UHECR and HADRONIC INTERACTIONS

Paolo Lipari
"Searching for the origin of Cosmic Rays"
Trondheim 18th June 2009

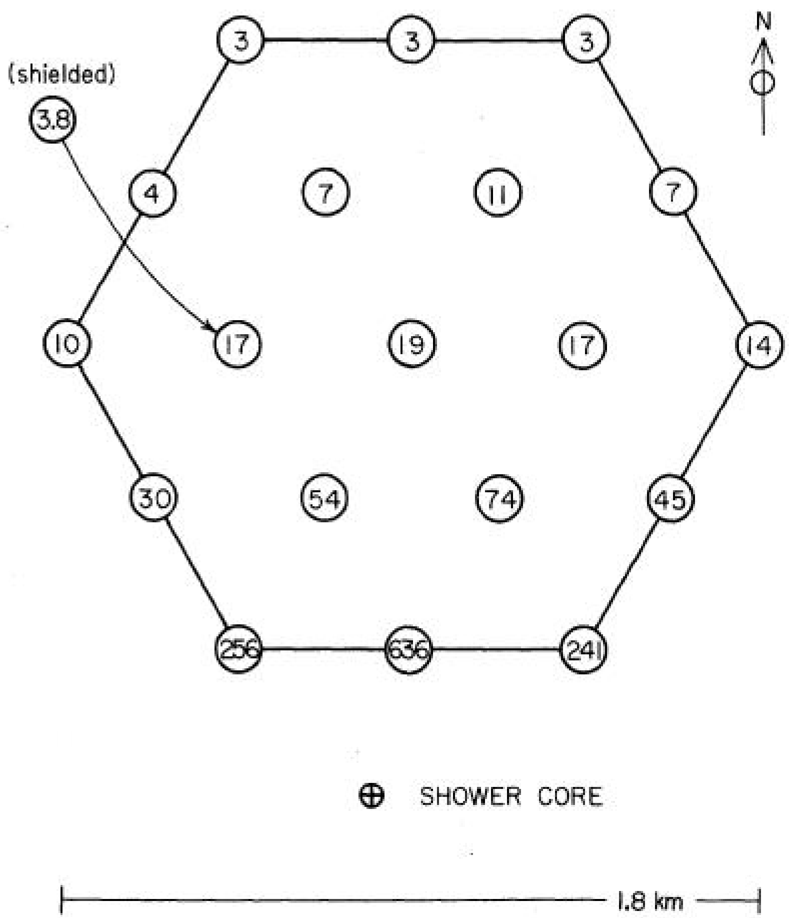
~60 years of UHECR

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.

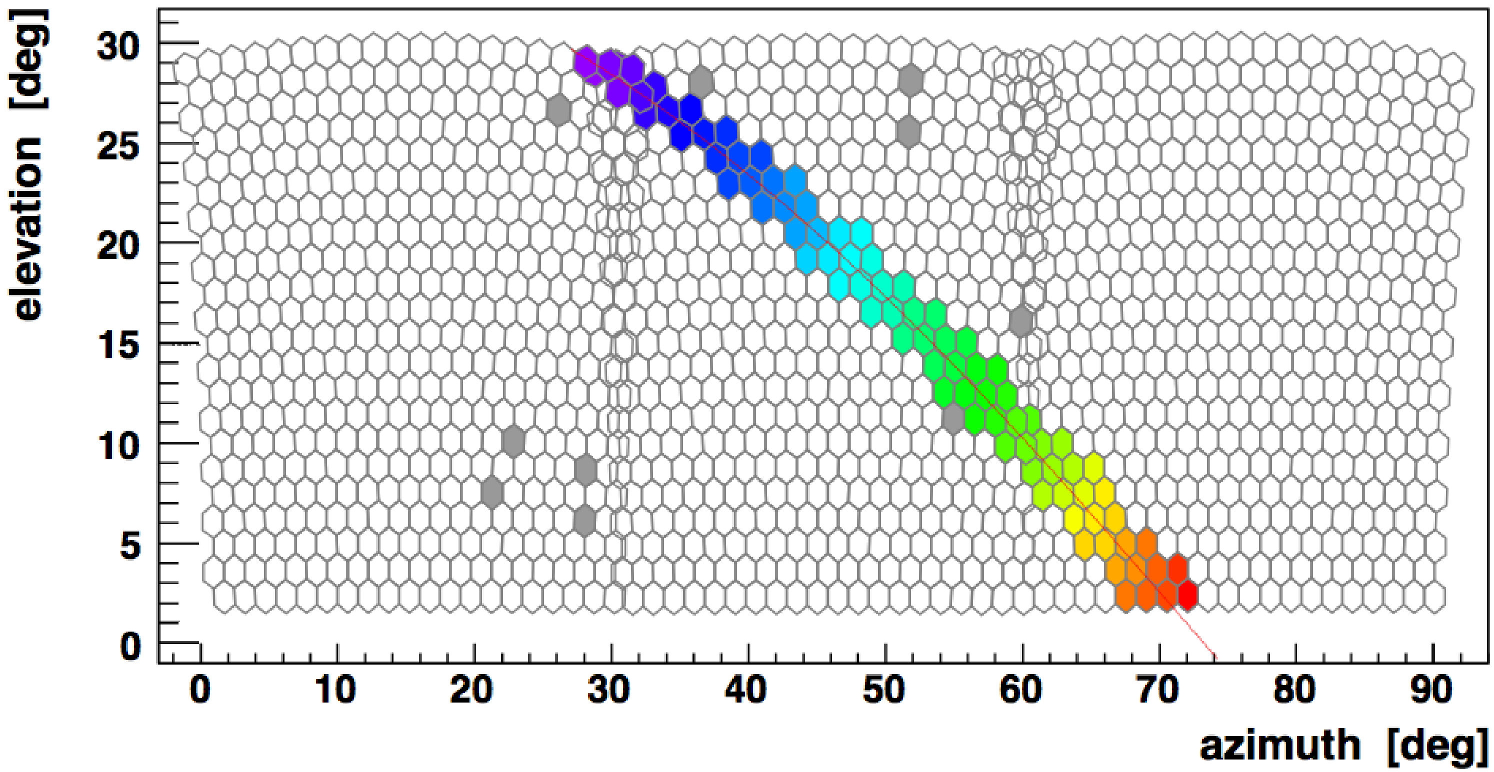
An important question is whether the primary particle was a proton or a heavier nucleus.

Hadronic interaction Modeling

Mass A

Energy measurement problem “solved”. “Fly's Eye”

1st Fly's Eye

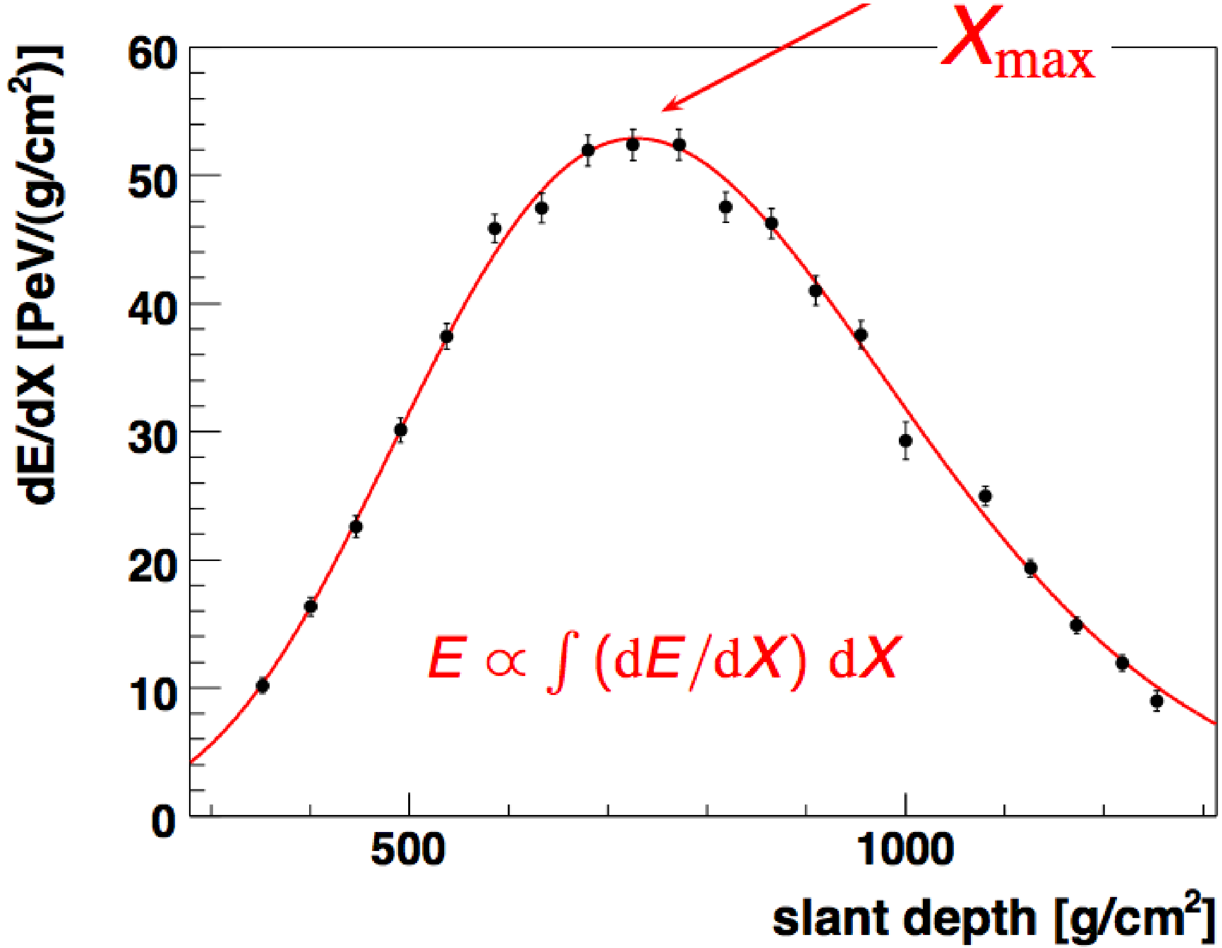


$$L(\Omega) \rightarrow F_{\gamma}(X) \rightarrow N_{e^{\pm}}(X)$$

Observed Light → Emitted Photons → Shower Size

Geometry
Atmospheric Absorption

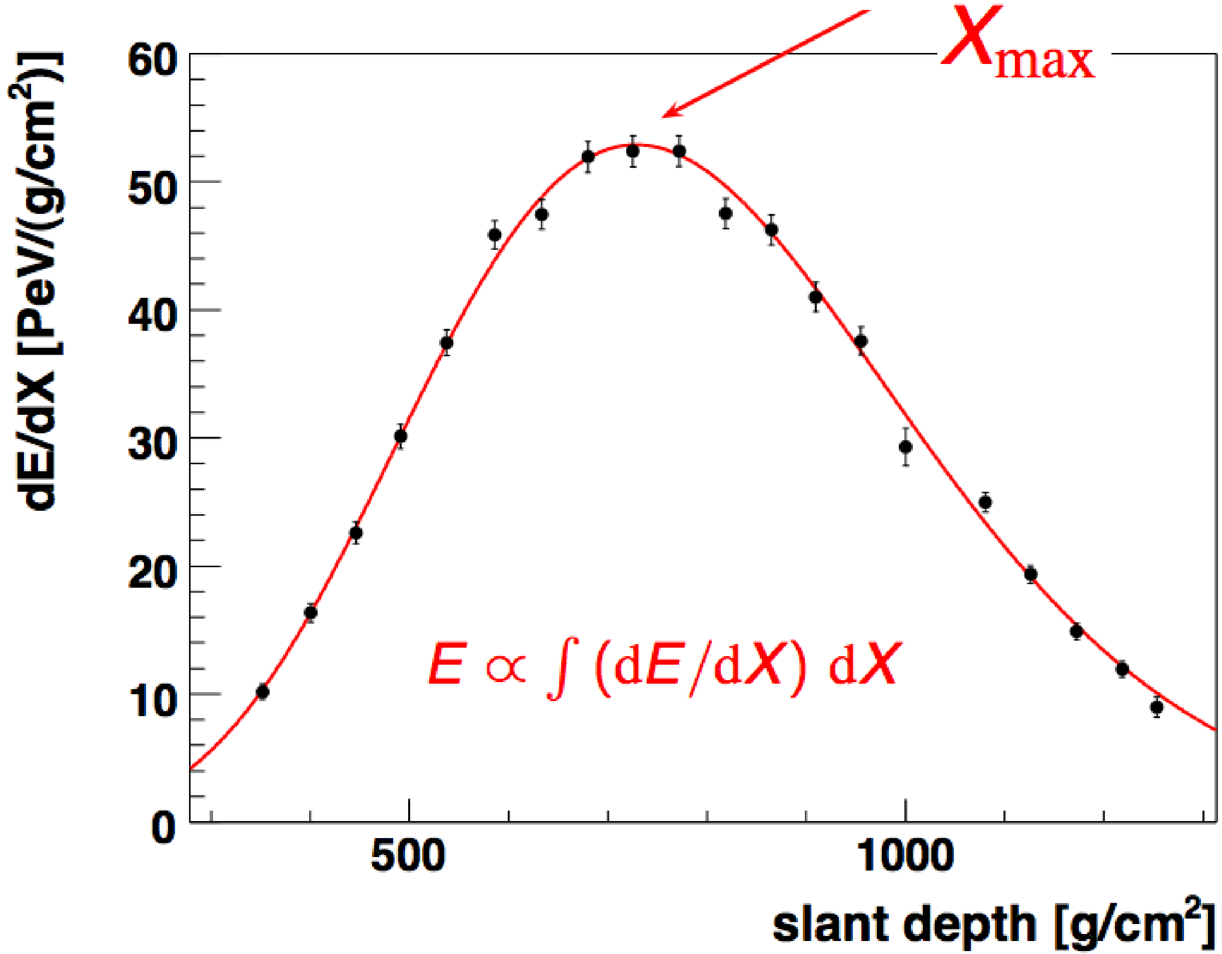
Fluorescence Yields



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

Small Model dependence

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



Area $\propto$ Energy

Shape depends on :

- Primary Identity
- Interaction Model

COMPOSITION of UHECR

Very high astrophysical importance

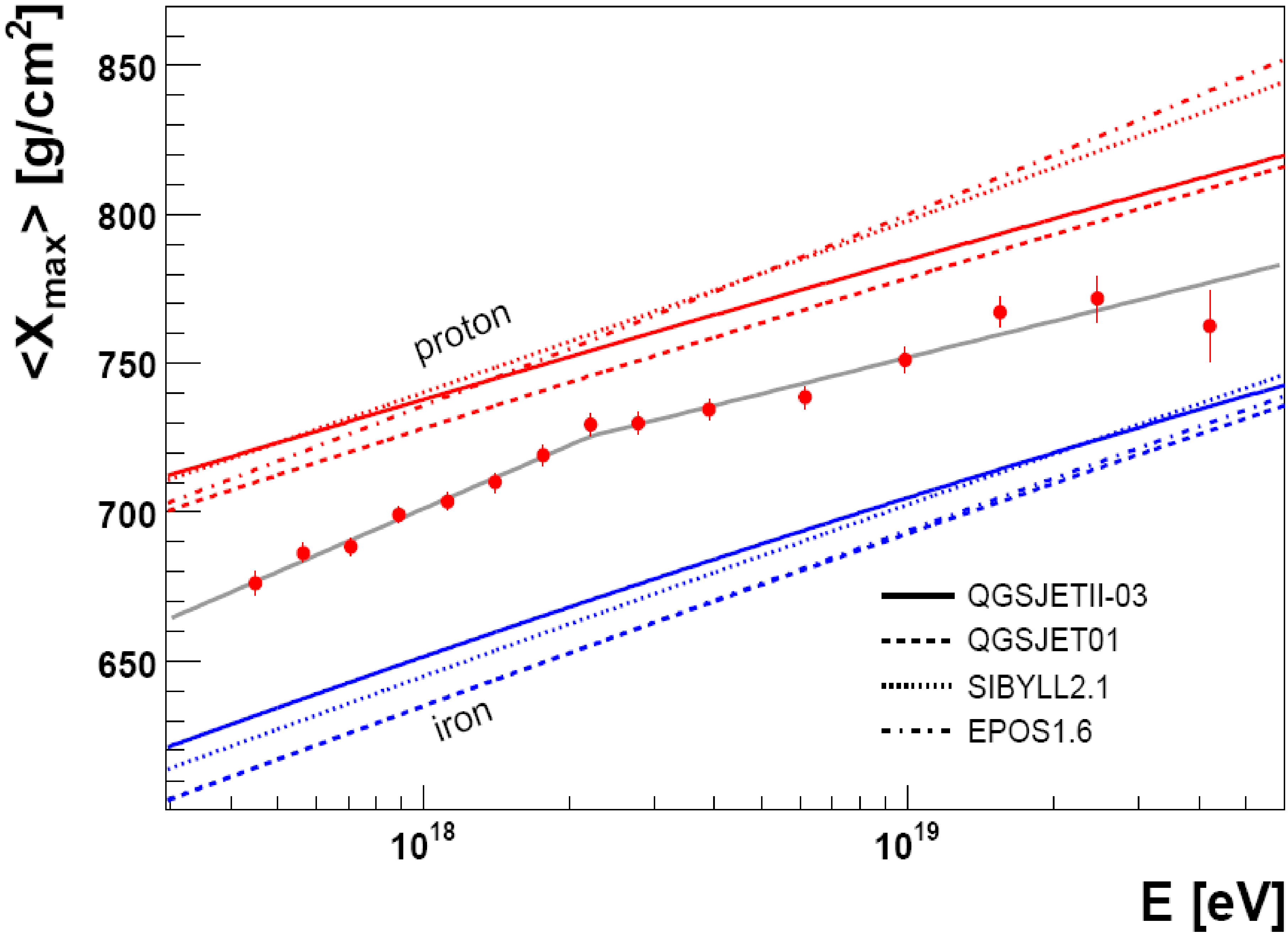
Controversial - inconsistent observations.

X_{max}

Fluctuations of X_{max}

Other methods

AUGER ICRC 2007



Elongation rate corrected for detector acceptance and comparison with previous results

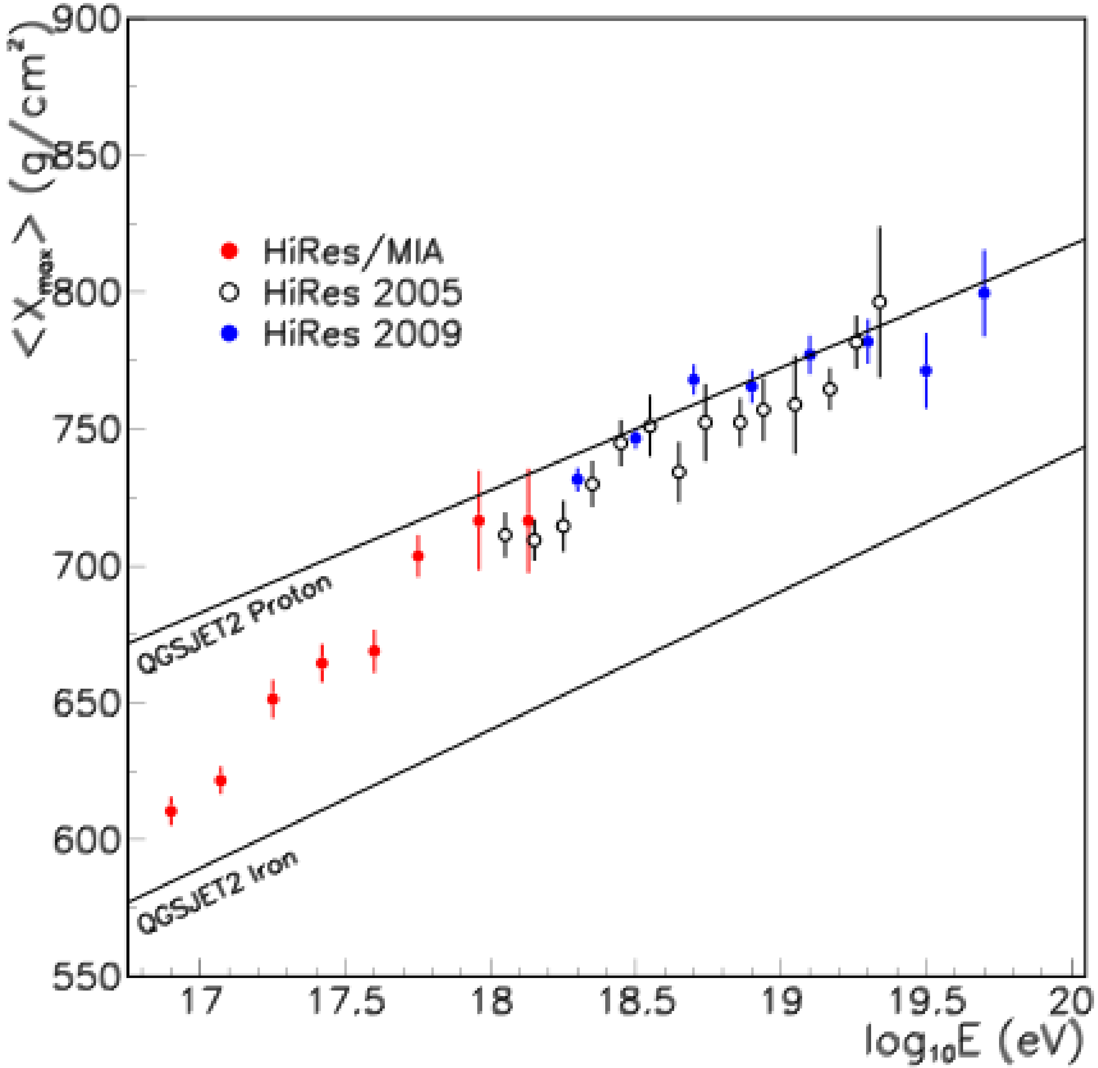
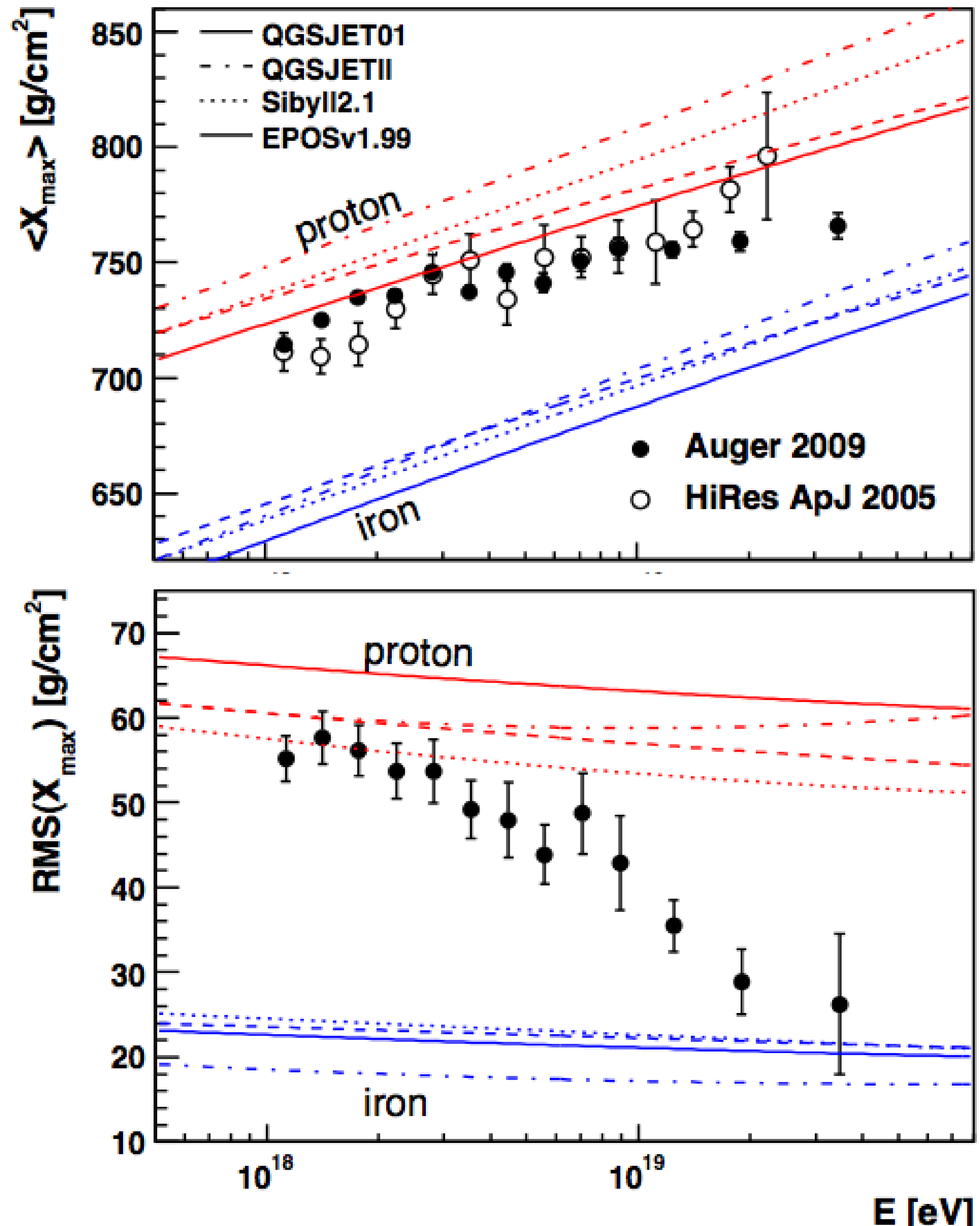


Fig. 25.— Comparison of current HiRes stereo $<X_{max}>$ results with results from the HiRes-prototype/MIA hybrid (Abu-Zayyad et al. 2001) and previously published HiRes stereo results (Abbasi et al. 2005).

FD Results

- $\langle X_{\max} \rangle$ and RMS vs E
- resolution correction
- broken line fit:
  slopes D $[\mathrm{g/cm^2}$/decade]
- comparison to air shower simulations
- published HiRes data (update cf. Pierre's talk)



The “theory curve”
$\langle X_{max}(E) \rangle$ is determined
by the parameters that describe
hadronic interactions.
(and by their energy dependence).

Interaction Lengths
Multiplicity
Inclusive Spectra
....

X_{max} and the Composition of Cosmic Rays

Proton Showers

$$X^p_{\rm max}(E) = X^p_{\rm max}(E^*) + D_p(E^*)\ \ln\left(\frac{E}{E^*}\right)$$

Logarithmic growth of average X_{max} with energy

$$X^A_{\rm max}(E) \simeq X^p_{\rm max}\left(\frac{E}{A}\right)$$

Mass dependence

X_{max} and the Composition of Cosmic Rays

Proton Showers

$$X_{\max}^{p}(E) = X_{\max}^{p}(E^*) + D_p(E^*) \ \ln\left(\frac{E}{E^*}\right)$$

Logarithmic growth of average X_{max} with energy

$$X_{\max}^{A}(E) \simeq X_{\max}^{p}\left(\frac{E}{A}\right)$$

Mass dependence

$$\langle X_{\max}(E)\rangle \simeq X_{\max}^{p}(E) - D_p(E) \ \langle \ln A \rangle$$

Obtain the average mass
and its variation
with energy

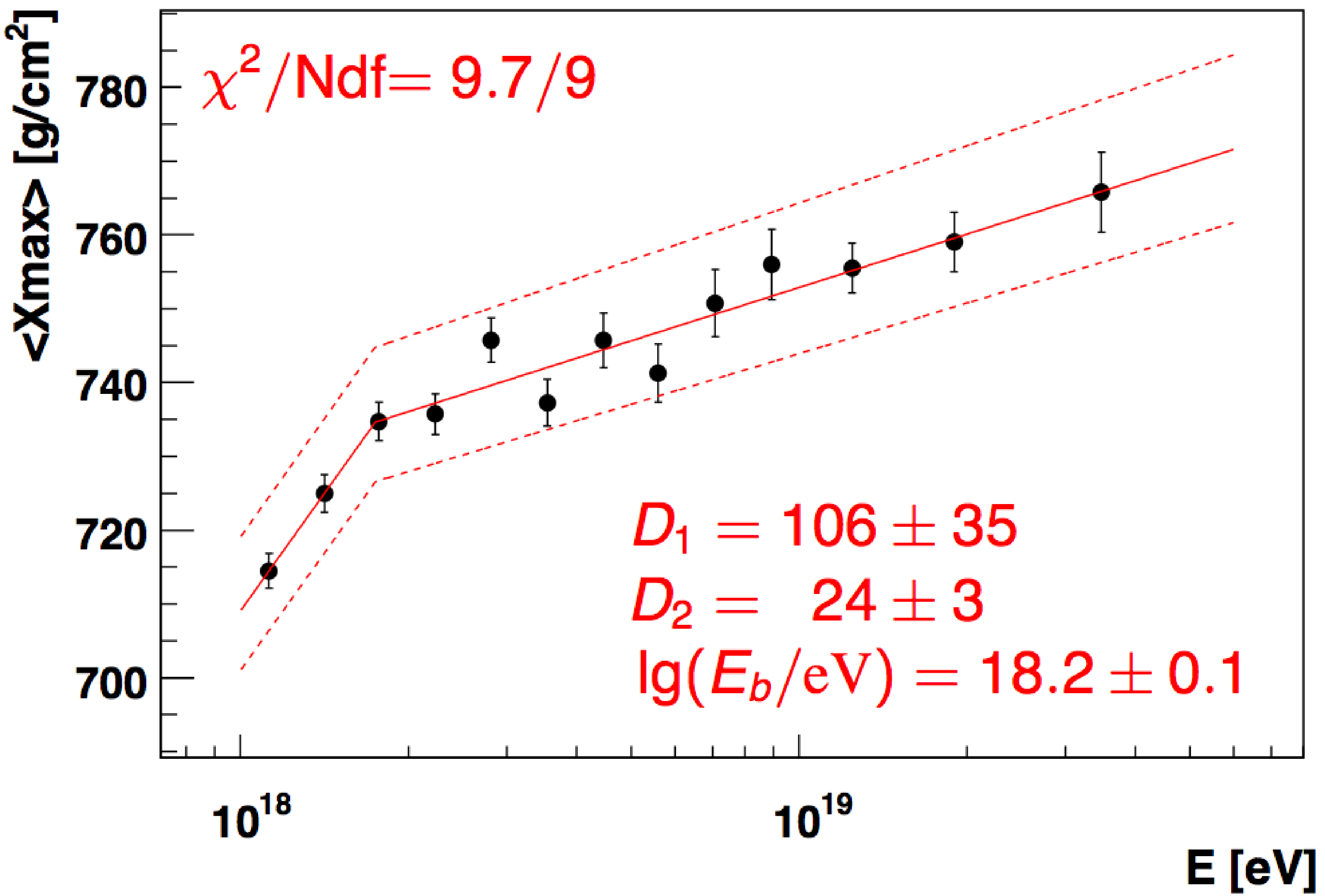
$$\langle \ln A \rangle_E = \frac{\sum_A \phi_A(E)\ \ln A}{\sum_A \phi_A(E)}$$

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

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

The importance of "CORNERS"

(when real)



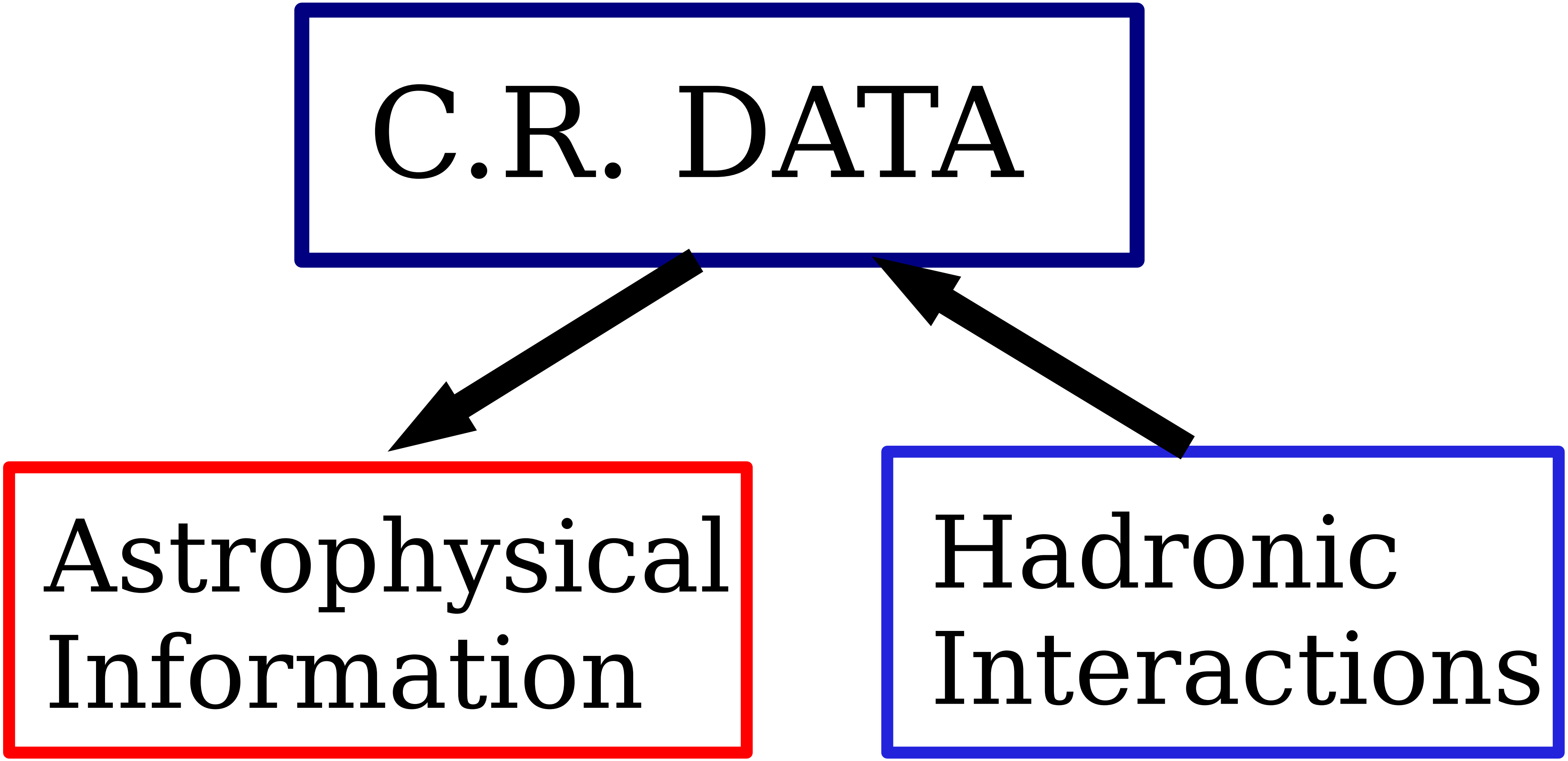
“METHODOLOGY”

