High Energy CR

HADRONIC

INTERACTIONS

Paolo Lipari

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

Ooty 12th december 2010

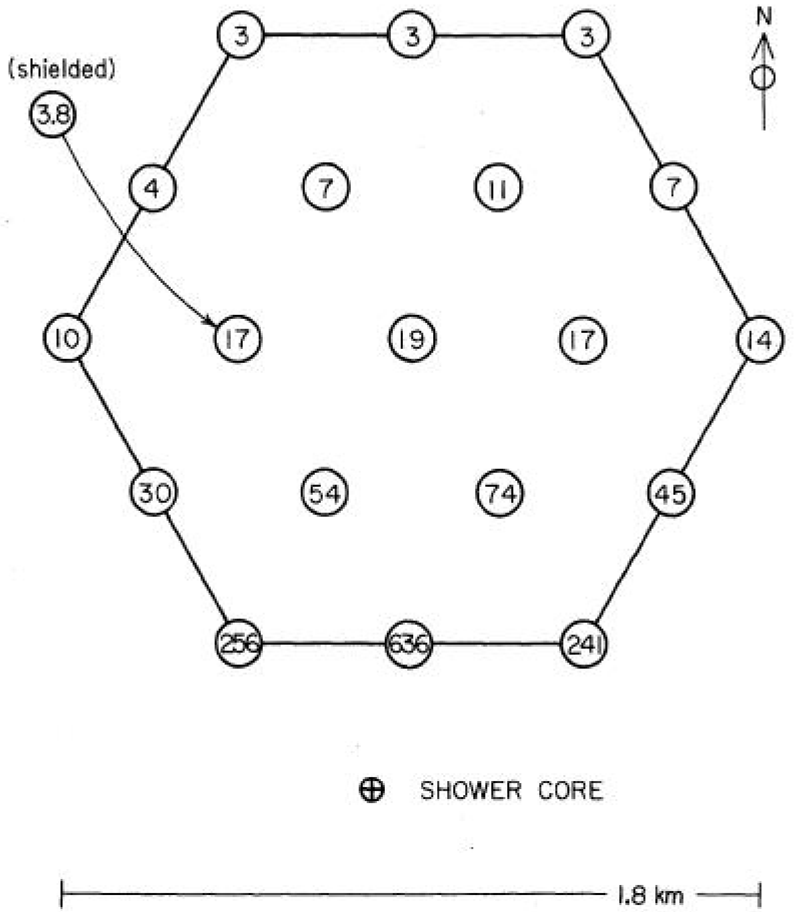
PHYSICAL REVIEW LETTERS

~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.

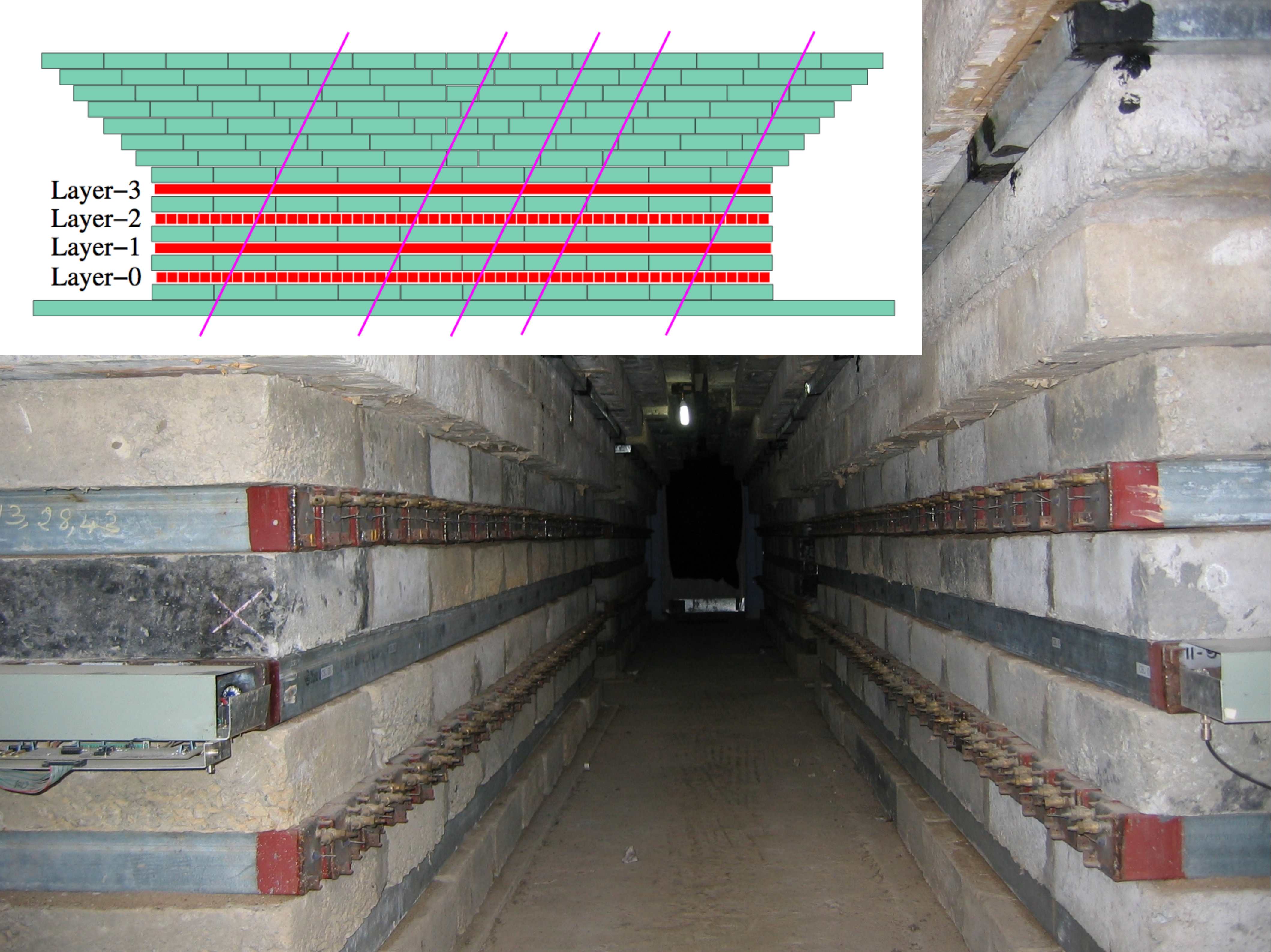
An important question is whether the primary particle was a proton or a heavier nucleus.

Mass A

Hadronic interaction Modeling

Measure a single slice of the shower at the ground


GRAPES Experiment, Ooty (India)



Layer–3
Layer–2
Layer–1
Layer–0

~50 years of UHECR

PHYSICAL REVIEW LETTERS

EXTREMELY ENERGETIC COSMIC-RAY EVENT*

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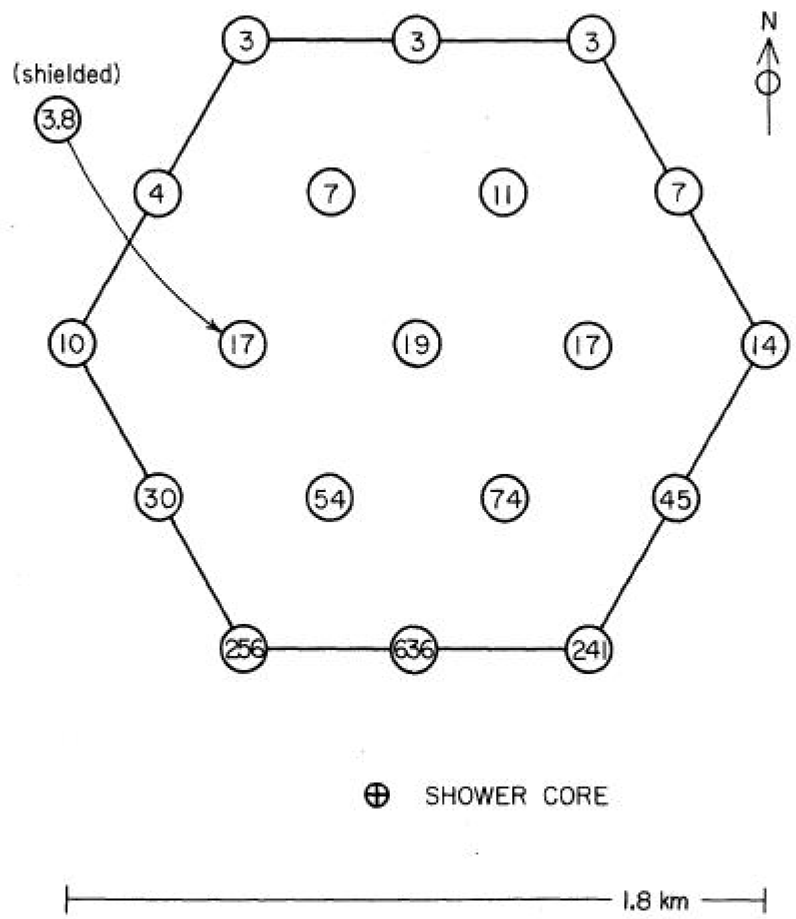


$e^{\pm}$ γ

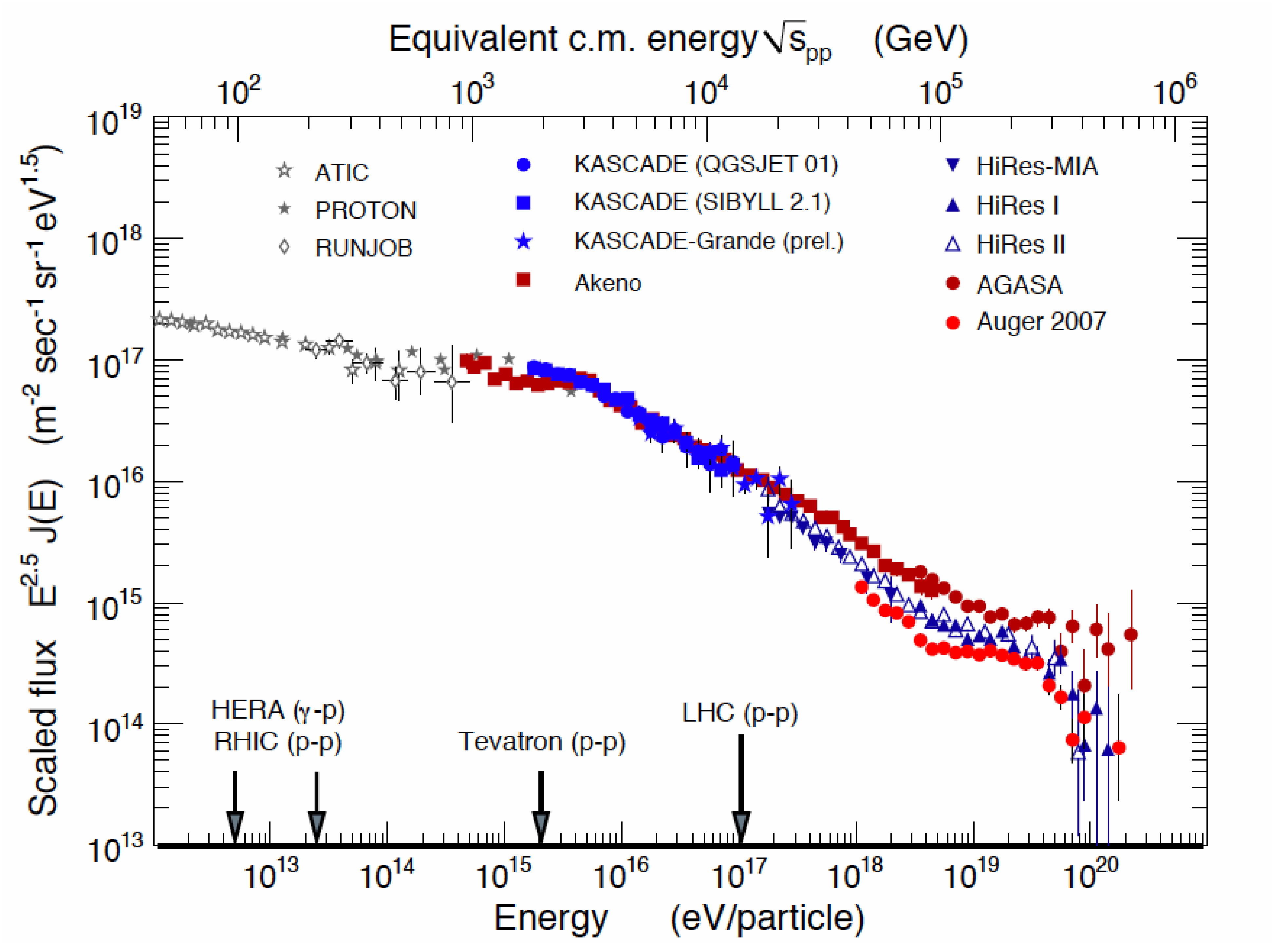
$\mu^{\pm}$

hadrons

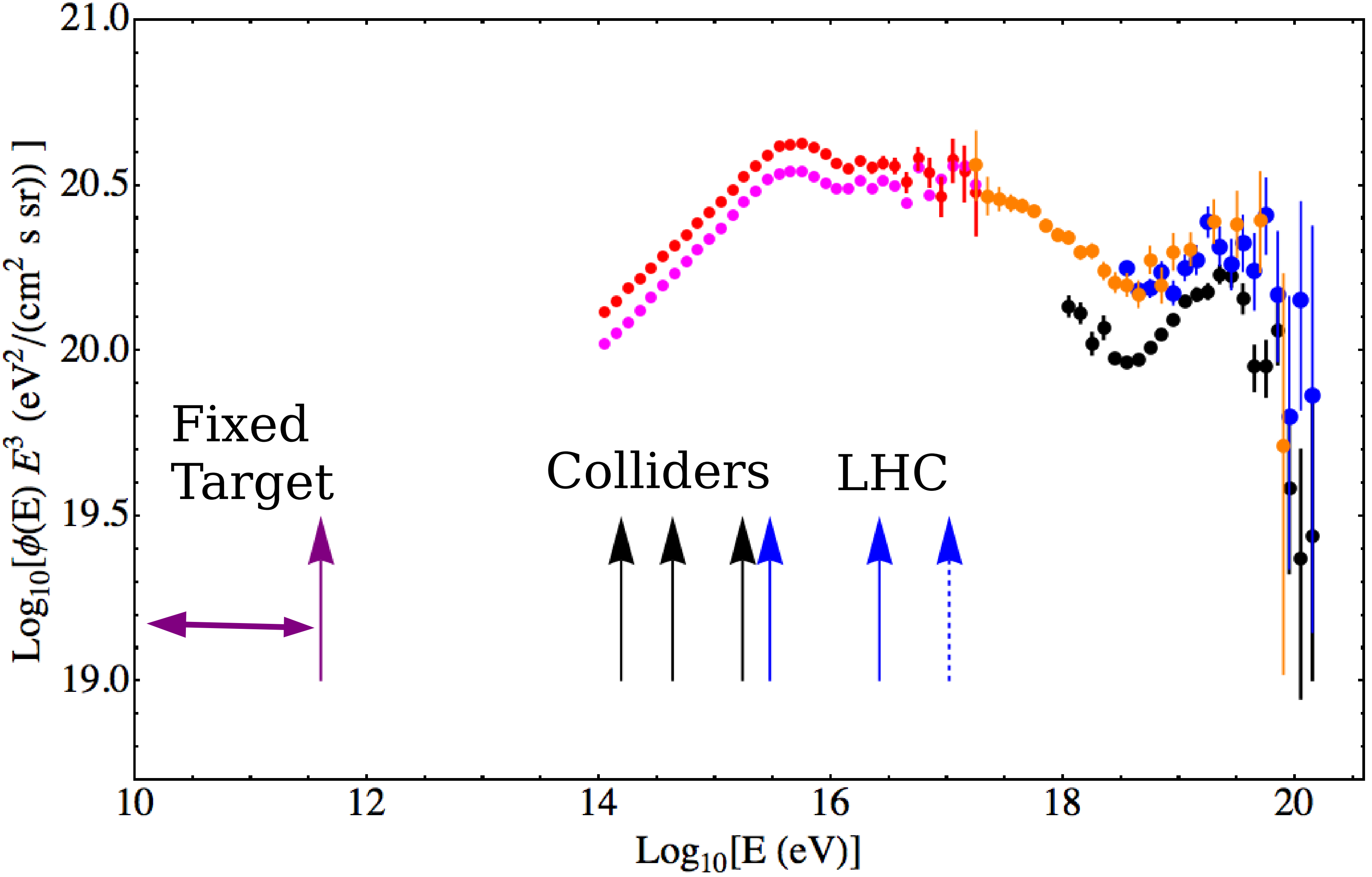
Different components

Measure a single slice of the shower at the ground

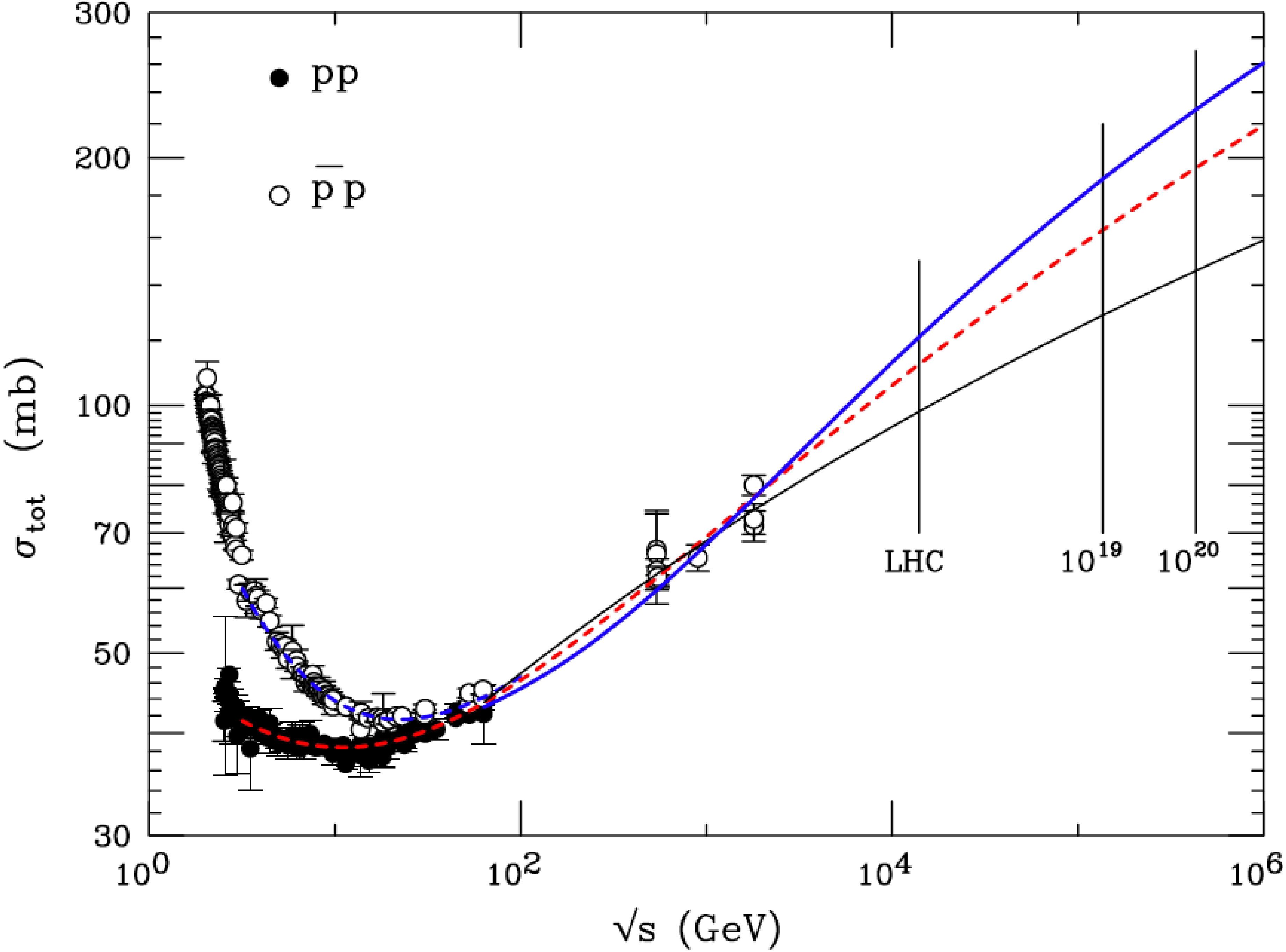
Hadronic interaction Modeling


Equivalent c.m. energy $\sqrt{s}_{pp}$ (GeV)
10^2
10^3
10^4
10^5
10^6
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande (prel.)
Akeno
HiRes-MIA
HiRes I
HiRes II
AGASA
Auger 2007
Scaled flux $E^{2.5} J(E)$ $(m^{-2} sec^{-1} sr^{-1} eV^{1.5})$
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
HERA (γ-p)
RHIC (p-p)
Tevatron (p-p)
LHC (p-p)
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy (eV/particle)

Structures in the CR energy spectrum

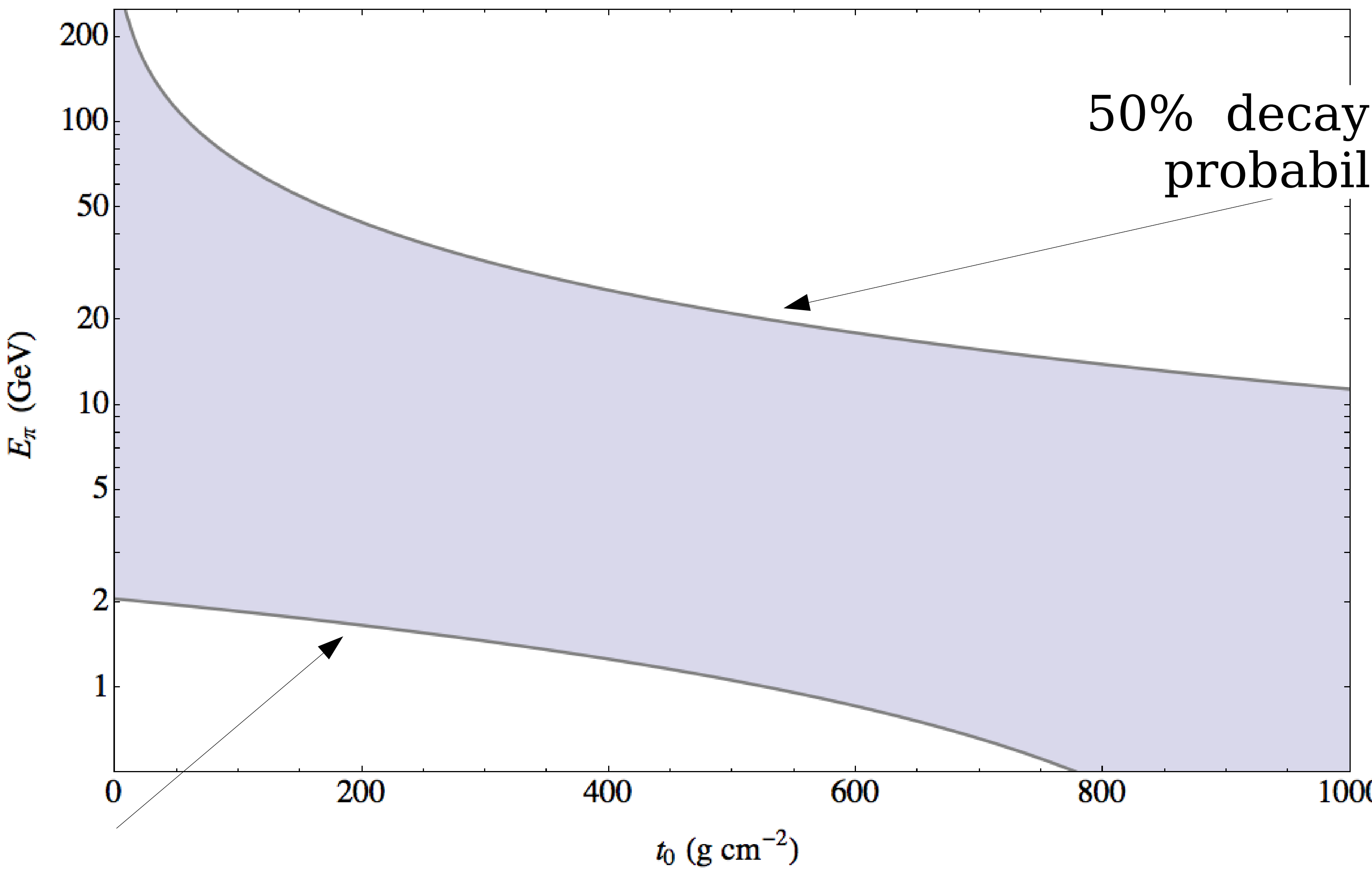


Total pp Cross Section



MUONS Source

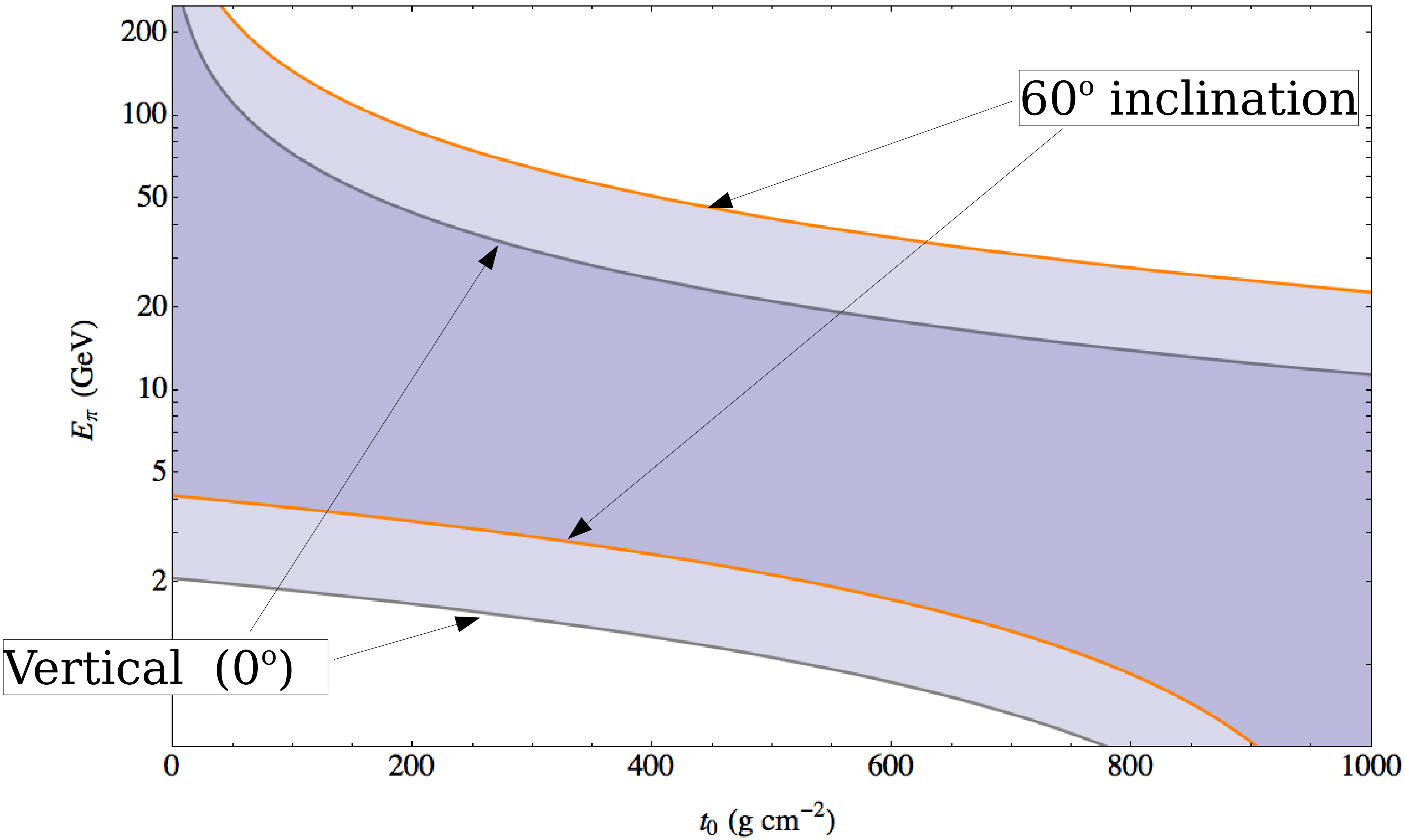
Pion decay
Vertical direction



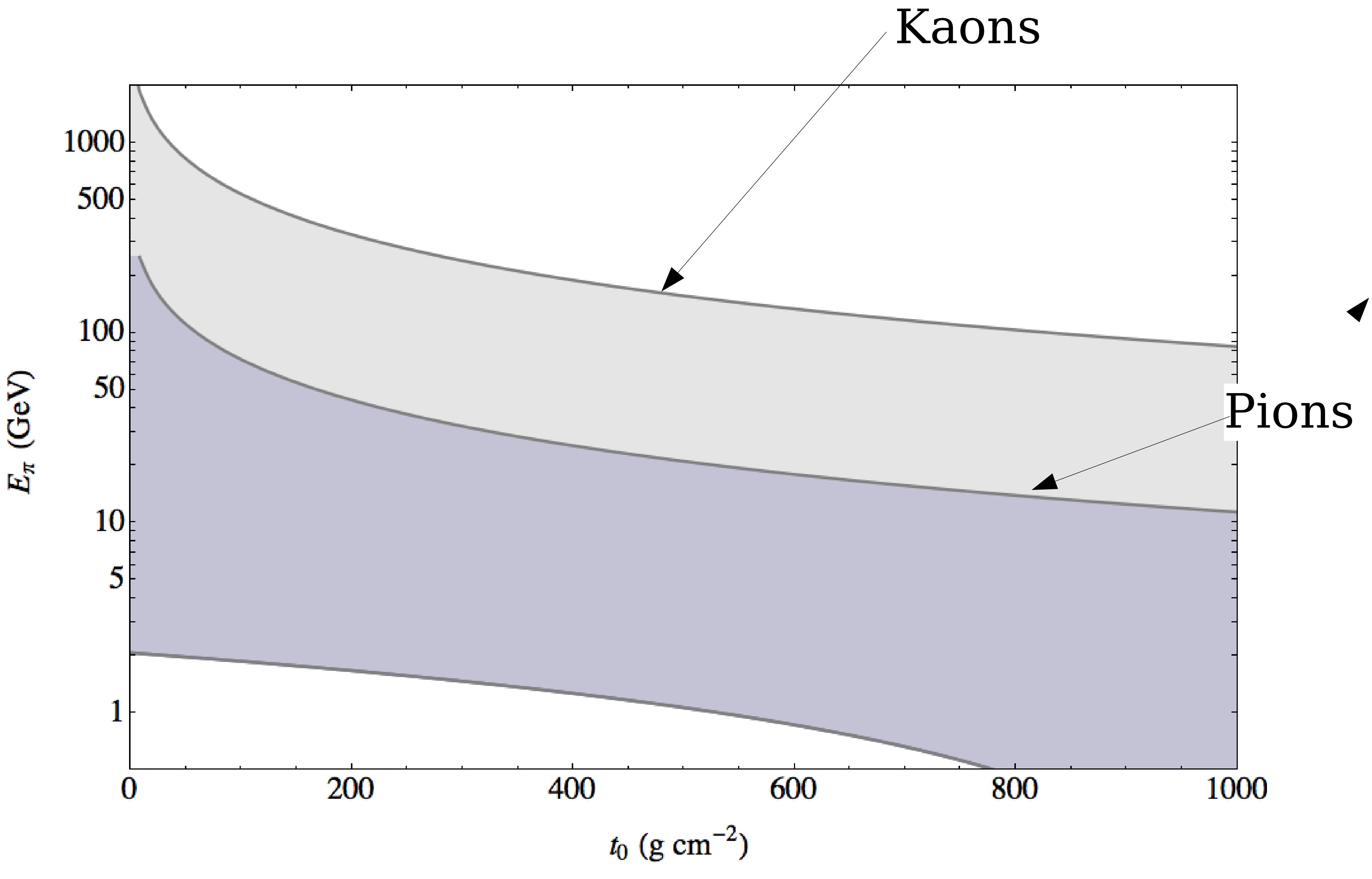
50% decay probability

Muons do not reach the ground

Pions that generate muons

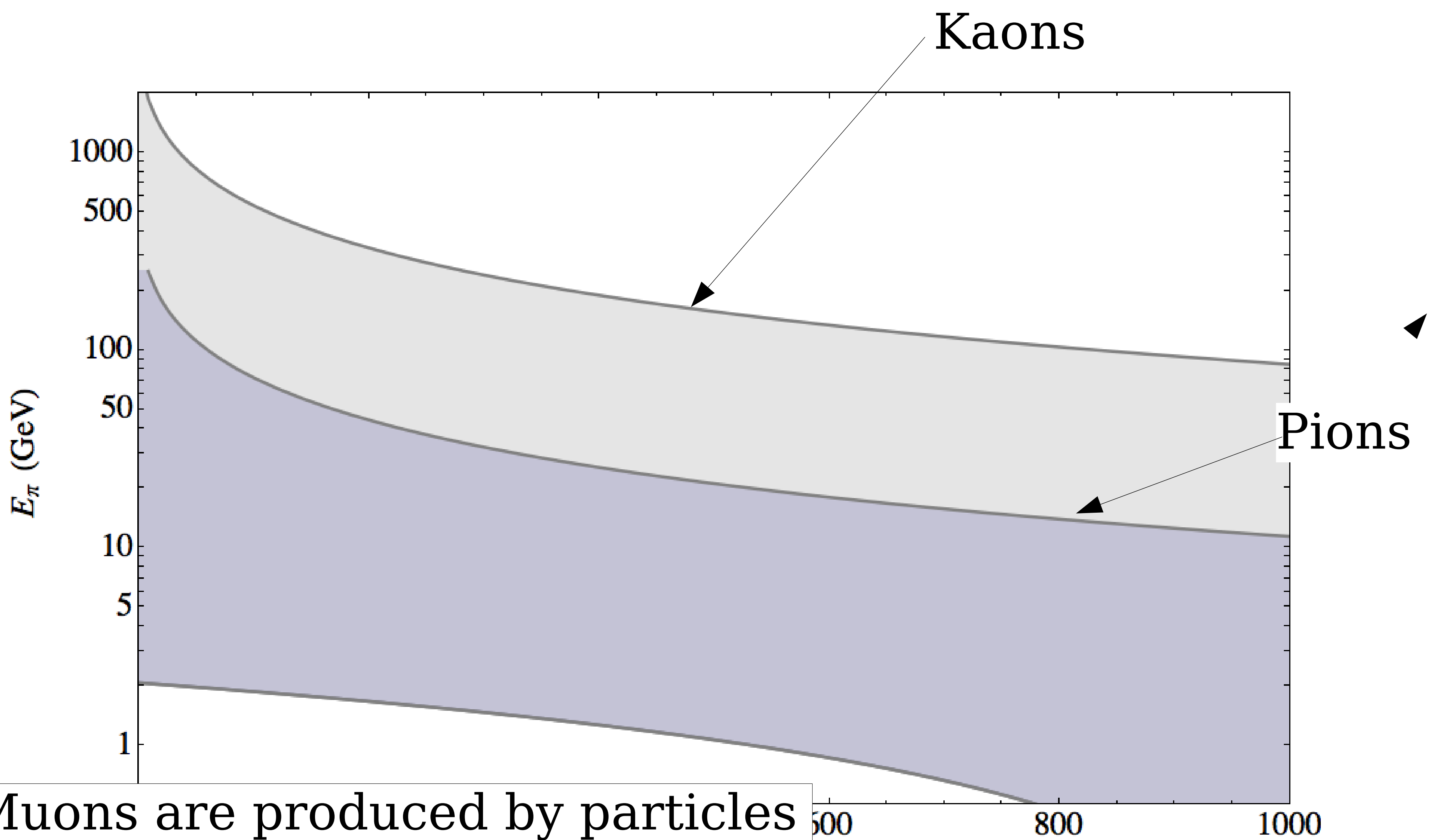


Source of Muons



Vertical direction

Source of Muons



Muons are produced by particles of few – to few hundred GeV.
Much softer in the shower.
Precise calculation is difficult.

