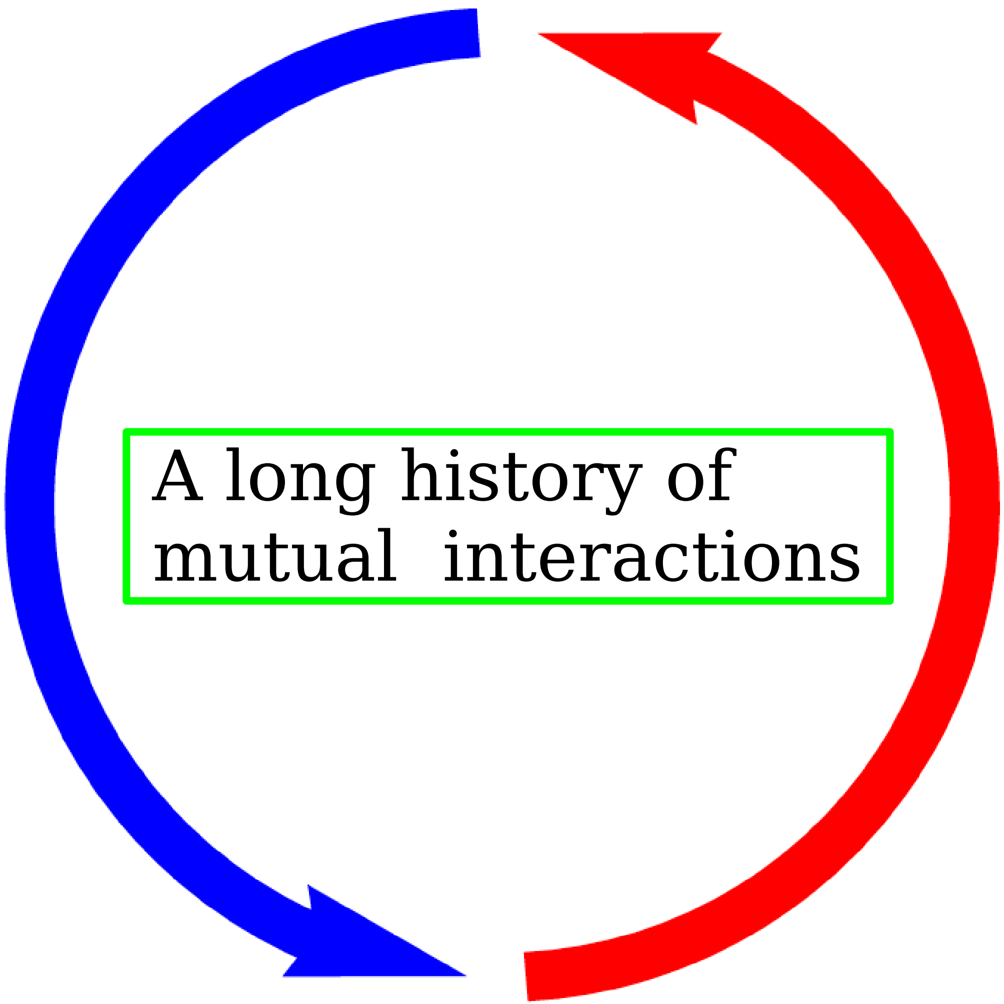
Cosmic Rays and

Hadronic Interactions

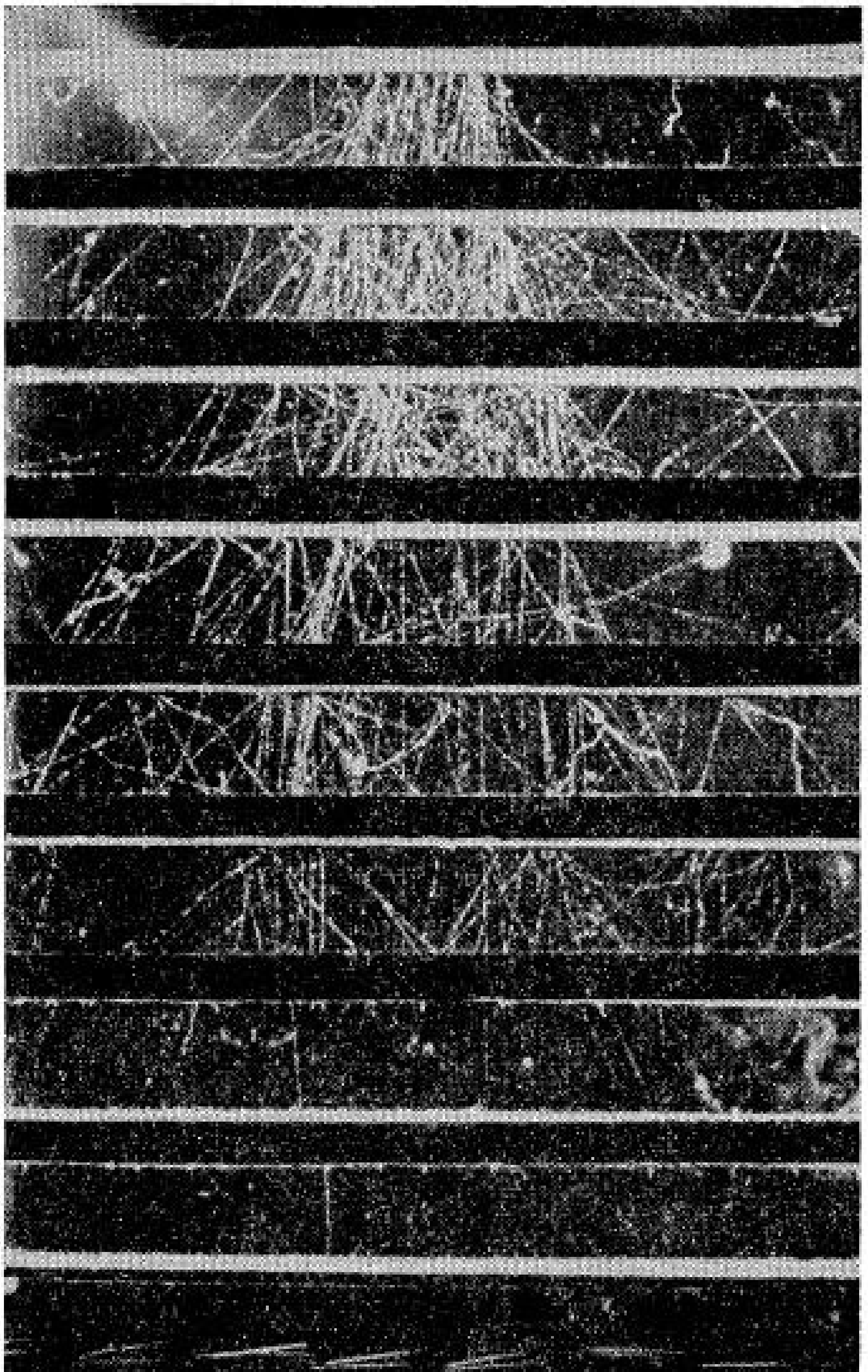
Paolo Lipari INFN Roma 1
28th may 2012

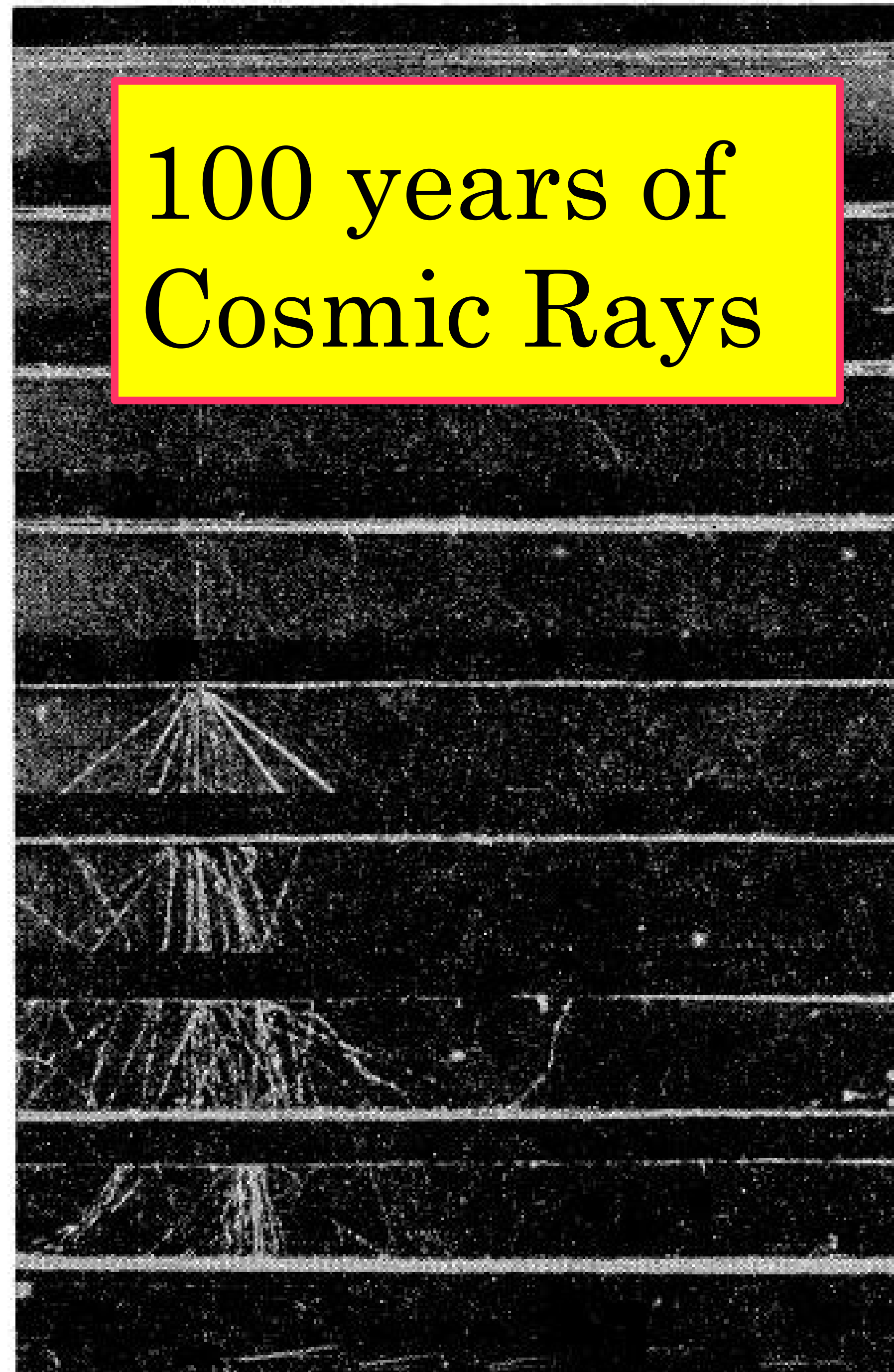
VULCANO workshop
Frontiers objects in Astrophysics
and Particle physics

PARTICLE PHYSICS



COSMIC RAYS ASTROPHYSICS



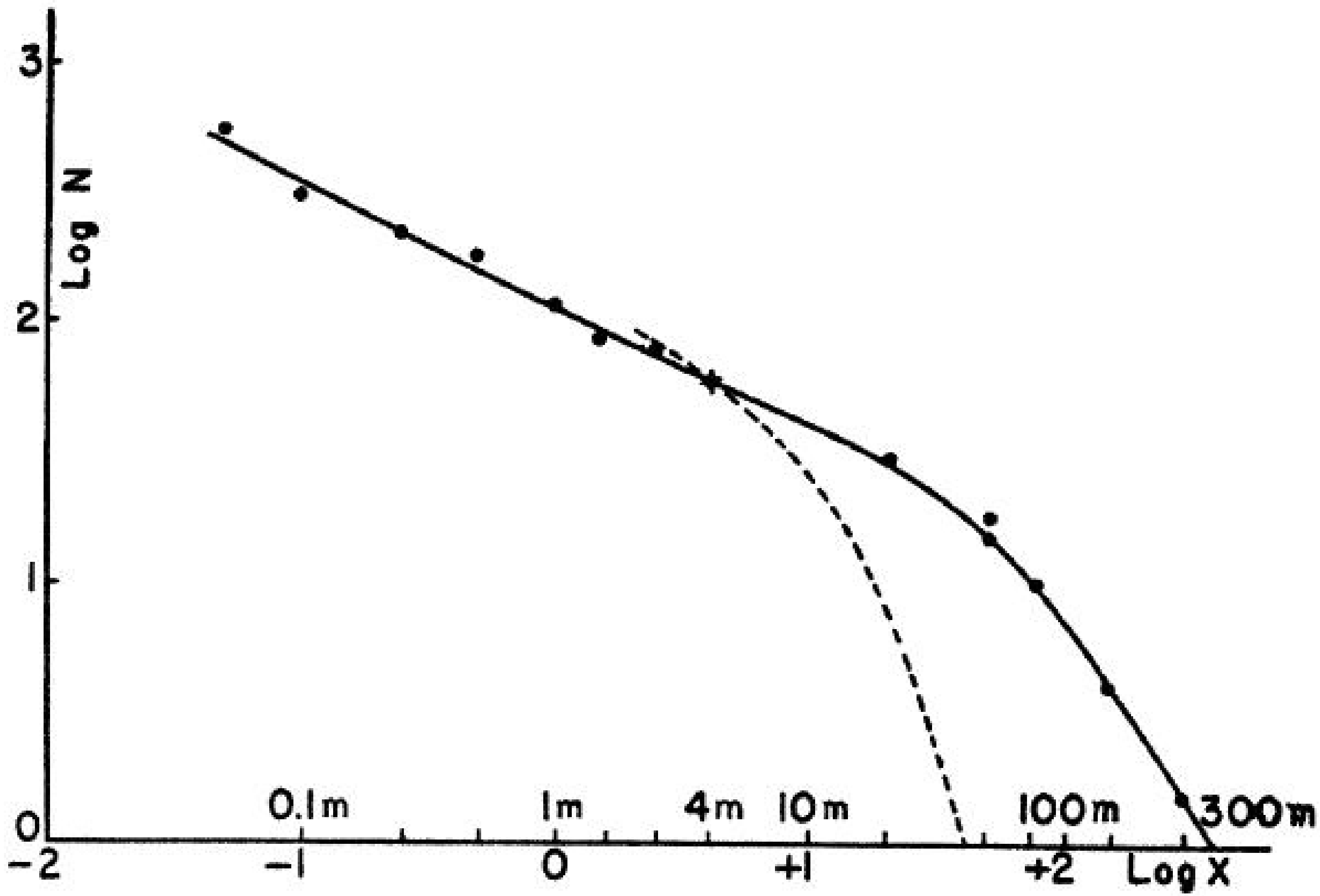

100 years of
Cosmic Rays

Pierre Auger

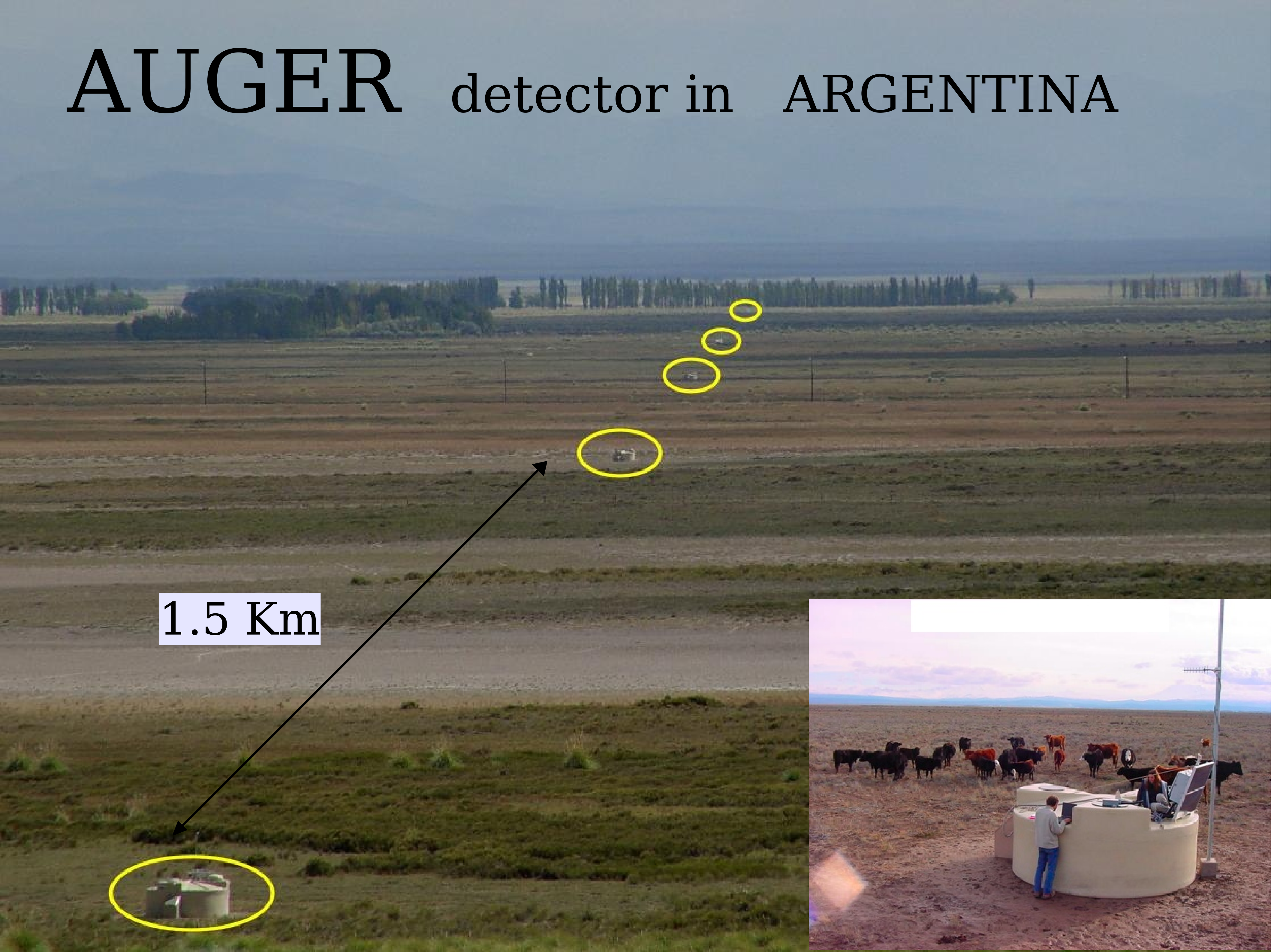
JULY–OCTOBER, 1939 REVIEWS OF MODERN PHYSICS

Extensive Cosmic-Ray Showers

PIERRE AUGER
In collaboration with
P. EHRENFEST, R. MAZE, J. DAUDIN, ROBLEY, A. FRÉON
Paris, France



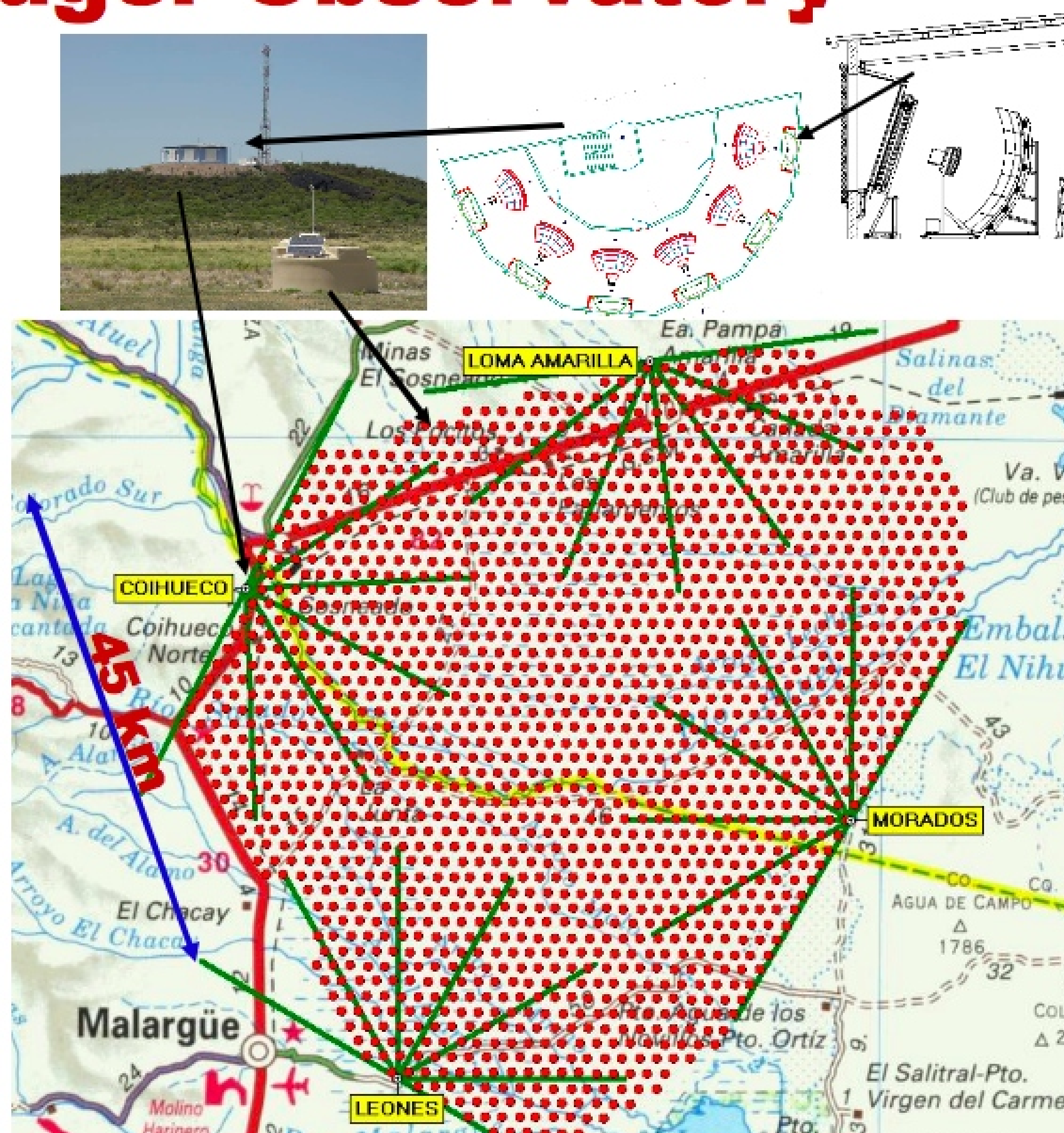
Extensive Air Showers


AUGER detector in ARGENTINA
1.5 Km

The Pierre Auger Observatory

Argentina, Mendoza, Malargue
1.4 km altitude, 870 g/cm²

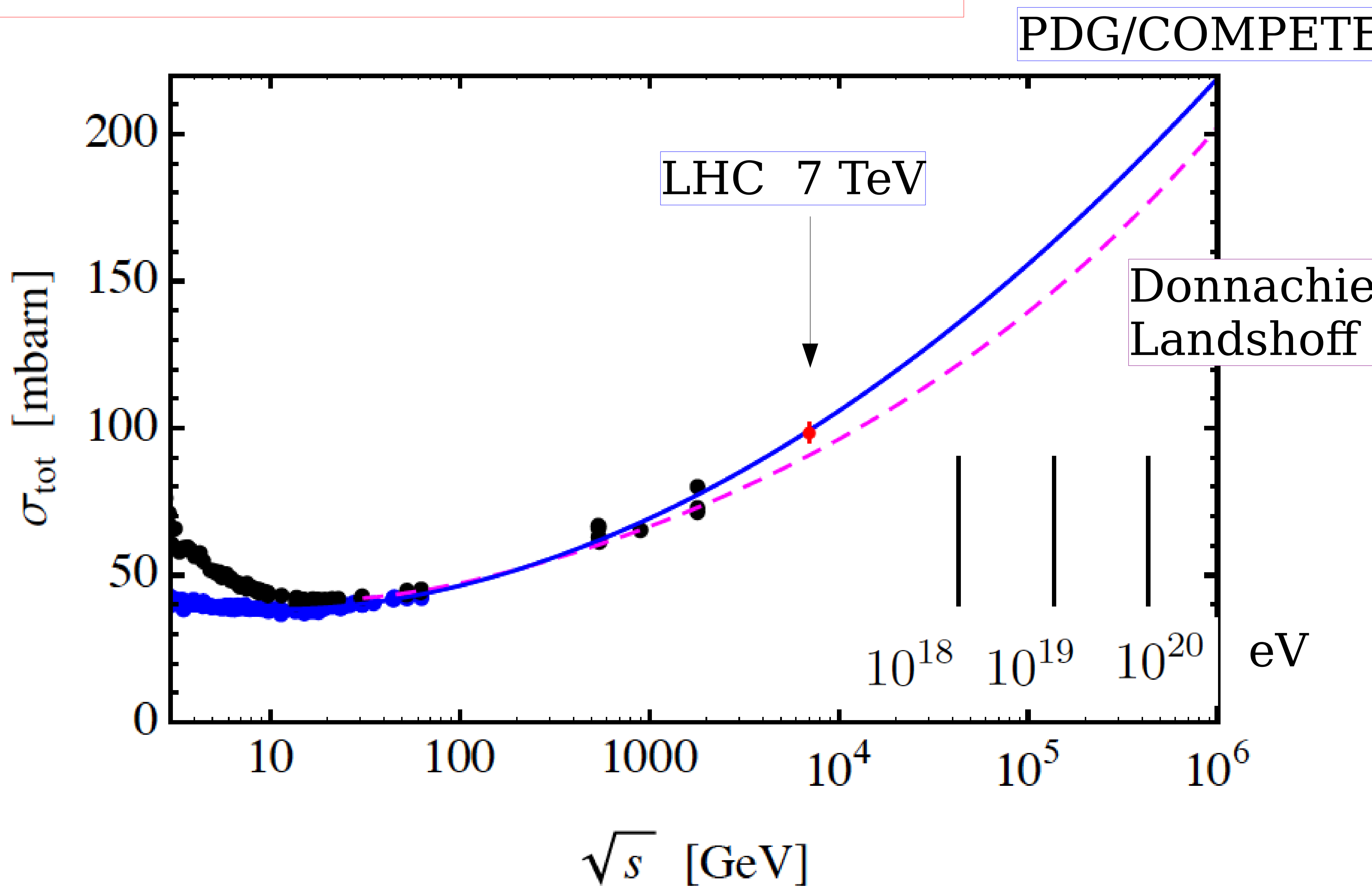
Argentina
Australia
Bolivia*
Brazil
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Slovenia
Spain
United Kingdom
USA
Vietnam*



