Cosmic-ray energy spectrum around the knee

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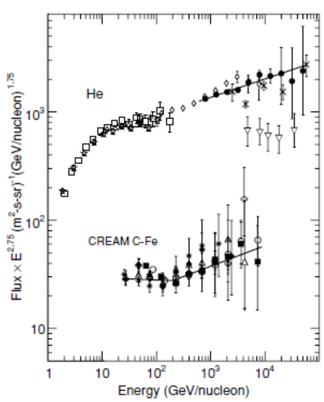
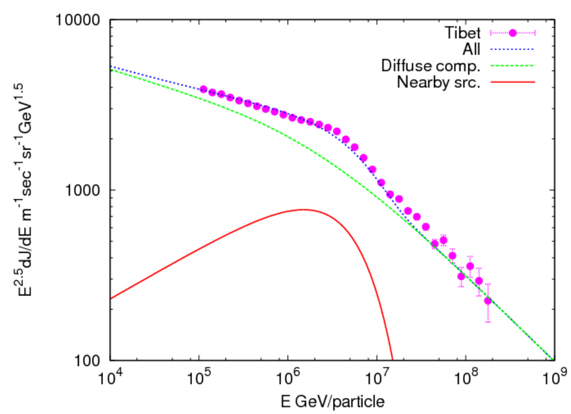
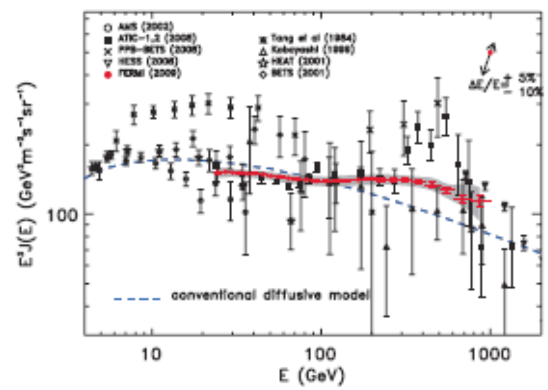


CREAM



Knee



Electron spectrum

EDS2011 Dec 20 Qui Nhon Vietnum

Contents

•Global and fine structures seen in cosmic-ray energy spectrum

•Chemical composition of CRs

•Interaction model dependence in AS exp.

-- MC codes and LHCf result

•Hardening of spectrum in ATIC/CREAM

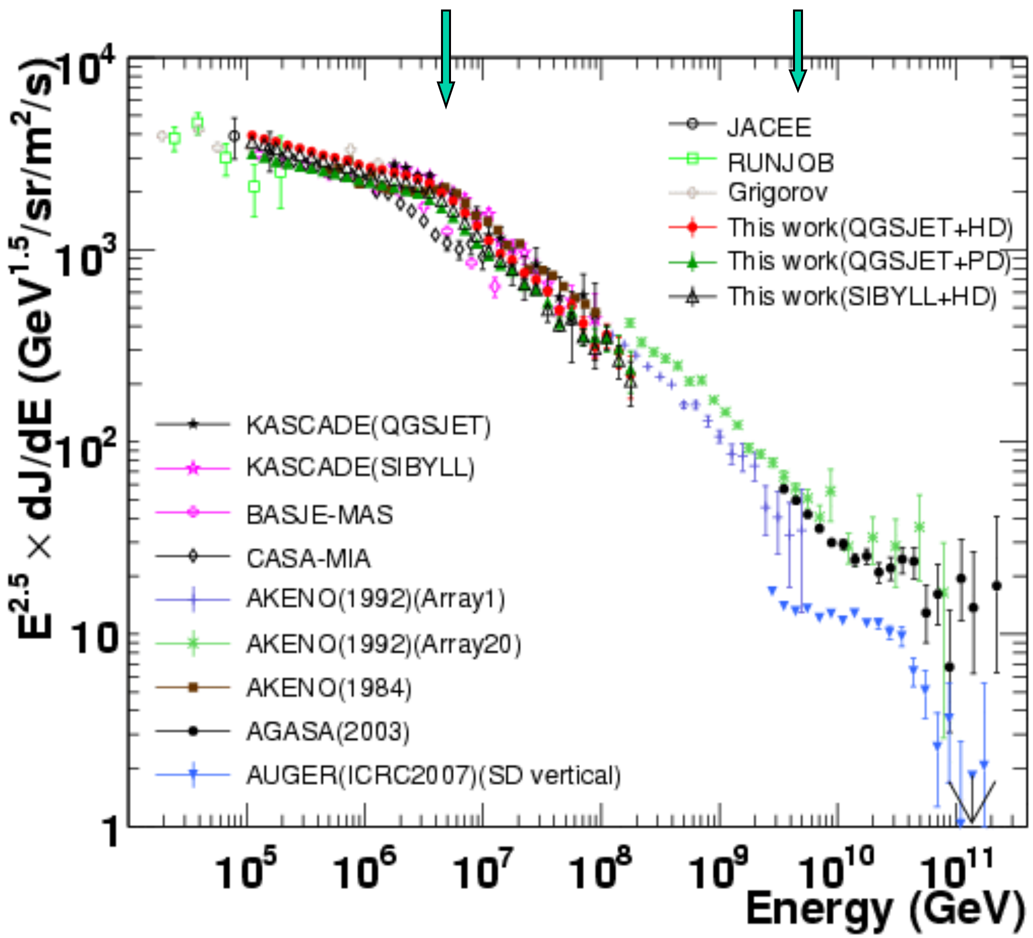
•Possible interpretation on the knee

•Enhancement of electron spectrum at several hundred GeV

CR spectrum in wide range

10^{15}-10^{16} eV 10^{18}-10^{19} eV

Knee Ankle



Tibet experiment

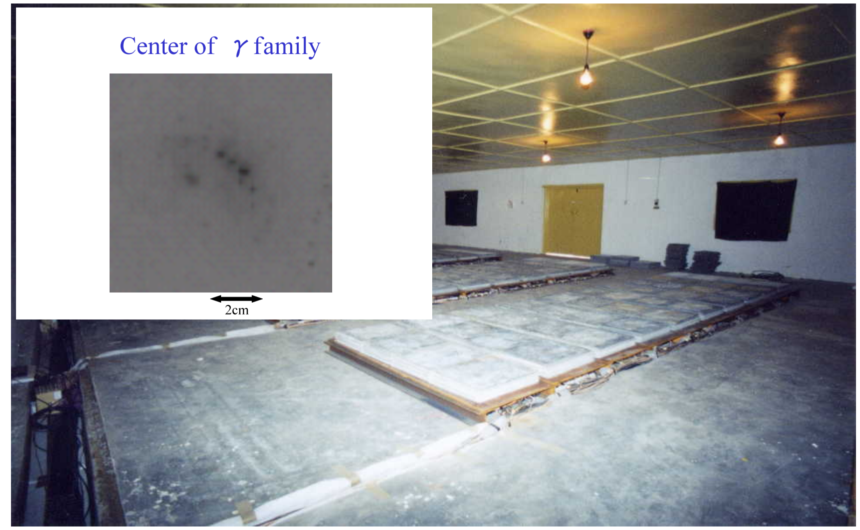
10^{14}-10^{17} eV

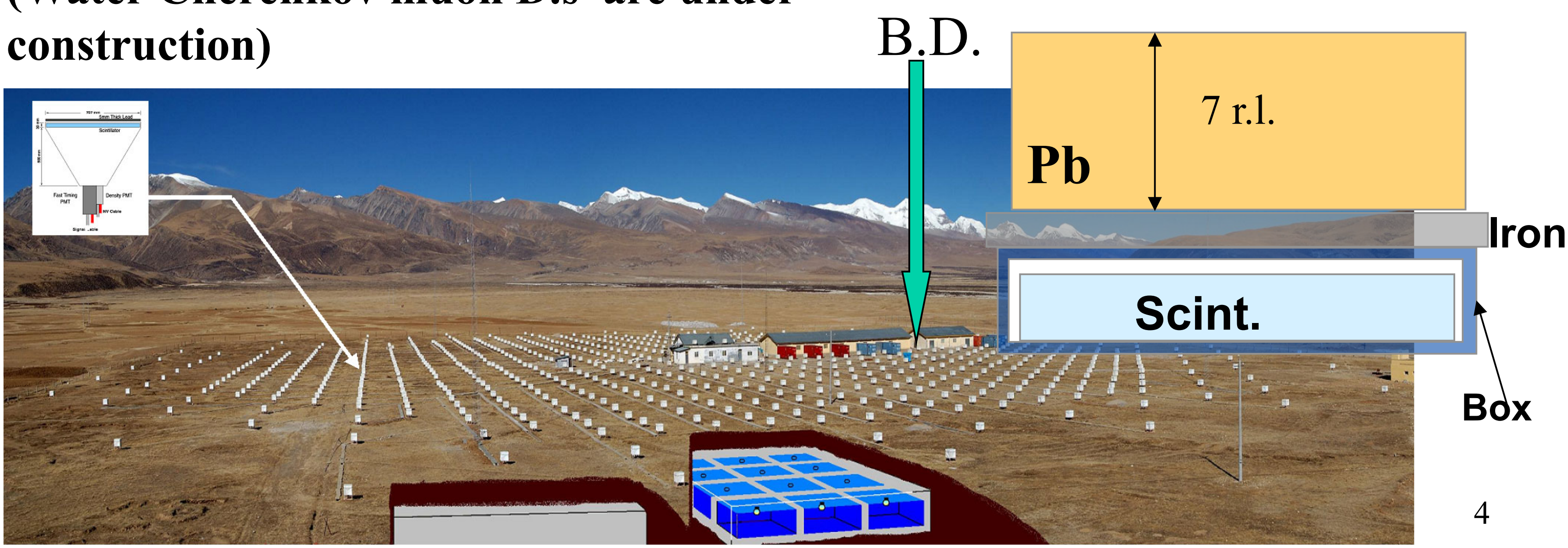
AS array at high altitude (4300m a.s.l.)
Area:37000m^2 with 789 scint.
Measure:energy spectrum around the kne
and chemical composition using sensitivity
of air showers to the primary nuclei throu
detection of high energy AS core.
Core detector: Burst D.
(Water Cherenkov muon D.s are under construction)

Merit of high altitude

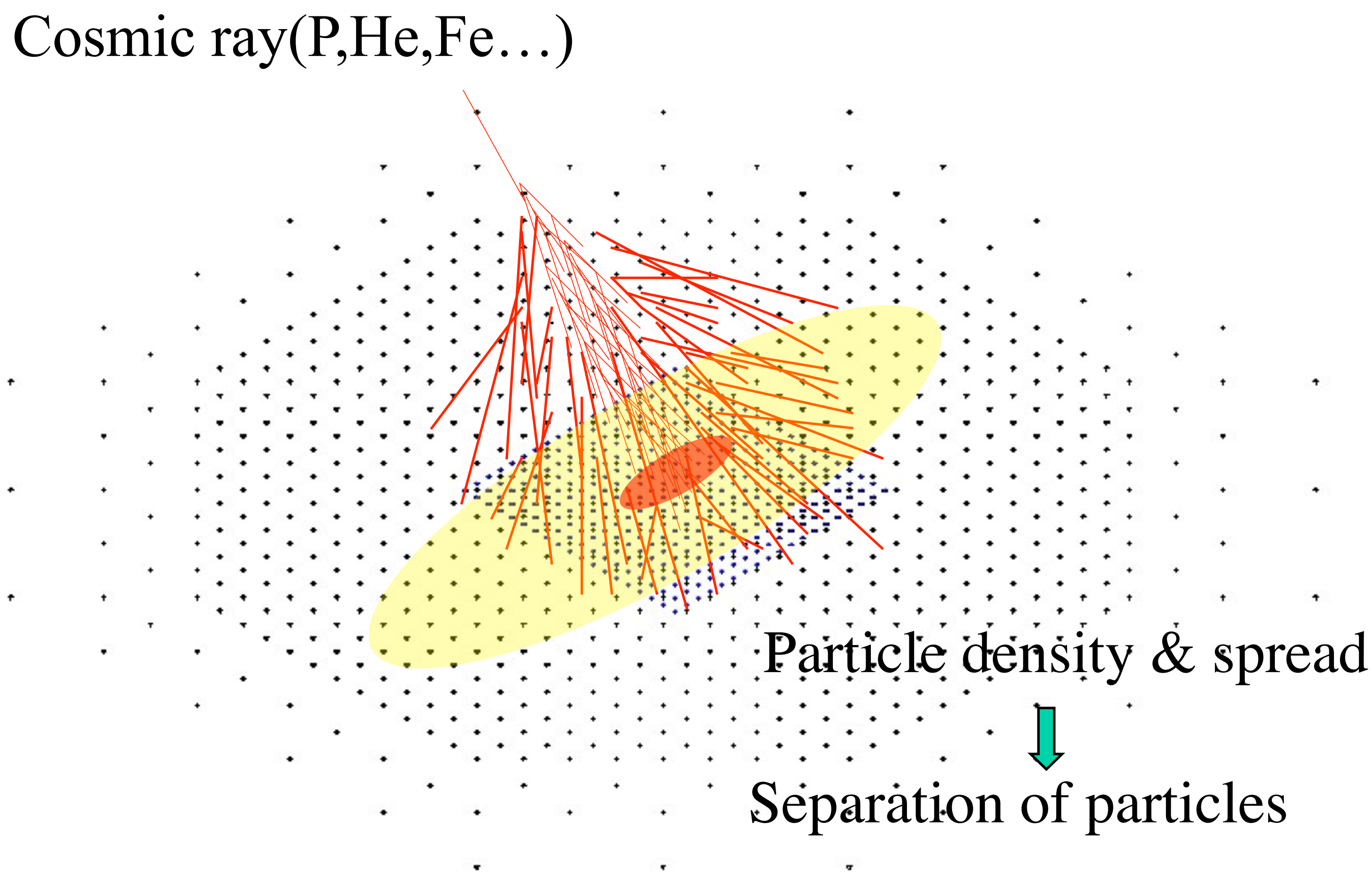
10^9

Emulsion Chambers and BDs





Tibet YAC array



Tibet III: **Energy and direction of air shower**

KASCADE experiment

40000 m^2 10^{14}-10^{17} eV

Measure electron and muon size at Karlsruhe, Germany (near sea level).
Energy spectra of 5 primary mass groups
are obtained from two dimensional Ne-Nμ spectrum
by unfolding method (P,He,CNO,Si,Fe).

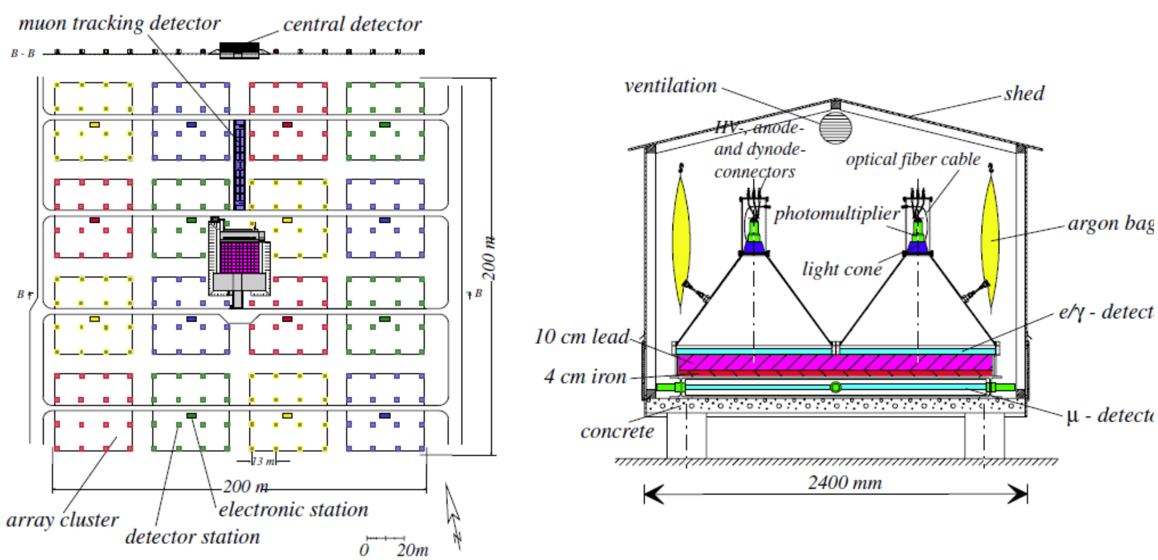


Fig. 1. Left: layout of the KASCADE air shower experiment; Right: sketch of a detector station with shielded and unshielded scintillation detectors.

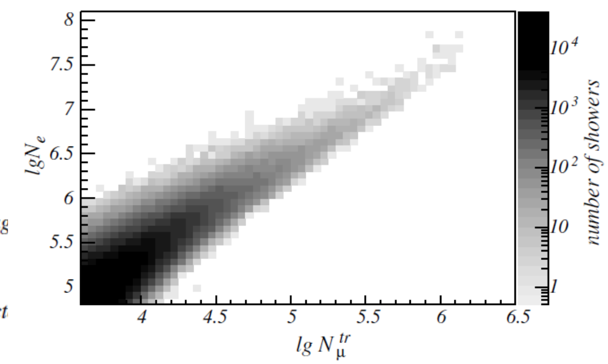


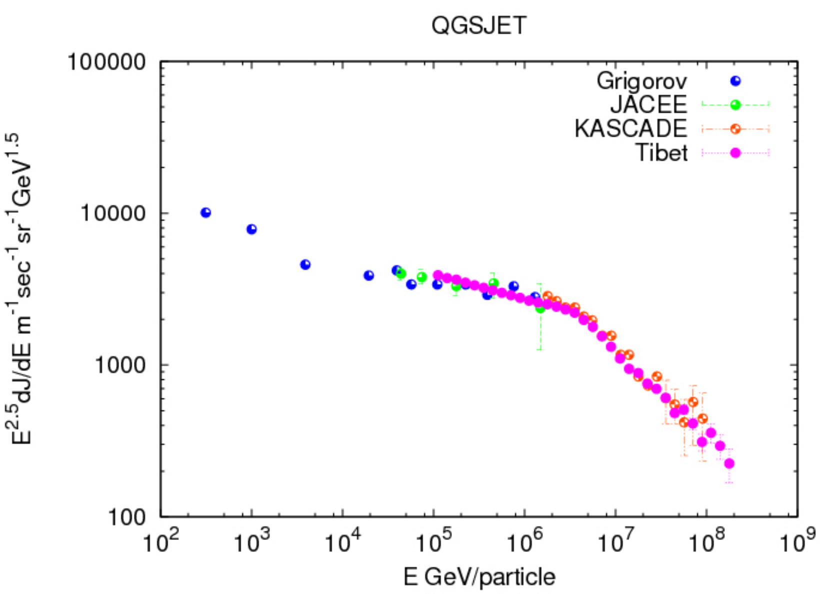
Fig. 2. Two-dimensional shower size spectrum used in the analysis. The range in $\lg N_e$ and $\lg N_\mu^{tr}$ is chosen to avoid influences of inefficiencies.

