

Percolation and high energy cosmic rays above 10^{17} eV

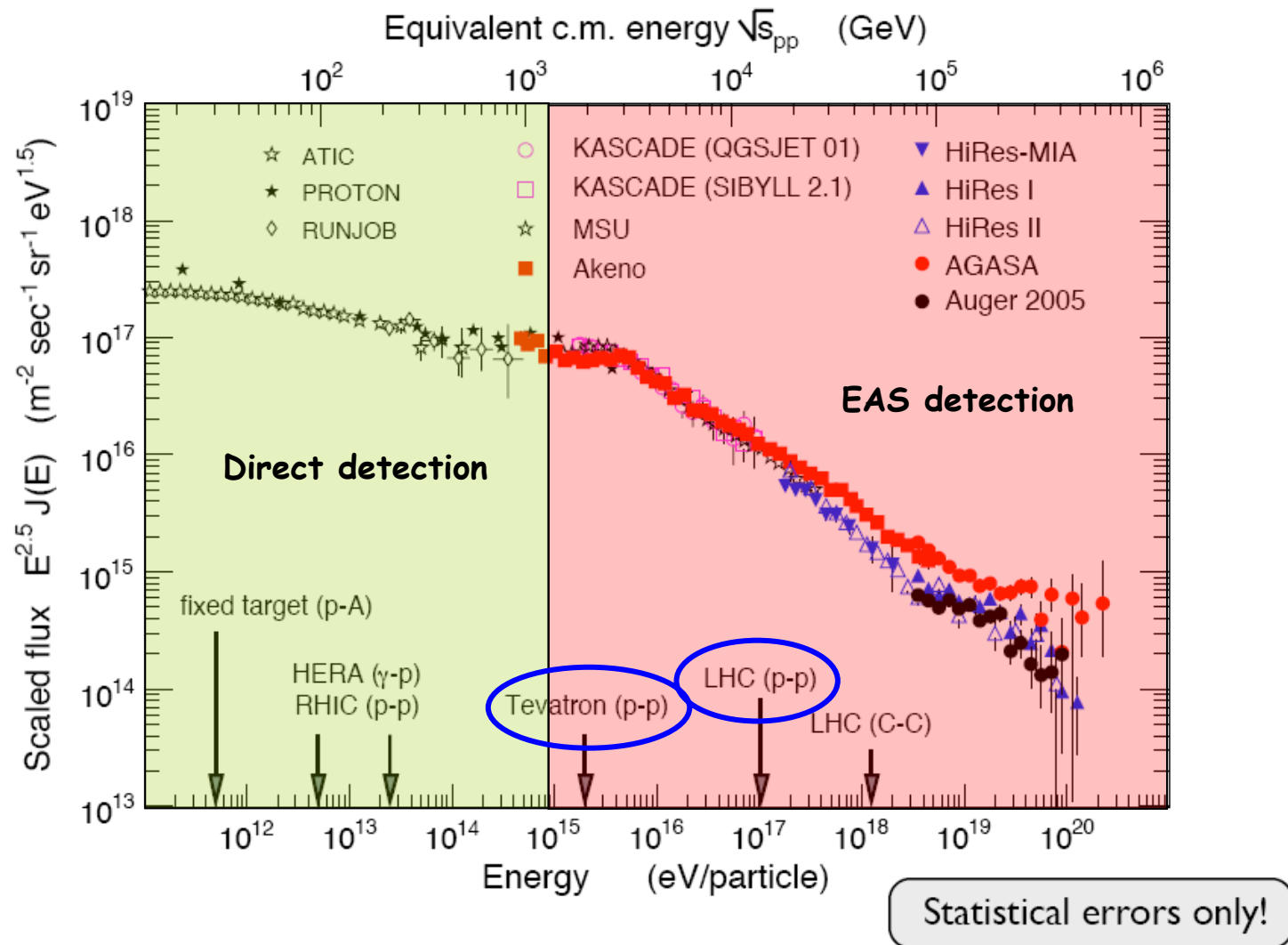
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The cosmic ray spectrum