1600 water Cherenkov detectors,

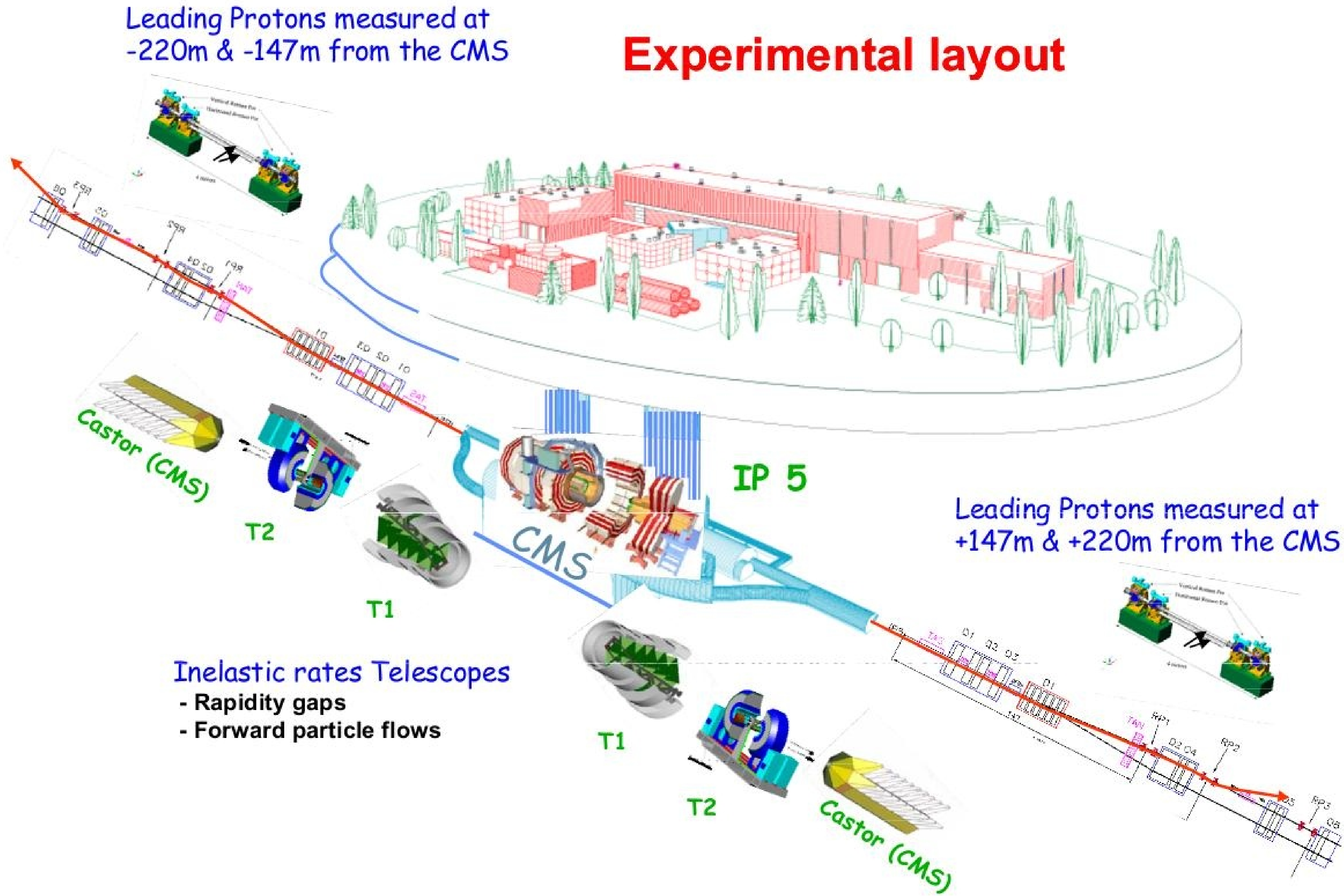
1.5 km spacing, 3000 km²,
4 x 6 fluorescence telescopes

$$E_{\text{lab}} = 10^{20}\ \text{eV} \longleftrightarrow \sqrt{s} = 433\ \text{TeV}$$



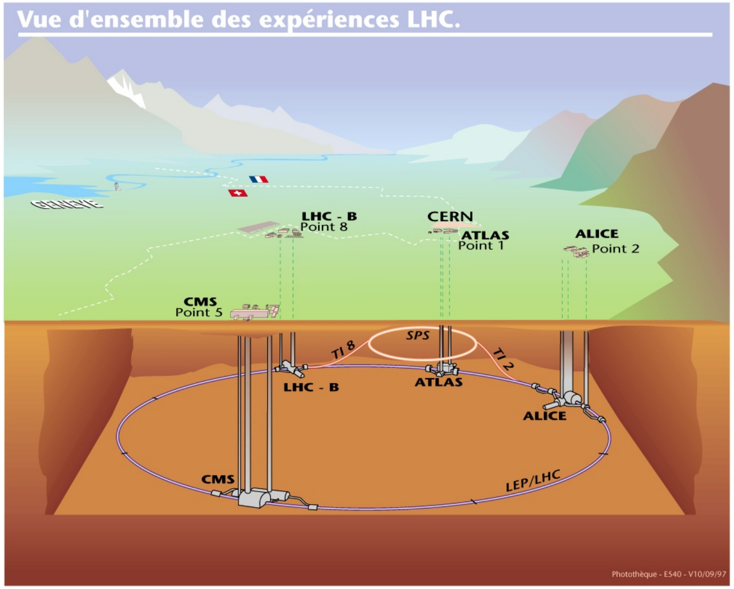
TOTEM

Experimental layout



TOTEM collaboration at LHC:

First measurement of the total proton-proton cross section at the LHC energy of $\sqrt{s} = 7$ TeV



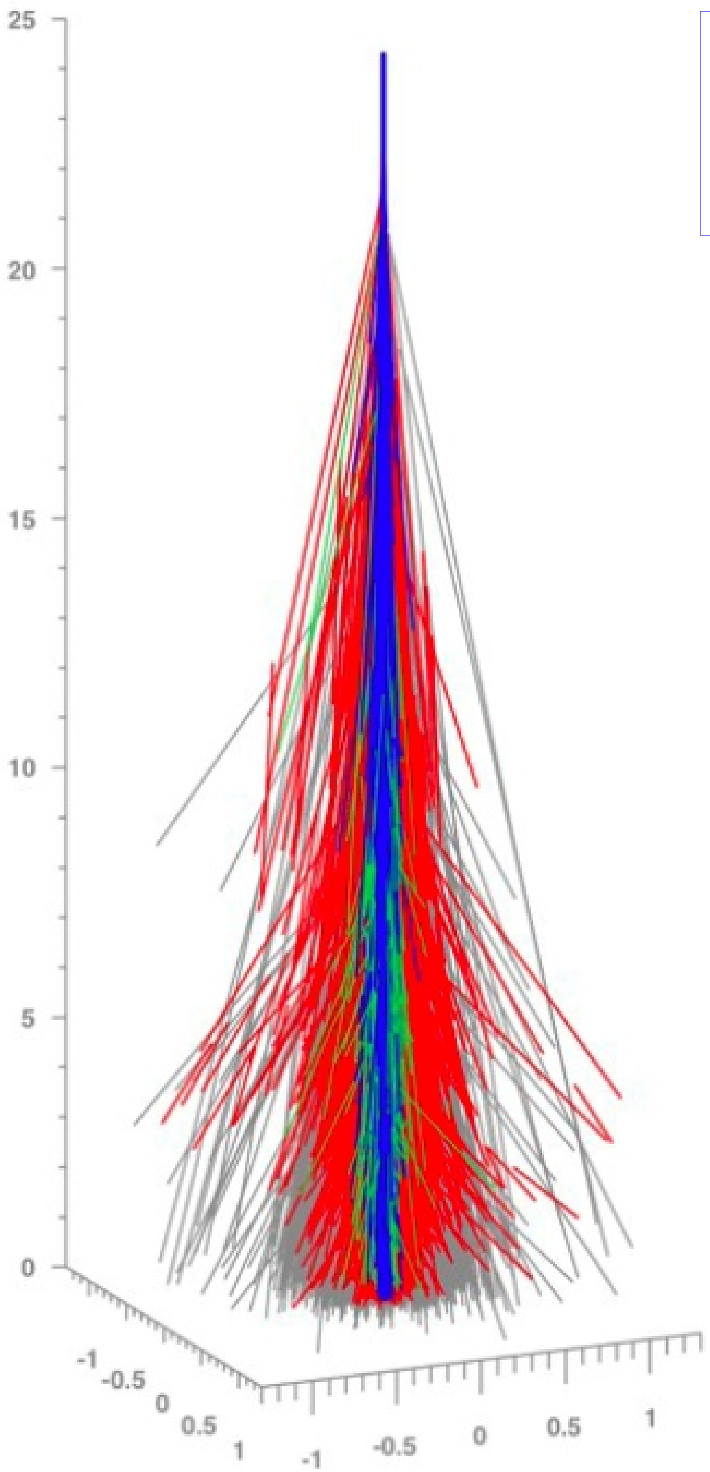
$$\sigma_{\text{tot}} = [98.3 \pm 0.2\ (\text{stat}) \pm 2.8\ (\text{syst})]\ \text{mbarn}$$

$$\sigma_{\text{el}} = [24.8 \pm 0.2\ (\text{stat}) \pm 1.2\ (\text{syst})]\ \text{mbarn}$$

$$\sigma_{\text{inel}} = \left[73.5 \pm 0.6\ (\text{stat})\ \ {}^{+1.8}_{-1.2}\ (\text{syst})\right]\ \text{mbarn}$$

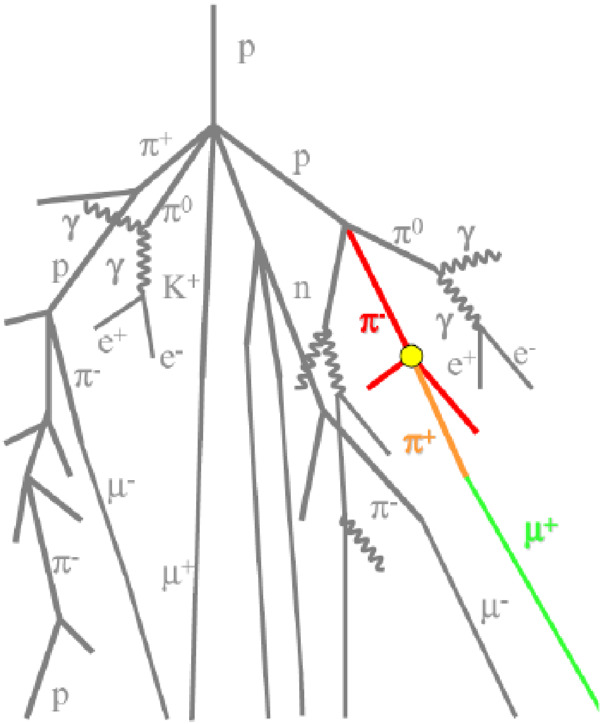
$$B_{\text{el}} = [20.1 \pm 0.2\ (\text{stat}) \pm 0.3\ (\text{syst})]\ \text{GeV}^{-2}$$

$$\frac{\sigma_{\text{el}}}{\sigma_{\text{tot}}} = 0.25 \pm 0.01\ (\text{stat} \oplus \text{sys})$$



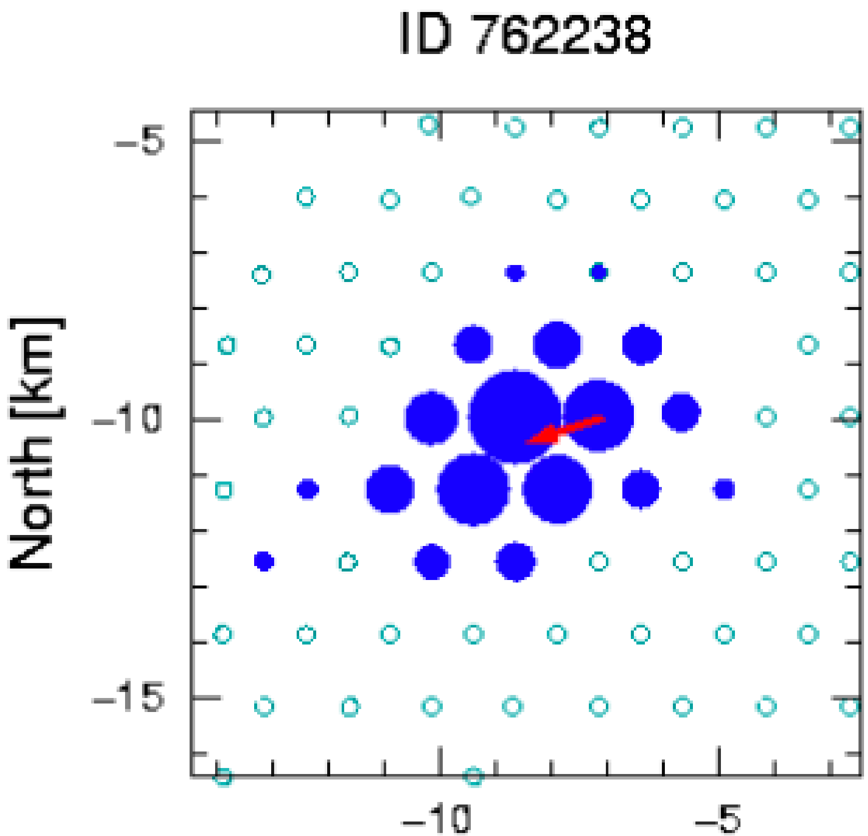
Description of
ULTRA High Energy Cosmic Rays
SHOWERS

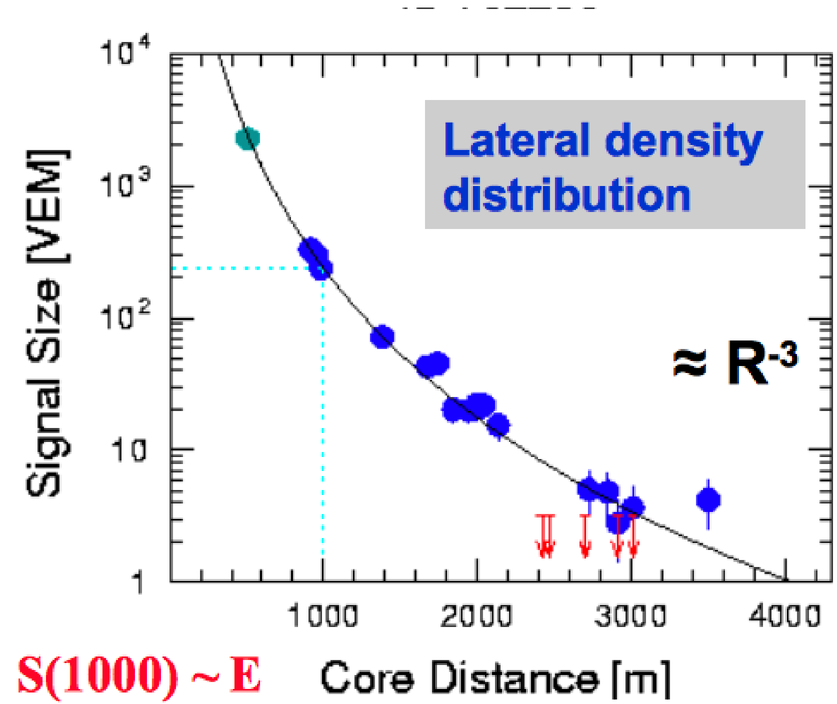
Need description of
hadronic interactions
beyond LHC energies



Auger surface detector

How can one estimate the energy ?

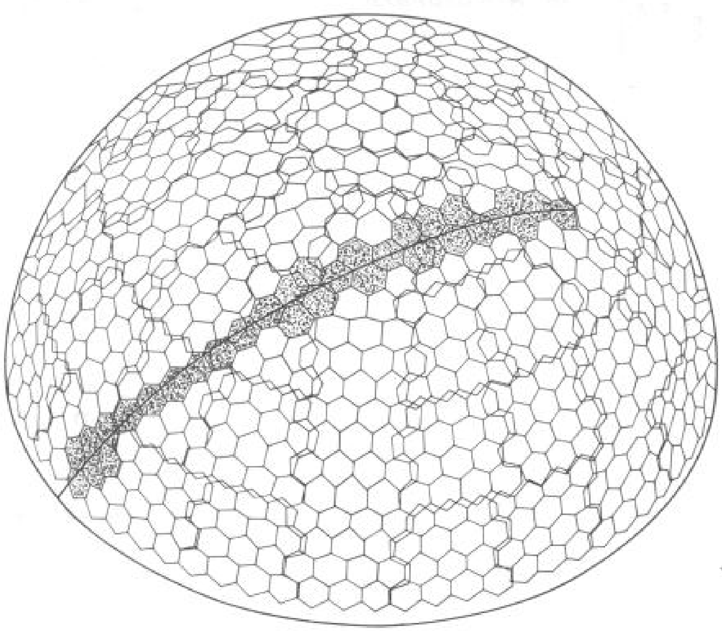


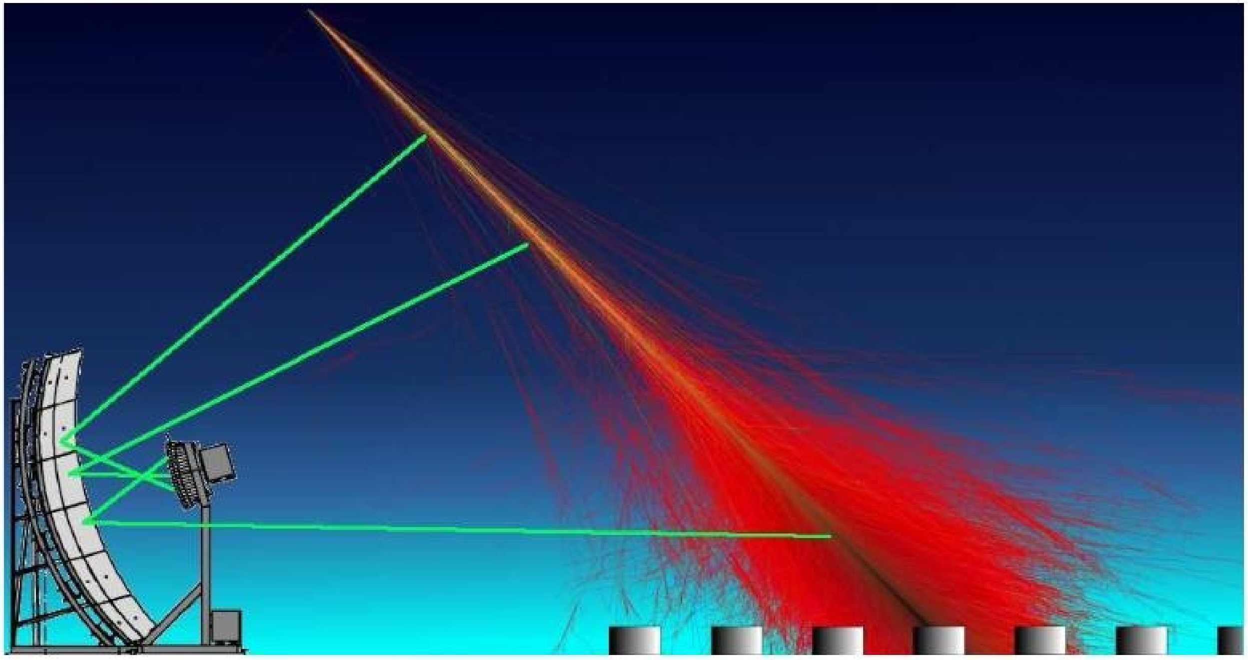


Timing of tank-signals give shower direction

VEM = Vertical-Equivalent-Muon

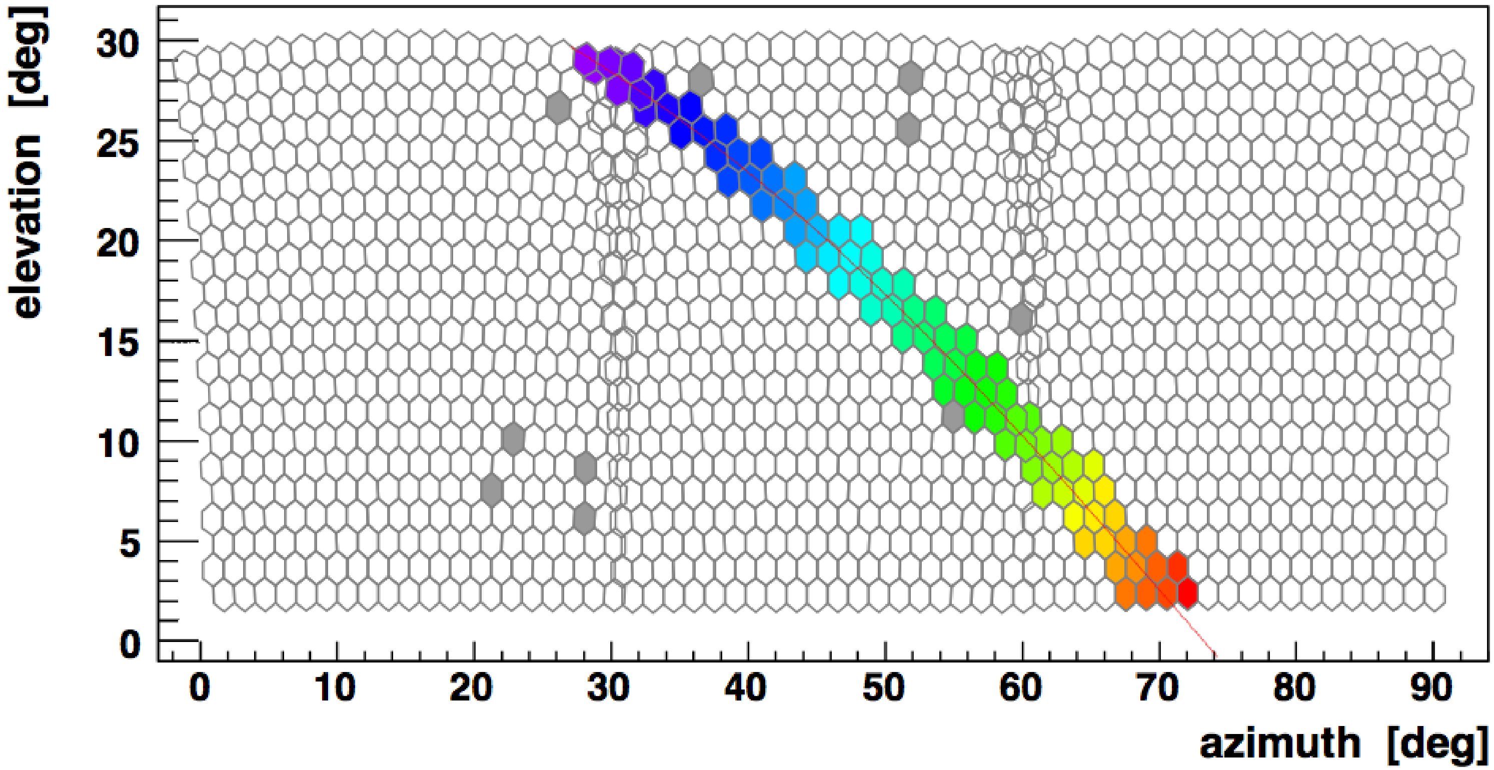
The **Fly's Eye** Detector concept

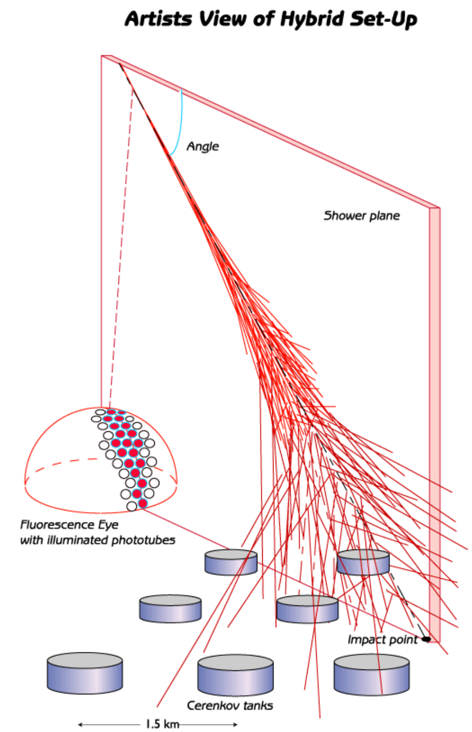




Fluorescence light emitted isotropically by excited Nitrogen molecules

Yield ~ 4 photons/meter
300-400 nm



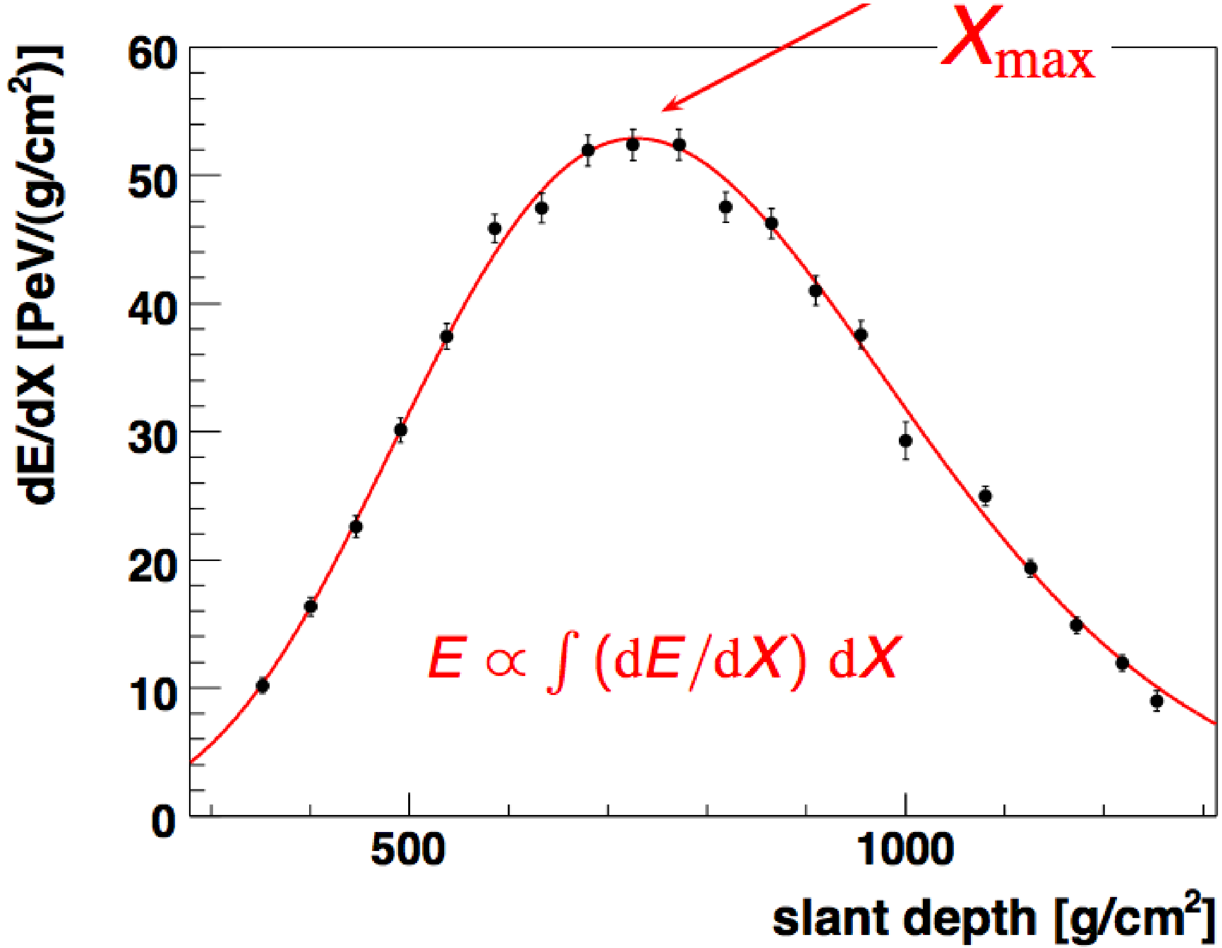


$$L(\Omega) \rightarrow F_{\gamma}(X) \rightarrow N_{e^{\pm}}(X)$$

Observed Light → Emitted Photons → Shower Size

Geometry, atmospheric absorption

Fluorescence yield



Energy Reconstruction:

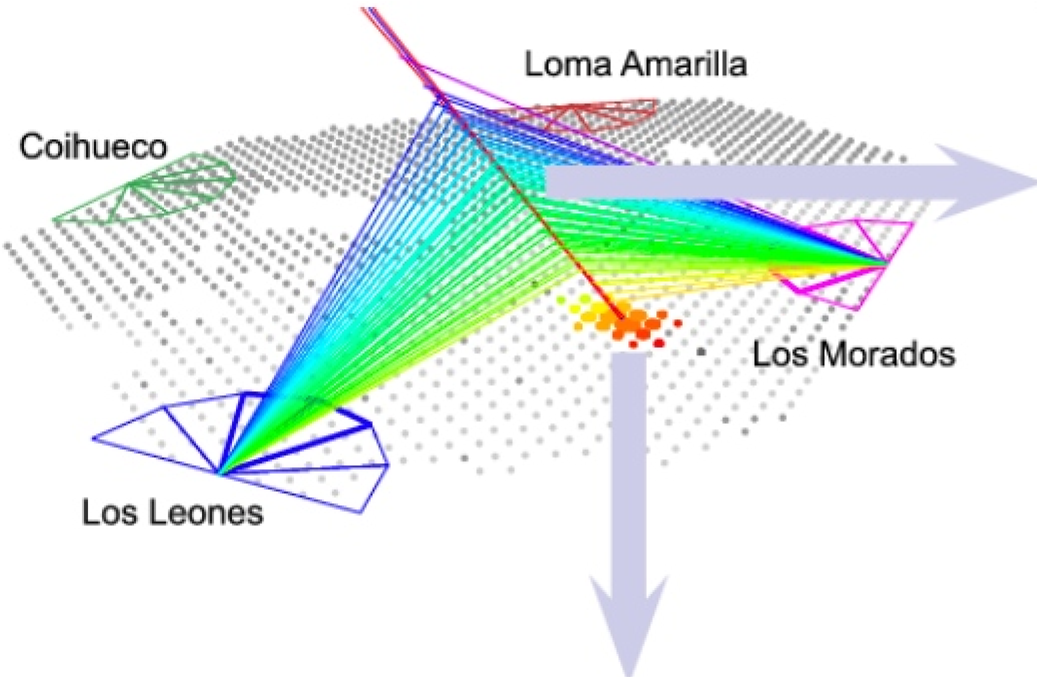
Area $\propto$ Energy

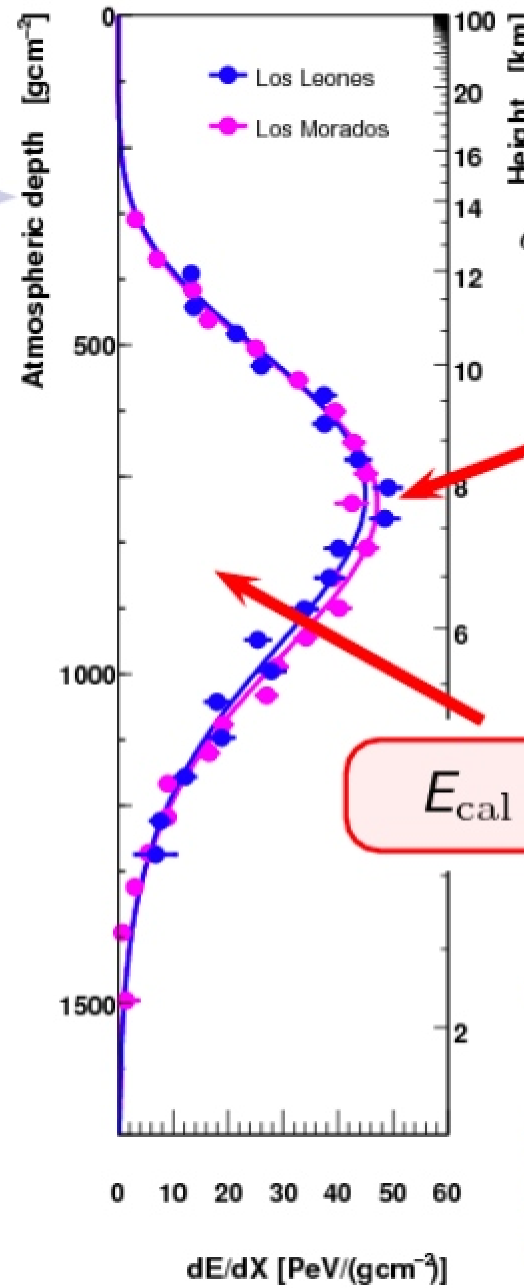
Small Model dependence

$$E_{\text{ionization}} = \int dX \; N_e(X) \left\langle -\frac{dE}{dX} \right\rangle$$

$$E_{\text{tot}} = E_{\text{ionization}} + E_\nu + E_\mu + E_{\text{ground}}$$

The Auger 'hybrid' detector





$\sigma_{X_{\max}} < 20\,\mathrm{g/cm^2}$

$\Delta_{\mathrm{sys}} \approx 15\,\mathrm{g/cm^2}$

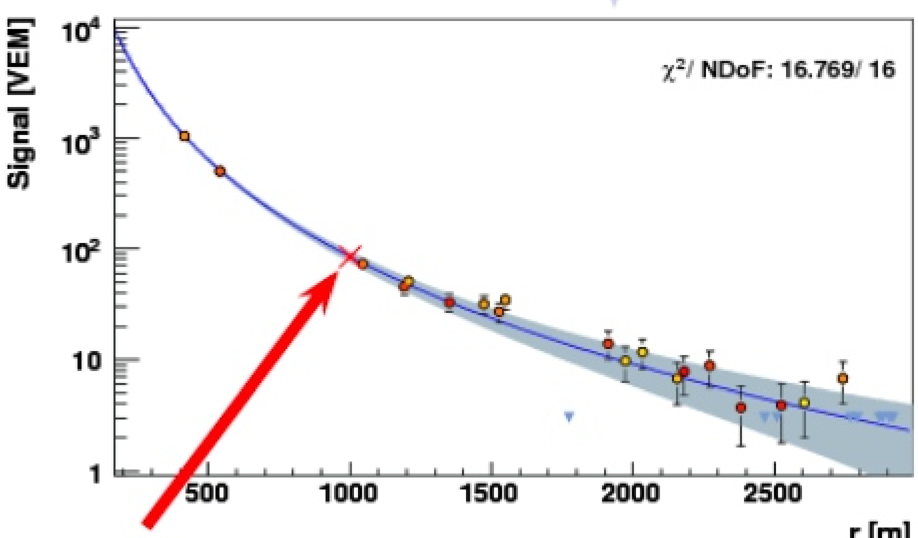
$X_{\max}$

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

$\sigma_E/E \sim 8\,\%$

$\Delta_{\mathrm{sys}} \approx 22\,\%$

Fluorescence yield ~14%

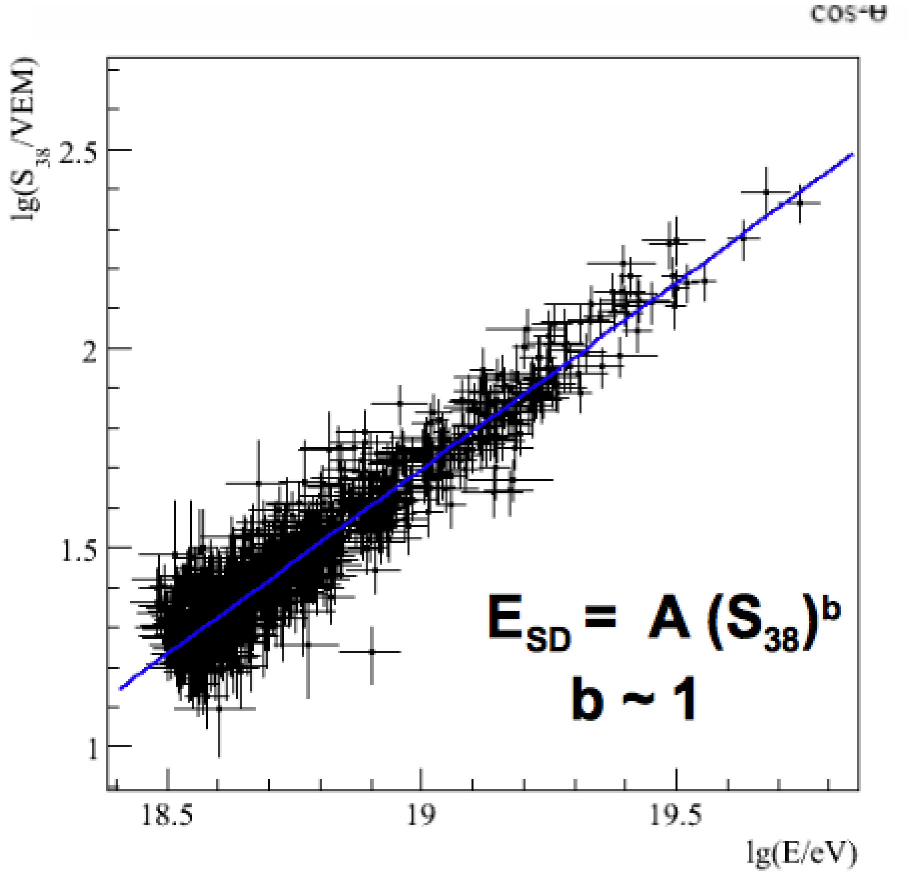


S_{1000}

$E_{\mathrm{surface}} = f(S_{1000},\ \theta)$

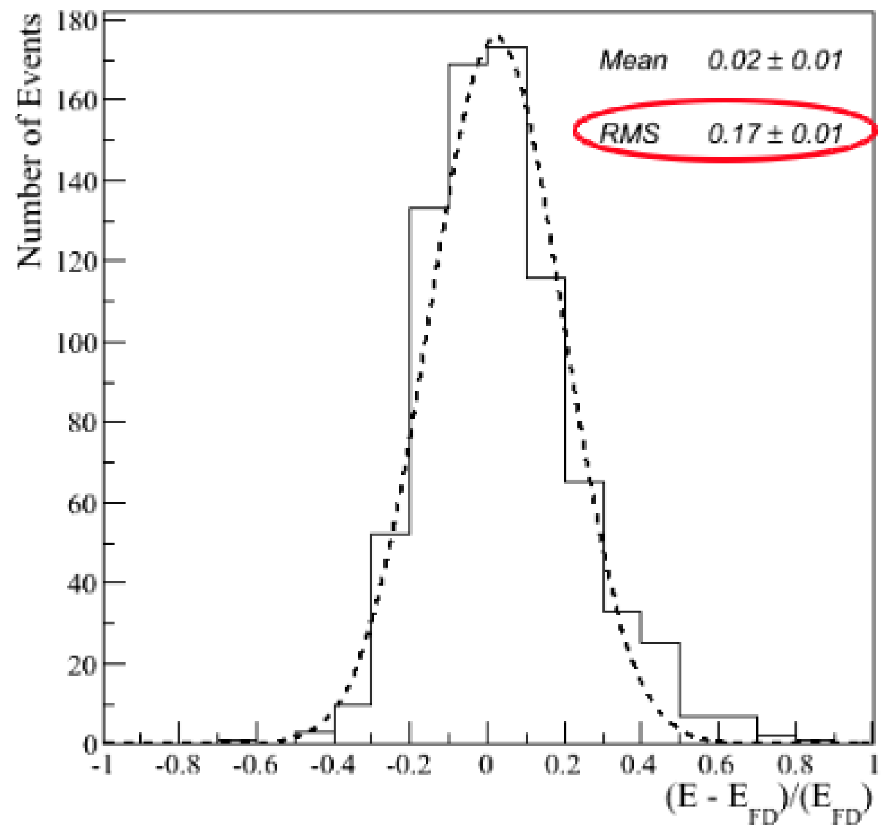
Calibration of Surface detector
With fluorescence light observations

SD

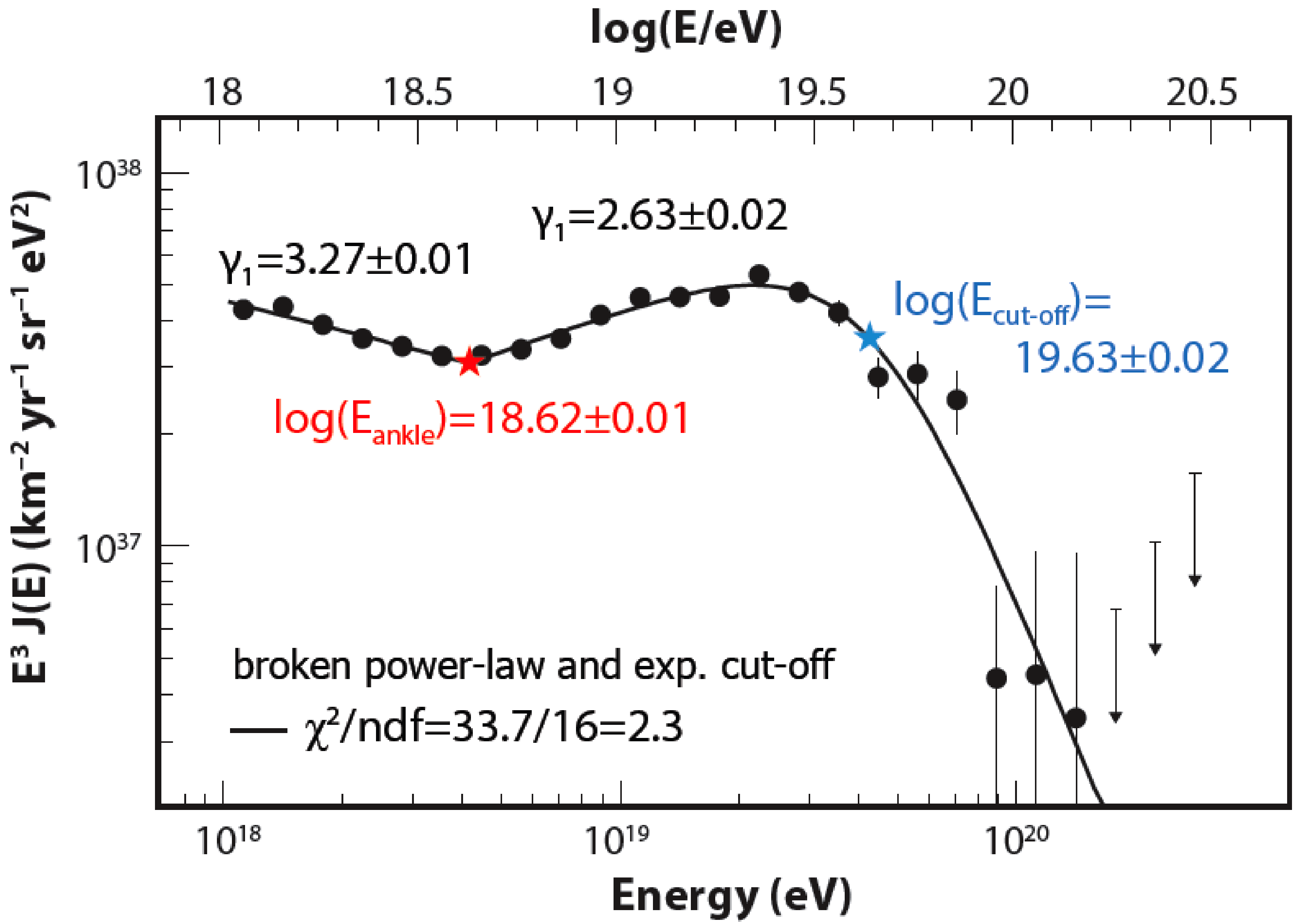


FD

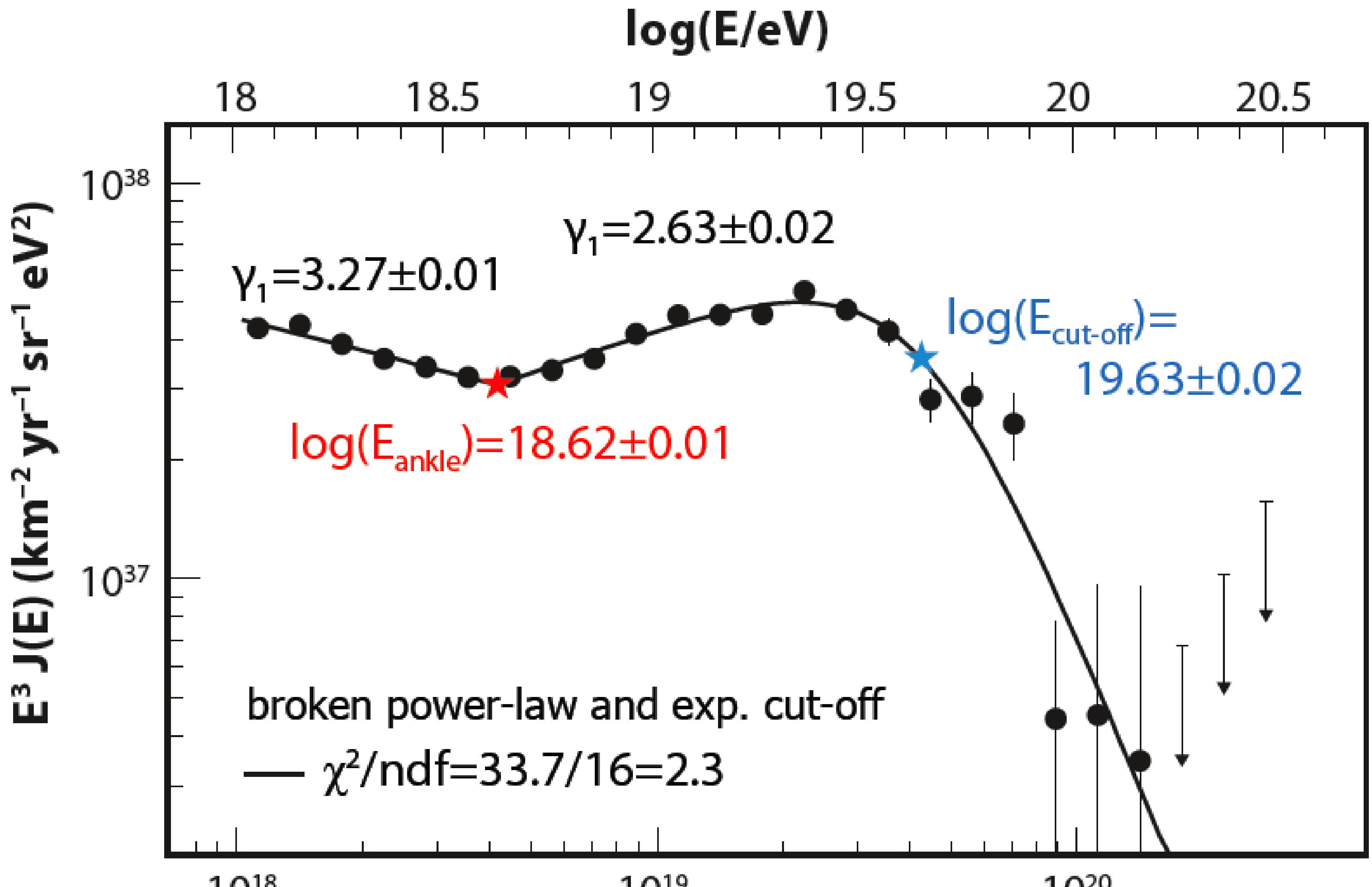
SD Energy resolution better than 20%



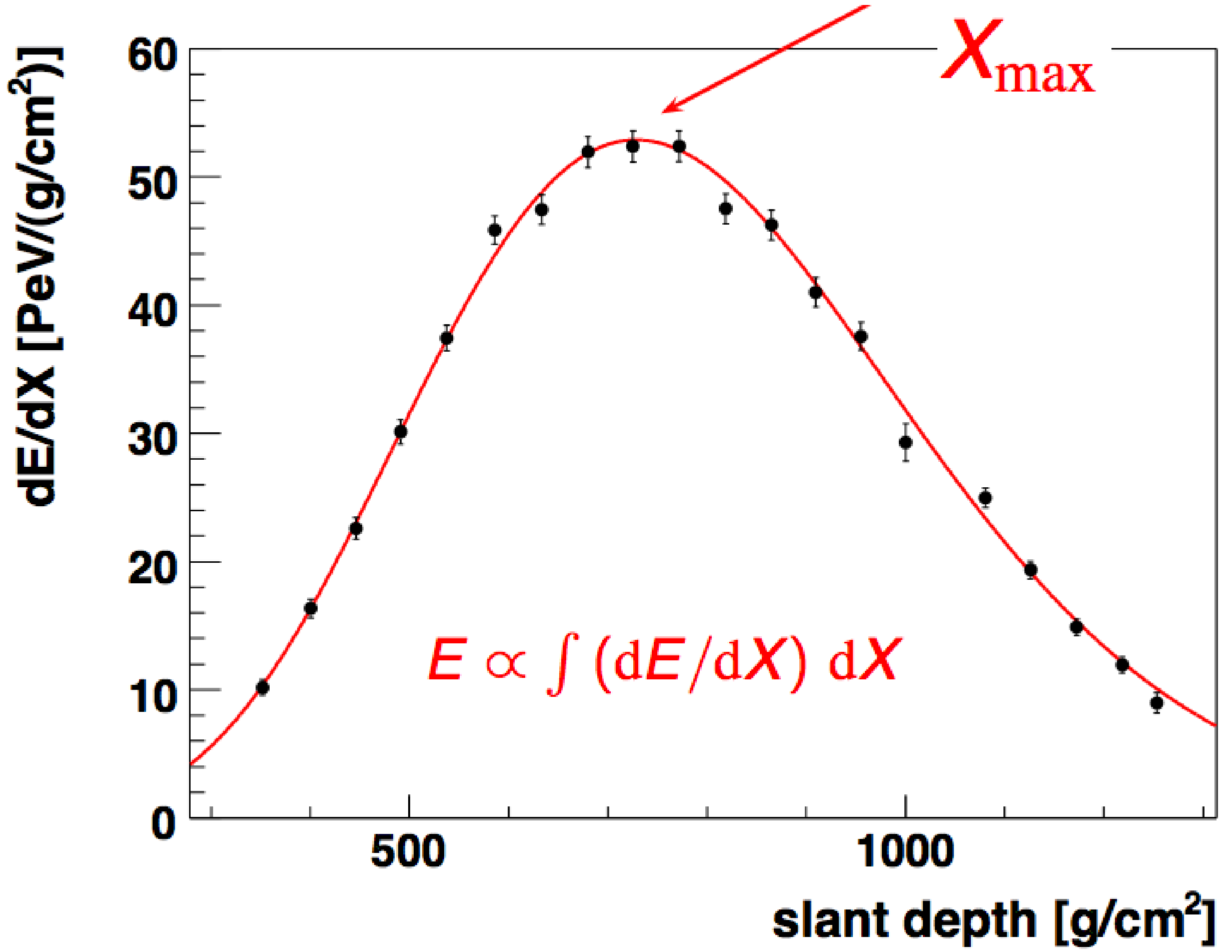
AUGER Energy Spectrum



AUGER Energy Spectrum



What is the physical origin
Of the features of the energy spectrum ?



