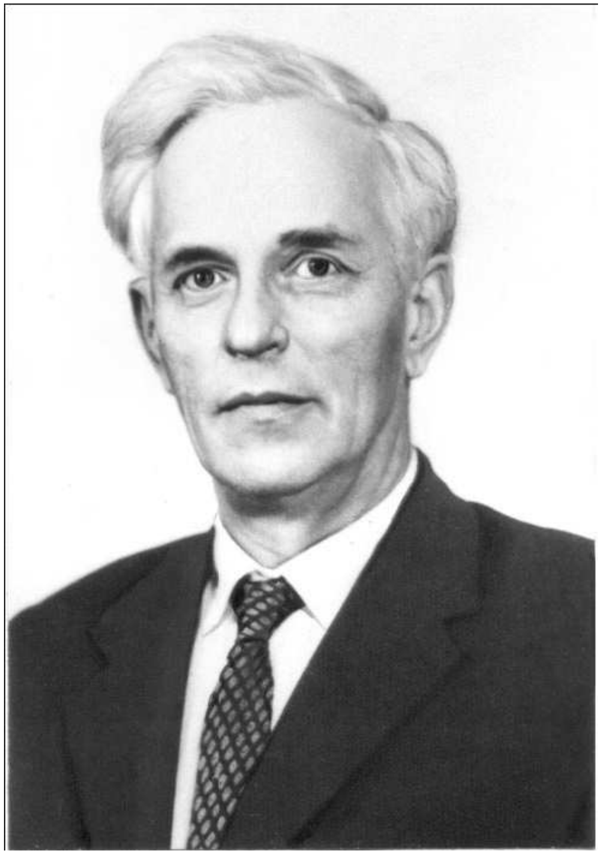
Spectrum and composition of cosmic rays by EAS Cerenkov light measurement

Vasily Prosin
(Skobeltsyn Institute of Nuclear Physics
Lomonosov Moscow State University)

The favorite russian teacher – Academician Alexandr Chudakov

The last visit of Gianni to Chudakov was in July 2000.



16.06.1921 – 25.01.2001

Start of EAS Cherenkov light experiments

Lateral Distribution Function (LDF):
Pamir Mounts experiments – Nina Nesterova and Aleksandr Chudakov – 1958, LDF simulation – Victor Zatsepin and Aleksandr Chudakov – 1962

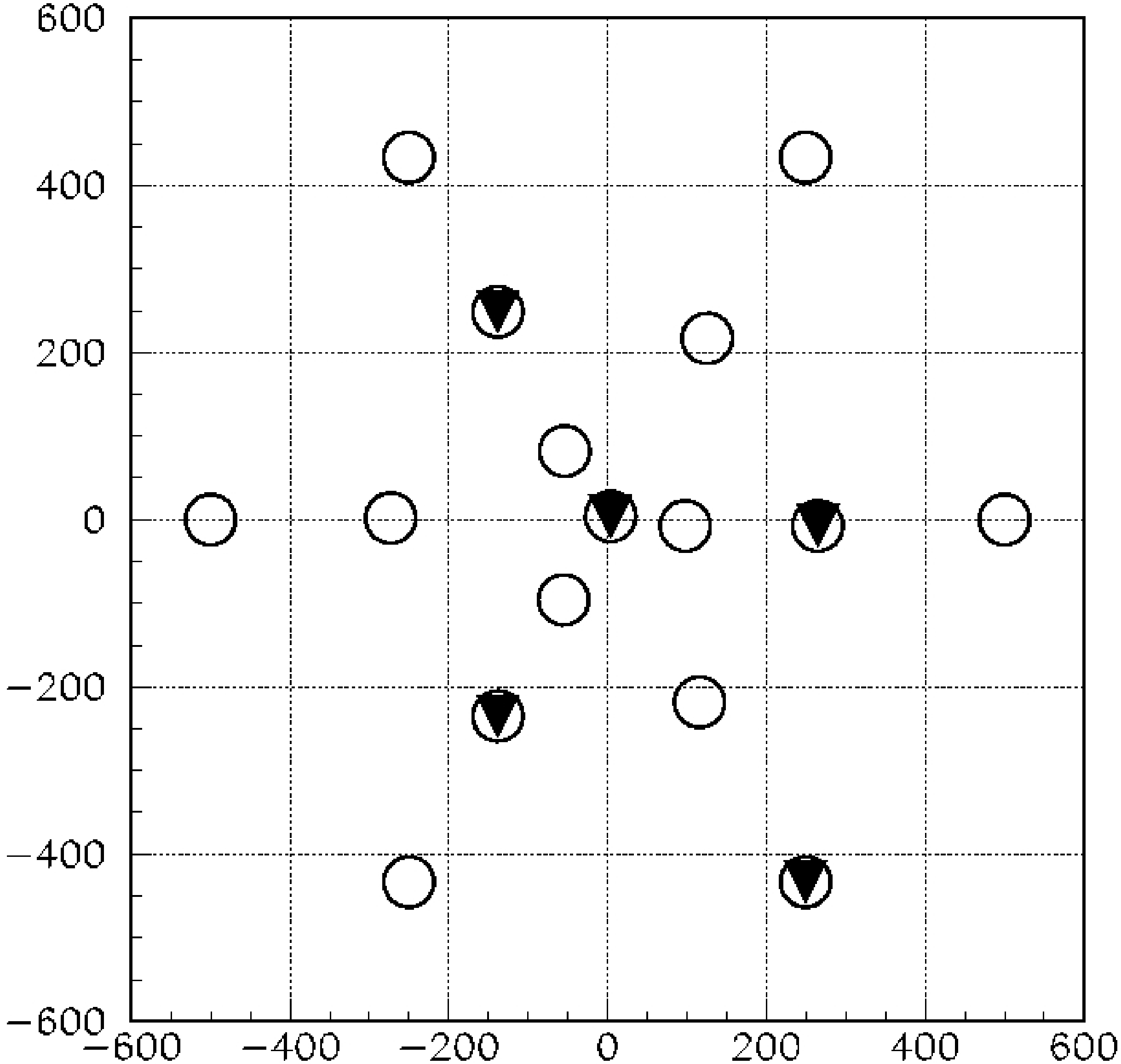
Pulse waveform:
Simulations – Yury Fomin and Georgy Khristiansen – 1971
Wide angle Yakutsk Experiments – Aleksandr Silaiev and Felix Shikalov – 1970 – 1973
Narrow angle Pic du Midi experiments – Gianni Navarra at al. – 1970-1975

The new approach to the X_{max} measurement – Nikolay Kalmykov and Vasily Prosin:

Don't try to reconstruct the total cascade curve but measure a single parameter for E_0 measurement and a single parameter for X_{max} measurement – 1975

Якутск

1973 – 1980 Yakutsk

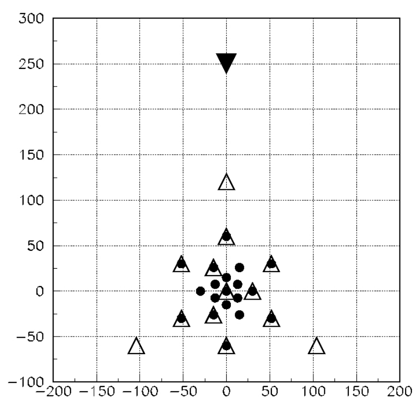


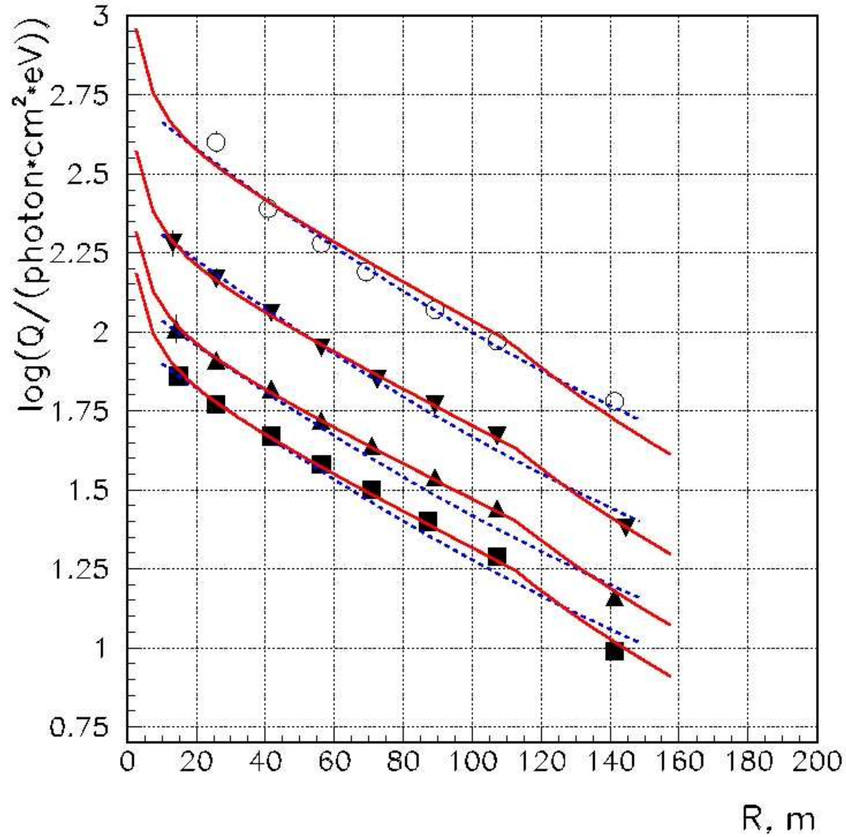
X_{max} = 560 g/cm^2 for E_0 =10^{16} eV,

$dX_{max}/d(lgE_0) < 60$ g/cm^2

▼- pulse waveform detector ○ - scintillation counters 2 - 4 m^2

1980 – 1985 – Samarkhand





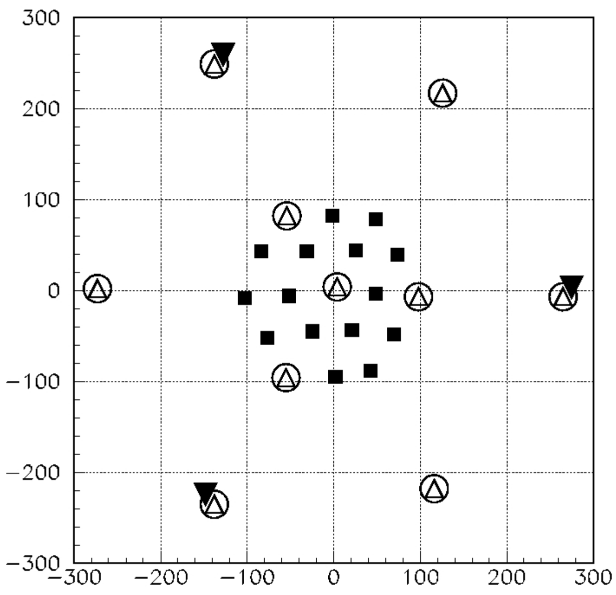
▼ – waveform , 13 XP-2041

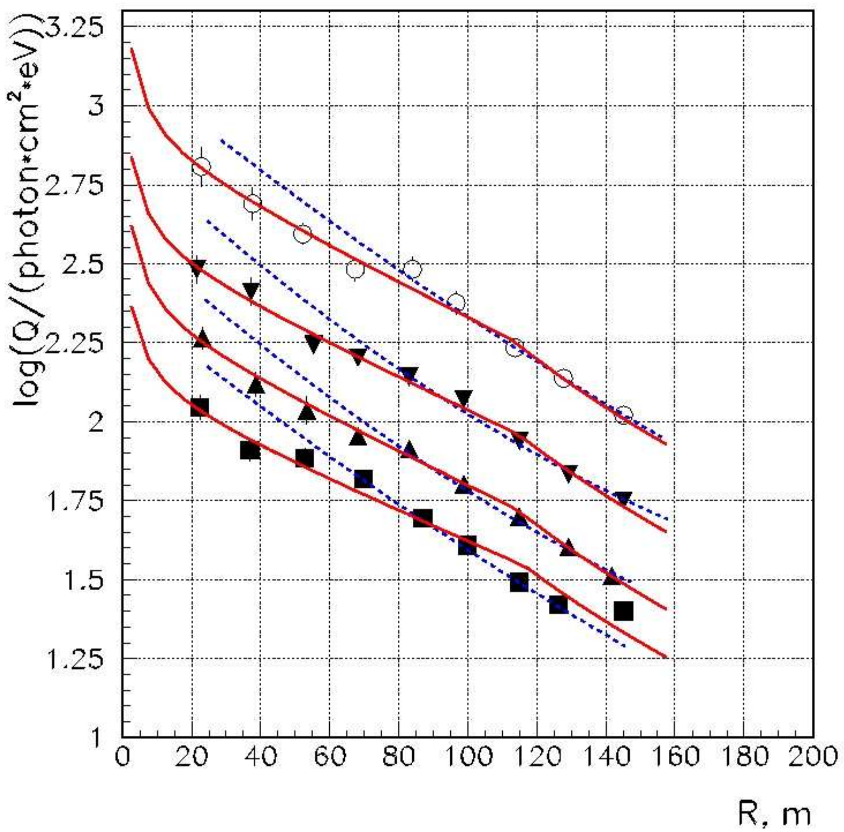
Δ – Cherenkov light , 1 – 7 PMT-49

Scintillation counters: ● from 0.5 to 2 m^2.

1984 – 1990… - Yakutsk

$\lambda = 150 \pm 5$ g/cm^2.





Δ – Cherenkov light

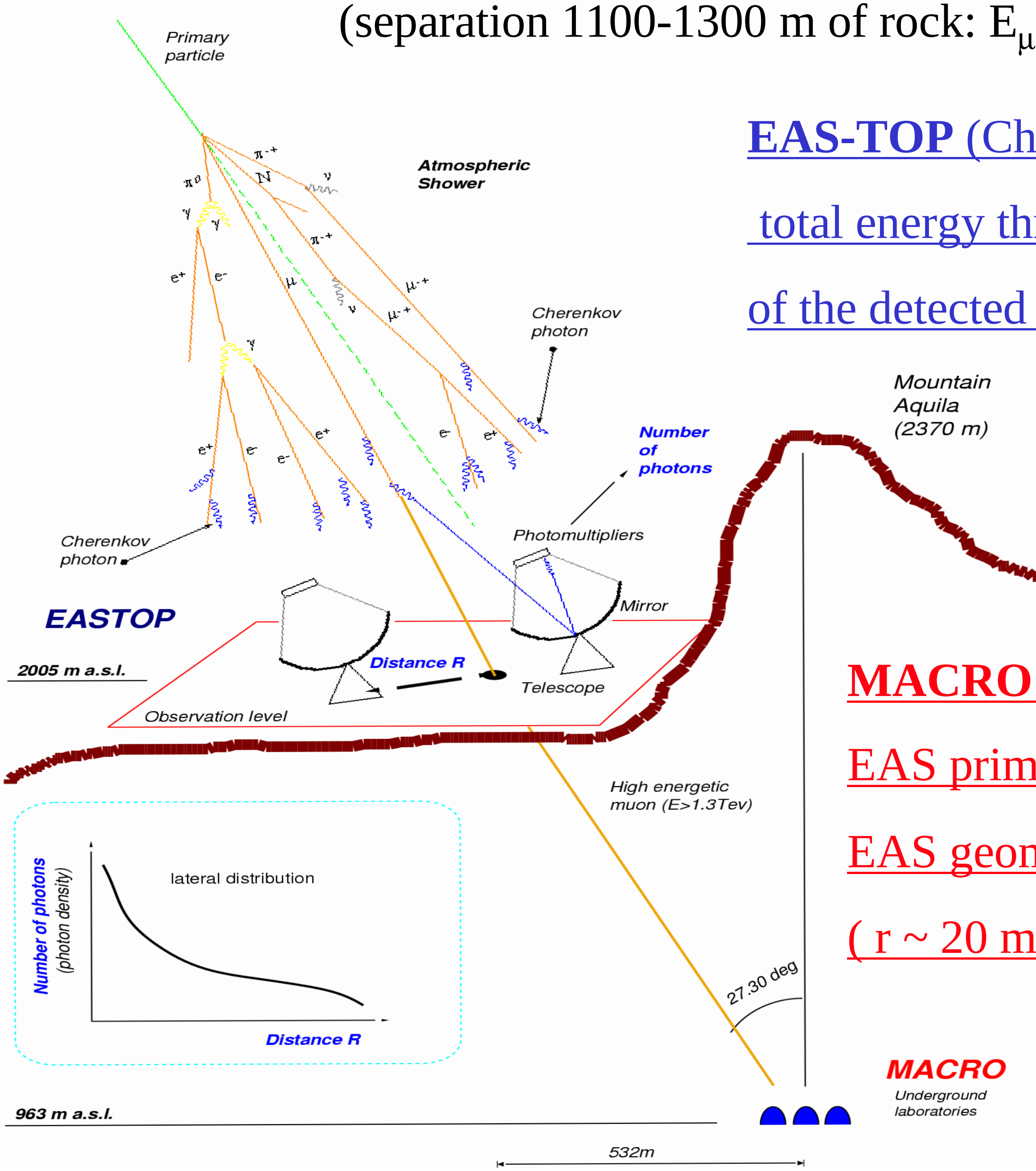
▼ - pulse waveform

Scintillation counter: ○ - 2 m^2, ■ - 0.25 m^2


EAS-TOP

p, He, CNO fluxes @ $E_0 \sim 100$ TeV from MACRO and EAS-TOP

(separation 1100-1300 m of rock: $E_\mu \approx 1.3 - 1.6$ TeV)



EAS-TOP (Cherenkov detector):

total energy through the amplitude

of the detected Cherenkov light signal.

MACRO (muon detector):

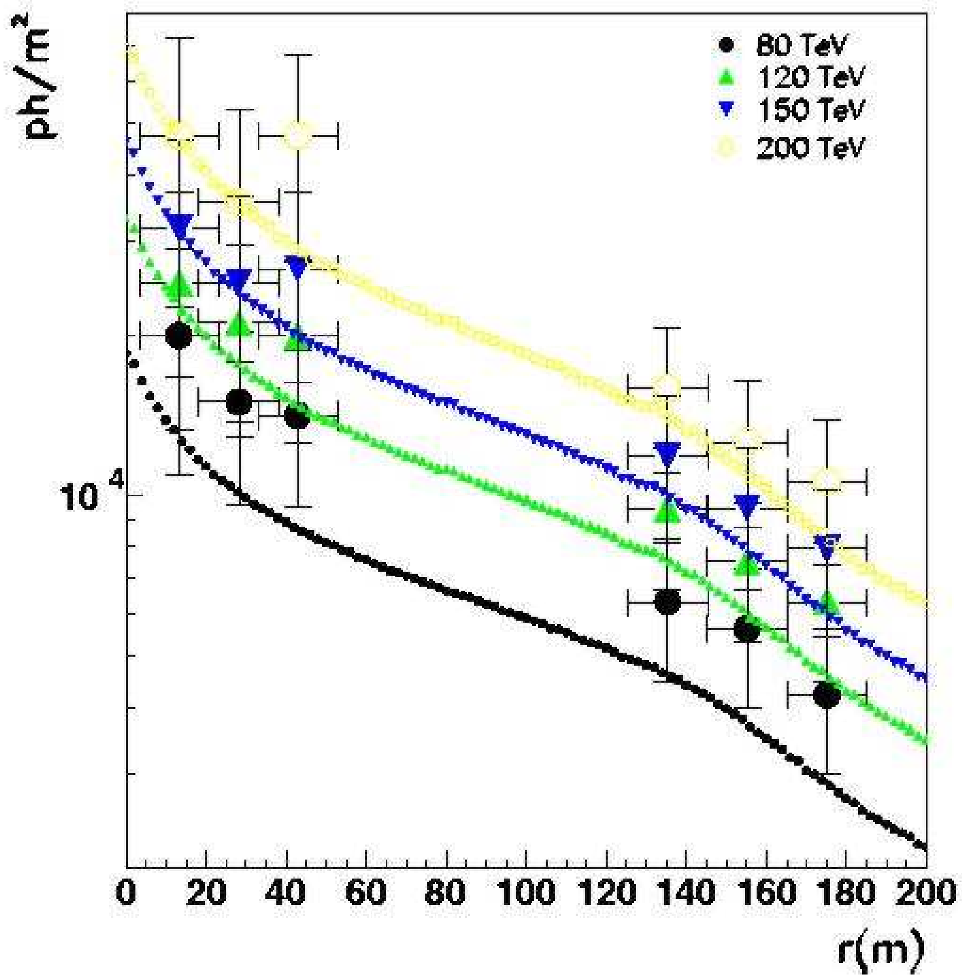
EAS primaries with $E_n > 1.3$ TeV/n

EAS geometry through the μ track

($r \sim 20$ m, $\theta \sim 1^0$ uncertainties)

LATERAL DISTRIBUTION OF CHERENKOV LIGHT EXPERIMENTAL DATA AND JACEE SIMULATION

- 20% systematic error summed in quadrature with statistical one scales all the curves by the same amount.
- 20% JACEE uncertainty on the spectra has not been included yet



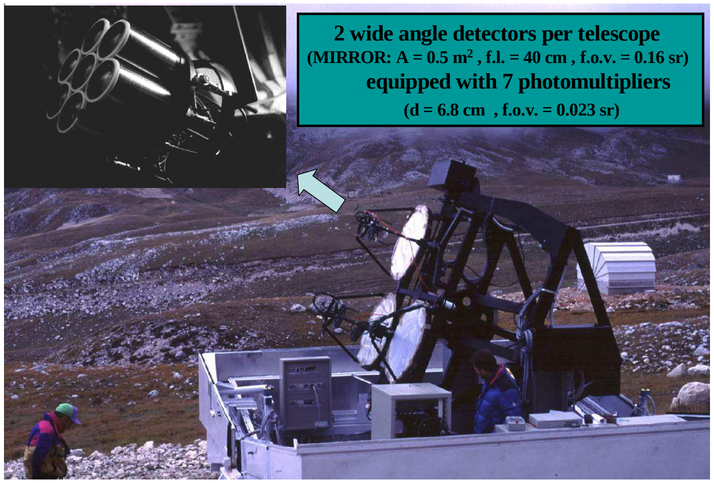
R=ph(42m)/ph(134m) is a good estimator of the longitudinal development of the shower (Hillas)

$\mathbf{(R_{ex}-R_{th})/R_{th}=0.13 \pm 0.09}$

- Inside the quoted uncertainties calculated and experimental. l.d.f.s match
- CORSIKA/QGSJET reproduces well the longitudinal development of the shower

EAS-TOP & MACRO

THE EAS-TOP CHERENKOV DETECTOR



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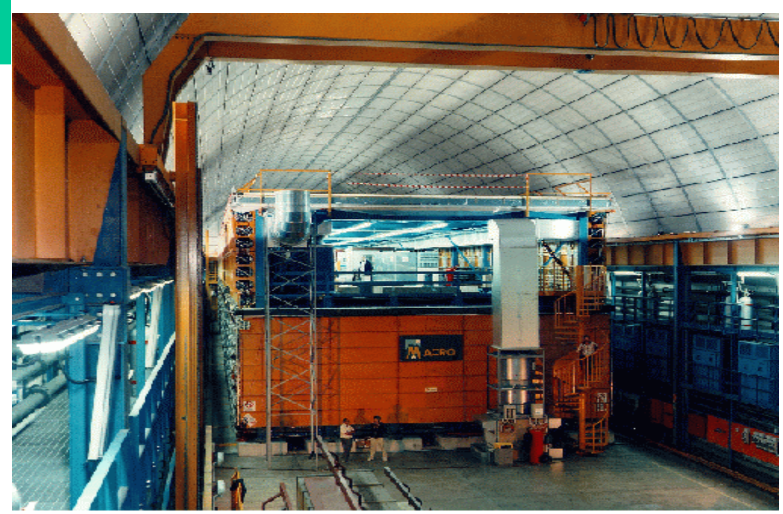
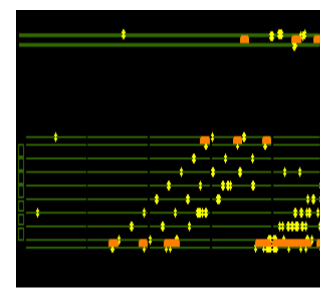
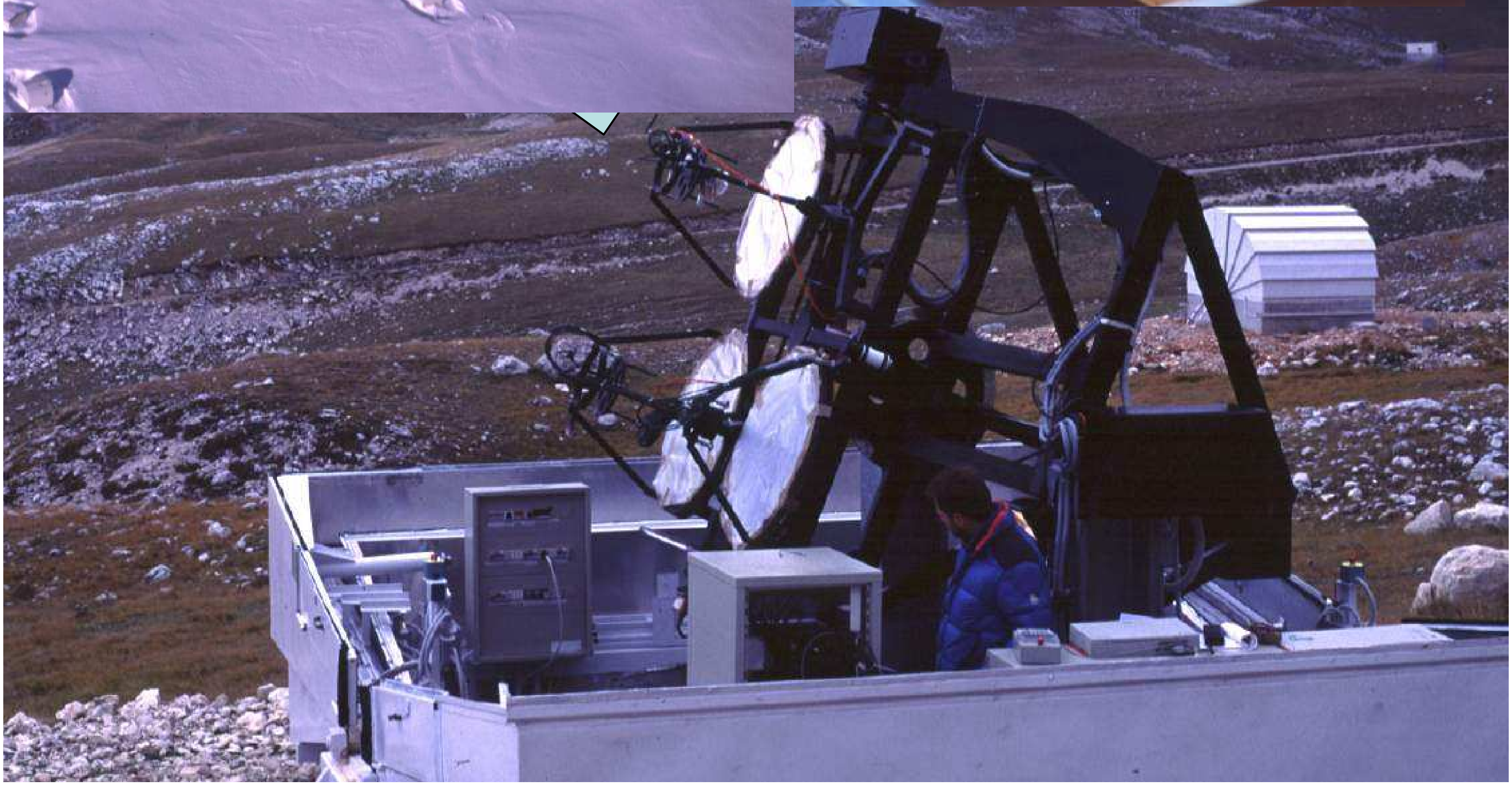
MACRO



Underground
Gran Sasso Labs.
depth: 3100 m w.e.
$E\mu^{th}$ ~ 1.3 TeV
76.6 x 12 x 4.8 m^3
$\sigma_\theta < 1^o$
20 m at surface level





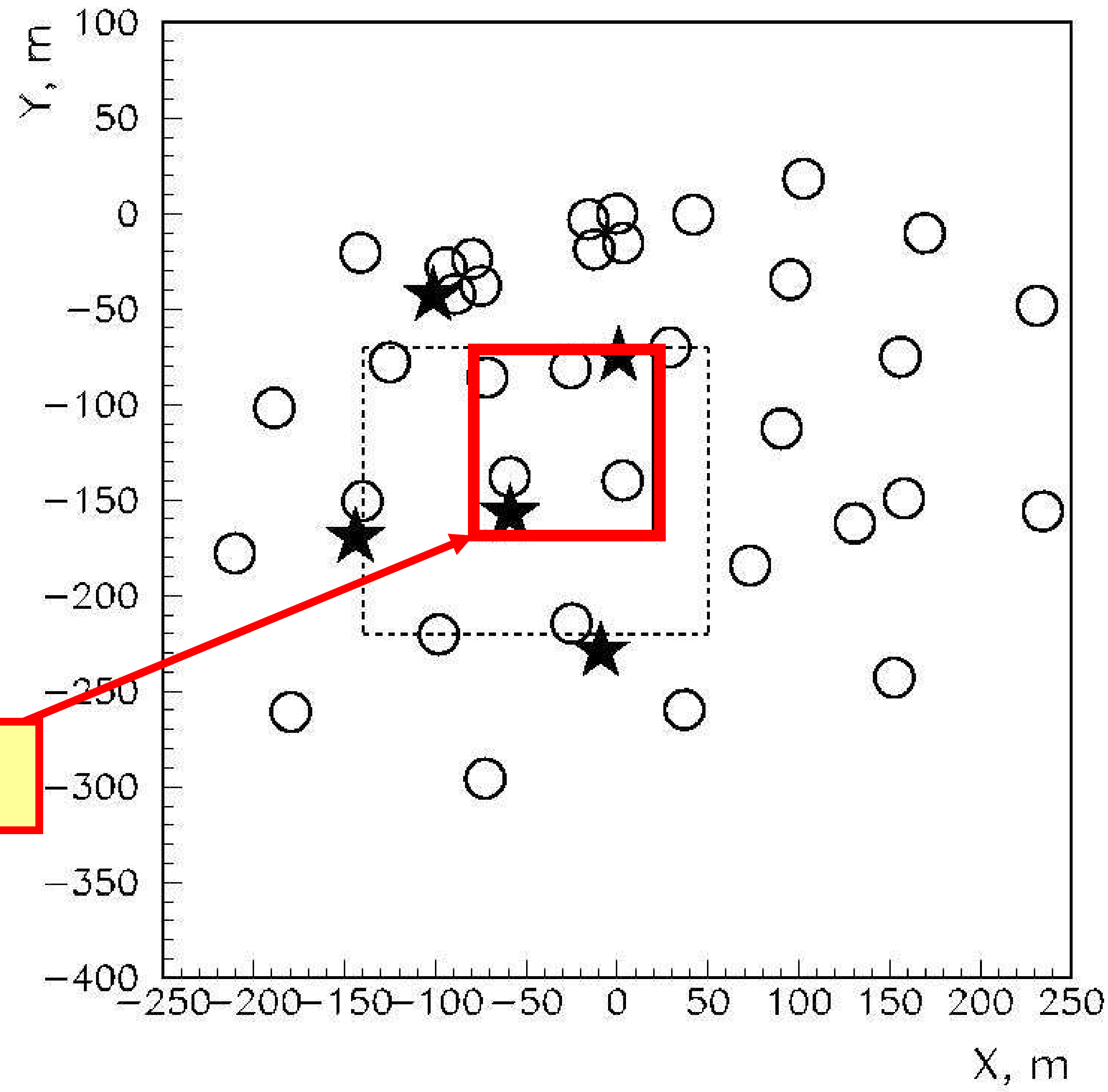


QUEST:

PMT QUASARs at EAS-TOP Array

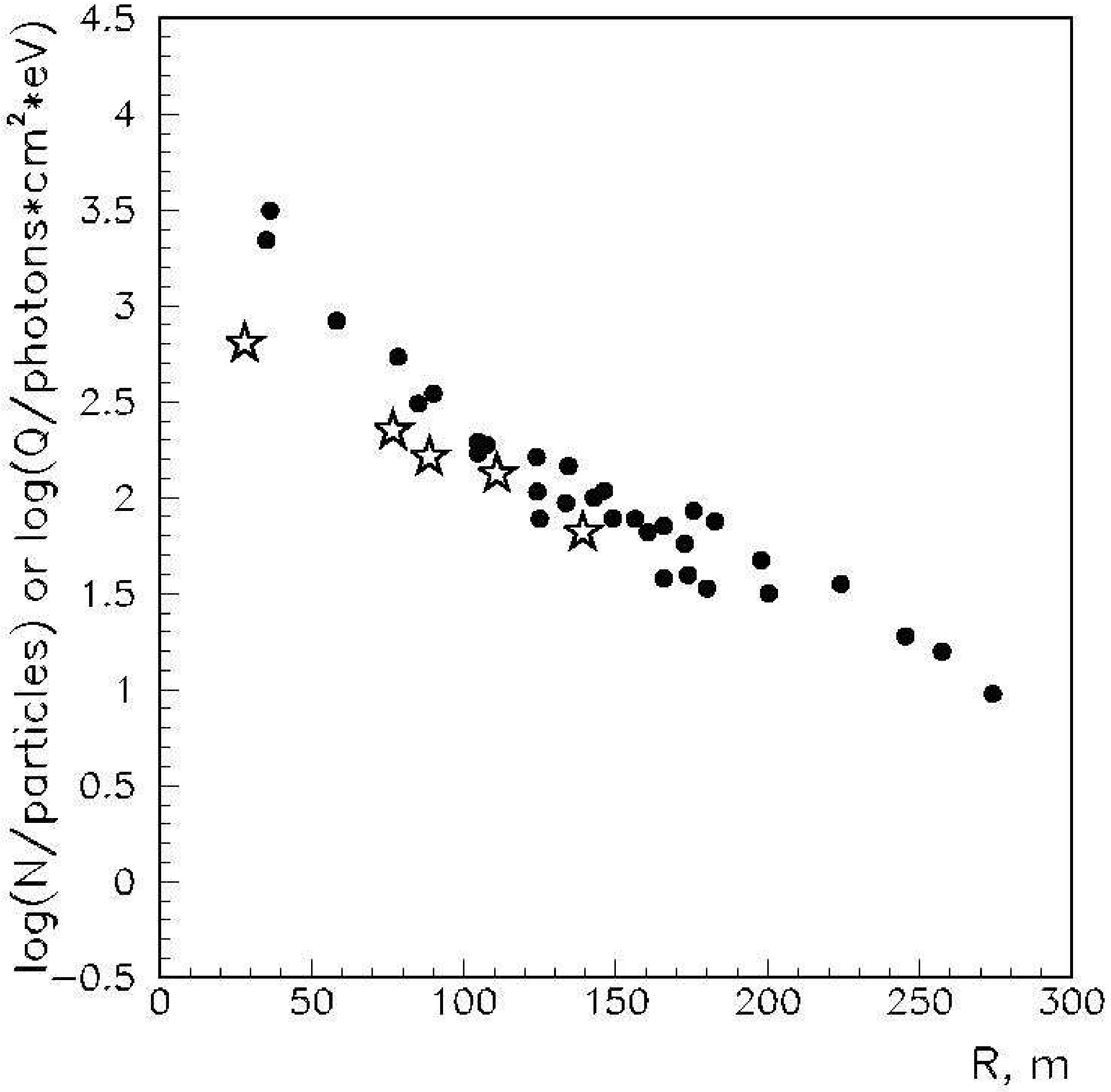
5 wide angle PMT QUASAR-370 with 37 cm diameter hemispheric photo-cathode has been disposed at 5 telescopes (stars) of the EAS-TOP array (circles).

