# Cosmic Rays and Hadronic Interactions

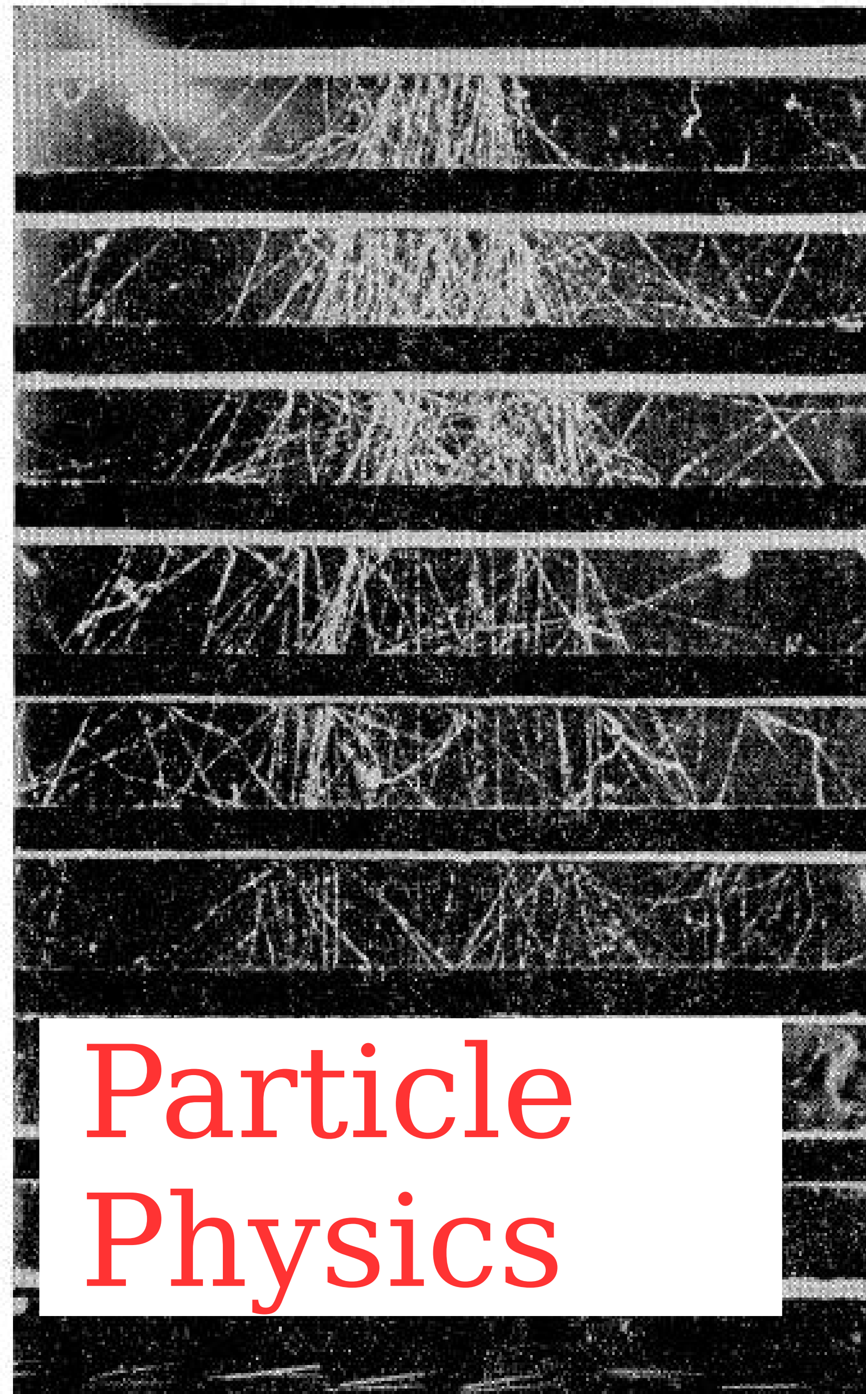
RICAP-2014

Roma International Conference on Astroparticle Physics

Paolo Lipari, INFN Roma “Sapienza”

Noto, 3rd october 2014

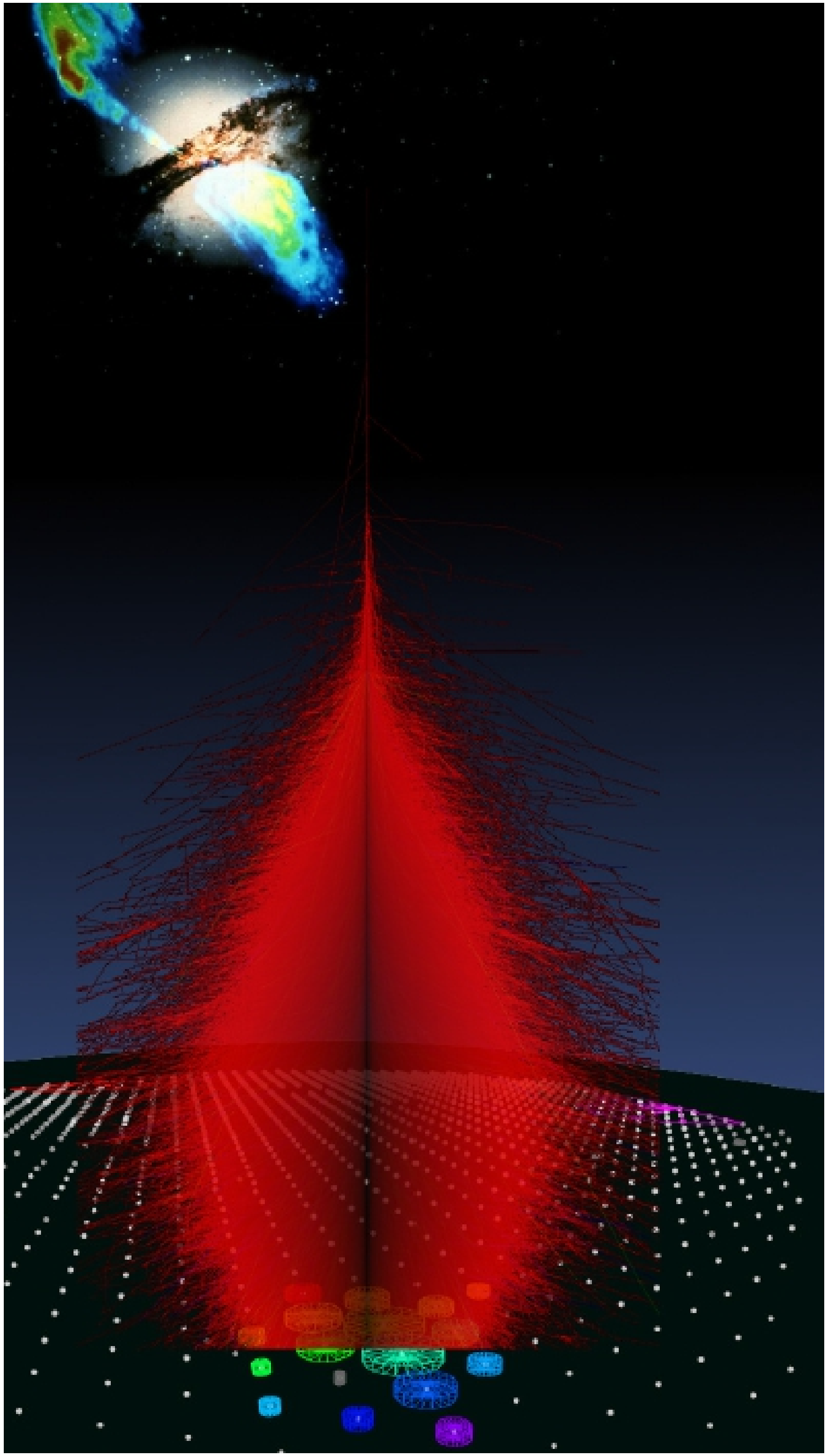

**Victor Hess**
before the balloon flight of 1912
Cosmic Rays


Particle Physics

# Air Shower Observation of Cosmic Rays

[determination of the
Energy and Mass
of the primary particles]

image by Ralf Ulrich

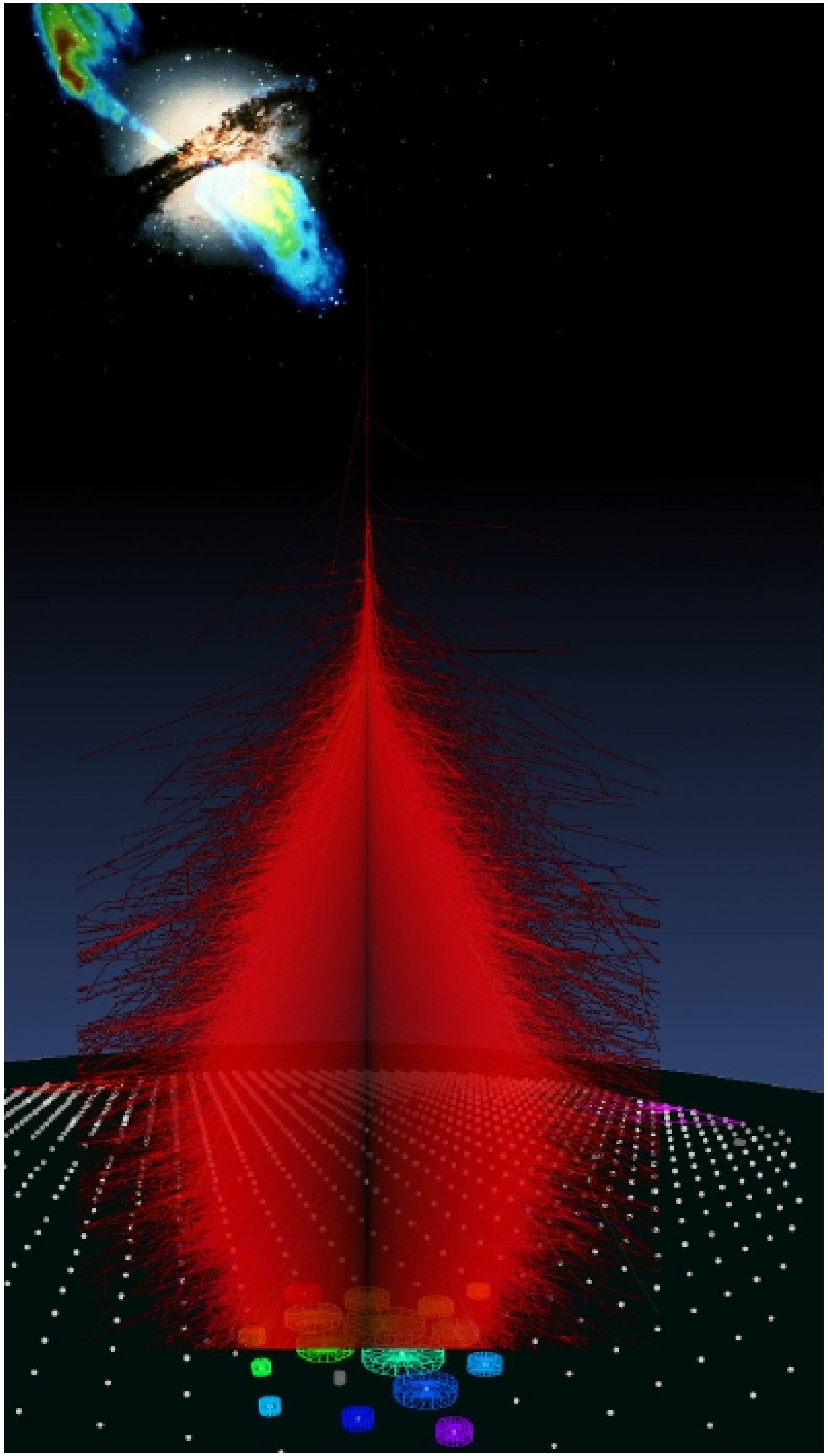


the Source

the Shower

the Data

image by Ralf Ulrich



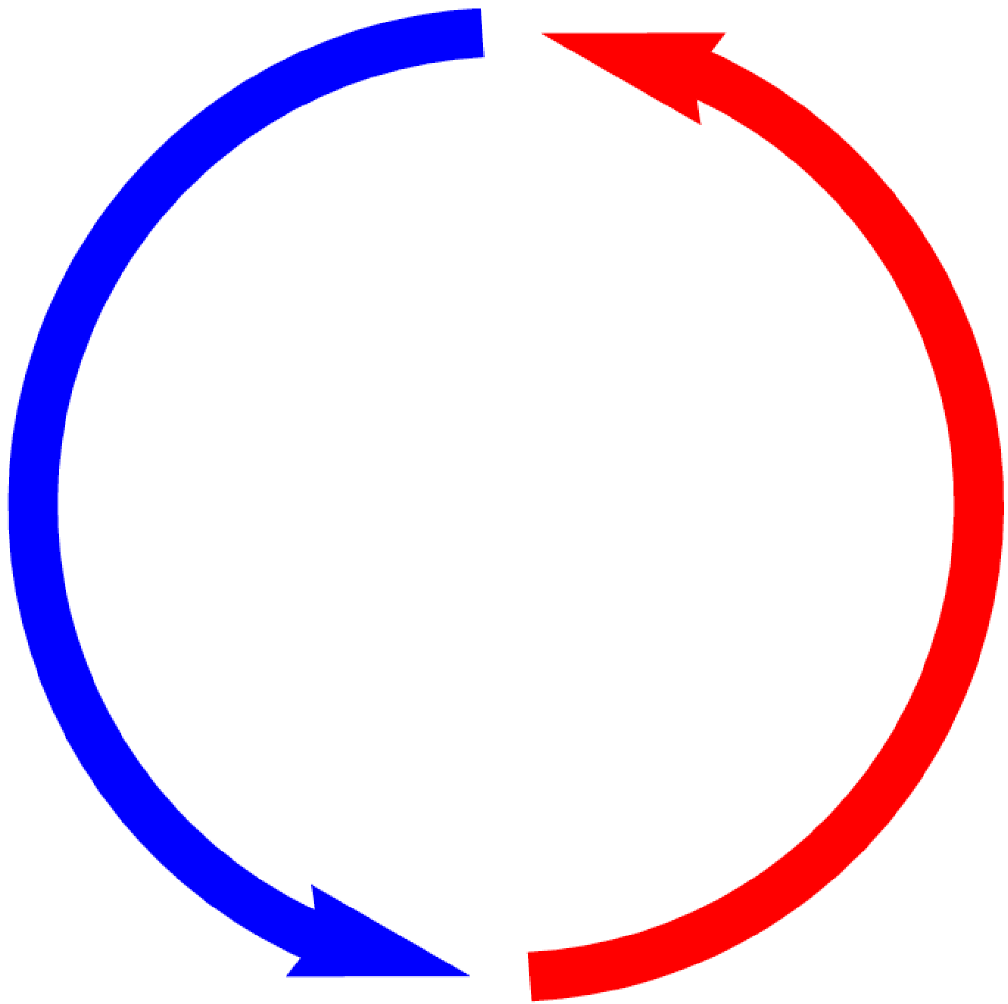
the Source

the Shower

[The estimate of the
Energy and Mass
of the shower requires the
detailed modeling of shower
development]

the Data

PARTICLE PHYSICS



COSMIC RAYS ASTROPHYSICS

Theory (QCD) +
[Accelerator Data]

HE Cosmic Ray
Data

**"Direct Route"** Program:

1. Obtain data at accelerators (LHC + others)

2. Develop a sound theoretical framework to extrapolate to high energy.

3. Interpret the CR data

Theory (QCD) +
[Accelerator Data]

HE Cosmic Ray
Data

**"Direct Route"** Program:

1. Obtain data at accelerators (LHC ! + others)

2. Develop a sound theoretical framework to extrapolate to high energy.

3. Interpret the CR data

Questions:

1. What new measurements are most important/possible ?

2. What are the best theoretical instruments to guide the extrapolation?

3. Where are we?
4. What can we achieve ?

Is it possible to obtain information about Particle Physics from the UHECR data ?

Particle Physics
[hadronic interactions, "exotica" ?]

HE Cosmic Ray Data

Is it possible to obtain information about Particle Physics from the UHECR data ?

Isn't (the lack of information about) composition an "impossible obstacle" ?

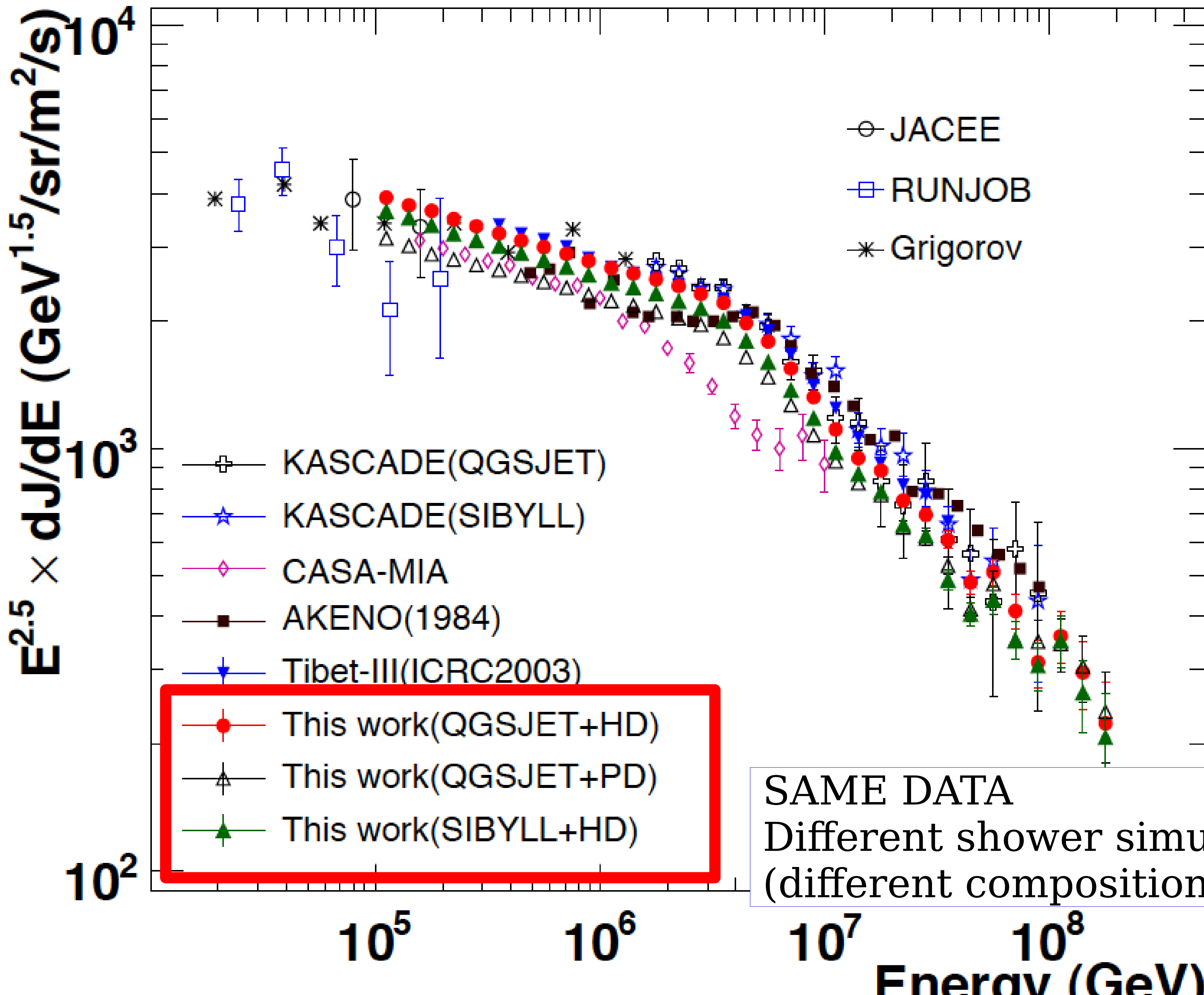
1. Astrophysical composition measurements:
   * Magnetic deviations
   * Energy losses imprints on the energy spectrum

2. "Self-consistency" or "Bootstrap" ?

Particle Physics
[hadronic interactions, "exotica" ?]

UHE Cosmic Ray Data

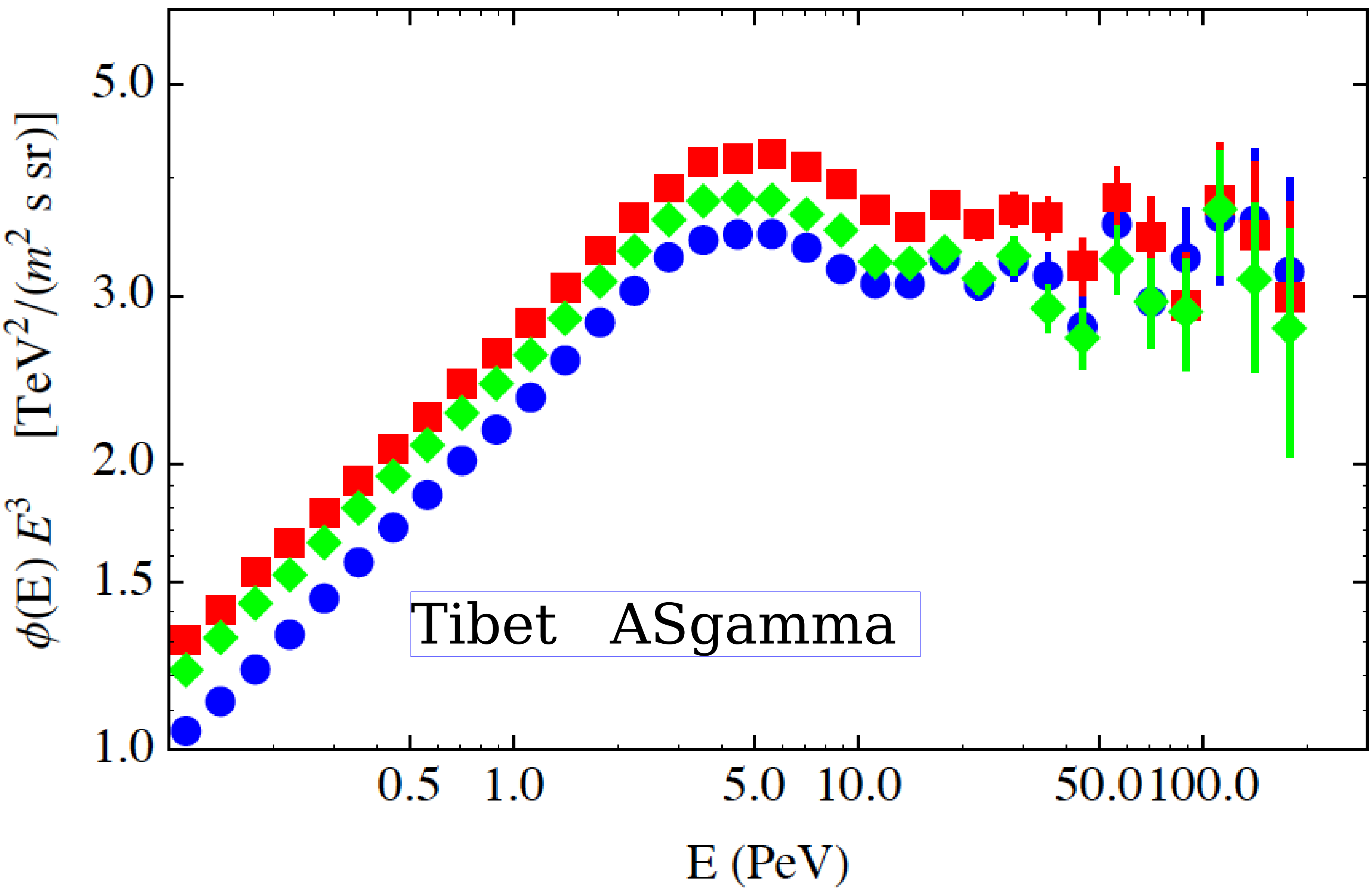
# Tibet Air Shower Energy Spectrum

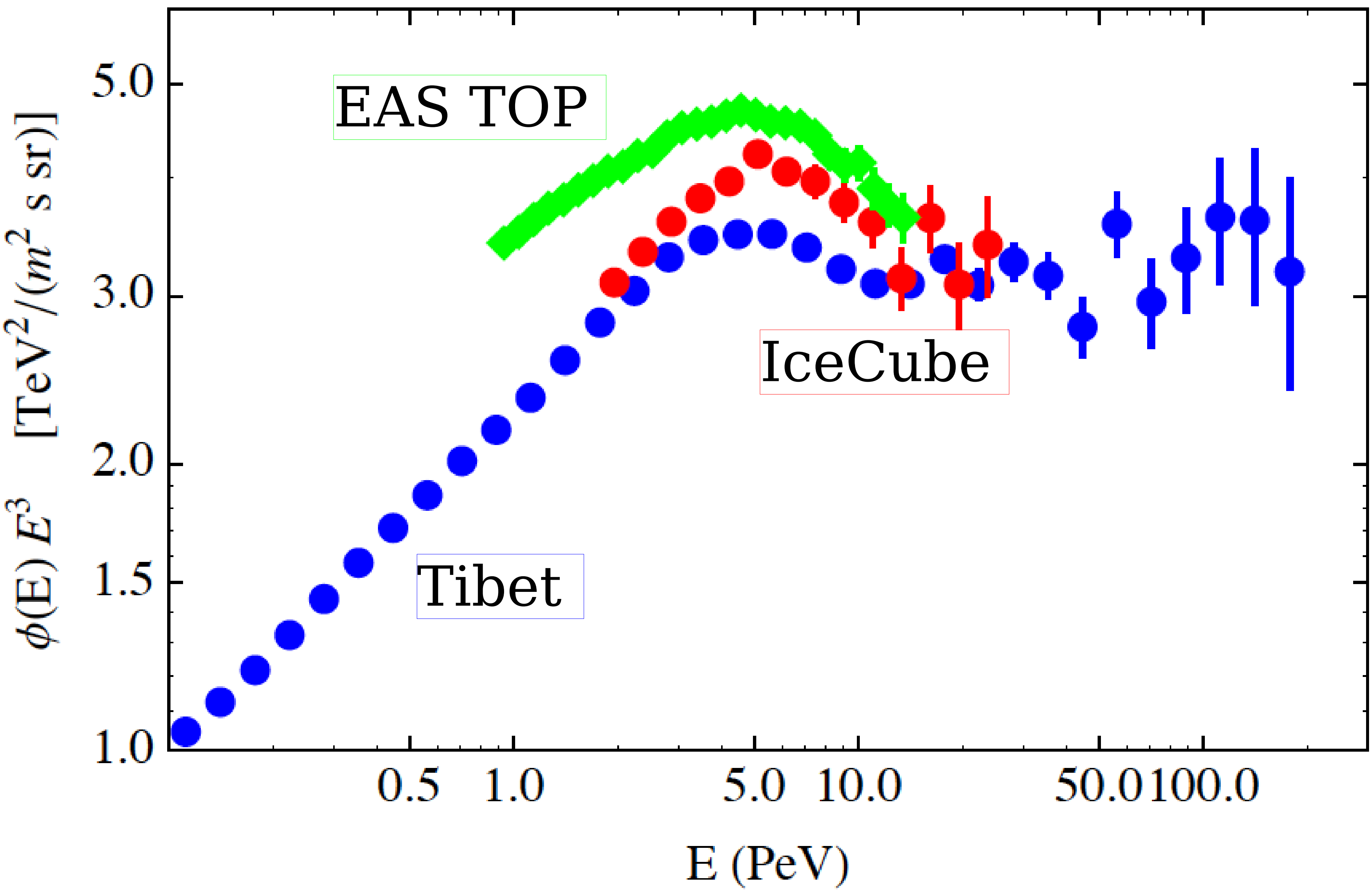



SAME DATA
Different shower simulation
(different composition models)

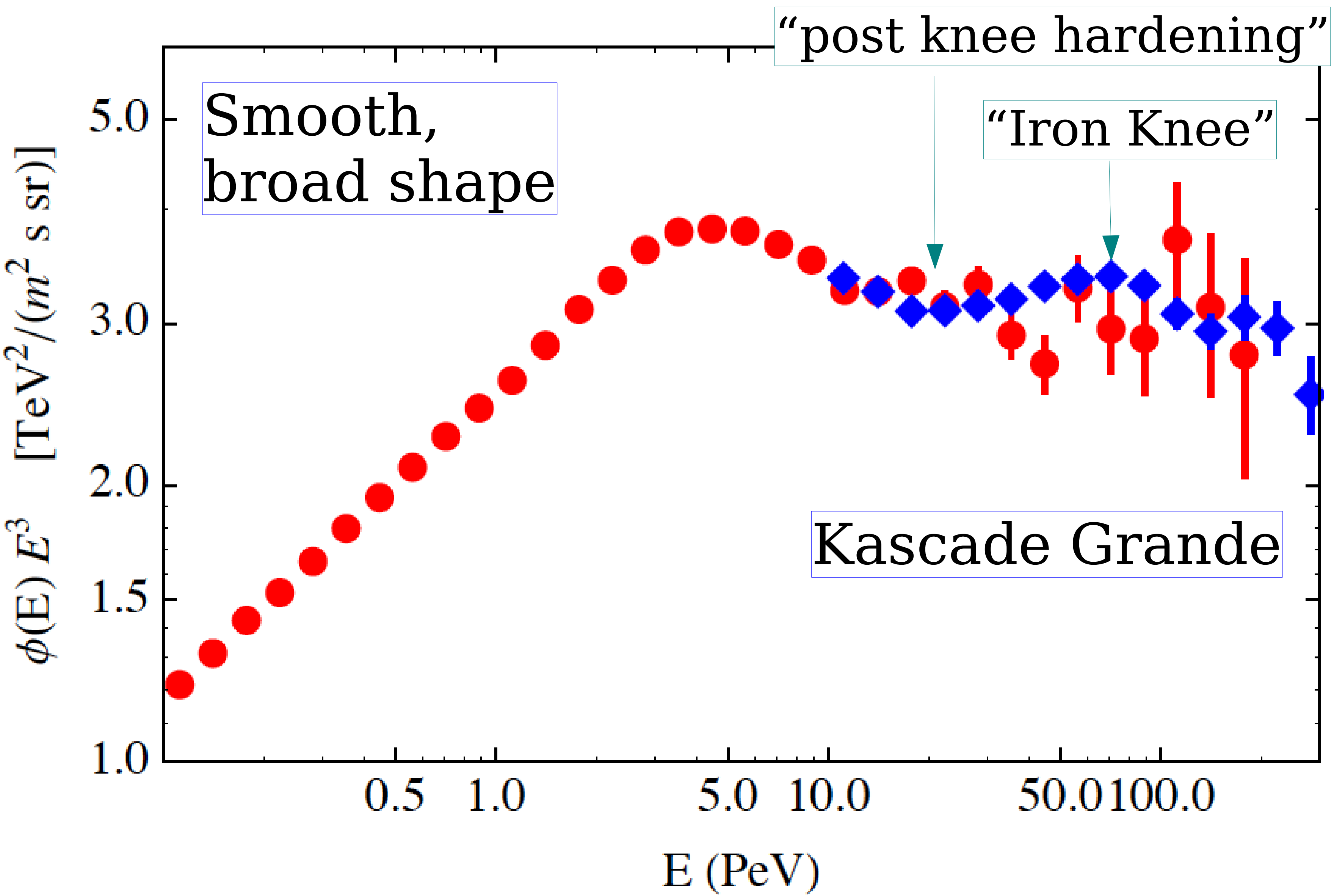
# The “Shape of the KNEE”

$$\boxed{E^3\ \phi(E)}$$

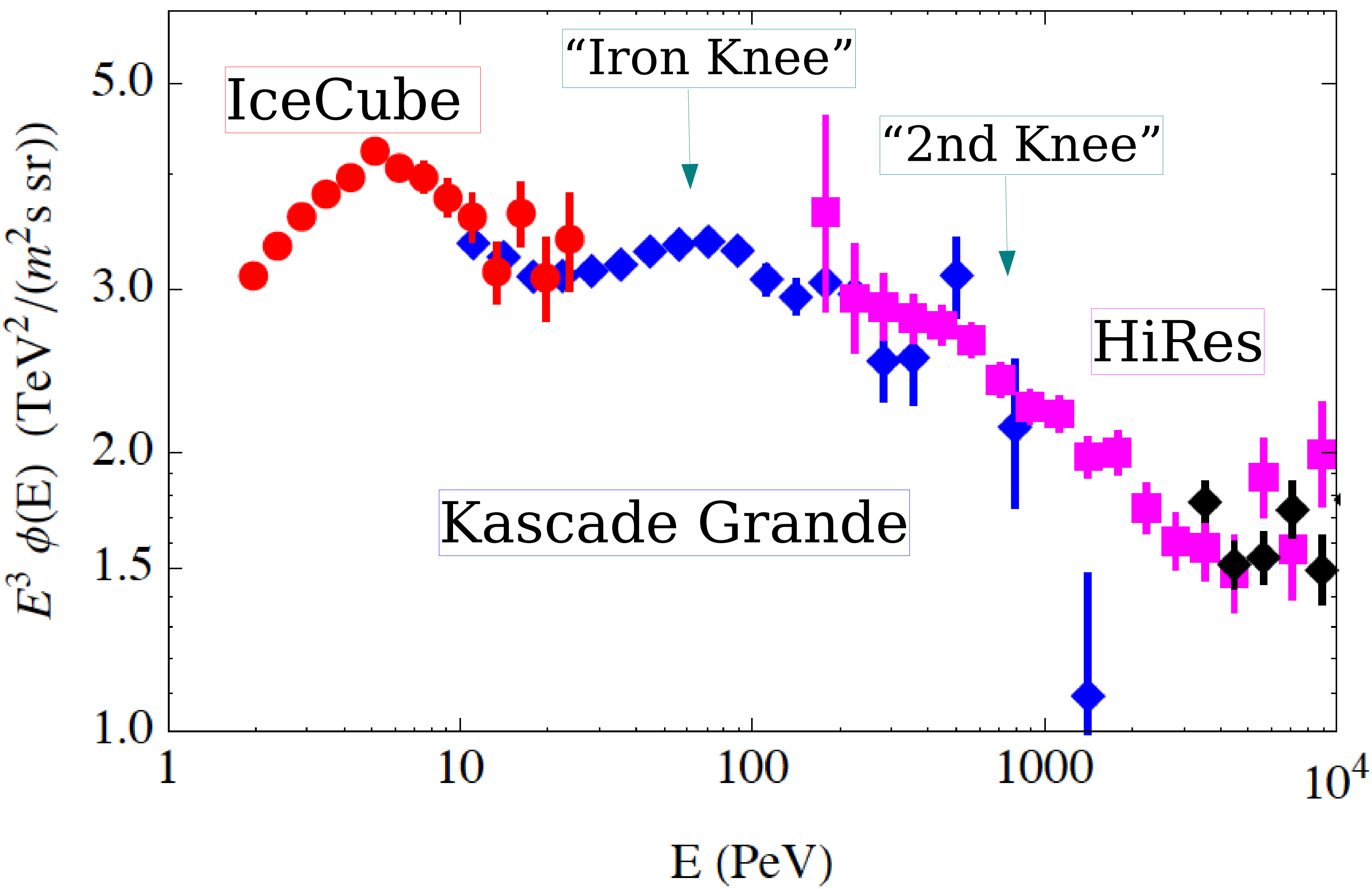




EAS TOP
IceCube
Tibet
5.0
3.0
2.0
1.5
1.0
0.5
1.0
5.0
10.0
50.0
100.0
E (PeV)
$\phi(E)\,E^3\quad [\mathrm{TeV}^2/(m^2\ \mathrm{s\ sr})]$

