Knee領域のComposition
Tibet空気シャワー連動実験
の結果と次期計画

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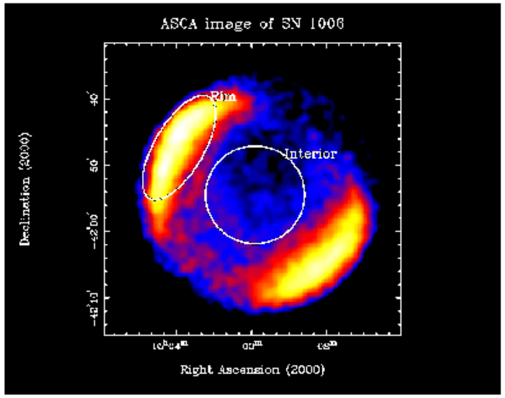
Contents

1. Present status of the composition measurement by direct observations and indirect ones.
2. Some details about the proton spectrum obtained by Tibet hybrid experiment.
3. YAC array (next phase of Tibet)

Origin of cosmic rays (protons and nuclei) is not confirmed yet.



If SNR is the origin,

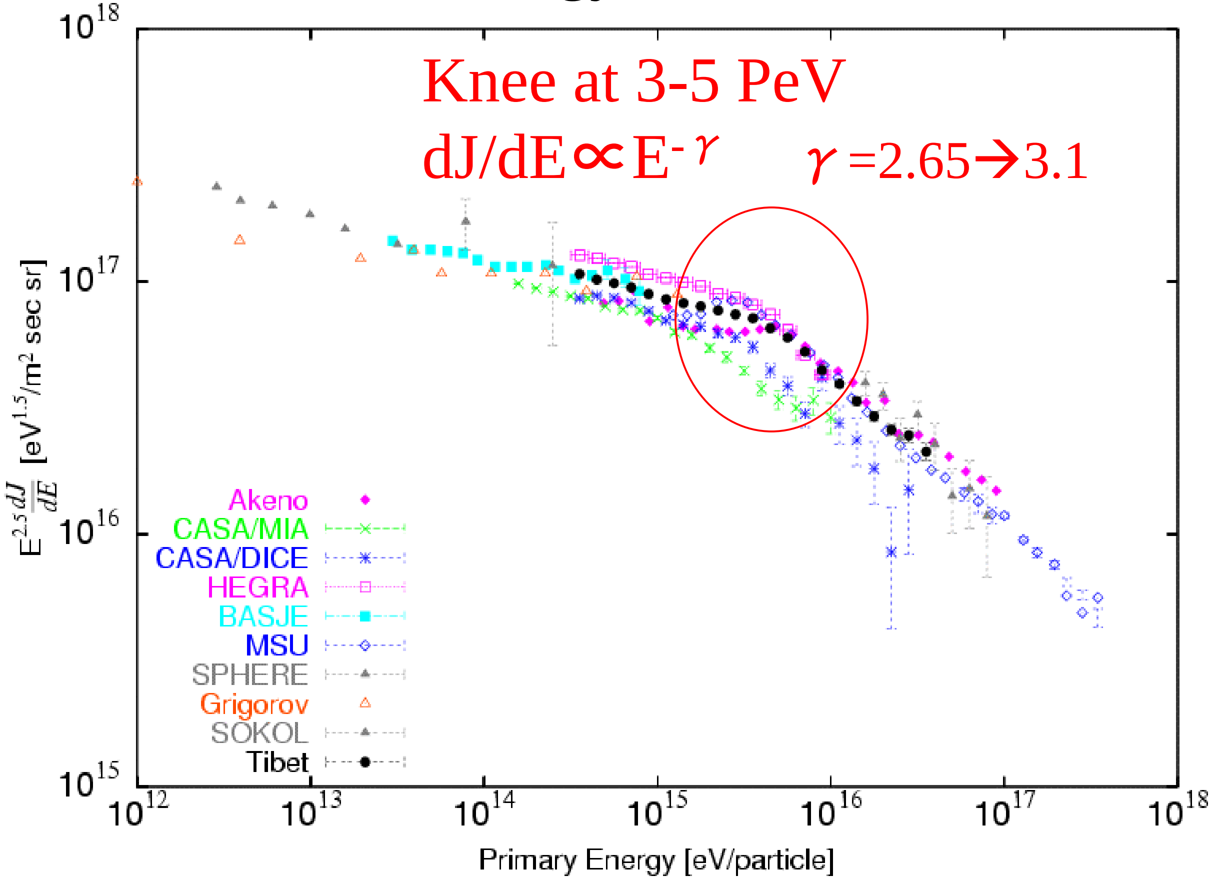
1. Observe $\pi^0 \rightarrow \gamma + \gamma$ spectrum from SNR

2. According to the DSA model;
   Acceleration limit ∼Z x 10^{14} eV
   (Oblique acceleration may shift the limit by some factor or an order.)

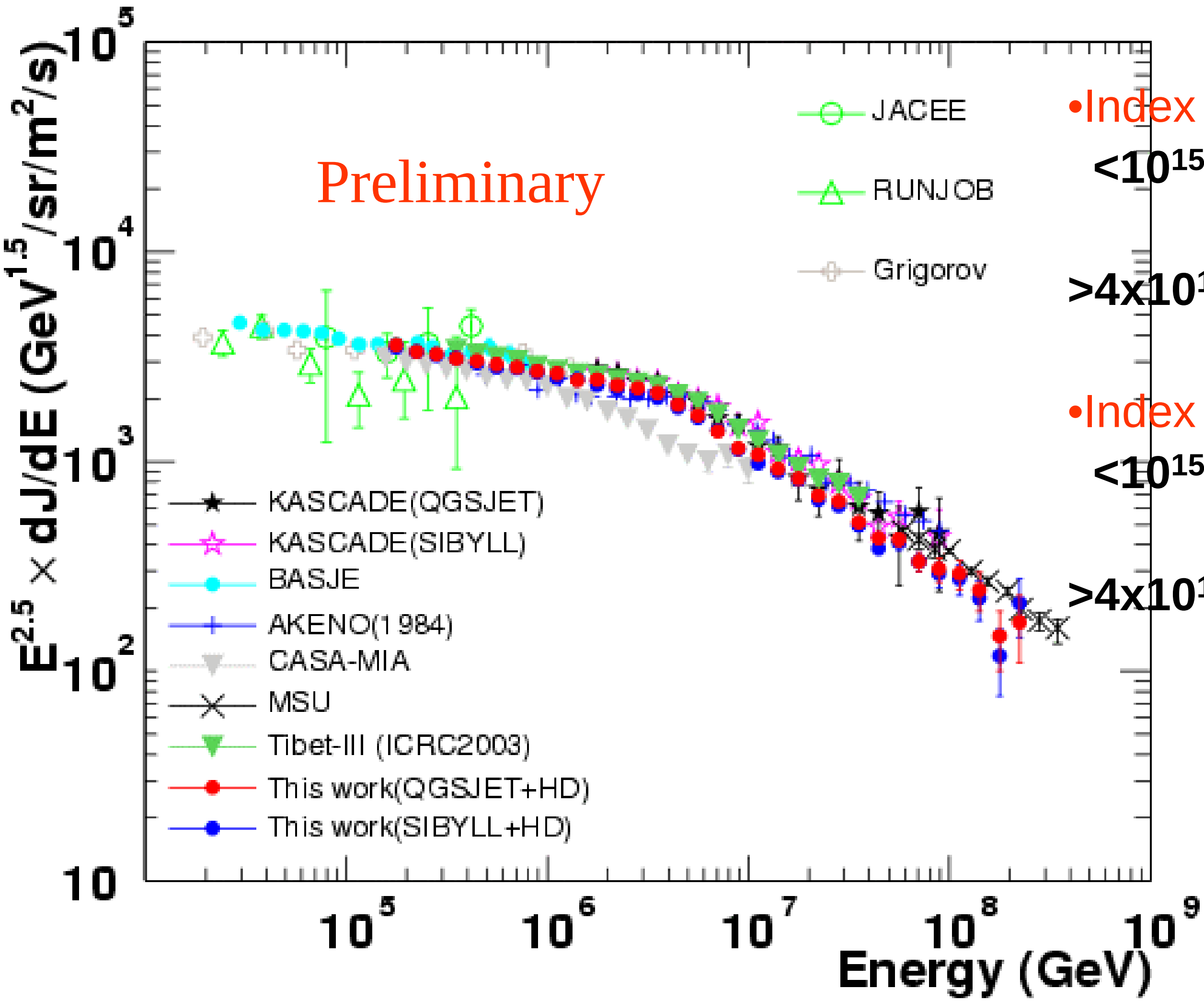
Investigate chemical composition of CRs.
Origin of the knee can be interpreted as the acceleration limit by SNRs if regidity dependent cut off of the each chemical component is observed.

Change of the power index in all particle spectrum at 3-5PeV is clearly seen.

All observations are consistent within the systematic error of ～20% in energy determination.

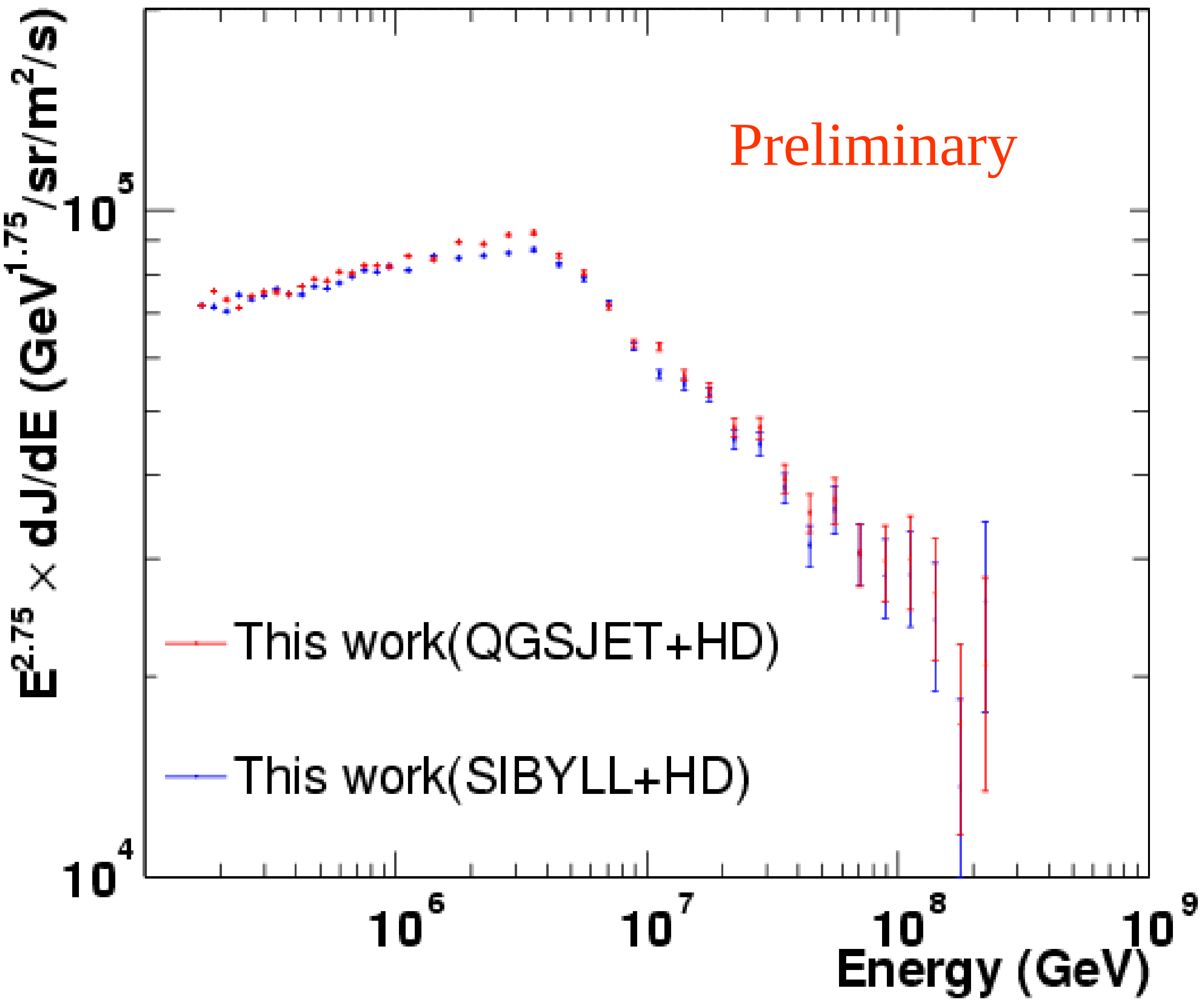


Energy spectrum (1)



- Index of spectrum
  - $<10^{15}$eV -2.681 ± 0.0005(stat.) $\pm$??(syst.)
  - $>4\times10^{15}$eV -3.120 ± 0.008(stat.) $\pm$??(syst.)
- Index of spectrum
  - $<10^{15}$eV -2.677 ± 0.0005(stat.) $\pm$??(syst.)
  - $>4\times10^{15}$eV -3.124 ± 0.008(stat.) $\pm$??(syst.)

Energy spectrum (2)



Present status of the study of the chemical composition

- Direct observations（Knee is inaccessible because of the low flux）
  - BESS,AMS (magnet) <1TeV （high statistics）
  - balloon,satellite（counter) < several 10TeV
  - balloon ECC (JACEE,RUNJOB) < 100 TeV (low stat.)
  - ATIC,CREAM,TRACER (Long duration flight at south pole) < 100TeV (high stat.)
  - CALET (Calorimetric Electron Telescope) plan (ISS) < 1000TeV
- Indirect observations （$\sigma_{inel} \propto A^{2/3}$） 10^{14}-10^{17} eV
  - Xmax : Fluorescence, Cherenkov, equi-intensity-cut
  - e-μ ratio : enriched muons in AS of nucleus origin (KASCADE)
  - Lateral structure of e, μ , hadrons
  - Time structure of Cherenkov (BASJE)
  - Energy spectrum at AS core（Tibet）

Direct Observations

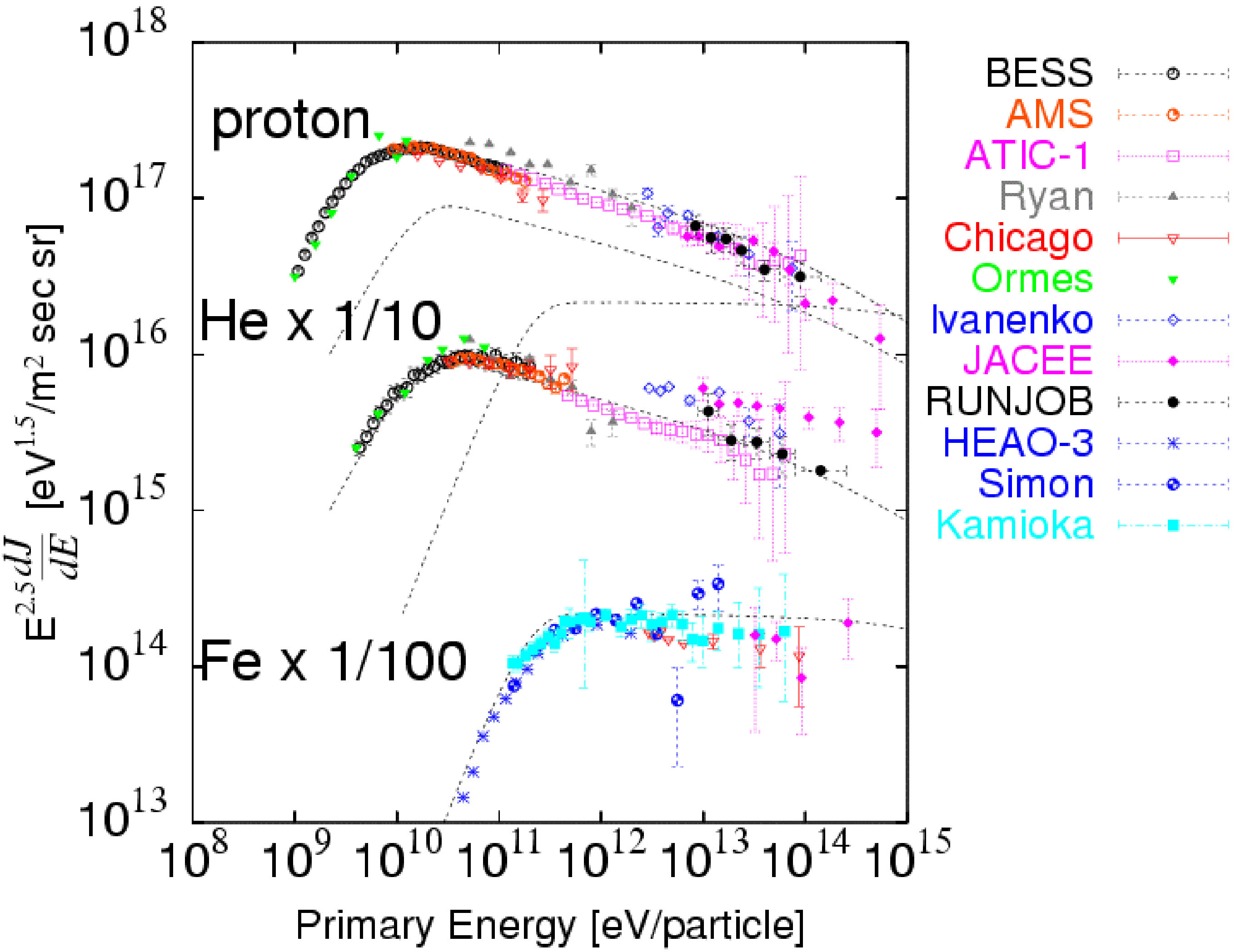
focus to proton, helium and Fe spectrum

break point ?

power index difference?

fraction?

P,He,Fe <100 TeV/particle



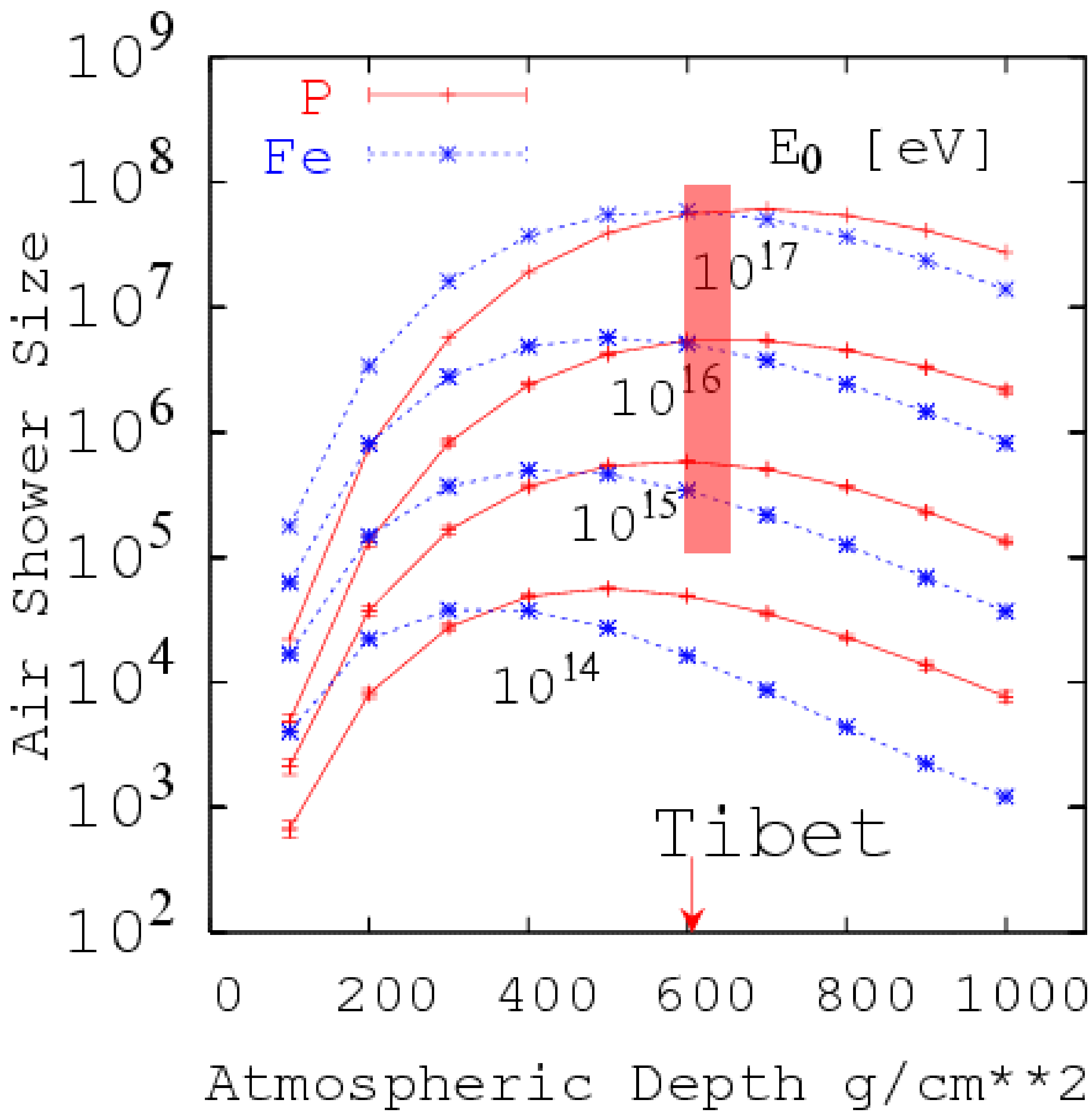
Indirect observations

1. Average mass <ln A>
2. Individual component or mass groups

Systematic errors come from

1. Primary composition dependence.
   → minimized at high altitude by observing AS of near maximum development. (also use appropriate zenith angle)
2. Interaction model dependence.
   Which model is the best among QGSJET,SIBYLL,DPMJET,NEXSUS,VENUS,.....?
   Present uncertainty of the forward region characteristics is estimated to be within 30% as shown later.
   →to be calibrated by forward region exp. by LHCf（Elab ～ 10^{17}eV）.
   Other calibration is also needed on Nucleus-Nucleus effect etc. especially for muon numbers.
   Present uncertainty of the muon numbers is still large as seen in the result of e-μ size analysis.
   →update simulation code.

