Charged Cosmic Rays up to the knee region and beyond (II)

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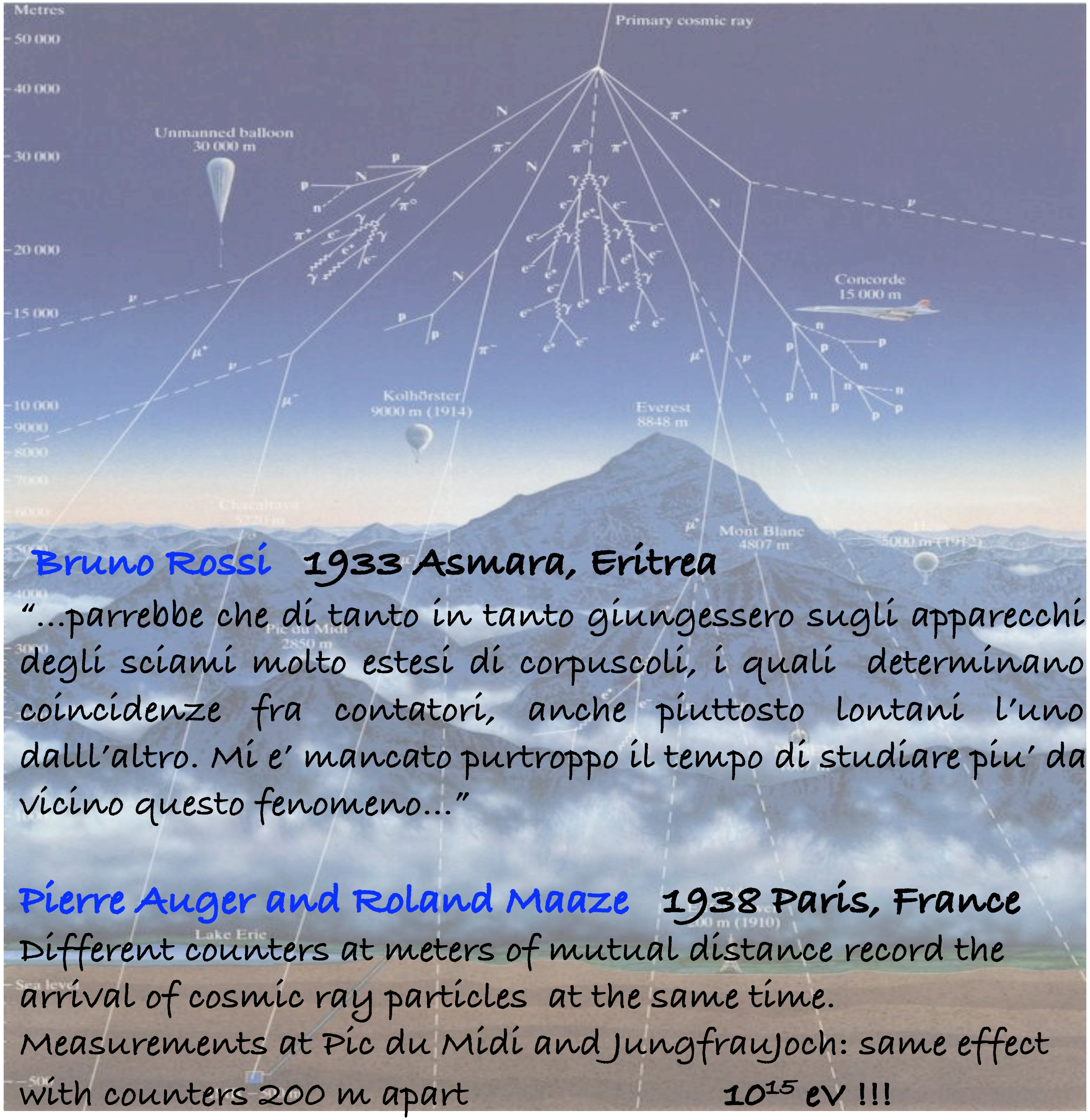
Outline of the lecture

- Introduction
- Origin, acceleration and propag
- Models of the knee
- **Extensive Air Showers**
- Energy spectrum and composi
- The measurement of the p-Air c
- Anisotropy studies with EAS arrays
- The Galactic to Extragalactic transition
- Future projects

Discovery
The components of an EAS
Observables
Experimental techniques
Existing detectors



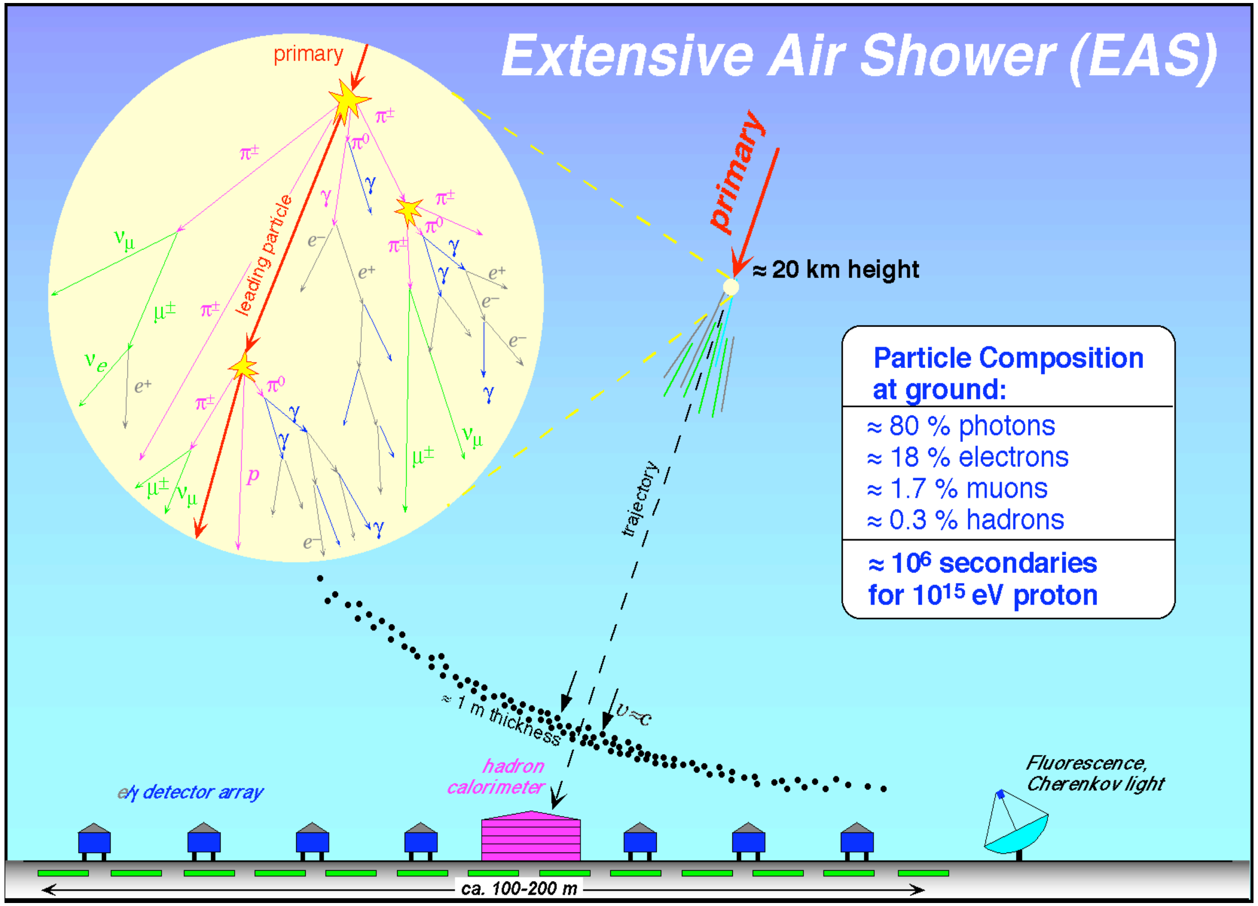
The discovery of the Extensive Air Showers

Bruno Rossi **1933 Asmara, Eritrea**

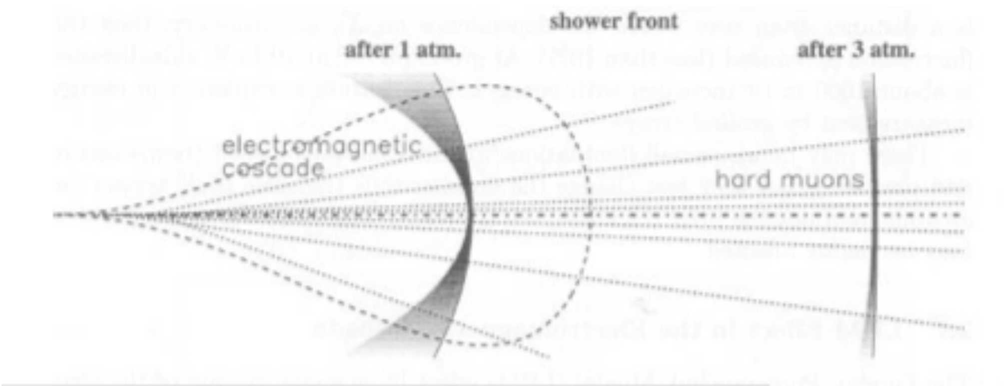
"...parrebbe che di tanto in tanto giungessero sugli apparecchi degli sciami molto estesi di corpuscoli, i quali determinano coincidenze fra contatori, anche piuttosto lontani l'uno dalll'altro. Mi e' mancato purtroppo il tempo di studiare piu' da vicino questo fenomeno..."

Pierre Auger and Roland Maaze **1938 Paris, France**

Different counters at meters of mutual distance record the arrival of cosmic ray particles at the same time.
Measurements at Pic du Midi and Jungfraujoch: same effect with counters 200 m apart 10^{15} eV !!!

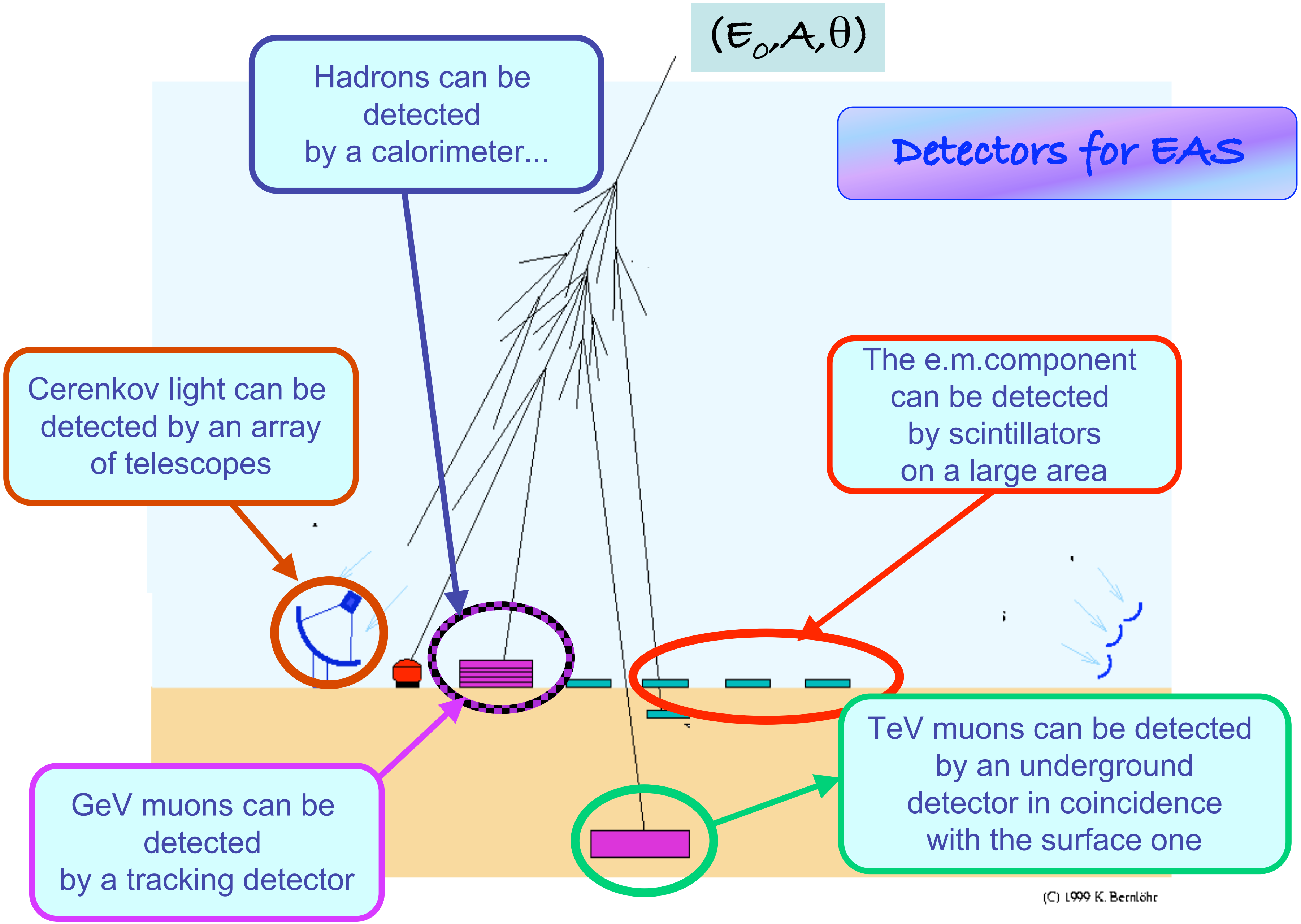


Typical energies at ground:
$\gamma, e \sim$ few MeV
$\mu \sim$ few GeV



1 μsec delay → 300 m longitudinal distance

Detectors for EAS



Observables	Detectors
Number and fluctuation of electrons	scintillator arrays, water Cerenkov detectors
Number, energy, deflection angle, h_{prod}, fluctuation of μ	buried detectors, tracking calorimeters
Number, energy and distribution of hadrons	deep hadronic calorimeters
Number and distribution of Cerenkov photons	wide angle Cerenkov detectors
Cerenkov angular distribution	imaging Cerenkov telescopes
Depth of shower maximum	Cerenkov, fluorescence detectors

Observables in EAS

Charged particles:
em, μ, hadrons
Cerenkov light
Fluorescence light

+

Monte Carlo simulations

E_0, A
hadronic interaction models
+ detectors response

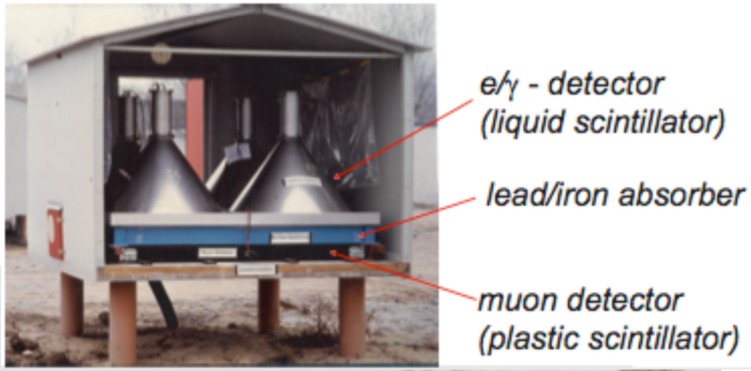
Energy spectra
Composition

Test of hadronic interaction models

Total area → E_{max}

Distance among counters → E_{min}

Number of counters → precision

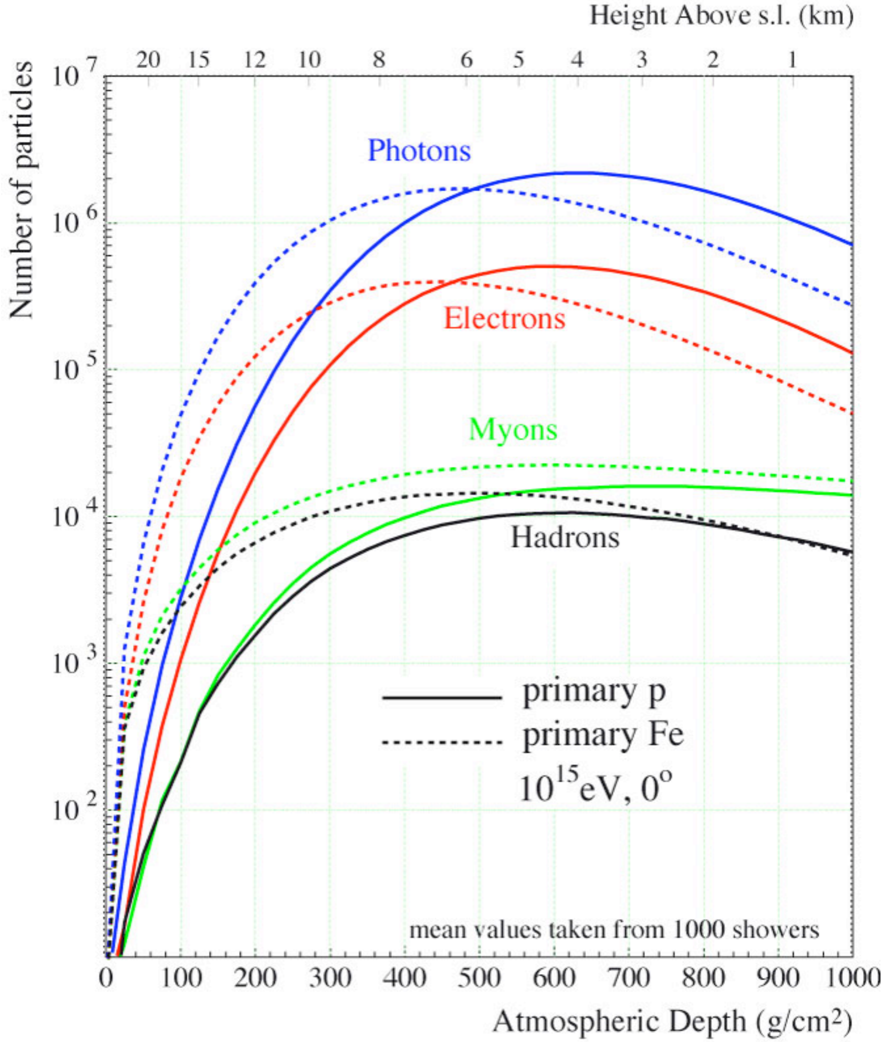


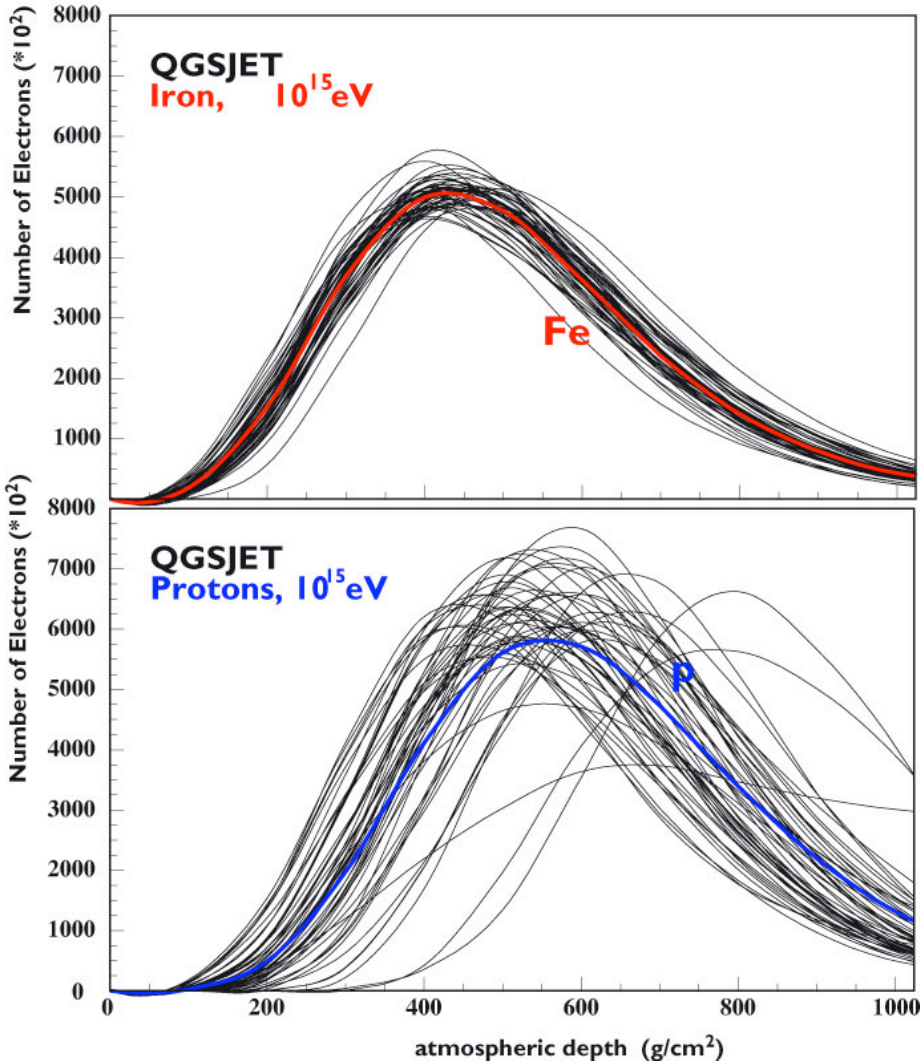
Frequency in number of counting Φ_{part}

Arrival times in each counter θ_o


Chacaltaya, 540 g cm^{-2}
Pamir, 600 g cm^{-2}
CASA-MIA, BLANCA, DICE , 700 g cm^{-2}
MAKET-ANI,GAMMA, 700 g cm^{-2}
BAKSAN 833 g cm^{-2}
GRAPES 800 g cm^{-2}
EASTOP, 820 g cm^{-2}
Tibet-III, 600 g cm^{-2}
KANBALA 520 g cm^{-2}
FUJI, SPASE/VULCAN 650 g cm^{-2}
TUNKA, 675 g cm^{-2}
HEGRA, 790 g cm^{-2}
KASCADE, 1000 g cm^{-2}
1 2 3 4 5 6 7 8 9 10 11

The longitudinal development





A primary Fe gives EAS with

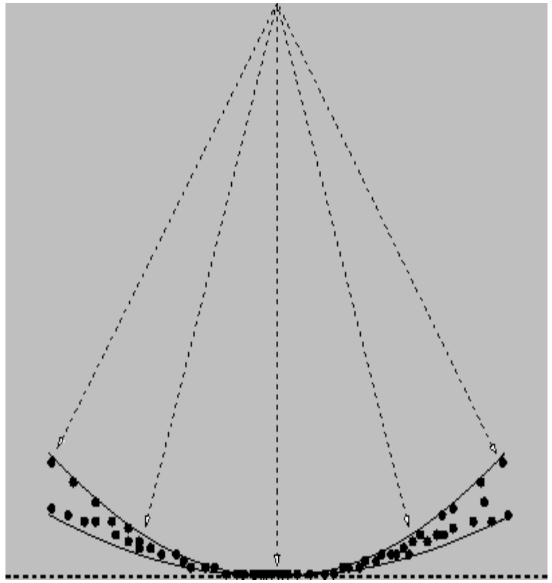
- **higher X_{max} [σ_{int} larger]**
- **more muons at ground**
- less electrons at ground
- similar number of hadrons

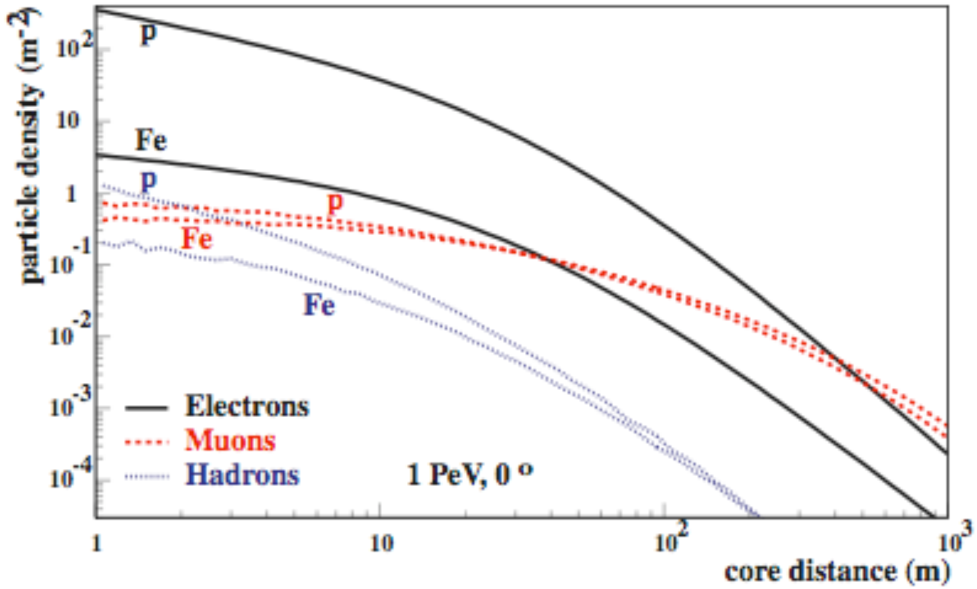
Fluctuations are lower for EAS from heavy nuclei