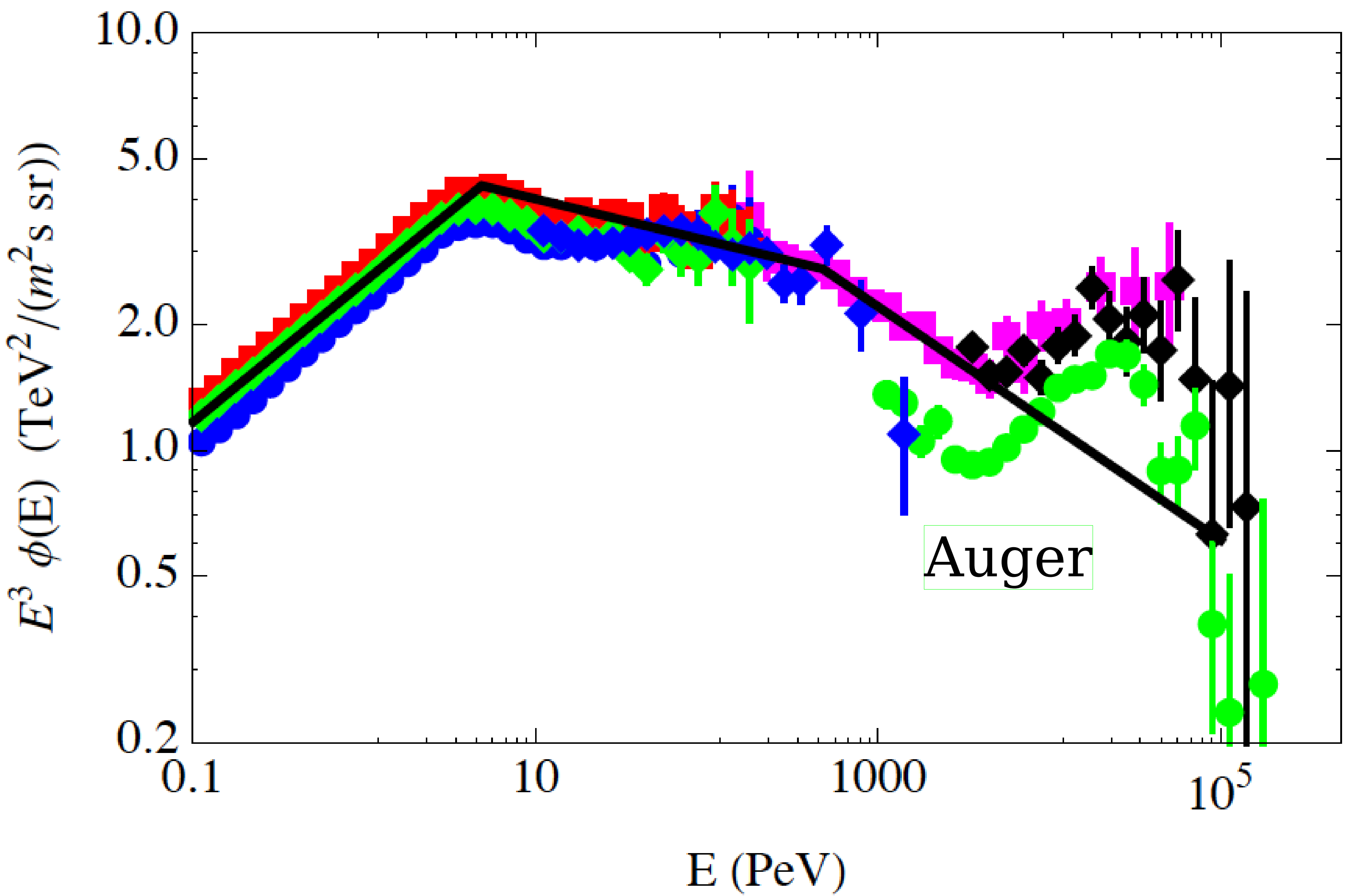


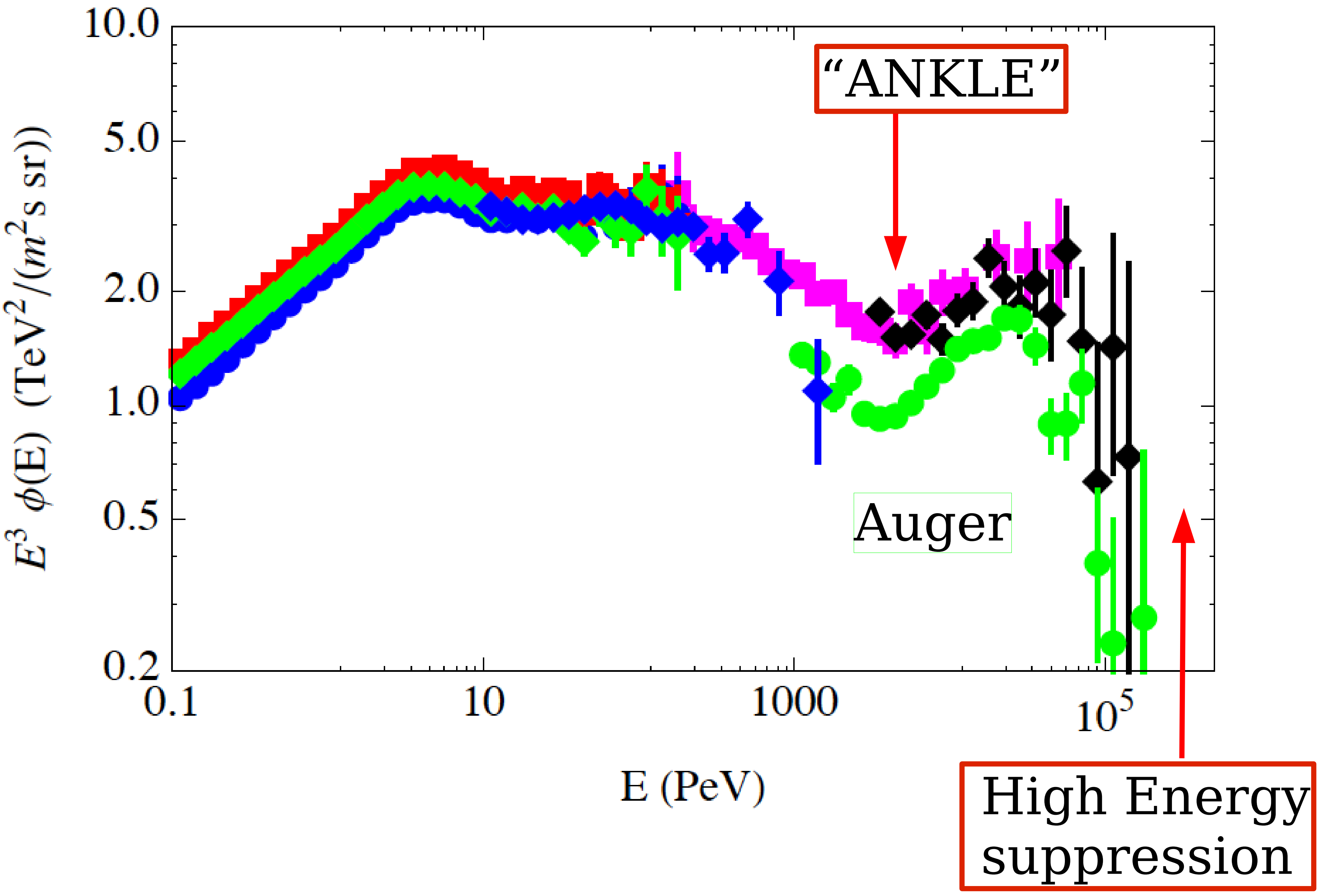
"post knee hardening"
"Iron Knee"
Smooth,
broad shape
Kascade Grande
5.0
3.0
2.0
1.5
1.0
0.5
1.0
5.0
10.0
50.0
100.0
E (PeV)
$\phi(\mathrm{E})\, E^3 \quad [\mathrm{TeV}^2/(m^2\ \mathrm{s\ sr})]$



IceCube
"Iron Knee"
"2nd Knee"
HiRes
Kascade Grande
5.0
3.0
2.0
1.5
1.0
1
10
100
1000
$10^4$
$E^3\ \phi(E)\ (\mathrm{TeV}^2/(m^2\,\mathrm{s\ sr}))$
E (PeV)

Simple "2 knees pictures" very likely insufficient.



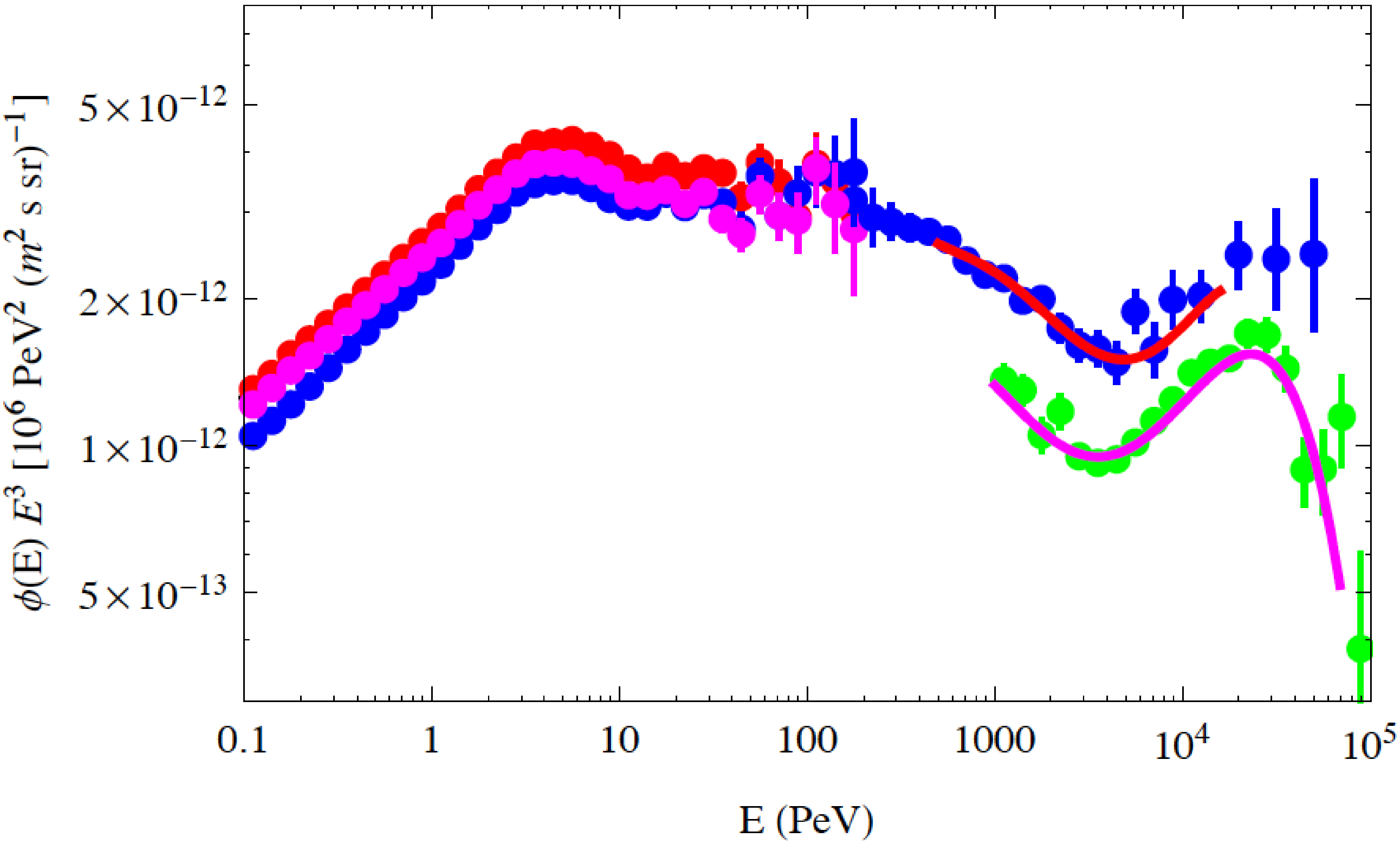


"ANKLE"
Auger
High Energy suppression
10.0
5.0
2.0
1.0
0.5
0.2
0.1
10
1000
$10^5$
E (PeV)
$E^3\ \phi(E)\ (\mathrm{TeV}^2/(m^2\,\mathrm{s\,sr}))$

TIBET AS-gamma CR spectra

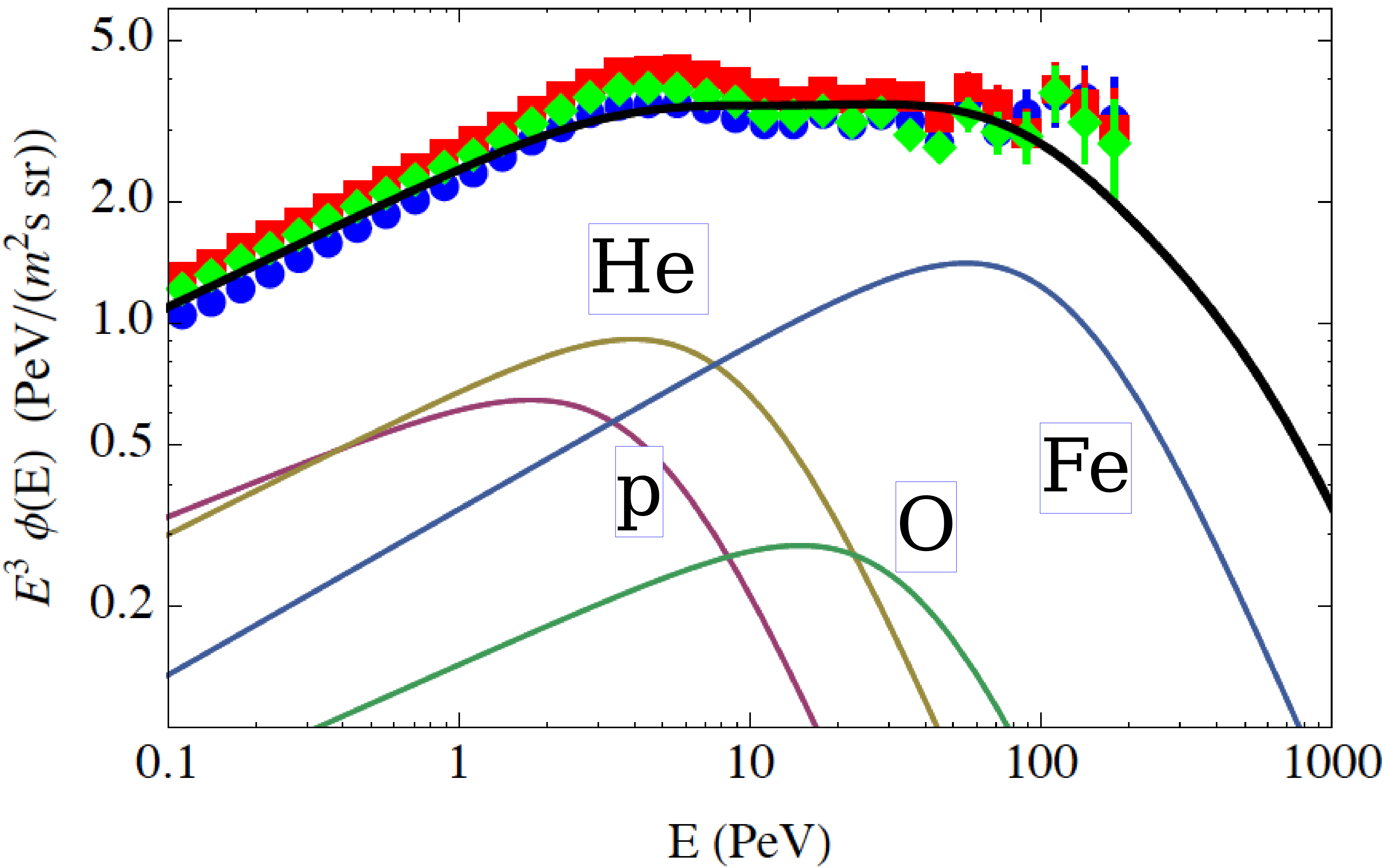
HIRES spectrum

AUGER spectrum Energy scale discrepancy.



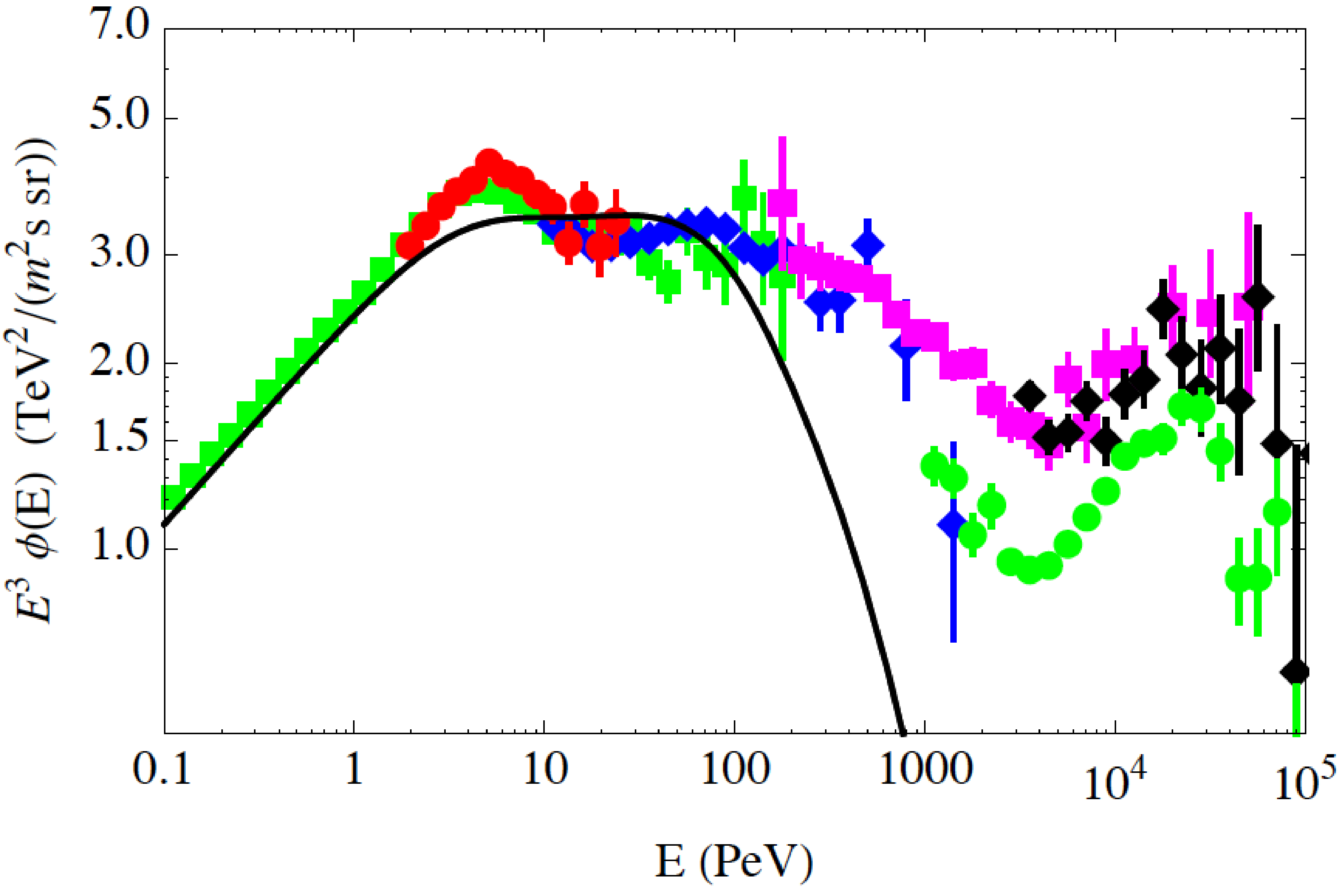
Horandel Model (largely motivated by Kascade data) for the evolution of composition

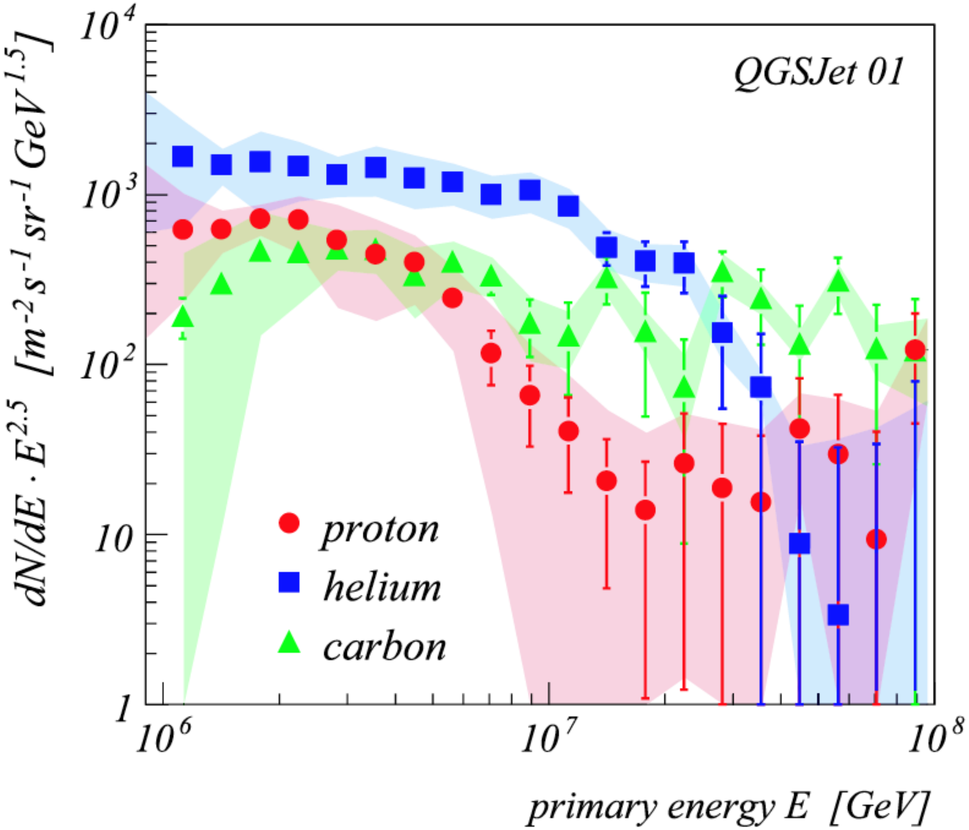
Same structure ["Peters cycle"] repeated "rescaled in Z"



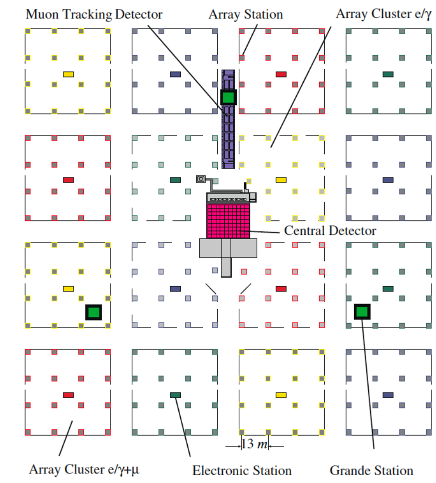
Proton Knee at 4.51 PeV

Where does the extragalactic component enters ?

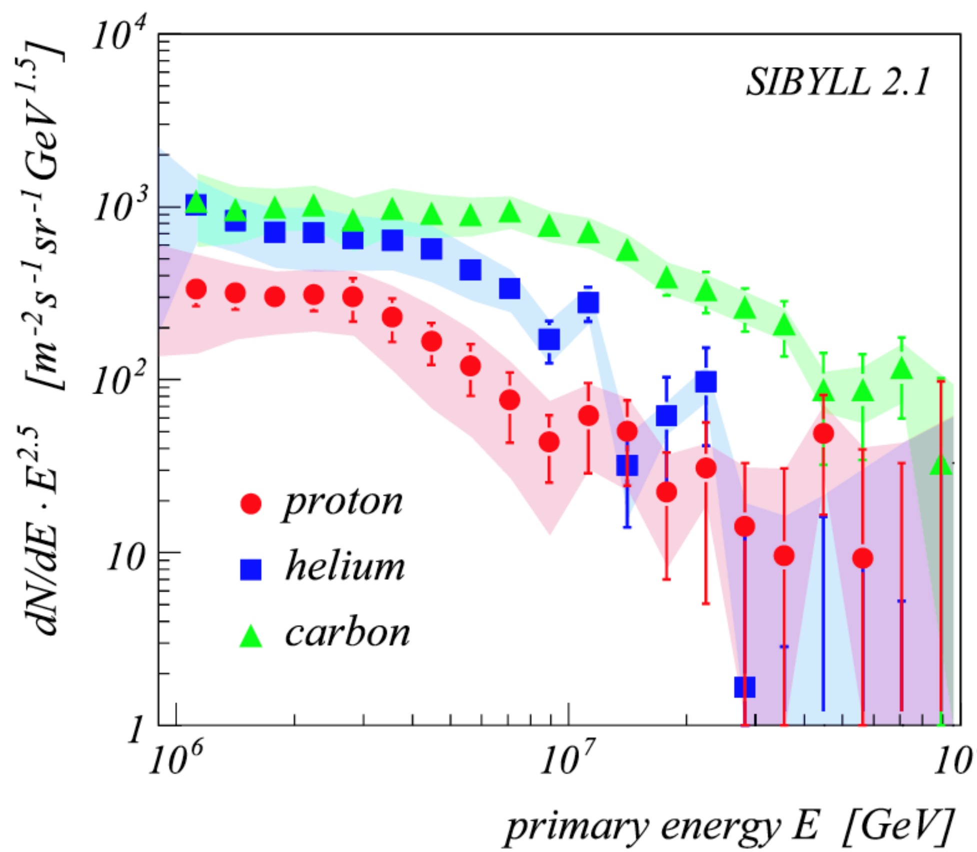




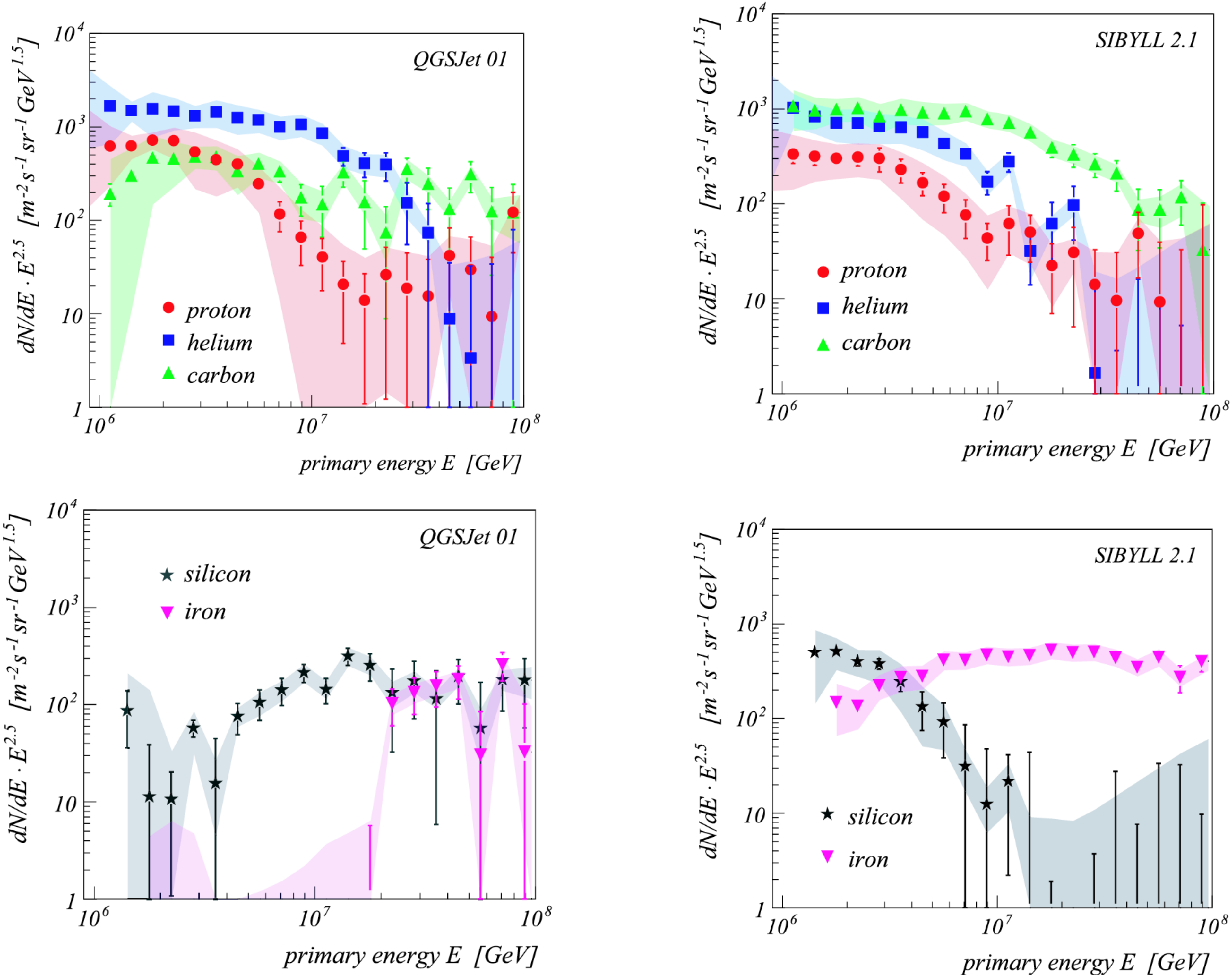

# KASCADE results



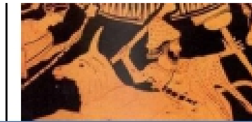

## Model Dependence !




KASCADE /KASCADE-GRANDE


QGSJet 01
SIBYLL 2.1
proton
helium
carbon
silicon
iron
$dN/dE \cdot E^{2.5}$ [$m^{-2} s^{-1} sr^{-1} GeV^{1.5}$]
primary energy E [GeV]

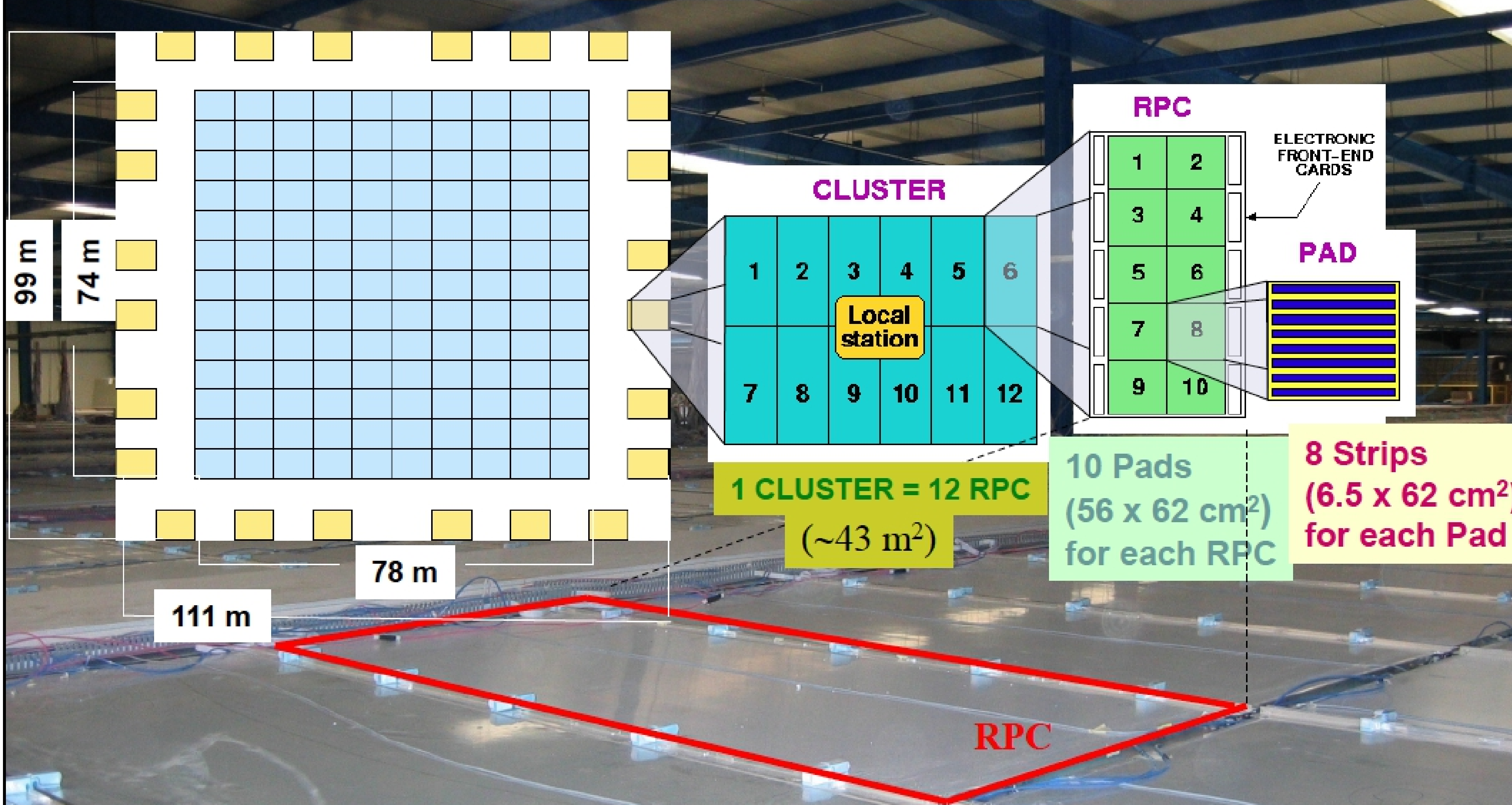
# The ARGO-YBJ experiment




**High Altitude Cosmic Ray Observatory @ YangBaJing,Tibet, China**

**Site Altitude: 4,300 m a.s.l. , ~ 600 g/cm$^2$**

# The ARGO-YBJ detector




Strip counting

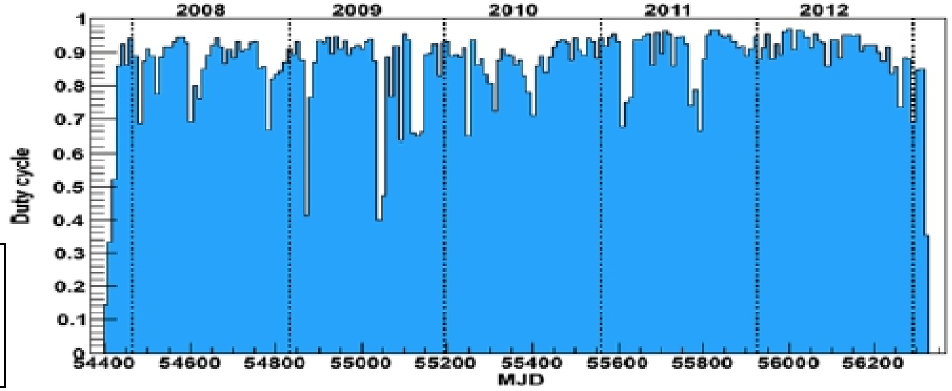
Pad = space-time pixel

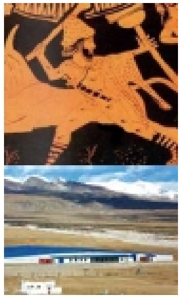
Time resolution ~1.8 ns

+ Analog charge read-out on “Big Pads”