Longitudinal development of AS

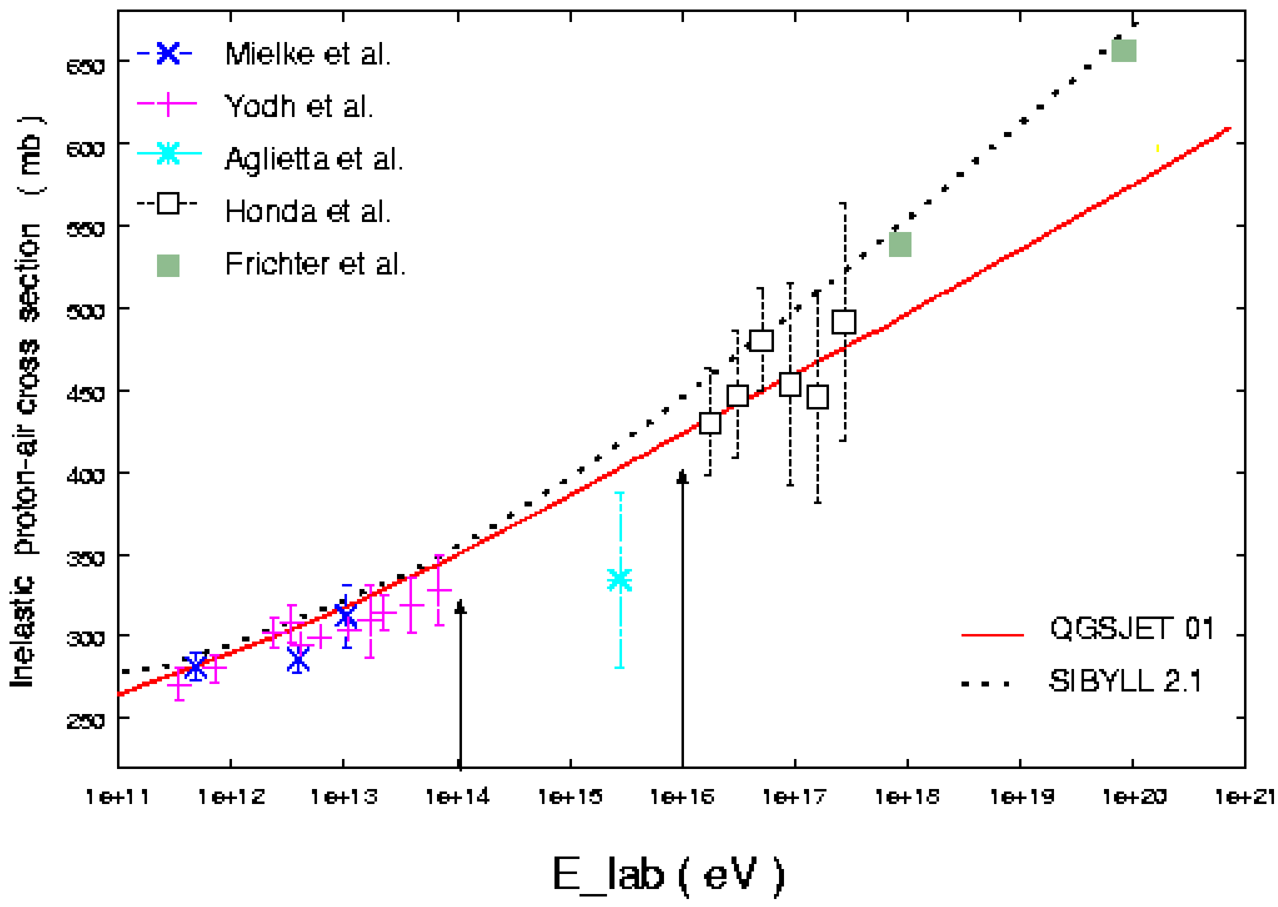


Hadronic Interactions at High Energies

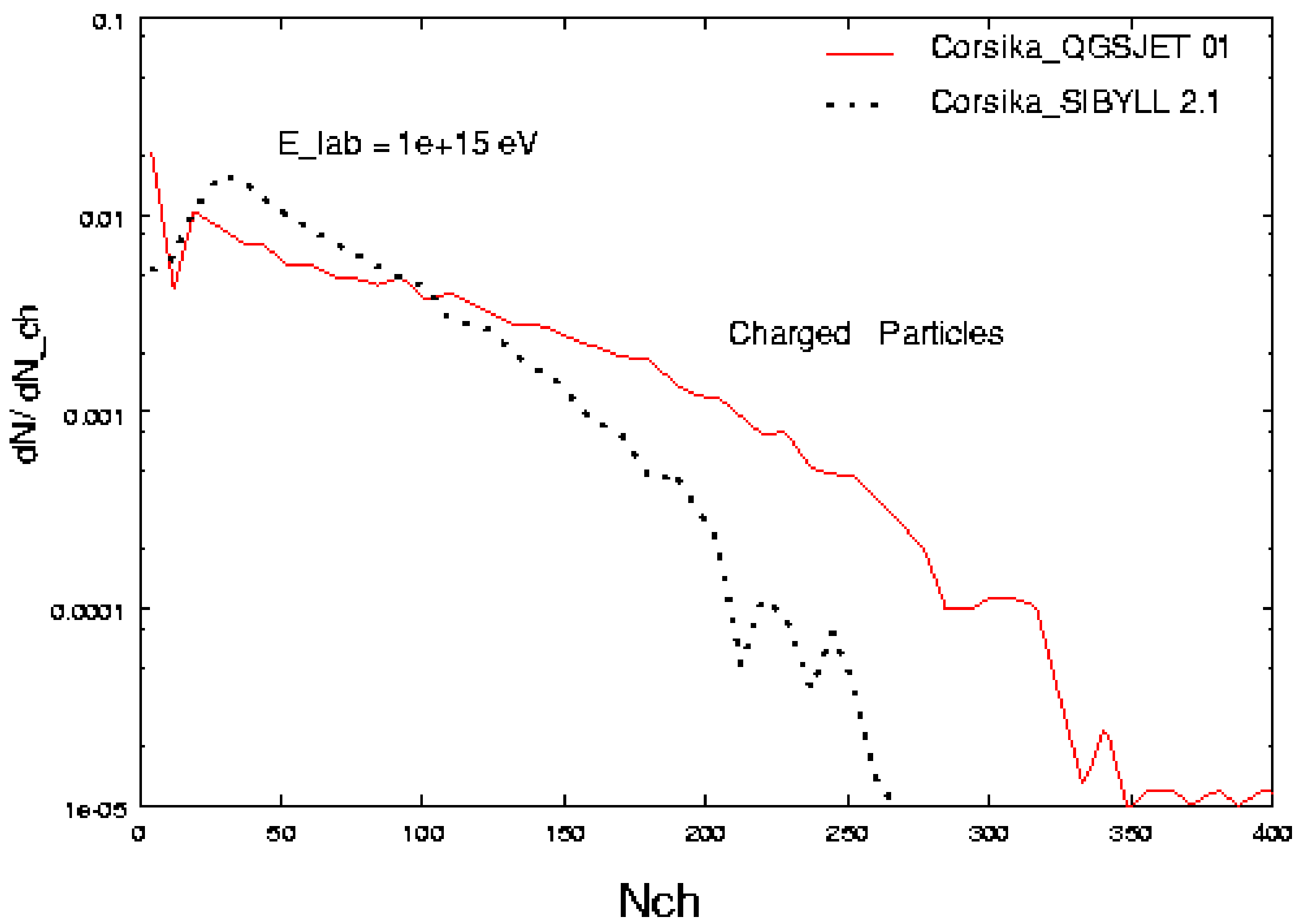
Simulation model: QGSJET01 SIBYLL2.1

- Inelastic cross section
- Multiplicity
- Feynman scaling

P-Air inelastic cross section

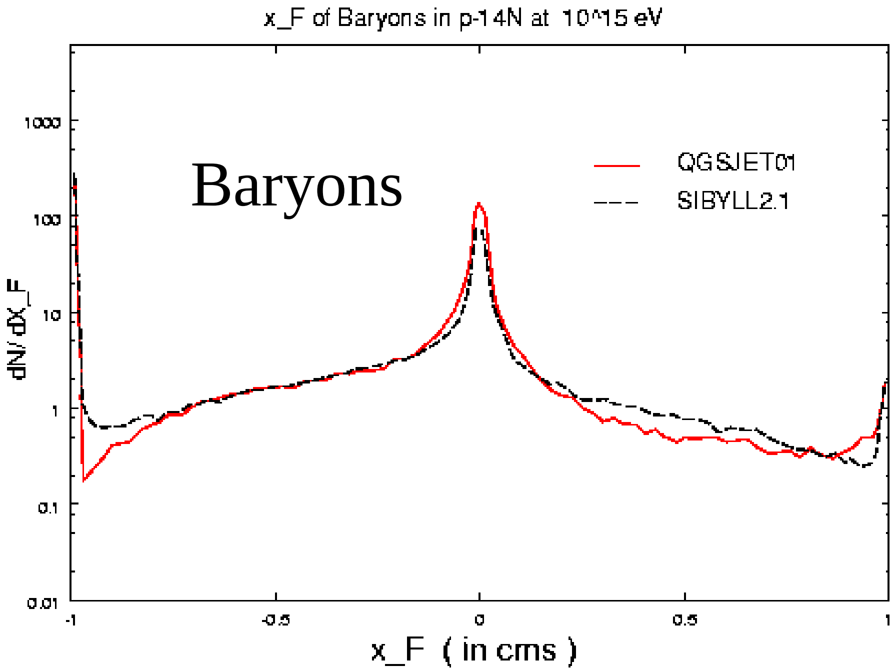


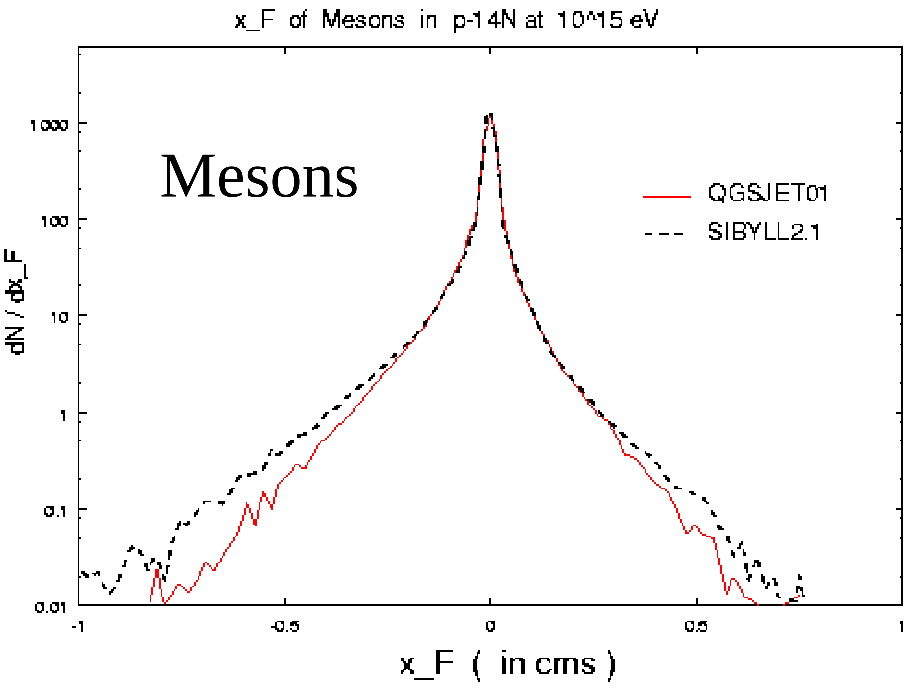
Charged multiplicity



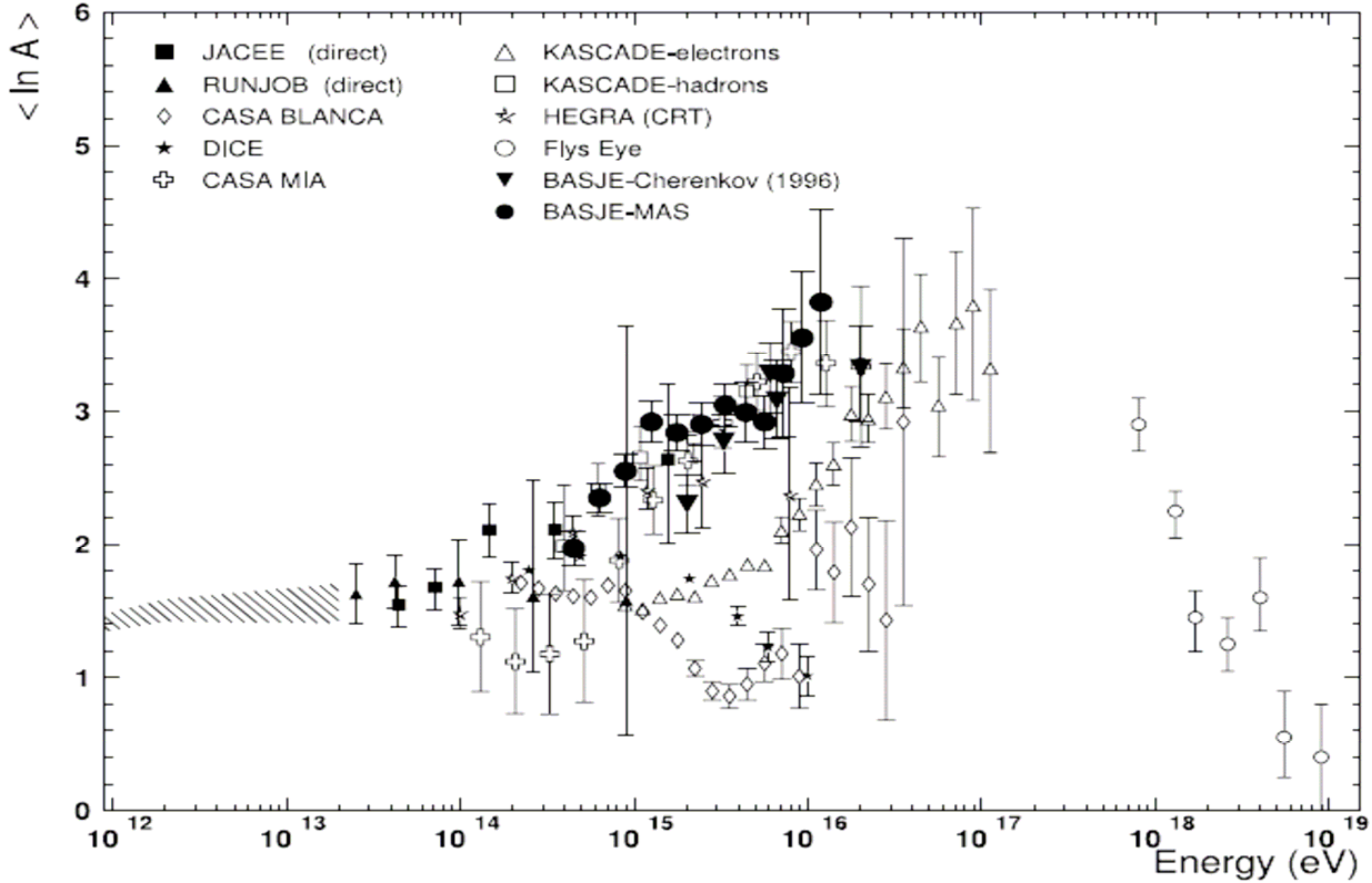
Production spectrum (p-^{14}N)

Feynman $x_F = \dfrac{2p_\ell}{\sqrt{S}} \approx \dfrac{E}{E_0}$ (in LS)





Average mass



S.Ogio et al. Ap.J 612(2004)268

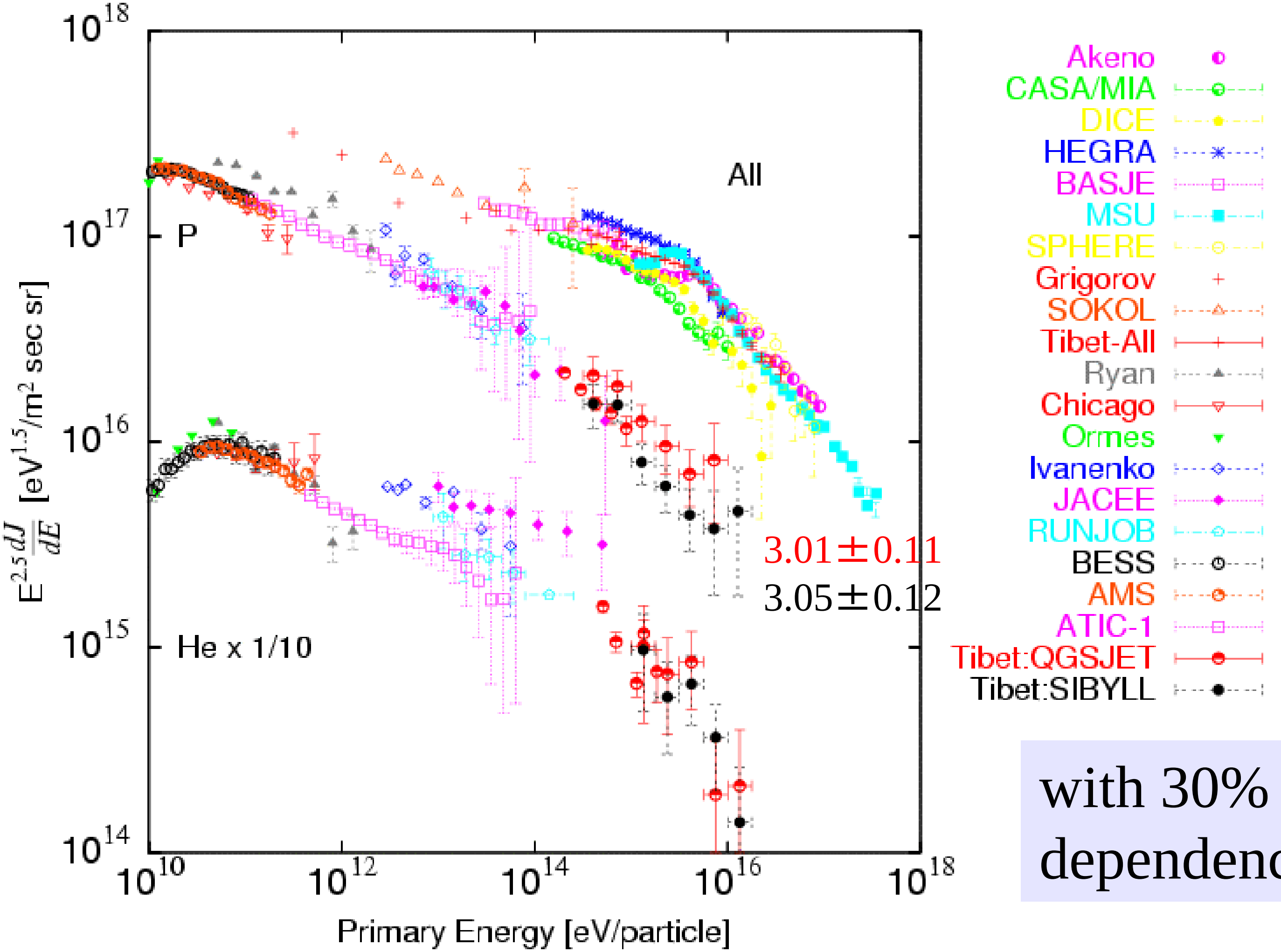
Separation of individual component or mass groups at the knee.

Two kinds of experiments are carried out.

