Collider Physics, High Energy Cosmic Rays and Neutrinos

[25-29 september 2017]

Paolo Lipari INFN Roma Sapienza

Collider Physics and the Cosmos
GGI Arcetri

13th october 2017

Format of the workshop:
6 talks + “free format” discussion

1. Neutrinos, 0nu-double beta decay and the LHC
   (Frank Deppisch)

2. Searching for Monopoles and Other Exotica
   at Colliders and in Cosmic Rays
   (James Pinfold)

3. Cosmic Rays from the “Knee” to the “Ankle”
   and Hadronic Interactions
   (Paolo Lipari)

4. Ultra High Energy Cosmic Rays and
   Hadronic Interactions. [Part 1]
   (Ralph Engel)

5. [Part 2] *(Ralph Engel)*

6. Telescope Array *(Kenji Kadota)*

Outline:

1. Search for “Exotic” Particles
   [MoEDAL experiment at LHC]

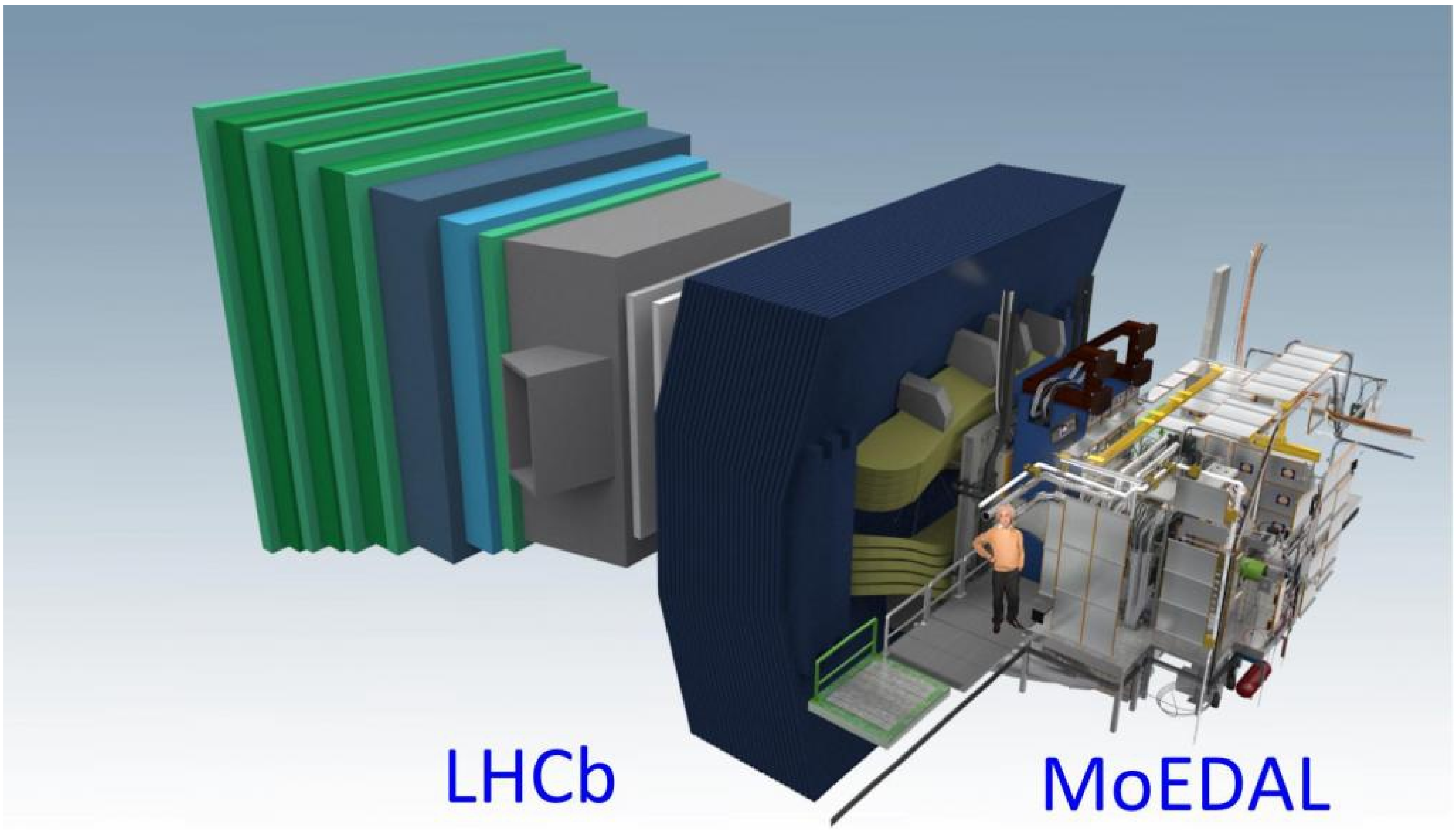
2. Cosmic Rays and
   The “High Energy Universe”

3. Hadronic Interactions

3a Indirect searches for Dark Matter

3b Very High Energy Cosmic Rays

MoEDAL experiment at LHC



MoEDAL is the newest experiment at the LHC that started data taking at √s=13 Tev in 2015

Aim to search for highly ionizing avatars of new physics, very long-lived particles and highly penetrating phenomena

Complementary to general purpose LHC detectors ATLAS & CMS

The search for the magnetic monopole up to 6-7 TeV mass is a key aim, but many others defined (Int.J.Mod.Phys. A29 (2014) 1430050)

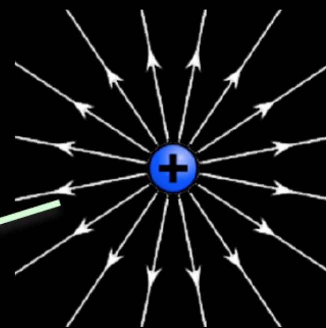
Possible use of MAPP (MoEDAL Apparatus for Long-Lived particles) subdetector detector propoed at this meeting, for

Searching for heavy sterile neutrinos

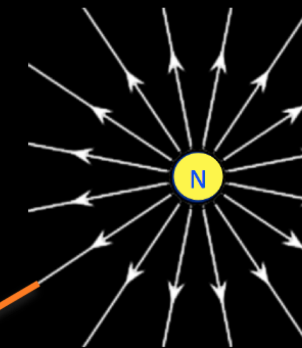
High energy muons studies useful in understanding cosmic muons may be possible – the possibility arose from the meeting (RE: Ralph's 2nd talk on the muon problem)

Monopoles Symmetrize Maxwell's Eqns

$$\vec{\nabla} \cdot \vec{E} = \rho_{\mathrm{E}}$$
$$\vec{\nabla} \cdot \vec{B} = 0$$
$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$
$$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + \vec{j}_{\mathrm{E}}$$

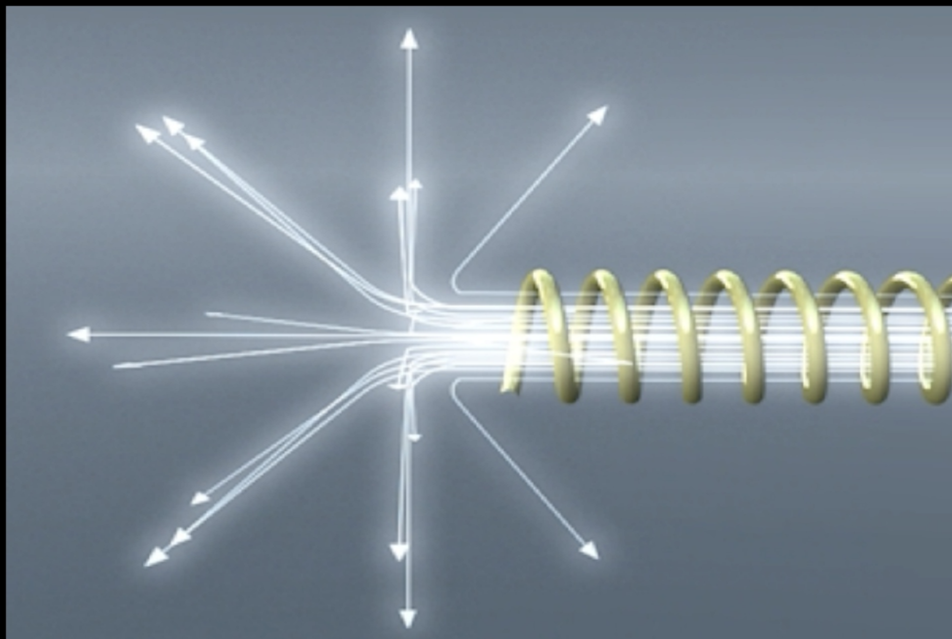


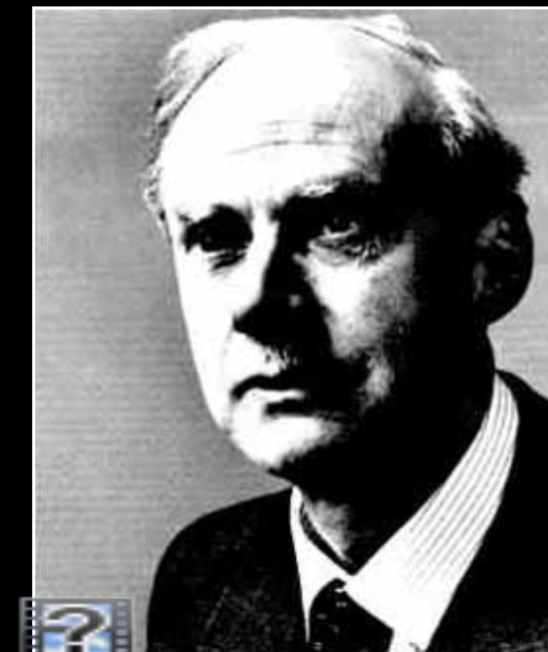
$$\vec{\nabla} \cdot \vec{E} = \rho_{\mathrm{E}}$$
$$\vec{\nabla} \cdot \vec{B} = \rho_{\mathrm{M}}$$
$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} - \vec{j}_{\mathrm{M}}$$
$$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + \vec{j}_{\mathrm{E}}$$



- *The symmetrized Maxwell's equations are invariant under rotations in the plane of the electric and magnetic field*
- *This symmetry is called Duality - the distinction between electric and magnetic charge is merely one of definition*

Dirac's Monopole





- *In 1931 Dirac hypothesized that the Monopole exists as the end of an infinitely long and thin solenoid - the "Dirac String"*
- *Requiring that the string is not seen gives us the Dirac Quantization Condition & explains the quantization of charge!*

$$ge = \left[\frac{\hbar c}{2}\right] n \quad OR \quad g = \frac{n}{2\alpha} e \quad \left(from \ \frac{4\pi e g}{\hbar c} = 2\pi n \quad n = 1,2,3..\right)$$

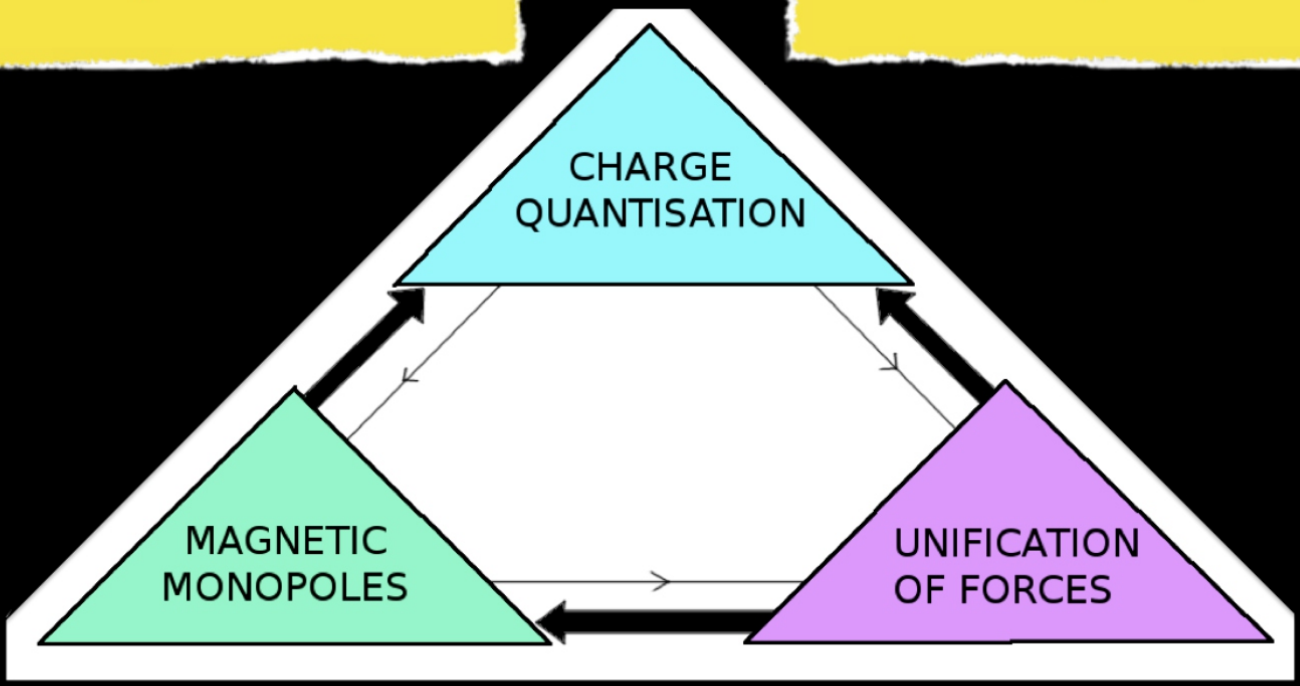
The ‘t Hooft-Polyakov Monopole

- *In 1974 ‘t Hooft and Polyakov showed that monopoles exist with the framework of Grand Unified Theories*
  - *Such monopoles are topological solitons (stable, non dissipative, finite energy solutions) with a topological charge*
  - *The topology of the soliton’s field configuration gives stability EG a knot in a rope fixed at the ends (boundary conditions)*

The Importance of the Monopole

They restore symmetry to Maxwell's Equations

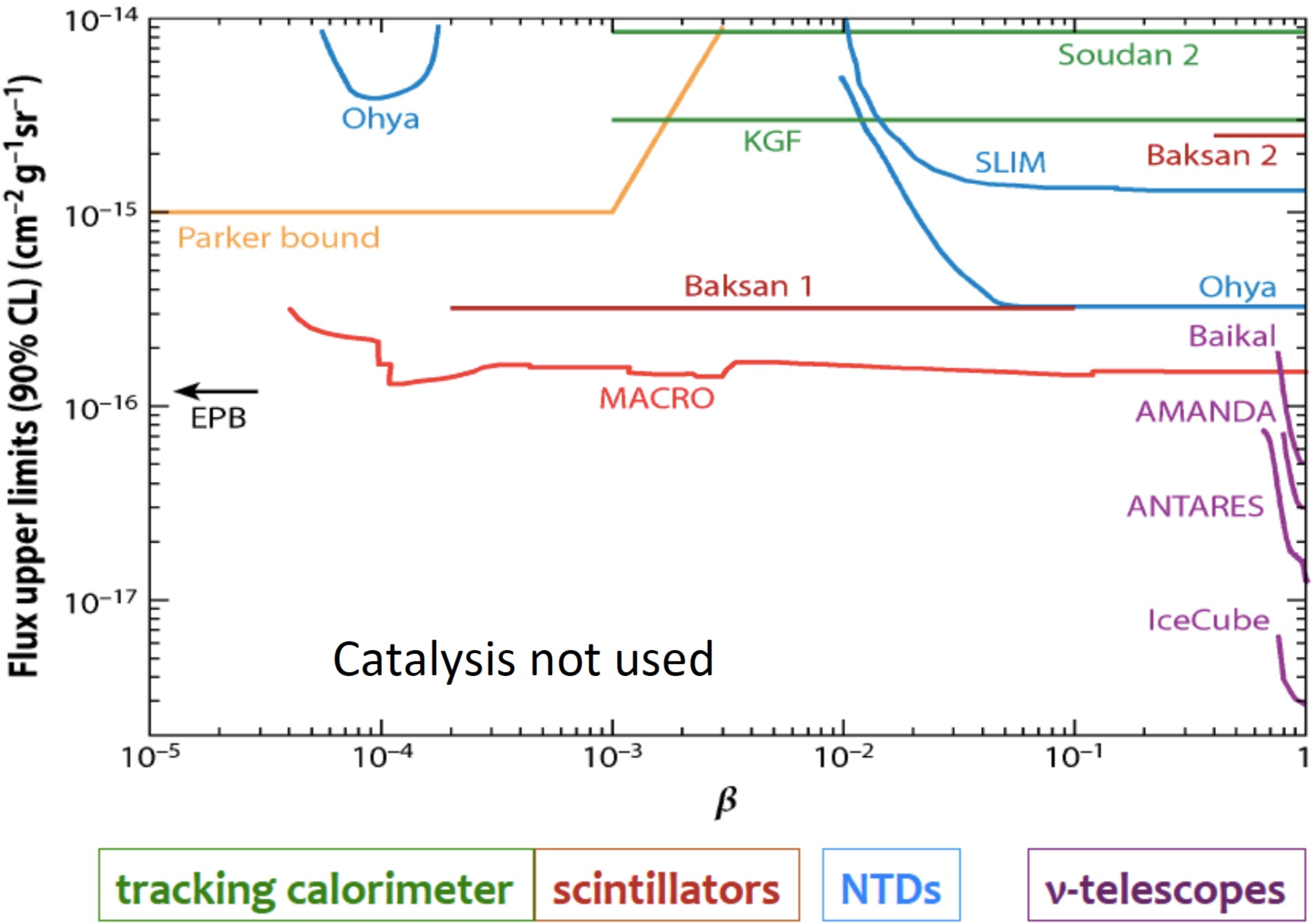
They explain electric charge quantization



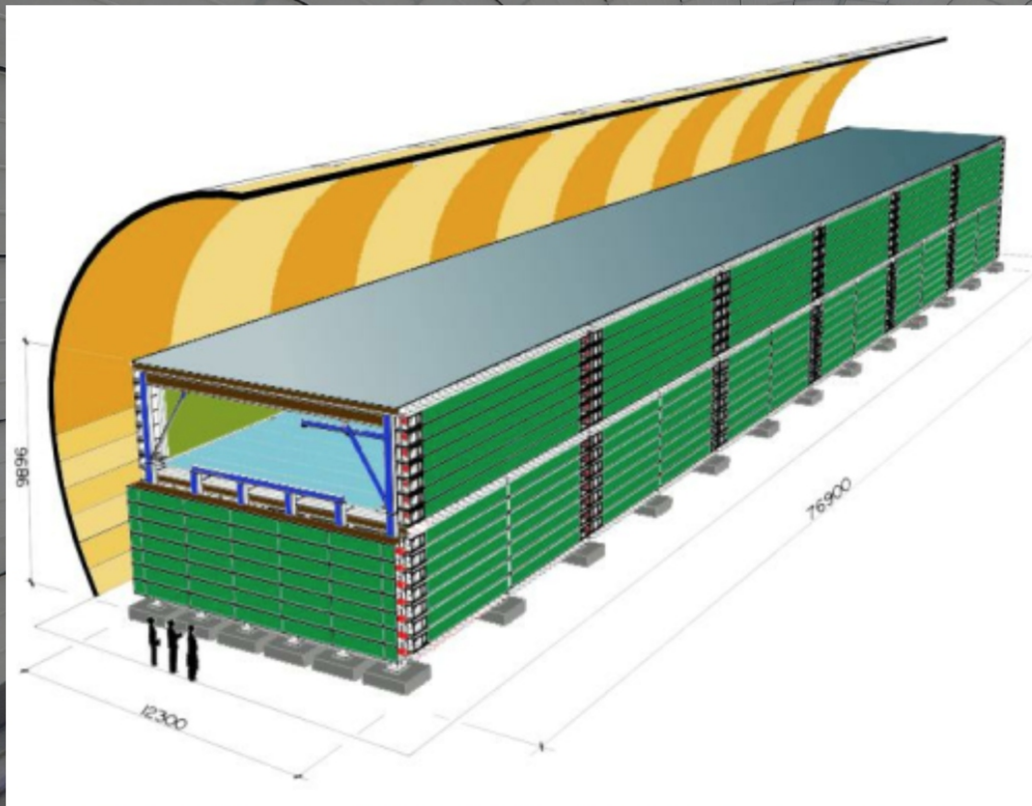
GUT & EW monopoles are excitations of the Higgs field

They are required by GUTs string theory & M-theory

Grand Unified Mass Monopoles limits



MACRO Observatory Grand Sasso (1989-2000)

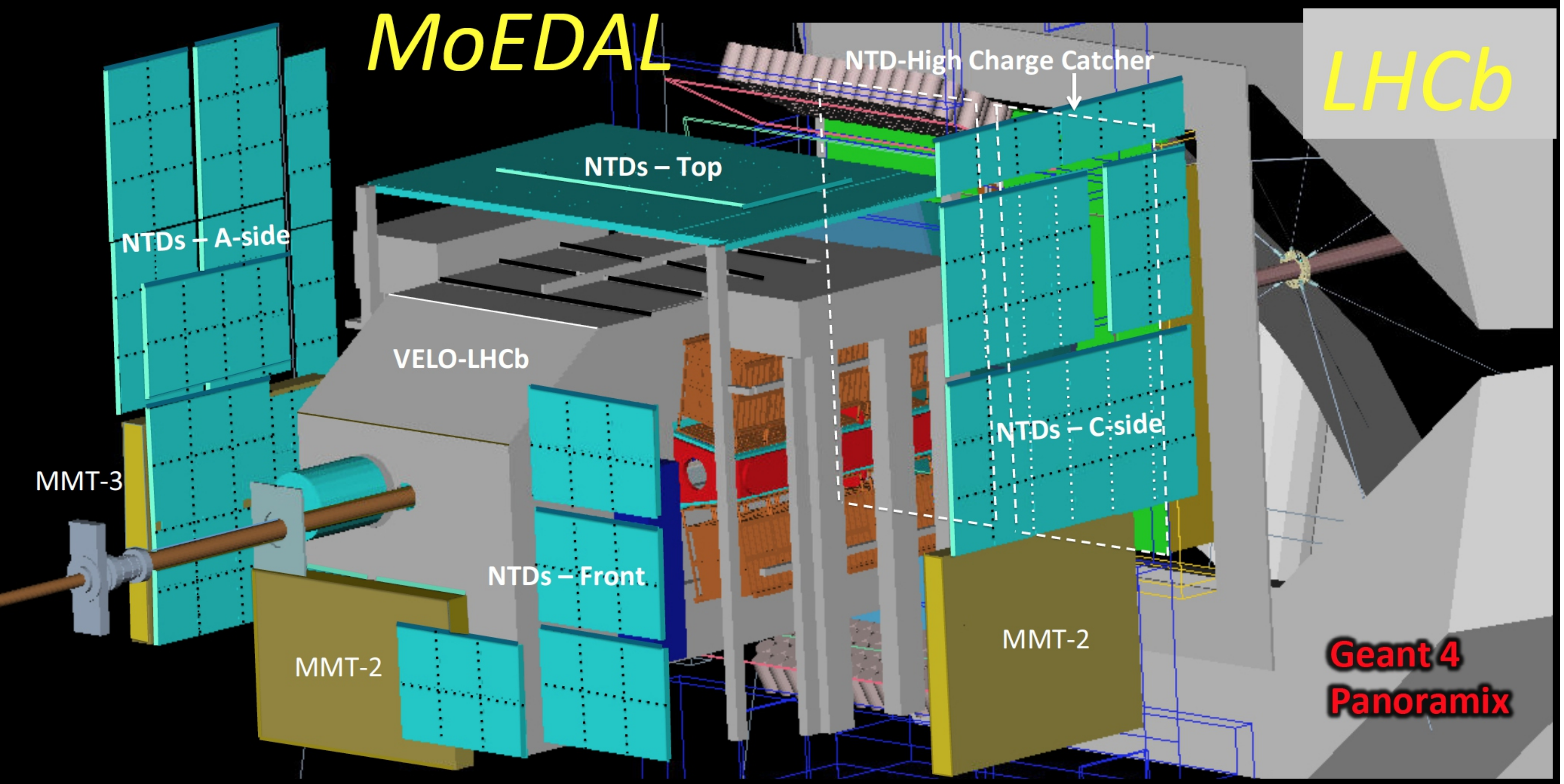


- *NTD surface : ~ 1300m^2*
- *$\Sigma\Omega_{\text{fast MM}}$ ~ 7100 m^2 sr*

- 3 Subdetectors:
  - *Scintillators*
  - *Limited Streamer Tubes*
  - *Nuclear Track Detectors*

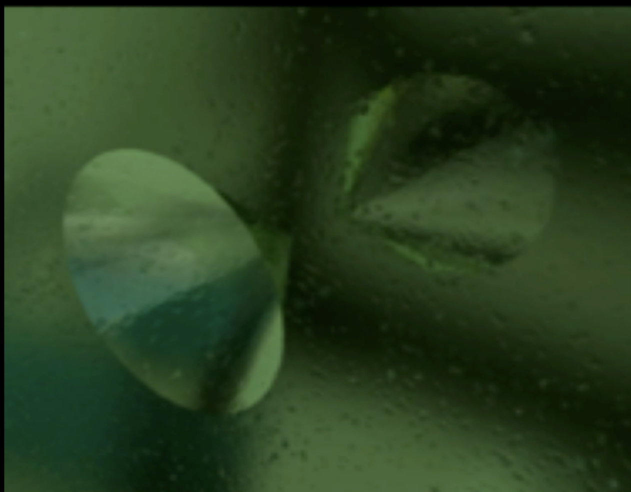
MACRO Limits on GUT Cosmic MMs still the best (on the PDG since 2000)

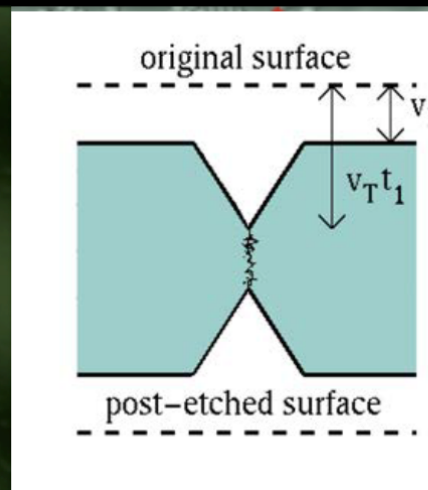
Full MoEDAL Deployment 2014-2015

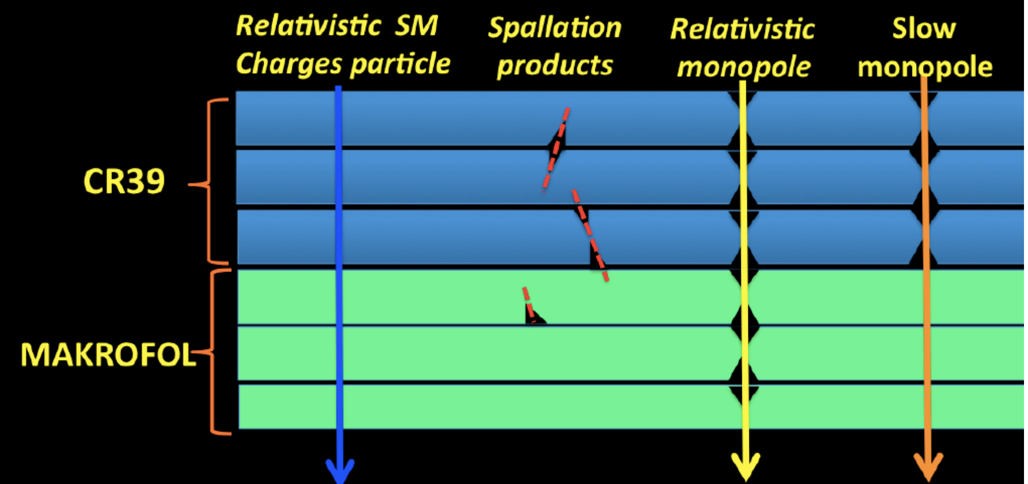


- *Acceptance for at least one monopole from monopole pair production to hit NTDs ~70% (over 150 m² of plastic)*

The Signal in the NTDS

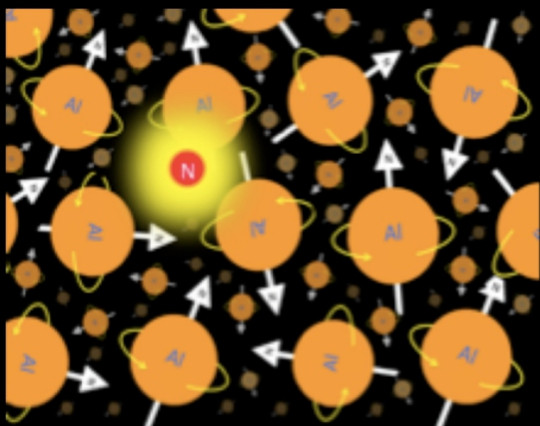






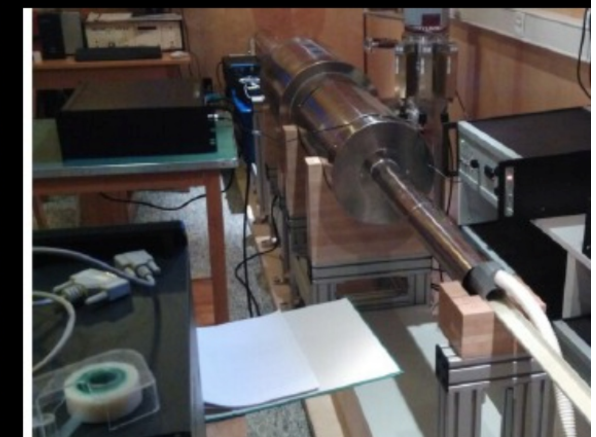
- *Largest NTD array (**150m² tot**) ever deployed at an accelerator*
  - *NTD tacks consist of CR39 (Thr. 5 mip) & Makrofol (Thr. 50 mip)*
  - *Damage revealed by controlled etching - etch pits are formed*
  - *Charge resolution is ~|0.1|e, where |e| is the electron charge*
  - *Precision of each etcha pit measurement ~20-50 microns*
- *NTDs are calibrated at heavy-ion beams at NSRL & NA61*
- *ATLAS and CMS cannot calibrate for highly ionizing plastic*

Signal in Squid MMT Detectors



Monopole trapped by aluminium nuclei

The MoEDAL trapping detectors at IP8



THE Zurich DC-SQUID magnetometer

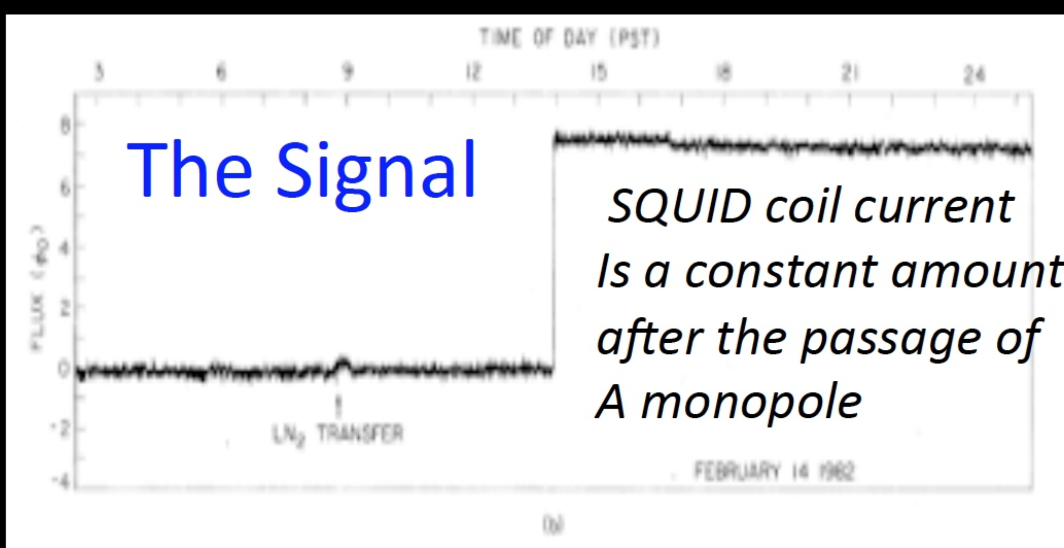
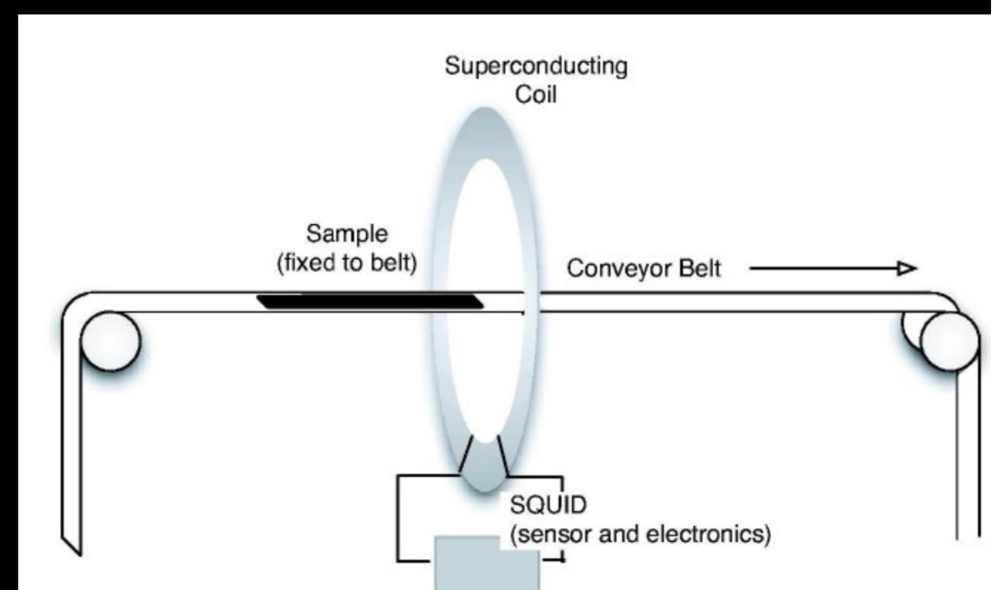
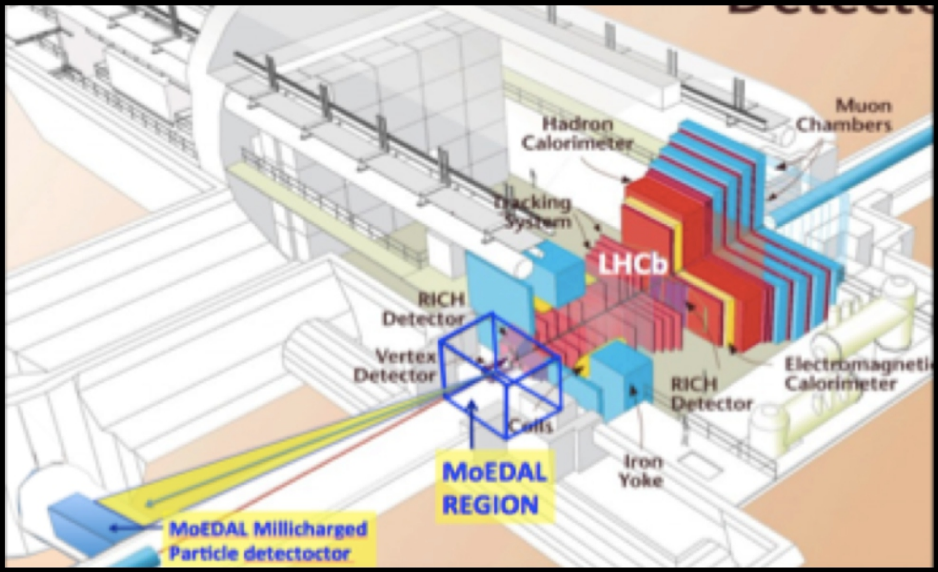
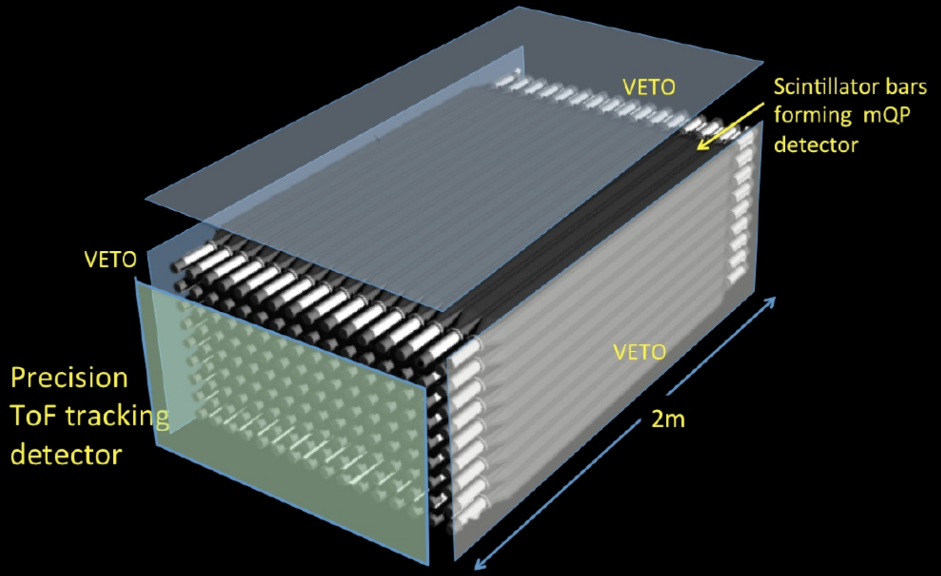


FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.



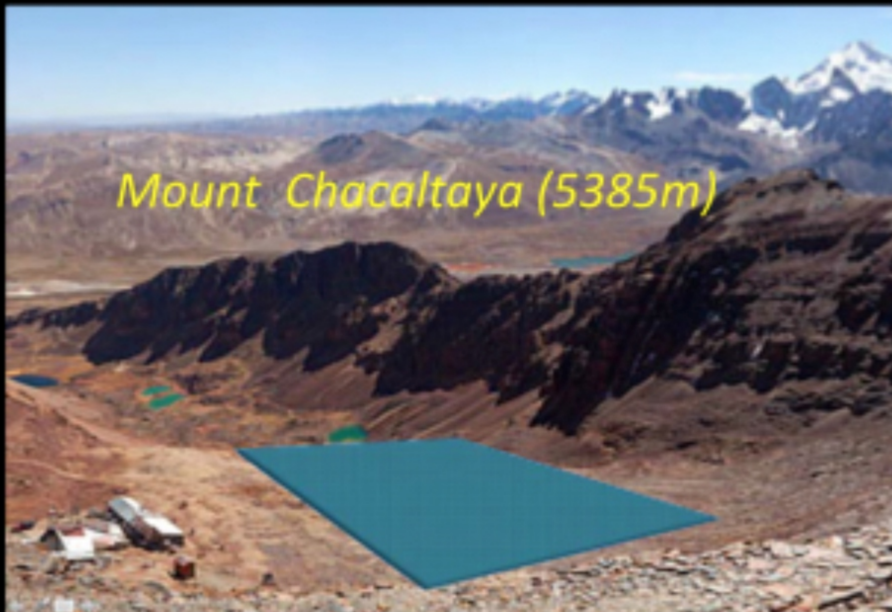
MoEDAL Apparatus for Penetrating Particles (MAPP)

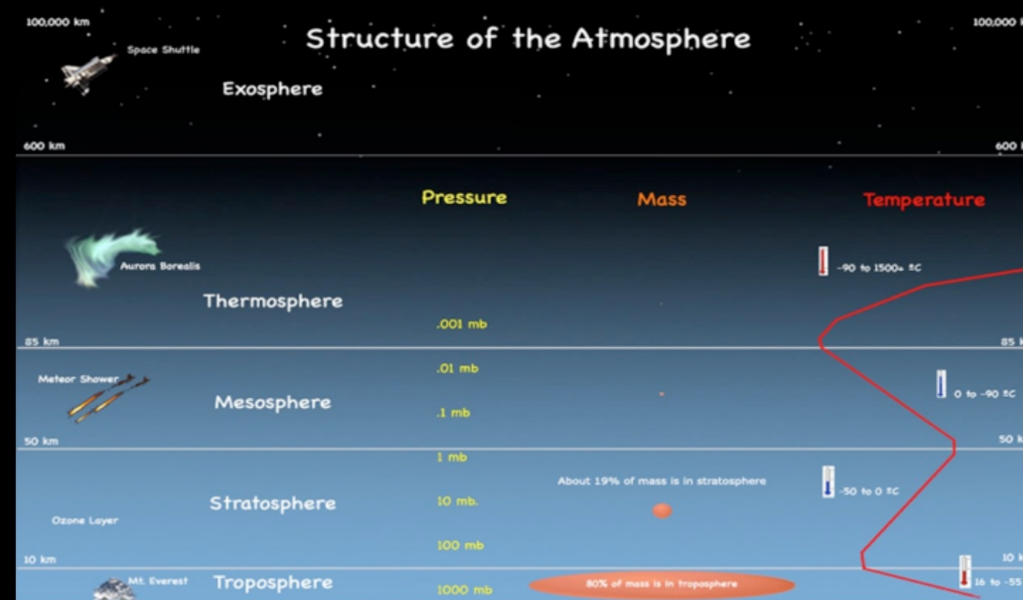




- *MAPP will be able to take data in p-p, p-A,A-A and also fixed target interactions using SMOG (an internal gas target in LHCb)*
- *MAPP has three motivations*
  - *To search for particles with charges <<1e (ATLAS & CMS limited to searches with particles of charge e ≥ 1/3)*
  - *To search for new pseudo-stable neutrals with long lifetime and anomalously penetrating particles*

The Future - Cosmic-MoEDAL?





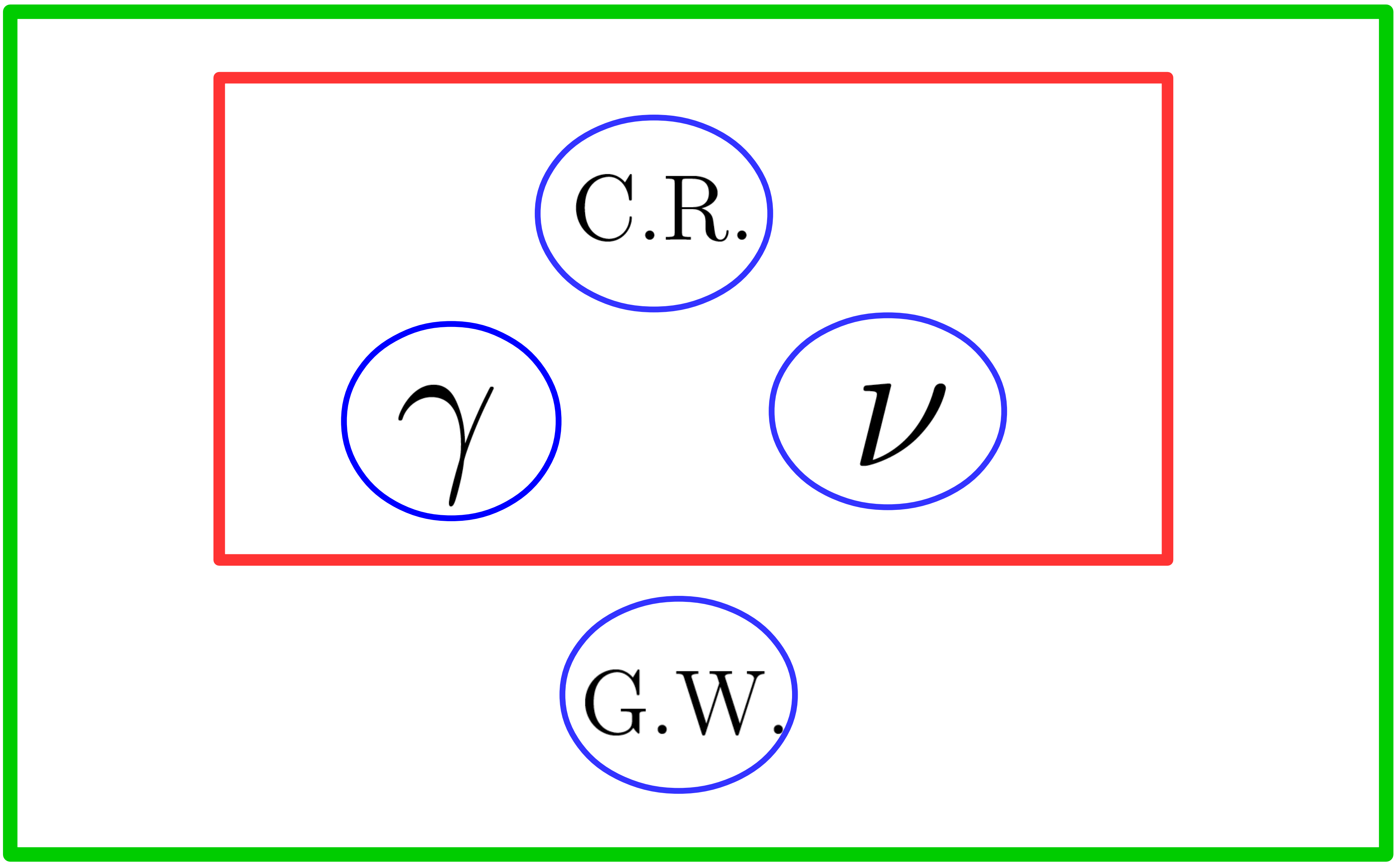
- Cosmic-MoEDAL envisage deployment of 5K-50K m^2 NTDs at high altitude - > 5/50 times larger than MACRO/SLIM
  - To detect remnants from the early universe: EW monopoles and monopoles from late phase transition & GUT scenarios with mass from ~10^4 to 10^{18} GeV, as well as strangelets, nuclearites, etc
  - We can also look for monopoles and massive (pseudo)-stable charged particles particles produced in very high energy air showers.
- Sites under consideration: Chacaltaya (5km); Tenerife -Tiede (3km); IceCube (3km); Jeju Island (2km)

Cosmic Rays as one MESSENGER from the "High Energy Universe"

The "High Energy Universe"

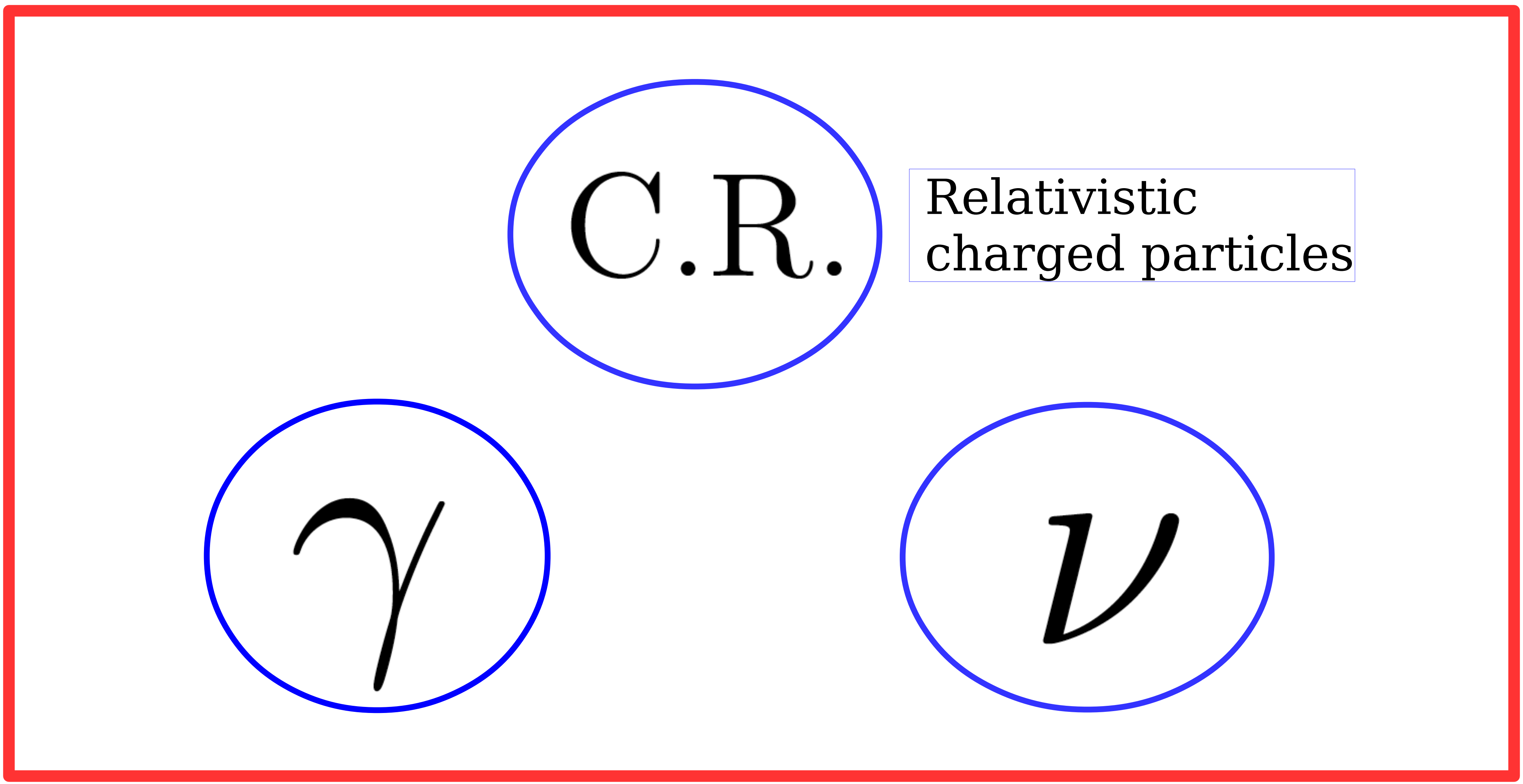
The ensemble of astrophysical objects, environments and mechanisms that generate and store very high energy relativistic particles in the Milky Way and in the entire universe.