# EAS reconstruction

Data taking with full configuration:
November 2007- February 2013

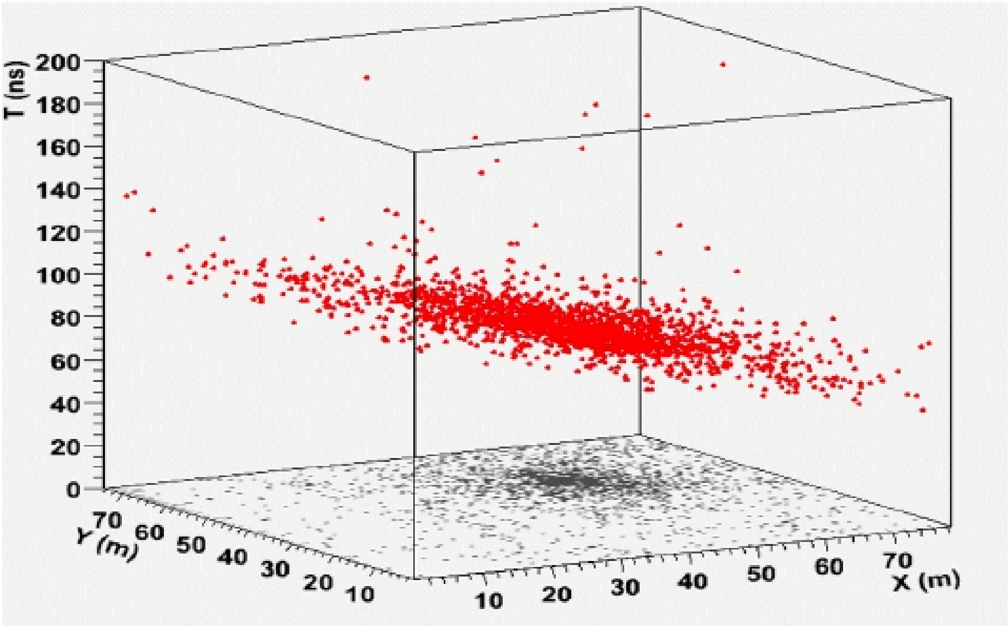


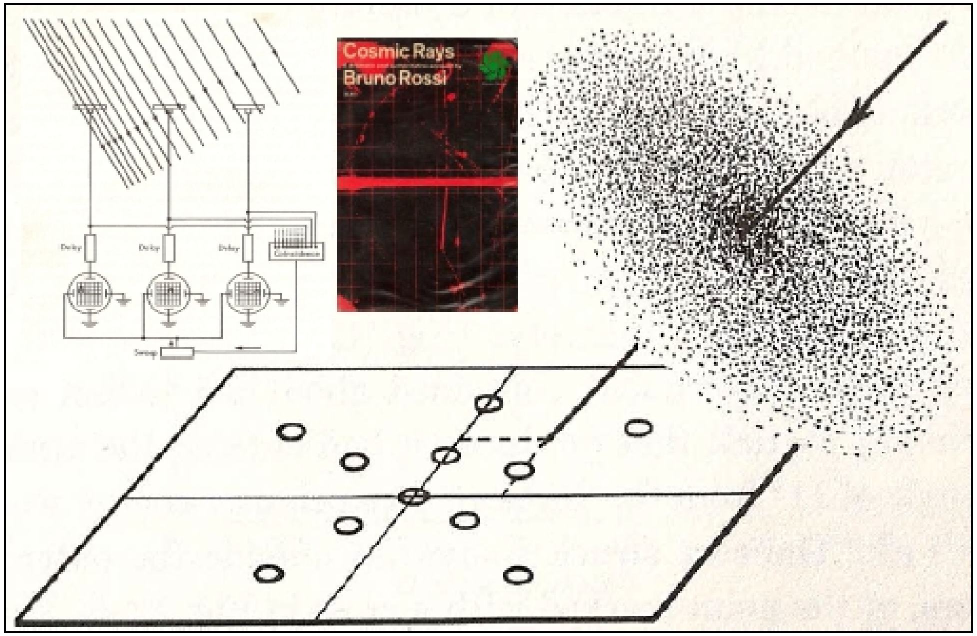
Event Rate ~ 3.5 kHz for $N_{hit}$ >20 - Duty cycle ~ 86% - $10^{11}$ evts/yr – 100TB/yr

**High space/time granularity**
**+ Full coverage**
**+ High altitude**

**detailed study on the EAS space/time structure with unique capabilities**




**3-D view of a detected shower**

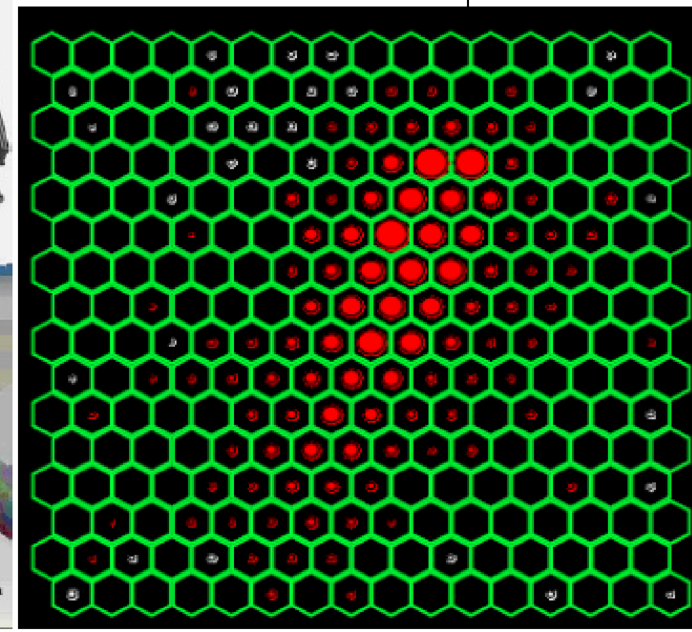



**Bruno Rossi conceptual EAS detector**

# p+He spectrum: measurement of Cerenkov light

Wide Field of View Cerenkov Telescope (Array): (WFCTA)

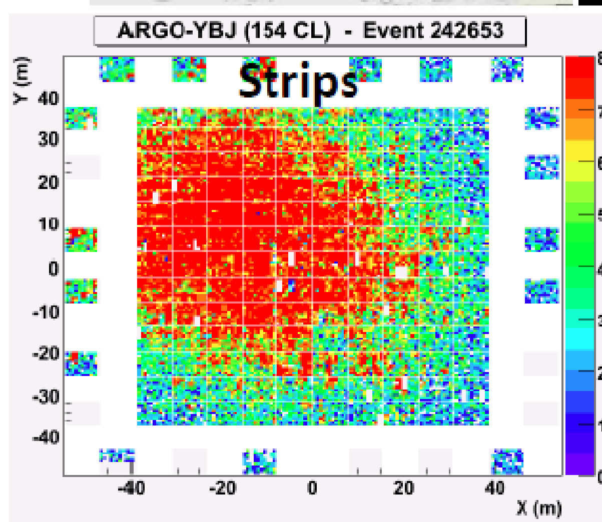
$5m^2$ spherical mirror
16×16 PMT array
14° ×16° Field Of View
Elevation angle: 60 °

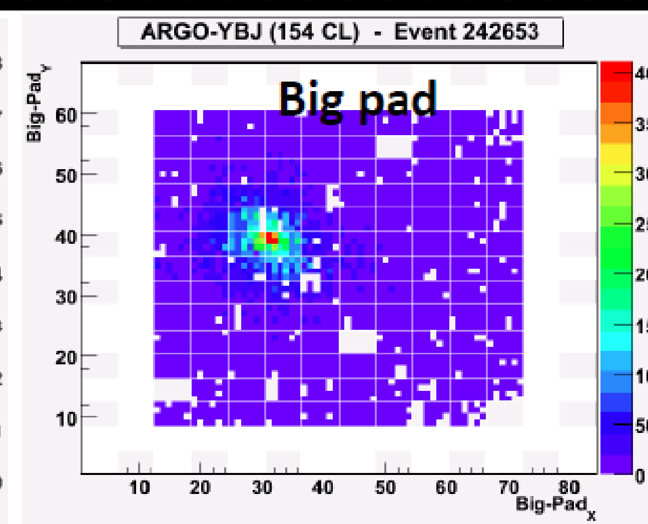


Energy easurement by using the Cerenkov signal and the shower geometry as reconstructed with the ARGO-YBJ analog data.

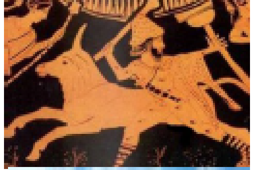
Light elements are selected by using information of particle desity near the core (ARGO-YBJ) and the shape of the Cerenkov image

**Chin. Phys. C 38 (2014) 045001**

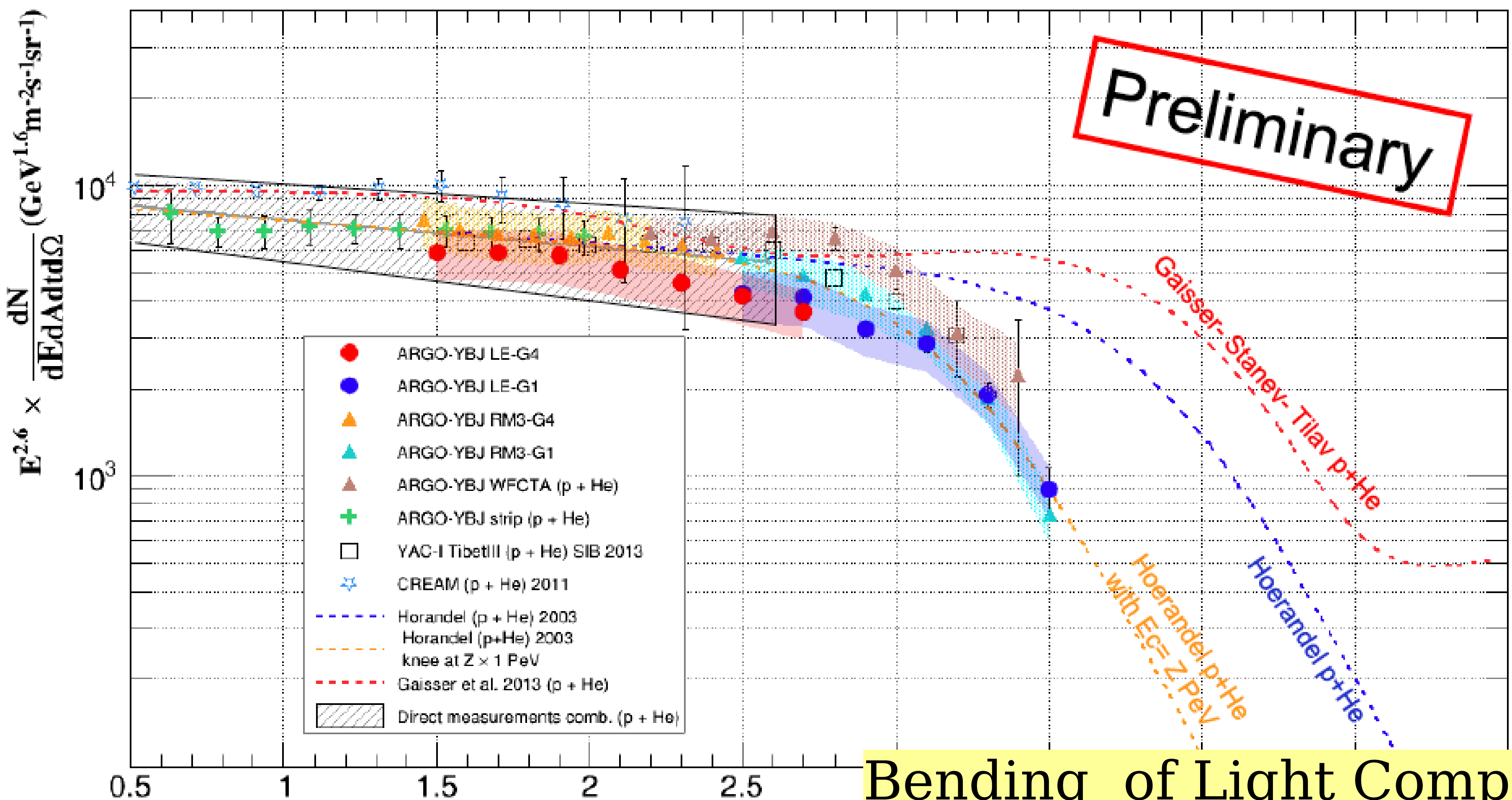


# Comparison with other p+He measurements



Consistent results with direct measurements (i.e. below 200 TeV) and YAC-Tibet

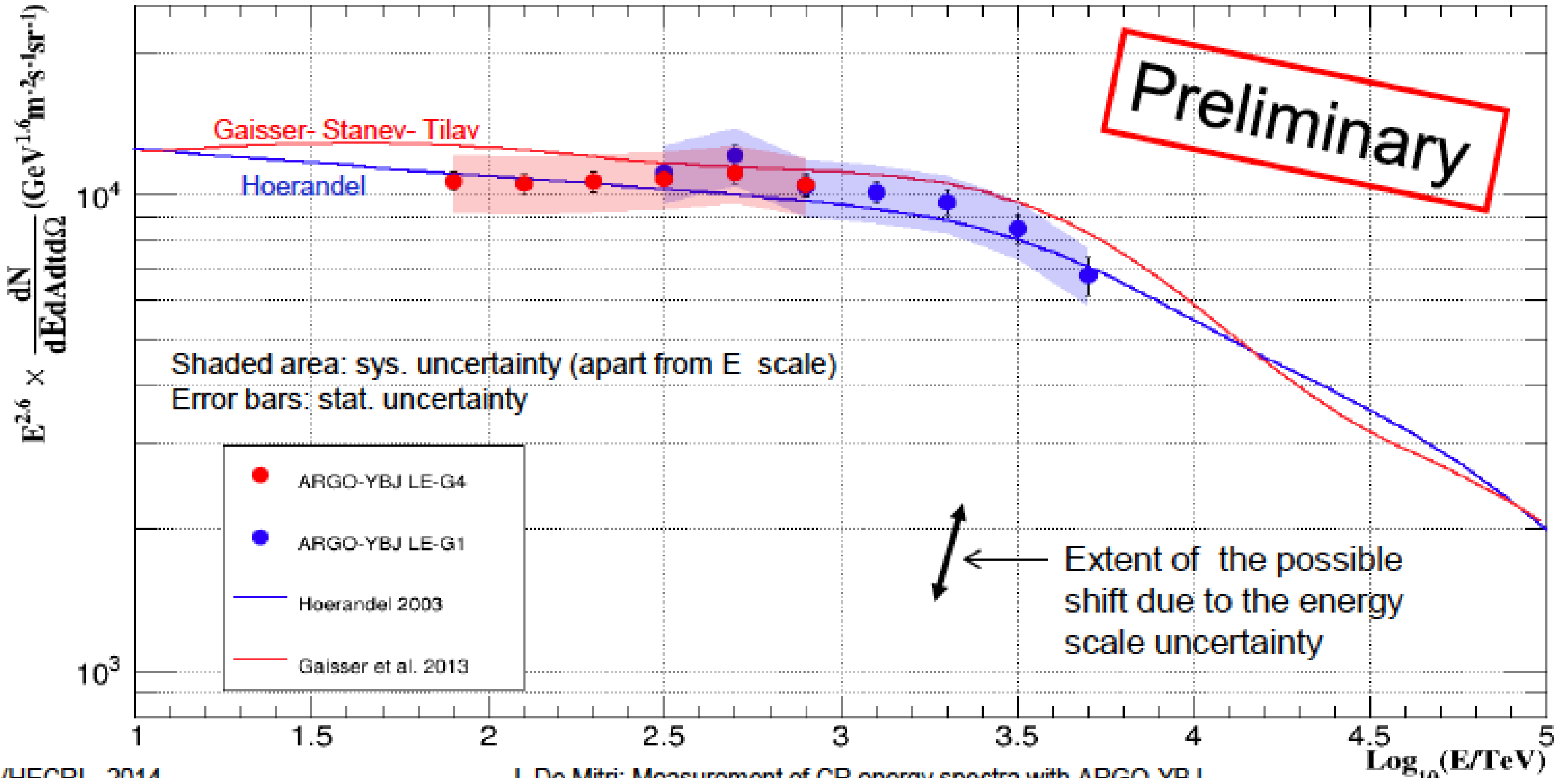



Bending of Light Component at lower energy

# The all particle spectrum

- Consistent picture with models and previous measurements
- Nice overlap with the two gain scales (different data,…)
- Suggest spectral index of -2.6 below 1 PeV and smaller at larger energes

- Ongoing extension to about 10 PeV thanks to more statistics and G0 and inclined data



If this “early bending” measurement of the bending of the proton/helium component is correct, this is important.

Questions/Comments after looking at the ARGO result:

Why the discrepancy with previous measurements ?

Different method of mass measurement

KASCADE : Muon content [Large A = large Nmu]

ARGO : Shape of the lateral distribution of the shower

Does this has something to do with the modeling of the shower ?

Energy Region

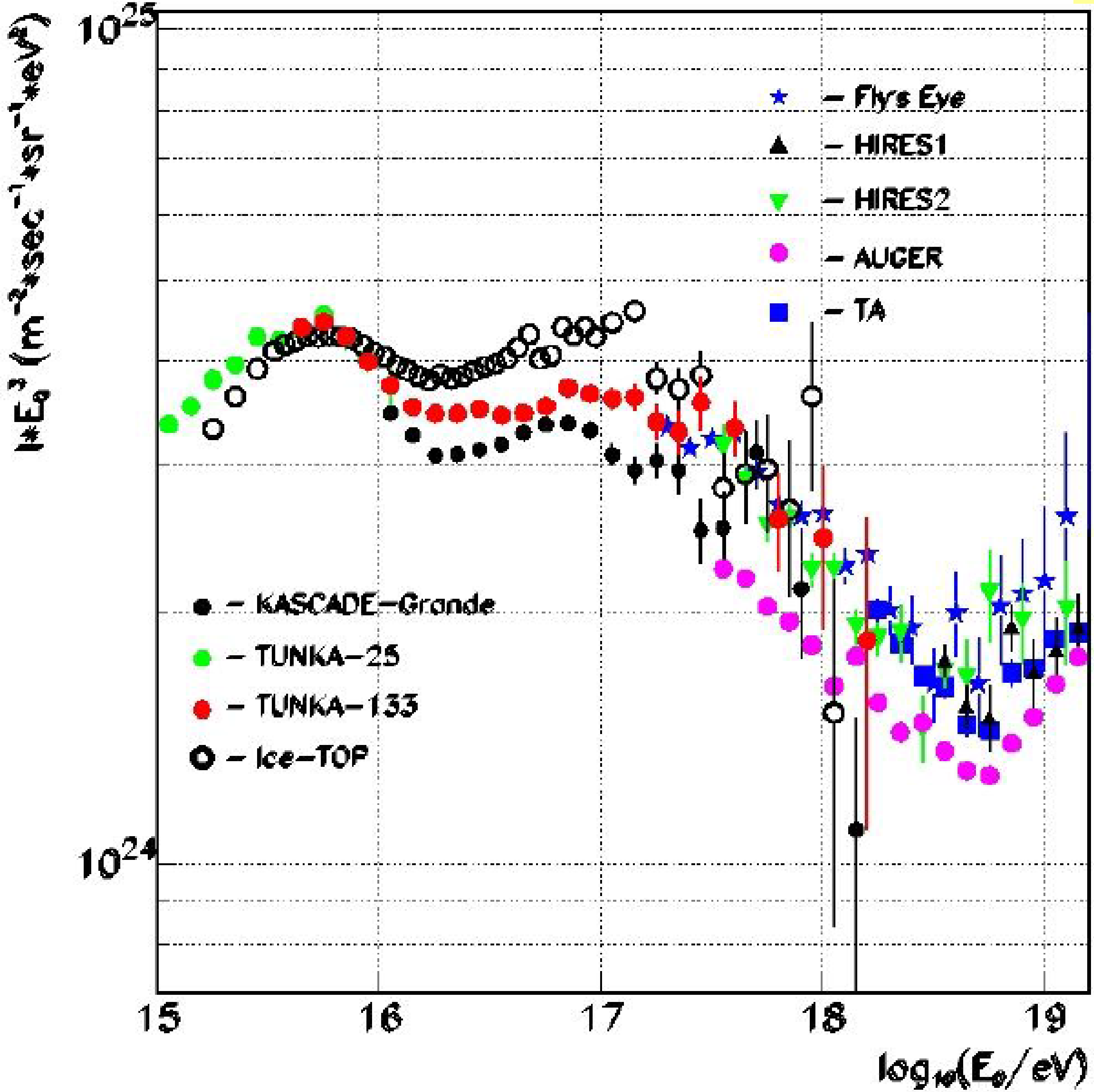
“from the Knee to the Ankle”

TUNKA

TELESCOPE ARRAY / TALE

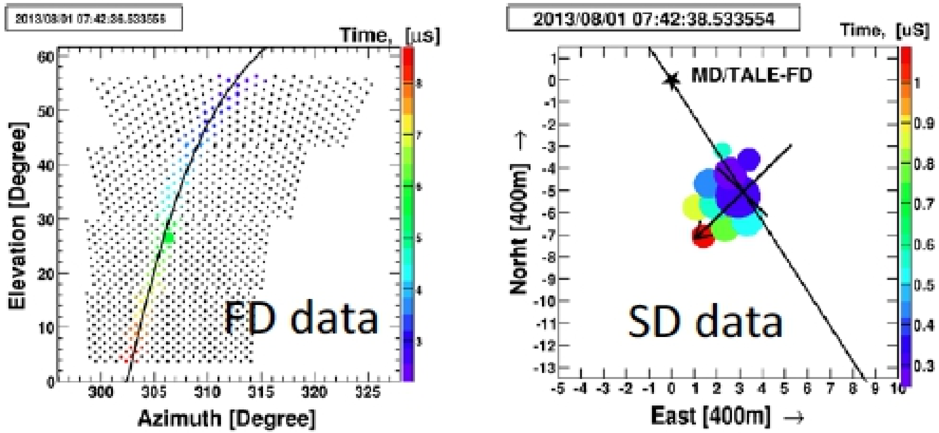
KASCADE GRANDE

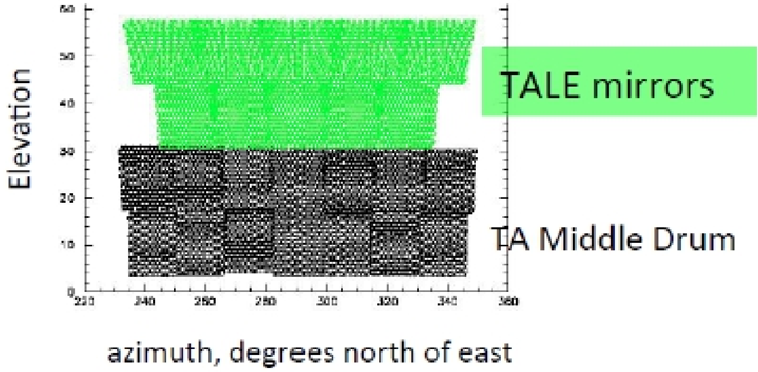
Vasily Prosin

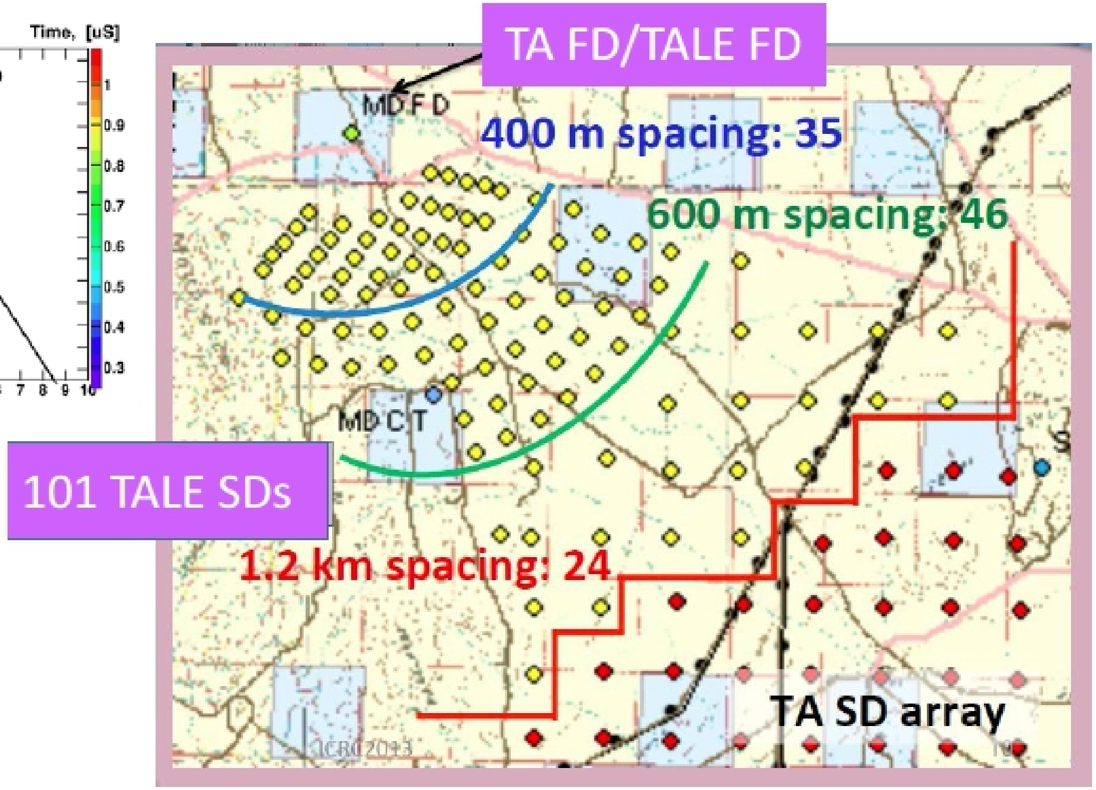


# TALE (TA Low-E Extension)

- Target range $10^{16.5}$-$10^{19}$eV
  - Second Knee
  - Change of mass composition
  - LHC center of mass E
- TALE is operating partly now

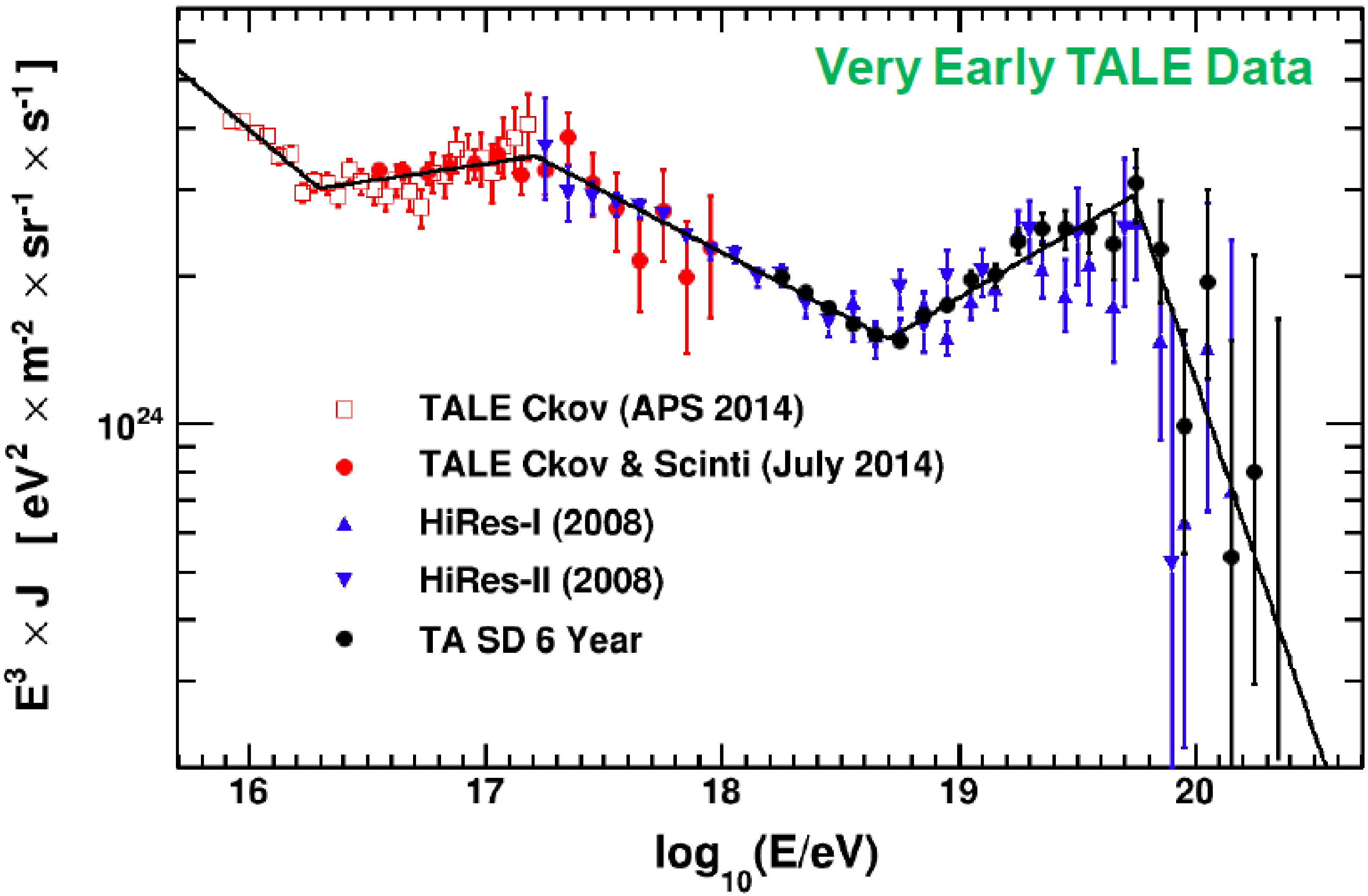



Masaki Fukushima

# CR Spectrum

SD Data (6 Yrs: 20080511-20140511)
+ high elevation TALE telescopes (no MD so far)
and events with large Cerenkov contribution