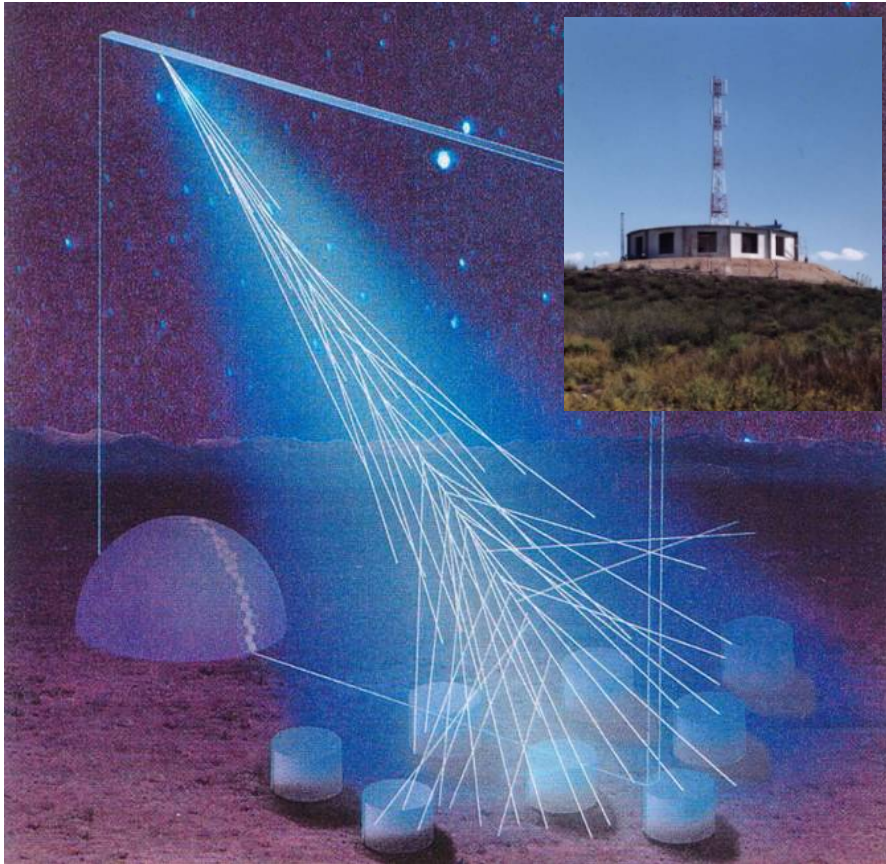


2 features in Cosmic Ray data above 10^{17} eV

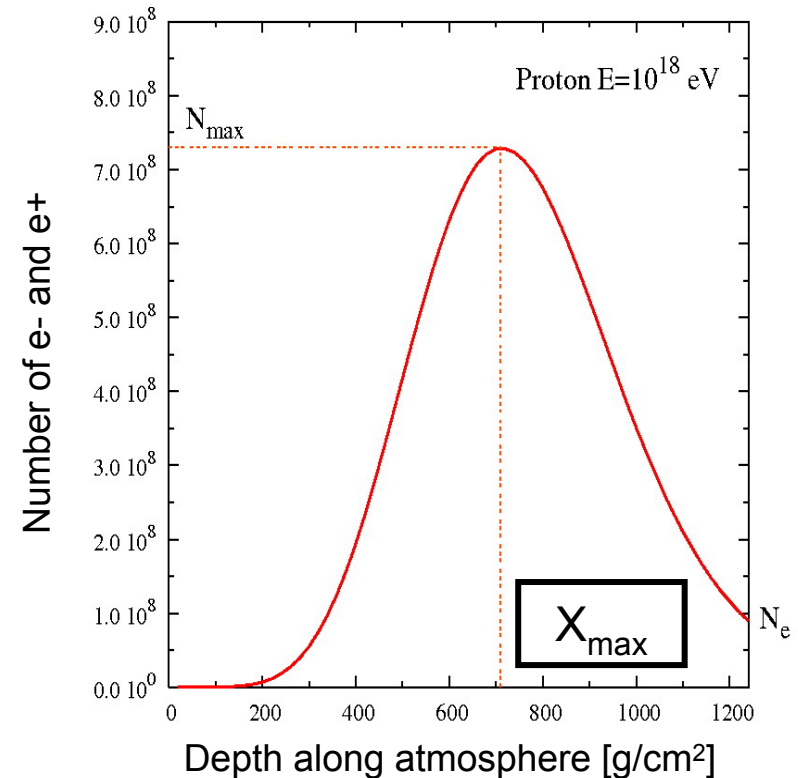
Depth of shower maximum X_{\max}

Fluorescence detector of the
Pierre Auger Observatory

...also HiRes in Utah.



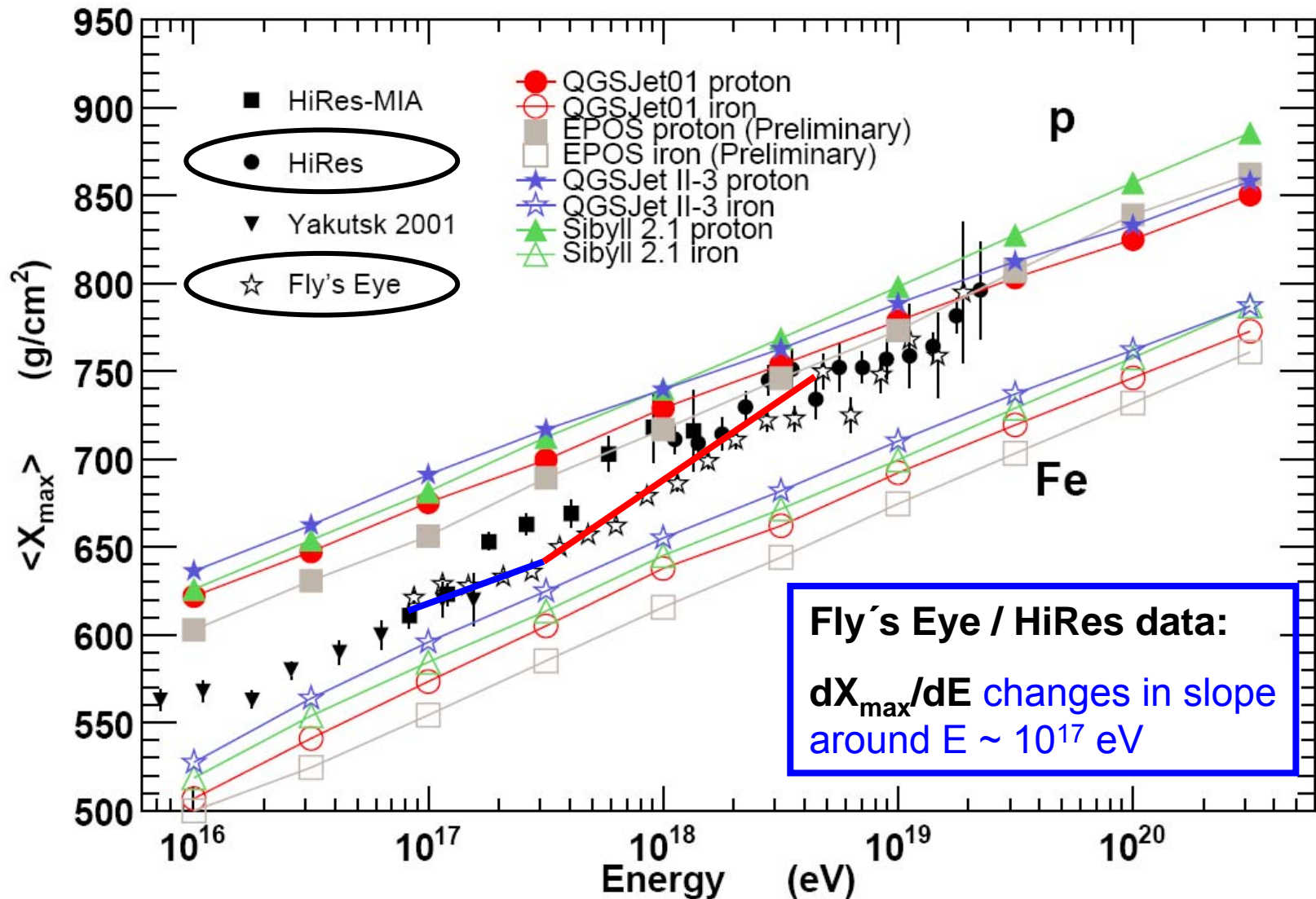
Longitudinal development
(MC simulation)



X_{\max} is sensitive to primary cosmic ray composition & to the hadronic model

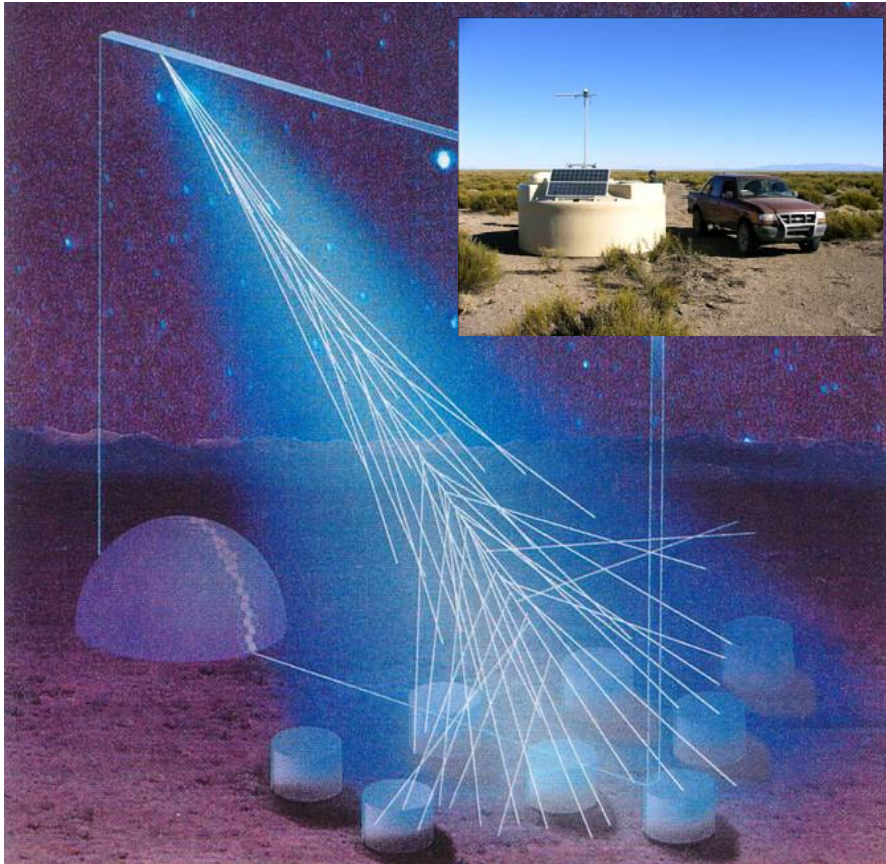
X_{\max} vs shower energy

Handle on composition: $\langle X_{\max} \rangle (\text{Fe}) \sim \langle X_{\max} \rangle (\text{p}) + 100 \text{ g/cm}^2$



