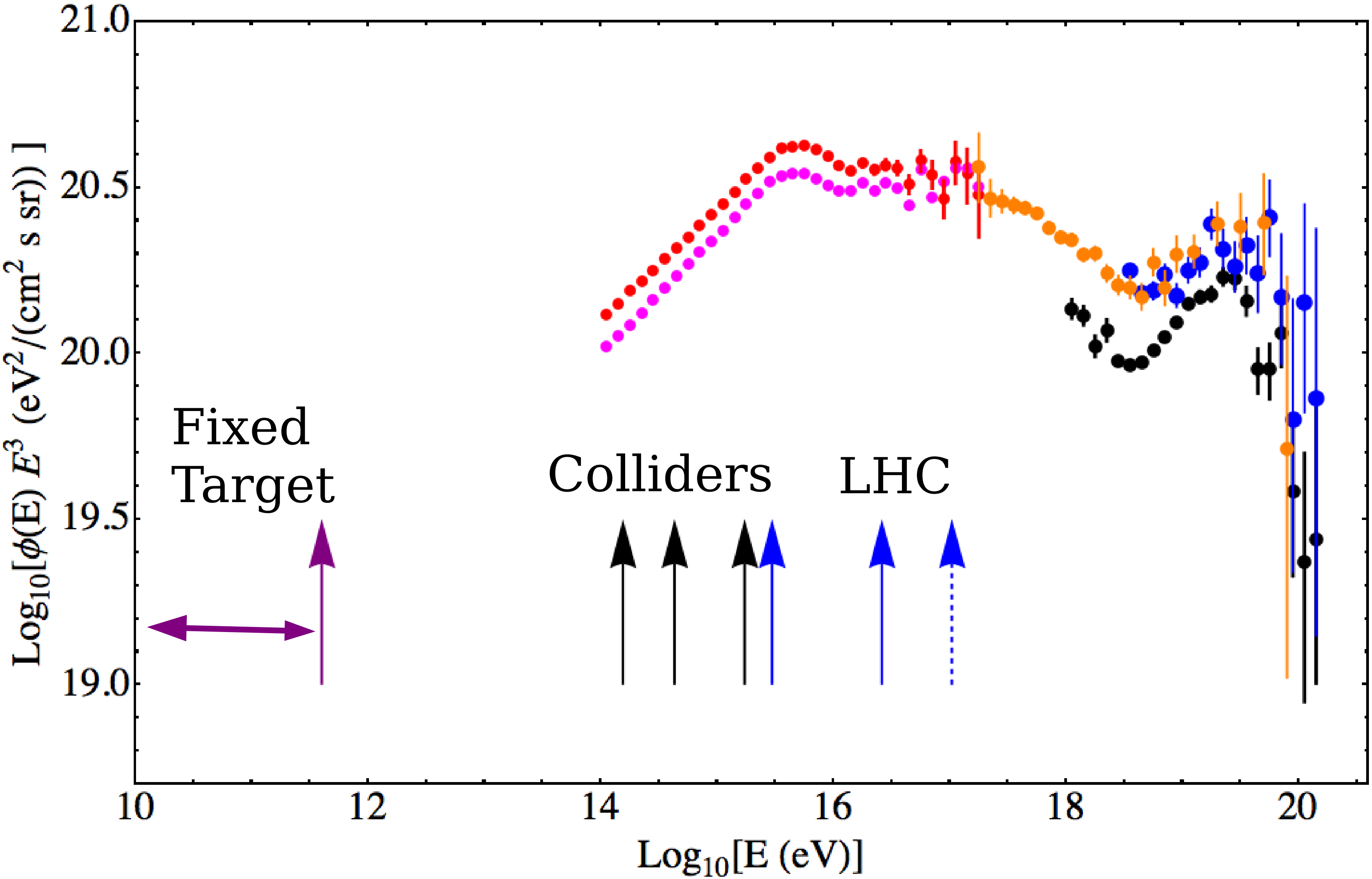
UHECR and HADRONIC INTERACTIONS

Paolo Lipari

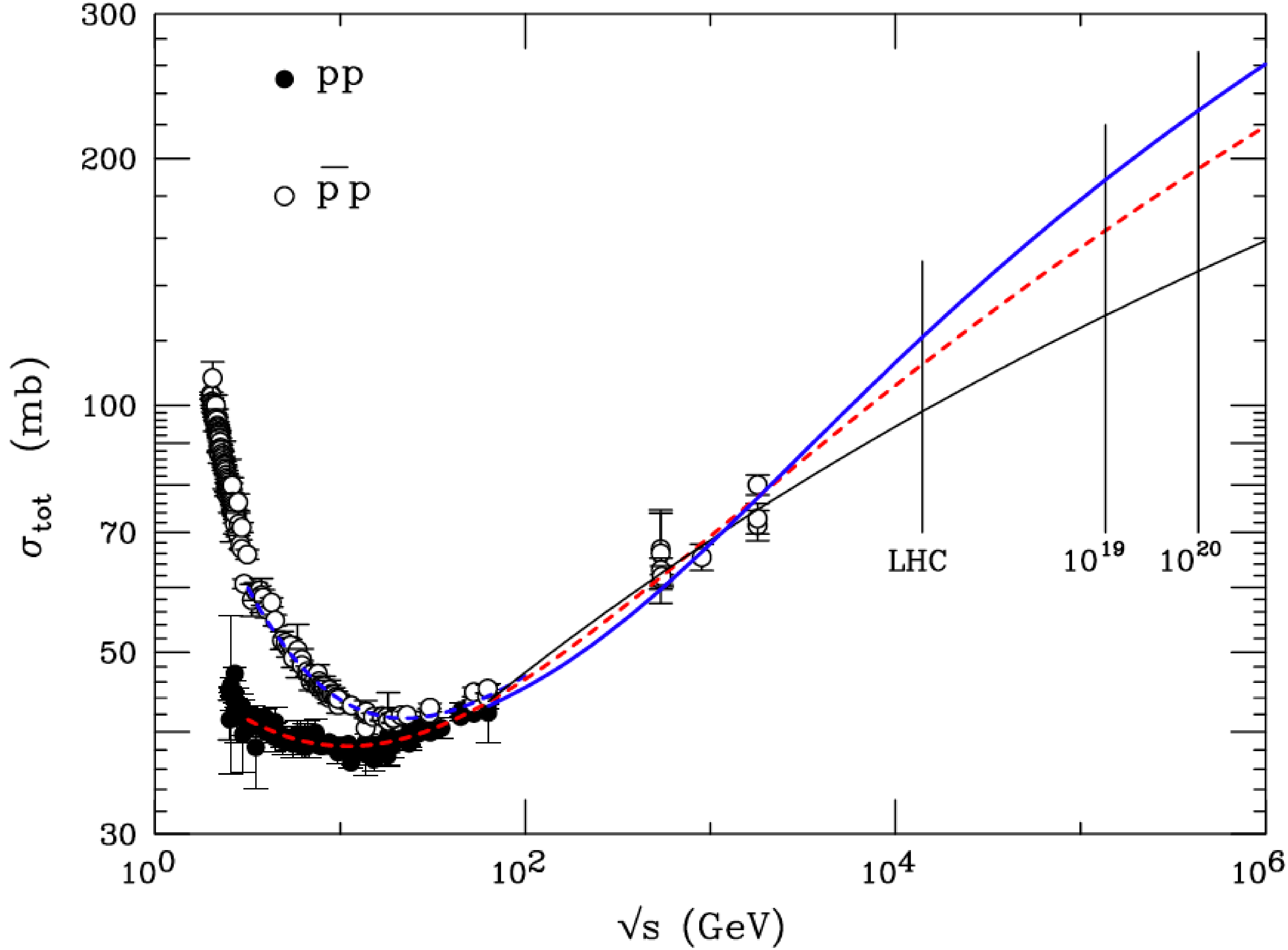
“Hadron-Hadron and Cosmic Rays Interactions at multi-TeV Energies”

ECT* Trento 2nd december 2010

Structures in the CR energy spectrum



Total pp Cross Section



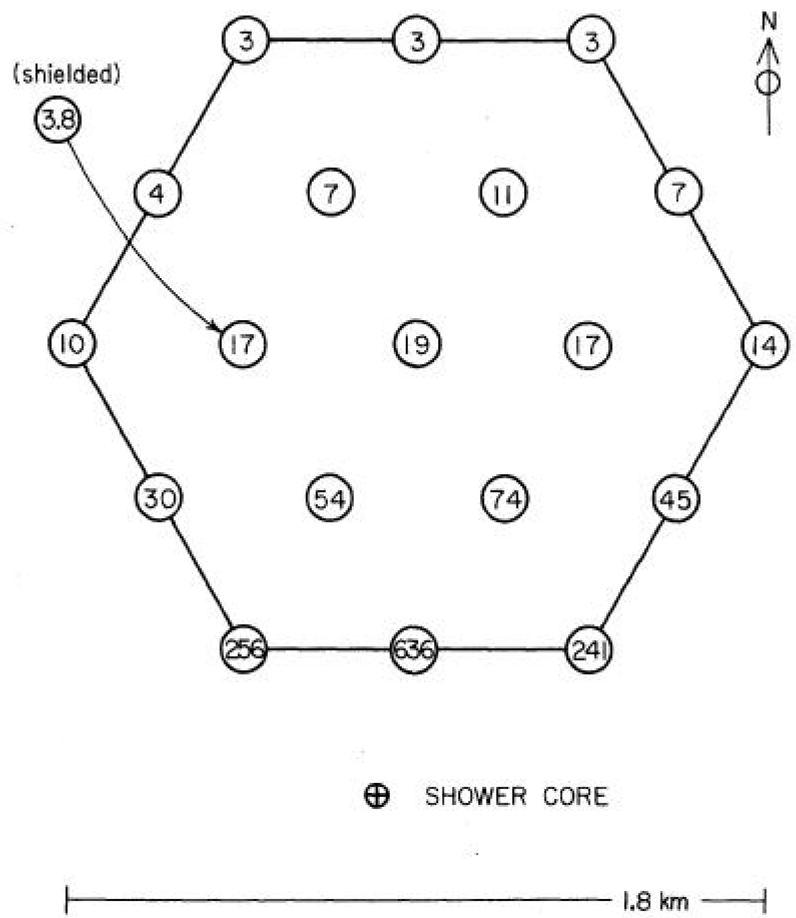
~50 years of UHECR

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

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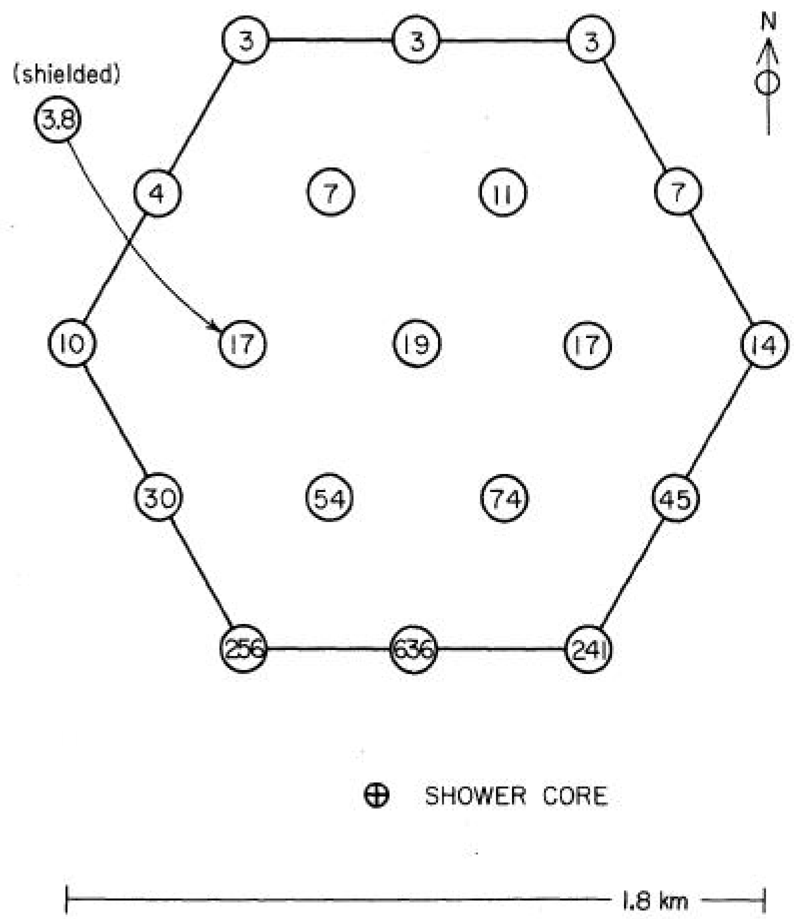


Hadronic interaction Modeling

$e^{\pm}$ γ

$\mu^{\pm}$

hadrons

Different components

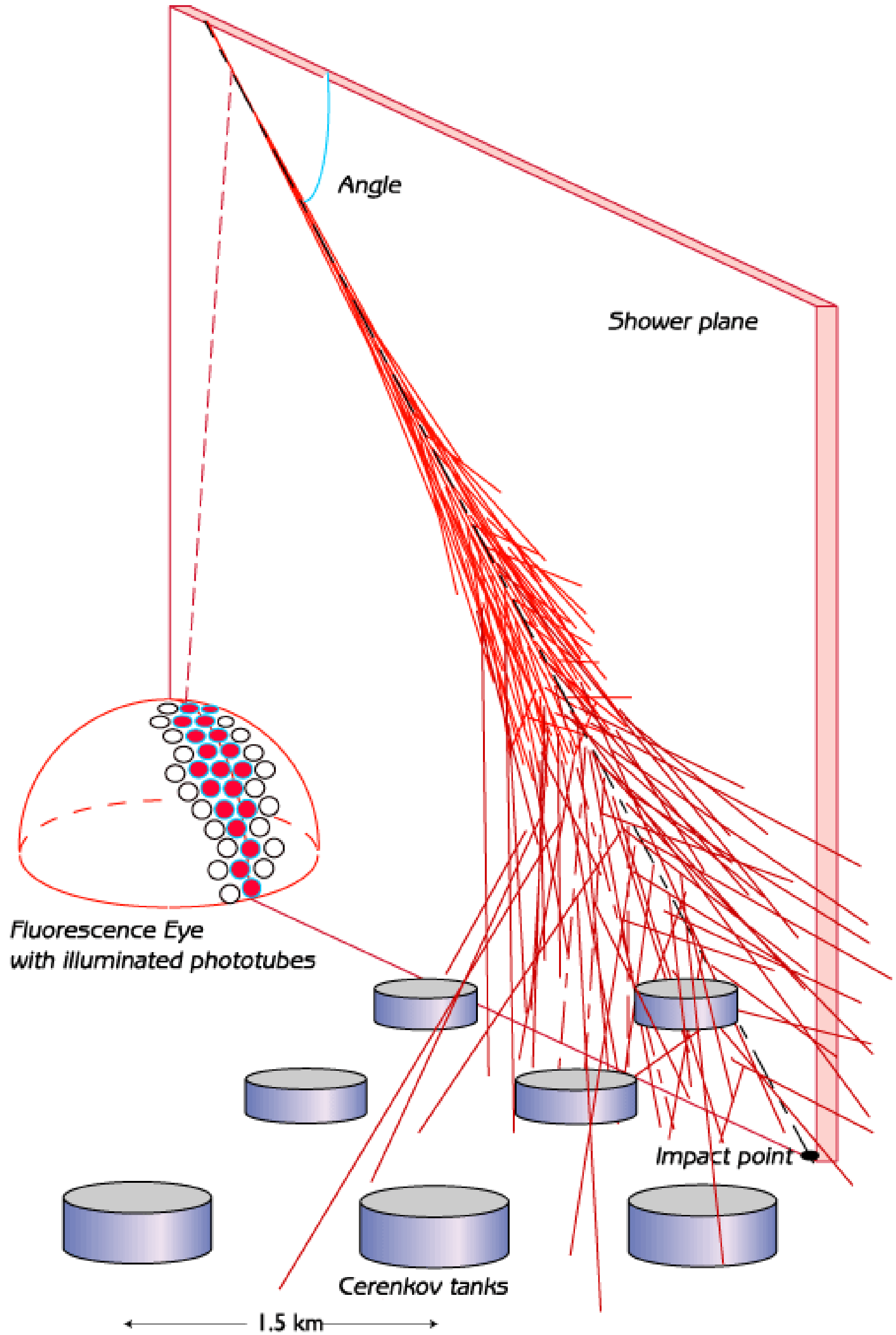
Measure a single slice of the shower at the ground

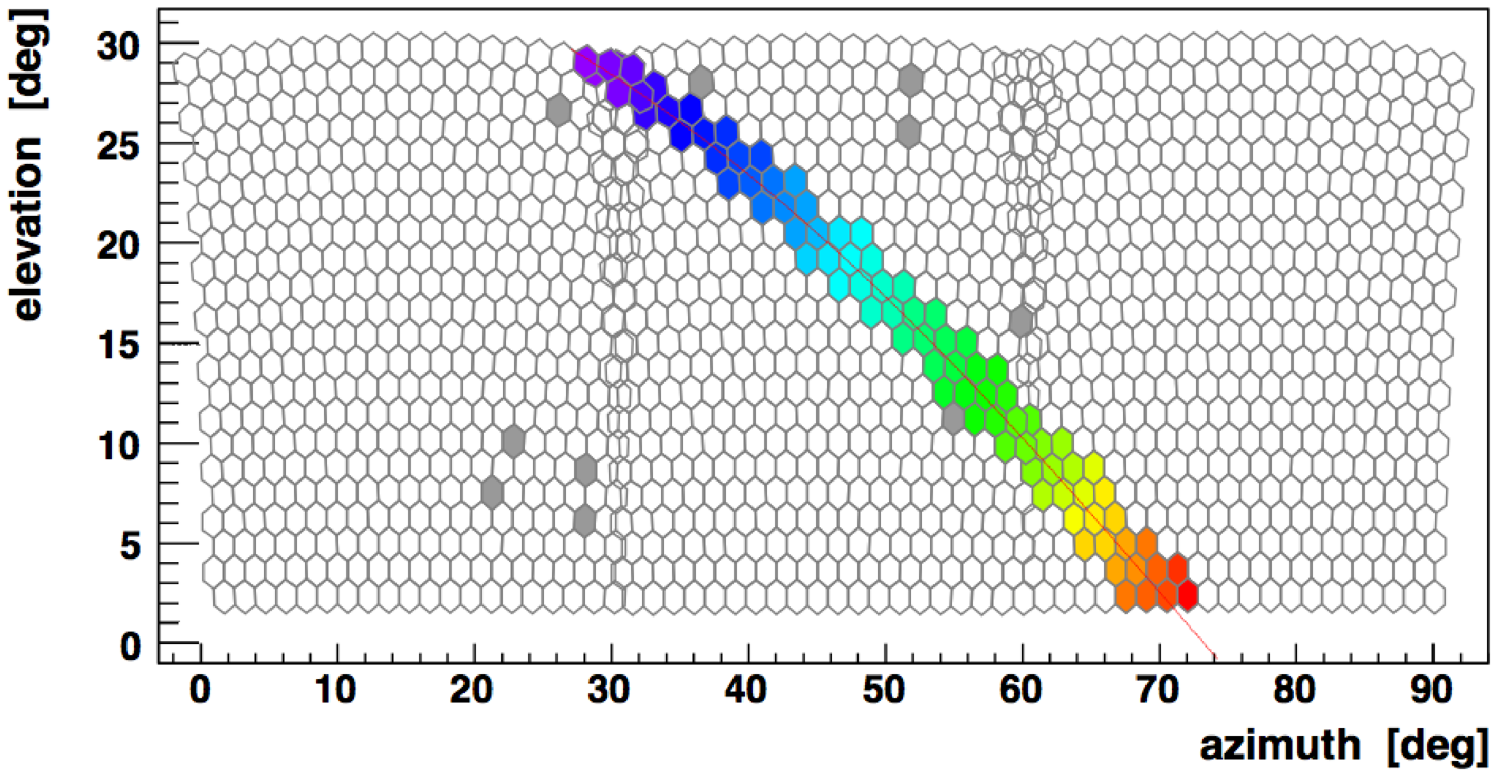
The **Fly's Eye** Detector concept

“Quasi-Calorimetric” Energy Measurement

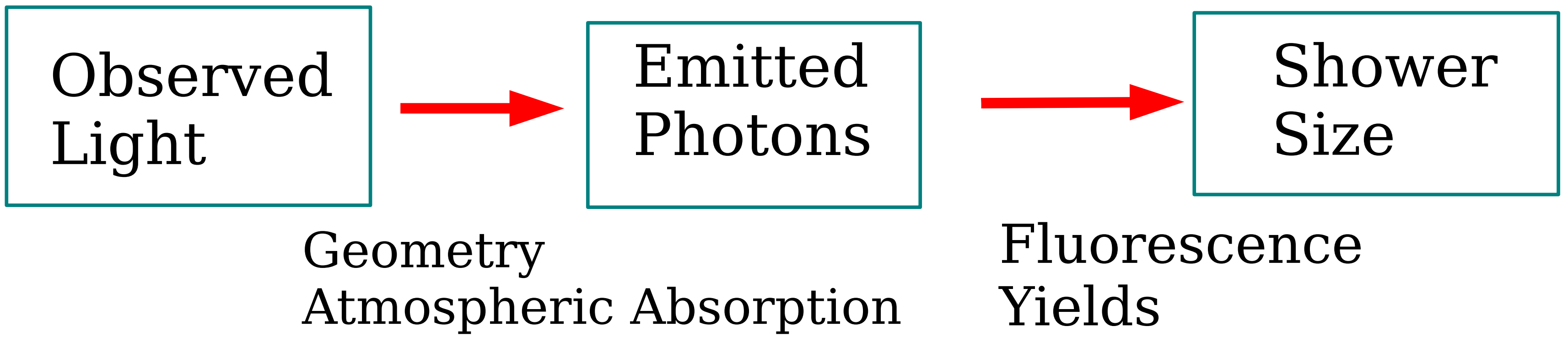
Fluorescence Light

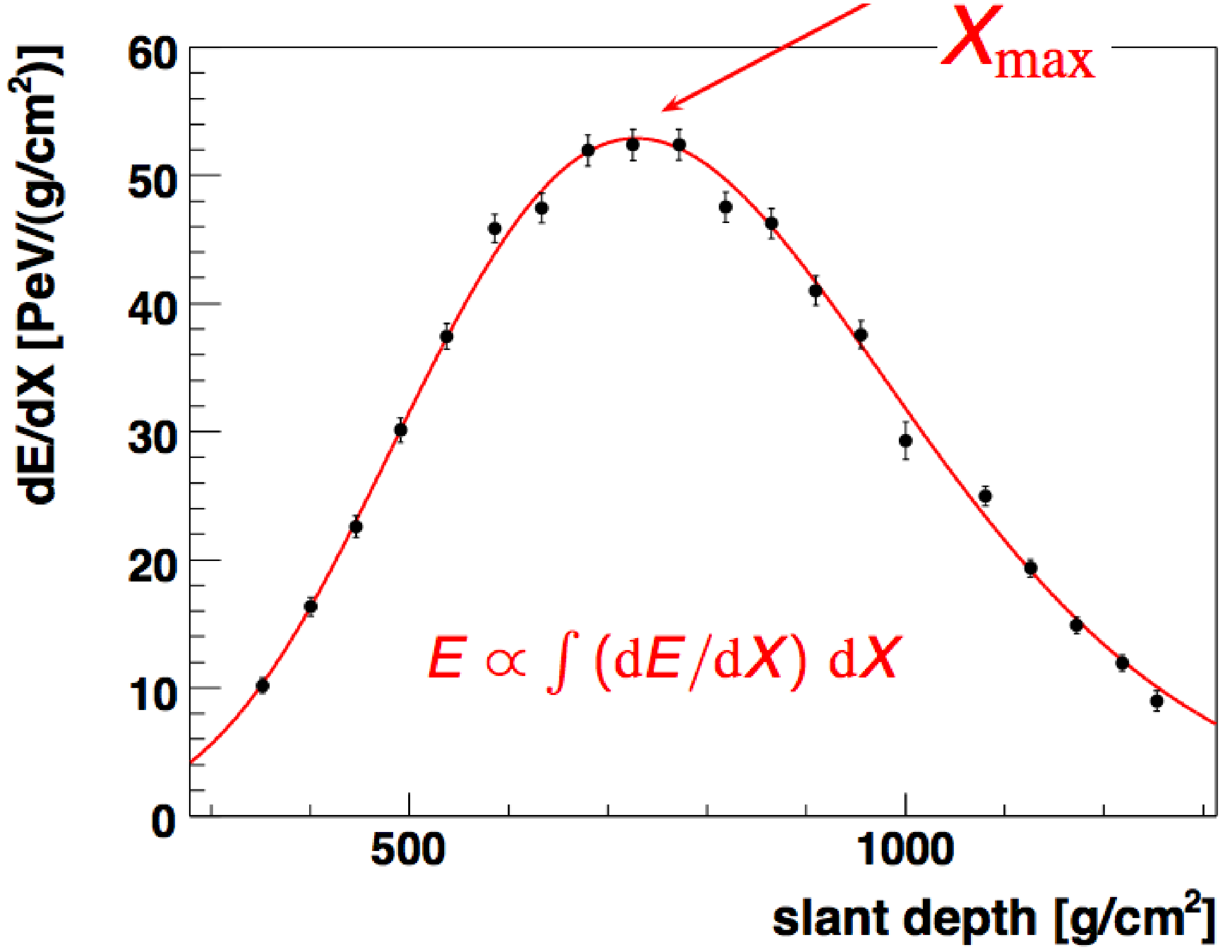
Artists View of Hybrid Set-Up





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

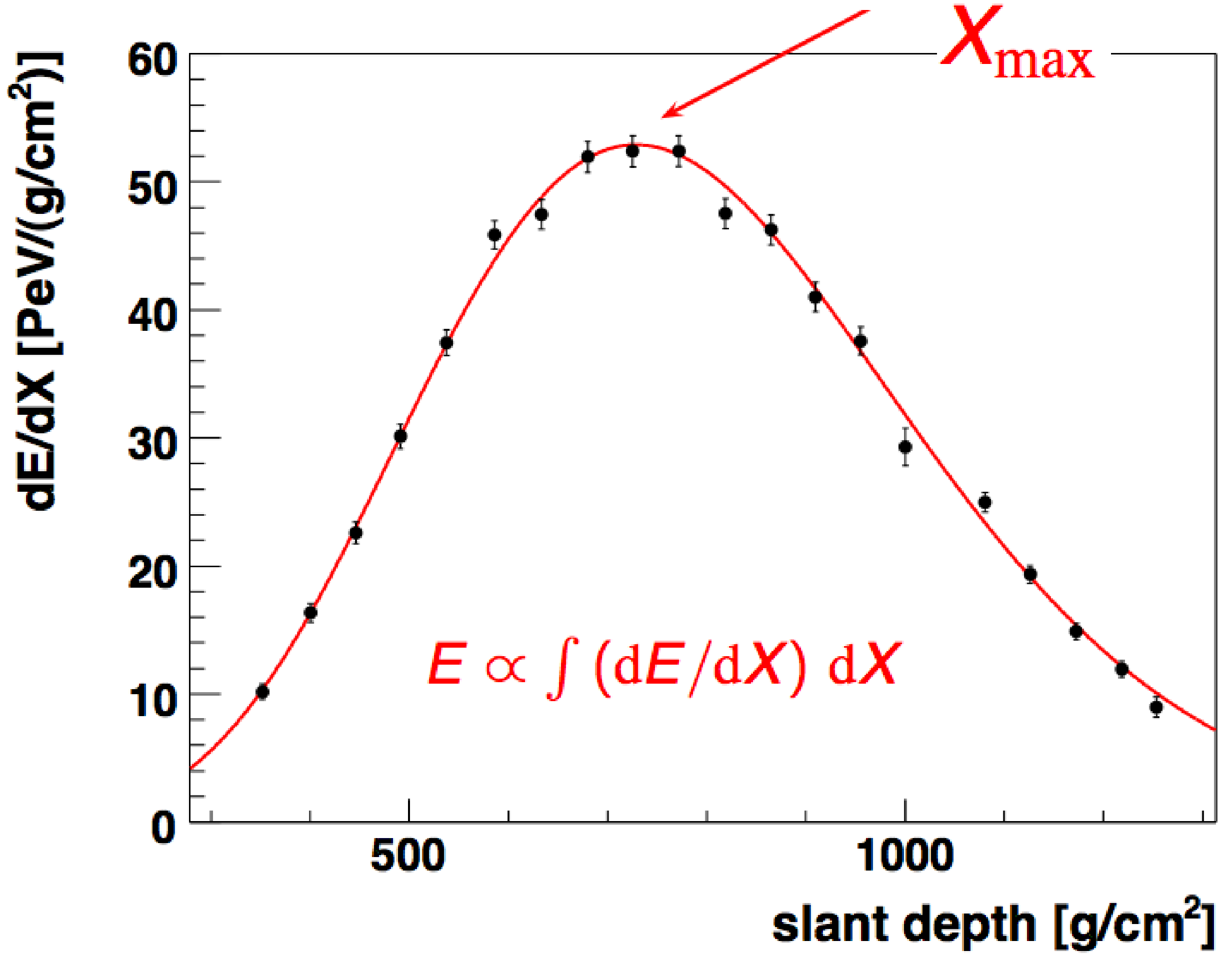




$$E_{\text{ionization}} = \int dX \; N_e(X) \left\langle -\frac{dE}{dX} \right\rangle$$

Small Model dependence

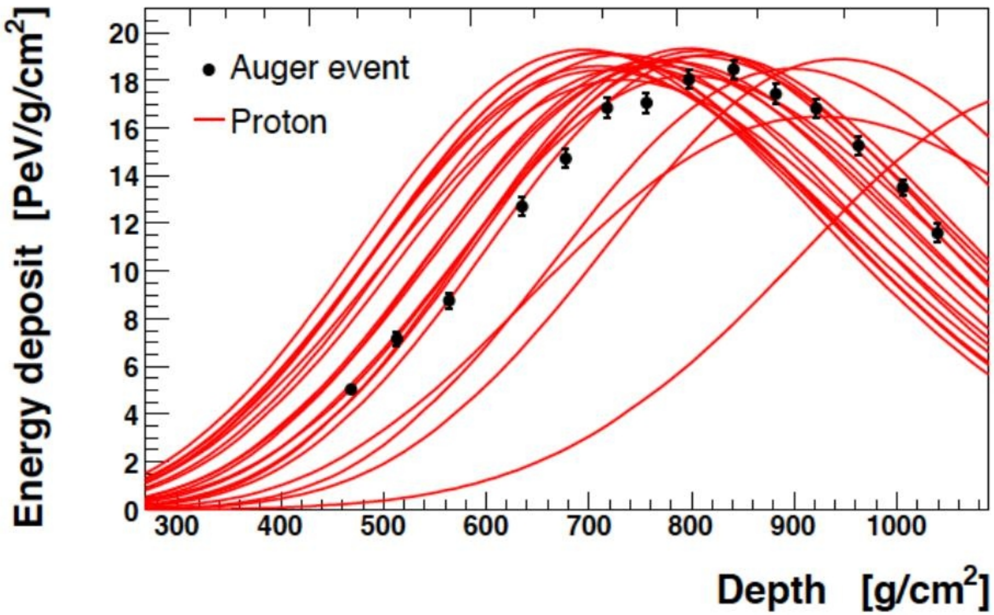
$$E_{\text{tot}} = E_{\text{ionization}} + E_\nu + E_\mu + E_{\text{ground}}$$



