UHECR and HADRONIC INTERACTIONS

Paolo Lipari

"Highlights of Astroparticle Physics"
In memory of Gianni Navarra
Torino 20th september 2010

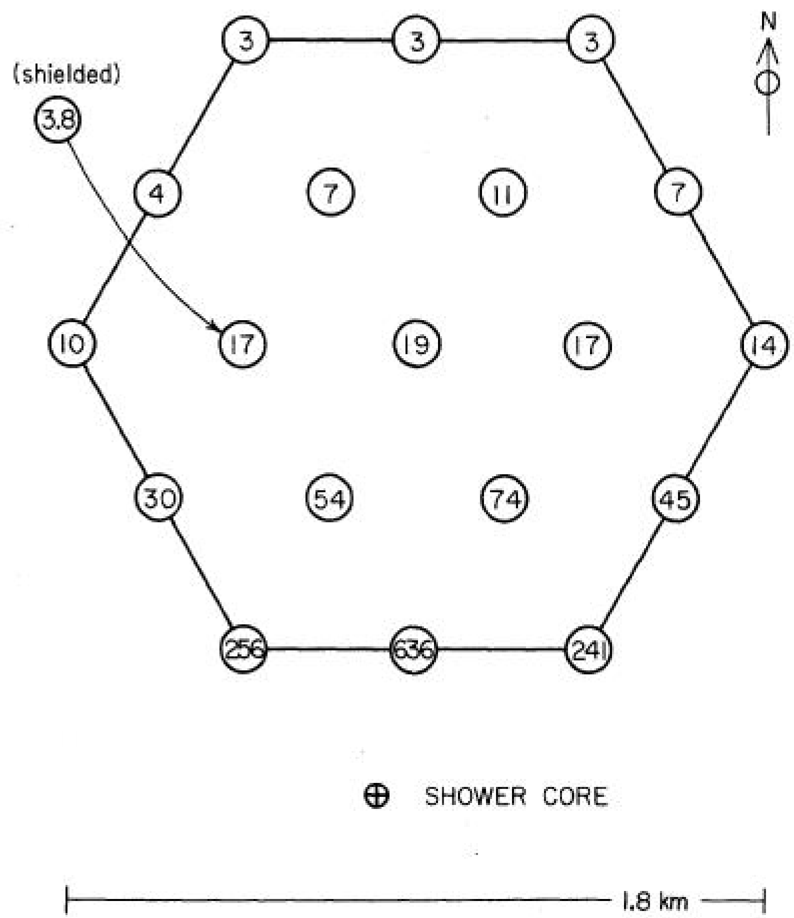
PHYSICAL REVIEW LETTERS

~50 years of UHECR

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

EXTREMELY ENERGETIC COSMIC-RAY EVENT*

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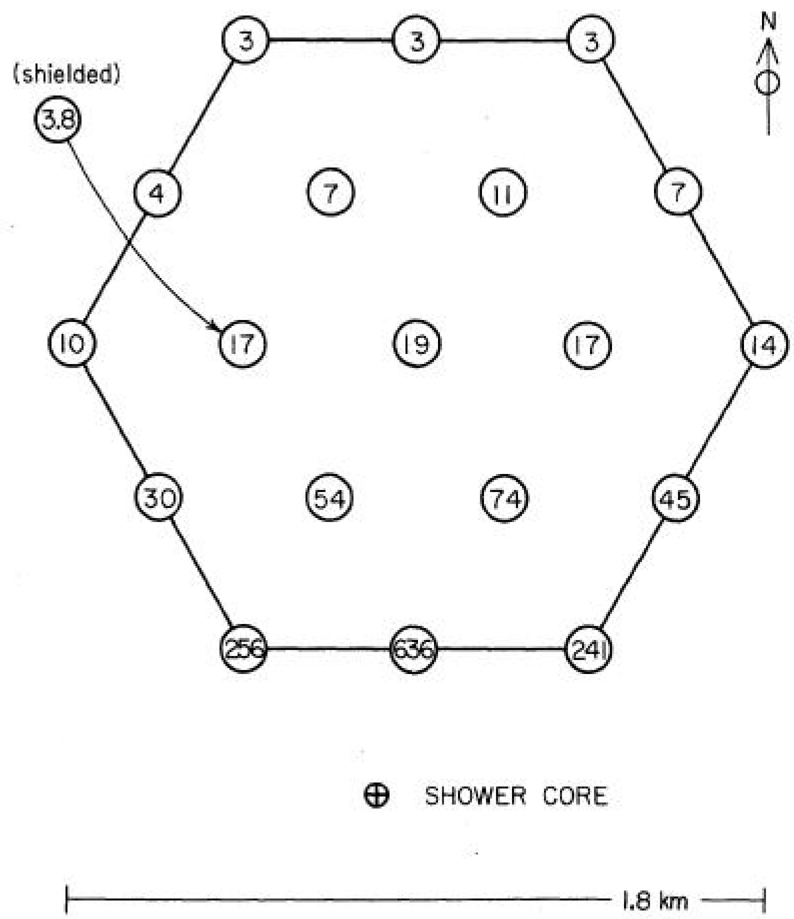


$e^{\pm}$ γ

$\mu^{\pm}$

hadrons

Different components

Hadronic interaction
Modeling

Measure a single slice of
the shower at the ground

“Multi Components Air Shower Array”

EASTOP at Gran Sasso

[A very important “jump of quality”:
 Electromagnetic part
 Hadronic calorimeter
 Cherenkov light
 Deep underground Muons]

Hadronic Model dependence.

“Multi Components Air Shower Array”

EASTOP at Gran Sasso

[A very important “jump of quality”:
Electromagnetic part
Hadronic calorimeter
Cherenkov light
Deep underground Muons (unique !!)]

Hadronic Model dependence.

A beautiful idea !!
That perhaps has not received the recognition it deserves.

Very valuable results that it would be useful
To re-analyze with the best “modeling instruments”
We are developing now.

"Multi Components Air Shower Array"

EASTOP at Gran Sasso

[A very important "jump of quality":
Electromagnetic part
Hadronic calorimeter
Cherenkov light
Deep underground Muons]

KASCADE (Karlsruhe)

"competitors"
and
collaborators

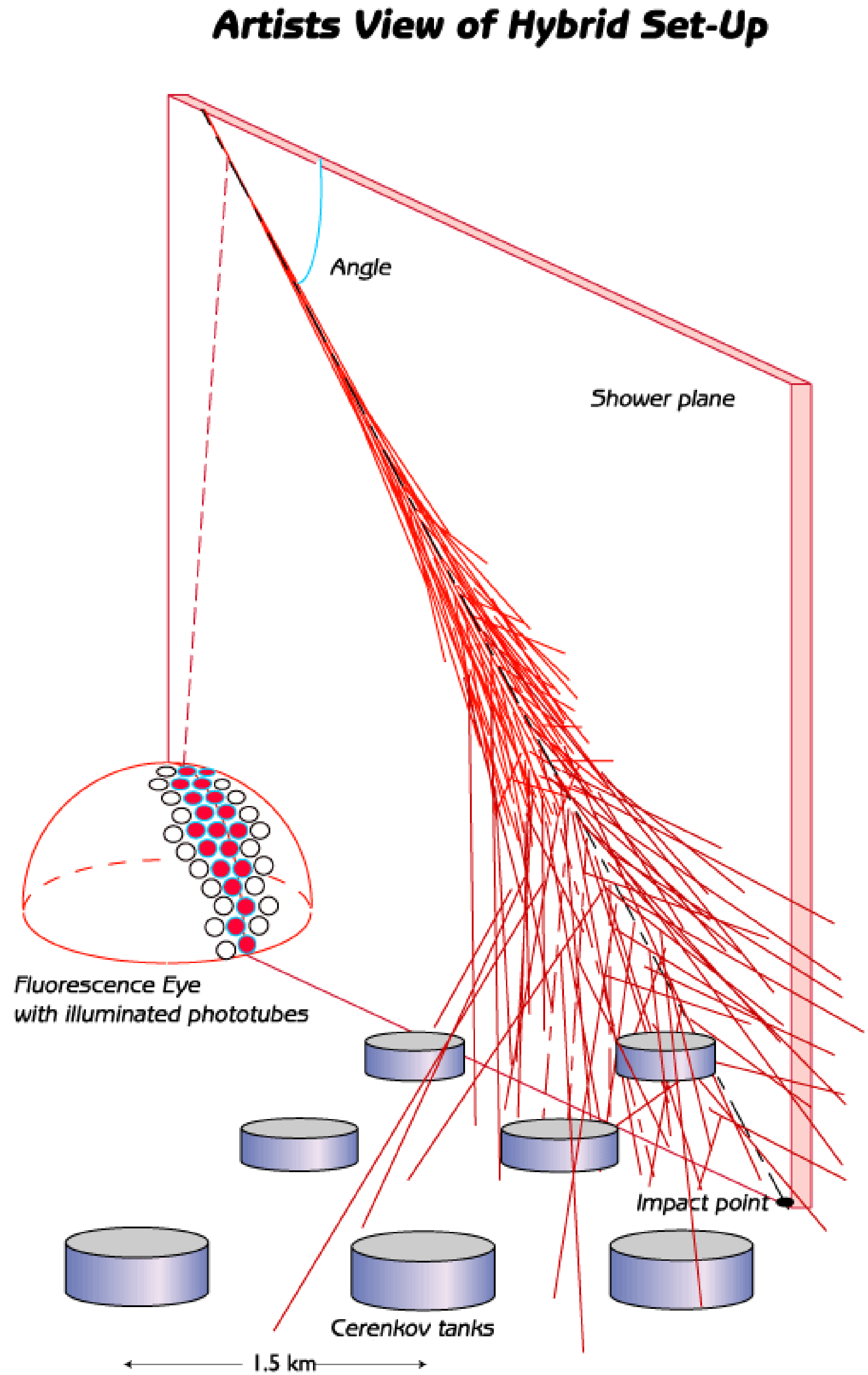
KASCADE-GRANDE
a "bridge to higher energy"

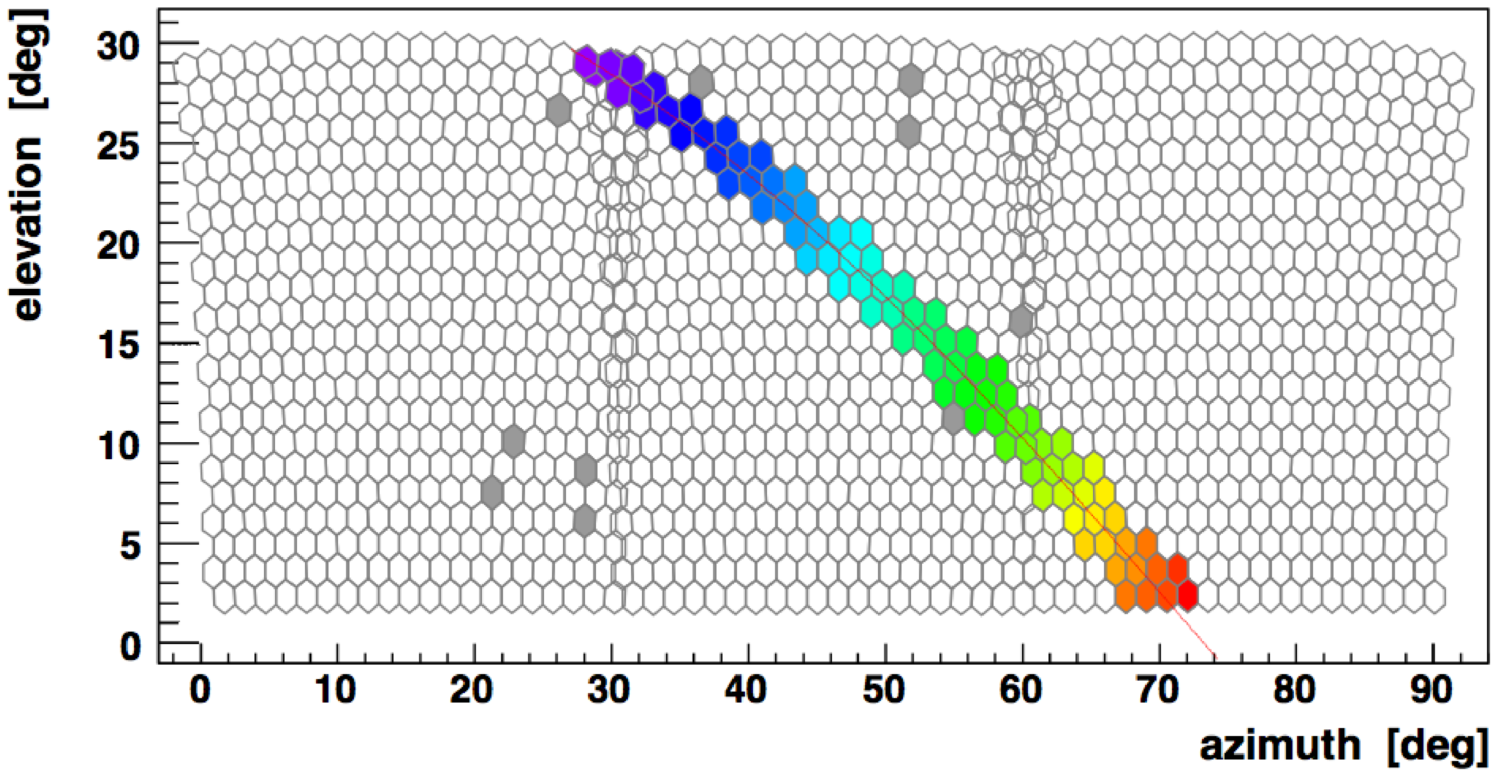
Common
project
New Results!

The **Fly's Eye** Detector concept

“Quasi-Calorimetric”
Energy Measurement

Fluorescence Light



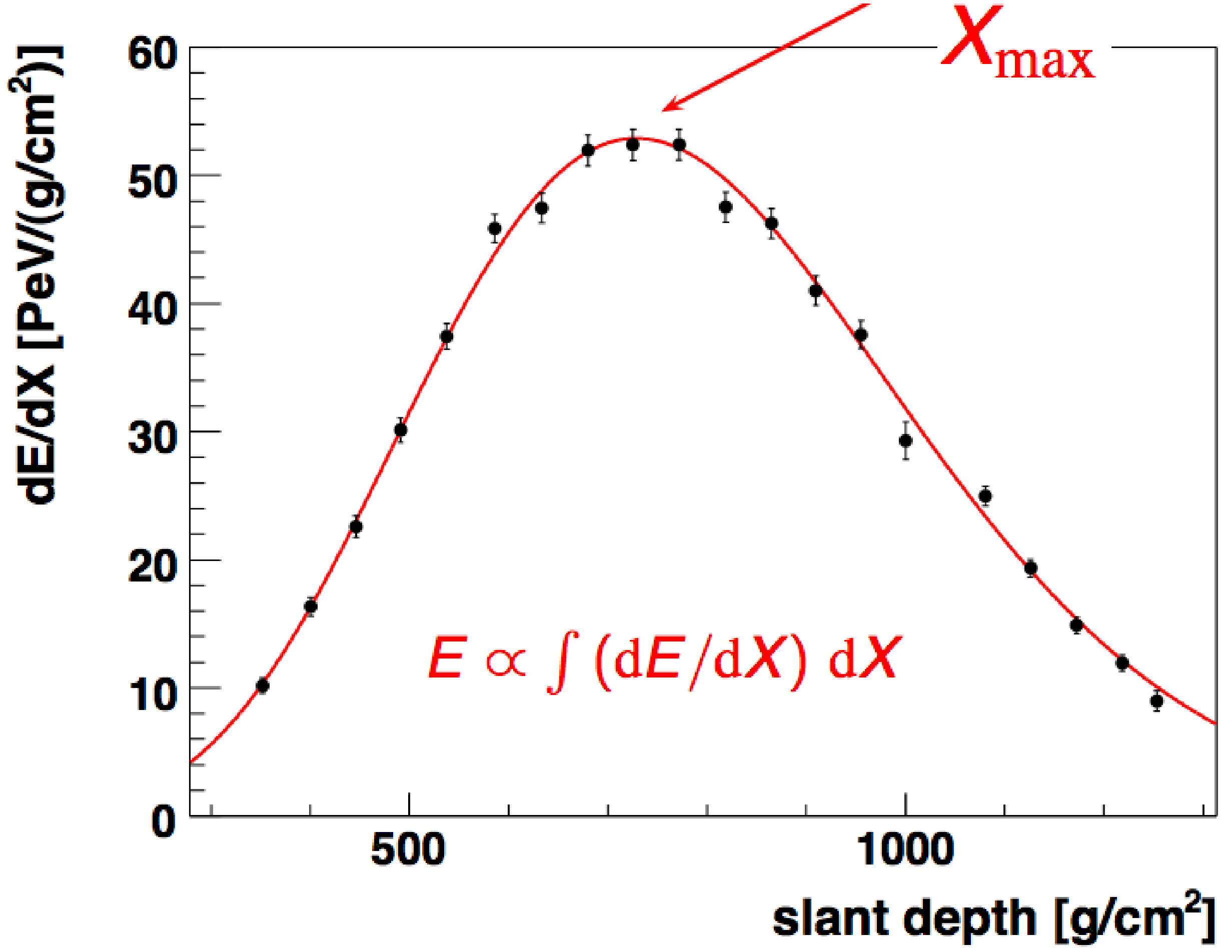


$$L(\Omega) \rightarrow F_{\gamma}(X) \rightarrow N_{e^{\pm}}(X)$$

Observed Light → Emitted Photons → Shower Size

Geometry
Atmospheric Absorption

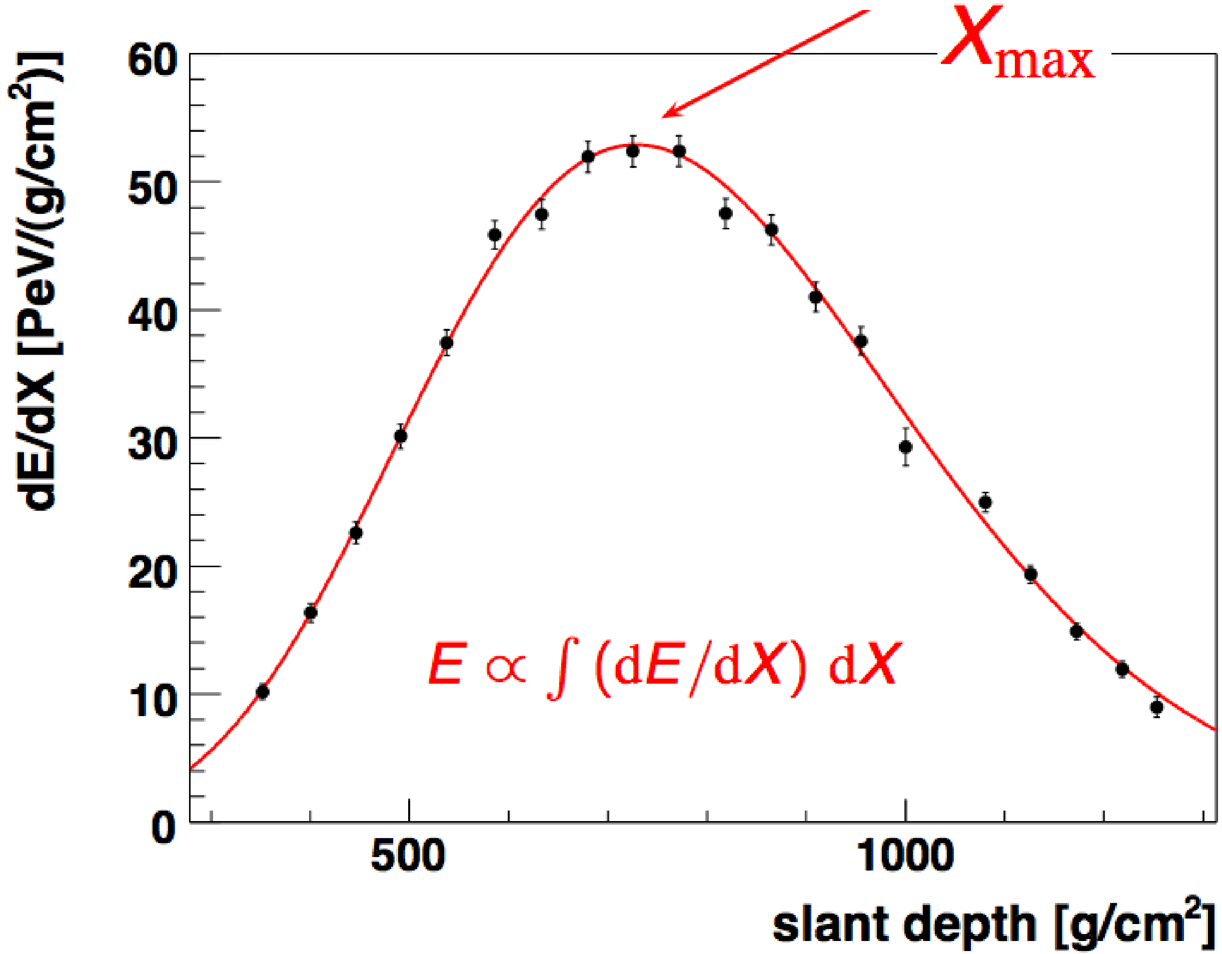
Fluorescence
Yields



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

Small Model dependence

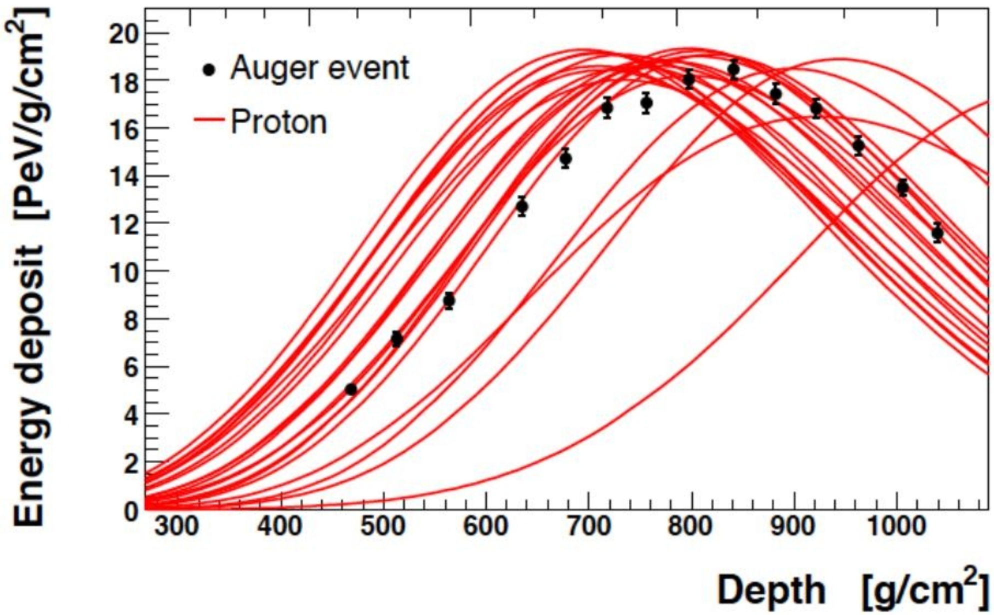
$$E_{\text{tot}} = E_{\text{ionization}} + E_\nu + E_\mu + E_{\text{ground}}$$



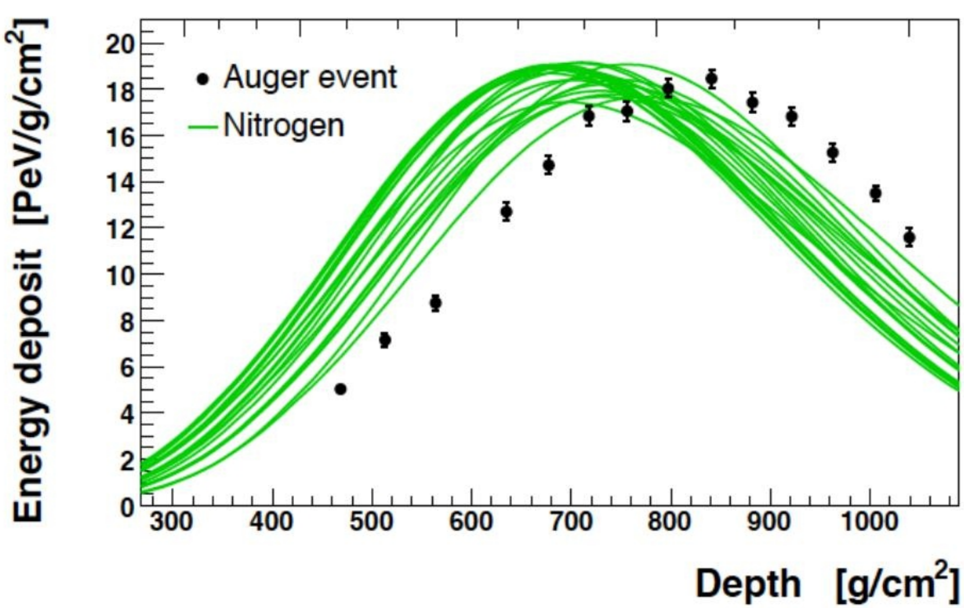
Area $\propto$ Energy

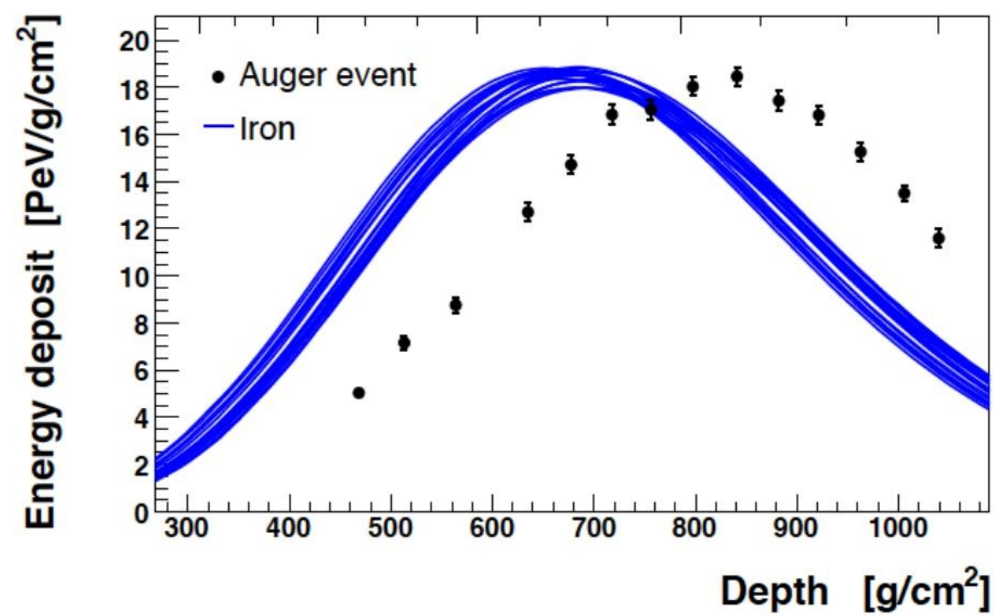
Shape depends on :

- Primary Identity
- Interaction Model



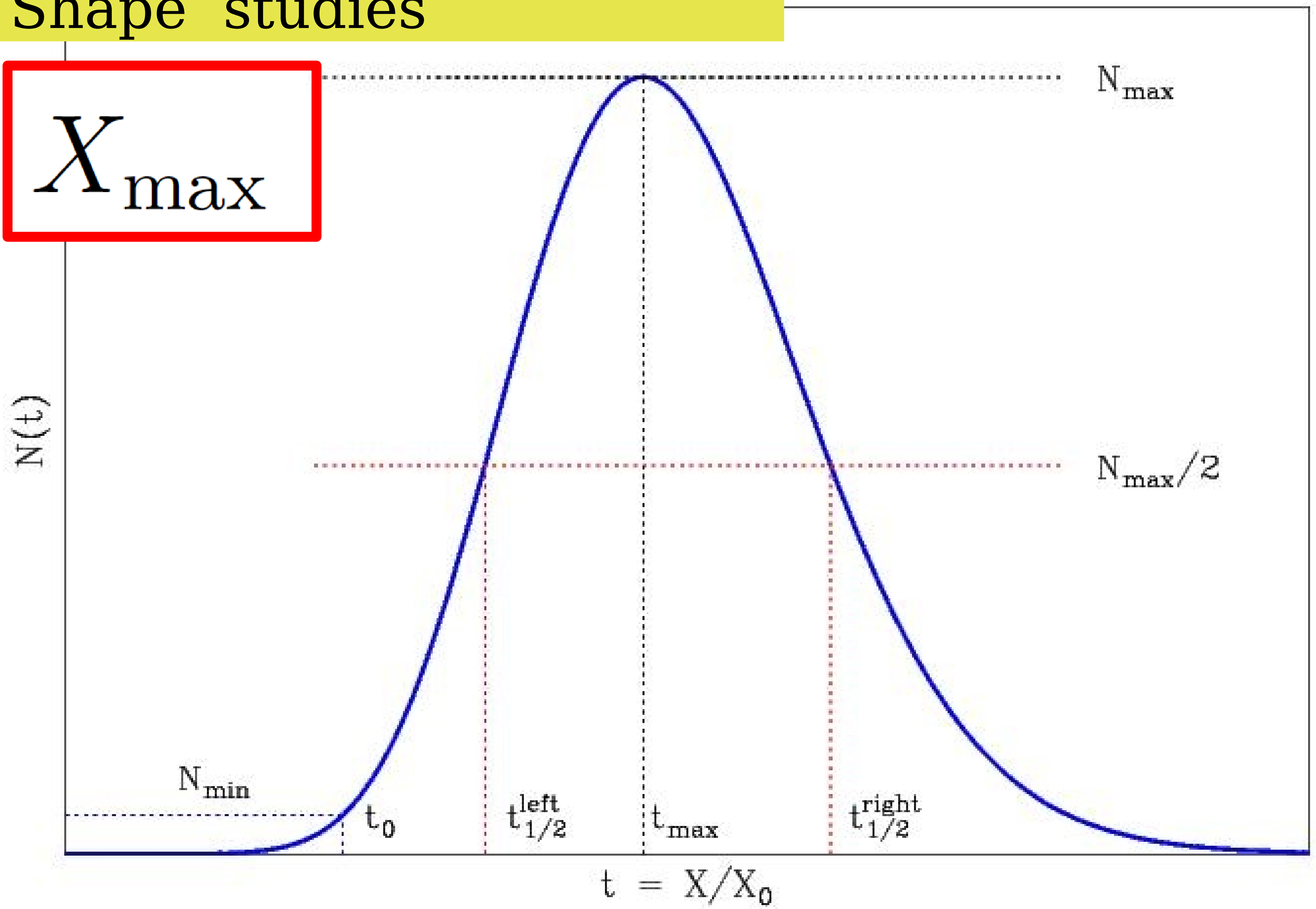
$$E \simeq 10^{20} \text{ eV}$$



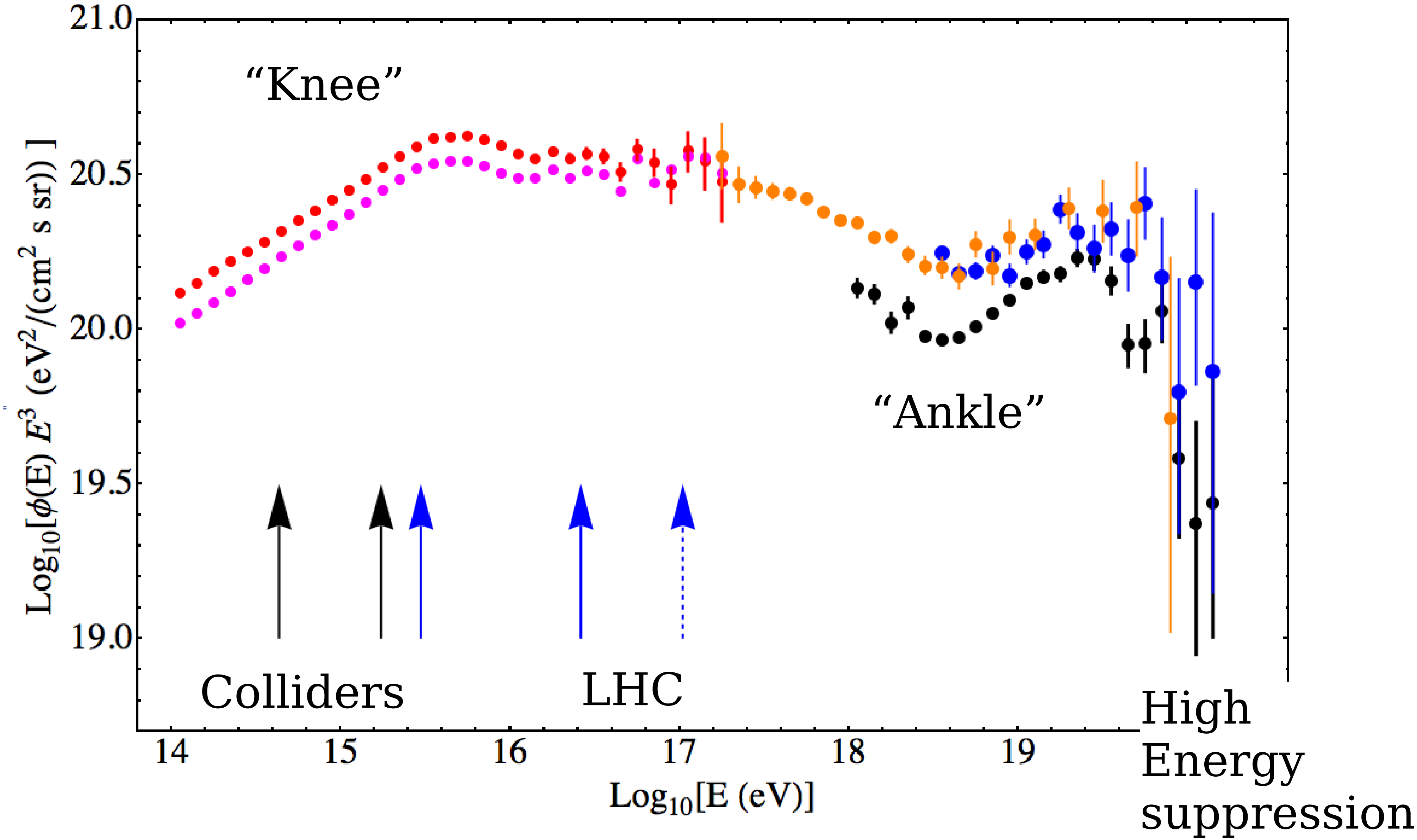


Longitudinal Development
Shape studies

X_{max}



Structure in the energy spectrum



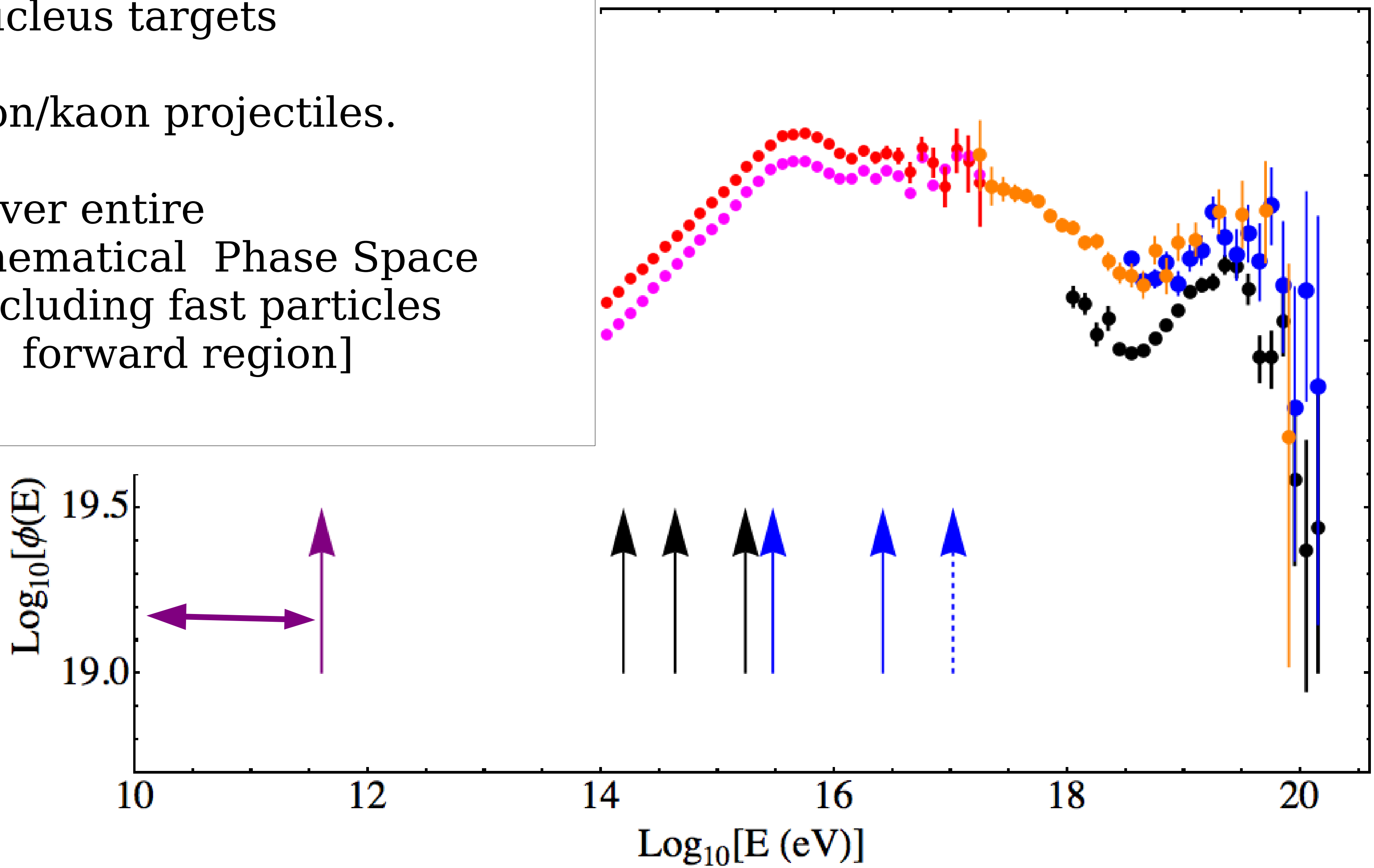
“Fixed Target” measurements

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

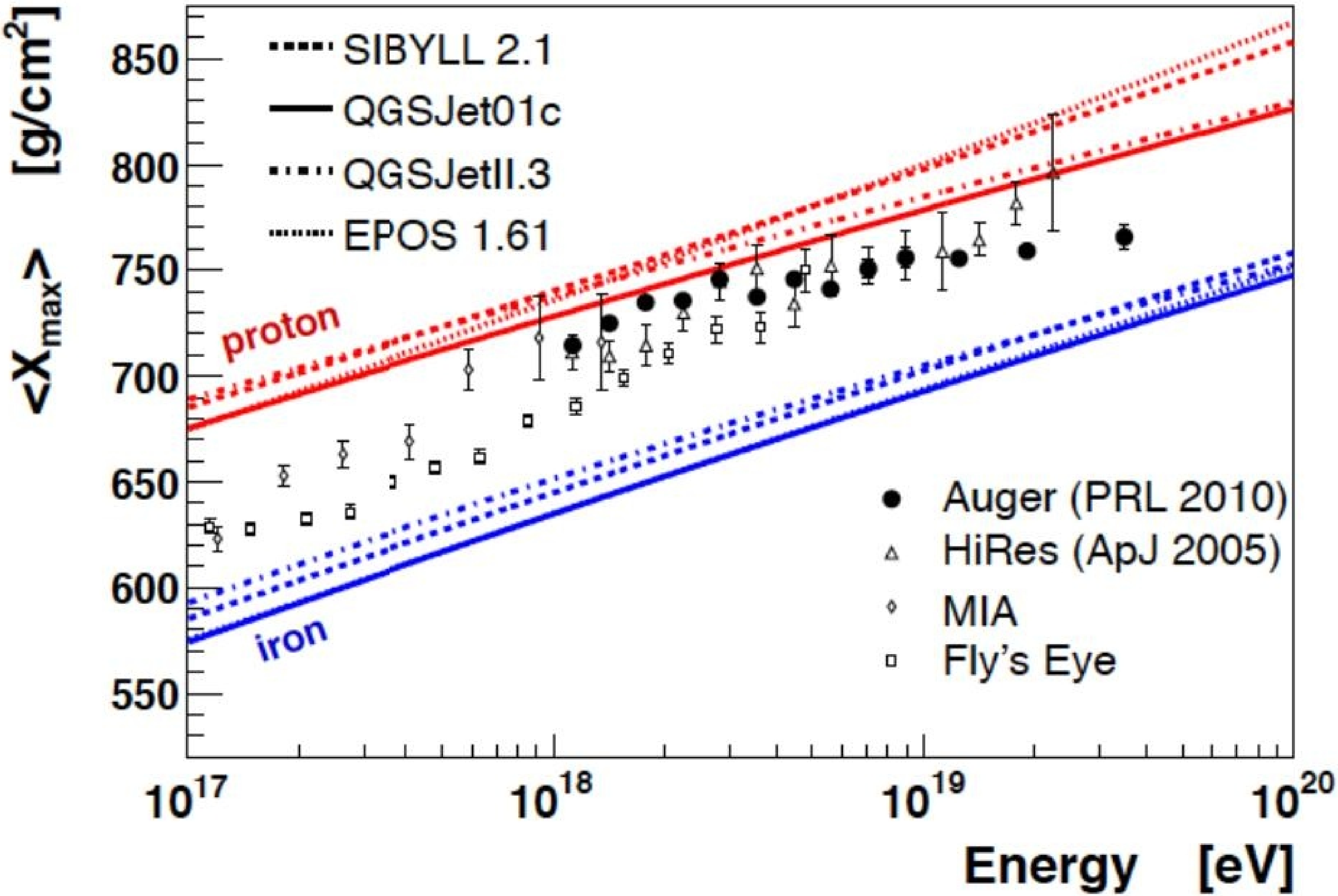
Controversial - inconsistent observations.