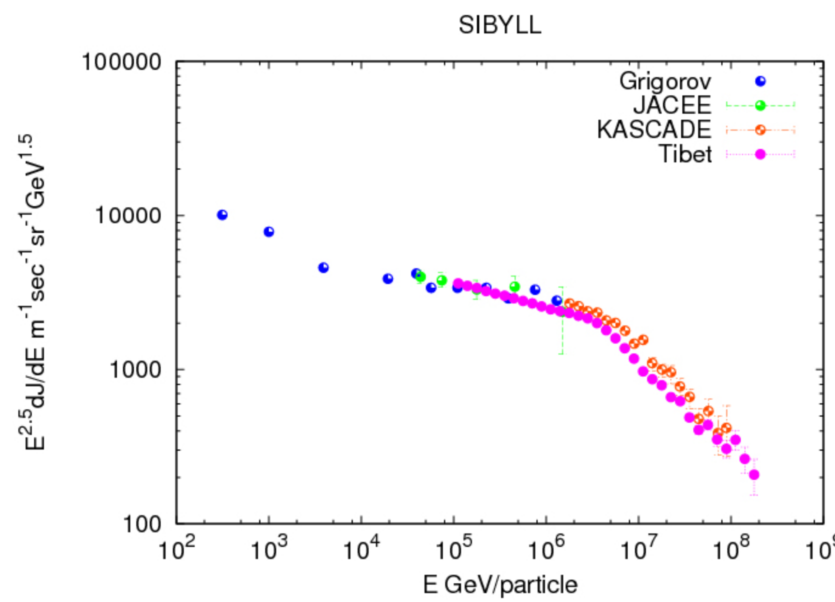
All particle spectrum.

The results agree well between Tibet and KASCADE.

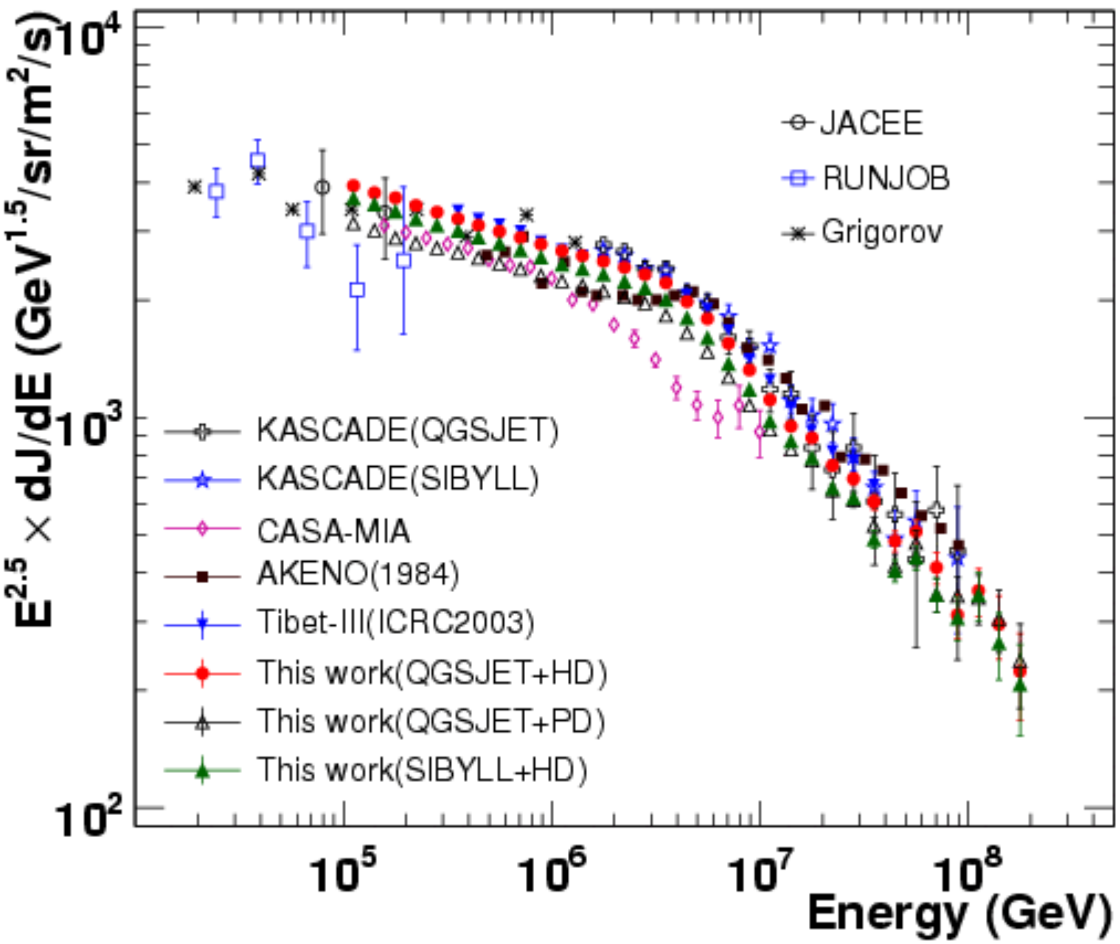
Knee at 4 PeV

$dJ/dE \propto E^{-\gamma}$ $\Delta\gamma = 0.4 \pm 0.1$





All particle spectrum by many experiments.



ApJ 678 (2008) 1165

Broken power law formula to describe energy spectrum

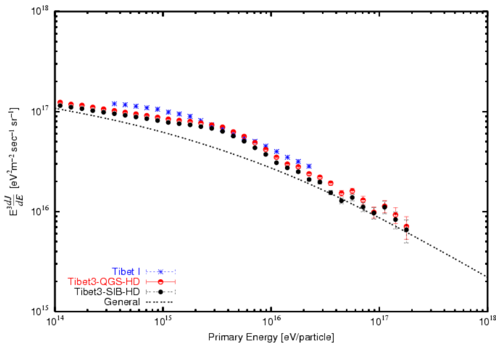
$$\frac{dj}{dE} = j_0 E^{-\gamma} [1 + \frac{E}{\varepsilon_b}]^{-\Delta\gamma}$$

ε_b : break point
$\Delta\gamma$: difference of power index before and after the break point
（ $\Delta\gamma$ ＝0.4±0.1）

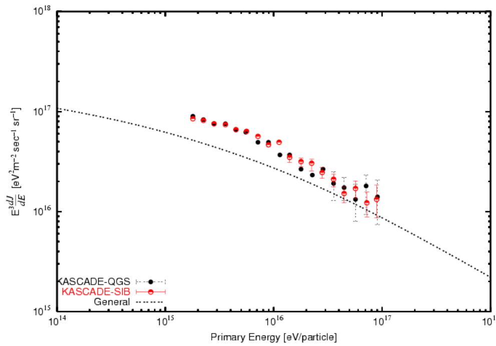
Above formula can be derived assuming multiple sources with various acceleration limit:

$$\Phi_s(E,\varepsilon) = j_0 E^{-\gamma_s} \exp[-\frac{E}{\varepsilon}]$$

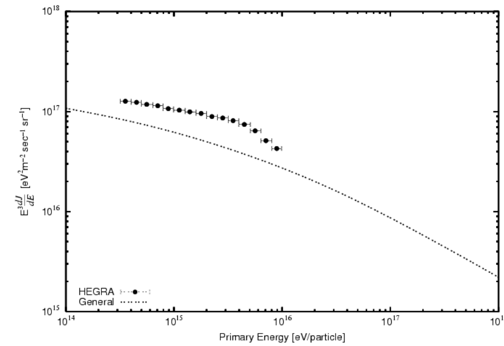
Energy spectrum around the knee measured by many experiments



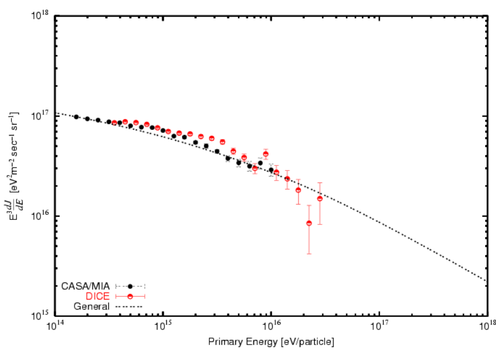
Tibet



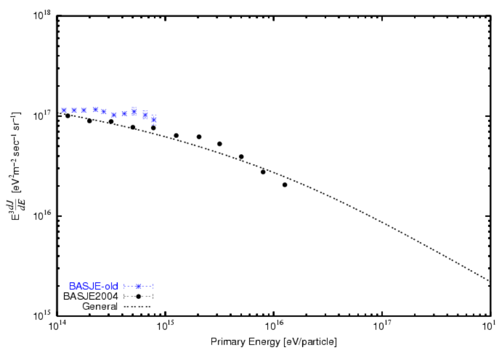
KASCADE



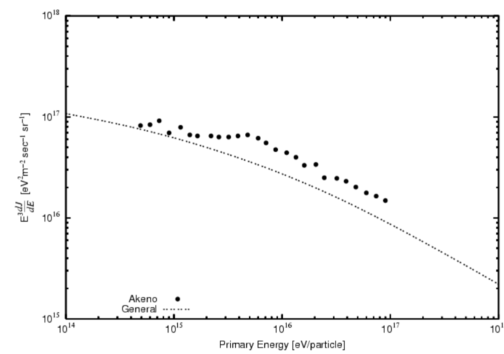
HEGRA



CASA/MIA
DICE

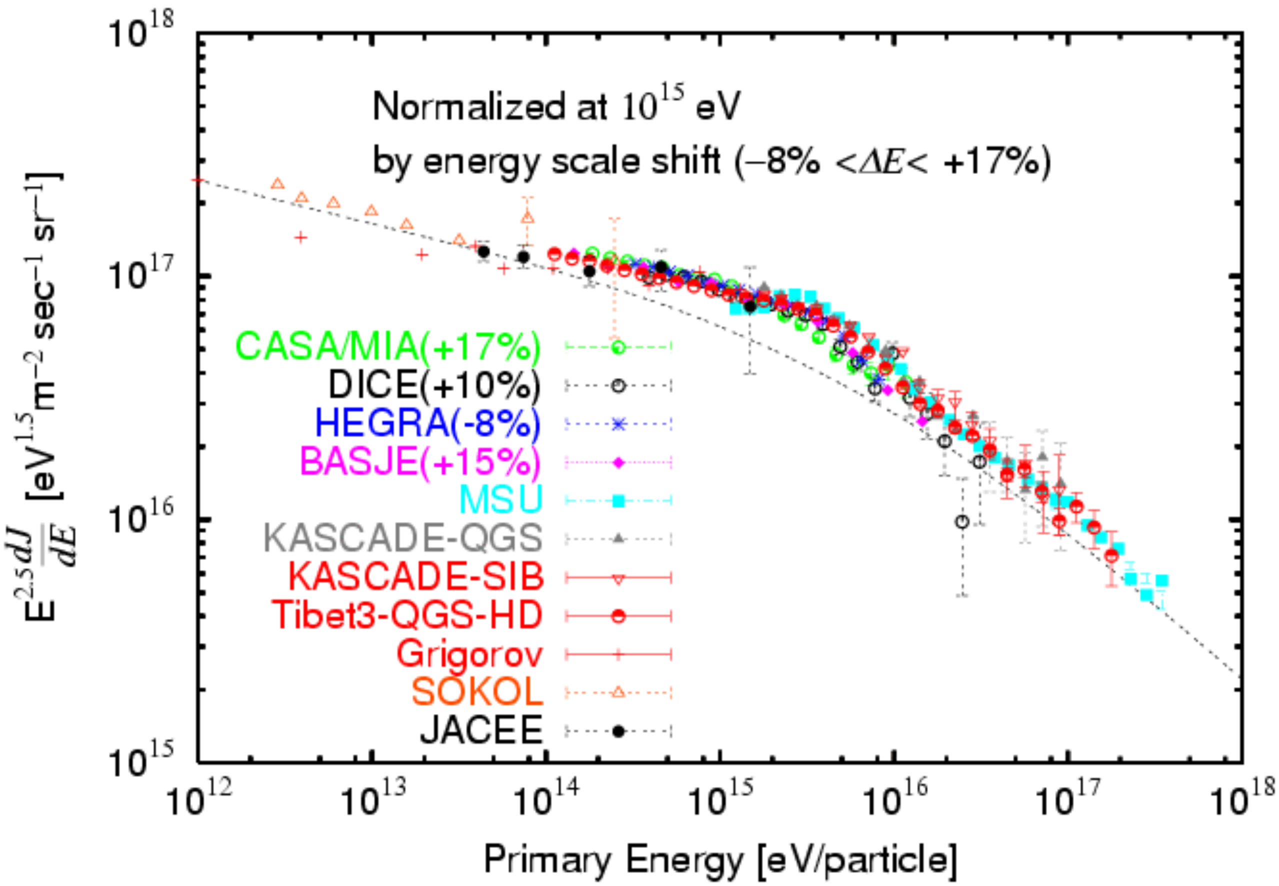


BASJE

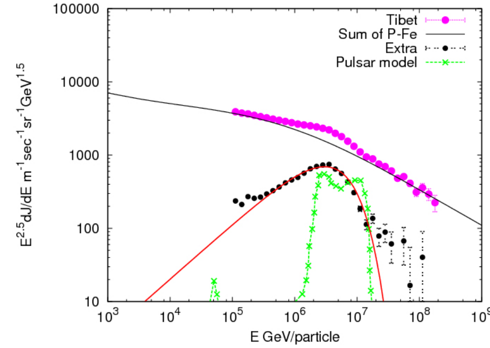


Akeno

Normalized spectrum



What is the origin of the sharp knee?



•Cannot be explained by propagation effect (diffusion during long confinement time in the galaxy)

•Additional component?

Astrophysical scenario : nearby source

Particle physics scenario : beyond STD model

•Acceleration mechanism?

High acceleration efficiency in diffusive shock acceleration (DSA) leads hard source spectrum at the acceleration limit due to nonlinear effect.

Composition measurement

Sensitivities to the primary chemical composition used in AS exp. are:

•Ne-Nμ correlation -- μrich showers are induced by heavy primary (traditional method)
•Detection of high energy core selects AS induced by light elements (P,He) -- Tibet
•Xmax -- fluorescence technique at VHE

Model dependence comes from σ_{inel} and $f(x_F)$.

KASCADE QGSJET01

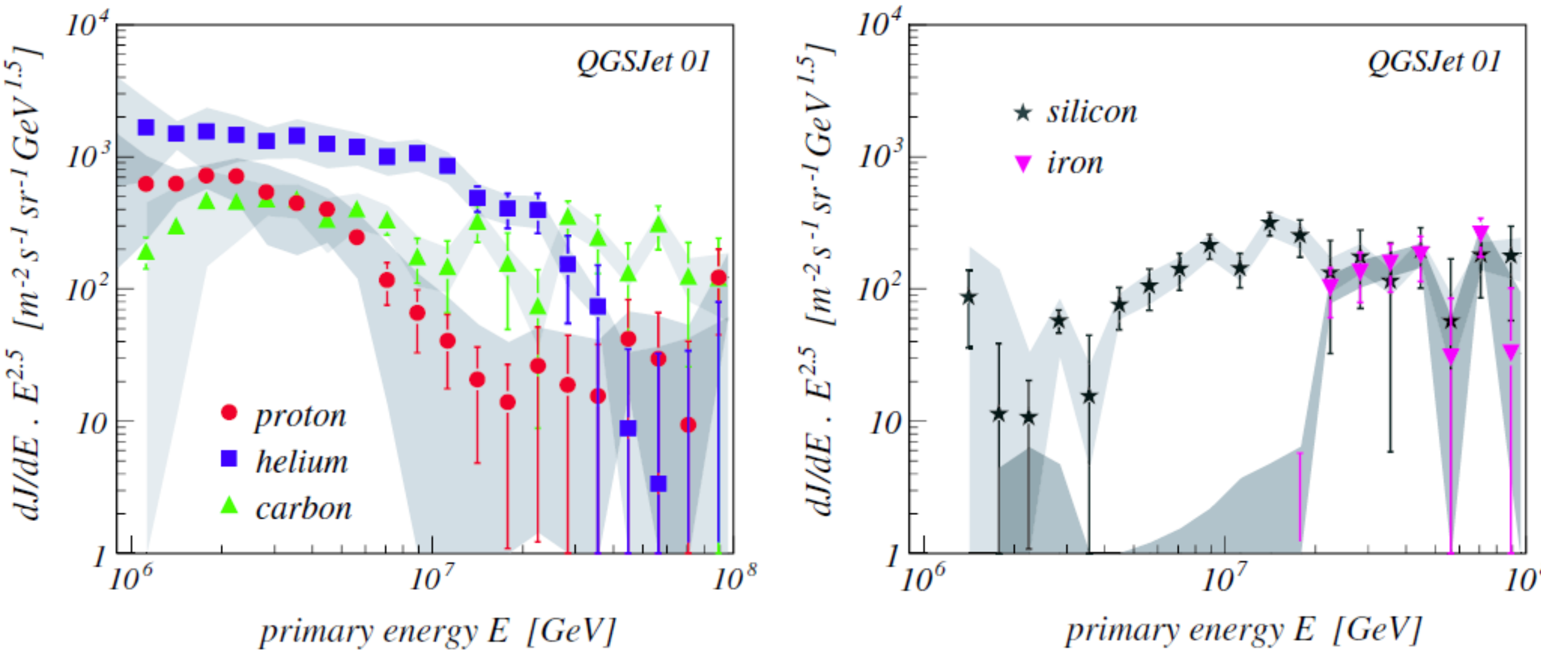


Fig. 14. Unfolded energy spectra for H, He, C (left panel) and Si, Fe (right panel) based on QGSJet simulations. The shaded bands are an estimate of the systematic uncertainties due to the used parameterizations and the applied unfolding method (Gold algorithm).