1. Tibet hybrid experiment AS+EC+BD at 4300m a.s.l.
   Select proton(helium) induced AS events associated by
   γ -families. → Reject contamination by ANN
2. KASCADE e- μ at sea level
   proton, helium, CNO, Si, Fe
   EASTOP, GRAPES similar to KASCADE

P, He by Tibet Experiment

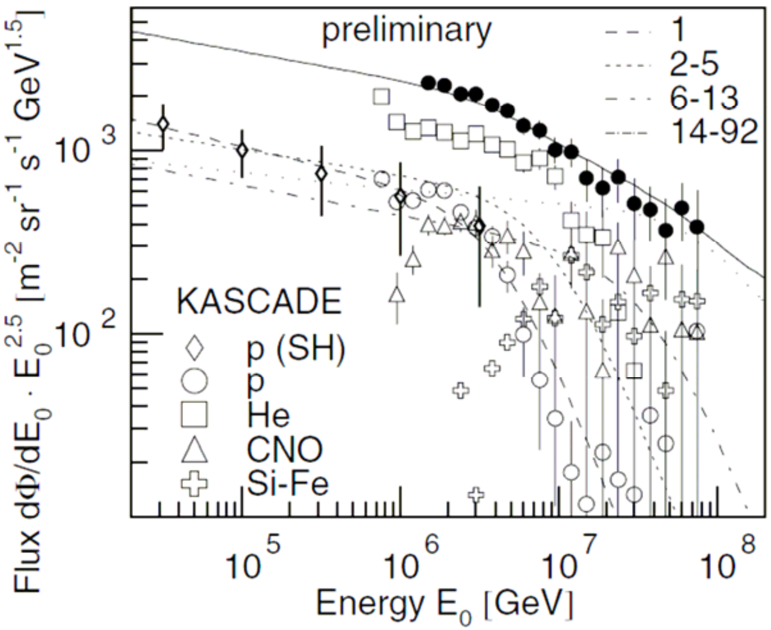
Phys. Lett. B **632** 58-64 (2006)



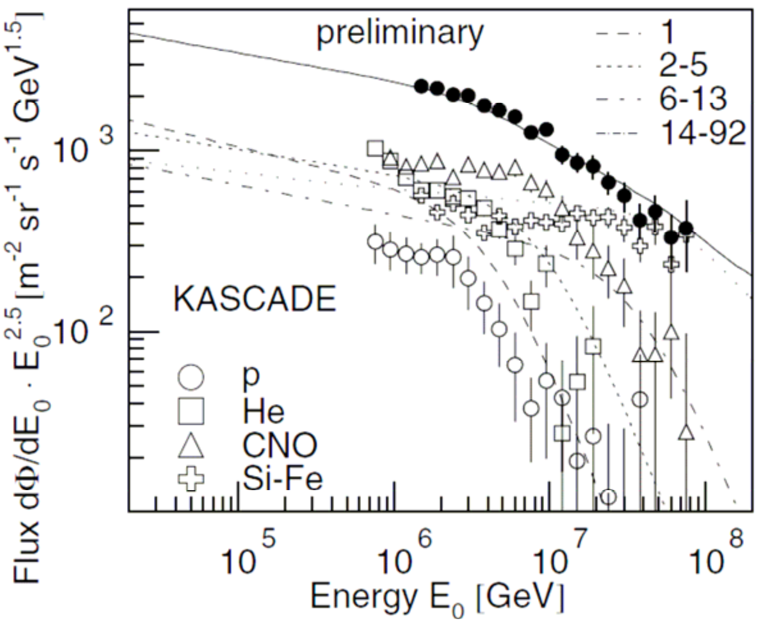
with 30% model dependence

KASCADE

QGSJET



SIBYLL



J.R.Hoerandel, Astroparticle Phys. 21,241-265(2004)

Tibet Hybrid Experiment

Tibet As$_\gamma$ Collaboration

1996—1999 AS+EC+BD

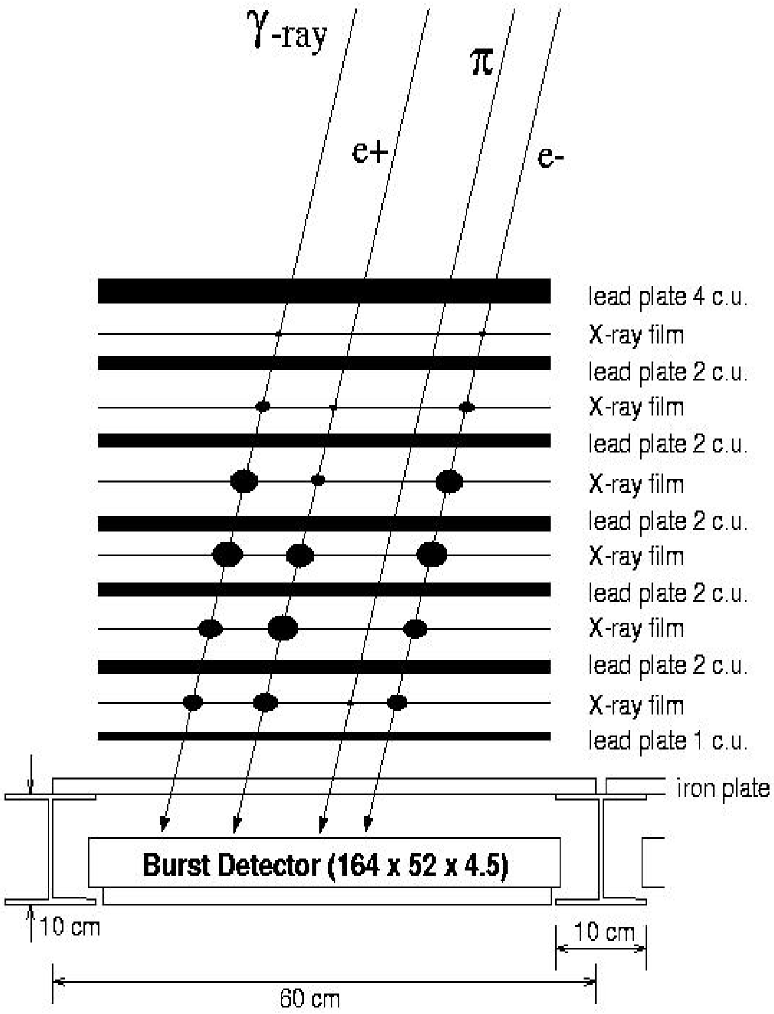
AS array 36,900 m^2

EC 80 m^2 (14 r.l. thick, 400 blocks)

177 events→P,He spectra

Emulsion Chambers and BDs

Design of Emulsion Chamber and Burst Detector



γ families

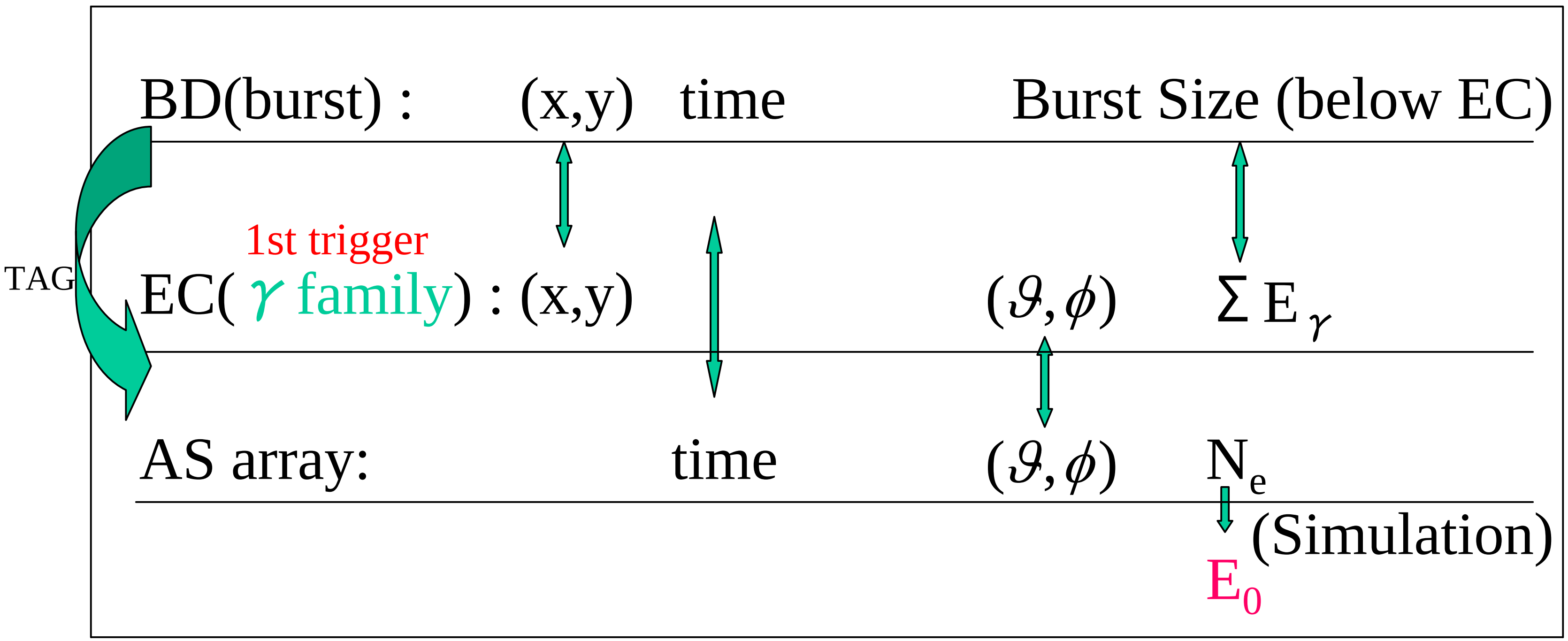
γ and e (> TeV) enter to EC with lateral spread of several cm.

They develop into cascade showers and shower spots are registered by X-ray films which consist of 6 layers.

Burst Detector below EC records the burst size, the position and arrival time stamp.
(4 PD are equipped at each corner of the BD.)

How to obtain proton spectrum?

Hybrid system



EC-Xray film image → Scanner → (GUI Software) family detection

AS+family matching event → ANN (Correlations) → Proton identification

Matching of EC - BD - AS

position time stamp

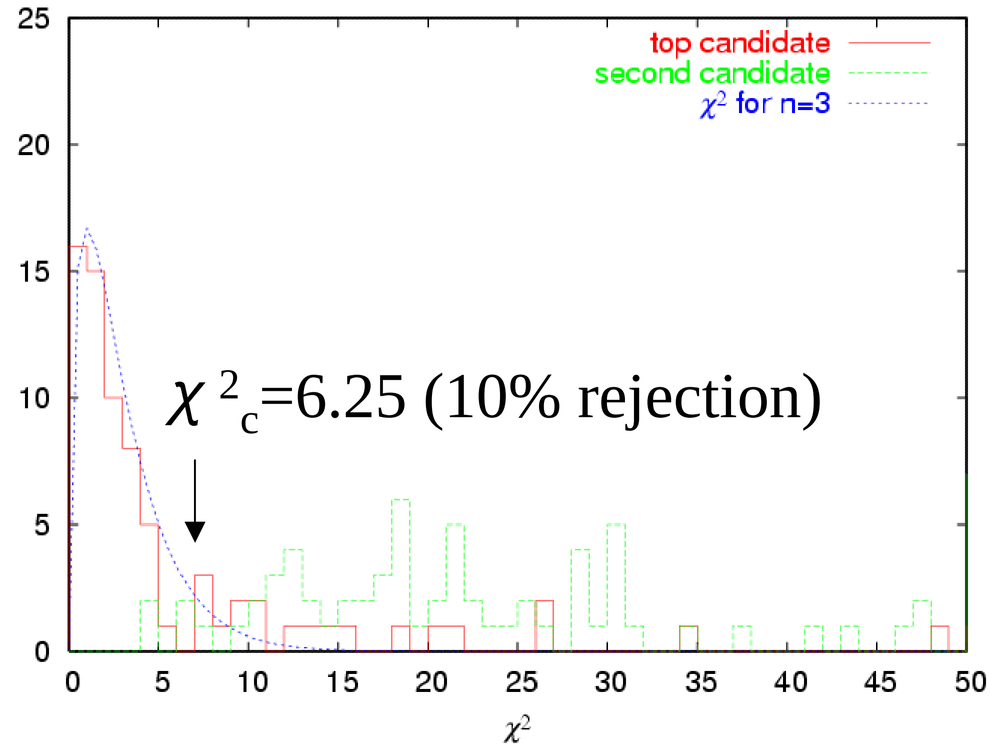
angle

$$\chi^2 = (\Delta\theta/\sigma_\theta)^2 + (\Delta x/\sigma_x)^2 + (\Delta y/\sigma_y)^2$$

$\Delta x, \Delta y$:distance between γ family and burst.
$\Delta\ \theta$: opening angle between arrival direction of γ family and AS.

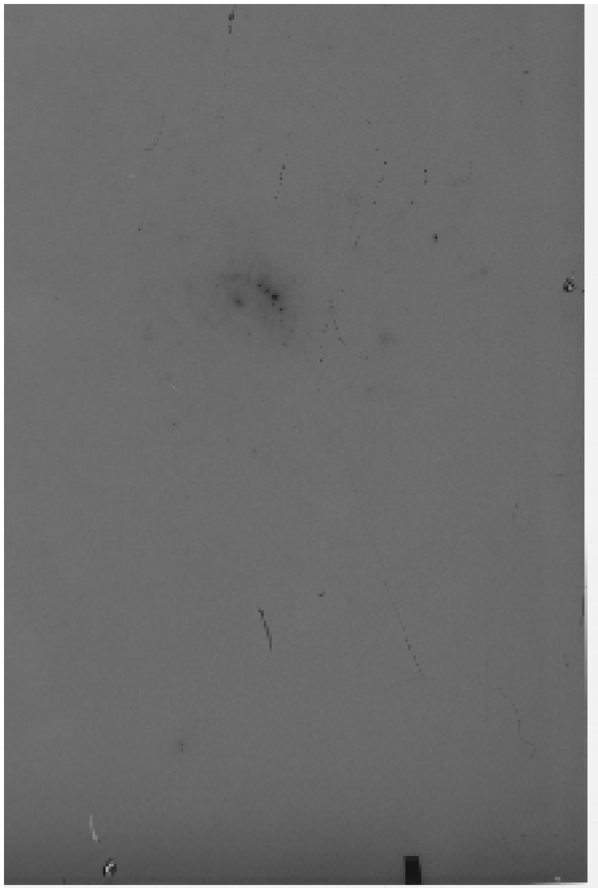
$$\sigma_x = \sigma_y = 10cm$$

$$\sigma_\theta = 2.5\,\text{deg}.$$



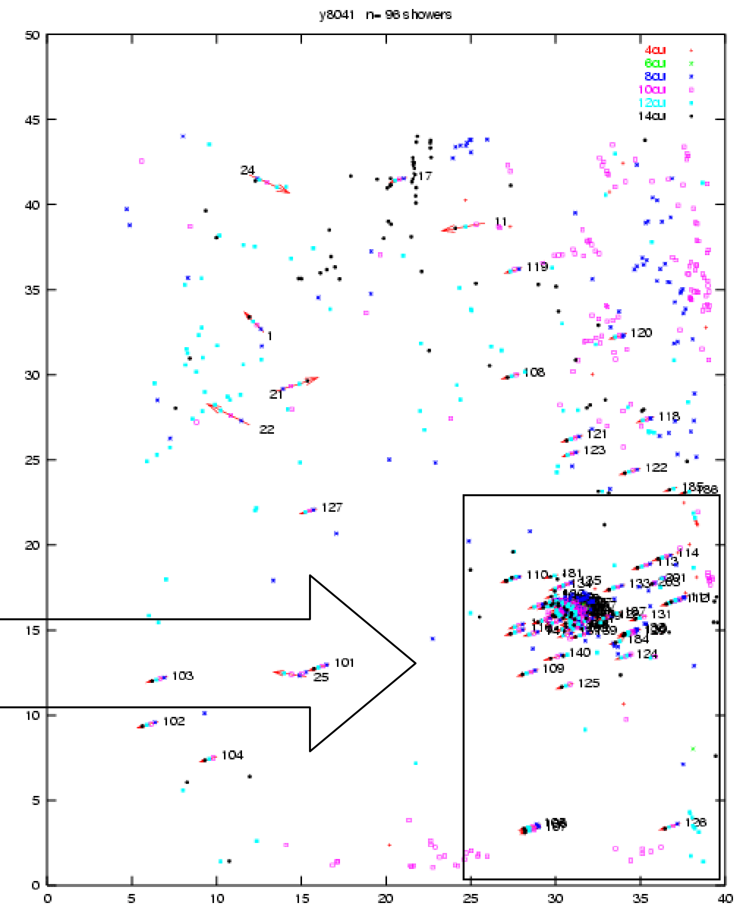
γ family analysis with use of image scanner

S.Ozawa et al. NIM A, **523**,193-205 (2004)



15cm

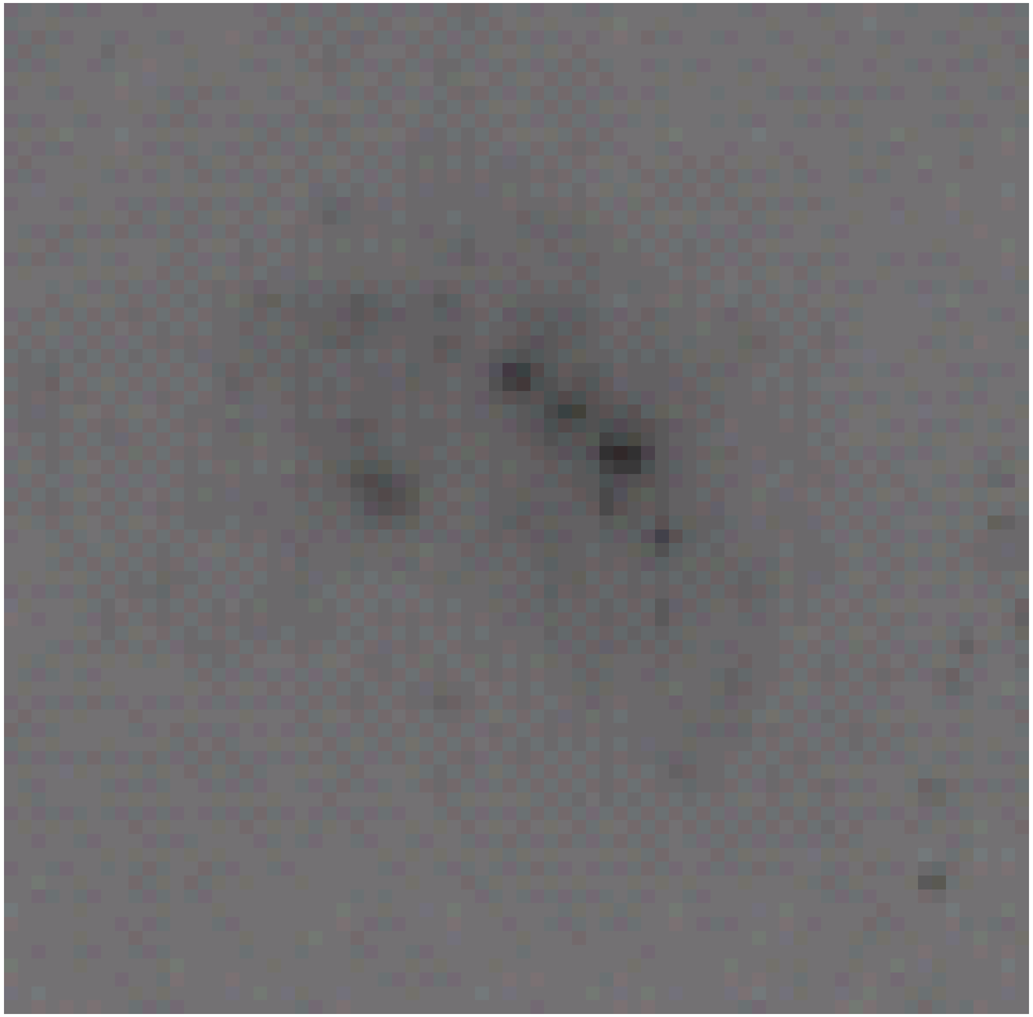
Image of X-ray film
600DPI (42.3 μ m resol.)



cm

Shower map reconstructed from
6 layers of X-ray film(40cm x 50cm)