Area $\propto$ Energy

Shape depends on :

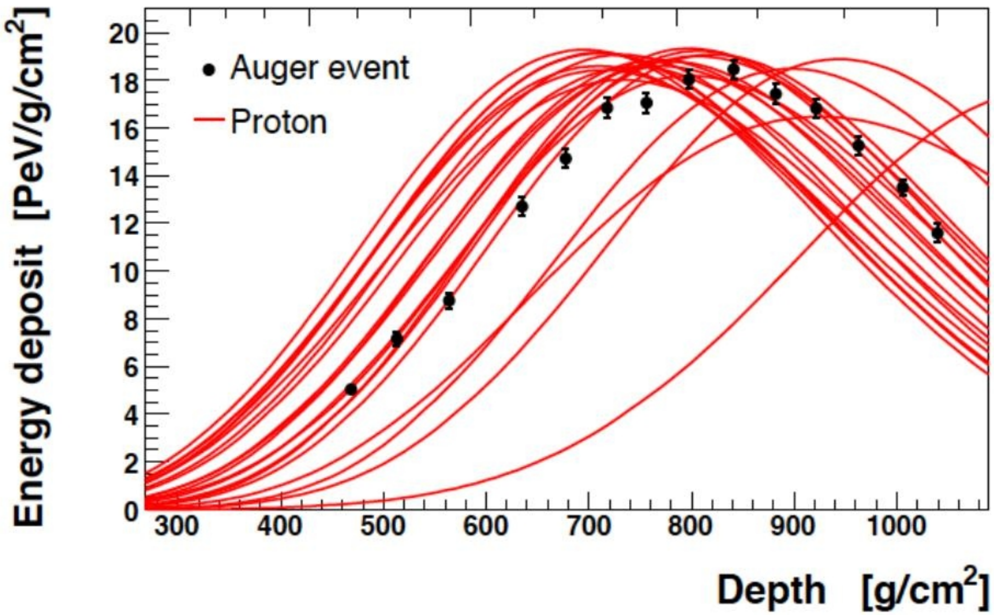
- Primary Identity
- Interaction Model

Study of the mass composition of Ultra High Energy Cosmic Rays

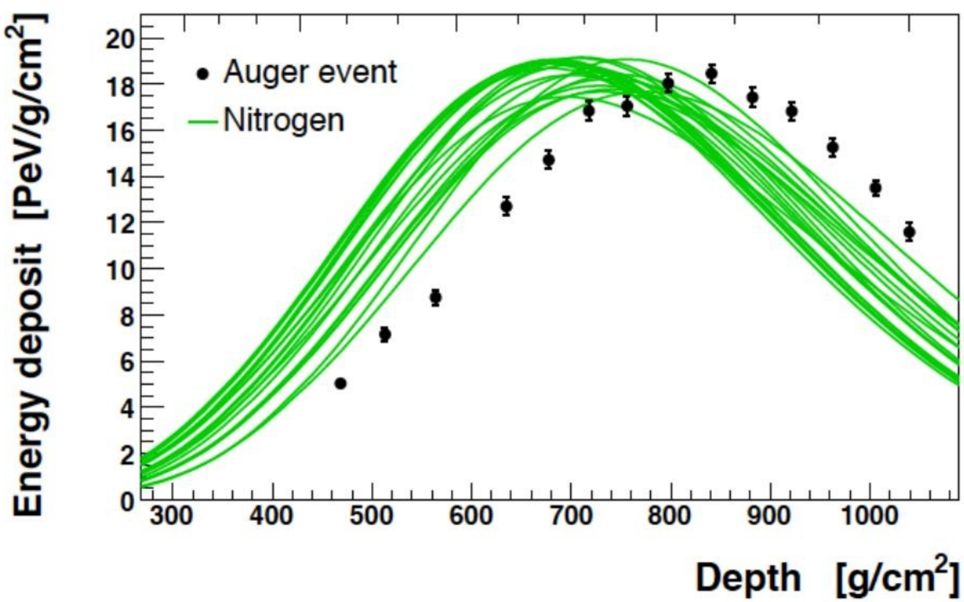
intimately associated with the modeling of hadronic-interactions.

Interplay:

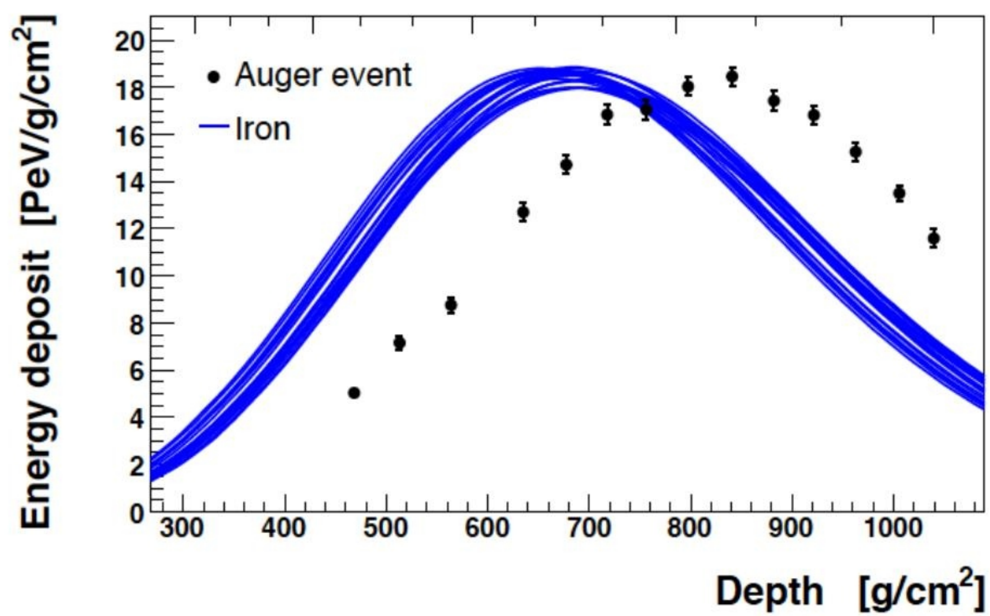
- Mass Composition
- Hadron interaction lengths in air
- Properties of particles in the final state



Auger event
Proton
Energy deposit [PeV/g/cm^2]
Depth [g/cm^2]

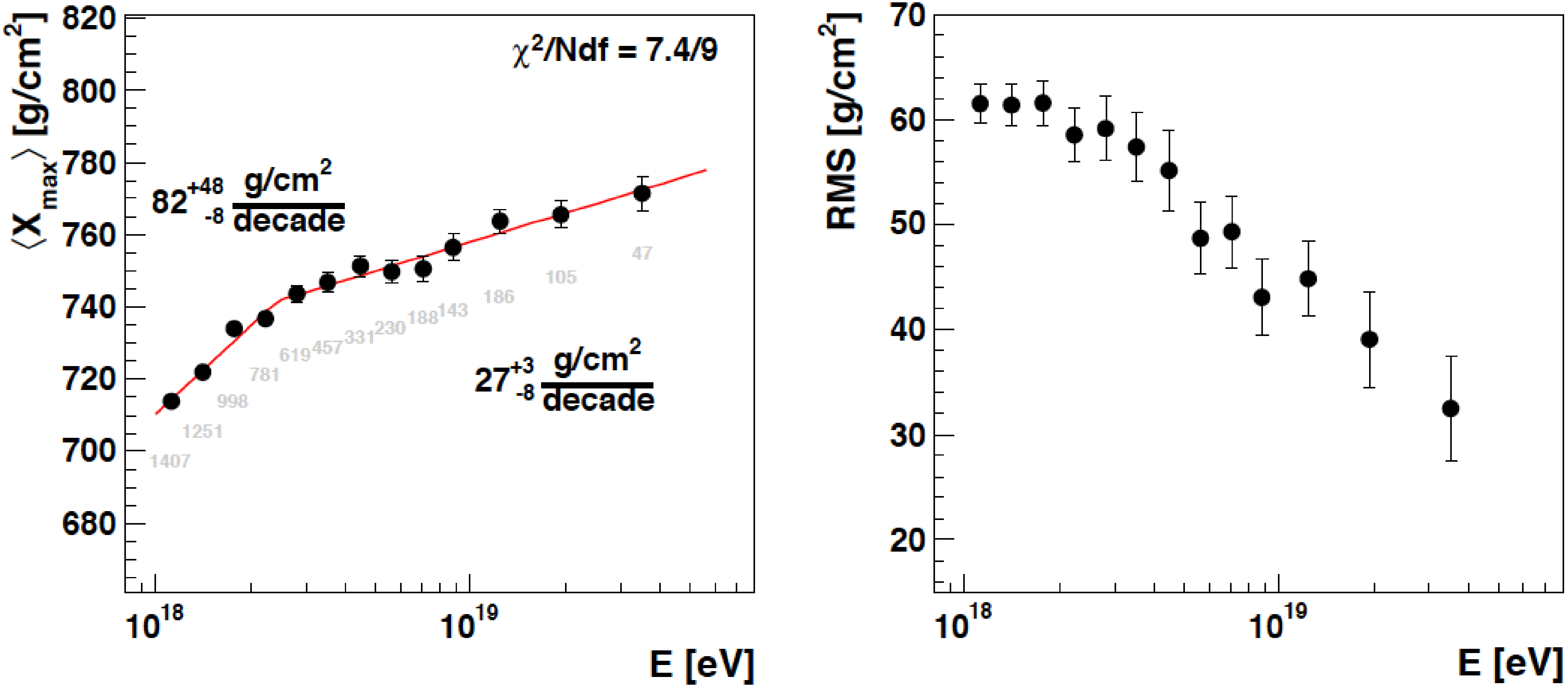


Auger event
Nitrogen
Energy deposit [PeV/g/cm^2]
Depth [g/cm^2]



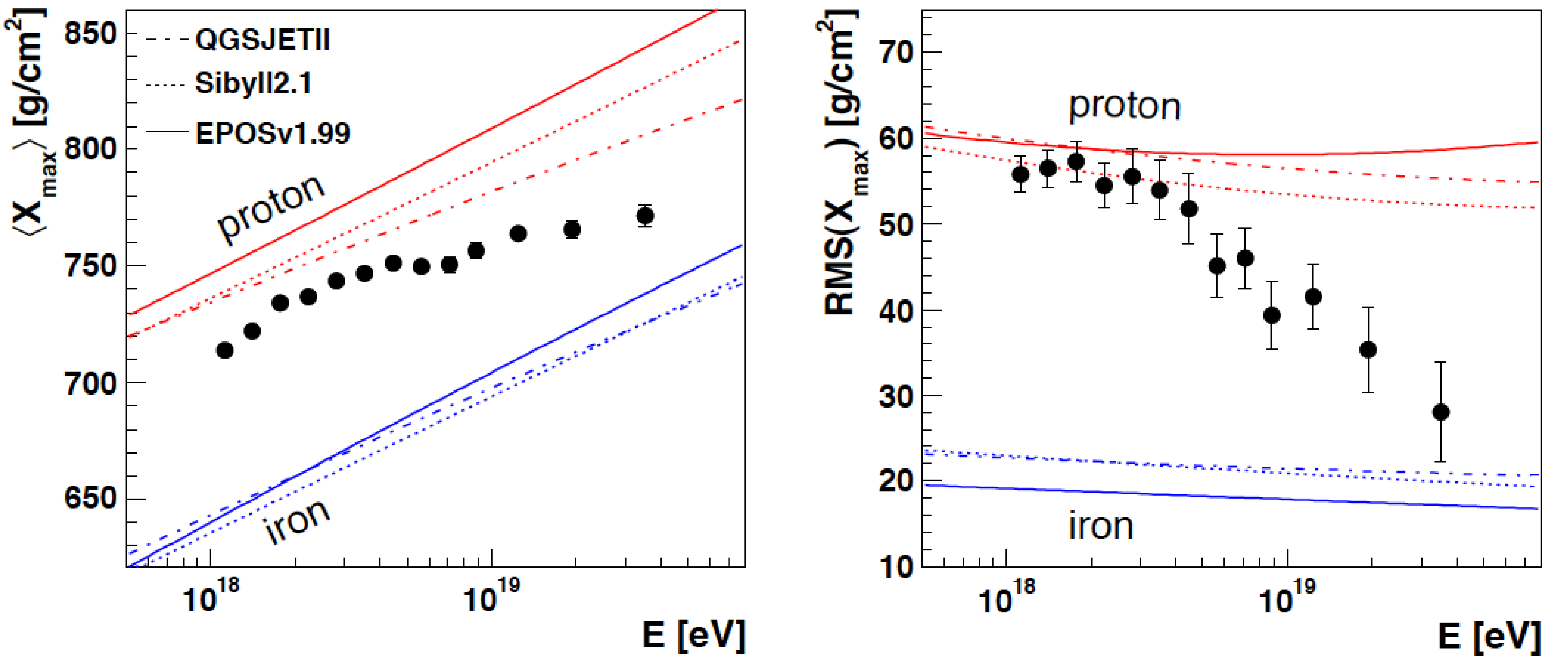
Auger event
Iron
Energy deposit [PeV/g/cm^2]
Depth [g/cm^2]

$\langle X_{max} \rangle$ and RMS



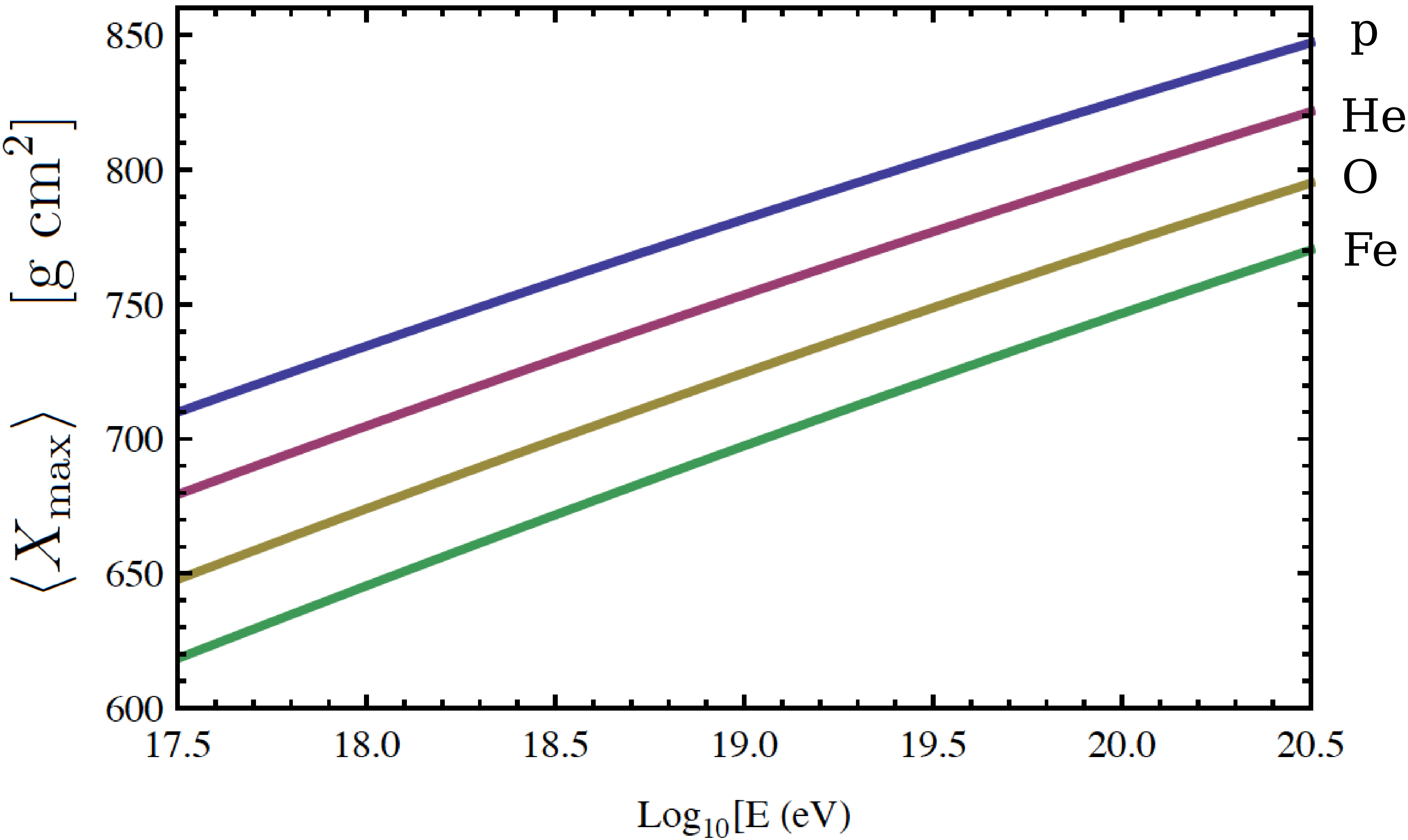
What is the
physical meaning
of these distributions?

$\langle X_{max} \rangle$ and RMS



Compare DATA with predictions based on several assumptions for hadronic interactions....

One Montecarlo Model: [Sibyll 2.1]



$$\langle X_p^{\rm max}(E) \rangle \simeq X_0 + D_p \ \log E$$

Small curvature

X_{max} and the Composition of Cosmic Rays

IF:
approximate validity of the relation:

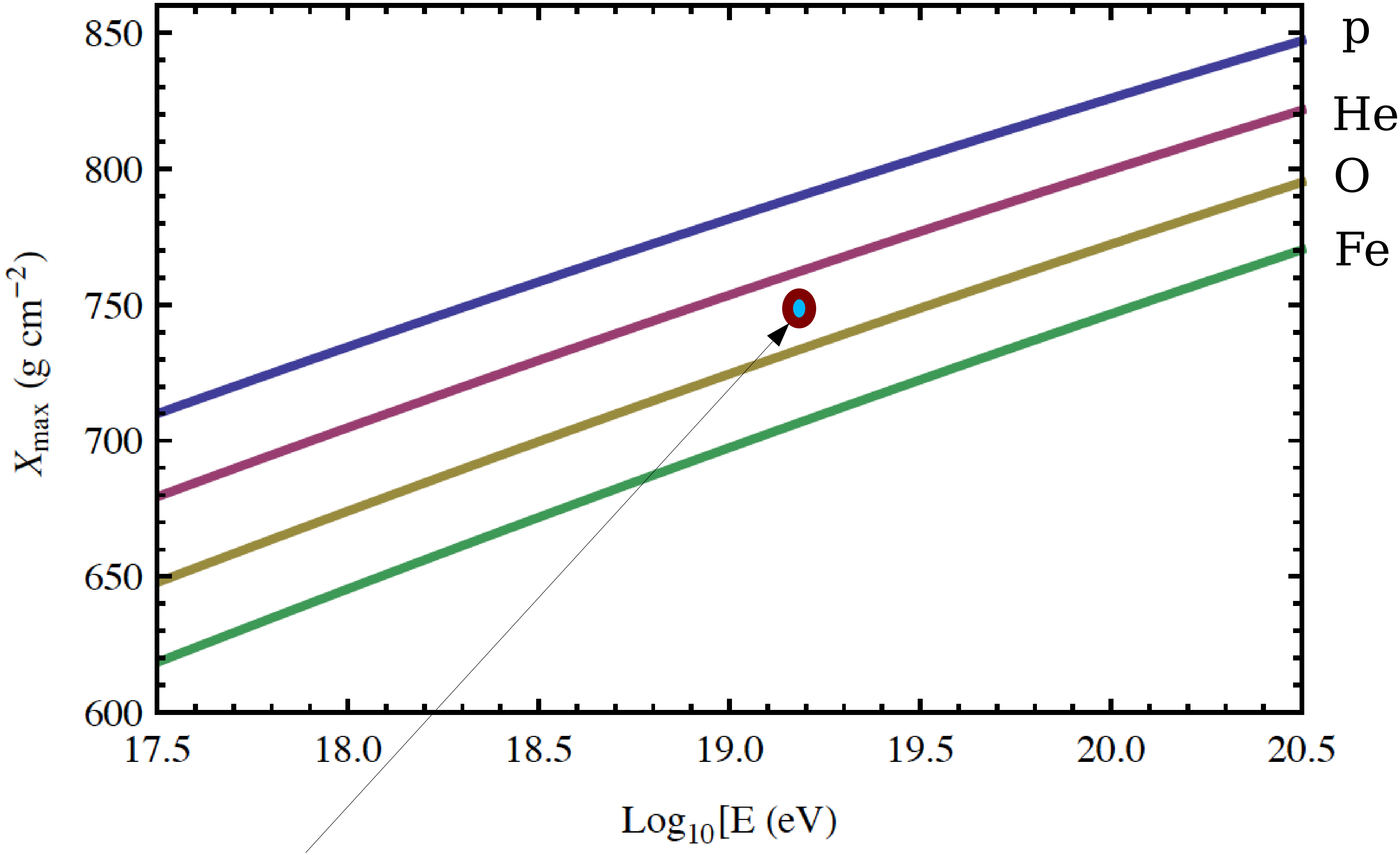
$$\langle X_A(E) \rangle \simeq \left\langle X_p \left(\frac{E}{A} \right) \right\rangle$$

and:

$$\langle X_p \rangle \simeq X_0 + D_p \, \log E$$

Then:

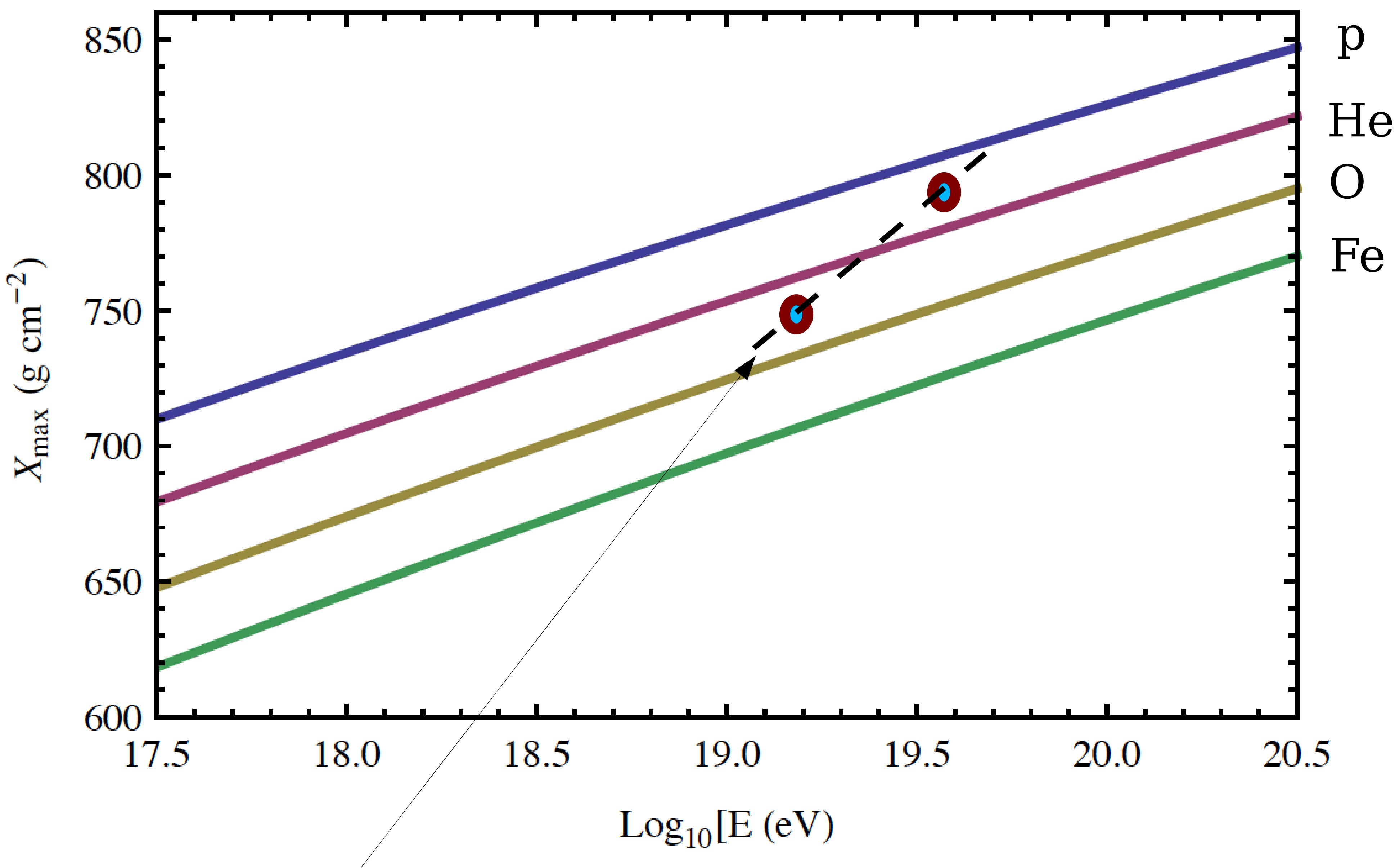
$$\langle X_A \rangle \simeq \langle X_p \rangle - D_p \, \log A$$



Measurements of

$$\langle \log A \rangle$$

$$\langle \ln A \rangle_E = \frac{\sum_A \phi_A(E)\ \ln A}{\sum_A \phi_A(E)}$$



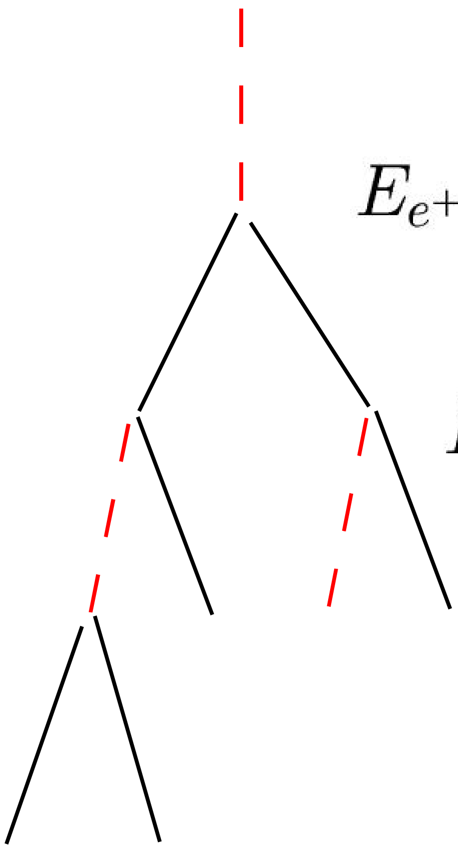
Measurements of composition evolution.