The em component

The shower size is determined through a fit of particle densities measured by different detectors to the NKG function

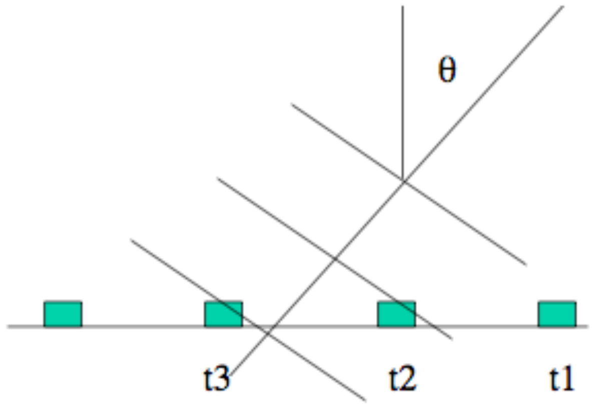
$$\rho_{ch} = \frac{N_{ch}}{2\pi r_0^2} \cdot C \cdot \left(\frac{r}{r_0}\right)^{s-2} \cdot \left(1 + \frac{r}{r_0}\right)^{s-4.5}$$



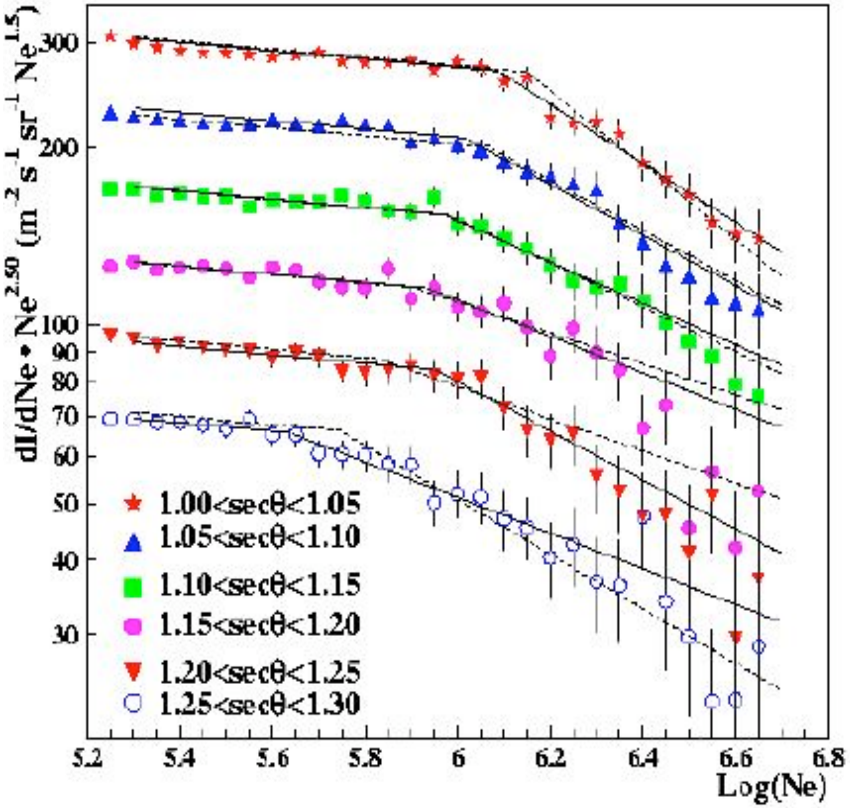


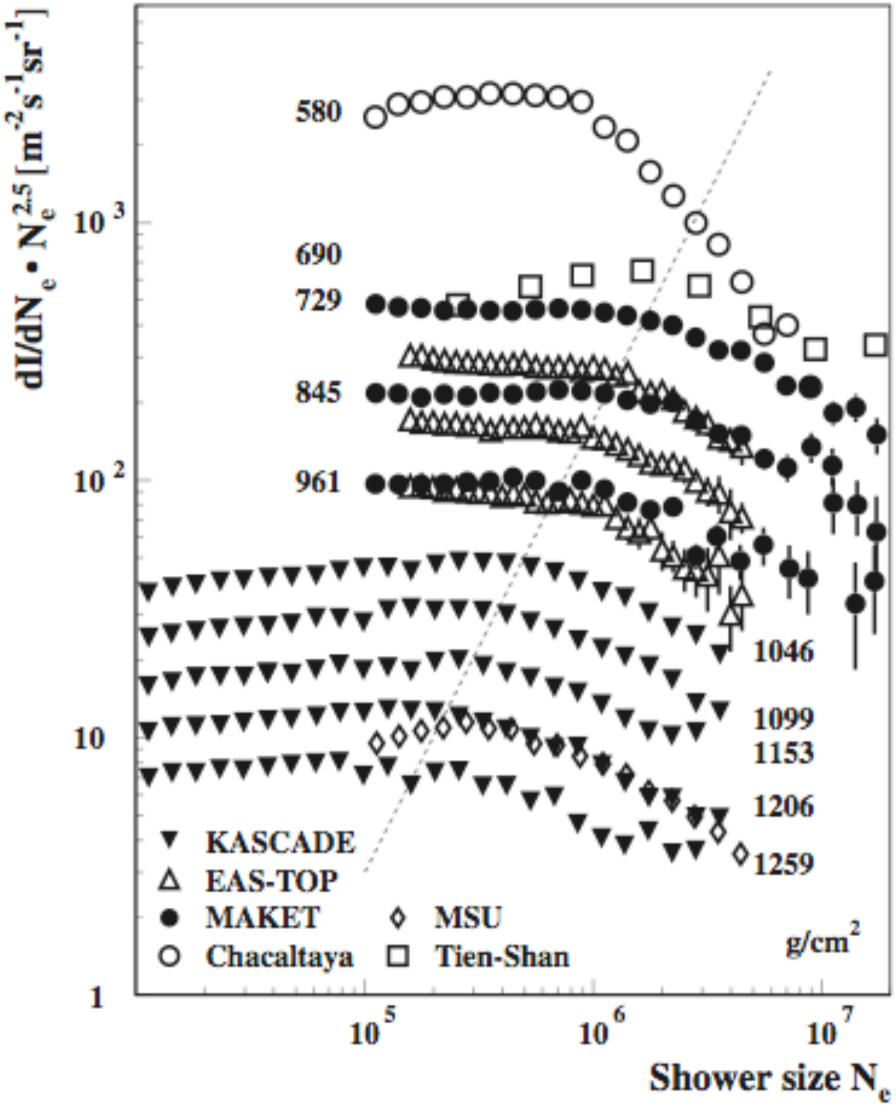
Scintillators / water detectors

The arrival direction is obtained from the relative times of arrival of the shower front at different detectors: $c\Delta t = d \cos\theta$



EASTOP





ELECTRON SIZE SPECTRUM:

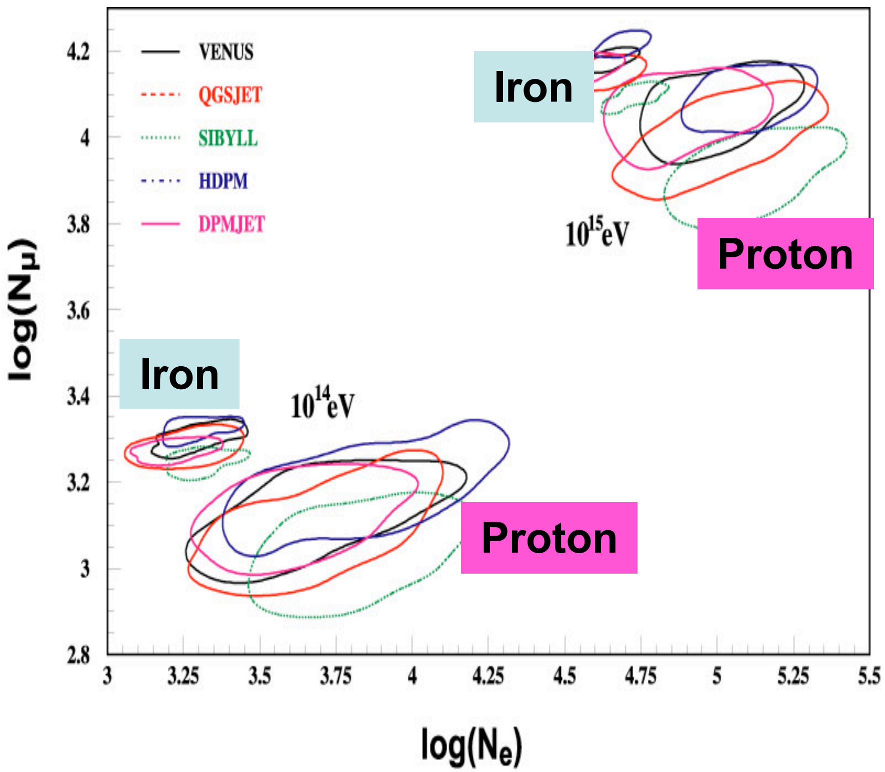
- measure at different θ
- the size N_e^k at the knee energy decreases for increasing t
- $\Lambda_{EAS} = (219 \pm 3)$ g cm^{-2}

[M.Aglietta et al, Astrop.Phys.10 (1999) 1]

The μ component

The muon size comes from a fit to the muon densities measured at different distances from the shower core (LDF by Greisen in 1960

$$\rho_\mu(r) \propto r^{-\alpha} \exp\left(-\frac{r}{r_0}\right) \qquad N_\mu^{tr} = 2\pi \int_{r_0}^{r_1} \rho_\mu(r) r \, dr$$



μ component directly coupled to hadronic: link to properties of initial hadron

The number of low energy (GeV) and high energy (TeV) muons depends on primary atomic number

With Ne, the muon number is the most sensitive parameter to primary mass

Scintillators below absorber or tracking, water cerenkov tanks for GeV muons. Underground detectors for TeV muons

For a proton

$$N_{max} = E_0 / E_c$$

$$X_{max} = \lambda_r \ln(E_0)$$

$$N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\alpha$$

$$\alpha = \frac{\ln n_{ch}}{\ln n_{tot}} \approx 0.82 \ldots 0.95$$

For heavier nuclei

Superposition model:

A shower from a primary with mass A and energy E is equivalent to A showers of energy E/A

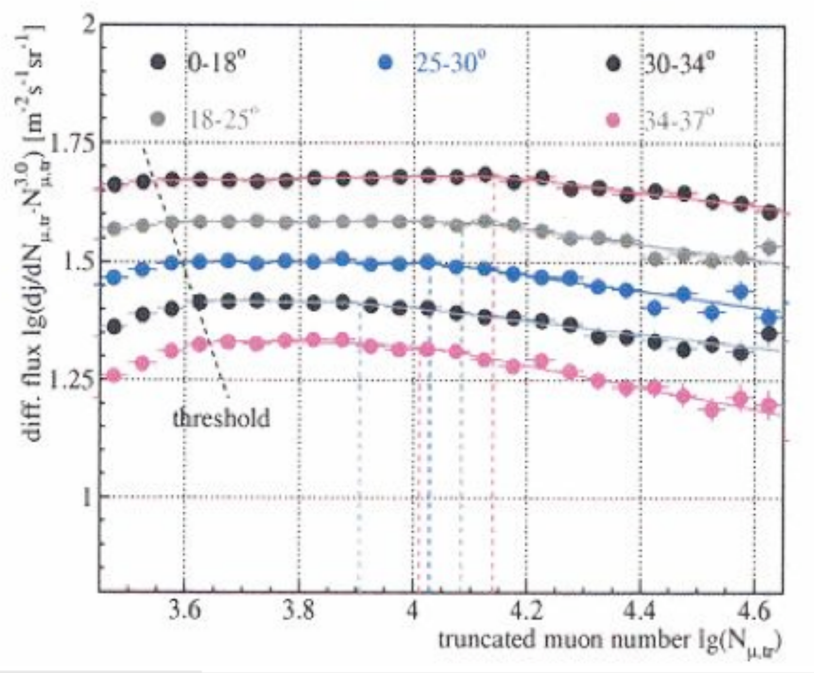
$$N^A_{max} = A\ E_n / E_c = E_0 / E_c$$

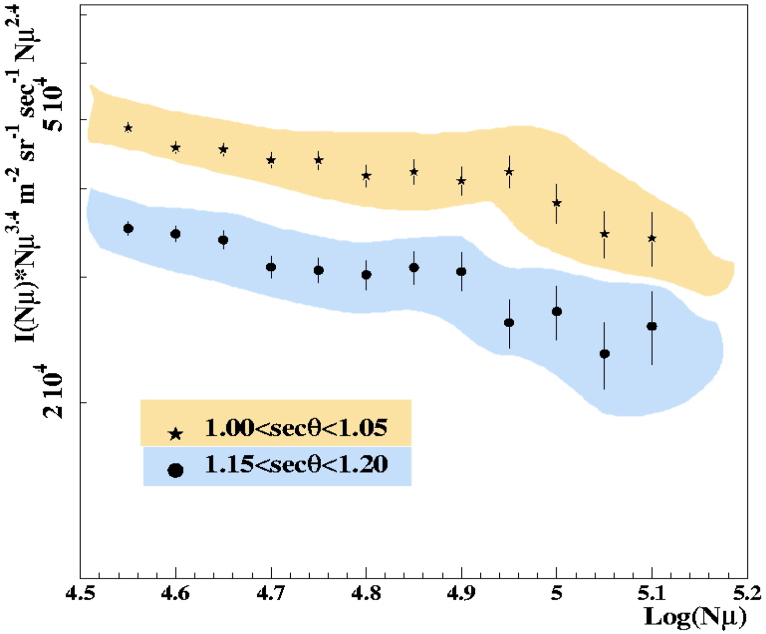
$$X^A_{max} \sim \lambda_r \ln(E_0 / A)$$

$$N^A_\mu = A \left(\frac{E_0 / A}{E_{dec}}\right)^\alpha = A^{1-\alpha} N_\mu$$

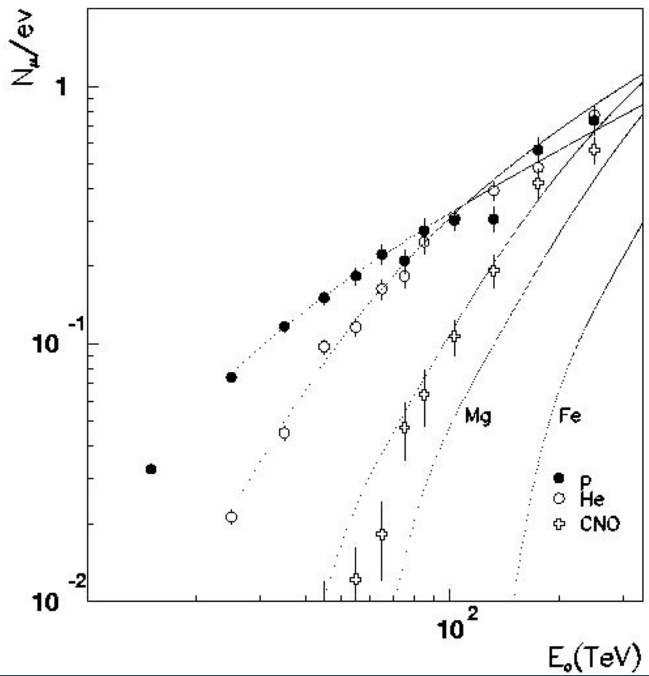
$D_e = dX_{max}/d\ln E \sim \lambda(1 - d\ln A/d\ln E)$

elongation rate ($D_{10} = 2.3 D_e$)





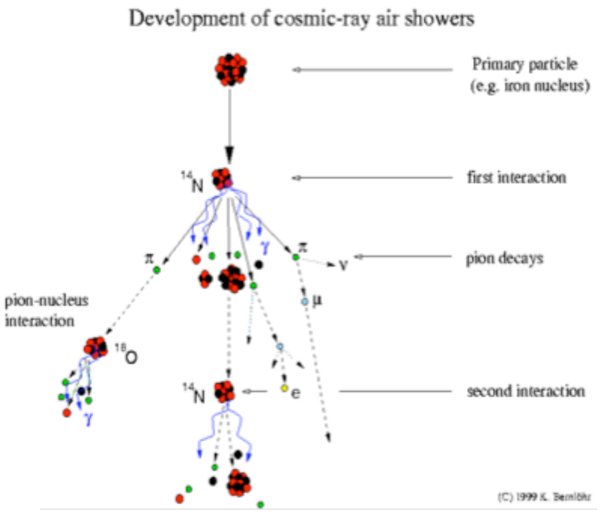
GeV μ

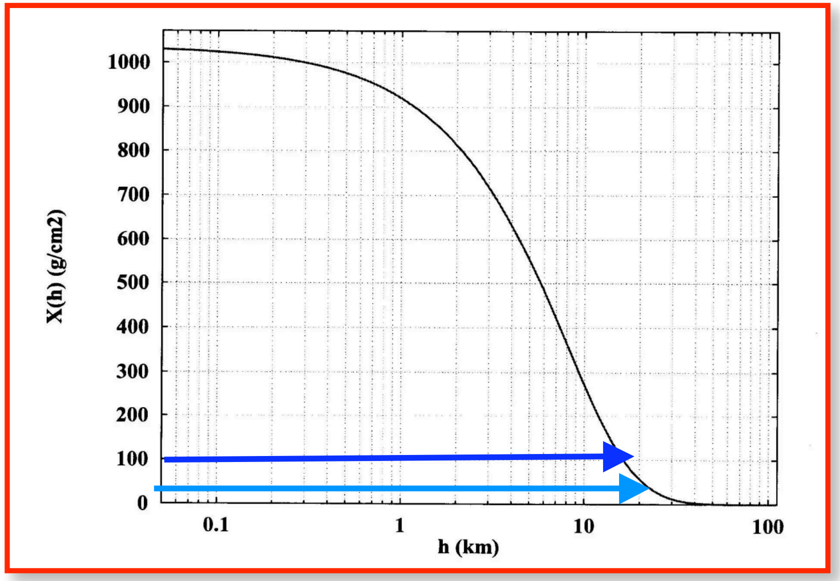


GeV μ from Kascade and Eas-Top

TeV μ from underground detectors

MACRO - EASTOP
BAKSAN - BUST
SPASE - AMANDA
...





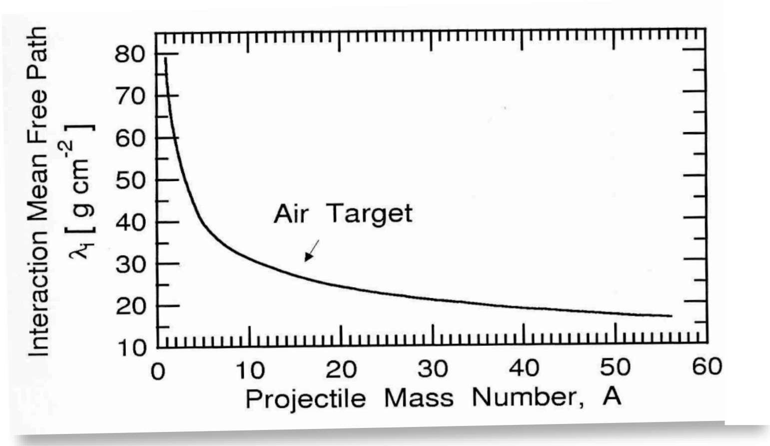
Burst detectors (high altitude), hadron calorimeters.

The hadronic component

Back bone of the air shower (hadronic core). They constantly feed the em component of the EAS through π^0s.

Secondary hadrons produced in early stages of showers

Reminder of first interaction features. Total number of hadrons nearly proportional to primary energy



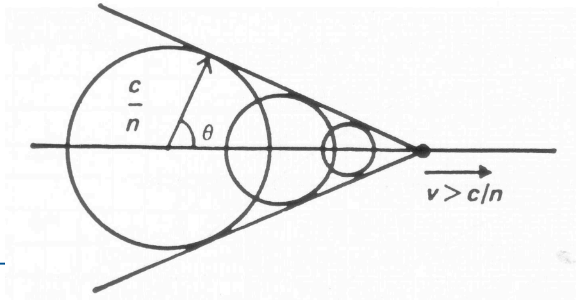
The Cerenkov light

n_{air} = 1.00029 (at sea level)
$E_{Ch}(e)$ = 21 MeV (35 MeV at 7.5 km) ➤ Almost all electrons of the EAS emit Cherenkov light.

Maximum opening angle of emitted light ≈ 1.3° (at sea level) ➤ All C-light associated to EAS contained in a narrow cone, keeping the shower direction

Weak absorption of light in atmosphere ➤ Most C-light reaches observation level. $N_{ph} \propto Ltr$ above observer, a very good measure of E_0

Lateral distribution and temporal structure depend on shower max position ➤ Information on longitudinal development. Primary mass



C-light detectors = reflectors + PMTs.

Outline of the lecture

Introduction

Origin, acceleration and propagation of cos[...]

Models of the knee

Extensive Air Showers

Energy spectrum and compositio[...] measurements and results

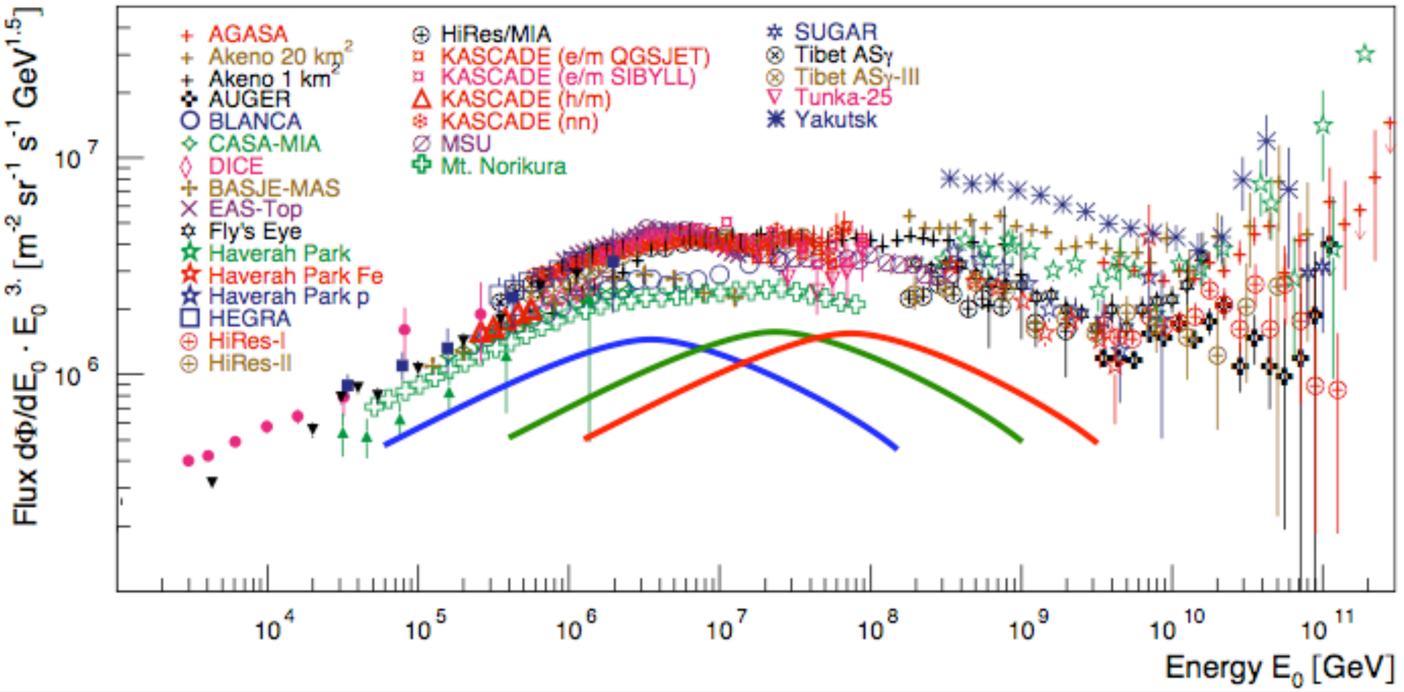
- The all-particle energy spectrum
- The link with direct measurement: spectra and comp. below the knee
- The high energy region
- Cerenkov detector results
- Models of the knee: comparison with data

The measurement of the p-Air cross section

Anisotropy studies with EAS arrays

The Galactic to Extragalactic transition

Future projects



Energy and composition are strictly related information

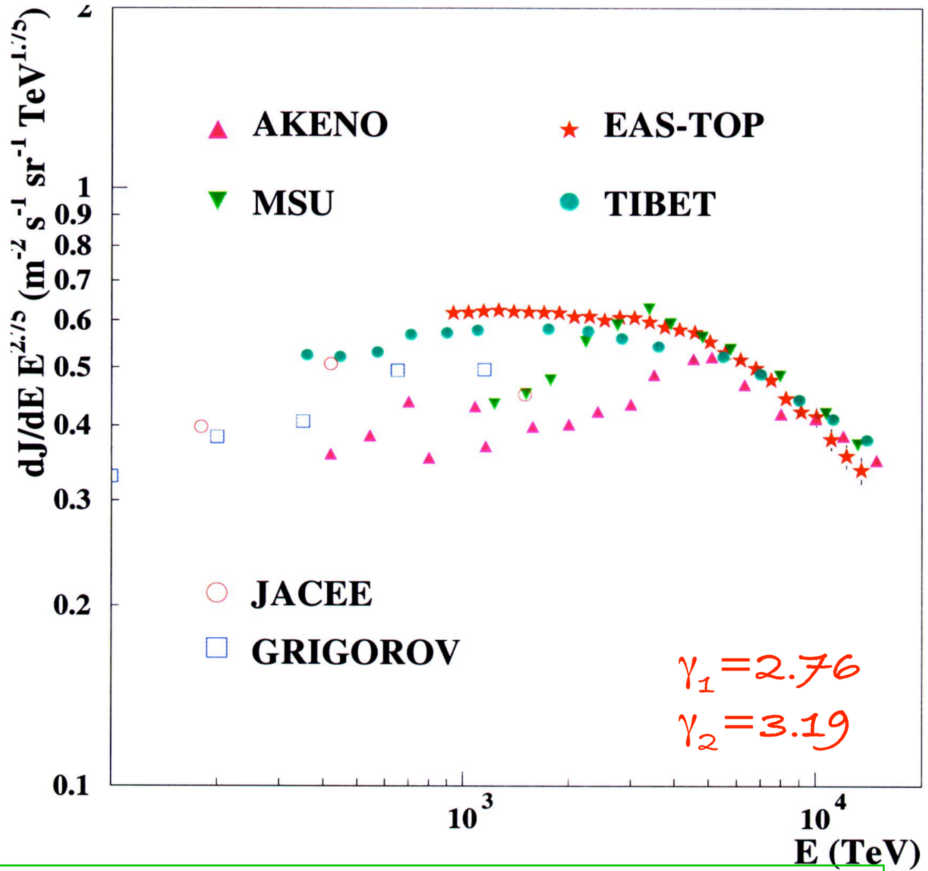
All observables are derived either from the lateral spread of EAS at a specific observation level or from its longitudinal development in atmosphere

Multi-detector arrays are more powerful, since they can correlate different observables

The understanding of data relies on the knowledge of the stochastic and systematic uncertainties.