4 Messengers for the High Energy Universe:

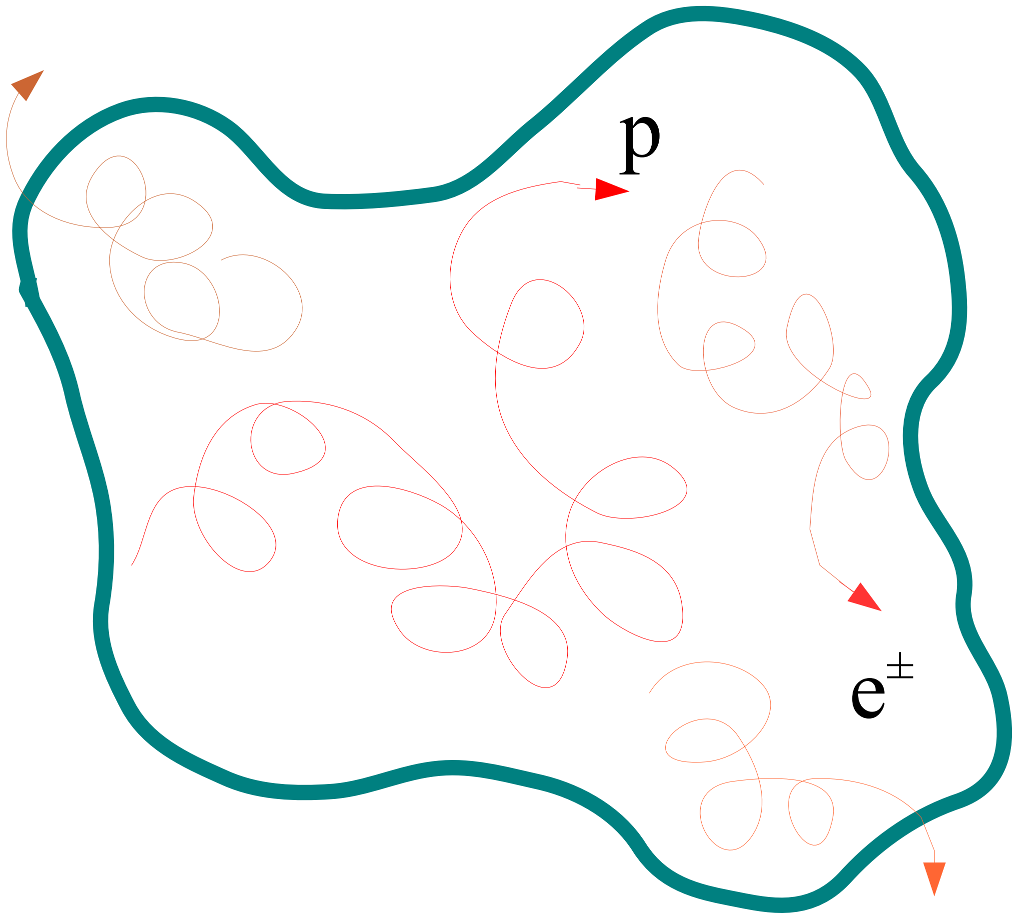


Three messengers are “inextricably” tied together

[Cosmic Rays, Gamma Rays, High Energy Neutrinos can really be considered as three probes that study the same underlying physical phenomena]



Cosmic Ray Accelerator



Astrophysical object accelerating particles to relativistic energies

Contains populations of relativistic protons, Nuclei electrons/positrons

Emission of

COSMIC RAYS

PHOTONS

NEUTRINOS

Fundamental Mechanism:

Acceleration of Charged Particles

to Very High Energy ("non thermal processes")
in astrophysical objects (or better "events").

Creation of Gamma Rays and Neutrinos
via the interactions of these relativistic charged particles.

"Hadronic"

$$p + \mathrm{X} \to \pi^+ \; \pi^- \; \pi^\circ \; \ldots$$

$$\pi^\circ \to \gamma \; \gamma$$

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

$$\hookrightarrow e^+ \; \nu_e \; \overline{\nu}_\mu$$

"Leptonic"

$$e^\pm \; \gamma_{\rm soft} \to e^\pm \; \gamma$$

$$e^\pm \; Z \to e^\pm \; \gamma \; Z$$

$$e^\pm \; \vec{B} \to e^\pm \; \gamma_{\rm syn}$$

Sources are transients

[with a variety of time scales
from a small fraction of a second to thousands of years]

Associated to Compact Objects

Neutron stars,
Black Holes (stellar and Supermassive)

FORMATION of Compact Objects
(very large acceleration of very large masses)

Natural connection to Gravitational Waves

Gamma Astronomy has revealed a
a *very rich, fascinating landscape*

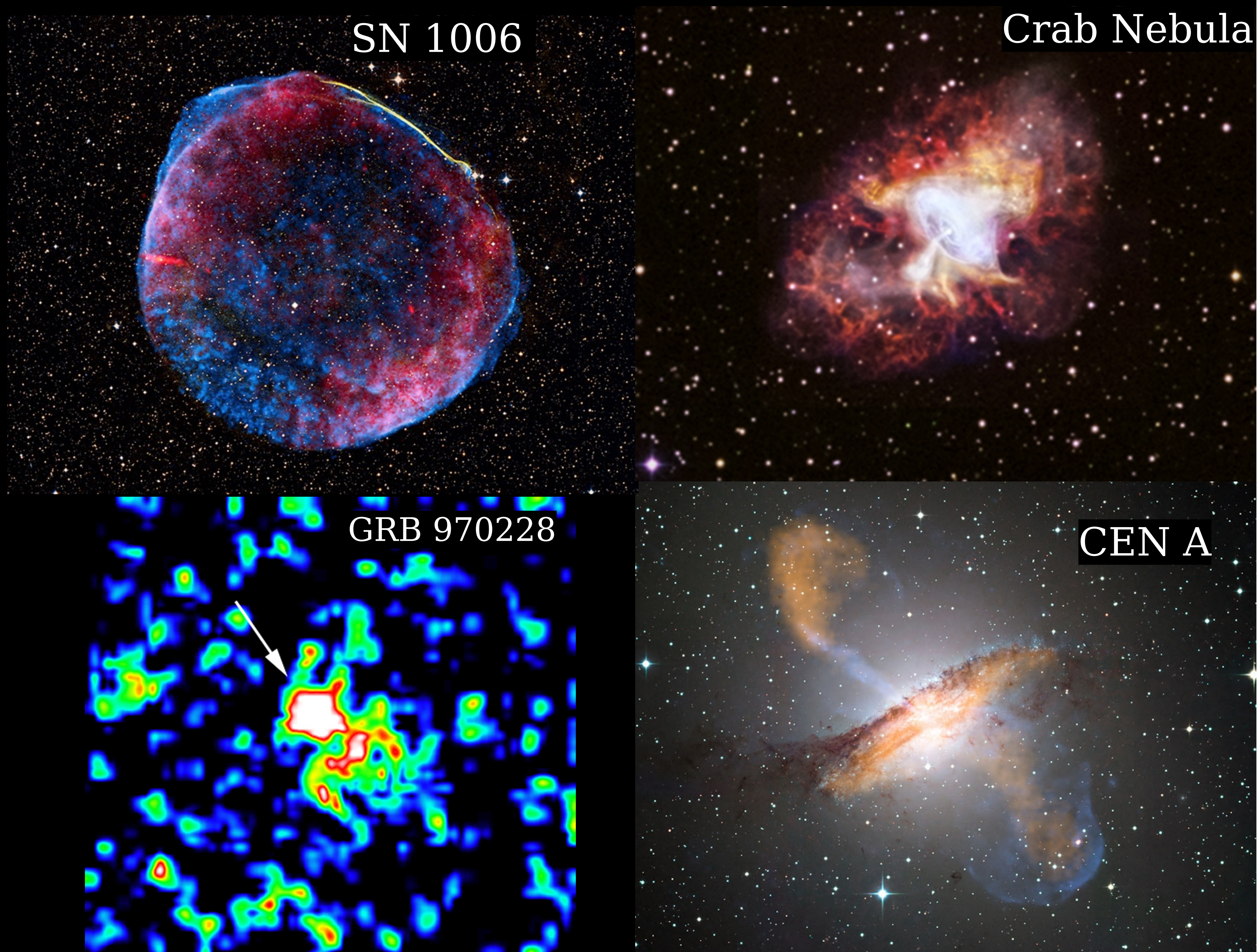
- Many sources have been identified
  [GeV , TeV ranges]

- Several classes of objects
  [SNR, Pulsars, PWN, AGN, GRB, ...]

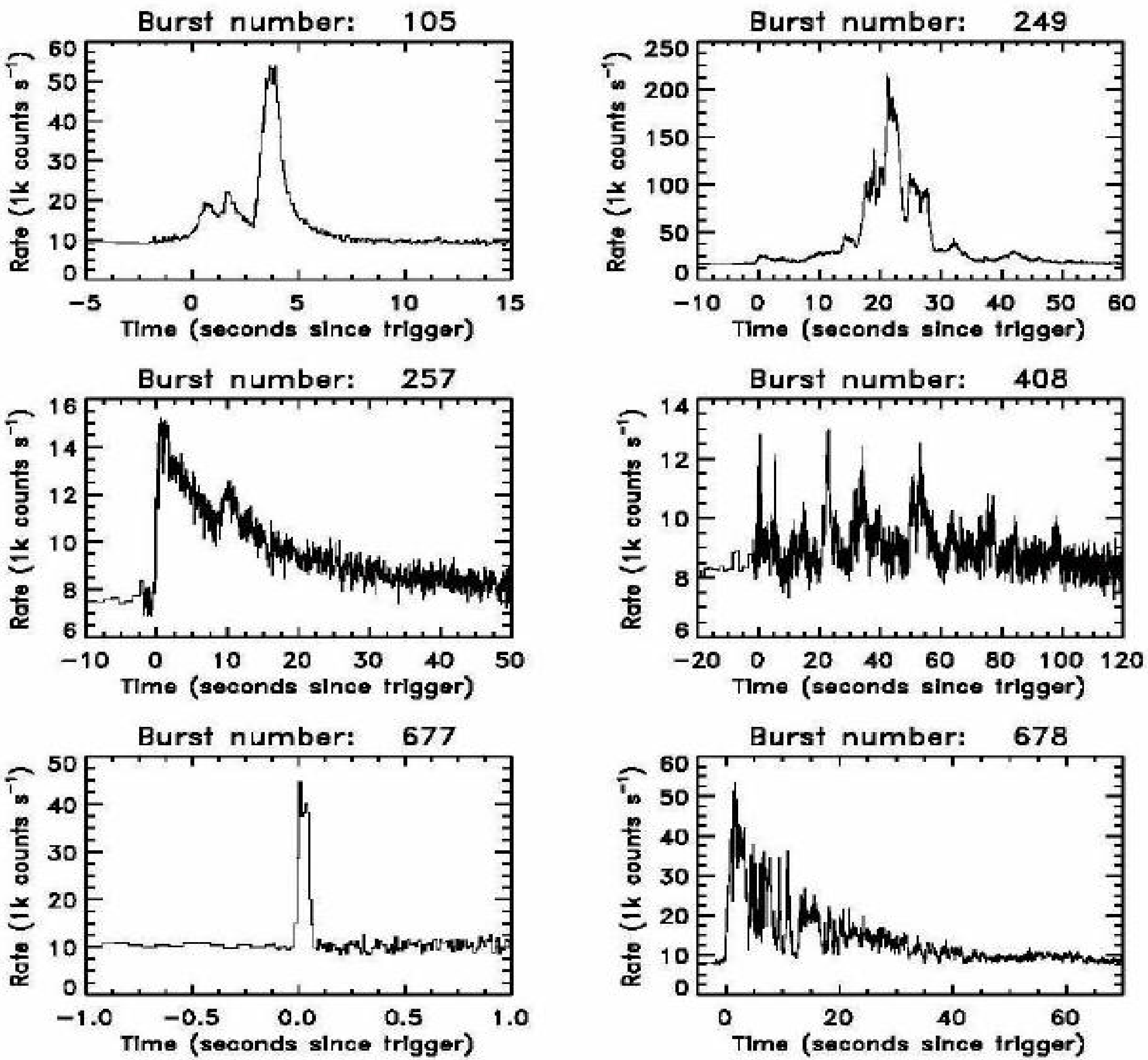
- Probably different acceleration mechanisms.

Still developing an understanding
many questions remain open

Extraordinary beasts in the sky


SN 1006
Crab Nebula
GRB 970228
CEN A

GAMMA RAY BURSTS (GRB's)

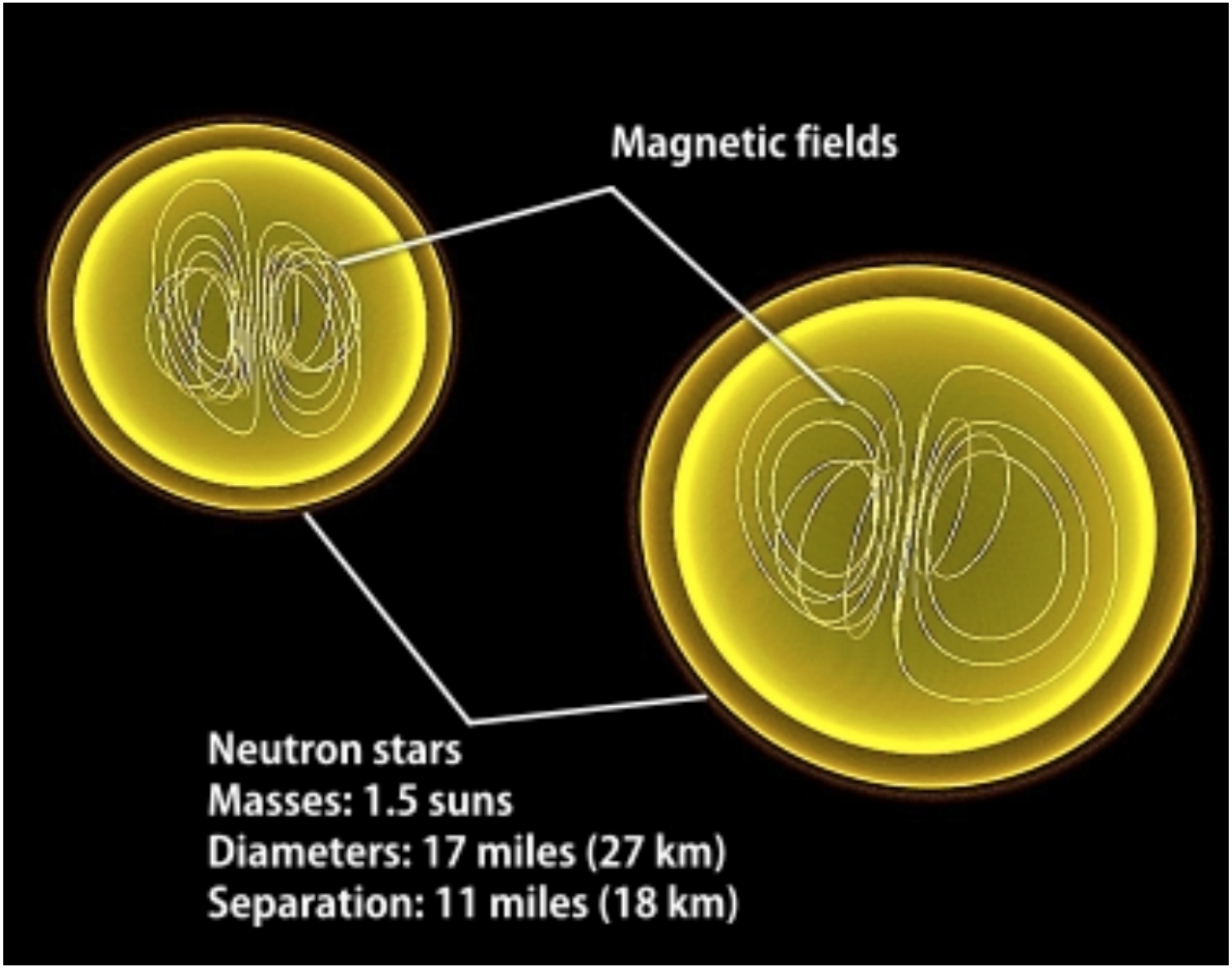


Proposed source
Of the CR

Next Monday (16th of october)
there will be the announcement of the first simultaneous detection of a (short) GRB in coincidence with the Gravitation Wave signal of two neutron stars

[Two objects of mass around the Chandrasekhar mass of 1.4 Solar masses]

Numerical Simulation [35 msec] of merging of 2 neutron stars



L. Rezzolla et al. ApJ (2011)

THE MISSING LINK: MERGING NEUTRON STARS NATURALLY PRODUCE JET-LIKE STRUCTURES AND CAN POWER SHORT GAMMA-RAY BURSTS

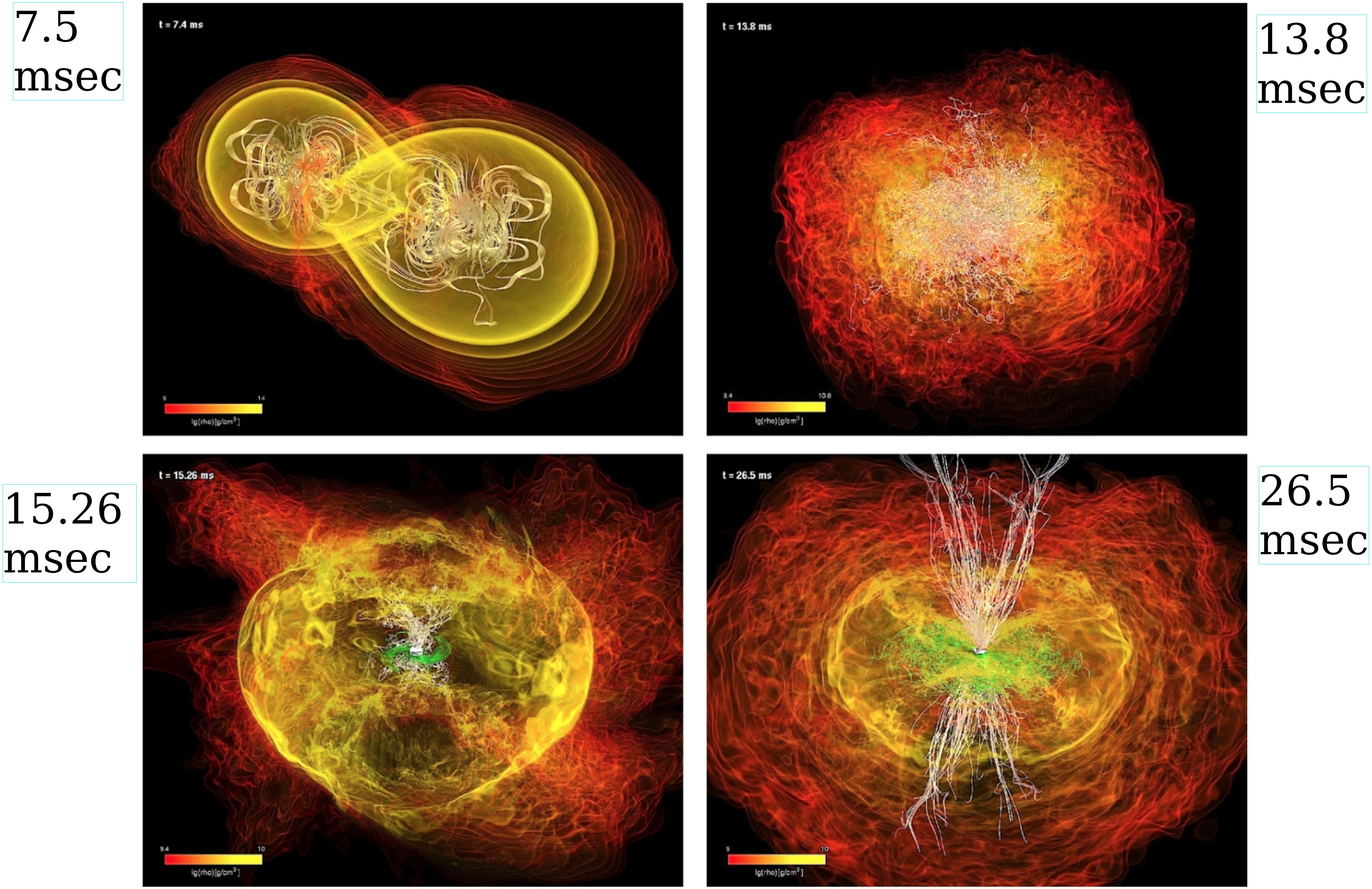


Figure 1. Snapshots at representative times of the evolution of the binary and of the formation of a large-scale ordered magnetic field. Shown with a color-code map is the density, over which the magnetic-field lines are superposed. The panels in the upper row refer to the binary during the merger ($t = 7.4$ ms) and before the collapse to BH ($t = 13.8$ ms), while those in the lower row to the evolution after the formation of the BH ($t = 15.26$ ms, $t = 26.5$ ms). Green lines sample the magnetic field in the torus and on the equatorial plane, while white lines show the magnetic field outside the torus and near the BH spin axis. The inner/outer part of the torus has a size of $\sim 90/170$ km, while the horizon has a diameter of $\simeq 9$ km.

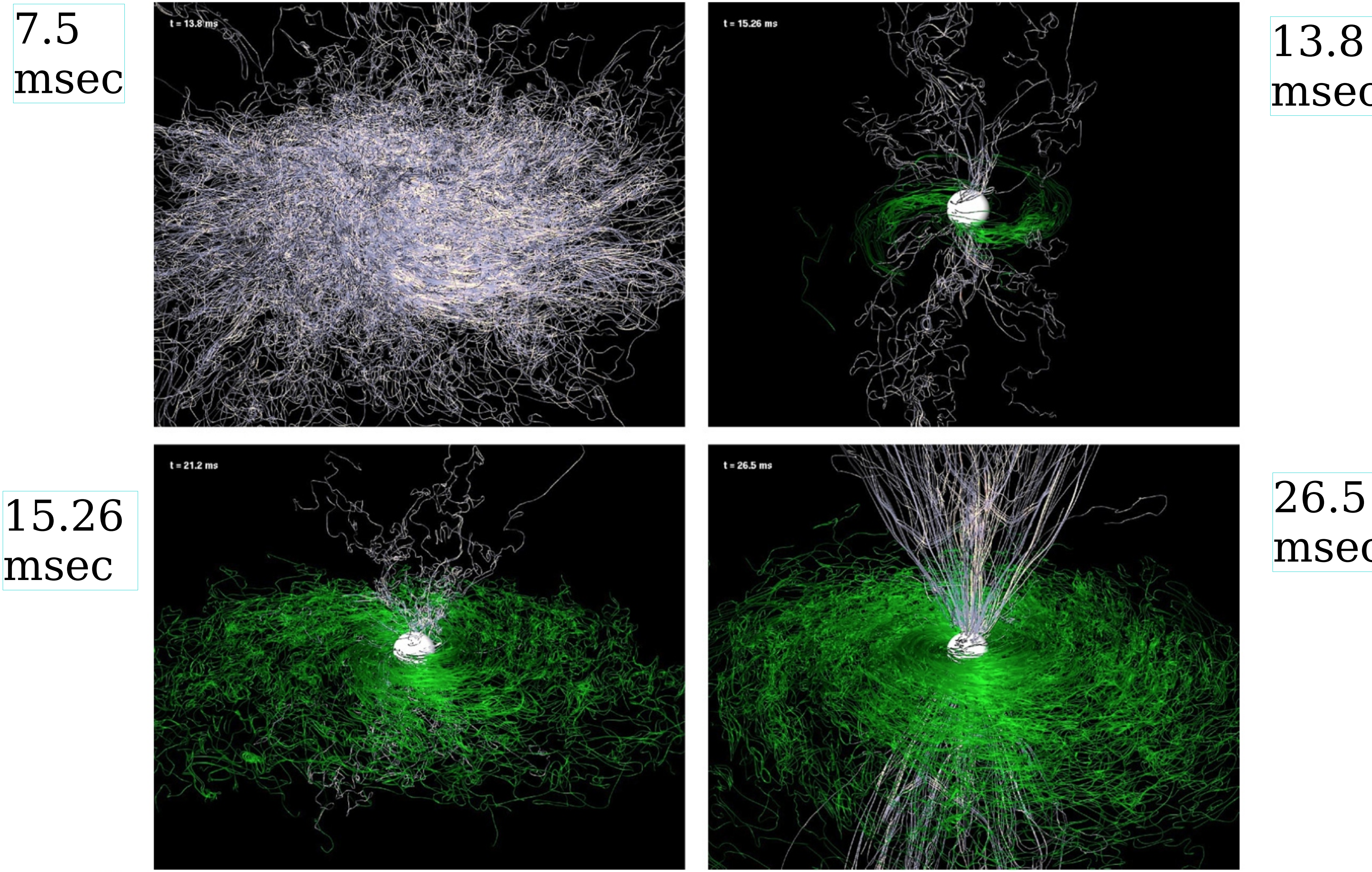


Figure 3. Magnetic-field structure in the HMNS (first panel) and after the collapse to BH (last three panels). Green refers to magnetic-field lines inside the torus and on the equatorial plane, while white refers to magnetic-field lines outside the torus and near the axis. The highly turbulent, predominantly poloidal magnetic-field structure in the HMNS (t = 13.8 ms) changes systematically as the BH is produced (t = 15.26 ms), leading to the formation of a predominantly toroidal magnetic field in the torus (t = 21.2 ms). All panels have the same linear scale, with the horizon diameter being of $\simeq$9 km.

L. Baiotti and L. Rezzolla,
"Binary neutron-star mergers: a review of Einstein's richest laboratory,"
Reports on Progress of Physics
arXiv:1607.03540 [gr-qc].

The *merger of binary neutron-stars* systems combines in a single process:

extreme gravity,
copious emission of gravitational waves,
complex microphysics,
and electromagnetic processes that can lead to astrophysical signatures observable at the largest redshifts.

* black-hole formation,
* torus accretion onto the merged compact object,
* *connection with gamma-ray burst engines,*
* ejected material, and its nucleosynthesis.

[... This phenomenon] could be considered
Einstein's richest laboratory.

Fundamental Physics

versus

“just Astrophysics”

Understanding the

"High Energy Universe"

is one of the most significant and fascinating "Frontiers" in Science today.

1. Understanding the *COSMOS* where we live

2. The sources of the High Energy radiation can be the "laboratories" where we test *(in conditions that are not achievable in "Earth based laboratories")* our Fundamental Laws of Physics.

Essentially all gamma astronomy and neutrino astronomy
can be seen as observations of Cosmic Rays
in different astrophysical sites

Cosmic Ray Observations at the Earth:

Space and time integrated average of particles
generated by many sources in the Galaxy
and in the universe, *also shaped by propagation effects*.

Single point, and (effectively) single time.

[Slow time variations,
geological record carries some information]

A *"Local Fog"* that is a nuisance for gamma rays and
neutrino observations but also carries
very important information

Measurements of Cosmic Rays
as Messengers at the Earth:

$$\phi_p(E,\Omega)\ ,\quad \phi_{\rm He}(E,\Omega)\ ,\quad \ldots\ ,\ \phi_{\{\rm A,Z\}}(E,\Omega)$$

protons+ nuclei

$$\phi_{e^-}(E,\Omega)$$

electrons

$$\phi_{e^+}(E,\Omega) \qquad \phi_{\overline{p}}(E,\Omega)$$

anti-particles

Antiparticles and Gamma rays
as tools to study:

Dark Matter in the form of WIMP's

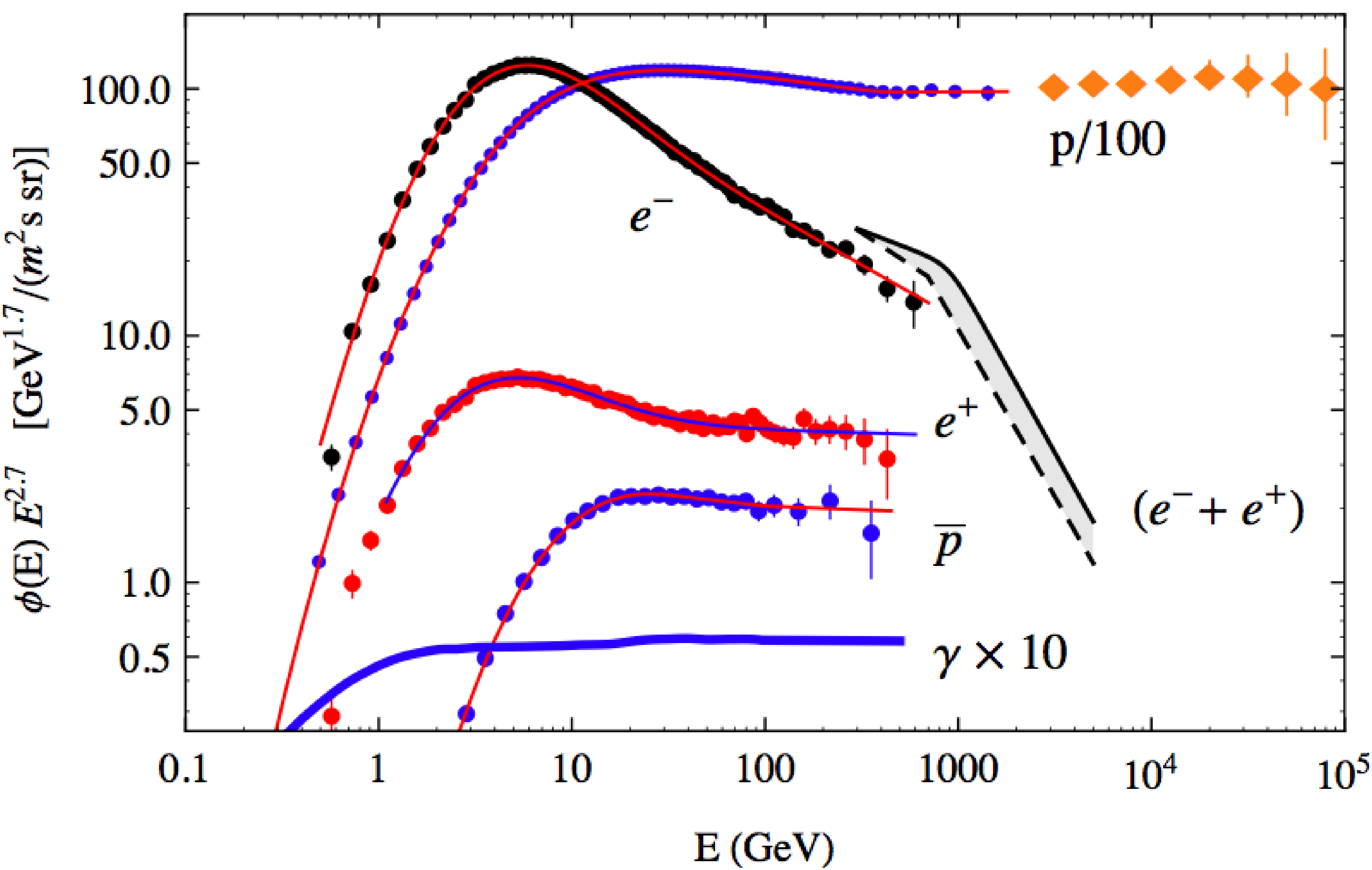
The propagation of
cosmic rays in the Galaxy

$\bar{p}$ e^+ γ

Relevance
of hadronic interaction
modeling

AMS02 p e^- e^+ $\overline{p}$

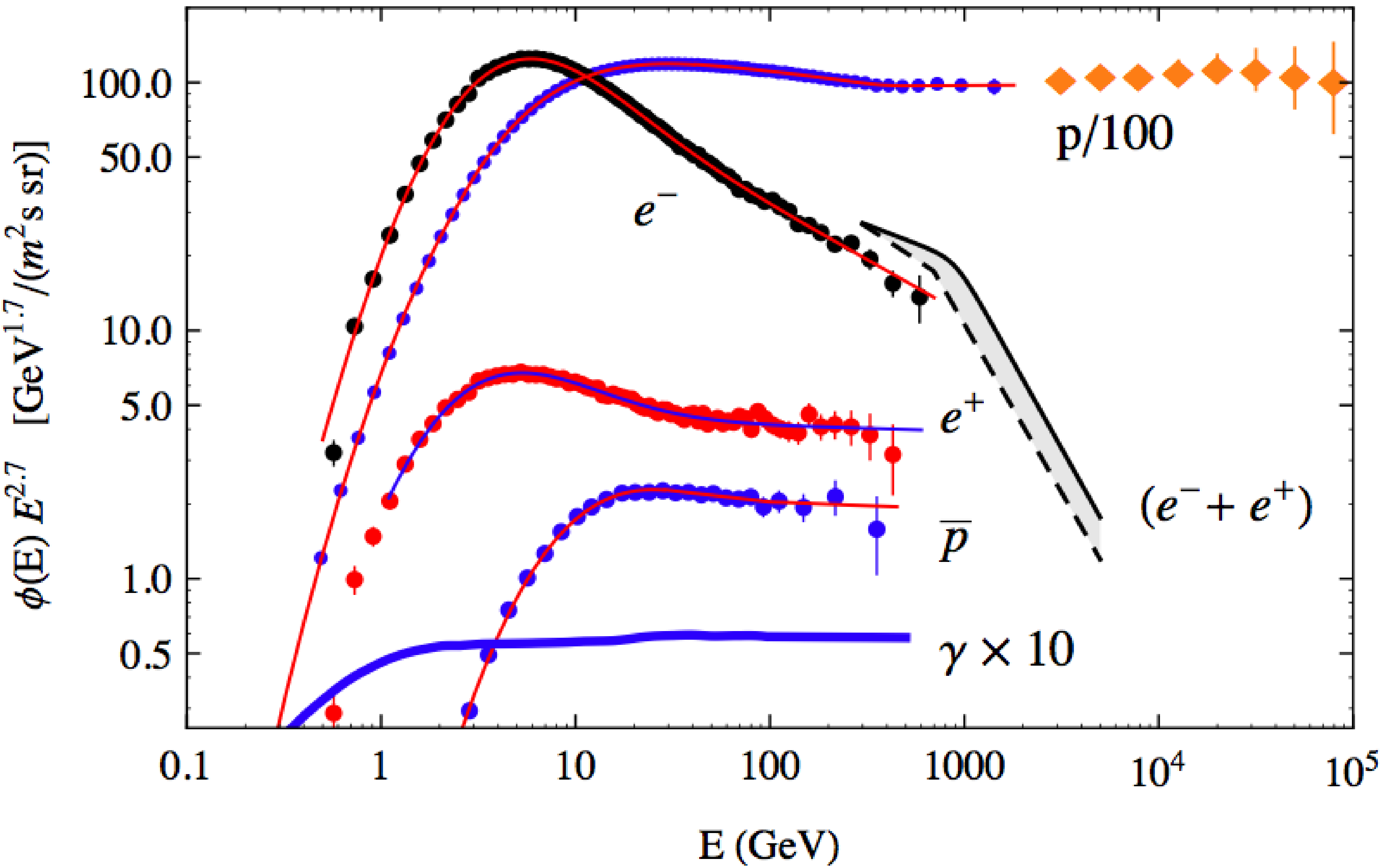
CREAM p data



angle averaged diffuse Galactic gamma ray flux (Fermi)

AMS02 p e^- e^+ $\bar{p}$

CREAM p data



Intriguing results

Soft electron spectrum

4 spectra have approximately the same slope

“Conventional mechanism”

for the production of positrons and antiprotons:

Creation of secondaries in the inelastic hadronic interactions of cosmic rays in the interstellar medium

$$pp \to \overline{p} + \ldots$$

$$pp \to \pi^+ + \ldots$$
$$\quad \hookrightarrow \mu^+ + \nu_\mu$$
$$\quad\quad \hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

$$pp \to \pi^\circ + \ldots$$
$$\quad \hookrightarrow \gamma + \gamma$$

“Standard mechanism” for the generation of positrons and anti-protons

Dominant mechanism for the generation of high energy gamma rays

intimately connected

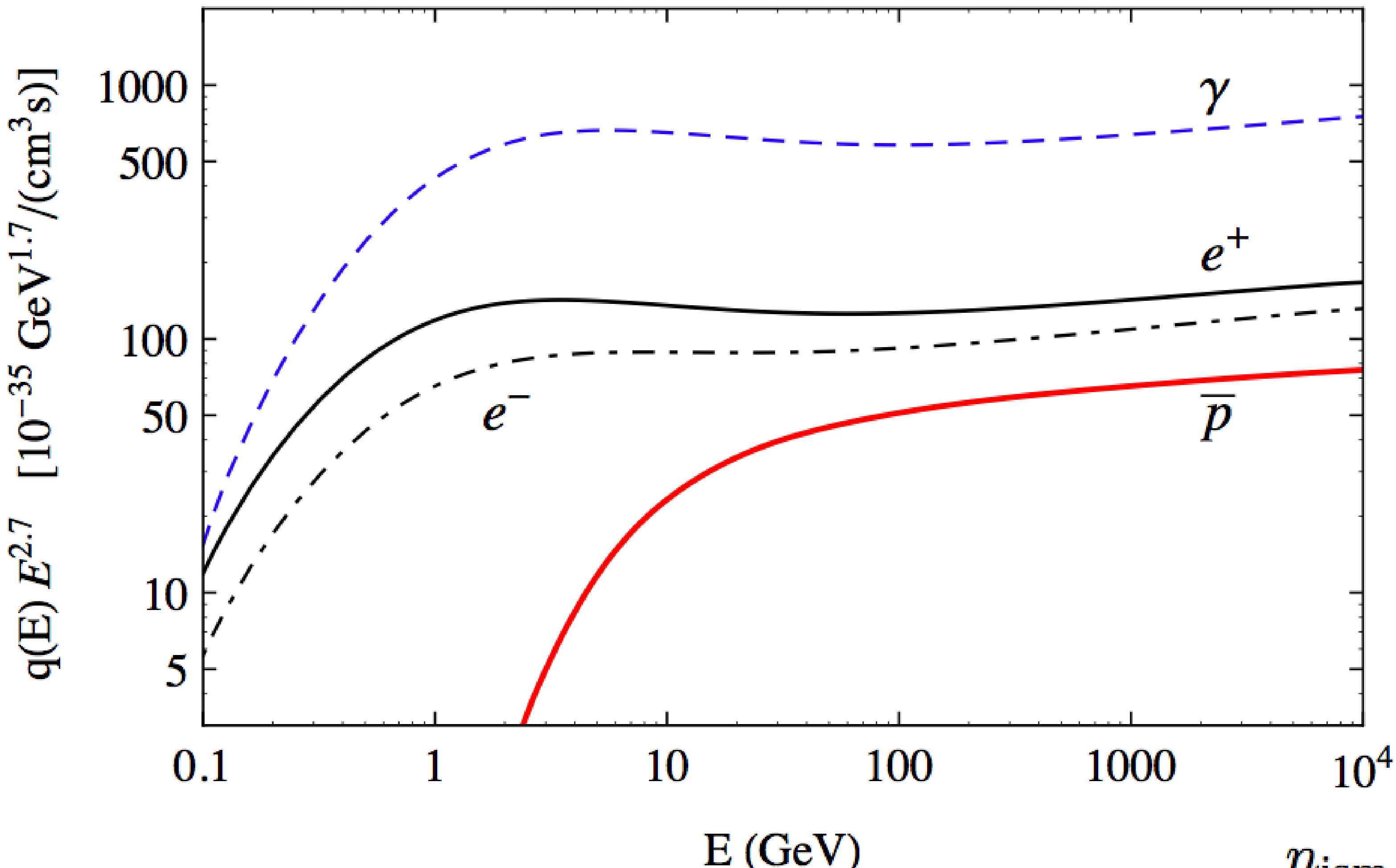
Straightforward [hadronic physics] exercise:

[1] Take spectra of cosmic rays (protons + nuclei) observed at the Earth

[2] Make them interact in the local interstellar medium (pp, p-He, He-p,...)