Electromagnetic Showers

versus

Hadronic Showers

Electromagnetic Shower



$$E_{e^+} = E_\gamma \; u$$

$$E_\gamma = E_e \; v$$

$\psi(u)$ — Pair production

$\varphi(v)$ — Bremsstrahlung

Vertices : theoretically understood
energy scaling.

$$\left.\frac{dE}{dX}\right|_{\text{ionization}} \simeq 2.2 \text{ g/cm}^2$$

$$\lambda_{\text{rad}} \simeq 37 \text{ g/cm}^2$$

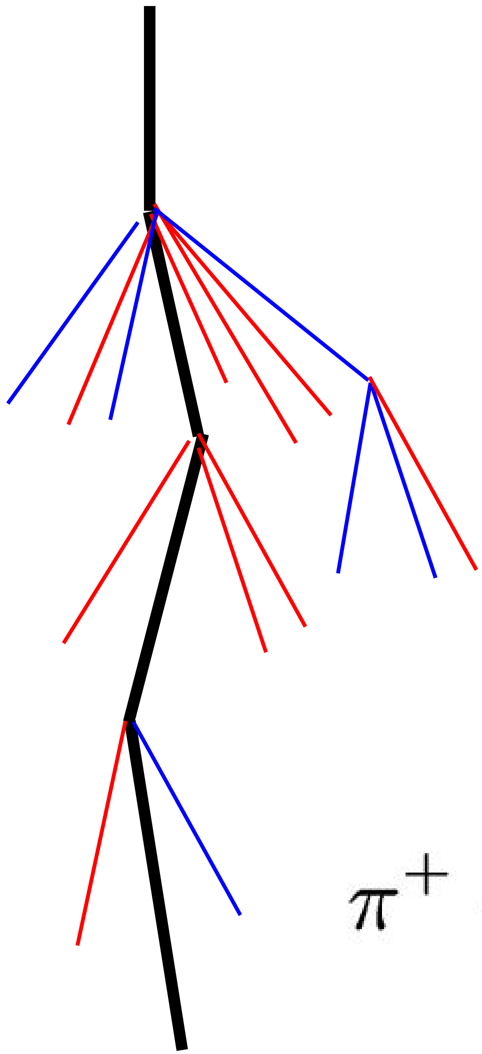
$$\lambda(\gamma \to e^+e^-) \simeq \frac{9}{7}\,\lambda_{\text{rad}}$$

Radiation Length
Pair production length
Energy independent !

Proton Shower

Vertices : theoretically not understood

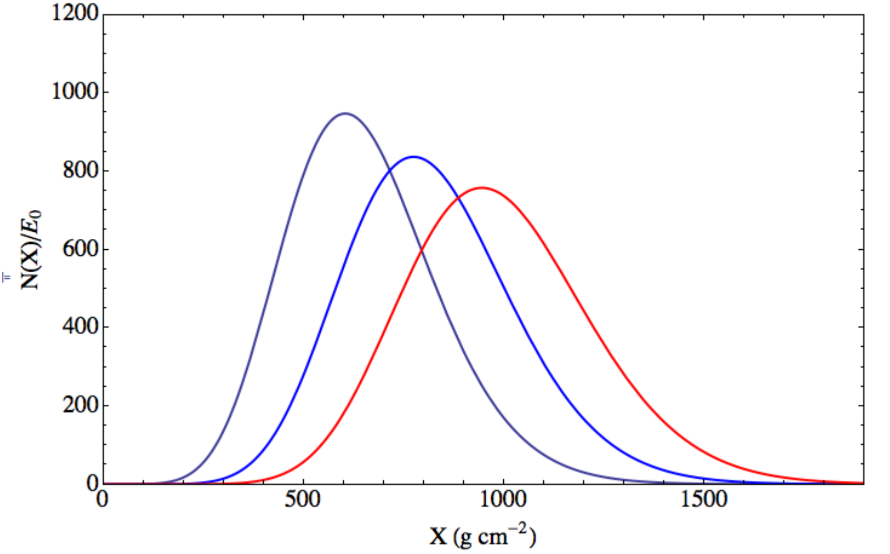
(and energy dependent)



$$\pi^0 \to \gamma\gamma$$

$$\pi^+ \to \mu^+ \nu_\mu$$

Electromagnetic Showers



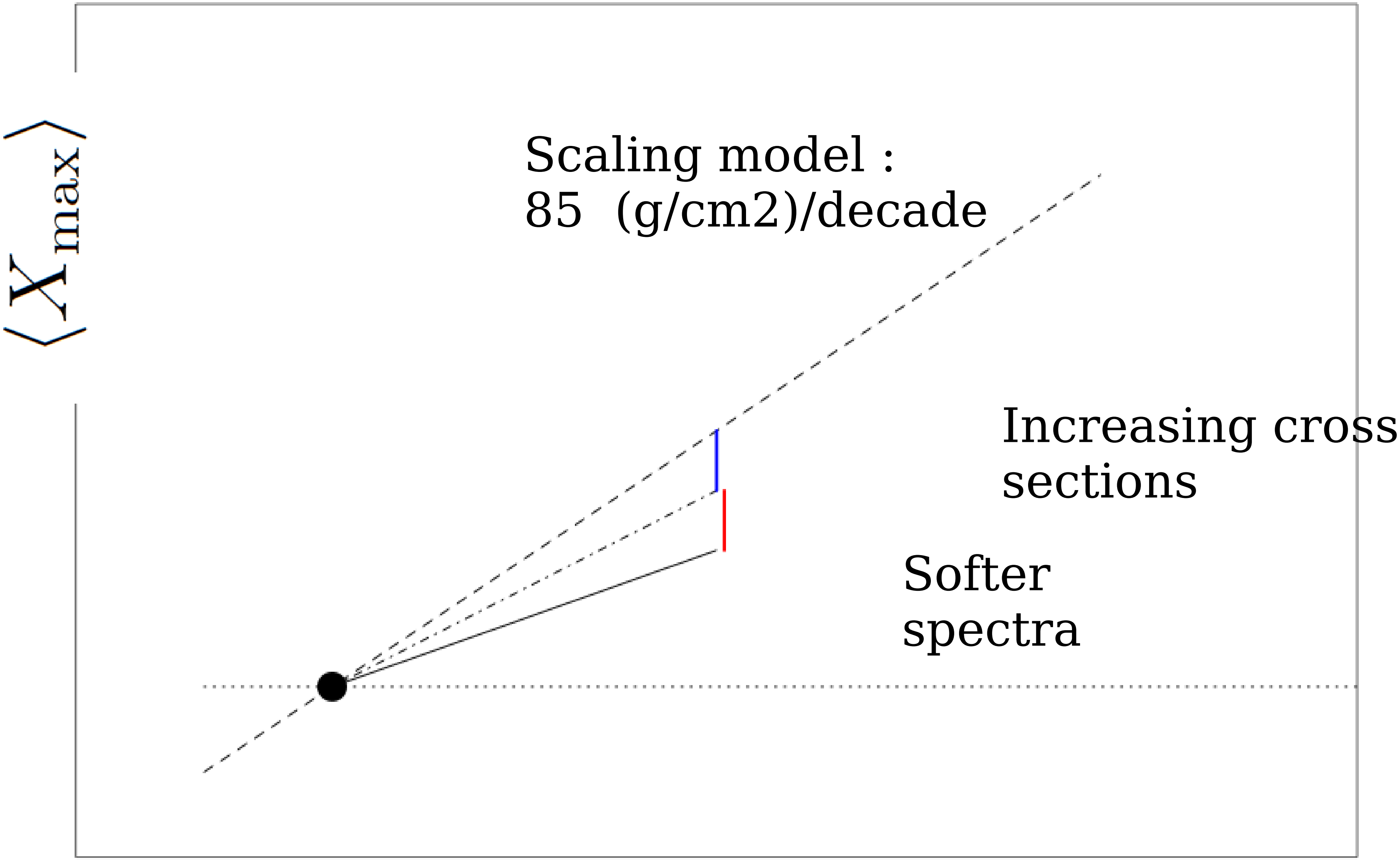
$$X_{\max}(E) \simeq \lambda_{\rm rad} \, \ln\left(\frac{E}{\varepsilon}\right)$$

Logarithmic growth of the penetration.

$$N_{\max}(E) \simeq \frac{E}{\varepsilon}\,\frac{1}{\sqrt{\ln(E/\varepsilon)}}$$

Energy Conservation

Elongation rate = 85 (g/cm^2)/decade



Elongation Rate
For protons

$\log[E(\mathrm{eV})]$

Different approaches to the [composition] vs [hadronic interaction modeling] problem.

Different approaches to the
[composition] vs [hadronic interaction modeling] problem.

1. "Direct Route" :

a. Obtain data at accelerators (LHC ! + others)
b. Develop a sound theoretical framework to extrapolate to higher energy (beyond accelerators)
c. Interpret the CR data

Different approaches to the
[composition] vs [hadronic interaction modeling] problem.

1. "Direct Route" :

a. Obtain data at accelerators (LHC ! + others)
b. Develop a sound theoretical framework to extrapolate to higher energy (beyond accelerators)
c. Interpret the CR data

2. "Astrophysics Route" :

Astrophysical composition measurements:
- * Magnetic deviations
- * Energy losses imprints on the energy spectrum
- * Acceleration Mechanism/Environment well understood [?!]

Use knowledge of composition to constrain hadronic interactions

Different approaches to the
[composition] vs [hadronic interaction modeling] problem.

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Astrophysical composition measurements:
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Use knowledge of composition to constrain hadronic interactions

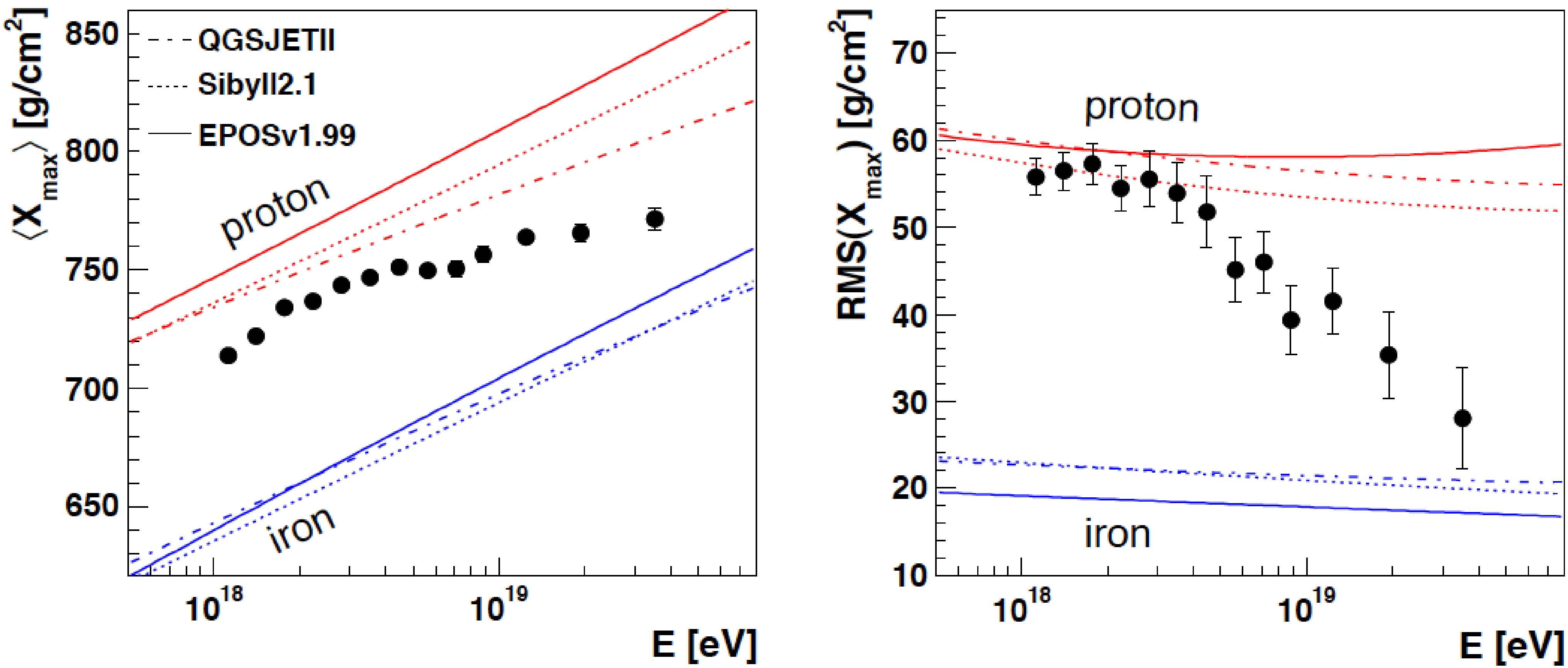
3. “Bootstrap Route” :

- * Self - consistency
- * Different masses “quasi-resolved”

The “astrophysics route”

Proton interpretation
for the UHECR ?? ....

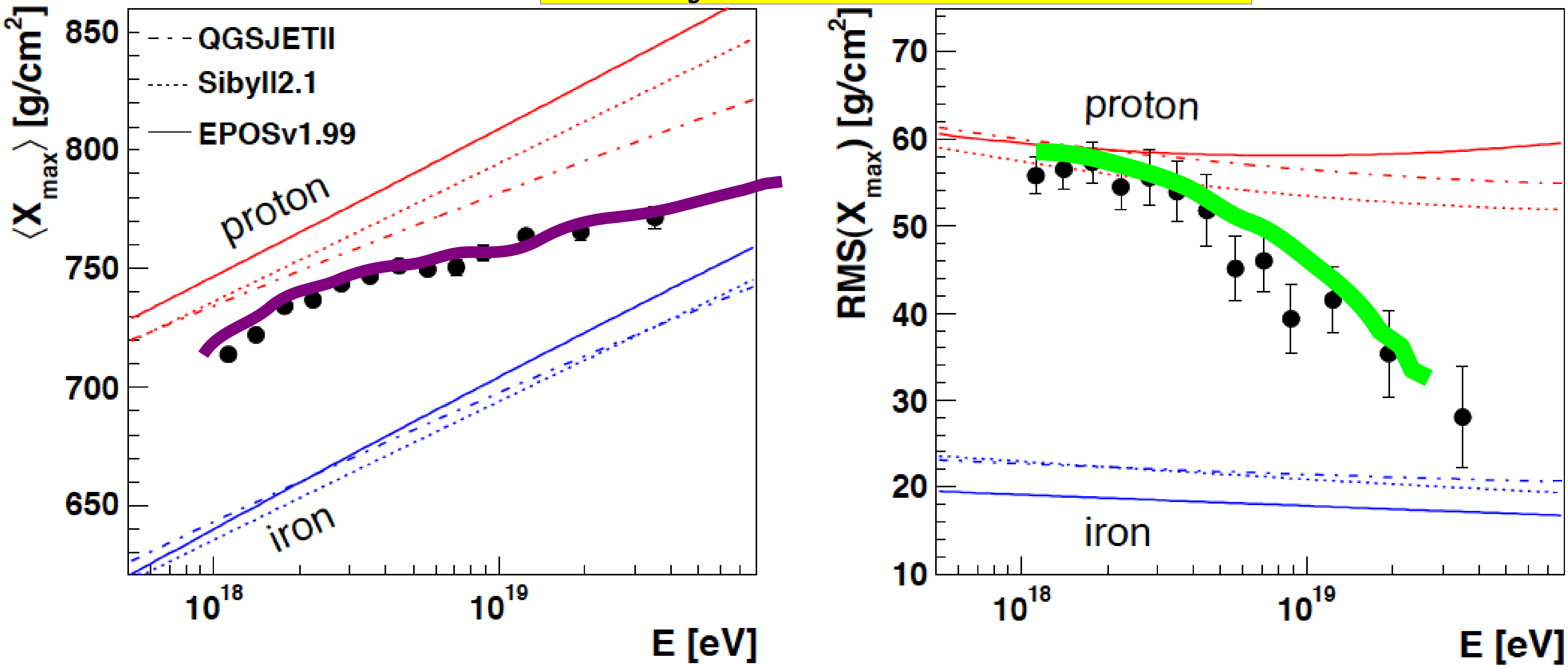
$\langle X_{max} \rangle$ and RMS



Compare DATA with predictions
based on several assumptions
for hadronic interactions....

$\langle X_{max} \rangle$ and RMS

Proton line ?
Modify interactions models?



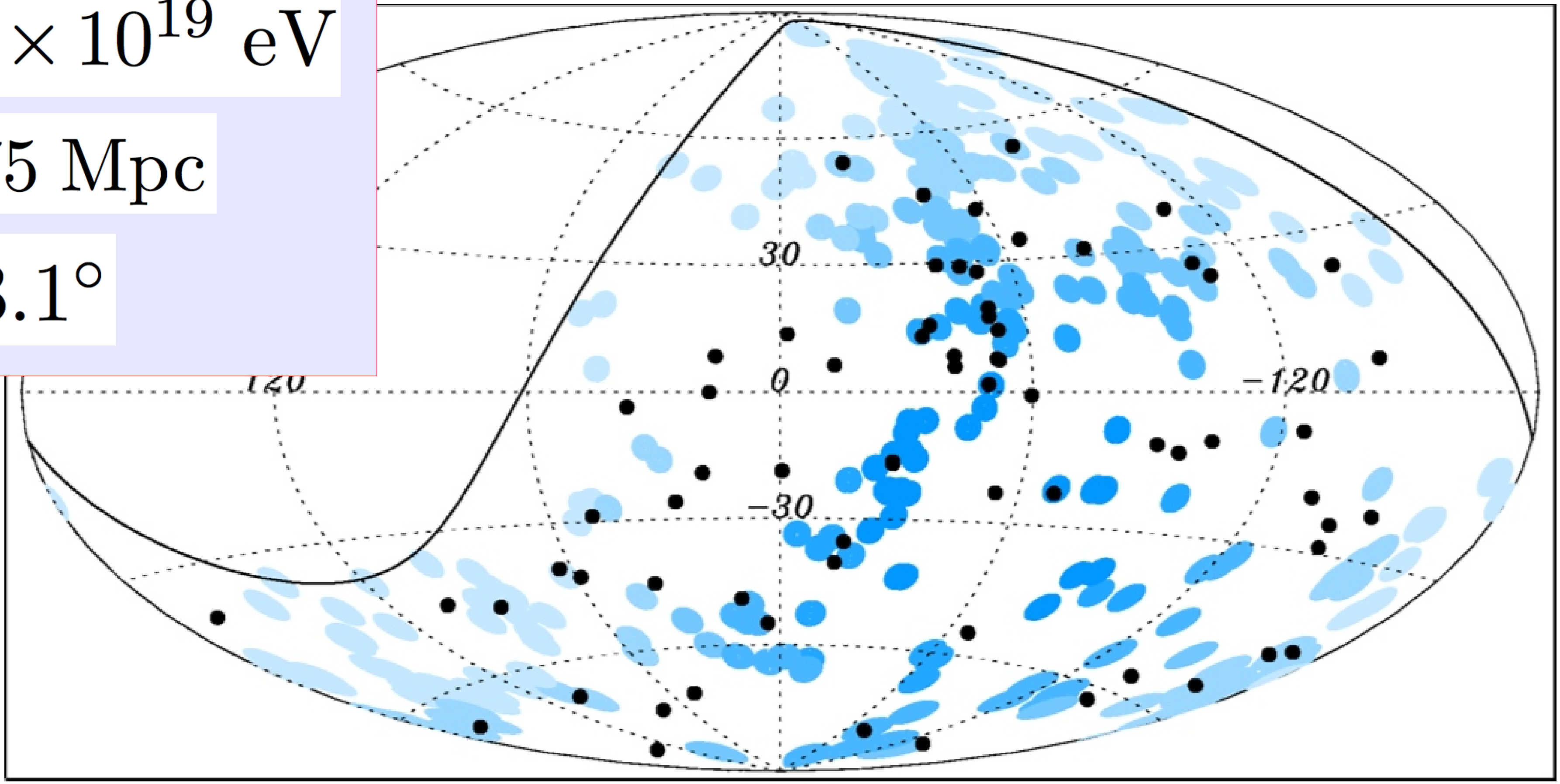
Compare DATA with predictions based on several assumptions for hadronic interactions….

AUGER result on Correlations with the VCV AGN catalogue
November 2007. Update september 2010.