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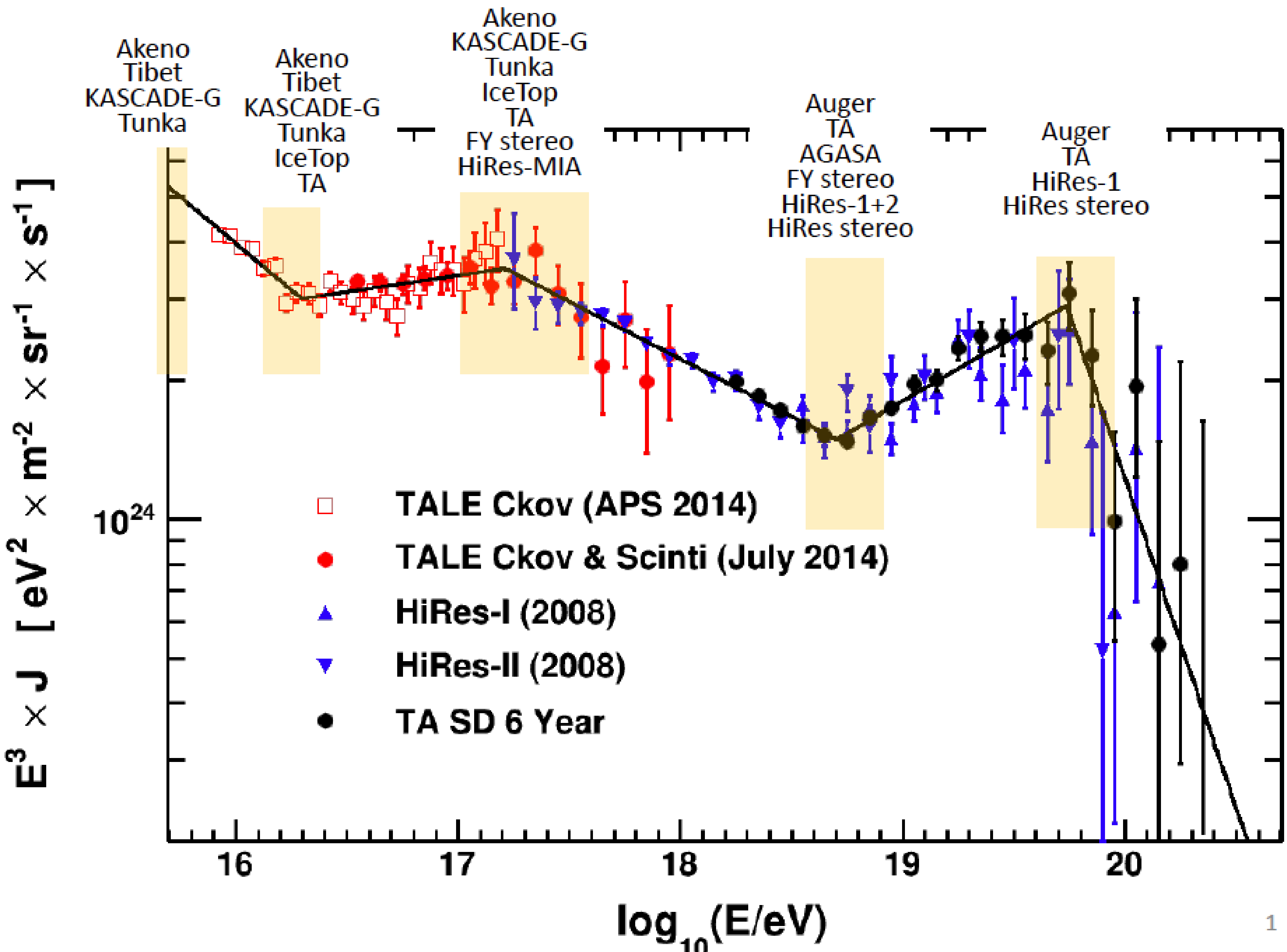
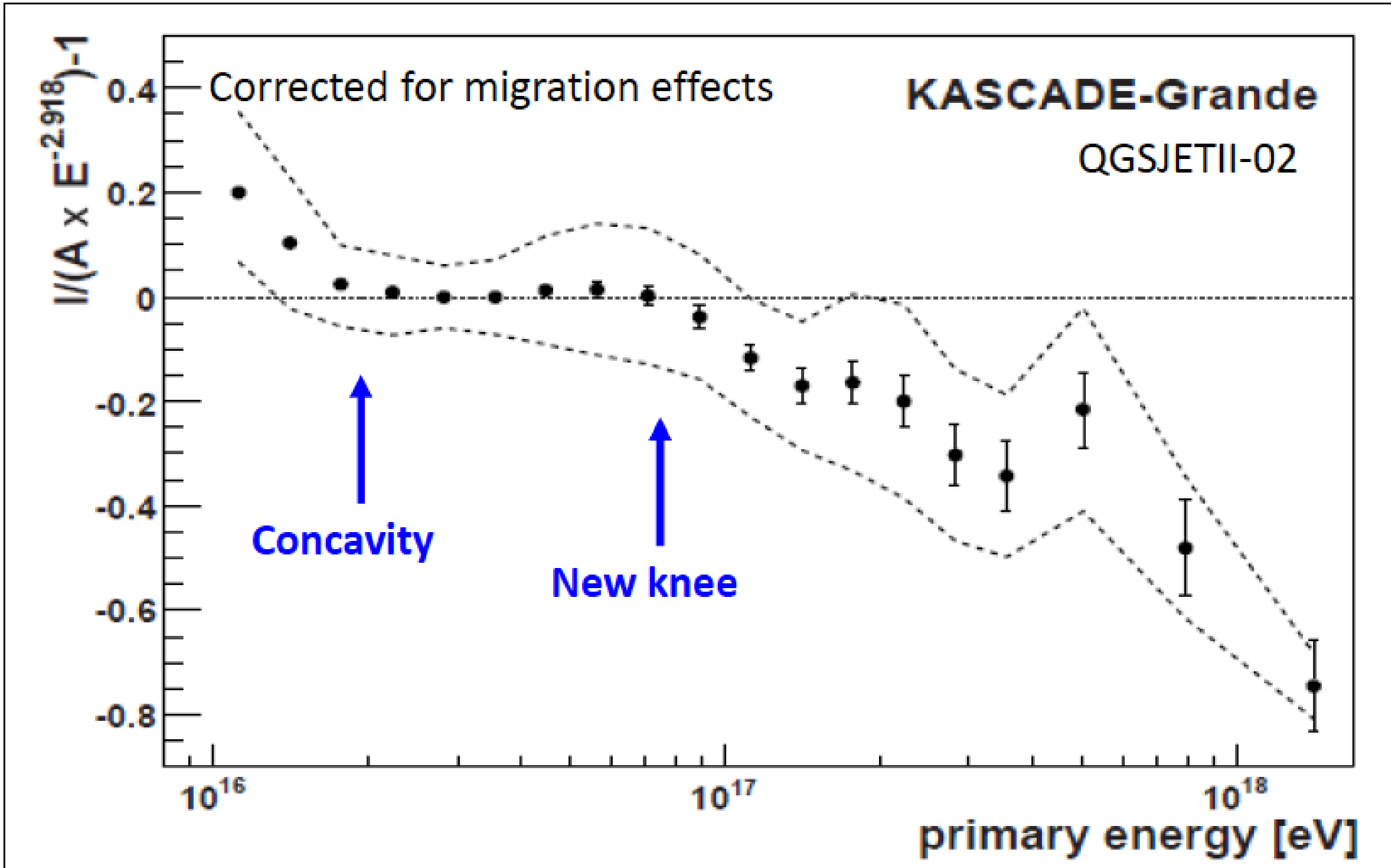
# SPECTRUM: from Knee to Cutoff



# 3) KASCADE-Grande experiment

***Energy spectrum: K-method***

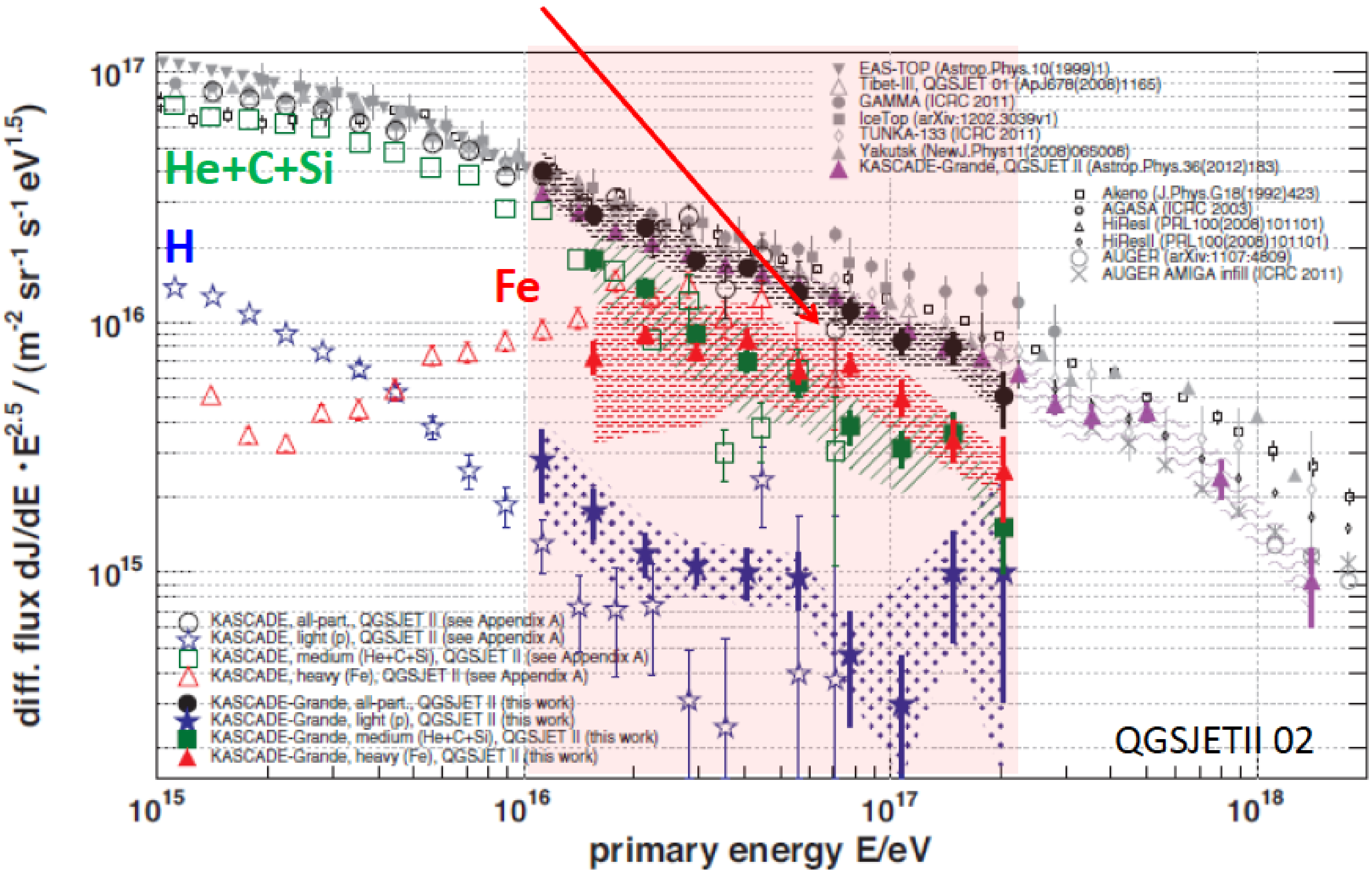
W.D.Apel, Astrop. Phys. 36 (2012) 183



Juan Carlos Arteaga-Velazquez

# 3) KASCADE-Grande experiment

Iron knee (E ≈ 80 PeV)
Consistent with position of break-off in heavy knee from K-method




KASCADE-Grande Coll., Astropart. Phys. 47 (2013)

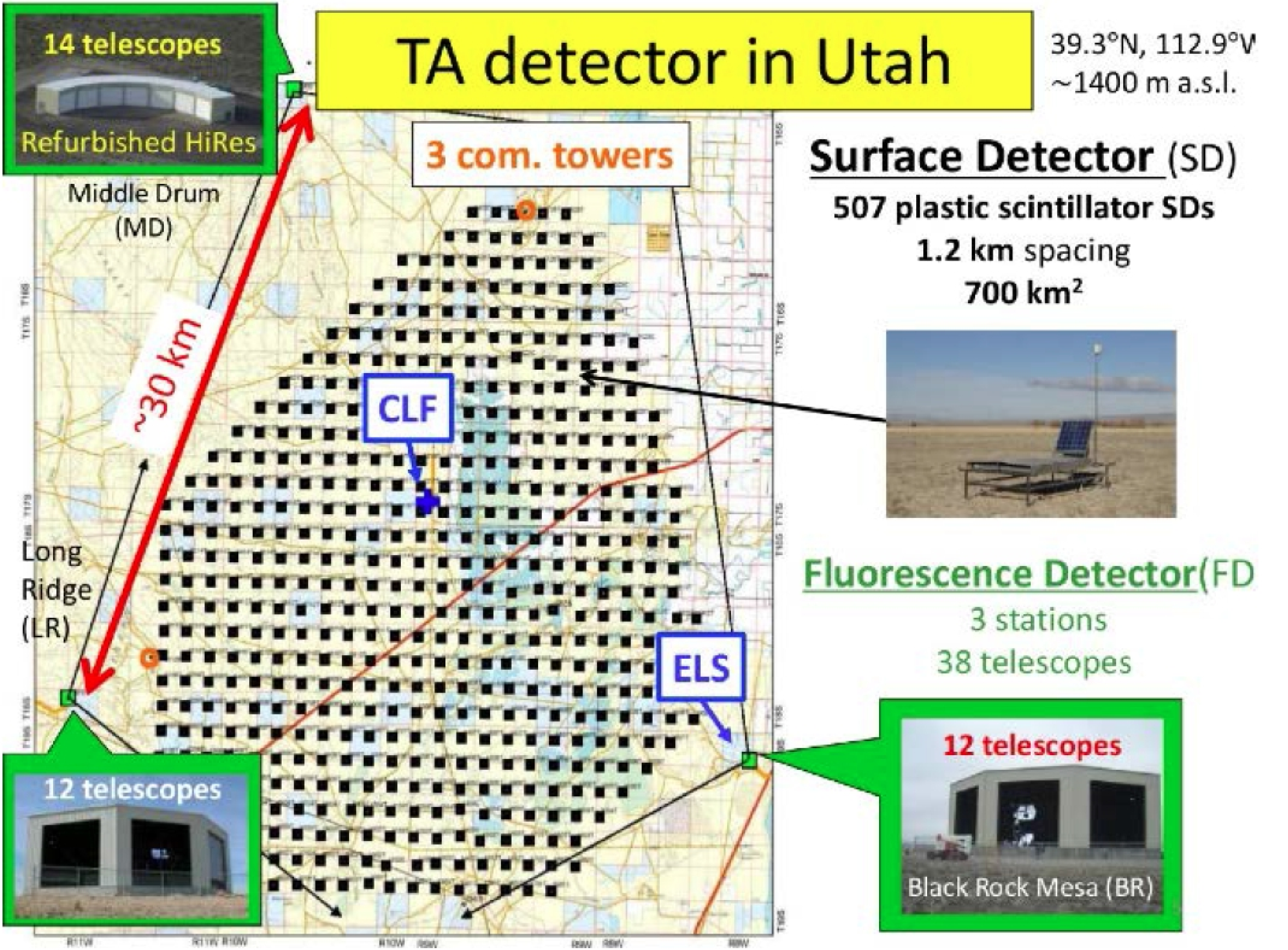
# ULTRA HIGH ENERGY COSMIC RAYS

Where the interplay between

*Hadronic physics* and
*Cosmic Ray Astrophysics*

is most important and most interesting

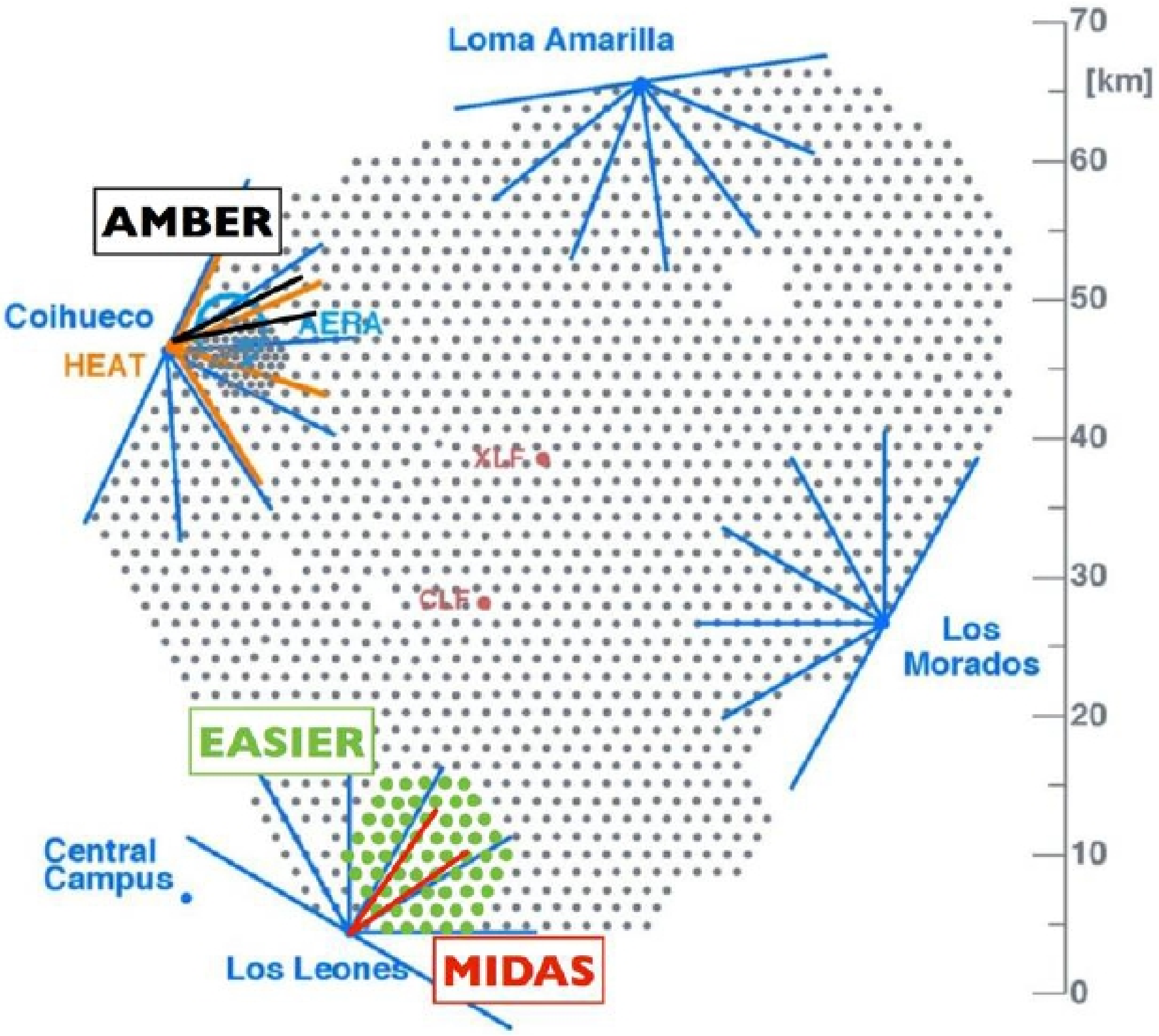
AUGER Observatory
TELESCOPE ARRAY


TA detector in Utah
39.3°N, 112.9°W
~1400 m a.s.l.
14 telescopes
Refurbished HiRes
Middle Drum
(MD)
3 com. towers
Surface Detector (SD)
507 plastic scintillator SDs
1.2 km spacing
700 km²
~30 km
CLF
Long
Ridge
(LR)
Fluorescence Detector(FD)
3 stations
38 telescopes
ELS
12 telescopes
12 telescopes
Black Rock Mesa (BR)

# Pierre Auger Observatory

**Fluorescence**:  4 telescopes

**Surface Array**:  covers 3000 km²
*1650 water-Cherenkov detectors*
*(10 m², 1.5 km separation)*



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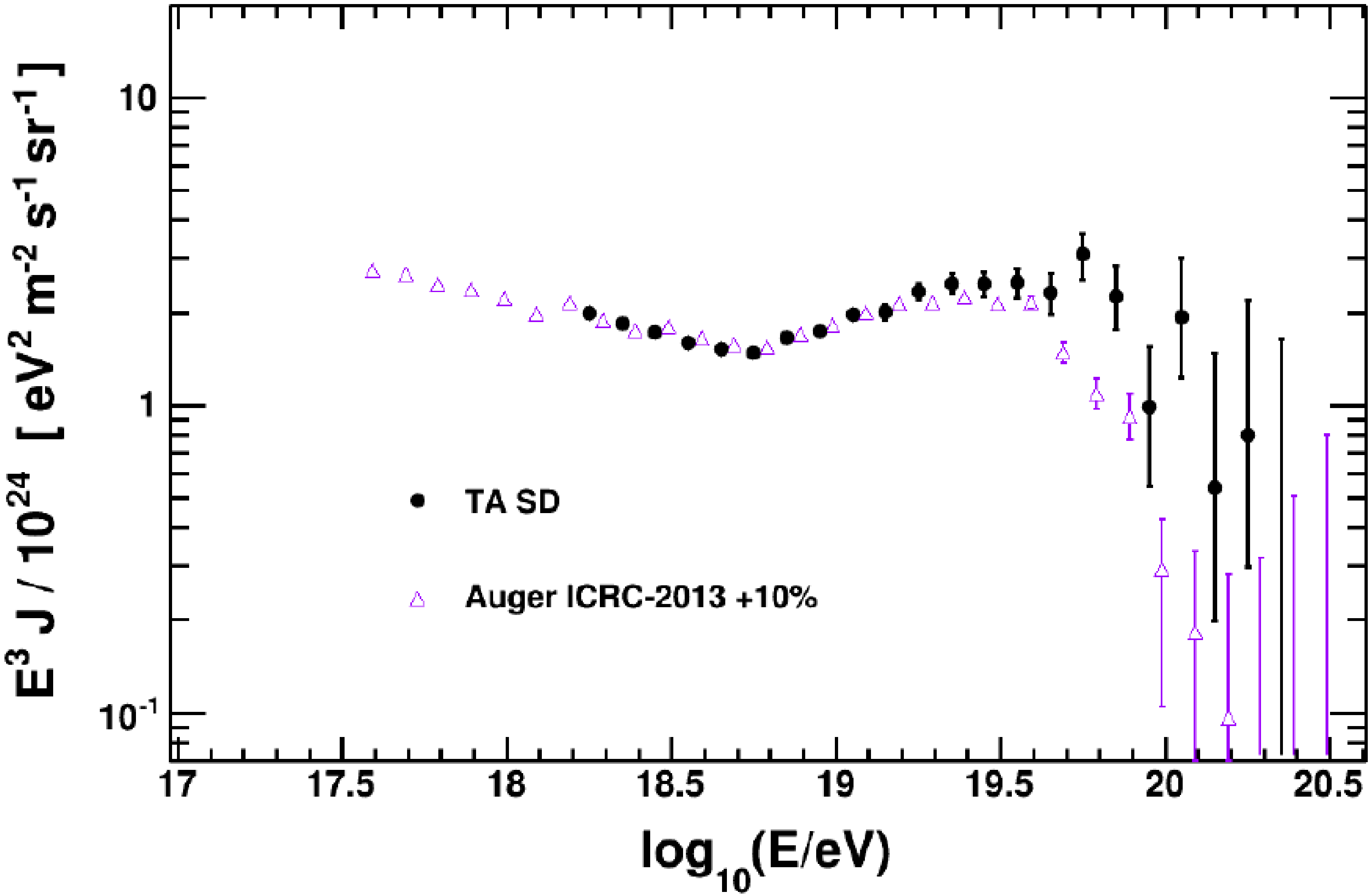
# CR Spectrum

**SD Data (6 Yrs: 20080511-20140511)**

**Comparison with Auger: ICRC 2013 + 10%**



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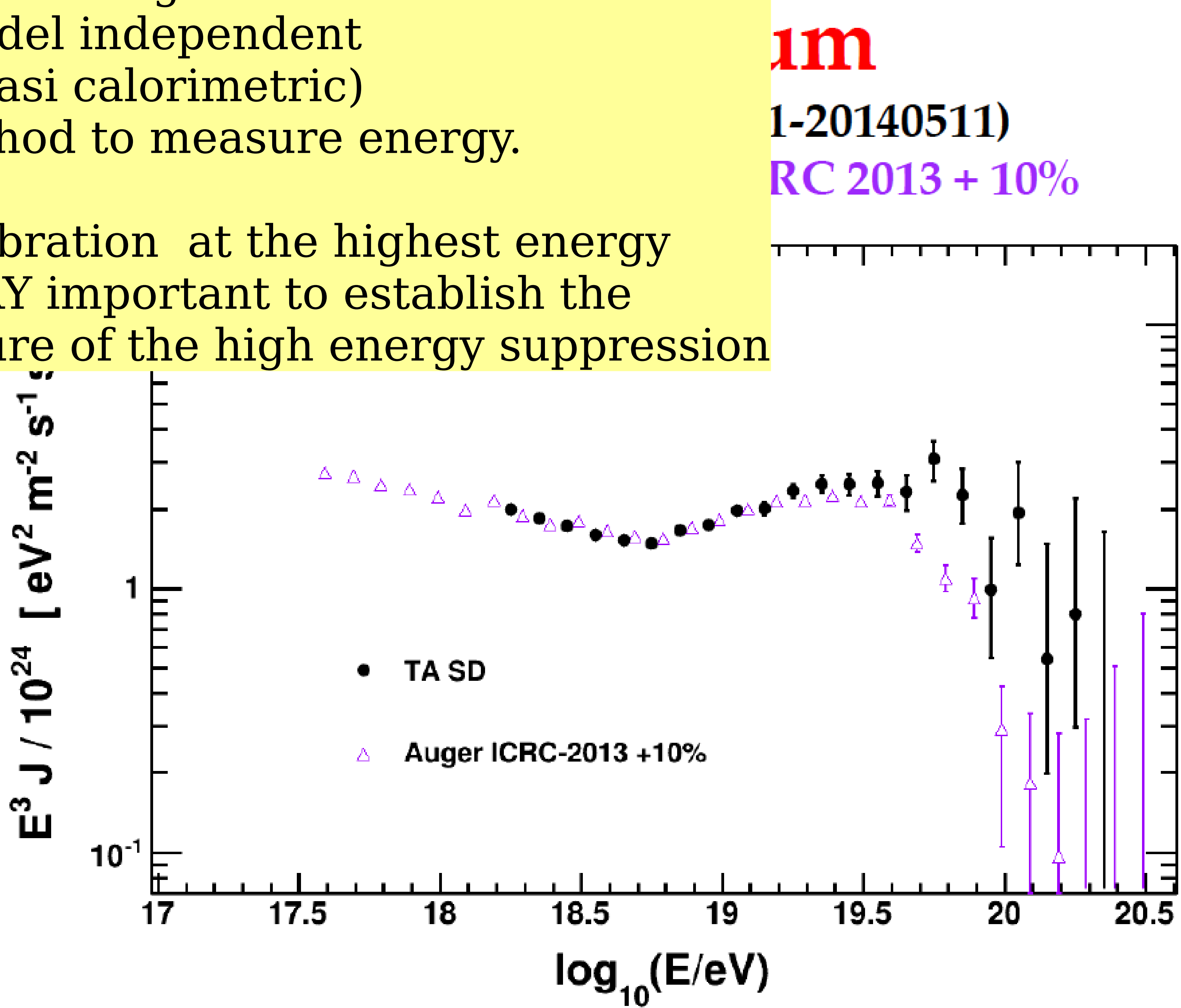
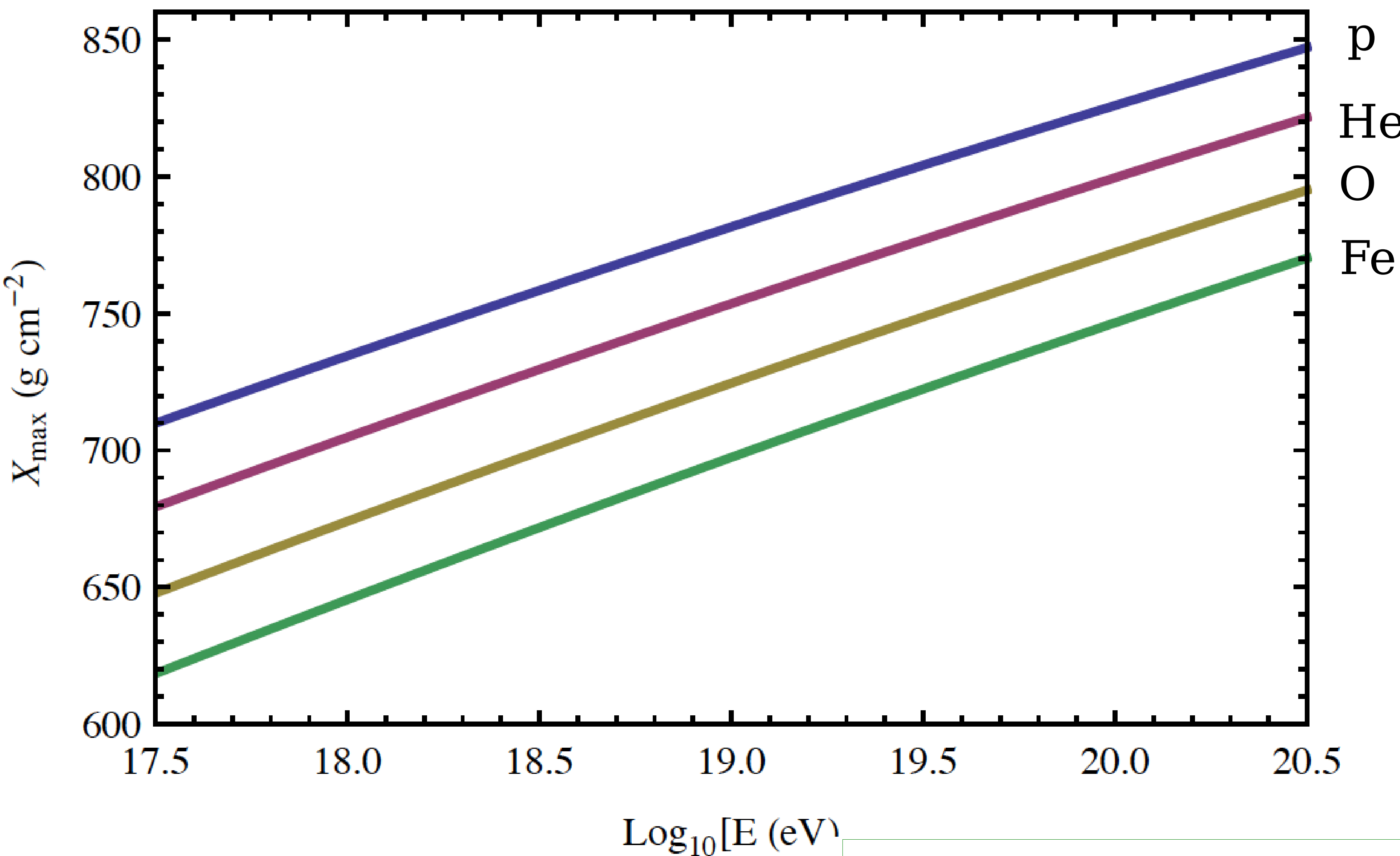
Beautiful agreement !
[Model independent
 (quasi calorimetric)
method to measure energy.

Calibration  at the highest energy
VERY important to establish the
nature of the high energy suppression



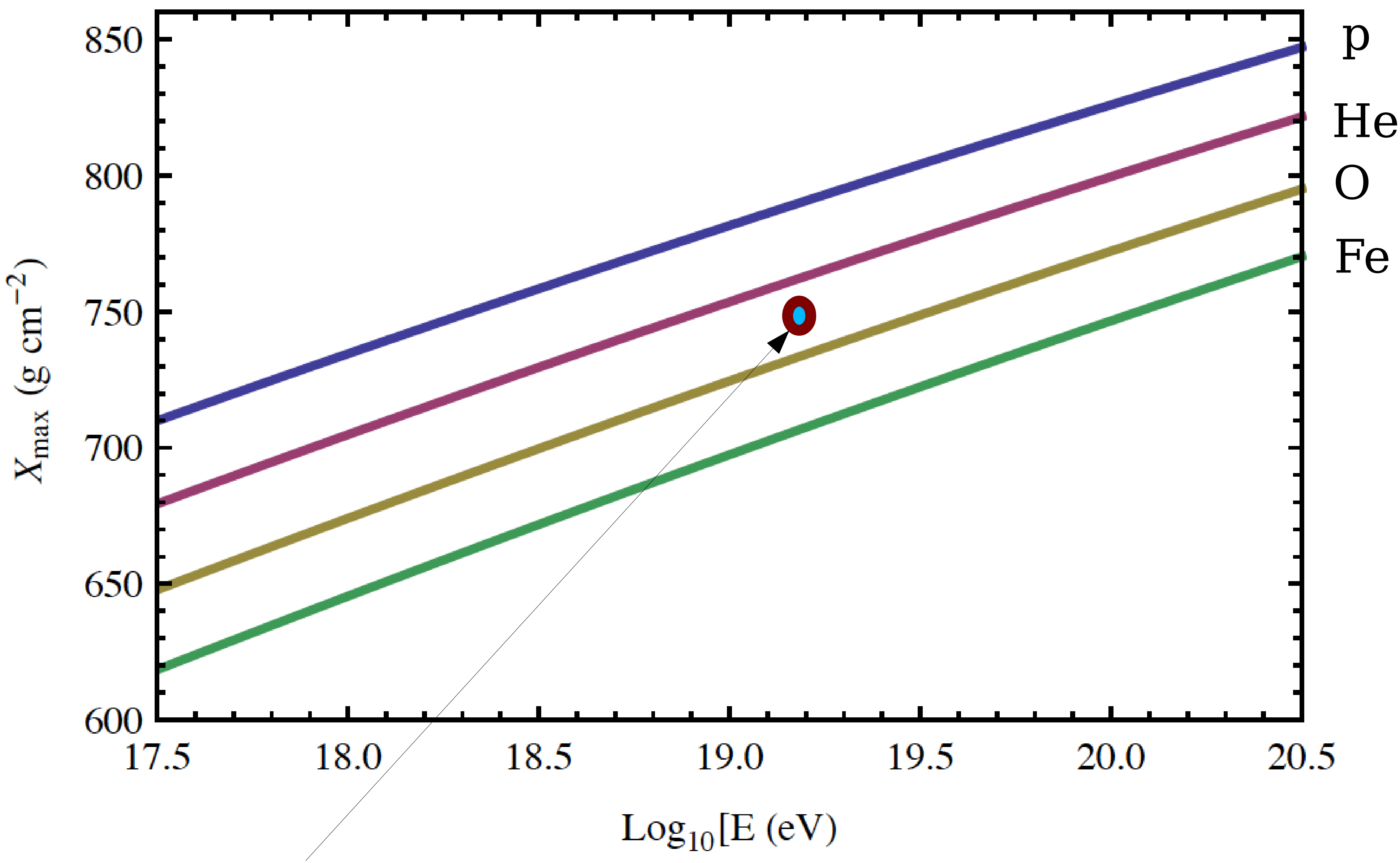



$$\boxed{\langle X_A \rangle \simeq \langle X_p \rangle - D_p \ \log_{10} A}$$

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

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

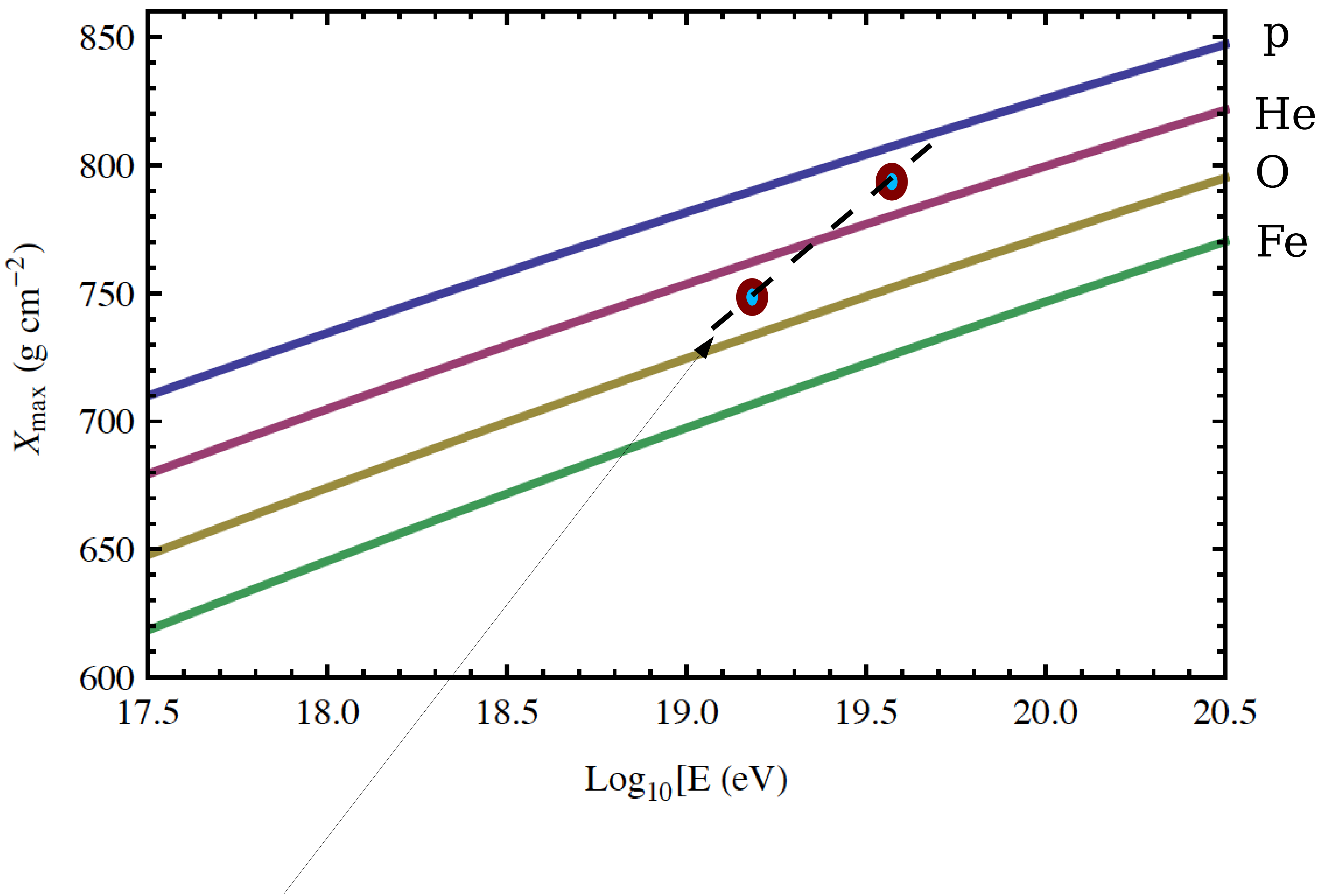
$$\langle X_{\mathrm{Fe}} \rangle \simeq \langle X_p \rangle - 90 \text{ g cm}^{-2}$$