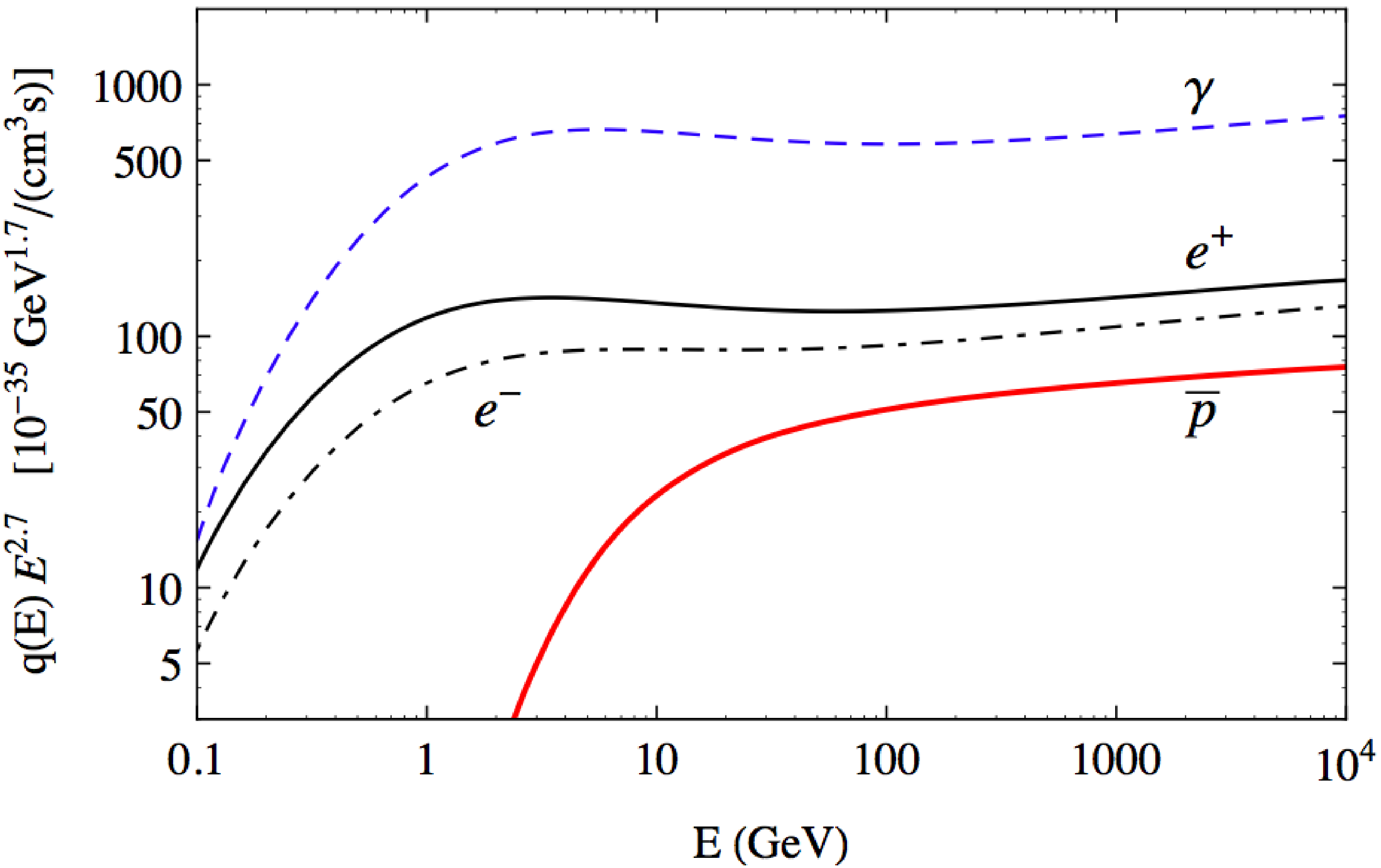
[3] Compute the rate of production of secondaries $q_j(E, \vec{x}_\odot)$

$[\mathrm{cm}^3 \ \mathrm{s} \ \mathrm{GeV}]^{-1}$



$n_{\mathrm{ism}}(\vec{x}_\odot) = 1\ \mathrm{cm}^{-3}$

“Local” Rate of production of secondaries



$$\frac{\gamma}{e^+} \approx 5.5$$

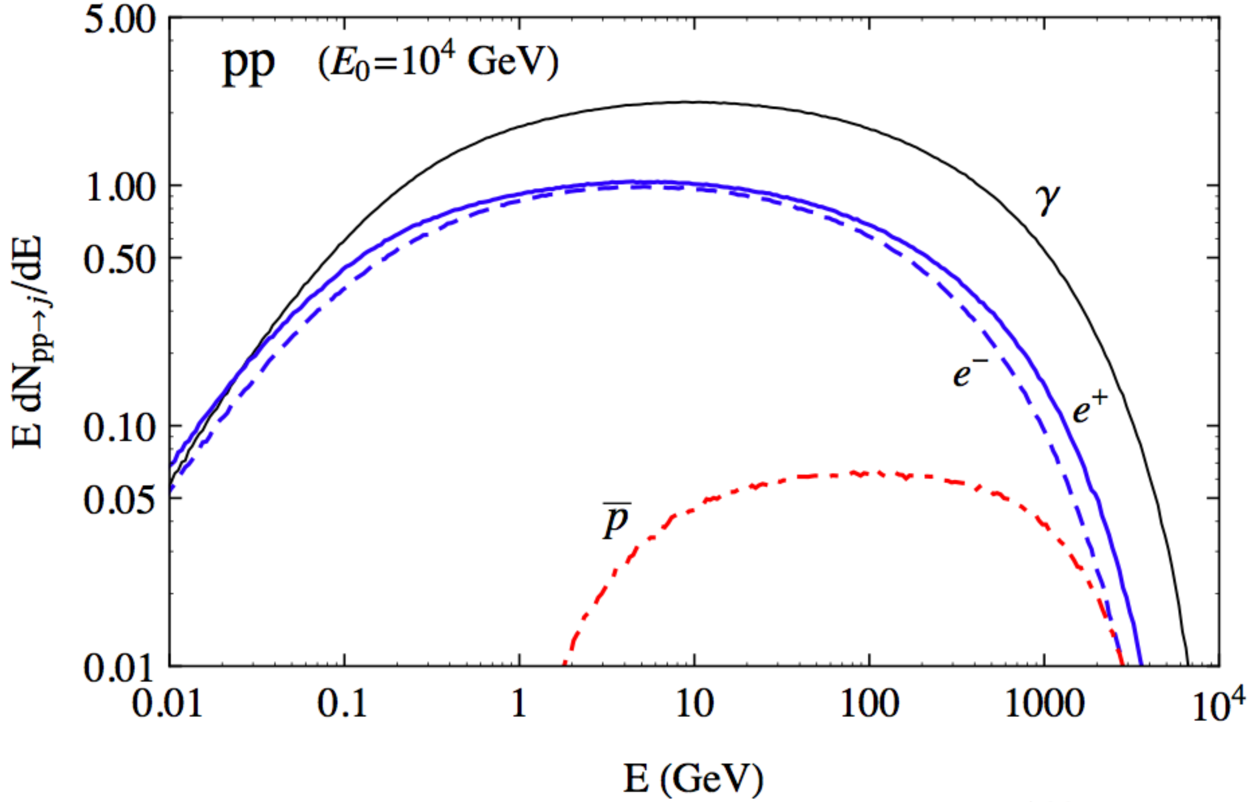
$$\frac{e^-}{e^+} \approx 0.8$$

$$\frac{e^+}{\overline{p}} \approx 2.0$$

Different low energy behaviors
(low energy antiproton production suppressed)

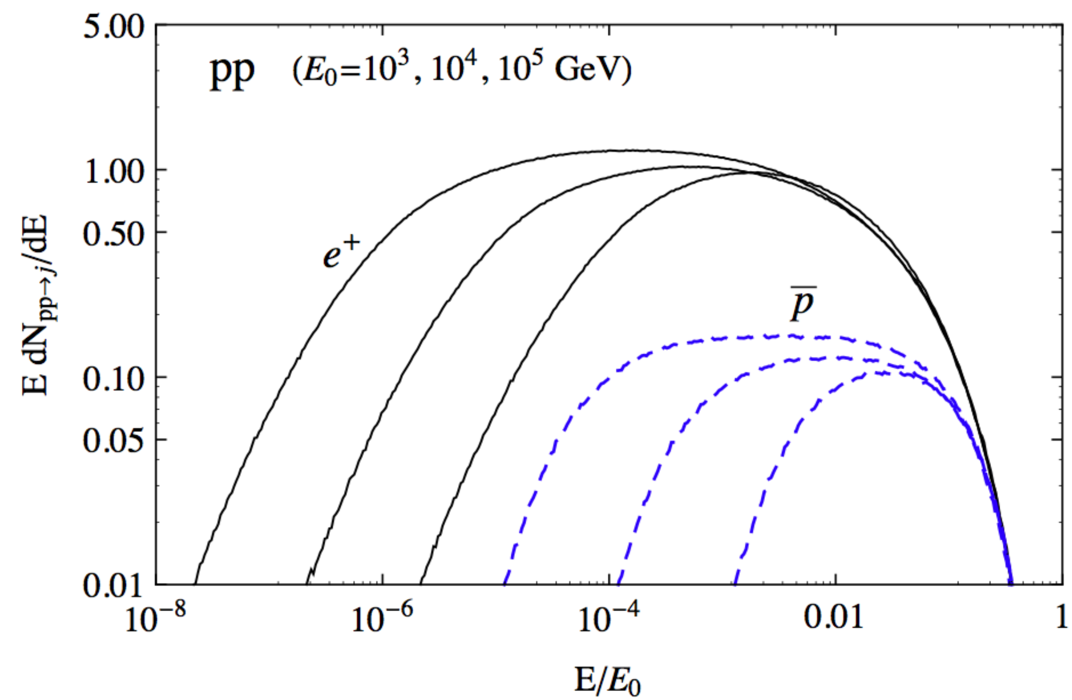
Power Law behavior at high energy

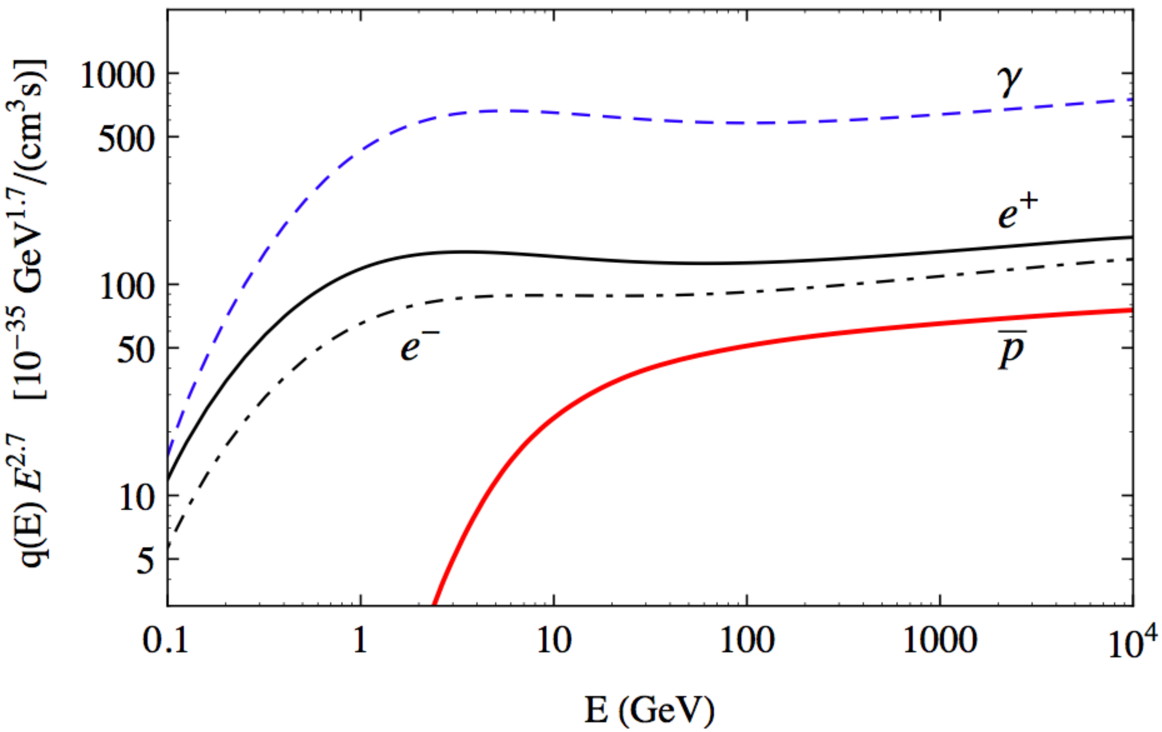
Secondary spectra



Approximate
scaling behavior
in forward region

power law → power law



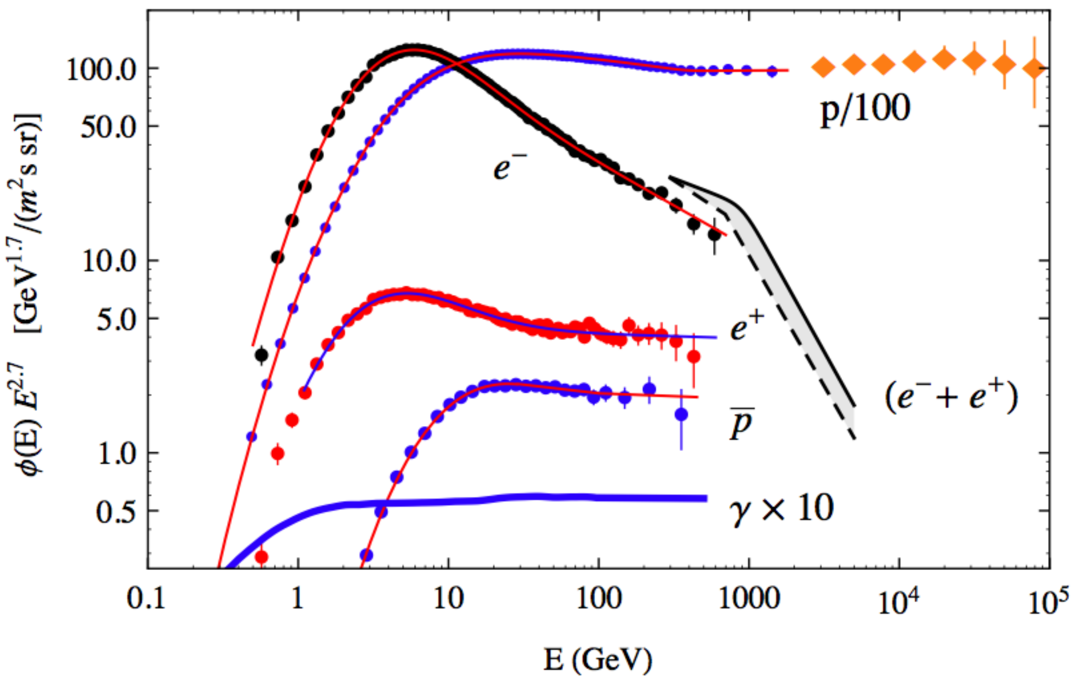


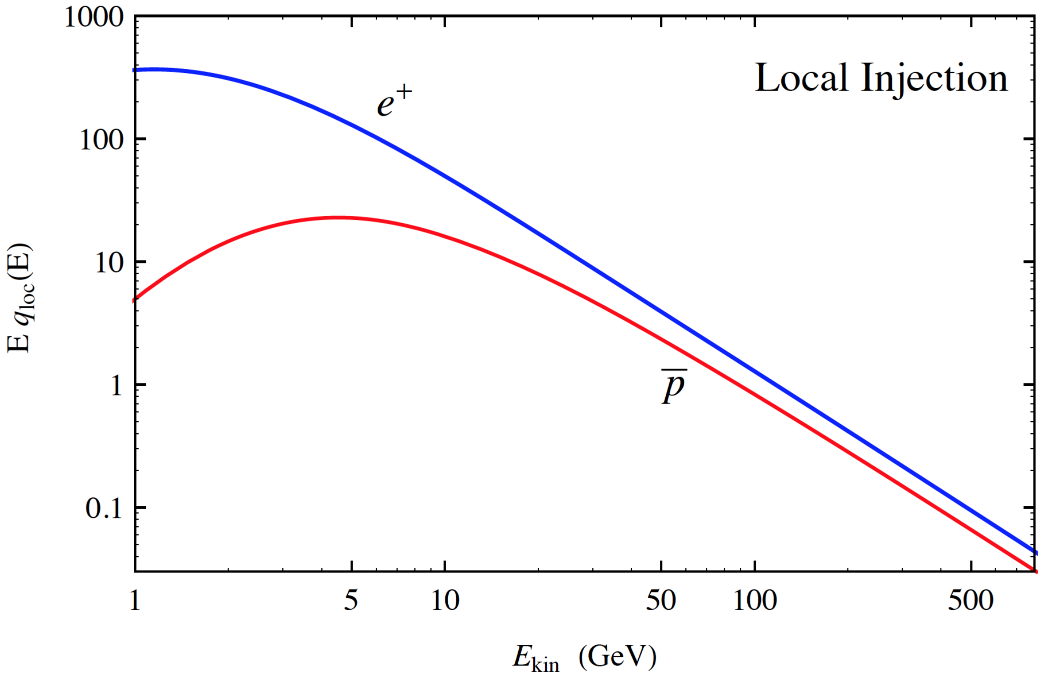
Local production rates of secondaries

$e^+ \quad \overline{p}$

"striking" similarity

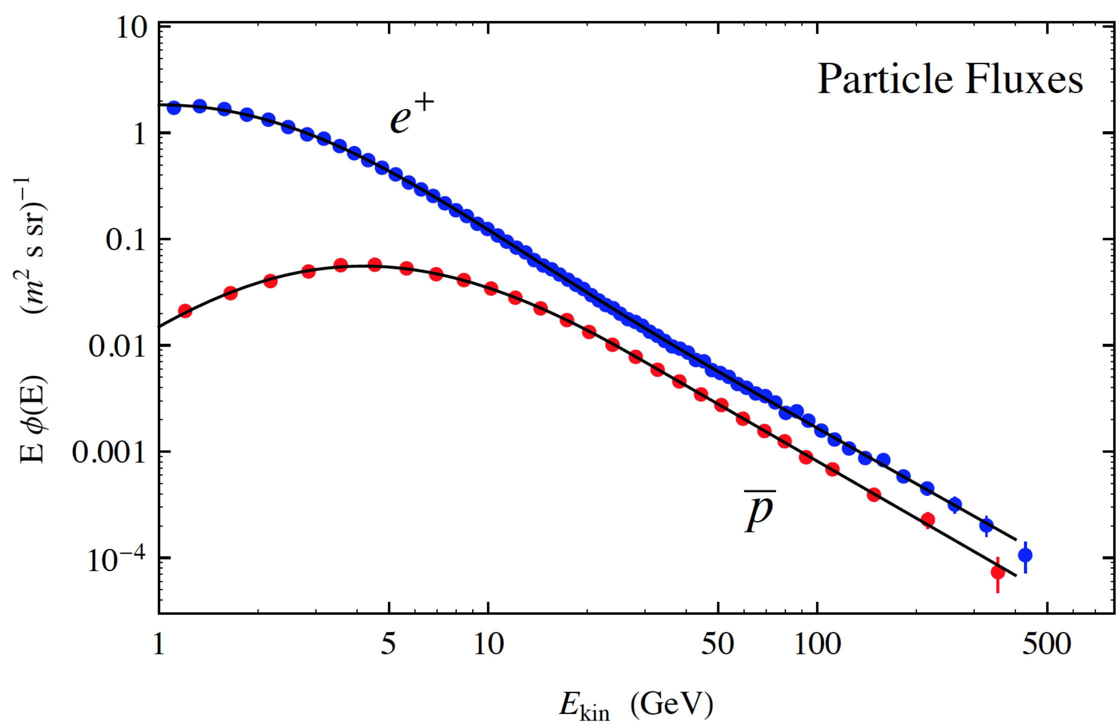
Observed fluxes





Local production rates of secondaries

"striking" similarity



Observed fluxes

$$\frac{\phi_{e^+}(E)}{\phi_{\overline{p}}(E)} \approx \frac{q_{e^+}^{\rm loc}(E)}{q_{\overline{p}}^{\rm loc}(E)}$$

The ratio positron/antiproton of
the injection is *(within systematic uncertainties)*
equal to the ratio of the observed fluxes

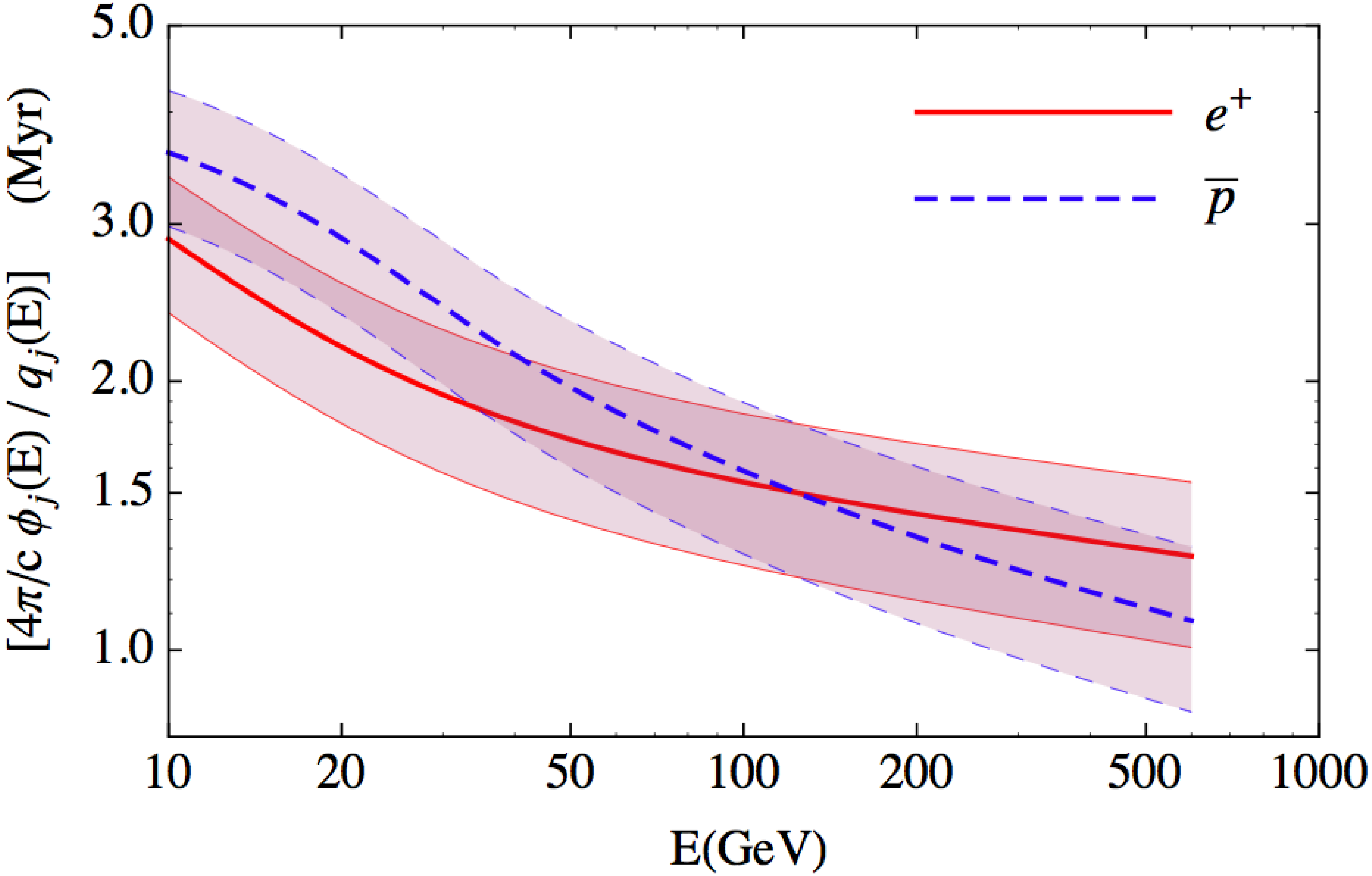
Does this result has a
"natural explanation" ?

There is a simple, natural interpretation that *"leaps out of the slide"* :

1. The "standard mechanism of secondary production is the main source of the antiparticles (and of the gamma rays)
2. The cosmic rays that generate the antiparticles and the photons have spectra similar to what is observed at the Earth.
3. *The Galactic propagation effects for positrons and antiprotons are approximately equal*
4. The propagation effects have only a weak energy dependence.

$$\frac{\phi_{\overline{p}}(E)}{q_{\overline{p}}^{\rm loc}(E)} \approx \frac{\phi_{e^+}(E)}{q_{e^+}^{\rm loc}(E)}$$

Distortion of the source spectra created by propagation



Weak energy dependence of the propagation effects !

$$j \in \{e^{\pm}, \bar{p}, \gamma\}$$

$$q_j(E, \vec{x}_\odot)$$

"Local" (solar neighborhood) production rate

$[\text{cm}^3 \text{ s GeV}]^{-1}$

$$\propto \phi_p(E, \vec{x}_\odot) \times n_{\text{ism}}(\vec{x}_\odot)$$

$$Q_j(E)$$

$[\text{s GeV}]^{-1}$

Milky Way production rate (integrated in all volume)

If shape of CR spectra equal in all Galaxy :

$$Q_j(E) = q_j(E, \vec{x}_\odot) \times V_Q$$

Effective production volume

Relation between the production rate of
a cosmic ray type and the observed flux at the Earth

$$\phi_j(E) = \frac{\beta\, c}{4\,\pi}\, Q_j(E)\; P_j(E)$$

Flux

Galactic Production Rate

Propagation Function

$$P_j(E) \approx \frac{T_j(E)}{V_j(E)} \approx \frac{\text{Average age}}{\text{Confinement volume}}$$

The study of the *diffuse gamma ray* flux allows to study the hypothesis that the shape of the CR spectra is approximately independent from position

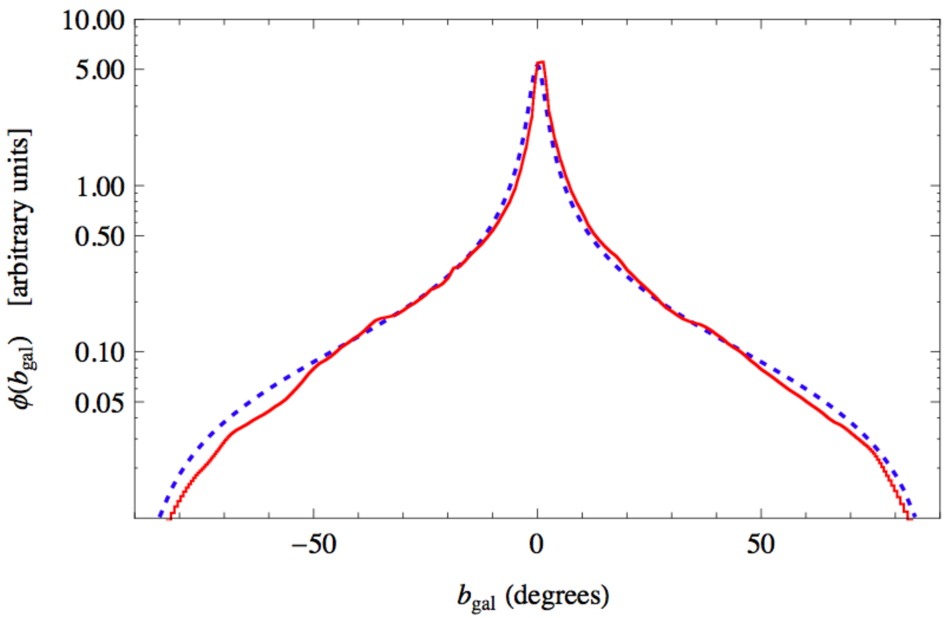
Flux : Integration of emission along the line of sight

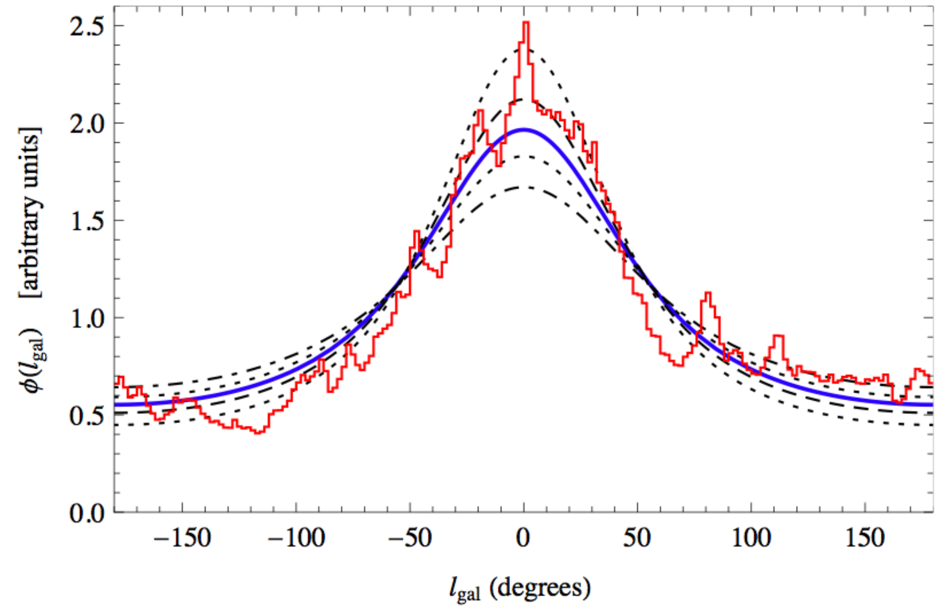
$$\phi_\gamma(E,\Omega) = \frac{1}{4\,\pi} \int_0^\infty d\ell \; q_\gamma[E, \vec{x}_\odot + \ell\,\hat{\Omega}]$$

$$\Phi_\gamma(E) = \int_{4\pi} d\Omega \; \phi_\gamma(E,\Omega)$$

$$= \frac{1}{4\,\pi} \int d^3x \; \frac{q_\gamma(E,\vec{x})}{|\vec{x} - \vec{x}_\odot|^2} = \frac{Q_\gamma(E)}{4\,\pi\, L_{\rm eff}^2(E)}$$

The angular distribution of the gamma ray flux encodes the space distribution of the emission





Estimate of the space distribution of the emission

$$q_\gamma(E, \vec{x}) = \frac{Q_\gamma(E)}{(2\pi)^{3/2} R^2 Z} \exp\left[-\frac{(x^2+y^2)}{2R^2} - \frac{z^2}{2Z^2}\right]$$

$$Z \simeq 0.22 \text{ kpc}$$

$$R \simeq 5.2 \text{ kpc}$$

$$V_Q \approx 160 \left[\frac{1 \text{ cm}^{-3}}{n_{\rm ism}(\vec{x}_\odot)}\right] \text{ kpc}^3$$

Two crucial problems emerge :

[1.] The energy dependence of the propagation effects is significantly smaller than expectations
[based on the B/C ratio]
[theoretically motivated]

Problem
also for antiprotons !

[2.] The propagation effects for positrons and antiprotons are approximately equal.

Is this possible ?

$$-\frac{dE}{dt} \propto \frac{q^4}{m^4}\; E^2$$

Rates of energy losses for
positrons and antiprotons
differ by many orders of magnitude

The much larger rate of energy loss for $e^{\pm}$ is irrelevant in propagation if the *time of residence* of the particles is sufficiently short, so that a particle loses only a small fraction of its energy before escape from the Galaxy

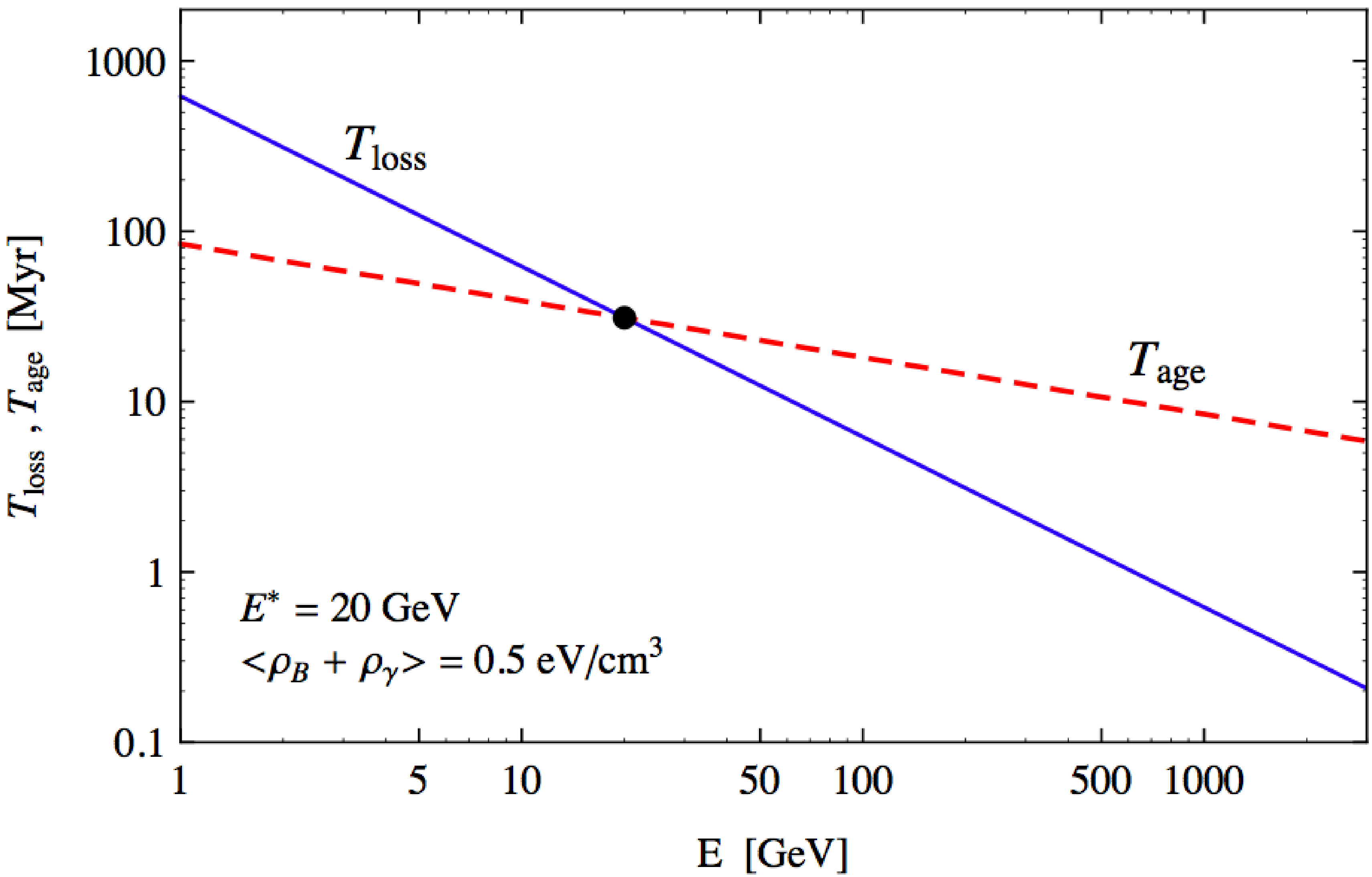
$$|dE/dt| \; T_{\rm age} \ll E$$

$$T_{\rm age} \ll \frac{E}{|dE/dt|} \equiv T_{\rm loss}(E)$$

$$T_{\rm loss}(E) = \frac{E}{|dE/dt|} \simeq 310.8 \left[\frac{\rm GeV}{E}\right] \left[\frac{\rm eV\ cm^{-3}}{\rho_B + \rho_\gamma^*(E)}\right] \rm Myr$$

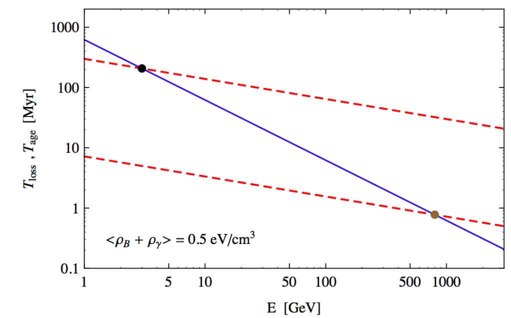
Critical energy E^*

$$T_{\text{loss}}(E^*) \simeq T_{\text{age}}(E^*)$$



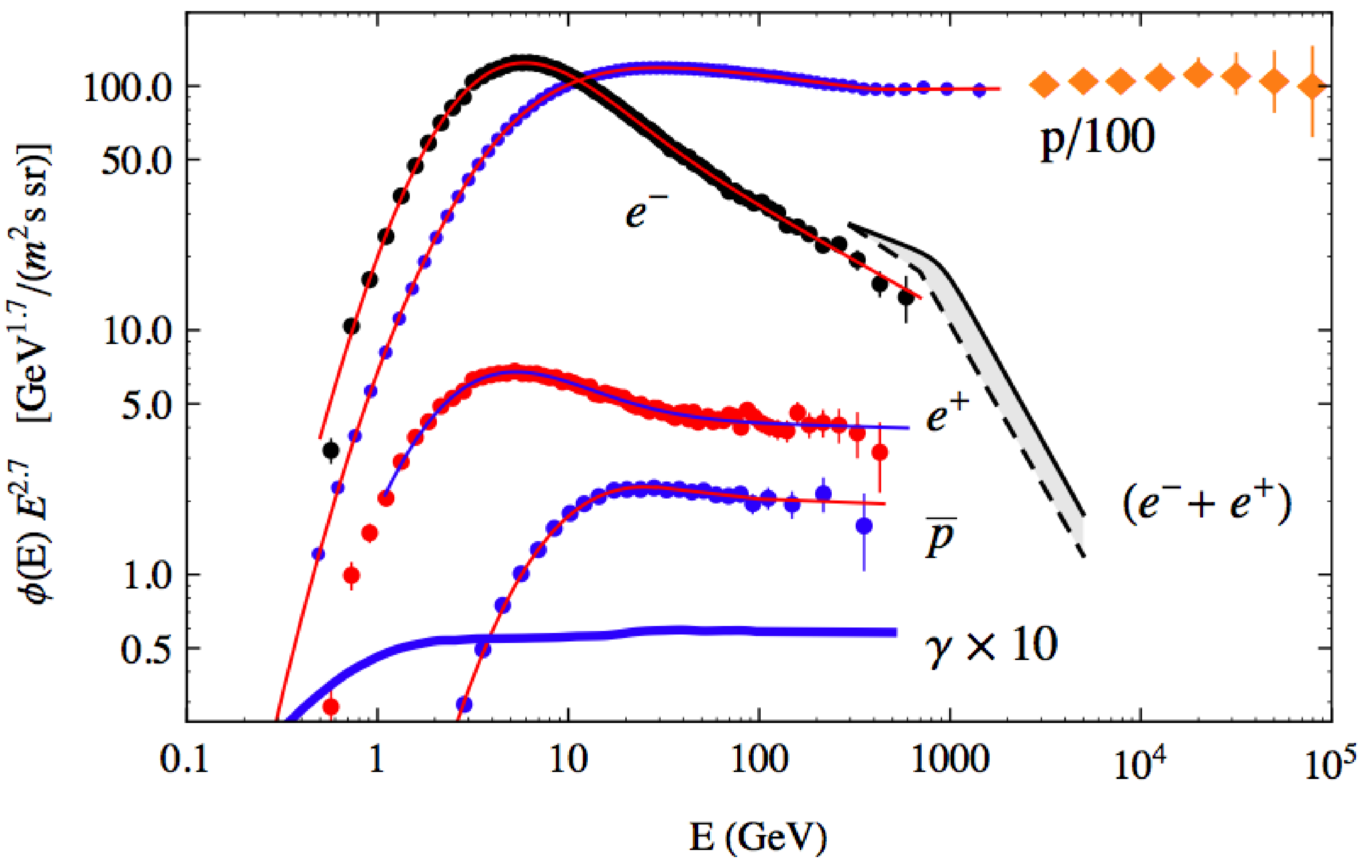
Expect softening feature in the spectra of $e^{\pm}$ at $E \approx E^*$

Use the electron spectrum
as a *"cosmic ray clock"*



Where is the spectral feature
associated to the critical energy ?

Very smooth electron spectrum



Fit =

$$K\ E^{-3.17}$$

$$\otimes$$

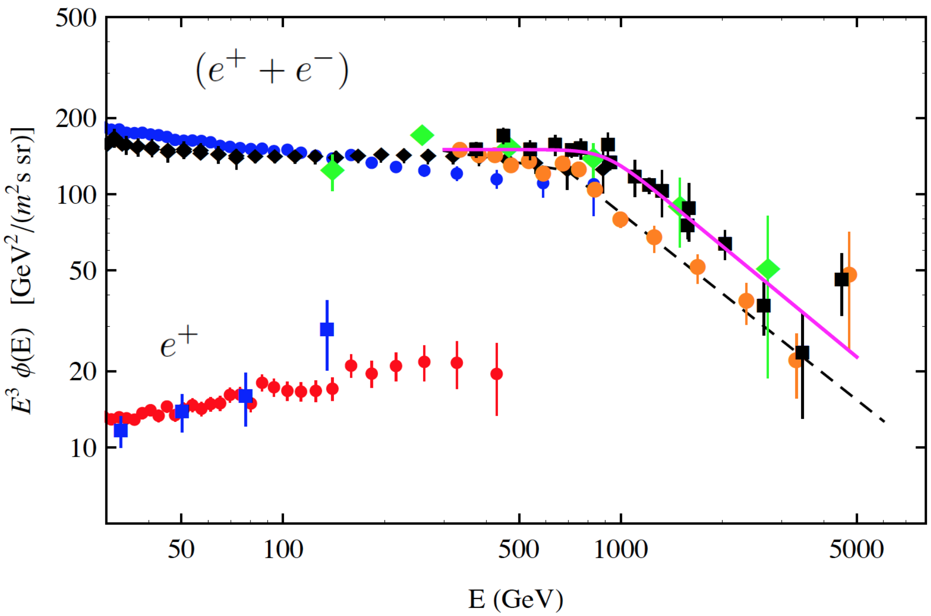
FFA Solar Modulations (1.44GeV)]

Possible (and "natural") choice: identification of the sharp softening observed by the Cherenkov telescopes in the spectrum of $(e^+ + e^-)$ as the critical energy

$$E^* = E_{\rm HESS} \simeq 900 \text{ GeV}$$

$$T_{\rm confinement}[E \simeq 900 \text{ GeV}] \simeq 0.7 \div 1.3 \text{ Myr}$$

Range depends on volume of confinement



Propagation of positrons and antiprotons is approximately equal for

$$E \lesssim E^* \simeq 900 \text{ GeV}$$

Possible (and "natural") choice: identification of the sharp softening observed by the Cherenkov telescopes in the spectrum of $(e^+ + e^-)$ as the critical energy

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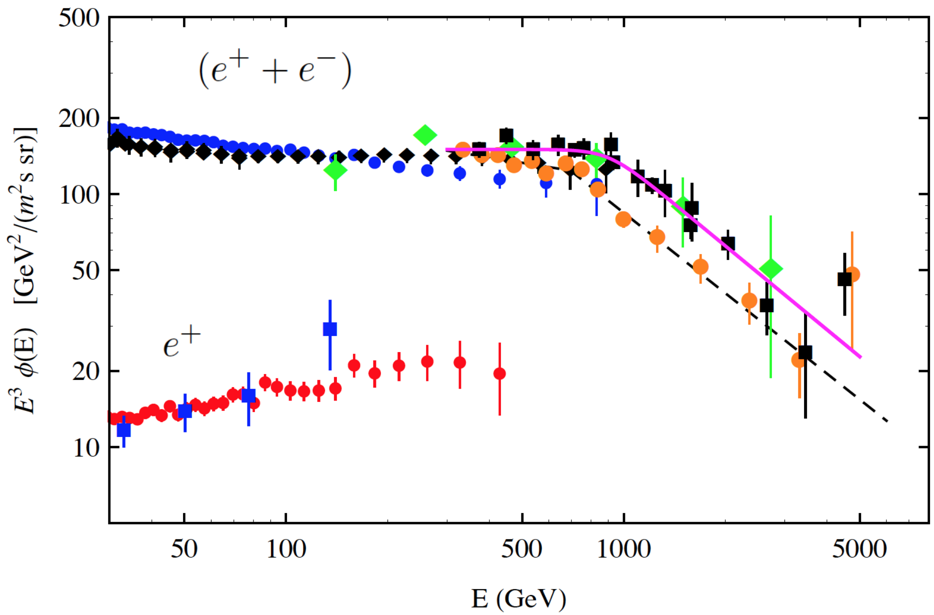


Propagation of positrons and antiprotons is approximately equal for

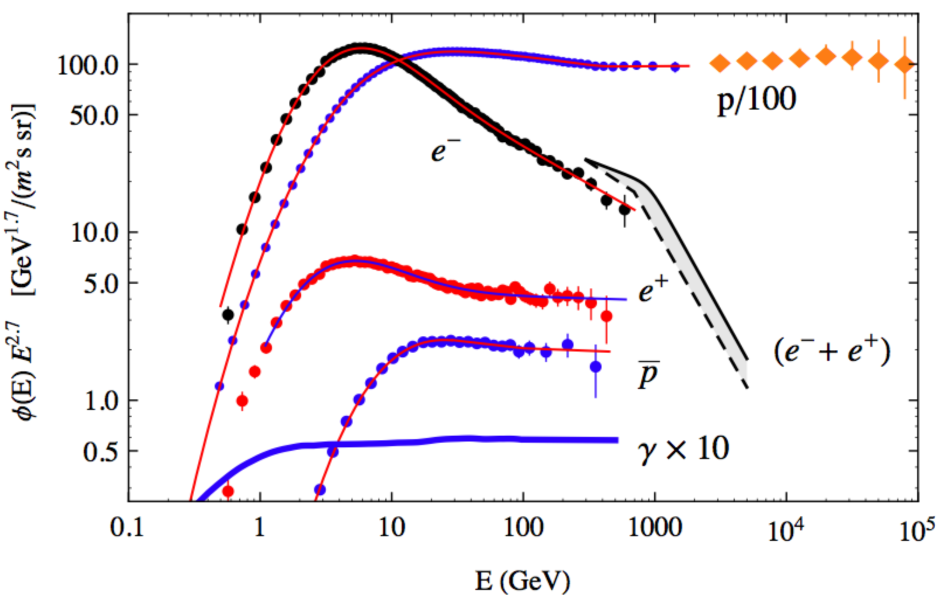
$$E \lesssim E^* \simeq 900 \text{ GeV}$$

This solution is simple and natural
but has a significant "theoretical" problem:

If: positrons and antiprotons have equal
propagation properties.

Then: also electron and protons have also the same
propagation properties

But then why are the electron the proton spectra
so different from each other ?! (with electrons much softer).

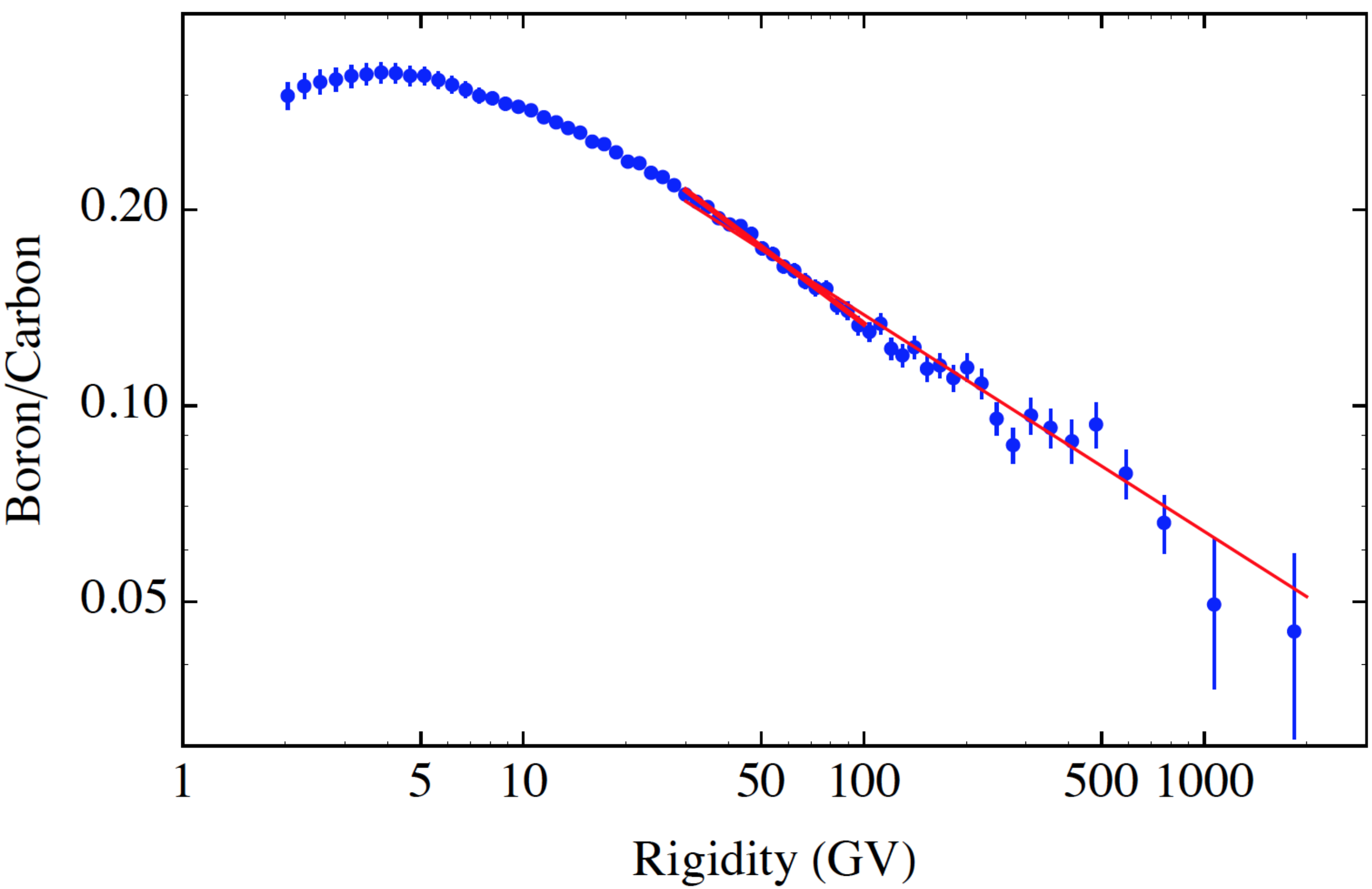


The e/p difference must be generated by the sources

What about secondary/primary nuclei ?

[normally the "cornerstone" of most propagation models]

$$\frac{\text{Boron}}{\text{Carbon}} \approx 0.21 \left(\frac{p/Z}{30 \text{ GV}} \right)^{-0.33}$$



AMS02 data

$$\frac{\text{Boron}}{\text{Carbon}} \approx 0.21 \left(\frac{p/Z}{30\ \text{GV}}\right)^{-0.33}$$

Approximation of constant fragmentation cross sections

Interpretation in terms of Column density

$$\langle X \rangle \approx 4.7 \left(\frac{p/Z}{30\ \text{GV}}\right)^{-0.33} \frac{\text{g}}{\text{cm}^2}$$

[Assuming that the column density is accumulated during *propagation in interstellar space*]

$$\langle T_{\text{age}} \rangle \simeq 30\ \text{Myr} \left[\frac{0.1\ \text{g}\,\text{cm}^{-3}}{\langle n_{\text{ism}} \rangle}\right] \left(\frac{|p/Z|}{30\ \text{GV}}\right)^{-0.33}$$

Residence time inferred from B/C ratio
assuming that the column density crossed by
the nuclei is accumulated in interstellar space

is *inconsistent* [as it is too long]
with the hypothesis that the energy losses of $e^{\pm}$
are negligibly small.

Possible solutions

1. [Energy dependence of fragmentation Cross sections]

2. Most of the column density inferred from the B/C ratio
   is integrated not in interstellar space
   but inside or in the envelope of the sources
   [Cowsik and collaborators]

Conventional (orthodox) *description :*

$$P_{e^+}(E) < P_{\overline{p}}(E)$$

The result :

$$\frac{\phi_{e^+}(E)}{\phi_{\overline{p}}(E)} \approx \frac{q^{\rm loc}_{e^+}(E)}{q^{\rm loc}_{\overline{p}}(E)}$$

is simply a (rather extraordinary)
but meaningless numerical coincidence

$$Q_{e^+}(E) = Q^{\rm secondary}_{e^+}(E) + Q^{\rm new}_{e^+}(E)$$

$$Q_{\overline{p}}(E) = Q^{\rm secondary}_{\overline{p}}(E)$$

Positrons
have an “extra source”
(dominant at high energy)

New source sufficiently “fine tuned” (in shape and normalization)

$$\left[Q^{\rm sec}_{e^+}(E) + Q^{\rm new}_{e^+}(E)\right] \; P_{e^+}(E) \approx Q^{\rm sec}_{e^+}(E) \; P_{\overline{p}}(E)$$

Conventional propagation scenario:

A1. Very long lifetime for cosmic rays

A2. Difference between electron and proton spectra shaped by propagation effects

A3. New hard source of positrons is required

A4. Secondary nuclei generated in interstellar space

Alternative propagation scenario:

B1. Short lifetime for cosmic rays

B2. Difference between electron and proton spectra generated in the accelerators

B3. antiprotons and positrons of secondary origin

B4. Most secondary nuclei generated in/close to accelerators

How can one discriminate between these two scenarios ?

