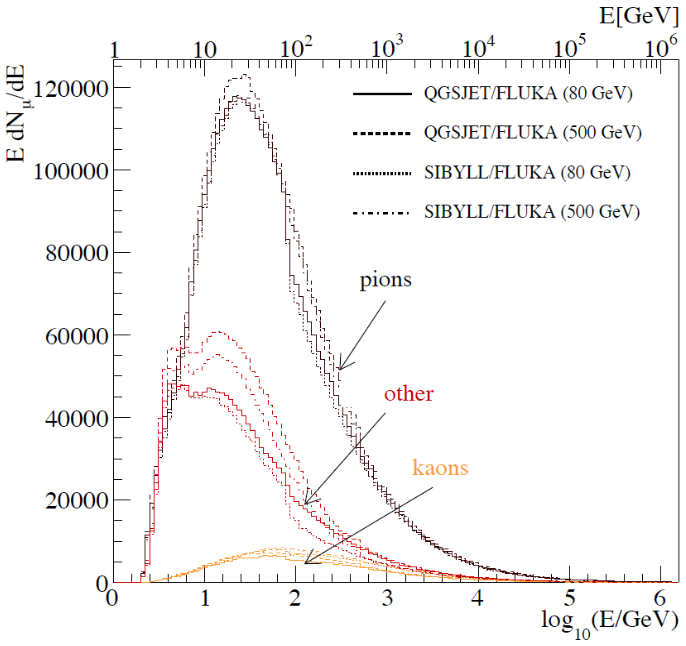




~ 100 GeV for KASCADE
~ 30 GeV for Auger

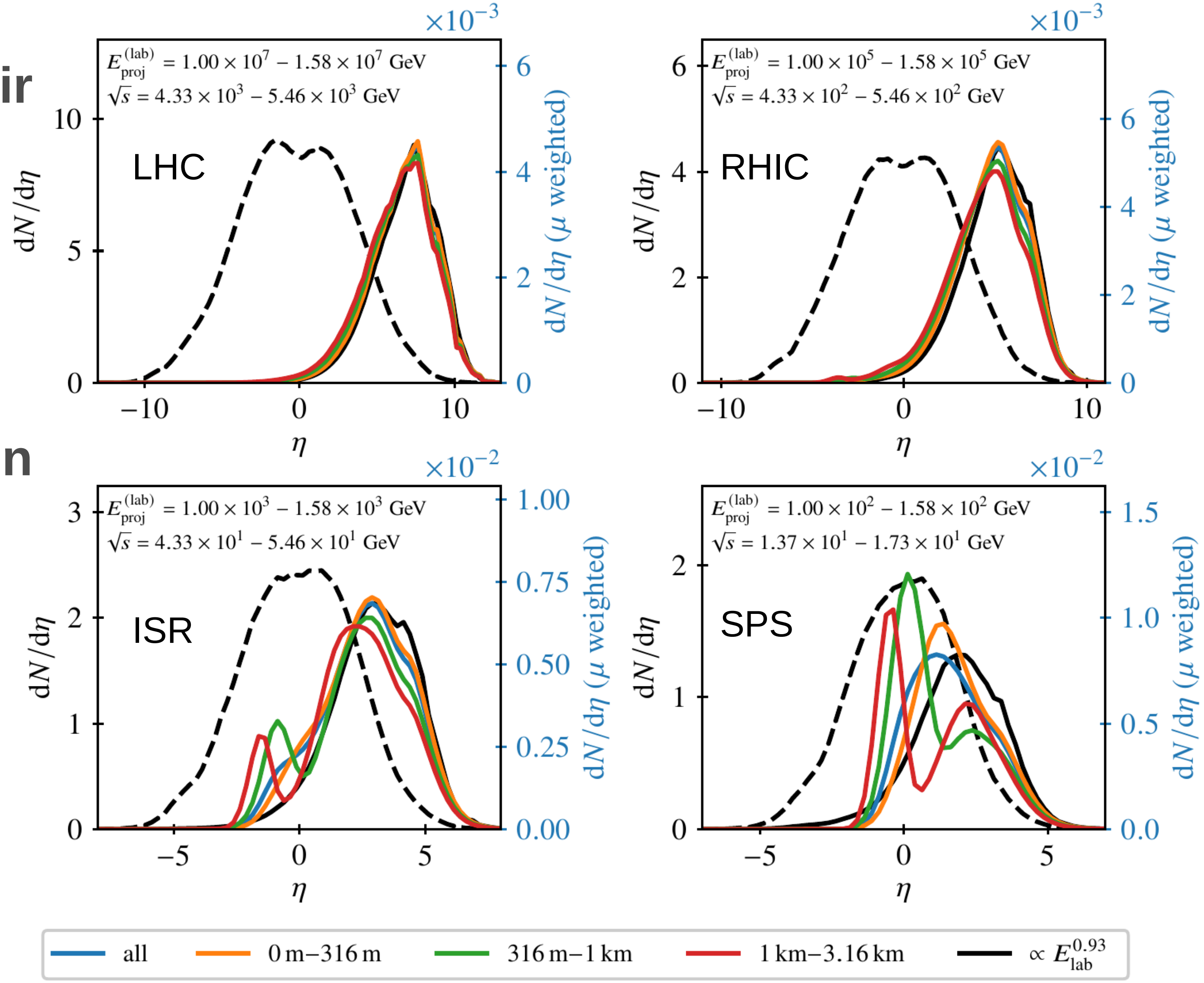
Muons/hadrons:
low-energy interactions





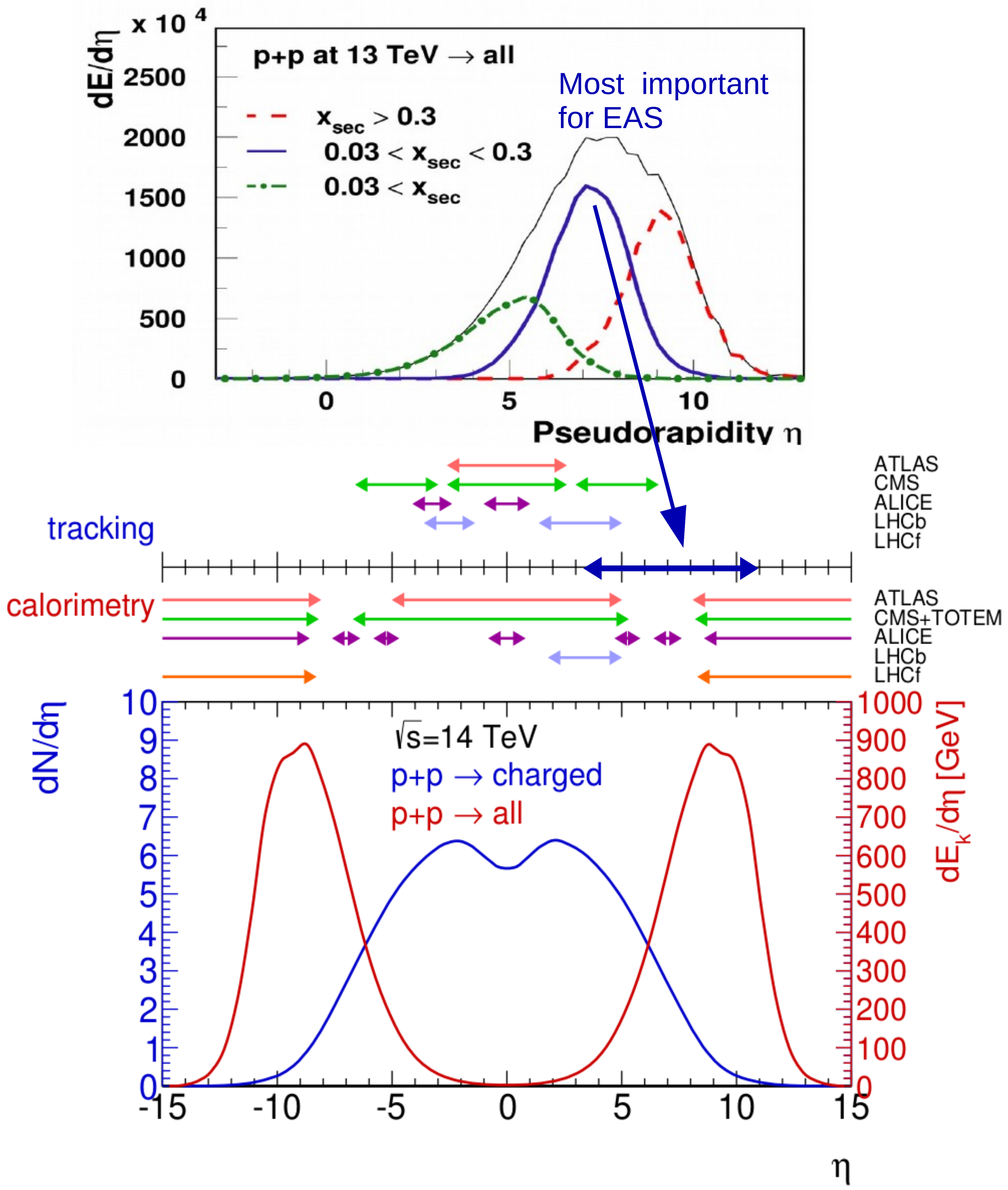
Relevant Phase Space in Air Showers

- **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 η=-ln(tan(θ/2))
  - θ=0 is midrapidity
  - θ>>1 is forward
  - θ<<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

