The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2036-16

International Workshop: Quantum Chromodynamics from Colliders to Super-High Energy Cosmic Rays

25 - 29 May 2009

Cross section measurements with cosmic ray experiments

Ivan De Mitri

University of Salento & Istituto Nazionale di Fisica Nucleare
Lecce
Italy

Cross section measurements with cosmic ray experiments

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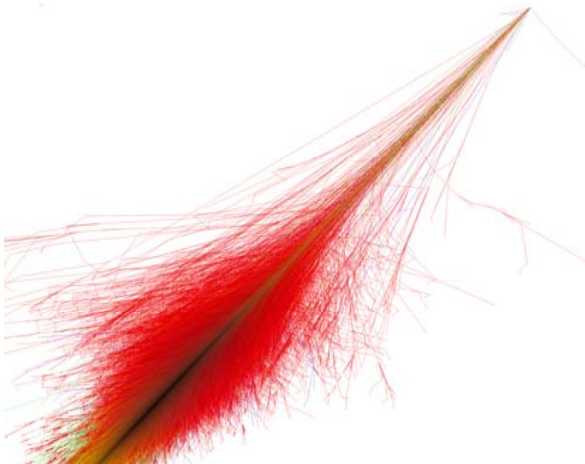
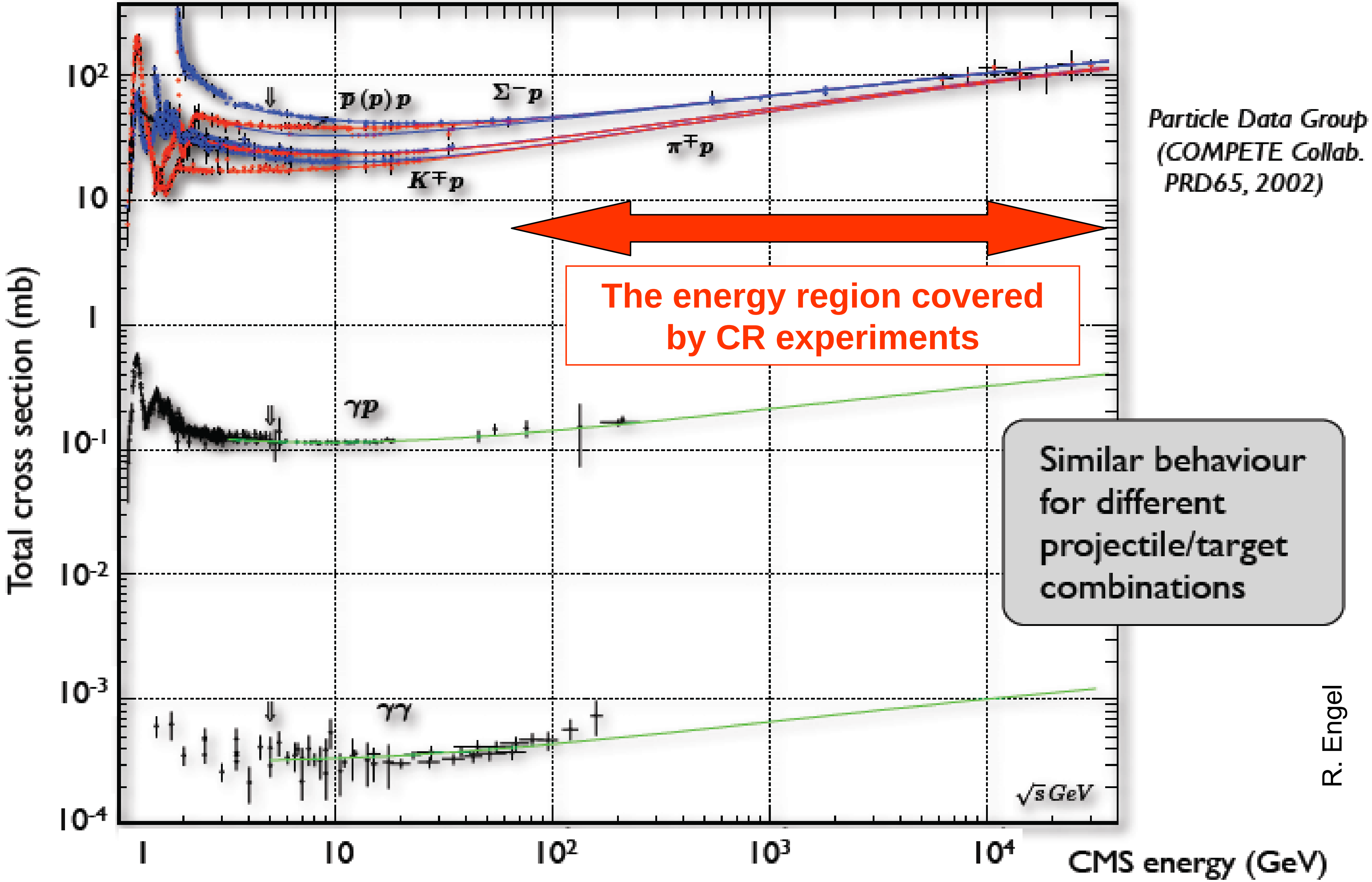
Lecce, Italy



Quantum Chromodynamics from Colliders to Super-High Energy Cosmic Rays
ICTP, Trieste, May 2009

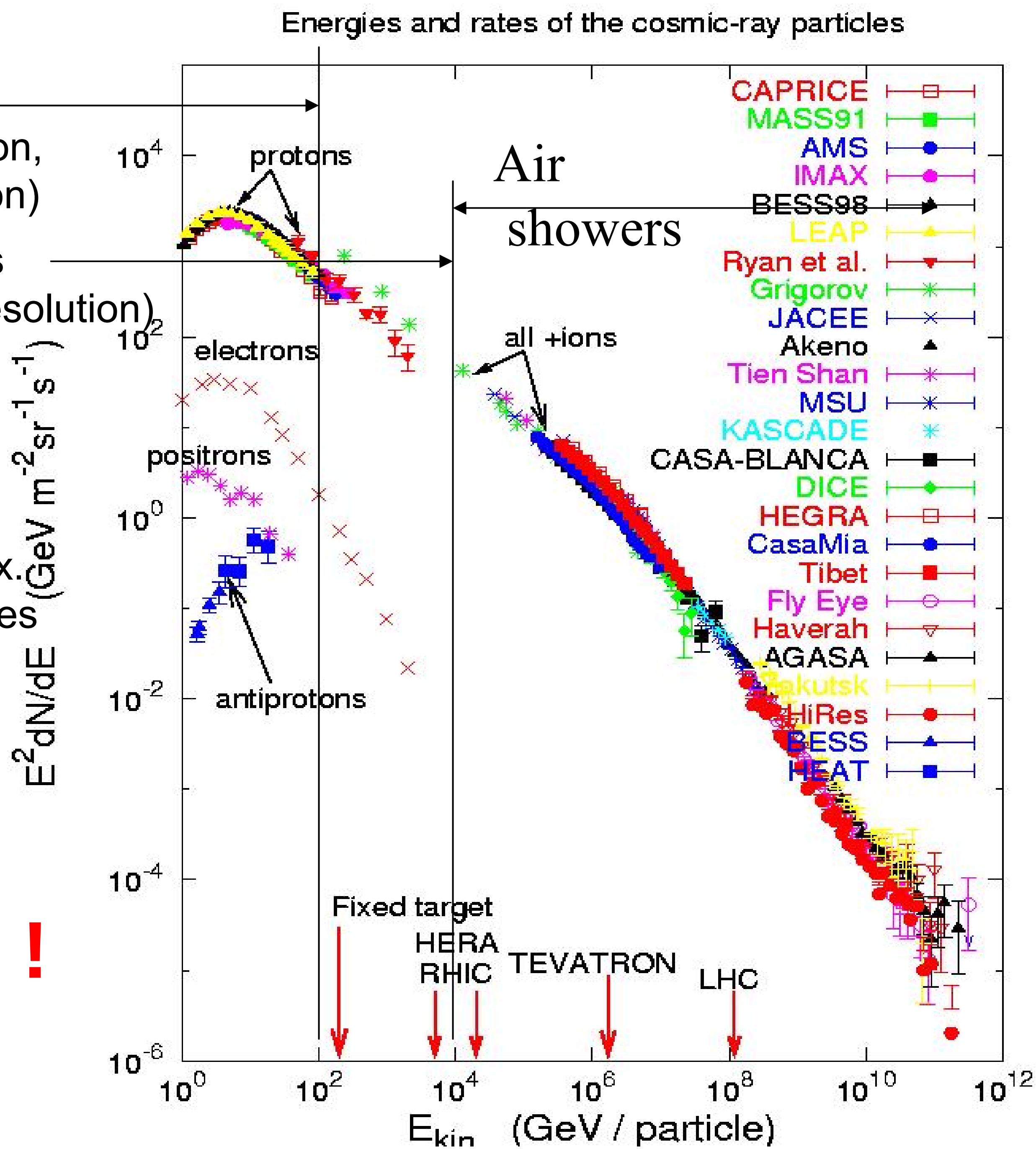
Compilation of total cross sections



Spectrometers
(ΔA = 1 resolution, good E resolution)

Calorimeters
(less good resolution)

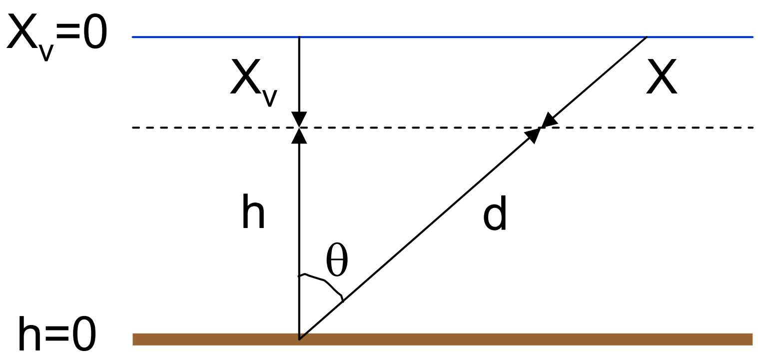
EAS arrays
on the ground to overcome low flux. Don't see primaries directly.



The beam !

The (high energy physicist) **atmosphere**

The target !



"*Standard*" atmosphere :

$X_v = X_0 \exp(-h/h_0)$

$X_0 \approx 1030$ g/cm^2

$h_0 \approx 6.4 – 8.4$ km

$\sigma_{p\text{-}Air} \sim 300$ mb @ $E \sim 1\text{-}100$ TeV

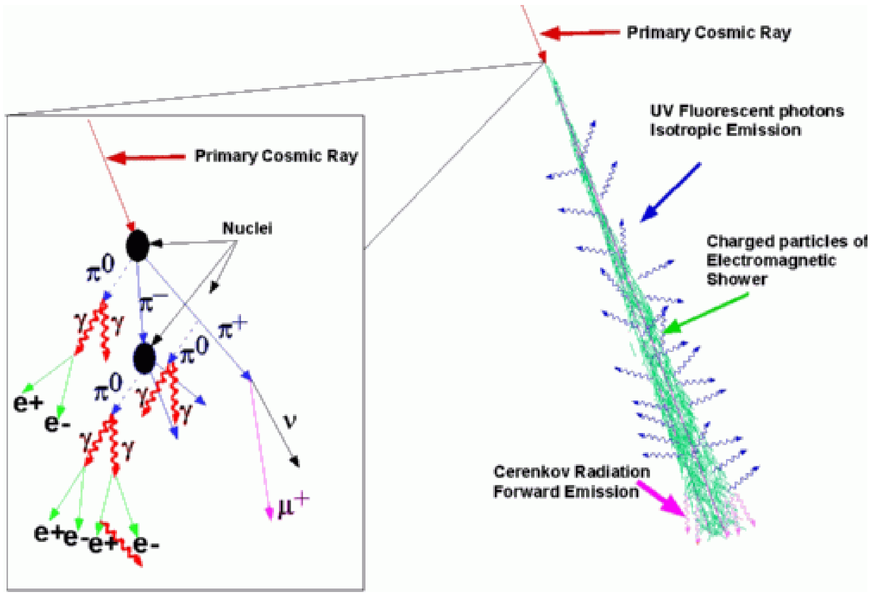
$\Lambda_p \sim 80$ g/cm^2 $\Lambda_{Fe} \sim 2\text{-}3$ g/cm^2 $\Lambda_{rad} \sim 37$ g/cm^2

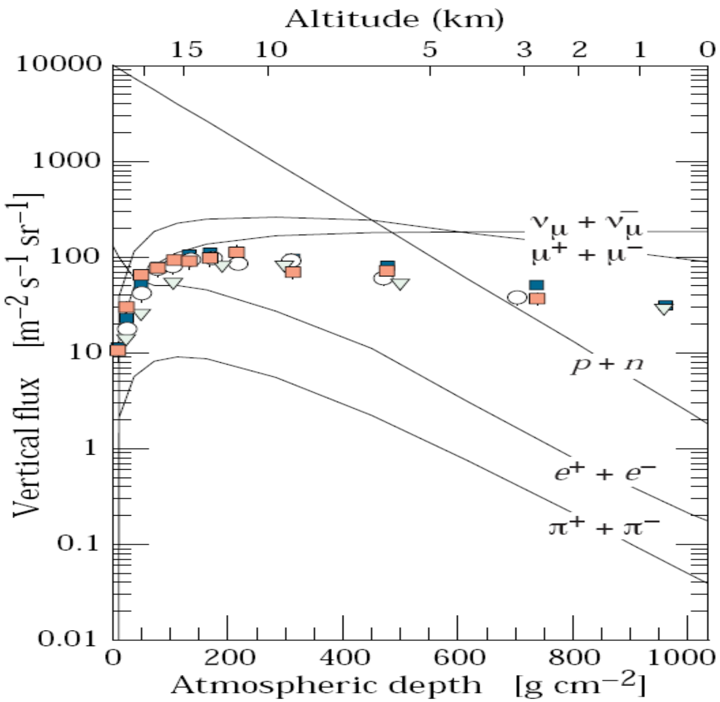
$X_0 \sim 13\Lambda_p \sim 28\,\Lambda_{rad}$

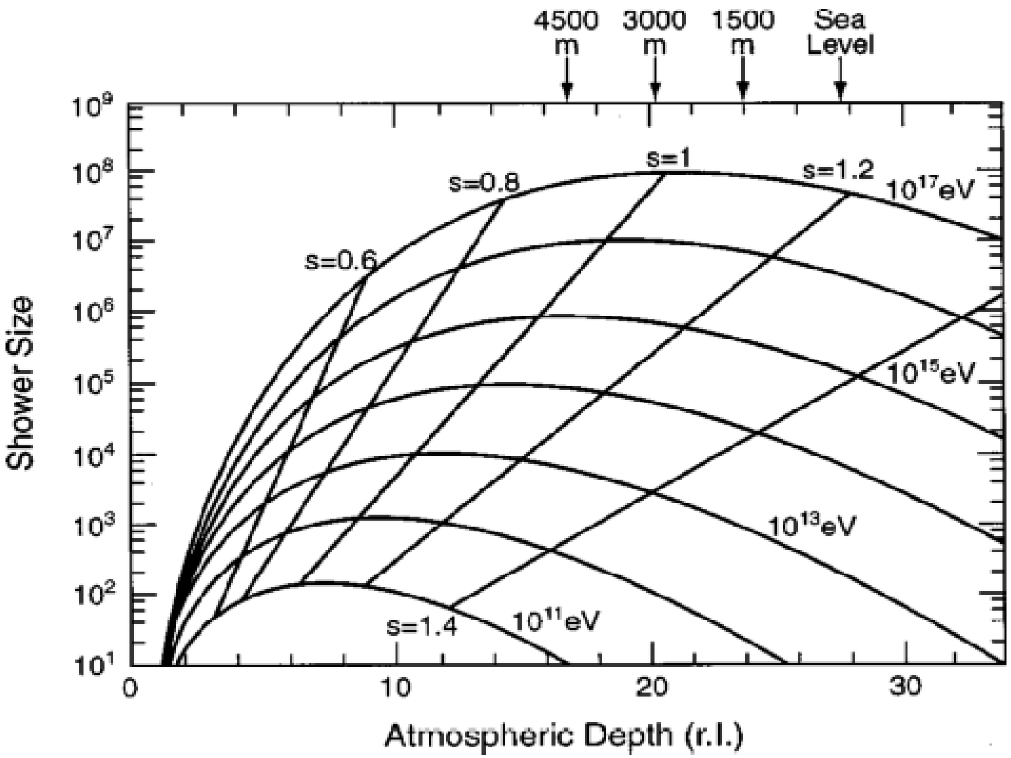
$X_v \sim \Lambda_p \Leftrightarrow h \sim 18$km