1. Extend measurements of e+- spectra
   Different cutoffs can confirm the conventional picture

2. Extend measurements of secondary nuclei
   [B, Be, Li]. Look for signatures of
   nuclear fragmentation inside/near the accelerators.

3. Study the space and energy distributions
   of the relativistic e+- in the Milky Way
   [from the analysis of diffuse Galactic gamma ray flux]

4. Study the populations of e- and p in young SNR
   (assuming that they are the main sources of CR)

A dedicated study of the production of pions and anti-nucleons in hadronic interactions can reduce systematic uncertainties

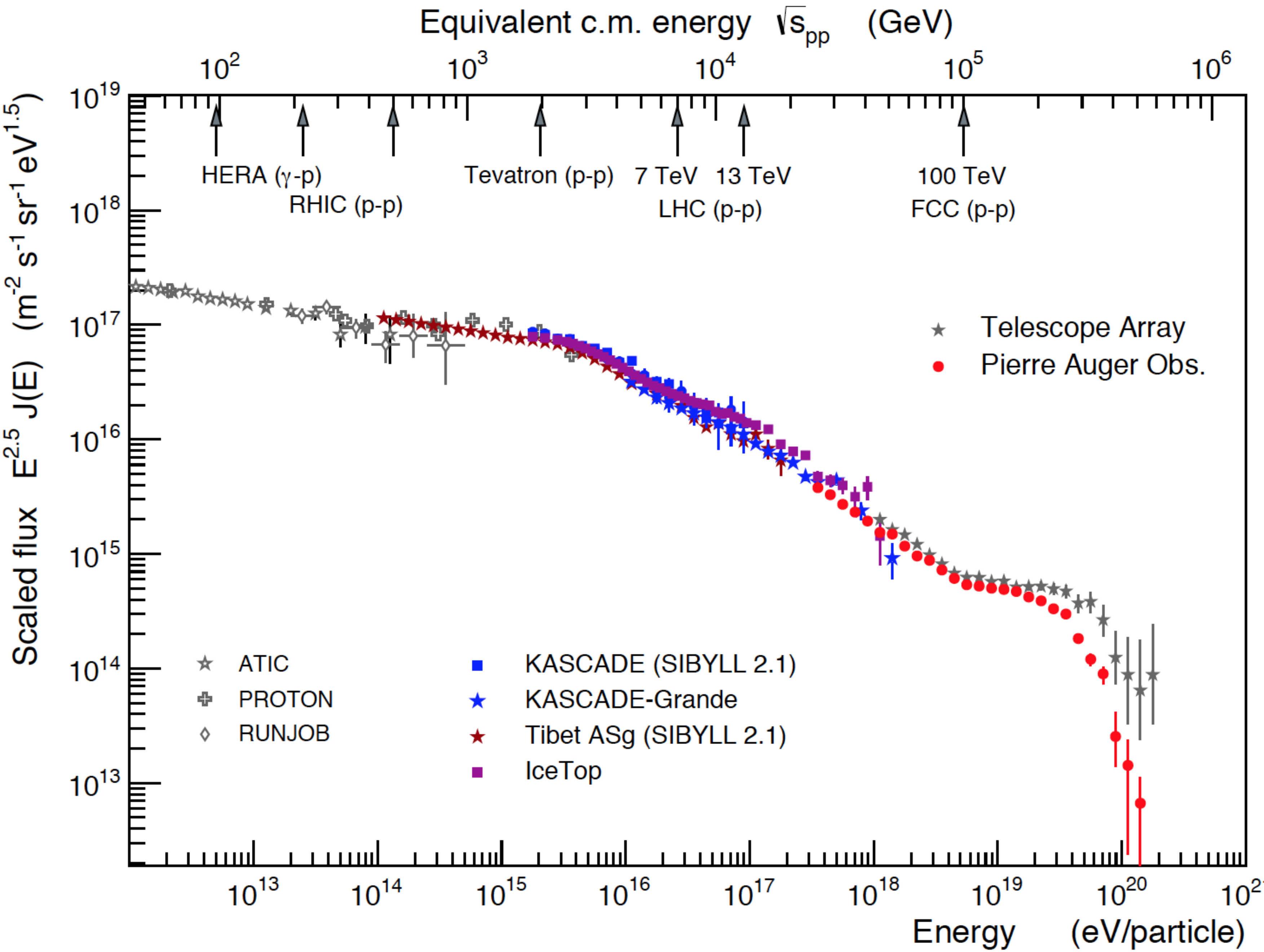
An understanding of the origin of the
positron and antiproton fluxes
is of central importance for High Energy Astrophysics.

This problem touches the
cornerstones of Cosmic Ray astrophysics
and it has profound and broad implications

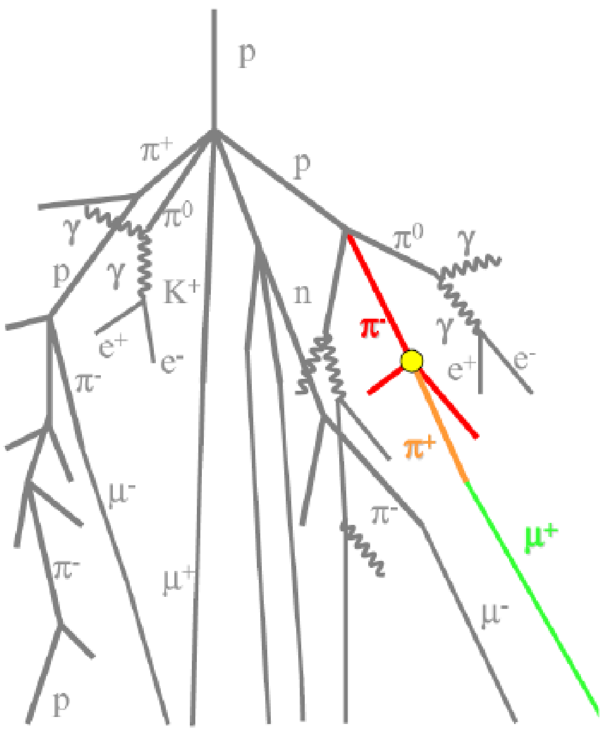
[Possible new antiparticle sources,
Spectra released by accelerators,
Fundamental properties of propagation]

Crucial crossroad for the field.

Cosmic Ray Spectrum extends to very high energies



Indirect [Air shower]
measurements
of Cosmic Rays

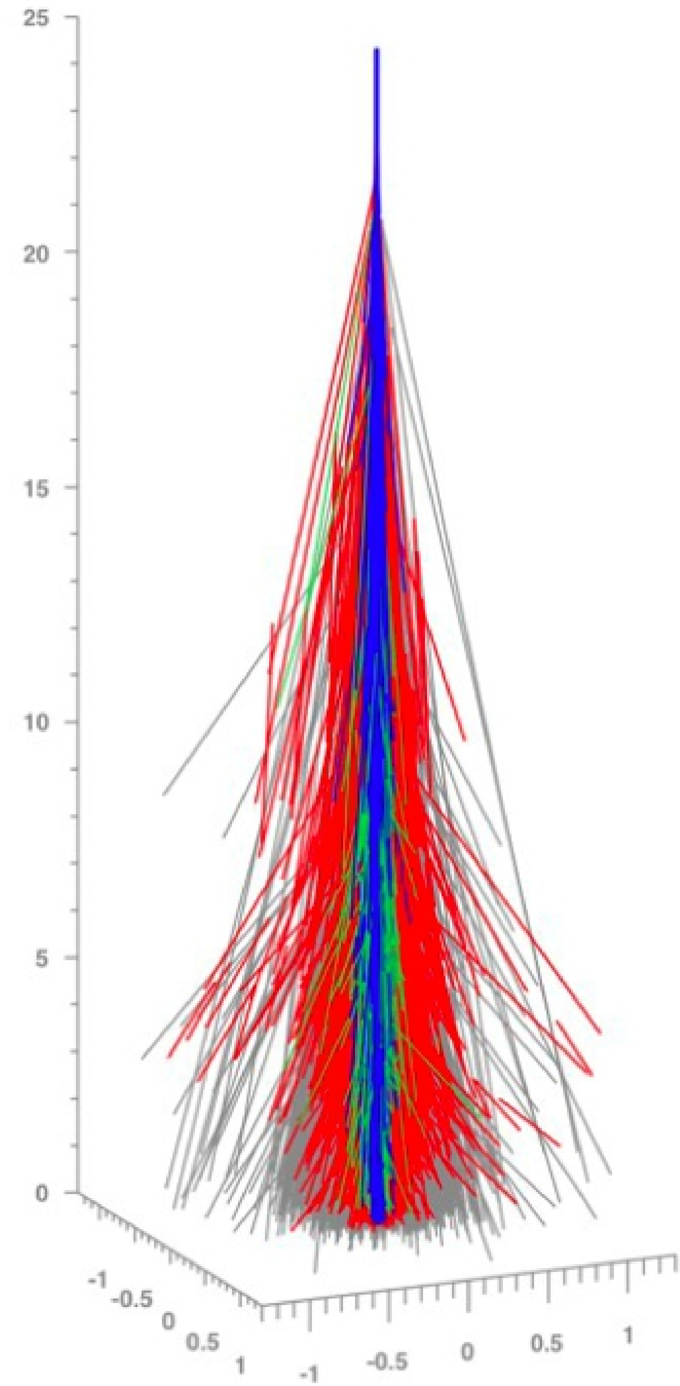


$$e^{\pm},\ \gamma$$

$$\mu^{\pm}$$

hadrons

Neutrinos



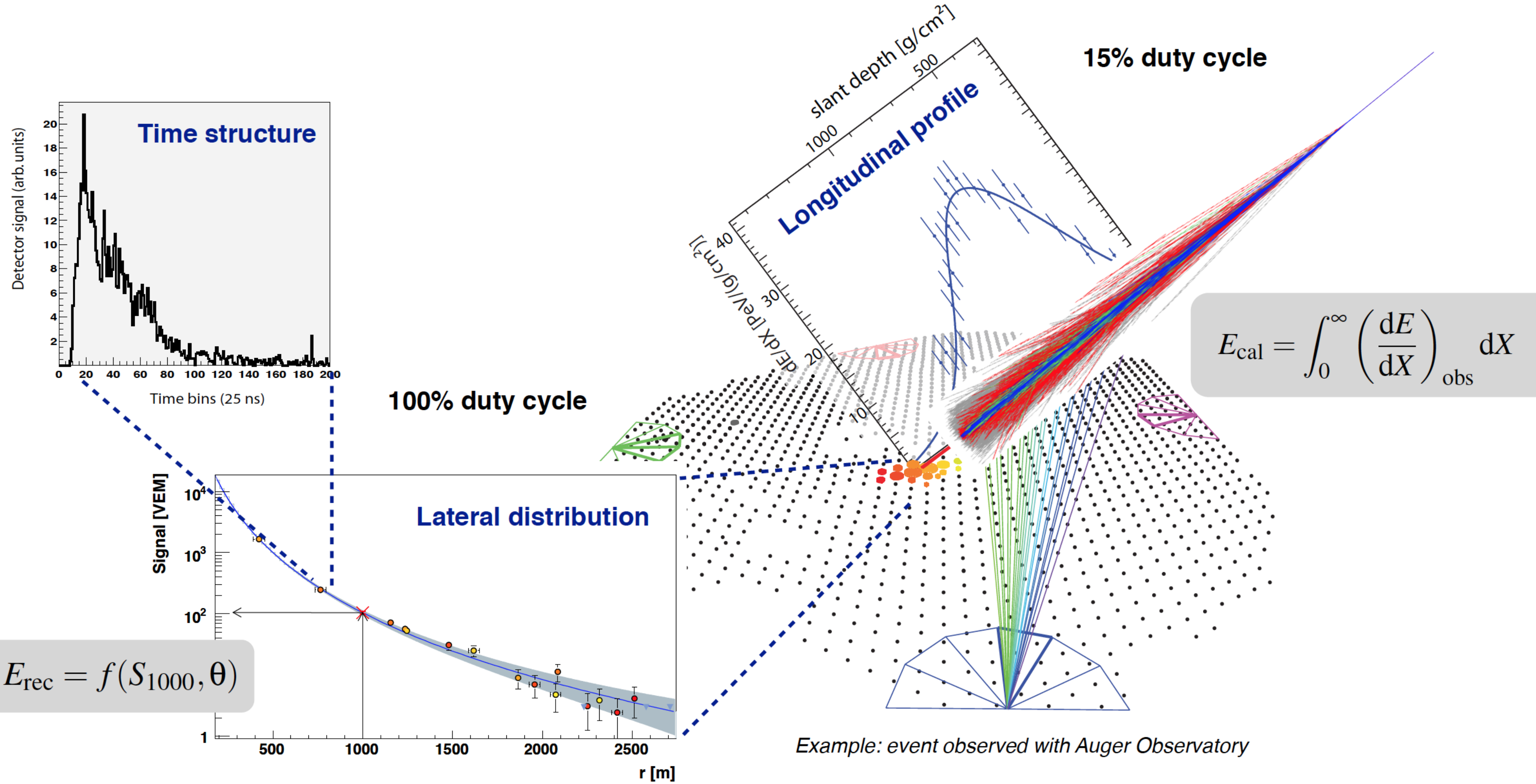
TA:
8.1 x 10^3 km^2 sr yr (spectrum)
8.6 x 10^3 km^2 sr yr (anisotropy)

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km^2
36 fluorescence telescopes

Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km^2
27 fluorescence telescopes

Auger:
6.7 x 10^4 km^2 sr yr (spectrum)
9 x 10^4 km^2 sr yr (anisotropy)

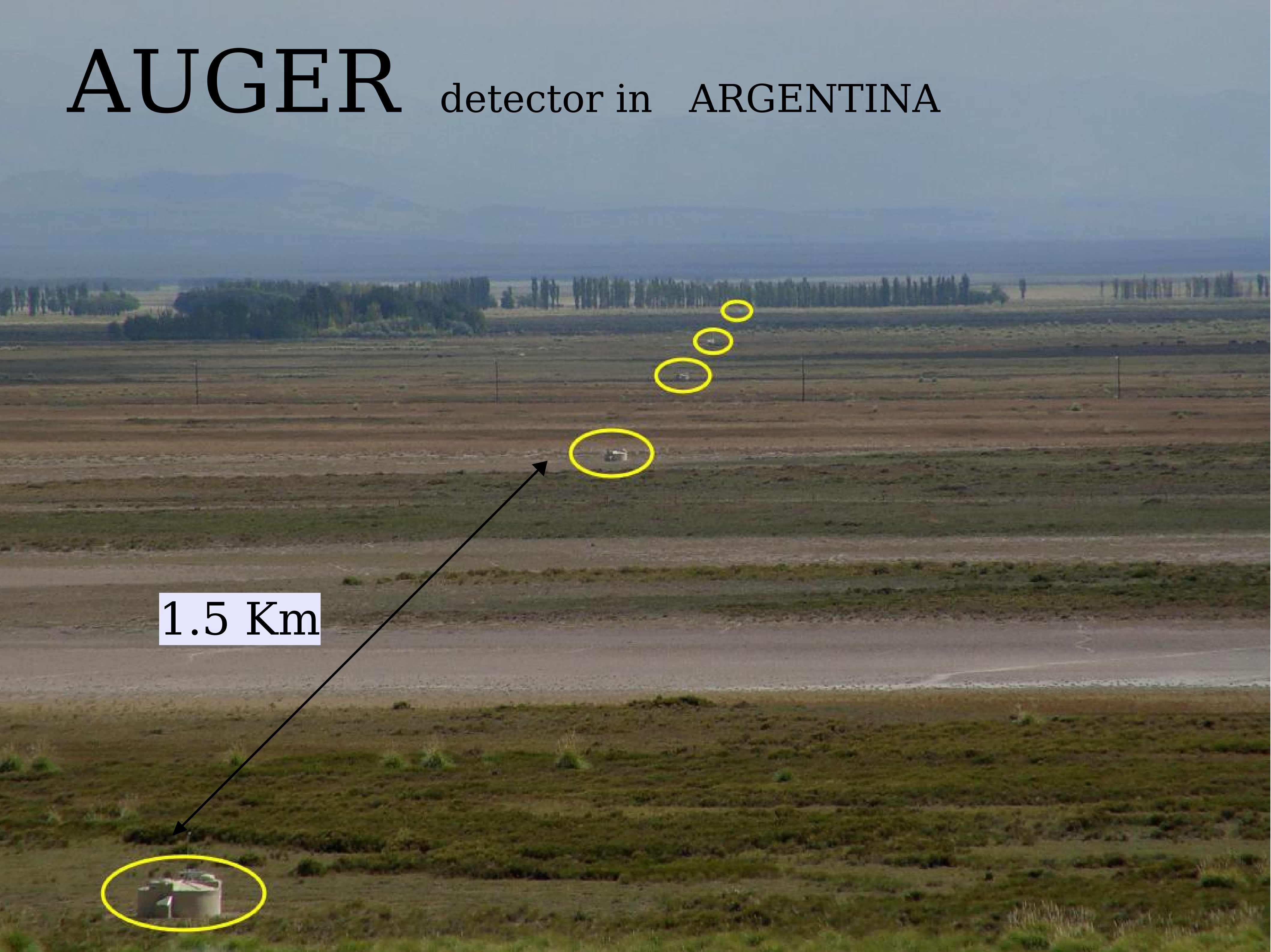
Detection of High Energy Shower [Auger Detector]



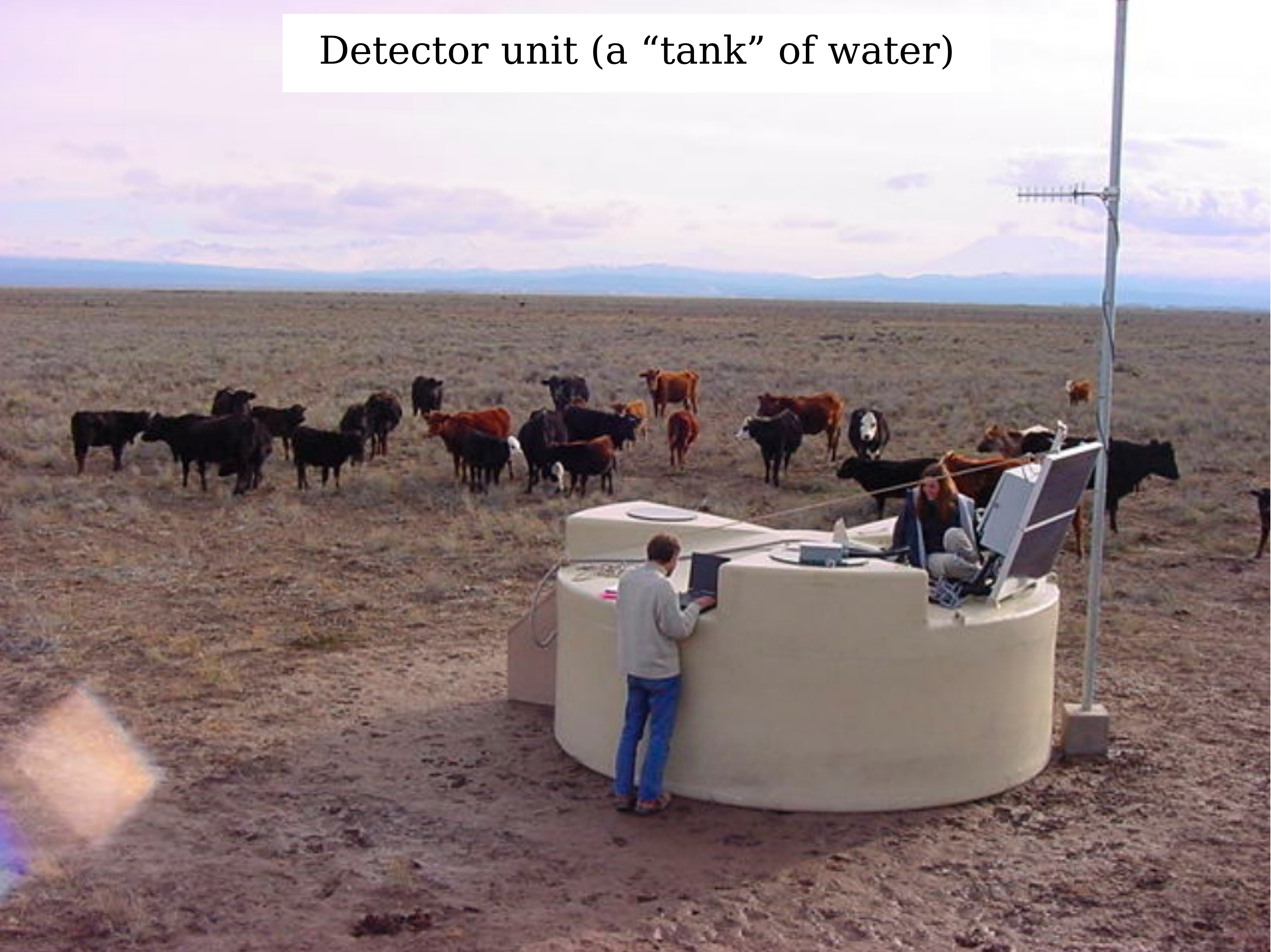
$$E_{\mathrm{rec}} = f(S_{1000}, \theta)$$

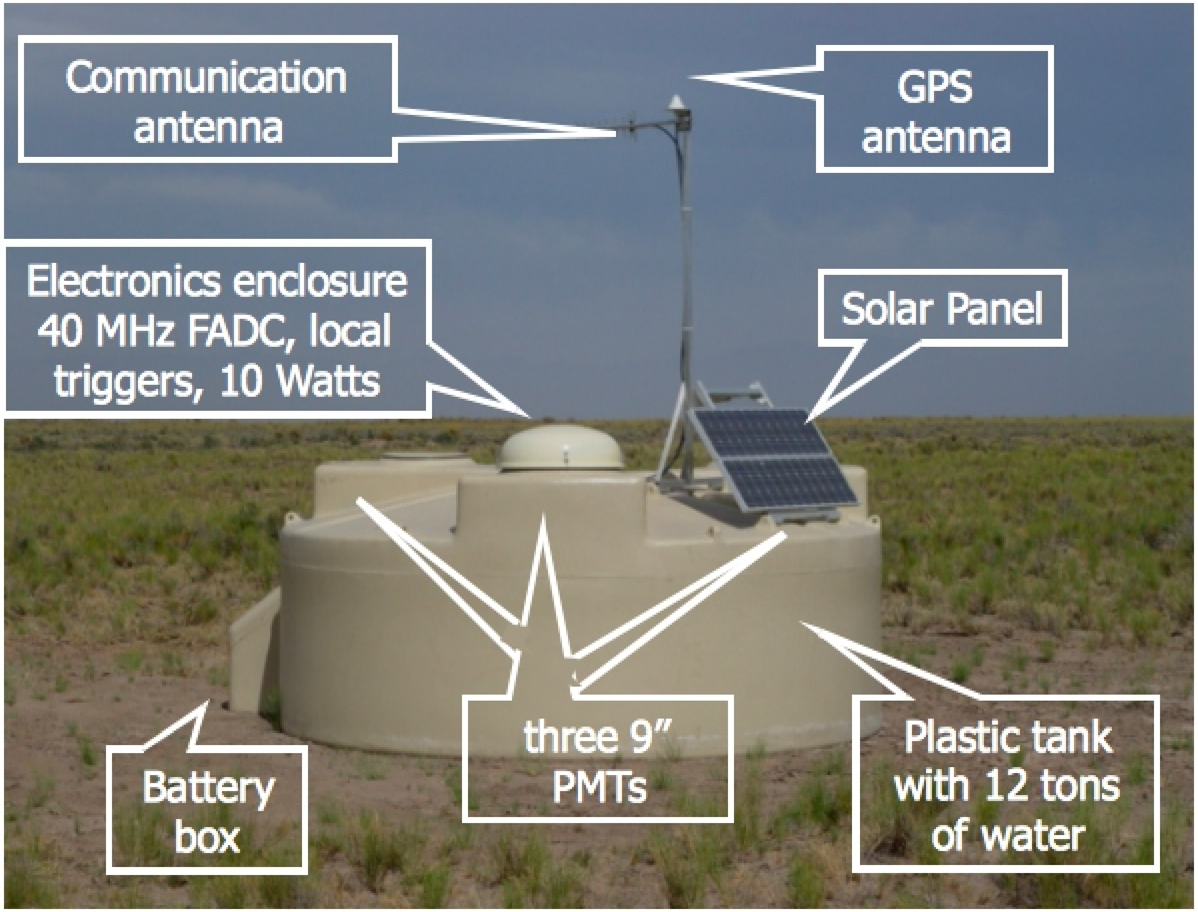
$$E_{\mathrm{cal}} = \int_0^\infty \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\mathrm{obs}} \mathrm{d}X$$

Example: event observed with Auger Observatory


AUGER detector in ARGENTINA
1.5 Km

Detector unit (a “tank” of water)



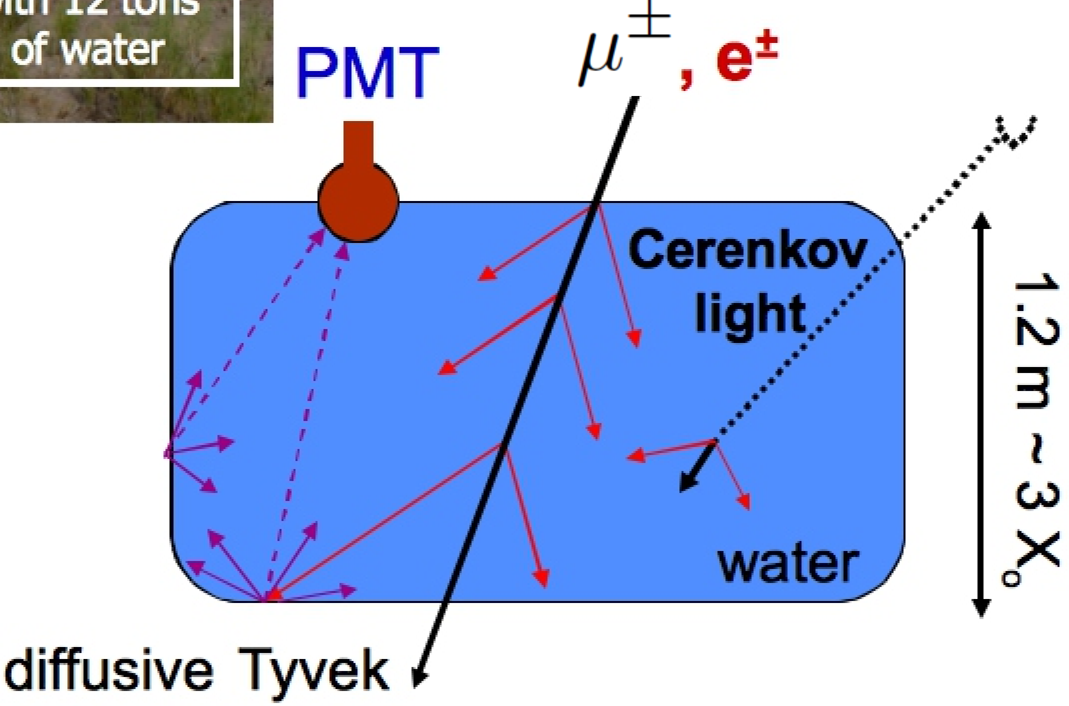


Auger Surface Detector

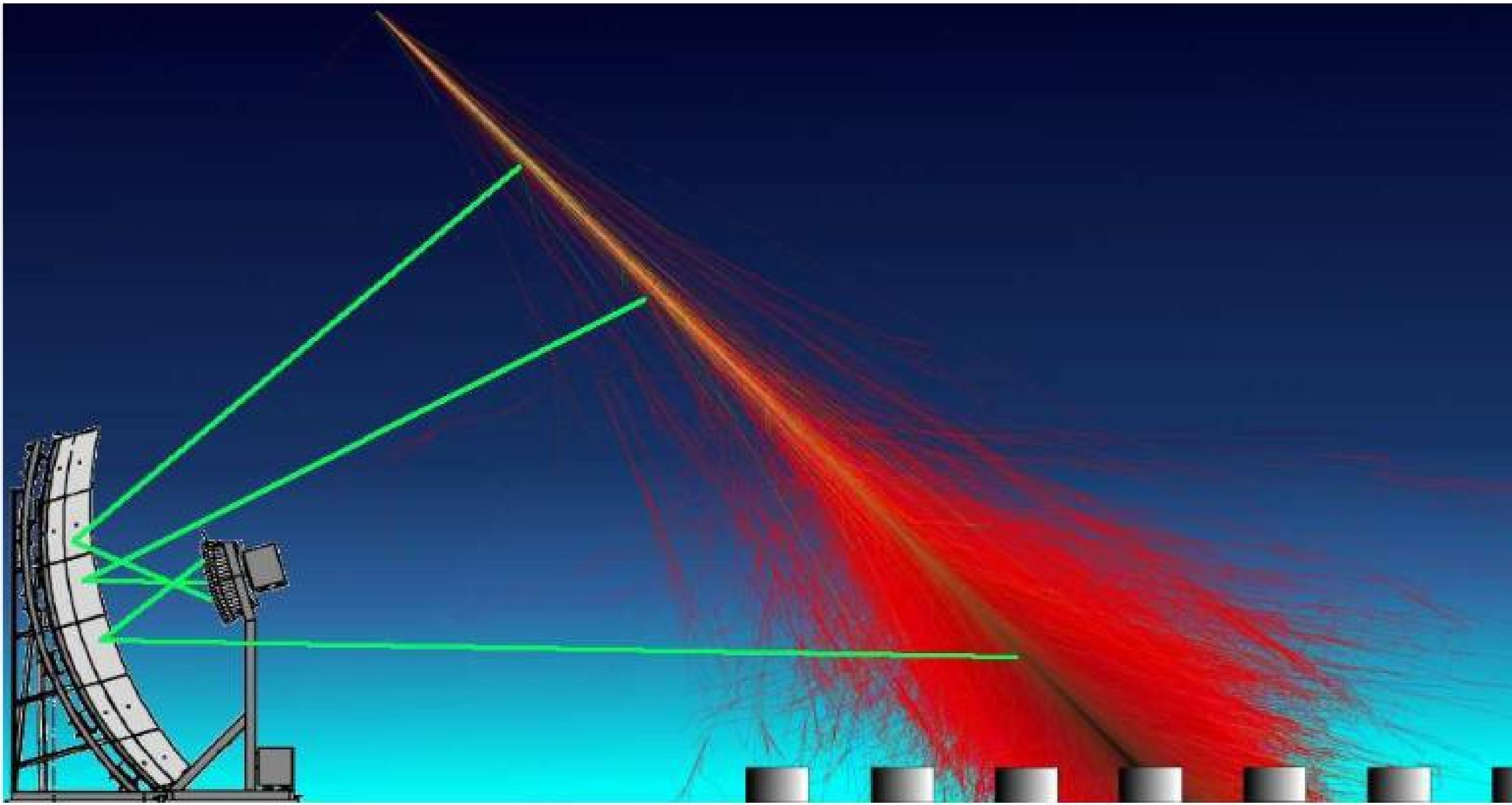
Overall tank array efficiency ~95%!

The tanks works like an "integrating sphere"

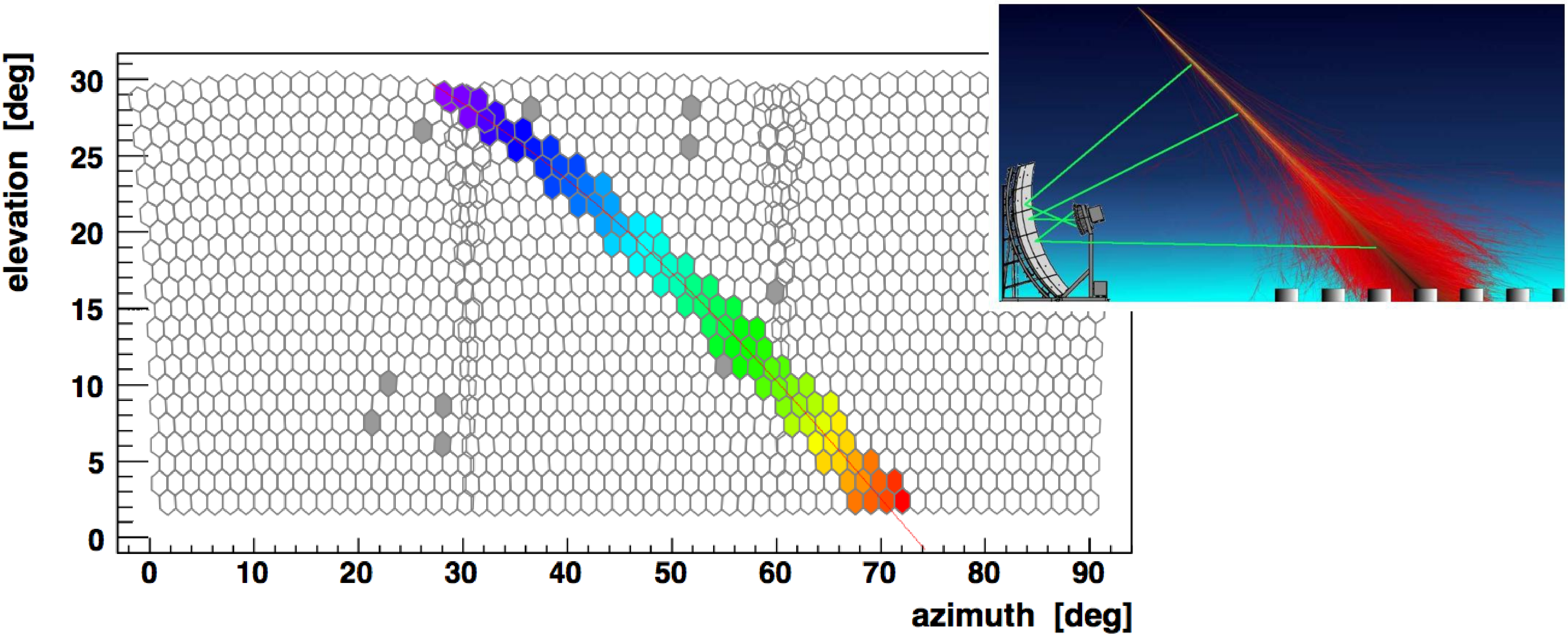
Time response for a single muon ~ 60 ns



Fluorescence Light emitted by Nitrogen Molecule excited by the passage of relativistic charged particles.



Technique possible only in clear, dark (moonless) nights

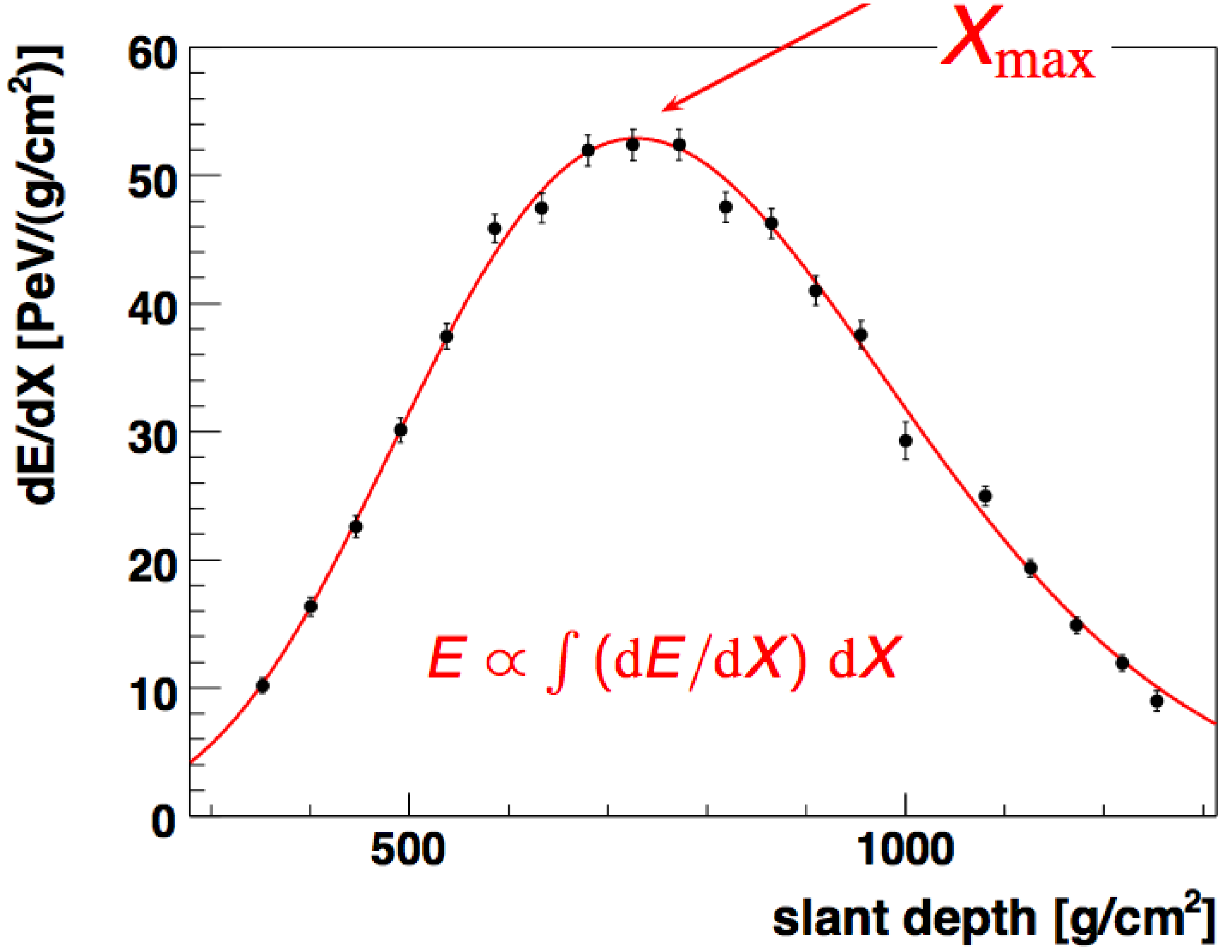


$$L(\Omega) \rightarrow F_{\gamma}(X) \rightarrow N_{e^{\pm}}(X)$$

Observed Light → Emitted Photons → Shower Size

Geometry
Atmospheric Absorption

Fluorescence Yields

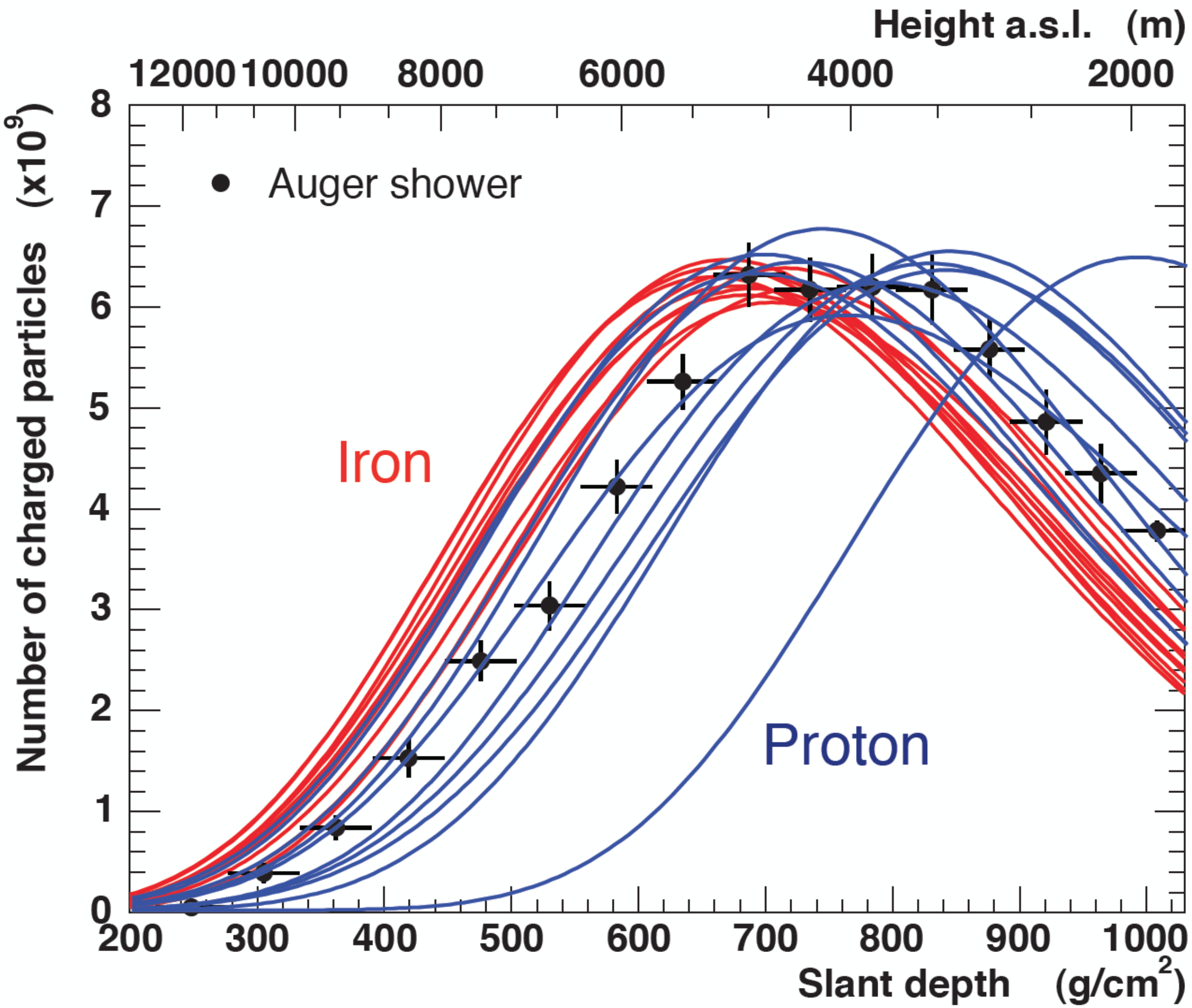


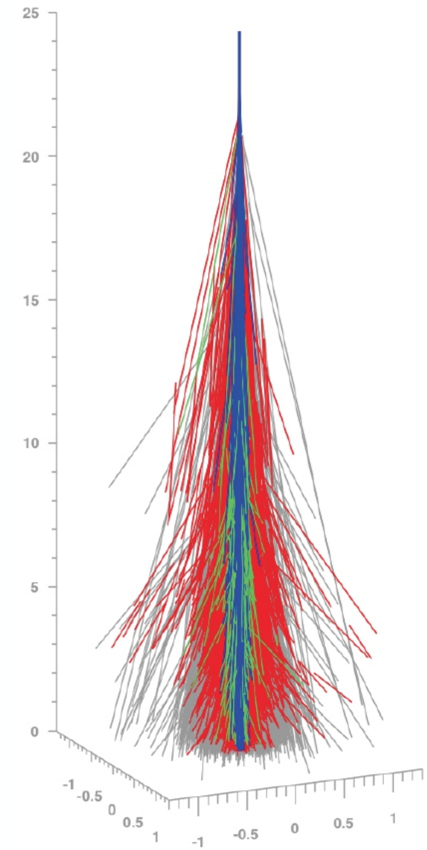
$$E_{\text{ionization}} = \int dX \; N_e(X) \left\langle -\frac{dE}{dX} \right\rangle$$

Small Model dependence

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

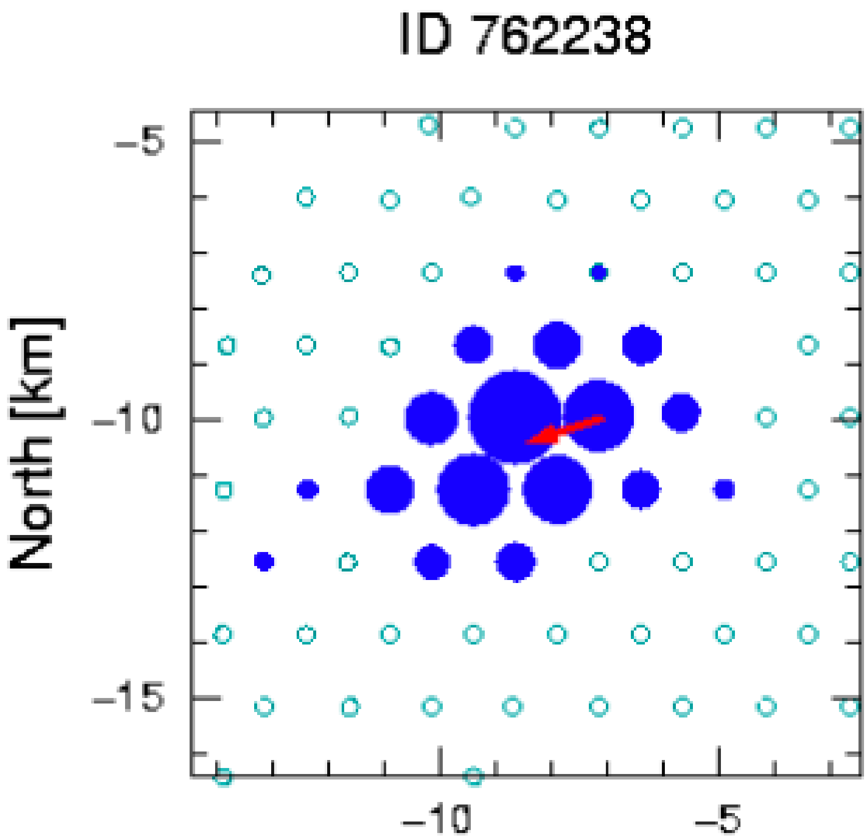
Real data of one Auger shower,
compared with Montecarlo calculations
[Fixed energy protons, Iron]