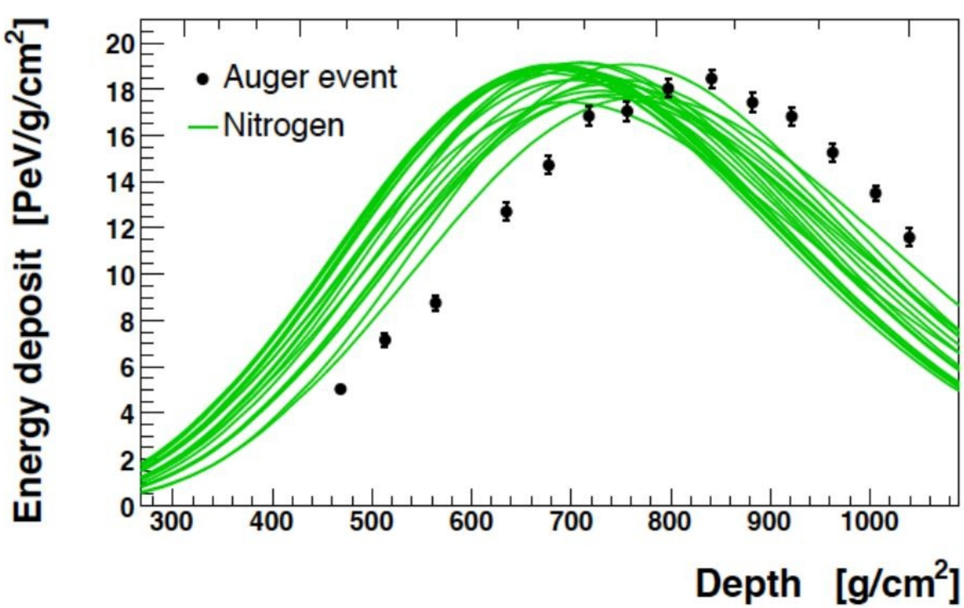
Area ∝ Energy

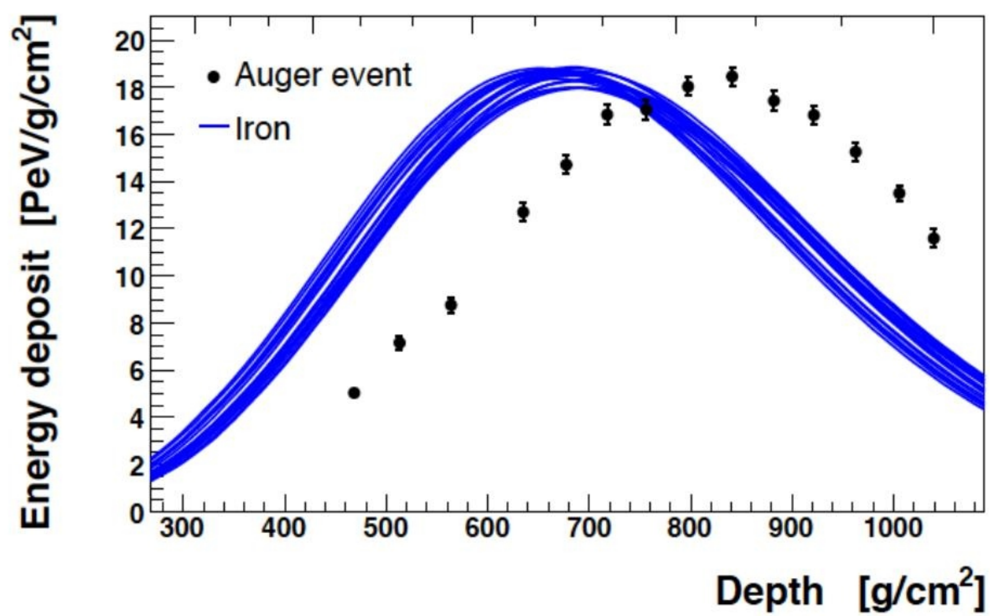
Shape depends on :

- Primary Identity
- Interaction Model



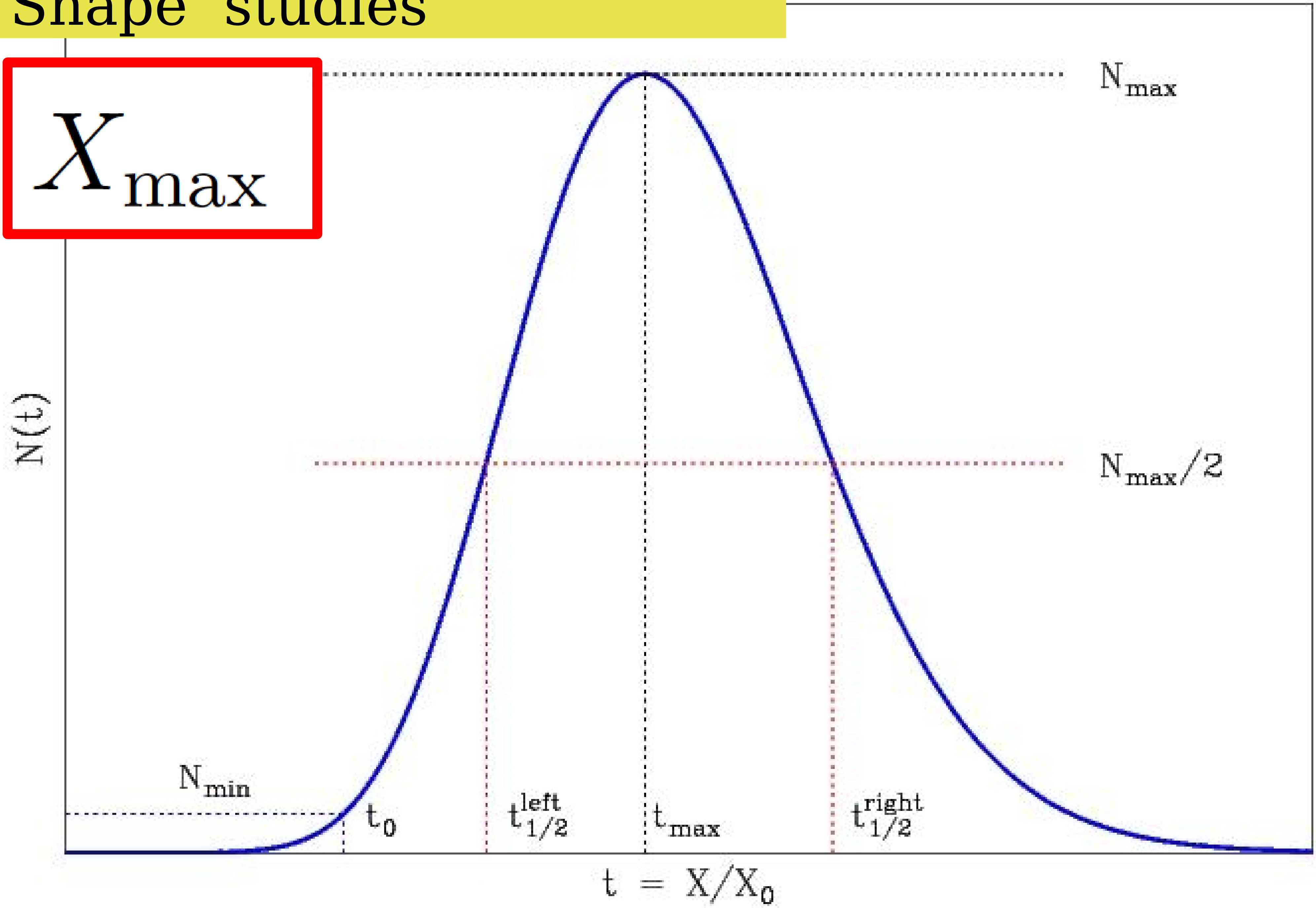
$$E \simeq 10^{20}\ \mathrm{eV}$$





Longitudinal Development
Shape studies

X_{max}

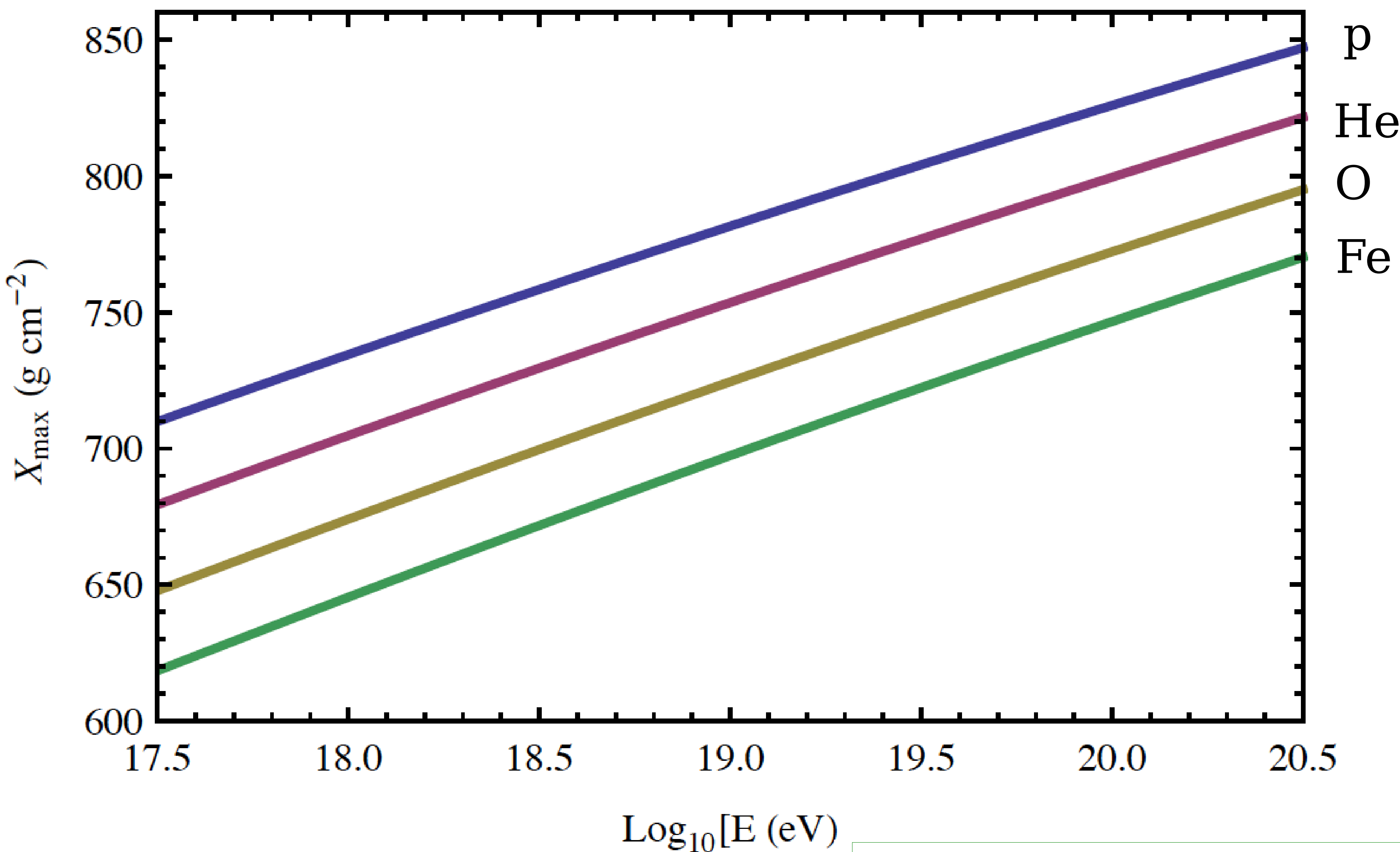


X_{max} and the Composition of Cosmic Rays

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

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

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

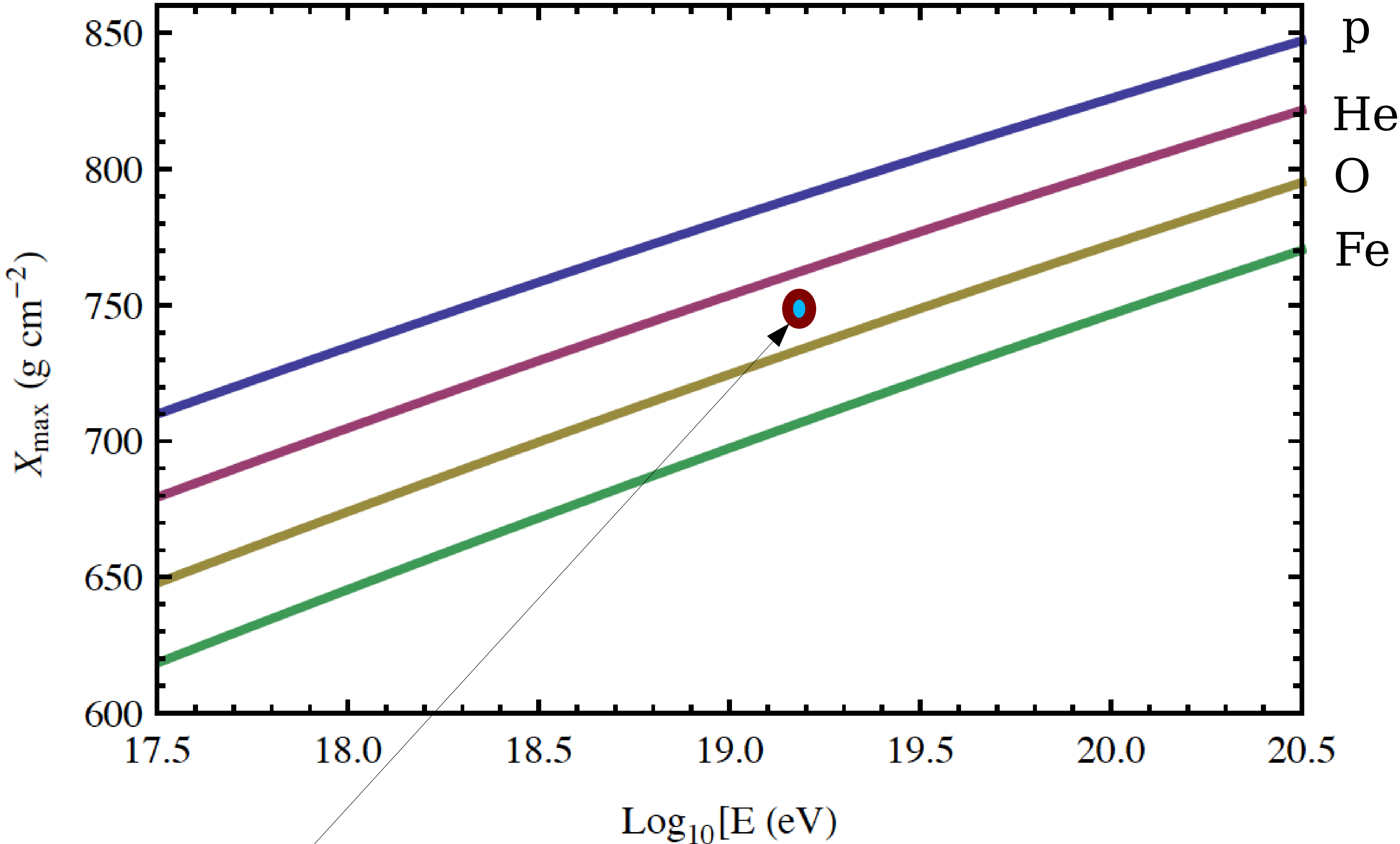


$$\langle X_A \rangle \simeq \langle X_p \rangle - D_p \ \log_{10} A$$

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

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

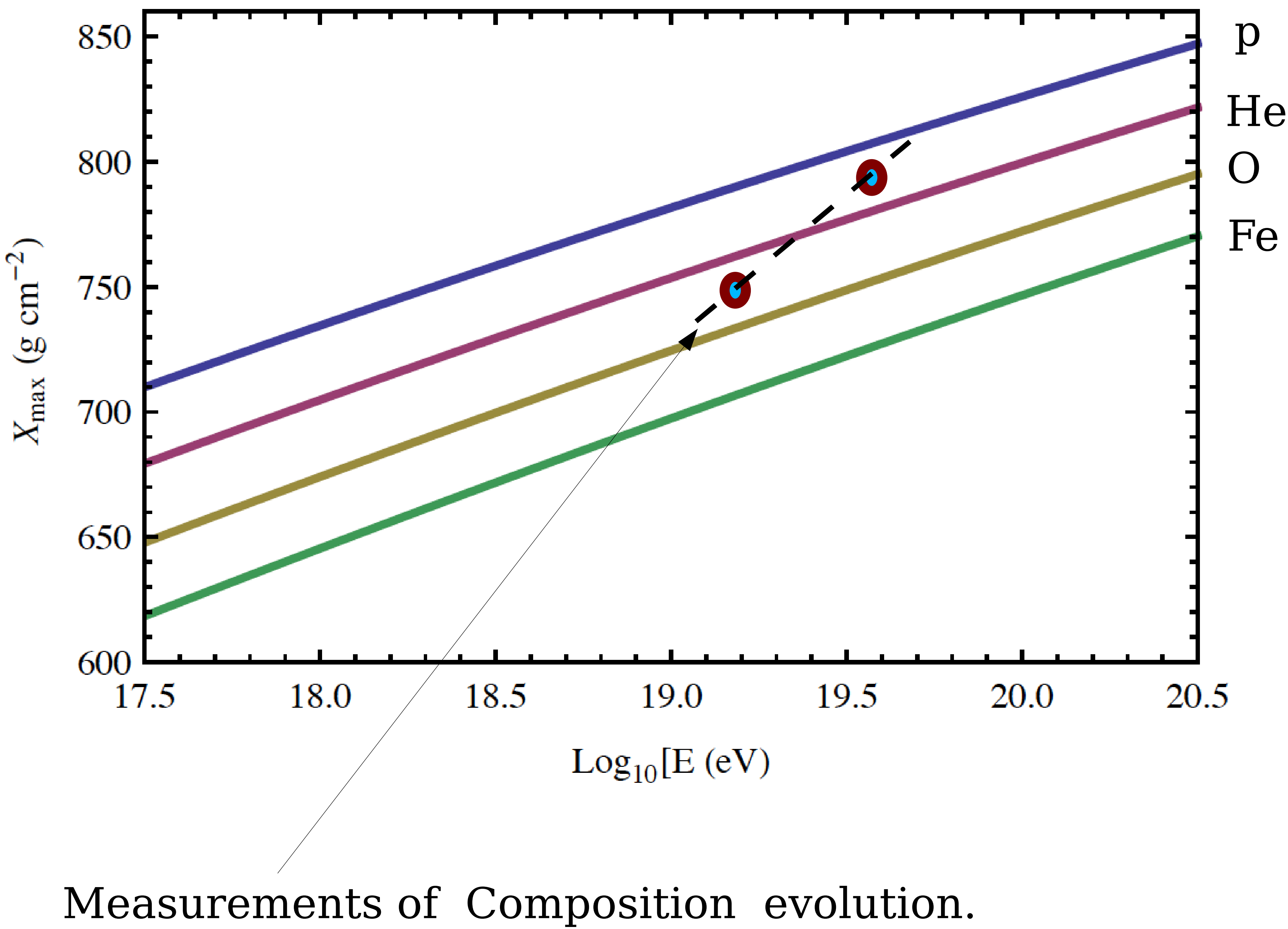
$$\langle X_{\rm Fe} \rangle \simeq \langle X_p \rangle - 90 \ {\rm g \ cm^{-2}}$$



Measurements of

$$\langle \log A \rangle$$

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


p
He
O
Fe
850
800
750
700
650
600
17.5
18.0
18.5
19.0
19.5
20.0
20.5
X_{max} (g cm^{-2})
Log$_{10}$[E (eV)]
Measurements of Composition evolution.

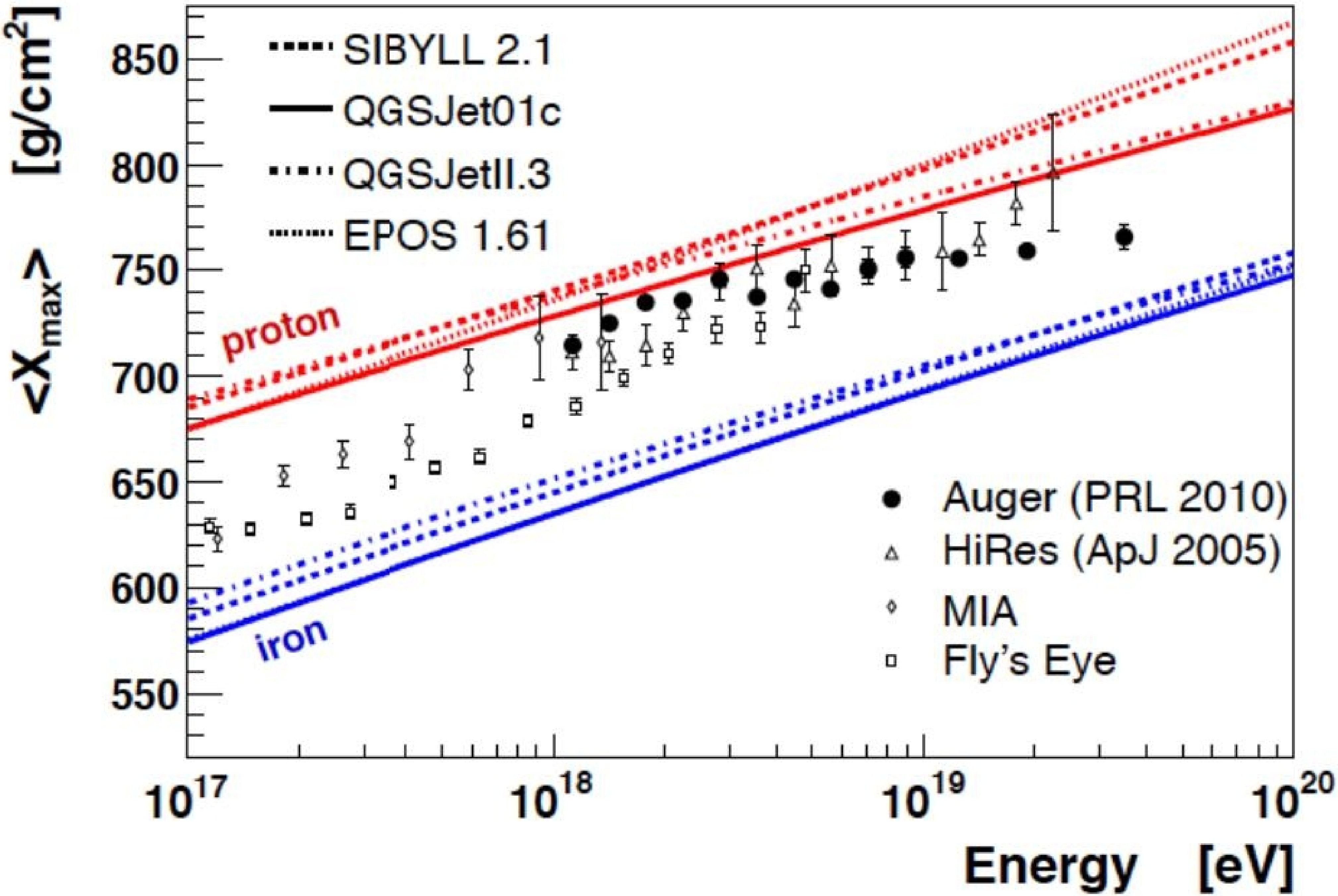
Obtain the average mass
and its variation
with energy

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

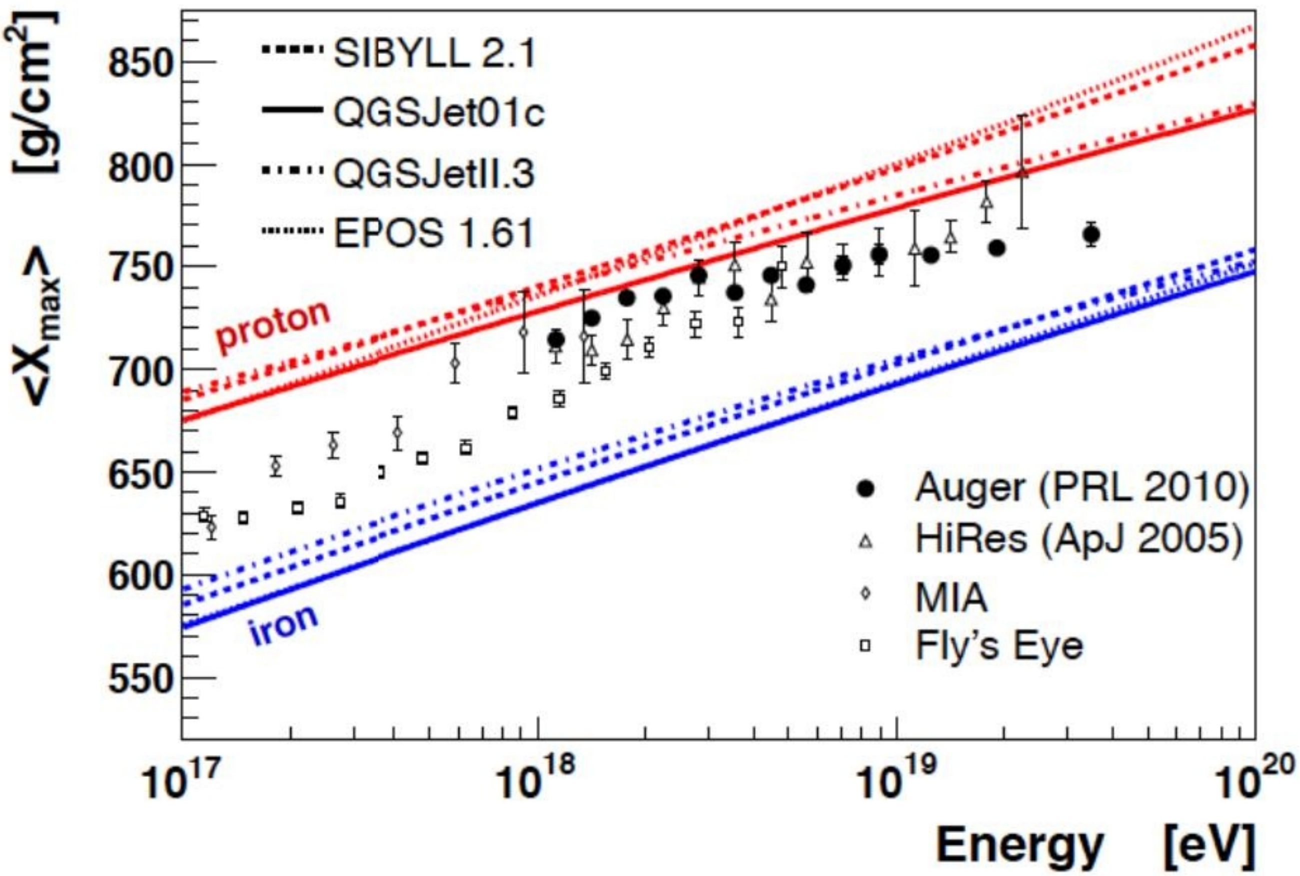
$$\langle \ln A \rangle_E = \frac{\langle X_{\max}(E) \rangle - X_p(E)}{D_p}$$

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

AUGER



SIBYLL 2.1
QGSJet01c
QGSJetII.3
EPOS 1.61
proton
iron
Auger (PRL 2010)
HiRes (ApJ 2005)
MIA
Fly's Eye
<X_max> [g/cm^2]
850
800
750
700
650
600
550
10^17
10^18
10^19
10^20
Energy [eV]



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
....

