Hadronic Interactions

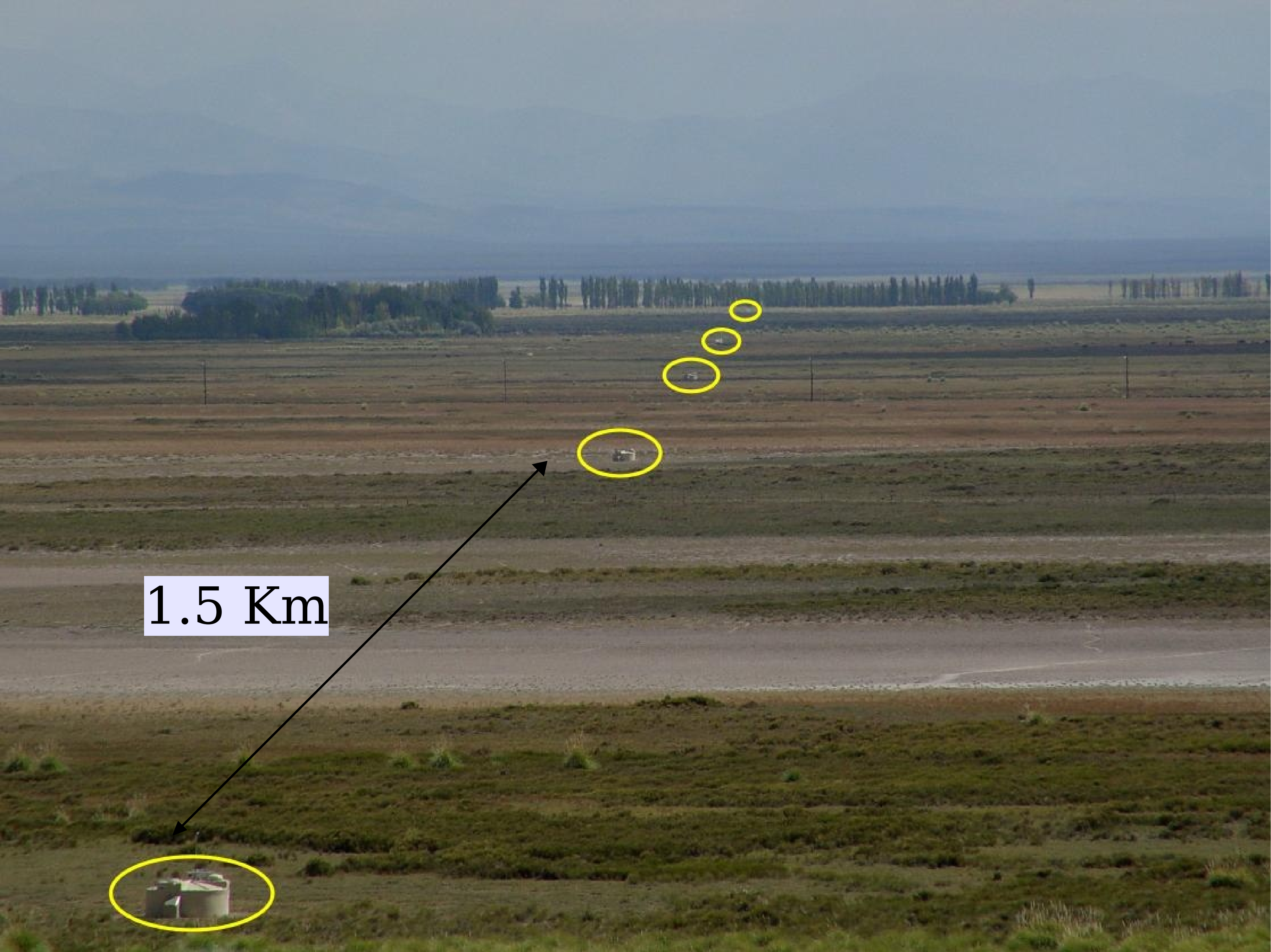
and

Cosmic Ray Showers

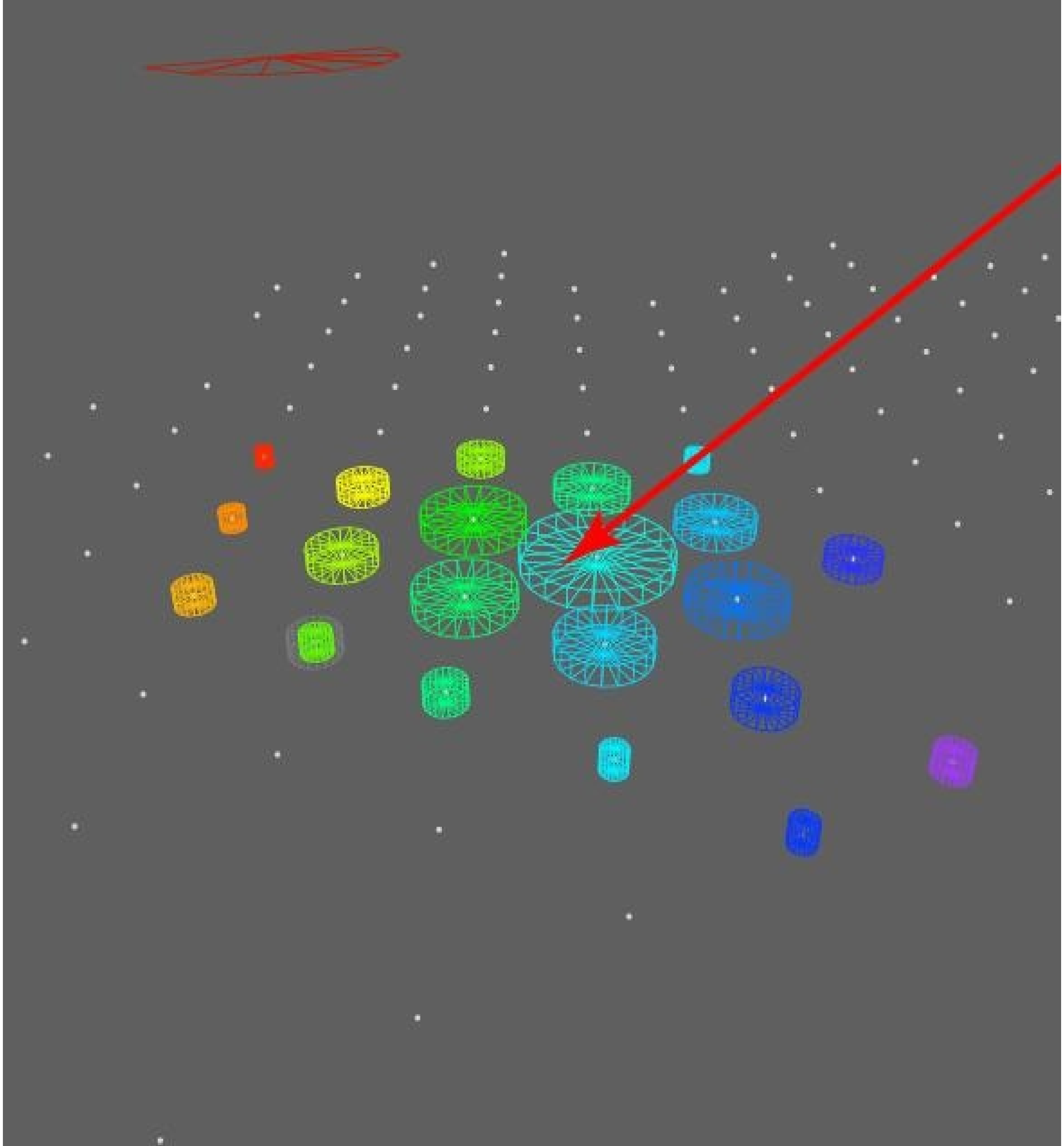
Paolo Lipari
MAPSES workshop

Lecce 23rd - 25th november 2011

AUGER detector in ARGENTINA


1.5 Km

Auger South on a cloudy day ...



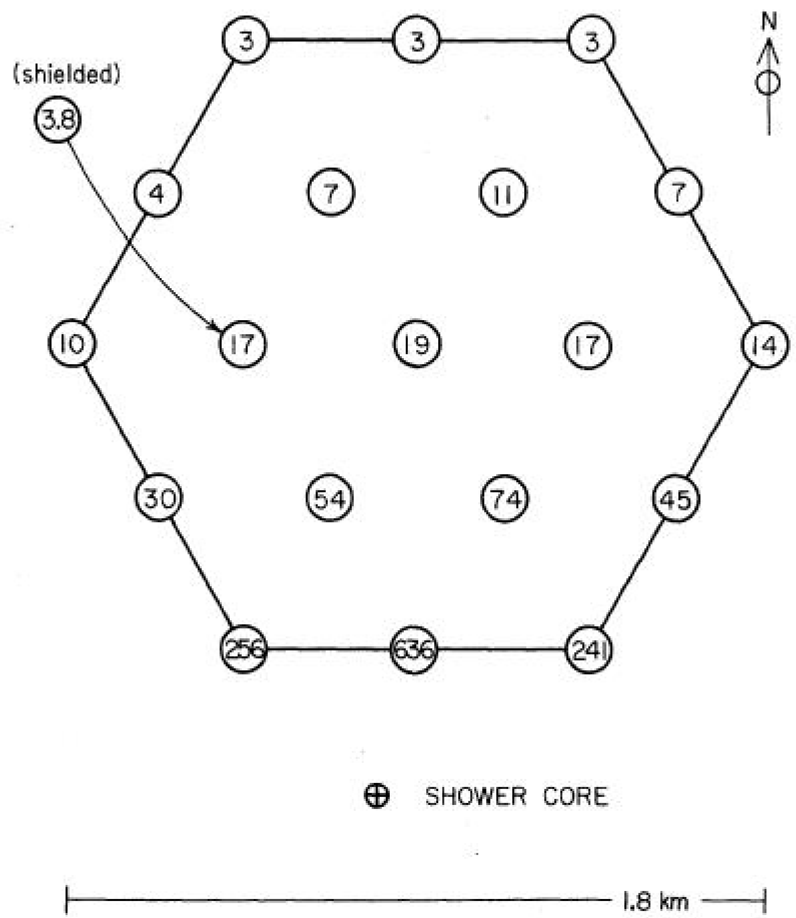
~50 years of UHECR

PHYSICAL REVIEW LETTERS

EXTREMELY ENERGETIC COSMIC-RAY EVENT*

John Linsley, Livio Scarsi,† and Bruno Rossi
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received April 12, 1961)

Energy



it follows on any reasonable shower model that the energy of the primary particle was about 10^{19} ev. Taking the usual estimate 3×10^{-6} gauss for the galactic magnetic field, one finds the radius of curvature of the path of a proton of such energy to be about 10^4 light years. Since, according to current estimates, the radius of the galactic halo is only about five times this value, while the thickness of the galactic disk is about five or ten times smaller, it seems certain that the primary particle acquired its energy outside our galaxy.

An important question is whether the primary particle was a proton or a heavier nucleus.

Mass A

Hadronic interaction Modeling

Measure a single slice of the shower at the ground

~50 years of UHECR

PHYSICAL REVIEW LETTERS

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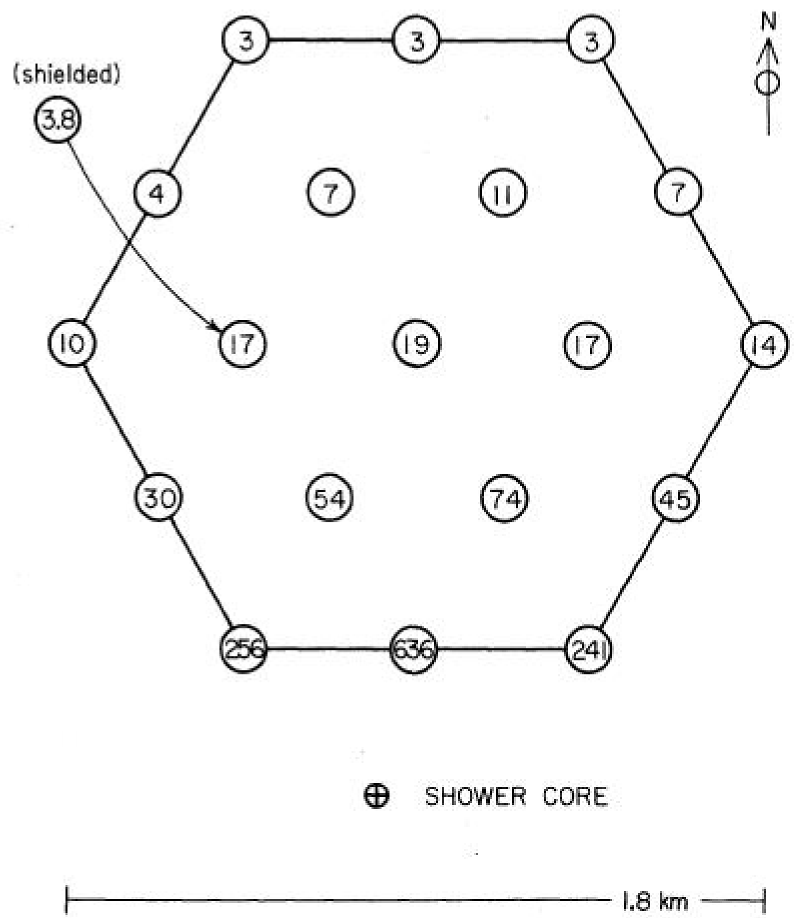


Hadronic interaction Modeling

$e^{\pm}$ γ

$\mu^{\pm}$

hadrons

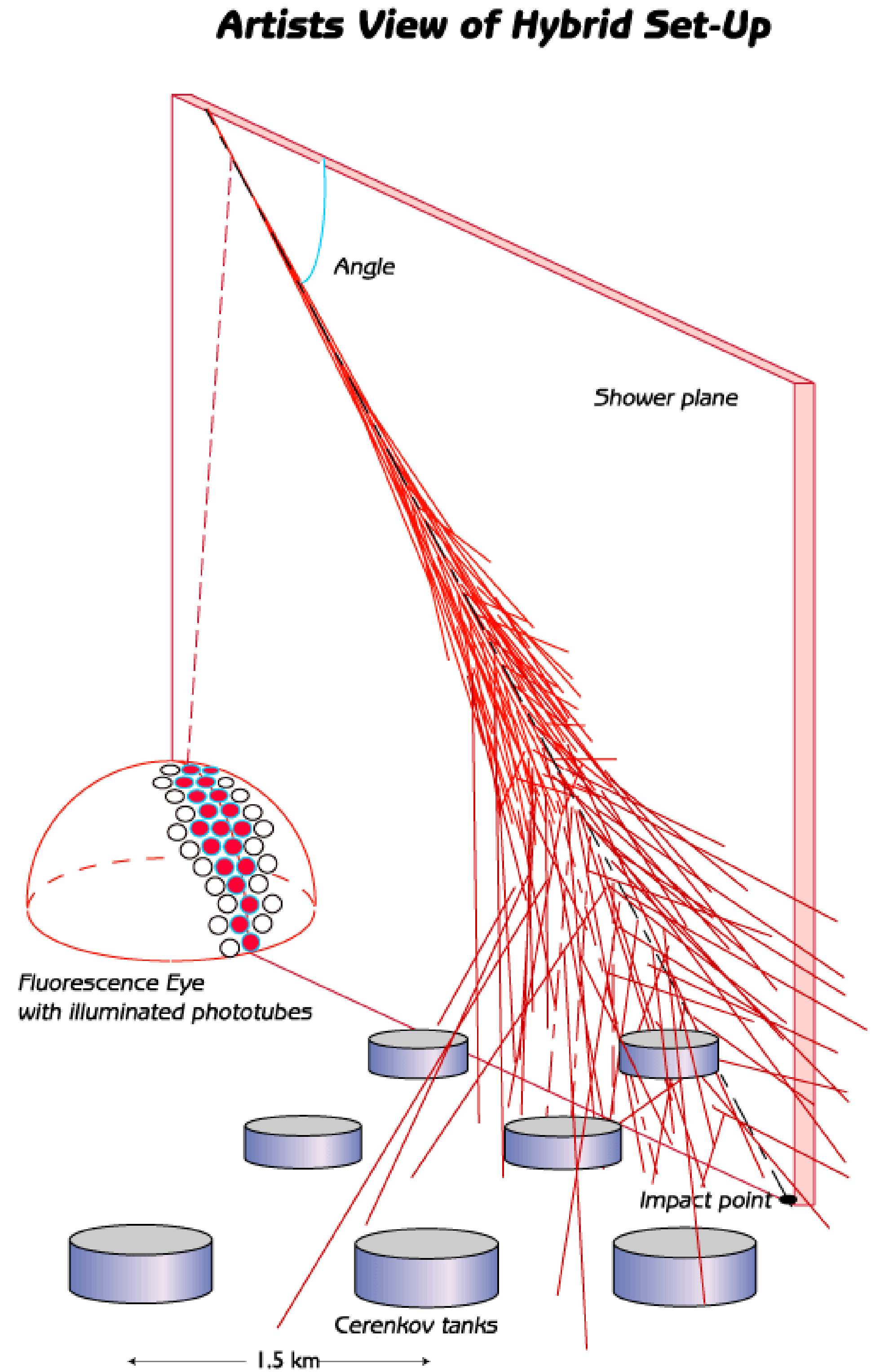
Different components

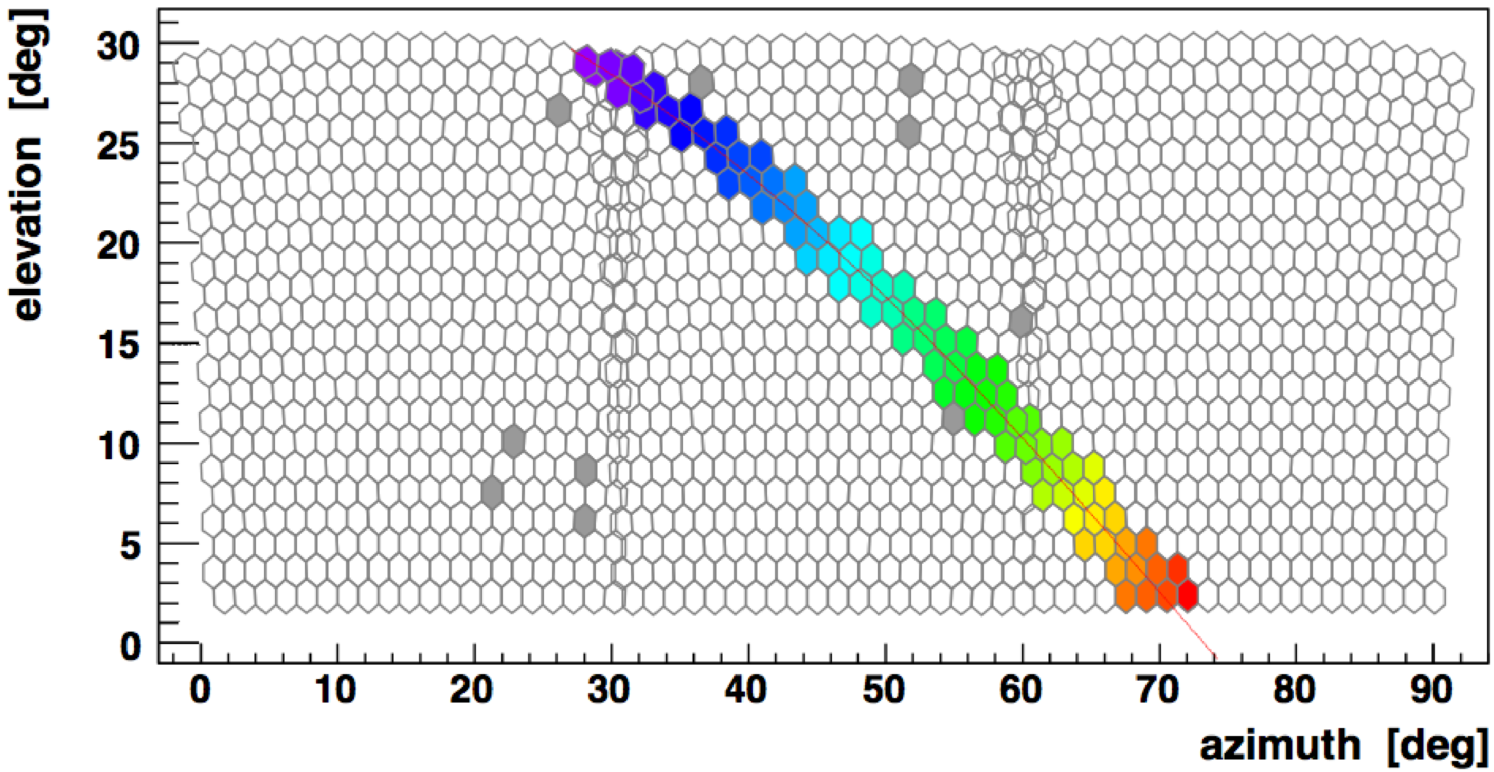
Measure a single slice of the shower at the ground

The **Fly's Eye** Detector concept

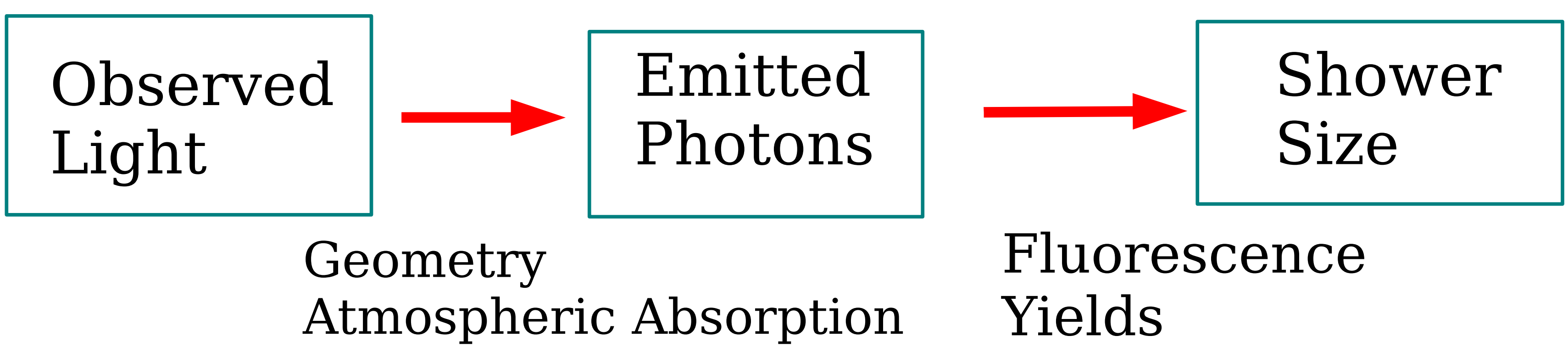
"Quasi-Calorimetric"
Energy Measurement

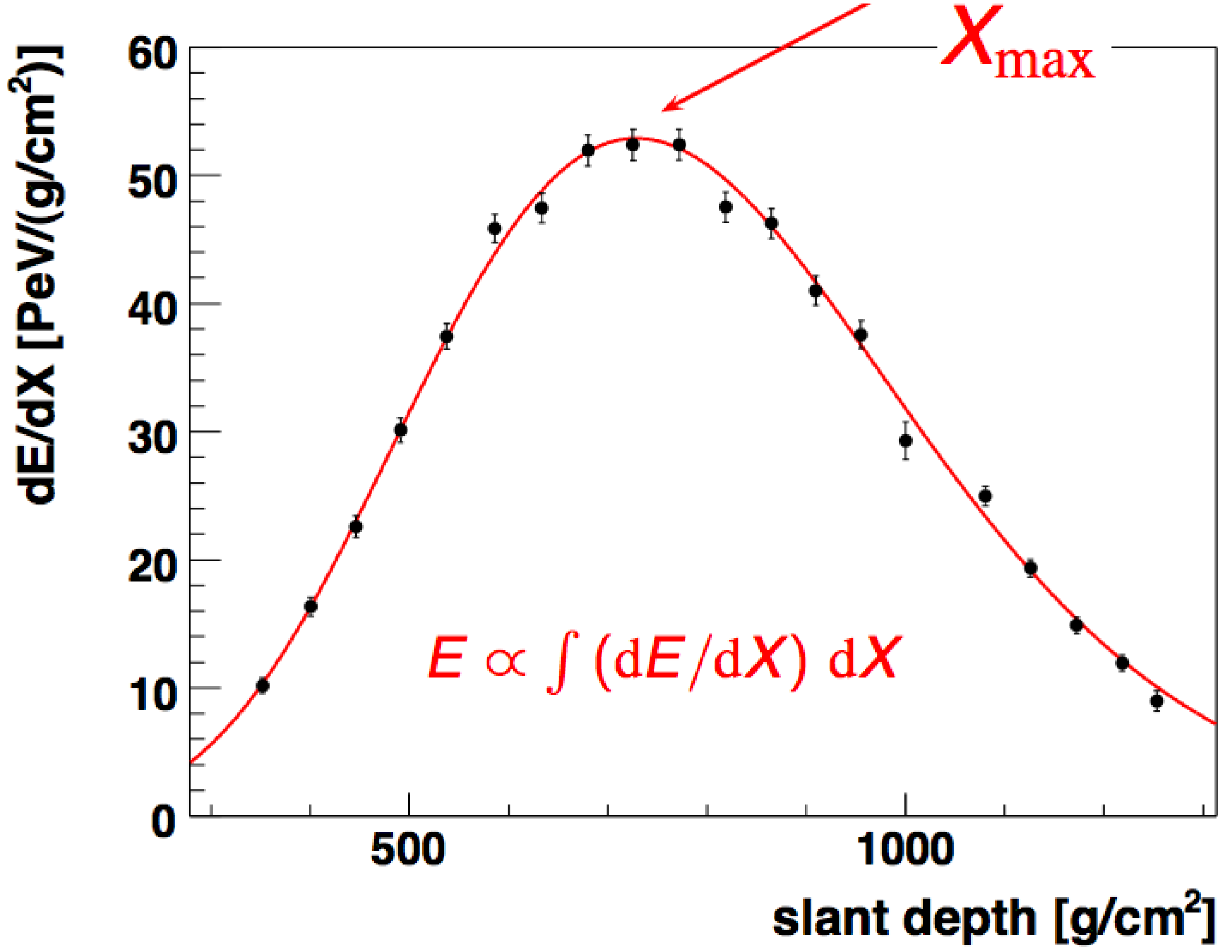
Fluorescence Light





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

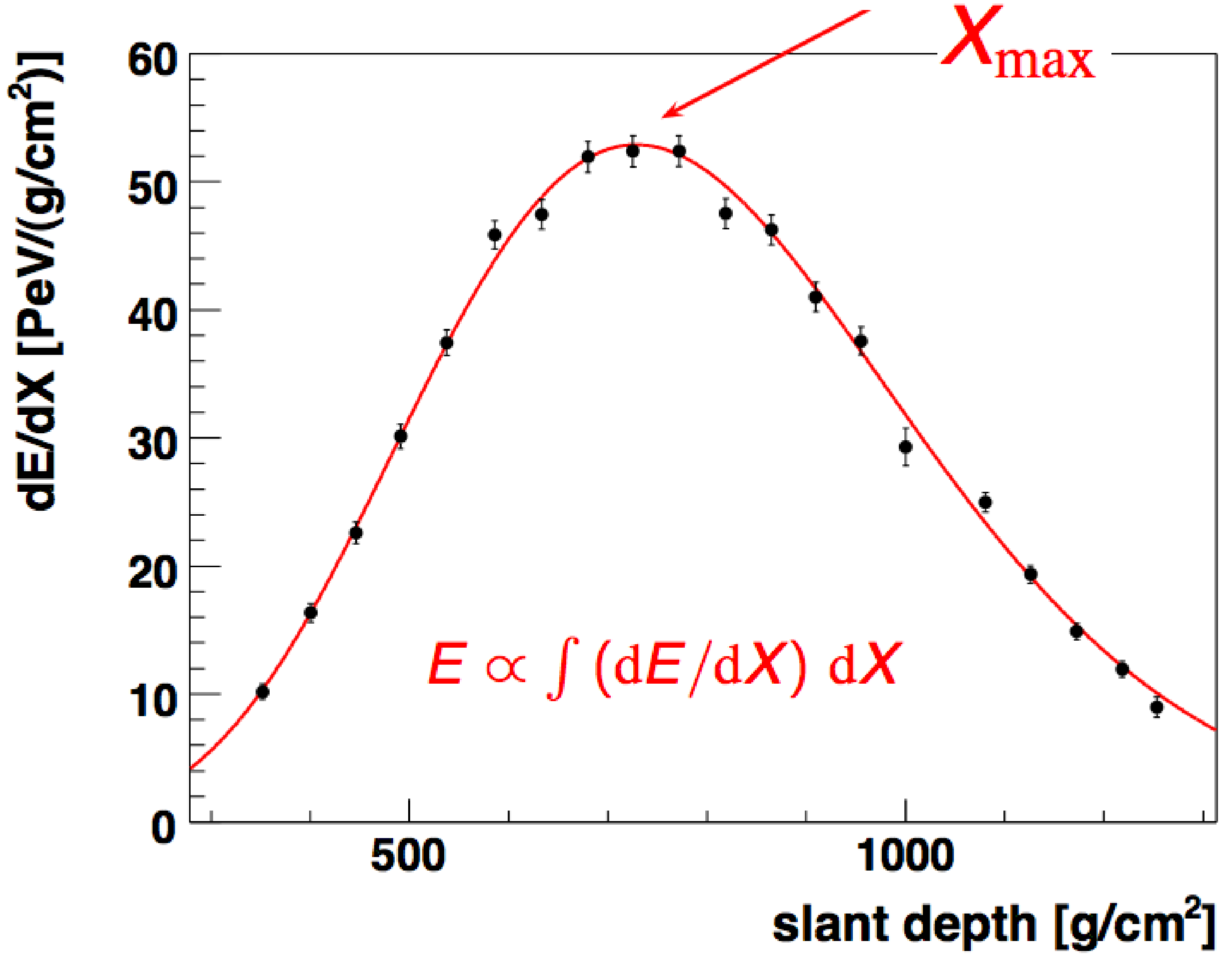




$$E_{\text{ionization}} = \int dX \; N_e(X) \left\langle -\frac{dE}{dX} \right\rangle$$

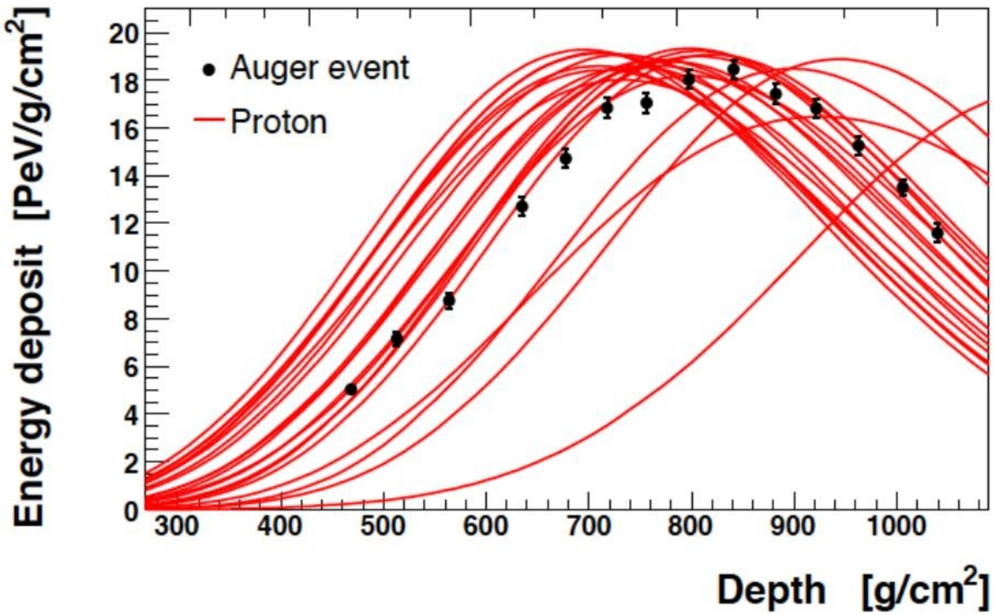
Small
Model
dependence

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

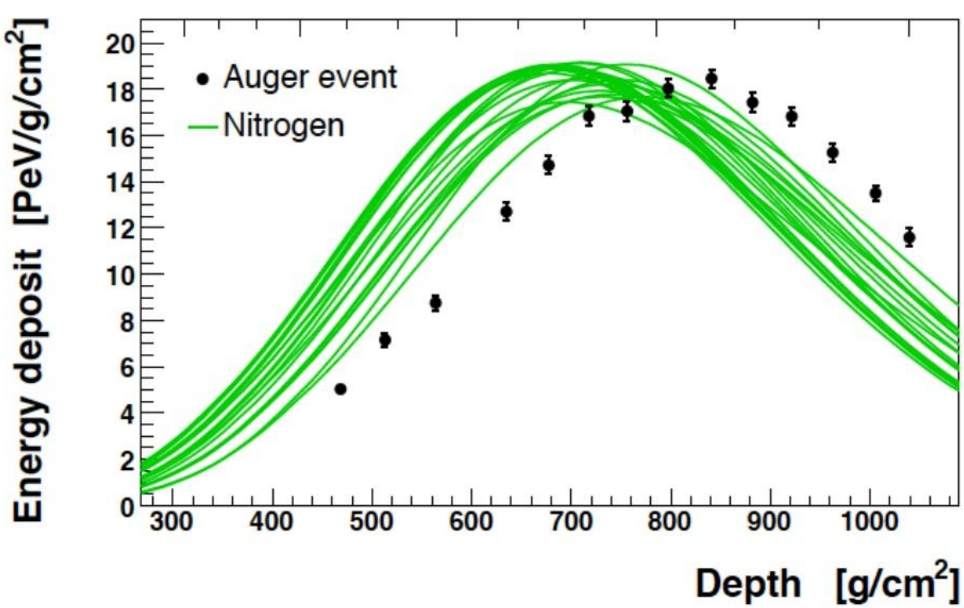


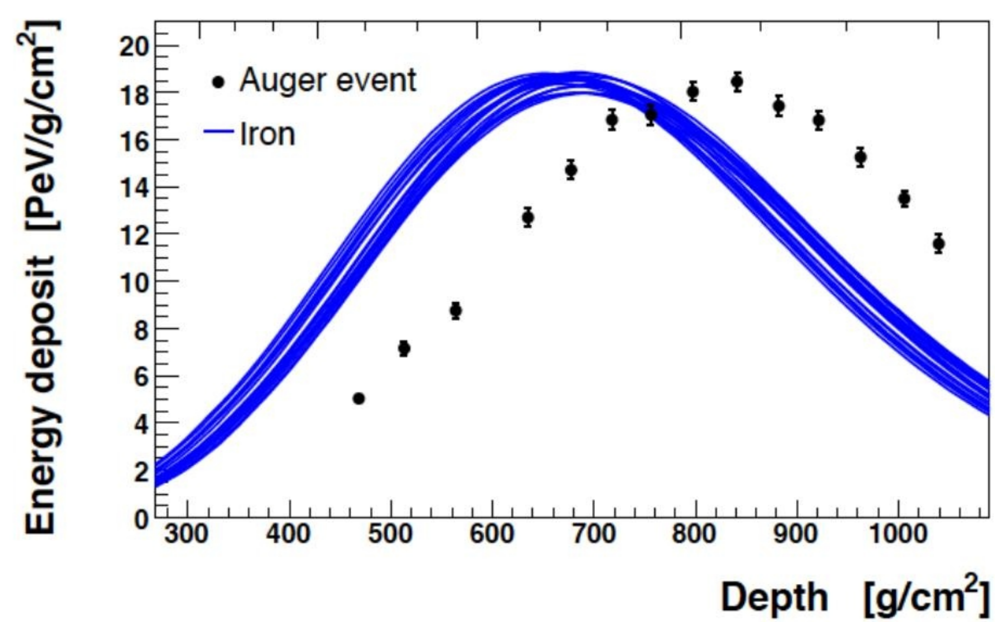
Area ∝ Energy

Shape depends on :
- Primary Identity
- Interaction Model



$$E \simeq 10^{20}\ \mathrm{eV}$$





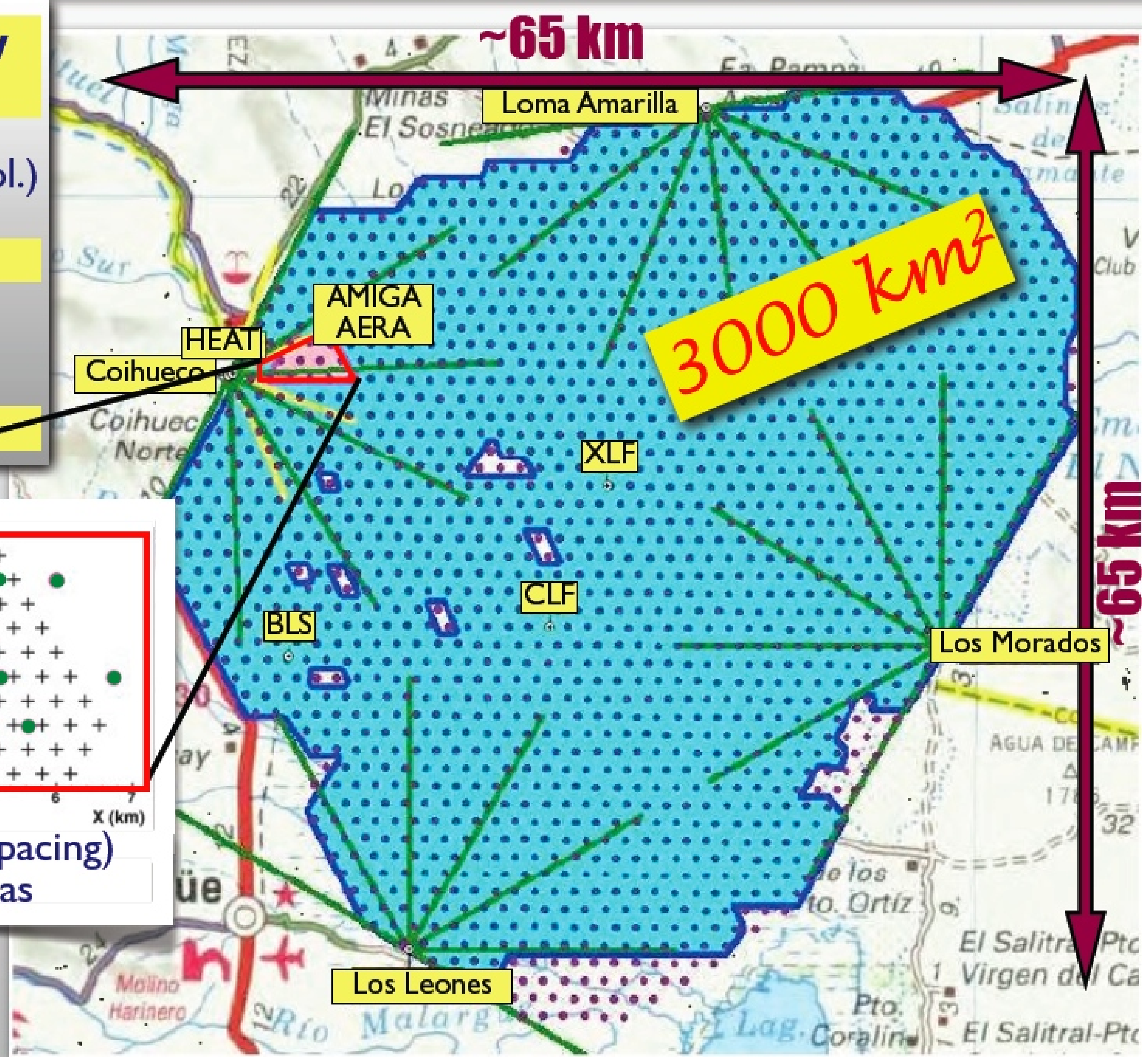
Pierre Auger Observatory in Argentina

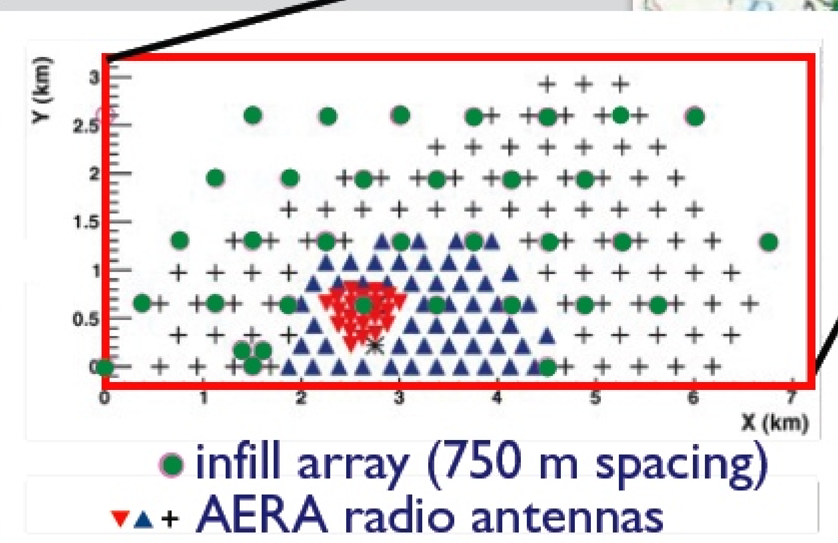
1660 Water-Cherenkov tanks

1.5 km standard grid
0.75 km infill-grid (53/61 depl.)