C.R. DATA

Astrophysical Information

Hadronic Interactions

From Accelerator Data + Theory → Astrophysics



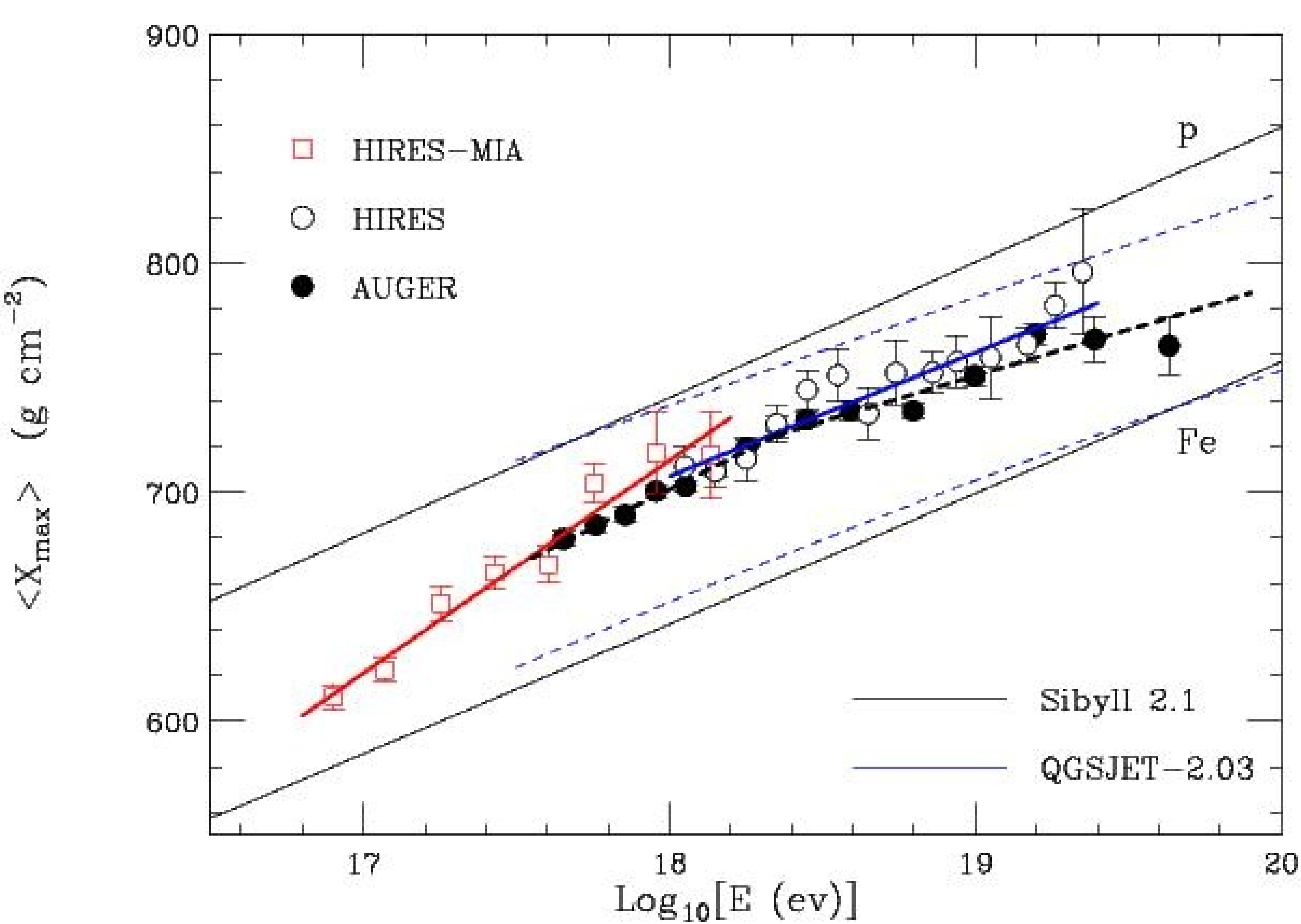
$$\langle \ln A \rangle_E = \frac{\langle X_{\max}(E) \rangle - X_p(E)}{D_p}$$

Data

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

Astrophysical Information

Hadronic Interactions



900
800
700
600
$\langle X_{max} \rangle$ (g cm^{-2})
HIRES−MIA
HIRES
AUGER
p
Fe
Sibyll 2.1
QGSJET−2.03
17
18
19
20
Log$_{10}$[E (ev)]

$$E^* = 10^{19}\ \mathrm{eV}$$

$$\langle X_{\mathrm{max}} \rangle = 750 \pm 5\ (\mathrm{stat}) \pm 10\ (\mathrm{syst})\quad \mathrm{g\ cm}^{-2}$$

$$\langle X_{\mathrm{max}} \rangle = 750 \pm 12\ \mathrm{g\ cm}^{-2}$$

$$D_{\mathrm{exp}} = 40 \pm 4\ \mathrm{g\ cm}^{-2}/\mathrm{decade}$$

$$[\langle X^{p}_{\mathrm{max}} \rangle]_{\mathrm{Sibyll}} = 800\ \mathrm{g\ cm}^{-2}$$

$$D_p^{\mathrm{Sibyll}} \simeq 59\ \mathrm{g\ cm}^{-2}$$

$$\langle X^{p}_{\mathrm{max}} \rangle_{\mathrm{QGSJet}} \simeq 784\ \mathrm{g\ cm}^{-2}$$

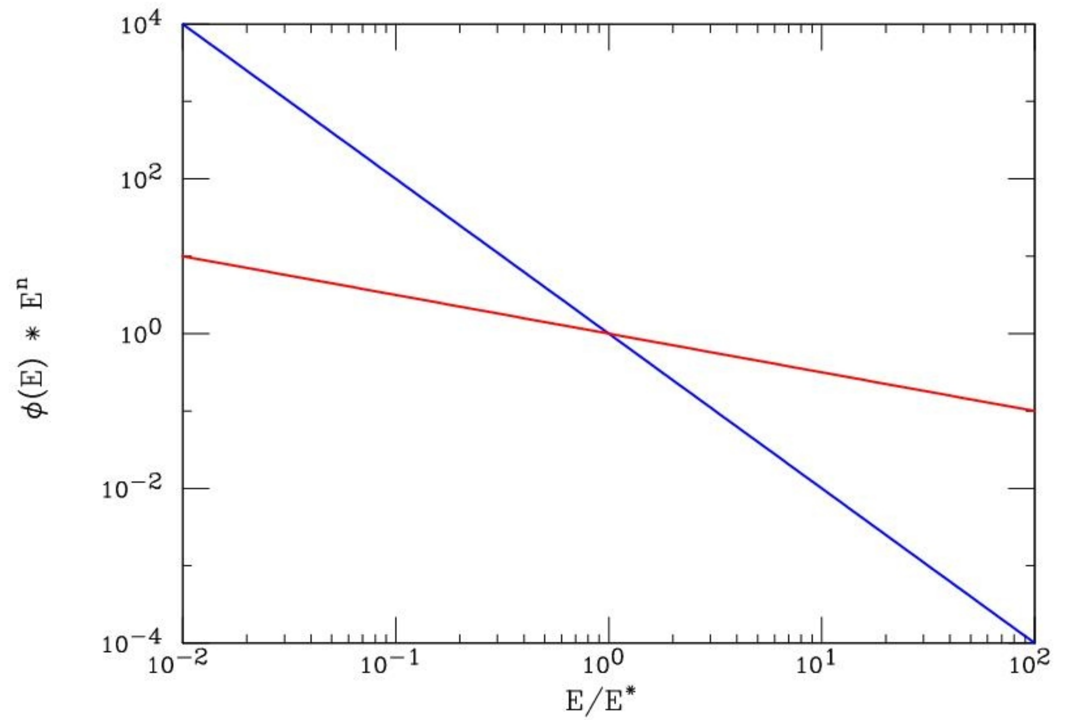
$$D_p^{\mathrm{QGSJet}} \simeq 46\ \mathrm{g\ cm}^{-2}$$

Naive 2-component model

$$\phi(E) = \phi_p(E) + \phi_{\mathrm{Fe}}(E)$$

$$\phi(E) \propto r \left(\frac{E}{E^*}\right)^{-\alpha_p} + \left(\frac{E}{E^*}\right)^{-(\alpha_p+\beta)}$$

$$E^* = 10^{19}\ \mathrm{eV}$$



Sibyll-Interpretation

$$\langle \log_{10} A \rangle_{\text{Sibyll}} \simeq 0.83 \pm 0.21$$

$$\langle \log_{10} A \rangle_{\text{Sibyll}} \simeq \log \left[6.8 \; {}^{+4.1}_{-2.1} \right]$$

$$\left[\frac{p}{\text{Fe}} \right]_{\text{Sibyll}} = 1.1 \pm 0.2$$

$$\left[\frac{d \langle \log A \rangle}{d \log E} \right]_{\text{Sibyll}} \simeq 0.32 \pm 0.07$$

$$[\beta]_{\text{Sibyll}} = -0.7 \pm 0.15$$

Sibyll-Interpretation

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$$\left[\frac{p}{\rm Fe} \right]_{\rm Sibyll} = 1.1 \pm 0.2$$

Composition
is Mixed

50% p
50% Fe

$$\left[\frac{d \langle \log A \rangle}{d \log E} \right]_{\rm Sibyll} \simeq 0.32 \pm 0.07$$

$$[\beta]_{\rm Sibyll} = -0.7 \pm 0.15$$

Composition
become heavier
with increasing Energy

QGSJet-Interpretation

Composition
is Mixed

60% p
40% Fe

$$\langle \log_{10} A \rangle_{\rm QGSJet} \simeq 0.72 \pm 0.26$$

$$\langle \log_{10} A \rangle_{\rm QGSJet} \simeq \log \left[5.28 \ ^{+4.3}_{-2.4} \right]$$

$$\left[\frac{p}{\rm Fe} \right]_{\rm QGSJet} = 1.4 \ ^{+0.4}_{-0.3}$$

Composition:
Indication (1.5 s)
of moderate increase
of A with Energy

$$\left[\frac{d\langle \log A \rangle}{d \log E} \right]_{\rm QGSJet} \simeq 0.12 \pm 0.09$$

$$[\beta]_{\rm QGSJet} = -0.3 \pm 0.2$$

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.

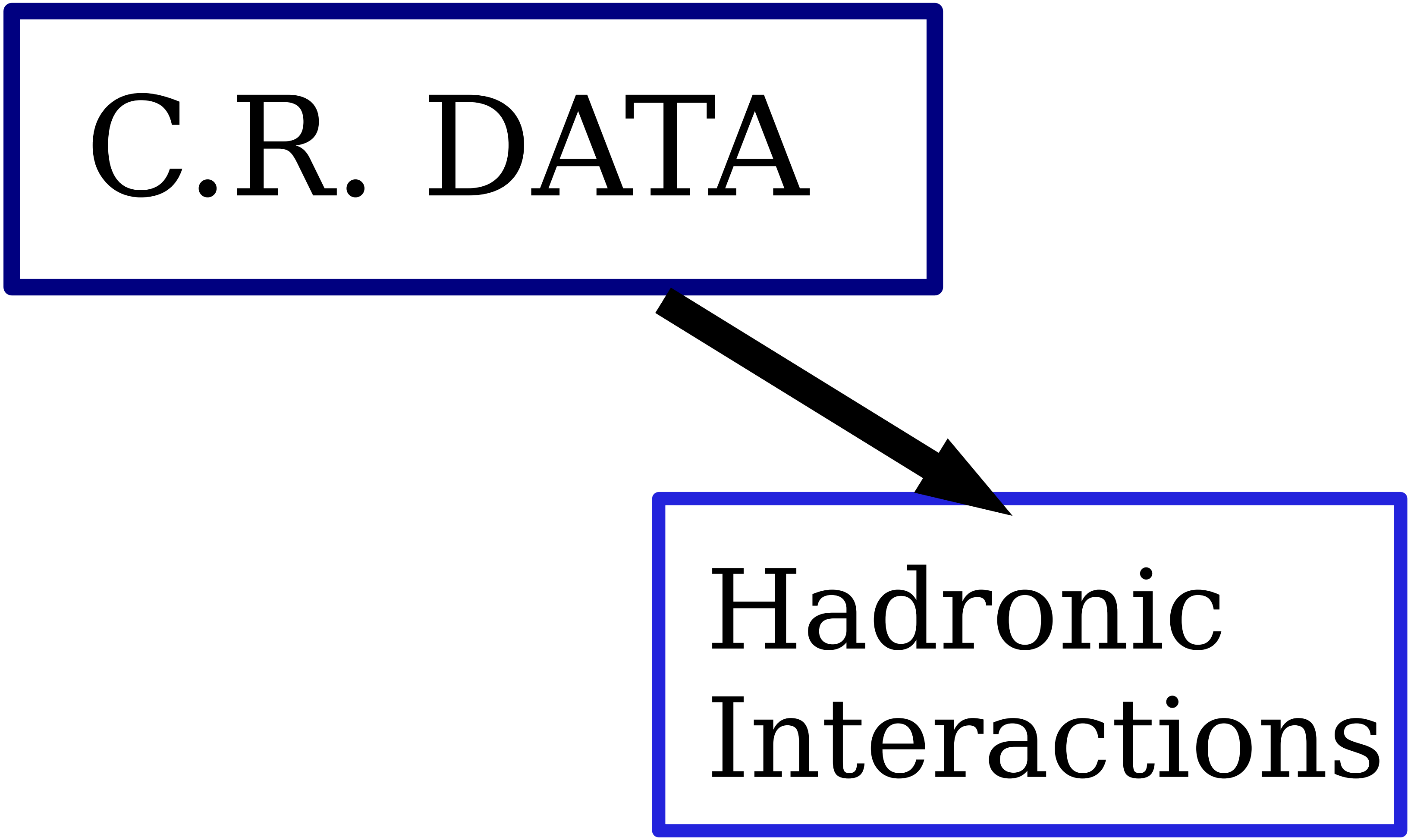
Overestimate ?

Some models are
lower quality.

Underestimate ?

Perhaps we are missing
something important.

"Alternative Approach" to the problem.

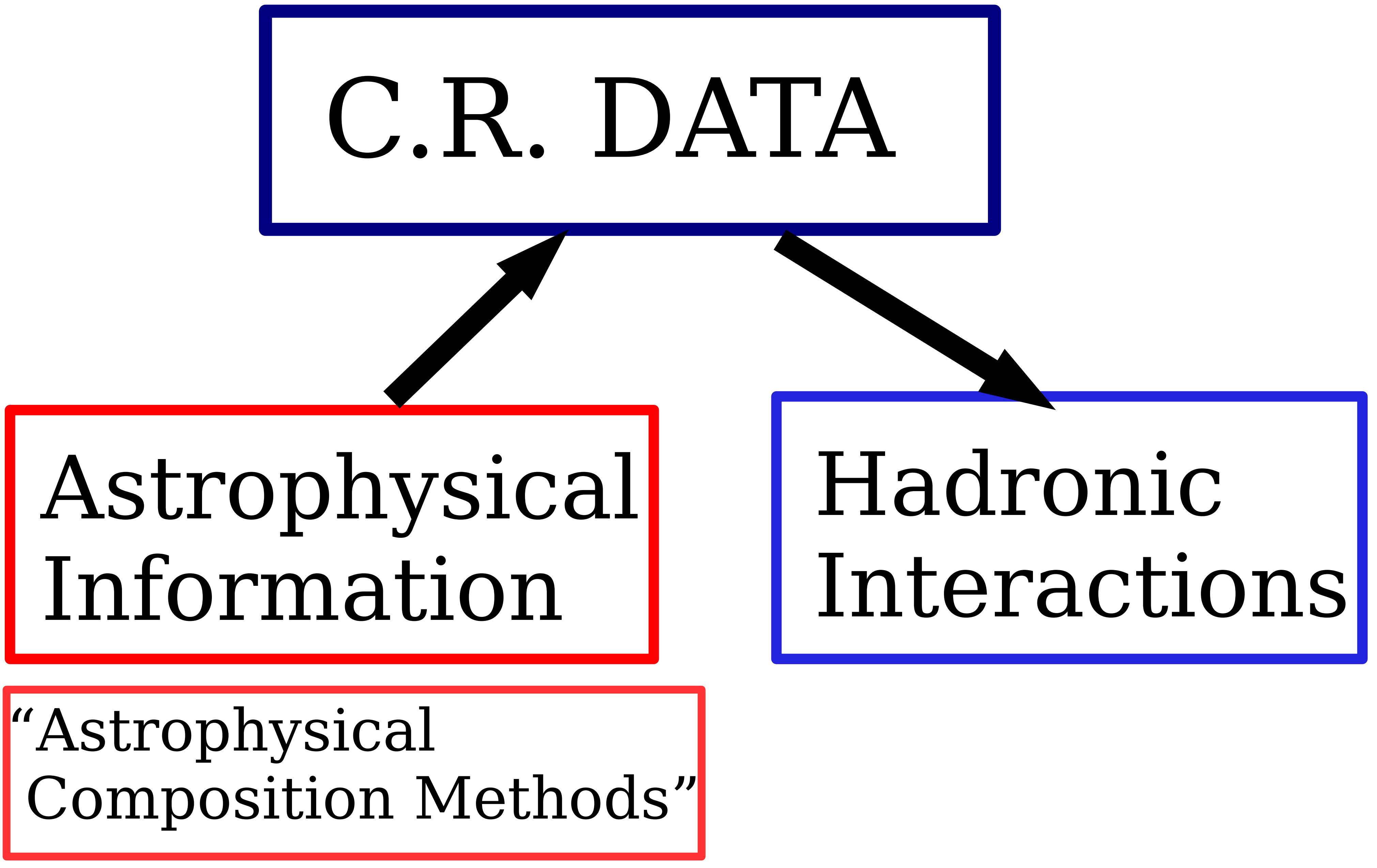


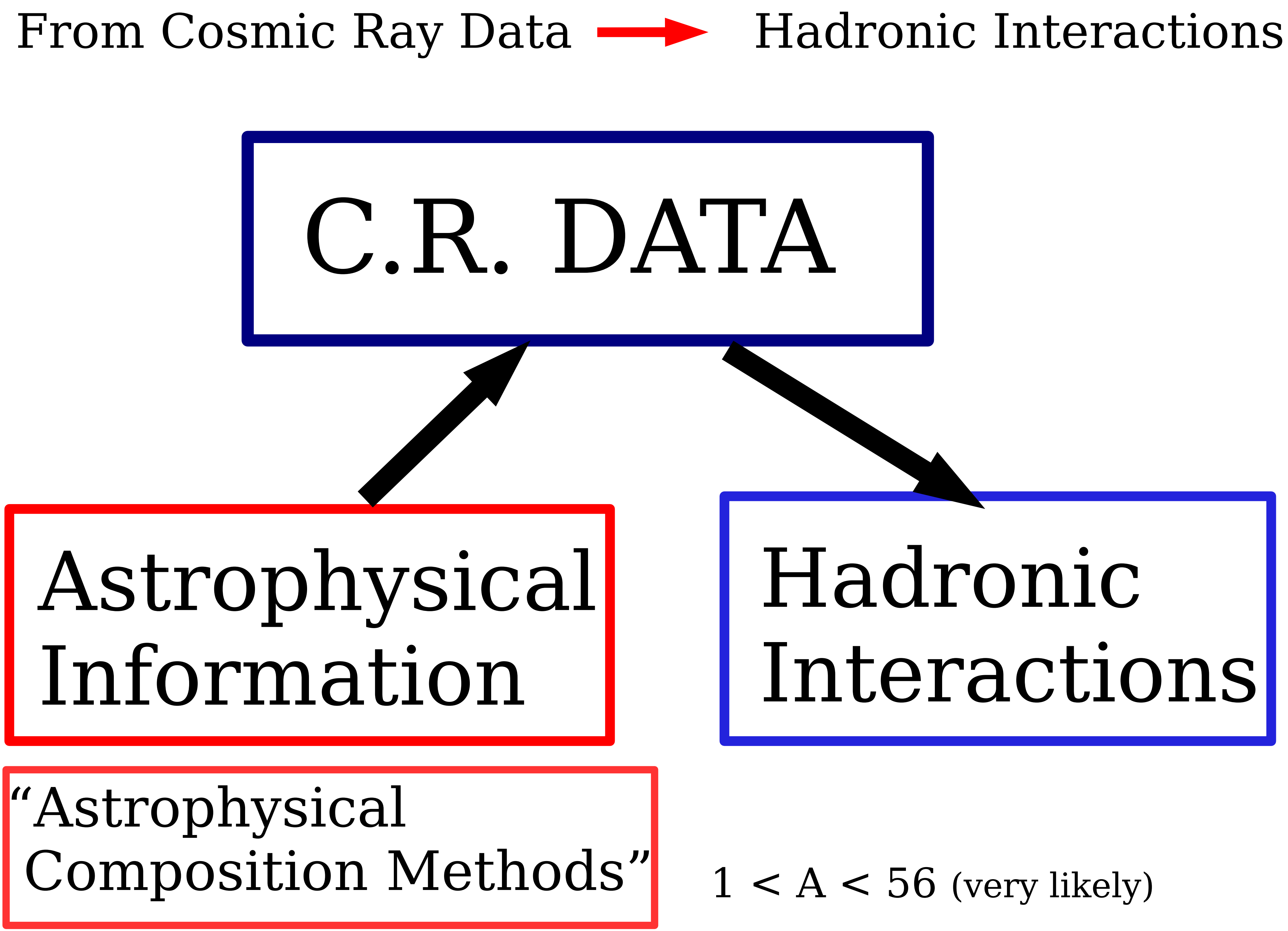
“CONSISTENCY”

Different Methods
to measure same physical quantity
must agree

- Fluorescence versus Surface detection
- X_{max} versus “Muons”
- .....

From Cosmic Ray Data → Hadronic Interactions




From Cosmic Ray Data
Hadronic Interactions
C.R. DATA
Astrophysical Information
Hadronic Interactions
“Astrophysical Composition Methods”
1 < A < 56 (very likely)

“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 :

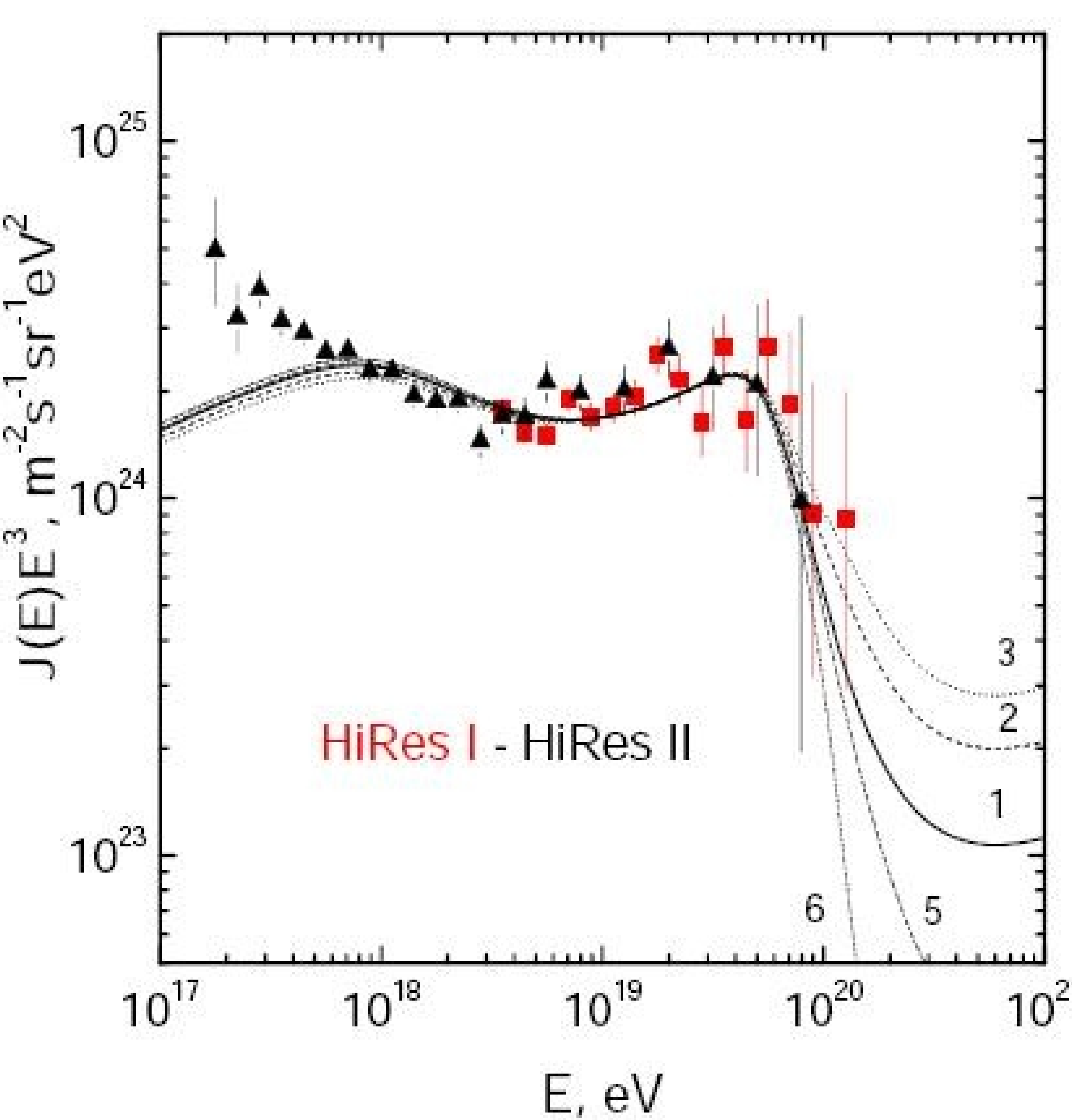
$$p\,\gamma \rightarrow p\pi^{\circ}$$

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

"GZK"

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

Pair Production



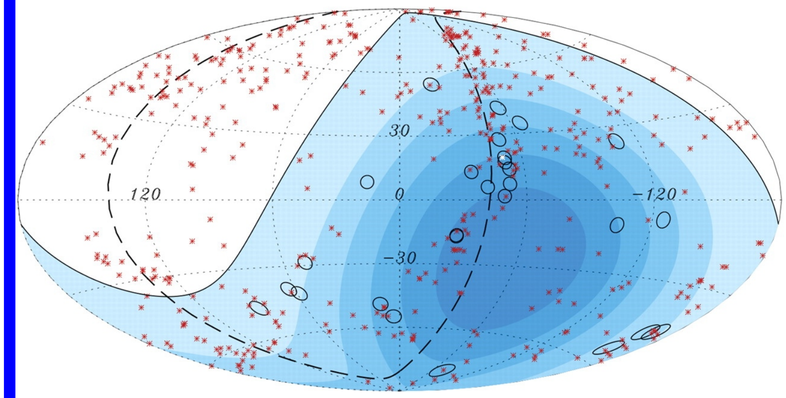
Berezinsky et al.

Inject Smooth power law Spectrum.

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

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

“COSMIC
MAGNETIC
SPECTROMETER”



Constraint on : B, Z

AUGER RESULT

Correlations of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects (AGN)

Protons are preferred [....? ....]

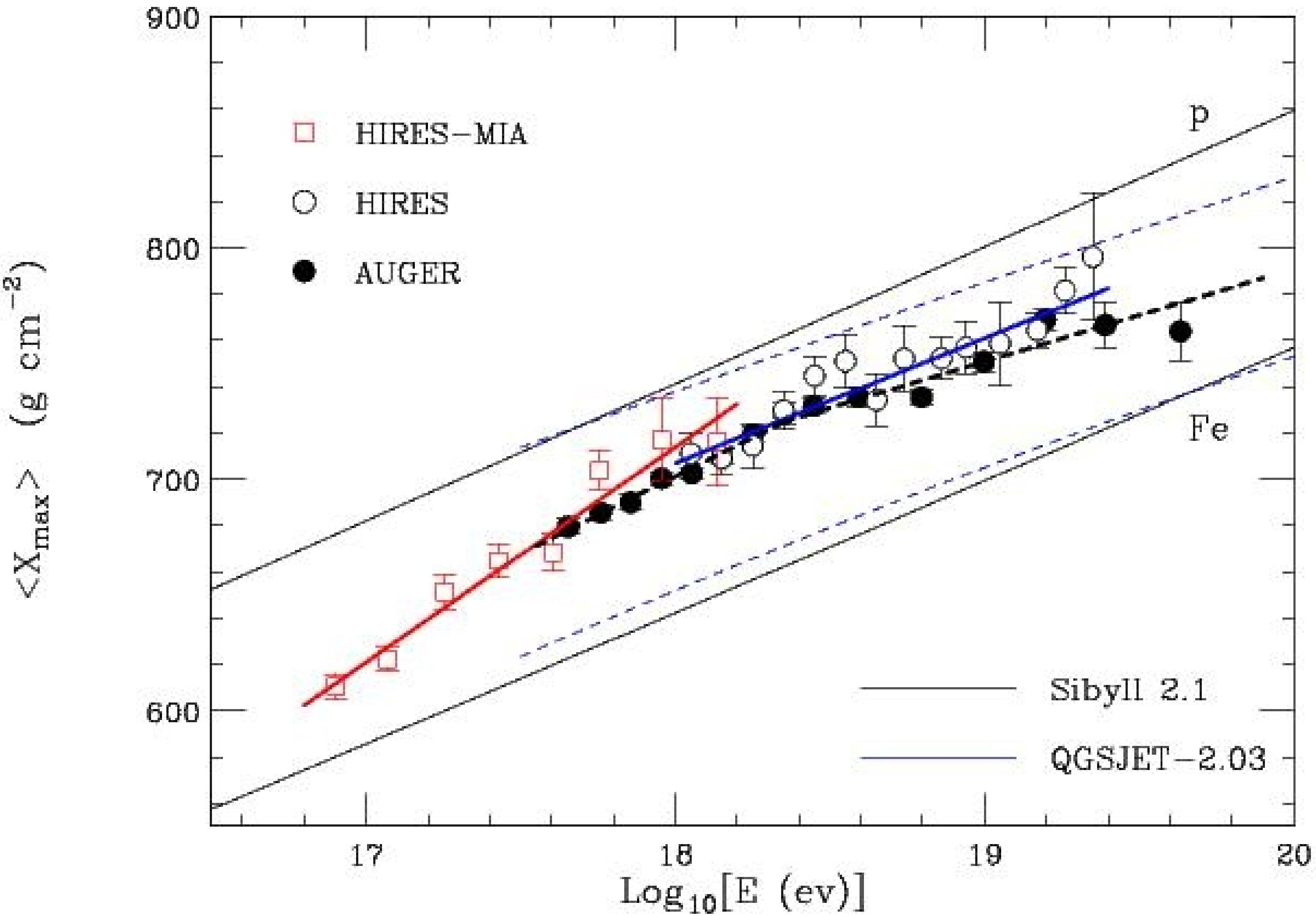
Deviation in GALACTIC Magnetic Field

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

Deviation in EXTRA-GLACTIC Magnetic Field

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

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



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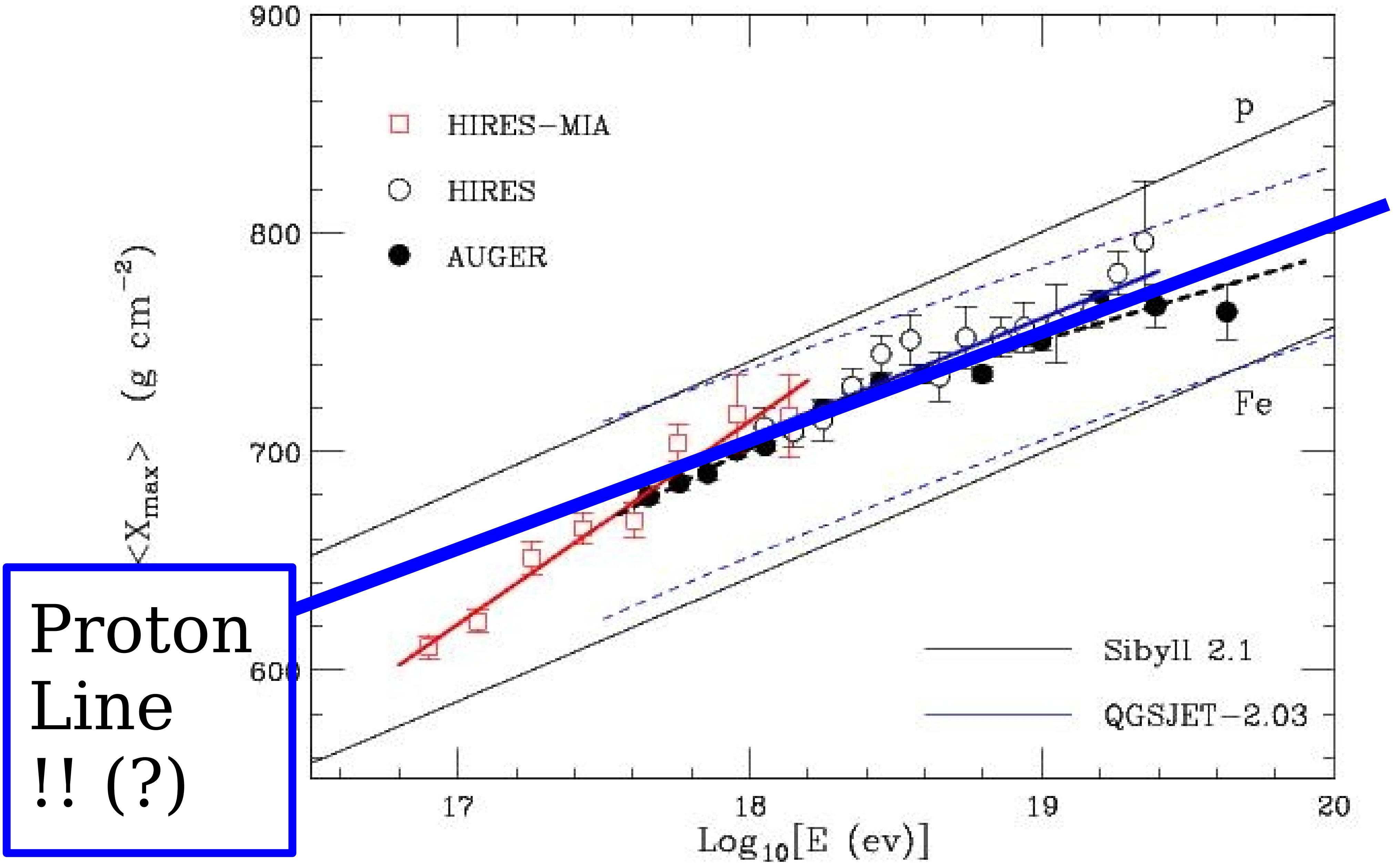


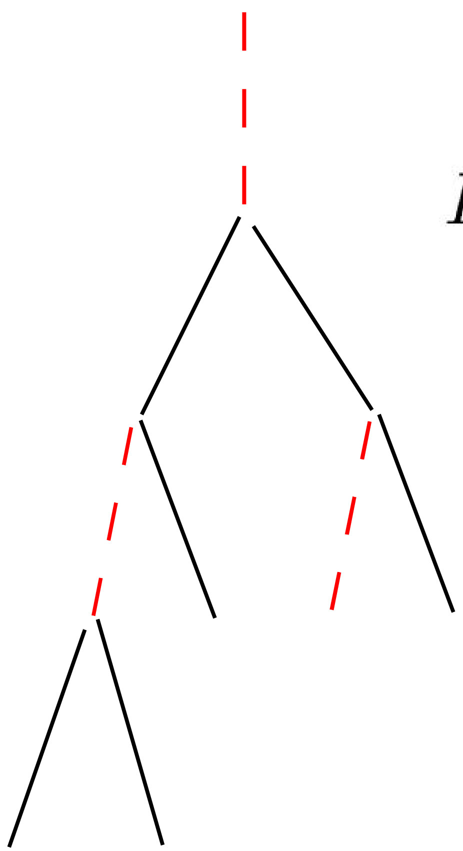
Electromagnetic Showers

versus

Hadronic Showers

Toy model discussion.