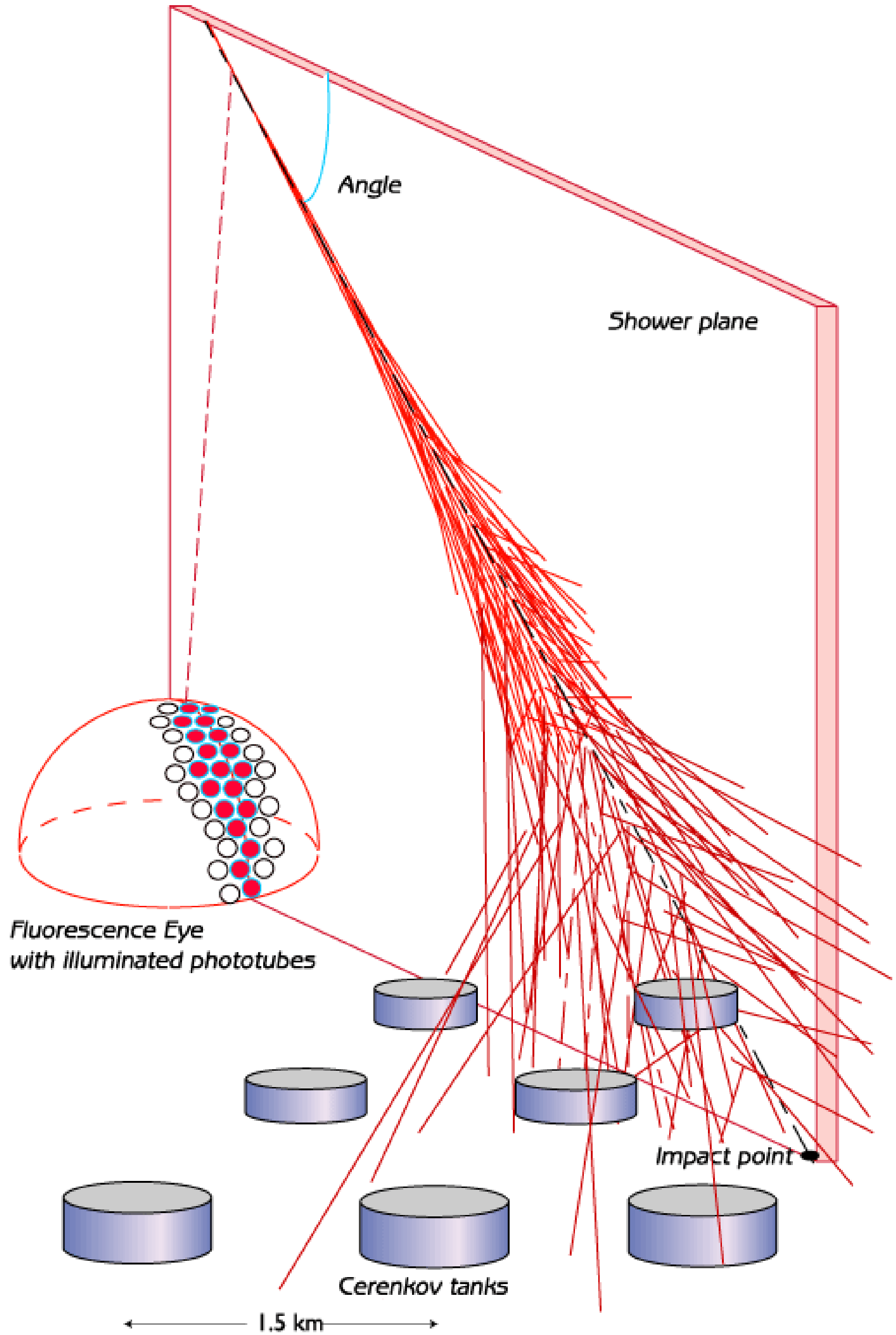
Vertical direction

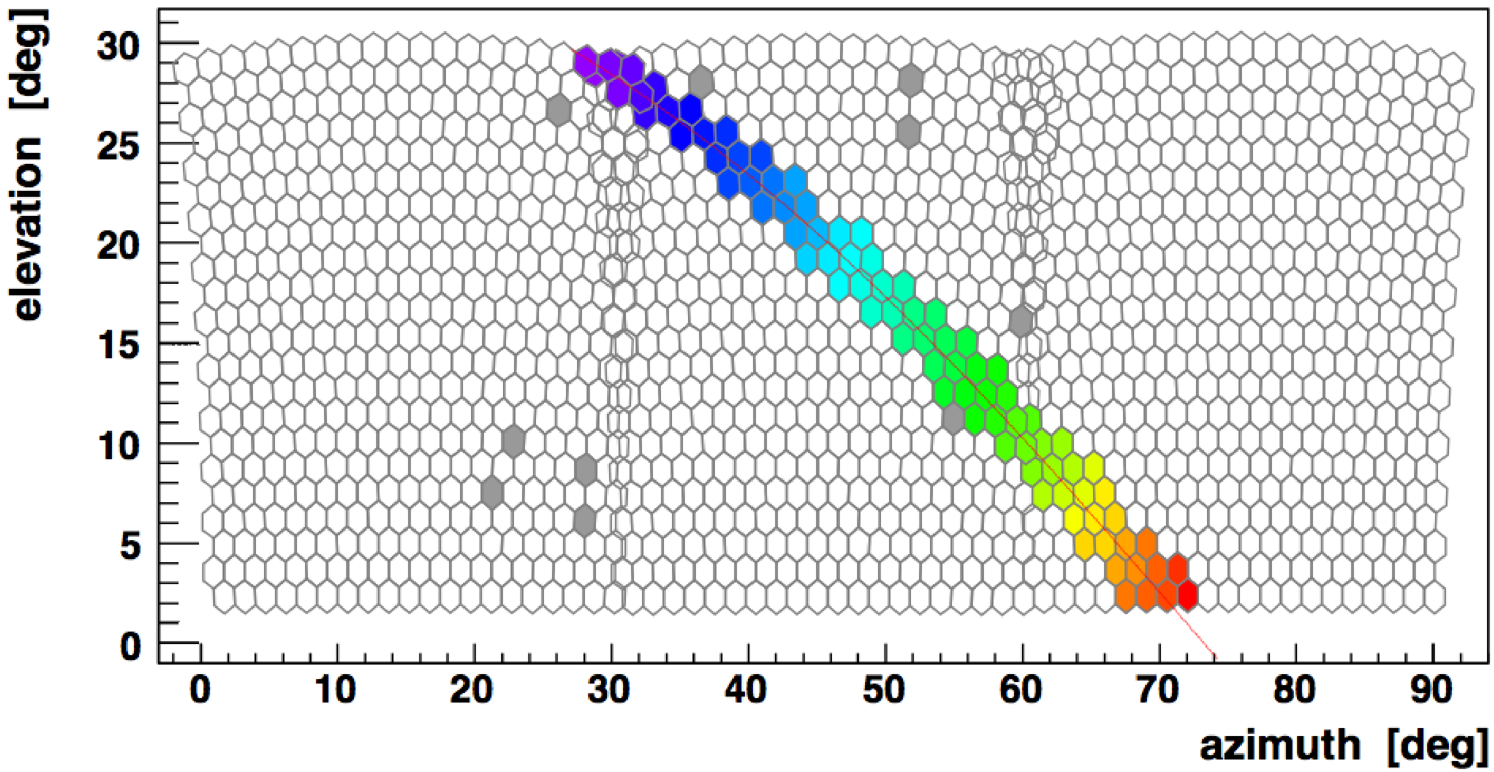
The **Fly's Eye** Detector concept

"Quasi-Calorimetric" Energy Measurement

Fluorescence Light

Artists View of Hybrid Set-Up



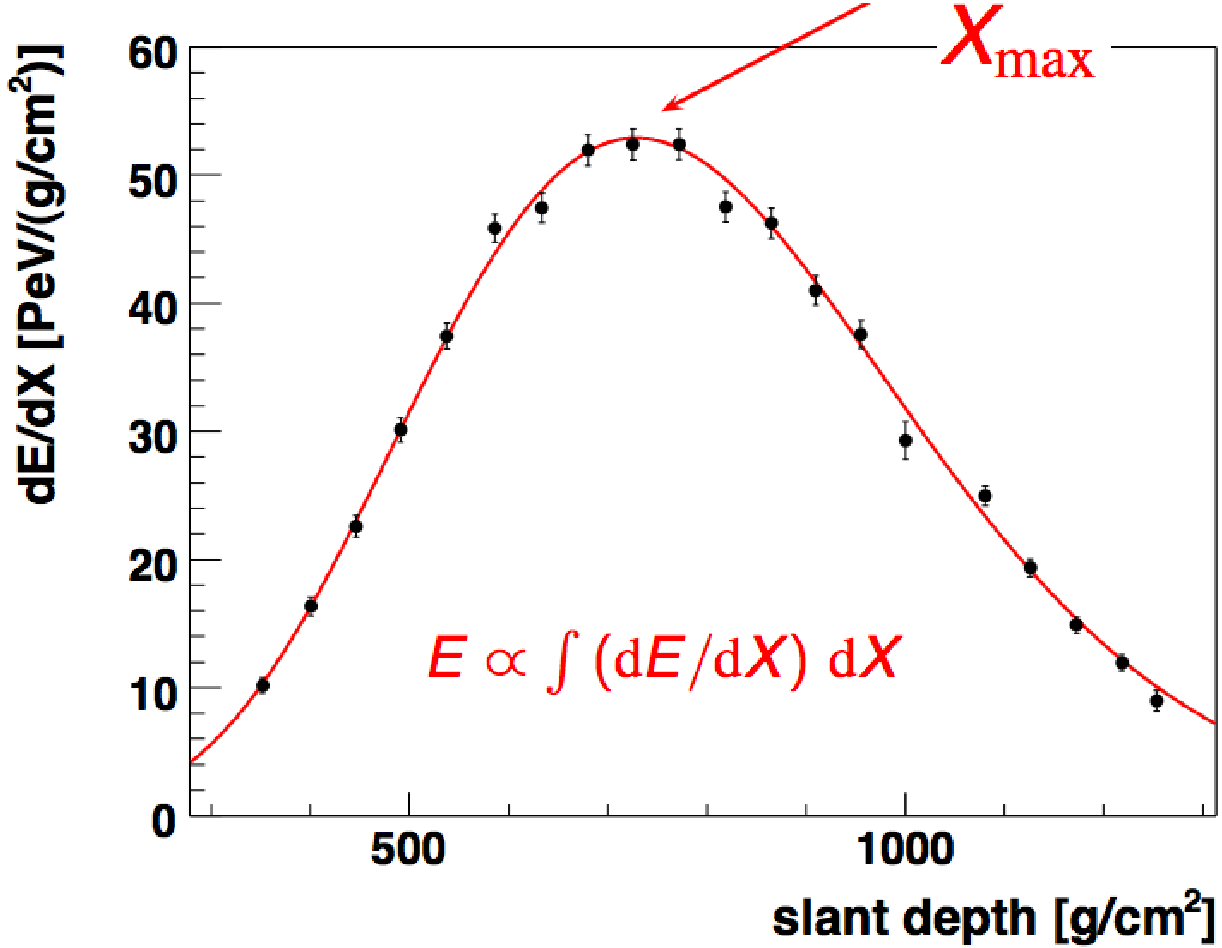


$$L(\Omega) \rightarrow F_{\gamma}(X) \rightarrow N_{e^{\pm}}(X)$$

Observed Light → Emitted Photons → Shower Size

Geometry
Atmospheric Absorption

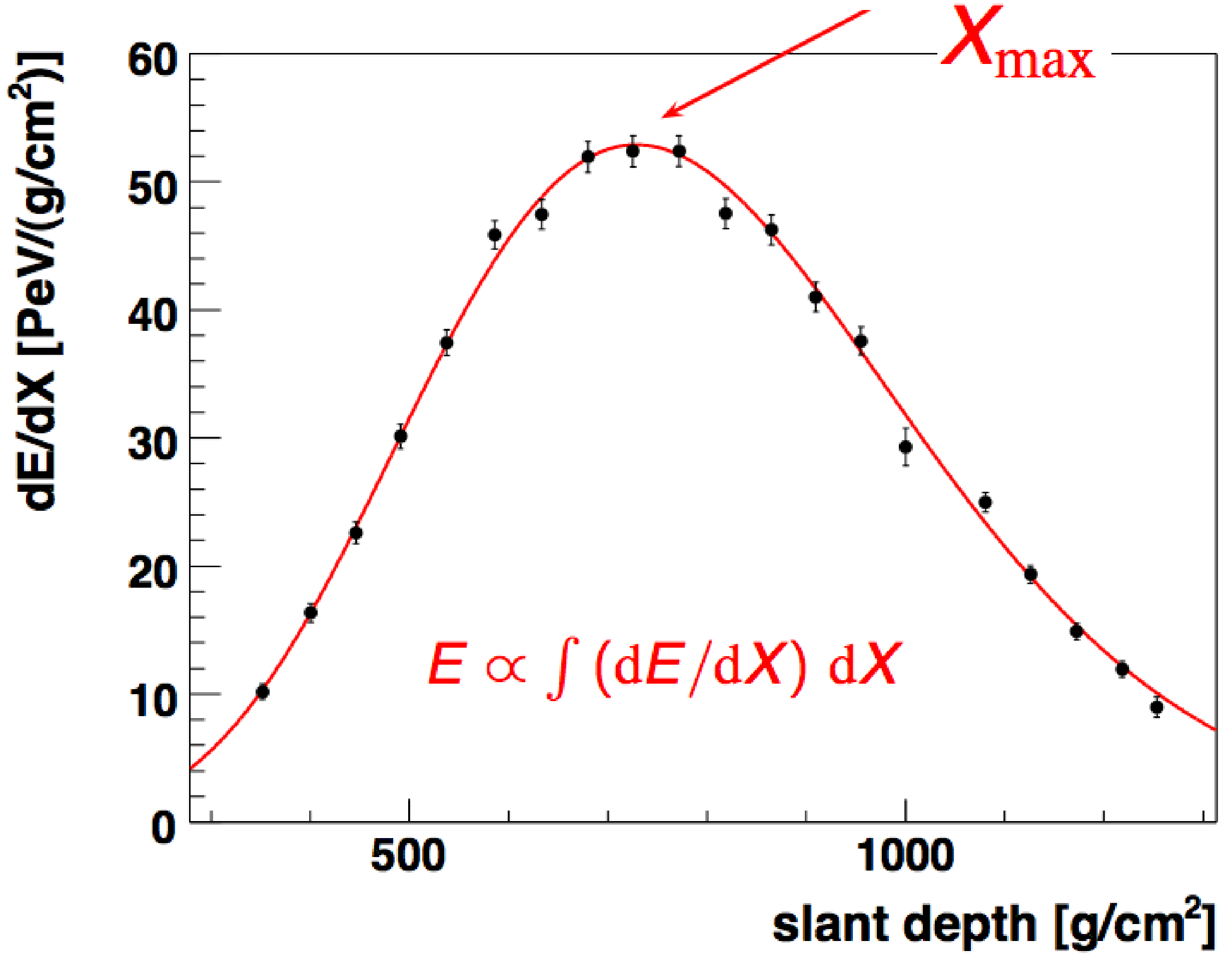
Fluorescence
Yields



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

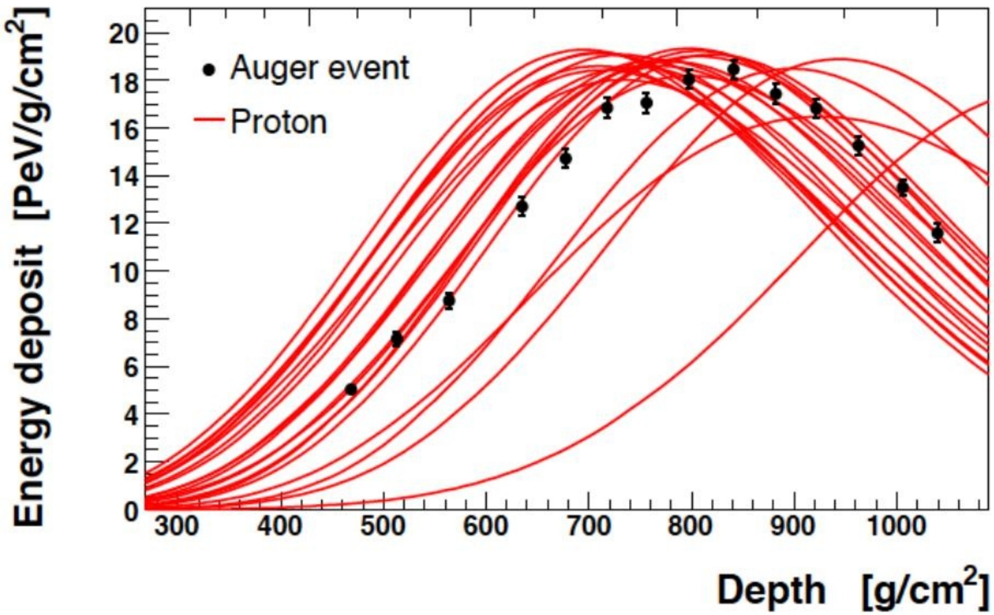
Small Model dependence

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

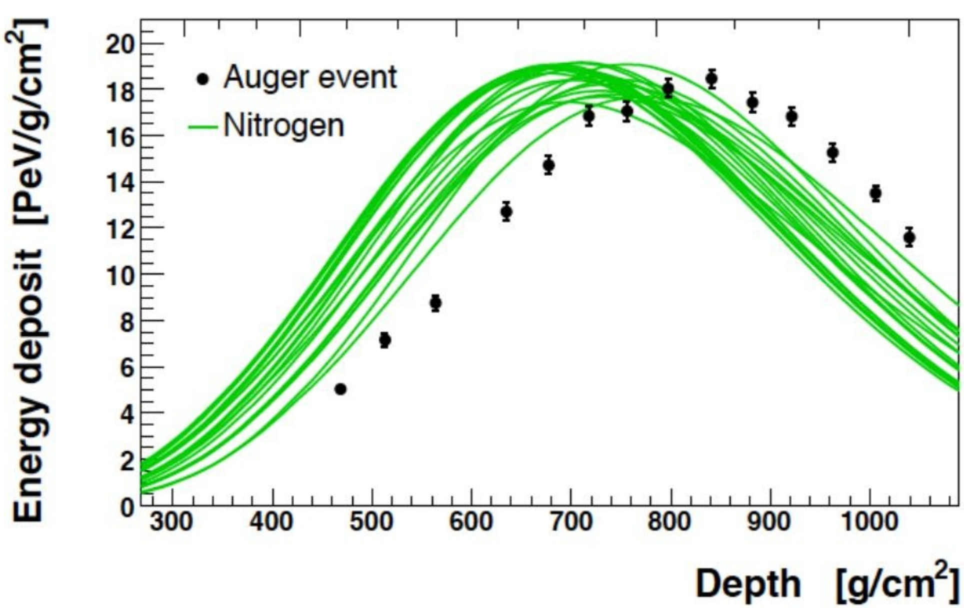


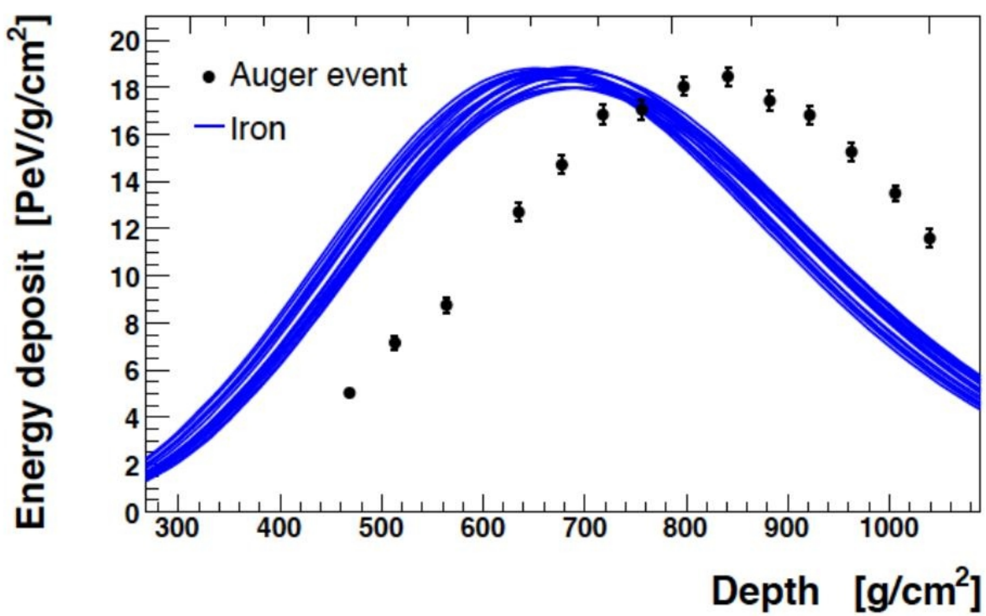
Area $\propto$ Energy

Shape depends on :
- Primary Identity
- Interaction Model



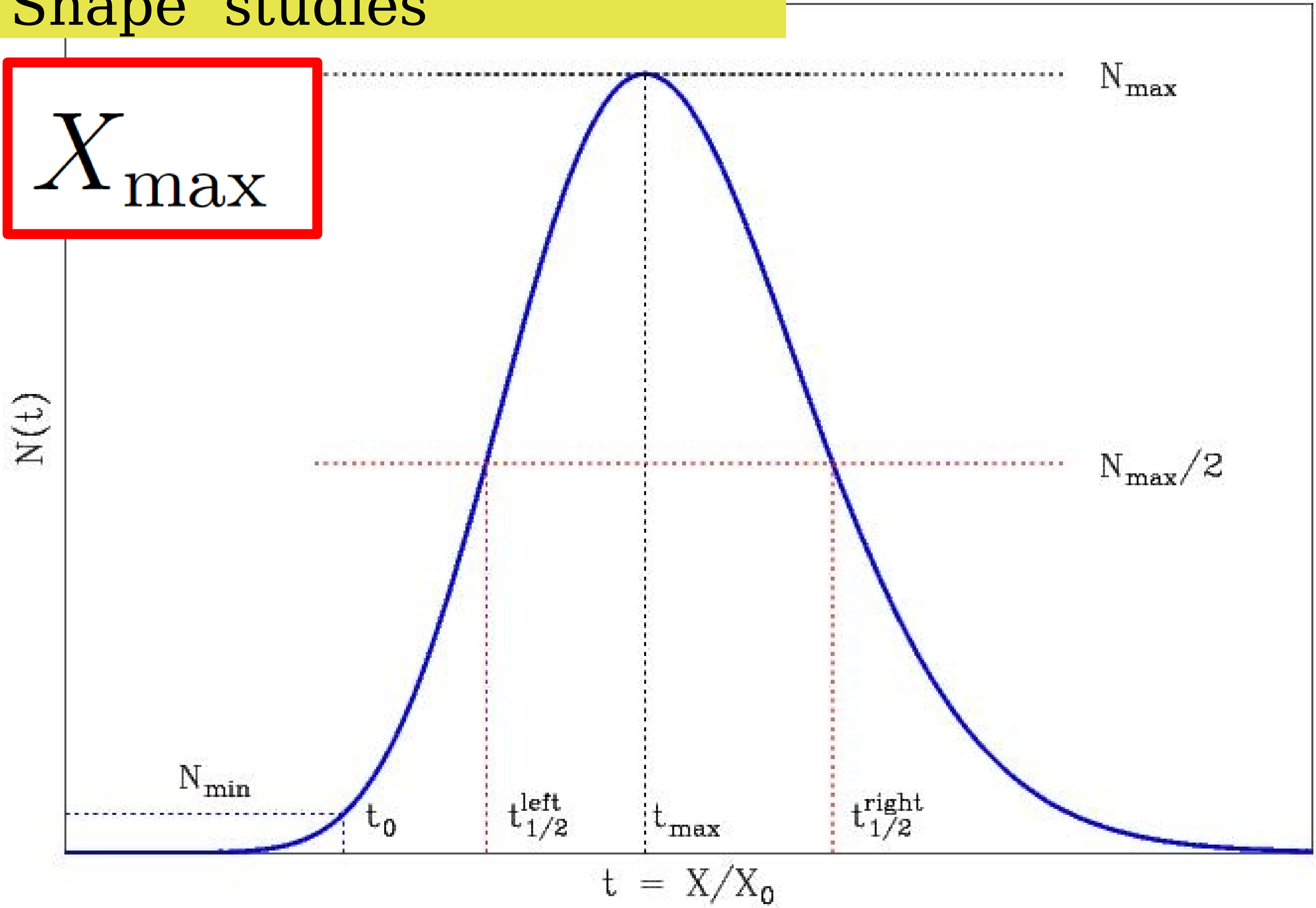
$$E \simeq 10^{19}\,\mathrm{eV}$$





Longitudinal Development
Shape studies

X_{max}

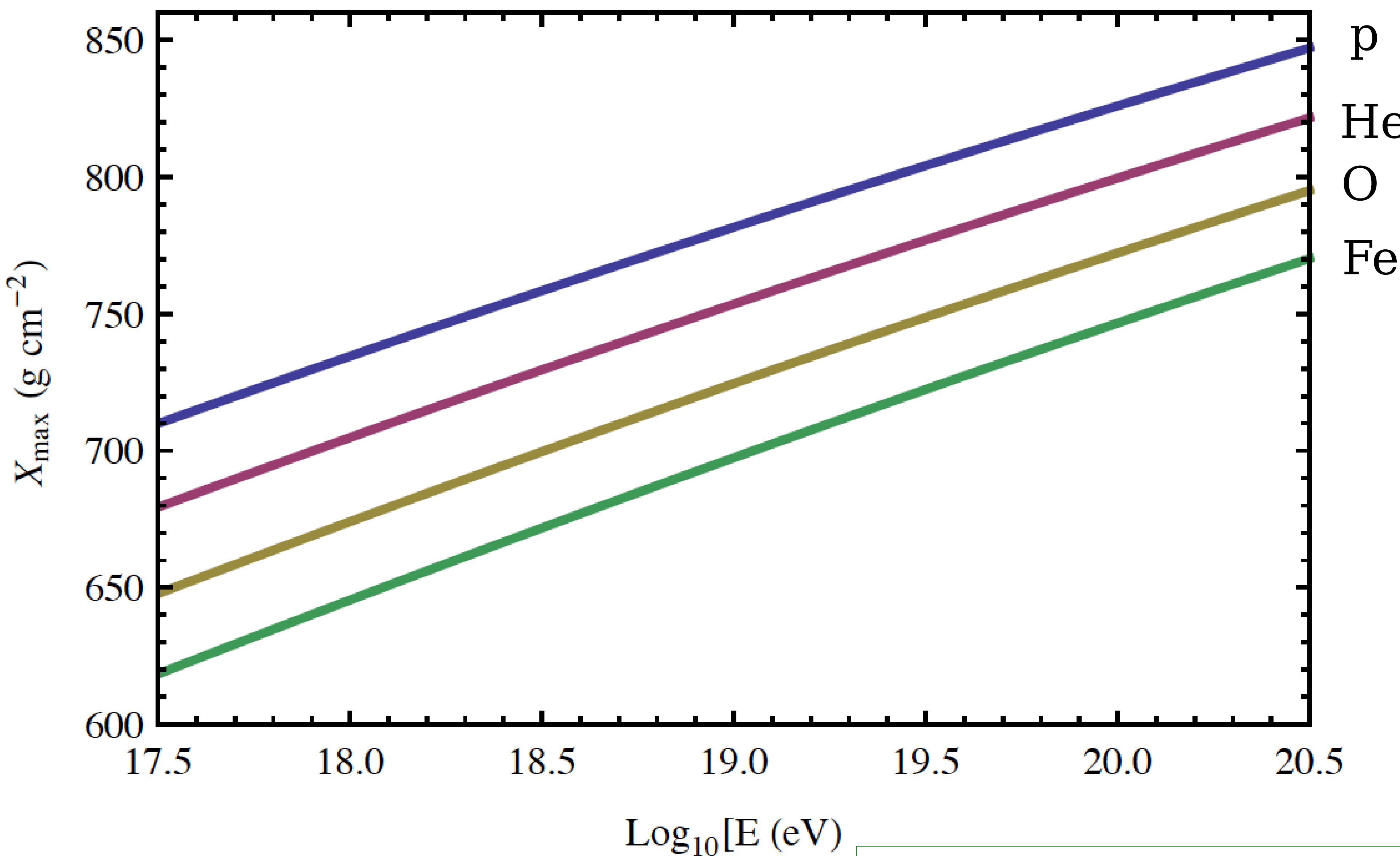


X_{max} and the Composition of Cosmic Rays

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

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

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

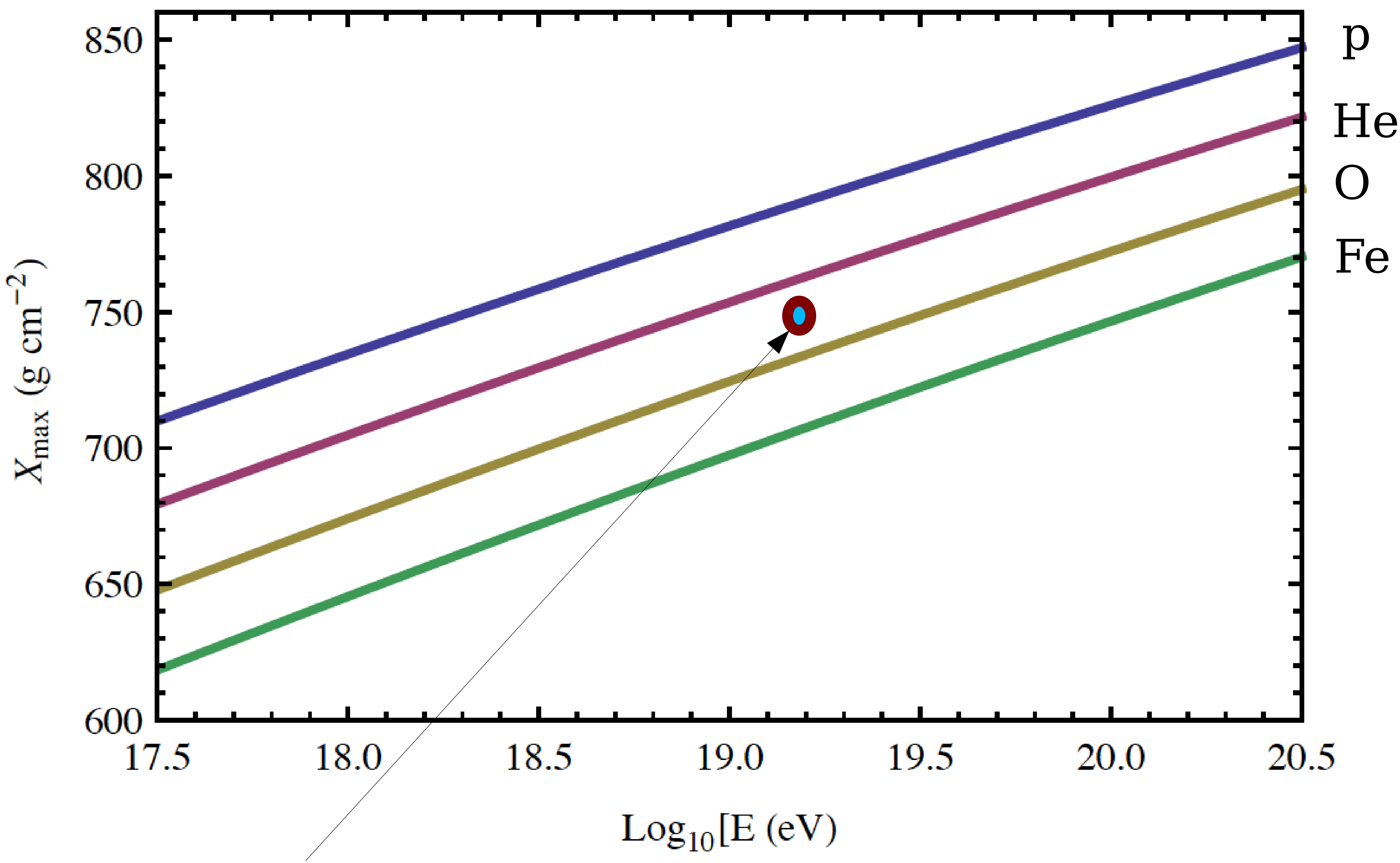


$$\boxed{\langle X_A \rangle \simeq \langle X_p \rangle - D_p \ \log_{10} A}$$

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

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

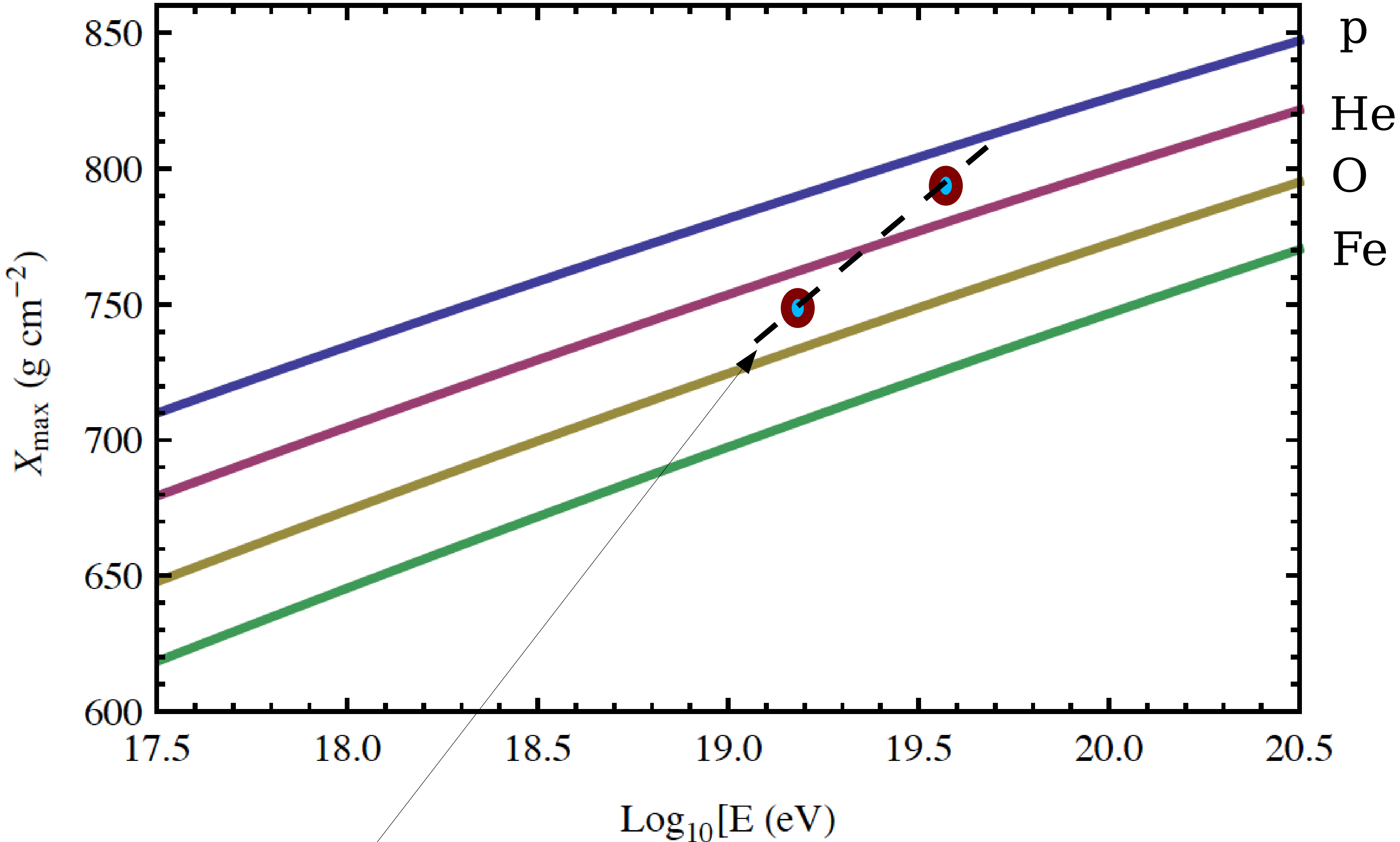
$$\langle X_{\rm Fe} \rangle \simeq \langle X_p \rangle - 90 \text{ g cm}^{-2}$$



Measurements of

$$\langle \log A \rangle$$

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



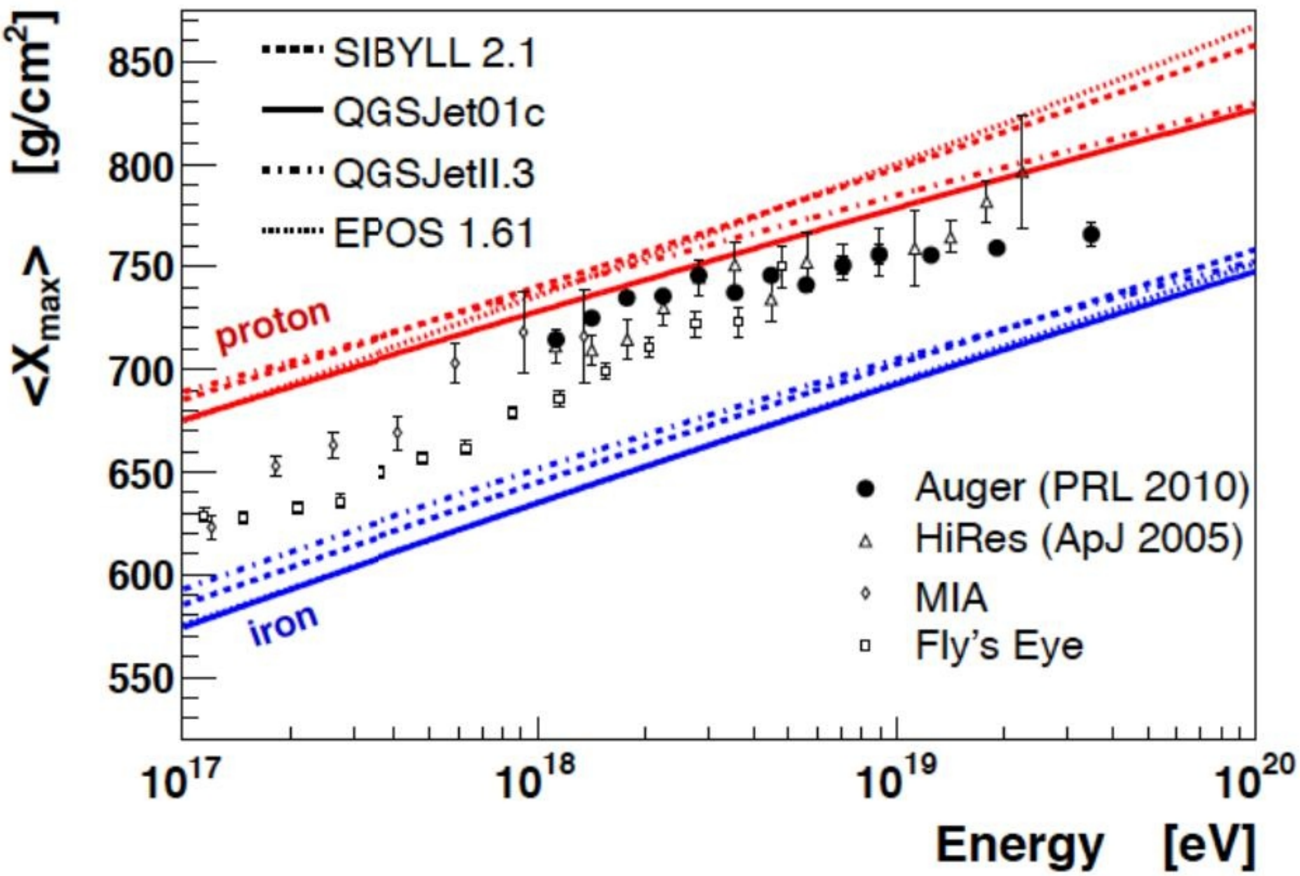
Measurements of Composition evolution.

Obtain the average mass
and its variation
with energy

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

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

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



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
....

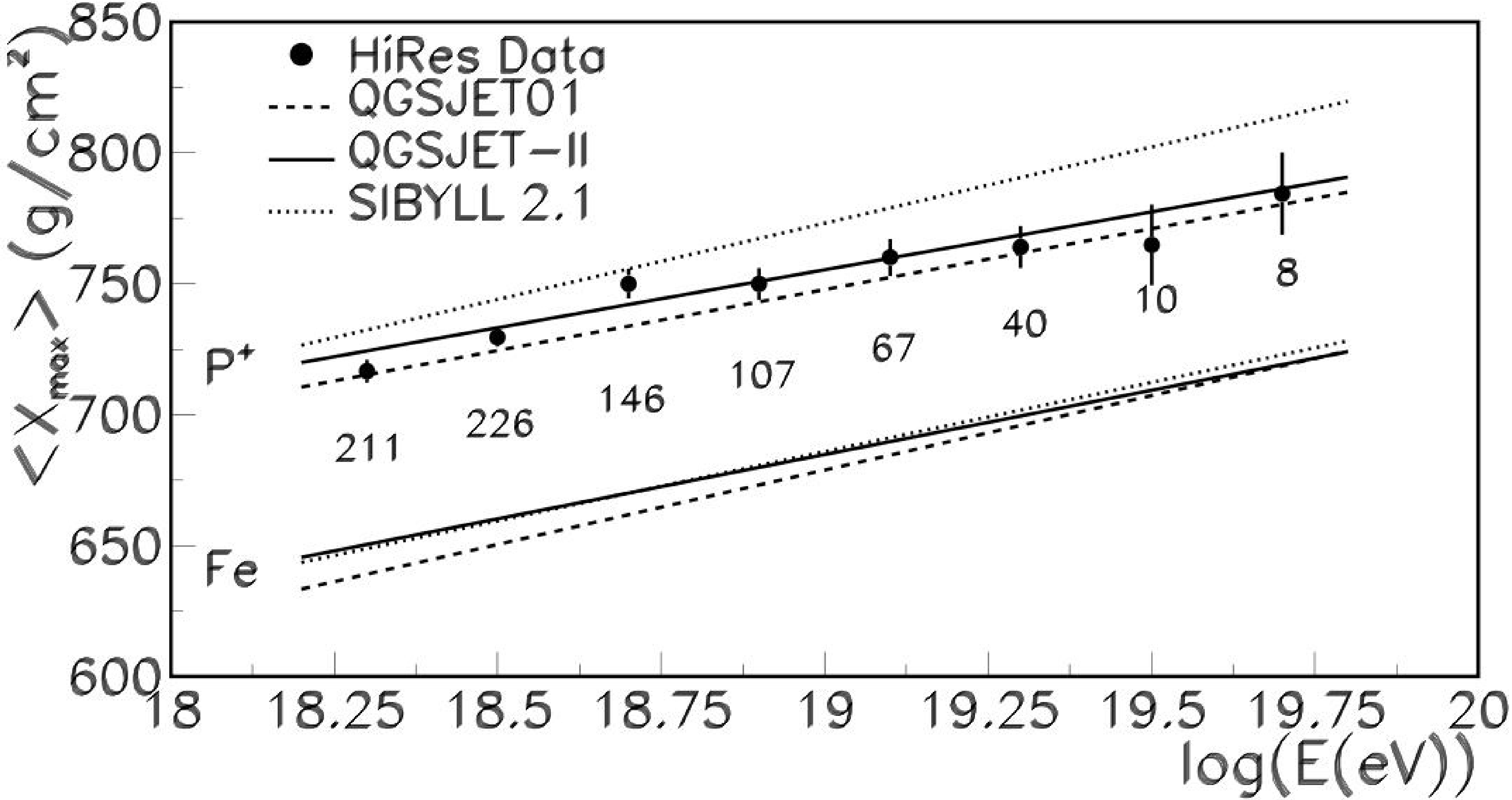
Theoretical curves:

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

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

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

HiRes 2009



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

Importance of
"CORNERS"

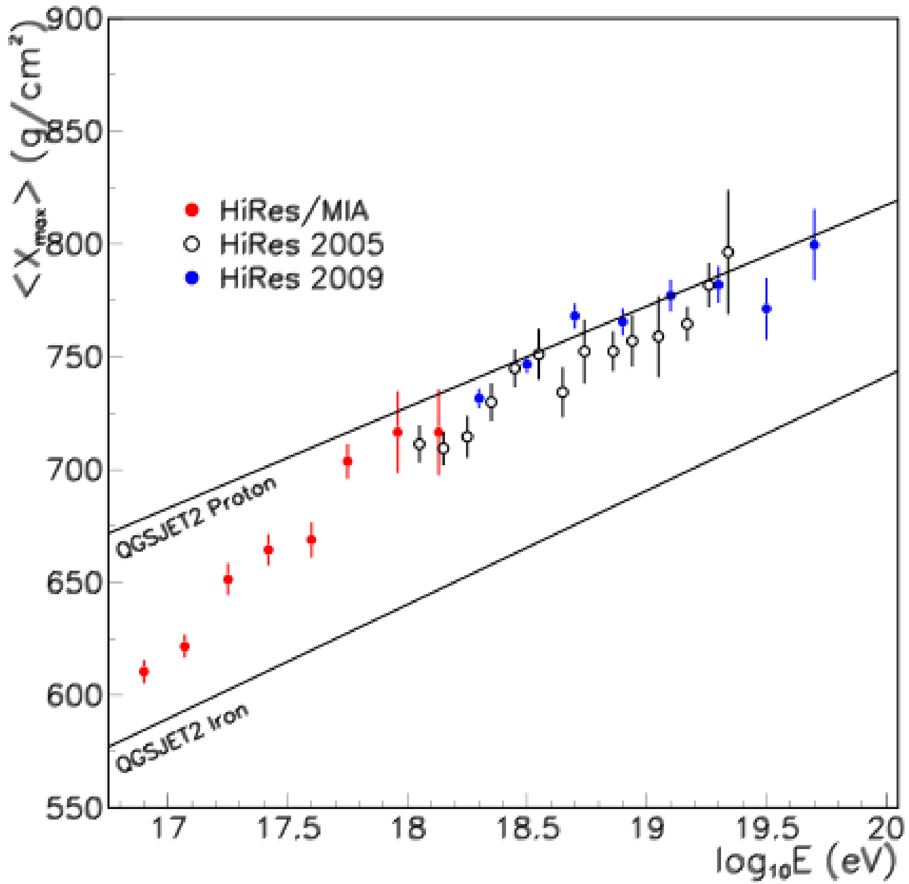
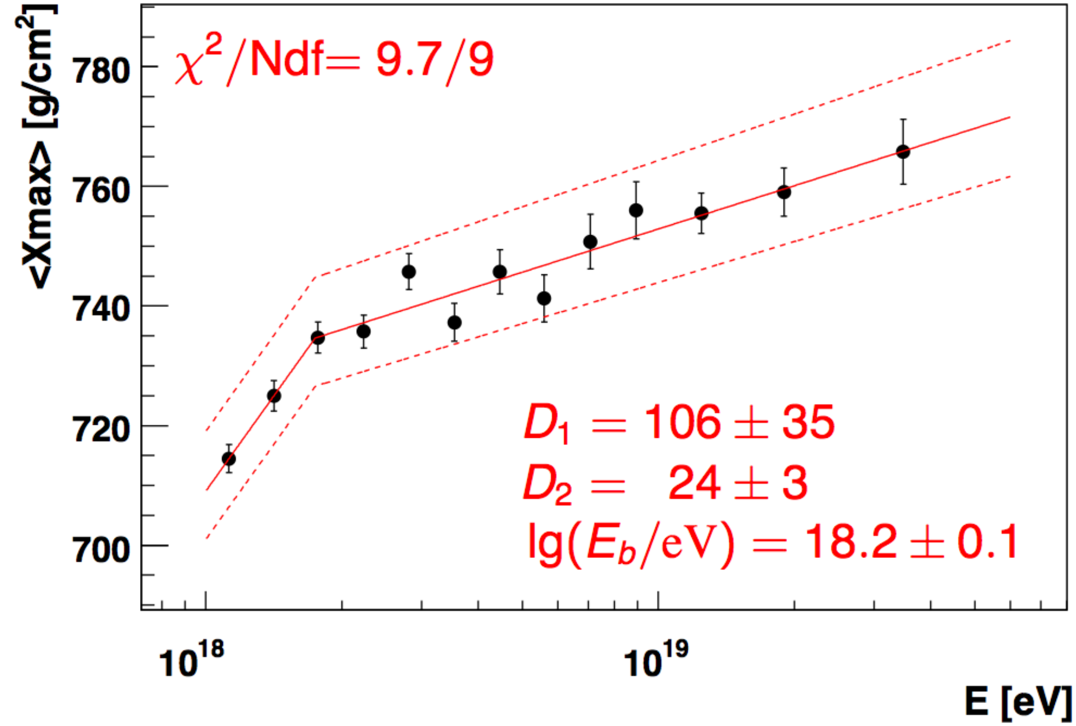


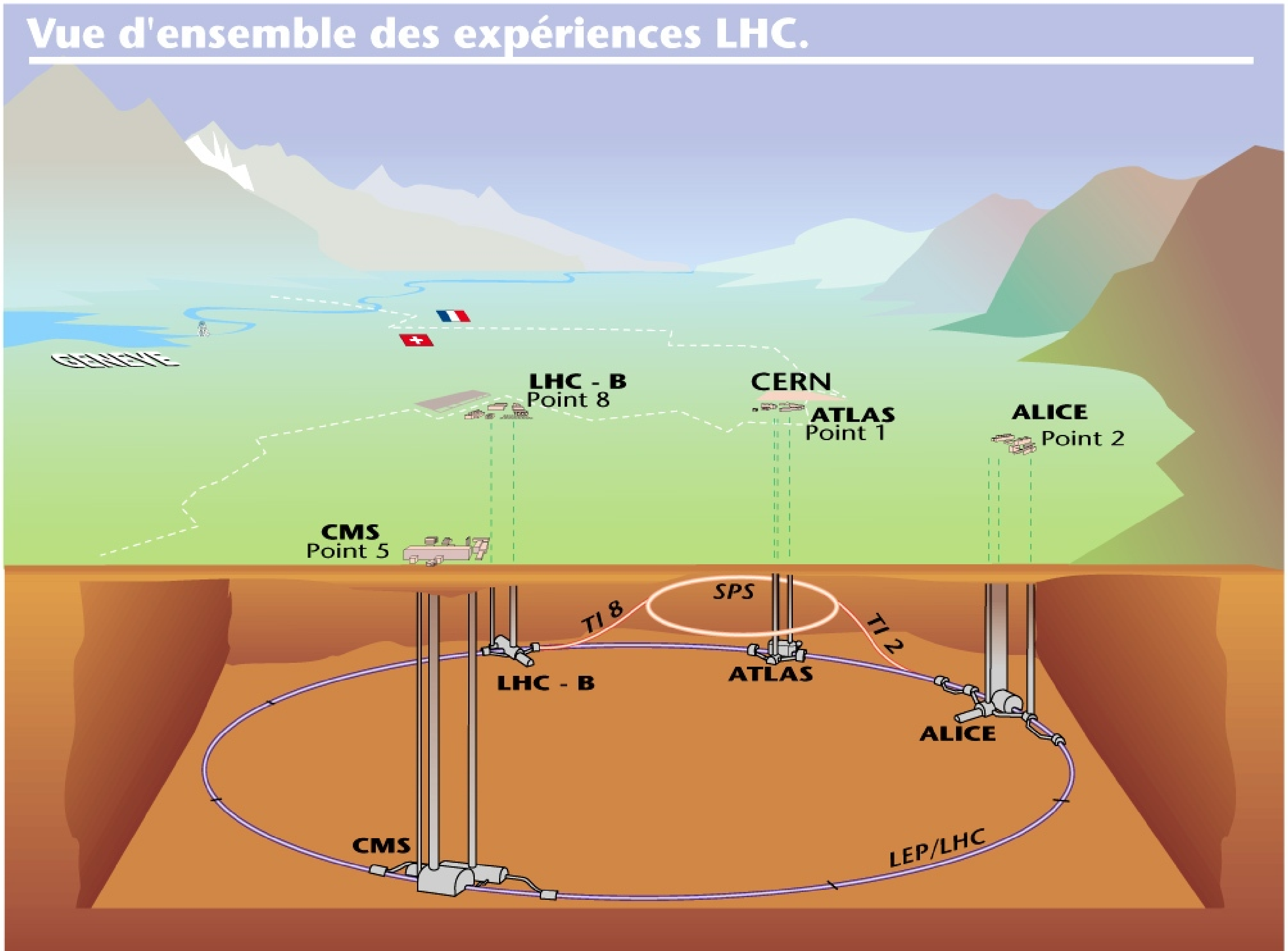
Fig. 25.— Comparison of current HiRes stereo $<X_{max}>$ results with results from the HiRes-prototype/MIA hybrid (Abu-Zayyad et al. 2001) and previously published HiRes stereo results (Abbasi et al. 2005).