X_{max}

Fluctuations of X_{max}

Other methods

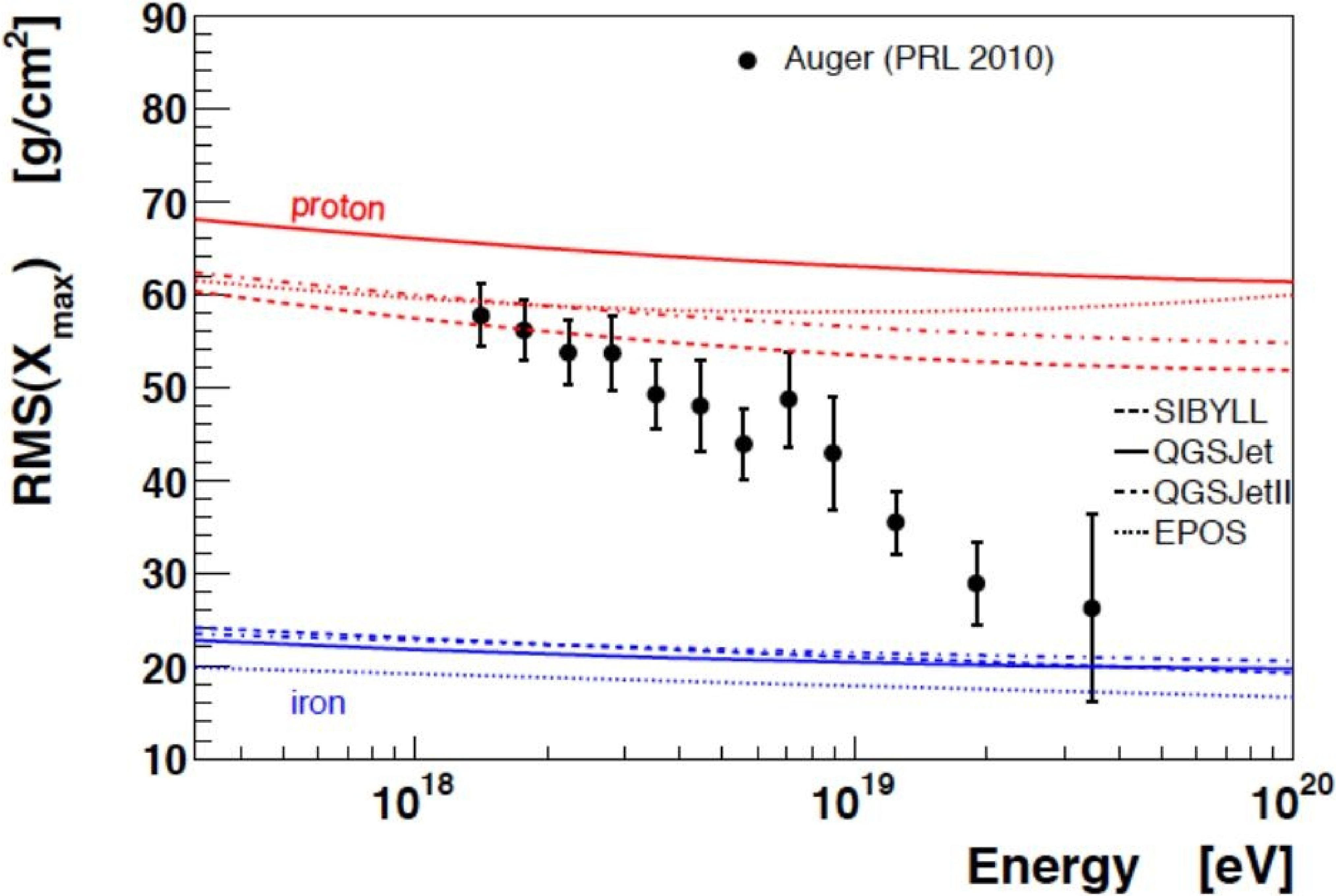
AUGER



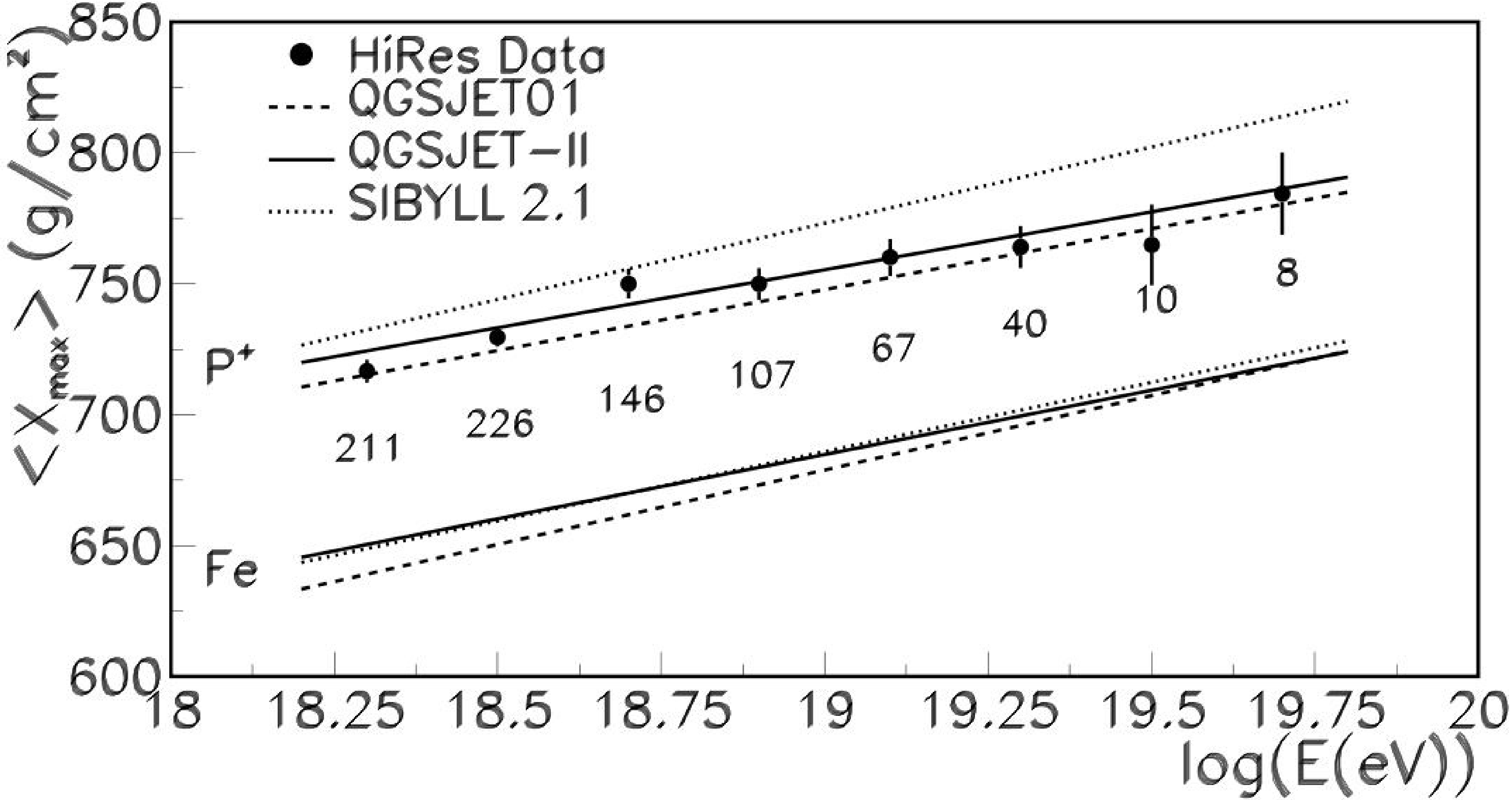
SIBYLL 2.1
QGSJet01c
QGSJetII.3
EPOS 1.61
proton
iron
Auger (PRL 2010)
HiRes (ApJ 2005)
MIA
Fly's Eye
850
800
750
700
650
600
550
<Xmax> [g/cm2]
10^17
10^18
10^19
10^20
Energy [eV]

AUGER

Shower fluctuations



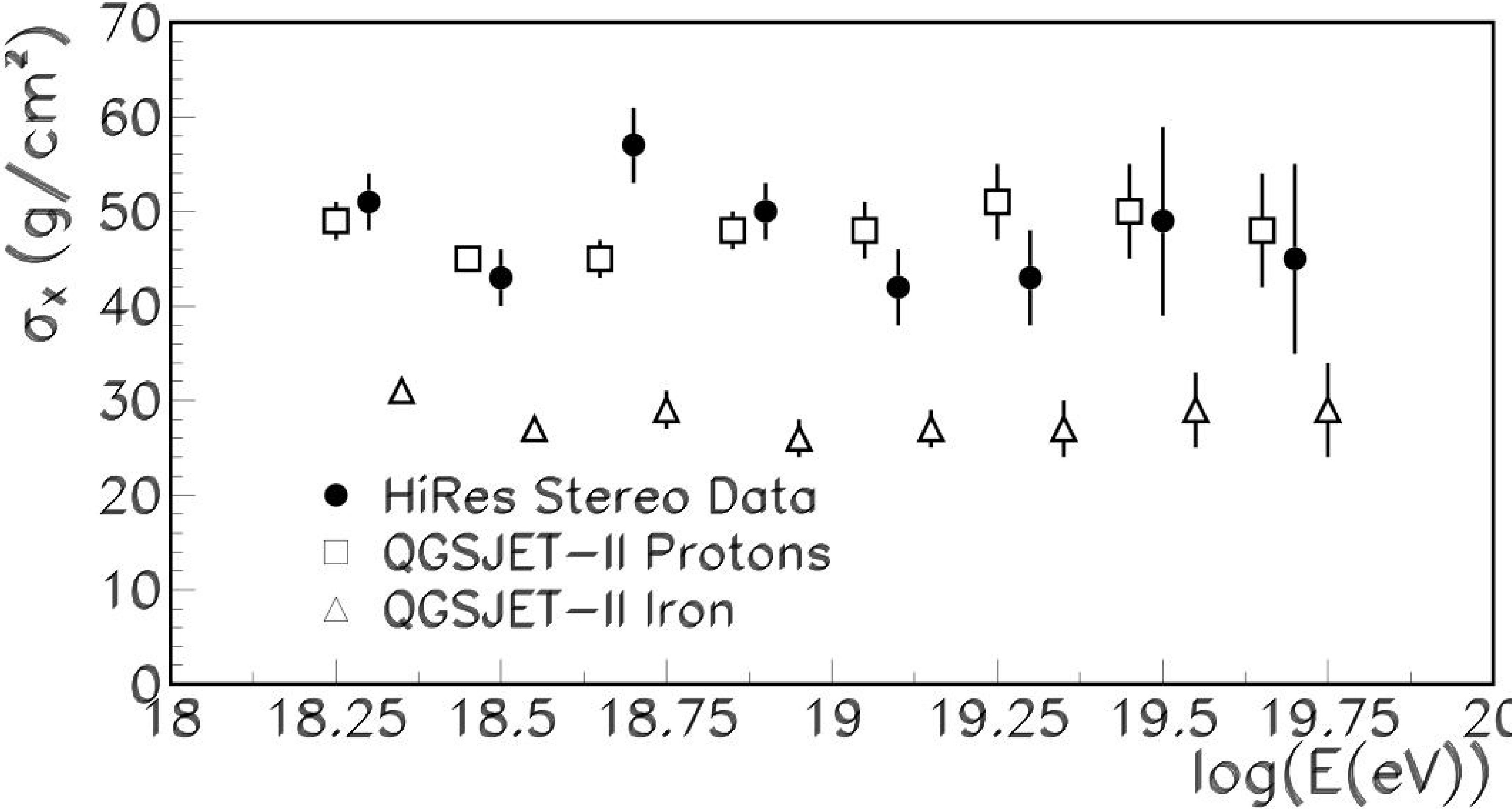
HiRes 2009

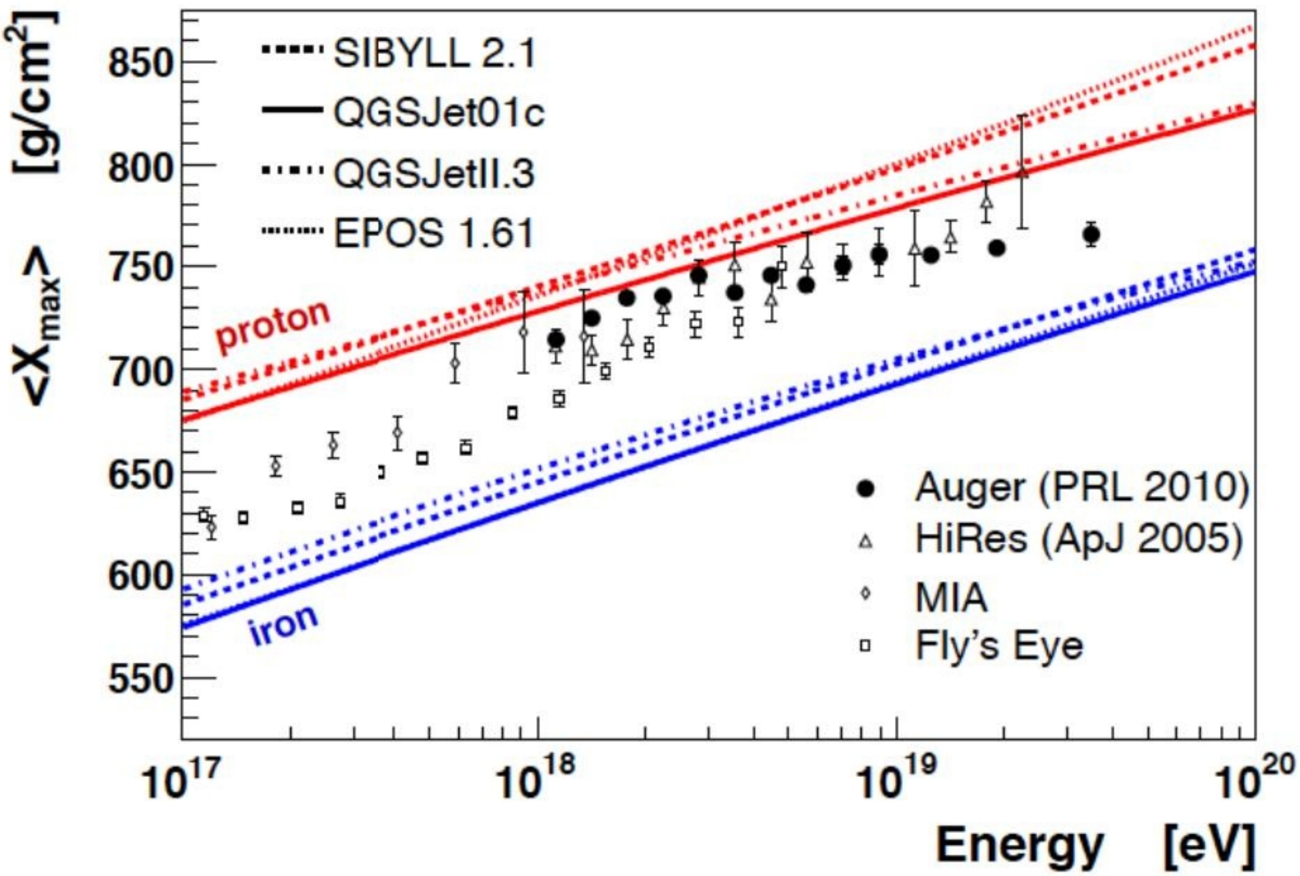


HiRes Data
QGSJET01
QGSJET-II
SIBYLL 2.1
$<X_{max}>$ (g/cm^2)
log(E(eV))
P+
Fe
211
226
146
107
67
40
10
8
850
800
750
700
650
600
18
18.25
18.5
18.75
19
19.25
19.5
19.75
20

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} eV

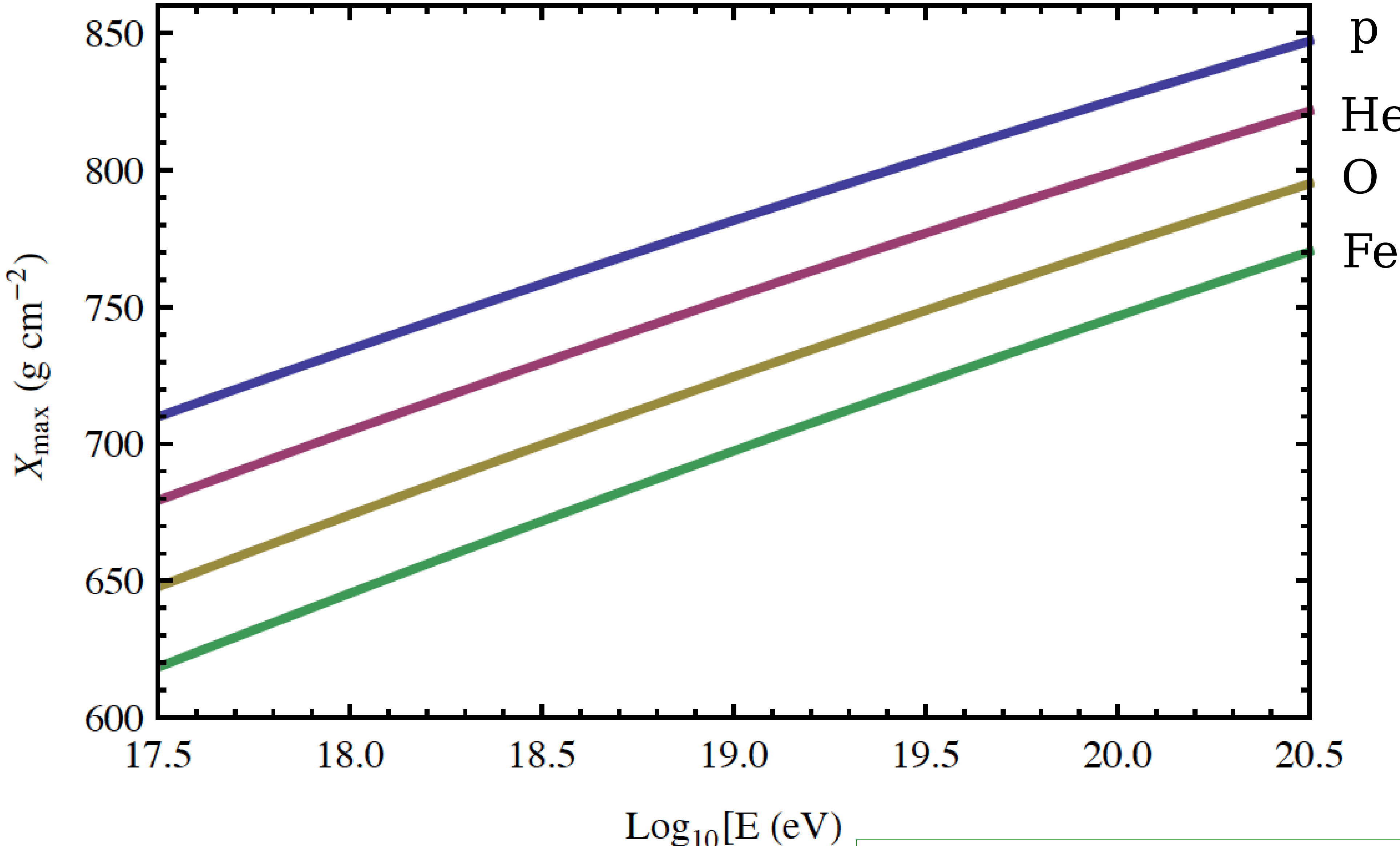
$$D_p = \frac{d\langle X_{\rm max}\rangle}{d\log_{10} E} \simeq 45 \ - \ 55 \text{ g cm}^{-2}$$

X_{max} and the Composition of Cosmic Rays

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

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

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

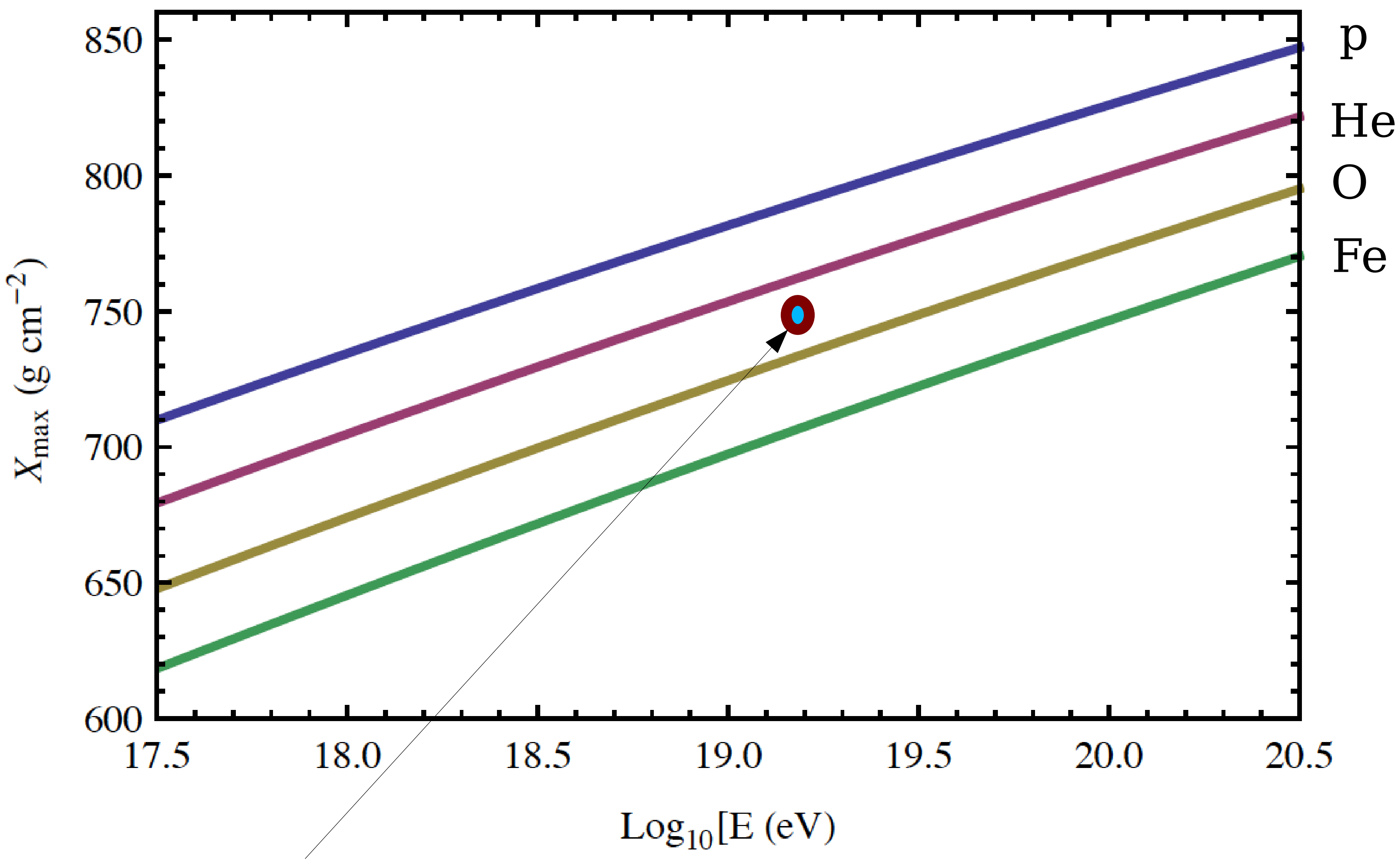


$$\langle X_A \rangle \simeq \langle X_p \rangle - D_p \ \log_{10} A$$

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

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

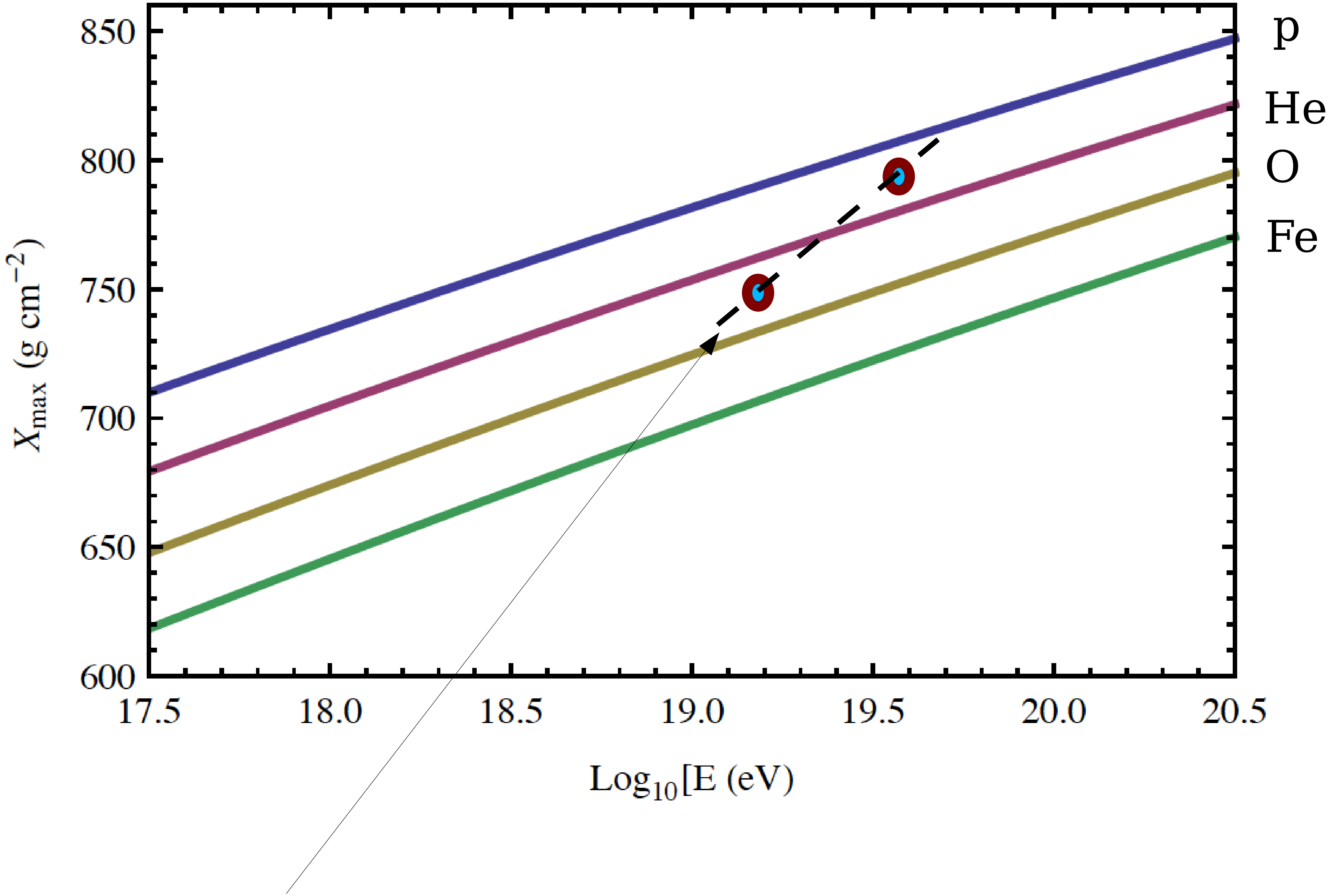
$$\langle X_{\mathrm{Fe}} \rangle \simeq \langle X_p \rangle - 90 \text{ g cm}^{-2}$$



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

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

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

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

Importance of "CORNERS"

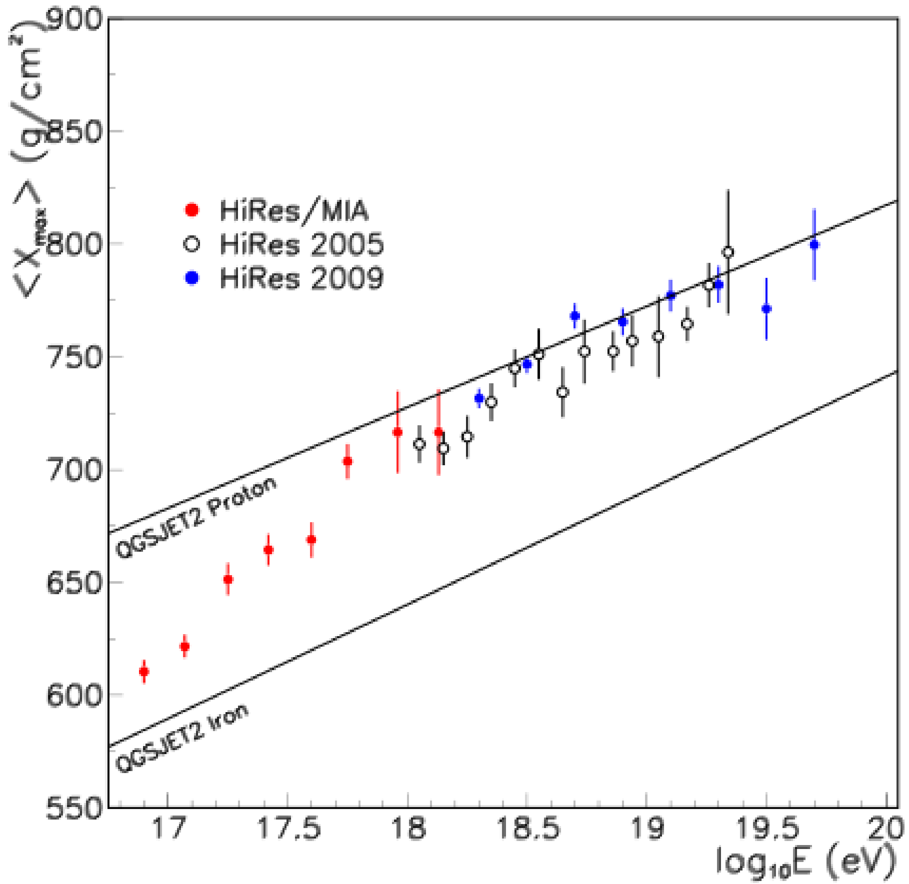
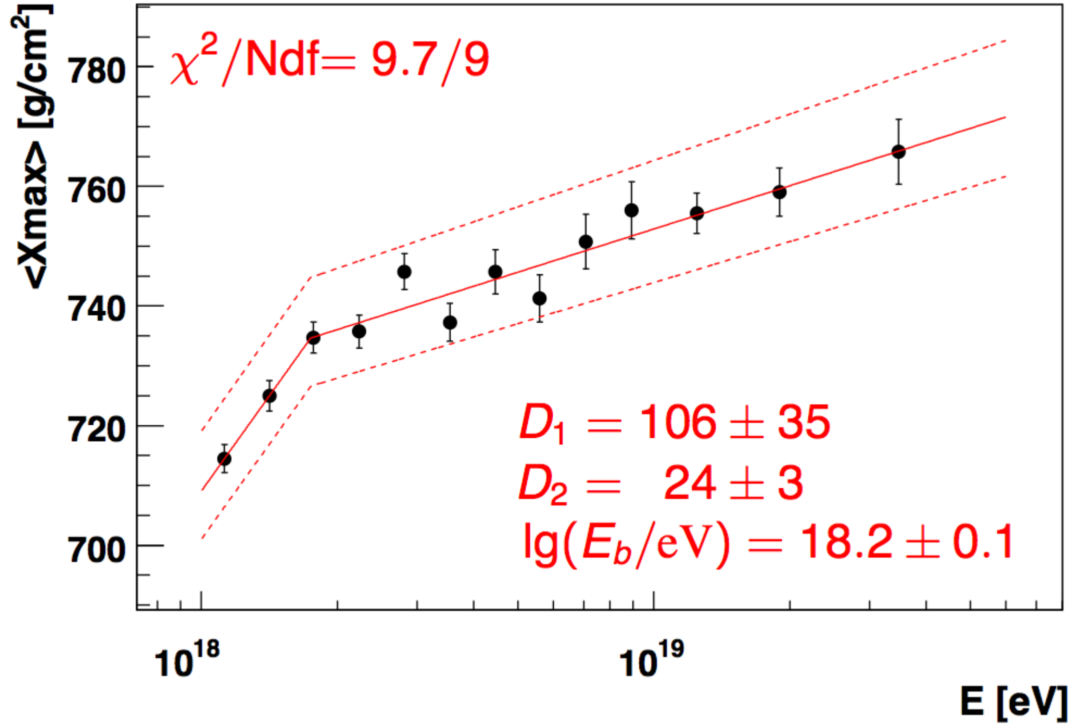


Fig. 25.— Comparison of current HiRes stereo $\langle X_{max} \rangle$ results with results from the HiRes-prototype/MIA hybrid (Abu-Zayyad et al. 2001) and previously published HiRes stereo results (Abbasi et al. 2005).