Electromagnetic Showers



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

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

Radiation Length
(Energy independent)

Vertices :
theoretically understood
(and scaling)

Electromagnetic Showers

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

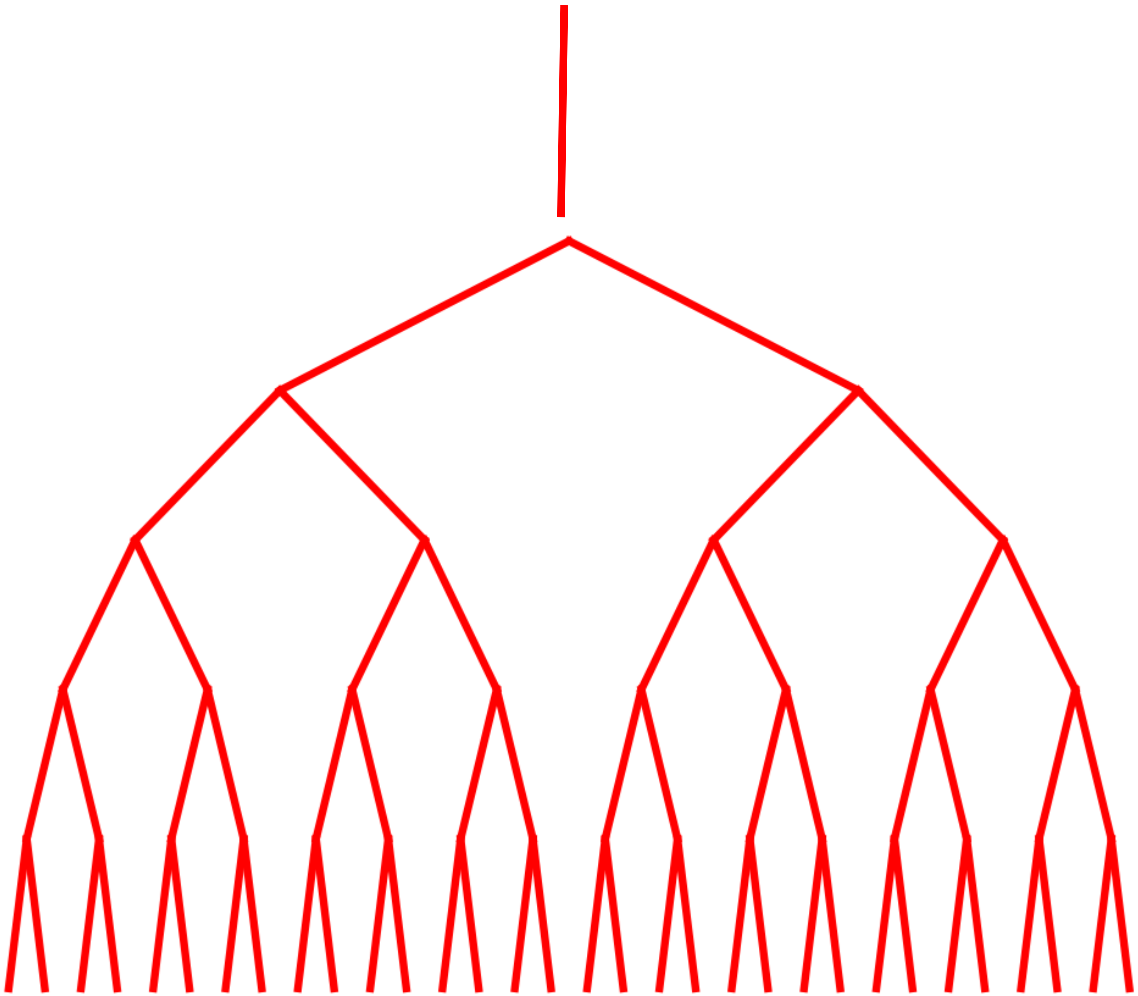
Logarithmic growth of the penetration.

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

Energy Conservation

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

Heitler toy model
for electromagnetic
showerws



“Electron-photon”

particle

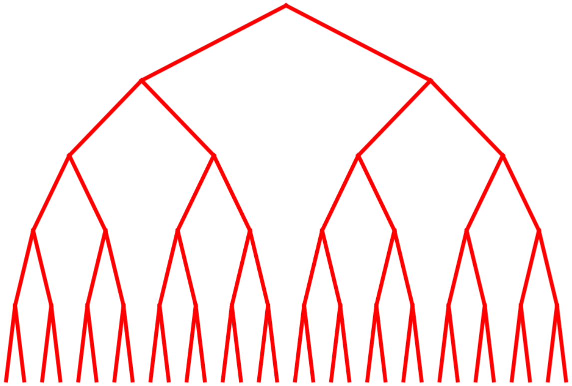
Splitting length λ
Critical energy ε

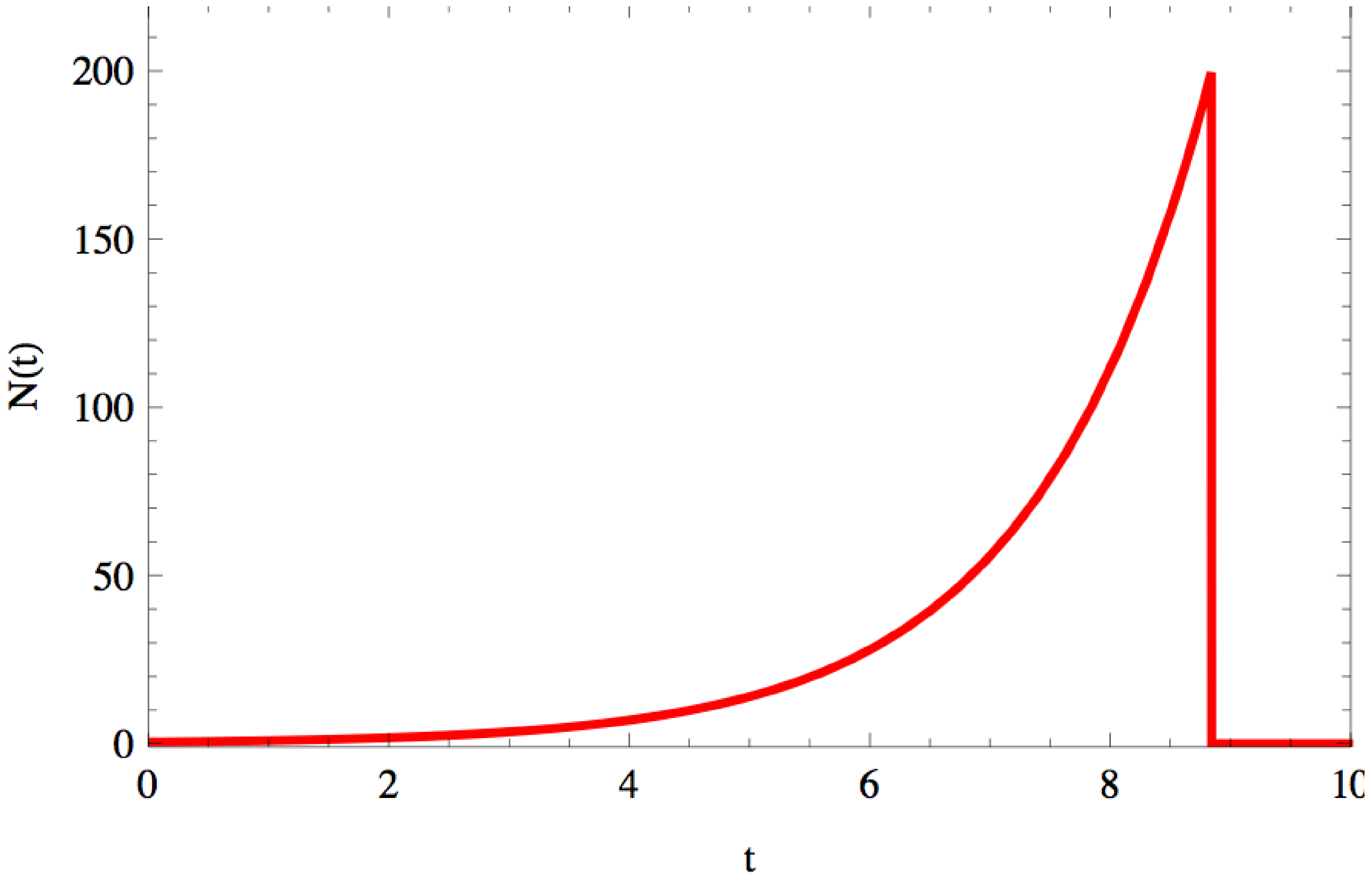
$$N(X, E) = 2^{X/\lambda}$$

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

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

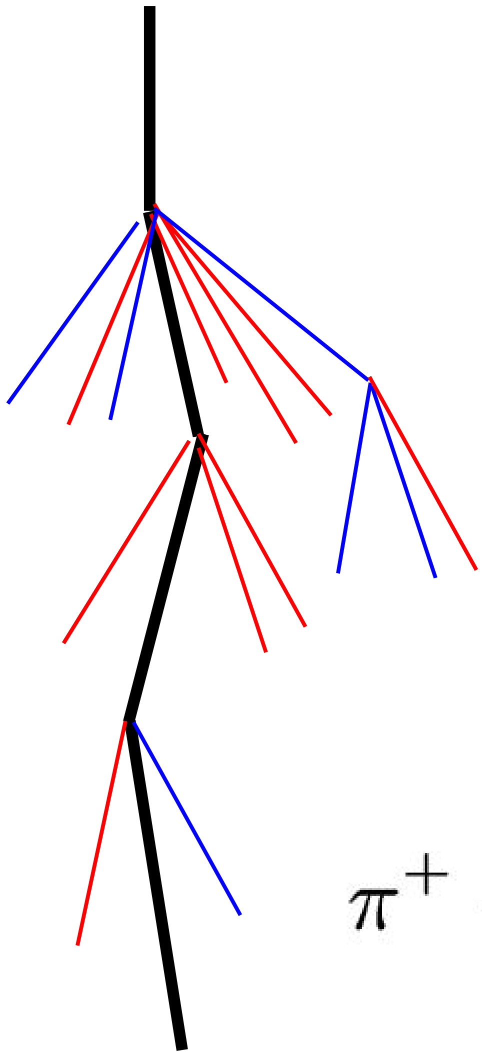
Shower development
in Heitler toy model:





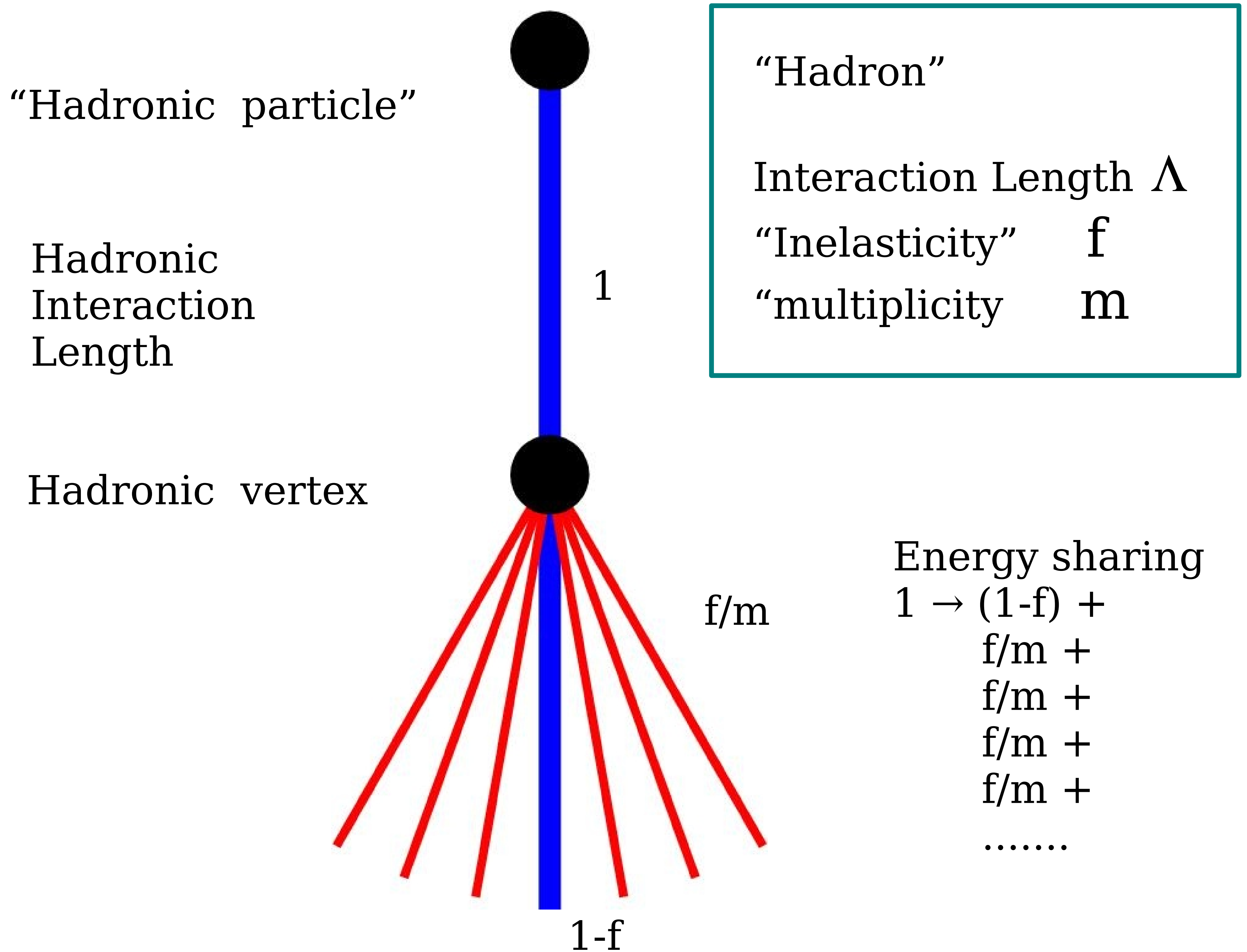
Proton Shower

Vertices : theoretically not
understood
(and not exactly scaling)

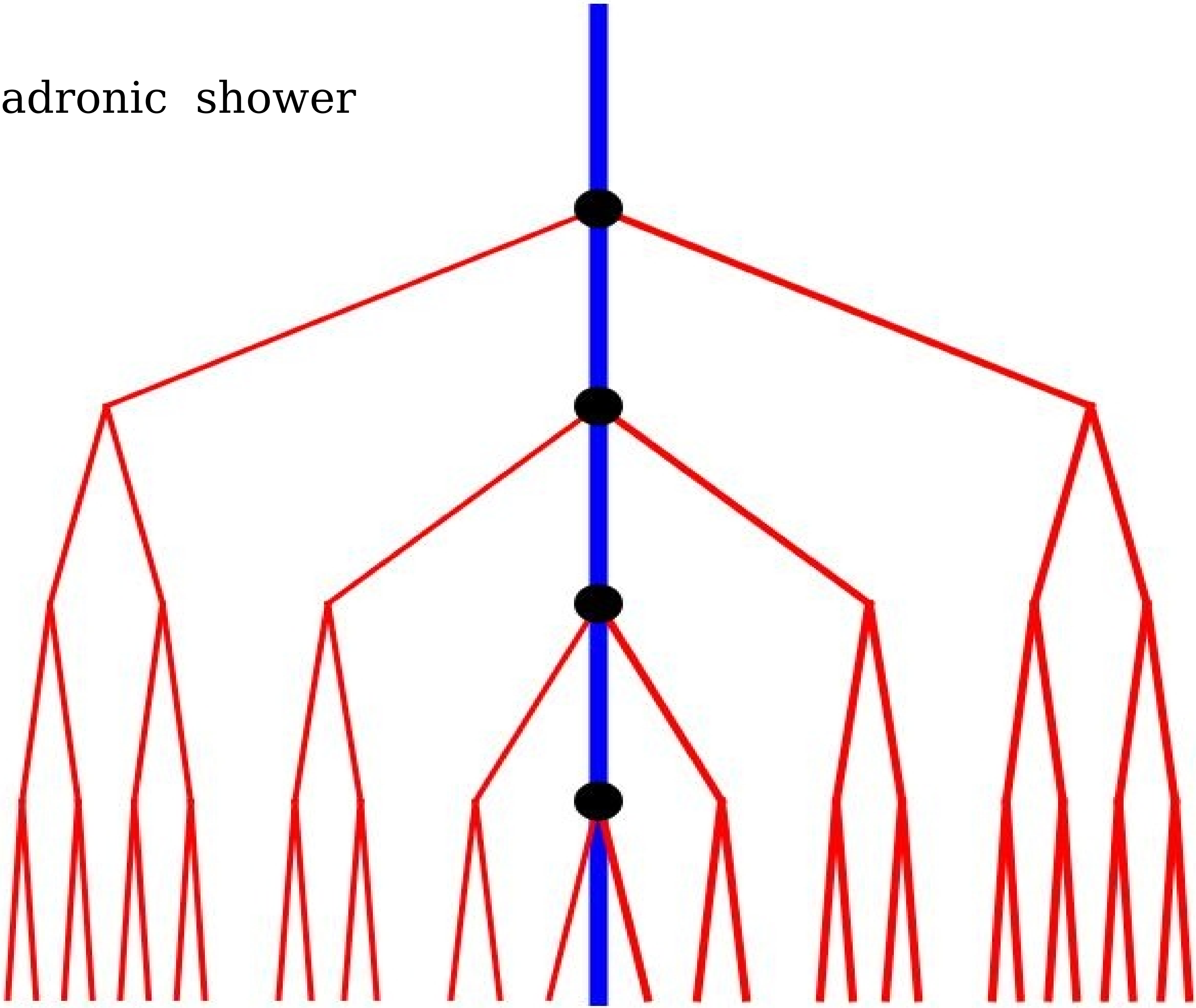


$$\pi^0 \rightarrow \gamma\gamma$$

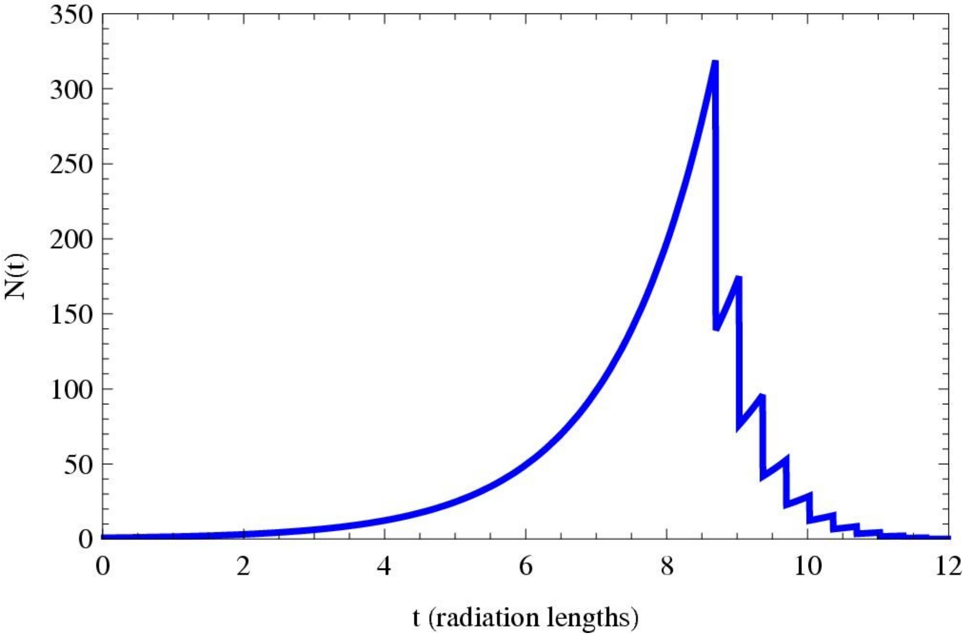
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

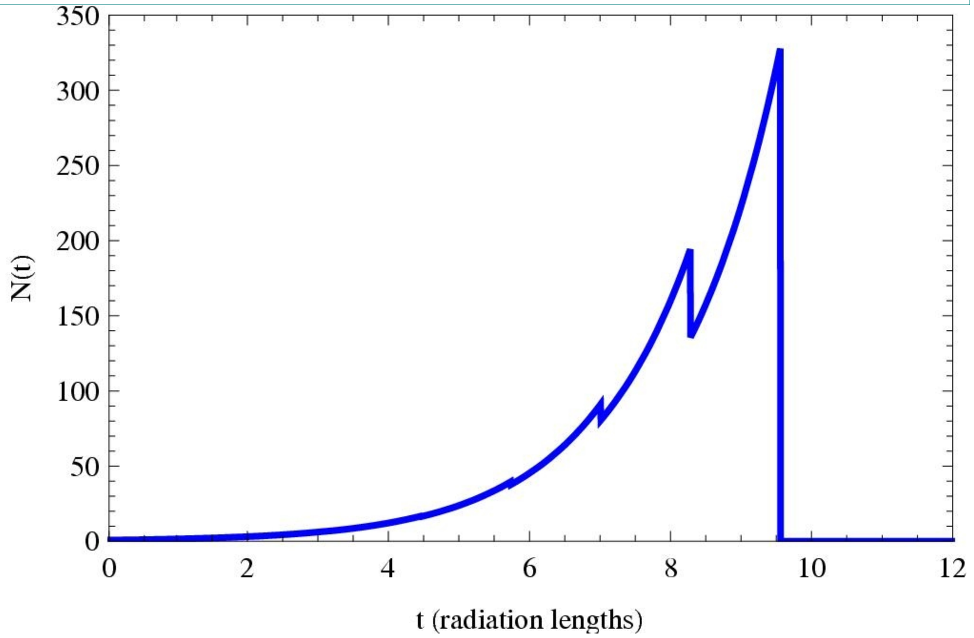

“Hadronic particle”
Hadronic
Interaction
Length
1
Hadronic vertex
f/m
1-f
“Hadron”
Interaction Length Λ
“Inelasticity” f
“multiplicity m
Energy sharing
1 → (1-f) +
f/m +
f/m +
f/m +
f/m +
....

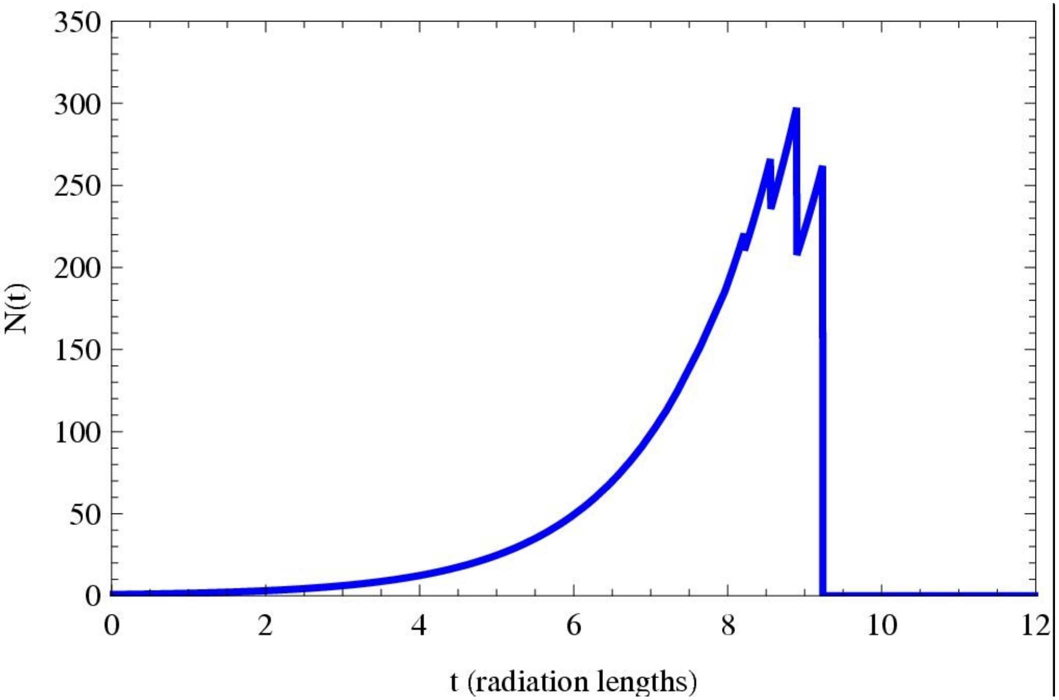
Hadronic shower

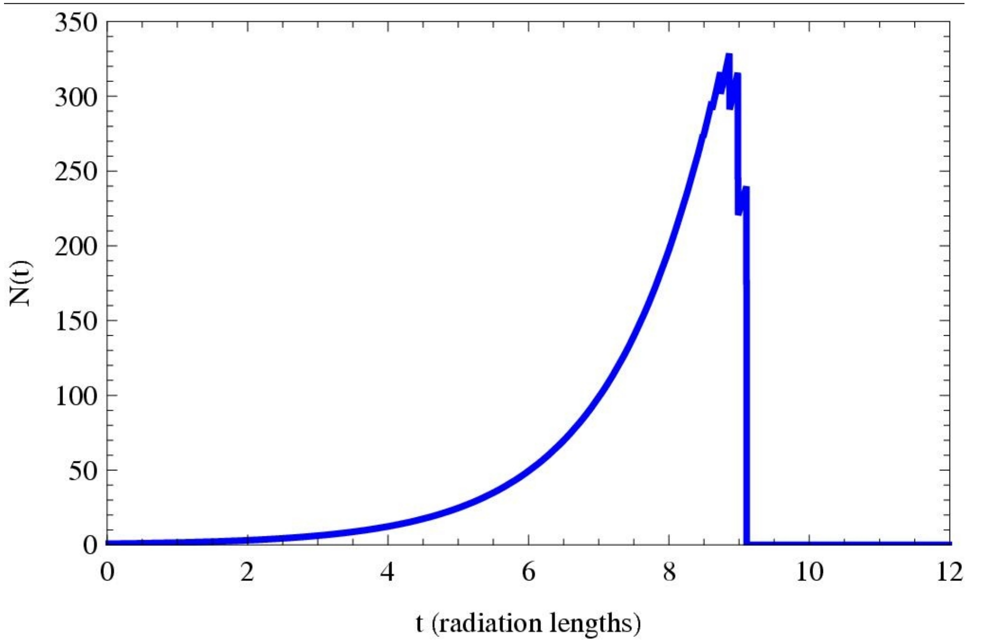


Hadronic parameters Λ, inelasticity, hardness

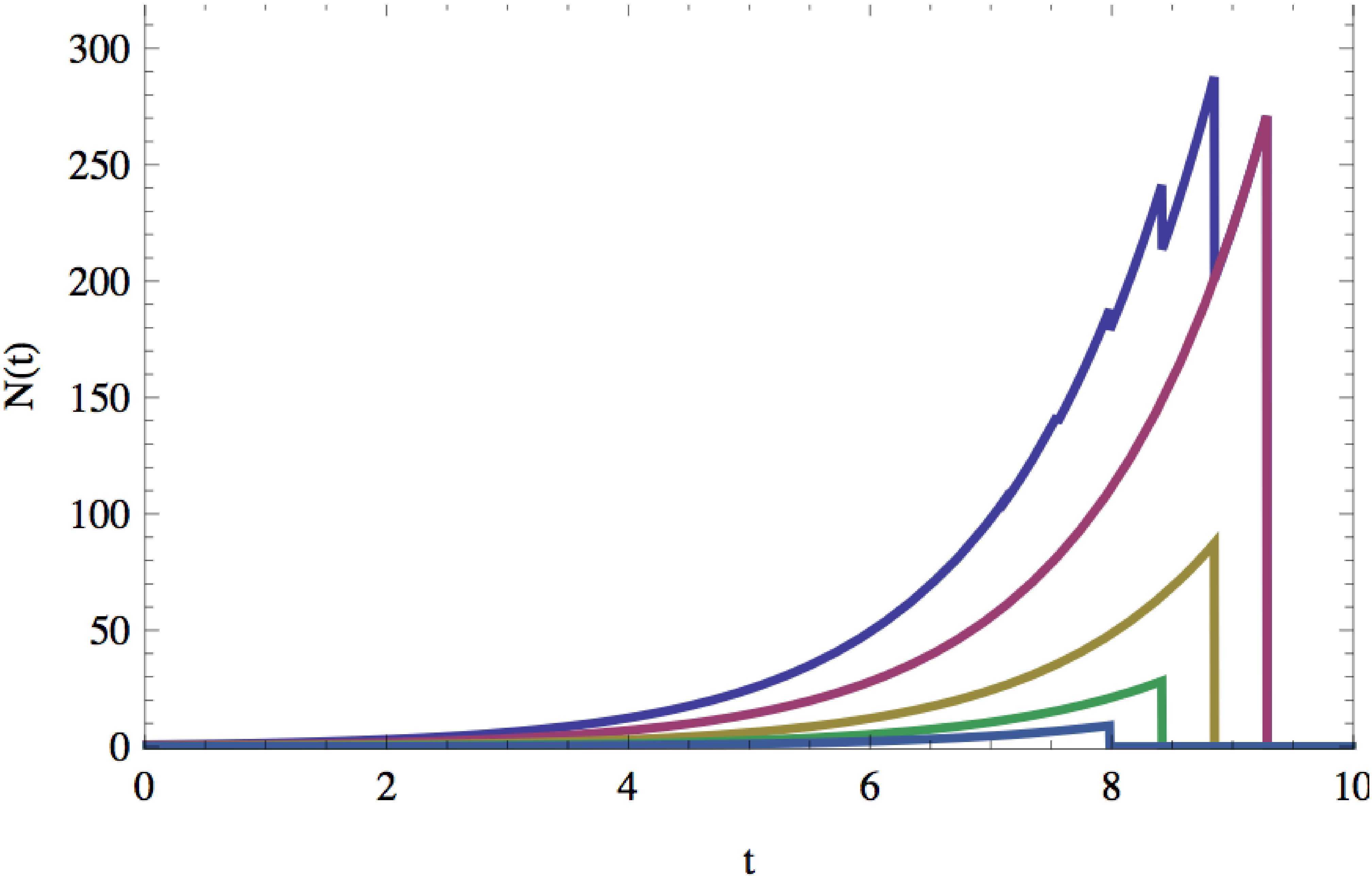


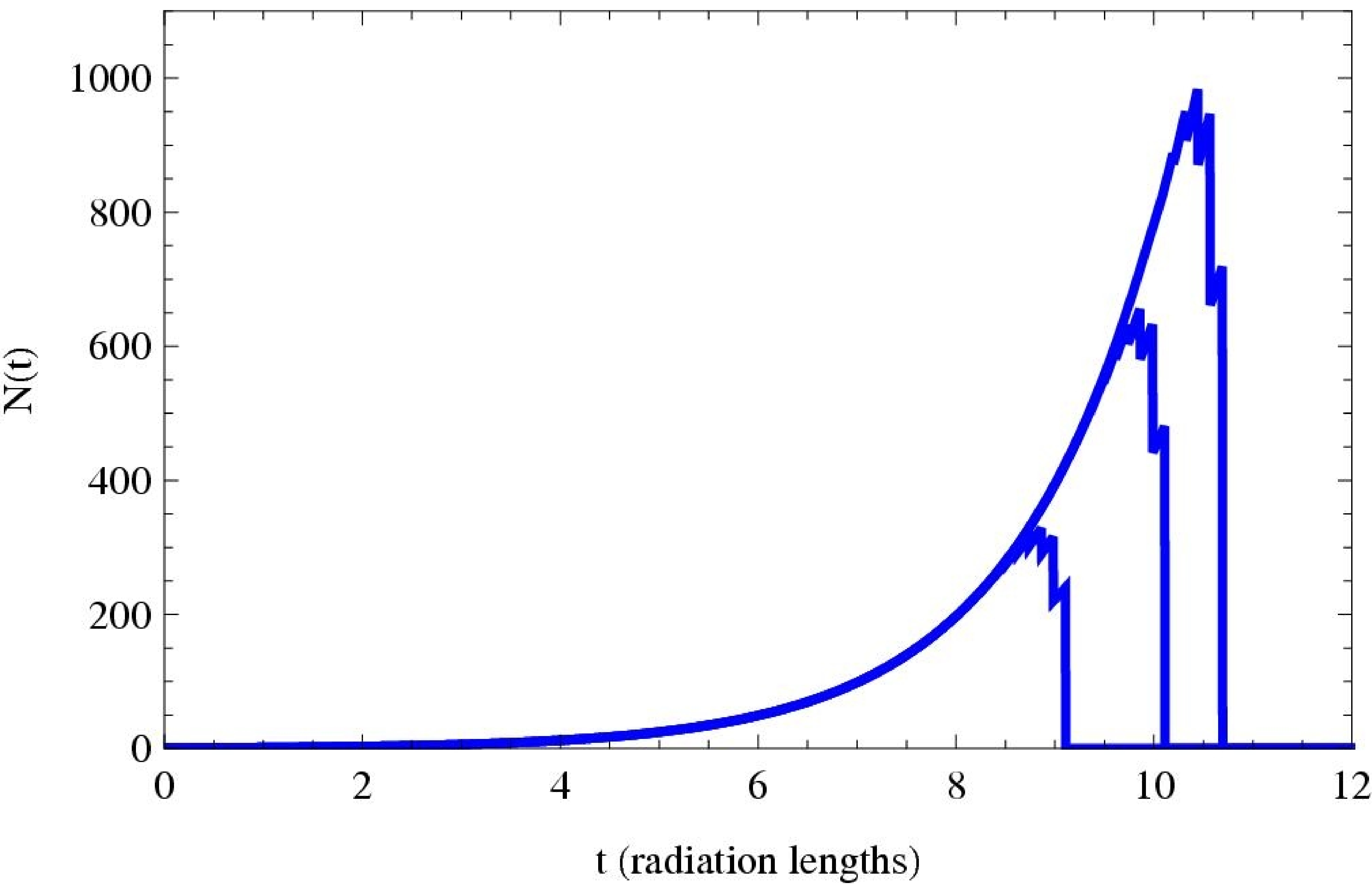




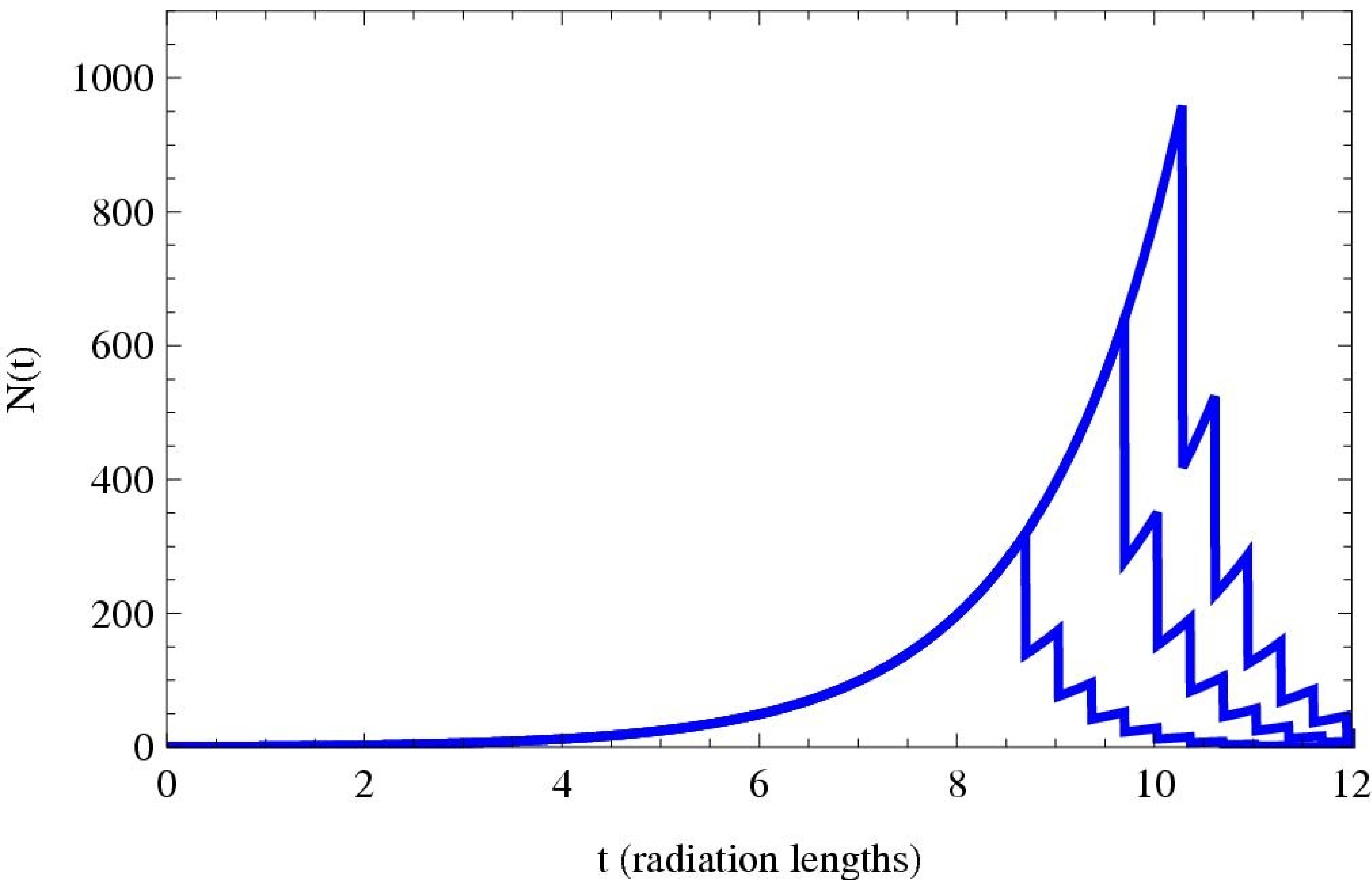


Hadronic shower in toy model.