6×10^{19} eV

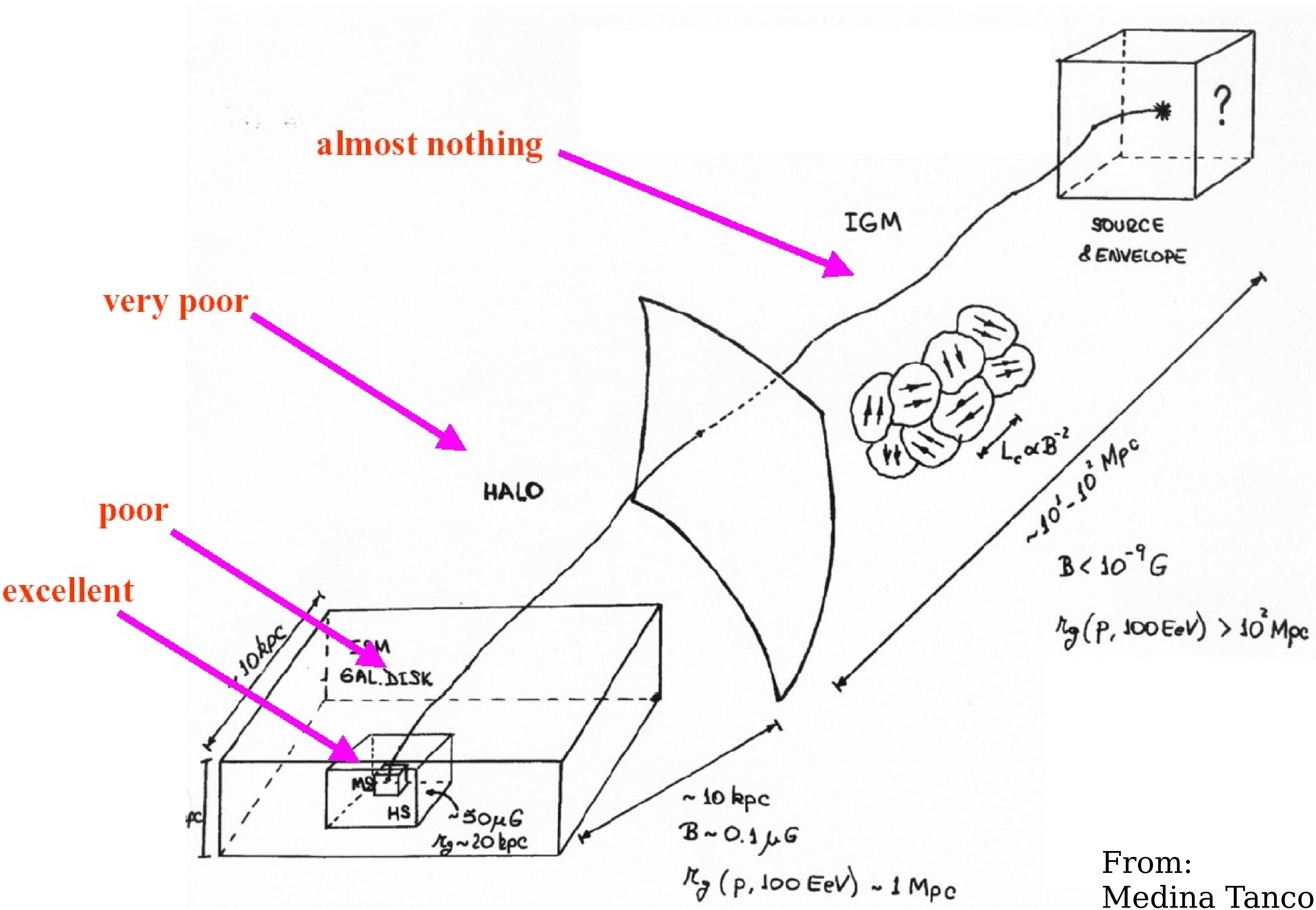
75 Mpc

3.1°



Significant dilution
[but not disappearance]
of the statistical significance

14 ev. 8 coincid. (2.9)
13 ev. 9 coincid. (2.7)
42 ev. 12 coincid.(8.8)

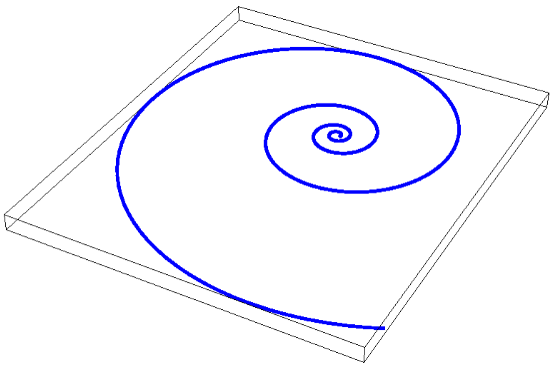


From:
Medina Tanco

$$\delta\theta = (\delta\theta)_{\text{Milky Way}} + (\delta\theta)_{\text{Intergalactic}} + (\delta\theta)_{\text{Source Envelope}}$$

Deviation in GALACTIC Magnetic Field

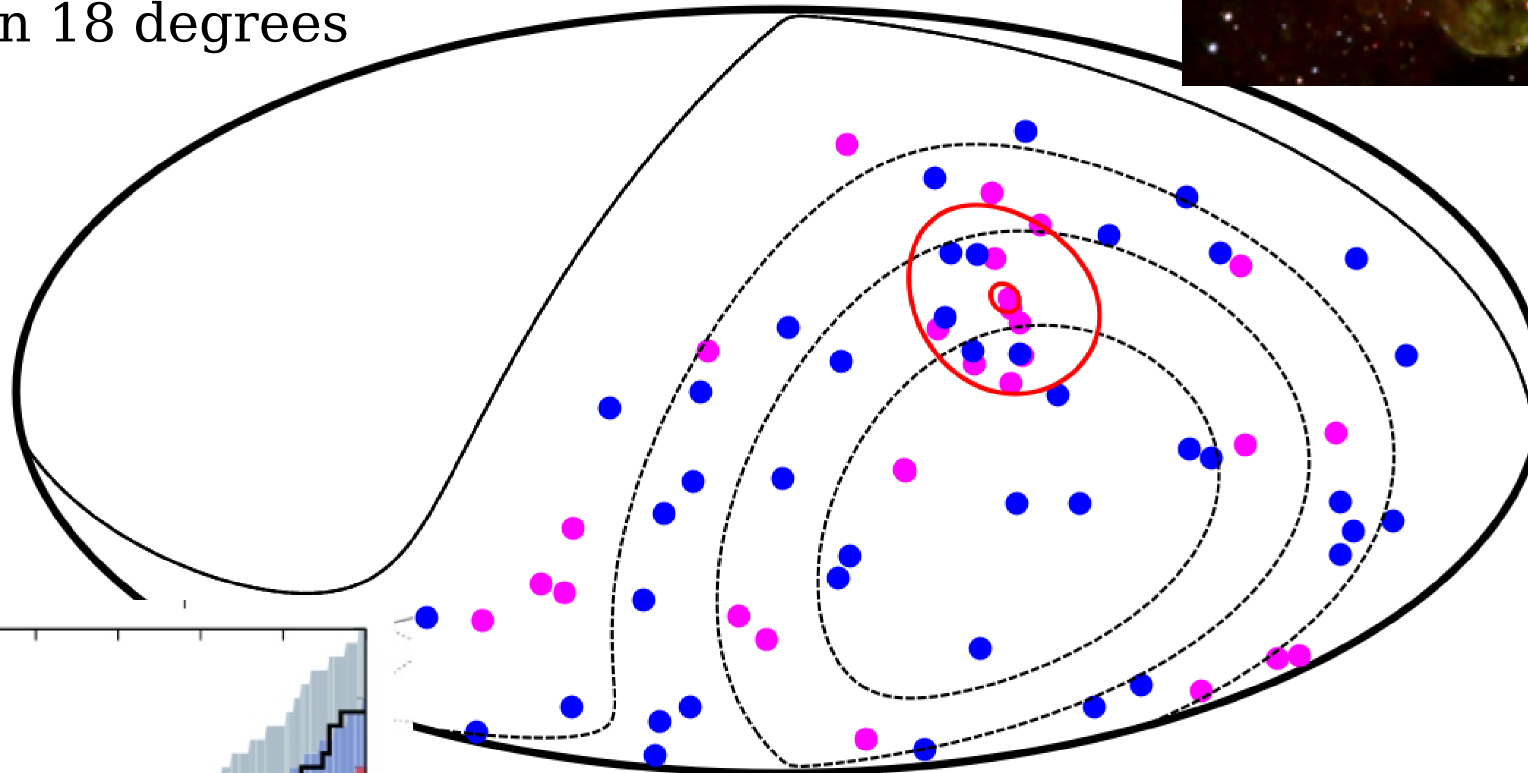
$$\delta \simeq 2.7^\circ \frac{60\ \text{EeV}}{E/Z} \left| \int_0^D \left(\frac{\mathrm{d}\mathbf{x}}{\text{kpc}} \times \frac{\mathbf{B}}{3\ \mu\text{G}} \right) \right|$$

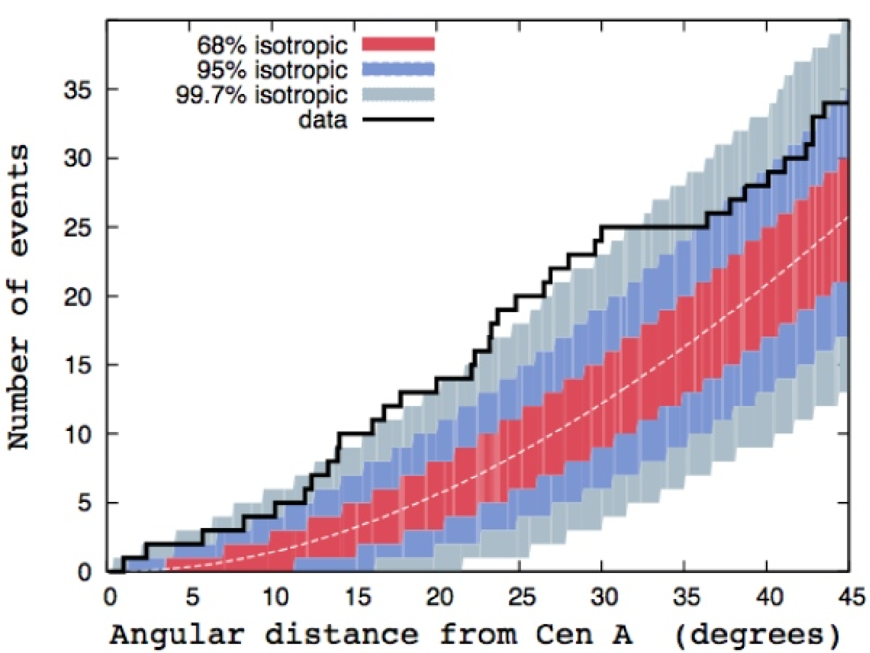


A deviation of few degrees for Particles with $E \sim 6 * 10^{19}$ eV implies a small charge $Z < 2(3\ ?)$

CEN A (the AGN closest to us d = 3.5 Mpc)

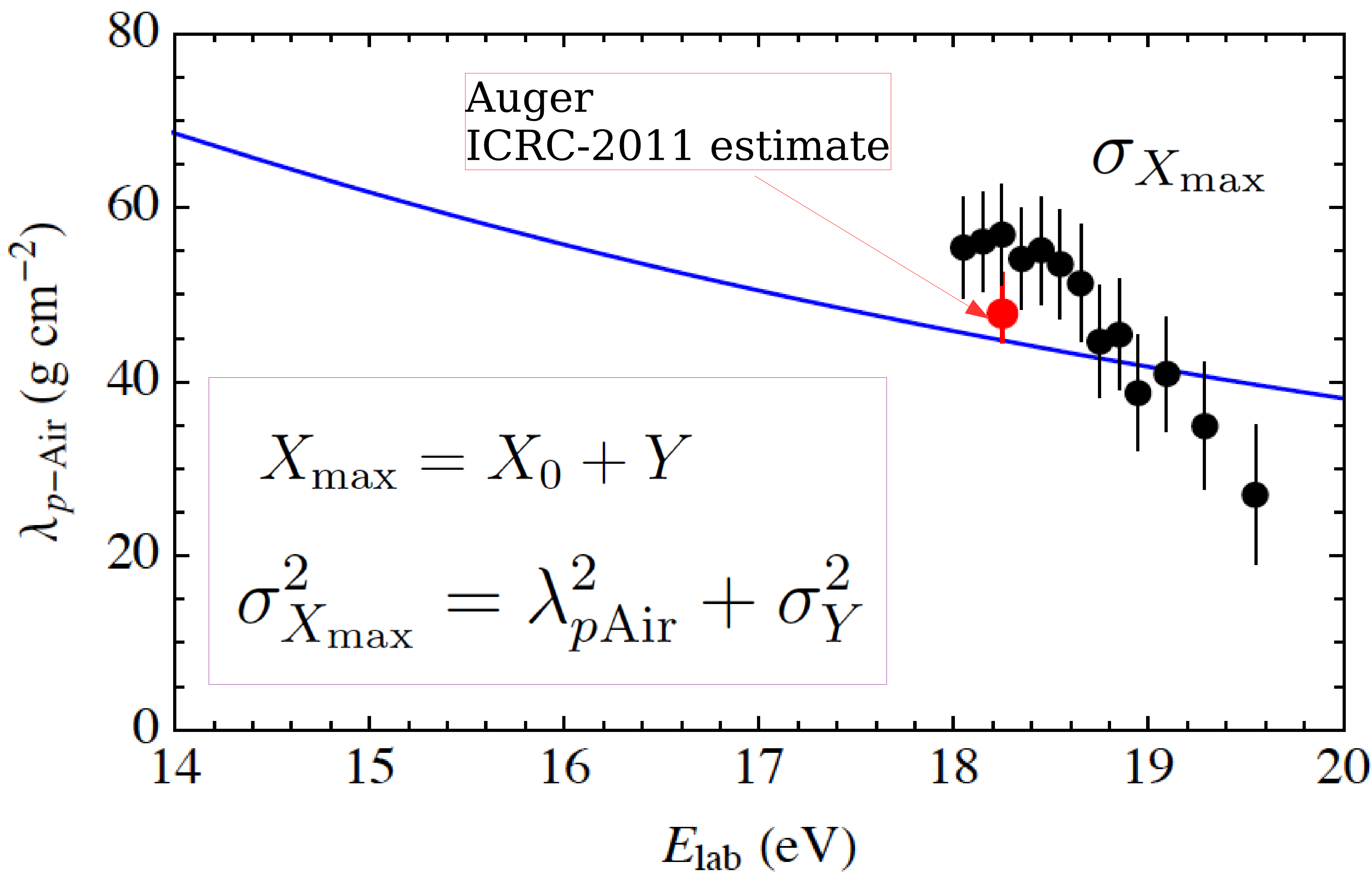
3 events within 3 degrees
13 events within 18 degrees





3, 20 degrees circles

PDG – Totem parametrizations
+ Glauber-Matthiae (1970) to estimate
p-nucleus cross sections



$$E_0 \simeq 10^{19.547}\ \mathrm{eV}$$

$$\sigma_{pp}^{\mathrm{inel}} \simeq 124\ \mathrm{mbarn}$$

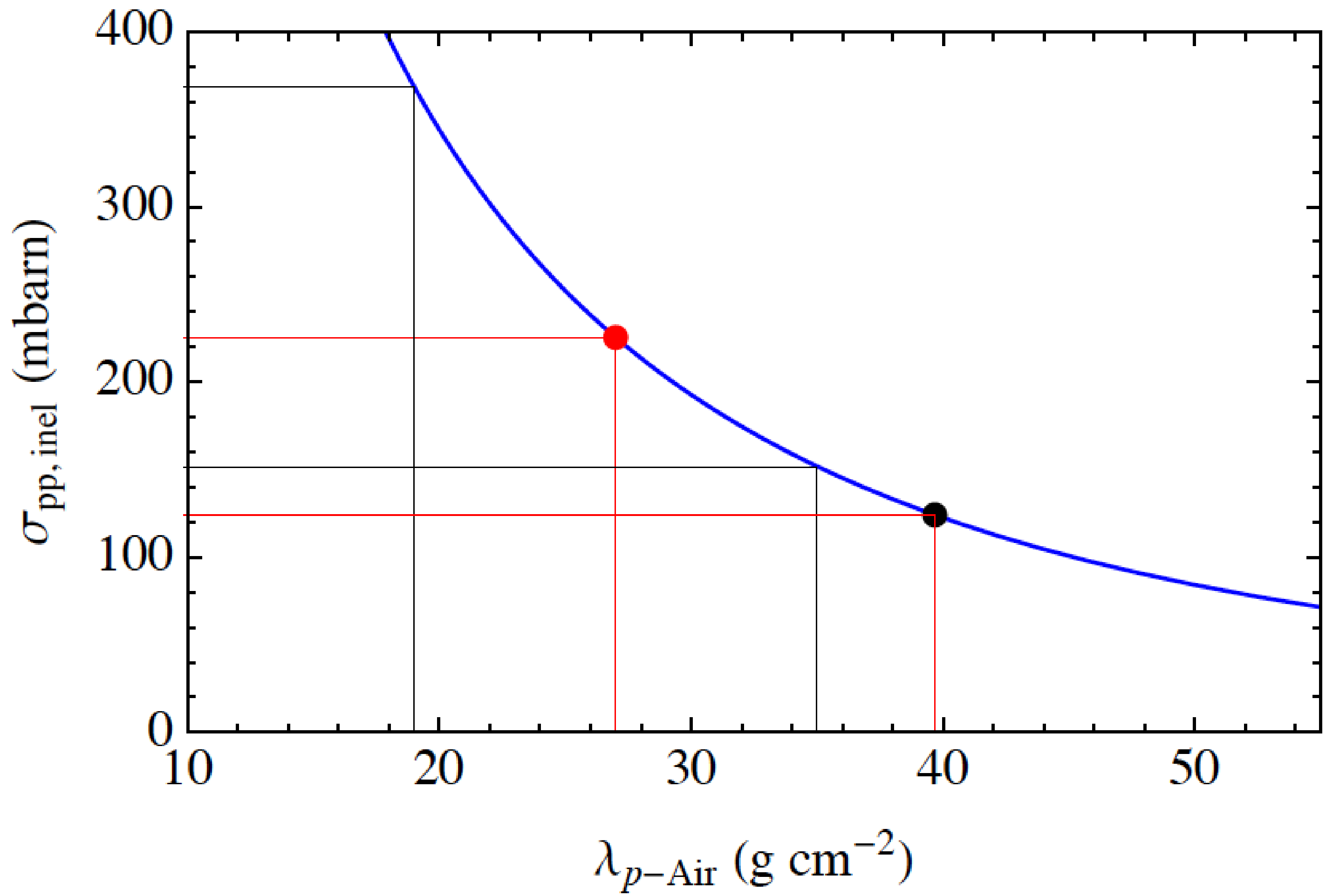
$$\lambda_{p\mathrm{Air}} \simeq 39.7\ \mathrm{g\,cm^{-2}}$$

$$\sigma_{pp}^{\mathrm{inel}} \simeq 225\ \mathrm{mbarn}$$

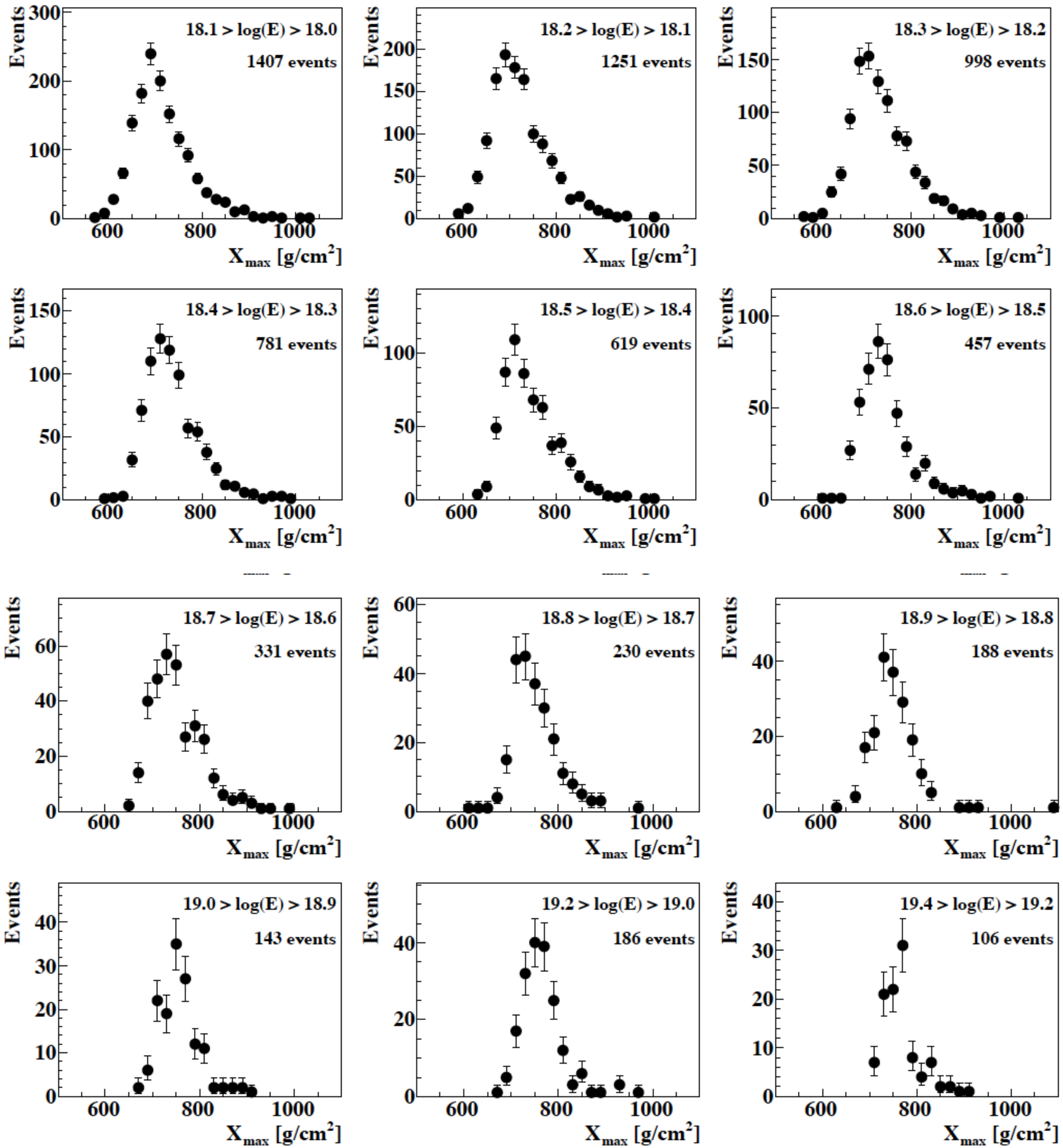
$$\lambda_{p\mathrm{Air}} \simeq 30\ \mathrm{g\,cm^{-2}}$$

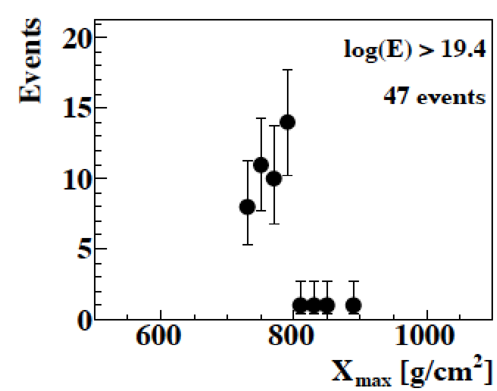
$$\sigma_{pp}^{\mathrm{inel}} \simeq 340\ \mathrm{mbarn}$$

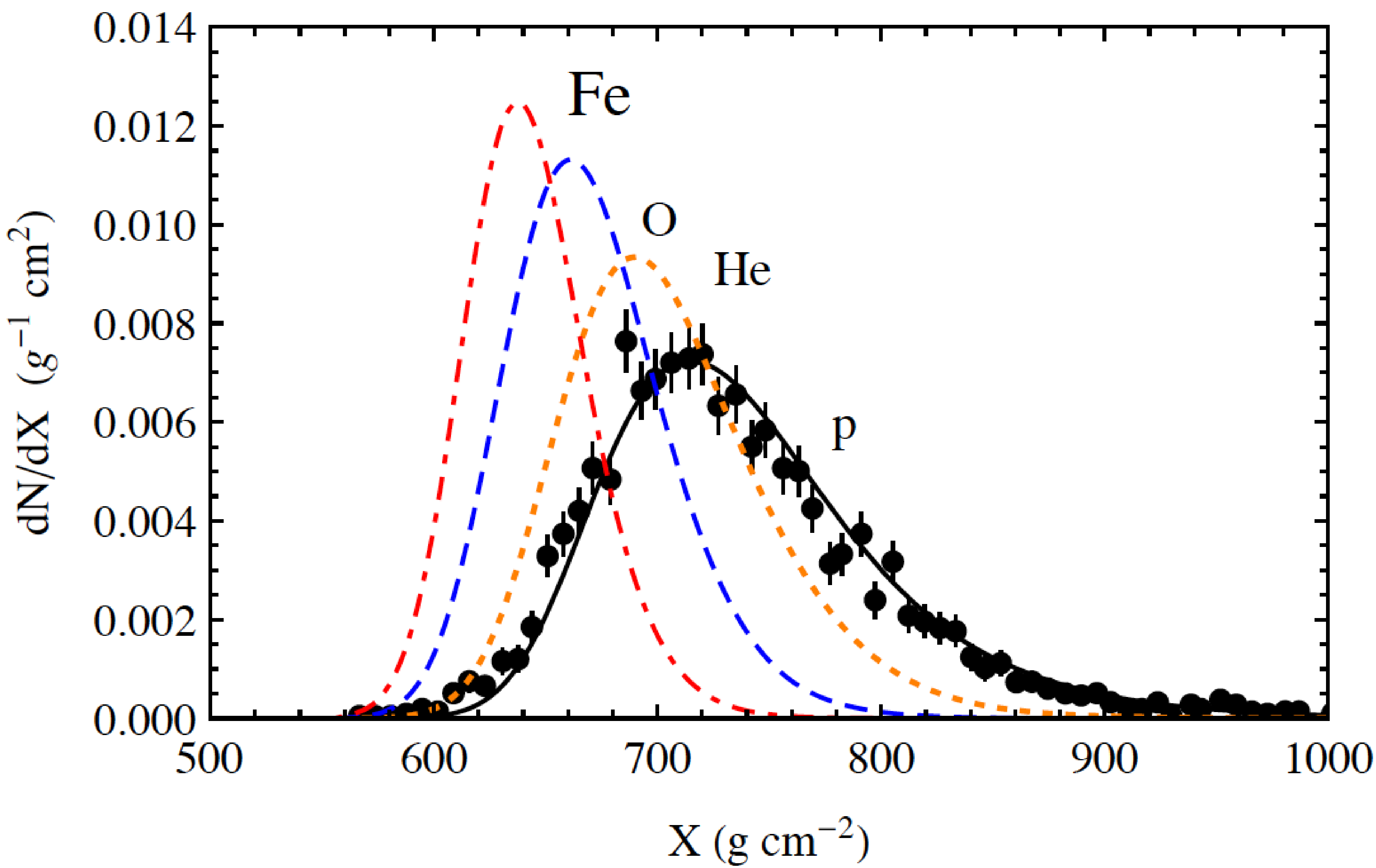
$$\lambda_{p\mathrm{Air}} \simeq 20\ \mathrm{g\,cm^{-2}}$$