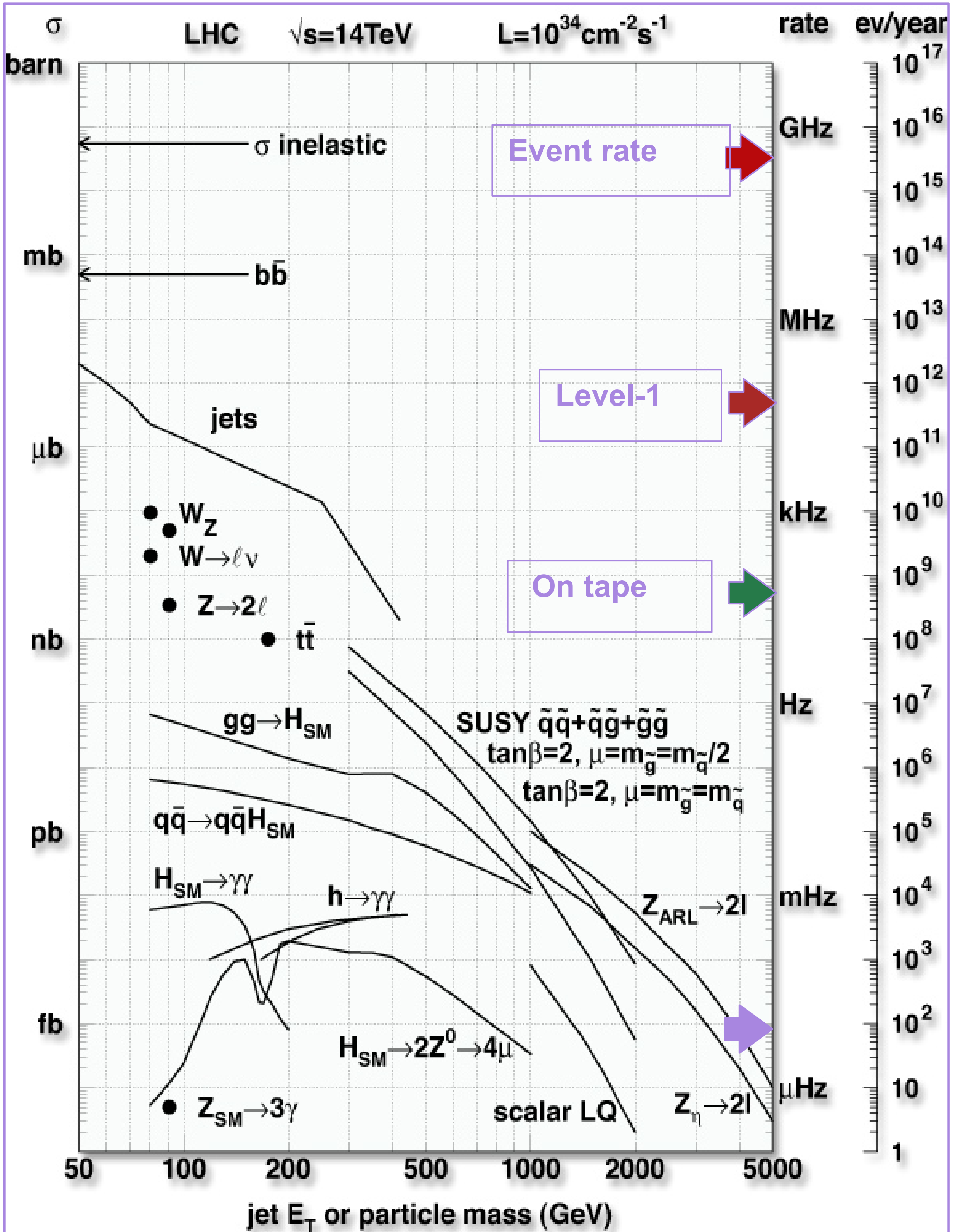
Abrupt change in the variation of the properties of hadronic interactions with energy

Abrupt change in the composition evolution.

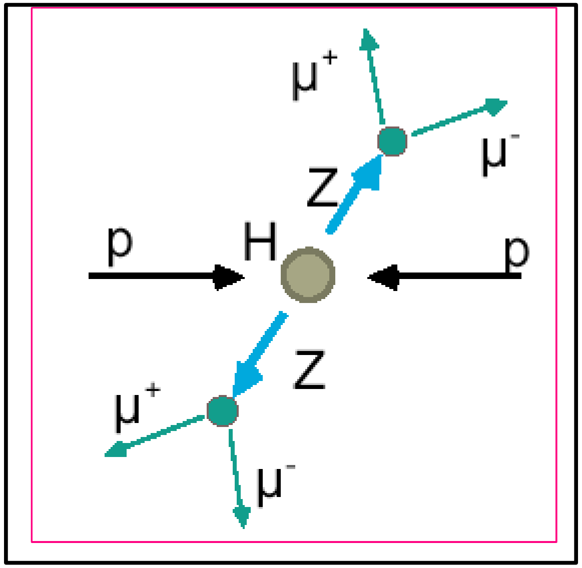
Very Important potential of LHC

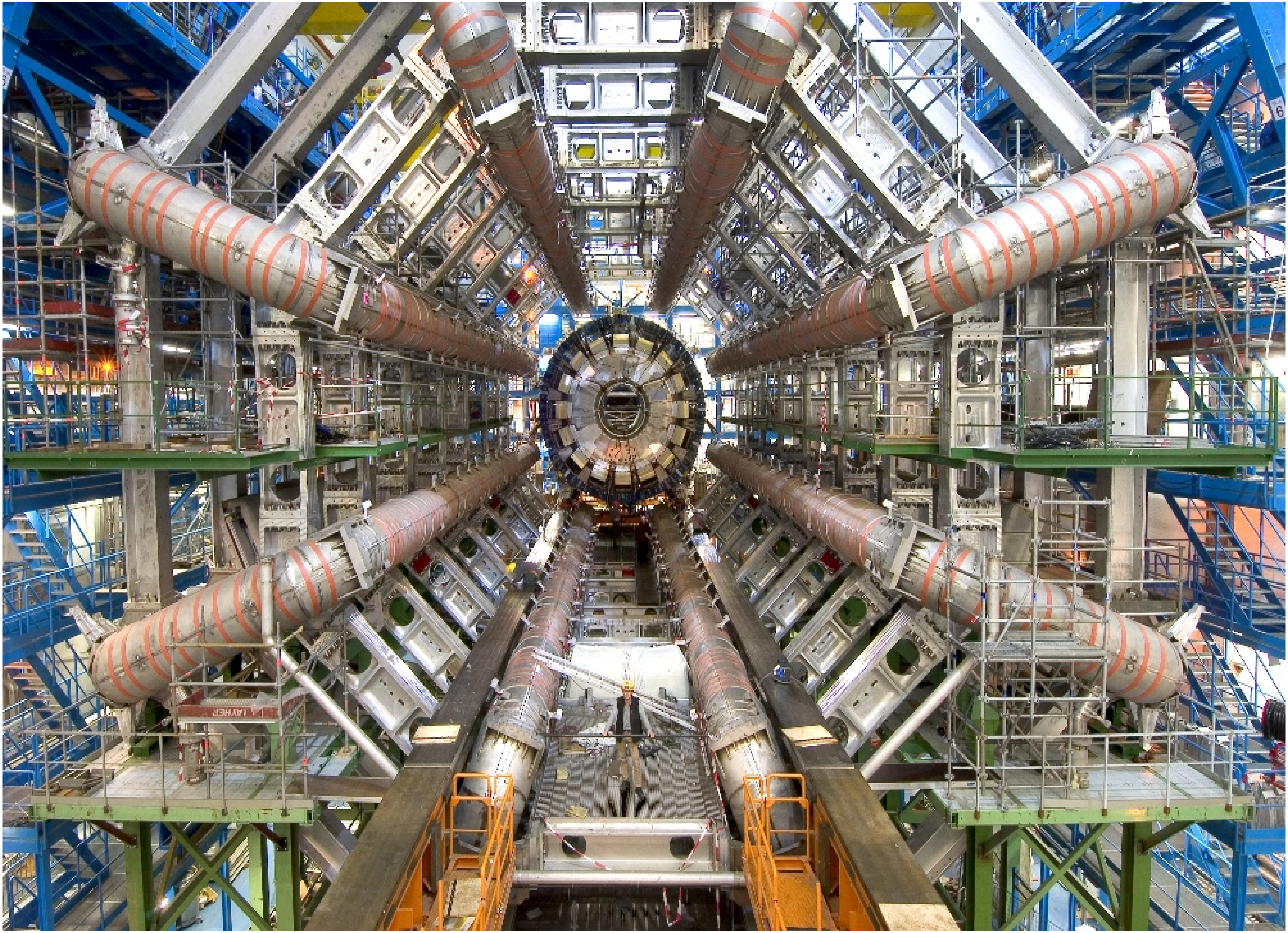


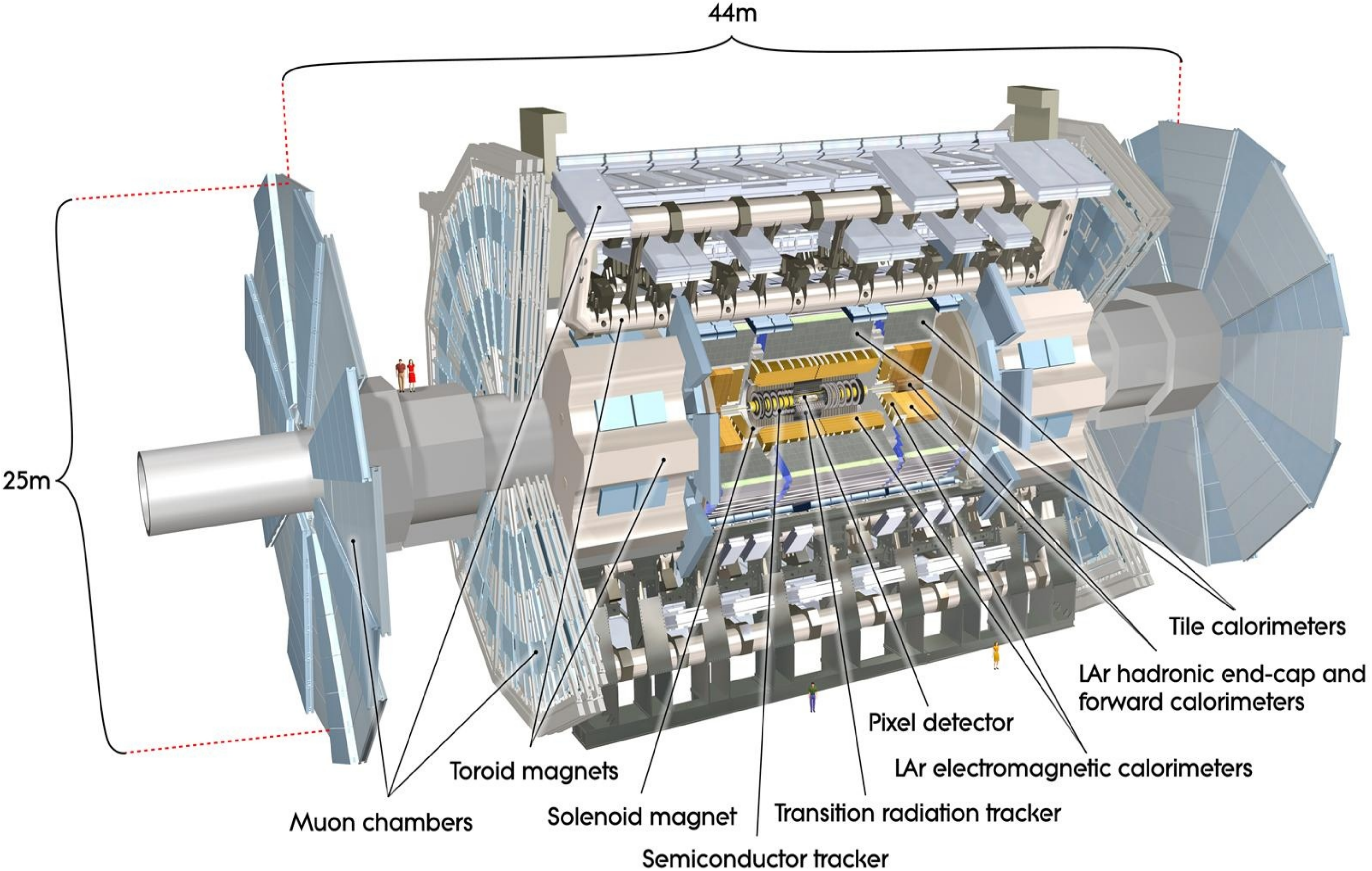
7 + 7 TeV
PP collider

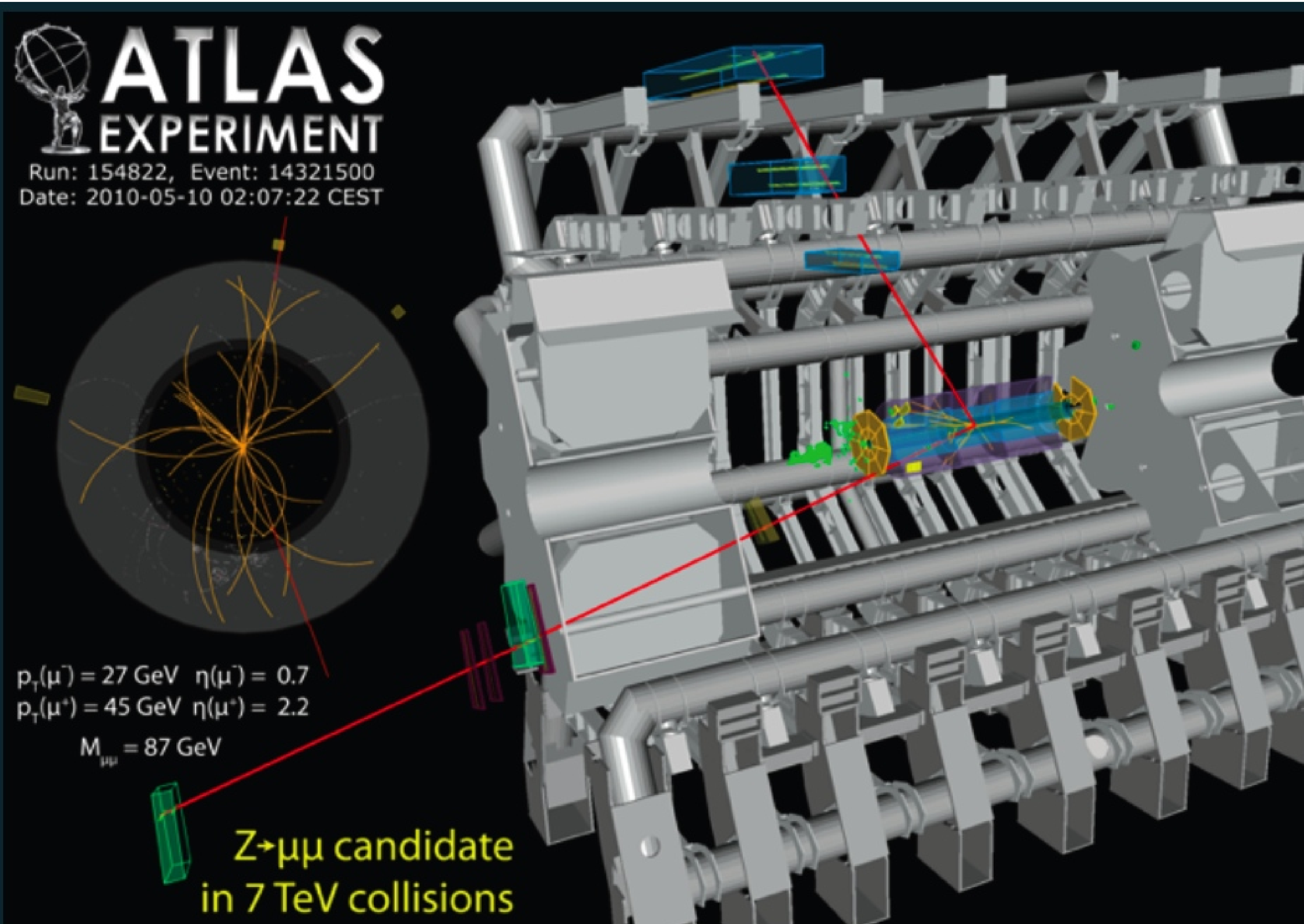


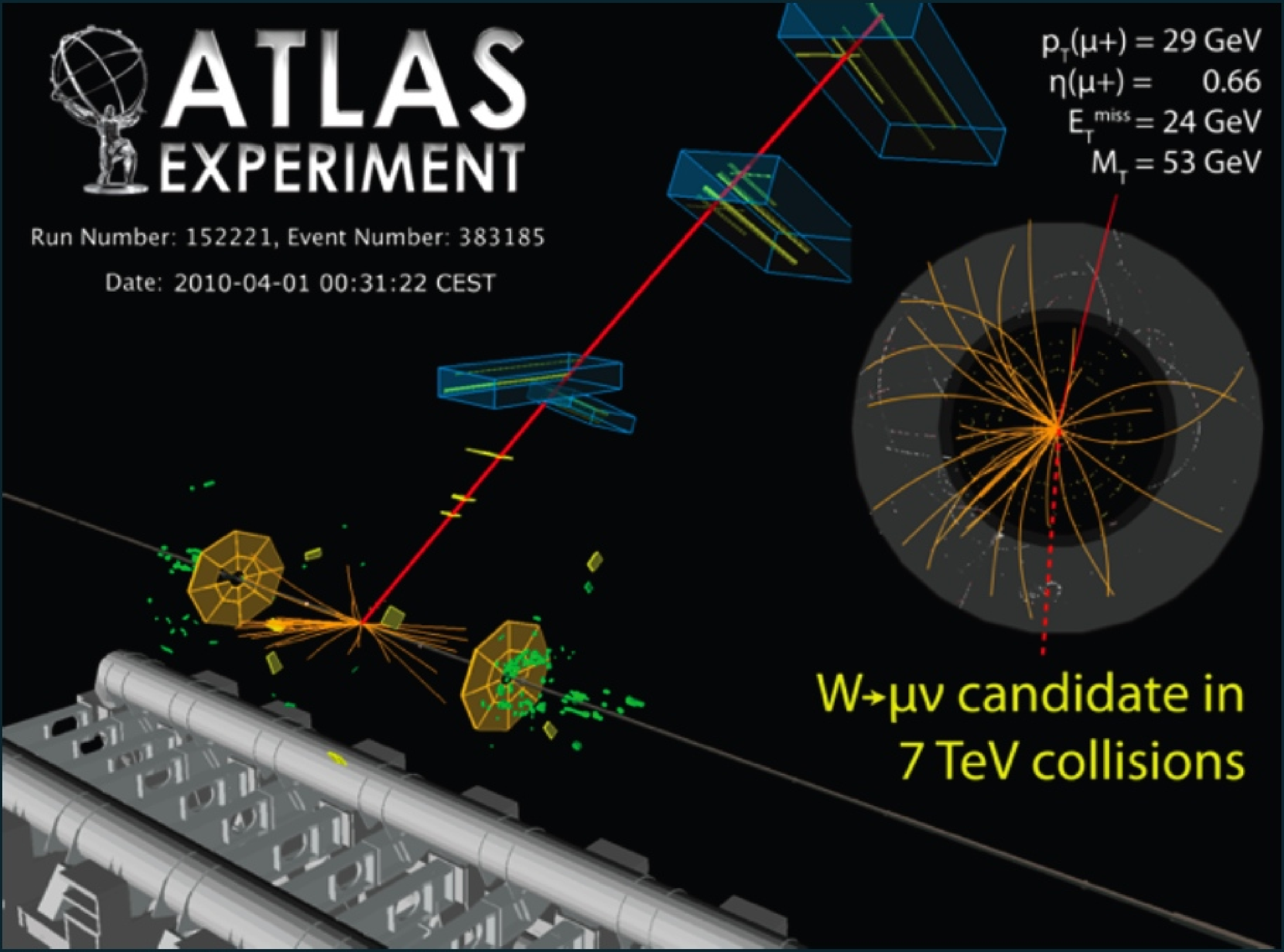
Higgs discovery golden channel

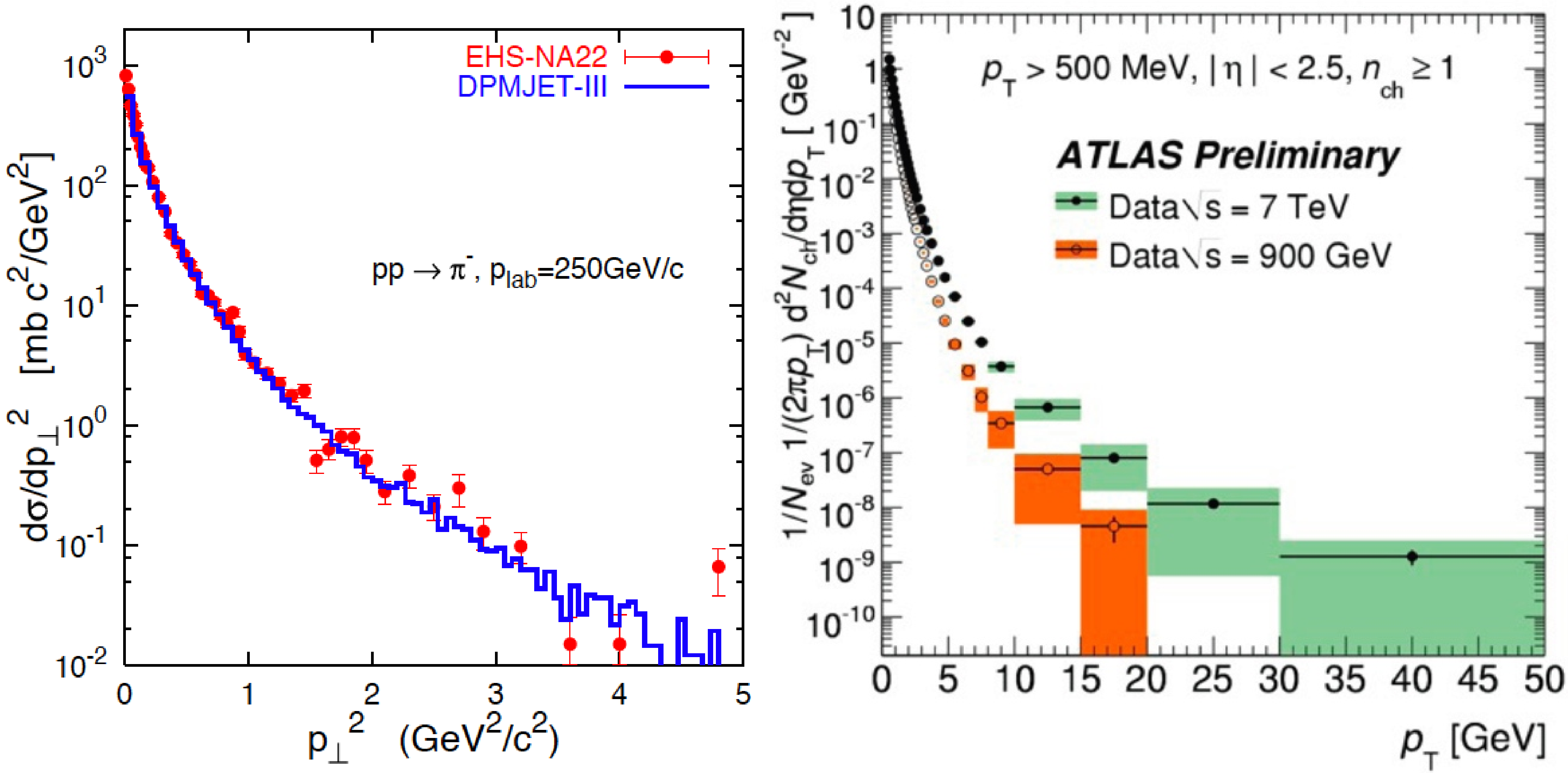





44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker


ATLAS
EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV
$Z \to \mu\mu$ candidate
in 7 TeV collisions

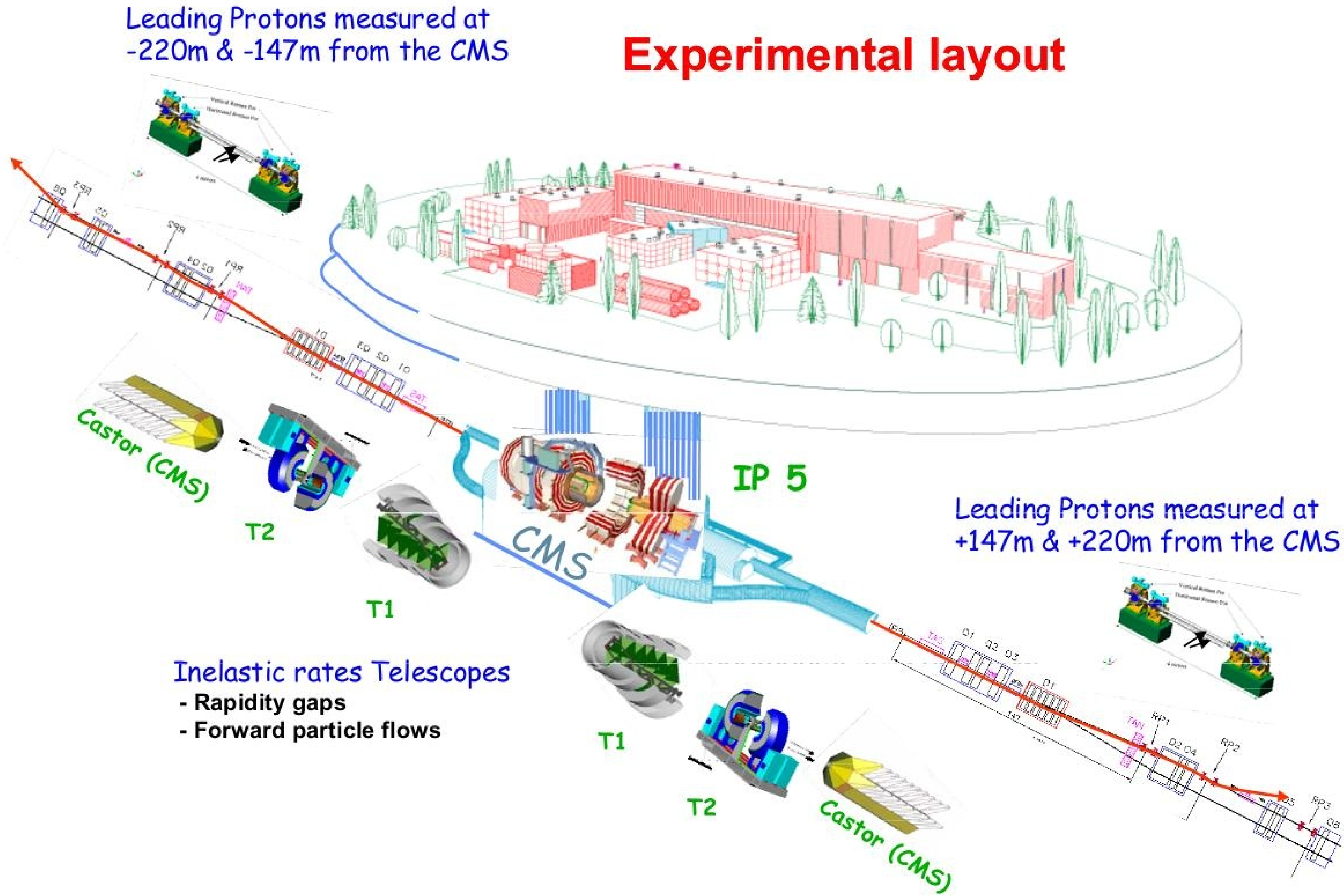

ATLAS EXPERIMENT
Run Number: 152221, Event Number: 383185
Date: 2010-04-01 00:31:22 CEST
$p_T(\mu+)$ = 29 GeV
$\eta(\mu+)$ = 0.66
E_T^{miss} = 24 GeV
M_T = 53 GeV
W→μν candidate in
7 TeV collisions



EHS-NA22
DPMJET-III
pp → π⁻, p_lab=250GeV/c
dσ/dp⊥² [mb c²/GeV²]
p⊥² (GeV²/c²)
p_T > 500 MeV, |η| < 2.5, n_ch ≥ 1
ATLAS Preliminary
Data √s = 7 TeV
Data √s = 900 GeV
1/N_ev 1/(2πp_T) d²N_ch/dηdp_T [GeV⁻²]
p_T [GeV]