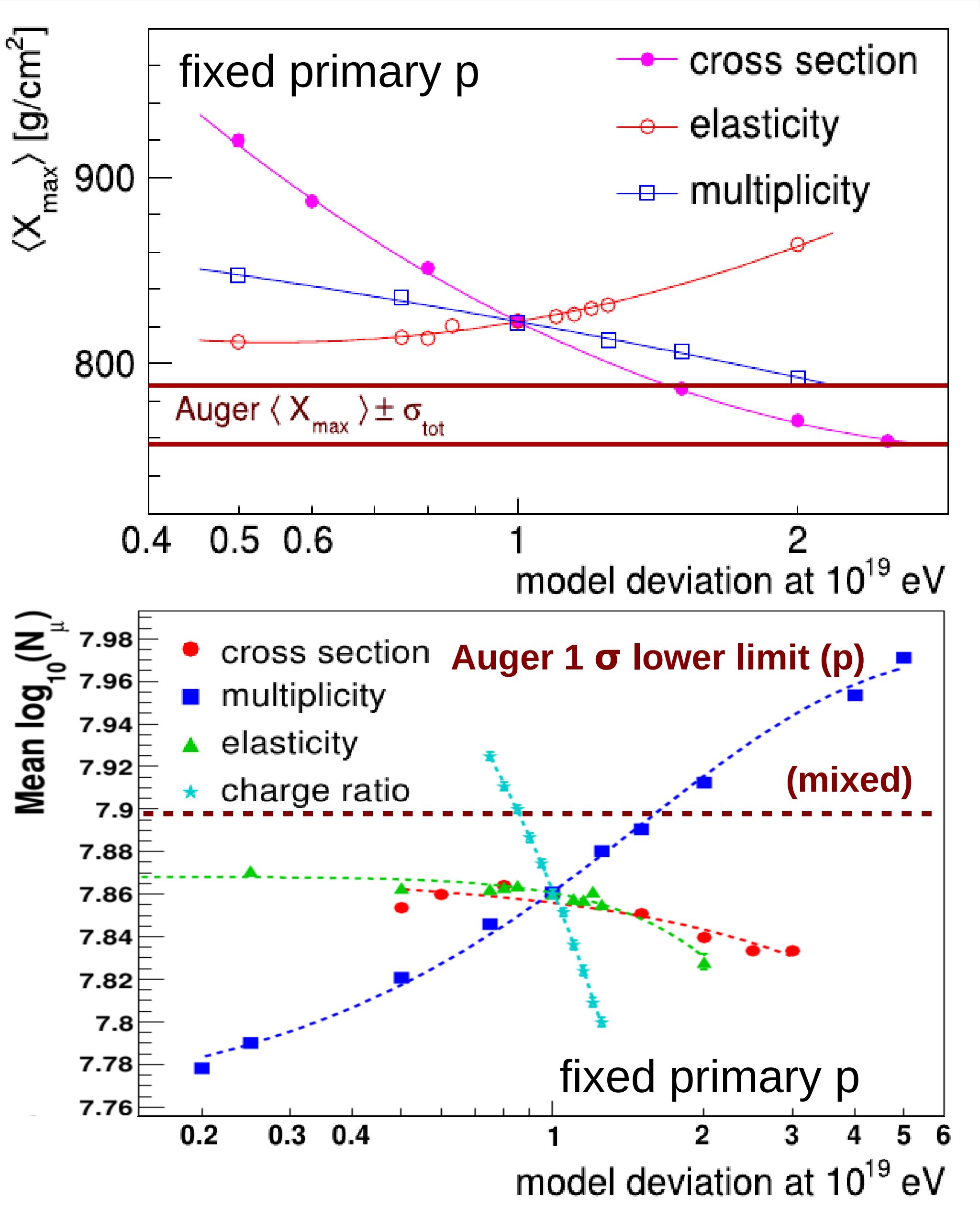
Lessons From Heitler Model

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