The conversion from the observable to the physical quantity relies on Monte Carlo simulations

EAS-TOP



N_e converted to 810 g cm^{-2} using the measured Λ_{abs} = (219 $\pm$3) g cm^{-2}

Corsika code + interaction model

$$N_e(E_o, A) = \alpha(A)\, E_o^{\beta(A)}$$

Effective A from direct measurements, with

$$E_k(A) = Z \times E_k^p(A)$$

Extrapolation checked by consistence with other measurements

Systematic uncertainties from model and composition, each 10 %.

[M.Aglietta et al., Astrop.Phys.10 (1999) 1]

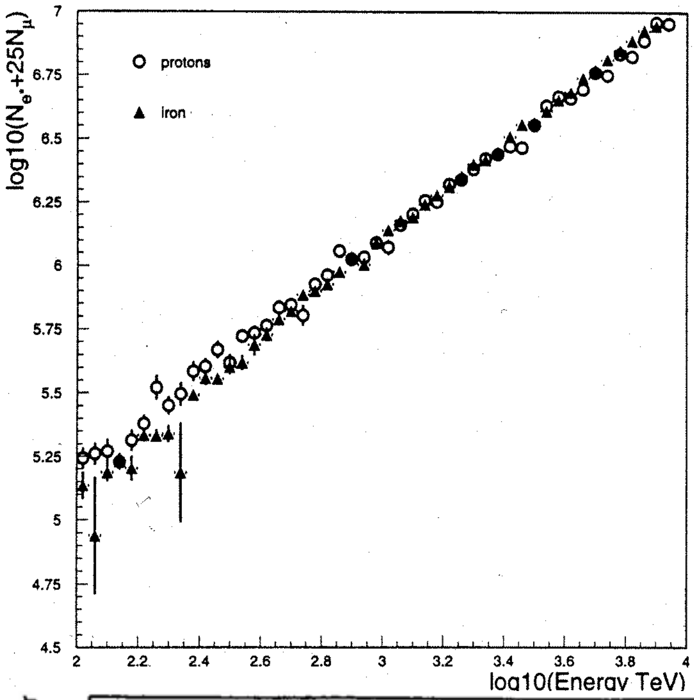
CASA-MIA

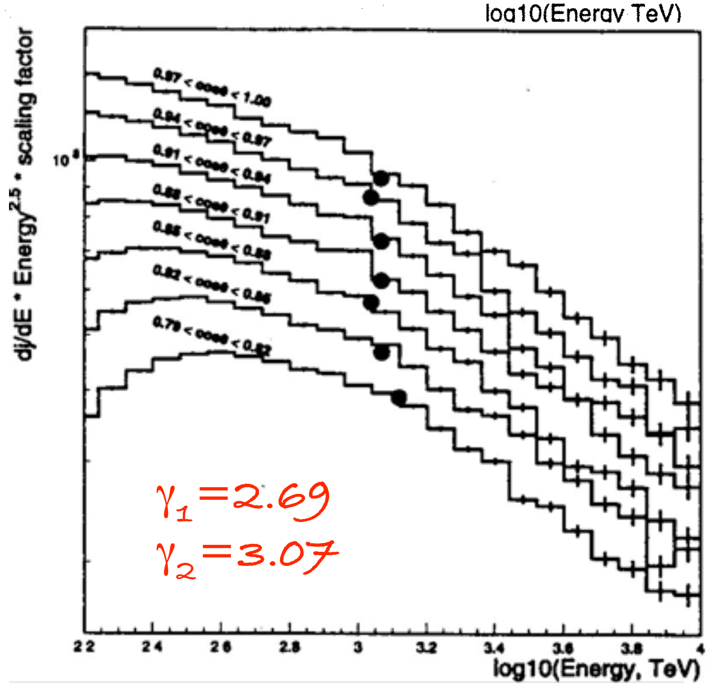
1089 particle detectors (0.25 km^2)

1024 muon detectors, 3 m underground

$$F = \log(N_e + \xi N_\mu)$$

- F does not depend on A: systematic differences in energy assignment less than 5 %
- F depens very little on θ but remains independent on composition
- ξ dependent on the model





- the energy is determined **independently** from composition
- the knee does not change with θ

[M.Glasmacher et al., Astrop.Phys.10 (1999) 291]

KASCADE

$200 \times 200\ m^2$ at $1020\ g/cm^2$
Array: 252 detector stations with e/γ- and muon counters
Central detector: $300\ m^2$ hadron calorimeter and 4 muon layers
MTD: $120\ m^2$ muon tunnel

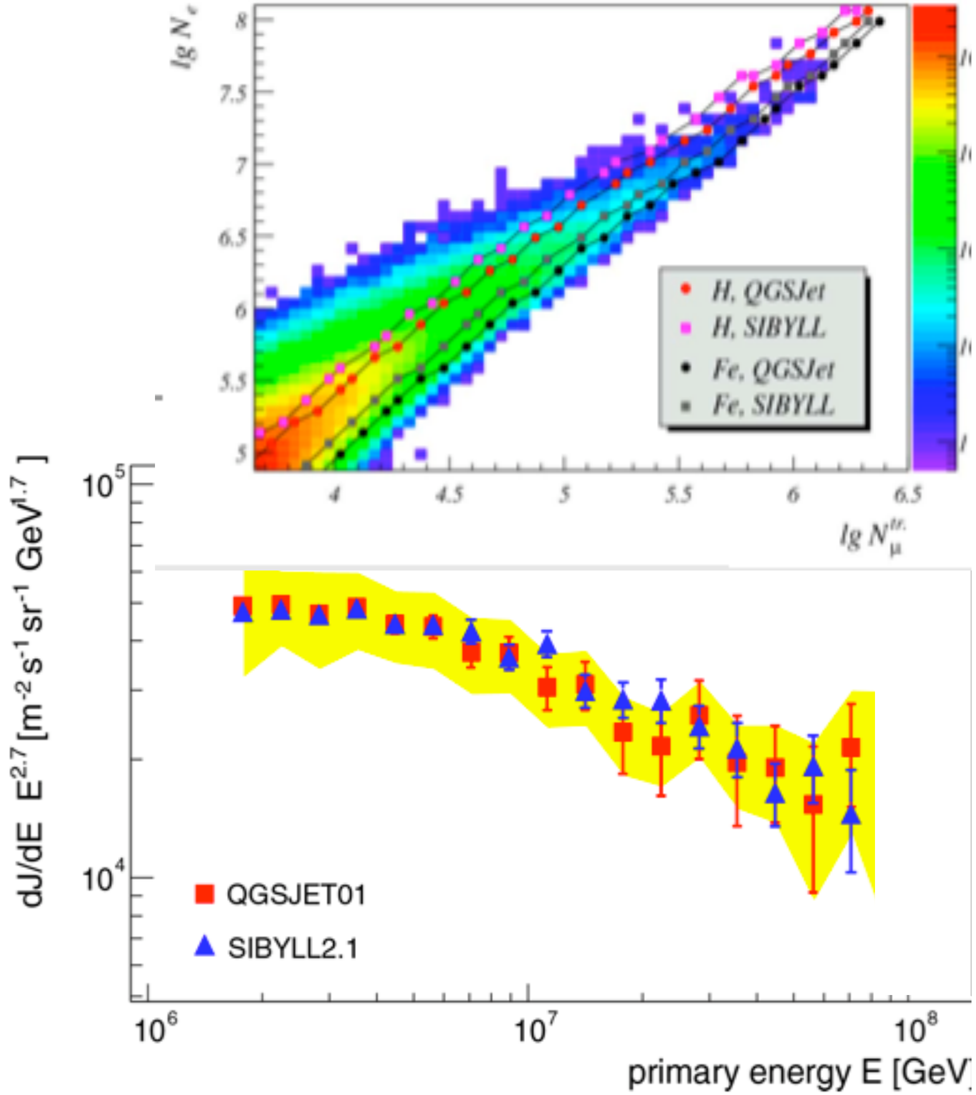
Combined χ^2 minimization to fit
Ne, Nμ size spectra simultaneously

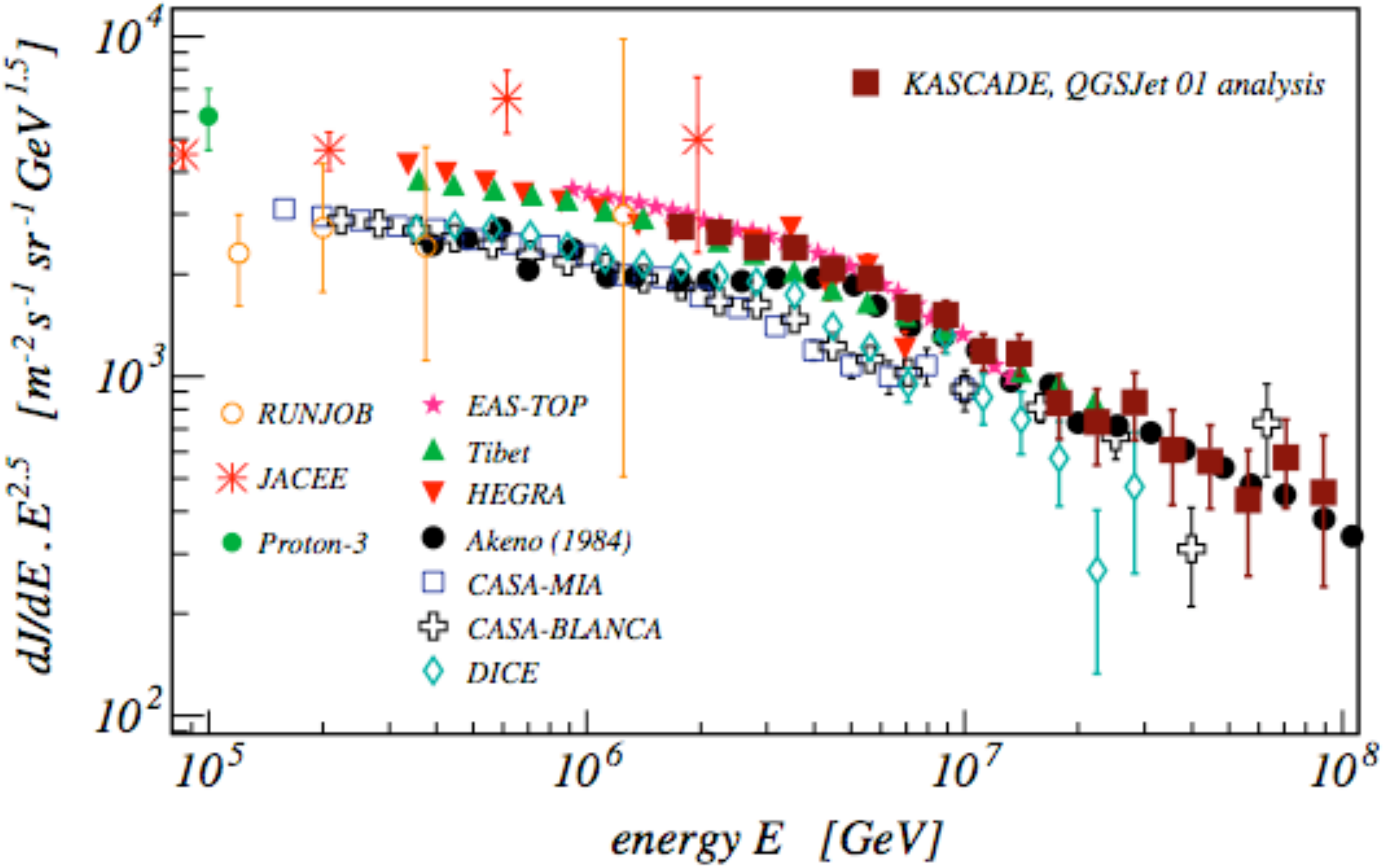
$$\frac{dJ}{d\log N_e\, d\log N_\mu} =$$

$$\Sigma_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\log E}\ p_A(\log N_e, \log N_\mu \mid \log E)\, d\log E$$

The all particle spectrum : sum of 5 mass groups spectra

[T.Antoni et al., Astrop.Phys.24 (2005) 1]





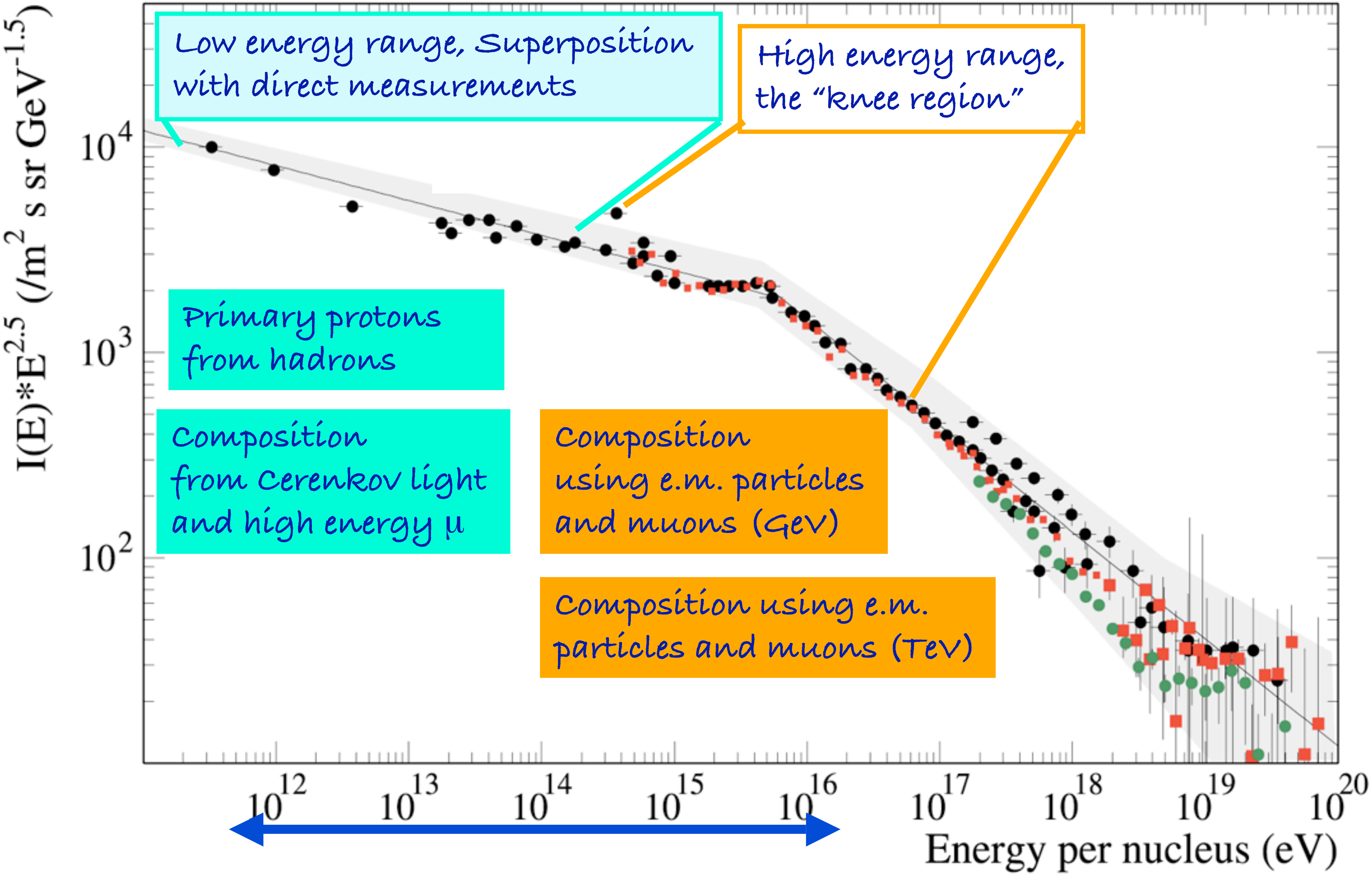
The spectra agree quite well in shape and knee position (despite different techniques, observables, atmospheric depths!)

15% systematic shift in energy needed to match fluxes

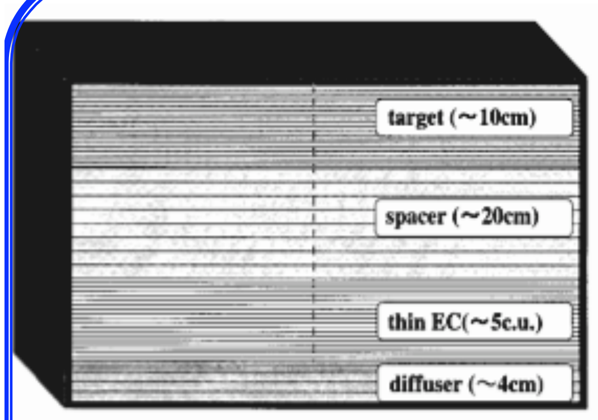
Smooth knee at ~4 PeV, γ_{below}~2.7, γ_{above}~3.1

...but need different mass groups spectra to discriminate among astrophysical models!

Spectrum and composition information



Direct measurements with balloons

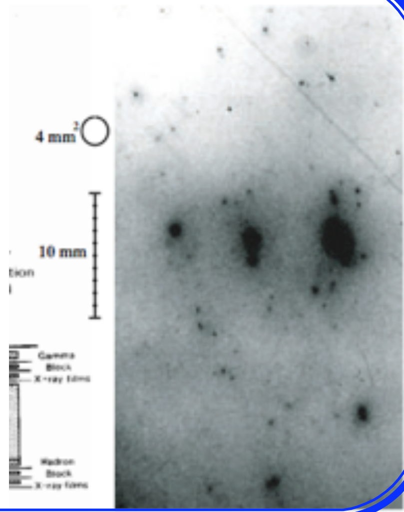


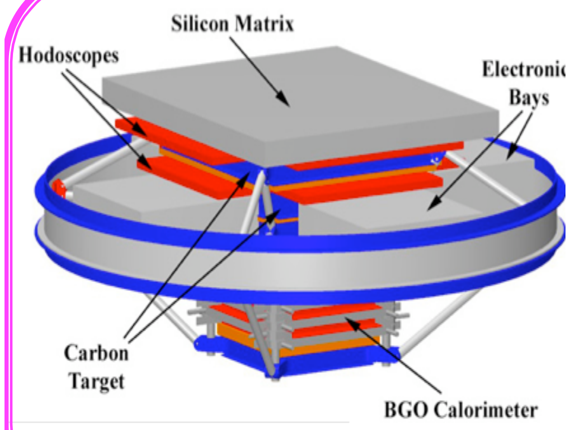
RUNJOB, JACEE

Passive detectors with nuclear emulsions

- must be recovered and developed in laboratory
- record the incoming particle and secondaries from interaction

p,He,heavy nuclei up to 500 TeV/nucleon





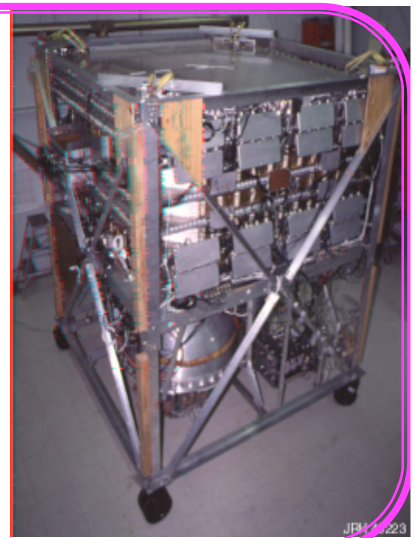
ATIC, TRACER, CREAM

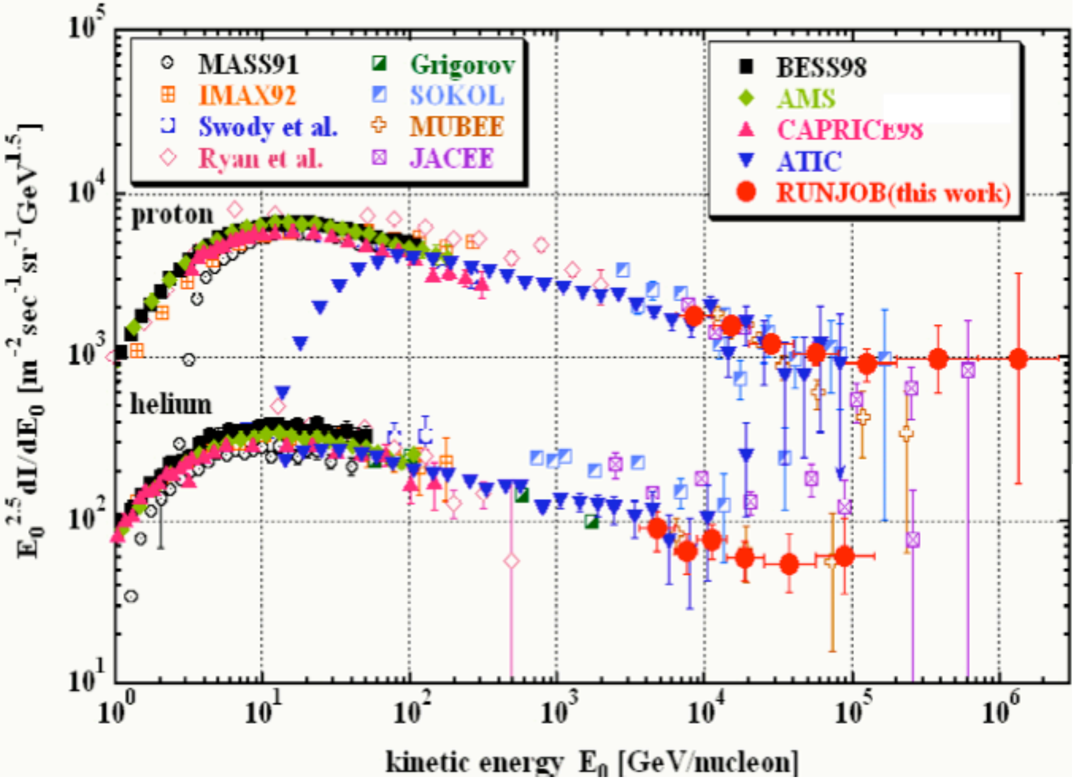
Include detectors for charge measurement (fine grain silicon matrix, scintillators) and for energy evaluation (calorimeters, transition radiation detectors,)

p-Ni from 50 GeV to 100 TeV total energy

O-Fe from 1 GeV/n to 10 TeV/n

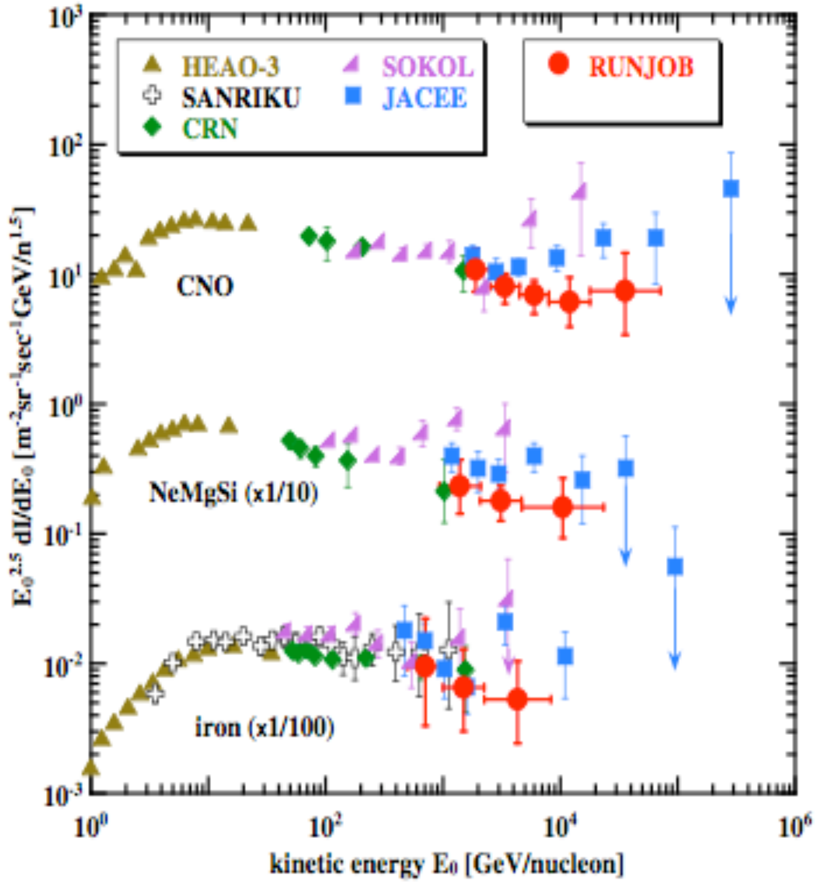
p-Fe from 10^{11} to 10^{15} eV





RUNJOB $\gamma_p \approx 2.74 \pm 0.08$
$\gamma_{He} \approx 2.78 \pm 0.20$
JACEE $\gamma_p \approx 2.80$, $\gamma_{He} \approx 2.68$