TOTEM

Experimental layout

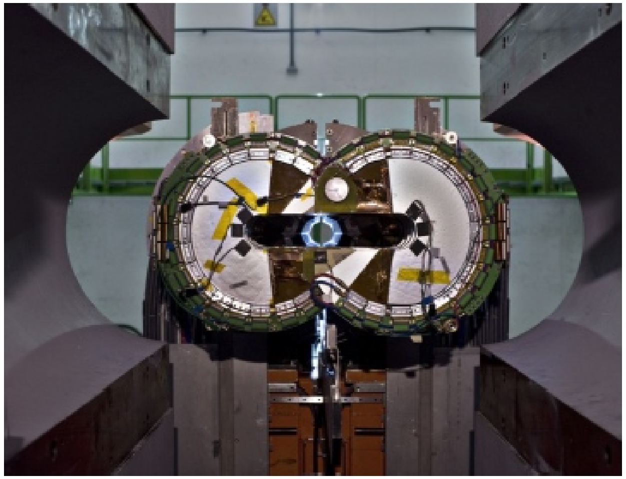


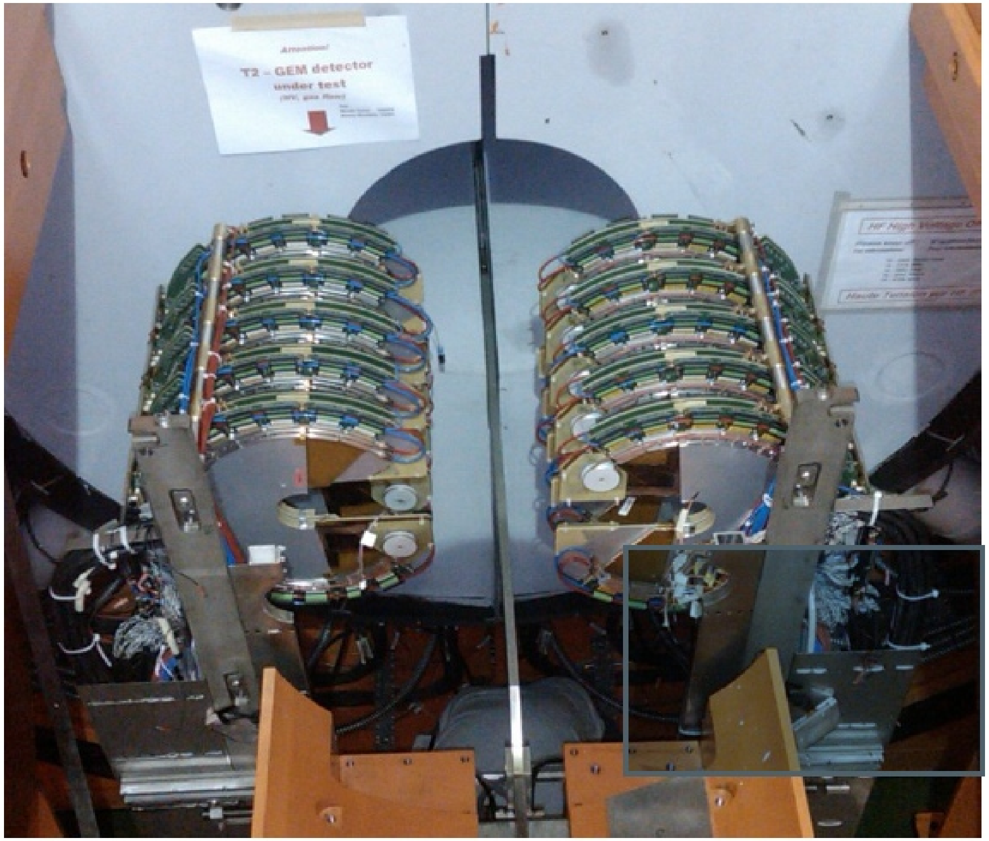
T2 Telescope

2 arms of GEMs for tracks and vertex reconstruction

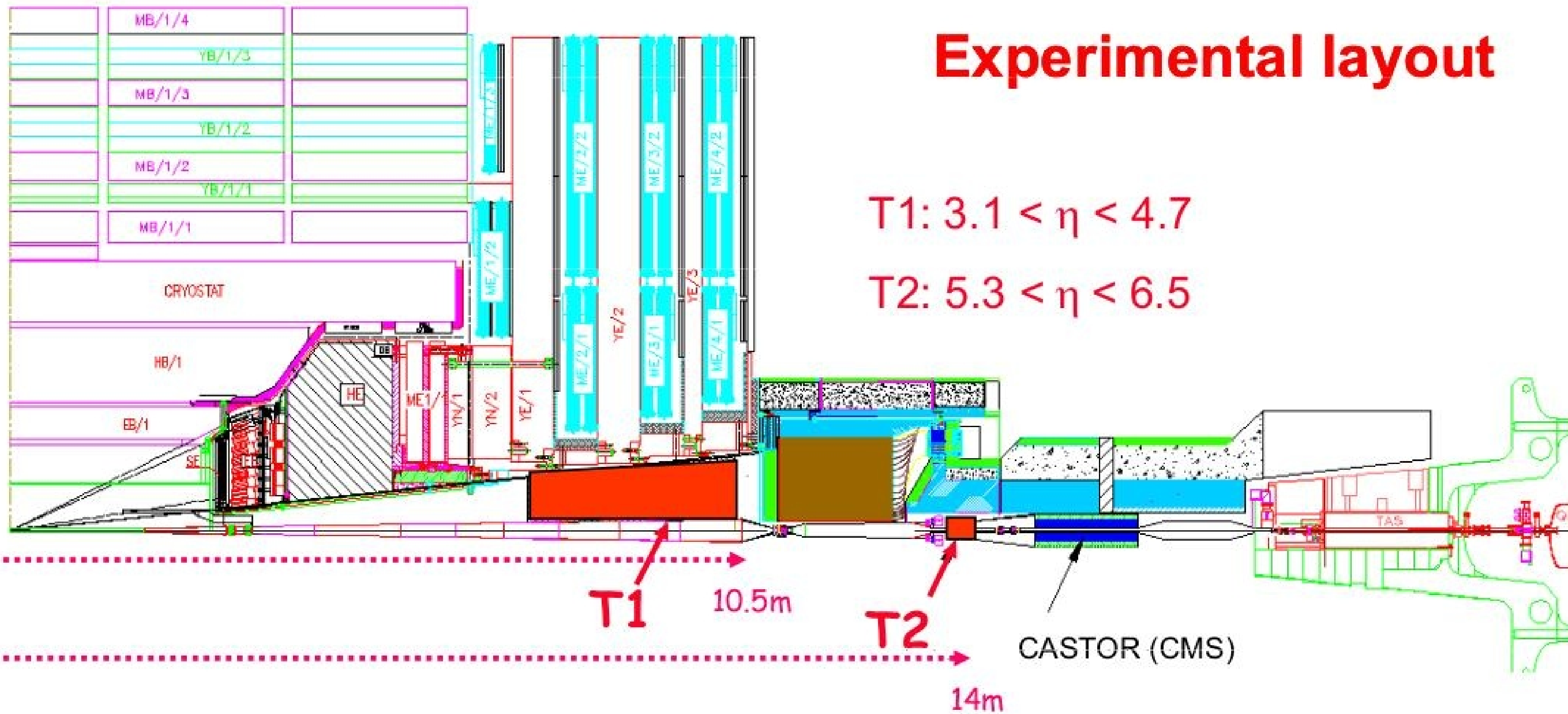
$5.2<|\eta|<6.5 \quad \Delta\phi=2\pi$

Both arms installed and taking data



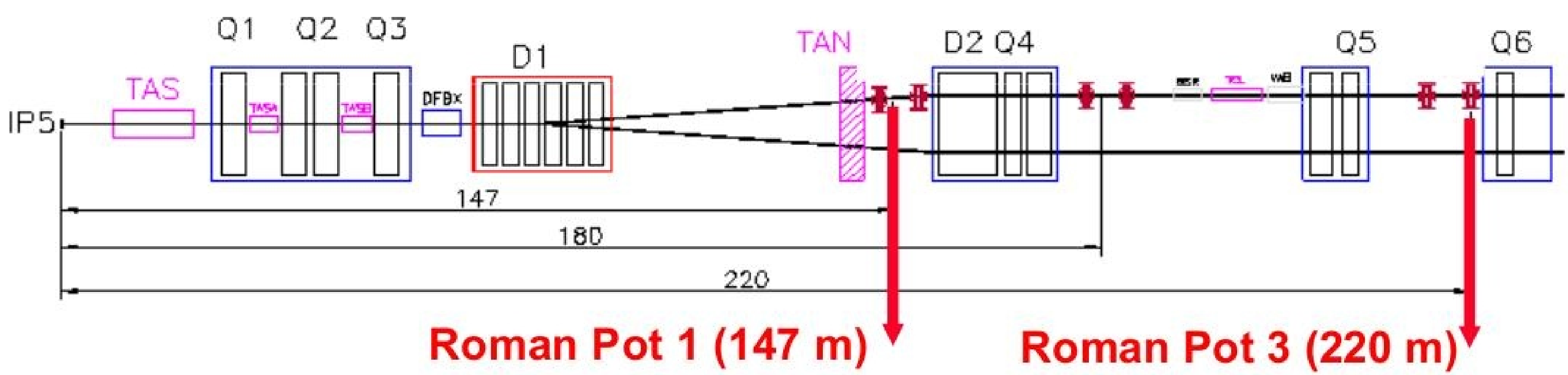


Experimental layout

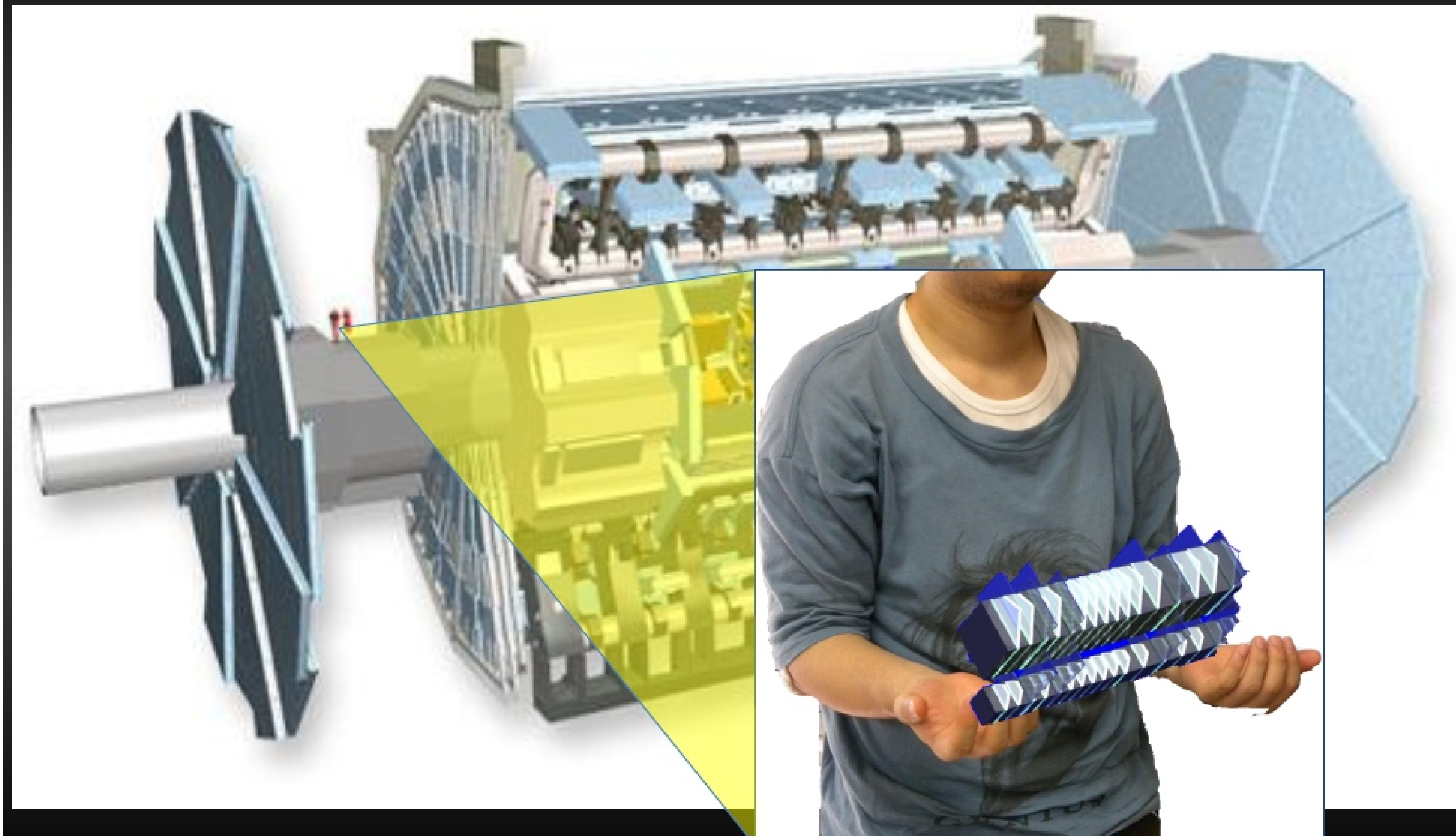


T1: $3.1 < \eta < 4.7$

T2: $5.3 < \eta < 6.5$

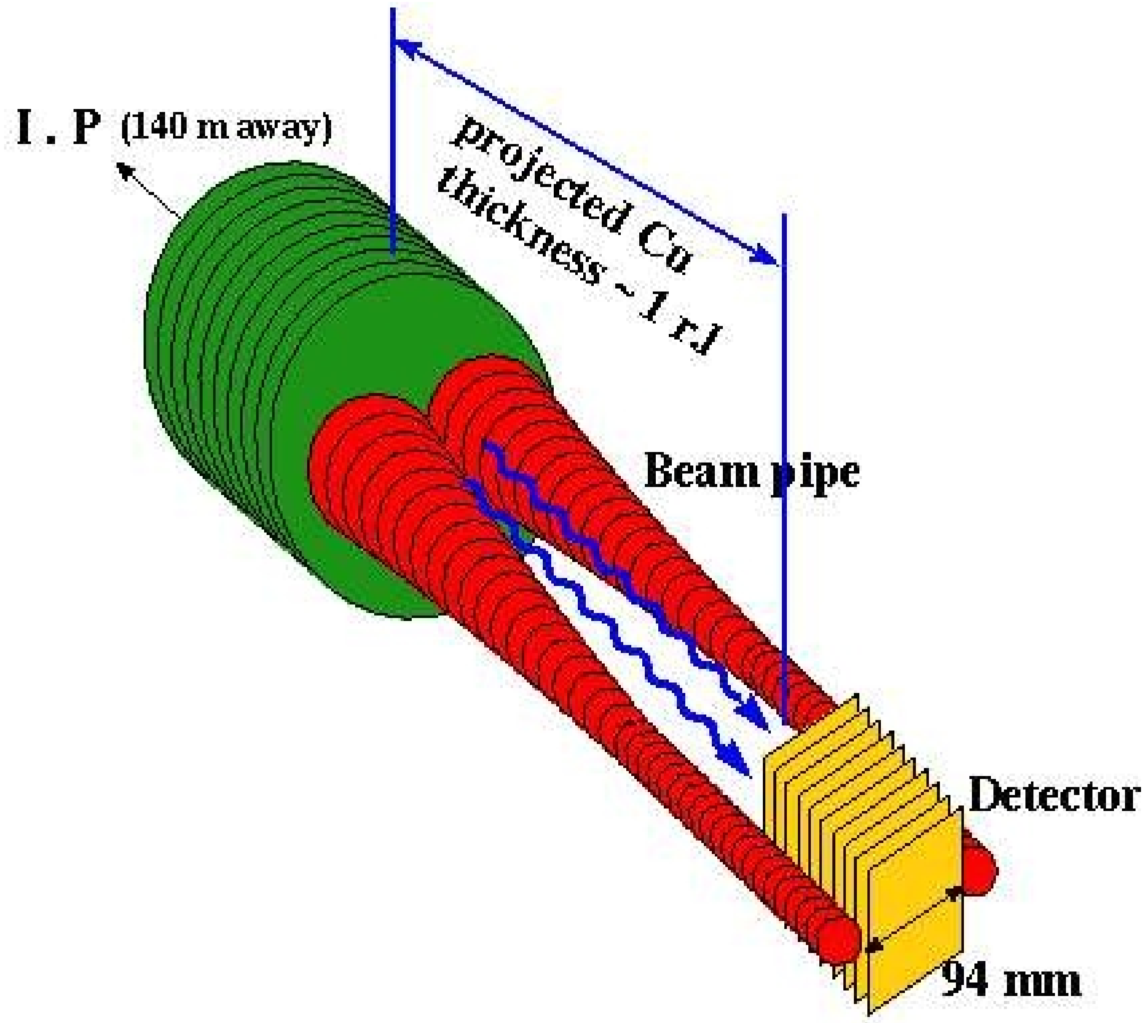


ATLAS & LHCf

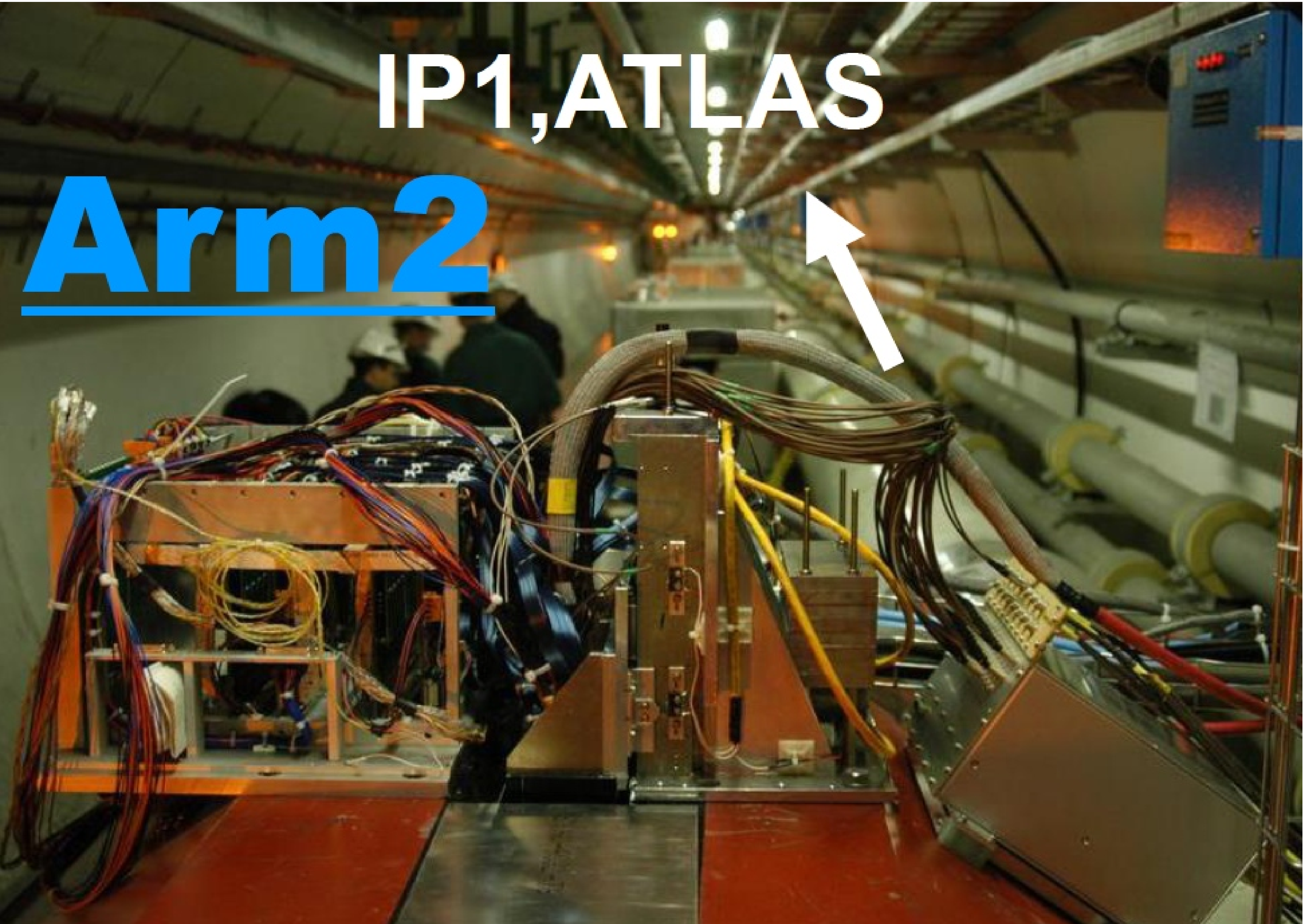


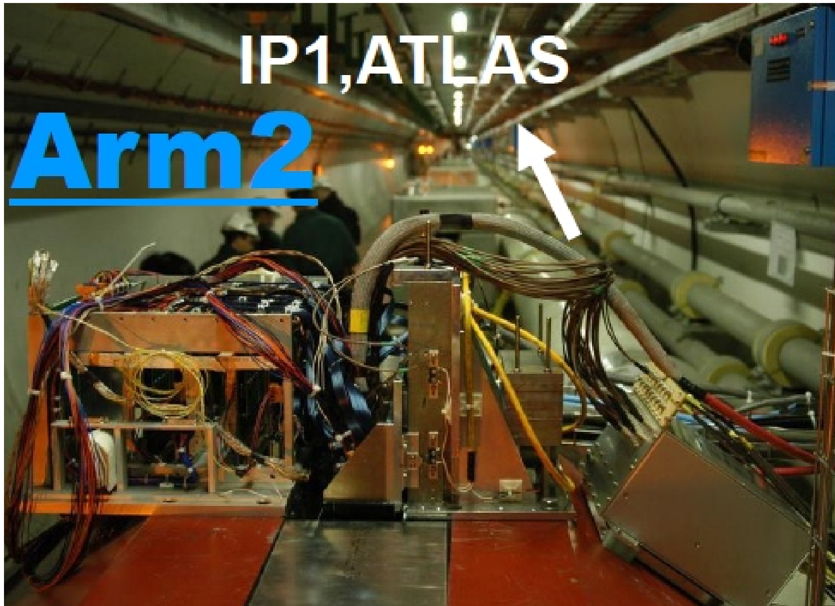
LHCF

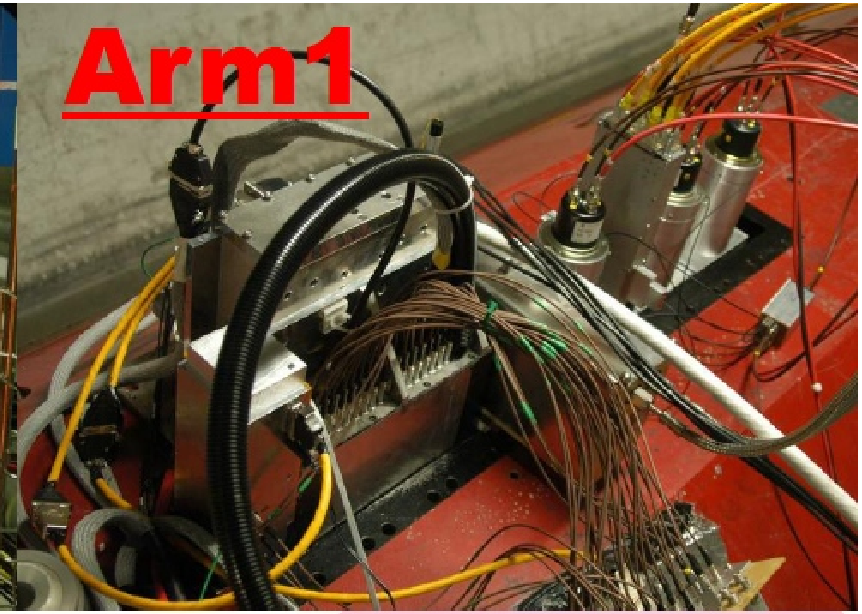
Calorimeter
for neutral particles
in the very forward region

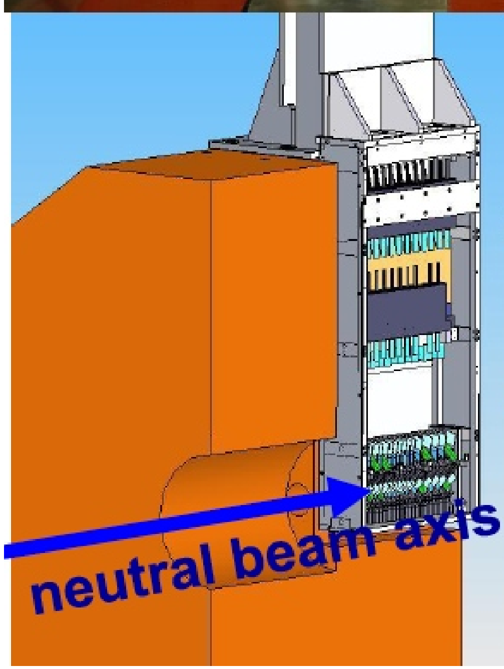


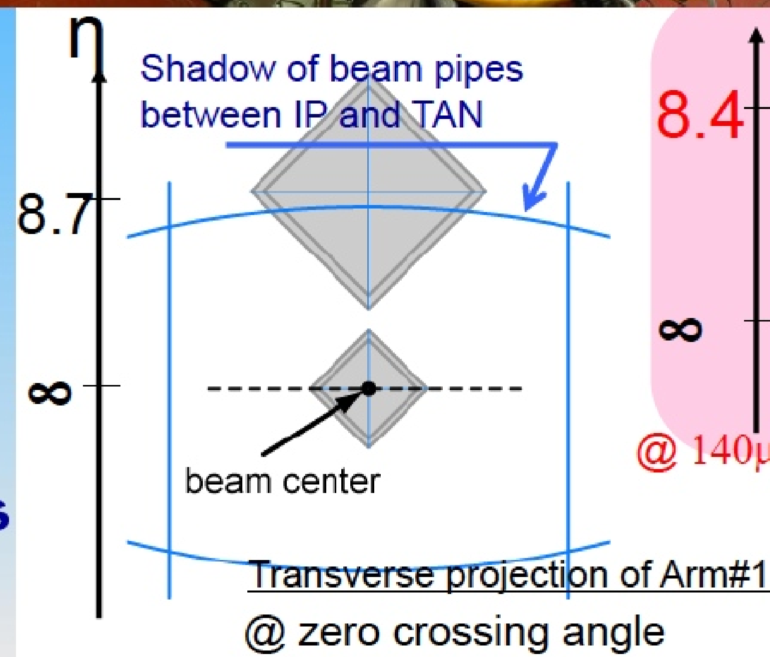
Two
non-identical
Detectors

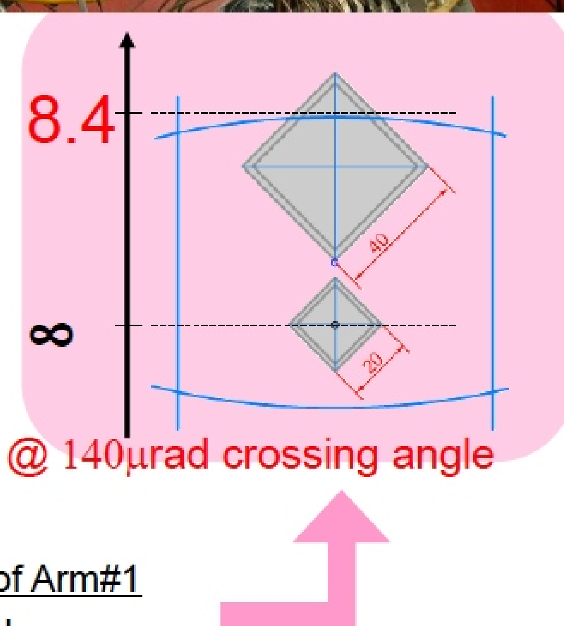

IP1,ATLAS
Arm2


IP1,ATLAS
Arm2

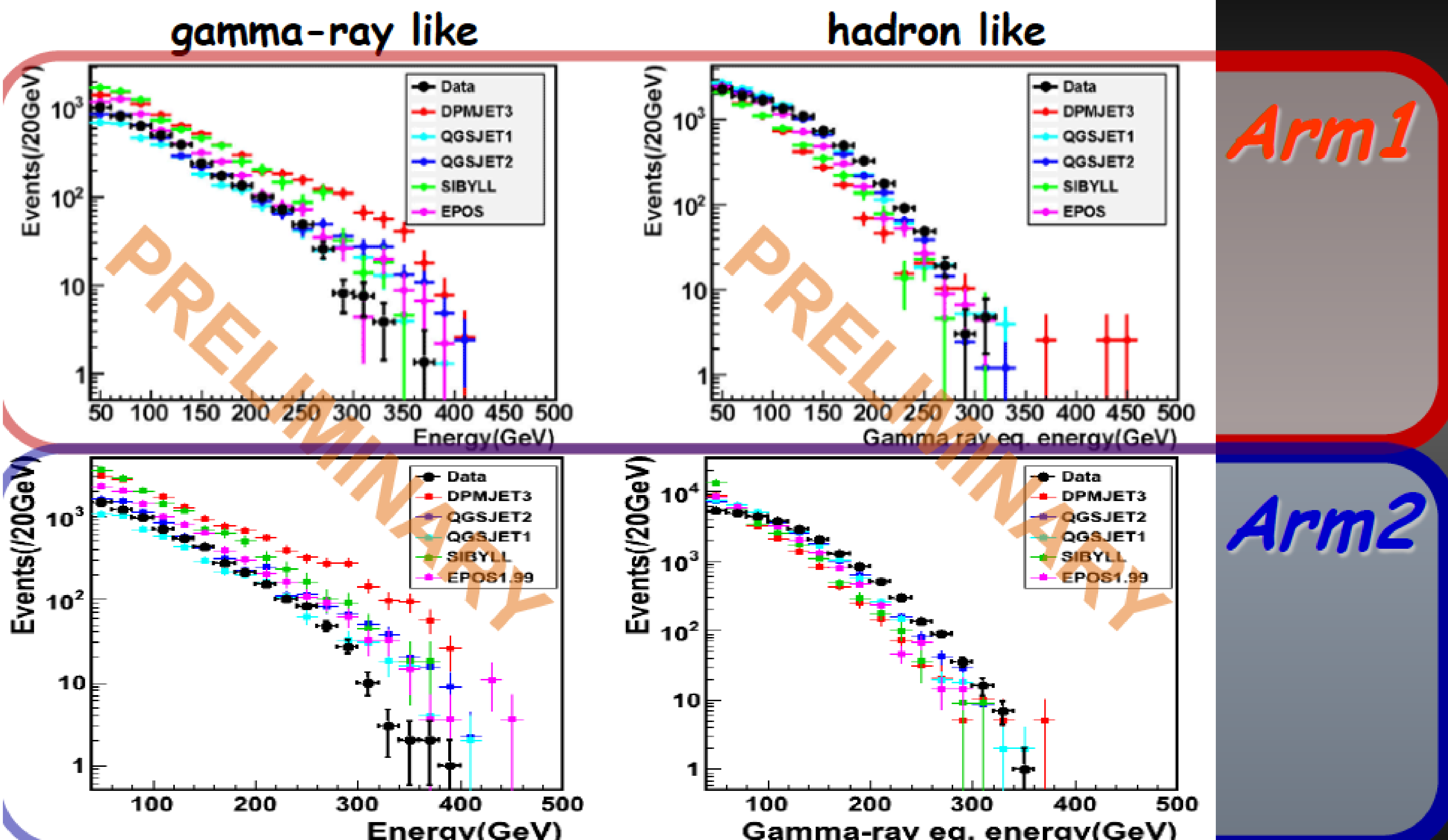

Arm1


neutral beam axis


η
Shadow of beam pipes
between IP and TAN
8.7
∞
beam center
Transverse projection of Arm#1
@ zero crossing angle


8.4
∞
40
20
@ 140μrad crossing angle

Energy spectra at 900 GeV



Acceptance is different for the two arms.
Spectra are normalized by # of γ-ray and hadron like events.
Response for hadrons and systematic errors are under study.

Only statistical errors are shown

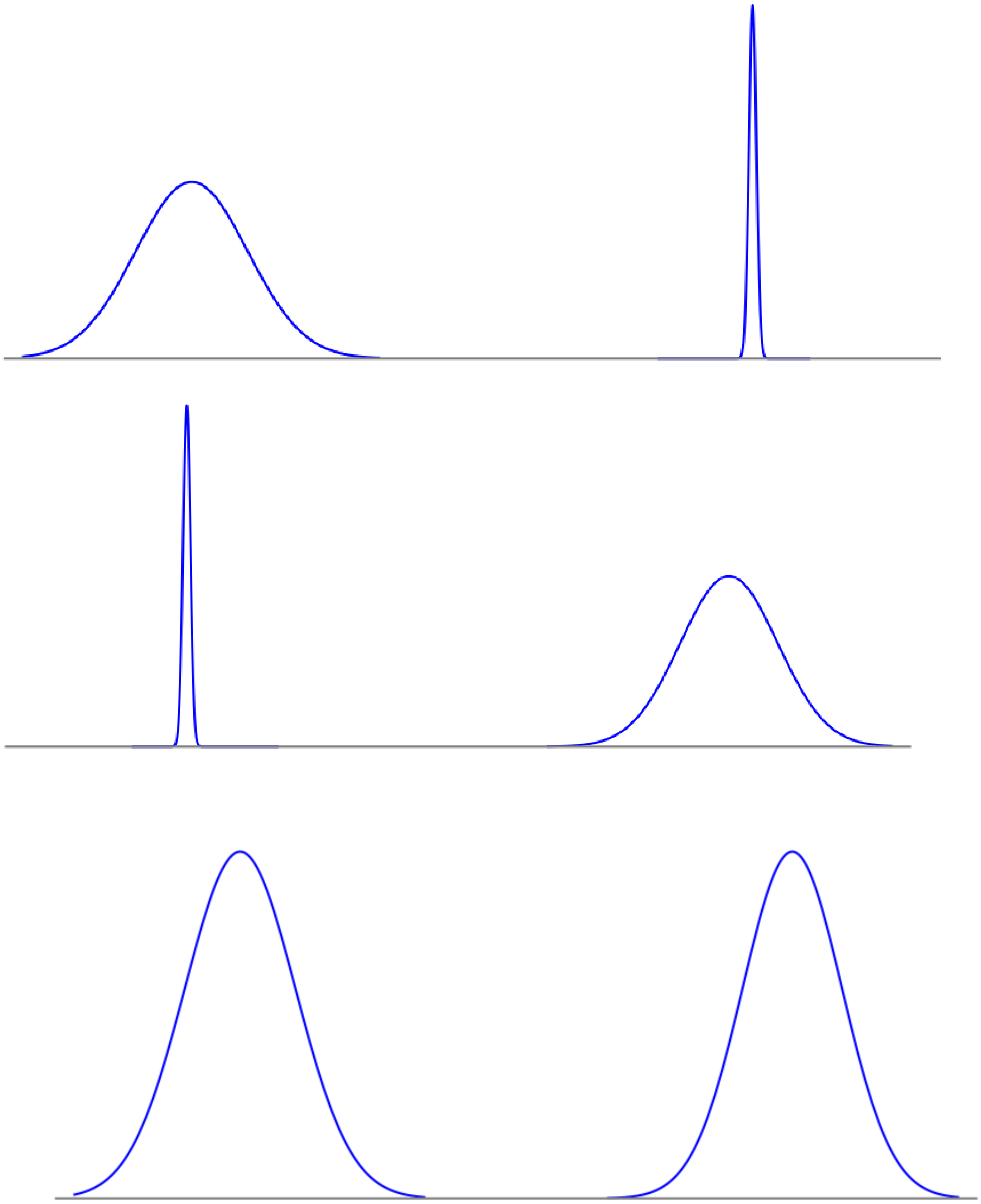
$$\sigma_{\mathrm{tot}} \qquad \sigma_{\mathrm{el}} \qquad \frac{d\sigma_{\mathrm{el}}}{dt}$$

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

$$\sigma_{\mathrm{diffractive}}$$

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

Diffraction

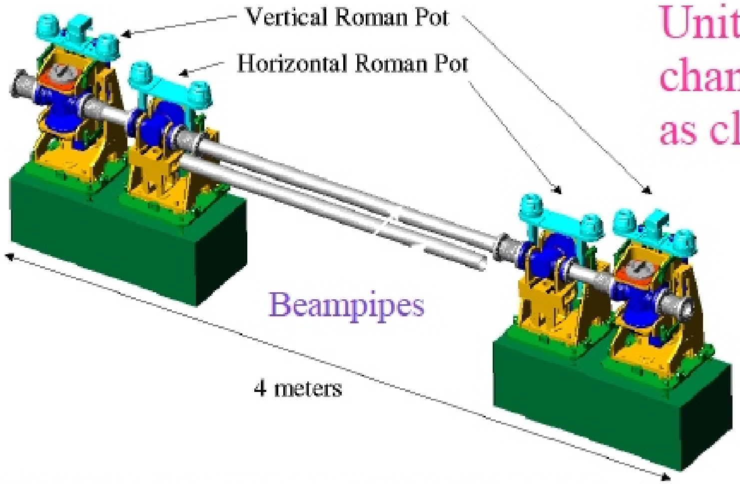


$$h_1 h_2 \to h_1^* h_2 \quad \text{(beam diffraction)},$$

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

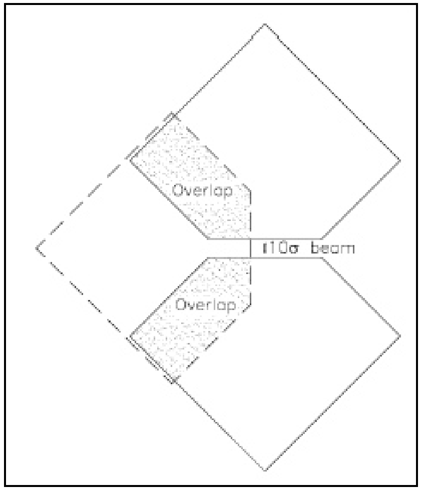
$$h_1 h_2 \to h_1^* h_2^* \quad \text{(double diffraction)}.$$

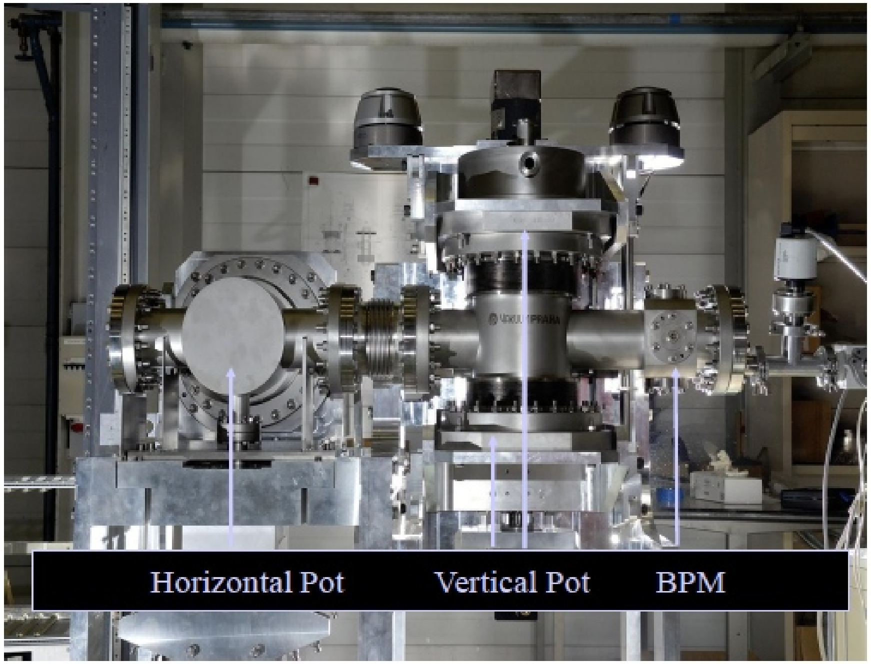
Units installed into the beam vacuum chamber allowing to put proton detectors as close as possible to the beam



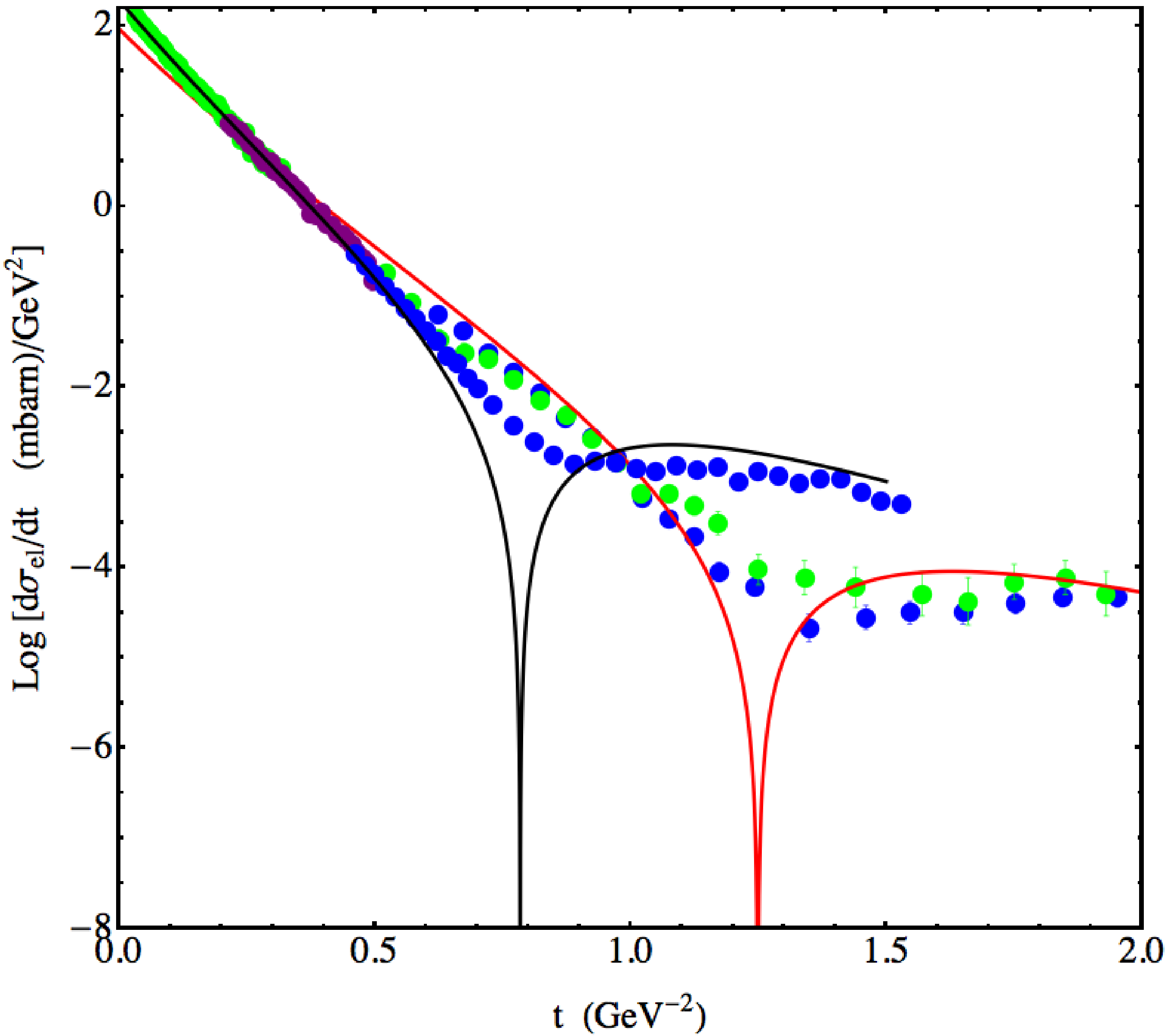
'Edgeless' detectors to minimize d

Each RP station has 2 units, 5m apart.
Each unit has 2 vertical insertions ('pots') and 1 horizontal

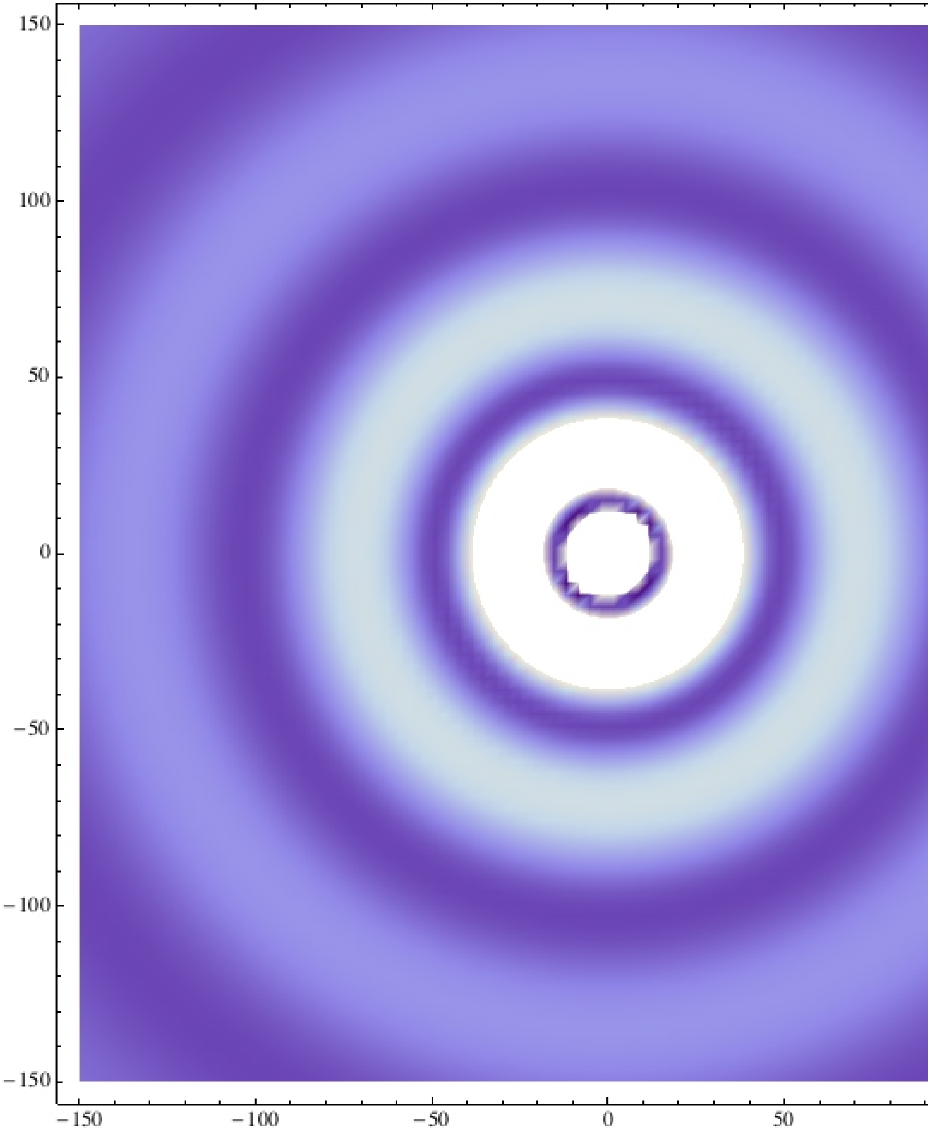




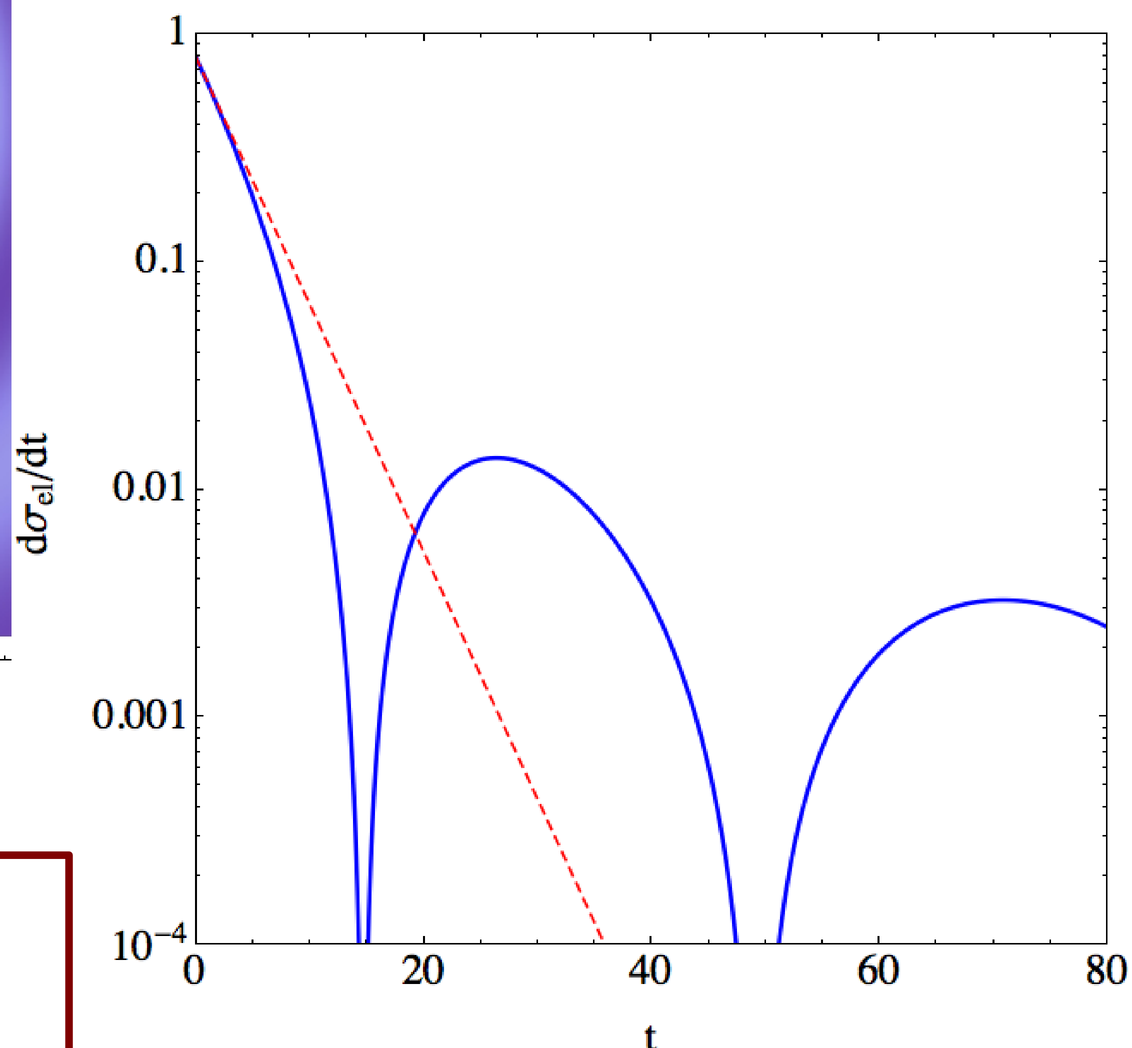
ISR   62.3 GeV
CERN UA4   546 GeV



Black Disk
Of radius R.