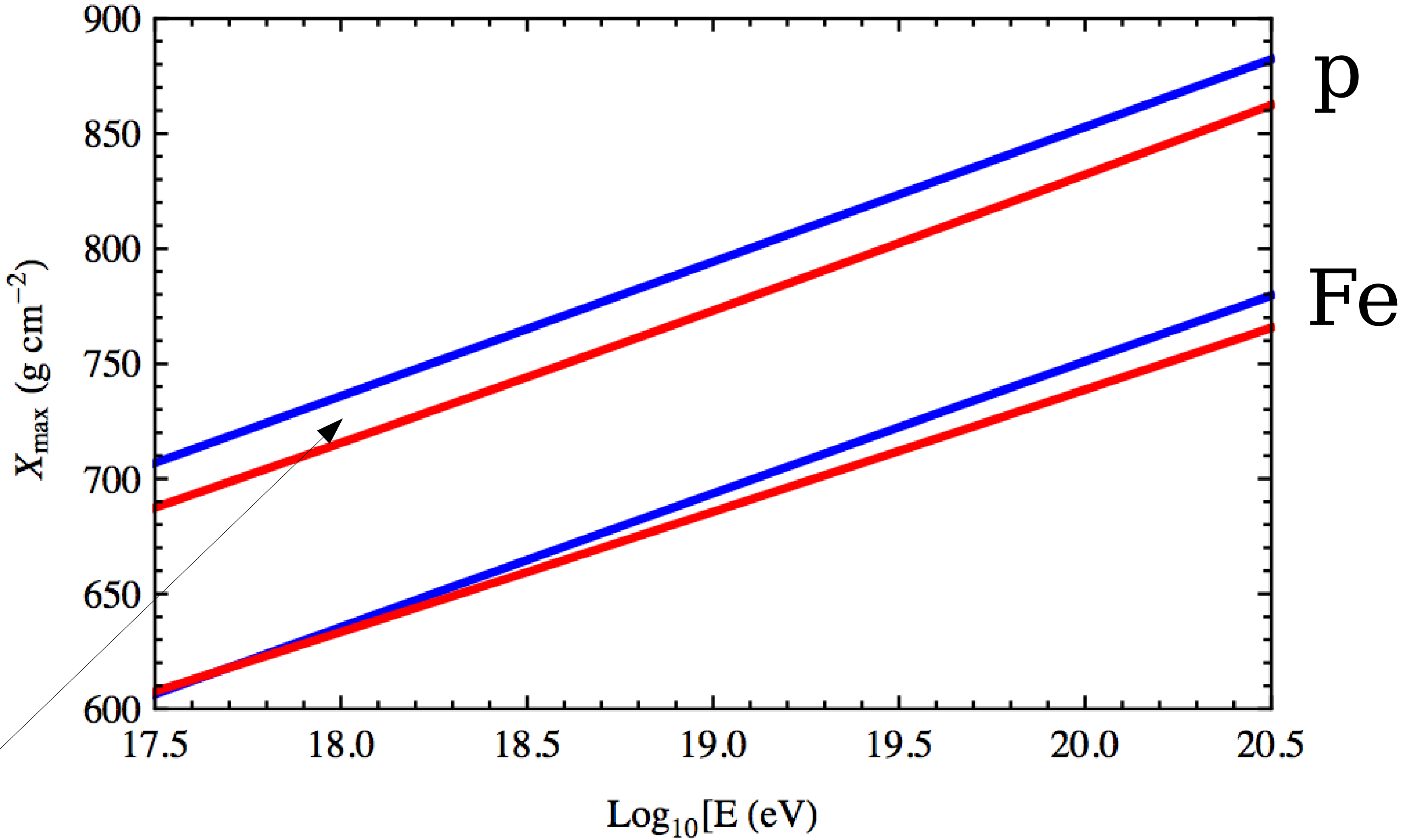
Abrupt change in the variation of the properties of hadronic interactions with energy

Abrupt change in the composition evolution.

Problems in comparing Auger and HiRes measurements:

Comparison of the "Theory curves"
(same model: Sibyll 2.1)

Auger (Blue)
HiRes (Red)



20 g cm^{-2} shift

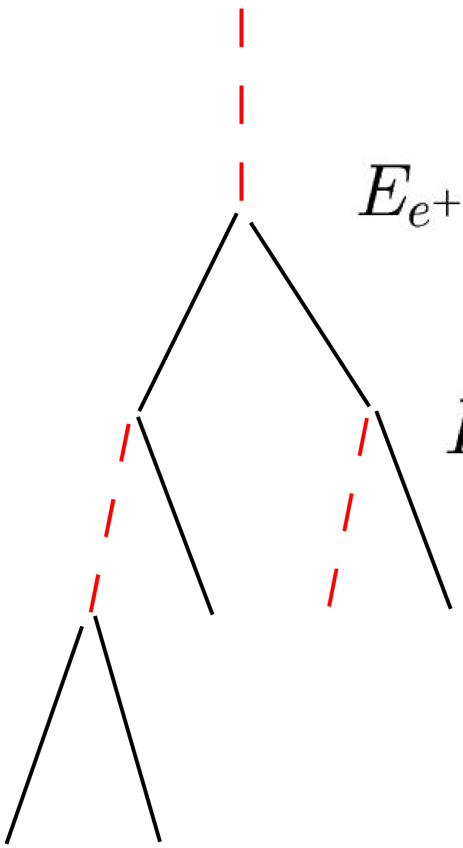
Electromagnetic   Showers

versus

Hadronic Showers

Toy model discussion.

Electromagnetic Shower



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

Pair production

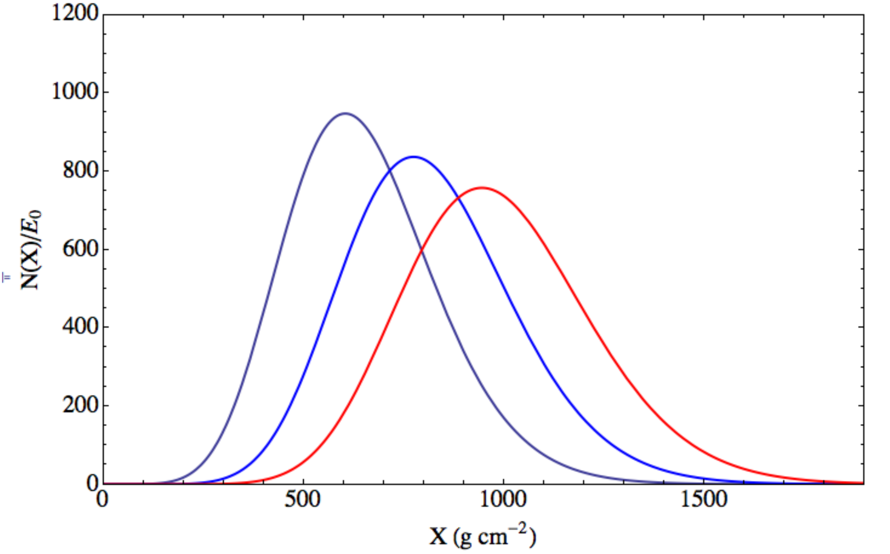
$$E_\gamma = E_e \; v \qquad \varphi(v)$$

Bremsstrahlung

Radiation Length
(Energy independent)

Vertices :
theoretically understood
(and scaling)

Electromagnetic Showers



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

Logarithmic growth of the penetration.

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

Energy Conservation

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

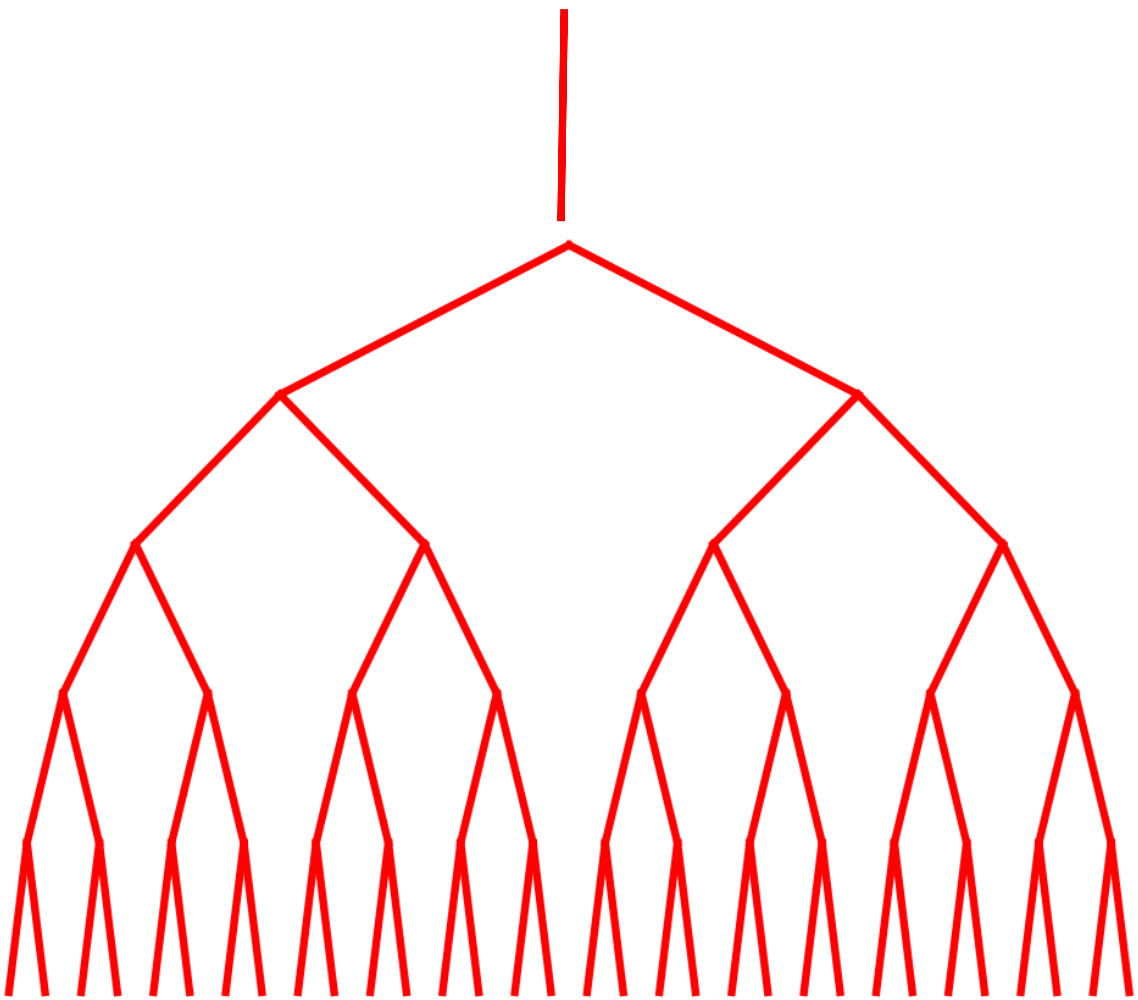
Heitler toy model

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:

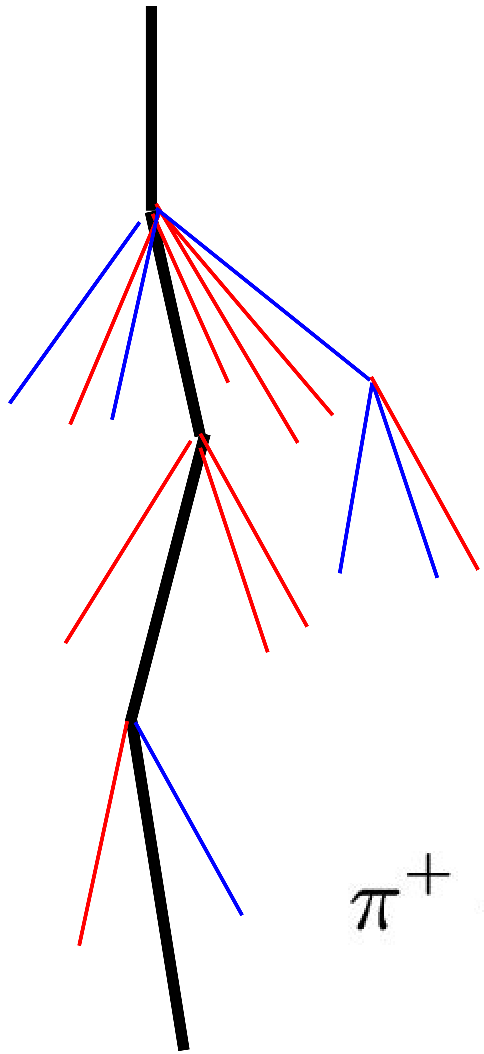
$$\sigma_X^2(\gamma, E) = \text{constant}$$

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

Proton Shower

Vertices : theoretically not Understood

(and energy dependent)



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

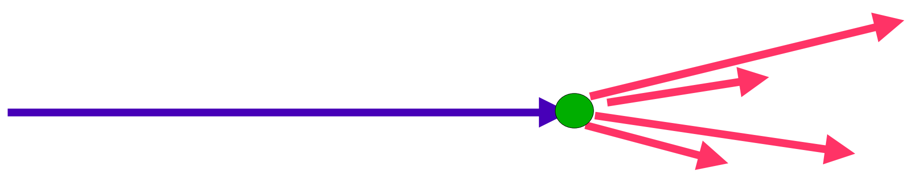
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

HADRONIC INTERACTIONS

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

Leading nucleon
~ 50% of energy

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



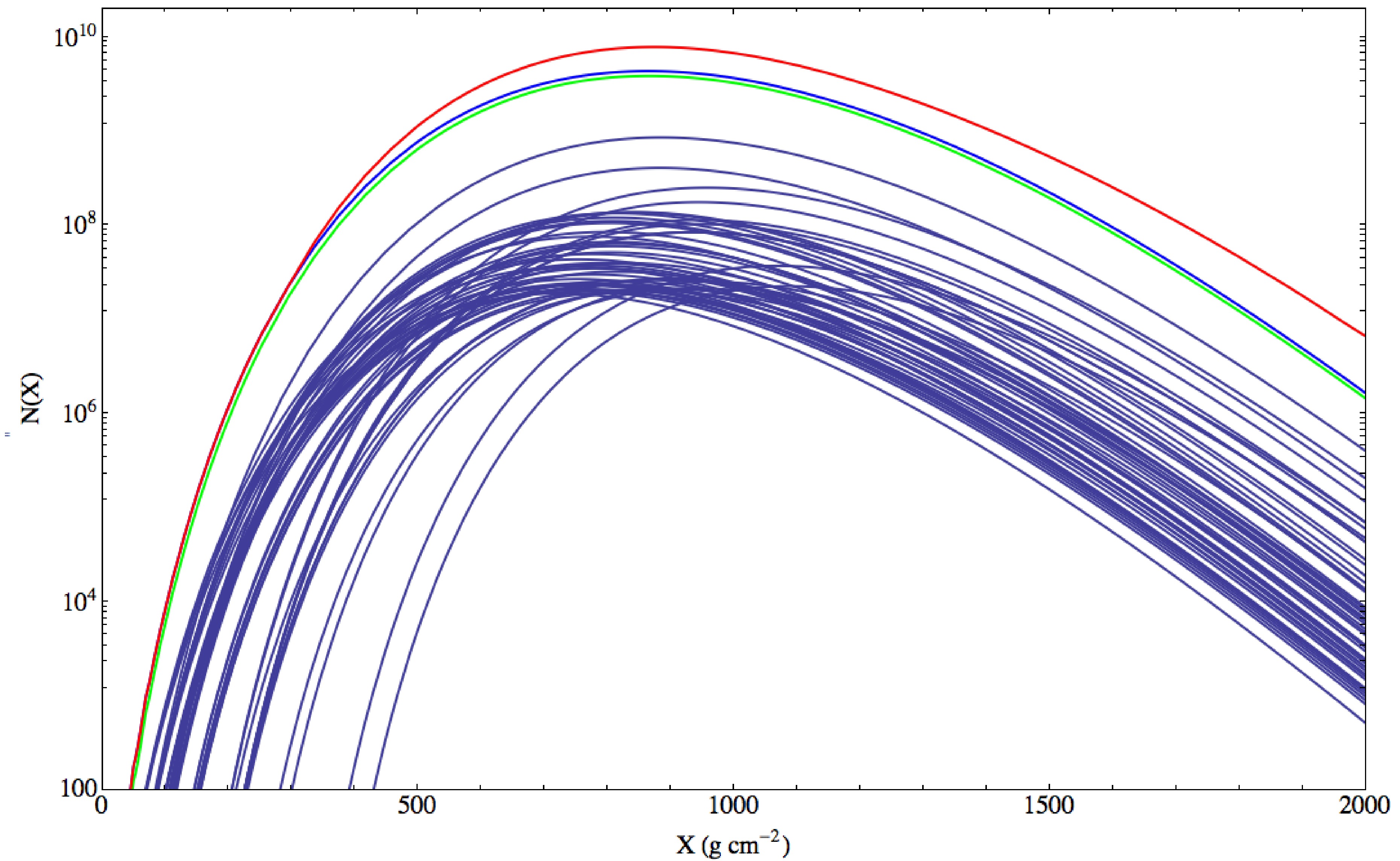
Decay

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

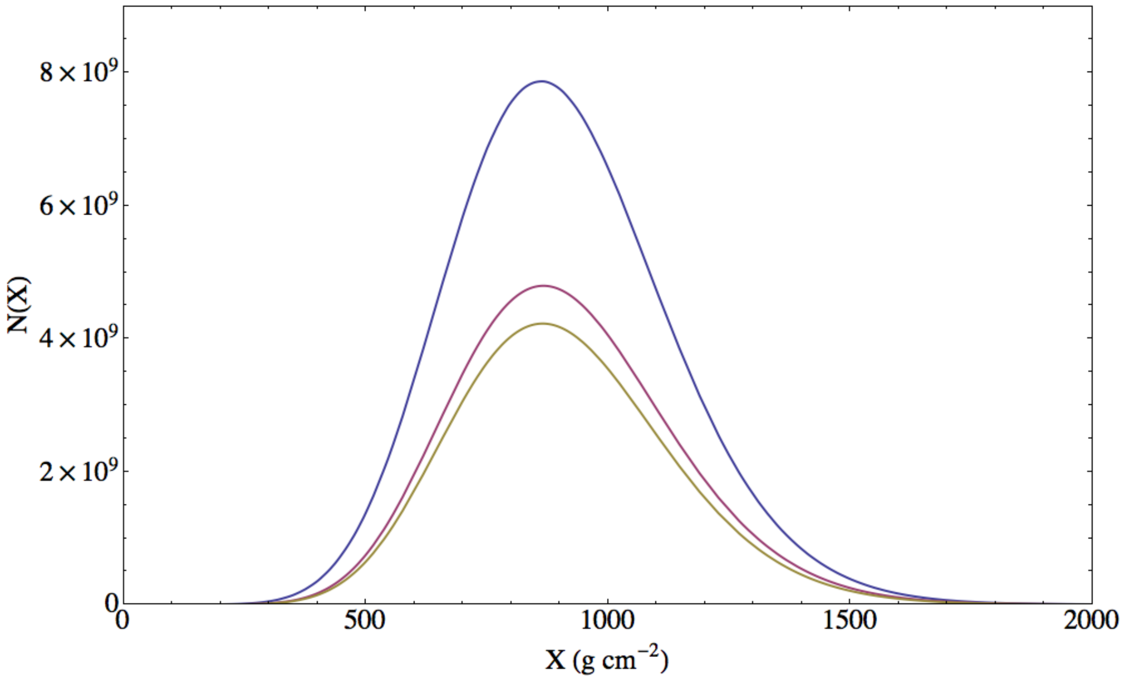
Interaction

Inclusive spectra
of secondary particles

One single proton Shower: $E_0 = 10^{19}$ eV

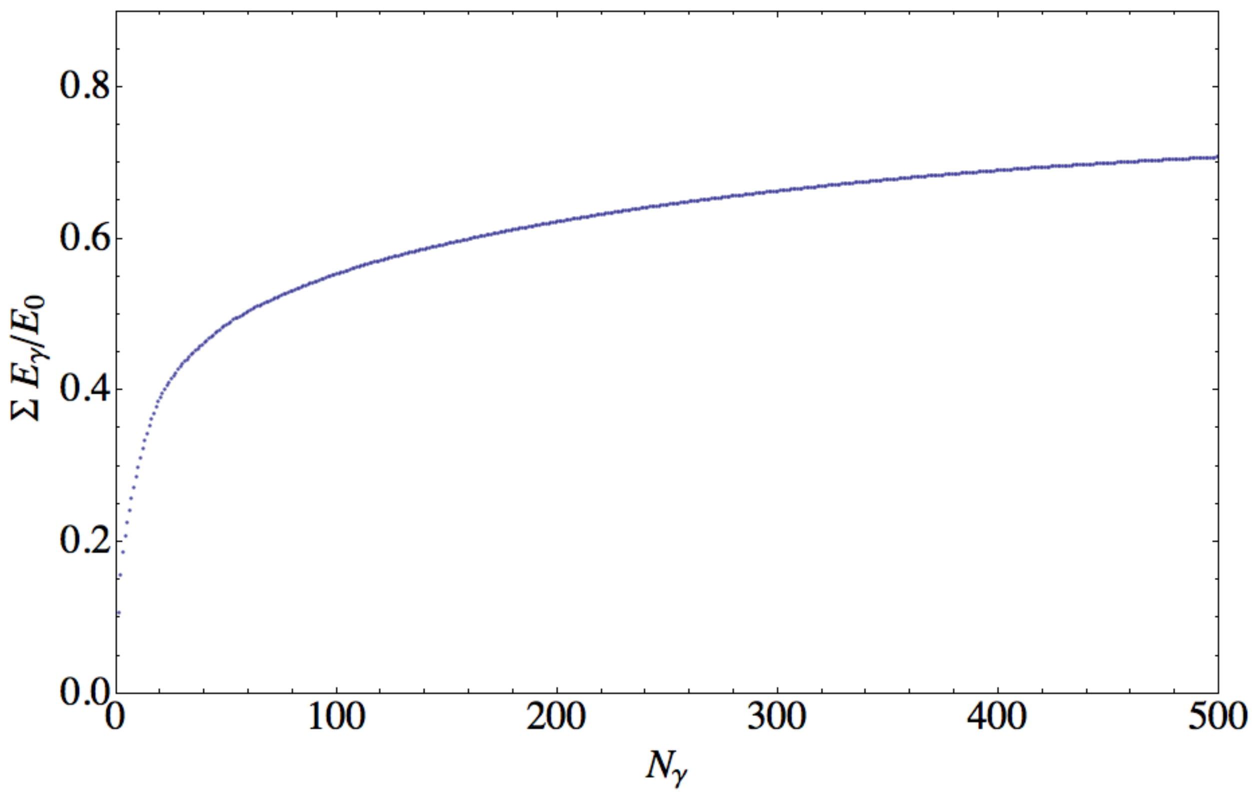


50 highest energy individual sub-showers



100 photons   ~50% of energy
1000 photons ~70% of energy

Approximately 100 photons in 30-40 interaction vertices control the structure of the shower: x ~ 0.1



Toy Model for hadronic shower

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

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

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

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

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

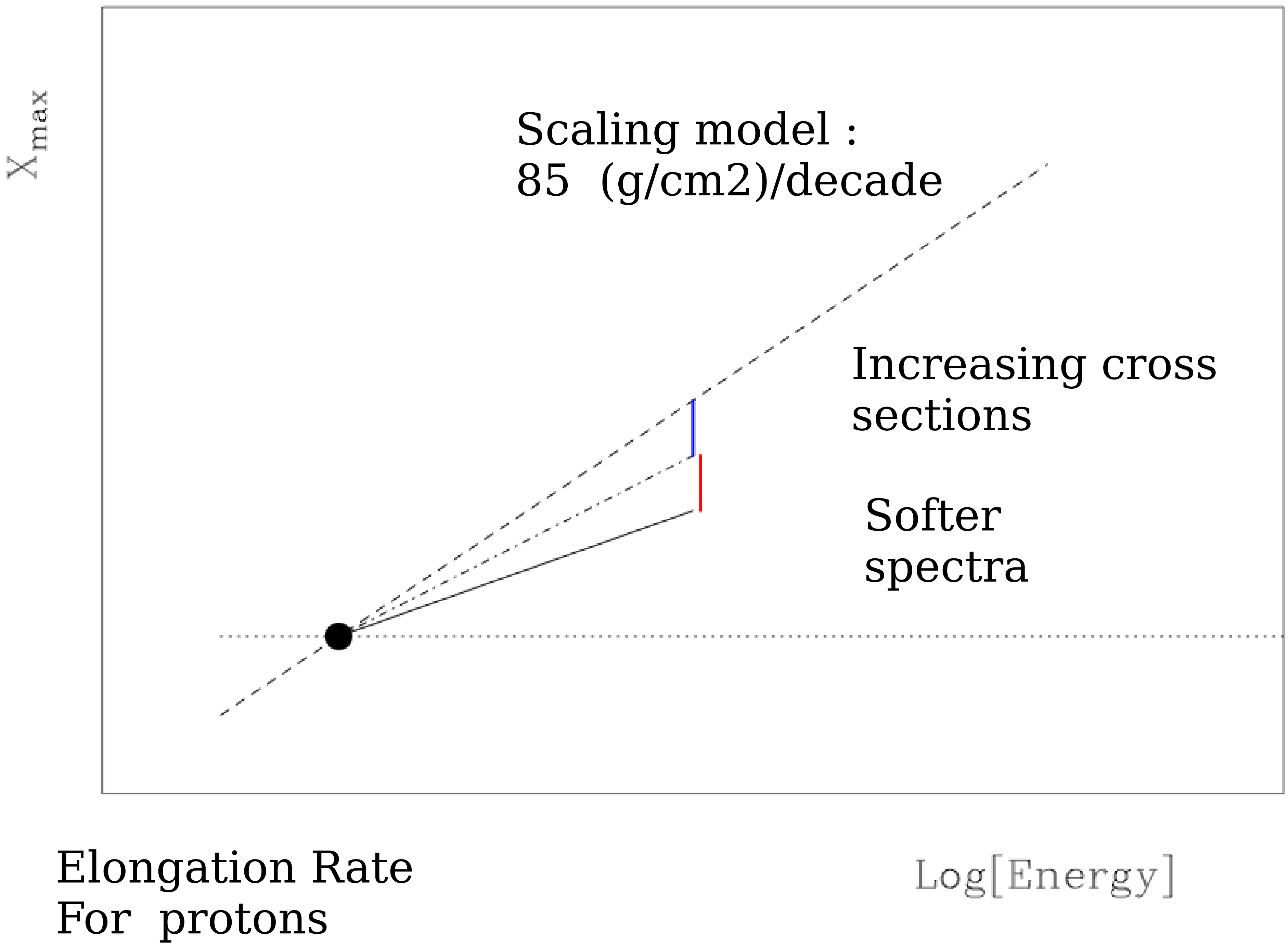
"Softness"

Elongation Rate

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

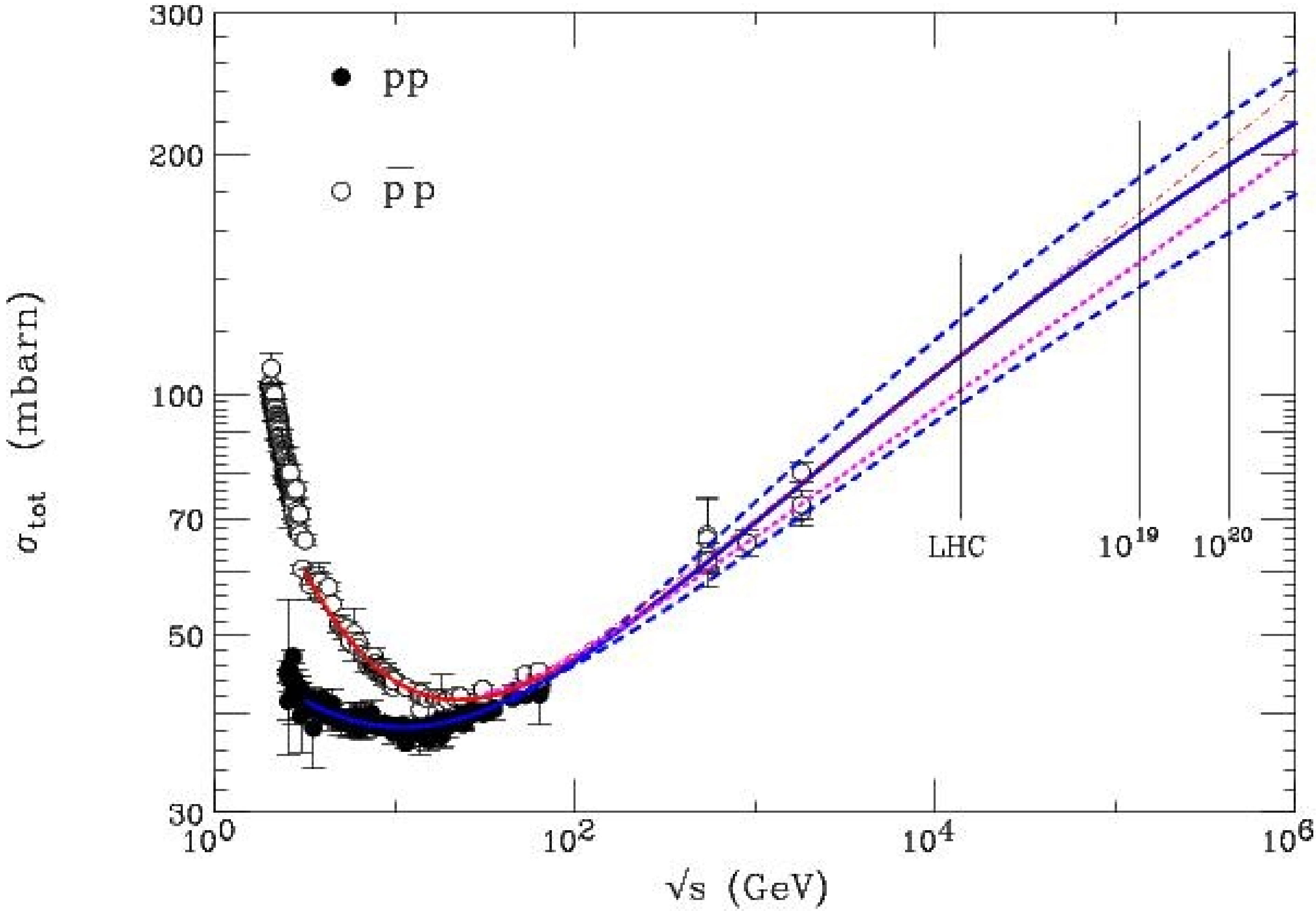
Evolution with Energy of the Interaction length

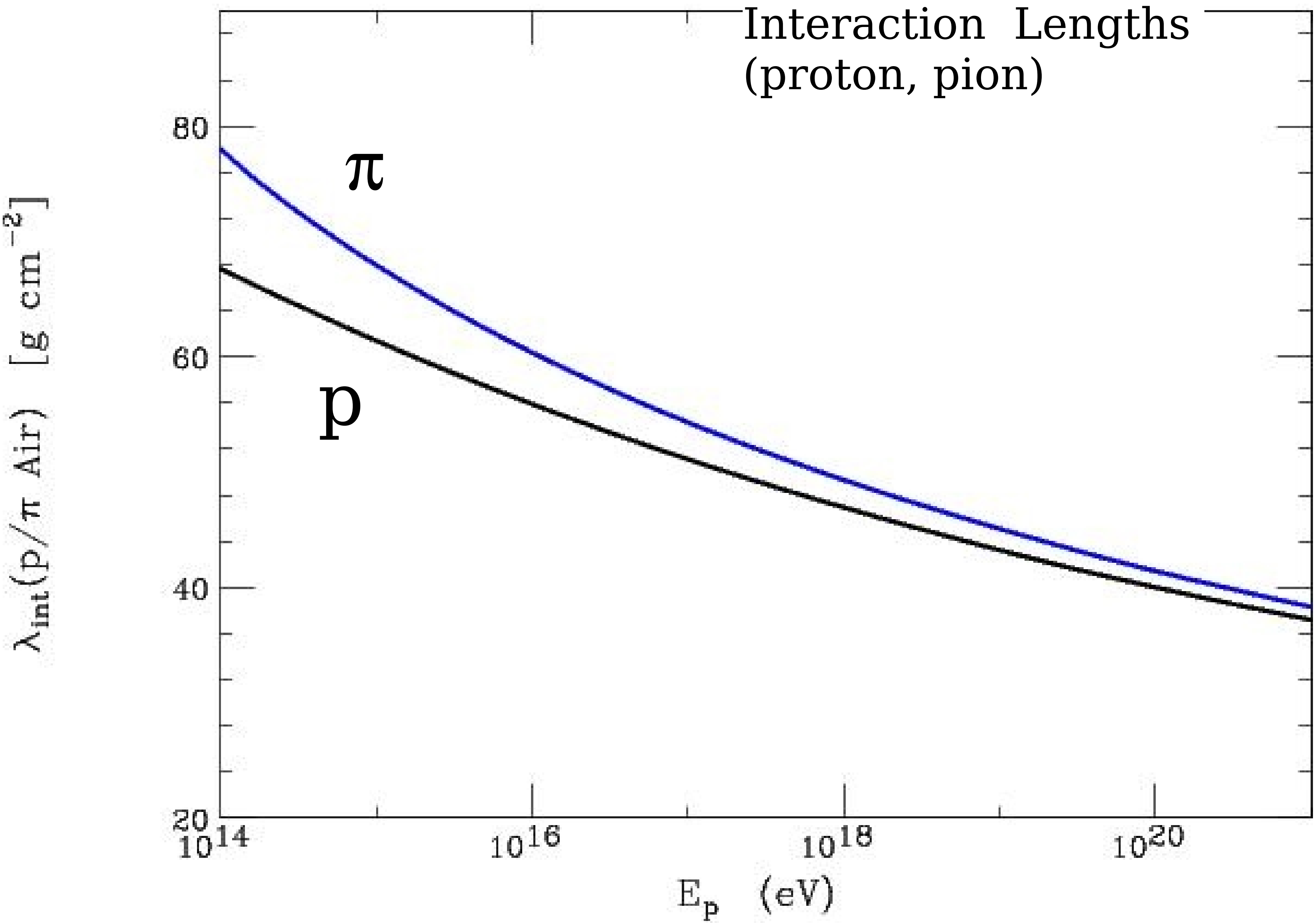
Evolution with energy of the "softness" of the spectrum