Effective area = 10^4 m^2



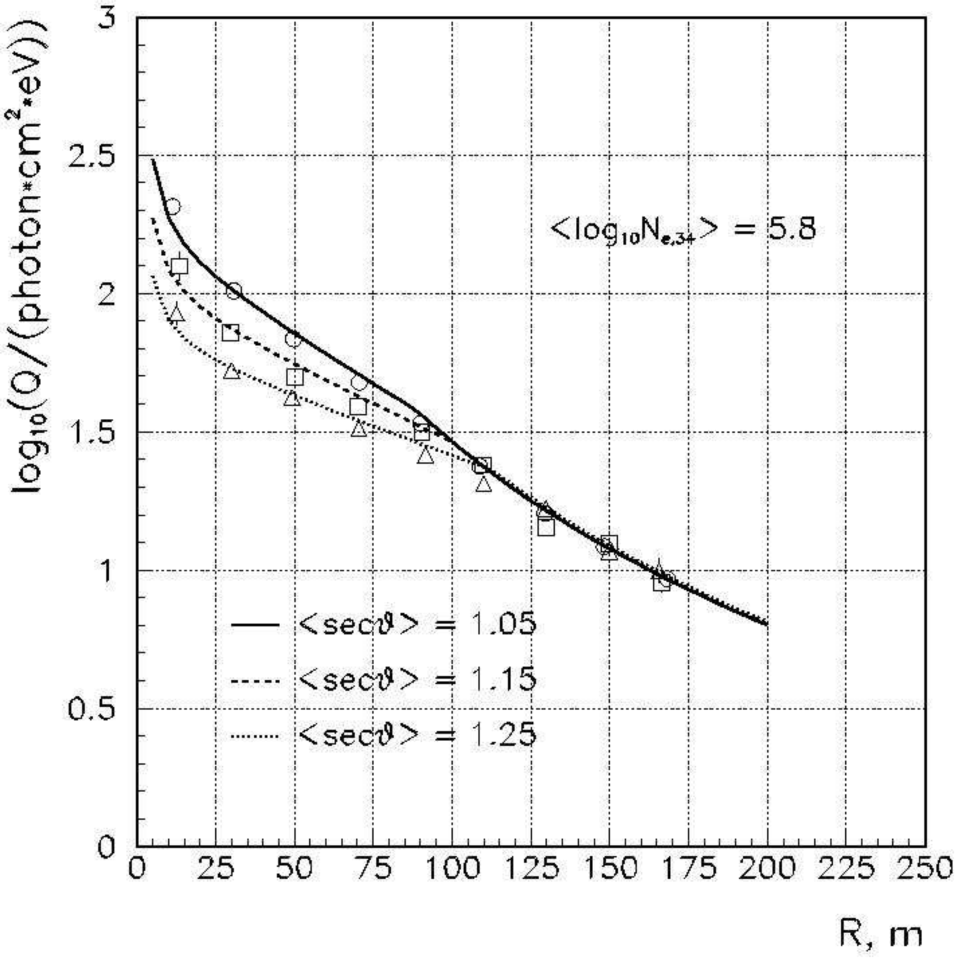
EXPERIMENT: An Example of Recorded Event

circle – logarithm of number of charged particles,
star – logarithm of Cherenkov light flux

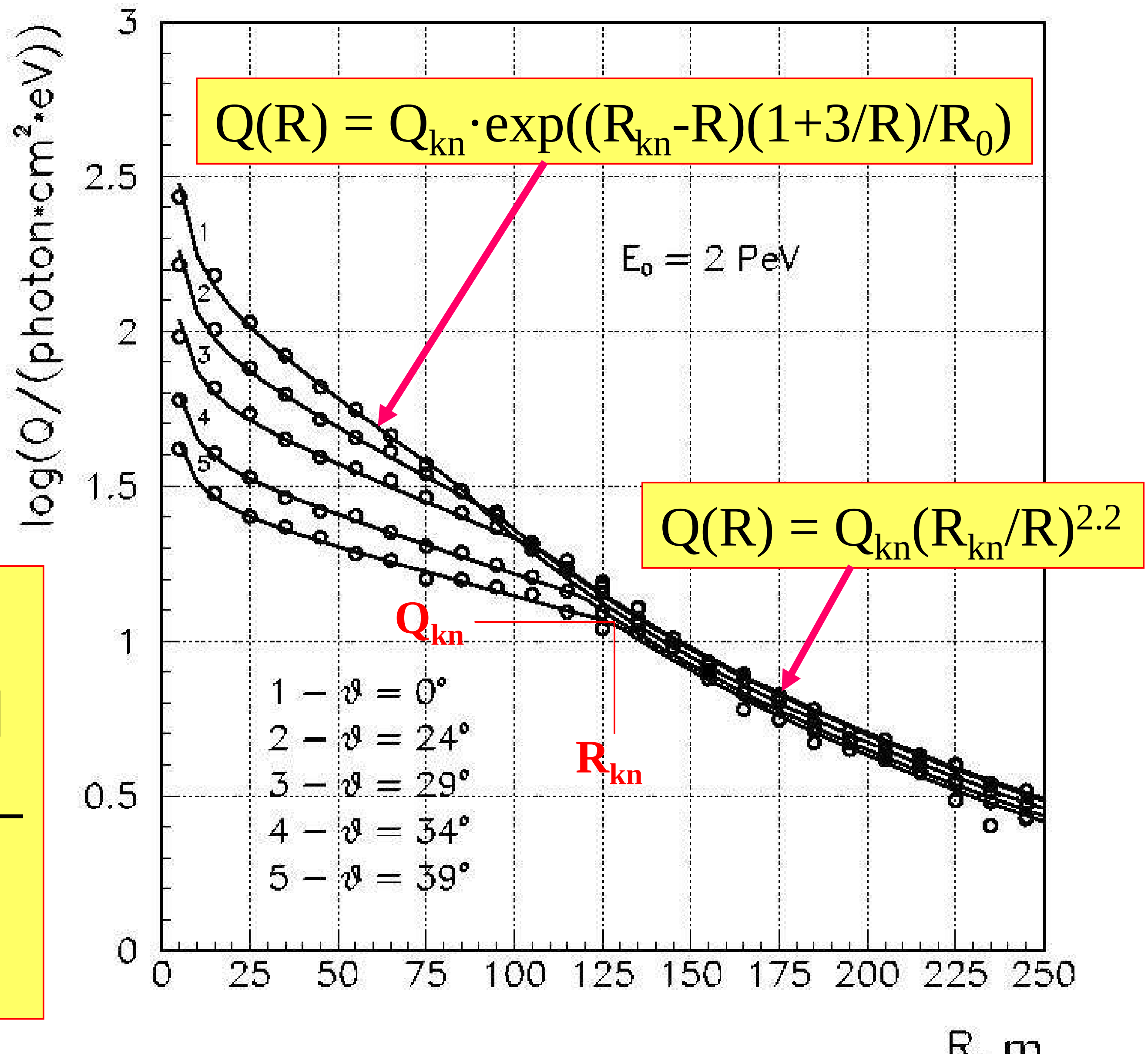


EXPERIMENT: Mean Cherenkov Light LDF

Classification parameter: $N_{e,34}$ – the size, recalculated to the fixed zenith angle θ = 34°.



CORSIKA simulation for QUEST: LDF parameterization



$R_0 = 10^{2.83-0.2 \cdot P}$ **[m]**

$R_{kn} = 200 - 20 \cdot P$ **[m]**

P – LDF steepness – a single parameter

$P = Q_{100}/Q_{200}$

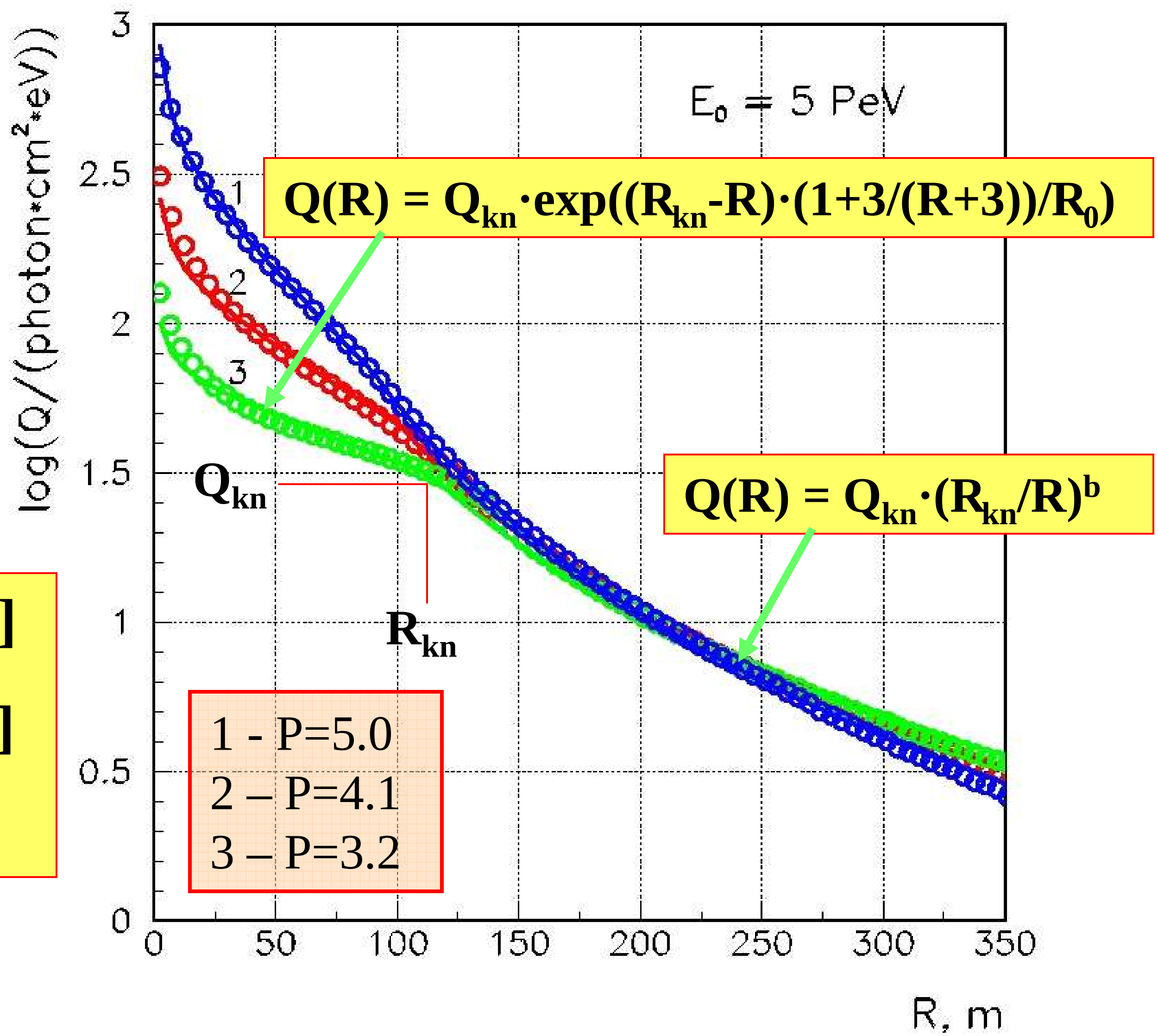
CORSIKA: Simulated lateral distributions and fitting function (LDF)

LDF has a single variable parameter of shape - **steepness: P=Q(100)/Q(200)**

$R_0 = 10^{2.95-0.245\cdot P}$ [m]

$R_{kn} = 155 - 13\cdot P$ [m]

$b = 1.19+0.23\cdot P$



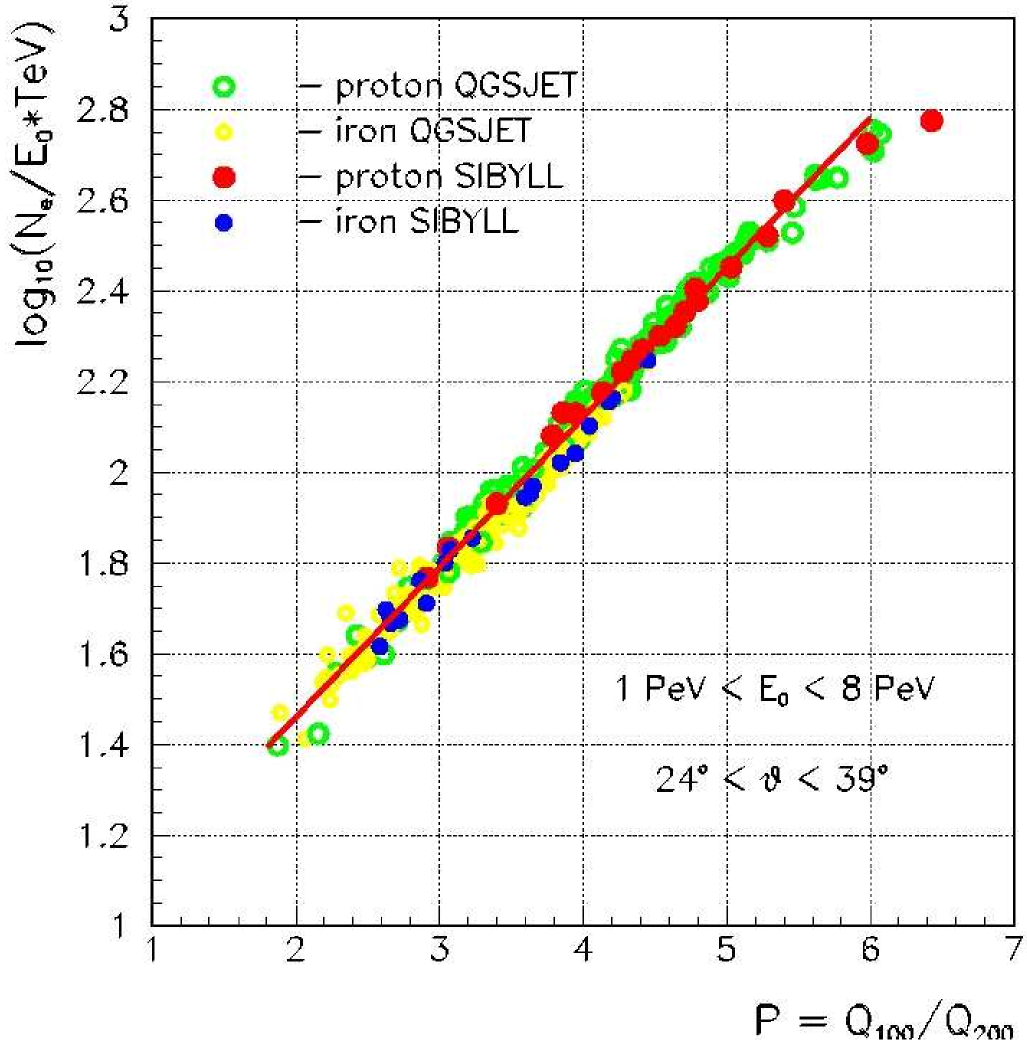
CORSIKA: Correlation of N_e/E_0 ratio and the sharpness P of EAS Cherenkov light LDF

The difference between N_e/E_0 is less than 6% for *p* and *Fe* and less than 2% for QGSJET and SIBYLL models.

Energy reconstruction, using this correlation (SIZE&CLDF method):

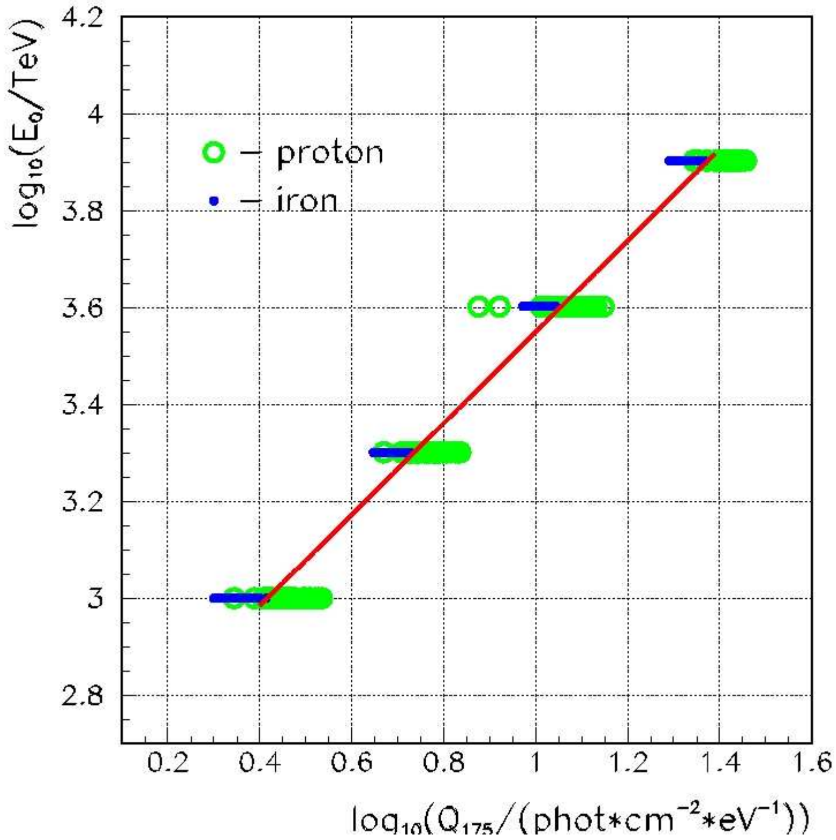
$$E_{SIZE}=1.59\cdot10^{11}N_e/\exp(0.76P),$$

[eV]



Primary Energy Reconstruction from EAS Cherenkov Light Flux at a Distance of 175 m from the Core Q_{175}

CORSIKA:



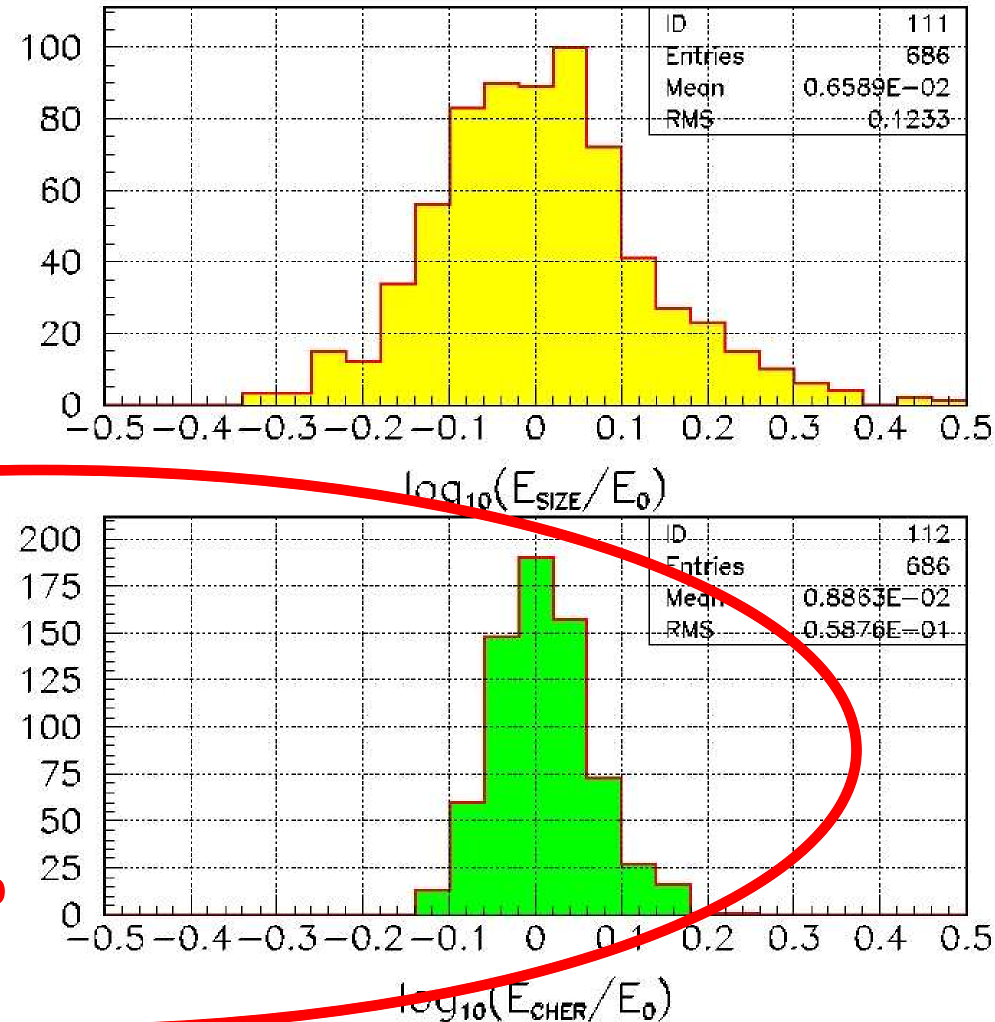
$$\mathbf{E_{CHER} = \langle E_{SIZE} / Q_{175}^{0.94} \rangle \cdot Q_{175}^{0.94}, [eV]}$$

Q_{175} is in units: [photon·cm^{-2}·eV^{-1}]

Model of experiment: energy resolution

$E_0 > 3\cdot10^{15}$ eV

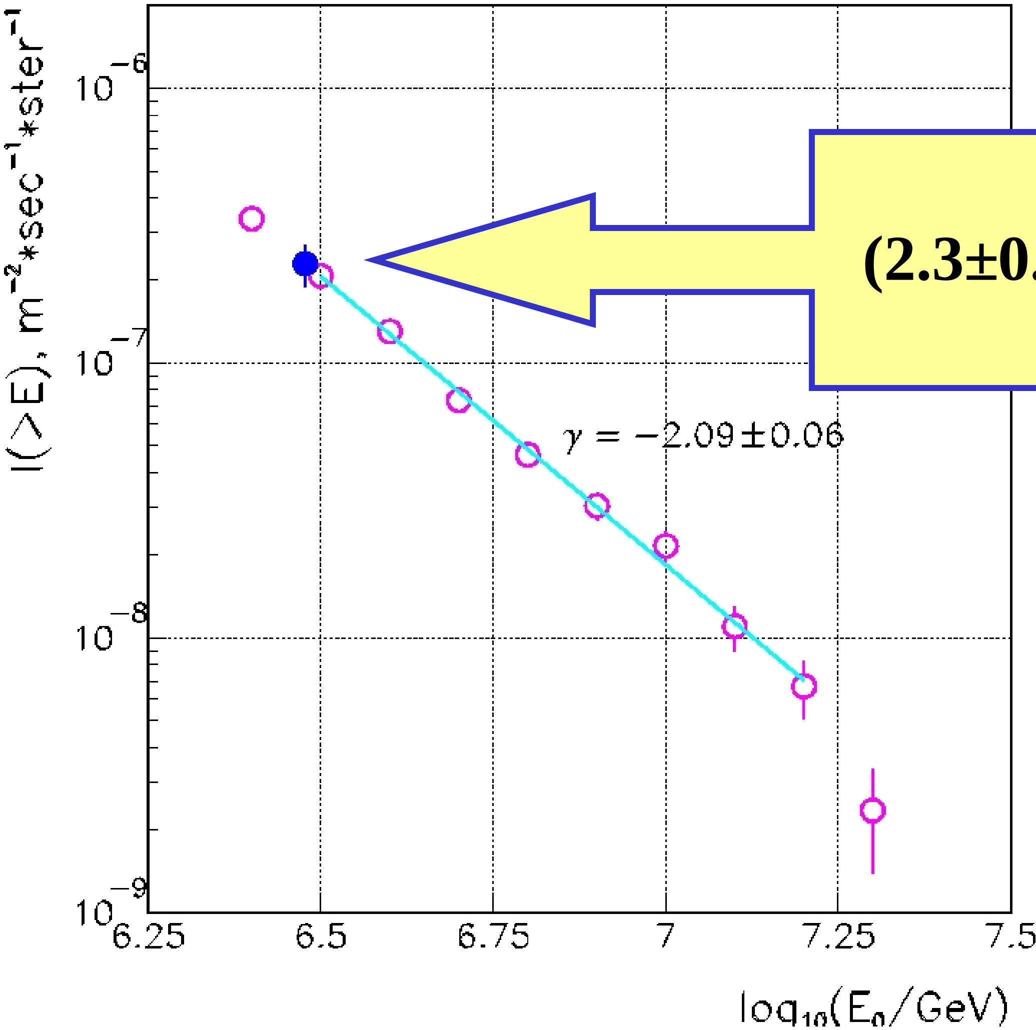
SIZE&CLDF method:
uncertainty is mostly due to the error of **P** reconstruction



Q_{175} method:

$\sigma E_0/E_0$ ~15%

Integral Energy Spectrum and Reference Intensity



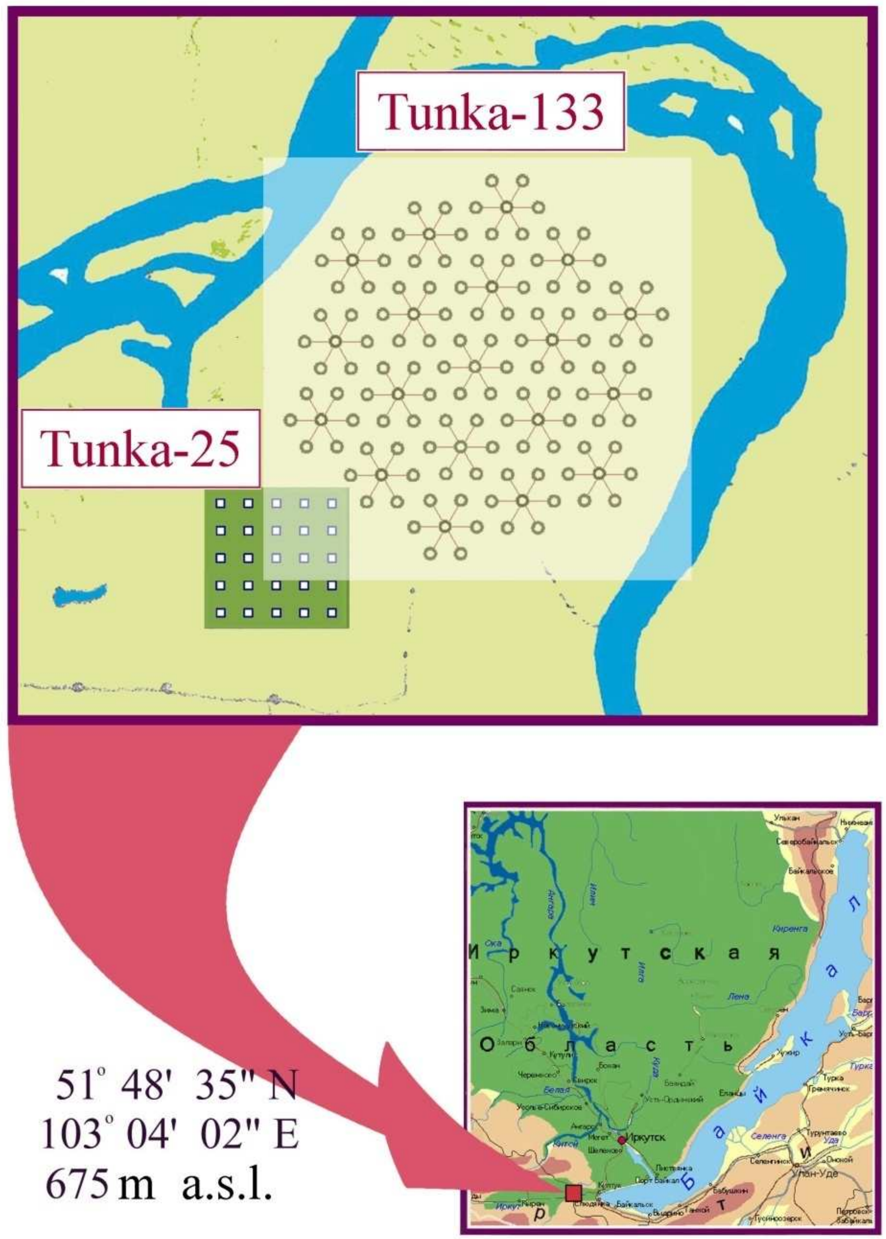
$I(E_0 > 3 \cdot 10^{15}$ eV) =
$(2.3 \pm 0.1(\text{stat.}) \pm 0.4(\text{syst.})) \cdot 10^{-7}$
$[m^{-2} \cdot s^{-1} \cdot sr^{-1}]$

E_0 is obtained by Q_{175} method, because the individual measurement error is 2 times less than for SIZE&CLDF method.

TUNKA array geography:

RUSSIA, Siberia, 50 km form Lake Baikal

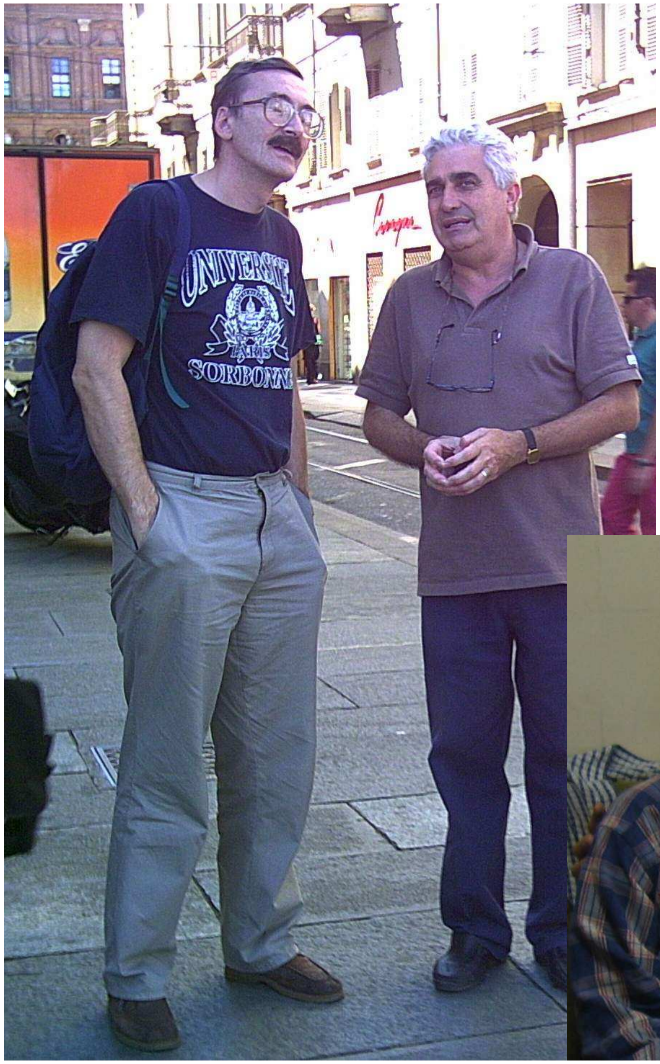
http://dbserv.sinp.msu.ru/tunka



Gianni Navarra include to the Tunka experiments from 1995 to 2009

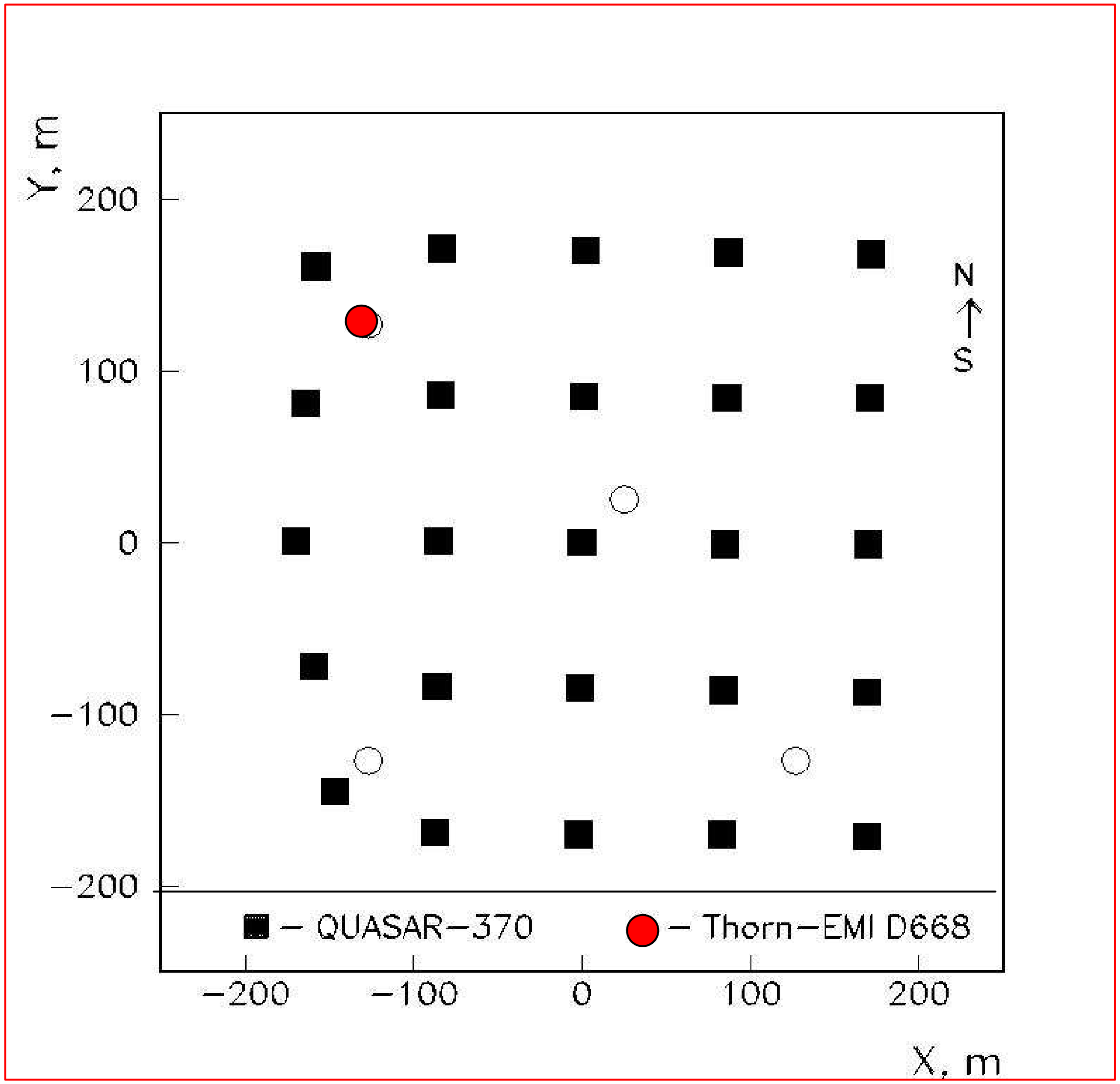
1. The first INTAS grant and contacts with A.M. Hillas (1995 – 2006)
2. Experiment QUEST at EAS-TOP (1998 – 2000)
3. PMT for Tunka-133 from MACRO and some other electronics parts (2002 – 2009)
4. The first CORSIKA simulation made by his PhD student (2000 – 2003)
5. Discussion of methods of analysis and common publications from 2003 to 2009