EAS Components

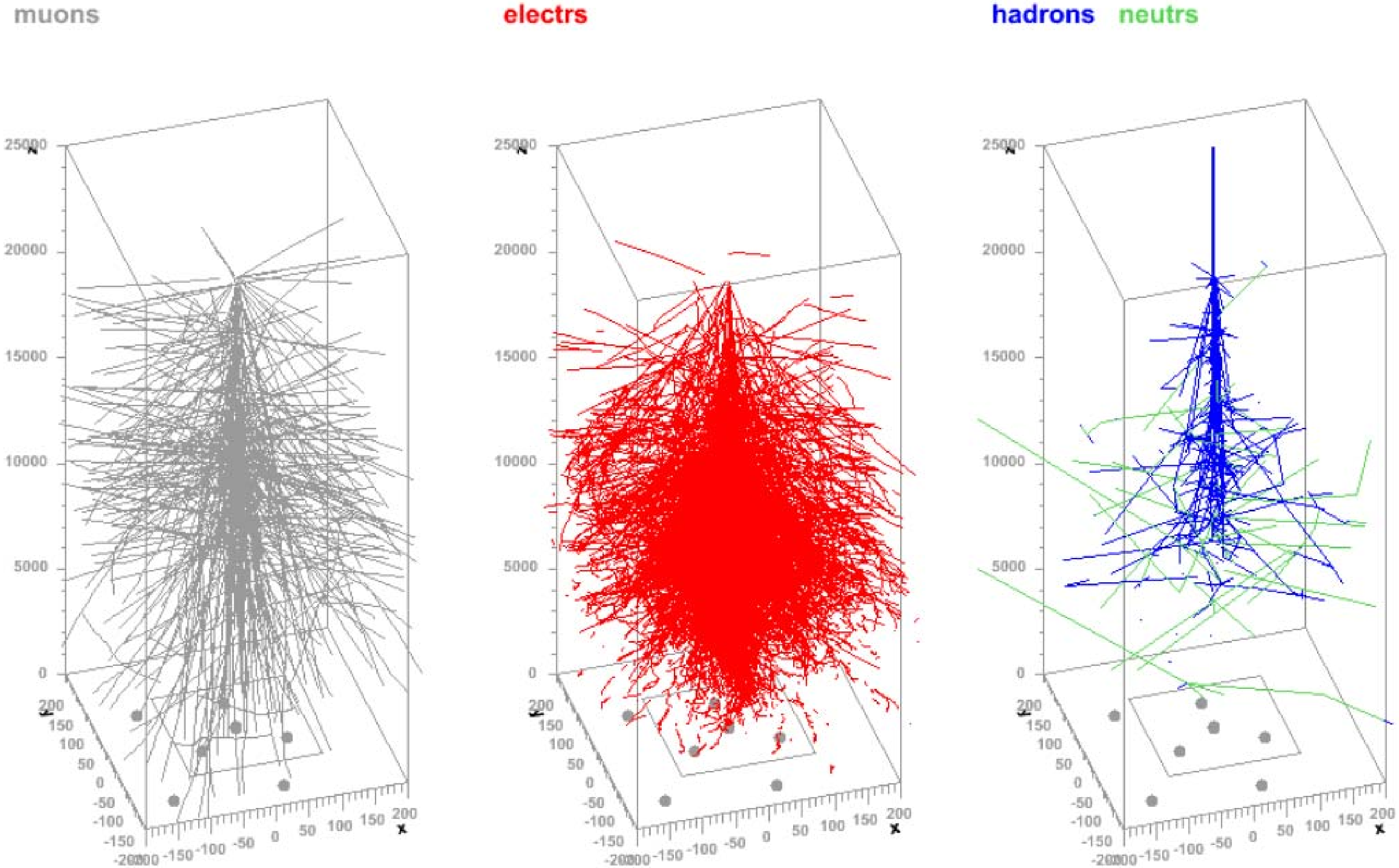
- Soft: p, n, π, e, γ,..
- Hard: μ, ν
- Čerenkov light (mainly produced by electrons)
- Fluorescence light

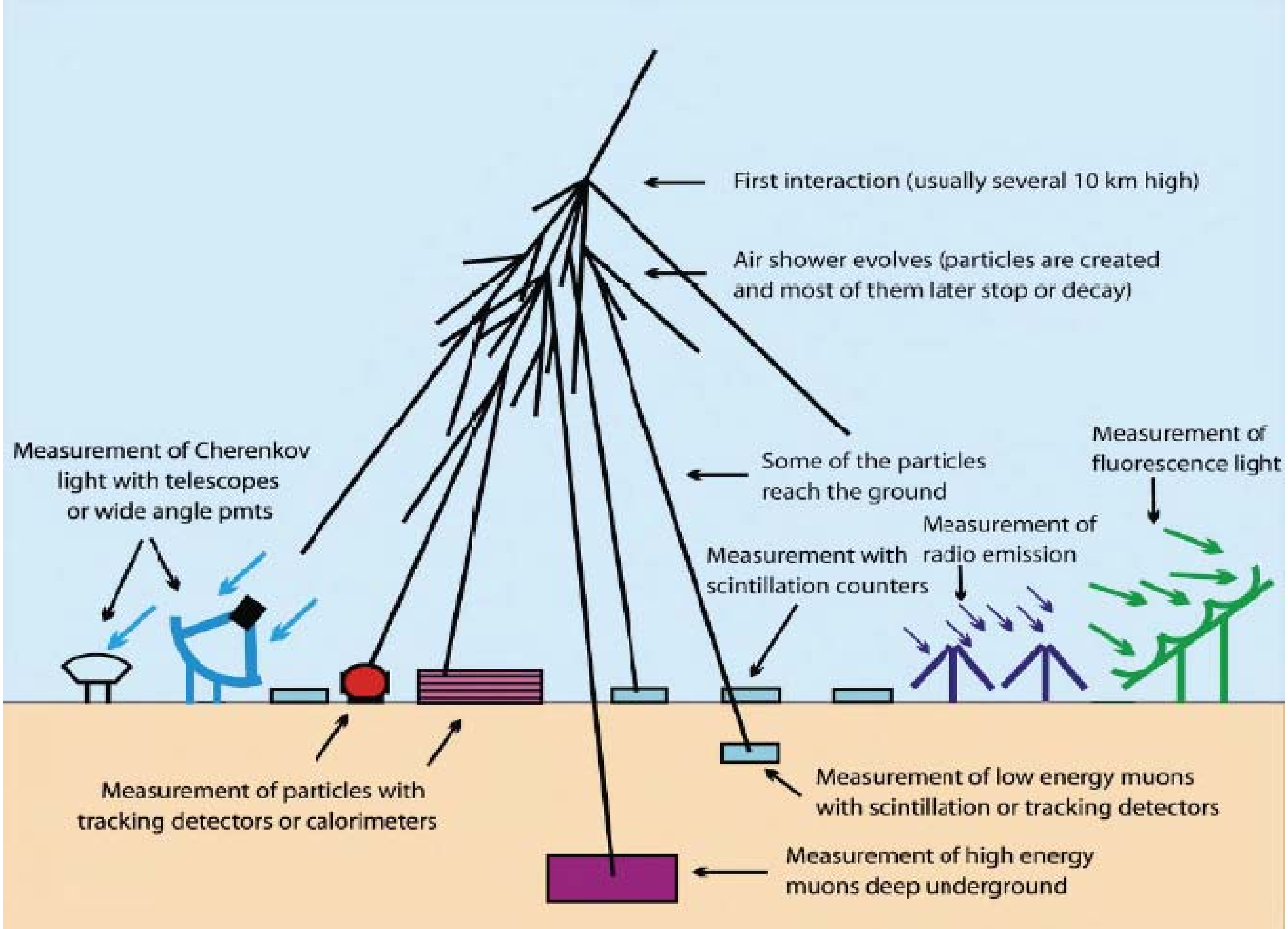






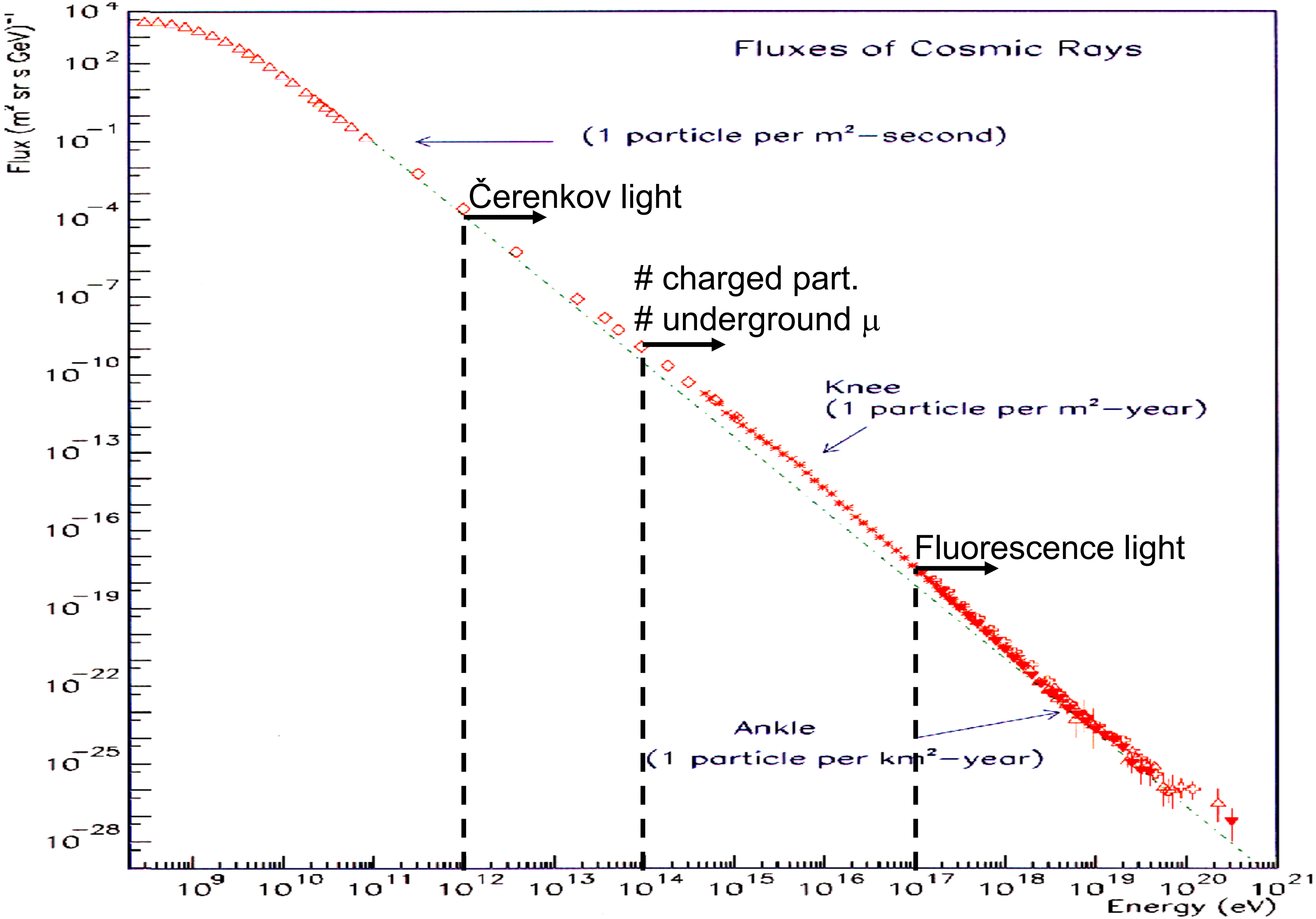
Shower particle tracks: proton




First interaction (usually several 10 km high)
Air shower evolves (particles are created and most of them later stop or decay)
Some of the particles reach the ground
Measurement of Cherenkov light with telescopes or wide angle pmts
Measurement of fluorescence light
Measurement of radio emission
Measurement with scintillation counters
Measurement of particles with tracking detectors or calorimeters
Measurement of low energy muons with scintillation or tracking detectors
Measurement of high energy muons deep underground

Approximate threshold value

(it depends on specific detector features and location)



Data Analysis flowchart in a “typical“ EAS experiments

- Shower axis
- Shape of the lateral distribution
- Measurement of the muon component
- Cerenkov light image and lateral distribution
- Shower development information provided by the fluorescence light

MC simulations of the shower development and of the detector response

Measurement of energy spectra and arrival directions

Information on the chemical composition vs energy

Information on particle interactions

- Detector features and performances
- Characteristics of the experimental site
- Reconstruction algorithms
- Analysis procedures

VOLUME 28, NUMBER 15 PHYSICAL REVIEW LETTERS 10 APRIL 1972

Evidence for Rapidly Rising p-p Total Cross Section from Cosmic-Ray Data

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and

Yash Pal
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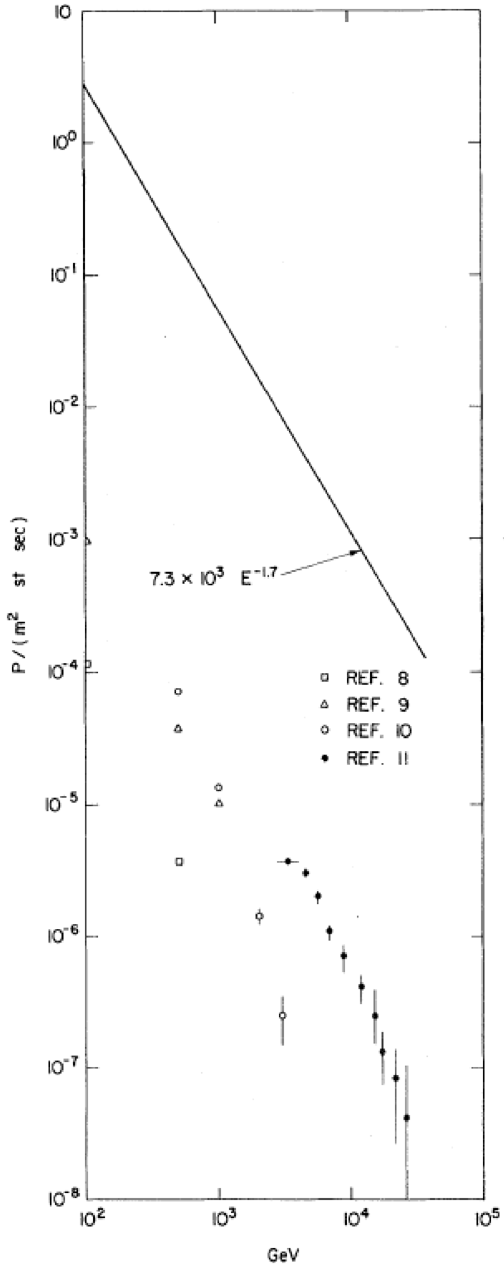
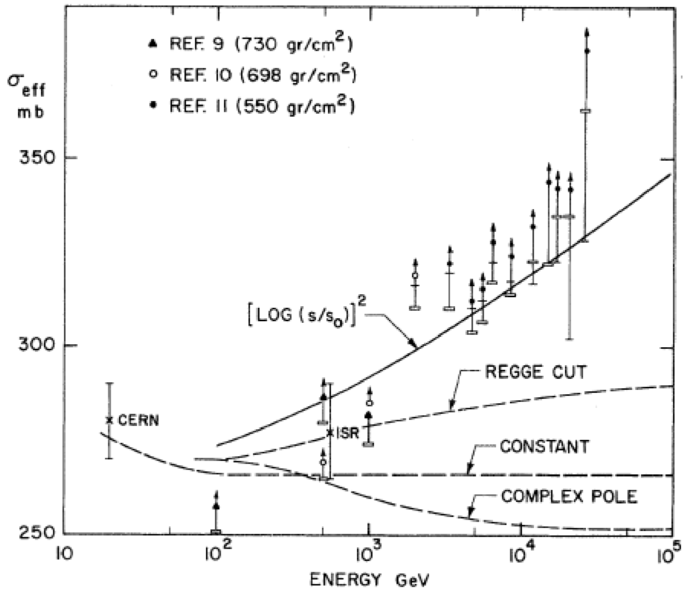
and

J. S. Trefil†
Department of Physics, University of Virginia, Charlottesville, Virginia 22901
(Received 16 March 1972)

We give estimates of lower bounds on the p-p total cross section based on cosmic-ray data. We find that σ_{pp} rises at least as rapidly as $38.8+0.4\ln^2(s/s_0)$ from $E\sim 10^3$ to 3×10^4 GeV incident energy, corresponding to $\sigma_{pp}\geq 60$ mb at the highest energy available. In view of large experimental errors at the highest energies, a value of $\sigma_{pp}\geq 48$ mb can be estimated at 95% confidence level at $E\sim 10^4$ GeV.