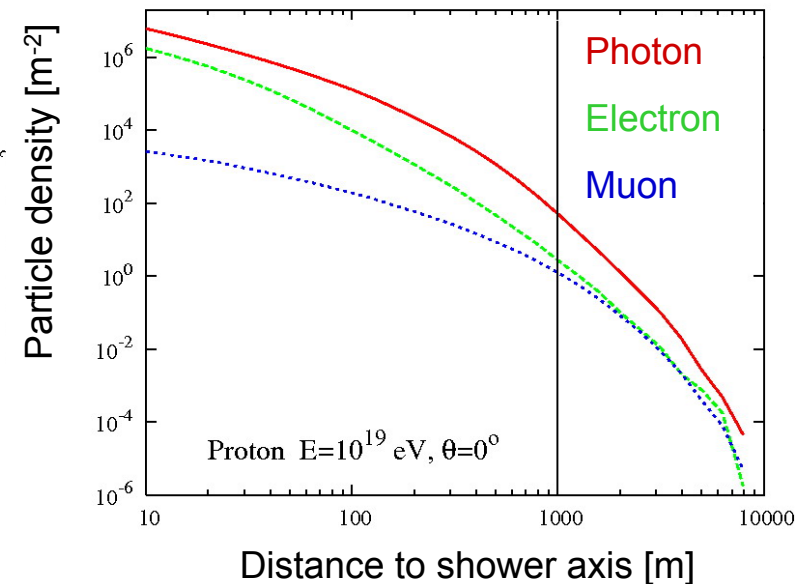
Muon content of air showers: N_μ

Surface detector of the Pierre Auger Observatory



Akeno-AGASA array is more sensitive to the muon content (specific shielded detector units)

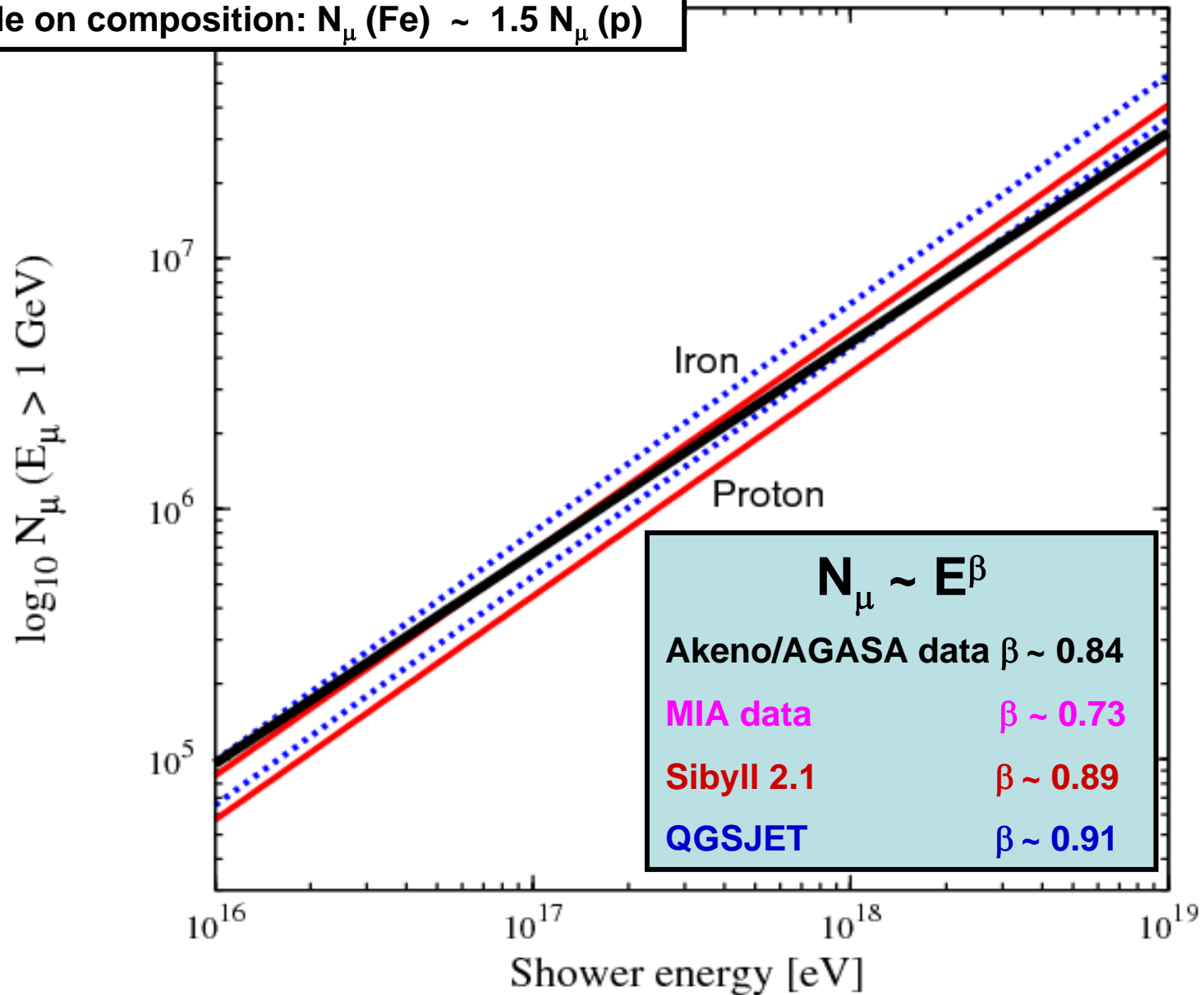
Lateral development
(MC simulation)



The muon content is sensitive to the hadronic model & composition

N_μ vs shower energy

Handle on composition: $N_\mu(\text{Fe}) \sim 1.5 N_\mu(\text{p})$



Composition interpretation of CR data

- 1) dX_{\max}/dE : change in slope above $E > 10^{17}$ eV.
- 2) N_{μ} vs E_{shower} : discrepancies between data & models.

1) and 2) seem to indicate a composition changing from heavy to light as shower energy increases...

But:

- Rather indirect measurement of the mass number A .
- Relatively scarce data at the highest energies ($E > 10^{17}$ eV)

Can other variables besides primary CR composition play a role in the explanation of CR data?