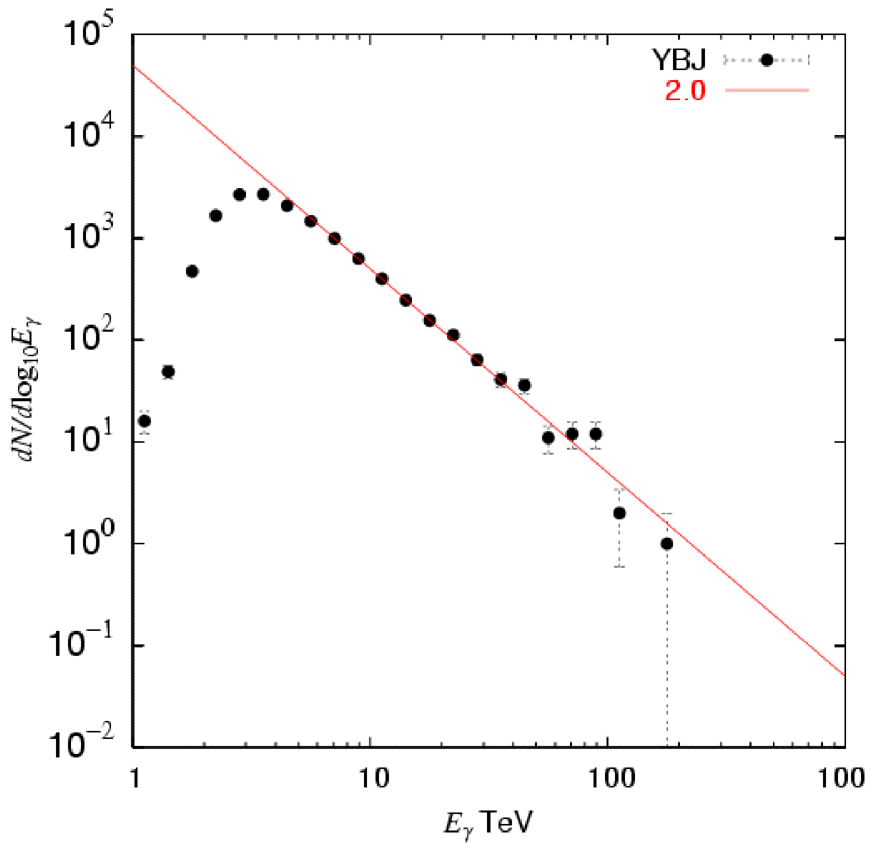
Center of γ family



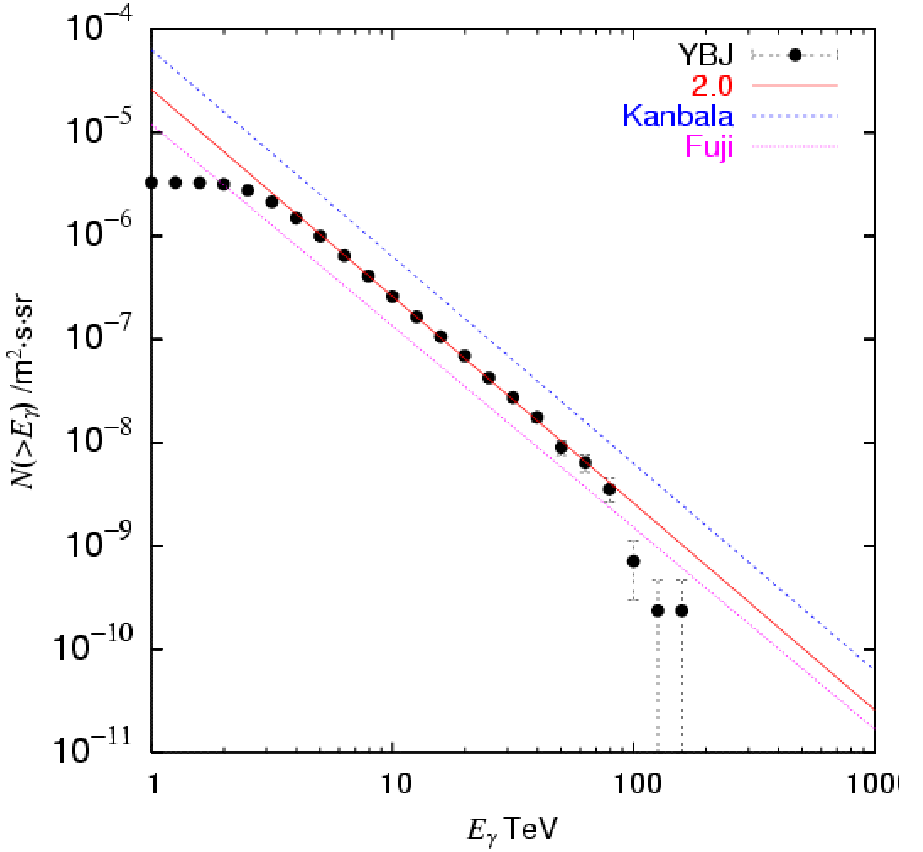
2cm

Single γ spectrum

Differential



Integral



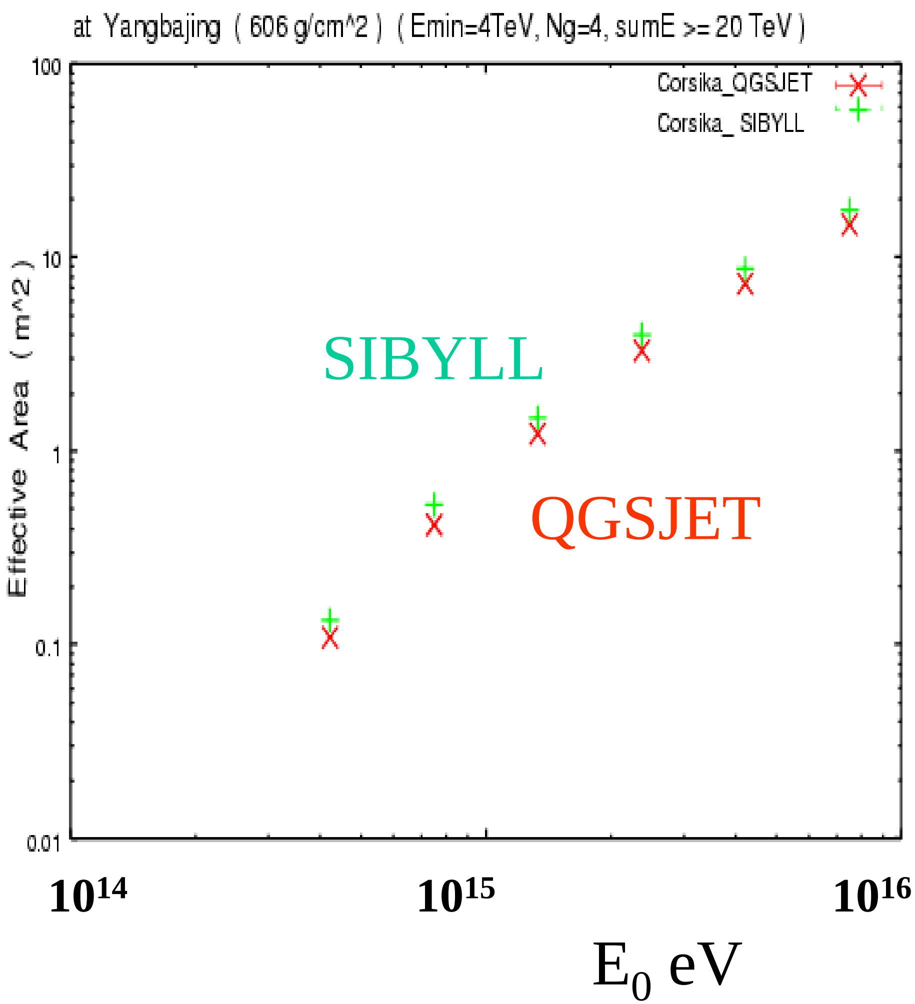
Simulation

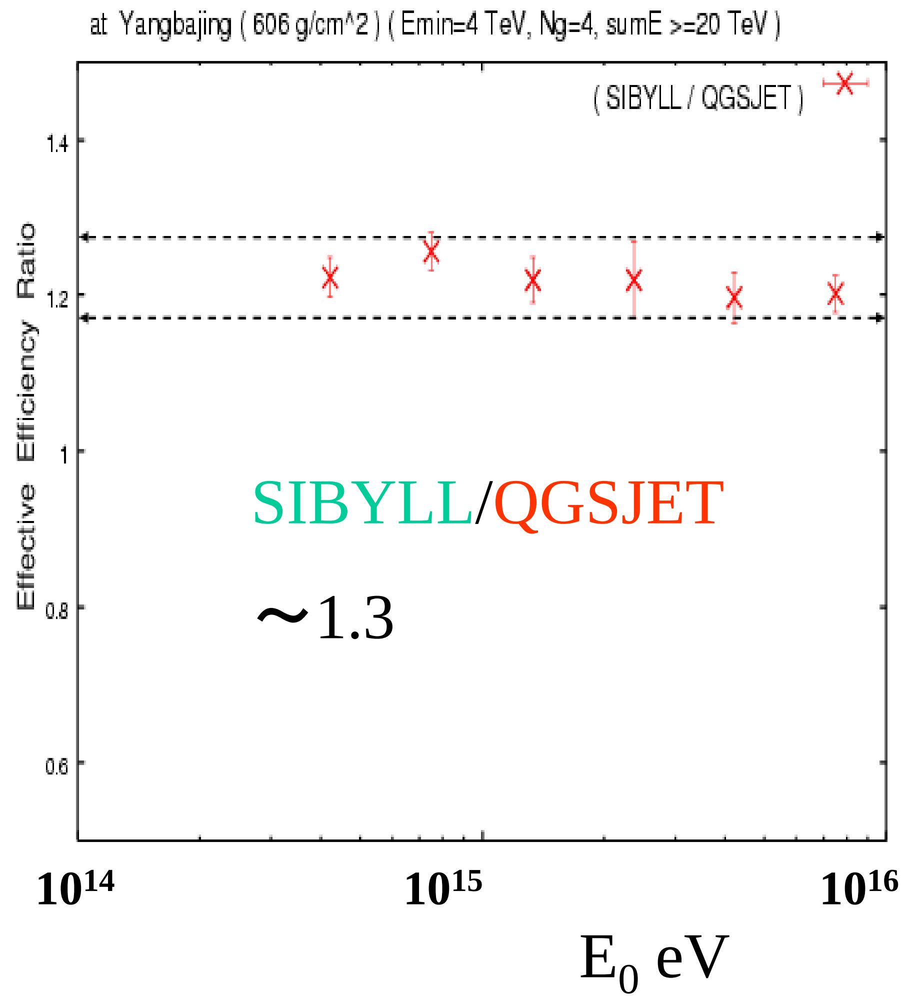
Corsika 6.030
QGSJET01,SIBYLL2.1 (high energy int. model)
x
Heavy Dominant Composition (HD)
Proton Dominant Composition (PD)
＝analyses under 4 models

Event Selection

AS size $Ne>2 \times 10^5$ accompanied by γ family of
$E_\gamma>4$TeV, $n_\gamma \geq 4$, $\Sigma E_\gamma>20$ TeV

Generation efficiency of γ family event by primary protons in QGSJET and SIBYLL

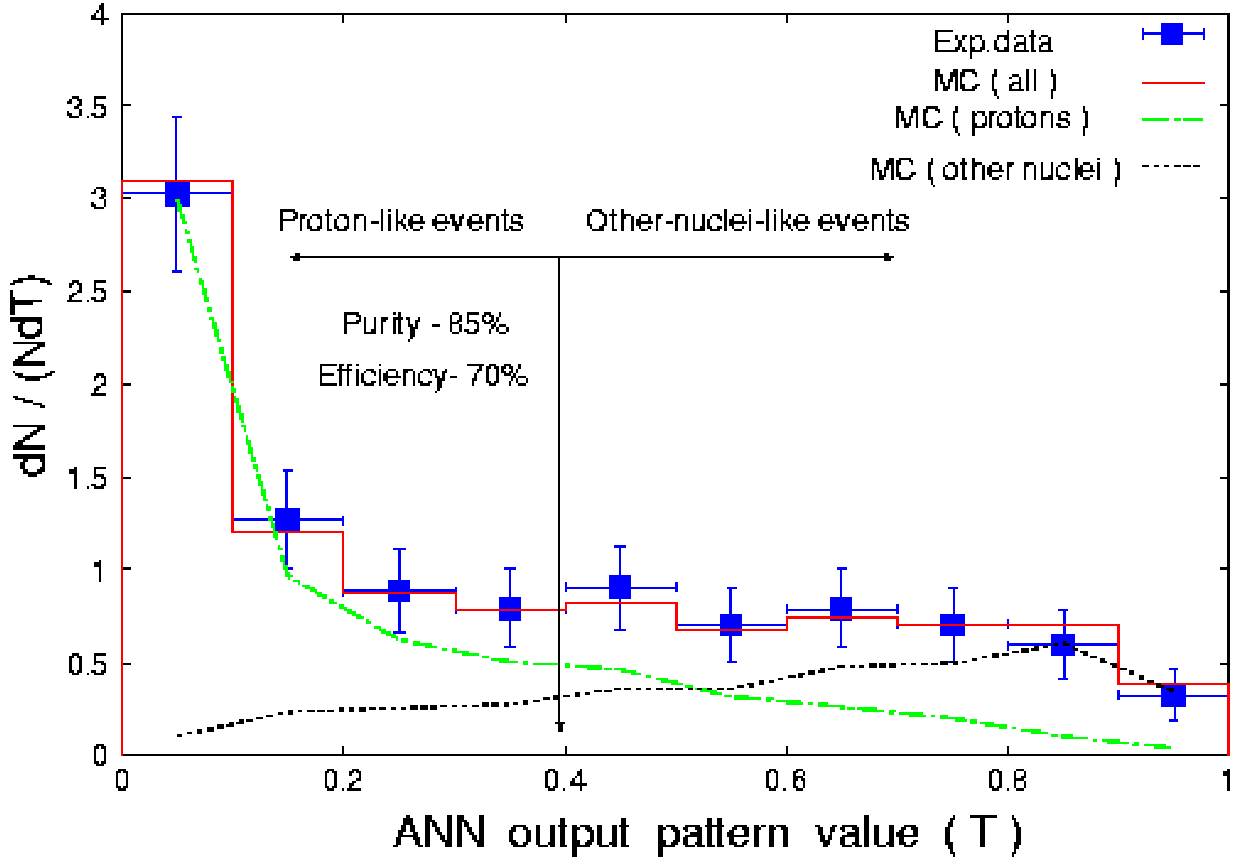




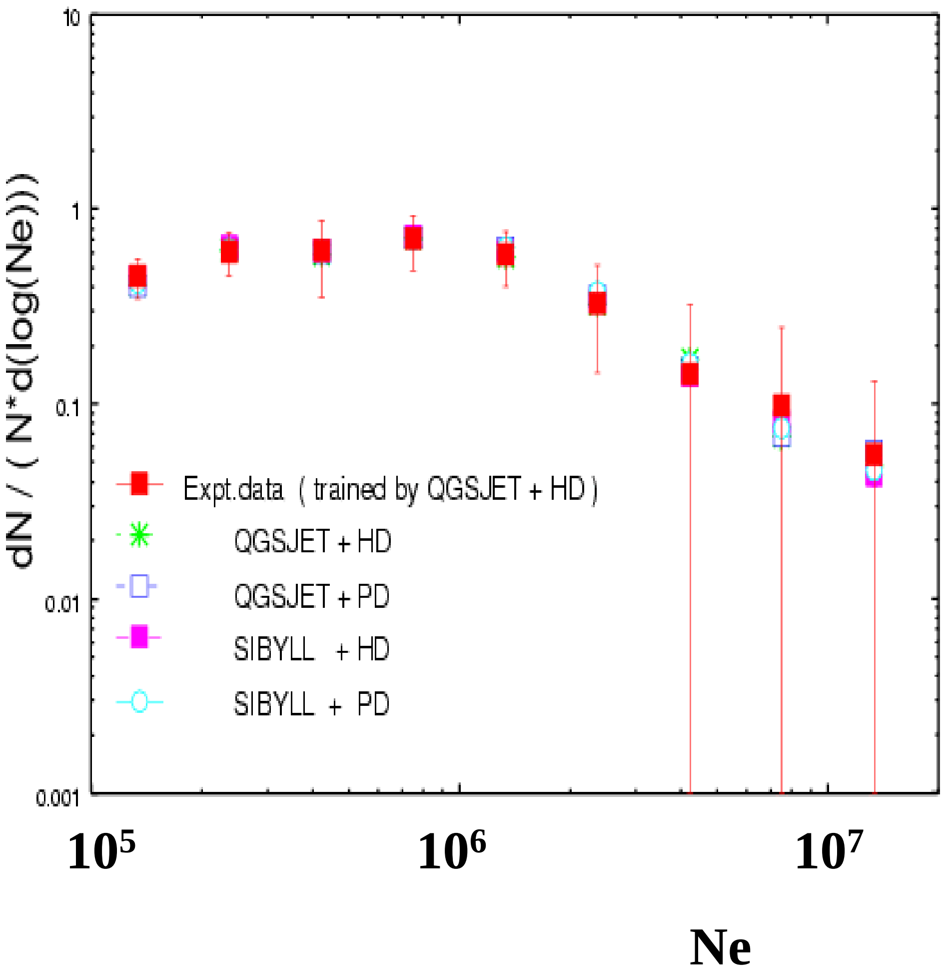
Artificial Neural Network

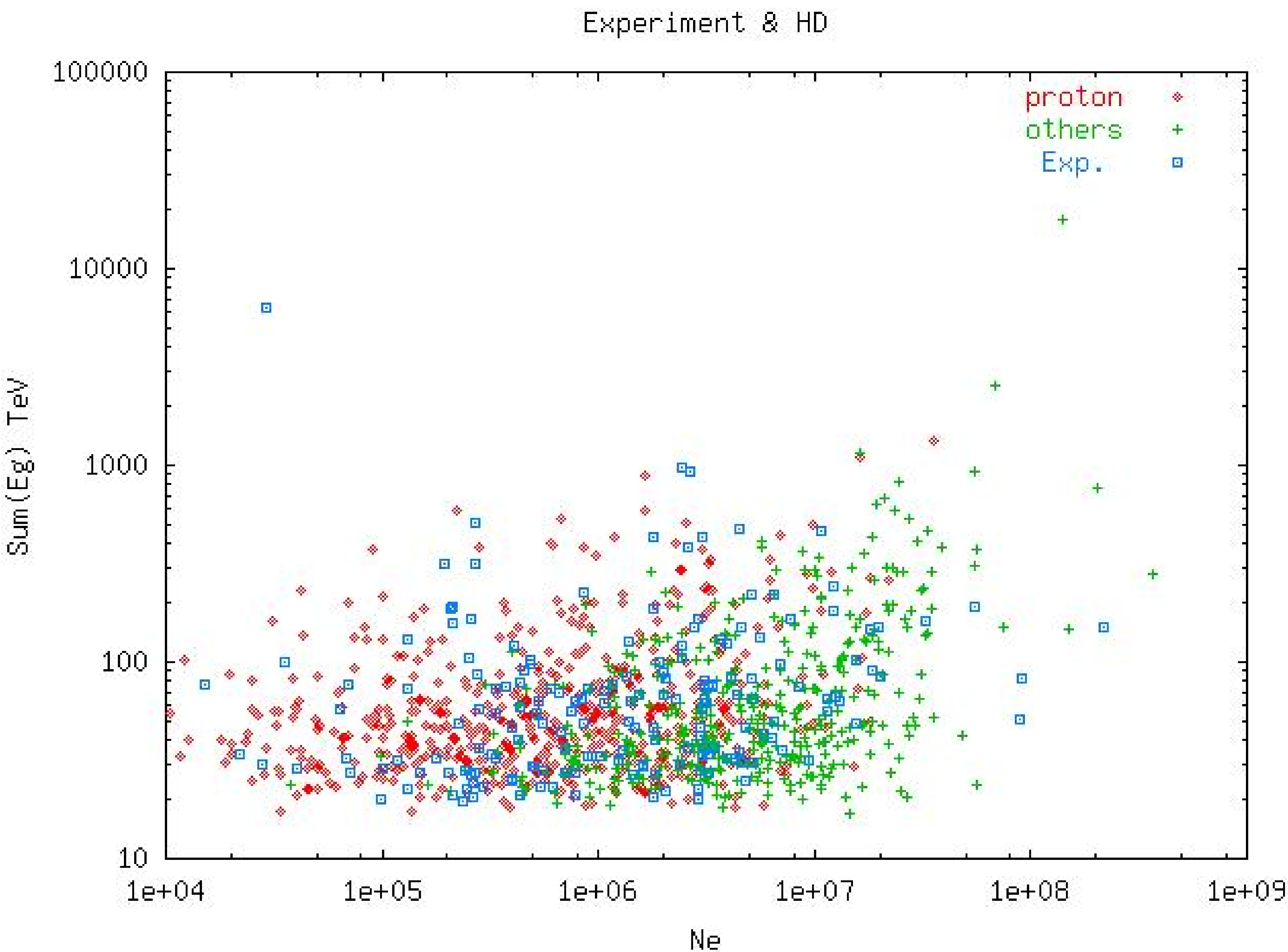
JETNET 3.5

Parameters for training: N_γ, ΣE_γ, $\langle R_\gamma \rangle$, $\langle ER_\gamma \rangle$, N_e, θ

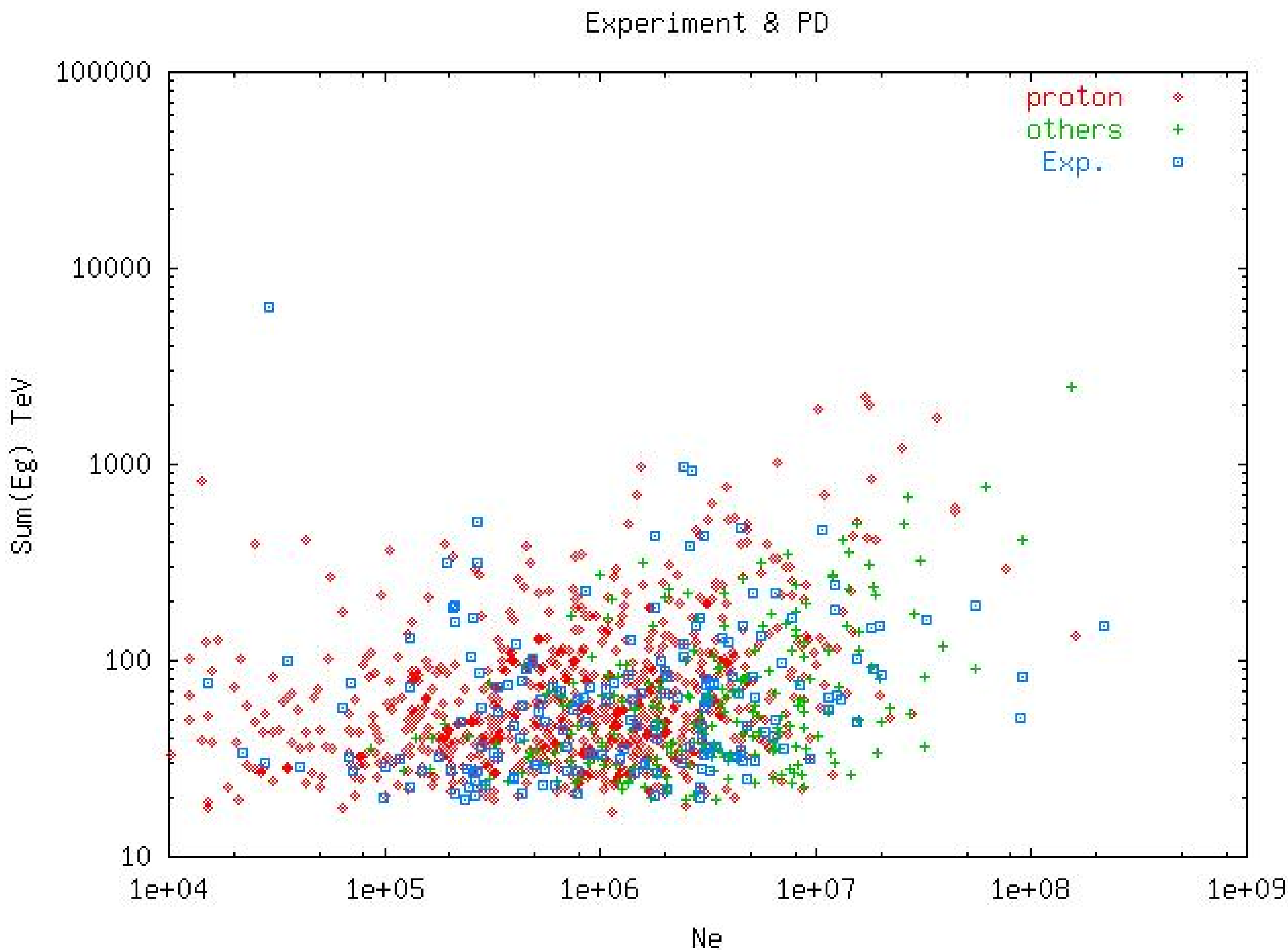


Comparison of the air shower size accompanied by γ families between QGSJET and SIBYLL (for proton like events (ANN output <=0.4))