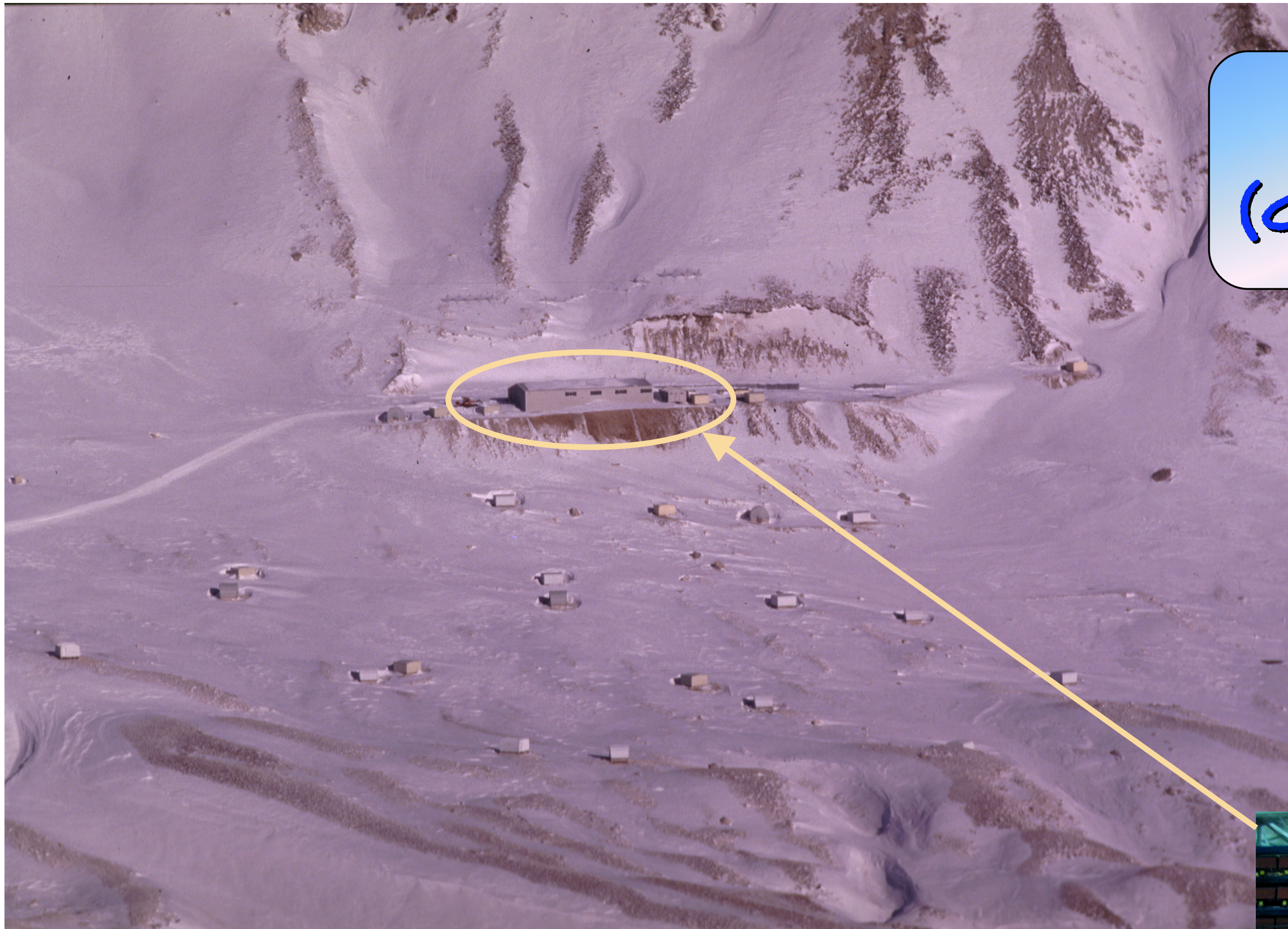
He(RUNJOB) ~1/2 He(JACEE)
at E = 100 TeV/n



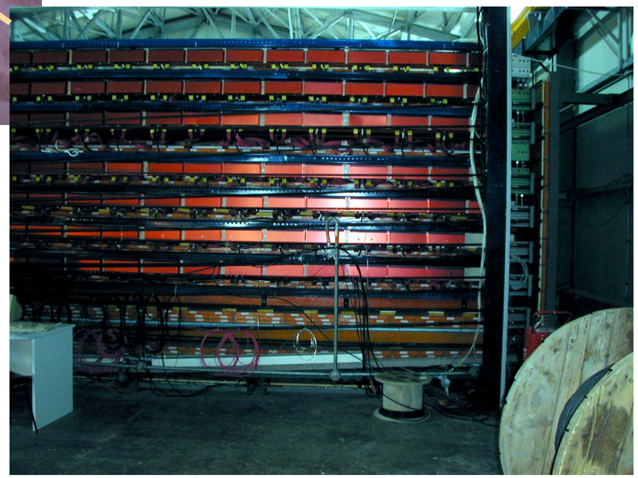
RUNJOB: γ~2.7 for CNO to ~2.6 for Fe
If Runjob/Sanriku gradual change in slope indicated a rigidity dependent form
If JACEE/Sokol different sources for protons and for He and heavier

[V.A.Derbina et al, Astrop.J 628 (2005)]

EAS-TOP (Gran Sasso, Italy)



2000 m asl
820 g cm^{-2}

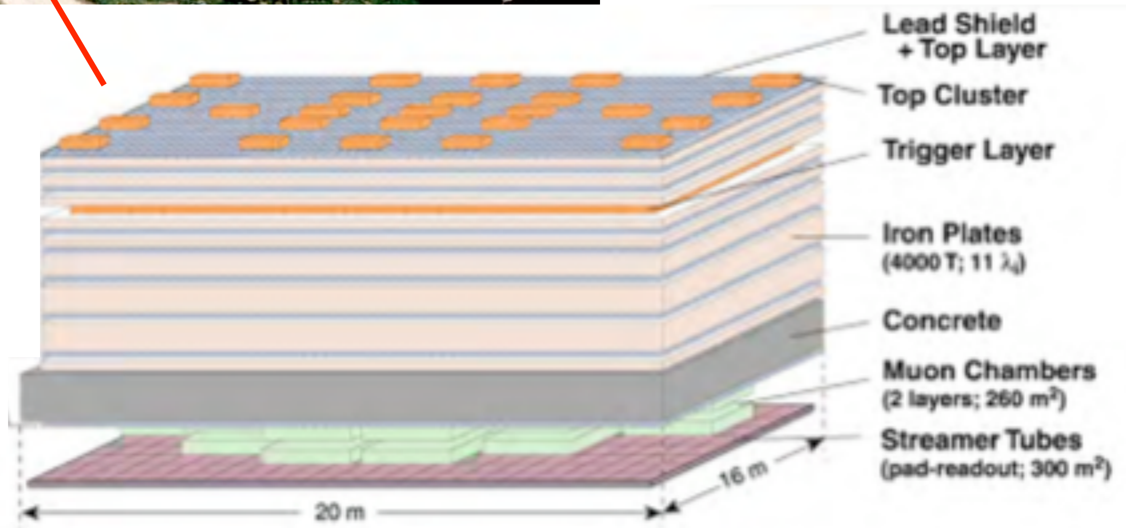


144 m^2 Hadron calorimeter:
9 layers x 13 cm Fe absorber,
2 layers streamer tubes
1 layer "quasi-proportional" tubes

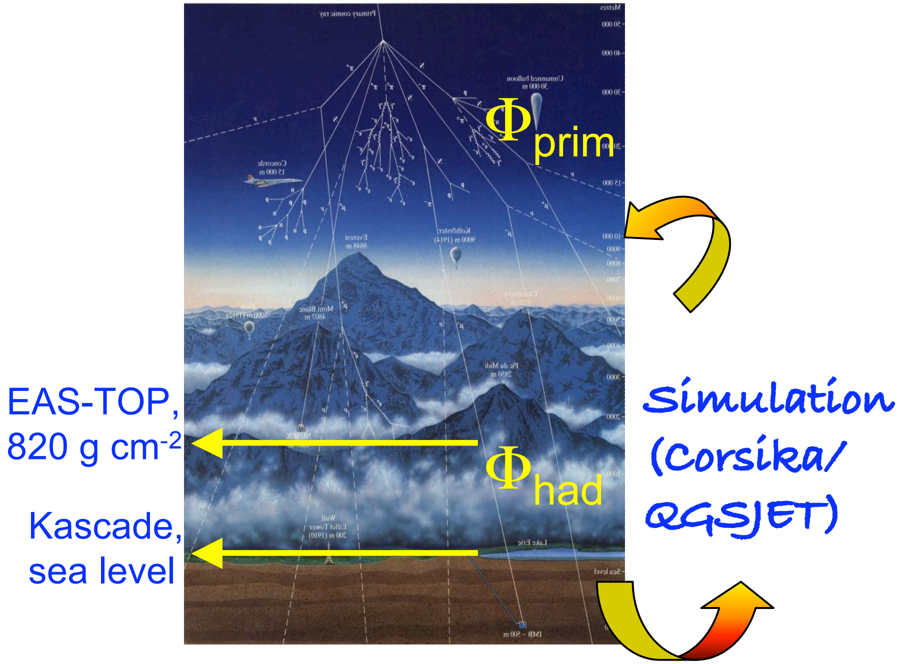
KASCADE (Karlsruhe, D)

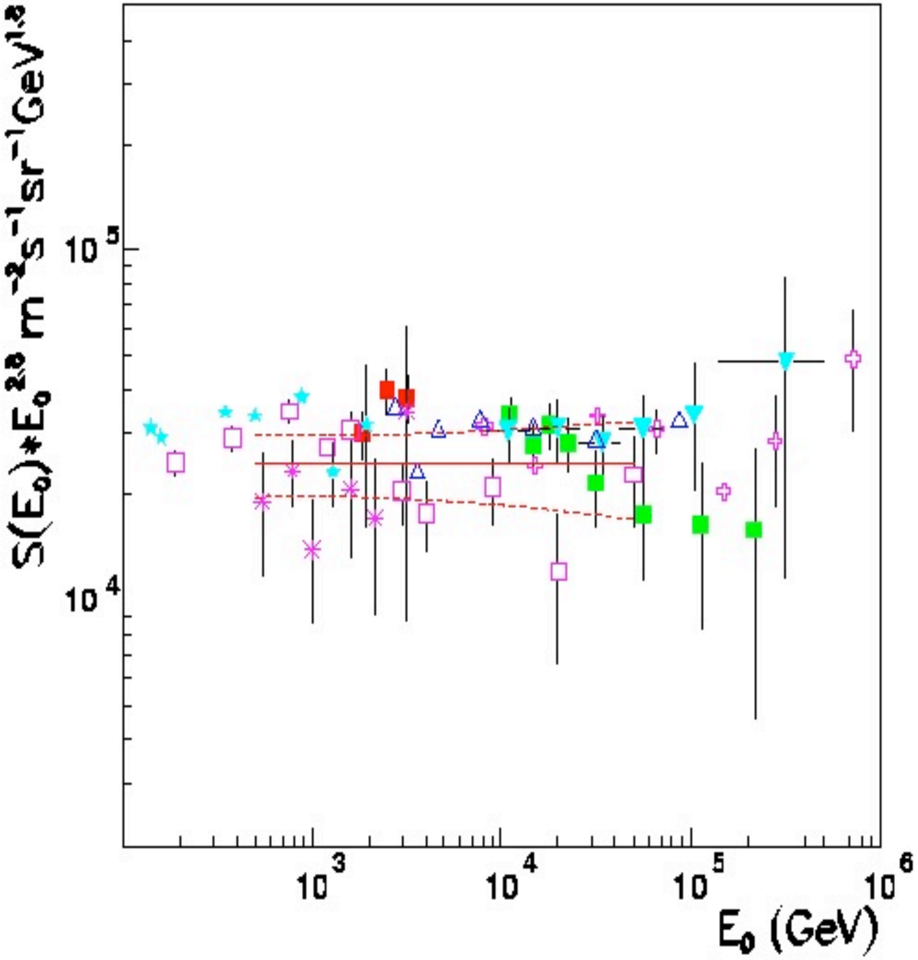
110 m asl

1100 g cm^{-2}



Proton primaries from hadron data





Measure the flux of single hadrons

Use Monte Carlo to subtract the Helium contribution to the hadron flux

CORSIKA/QGSJET tested in EAS data: the model reproduces the experimental ratio at better than 10%

Minimize the difference between measured and expected (from different proton spectra) hadron flux

[M.Aglietta et al, Astrop.Phys. 19 (2003) 329
T.Antoni et al., ApJ 612 (2004) 914]

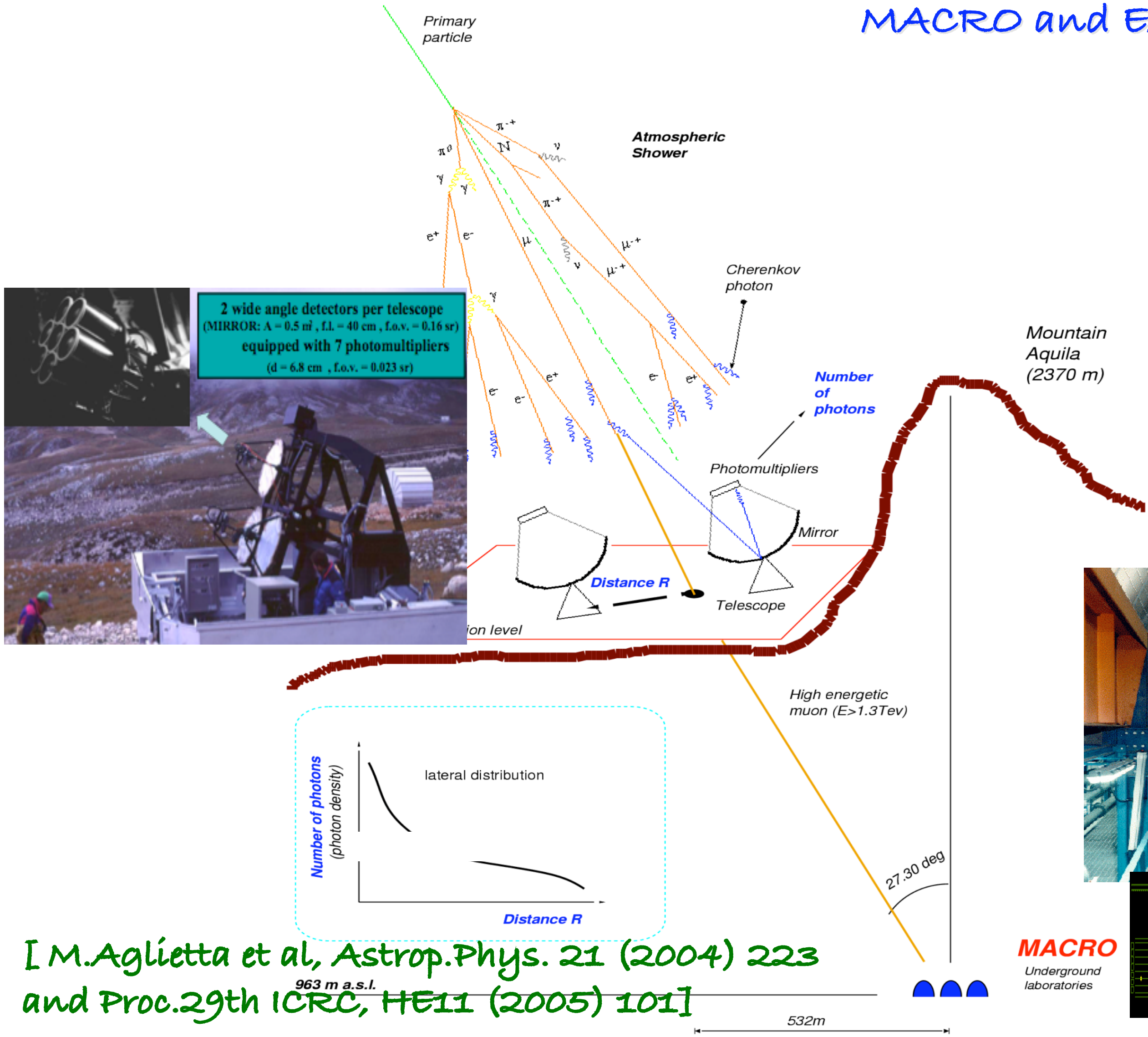
Composition from Cerenkov light and HE muons

MACRO and EAS-TOP separated by 1100 - 1300 m of rock

($E\mu$ » 1.3 - 1.8 TeV)

Common angular field

$16^o<\theta<58^o$, $127^o<\phi<210^o$



$76.6 \times 12 \times 4.8\ m^3$

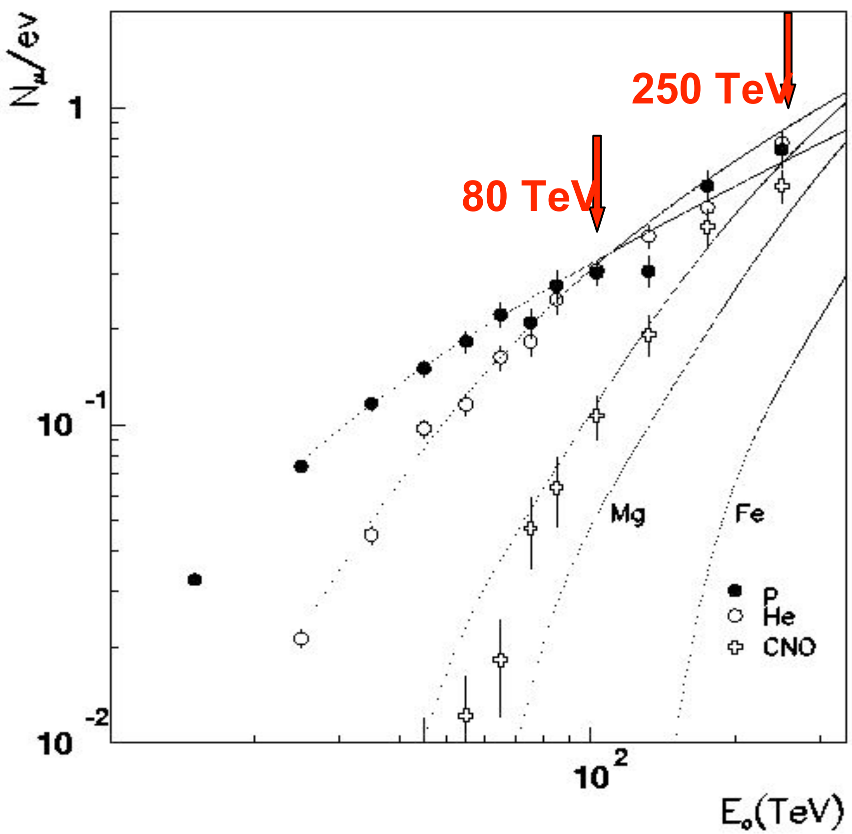
$E_\mu \sim 1.3$ TeV

[M.Aglietta et al, Astrop.Phys. 21 (2004) 223 and Proc.29th ICRC, HE11 (2005) 101]

What is measured:

MACRO : selection of primaries based on the energy/nucleon by means of the TeV μ and EAS geometry by means of the muon tracking ($E_\mu^{thr} \sim 1.3$ TeV)

EASTOP : Cerenkov light intensity and average Cerenkov lateral distribution (E^{thr} =20 TeV)



Key points of the analysis:

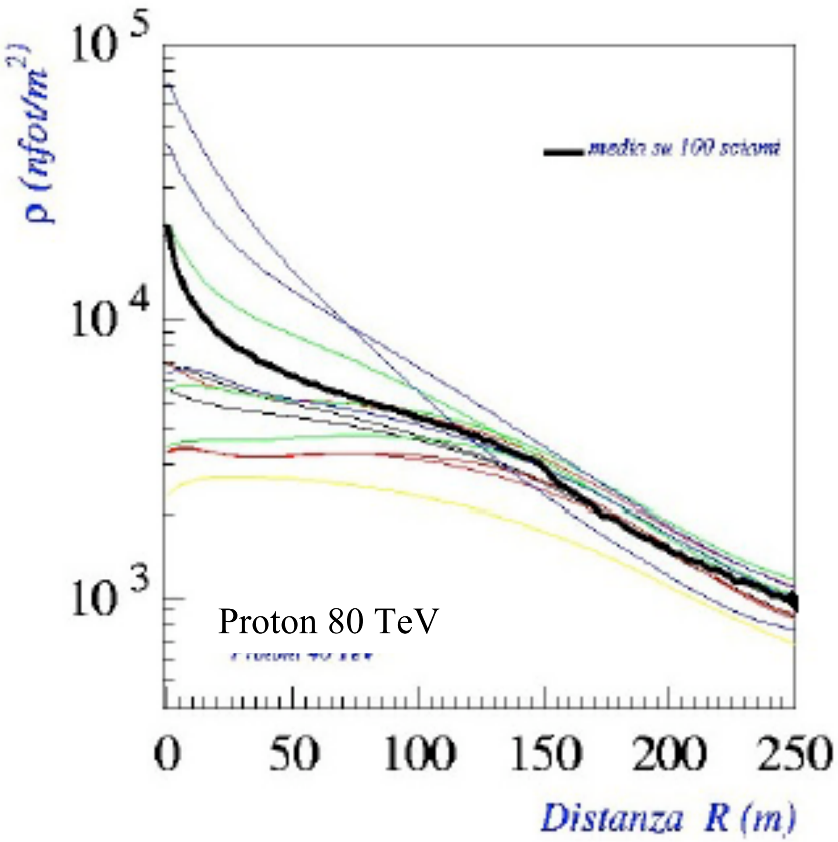
The beams are well defined:

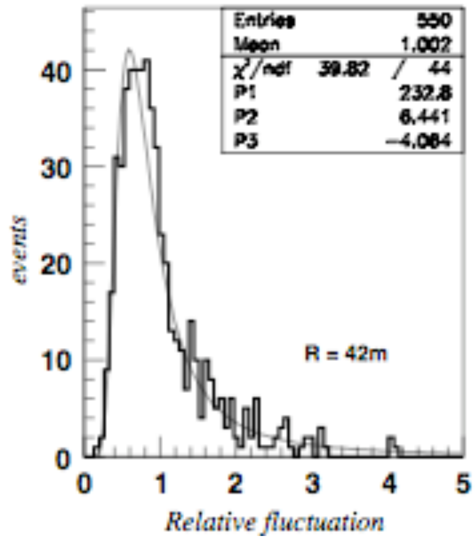
- p at $E_0 < 40$ TeV
- p+He at $40 < E_0 < 100$ TeV
- p+He+CNO at $E_0 > 100$ TeV

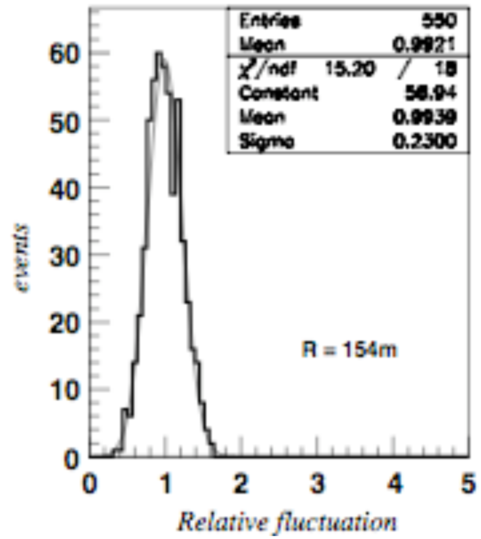
$E \approx 80$ TeV $N_m^{p} \approx N_m^{He}$

$E \approx 250$ Tev $N_m^{p} \approx N_m^{He} \approx N_m^{CNO}$

Same efficiency (inside 15%) in TeV μ production.