Gianni Navarra include to the Tunka experiments from 1995 to 2009



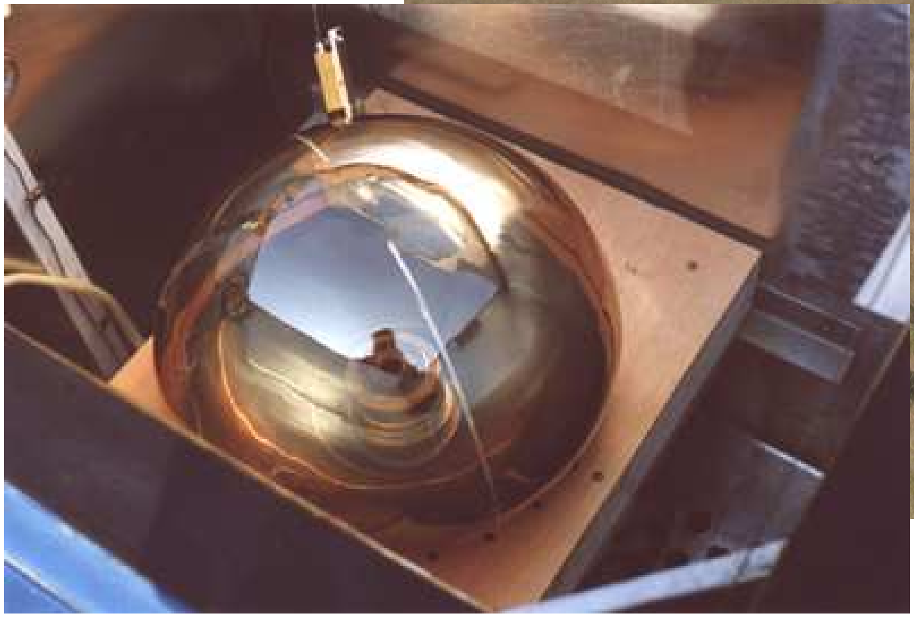
Tunka-25
October 2005

The Tunka-25 array



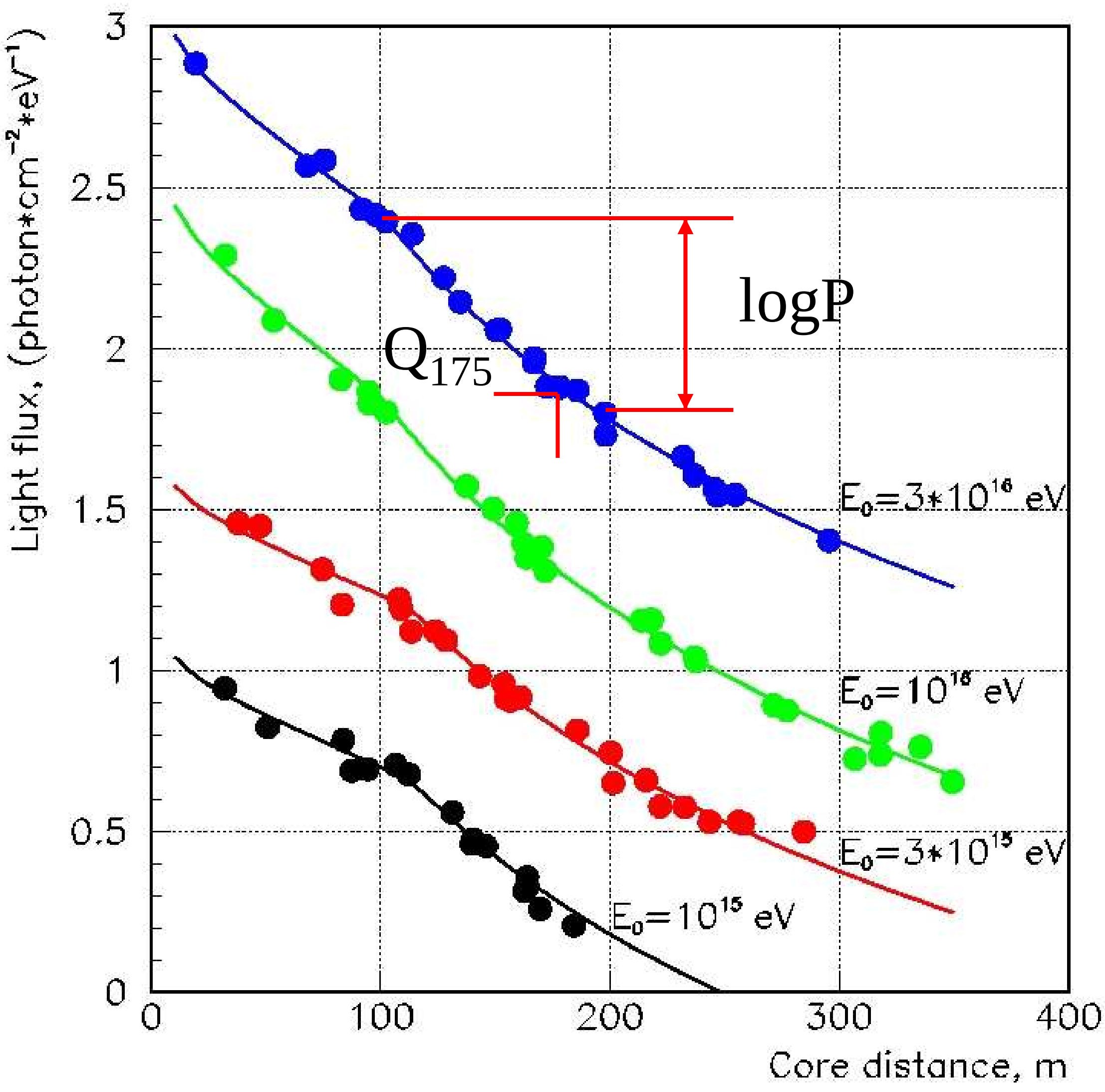
- **25 QUASAR-370 tubes**
  - 37 cm diameter
  - integrating

Cherenkov Light Detectors

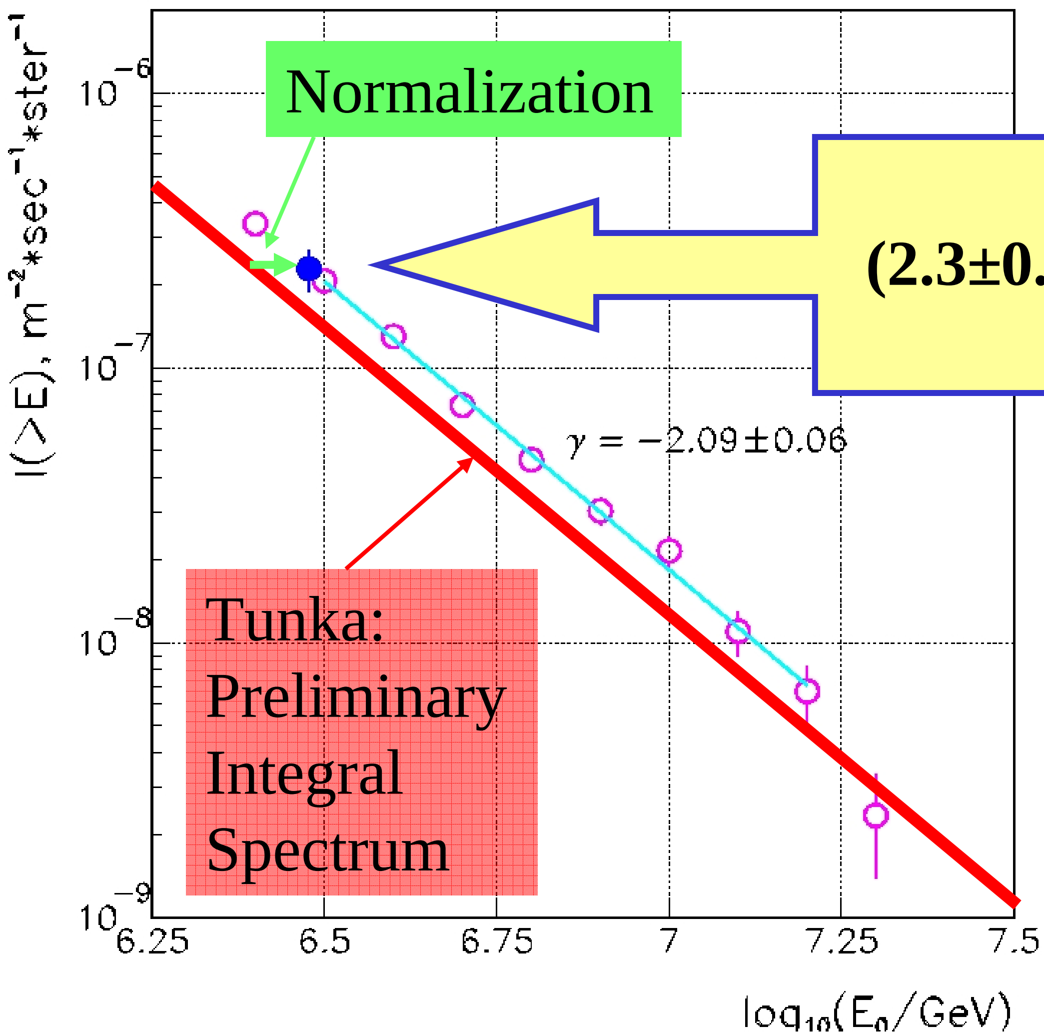


EXPERIMENT: Reconstruction of EAS Parameters

1. core position **- x, y**
2. light flux at core distance 175 m - $\mathbf{Q_{175}}$
3. steepness of LDF - **P=Q(100)/Q(200)**



Absolute Energy Calibration



QUEST:

Reference Intensity

$I(E_0>3\cdot10^{15}$ eV) =

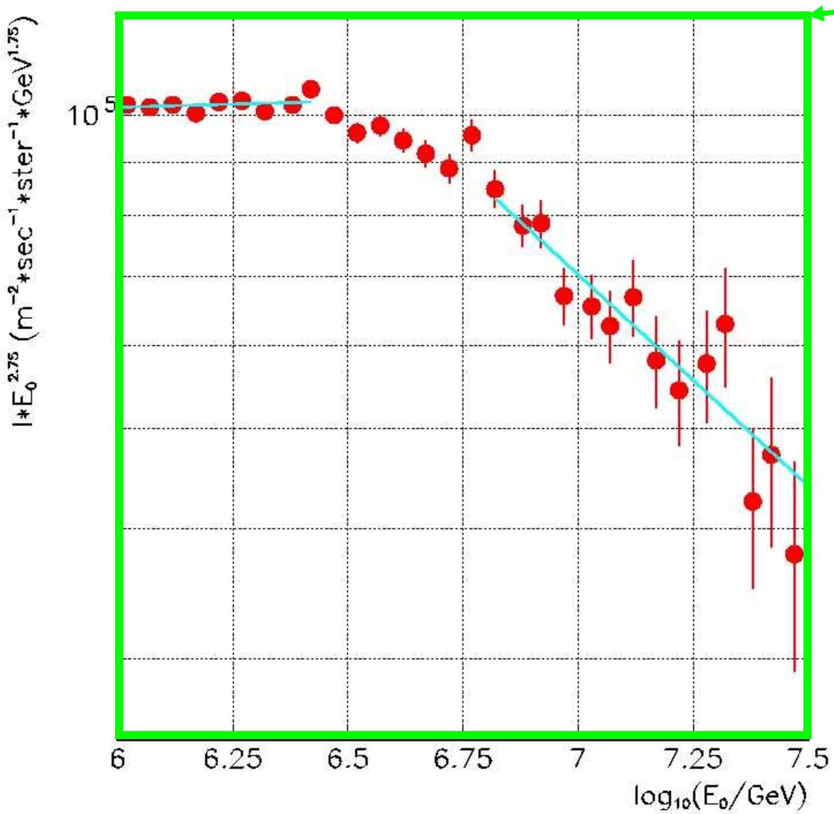
$(2.3\pm0.1$(stat.) ±0.4(syst.)$)\cdot10^{-7}$

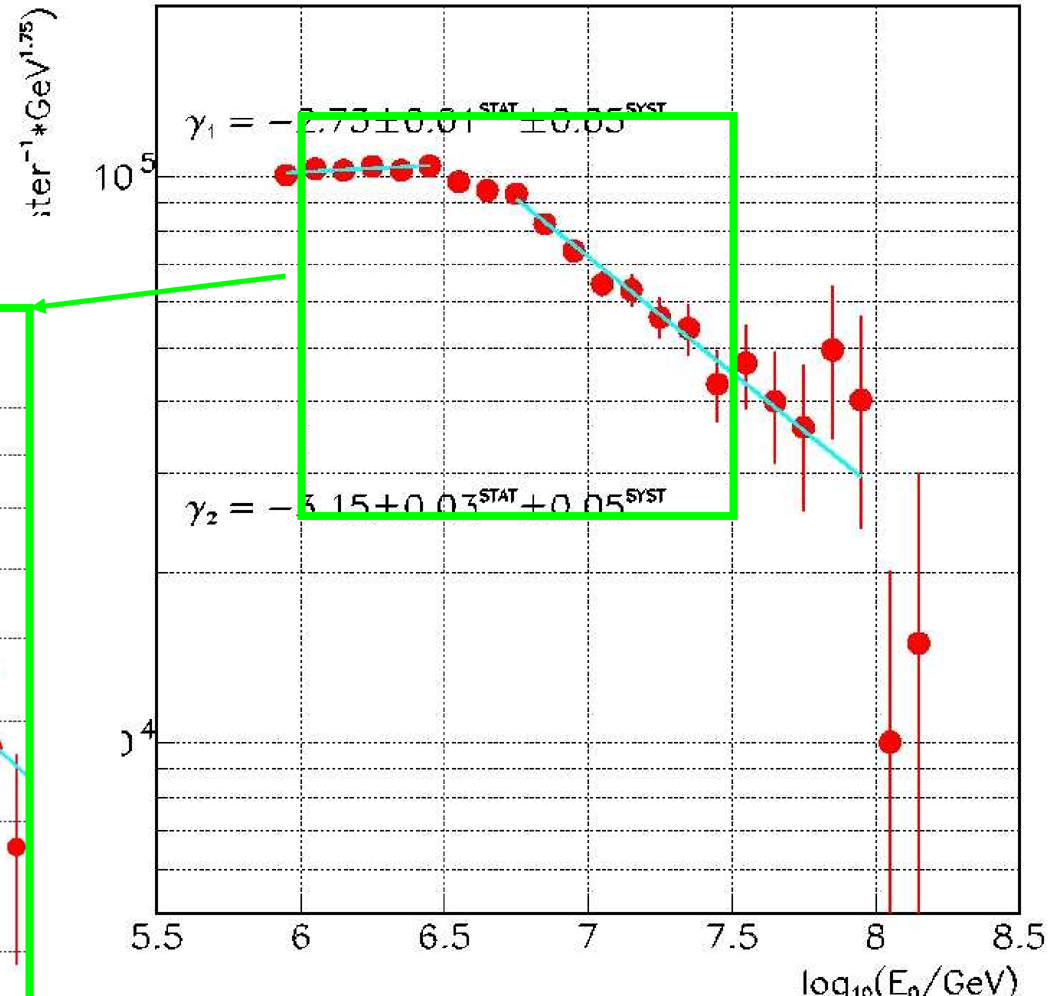
$[m^{-2}\cdot s^{-1}\cdot sr^{-1}]$

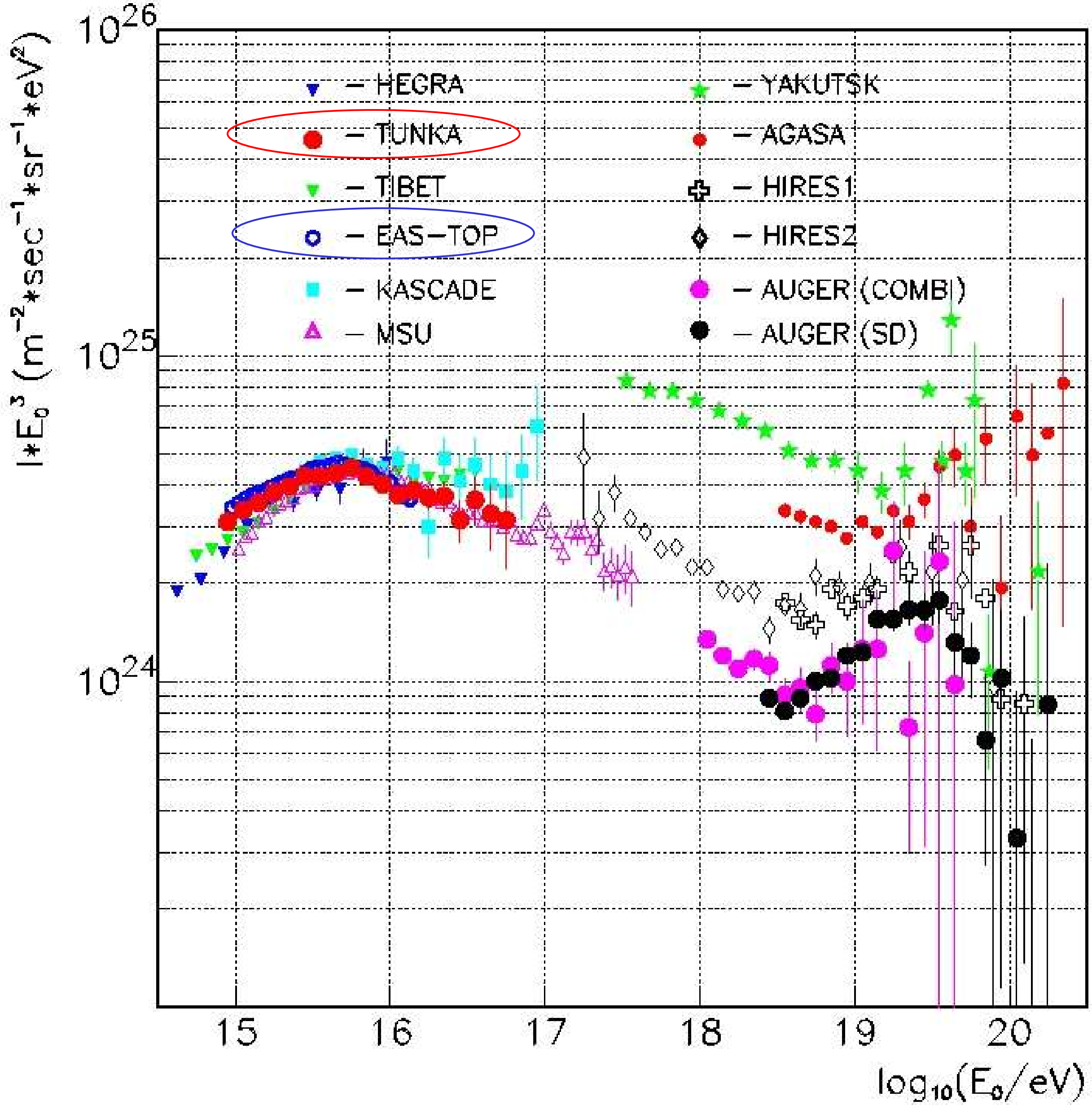
This method provides the uncertainty of absolute energy less than 10%.

Differential energy spectrum: power law fitting

300 hours   **θ**<25°
140000 events 10000 events with
$\mathbf{E_0} > 3 \cdot 10^{15}$ eV





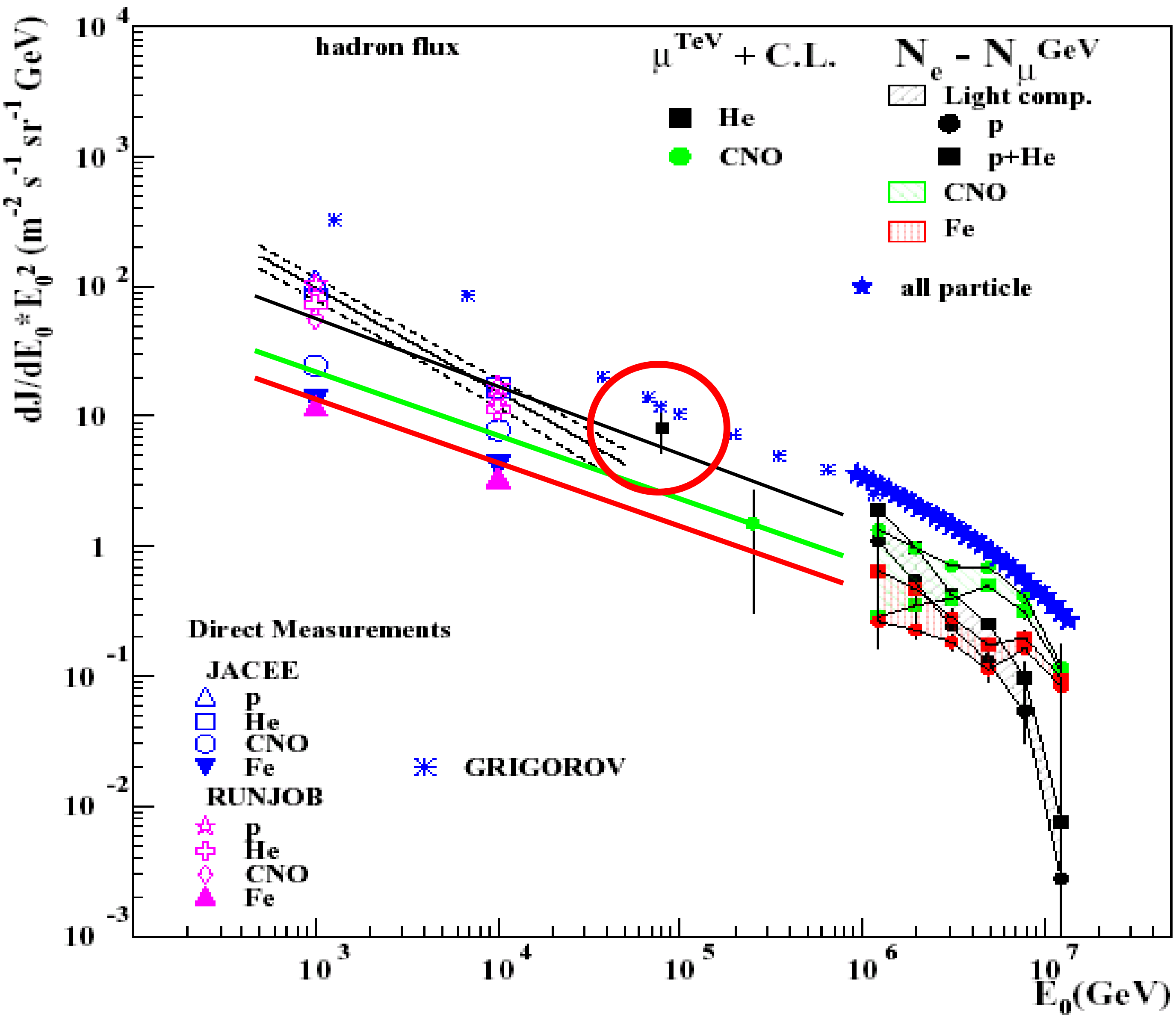


$I*E_0^3$ ($m^{-2}*sec^{-1}*sr^{-1}*eV^2$)
10^{26}
10^{25}
10^{24}
– HEGRA
– TUNKA
– TIBET
– EAS–TOP
– KASCADE
– MSU
– YAKUTSK
– AGASA
– HIRES1
– HIRES2
– AUGER (COMBI)
– AUGER (SD)
15
16
17
18
19
20
$\log_{10}(E_0/eV)$

CONCLUSIONS

1. Energy spectrum has a sharp knee at $3 \cdot 10^{15}$ eV
2. Change of the next power law index at about $6 \cdot 10^{15}$ eV

The primary spectrum from EAS-TOP



Primary nucleus $\mathbf{E_0}$, **A**?

1. $\mathbf{E_0 \sim Q_{175}}$ – Cherenkov light flux

2. $\mathbf{X_{max}}$(model independent)**:**

$\underline{\mathbf{X_{max}}} = \mathbf{Xp - \delta X_{max}/\delta lnE \cdot \underline{lnA}}$

<u>Two methods:</u>

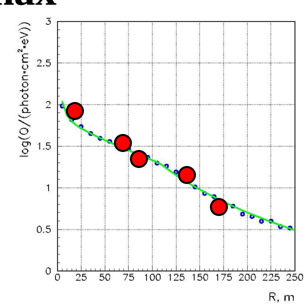
Pulse width:

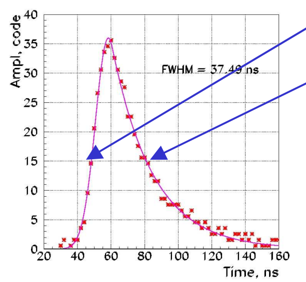
$\mathbf{\Delta X = a - b \cdot FWHM\ [g/cm^2]}$

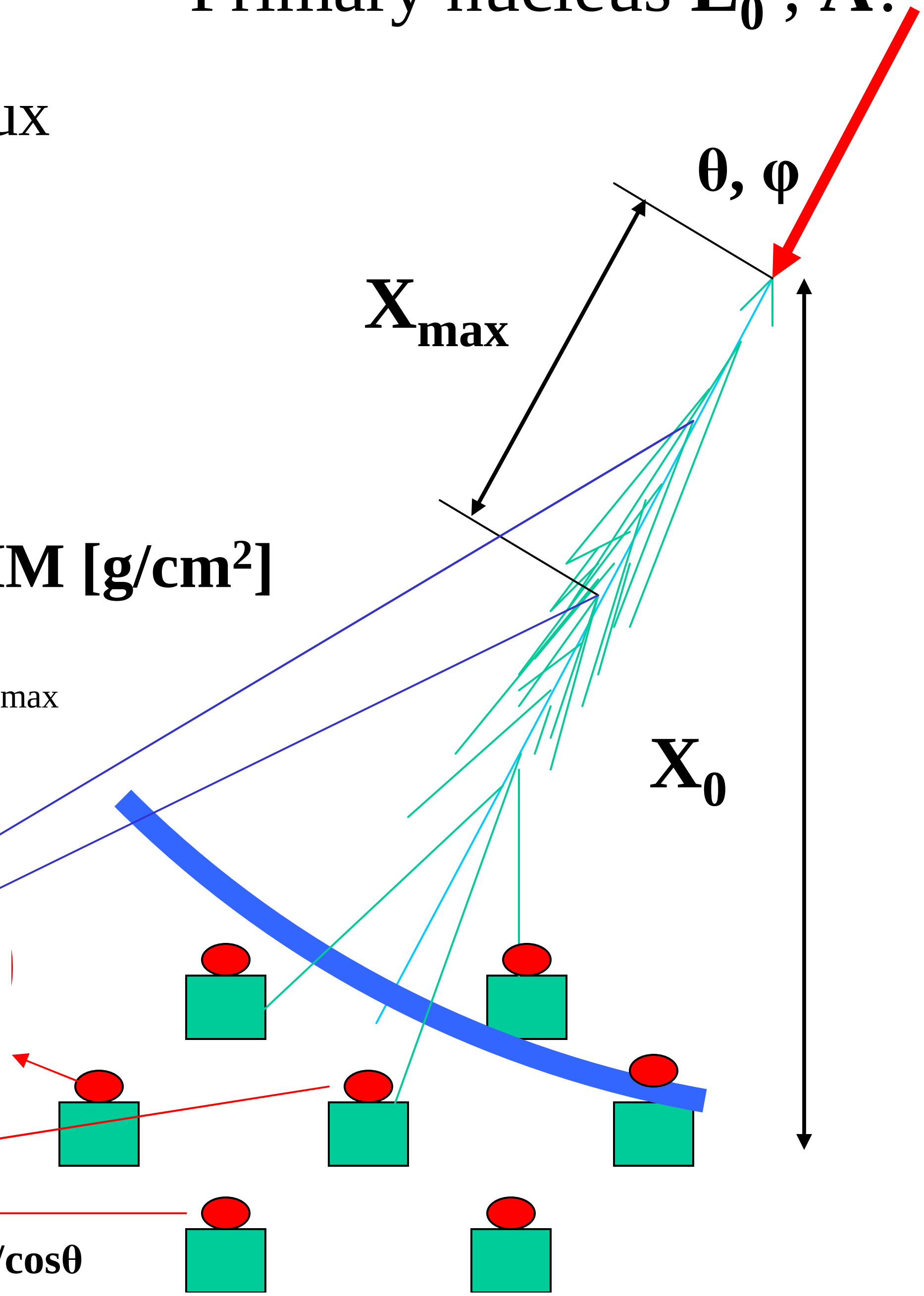
$\Delta X = X_0/\cos\theta - X_{max}$

LDF steepness P:

$\mathbf{H_{max} = c - d \cdot P}$





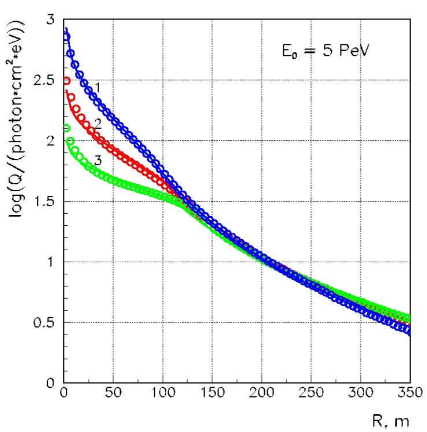


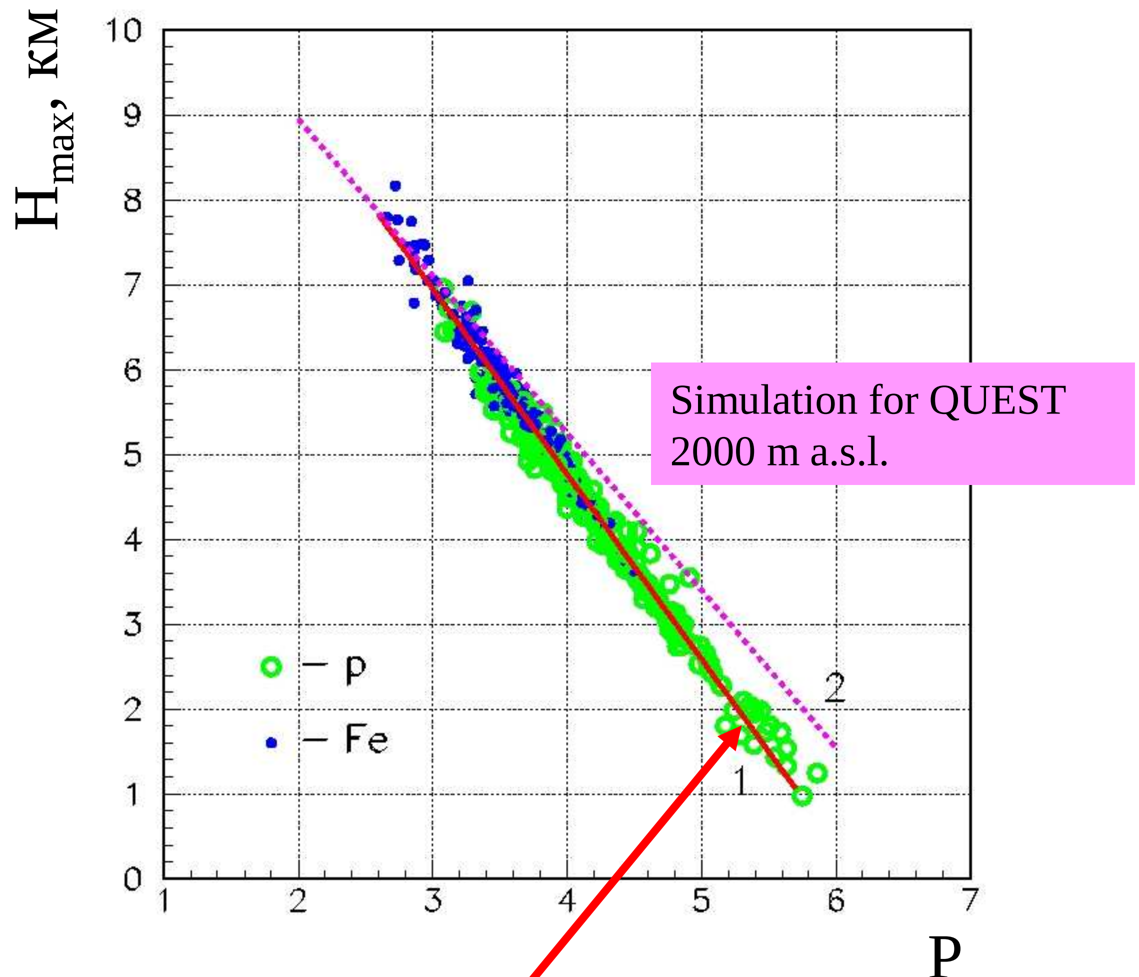
$\mathbf{H_{max} = (T_0/grad(T)((X_{max} \cos\theta / X_0)^{C/grad(T)} - 1) - H_{arr})/\cos\theta}$

Simulation for Tunka.

CORSIKA:
Measurement of
a distance to EAS
maximum with the
Cherenkov light LDF
steepness P

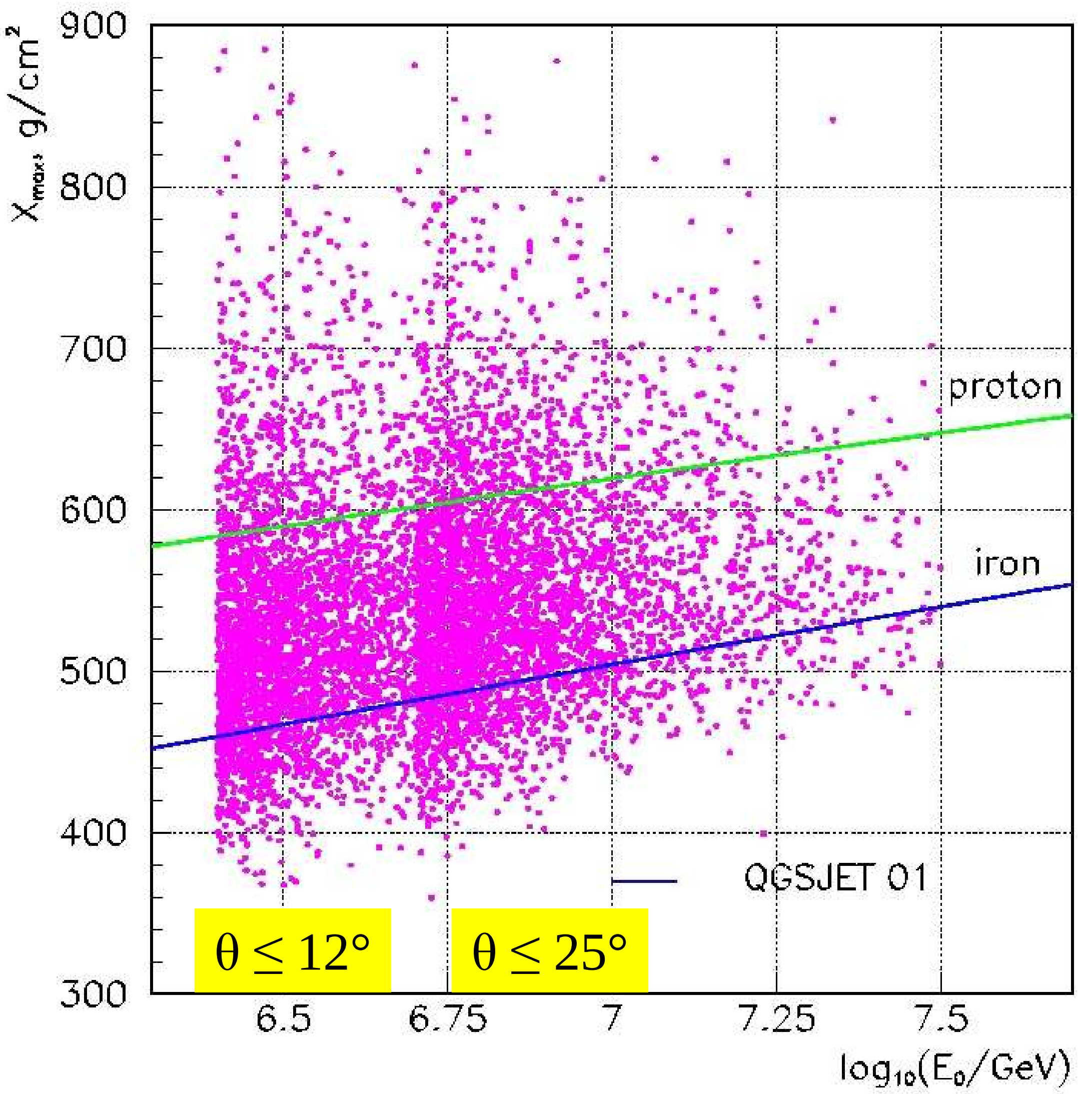
480 simulated events with E_0 from 1 PeV to 20 PeV and zenith angles θ from 0° to 25°



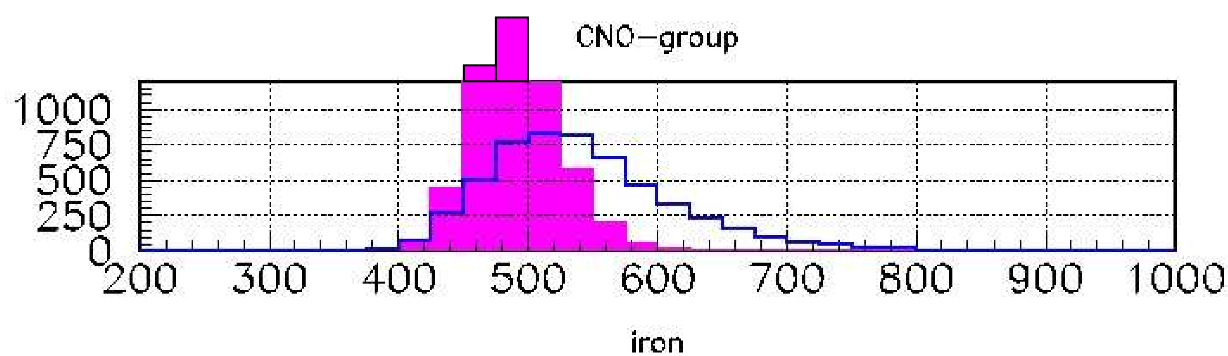


$$H_{max} = 13.61 - 2.18 \cdot P\ ,\ [\mathrm{km}]$$

X_{max} individual measurements with LDF steepness method.