KASCADE SIBYLL

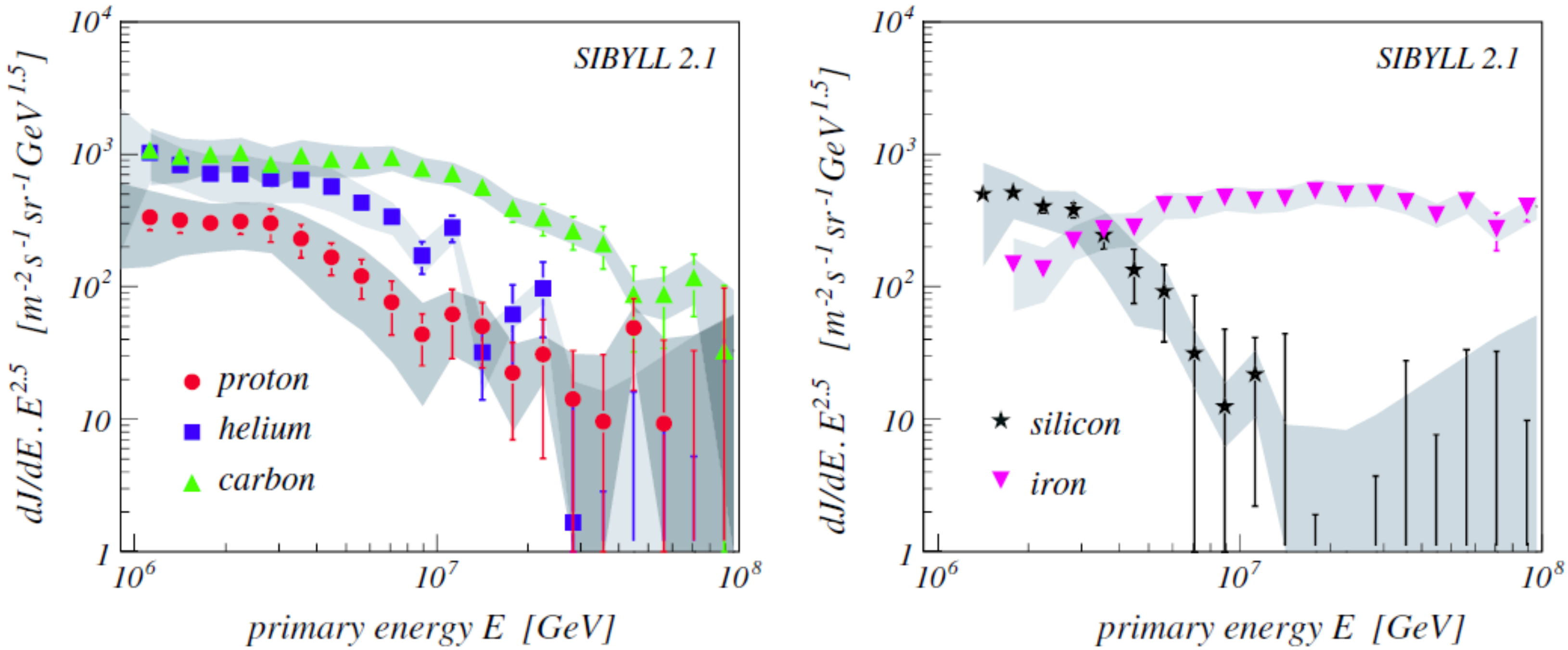
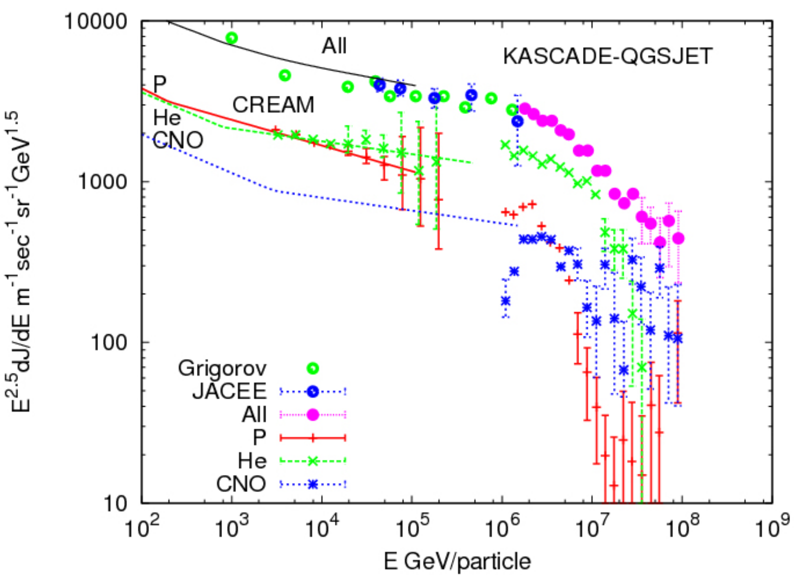
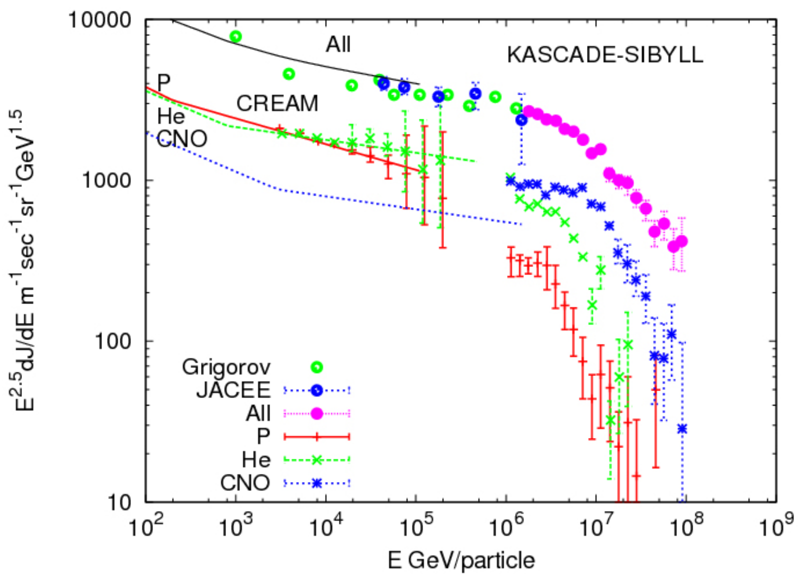


Fig. 15. Unfolded energy spectra for H, He, C (left panel) and Si, Fe (right panel) based on SIBYLL simulations. The shaded bands are estimates of the systematic uncertainties due to the used parameterizations and the applied unfolding method (Gold algorithm).

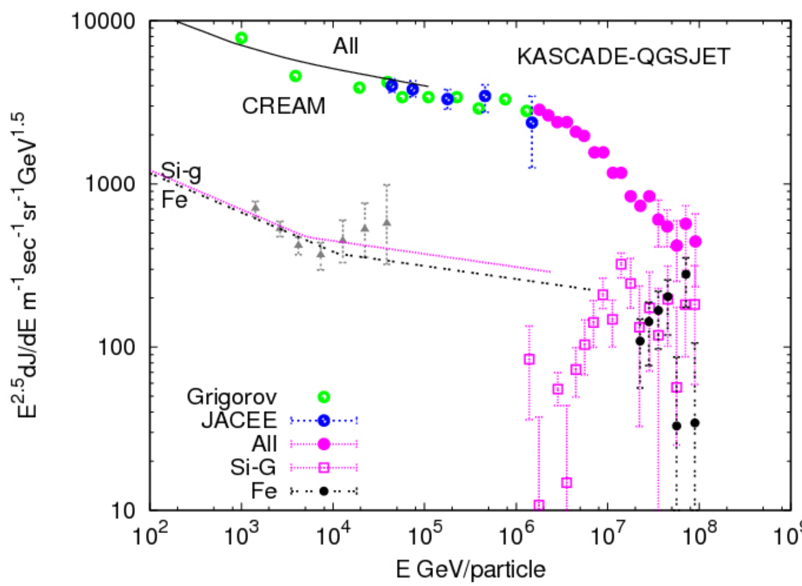
KASCADE P,He,CNO compared with direct observations