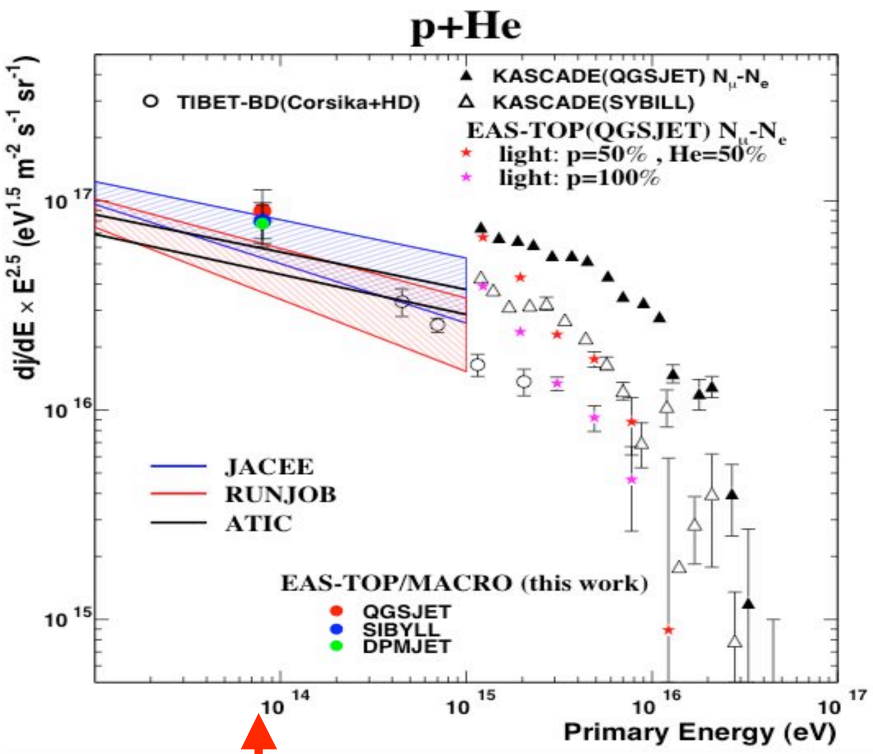
Photon density as a function of core distance:

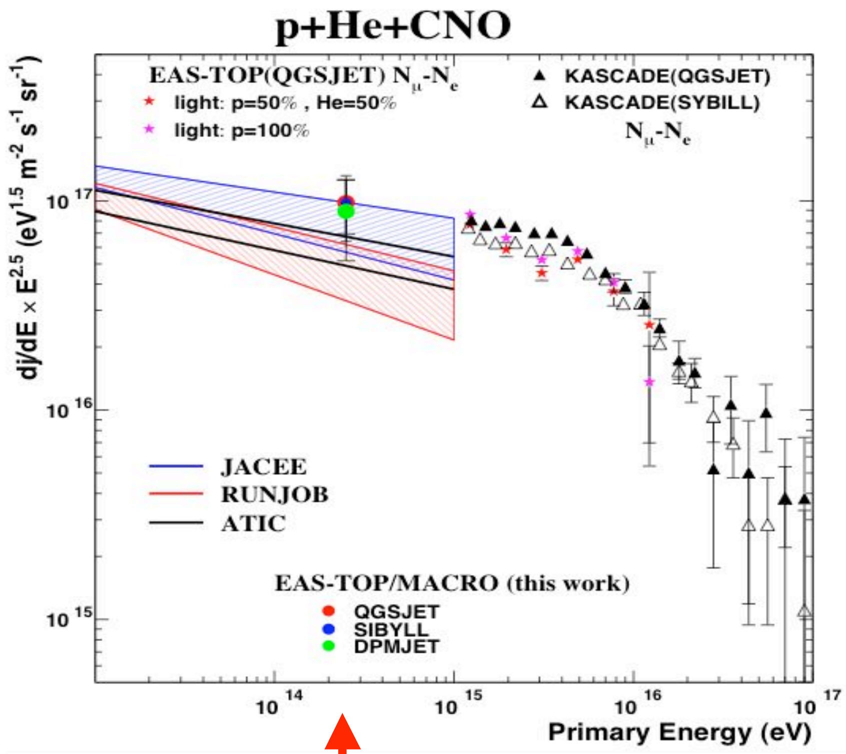
r<30 m : γ density dominated by fluctuations

r=30-140 m: exp density, with slope related to X_{max}

r>140 m : almost constant light, information on E_0

The Cerenkov photon density for r>140 m is a good estimator of the primary energy





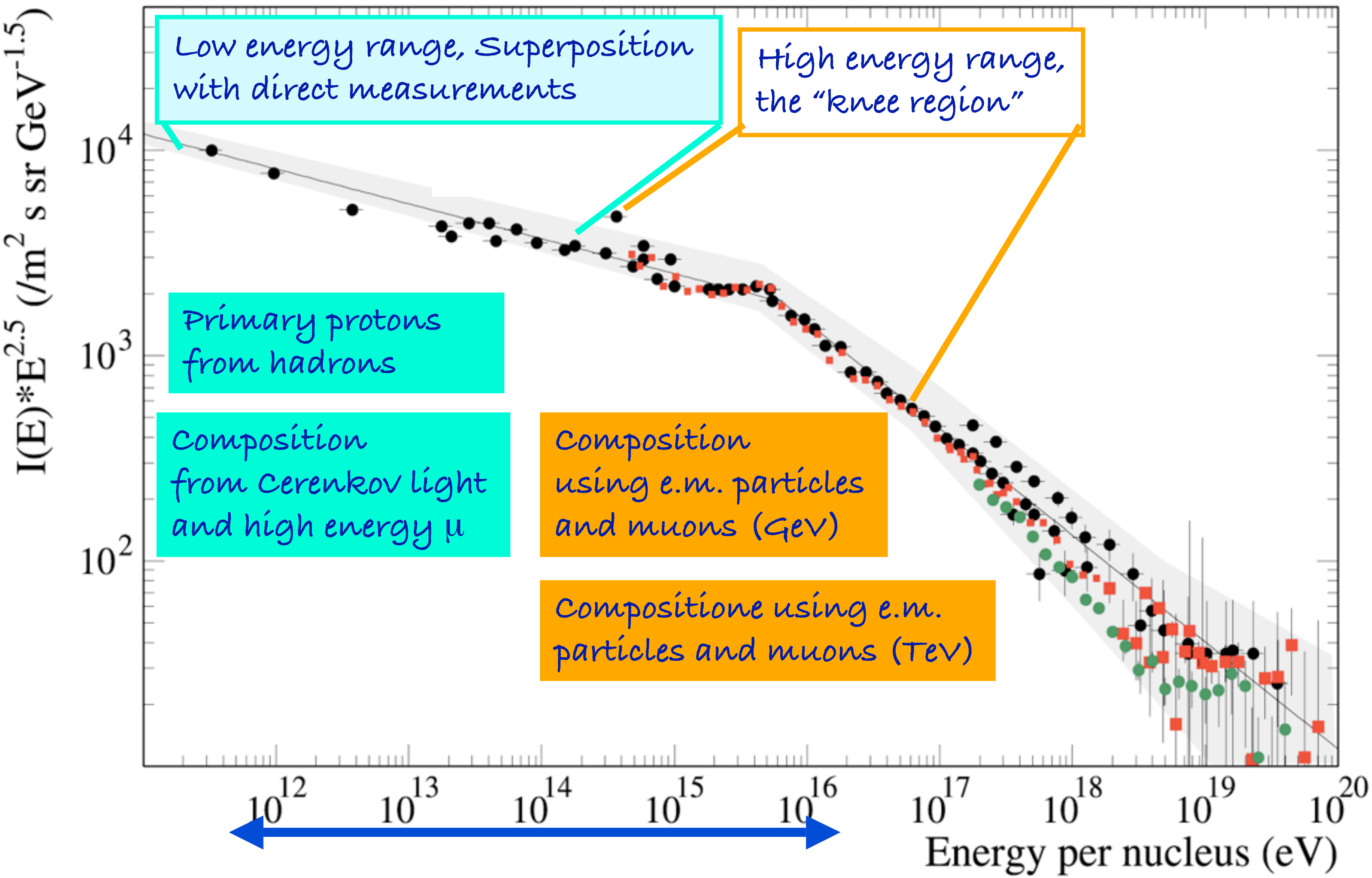
J_p / J_{p+He} (80 TeV) = (0.34 $\pm$ 0.11)

$J_{p+He} / J_{p+He+CNO}$ (250 TeV) = (0.73 $\pm$ 0.18)

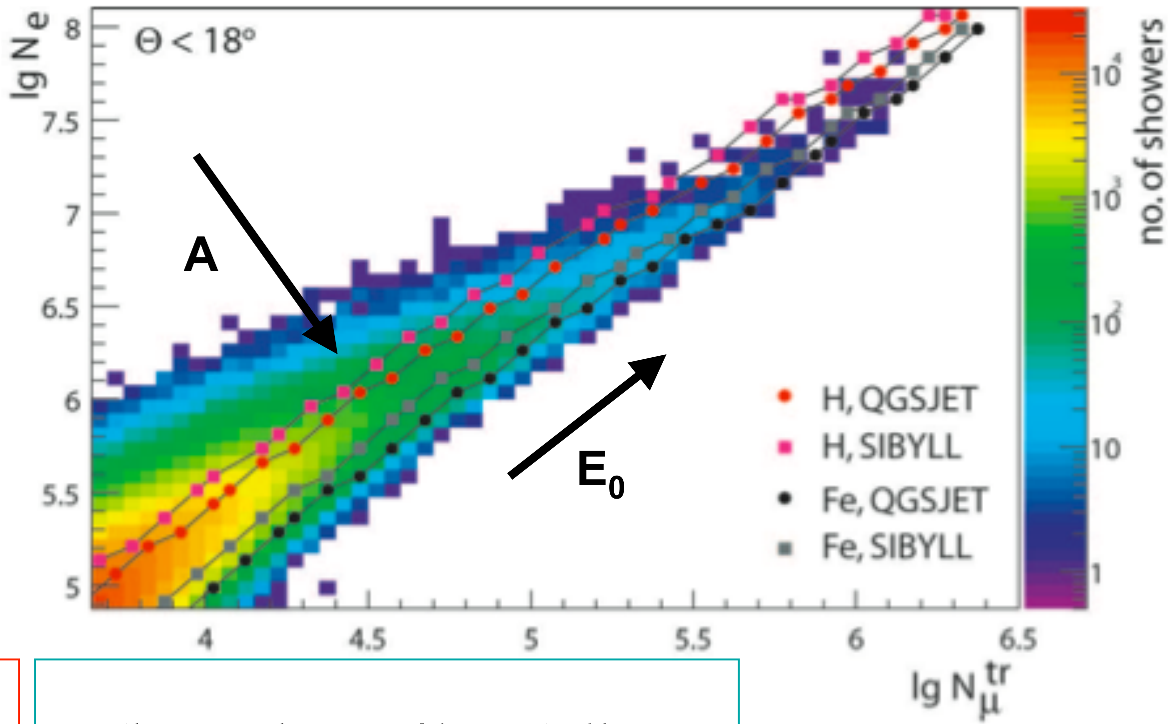
He dominates around 100 TeV
CNO contribute significantly
in the 100-1000 TeV region

At 250 TeV : $J_p : J_{He} : J_{CNO}$
(0.21 $\pm$ 0.09) : (0.52 $\pm$ 0.19) : (0.27 $\pm$ 0.18)

Spectrum and Composition information



KASCADE: From N_e, N_μ to E_0, A



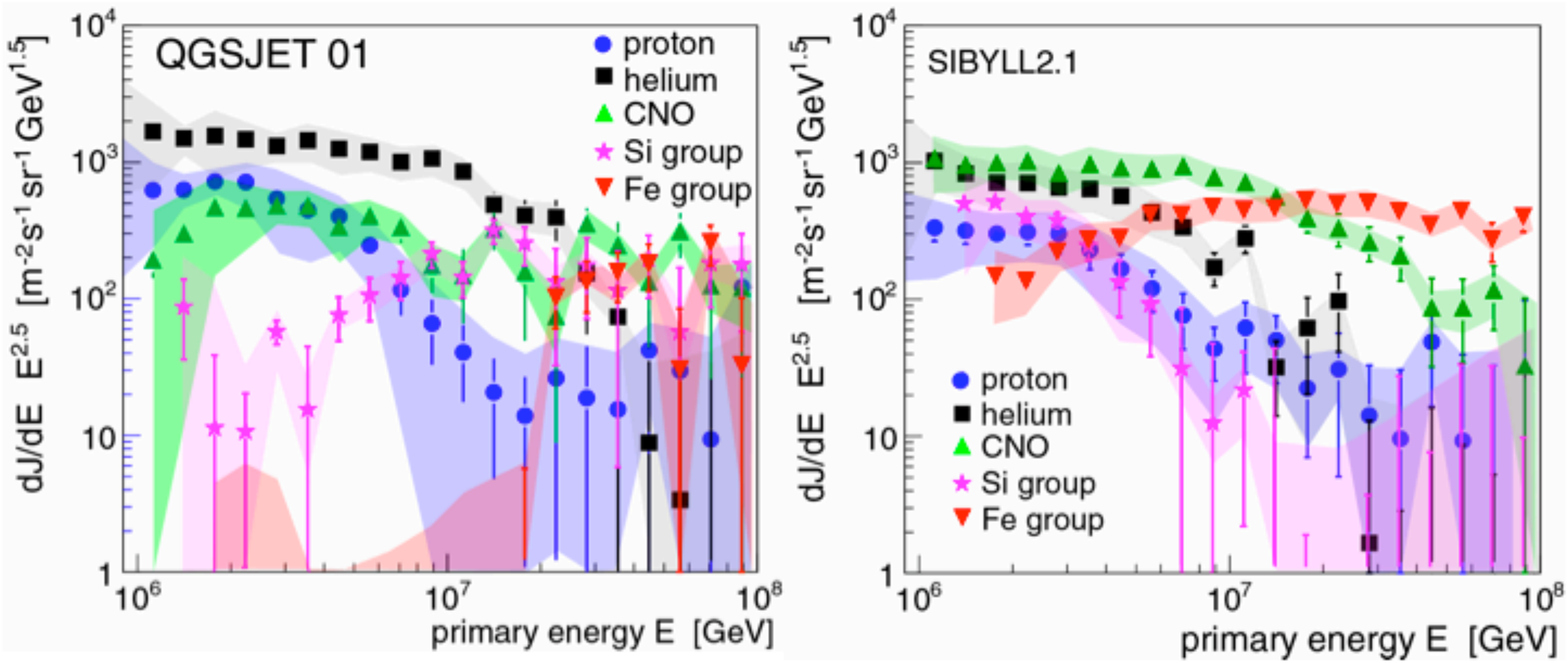
$$\frac{dJ}{d\log N_e \, d\log N_\mu} = \Sigma_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\log E} \, p_A(\log N_e, \log N_\mu \mid \log E) \, d\log E$$

measured

Probability to get Ne, N_μ from a primary with (E_0, A)

$$p_A = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} s_A \epsilon_A r_A \, \mathrm{d}\lg N_e^{\mathrm{true}} \, \mathrm{d}\lg N_\mu^{\mathrm{tr,true}}$$

- s_A: Intrinsic shower fluctuations
- ϵ_A: Trigger and Reconstruction efficiency
- r_A: Reconstruction, resolution, systematics



The knee is due to a cutoff in the light component

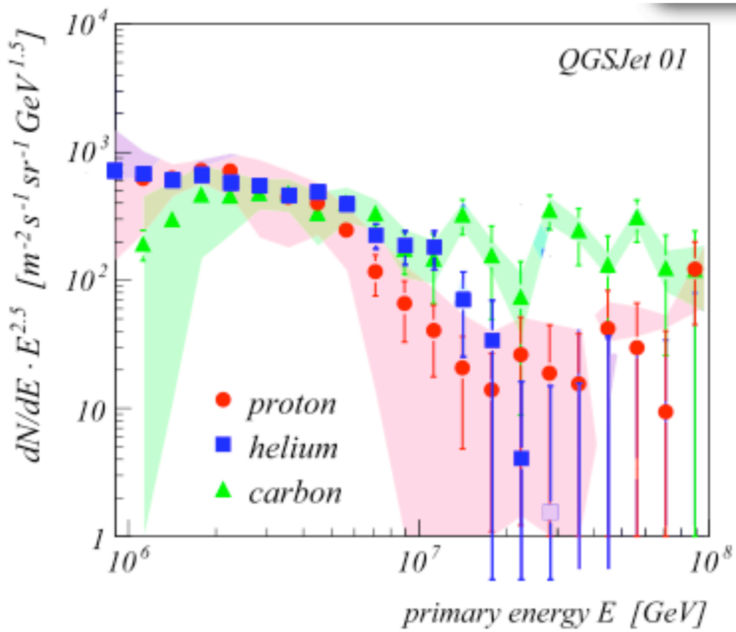
The cutoff moves to higher energies for heavier nuclei

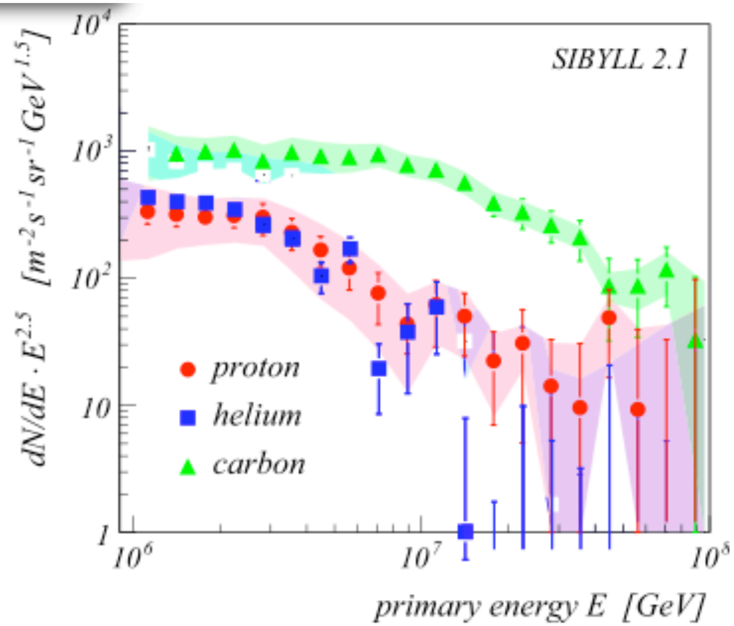
The interpretation is limited by knowledge of the properties of the hadronic interaction properties

[T.Antoni et al, Astrop.Phys. 24 (2005) 1]

$E_{knee}^{A} = Z E_{knee}^{p}$

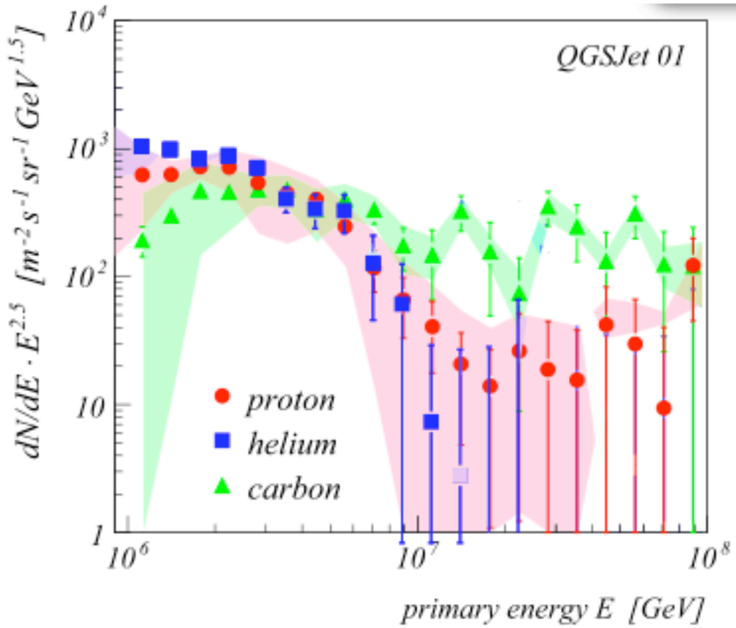
$E_{He}/2$

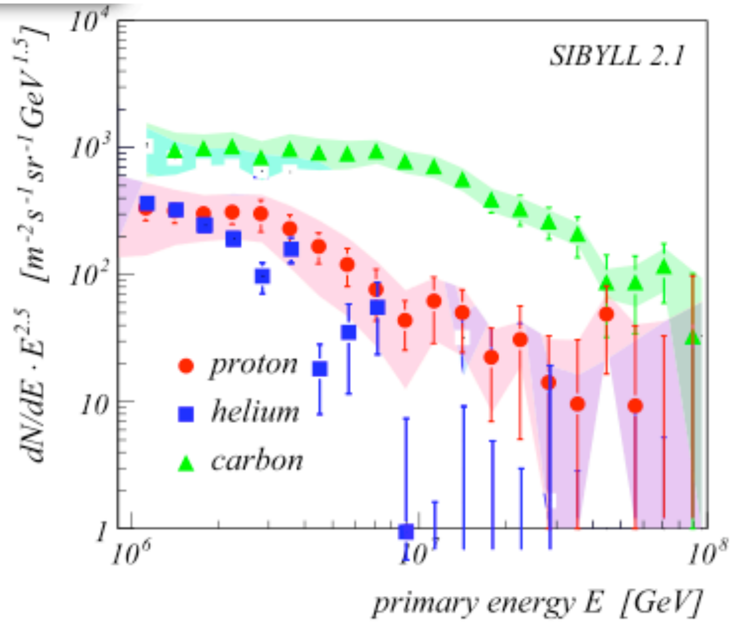




$E_{knee}^{A} = A E_{knee}^{p}$

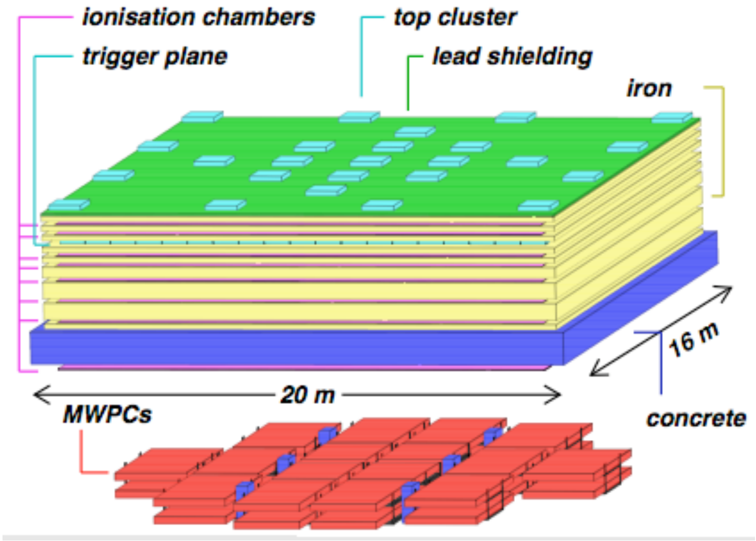
$E_{He}/4$



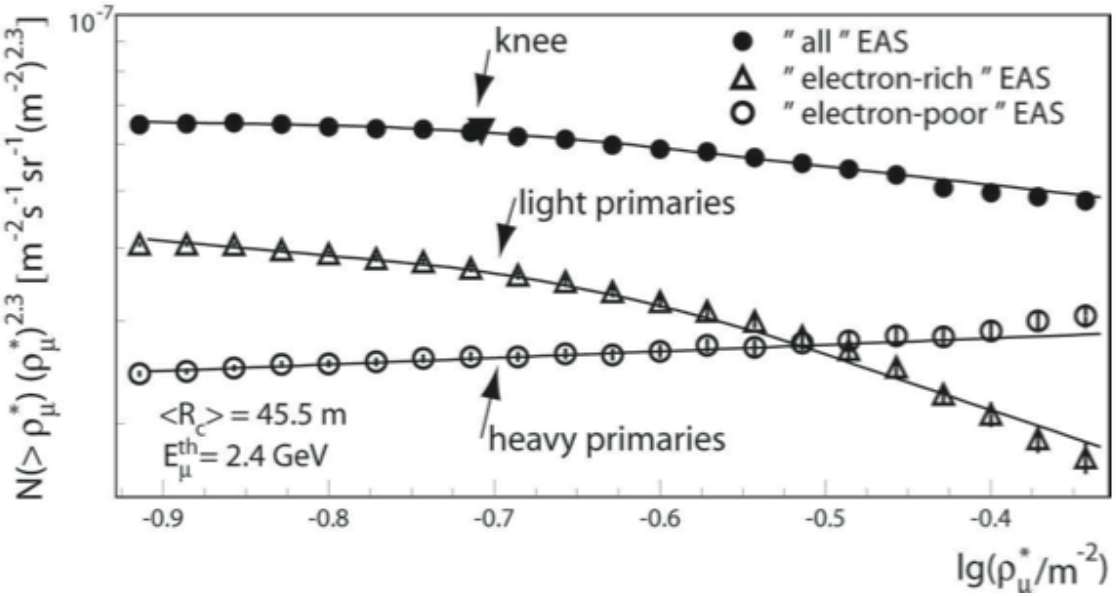


[K.H.Kampert, CRIS Conf. 2006]