Measurements of

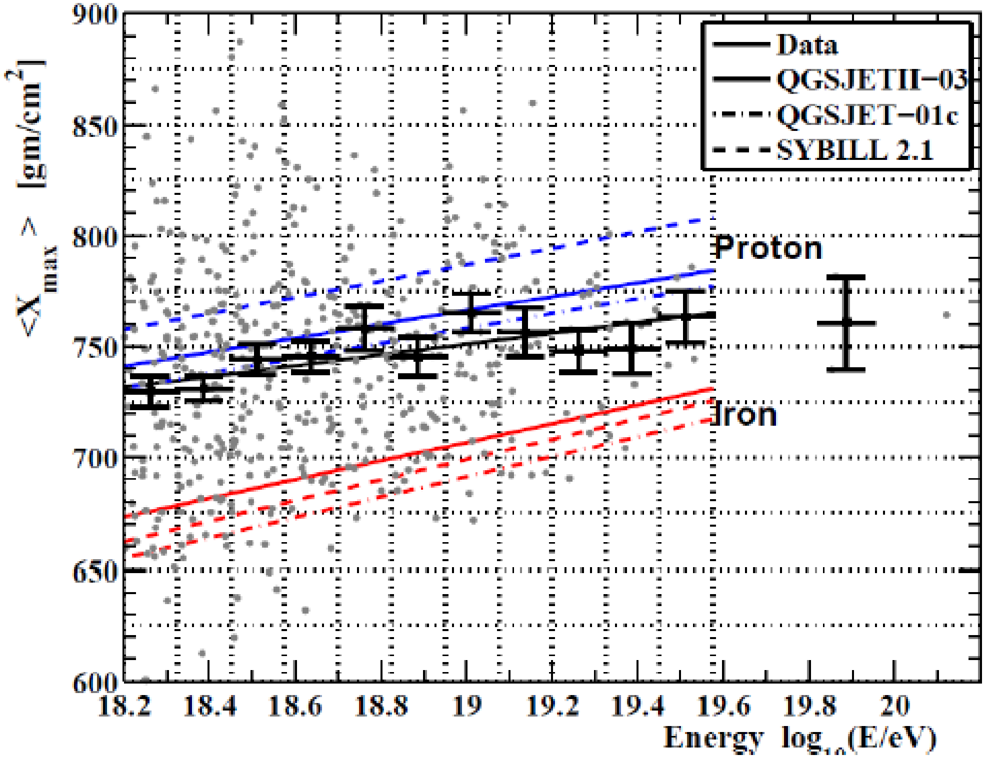
$$\langle \log A \rangle$$

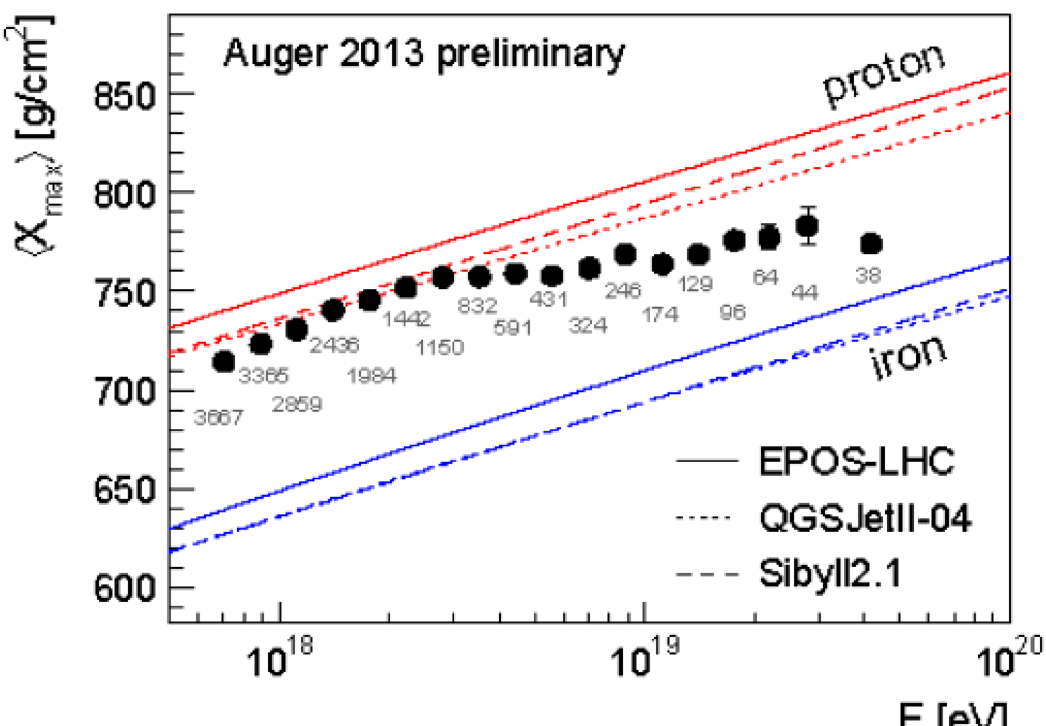
$$\langle \ln A \rangle_E = \frac{\sum_A \phi_A(E) \; \ln A}{\sum_A \phi_A(E)}$$




Measurements of Composition evolution.

Jim Matthews




# Composition

Measured using **depth of shower maximum** (*closely related to interaction length of primary*)

**TA and Auger apparently differ**

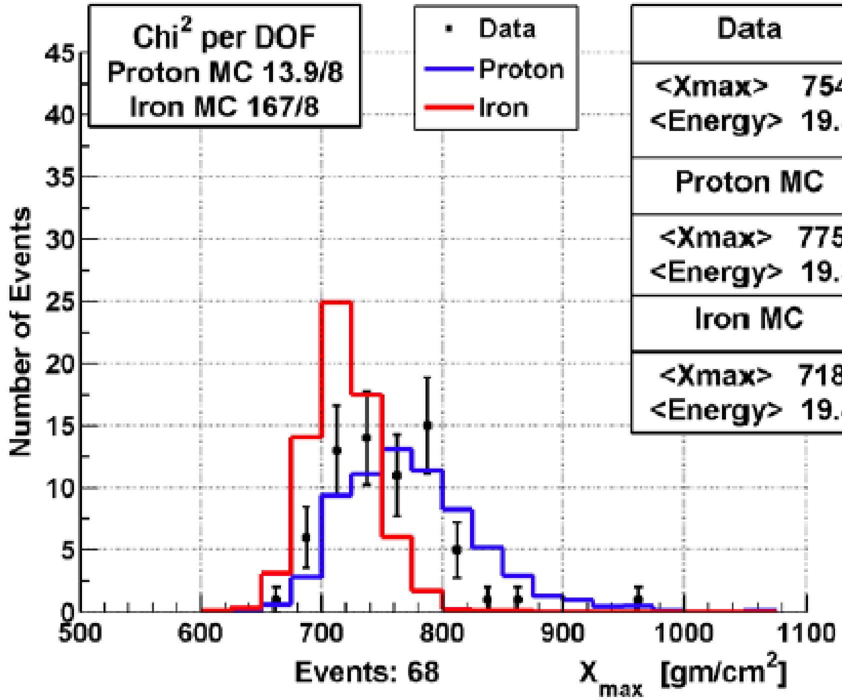
*(Opinion: the data differ less than the interpretation based on models)*

*Abbasi et al. arXiv:1408.1726v1*

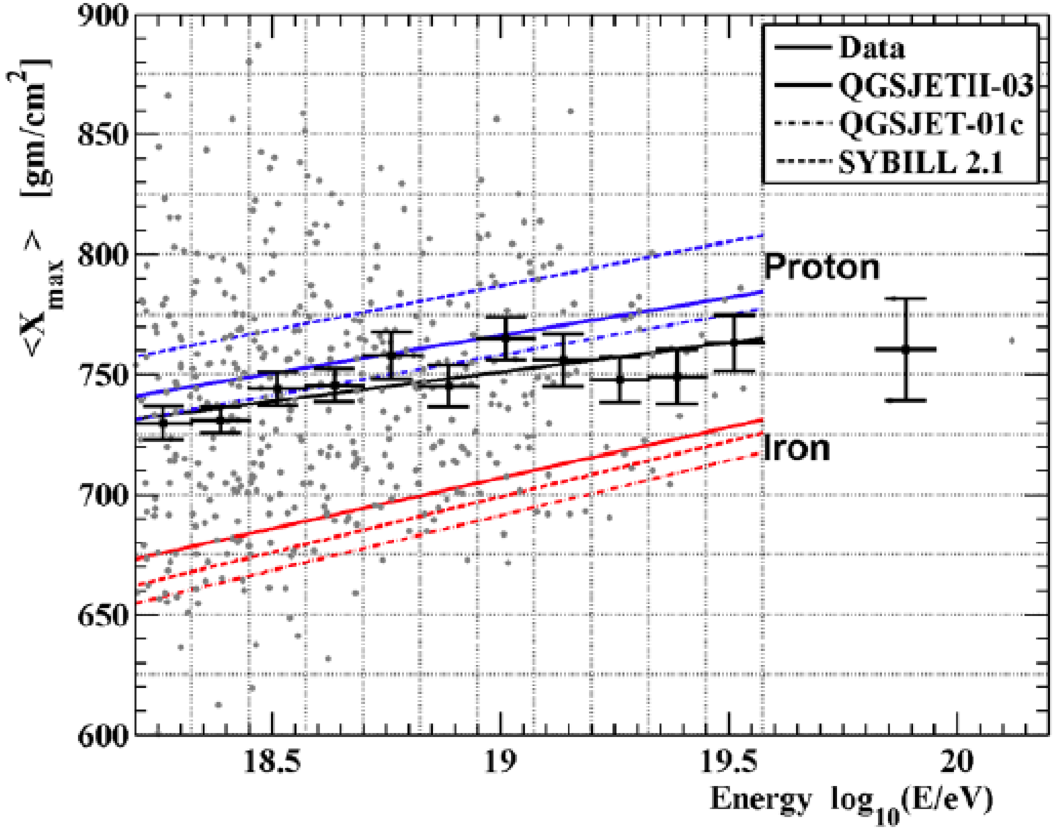
*Letessier-Selvon et al. arXiv:1310.4620*

Masaki Fukushima

# Xmax in Energy Slices
# Comparison to p/Fe MC



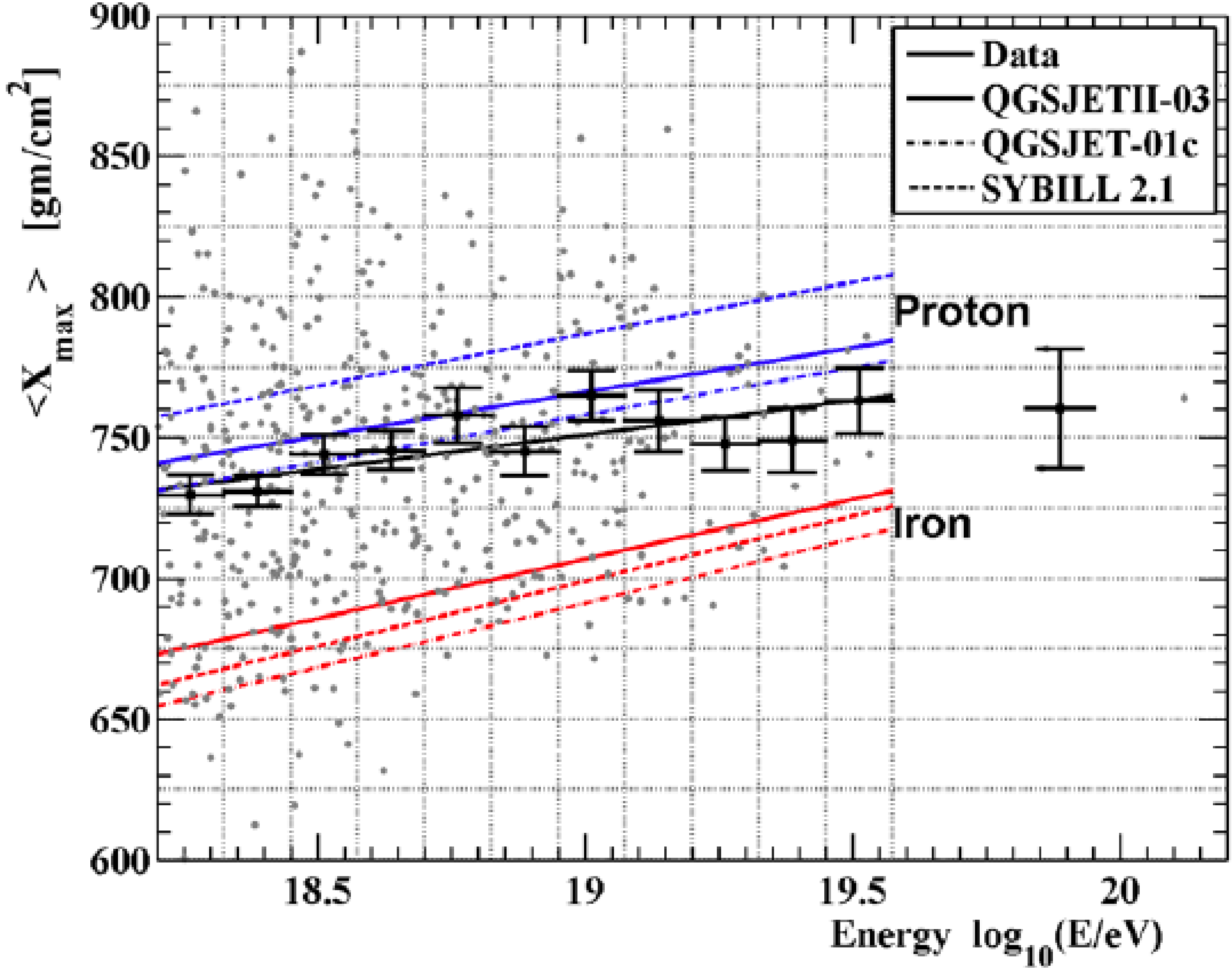

Log10(E/eV) > 19.0



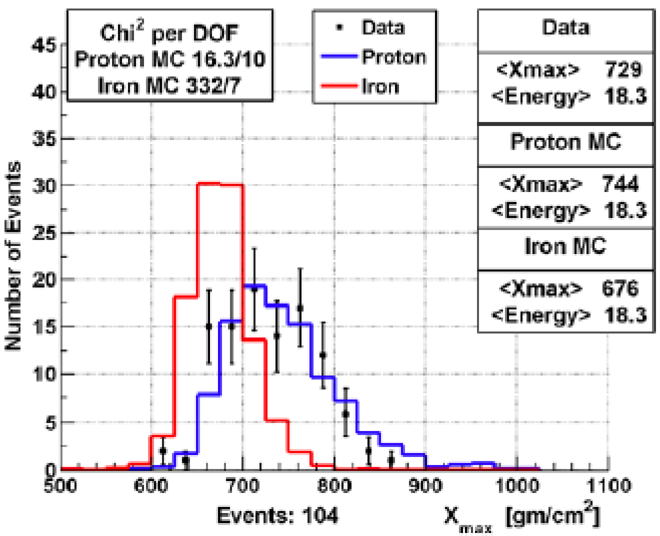

Results are consistent with proton at all energies and inconsistent with iron.

# Telescope Array

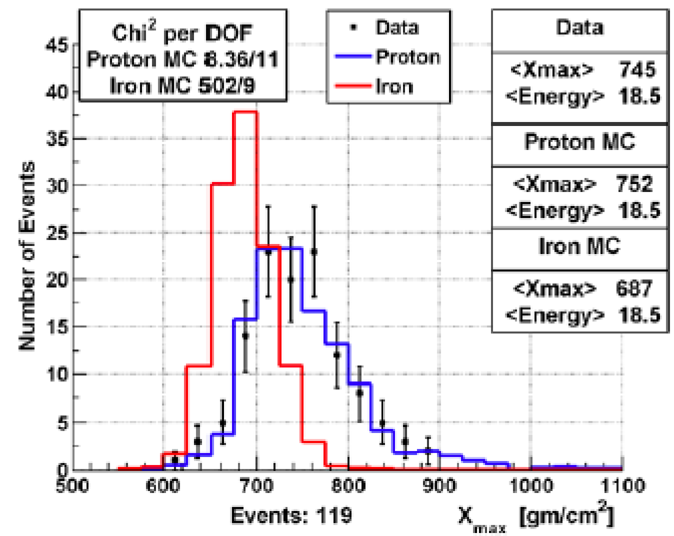
Masaki Fukushima



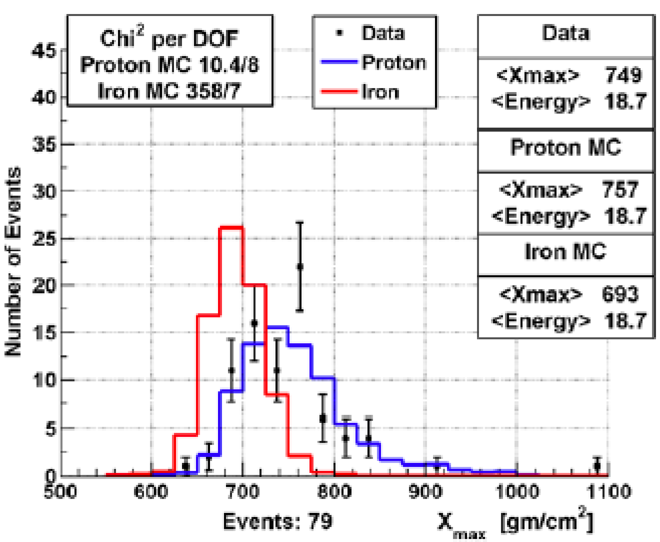
# Xmax in Energy Slices Comparison to p/Fe MC



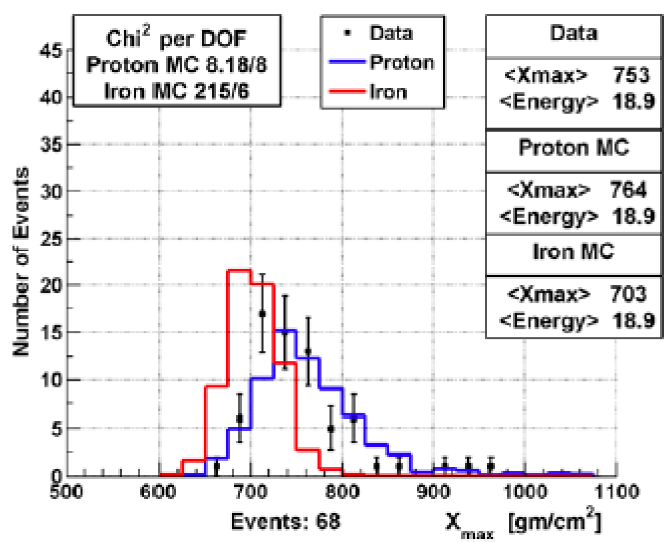

18.2 < Log10(E/eV) < 18.4




18.4 < Log10(E/eV) < 18.6




18.6 < Log10(E/eV) < 18.8

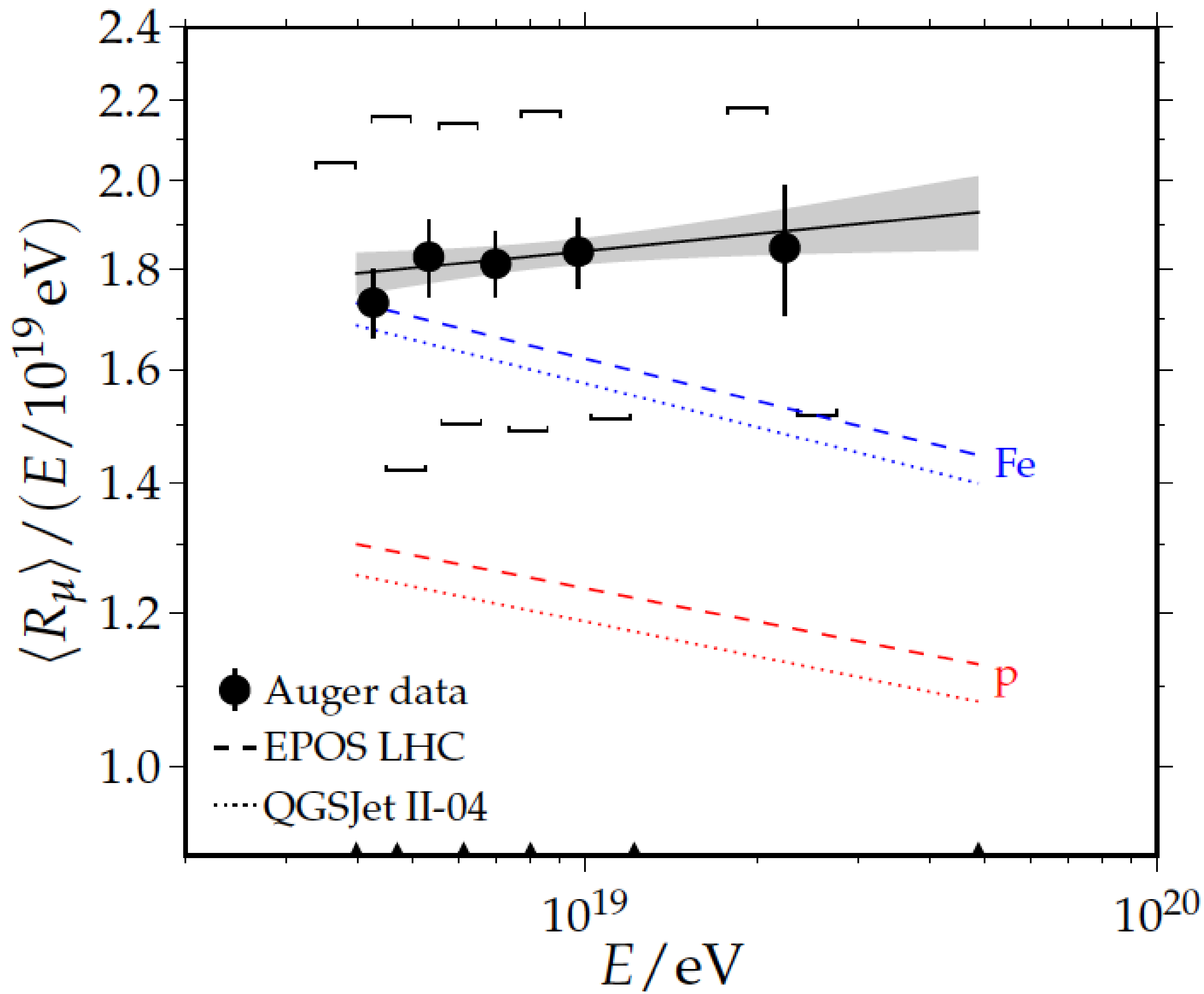



18.8 < Log10(E/eV) < 19.0

AUGER Coll.
astro/ph 1408.4121

Average Muon number
in UHECR hybrid events

$R_\mu = 1$ corresponds to $N_\mu = 1.455 \times 10^7$



# Modeling of

# HADRONIC INTERACTIONS

# Quantum
# Chromo
# Dynamics

*Fundamental theory of the strong interactions*

# Quantum Chromo Dynamics

Instant history
of QCD in 4 nobel prizes

The proton is NOT point-like
(1955-1956)

$$\sqrt{\langle r^2 \rangle} \simeq 0.81 \text{ fm}$$

$$1 \text{ fm} \equiv 10^{-13} \text{ cm}$$

Robert Hofstadter

1961 Nobel prize to Robert Hofstadter
“for his pioneering studies in electron scattering
in atomic nuclei and for his thereby achieved discoveries
Concerning the structure of the nucleons

$$\left.\frac{d\sigma}{dQ^2}\right|_{ep\to ep} \simeq \left.\frac{d\sigma}{dQ^2}\right|_{\text{point}} \times \left|F(Q^2)\right|^2$$

$$F(Q^2) = \frac{1}{(1 + Q^2\, r_0^2)^2}$$

$$\boxed{\begin{aligned} q &= k - k' \\ Q^2 &= -q^2 \end{aligned}}$$

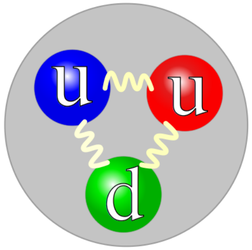
The electromagnetic form factor of the proton

$$\rho_p(r) \propto e^{-r/r_0}$$

$$\boxed{\sigma_{pp} \sim \pi\, R_p^2 \simeq \ 3 \text{ fm}^2 \simeq 30 \text{ mbarn}}$$

# A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
*California Institute of Technology, Pasadena, California*




Received 4 January 1964

Baryons and Mesons are (formally) made of "Fundamental Entities"

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

6) James Joyce, Finnegan's Wake (Viking Press, New York, 1939) p.383.

Three quarks for Muster Mark!

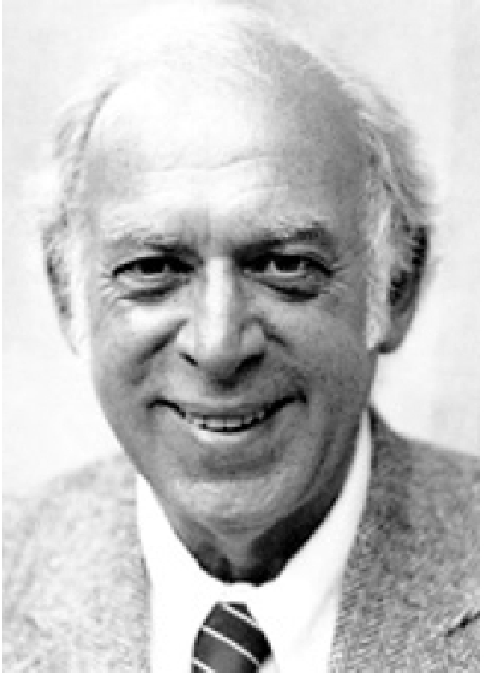
Sure he has not got much of a bark

And sure any he has it's all beside the mark.

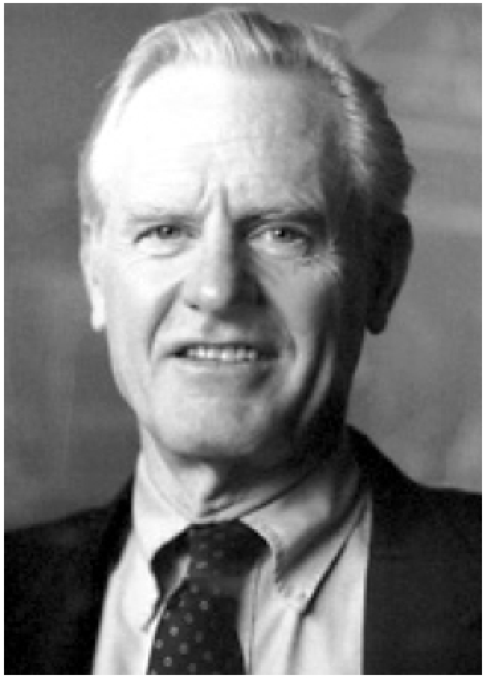
—James Joyce, *Finnegans Wake*[44]

The Nobel Prize in Physics 1990
Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor

# Quarks as “Partons” (1969)



Jerome I. Friedman



Henry W. Kendall

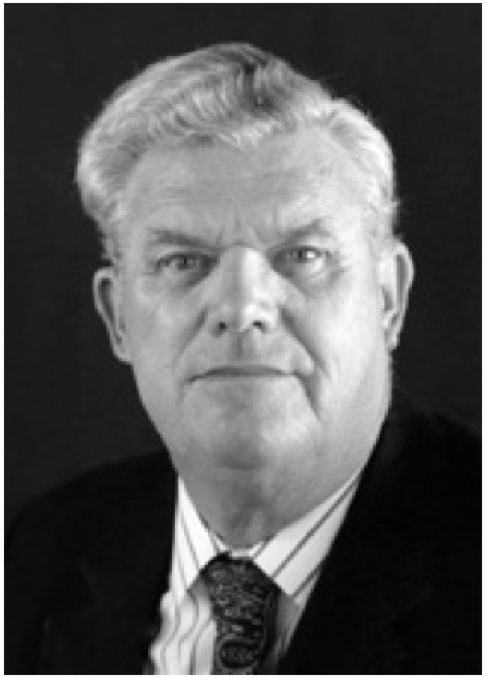


Photo: T. Nakashima

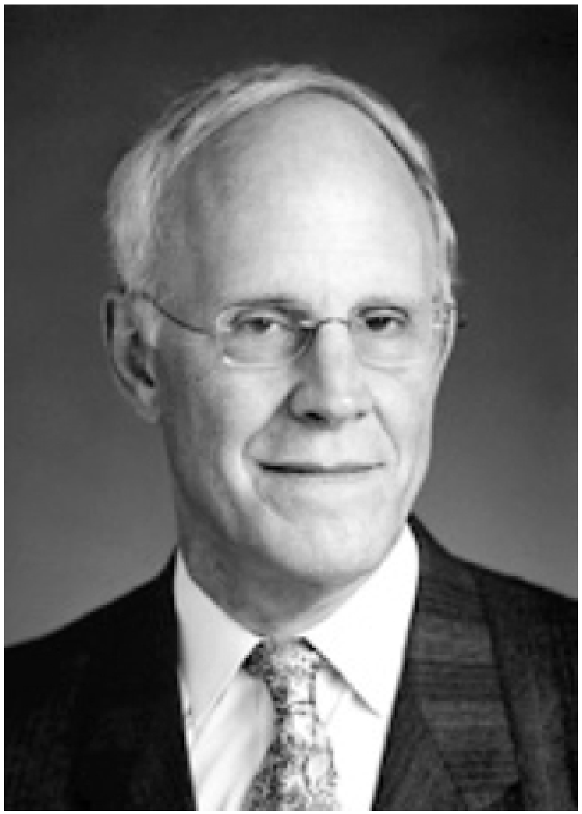
Richard E. Taylor

The Nobel Prize in Physics 1990 was awarded jointly to Jerome I. Friedman, Henry W. Kendall and Richard E. Taylor *"for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics"*.

# The Nobel Prize in Physics 2004

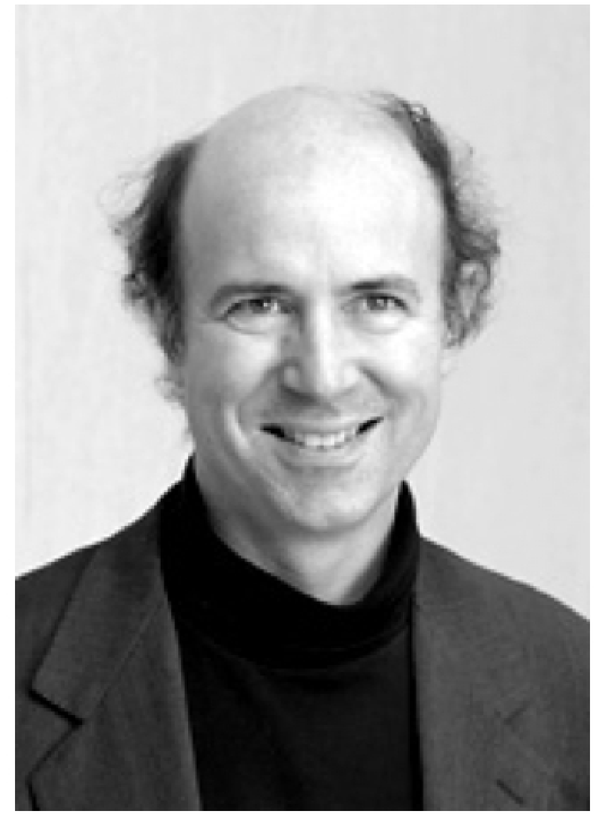
## David J. Gross, H. David Politzer, Frank Wilczek

QCD



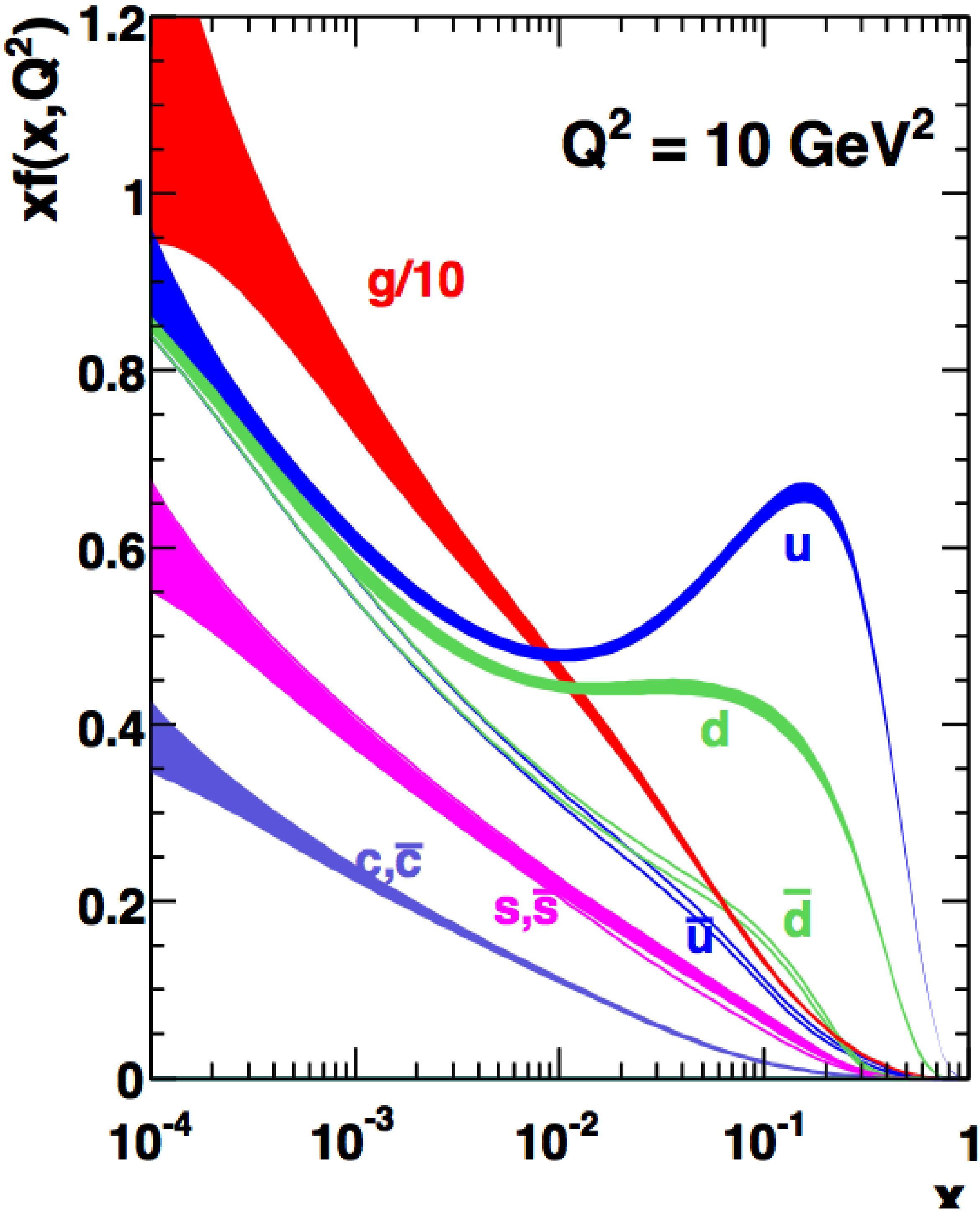
David J. Gross

H. David Politzer



Frank Wilczek

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek *"for the discovery of asymptotic freedom in the theory of the strong interaction"*.