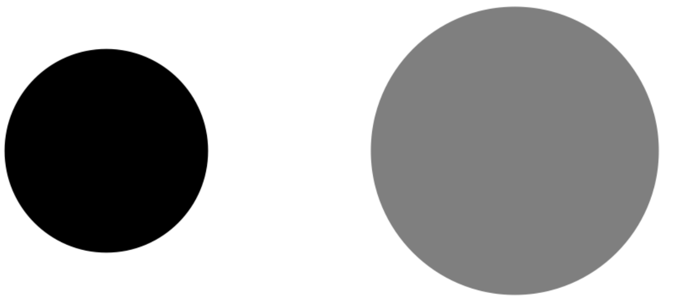


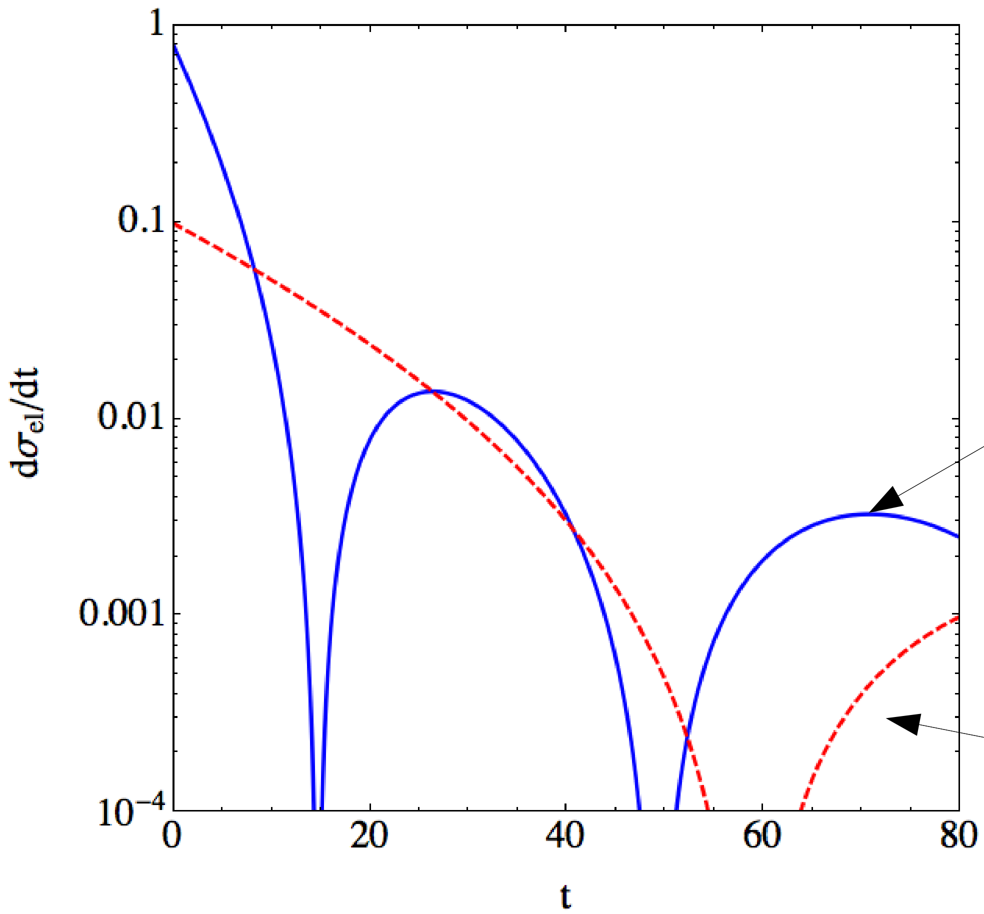
Diffraction Pattern



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

Elastic scattering distributions





Larger
Gray Disk

smaller
Black Disk

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

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]

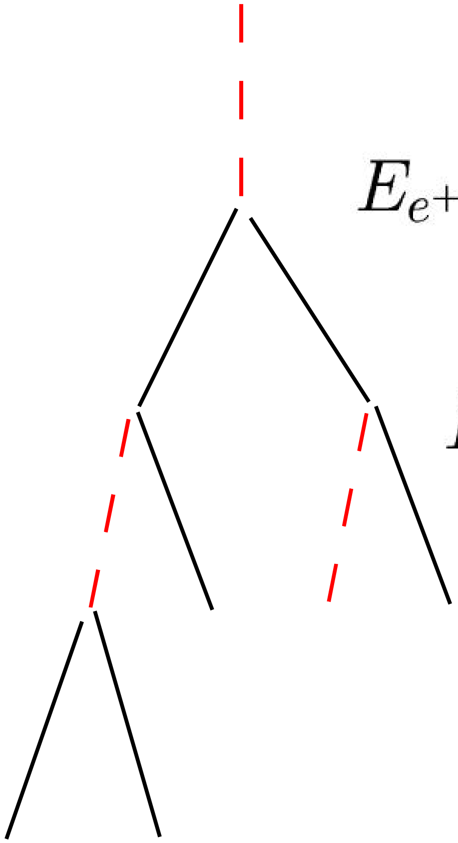
Electromagnetic Showers

versus

Hadronic Showers

Toy model discussion.

Electromagnetic Shower



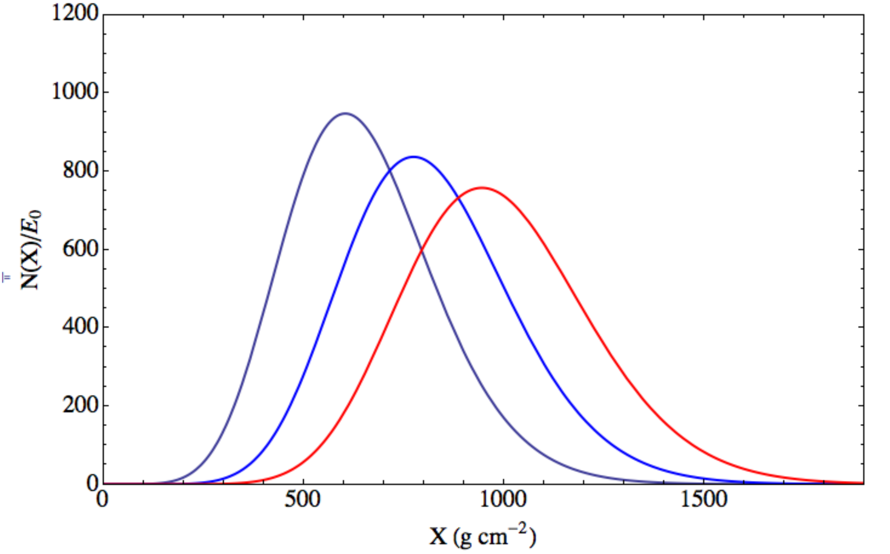
$E_{e^+} = E_\gamma \; u$ $\psi(u)$ Pair production

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

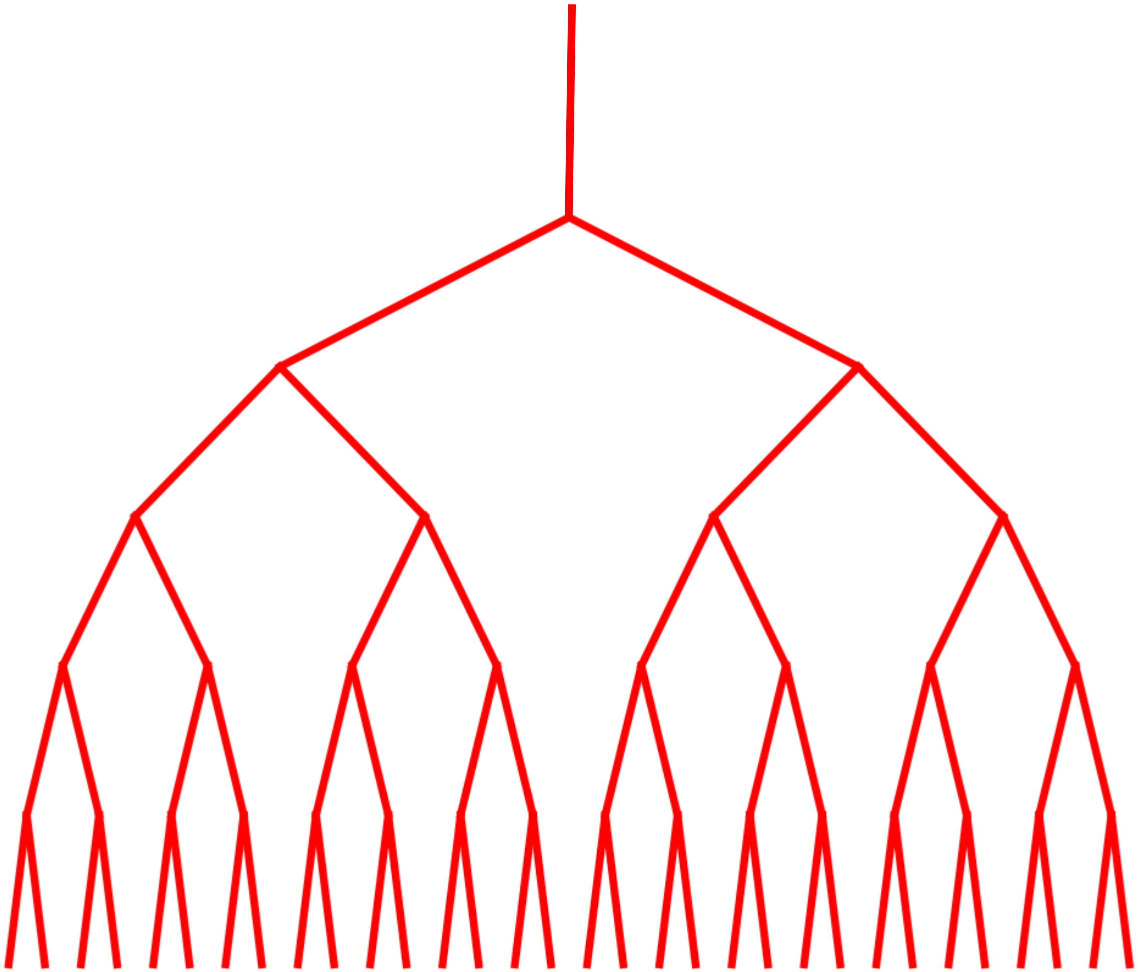
Heitler toy model

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:

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

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

Fluctuations:

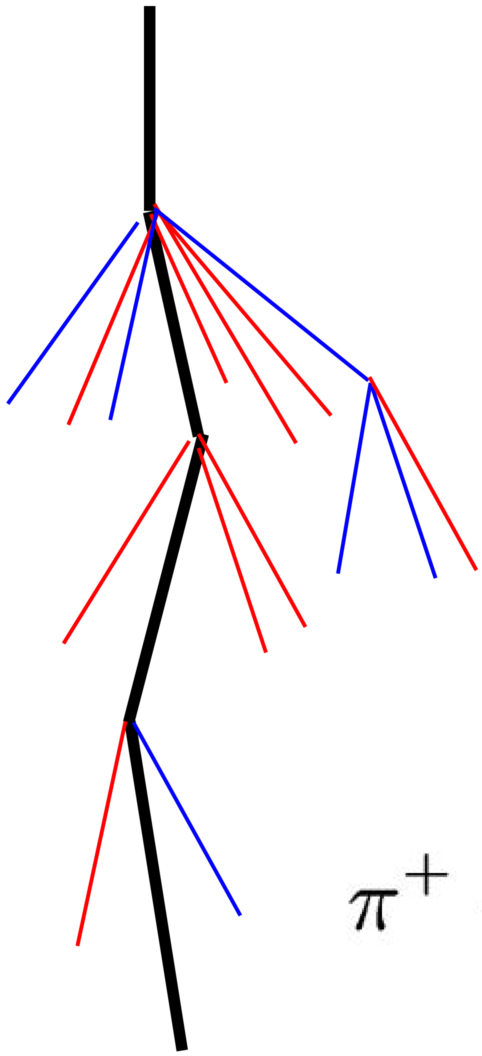
$$\sigma_X^2(\gamma, E) = \text{constant}$$

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

Proton Shower

Vertices : theoretically not
Understood

(and energy dependent)



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

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

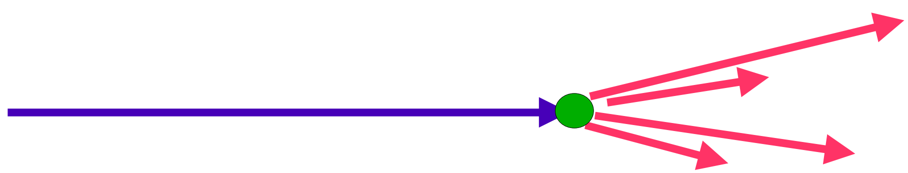
All energy transferred
to an electromagnetic shower

HADRONIC INTERACTIONS

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

Leading nucleon
~ 50% of energy

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



Decay

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

Interaction

Inclusive spectra
of secondary particles

Theorem:

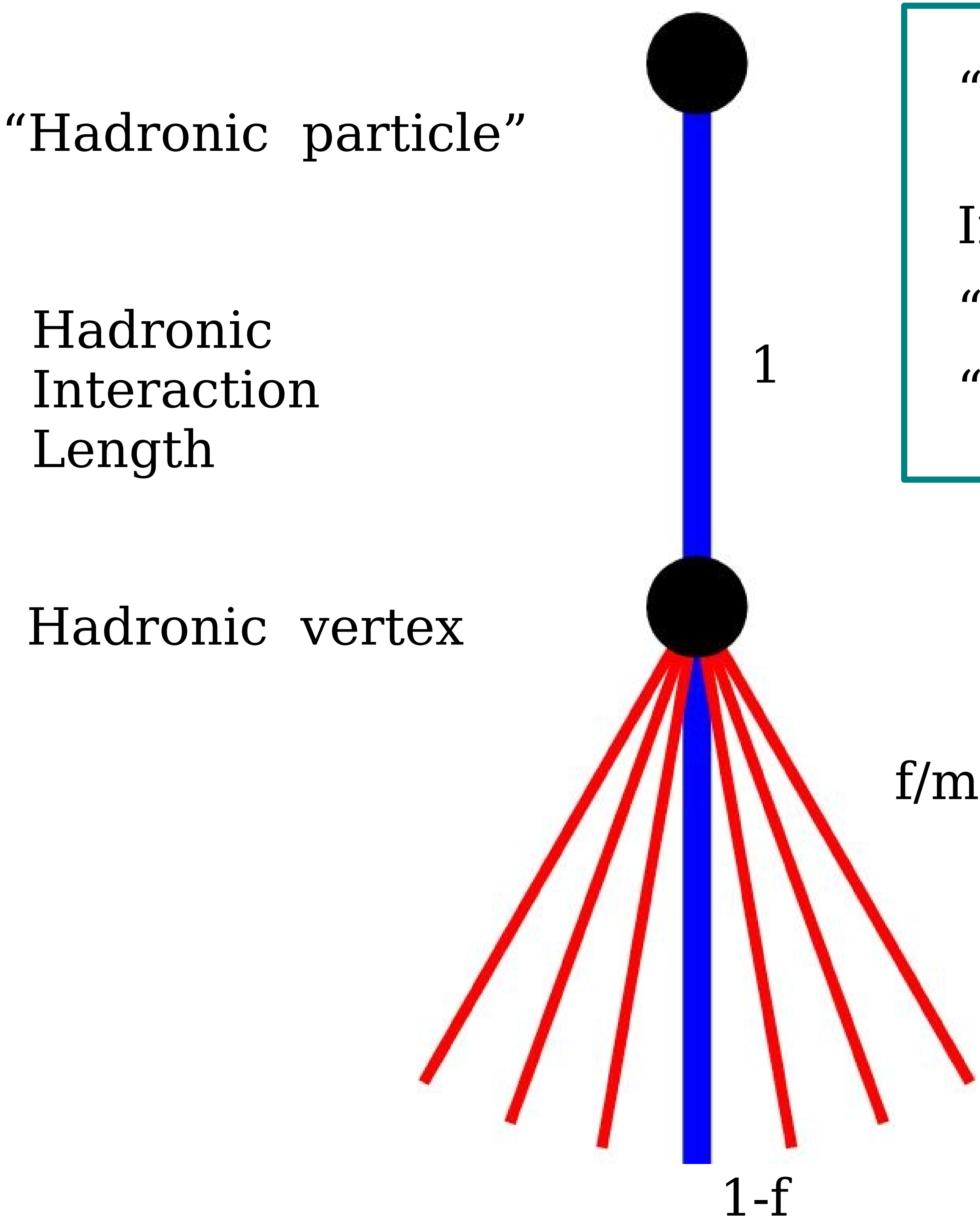
If:

$$\lambda_{\mathrm{int}}^{\mathrm{hadron}} = \mathrm{constant}$$

Hadronic Interactions SCALING

Then:

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



“Hadron”

Interaction Length Λ

“Inelasticity” f

“multiplicity m

Energy sharing

$1 \rightarrow (1\text{-}f) +$

$f/m +$

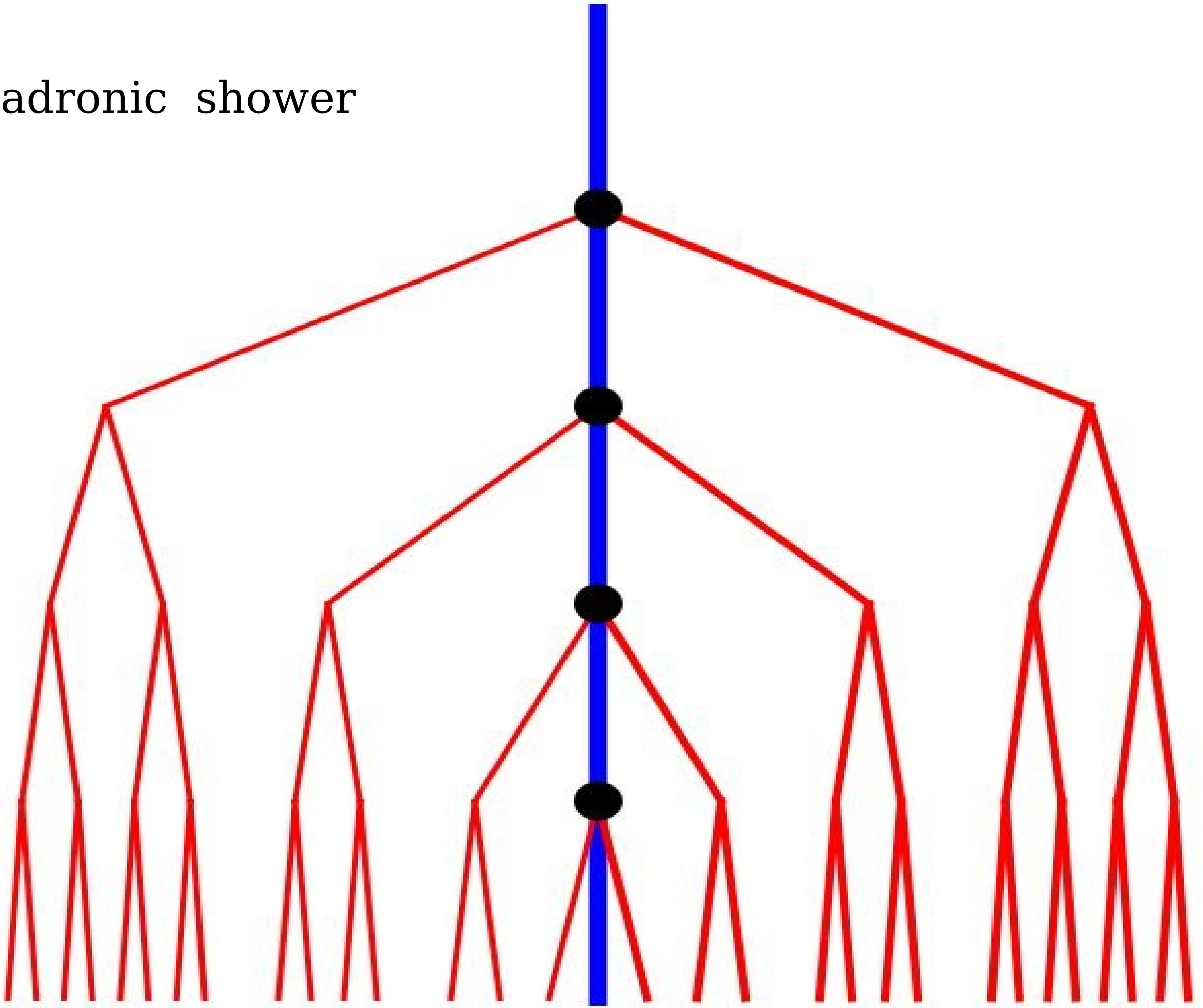
$f/m +$

$f/m +$

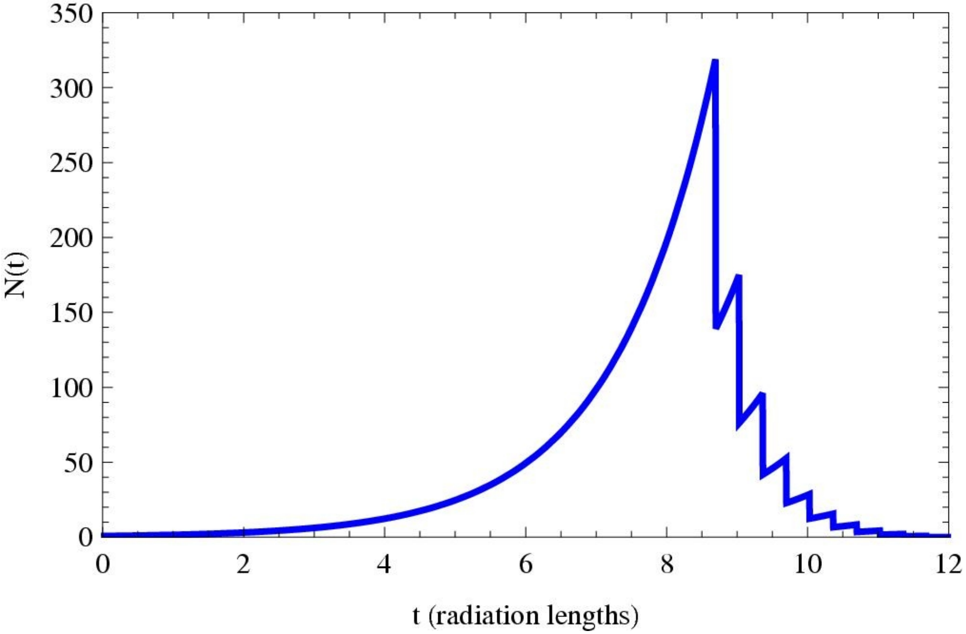
$f/m +$

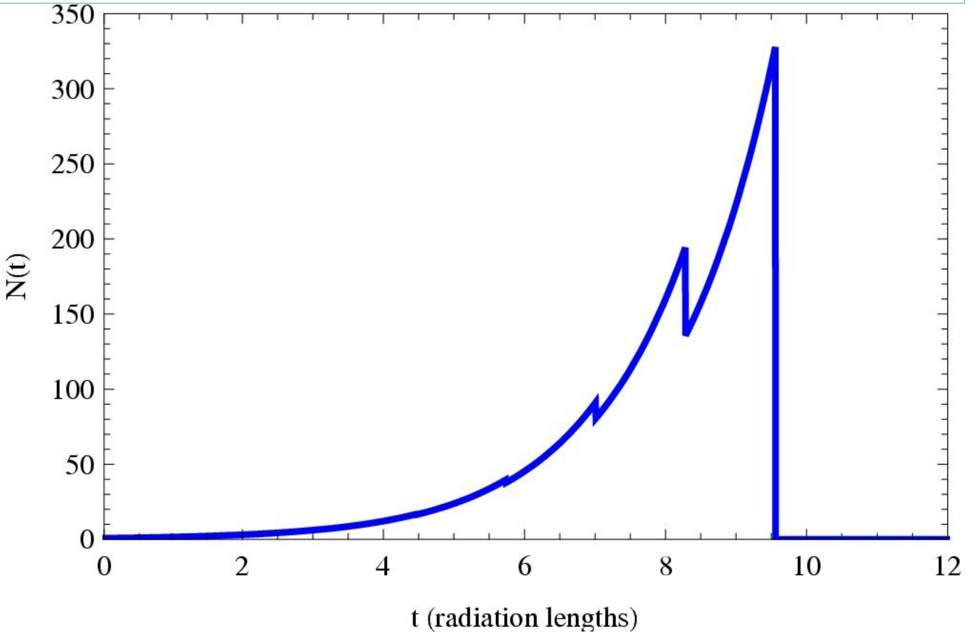
....

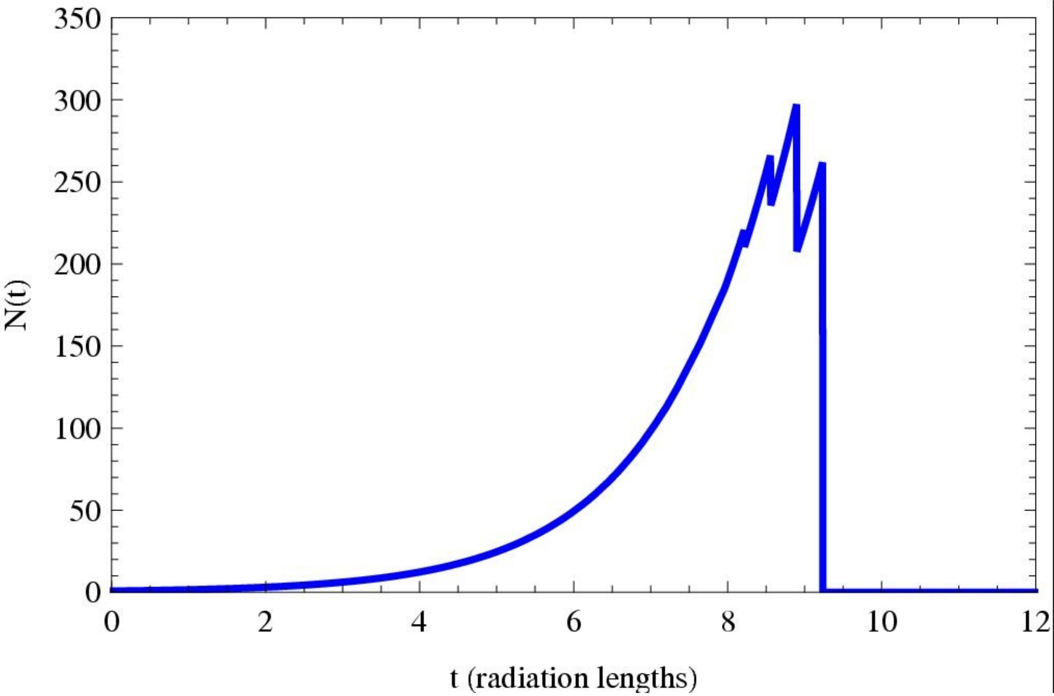
Hadronic shower

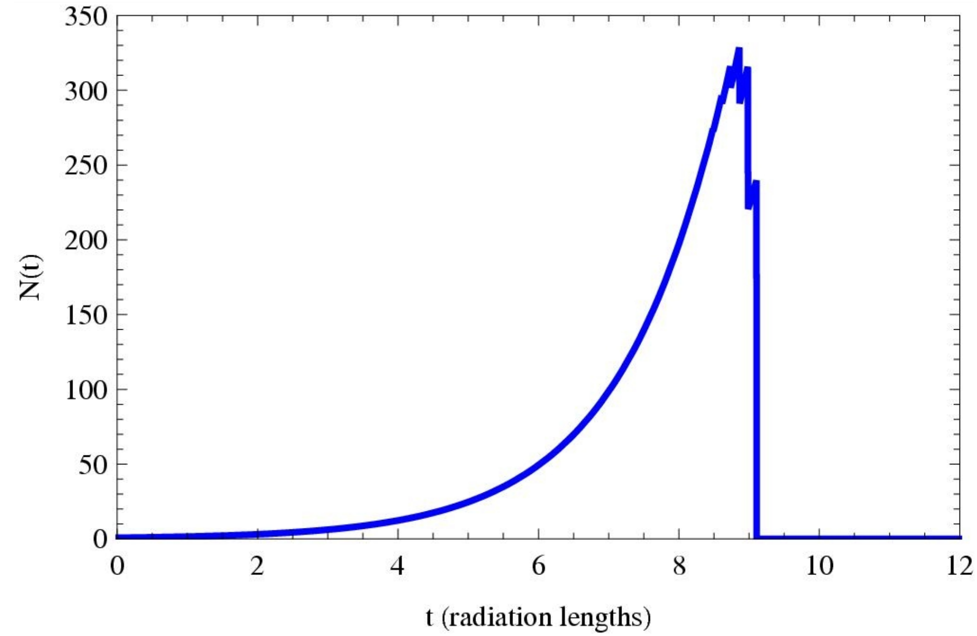


Hadronic parameters Λ, inelasticity, hardness

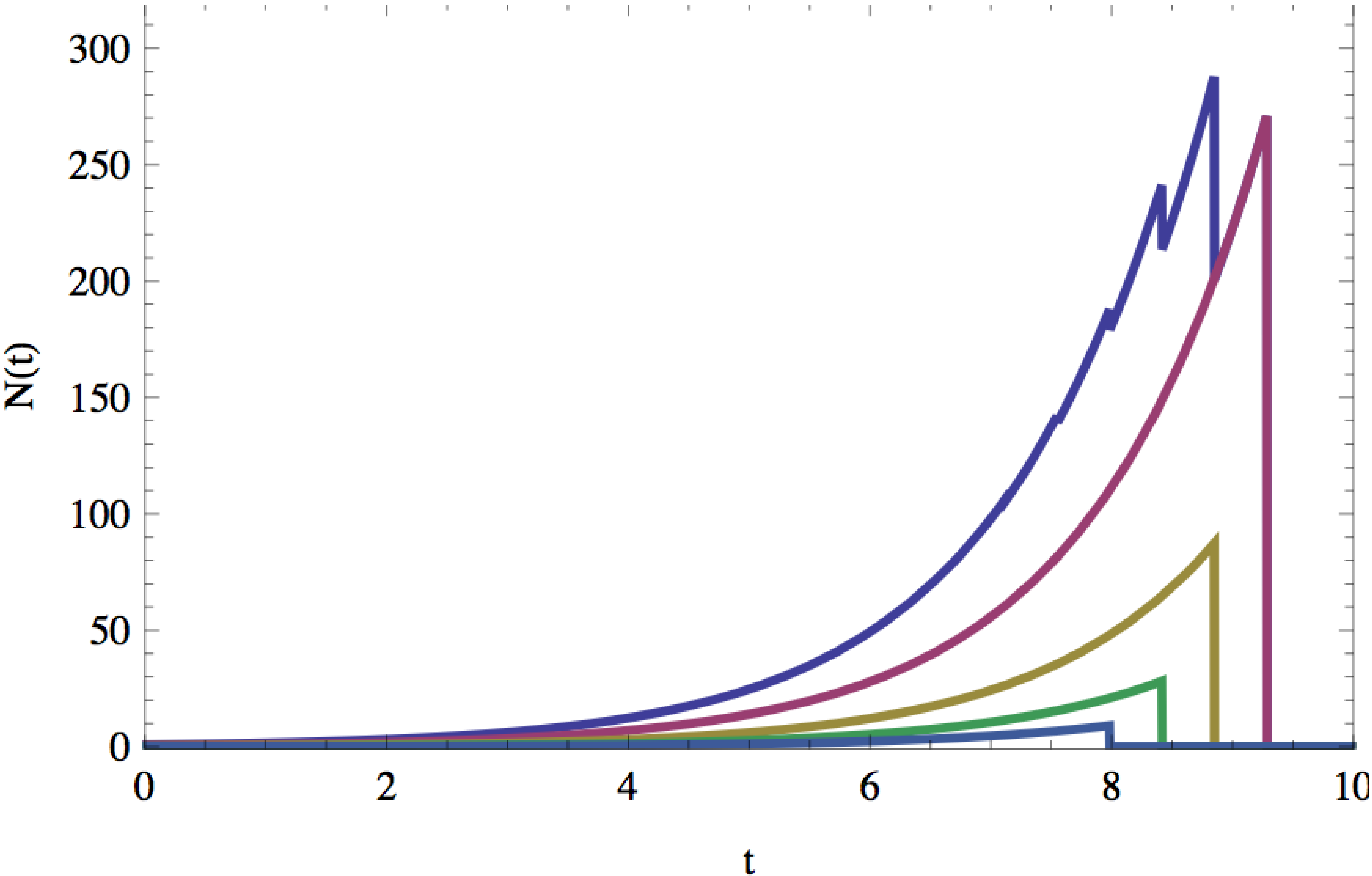


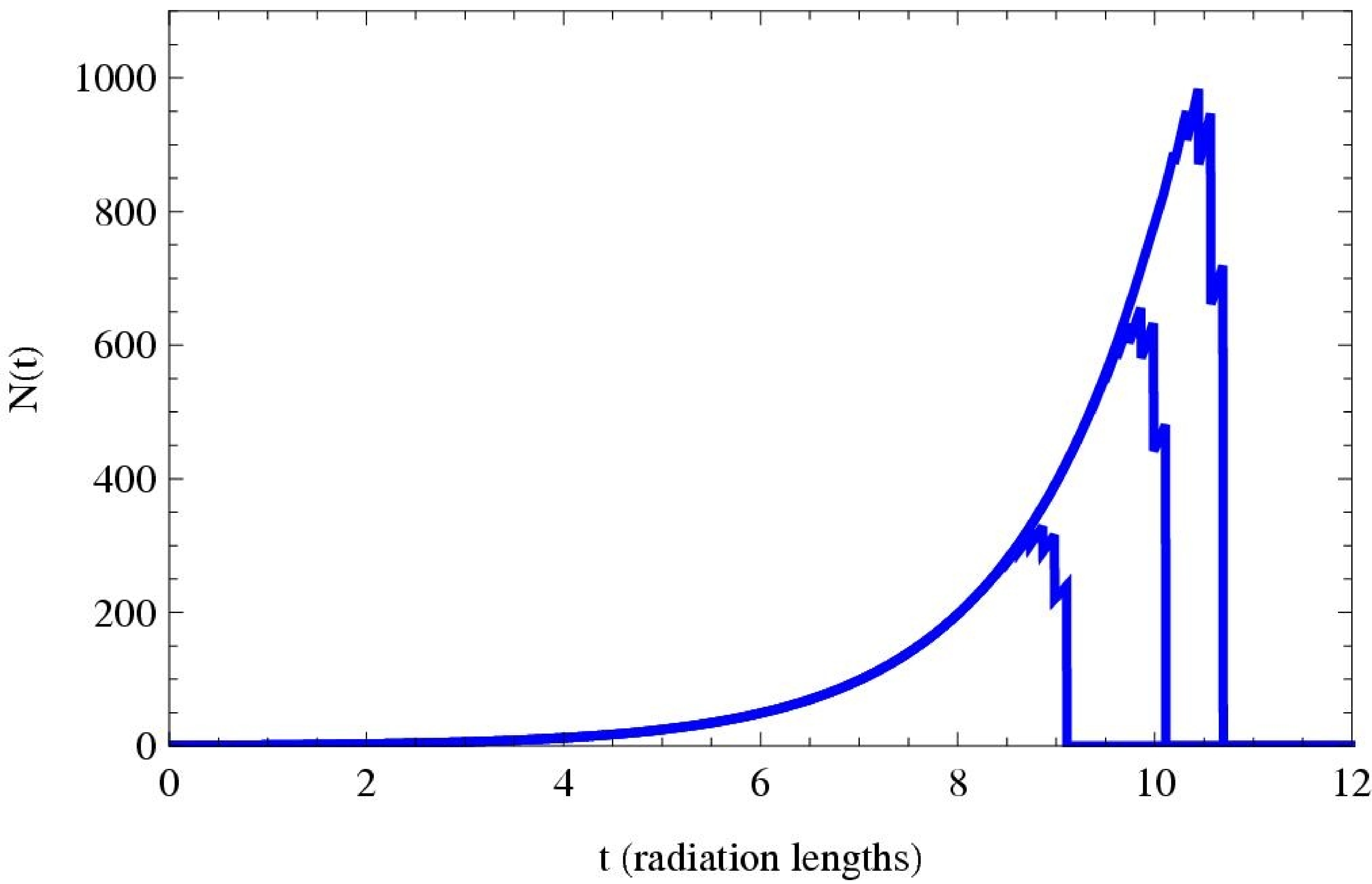




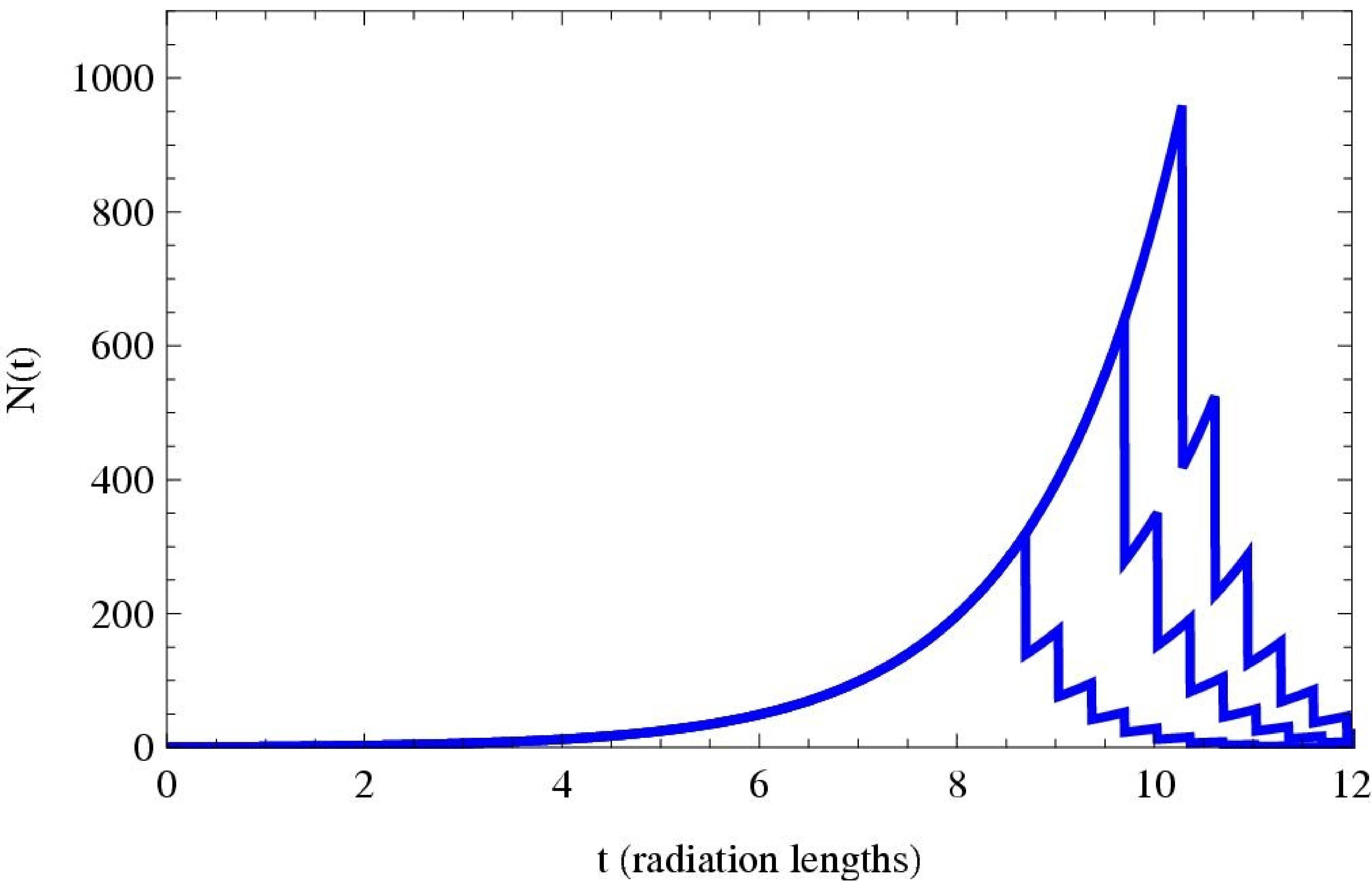


Hadronic shower in toy model.





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



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

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.

