Interactions of Cosmic Rays in the primary energy range (0.1-1) PeV studied by the ARGO-YBJ experiment

A. Surdo
INFN – Sezione di LECCE
on behalf of ARGO-YBJ collaboration

ARGO-YBJ experiment

An unconventional EAS-array exploiting the full coverage approach at very high altitude, with the aim of studying:

- ✓ Cosmic Ray Physics
- ✓ VHE γ-Ray Astronomy
- ✓ Gamma Ray Burst Physics

Longitude 90° 31’ 50” East
Latitude 30° 06’ 38” North

90 Km North from Lhasa (Tibet)

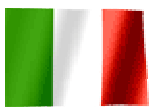
4300 m above the sea level
(606 g/cm^2 vertical depth)

High Altitude Cosmic Ray Observatory @ YangBaJing

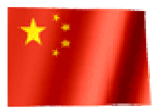
ARGO-YBJ collaboration

International Collaboration:

- ✓ Chinese Academy of Science (CAS)
- ✓ Istituto Nazionale di Fisica Nucleare (INFN)

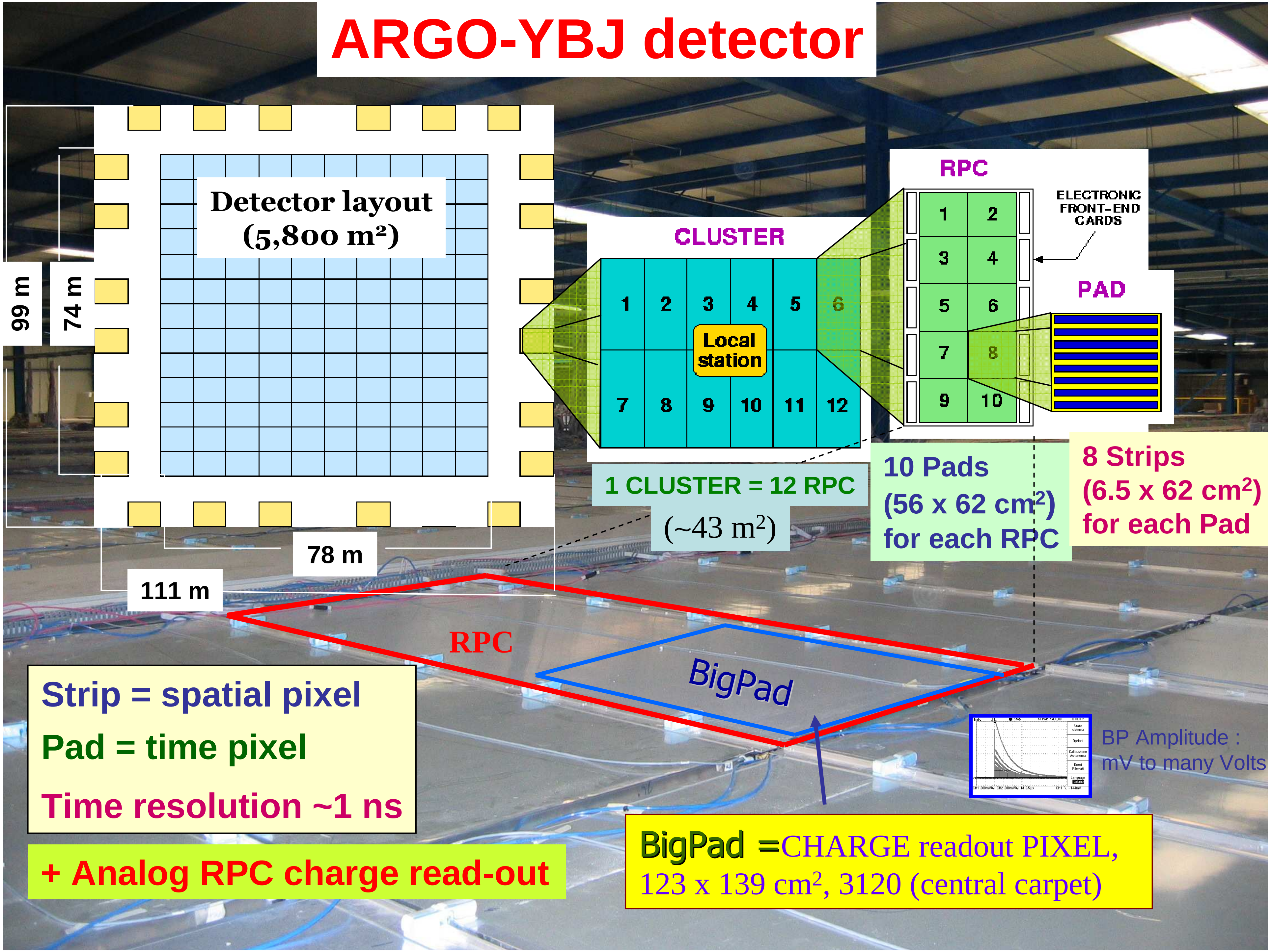


INFN and Dpt. di Fisica Università, Lecce
INFN and Dpt. di Fisica Universita', Napoli
INFN and Dpt. di Fisica Universita', Pavia
INFN and Dpt di Fisica Università "Roma Tre", Roma
INFN and Dpt. di Fisica Univesità "Tor Vergata", Roma
INAF/IFSI and INFN, Torino
INAF/IASF, Palermo and INFN, Catania



HeBei Normal Unversity, Shijiazhuang
IHEP, Beijing
Shandong University, Jinan
South West Jiaotong University, Chengdu
Tibet University, Lhasa
Yunnan University, Kunming

ARGO-YBJ detector



Strip = spatial pixel

Pad = time pixel

Time resolution ~1 ns

+ Analog RPC charge read-out

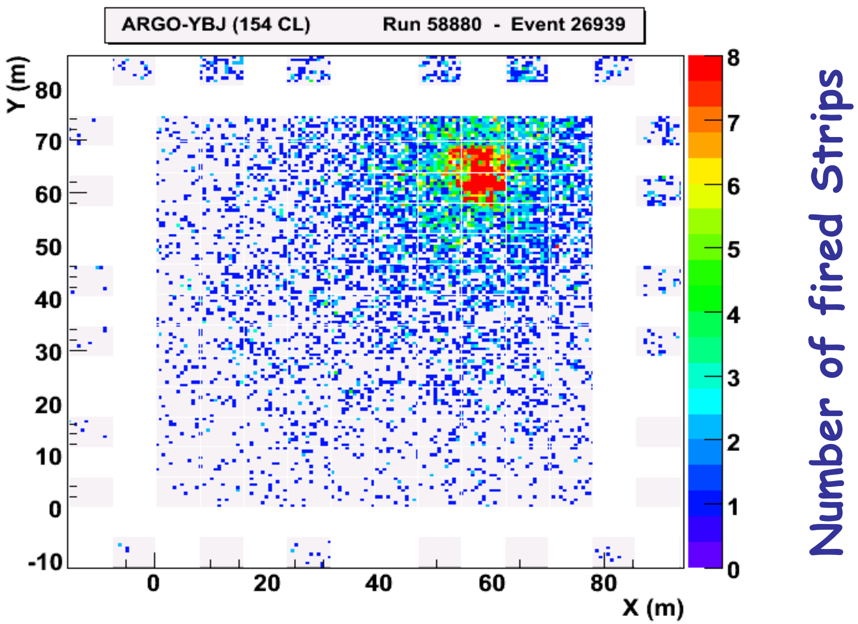
BigPad =CHARGE readout PIXEL, 123 x 139 cm², 3120 (central carpet)