# Parton Distribution Functions

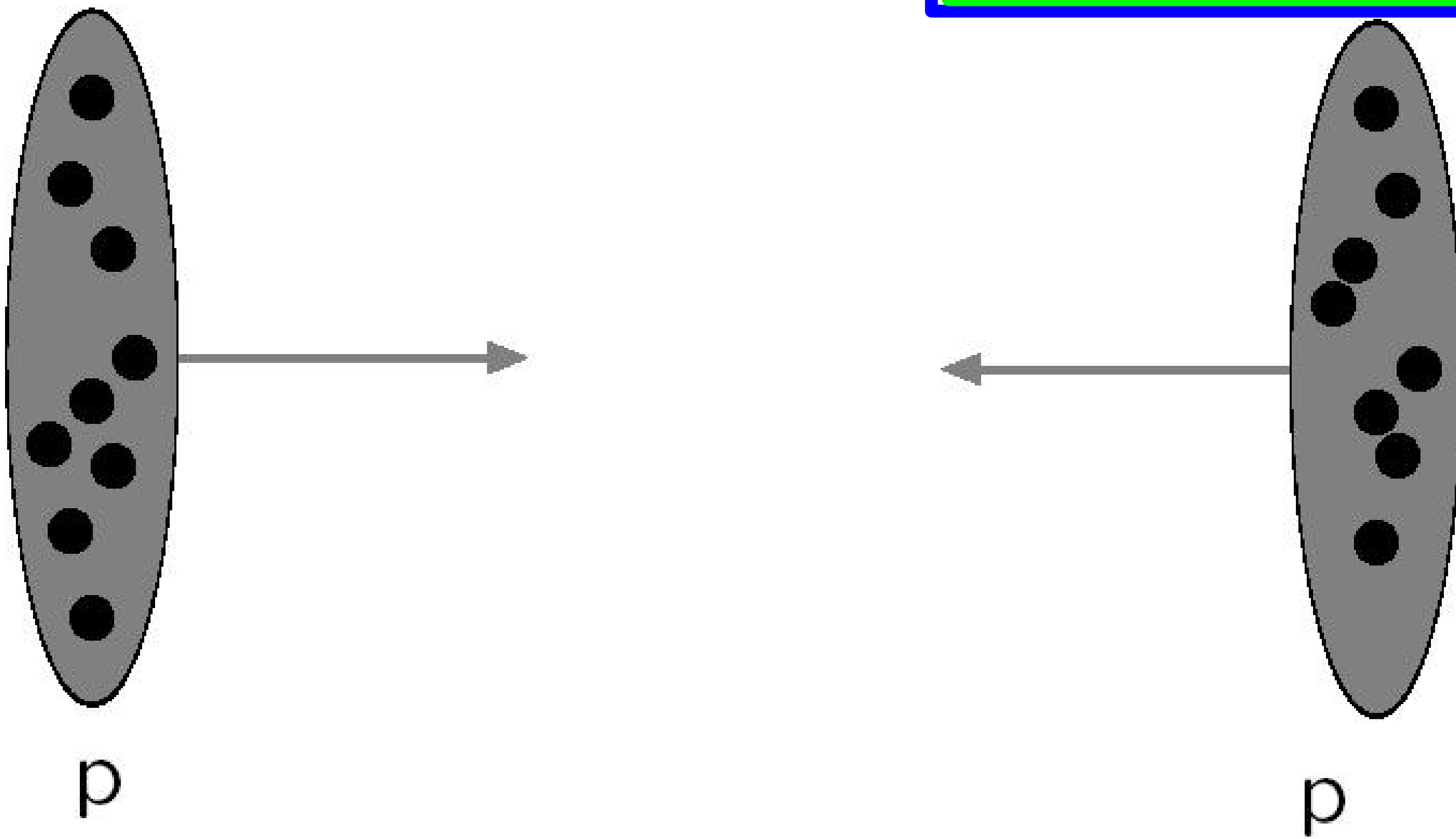
$$f_j(x) \propto \frac{1}{x^{1+\delta}}$$

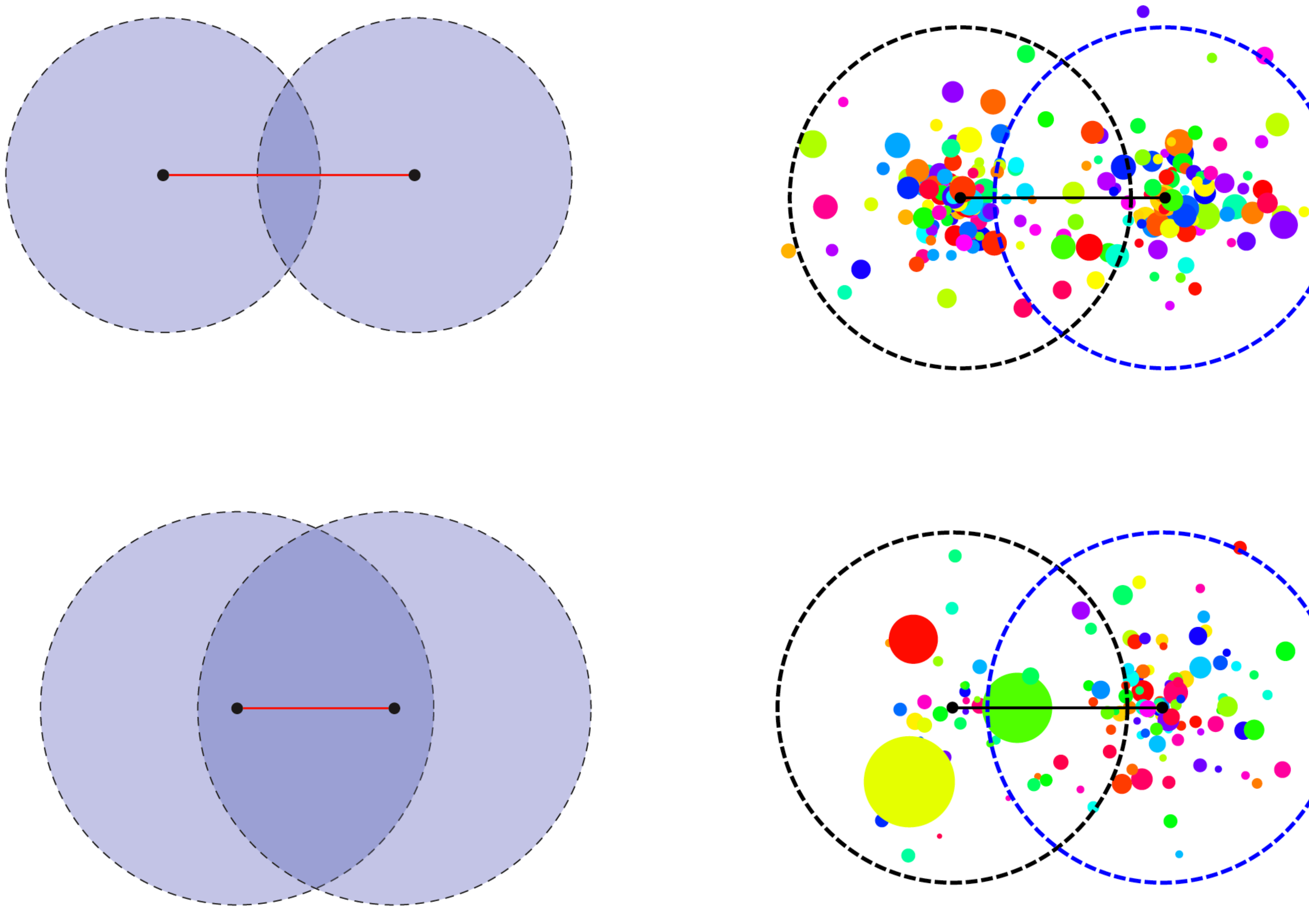
Rapid growth
for x → 0

Hadronic Interactions

Composite (complex) Objects
Multiple interaction structure

QCD



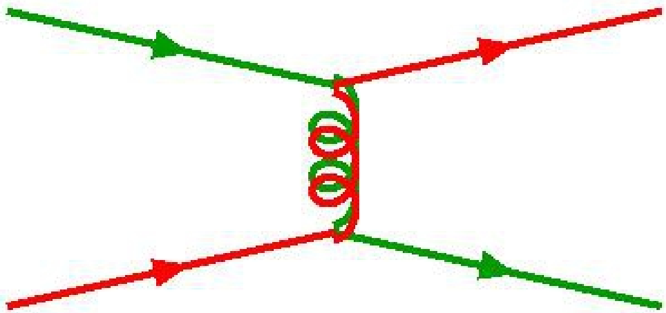


Multiple Parton Interactions
(in the same collision)
is the essential element in the modeling

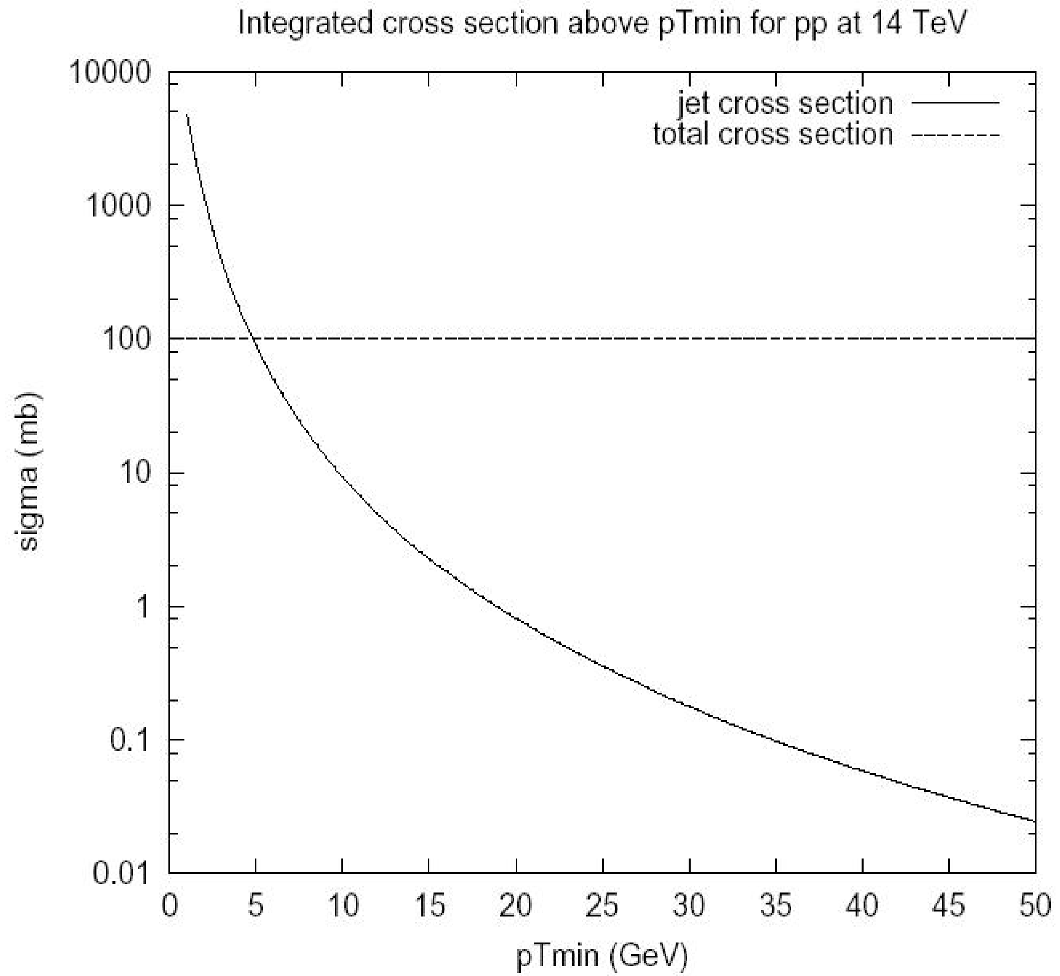
Problem of
“correlated PdF's” (energy conservation).

Problem of the “b-dependence” of the PdF's.

# QCD $2 \to 2$



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




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

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

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

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

Interacting Partons

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

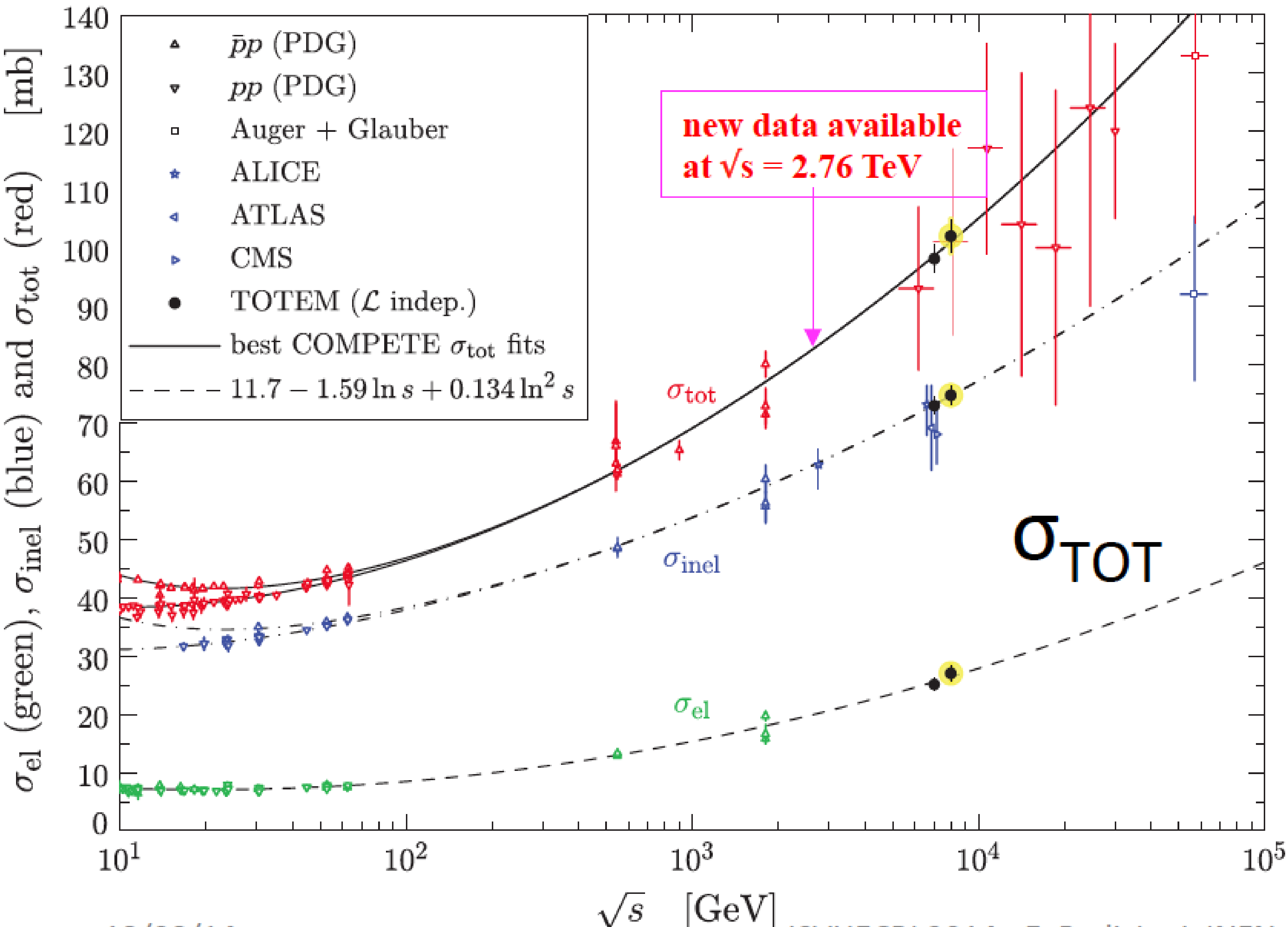
$$x_1 \ x_2 \gtrsim \frac{Q^2_{\rm min}}{s}$$ hard

Increasing the
c.m. Energy:

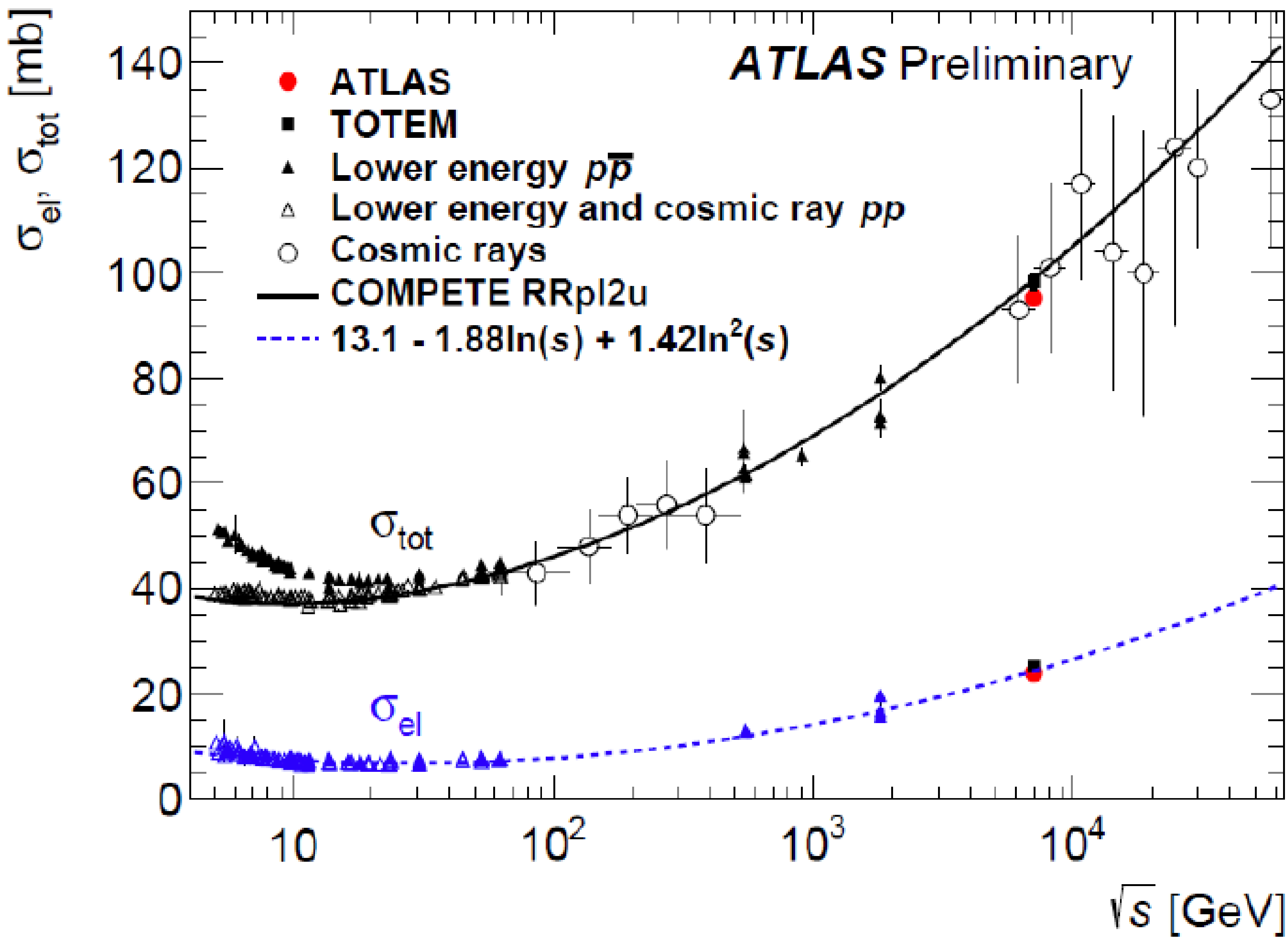
More parton-parton
Interactions

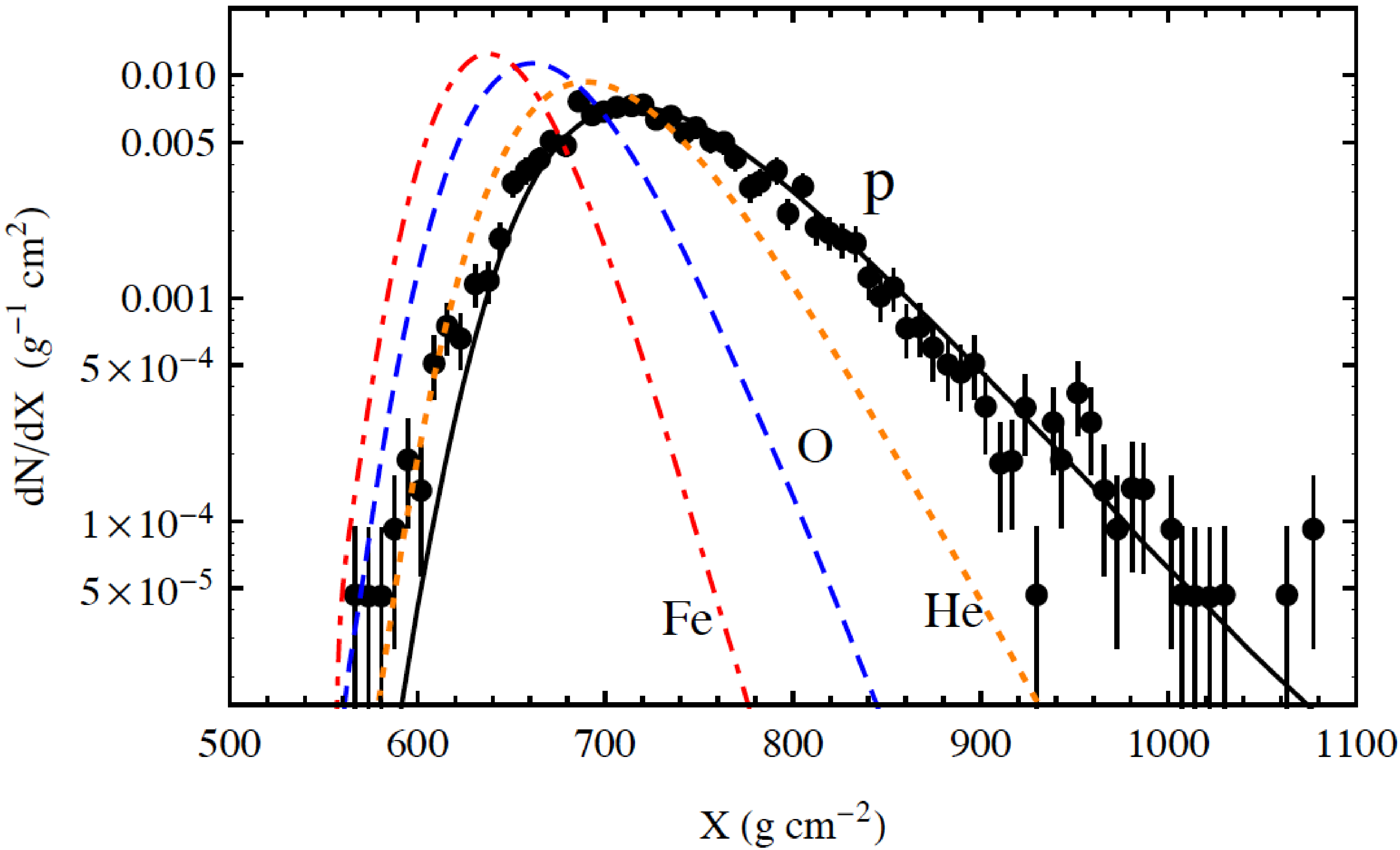
pp cross section grows
Higher multiplicity.
More complex event.
Softer energy spectra.

# TOTEM measurements of total, elastic inelastic cross sections sqrt[s] = 7,8 TeV



# Recent ATLAS  measurement at 7 TeV





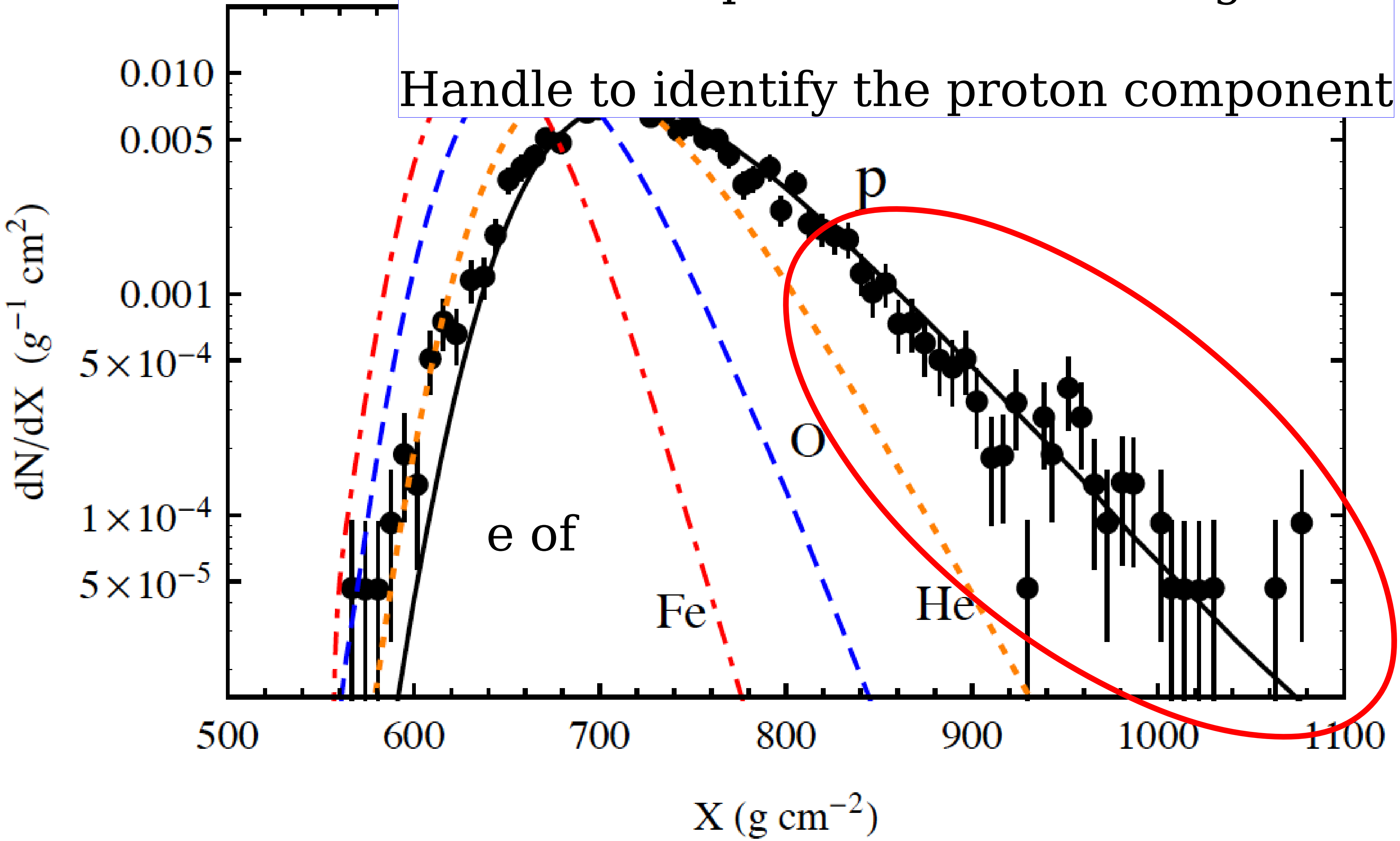

AUGER DATA
(Sibyll simulation)

Logarithmic scale

$$E = 10^{18.25}\ \mathrm{eV}$$

Estimate of p-Air interaction length.

Handle to identify the proton component




Logarithmic scale

$$E = 10^{18.25}\ \mathrm{eV}$$

VOLUME 52, NUMBER 16 PHYSICAL REVIEW LETTERS 16 APRIL 1984

# Total Proton-Proton Cross Section at $s^{1/2} = 30$ TeV

R. M. Baltrusaitis, G. L. Cassiday, J. W. Elbert, P. R Gerhardy,
S. Ko, E. C. Loh, Y. Mizumoto, P. Sokolsky, and D. Steck
*University of Utah, Salt Lake City, Utah 84112*
(Received 16 January 1984)

We have measured the proton-air inelastic cross section at $s^{1/2} = 30$ TeV by observing the distribution of extensive-air-shower maxima as a function of atmospheric depth. This distribution has an exponential tail whose slope is $\lambda = 72 \pm 9$ g cm$^{-2}$ which implies that $\sigma_{p-\mathrm{air}}^{\mathrm{inel}} = 530 \pm 66$ mb. Using Glauber theory and assuming that the elastic-scattering slope parameter $b$ is proportional to $\sigma_{pp}^{\mathrm{tot}}$, we infer a value of $\sigma_{pp}^{\mathrm{tot}} = 120 \pm 15$ mb which lies between a $\log s$ and a $\log^2 s$ extrapolation of the total $pp$ cross section as measured at lower energies.

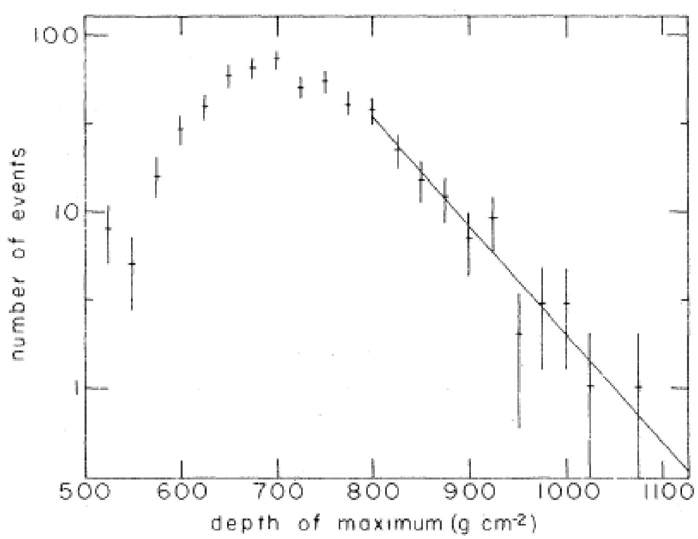
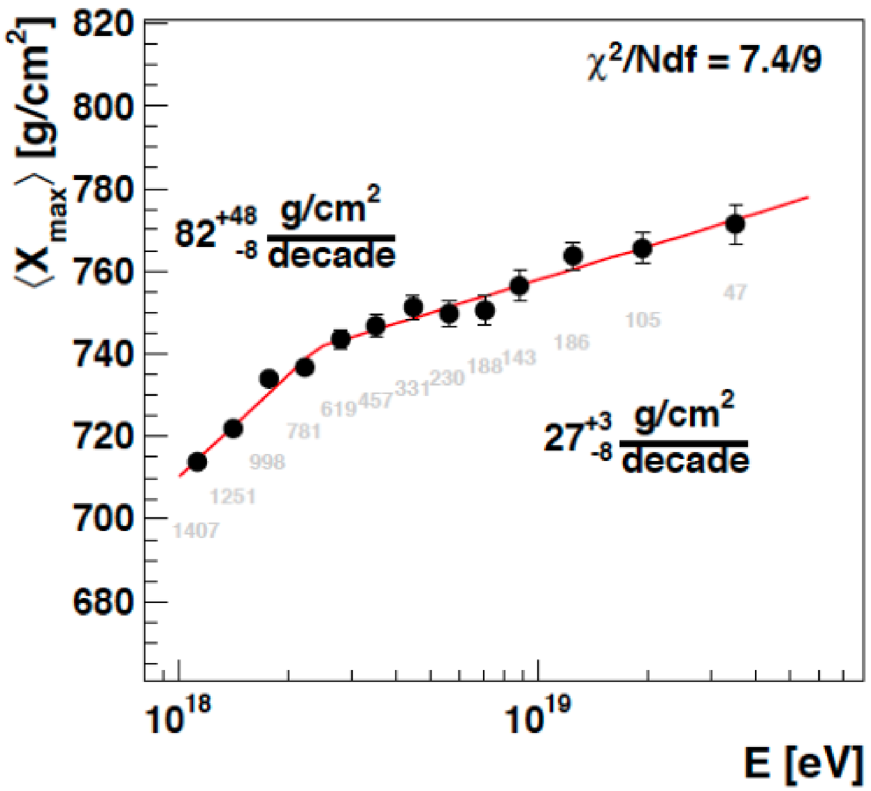



FIG. 5. Distribution of depth of maxima $X_{\max}$ for data whose fitting errors are estimated to be $\delta x < 125$ g cm$^{-2}$. The slope of the exponential tail is $\lambda = 73 \pm 9$ g cm$^{-2}$.