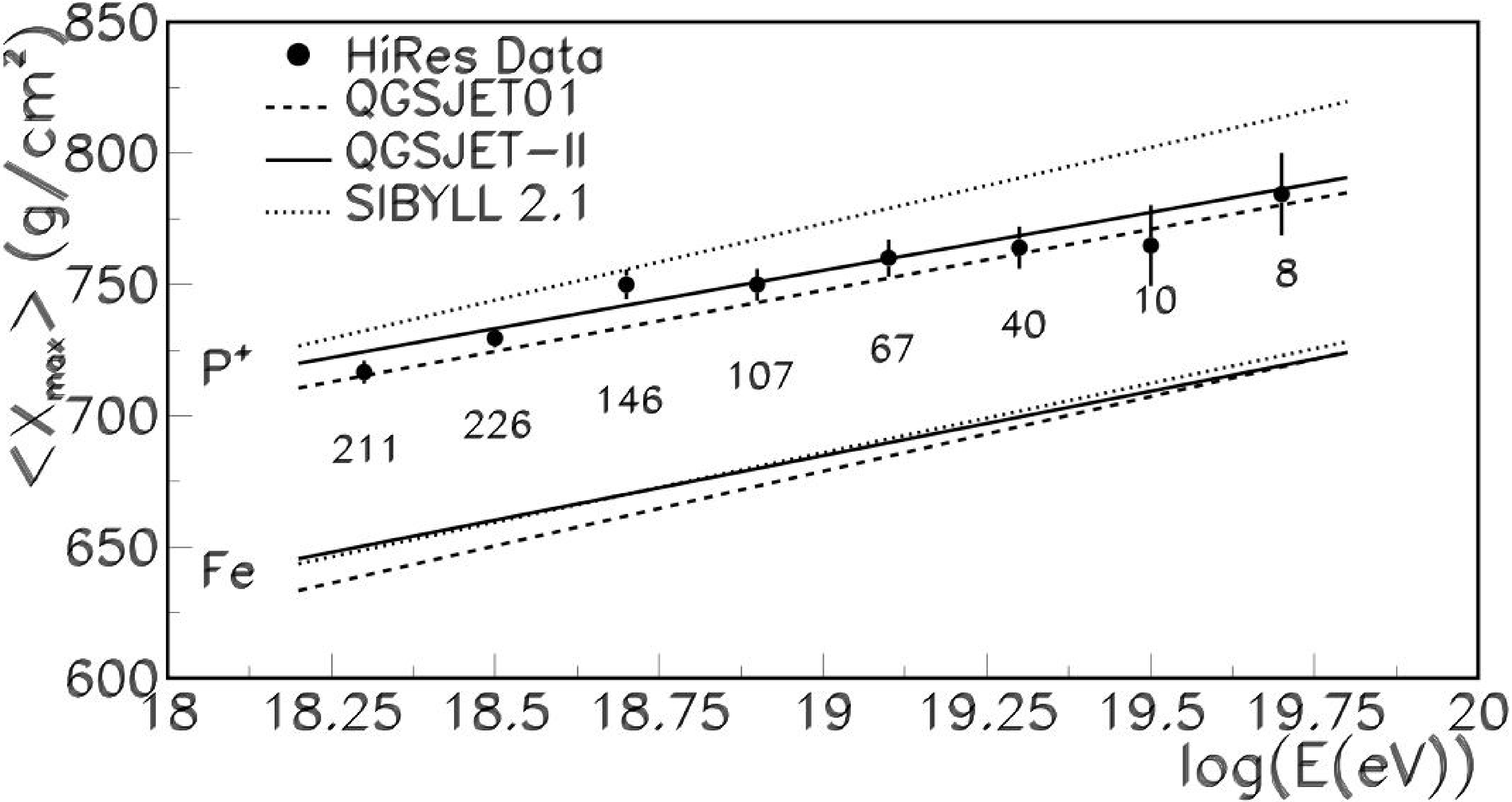
Theoretical curves:

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

10^{19} eV

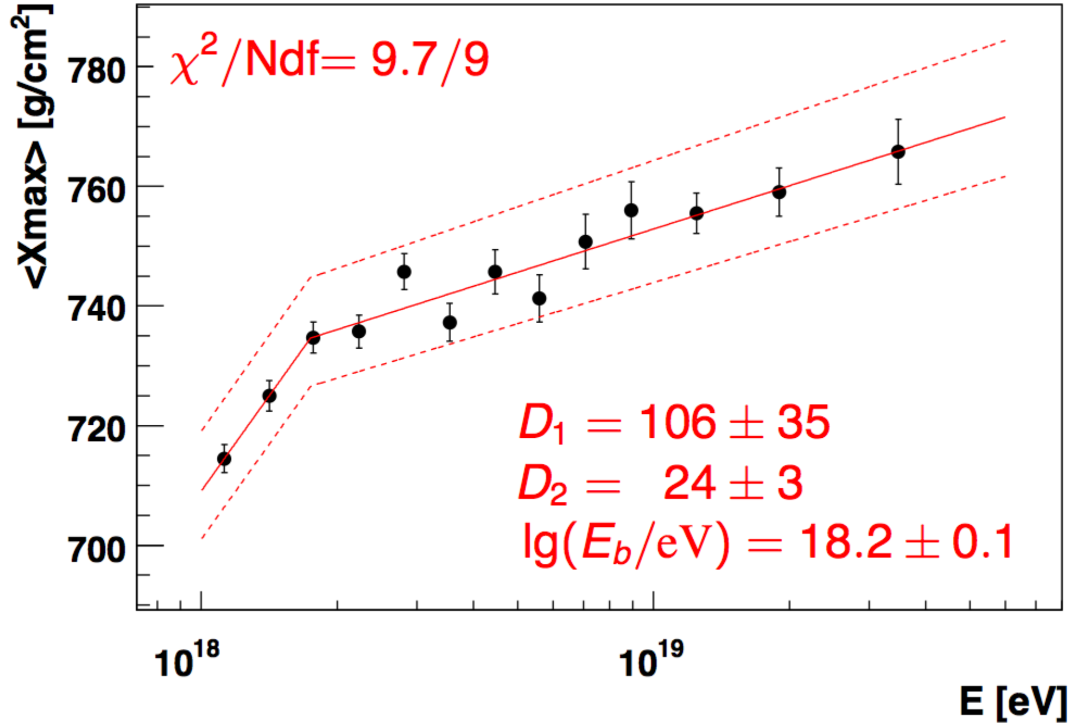
$$D_p = \frac{d\langle X_{\rm max}\rangle}{d\log_{10} E} \simeq 45\ -\ 55 \text{ g cm}^{-2}$$

HiRes 2009



HiRes Data
QGSJET01
QGSJET-II
SIBYLL 2.1
<Xmax> (g/cm2)
850
800
750
700
650
600
P+
Fe
211
226
146
107
67
40
10
8
18
18.25
18.5
18.75
19
19.25
19.5
19.75
20
log(E(eV))

Importance of “CORNERS”



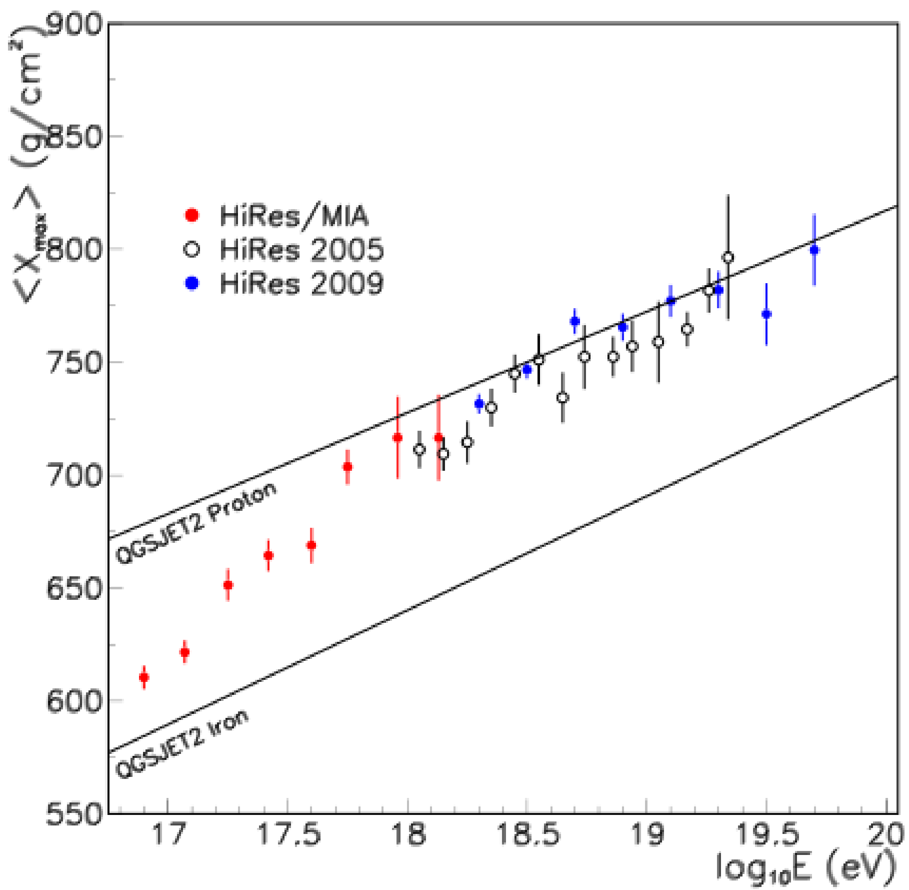


Fig. 25.— Comparison of current HiRes stereo $<X_{max}>$ results with results from the HiRes-prototype/MIA hybrid (Abu-Zayyad et al. 2001) and previously published HiRes stereo results (Abbasi et al. 2005).

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

Abrupt change in the composition evolution.

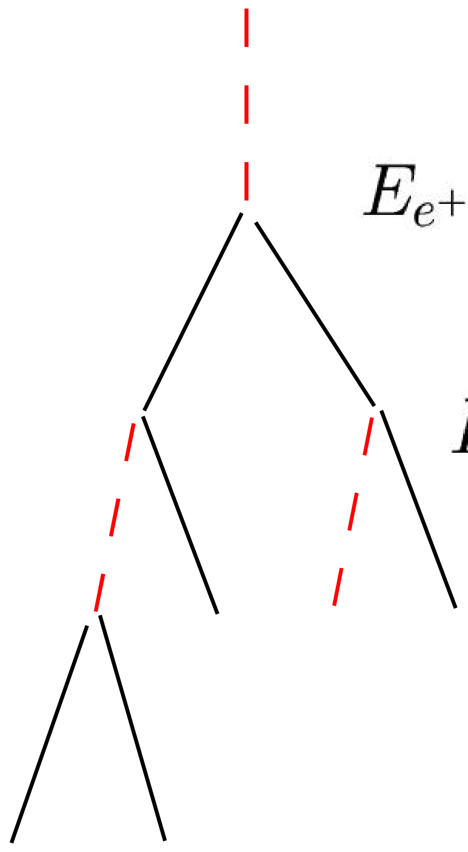
Electromagnetic Showers

versus

Hadronic Showers

Toy model discussion.

Electromagnetic Shower



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

Pair production

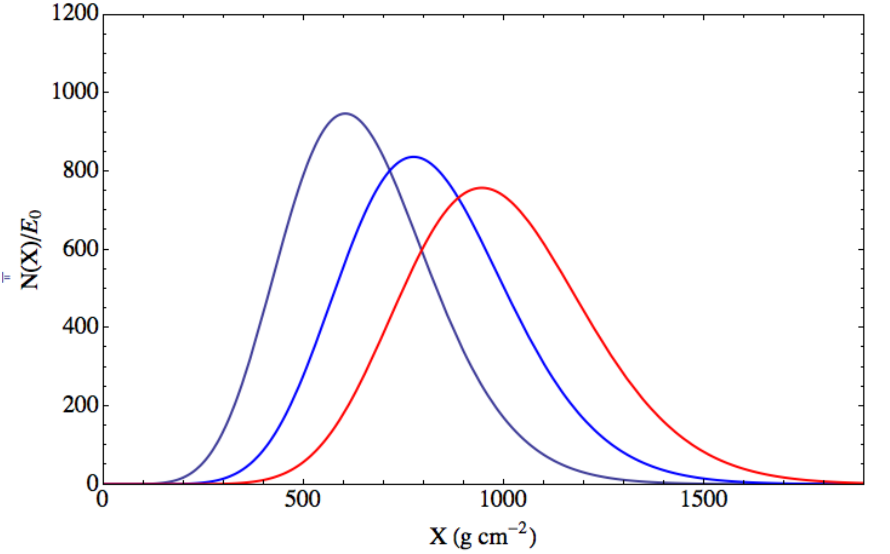
$$E_\gamma = E_e \; v \qquad \varphi(v)$$

Bremsstrahlung

Radiation Length
(Energy independent)

Vertices :
theoretically understood
(and scaling)

Electromagnetic Showers



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

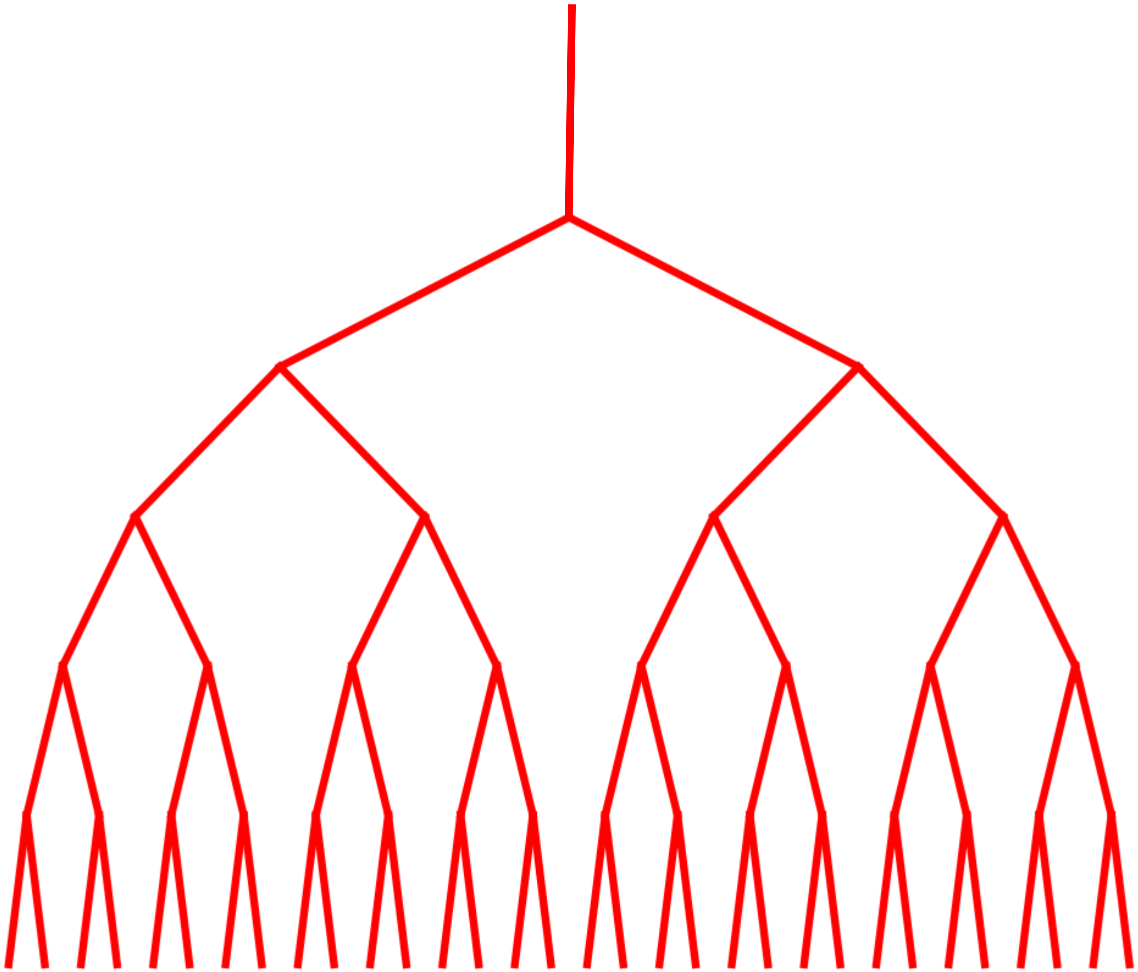
Logarithmic growth of the penetration.

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

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:

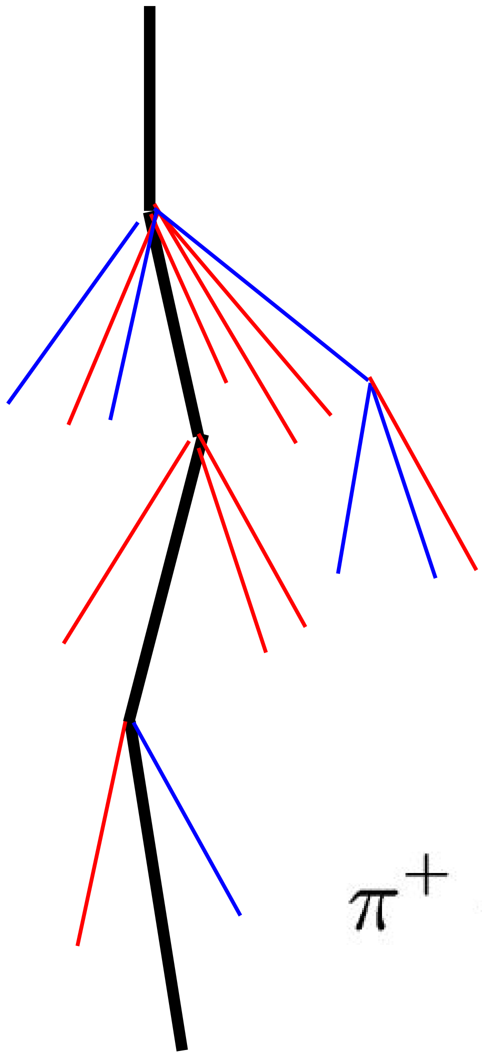
$$\sigma_X^2(\gamma, E) = \text{constant}$$

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

Proton Shower

Vertices : theoretically not
Understood

(and energy dependent)



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

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

All energy transferred
to an electromagnetic shower

Theorem:

If:

$$\lambda_{\rm int}^{\rm hadron} = \text{constant}$$

Hadronic Interactions SCALING

Then:

$$\langle X_{\rm max}^{p} \rangle = \lambda_{\rm rad} \; \log E + \text{constant}$$

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.

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

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

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

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

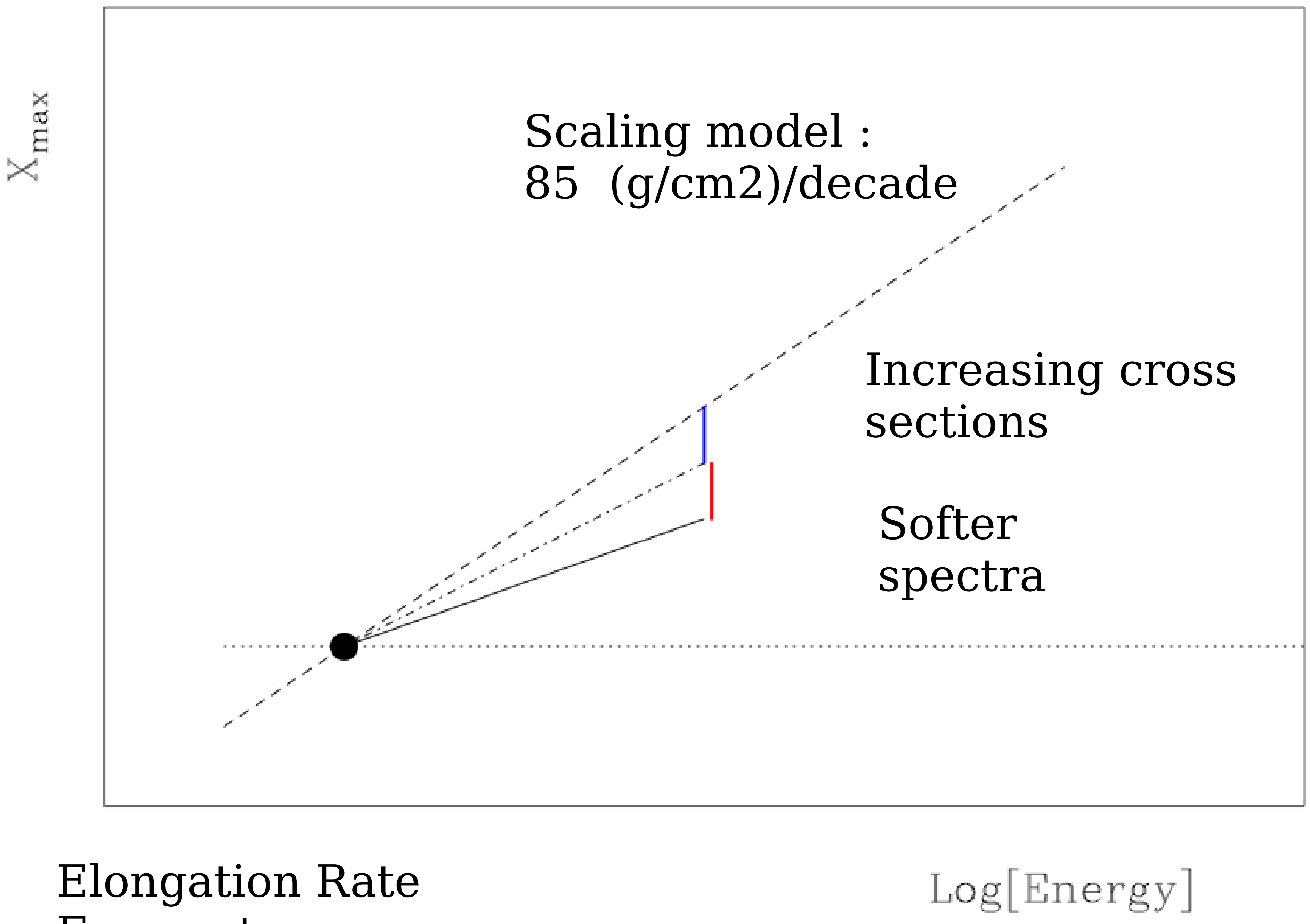
"Softness"

Elongation Rate

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

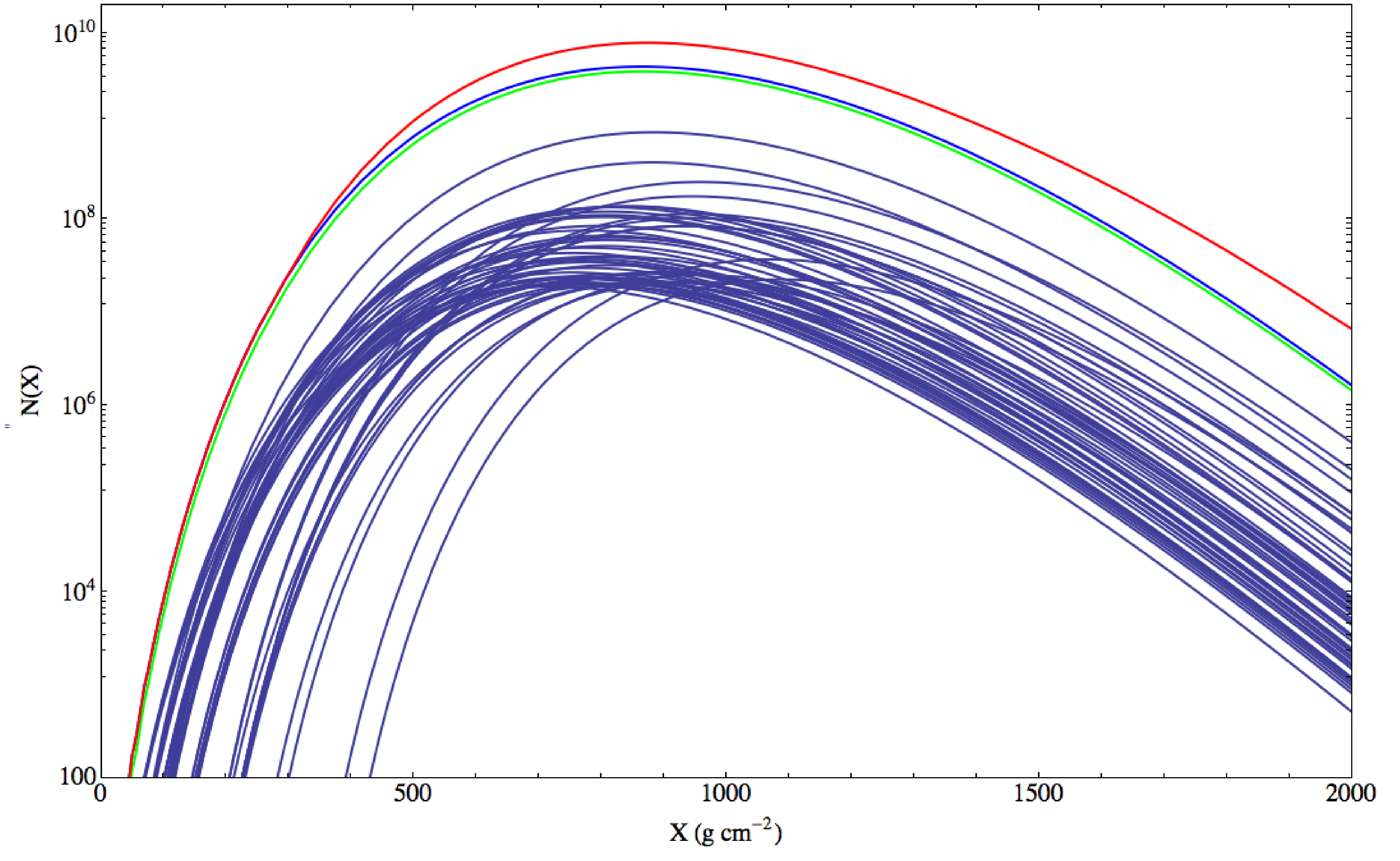
Evolution with Energy of the Interaction length

Evolution with energy of the "softness" of the spectrum

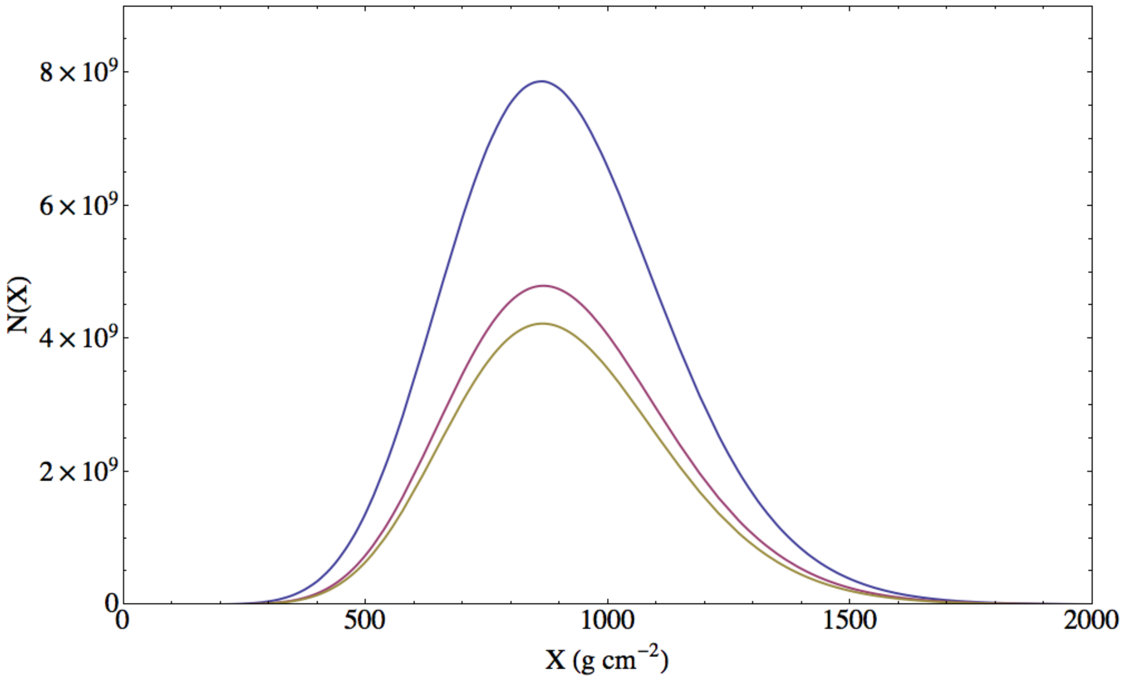


Elongation Rate
For protons

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

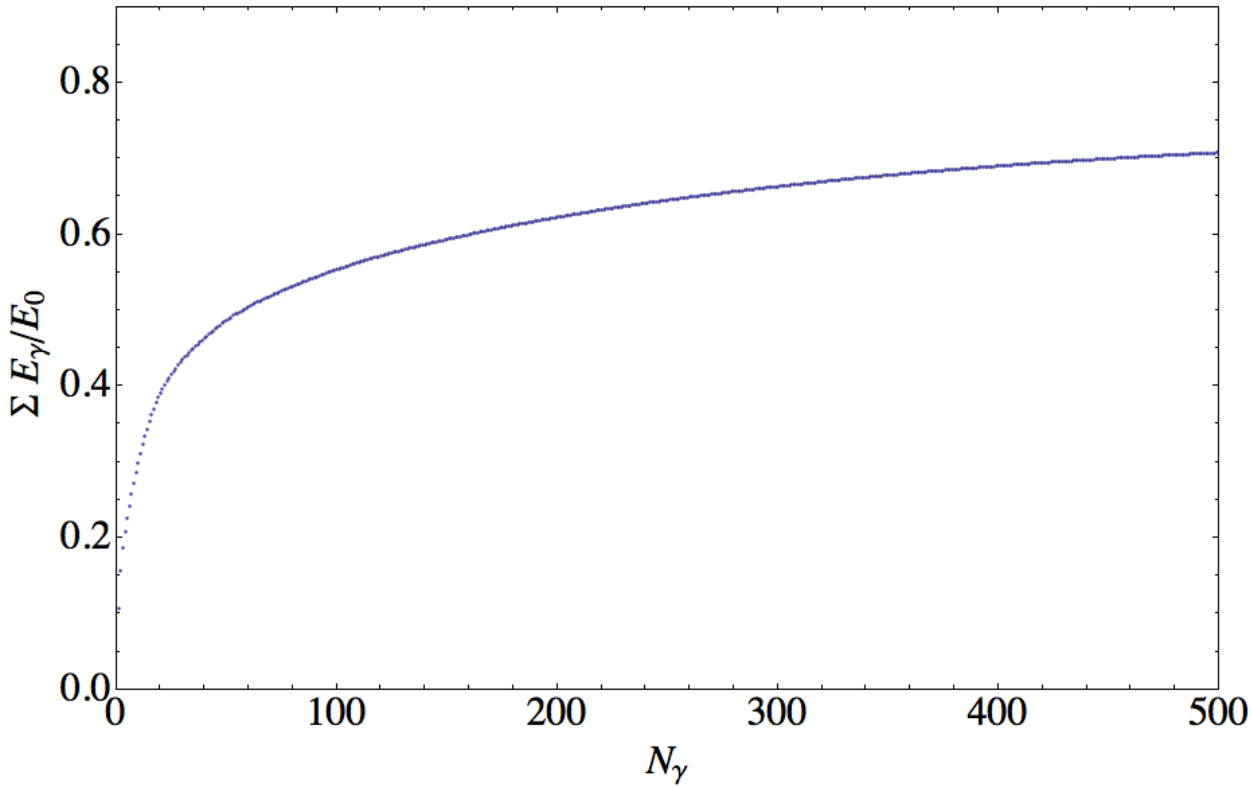


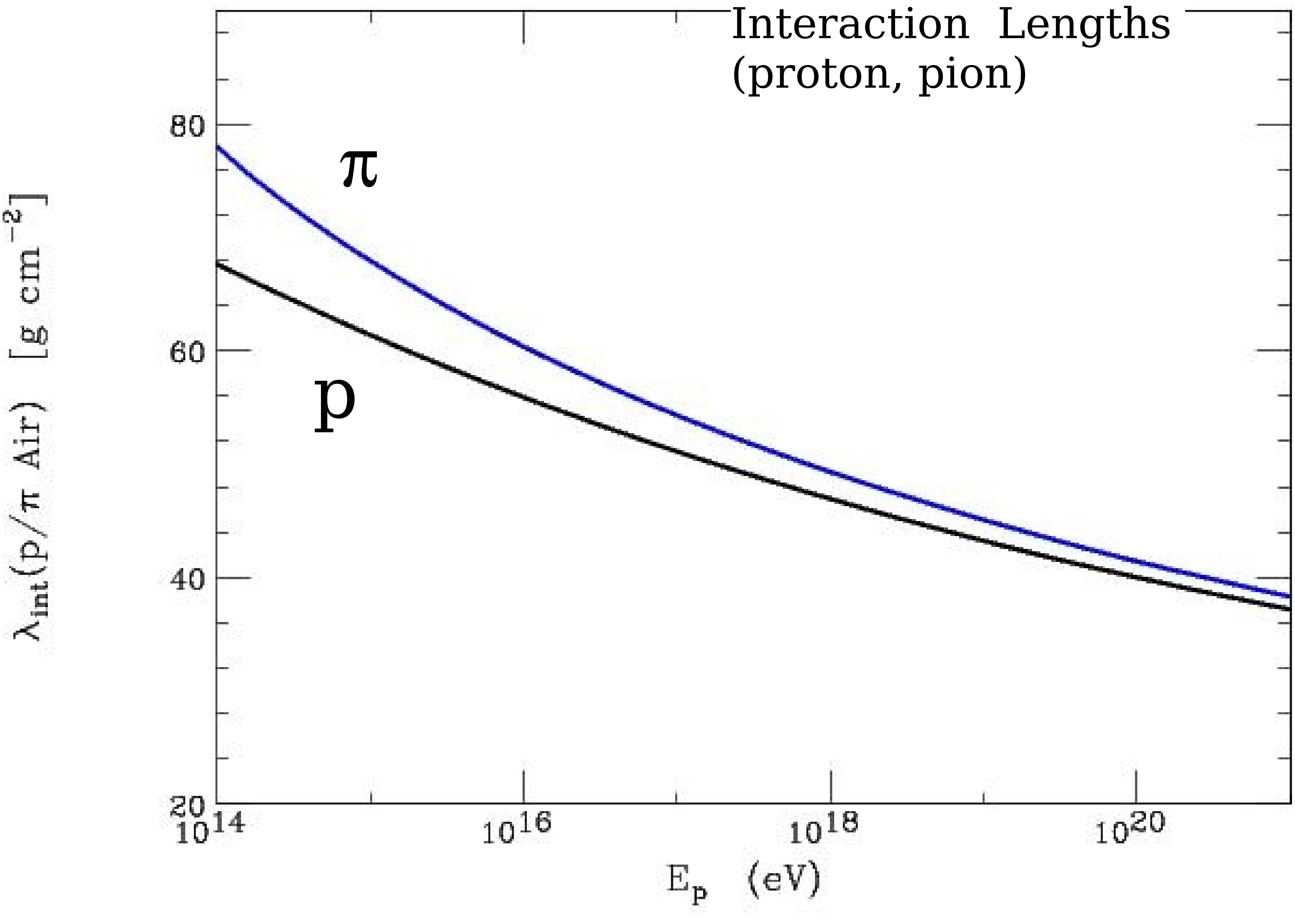
50 highest energy individual sub-showers