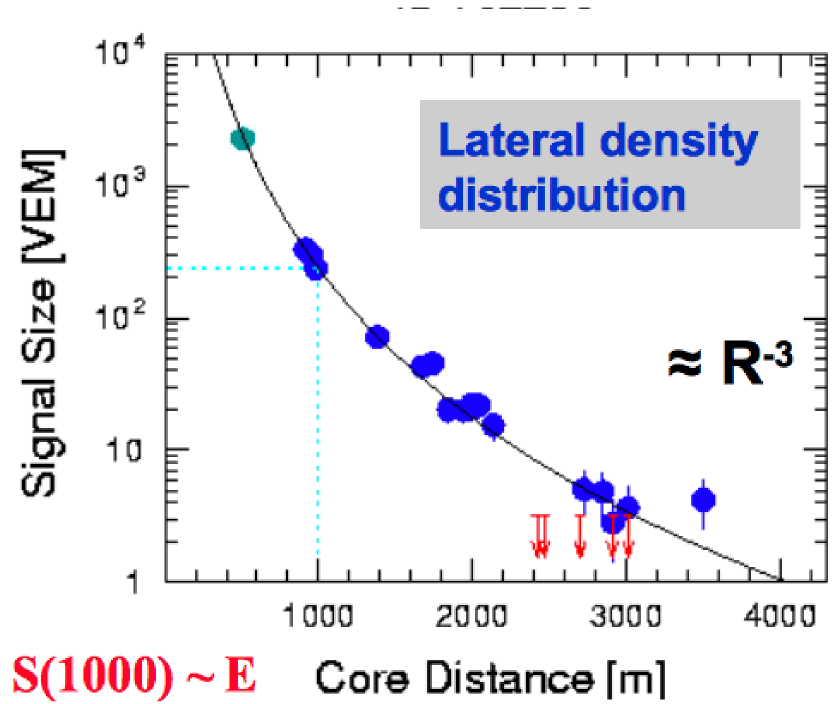




Auger – Surface-Detector

“Calibration” with the fluorescence detector

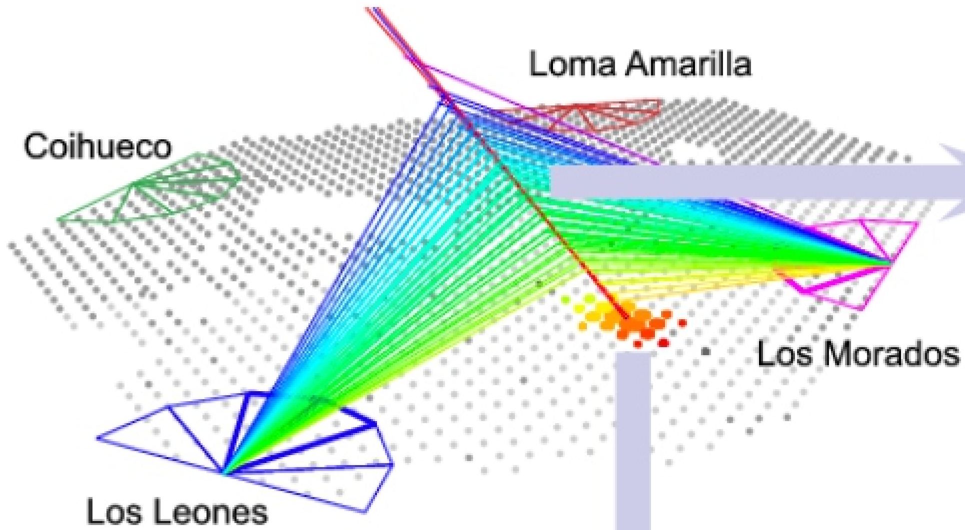


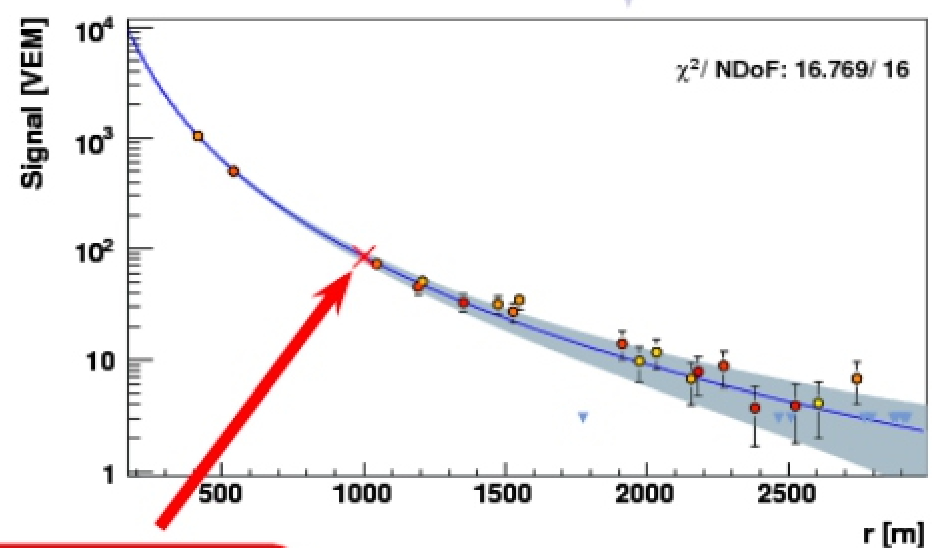


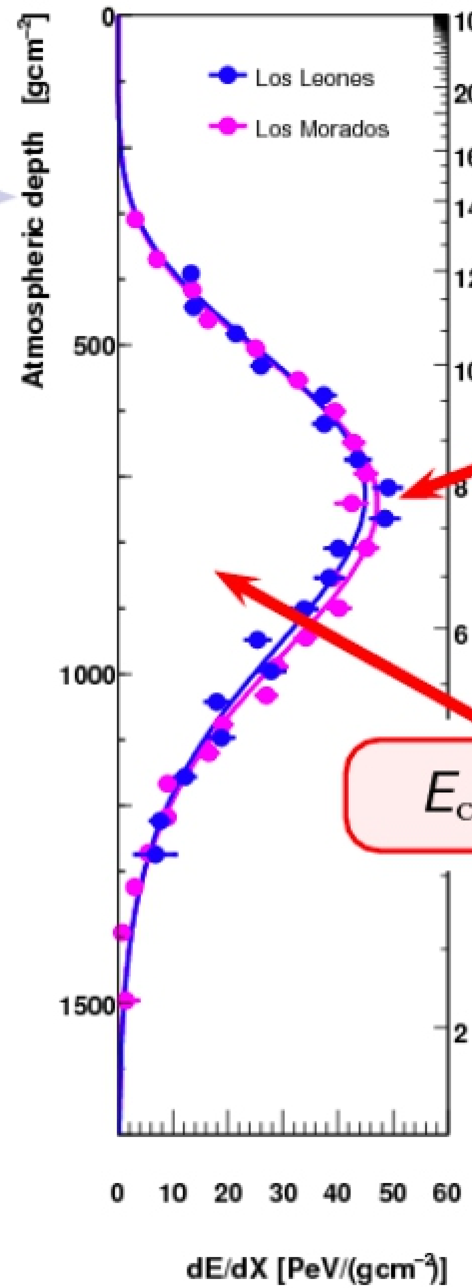
Timing of tank-signals give shower direction

VEM = Vertical-Equivalent-Muon

The Auger ‘hybrid’ detector







$\sigma_{X_{\mathrm{max}}} < 20\,\mathrm{g/cm^2}$

$\Delta_{\mathrm{sys}} \approx 15\,\mathrm{g/cm^2}$

X_{max}

$E_{\mathrm{cal}} = \int \mathrm{d}X\ \frac{\mathrm{d}E}{\mathrm{d}X}$

$\sigma_E/E \sim 8\,\%$

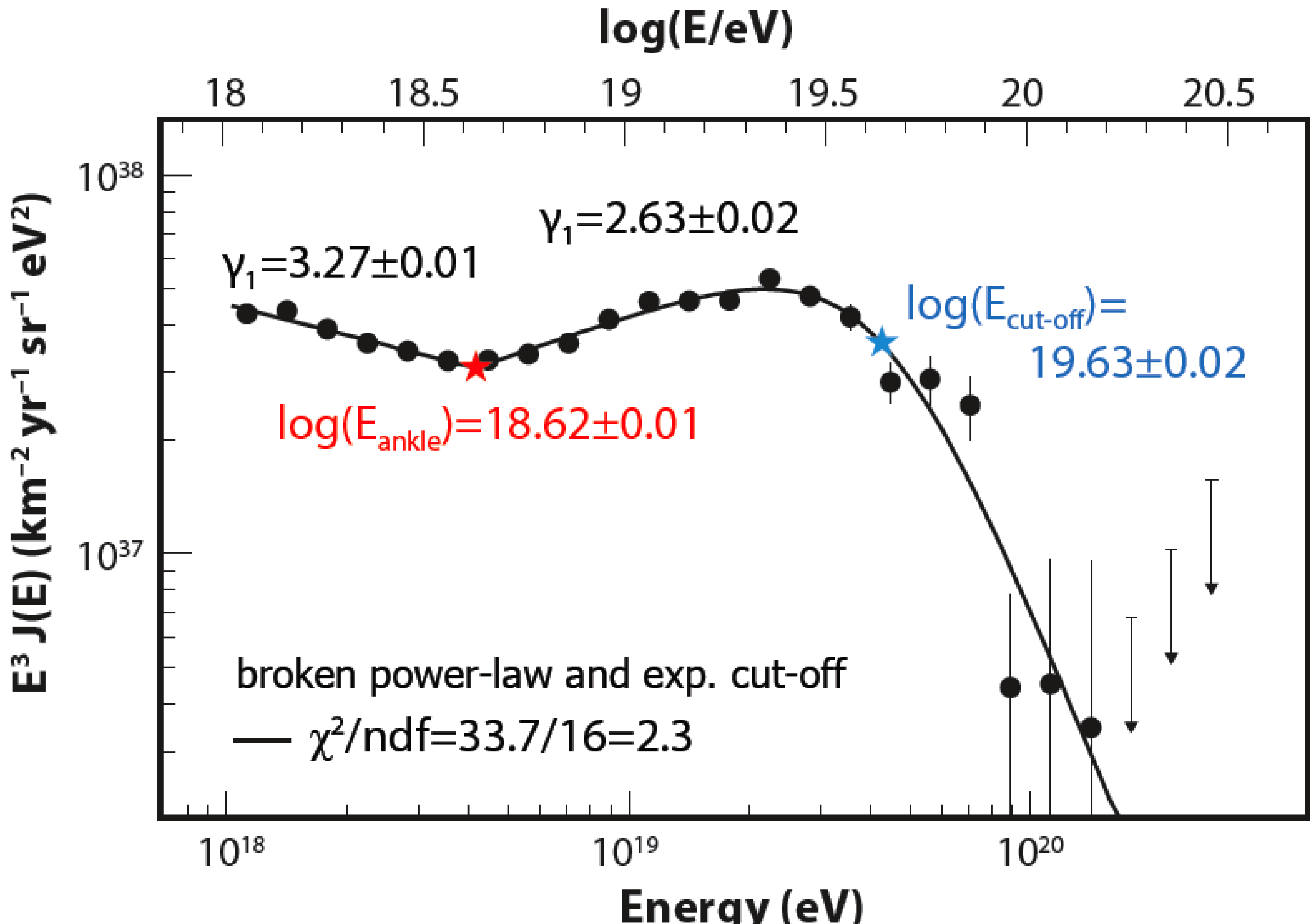
$\Delta_{\mathrm{sys}} \approx 22\,\%$

Fluorescence yield ~14%

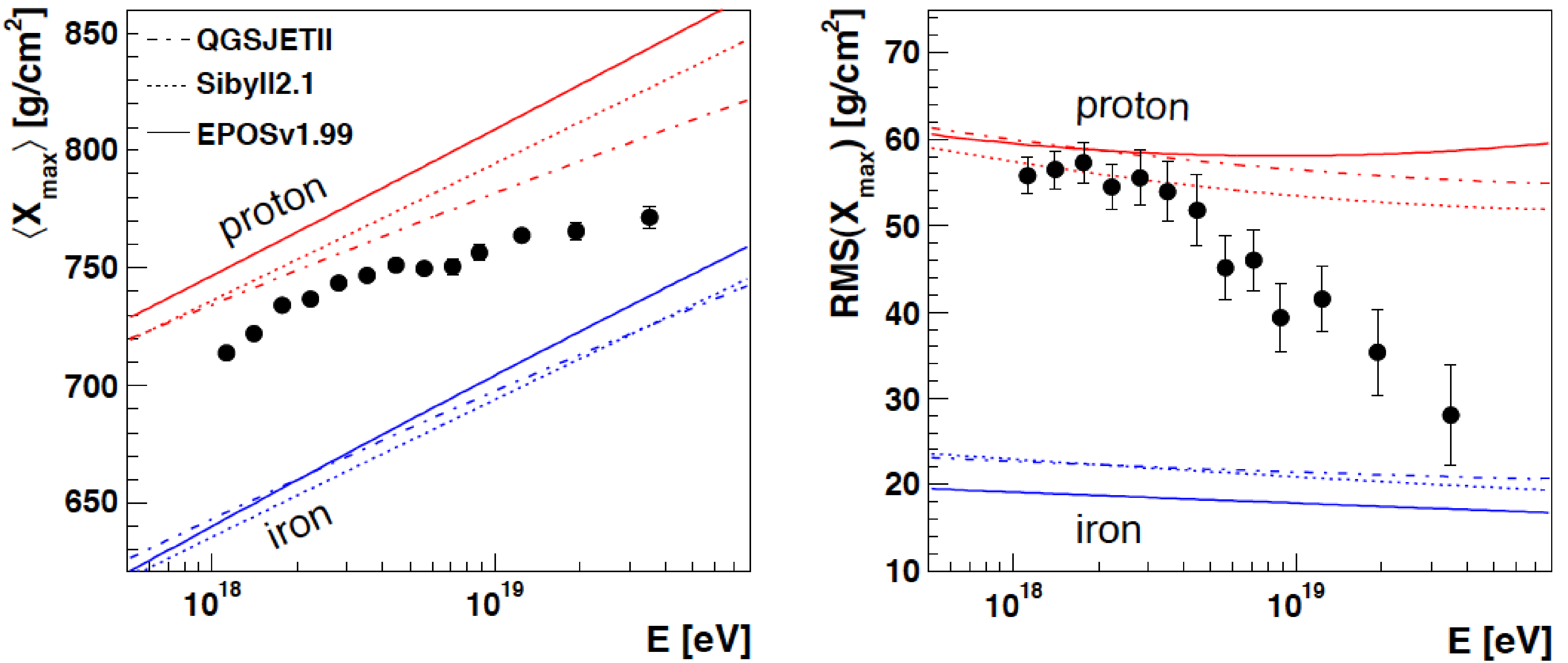
S_{1000}

$E_{\mathrm{surface}} = f(S_{1000},\ \theta)$

AUGER Energy Spectrum



$\langle X_{max} \rangle$ and RMS



Compare DATA with predictions based on several assumptions for hadronic interactions....

Shower Components at Ground Level:

Electromagnetic Component $e^{\mp}, \ \gamma$

Muon Component $\mu^{\mp}$

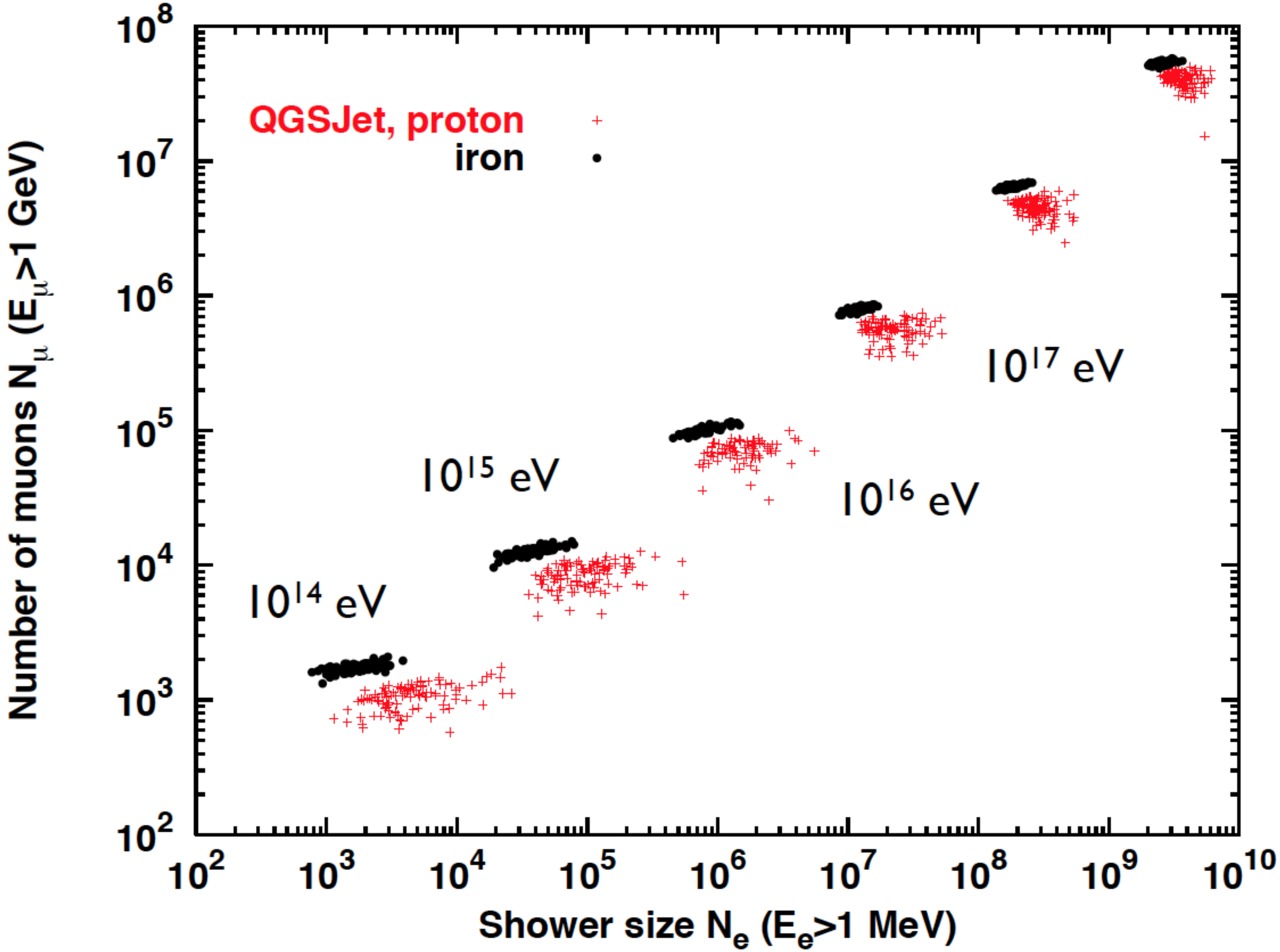
Hadronic component
[small and close to the shower axis]

(Invisible) Neutrino component

Alternative method to study the composition of cosmic ray showers:

Study the **muon content**

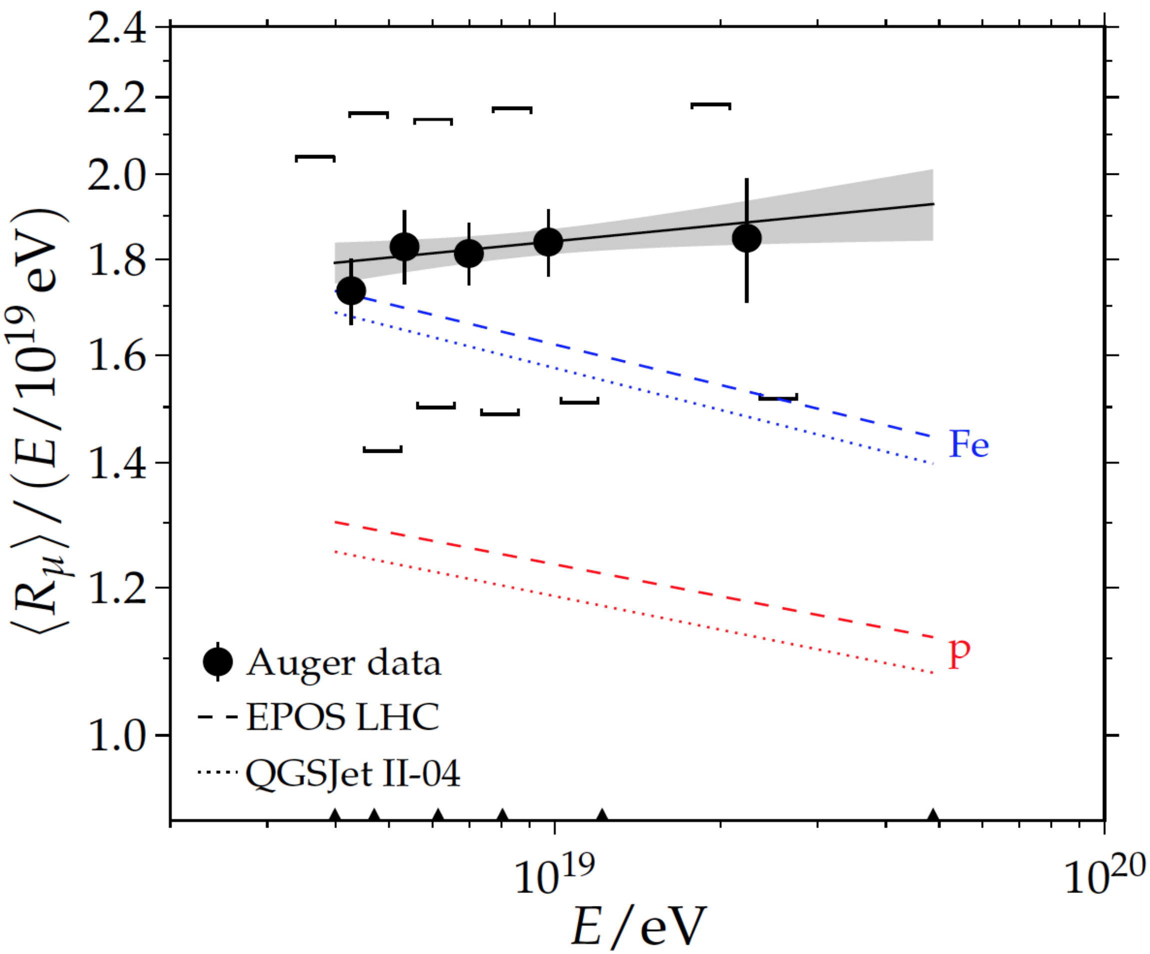
[Large A: more muons]



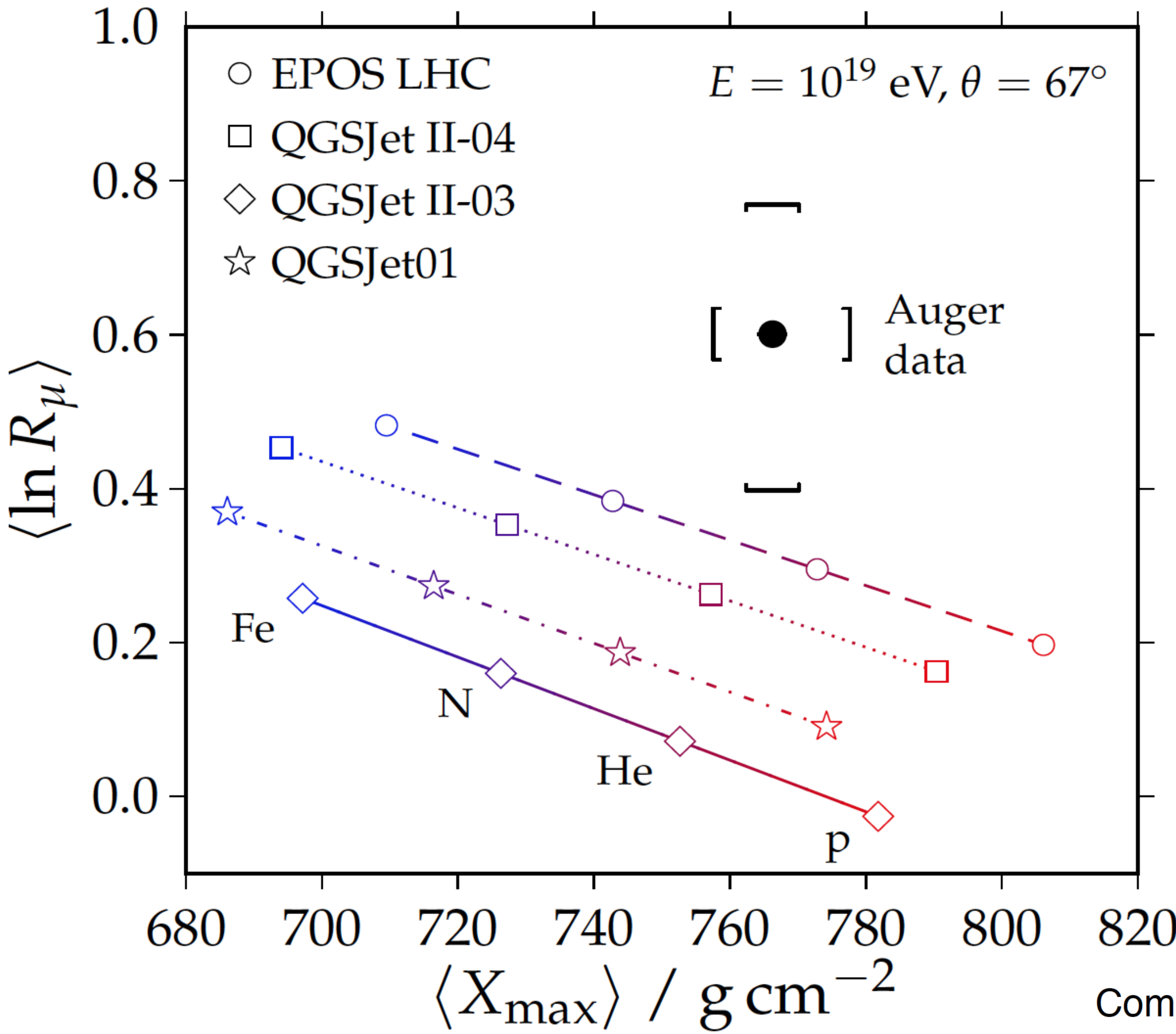
The “Muon problem” in AUGER

Inclined showers
(electromagnetic components absorbed)

Number of muons in showers with θ>60°



The "Muon problem" in AUGER



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

Combination of information on mean depth of shower maximum and muon number at ground

Planned upgrade of Auger

Scintillator
Detector

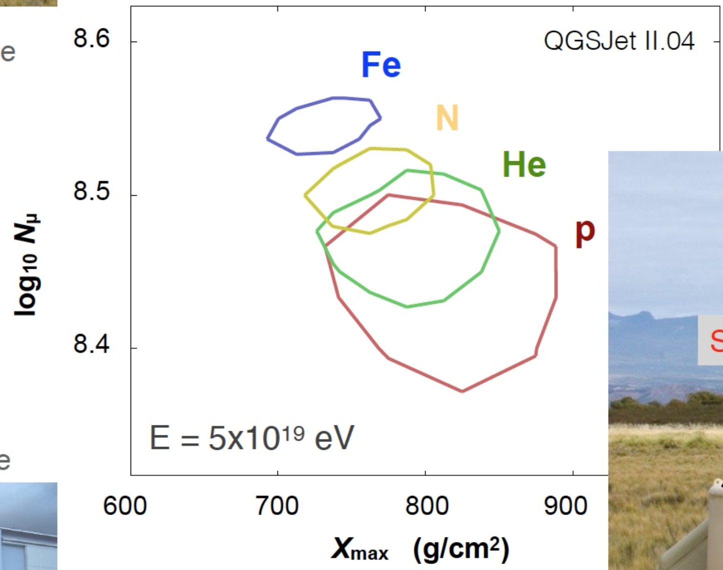
Combine:
Tank
Scintillator

to separate
muon / e.m.
components

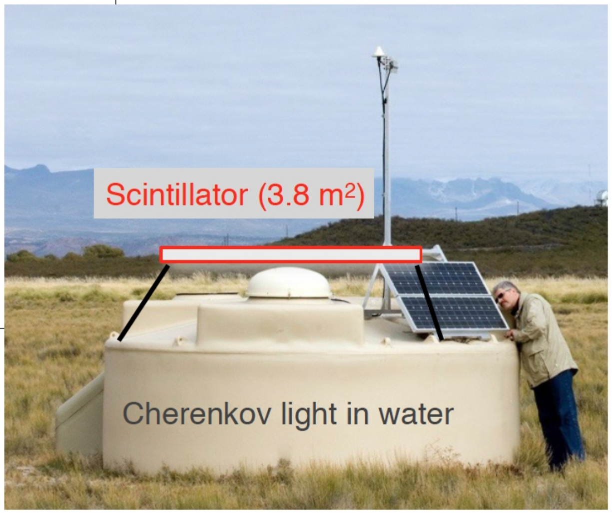
Upgrade of Auger Observatory: AugerPrime

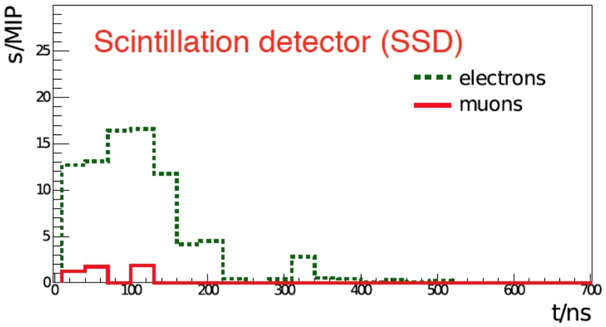
Complementarity of particle response used to discriminate em. and muonic components

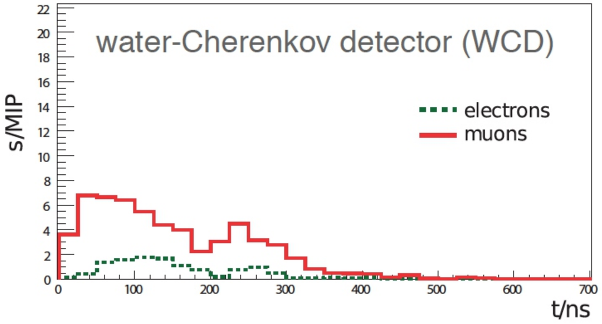
100% duty cycle



15% duty cycle







$$S_{\mu,\mathrm{WCD}} = a\,S_{\mathrm{WCD}} + b\,S_{\mathrm{SSD}}$$
$$S_{\mathrm{em},\mathrm{WCD}} = c\,S_{\mathrm{WCD}} + d\,S_{\mathrm{SSD}}$$

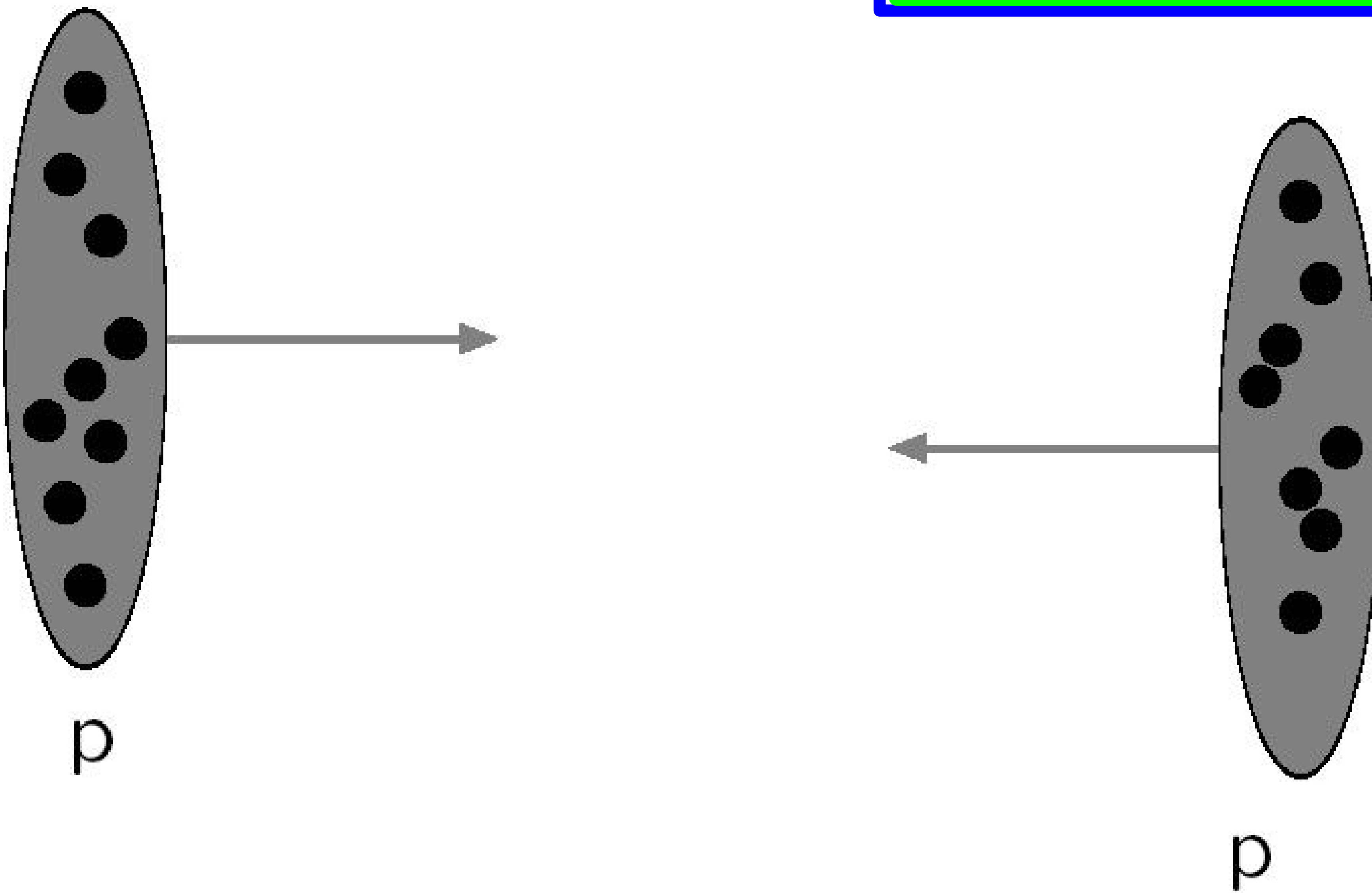
(Martello, ICRC 2017)

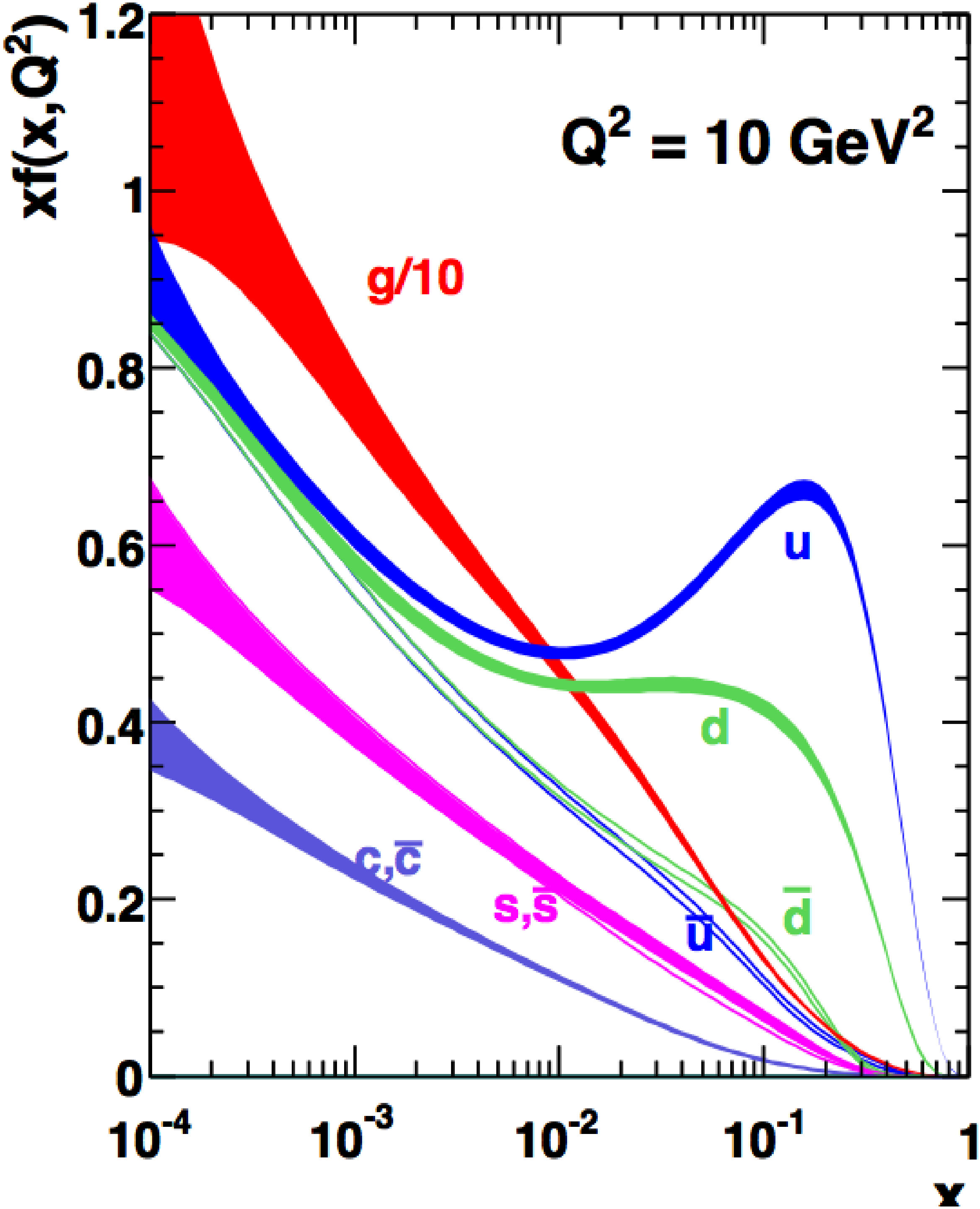
(AugerPrime design report 1604.03637)

Hadronic Interactions

QCD

Composite (complex) objects
Multiple interaction structure

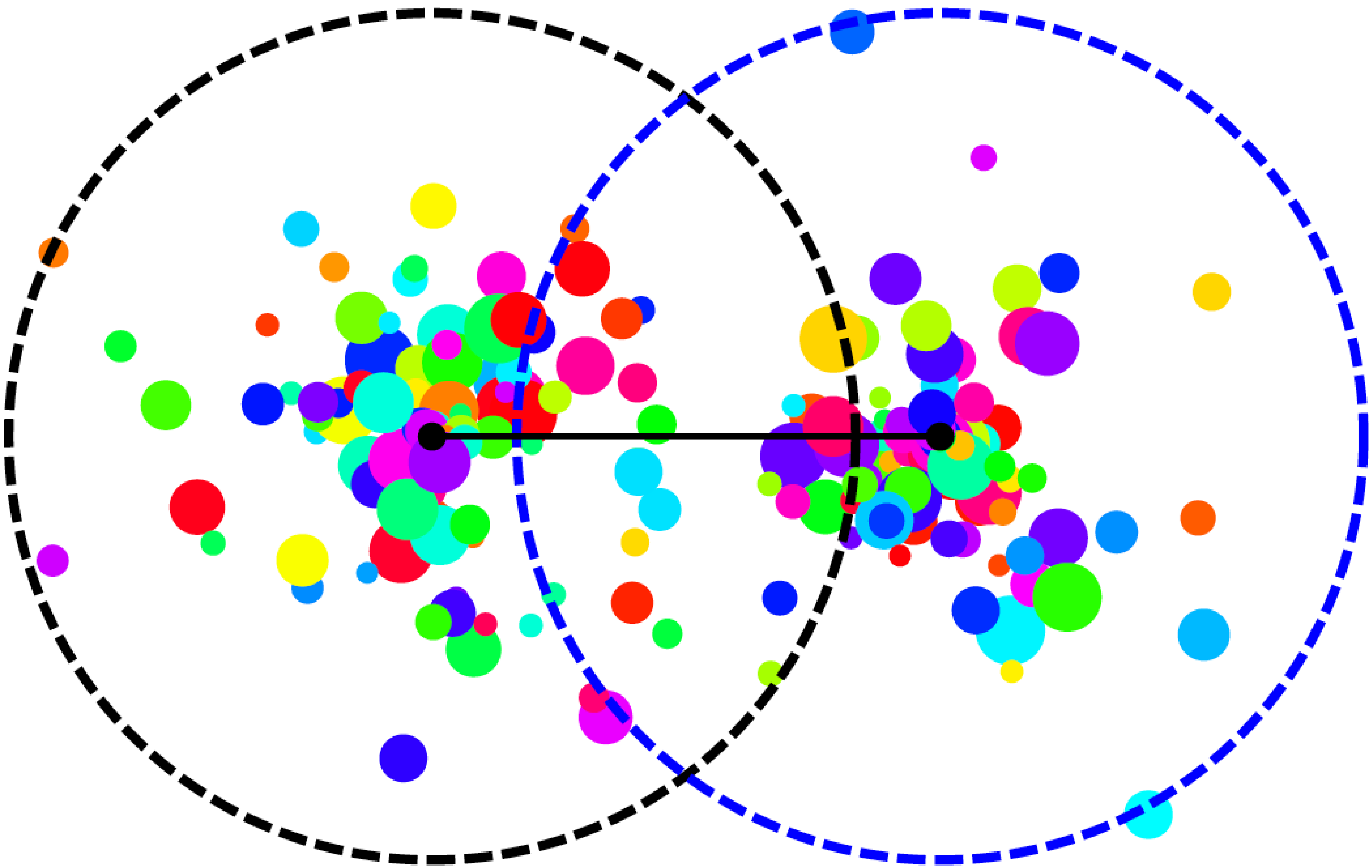


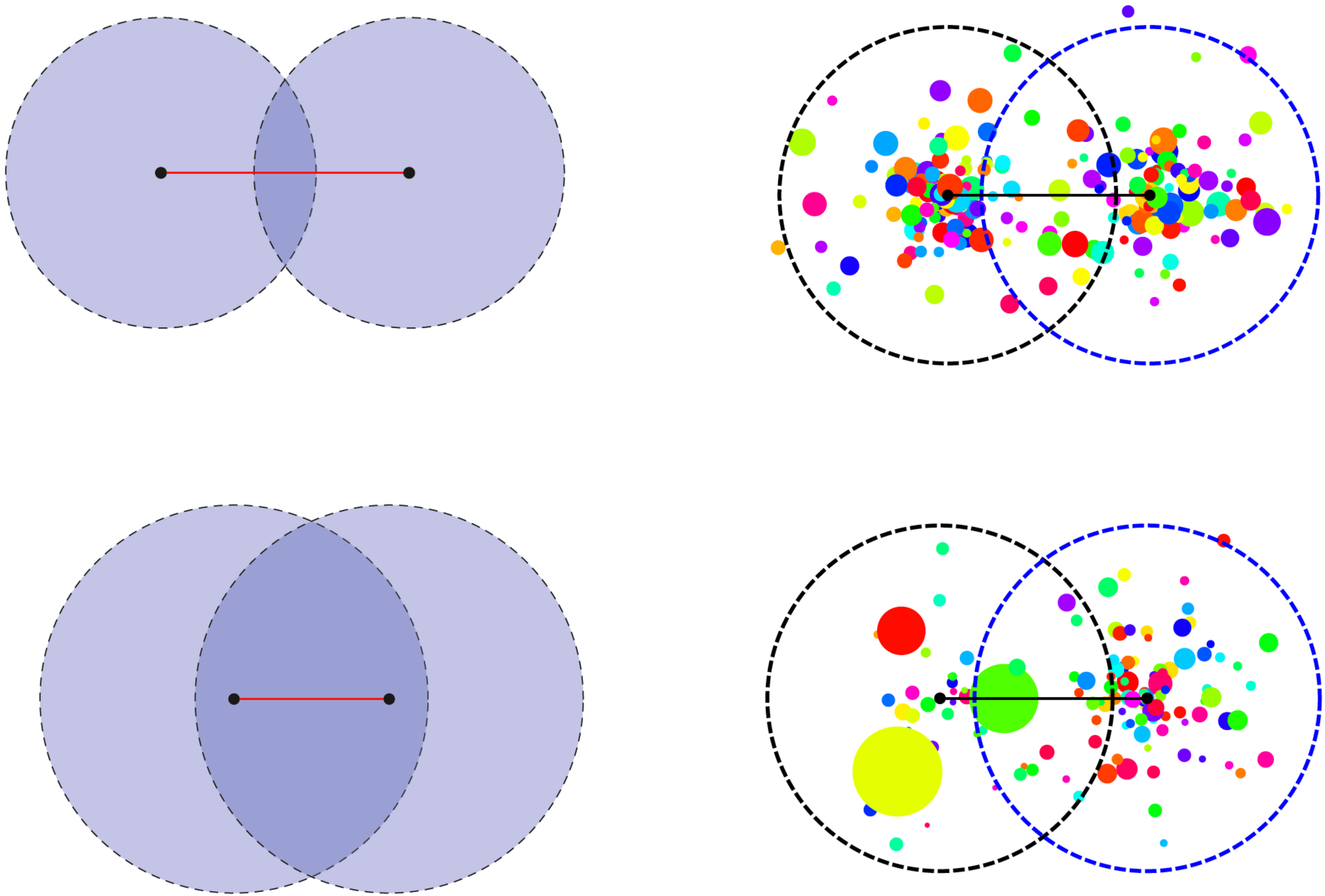


Parton Distribution Functions

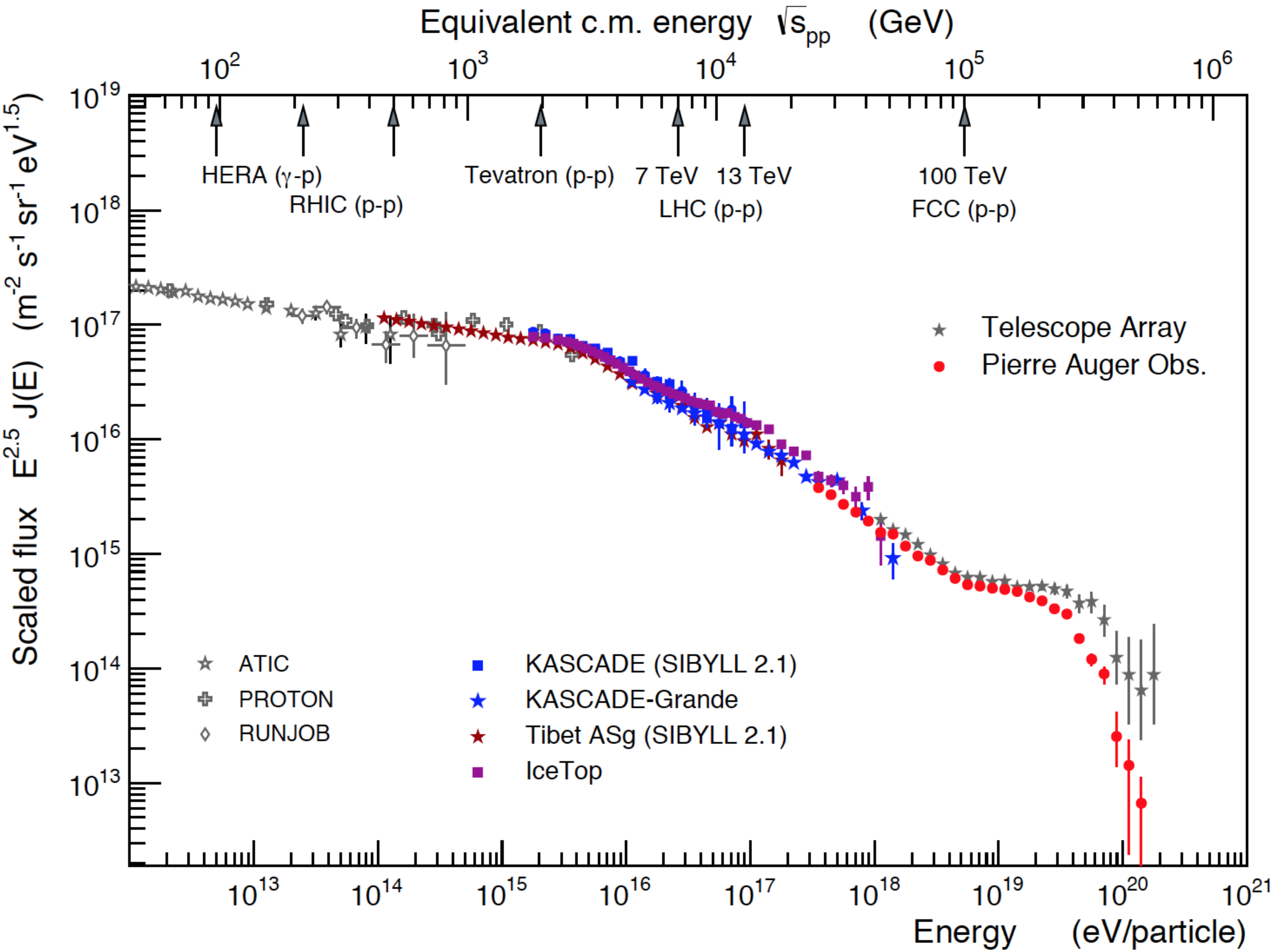
Perturbative calculation of hard processes