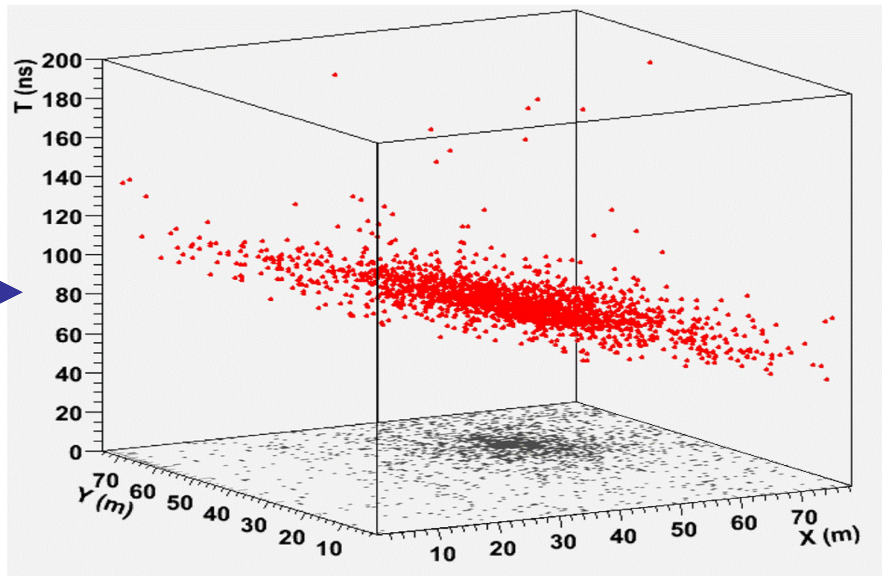
Shower detection by ARGO-YBJ:

Space pixel: 7×62 cm^2 (single strip)
Time pixel: 56×62 cm^2
(8 ORed strips = 1 Pad) **Time resolution:** ≈ 1 ns

The size of pixels, the time resolution and the full coverage allow the event imaging with unprecedented details

A real event from digital information

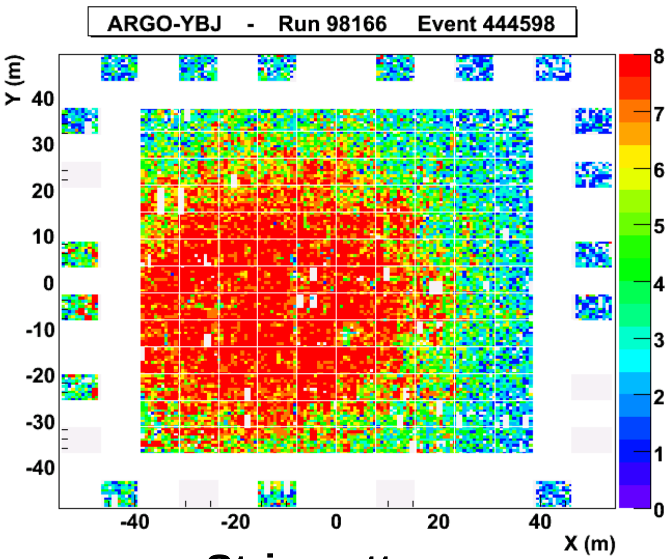




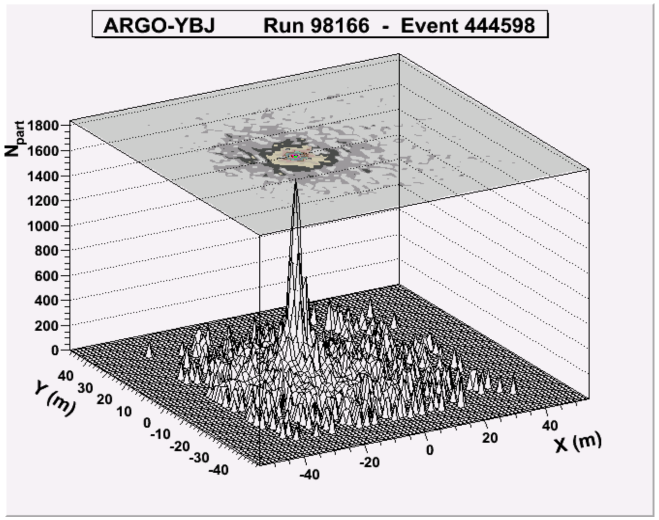
Analog charge readout system

⇒ **extending the explorable Energy range above 100 TeV**

⇒ **access values of local particle densities up to ~10^4/m^2**



Strip pattern



Particle distribution from analog charge

Main objective of this data analysis:

- **measurement of p-air cross section in the 0.1-1 PeV E range**
- **study of very high energy hadronic interactions**
- **spectrum and composition studies**

Measurement of p-air cross section

Use the shower frequency vs (secθ -1)

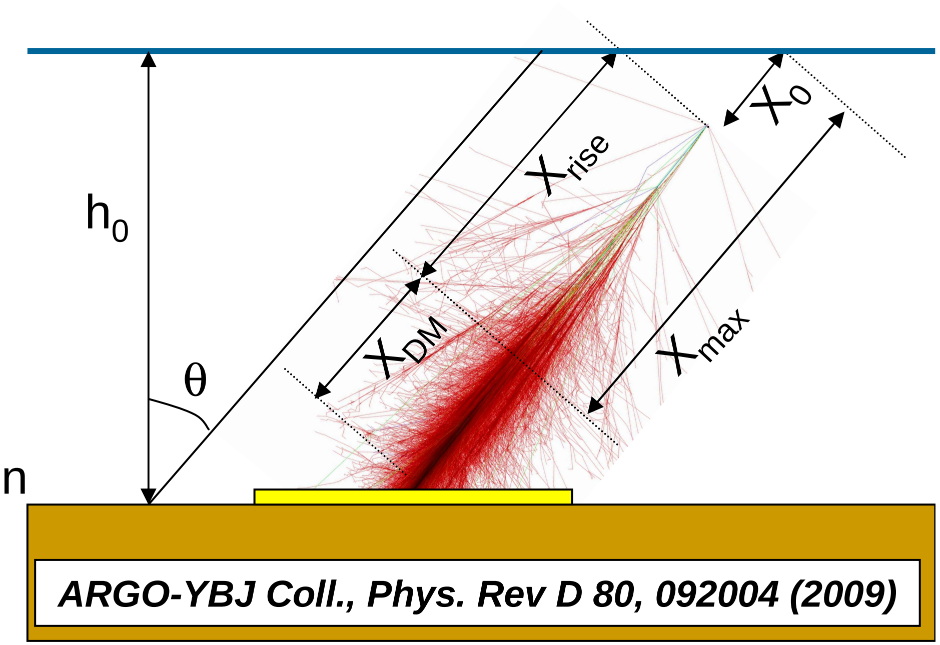
$$I(\theta) = I(0) \cdot e^{-\frac{h_o}{\Lambda}(\sec\theta - 1)}$$

for fixed energy and shower age.

The lenght Λ is connected to the p interaction lenght by the ralation **Λ = k λ_{int}** where k is determined by simulations and depends on:

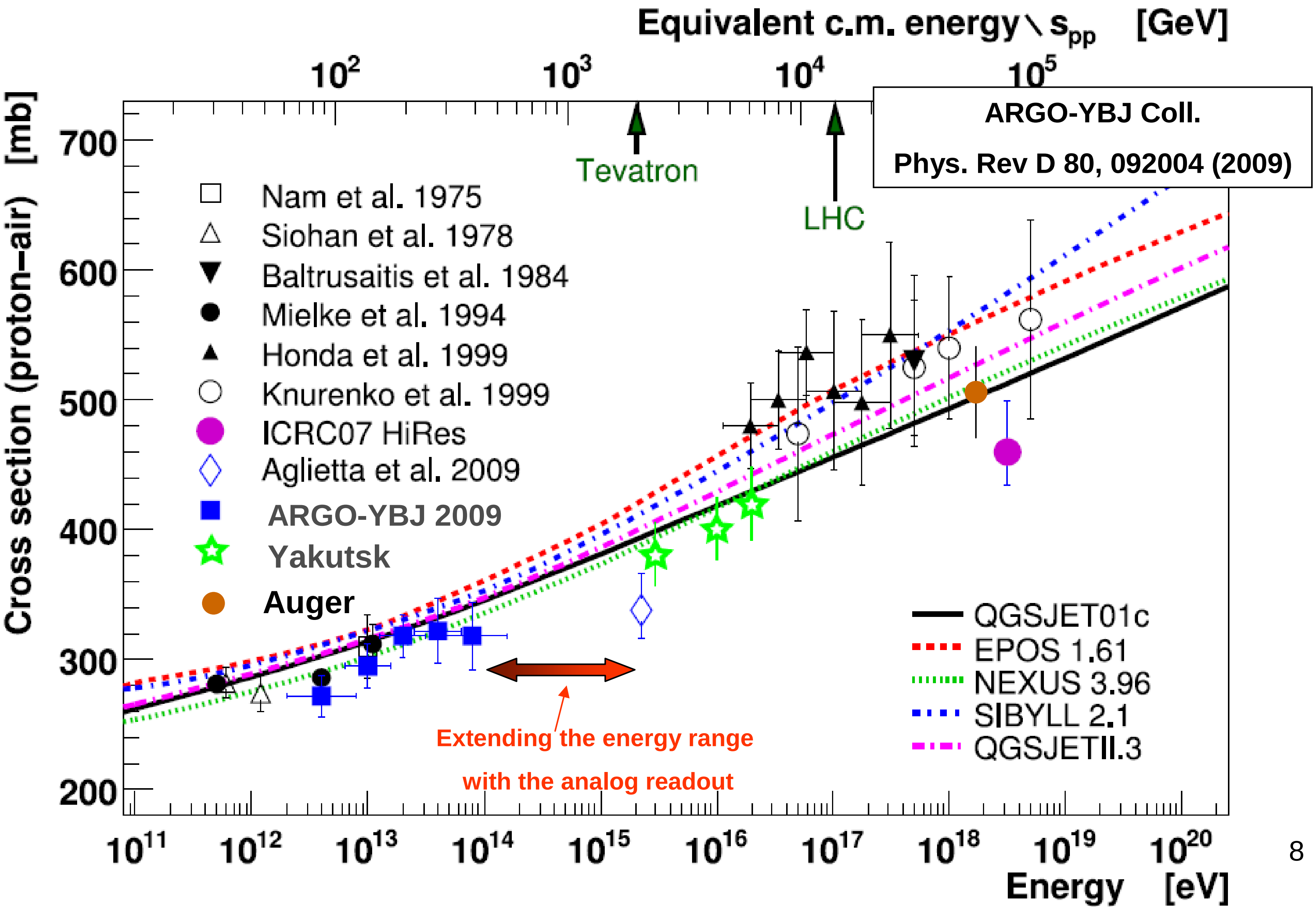
- **hadronic interactions**
- **detector features and location (atm. depth)**
- **actual set of experimental observables**
- **analysis cuts**
- **energy, ...**

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

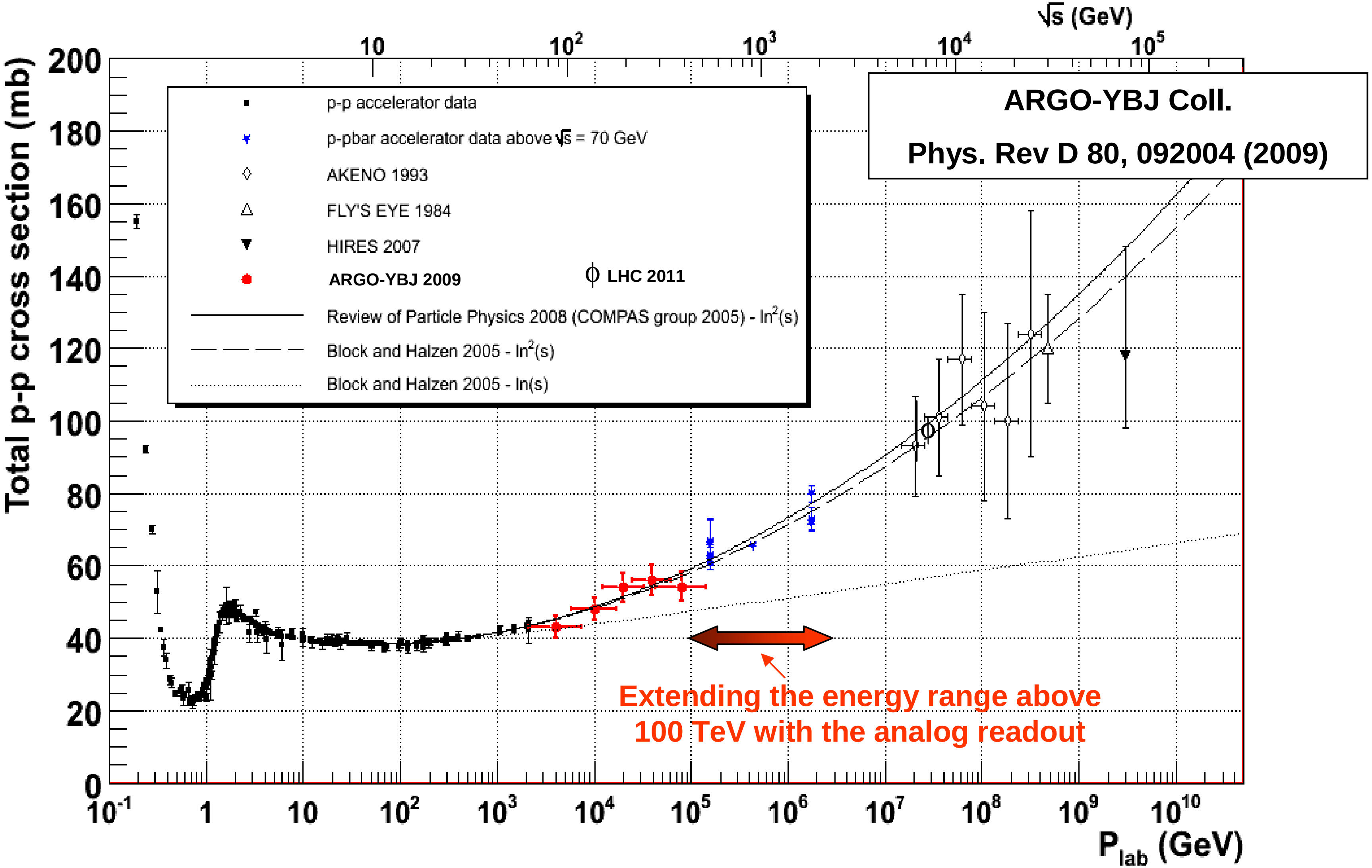


- **Constrain** $X_{DM} = X_{det} - X_{max}$
- **Select** deep showers (large X_{max}, i.e. small X_{DM}) to access exponential tail and reduce shower fluctuations $\rightarrow$ cut on Rs_{70} (strip concentration parameter)
- **Exploit** detector features (space-time pattern) and location (depth).

p-air cross section measurements



The total p-p cross section



- Energy interval scarcely explored by p-p (and pbar-p) accelerator experiments
- The $\log^2(s)$ asymptotic behaviour is favoured

ARGO layout + Charge readout system

Full-coverage + Charge readout segmentation + dynamical range

$\Rightarrow$ **unique opportunity to measure the particle density just <u>near the core position</u> at ground (without saturation)**