... other variables besides A may play a role !

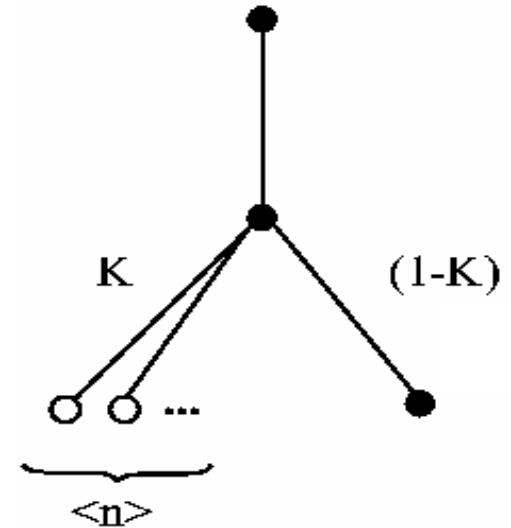
- First few high energy hadronic collisions are crucial in the shower development:
 - Inelasticity K
 - Multiplicity
 - Nature of the most energetic particle
- Interaction models are extrapolated from much lower energies (3 - 4 orders of magnitude at least) & in regions of parameter space of the collisions not probed in accelerators (forward region, small p_t, \dots)

Inelasticity K and X_{\max}

- Inelasticity K

fraction of collision E carried by secondaries except for the most energetic one.

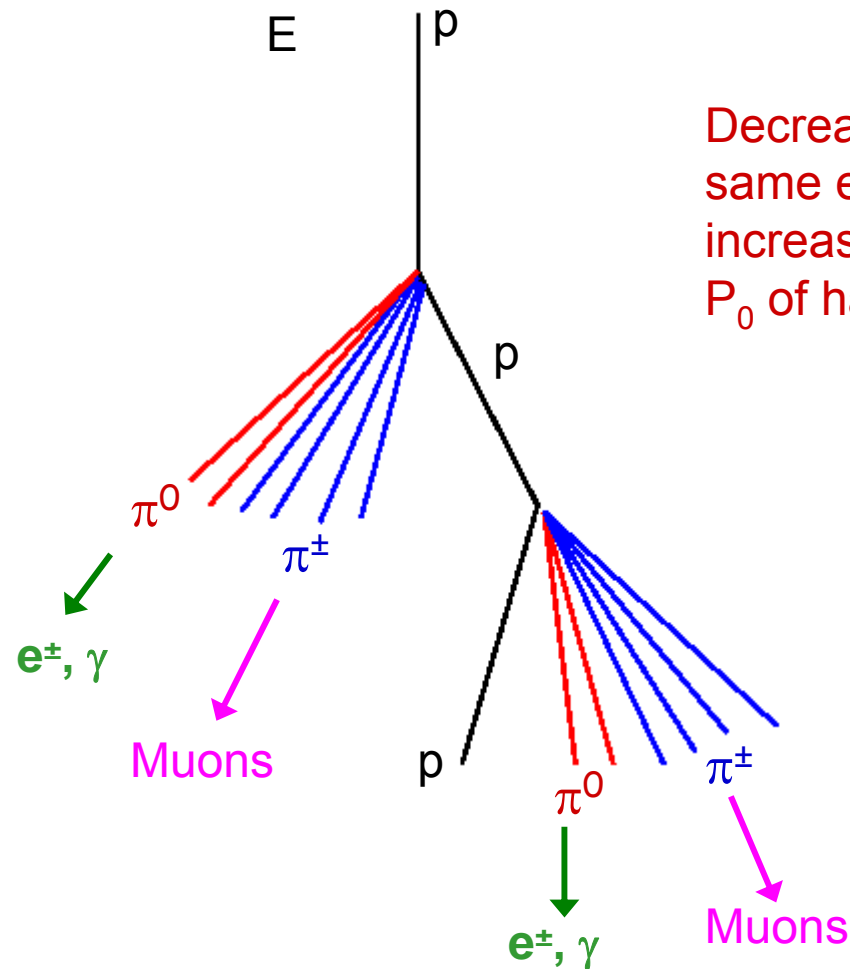
$1 - K$ is the fraction of the shower energy carried by the fastest (leading) particle



- Fast particles flow along the $(1 - K)$ branch & essentially determine X_{\max} ...
- A decrease in A has the same effect on X_{\max} as a decrease in K :
 - Going from Fe to proton, the shower will develop deeper.
 - The same is true if K decreases with the energy.

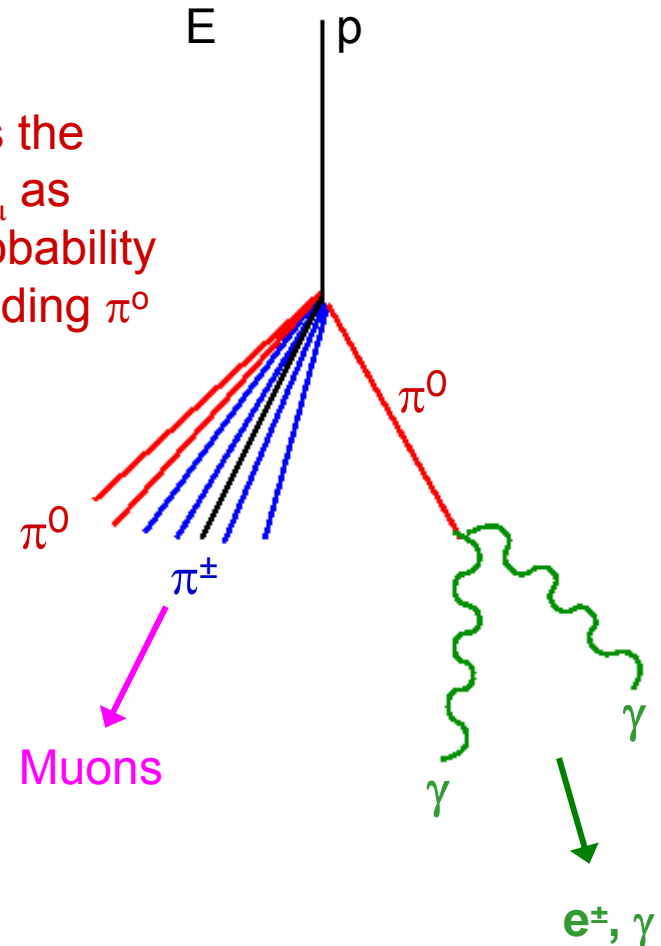
The nature of the leading particle and N_μ

Leading proton



$$E_\mu \sim \frac{2}{3} KE + \frac{2}{3} K(1-K) E + \dots$$

Leading π^0



$$E_\mu \sim \frac{2}{3} KE$$

Decreasing A has the same effect on N_μ as increasing the probability P_0 of having a leading π^0