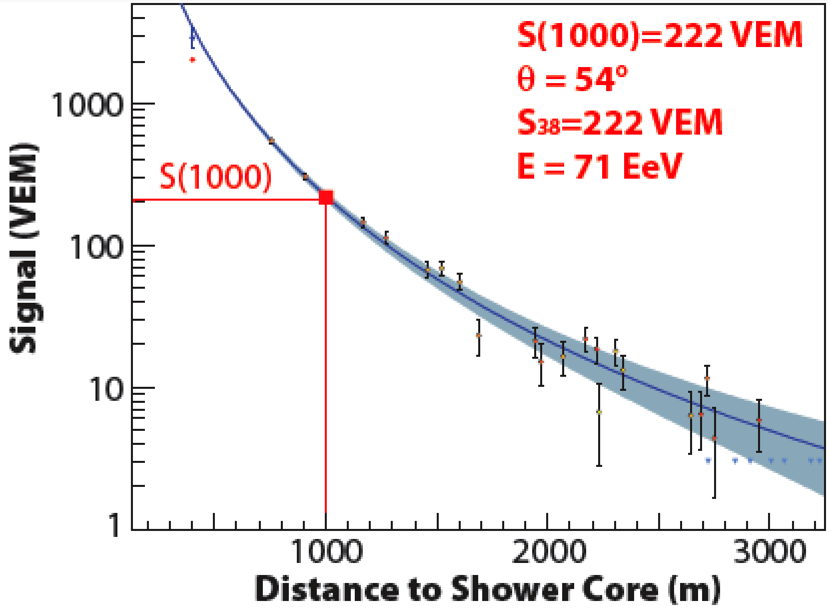
27 telescopes
in 4+1 buildings at the periphery

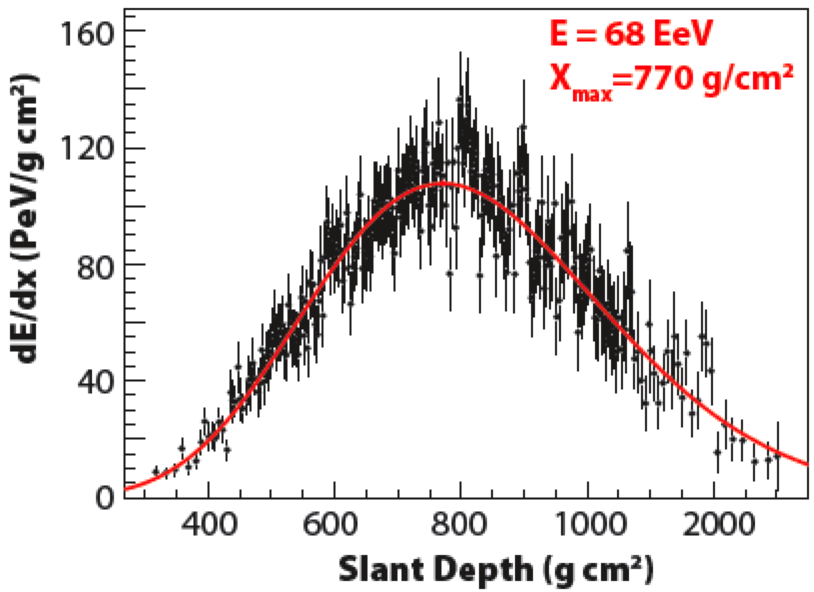
3000 km² area

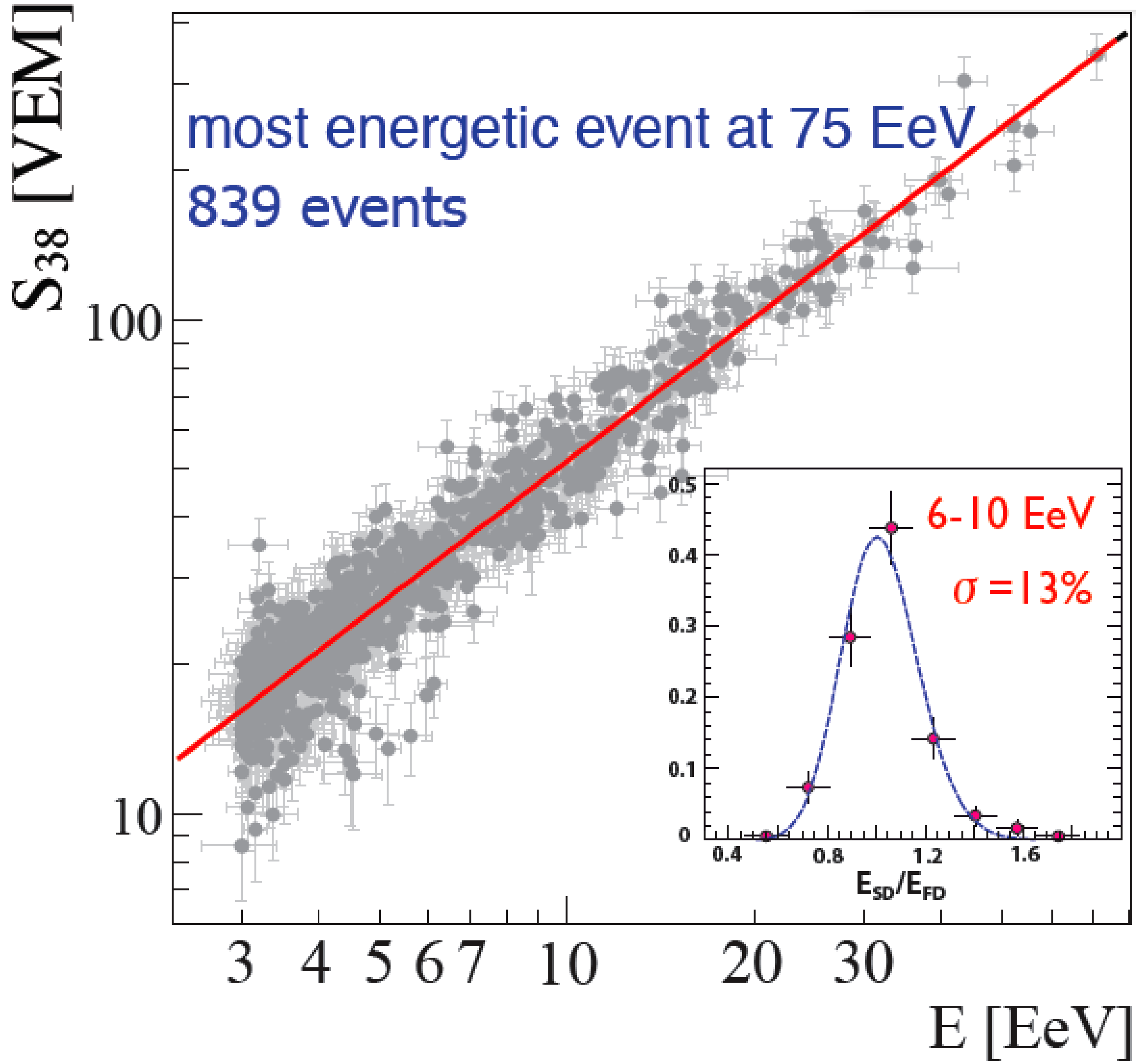




SD Energy Calibration by FD



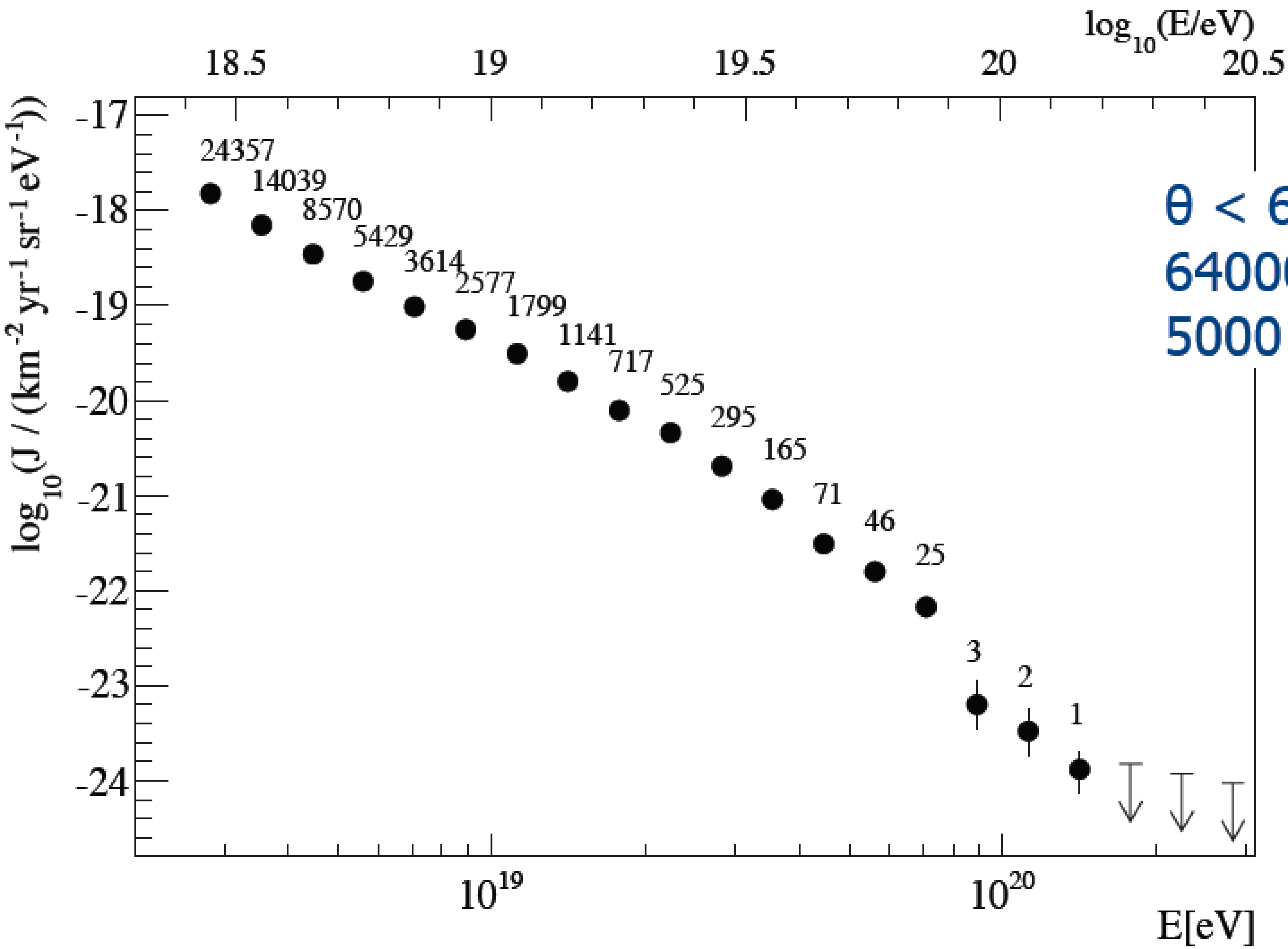




Systematic uncertainty 7% (15%) at 10 EeV (100 EeV)

Total uncertainty of E-scale: 22% (dominated by Fl.-yield. 14%)

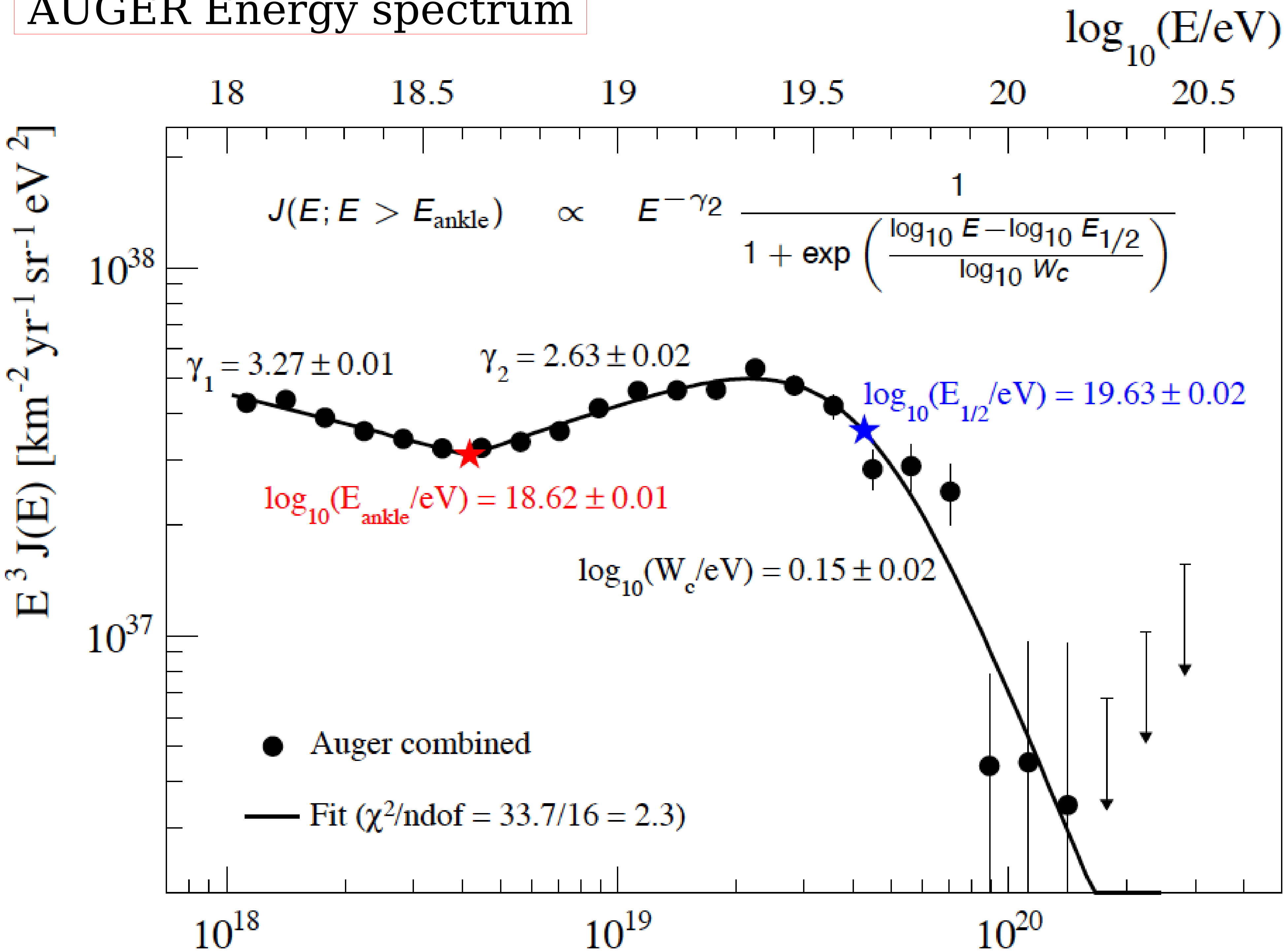
Surface Detector Spectrum (FD calibrated)



θ < 60°
64000 events > 3 EeV
5000 events > 10 EeV

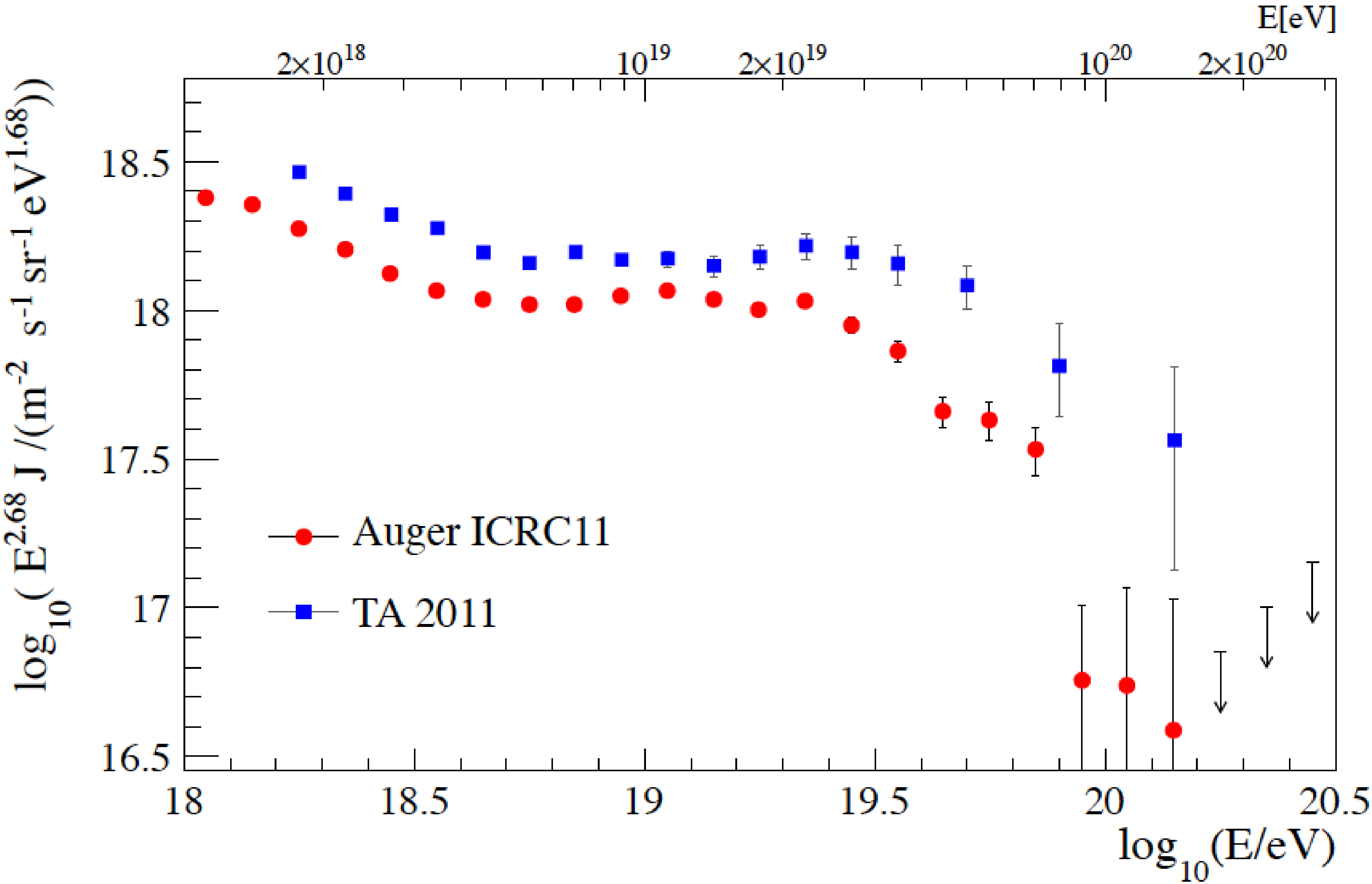
Not corrected for energy resolution
Uncertainty in exposure < 3%

AUGER Energy spectrum



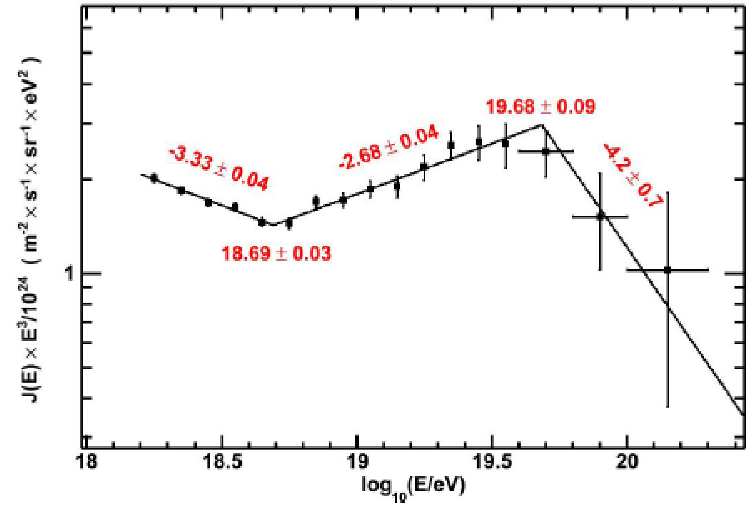
Comparison of Spectra

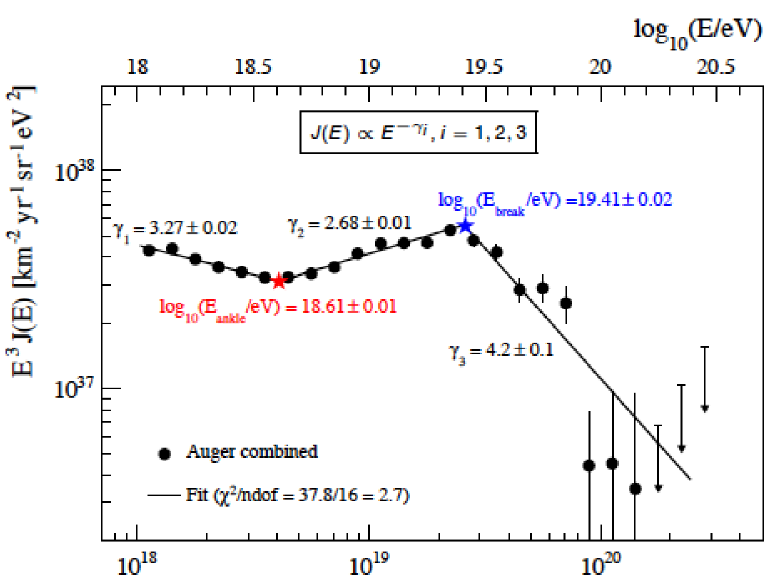
Auger
Telescope Array (TA)



energy scale difference of ∼ 20%?

Comparison of spectral features



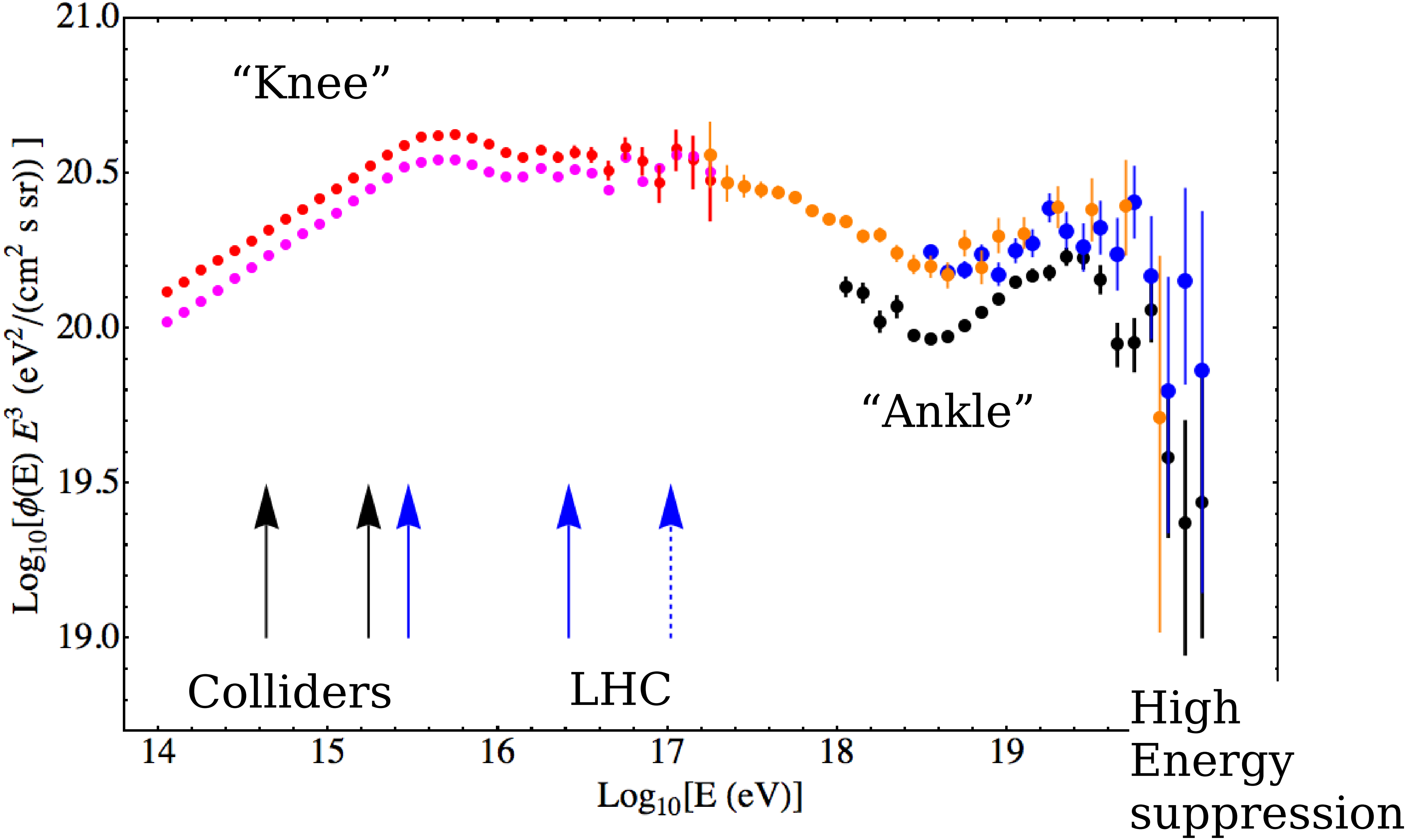


	TA	Auger
γ_1	3.33 ± 0.04	3.27 ± 0.02
γ_2	2.68 ± 0.04	2.68 ± 0.01
γ_3	4.2 ± 0.7	4.2 ± 0.1
$\lg(E_1/\mathrm{eV})$	18.69 ± 0.03	18.61 ± 0.01
$\lg(E_2/\mathrm{eV})$	19.68 ± 0.09	19.41 ± 0.02

B. Stokes [TA Coll.], icrc1297

F. Salamida [Auger Coll.], icrc893

Structure in the energy spectrum



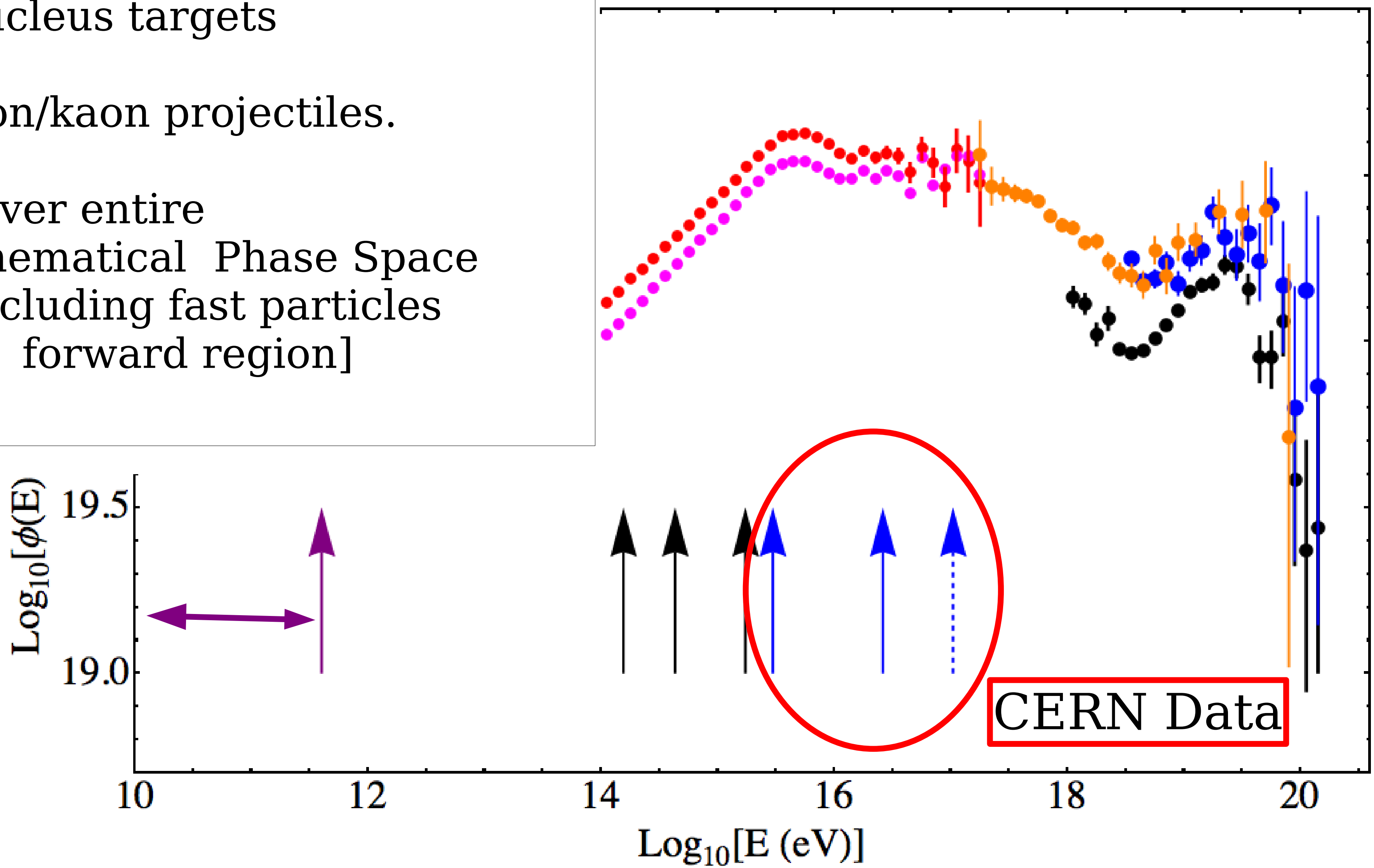
“Fixed Target” measurements

Nucleus targets

Pion/kaon projectiles.

Cover entire kinematical Phase Space [including fast particles in forward region]

COLLIDERS



Fixed Target

Cern Tevatron

LHC

COMPOSITION of UHECR

Very high astrophysical importance

Controversial - [inconsistent?] observations.