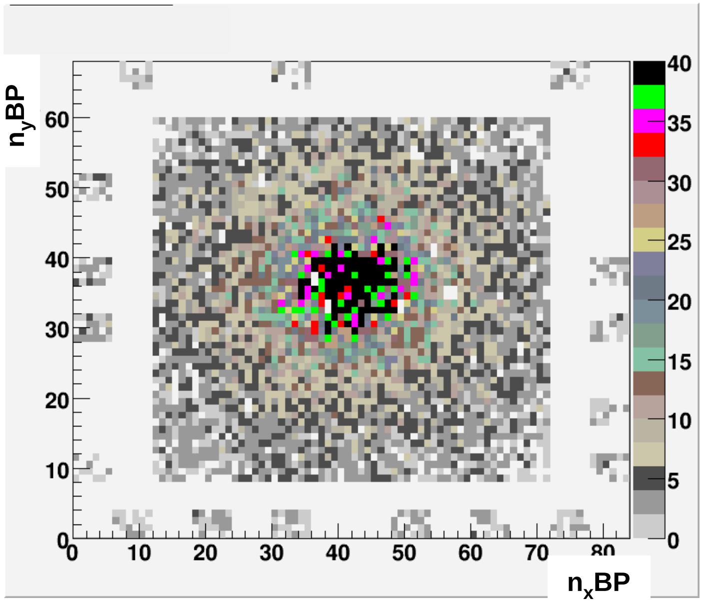
$\Rightarrow$ **possibility to study in detail the particle density profile in the whole significant range of core distances (most particles lie in few tens of meters for the considered energy range)**

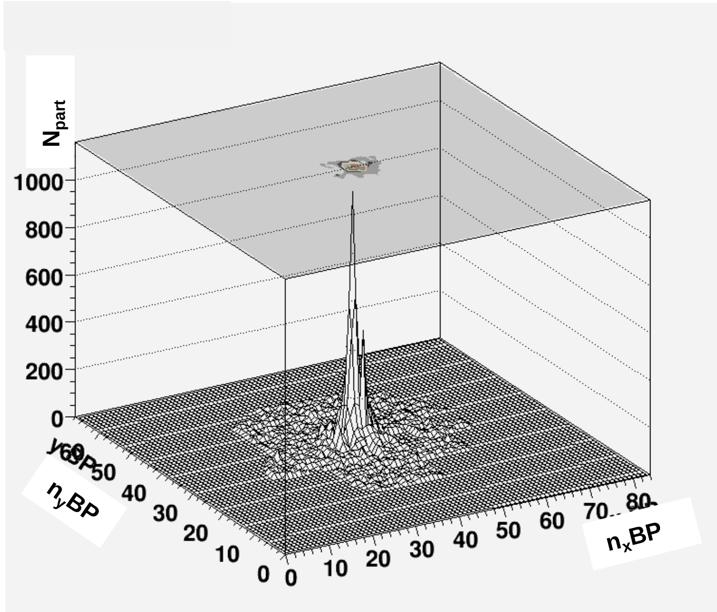
$\Downarrow$

- **investigate several features of the hadronic interactions and compare different hadronization models**
- **infer the longitudinal development stage of showers by fully inspecting the Lateral Distribution Function (LDF)**

$\rightarrow$ **constrain X_{max} intervals**

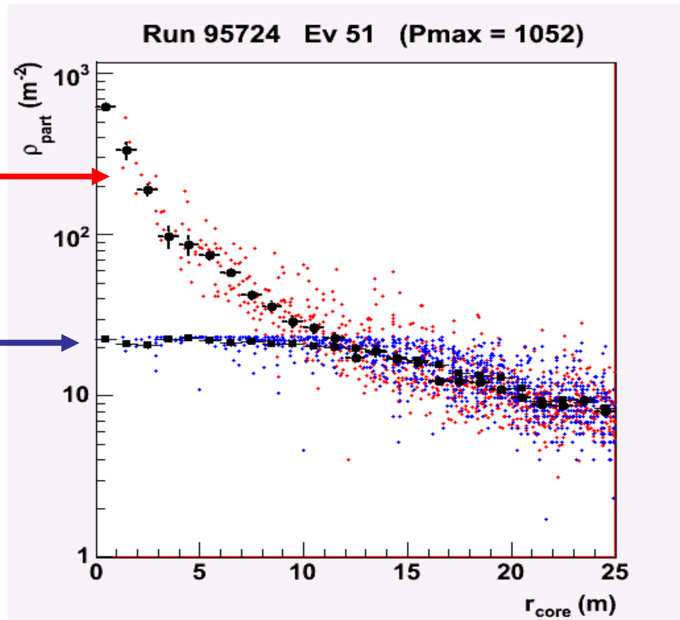
Events imaged by the Analog Readout (1)





Particle density

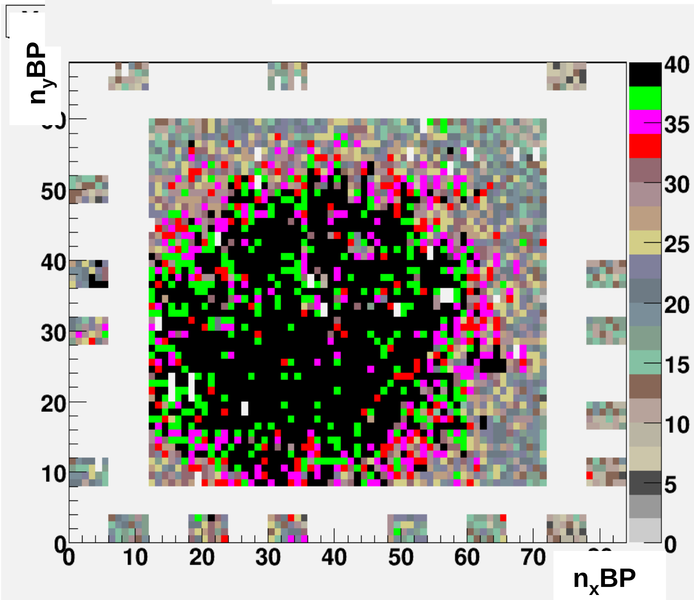
Strip density
(saturated)

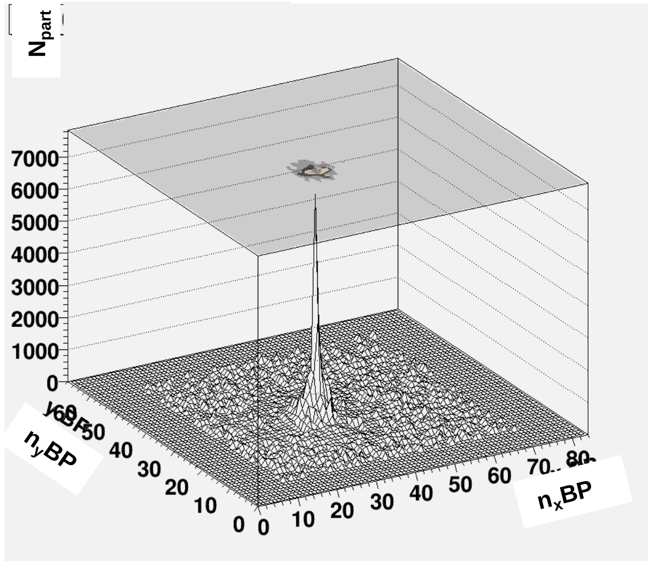


Charge readout system:

2.5 V fs

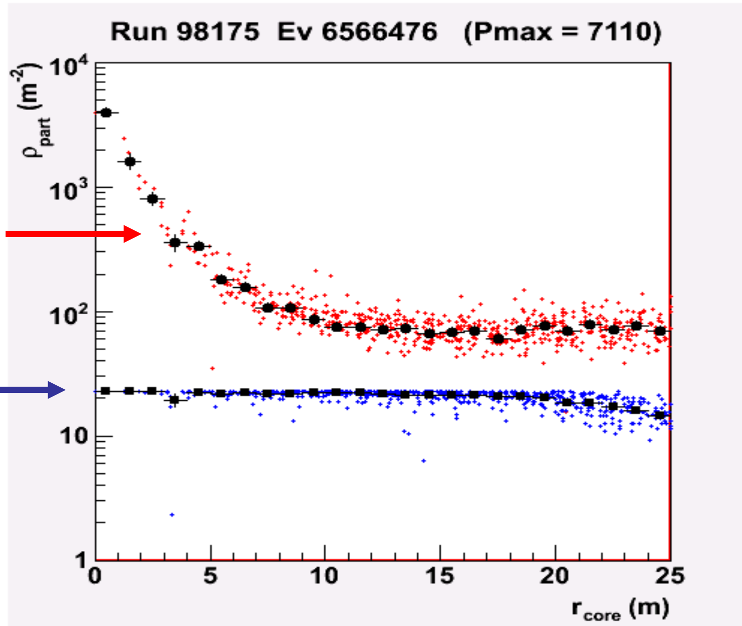
Events imaged by the Analog Readout (2)