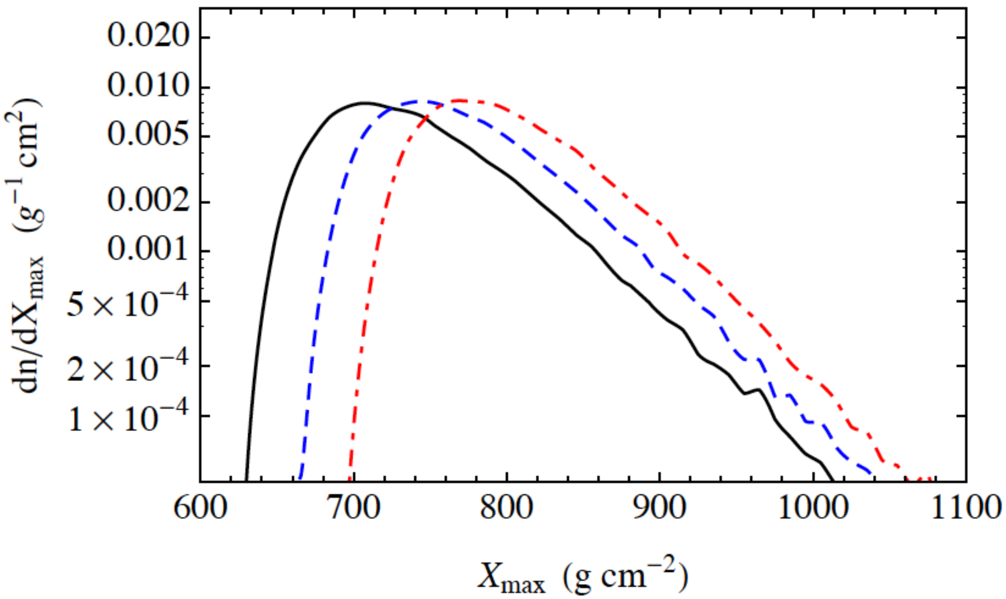
# Pioneering work of Fly's Eye

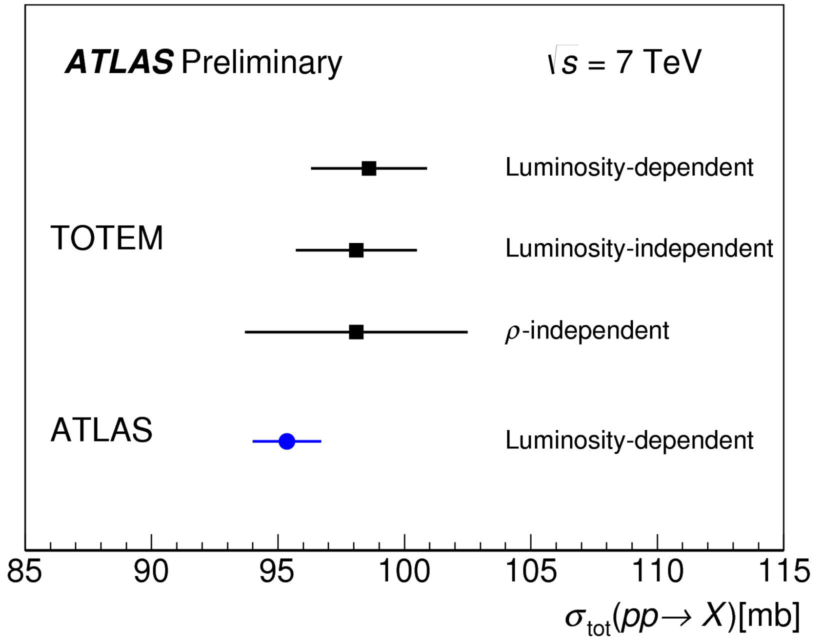
The (p-air) “Pierre” cross section

Very attractive
[.... and also "unavoidable" ]
to extend this type of analysis
to lower and higher energies

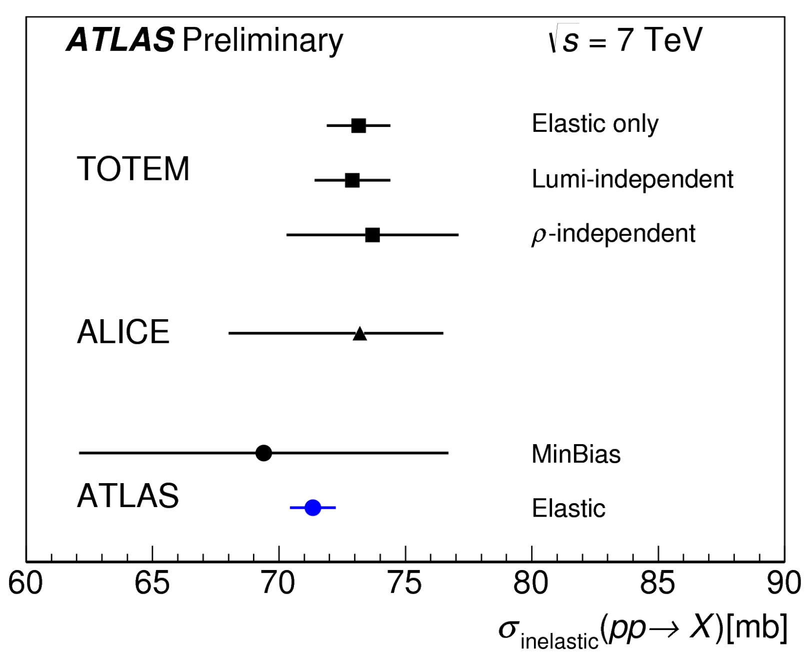


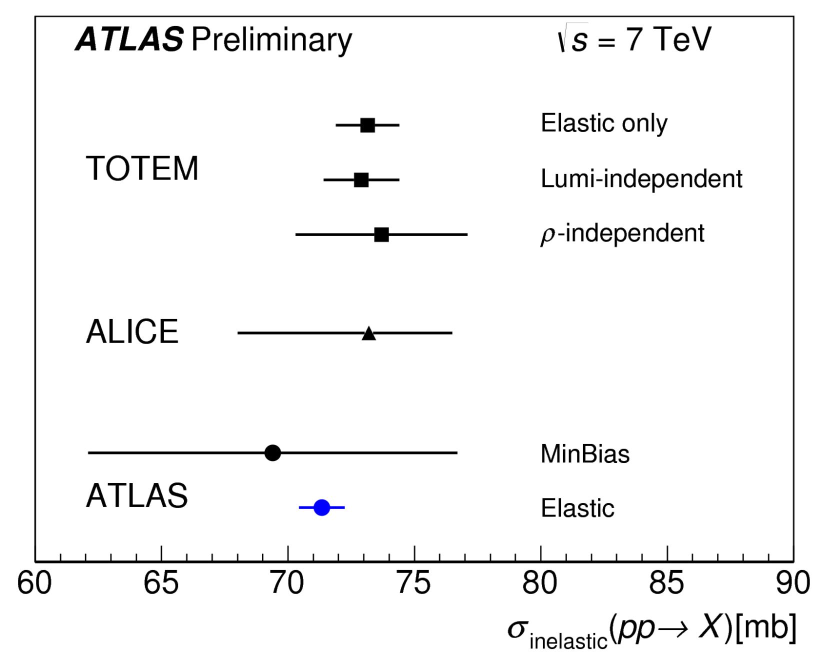

Proton-showers
[growing energy]



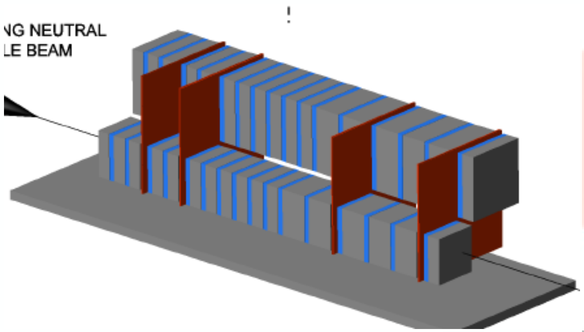


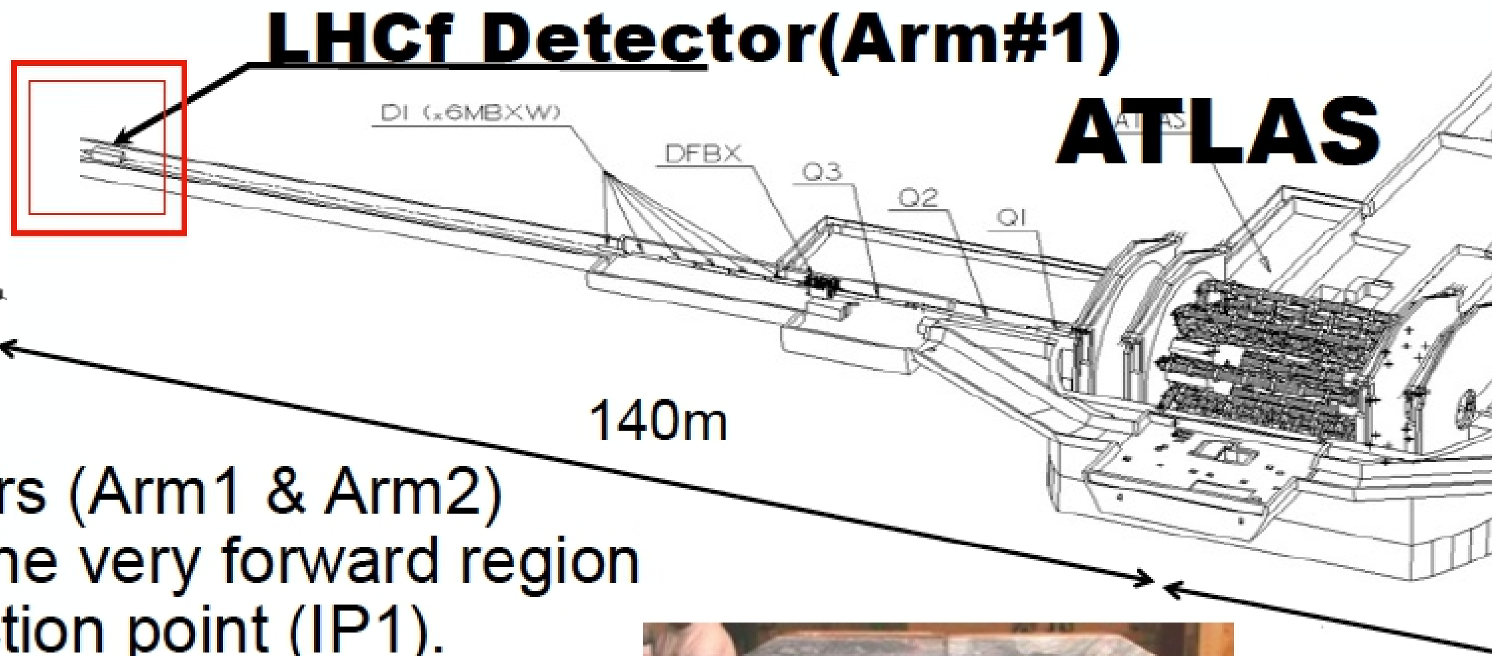

$$\text{ATLAS} \quad \sigma_{tot} = 95.4 \pm 1.4 \text{ mb}$$
$$\text{TOTEM} \quad \sigma_{tot} = 98.6 \pm 2.2 \text{ mb}$$



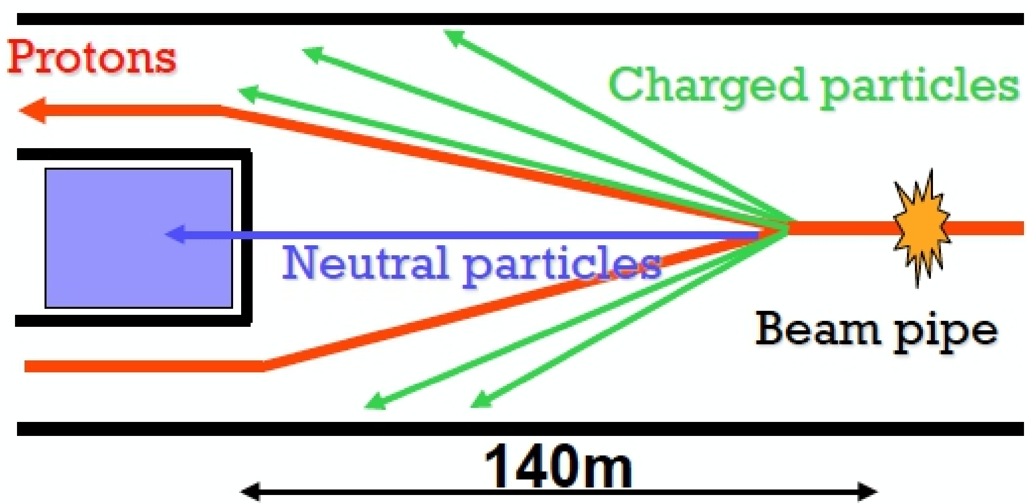



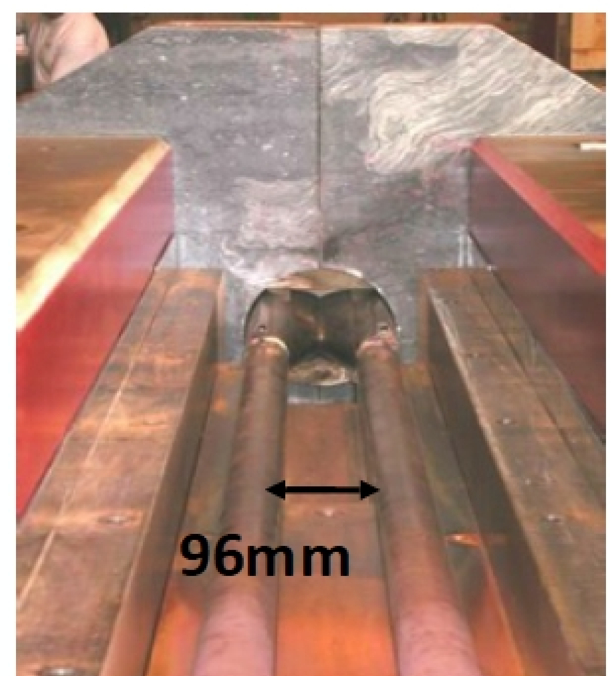
# LHCf Experiment



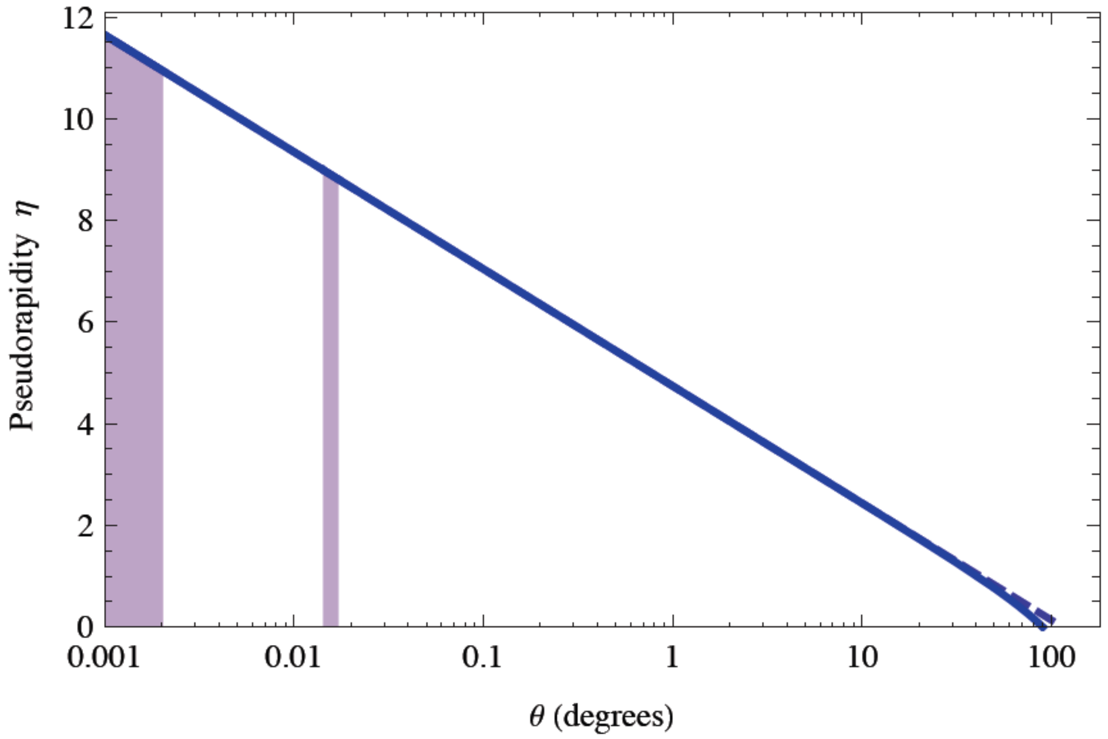

Two LHCf detectors (Arm1 & Arm2) are installed into the very forward region of the LHC interaction point (IP1). LHCf can measure neutral particles (γ, n) at the rapidity range **$\eta > 8.4$.**

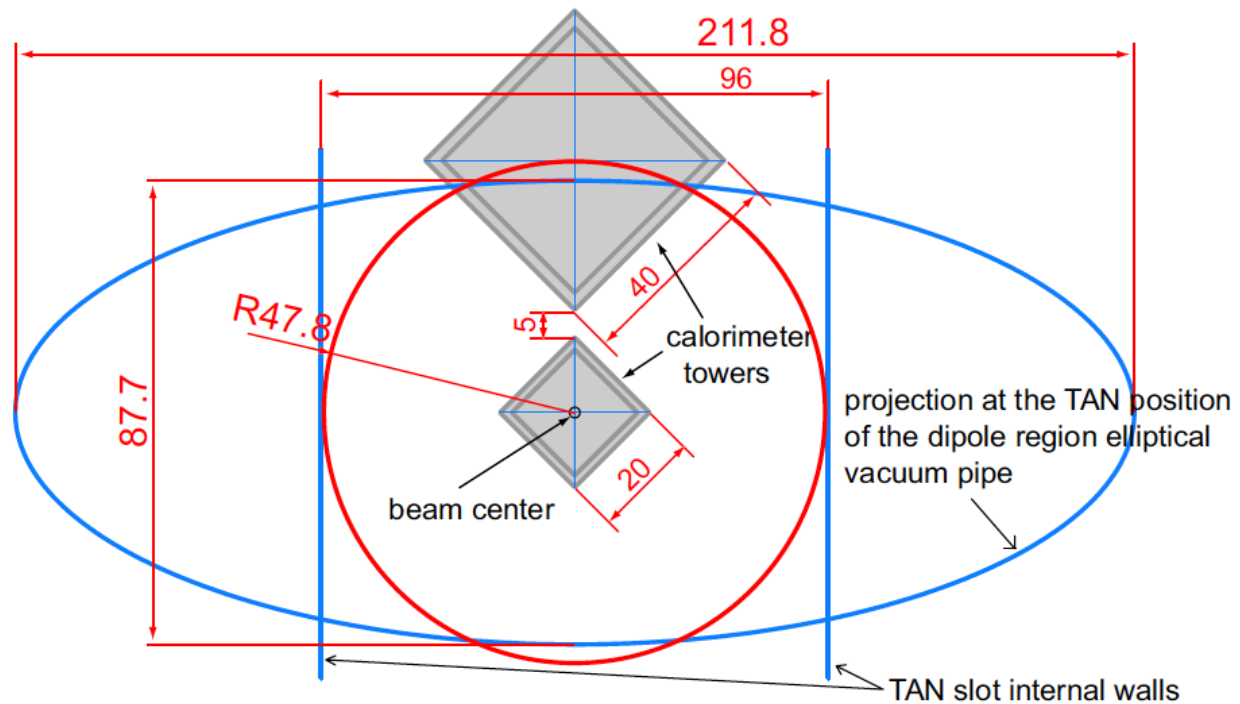


Pseudo-Rapidity versus angle:

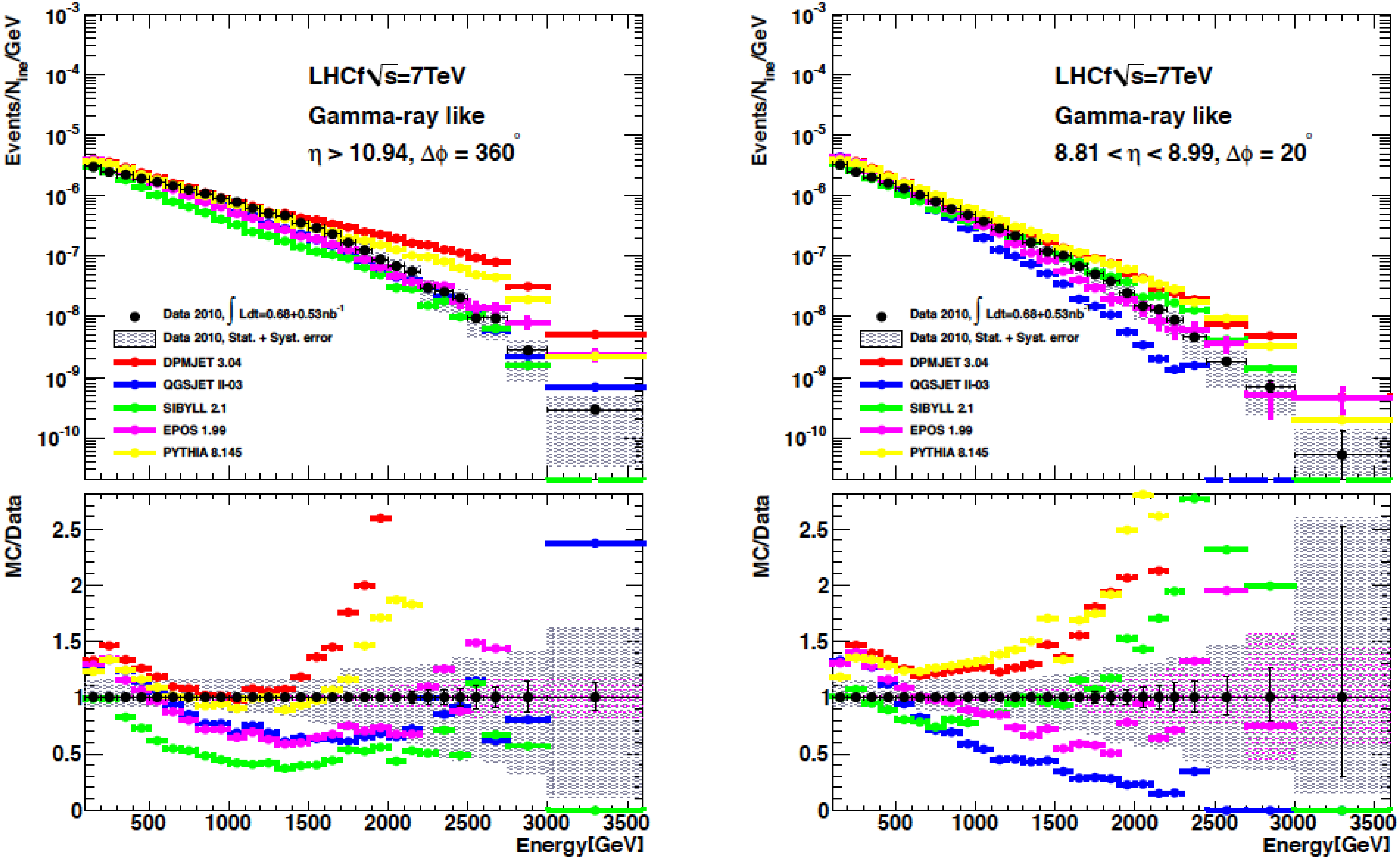
Very small angle production:



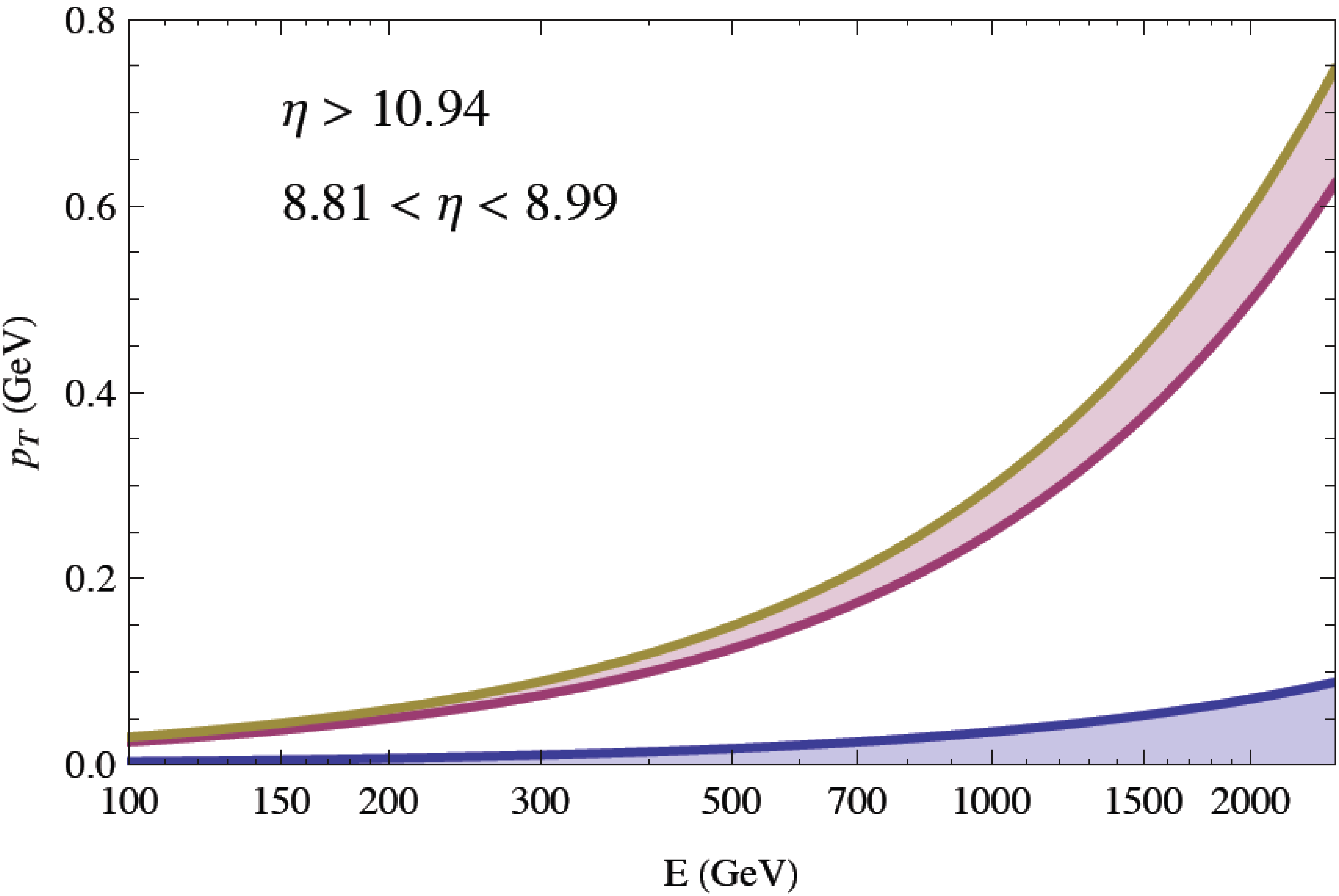
LHCf data hep-ex/1104.5294

[photon distributions
in 2 very forward
angular regions]



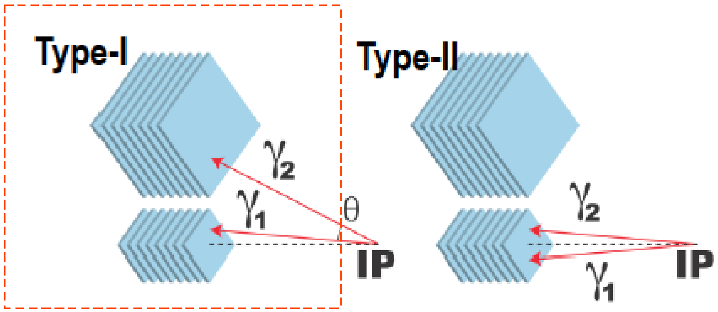
$$p_\perp = \sqrt{E^2 - m^2}\ \sin\left[2\ \tan^{-1}\left(e^{-\eta}\right)\right]$$

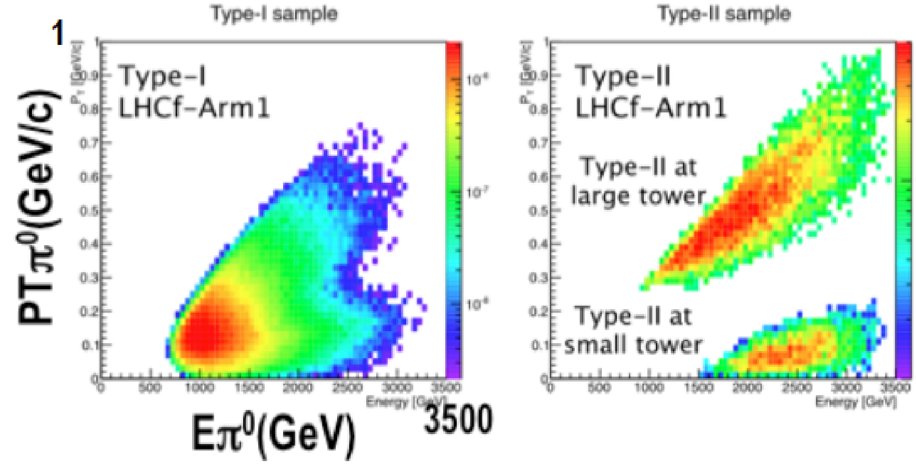
$$p_\perp \simeq p\ 2\ e^{-\eta}$$

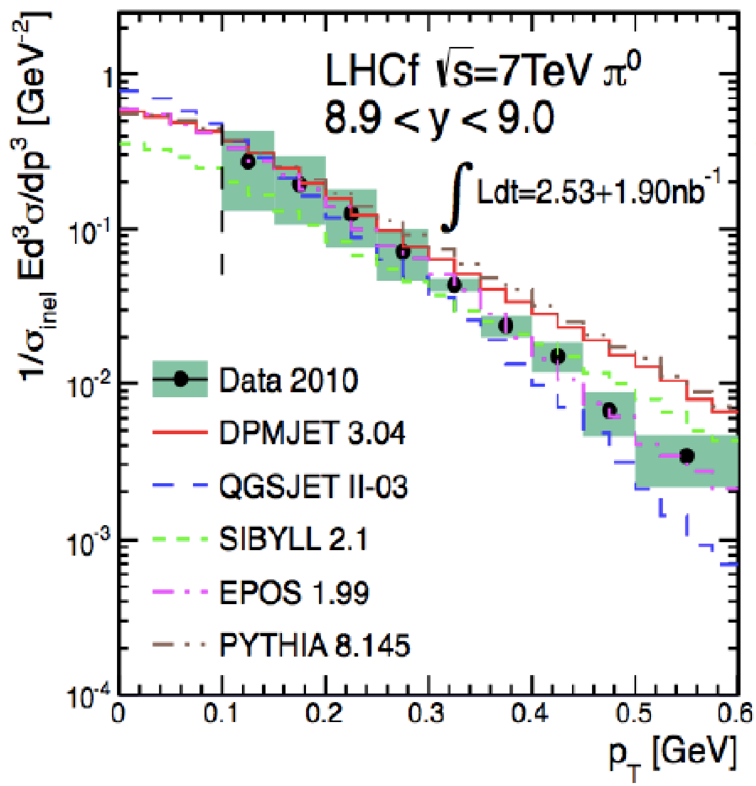


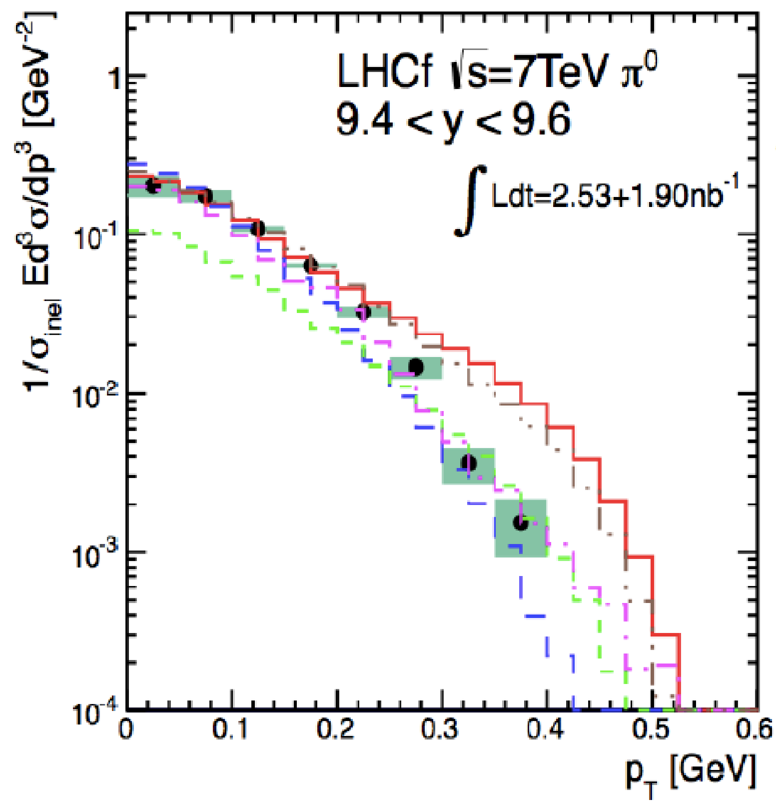
# LHCf $\pi^0$ $P_T$ at 7TeV pp

PRD 86 (2012) 092001



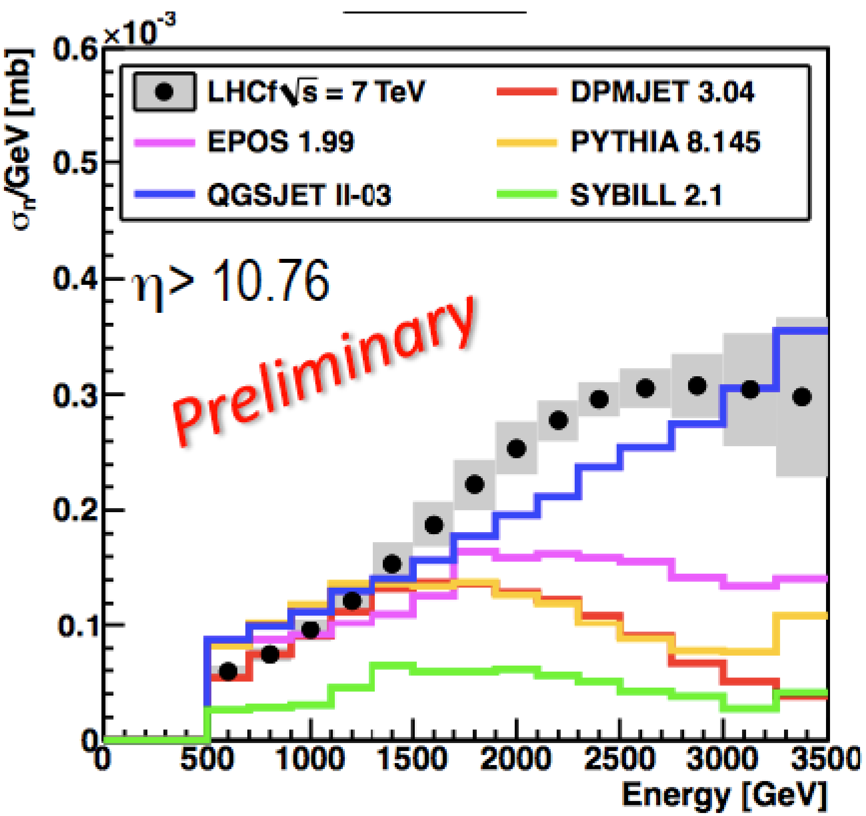



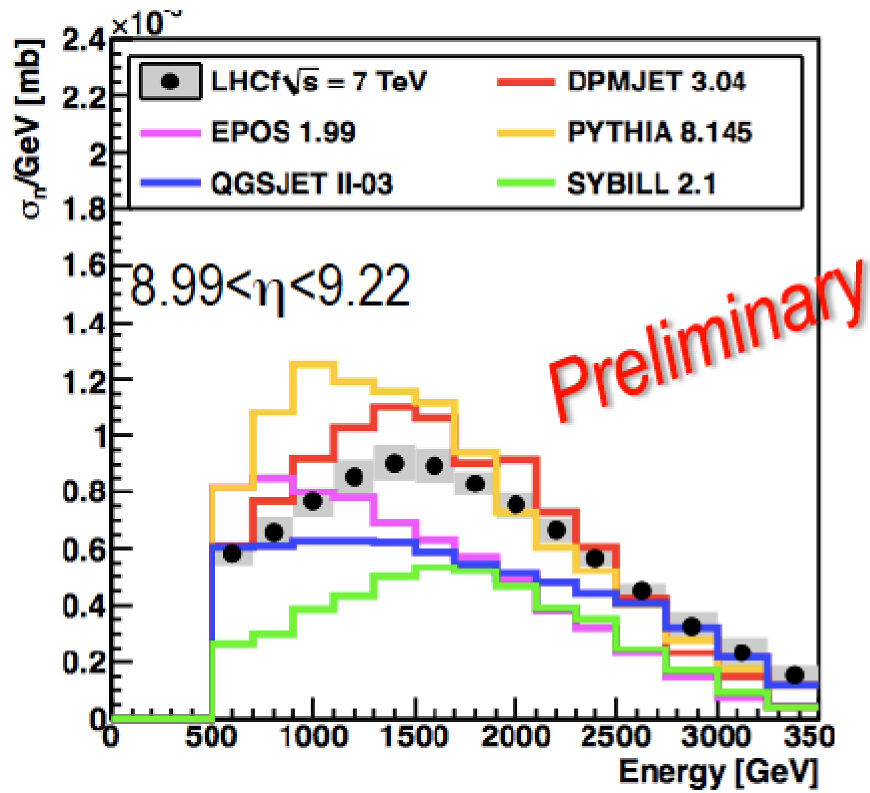



# Very forward neutron at 7TeV p-p

- η>10.76 : QGSJET03 good, >h>9.22 DPMJET3 good
- Larger neutron / gamma ratio than expected