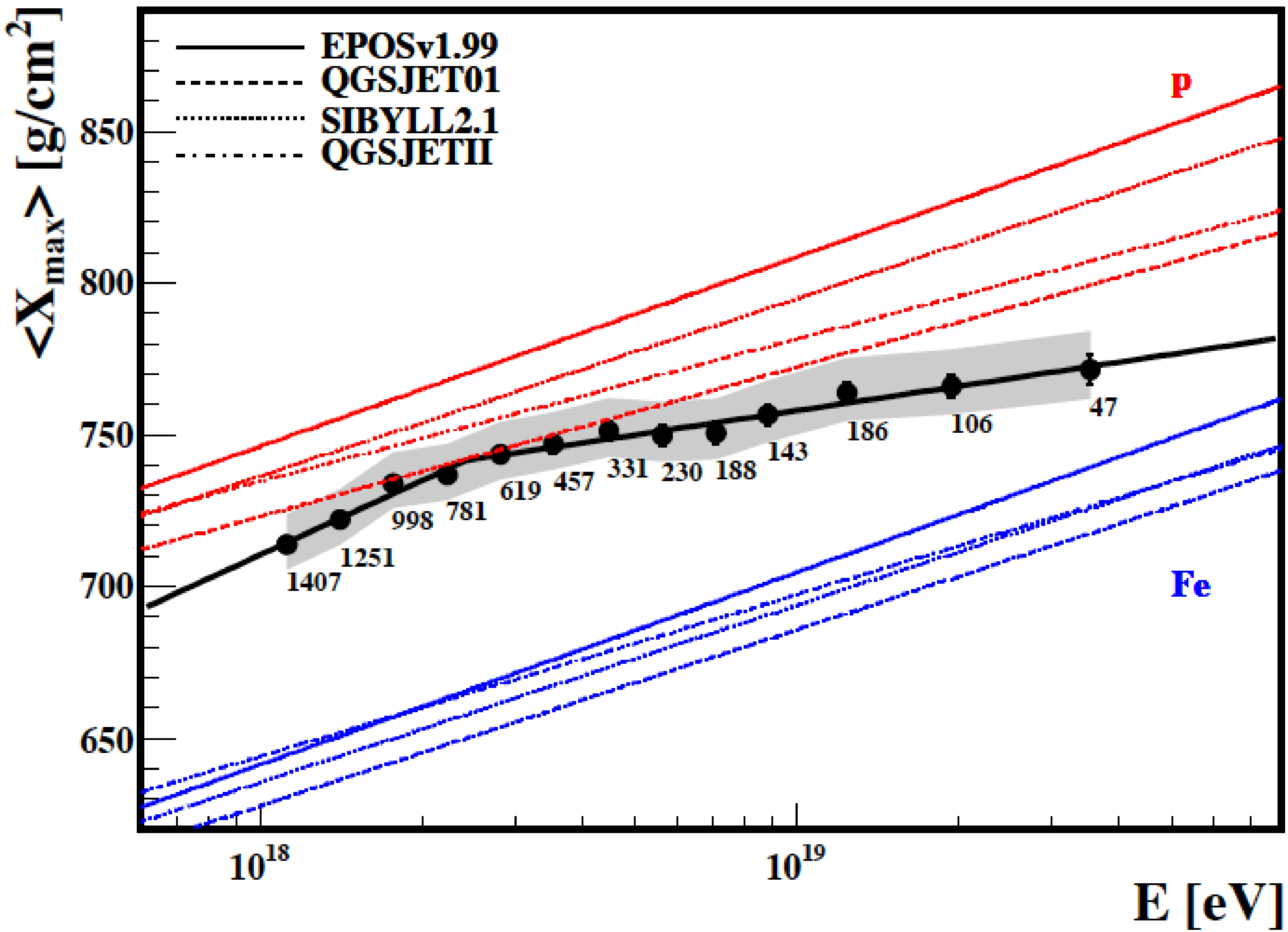
X_{max}

Fluctuations of X_{max}

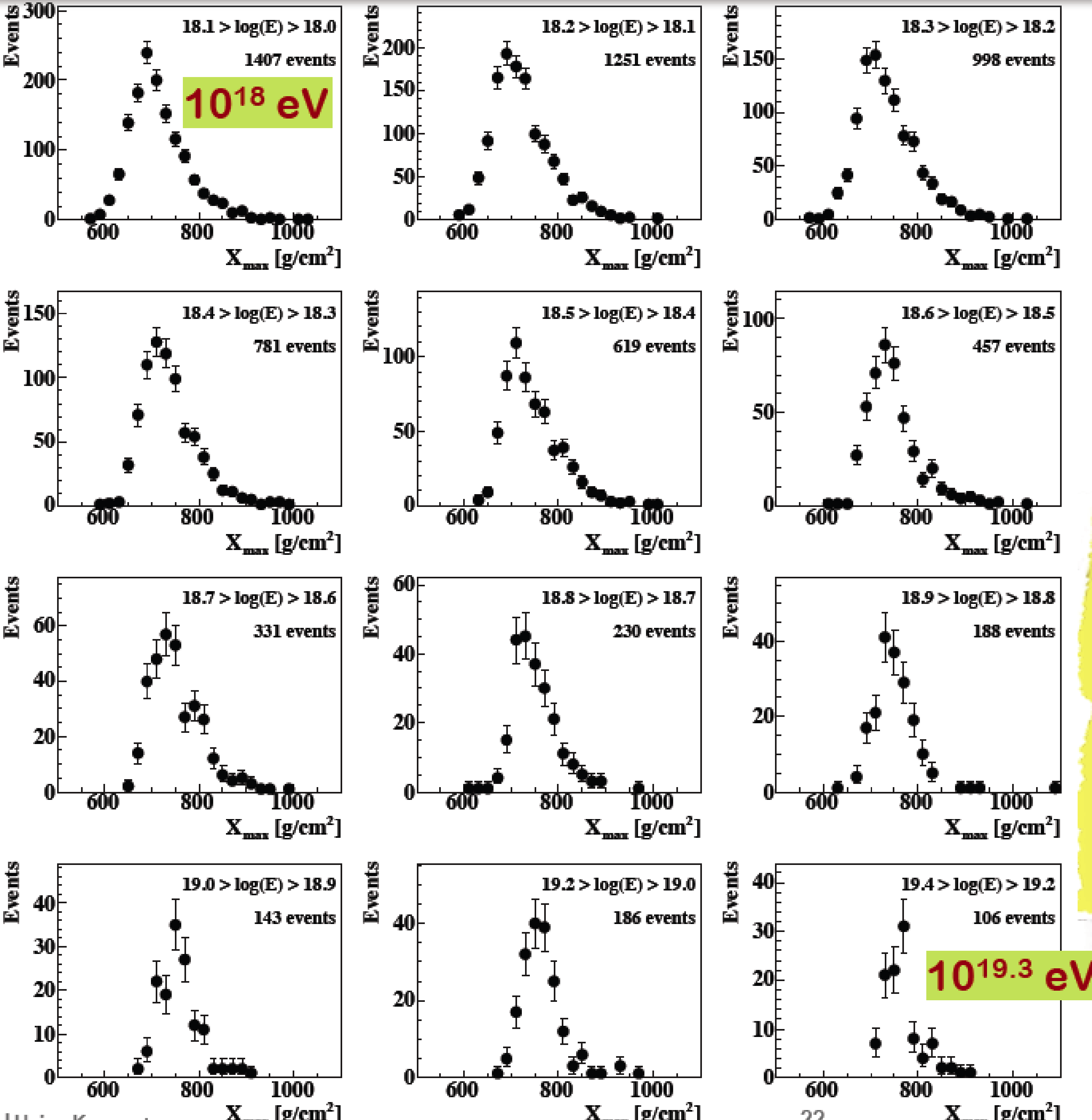
Other methods

average depth

AUGER



X_{max} Distributions

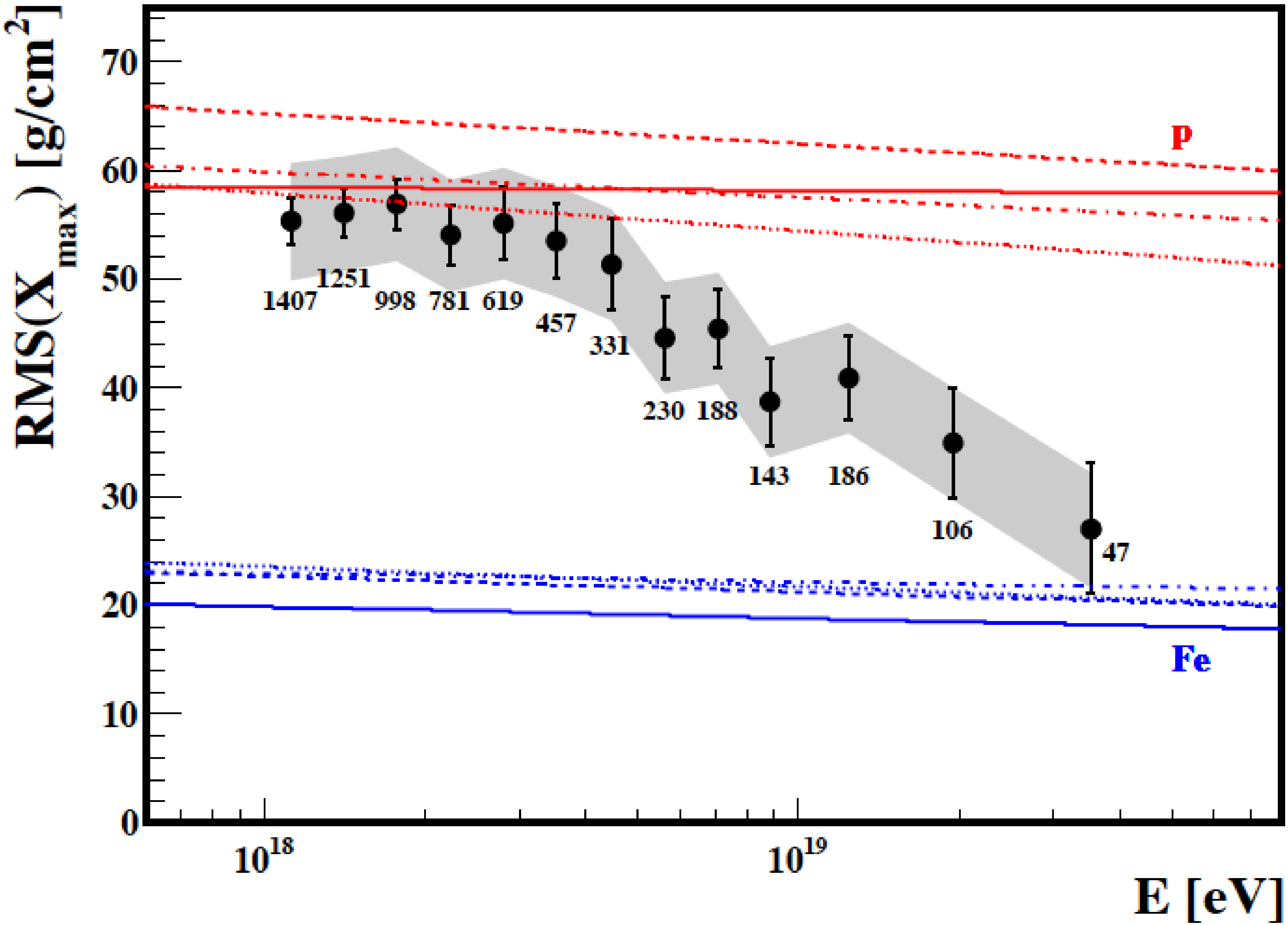


With increasing energy:

- distributions become narrower
- deep X_{max} tail reduced

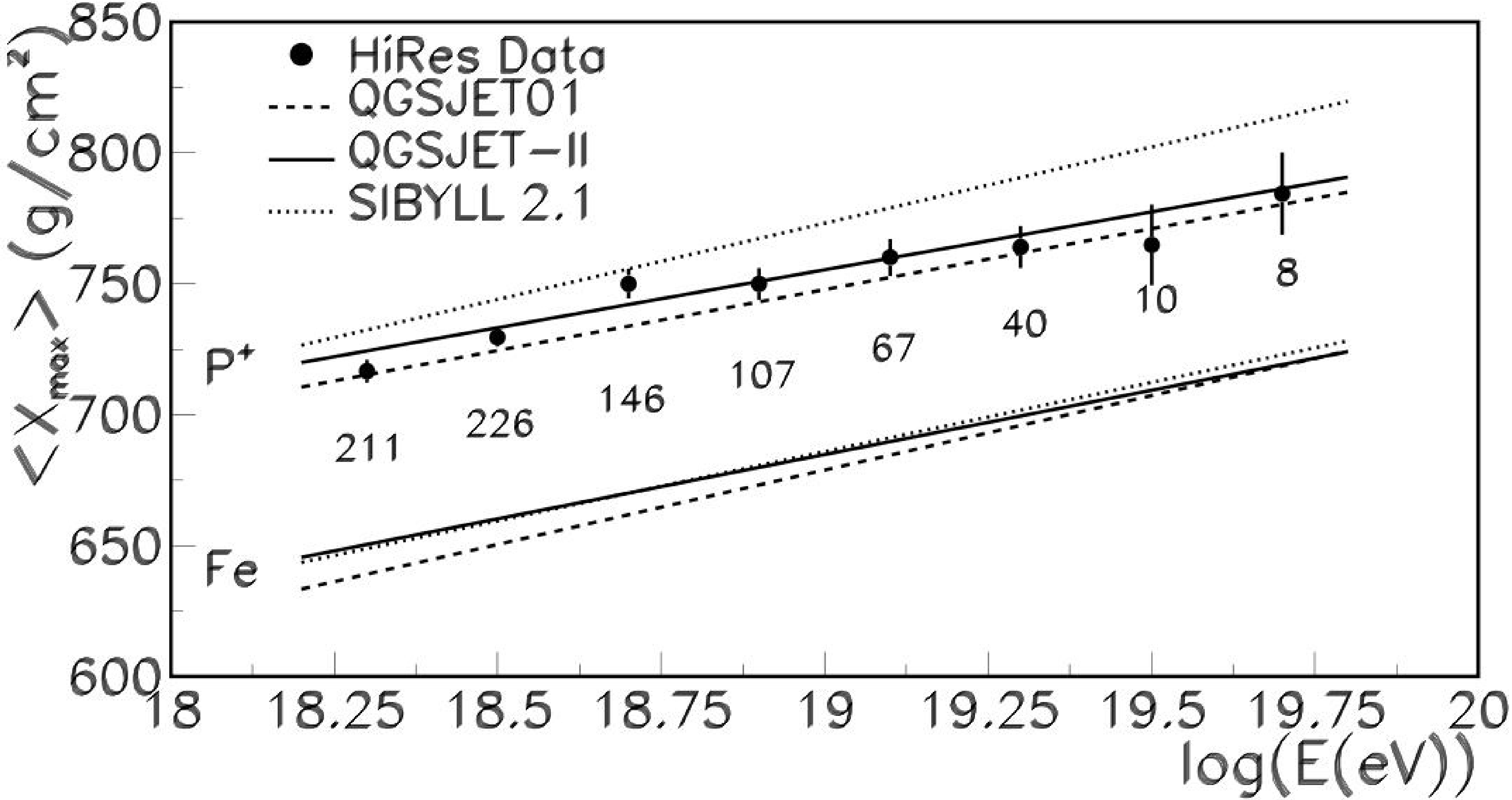
fluctuations

AUGER



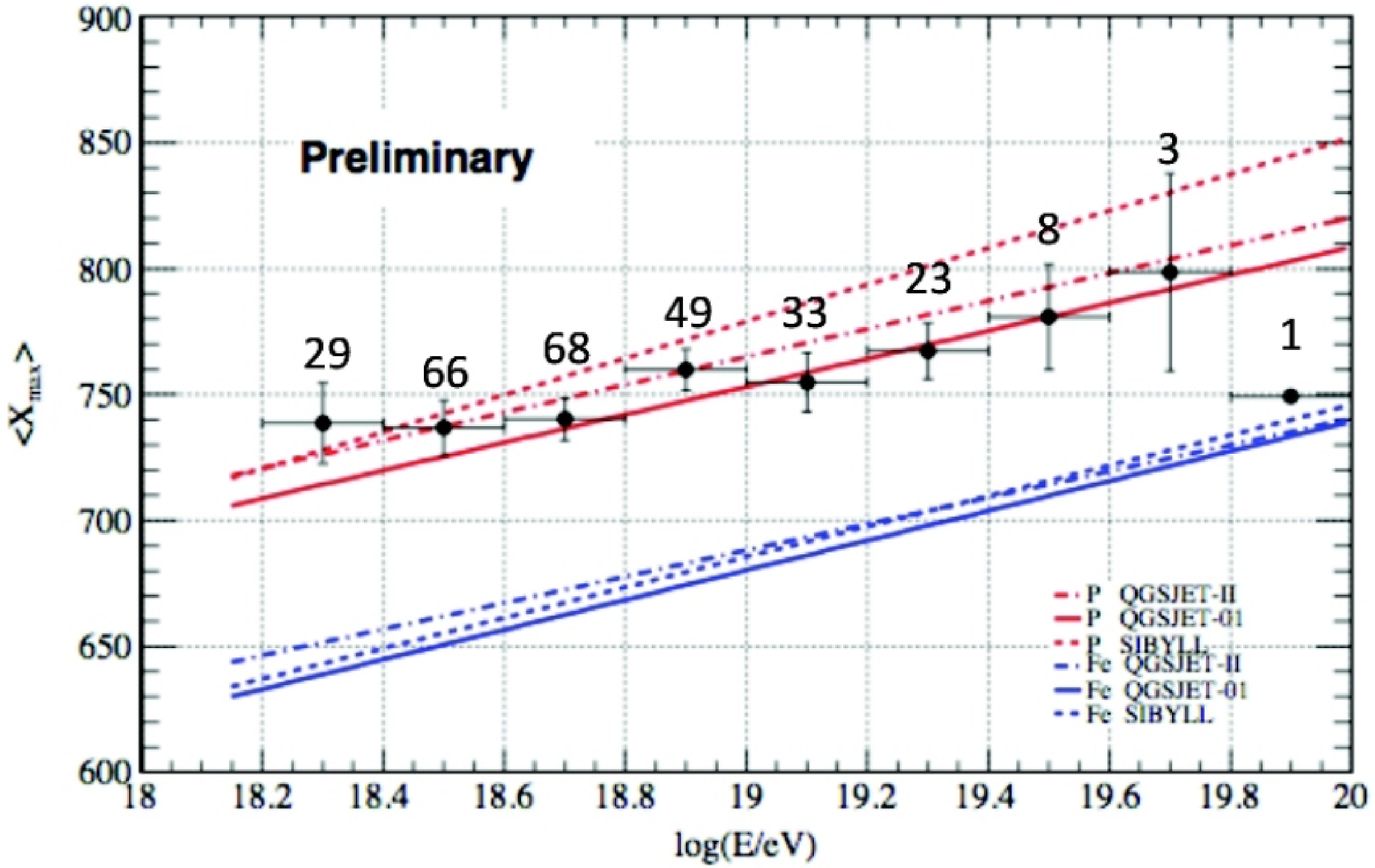
[Inconsistent result/interpretation]

HiReS (2009)

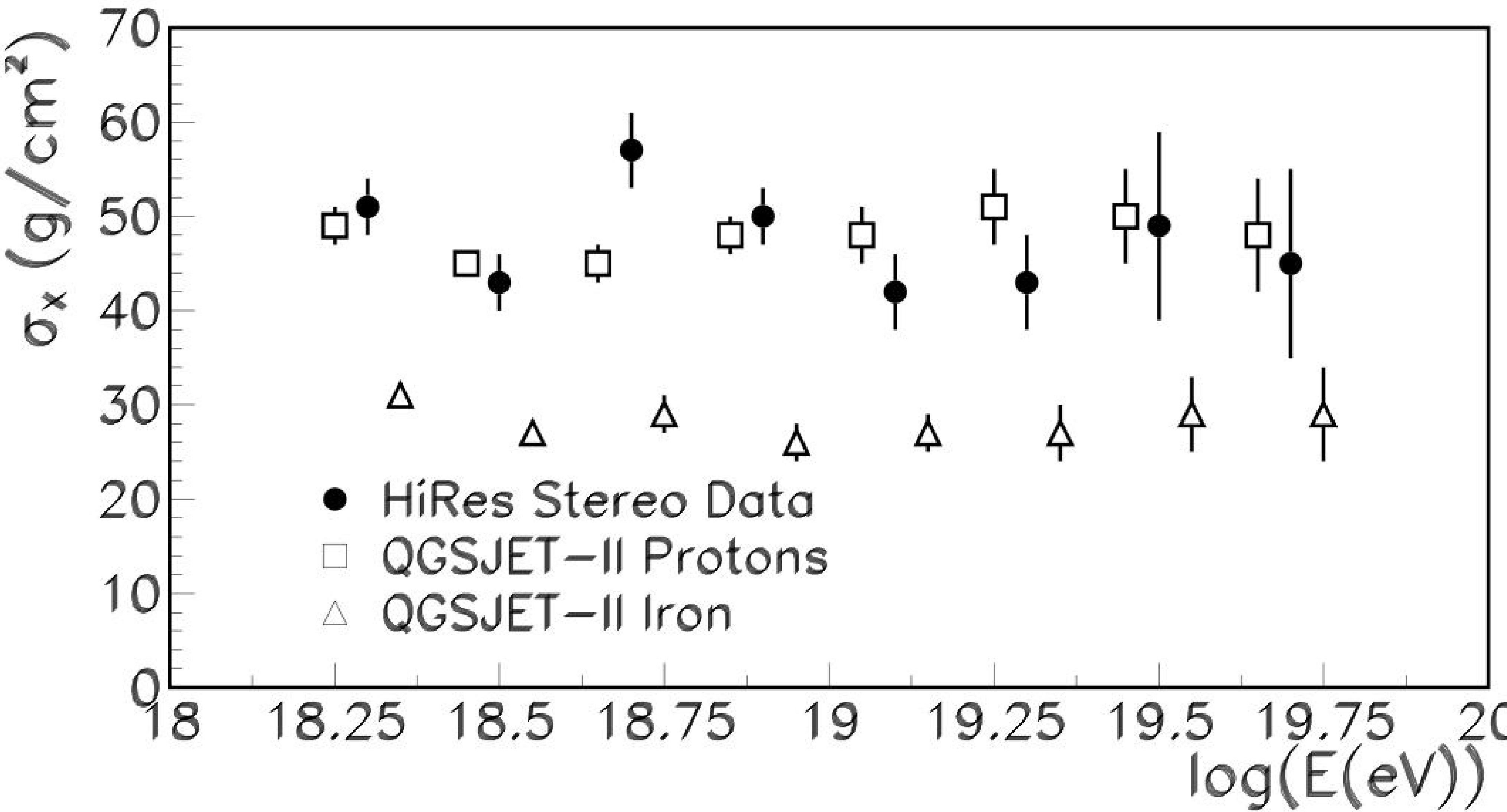


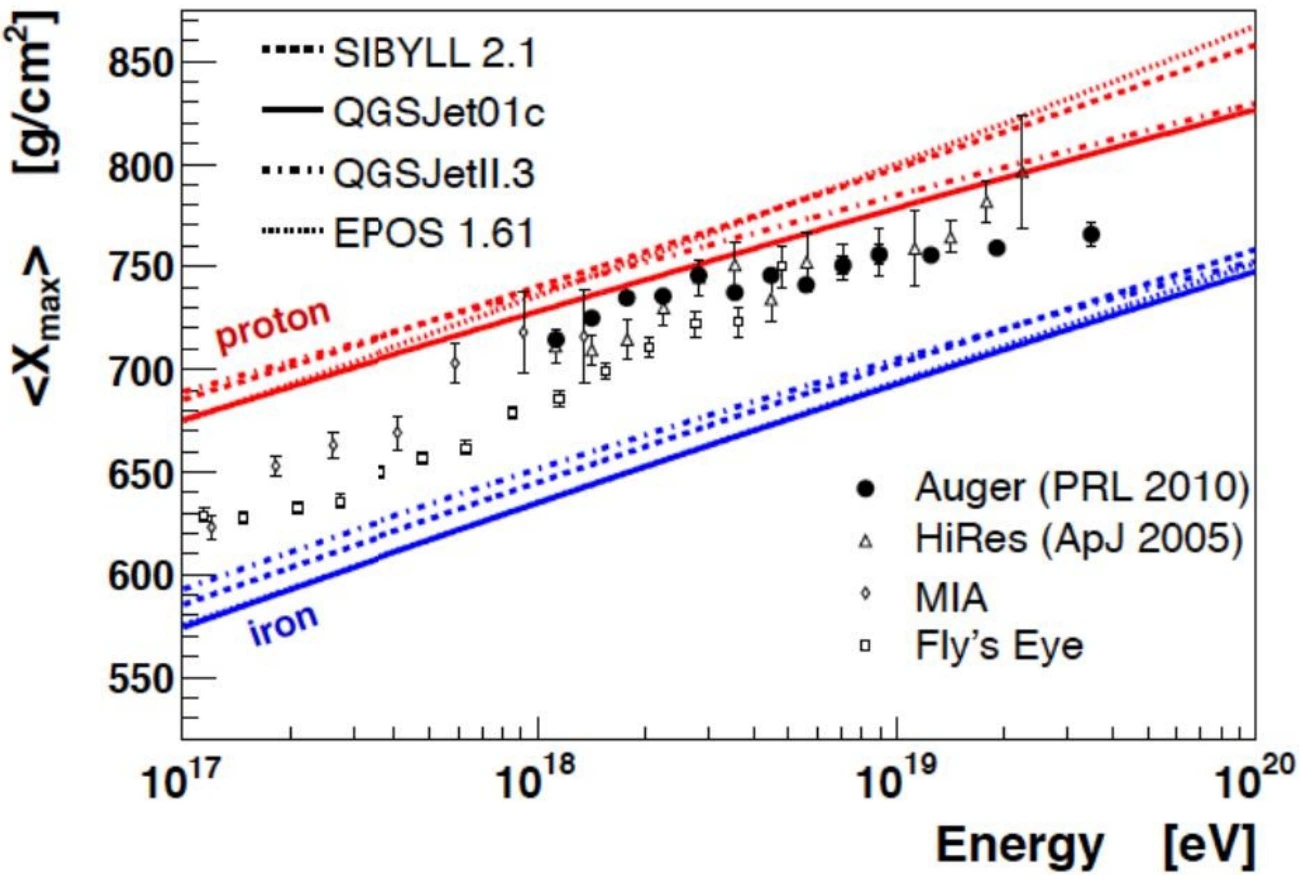
Telescope Array (TA)

Longitudinal EAS Development with TA Stereo FD



HIRES 2009 Fluctuations on X_{max}





The "theory curves" <X_{max}(E)> are determined by the parameters that describe hadronic interactions. (and by their energy dependence).

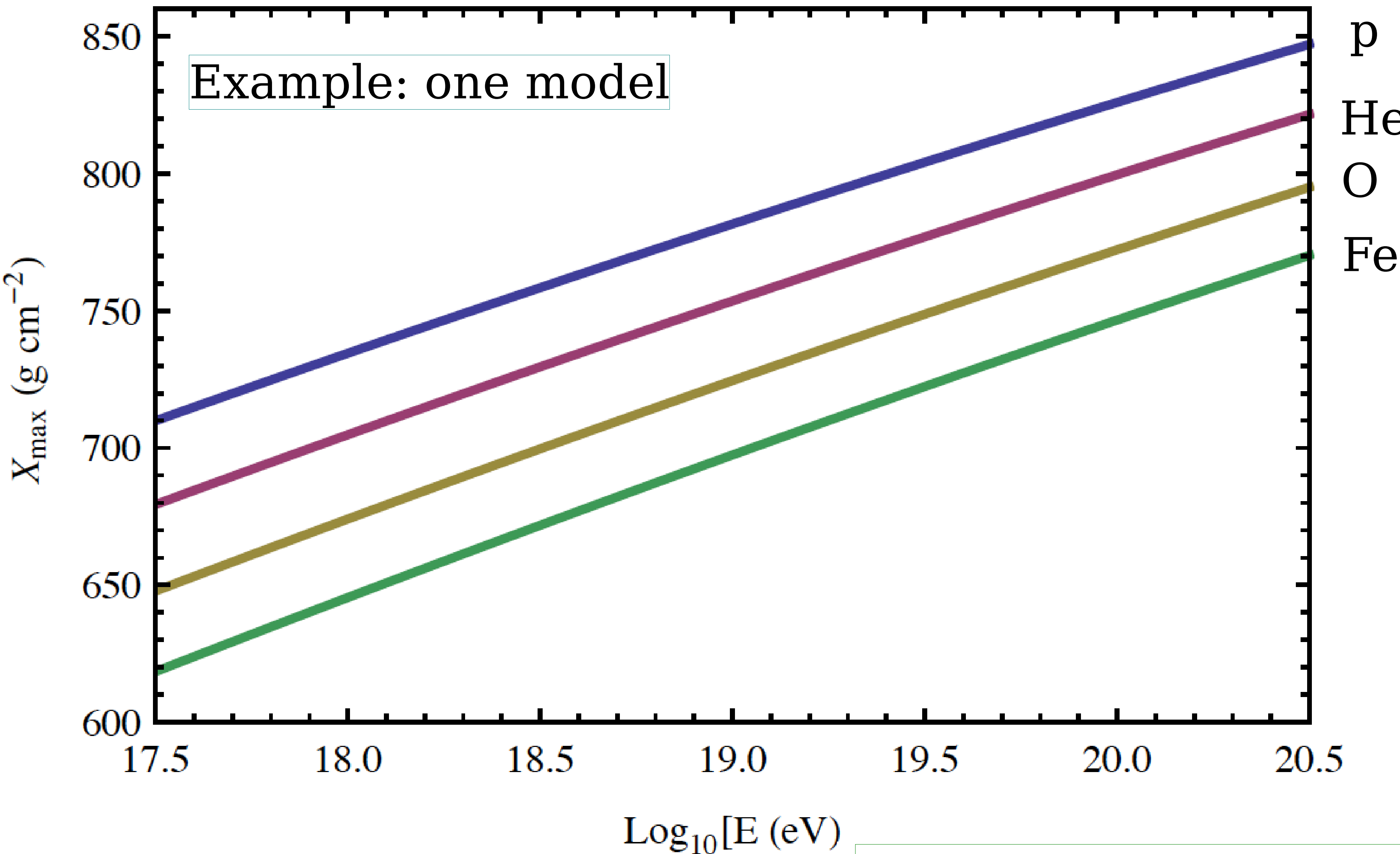
- Interaction Lengths
- Multiplicity
- Inclusive Spectra
- ....

Theoretical curves:

$$|\langle X_p \rangle_{\rm Model\ 1} - \langle X_p \rangle_{\rm Model\ 2}| \lesssim 20 \text{ g cm}^{-2}$$

$$10^{19} \text{ eV}$$

$$D_p = \frac{d\langle X_{\rm max}\rangle}{d\log_{10} E} \simeq 45 \ - \ 55 \text{ g cm}^{-2}$$



$$\langle X_A \rangle \simeq \langle X_p \rangle - D_p \ \log_{10} A$$

$$\langle X_{\mathrm{He}} \rangle \simeq \langle X_p \rangle - 30 \text{ g cm}^{-2}$$

$$\langle X_{\mathrm{O}} \rangle \simeq \langle X_p \rangle - 60 \text{ g cm}^{-2}$$

$$\langle X_{\mathrm{Fe}} \rangle \simeq \langle X_p \rangle - 90 \text{ g cm}^{-2}$$

X_{max} and the Composition of Cosmic Rays

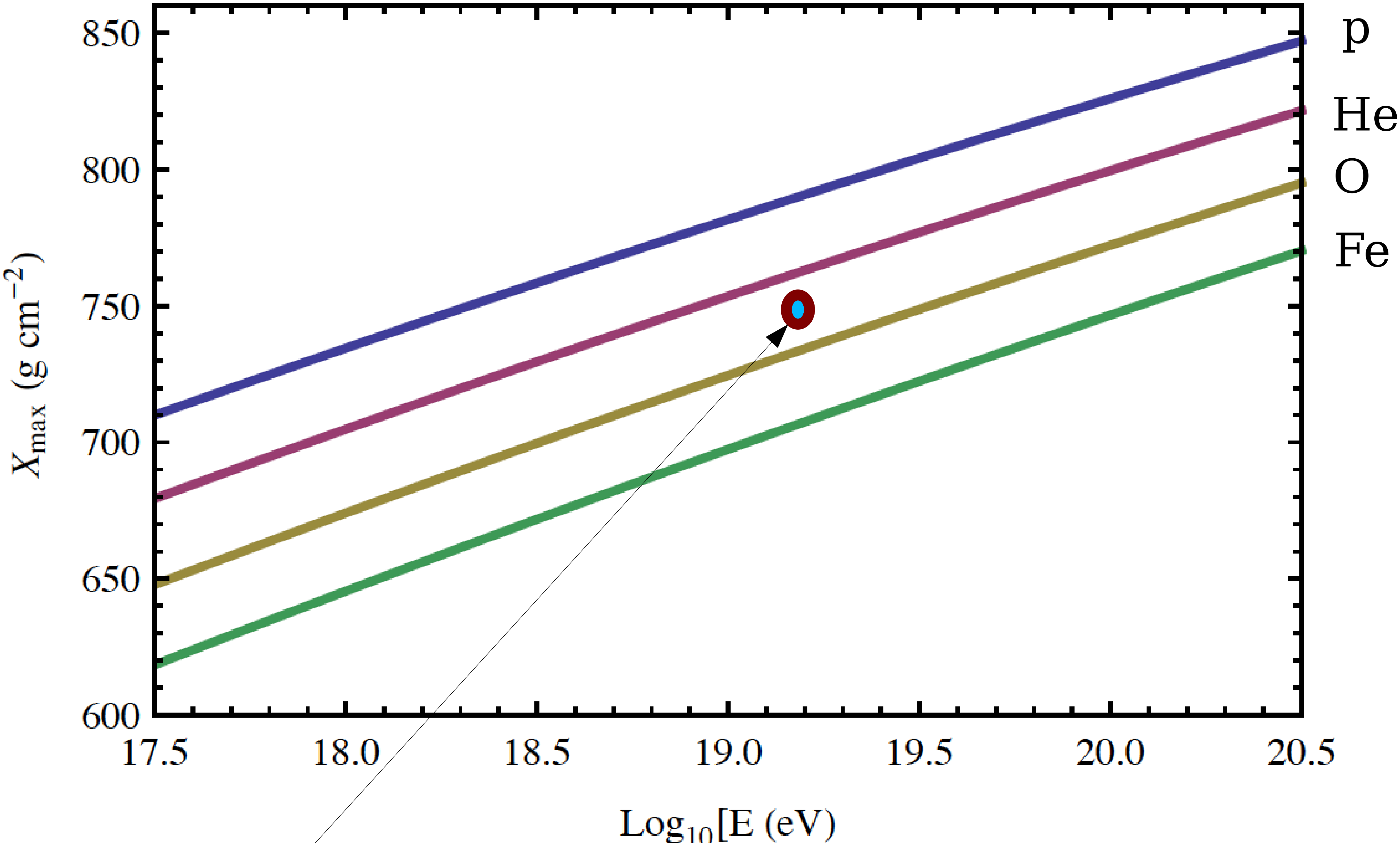
$$\langle X_p(E) \rangle \simeq X_0 + D_p \, \log_{10} E$$

Logarithmic dependence

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

"Superposition"

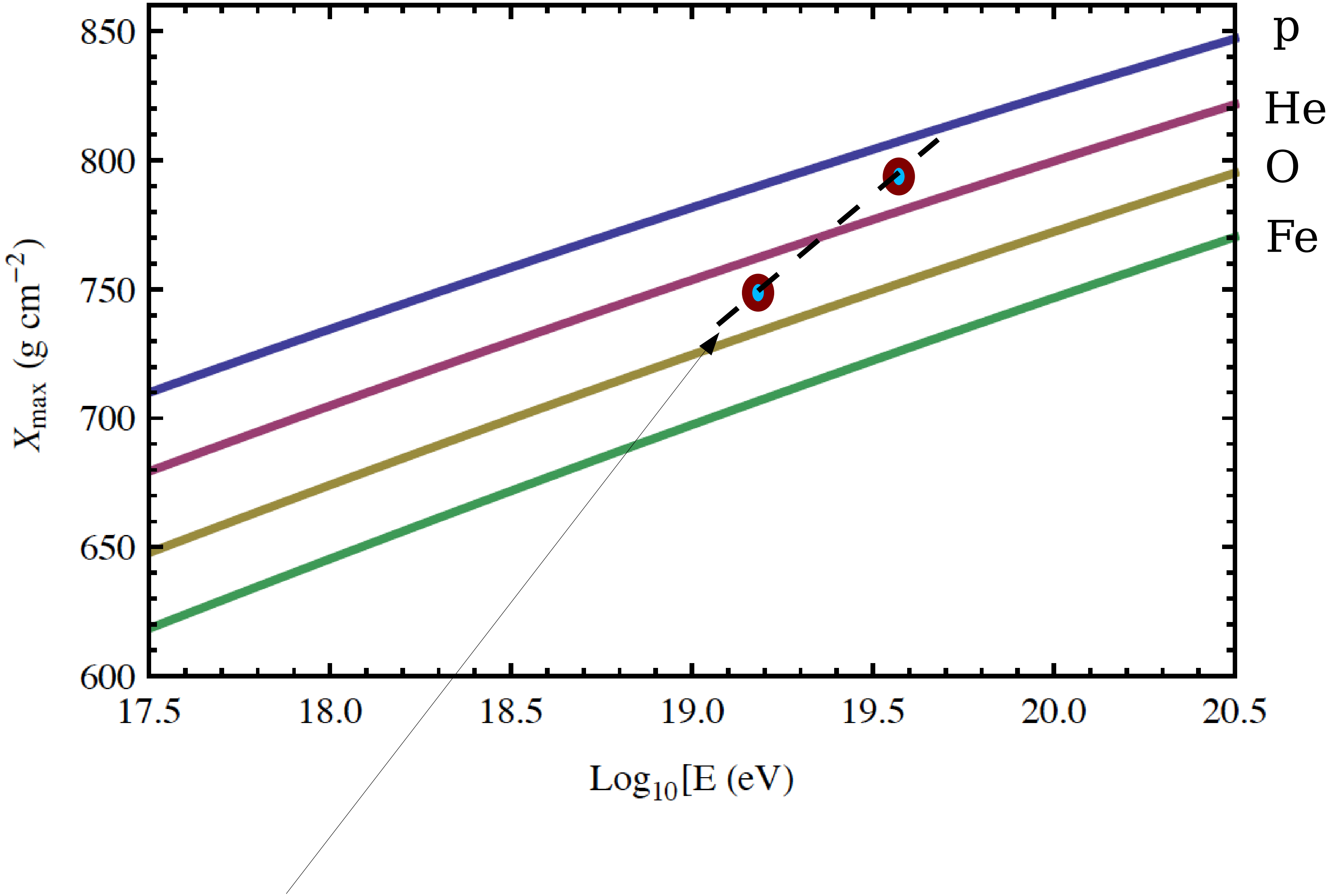
$$\langle X_A \rangle \simeq \langle X_p \rangle - D_p \, \log_{10} A$$



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.