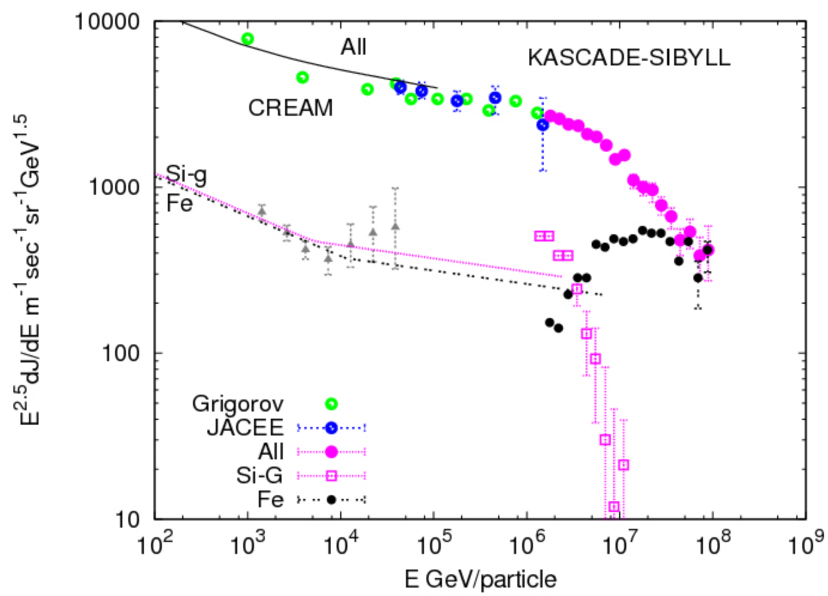




KASCADE Si, Fe

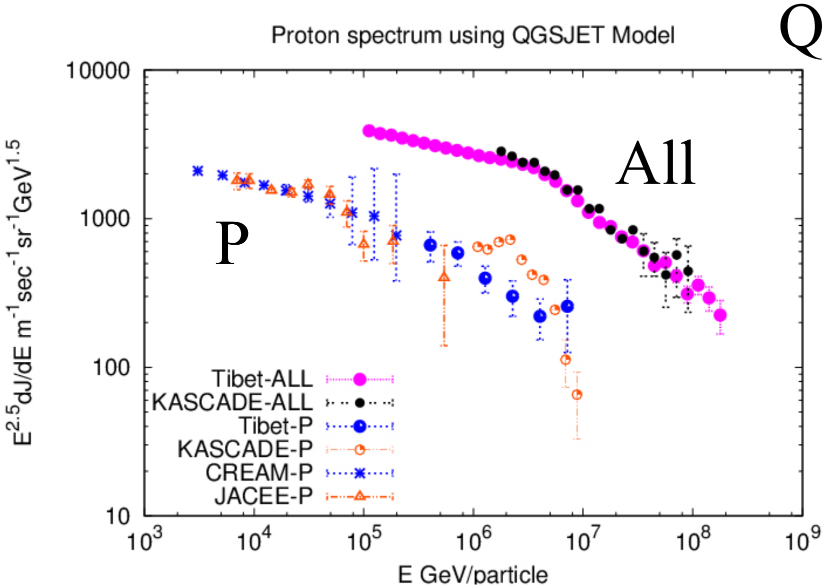
compared with direct observations

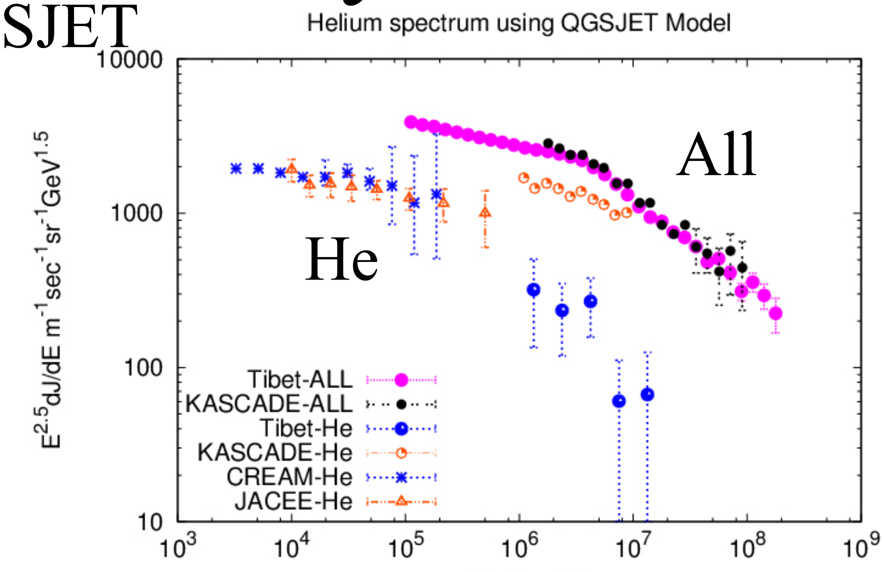




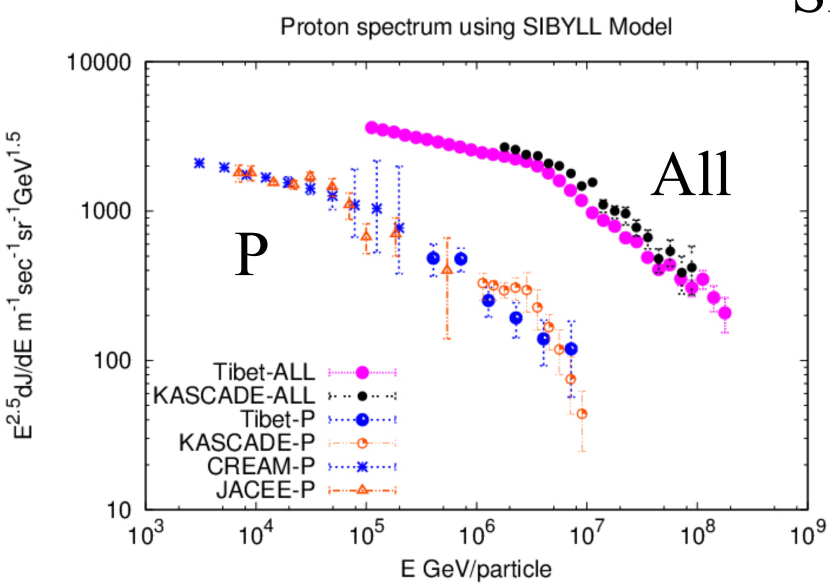
Proton and Helium by Tibet

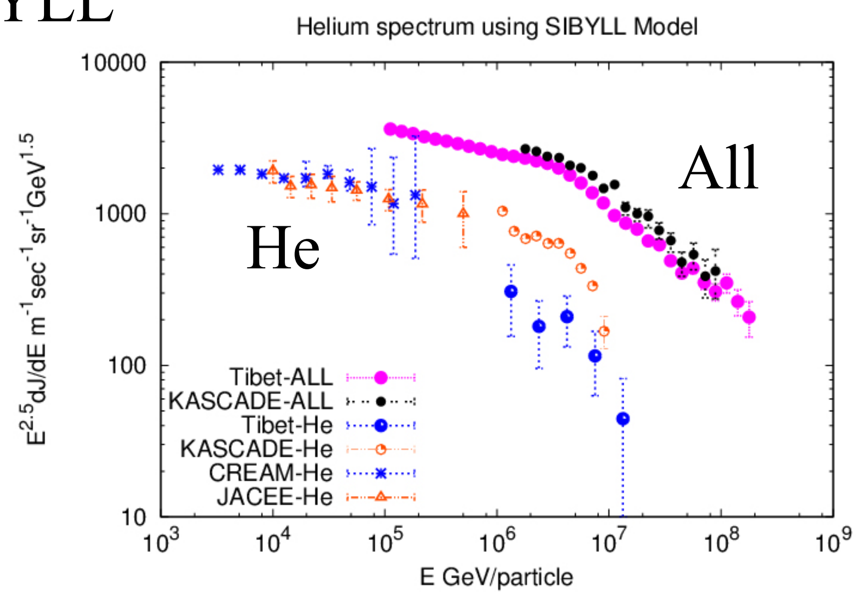
QGSJET



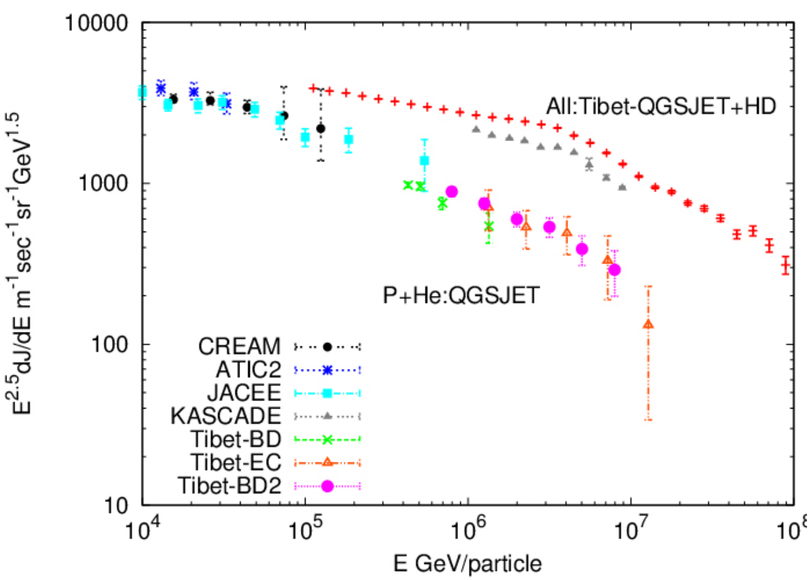


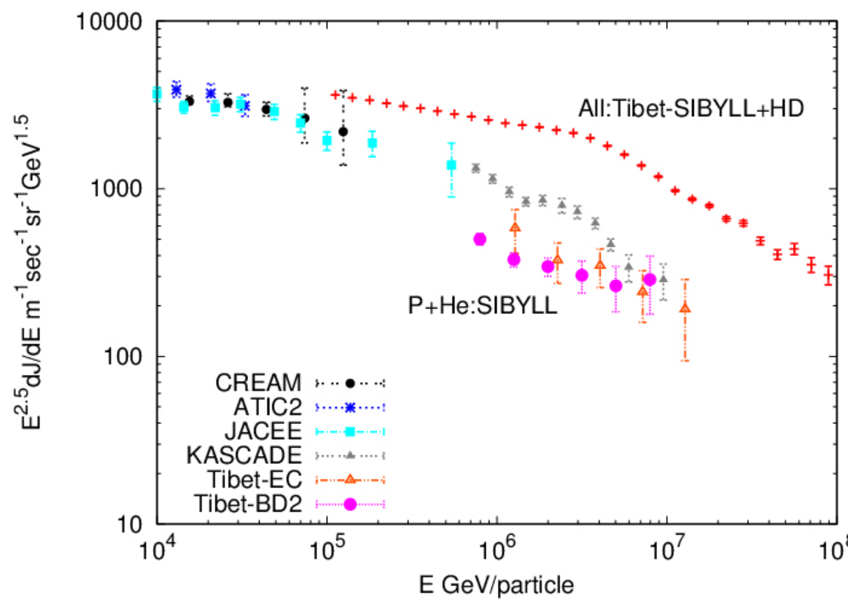
SIBYLL



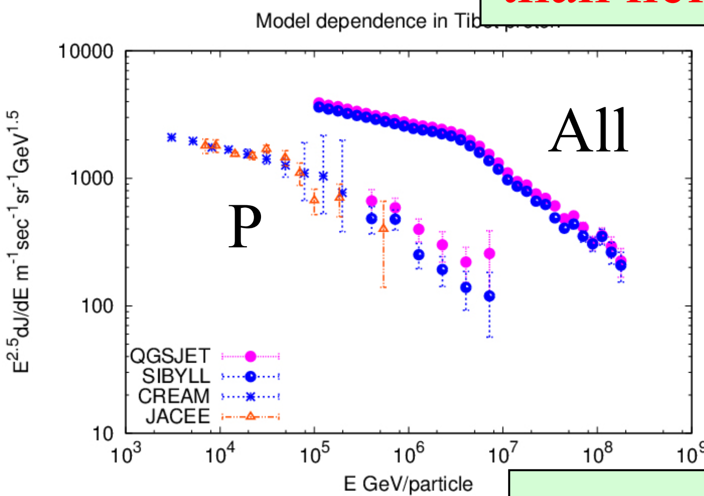


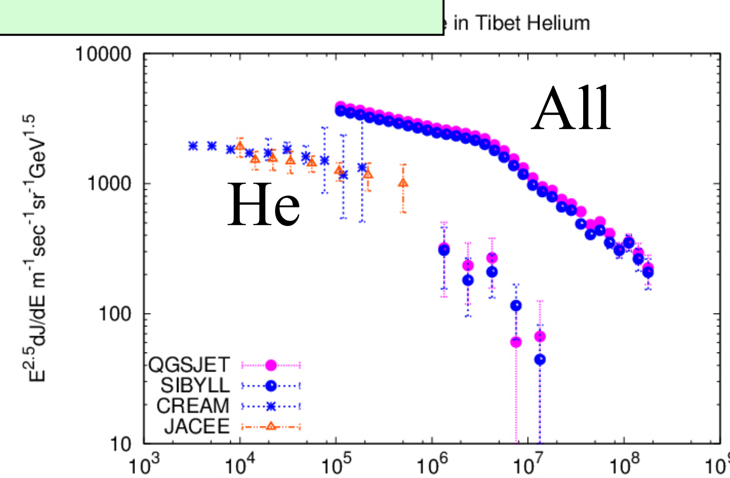
P+He spectrum



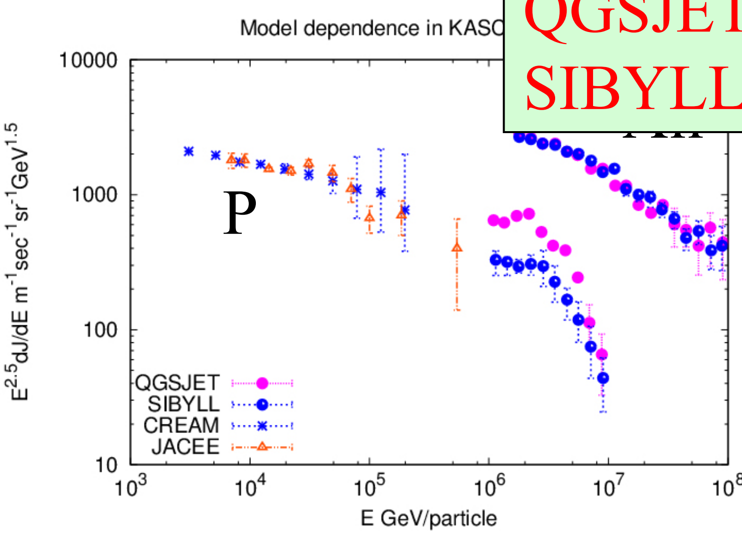


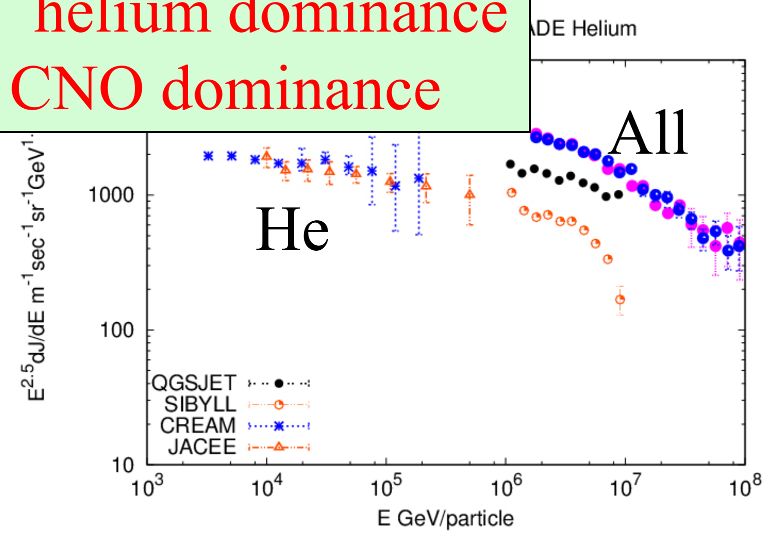
Tibet concludes
"Knee is dominated by nuclei heavier than helium.





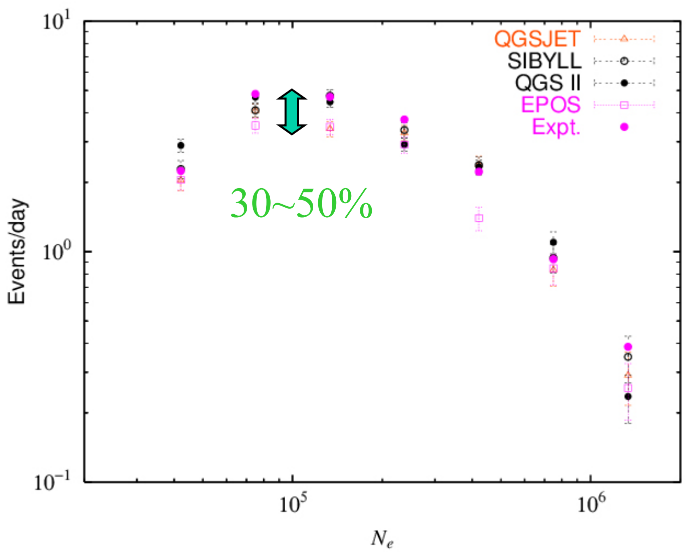
KASCADE
QGSJET analysis : helium dominance
SIBYLL analysis : CNO dominance



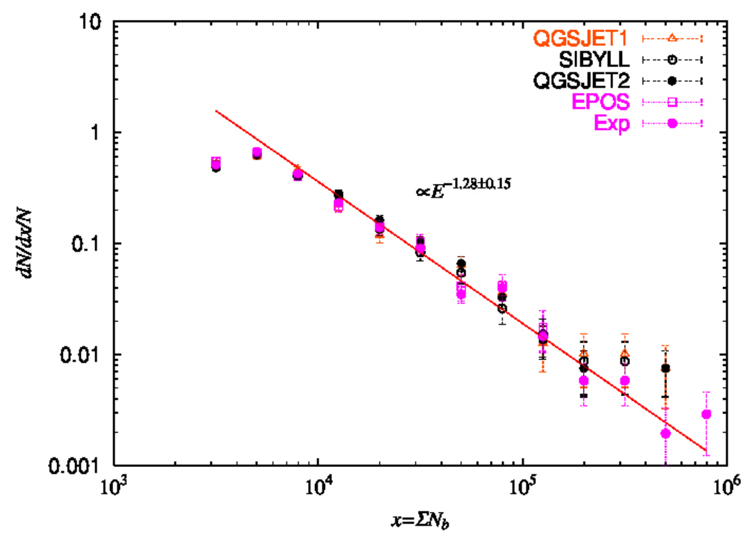


Degree of interaction model dependence in HE core observation by Tibet

Absolute value of AS size distribution measured by AS array



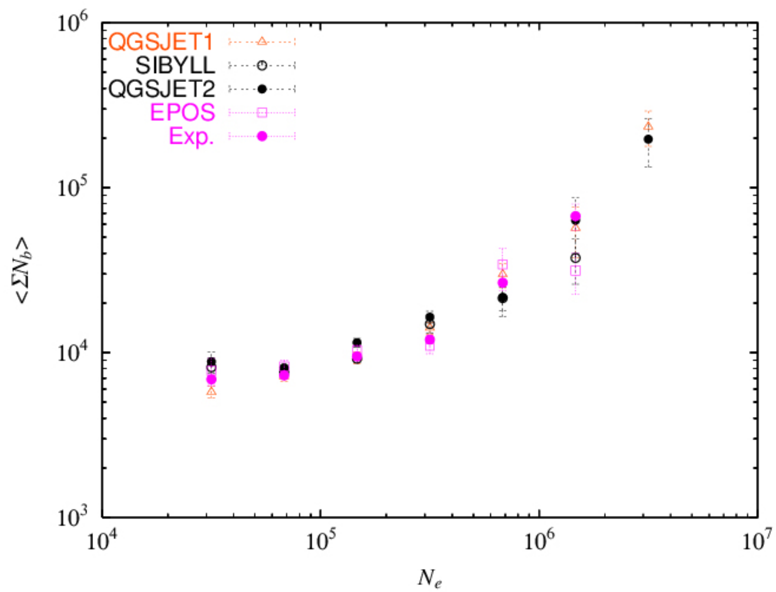
Burst size spectrum (Electron size under lead of 7 r.l. thick in core detector)

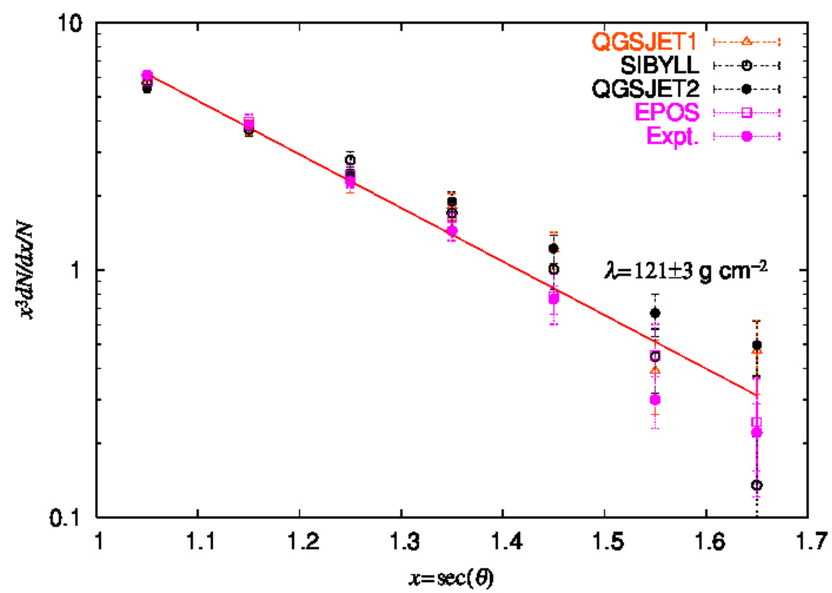


Model dependences in Tibet data

Correlation between AS size and Burst size

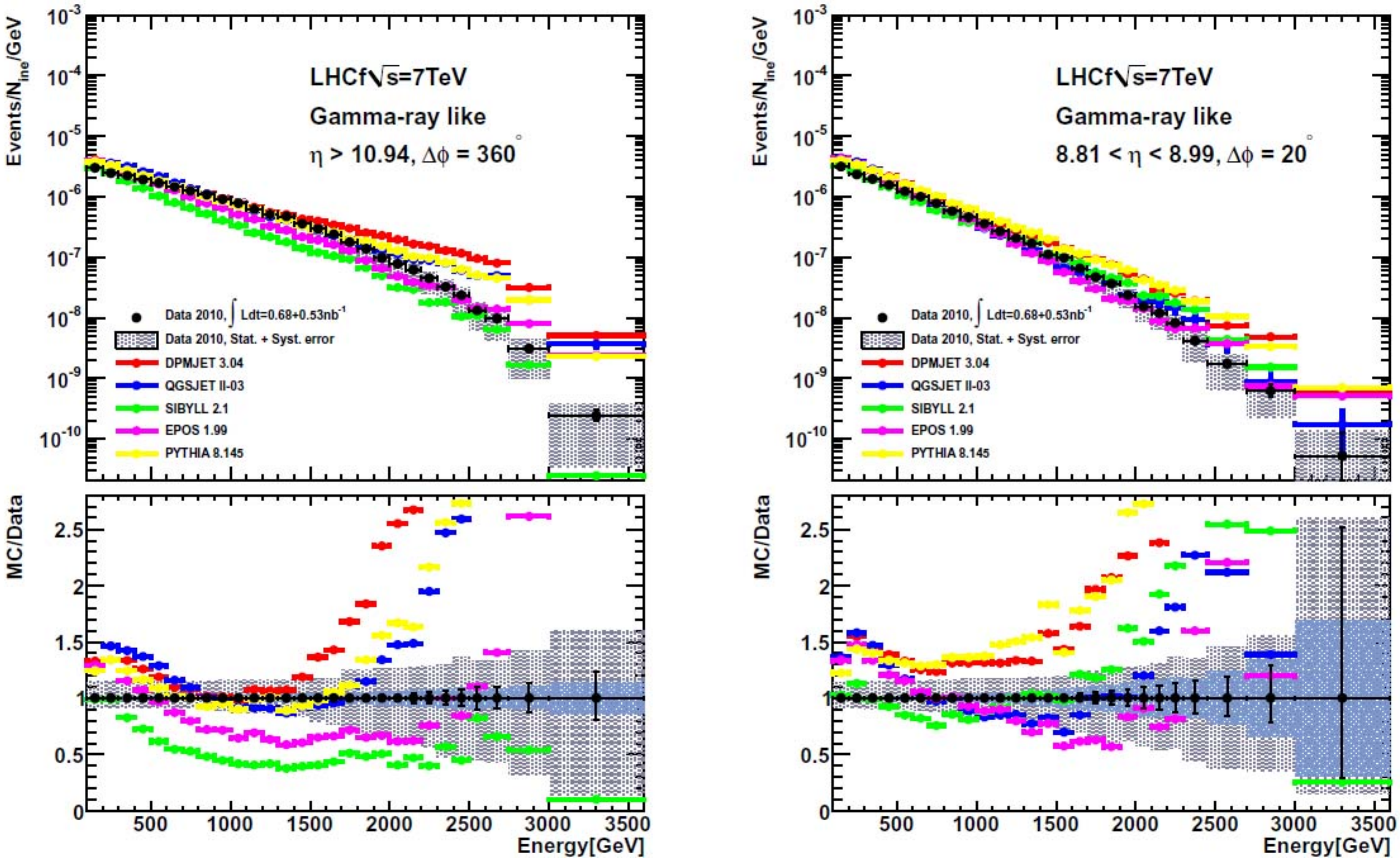
Zenith angle distribution





10 10^2 10^3 10^4 E TeV

LHCf experiment



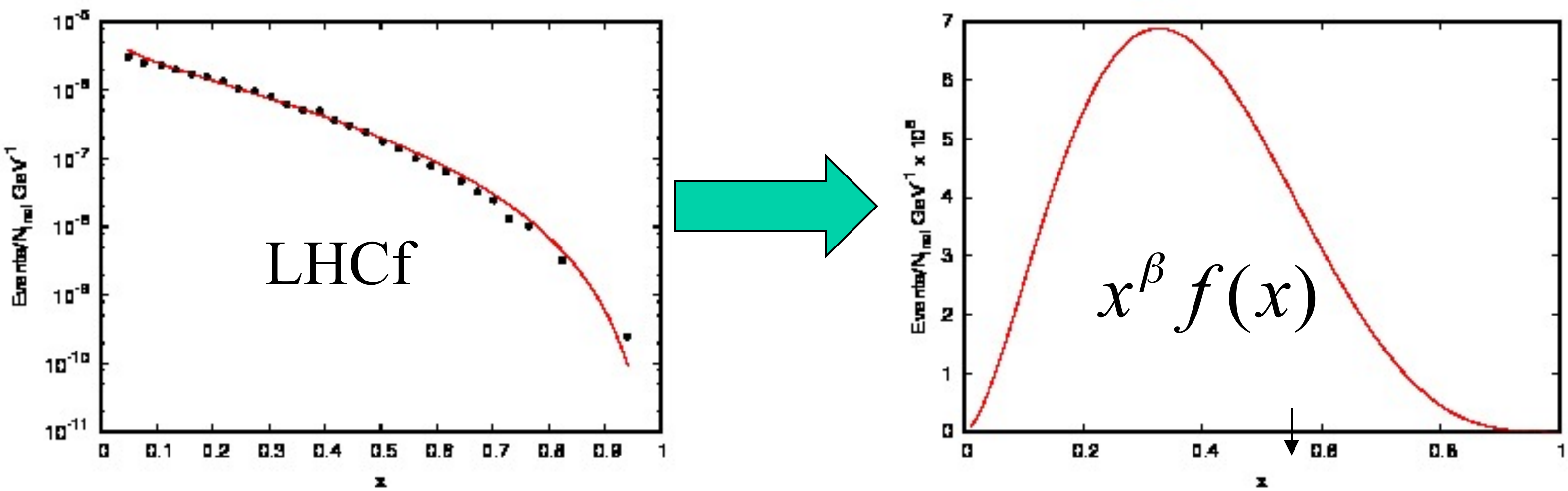
Important range of Feynman x for AS development