N(t)
1000
800
600
400
200
0
0
2
4
6
8
10
12
t (radiation lengths)



1000
800
600
400
200
0
N(t)
0
2
4
6
8
10
12
t (radiation lengths)

$$X_{\max}(E) = k\,\Lambda + \lambda\,\log_2\left[\frac{E\,(1-f)^k\,f}{m\,\varepsilon}\right]$$

[integer]

$$X_{\max}(E) = \lambda_{\rm rad}\,\ln E + \text{constant}$$

$$k = k(\Lambda/\lambda, f)$$

$$k = \begin{cases} 1 & \text{for } 0 \le f < 1 - 2^{-x} \\ \left[-\frac{1}{x}\,\log_2\left(\frac{1-2^x\,(1-f)}{f}\right)\right] & \text{for } 1 - 2^{-x} < f \le 1 \end{cases}$$

Hadronic interaction parameters

IF Λ, and the other hadronic interactions parameters are energy independent

$$\frac{dX_{\max}}{d\ln E} = \frac{\lambda}{\ln 2} \equiv \lambda_{\mathrm{rad}}$$

"Elongation rate" is equal to the radiation length

IF Λ, and the other hadronic interactions parameters are energy independent

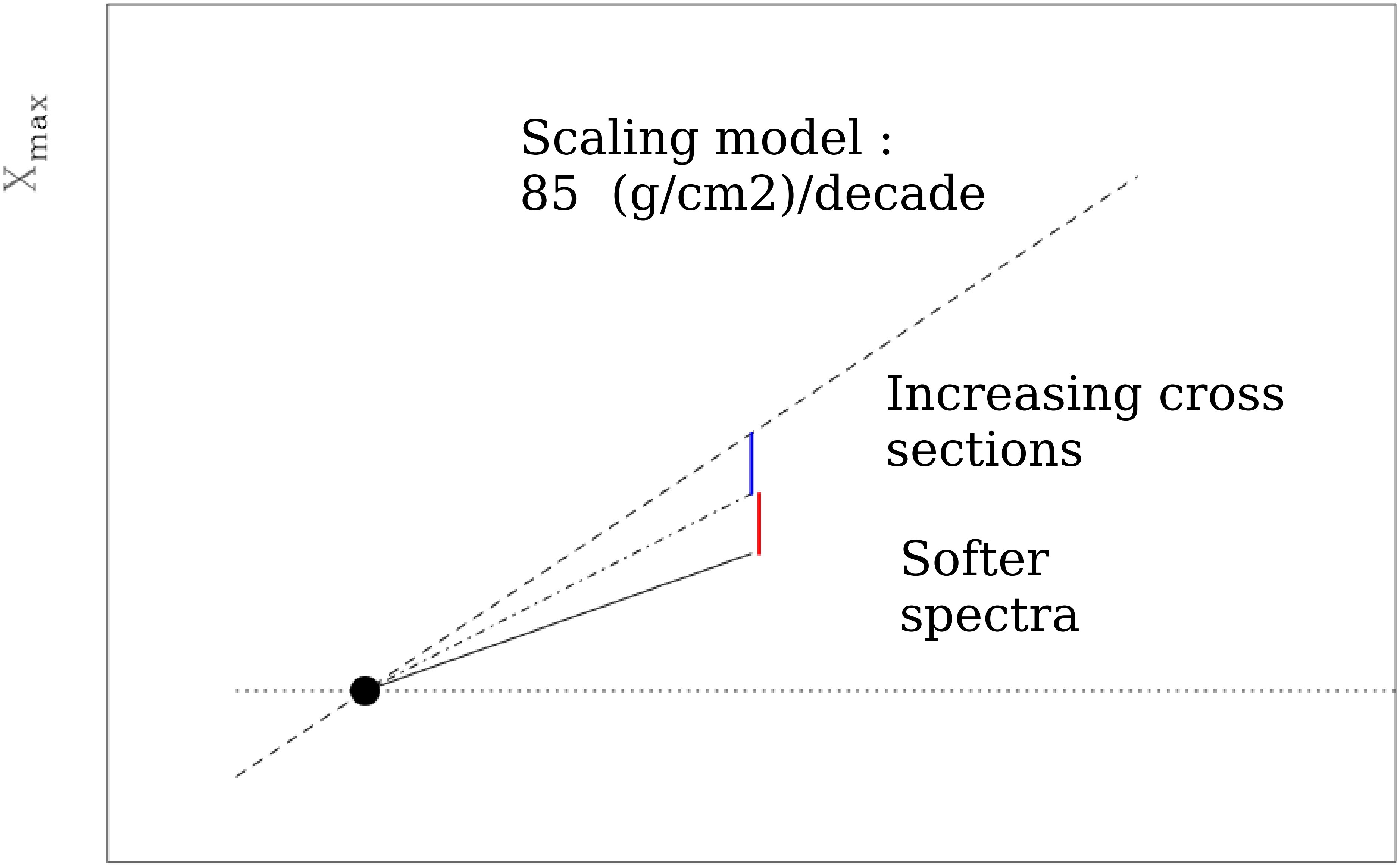
$$\frac{dX_{\max}}{d\ln E} = \frac{\lambda}{\ln 2} \equiv \lambda_{\rm rad}$$

"Elongation rate" is equal to the radiation length

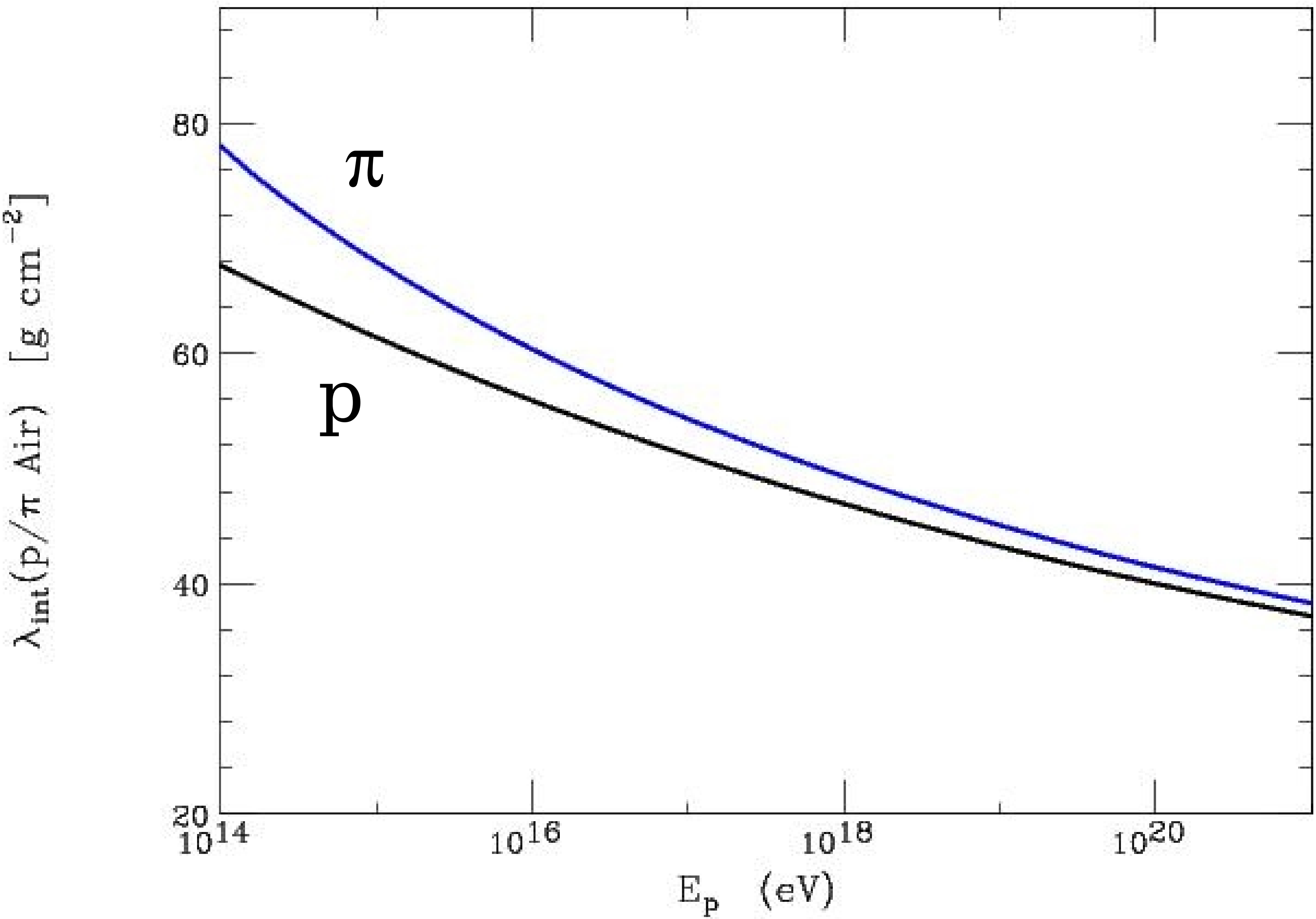
Energy dependent parameters: Elongation rate changes

$$\frac{dX_{\max}(E)}{d\ln E} = \lambda_{\rm rad} \left[1 - \frac{dm(E)}{d\ln E} - \frac{d\ln f(E)}{d\ln E} \left(\frac{1 - f(E)\,(1+k)}{1 - f(E)}\right)\right]$$

$$+ k\,\frac{d\Lambda(E)}{d\ln E}$$

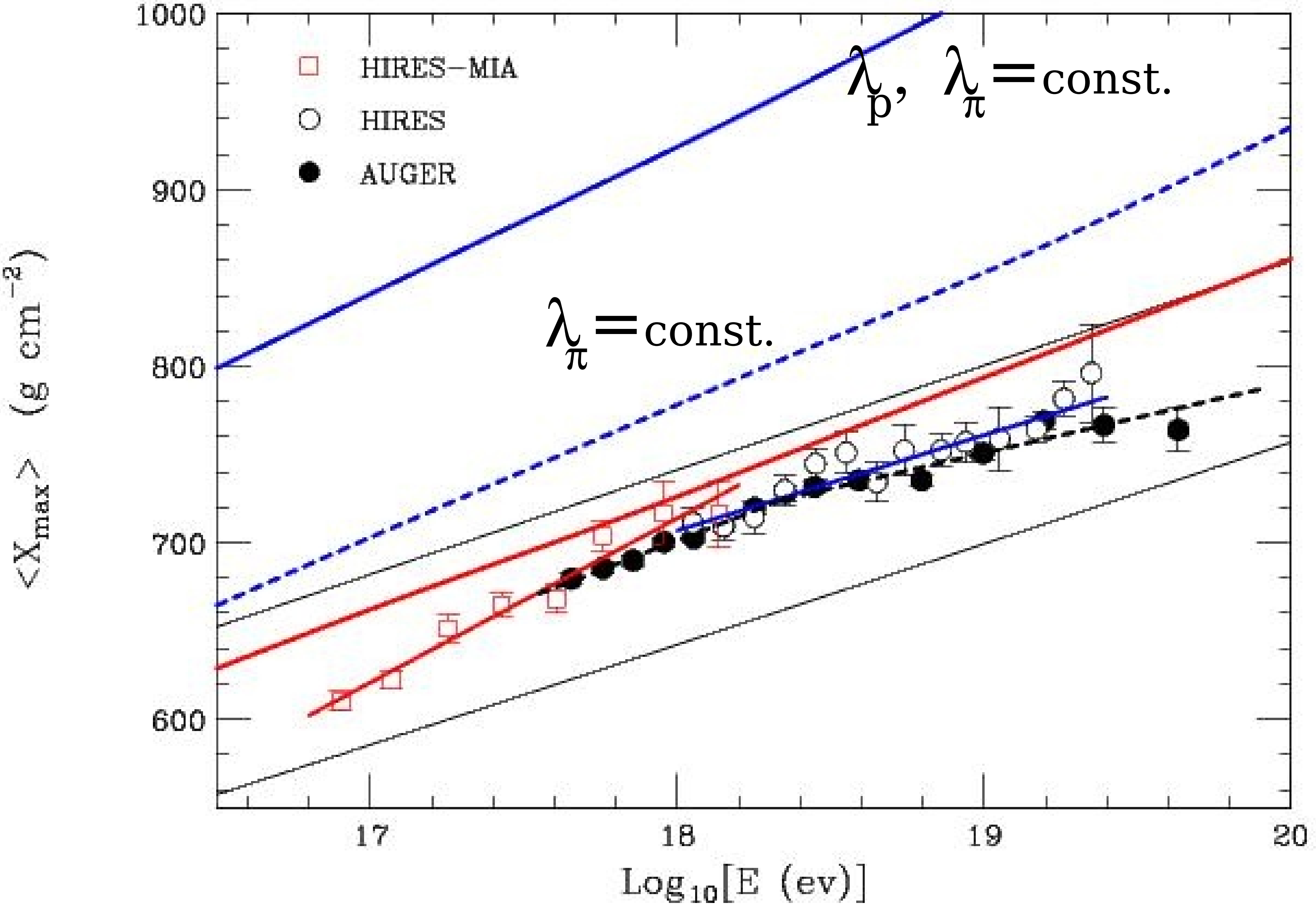


Elongation Rate
For protons



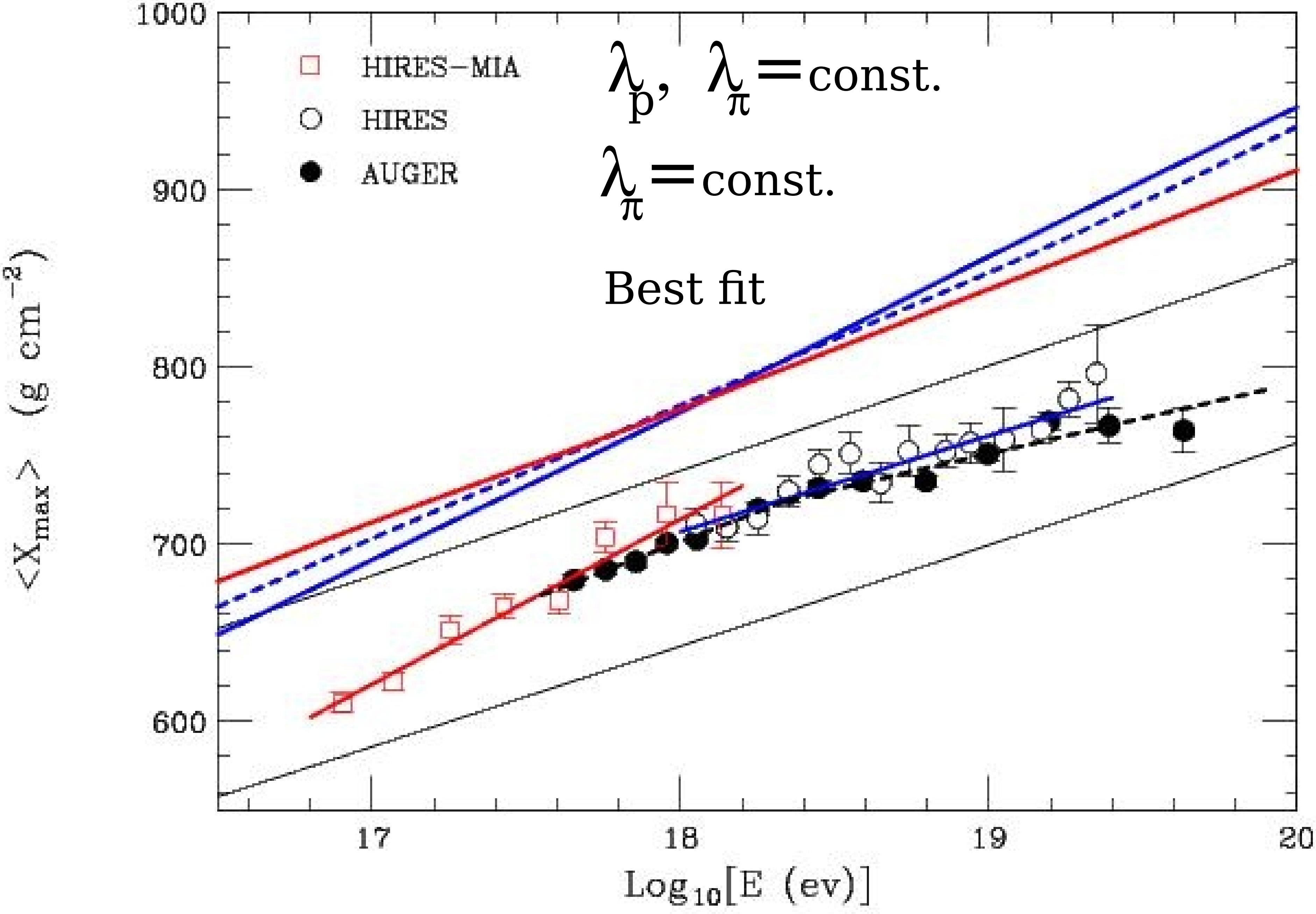
π
p
80
60
40
20
10^{14}
10^{16}
10^{18}
10^{20}
$\lambda_{int}(p/\pi\ Air)$ [g cm^{-2}]
E_p (eV)

Exactly Scaling Interactions

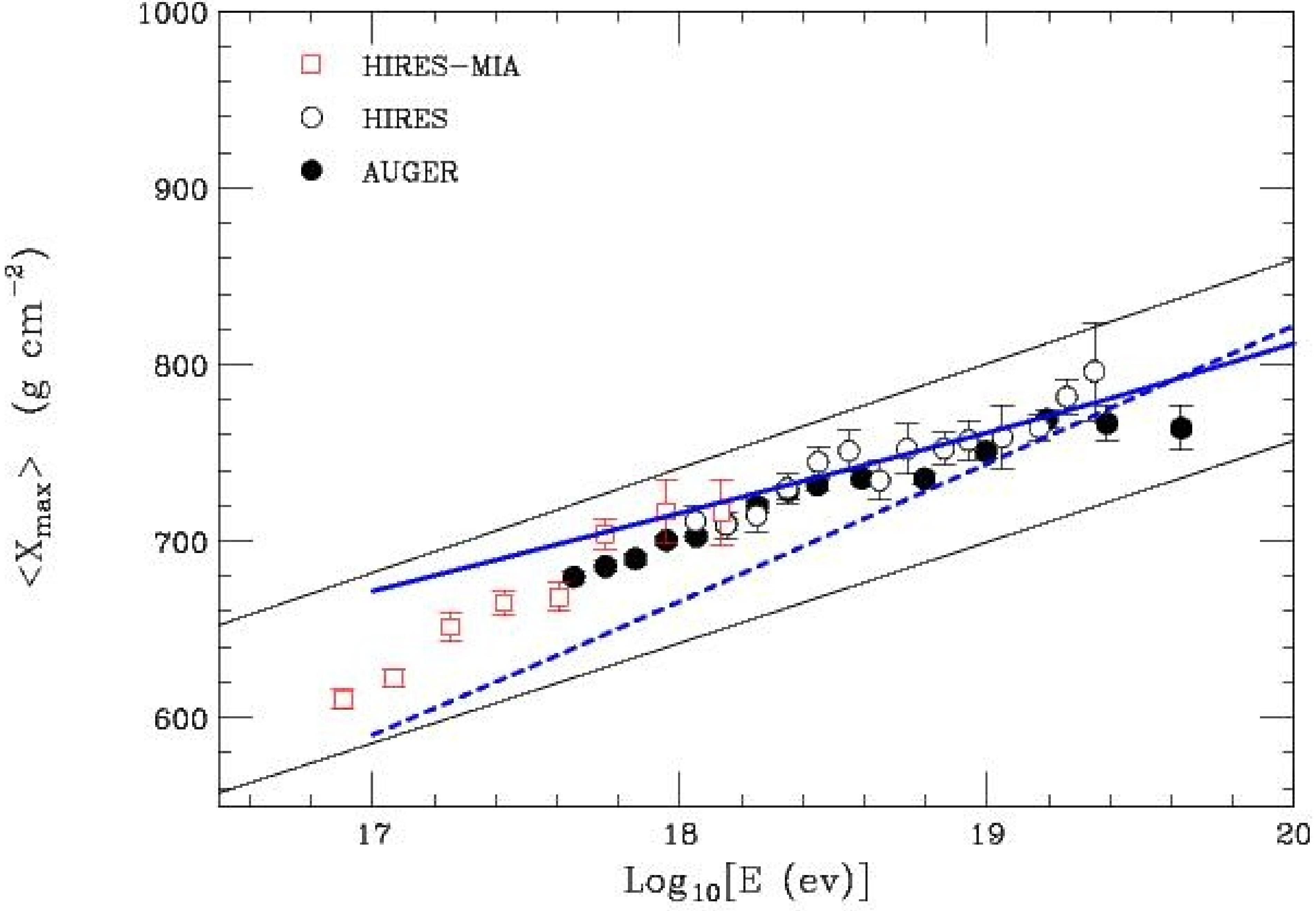


Exactly scaling models

Different elongation ra



Introduce Energy dependent softening of the spectra



- It is possible to "reproduce"
  A "desired" composition with
  (in this example) an appropriate gradual softening
  of secondary meson spectra.

- Possible also to introduce
  A faster rise of the cross section

- Ambiguities !
  May possibilities....
  How can we distinguish among them ?

Predictions
for LHC !!?

- It is possible to “reproduce”
  A “desired” composition with
  (in this example) an appropriate gradual softening
  of secondary meson spectra.

- Possible also to introduce
  A faster rise of the cross section

- Ambiguities !
  May possibilities….
  How can we distinguish among them ?

WARNING !!

Perhaps : this approach is completely incorrect
the mass composition is indeed mixed ….
We have to rely on [accelerator data + theory]

Fluctuations on X_{max}

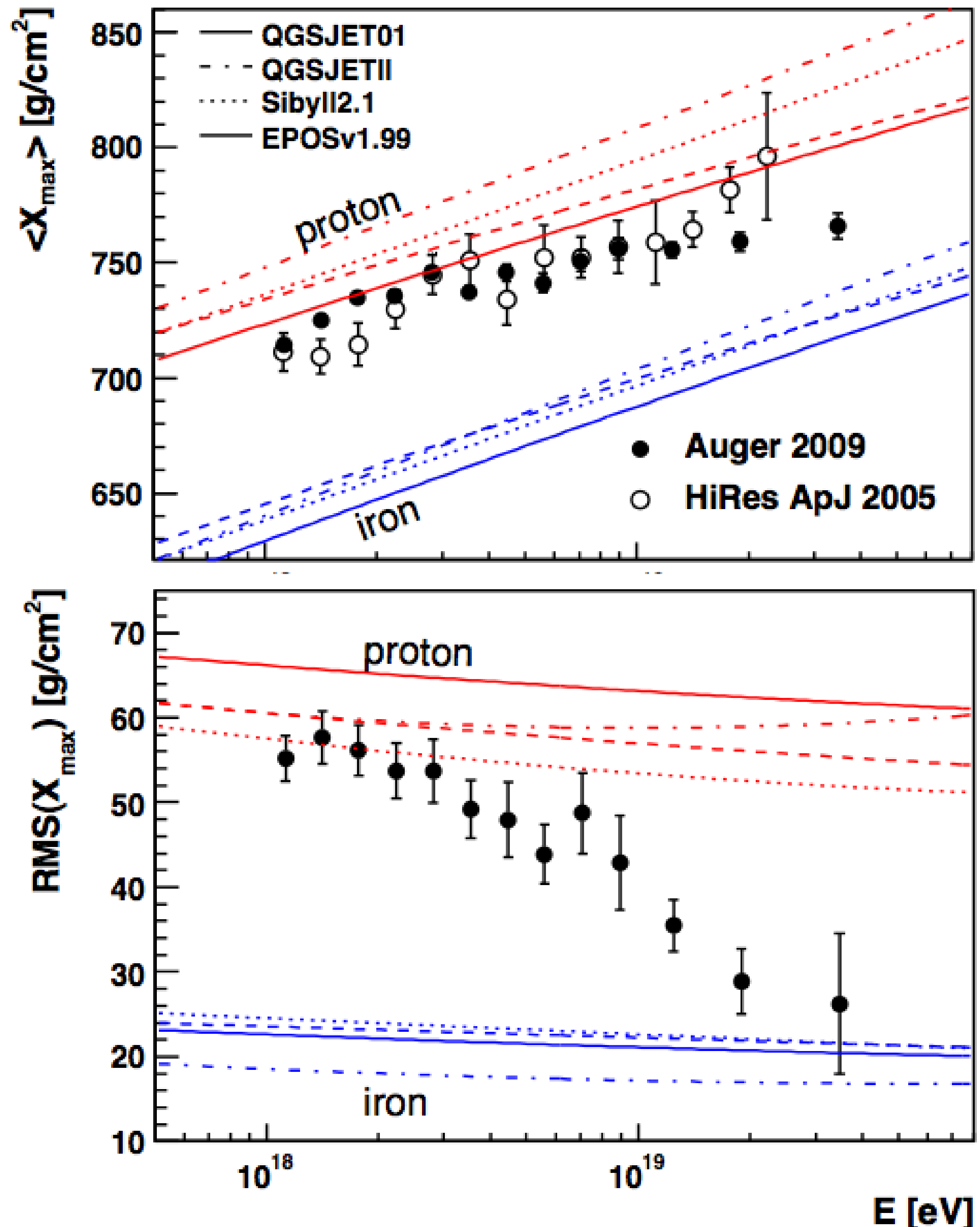
Very Interesting an puzzling piece of information !

Not confirmed by HIRES

Potentially very important

FD Results

- $\langle X_{\max} \rangle$ and RMS vs E
- resolution correction
- broken line fit:
  slopes D [g/cm^2/decade]
- comparison to air shower simulations
- published HiRes data (update cf. Pierre's talk)



Comparison of data and p-QGSJET02 fluctuation widths
Use 2-sigma truncated gaussian width to fit Xmax distr.
Detector resolution is NOT deconvoluted!

HIRES
P.Sokolski

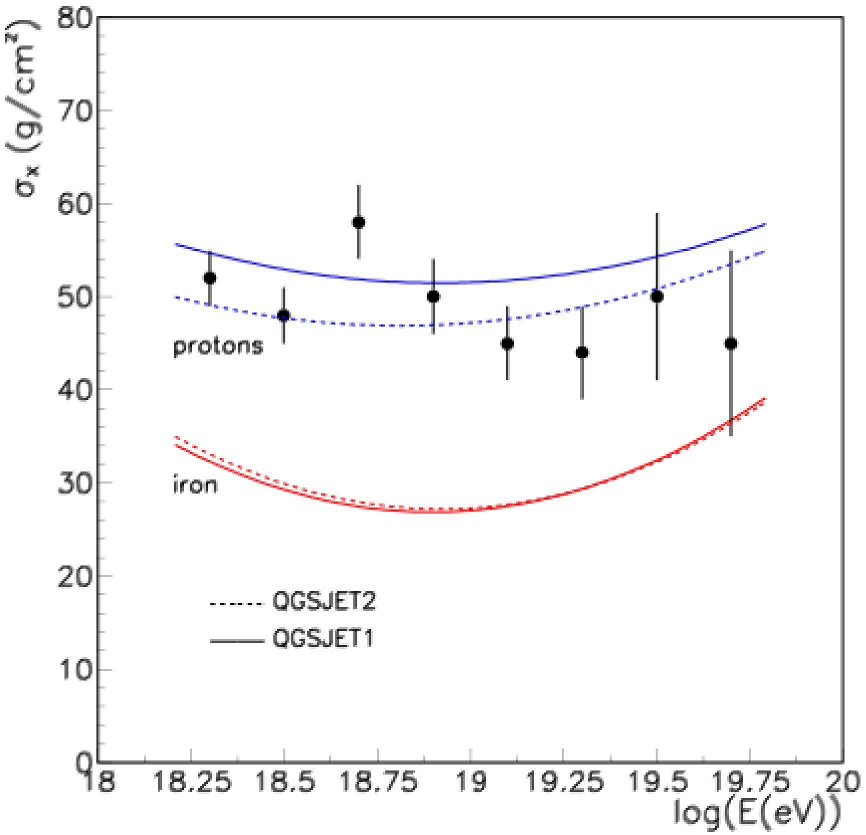


Fig. 28.— Results of fitting HiRes stereo data X_{max} distribution to Gaussian truncated at 2 × RMS (black points). Superimposed are curves representing expectations based on QGSJET1 and QGSJET2 proton and iron Monte Carlo. Gaussian-in-age parametrization used in reconstruction.

Overall comparison of Xmax data with QGSJET02 p and FE

HIRES

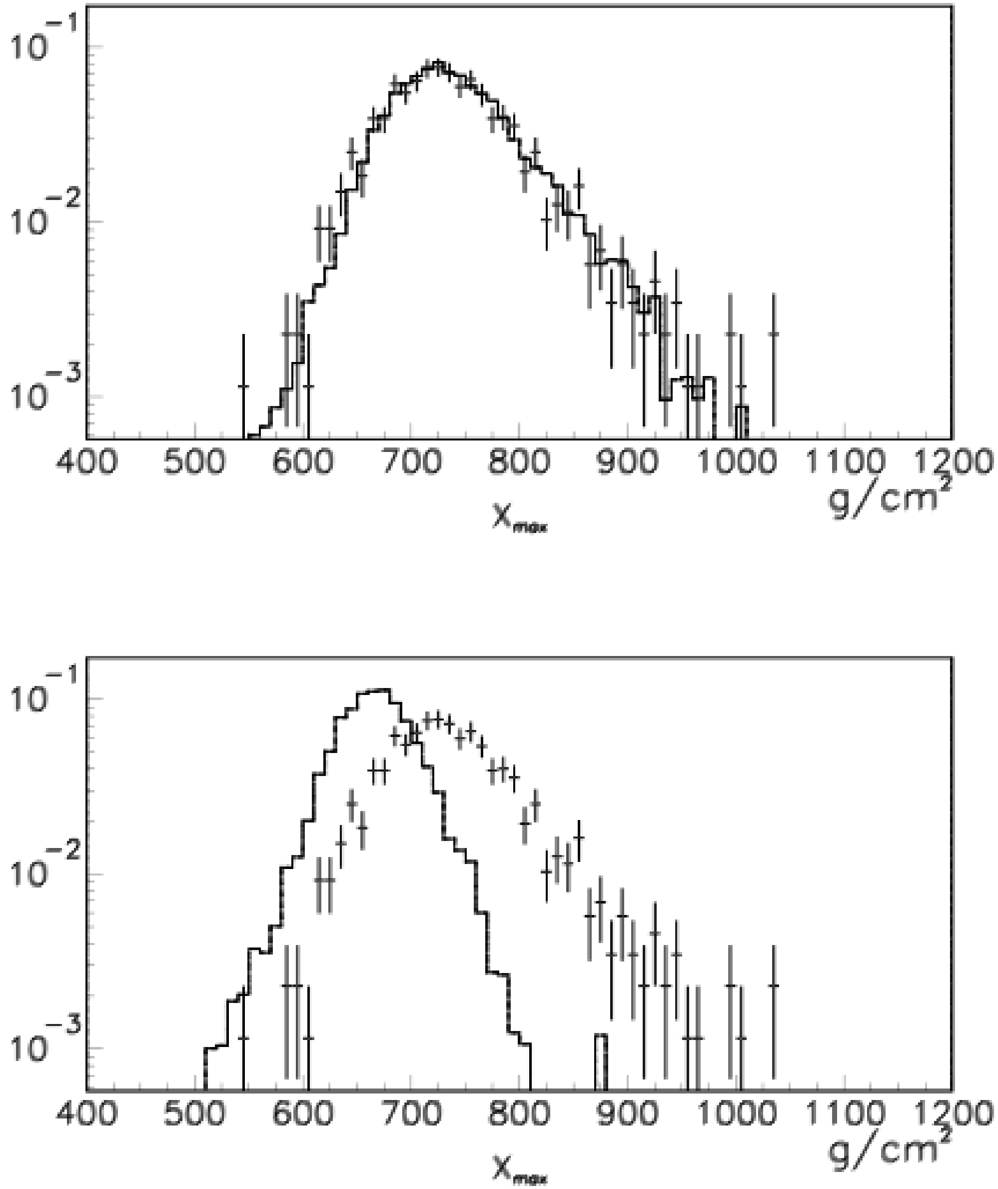


Fig. 11.— *Top:* X_{max} overlay of HiRes data (points) with QGSJET02 proton Monte Carlo airshowers after full detector simulation. *Bottom:* X_{max} overlay of HiRes data (points) with QGSJET02 iron Monte Carlo airshowers after full detector simulation.