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

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

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

1^{st} 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

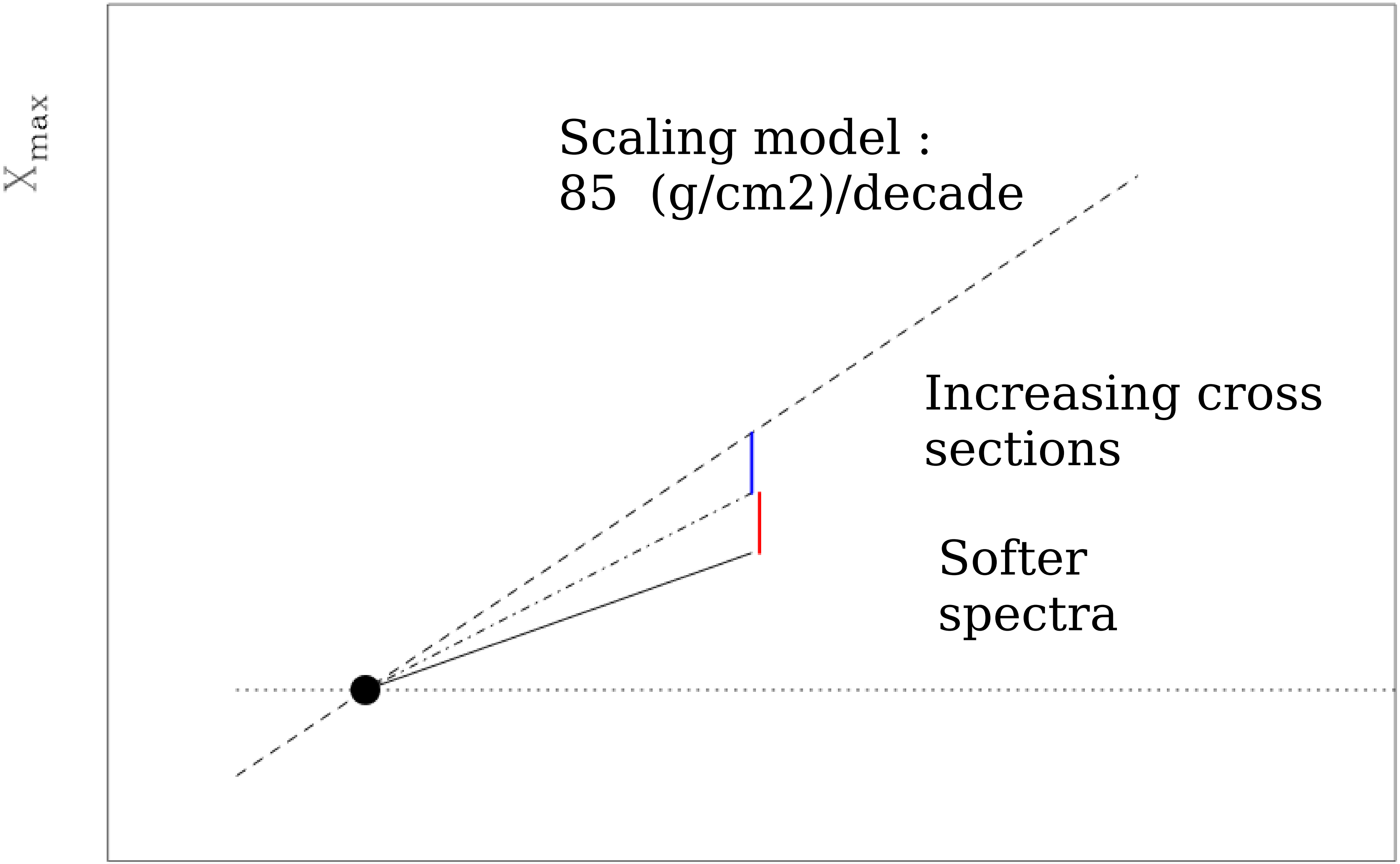
"Softness"

Elongation Rate

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

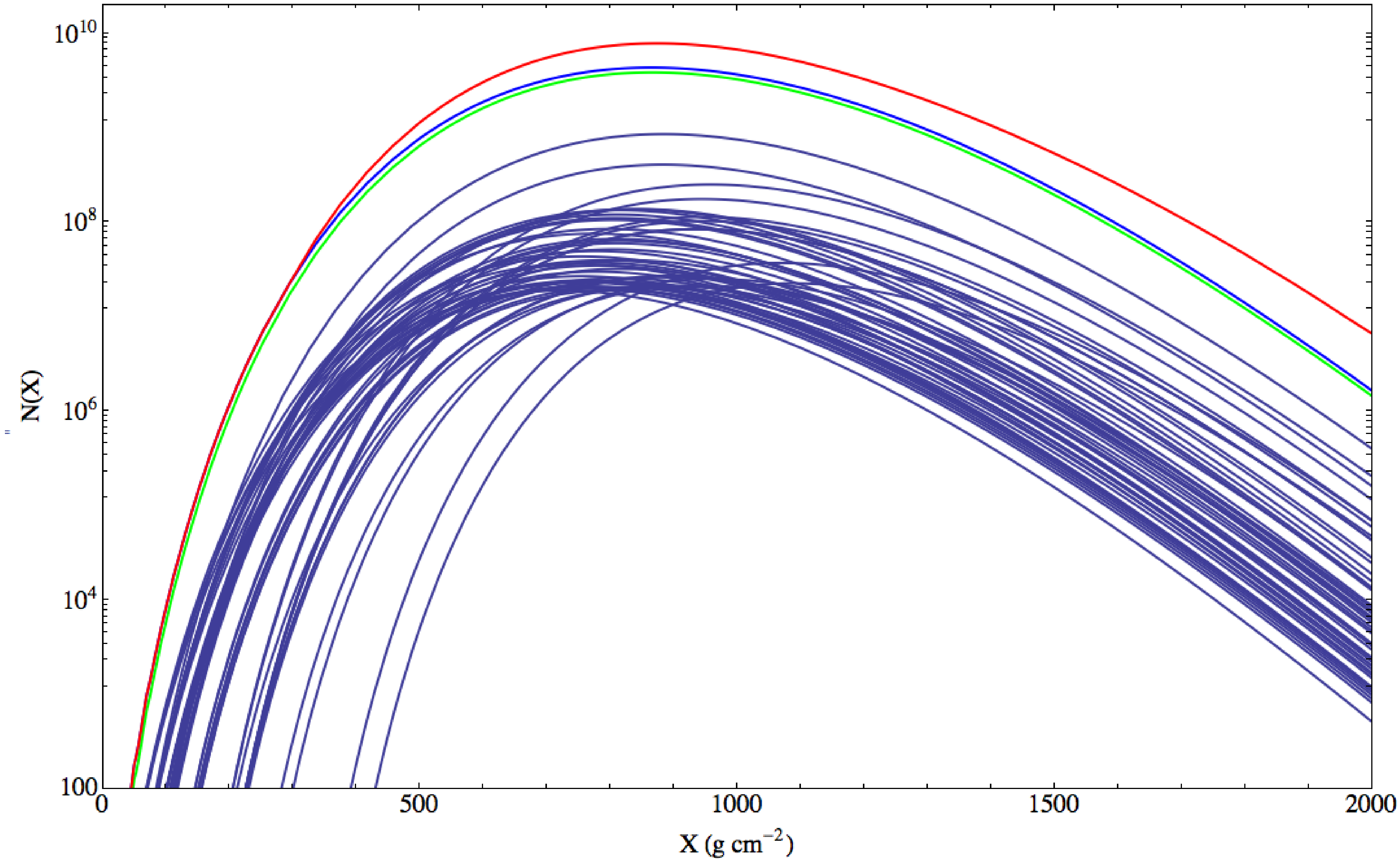
Evolution with Energy of the Interaction length

Evolution with energy of the "softness" of the spectrum

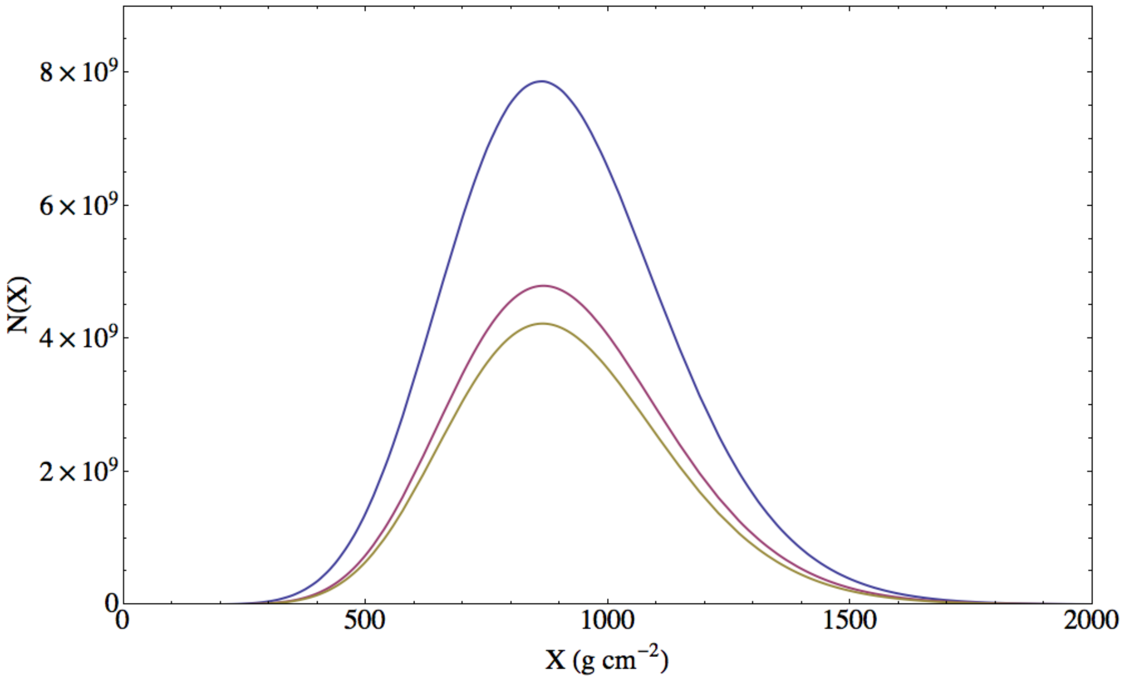


Elongation Rate
For protons

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

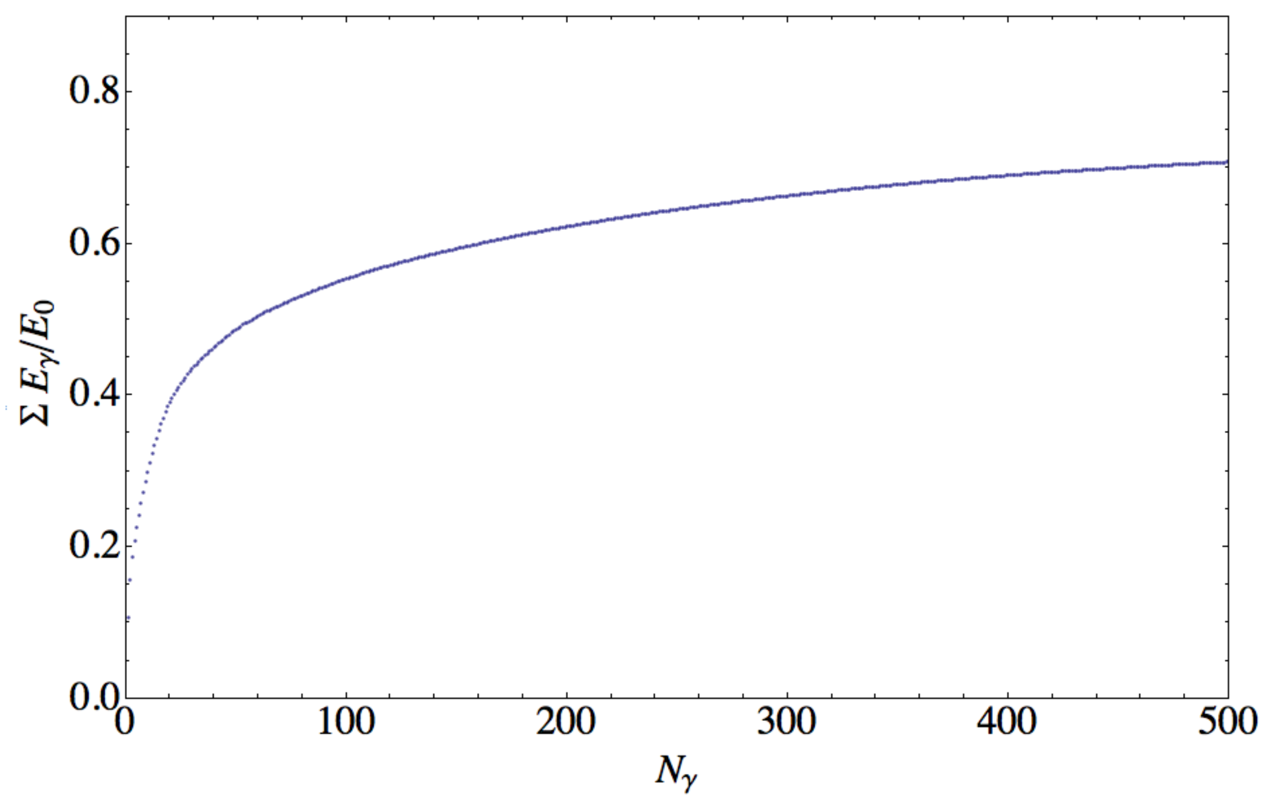


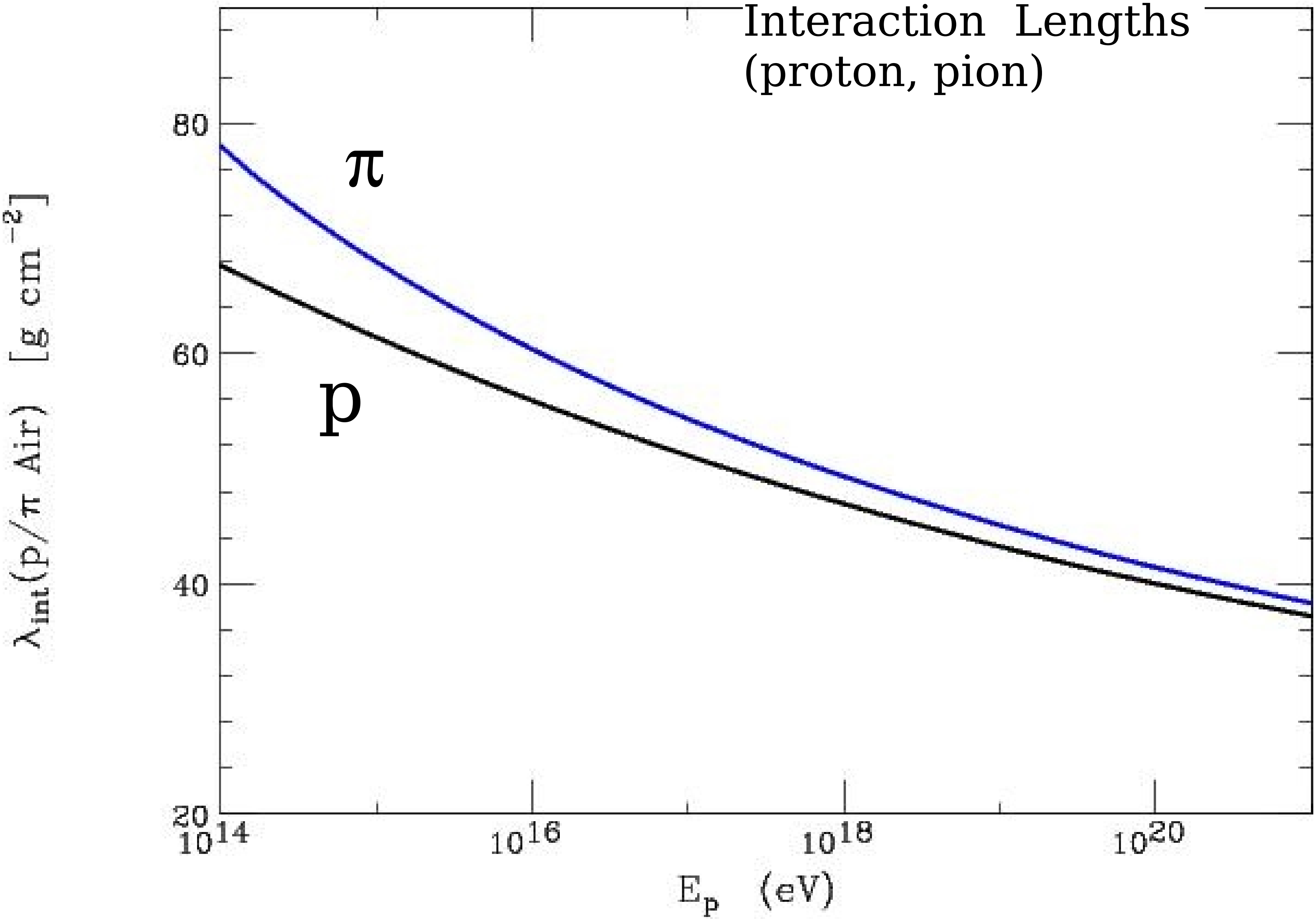
50 highest energy individual sub-showers



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

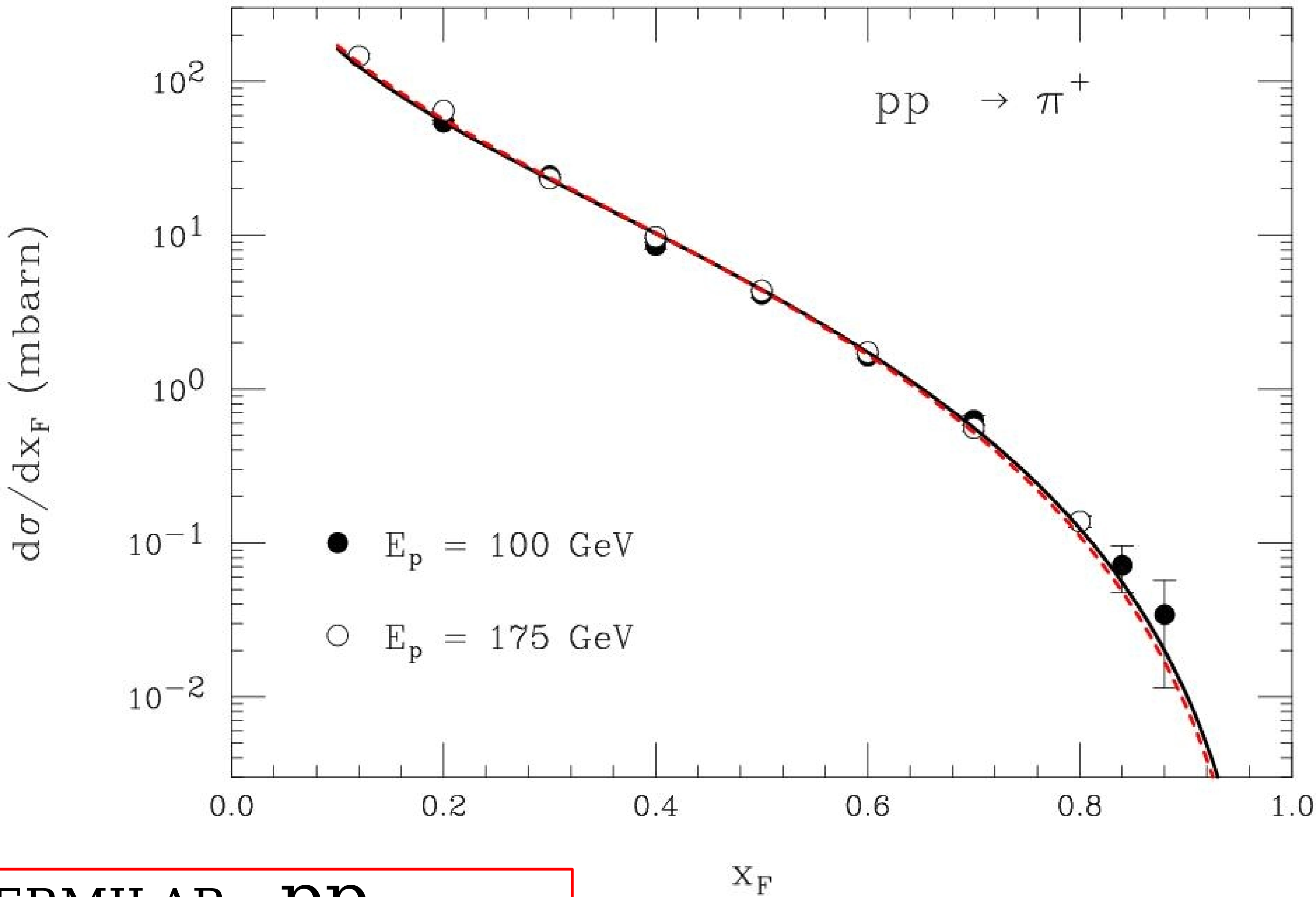
Approximately 100 photons in 30-40 interaction vertices control the structure of the shower: x ~ 0.1





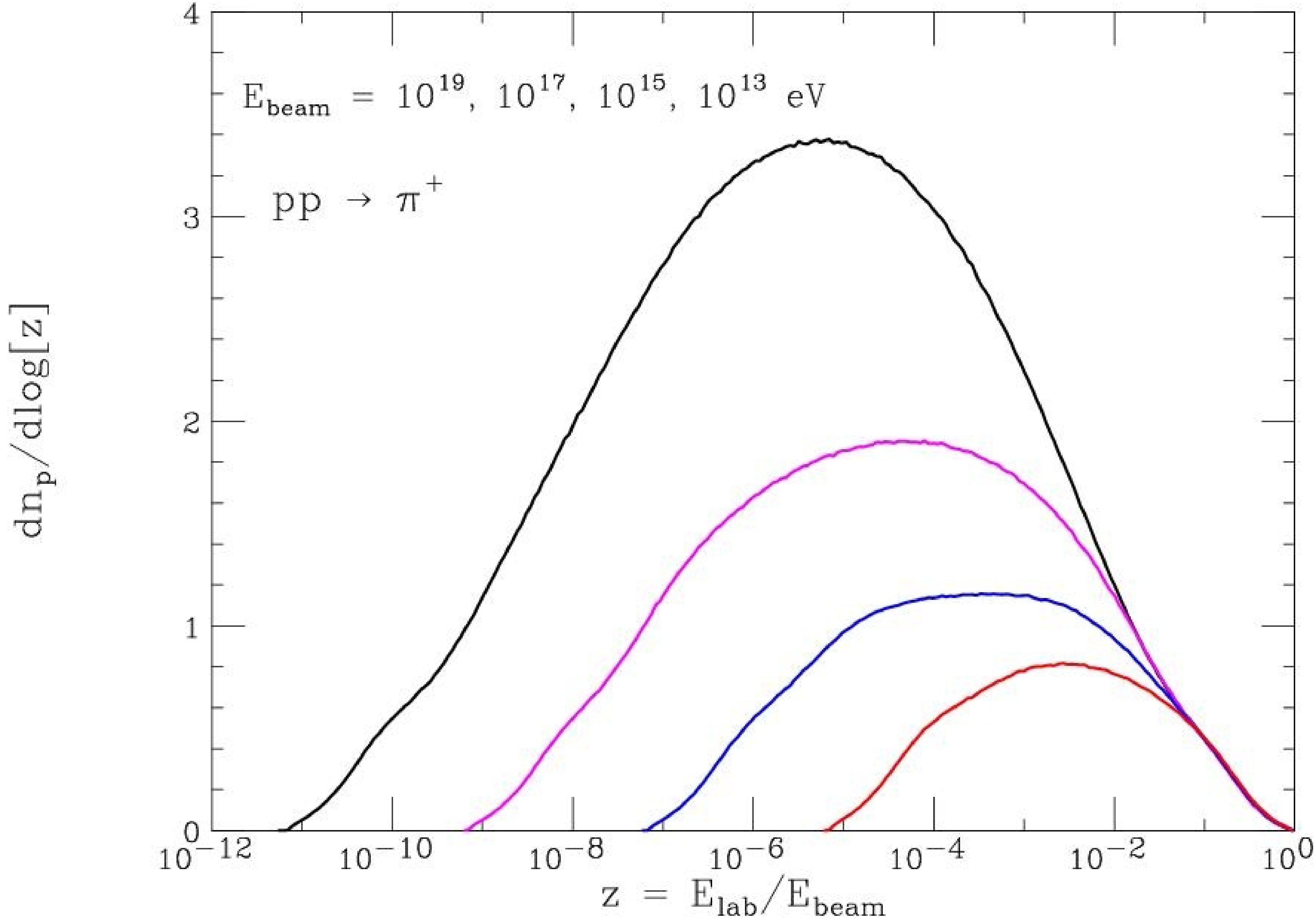
Interaction Lengths
(proton, pion)
π
p
80
60
40
20
10^14
10^16
10^18
10^20
E_p (eV)
λ_int(p/π Air) [g cm^-2]

Phenomenological Evidence for SCALING

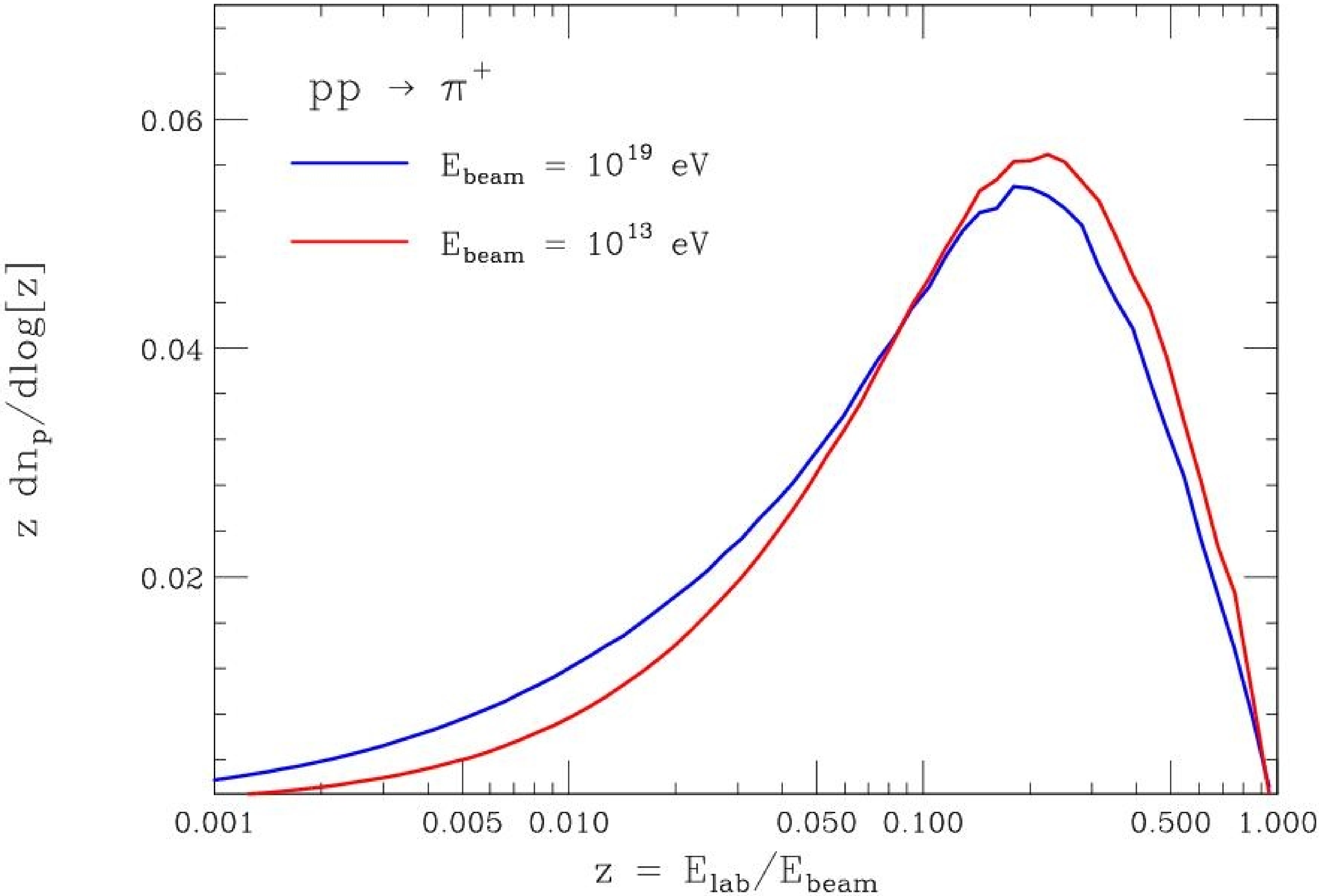


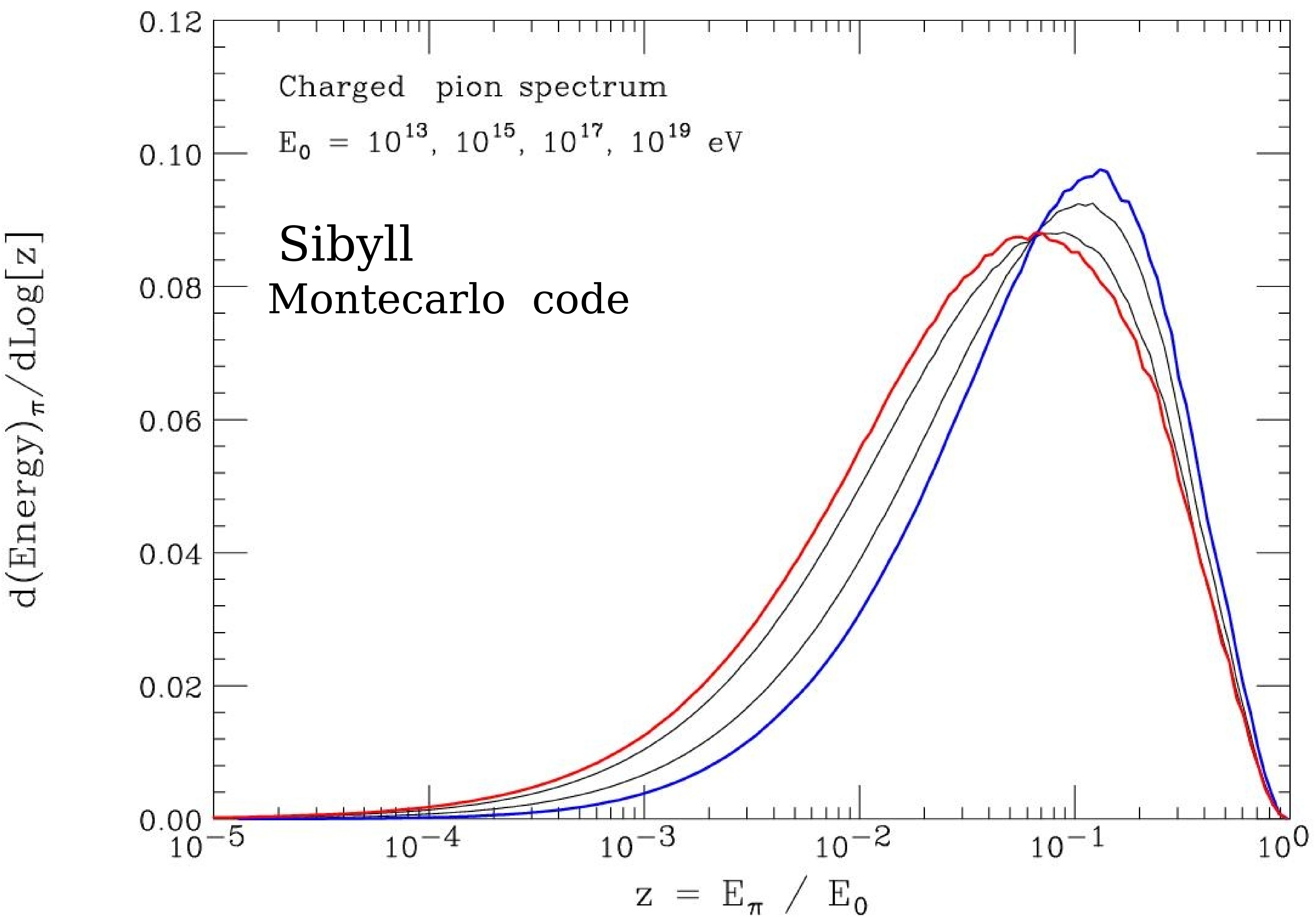
FERMILAB: pp
Brenner et al (1982)

EXTRAPOLATION to HIGH ENERGY (Pythia pp)



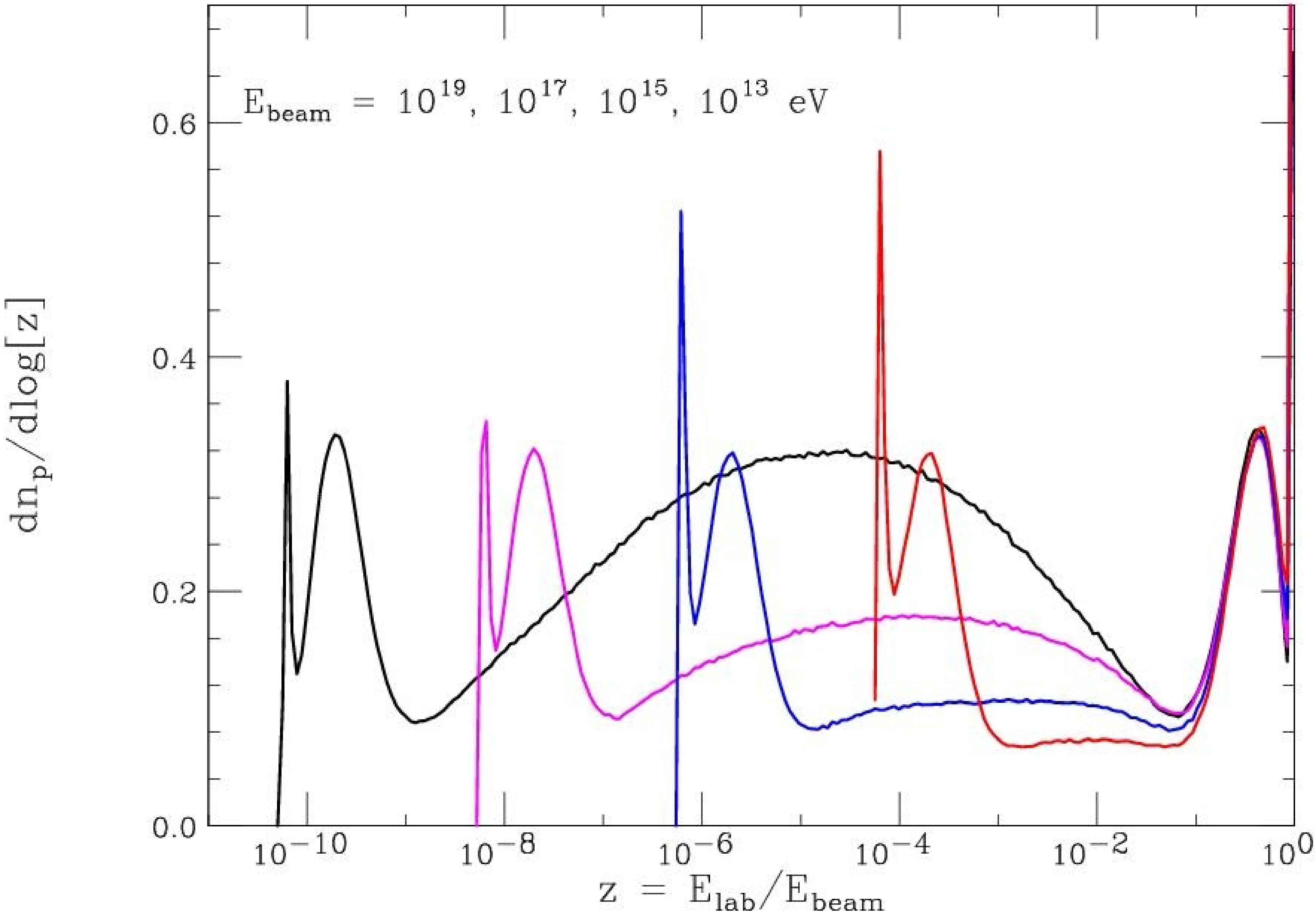
EXTRAPOLATION to HIGH ENERGY (Pythia pp)



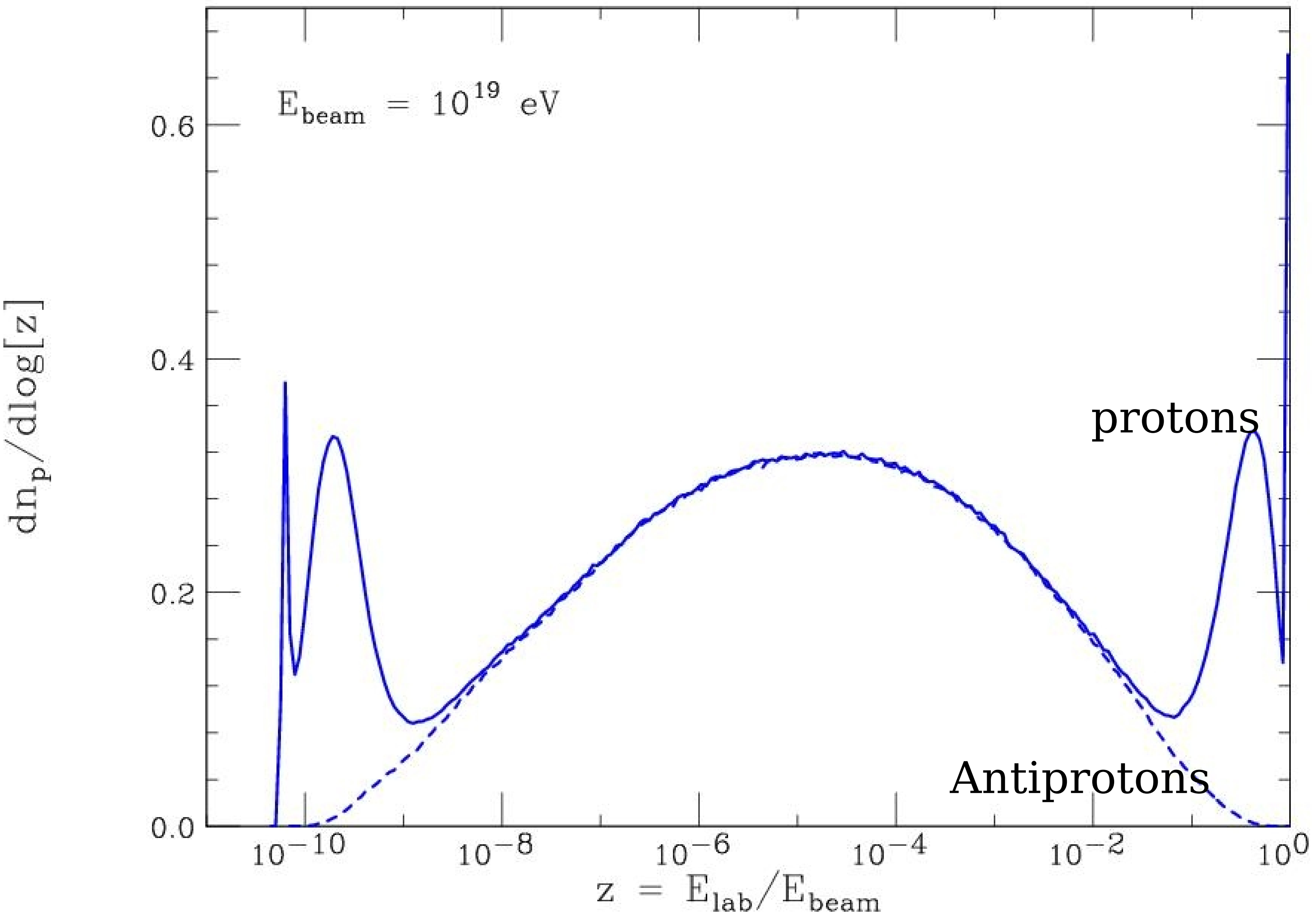


Charged pion spectrum
$E_0 = 10^{13}, 10^{15}, 10^{17}, 10^{19}$ eV
Sibyll
Montecarlo code
$d(\mathrm{Energy})_\pi/d\mathrm{Log}[z]$
$z = E_\pi / E_0$
0.00
0.02
0.04
0.06
0.08
0.10
0.12
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}

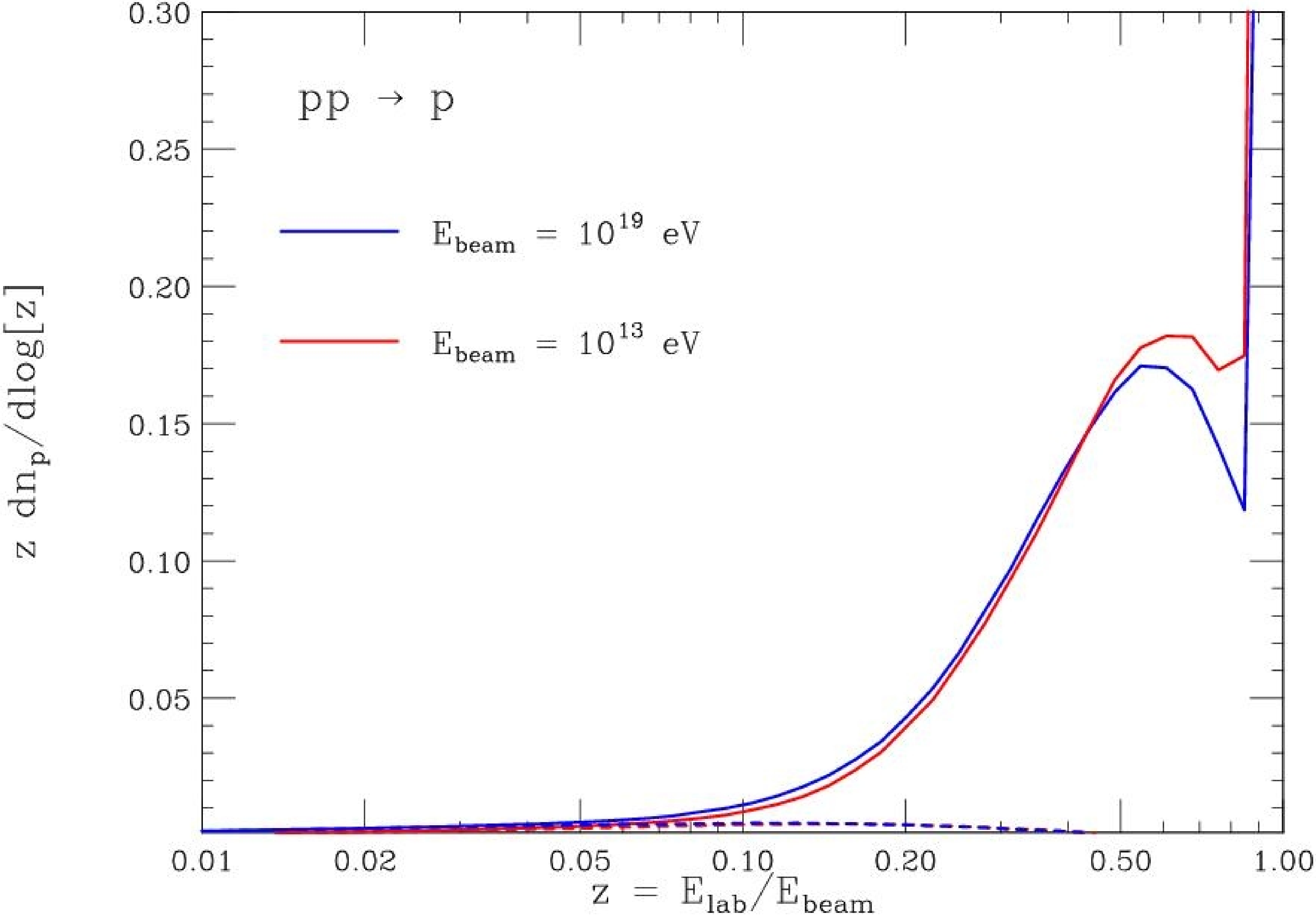
PROTON Spectra (elasticity spectra)



PYTHIA PROTON Spectra

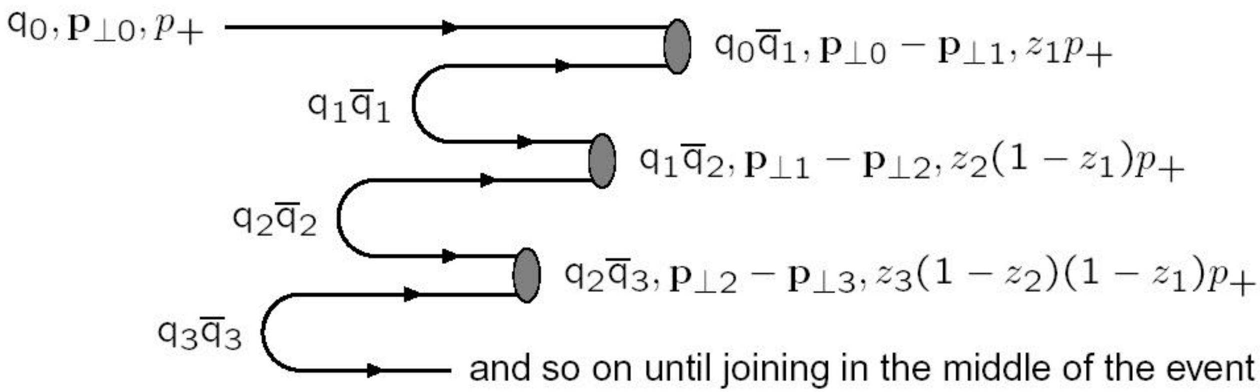


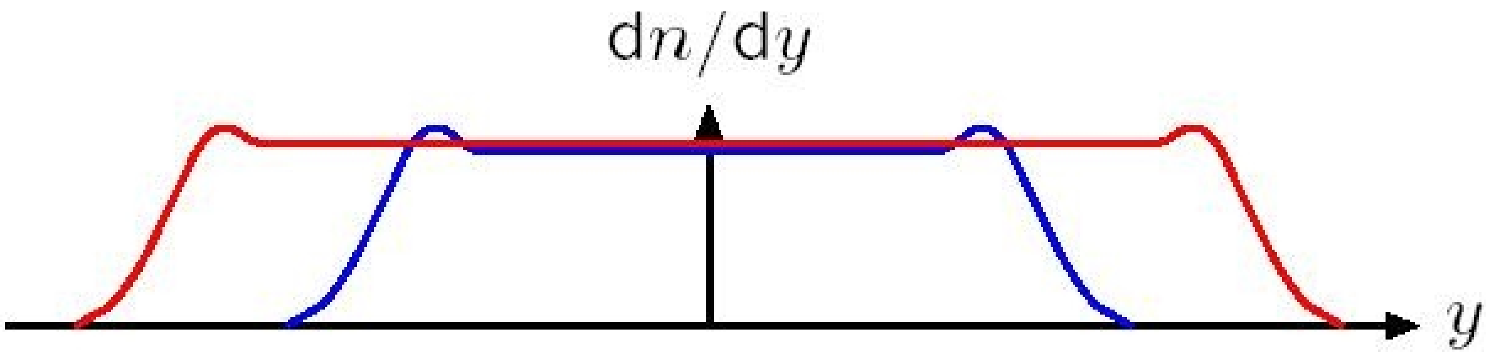
PROTON Spectra (elasticity spectra)



Where does the approximate Feynman scaling comes from ?