Obtain the average mass and its variation with energy

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

$$\langle \ln A \rangle_E = \frac{\langle X_{\max}(E) \rangle - X_p(E)}{D_p}$$

$$\frac{d\langle \ln A \rangle_E}{d \ln E} = 1 - \frac{D_{\exp}}{D_p}$$

Obtain the average mass and its variation with energy

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

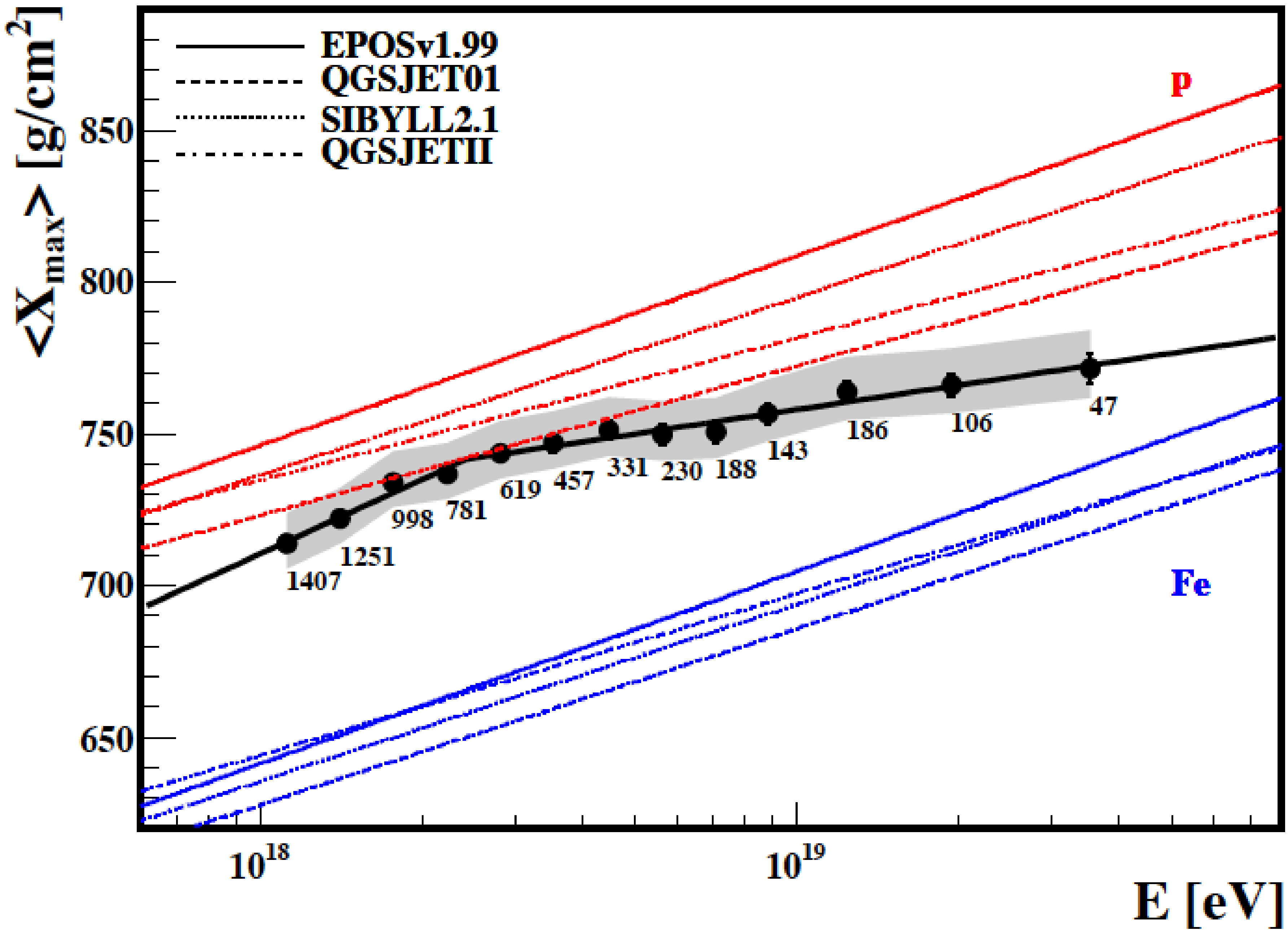
$$\langle \ln A \rangle_E = \frac{\langle X_{\max}(E) \rangle - X_p(E)}{D_p}$$

$$\frac{d \langle \ln A \rangle_E}{d \ln E} = 1 - \frac{D_{\exp}}{D_p}$$

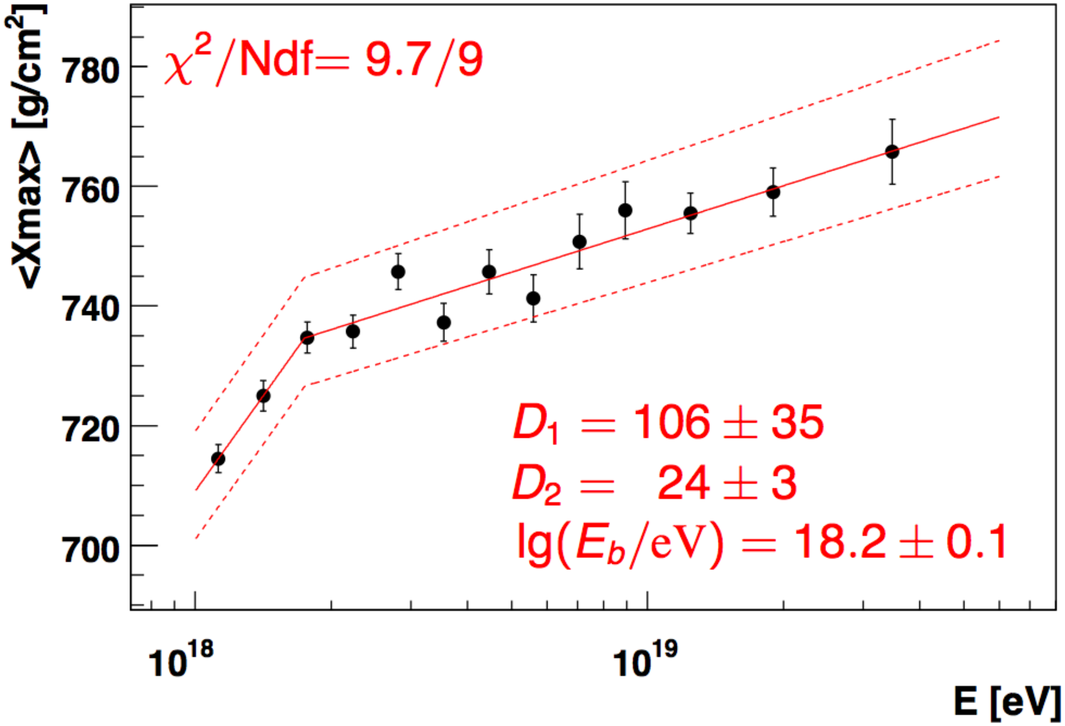
Theory

average depth

AUGER



Importance of
"CORNERS"



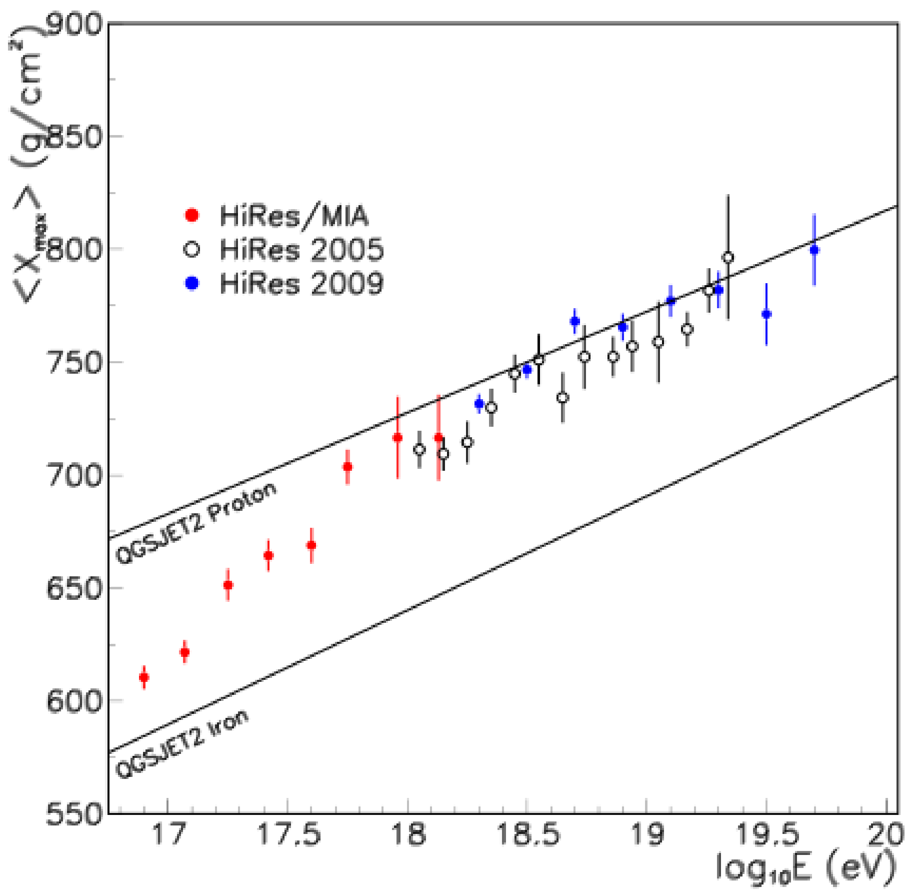


Fig. 25.— Comparison of current HiRes stereo <X_{max}> results with results from the HiRes-prototype/MIA hybrid (Abu-Zayyad et al. 2001) and previously published HiRes stereo results (Abbasi et al. 2005).

Abrupt change in the variation of the properties of hadronic interactions with energy

Abrupt change in the composition evolution.

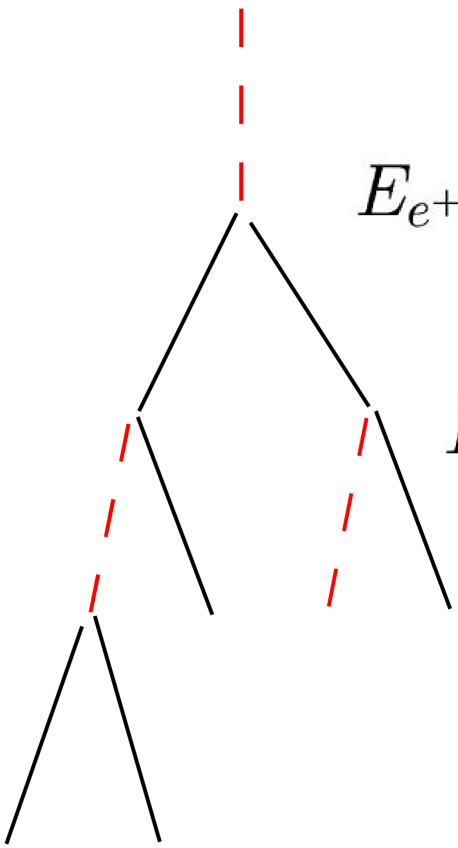
Electromagnetic Showers

versus

Hadronic Showers

Toy model discussion.

Electromagnetic Shower



$$E_{e^+} = E_\gamma \; u \qquad \psi(u)$$

Pair production

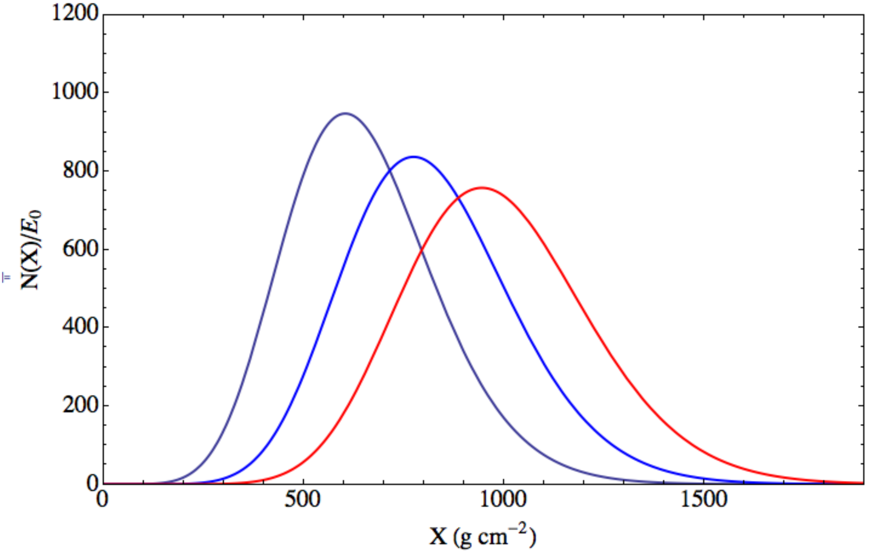
$$E_\gamma = E_e \; v \qquad \varphi(v)$$

Bremsstrahlung

Radiation Length
(Energy independent)

Vertices :
theoretically understood
(and scaling)

Electromagnetic Showers



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

Logarithmic growth of the penetration.

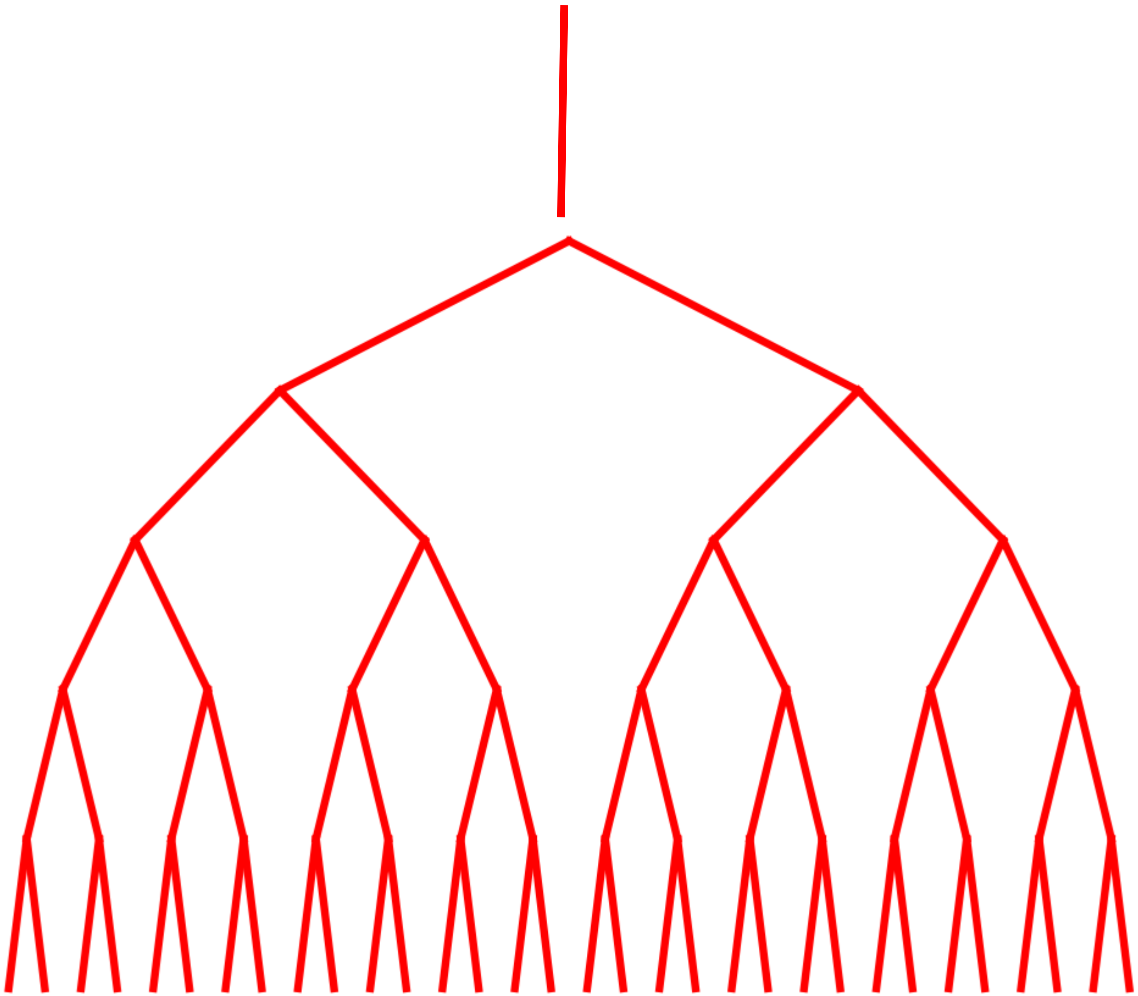
$$N_{\max}(E) \simeq \frac{E}{\varepsilon}\ \frac{1}{\sqrt{\ln(E/\varepsilon)}}$$

Energy Conservation

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

Heitler toy model

for electromagnetic showerws



"Electron-photon" particle

Splitting length λ

Critical energy ε

$$N(X, E) = 2^{X/\lambda}$$

$$N_{\max}(E) = \frac{E}{\varepsilon}$$

$$X_{\max}(E) = \lambda \log_2 \left(\frac{E}{\varepsilon}\right)$$

Electromagnetic showers:

$$\langle X_{\max}(E) \rangle = X_0 + D_\gamma \ \log E$$

$$D_\gamma = \ln 10 \ X_{\rm rad} \simeq 85 \text{ g cm}^{-2}$$

Fluctuations:

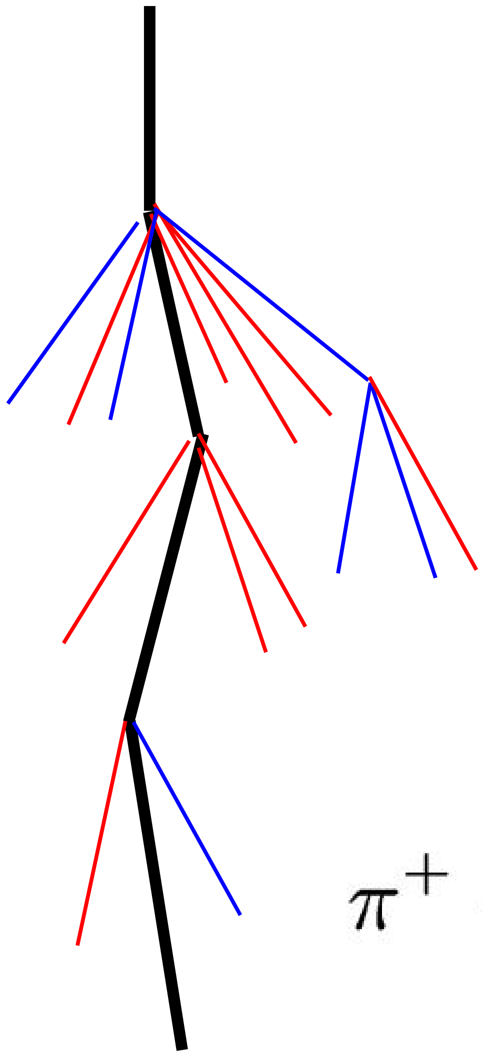
$$\sigma^2_X(\gamma, E) = \text{constant}$$

$$\sigma^2_X(\gamma, E) \simeq 1.1 \ X_{\rm rad} \ \simeq 40 \text{ g cm}^{-2}$$

Proton Shower

Vertices : theoretically not
Understood

(and energy dependent)



$$\pi^0 \rightarrow \gamma\gamma$$

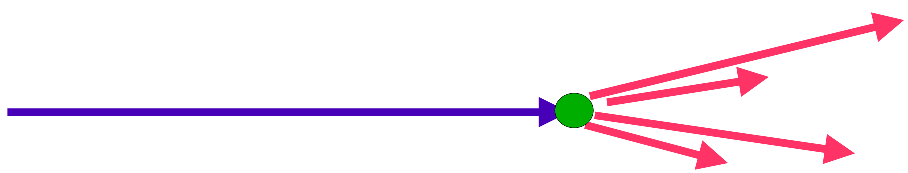
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

HADRONIC INTERACTIONS

$$p + A_{\mathrm{Air}} \rightarrow p, n, \quad \pi^\circ, \quad \pi^\pm, \quad K^\pm, K_L \ldots$$

Leading nucleon
~ 50% of energy

$\pi^{o} \rightarrow \gamma\gamma$
Electromagnetic
Shower



Decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \nu_e + \overline{\nu}_\mu$$

Interaction

Inclusive spectra
of secondary particles

Toy Model for hadronic shower

$$p + \mathrm{air} \rightarrow \left(\frac{n}{2}\right) \ \pi^{\circ} \rightarrow n\ \gamma$$

Energy equally divided
among n photons.

$$E_\gamma \simeq \frac{E_0}{n}$$

$$\frac{dN_\gamma}{dz} = \sum_n P_n \ \delta\left[z - \frac{1}{n}\right] n$$

$$\langle X_{\max}^{(p)} \rangle = \langle X_{1\mathrm{st}} \rangle + X_{\mathrm{rad}} \left\langle \log \left(\frac{E_0}{n_\gamma \ \varepsilon} \right) \right\rangle$$

1st interaction

Development of photon shower of energy E/n

$$\langle X_{\max}^{(p)} \rangle = \langle X_{1\text{st}} \rangle + X_{\text{rad}} \left\langle \log \left(\frac{E_0}{n_\gamma \, \varepsilon} \right) \right\rangle$$

$$\langle X_{\max}^{(p)} \rangle = \lambda_p + X_{\text{rad}} \log \left[\frac{E_0}{\varepsilon} \right] - X_{\text{rad}} \langle \log n_\gamma \rangle$$

Interaction Length

Photon Shower

Particle production properties

$$\langle X_{\max}^{(p)} \rangle = \lambda_p + X_{\rm rad} \ \log\left[\frac{E_0}{\varepsilon}\right] - X_{\rm rad} \ \langle \log n_\gamma \rangle$$

Interaction length

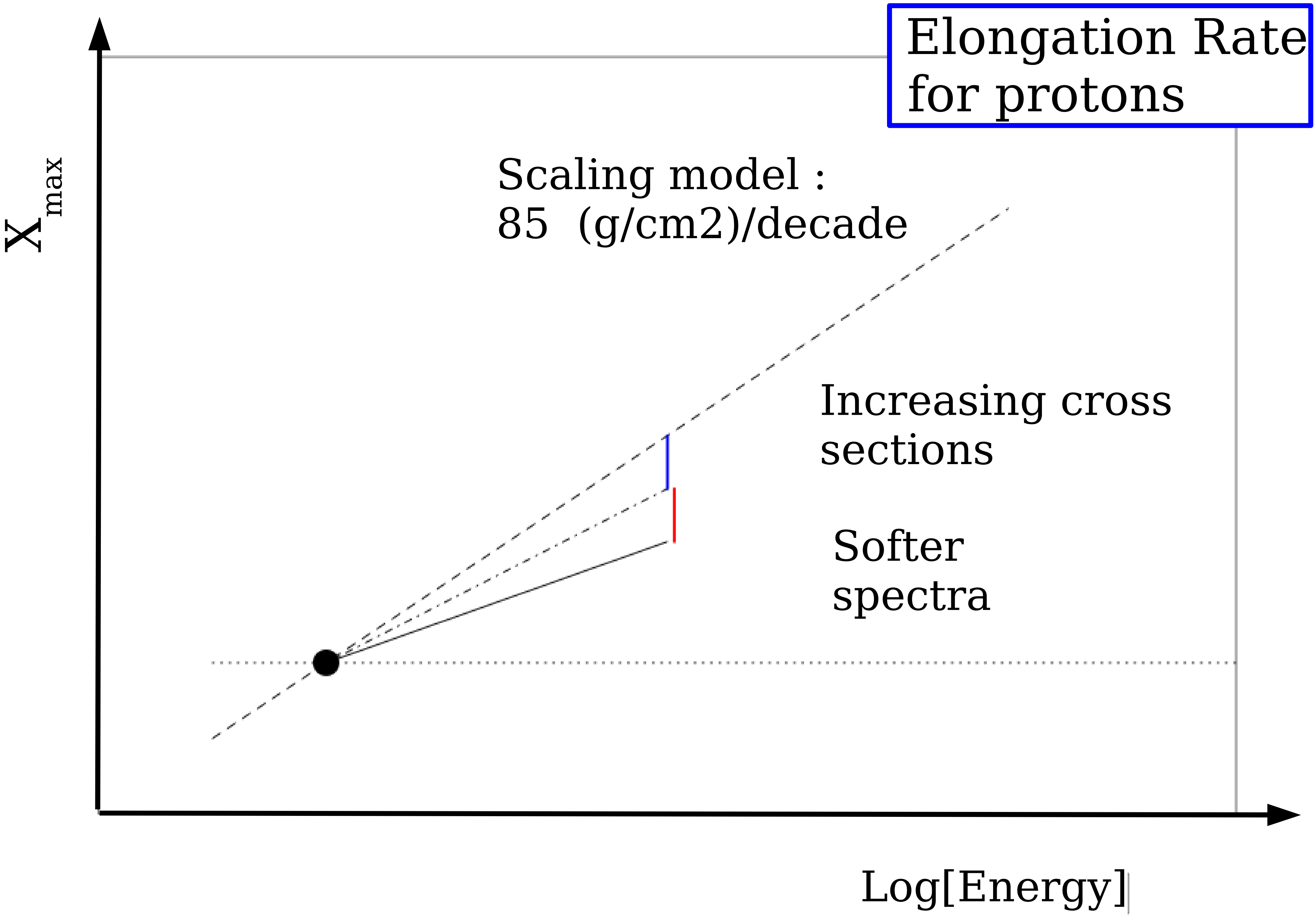
"Softness"

Elongation Rate

$$\frac{d\langle X_{\max}^{(p)}(E)\rangle}{d\log E} = X_{\rm rad} + \frac{d\lambda_p(E)}{d\log E} - X_{\rm rad}\ \frac{d\langle \log n_\gamma(E)\rangle}{d\log E}$$

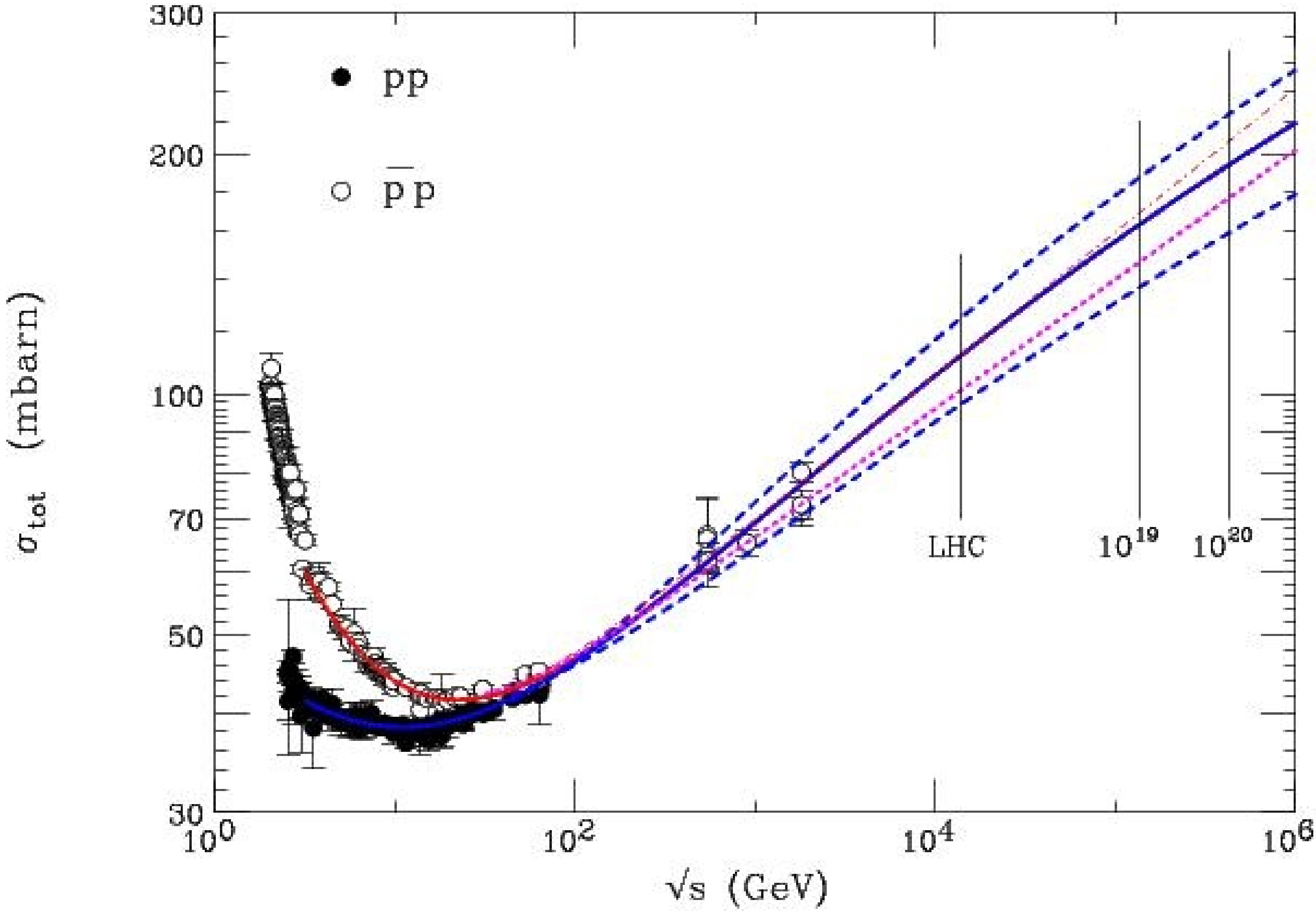
Evolution with Energy of the Interaction length

Evolution with energy of the "softness" of the spectrum

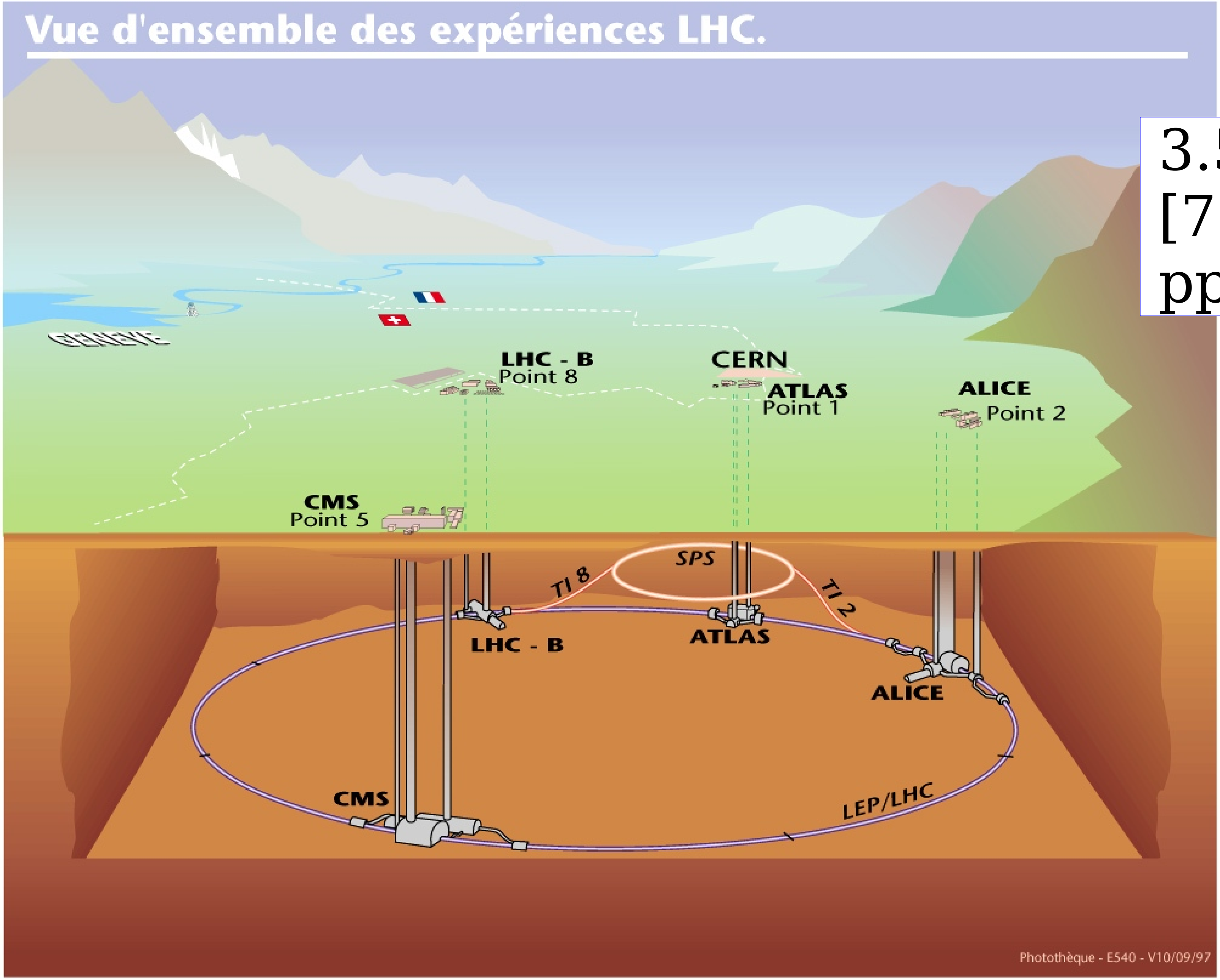


Elongation Rate
for protons
Scaling model :
85 (g/cm2)/decade
Increasing cross
sections
Softer
spectra
X_{max}
Log[Energy]

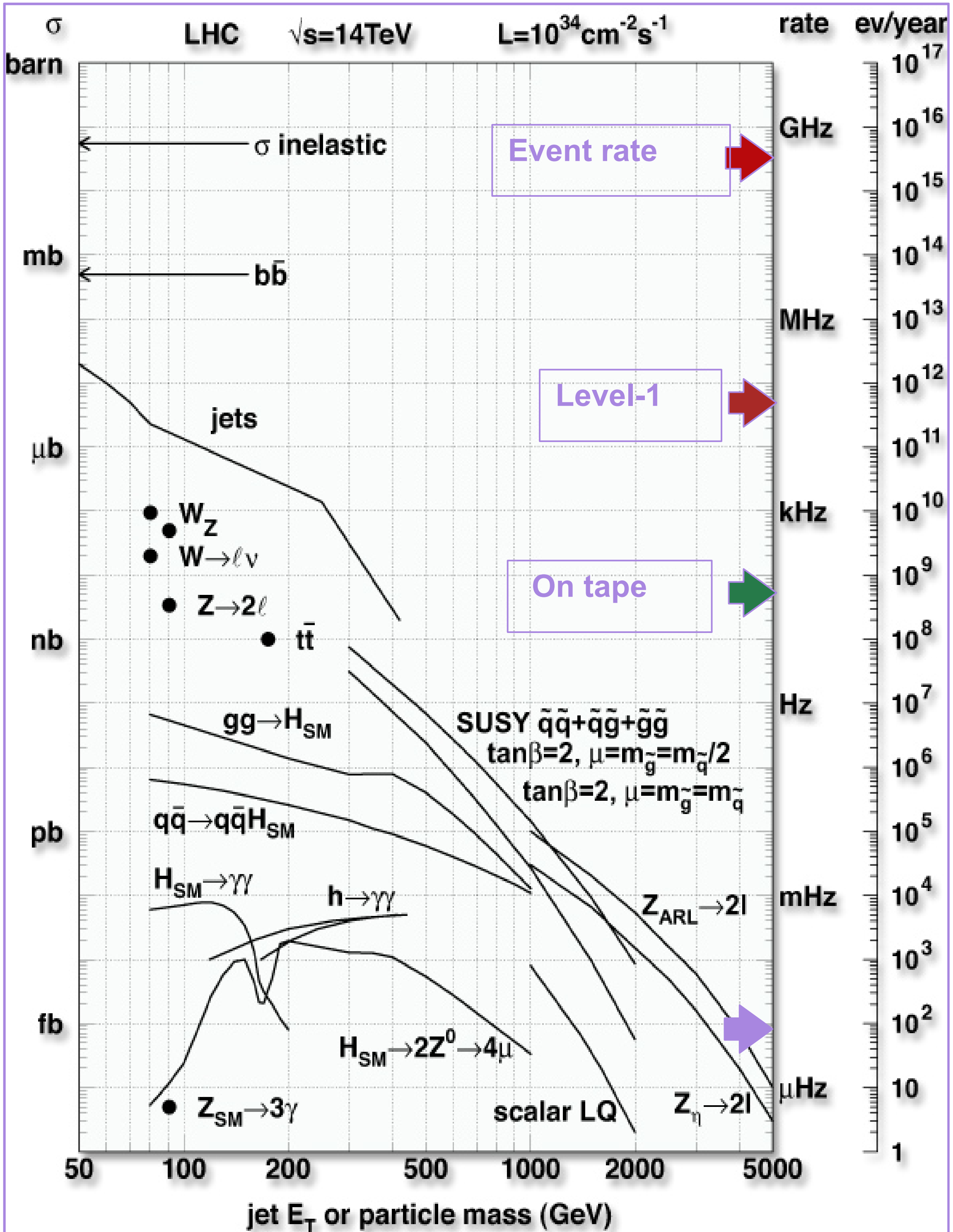
Total pp Cross Section



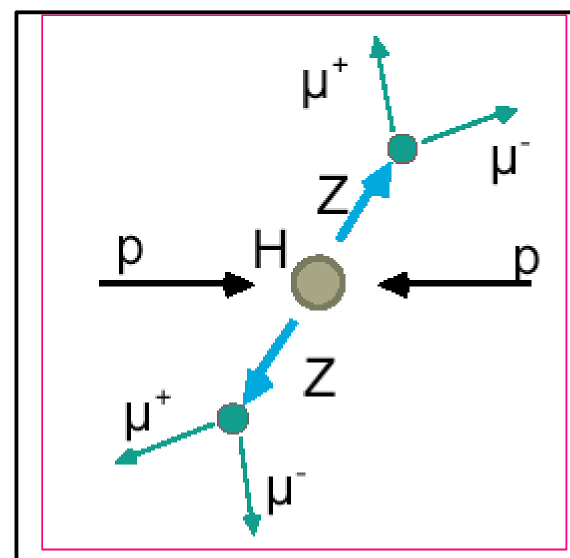
Extension of energy with LHC



3.5 + 3.5 TeV
[7 + 7 TeV]
pp collider



Higgs discovery golden channel



Pseudo-rapidity Distribution

$$\eta = \ln[(p + p_{\parallel})/p_{\perp}]$$

$$\eta = -\ln\left[\tan\theta/2\right]$$

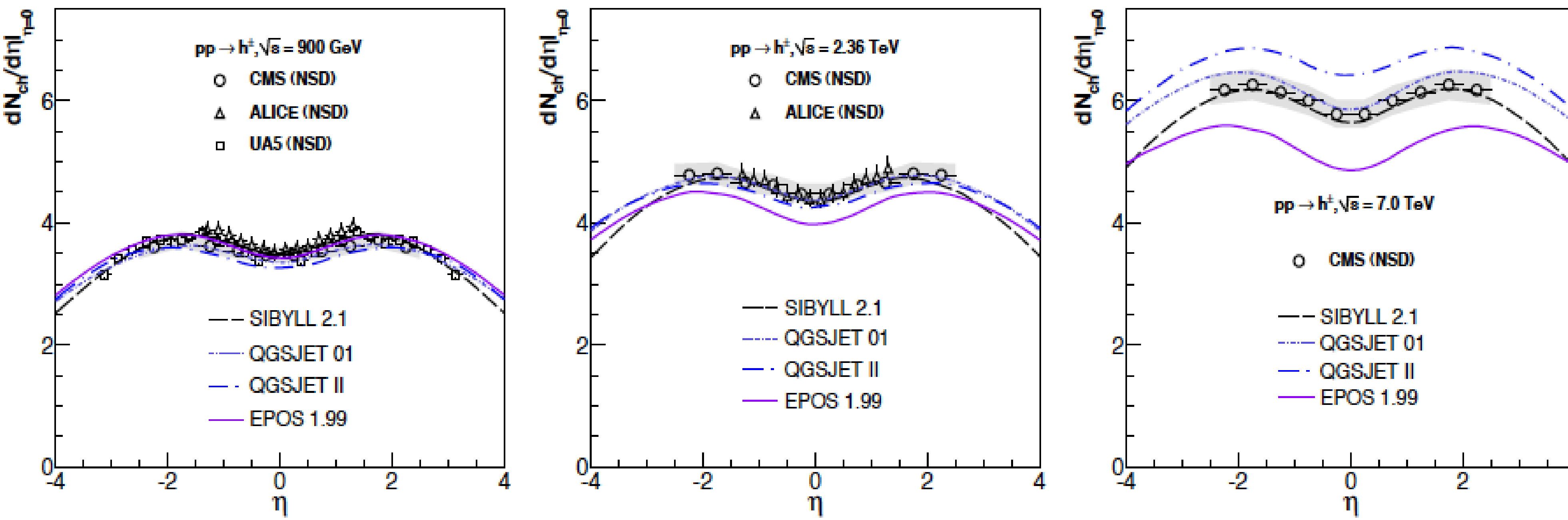


FIG. 3: Pseudorapidity distributions of charged hadrons, $h^{\pm} \equiv (h^{+} + h^{-})/2$, measured in NSD p-p events at the LHC (0.9, 2.36 and 7 TeV) by ALICE [36, 37] and CMS [38, 39] (and by UA5 [42] in p-$\bar{p}$ at 900 GeV) compared to the predictions of QGSJET01 and II, SIBYLL, and EPOS. The dashed band is the systematic uncertainty of the CMS experiment which is similar to those of the two other measurements.