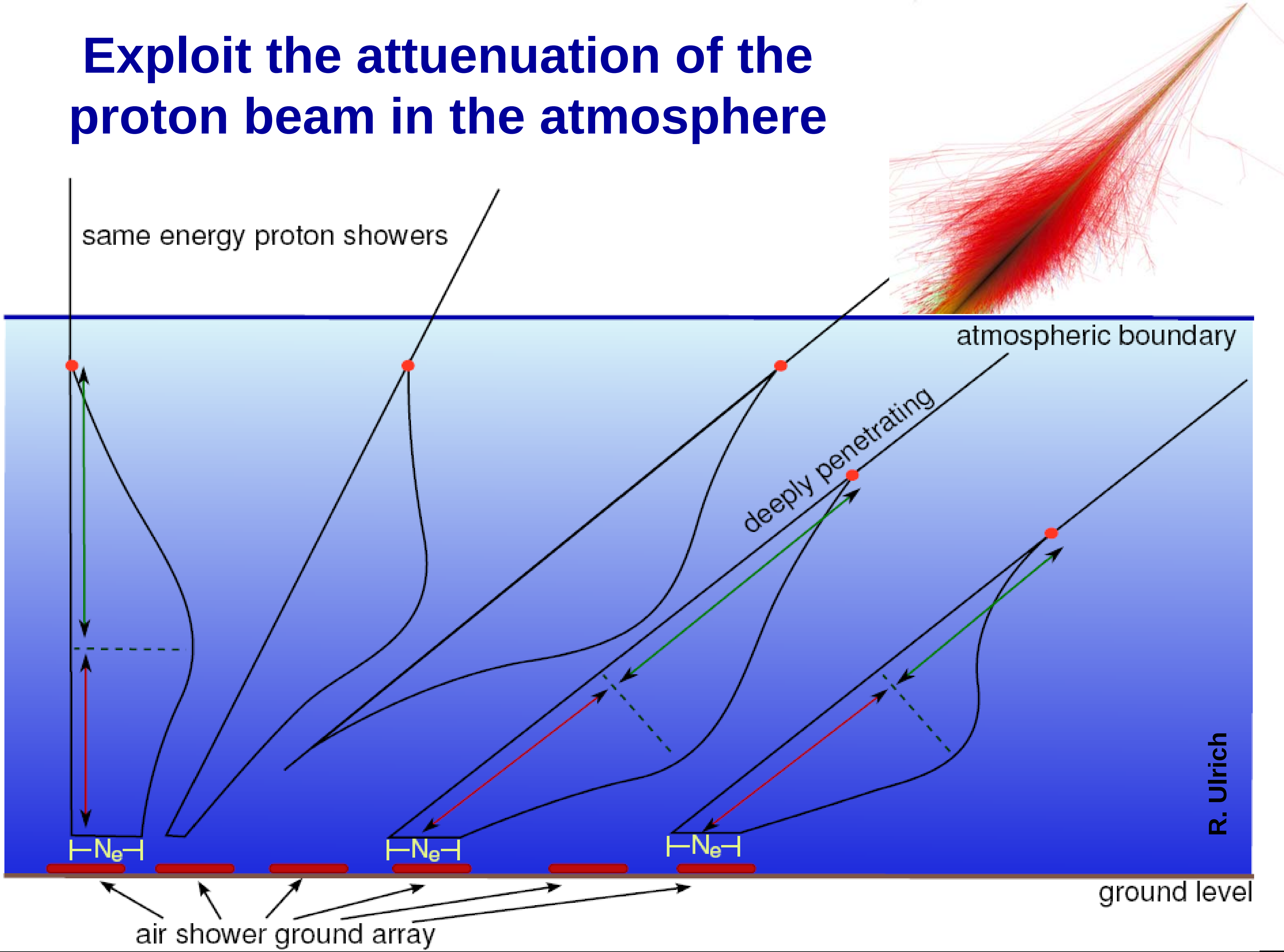


Measurement of the unaccompanied hadron flux with high altitude calorimeters with suitable veto systems



Measurements on Air Showers

Exploit the attuenuation of the proton beam in the atmosphere



Measuring the shower profile: The FD

•The passage of charged particles in an EAS through the atmosphere ionizes and excites N molecules. This excitations produces isotropical UV fluorescence emission (properly “luminescence” or “scintillation”)

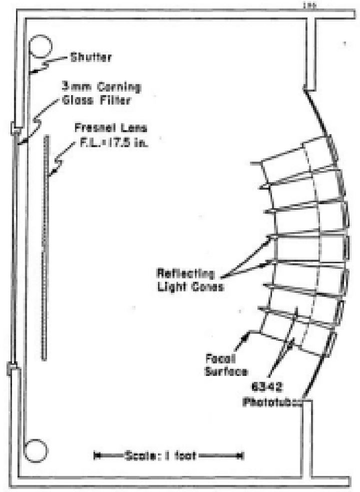
•Air fluorescence studied (early 60’s) by Los Alamos Sc. Lab. as a method for detecting the yield on nuclear explosions in atmospheric tests.

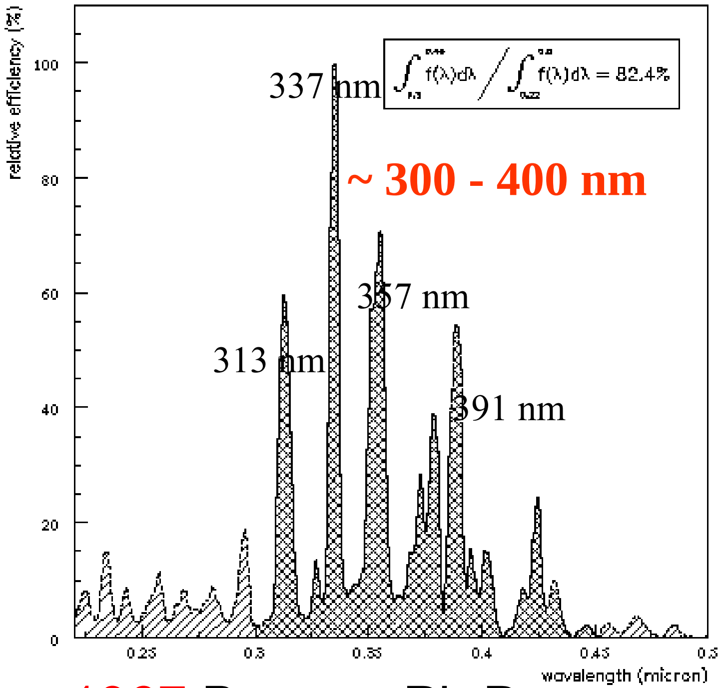
•Emission spectrum studied by A. Bunner (PhD thesis, 1967) , a student of Rossi and Greisen (formerly in Manhattan Project).

FD: the beginning…

Excitation of the nitrogen molecules and their radiative dexcitation .
Collisional quenching

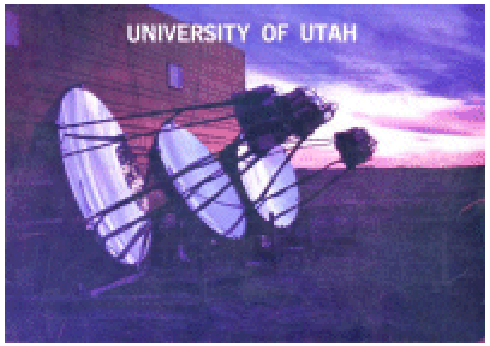
1967 First full-scale experiment by Greisen's group at Cornell



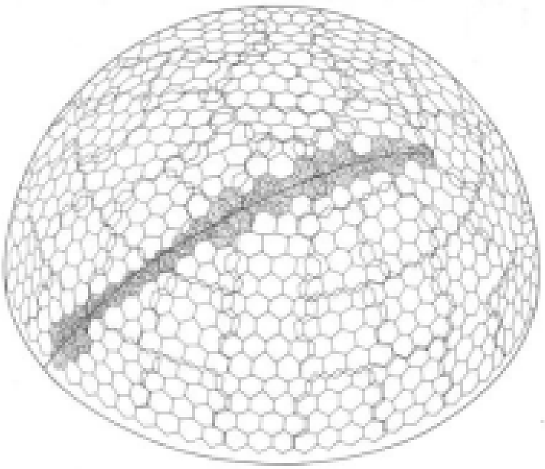


1967 Bunner, Ph.D Thesis Cornell Univ.

1976 Fluorescence Detector realized by Utah University and installed at Volcano Ranch, New Mexico

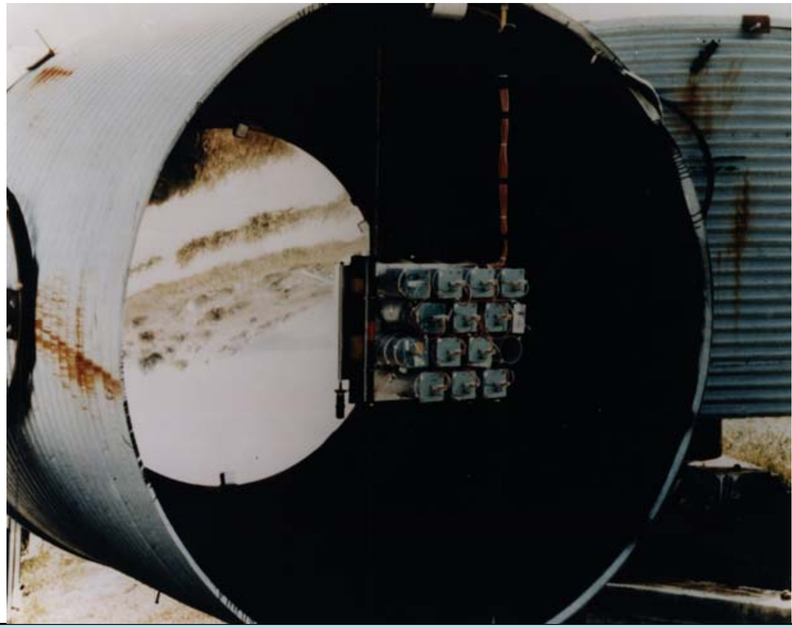


The Fly's Eye experiment



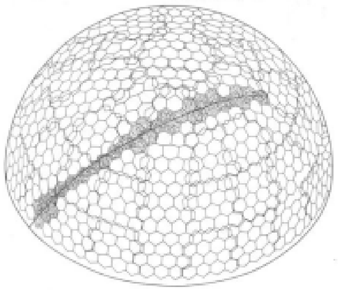
1981 The University of Utah Cosmic Ray group (G.Cassiday and coworkers) constructed Fly's Eye, a full-scale observatory based on the Volcano Ranch prototype basic design.
The experiment was located in the West Desert of Utah, within the US Army Dugway Proving Ground (DPG), 160 km southwest of Salt Lake City.

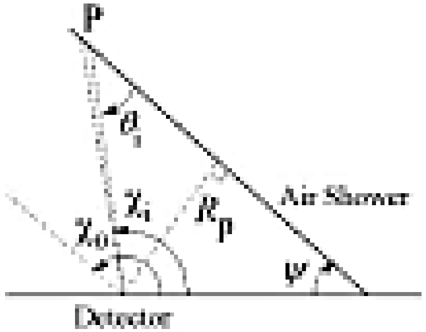
(Baltrusaitis et al., 1985)



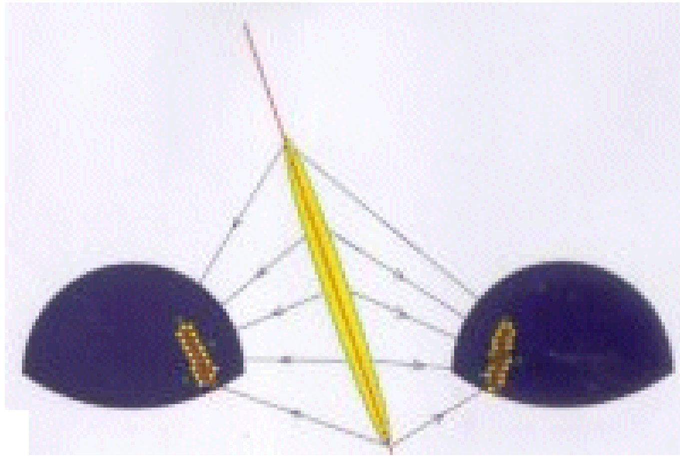
Better reconstruction (geometry)