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

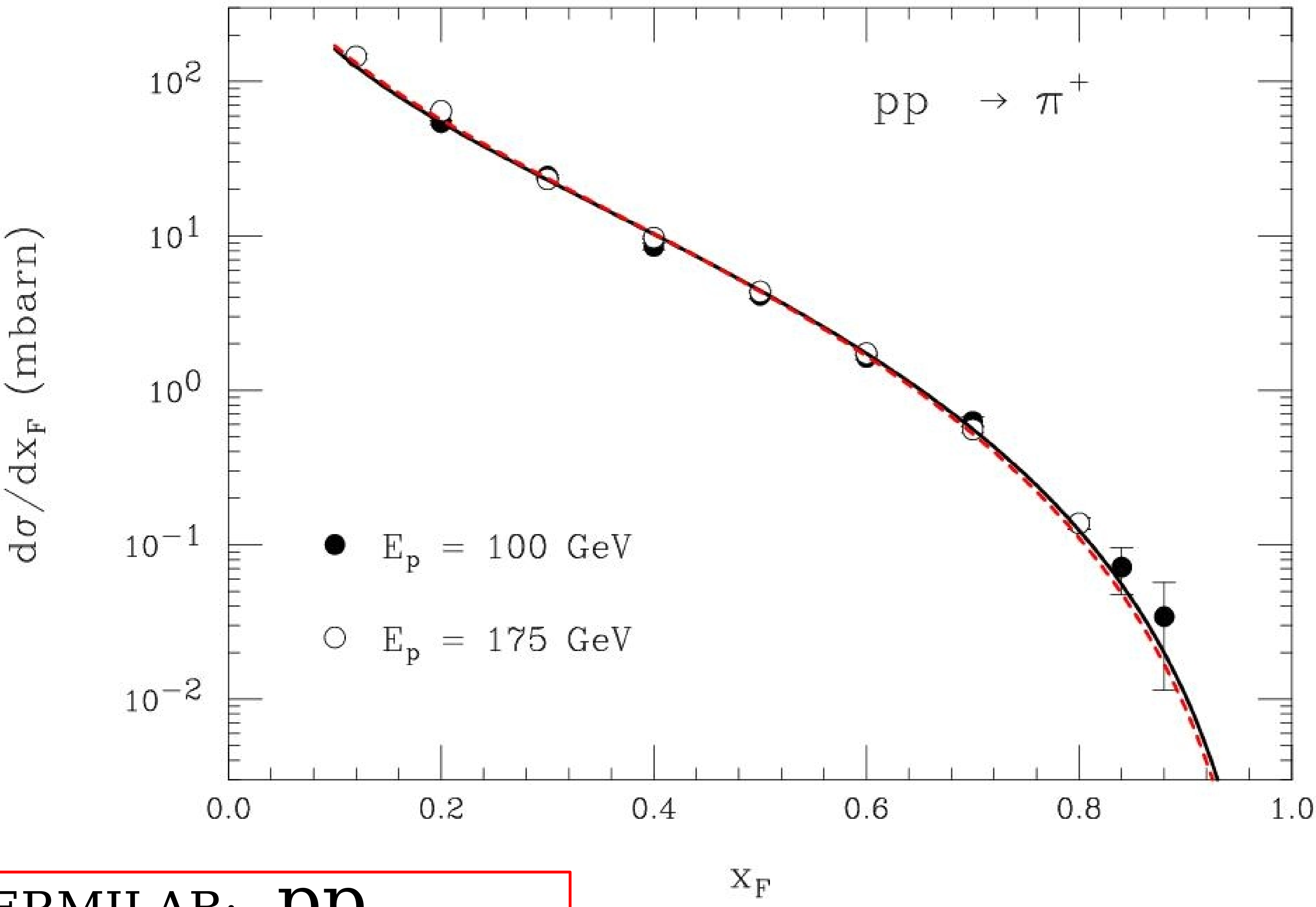
Total pp Cross Section





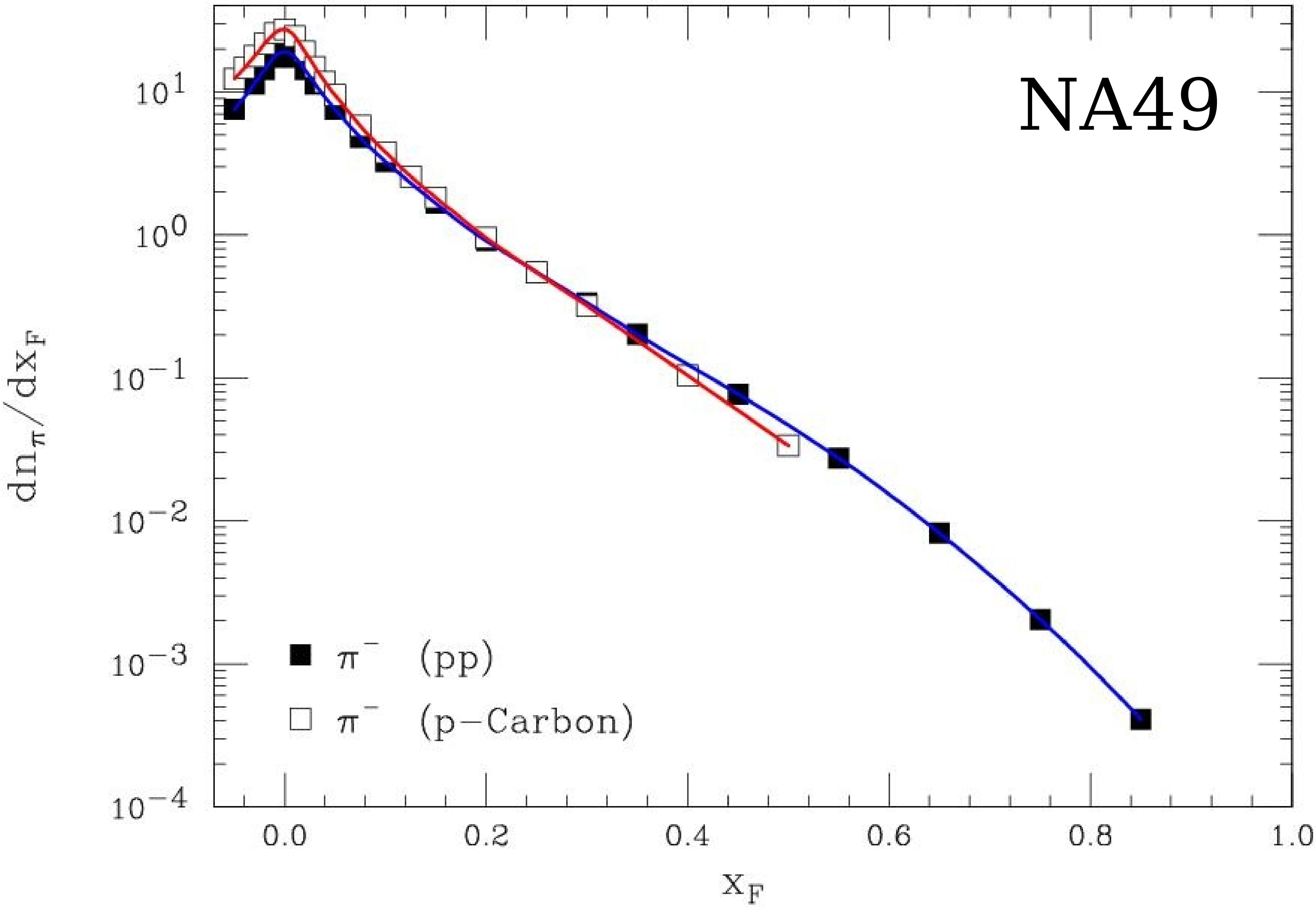
Interaction Lengths
(proton, pion)
π
p
80
60
40
20
10^{14}
10^{16}
10^{18}
10^{20}
E_p (eV)
$\lambda_{int}(p/\pi\ Air)$ [g cm^{-2}]

Phenomenological Evidence for SCALING

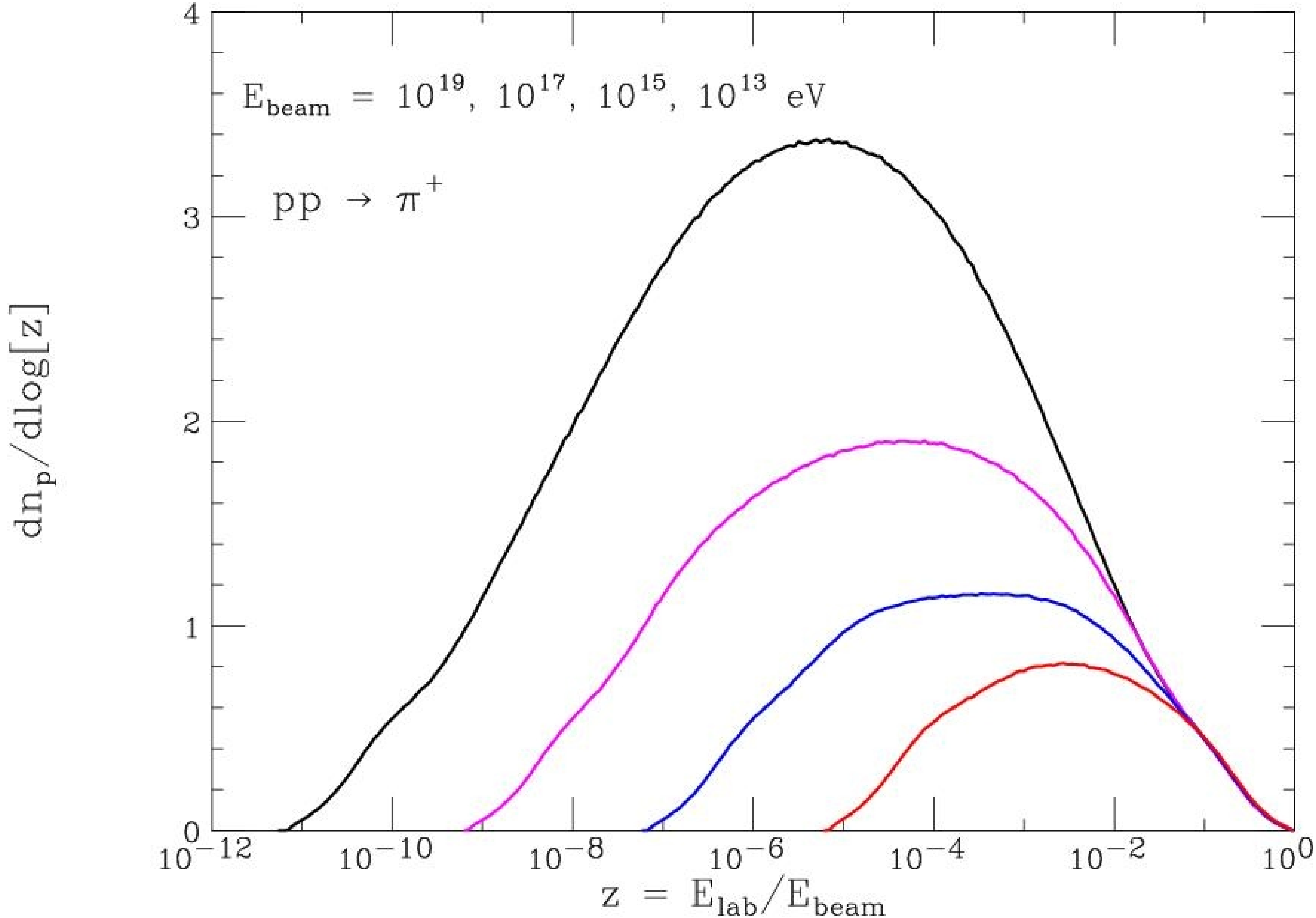


FERMILAB: pp
Brenner et al (1982)

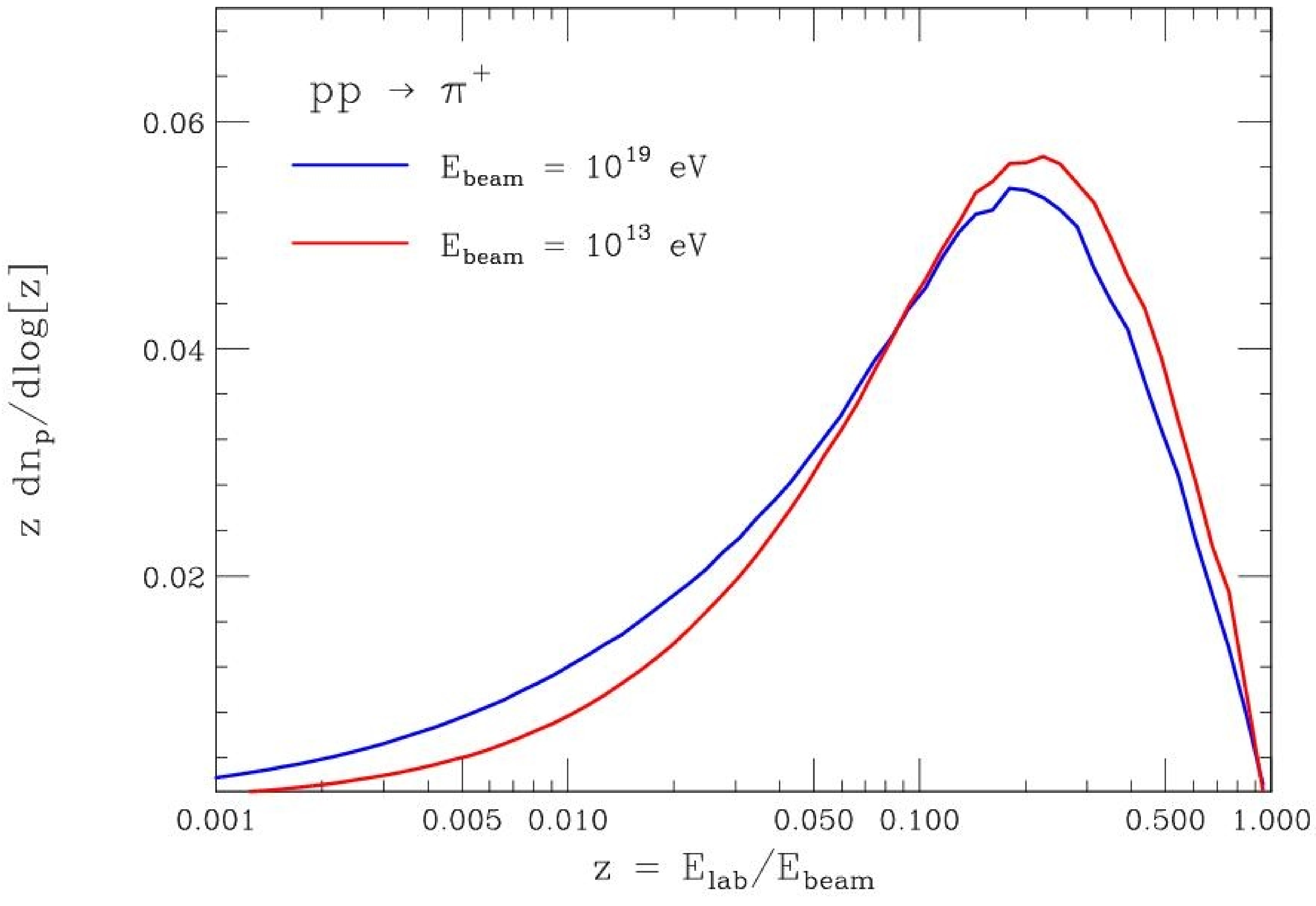
NUCLEAR effects: pp vs p-^{12}C

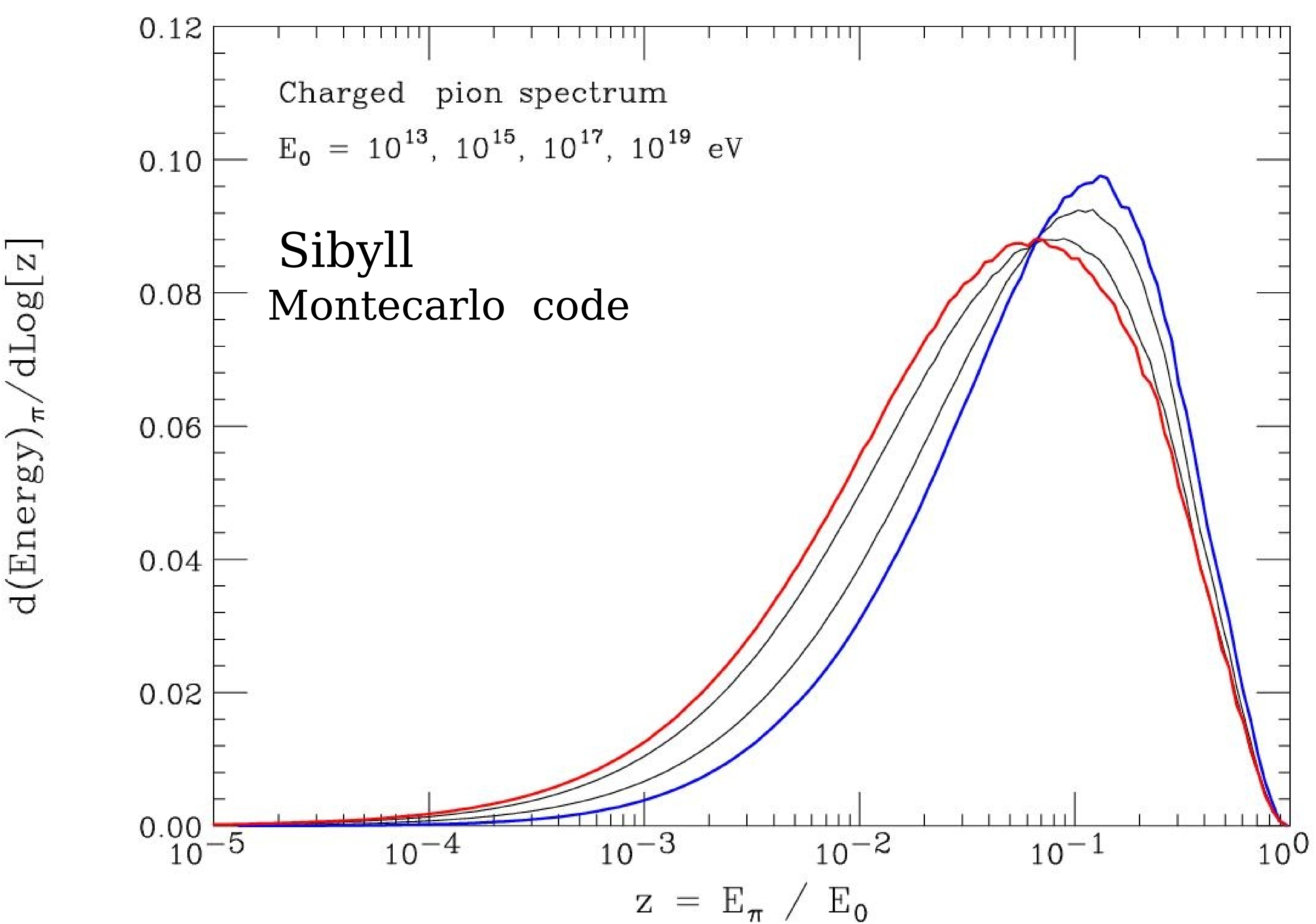


EXTRAPOLATION to HIGH ENERGY (Pythia pp)



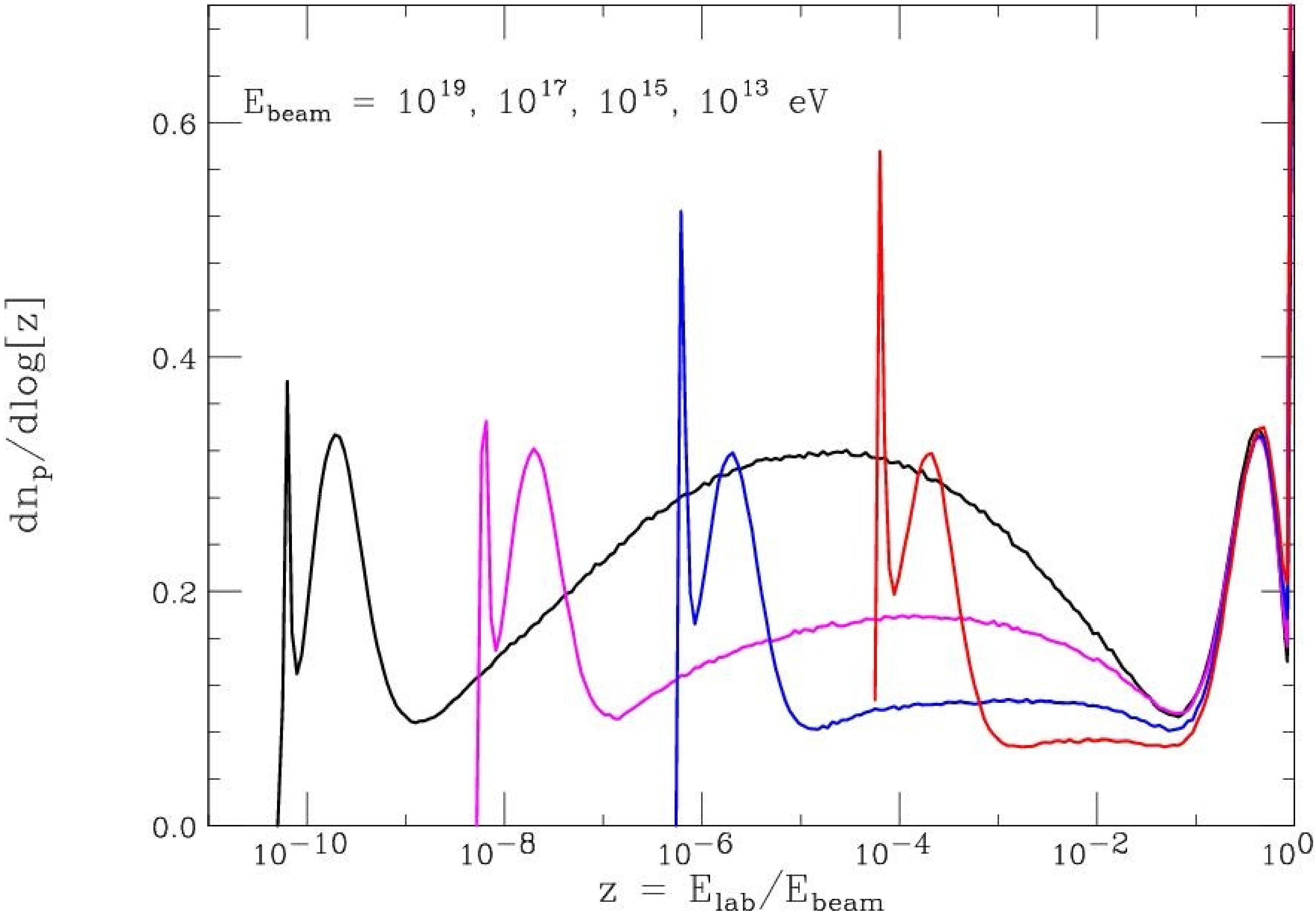
EXTRAPOLATION to HIGH ENERGY (Pythia pp)



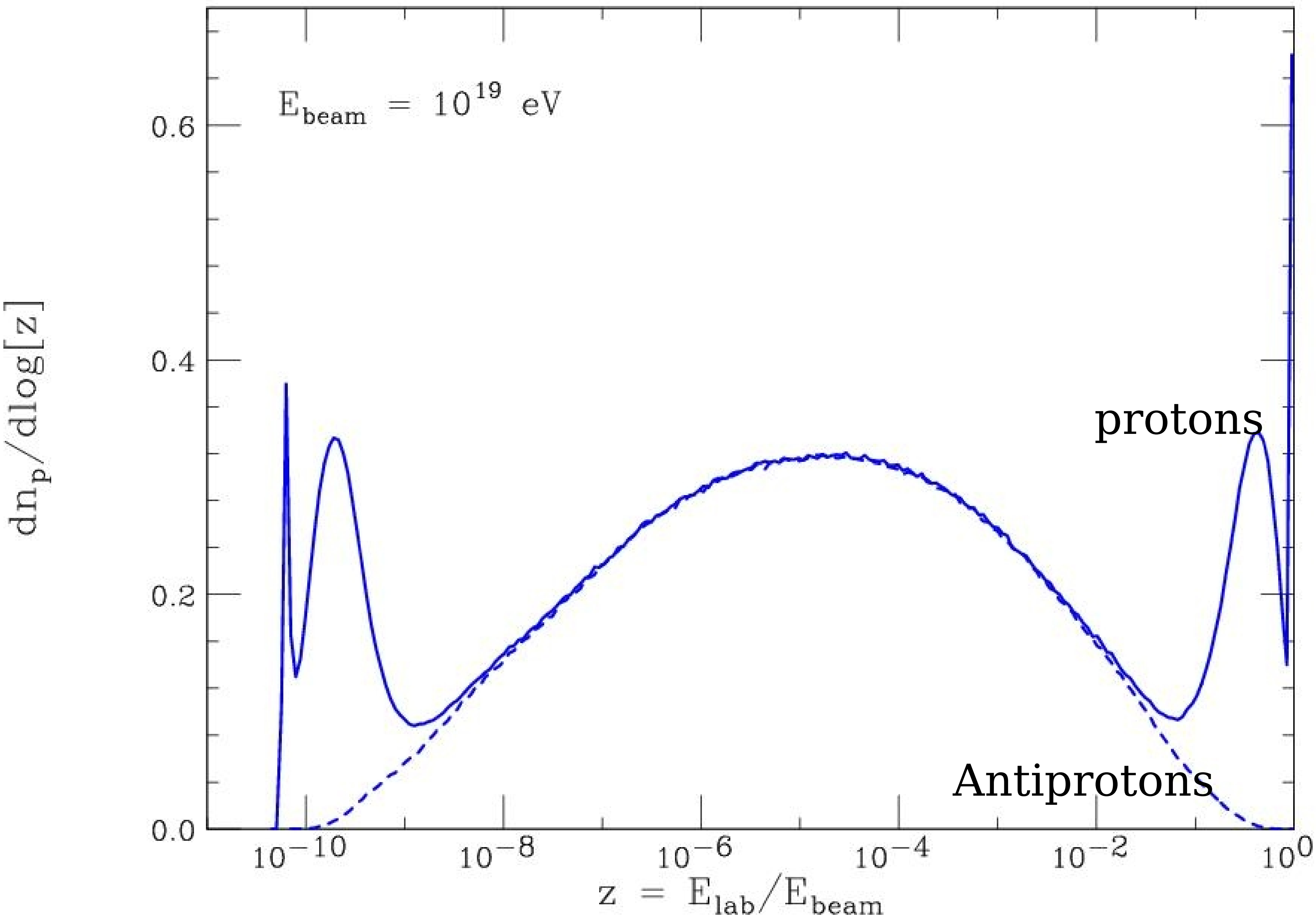


Charged pion spectrum
$E_0 = 10^{13}, 10^{15}, 10^{17}, 10^{19}$ eV
Sibyll
Montecarlo code
d(Energy)$_\pi$/dLog[z]
z = E_π / E_0
0.12
0.10
0.08
0.06
0.04
0.02
0.00
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}

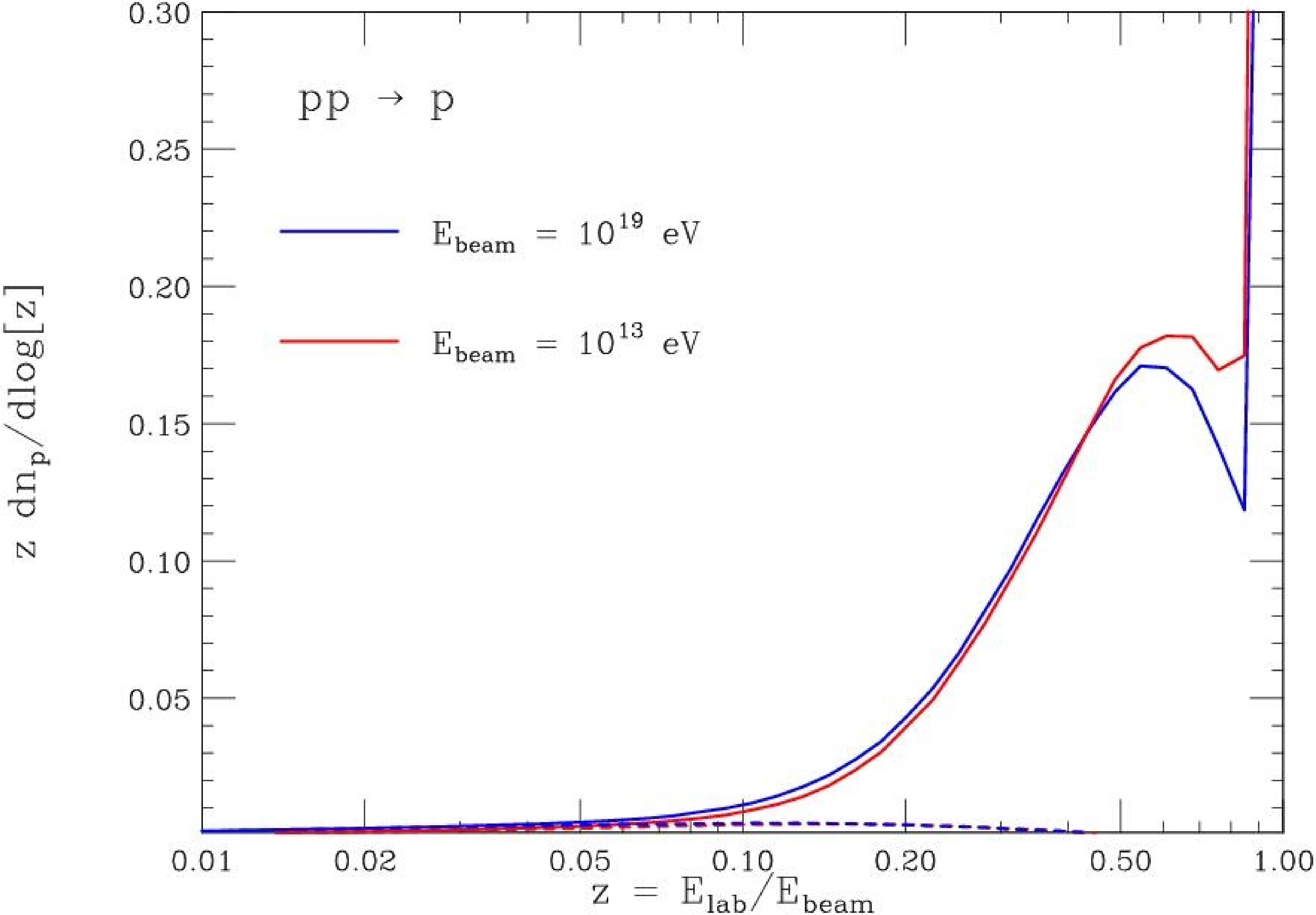
PROTON Spectra (elasticity spectra)



PYTHIA PROTON Spectra



PROTON Spectra (elasticity spectra)



C.R. DATA

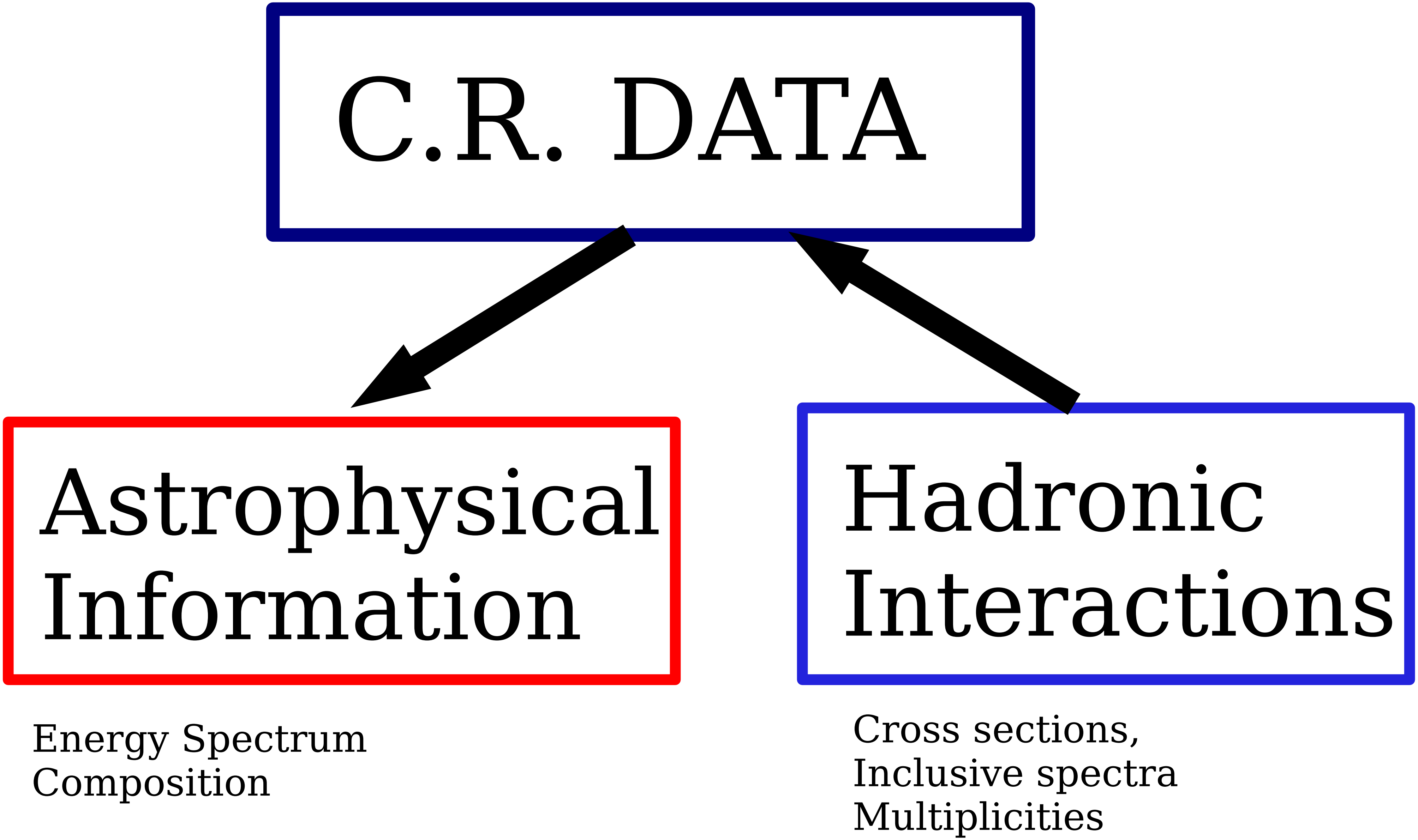
Astrophysical Information

Energy Spectrum
Composition

Hadronic Interactions

Cross sections,
Inclusive spectra
Multiplicities

From Accelerator Data + Theory → Astrophysics



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

Data

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

Astrophysical Information

Hadronic Interactions

How can we include systematic uncertainties
in the modeling of hadronic interactions
in the estimate of properties
of Cosmic Rays?

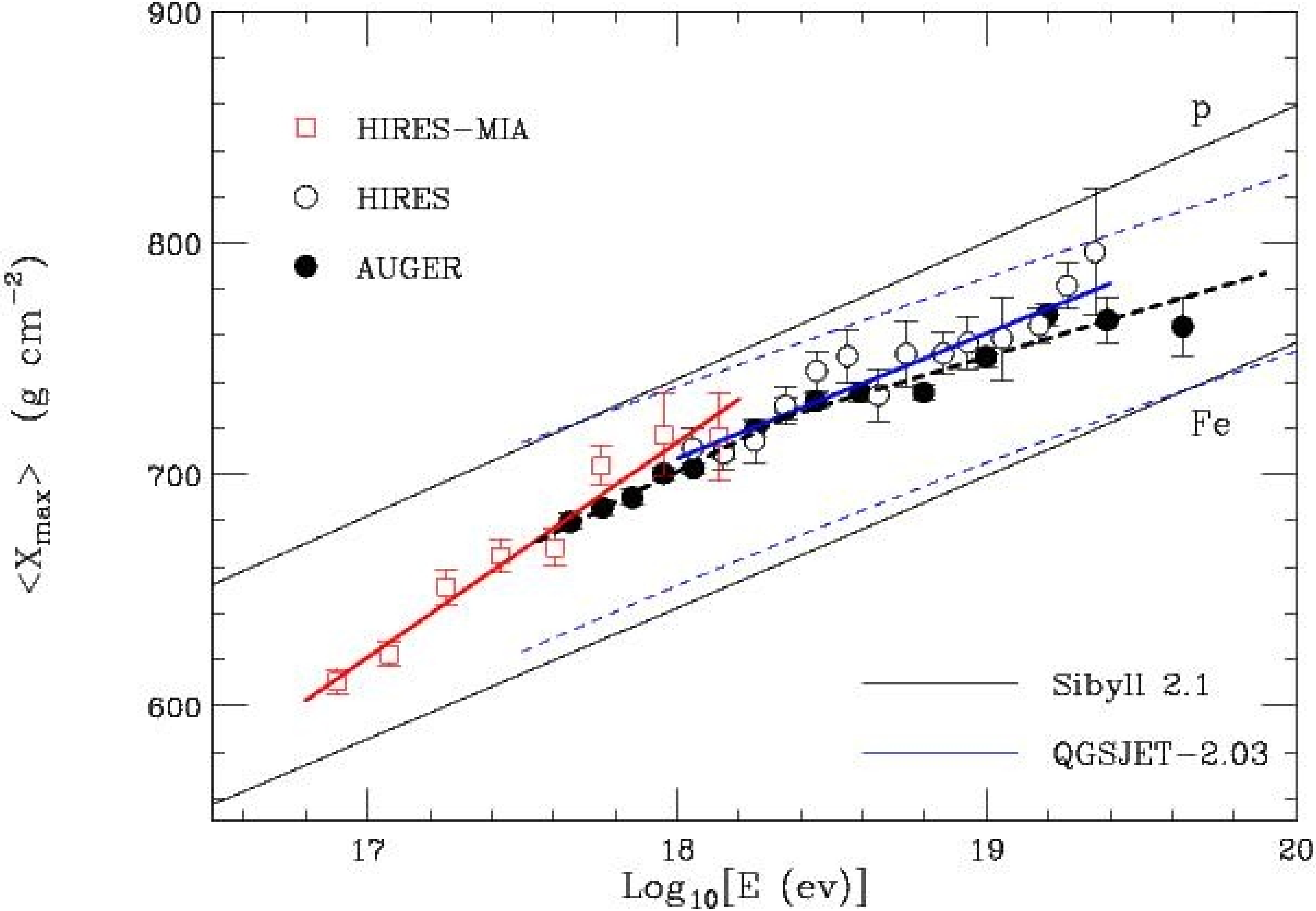
"Spread" of predictions
for different model.

Overestimate ?