Cosmic-ray energy spectrum: $j(E)dE \propto E^{-\beta-1}dE$

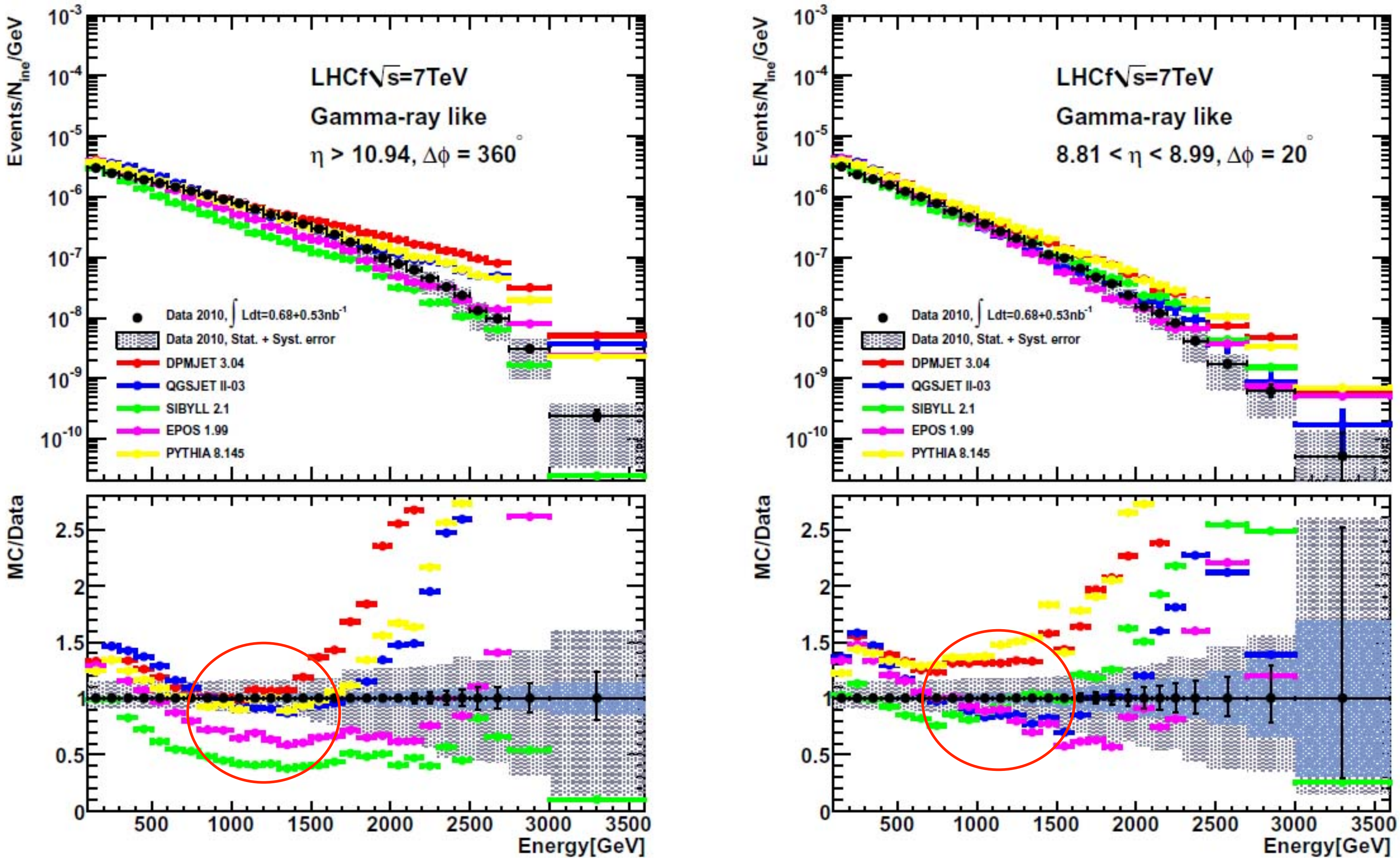
Then, effective value of x to produce secondary particle of given energy is written as

$$x_{eff} = \int x^{\beta+1} f(x)dx \Big/ \int x^{\beta} f(x)dx \qquad (\beta \sim 2)$$

Using LHCf data, $x_{eff} \approx 0.37$



LHCf experiment



Agreement of interaction models with LHCf data around $x \sim 0.4$

in range $\eta > 10.94$

QGSJETII~PYTHIA8.145~DPMJET3.04>EPOS1.99>SIBYLL2.1

-40% -60%

in range $8.81 < \eta < 8.99$

QGSJETII~ SIBYLL2.1 ~ EPOS1.99 > DPMJET3.04>PYTHIA8.145

+30% +50%

LHCf data are limited for single photon events.
Further data for inclusive spectrum and tuning of MC codes are necessary.

Common results between Tibet and KASCADE

- Knee is located at 4 PeV. (γ=2.65→3.1)
- Steep spectrum of protons at the knee (protons are not the majority).
- Fraction of heavy nuclei increases with increasing energy.

Direct observations

Cosmic ray energy spectrum below the knee has been considered to follow simple power law.

Recently, hardening of the spectrum has been reported by ATIC and CREAM @ 200 GeV/n.

ATIC >200 GeV/n
Hardening of the energy spectrum

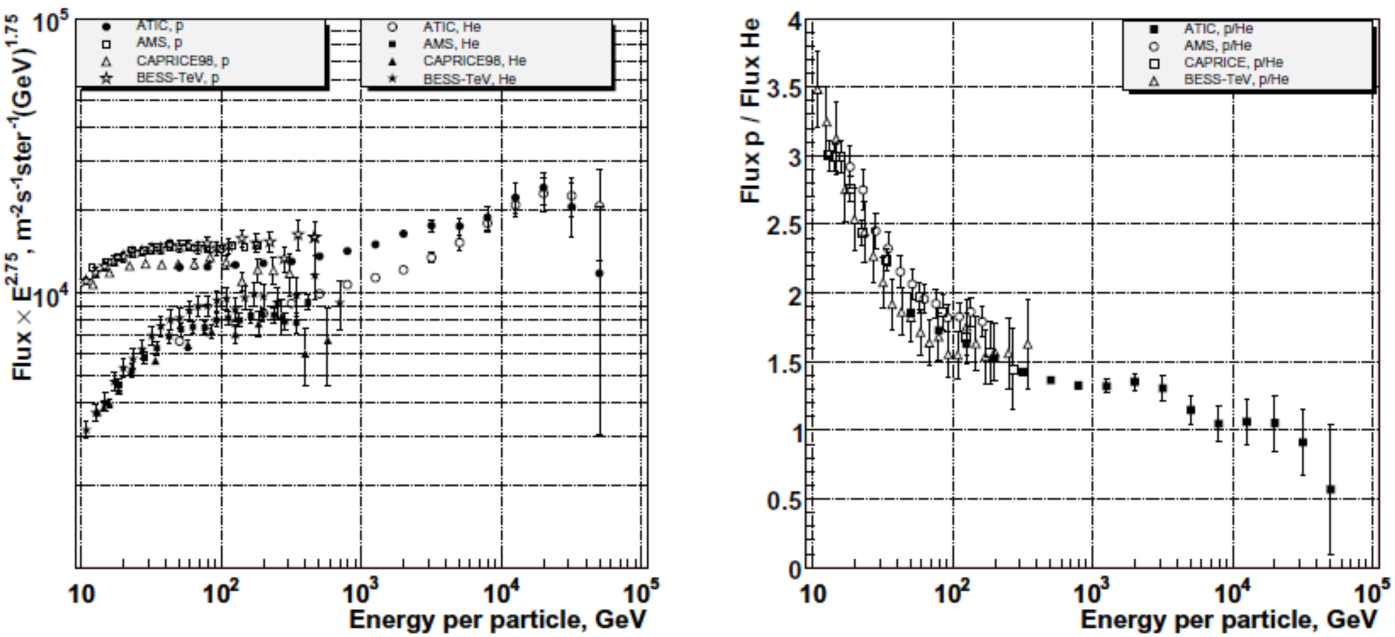
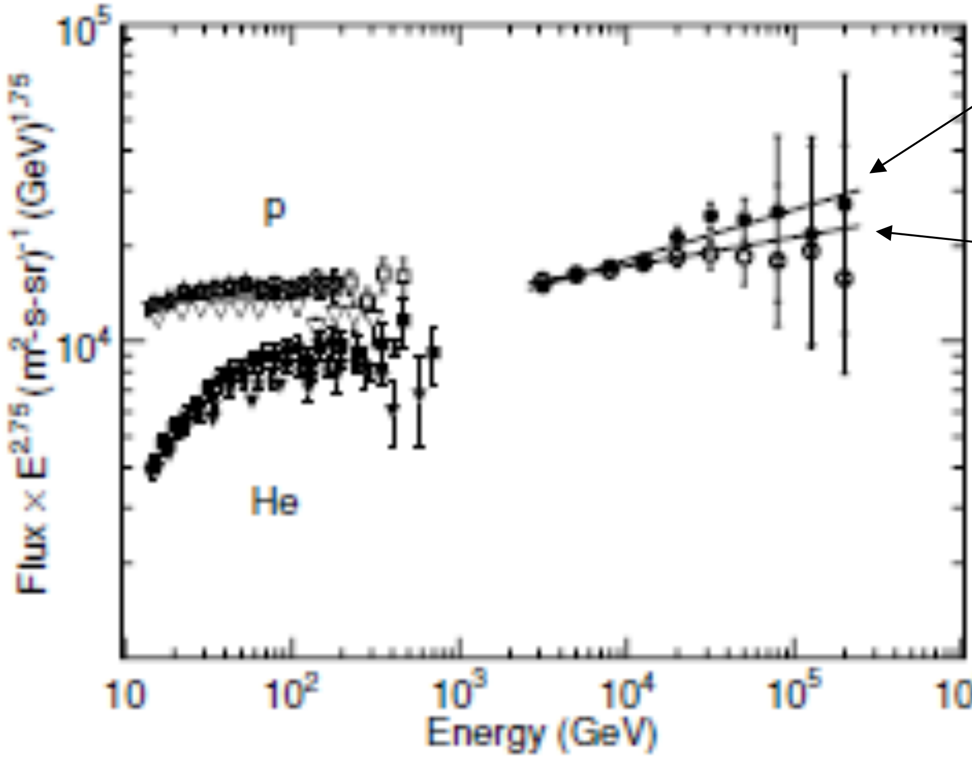


Figure 1: The spectra of protons and helium nuclei (at the left) and the ratio of the pronon flux the helium flux (at the right)

A.D.Panov et al., Arxiv:astro-ph/0612377v1 (2006)

CREAM data



He γ_{He}=2.58±0.02

P γ_p= 2.66 ±0.02

H.S.Ahn et al., ApJ, 714, L93 (2009)

Figure 3. Measured energy spectra of cosmic-ray protons and helium nuclei. The CREAM-I spectra are compared with selected previous measurements (Alcaraz et al. 2000; Haino et al. 2004; Boezio et al. 2003) using open symbols for protons and filled symbols for helium: CREAM (circles), AMS (stars), BESS (squares), CAPRICE (inverted triangles). The error bars represent one standard deviation, which is not visible when smaller than the symbol size. The lines represent power-law fits to the CREAM data.

Heavy dominance toward the Knee

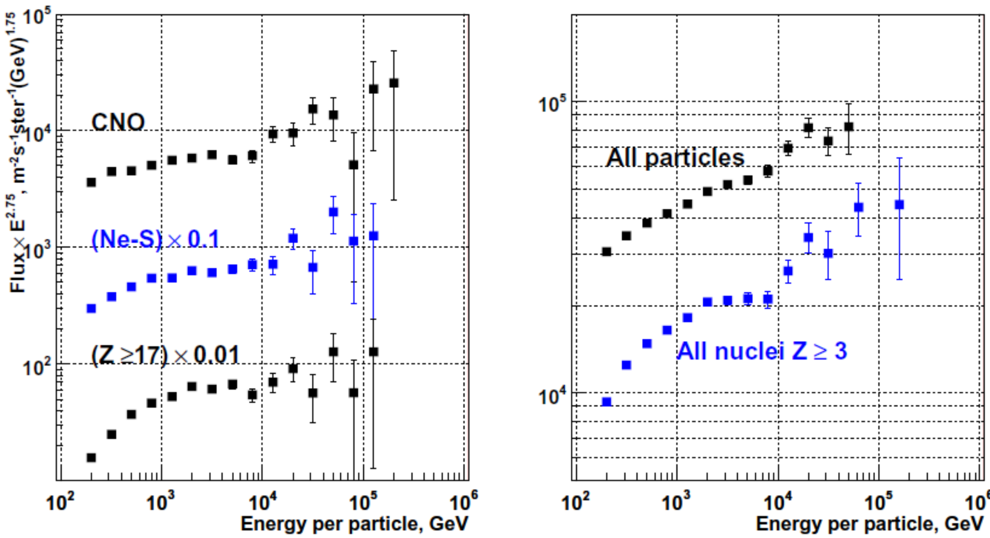
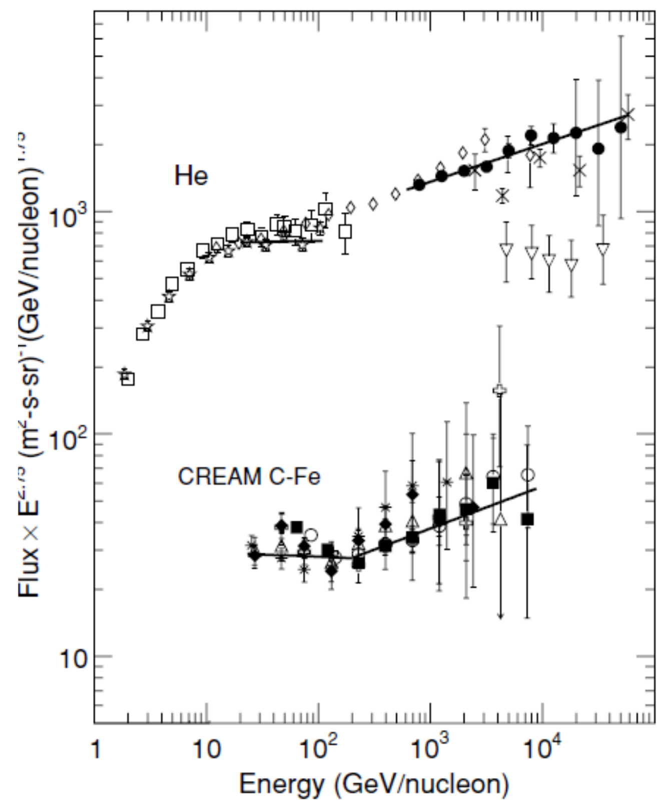


Figure 3: The spectra of different nuclei groups and the spectrum of all particles. The upper threshold in the spectrum of all nuclei $Z \geq 3$ is higher than in the spectrum of all particles because the spectra of protons and helium (see. fig. 1) can be reconstructed by the method of regularization only up to 80 TeV.