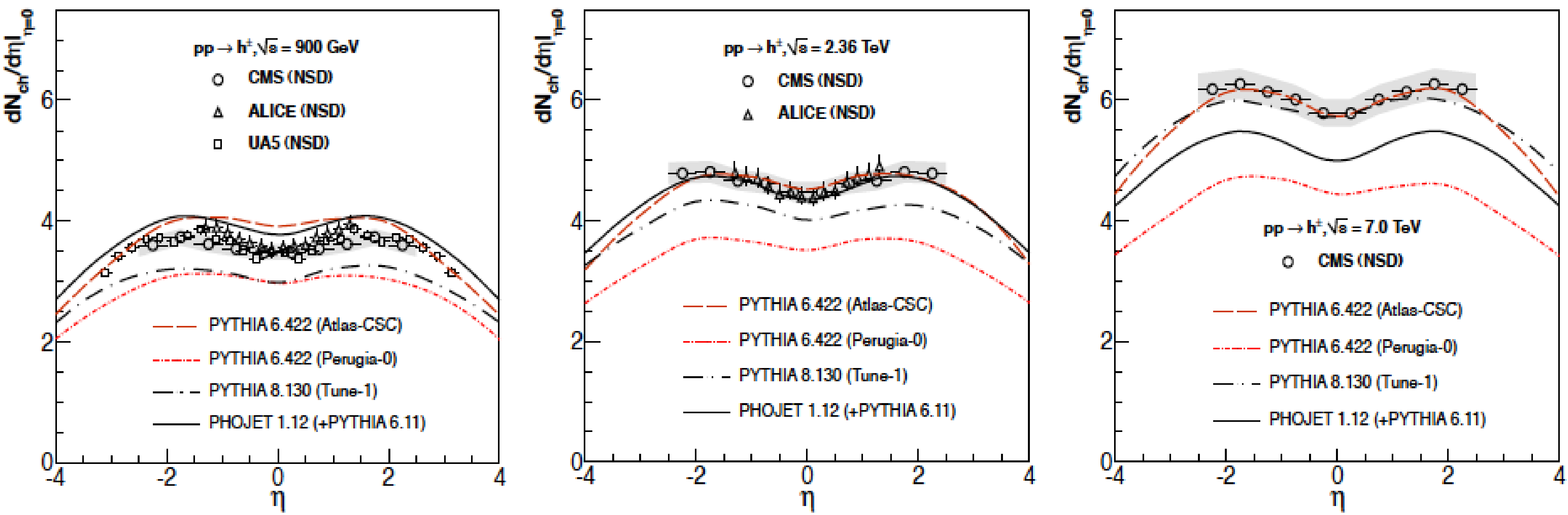
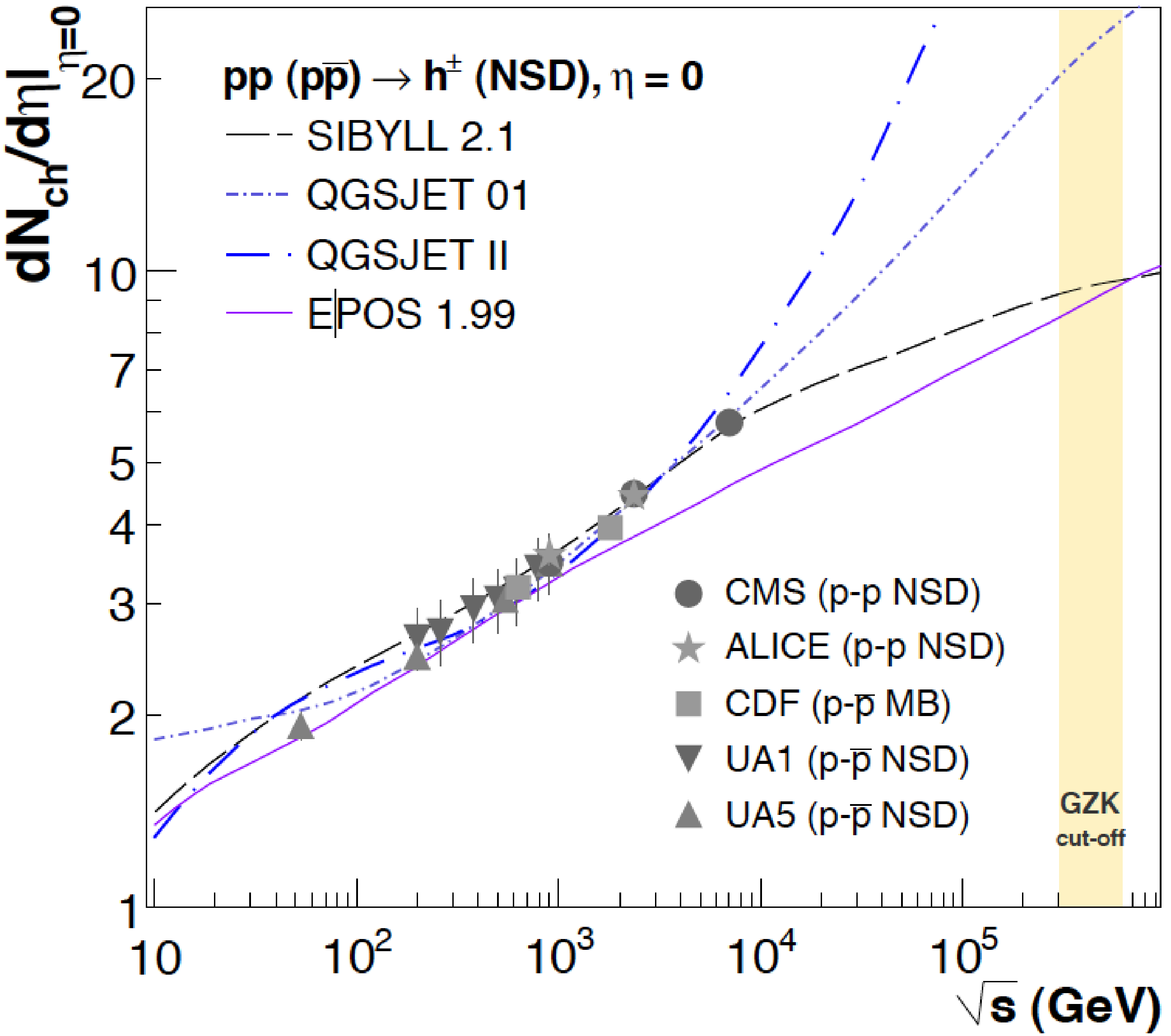
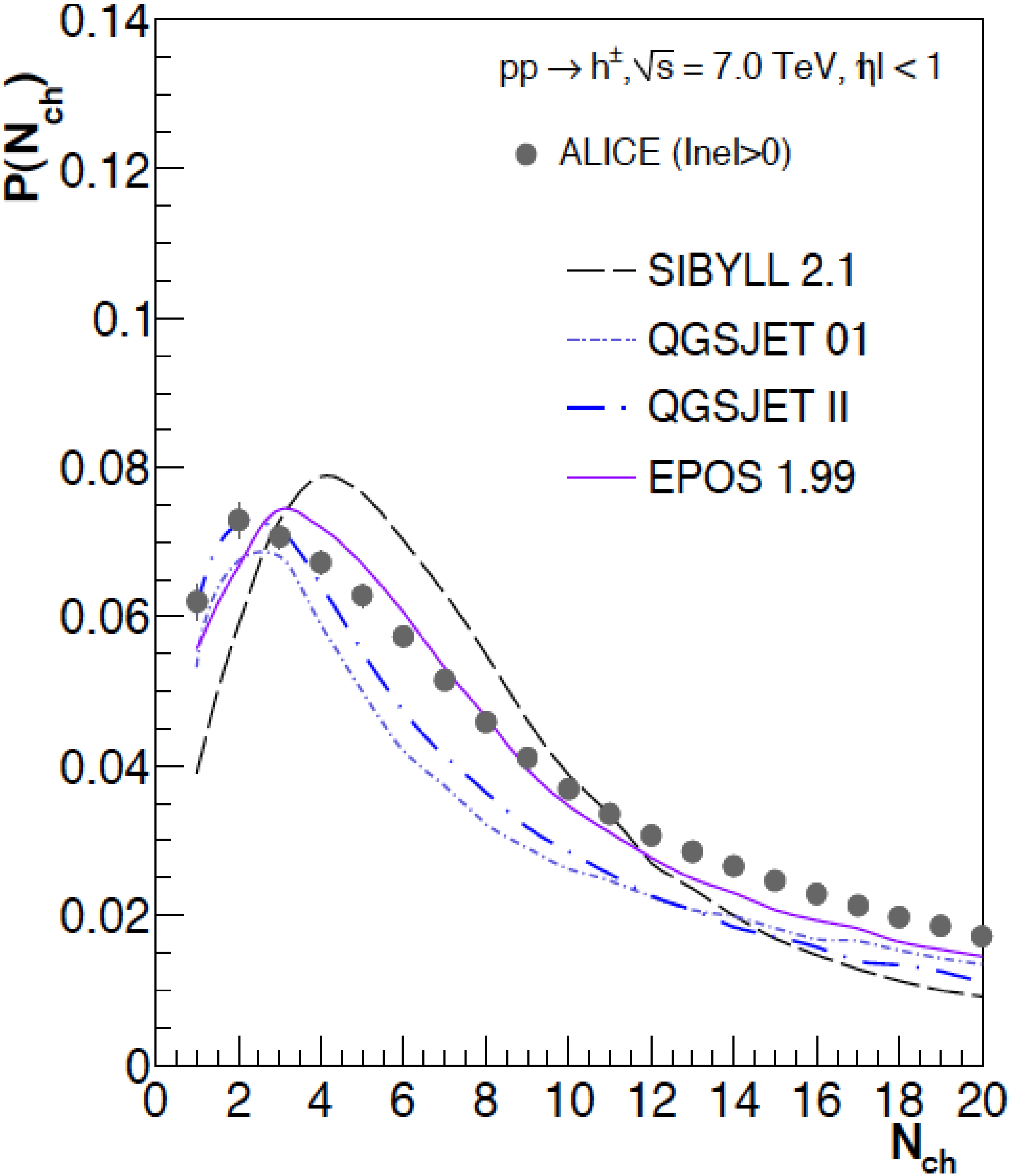


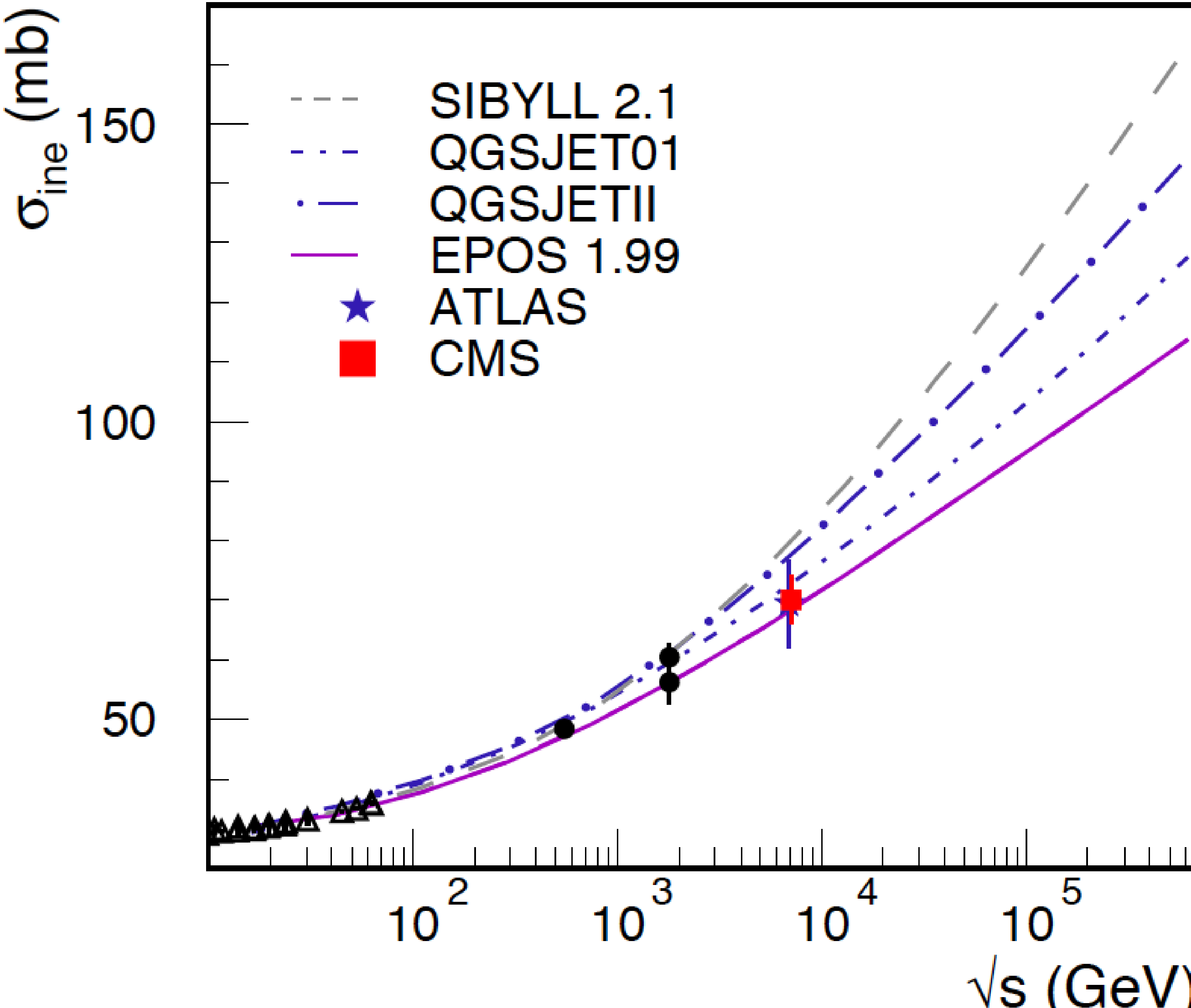
FIG. 2: Pseudorapidity distributions of charged hadrons, $h^{\pm} \equiv (h^{+} + h^{-})/2$, measured in NSD p-p events at the LHC ($\sqrt{s} = 0.9$, 2.36 and 7 TeV) by ALICE [36, 37] and CMS [38, 39] (and by UA5 [42] in p-$\bar{p}$ at 900 GeV) compared to three different versions of PYTHIA and to the PHOJET MC. The dashed band is the systematic uncertainty of the CMS experiment which is similar to those of the two other measurements.



dN_ch/dη|_η=0
pp (pp̄) → h± (NSD), η = 0
SIBYLL 2.1
QGSJET 01
QGSJET II
EPOS 1.99
CMS (p-p NSD)
ALICE (p-p NSD)
CDF (p-p̄ MB)
UA1 (p-p̄ NSD)
UA5 (p-p̄ NSD)
GZK
cut-off
1
2
3
4
5
7
10
20
10
10^2
10^3
10^4
10^5
√s (GeV)



Multiplicity distribution [3.5+3.5 TeV]



σ_{ine} (mb)
150
100
50
SIBYLL 2.1
QGSJET01
QGSJETII
EPOS 1.99
ATLAS
CMS
10^2
10^3
10^4
10^5
$\sqrt{s}$ (GeV)

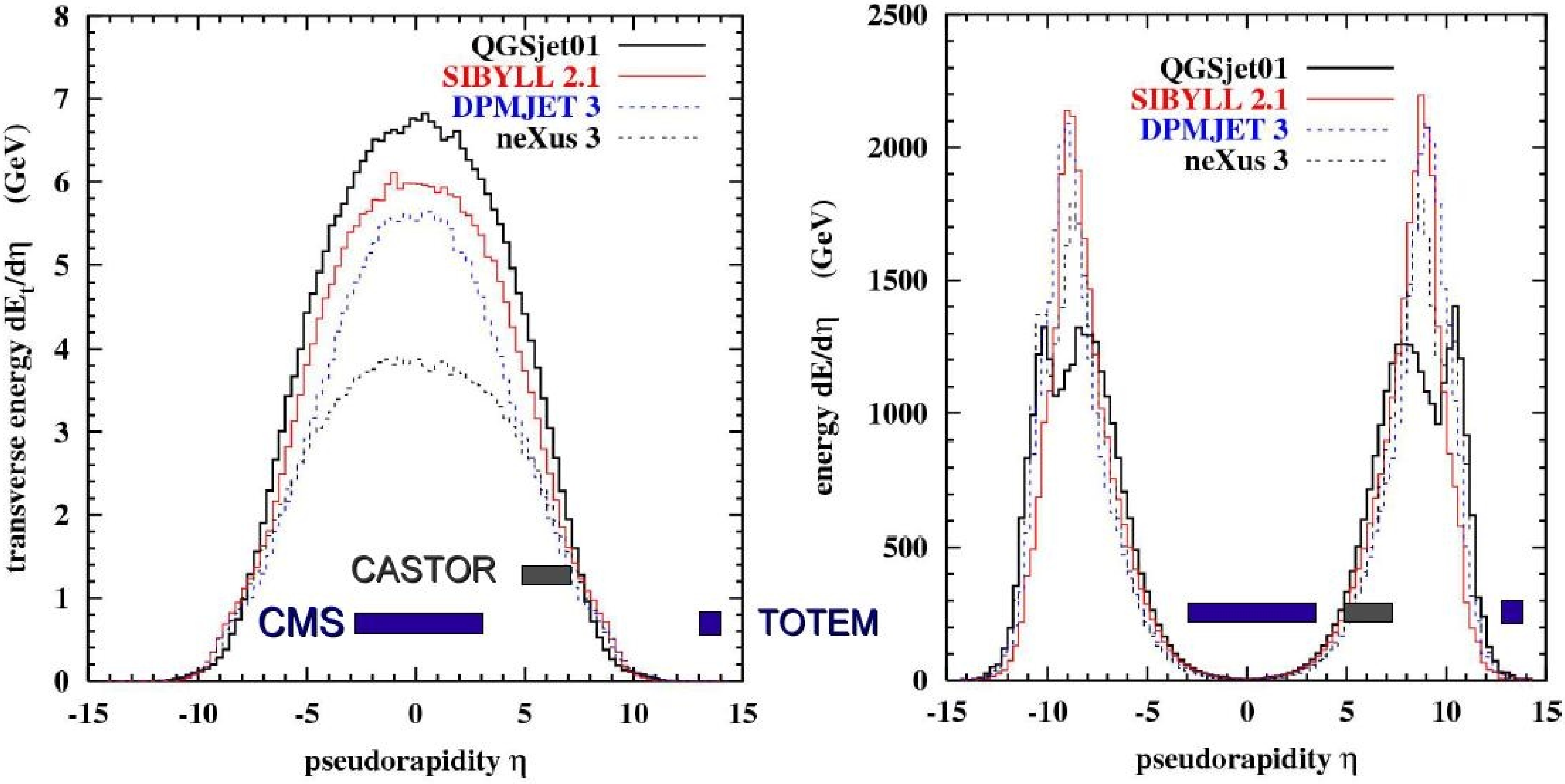
The strong interaction at the collider and cosmic-rays frontiers

David d'Enterria · Ralph Engel · Tanguy Pierog · Sergey Ostapchenko · Klaus Werner

arXiv:1106.2453

Model	SIBYLL 2.1			QGSJET01			QGSJETII			EPOS 1.99		
$\sqrt{s}$ (TeV)	0.9	2.36	7	0.9	2.36	7	0.9	2.36	7	0.9	2.36	7
σ_{inel}	✓	⇑	⇑	✓	✓	✓	✓	⇑	⇑	✓	✓	✓
$dN_{ch}/d\eta\|_{\eta=0}$	✓	✓	✓	✓	✓	✓	✓	✓	⇑	✓	⇓	⇓
$P(N_{ch} < 5)$	⇑	⇑	⇑	⇑	⇑	⇓	⇑	⇑	⇑	✓	✓	✓
$P(N_{ch} > 30)$	⇑	✓	⇑	✓	⇓	⇓	✓	✓	⇑	⇓	⇓	⇓
$\langle p_\perp \rangle$	✓	⇓	⇓	⇑	⇑	✓	⇑	⇑	⇑	✓	✓	✓

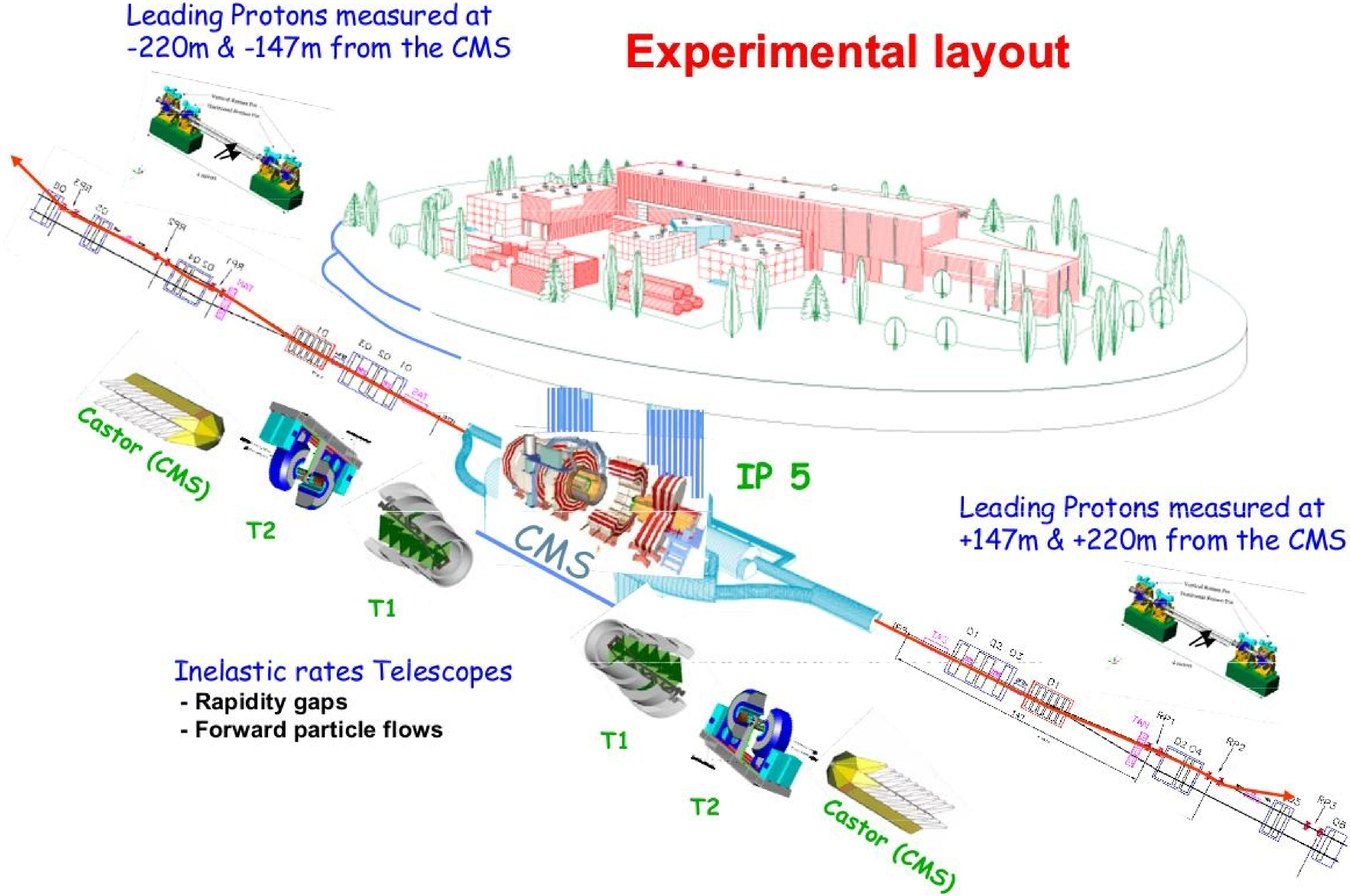
Table 1 Level of overall agreement between QGSJET01, QGSJETII, SIBYLL 2.1 and EPOS 1.99 with inclusive charged hadron results measured in collisions at 0.9, 2.36 and 7 TeV: inelastic cross section σ_{inel}, pseudorapidity densities $dN_{ch}/d\eta|_{\eta=0}$, multiplicity probabilities $P(N_{ch})$ for low and high values of N_{ch}, and mean transverse momentum $\langle p_\perp \rangle$. A tick (✓) indicates a reasonable data–model agreement within experimental uncertainties, and ⇑ (⇓) that the MC tends to over (under) estimate the measurements.



PROBLEM of PHASE SPACE COVERING

TOTEM

Experimental layout

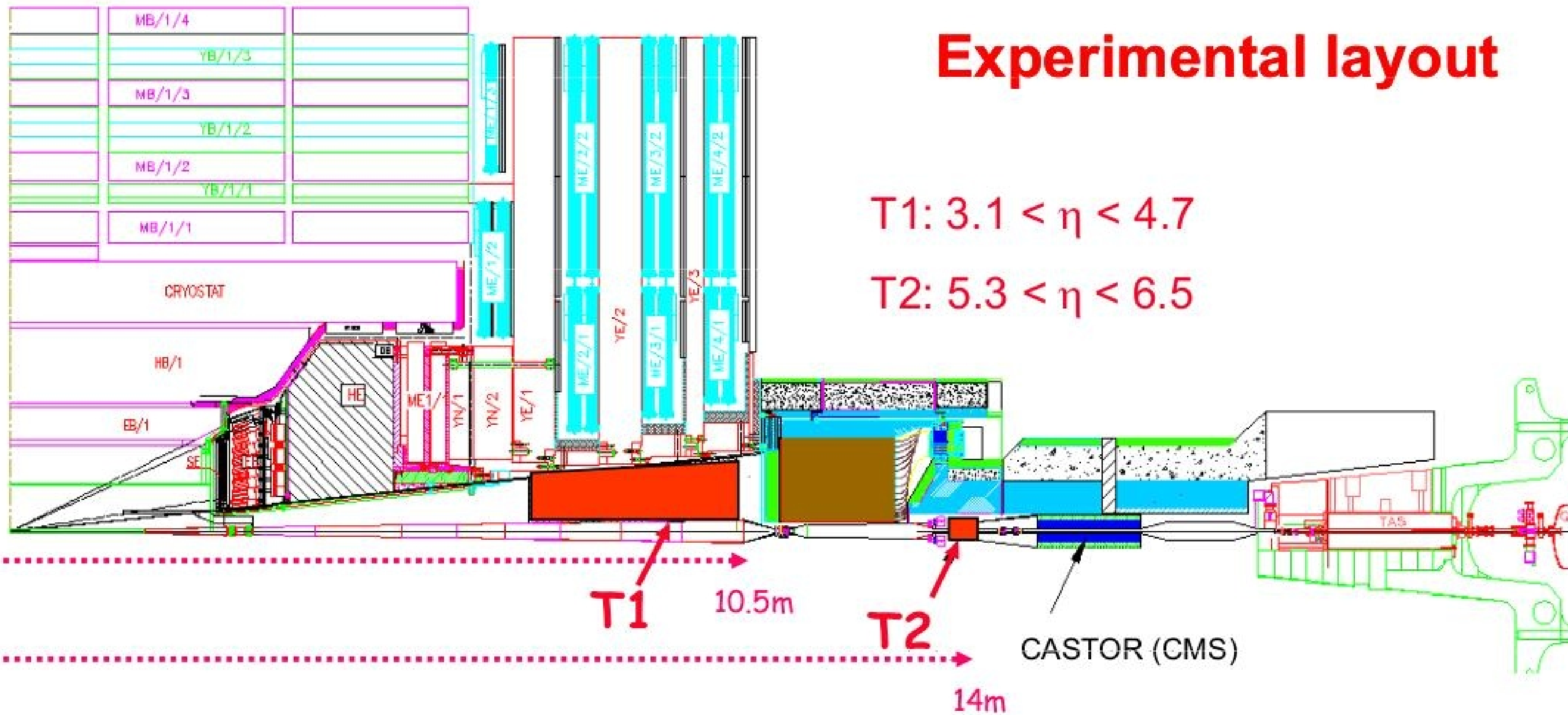


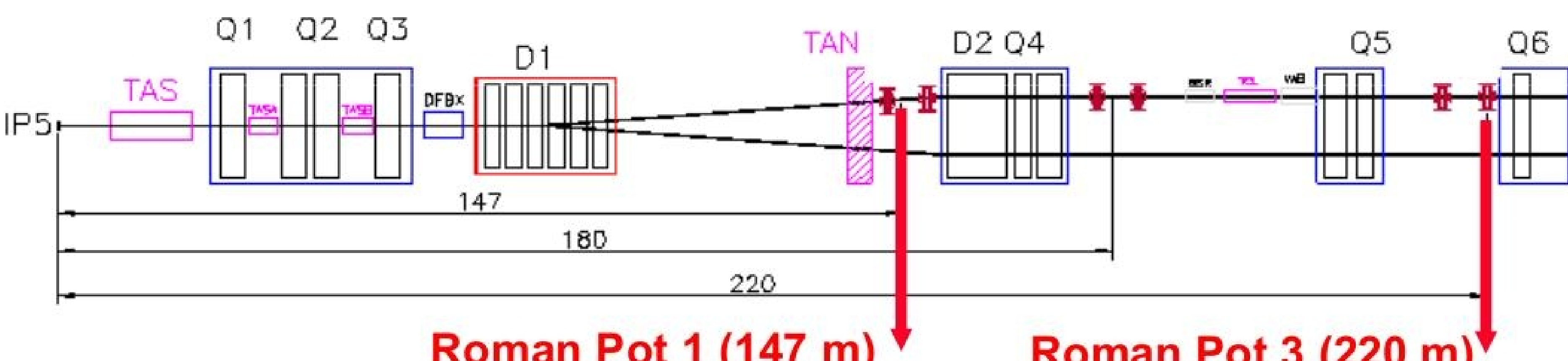
TOTEM

Experimental layout

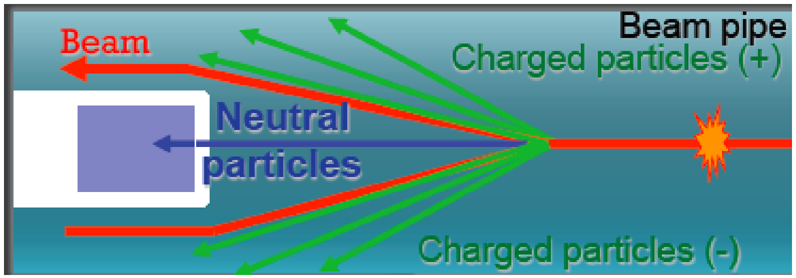
T1: $3.1 < \eta < 4.7$

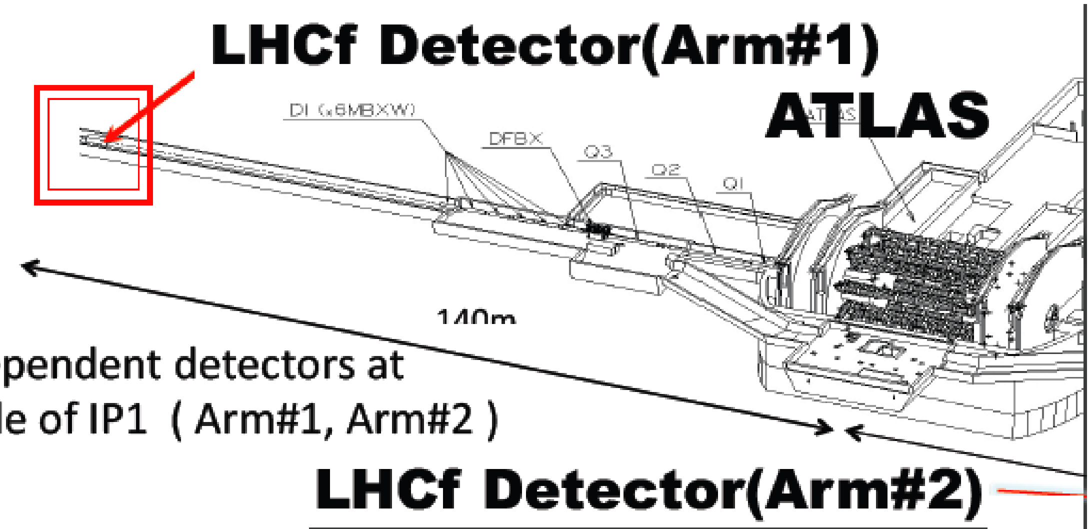
T2: $5.3 < \eta < 6.5$



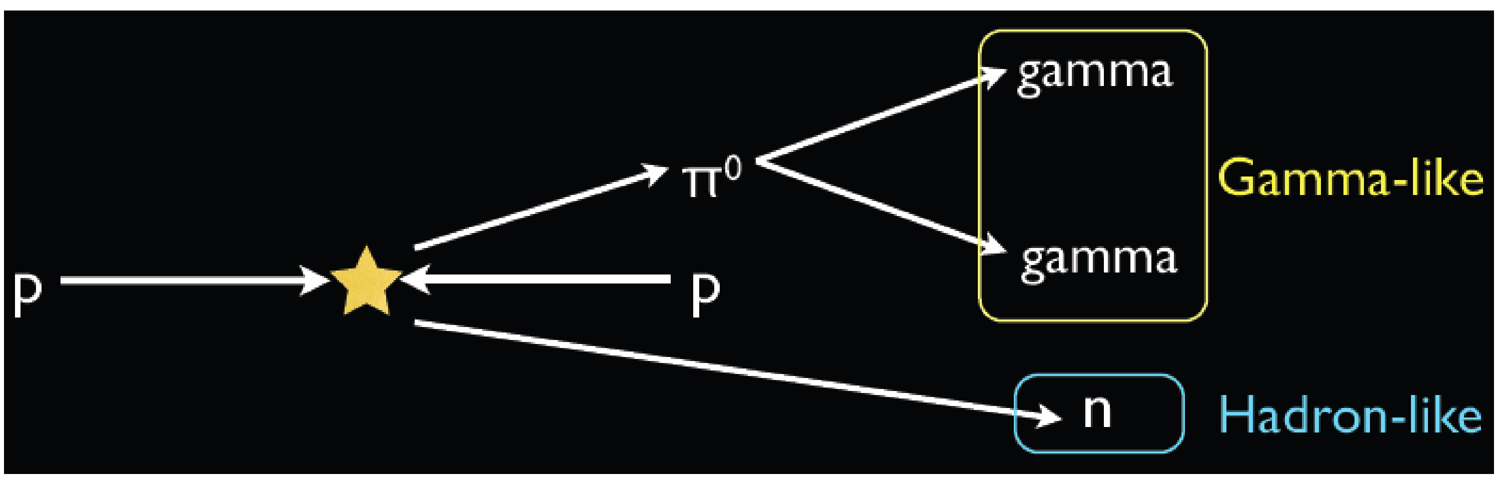


Inclusive photon energy spectra at zero degree of the LHC 7 TeV proton-proton collisions by the LHCf experiment



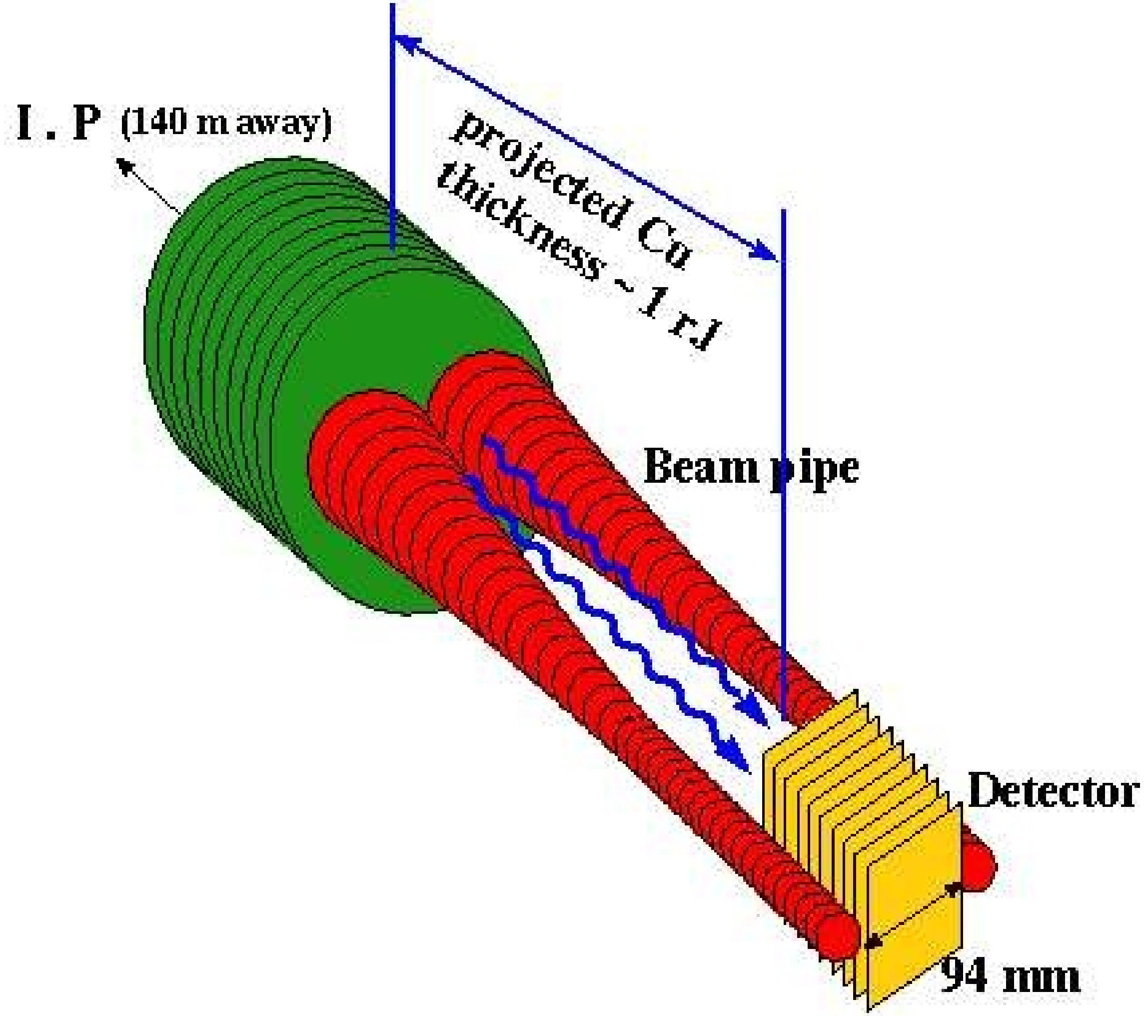


Two independent detectors at either side of IP1 (Arm#1, Arm#2)