“Cartoon” of a pp interaction in the transverse plane



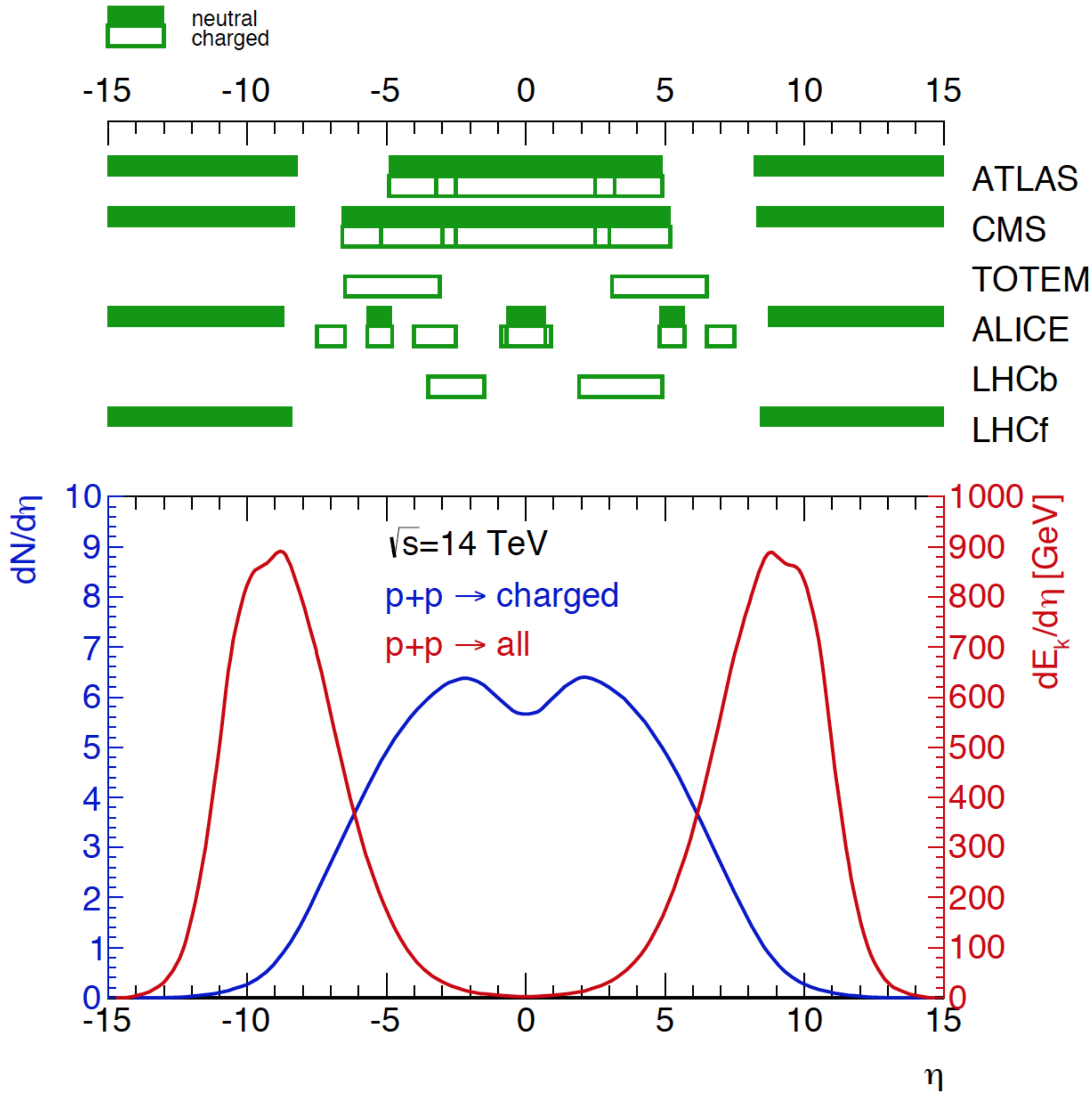


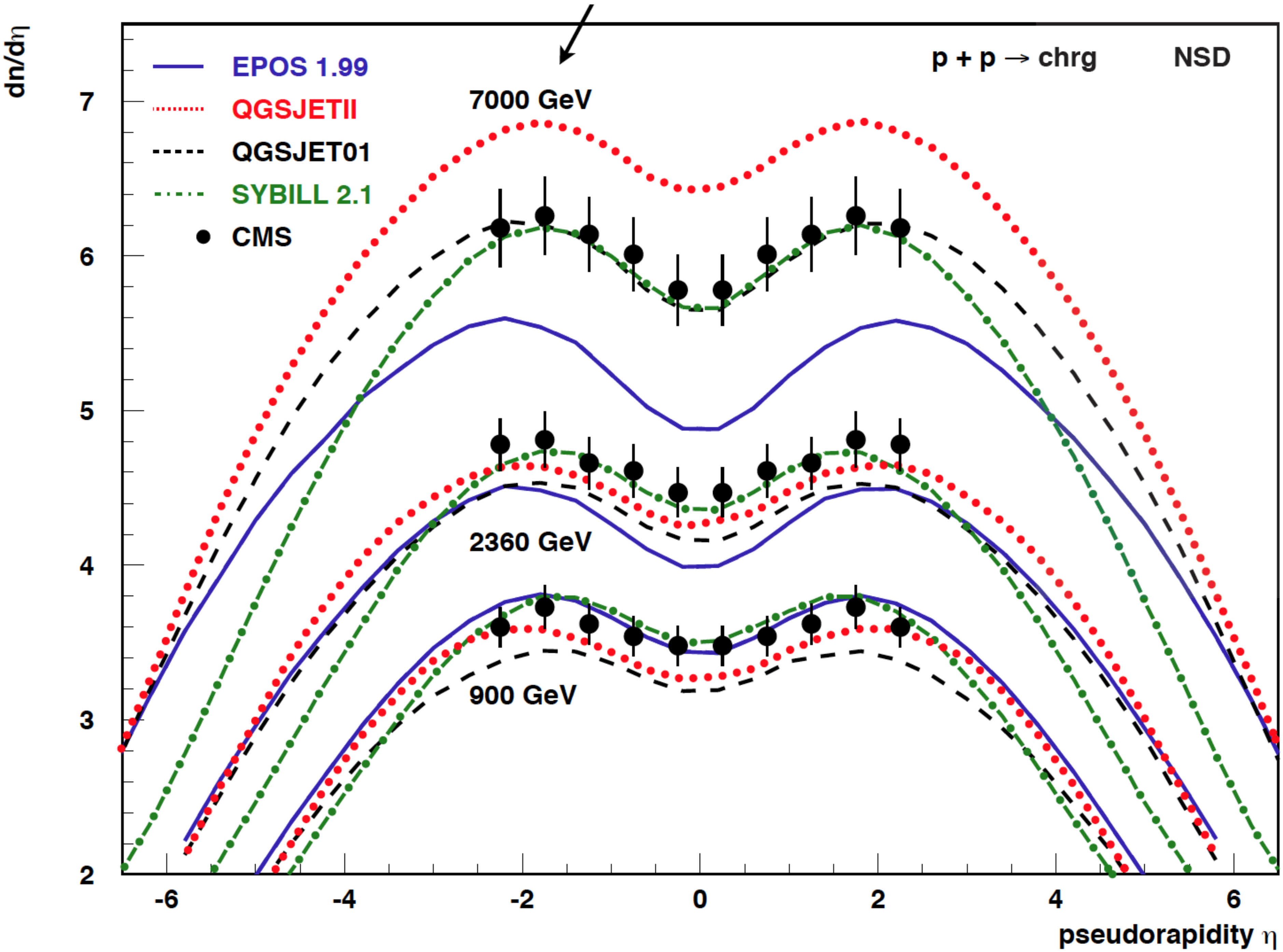
High Energy Cosmic Ray Spectrum



Partial cover of kinematical space at colliders

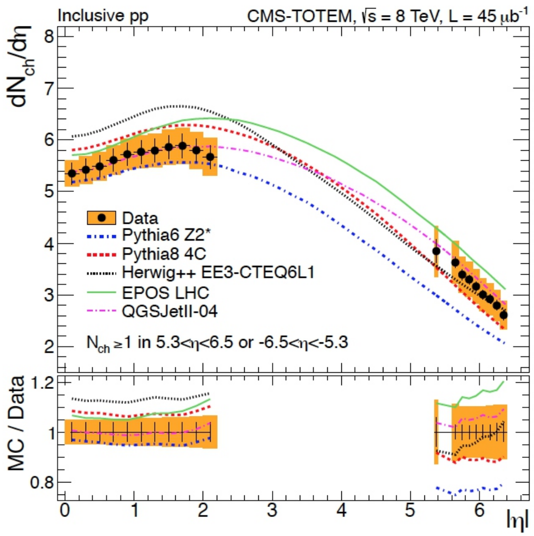
$$E = p_{\perp} \frac{(e^{+\eta} + e^{-\eta})}{2}$$

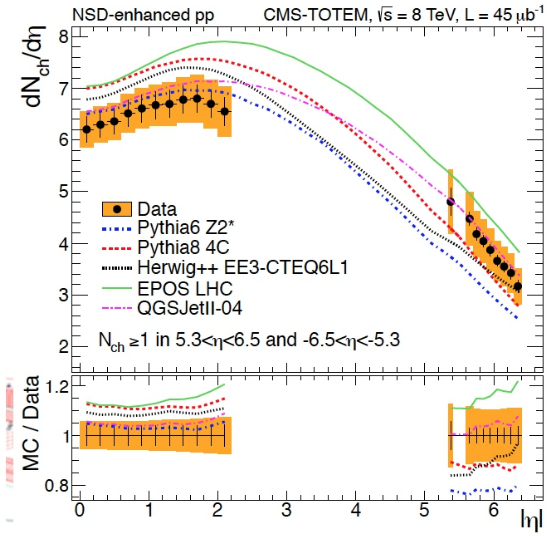


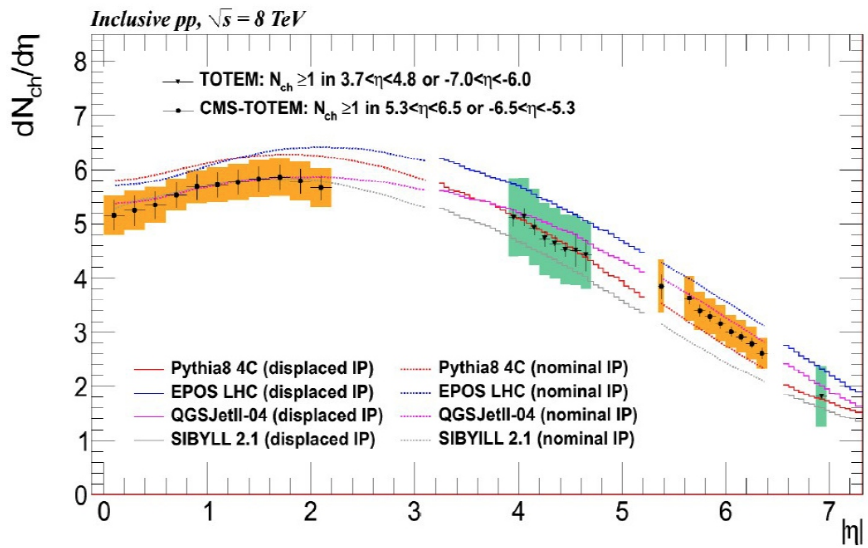


dn/dη
EPOS 1.99
QGSJETII
QGSJET01
SYBILL 2.1
CMS
p + p → chrg
NSD
7000 GeV
2360 GeV
900 GeV
7
6
5
4
3
2
-6
-4
-2
0
2
4
6
pseudorapidity η

Combined CMS and TOTEM measurements

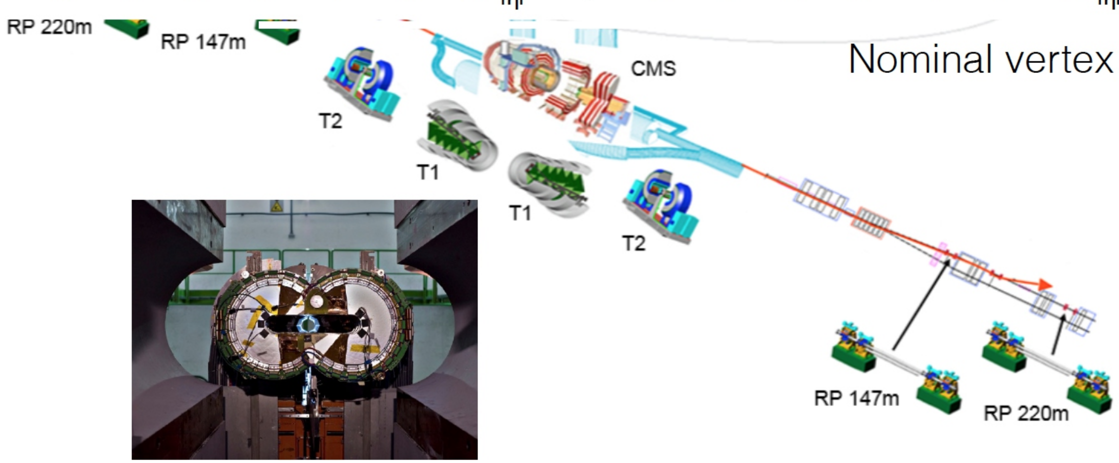


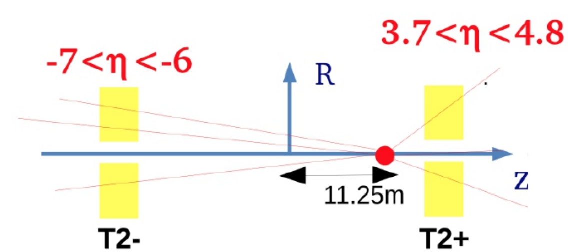




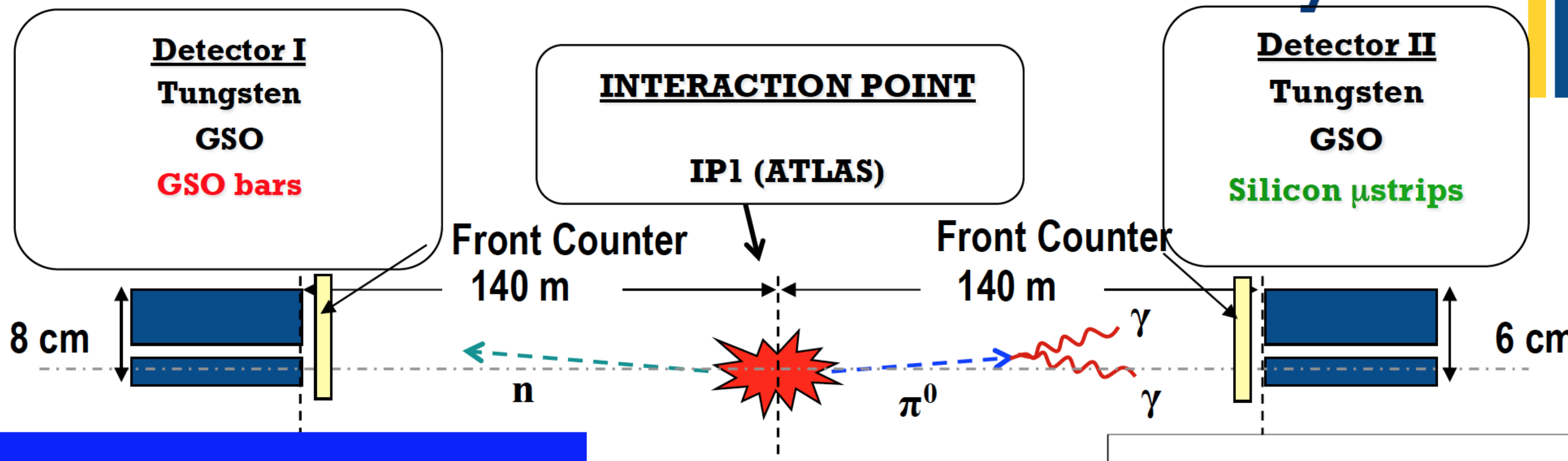
Nominal vertex

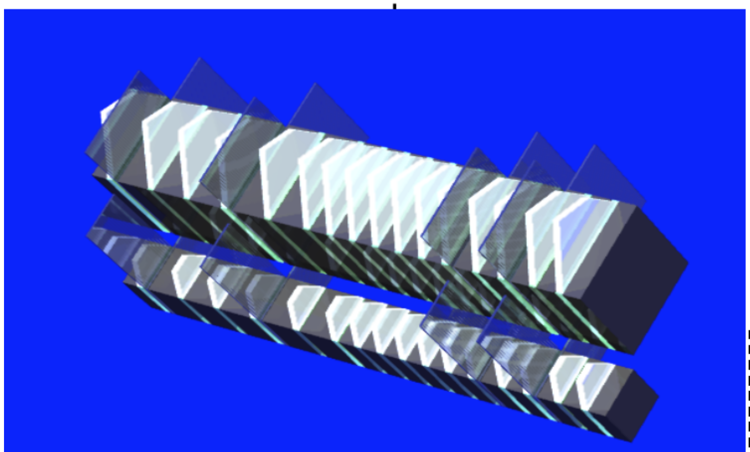
Shifted vertex



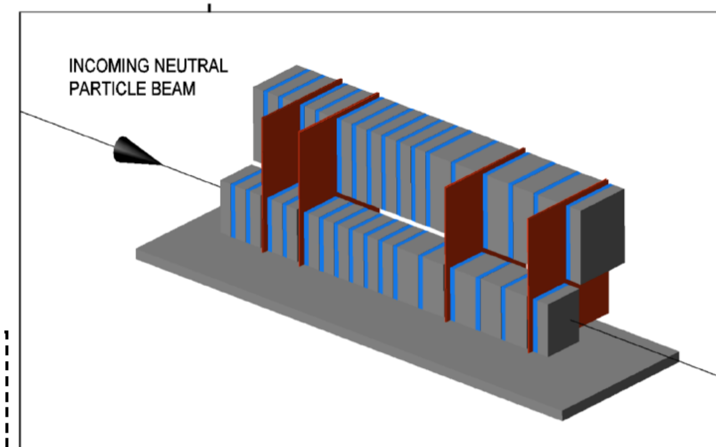


+ LHCf: location and detector layout





$44X_0$,
$1.6\ \lambda_{int}$



Arm#1 Detector
20mmx20mm+40mmx40mm
4 X-Y GSO Bars tracking layers

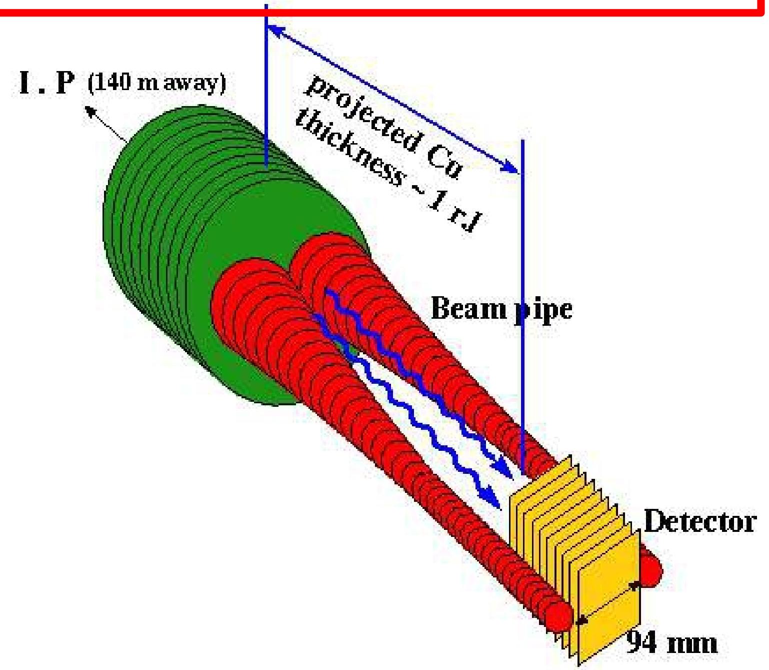
Energy resolution:
- $< 5\%$ for photons
- 30% for neutrons

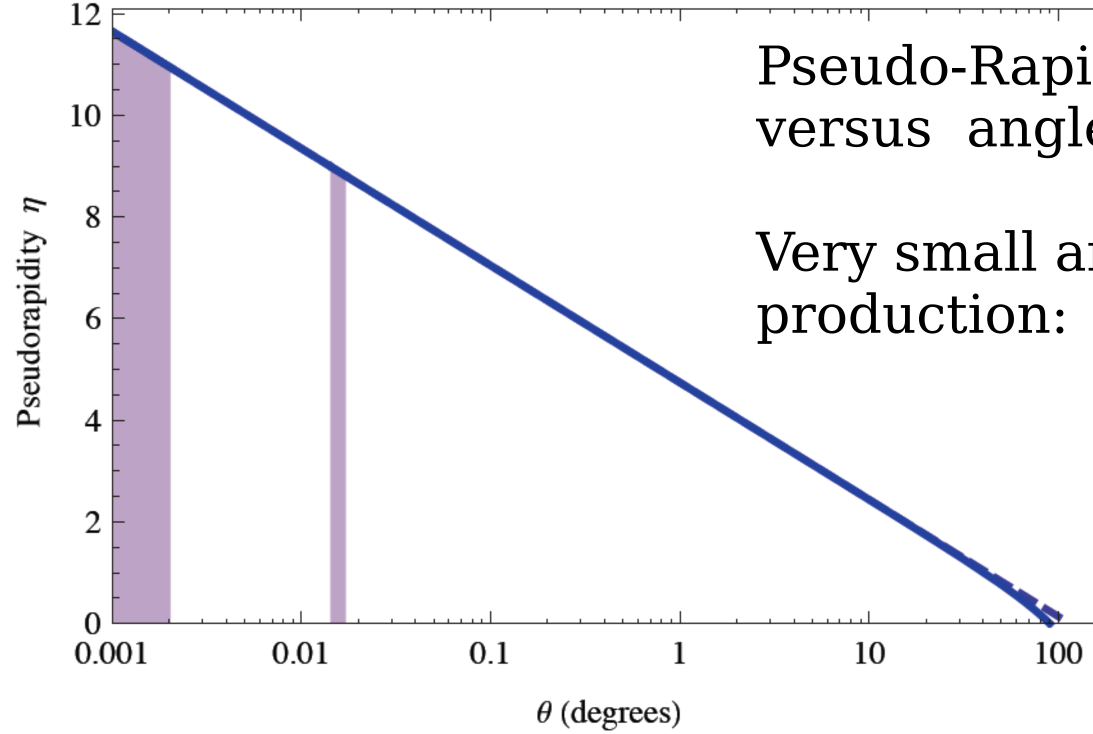
Position resolution:
- $< 200\ \mu$m (Arm#1)
- $40\ \mu$m (Arm#2)

Pseudo-rapidity range:
- $\eta > 8.7$ @ zero Xing angle
- $\eta > 8.4$ @ 140urad

Arm#2 Detector
25mmx25mm+32mmx32mm
4 X-Y Silicon strip tracking layers

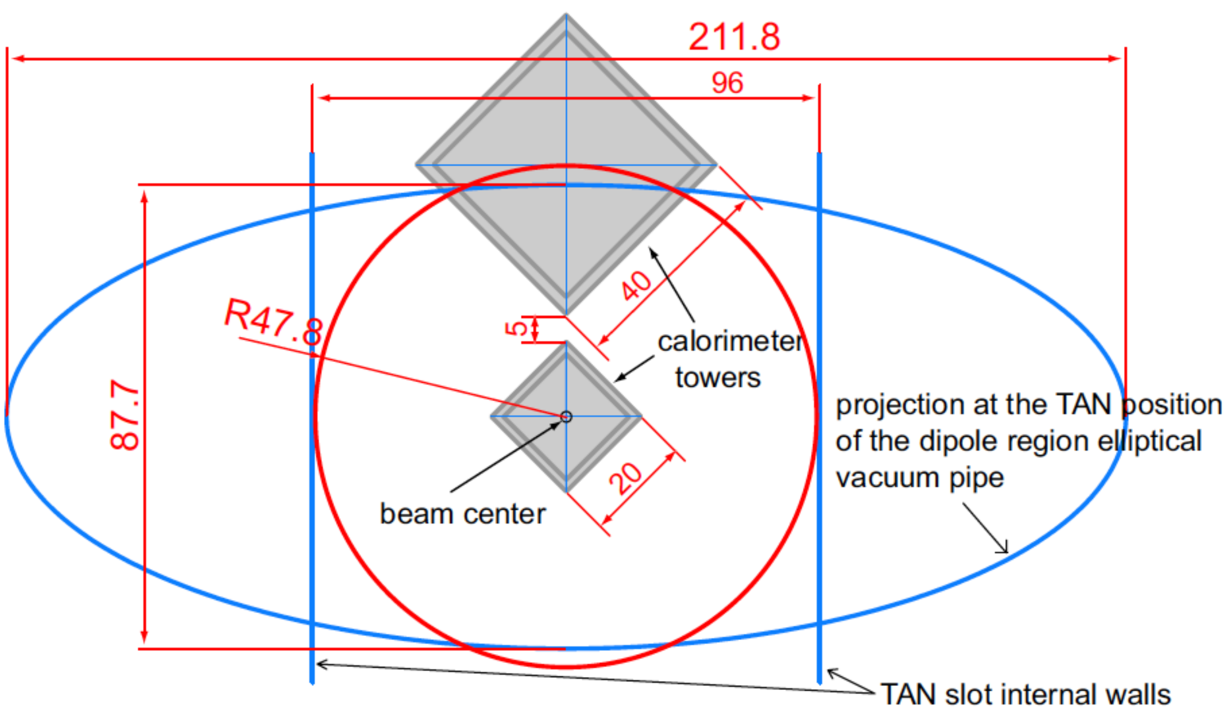
LHCF experiment

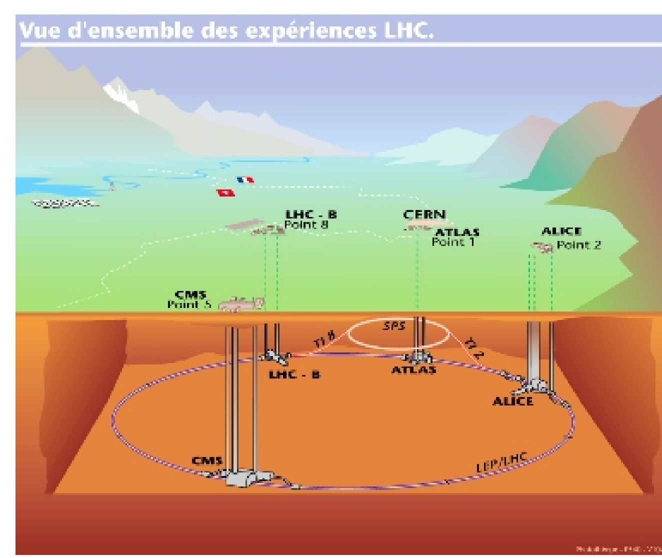




Pseudo-Rapidity versus angle:

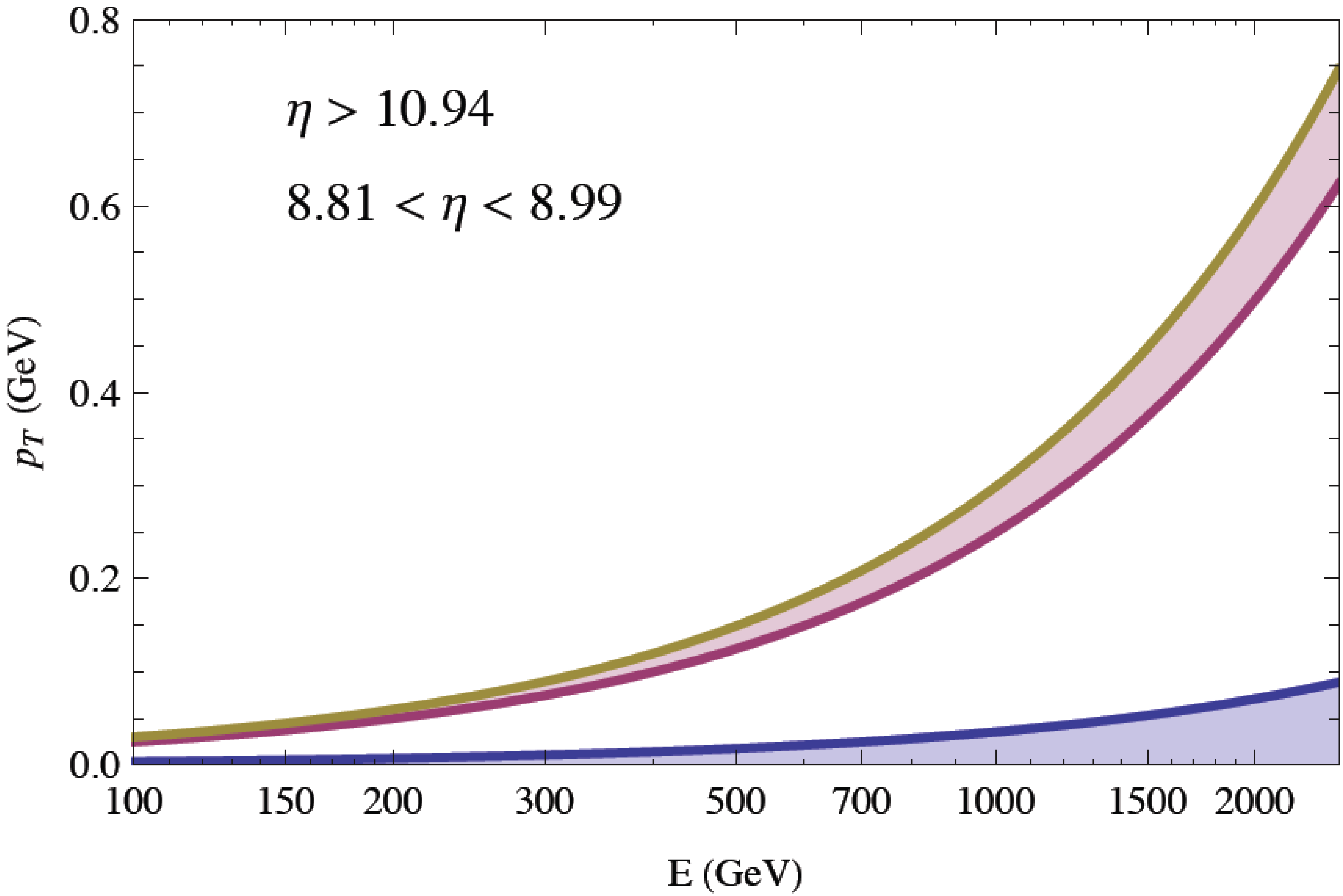
Very small angle production:





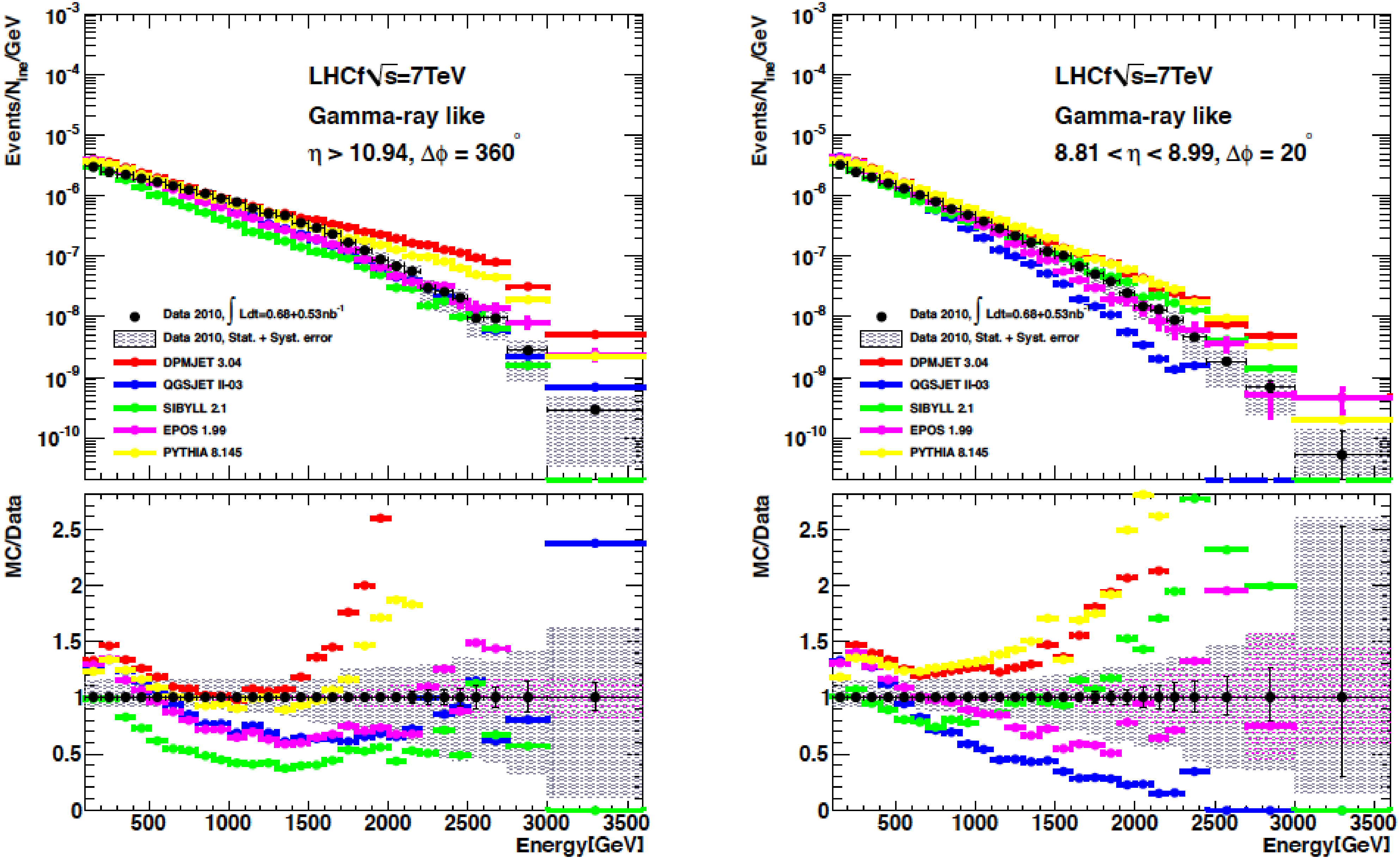
$$p_\perp = \sqrt{E^2 - m^2}\ \sin\left[2\ \tan^{-1}\left(e^{-\eta}\right)\right]$$

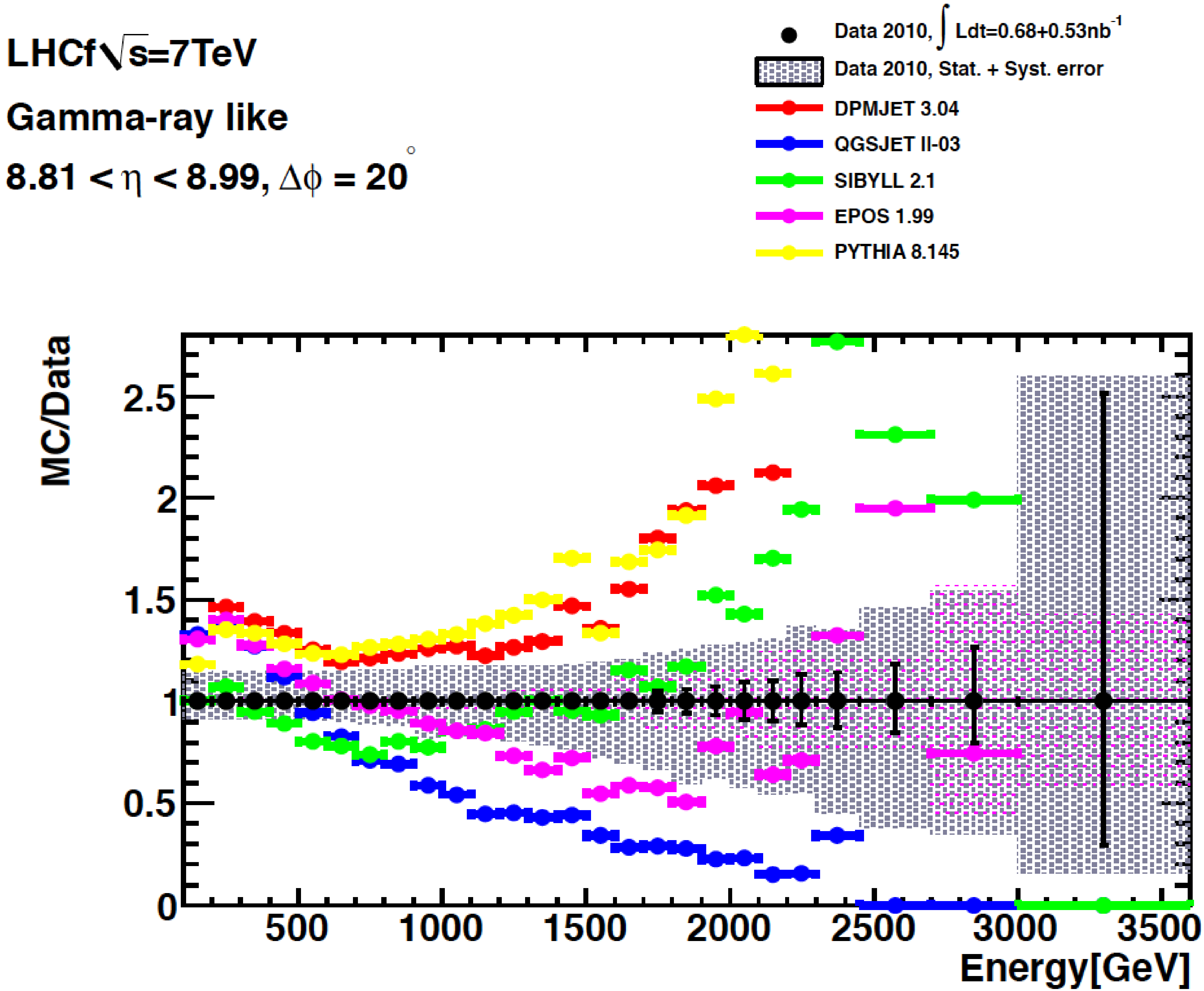
$$p_\perp \simeq p\ 2\ e^{-\eta}$$



LHCf data   hep-ex/1104.5294

[photon distributions in 2 very forward angular regions]





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

Cross sections Measurements

total, elastic

inelastic, diffractive

$$\sigma^{pp}_{\mathrm{tot}} = \sigma^{pp}_{\mathrm{el}} + \sigma^{pp}_{\mathrm{inel}}$$

$$\sigma_{\mathrm{inel}} = \sigma_{\mathrm{ND}} + \sigma_{SD} + \sigma_{DD}$$

Higher cross section

↕

Larger Multiplicity

More "complex" events

Theoretical understanding of these cross sections

[Relation with particle production properties (multiplicities, inclusive spectra, p_T, ...)]

Optical theorem
connects the total cross section to the imaginary part of the forward elastic scattering amplitude

$$p + p \rightarrow p + p$$

$$\frac{d\sigma_{\rm el}}{dt}(t,s) = \pi \; |F_{\rm el}(t,s)|^2$$

$$t = (p_i - p_f)^2$$

transfer momentum

$$F_{\rm el}(0,s) = \Im\left[F_{\rm el}(0,s)\right] \; (i+\rho)$$

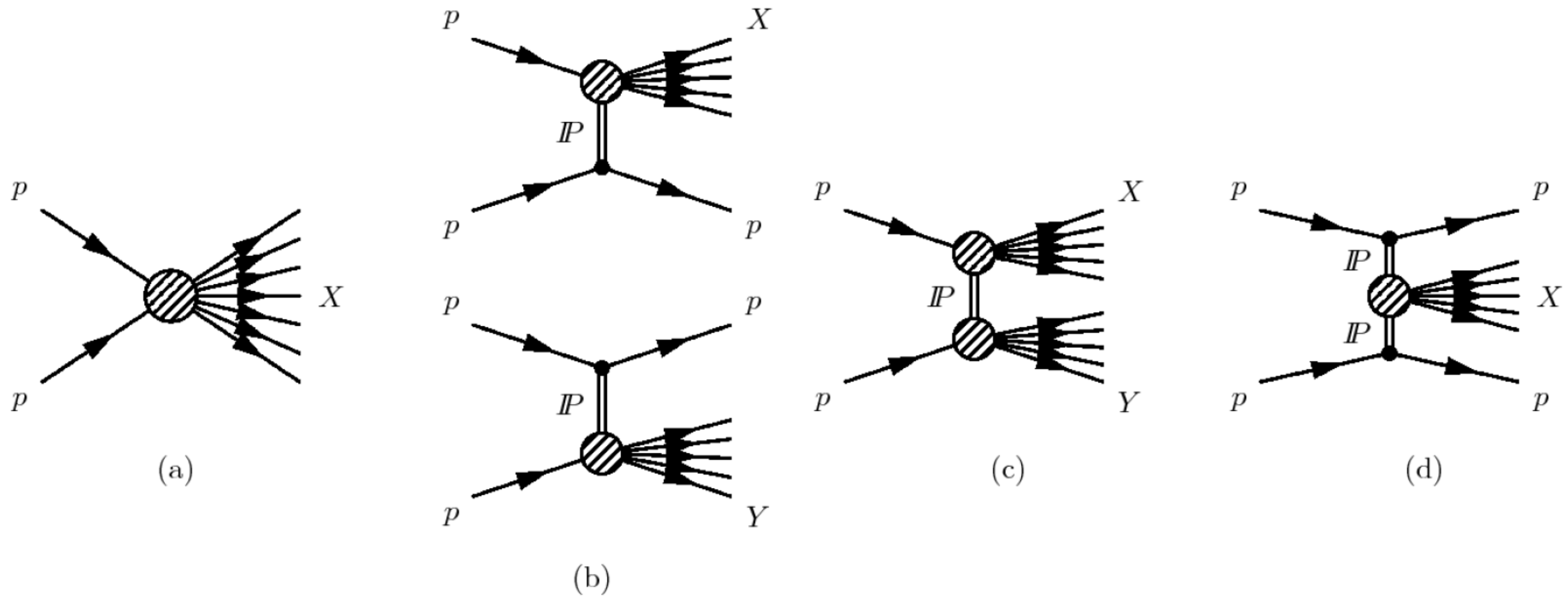
$$\sigma_{\rm tot}(s) = 4\,\pi\,\Im[F_{\rm el}(0,s)]$$

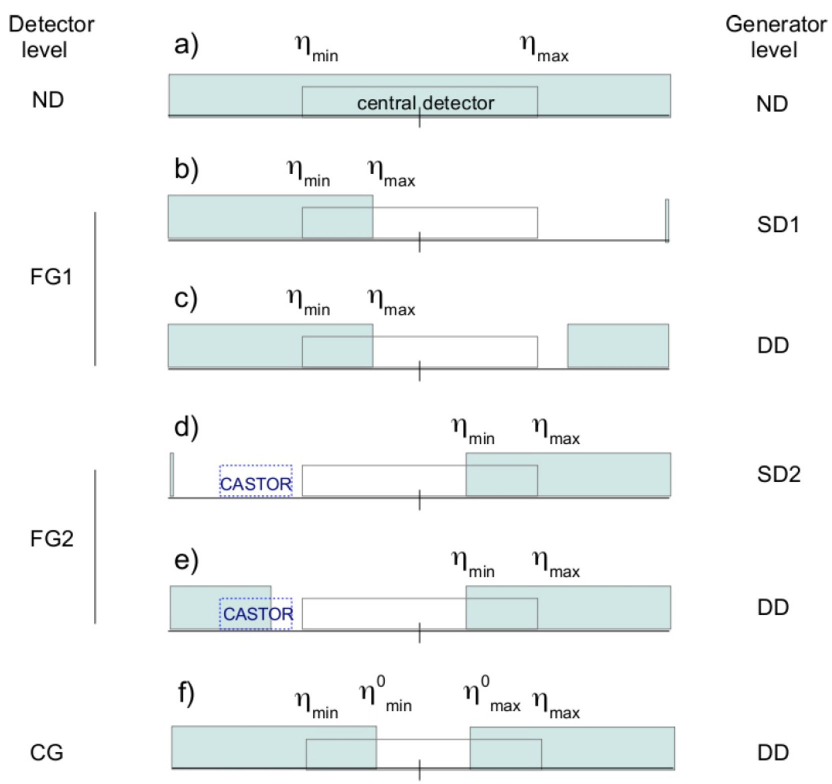
$$= \frac{4\sqrt{\pi}}{\sqrt{1+\rho^2}} \left[\left.\frac{d\sigma_{\rm el}}{dt}\right|_{t=0} \right]^{1/2}$$

Measurement of inelastic cross section
by counting all (minimum bias) events
[and measuring the luminosity in an independent way]

Problem: Correct for fraction of events
that do not trigger the detectors
[only particles in the very forward region]

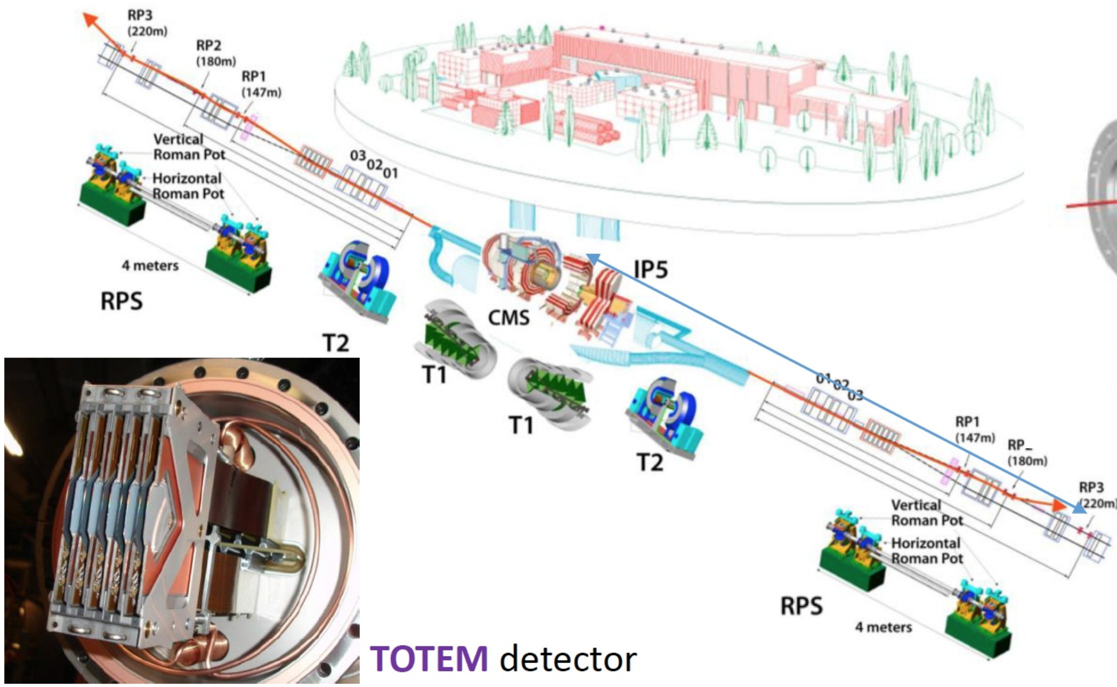
Question of diffractive [inelastic diffractive]
cross section


p
p
X
(a)
p
X
IP
p
p
p
p
IP
p
Y
(b)
p
X
IP
p
Y
(c)
p
p
IP
X
IP
p
p
(d)