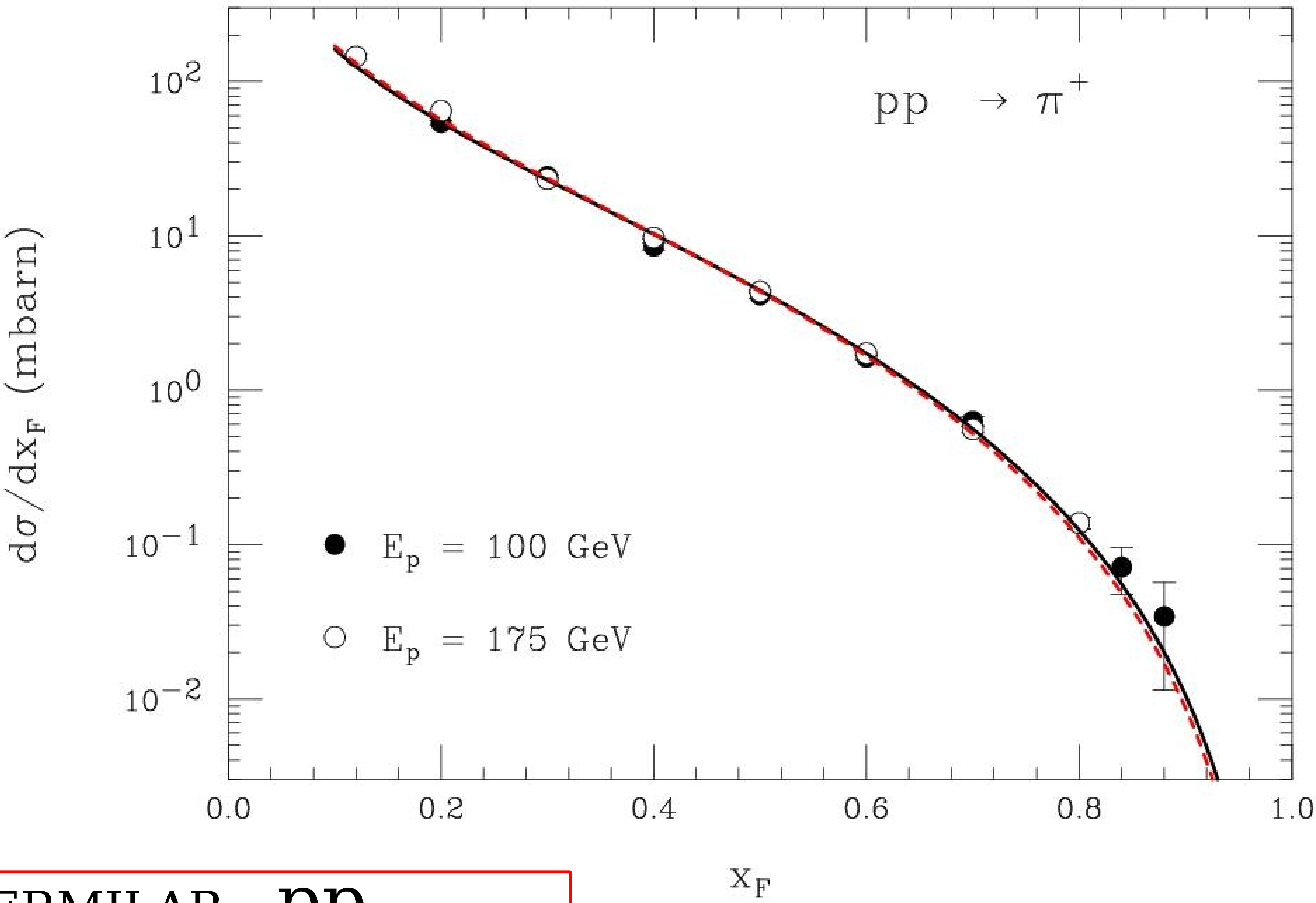
100 photons ~50% of energy
1000 photons ~70% of energy

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



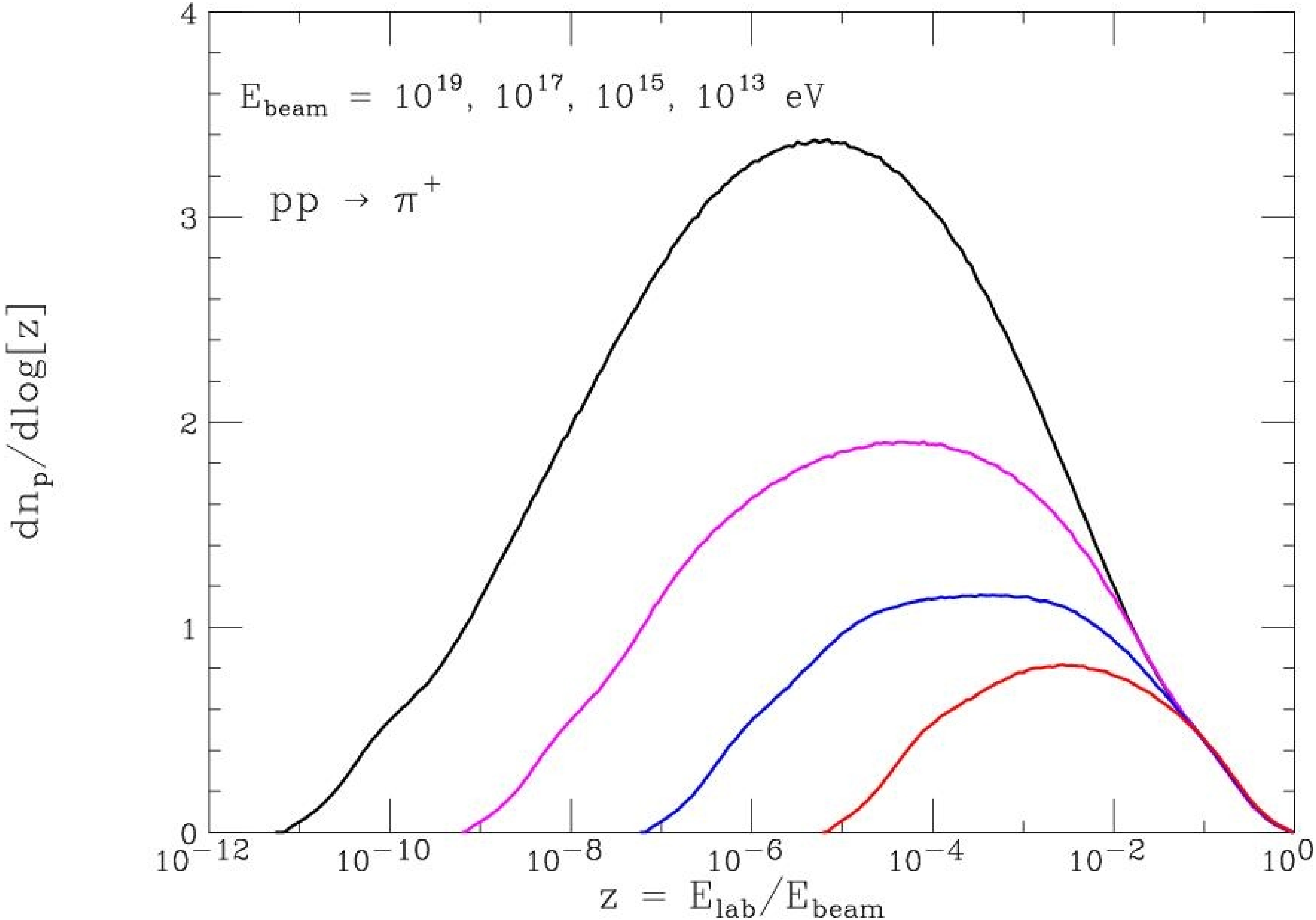

Interaction Lengths
(proton, pion)
π
p
80
60
40
20
10^14
10^16
10^18
10^20
λ_int(p/π Air) [g cm^-2]
E_p (eV)

Phenomenological Evidence for SCALING

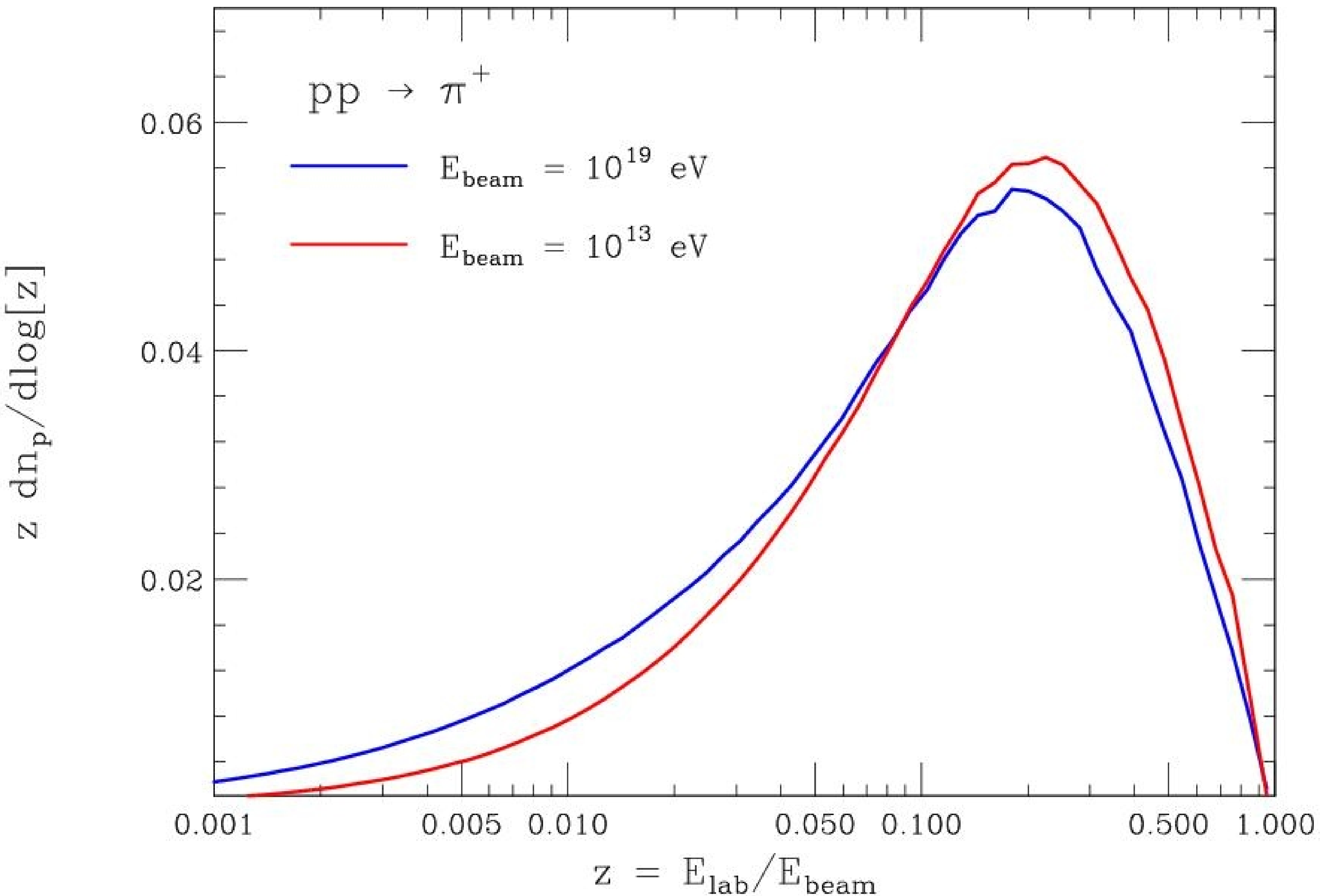


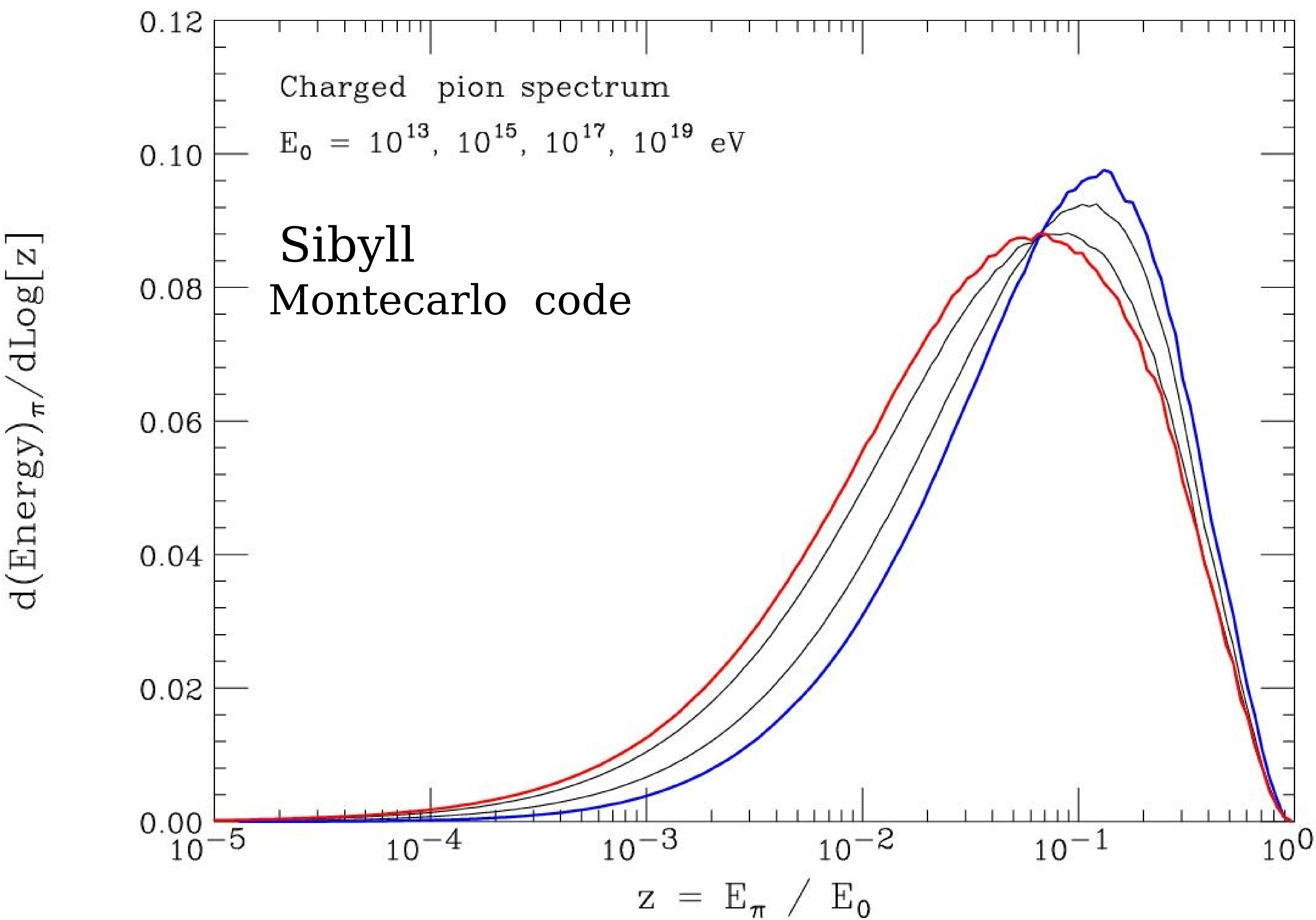
FERMILAB: pp
Brenner et al (1982)

EXTRAPOLATION to HIGH ENERGY (Pythia pp)



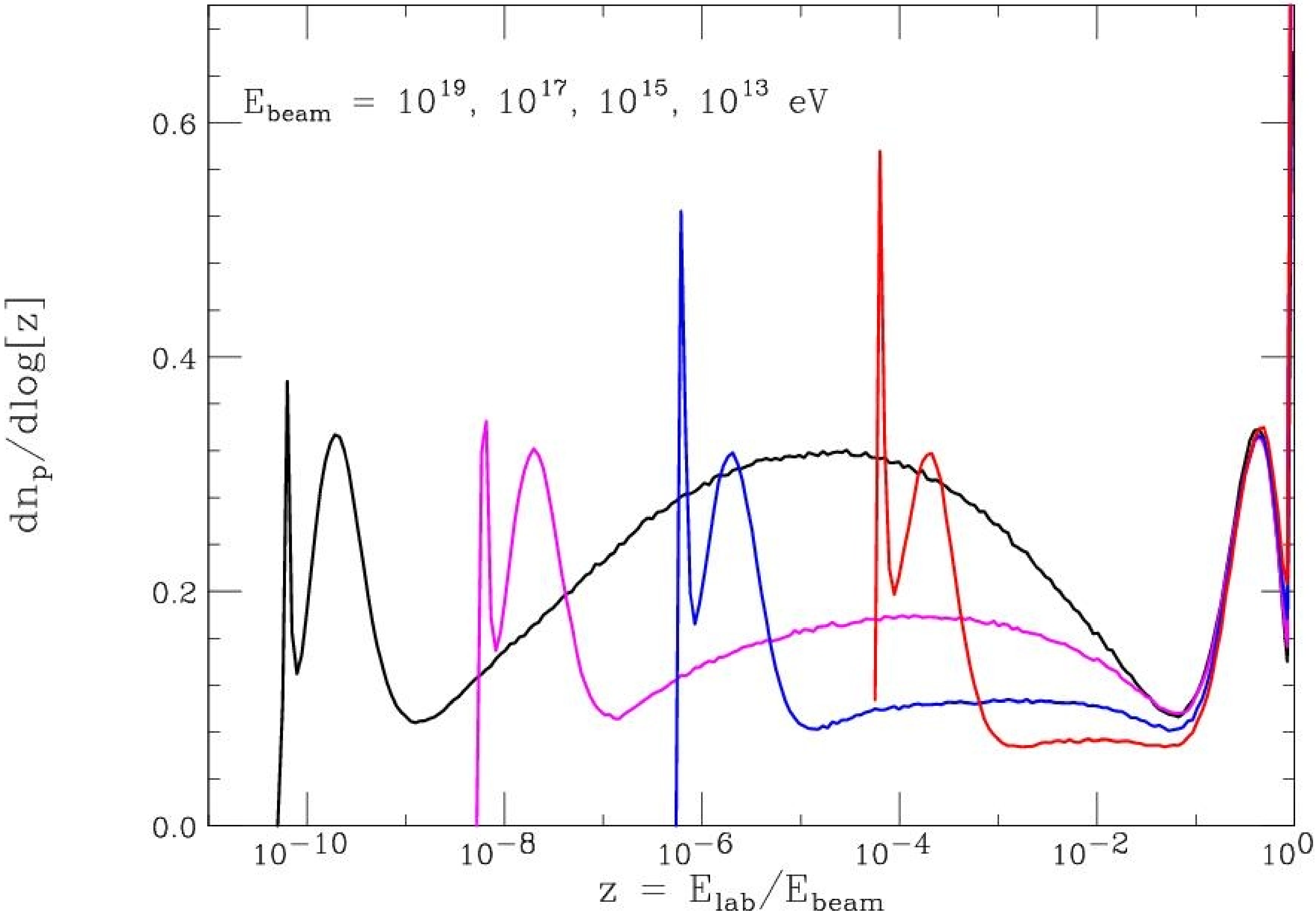
EXTRAPOLATION to HIGH ENERGY (Pythia pp)



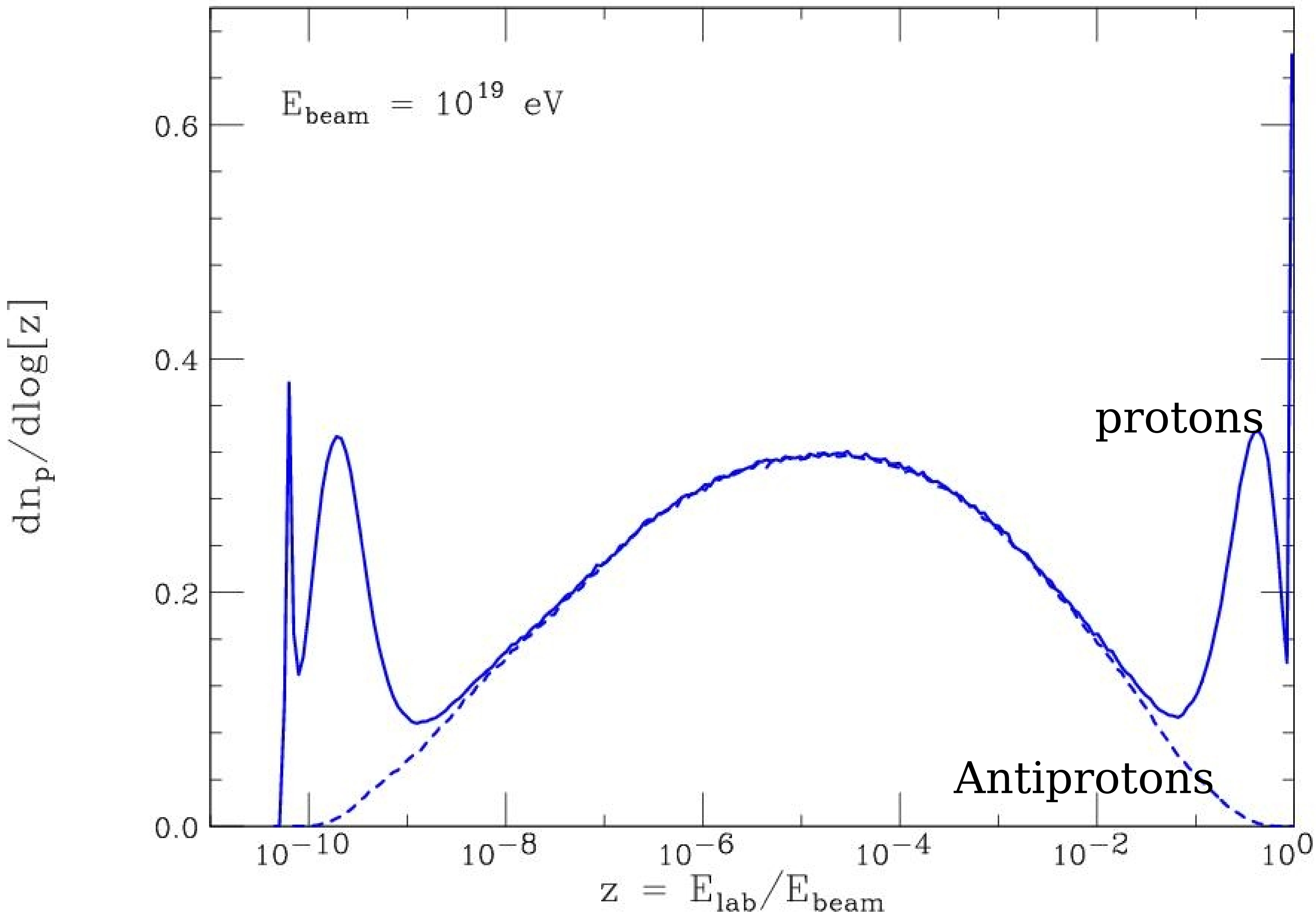


Charged pion spectrum
E0 = 10^13, 10^15, 10^17, 10^19 eV
Sibyll
Montecarlo code
d(Energy)π/dLog[z]
z = Eπ / E0
0.12
0.10
0.08
0.06
0.04
0.02
0.00
10^-5
10^-4
10^-3
10^-2
10^-1
10^0

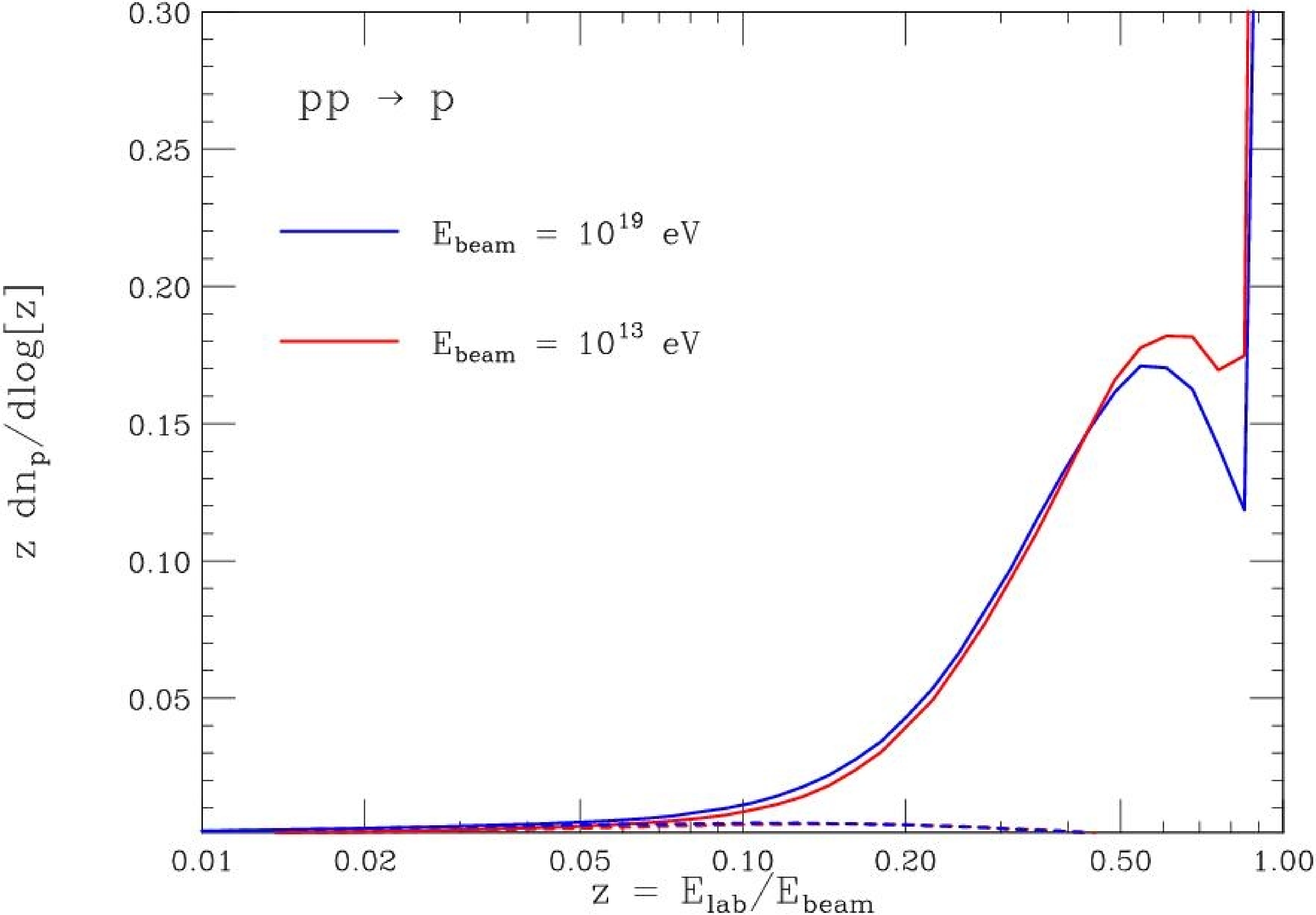
PROTON Spectra (elasticity spectra)



PYTHIA PROTON Spectra

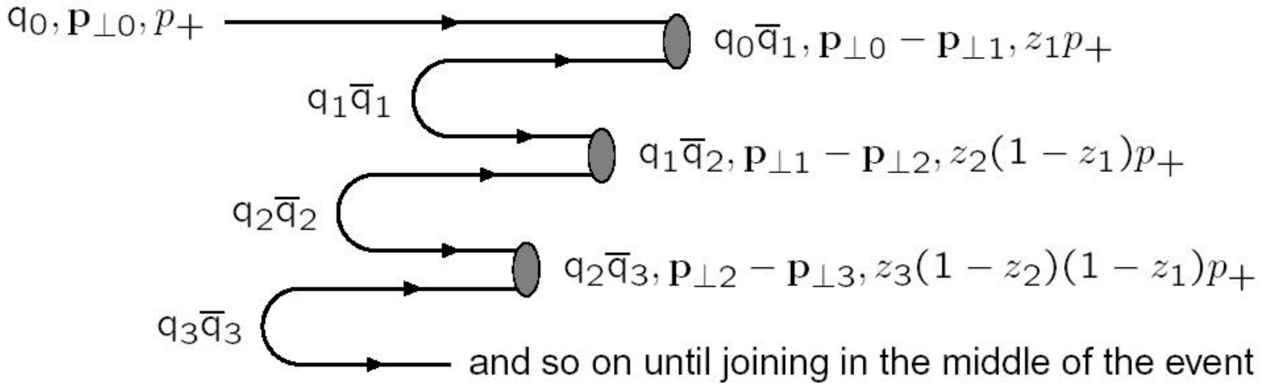


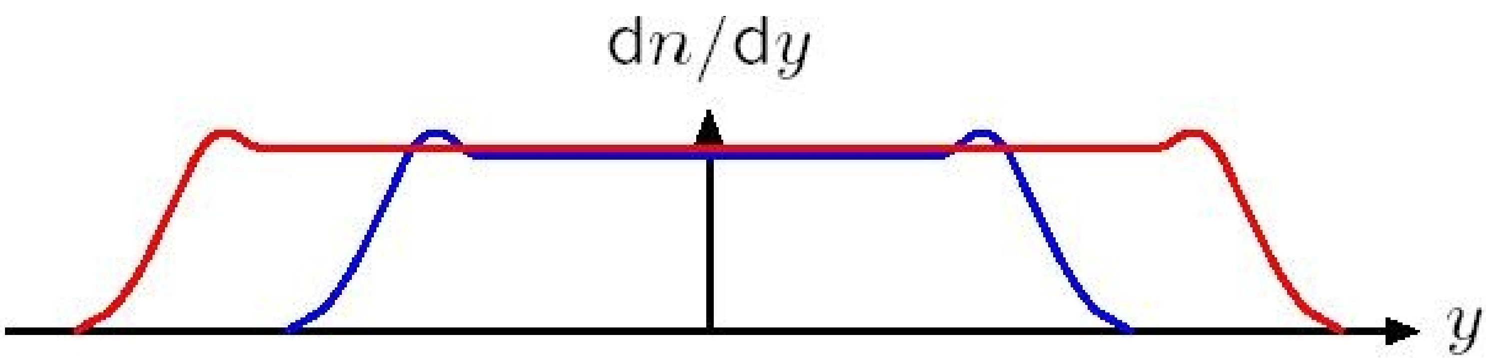
PROTON Spectra (elasticity spectra)



Where does the approximate Feynman scaling comes from ?