String Percolation

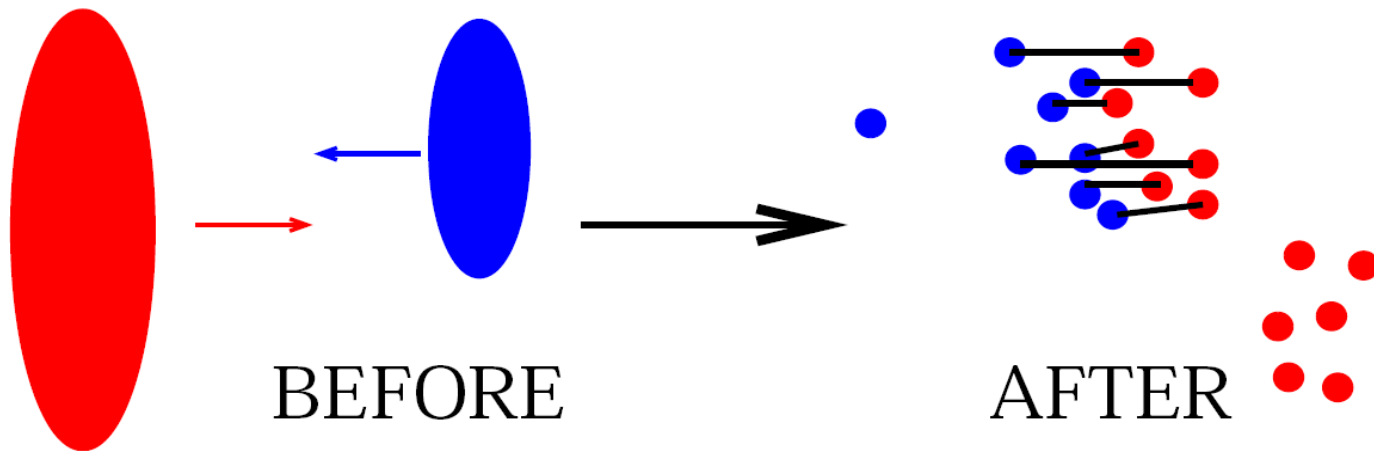
- Looking for a model that is able to give a consistent interpretation of X_{\max} & N_{μ} vs E_{shower} :
 - K decreasing with energy.
 - A considerable fraction of leading π^0 's (relatively large P_0).
- Two puzzles, one solution: **string percolation.**

The (very) basics of percolation model (I)

Percolation is a string model: multiparticle production is described in terms of color strings stretched between partons of projectile and target, which decay (hadronize) into the final particles.

Collision as viewed in the longitudinal space

Transverse space of the collision



The number of exchanged strings increases with energy (density) and mass.

Pajares, EPJC 43 (05) 9 (hep-ph/0501125); Armesto et al., PRL 77 (96) 3736 (hep-ph/9607239); Nardi & Satz, PLB 442 (98) 14 (hep-ph/9805247).

The (very) basics of percolation model (II)

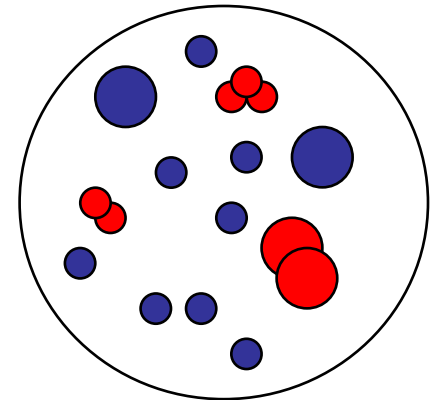
- As energy (density) increases, the color fields carried by strings start to overlap (they are no longer independent objects) and percolation occurs ...

Transverse density: $\eta \equiv \left(\frac{r}{\bar{R}} \right)^2 \bar{N}_s$

\bar{N}_s average nb. of strings
 r transverse radius of a string
 \bar{R} effective radius of interaction area

$\eta < \eta_c \approx 1.13 \rightarrow$ Strings act as independent objects.

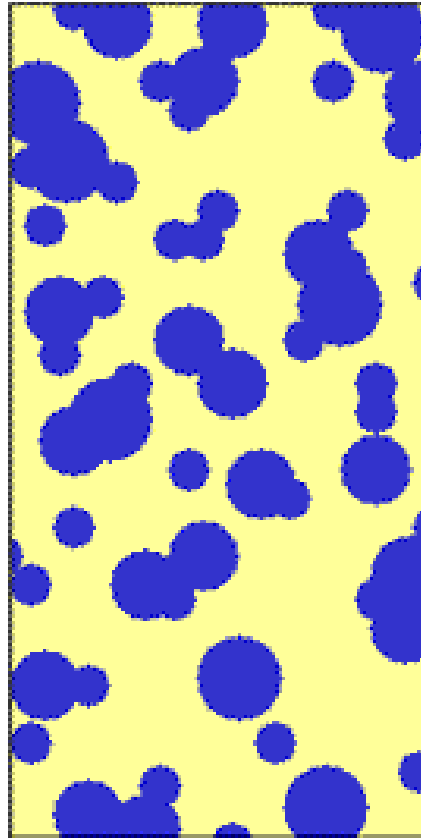
$\eta > \eta_c \approx 1.13 \rightarrow$ Strings begin to overlap.



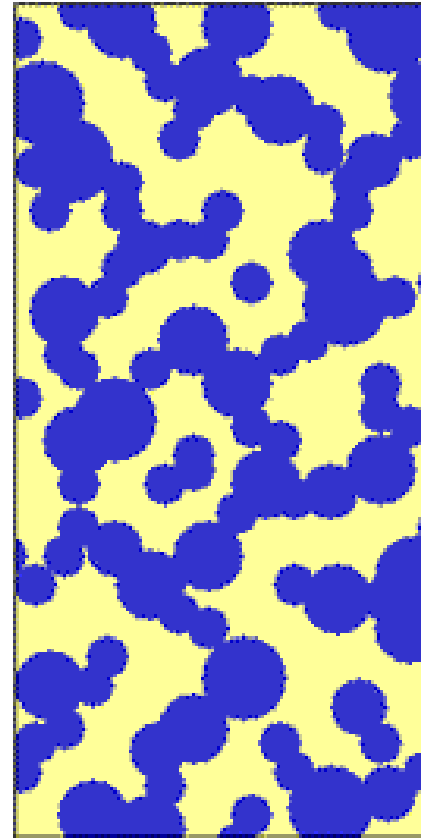
$\eta_c \approx 1.13$ can be seen to correspond to $\sqrt{s} \sim 10^4$ GeV or $E_{\text{lab}} \sim 10^{17}$ eV

Percolation

Below the
Percolation
Threshold



Above the
Percolation
Threshold



- String viewed in the space transverse to the collision axis

Predictions of percolation relevant to EAS

At relatively low E:

- Valence strings (forward/backward) contain most of the collision energy
- As the energy increases, sea strings (central in rapidity) take away part of the energy and softer secondaries are produced.