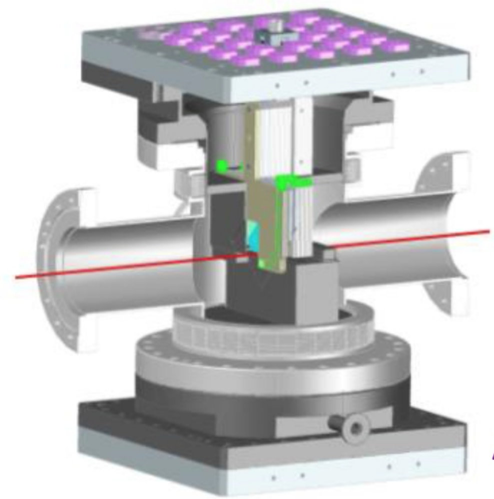

Detector level
Generator level
a) η min η max
ND
central detector
ND
b) η min η max
SD1
FG1
c) η min η max
DD
d) η min η max
CASTOR
SD2
FG2
e) η min η max
CASTOR
DD
f) η min η0 min η0 max η max
CG
DD

elastic differential rate

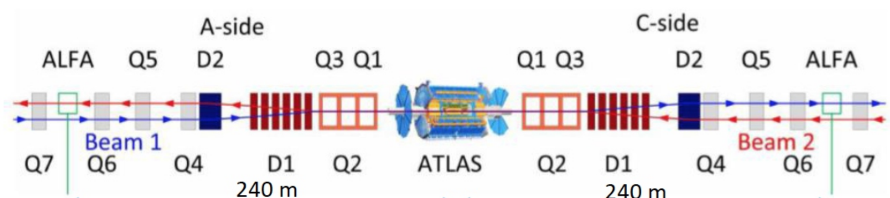
- to establish $\left(\frac{dN_{\mathrm{el}}}{dt}\right)_{t=0}$ we need to measure distribution covering very small angles
- appropriate accelerator optics: separation of elastically scattered protons from beam & beam halo, a small divergence of the beams at interaction point, monoenergetic beam, knowledge of the optics, knowledge of luminosity, …



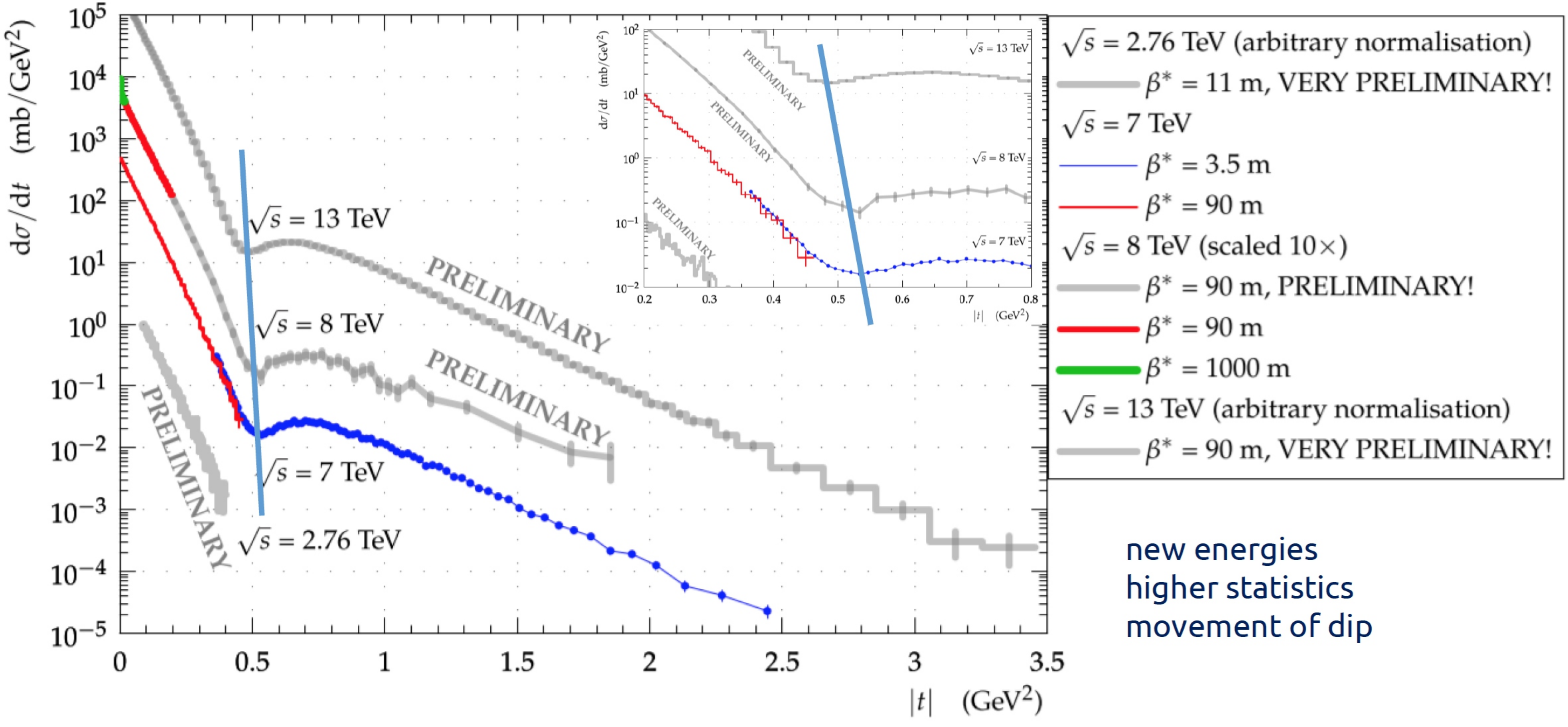
TOTEM detector



ALFA detector (left in Roman Pot)

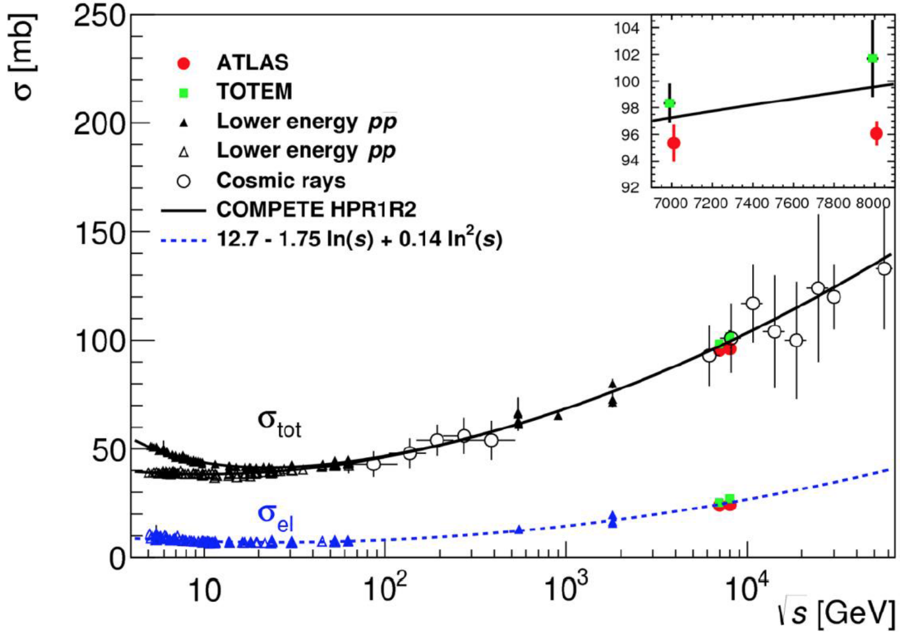


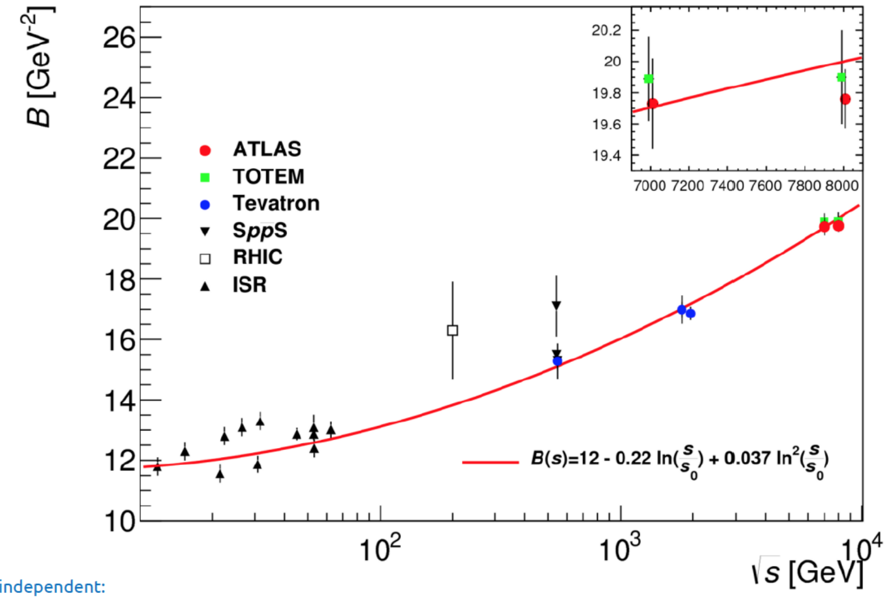
TOTEM further (preliminary) measurements



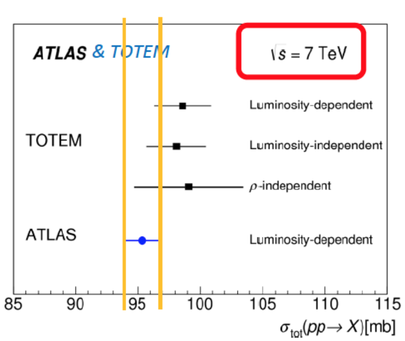
new energies
higher statistics
movement of dip

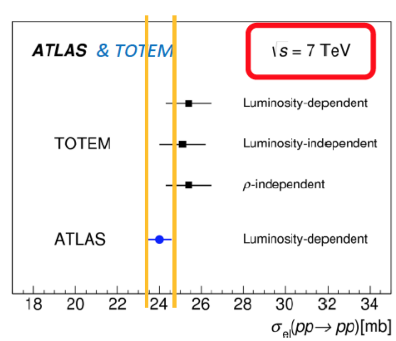
ATLAS ALFA vs earlier measurements





8 TeV
TOTEM lumi independent:
Phys. Rev. Lett. 111, 012001 (2013)
σ_{tot} = (101.7±2.9) mb
σ_{el} = (27.1±1.4) mb



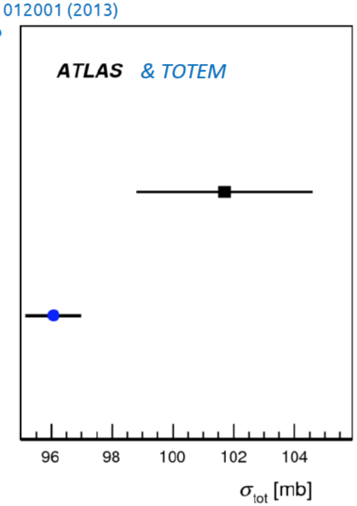


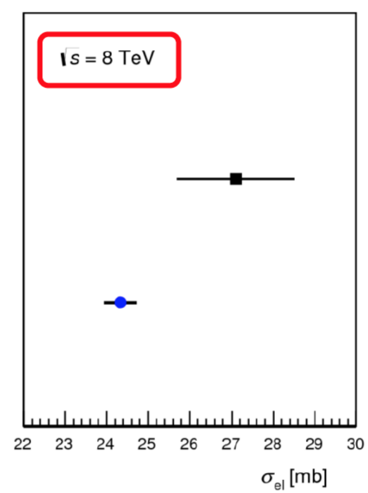
7 TeV
TOTEM lumi dependent:
σ_{tot} = (98.3 ± 2.8) mb EPL 96 (2011) 21002
σ_{tot} = (98.6 ± 2.2) mb EPL 101 (2011) 21002

TOTEM lumi independent
σ_{tot} = (98.0 ± 2.5) mb EPL 101(2013) 21004

TOTEM ρ independent:
σ_{tot} = (99.1 ± 4.3) mb EPL 101(2013) 21004

ATLAS lumi dependent:
Nuclear Physics, B (2014) 889
σ_{tot} = (95.35 ± 1.36) mb
σ_{el} = (95.35 ± 0.6) mb



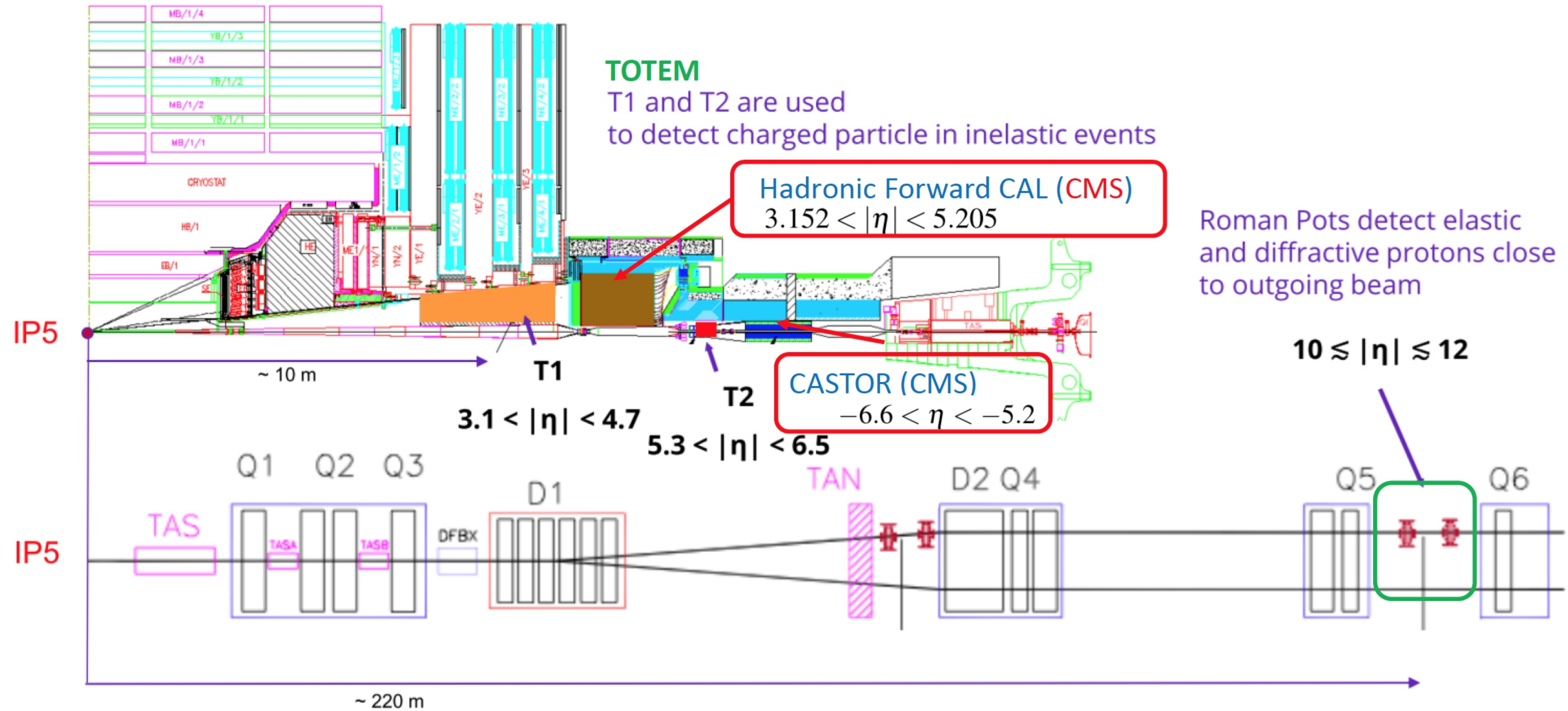


TOTEM
sl. 12 more measurements

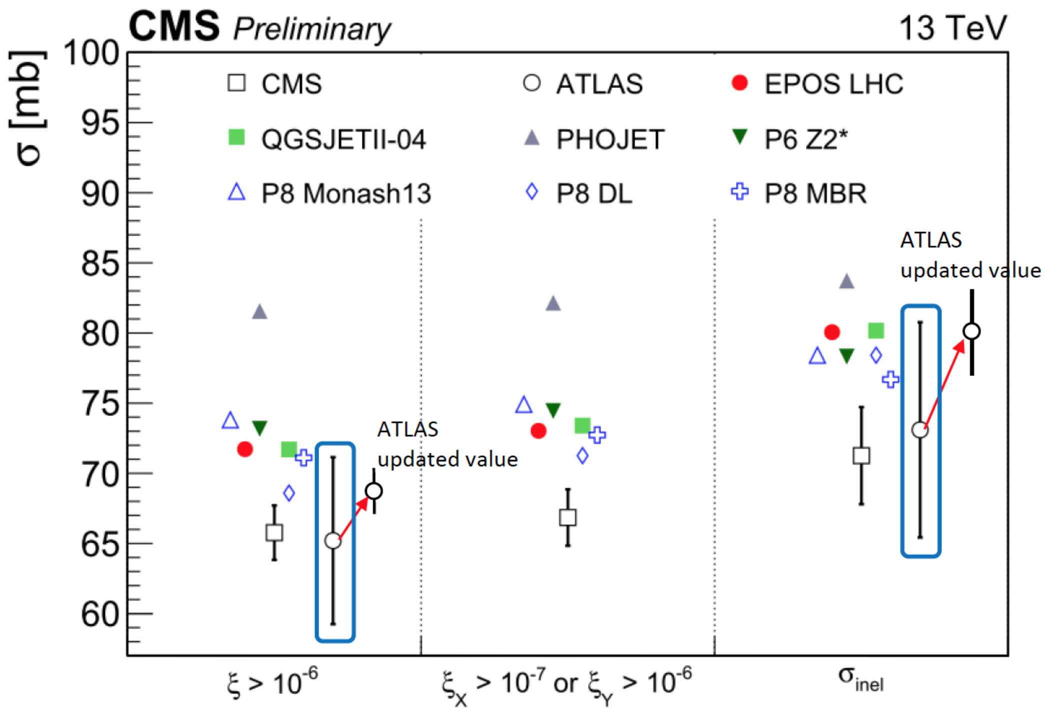
ATLAS

CMS – forward detectors and σ_{inel} at 13 TeV

CMS-PAS-FSQ-15-005



CMS – σ_{inel} at 13 TeV



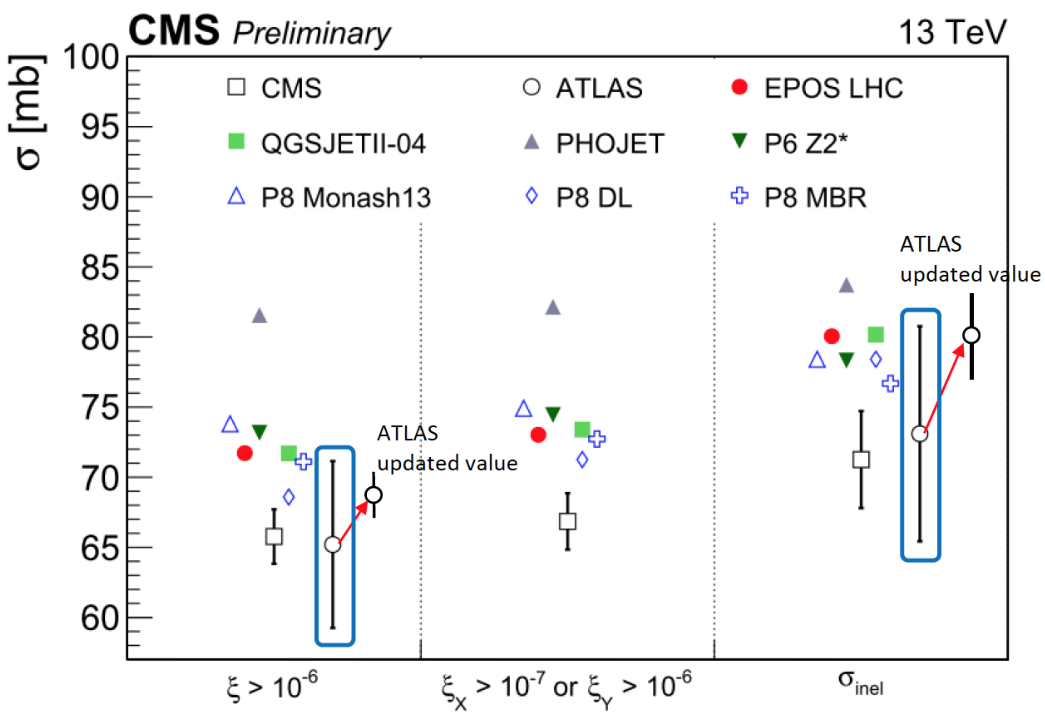
$$\sigma\left(\xi > 10^{-6}\right) = 65.8 \pm 0.8\ (\text{exp.}) \pm 1.8\ (\text{lum.})\ \text{mb}$$

$$\sigma\left(\xi_X > 10^{-7}\ \text{or}\ \xi_Y > 10^{-6}\right) = 66.9 \pm 0.4\ (\text{exp.}) \pm 2.0\ (\text{lum.})\ \text{mb}$$

$$\sigma_{\text{inel}} = 71.3 \pm 0.5\ (\text{exp.}) \pm 2.1\ (\text{lum.}) \pm 2.7\ (\text{ext.})\ \text{mb}$$

measured cross section is significantly lower than predicted by models for hadronic scattering and ATLAS

CMS – σ_{inel} at 13 TeV



$$\sigma\left(\xi > 10^{-6}\right) = 65.8 \pm 0.8\ (\text{exp.}) \pm 1.8\ (\text{lum.})\ \text{mb}$$

$$\sigma\left(\xi_X > 10^{-7}\ \text{or}\ \xi_Y > 10^{-6}\right) = 66.9 \pm 0.4\ (\text{exp.}) \pm 2.0\ (\text{lum.})\ \text{mb}$$

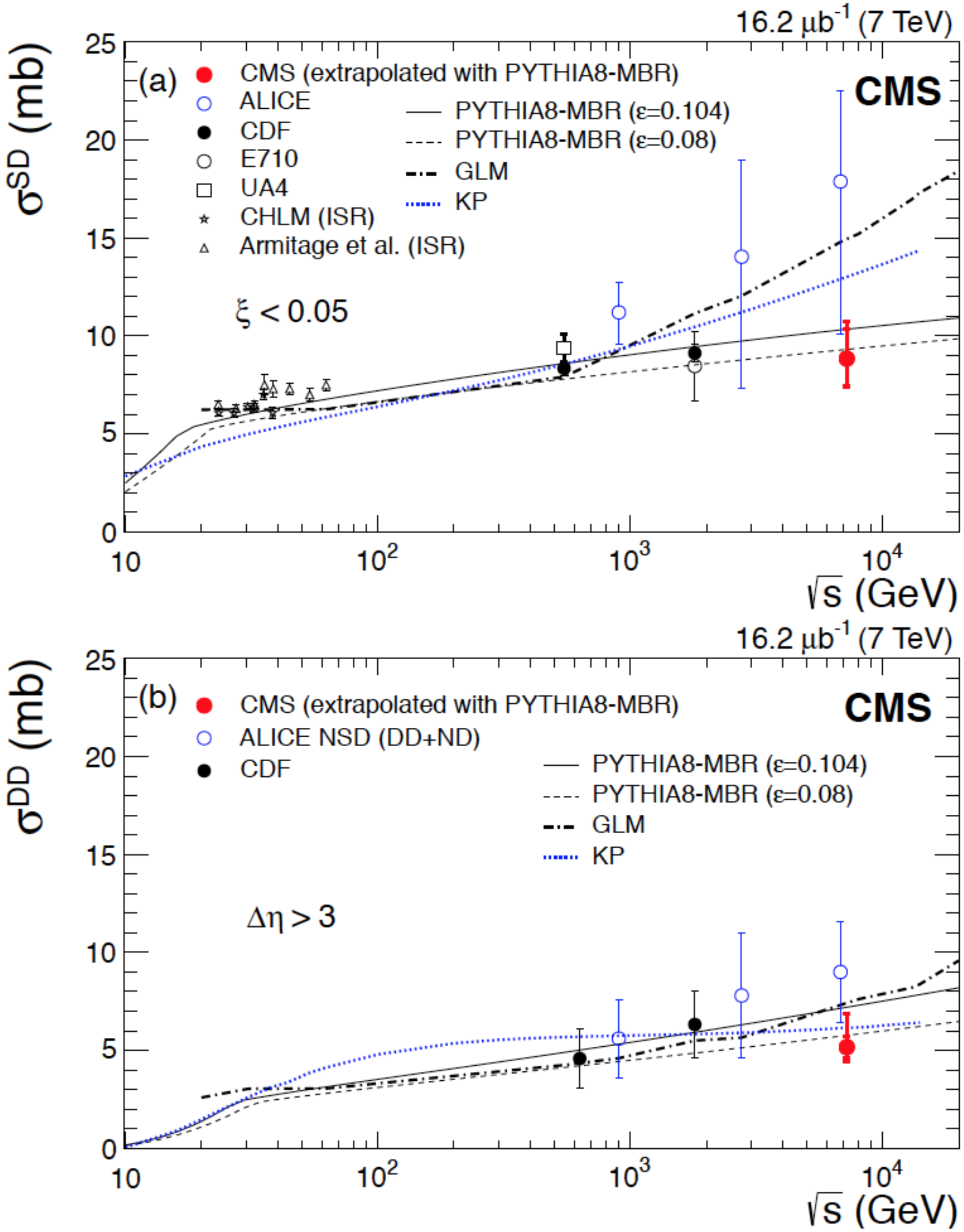
$$\sigma_{\text{inel}} = 71.3 \pm 0.5\ (\text{exp.}) \pm 2.1\ (\text{lum.}) \pm 2.7\ (\text{ext.})\ \text{mb}$$

measured cross section is significantly lower than predicted by models for hadronic scattering and ATLAS

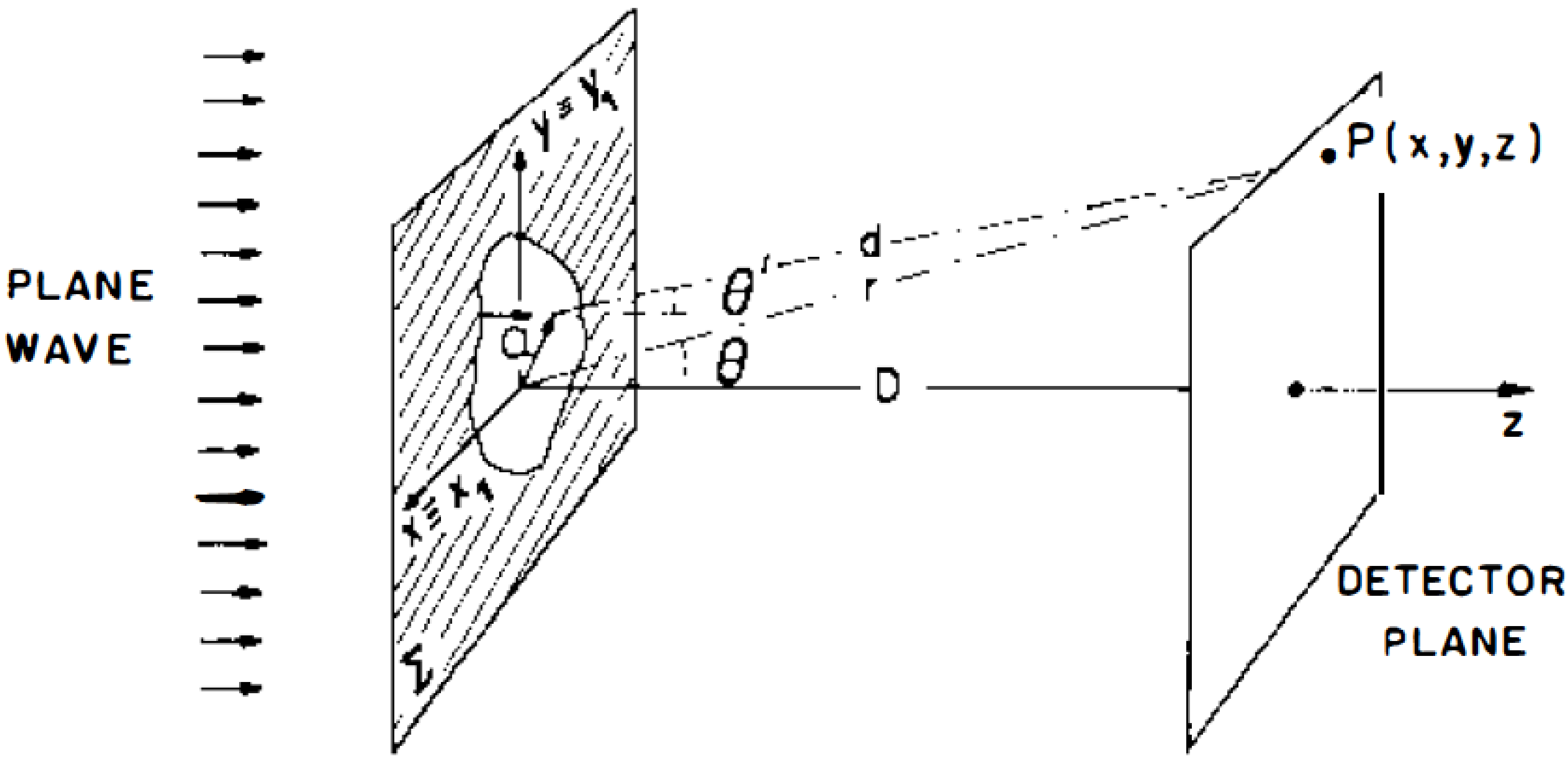
Measurements of the Diffractive cross sections

ALICE

CMS

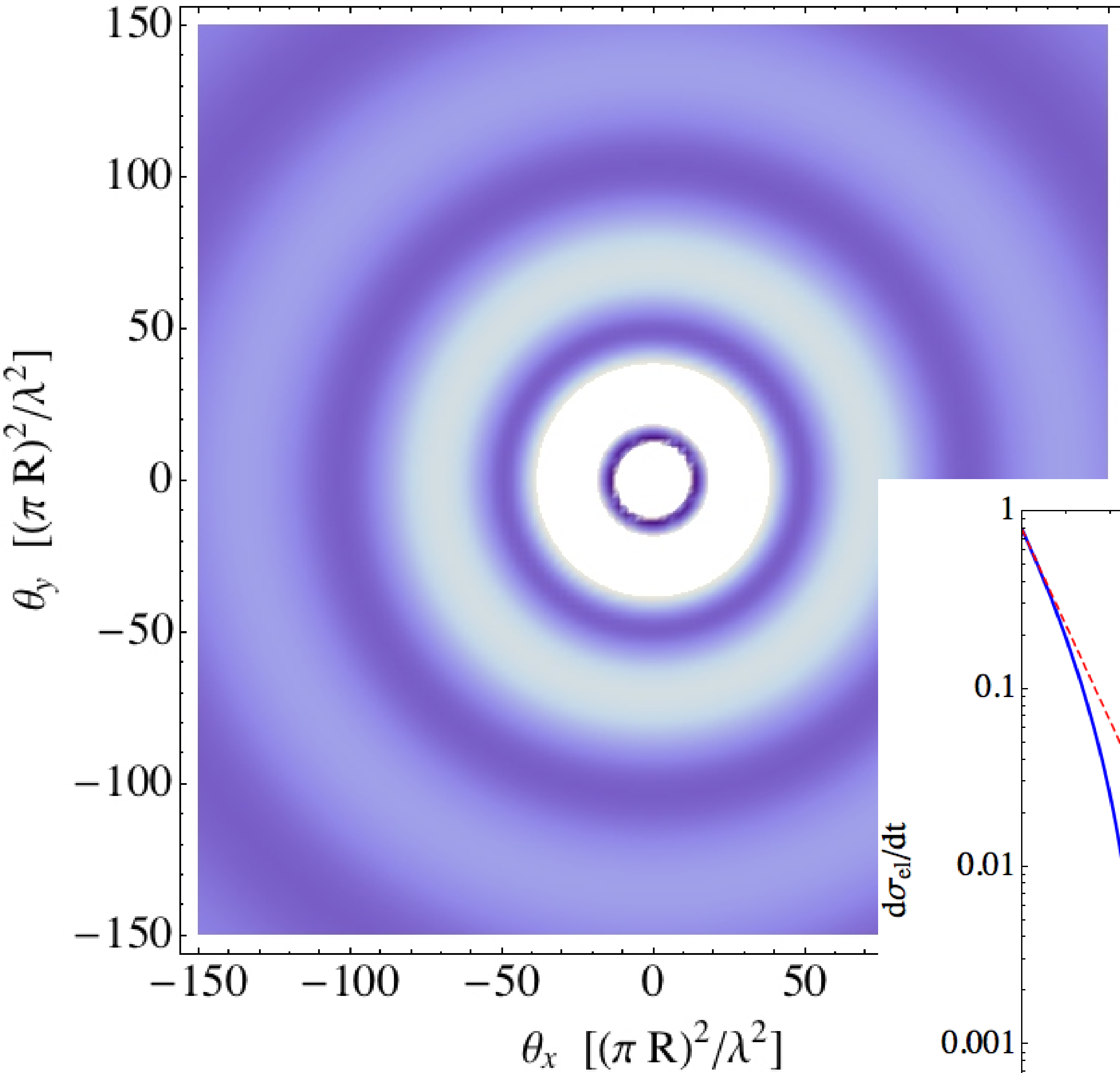


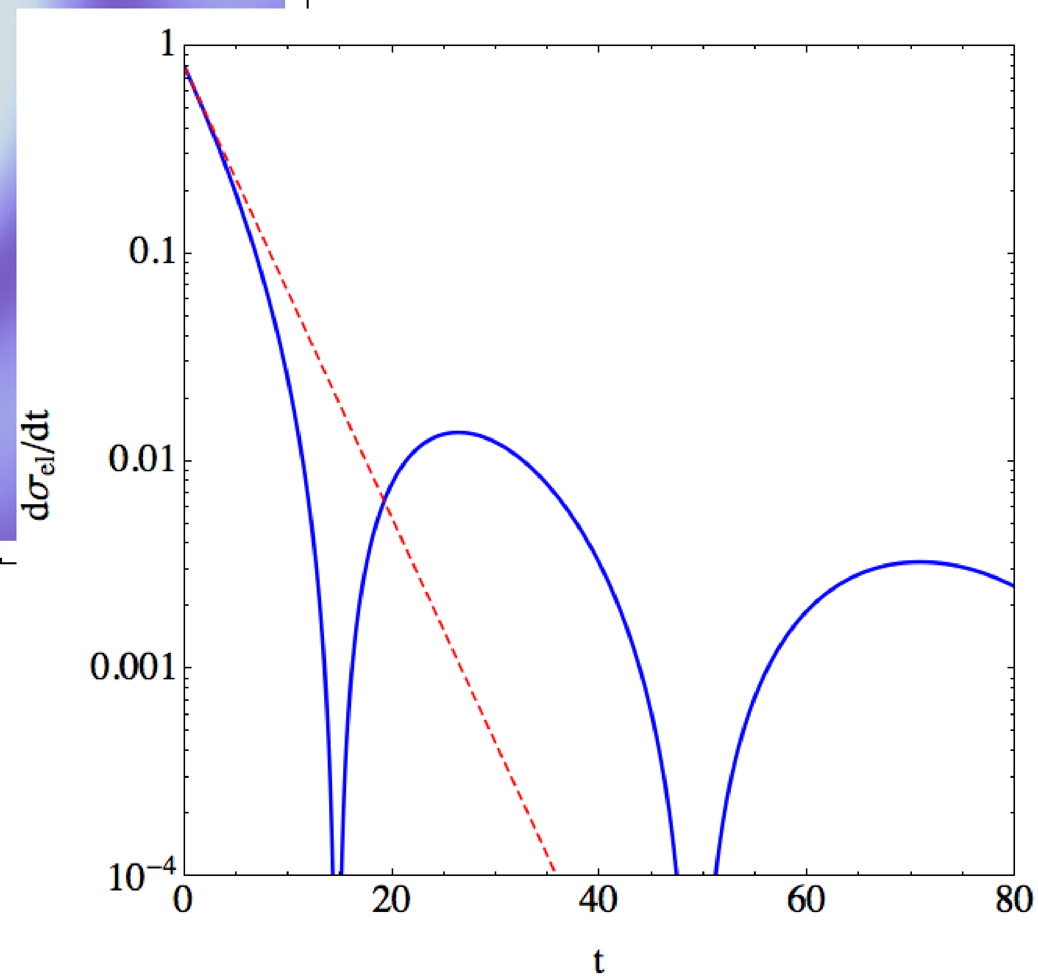
The OPTICAL ANALOGY.



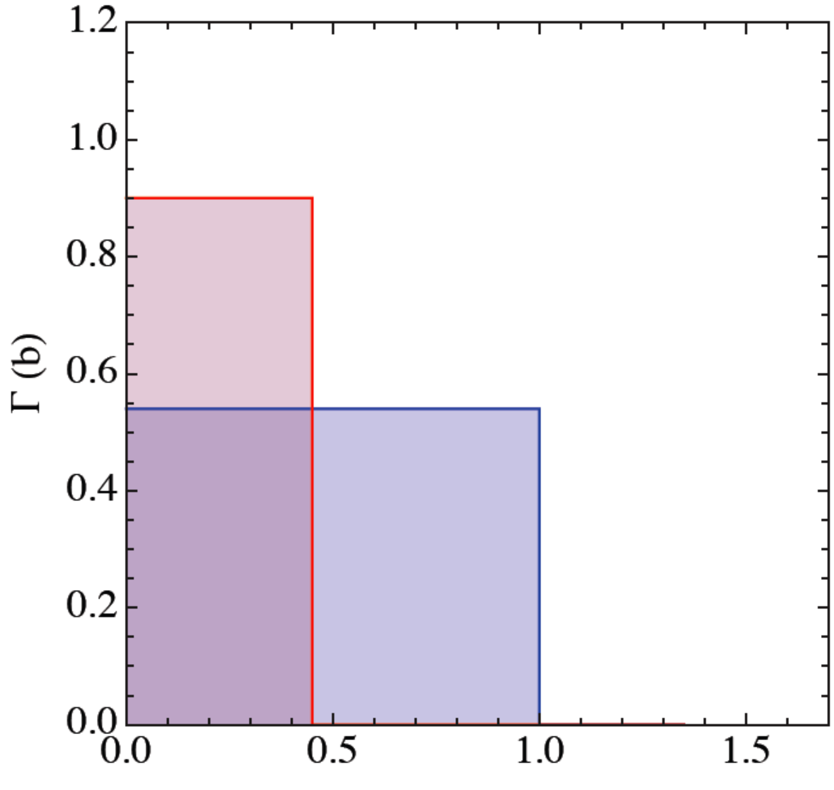
Relation between Absorption and Scattering of light from a (partially) absorbing screen.

Diffractive scattering of light from a black absorbing disk of radius R

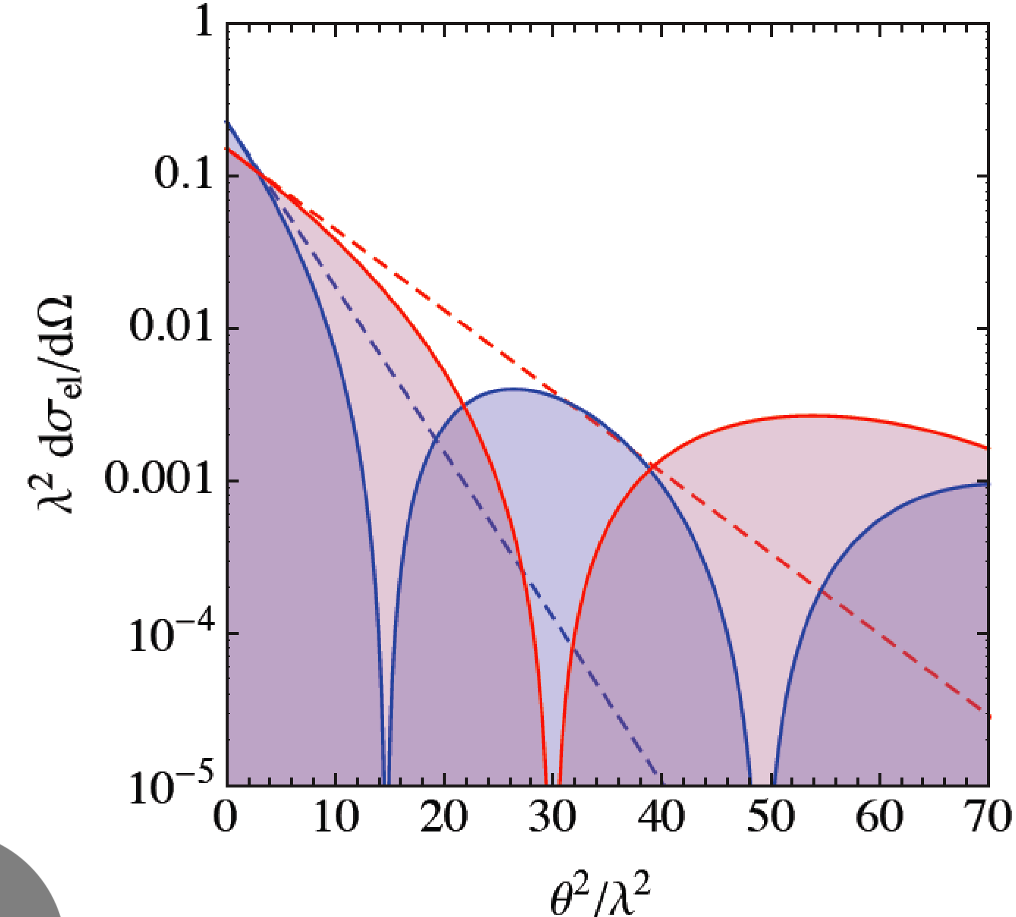




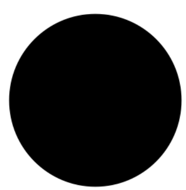
Absorbing profile

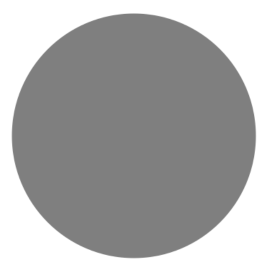


Elastic Scattering (wave diffraction)