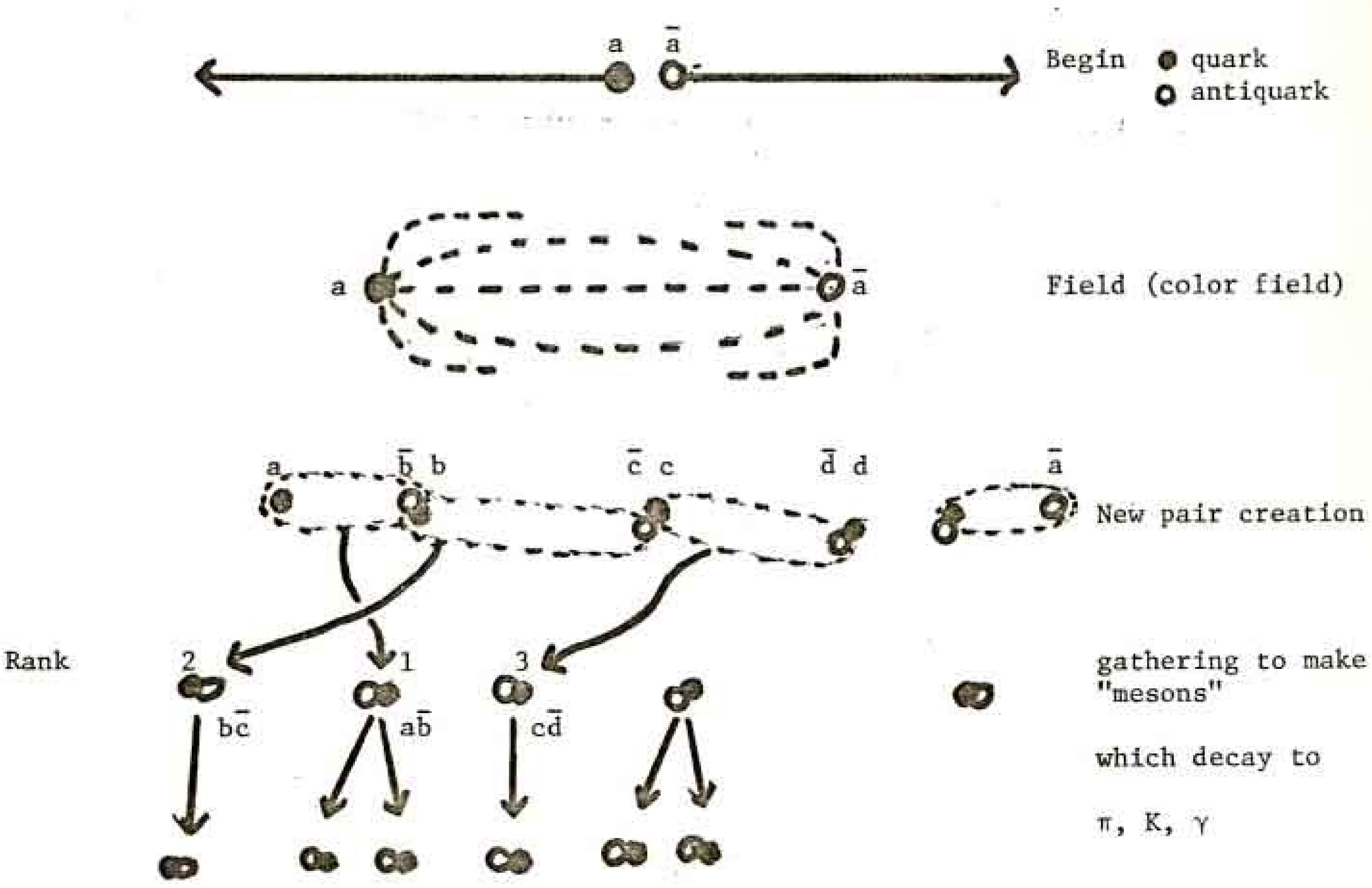
The (iterative) Fragmentation of one COLOR STRING produces a SCALING SPECTRUM of HADRONS



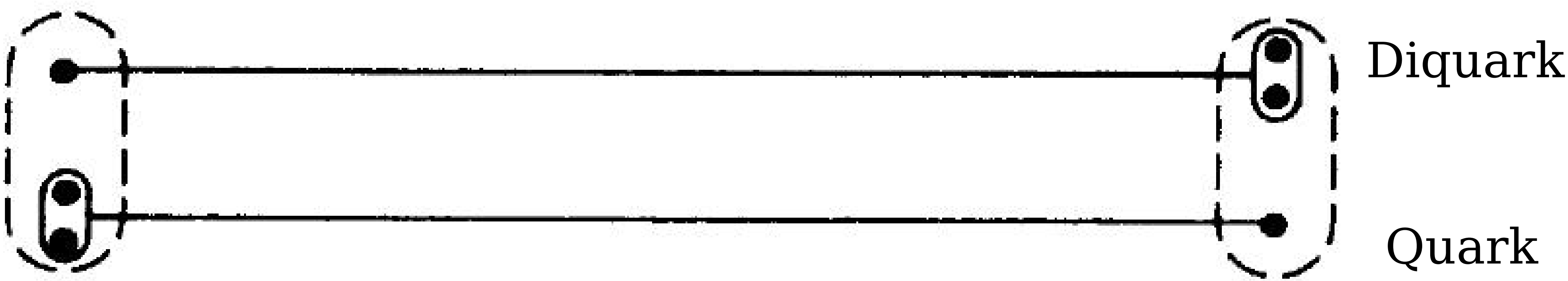


$\langle n_{\rm ch} \rangle \approx c_0 + c_1 \ln E_{\rm cm}$, $\sim$ Poissonian multiplicity distribution

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



Field -Feynman : Quark - Fragmentation



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

hard/semihard interactions
result in additional strings

Color Structure

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

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

C.R. DATA

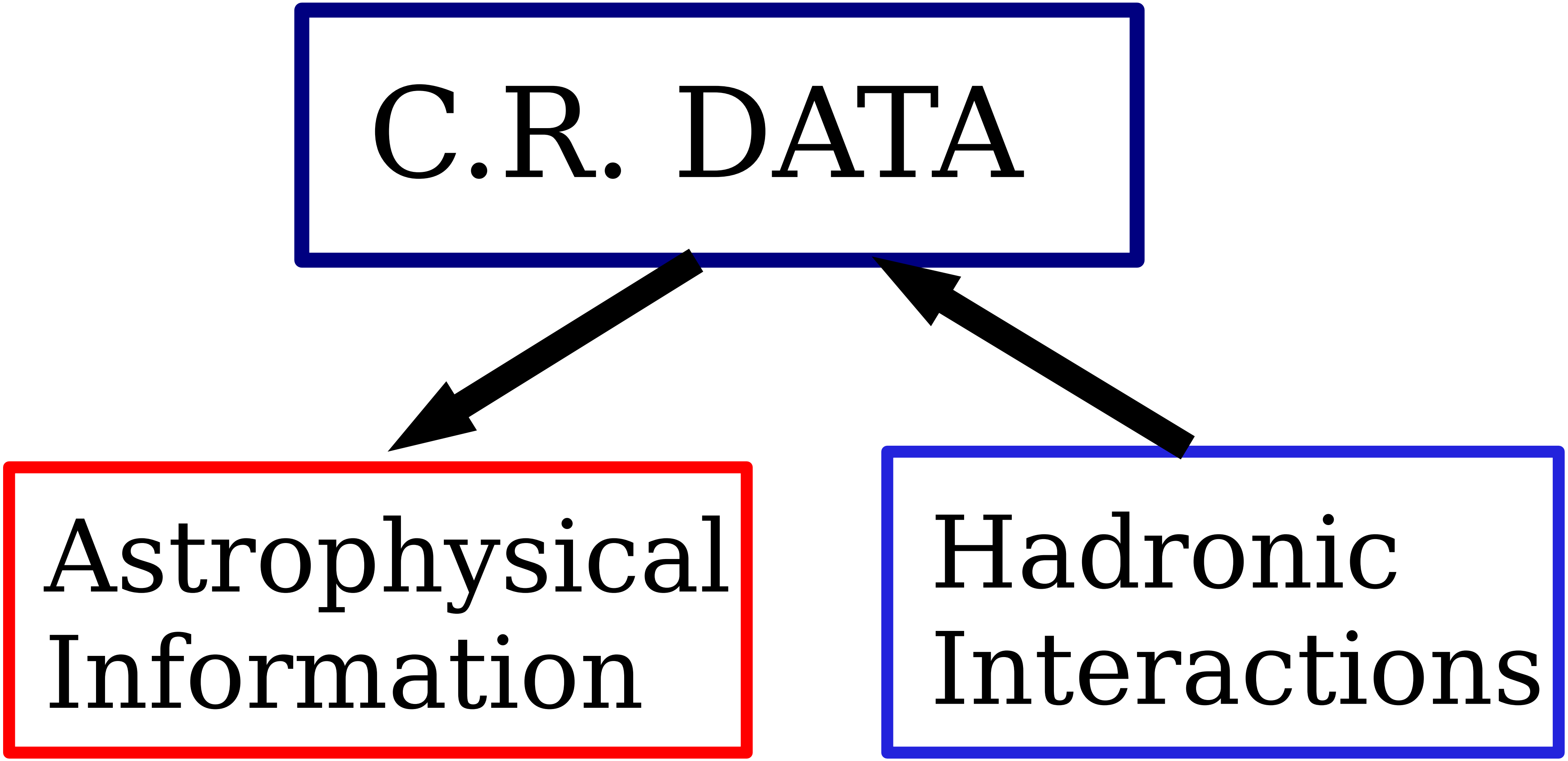
Astrophysical Information

Energy Spectrum
Composition

Hadronic Interactions

Cross sections,
Inclusive spectra
Multiplicities

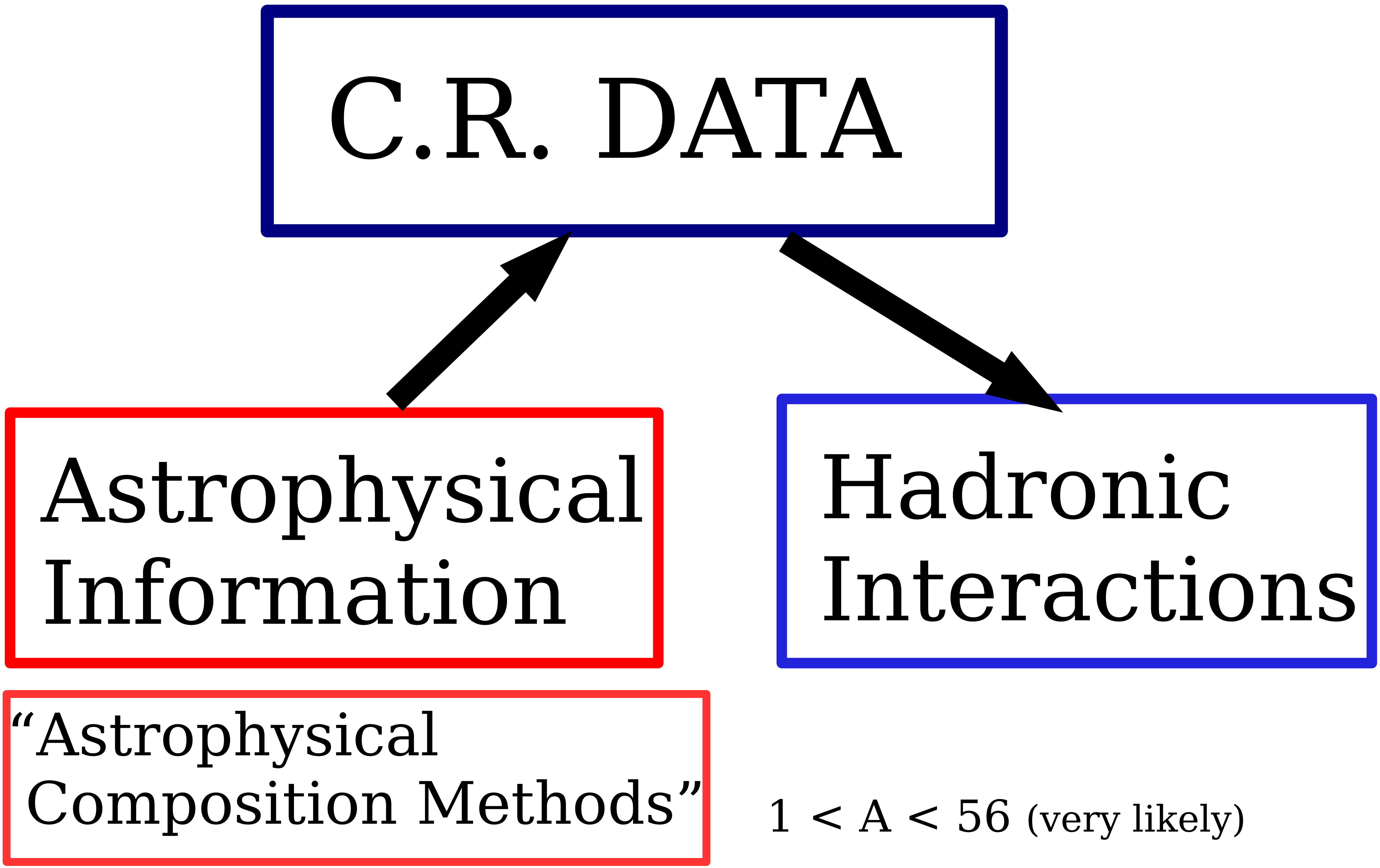
From Accelerator Data + Theory → Astrophysics



Energy Spectrum
Composition

Cross sections,
Inclusive spectra
Multiplicities

From Cosmic Ray Data → Hadronic Interactions

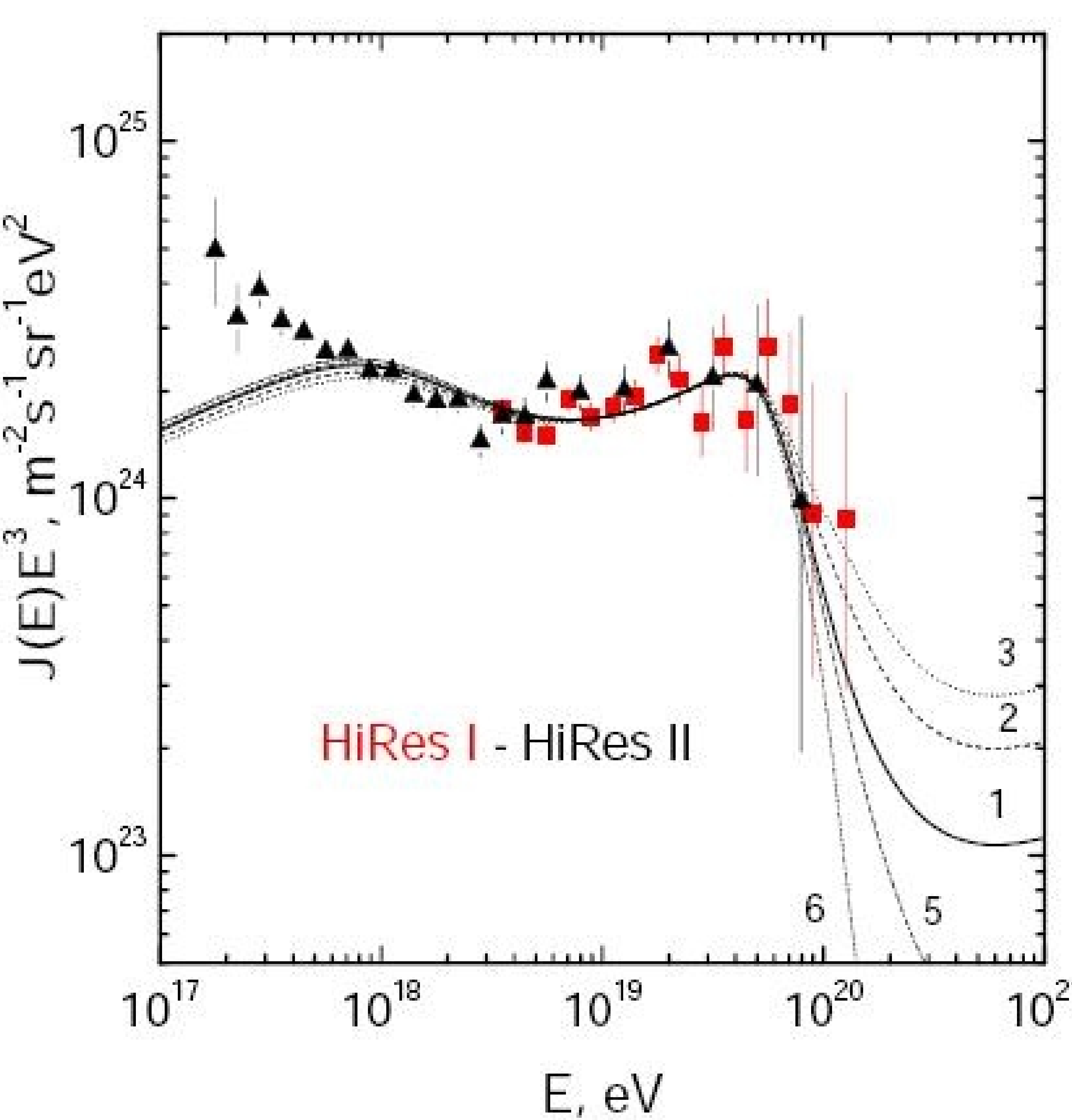


"Astrophysical Composition Methods"

- Energy Spectrum

  "imprints" of Energy Loss

- "Cosmic Magnetic Spectrometer"



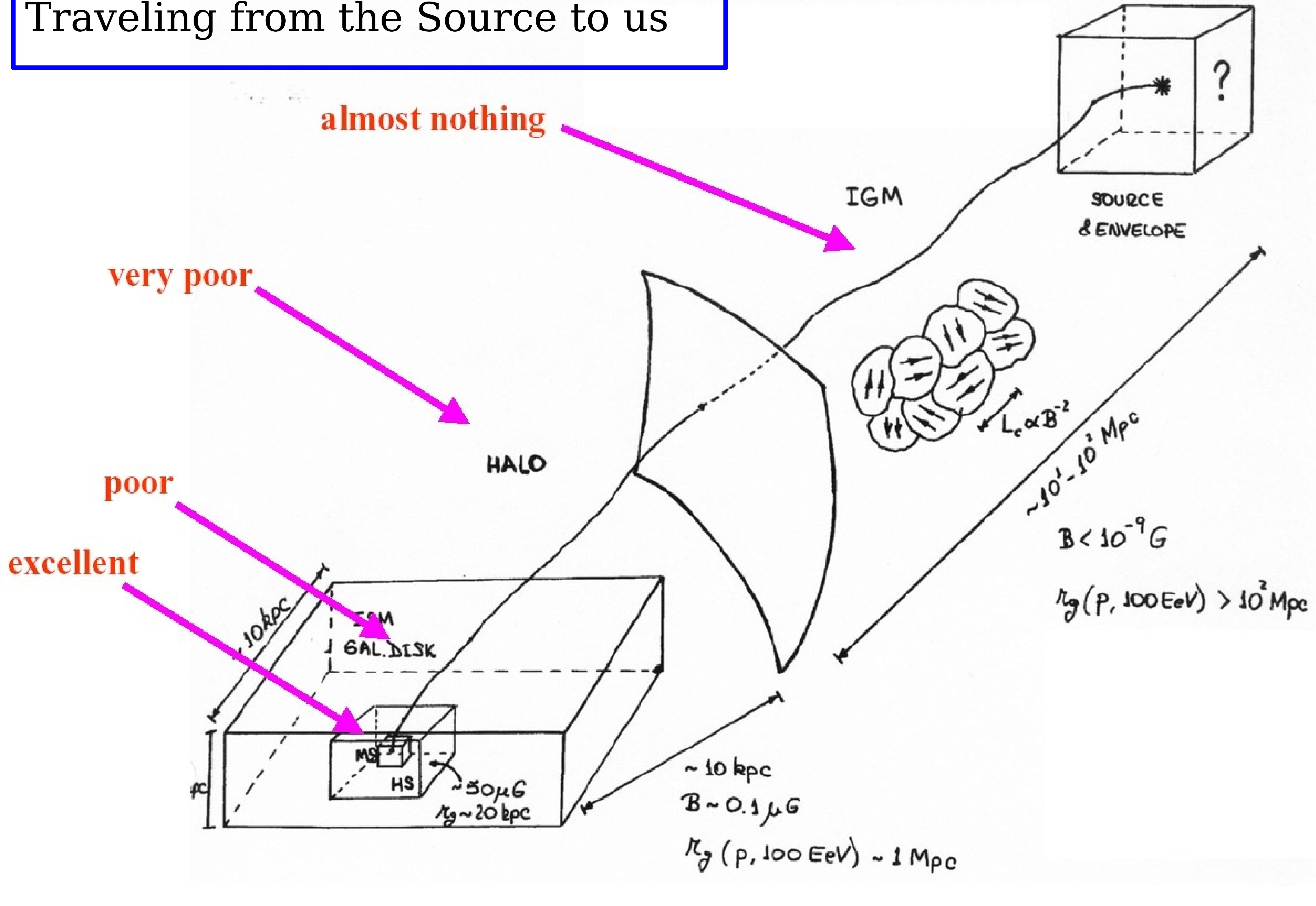
Berezinsky et al.

Inject Smooth power law Spectrum.

Let propagation leave its "imprint" on the shape of the spectrum.

"ANKLE" --> "DIP" e+e- production

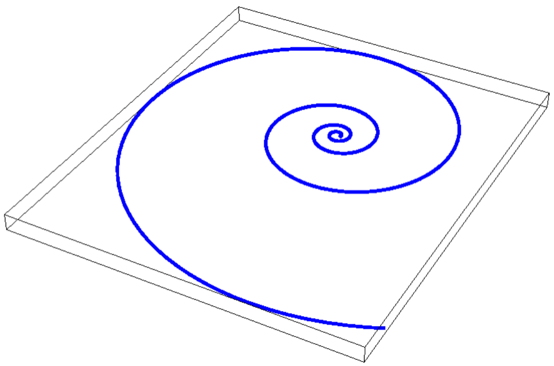
Deviation of a CR trajectory
Traveling from the Source to us



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

Deviation in GALACTIC Magnetic Field

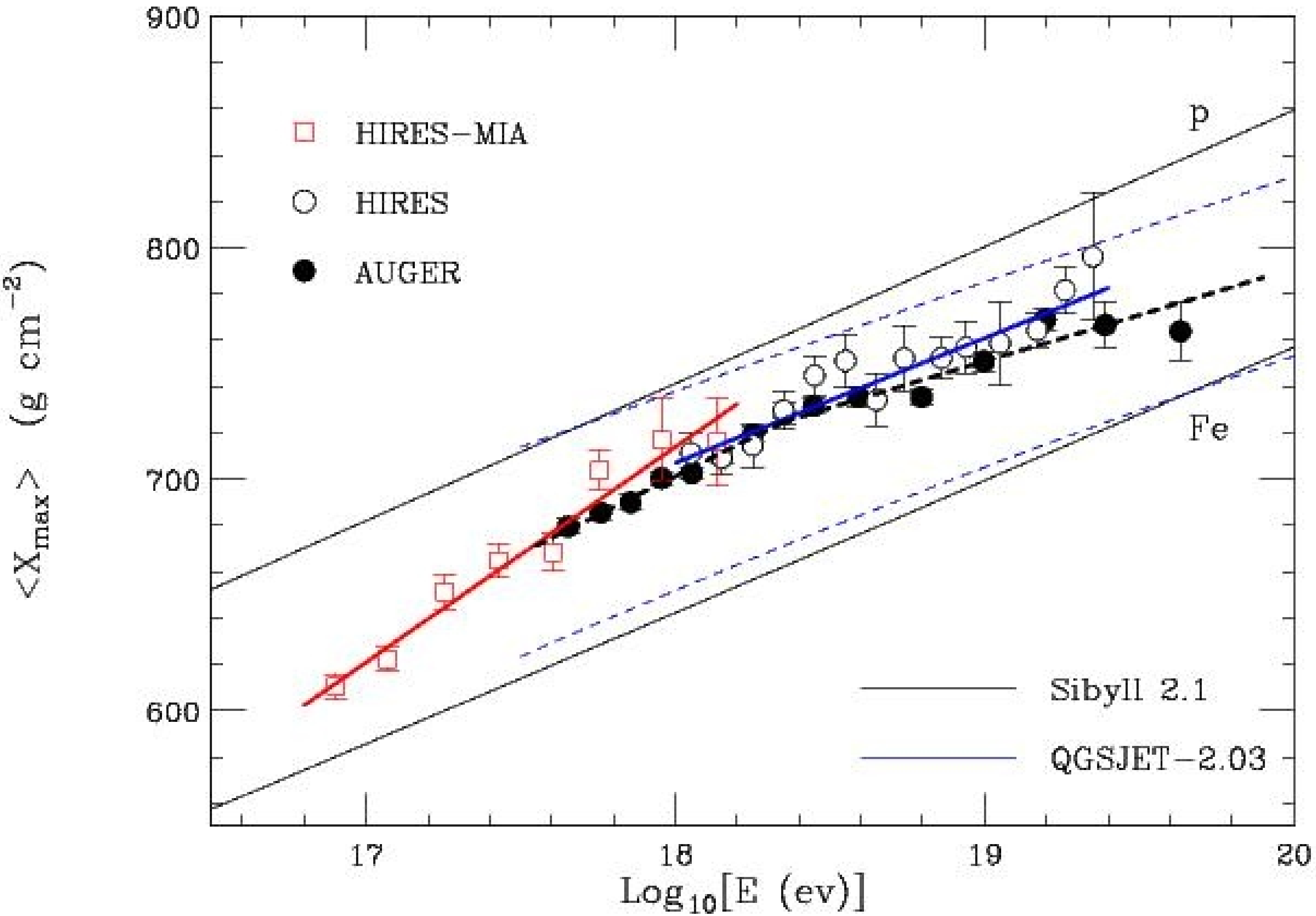
$$\delta \simeq 2.7^\circ \frac{60\ \text{EeV}}{E/Z} \left| \int_0^D \left(\frac{\mathrm{d}\mathbf{x}}{\text{kpc}} \times \frac{\mathbf{B}}{3\ \mu\text{G}} \right) \right|$$



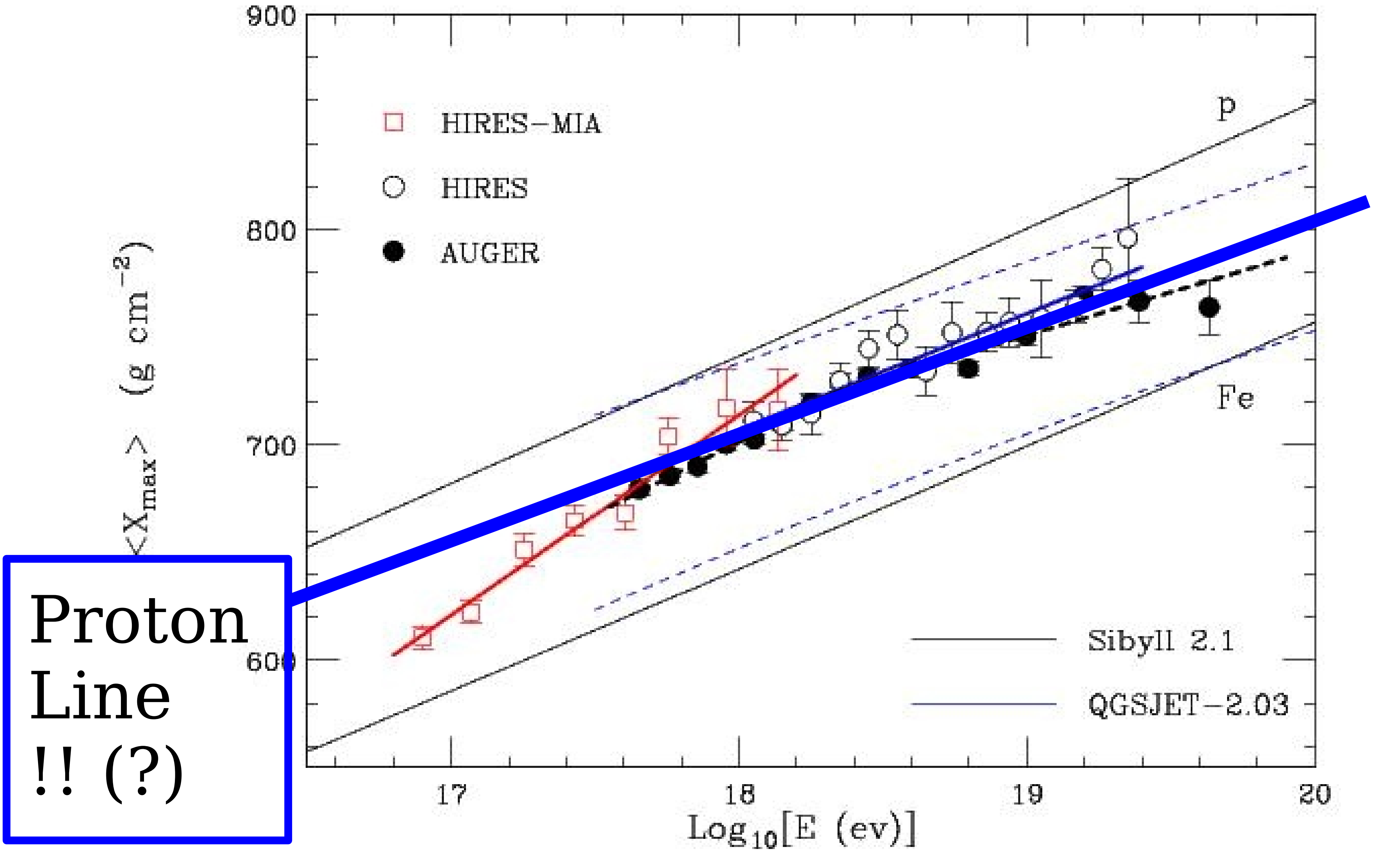
Deviation in EXTRA-GLACTIC Magnetic Field

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

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

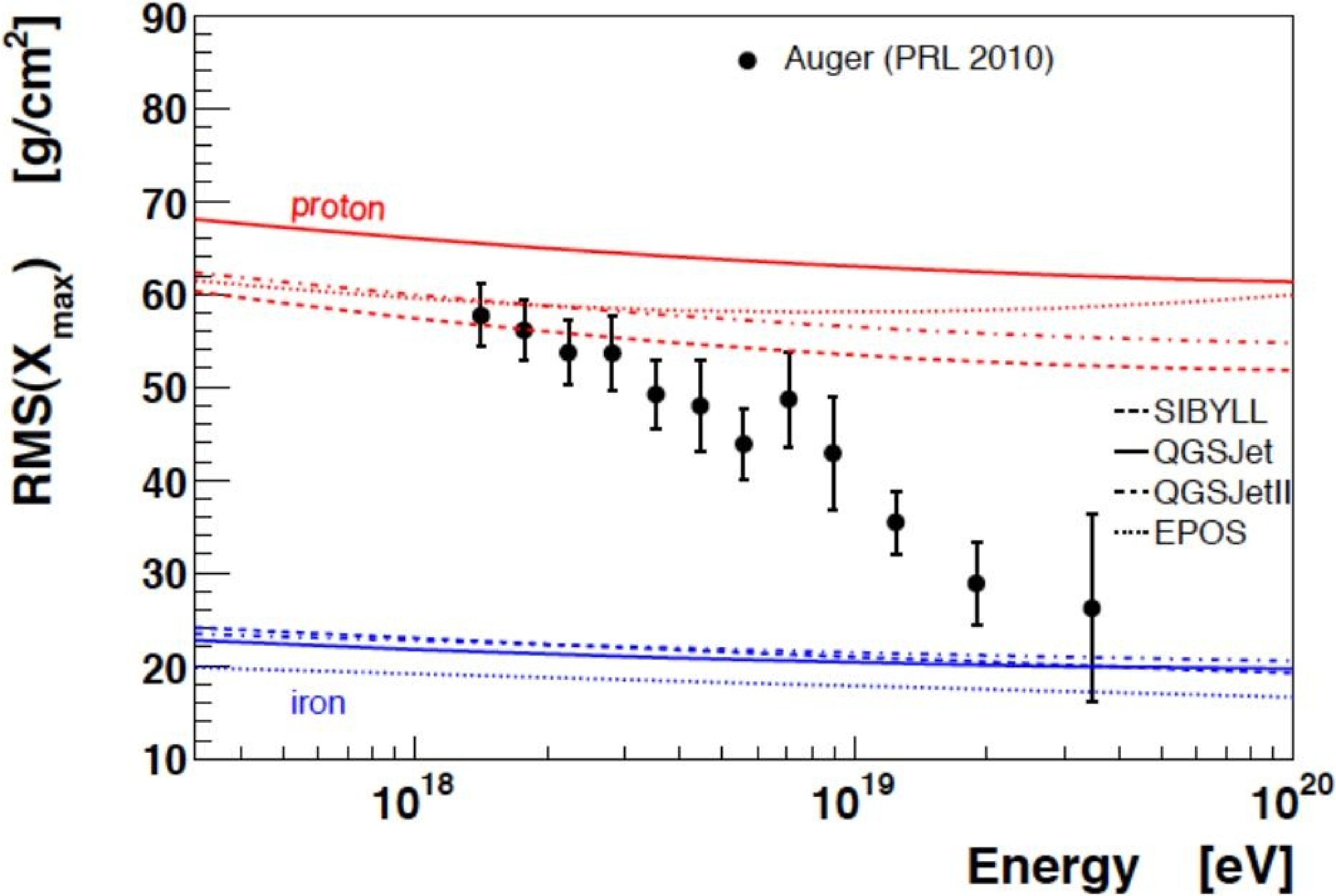


IF one accepts (at least for the sake of discussion) the astrophysical hints of a proton dominated composition....