LHCF

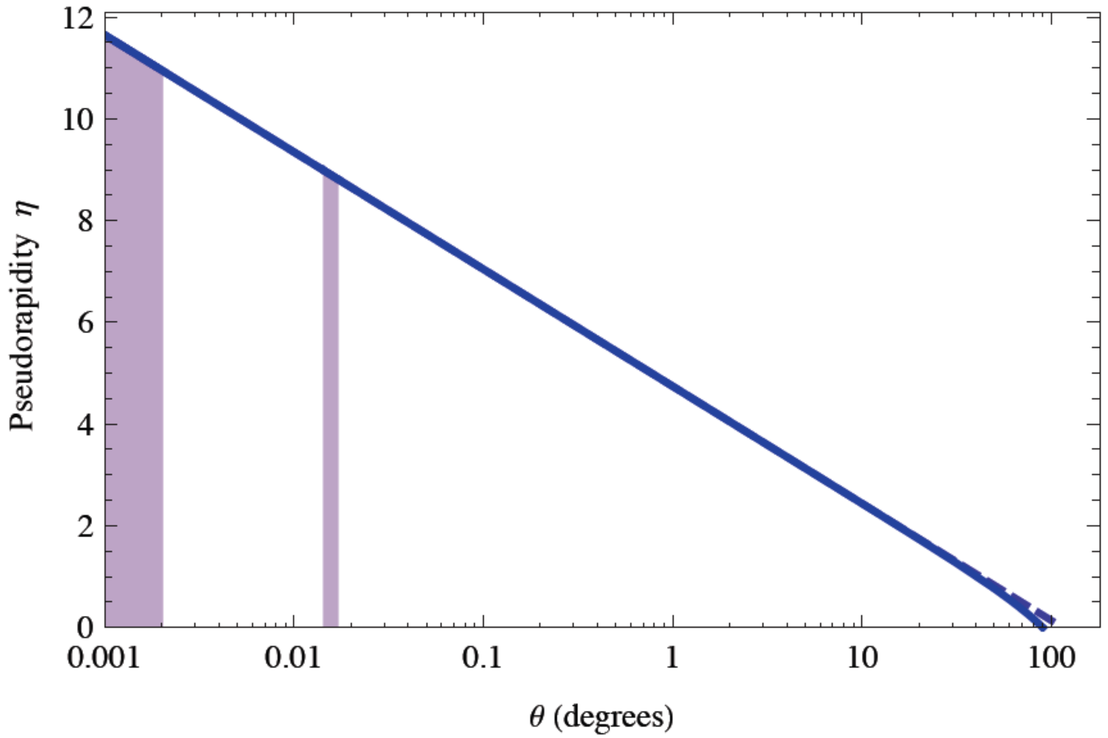
Calorimeter
for neutral particles
in the very forward region

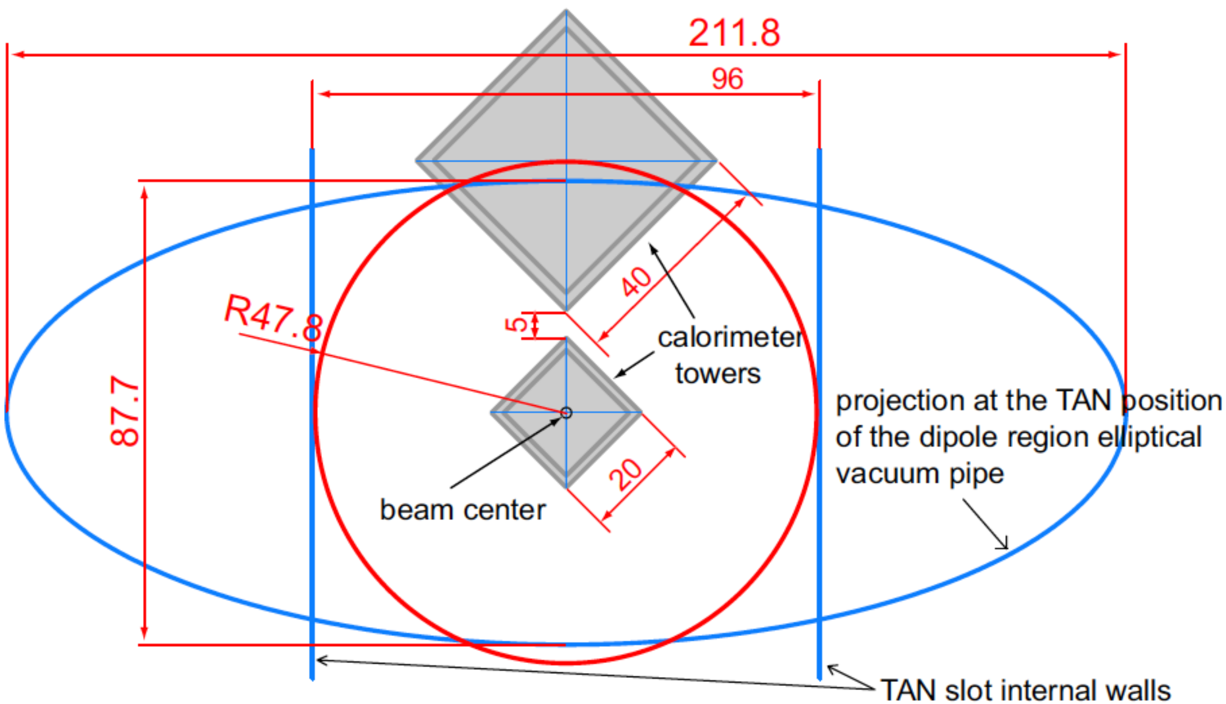


Two
non-identical
Detectors

Pseudo-Rapidity versus angle:

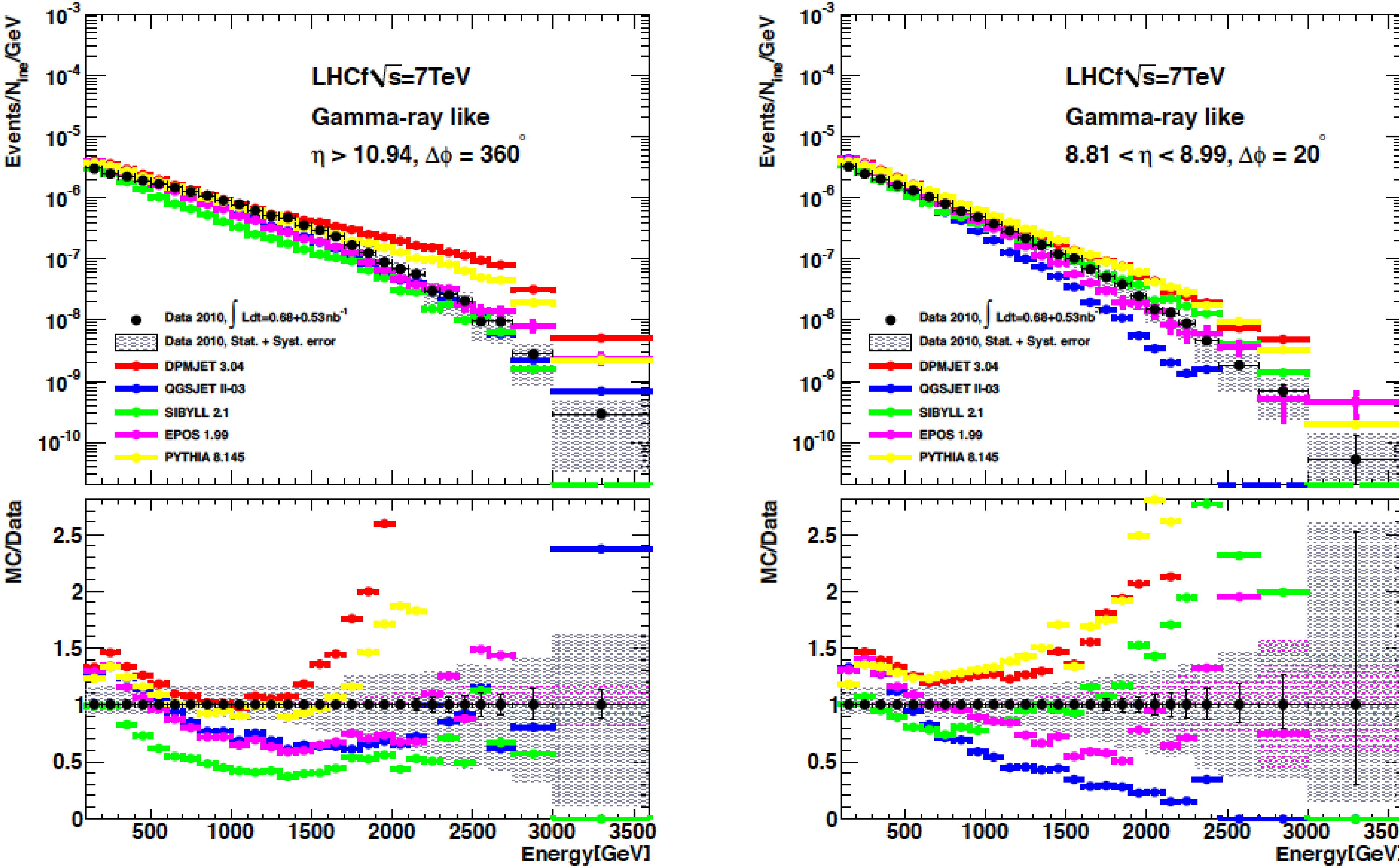
Very small angle production:

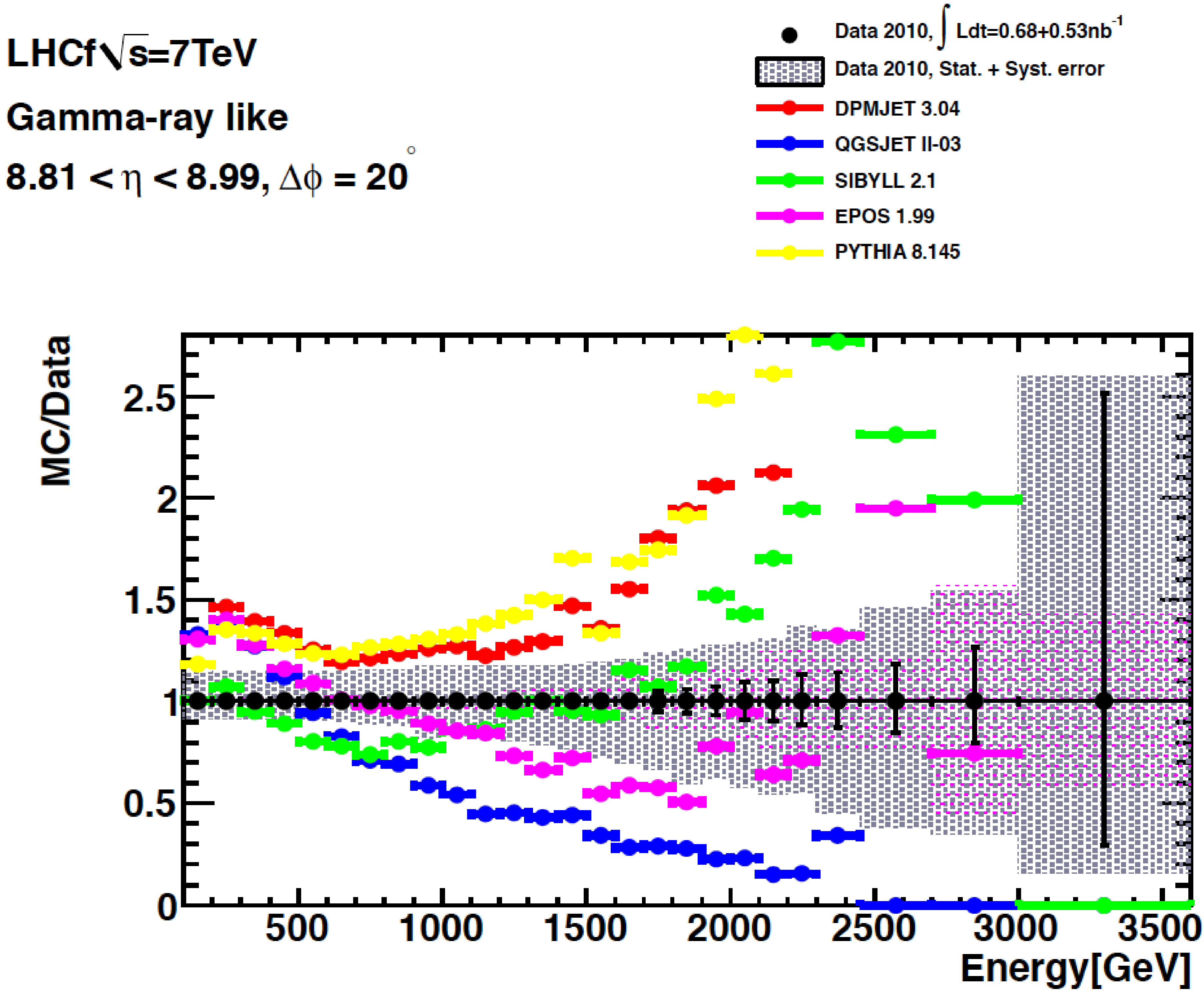




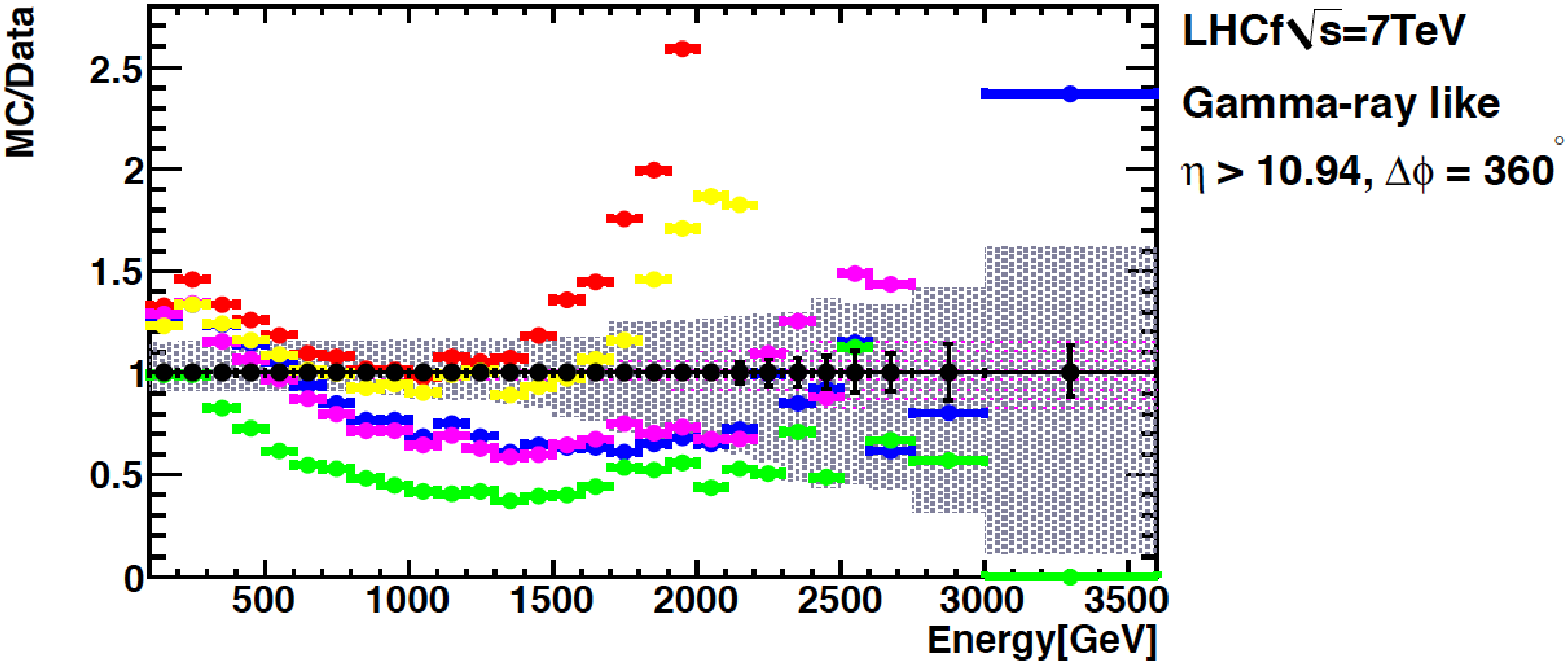
LHCf data   hep-ex/1104.5294

[photon distributions in 2 very forward angular regions]





LHCf $\sqrt{s}$=7TeV
Gamma-ray like
$8.81 < \eta < 8.99$, $\Delta\phi = 20^\circ$
Data 2010, $\int Ldt$=0.68+0.53nb^{-1}
Data 2010, Stat. + Syst. error
DPMJET 3.04
QGSJET II-03
SIBYLL 2.1
EPOS 1.99
PYTHIA 8.145
MC/Data
0
0.5
1
1.5
2
2.5
500
1000
1500
2000
2500
3000
3500
Energy[GeV]



LARGE DISCREPANCIES !!

What is the significance
for the understanding of hadronic interactions ?

What is the impact on
the interpretation of UHECR ?

$$\left[\frac{dN_\gamma}{dE_\gamma}(E_\gamma)\right]_{8.81\leq\eta\leq8.99} = \frac{dN_\gamma}{dE_\gamma}(E_\gamma) \times \frac{dN_\gamma[8.81 \leq \eta \leq 8.99]}{dN_\gamma[\text{all } \eta]}$$

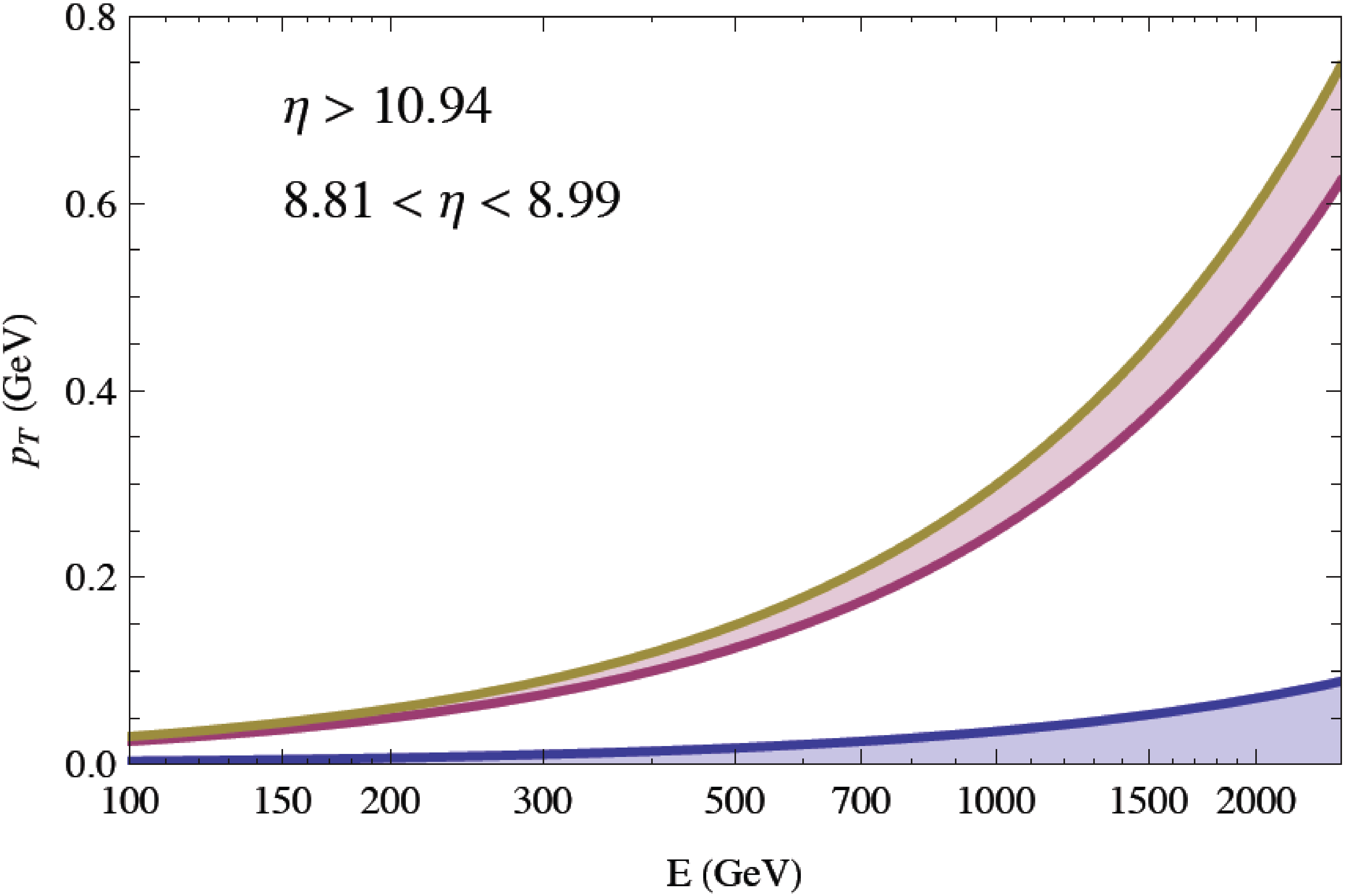
$$\left[\frac{dN_\gamma}{dE_\gamma}(E_\gamma)\right]_{\eta>10.94} = \frac{dN_\gamma}{dE_\gamma}(E_\gamma) \times \frac{dN_\gamma[\eta > 10.94]}{dN_\gamma[\text{all } \eta]}$$

Directly relevant for UHECR shower development

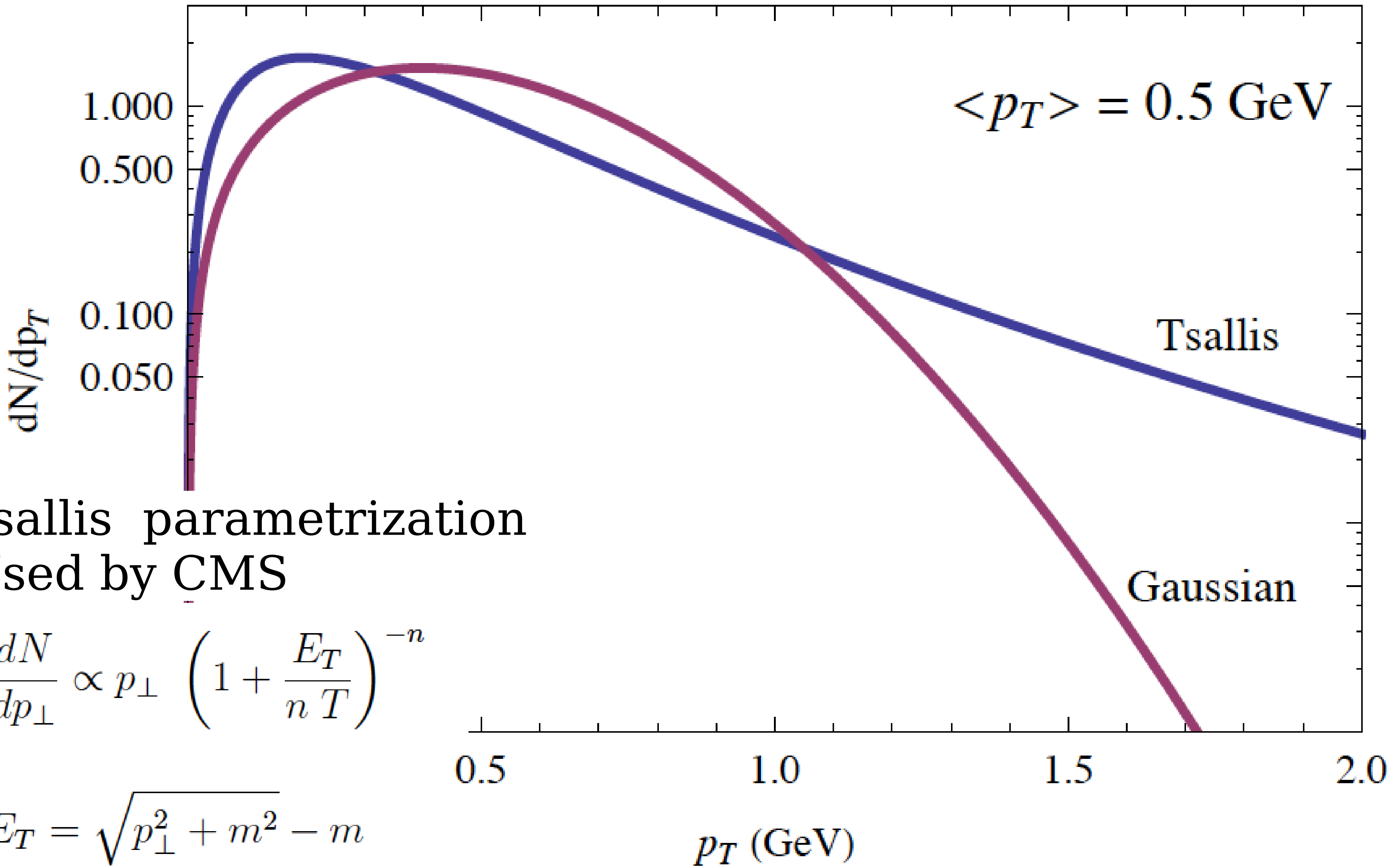
pT distribution dependence

$$p_\perp = \sqrt{E^2 - m^2}\ \sin\left[2\ \tan^{-1}\left(e^{-\eta}\right)\right]$$

$$p_\perp \simeq p\ 2\ e^{-\eta}$$



Transverse-Momentum Distribution

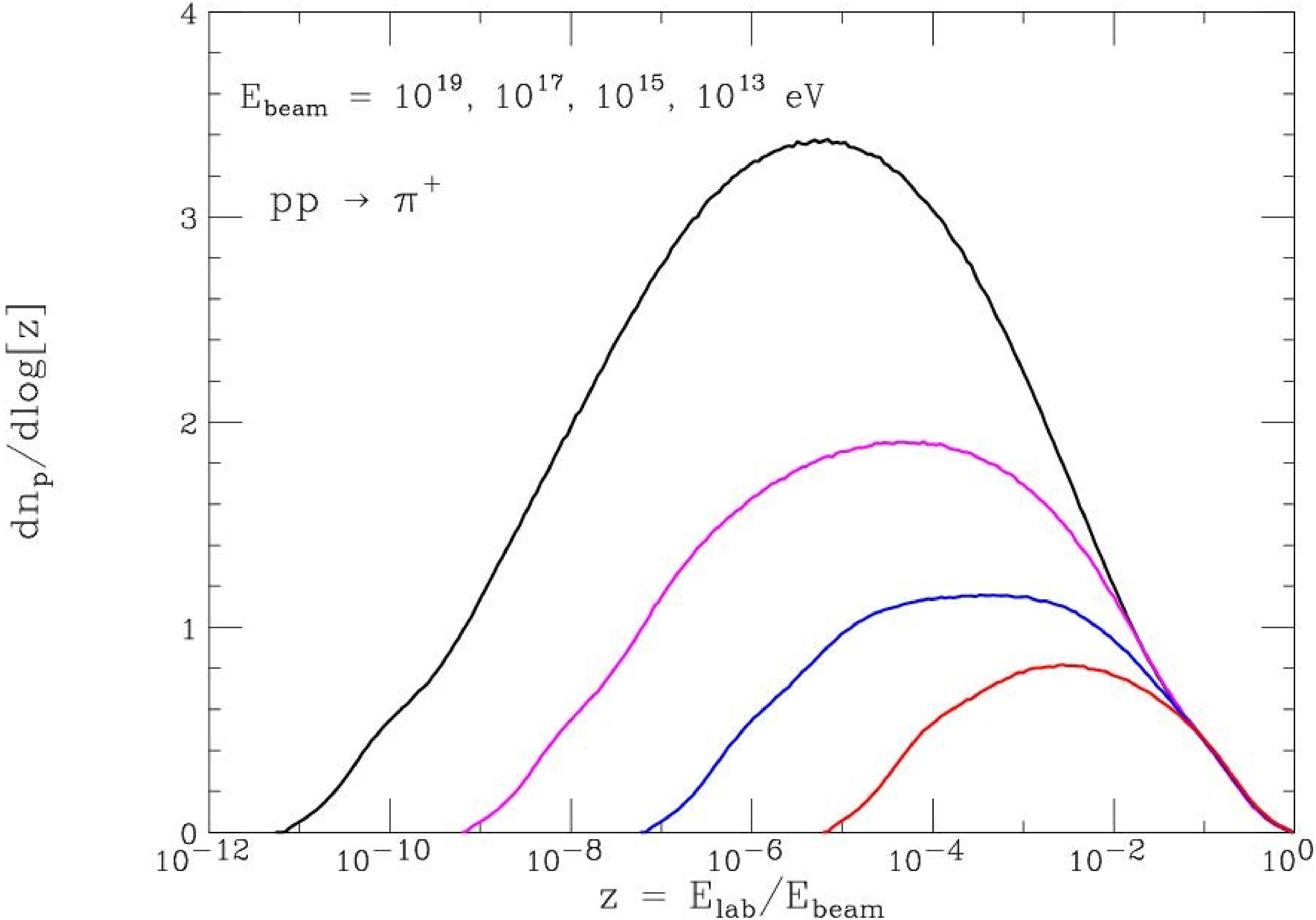


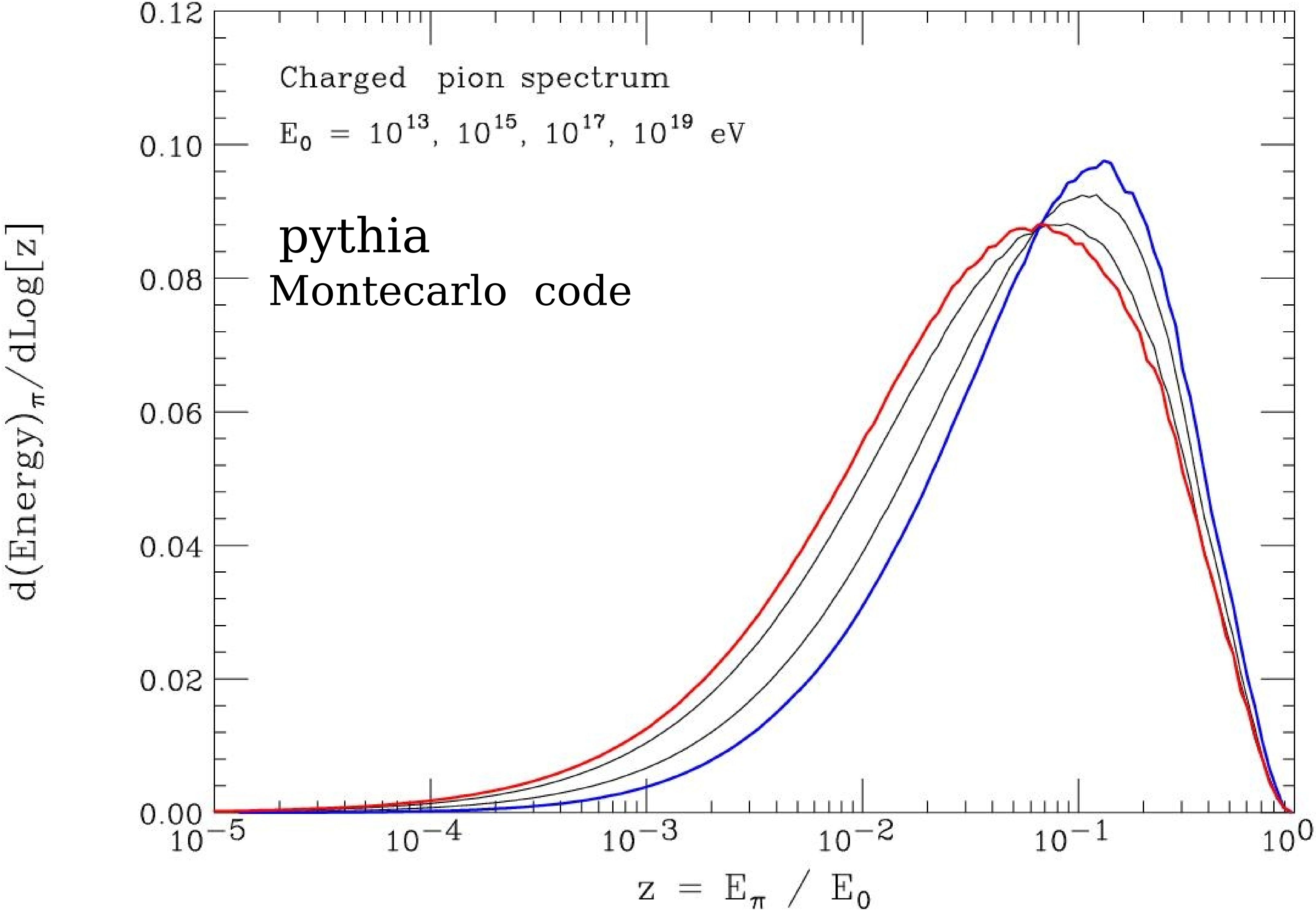
Tsallis parametrization
Used by CMS

$$\frac{dN}{dp_\perp} \propto p_\perp \left(1 + \frac{E_T}{n\,T}\right)^{-n}$$

$$E_T = \sqrt{p_\perp^2 + m^2} - m$$

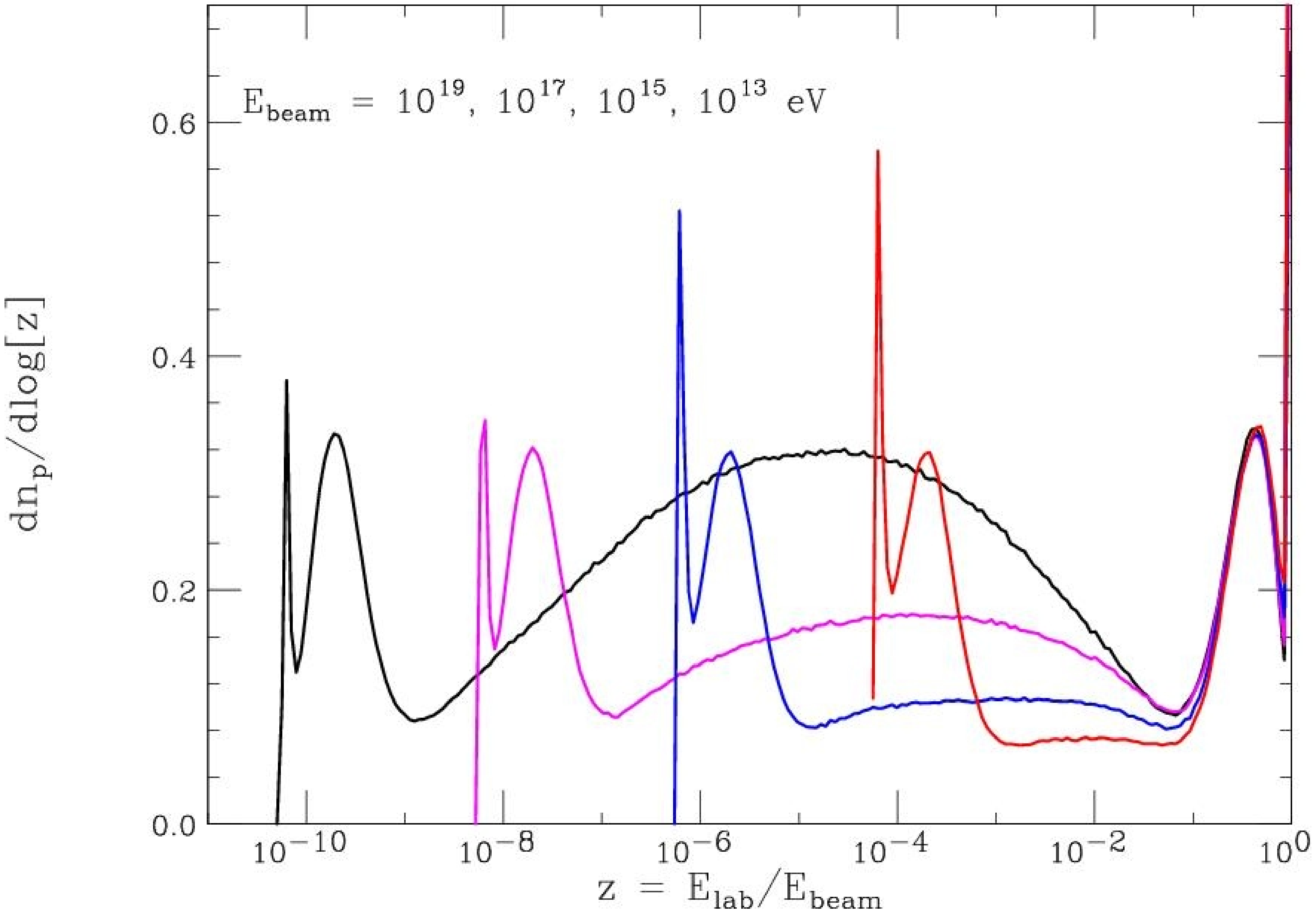
EXTRAPOLATION to HIGH ENERGY (Pythia pp)