40% E res. unfolded

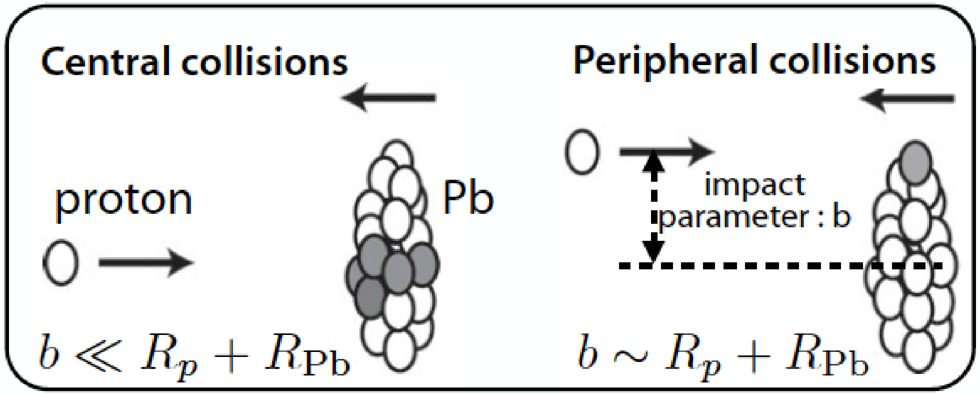


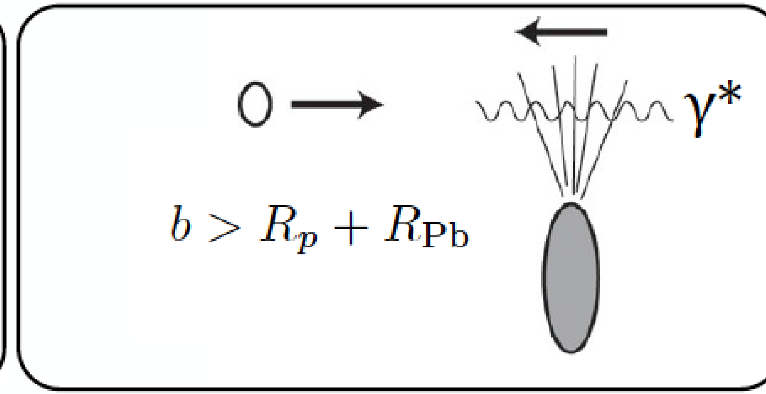



# $\pi^0$ event analysis in p-Pb collisions

**(Soft) QCD :**
central and peripheral collisions

**Ultra peripheral collisions :**
virtual photon from rel. Pb collides a proton.



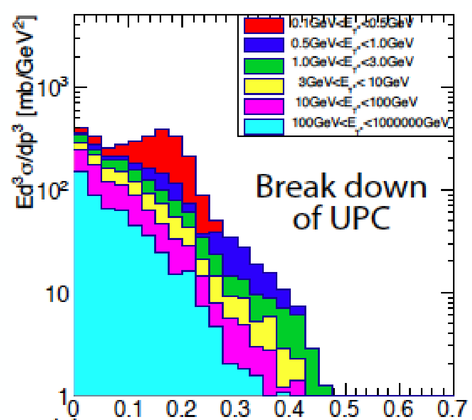

Momentum distribution of the UPC induced secondary particles is estimated as
1. energy distribution of virtual photons is estimated by the Weizsacker Williams approximation.
2. photon-proton collisions are simulated by the SOHIA model (E > pion threshold).
3. produced mesons and baryons by γ-p collisions are boosted along the proton beam.

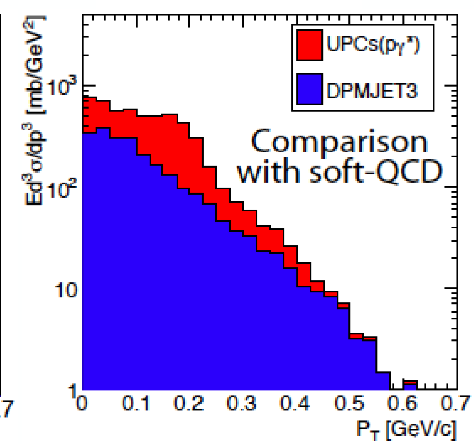
] proton rest frame

Dominant channel to forward $\pi^0$ is

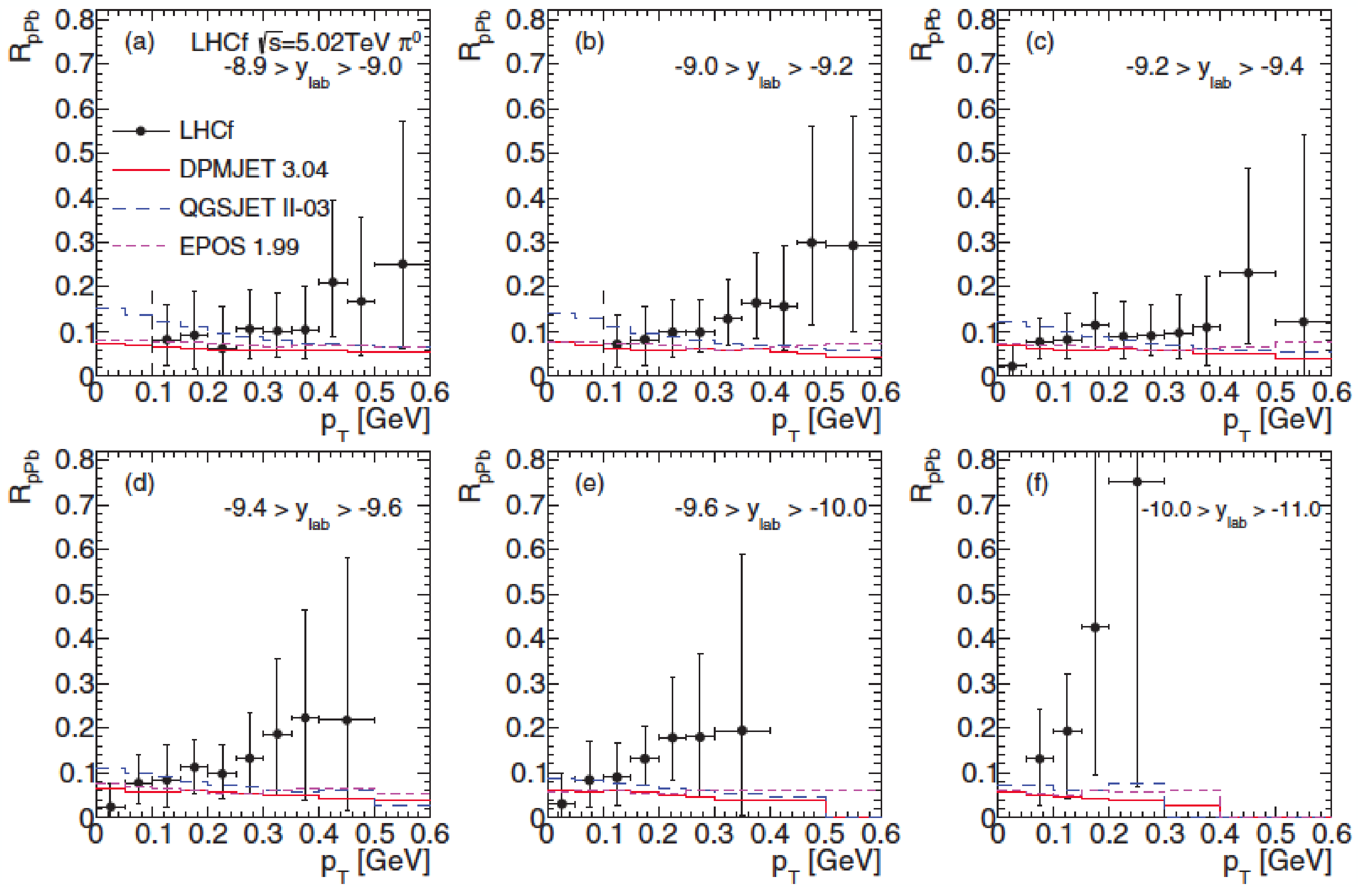
$$\gamma + p \rightarrow \Delta(1232) \rightarrow p + \pi^0$$

About half of the observed $\pi^0$ may originate in UPC, another half is from soft-QCD.



# Nuclear modification factor




$$R_{\mathrm{pPb}}(p_{\mathrm{T}}) \equiv \frac{d^2N^{\mathrm{pPb}}_{\pi^0}/dydp_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle d^2N^{\mathrm{pp}}_{\pi^0}/dydp_{\mathrm{T}}}$$

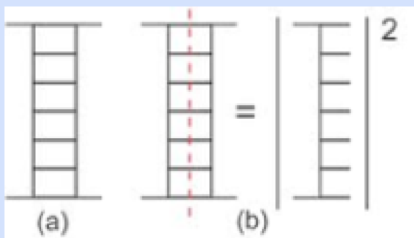
$\langle N_{coll}\rangle = 6.9$

- Both LHCf and MCs show strong suppression.
- But LHCf grows as increasing $p_T$, understood by the softer $p_T$ spectra in p-p at 5TeV than those in p-Pb.

# Soft Physics : Theory Models

See e.g. Reviews by MCnet [arXiv:1101.2599] and KMR [arXiv:1102.2844]

## A Regge Theory




Optical Theorem

+ Eikonal multi-Pomeron exchanges

$\sigma_{\text{tot,inel}} \propto s^{\varepsilon}$ or $\log^2(s)$

Cut Pomerons → Flux Tubes (strings)

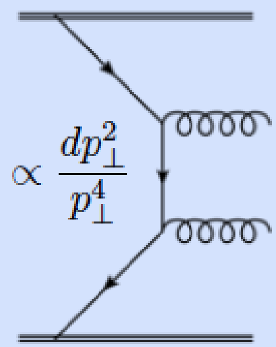
Uncut Pomerons → Elastic (& eikonalization)

Cuts unify treatment of all soft processes

EL, SD, DD, … , ND

Perturbative contributions added above $Q_0$

## B Parton Based



$$d\sigma_{2\to 2} \propto \frac{dp_\perp^2}{p_\perp^4} \otimes \text{PDFs}$$

+ Unitarity & Saturation

→ Multi-parton interactions (MPI)

+ Parton Showers & Hadronization

Regulate $d\sigma$ at low $p_{T0}$ ~ few GeV

Screening/Saturation → energy-dependent $p_{T0}$

Total cross sections from Regge Theory

(Donnachie-Landshoff + Parametrizations)

+ "Mixed"

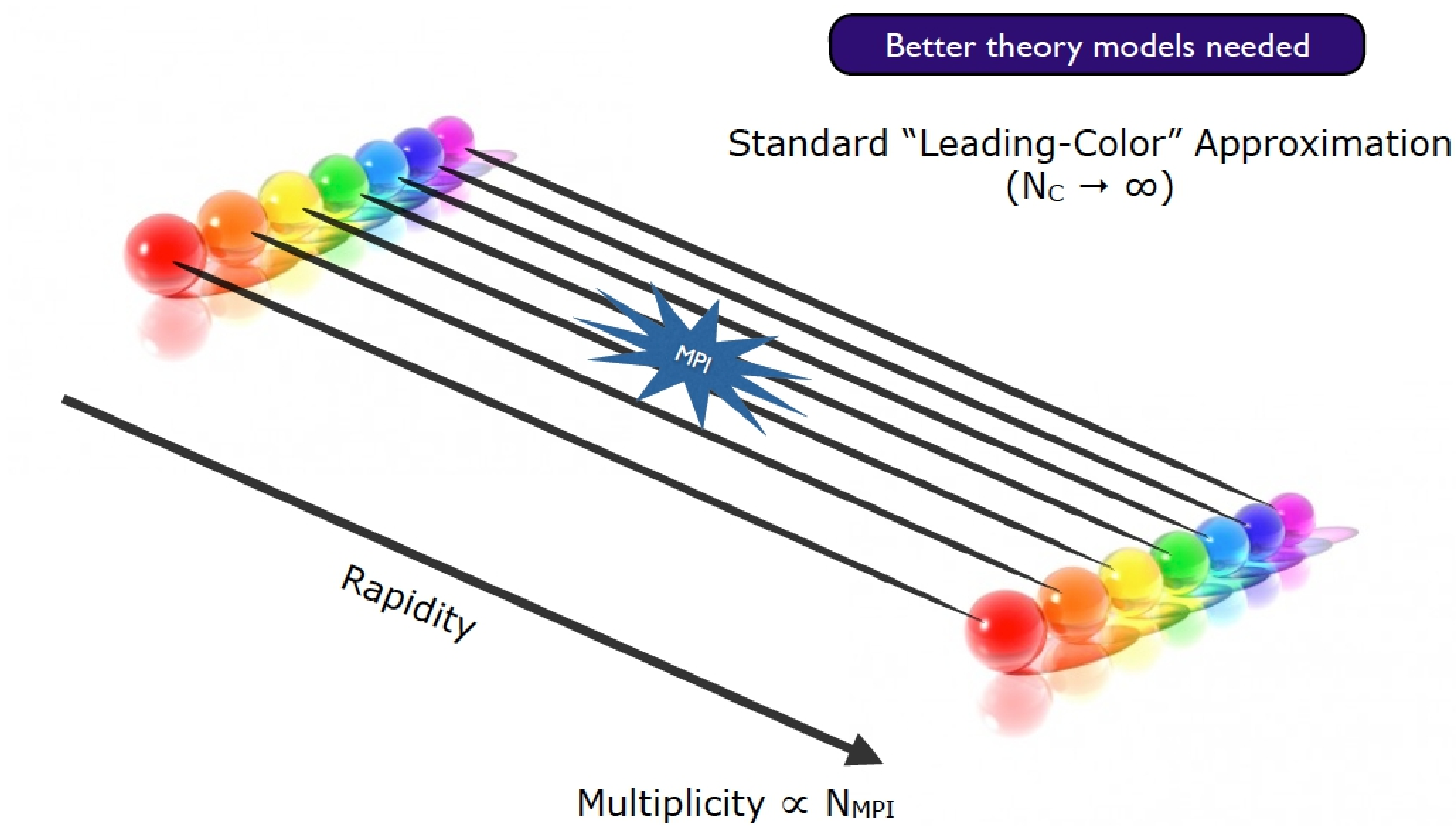
E.g., QGSJET,

E.g., PHOJET, EPOS, SHERPA-KMR

E.g., PYTHIA, HERWIG, SHERPA

# MPI and Colour

Better theory models needed

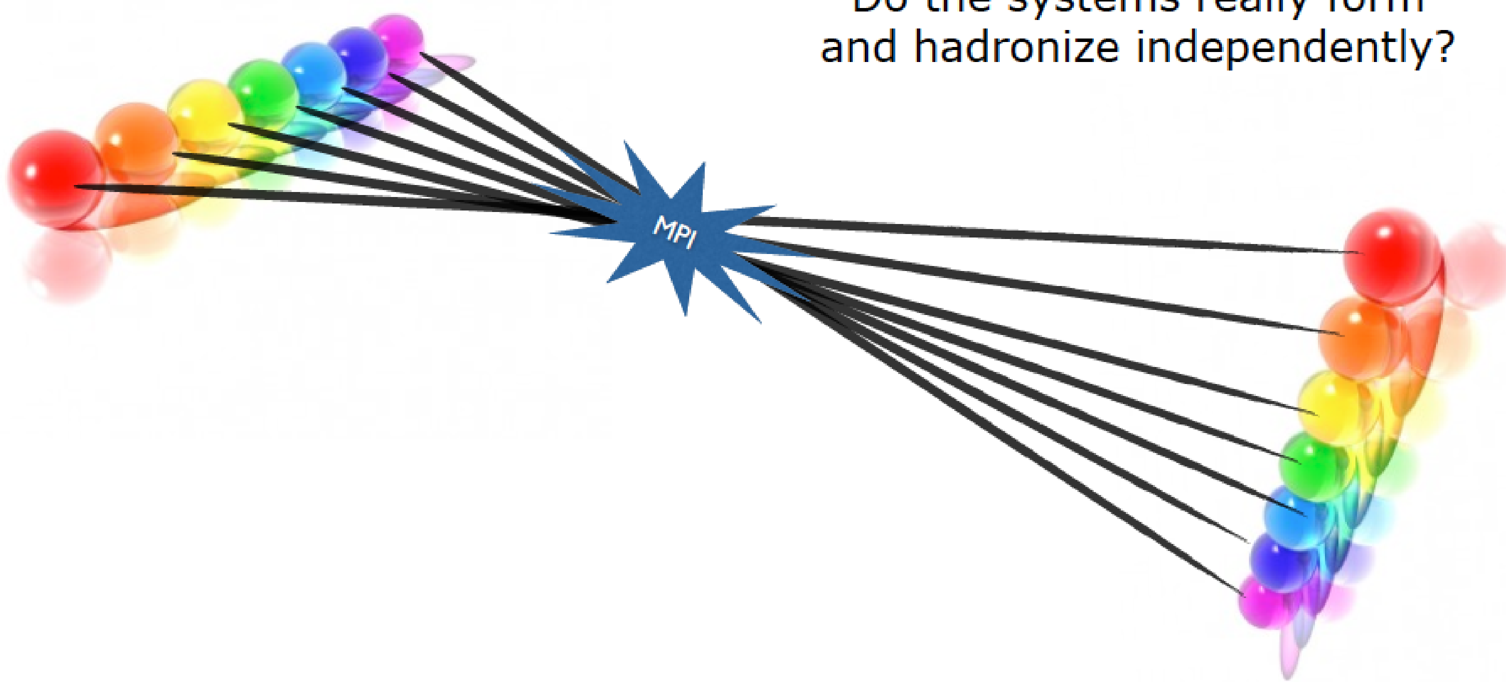


# Color Reconnections?

E.g.,
Generalized Area Law (Rathsman: Phys. Lett. B452 (1999) 364)
Color Annealing (Skands, Wicke: Eur. Phys. J. C52 (2007) 133)
Herwig++ model (Gieseke, Rohr, Siodmok : Eur.Phys.J. C72 (2012) 2225)

Better theory models needed

Do the systems really form
and hadronize independently?



# Color Reconnections?

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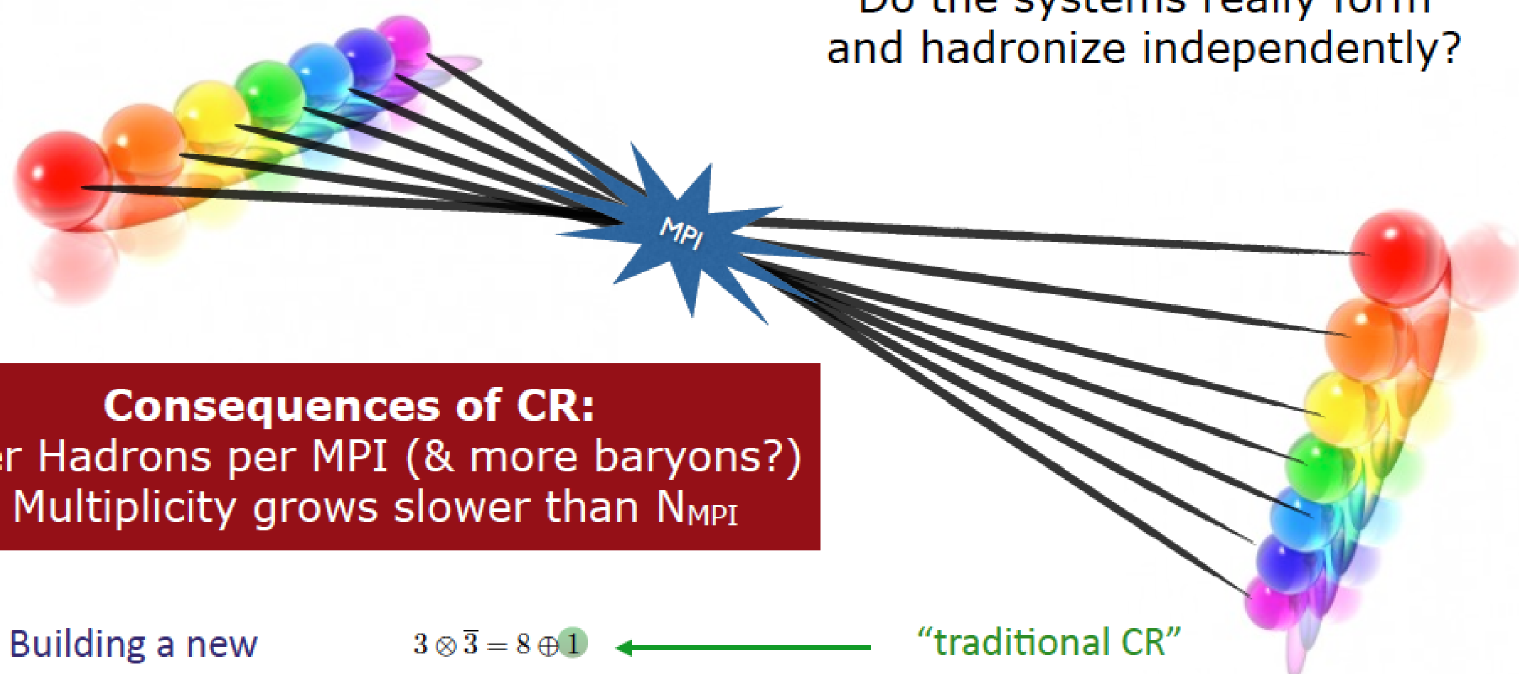


**Consequences of CR:**
Fewer Hadrons per MPI (& more baryons?)
↳ Multiplicity grows slower than $N_{MPI}$

**New:** Building a new model for PYTHIA 8, based on SU(3) weights
*[with J. Christiansen (Lund U)]*

$3 \otimes \bar{3} = 8 \oplus 1$ ← "traditional CR"

$3 \otimes 3 = 6 \oplus \bar{3}$ ← "new" sources of baryons (& antibaryons)

$8 \otimes 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 1,$

$3 \otimes 8 = 15 \oplus 6 \oplus 3,$

also indicated by LHC data!

# What's Next ?

For fundamental Science ?

(and how INFN should best continue its activity ?)

# INFN “What's Next”

“White paper” of *Commissione-1* (accelerator Physics)
about future projects for Accelerator Physics

A question that has been asked to the
“Astroparticle Physics Community”:

What measurements and what experimental programs
at accelerators are relevant (and are possible)
and important for Cosmic Ray Studies ?

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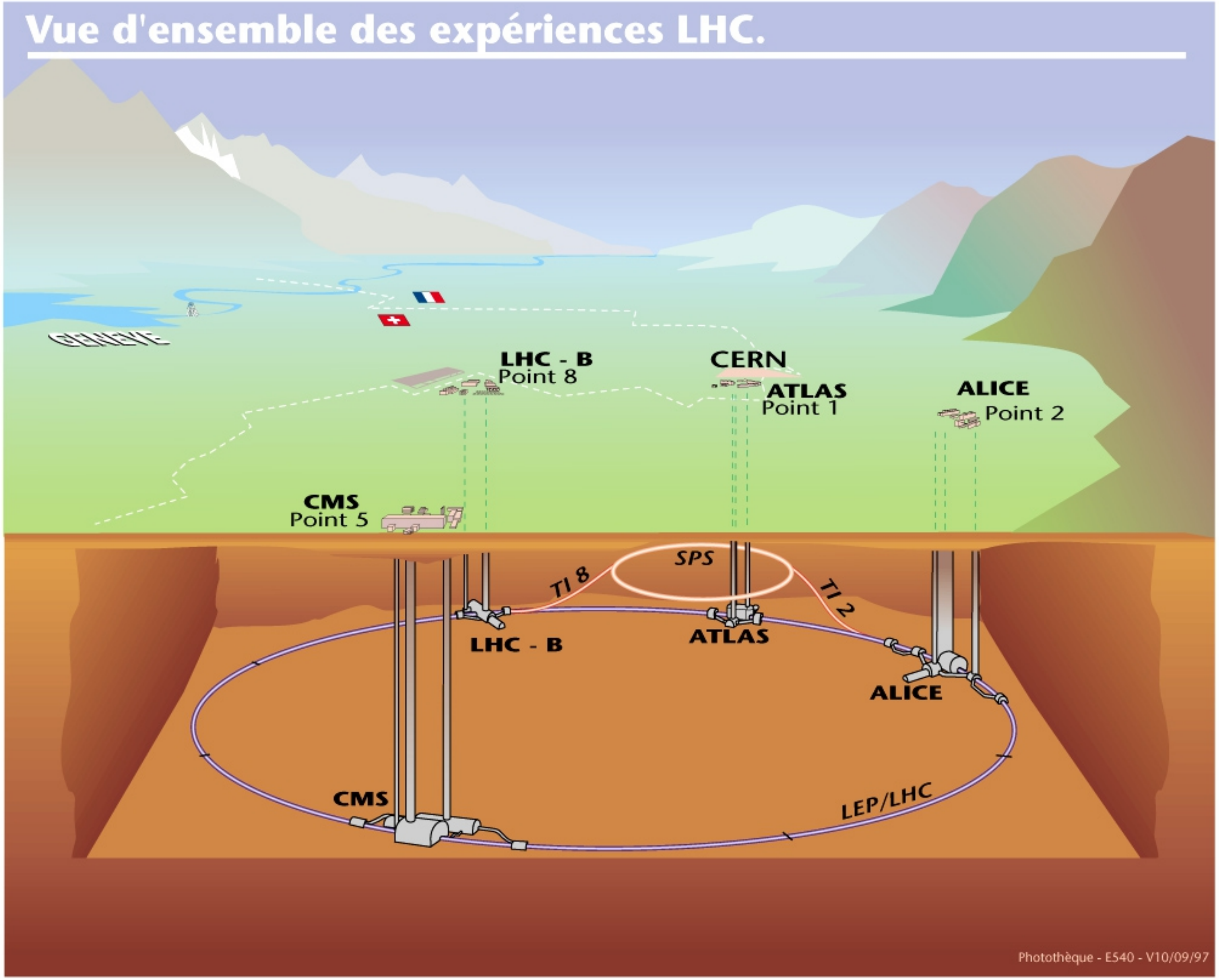
at accelerators are relevant (and are possible)
and important for Cosmic Ray Studies ?

*It is important to try to answer to this question*
*in a complete and convincing way.*

Quantify what are the uncertainties due to
hadronic interaction modeling in air-shower measurements
in different energy ranges
(from the "Knee" to the UHE/GZK suppression)

Discuss, propose (and support) measurements
that are can reduce these uncertainties.
(at LHC but also at lower energy).

# What have we learned at LHC about "soft" hadronic interactions ?



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below LHC energies
(above LHC energies [extrapolation needed])

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below LHC energies
(above LHC energies [extrapolation needed])

.... I'm personally somewhat more cautious than at least some of my colleagues.
Our models stands reasonably well, but uncertainties still quite significant.

What are the most significant measurements
(for cosmic ray studies) to be performed at LHC ?

0. c.m. Energy extension (...obvious)

1. *Observed* ***Phase Space*** *extension*
   (very difficult .. but in my view also very important)

2. Better **diffraction cross section** determination.

3. Program of **proton/light-nucleus** observations

3a. Program of nucleus/light-nucleus

The interest of the Cosmic Ray community
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A full understanding of the Multi-Parton-Interaction structure of inelastic collisions *requires* a coverage of the entire phase space including the very-forward – very/backward Fragmentation region.

So significant "intrinsic" (Particle Physics) interest in these programs

*More in general:*

Uncertainties on soft hadronic interactions remain
a significant source of systematic uncertainties
for many different studies on a broad energy range

[From very low energy: pp → p p + few pions]
Study of acceleration in SN remnants
Production of neutral pions (that decay into gammas)

Up to sqrt[s] = 430 TeV]

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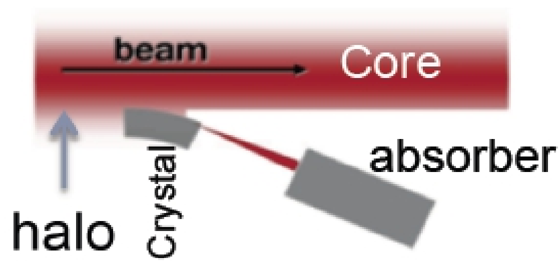
1. Fixed Target program at LHC
   (allow studies of meson interactions)

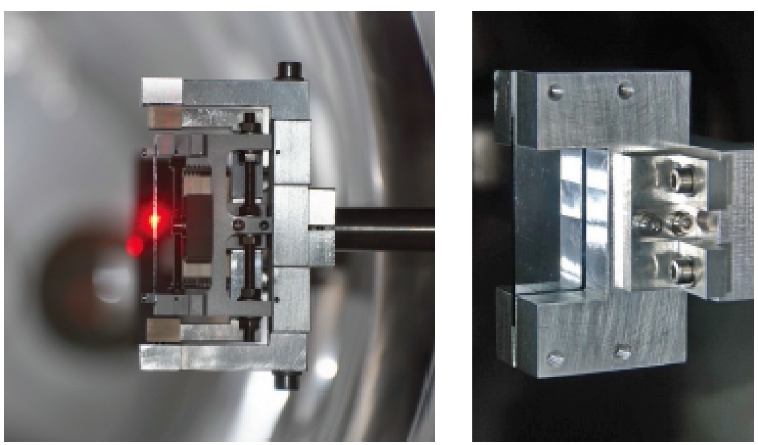
2. Lower energy (anti-proton production)
   Atmospheric neutrinos

# *CRYSBEAM* basic idea

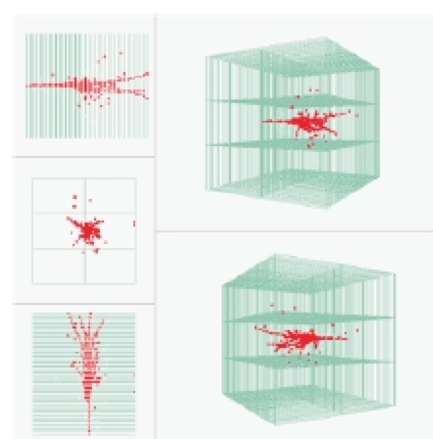
***PARASITIC*** *EXTRACTION of BEAM with* ***a bent crystal***
*in* ***channeling orientation***
*Low background, continuous extraction of the beam halo*
*10^8 particle per second might be possible*




Instrumented ("smart") absorber to measure the hadronic shower structure



*UA9 crystals*



*CALICE Digital HCAL*

# Bridging the Gap

between

# Soft and Hard
# Hadronic Interactions

Bridging the Gap

between

Soft and Hard

Hadronic Interactions

Problem of CONFINEMENT

# SOFT QCD studies

Have NOT only a simple “engineering” interest
as a instrument to reconstruct the primary particle
mass and energy in a shower.

They confront a very significant scientific
open problem for the Standard Model

(In my view) they deserve a strong, broad
Experimental *and theoretical* program.

My final message:

The interconnection between

# Particle Physics

and

# Cosmic Ray science

[High Energy, multi-messenger-Astrophysics]

has a very long past-history

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*... and a very promising future.*