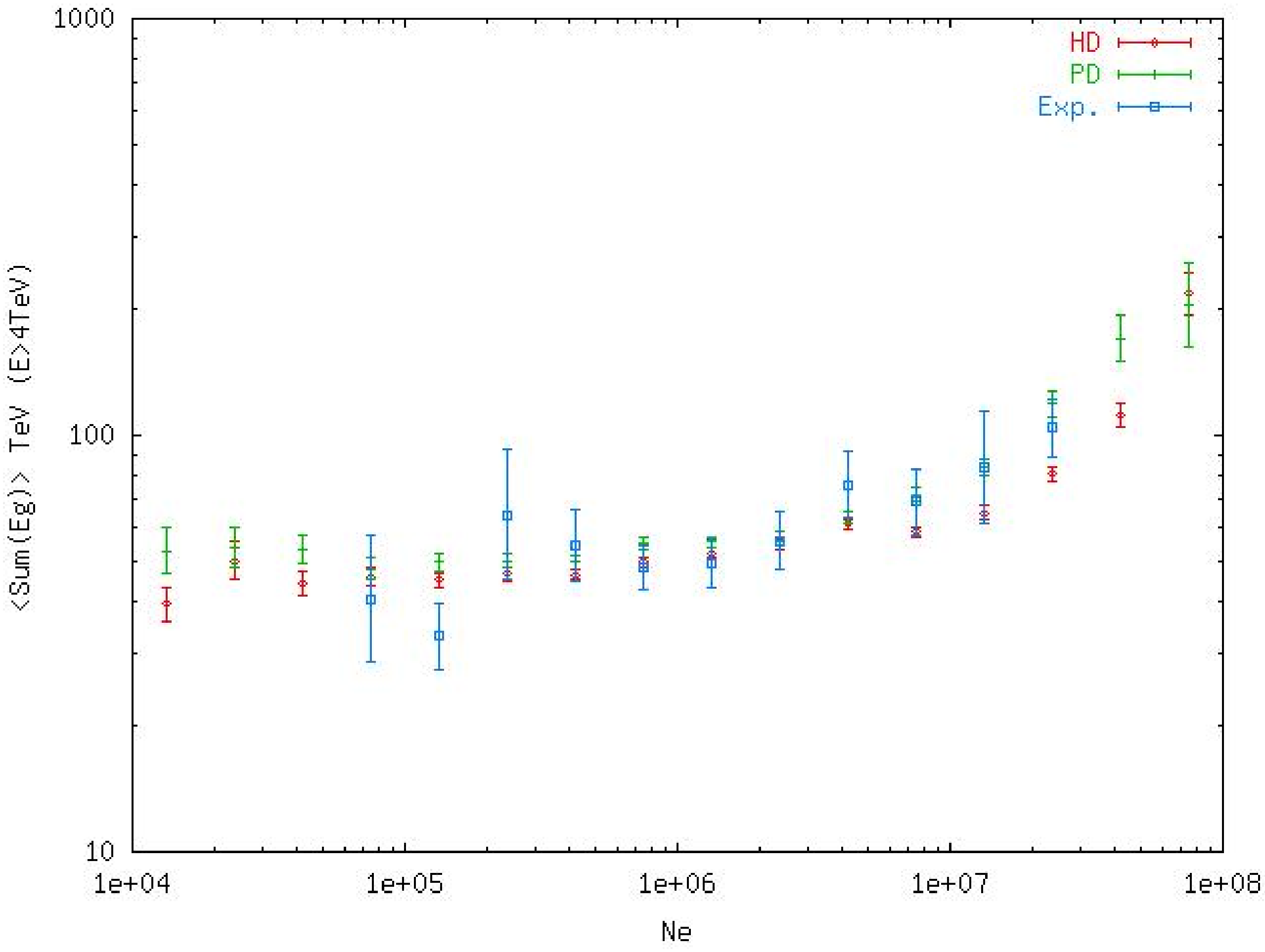




Experiment & HD
proton
others
Exp.
Sum(Eg) TeV
Ne
100000
10000
1000
100
10
1e+04
1e+05
1e+06
1e+07
1e+08
1e+09

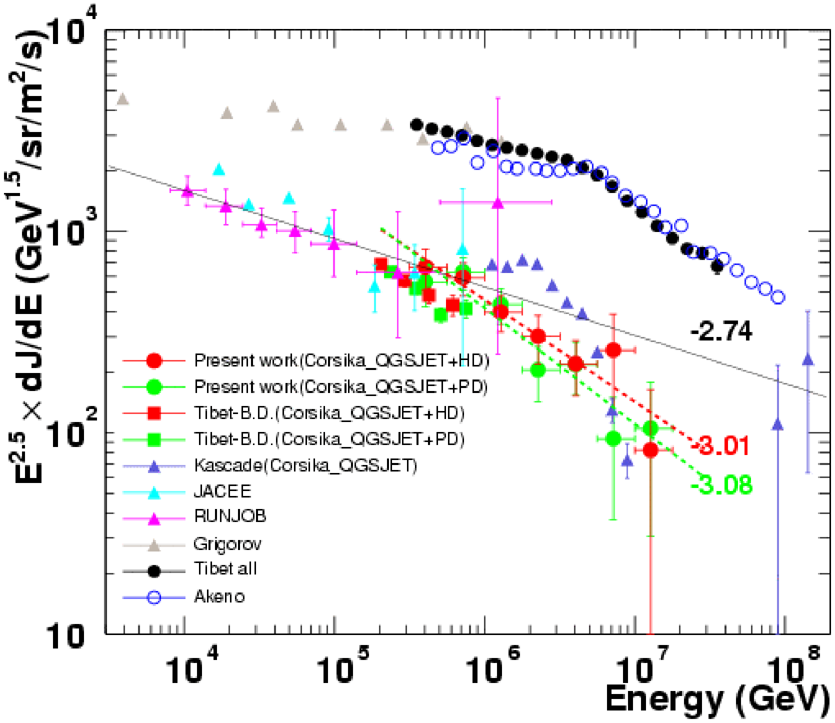

Experiment & PD
proton
others
Exp.
100000
10000
1000
100
10
Sum(Eg) TeV
1e+04
1e+05
1e+06
1e+07
1e+08
1e+09
Ne

Mean ΣE_γ vs N_e

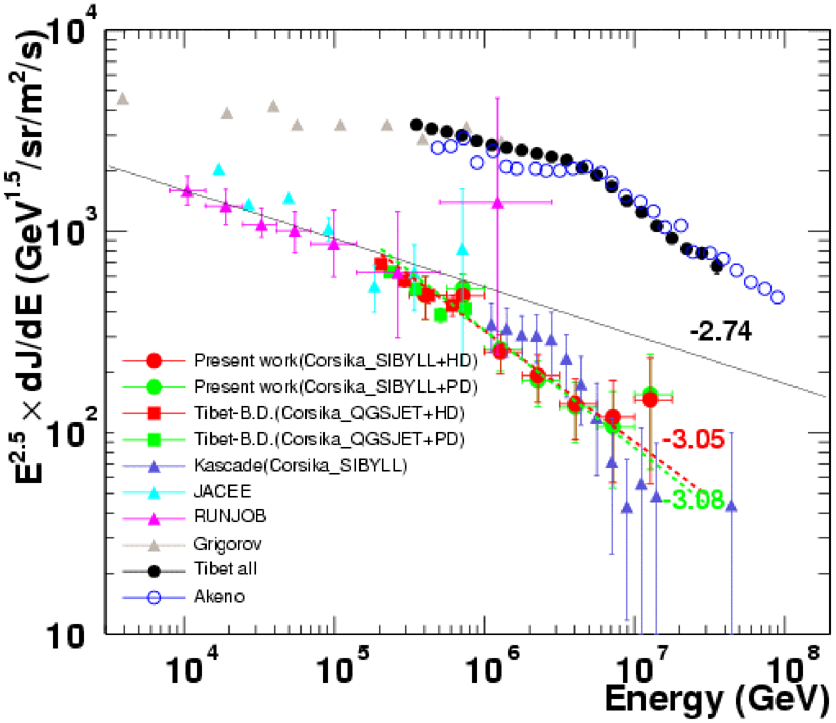


Primary proton spectrum

(a) (by QGSJET model)



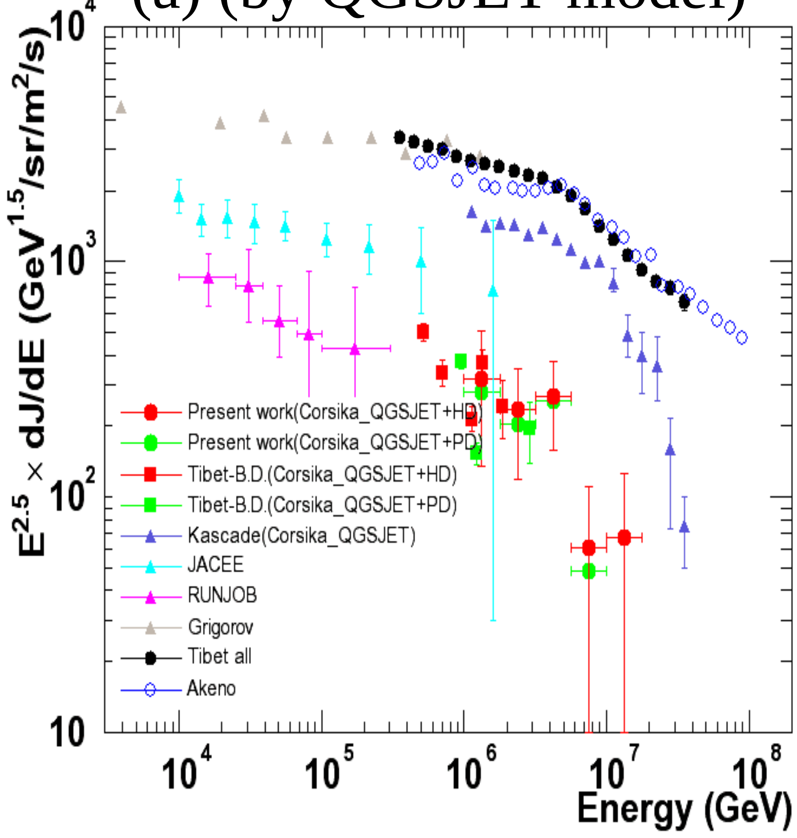
(b) (by SIBYLL model)



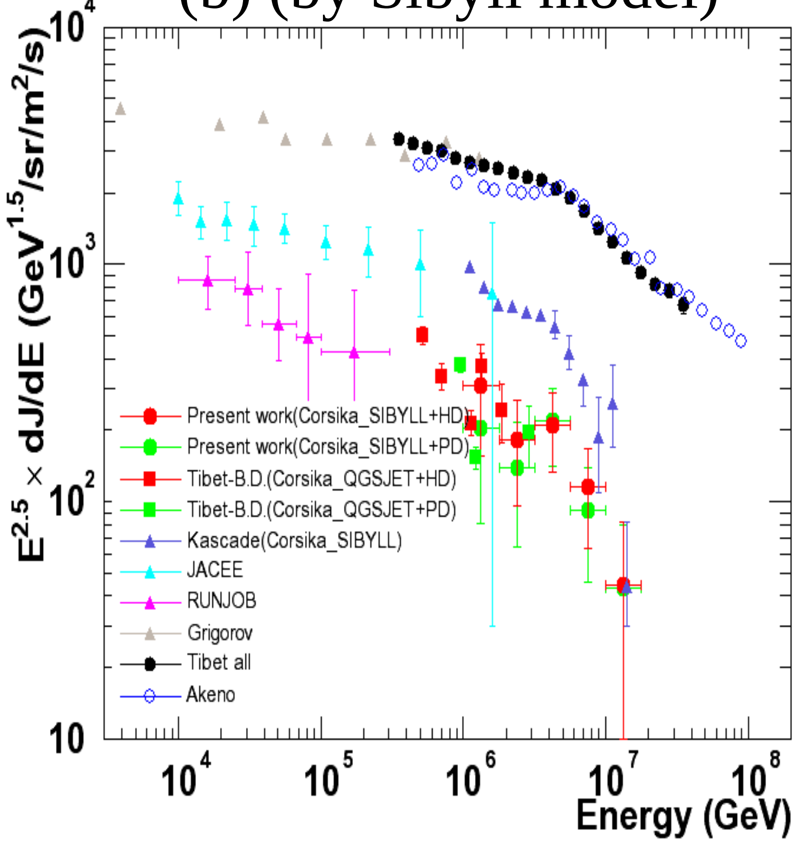
(KASCADE data: astro-ph/0312295)

Primary helium spectrum

(a) (by QGSJET model)

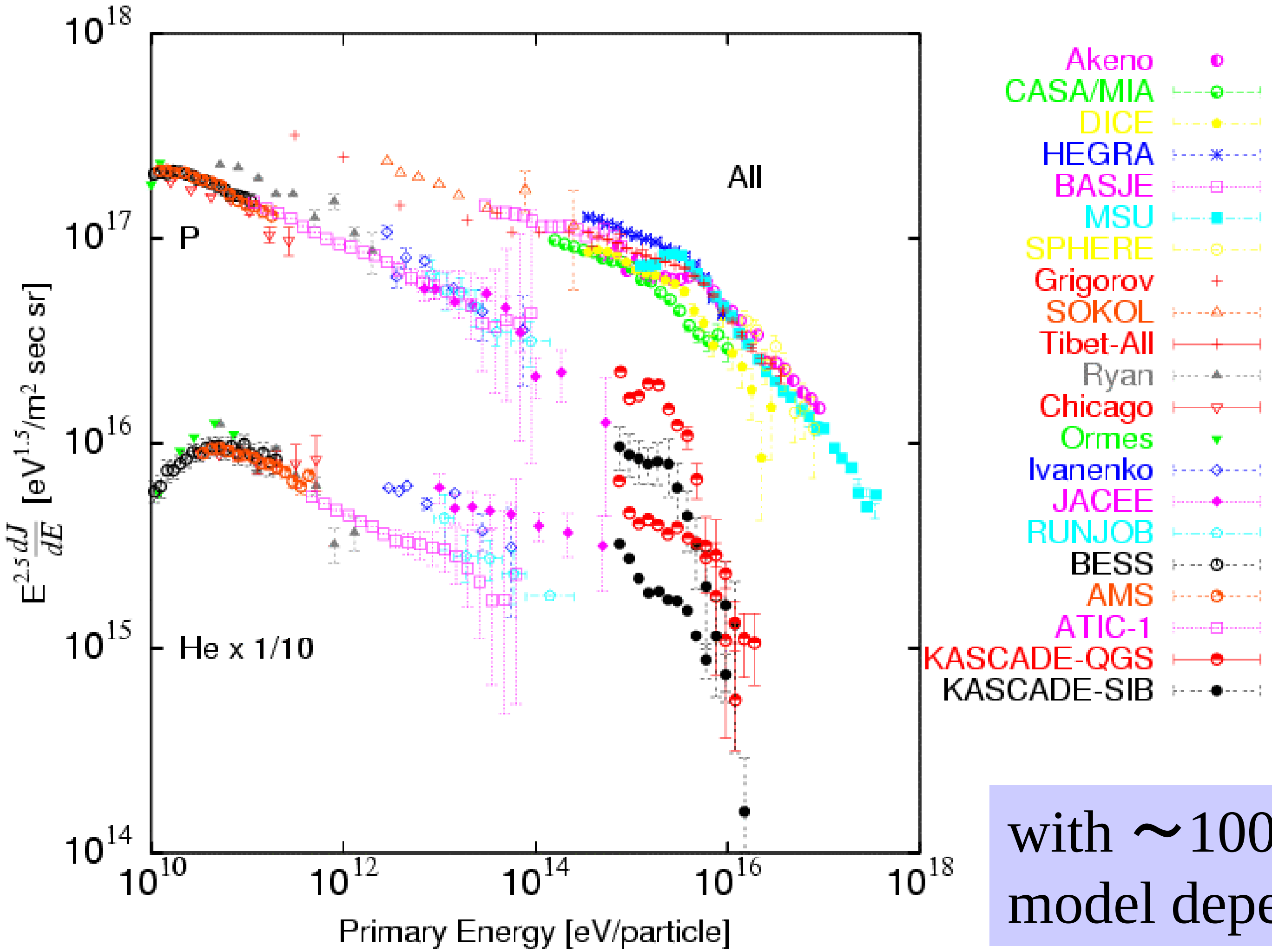


(b) (by Sibyll model)



p+helium selection: purity=93%, efficiency=70%

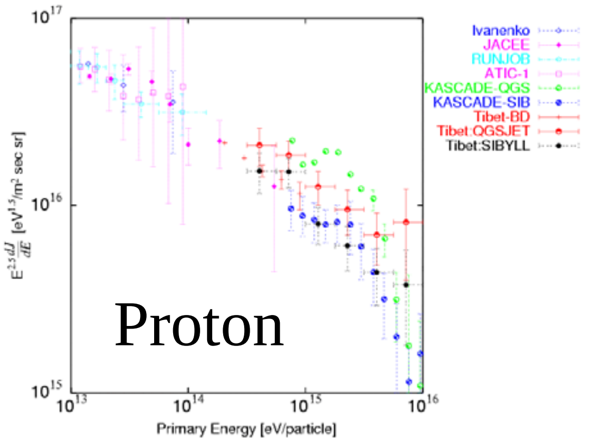
P, He by KASCADE Experiment

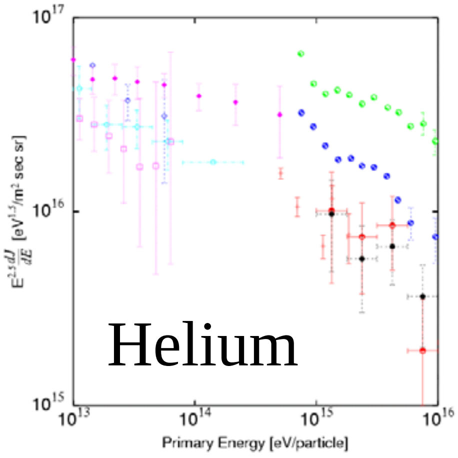


with ～100% model dependence

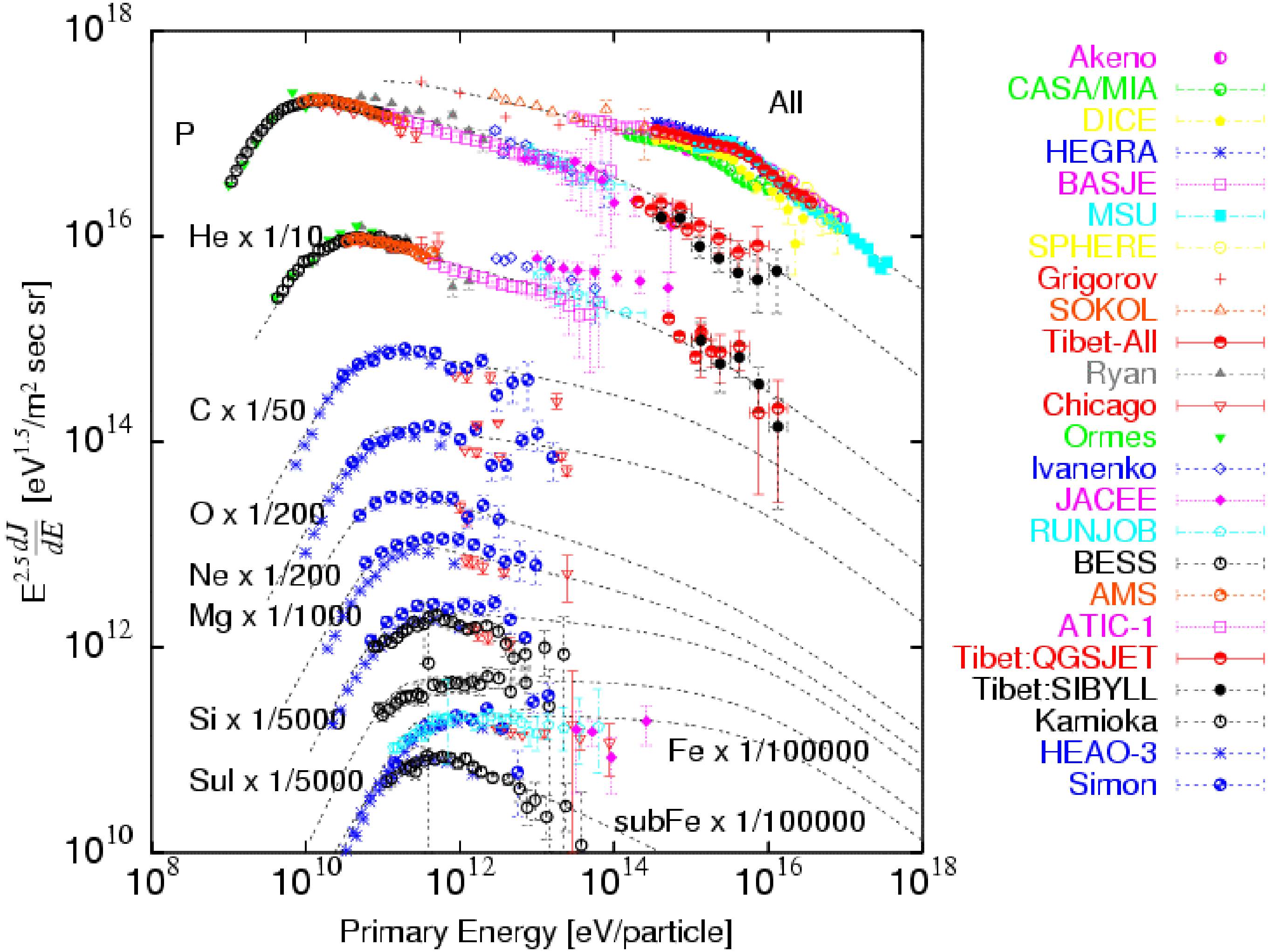
Comparison between Tibet and KASCADE

	Tibet	KASCADE
site (E_0 resol.)	606 g/cm^2	Sea level
observation	HE γ family by EC	e- μ
primary selection	p, He (quasi direct)	4(5) groups (statistical)
separation method	high E core and ANN	unfolding
statistics	low	high
model dep.	30%	100%
phase space	forward	central, bwd