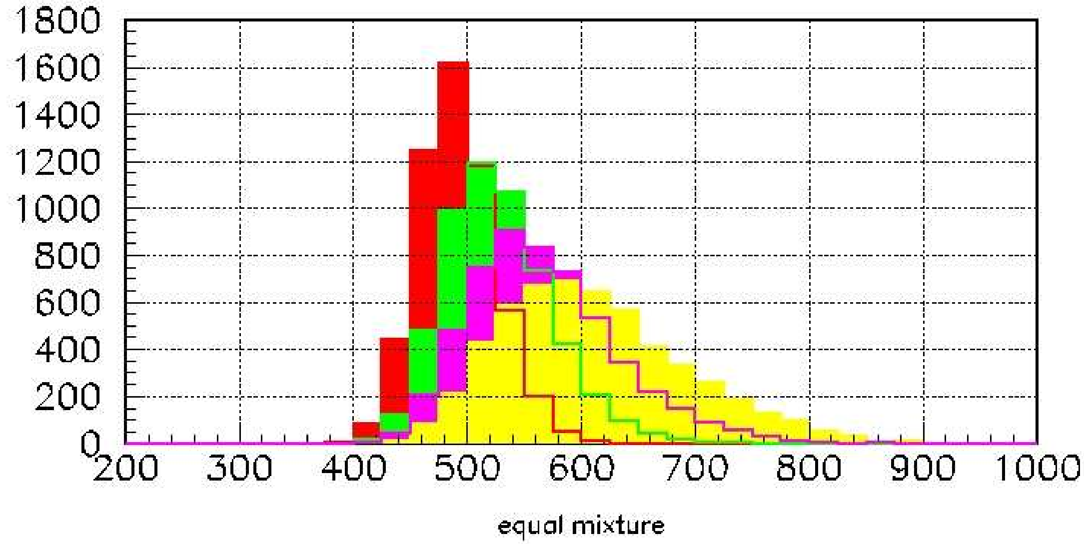


Simulated X_{max} distributions for 4 different nuclei groups taking into account all apparatus uncertainties. Model QGSJET-01.

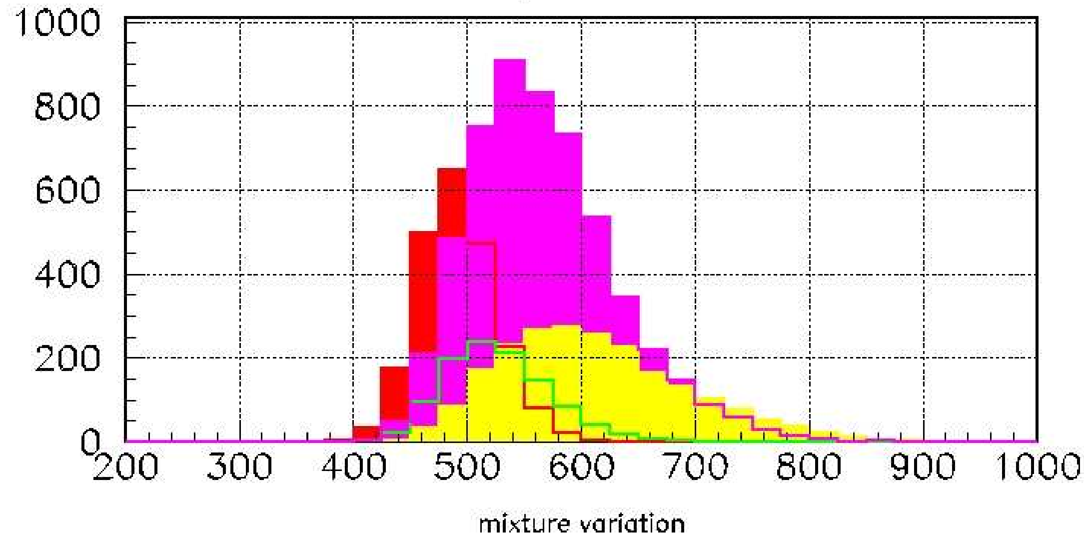


Mass composition fit.

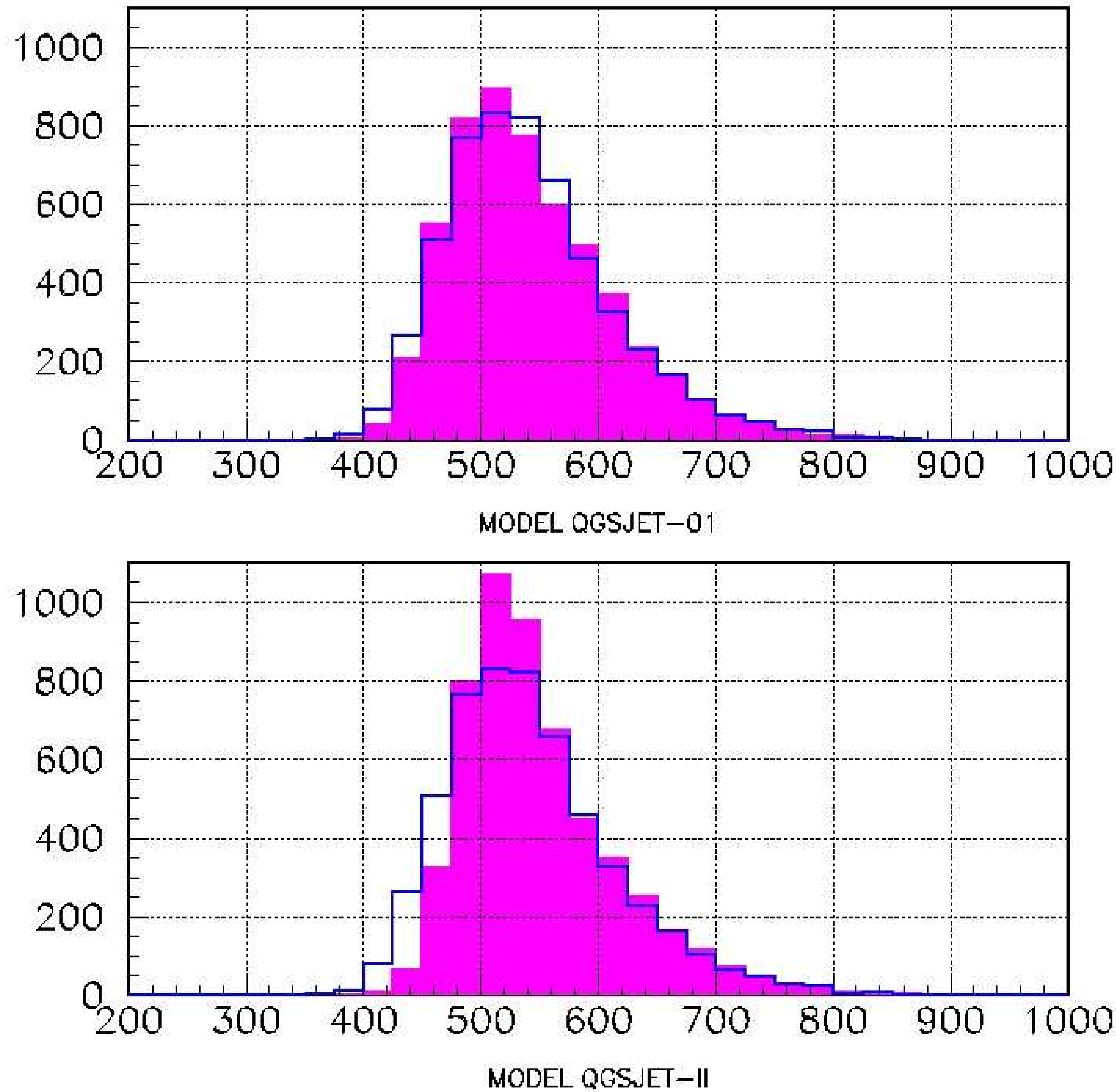
4 groups with equal weights:



Weights fit for the best agreement with the experimental distribution:



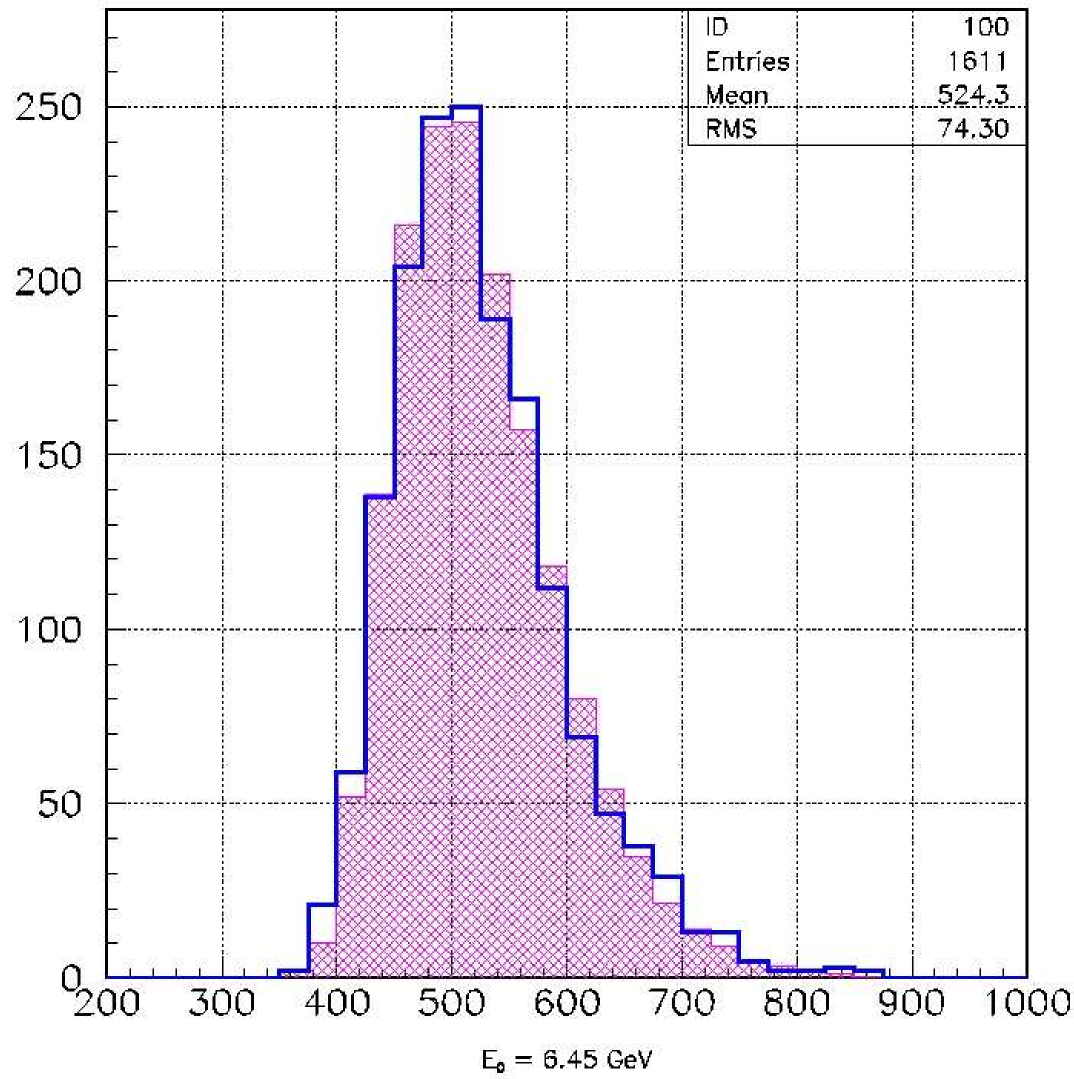
Comparison of experimental (line) and simulated (filled area) X_{max} distributions for $E_0=5\cdot10^{15}$ eV