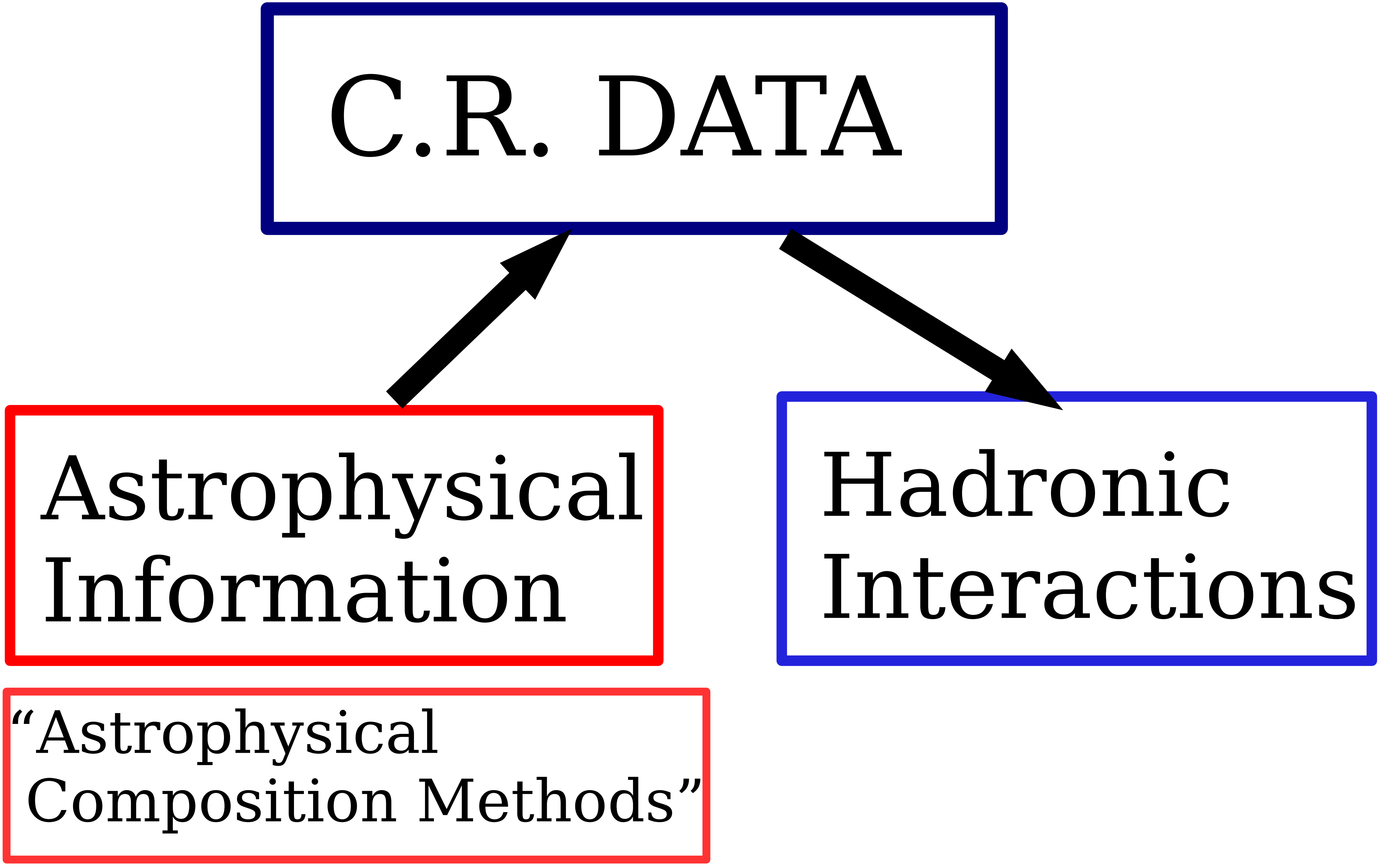
Some models are
lower quality.

Underestimate ?

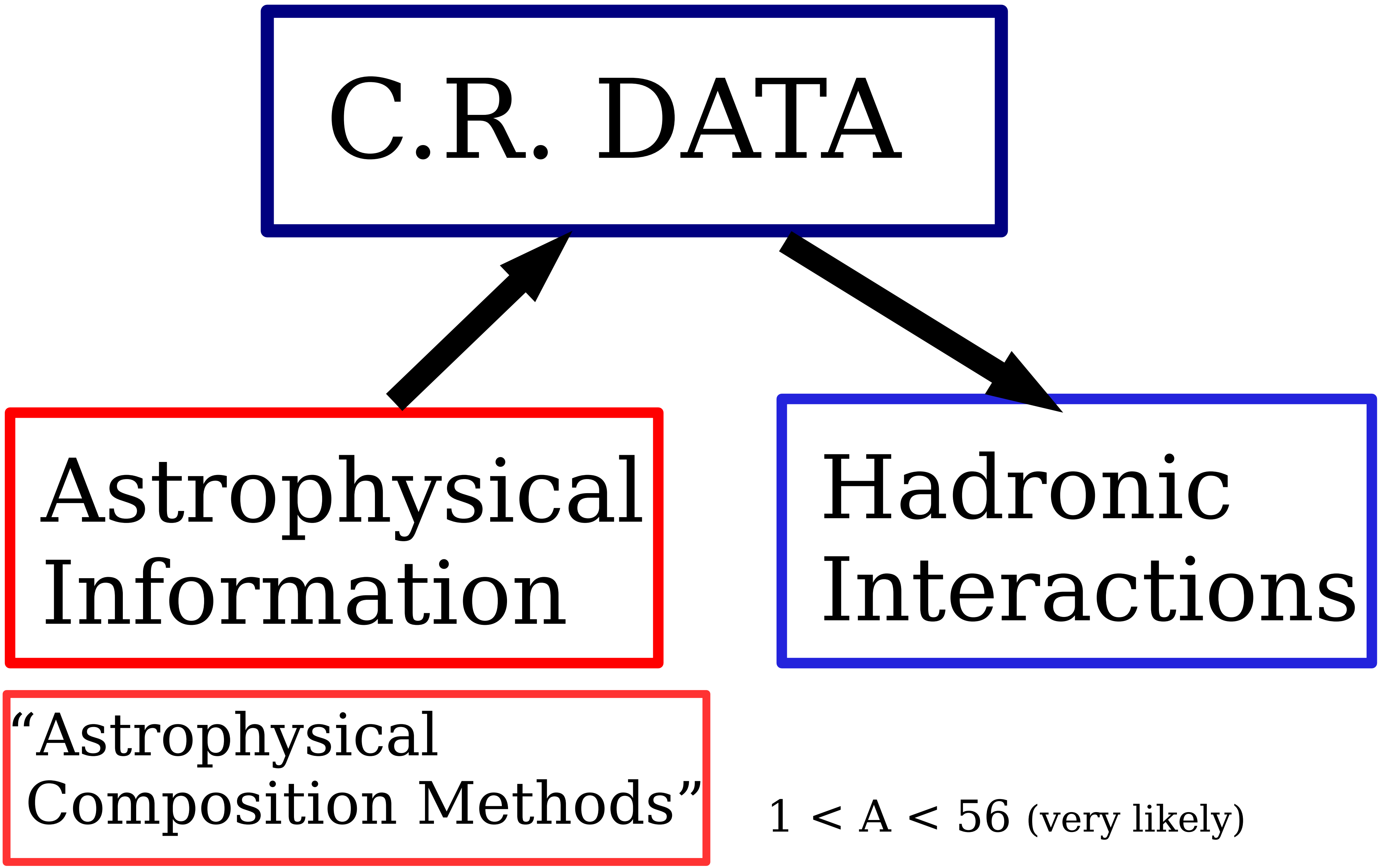
Perhaps we are missing
something important.


900
800
700
600
<X_max> (g cm^-2)
17
18
19
20
Log10[E (ev)]
HIRES−MIA
HIRES
AUGER
p
Fe
Sibyll 2.1
QGSJET−2.03

From Cosmic Ray Data → 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 :

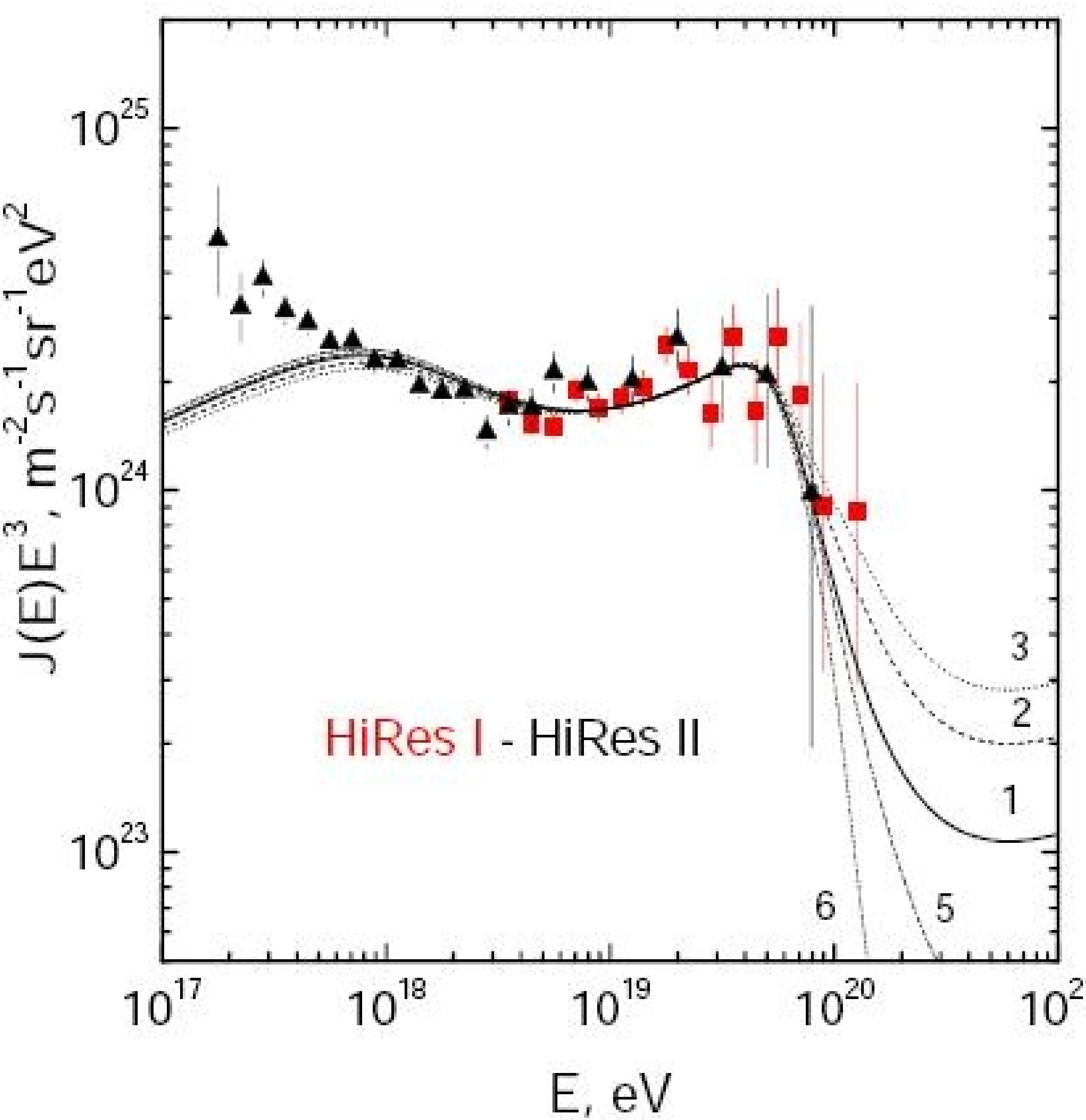
$$p\,\gamma \rightarrow p\pi^{\circ}$$

$$p\,\gamma \rightarrow n\pi^{+}$$

"GZK"

$$p\,\gamma \rightarrow p\,e^{+}e^{-}$$

Pair Production



Berezinsky
et al.

Inject Smooth
power law
Spectrum.

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

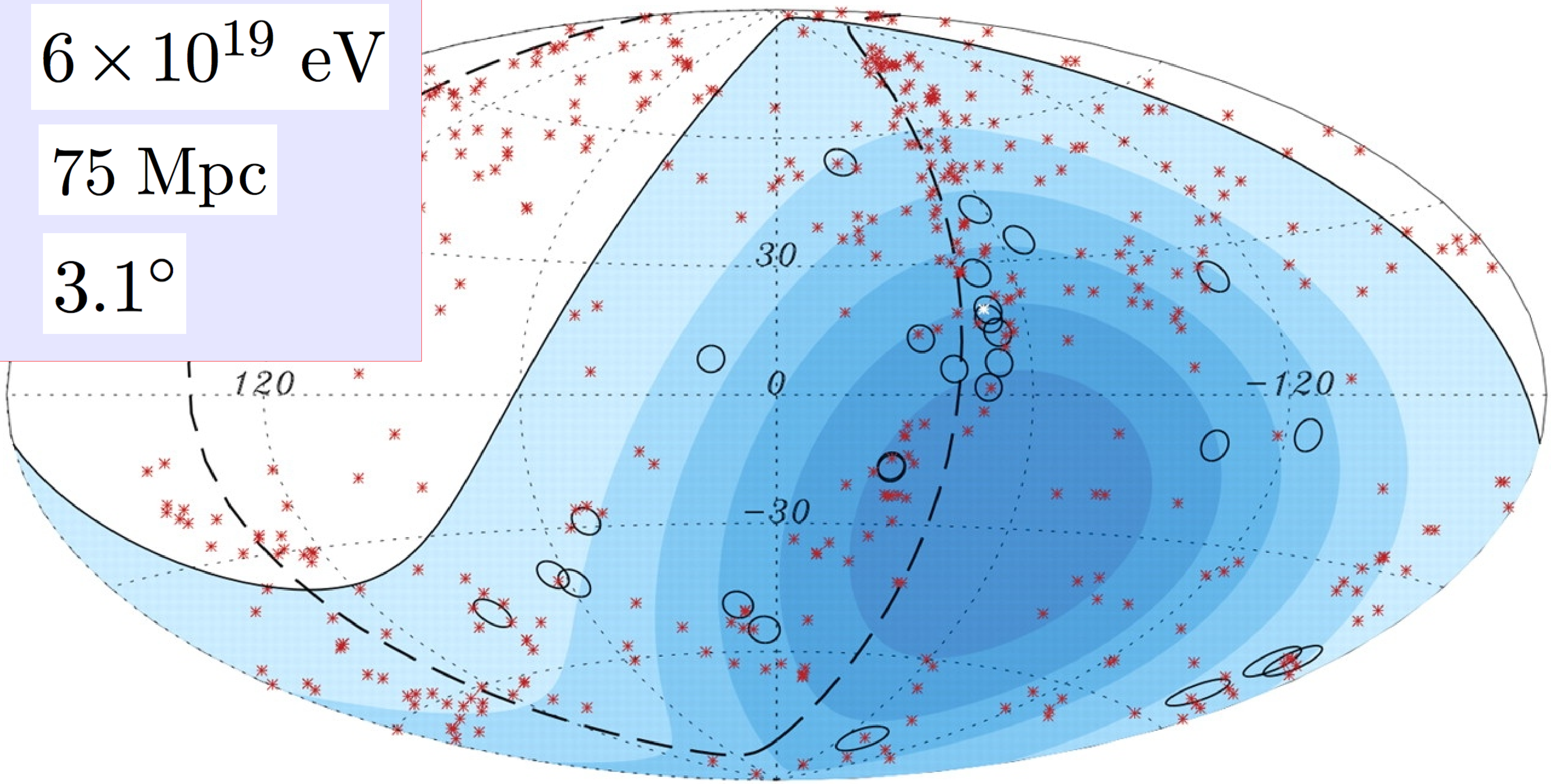
“ANKLE”
-->
“DIP”
e+e- production

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

6×10^{19} eV

75 Mpc

3.1°



Select highest energy Showers.

14 ev. 8 coincid. (2.9)
13 ev. 9 coincid. (2.7)

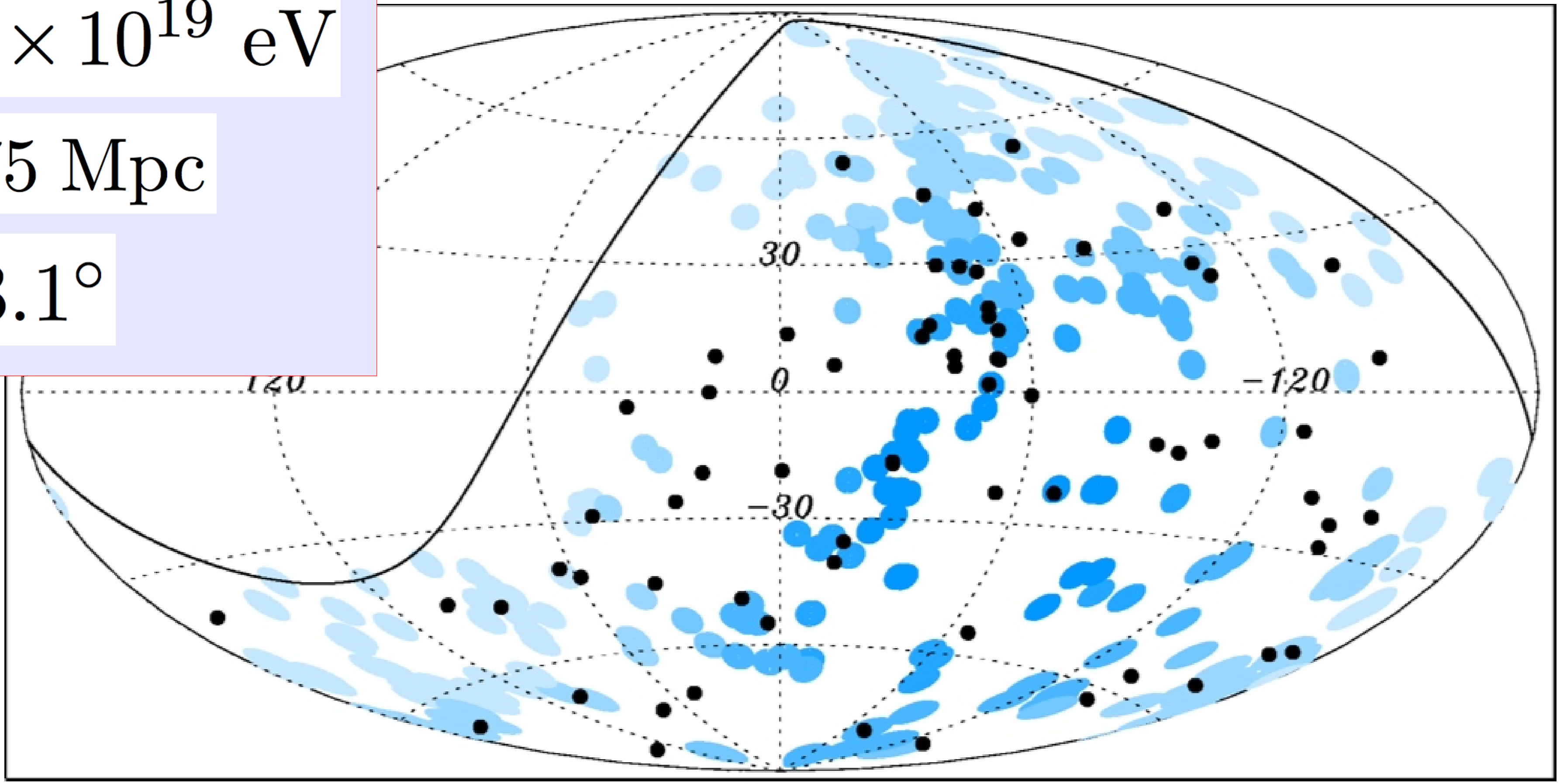
AUGER result on Correlations with the VCV AGN catalogue

Update september 2010.

6×10^{19} eV

75 Mpc

3.1°



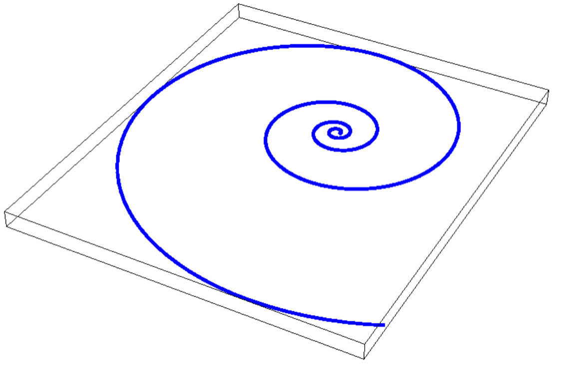
Significant dilution
[but not disappearance]
of the statistical significance

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

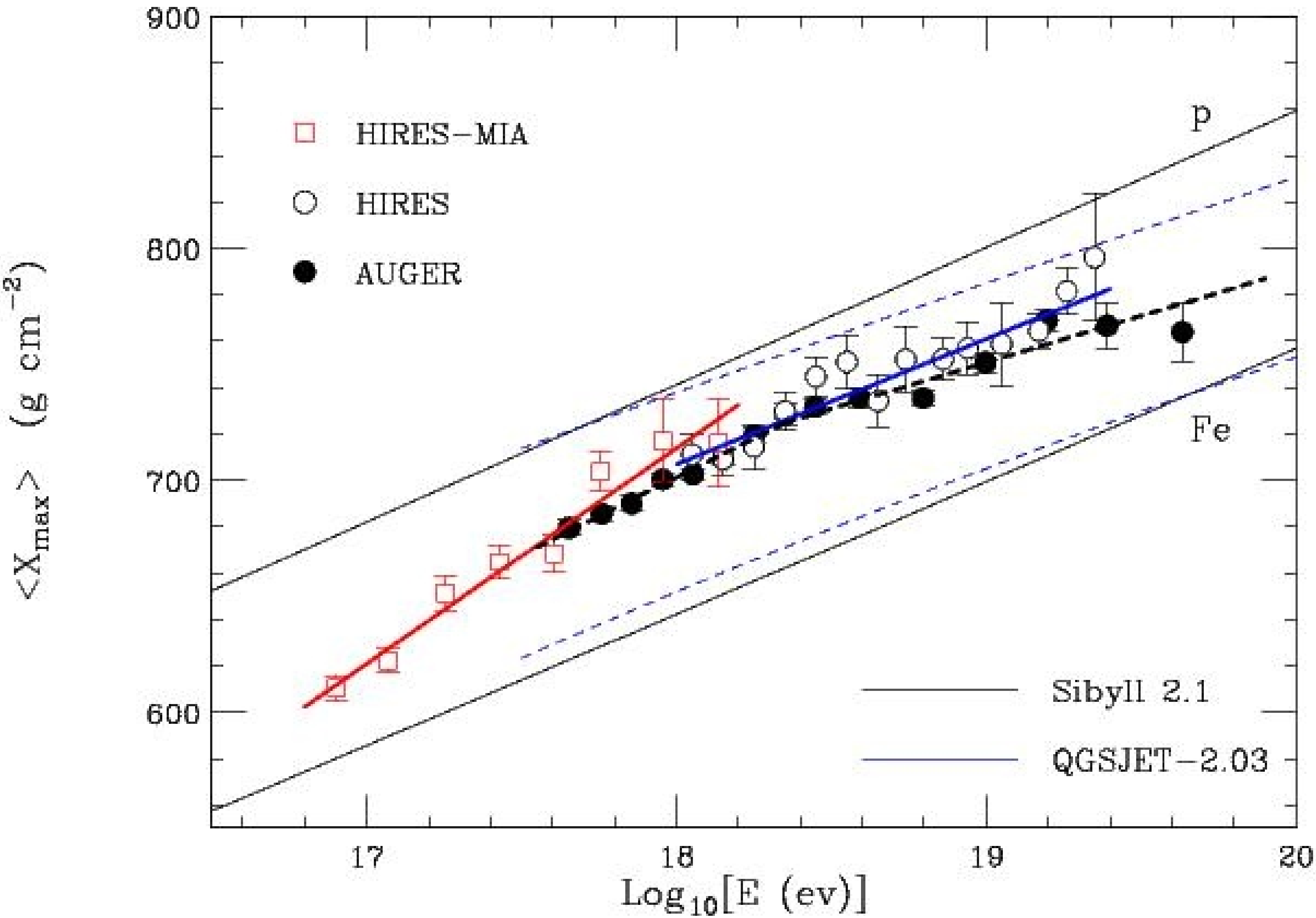
$$\delta \simeq 2.7^\circ \frac{60\ \text{EeV}}{E/Z} \left| \int_0^D \left(\frac{\mathrm{d}\mathbf{x}}{\text{kpc}} \times \frac{\mathbf{B}}{3\ \mu\text{G}} \right) \right|$$



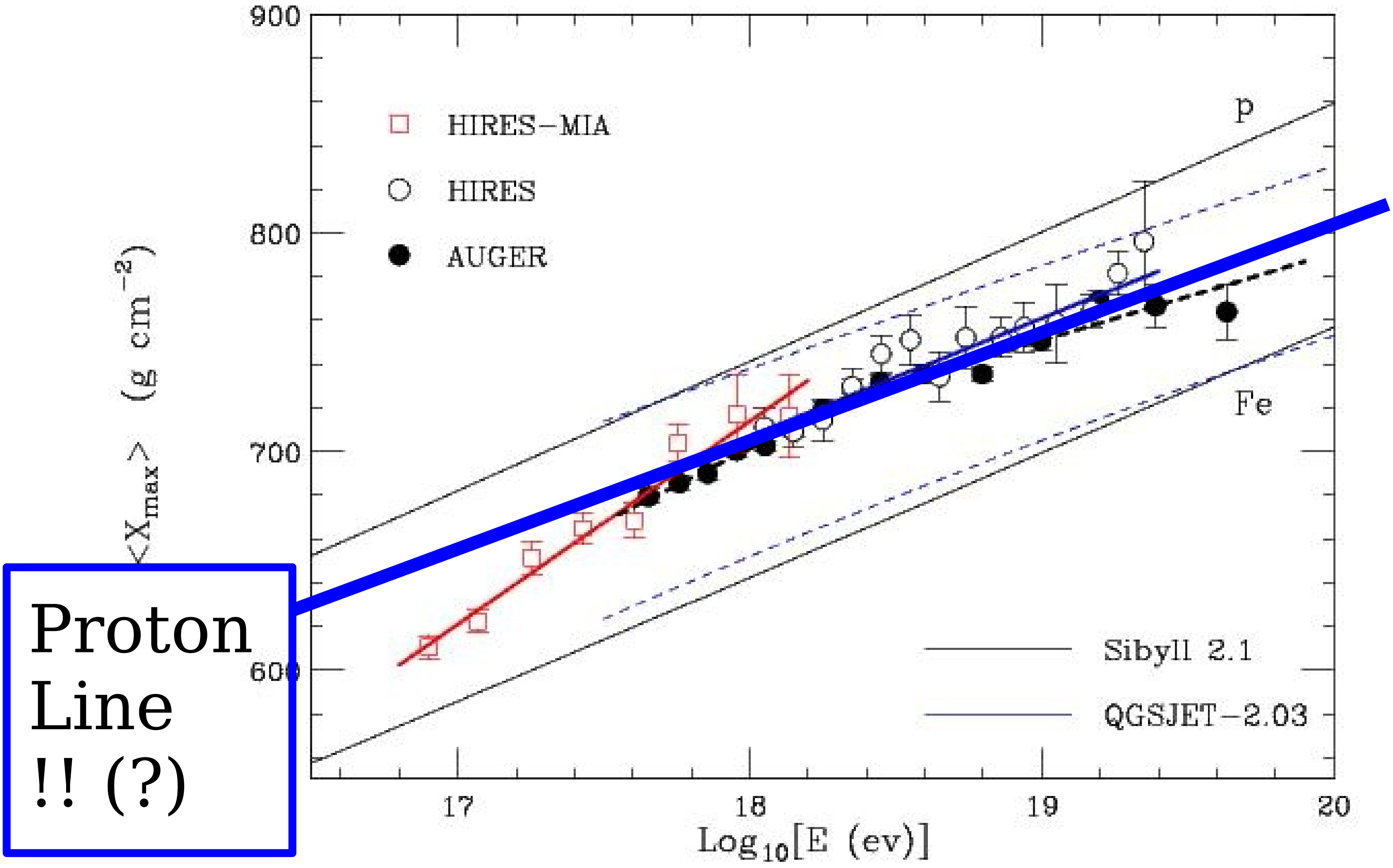
Deviation in EXTRA-GLACTIC Magnetic Field

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

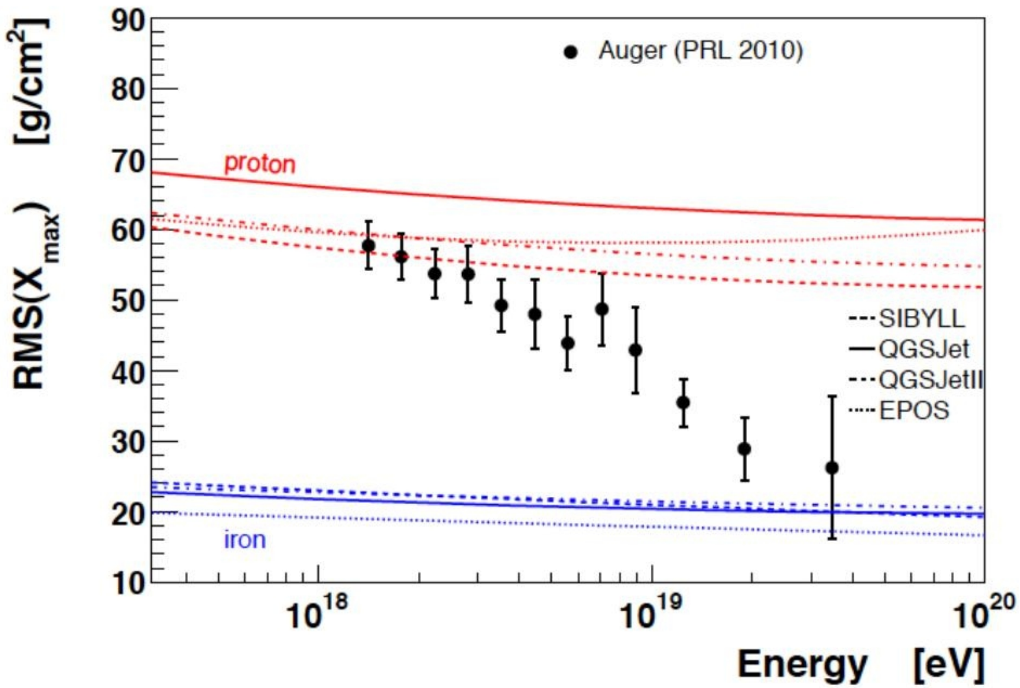
IF one accepts (at least for the sake of discussion) the astrophysical hints of a proton dominated composition....



IF one accepts (at least for the sake of discussion) the astrophysical hints of a proton dominated composition....

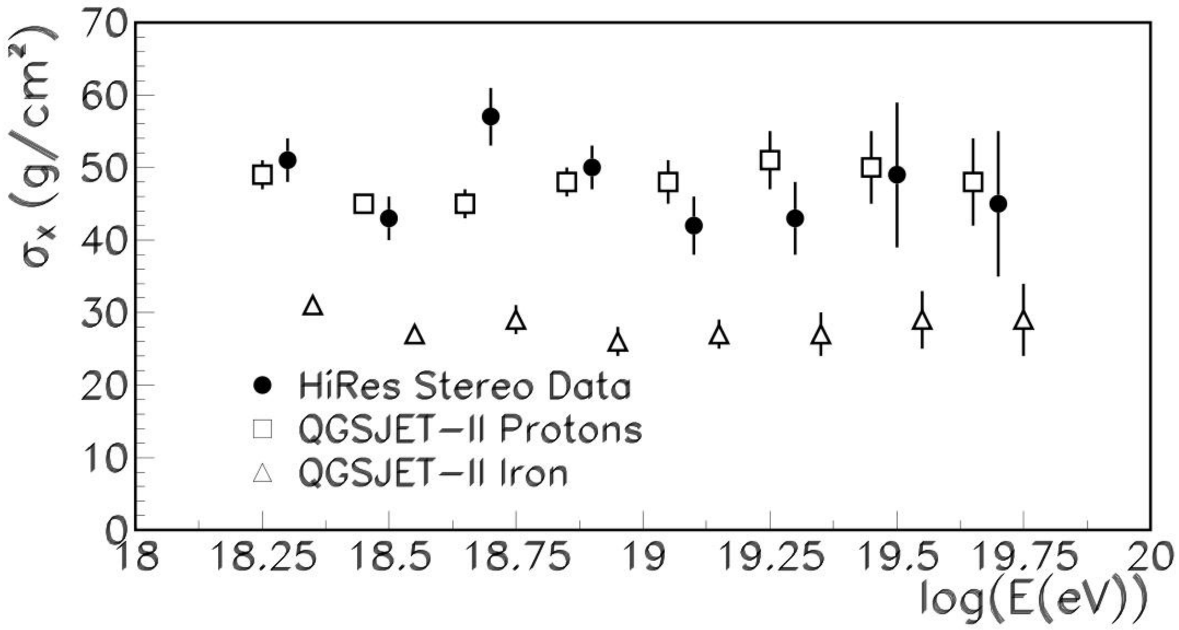


X_{max} fluctuations

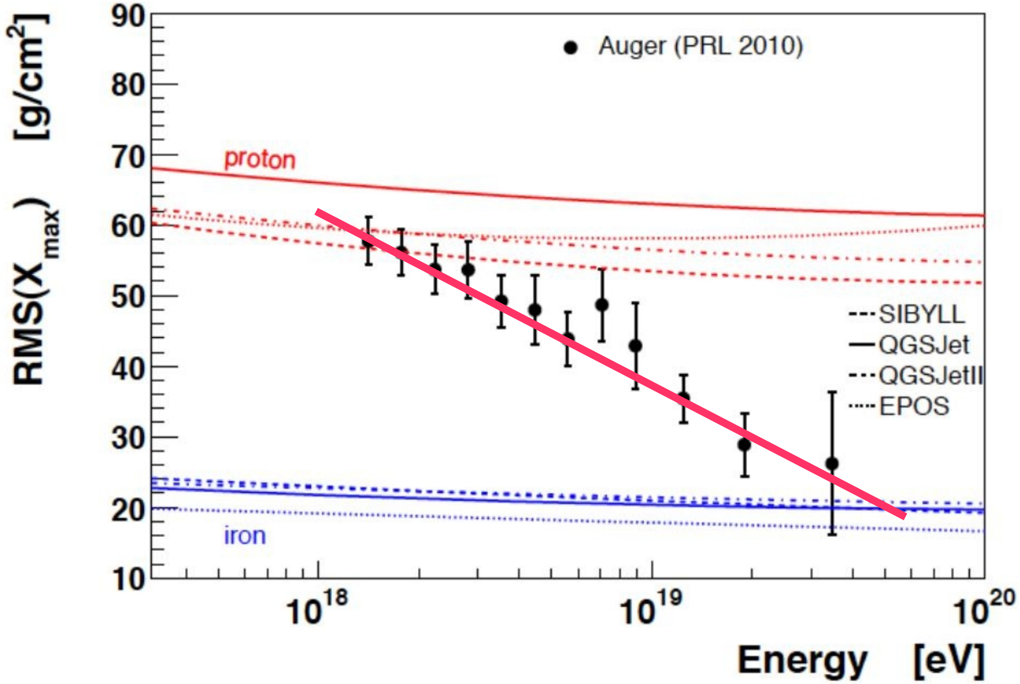


Auger

HiRes



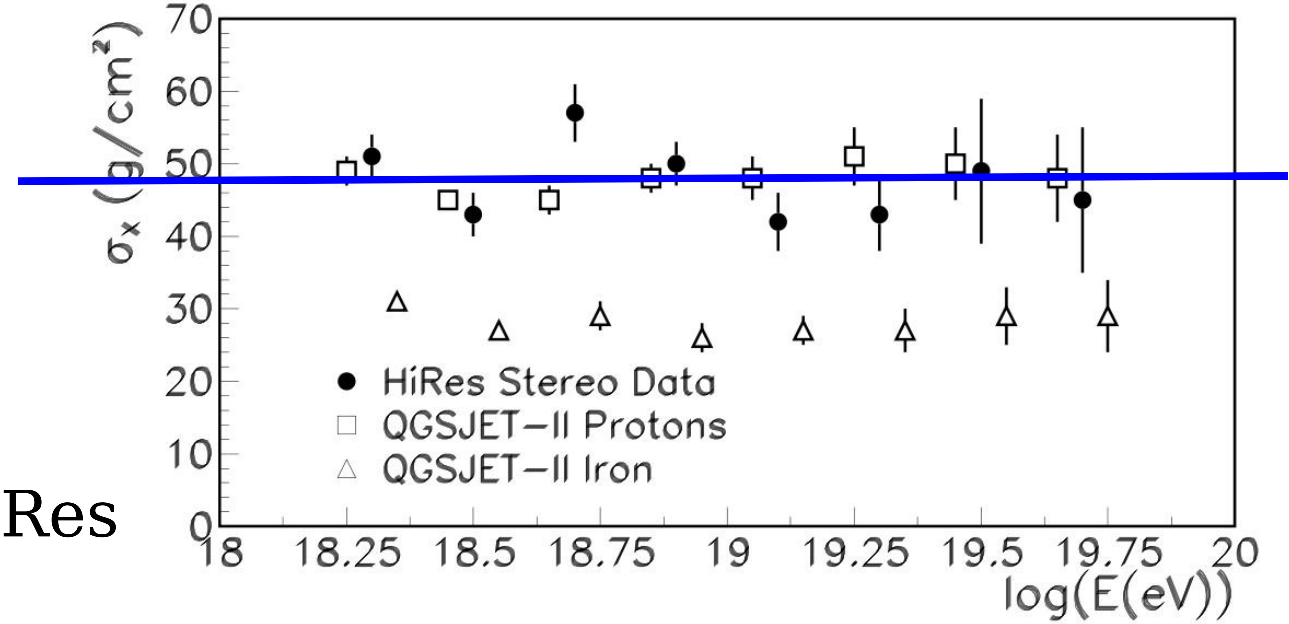
X_{max} fluctuations



Auger

Quasi – monotonically
Decreasing RMS

Constant RMS



HiRes

Overall comparison of Xmax data with QGSJET02 p and FE

HIRES

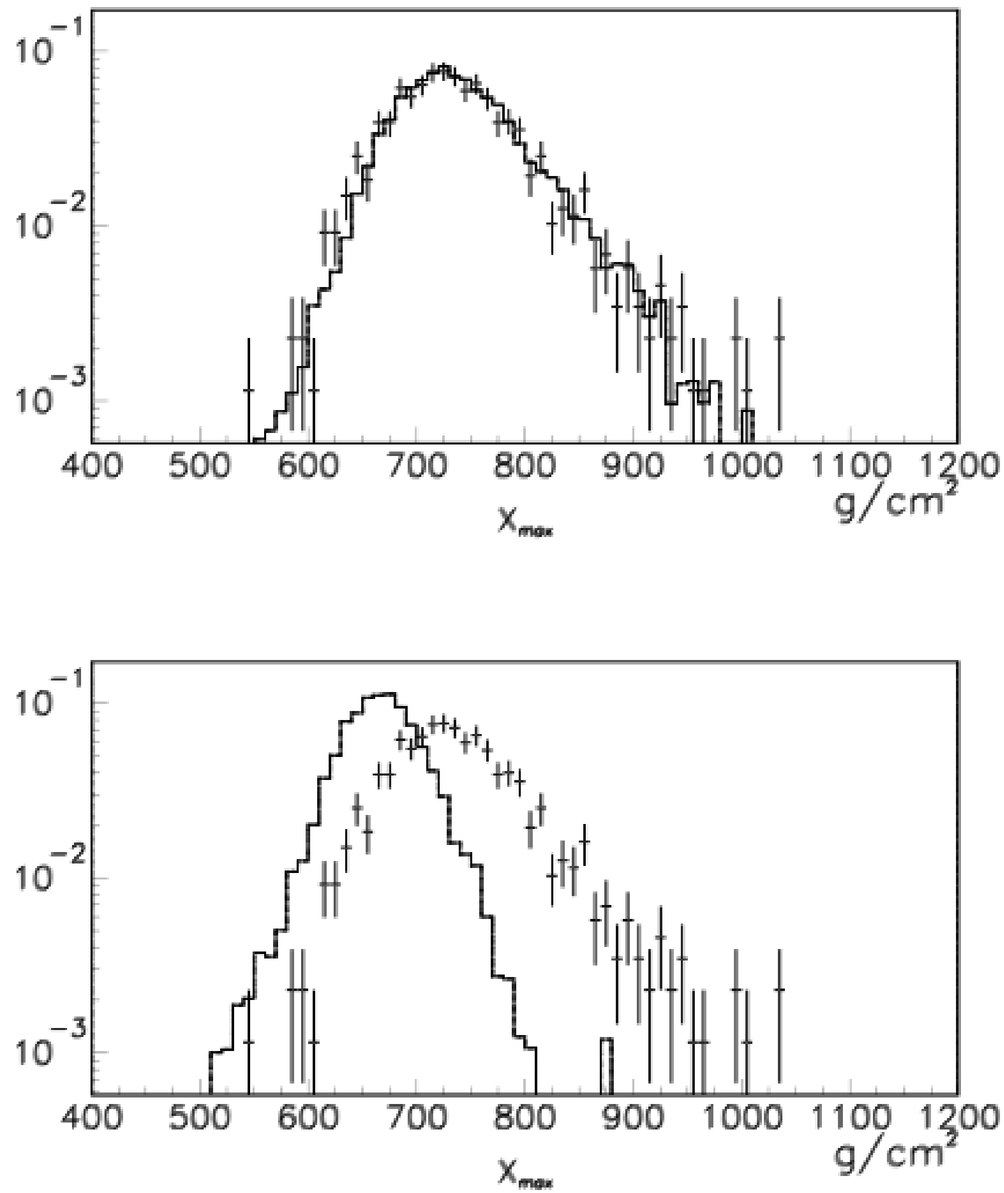


Fig. 11.— *Top:* X_{max} overlay of HiRes data (points) with QGSJET02 proton Monte Carlo airshowers after full detector simulation. *Bottom:* X_{max} overlay of HiRes data (points) with QGSJET02 iron Monte Carlo airshowers after full detector simulation.