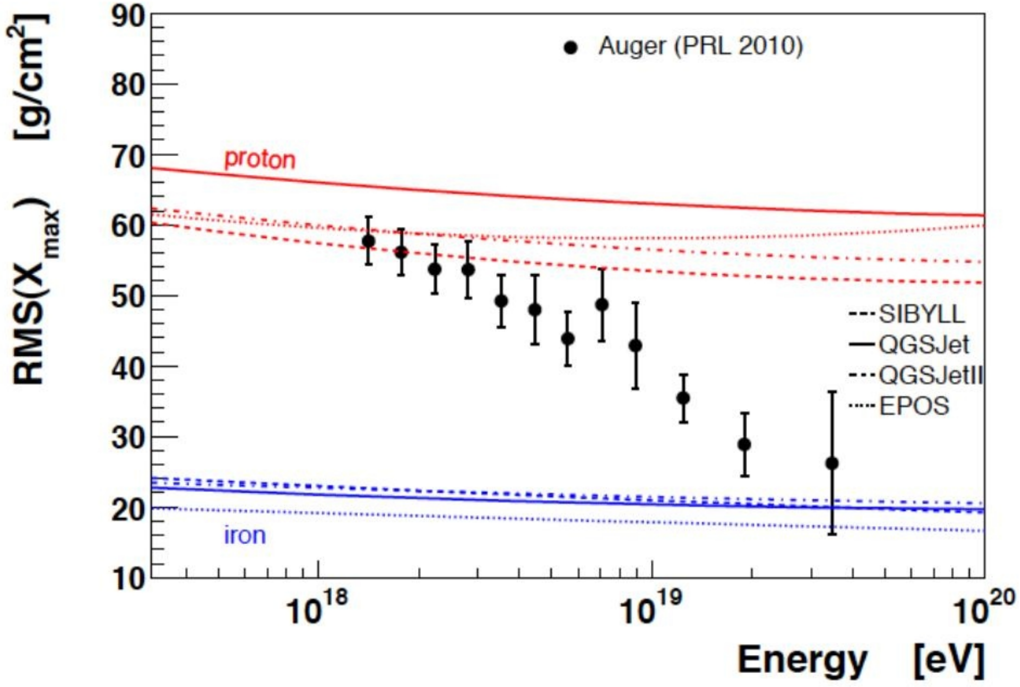


AUGER

Shower fluctuations

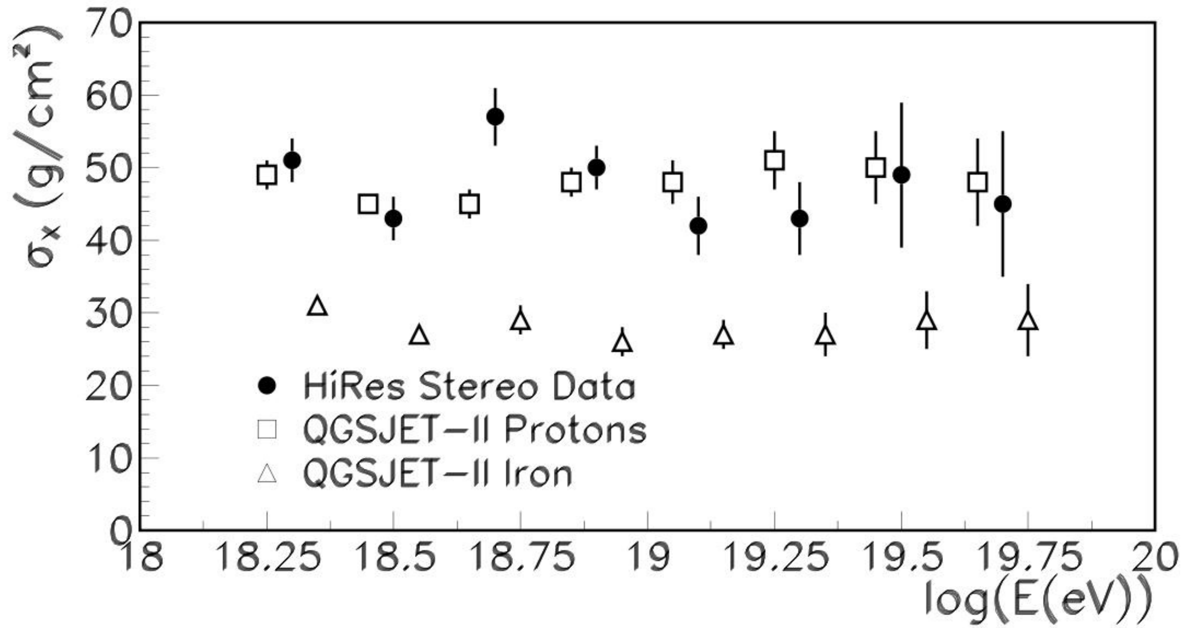


X_{max} fluctuations

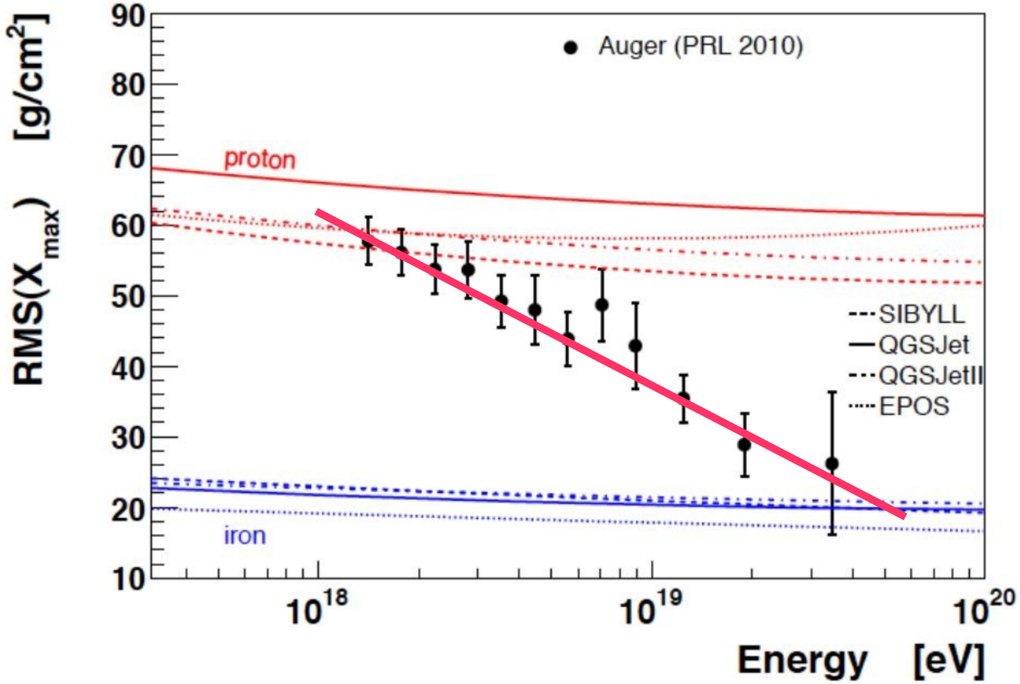


Auger

HiRes



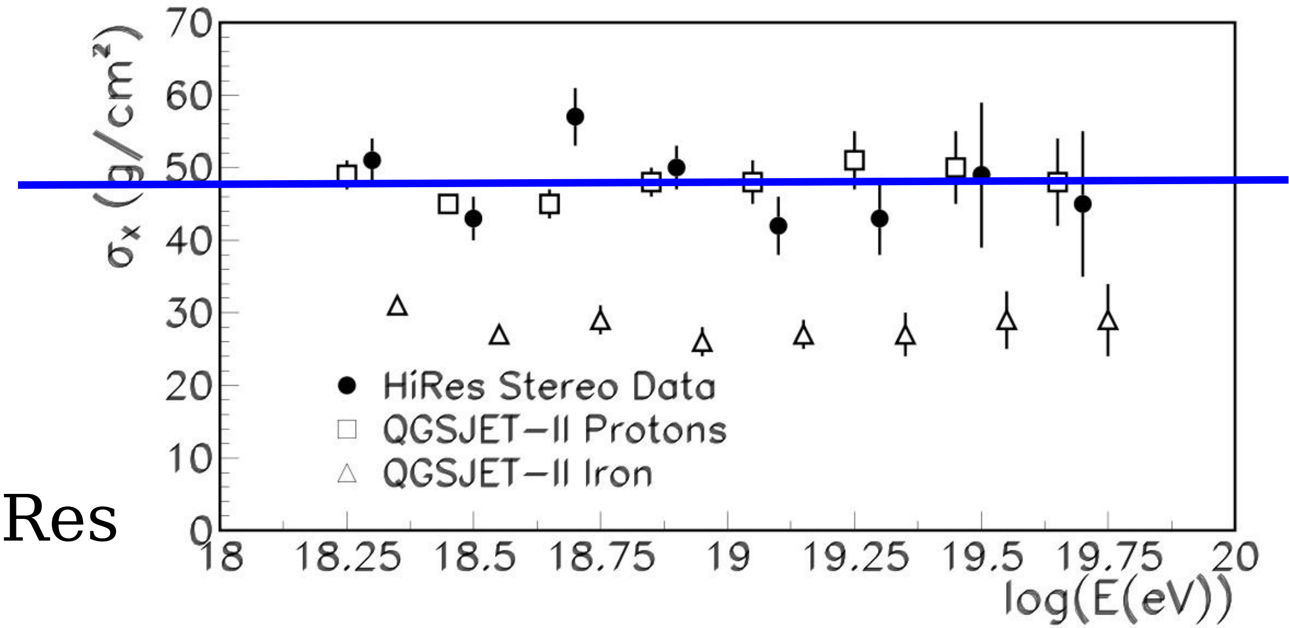
X_{max} fluctuations



Auger

Quasi – monotonically
Decreasing RMS

Constant RMS



HiRes

FLUCTUATIONS on $X_{\max}$

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

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

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

Toy model

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

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

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

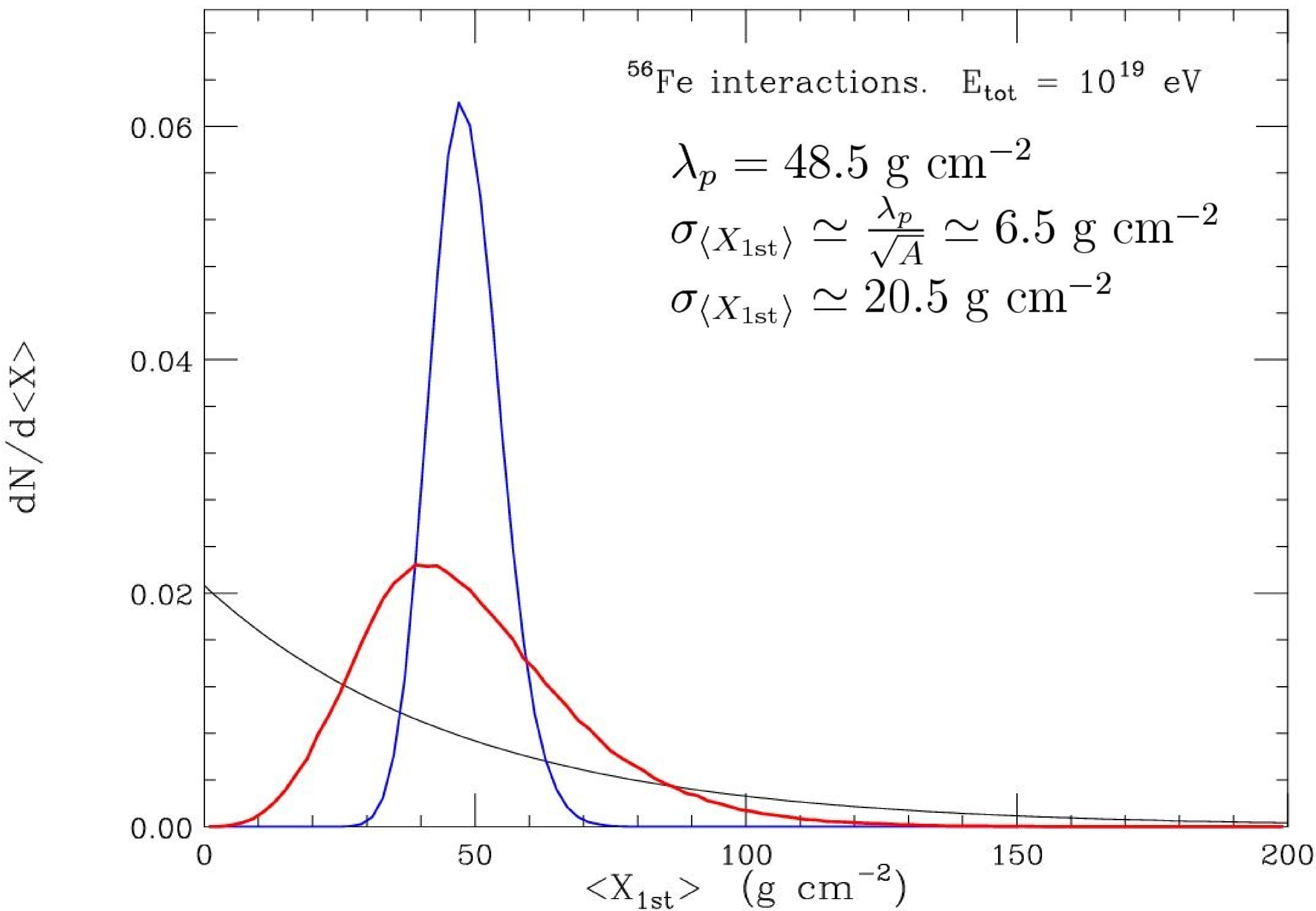
$$A = 56$$

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

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

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

Nuclear interaction.
Several Nucleons
Interact at same point.



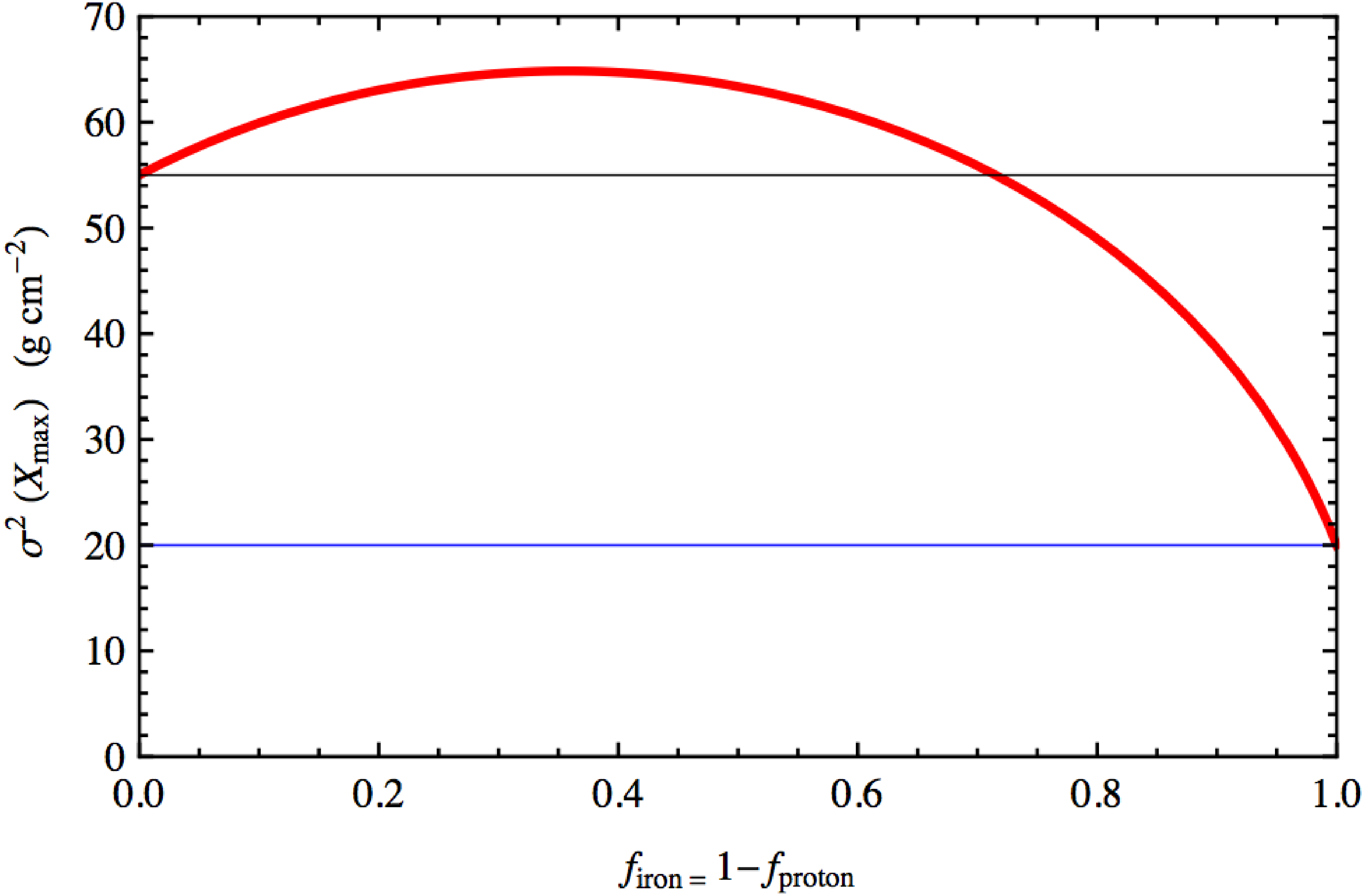
^{56}Fe interactions. $E_{tot} = 10^{19}$ eV
$\lambda_p = 48.5$ g cm^{-2}
$\sigma_{\langle X_{1st} \rangle} \simeq \frac{\lambda_p}{\sqrt{A}} \simeq 6.5$ g cm^{-2}
$\sigma_{\langle X_{1st} \rangle} \simeq 20.5$ g cm^{-2}
dN/d<X>
0.06
0.04
0.02
0.00
0
50
100
150
200
$\langle X_{1st} \rangle$ (g cm^{-2})