X_{max} distribution

blue line is experiment

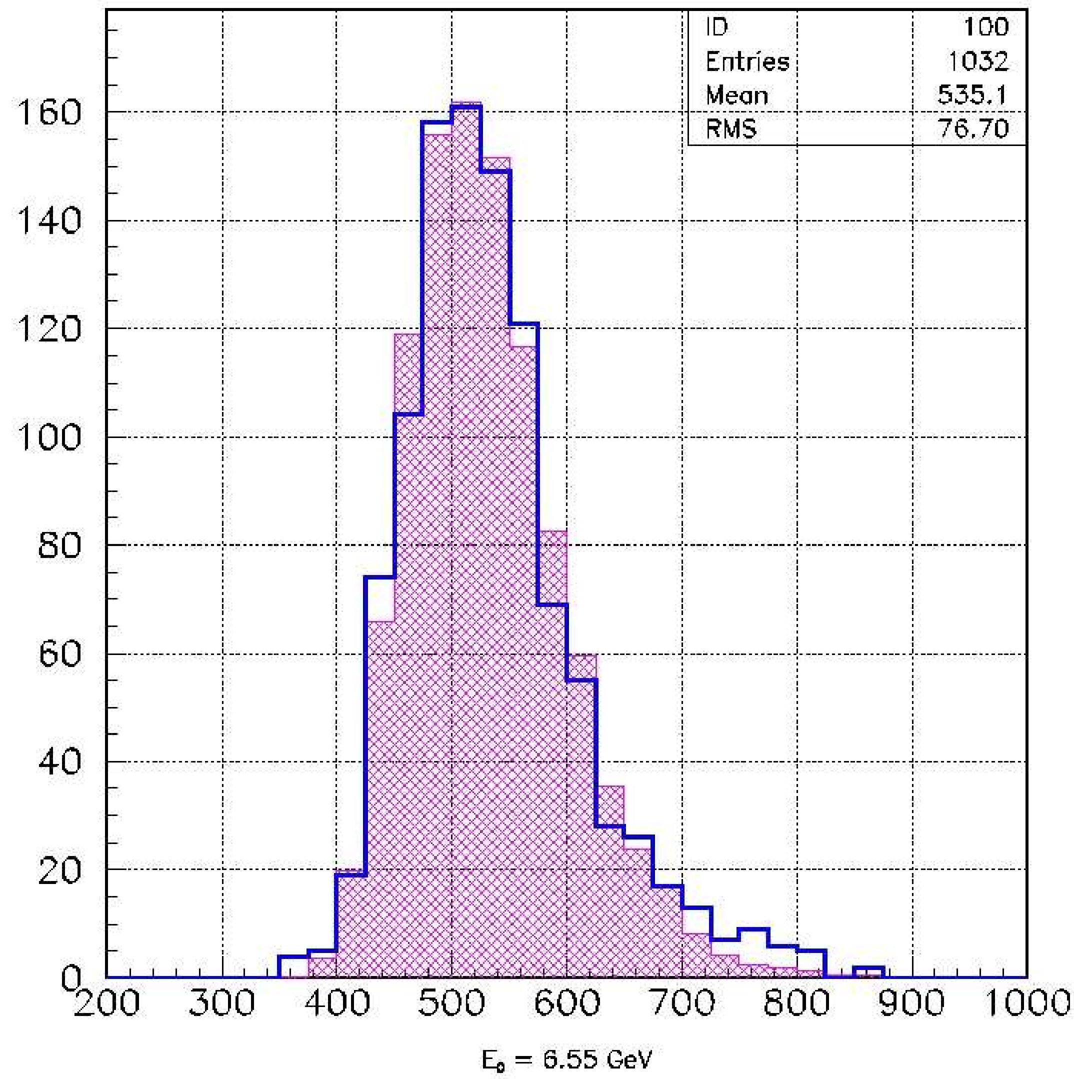
filled area is the simulation



X_{max} distribution

line – experiment

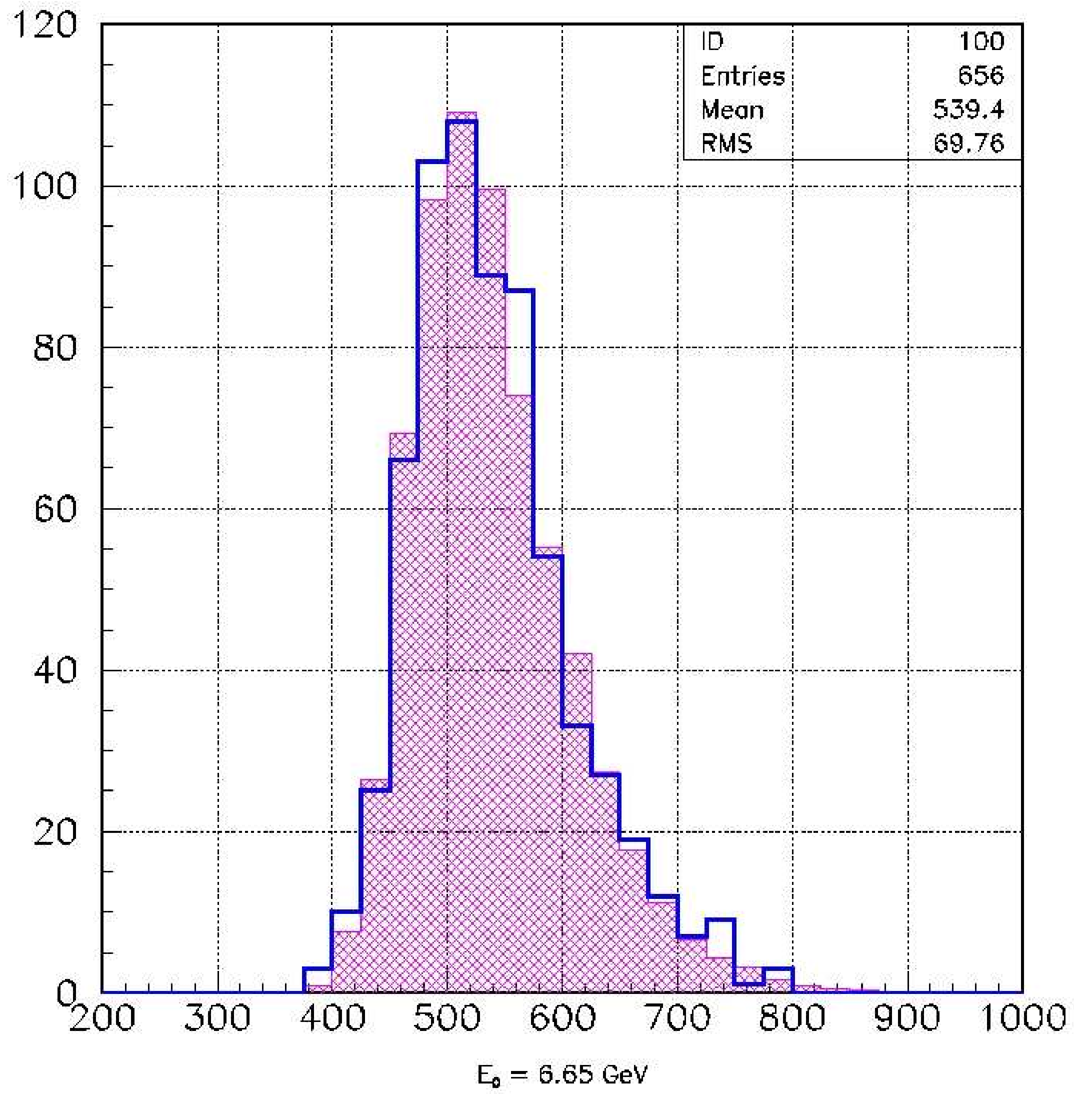
filled area – simulation



X_{max} distribution

line – experiment

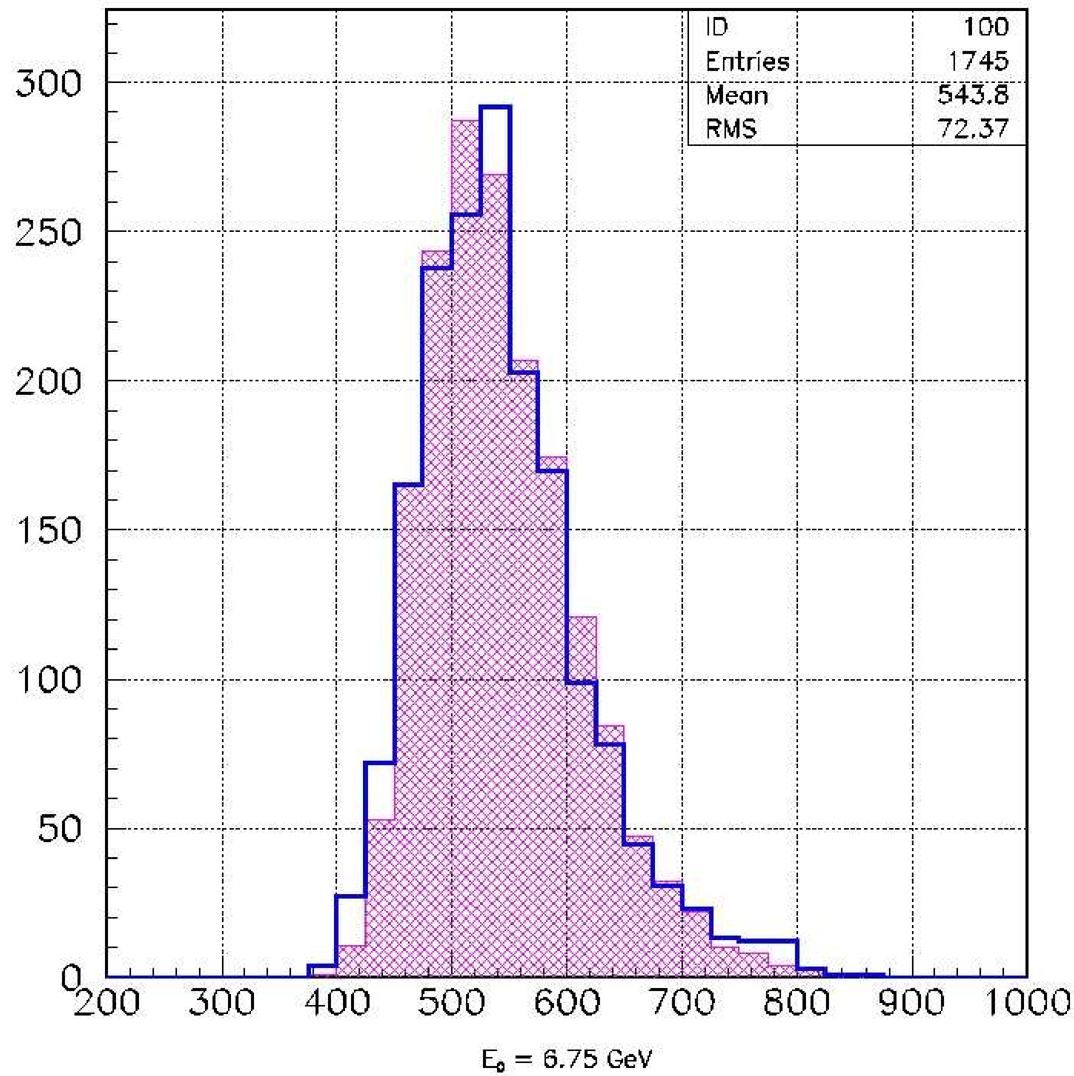
filled area – simulation



X_{max} distribution

line – experiment

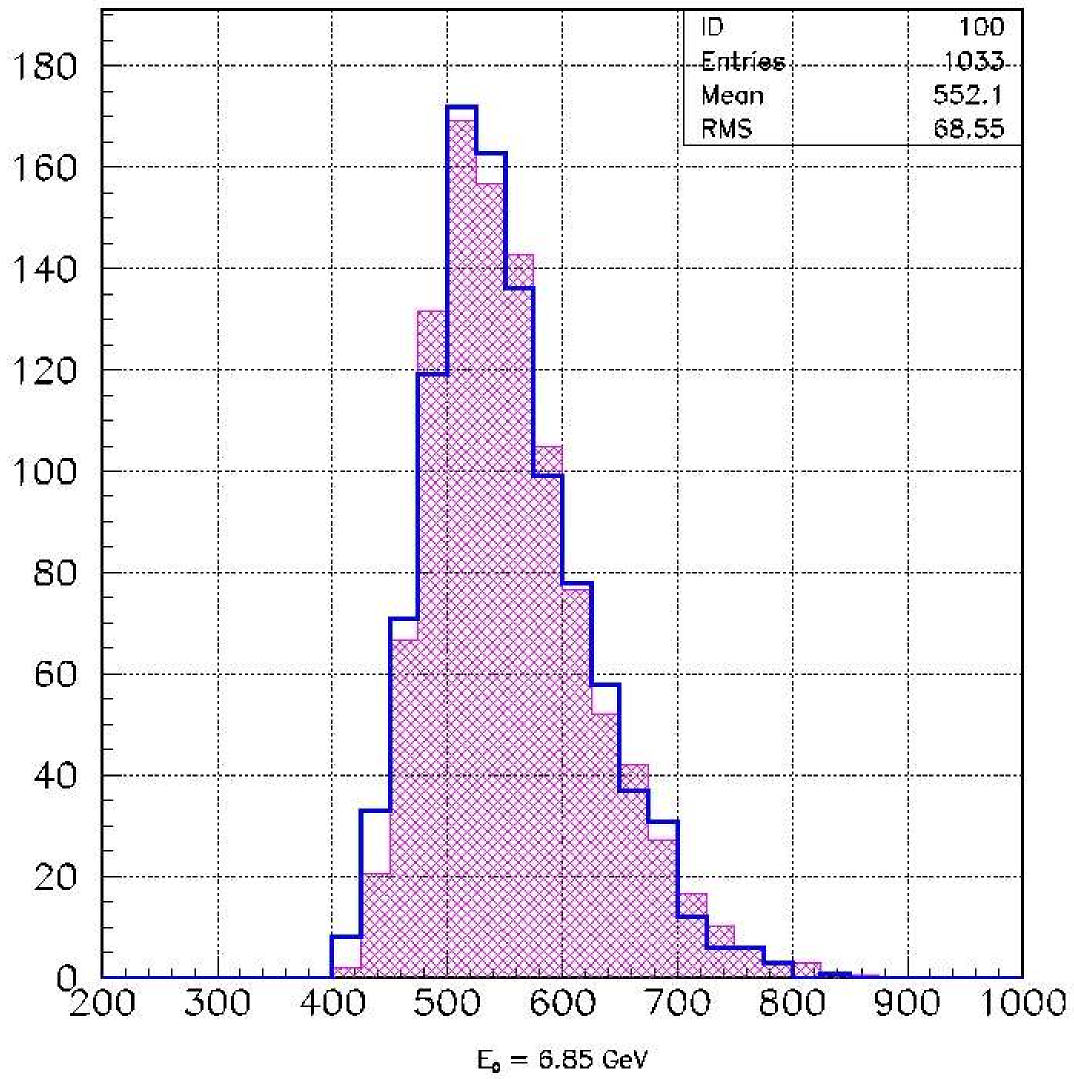
filled area – simulation



X_{max} distribution

line – experiment

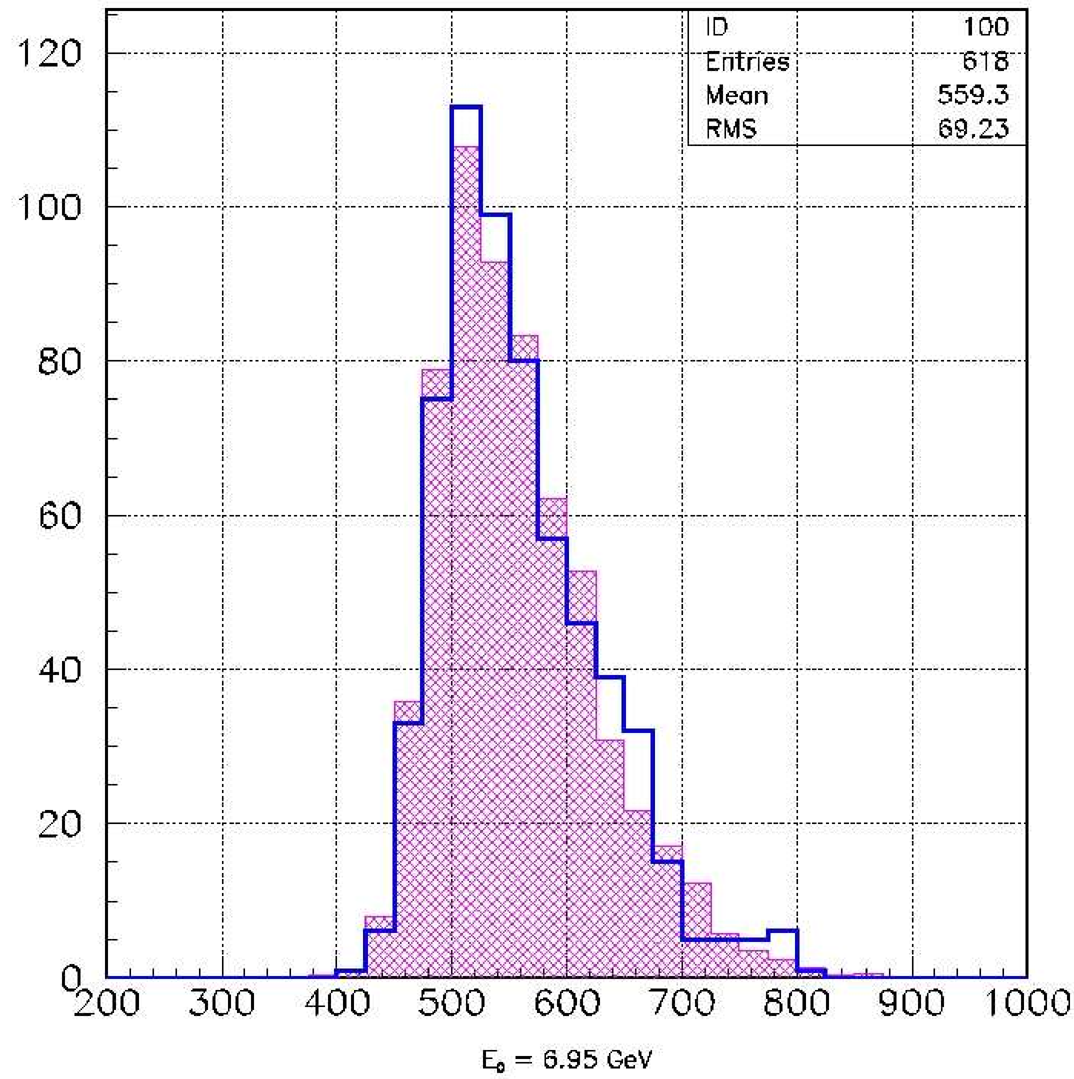
filled area – simulation



X_{max} distribution

line – experiment

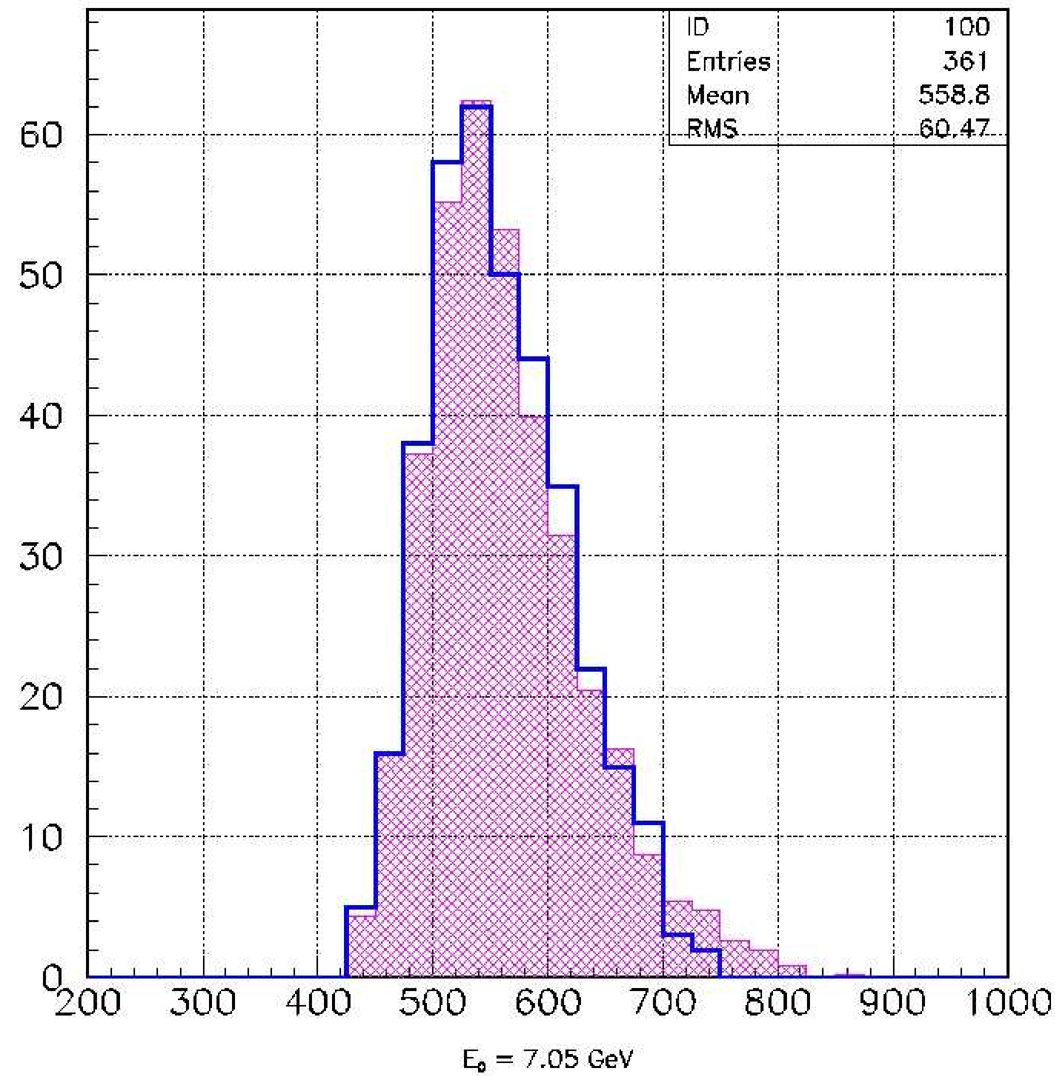
filled area – simulation



X_{max} distribution

line – experiment

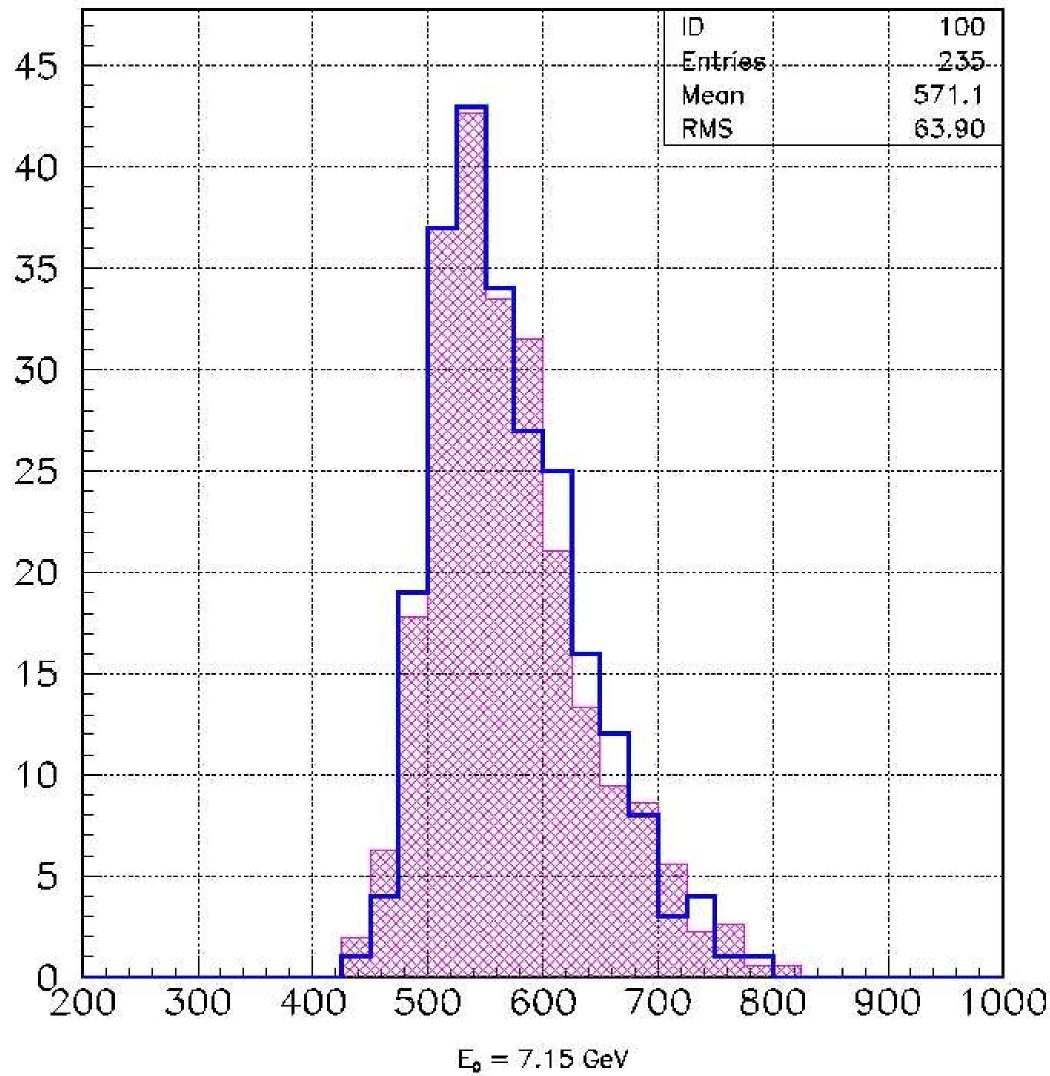
filled area – simulation



X_{max} distribution

line – experiment

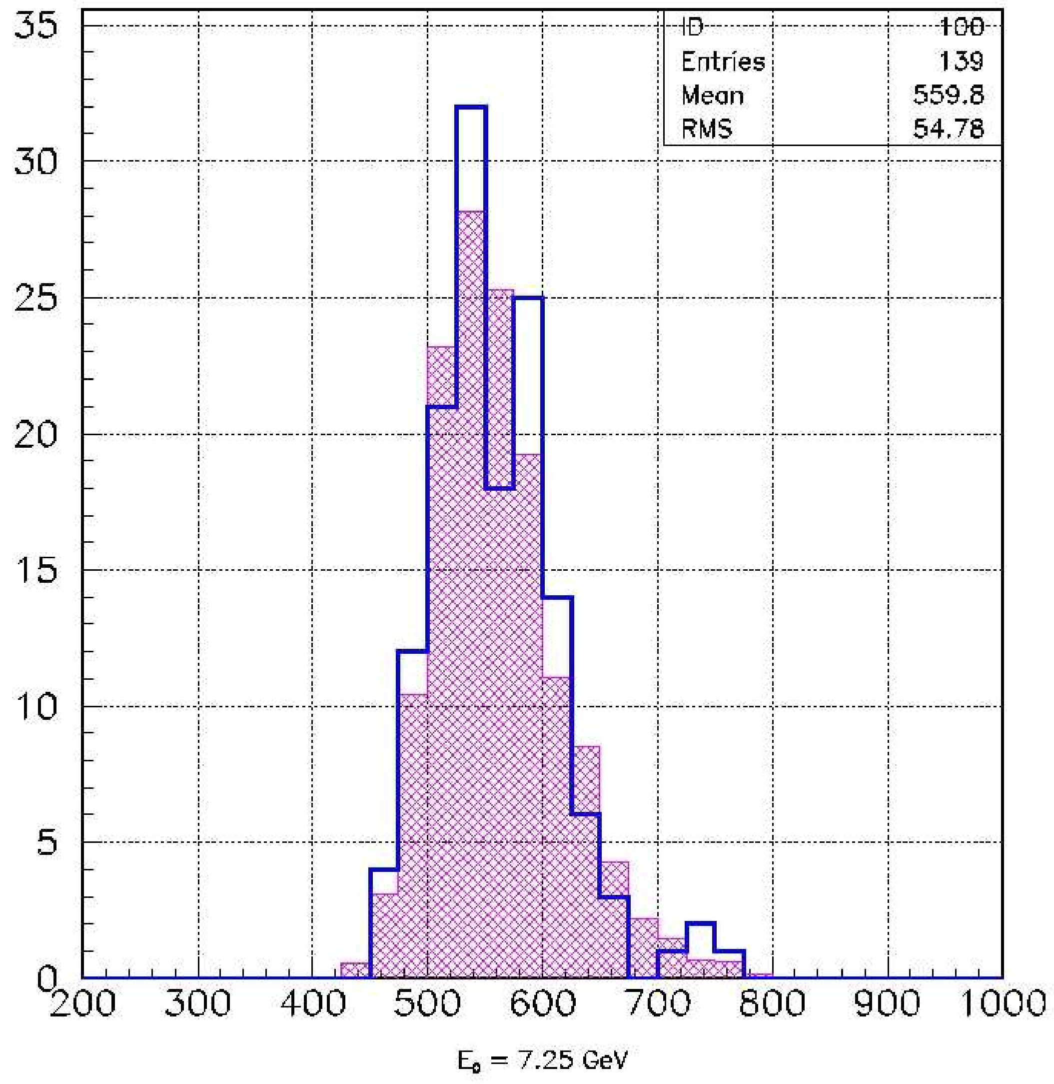
filled area – simulation



X_{max} distribution

line – experiment

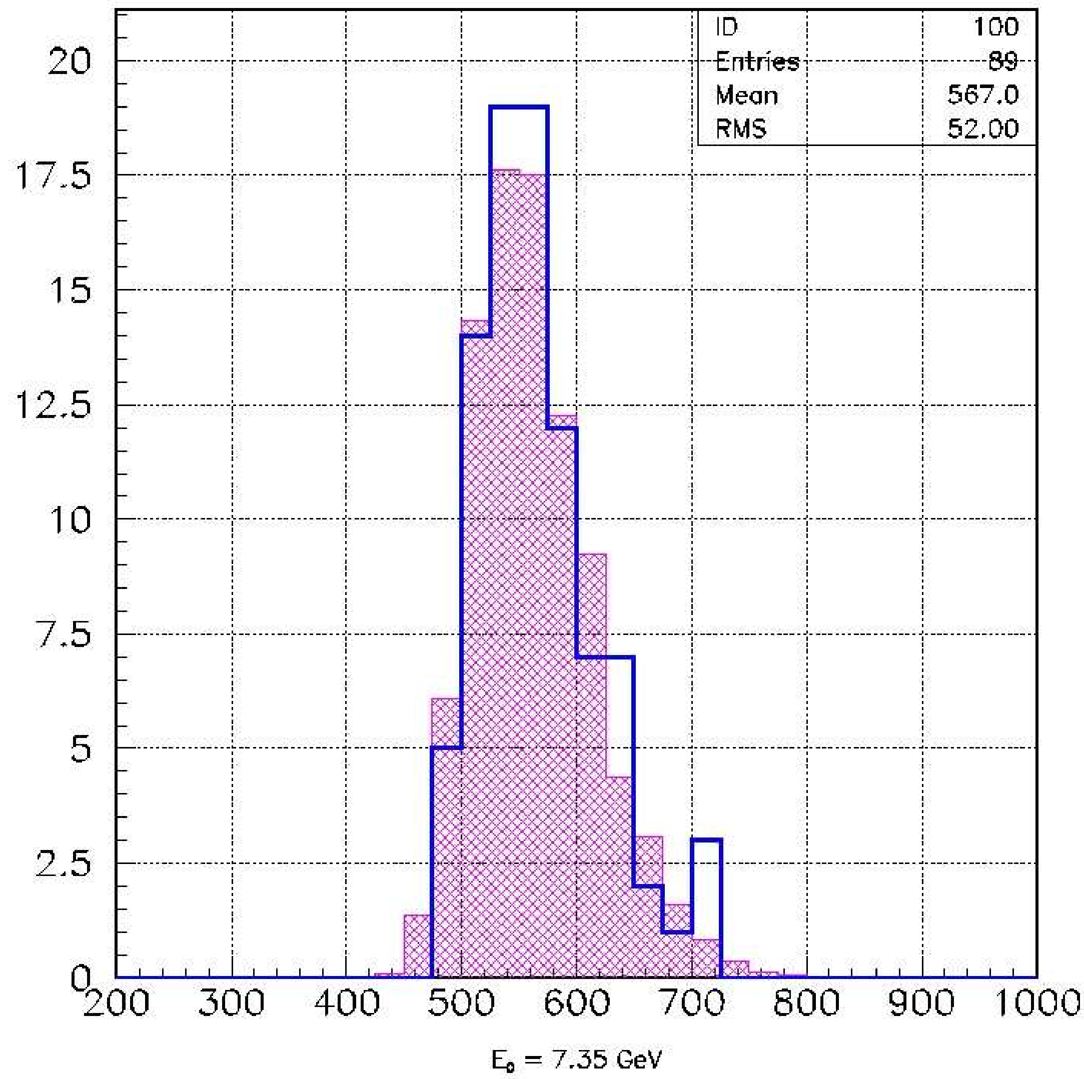
filled area – simulation



X_{max} distribution

line – experiment

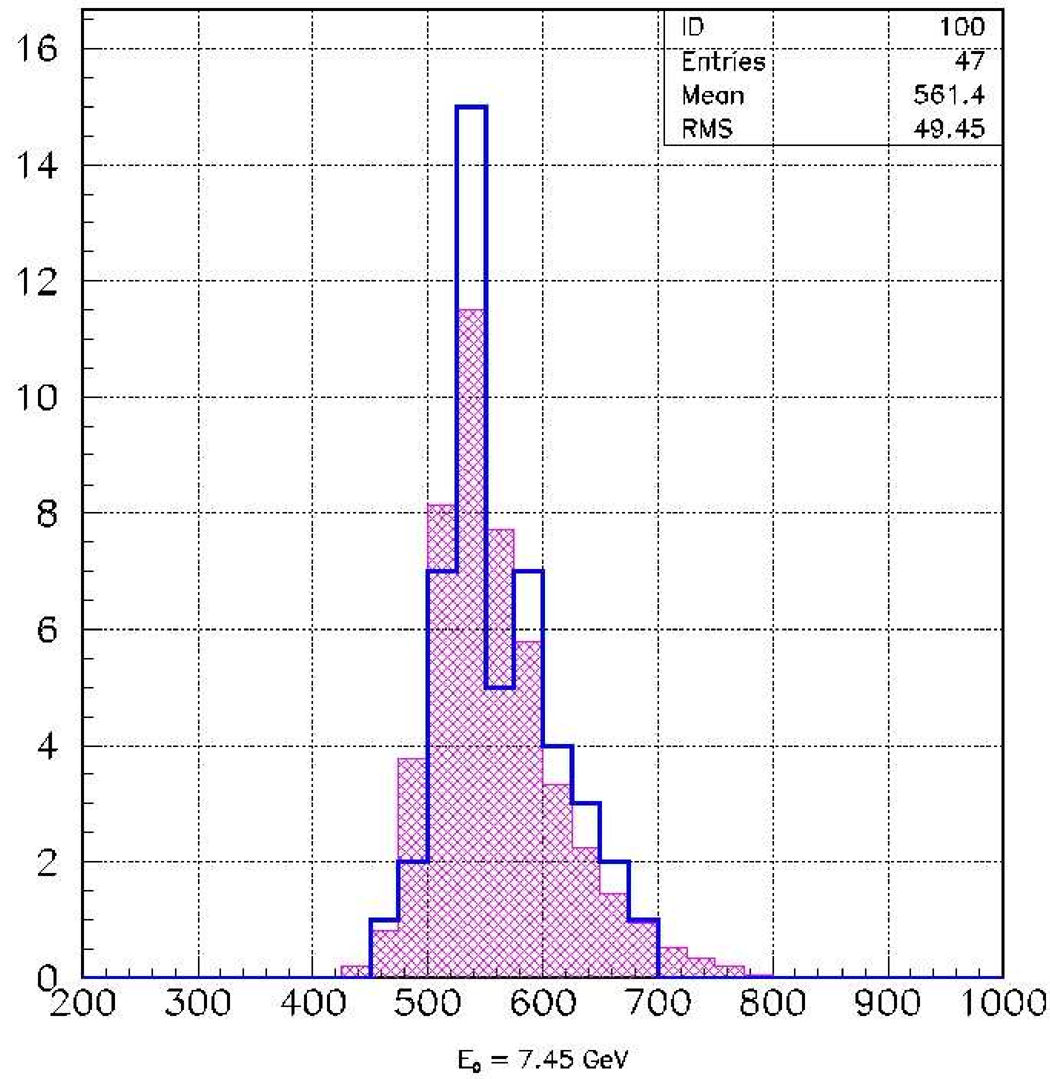
filled area – simulation



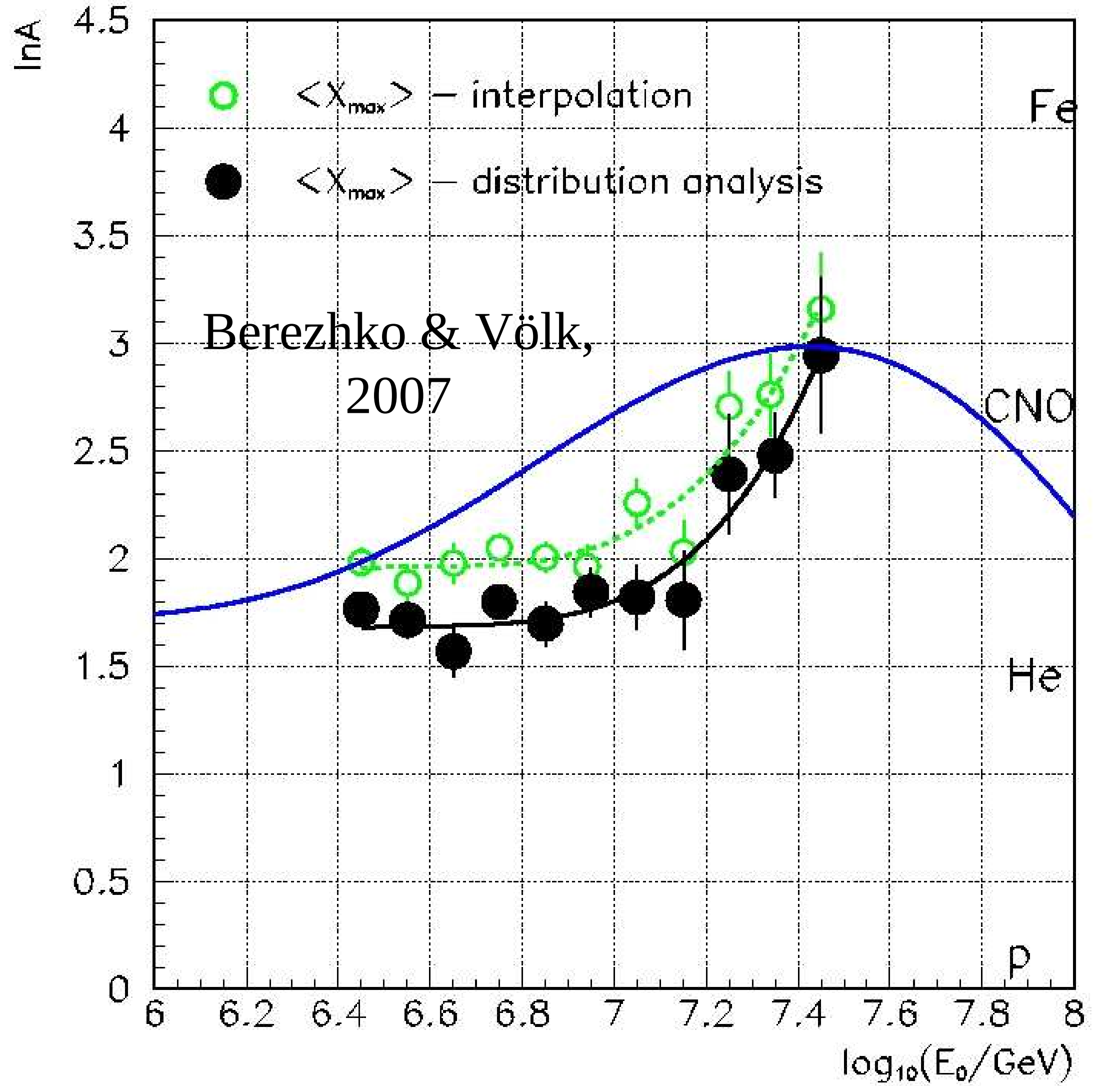
X_{max} distribution

line – experiment

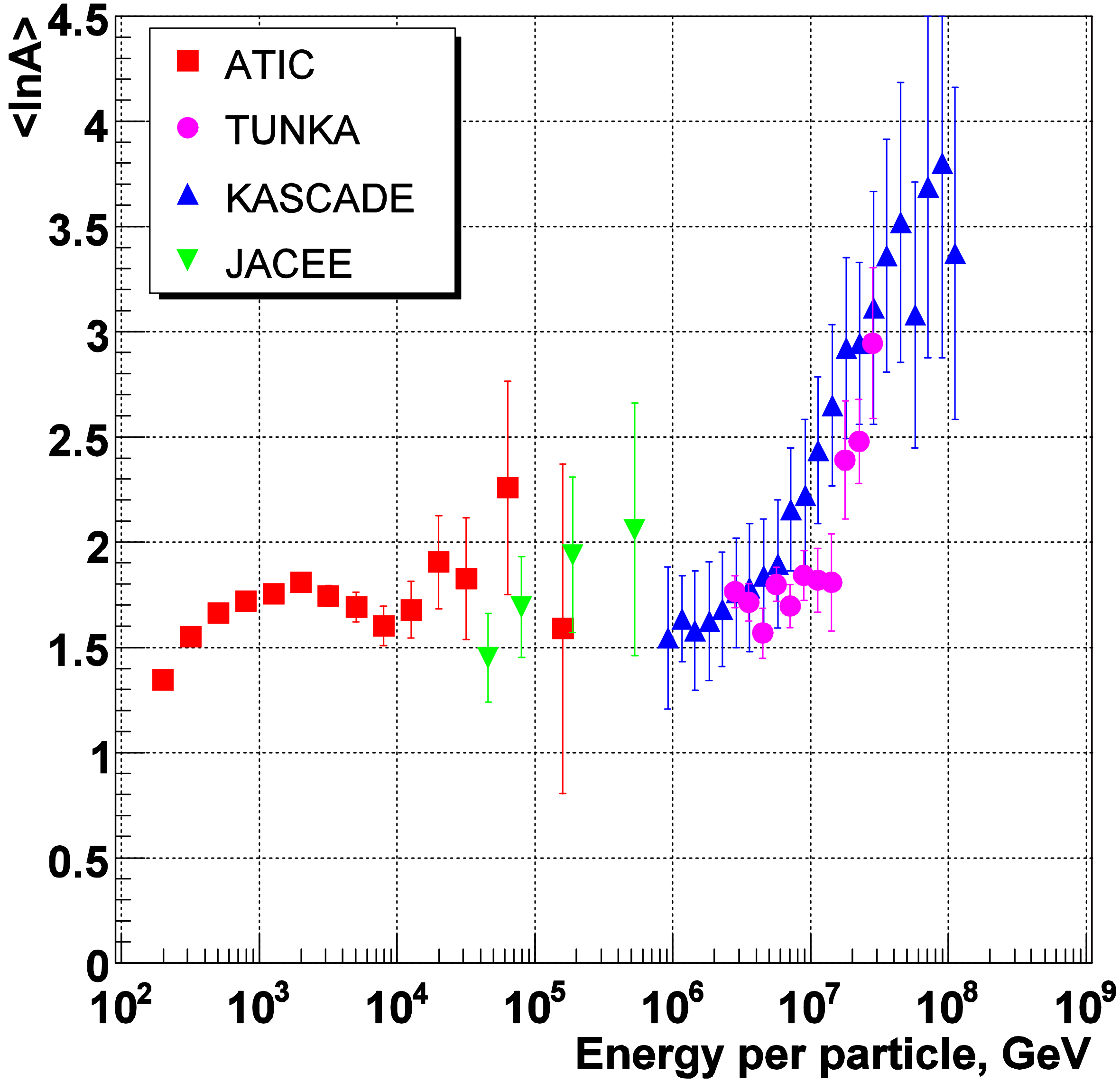
filled area – simulation



Mean mass composition



Mean mass composition



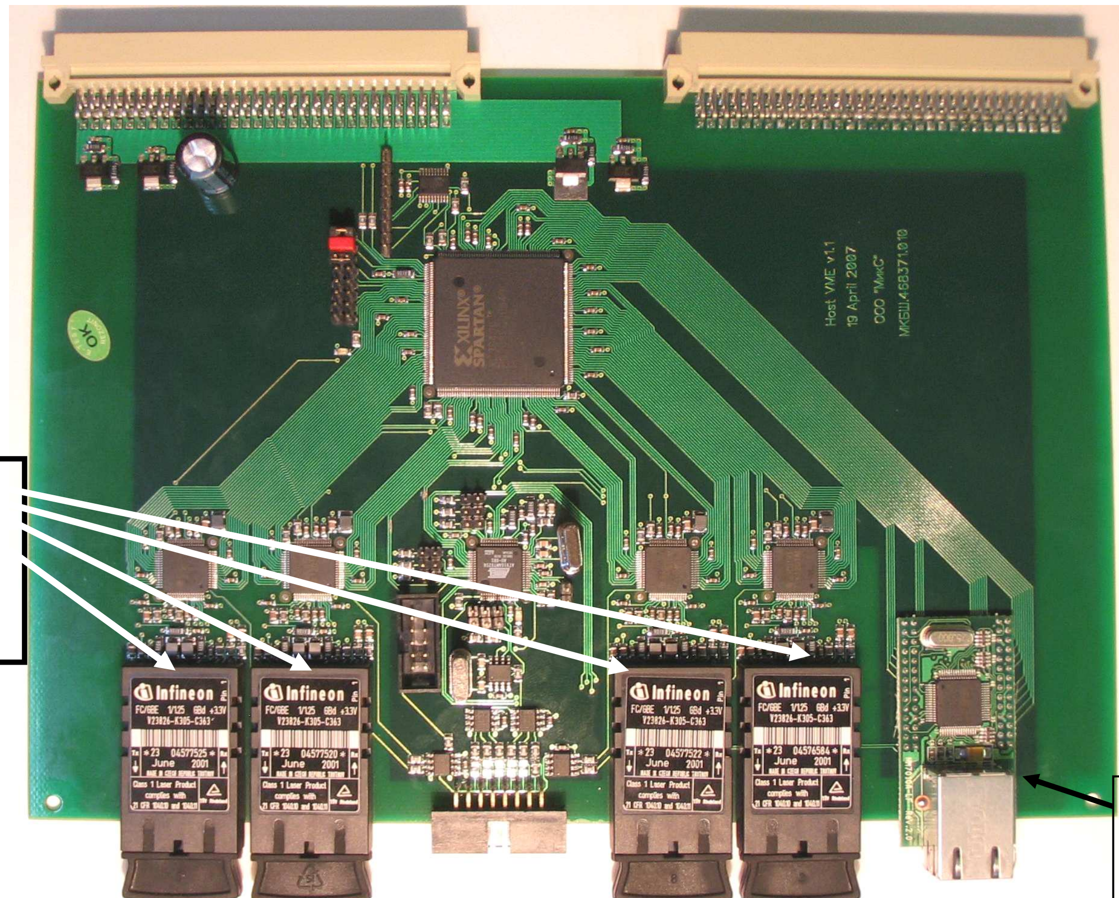
CONCLUSIONS

1. Composition before the knee and in the knee is light 70% of p+He, 30% of others.
2. Composition at $3 \cdot 10^{16}$ is heavy 30% of p+He, 70% of others.

Some important steps towards Tunka-133

1. 2002: G. Navarra suggested to use PMTs from former MACRO experiment.
2. 30.12 2003: 200 PMTs arrived in Moscow.
3. 2004: Starting of financial support from DFG-RFBR funds.
4. 2005: Optical cable (~10km) from the terminated EAS-1000 project.
5. 2006: Starting of financial support from Russian Ministry of Education and Science. Project budget ~ 130 – 150 KEuro per year.
6. 2006 – 2009: ADC AD9430 chips from G. Navarra (Italia) and C. Spiering (Germany).

Central DAQ board
(produced in SINP MSU)




06-6

truction. Sum

The array deployment

Optical cables

The detector installation

PMT prerparing

Measuring of the detectors coordinates (x,y,z) – accuracy ~ 10 cm.

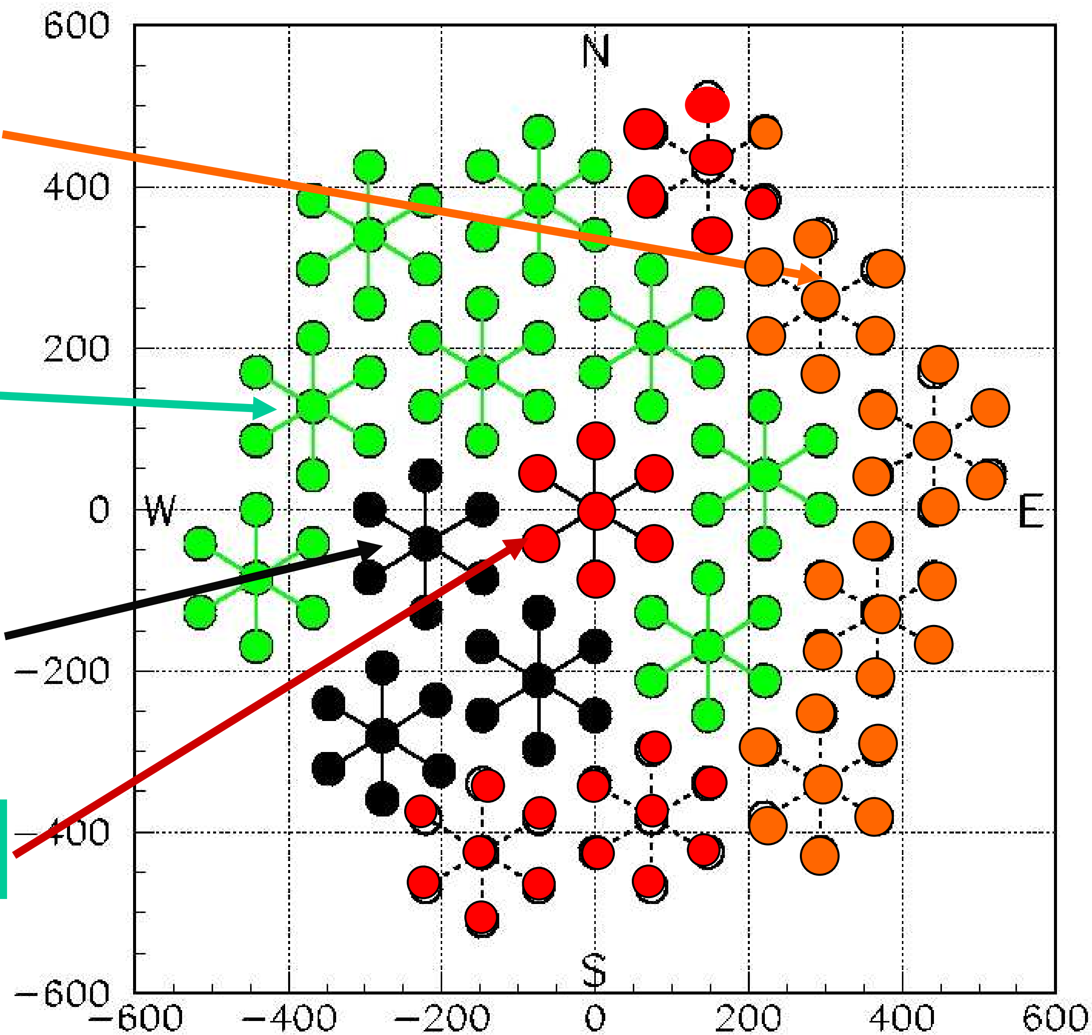
Tunka-133 deployment

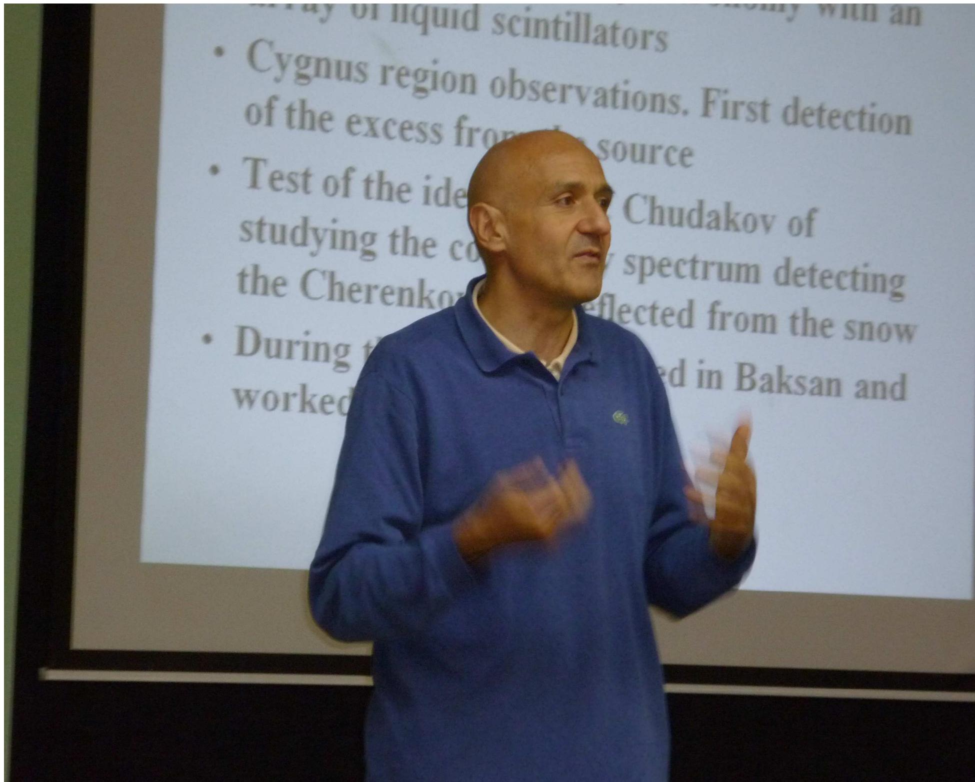
2009 – 19 clusters

2008 – 12 clusters

2007 – 4 clusters

2006 – the first cluster




of liquid scintillators
• Cygnus region observations. First detection
of the excess
source
• Test of the
Chudakov of
studying the
spectrum detecting
from the snow
• During
in Baksan and


VAIO

Lake Baikal trip

Tunka Collaboration

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A. Chiavassa
– Dip. di Fisica Generale Universita' di Torino and INFN, Torino, Italy.

D. Besson, J. Snyder, M. Stockham
– Department of Physics and Astronomy, University of Kansas, USA

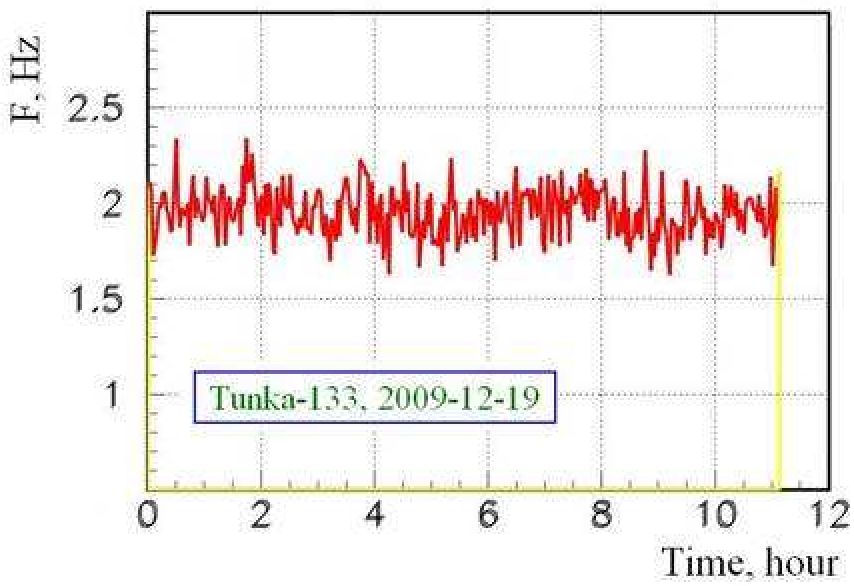
The first season of observation: November 2009 – March 2010

286 h. of clean weather

> $2\cdot10^6$ events with energy $\geq10^{15}$ eV.