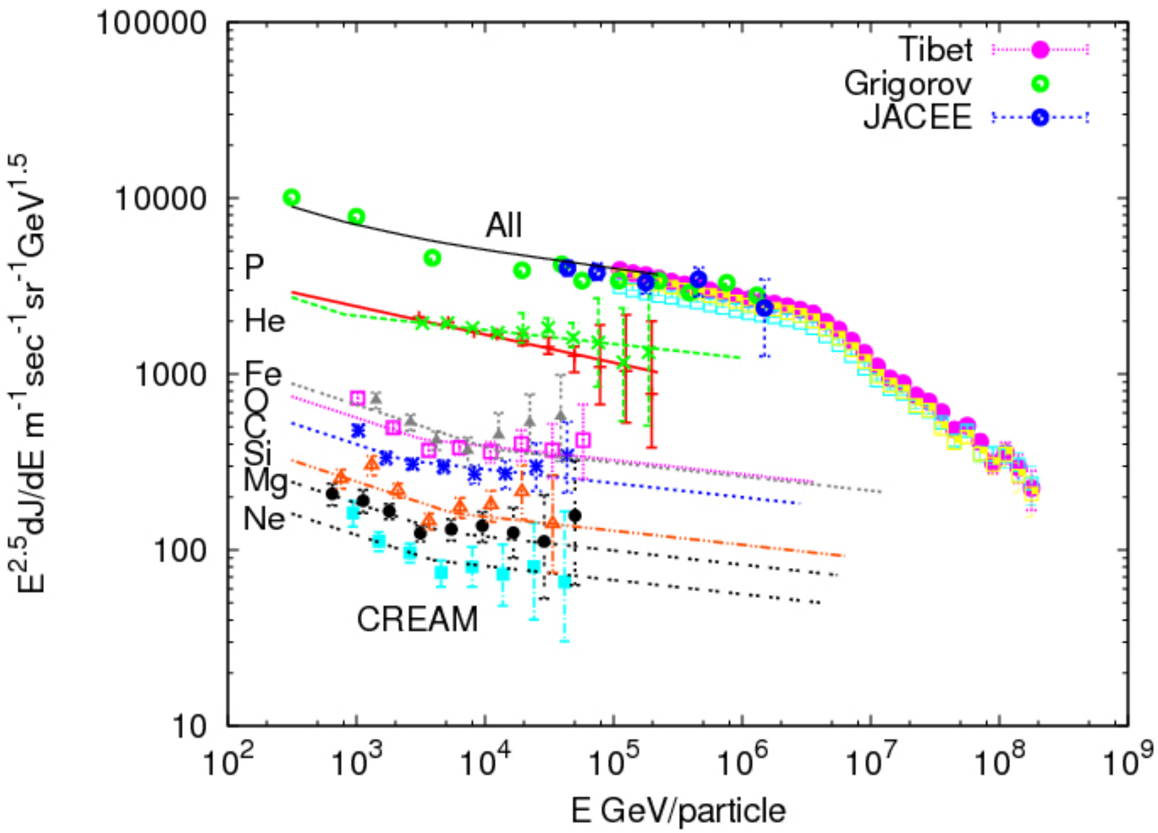
ATIC

CREAM

A.D.Panov et al., Arxiv:astro-ph/0612377v1 (2006)

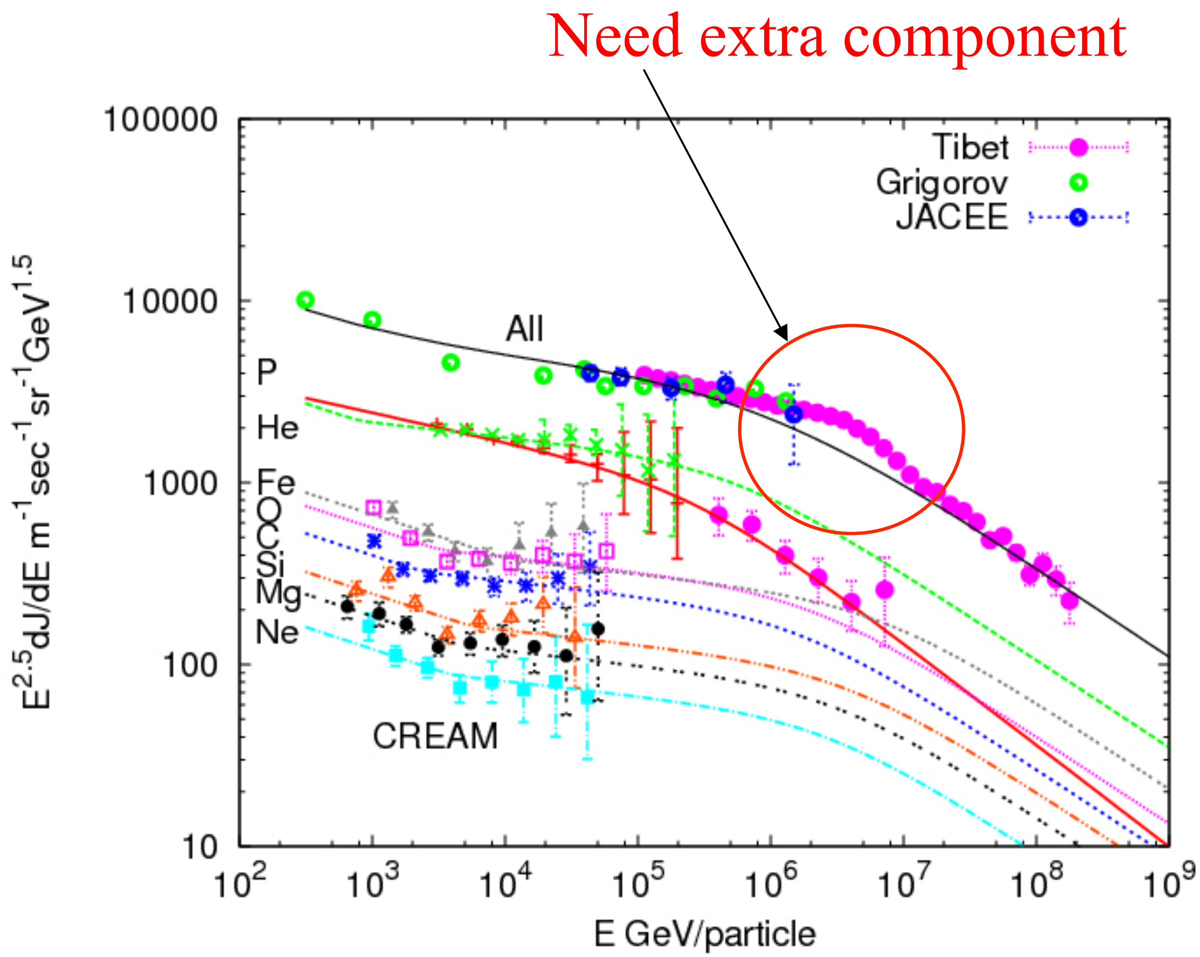
H.S.Ahn et al., ApJ, 714, L93 (2009)

Spectrum of nuclei by CREAM as a function of energy/particle



Simple extrapolation does not work to fit the knee region. Change of power index is required for all elements again.

Extrapolation of CREAM data using broken power law cannot fit to the sharp knee



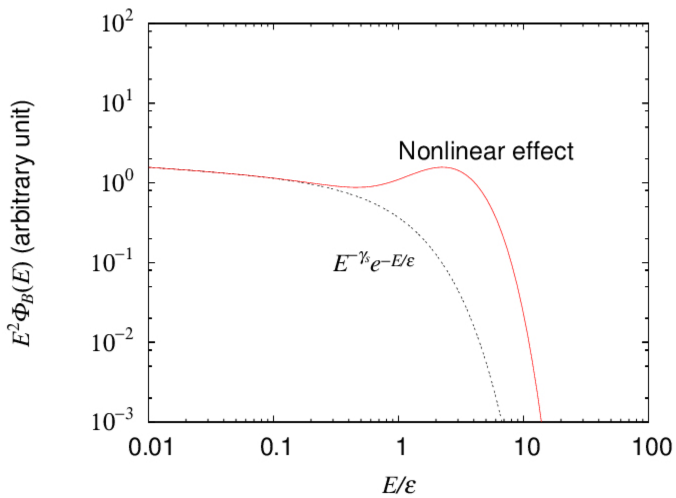
Assumptions:
$E_b(p)$=300 TeV,
Rigidity dependence of break point for nuclei,
$E_b(Z)$=Zx300 TeV
$\Delta\gamma$=0.4

Nonlinear effect in DSA process

Malkov, E. & Drury, L.O.C. 2001, Rep. Prog. Phys. 64, 429
Ptuskin, V.S., & Zirakashvili, V.N., 2006, Adv. Space Res., 37, 1898

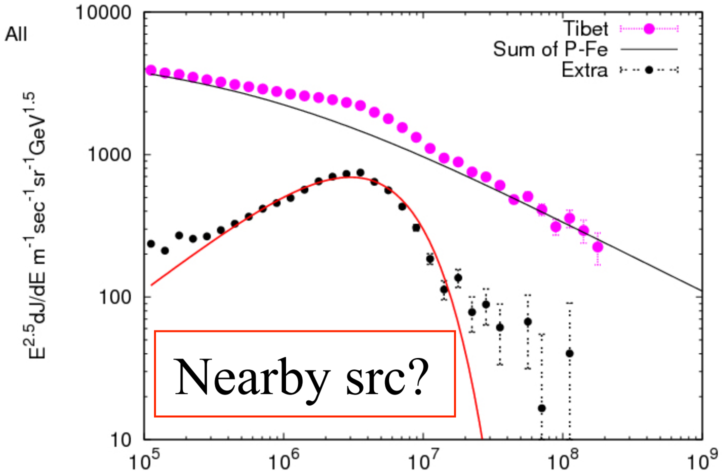
Assume source spectrum as

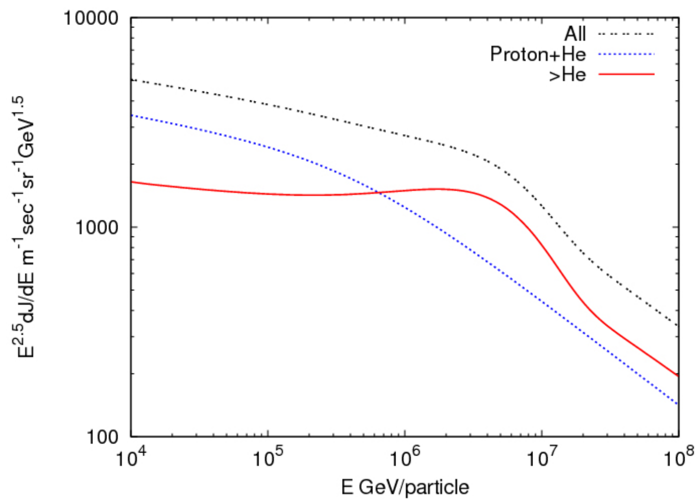
$$\Phi_s(E,\varepsilon) = j_0 E^{-\gamma_s}[1+\alpha(\frac{E}{\varepsilon})^{\beta}]\exp[-\frac{E}{\varepsilon}]$$



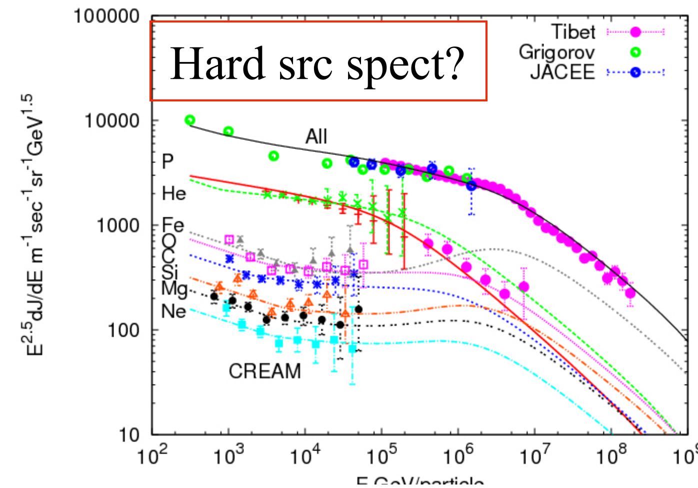
Shibata, M et al. ApJ,716,1076–1083 (2010)

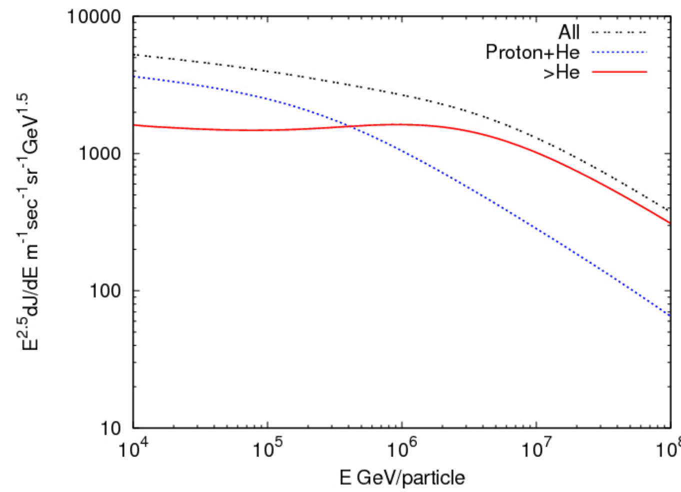
Scenario A





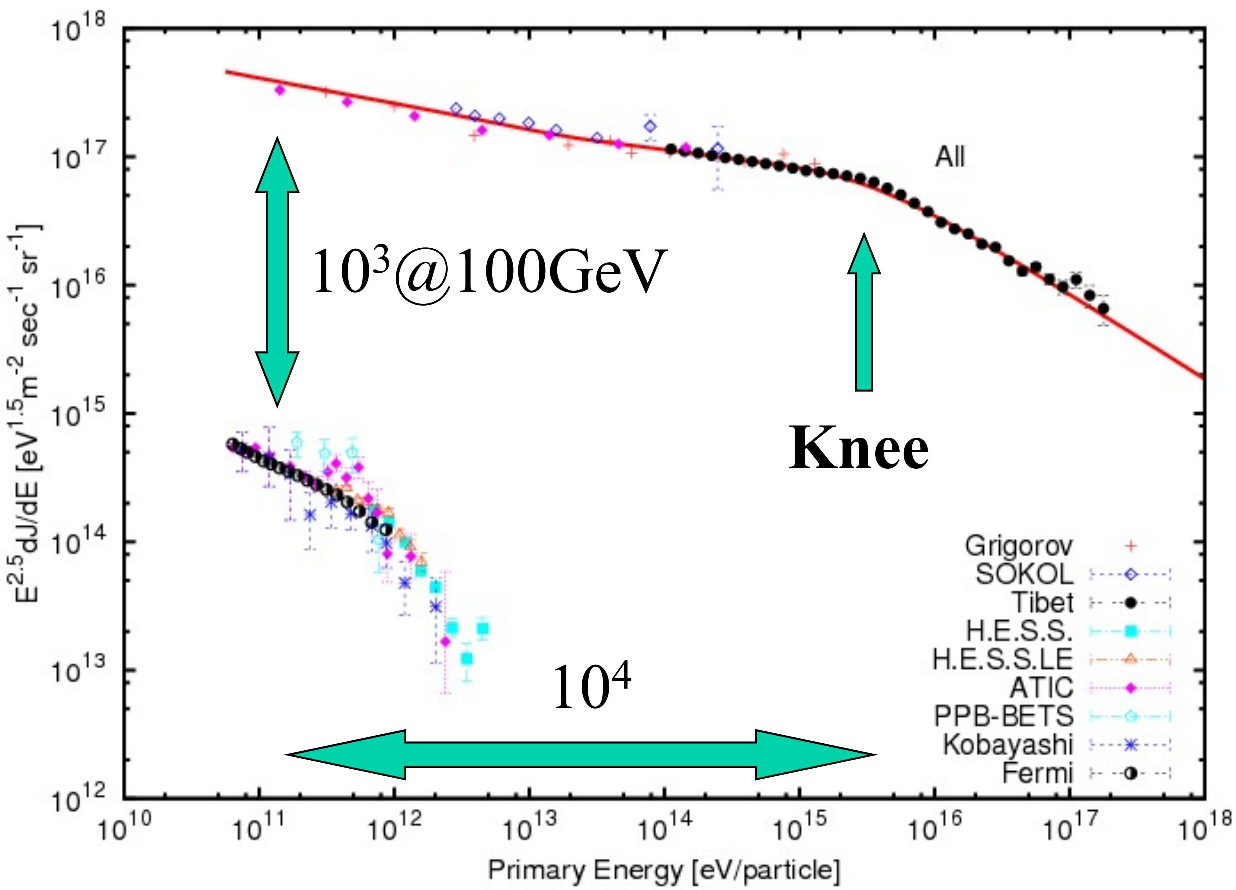
Scenario B





Possible knee scenario

Flux of nuclei and electrons



Primary electrons

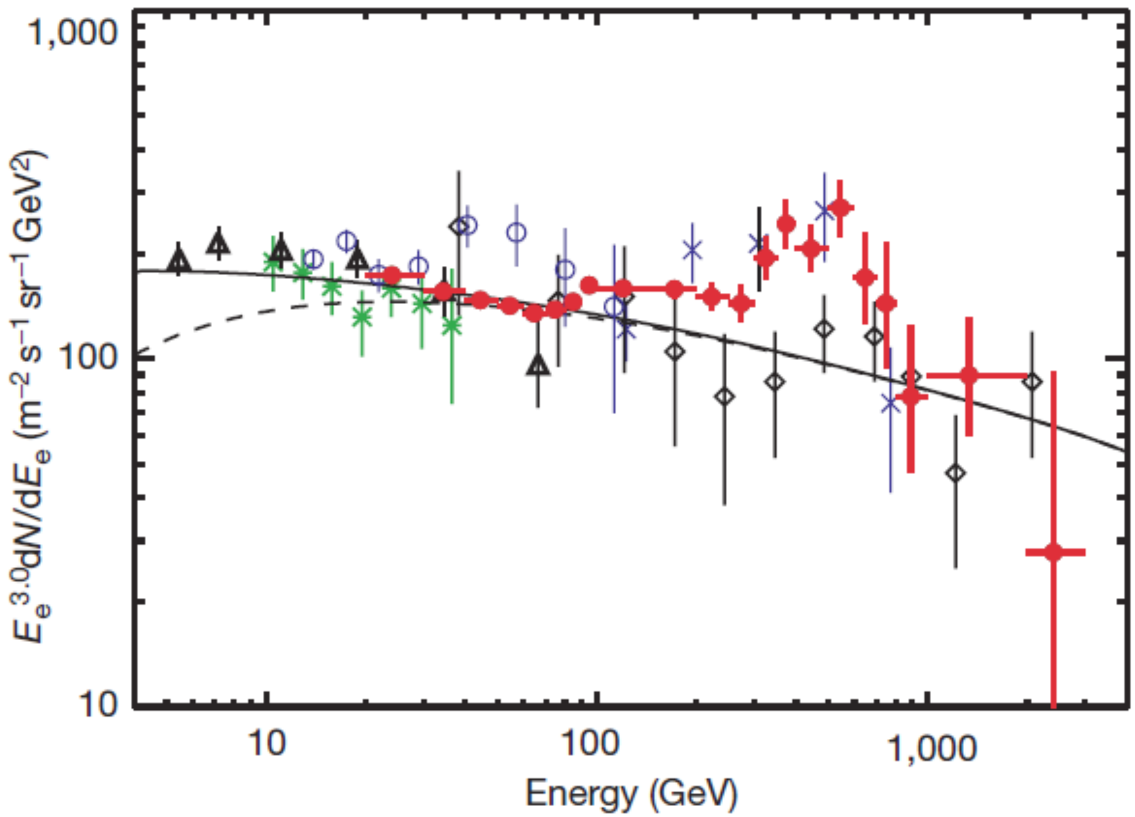
High energy electrons cannot travel long distance due to their energy loss proportional to E^2.