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

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

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

Mixing Protons with Iron-nuclei



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

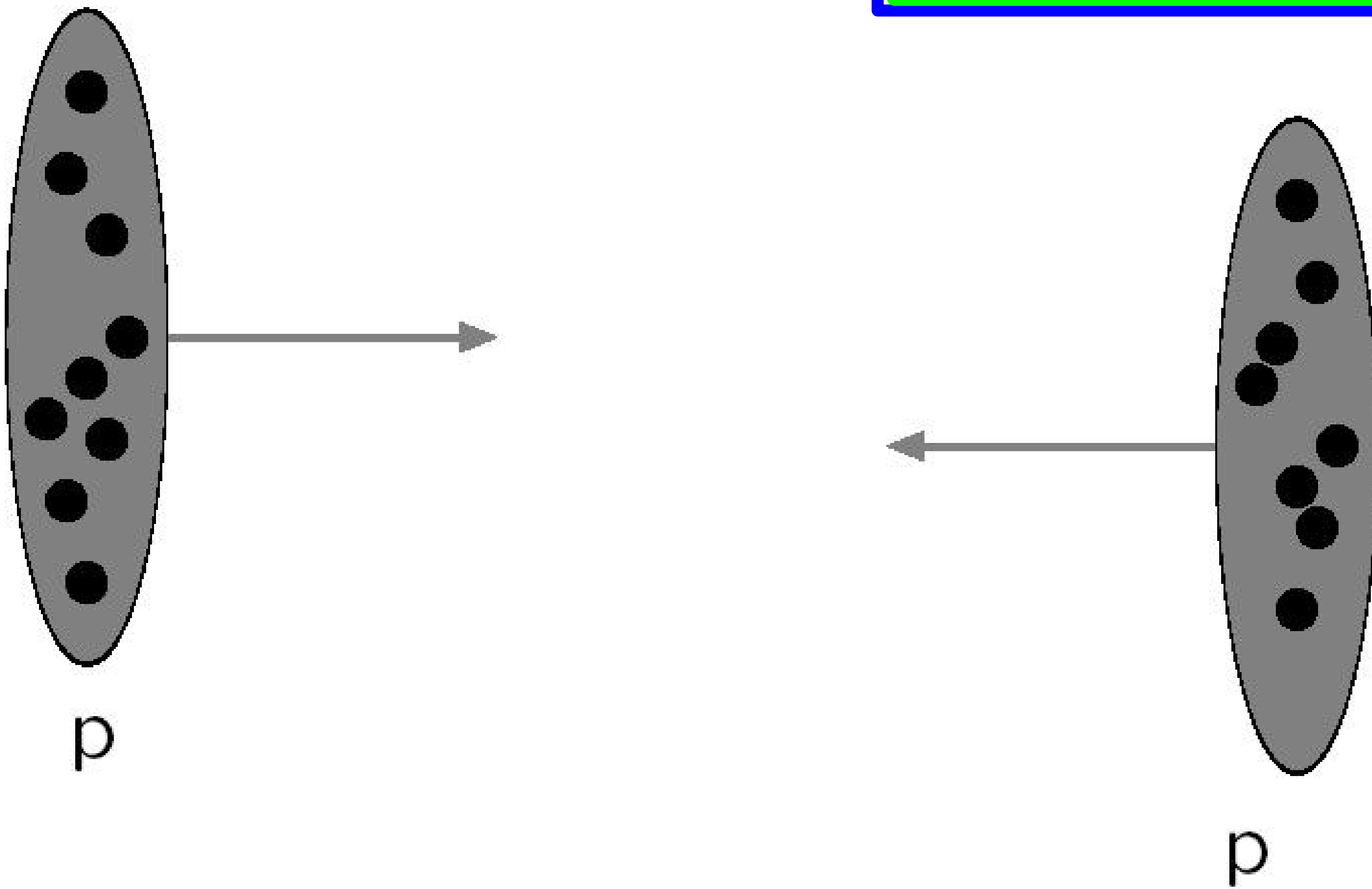
THEORY

Construction of Hadronic Models

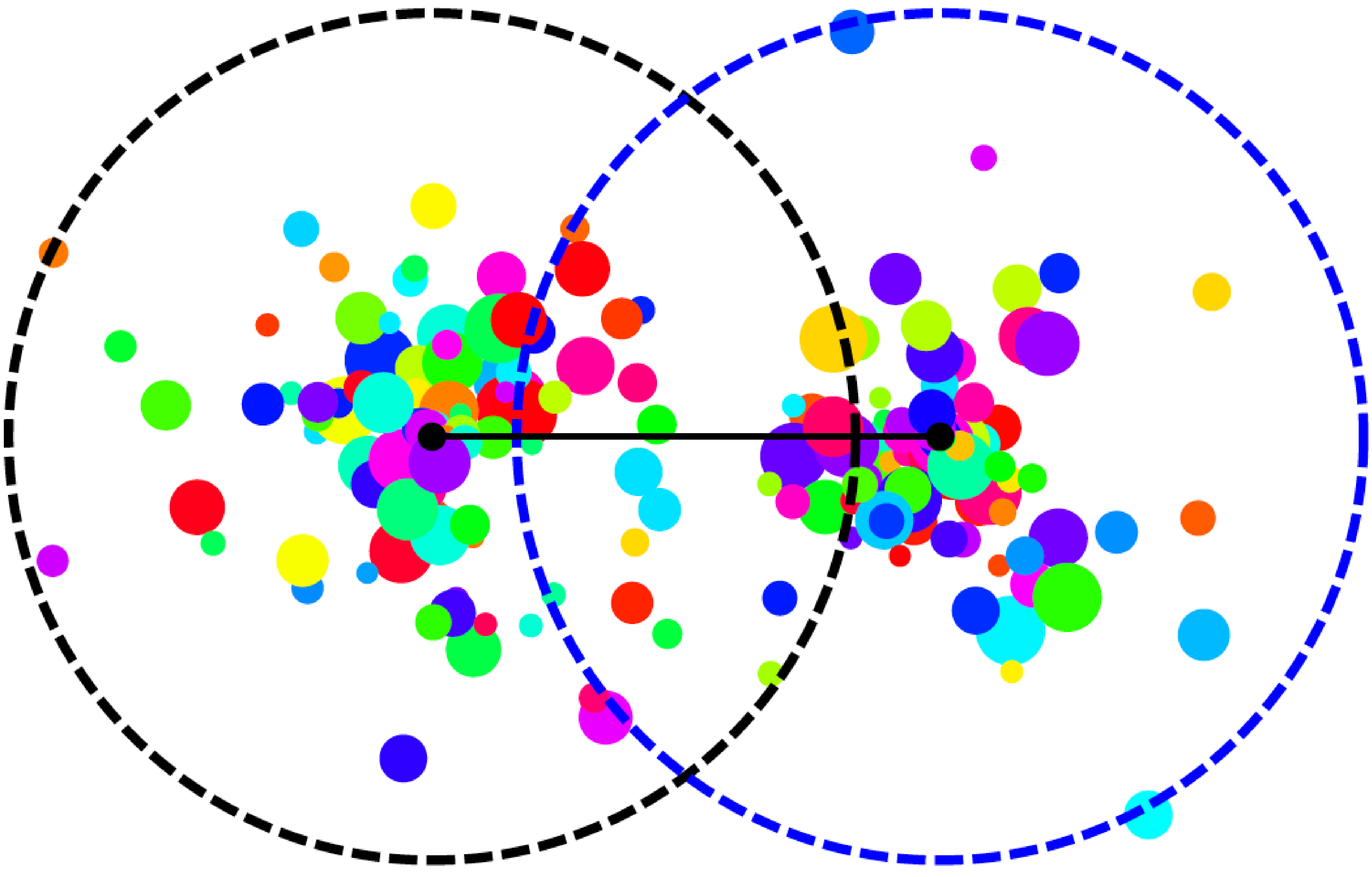
Hadronic Interactions

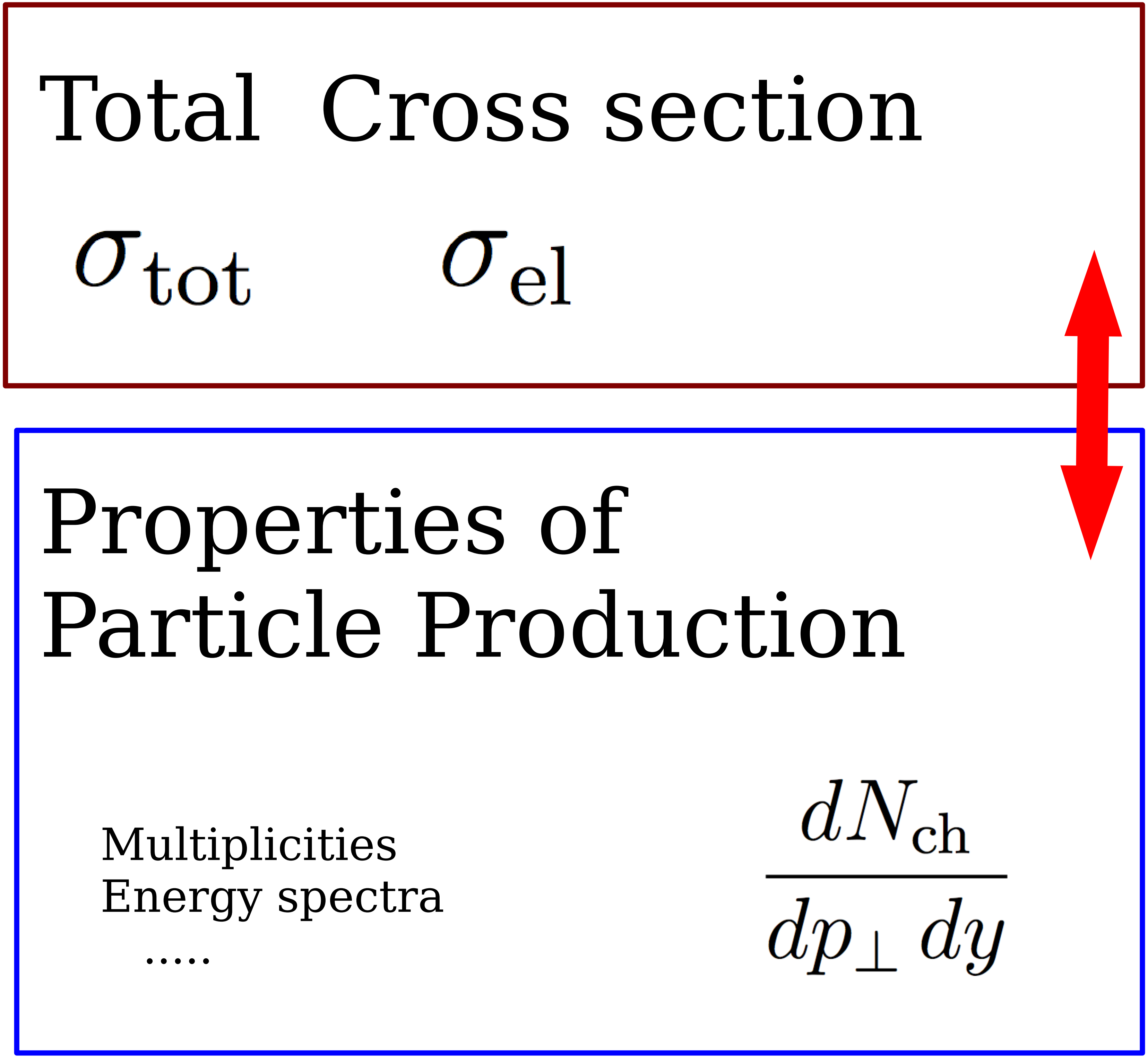
QCD

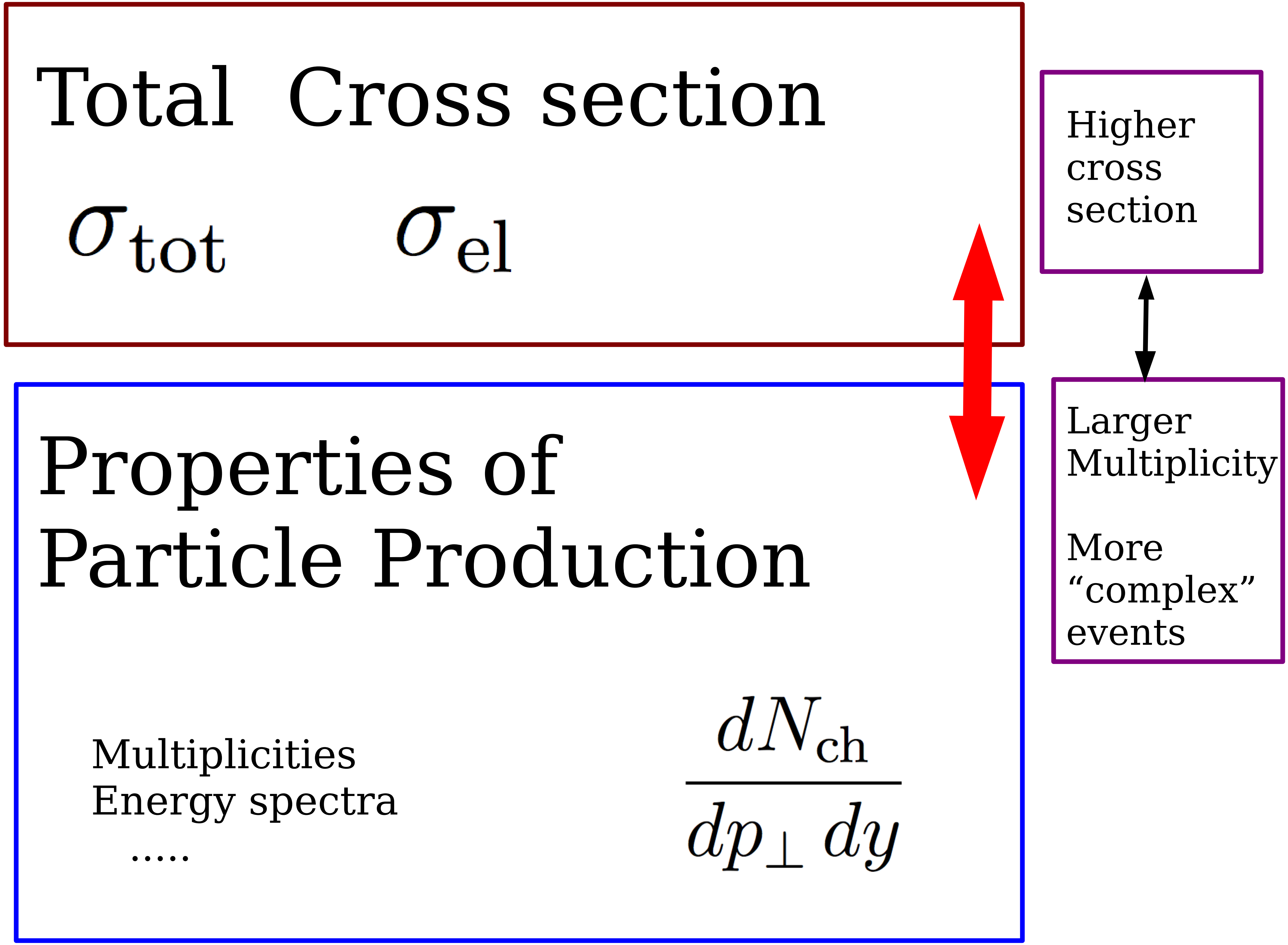
Composite (complex) Objects
Multiple interaction structure



“Cartoon” of a pp interaction in the transverse plane




Total Cross section
$\sigma_{\rm tot}$ $\sigma_{\rm el}$
Properties of
Particle Production
Multiplicities
Energy spectra
.....
$\frac{dN_{\rm ch}}{dp_\perp\, dy}$


Total Cross section
$\sigma_{\rm tot}$
$\sigma_{\rm el}$
Higher cross section
Larger Multiplicity
More "complex" events
Properties of Particle Production
Multiplicities
Energy spectra
.....
$\frac{dN_{\rm ch}}{dp_\perp \, dy}$

Elastic Scattering Amplitude :

$$\frac{d\sigma_{\text{el}}}{dt}(t, s) = \pi \frac{d\sigma_{\text{el}}}{d^2q}(\vec{q}, s) = \pi |F_{\text{el}}(\sqrt{-t}, s)|^2$$

$$F_{\text{el}}(q, s) = i \int \frac{d^2b}{2\pi} e^{i\vec{q}.\vec{b}} \Gamma_{\text{el}}(b, s)$$

PROFILE Function

$$\Gamma_{\text{el}}(b, s) = 1 - e^{-\chi(b,s)}$$

EIKONAL Function

$$\sigma_{\mathrm{el}}(s) = \int d^2b |\Gamma_{\mathrm{el}}(b, s)|^2$$

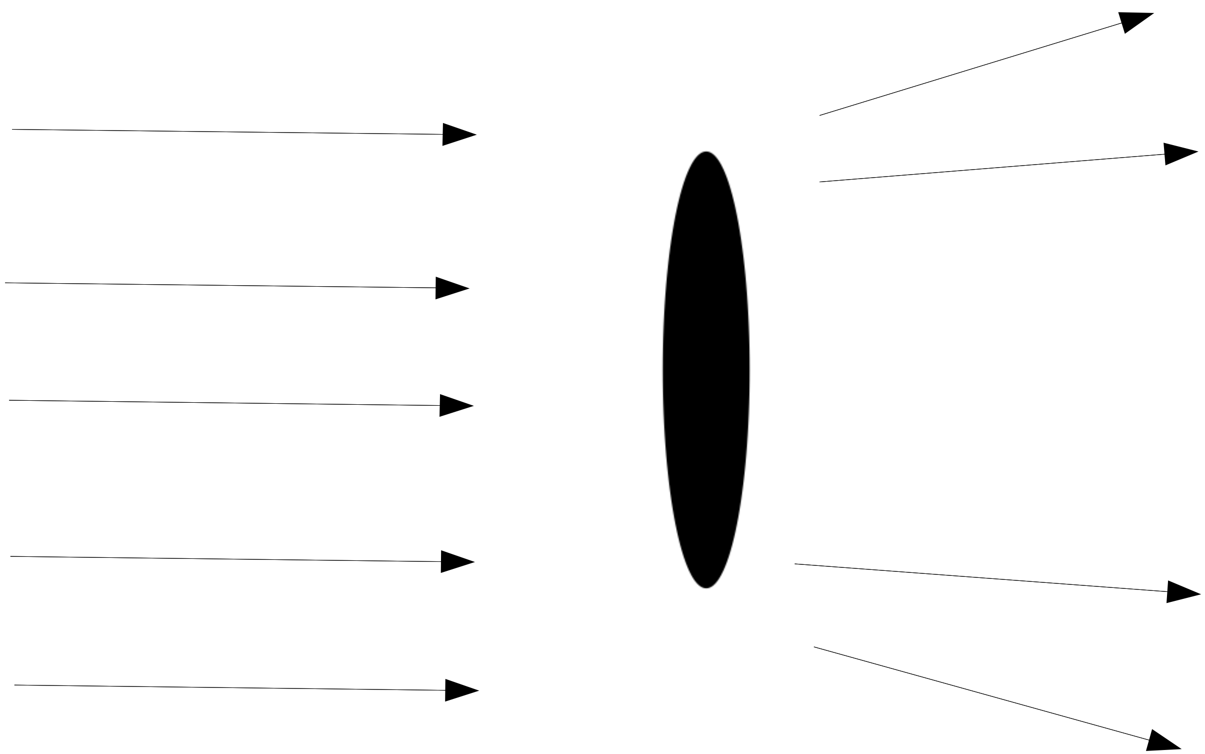
$$\sigma_{\mathrm{tot}}(s) = 4\pi \mathrm{Im}[F_{\mathrm{el}}(0, s)] = 2 \int d^2b \mathrm{Re}[\Gamma_{\mathrm{el}}(b, s)]$$

$$\sigma_{\mathrm{inel}}(s) = \int d^2b \{1 - |1 - \Gamma_{\mathrm{el}}(b, s)|^2\}$$

Total, elastic, inelastic cross section
Expressed in terms of the profile function

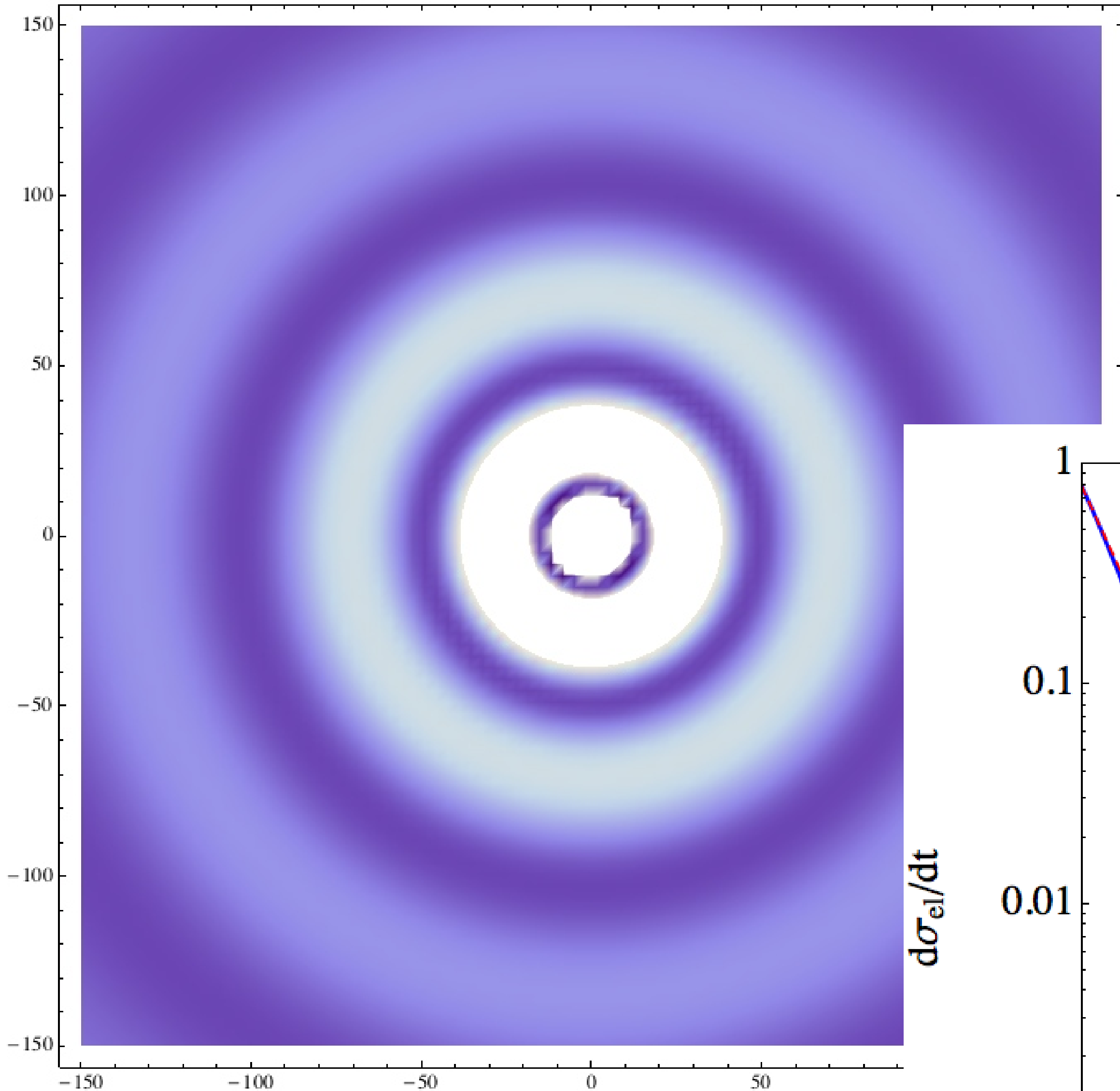
Total, Elastic, Diffractive Cross Sections:

1 minute of "19th century physics":
The OPTICAL ANALOGY.

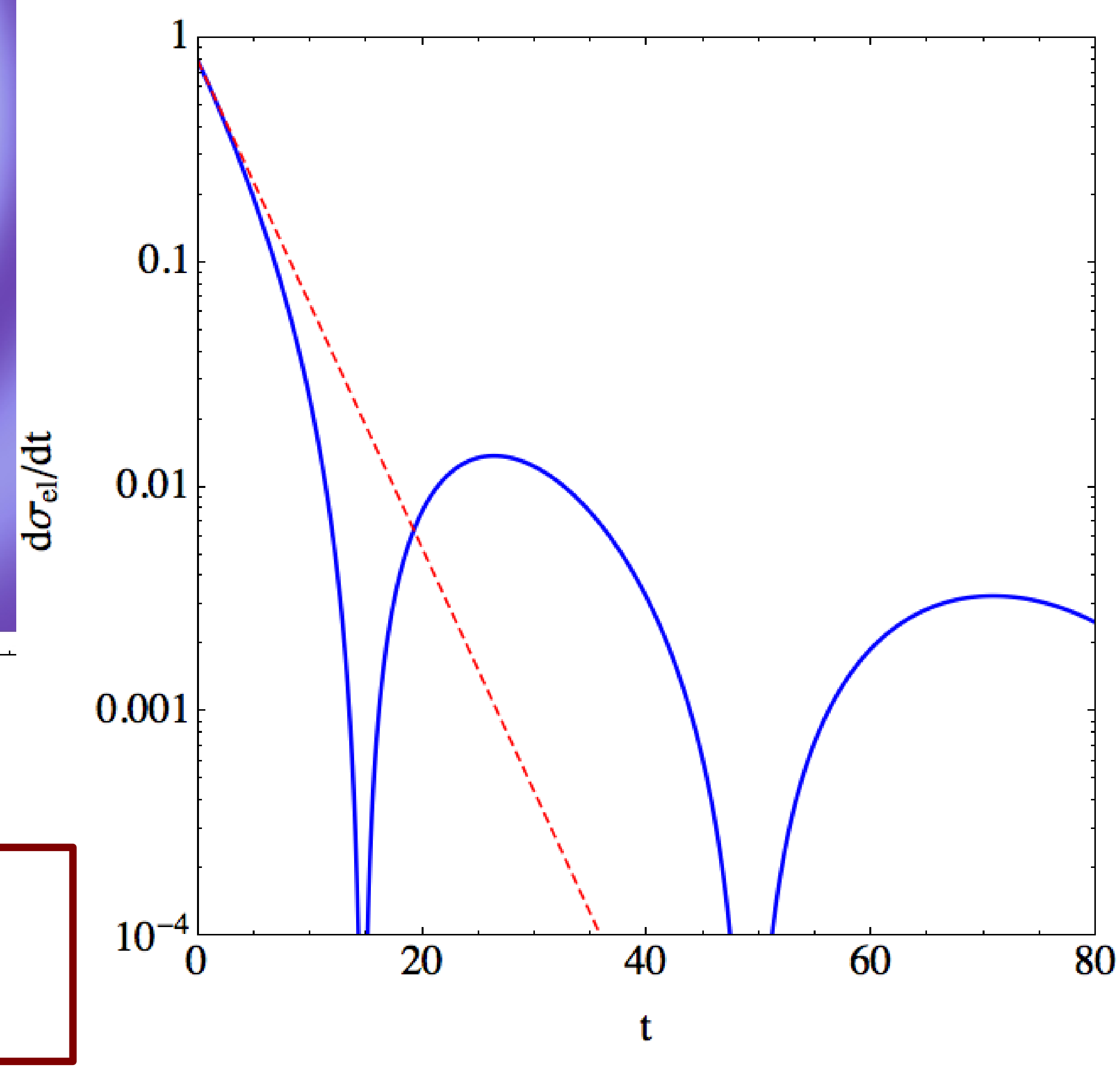


Absorption
and
Scattering
of light
from an
Opaque screen

Black Disk
Of radius R.

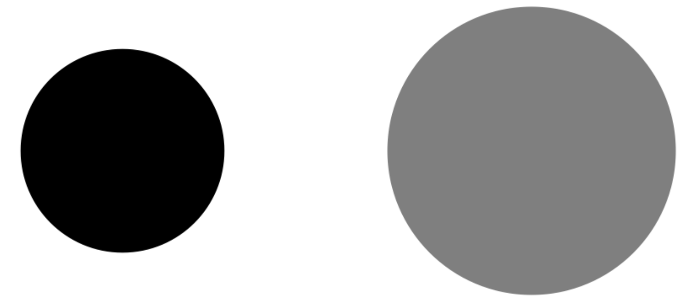


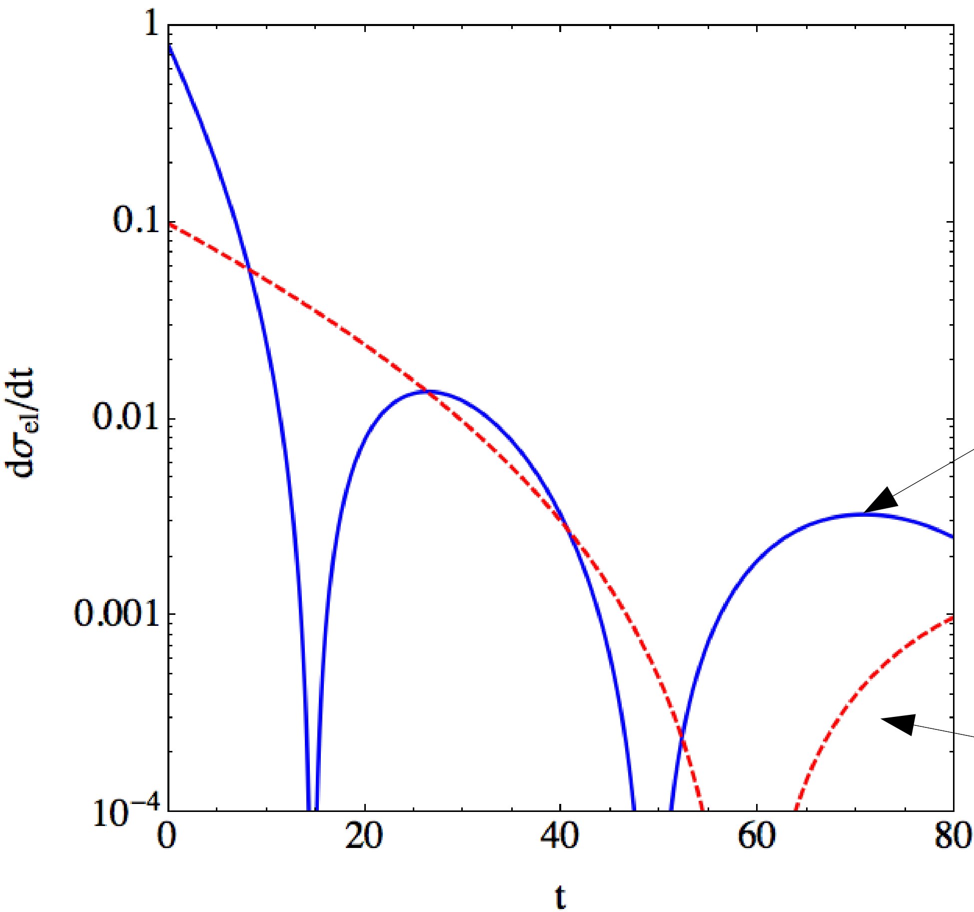
Diffraction Pattern



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

Elastic scattering distributions





Larger
Gray Disk

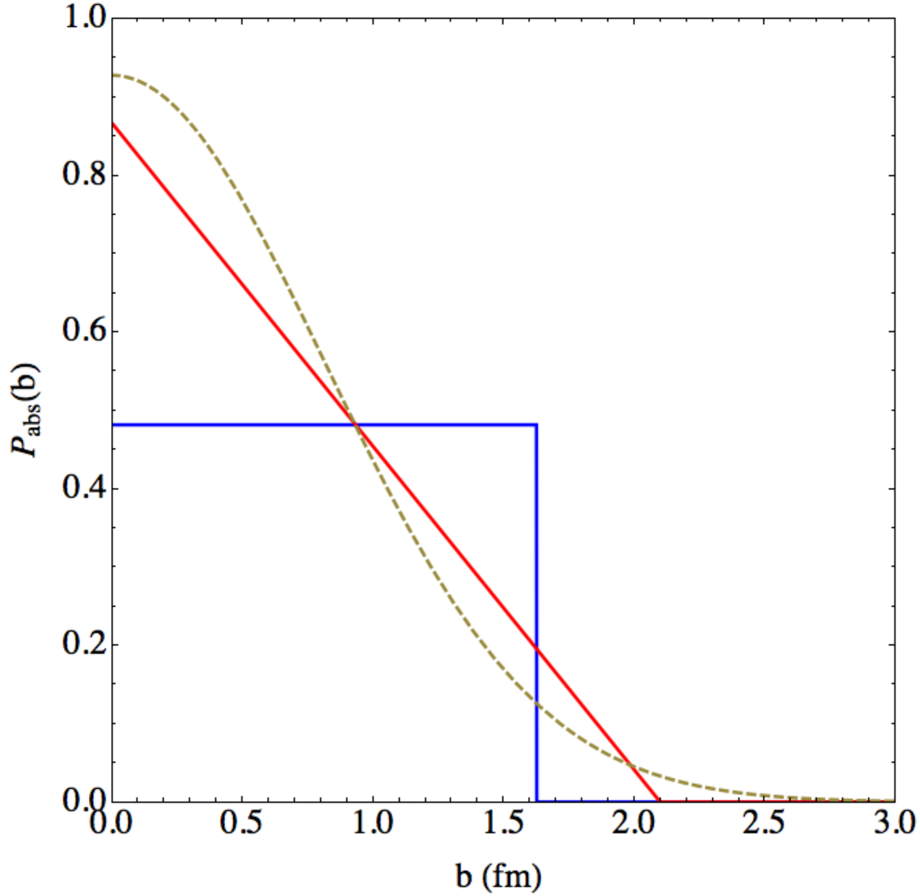
smaller
Black Disk

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

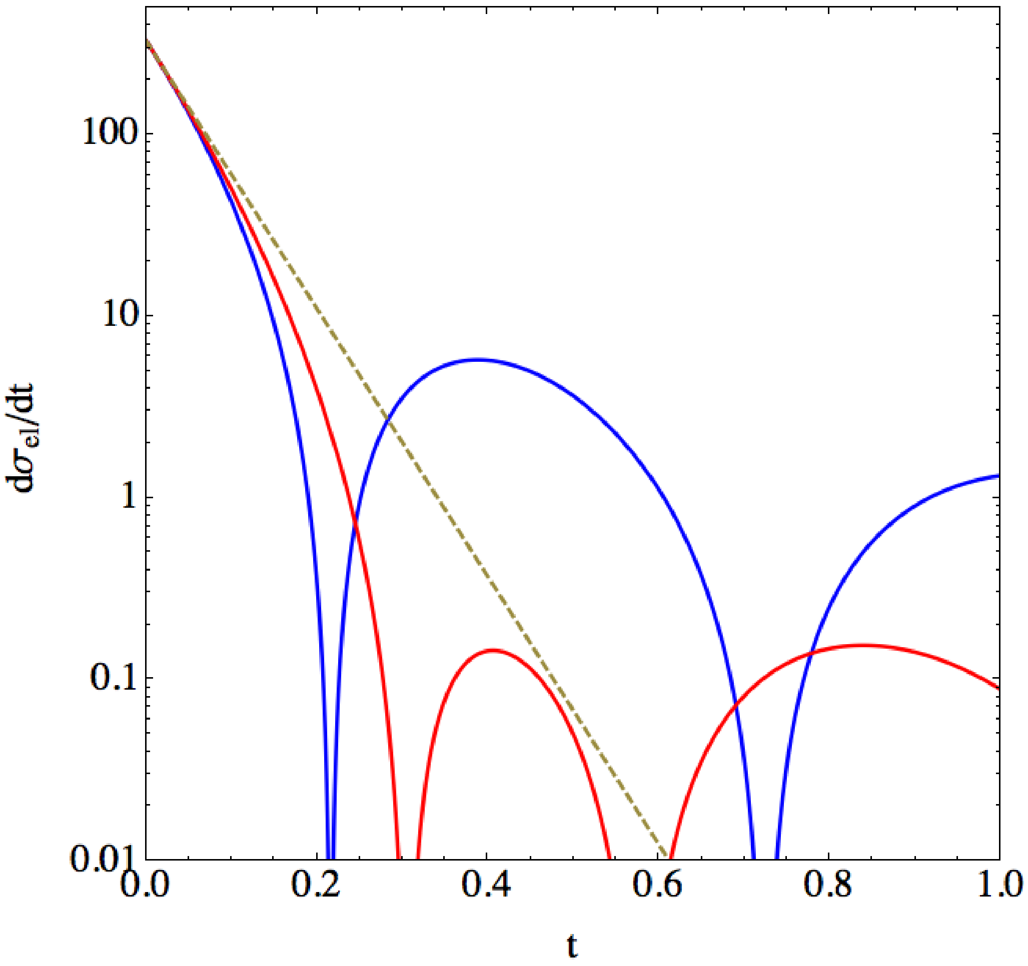
$$\sigma_{\rm abs} = g \; \pi \; R^2$$

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

Absorption profiles

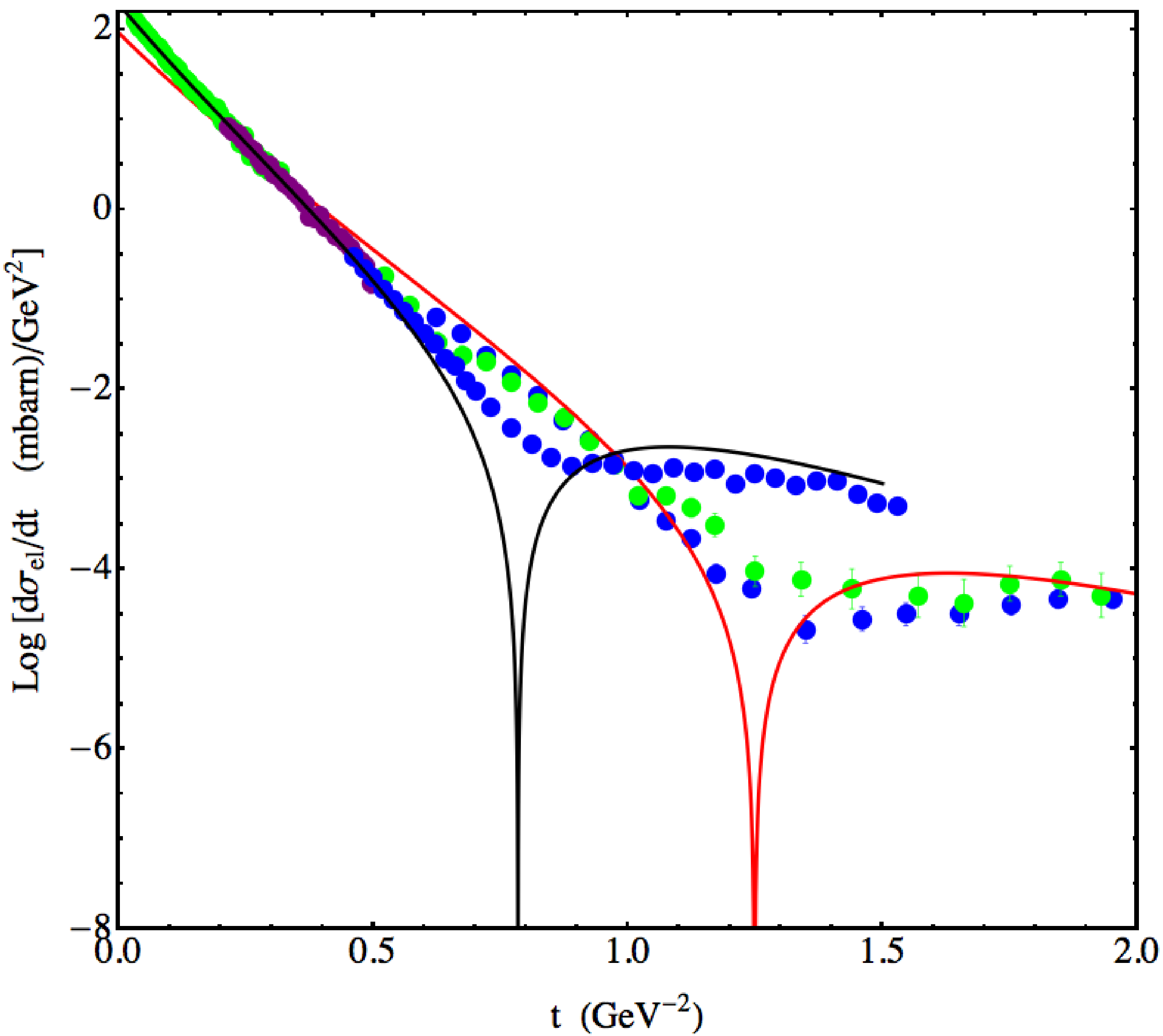


Elastic scattering



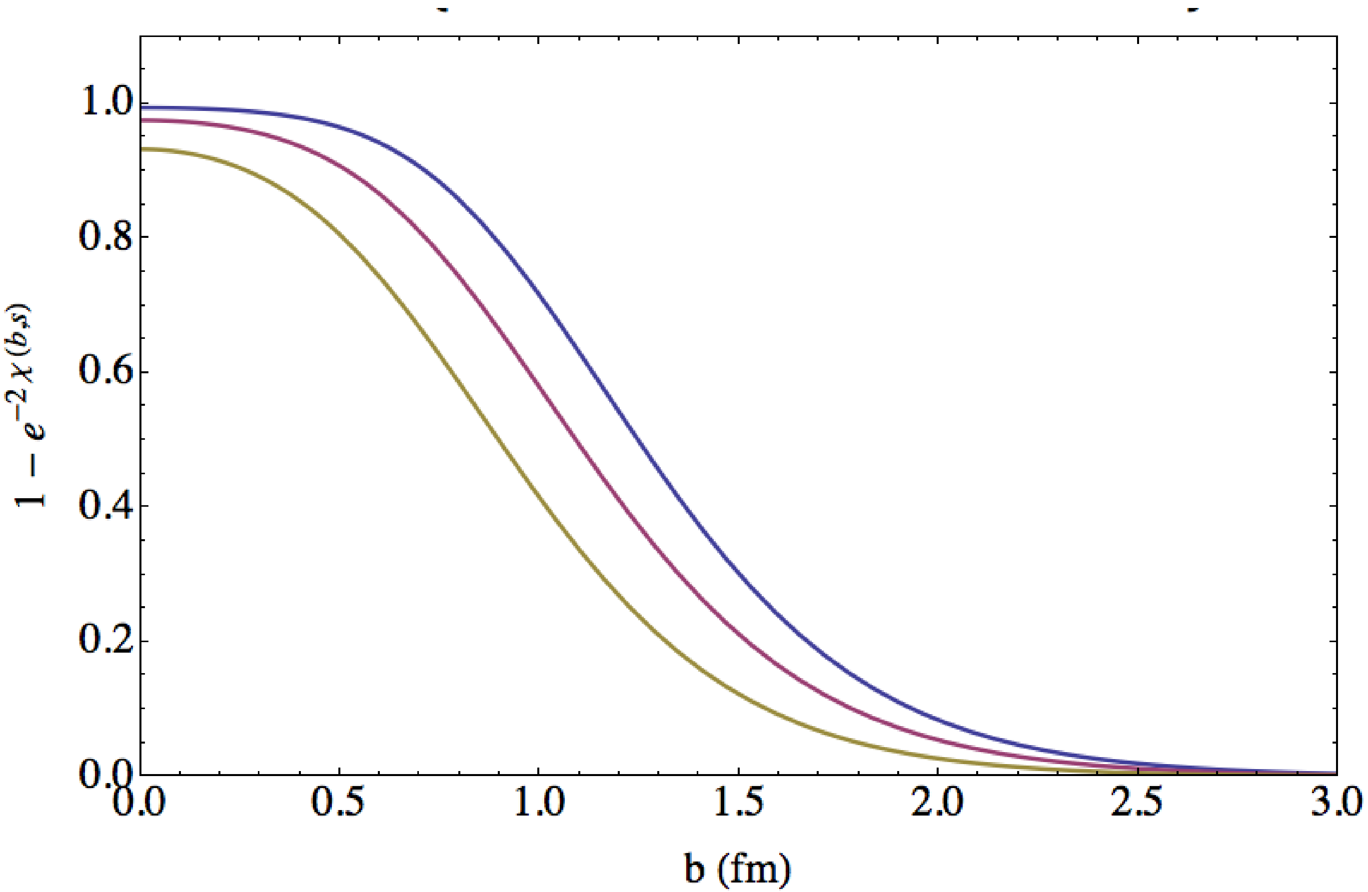
$$B = \frac{\langle b^2 \rangle}{2}$$

ISR 62.3 GeV
CERN UA4 546 GeV



“Absorption profile”
obtained from the elastic scattering of pp

ISR, CERN SpS (UA4) , CDF



$$\chi(b, s)$$

$$\Gamma_{\rm el}(b, s) \neq 1 - e^{-A(b)\,\sigma_{\rm eik}(s)/2}$$

Failure of factorization

$$\sigma_{\text{tot}}(s) = 4\pi \text{Im}[F_{\text{el}}(0, s)] = 2 \int d^2b \text{Re}[\Gamma_{\text{el}}(b, s)]$$

$$\sigma_{\text{el}}(s) = \int d^2b |\Gamma_{\text{el}}(b, s)|^2$$

$$\sigma_{\text{inel}}(s) = \int d^2b \{1 - |1 - \Gamma_{\text{el}}(b, s)|^2\}$$

Interaction Probability

$$\Gamma_{\text{el}}(b, s) \equiv 1 - e^{-\chi(b,s)} = 1 - \sqrt{P_0(b, s)} = 1 - \exp\left[-\frac{\langle n(b, s)\rangle}{2}\right]$$

Multiple interactions

"Interpretation" of the eikonal function

$$\chi(b,s) = \frac{\langle n(b,s) \rangle}{2}$$

Identification of Eikonal function with
The average number of "elementary interactions"
At impact parameter b.

$$\int d^2b \ \langle n(b,s) \rangle = \sigma_{\rm parton}(s)$$

Cross section for "elementary interactions"

$$\chi(b,s) = \frac{\langle n(b,s) \rangle}{2}$$

Identification of Eikonal function with
The average number of "elementary interactions"
At impact parameter b.