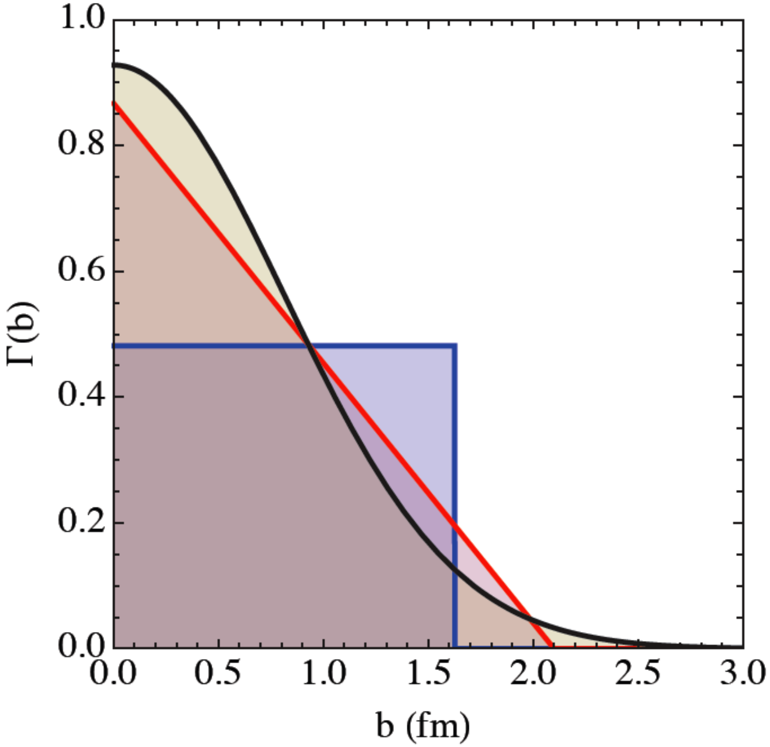
$$\theta \to 0$$

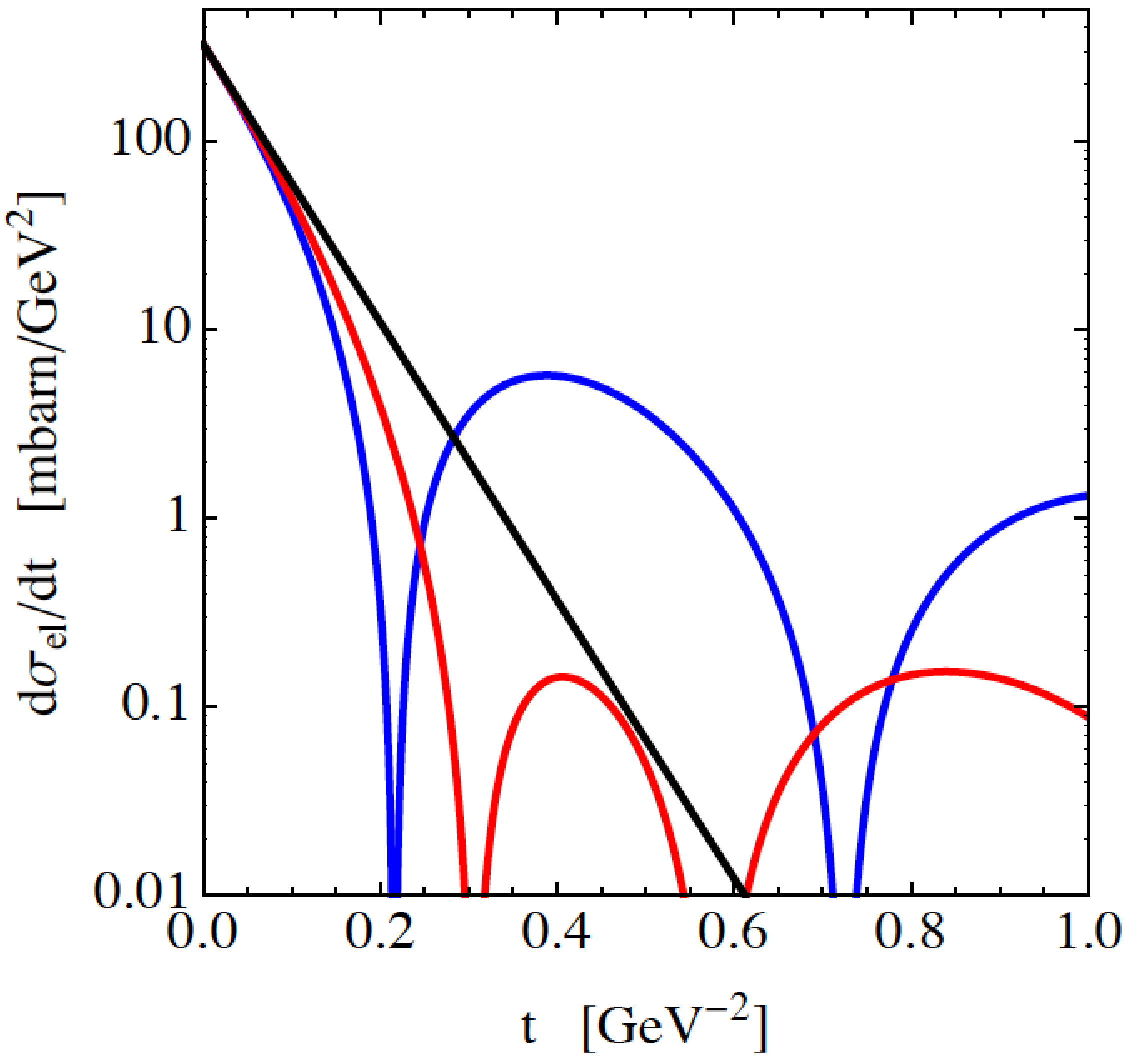




$$\frac{d\sigma}{d\Omega} \propto \quad \exp\left[-B_\theta\ \theta^2\right]$$

$$B_\theta = \frac{R^2 \pi^2}{\lambda^2}$$

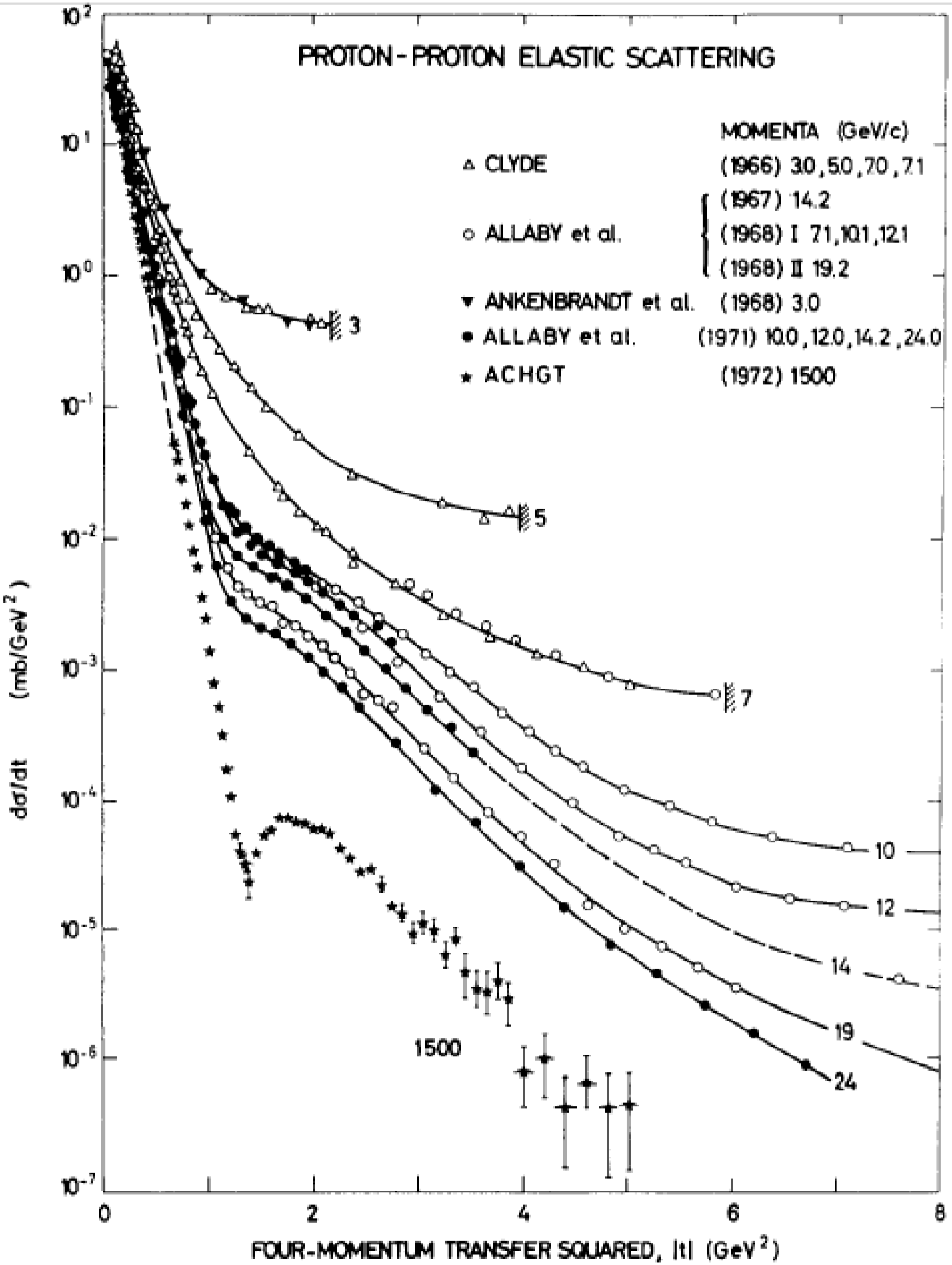


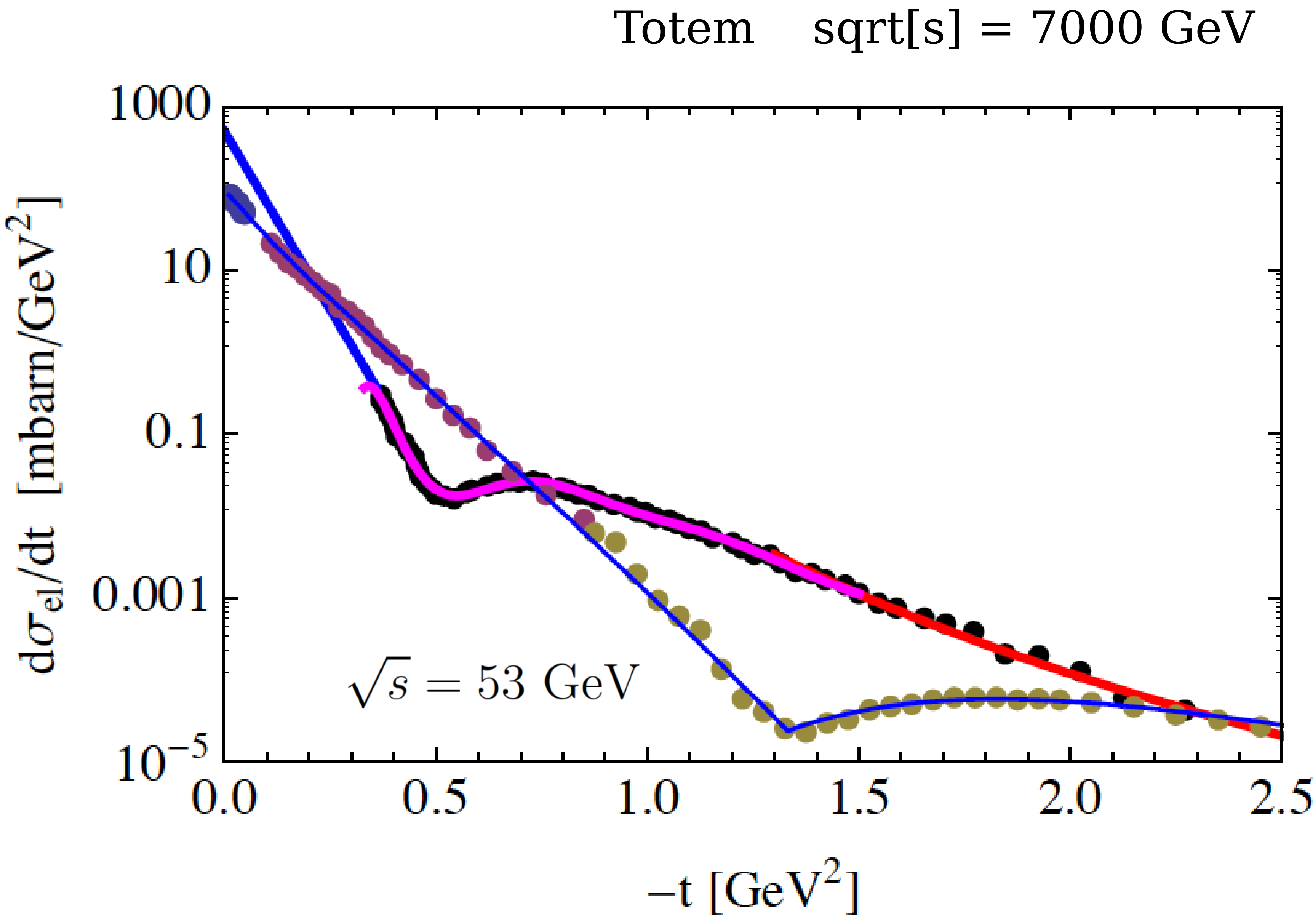


$$|t| \to 0$$

$$\frac{d\sigma}{dt} \propto \exp\left[-B\ |t|\right]$$

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


PROTON-PROTON ELASTIC SCATTERING
MOMENTA (GeV/c)
△ CLYDE (1966) 3.0, 5.0, 7.0, 7.1
○ ALLABY et al. (1967) 14.2
(1968) I 7.1, 10.1, 12.1
(1968) II 19.2
▼ ANKENBRANDT et al. (1968) 3.0
● ALLABY et al. (1971) 10.0, 12.0, 14.2, 24.0
★ ACHGT (1972) 1500
3
5
7
10
12
14
19
24
1500
dσ/dt (mb/GeV²)
FOUR-MOMENTUM TRANSFER SQUARED, |t| (GeV²)



Totem sqrt[s] = 7000 GeV
1000
10
0.1
0.001
10^{-5}
0.0
0.5
1.0
1.5
2.0
2.5
$d\sigma_{el}/dt$ [mbarn/GeV^2]
$-t$ [GeV^2]
$\sqrt{s} = 53$ GeV

Elastic Scattering Amplitude :

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

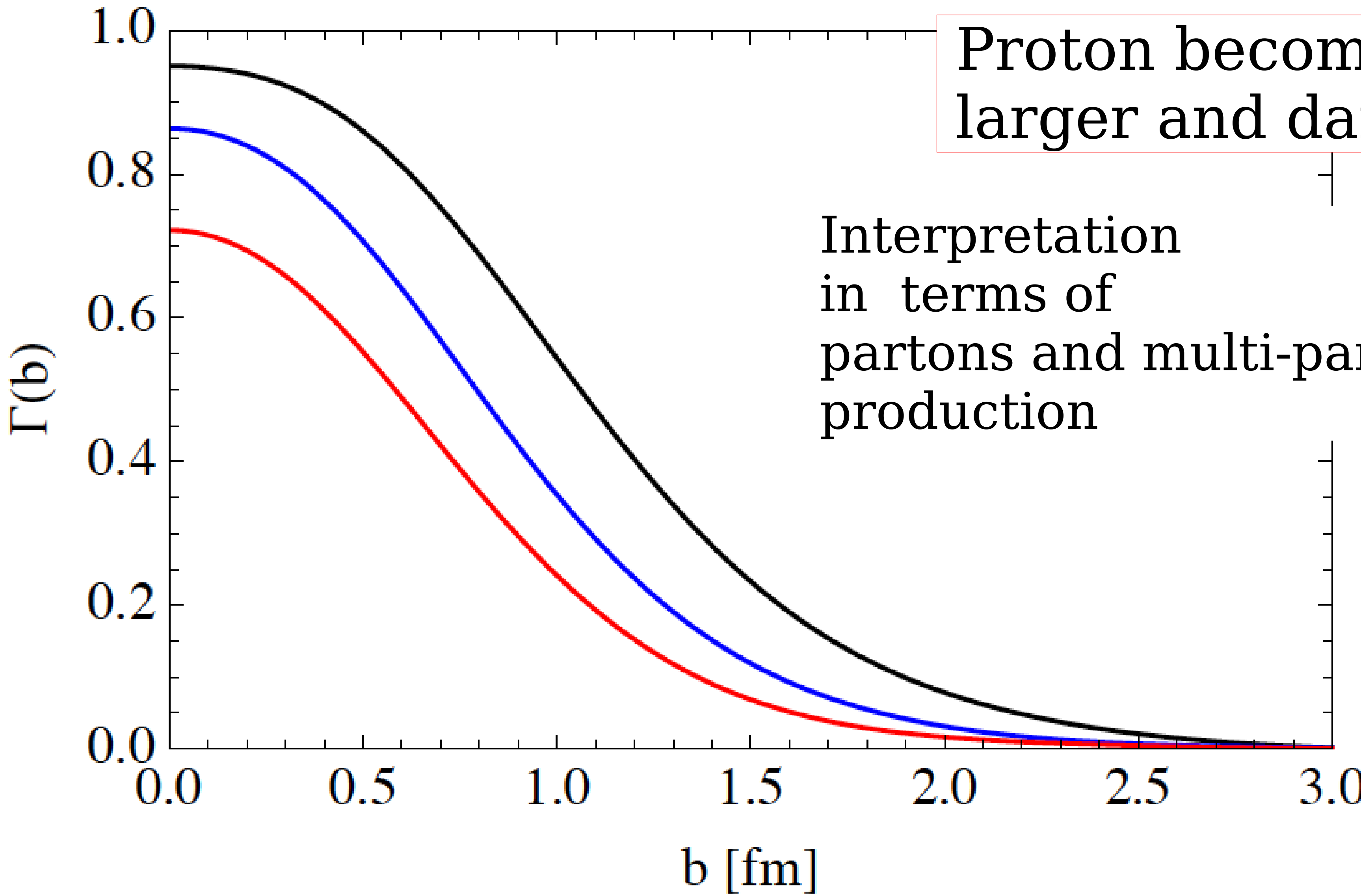
$$F_{\text{el}}(q, s) = i \int \frac{d^2b}{2\pi} e^{i\vec{q}.\vec{b}} \Gamma_{\text{el}}(b, s)$$

PROFILE Function

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

EIKONAL Function

Profile functions at $\sqrt{s} = 53,\ 546,\ 7000\ \mathrm{GeV}$
extracted from the elastic cross section
(assuming purely imaginary amplitude)



Proton becoming larger and darker

Interpretation in terms of partons and multi-particle production

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

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

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

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

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

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

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

Interaction Probability

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

"Interpretation" of the eikonal function

Multiple interactions

$$\hat{s} = s\, x_1\, x_2$$

(c.m. energy)^2
of parton-parton system

$$Q^2 \leq \frac{\hat{s}}{2}$$

Interacting Partons

$$x_1 \; x_2 \gtrsim \frac{(\Lambda_{\mathrm{QCD}})^2}{s}$$ all

$$x_1 \; x_2 \gtrsim \frac{Q^2_{\mathrm{min}}}{s}$$ hard

Increasing the
c.m. Energy:

More parton-parton
Interactions!

pp cross section grows
Higher multiplicity.
More complex event.
Softer energy spectra.

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

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

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

Cross section for "elementary interactions"

Perturbative calculation of parton-parton scattering

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

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

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

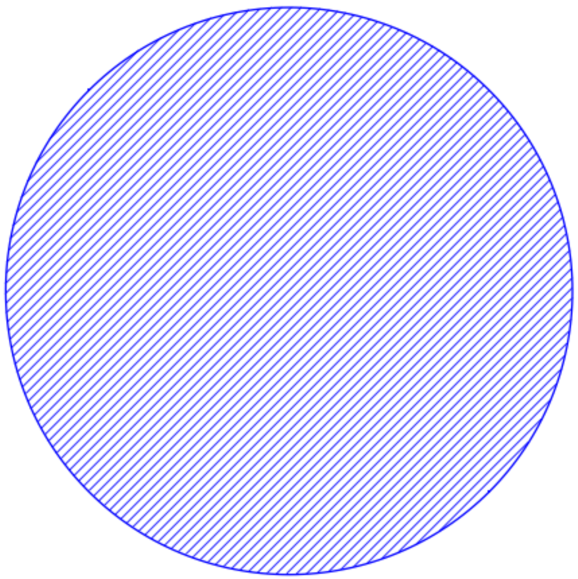
$$\sigma_{\text{jet}} \to \infty$$

Infrared Divergence !!
(complete failure of perturbation theory)

Attempts to "resum" the soft part.

“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)

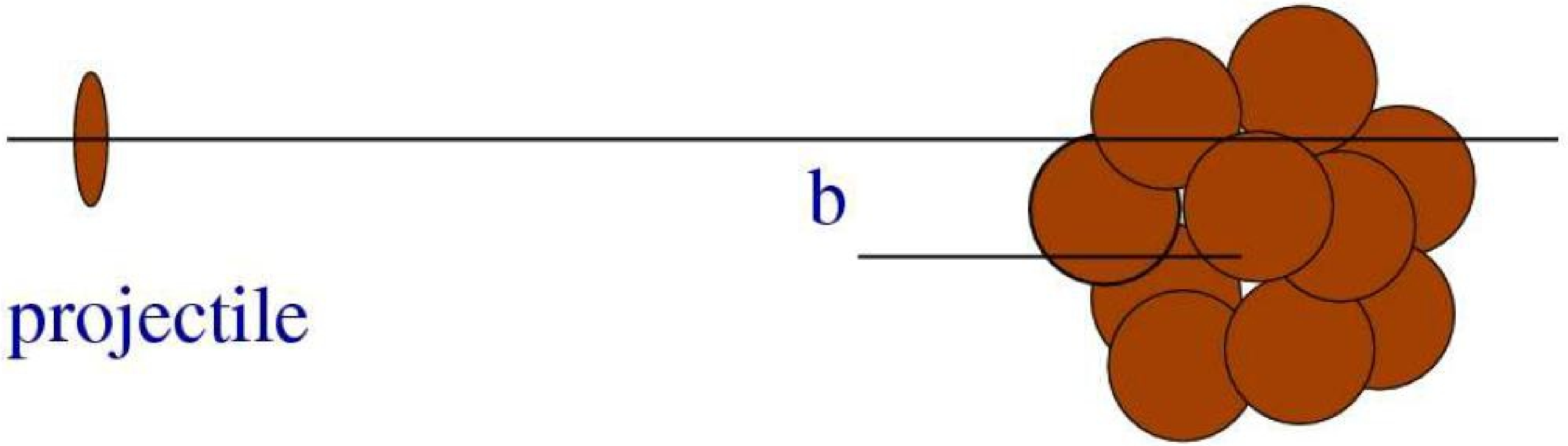
2 orthonormal basis
In Hilbert space

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

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

From pp to pA (and viceversa)

is Glauber formalism adequate?



The following slides show results of ongoing study, to be published as journal article

Air Shower Physics at the LHC: On the Importance of Measuring Proton Interactions with Light Nuclei

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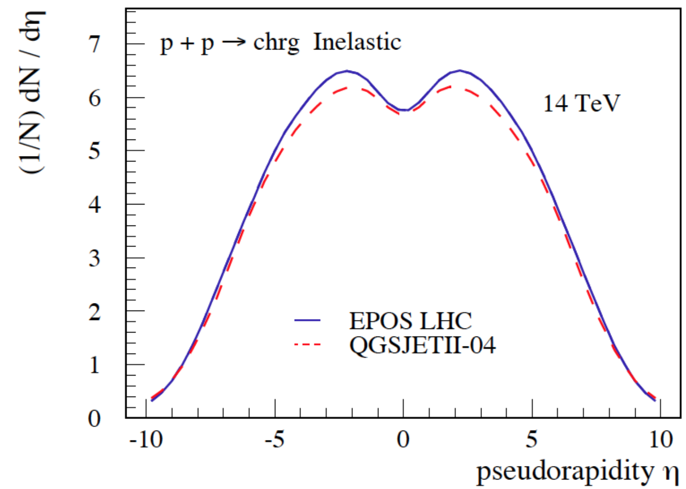
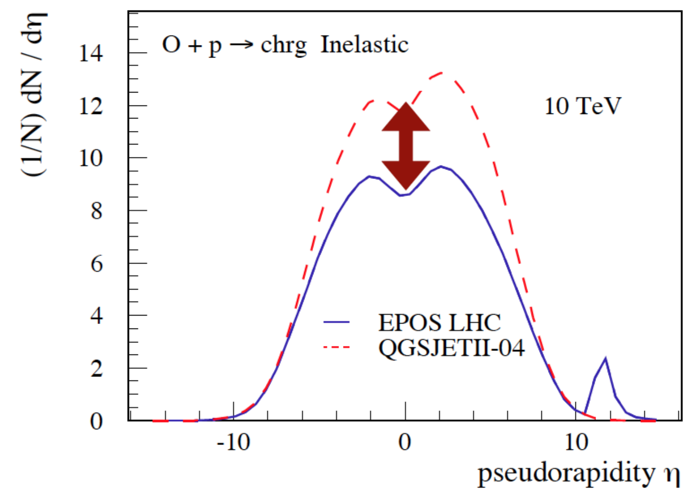
April 2014

Abstract

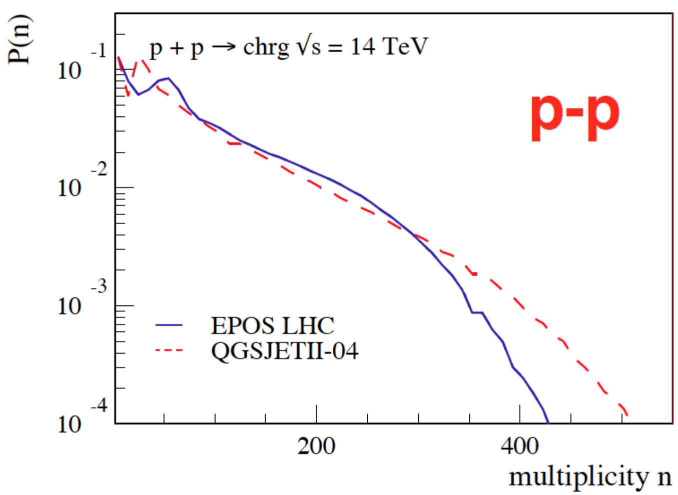
The properties of cosmic rays of energies higher than 10^{15} eV can only be studied indirectly by observing the particle cascades they produce in the Earth's atmosphere. The detailed modeling of particle production in high-energy interactions is one of the key ingredients for predicting the characteristics of these air showers and relating them to the mass and energy of the primary particle. Measurements at LHC have allowed us to obtain, for the first time, direct data on hadronic interactions at equivalent air shower energies as high $10^{16.5}$ eV. The study of of p-p, p-Pb, and Pb-Pb interactions has considerably improved our knowledge of multi-particle processes of direct relevance to air shower physics. At the same time, there are still important uncertainties in predicting air shower properties that could be reduced significantly by measuring directly p-N or p-O interactions at LHC. In this article we discuss the progress made in air shower simulations due to LHC measurements made so far and show examples where the measurement of proton interactions with light nuclei will be of decisive importance to understand cosmic ray data.

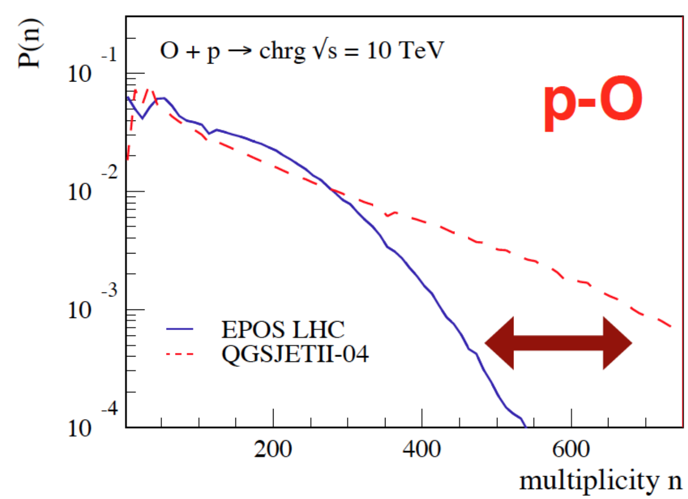
Outlook: further improvement due to p-O collisions at LHC





Currently predicted uncertainty in most optimistic case





p-O technically feasible (O used as ion for Pb)

Light Ions in the LHC?

Of interest for cosmic ray studies would be collisions of light nuclei

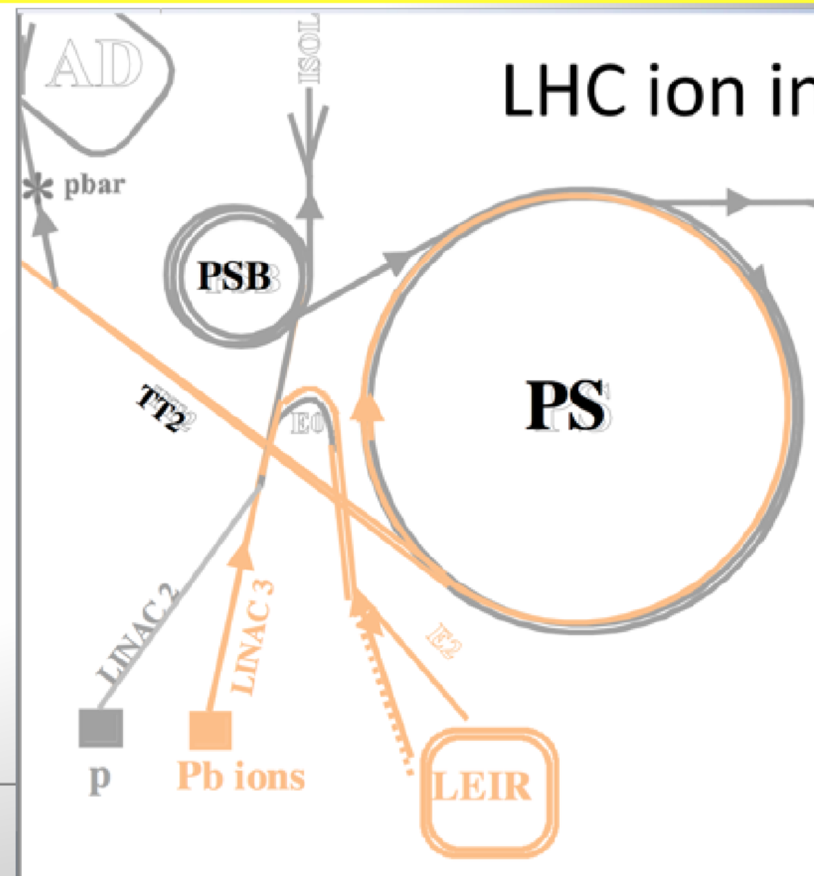
→Initial study at the LHC by D. Mangluki in 2012. Still preliminary results and an in depth study is required. See: https://indico.cern.ch/event/223562

Main conclusions:

- CERN can provide light nucleon beams for the LHC
- Collisions can be pA, AA, and AB

ECR source

- The source can "deliver anything", however…
  - It takes time to commission the whole chain with new species (16 weeks minimum for LEIR/PS/SPS)
  - Switching between two species within one year is difficult (~ 4 weeks to switch ECR for completely different species) -> competition with Pb-Pb and p-Pb in LHC, and primary ions in North Area (Ar, Xe, Pb)
- Oxygen is support gas for Pb
  - One can imagine running O for a short period within Pb year
    - Opens possibility for O-O and p-O
- Other ion mixtures
  - N + O , S + O "Easy"
  - MIVOC (Metal Ions from Volatile Compounds) for Fe…



In cosmic rays is also very relevant
the value of the pion-nucleon (and kaon-nucleon) cross sections.

$$\log^2(s/s_0)$$

Universal coefficient
Asymptotically all cross sections become equal.

$$\sigma^{as}_{\pi N} > \sigma^{as}_{NN}$$

2. K. Igi and M. Ishida, Phys. Rev. **D66**, 034023 (2002),
Phys. Lett. **B622**, 286 (2005).

$$\sigma^{as}_{\pi N} \sim 2/3\sigma^{as}_{NN}$$

3. M. M. Block and F. Halzen, Phys. Rev. **D70**, 091901 (2004),
Phys. Rev. **D72**, 036006 (2005).

Meson Cross Sections

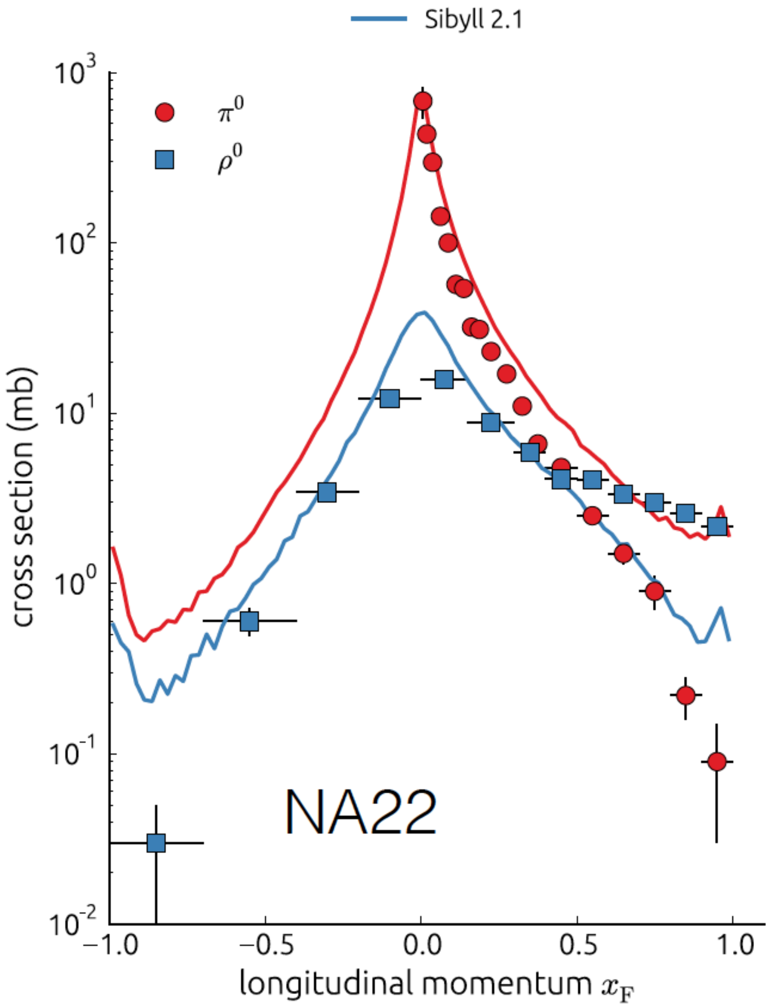
$$\sigma_{pp} \qquad \sigma_{\pi p} \qquad \sigma_{Kp}$$

$$\lim_{s \to \infty} \frac{\sigma_{\pi p}(s)}{\sigma_{pp}(s)} = 1$$

Several models
(including PDG fit)

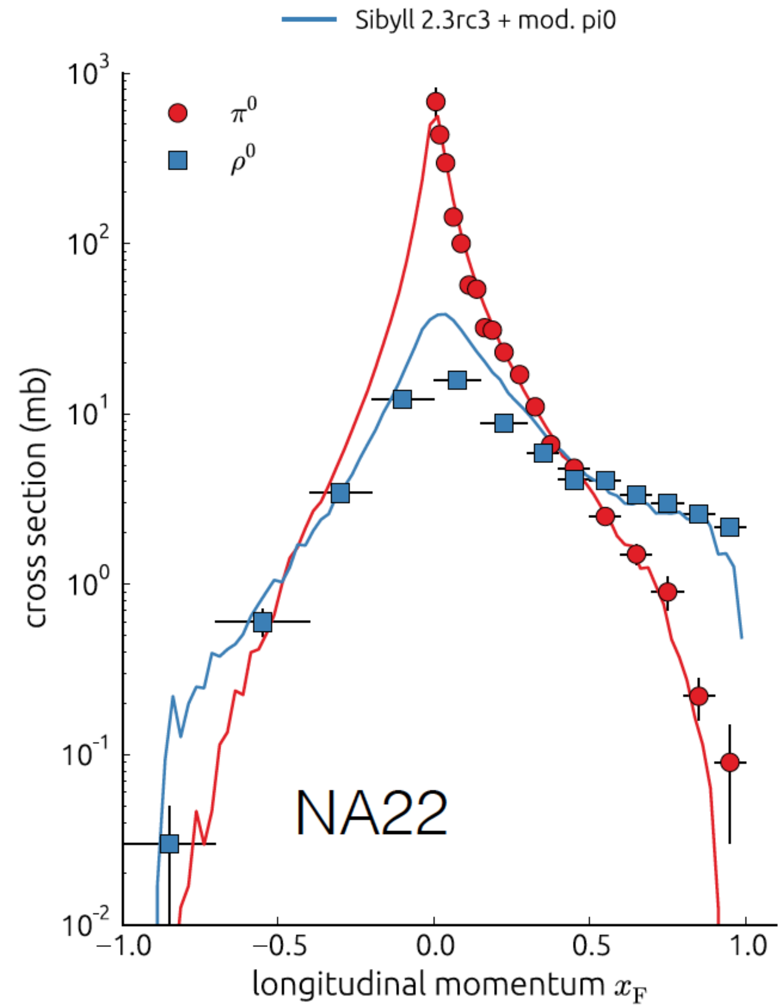
$$\frac{\sigma_{\pi p}(s)}{\sigma_{pp}(s)} \simeq \frac{2}{3}$$

Block-Halzen
(quark counting rule)



$x_F = p_{\parallel}/p_{max}$

Sibyll 2.1



$x_F = p_{\parallel}/p_{max}$

Sibyll 2.3 [modified]

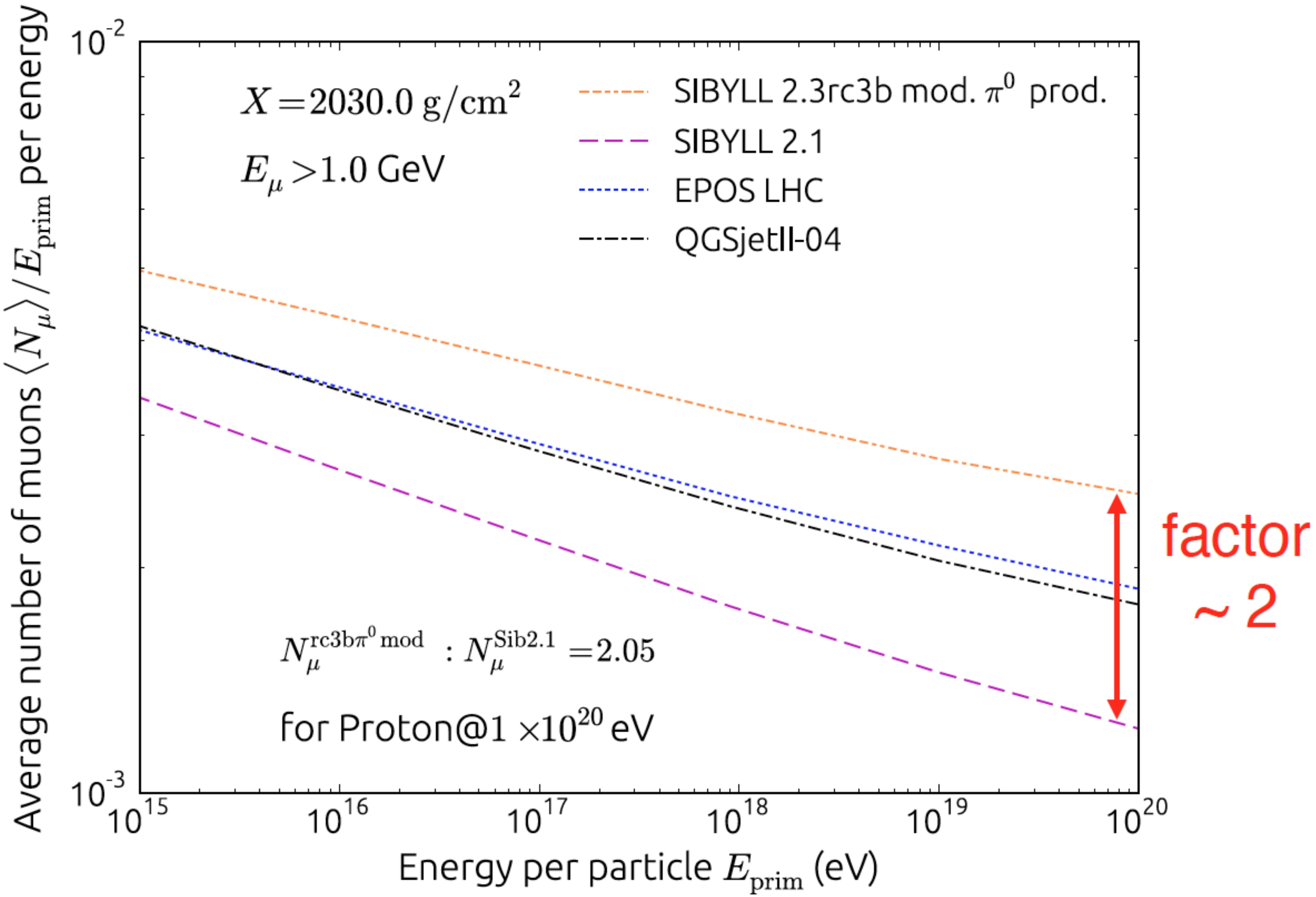
$\pi^+ p \to \pi^0 \to 2\gamma$

$\pi^+ p \to \rho^0 \to \pi^+ \pi^-$

$E_{lab} = 250\,\mathrm{GeV}$

Low Energy Pion Interactions

Large effect in the number of muons at the ground

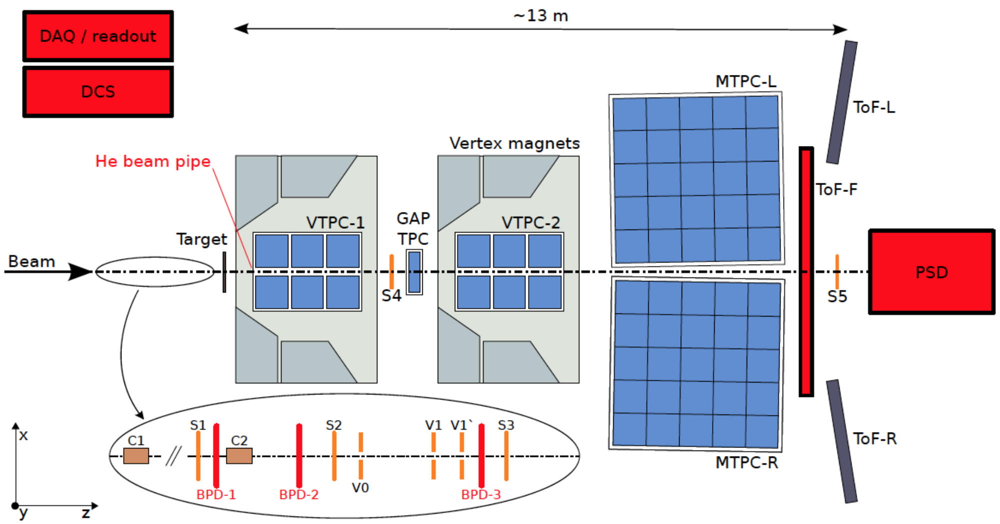


Sibyll 2.3 (mod. π^0)

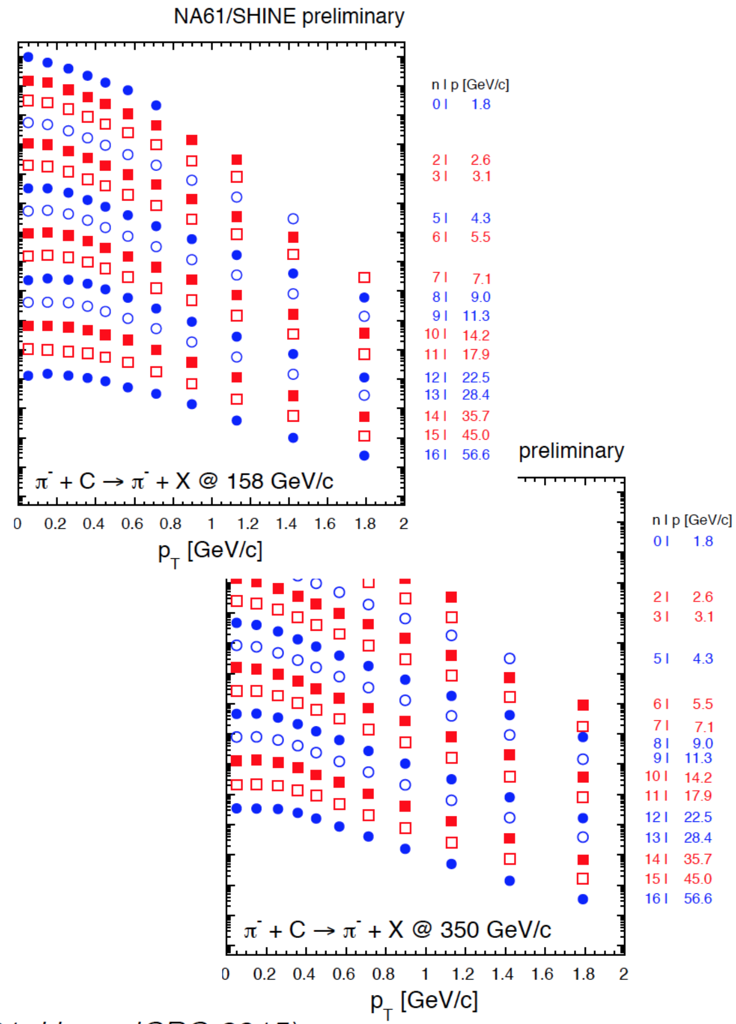
Note: change in Xmax due to enhanced ρ^0 production very small (negligible)

NA61 experiment at CERN SPS

Dedicated cosmic ray runs (π-C at 158 and 350 GeV)

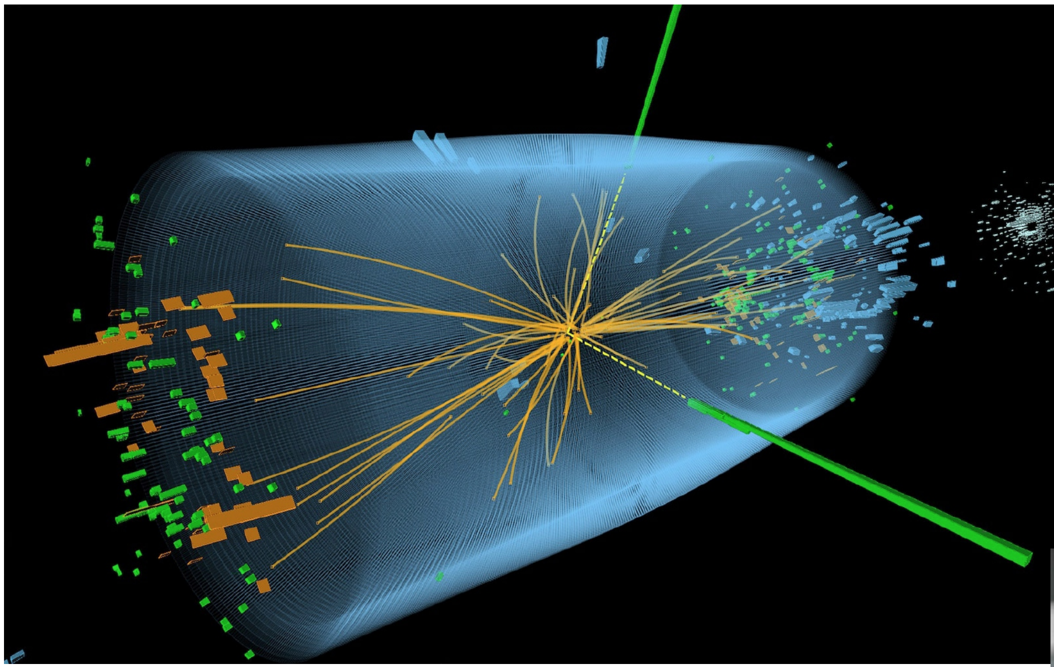


(former NA49 detector, extended)



(NA61, Herve ICRC 2015)

Where is “Fundamental Science”
after the discovery of the Englert-Brout-Higgs boson ?



The Higgs sector at the LHC: from triumph to nightmare?

[Abdelhak Djouadi (10th october 2017)]

[discovery of the Higgs]

[No evidence for new physics]

We have “Deep Problems” we want to address
but need new observations, new laboratories to explore
the open questions on the “Boundaries of Science”.

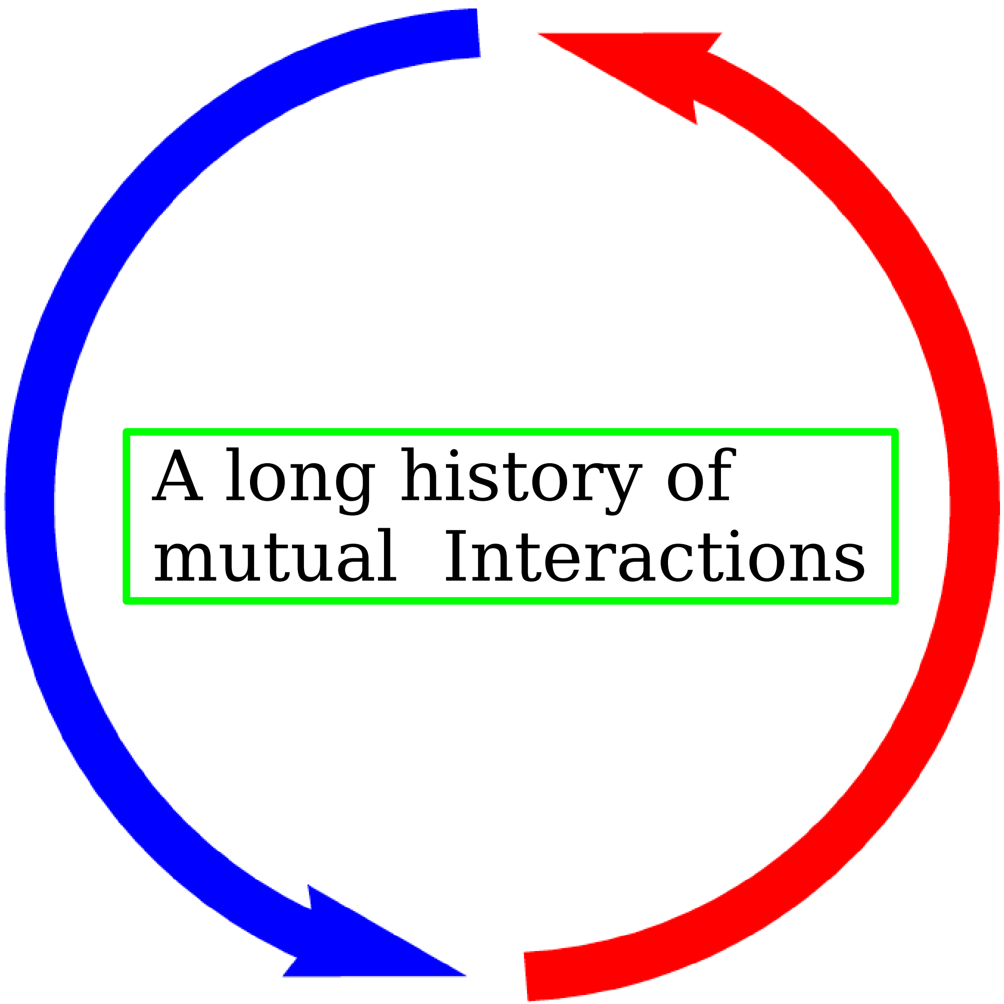
The laboratories to “explore the boundaries”
could be **future accelerators**.
(perhaps already LHC 13 TeV)

but also [in many cases only] in

Astrophysical objects/environments

and in
Cosmology studies

PARTICLE PHYSICS



COSMIC RAYS ASTROPHYSICS

QCD

The “Dark Side” of the Standard Model

Conclusions

:

1. High Energy Astrophysics is a rich field
   of great interest for Fundamental Physics

2. An understanding of non-perturbative QCD
   is very important for several problems

   Very high energy cosmic rays,
   Dark matter studies
   ...... (gamma ray emisssion, neutrino production)

4. The data of LHC has been of great importance
   to improve the modeling of shower development.

   Additional data is very desirable
   Priority p-Oxygen (p-Light nucleus) interactions

5. *More data at lower energy* is also important.

6. A theoretical effort in understanding
   non perturbative QCD is necessary
   and of great interest