~ 200 EAS with energy $>10^{17}$ eV inside the circle R<500 m and θ<45°

>10 events with 19 clusters hit every night

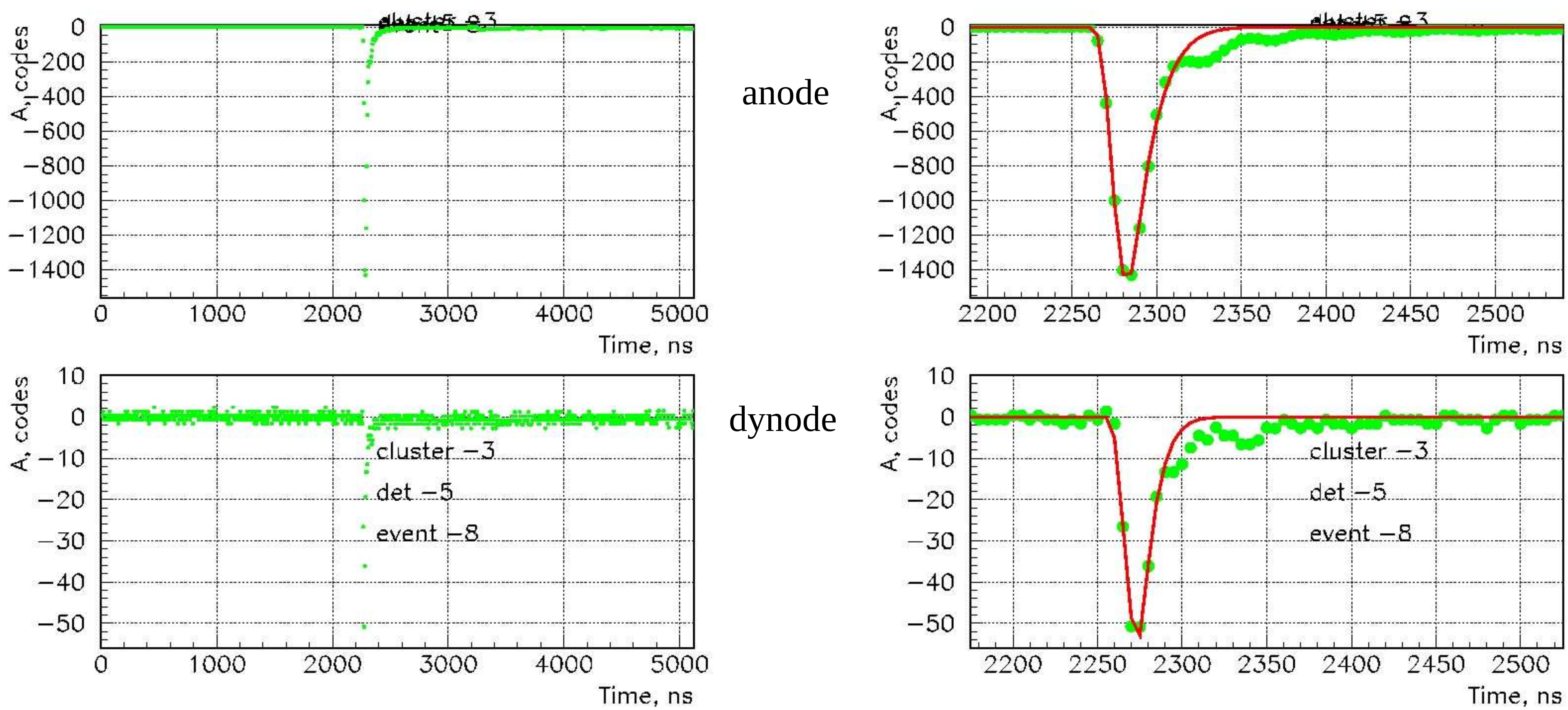


Tunka-133 <u>single night</u> statistics is comparable with that of Tunka-25 <u>single winter</u>

EXPERIMENT:
Every event = 7 – 133 pairs of records:

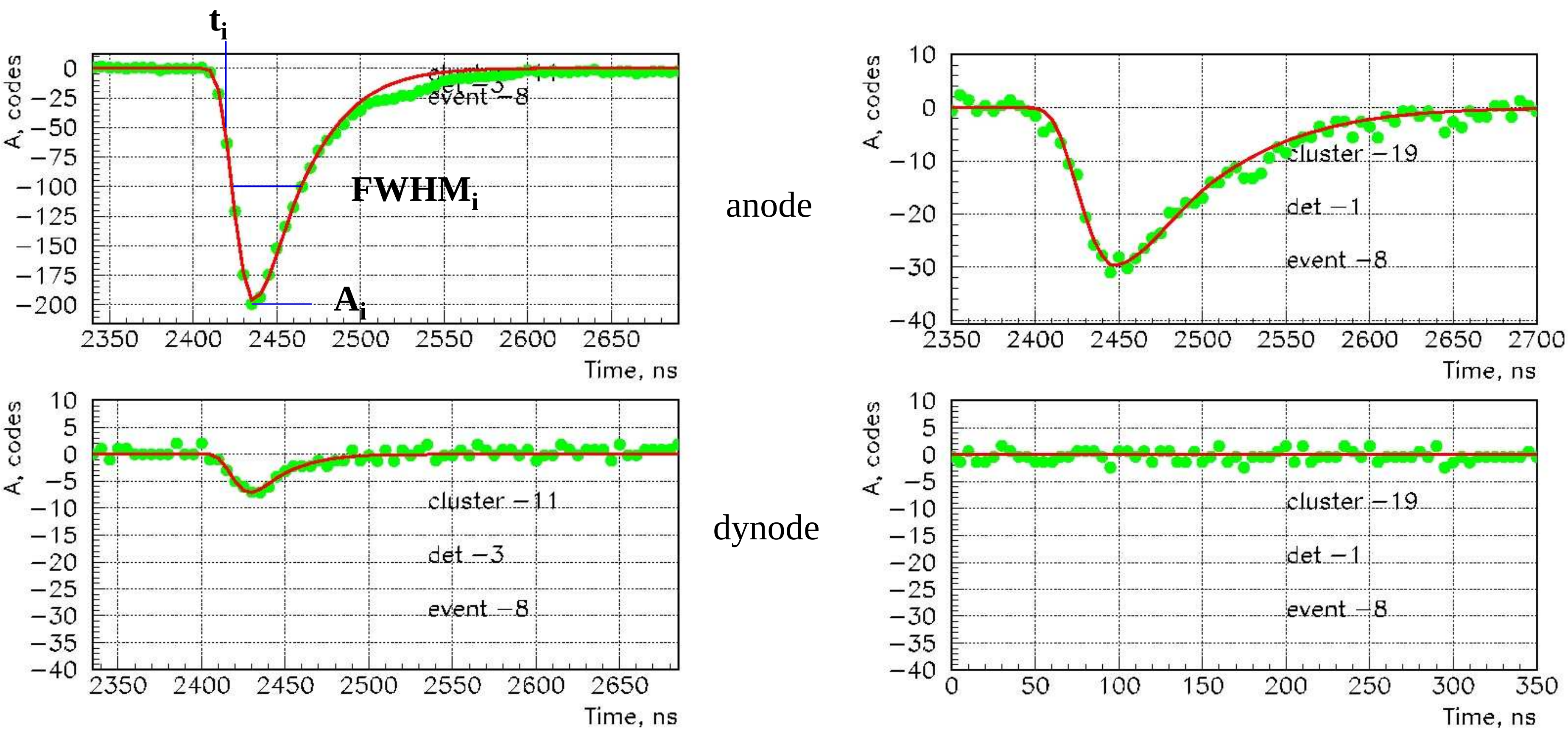
The primary data record for each Cherenkov light detector containes 1024 points of amplitude vs. time with the 5 ns time step:

1. Pulse selection
2. Apparatus distortions correction
3. Pulse waveform fitting



EXPERIMENT:

The main parameters determination – area (light flux) Q_i, amplitude A_i, width $FWHM_i$ and front delay t_i at $0.25A_i$.
(The more accurate $FWHM = \tau_{eff}/1.24$, $\tau_{eff} = Q_i/A_i$)



EAS parameters reconstruction

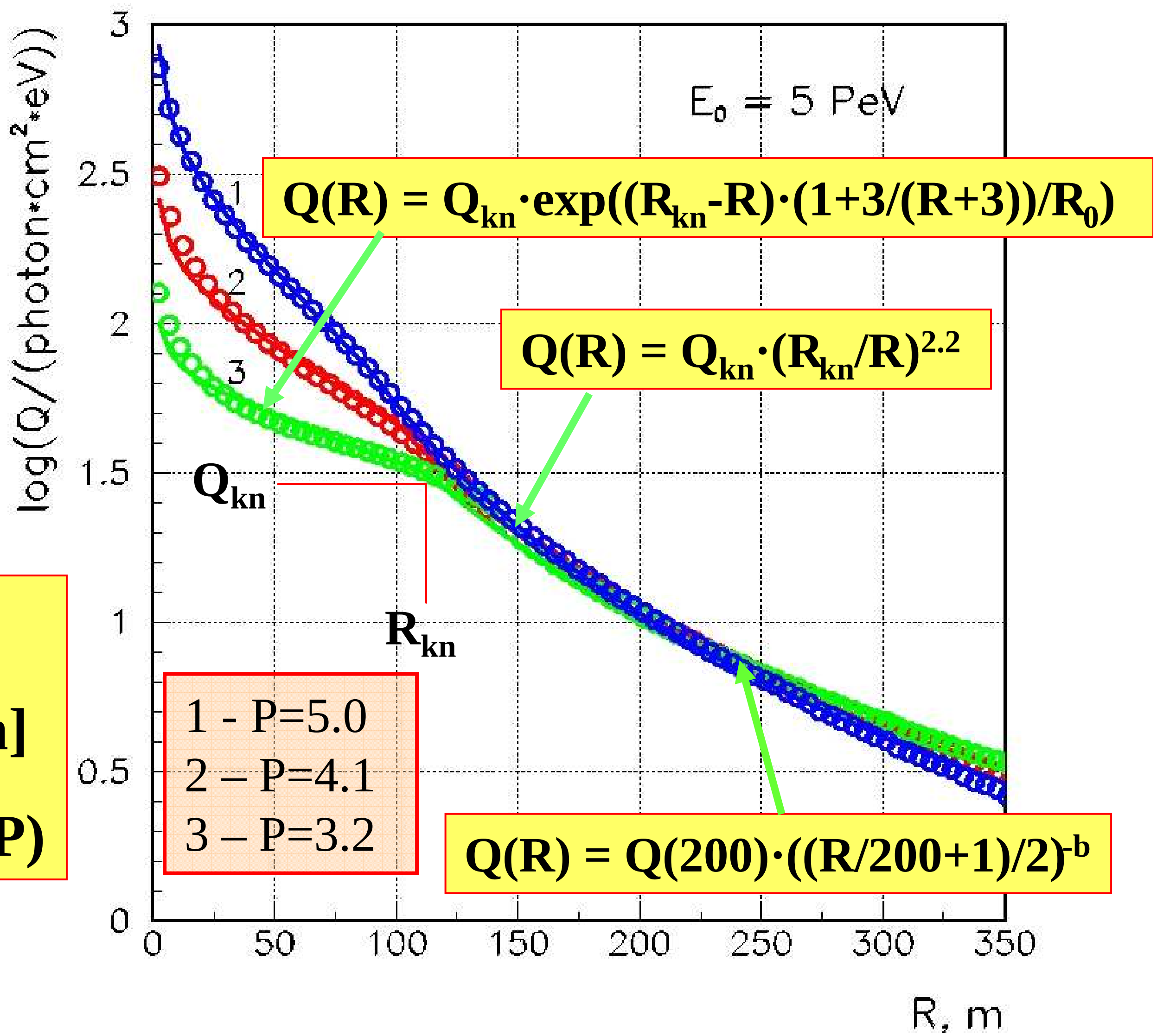
1. Traditional: Reconstruction of EAS core position by the method of Q_i fitting with LDF.
   Measuring of the LDF steepness P. Getting of WDF for the event and measuring of FWHM(400).

2. The new: Reconstruction of EAS core position by the method of FWHM fiiting with WDF.
   Getting of FWHM(400) and the LDF steepness P for this core position.

CORSIKA: Simulated lateral distributions and fitting function (LDF)

LDF has a single variable parameter of shape - **steepness:**
P=Q(100)/Q(200)

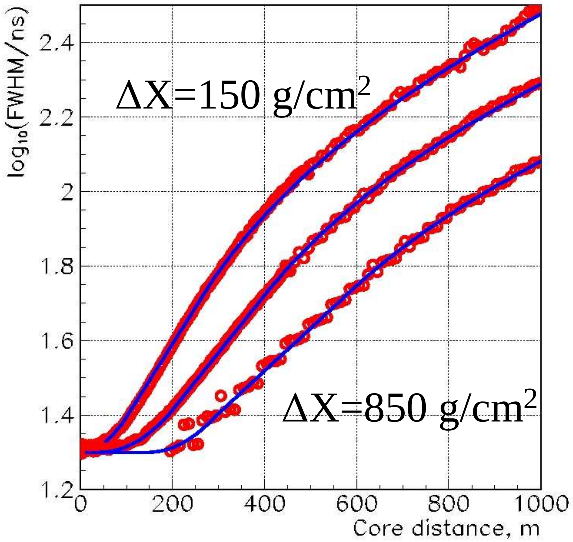
0 < R < 700 m



$R_0 = 10^{2.95-0.245\cdot P}$ **[m]**

$R_{kn} = 109 - 24.5\cdot(P-4)$ **[m]**

$b = 4.84 - 2.83\cdot\log_{10}(6.5-P)$

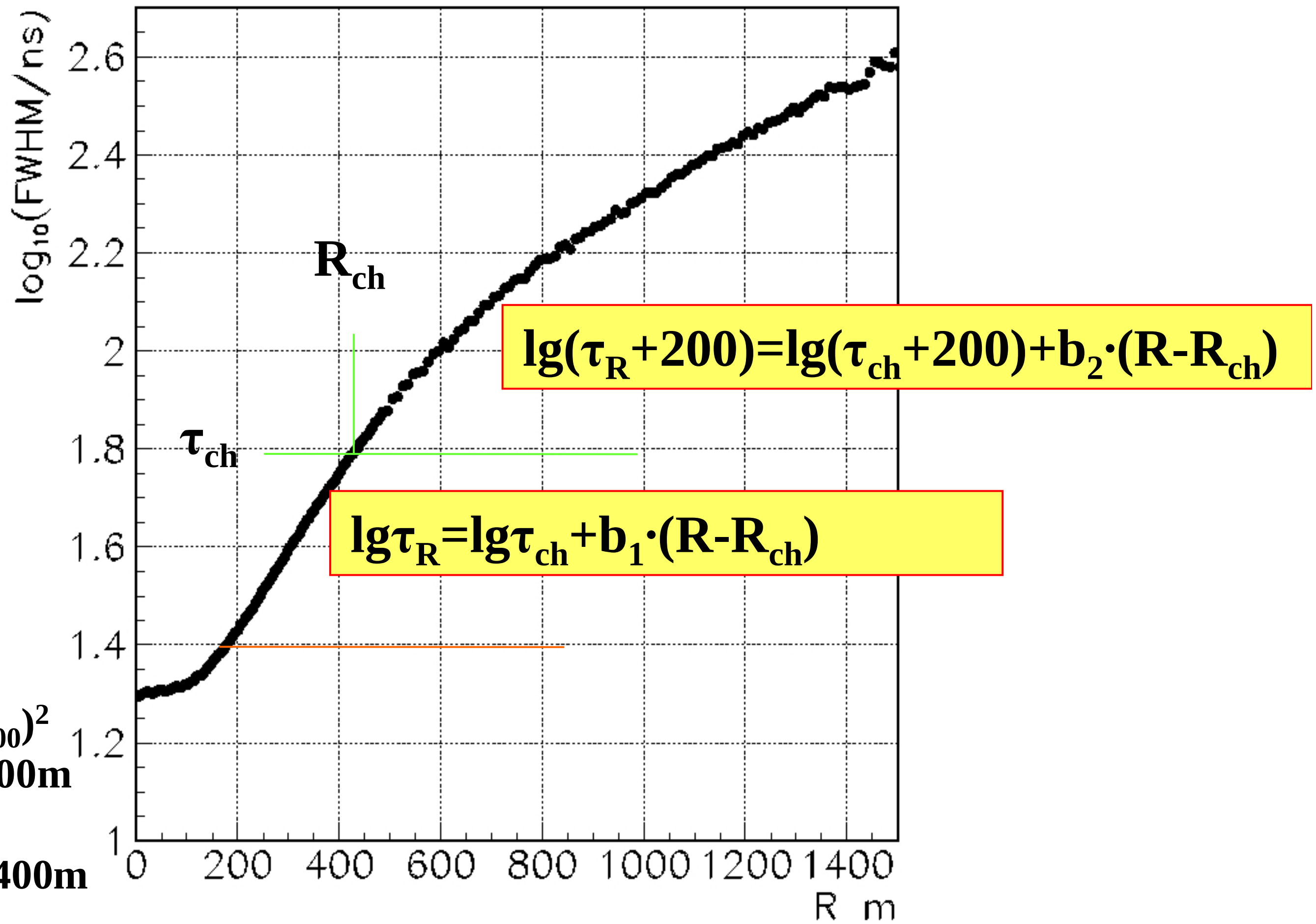


CORSIKA: Width vs. Distance Function (WDF)

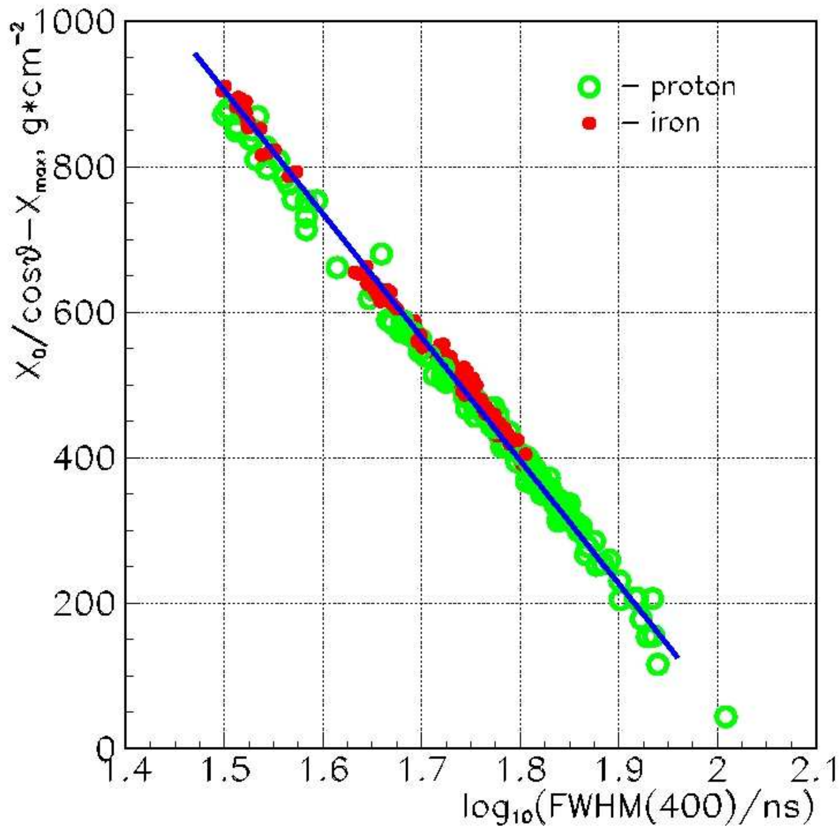
τ_R=FWHM(R)

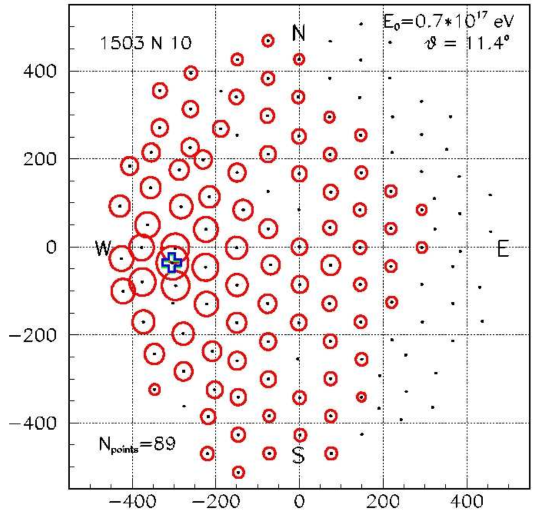
WDF has a single variable - FWHM(400)

$b_1=0.00196\cdot lg\tau_{400}-0.00183$
$b_2=0.000381\cdot lg\tau_{400}-0.000335$
$R_{ch}=3976-3429\cdot lg\tau_{400}+786\cdot(lg\tau_{400})^2$
$lg\tau_{ch}=lg\tau_{400}+b_1(R_{ch}-400)$, $R_{ch}<400$m
$lg(\tau_R+200)=$
$lg(\tau_{ch}+200) + b_2(R_{ch}-400)$, $R_{ch}>400$m

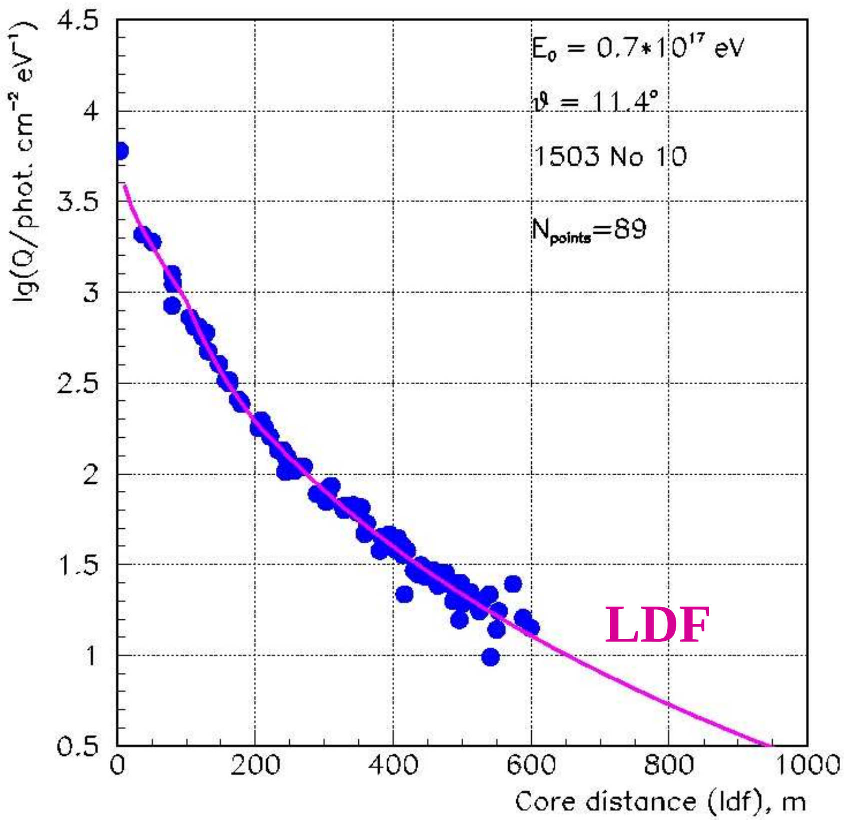


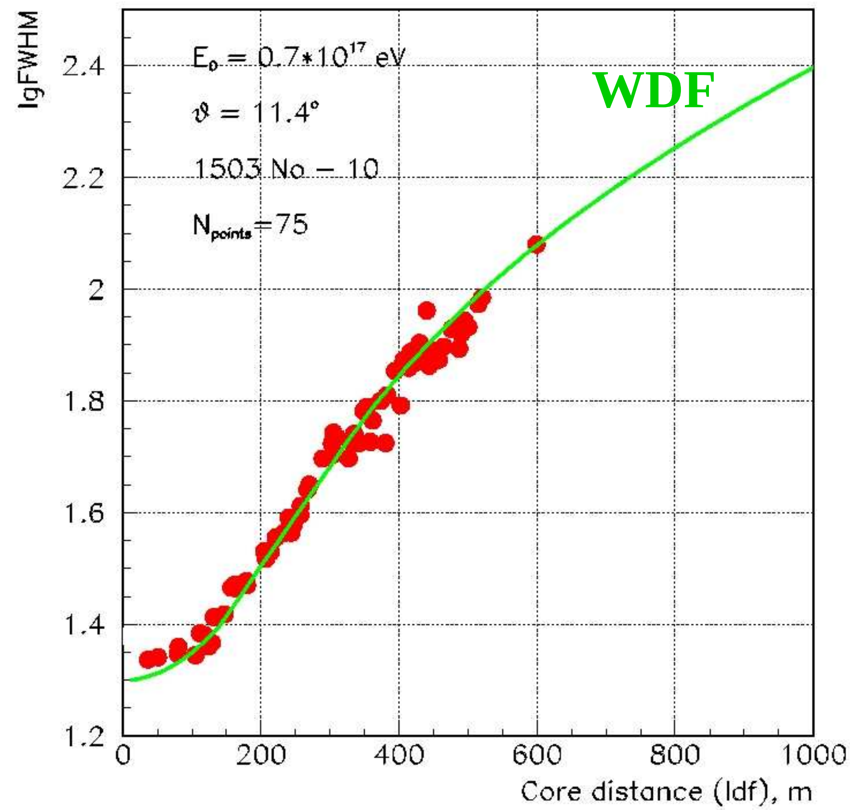
CORSIKA: X_{max} vs. FWHM(400)