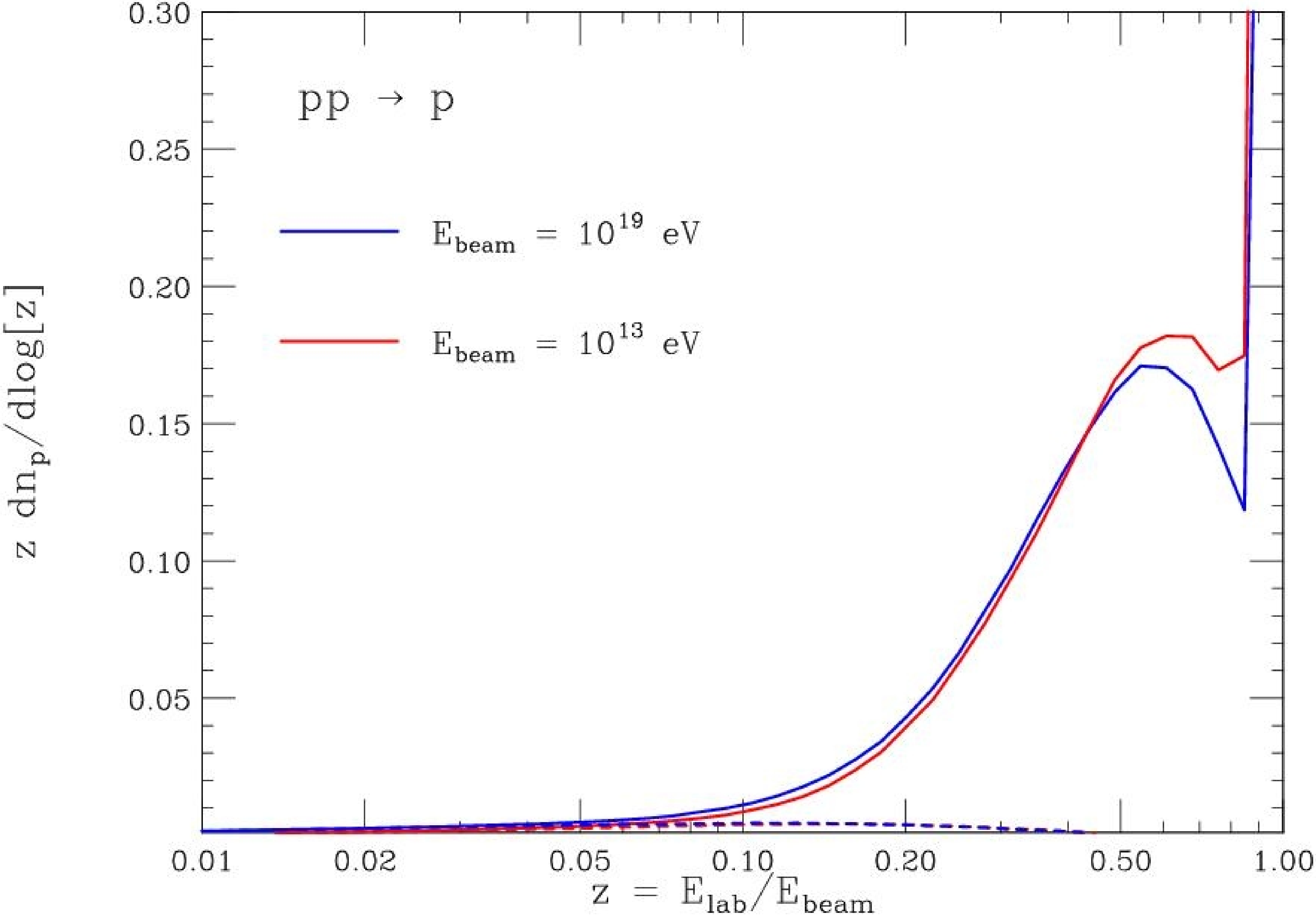


Charged pion spectrum
$E_0 = 10^{13}, 10^{15}, 10^{17}, 10^{19}$ eV
pythia
Montecarlo code
$d(\text{Energy})_\pi / d\text{Log}[z]$
0.12
0.10
0.08
0.06
0.04
0.02
0.00
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
$z = E_\pi / E_0$

PROTON Spectra (elasticity spectra)



PROTON Spectra (elasticity spectra)



C.R. DATA

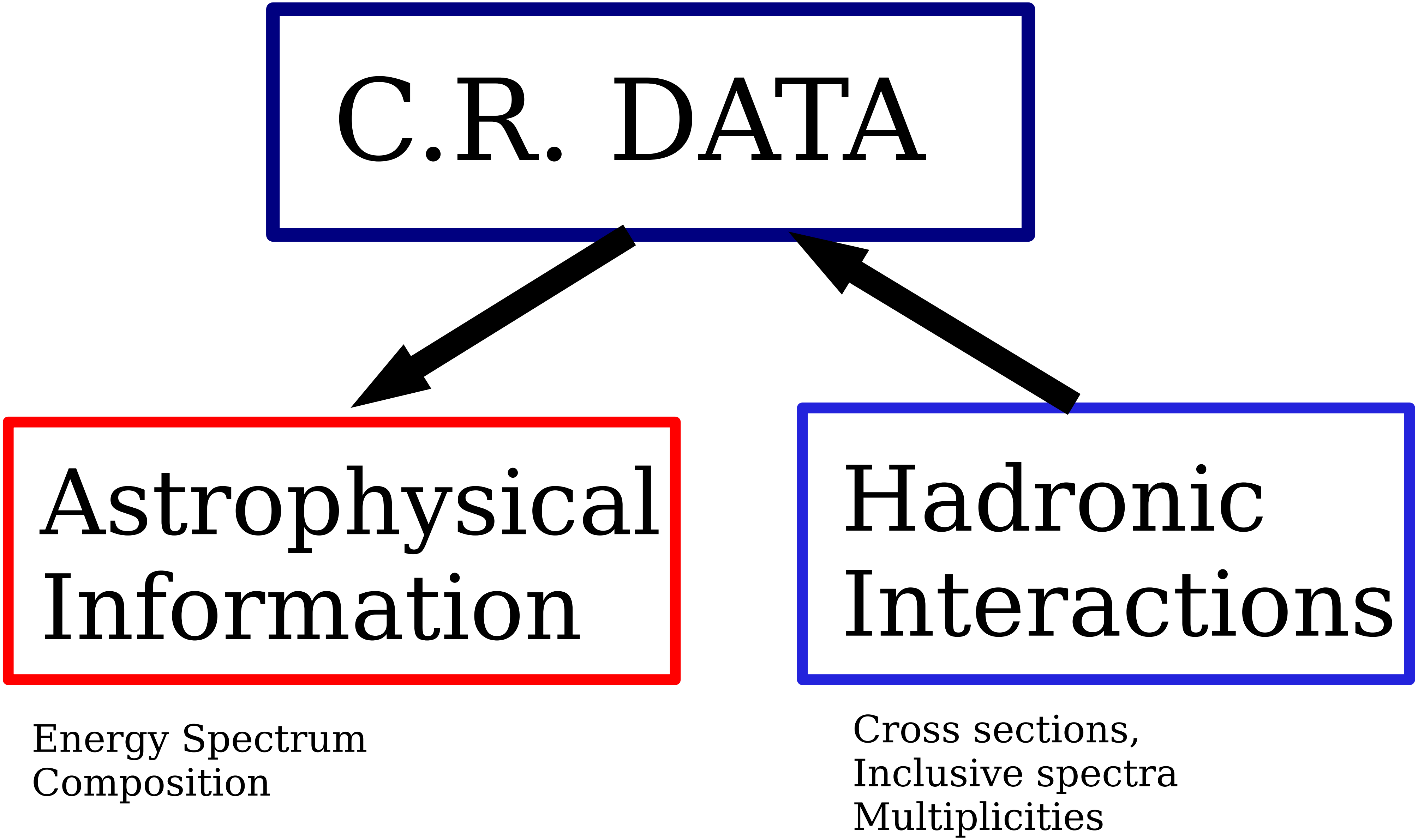
Astrophysical Information

Energy Spectrum
Composition

Hadronic Interactions

Cross sections,
Inclusive spectra
Multiplicities

From Accelerator Data + Theory → Astrophysics



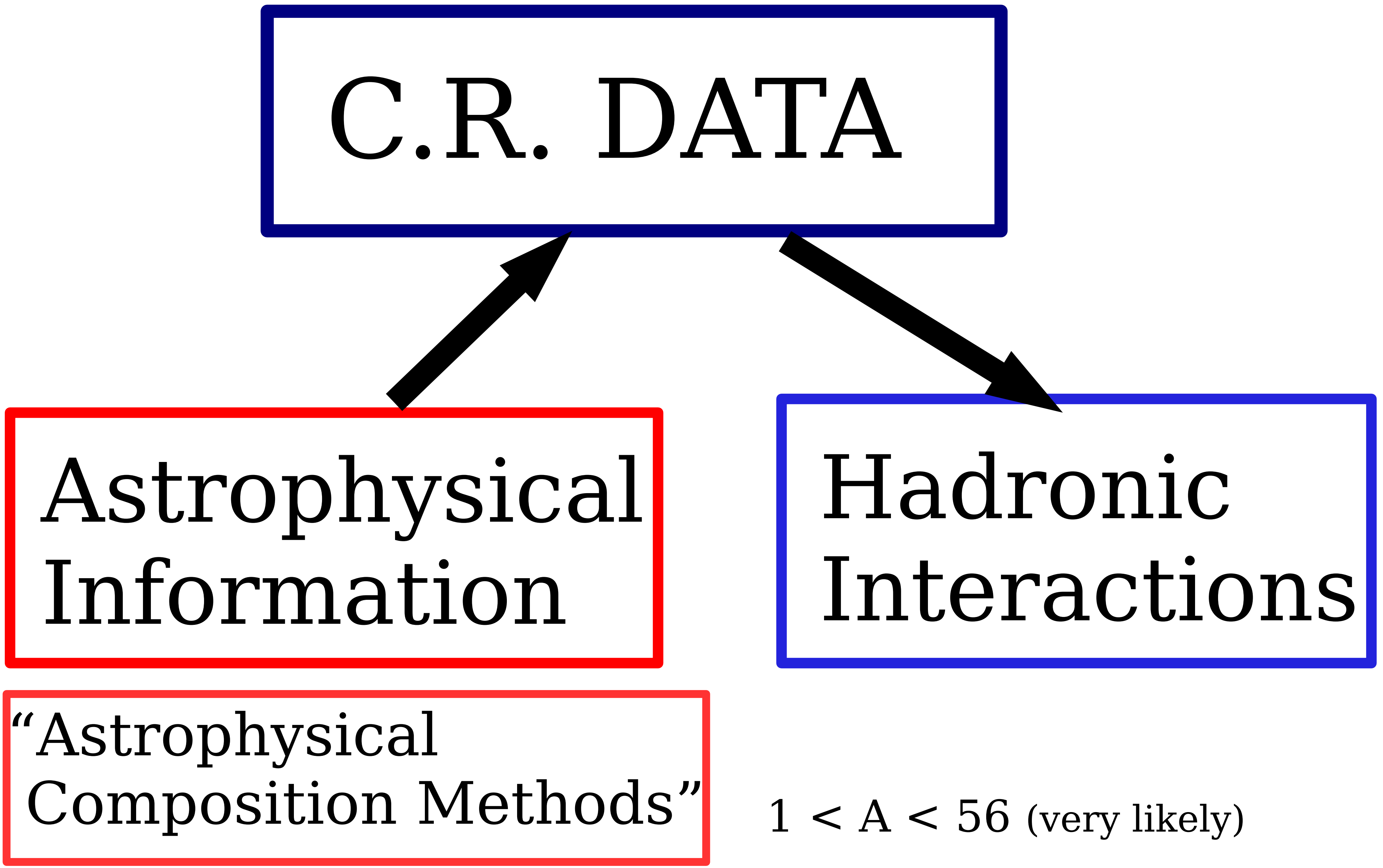
Data

$$\langle \ln A \rangle_E = \frac{\langle X_{\max}(E) \rangle - X_p(E)}{D_p}$$

Astrophysical Information

Hadronic Interactions

From Cosmic Ray Data → Hadronic Interactions



“Astrophysical Composition Methods”

- Energy Spectrum

  “imprints” of Energy Loss

- “Cosmic Magnetic Spectrometer”

Features in the Cosmic Ray Energy Spectrum
can in principle give information
on the nature of the particle

Interpreted as the effect
of energy loss during propagation
from their extragalactic sources.

Known target: 2.7 K CMBR radiation field

Energy Thresholds for protons :

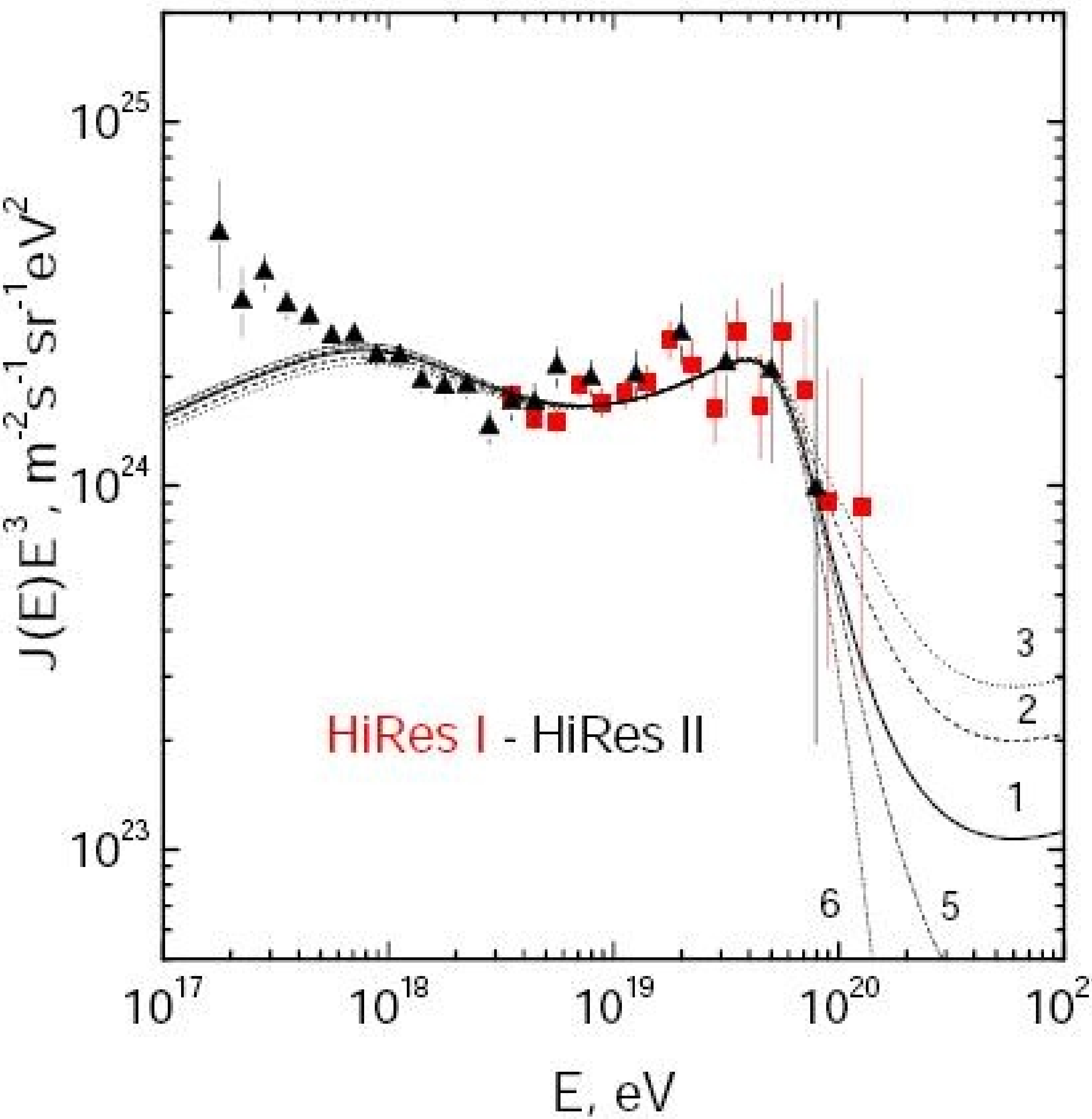
$$p\,\gamma \to p\pi^\circ$$

$$p\,\gamma \to n\pi^+$$

"GZK"

$$p\,\gamma \to p\,e^+e^-$$

Pair Production



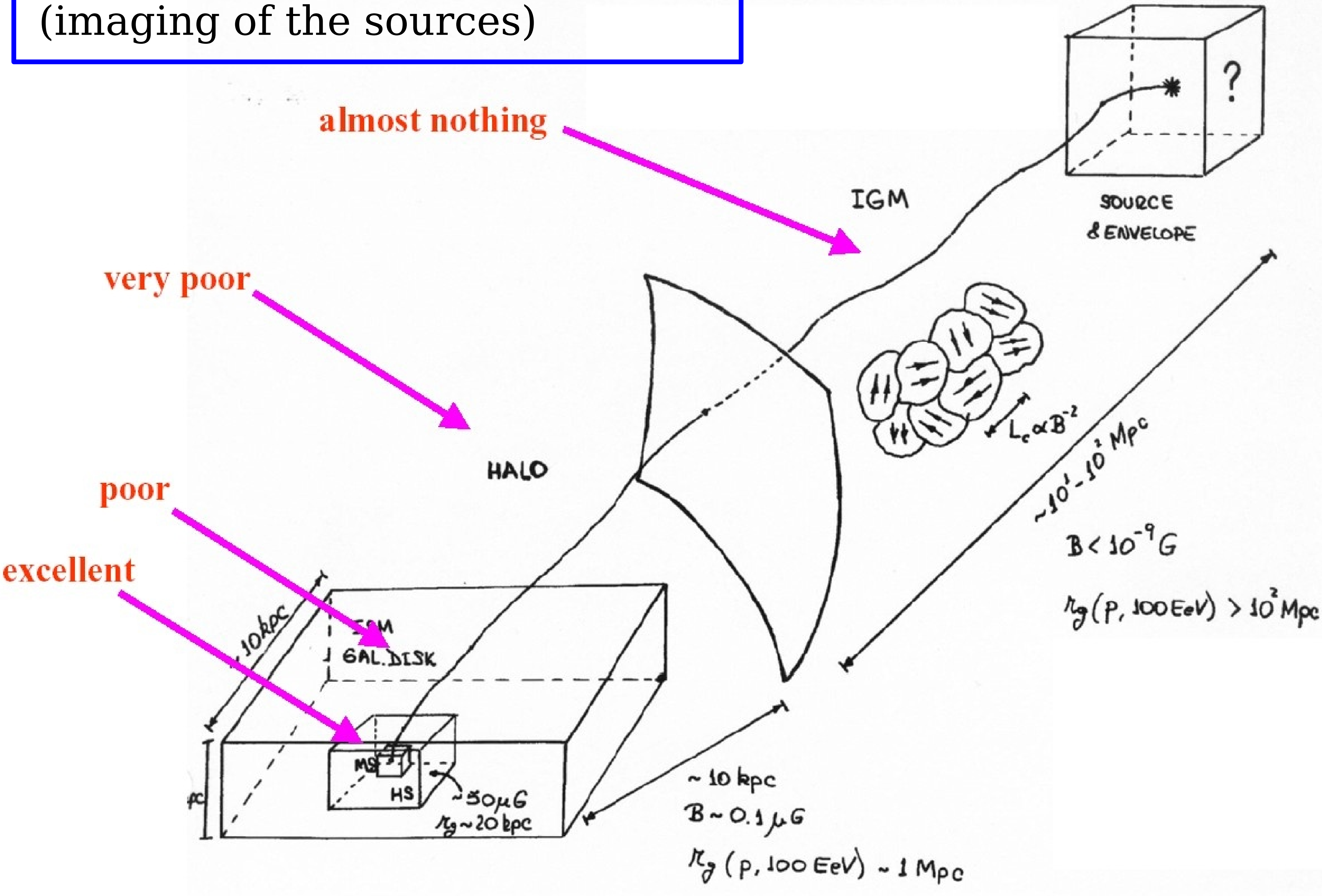
Berezinsky
et al.

Inject Smooth
power law
Spectrum.

Let propagation
leave its
“imprint”
on the shape
of the spectrum.

“ANKLE”
-->
“DIP”
e+e- production

COSMIC Ray ASTRONOMY [?!]
(imaging of the sources)



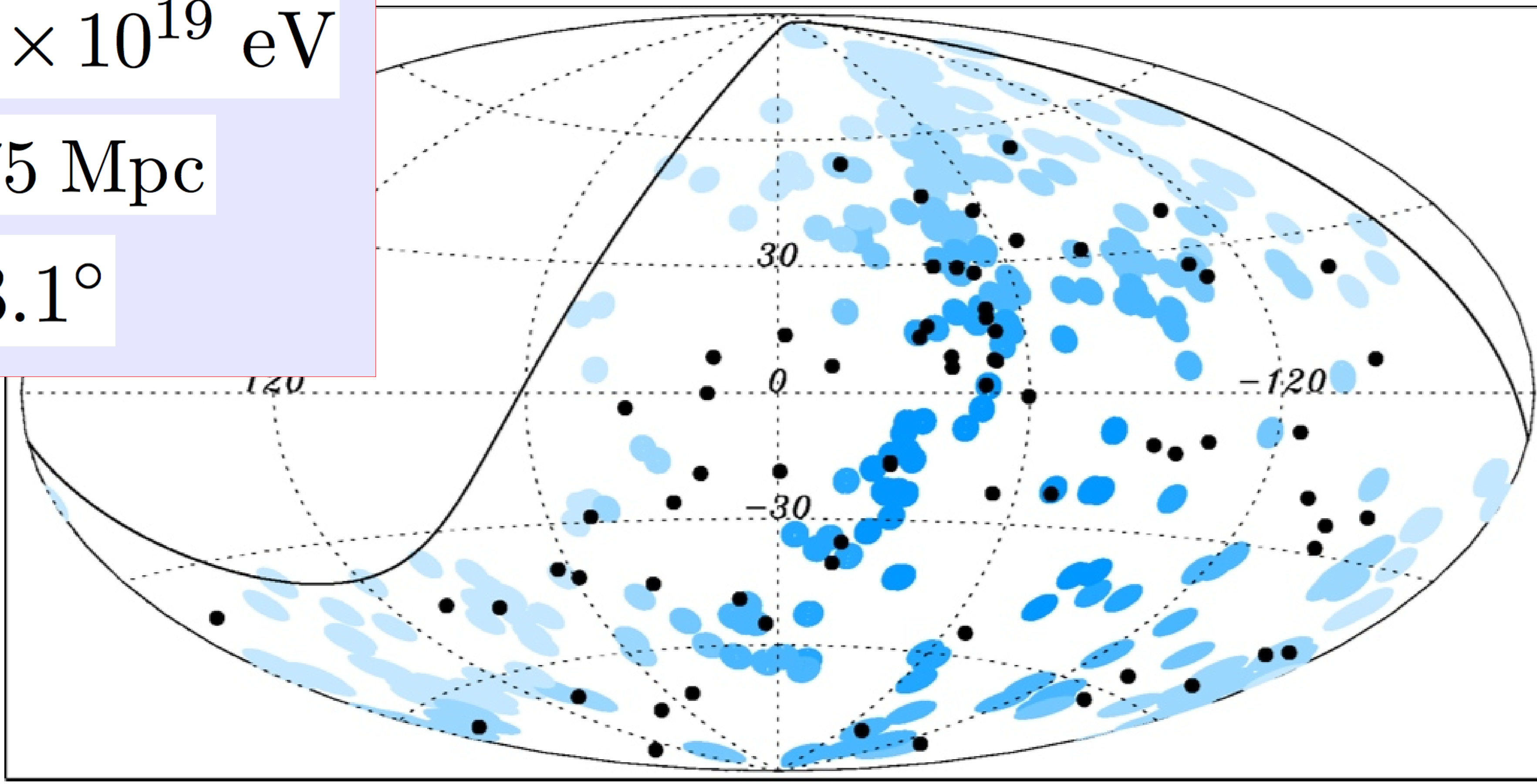
AUGER result on Correlations with the VCV AGN catalogue

Update september 2010.

6×10^{19} eV

75 Mpc

3.1°



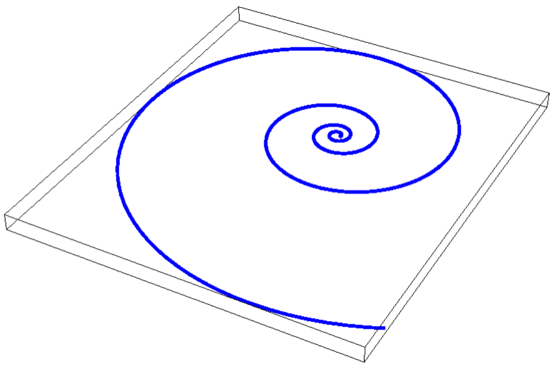
Significant dilution
[but not disappearance]
of the statistical significance

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

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

Deviation in GALACTIC Magnetic Field

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

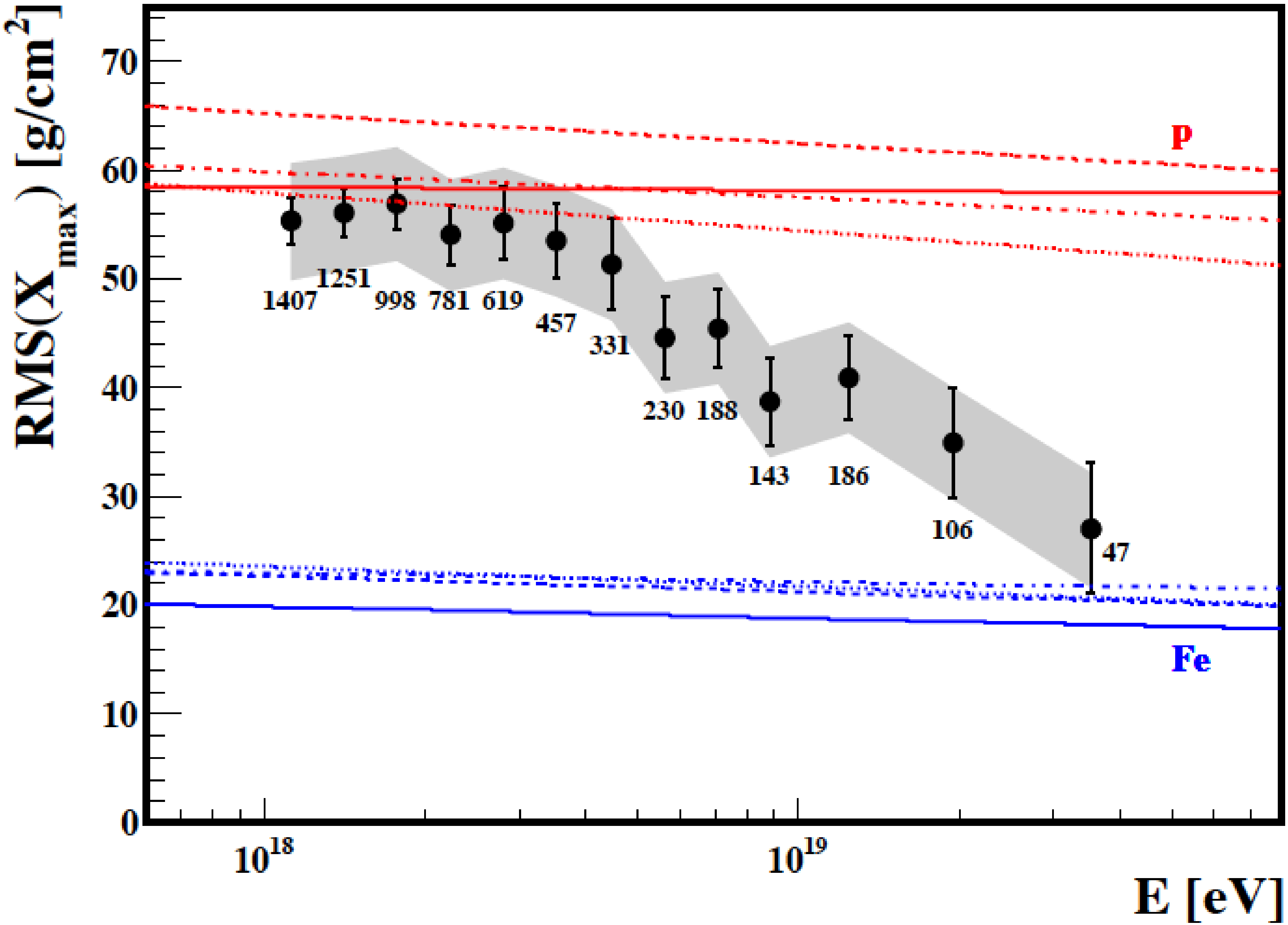


Deviation in EXTRA-GLACTIC Magnetic Field

$$\delta_{rms} \approx 4^\circ \frac{60\ \text{EeV}}{E/Z} \frac{B_{rms}}{10^{-9}\text{G}} \sqrt{\frac{D}{100\ \text{Mpc}}} \sqrt{\frac{L_c}{1\ \text{Mpc}}}$$

fluctuations

AUGER



$$\left(\sigma^{\mathrm{proton}}_{\langle X_{\mathrm{max}}\rangle}\right)^2 \simeq \lambda_p^2 + \sigma^2_{Y_{\mathrm{max}}}$$

$$\left(\sigma^{A}_{\langle X_{\mathrm{max}}\rangle}\right)^2 \simeq f(A)\,\lambda_p^2 + \frac{\sigma^2_{Y_{\mathrm{max}}}}{A}$$

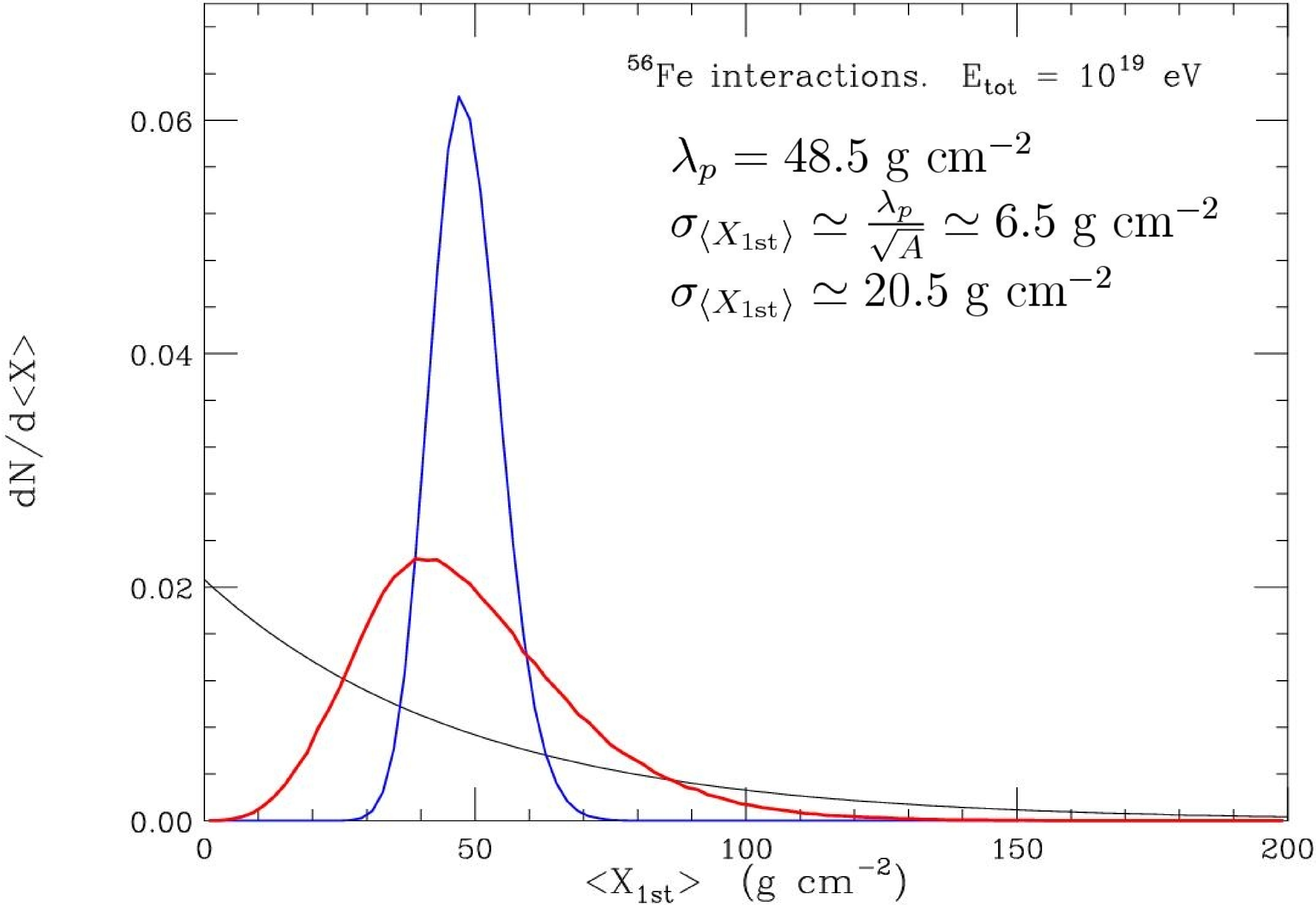
$$A = 56$$

$$\frac{1}{\sqrt{A}} = 0.13$$

$$\sqrt{f(A)} \simeq 0.4$$

$$f(A) > \frac{1}{A}$$

Nuclear interaction.
Several Nucleons
Interact at same point.