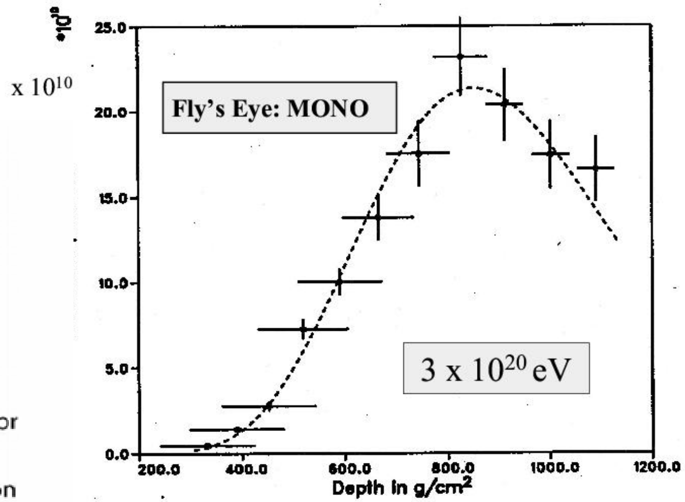
for “stereo” events

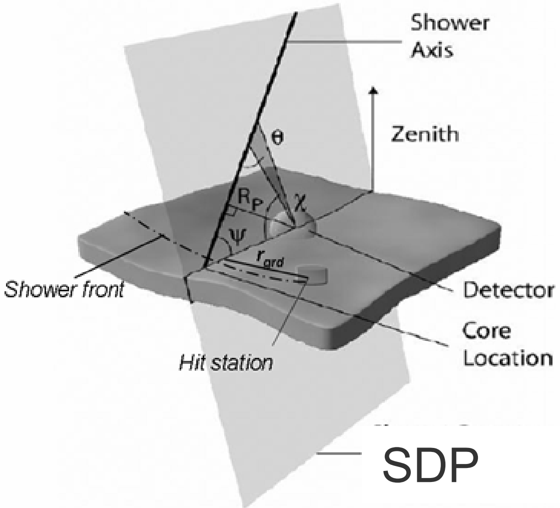


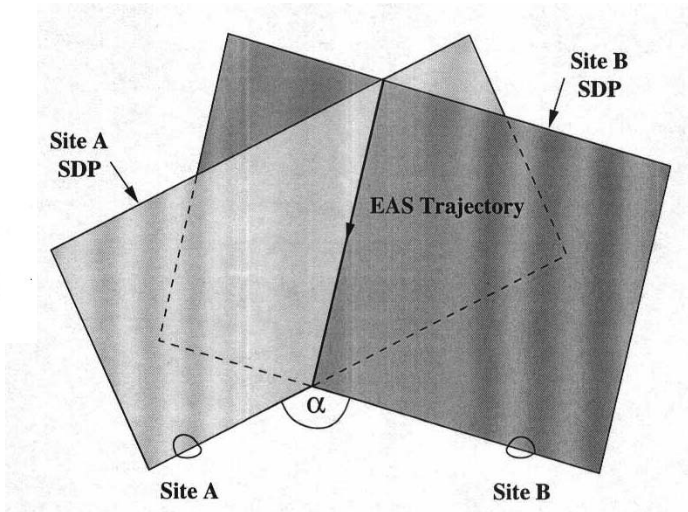


Fit: $t_i = t_0 + (R_p/c)\tan(\chi_0/2 - \chi_i/2)$

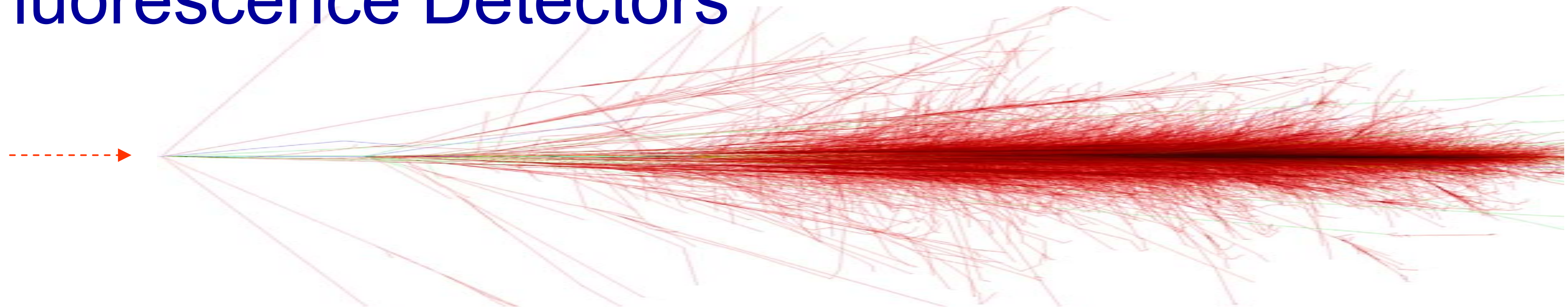


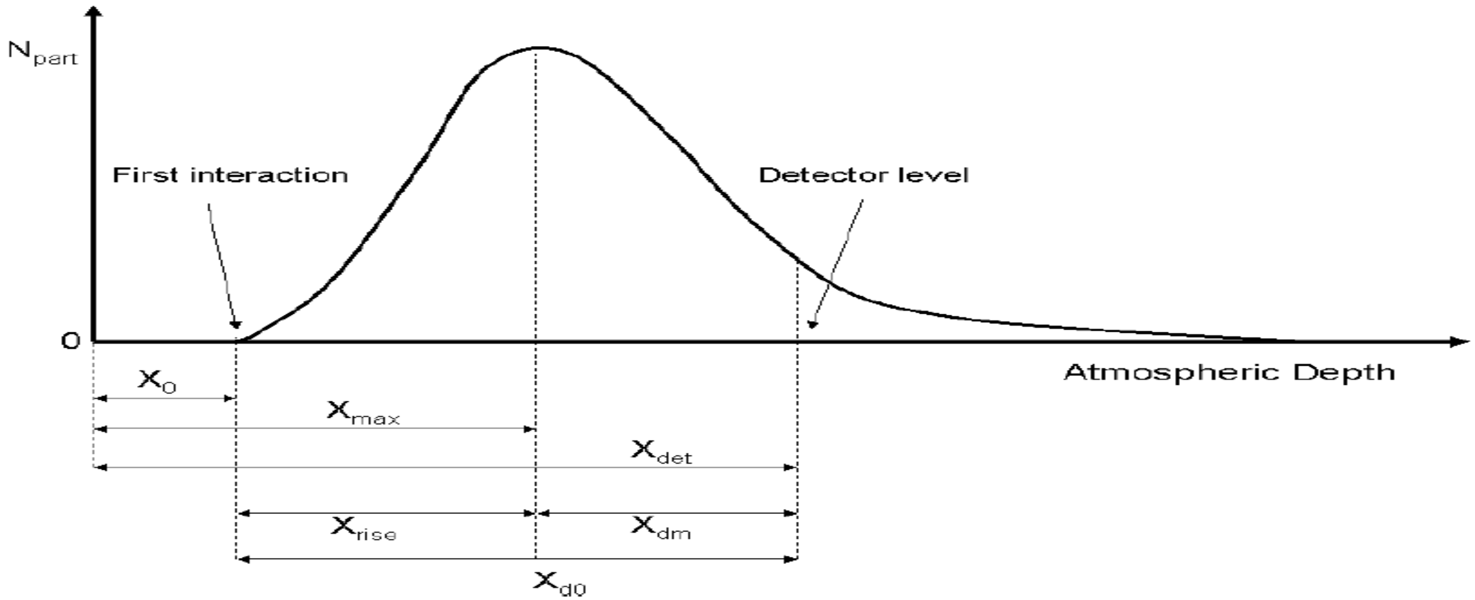






Measuring the shower profile with air Fluorescence Detectors





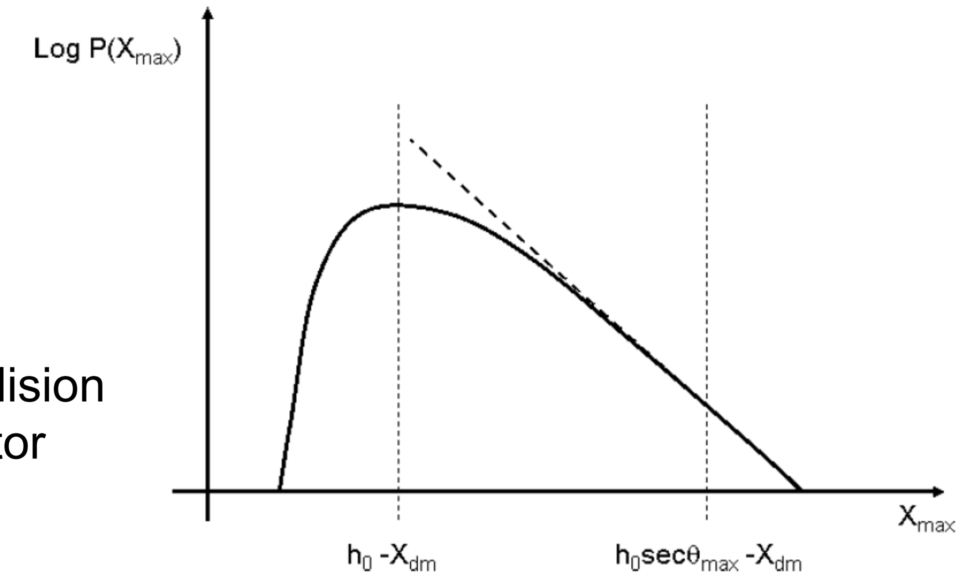
$$P(X_{\max}) = P(X_0) \otimes P(X_{rise})$$

… and the experiment resolution has to be taken into account

Measure the shower profile with air Fluorescence Detectors

For sufficiently large X_{max} values and fixed energy

$$P(X_{max}) \propto e^{-\frac{X_{max}}{\Lambda}}$$



However Λ **= k** λ_{int} mainly because of collision inelasticity, shower fluctuations and detector resolution.

The factor k is determined by simulations and depends on:

- **hadronic interactions**
- **detector features and location (atm. depth)**
- **actual set of experimental observables**
- **analysis cuts**
- **energy, ...**

Then: $\boldsymbol{\sigma_{p\text{-}Air}\,(mb) = 2.4\ 10^4 / \lambda_{int}(g/cm^2)}$

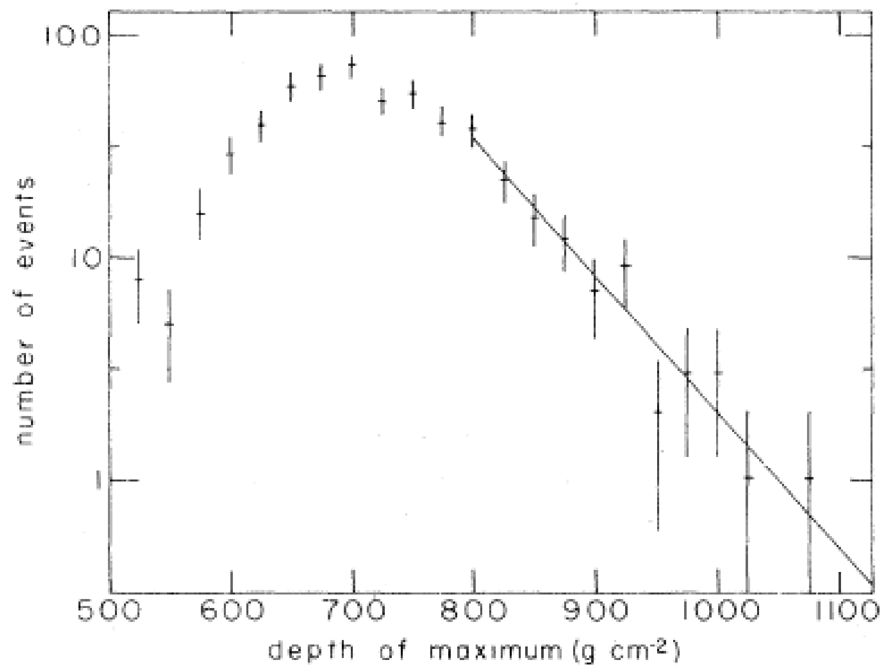
The Fly's Eye result

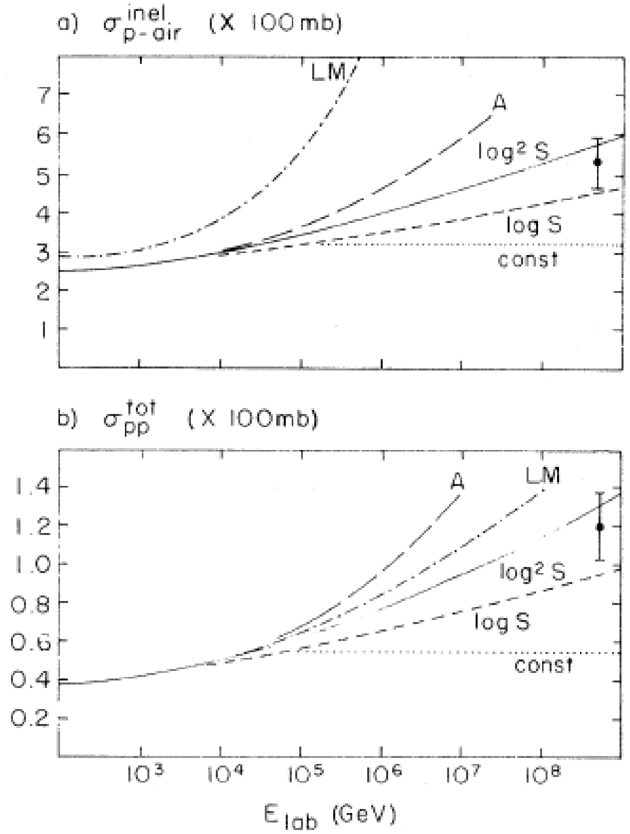
VOLUME 52, NUMBER 16 PHYSICAL REVIEW LETTERS 16 APRIL 1984

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 lo and a $\log^2 s$ extrapolation of the total pp cross section as measured at lower energies.





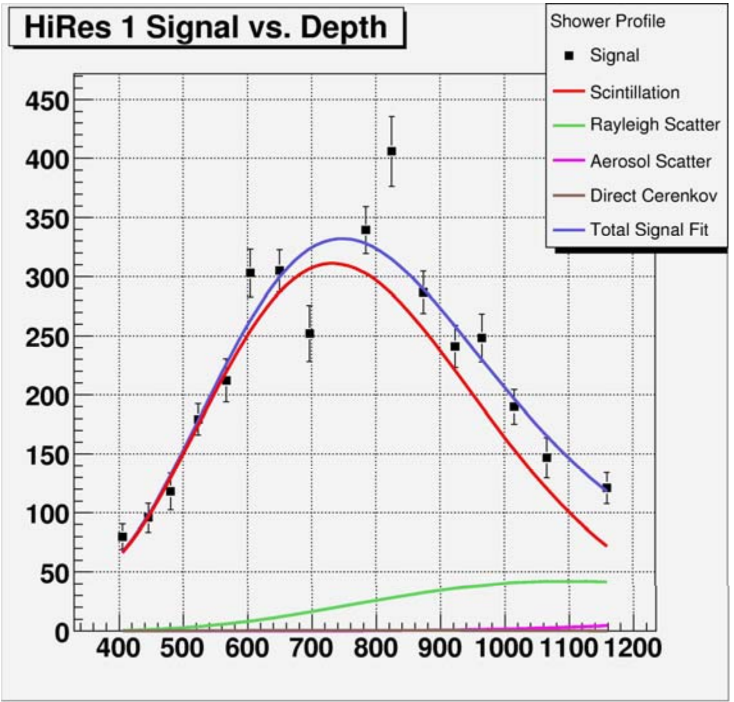
The HiRes experiment

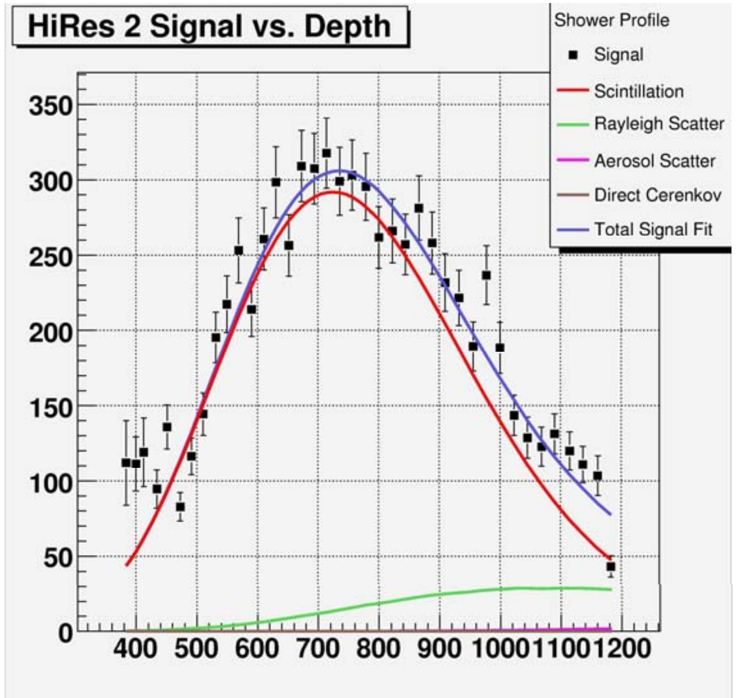
- HiRes1: atop Five Mile Hill
- 21 mirrors, 1 ring

- HiRes2: Atop Camel's Back Ridge
- 12.6 km SW of HiRes1.
- 42 mirrors, 2 rings

The two telescopes are 12.6 km apart

HiRes: Measured shower profile





K.Belov

Measured shower parameters.

Event by event:

- X_{max} in g/cm^2;
- Total energy of the primary particle:
- Arrival direction

Statistically:

- *p*-air inelastic cross-section;
- Mass composition.