Particle density

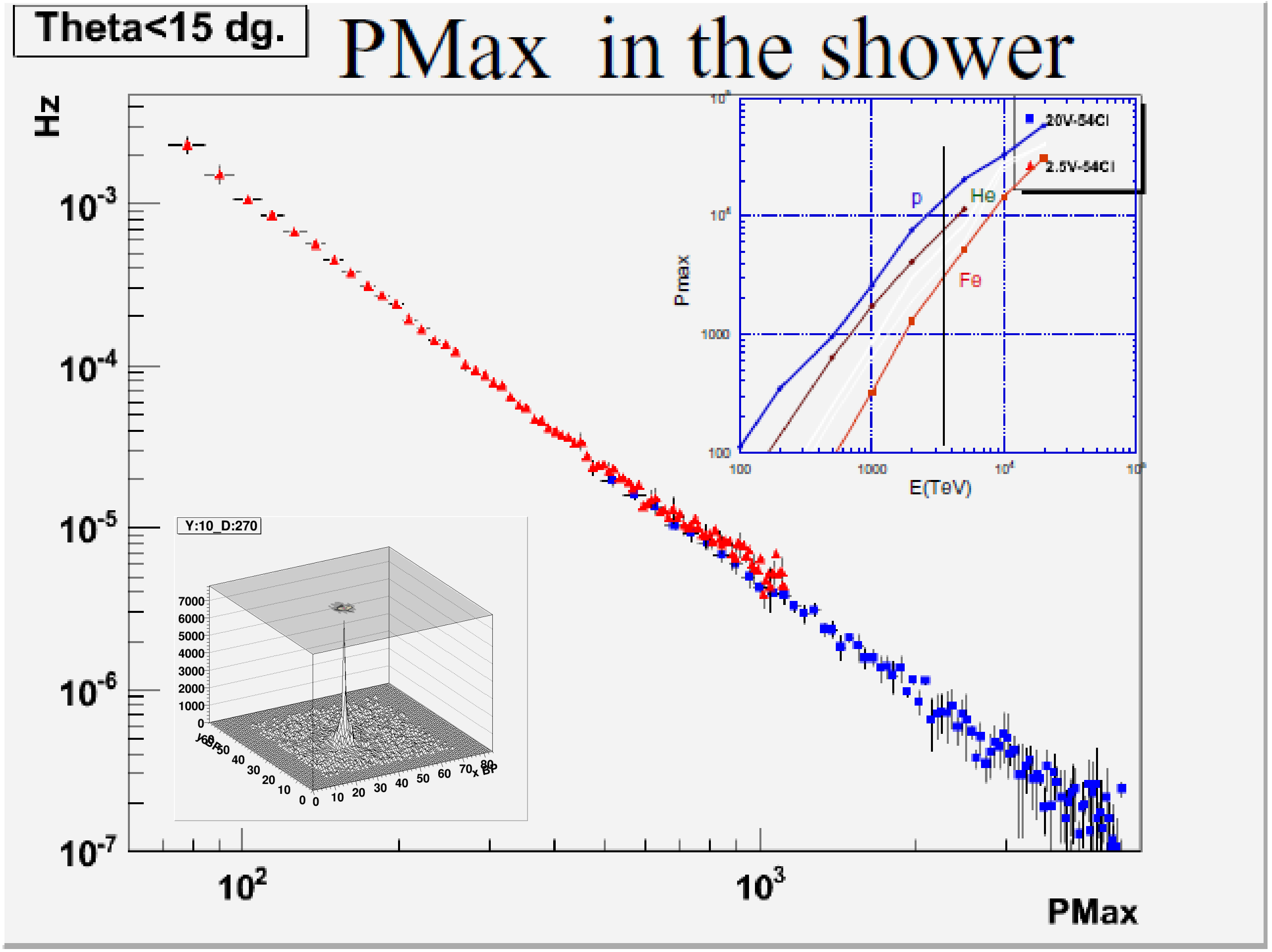
Strip density (saturated)



Charge readout system:

20 V fs

ARGO-YBJ data: PMax distribution



2.5 V fs

20 V fs

- ✓ 30% spread of the gain distribution (amplitude/particle)
- ✓ homogeneity $\approx$ 4 % (after calibration)

Requirements for $\sigma_{p\text{-}air}$ measurement

Event selections and analysis cuts

- <u>primary E estimate</u> for well reconstructed events (core in A_{fid})
  → correlation with observable like Pmax, shower particle size, ...

- <u>constant X_{dm} constraint</u> for different zenith angles
  → from local LDF-slope near the core, front conical shape, Rp_{70}, ...
  → 'age parameter' from LDF fit

- selection of <u>proton-enriched samples</u> by rejecting heavier primaries (He, CNO, ...)

Evaluation of systematic uncertainties from:

(a) interaction models used in the MC

(b) residual contamination by heavy elements

⇒ <u>use of full MC simulation</u>

MC simulation

- **Simulated air shower samples:**

  (a) p showers (1- 3000)TeV, Theta<45°
  (b) He showers (1-3000)TeV, Theta<45°
  (c) Fe showers " "

produced using *CORSIKA* code (*QGSJET-II.03*)

  (d) p showers (1- 3000)TeV, Theta<45°

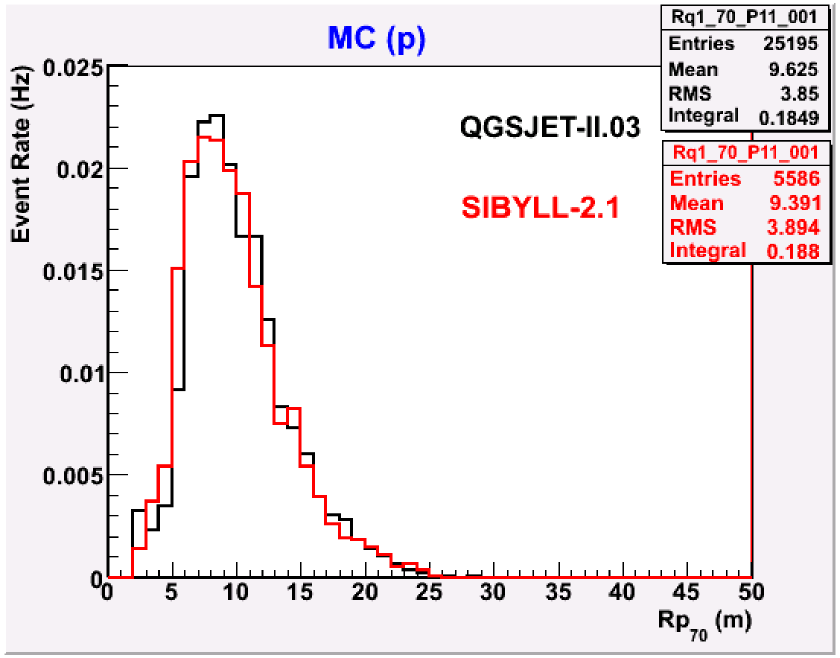
produced using *CORSIKA* code (*SIBYLL-2.1*)

- **Simulated showers (sampled on large areas) given in input to the ARGO MC (based on *Geant*-3) fully simulating the detector response (analog charge trigger and readout system included)**

- **MC data processed by the same reconstruction program used for real data.**

- **Event selection: core inside a fiducial area A_{fid} = (64 x 64) m^2 (θ_{zen} < 15° used in this analysis)**