CR composition at the knee

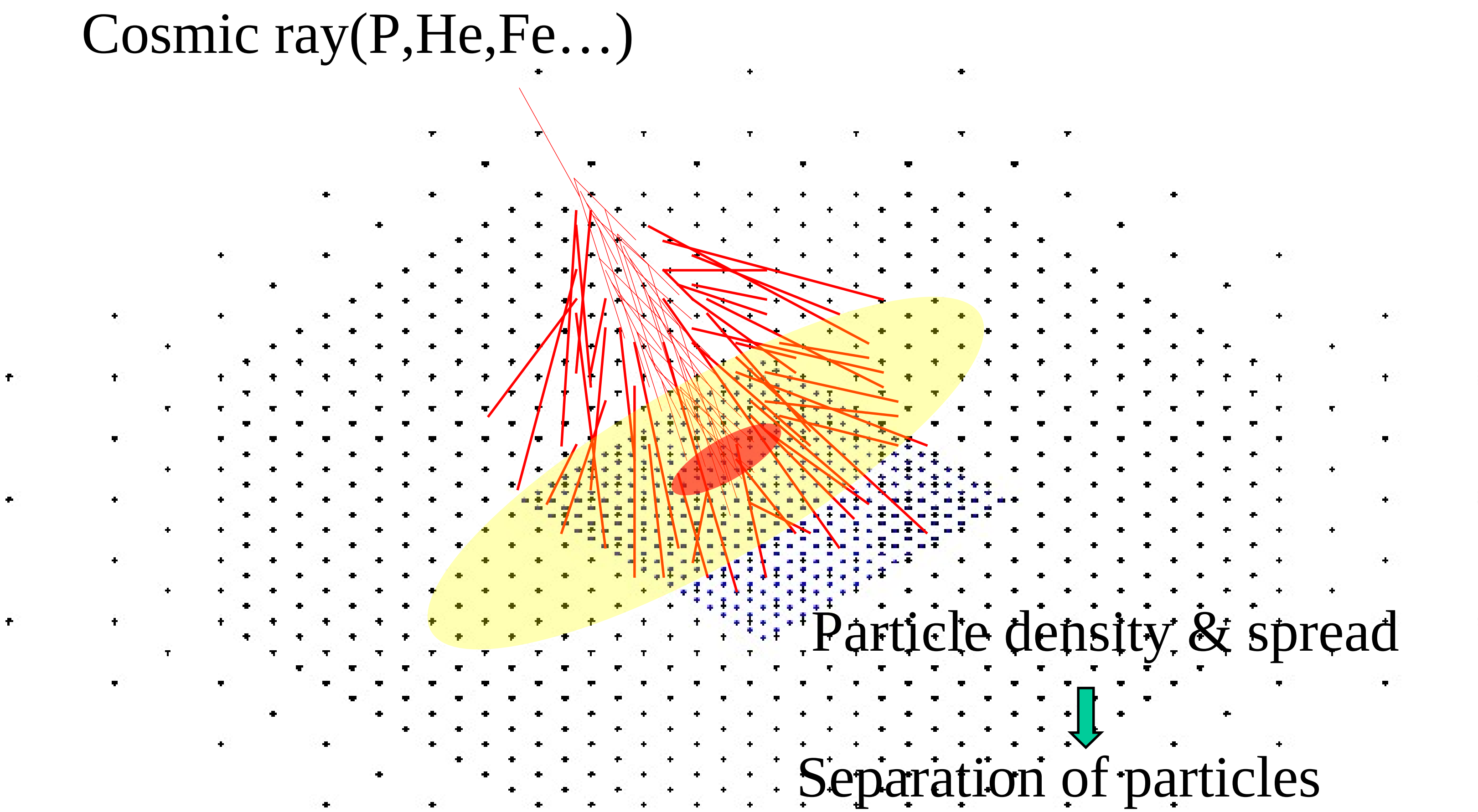


Next phase of Tibet hybrid exp. YAC

Yangbajing Air shower Core detector

- Measure the energy spectrum of the main component at the knee.
- Detector：Low threshold BD grid ＋AS array。
- Observe energy flow of AS core within several x 10m from the axis.

YAC array

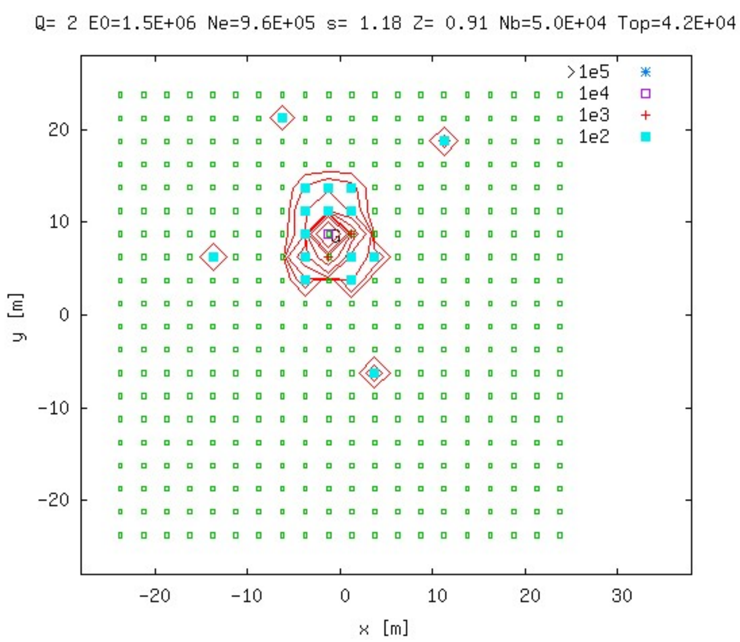


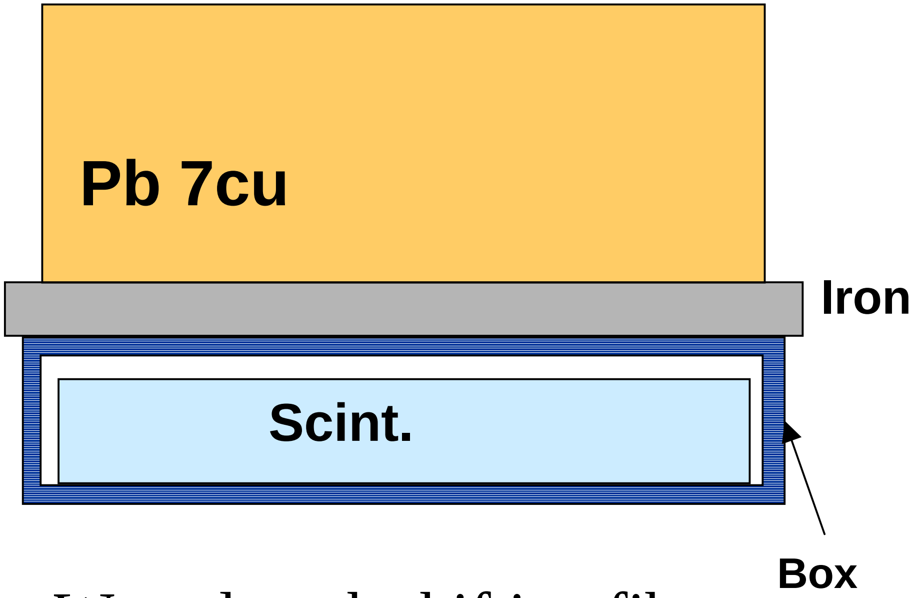
Tibet III: **Energy and direction of air shower**

Design of YAC

40cm x 50cm, 20x20 channels

$S=5000m^2$



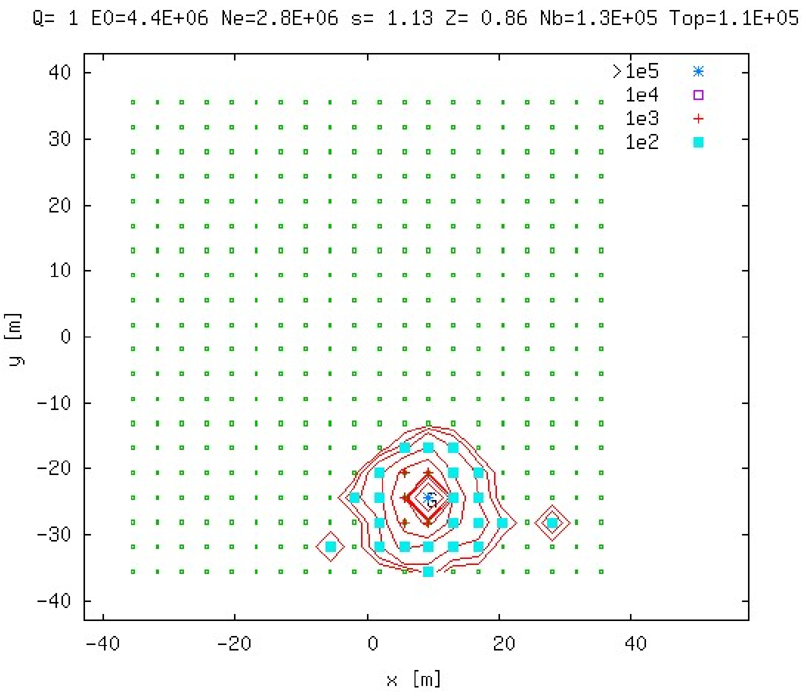


3.75m spacing 400ch
$N_b>100$, any 5
(>30GeV)

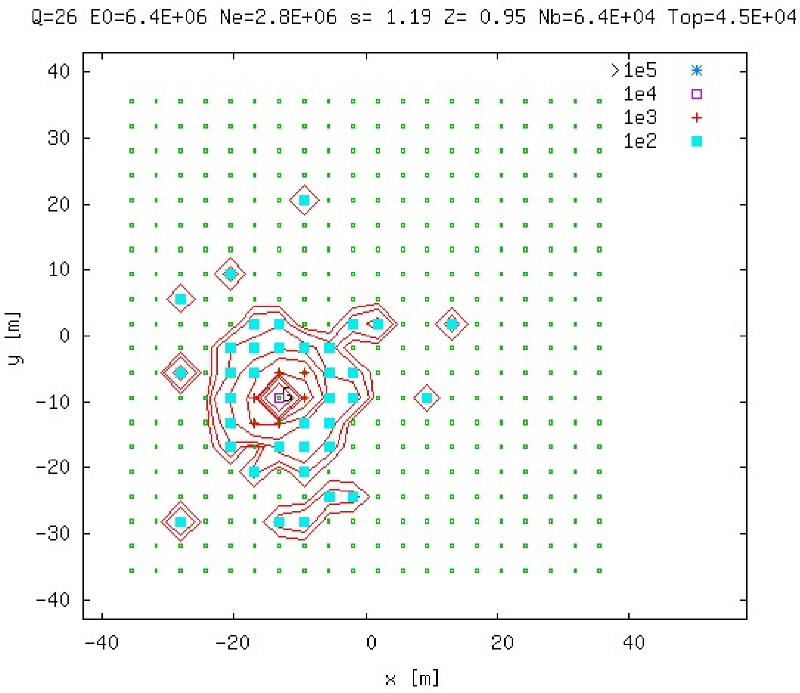
Wave length shifting fiber
+ 2 PMTs
(Low gain & High gain)
$10^2<N_b<10^6$

MC Event Map

Proton

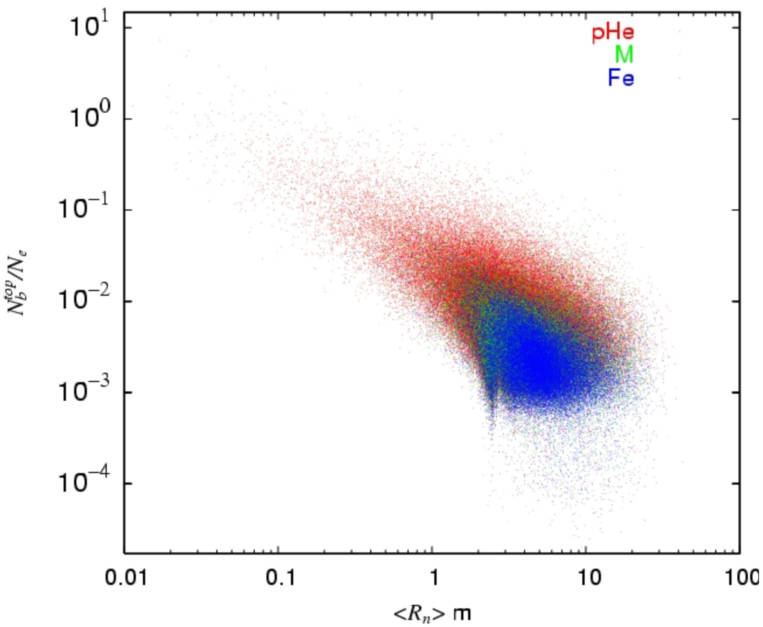


Fe

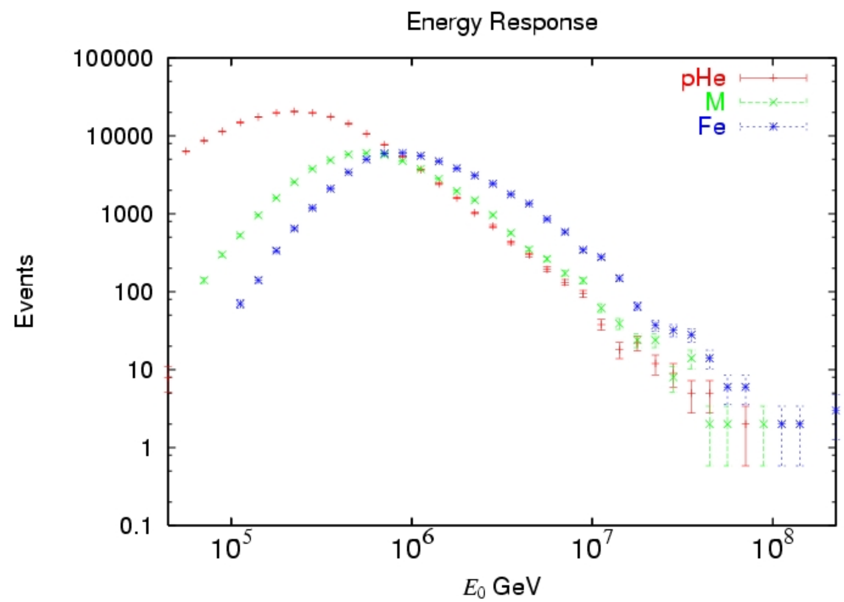


Profile of burst event

Core profile



Energy response



Trigger condition : N_b>100, $N_{hit} \geqq 3$

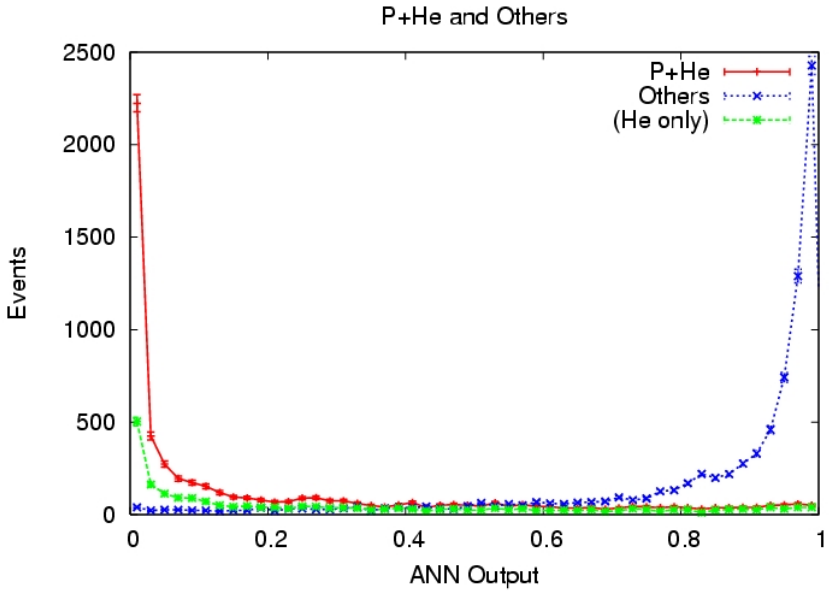
Separation of Elements by YAC(use ANN)

ANN parameters :

N_{hit}, N_b^{top} , ΣN_b , <R>, Ne, s, θ

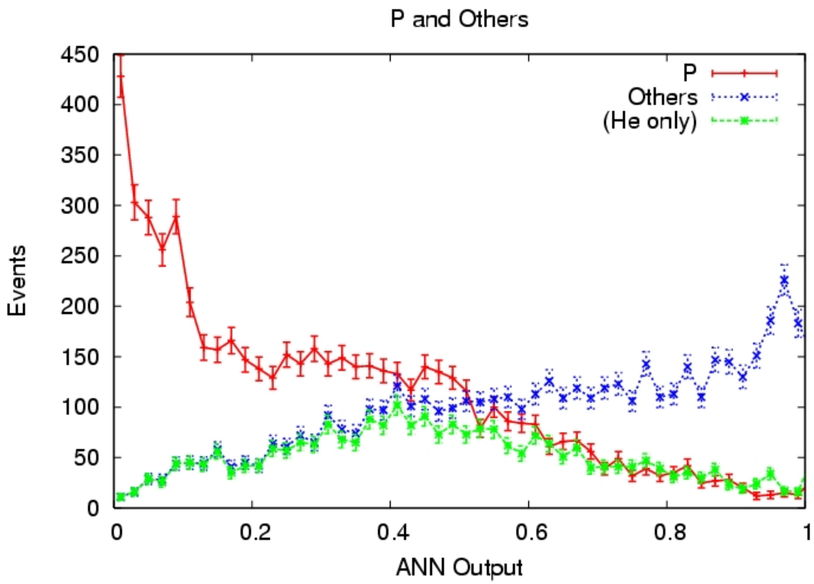
(add muon information)

$N_{hit} \geqq 8$

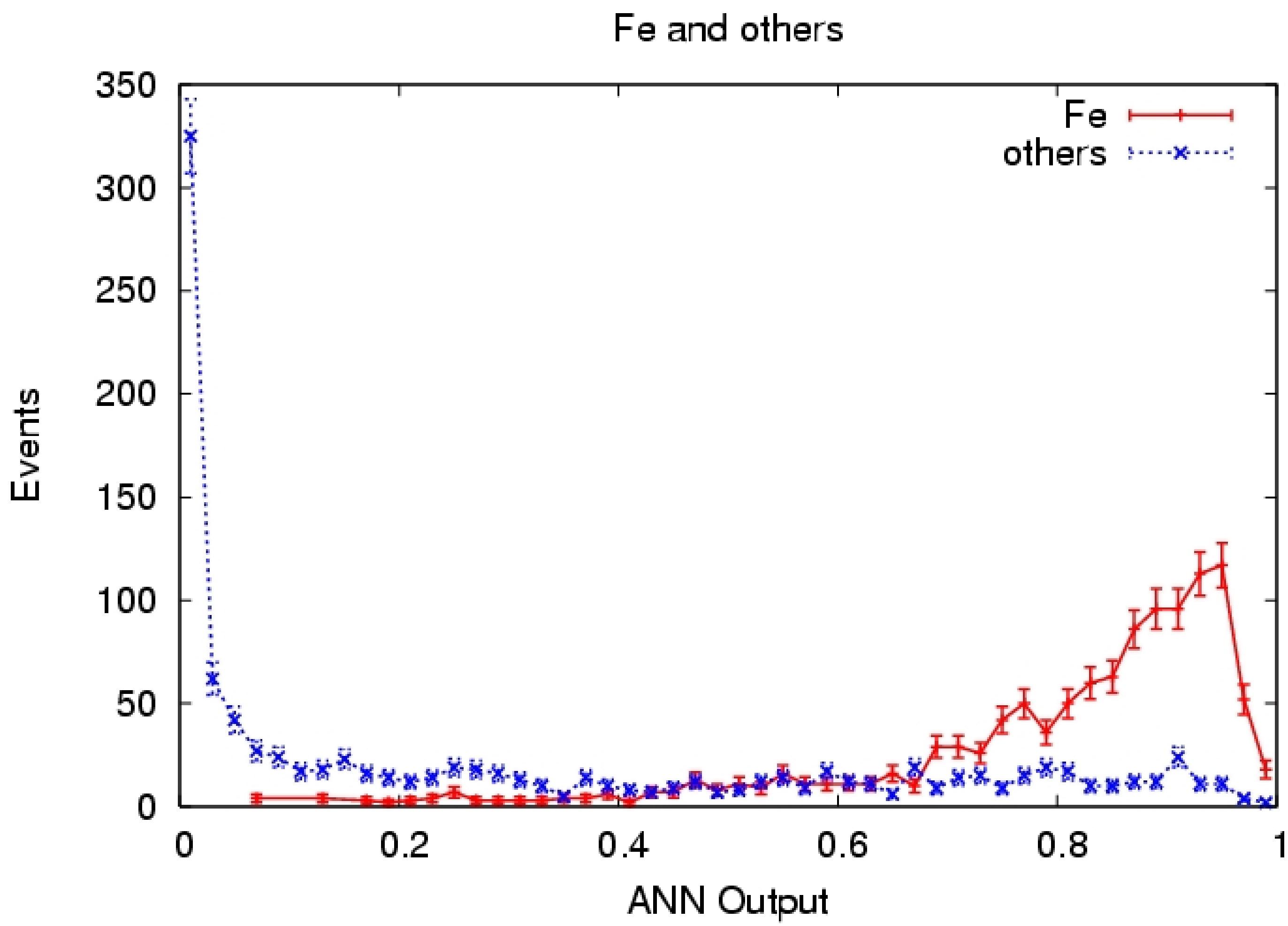


Light component selection

(<R><1.5 or N_b^{top}/N_e>0.01)