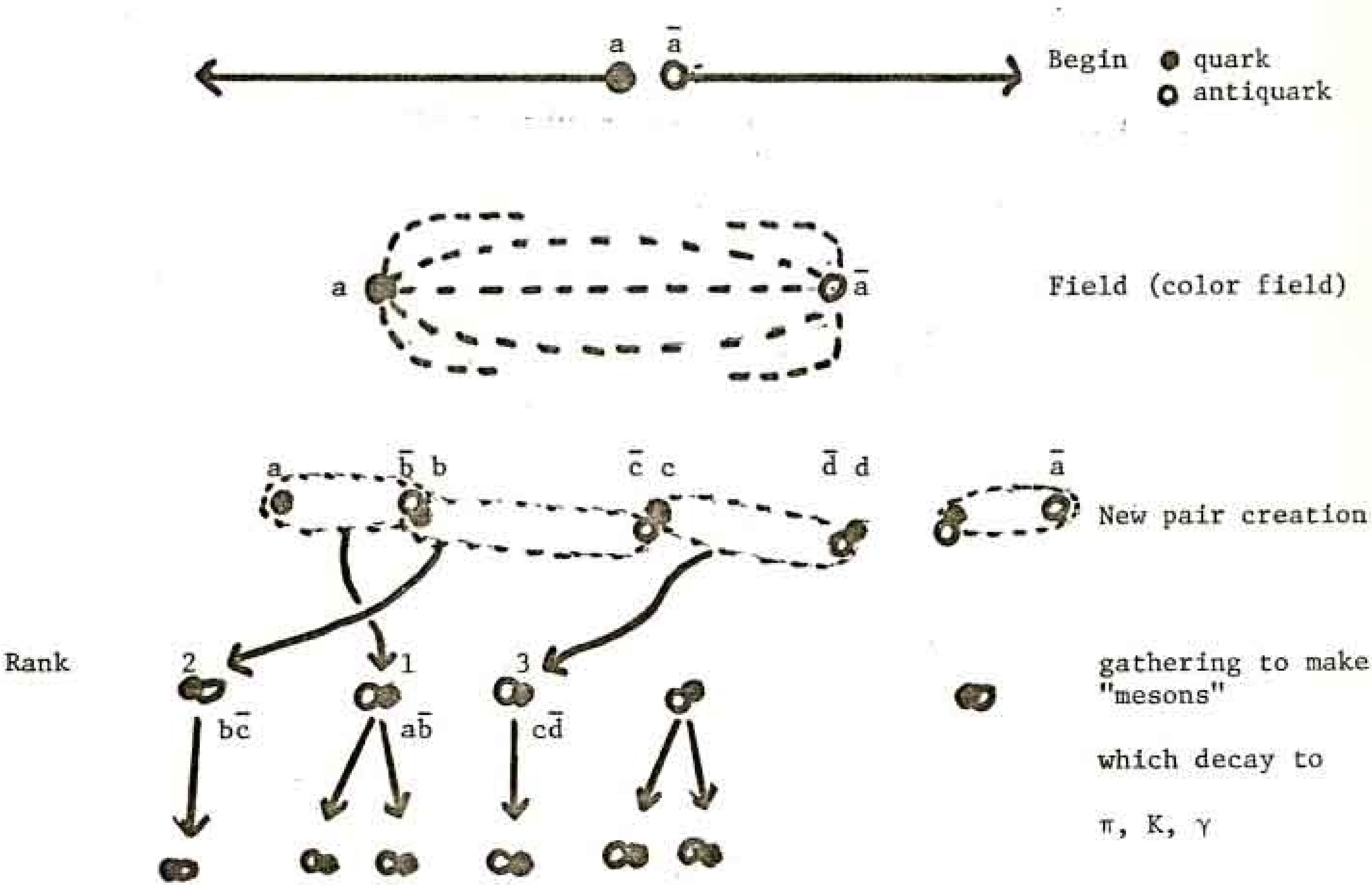
The (iterative) Fragmentation of one COLOR STRING produces a SCALING SPECTRUM of HADRONS



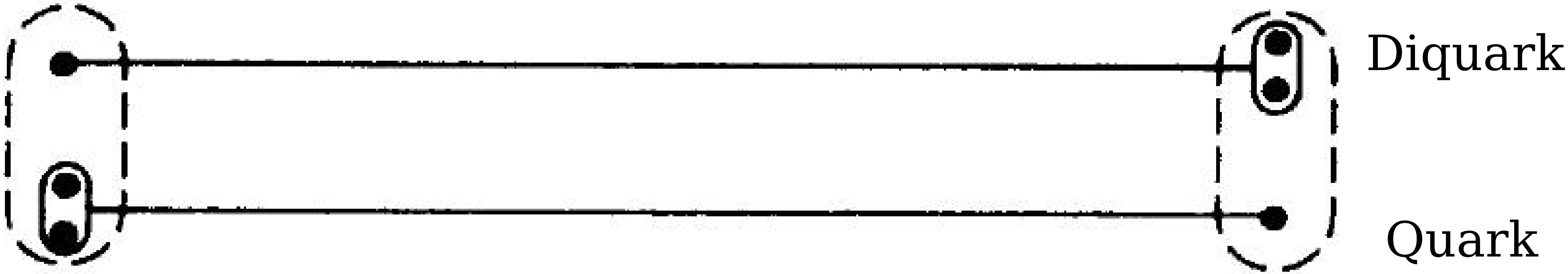


$\langle n_{\rm ch} \rangle \approx c_0 + c_1 \ln E_{\rm cm}$, $\sim$ Poissonian multiplicity distribution

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

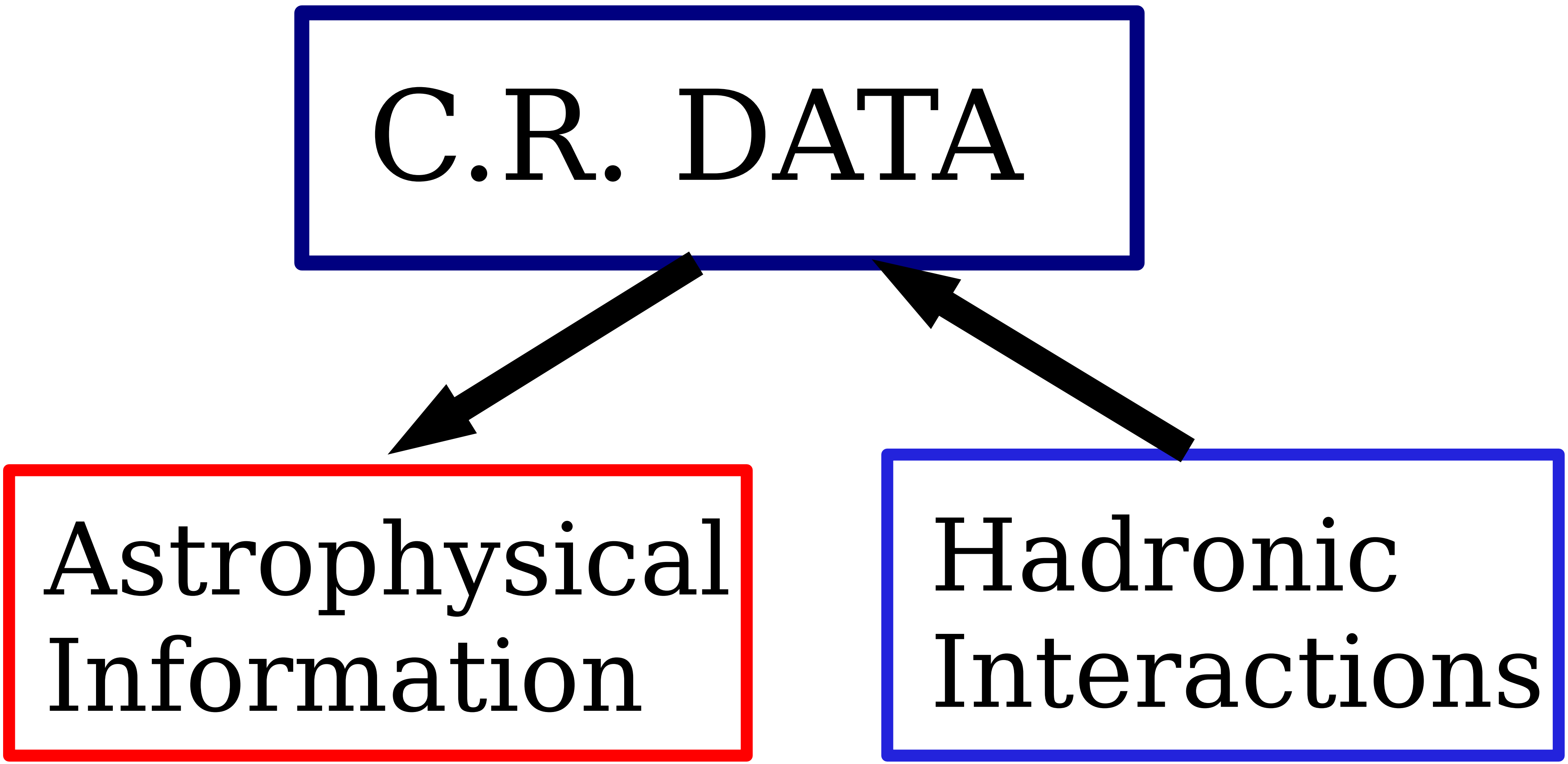
Astrophysical Information

Energy
Spectrum
Composition

Hadronic Interactions

Cross sections,
Inclusive
spectra
Multiplicities

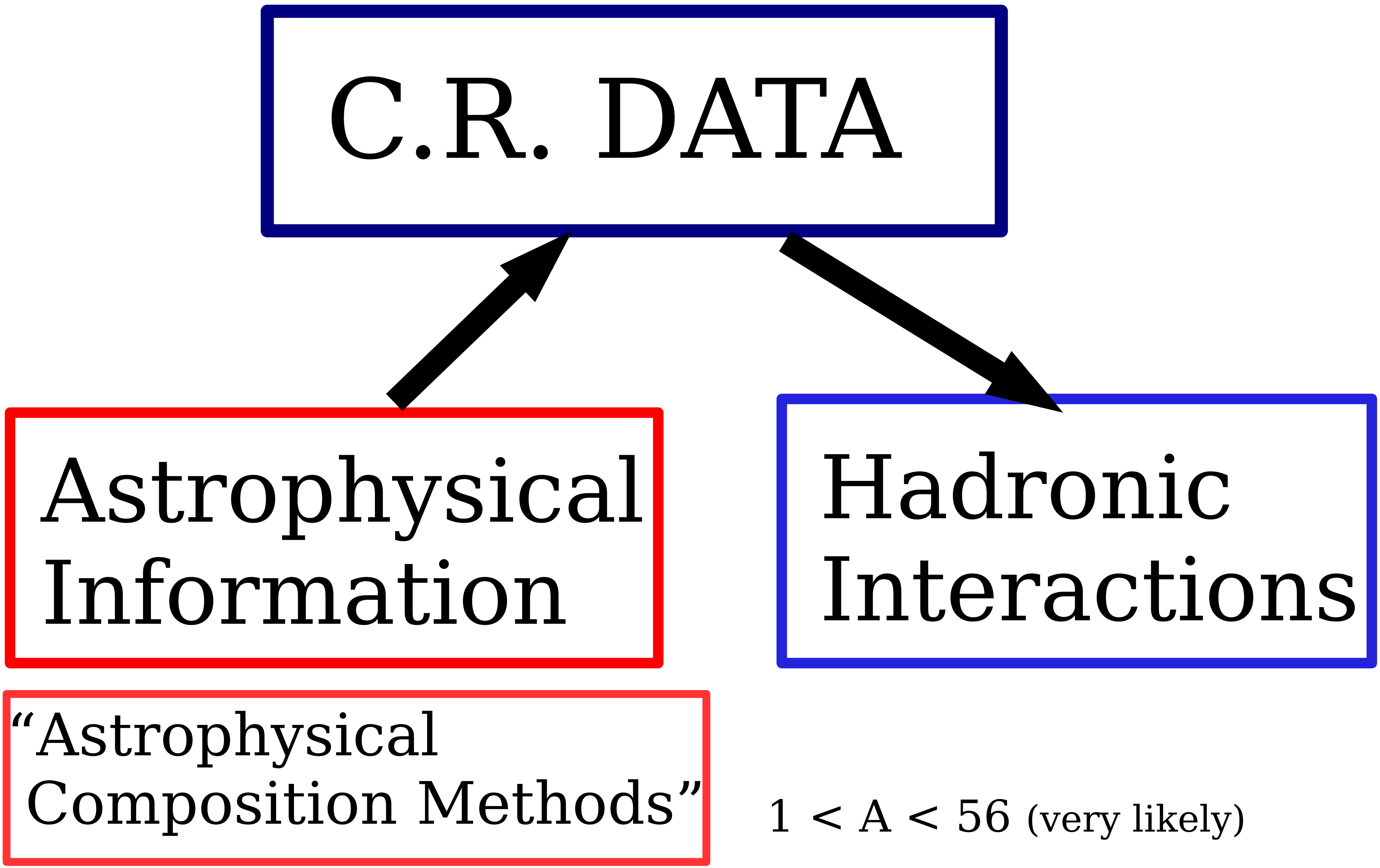
From Accelerator Data + Theory $\longrightarrow$ Astrophysics



Energy
Spectrum
Composition

Cross sections,
Inclusive
spectra
Multiplicities

From Cosmic Ray Data → Hadronic Interactions

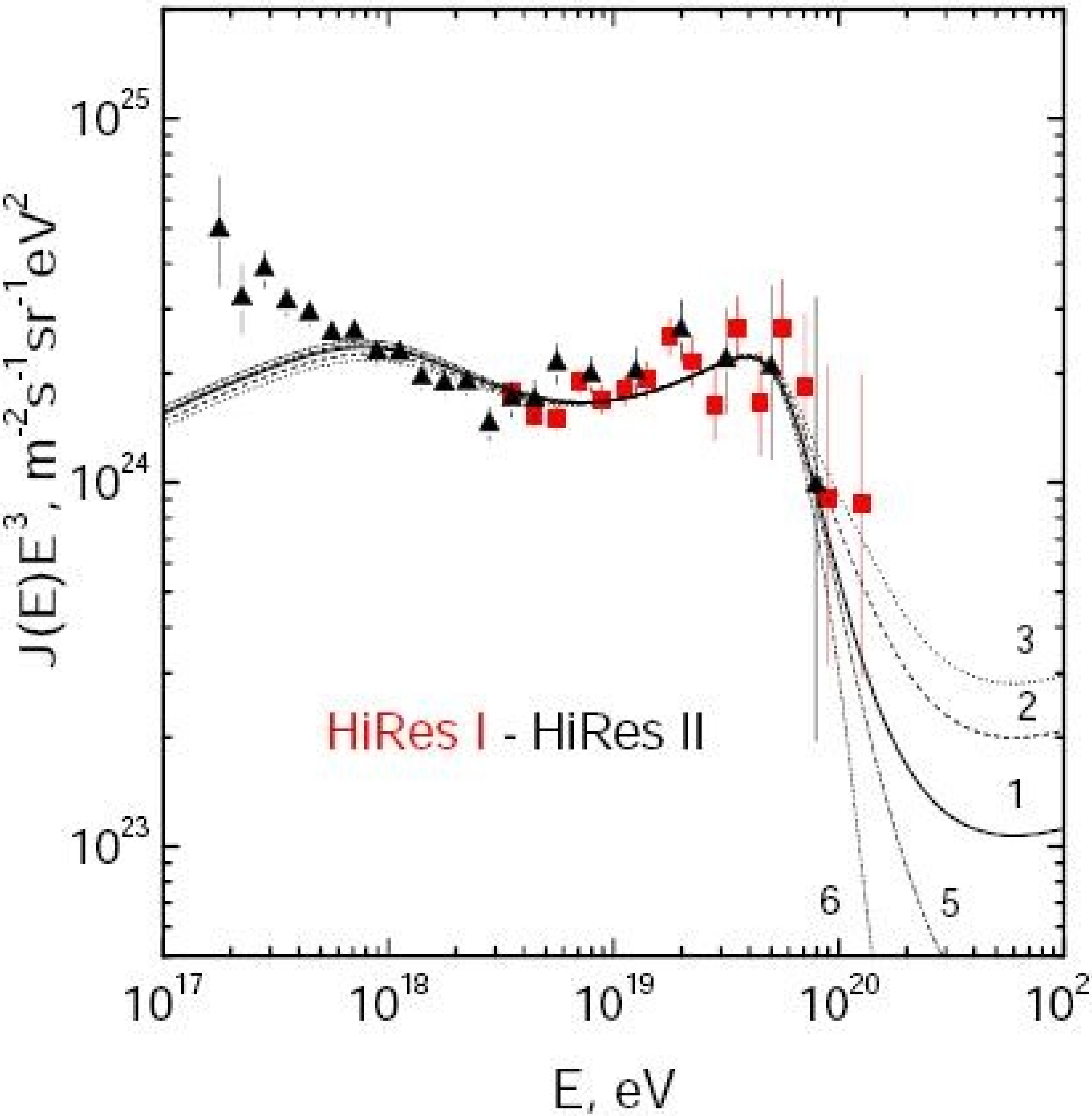


“Astrophysical Composition Methods”

- Energy Spectrum

  “imprints” of Energy Loss

- “Cosmic Magnetic Spectrometer”



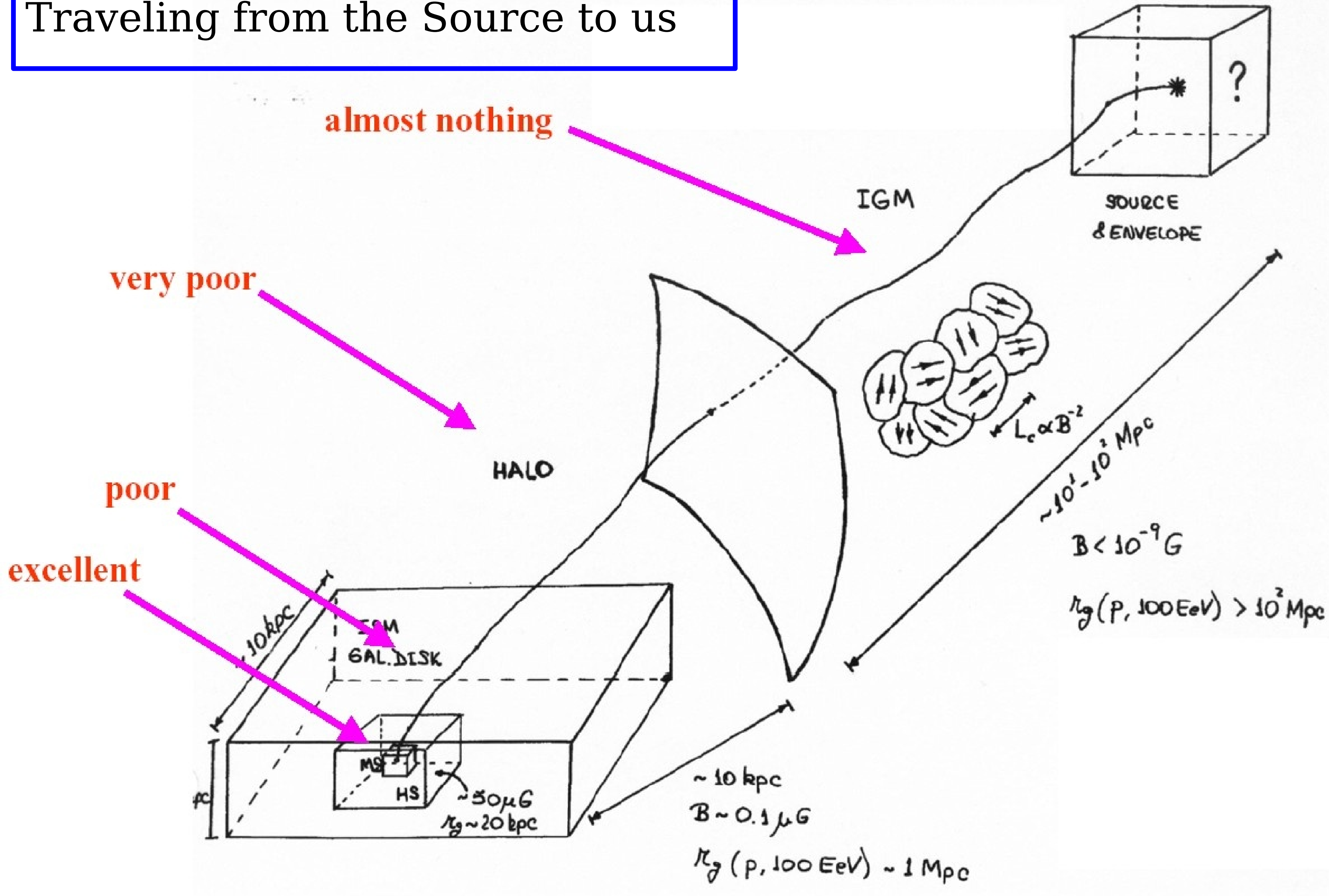
Berezinsky et al.

Inject Smooth power law Spectrum.

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

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

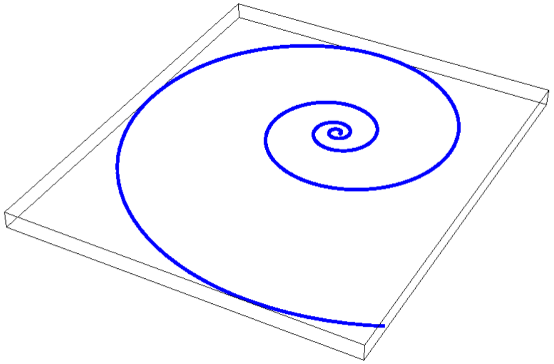
Deviation of a CR trajectory
Traveling from the Source to us



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

Deviation in GALACTIC Magnetic Field

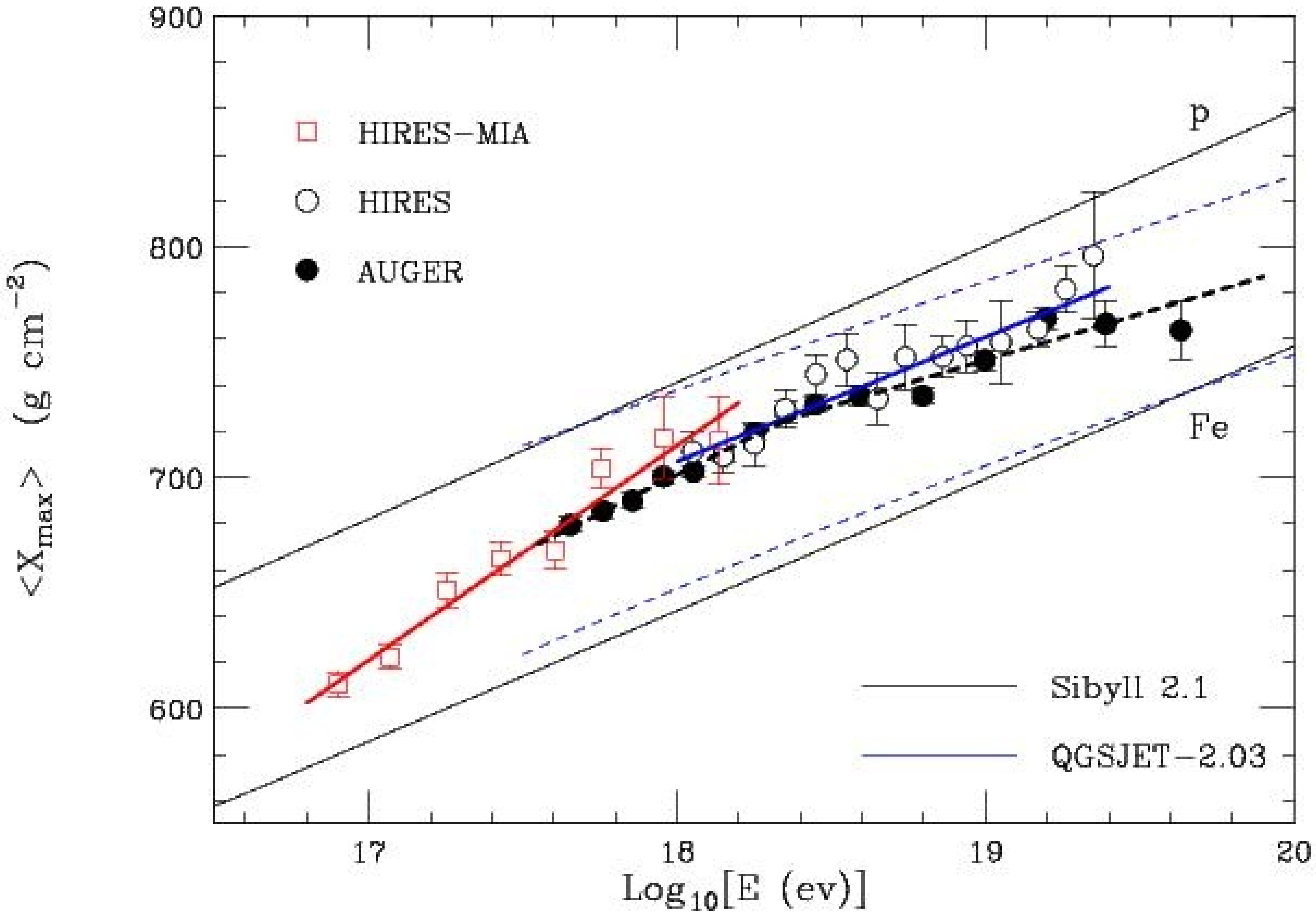
$$\delta \simeq 2.7^\circ \frac{60 \text{ EeV}}{E/Z} \left| \int_0^D \left(\frac{\mathrm{d}\mathbf{x}}{\text{kpc}} \times \frac{\mathbf{B}}{3\ \mu\text{G}} \right) \right|$$



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)
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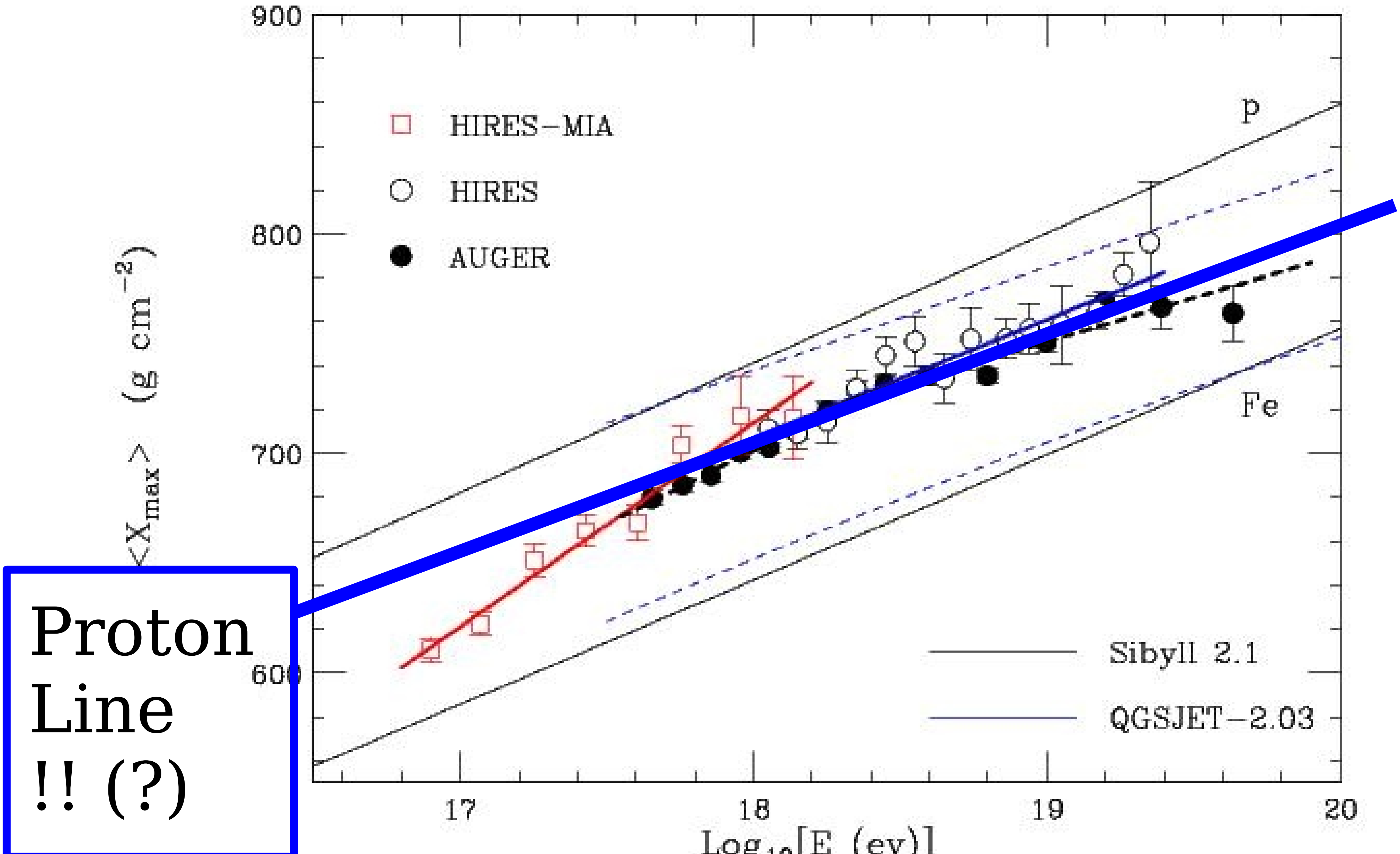
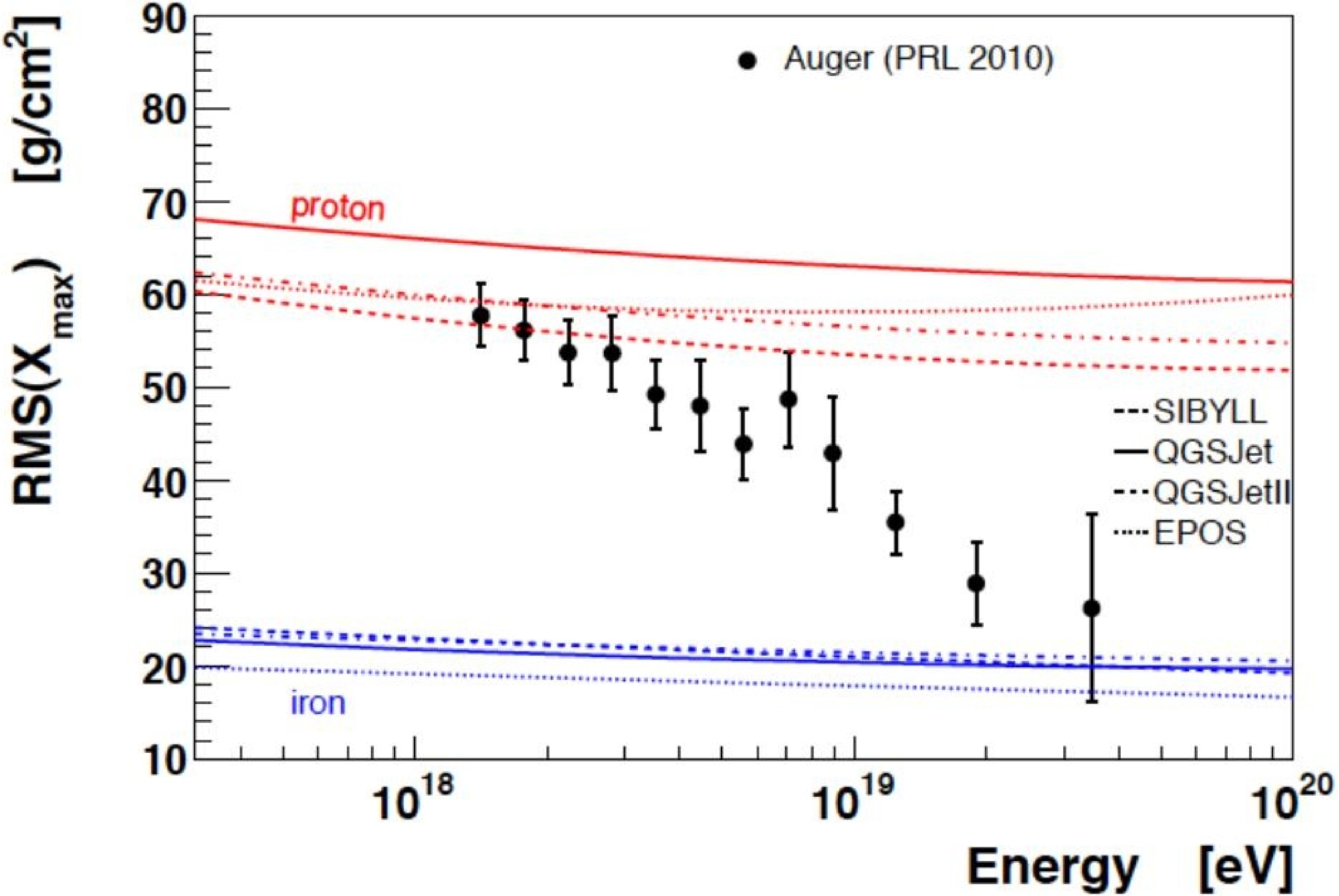
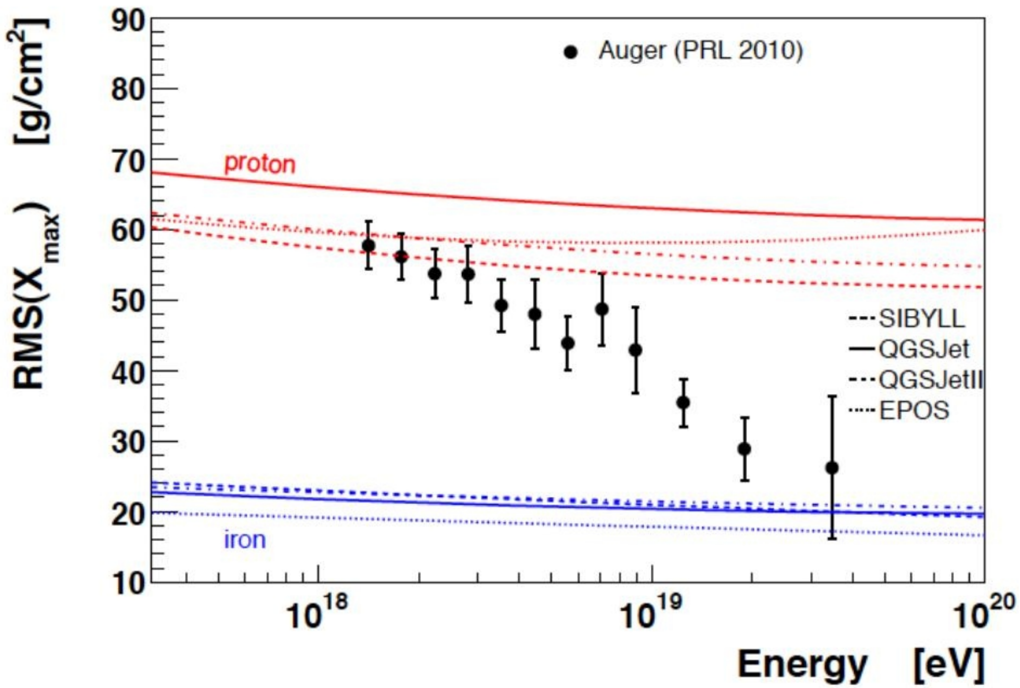


AUGER

Shower fluctuations

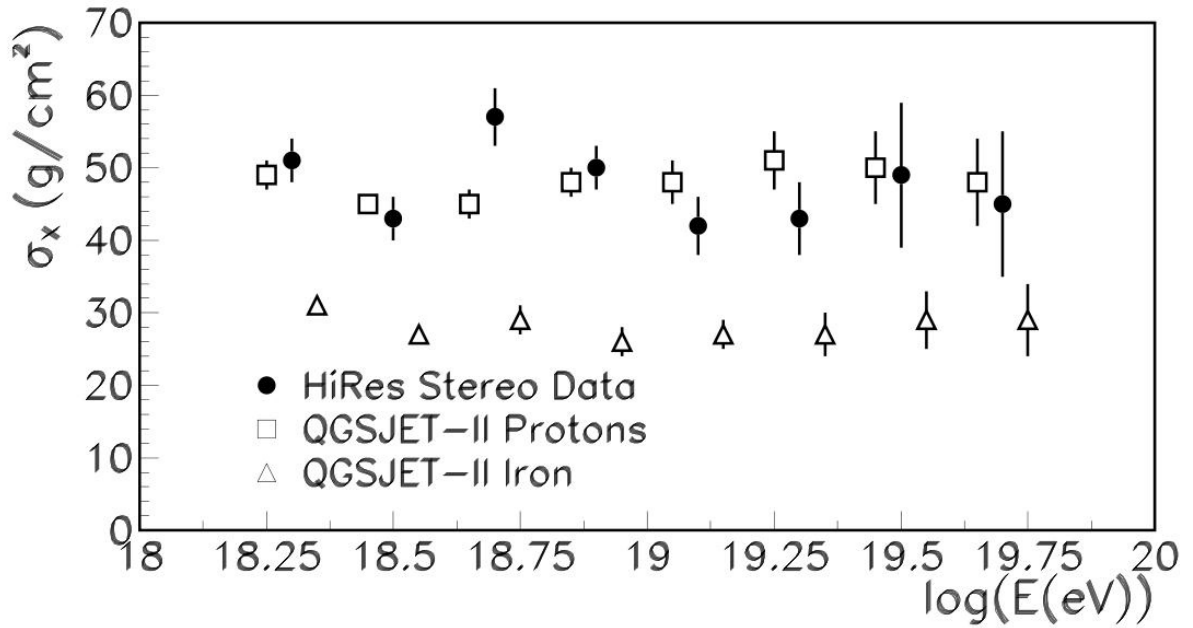


X_{max} fluctuations

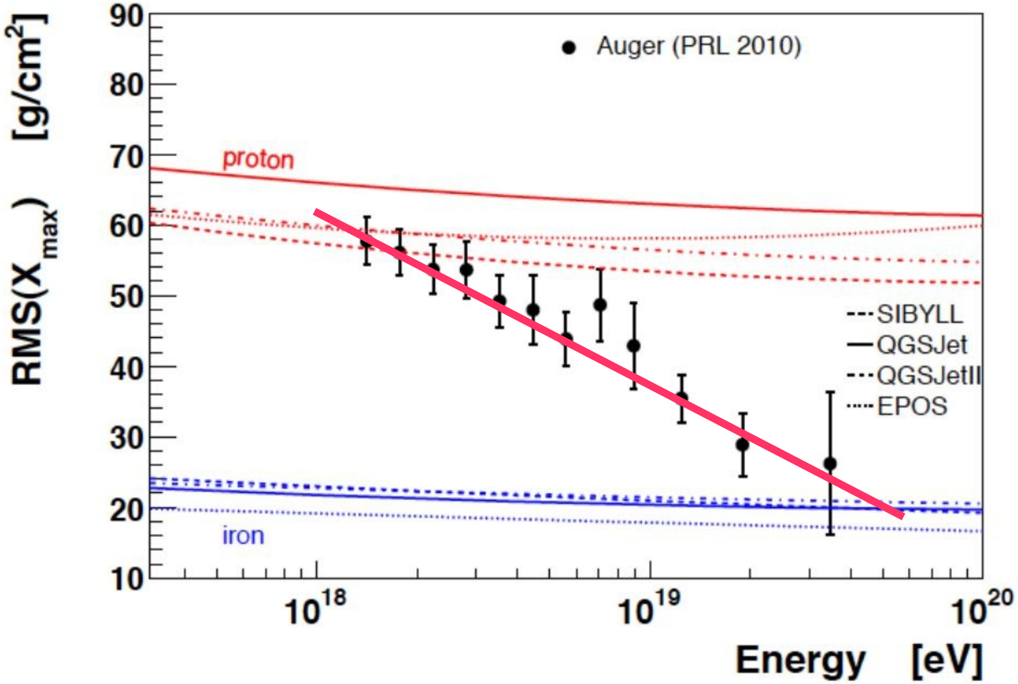


Auger

HiRes



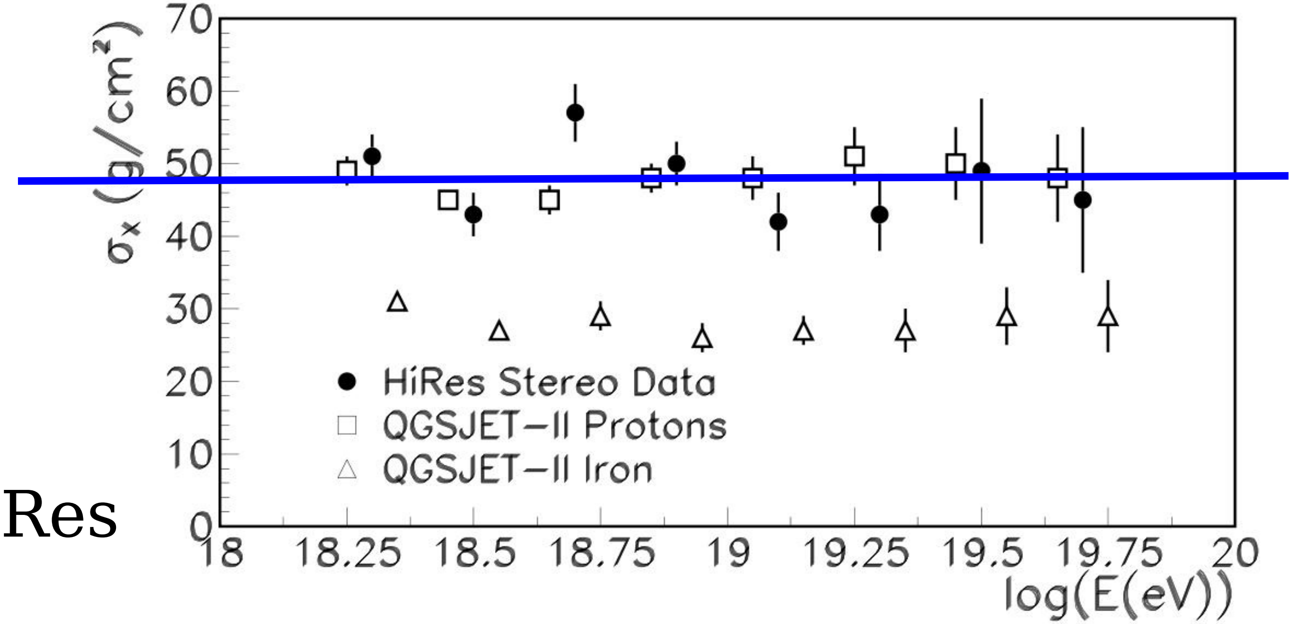
X_{max} fluctuations



Auger

Quasi – monotonically
Decreasing RMS

Constant RMS



HiRes

FLUCTUATIONS on $X_{\max}$

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

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

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

Toy model

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

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

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

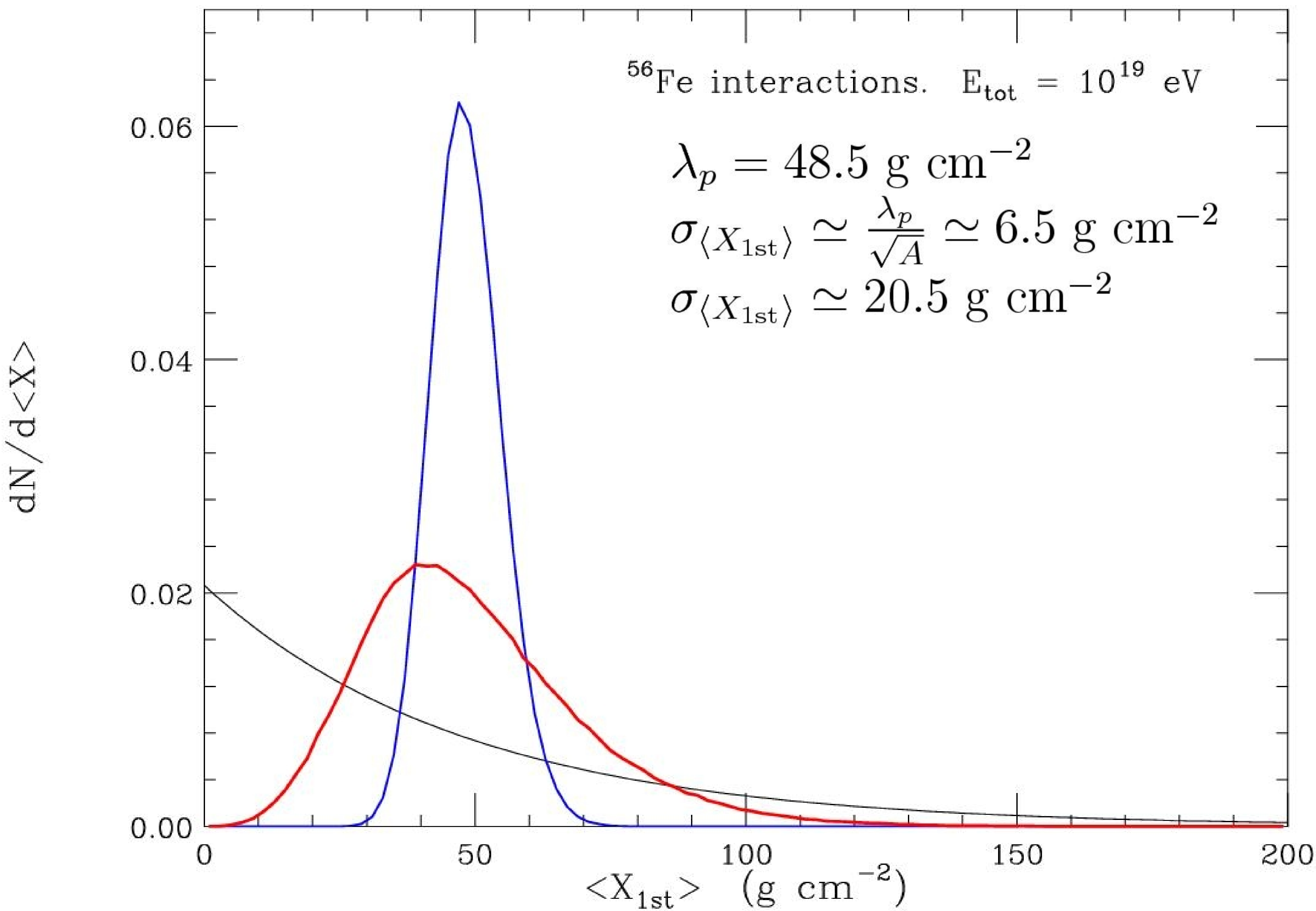
$$A = 56$$

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

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

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

Nuclear interaction.
Several Nucleons
Interact at same point.