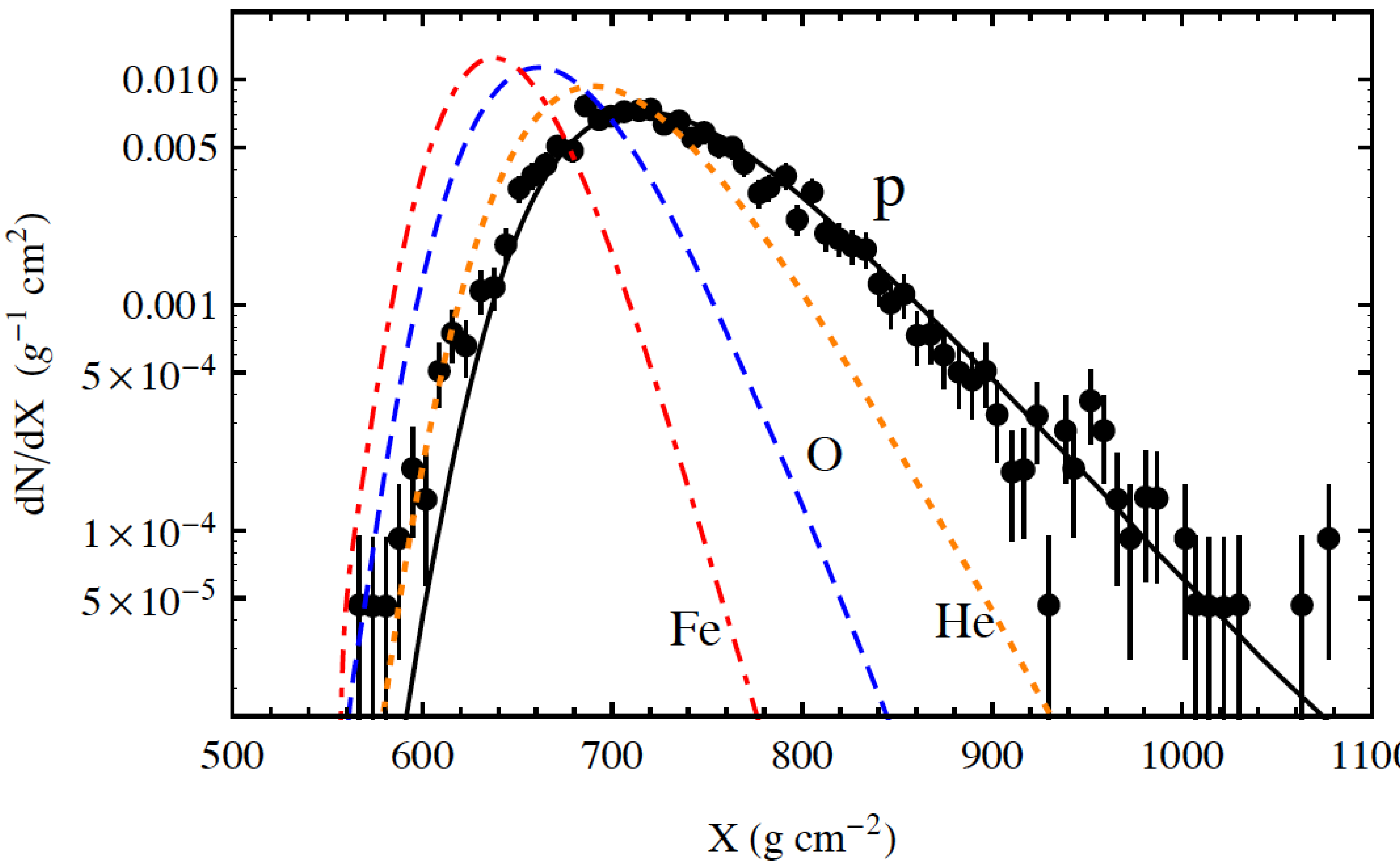
Xmax distributions !







$$E = 10^{18.25}\ \text{eV}$$

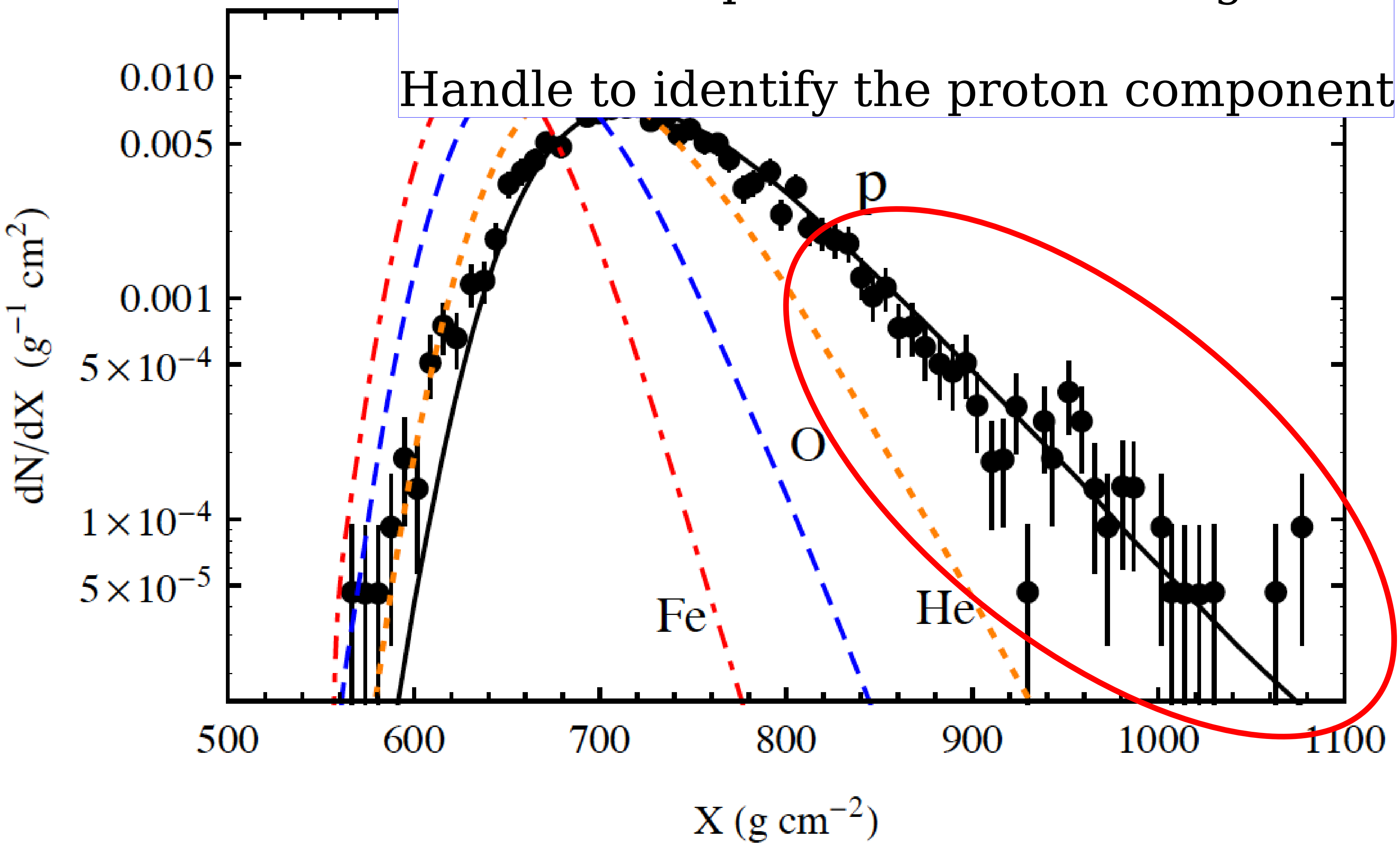


Logarithmic scale

$$E = 10^{18.25}\ \mathrm{eV}$$

Estimate of p-Air interaction length.

Handle to identify the proton component



Logarithmic scale

$$E = 10^{18.25}\ \text{eV}$$

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Total Proton-Proton Cross Section at $s^{1/2} = 30$ TeV

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(Received 16 January 1984)

We have measured the proton-air inelastic cross section at $s^{1/2} = 30$ TeV by observing the distribution of extensive-air-shower maxima as a function of atmospheric depth. This distribution has an exponential tail whose slope is $\lambda = 72 \pm 9$ g cm^{-2} which implies that $\sigma_{p-\mathrm{air}}^{\mathrm{inel}} = 530 \pm 66$ mb. Using Glauber theory and assuming that the elastic-scattering slope parameter b is proportional to $\sigma_{pp}^{\mathrm{tot}}$, we infer a value of $\sigma_{pp}^{\mathrm{tot}} = 120 \pm 15$ mb which lies between a log$s$ and a log$^2 s$ extrapolation of the total pp cross section as measured at lower energies.

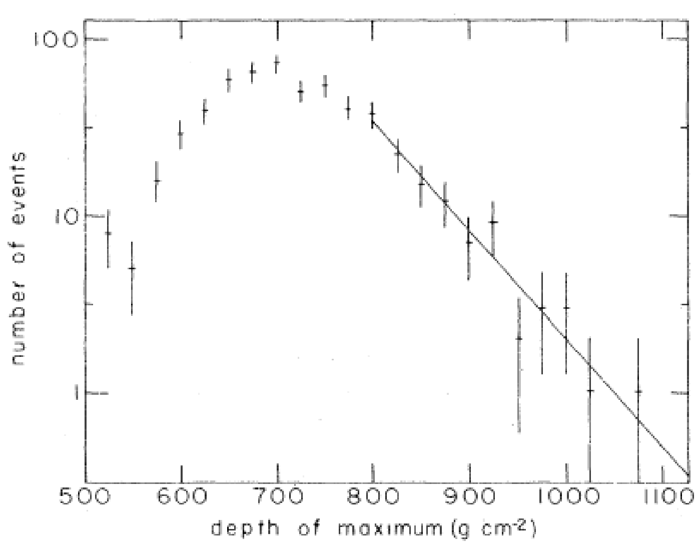


FIG. 5. Distribution of depth of maxima $X_{\max}$ for data whose fitting errors are estimated to be $\delta x < 125$ g cm^{-2}. The slope of the exponential tail is $\lambda = 73 \pm 9$ g cm^{-2}.

Pioneering work of Fly's Eye

The (p-air) “Pierre” cross section

Measurement of the p-Air Interaction Length:

$$X_{\rm max} = X_0 + Y$$

Position 1st interaction
Shower Development

$$F(X_{\rm max}) \equiv \frac{dN_{\rm shower}}{dX_{\rm max}}$$

$$G(Y) \equiv \frac{dN_{\rm shower}}{dY}$$

$$\begin{aligned} F(X_{\rm max}) &= \int_0^\infty dY \int_0^\infty dX_0 \; G(Y) \; \frac{e^{-X_0/\lambda_p}}{\lambda_p} \; \delta[X_{\rm max} - (X_0 + Y)] \\ &= \frac{e^{-X_{\rm max}/\lambda_p}}{\lambda_p} \left[\int_0^{X_{\rm max}} dY \; G(Y) \; e^{Y/\lambda_p} \right] \end{aligned}$$

$$X_{\max} \to \infty$$

$$F(X_{\max}) = \frac{e^{-X_{\max}/\lambda_p}}{\lambda_p} \left[\int_0^{X_{\max}} dY \; G(Y) \; e^{Y/\lambda_p} \right]$$

constant

Asymptotically: Exponential Distribution

Slope = Interaction Length

$$G(X) = F(X) + \lambda_p \frac{dF}{dX}$$

$$\Lambda(X) \equiv -\left[\frac{1}{F(X)} \frac{dF(X)}{dX}\right]^{-1} = \lambda_p \left(1 - \frac{G(X)}{F(X)}\right)^{-1}$$

"Local slope"
(directly measurable)

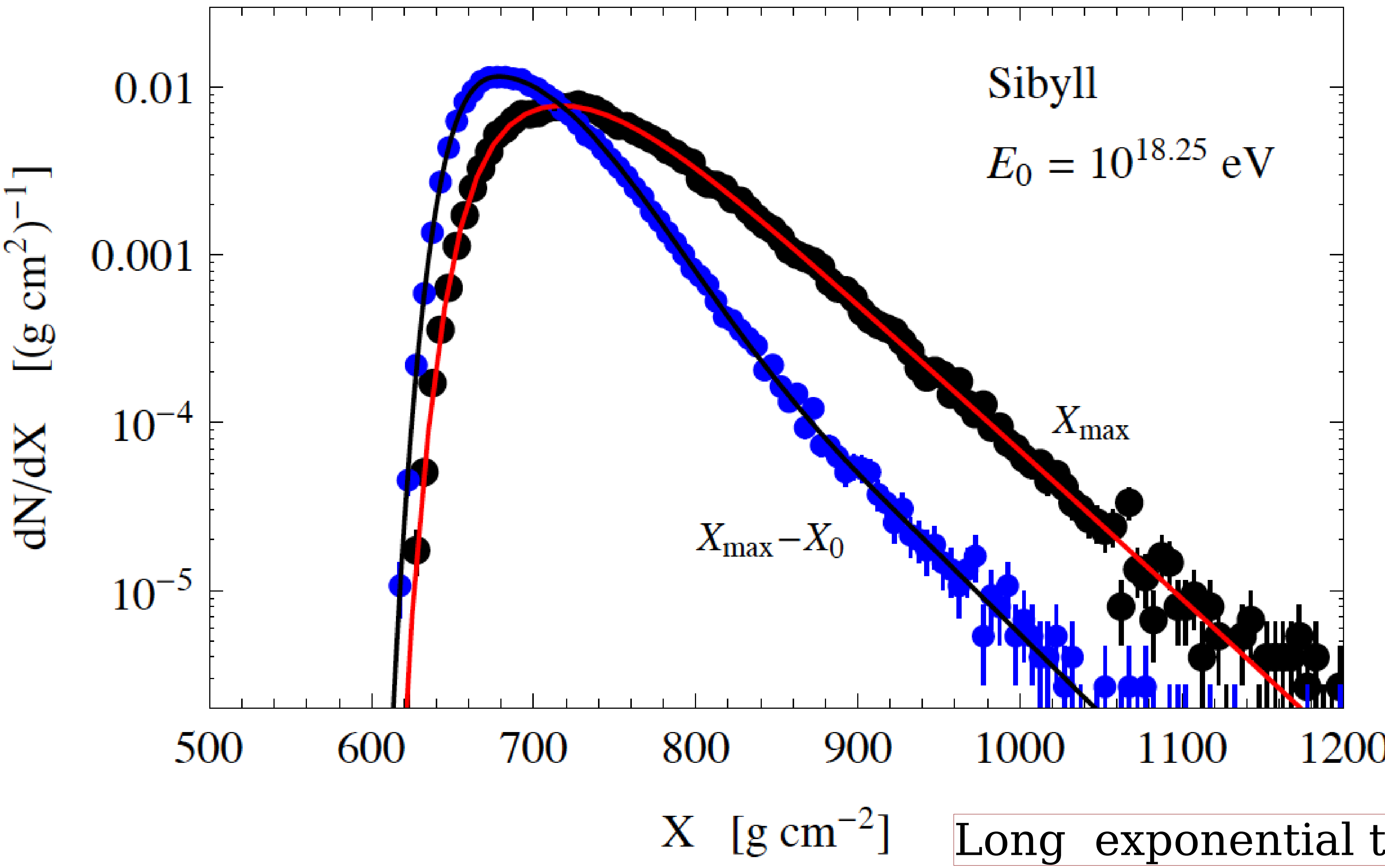
Interaction Length

$$X_{\max} \to \infty$$

$$\Lambda(X_{\max}) \to \lambda_p$$

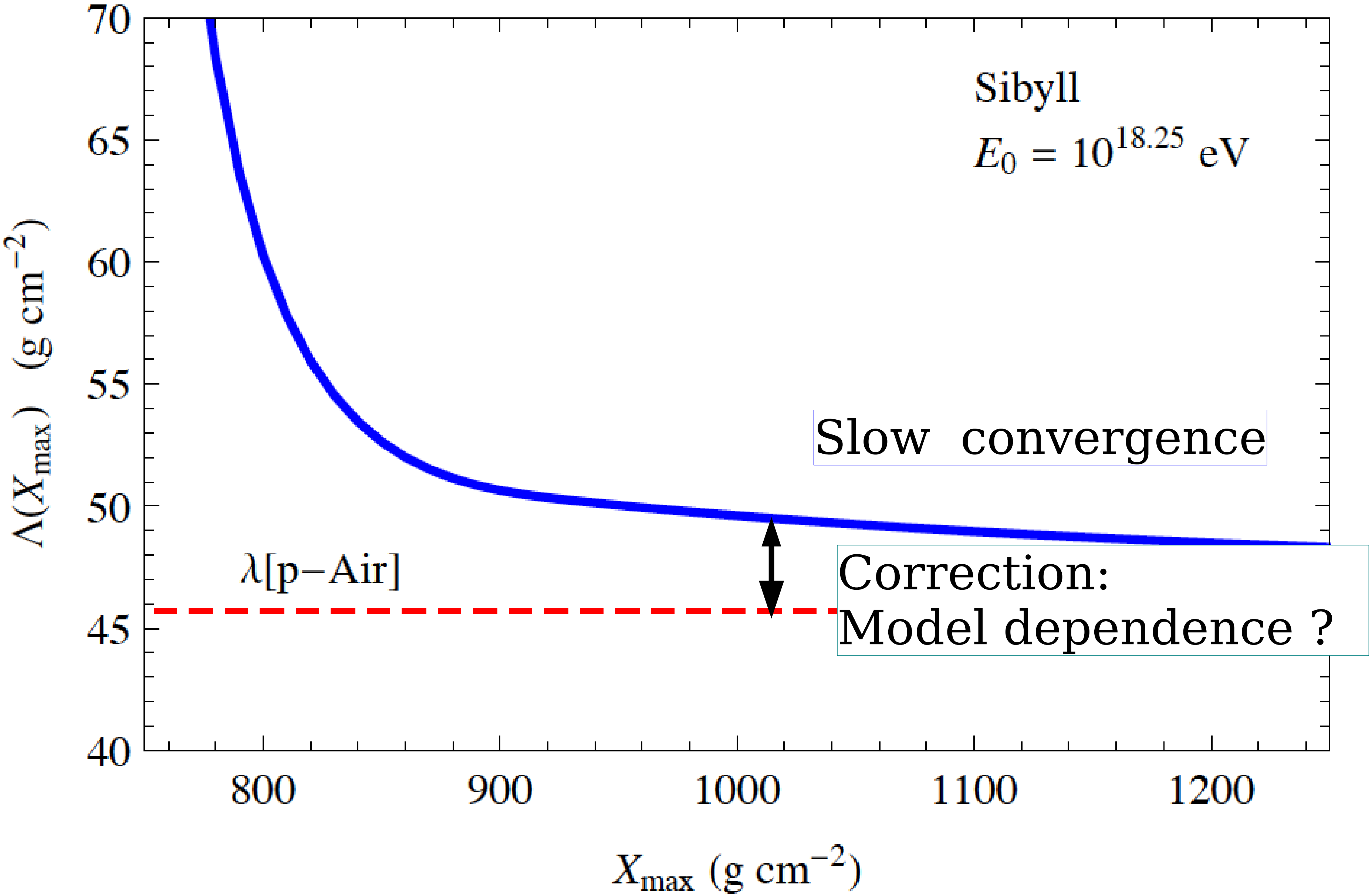
$$G(X)/F(X) \to 0$$

Montecarlo calculation Using Sibyll
[+PDG cross sections + original Glauber]



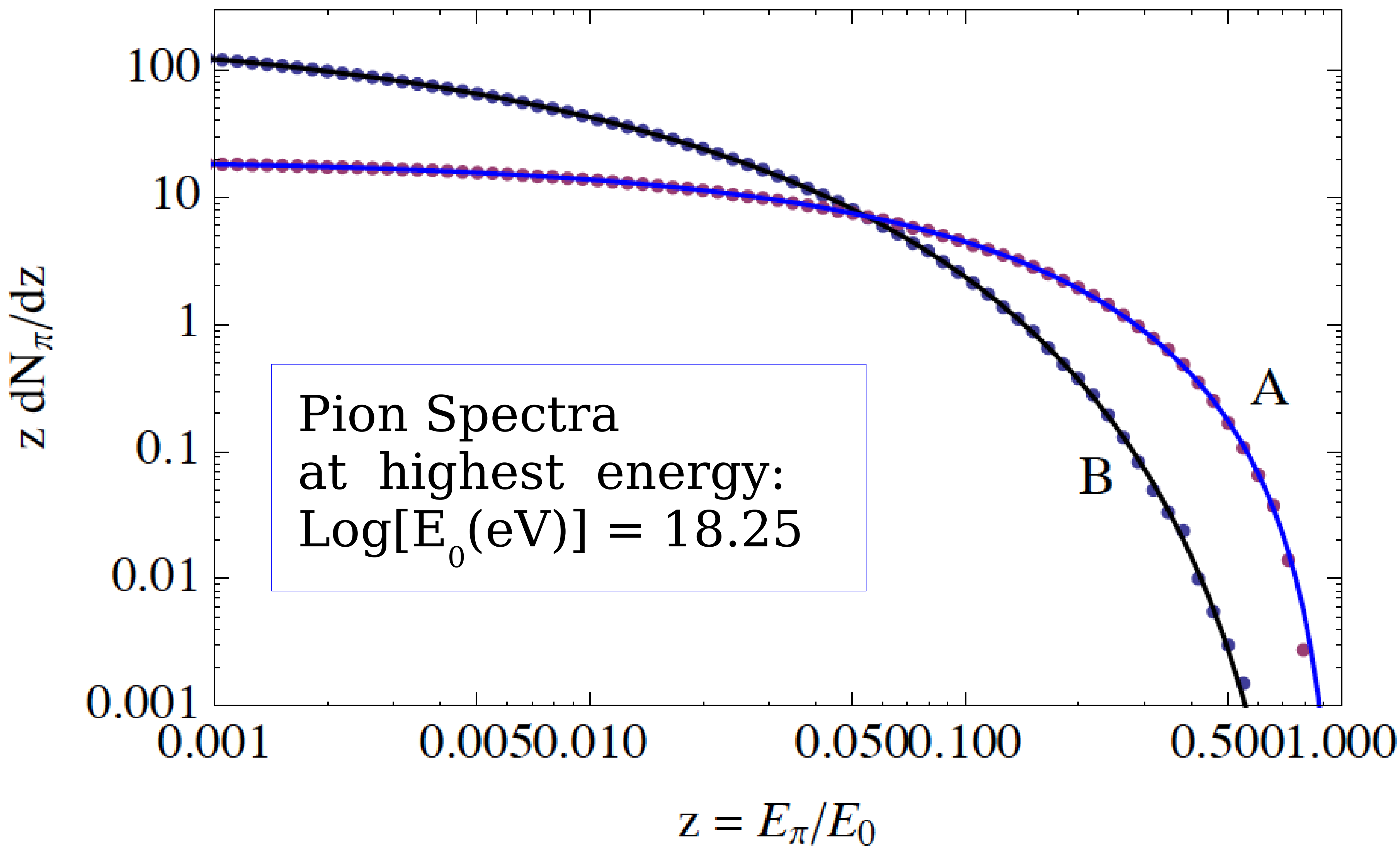
Long exponential tail

Slow convergence of slope the interaction Length:

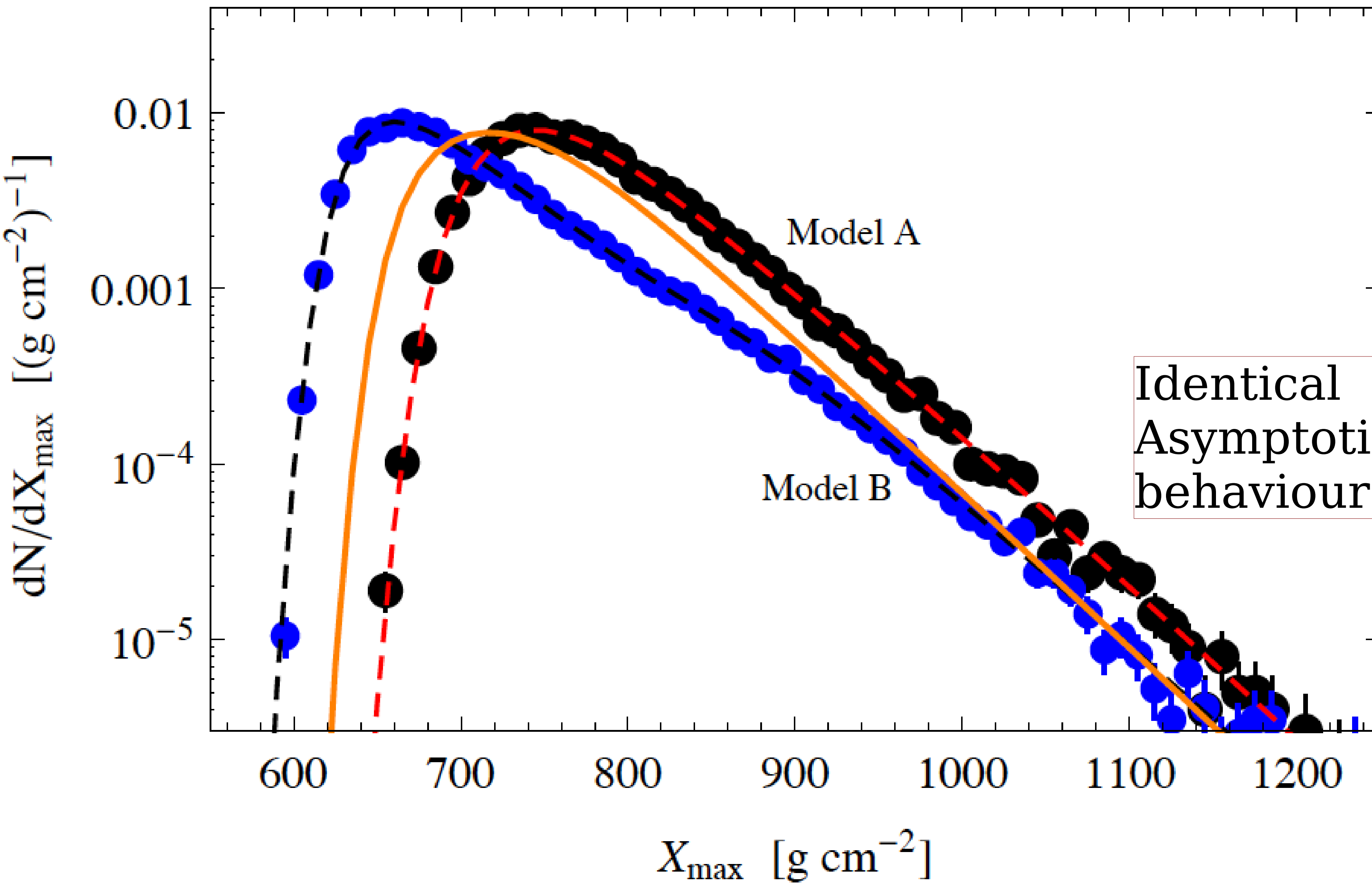


“Toy Models”
(Analytic representation of particle spectra):