$N_{hit} \geqq 21$



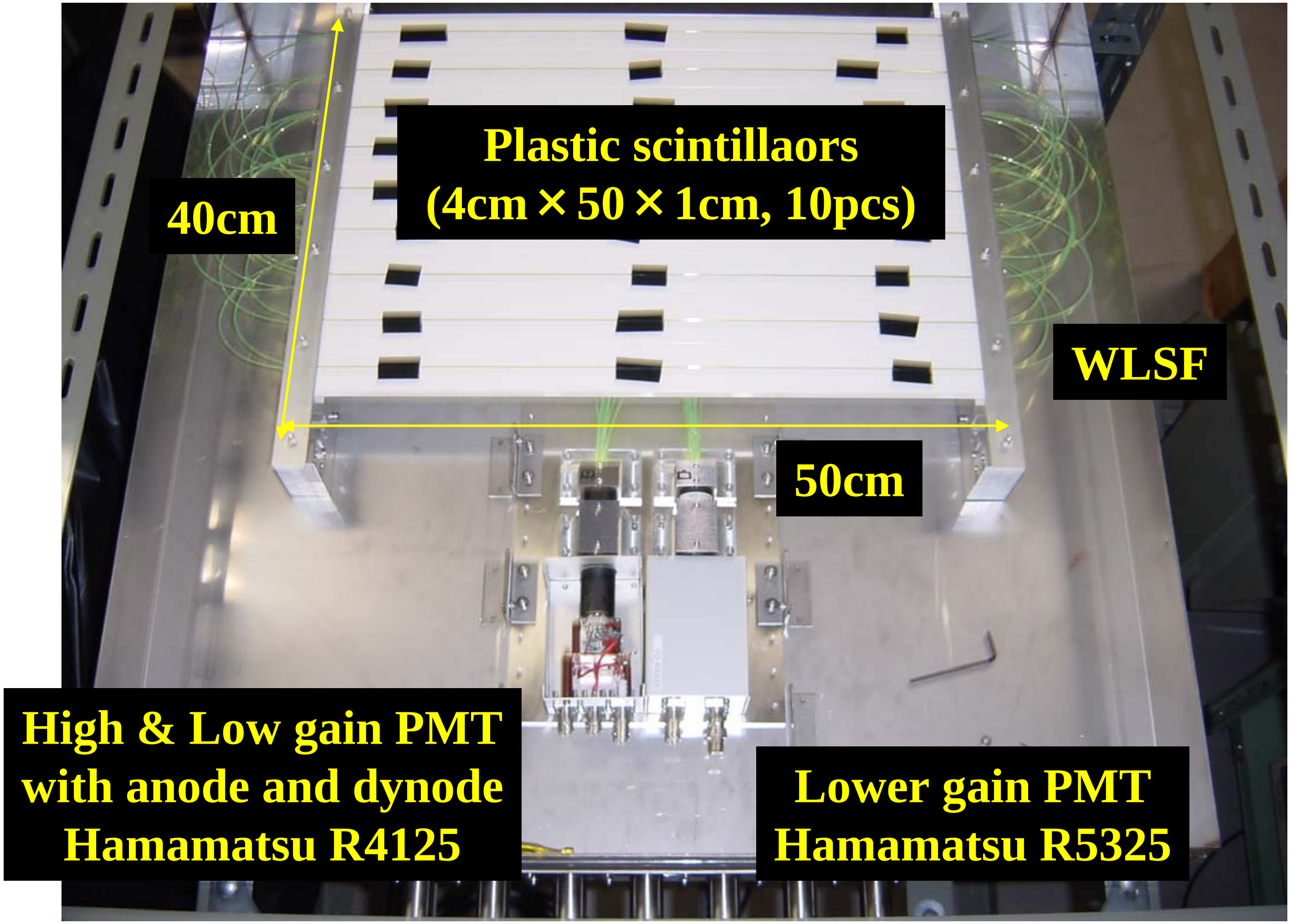
Fe and others
Fe
others
Events
ANN Output
0
50
100
150
200
250
300
350
0
0.2
0.4
0.6
0.8
1

Summary

- Direct observations are going to provide high statistics results up to 100 TeV in very near future (LDF:ATIC,CREAM,TRACER).
- The composition of the knee can be studied by indirect measurement on the basis of these direct measurements and well tuned MC (LHCf).
- Proton and helium spectra at the knee measured by Tibet hybrid experiment show steep power index of around 3.0 and low fraction to the all particles. Systematic error is within 30%.
- Next phase of Tibet experiment, YAC, will measure the heavy component at the knee to solve the problem of the "Origin of the Cosmic Rays."

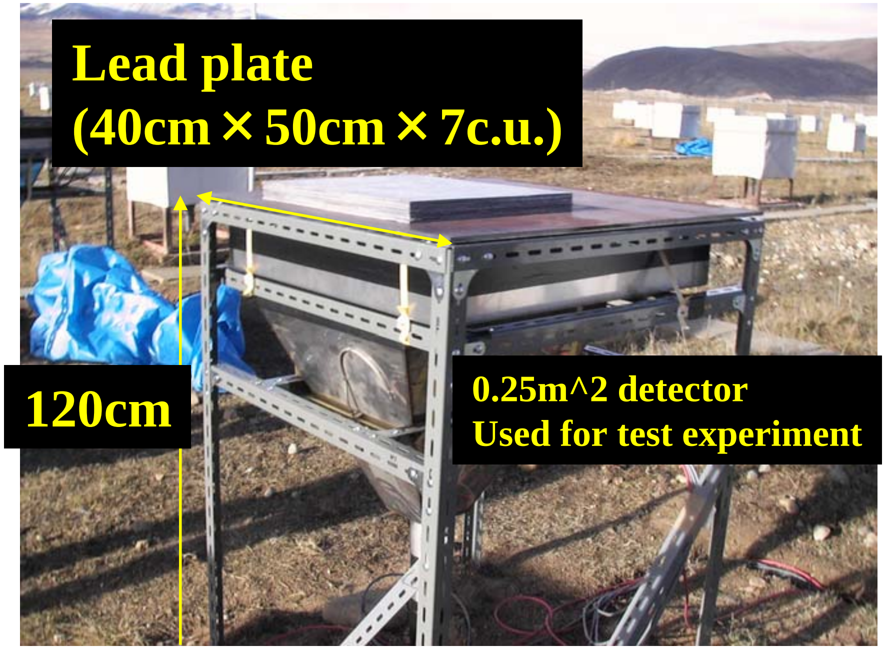
Thank you

Test detector

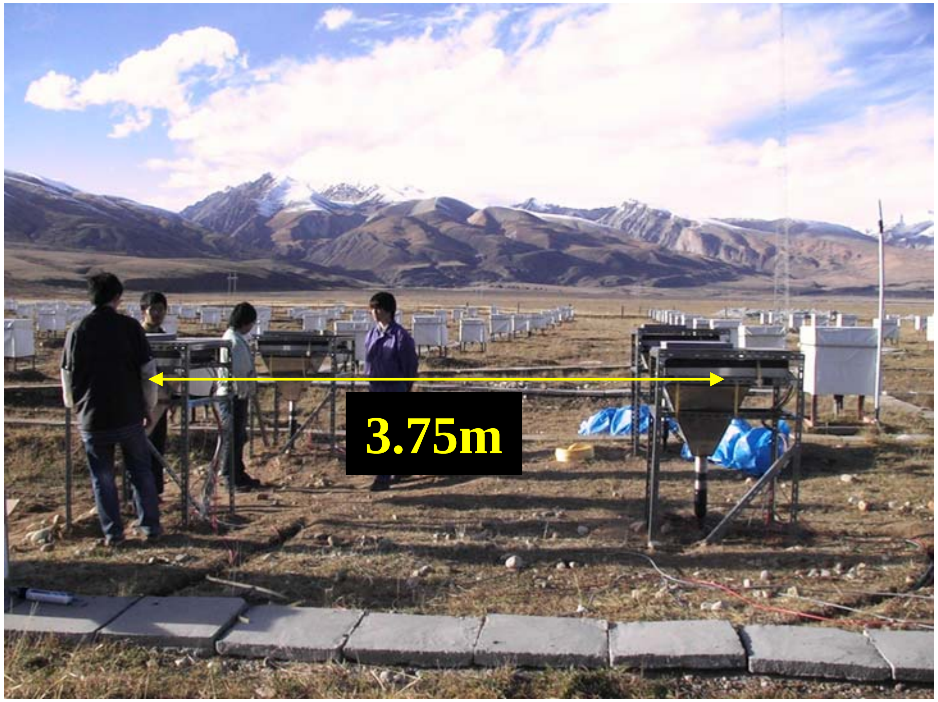


Test experiment at Tibet Yangbajing

2004.11 ~

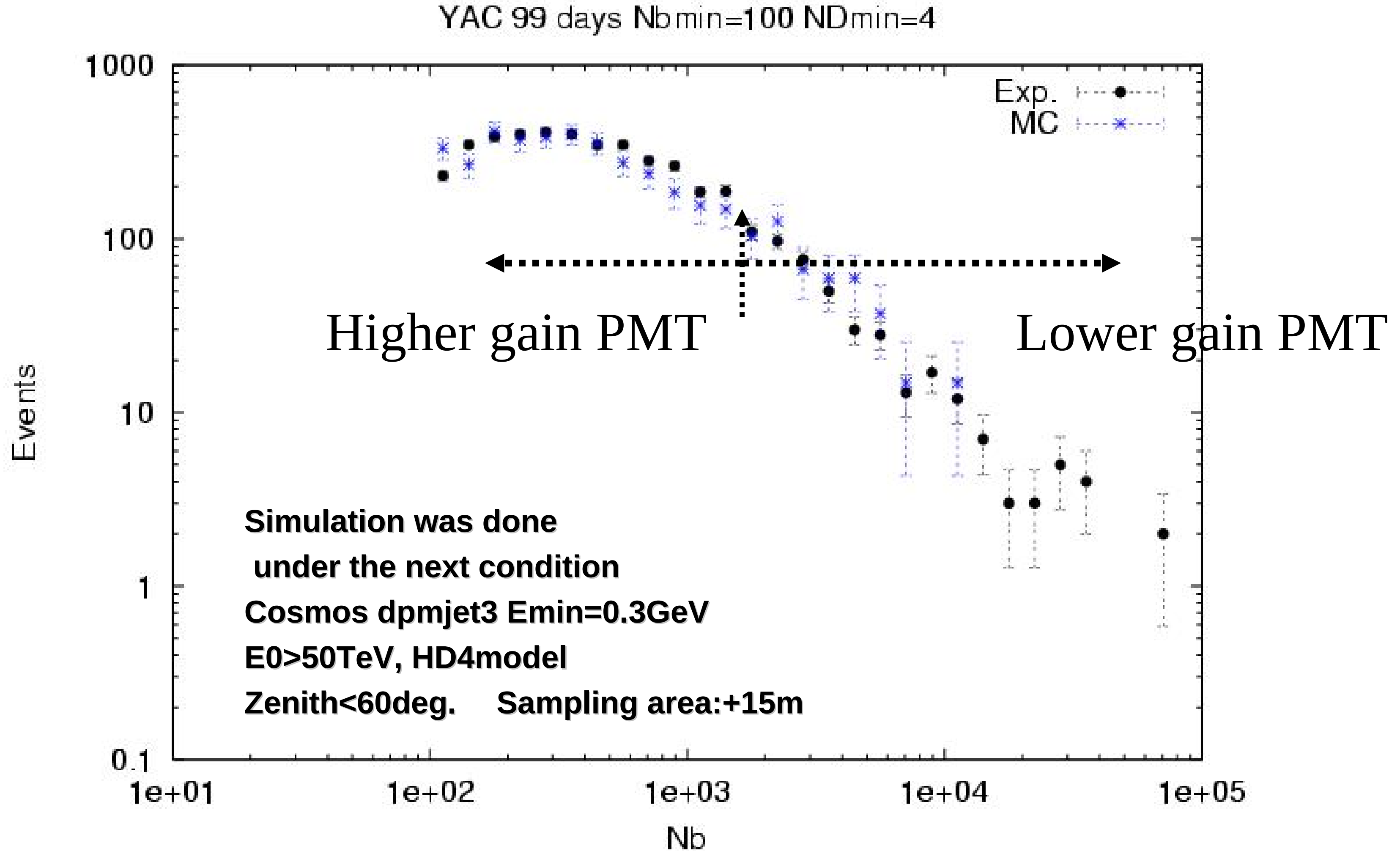


YAC



Trigger condition: Nb >40 particles(~150mV） Any1
Trigger rate： ~0.15Hz

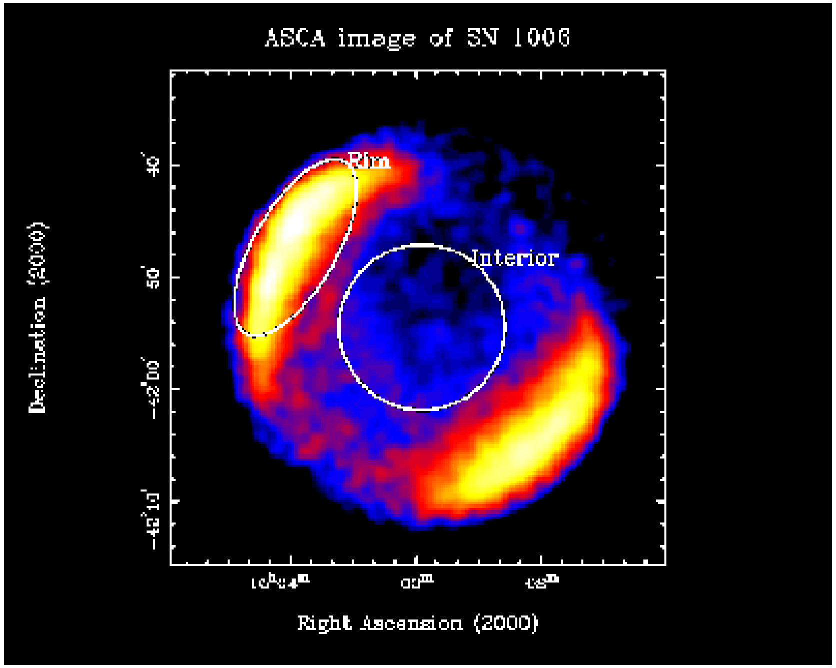
Observed spectrum of the burst size (Nb)

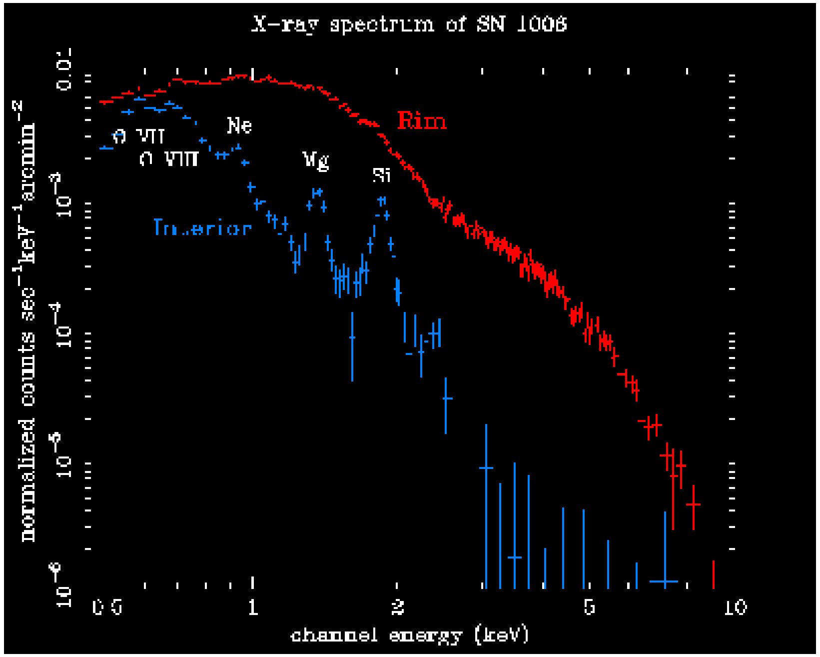


まとめ：ASコア観測（YAC)により期待される成果

- 4成分のエネルギースペクトル
  陽子・ヘリウム・M・鉄グループ
  →Knee 領域の主成分の解明
- それぞれの成分のbreak point（加速限界）
  →超新星衝撃波加速モデルの検証
- 10^{16}eVまでのCompositionを確立
  低エネルギー側への寄与→ν 物理, γ 線源探索（AS,Cherenkov B.G.)
  高エネルギー側への寄与→ 10^{16}eV以上の観測に対する基礎データ、
  最高エネルギー宇宙線（GZK問題）

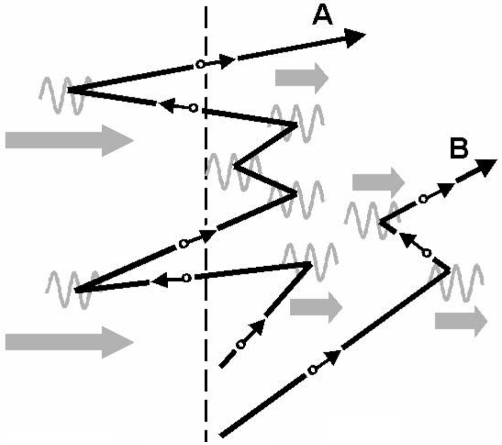
Evidence of electron acceleration at SNR





Diffusive Shock Acceleration mechanism

First order Fermi acceleration takes place efficiently at the shock front.



$$E_{max} = 3.2\times 10^4\ \mathrm{GeV}\cdot Z(\frac{u_1}{5\times 10^8\ \mathrm{cm/s}})(\frac{B}{3\mu\mathrm{G}})$$

$$\times[(\frac{M_{ejecta}}{10M_\odot})\cdot(\frac{1\ \mathrm{proton/cm^3}}{\rho_{ISM}})]^{\frac{1}{3}}$$

Tibet Hybrid Experiment

Tibet As$_\gamma$ Collaboration

1996—1999 AS+EC+BD

～200 events→P,He spectrum

Phase2:2002—2005 AS+BD

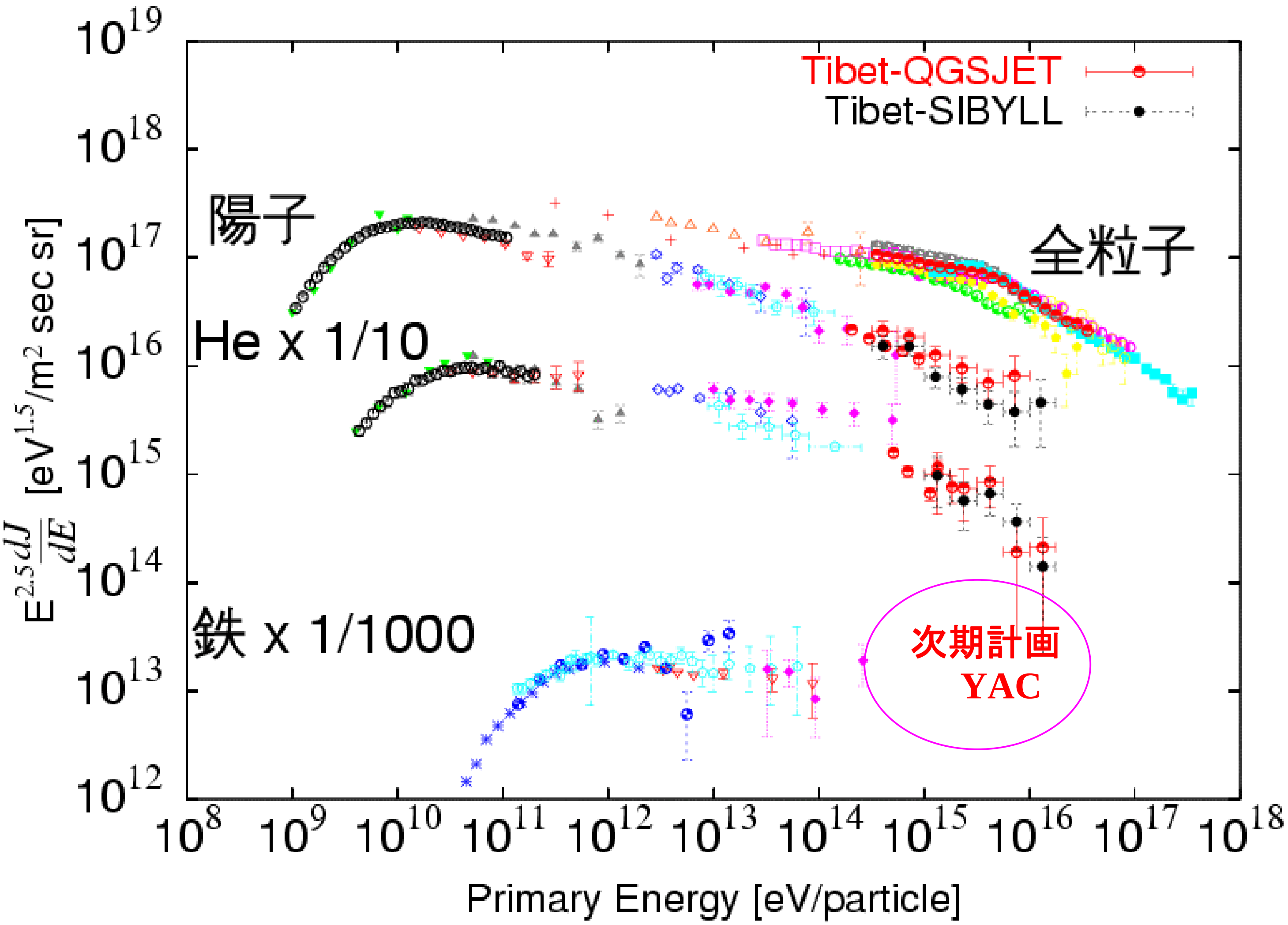
Light component(P+He)

with high statistics～3000 events

Phase3:in preparation AS+BD grid array

Observe heavy component at the knee

Result of Tibet Hybrid Exp.