The energy spectrum can show the contribution of nearby sources (say ~1kpc)

or new physics such as dark matter decay or beyond STD model.

ATIC, Pamela, Fermi-LAT, H.E.S.S.

ATIC electron spectrum



J.Chang et al, Nature, 456,362,(2008)

Anomalous positron abundance

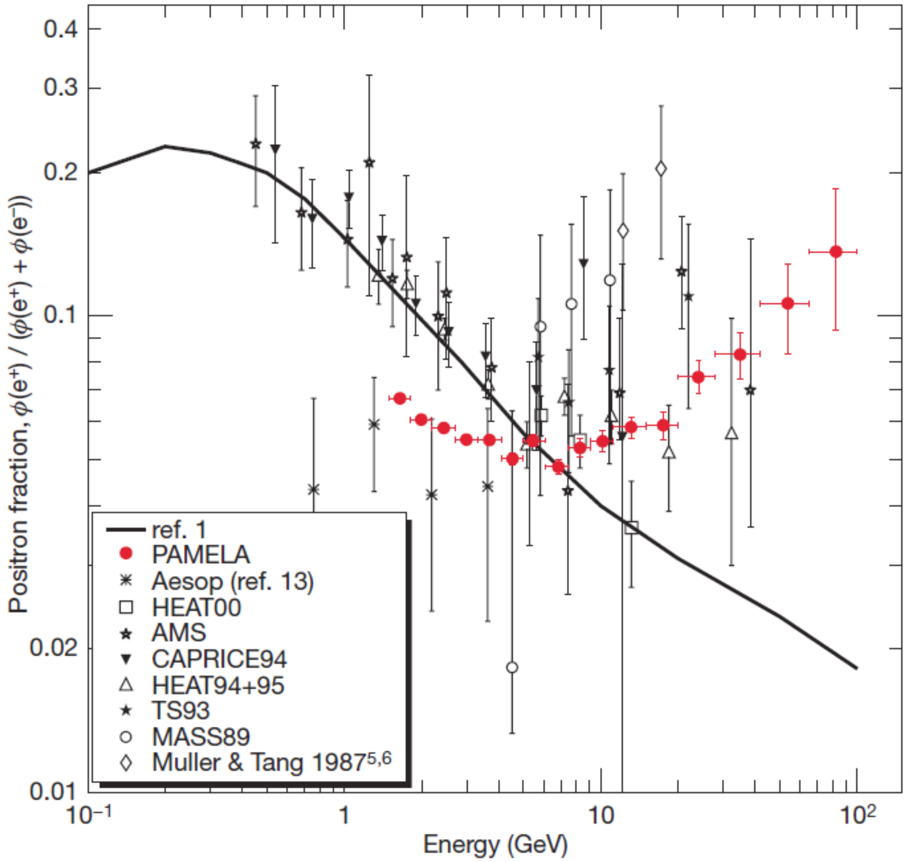
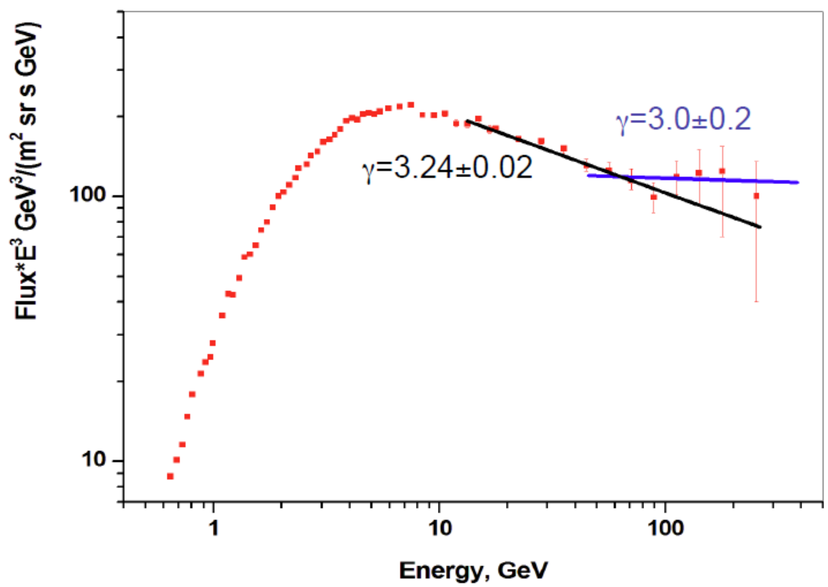


Figure 2 | PAMELA positron fraction with other experimental data and with secondary production model. The positron fraction measured by the PAMELA experiment compared with other recent experimental data (see refs 5–7, 11–13, 30, and references within). The solid line shows a calculation[1] for pure secondary production of positrons during the propagation of cosmic rays in the Galaxy without reacceleration processes. Error bars show 1 s.d.; if not visible, they lie inside the data points.

O.Adriani et al., Nature, 458,607(2009)

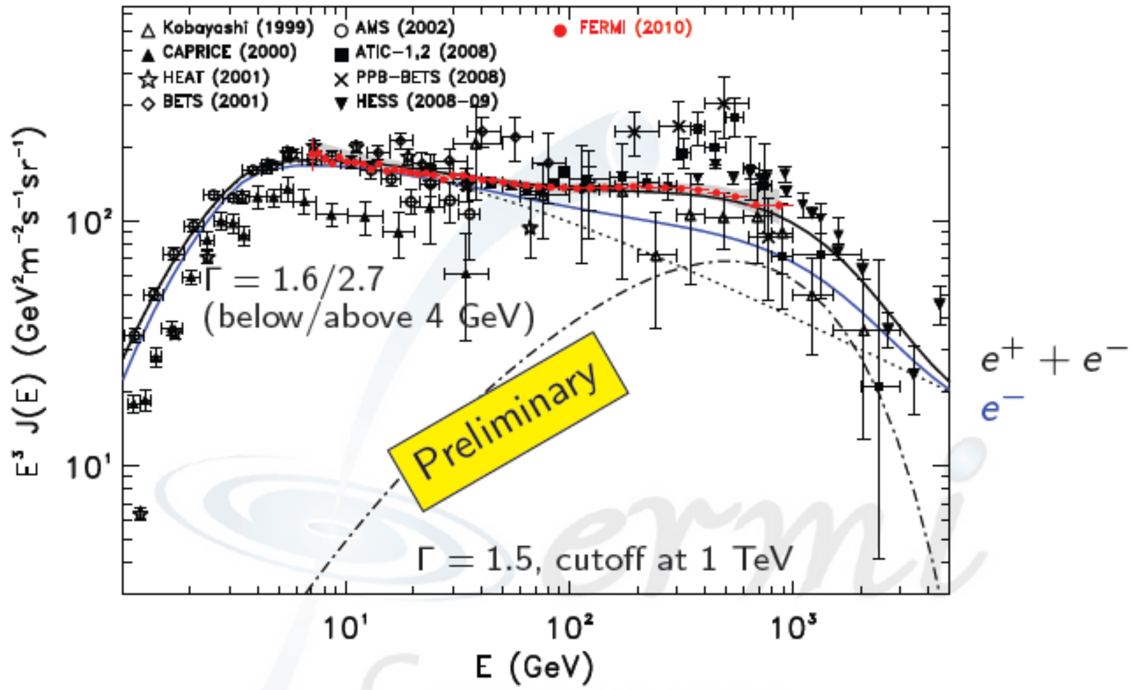
Electron spectrum



V.Mikhailov et al.ESCR 2010, Turku, 3 August

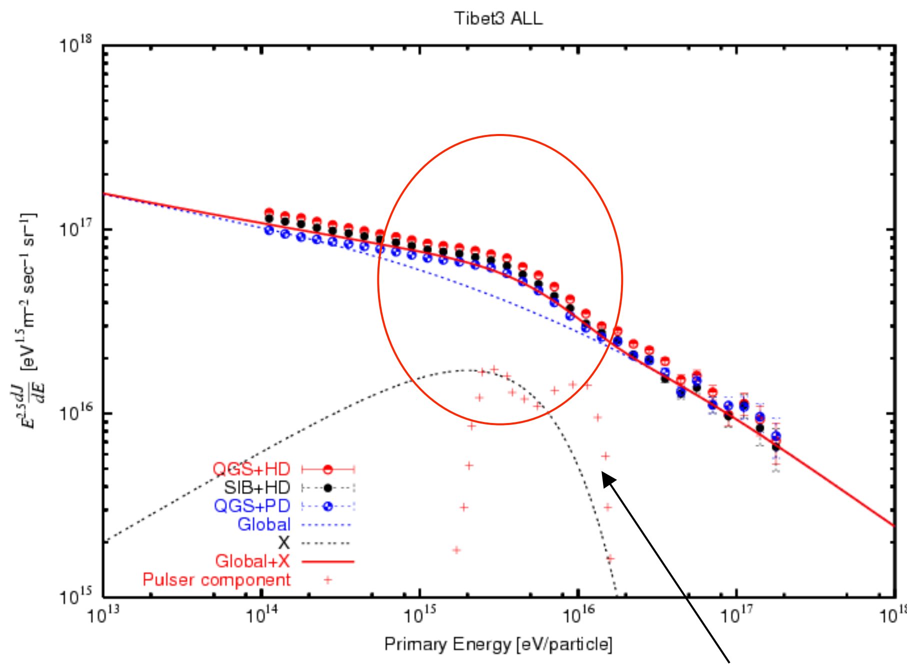
Fermi-LAT

SPECTRUM INTERPRETATION



- Hard to get a good fit with a single-component diffusive model
- Good fit possible with an additional high-energy component
  - If it's an e^+/e^- (e. g. nearby pulsars or dark matter), the Fermi spectrum and Pamela positron fraction can be simultaneously fitted

Relation between Fermi $e^{\pm}$ and extra component at the knee?



(W.Bednarek and R.J.Protheroe ,2002,APh)

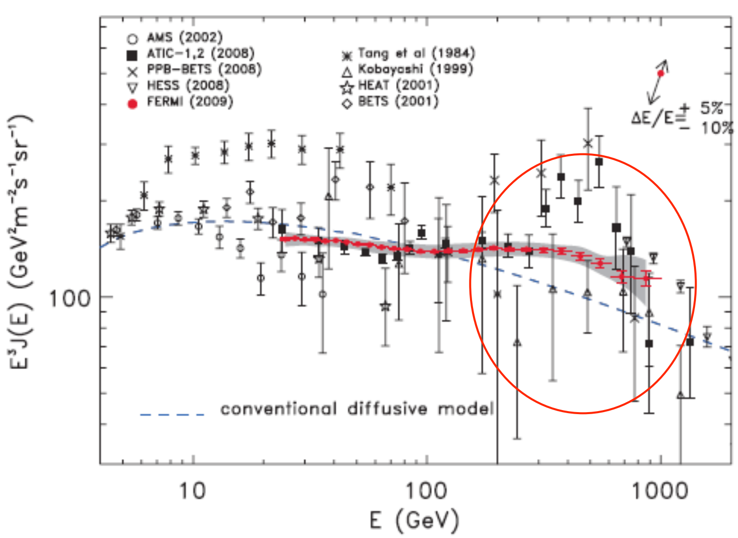


FIG. 3 (color). The Fermi LAT CR electron spectrum (red filled circles). Systematic errors are shown by the gray band. The two-headed arrow in the top-right corner of the figure gives size and direction of the rigid shift of the spectrum implied by a shift of $^{+5\%}_{-10\%}$ of the absolute energy, corresponding to the present estimate of the uncertainty of the LAT energy scale. Other high-energy measurements and a conventional diffusive model [1] are shown.

PeV nuclei + target
(∗ 10TeV/n)

? → π^0 → γ
→ ∗ 100GeV $e^{\pm}$

This may be quite possible scenario.

Summary

- Knee is located at 4 PeV exhibiting sharp structure with $\Delta\gamma=0.4\pm0.1$
- Disagreement of chemical composition between KASCADE and Tibet is due to interaction model dependence of Air Shower MC which is larger in Ne−Nμ correlation used by KASCADE.

  Comparison of 4 models with Tibet data is within 50% deviation in absolute intensity. Other features of AS are reproduced with less deviation.
- Extrapolation of CREAM data using broken power law formula cannot fit to the AS data at the knee.

- Tibet data and ATIC/CREAM spectra of nuclei suggests knee is dominated by heavy nuclei, which can be attributed to nearby source dominated by heavy element (Pulsar?) or hard cosmic-ray source spectrum.
- Enhancement of electron spectrum at hundreds GeV range might be correlated with the structure of cosmic-ray spectrum. --- possible contribution of nearby sources?
- Further study of the chemical composition up to the knee and beyond is necessary to resolve the questions. → CALET@ISS and indirect observations (Tibet, KASCADE-G, BASJE, Grapes, TA-TAIL).

Thank you

CR source distribution

Let *S(ε)* be the probability of cosmic-ray accelerators with the acceleration limit energy in *dε* at *ε*. Then, the observed cosmic-ray energy spectrum is a superposition of the spectra after the propagation ($\gamma=\gamma_s+\delta$, $\delta\sim0.6$) from sources with weight *S(ε)*.

$$\int_0^\infty \Phi(E,\varepsilon) S\left(\frac{\varepsilon}{\varepsilon_b}\right)\frac{d\varepsilon}{\varepsilon_b} = j_0 E^{-\gamma}\left[1+\frac{E}{\varepsilon_b}\right]^{-\Delta\gamma}$$

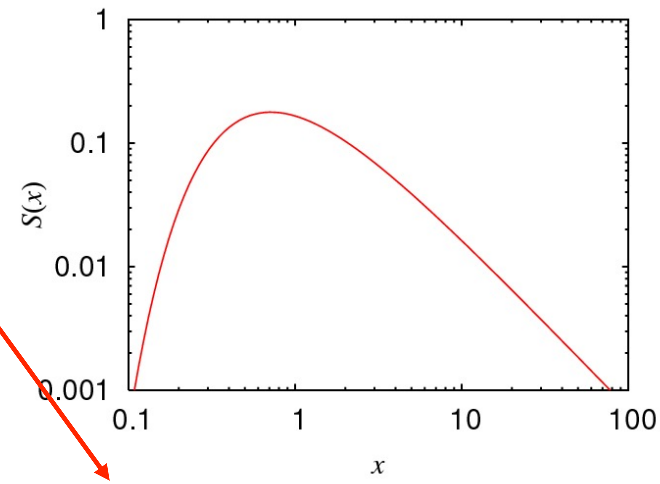
The solution is found as

$$S(x)=\frac{1}{\Gamma(\Delta\gamma)}\frac{1}{x^{1+\Delta\gamma}}\exp\left[-\frac{1}{x}\right],$$

$$x=\frac{\varepsilon}{\varepsilon_b}$$

Green's function of diffusion eq. if
x ←**t** and $\Delta\gamma=1/2$

Distribution of acceleration power of cosmic rays



Threshold effect

TRACER

M.Ave et al., ApJ, 678, 262 (2008)