HiRes: Measuring the cross section

A suitable deconvolution procedure, allows

the exrtaction of λ_{int} from data:

$$P(X_{\max}) = P(X_0) \otimes P(X_{rise})$$

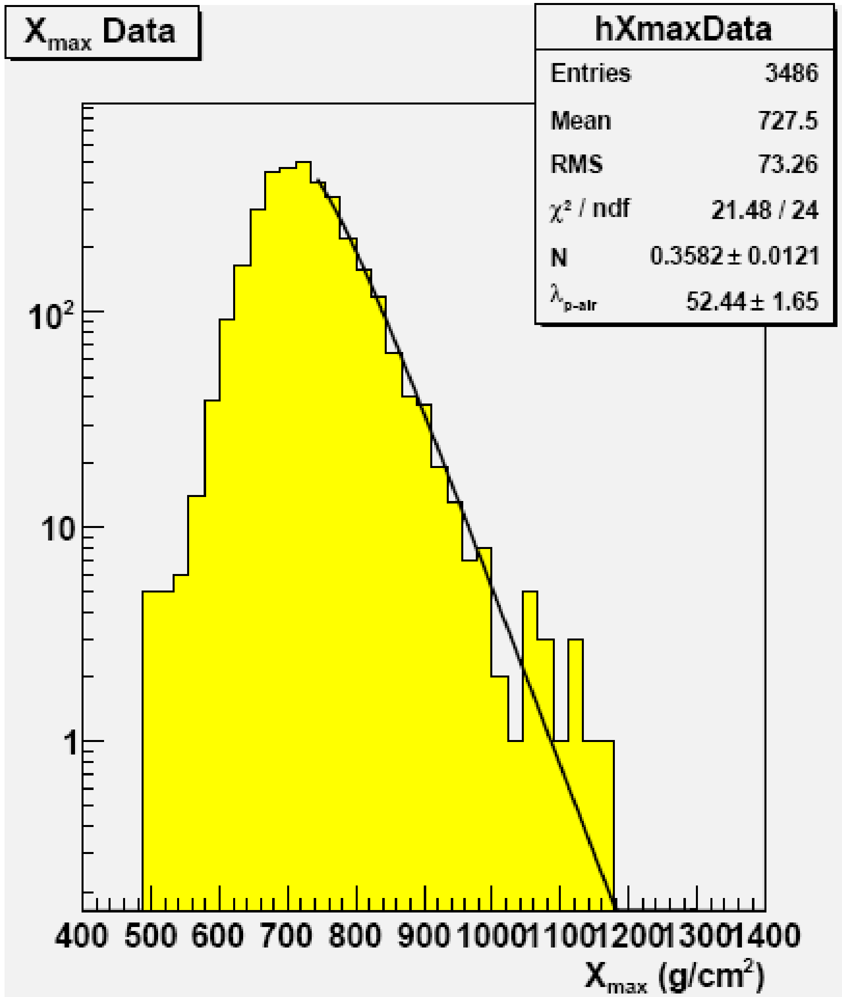
The data from december 1999 till november 2005 were analyzed.

After taking into account the effect of heavier primaries, the result is:

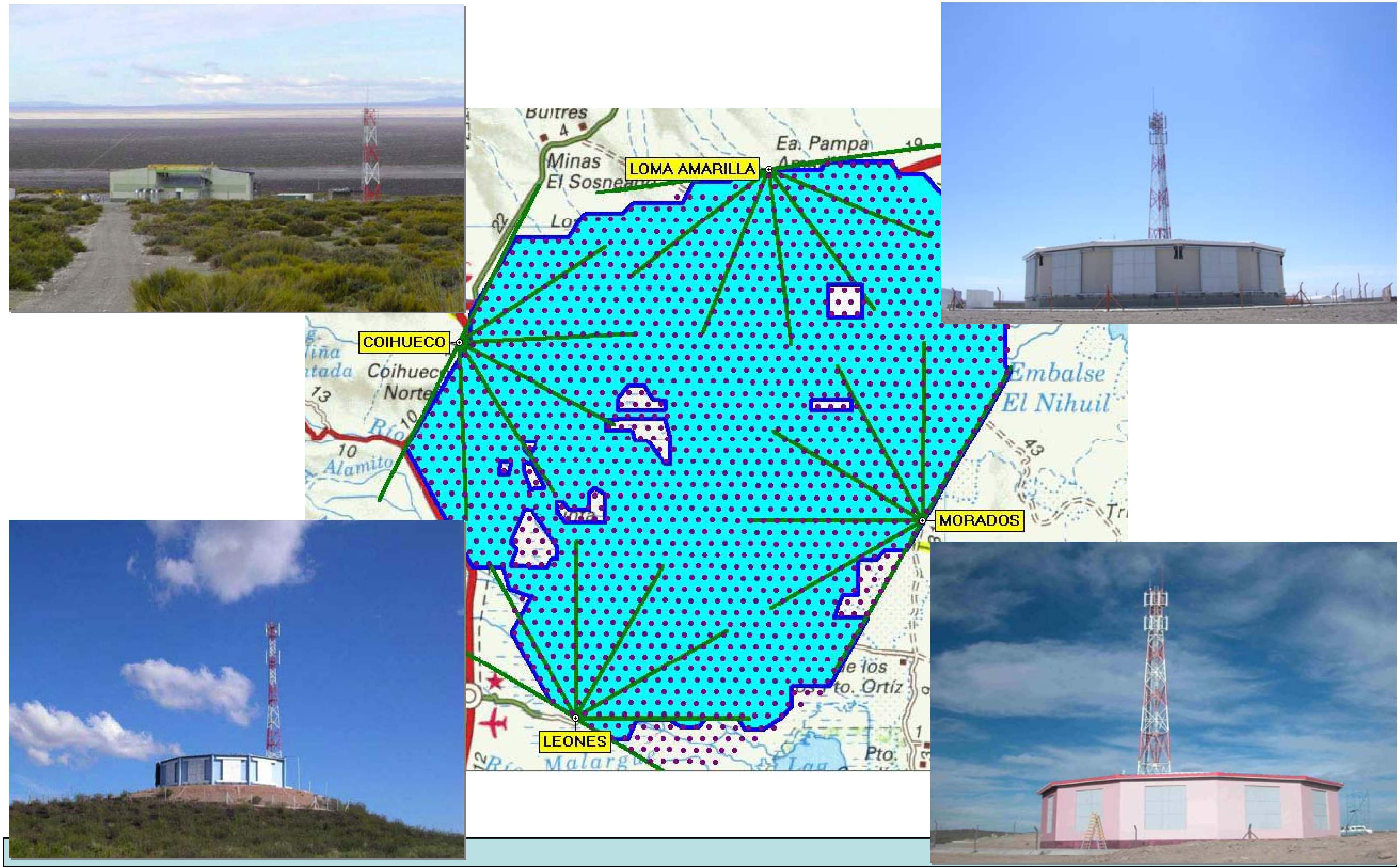
$$\sigma_{inel}^{p-air} = 460 \pm 14(stat) + 39(sys) - 26(sys)$$

at E = $10^{18.5}$ eV.

By assuming an asymptotic $\log^2(s)$ behaviour of σ_{pp} cross section, a value of (107.3 ±1.2) mb is foreseen for LHC

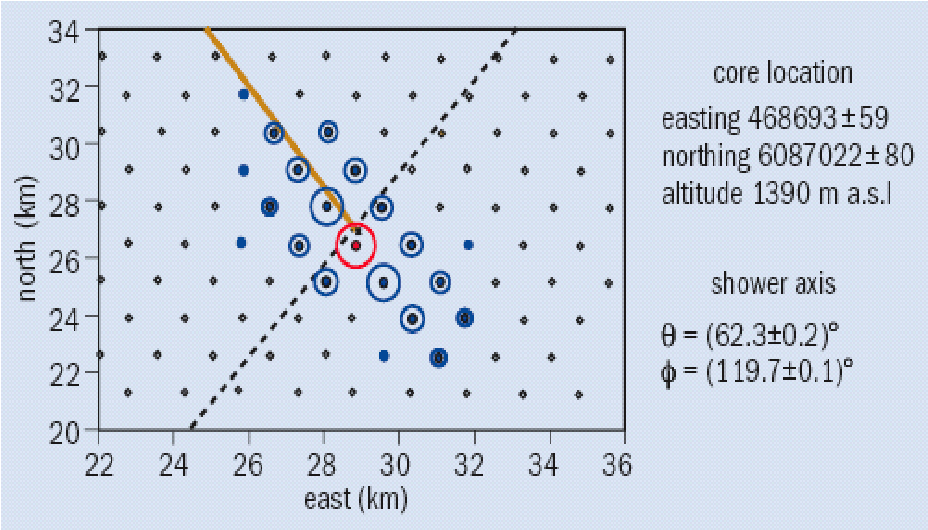


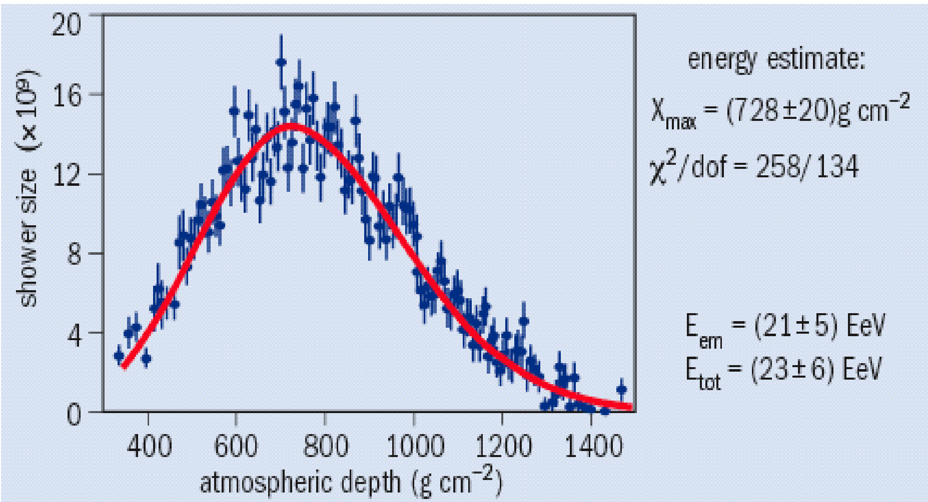
The AUGER experiment



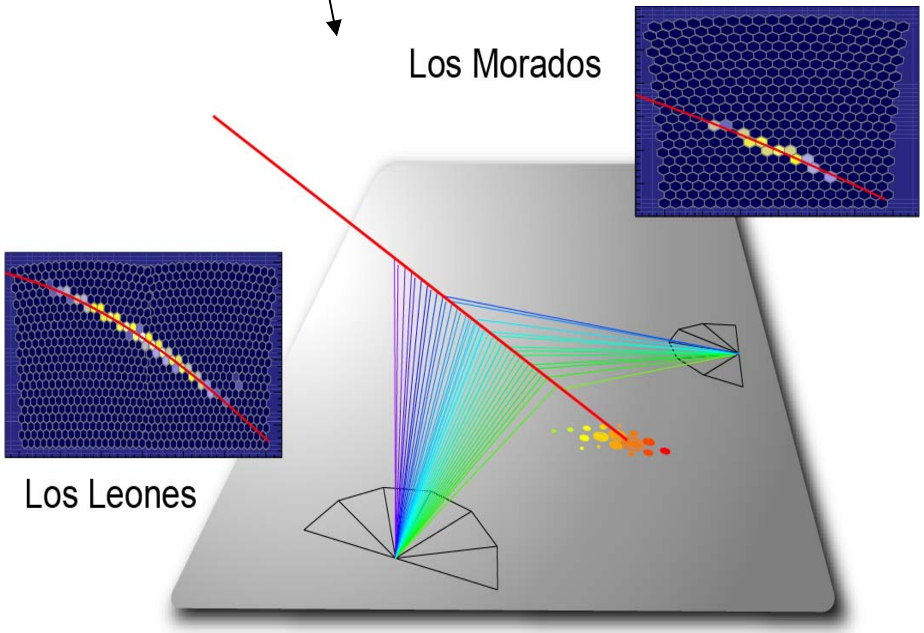
The AUGER experiment

Hybrid reconstruction

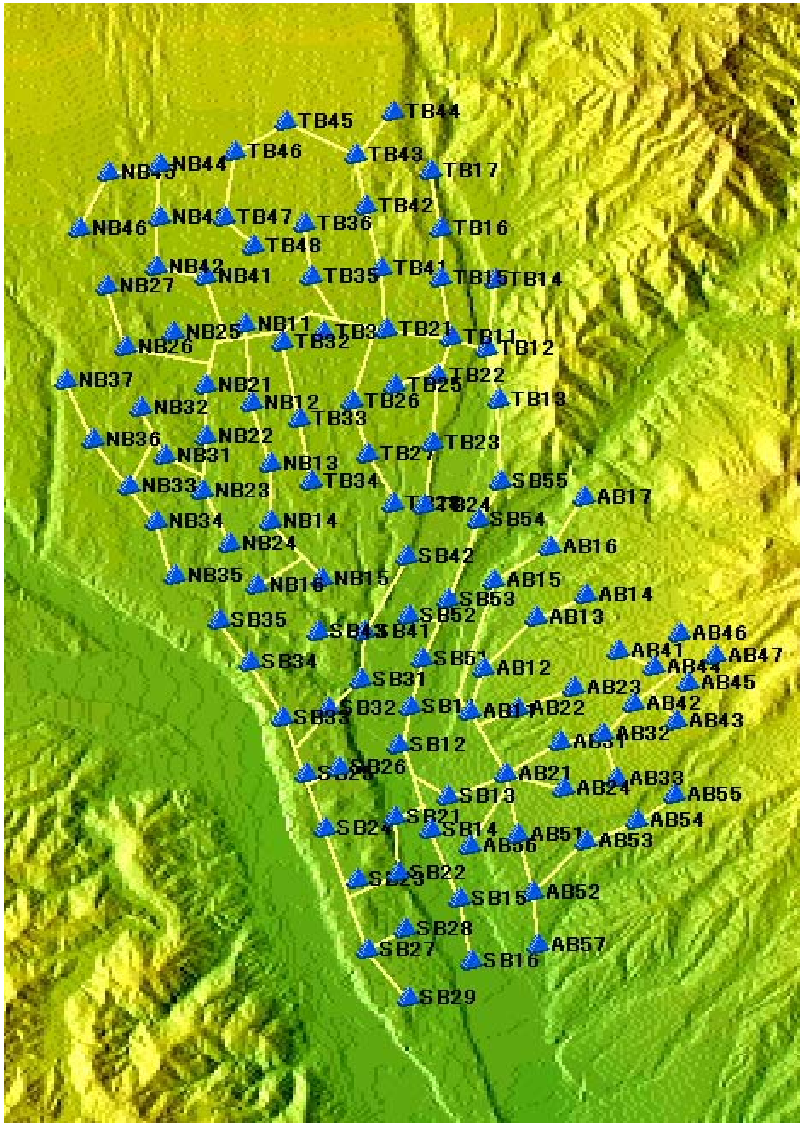


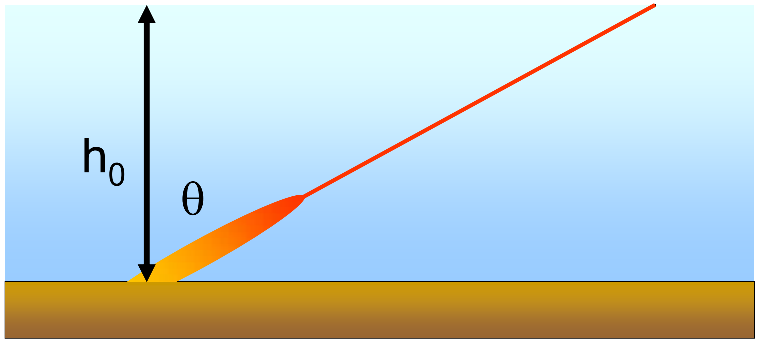


Stereo events,….



The AGASA experiment





Use the shower frequency vs (secθ -1)

$$I(\theta) = I(0) \cdot e^{-\frac{h_o}{\Lambda}(\sec(\theta)-1)}$$

for fixed energy (Nμ) and shower age (Ne).