MC: Comparison of interaction models



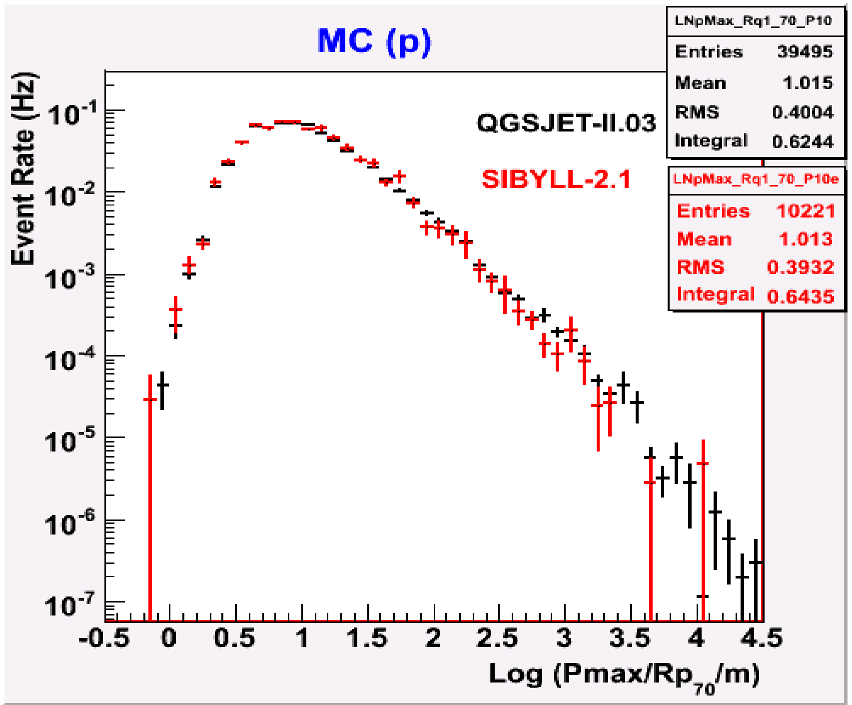
Rp_{70}:

radius including 70% of particles

(particle concentration parameter)

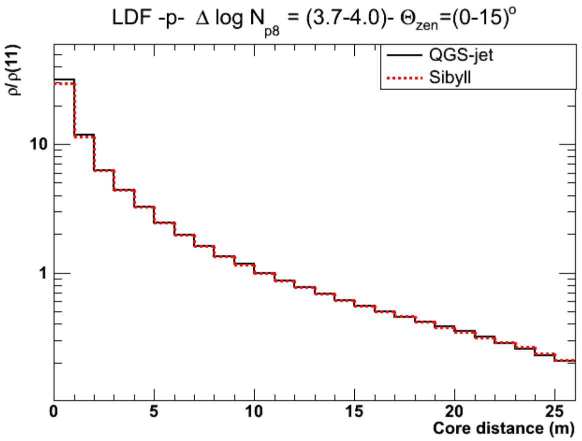
$Pmax / Rp_{70}$ ratio

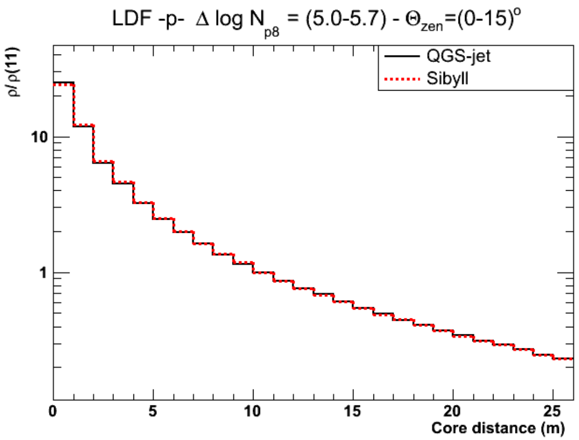
(steepness parameter)



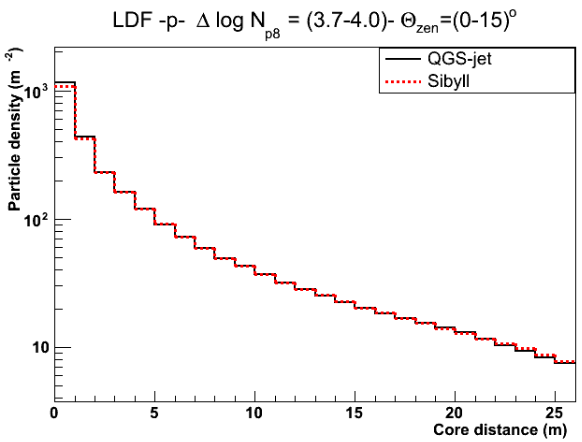
MC: LDF from QGSJET and SIBYLL

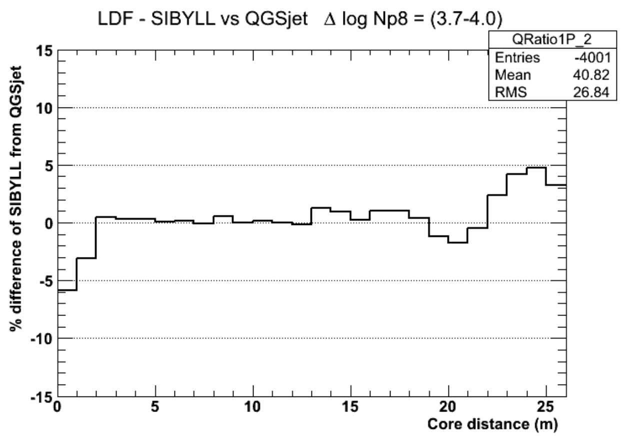
Shape comparison:





Absolute comparison:





The differences of the two models are within few percent

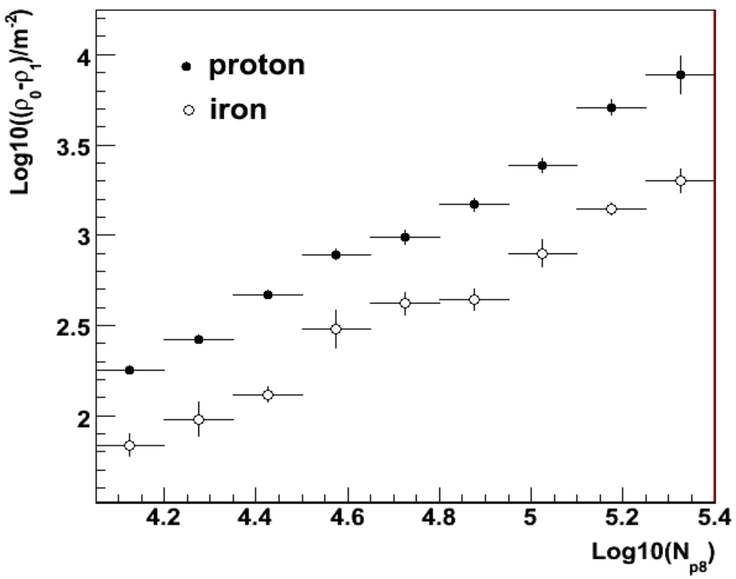
Sensitivity to the primary mass (1)

Several observables under investigation:

- **LDF-Slope**
- **Rp_{70}**
- **conical front shape parameter (α) $\rightarrow$ related to particle arrival times**