Construction of

$$\langle n(b,s) \rangle$$

Fluctuations of this average quantity.

Explicit construction of the final state
At the "parton level".

Perturbative contribution to the Parton cross section

$$\left.\frac{d^3\sigma}{dp_\perp dx_1 dx_2}\right|_{\text{jet pair}}(p_\perp, x_1, x_2; \sqrt{s}) = \sum_{j,k,j',k'} f_j^{h_1}(x_1, \mu^2) f_k^{h_2}(x_2, \mu^2) \frac{d\hat{\sigma}_{jk\to j'k'}}{dp_\perp}(p_\perp, \hat{s}).$$

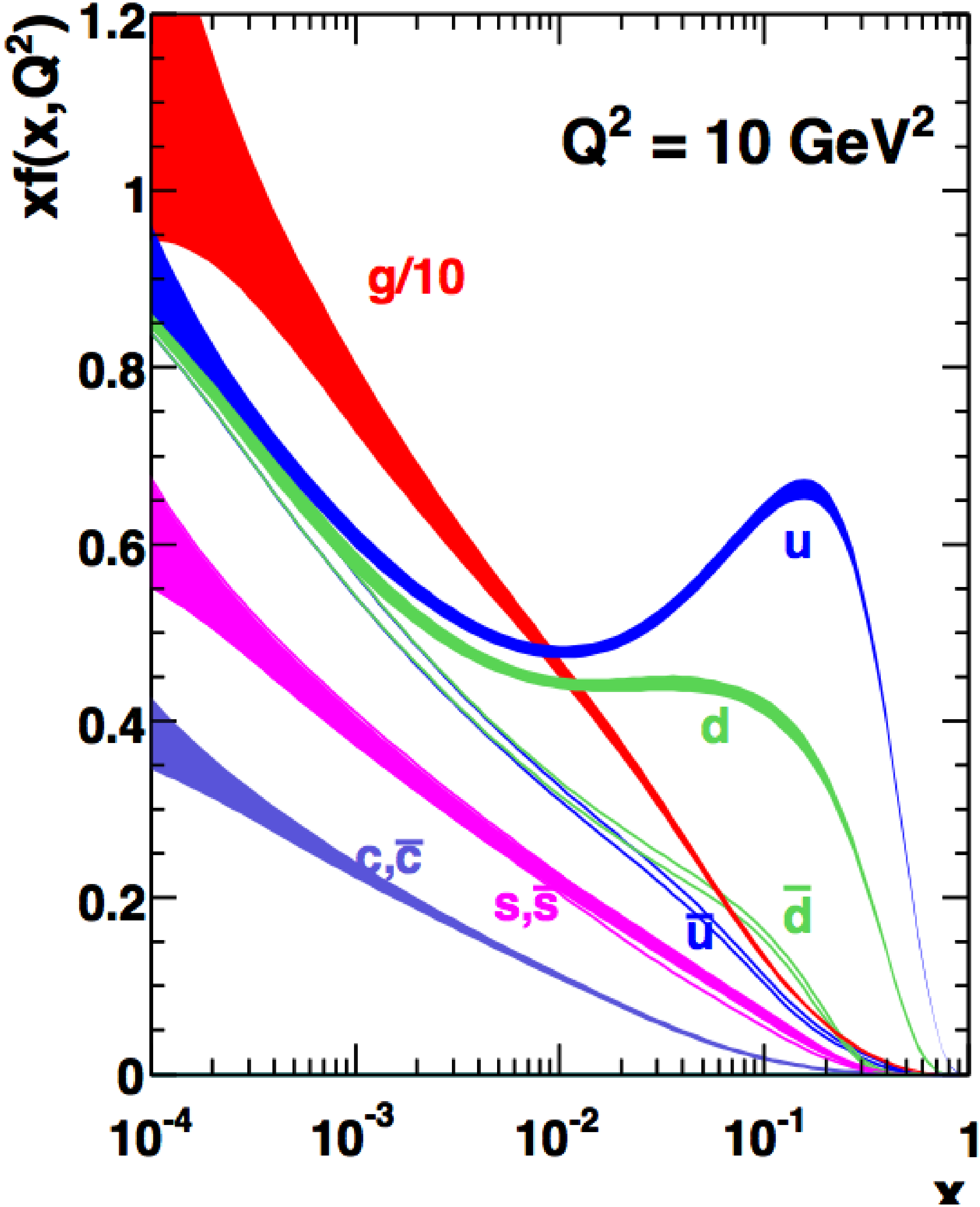
$$\sigma_{\text{jet}}(p_\perp^{\text{min}}, \sqrt{s}) = \int_{p_\perp^{\text{min}}}^{\sqrt{s}/2} dp_\perp \int_{4p_\perp^2/s}^{1} dx_1 \int_{4p_\perp^2/(sx_1)}^{1} dx_2 \left\{ \sum_{j,k,j',k'} f_j^{h_1}(x_1, \mu^2) f_k^{h_2}(x_2, \mu^2) \frac{d\hat{\sigma}_{jk\to j'k'}}{dp_\perp}(p_\perp, \hat{s}) \right\}$$

$$p_\perp^{\text{min}} \to 0$$

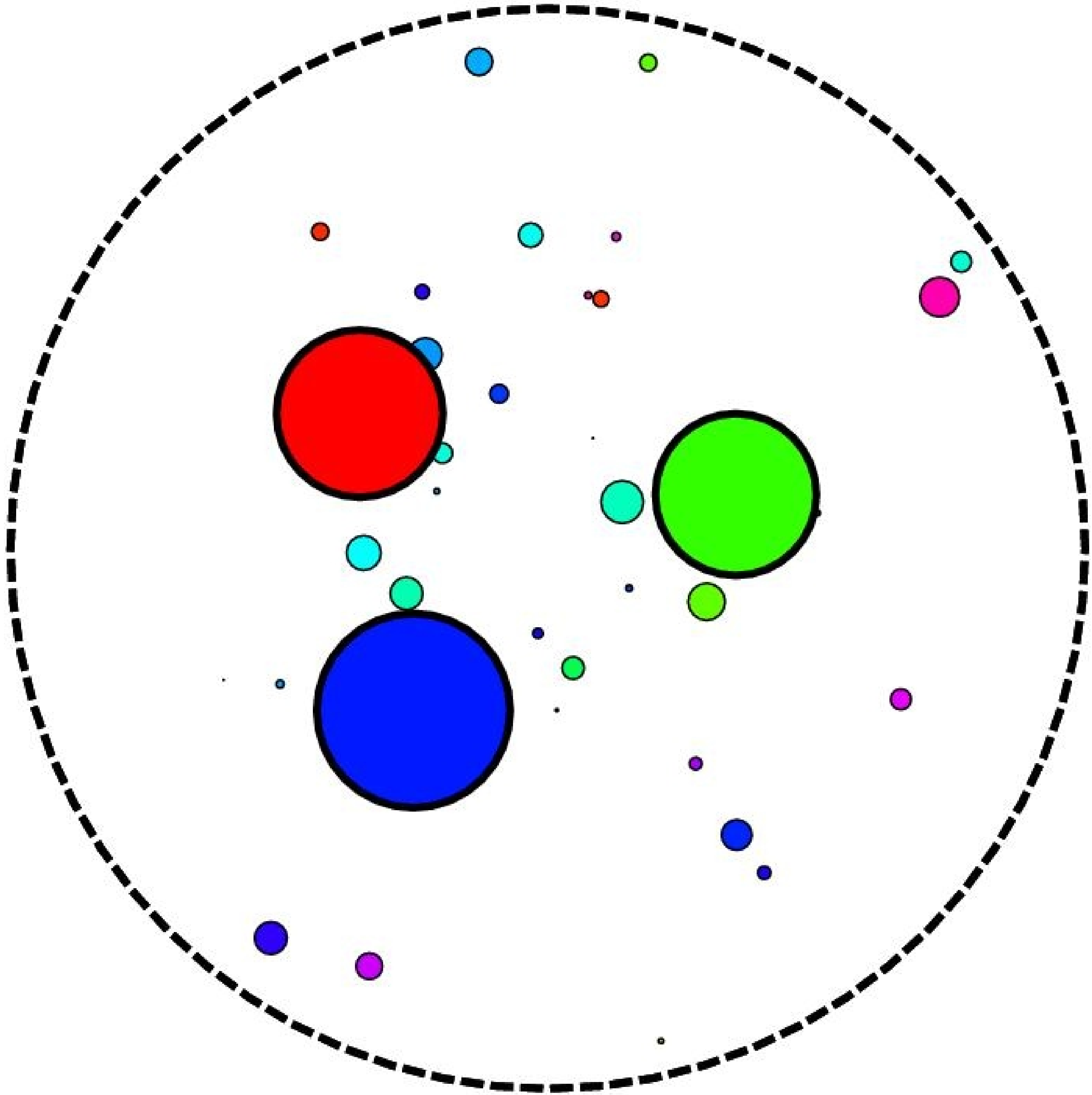
$$\sigma_{\text{jet}} \to \infty$$

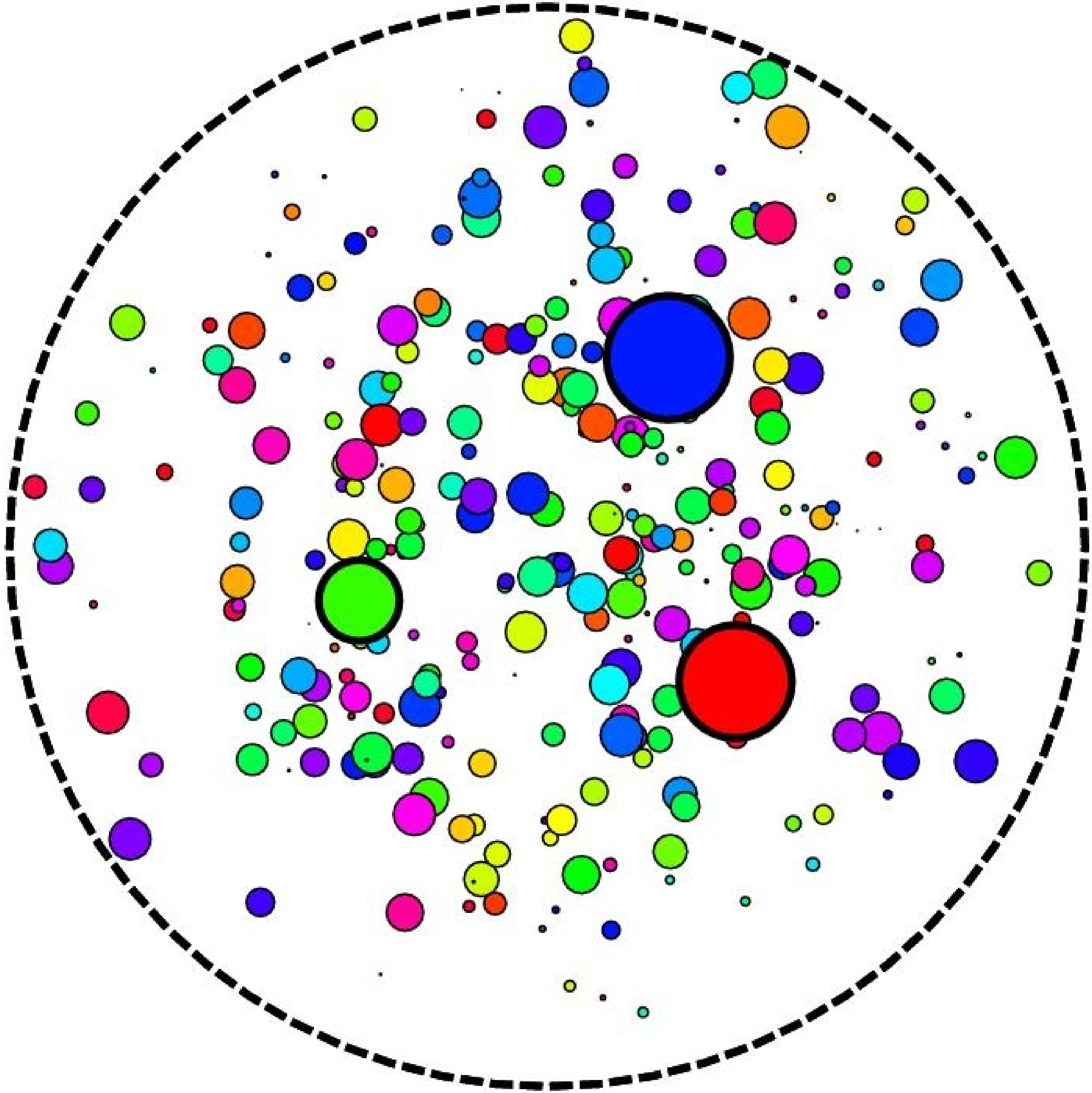
Infrared Divergence !!
(complete failure of perturbation theory)

Attempts to “resum” the soft part.



Parton Distribution Function





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.

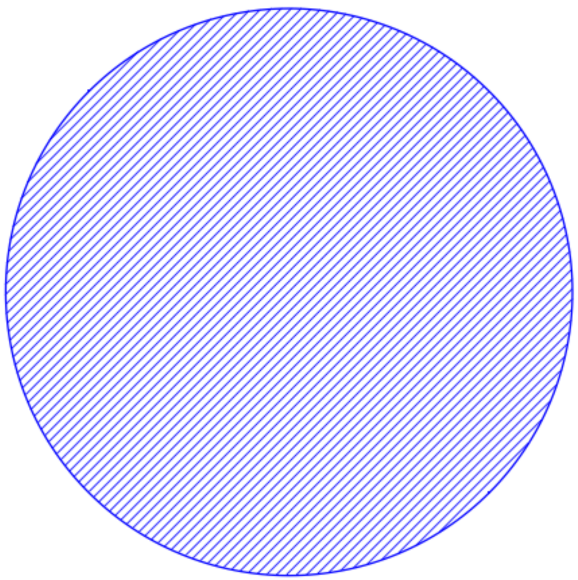
Beyond PDF's
Parton Distribution Functions

“Good-Walker ansatz” for inelastic diffraction.

[Extension of the optical analogy]

Scattering of polarized light from a “polarimeter”

Polarizing gray disk



Incident beam: $|x\rangle$

Absorption of $|x'\rangle$

$$|x'\rangle = \cos\varphi|x\rangle + \sin\varphi|y\rangle,$$

$$|y'\rangle = -\sin\varphi|x\rangle + \cos\varphi|y\rangle$$

Out scattered light
In polarizations

$|x\rangle$ Elastic scattering

$|y\rangle$ “inelastic diffraction”

Extension of the "Good-Walker Ansatz to the scattering of Hadronic Waves.

$|\varphi_m\rangle$ Observable states.

$|pp\rangle$ $|p\,\Delta\rangle$ $|p\,\Delta'\rangle$

$|\Delta\,\Delta\rangle$ $|\Delta'\,\Delta\rangle$

$|\psi_j\rangle$ "Transmission eigenstates"

$$T|\psi_j\rangle = t_j|\psi_j\rangle$$

["Parton Configuration states"]
(Miettinen-Pumplin)

2 orthonormal basis
In Hilbert space

$$|\varphi_m\rangle = \sum_j C_{mj}|\psi_j\rangle$$

$$|\psi_j\rangle = \sum_m C^*_{mj}|\varphi_m\rangle$$

$$t_j(b) = 1 - \exp\left[-\frac{n_j(b)}{2}\right]$$

One profile function for each "transmission eigenstate"

$$\sigma_{\mathrm{tot}} = \int d^2b \sum_j |C_{1j}|^2 2\mathrm{Re}[t_j(b)]$$

$$\sigma_{\mathrm{abs}} = \int d^2b \left[1 - \sum_j |C_{1j}\{1 - t_j(b)\}|^2\right]$$

$$\sigma_{\mathrm{diff+el}} = \sum_m \sigma_m = \int d^2b \sum_j |C_{1j}|^2 |t_j(b)|^2$$

$$\frac{d\sigma_{\mathrm{abs}}}{d^2b} = 1 - e^{-n(b)}$$

$$1 - \sum_j |C_{1j}|^2 \, e^{-n_j(b)}$$

$$1 - \int d\mathbb{C}_1 \int d\mathbb{C}_2 \; P_{h_1}(\mathbb{C}_1) \; P_{h_2}(\mathbb{C}_2) \exp\left[-\frac{n(b, \mathbb{C}_1, \mathbb{C}_2)}{2}\right]$$

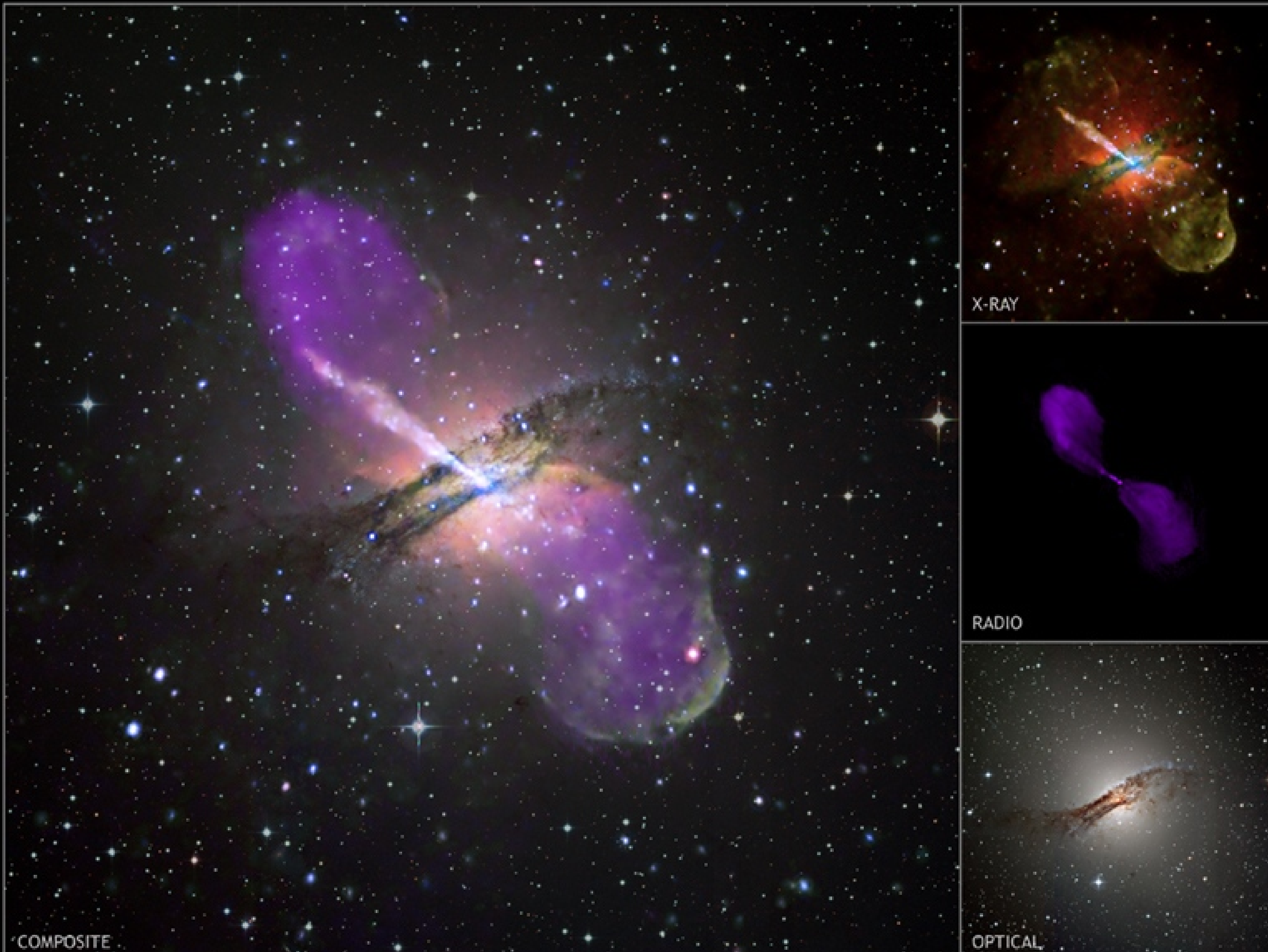
Description of the "Underlying Event"

Qualitative result:

Events with 1 hard scatterings
Have more "activity" (larger multiplicity, ...)
Than the average event.

1. Select more "central" (lower b) interactions.

2. Select events where the colliding hadrons
   have certain "parton configurations"
   (for example: more gluons in appropriate x interval)


X-RAY
RADIO
COMPOSITE
OPTICAL

We are studying at the same time

"Gigantic Astrophysical Beasts"

Millions of light years away

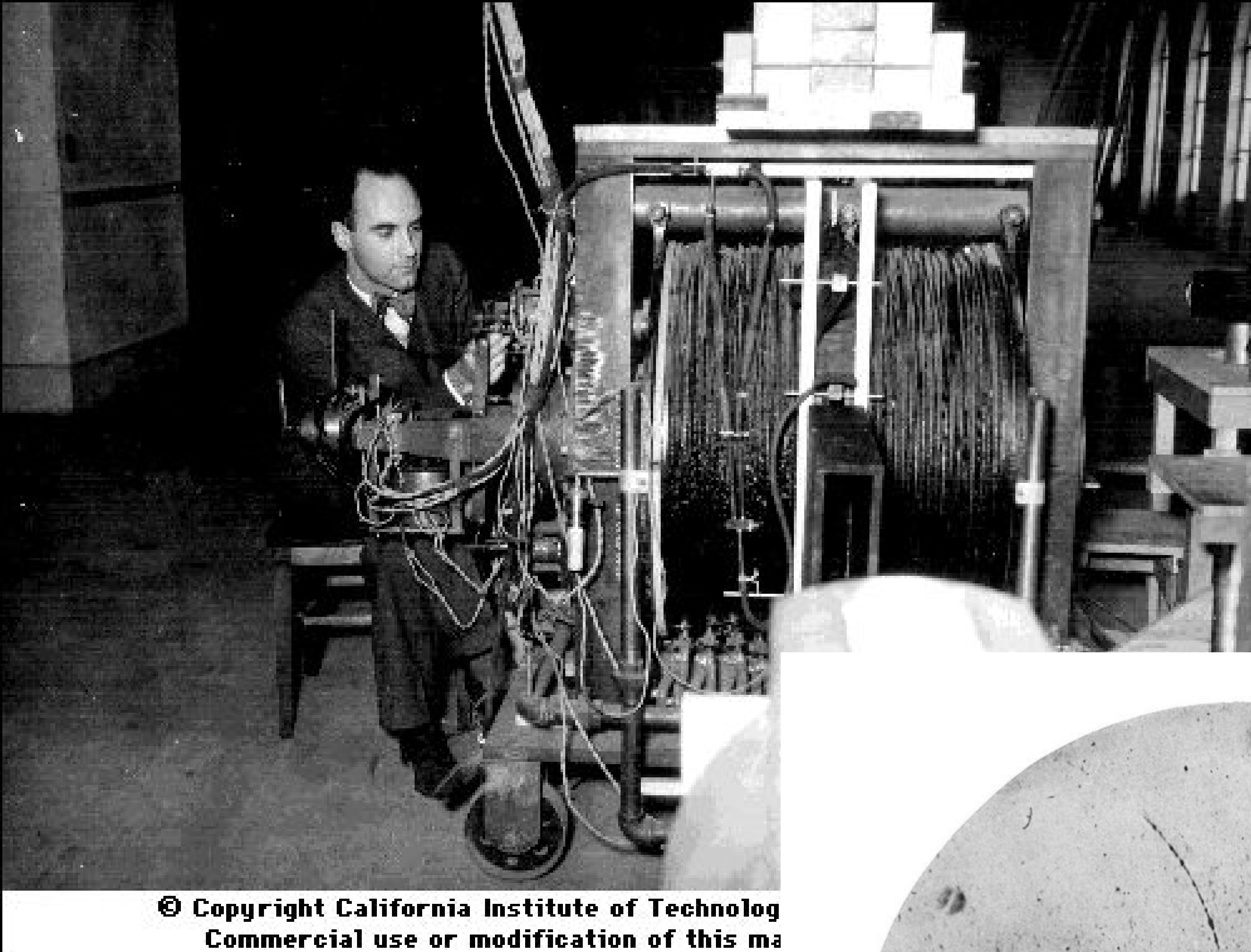
Length scale 10^{+24} cm

Microscopic

Partonic constituents of matter

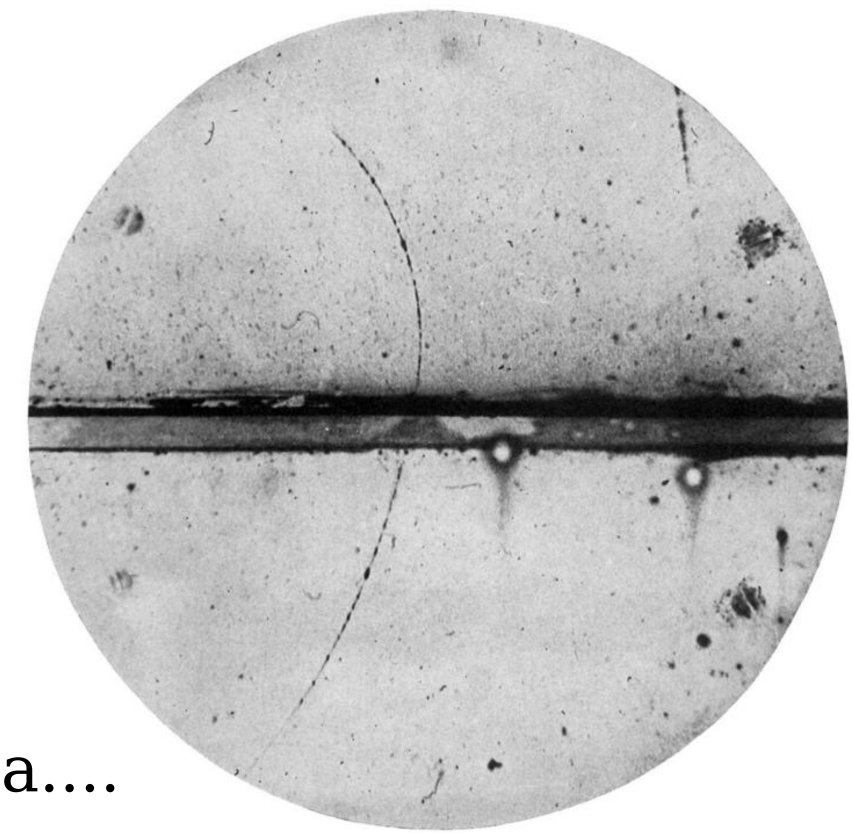
Length scale 10^{-13} cm

Exciting Difficult



Carl Anderson
(february 1933)

Near his
“Wilson chamber”



23 MeV

6 mm
Lead plate

63 MeV

Discovery of the
POSITRON

Muon, Pion, Kaon, Lambda….