Warning

Shower to shower fluctuations may seriously compromise the experimental sensitivity to the p-air cross section

Inelastic p-Air Cross Section at Energies between 10^{16} and 10^{18} eV Estimated from Air-Shower Experiments

T. Hara, Y. Hatano, N. Hayashida, M. Honda, K. Kamata, K. Kasahara, T. Kifune, Y. Mizumoto,[a] M. Nagano, G. Tanahashi, and S. Torii
Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo 188, Japan

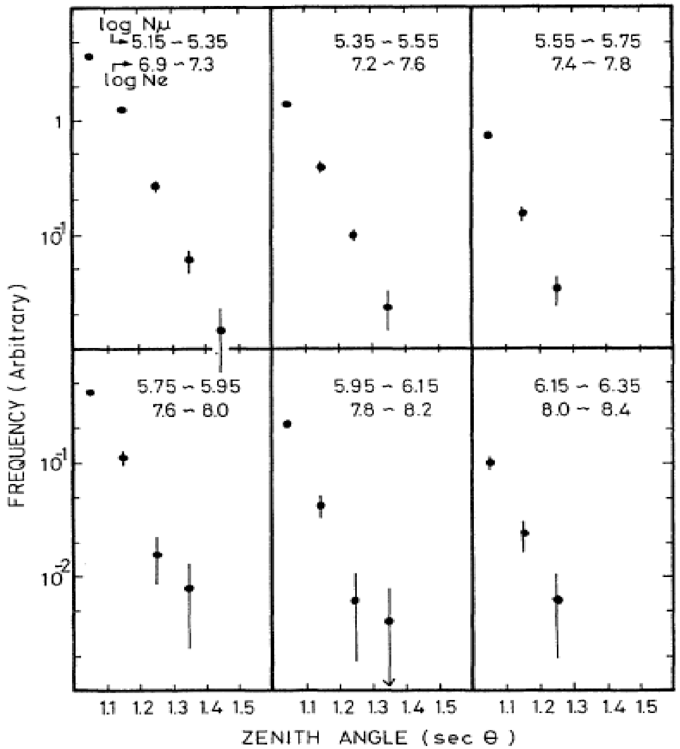
and

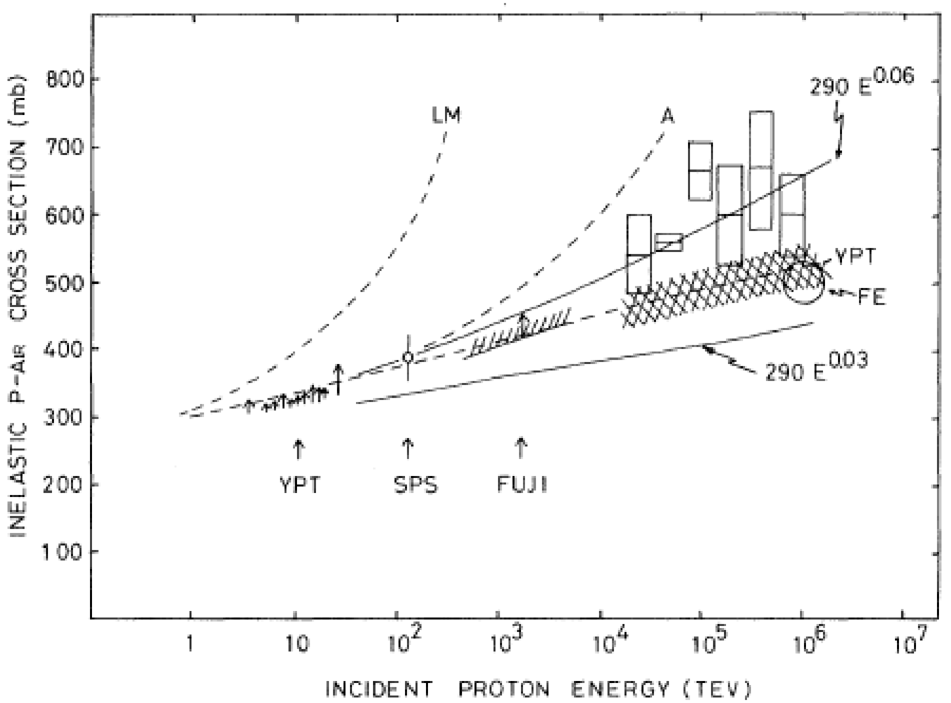
S. Kawaguchi
Faculty of General Education, Hirosaki University, Bunkyocho, Hirosaki 036, Japan

(Received 15 March 1983)

The inelastic cross section of p-air collisions [$\sigma_{\rm in}(p\text{-air})$] between 10^{16} and 10^{18} eV is estimated by the observation of extensive air showers at Akeno. The flux of air showers at different zenith angles is analyzed with both a fixed muon number and a fixed electron number. $\sigma_{\rm in}(p\text{-air})$ increases with energy as $290\times E_{\rm lab}^{0.06\pm0.01}$ mb ($E_{\rm lab}$ in teraelectronvolts) up to 10^{18} eV with the assumptions of Feynman scaling in the fragmentation region and at least 10% of the primary particles being protons.

The AGASA result





EAS-TOP

On top of Gran Sasso, L'Aquila
2000 m a.s.l. 820 $g \cdot cm^{-2}$
1989-2000

- Hadrons (iron/streamer tube calorimeter)
- E.M. (scintillator counters)
- Low Energy μ (E_μ > 1 GeV)
- Atmospheric Čerenkov Imaging
- H.E. μ (E > 1.3 TeV) (MACRO & LVD)

PHYSICAL REVIEW D 79, 032004 (2009)

Measurement of the proton-air inelastic cross section at $\sqrt{s} \approx 2$ TeV from the EAS-TOP experiment

M. Aglietta,[1,2] B. Alessandro,[2] P. Antonioli,[3] F. Arneodo,[4] L. Bergamasco,[2,5] M. Bertaina,[2,5] A. Castellina,[1,2] E. Cantoni,[1,5] A. Chiavassa,[2,5] B. D'Ettorre Piazzoli,[6] G. Di Sciascio,[6,*] W. Fulgione,[1,2] P. Galeotti,[2,5] P. L. Ghia,[1,†] M. Iacovacci,[6] G. Mannocchi,[1,2] C. Morello,[1,2] G. Navarra,[2,5] O. Saavedra,[2,5] A. Stamerra,[5,‡] G. C. Trinchero,[1,2] P. Vallania,[1,2] S. Vernetto,[1,2] and C. Vigorito[2,5]

(EAS-TOP Collaboration)

High energy hadronic interaction model	$\lambda_{\rm int}^{\rm sim}$ [g/cm^2]	$\lambda_{\rm obs}^{\rm sim}$ [g/cm^2]	k	$\lambda_{\rm obs}^{\rm exp}$ [g/cm^2]	$\lambda_{\rm int}^{\rm exp}$ [g/cm^2]	$\sigma_{p\text{-air}}^{\rm inel}$ [mb]
SIBYLL 2.1	59.4 ± 0.1	69.9 ± 1.4	1.18 ± 0.02	84.7 ± 5.0	71.8 ± 4.5	336 ± 21
QGSJET II	60.3 ± 0.1	68.5 ± 1.4	1.14 ± 0.02	80.2 ± 4.3	70.7 ± 4.2	341 ± 20

The Ne-Nμ method was used

$$\boxed{\sigma_{p\text{-air}}^{\rm inel} = 338 \pm 21_{\rm stat} \pm 19_{\rm syst} - 29_{\rm syst(He)}\ {\rm mb}.}$$

Experiment	SIBYLL 2.1 ($\sigma_{p\text{-air}}^{\rm inel} = 406 \pm 1$ mb)		QGSJET II ($\sigma_{p\text{-air}}^{\rm inel} = 400 \pm 1$ mb)		QGSJET II$_{\rm HDPM}$ ($\sigma_{p\text{-air}}^{\rm inel} = 367 \pm 1$ mb)	
Analysis	$\sigma_{p\text{-air}}^{\rm inel}$ [mb]	$\Delta\sigma_{p\text{-air}}^{\rm inel}$ [mb]	$\sigma_{p\text{-air}}^{\rm inel}$ [mb]	$\Delta\sigma_{p\text{-air}}^{\rm inel}$) [mb]	$\sigma_{p\text{-air}}^{\rm inel}$ [mb]	$\Delta\sigma_{p\text{-air}}^{\rm inel}$ [mb]
SIBYLL 2.1	...	...	419 ± 12	$+19 \pm 12$	372 ± 13	$+5 \pm 13$
QGSJET II	393 ± 11	-13 ± 11	...	...	361 ± 12	-6 ± 12

The ARGO-YBJ experiment

High Altitude Cosmic Ray Laboratory @ YangBaJing,Tibet, China

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

The ARGO-YBJ physics goals

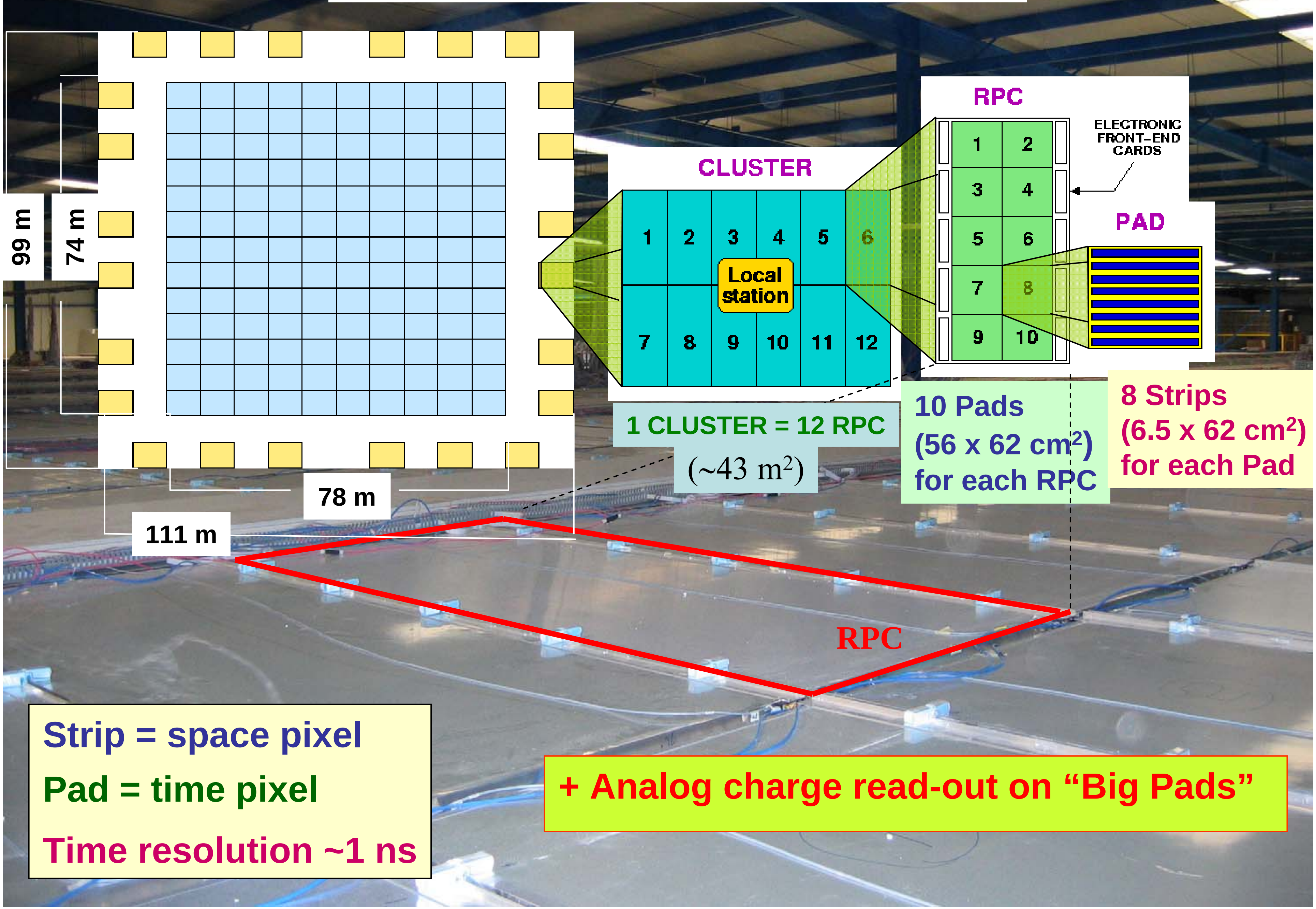
- **Cosmic ray physics**:
  spectrum and composition (E_{th} few TeV),
  study of the shower space-time structure,
  p-Air cross section measurement,
  anti-p / p ratio at TeV energies,
  …..

- **VHE γ-Ray Astronomy**:
  search for point-like (and diffuse) galactic and
  extra-galactic sources at few hundreds GeV energy threshold
- **Search for GRB's** (full GeV / TeV energy range)
- **Sun and Heliosphere physics**

through the…

Observation of *Extensive Air Showers* produced in the atmosphere by primary γ's and nuclei