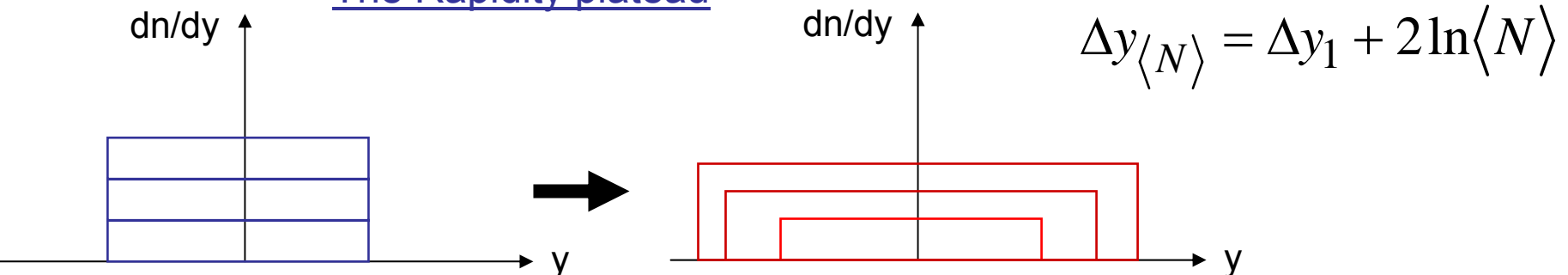
→ **K increases with E**

At higher E (above the percolation threshold at $\sim 10^{17}$ eV):

- As density increases, strings start to overlap and percolation occurs.
- From the larger percolated strings (clusters) faster secondaries are produced.
- Percolation is a mechanism for producing fast leading particles.

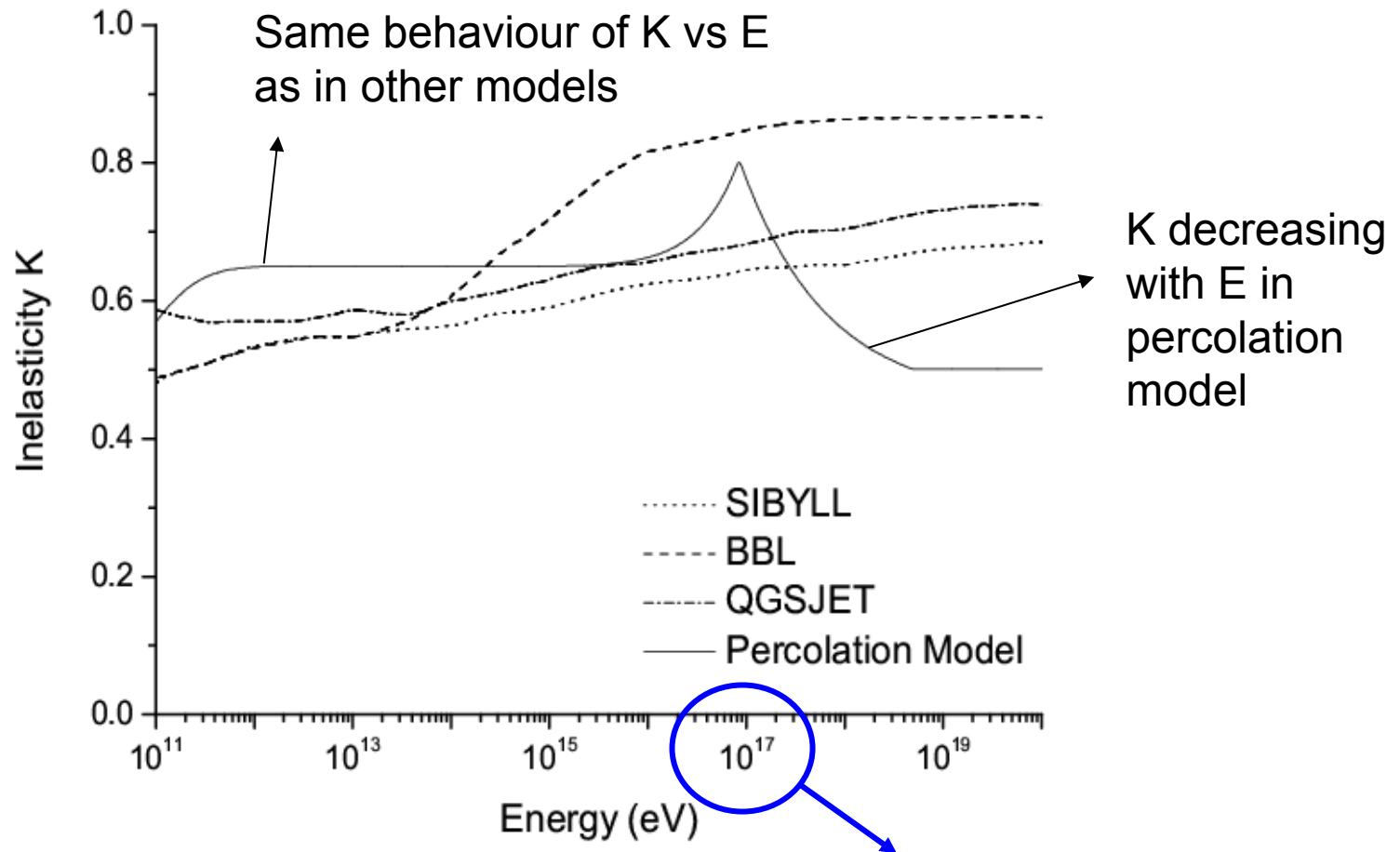
→ **K decreases with E**

The Rapidity plateau



Predictions of percolation relevant to EAS

Inelasticity decreases with E above the percolation threshold: sea strings fuse and take over the valence strings: less small-Energy secondaries are produced and fast leading particles are generated.



Predictions of percolation relevant to EAS

Multiplicity reduction: due to percolation there are less sea strings because they fuse, i.e. there are **less secondaries** than in models where strings hadronize independently.

$$\frac{dn}{dy} \equiv F(\eta) \cdot \overline{N_s} \cdot \overline{n}$$

$F(\eta)$ colour summation factor
 \overline{n} particle density for one string

$$F^2(\eta) \equiv \frac{S_n}{nr^2} \text{ with } S_n = \text{area occupied by a cluster of } n \text{ strings}$$

Increased probability of having a leading π^0 : sea clusters of strings of quark-antiquark type are formed, i.e. **fast mesons** are generated.

Prediction: probability of π^0 leading $P_0 \sim 0.3$ (models without string percolation predict $P_0 \sim 0.1$ at most).