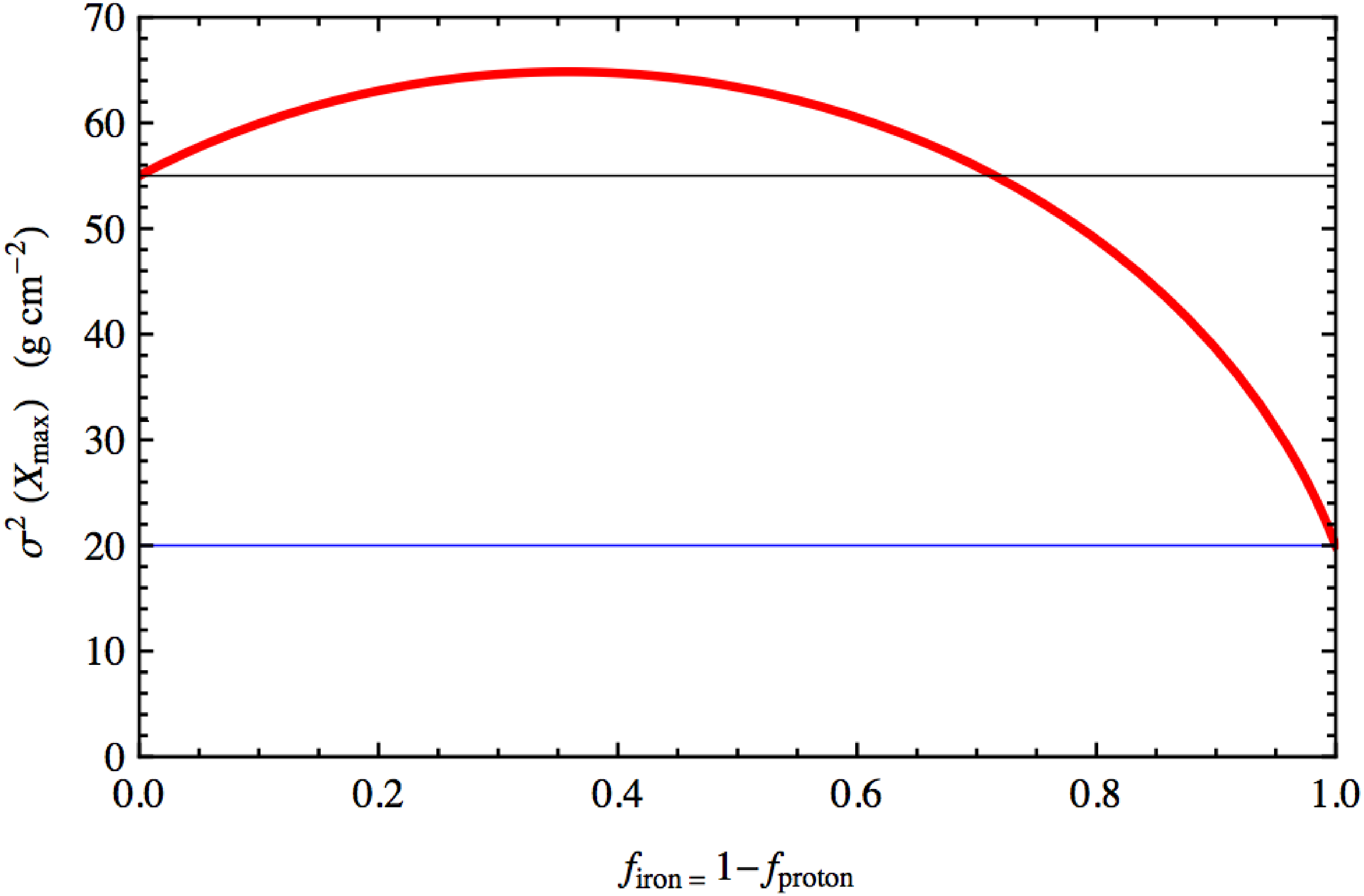

^{56}Fe interactions. $E_{tot} = 10^{19}$ eV
$\lambda_p = 48.5$ g cm^{-2}
$\sigma_{\langle X_{1st} \rangle} \simeq \frac{\lambda_p}{\sqrt{A}} \simeq 6.5$ g cm^{-2}
$\sigma_{\langle X_{1st} \rangle} \simeq 20.5$ g cm^{-2}
dN/d<X>
0.00
0.02
0.04
0.06
0
50
100
150
200
<X_{1st}> (g cm^{-2})

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

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

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

Mixing Protons with Iron-nuclei



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

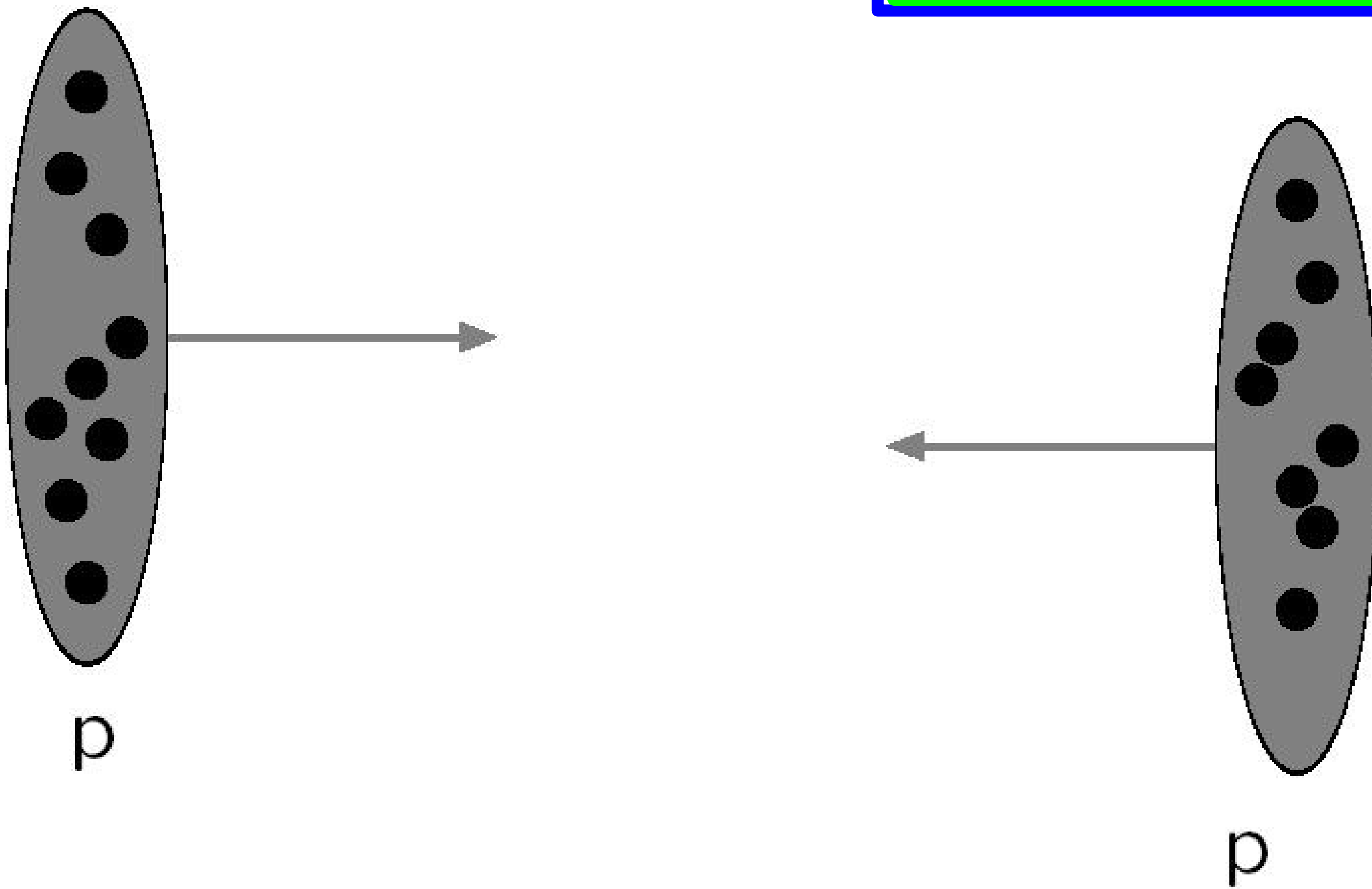
THEORY

Construction of Hadronic Models

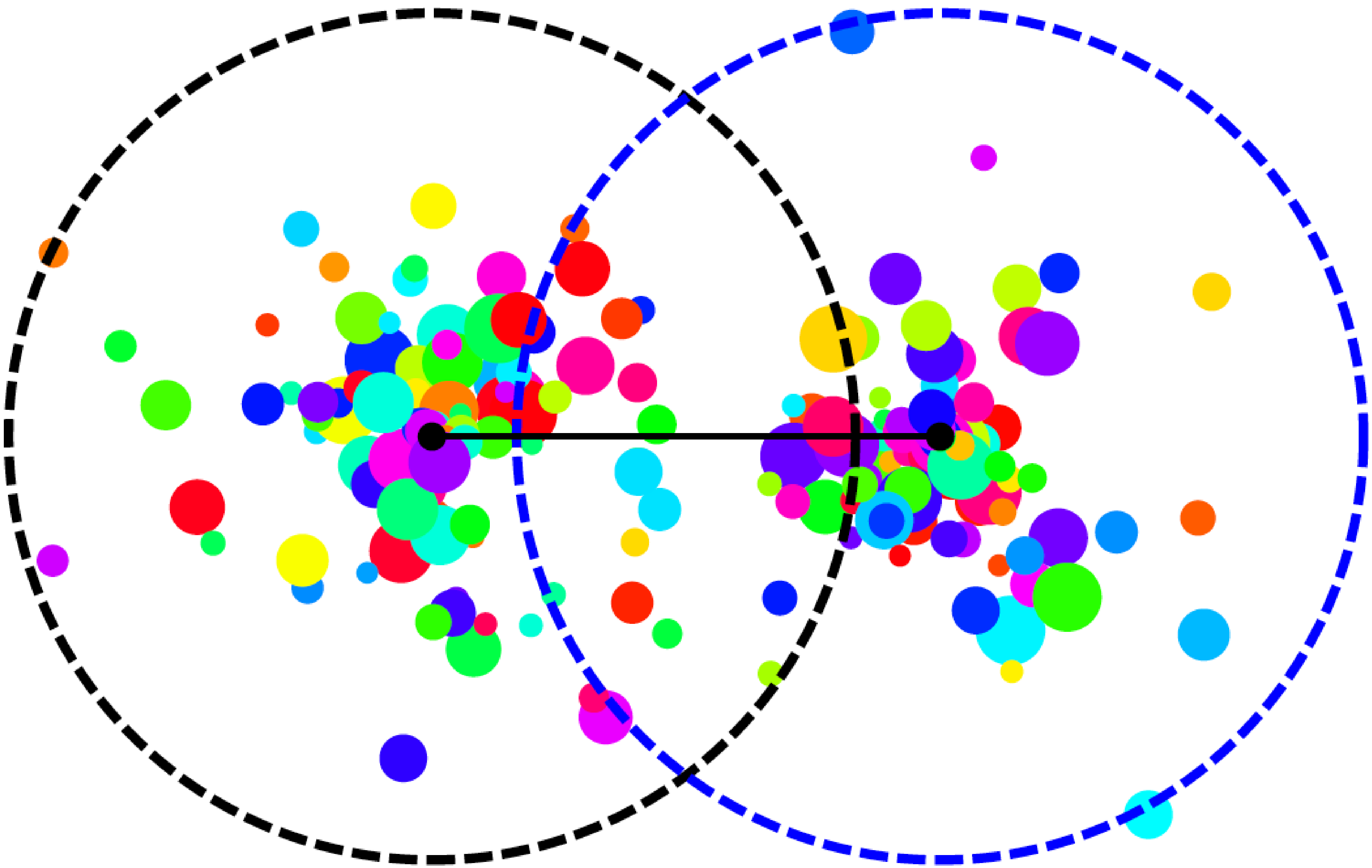
Hadronic Interactions

QCD

Composite (complex) Objects
Multiple interaction structure



“Cartoon” of a pp interaction in the transverse plane



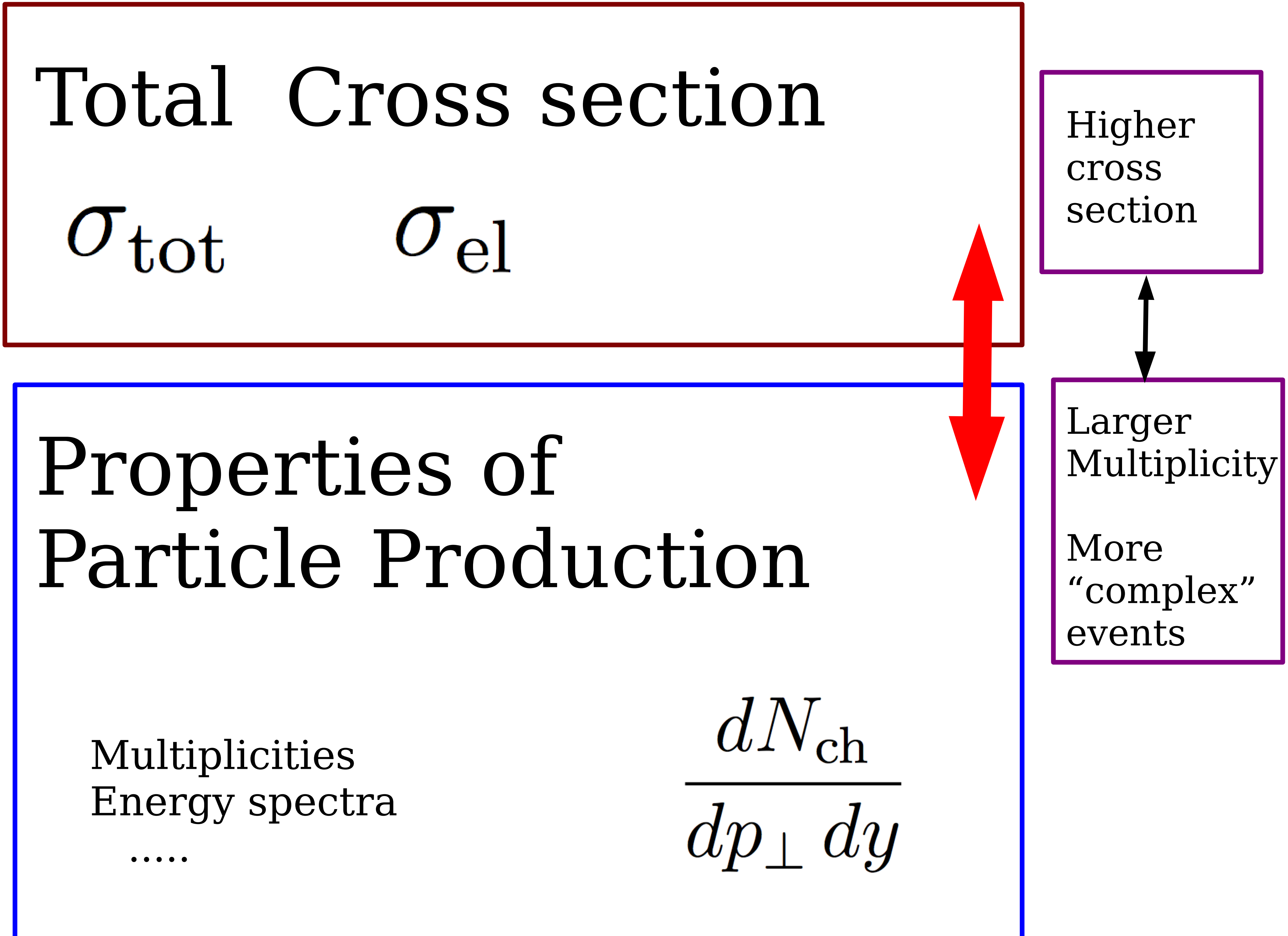
Total Cross section

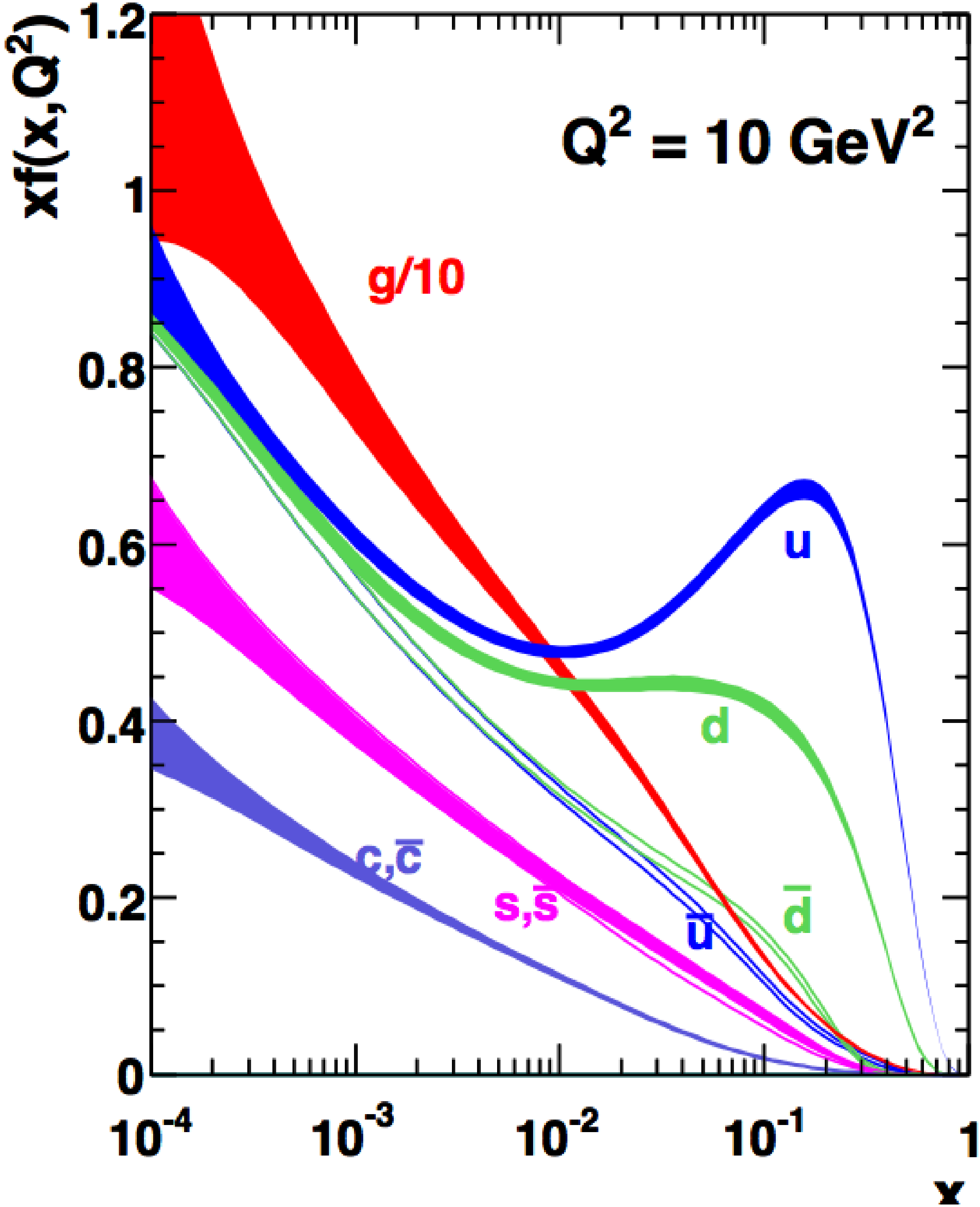
$\sigma_{\rm tot}$ $\sigma_{\rm el}$

Properties of
Particle Production

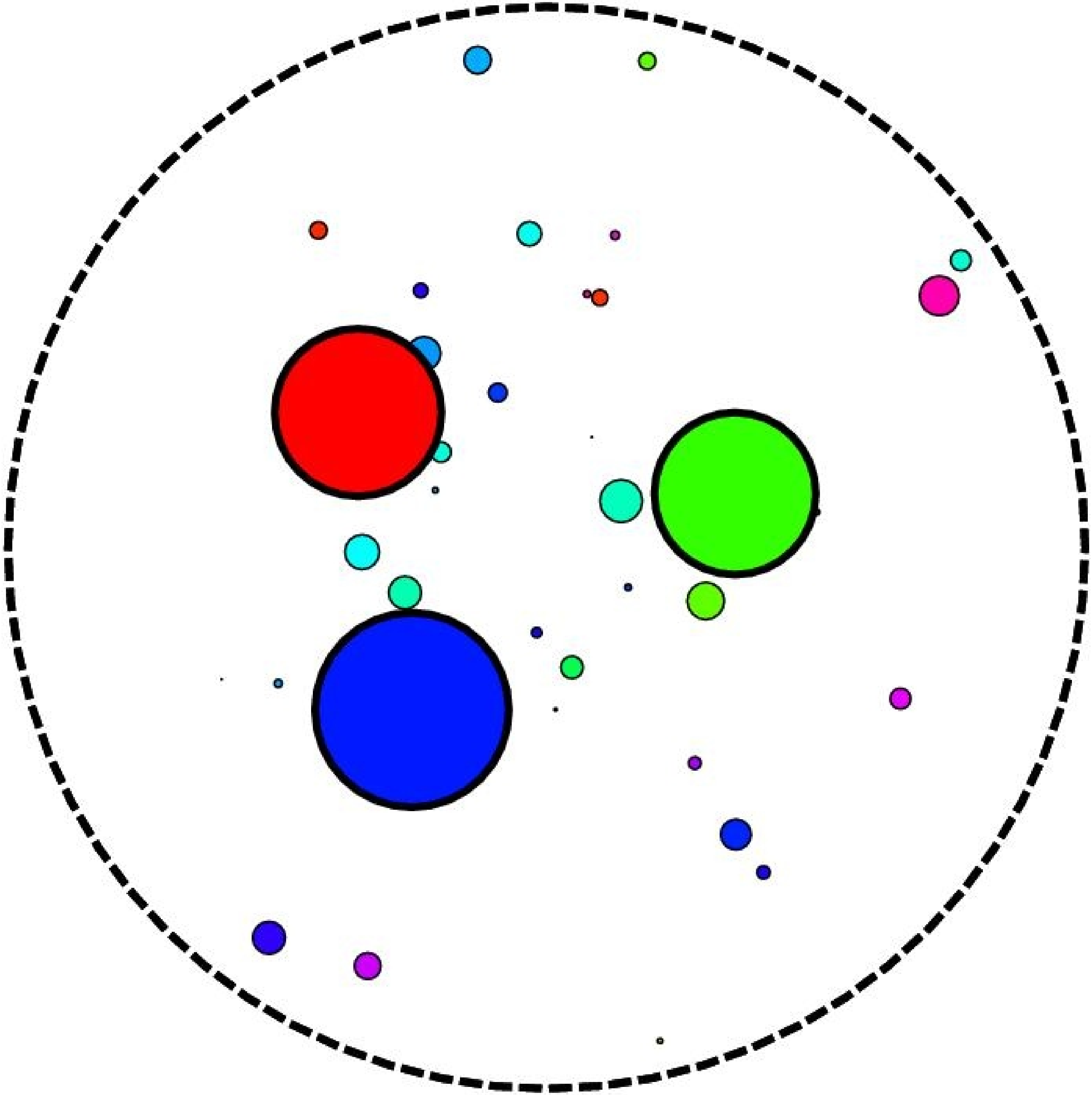
Multiplicities
Energy spectra
.....

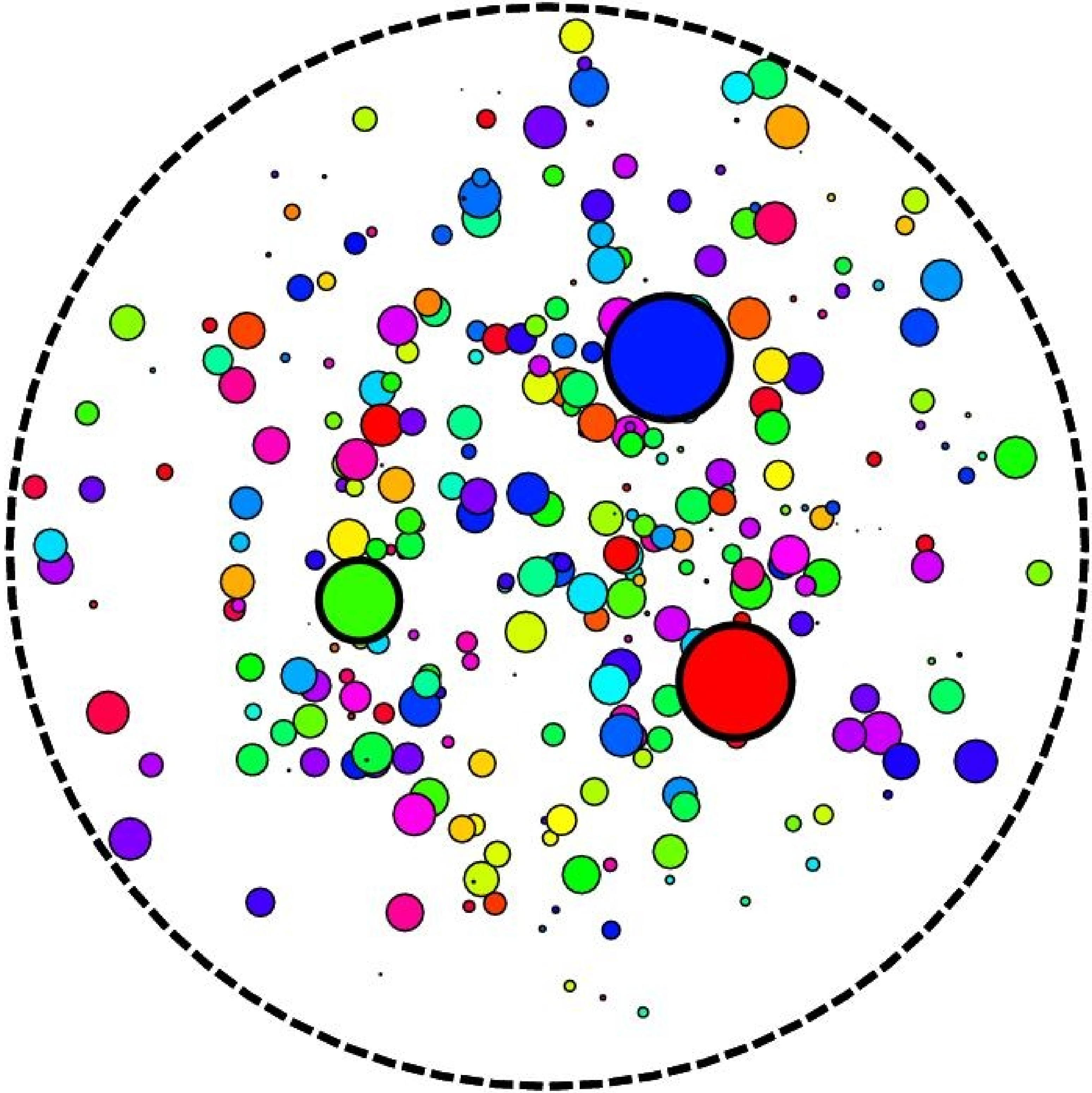
$$\frac{dN_{\rm ch}}{dp_\perp\, dy}$$


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



Parton
Distribution
Function

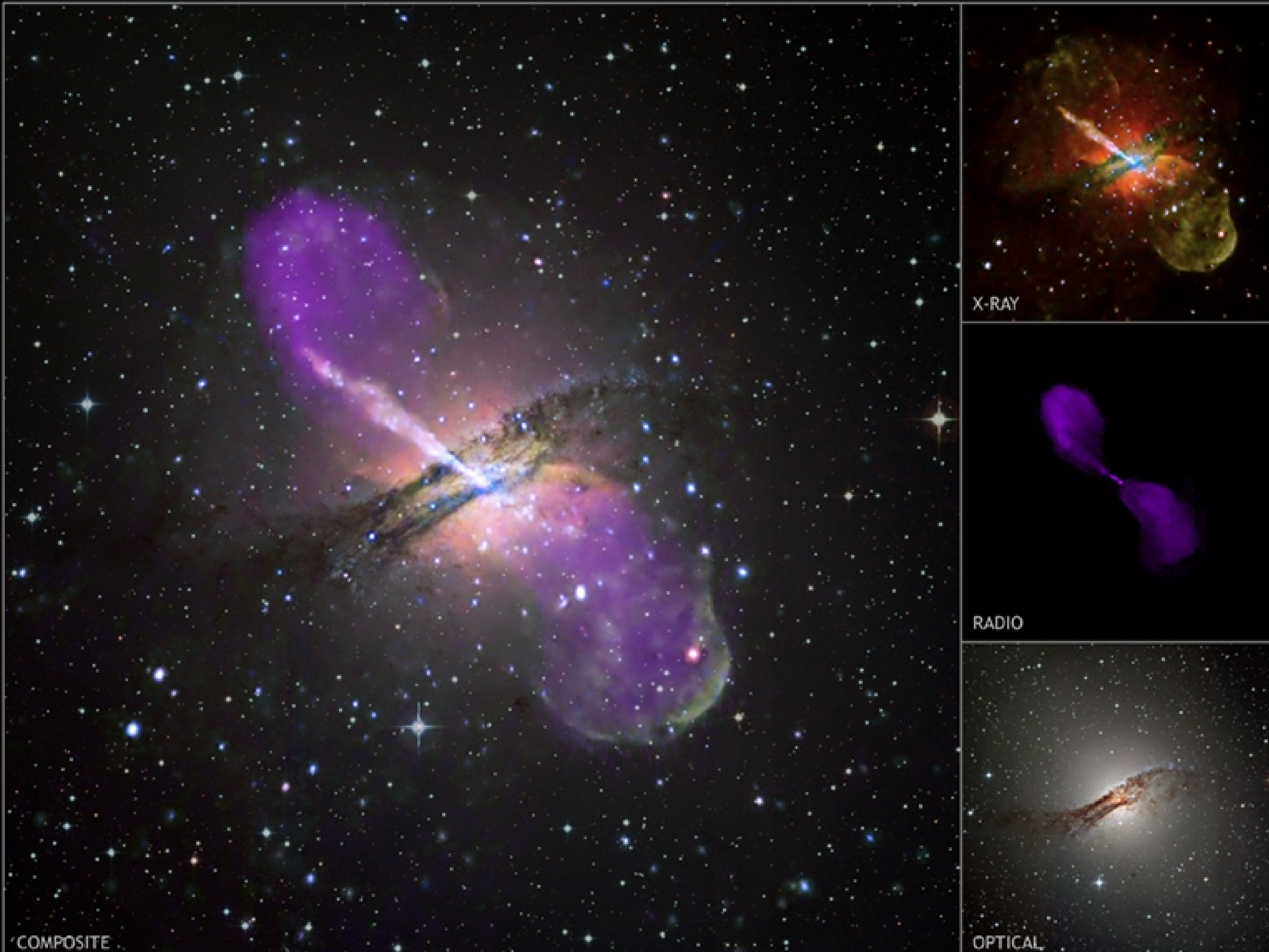




MULTIPLE INTERACTIONS

- 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


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

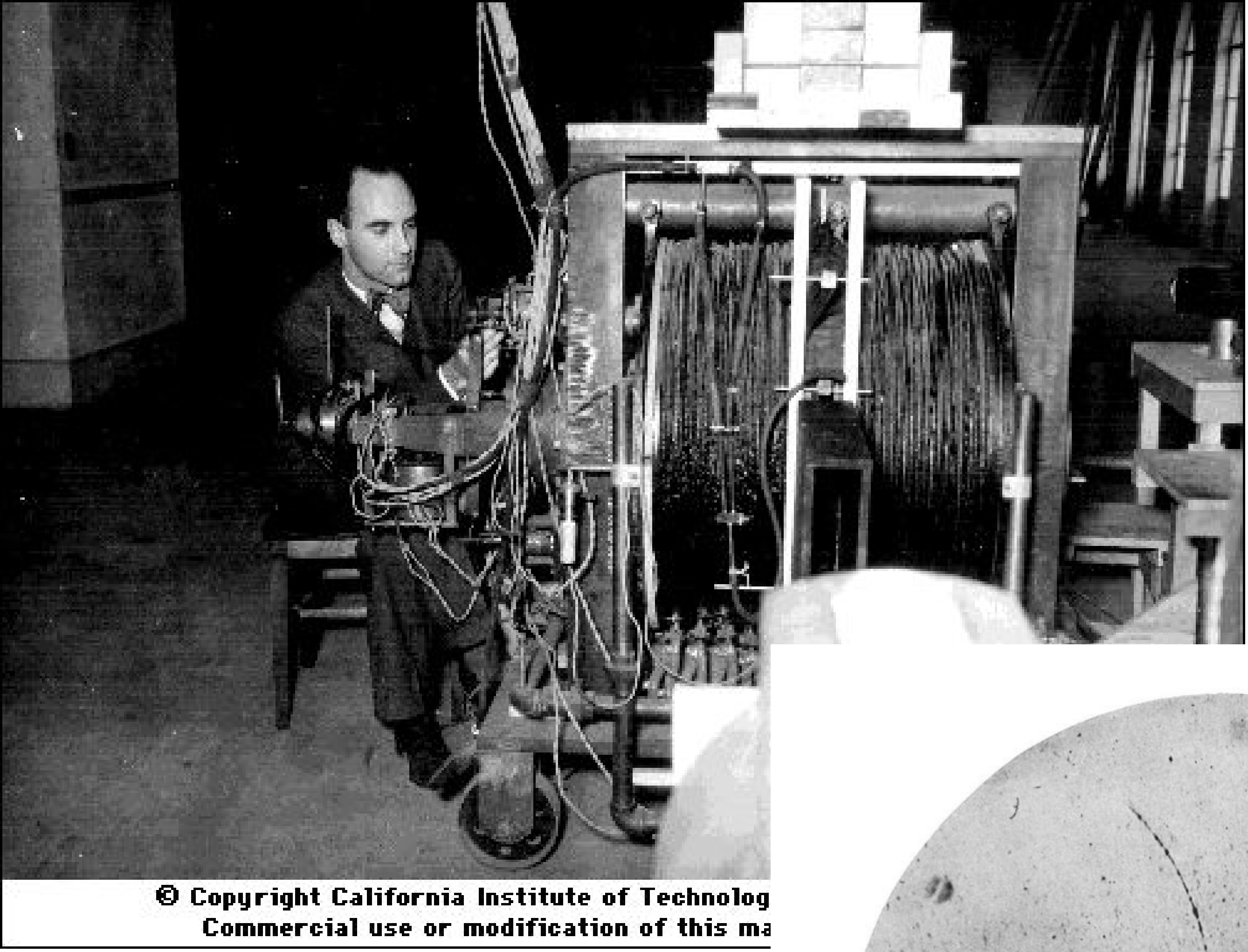
Microscopic

Partonic constituents of matter

Length scale 10^{-13} cm

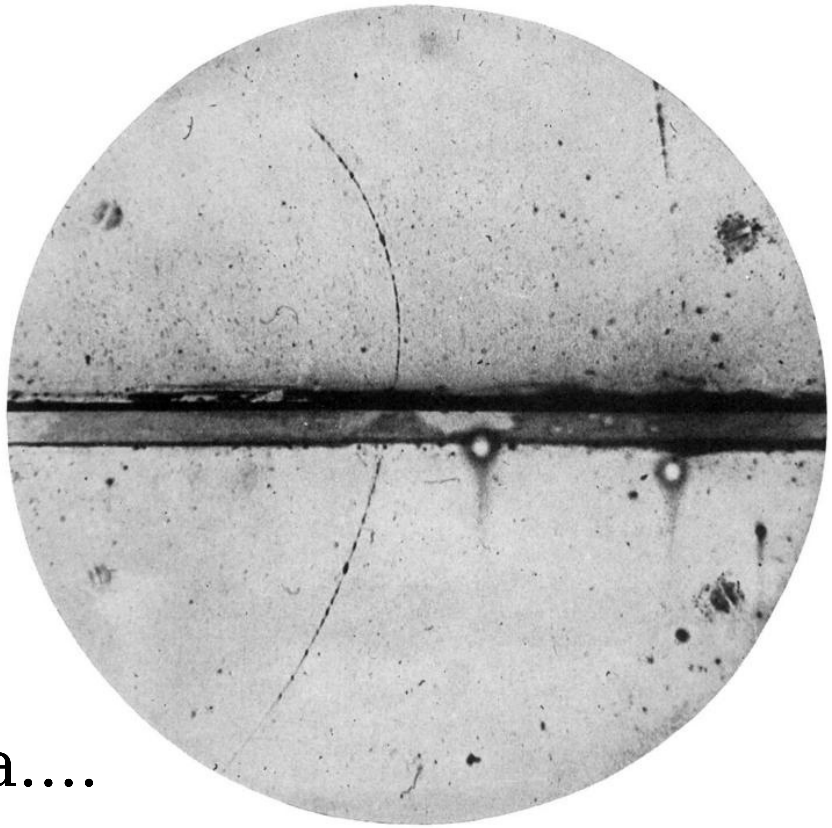
Exciting

Difficult



Carl Anderson
(february 1933)

Near his
“Wilson chamber”



23 MeV

6 mm
Lead plate

63 MeV

Discovery of the
POSITRON

Muon, Pion, Kaon, Lambda....