The local muon density KASCADE



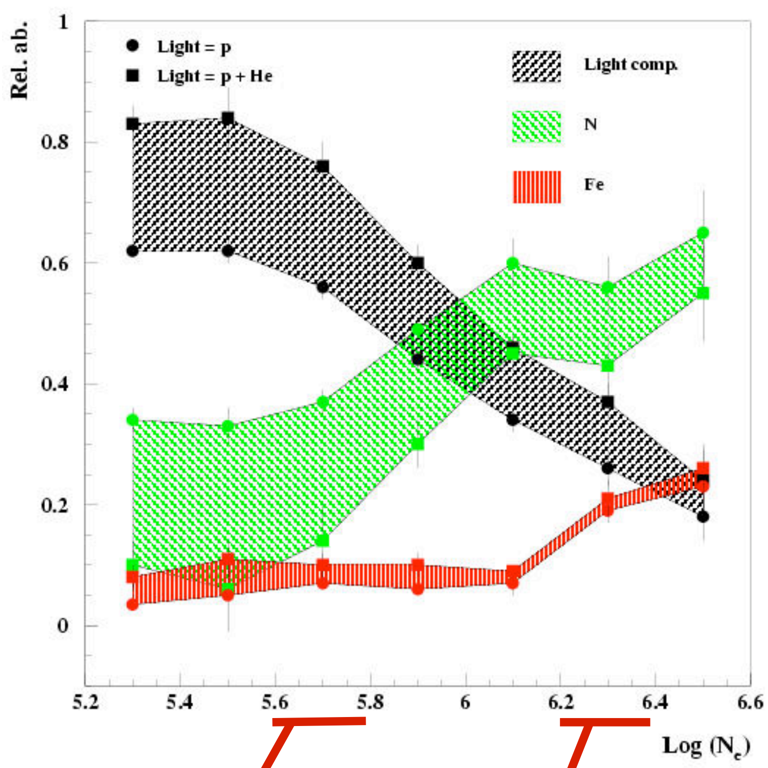
More direct approach, less dependent on interaction models

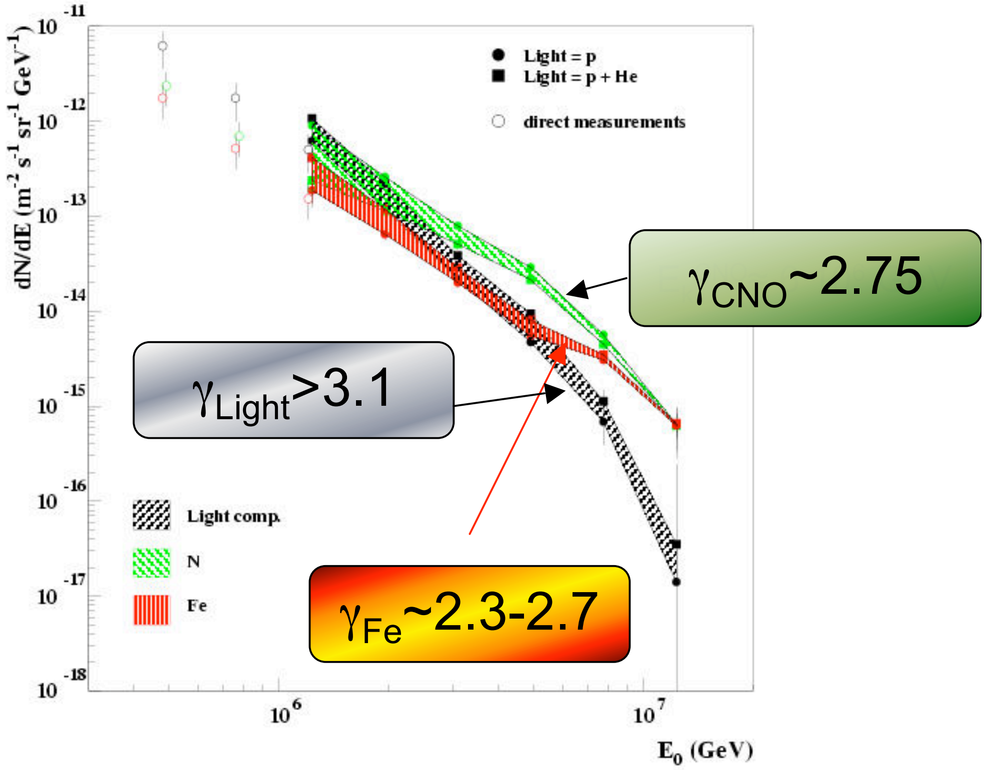


The knee is clearly seen in the light component only

[T.Antoni et al., Astrop.Phys., 16 (2002) 343]

EASTOP





Relative abundances

0.76 (p+He)
0.14 (N)
0.10 (Fe)

0.37 (p+He)
0.43 (N)
0.21 (Fe)

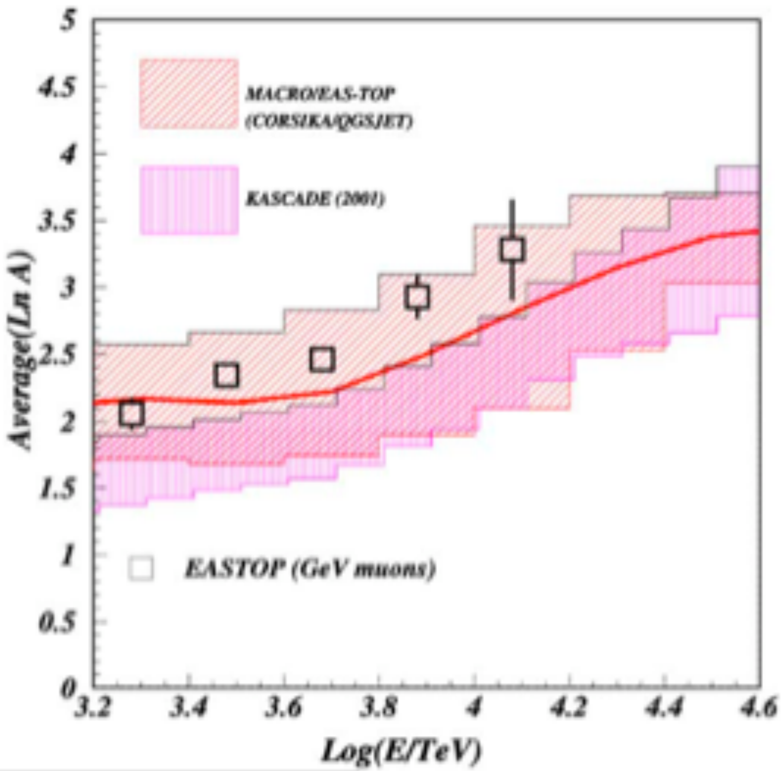
+ experimental size spectra
+ simulation

Energy spectra of each component

Composition from em and TeV muon data

EAS-TOP:
em size N_e
MACRO :
HE muons N_μ

Study of TeV muon multiplicity distribution in different intervals of N_e around the knee



increase in <lnA> across the knee

consistency of the model among GeV and TeV muons

Tibet Yangbaijing

EAS array : 221 scintillation counters
(15 m grid, 3.7 10^4 m^2)
+ emulsion chambers (80 m^2)
+ burst detector (80 m^2)

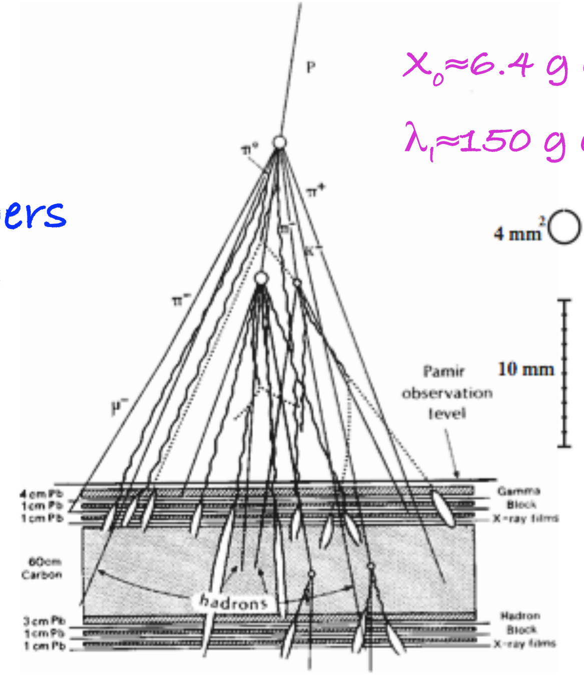
4300 m asl (606 g cm^{-2})

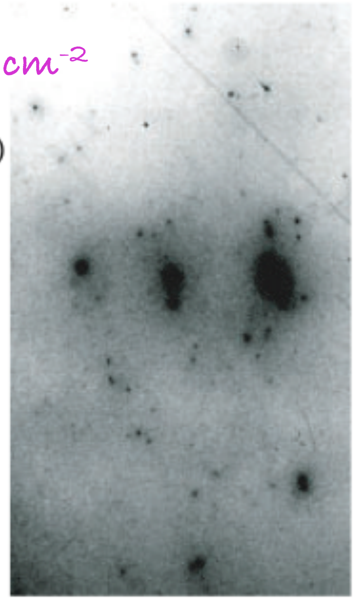
Hybrid: sensitivity of EAS array
Improved by with large emulsion chambers
Enrich the proton and Helium events by
tagging them with γ-families
+ very high altitude

Selection of primary protons
event by event

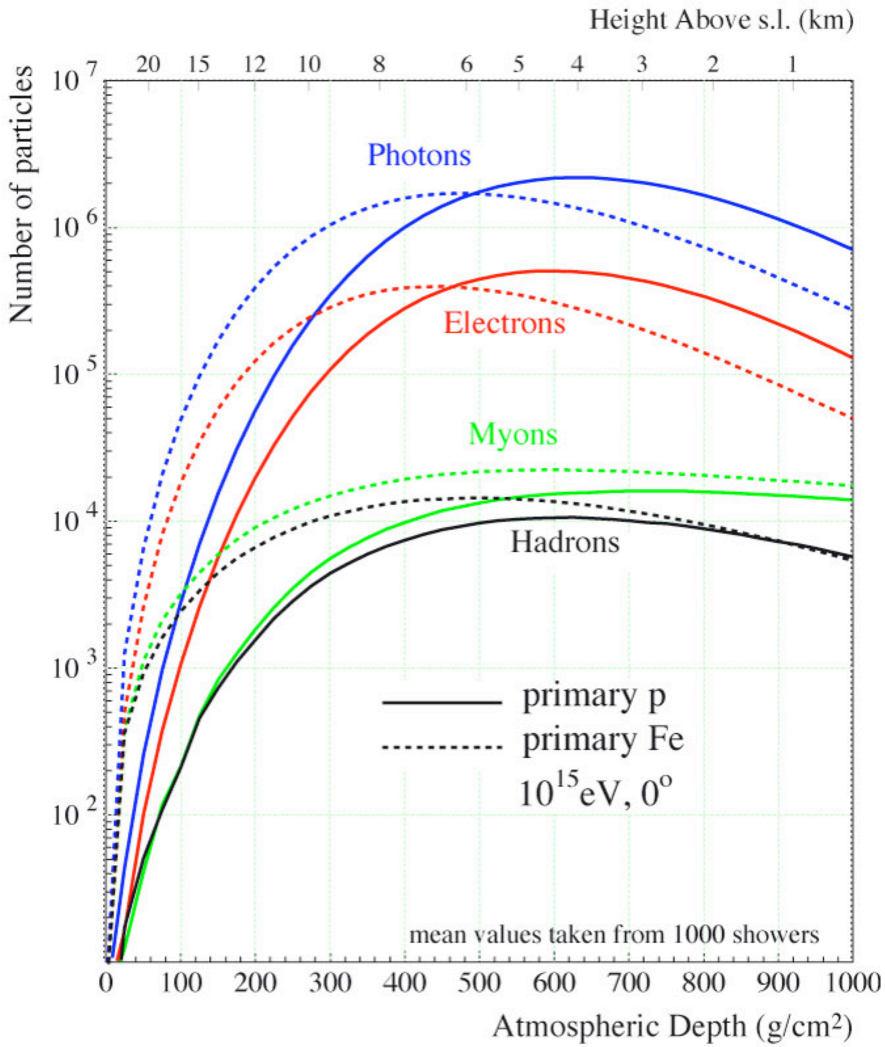
$X_0 \approx 6.4$ g cm^{-2}

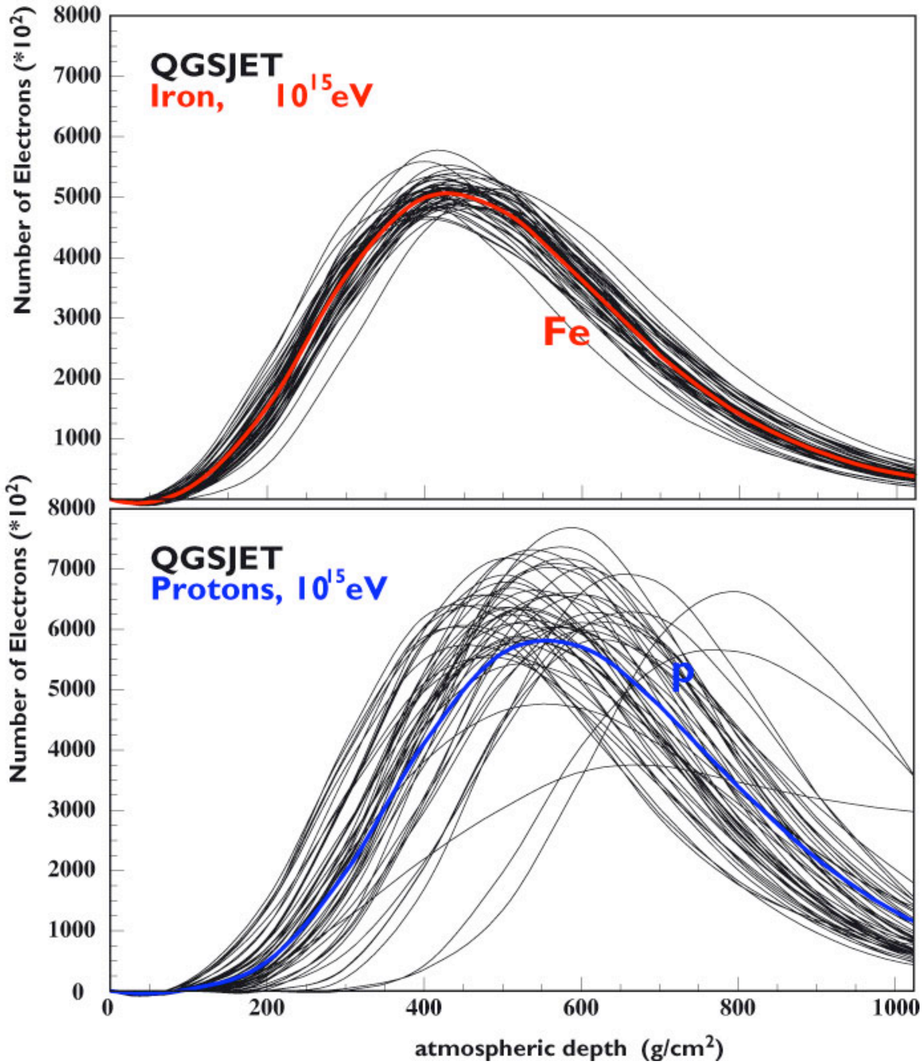
$\lambda_I \approx 150$ g cm^{-2}





The longitudinal development

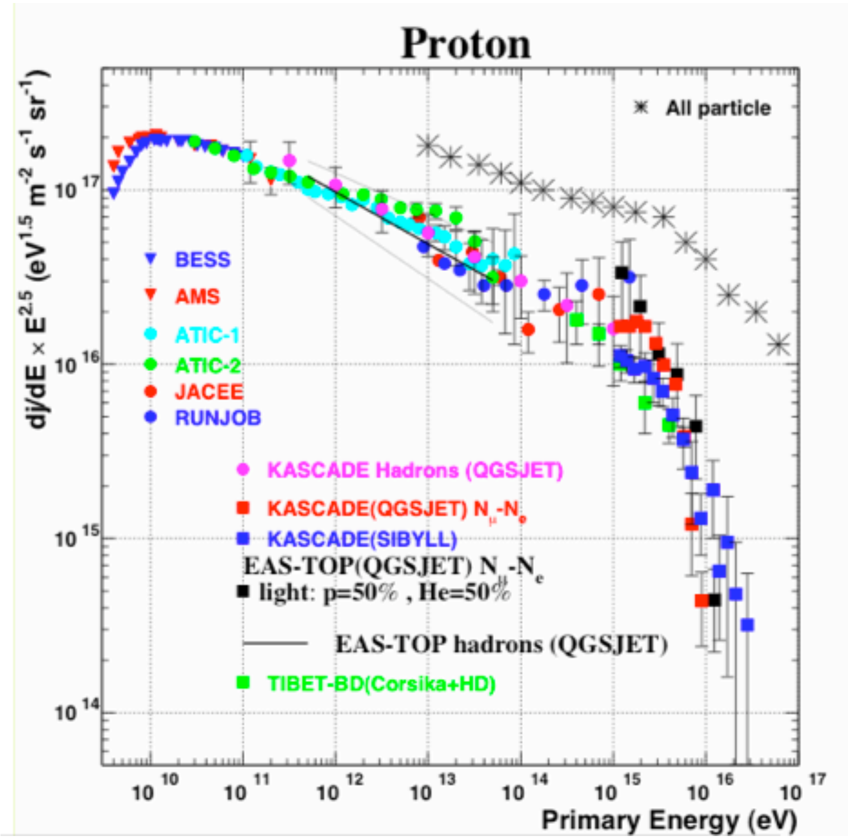


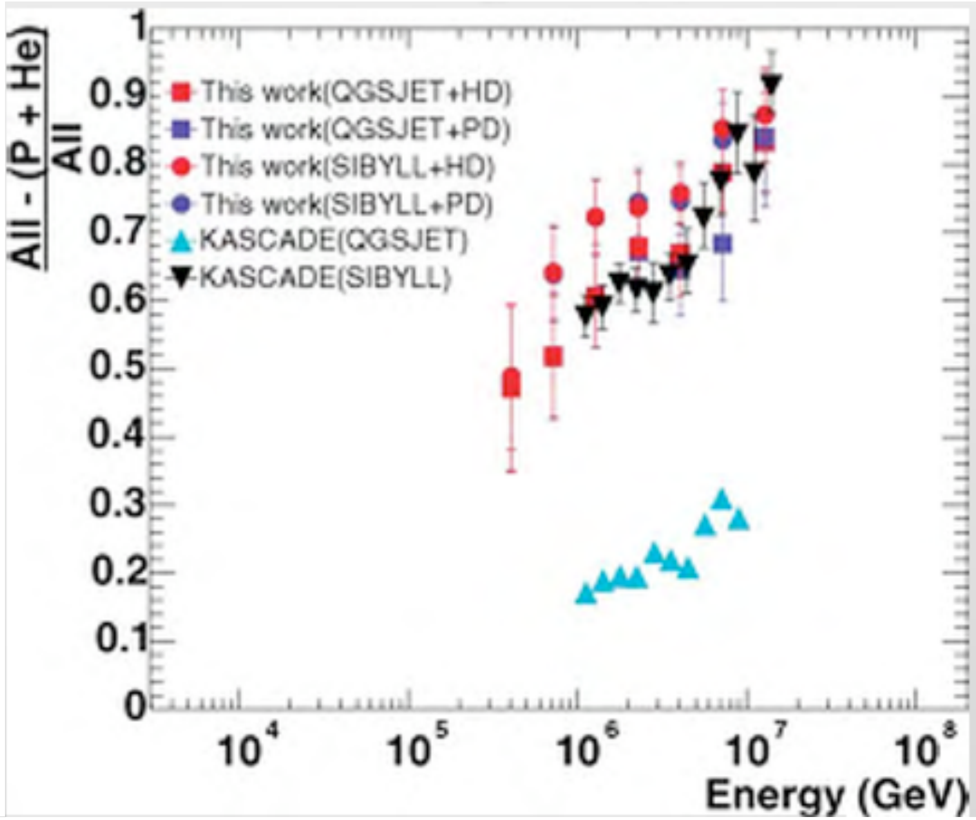


A primary Fe gives EAS with

- **higher X_{max} [σ_{int} larger]**
- **more muons at ground**
- less electrons at ground
- Similar number of hadrons

Fluctuations are lower for EAS from heavy nuclei





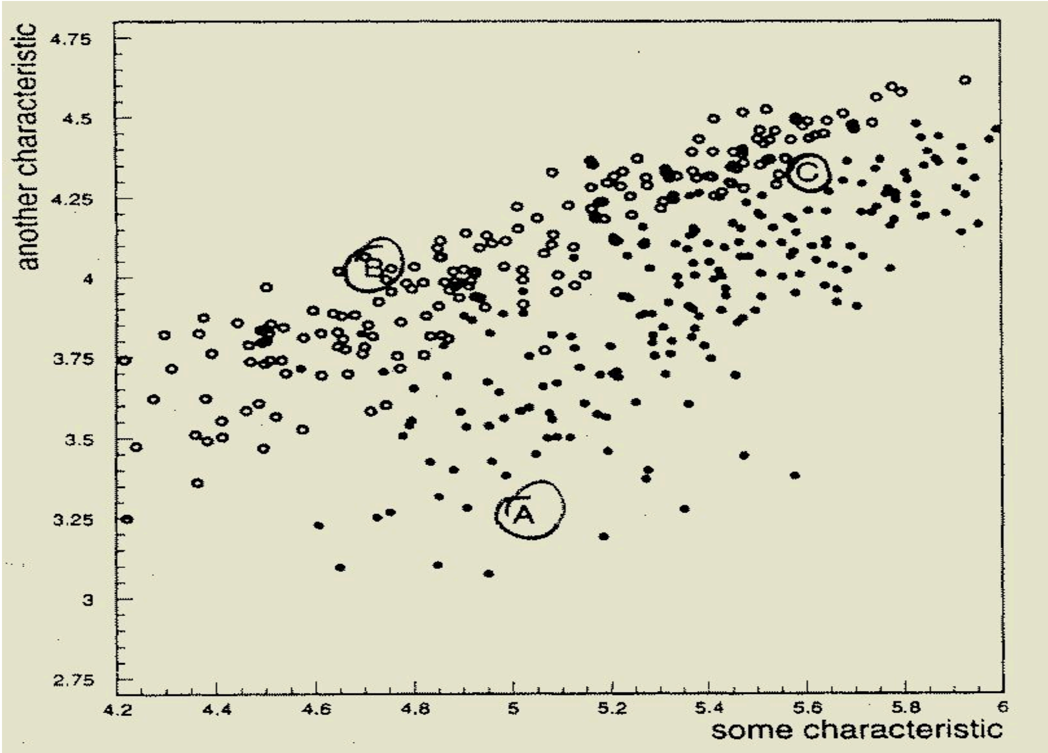
TIBET results

p spectrum agrees with satellite and Kascade (Sibyll)
The knee in the all particle spectrum is due to nuclei
Heavier than Helium
Claim less dependence on models

but....