Overall comparison of Xmax data with QGSJET02 p and FE

HIRES

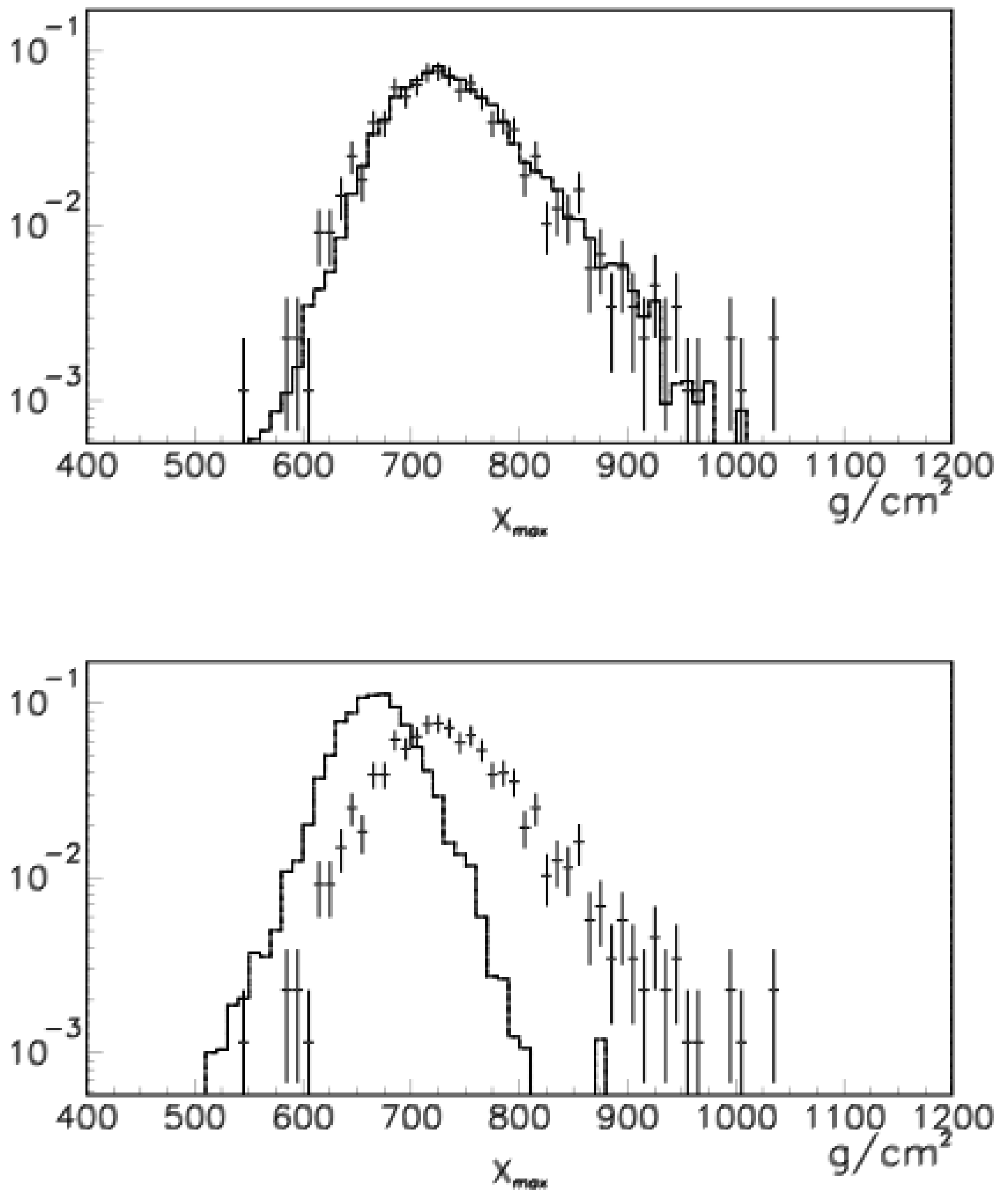


Fig. 11.— *Top:* X_{max} overlay of HiRes data (points) with QGSJET02 proton Monte Carlo airshowers after full detector simulation. *Bottom:* X_{max} overlay of HiRes data (points) with QGSJET02 iron Monte Carlo airshowers after full detector simulation.

AUGER
People
Keeping this
distribution
for themselves
At the moment.

Good work
to you !

RMS [Xmax] decreasing with energy !

Need robust confirmation.

What does it imply ?

- Composition getting heavier !
- Proton shower fluctuations becoming smaller.

Much larger cross sections
(shorter interaction length)

Particle production properties.
(seems unlikely to me....) [but ....]

THEORY

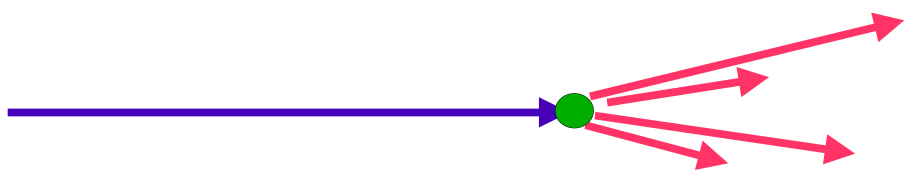
Construction of Hadronic Models

HADRONIC INTERACTIONS

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

Leading nucleon
~ 50% of energy

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



Decay

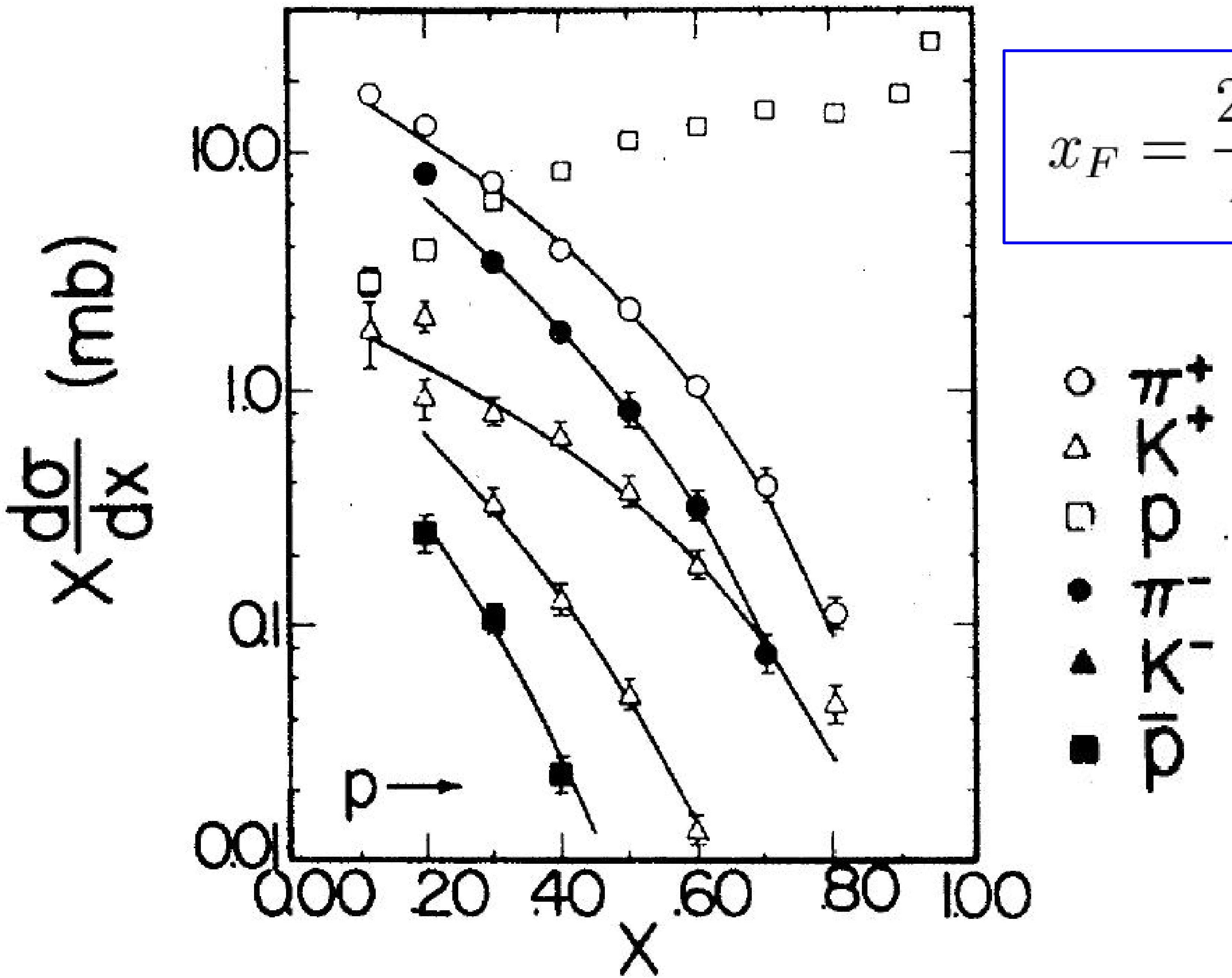
$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$
$$\downarrow$$
$$e^{+} + \nu_{e} + \overline{\nu}_{\mu}$$

Interaction

Inclusive spectra
of secondary particles

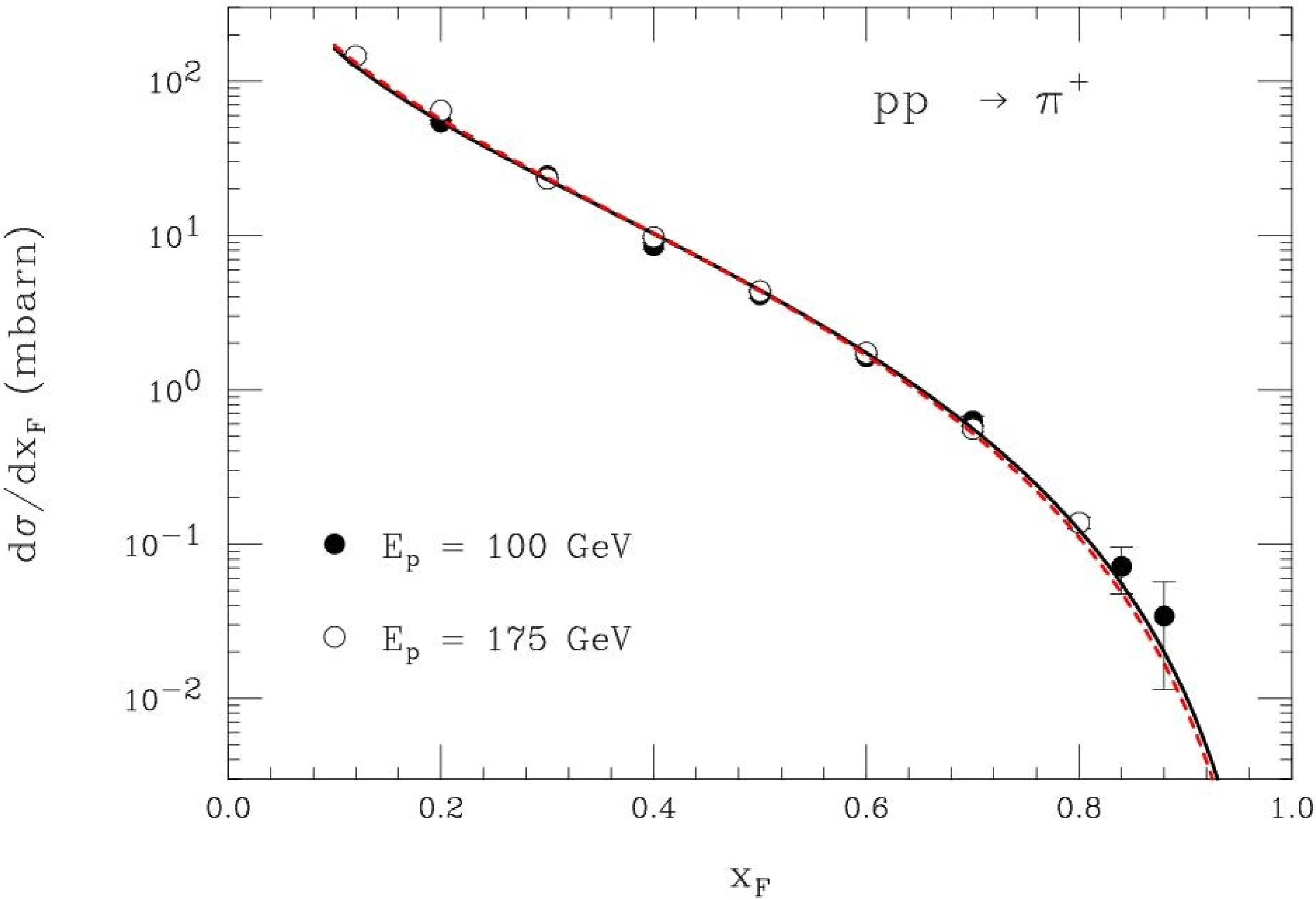
E_{beam} = 175 GeV

FERMILAB SAS pp
Brenner et al (1982)

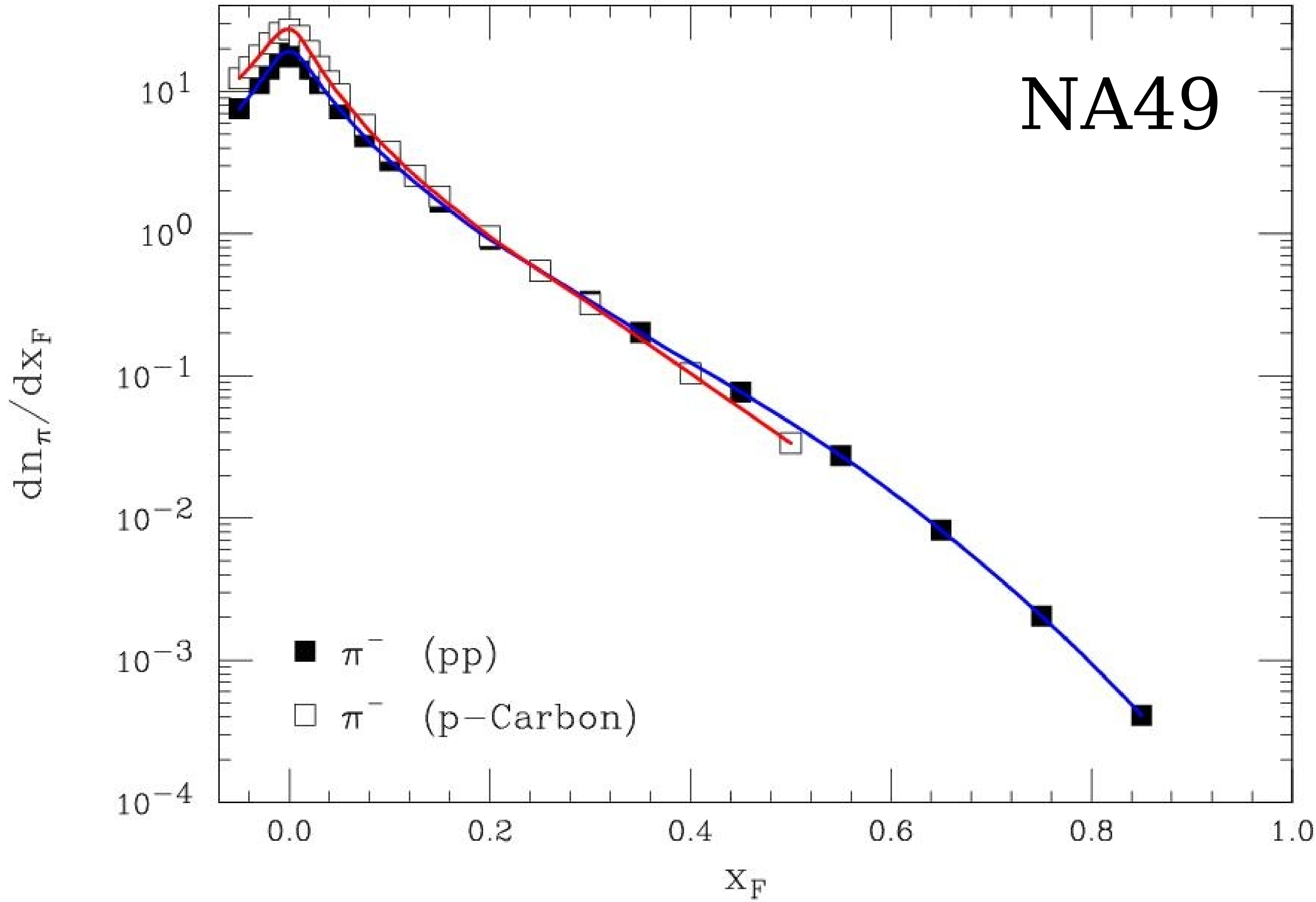


$$x_F = \frac{2\,p_z^*}{\sqrt{s}}$$

Phenomenological Evidence for FEYNMAN SCALING



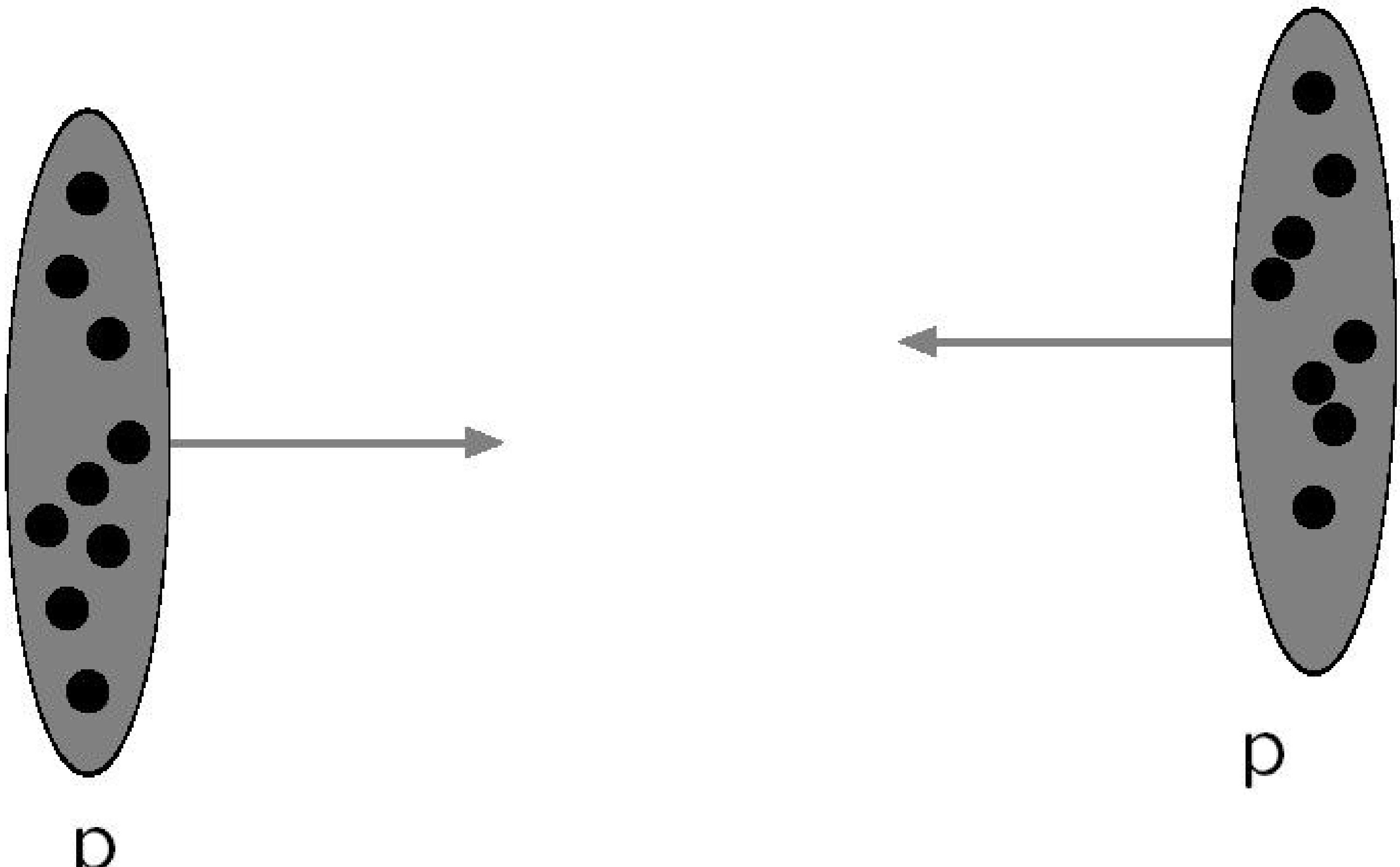
NUCLEAR effects: pp vs p-^{12}C



Hadronic Interactions

Composite (complex) Objects
Multiple interaction structure

QCD



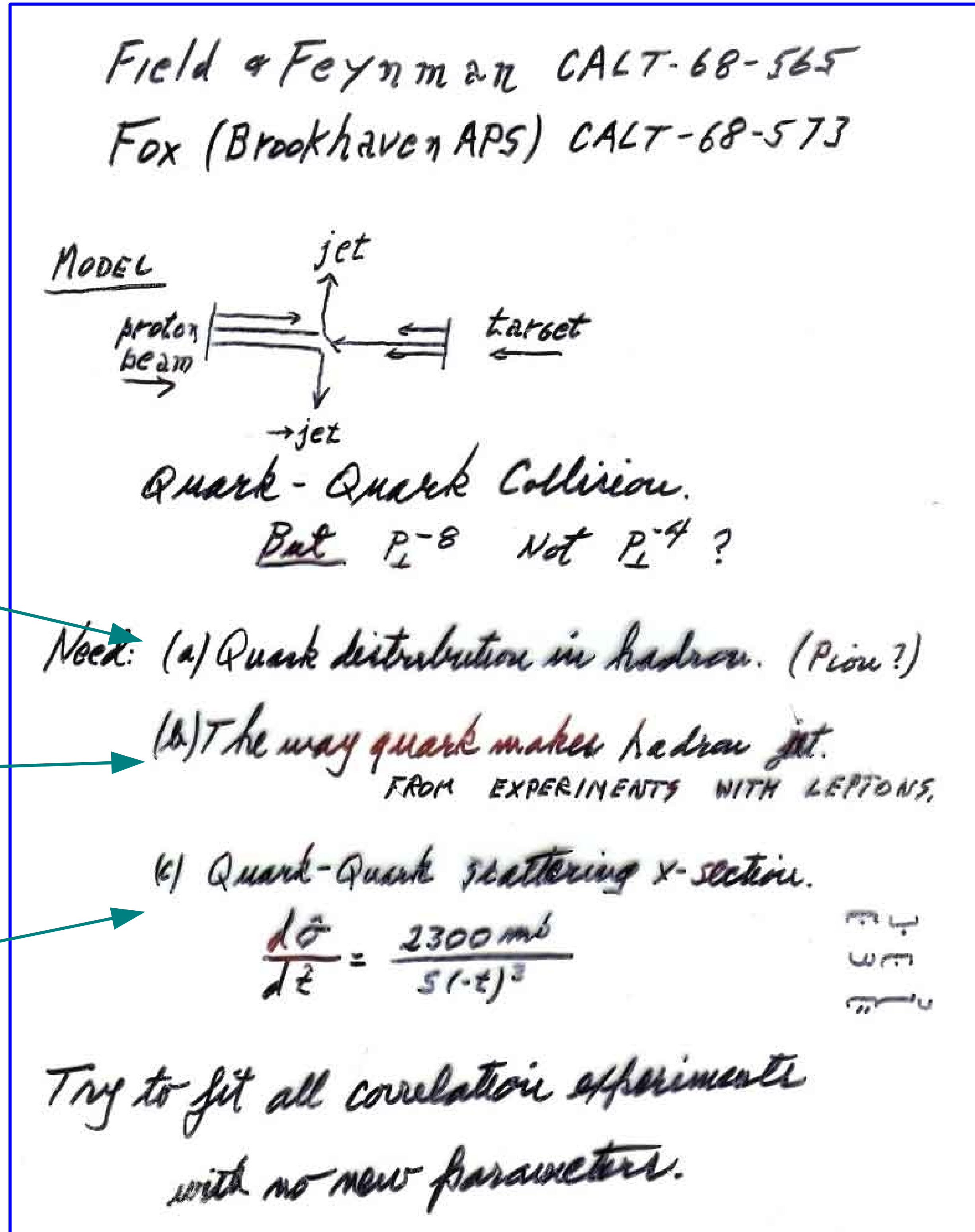
1st Slide
from R.Feynman
seminar in 1976.

ISR high pT
Pion production

Deep Inelastic
Scattering

Develop quark
fragmentation Model
from e+ e- Scattering

Data consistent
with QCD



From R.Field

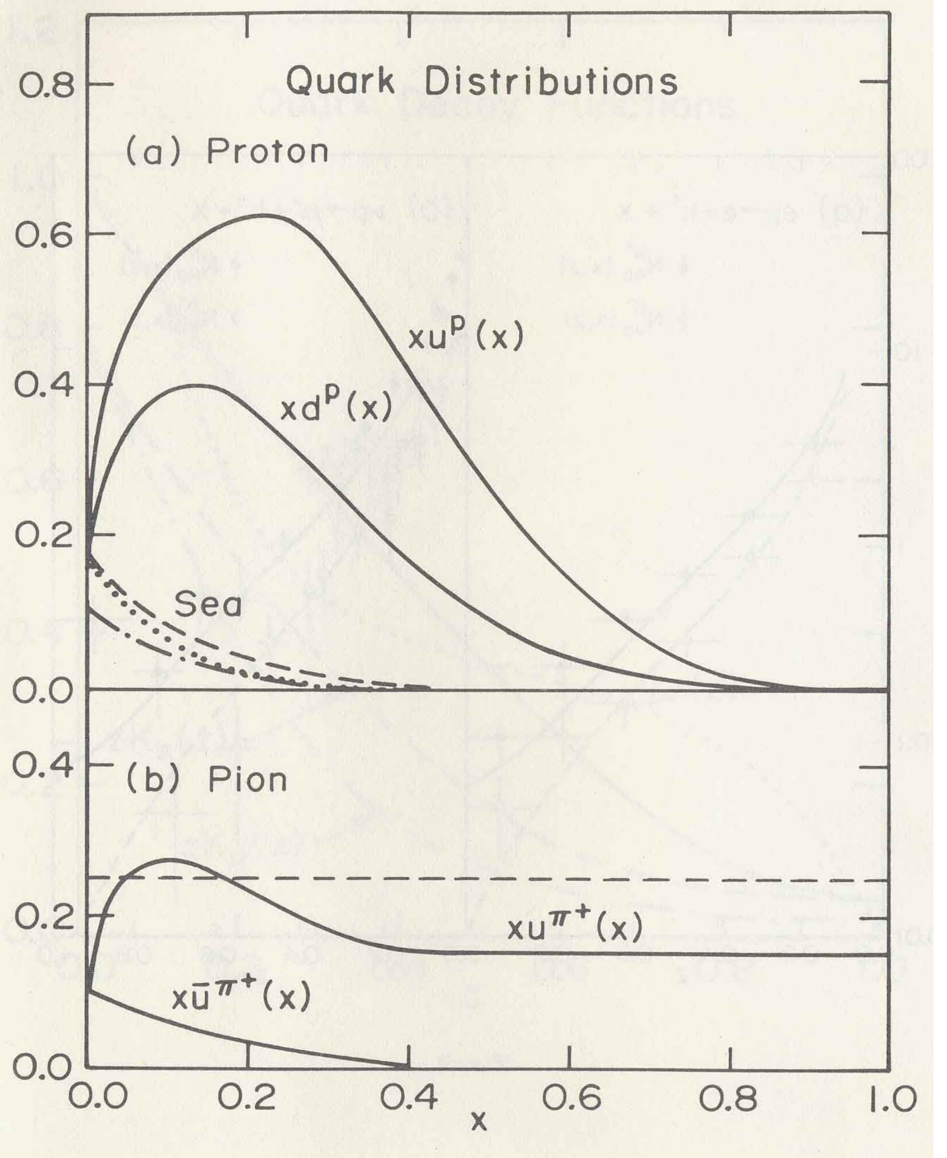


Fig. 4

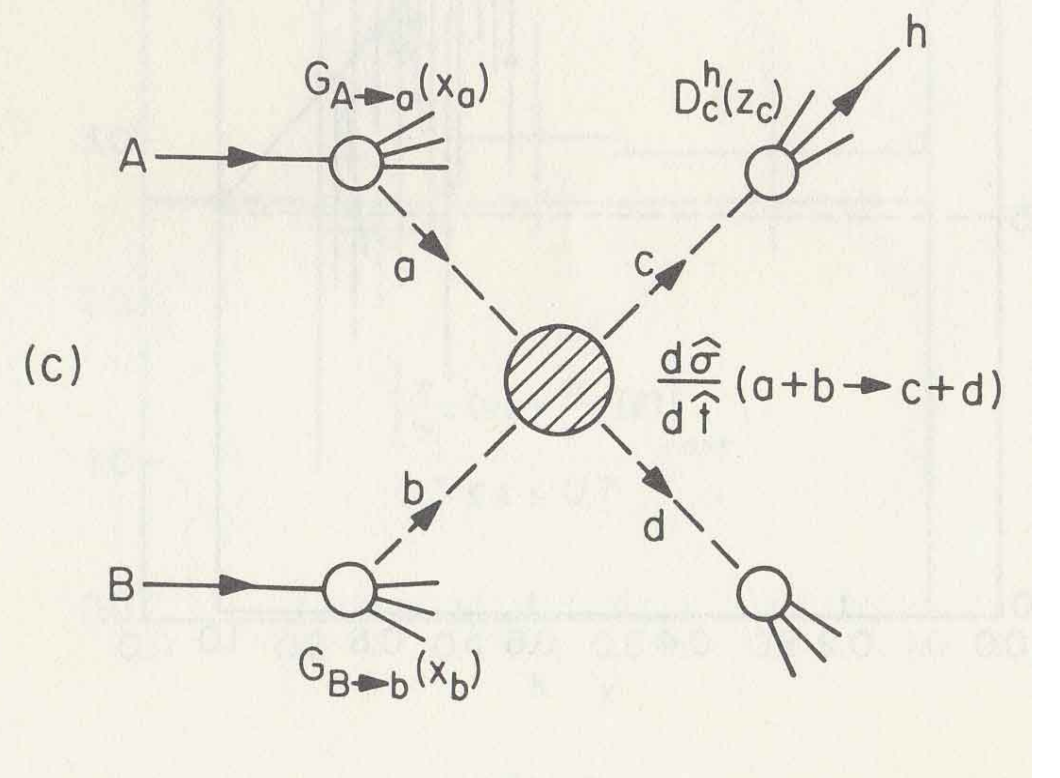
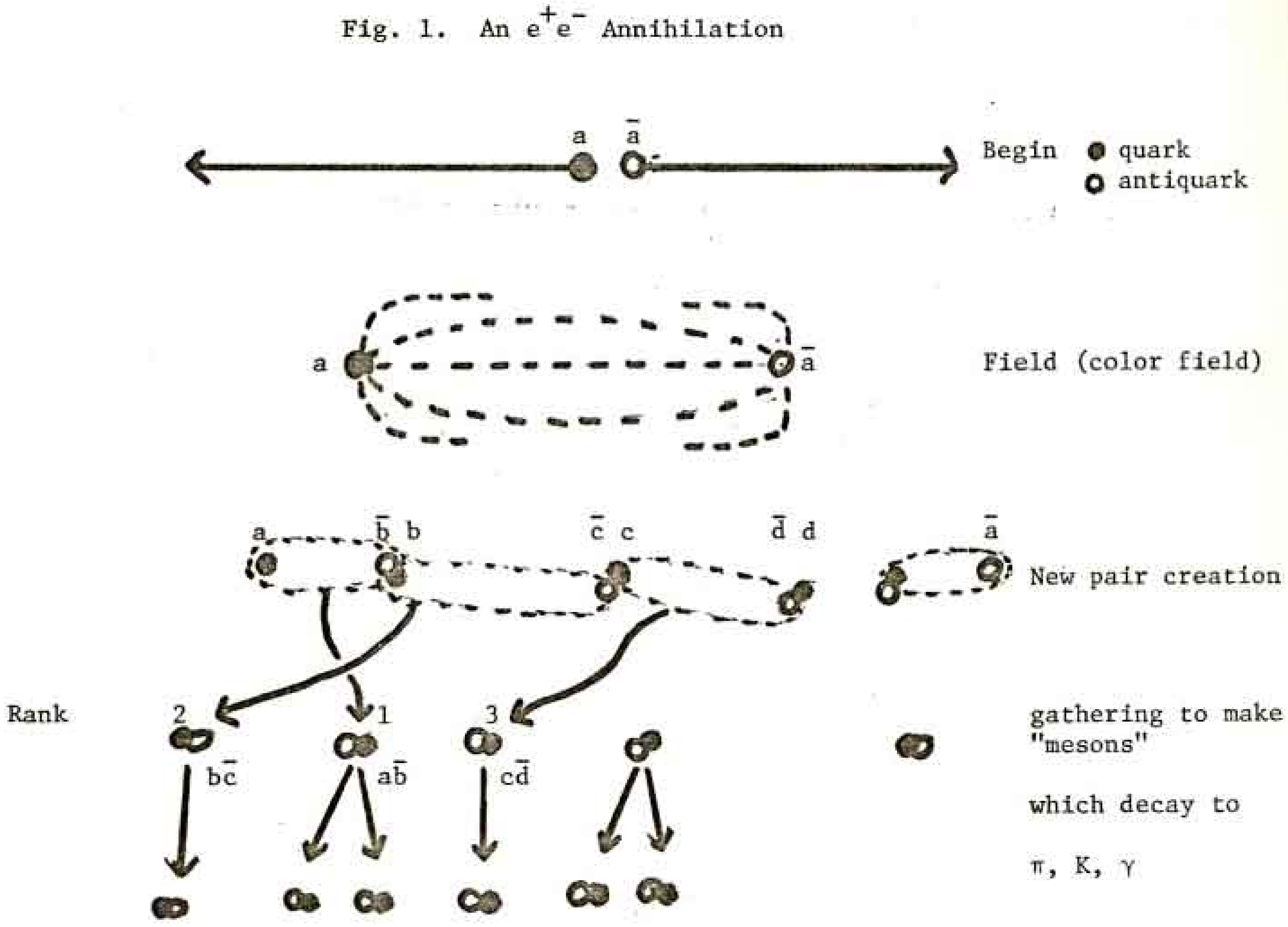