Model A : Hard spectra, more penetrating showers
Model B : Soft spectra, less penetrating showers

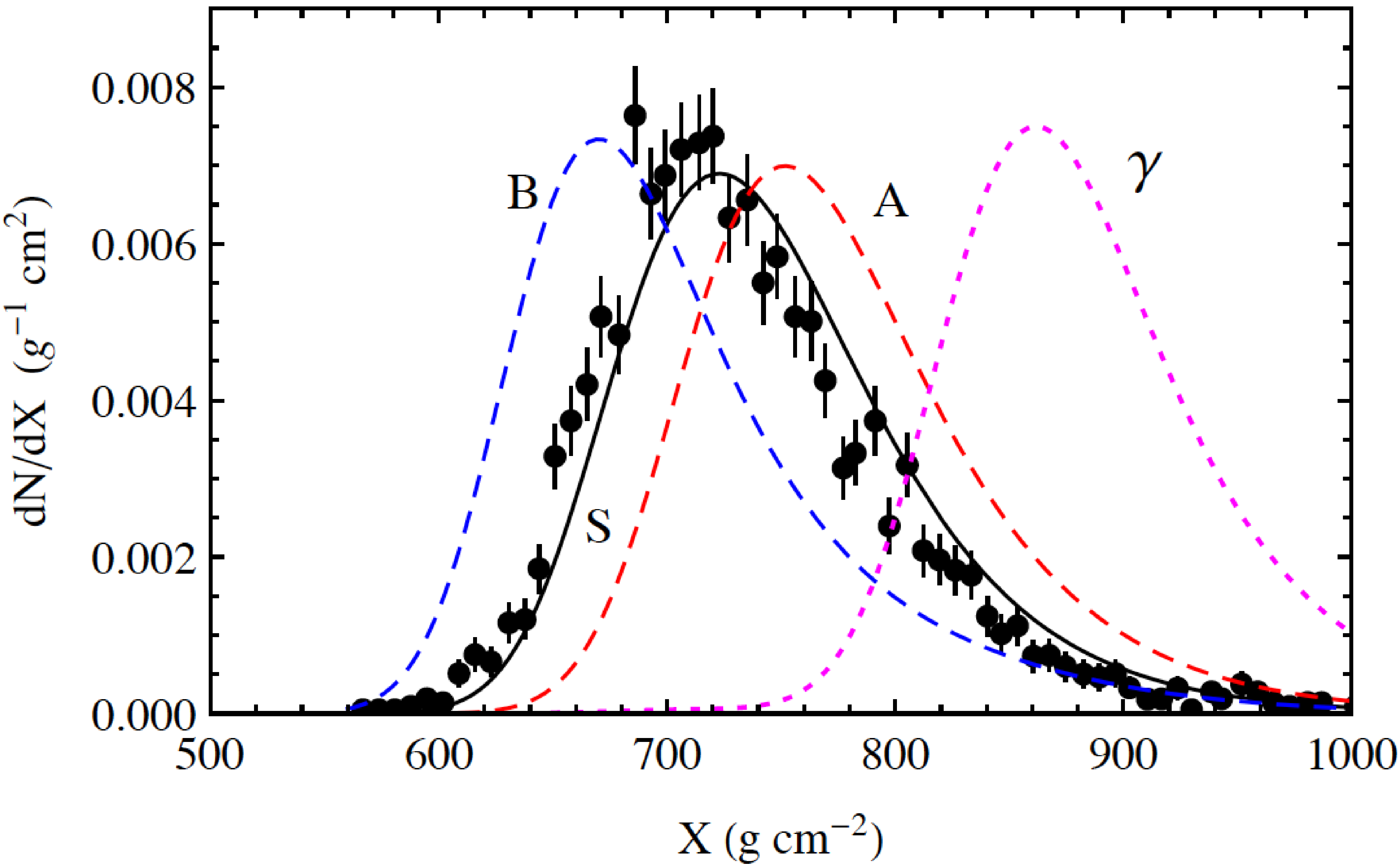


Xmax Distributions:

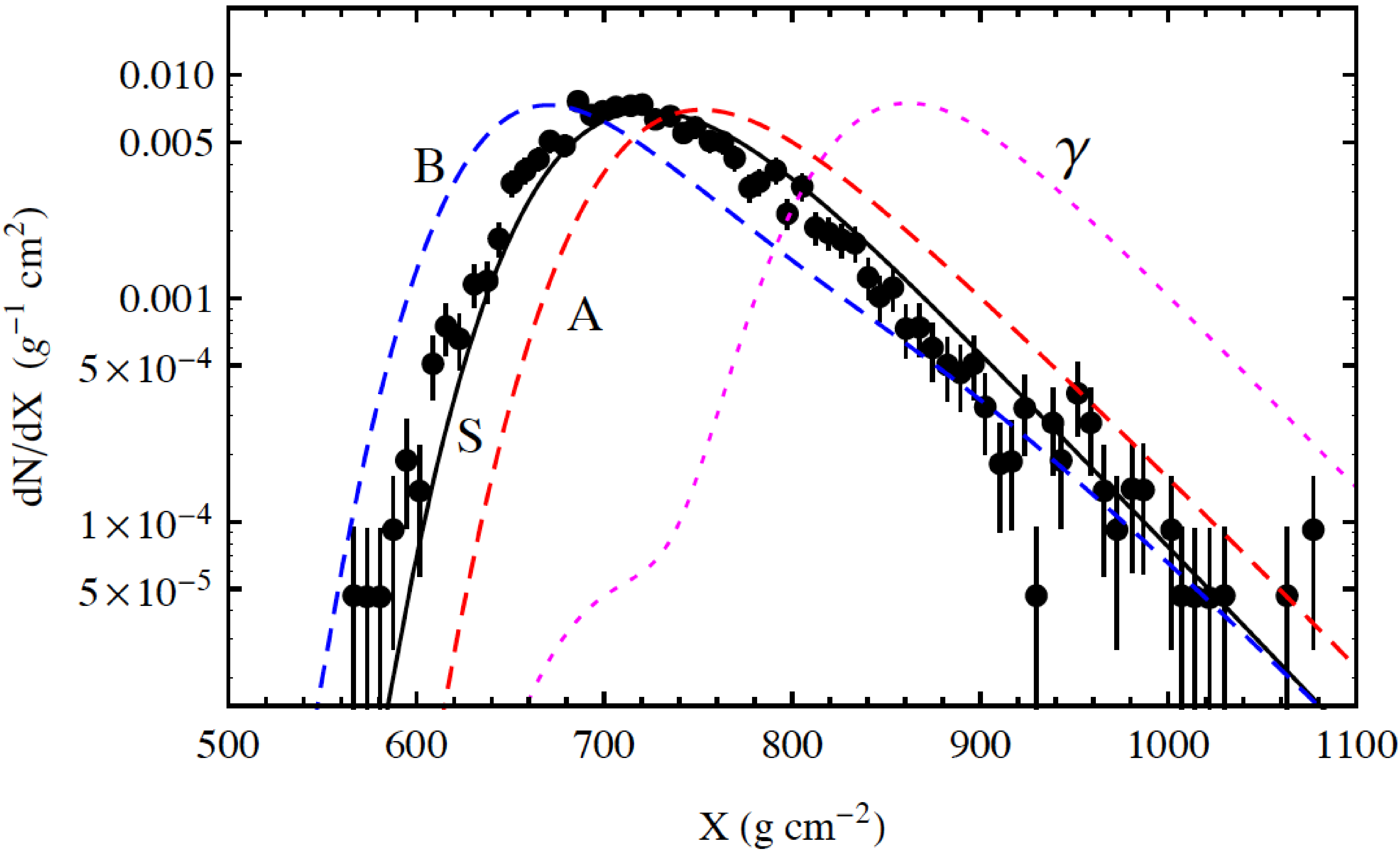


Identical Asymptotic behaviour

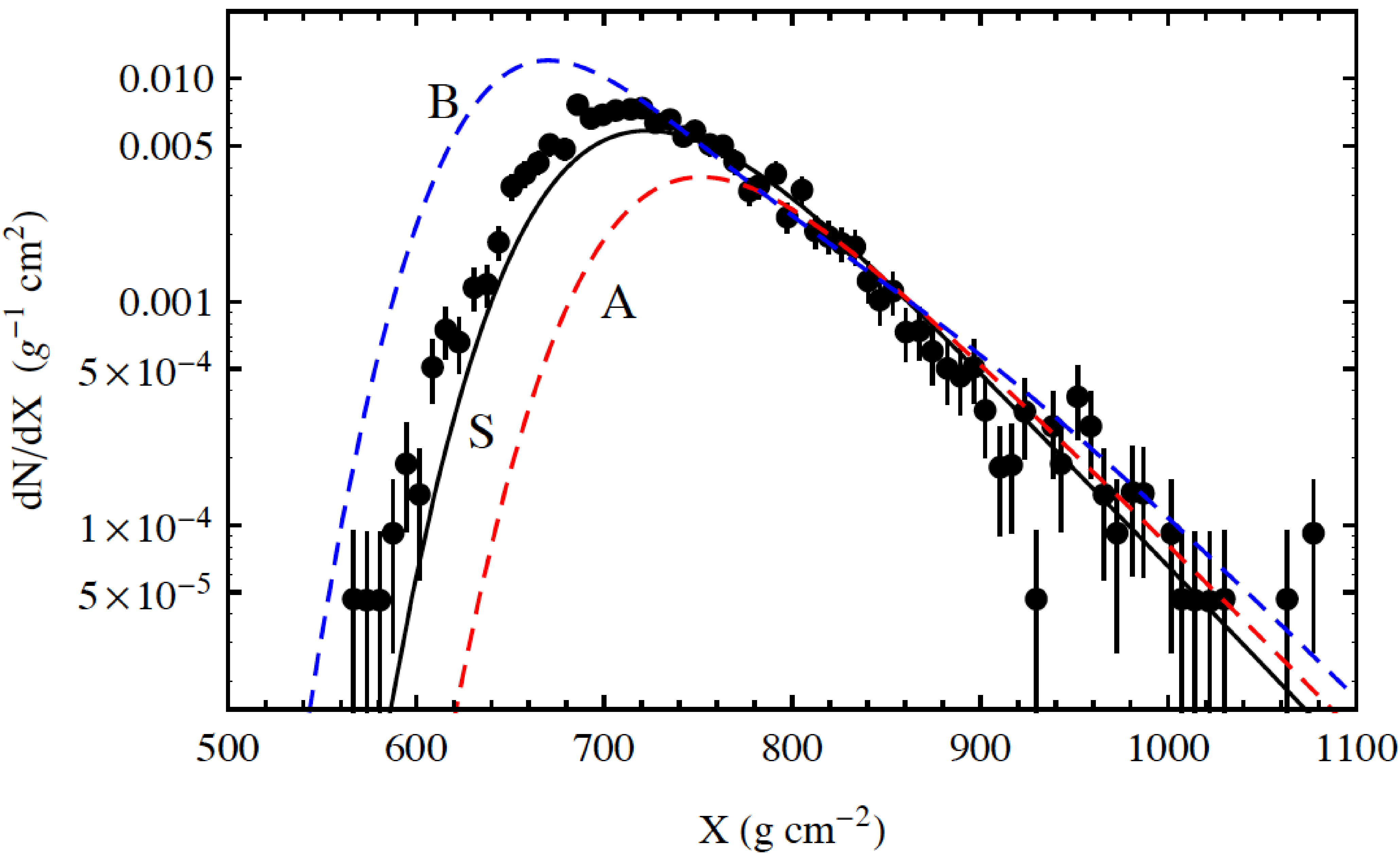
Compare with Auger data. Normalization: equal area.



Compare with Auger data. Normalization: equal area.

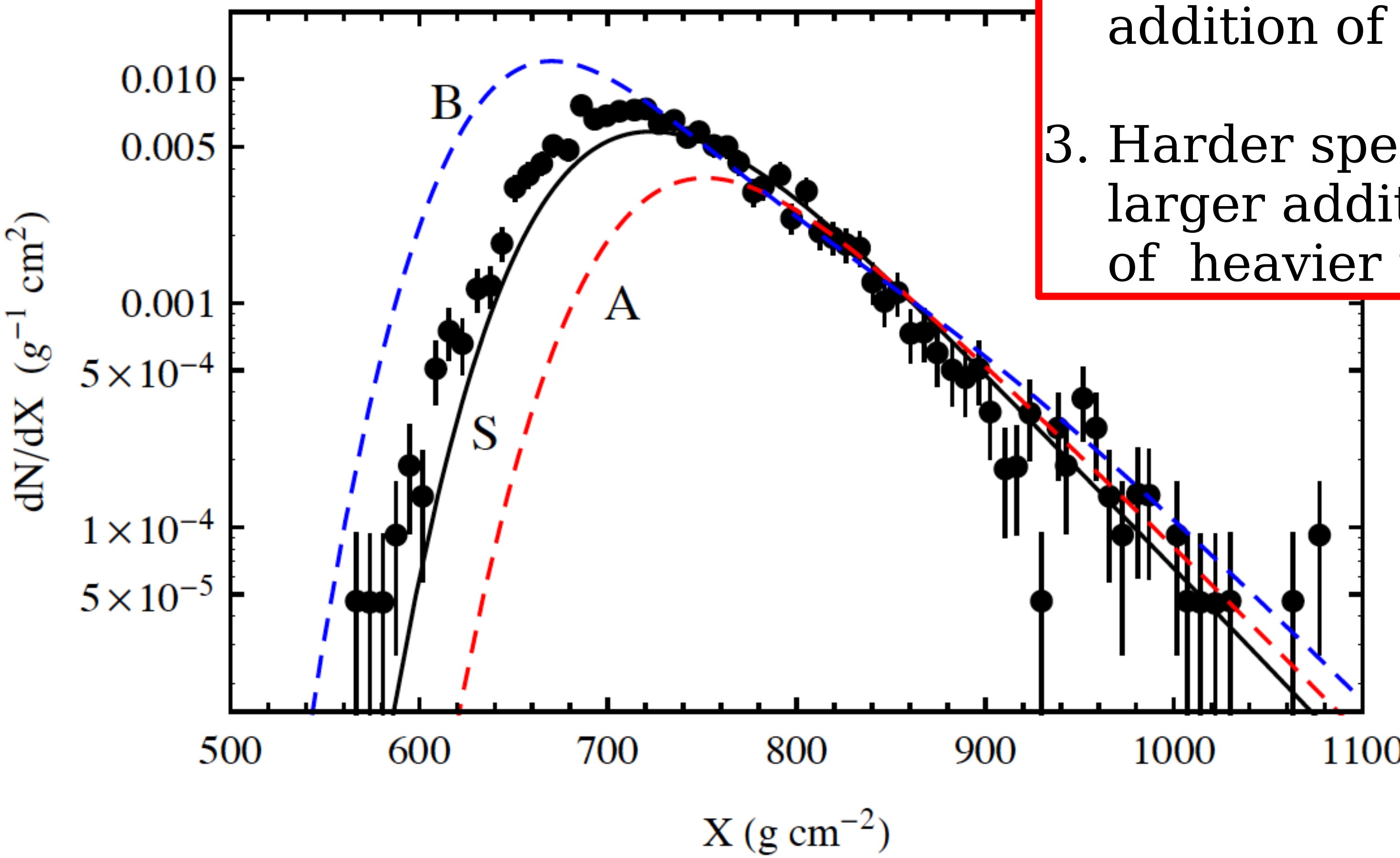


Normalization: same # of events for: $X_{\max} \geq 800 \text{ g/cm}^2$



Normalization: same #
of events for:

$$X_{\max} \geq 800 \text{ g/cm}^2$$



Tentative conclusions:

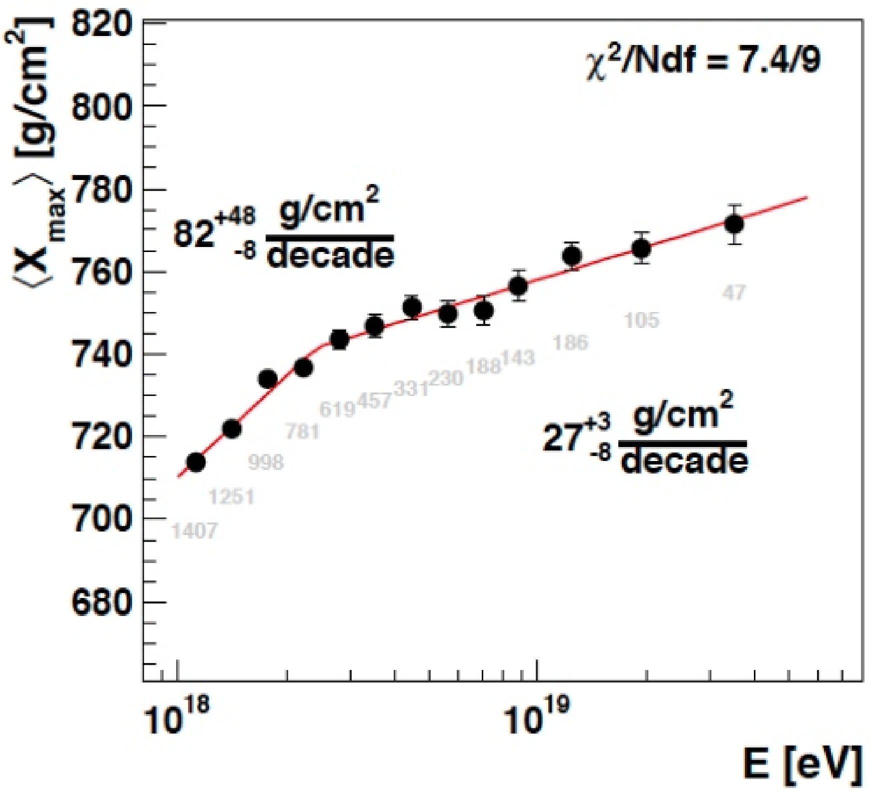
1. A very soft model Like "model B" is EXCLUDED by the data !

2. A Model like "Sibyll" (moderate softening with increasing energy). allows/needs only a small addition of helium + (Z>2 nuclei)

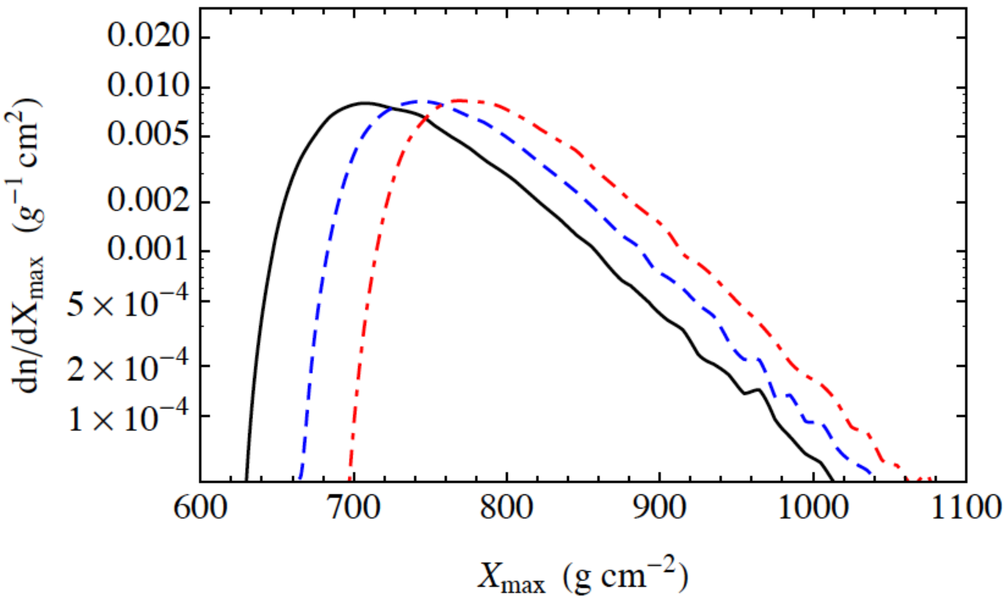
3. Harder spectra require larger additional component of heavier nuclei.

Very attractive line of study:

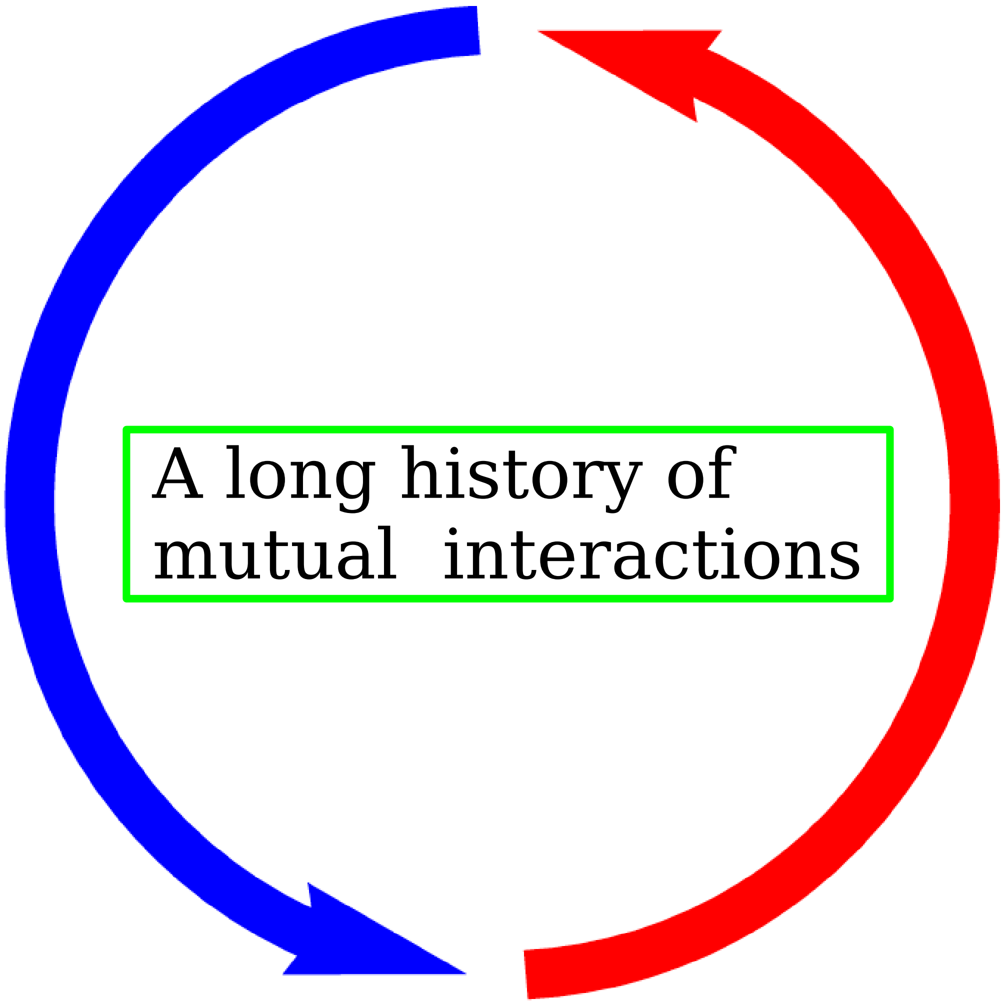
Extension of this type of analysis to lower and higher energies



Proton-showers [growing energy]



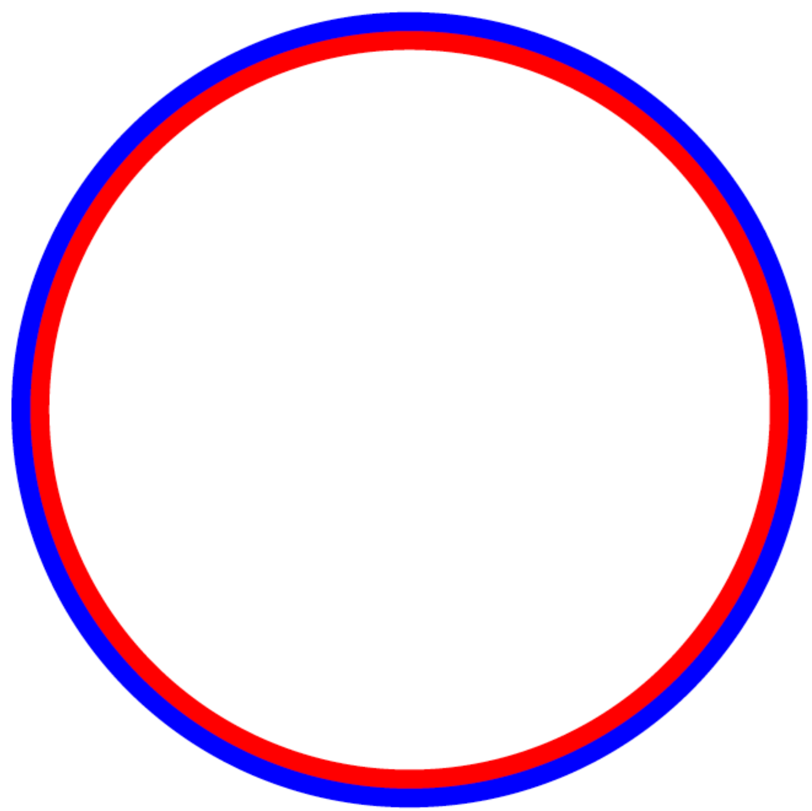
PARTICLE PHYSICS



COSMIC RAYS ASTROPHYSICS

(more than) a dream : closing the circle!

PARTICLE PHYSICS



COSMIC RAYS ASTROPHYSICS

With UHECR one studies at the same time

"Gigantic Astrophysical Beasts"

Millions of light years away

Length scale 10^{+24} cm

Microscopic

Partonic constituents of matter

Length scale 10^{-15} cm

Exciting

Difficult