Summary (2)

(1) The measured proton energy spectra can be expressed by a single power-law function with a differential spectral index,

$J(E)(m^{-2}s^{-1}sr^{-1}GeV^{-1}) = A \times 10^{-13} \times (E / 10^{6}\ GeV)^{-B}$

(A,B)= (4.56 +- 0.46, 3.01 +- 0.11) (by QGSJET + HD)

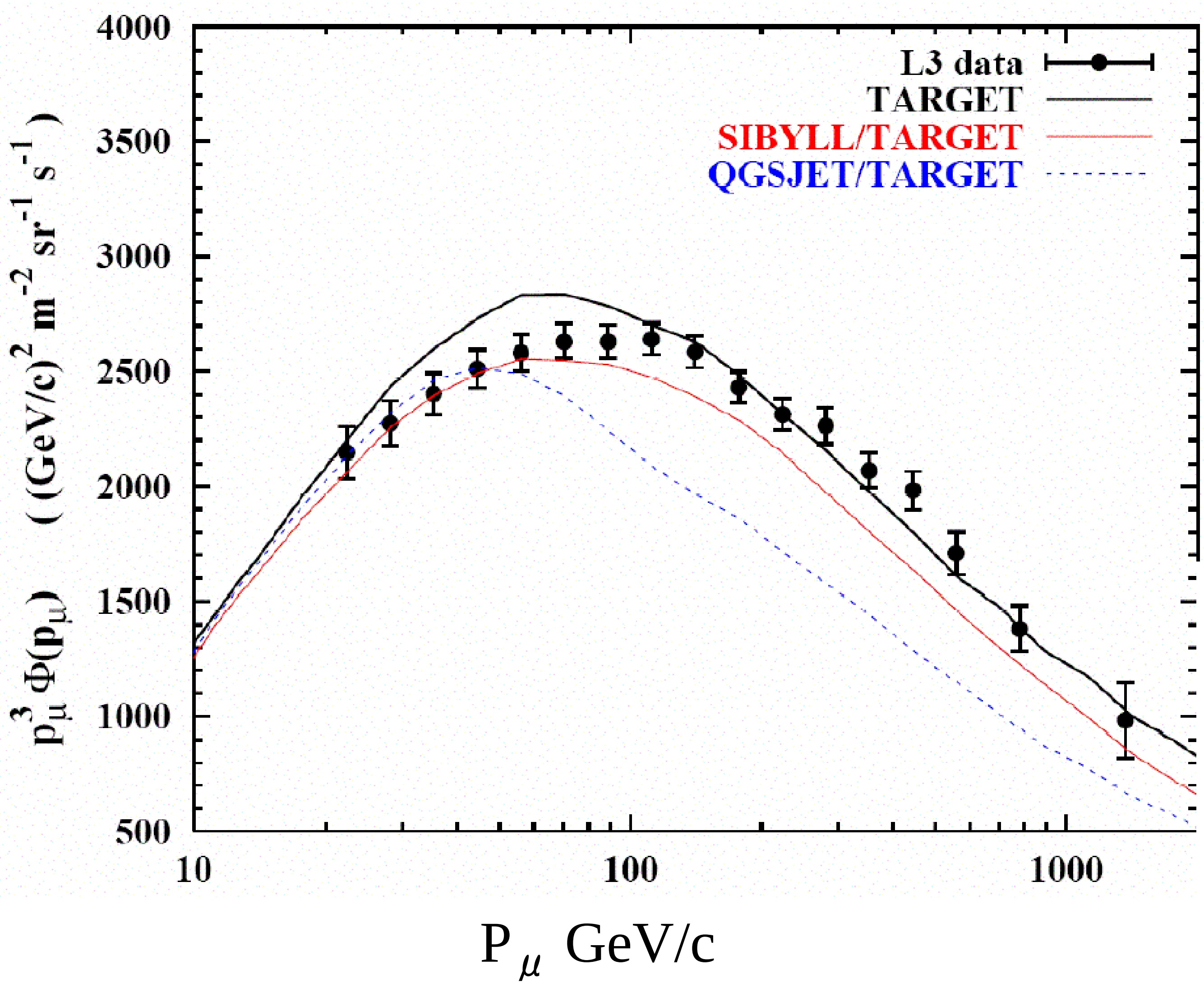
= (4.14 +- 0.44, 3.08 +- 0.11) (by QGSJET + PD)

= (3.21 +- 0.34, 3.05 +- 0.12) (by SIBYLL + HD)

= (3.24 +- 0.34, 3.08 +- 0.12) (by SIBYLL + PD)

(2) Our experiment suggests that the main component responsible for making the knee structure of the all-particle spectrum is composed of nuclei heavier than helium.

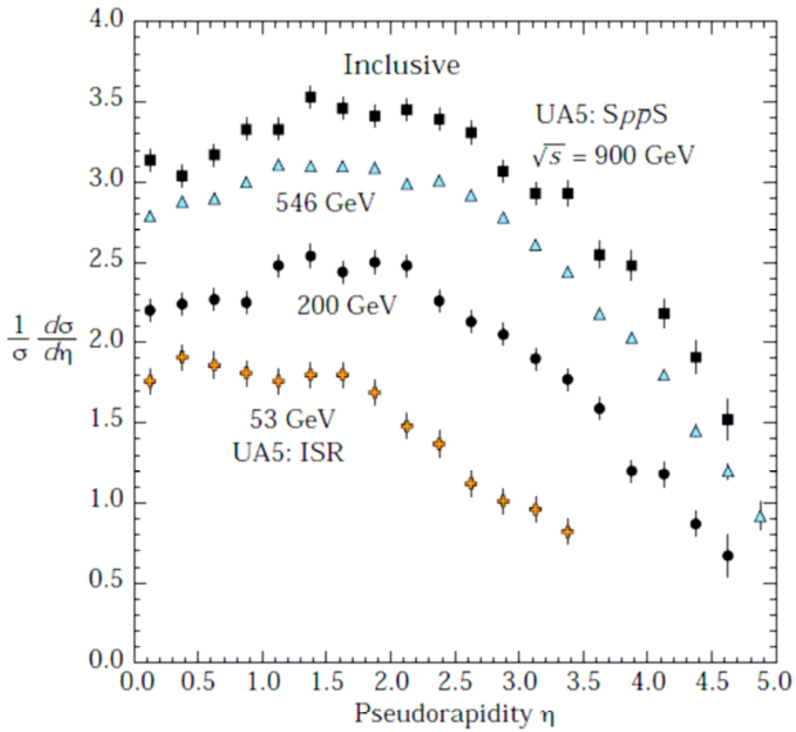
Vertical muon flux at sea level

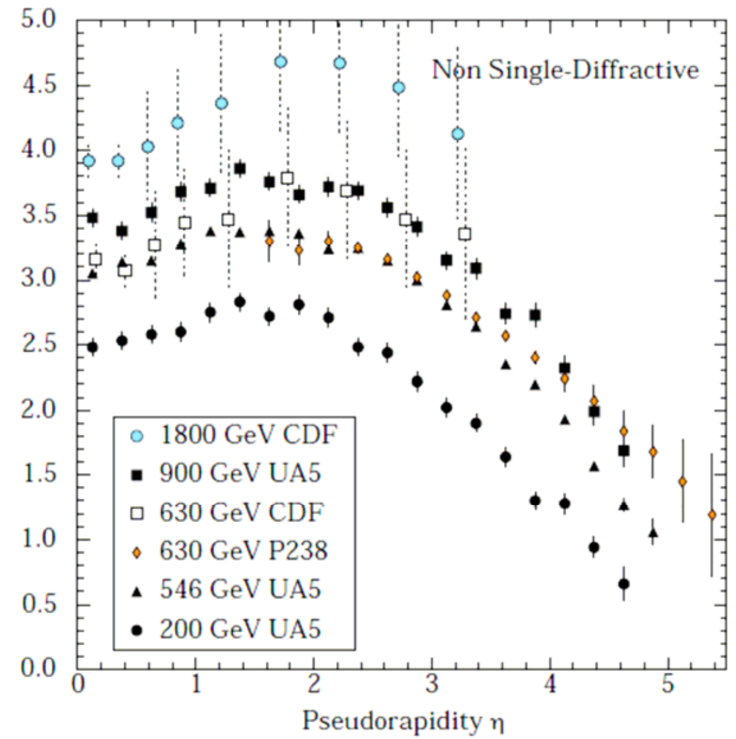


Pseudo rapidity ($\bar{p}p$)

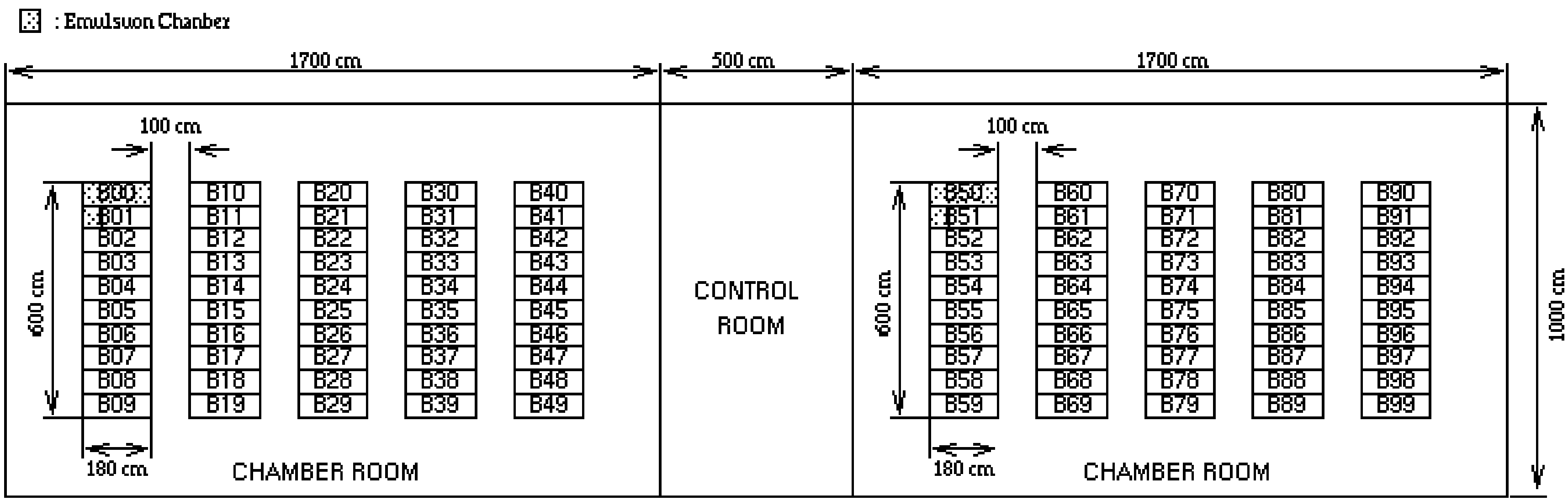
$$\eta = -\log(\tan\frac{\theta}{2})$$

θ : emission angle of charged particles

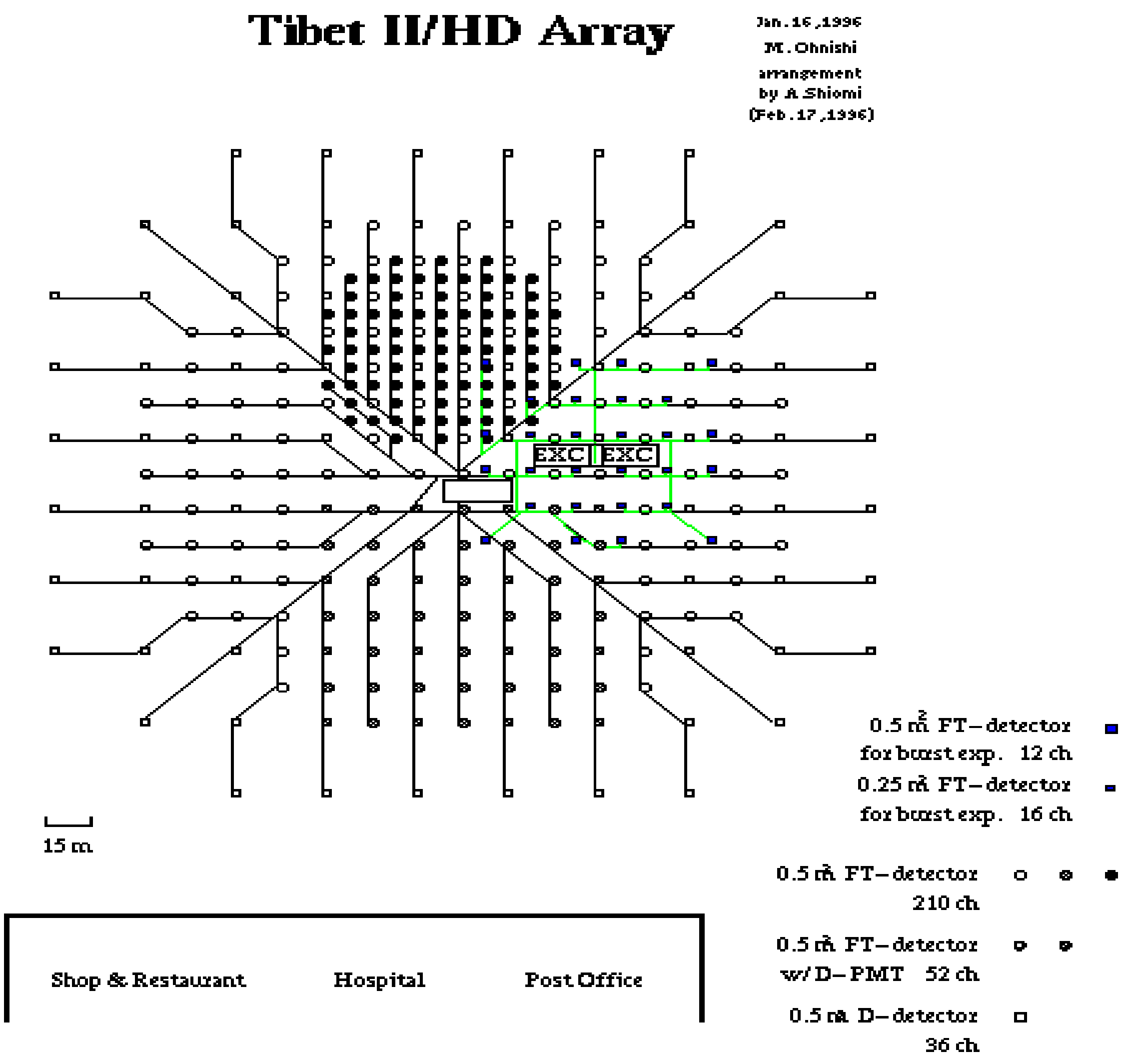




Burst detectors

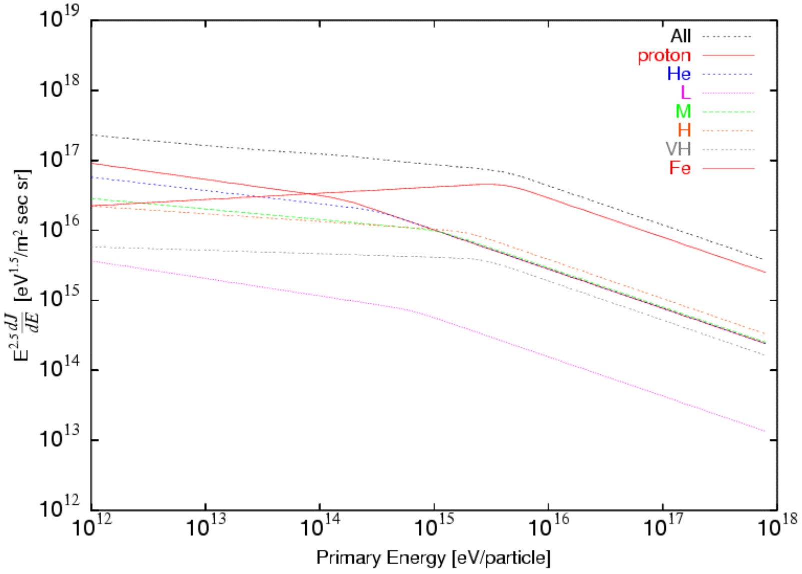


Tibet II/HD array

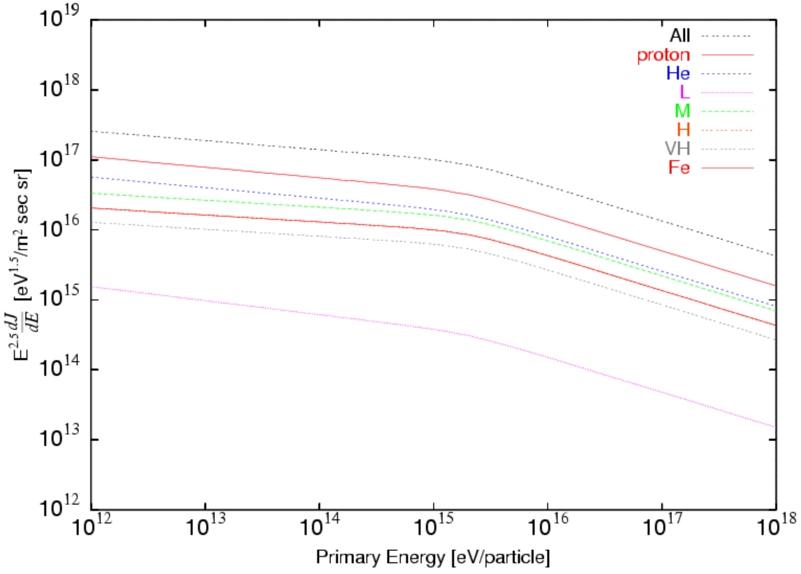


Primary composition model

HD model



PD model

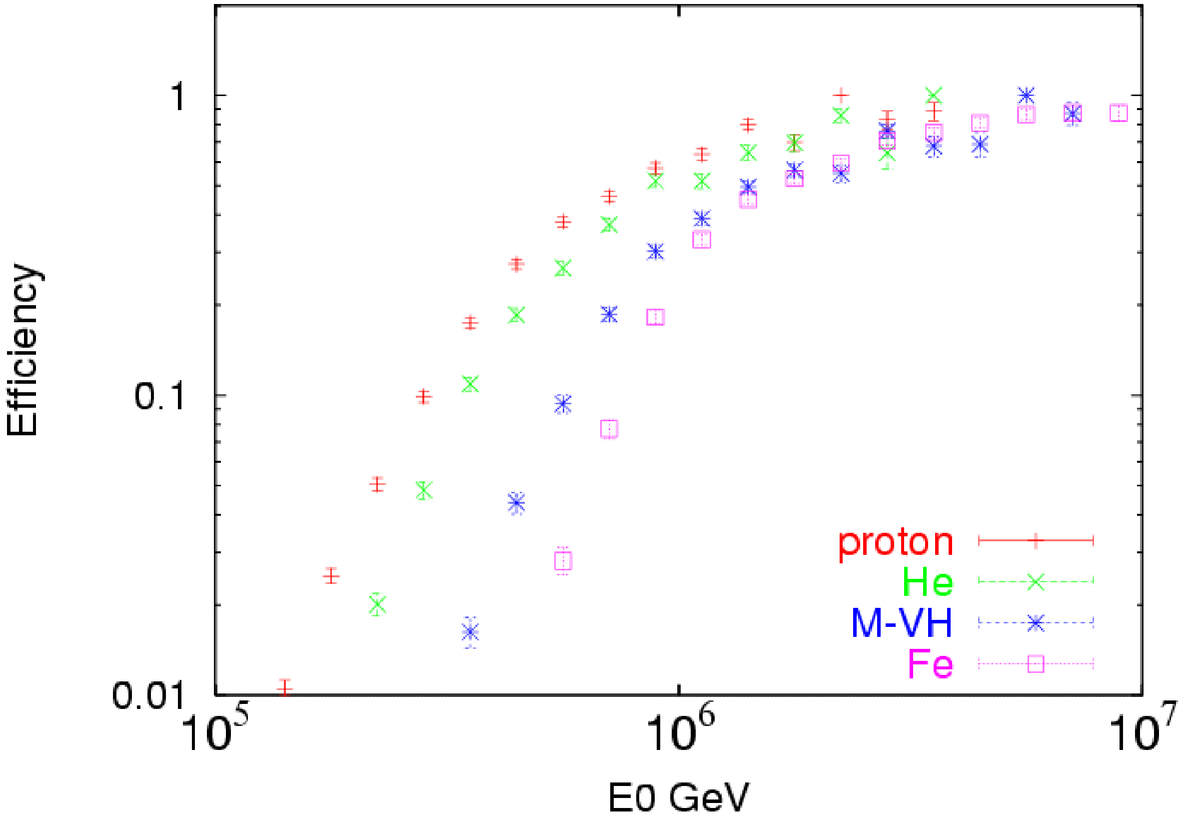


Fraction of elements

HD model			
	10^{14}eV	10^{15}eV	10^{16}eV
Proton	22.6	11.0	8.1
He	19.2	11.4	8.4
CNO	21.0	22.6	17.8
NaMgSi	9.0	9.4	8.1
SClAr	5.6	6.2	5.8
Iron	22.2	39.1	51.7

PD model			
	10^{14}eV	10^{15}eV	10^{16}eV
Proton	39.0	38.1	37.5
He	20.4	19.4	19.1
CNO	15.2	16.1	16.5
NaMgSi	9.4	9.9	10.2
SClAr	5.8	6.2	6.3
Iron	9.4	9.9	10.2

Detection efficiency of YAC



Expected results by YAC