Summary: Consequences of percolation

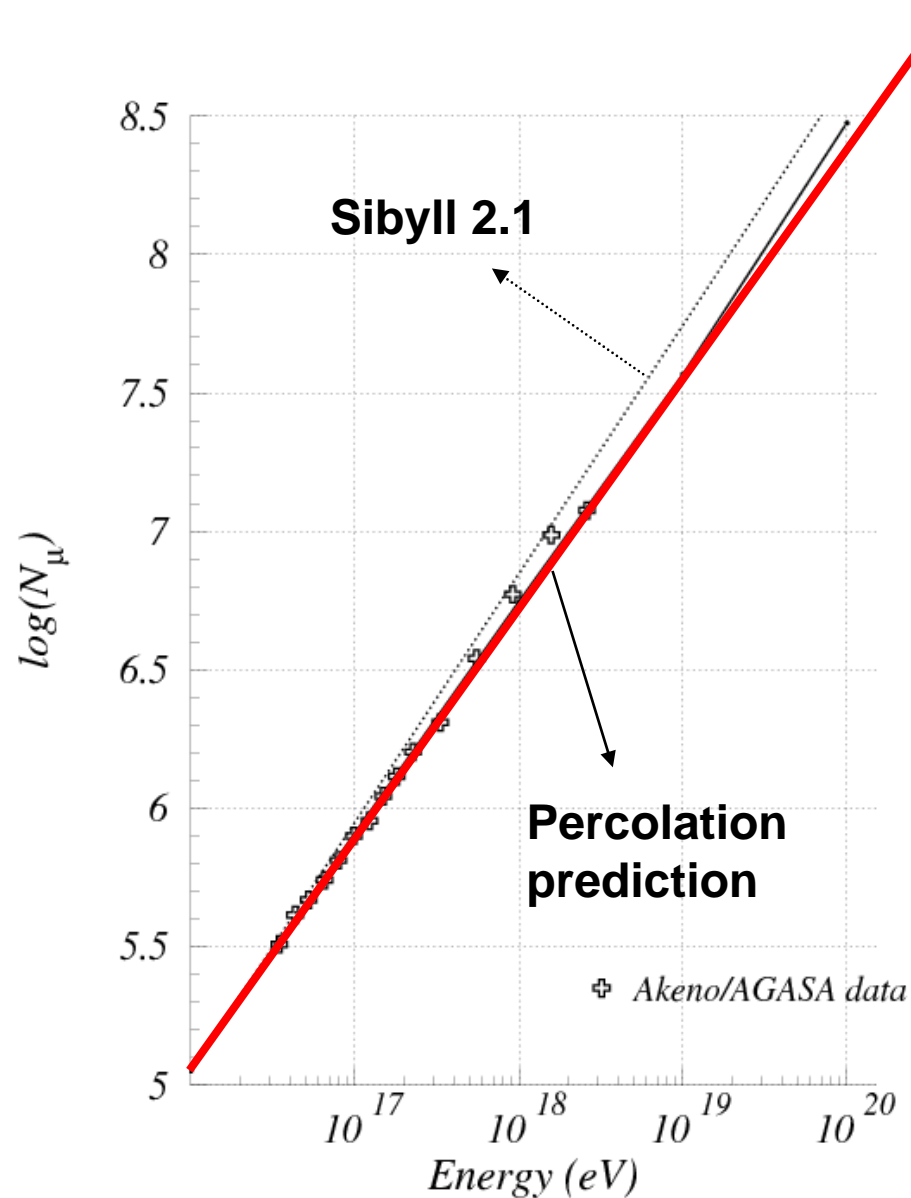
- Above the percolation threshold ($\sim 10^{17}$ eV in lab) :
 1. K is a decreasing function of the energy
 2. The probability P_0 of having a leading π^0 tends to $1/3$
 3. The multiplicity increases slower with energy than in models with no percolation
- All these features were introduced in a fast 1D hybrid simulator of EAS (J.A-M et al. PRD 66, 033011, 2002) in **ALL** the highest E interactions (most important for shower development) above the percolation threshold.
- Predictions for X_{\max} vs E_{shower} and N_{μ} vs E_{shower} were derived.

Implementation of percolation in an EAS simulation

1. **Inelasticity** predicted by percolation in **ALL** hadronic interactions with $E \geq 10^{16}$ eV.
2. **Multiplicity reduction** (color summation reduction factor [M. Braun et al. PRC 65, 024907, 2002]) in **ALL** collisions with $E \geq 10^{17}$ eV.
3. **Probability of leading being a π^0** = 1/3 in **ALL** hadronic collisions with $E \geq 10^{17}$ eV.

Underlying model SIBYLL 2.1 or QGSJET01: Percolation model has to be coded into a Monte Carlo usable in EAS simulations.