The distribution of X_{max} encodes valuable informations on the detector performance and on the fundamental properties of the showers that is only partially captured by the first 2 momenta

Personal opinion:

The X_{max} distributions are valuable "intellectual property" of the scientists that measure it.

But for a healthy scientific discussion, they should be made available to our entire community in a reasonable time

FLUCTUATIONS on $X_{\rm max}$

$$X_{\rm max} = X_{\rm 1st} + Y_{\rm max}$$

$$\sigma^2_{X_{\rm max}} = \sigma^2_{X_{\rm 1st}} + \sigma^2_{Y_{\rm max}}$$

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

Toy model

$$\left(\sigma^{\rm proton}_{\langle X_{\rm max}\rangle}\right)^2 \simeq \lambda_p^2 + X^2_{\rm rad} \;\left[\left\langle (\ln n_\gamma)^2 \right\rangle - \langle \ln n_\gamma \rangle^2\right]$$

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

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

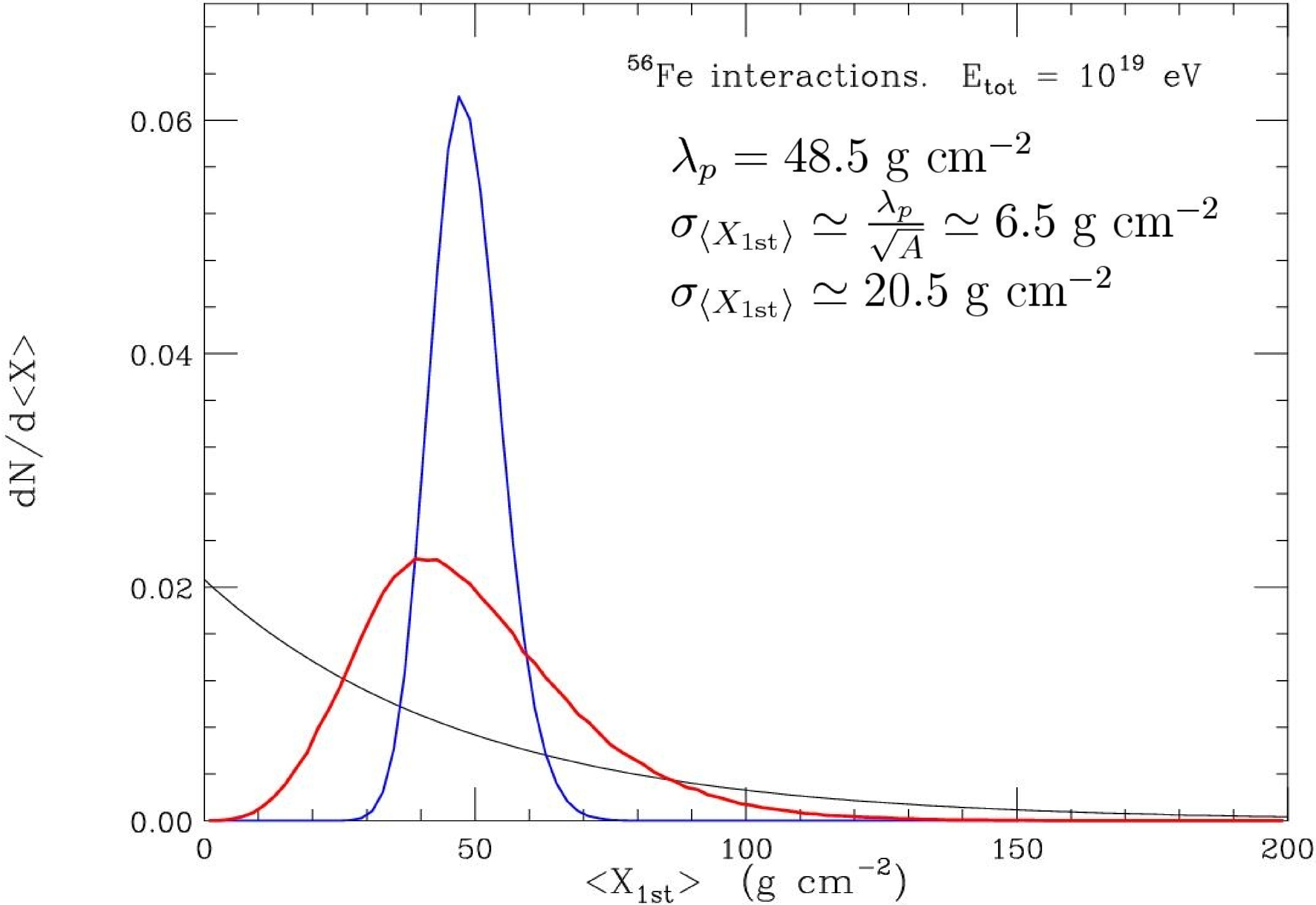
$$A = 56$$

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

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

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

Nuclear interaction.
Several Nucleons
Interact at same point.



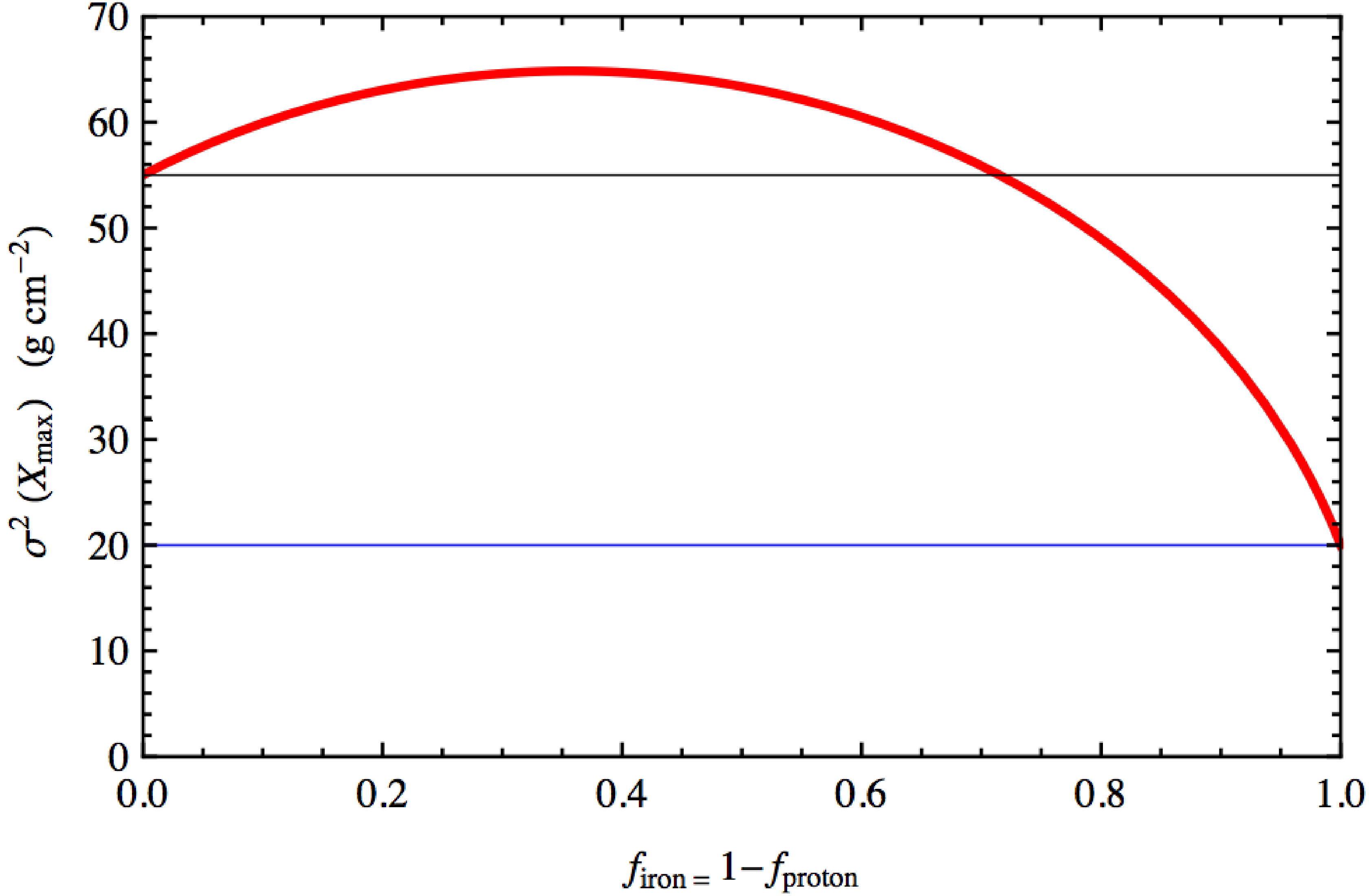
^{56}Fe interactions. $E_{tot} = 10^{19}$ eV
$\lambda_p = 48.5$ g cm^{-2}
$\sigma_{\langle X_{1st} \rangle} \simeq \frac{\lambda_p}{\sqrt{A}} \simeq 6.5$ g cm^{-2}
$\sigma_{\langle X_{1st} \rangle} \simeq 20.5$ g cm^{-2}
dN/d<X>
0.00
0.02
0.04
0.06
0
50
100
150
200
<X_{1st}> (g cm^{-2})

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

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

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

Mixing Protons with Iron-nuclei



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

THEORY

Construction of Hadronic Models

Hadronic Interactions

Composite (complex) Objects
Multiple interaction structure

QCD

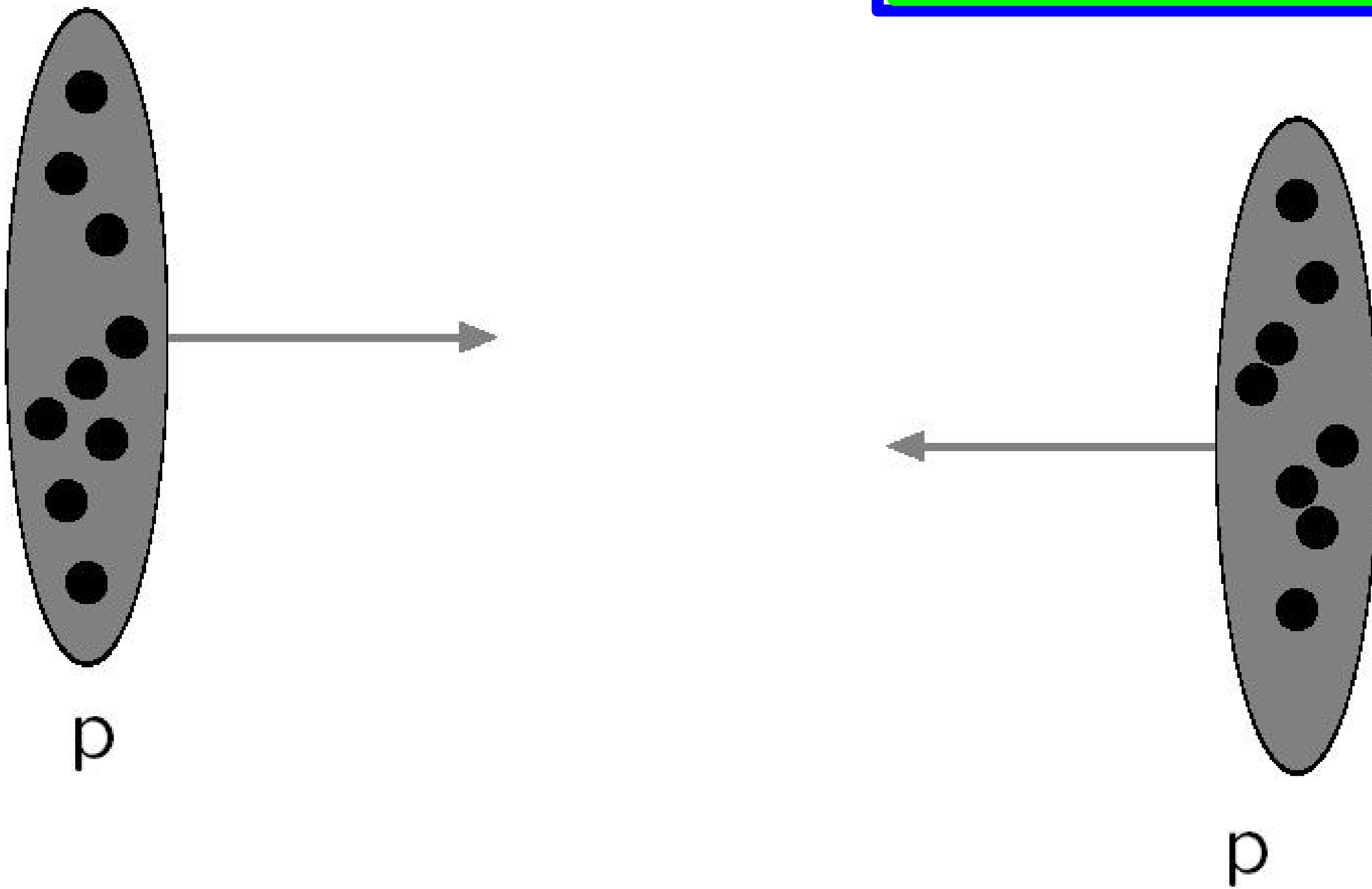
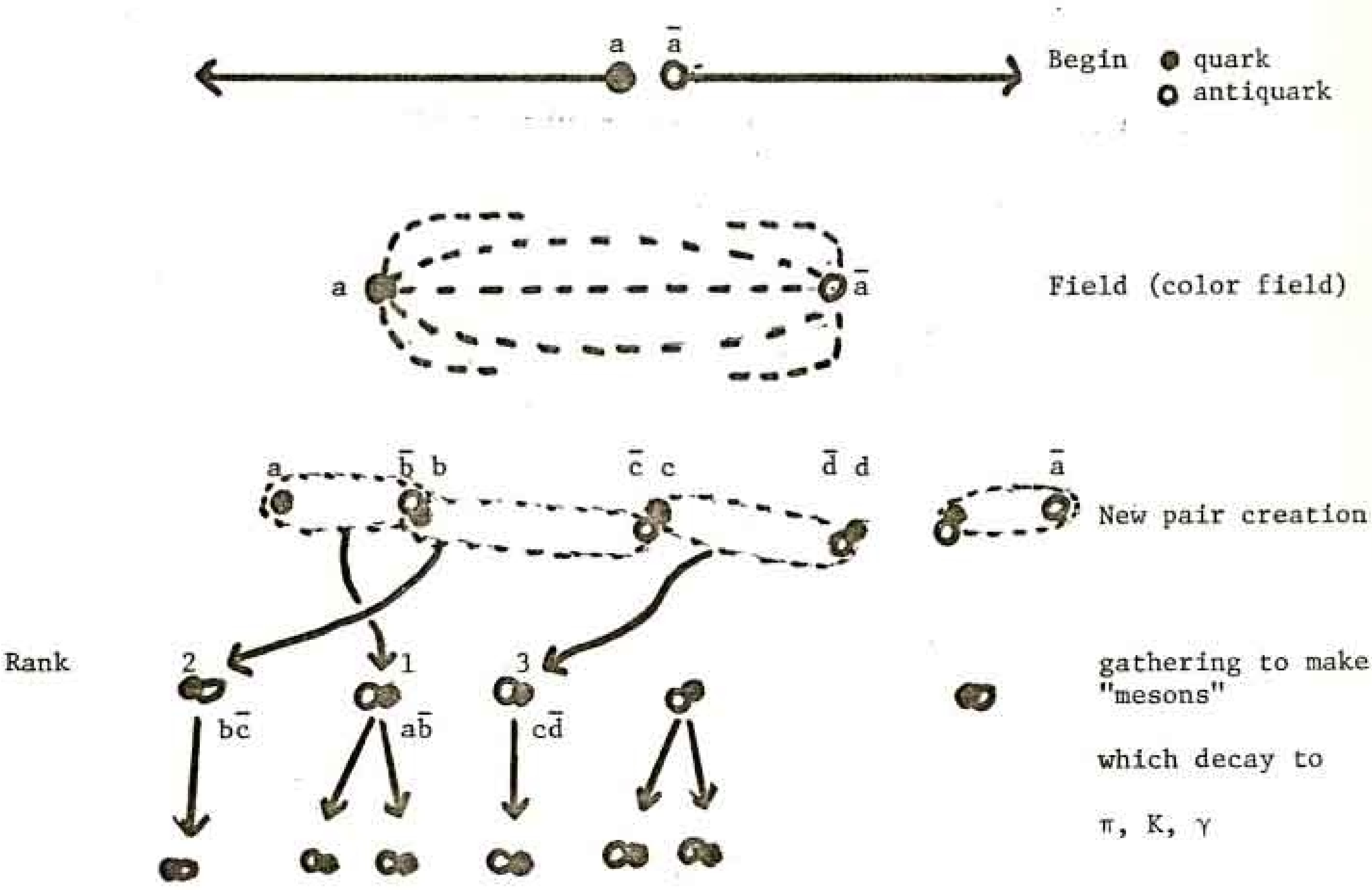


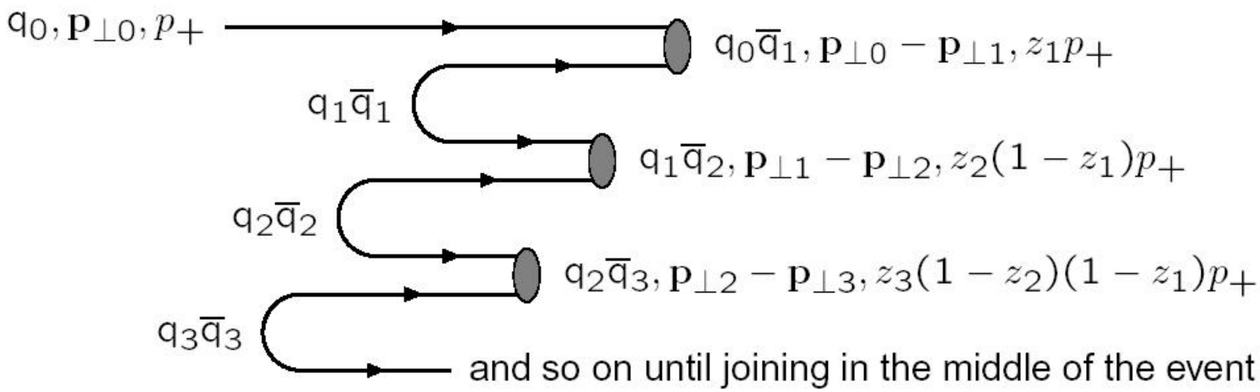
Fig. 1. An e^+e^- Annihilation

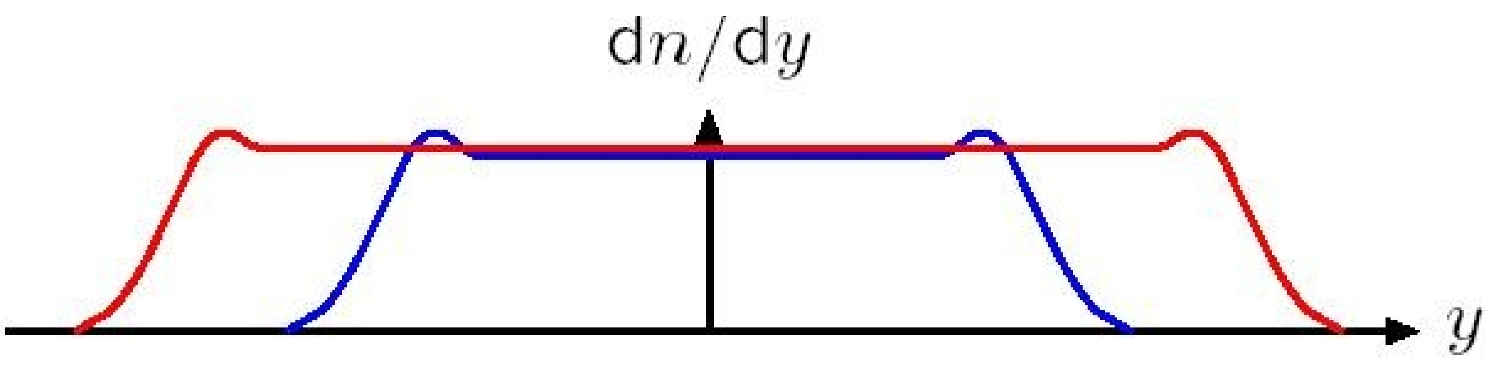


Field -Feynman : Quark - Fragmentation

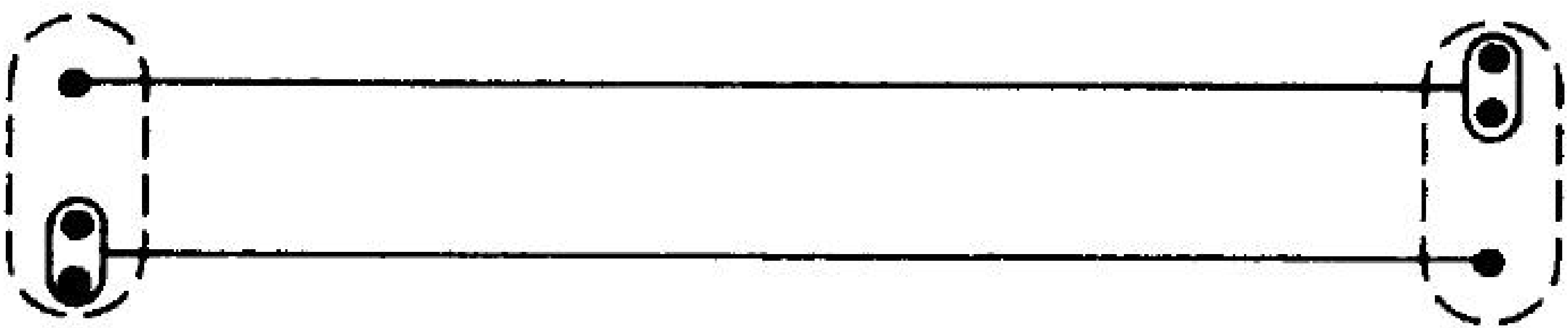
Where does the approximate Feynman scaling comes from ?

The (iterative) Fragmentation of one COLOR STRING produces a SCALING SPECTRUM of HADRONS





$\langle n_{\rm ch} \rangle \approx c_0 + c_1 \ln E_{\rm cm}$, $\sim$ Poissonian multiplicity distribution



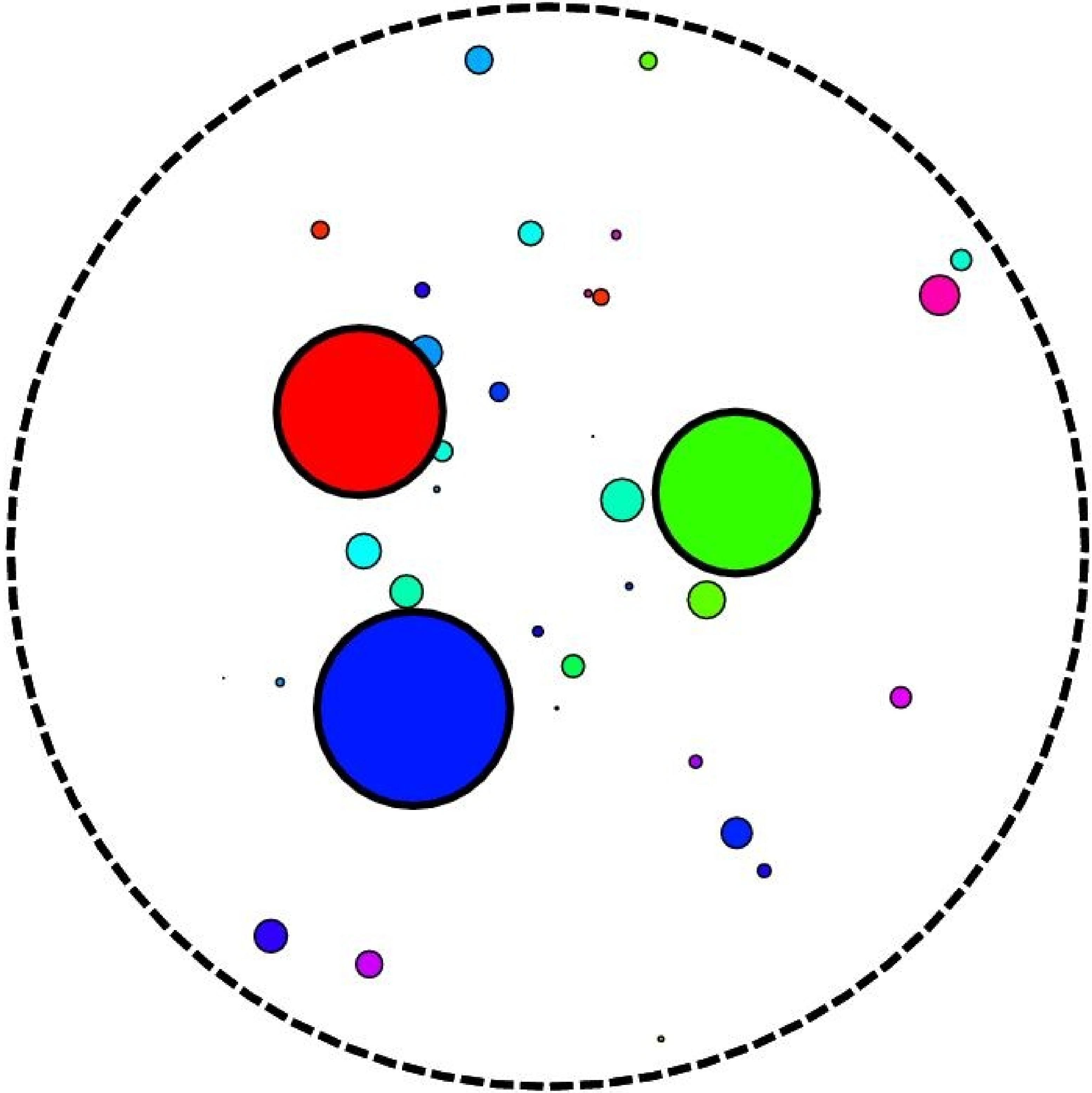
Basic Structure of
a NON diffractive PP interactions
is made of TWO STRINGS

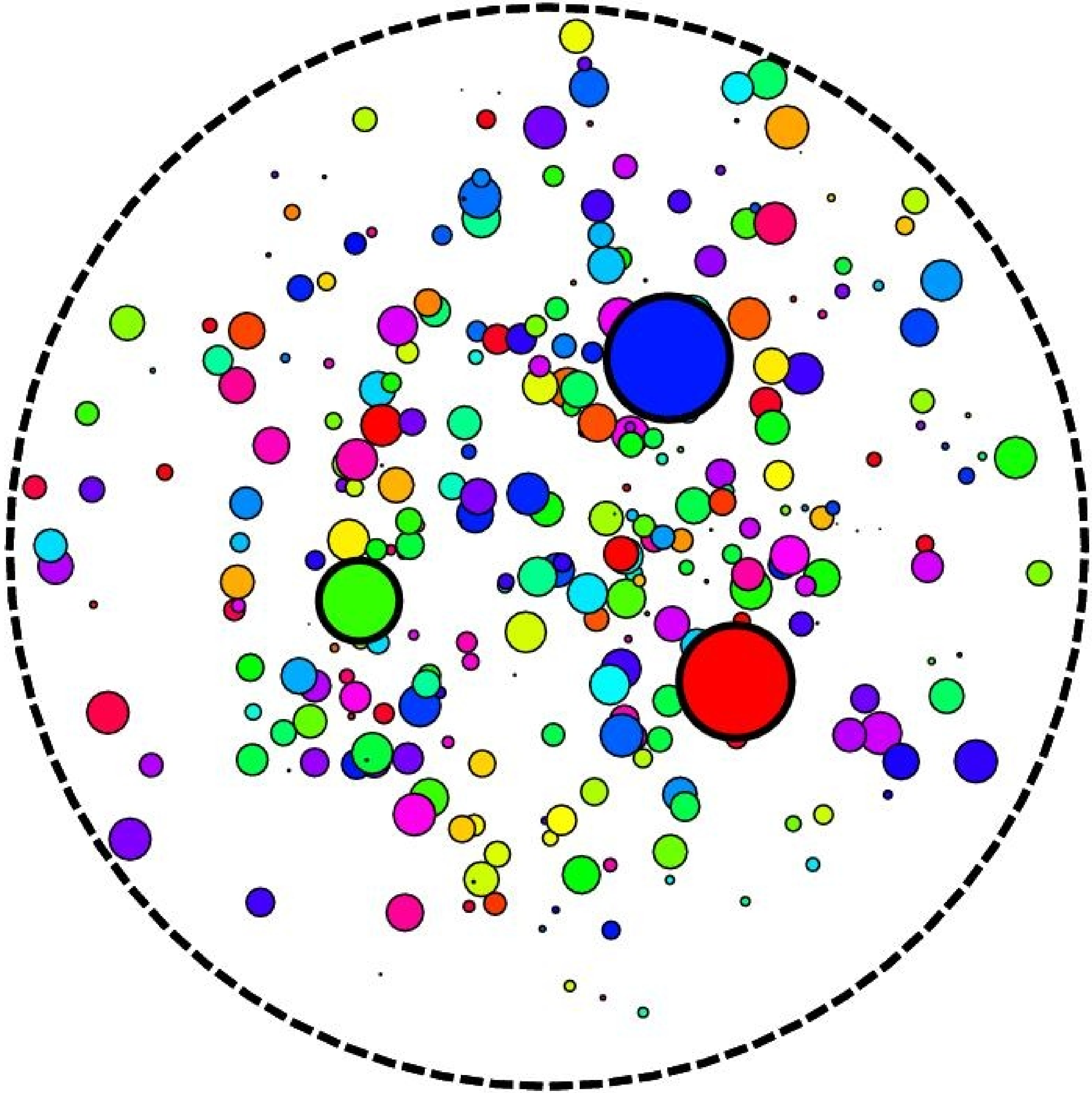
hard/semihard interactions
result in additional strings

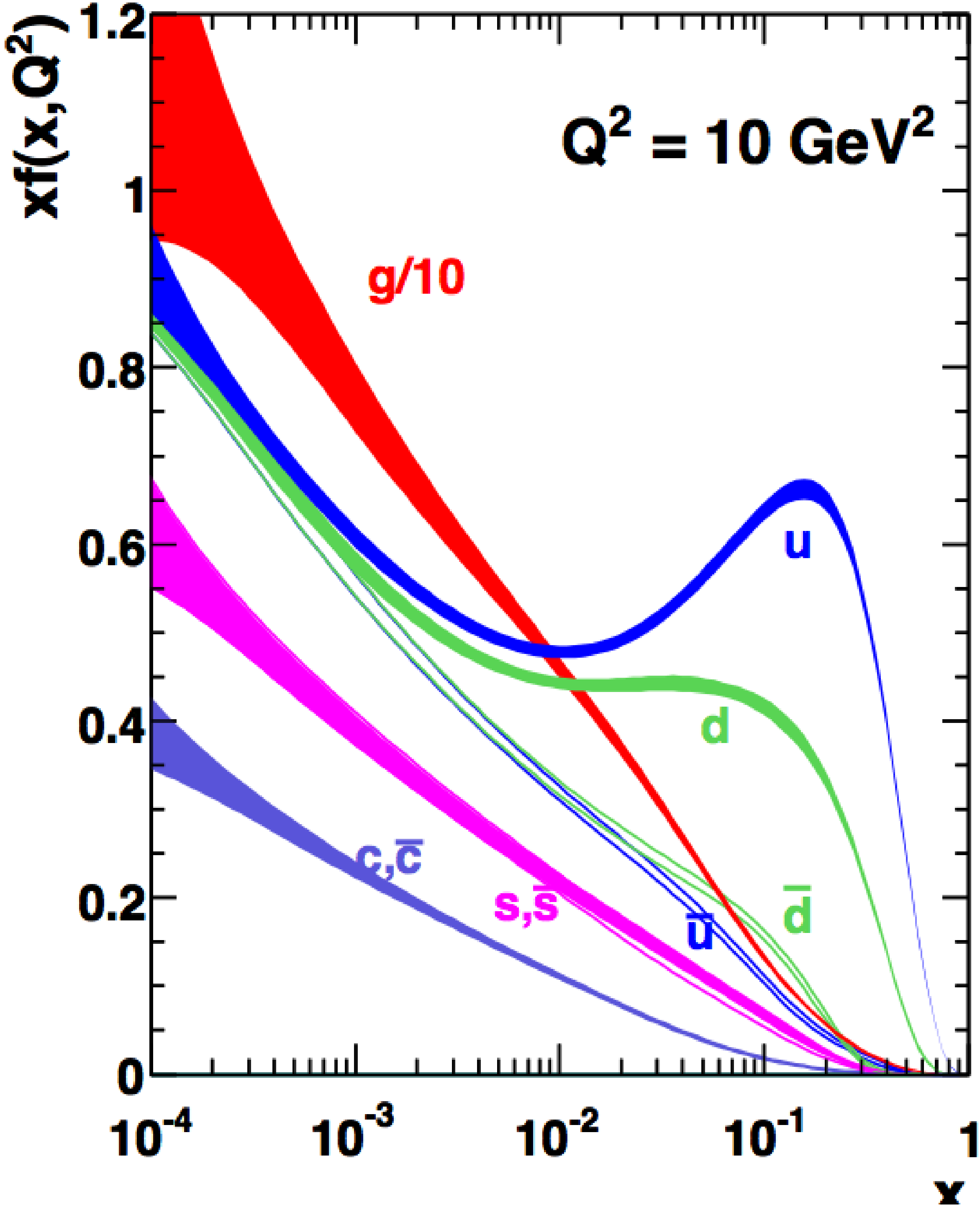
Color Structure

$$3 \otimes 3 = \overline{3} \oplus 6$$

$$3 \otimes \overline{3} = 1 \oplus 8$$



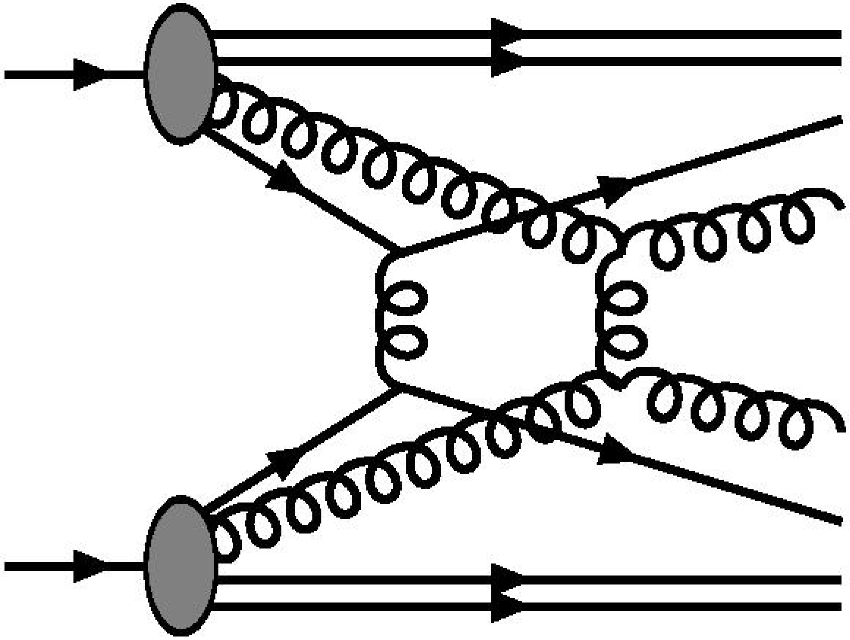




Parton Distribution Function

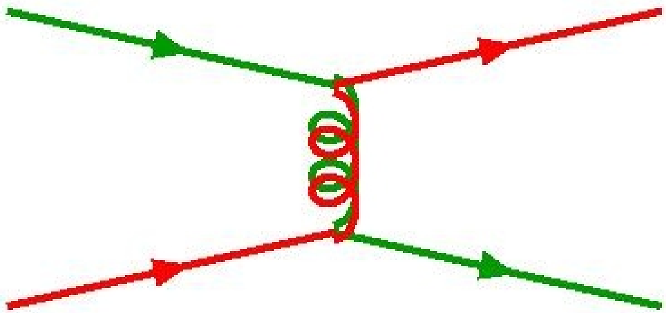
Typically 2 – 3 interactions/event at the Tevatron, 4 – 5 at the LHC, but may be more in "interesting" high-$p_\perp$ ones.