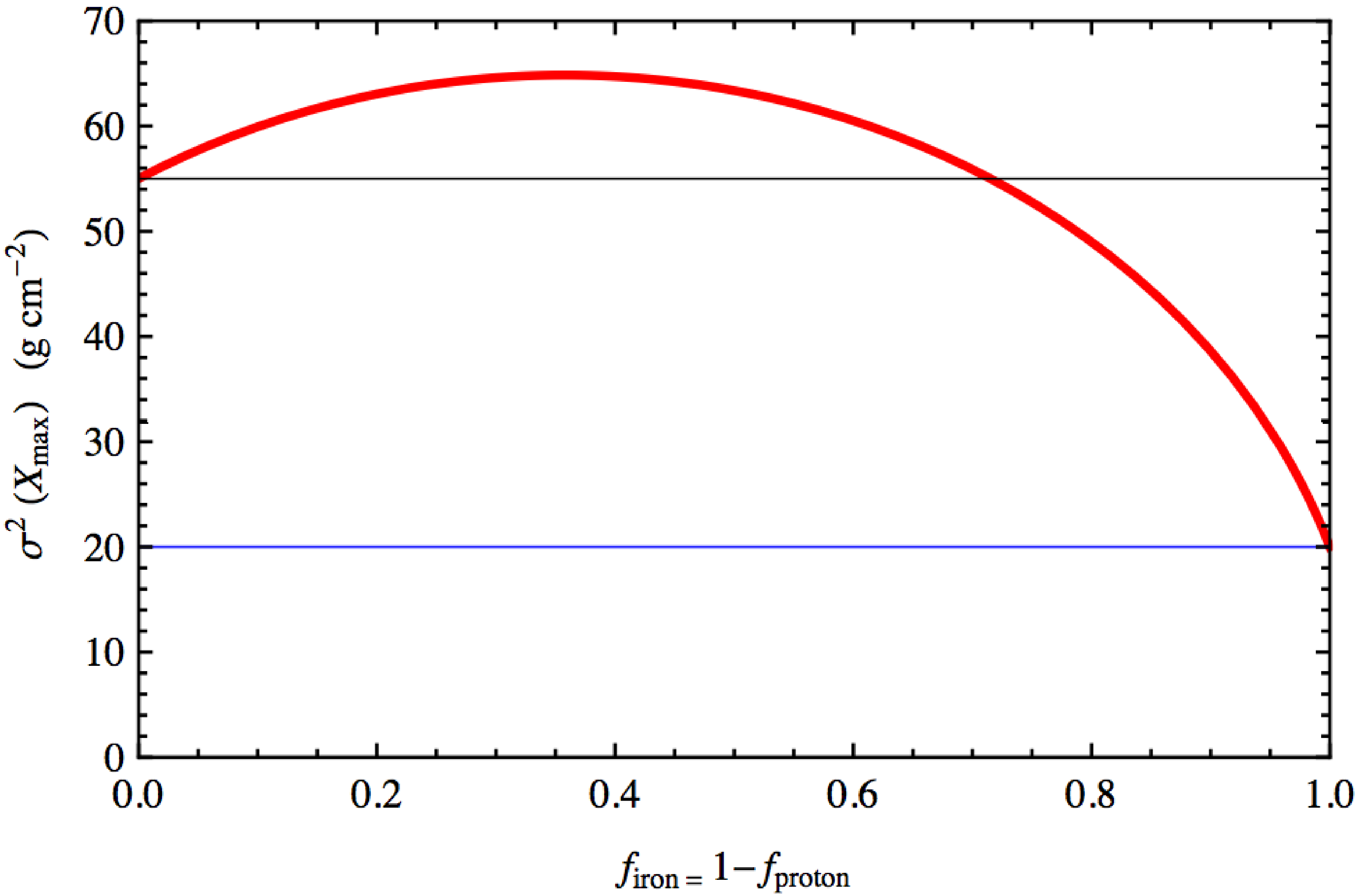
^{56}Fe interactions. $E_{tot} = 10^{19}$ eV
$\lambda_p = 48.5$ g cm^{-2}
$\sigma_{\langle X_{1st}\rangle} \simeq \frac{\lambda_p}{\sqrt{A}} \simeq 6.5$ g cm^{-2}
$\sigma_{\langle X_{1st}\rangle} \simeq 20.5$ g cm^{-2}
dN/d<X>
0.00
0.02
0.04
0.06
0
50
100
150
200
$\langle X_{1st}\rangle$ (g cm^{-2})

$$\sigma_X^2 = \sum_j f_j \, \sigma_{A_j}^2 + \sum_j f_j \langle X_{A_j} \rangle^2 - \left(\sum_j f_j \langle X_{A_j} \rangle \right)^2$$

$$\sigma_X^2 = \langle \sigma_A^2 \rangle + D_p \; \left[\langle (\log A)^2 \rangle - \langle \log A \rangle^2 \right]$$

$$\sigma_X^2 \simeq \langle \sigma_A^2 \rangle + D_p \, \sigma_{\log A}^2$$

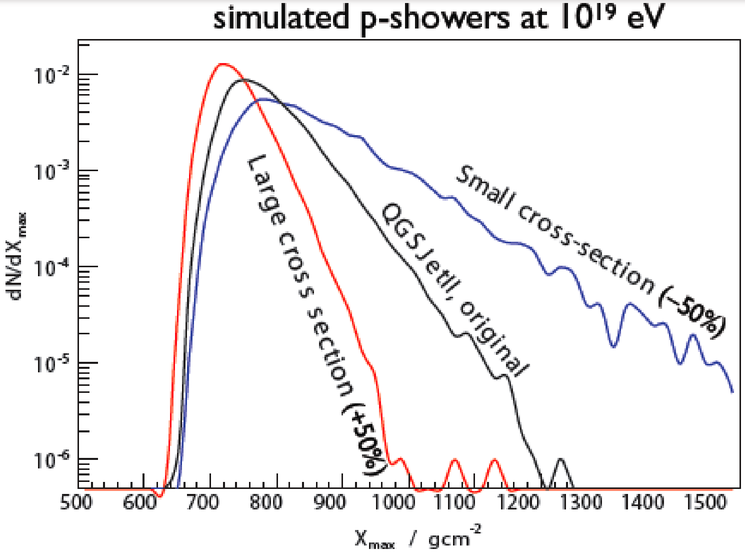
Mixing Protons with Iron-nuclei



$$\sigma_X^2 = f_p \, \sigma_p^2 + (1 - f_p) \, \sigma_{Fe}^2 + f_p (1 - f_p) \, (\langle X_p \rangle - \langle X_{Fe} \rangle)^2$$

p-Air & pp Cross-Section at √57 TeV

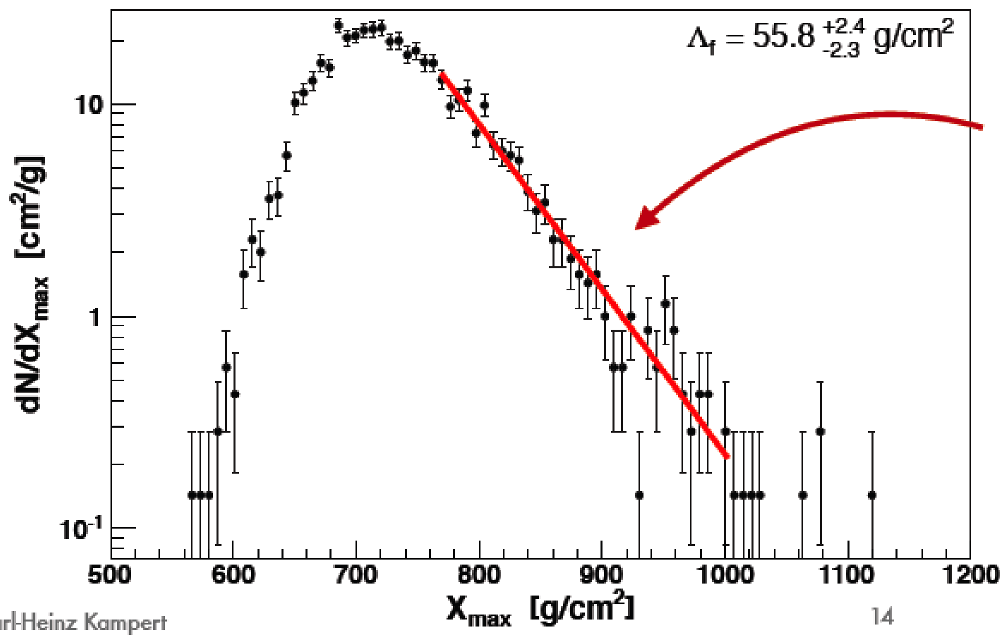
#946: Ulrich



Tail of X_{max} distribution

⇕

Inelastic cross-section



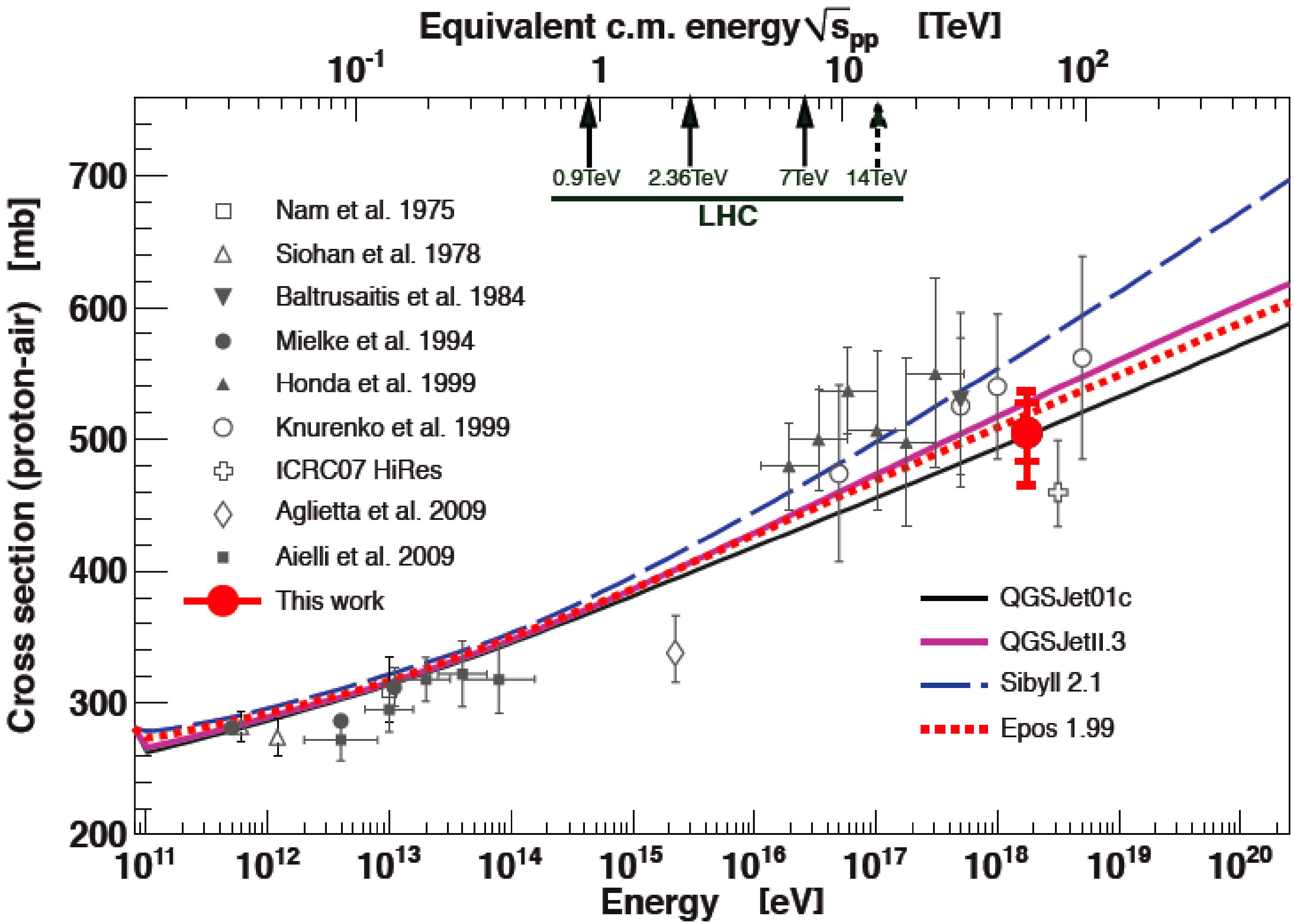
10^{18} eV < E < $10^{18.5}$ eV

tail dominated by protons

$$dN/dX_{max} \propto \exp\left(-X_{max}/\Lambda_\eta\right)$$

$\Lambda \rightarrow \sigma_{p\text{-}Air}$
by tuning models to
describe tail seen in data

p-Air Cross-Section

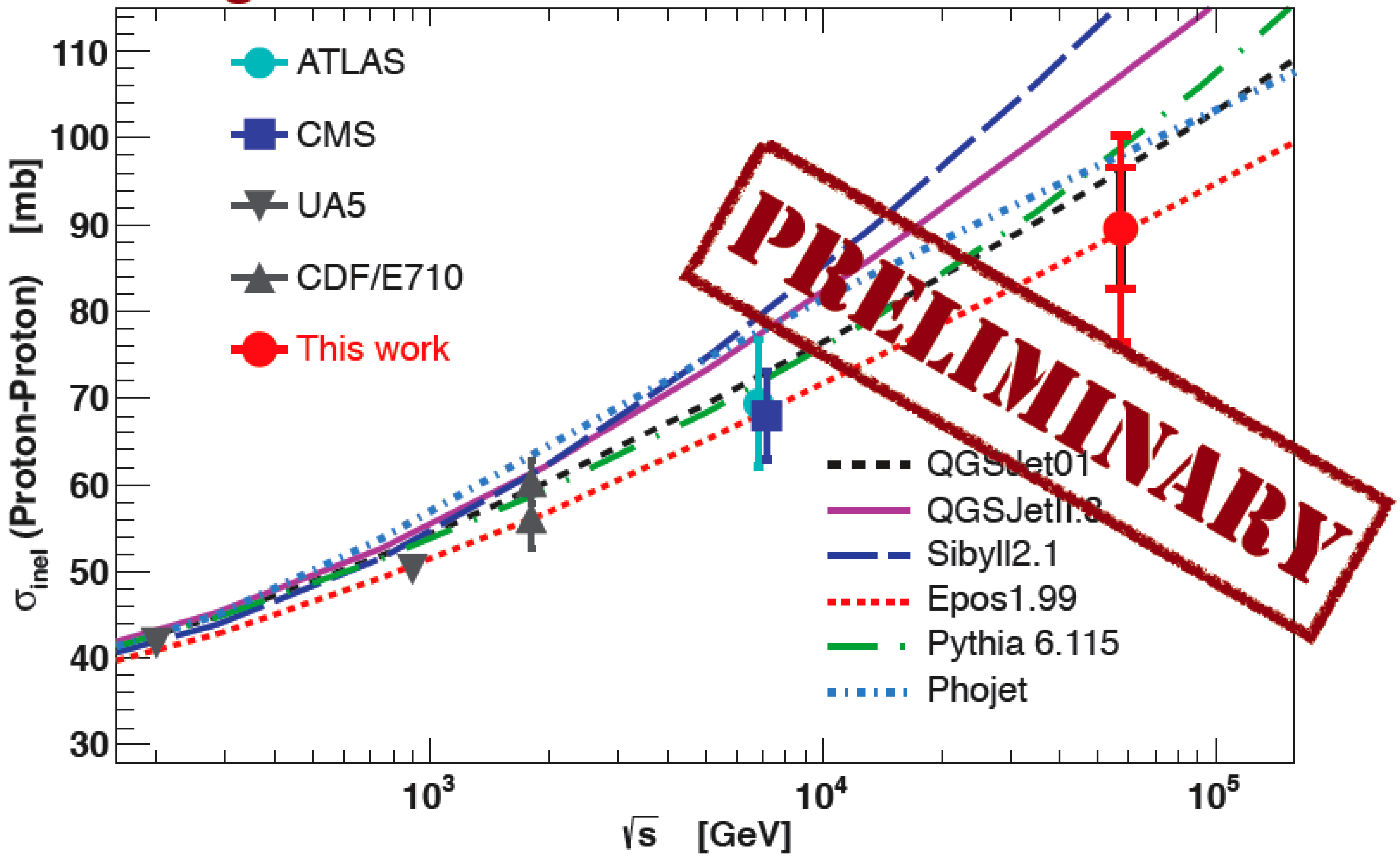


$$\sigma_{p\text{-}Air} = (505 \pm 22_{stat} \, (^{+26}_{-34})_{sys}) \text{ mb}$$

systematic uncertainties assume <0.5% photons and <25% He

p-p Cross-Section at √57 TeV

using Glauber model



$$\sigma_{pp} = (90 \pm 7_{stat} \left(^{+8}_{-11}\right)_{sys} \pm 1.5_{Glauber})\ \text{mb}$$

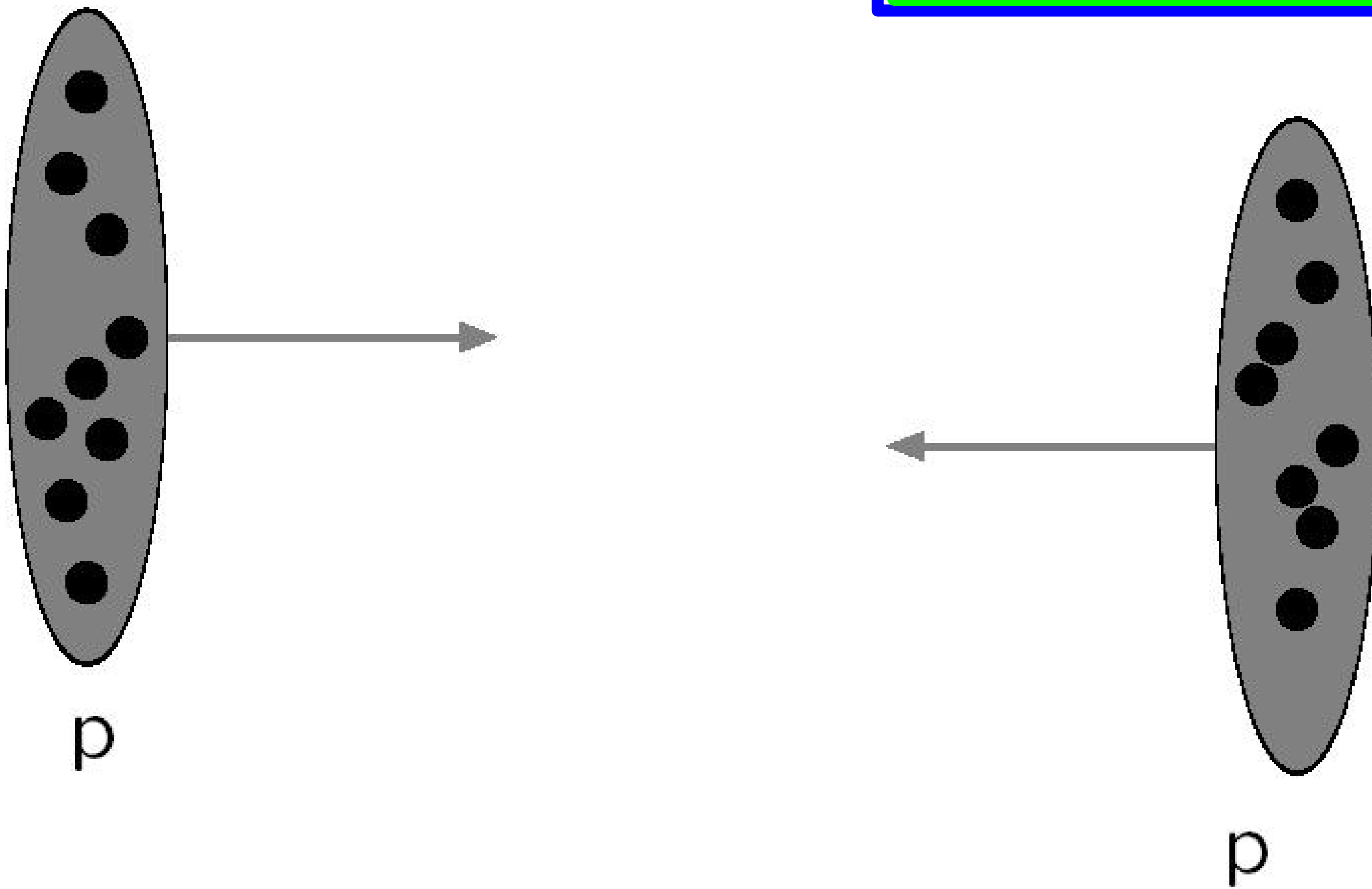
THEORY

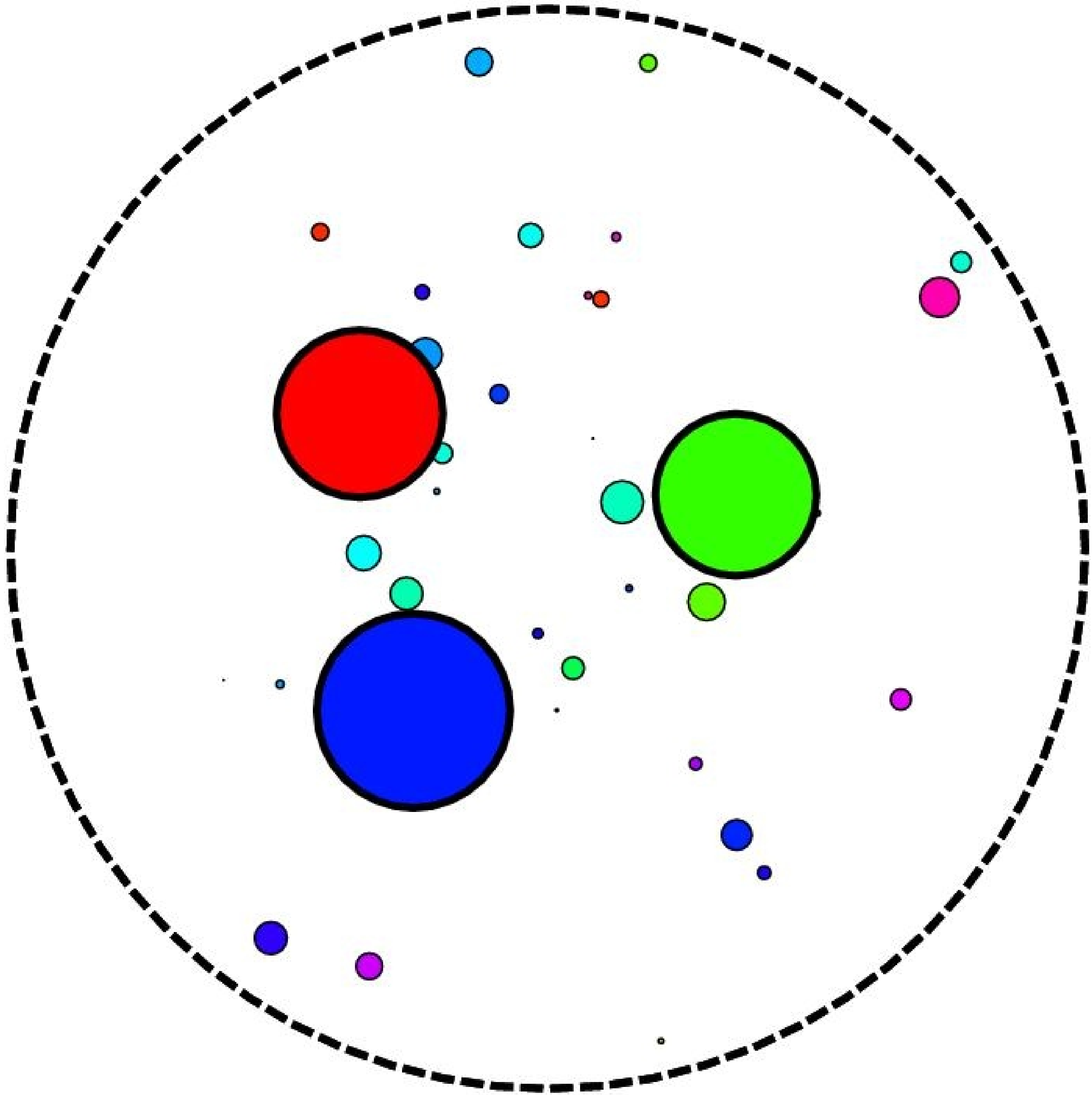
Construction of Hadronic Models

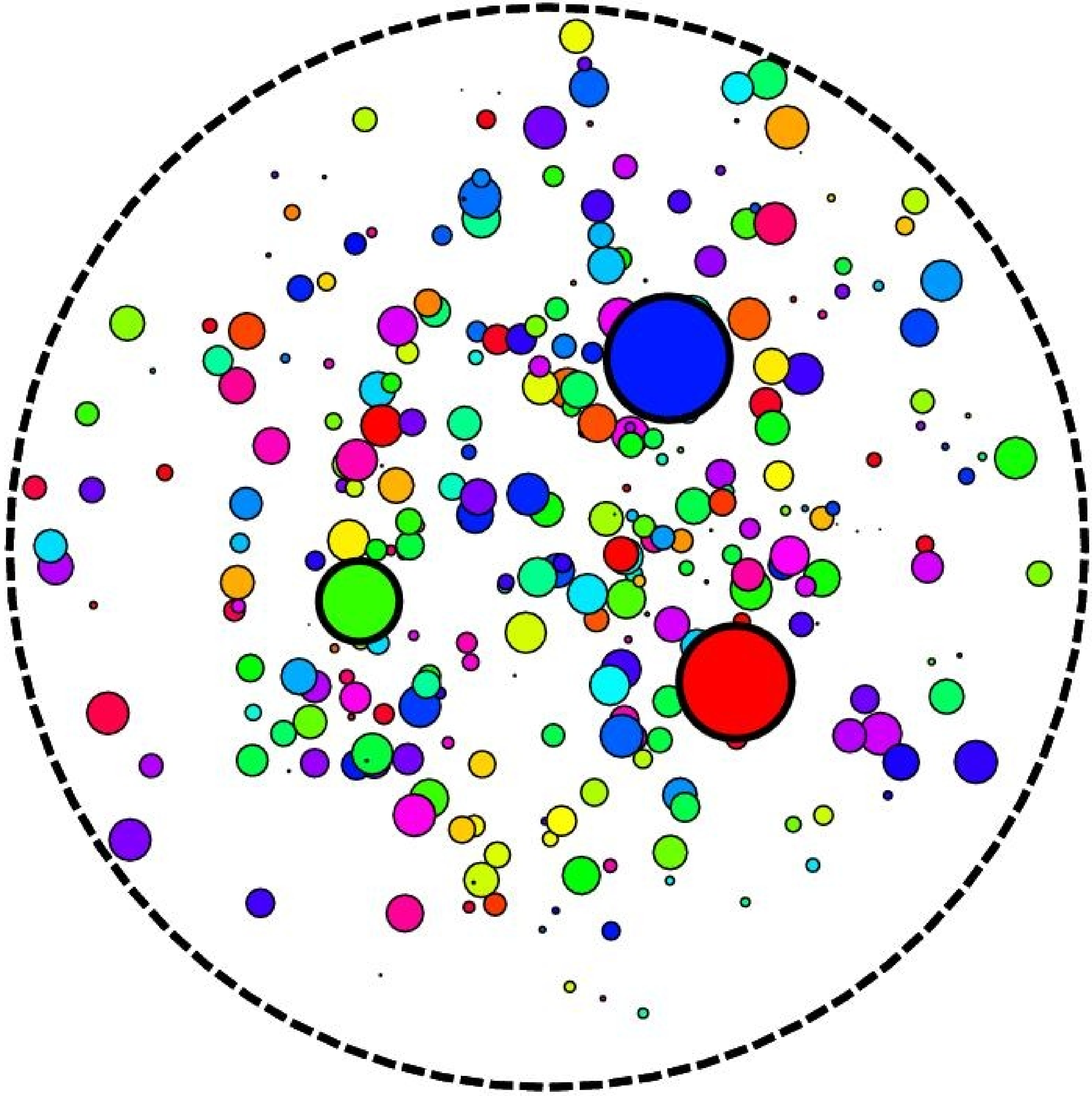
Hadronic Interactions

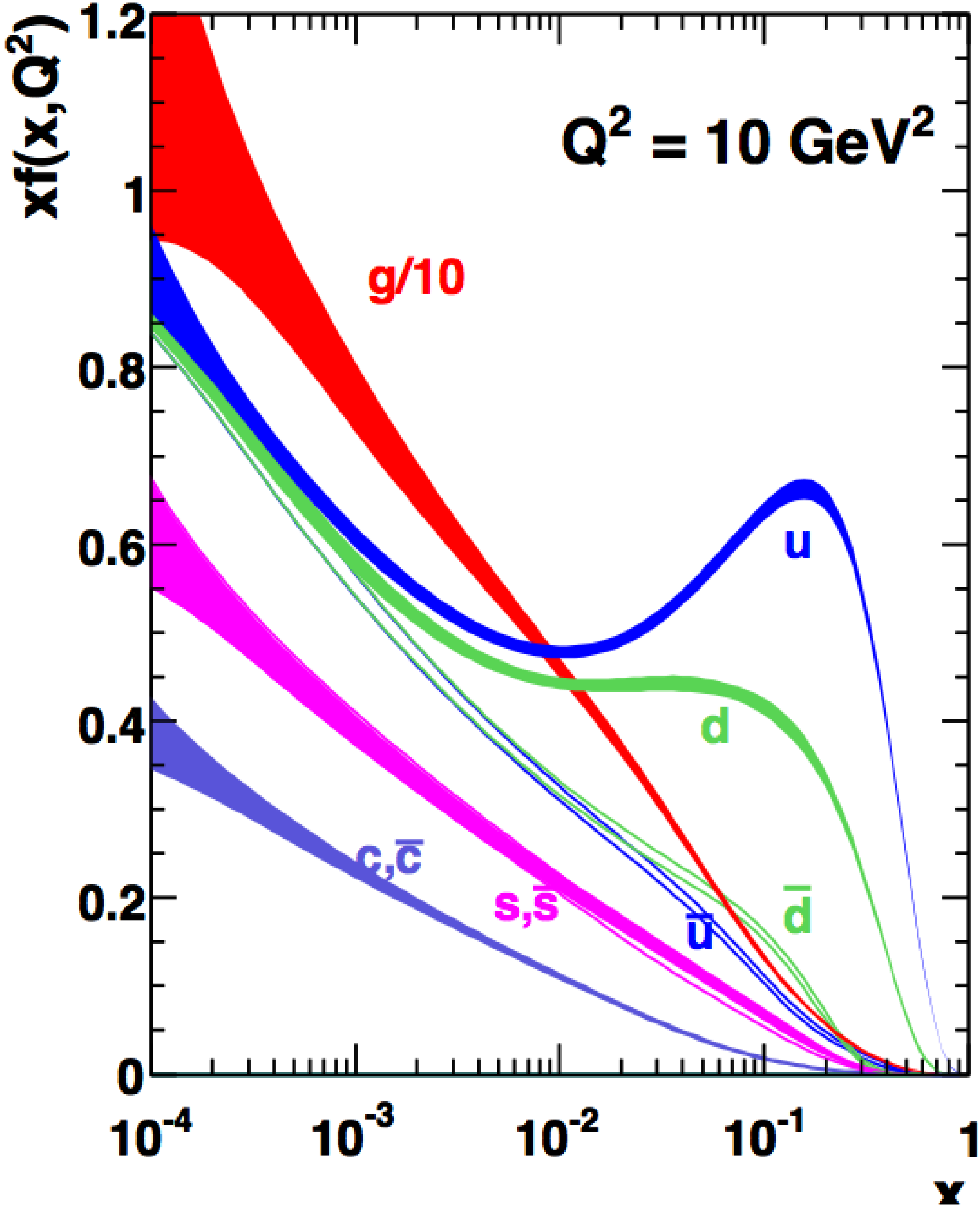
QCD

Composite (complex) Objects
Multiple interaction structure





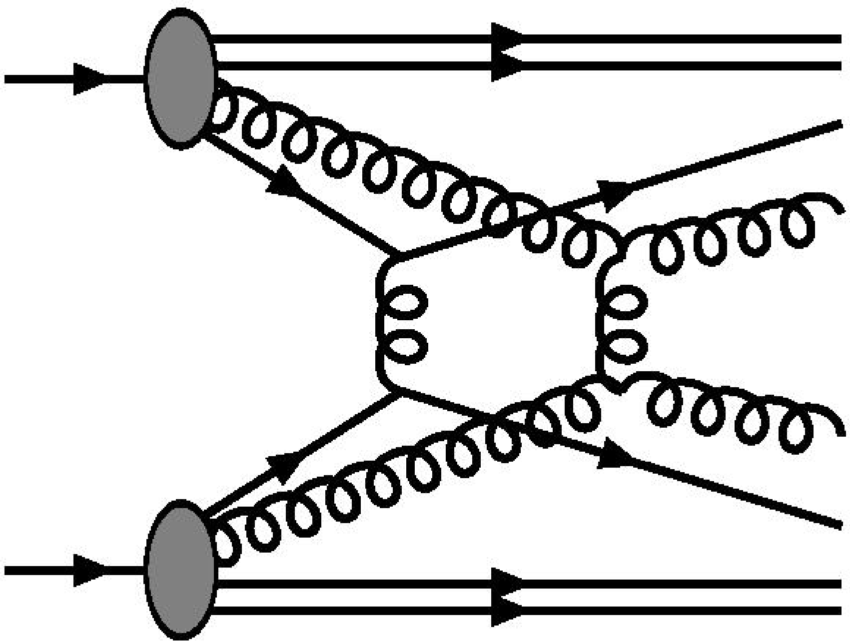




Parton
Distribution
Function

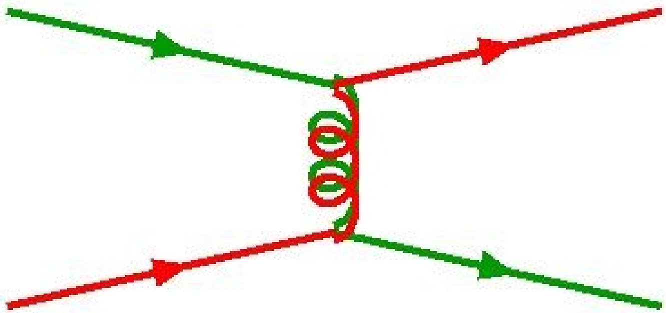
Typically 2 – 3 interactions/event at the Tevatron, 4 – 5 at the LHC, but may be more in "interesting" high-$p_\perp$ ones.

Pythia MC

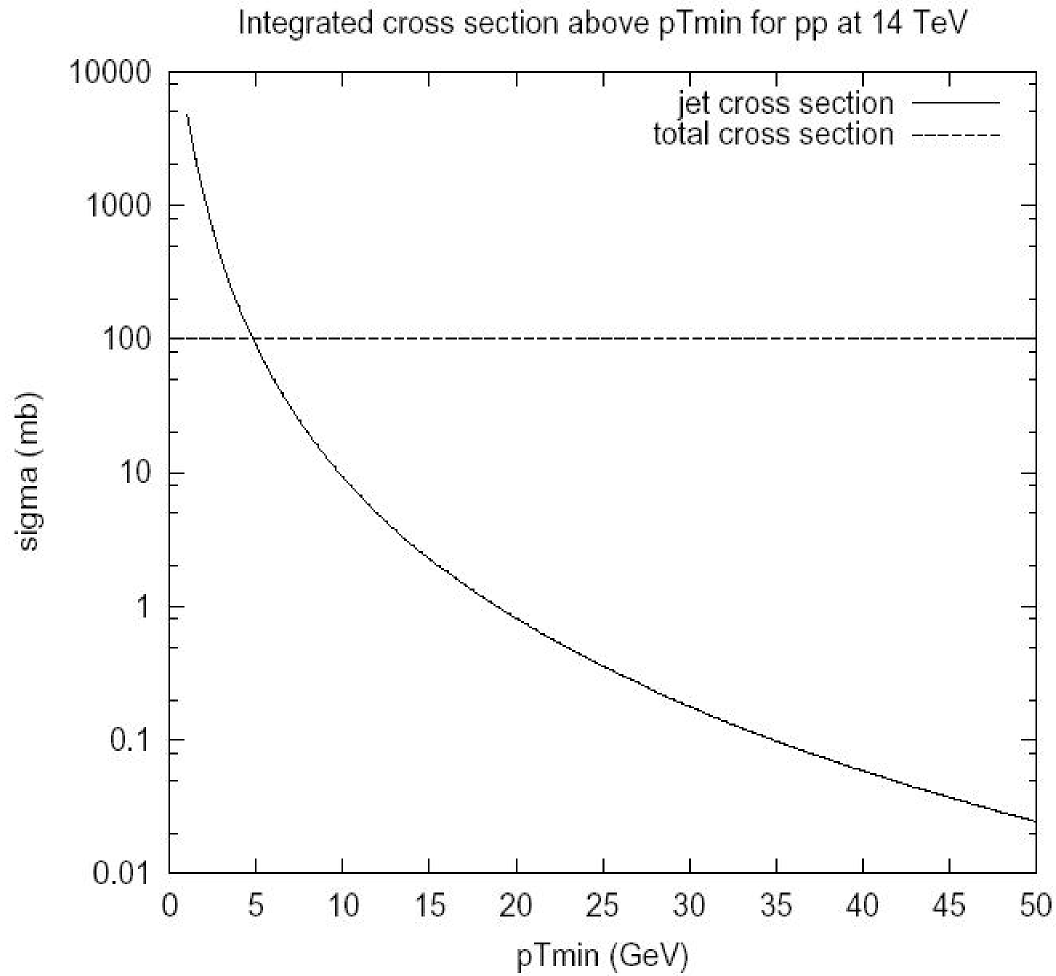


Most particles in Fragmentation Regions Described by the "beam remnants strings"

QCD $2 \to 2$



$$qq' \to qq'$$
$$q\overline{q} \to q'\overline{q}'$$
$$q\overline{q} \to gg$$
$$qg \to qg$$
$$gg \to gg$$
$$gg \to q\overline{q}$$

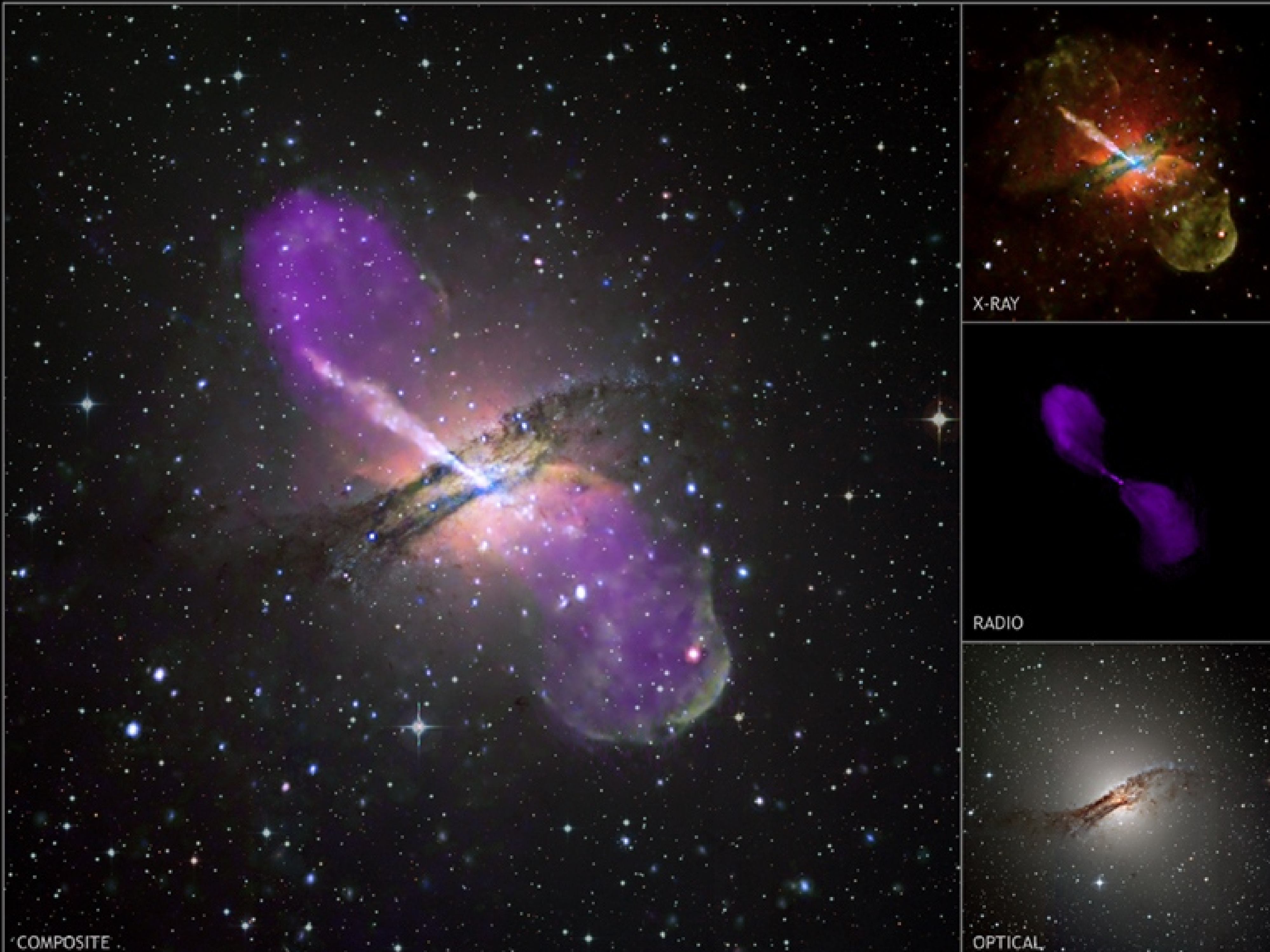


$$d\sigma/dp_\perp^2 \approx 1/p_\perp^4 \text{ for } p_\perp \to 0.$$

MULTIPLE INTERACTIONS

- Estimate of the average number of Elementary interactions per pp scattering
- “Spatial Distribution” (Transverse coordinates) of the partonic constituents. [proton spin]
- Fluctuations of the “parton configuration” of an interactig hadron.

Beyond PDF's
Parton Distribution Functions


X-RAY
RADIO
OPTICAL
COMPOSITE

We are studying 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^{-13} cm

Exciting Difficult