Results on N_μ vs E



\times Akeno/AGASA data

$$N_\mu \sim E^{0.84 \pm 0.02}$$

Sibyll 2.1

$$N_\mu \sim E^{0.89}$$

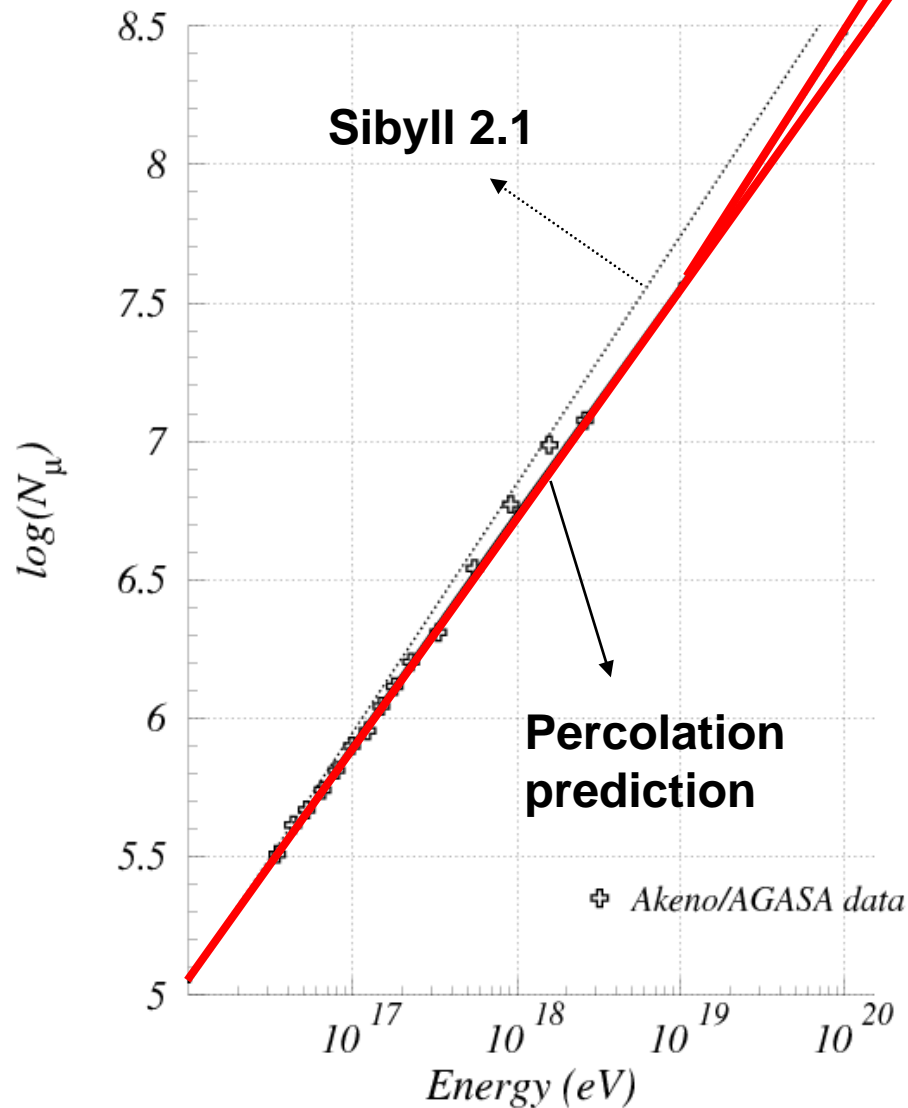
QGSJET01

$$N_\mu \sim E^{0.91}$$

Percolation model

$$N_\mu \sim E^{0.83}$$

Results on N_μ vs E



\times Akeno/AGASA data

$$N_\mu \sim E^{0.84 \pm 0.02}$$

Sibyll 2.1

$$N_\mu \sim E^{0.89}$$

QGSJET01

$$N_\mu \sim E^{0.91}$$

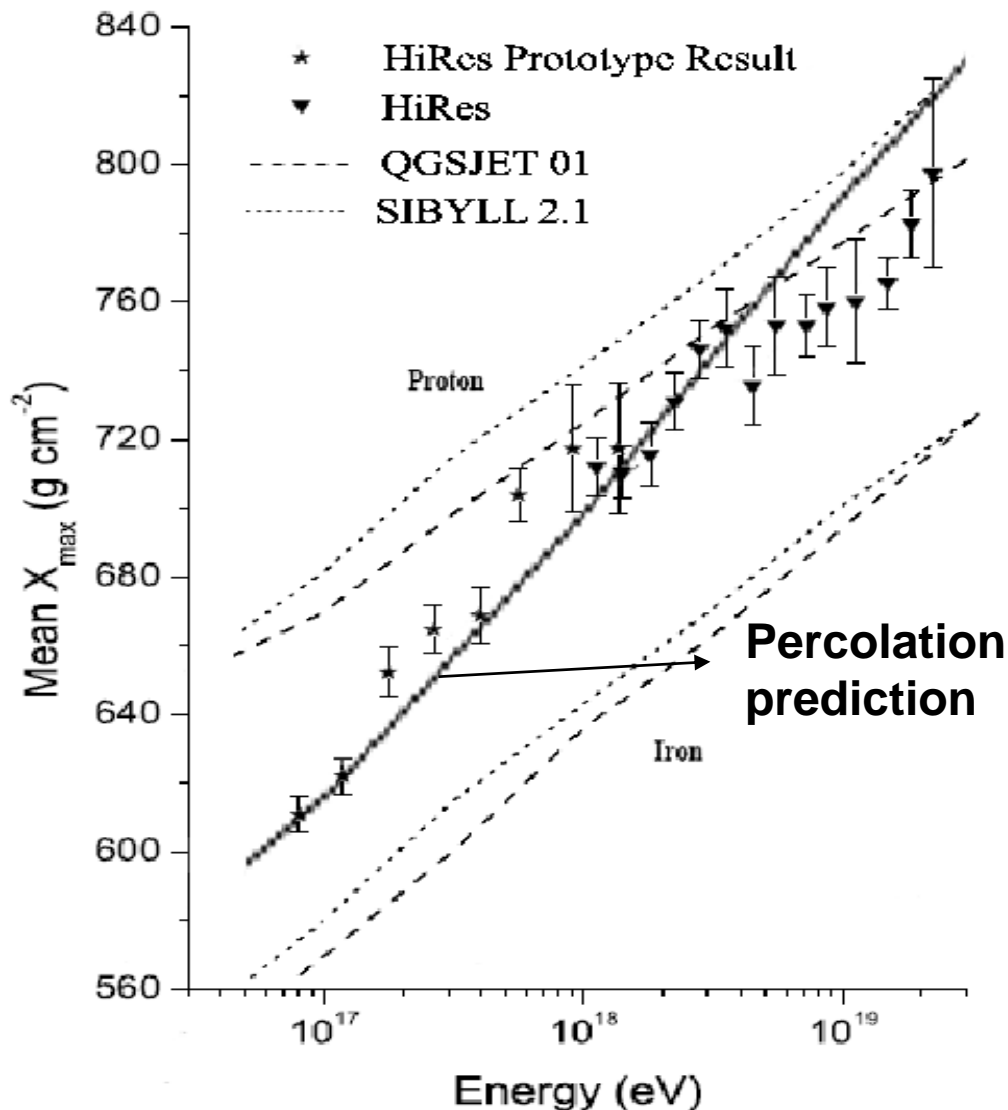
Percolation model

$$N_\mu \sim E^{0.83}$$

Prediction:

For $E > 10^{19}$ eV π^0 's start to interact in the shower & the slope of N_μ vs E should increase.

Results on $\langle X_{\max} \rangle$ vs E



Percolation reproduces the **right tendency** of X_{\max} vs E (the change of slope) **without the need for a change in composition**.

Normalization to X_{\max} and N_{μ} data suggest a medium-light composition $A \sim 15$

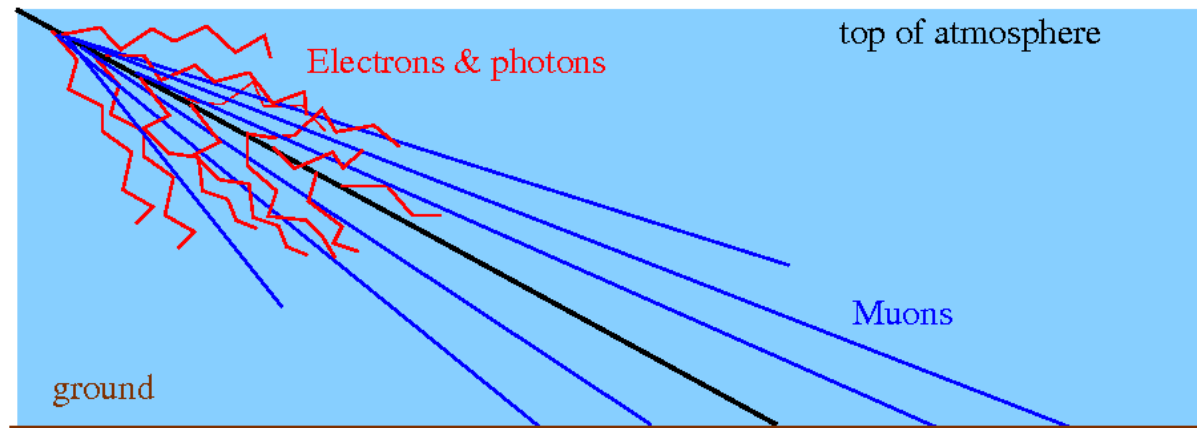
Overshooting at $E > 3 \times 10^{18}$ eV
(too simplified implementation?, probability of π^0 being leading should depend on energy).

Conclusions

- Cosmic ray data probes a region of phase space not yet reached by accelerators: extremely high-E, forward region,...
- X_{\max} and N_{μ} vs E_{shower} data usually interpreted in terms of CR composition changing with E.
- Other variables besides composition may play a role: those characterising the first (high energy) hadronic collisions (K , P_0 , $\langle n \rangle$) have been discussed.
- Within a percolation model with predictions for K , P_0 , $\langle n \rangle$, a consistent explanation of the observed N_{μ} and X_{\max} behaviour vs E was achieved (without the need for a changing composition).
 - Importance of the nature of the leading particle.

Outlook

- Dedicated **Monte Carlo code implementing percolation** usable in air shower simulations is needed !!
- Explore effects of percolation in **inclined showers**: Electromagnetic component is (largely) absorbed, mainly high energy muons reach ground (very sensitive to hadronic model).



- Effects on **other shower observables**?: Energy determination by shower arrays vs fluorescence detectors [see Dias de Deus et al. PRL 96, 162001 (2006)]

End of talk