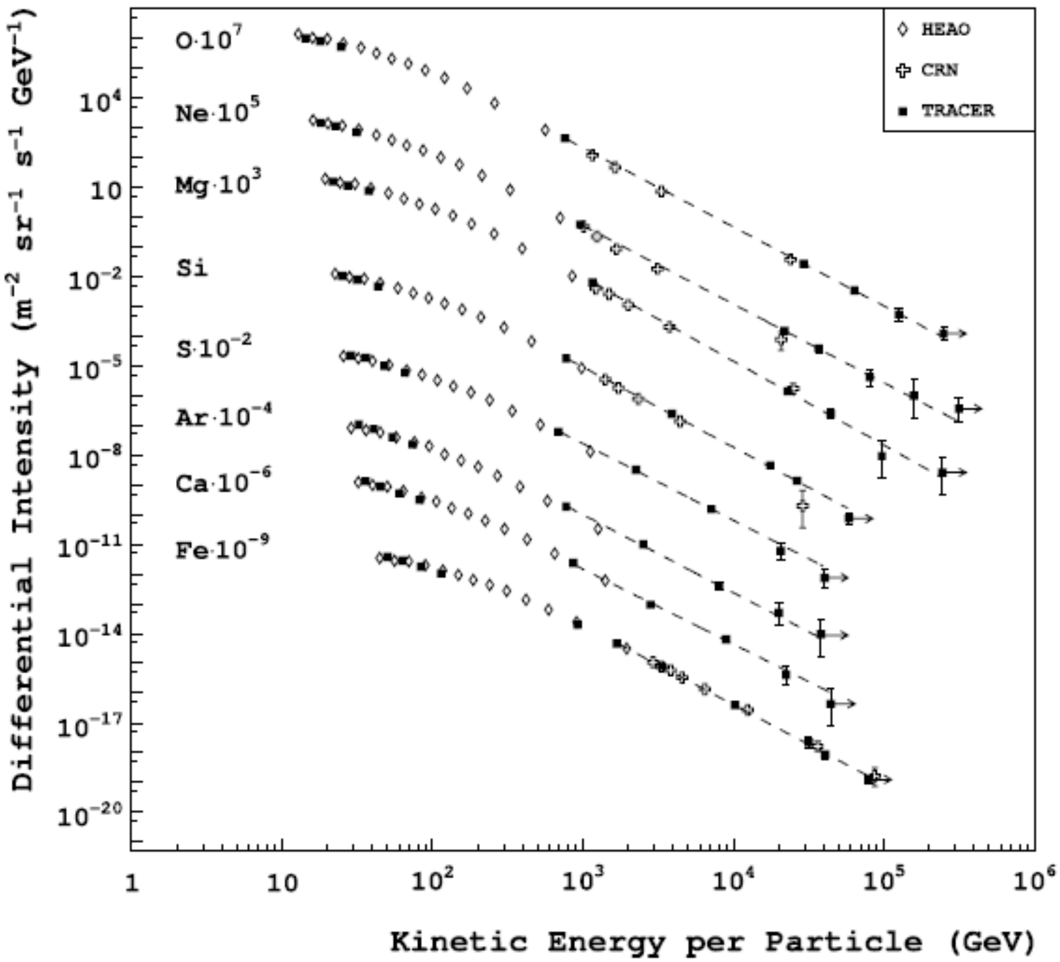


FIG. 12.—Differential energy spectra vs. energy per particle of the cosmic-ray nuclei: O, Ne, Mg, Si, S, Ar, Ca, and Fe. Results from the TRACER 2003 flight are indicated by the filled squares. Existing data from the HEAO-3 experiment (*open diamonds*; Engelmann et al. 1990) and the CRN experiment (*open crosses*; Müller et al. 1991) are shown for comparison. The dashed line represents an independent power-law fit to each spectrum above 20 GeV amu^{-1}. [*See the electronic edition of the Journal for a color version of this figure.*]

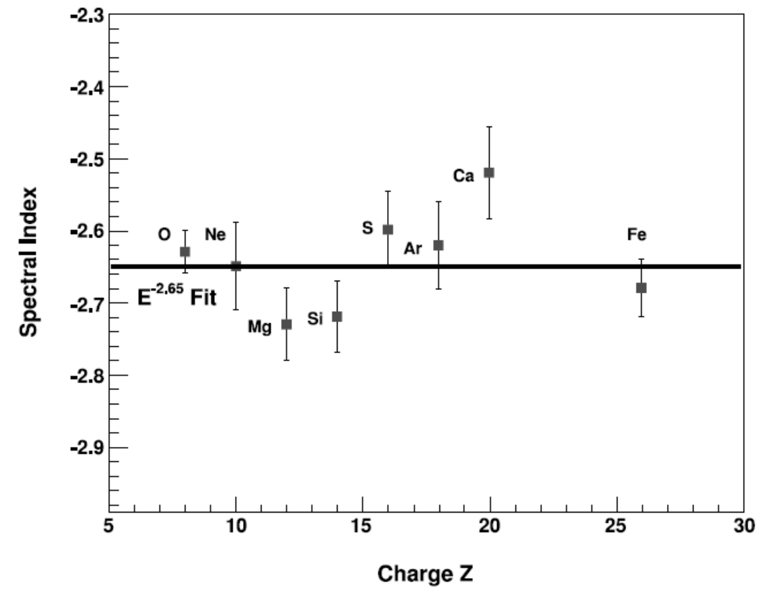


FIG. 13.—Spectral indices of a best power-law fit to the combined TRACER and CRN data above 20 GeV amu^{-1}. The line indicates an average spectral fit of $E^{-2.65}$. [*See the electronic edition of the Journal for a color version of this figure.*]

KASCADE all particle spectrum

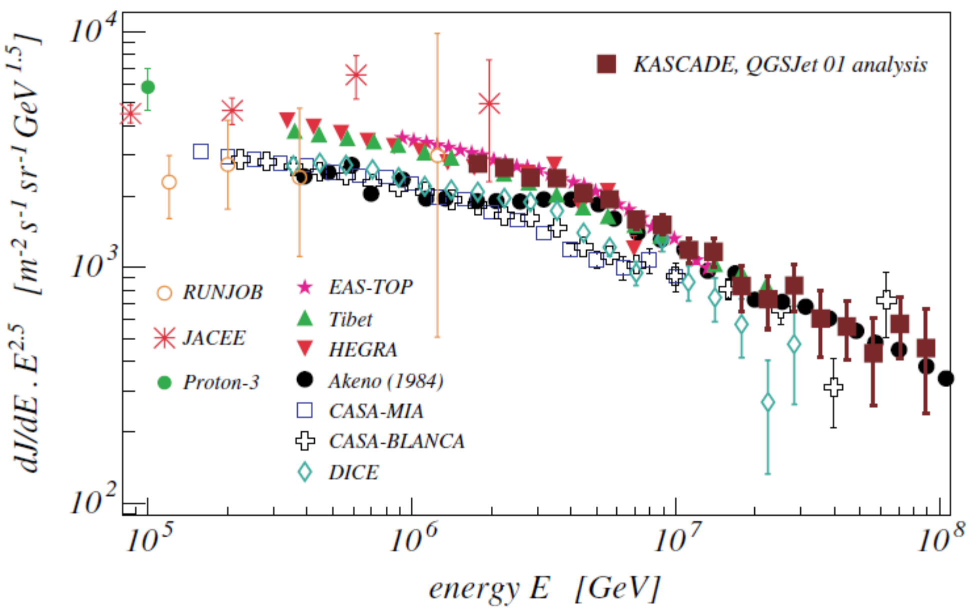
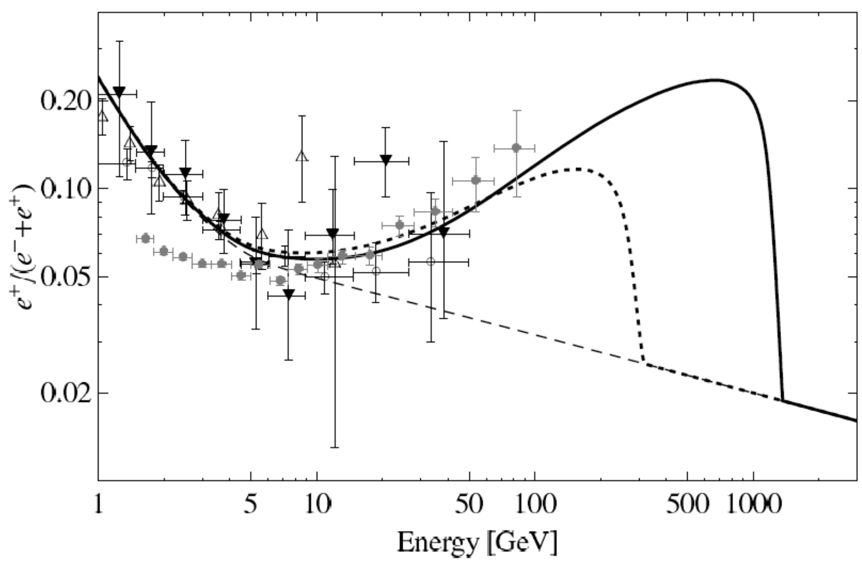


Fig. 17. All particle spectrum for the QGSJet 01 based analysis in comparison with results from RUNJOB [33], JACEE [34], Proton-3 [35], EAS-TOP [36], Tibet [37], HEGRA [38], Akeno [39], CASA-MIA [40], CASA-BLANCA [41], and DICE [42].

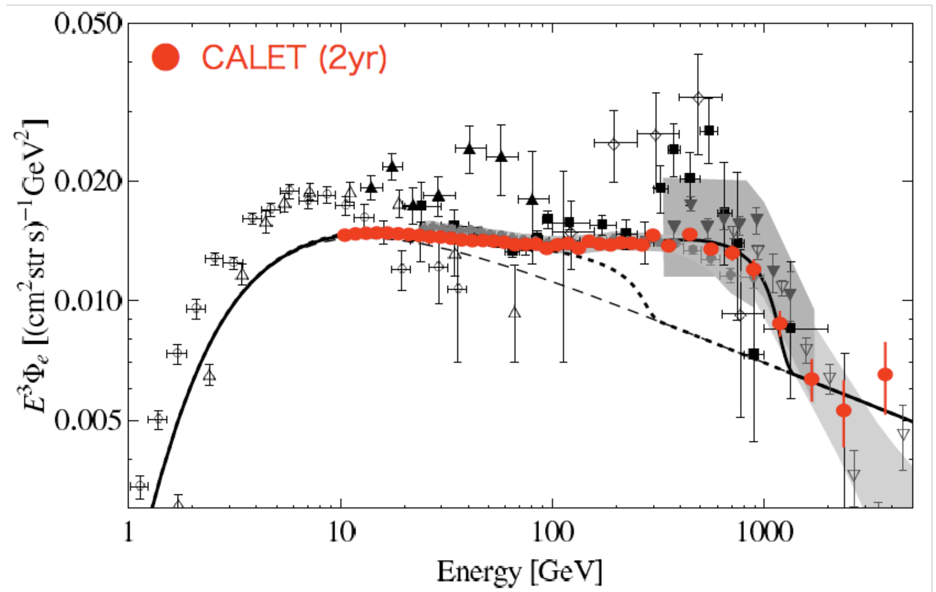
Electron and Positron from Dark Matter Decay

Decay Mode: D.M. -> $l^+l^-\nu$
Mass: $M_{D.M.}$=2.5TeV
Decay Time: $\tau_{D.M.}$ = 2.1x10^{26} s

Expected $e^+/(e^-+e^+)$ ratio by a theory and the observed data



Expected e^-+e^+ energy spectrum by CALET observation



Observation in the trans-TeV region

Dark Matter signal

Ibarra et al. (2010)

Discriminating scenario A and B

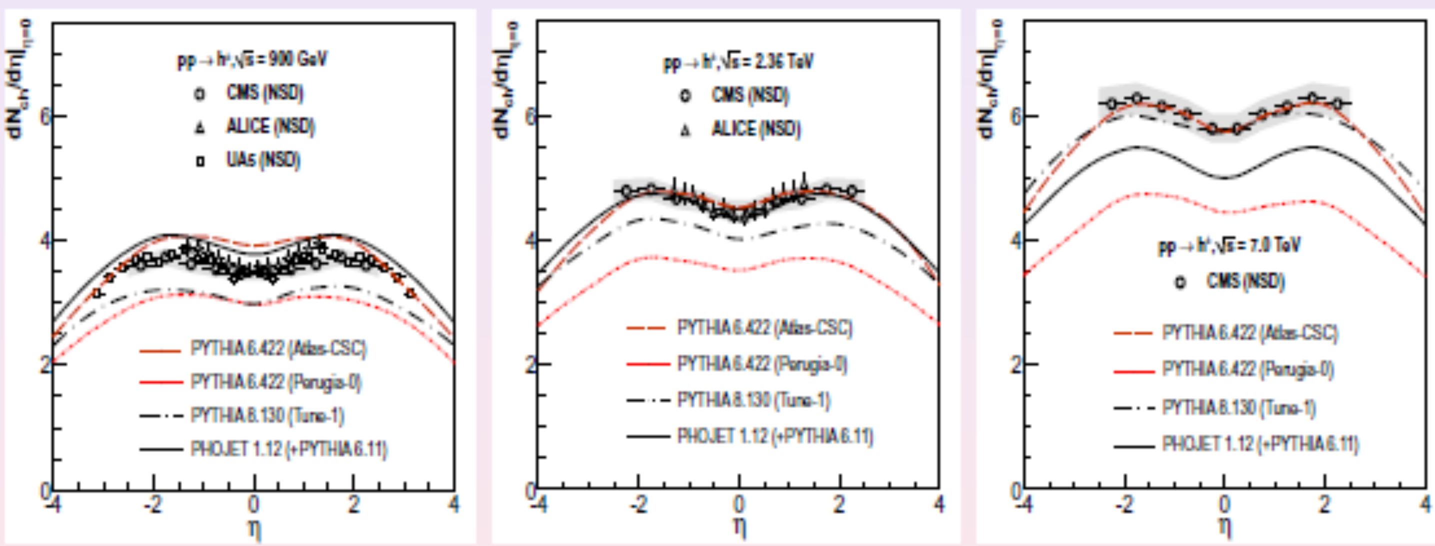
A : Find candidate of nearby source.
B : Does break point show rigidity dependence?

Chemical composition after the knee:
A : becomes lighter between 10^{16} and 10^{17} eV.
KASCADE-GRANDE claimed second knee at 8×10^{16} eV.
B : Heavy dominance up to the maximum energy of GCR.

S.Ostapchenko, 32nd ICRC

MC generators & LHC data

- LHC data: $N_{\mathrm{ch}}(s)$ rises quicker than predicted by collider MCs



(plots from [d'Enterria et al., 2011])

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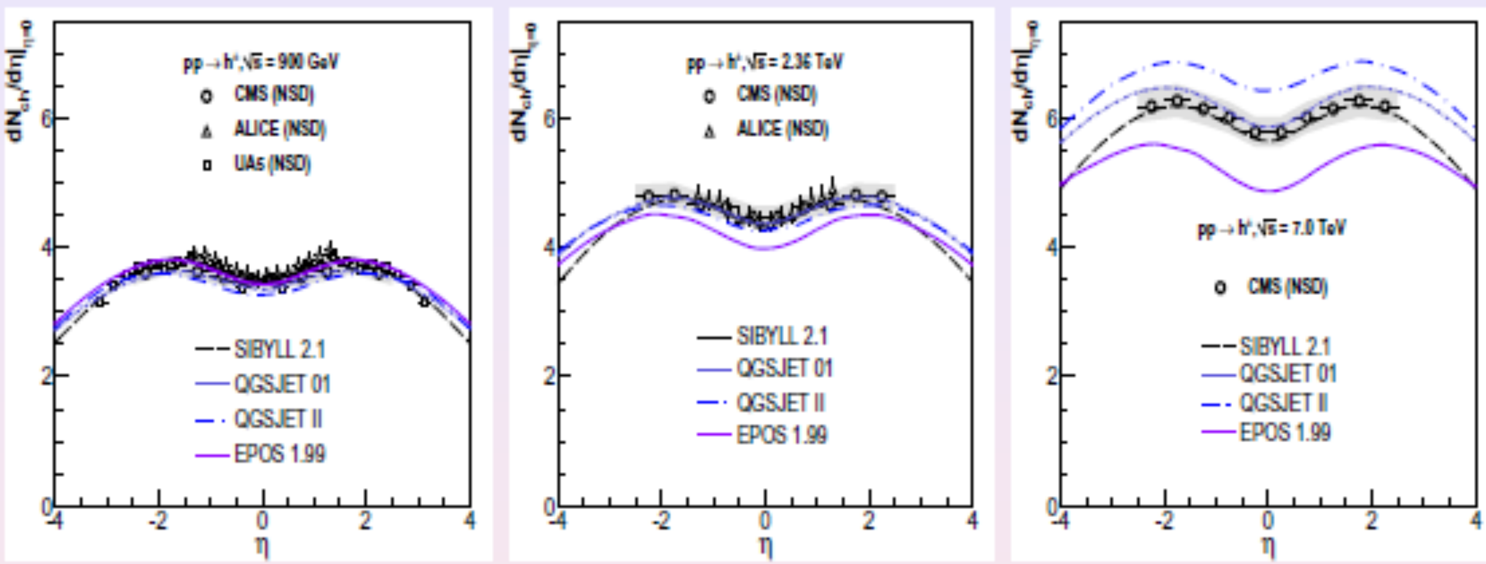
MC generators & LHC data

- $N_{\rm ch}(s)$ - described better by CR interaction models



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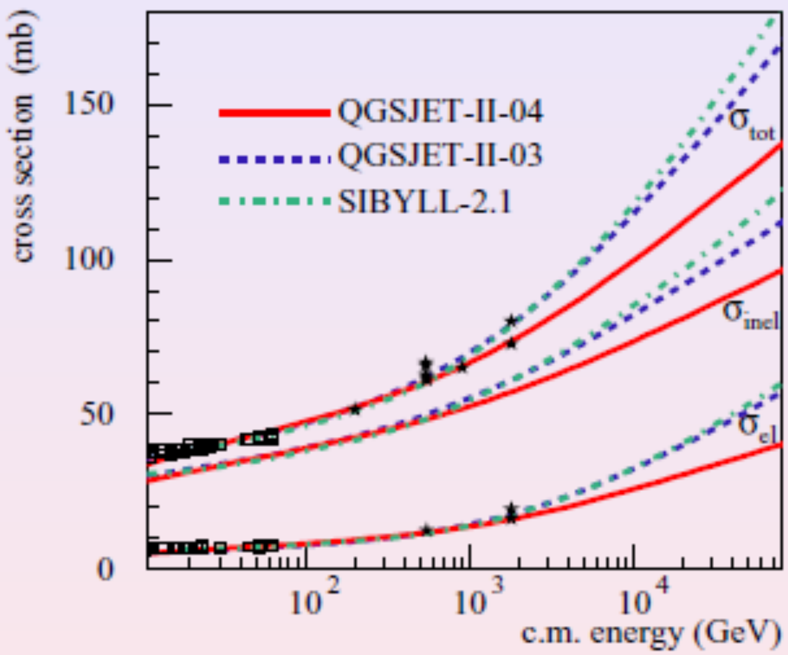
Inelastic cross section



- side-effect of N_{ch}-reduction: slower rise of cross sections
- e.g., σ_{pp}^{tot} - consistent with E710 data at 1.8 TeV

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