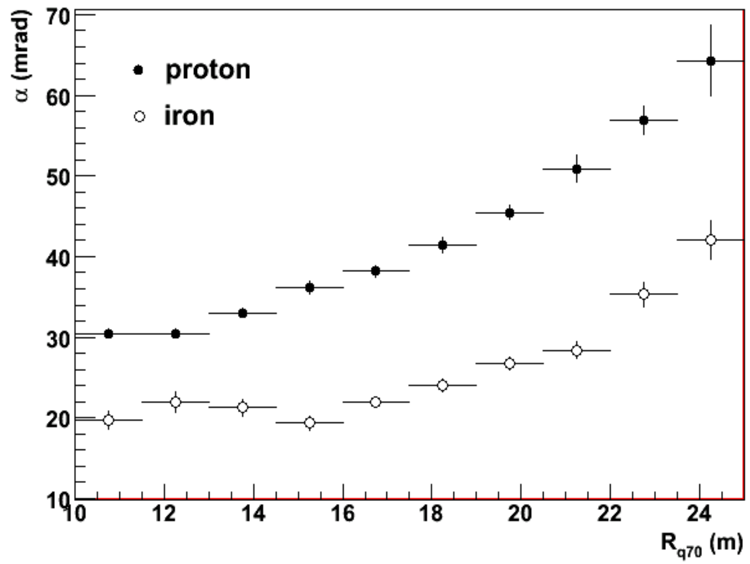
MC: (ρ_0-ρ_1) vs N_{p8}

$\rho_0 = \rho_{part}$ on the core
$\rho_1 = \rho_{part}$ 1m from the core



MC: α (mrad) vs Rp_{70} (m)

α = conicity of shower front
Rp_{70} = radius including 70% particles

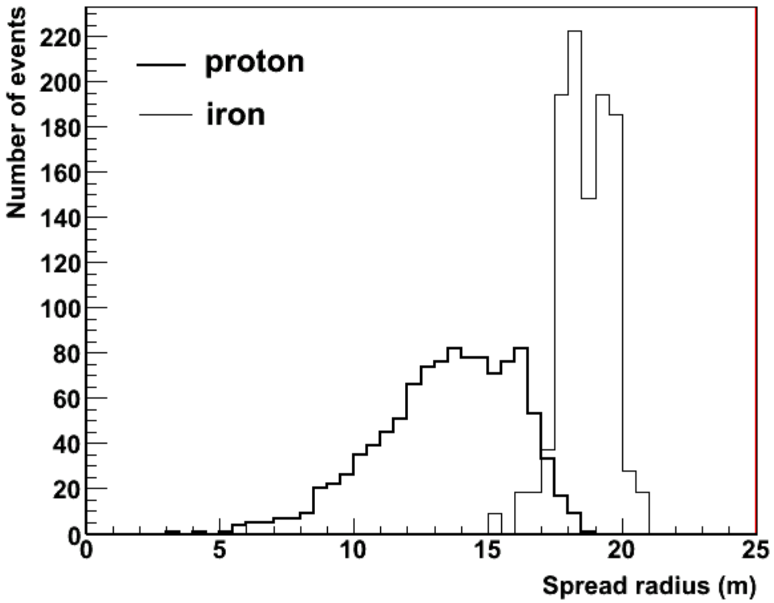


Sensitivity to the primary mass (2)

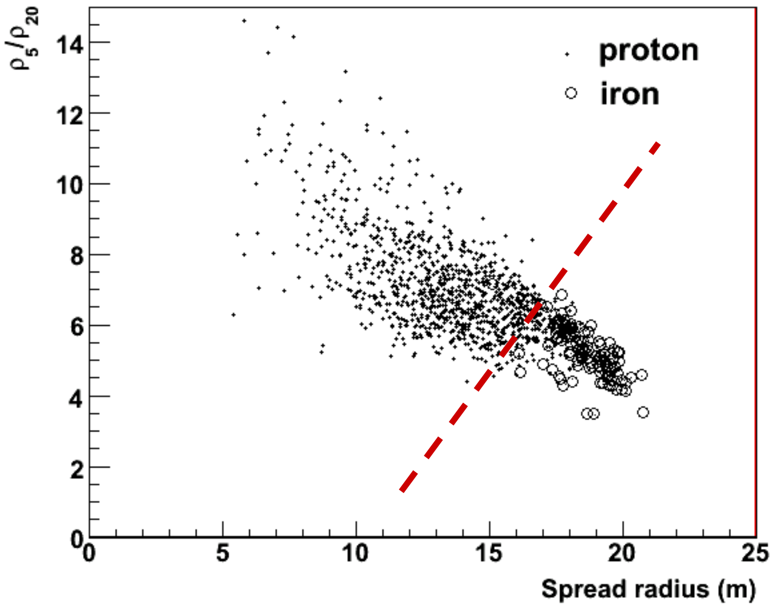
Moreover:

- **particle spread parameter R_{spread} (m)**
- **ratio of local particle densities**
- **...**

$$R_{spread} = \frac{\sum r_{BigPad_i - Core} \times N_{part_i}}{\sum N_{part_i}}$$



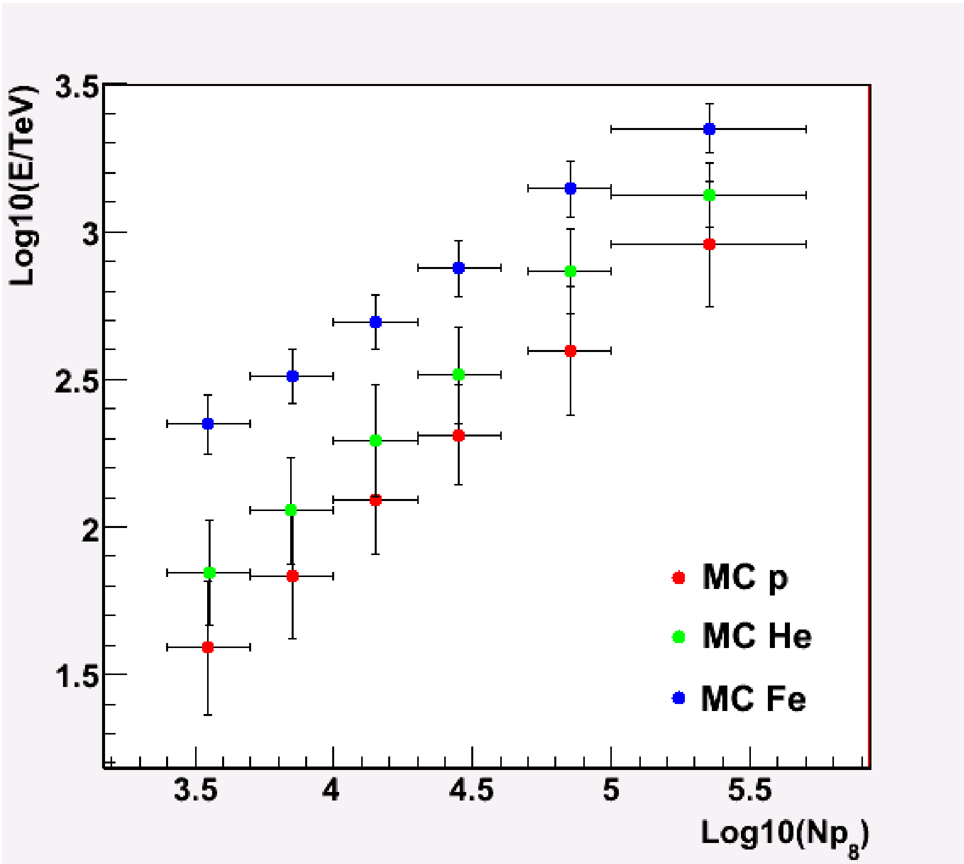
ρ_5/ρ_{20} vs R_{spread}



MC: Np_8 as an energy estimator

Np_8 (particle size truncated at 8m of core distance):