Pythia MC

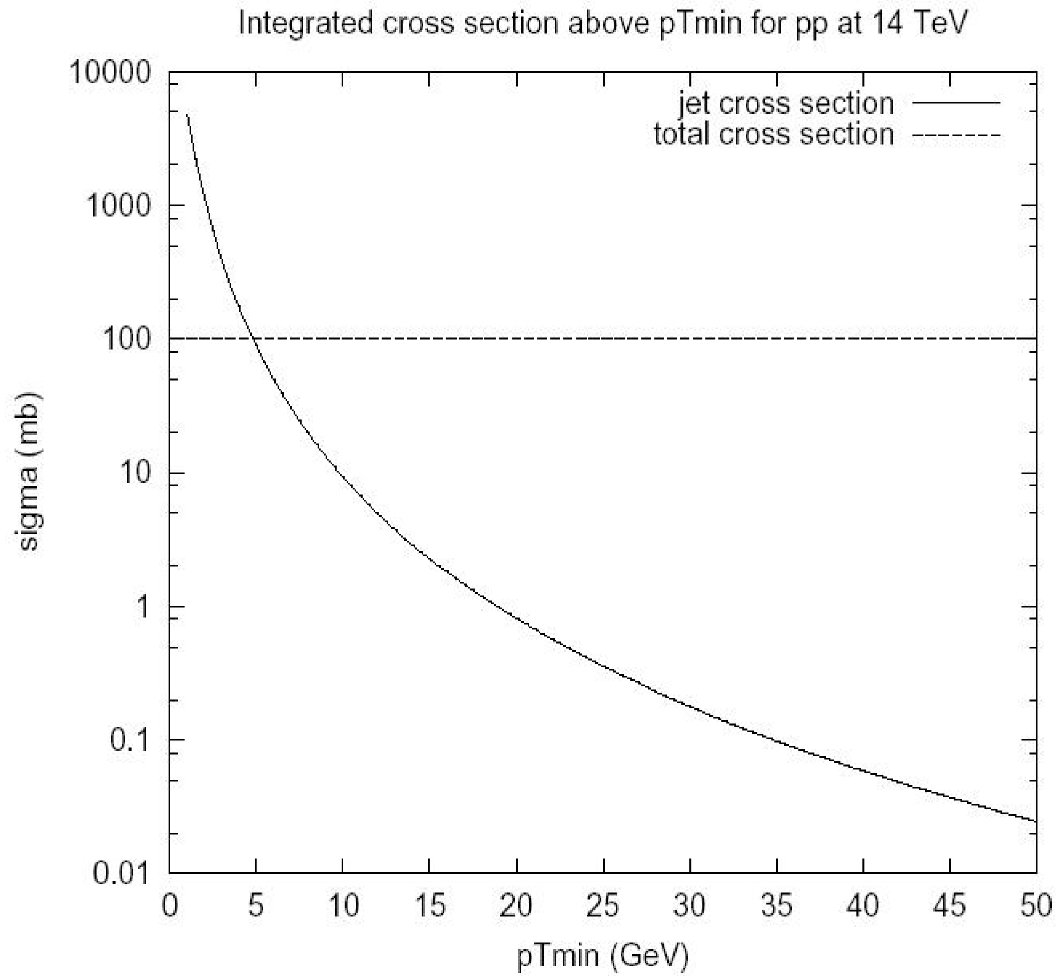


Most particles in Fragmentation Regions Described by the "beam remnants strings"

QCD $2 \to 2$



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



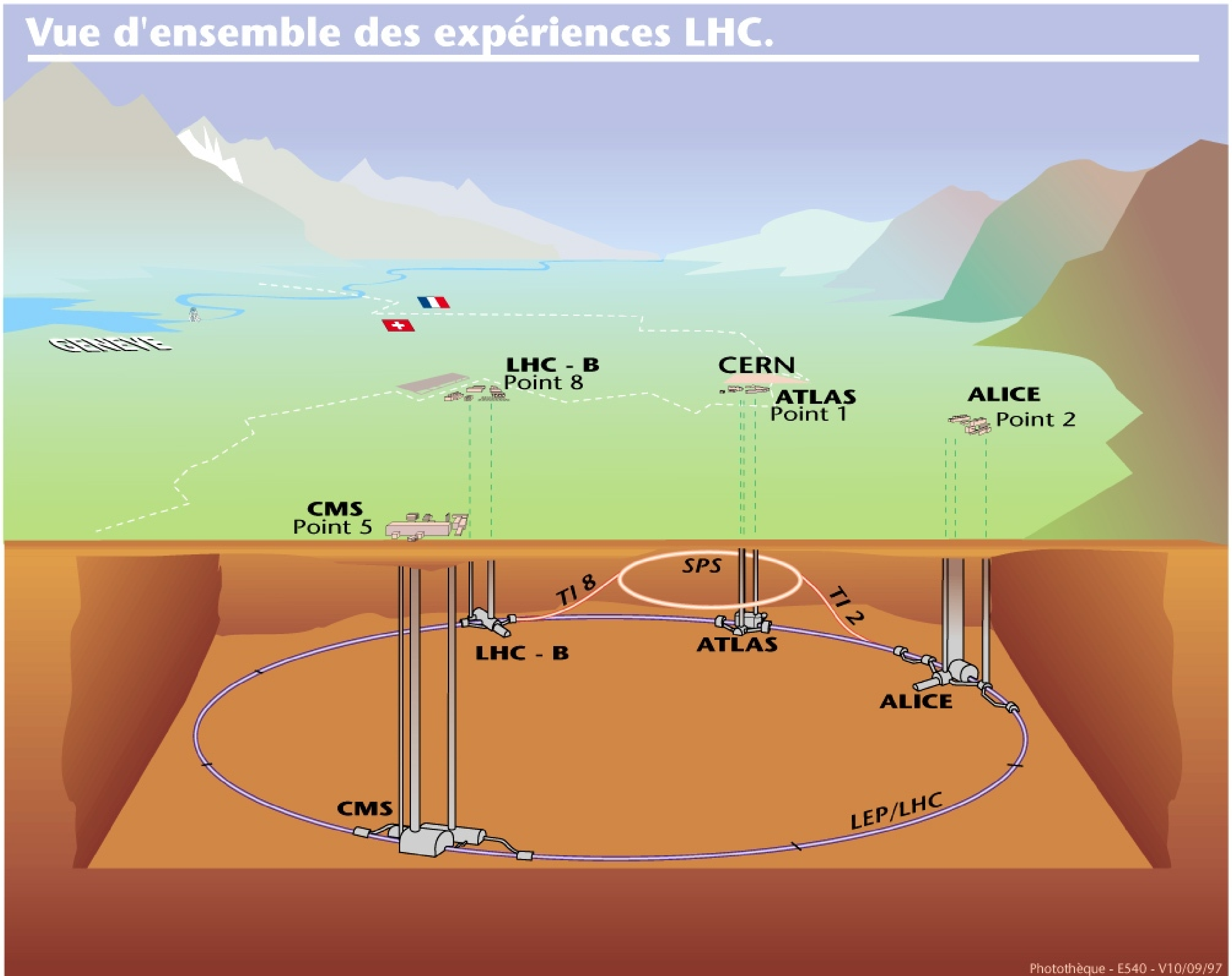
$$d\sigma / dp_\perp^2 \approx 1/p_\perp^4 \text{ for } p_\perp \to 0.$$

MULTIPLE INTERACTIONS

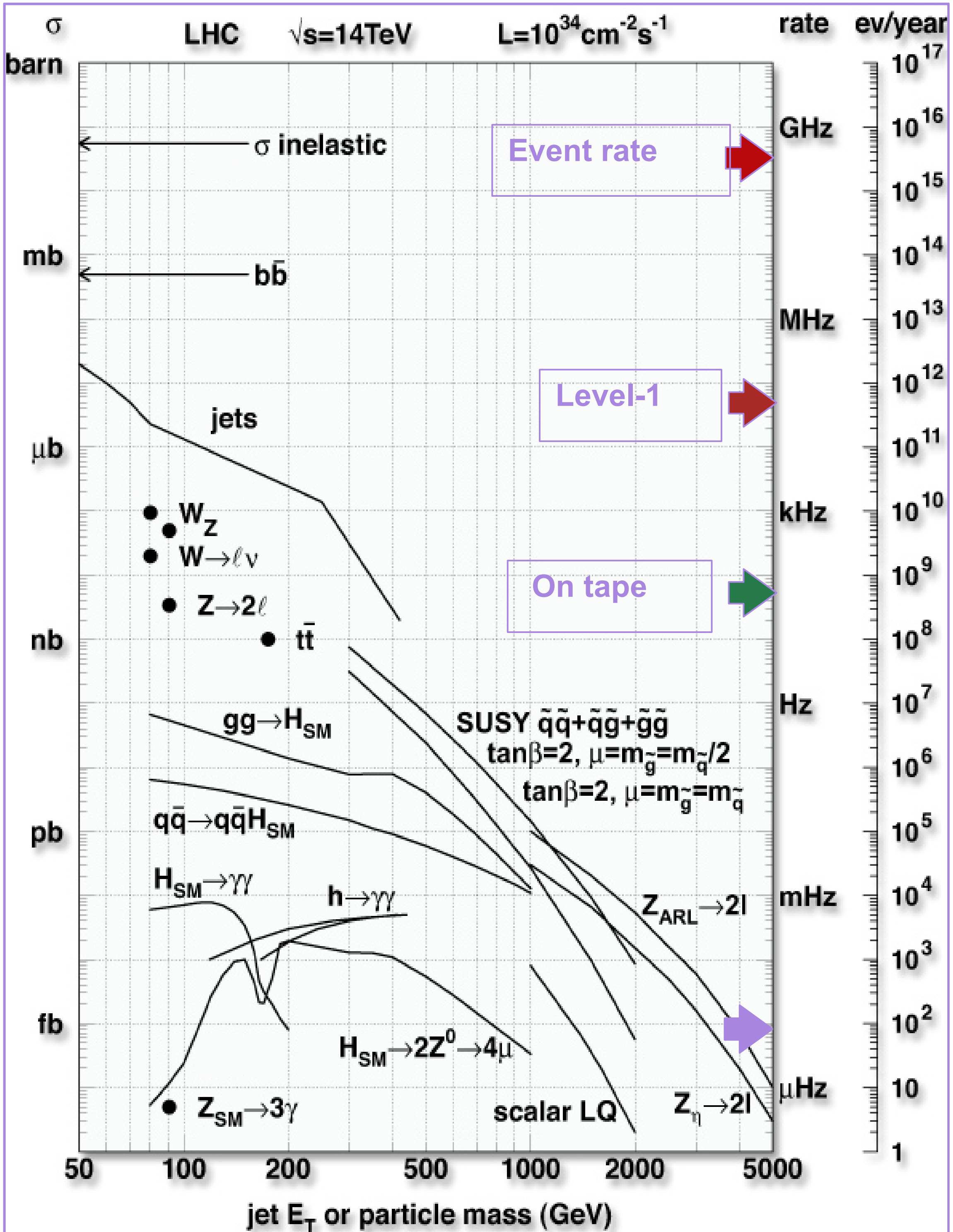
- Estimate of the average number of Elementary interactions per pp scattering
- "Spatial Distribution" (Transverse coordinates) of the partonic constituents. [proton spin]
- Fluctuations of the "parton configuration" of an interactig hadron.

Beyond PDF's
Parton Distribution Functions

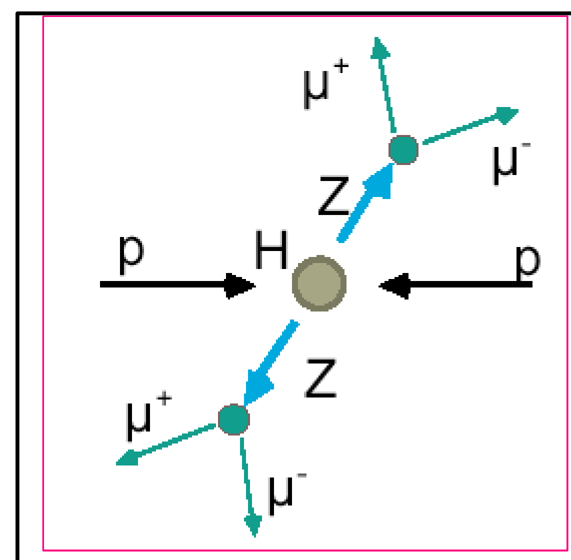
Very Important potential of LHC



7 + 7 TeV
PP collider



Higgs discovery golden channel



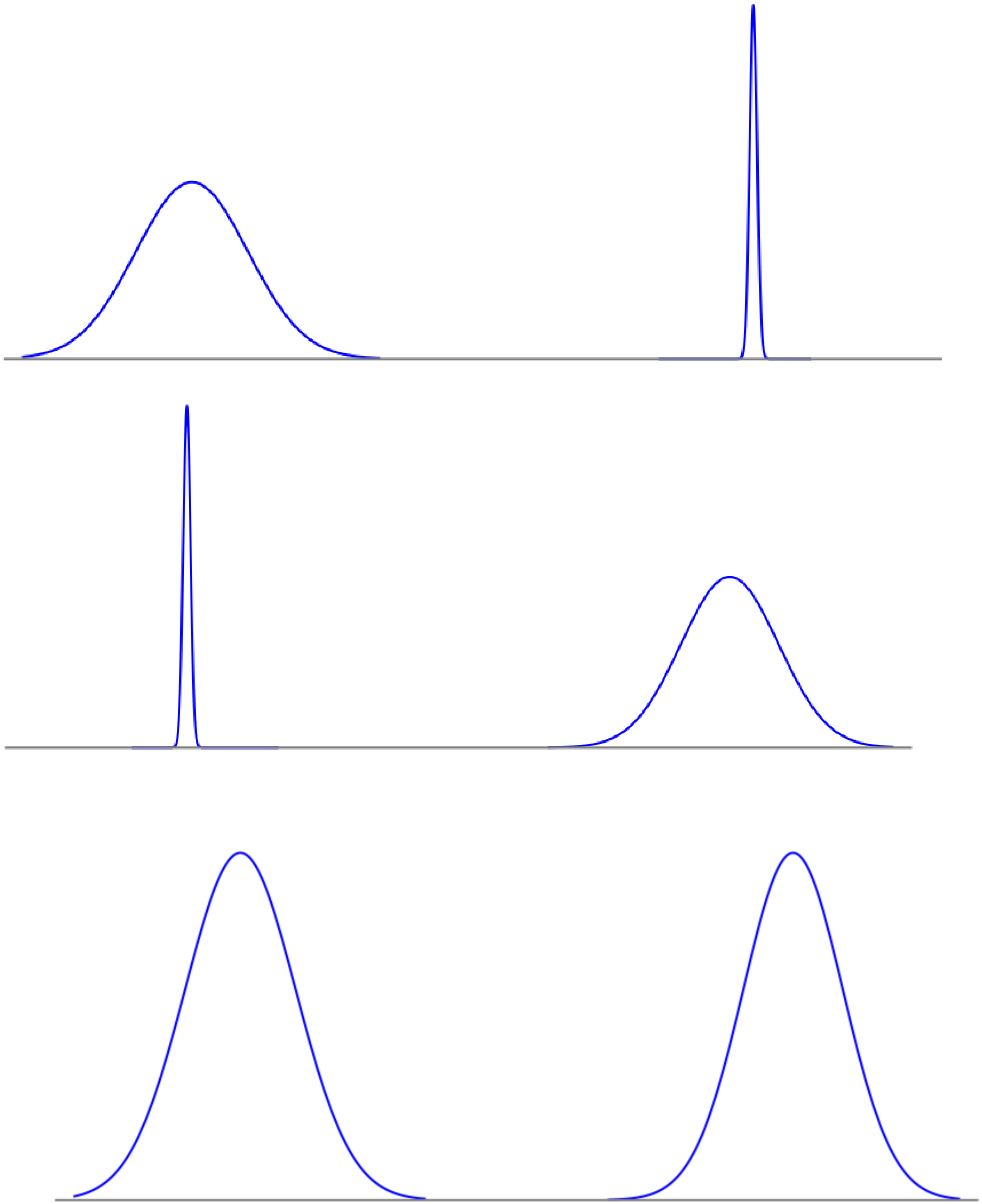
$$\sigma_{\text{tot}} \qquad \sigma_{\text{el}} \qquad \frac{d\sigma_{\text{el}}}{dt}$$

$$\frac{dN_{\text{ch}}}{dy} \qquad \frac{dN_{\text{ch}}}{d\eta} \qquad \frac{dN_{\text{ch}}}{dp_\perp\, dy}$$

$$\sigma_{\text{diffractive}}$$

$$\sigma_{\text{FD}} \qquad \sigma_{\text{BD}} \qquad \sigma_{\text{DD}} \qquad \frac{d^2\sigma_{\text{diff}}}{dt\, dM_X^2}$$

Diffraction

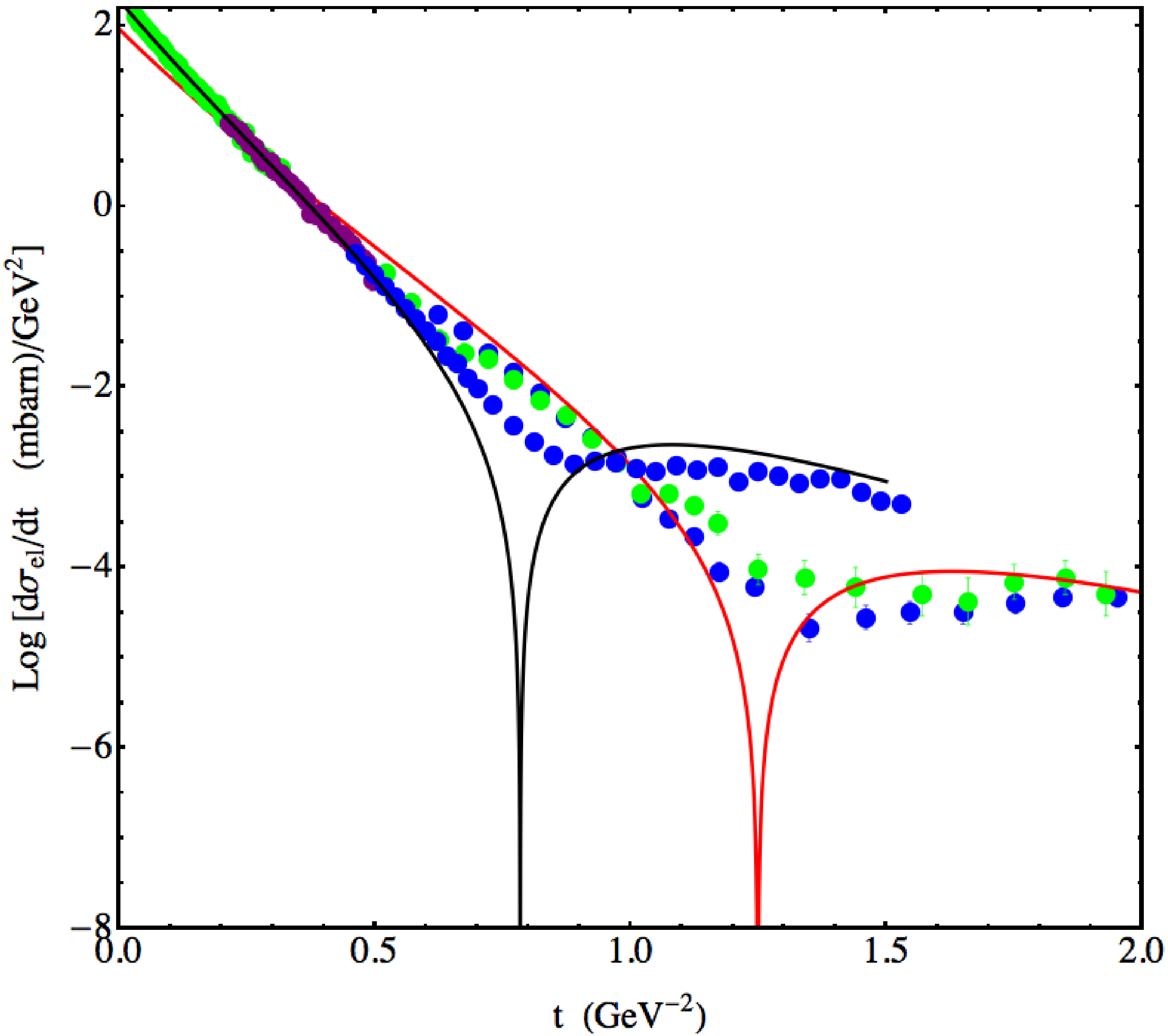


$$h_1 h_2 \longrightarrow h_1^* h_2 \quad \text{(beam diffraction)},$$

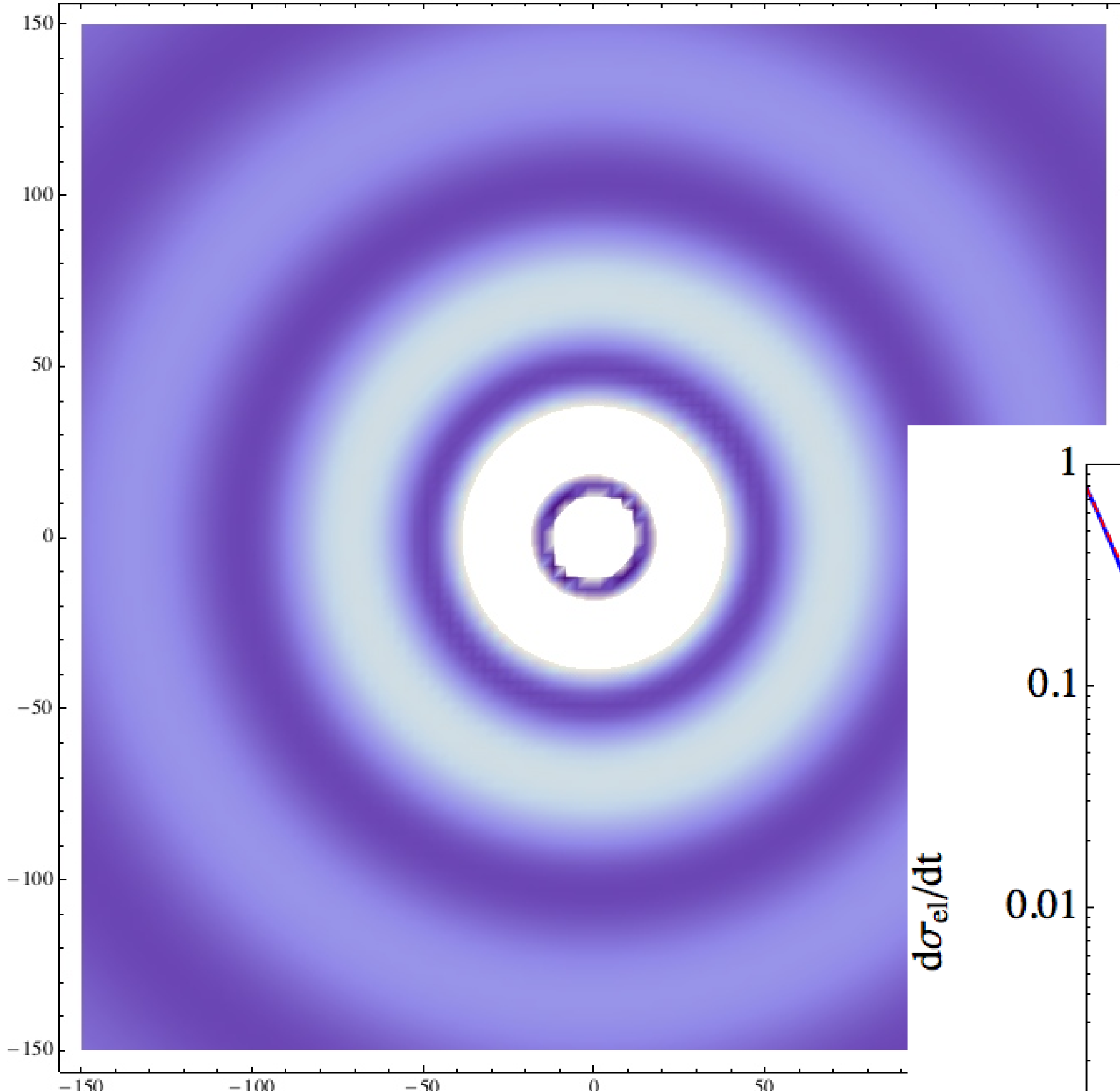
$$h_1 h_2 \longrightarrow h_1 h_2^* \quad \text{(target diffraction)},$$

$$h_1 h_2 \longrightarrow h_1^* h_2^* \quad \text{(double diffraction)}.$$

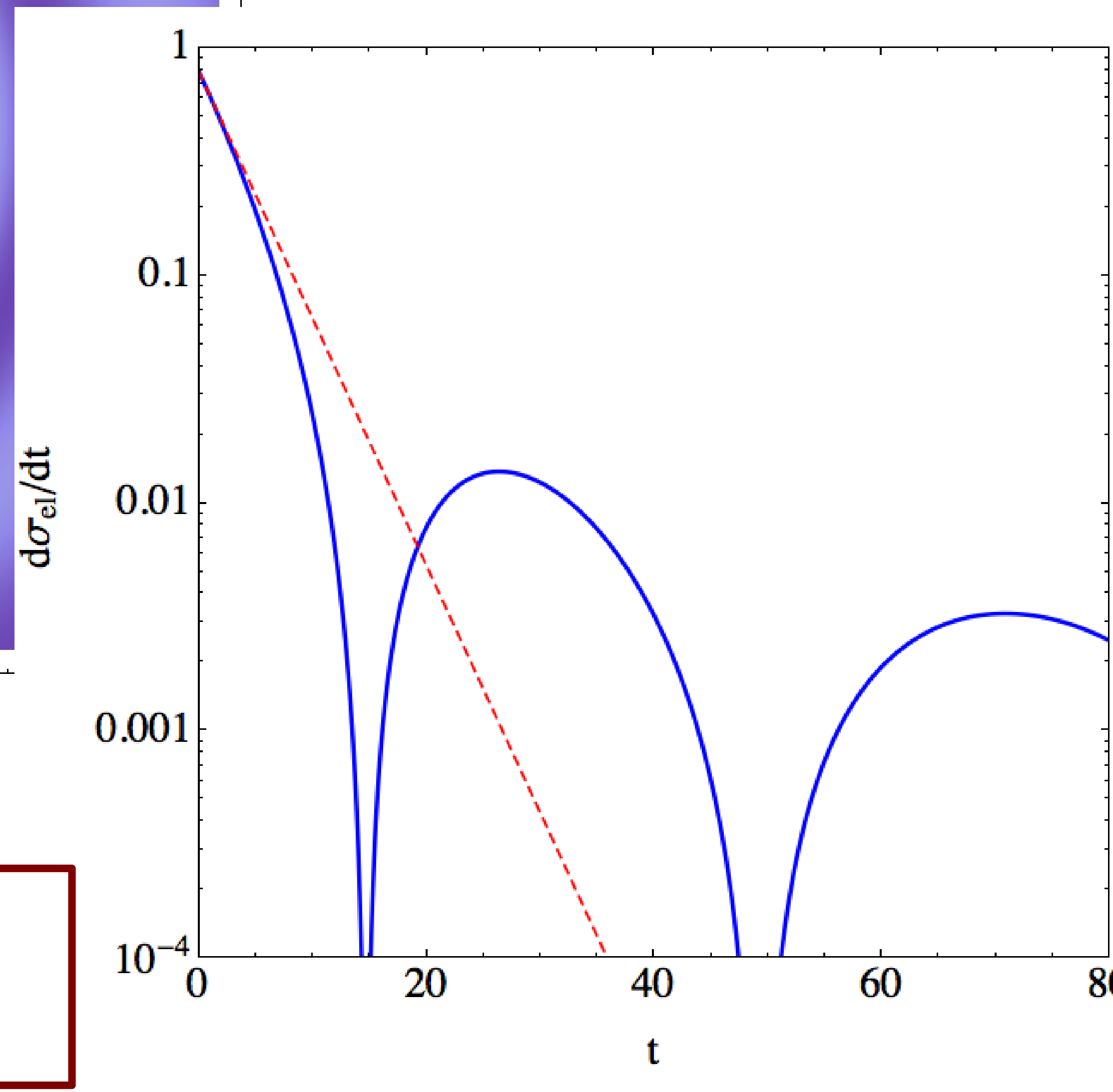
ISR   62.3 GeV
CERN UA4   546 GeV



Black Disk
Of radius R.