The ARGO-YBJ detector

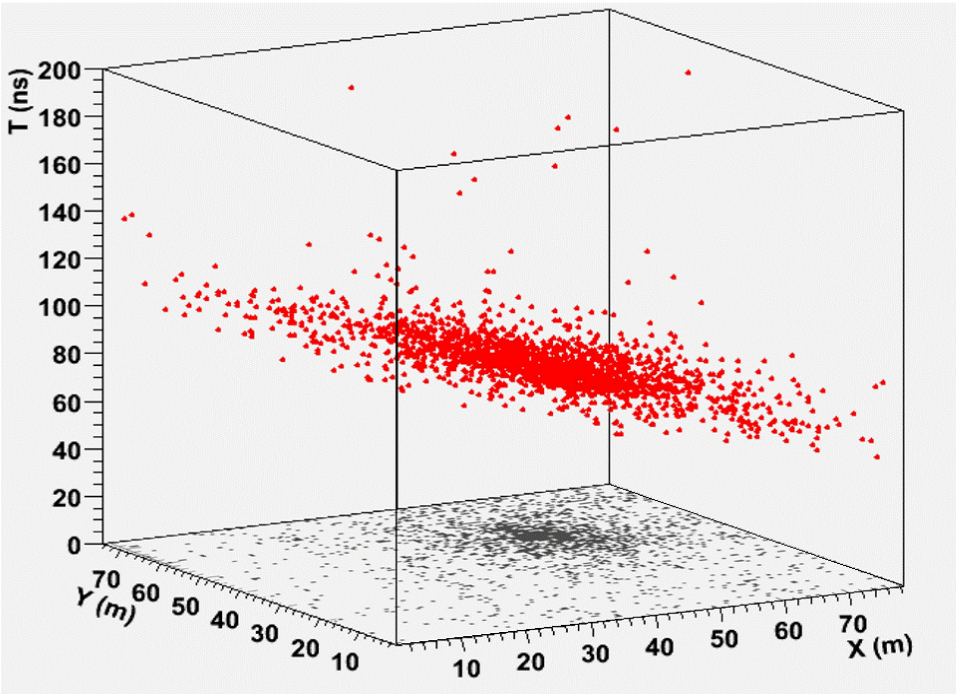


EAS reconstruction

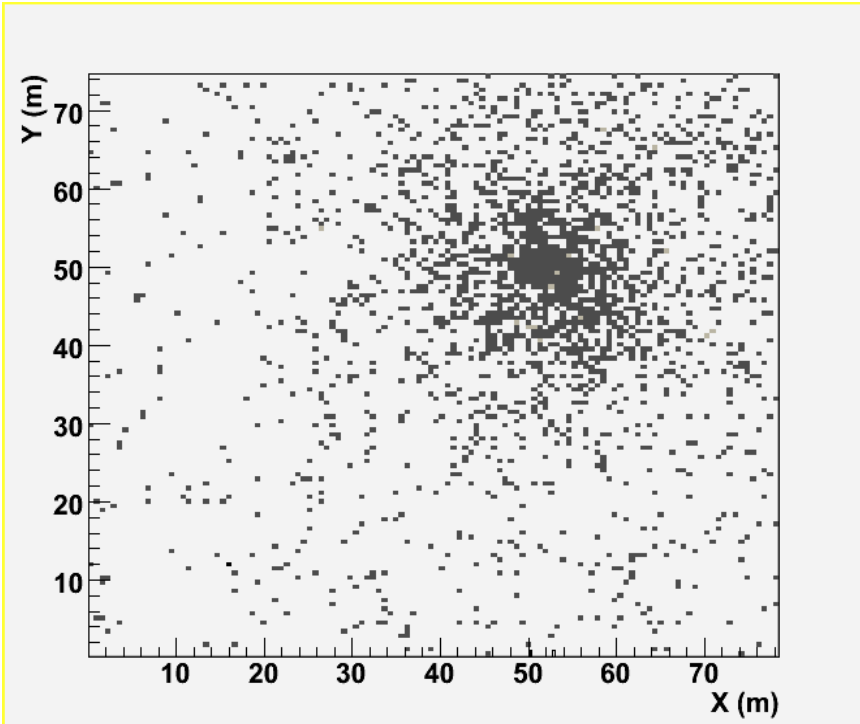
Event Rate ~ 4 kHz for N_{hit} >20

High space/time granularity
+ Full coverage
+ High altitude

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

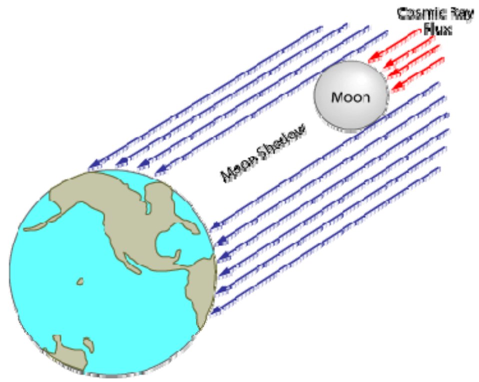


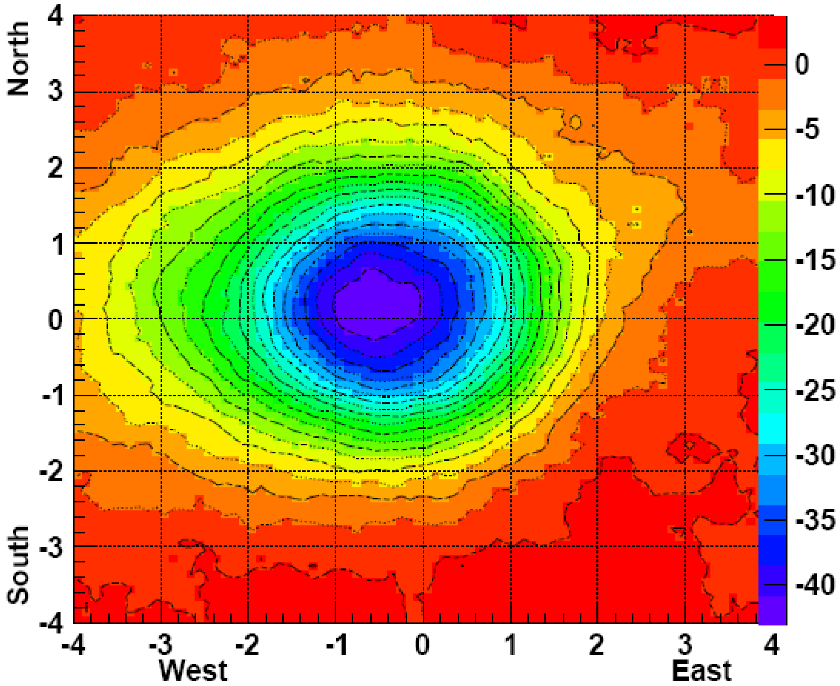
3-D view of a detected shower

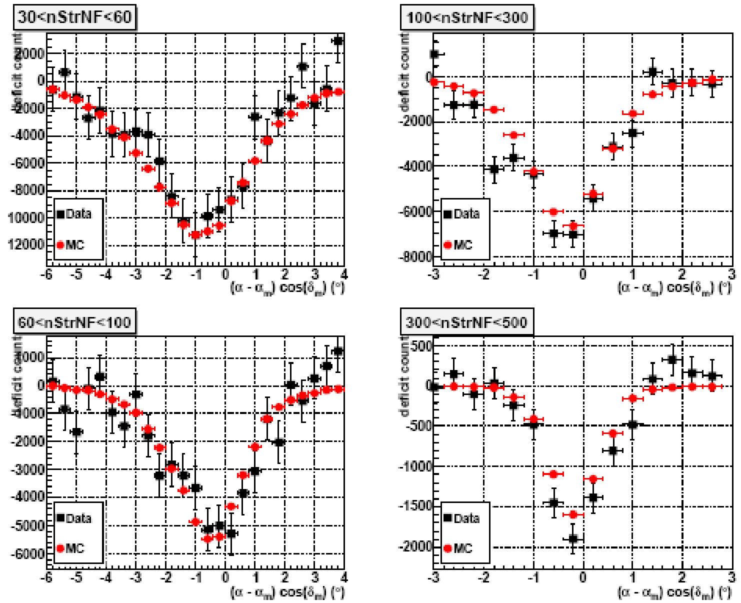


Top view of the same shower

The Moon Shadow







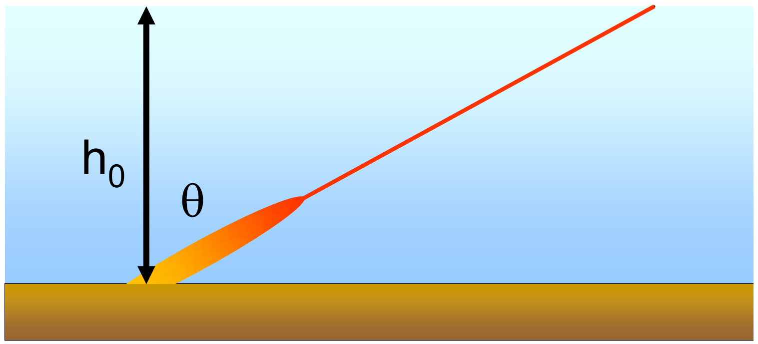
- Size of the deficit $\Rightarrow$ **angular resolution**
- Position $\Rightarrow$ **pointing accuracy**
- West displacement $\Rightarrow$ **Energy calibration** (Geomagnetic bending $\approx$ 1.57° / E (TeV))
- **Antiprotons** should give a shadow on the opposite side (measure the pbar/p flux ratio)

The proton-air cross section measurement

Use the shower frequency vs (secθ -1)

$$I(\theta) = I(0) \cdot e^{-\frac{h_o}{\Lambda}(\sec(\theta)-1)}$$

for fixed energy and shower age.



However Λ **= k** λ_{int} mainly because of collision inelasticity, shower fluctuations and detector resolution.

It is determined by simulations and depends on:

- **hadronic interactions**
- **detector features and location (atm. depth)**
- **actual set of experimental observables**
- **analysis cuts**
- **energy, ...**

Then: $\boldsymbol{\sigma_{p\text{-}Air}}$ **(mb) = 2.4 10**^{4} **/** $\boldsymbol{\lambda_{int}}$**(g/cm**^{2}**)**

Warning

Take care of shower fluctuations

- **Constrain** $X_{DO} = X_{det} - X_0$ or $X_{DM} = X_{det} - X_{max}$
- **Select** deep showers (large X_{max}, i.e. small X_{D0} or X_{DM})
- **Exploit** detector features (space-time pattern) and location (depth).

Data selection

➢ **Event selection based on:**

(a) "shower size" on detector, N_{strip} (strip multiplicity)

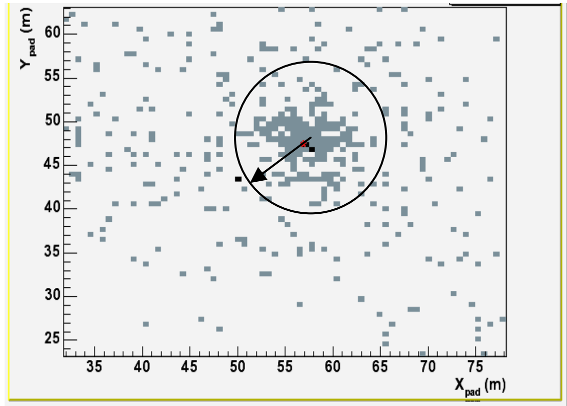
(b) core reconstructed in a fiducial area (64 x 64 m^2)

(c) constraints on Strip density (> 0.2/m^2 within R_{70})

and shower extension (R_{70} < 30m)

N_{strip} is used to get defferent E sub-samples

R_{70}: radius of circle including 70% of hits

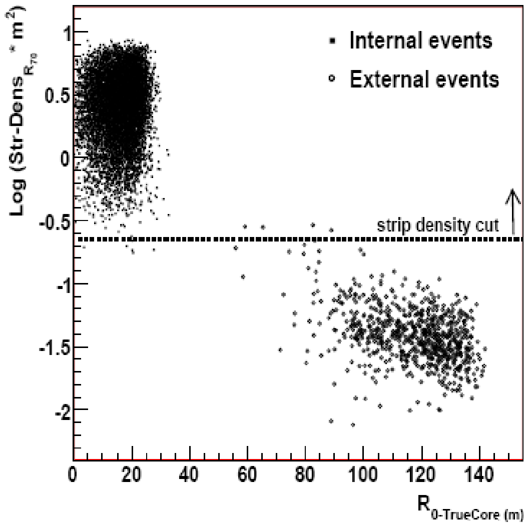


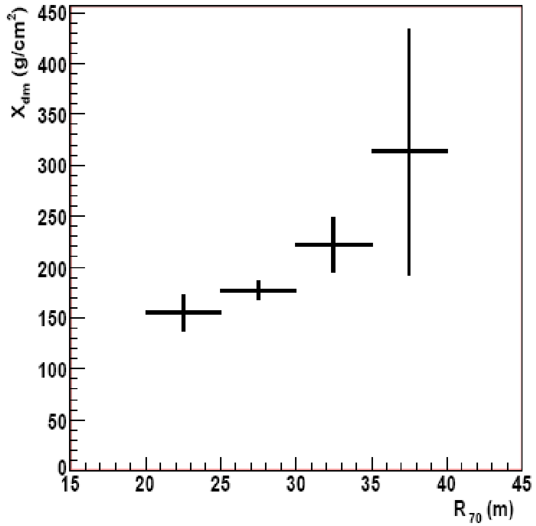
Full Monte Carlo simulation:

Corsika showers

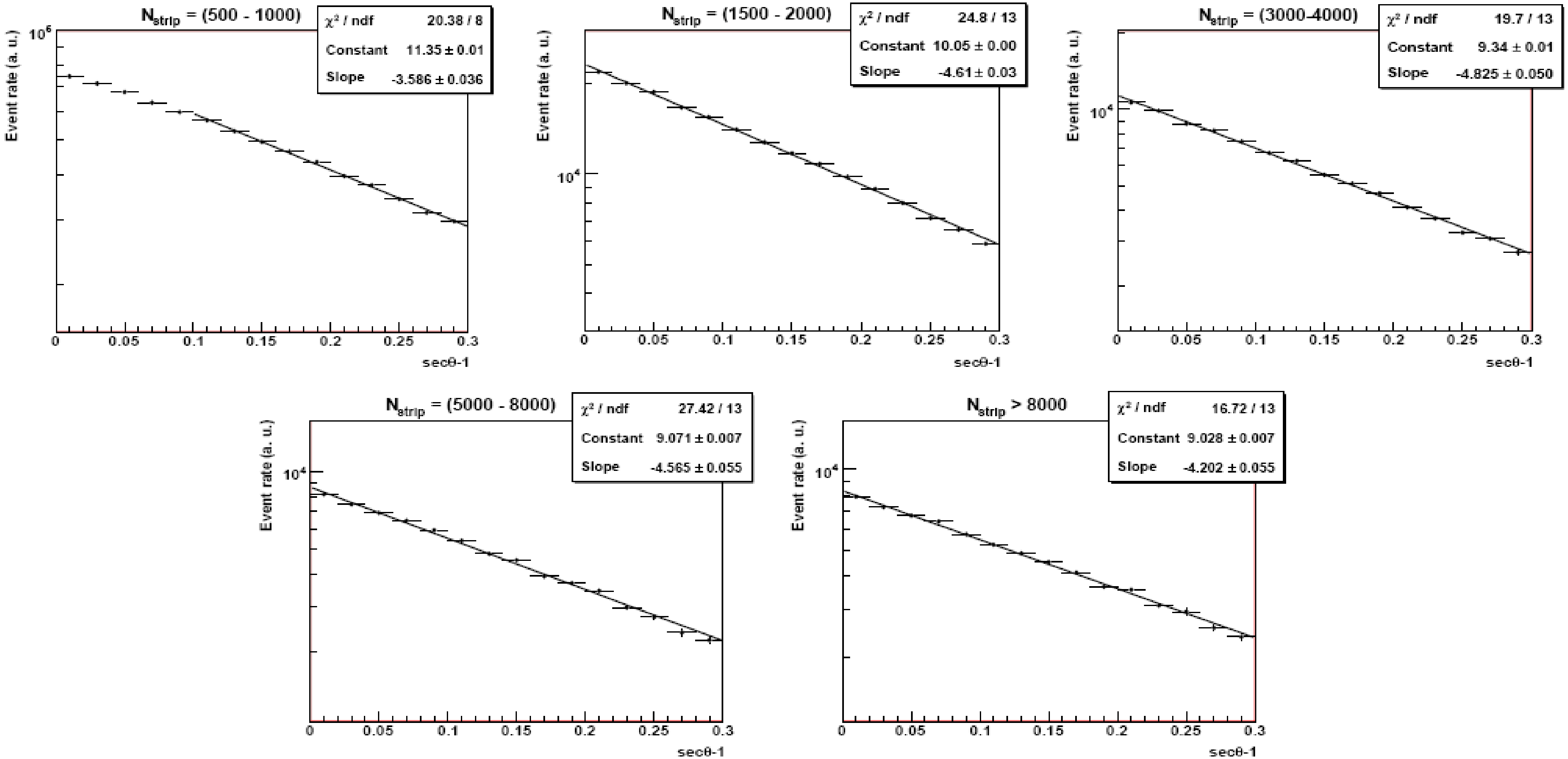
QGSJET I and II, SYBILL int. models

GEANT detector simulation





Experimental data



Wheather effects, namely the atmospheric pressure dependence on time, have been shown to be at the level of 1 %

h_0^{MC} = 606.7 g/cm^2 (4300m a.s.l. standard atm.) h_0^{MC} / h_0 = 0.988 ± 0.007 (↔ 4200 m a.s.l.)

Heavy primaries contribution

Hoerandel AP 19 (2003) 193 taken as reference.