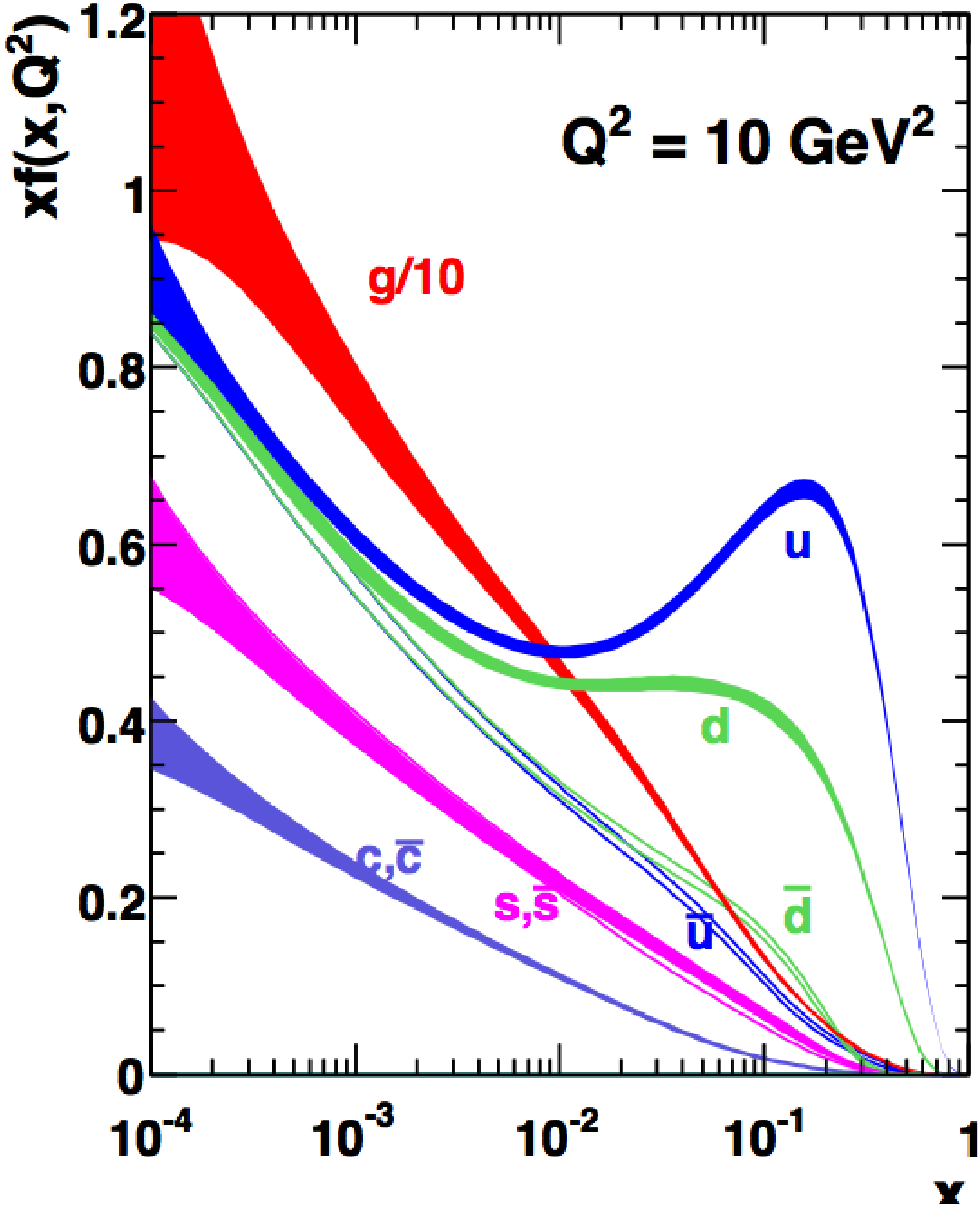
Fig. 1

HARD scattering

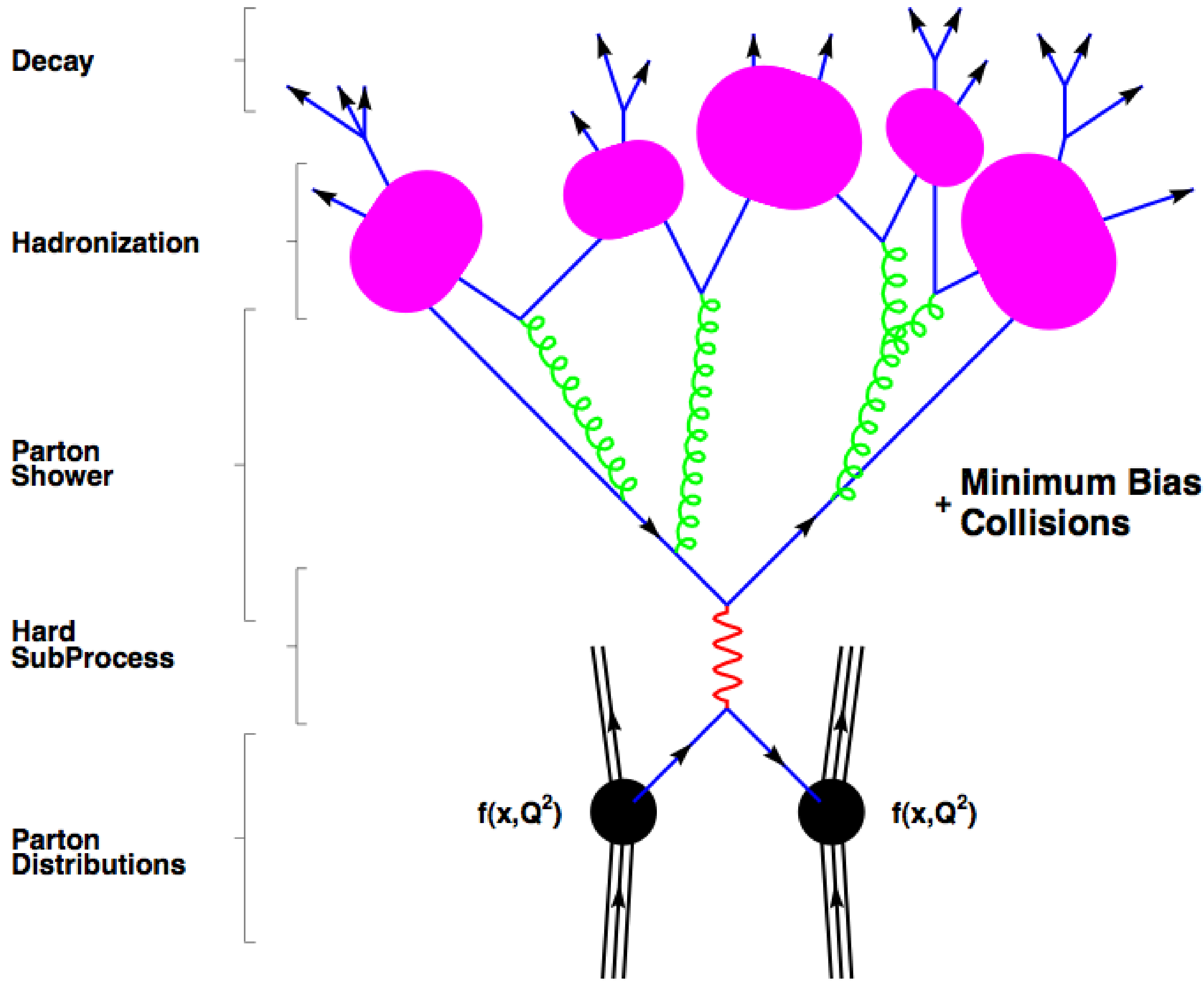
Parton Distribution Functions



Field -Feynman : Quark - Fragmentation



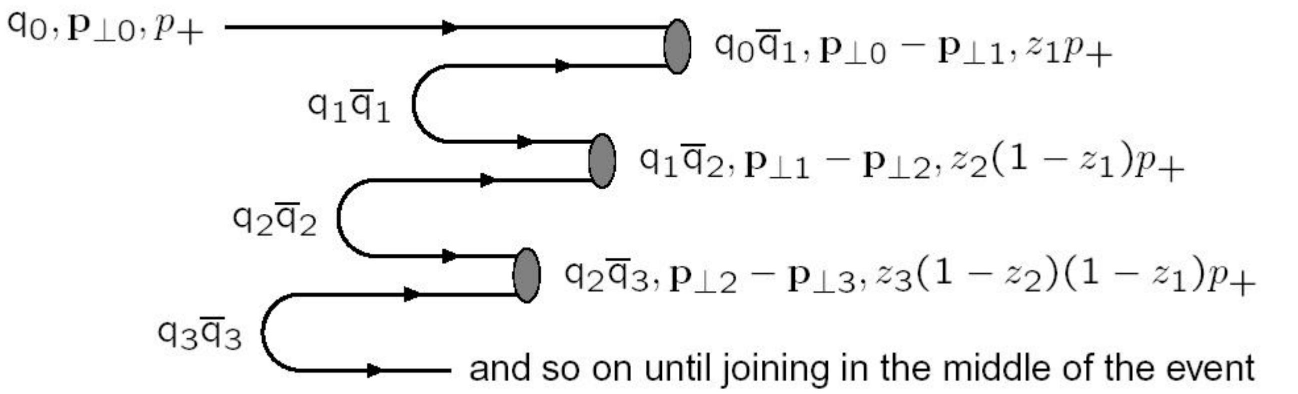
Parton Distribution Function

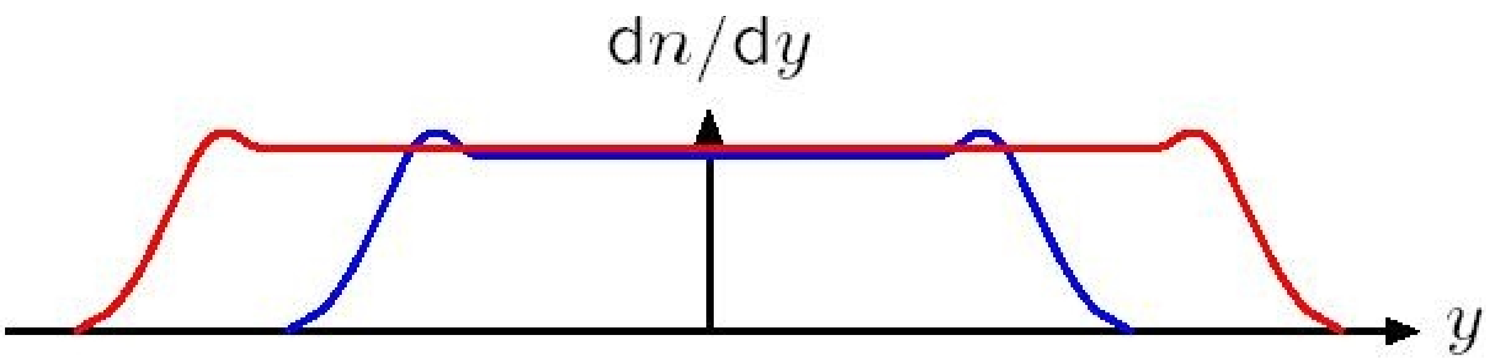


Decay
Hadronization
Parton
Shower
Hard
SubProcess
Parton
Distributions
+ Minimum Bias
Collisions
f(x,Q²)
f(x,Q²)

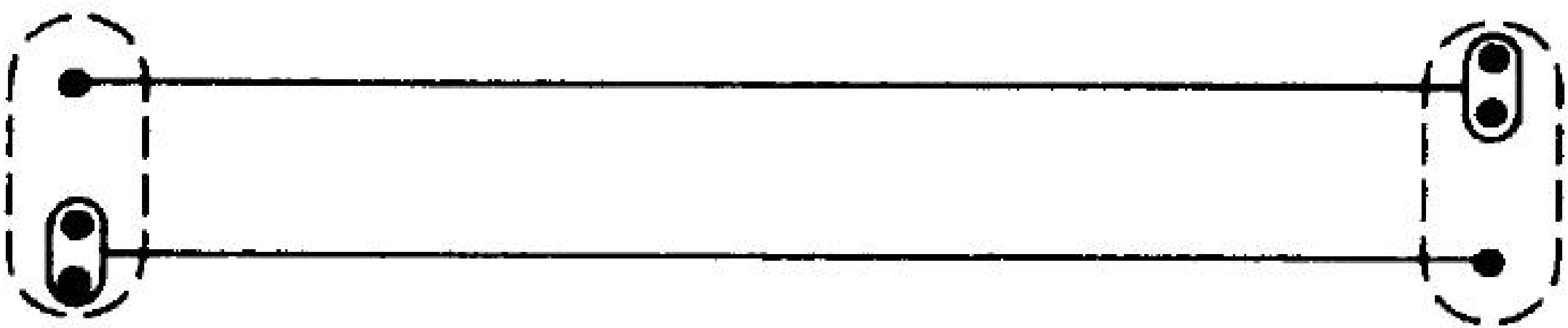
Where does the approximate Feynman scaling comes from ?

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





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



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

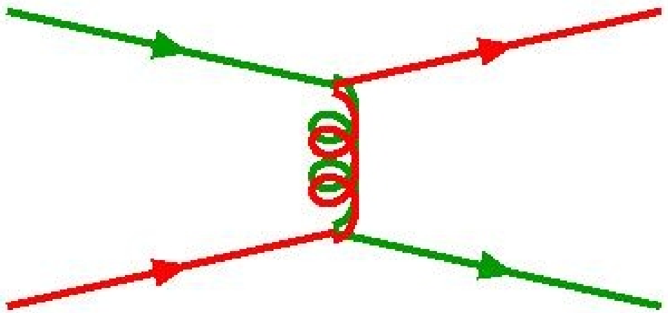
hard/semihard interactions
result in additional strings

Color Structure

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

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

QCD $2 \to 2$



$qq' \to qq'$

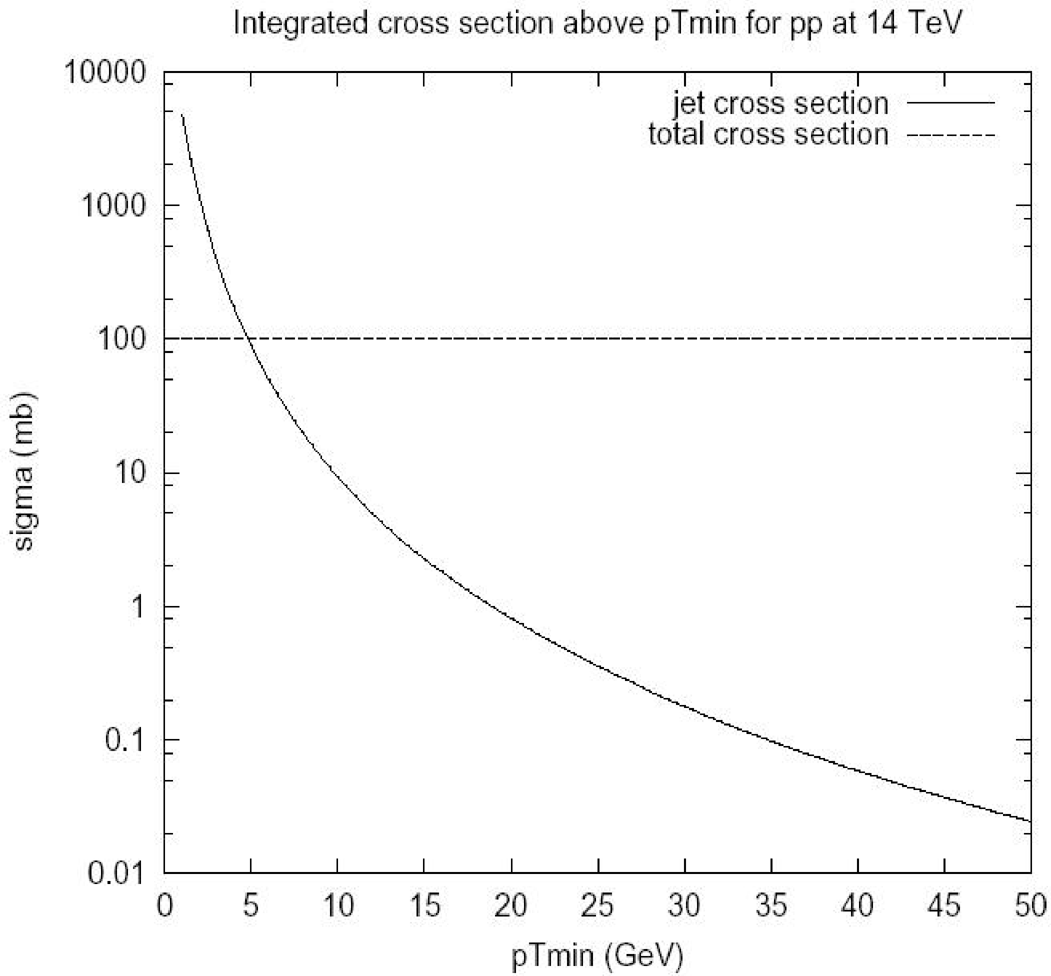
$q\overline{q} \to q'\overline{q}'$

$q\overline{q} \to gg$

$qg \to qg$

$gg \to gg$

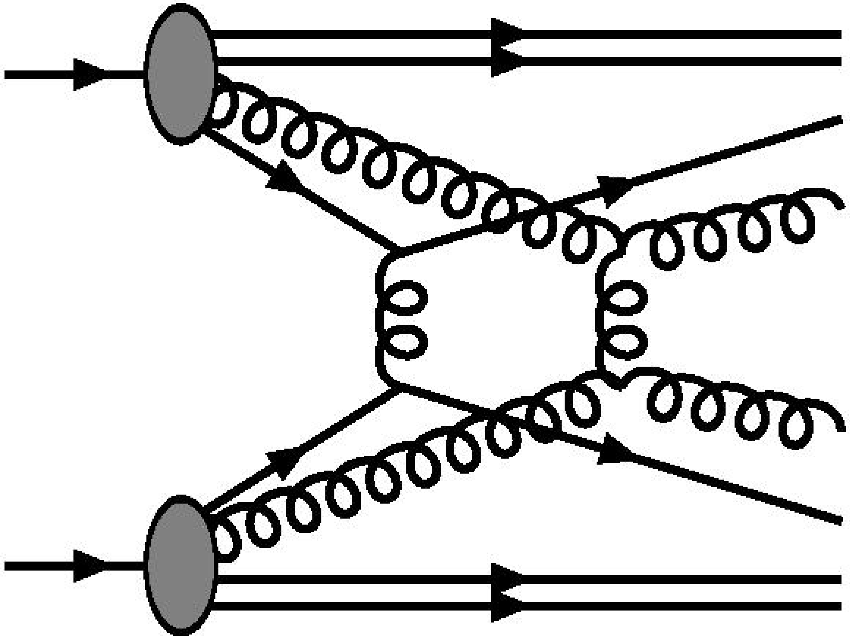
$gg \to q\overline{q}$



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

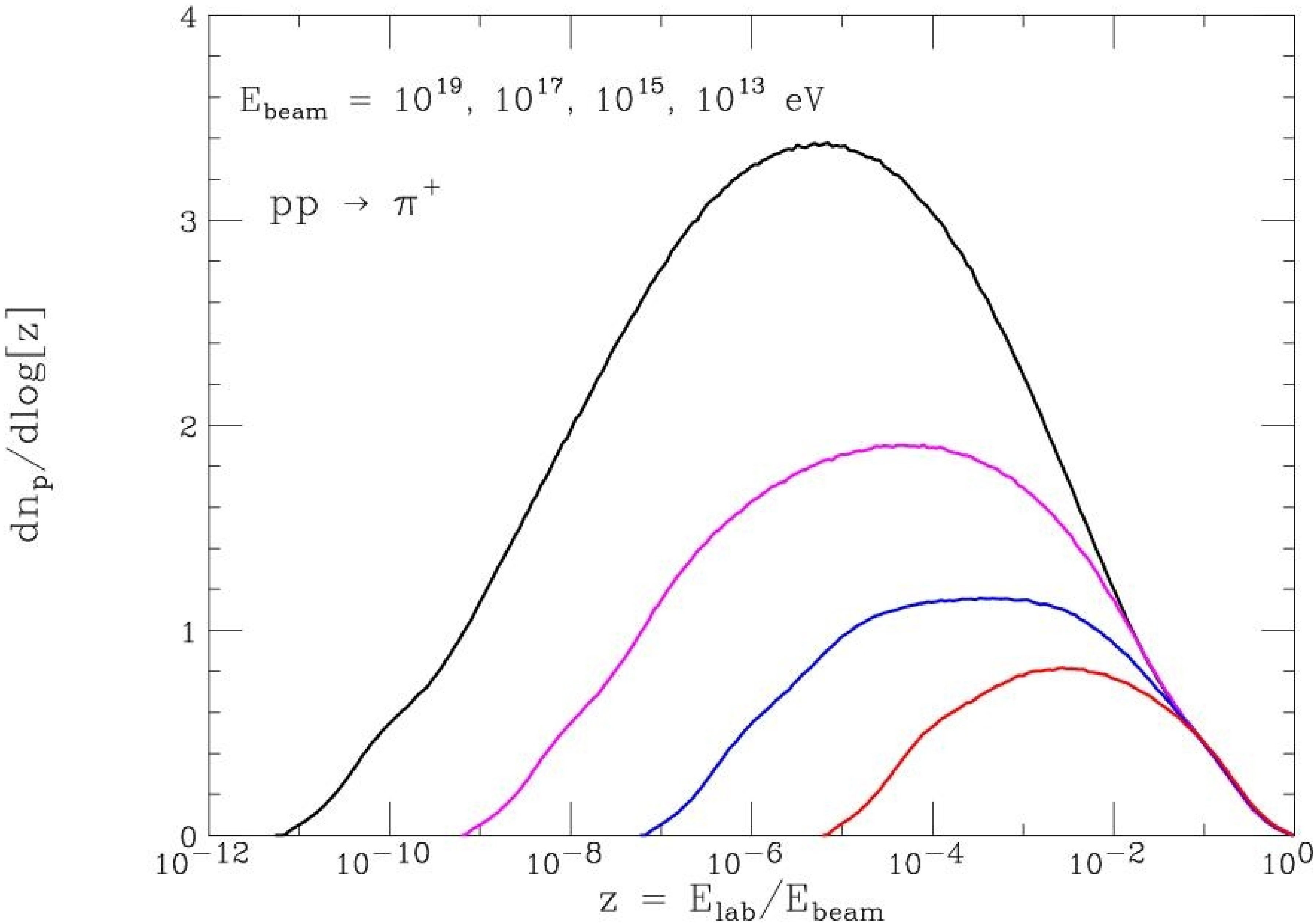
Typically 2 – 3 interactions/event at the Tevatron, 4 – 5 at the LHC, but may be more in “interesting” high-$p_\perp$ ones.

Pythia MC

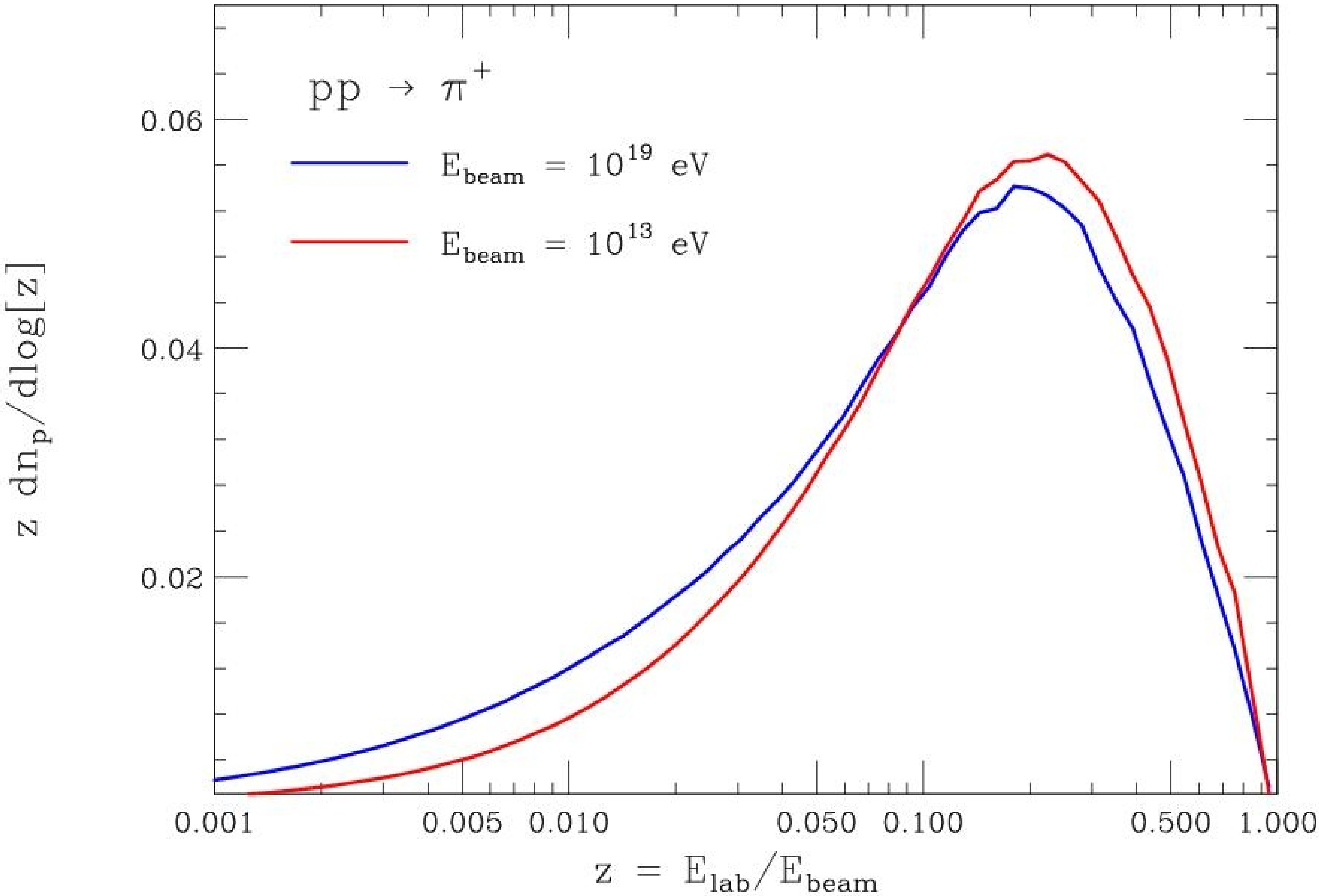


Most particles in Fragmentation Regions Described by the “beam remnants strings”

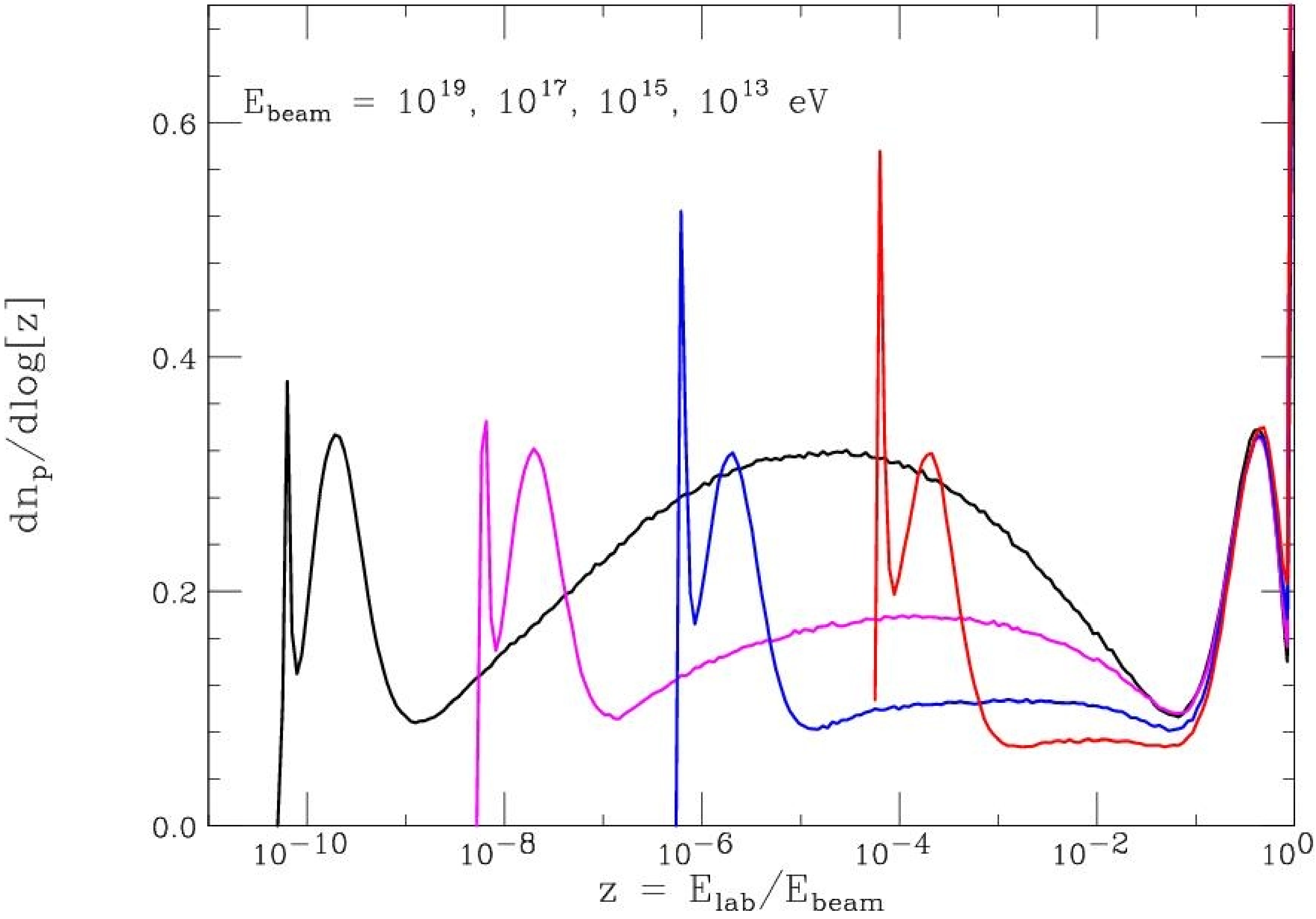
EXTRAPOLATION to HIGH ENERGY (Pythia pp)



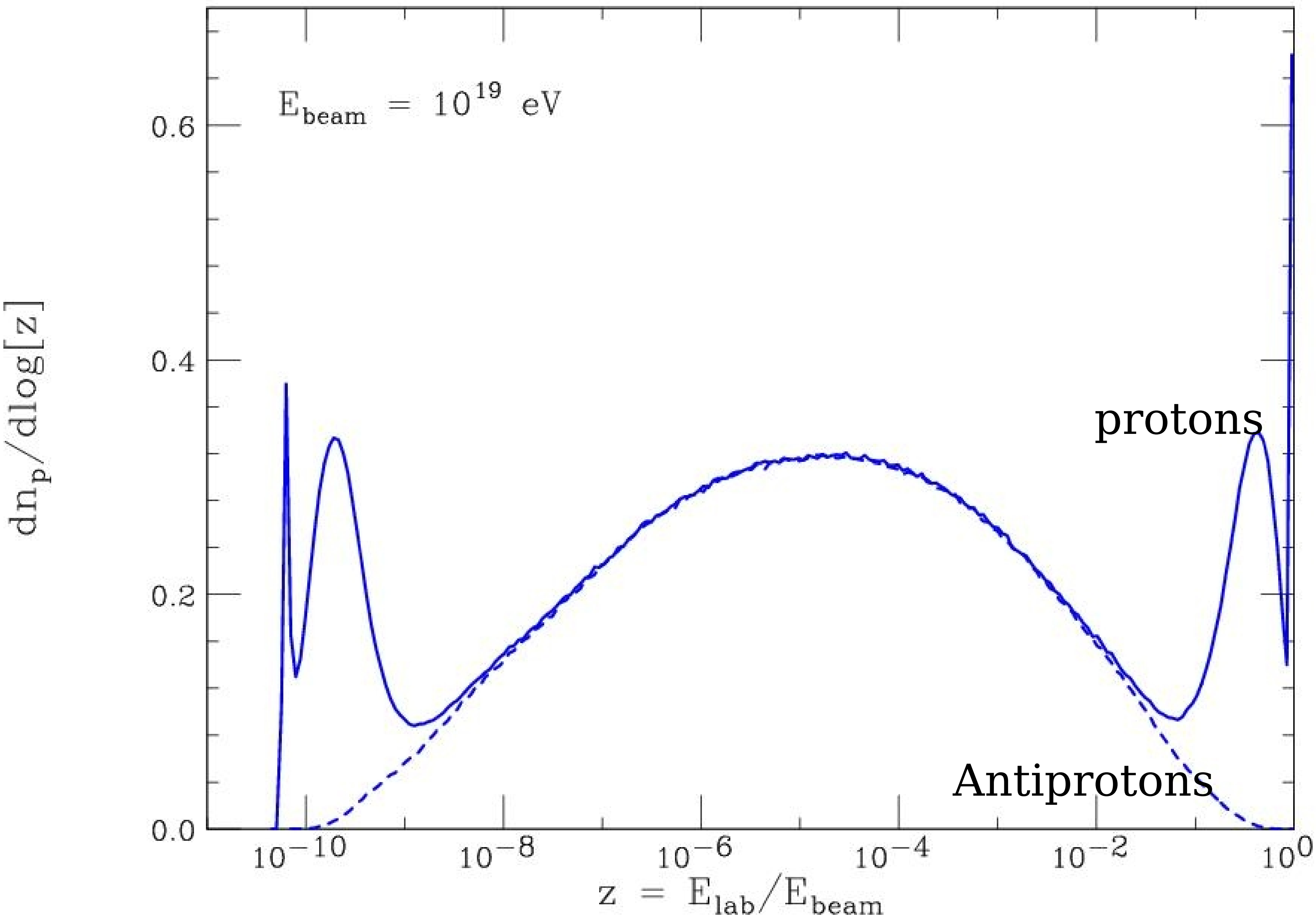
EXTRAPOLATION to HIGH ENERGY (Pythia pp)



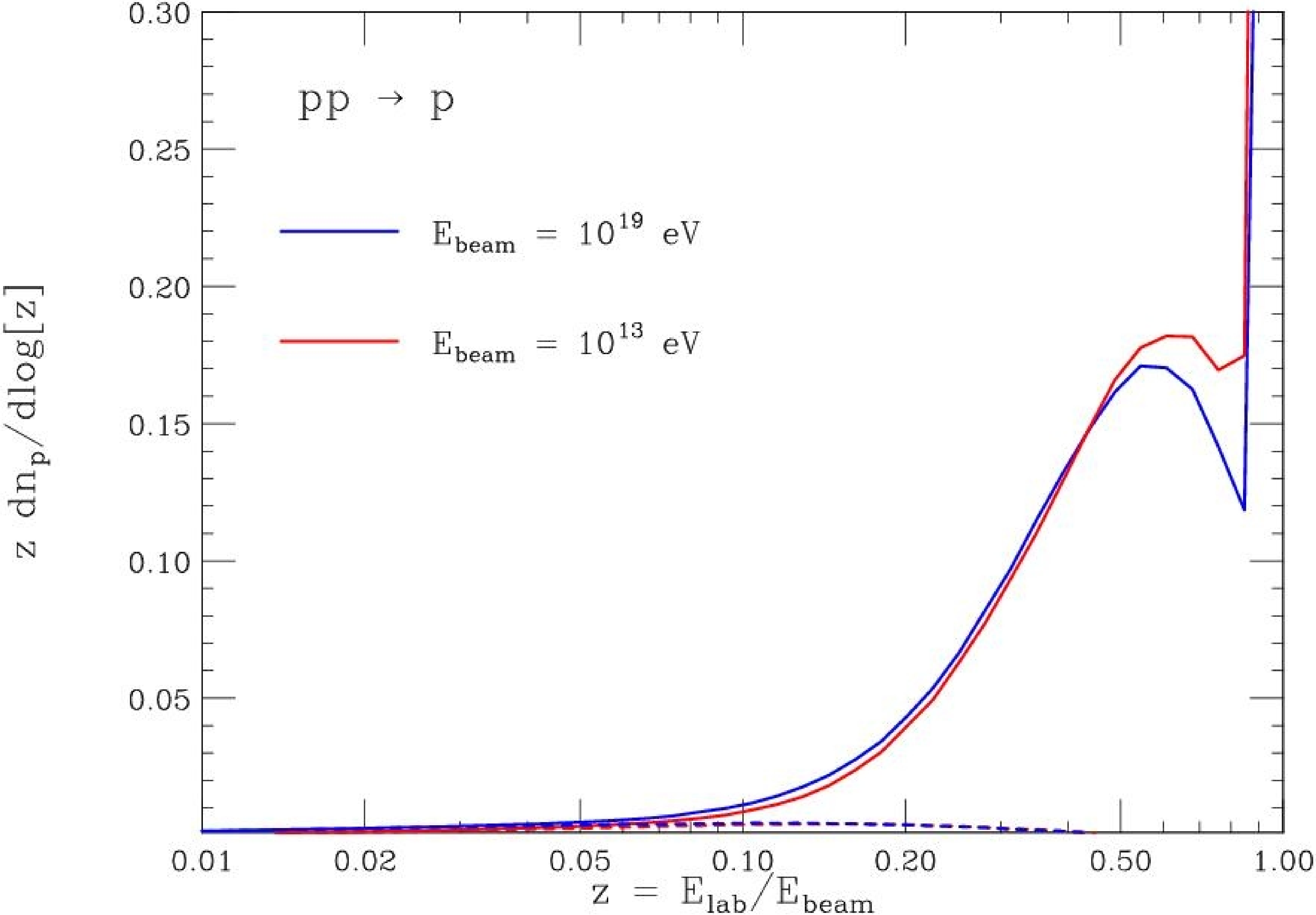
PROTON Spectra (elasticity spectra)