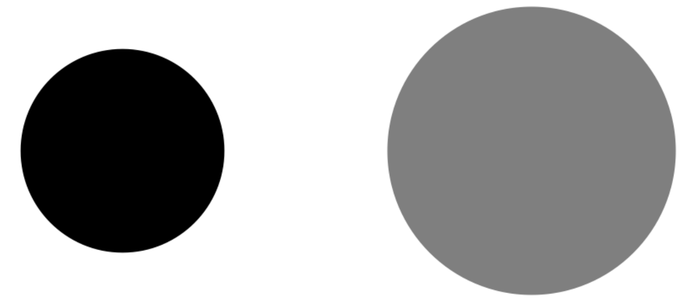


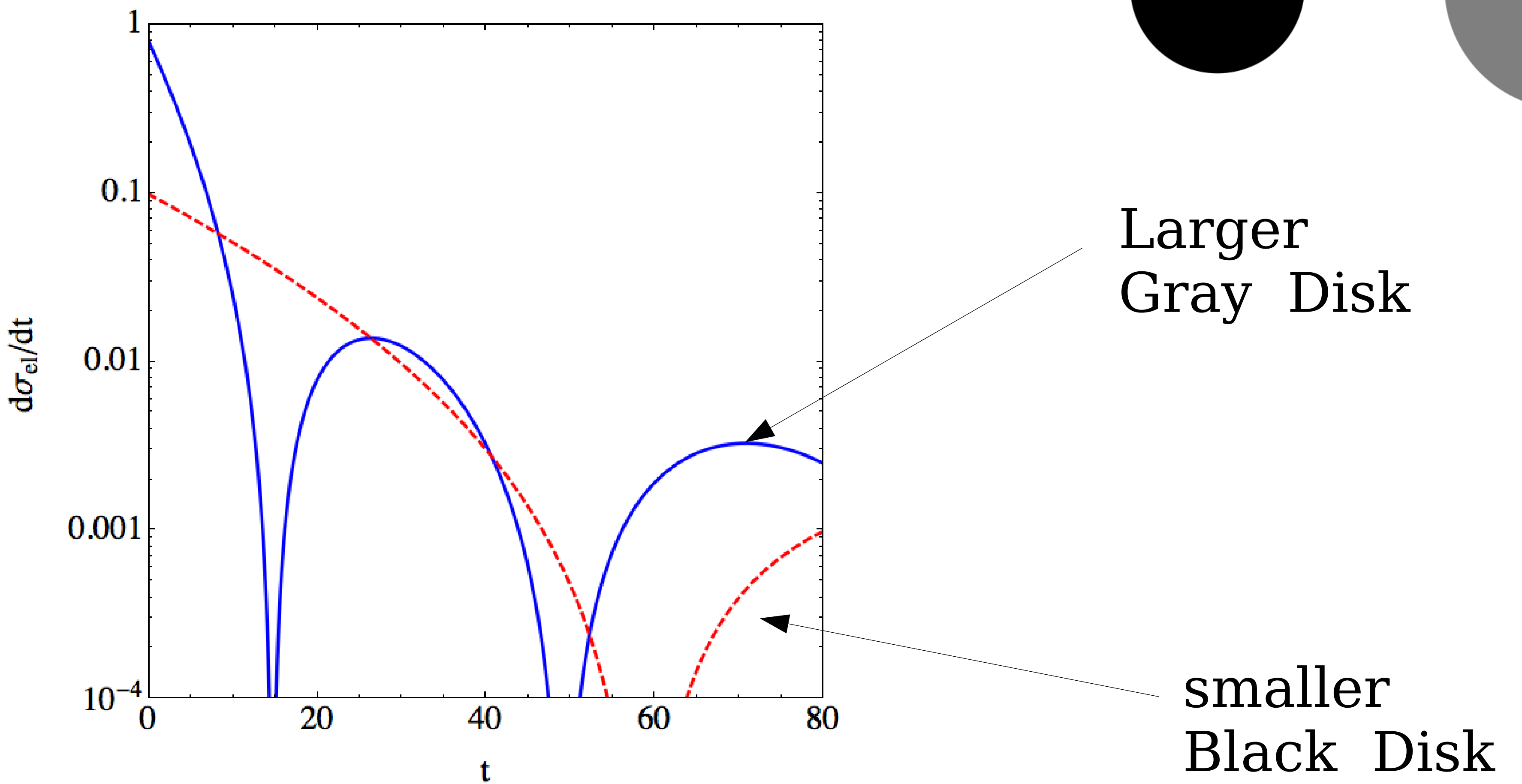
Diffraction Pattern



$$\sigma_{el} = \sigma_{abs} = \pi \; R^2$$

Elastic scattering distributions

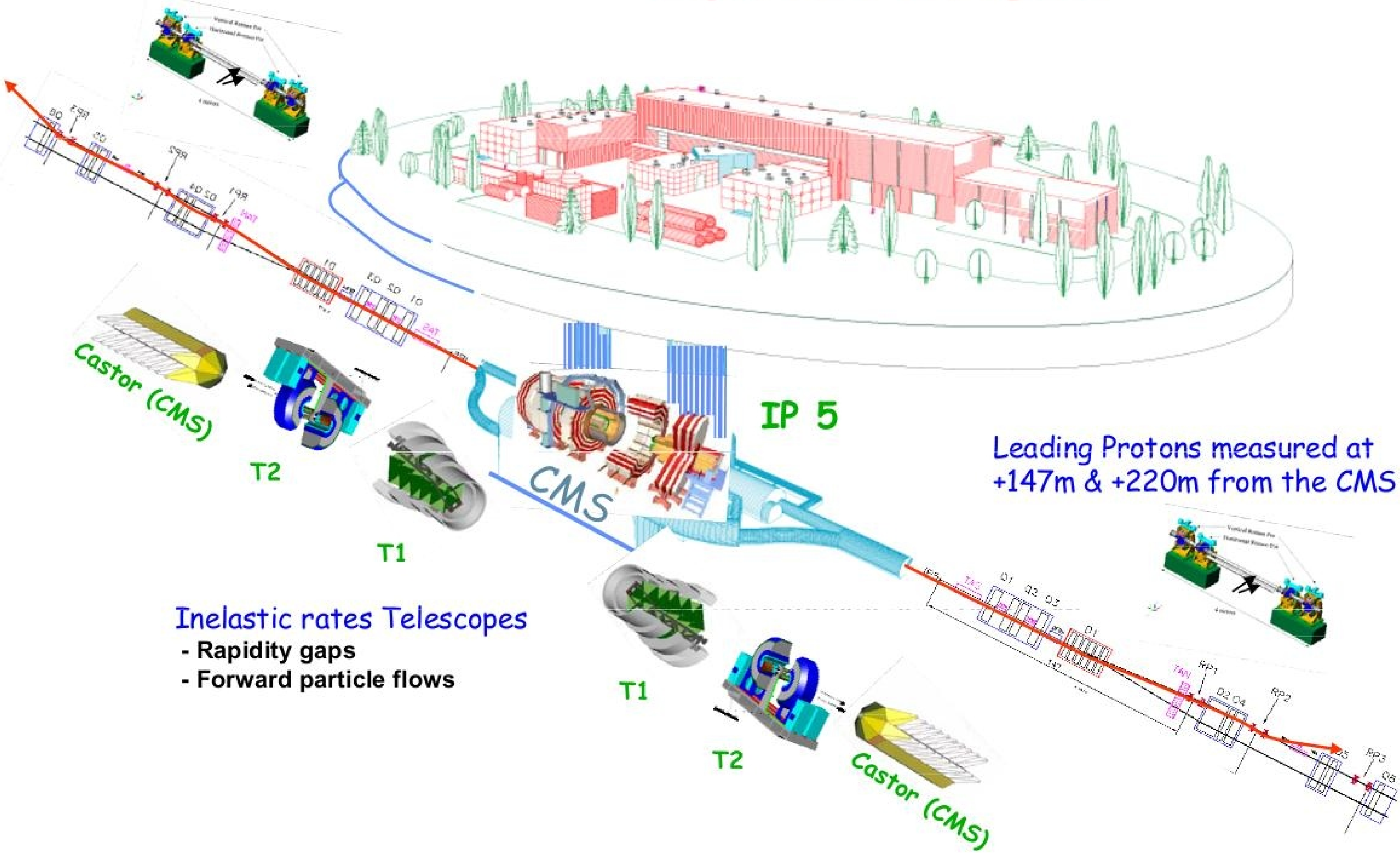




$$\sigma_{\mathrm{el}} = \frac{\sigma_{\mathrm{tot}}^2 (1 + \rho^2)}{16 \pi B_{\mathrm{el}}}$$

Experimental layout

Leading Protons measured at
-220m & -147m from the CMS

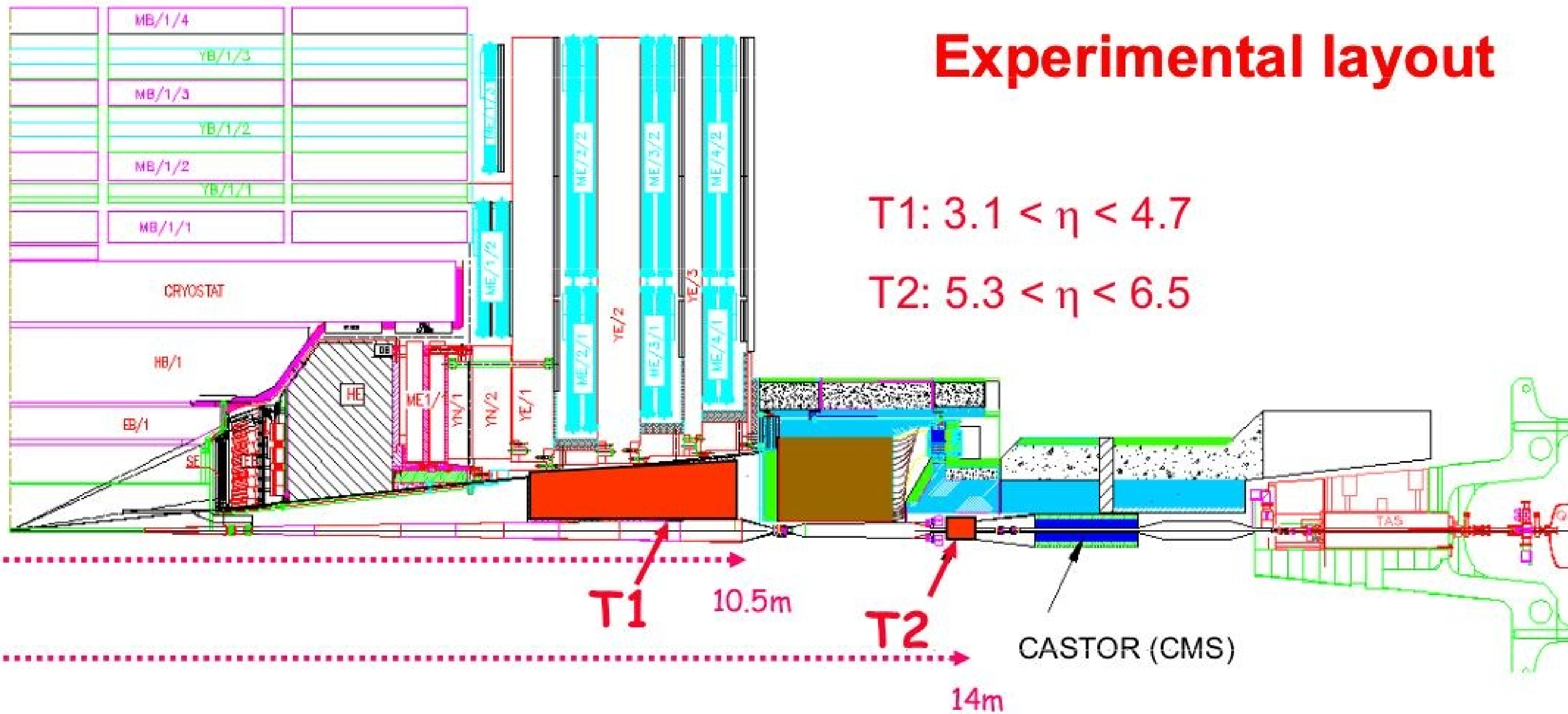


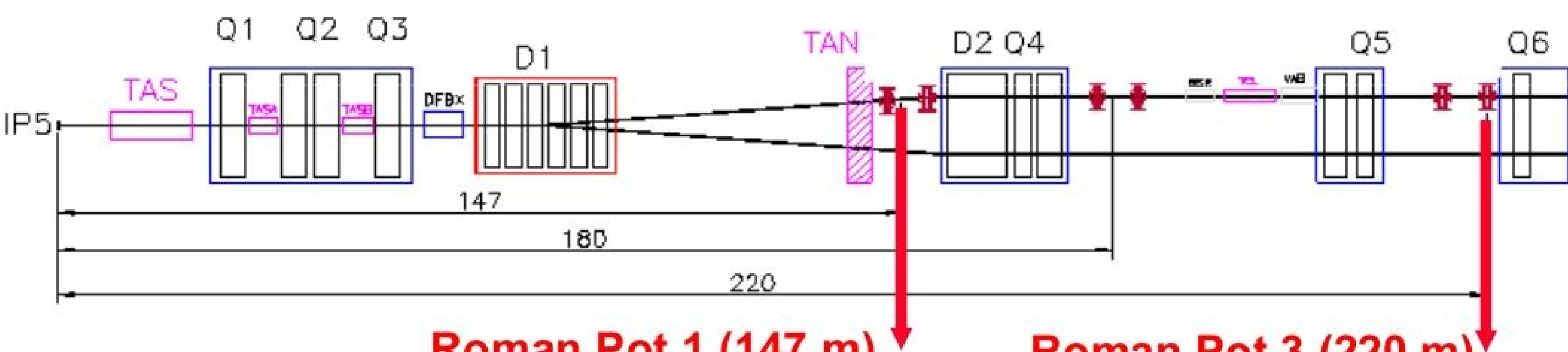
TOTEM

Experimental layout

T1: $3.1 < \eta < 4.7$

T2: $5.3 < \eta < 6.5$





CROSS SECTION MEASUREMENT

$$L \sigma_{tot}^{2} = \frac{16\pi}{1+\rho^{2}} \times \frac{dN_{el}}{dt}\bigg|_{t=0}$$

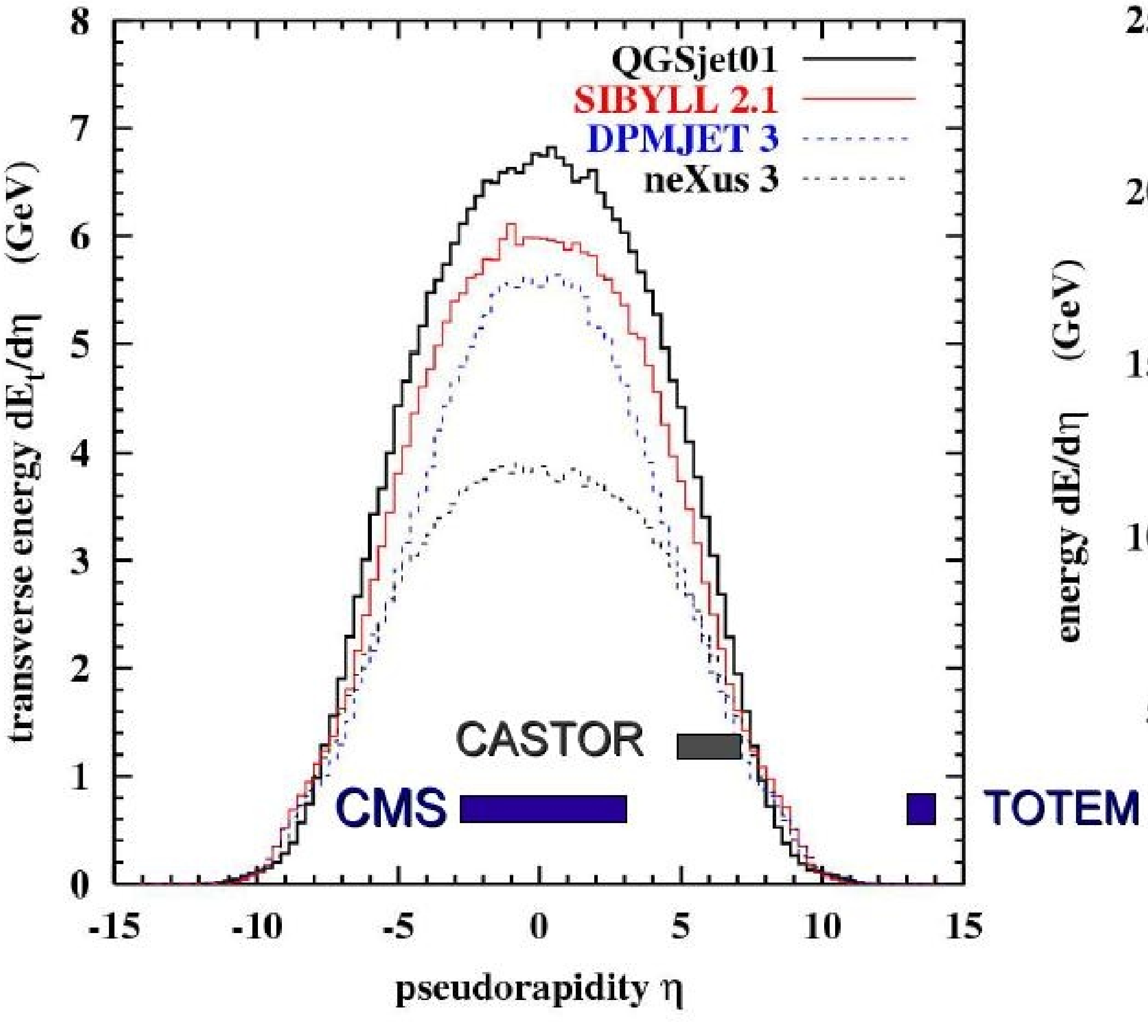
Optical Theorem

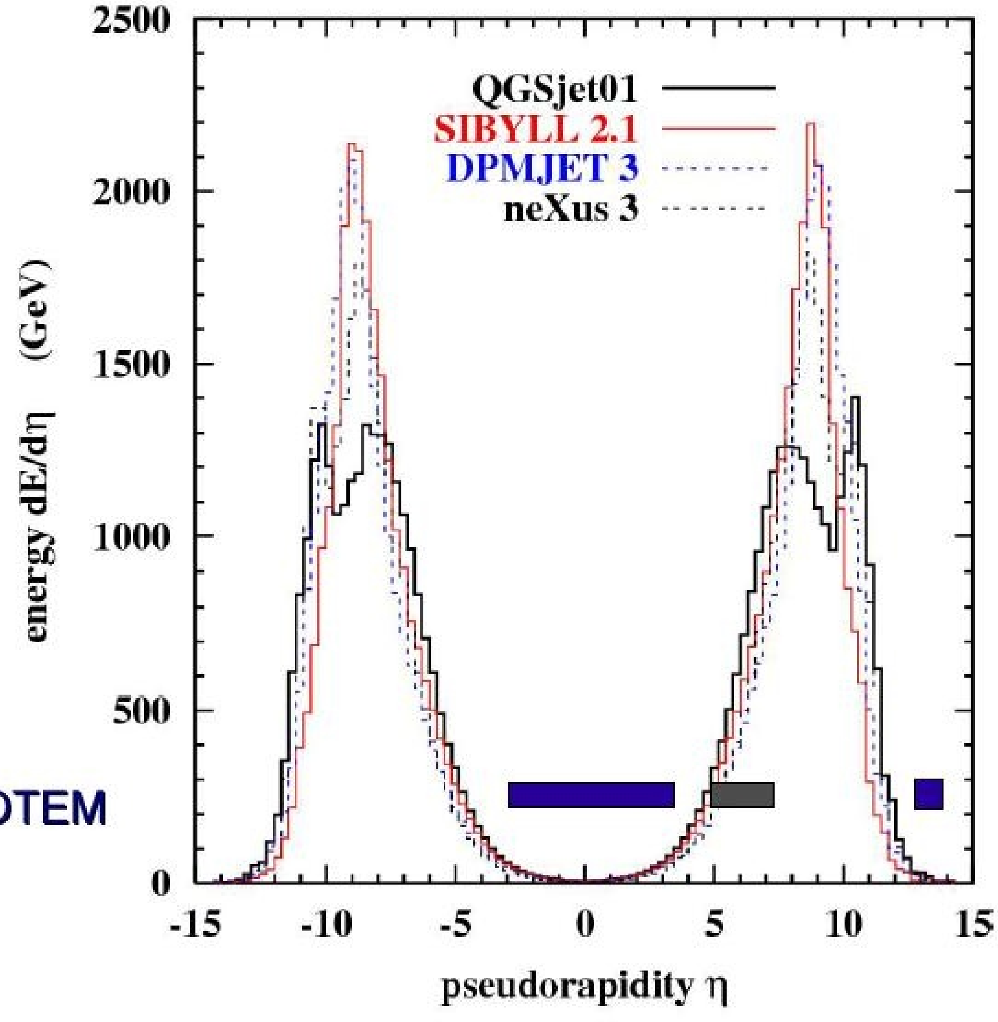
$$L \sigma_{tot} = N_{el} + N_{inel}$$

$$\sigma_{tot} = \frac{16\pi}{1+\rho^{2}} \times \frac{(dN_{el}/dt)|_{t=0}}{N_{el} + N_{inel}}$$

$$\mathcal{L} = \frac{1+\rho^{2}}{16\pi} \frac{(N_{el} + N_{inel})^{2}}{(dN_{el}/dt)|_{t=0}}$$

[Luminosity Determination]

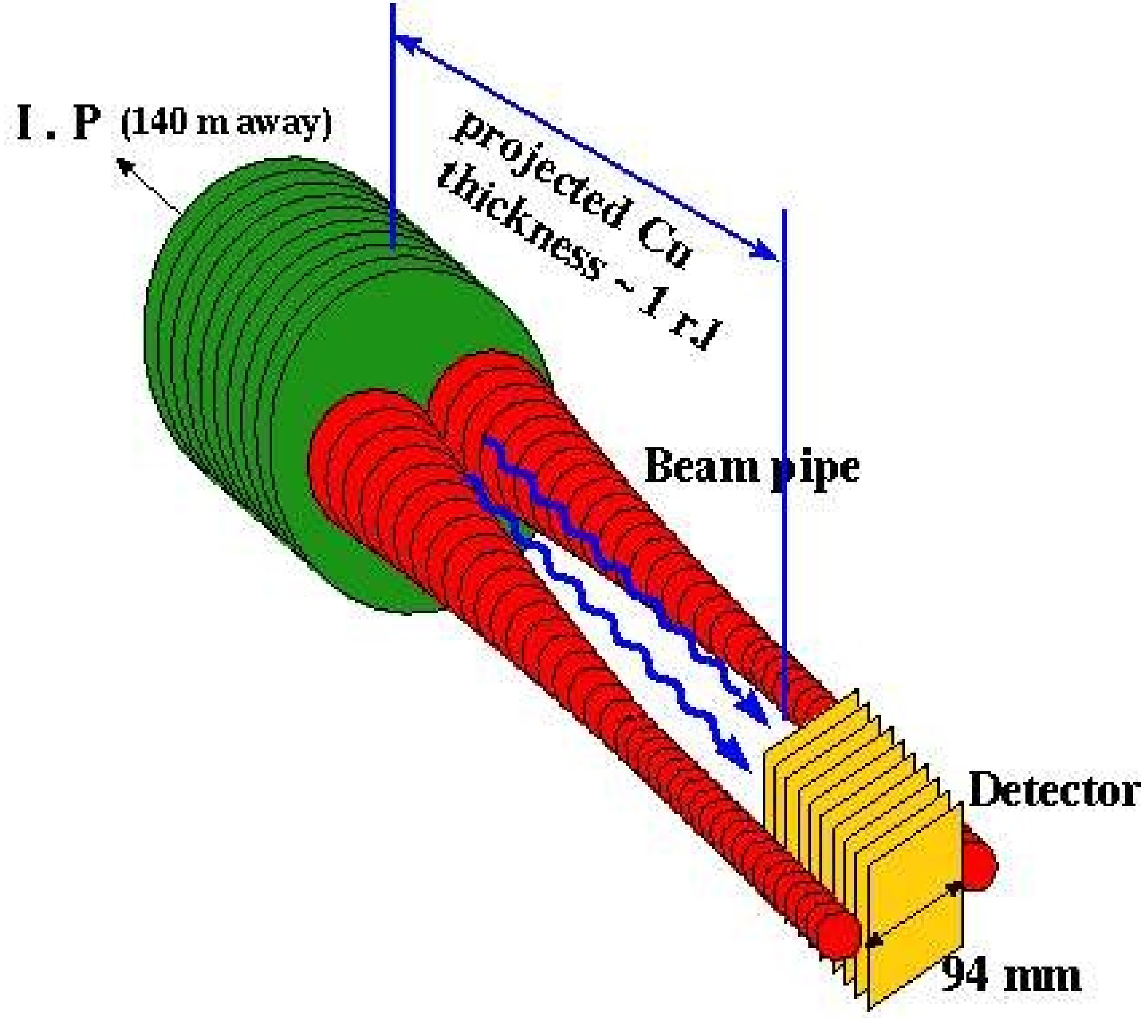




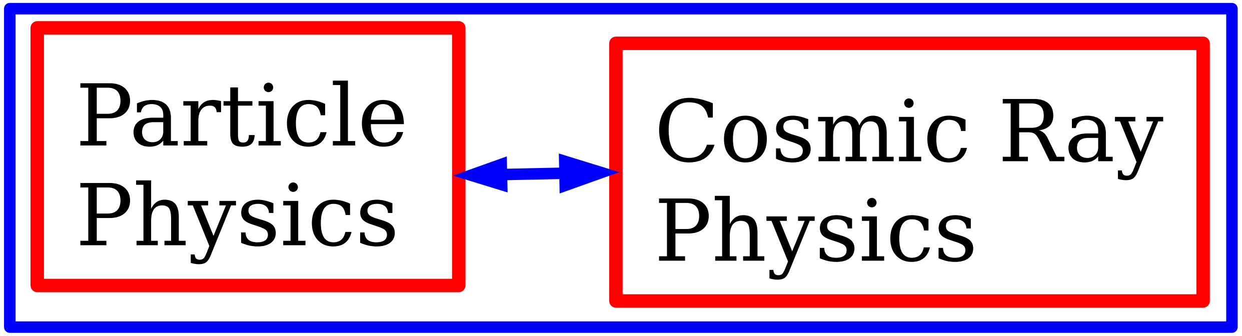
PROBLEM of PHASE SPACE COVERING

LHCF

Calorimeter
for neutral particles
in the very forward region



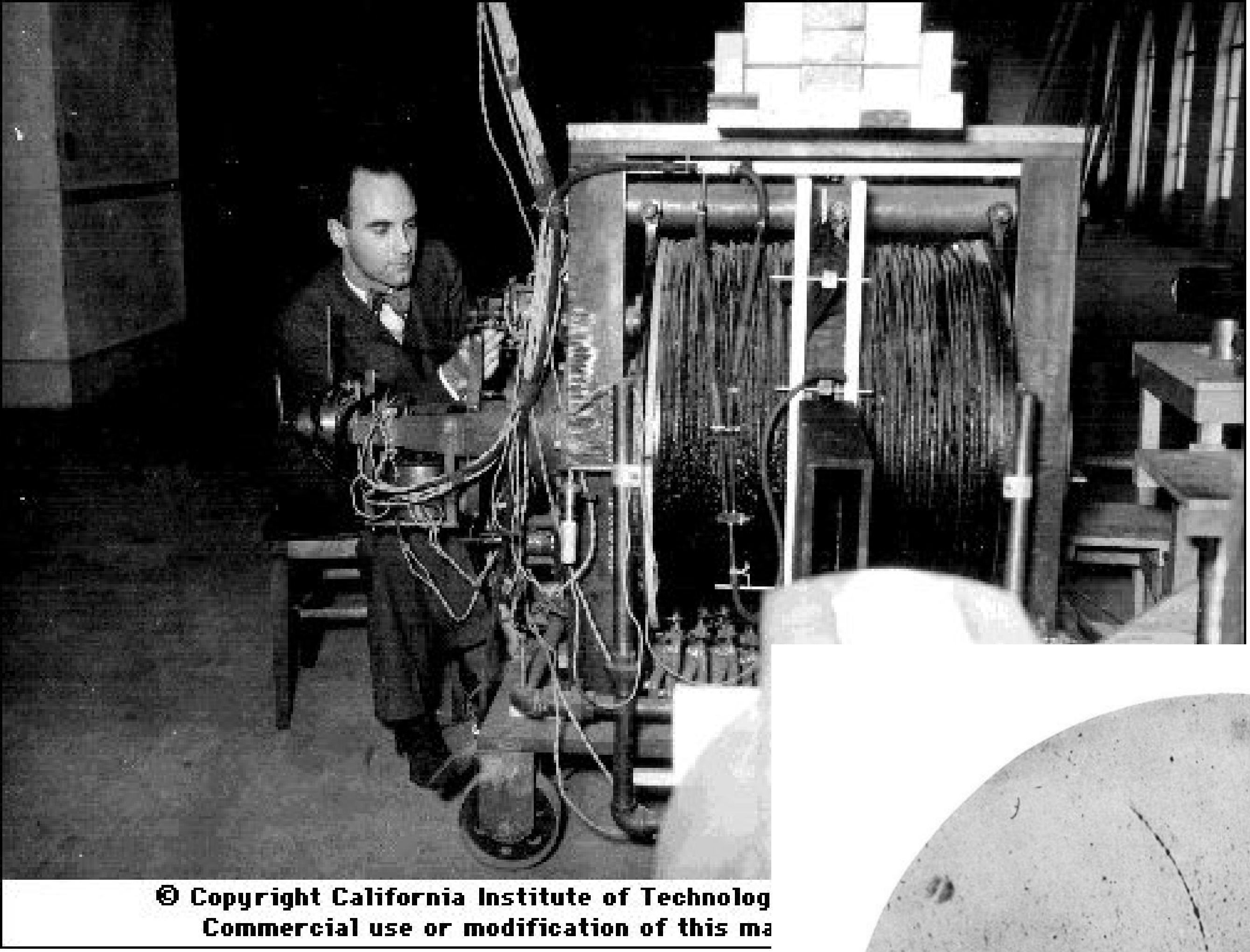
Two
non-identical
Detectors

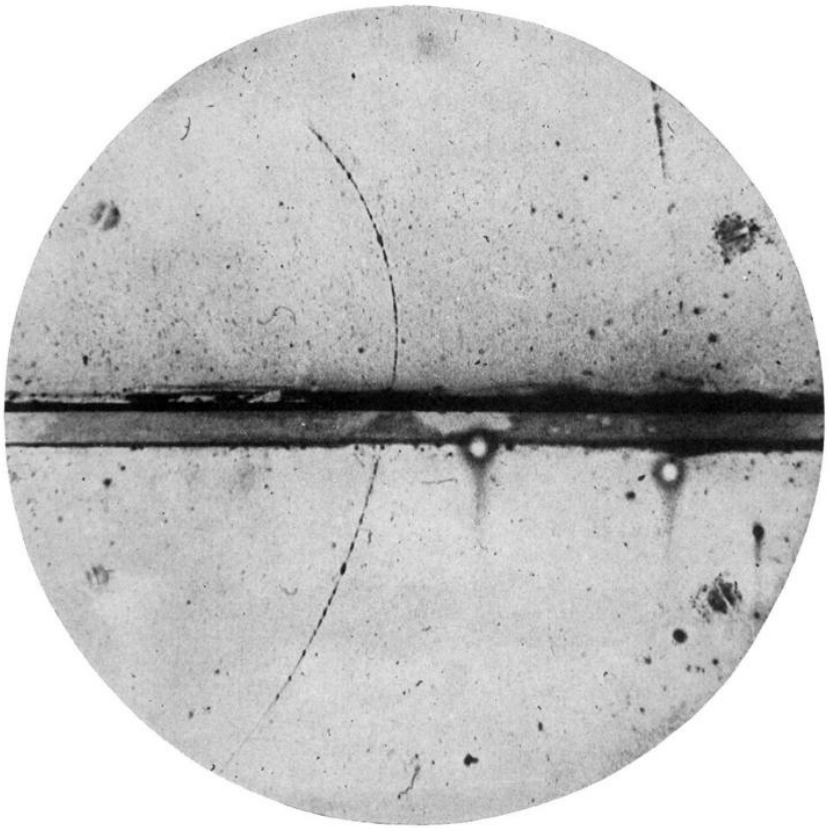


A long Common History

Carl Anderson
(february 1933)

Near his
“Wilson chamber”



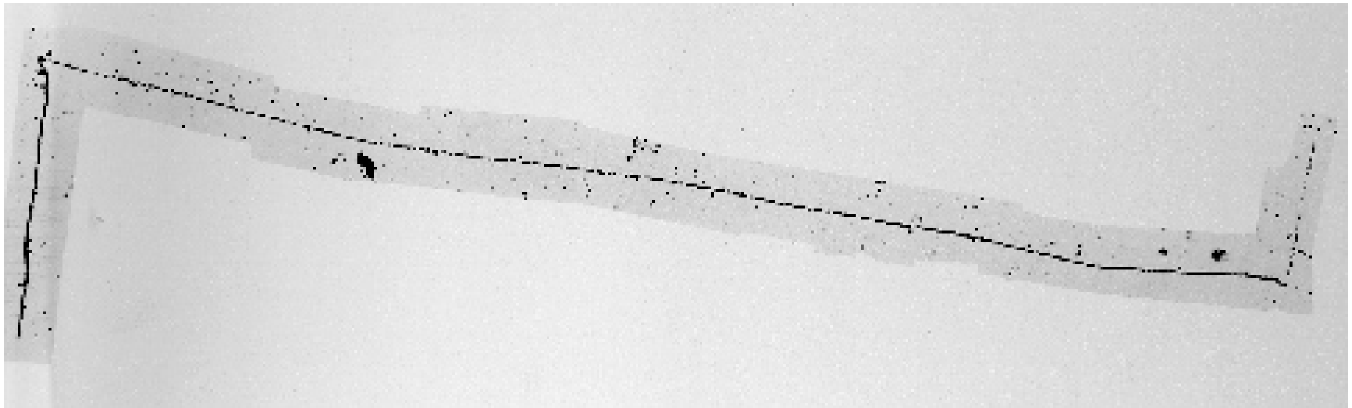


23 MeV

6 mm
Lead plate

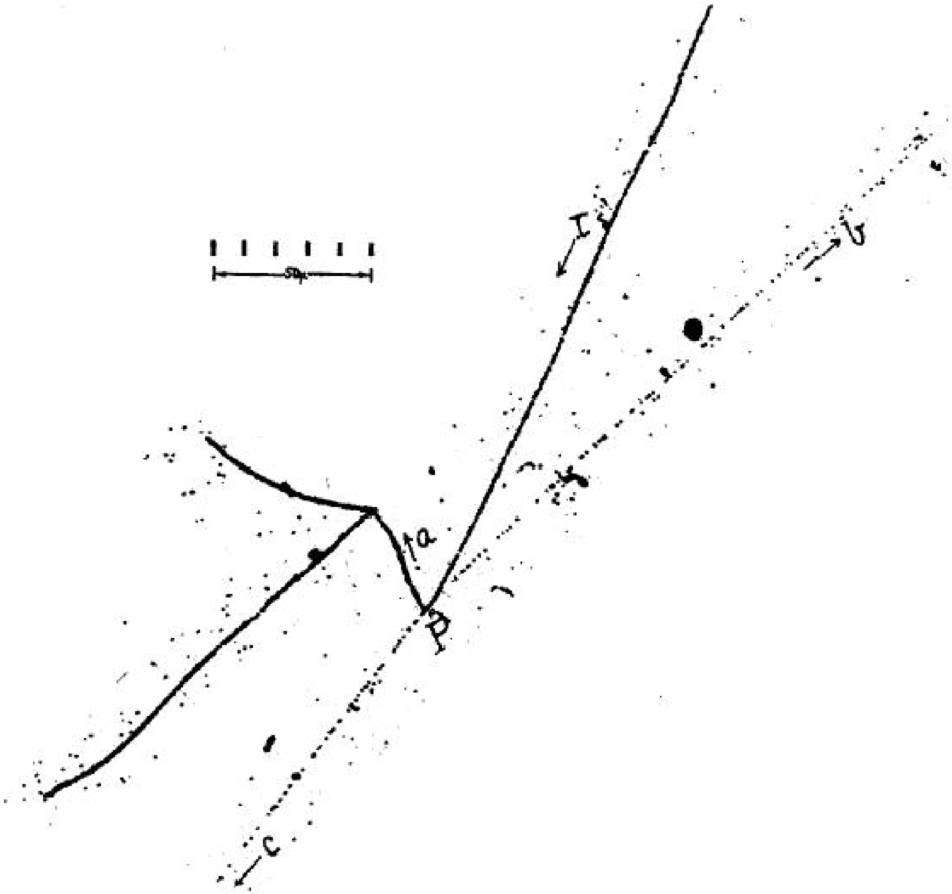
63 MeV

Discovery of the
POSITRON

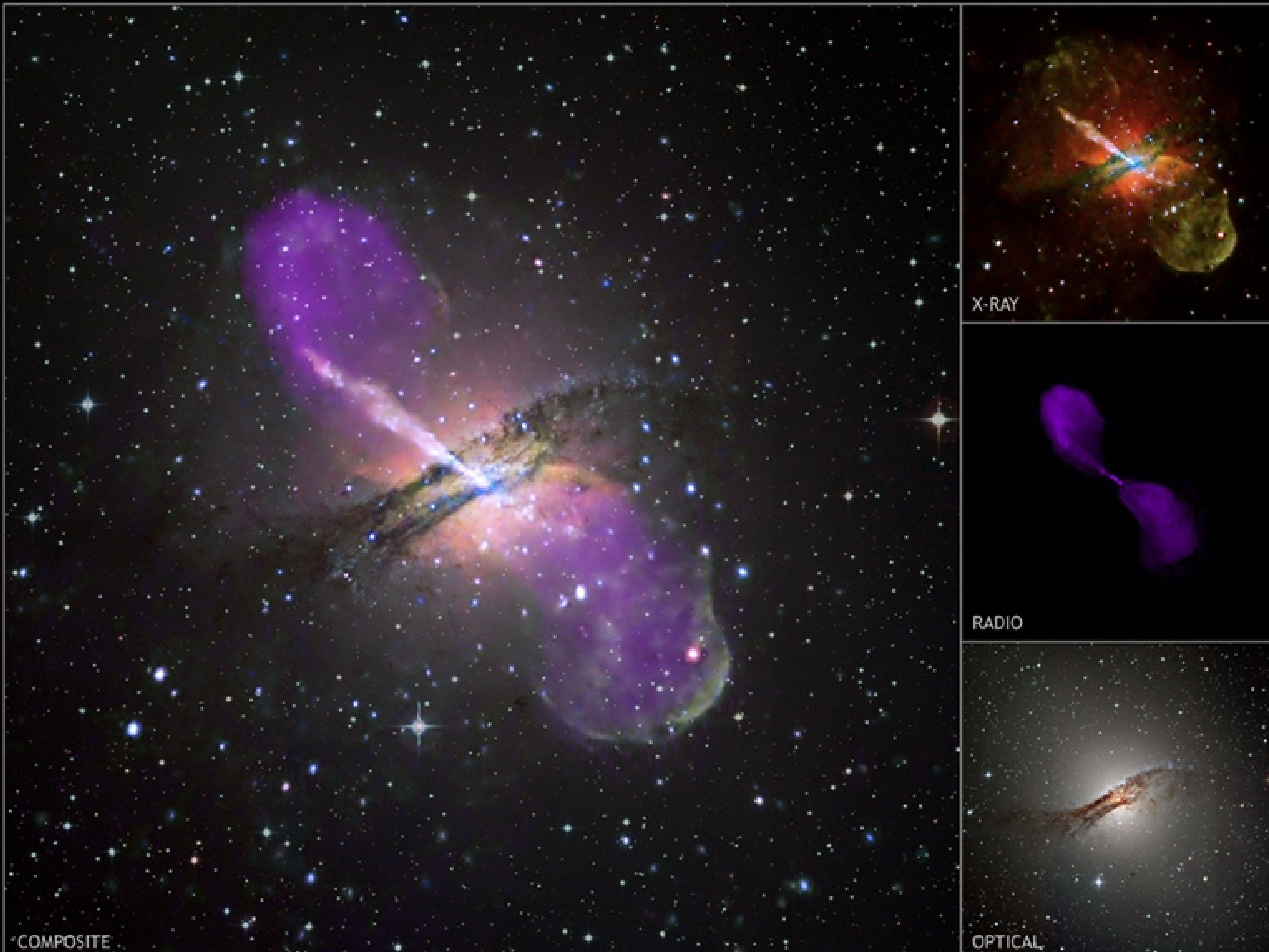


$\pi^{\pm}$

Occhialini , Powell



$K^{\pm}$


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

Many Questions....

The fascinating "Intellectual Adventure"
of exploring and understanding
the "High Energy Universe" is continuing.

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The fascinating “Intellectual Adventure”
of exploring and understanding
the “High Energy Universe” is continuing.

I believe that Gianni Navarra
continues to contribute to this scientific “quest”.

- Via the observatories he contributed to build
  and that continue to produce new data (and surprises).

- In the activities of community of younger scientists
  he played a crucial role to form
  [thanks for organizing this meeting!]

- In the ideas and enthusiasm he communicated
  to so many of us (including me…).