JACEE and RUNJOB for the evaluation of systematic error

$$\frac{dN}{dE} = \Phi(E) = \Phi_Z^0 \cdot \left(\frac{E}{TeV} \right)^{-\gamma_Z}$$

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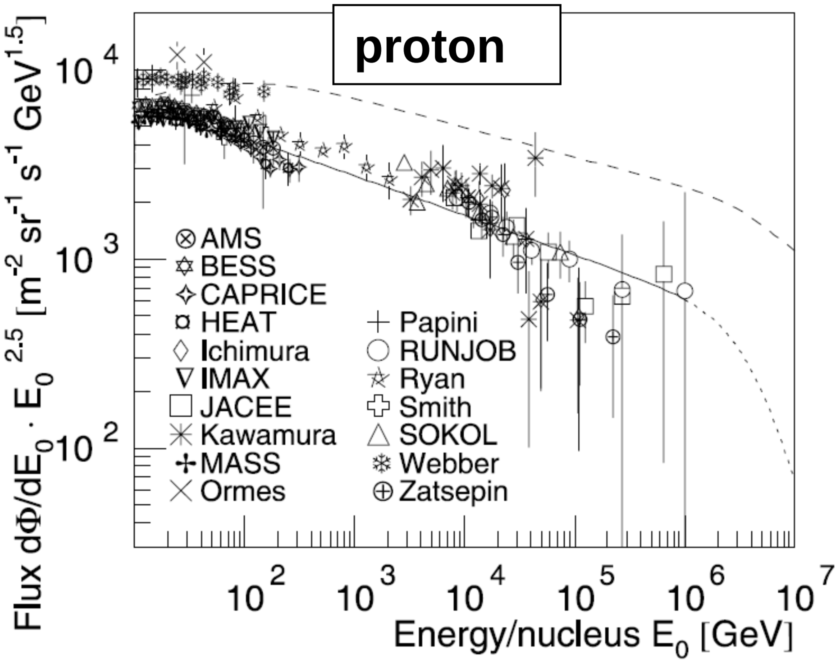
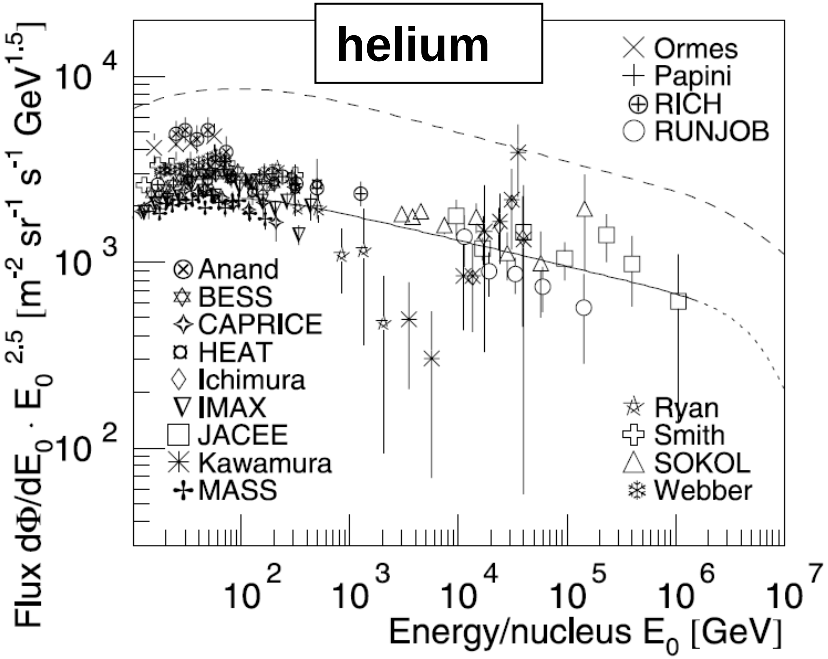
Table 1
Absolute flux Φ_Z^0 ((m^2 sr s TeV)$^{-1}$) at $E_0 = 1$ TeV/nucleus and spectral index γ_Z of cosmic-ray elements

Z		Φ_Z^0	$-\gamma_Z$	Z		Φ_Z^0
1[a]	H	8.73×10^{-2}	2.71	47[c]	Ag	4.54
2[a]	He	5.71×10^{-2}	2.64	48[c]	Cd	6.30
3[b]	Li	2.08×10^{-3}	2.54	49[c]	In	1.61
4[b]	Be	4.74×10^{-4}	2.75	50[c]	Sn	7.15
5[b]	B	8.95×10^{-4}	2.95	51[c]	Sb	2.03
6[b]	C	1.06×10^{-2}	2.66	52[c]	Te	9.10
7[b]	N	2.35×10^{-3}	2.72	53[c]	I	1.34
8[b]	O	1.57×10^{-2}	2.68	54[c]	Xe	5.74
9[b]	F	3.28×10^{-4}	2.69	55[c]	Cs	2.79
10[b]	Ne	4.60×10^{-3}	2.64	56[c]	Ba	1.23

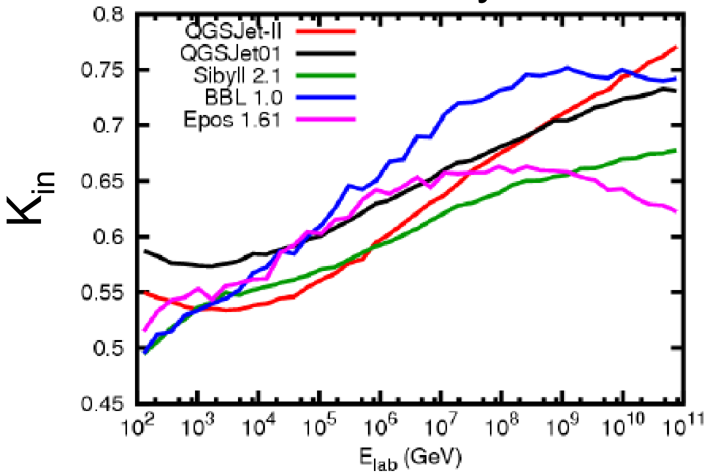




The ARGO-YBJ results

$$k = k_0 \, k_{det} \qquad k_0 \simeq \frac{1}{1 - \langle (1-K_{in})^{\gamma-1} \rangle}$$

Inelasticity



$$\Rightarrow k_{det} \simeq 1.15 \div 1.45$$

Apart from the boundaries of the covered energy region (systematic effects)

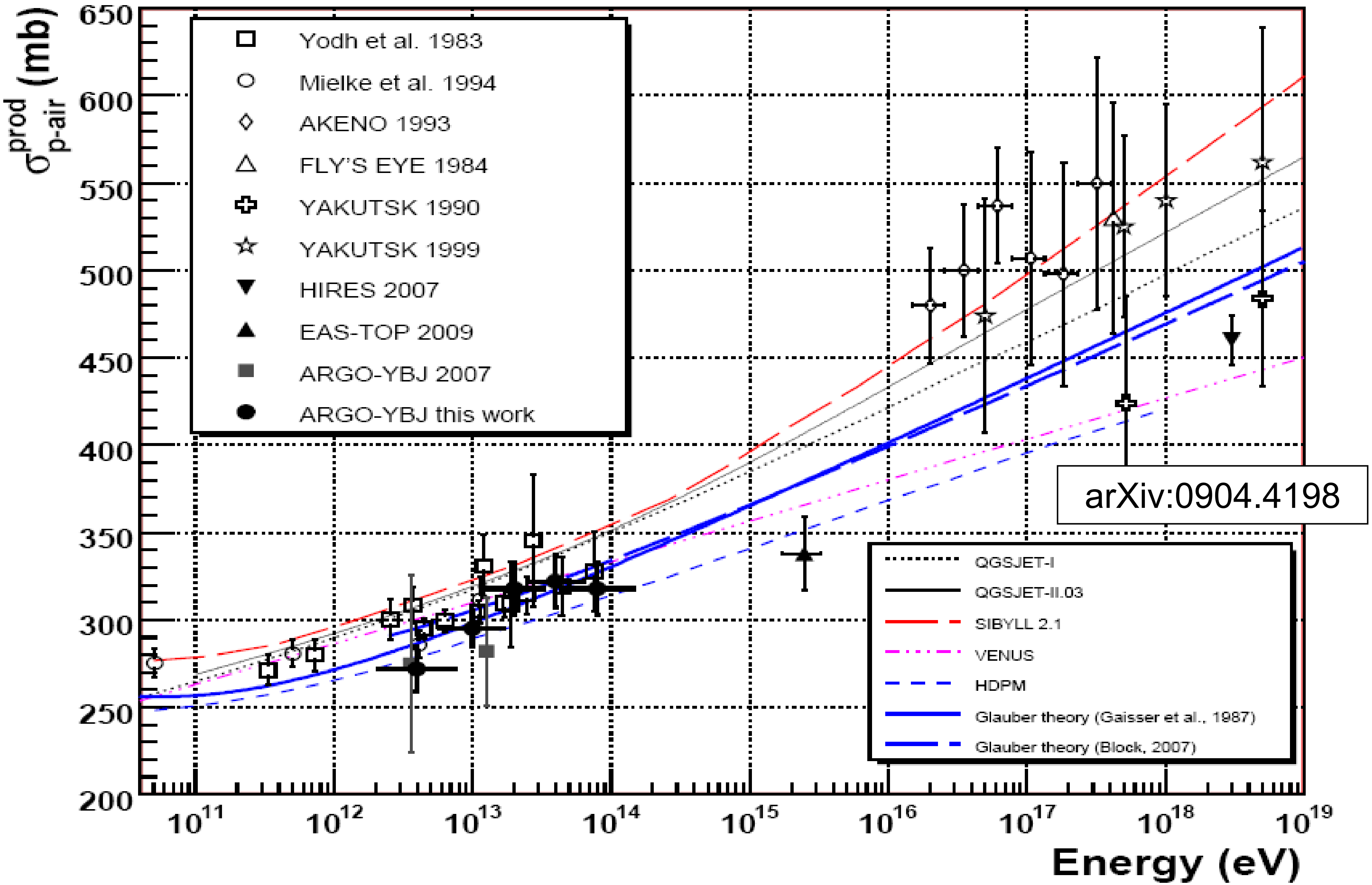
ΔN_{strip}	$\mathrm{Log}(E/\mathrm{eV})$	$k_{QGSJET-I}$	$k_{QGSJET-II.03}$	$k_{SIBYLL-2.1}$	k
$500 \div 1000$	12.6 ± 0.3	$1.98 \pm 0.06 \pm 0.05$	$1.84 \pm 0.14 \pm 0.05$	$1.87 \pm 0.08 \pm 0.04$	$1.93 \pm 0.05 \pm 0.06$
$1500 \div 2000$	13.0 ± 0.2	$1.59 \pm 0.03 \pm 0.04$	$1.75 \pm 0.12 \pm 0.04$	$1.76 \pm 0.06 \pm 0.04$	$1.63 \pm 0.03 \pm 0.08$
$3000 \div 4000$	13.3 ± 0.2	$1.69 \pm 0.05 \pm 0.03$	$1.63 \pm 0.13 \pm 0.03$	$1.72 \pm 0.05 \pm 0.03$	$1.70 \pm 0.03 \pm 0.04$
$5000 \div 8000$	13.6 ± 0.2	$1.74 \pm 0.05 \pm 0.03$	$1.97 \pm 0.17 \pm 0.04$	$1.91 \pm 0.05 \pm 0.03$	$1.84 \pm 0.03 \pm 0.10$
> 8000	13.9 ± 0.3	$2.04 \pm 0.06 \pm 0.05$	$2.23 \pm 0.19 \pm 0.05$	$2.01 \pm 0.05 \pm 0.05$	$2.03 \pm 0.04 \pm 0.10$

arXiv:0904.4198

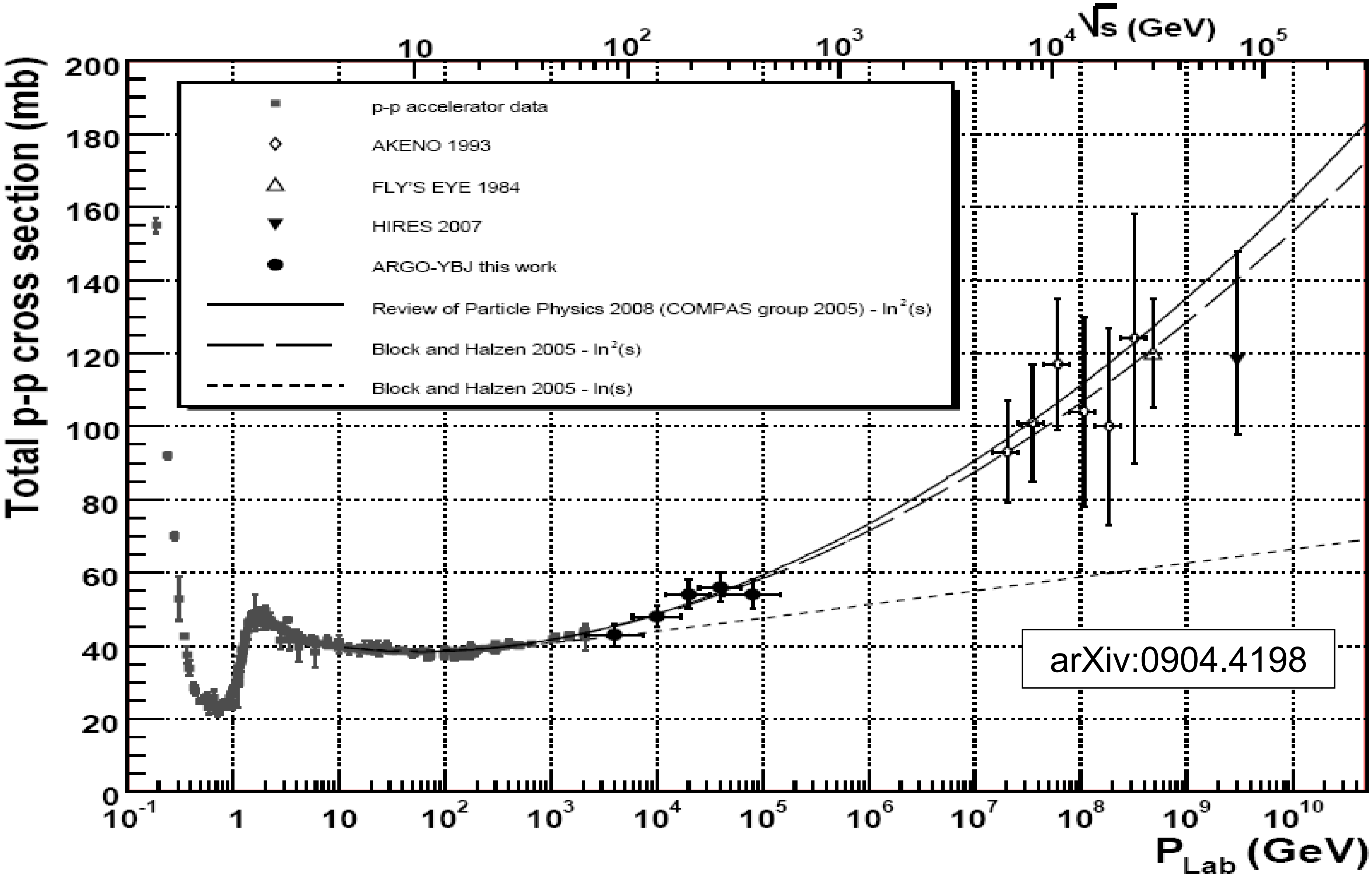
Correction due to He contamination

ΔN_{strip}	η	σ_{p-air} (mb)	σ_{p-p} (mb)
$500 \div 1000$	$1.00 \pm 0.04 \pm 0.01$	$272 \pm 13 \pm 9$	$43 \pm 3 \pm 5$
$1500 \div 2000$	$1.00 \pm 0.03 \pm 0.01$	$295 \pm 10 \pm 14$	$48 \pm 3 \pm 6$
$3000 \div 4000$	$0.99 \pm 0.04 \pm 0.01$	$318 \pm 15 \pm 8$	$54 \pm 4 \pm 6$
$5000 \div 8000$	$0.98 \pm 0.04 \pm 0.03$	$322 \pm 15 \pm 20$	$56 \pm 4 \pm 7$
> 8000	$0.95 \pm 0.04 \pm 0.04$	$318 \pm 15 \pm 21$	$54 \pm 4 \pm 8$

The proton-air cross section



The total p-p cross section



Summary

- Many possible approaches in a wide energy region
- Results suggest asymptotic $\log^2(s)$ behaviour of the cross section
- Errors at large energies still large
- The CR composition and the uncertainties on interaction models are among the major sources of systematics
- Better situation after new inputs for interaction models from new accelerator experiments (LHCf,….)

Unique opportunity to explore hadronic interactions up to extreme energies

($\sqrt{s}$ ~ 100TeV)

Stay tuned …


RAK TAC TAC TAC TAC
HEAR THAT?? IT'S THE COSMIC RAYS!! I--I WARNED YOU ABOUT 'EM!!