PYTHIA PROTON Spectra



PROTON Spectra (elasticity spectra)



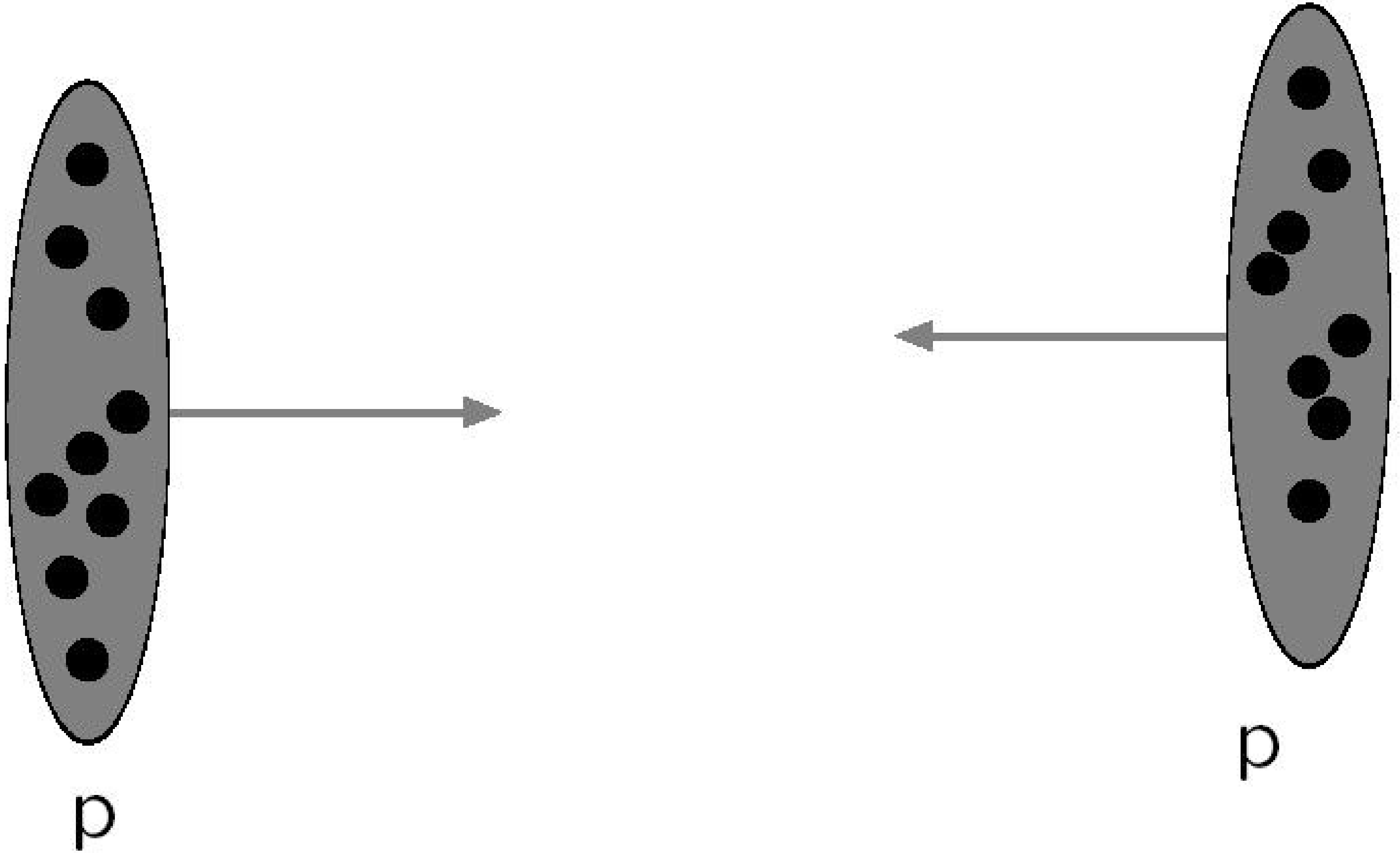
MULTIPLE INTERACTIONS

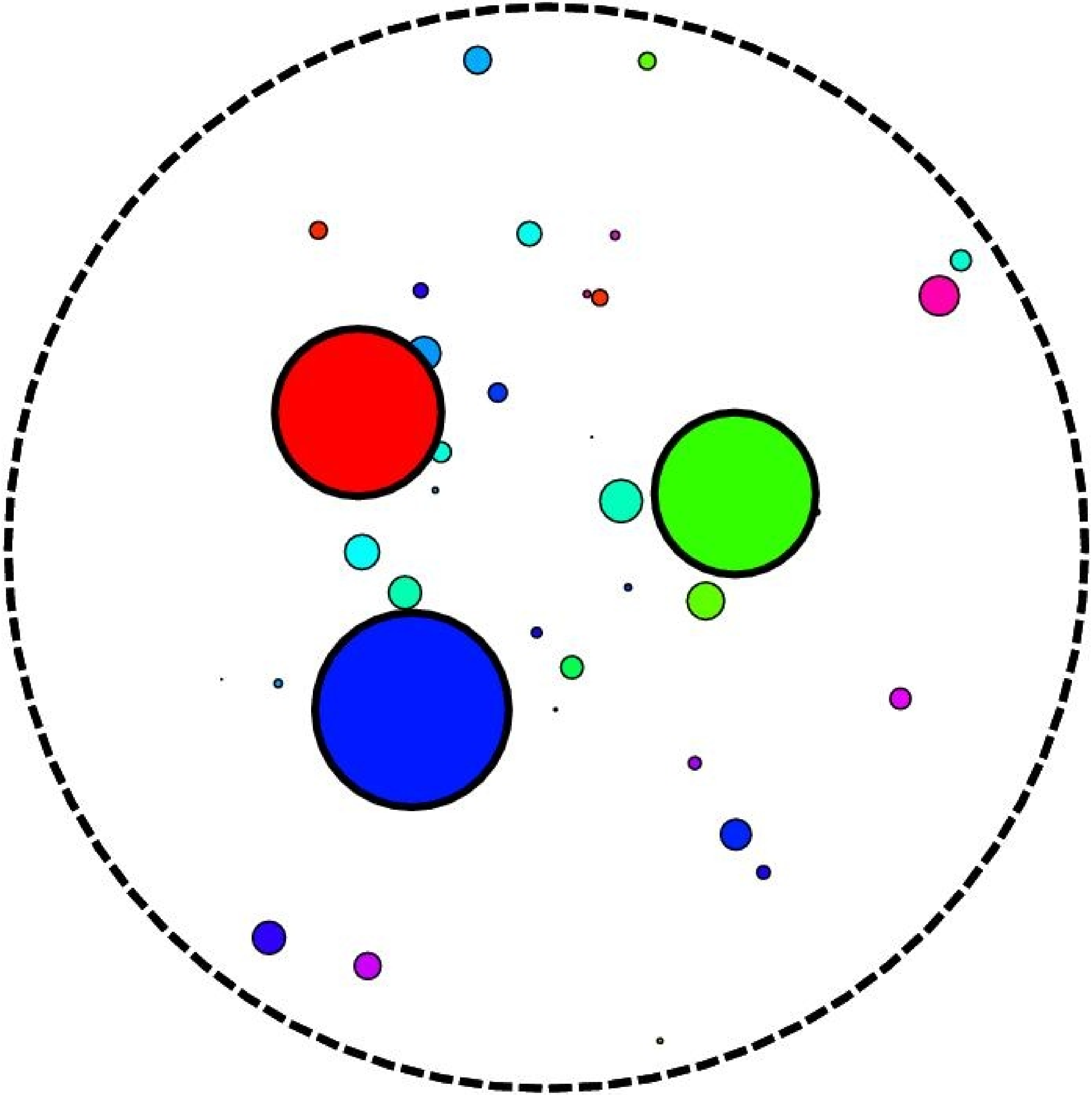
- Estimate of the average number of Elementary interactions per pp scattering
- "Spatial Distribution" (Transverse coordinates) of the partonic constituents. [proton spin]
- Fluctuations of the "parton configuration" of an interactig hadron.

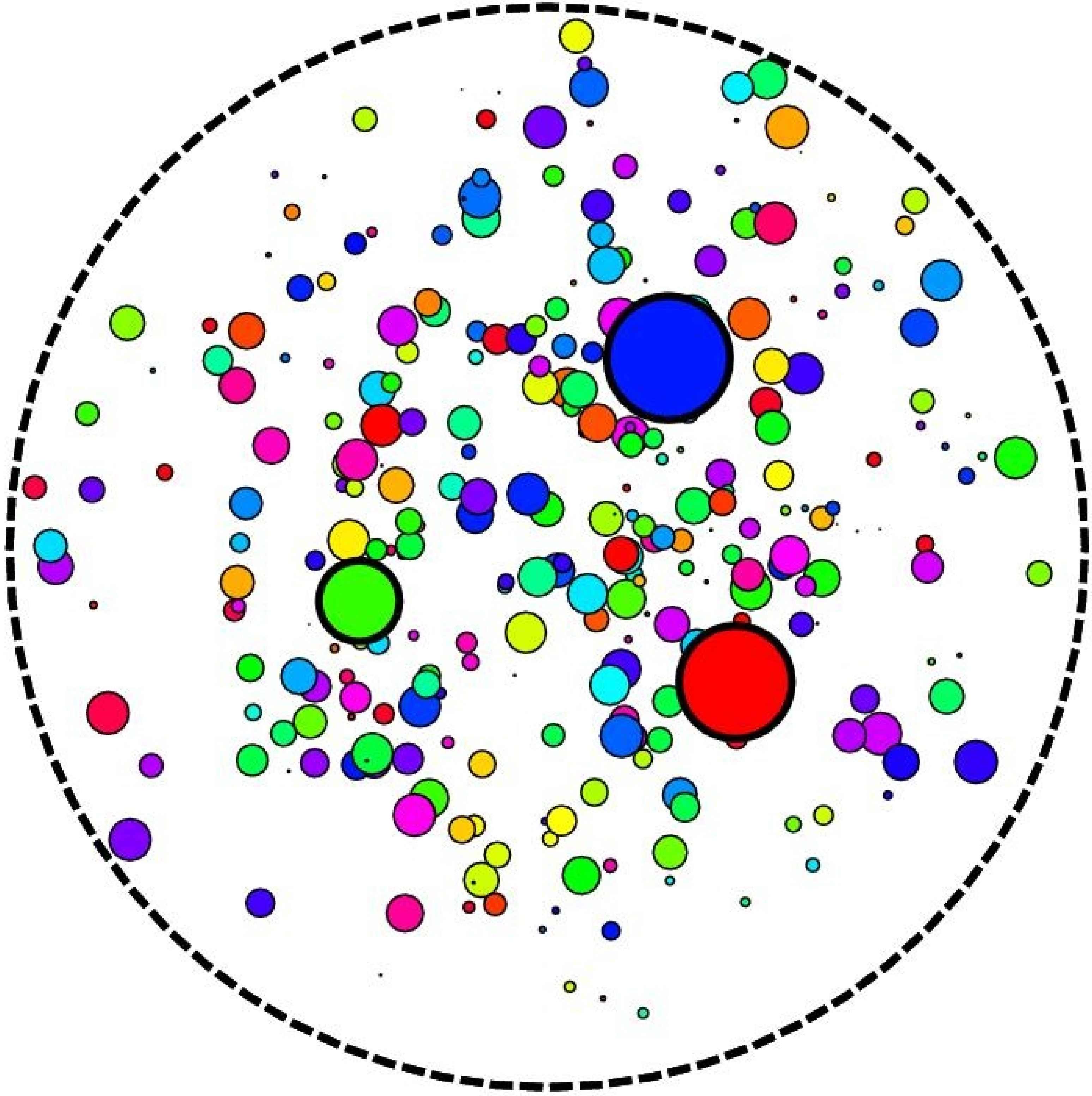
Beyond PDF's
Parton Distribution Functions

Hadrons crossing time short

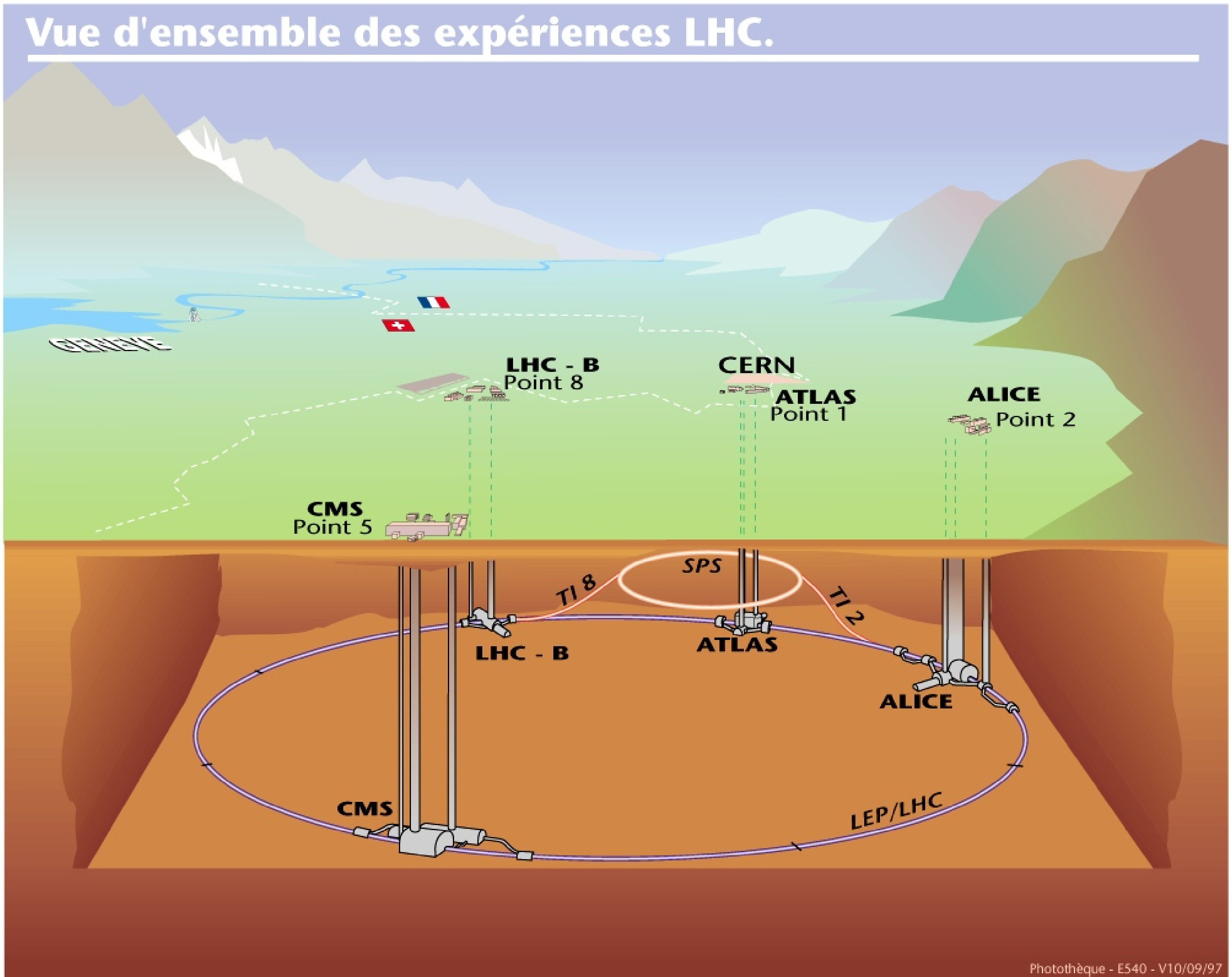
“Snapshot” of the Parton Configuration.







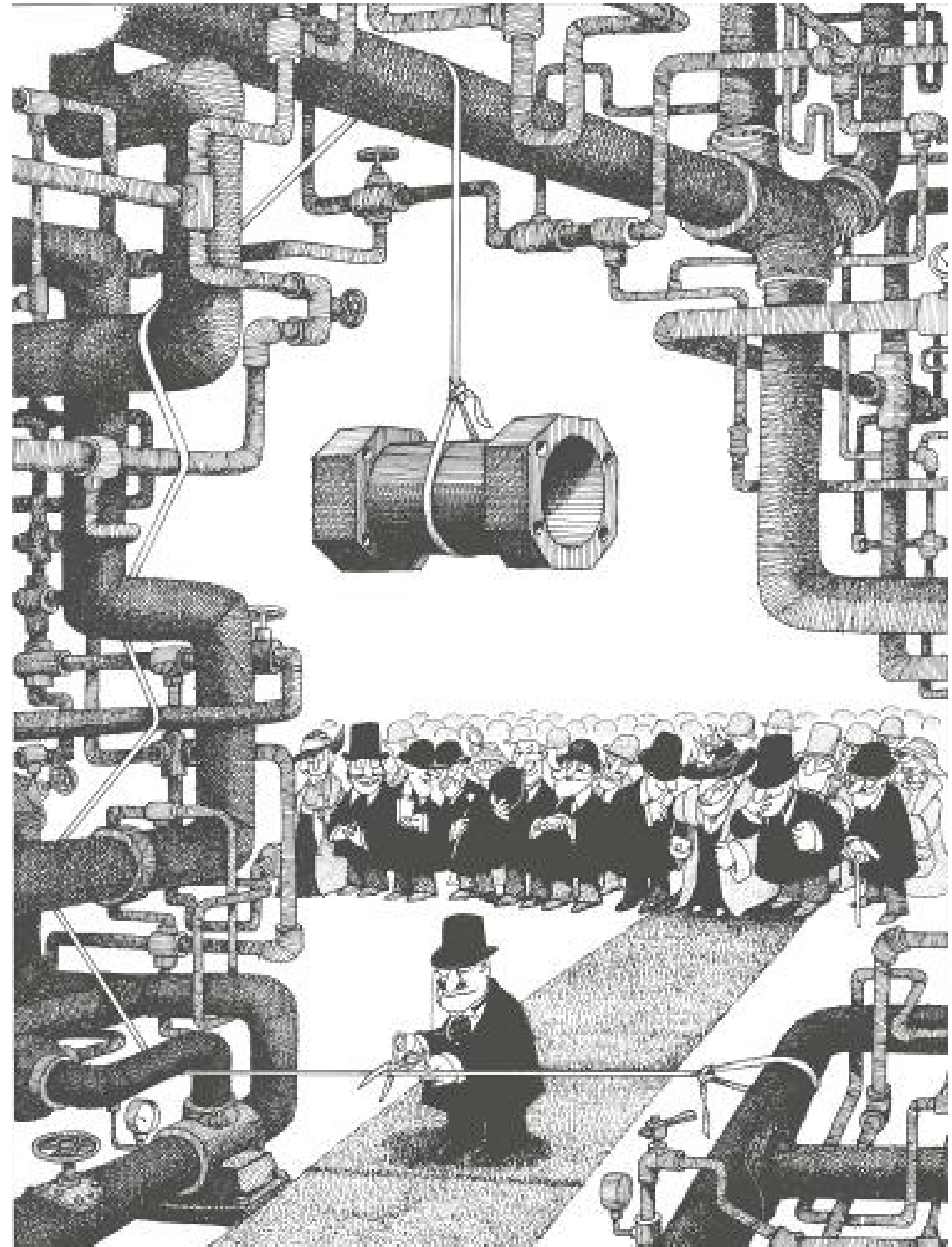
Very Important potential of LHC



7 + 7 TeV
PP collider

Problems at the Beginning of Commissioning

19th september 2008



Dates...

- Tests of the transfer lines SPS-LHC:

  June-August (3 weekends).

- Injection tests into parts of the LHC:

  ~September.

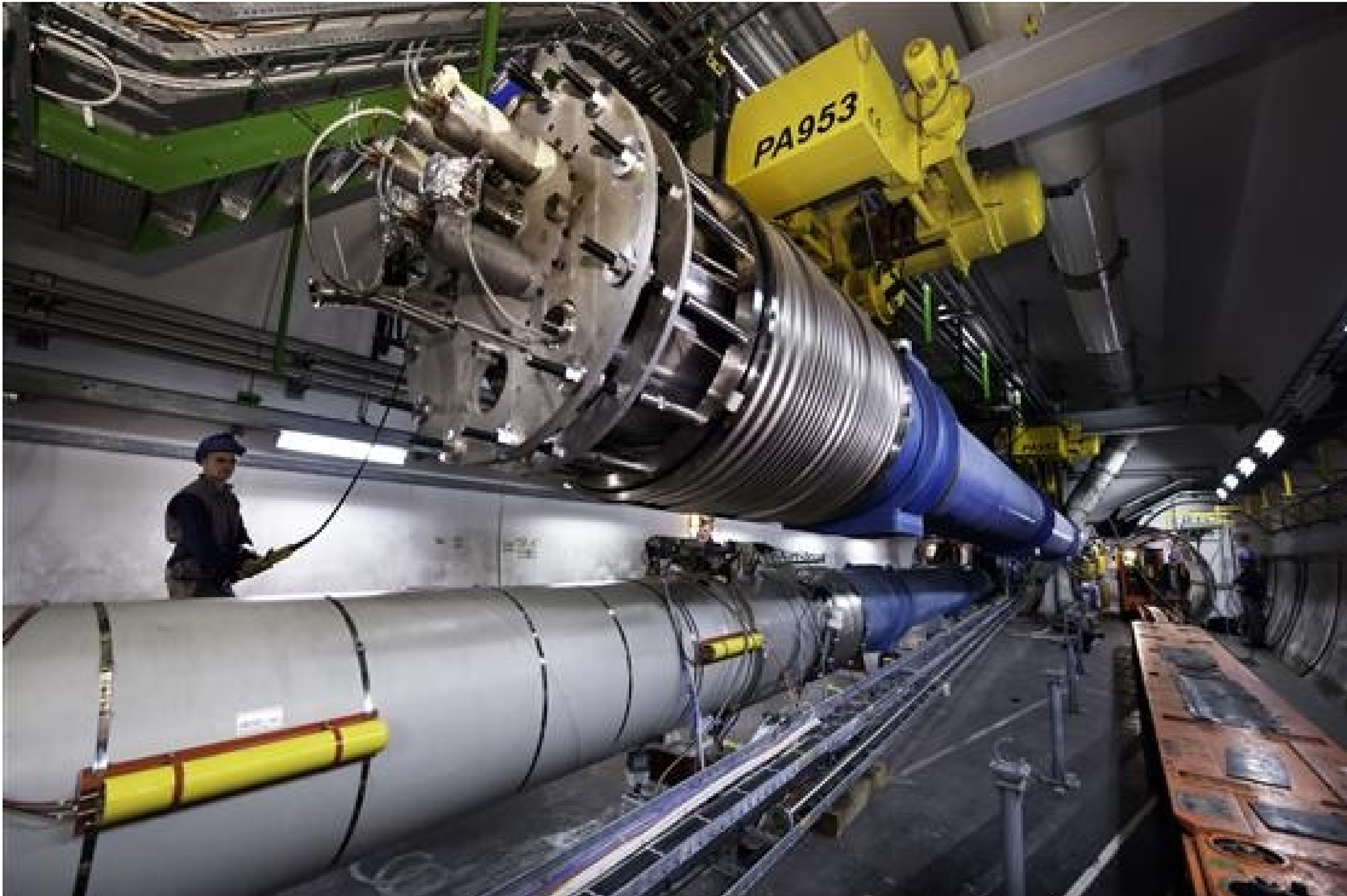
- First circulating beam:

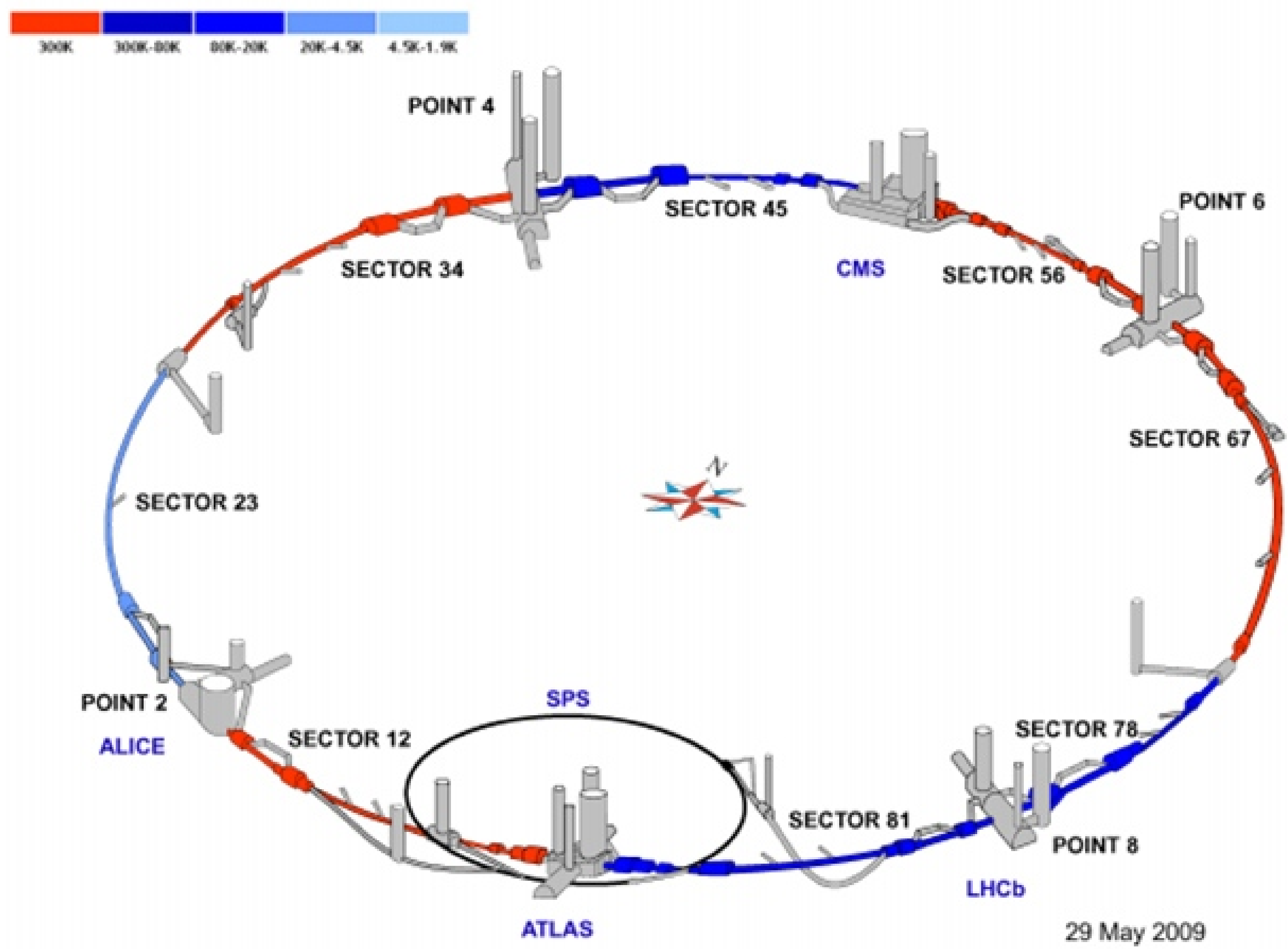
  ~October.

- First collisions at a few TeV: *(Very low luminosity...)*

  ~November.

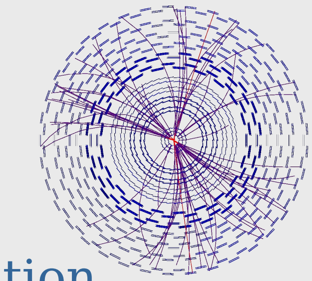
... then a run over winter until November 2010.


PA953



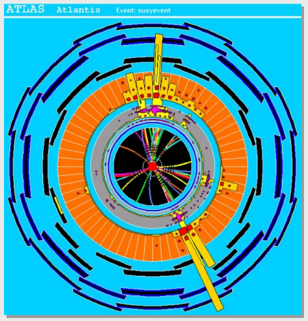
LHC Cooldown Status

LHC Physics in 2009/2010



First beams: very early physics - **rediscover SM physics**

Detector synchronization, in-situ alignment and calibration



10 pb^{-1}: Standard Model processes

measure jet and lepton rates, observe W, Z bosons

first look at possible **extraordinary signatures**…

30 pb^{-1}

Measure Standard Model Processes (at 10TeV need ~ 30pb^{-1}):

~ 10^4 $Z \rightarrow e^+e^-$ (golden Z's for detector studies (1%))

~ 10^5 $W \rightarrow e\nu$

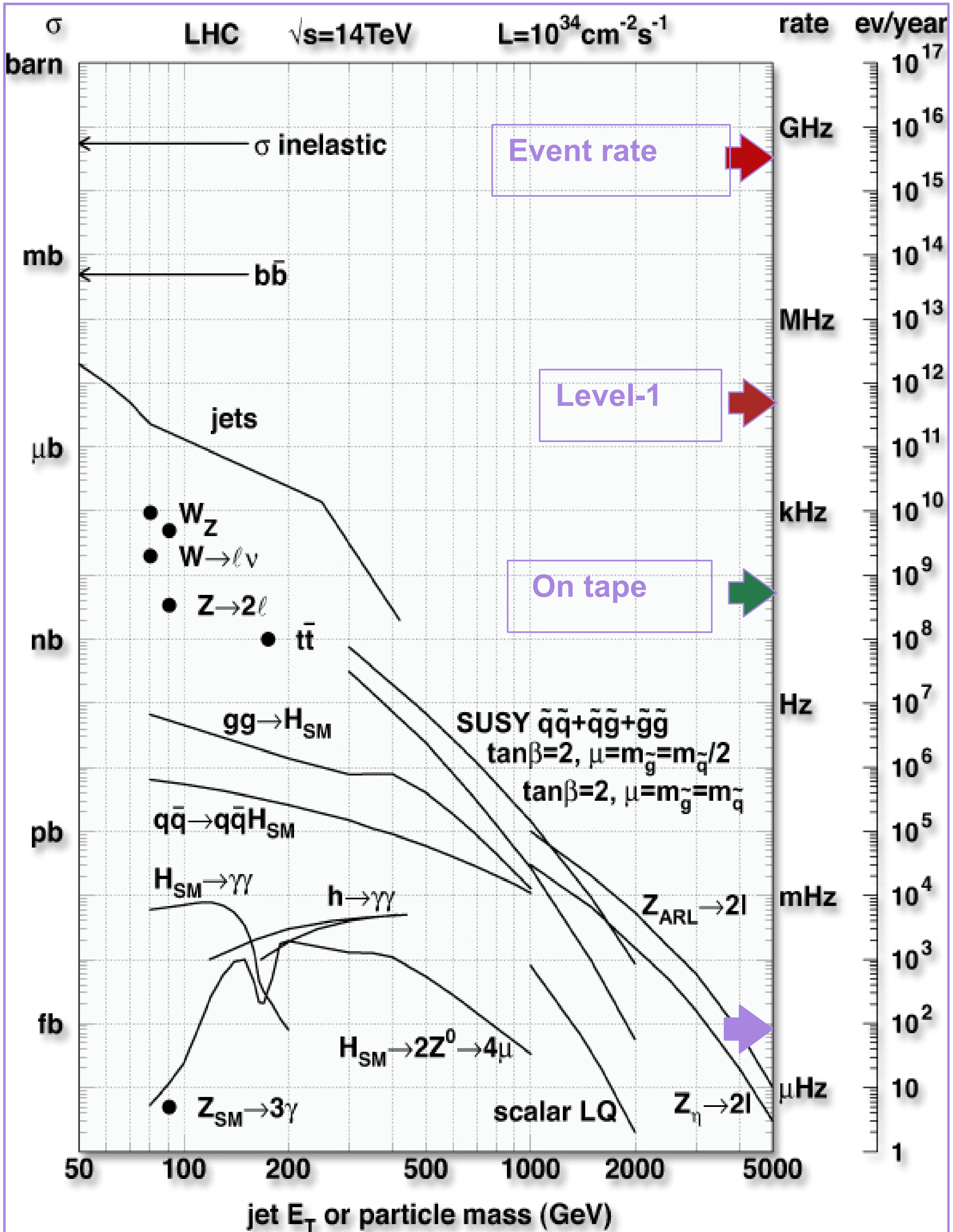
~ 10^3 ttbar (measure σ to 10%)

Background for new physics
Need to understand very well

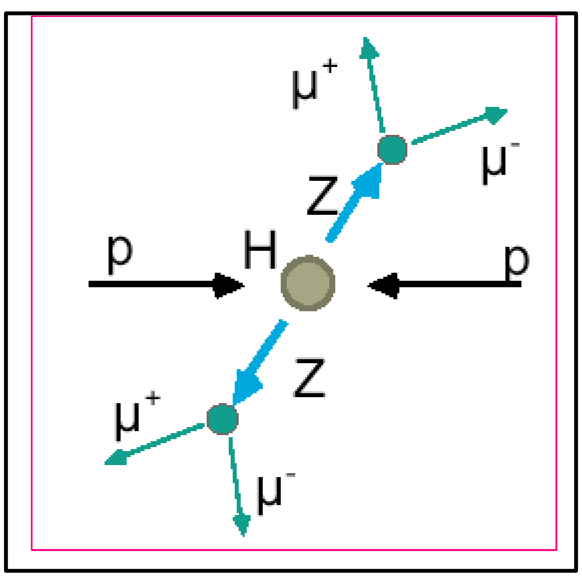
Initial Higgs searches and searches for physics beyond the SM