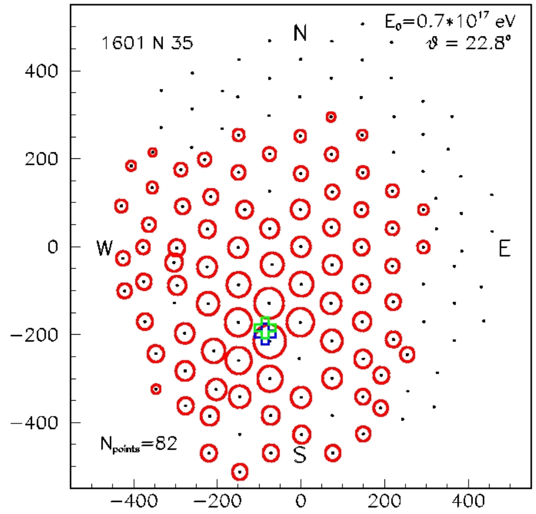


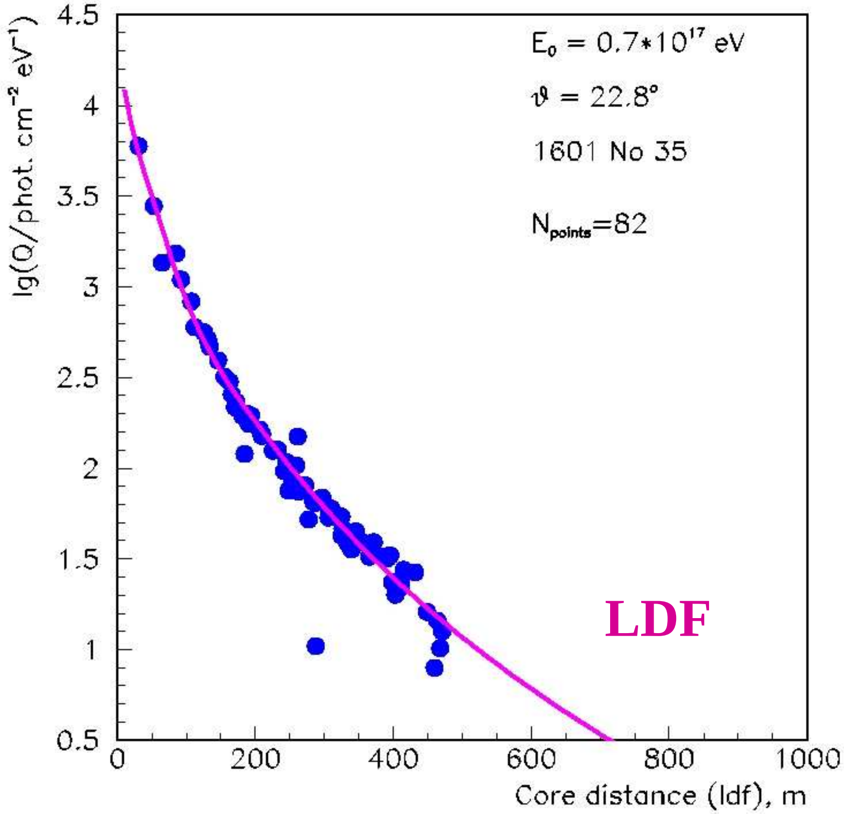
The event example.
15.03.2010

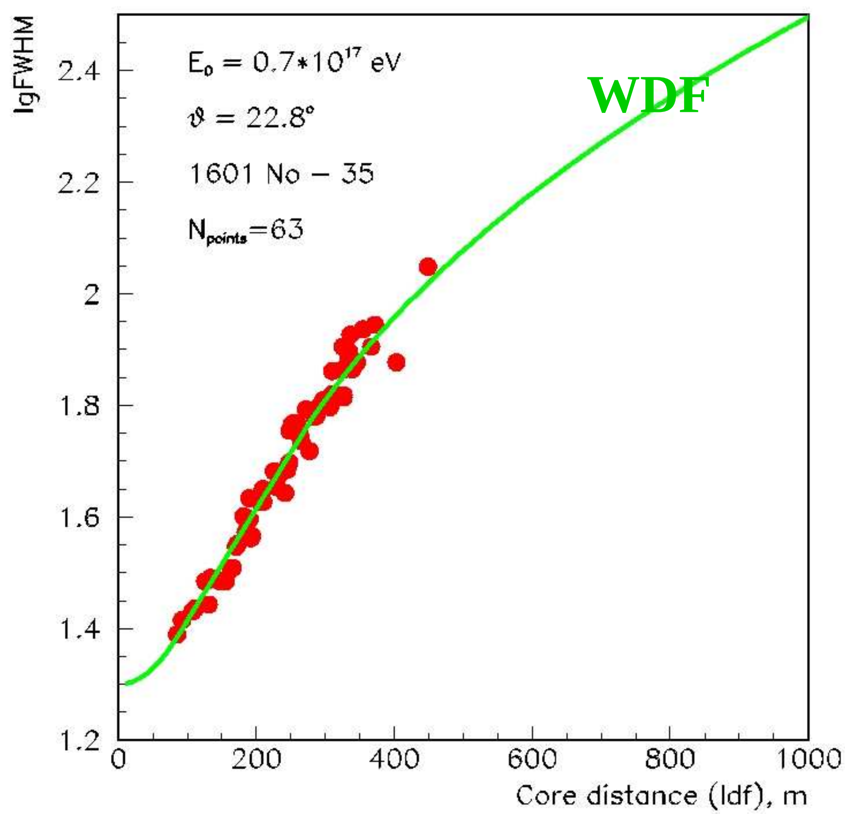


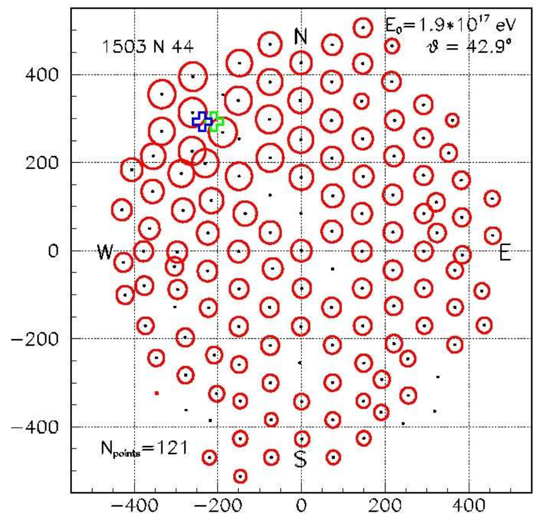


The most steep event.
16.01.2010

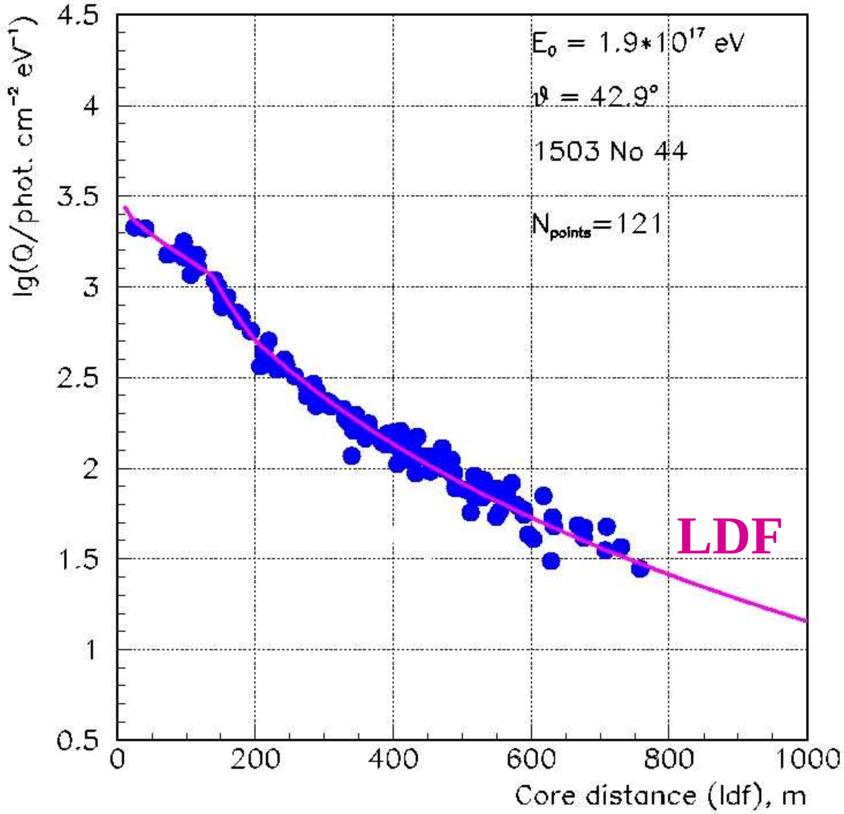


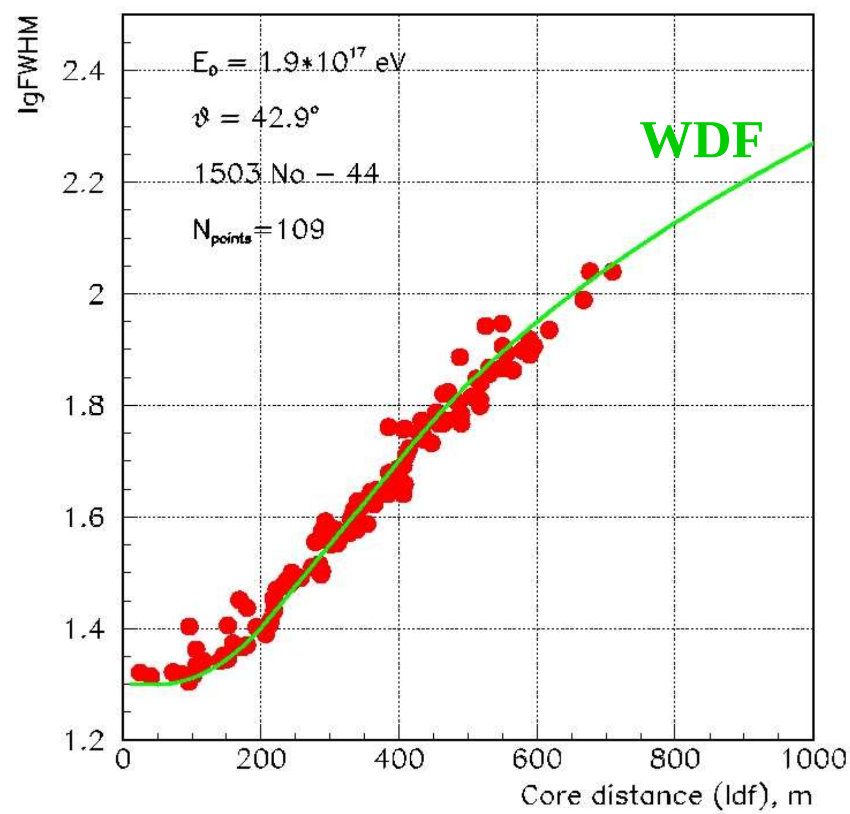


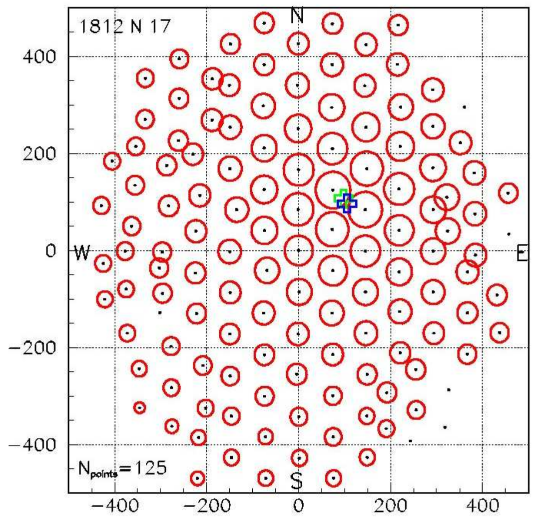




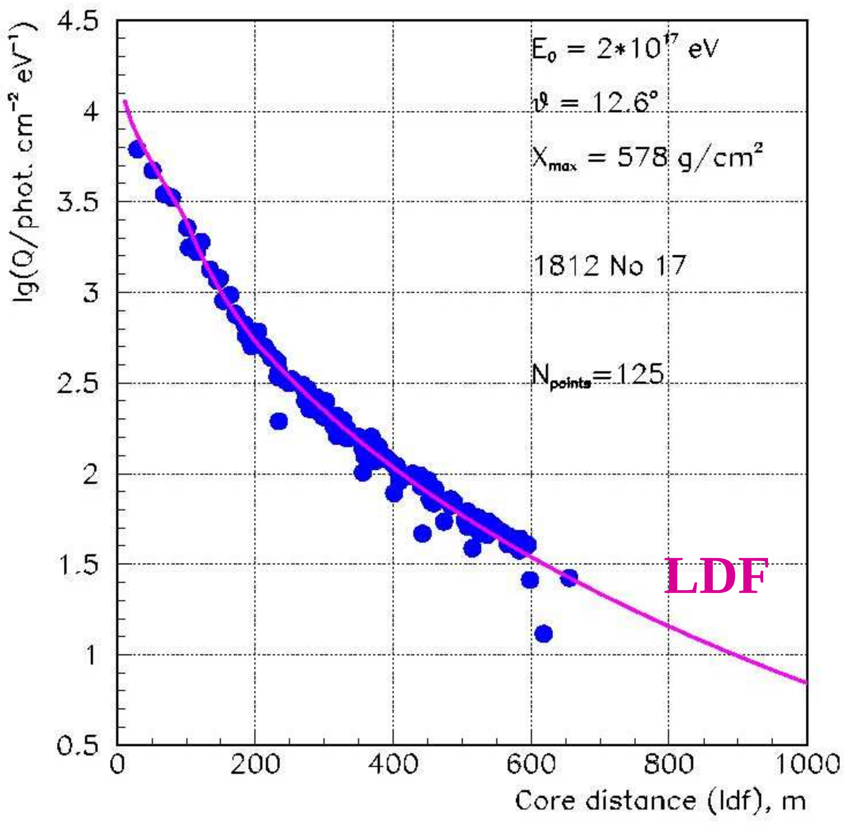
One of the most flat events. 15.03.2010

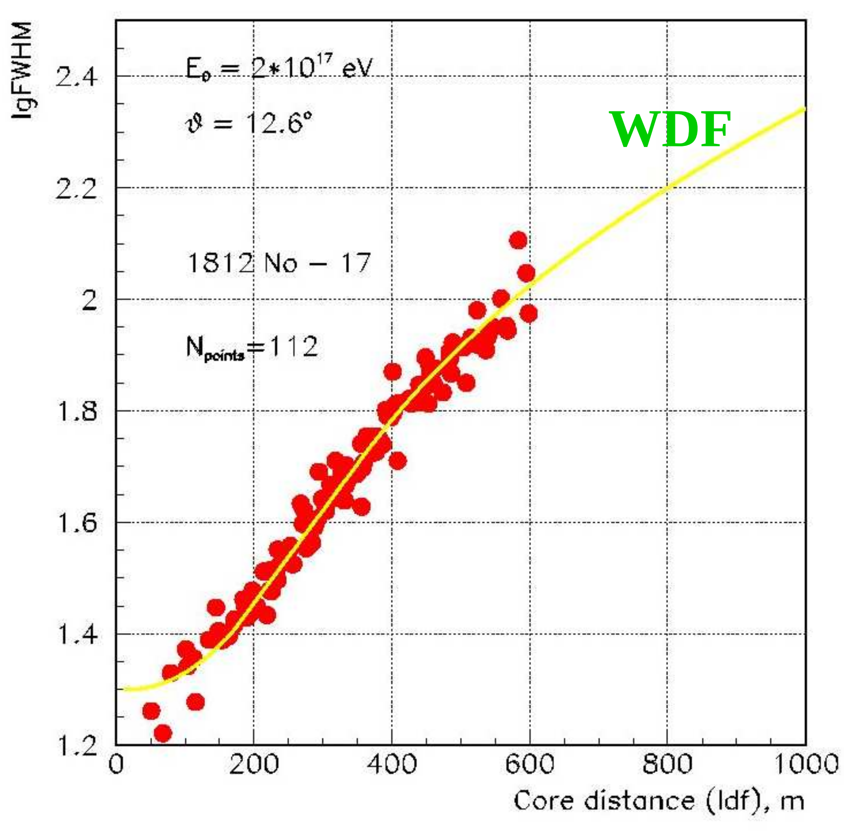


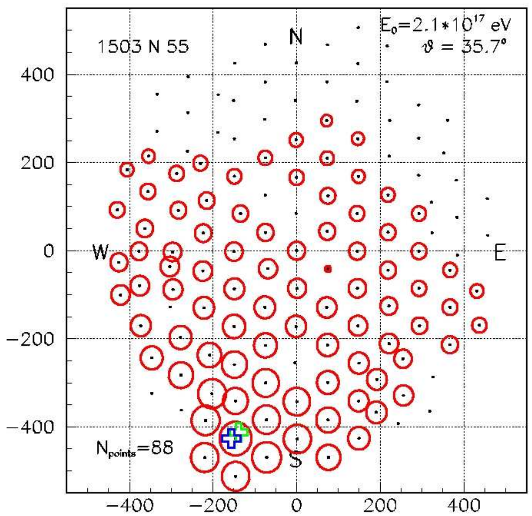




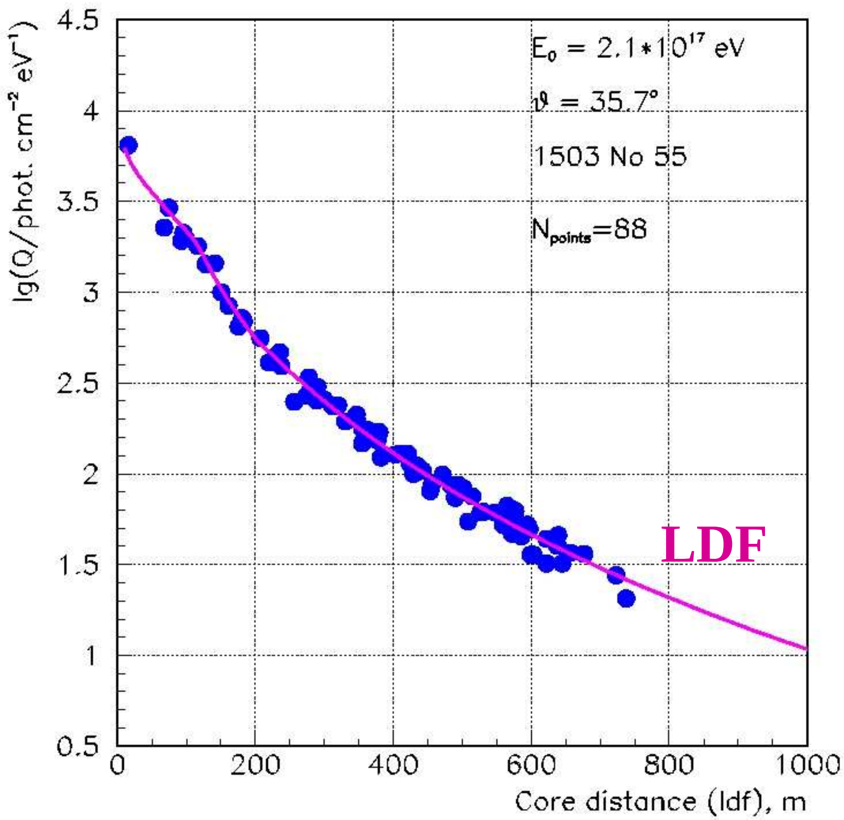
EAS core is close to the array center. 18.12.2009

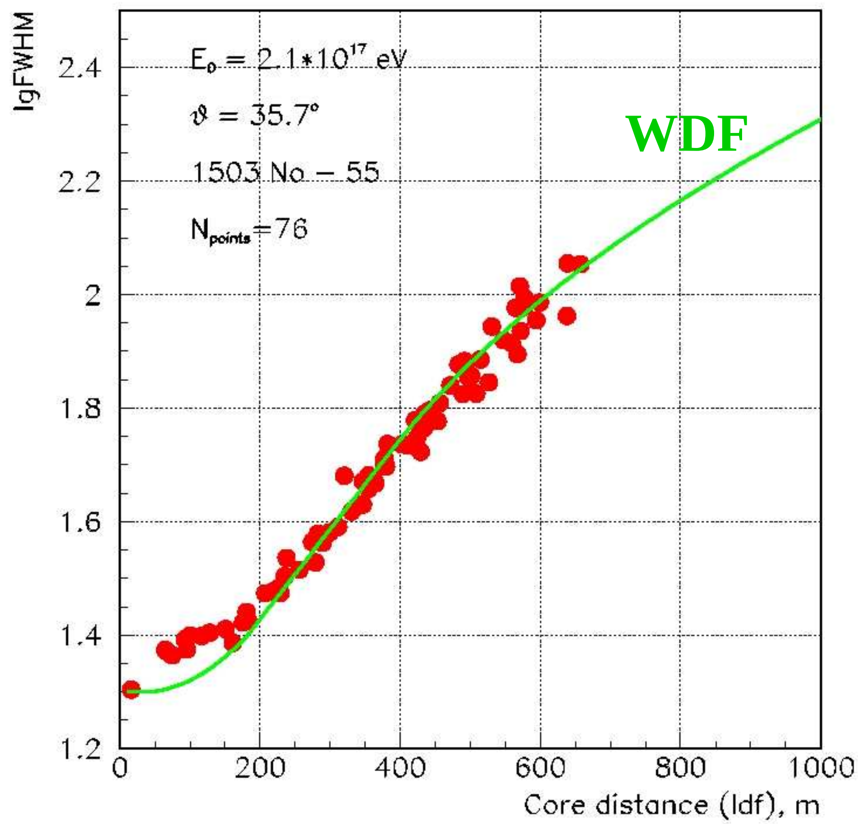




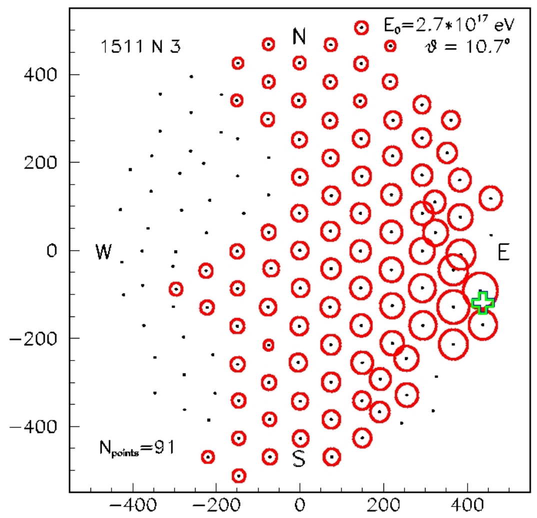


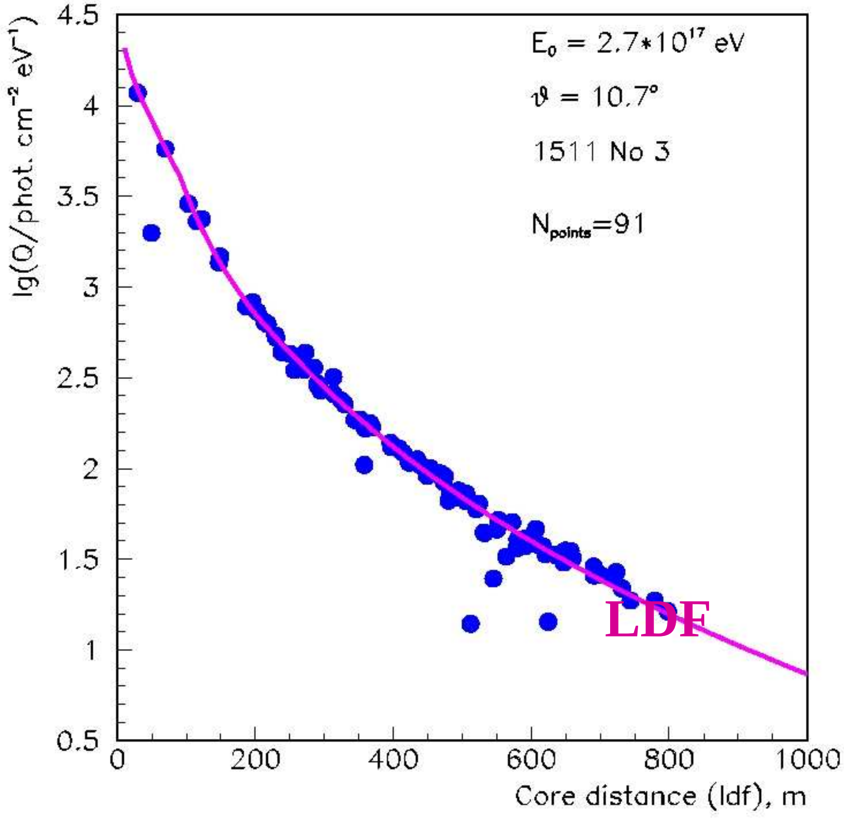
Core is in the center of border cluster. 15.03.2010

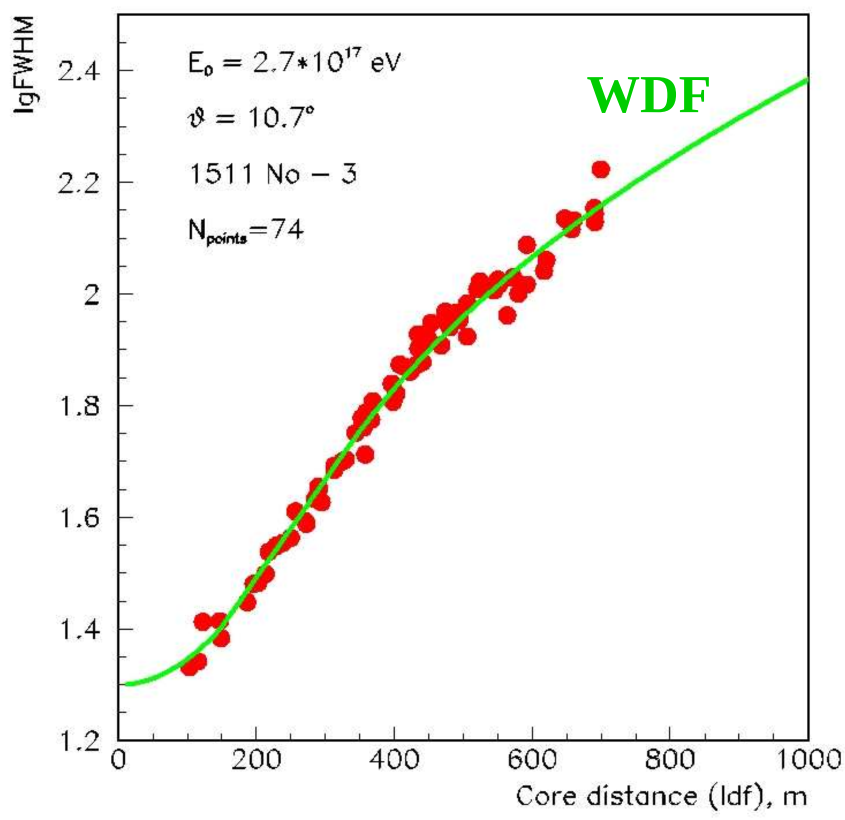


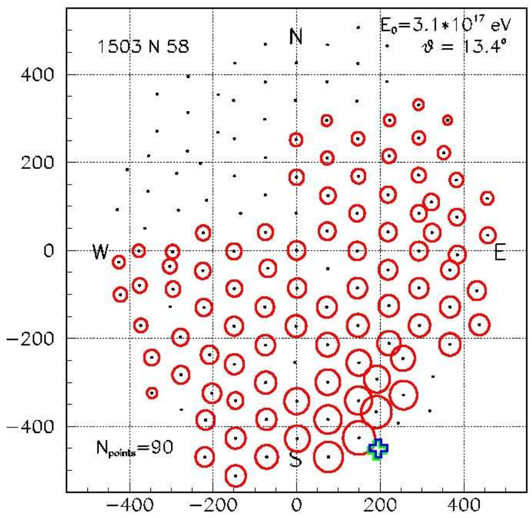


Core is on the boarder of the array. 15.11.2009

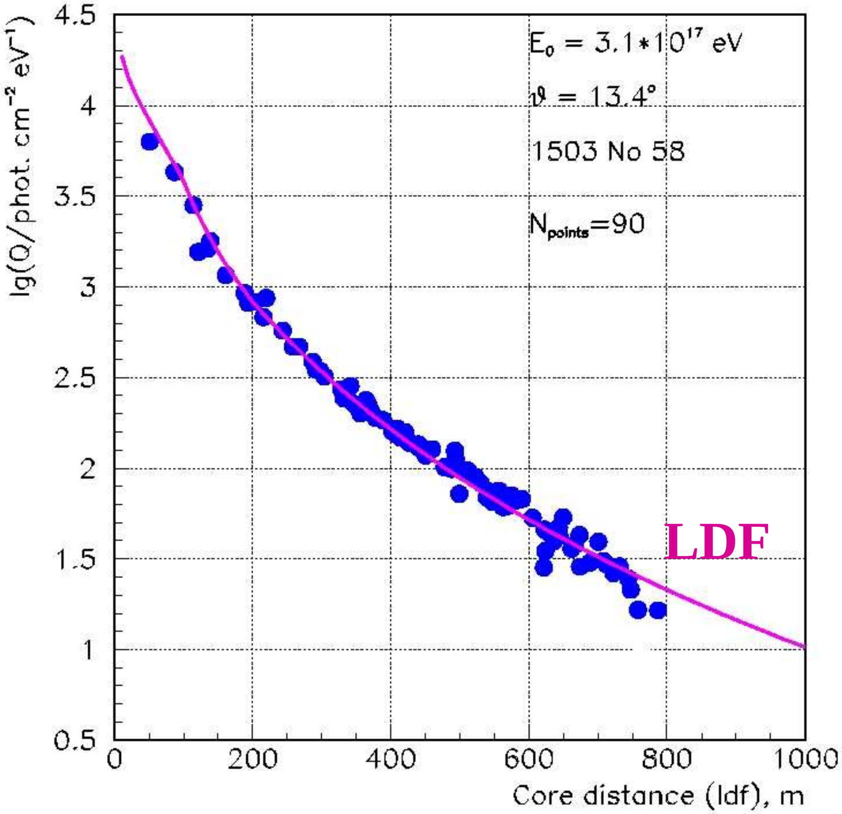


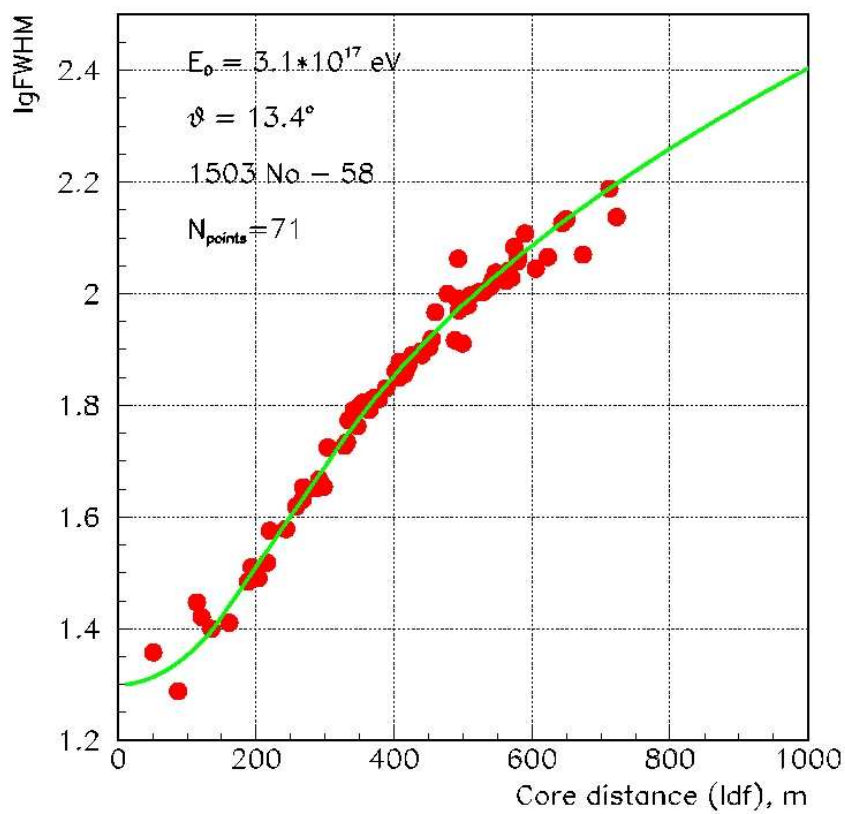


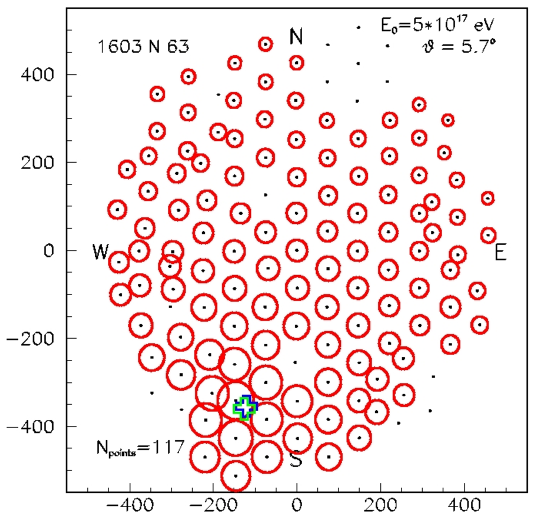



1503 N 58
N
E_0=3.1*10^17 eV
ϑ = 13.4°
W
E
S
N_{points}=90

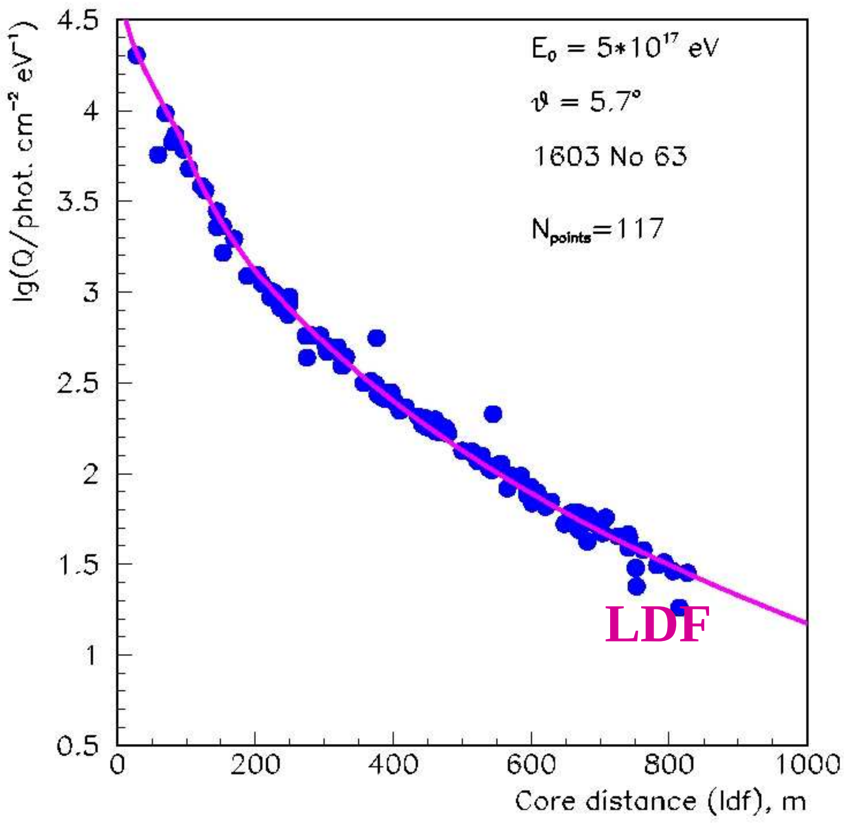
15.03.2010

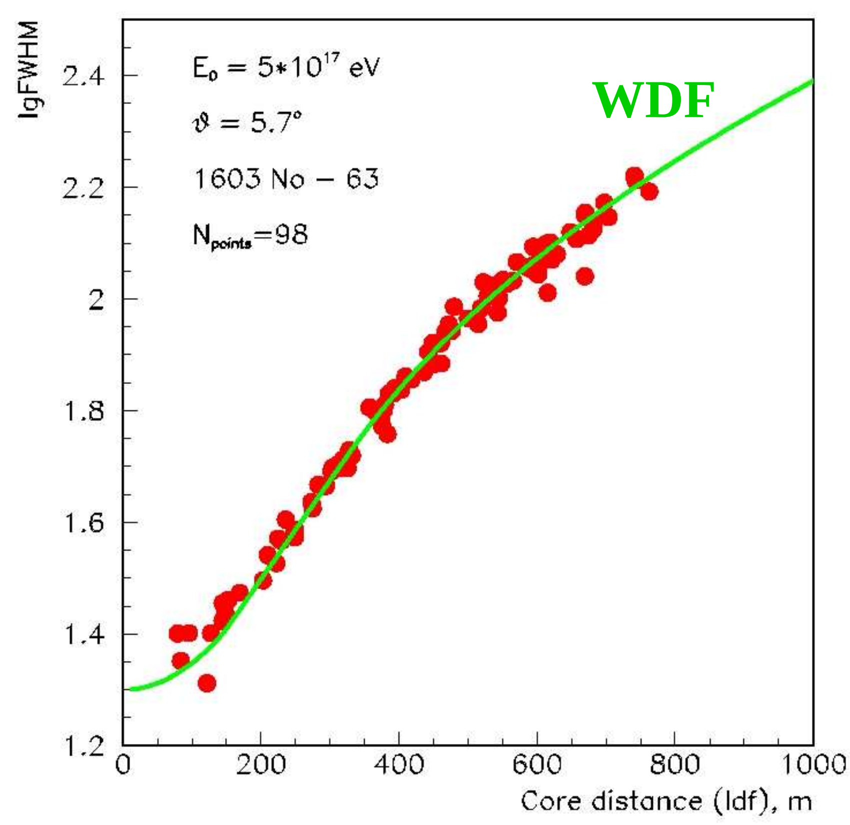

lg(Q/phot. cm^-2 eV^-1)
E_0 = 3.1*10^17 eV
ϑ = 13.4°
1503 No 58
N_{points}=90
LDF
Core distance (ldf), m


lgFWHM
E_0 = 3.1*10^17 eV
ϑ = 13.4°
1503 No − 58
N_{points}=71
Core distance (ldf), m

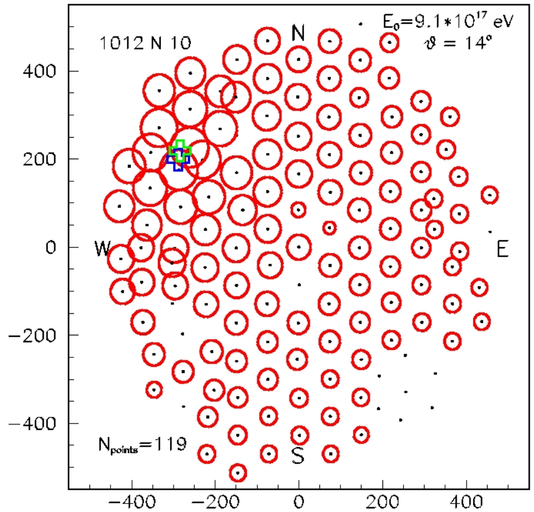

1603 N 63
N
$E_0=5*10^{17}$ eV
$\vartheta = 5.7°$
W
E
S
$N_{points}=117$

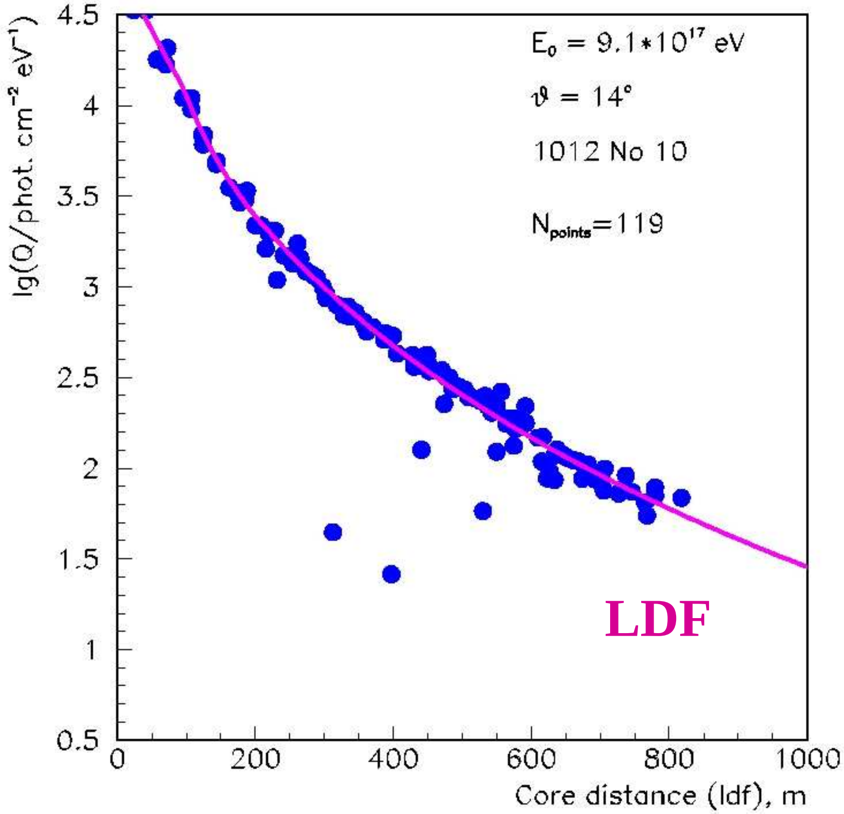
16.03.2010

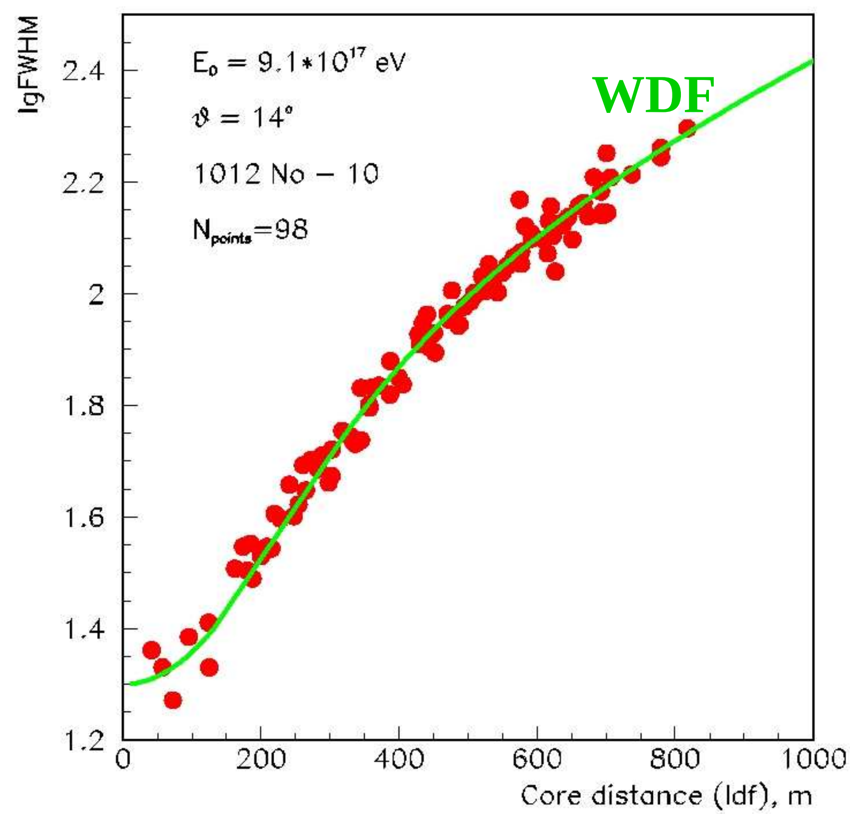

$\lg(Q/phot.\ cm^{-2}\ eV^{-1})$
$E_0 = 5*10^{17}$ eV
$\vartheta = 5.7°$
1603 No 63
$N_{points}=117$
LDF
Core distance (ldf), m


lgFWHM
$E_0 = 5*10^{17}$ eV
$\vartheta = 5.7°$
1603 No – 63
$N_{points}=98$
WDF
Core distance (ldf), m