Knee assumed at 1.5 Z PeV very low and
below the range of experiment
Separation p/He : strong correlation errors on He spectrum
Cannot see heavy nuclei

CASA-MIA



KNN TEST

Monte Carlo simulation and classification according to some "characteristics" : ρ_e, ρ_μ, s

Each event is assigned a "class" in the plane of "characteristics"

K nearest neighbor:

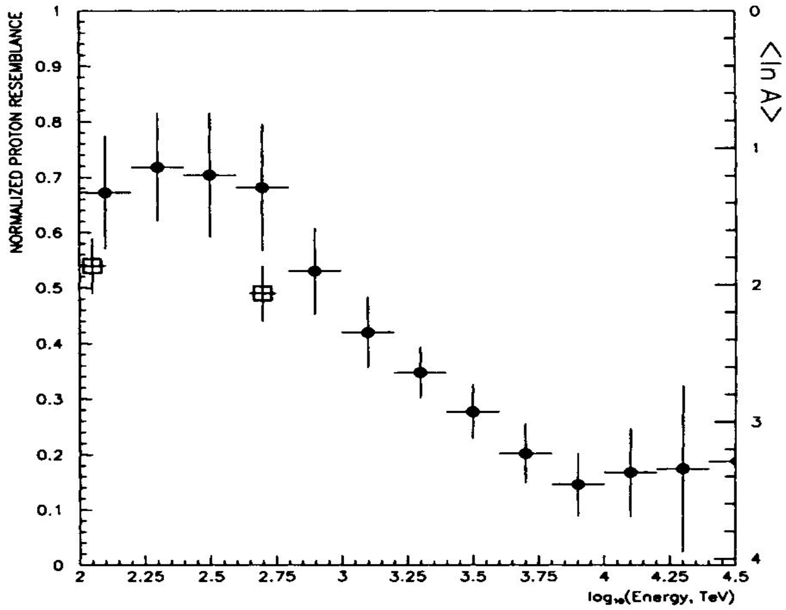
- event A : 100% class 1
- event B : 100% class 2
- event C : 50% - 50%

Fluctuations tend to superimpose classes:
only "p-like" and "Fe-like" events

Proton resemblance plot

average fraction of 5NN protons

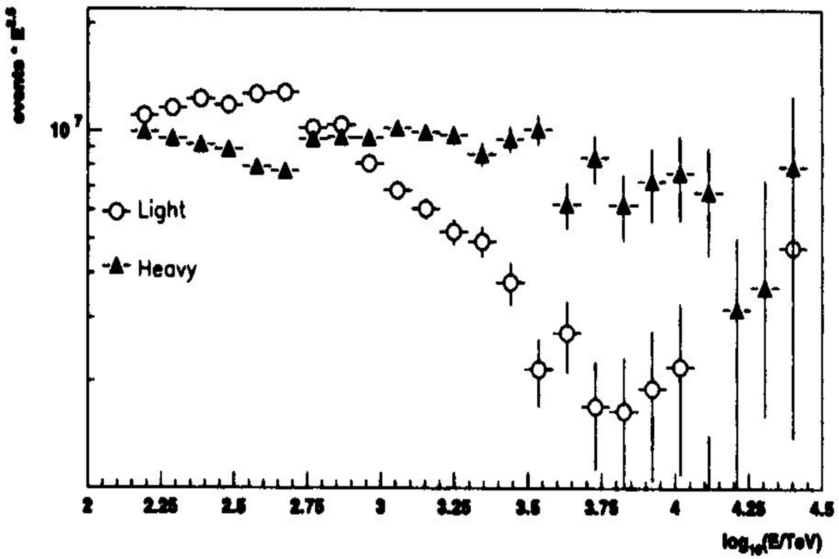
- ✓ Heavier composition above the knee
- ✓ no model dependence



Consistency check

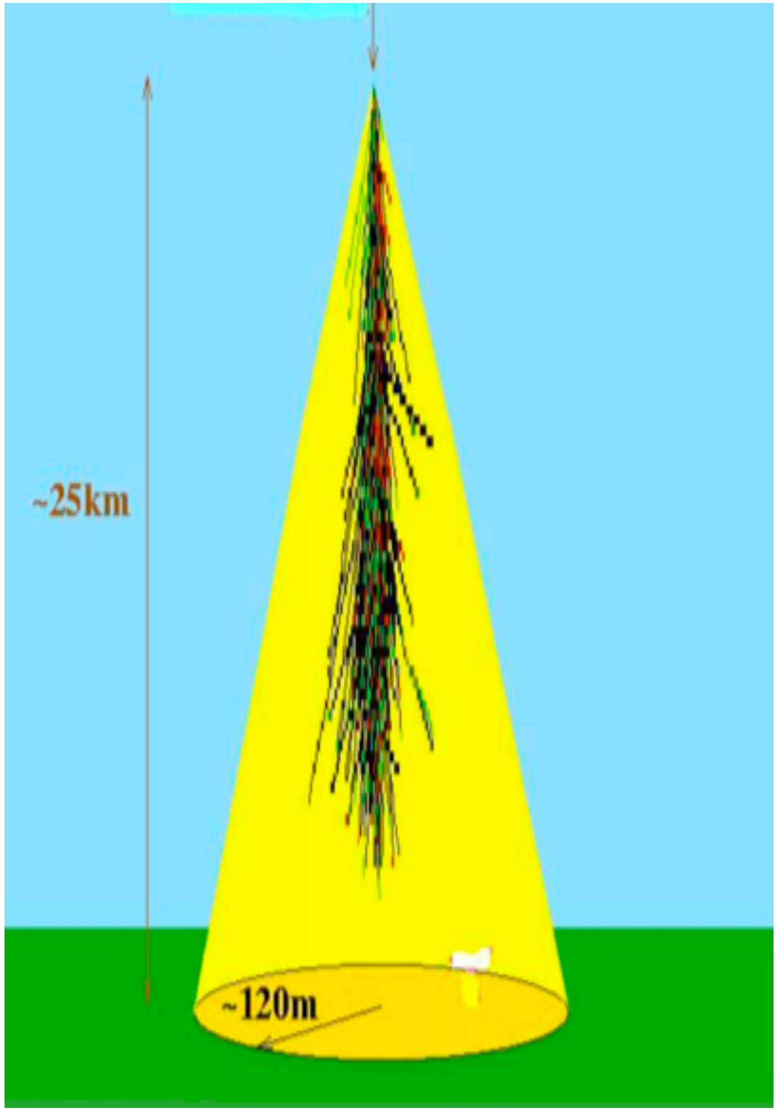
p-like events if >50% 5NN protons

Fe-like if less



- ✓ composition heavier above the knee
- ✓ bend due to light component
- ✓ not enough statistics to see the bend in the heavy one

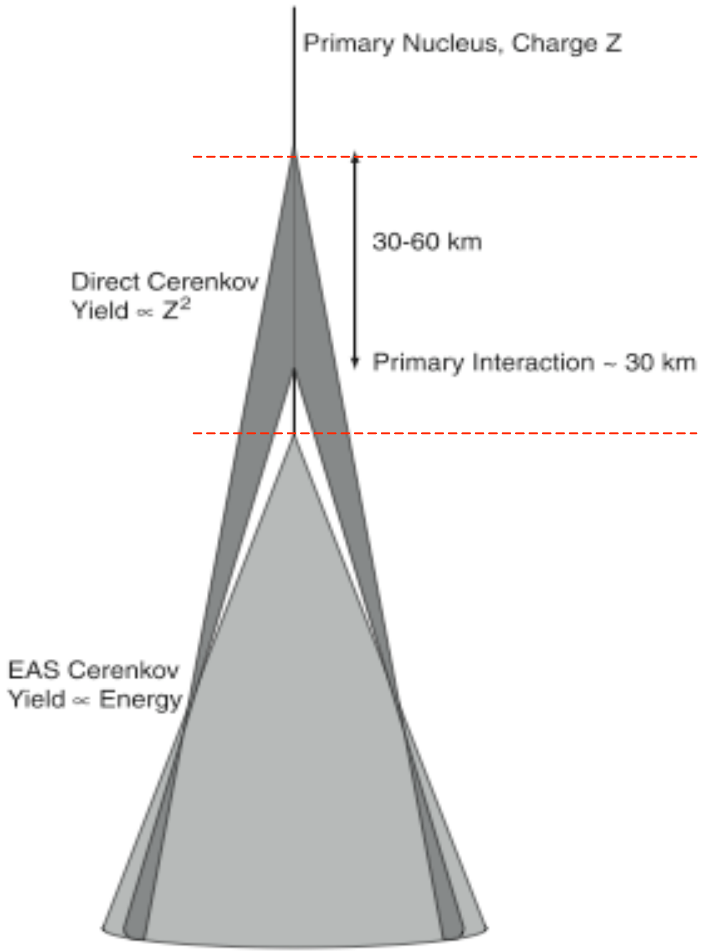
Using Cerenkov detectors…



High photon number density ☺ Higher Signal-to-noise ratio with arrays with smaller area or larger separation

Smaller absorption of γ in atmosphere ☺ Broader lateral distribution

Only moonless nights ⚡ Low duty cycle



Direct emission by the primary particle

Yield ∝ Z^2

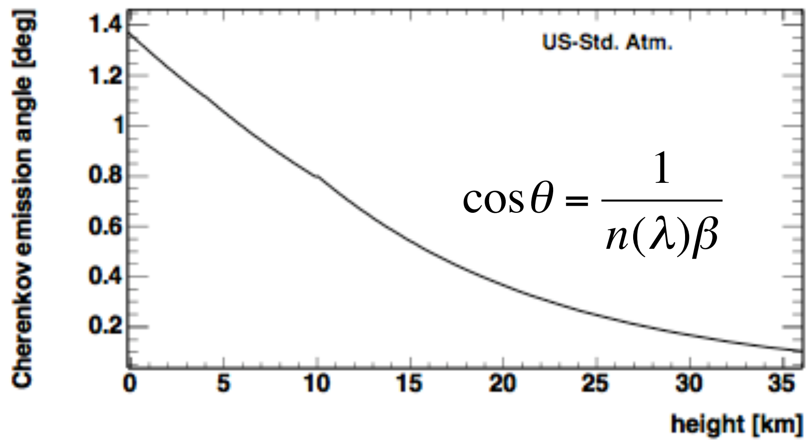
E_{max} detectable : $C_{EAS} \sim C_{DIR}$

Emission angle 0.15°-0.3°

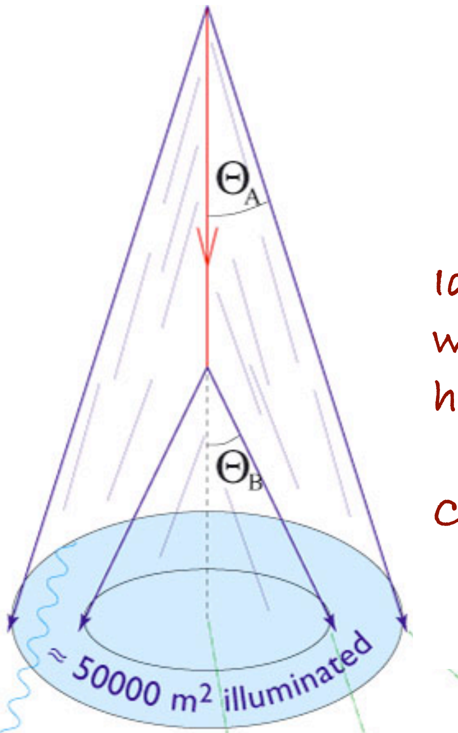
Cerenkov emission by EAS particles

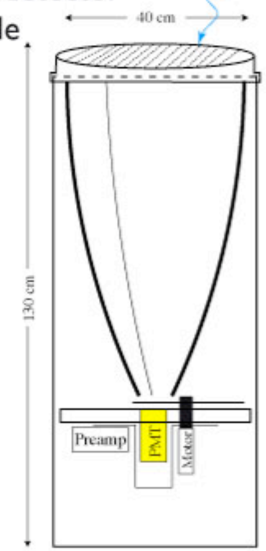
Yield ∝ E^2

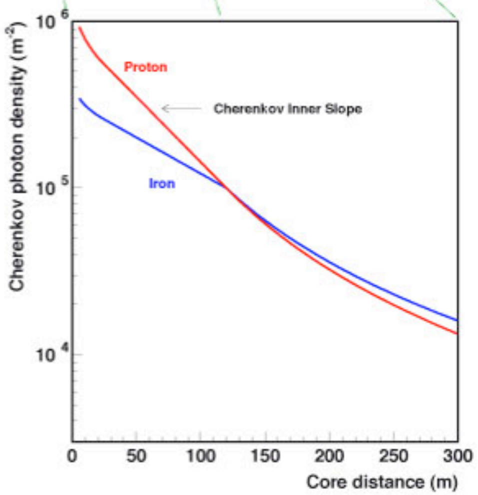
Emission angle >1°



(I) Wide-angle Cerenkov detectors







Idea: sampling the Cerenkov lateral distribution, which is a superposition of the light generated at all heights

Characteristic ring of light at ≈ 100-150 m from core

$C(r) = C_{120}(r/120)^{-\beta}$ $r=120\text{-}350$ m

$C(r) = C_{120}\, e^{-sr}$ $r<120$ m

Inner Slope $\propto X_{max}$
Mass

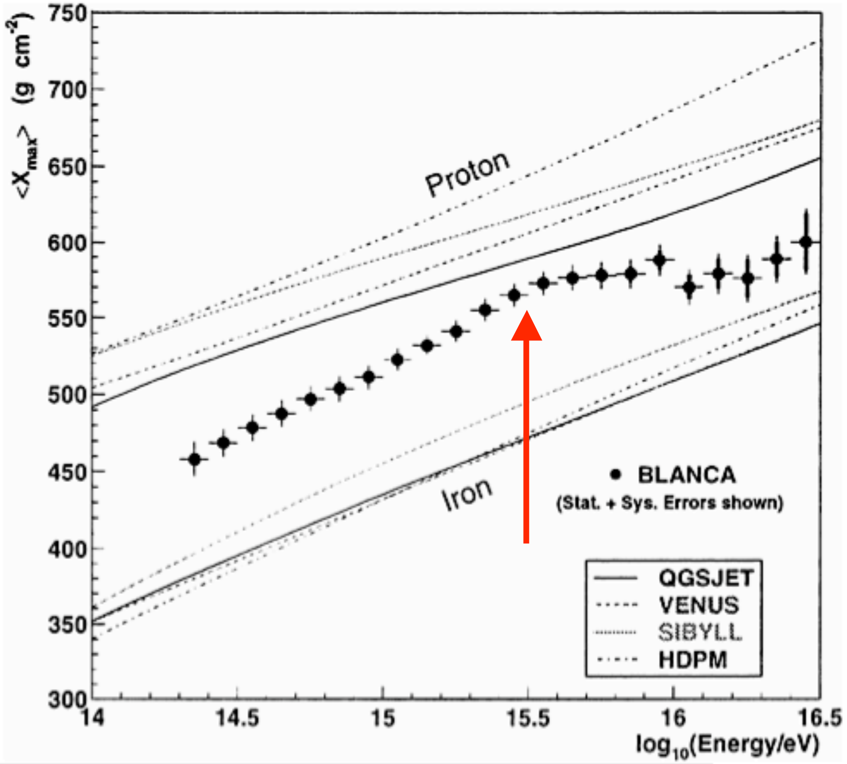
Intensity at 120 m
$C_{120} \propto$ **Energy**

BLANCA – 144 angle integrating detectors

<X_{max}> derived directly from the slope of the Cerenkov ldf (through MC)

weak dependence on model: **mixed composition lighter approaching the knee, then heavier**

systematic uncertainty <10 % in the whole range



[J.W.Fowler et al, Astrop.Phys.15 (2001) 49]

(II) Imaging Cerenkov detectors

(i) CR within the field of view produces an image of the shower on the focal plane

(ii) Need to know

from EAS array

- distance to core and shower direction

from Monte Carlo

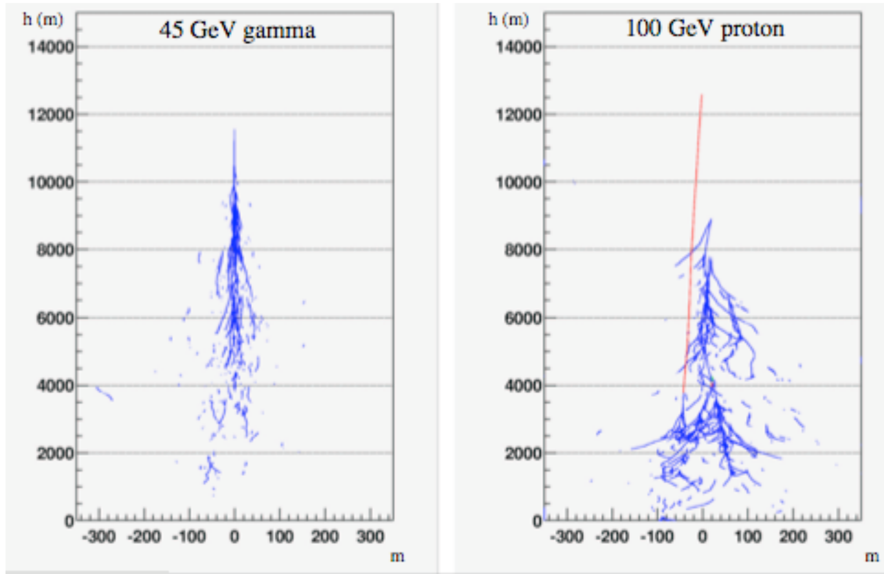
- the Cerenkov light distr. around the axis at each depth

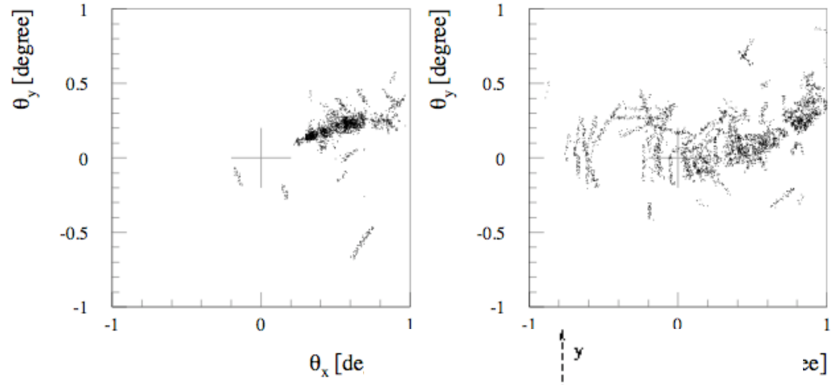
(iii) Fit to the Longitudinal distribution

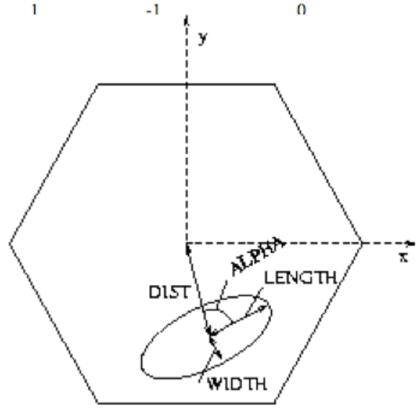
X_{max}, N_γ and width

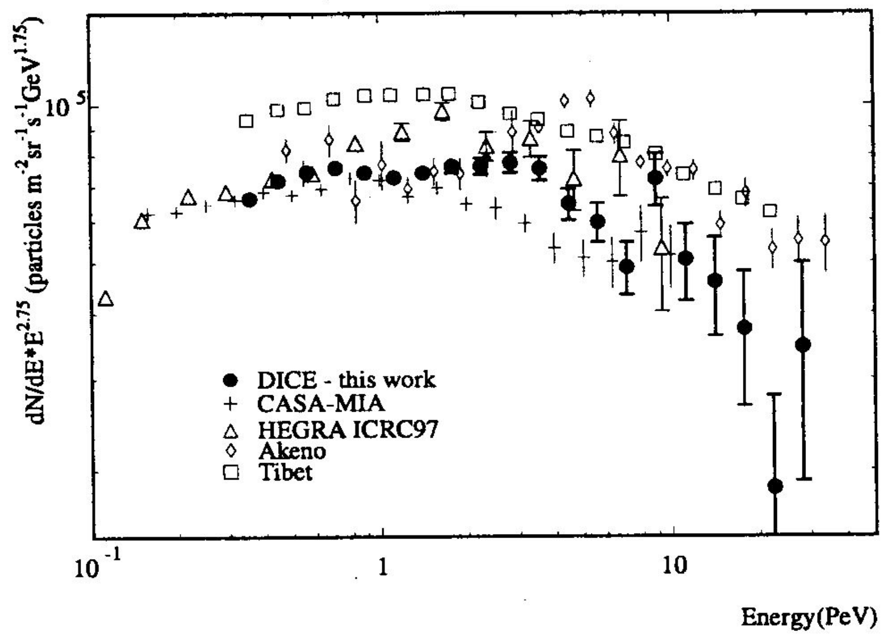
(iv) Total intensity of Cerenkov light

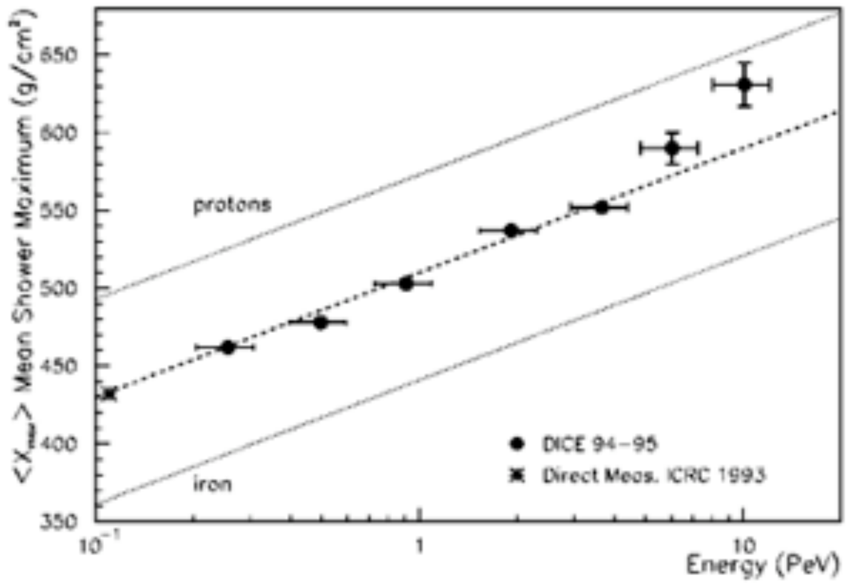
E from total intensity of C light







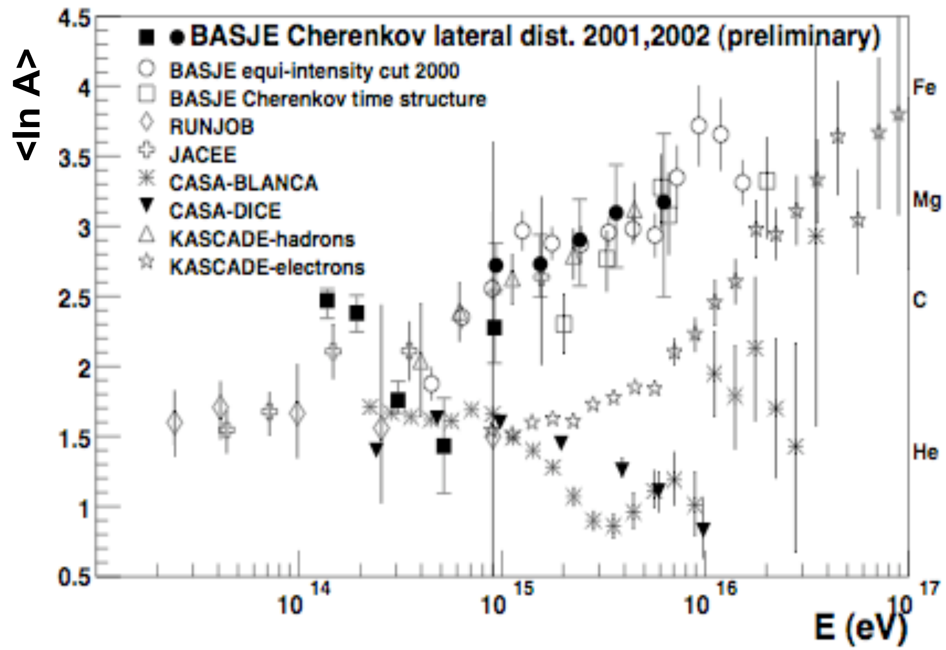




DICE – 2 Cerenkov imaging telescopes

Knee near 3 PeV, smooth change

Composition in agreement with BLANCA



(III) Direct Cerenkov detection by IACT

Before the first interaction...
$\delta(h) = (n-1)$, n=local atmosphere refraction index

$$N_C \propto Z^2 \left(\frac{1}{\gamma_{thr}^2} - \frac{1}{\gamma^2} \right)$$

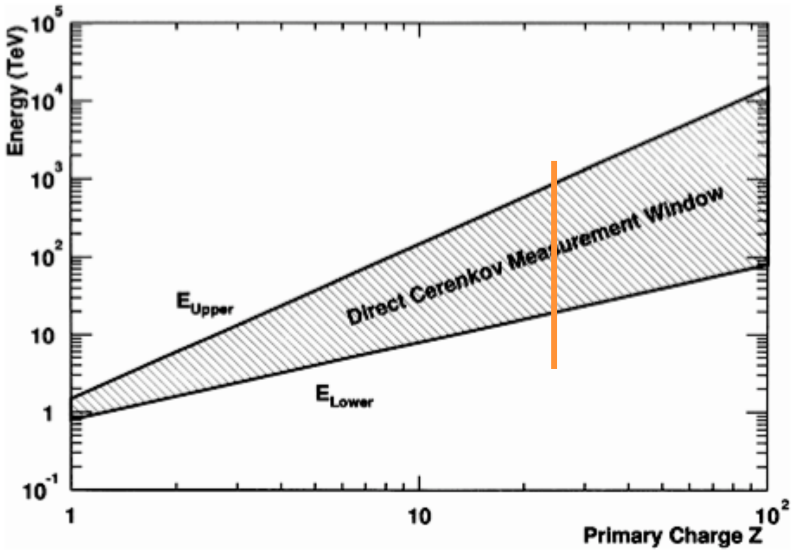
Cerenkov emission rate

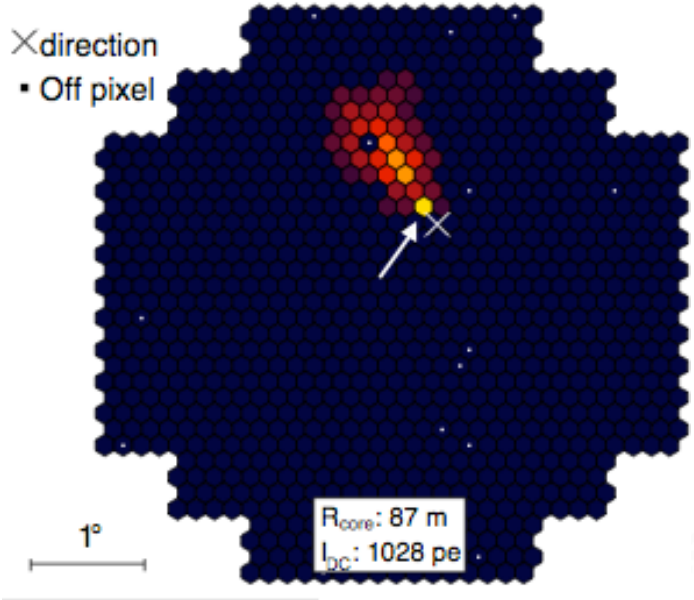
$$\gamma_{thr} \approx \frac{1}{\sqrt{2\delta(h)}} \rightarrow E_{MIN}(h) \approx \frac{mc^2}{\sqrt{2\delta(h)}}$$