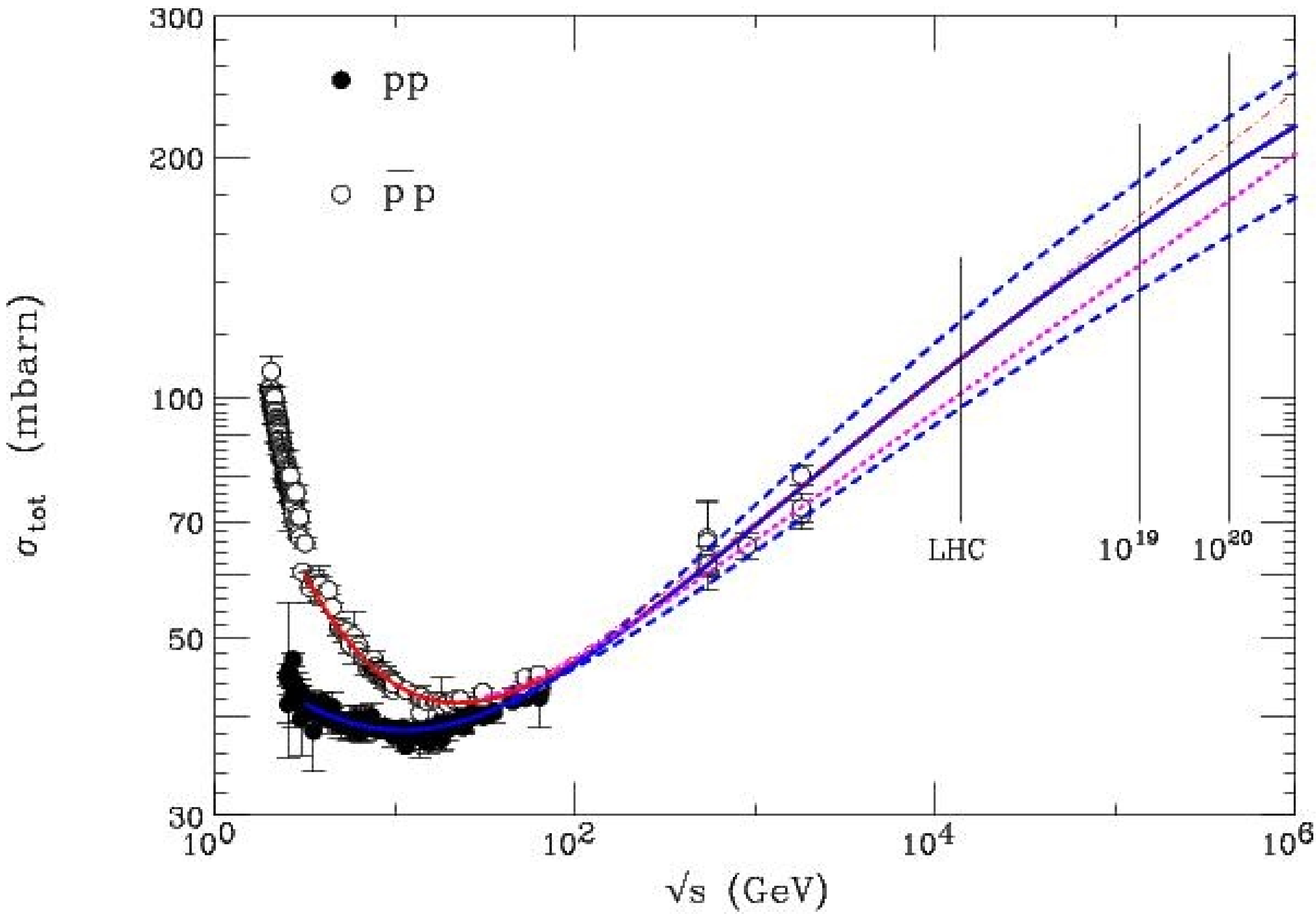
> 200 pb^{-1}

Entering Higgs discovery era and explore large part of SUSY and new resonances at ~ few TeV



Higgs discovery golden channel

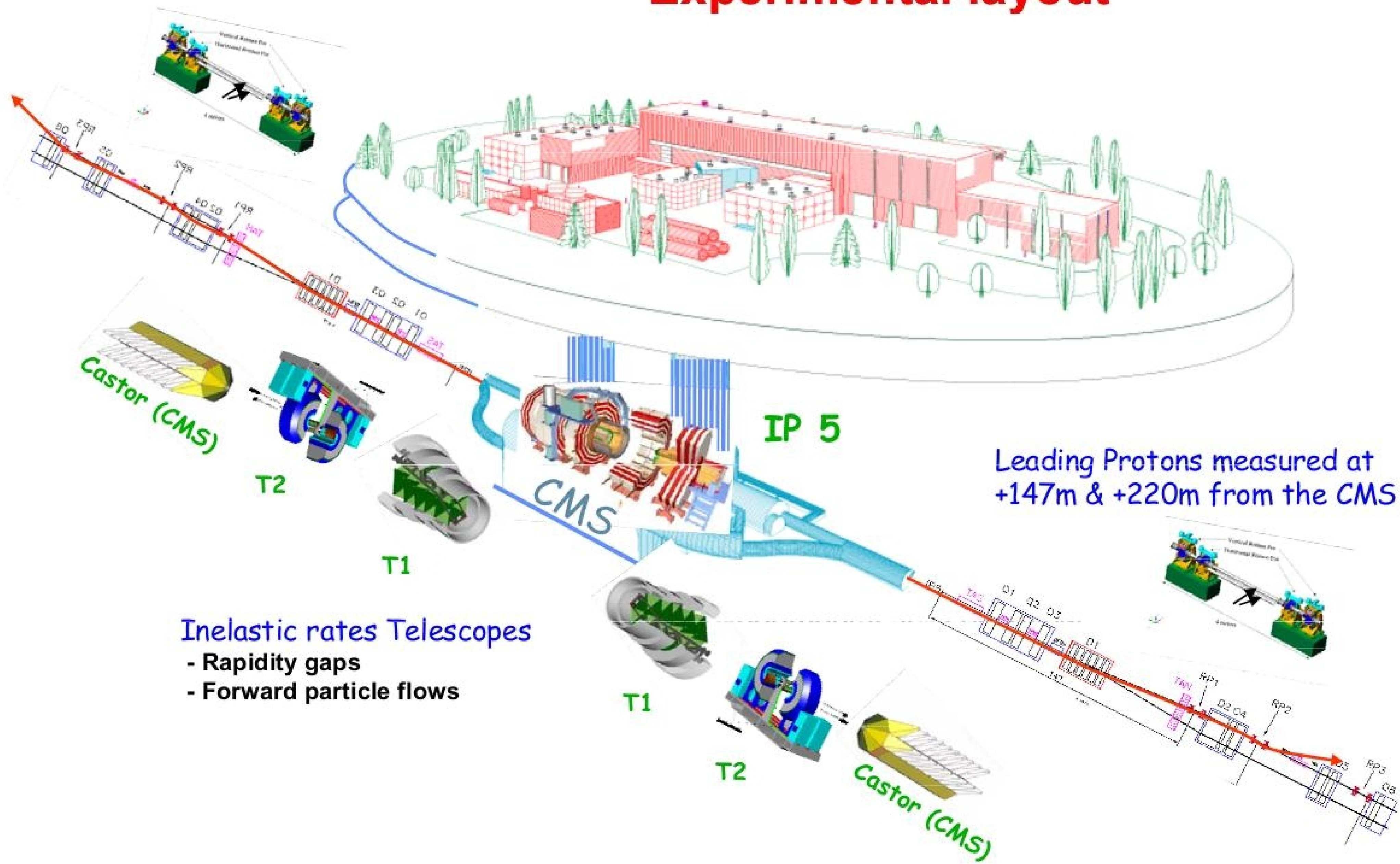




pp
p̄p
LHC
10^{19}
10^{20}
300
200
100
70
50
30
10^0
10^2
10^4
10^6
σ_{tot} (mbarn)
√s (GeV)

Experimental layout

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



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

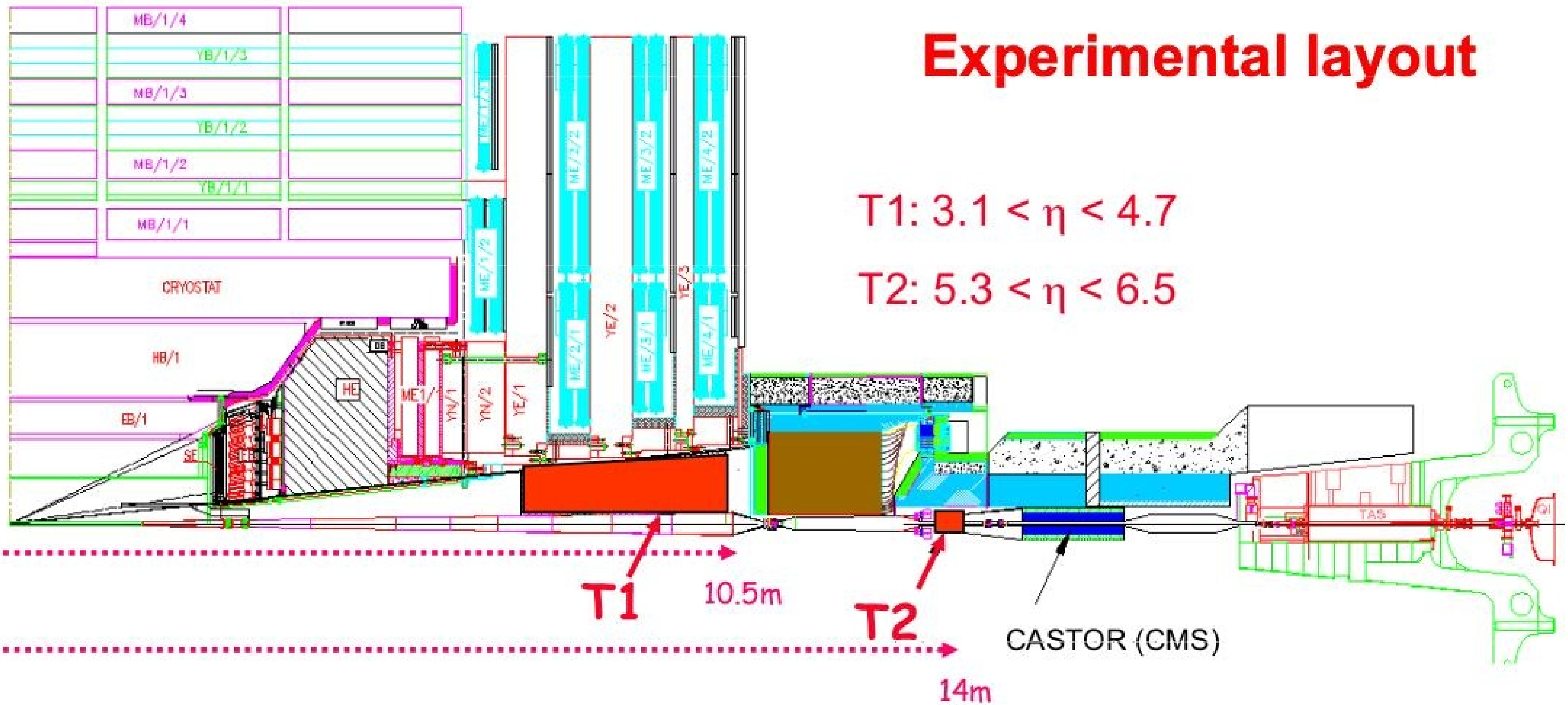
Inelastic rates Telescopes
- Rapidity gaps
- Forward particle flows

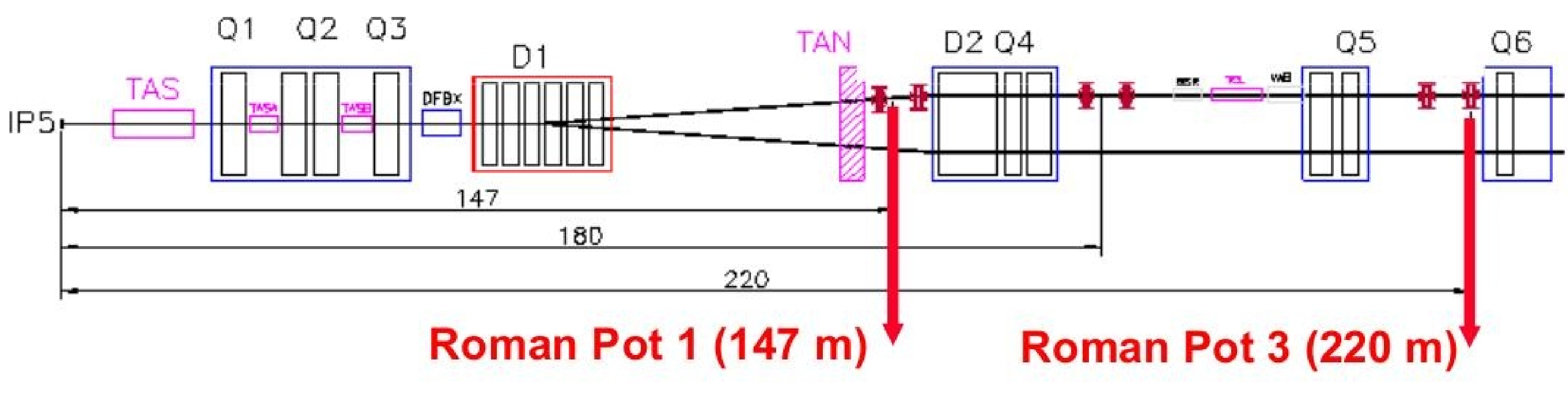
TOTEM

Experimental layout

T1: $3.1 < \eta < 4.7$

T2: $5.3 < \eta < 6.5$





Tevatron:

E710:

1.8 TeV: $\sigma_{tot} = 72.8 \pm 3.1$ mb

E811:

1.8 TeV: $\sigma_{tot} = 71.42 \pm 2.41$ mb

CDF:

546 GeV: $\sigma_{tot} = 61.26 \pm 0.93$ mb
(agrees with UA4)

1.8 TeV: $\sigma_{tot} = 80.03 \pm 2.24$ mb

Cross section Measurements

$$\sigma_{tot} = 111.5 \pm 1.2 \begin{array}{l} +4.1 \\ -2.1 \end{array} \text{ mb}$$

[PRL 89 201801 (2002)]

Prediction for LHC at sqrt[s] = 14 TeV

CROSS SECTION MEASUREMENT

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

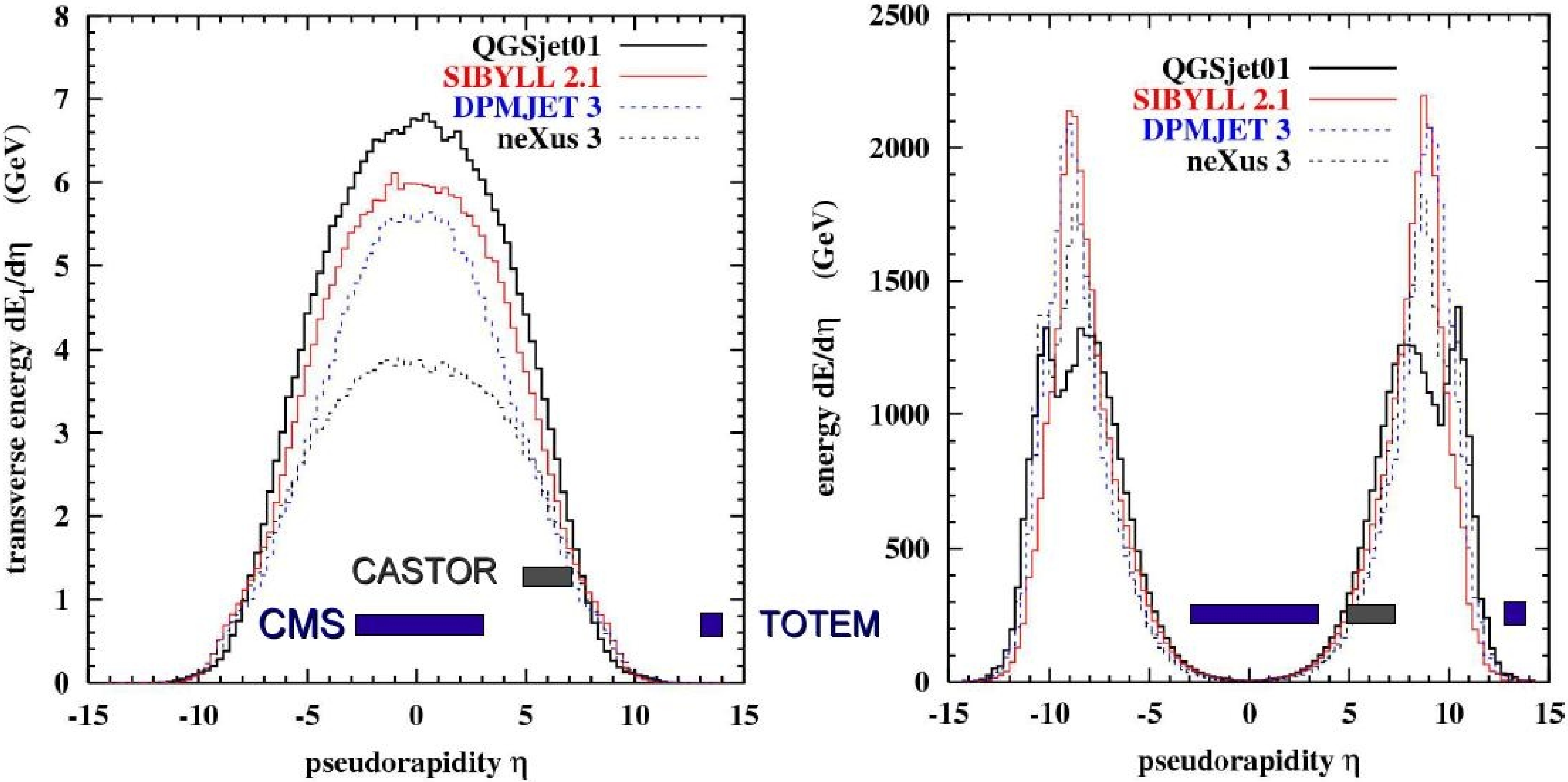
Optical Theorem

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

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

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

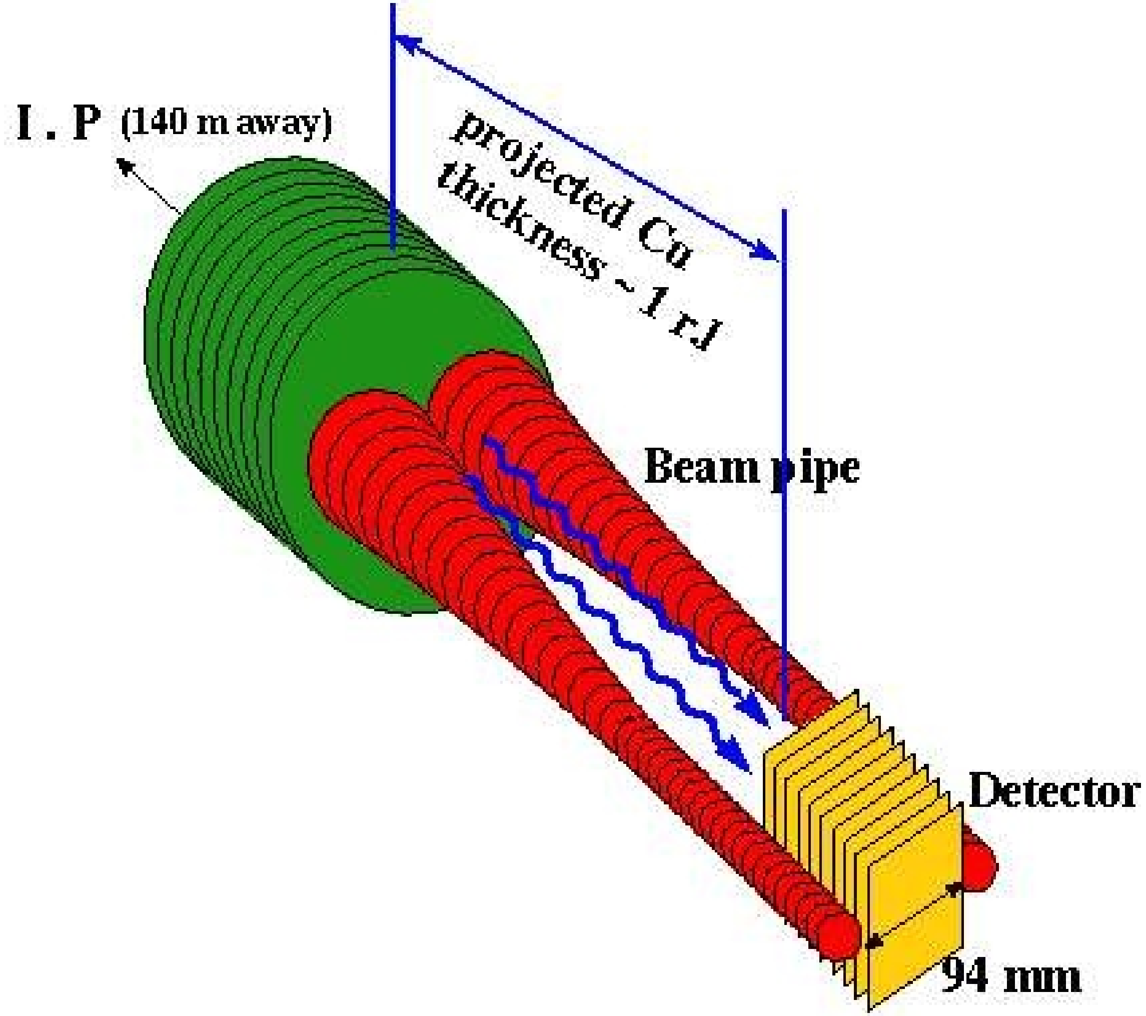
[Luminosity Determination]



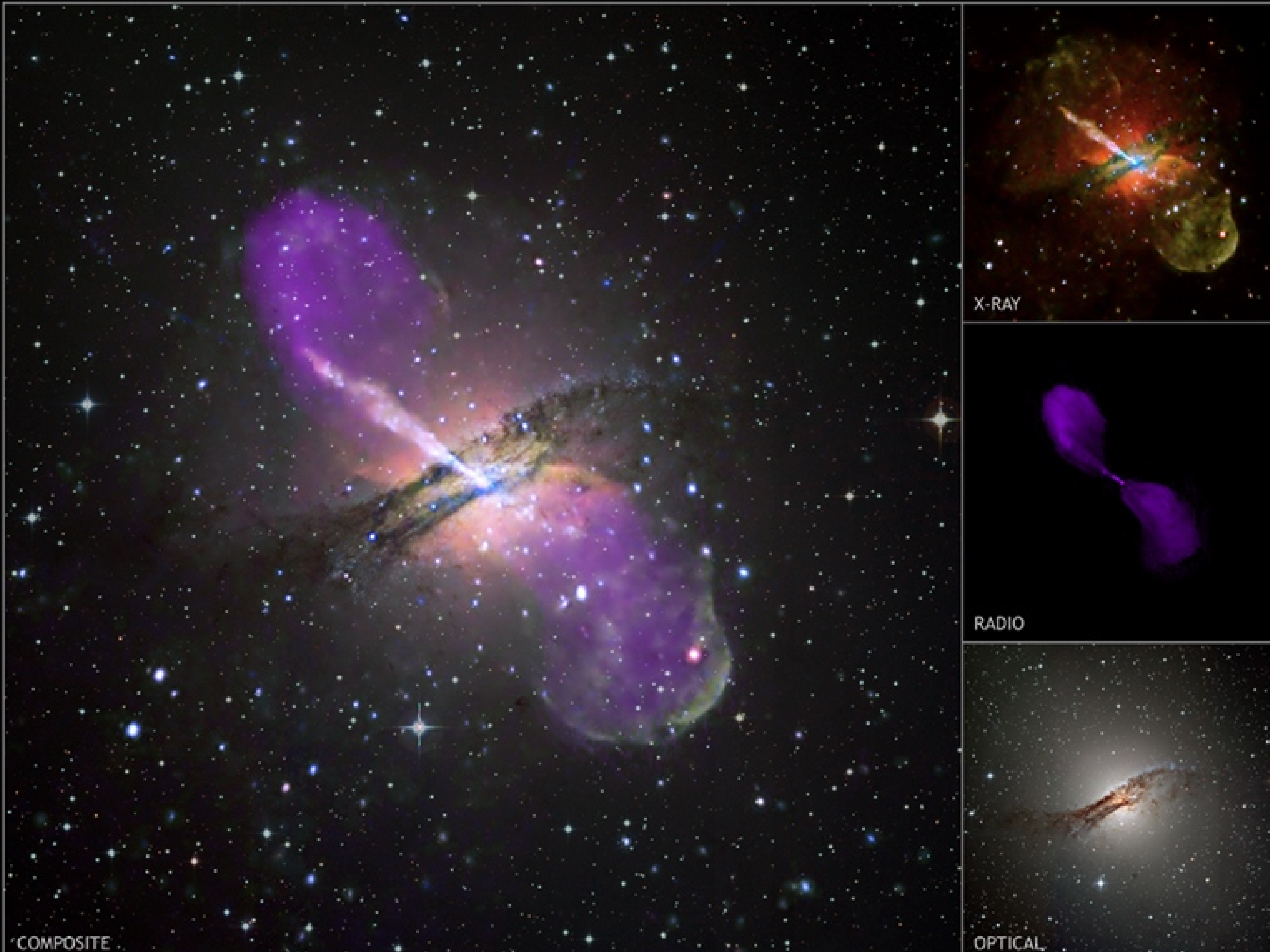
PROBLEM of PHASE SPACE COVERING

LHCF

Calorimeter
for neutral particles
in the very forward region



Two
non-identical
Detectors


COMPOSITE
X-RAY
RADIO
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

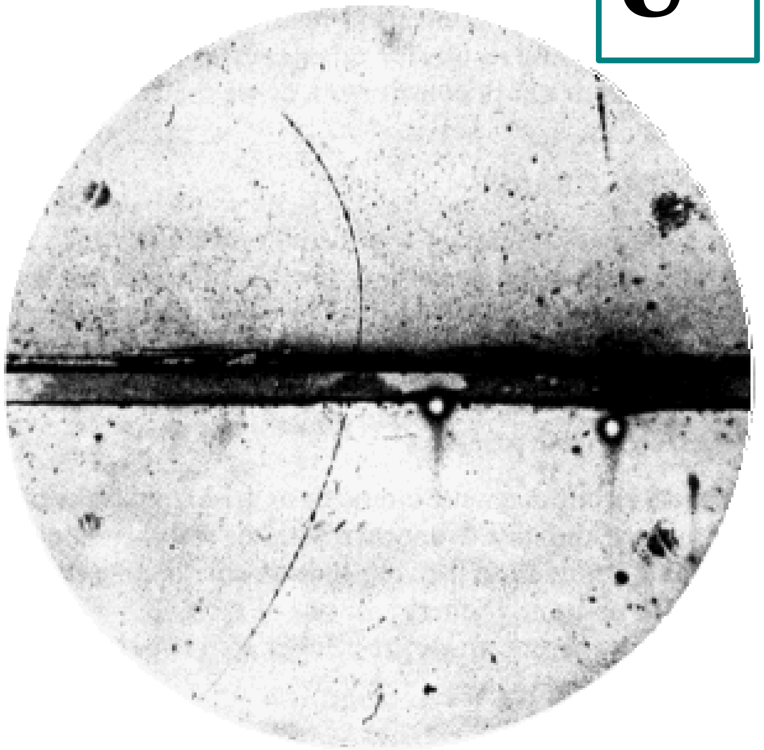
Length scale 10^{-13} cm

Exciting

Difficult

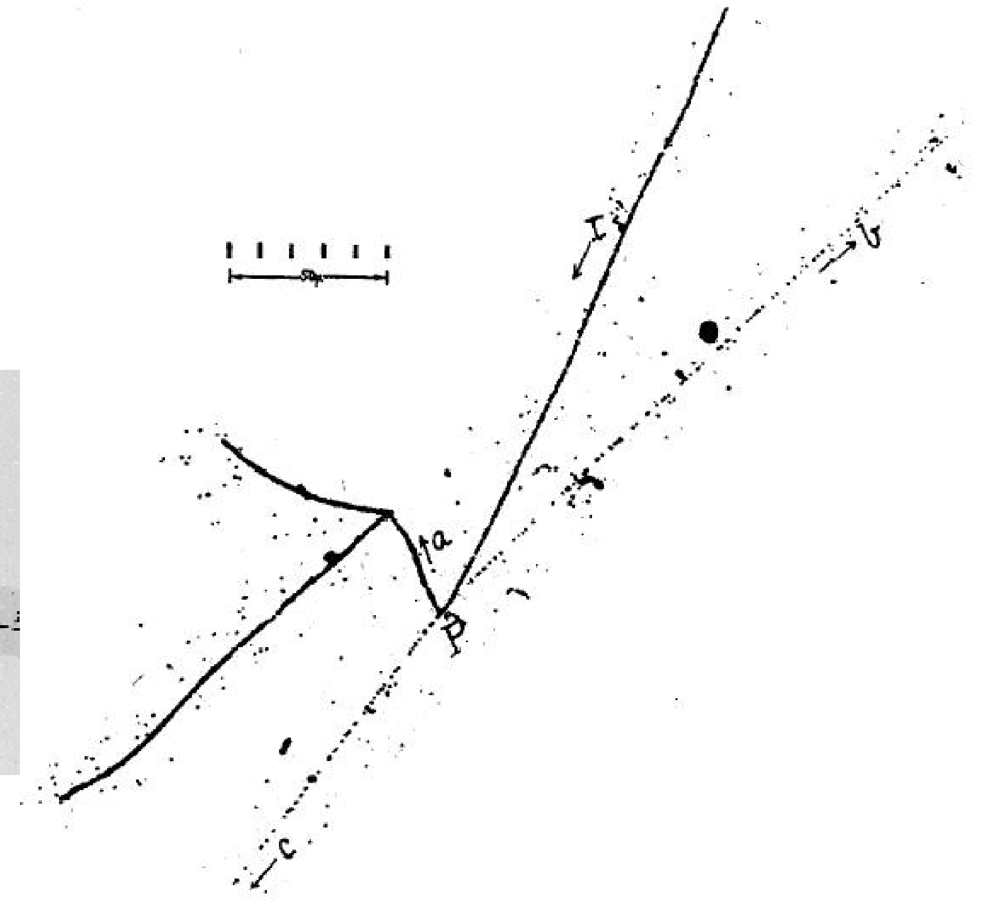
e^{+}

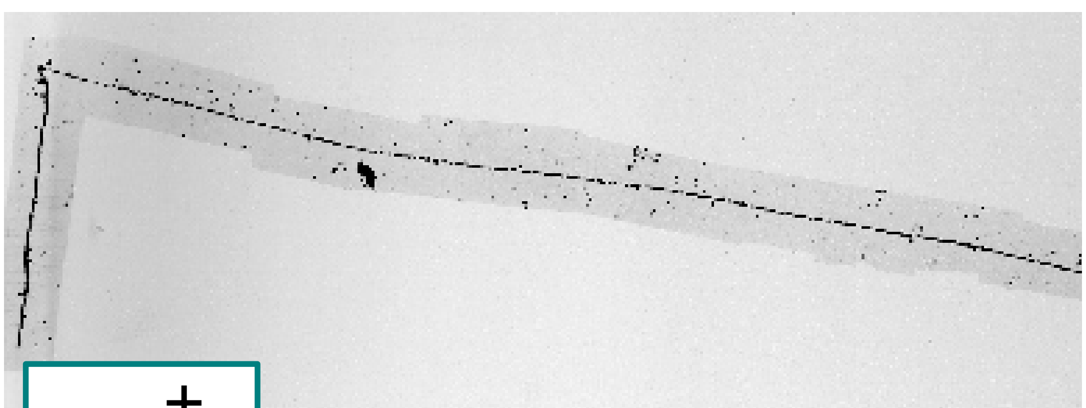
Particle Physics ↔ Cosmic Ray Physics



Anderson discovery of positron

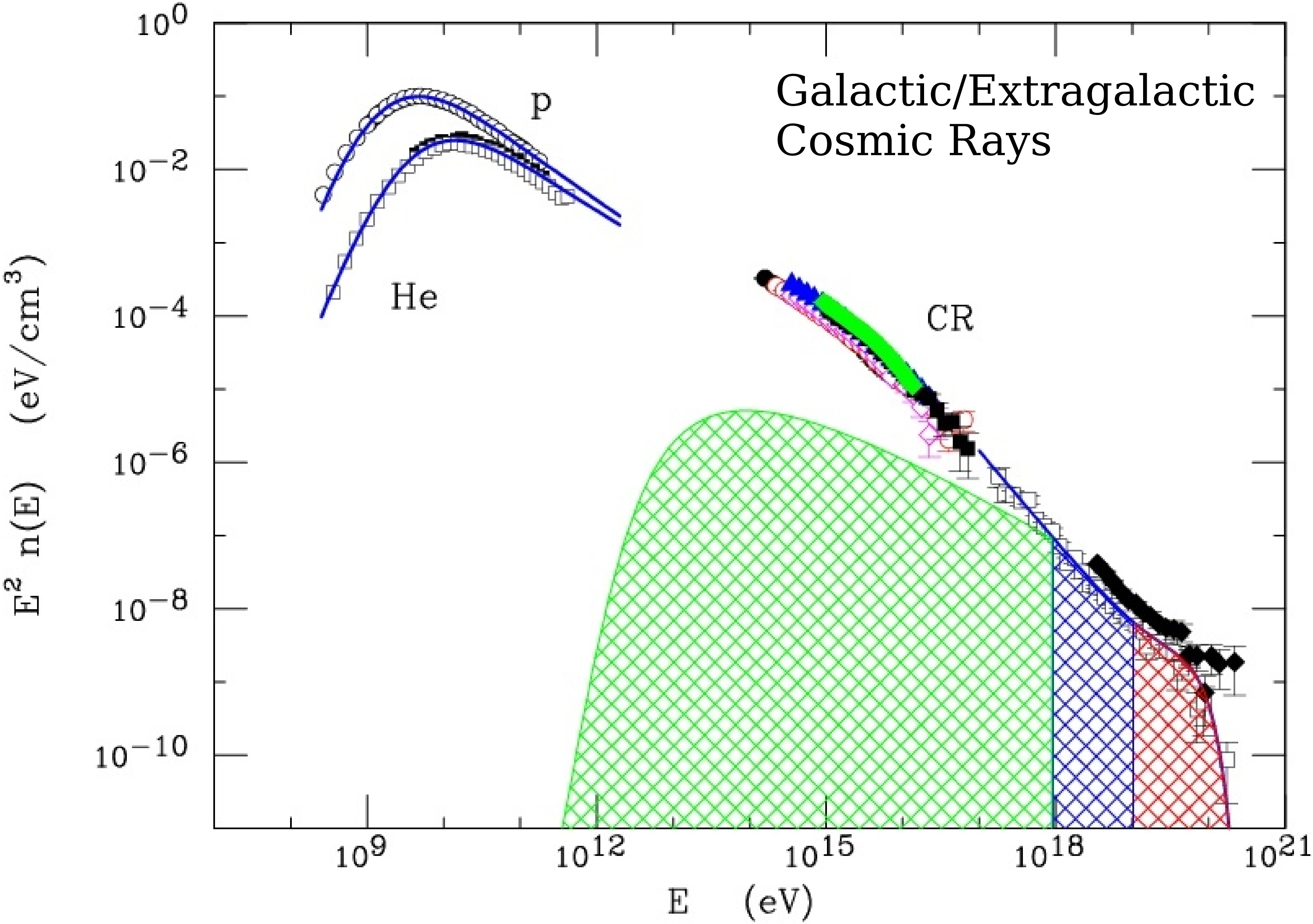
$K^{\pm}$





$\pi^{\pm}$

Occhialini , Powell



Galactic/Extragalactic
Cosmic Rays
p
He
CR
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
E^2 n(E) (eV/cm^3)
10^9
10^{12}
10^{15}
10^{18}
10^{21}
E (eV)