The highest energy event. 10.12.2009

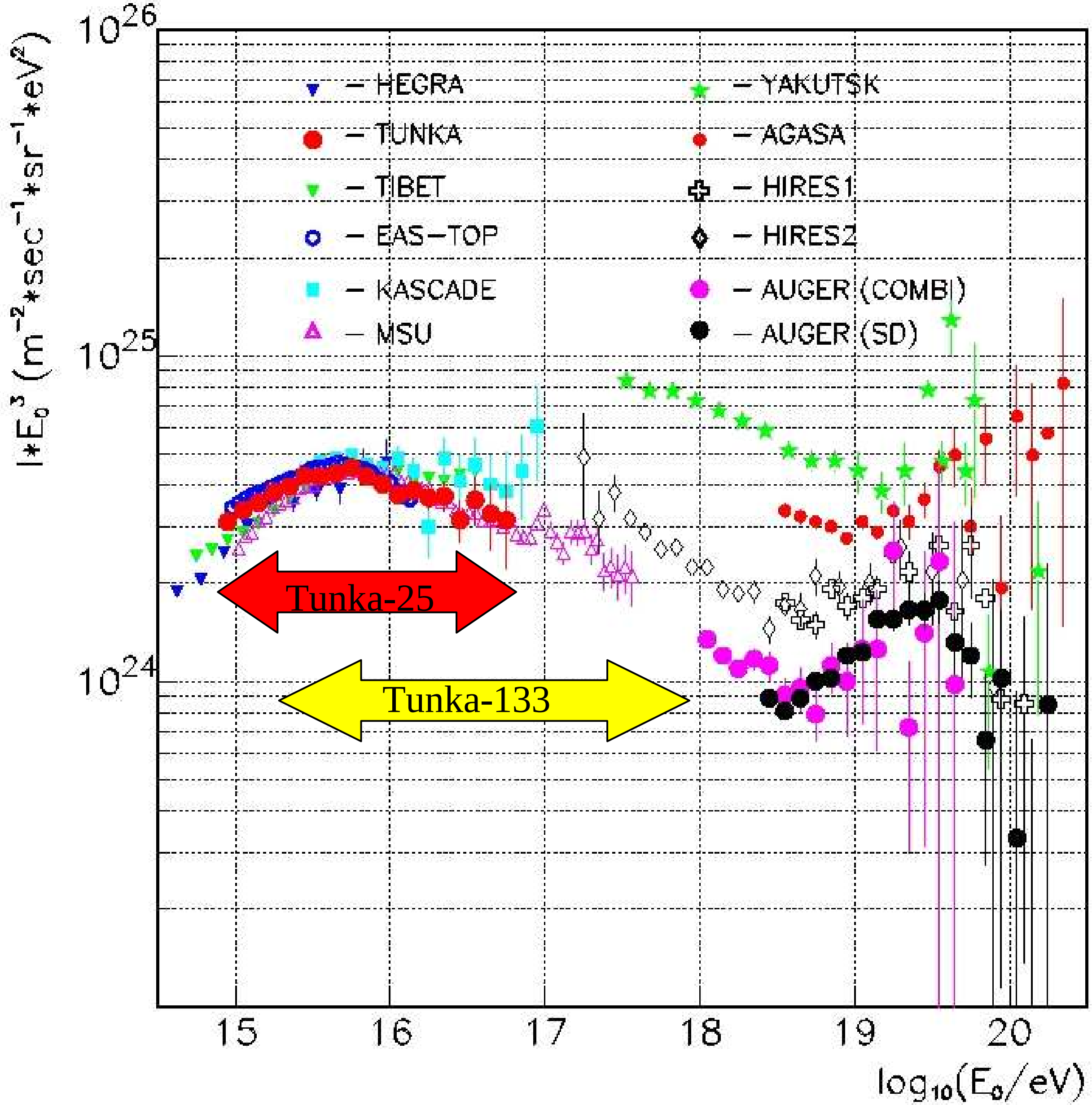


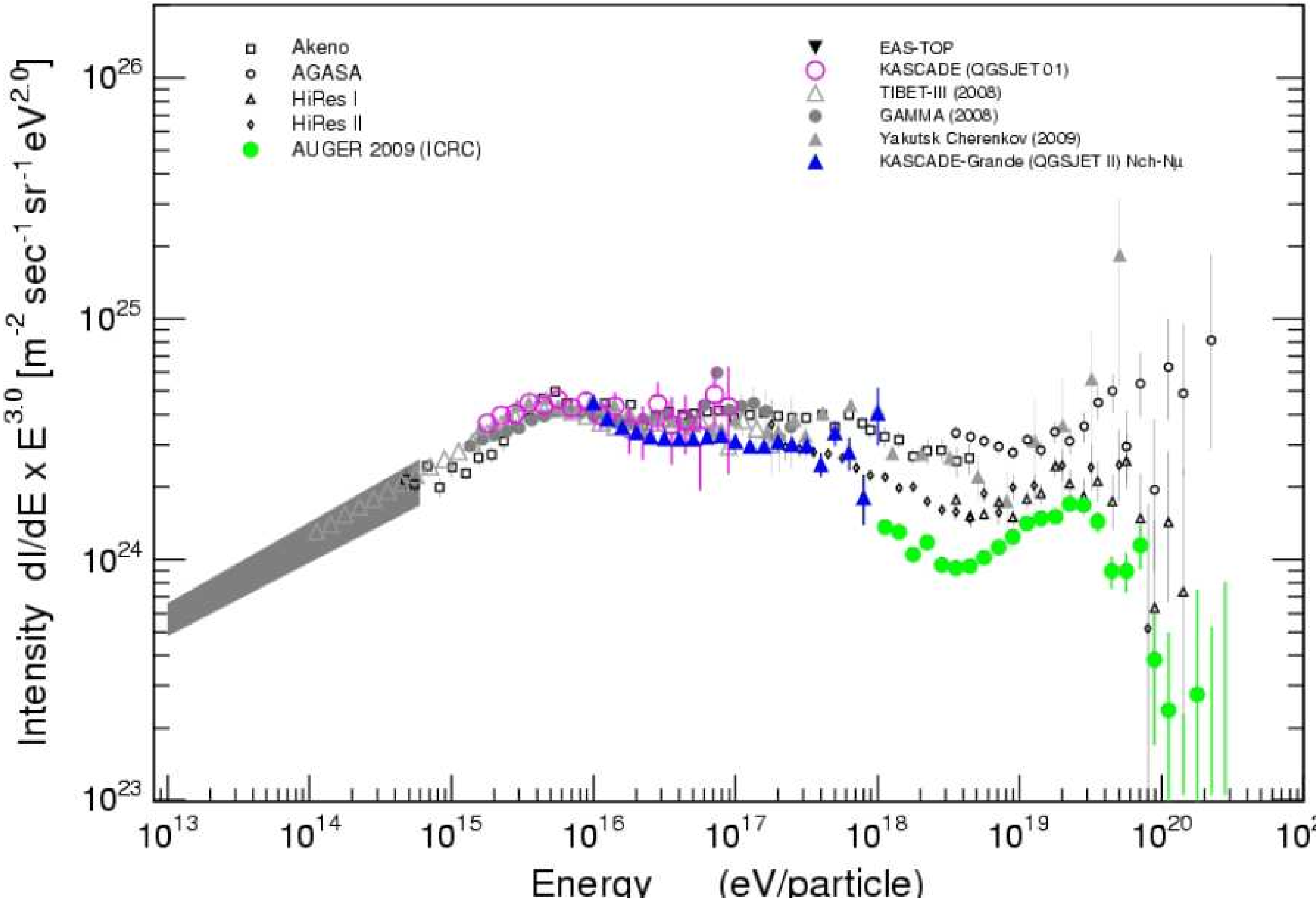




Further information analysis: the results to be published next year (2011)

1. The differential energy spectrum in the energy range $3 \cdot 10^{15} – 10^{18}$ eV.
2. X_{max} distributions in the narrow lgE_0 bins.
3. Simulation of X_{max} distributions for the different primary mass groups.
4. Comparison of the experimental and combined simulated distributions and thus estimation of the most probable primary composition for the every energy bin.
5. Estimation of <lnA> vs. E_0 in the energy range $3 \cdot 10^{15} – 3 \cdot 10^{17}$ eV.

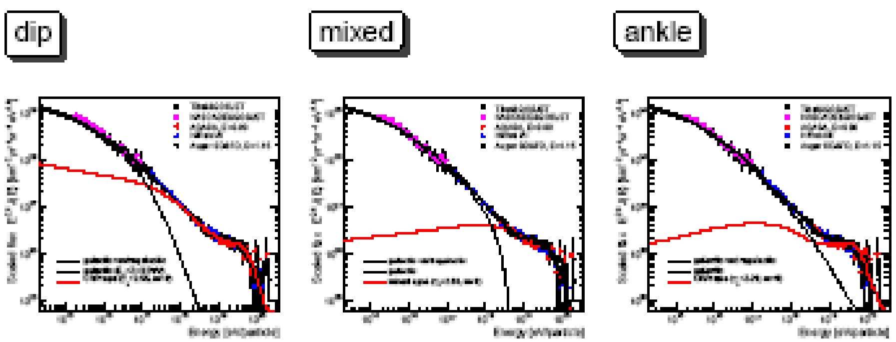

$I*E_0^3$ ($m^{-2}*sec^{-1}*sr^{-1}*eV^2$)
10^{26}
10^{25}
10^{24}
15
16
17
18
19
20
$\log_{10}(E_0/eV)$
– HEGRA
– TUNKA
– TIBET
– EAS–TOP
– KASCADE
– MSU
– YAKUTSK
– AGASA
– HIRES1
– HIRES2
– AUGER (COMBI)
– AUGER (SD)
Tunka-25
Tunka-133


Akeno
AGASA
HiRes I
HiRes II
AUGER 2009 (ICRC)
EAS-TOP
KASCADE (QGSJET 01)
TIBET-III (2008)
GAMMA (2008)
Yakutsk Cherenkov (2009)
KASCADE-Grande (QGSJET II) Nch-Nμ
Intensity dI/dE x E^3.0 [m^-2 sec^-1 sr^-1 eV^2.0]
10^26
10^25
10^24
10^23
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21
Energy (eV/particle)

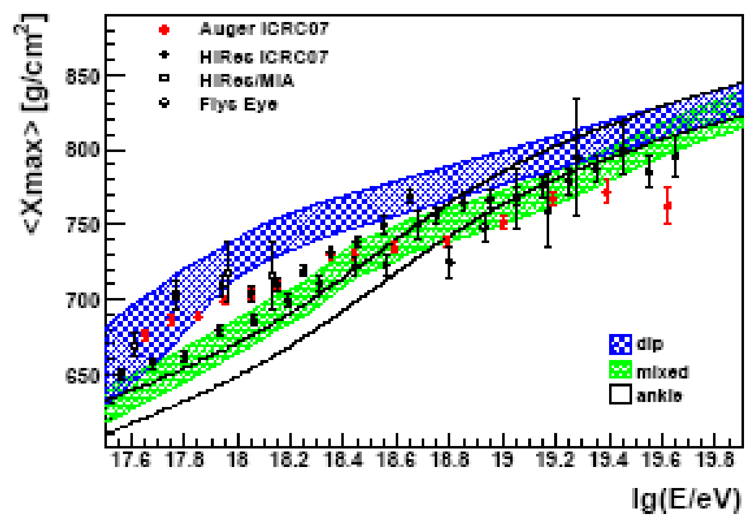
Possible change of primary composition at the EeV energies

(Michael Unger review at ECRS-2008)

Overview over transition models



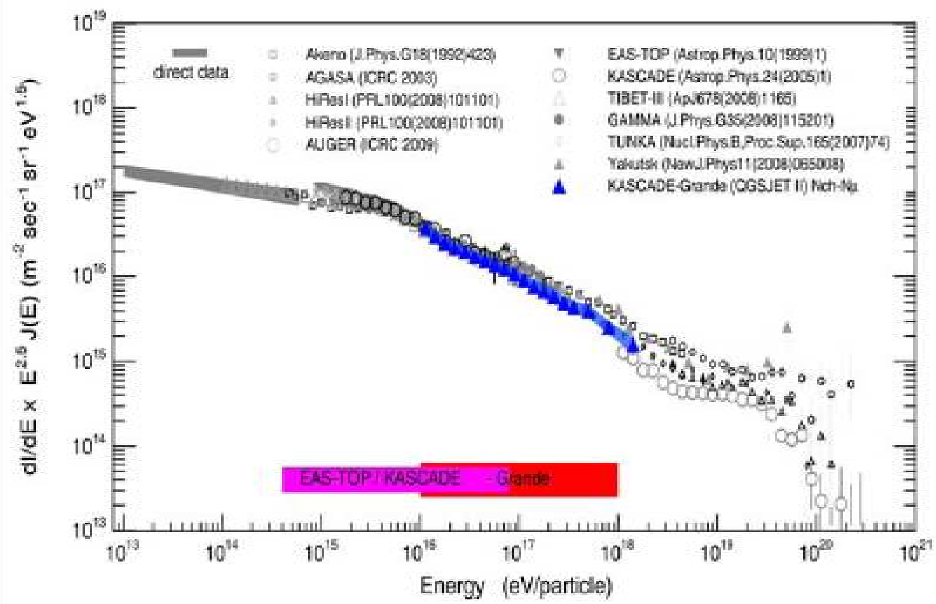
Chemical Composition- Xmax vs E

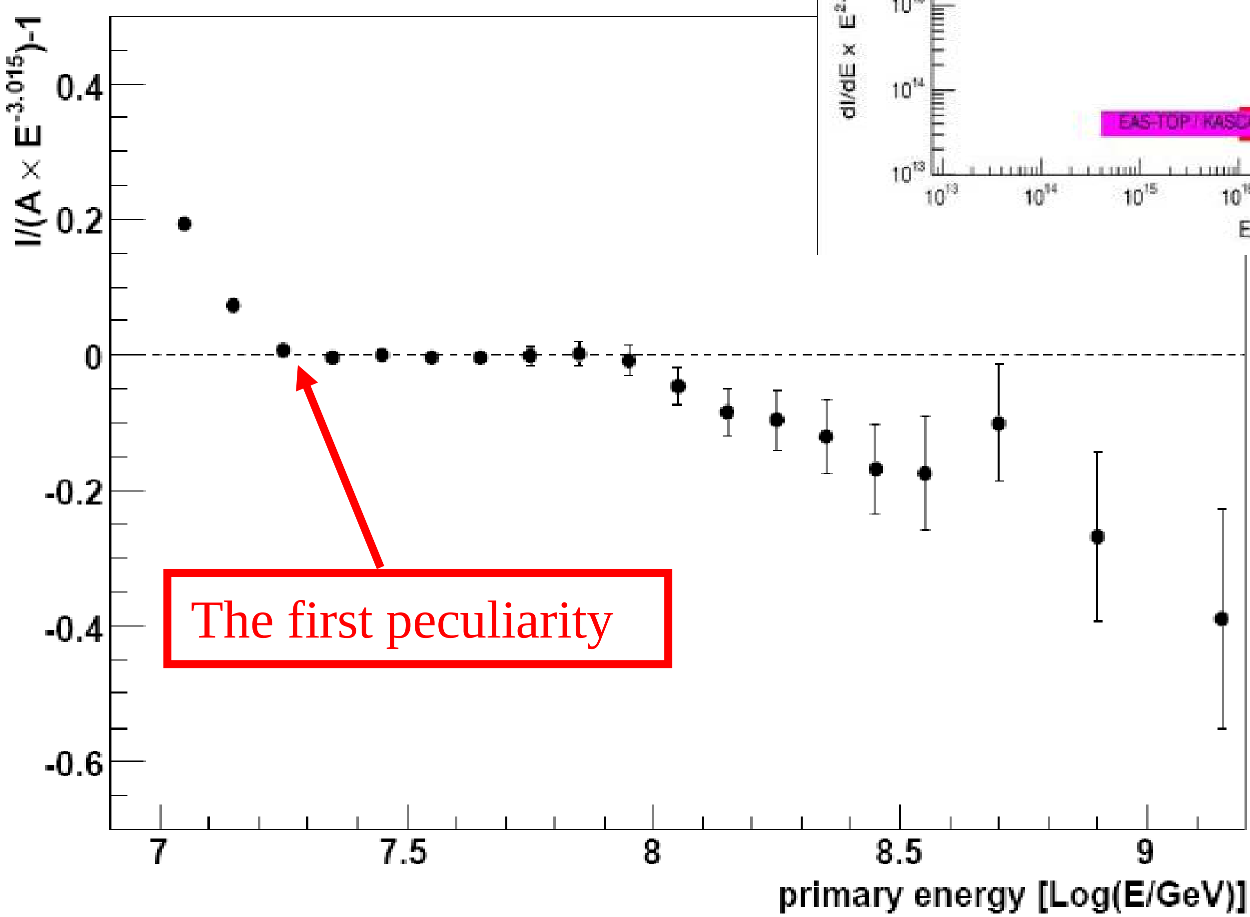


(model curves from Allard et al. 2005)

The curious features of the spectrum in the intermediate range.

From A. Haungs report at ECRS 2010, Turku, Finland.

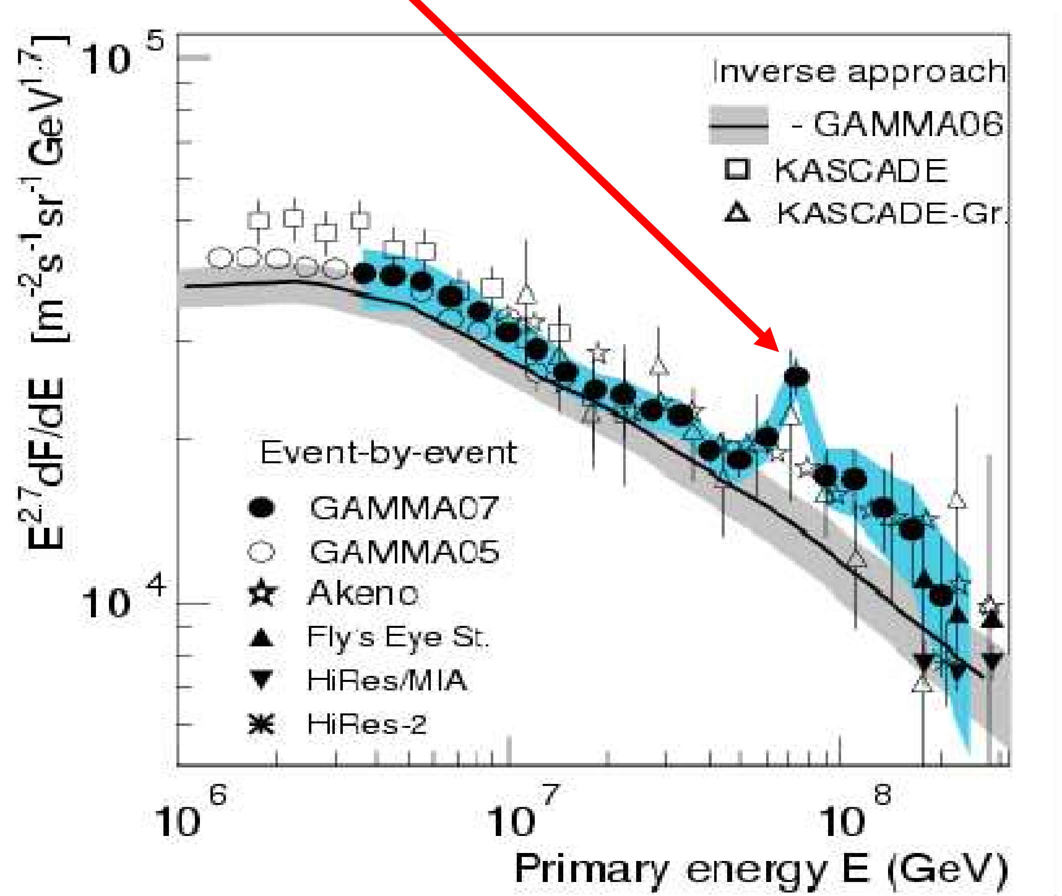




From A. Haungs report at ECRS 2010, Turku, Finland.

GAMMA (Mt. Aragaz, 3200 a.s.l.)

The second peculiarity



GAMMA Coll., Nucl. Phys. G: Nucl. Part. Phys. 35 (2008) 115201

The partial preliminary conclusion.

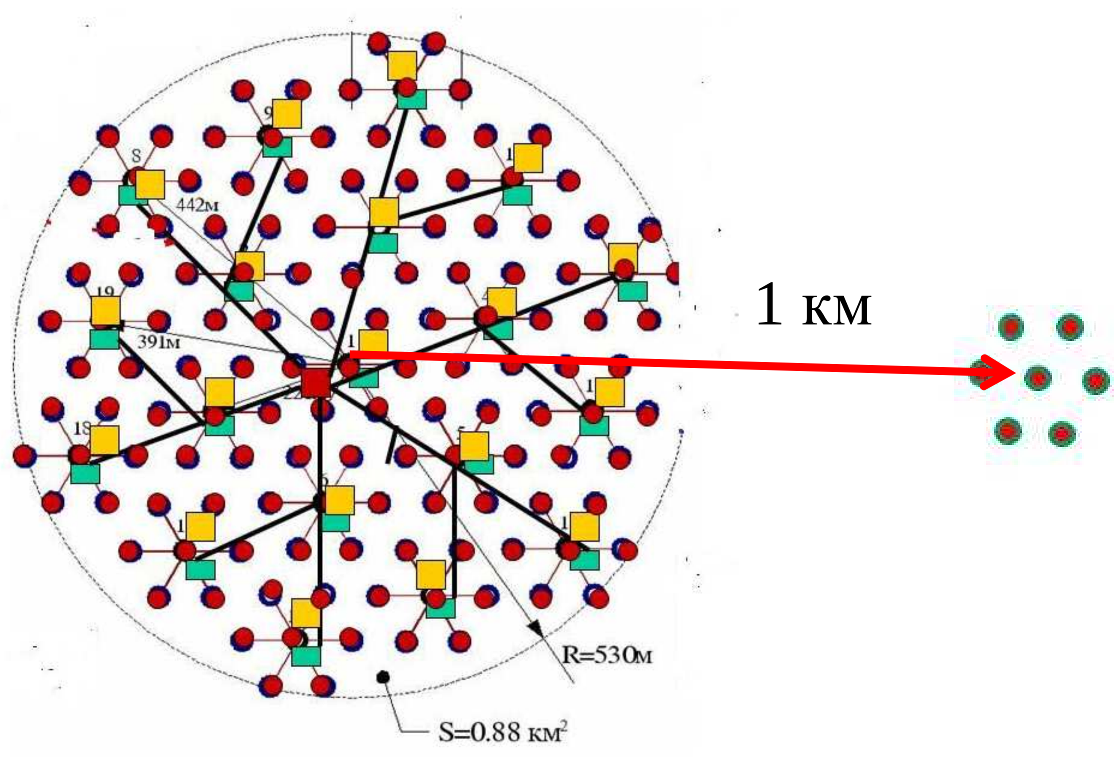
1. Our preliminary analysis (based upon more than 10000 events with $E_0>10^{16}$ eV) confirms these both features of the energy spectrum.

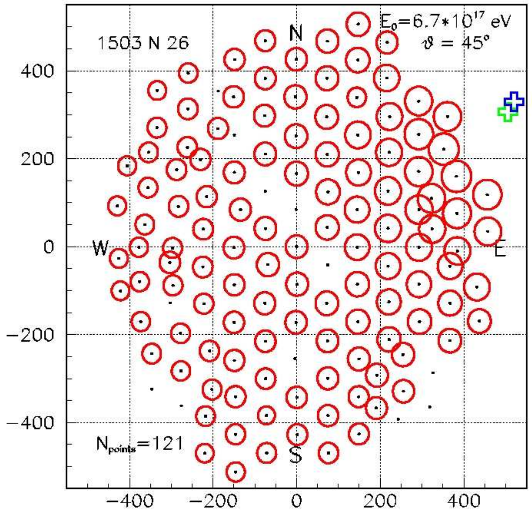
2. Next year we’ll show the X_{max} distribution for the both interesting energy ranges as well as for all the range $10^{16} – 10^{17}$ eV.

2012

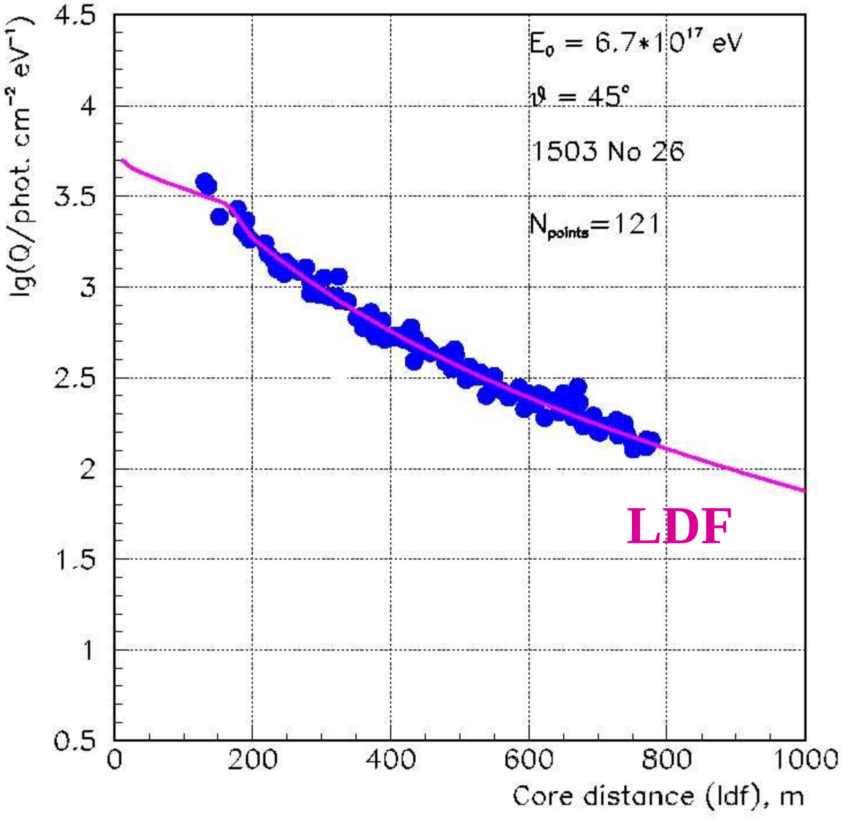
To the ultra-high energy!

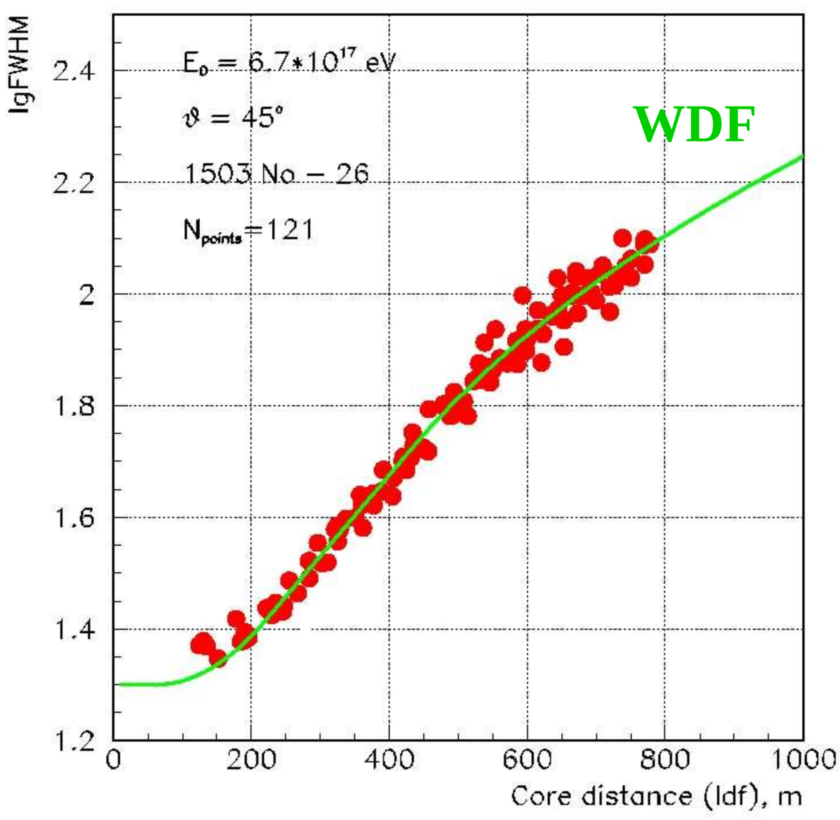
Tunka-133,
addition of 6
distant clusters





The event example.
15.03.2010

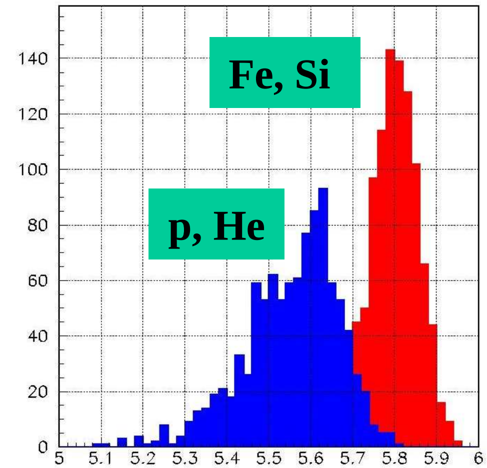




Muon number vs. X_{max}

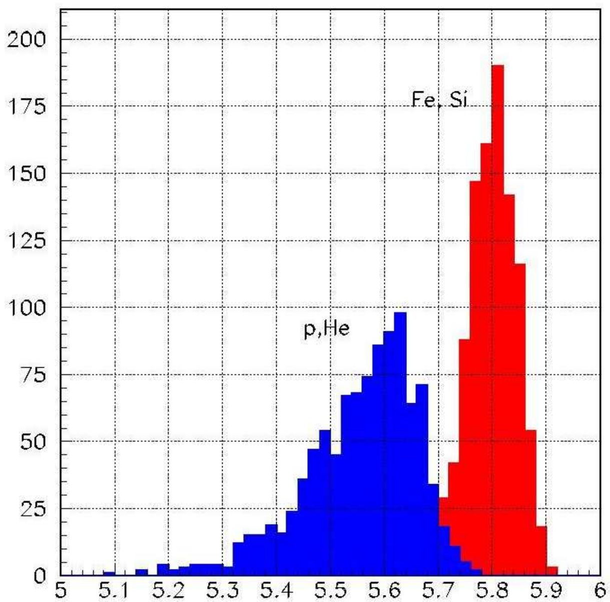
Poster HE 1.3 : 1073

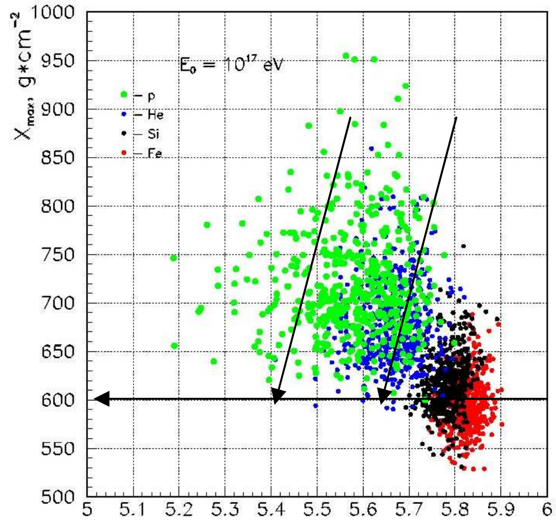
AIRES 2.8.4a
QGSJET-II
E_μ > 1 Gev, $\theta = 0°$
$\delta N_\mu / N_\mu = 10\%$,
$\delta X_{max} = 20\ g/cm^2$

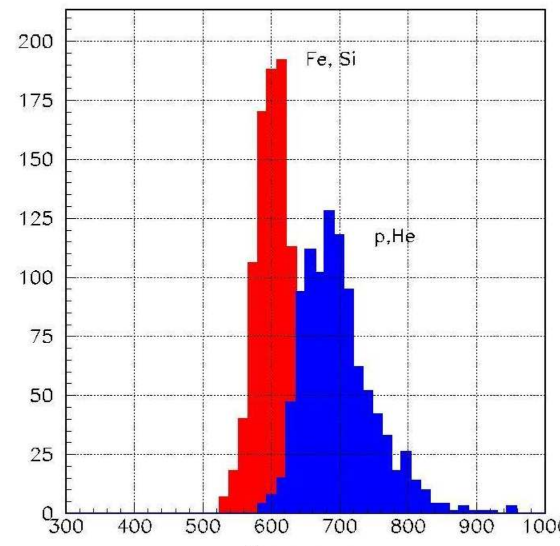


lgN_μ

- p (500 events)
- He (500 events)
- Si (500 events)
- Fe (500 events)







X_{max}

$$lgN_\mu(corr) = lgN_\mu - \frac{X_{max} - 600}{1500}$$

lgN_μ

Robotic optical telescope

System of wide angle automatic telescopes.

Search for optical point sources responsible for GRBs

Search for SN

Search for asteroids and comets

For Tunka-133:
Observation of clouds in the field of view of the

Registration of radio signals from EAS

Choosing of the antenna type:
2 types of antennas were installed at Tunka Array till now

Log-periodic antenna
(D. Besson et al. University of Kansas, USA)

Short Aperiodic Loaded Loop Antenna (SALLA)
(A. Haungs et al. Institute fur Kernphysik, Forschungszentrum, Karlsruhe, Germany

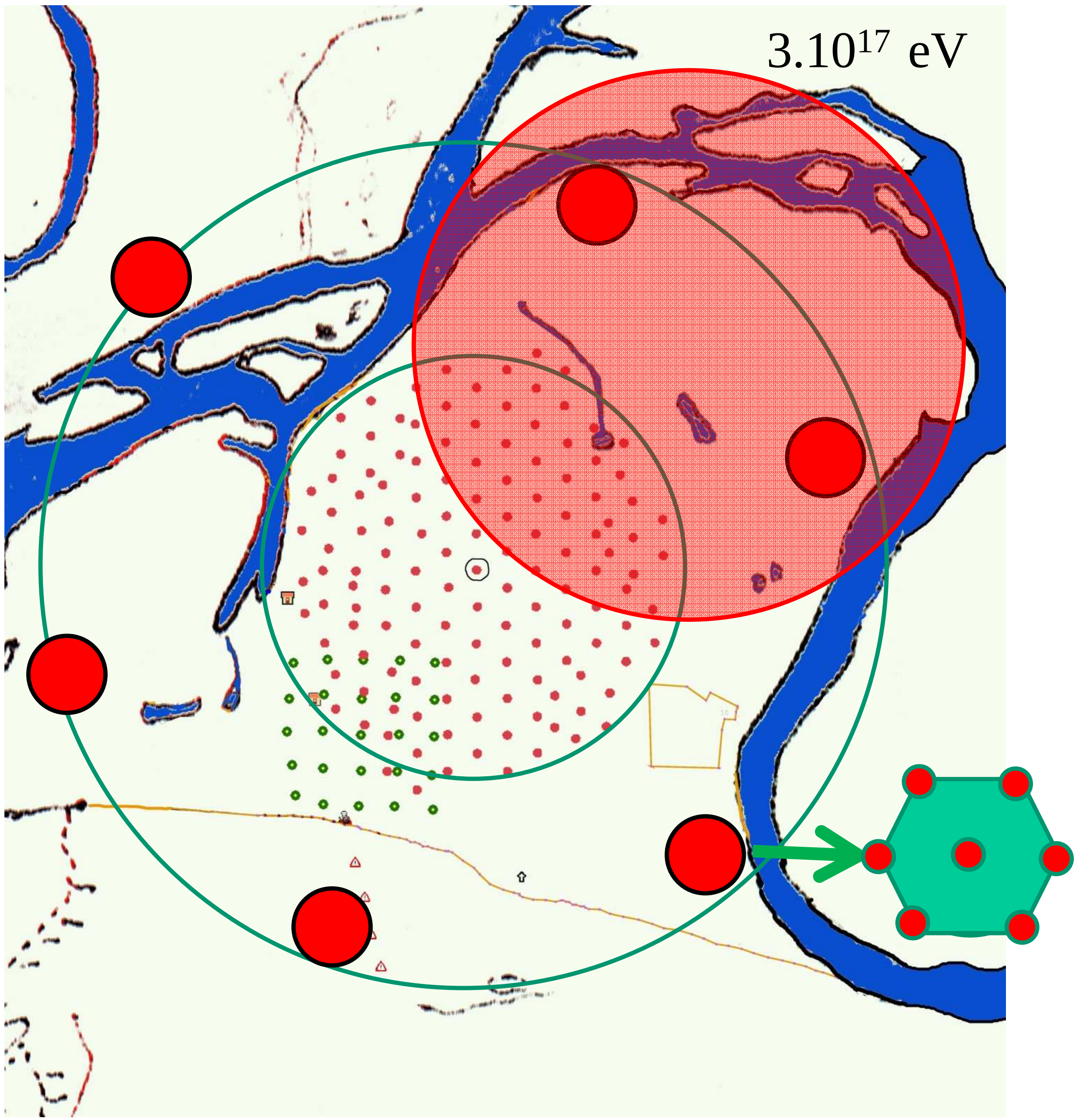
Antennas are connected to the free FADC channels of Tunka-133 cluster electronics

2010: Net of 20 antennas

6 distant clusters (42 optical detectors)

The effective area enlarging to about 4 times for the EAS with the energy > 10^{17} eV

Further possibility of the effective area enlarging to about 10 times for the external EAS with the energy > $5 \cdot 10^{17}$ eV



Thank you!