E.g. Fe nucleus: At sea level $\gamma_{thr} \sim 42$ $E_{thr} \sim 2$ TeV
At 50 km $\gamma_{thr} \sim 680$ $E_{thr} \sim 36$ TeV

$$Y_{DIR} \approx Y_{EAS} \rightarrow E_{MAX}$$

$\Delta E/E \propto Z$





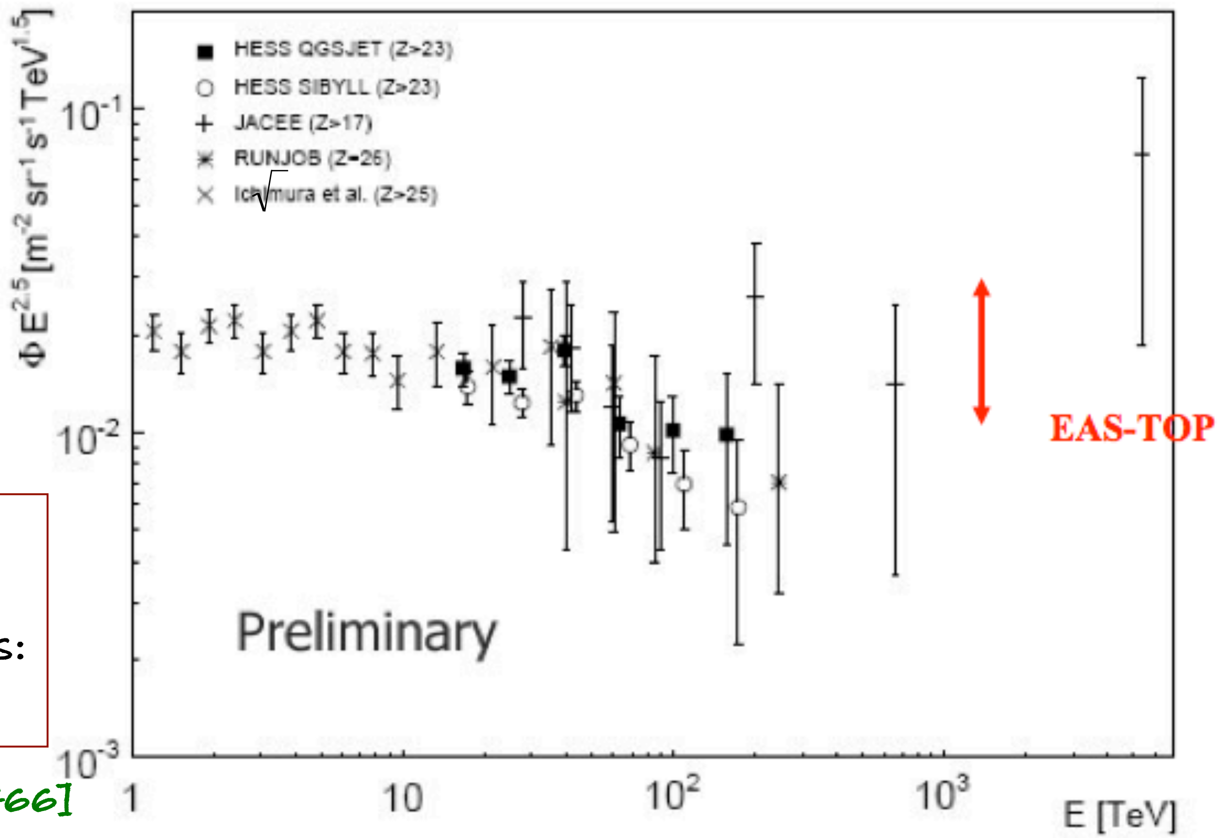
HESS IACT - direct Cerenkov

C_{DIR} separated by IACT as a single high intensity pixel between the reconstructed EAS direction and the centre of gravity of the shower

pixel size = 0.1°

E from total intensity of image (E_{thr}=13 TeV)

$Z = \sqrt{I_{DC}}$



Increase in statistics
increase energy range
Good agreement with others:
more precise

[F.Aharonian et al., astro-ph/0701766]

Summary on spectrum and composition

Type	Technique	Energy Range	Experiment and Sensitive Components
dir.	Spectrometer	1-200 GeV	AMS(p-He), BESS(p,He), HEAO(CNO-Fe)
dir.	Calorimeter	30GeV - 500 TeV	ATIC(all), CREAM(all)
dir.	Emulsion chambers	10-500 TeV	JACEE, RUNJOB (all)
ind.	Hadron calorimeter	500 GeV -1 PeV	KASCADE, EAS-TOP (p)
ind.	Muon spectrometer	100 GeV - 10 TeV	L3+C(mostly p and He)
ind.	Cherenkov + TeV μ	50-300 TeV	EAS-TOP/MACRO(p,He,CNO)
ind.	N_e-N_μ	100 TeV - 10 PeV	GRAPES, KASCADE, EAS-TOP (all)
ind.	Emulsion chambers	5-300 TeV	Tibet ASγ (p,He)

The spectra from direct and EAS measurements in the "low" energy region do agree quite well

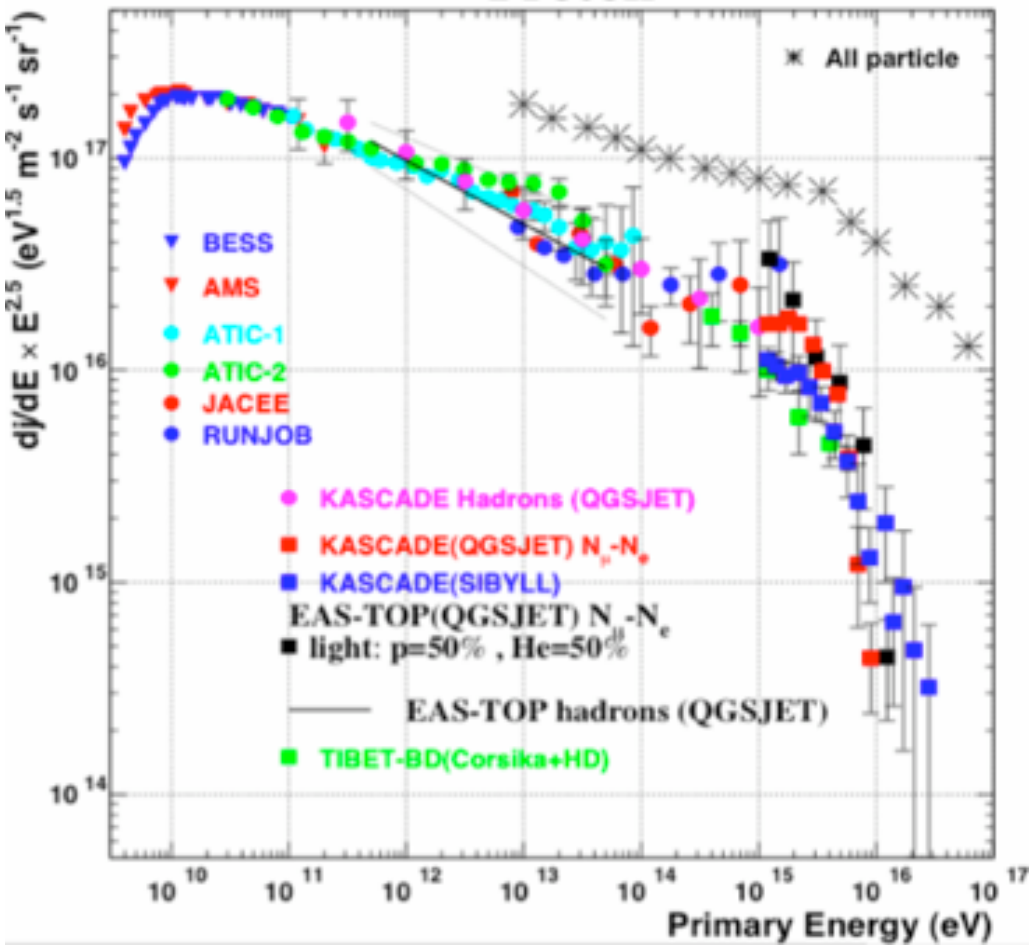
The knee in the all particle spectrum exists at 3-4 PeV

The knee of the cr spectrum is most probably due to light elements (He); the mean composition gets heavier above the knee.

Does the knee scale as E/Z or as E/A ? Uncertain...

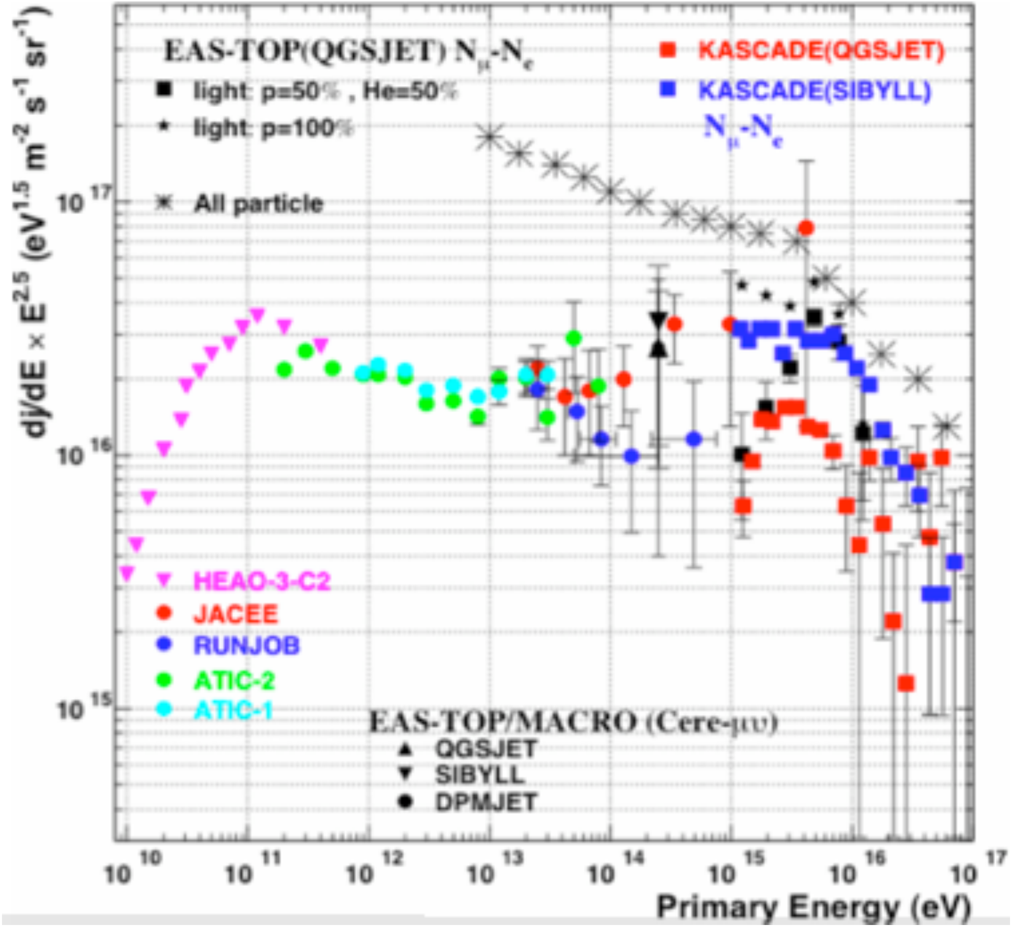
Hadronic interaction models are the main source of systematics

The proton spectrum



Good agreement for all measurements

Global fit to the spectrum $dN/dE \propto E^{-2.75}$



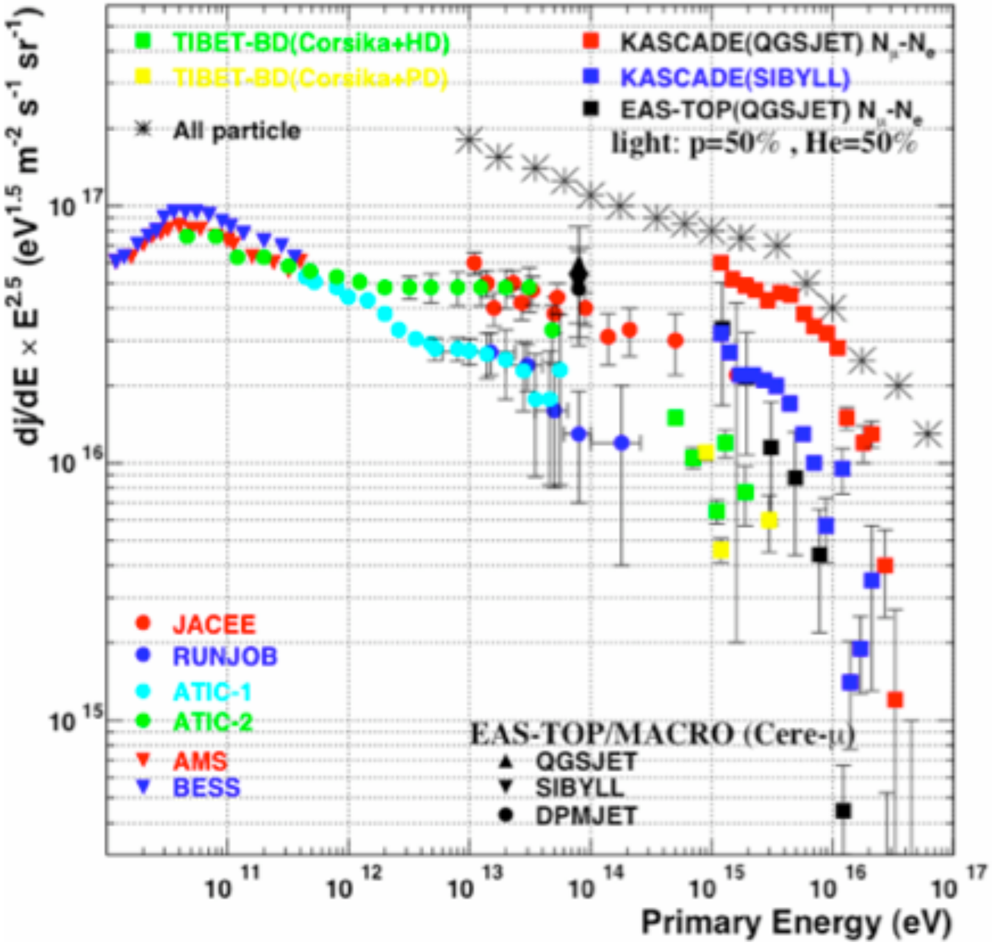
The Helium spectrum

Discrepancy between Jacee and RunJob results: ATIC2 agrees with Jacee

Global fit to the spectrum $dN/dE \propto E^{-2.61}$

Accuracy for the Ne-Nμ results ~ direct measurements

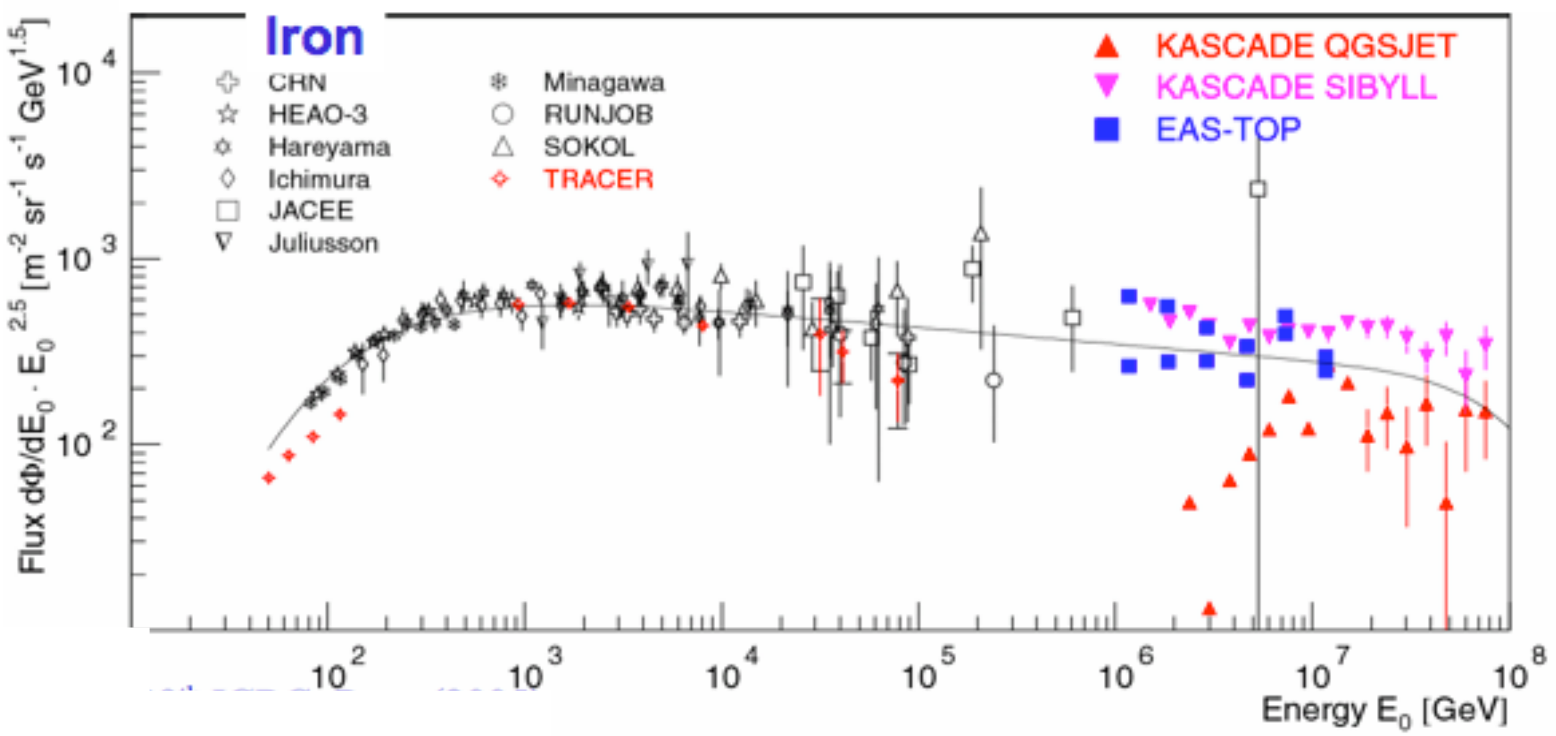
The CNO spectrum



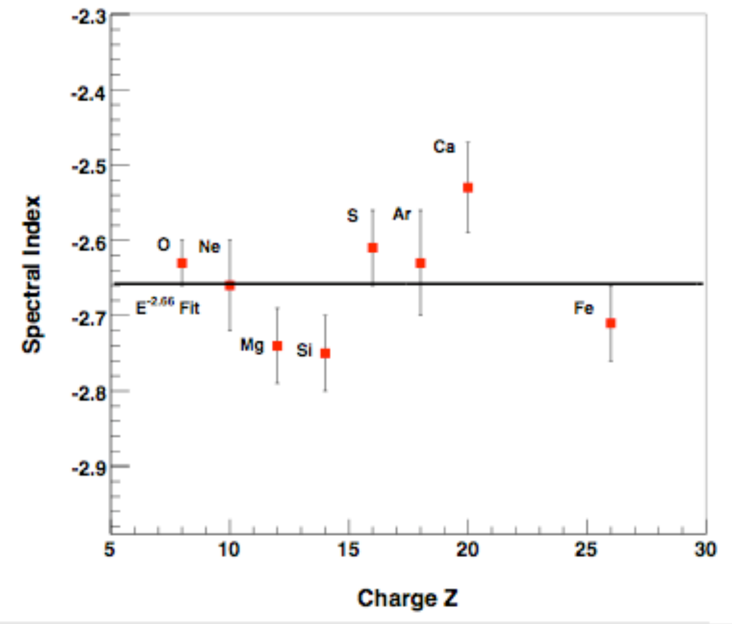
Different definitions of CNO group

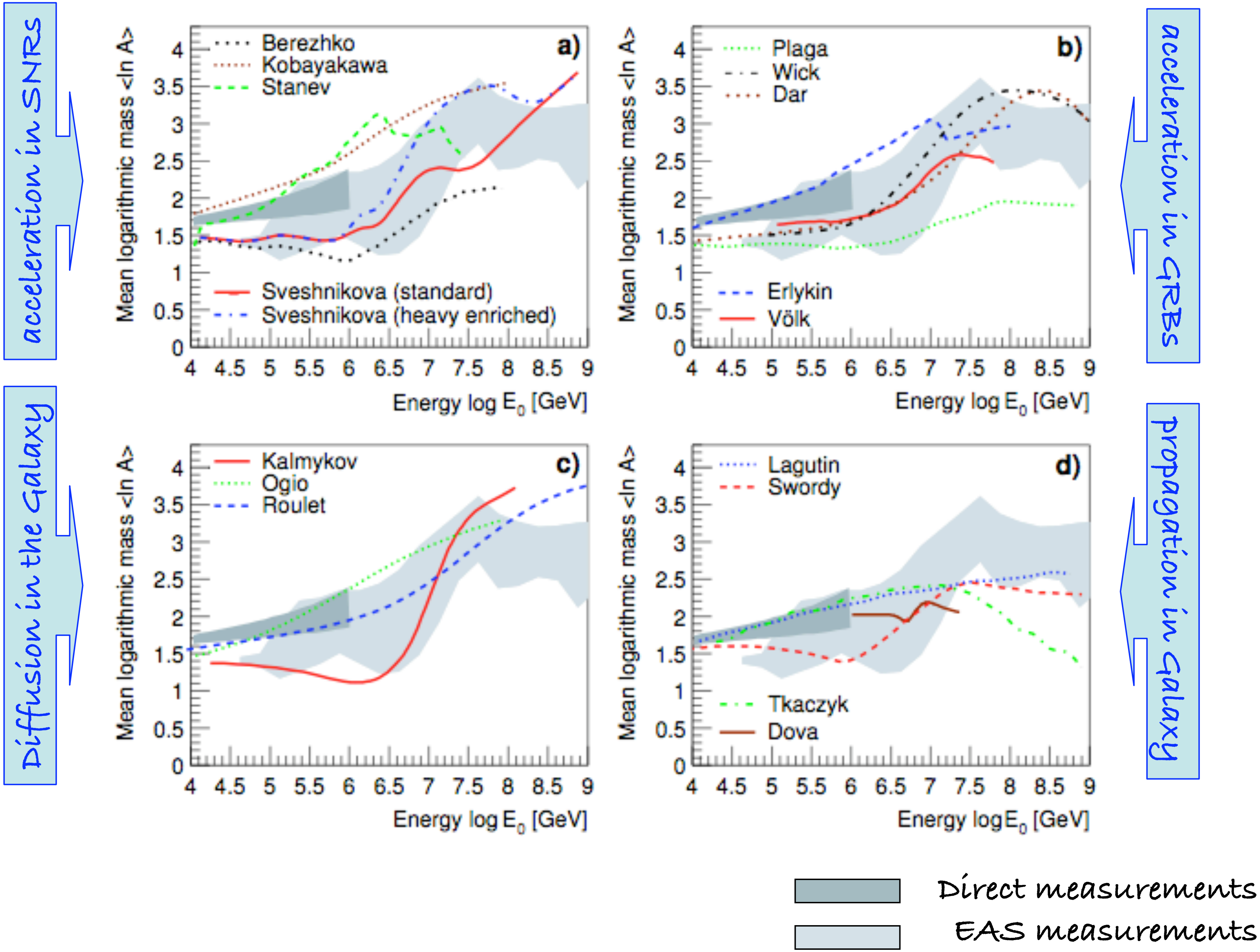
Global fit to the spectrum $dN/dE \propto E^{-2.61}$

The Iron spectrum



The overlap direct/indirect is not reached
but gap is smaller
The best fit to Tracer+CRN globally gives
$\gamma \sim 2.65$





acceleration in SNRs
acceleration in GRBs
Diffusion in the Galaxy
Propagation in Galaxy
Mean logarithmic mass <ln A>
Energy log E_0 [GeV]
a)
Berezhko
Kobayakawa
Stanev
Sveshnikova (standard)
Sveshnikova (heavy enriched)
b)
Plaga
Wick
Dar
Erlykin
Völk
c)
Kalmykov
Ogio
Roulet
d)
Lagutin
Swordy
Tkaczyk
Dova
Direct measurements
EAS measurements