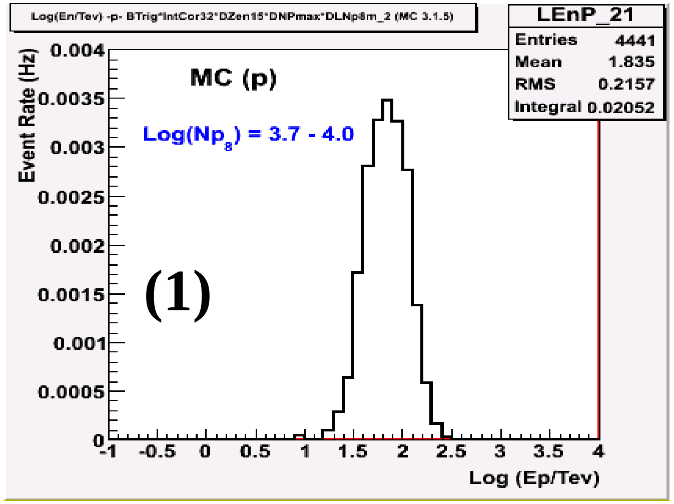
- **well correlated with primary energy**
- **not biased by finite detector size effects**
- **weakly affected by shower fluctuations**



QGSJET-II based MC samples

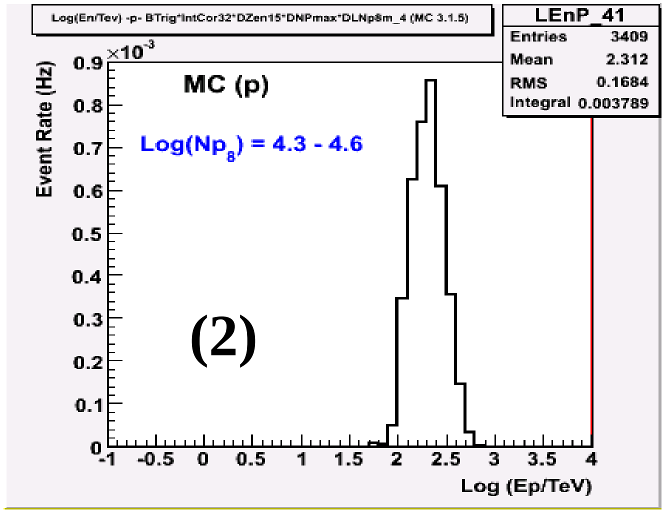
Vertical error bars: RMS(Energy)

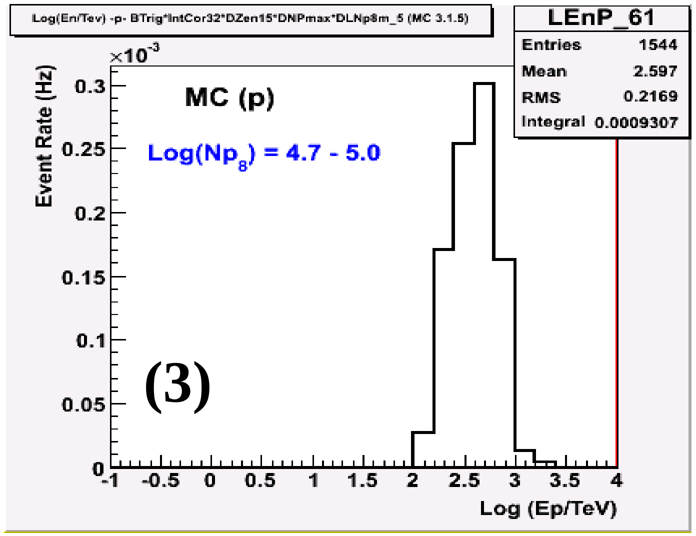
MC: energy bins for primary protons



(1) ΔLog(Np$_8$) = (3.7- 4.0) $\rightarrow$ Ep ~70 TeV

(2) ΔLog(Np$_8$) = (4.3- 4.6) $\rightarrow$ Ep ~200 TeV



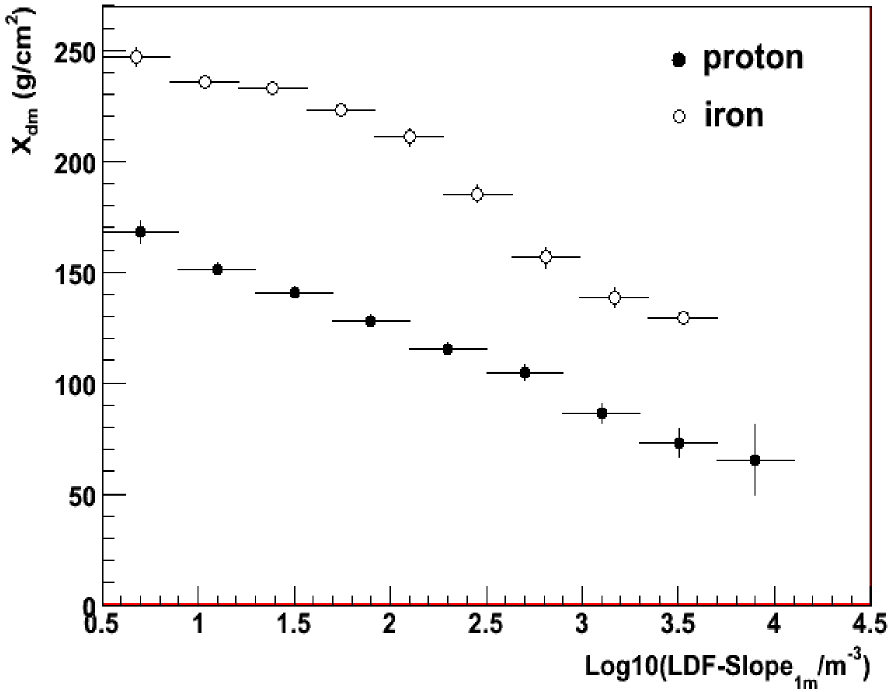


(3) ΔLog(Np$_8$) = (4.7- 5.0) $\rightarrow$ Ep ~400 TeV

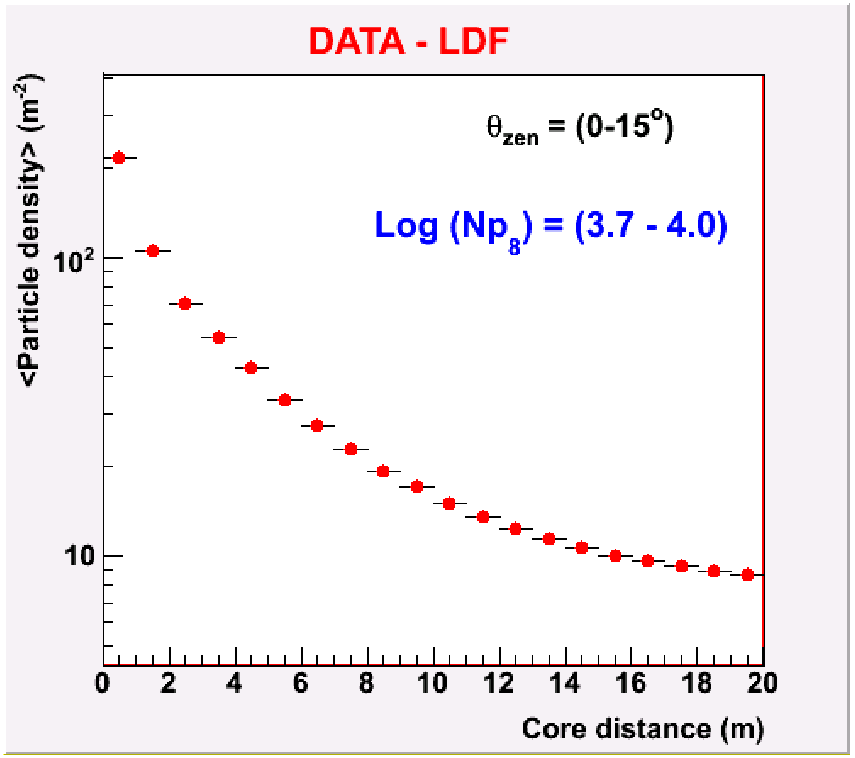
Sensitivity to X_{max}: LDF-Slope$_{(1m)}$

X_{dm}: distance of shower X_{max} from the detector

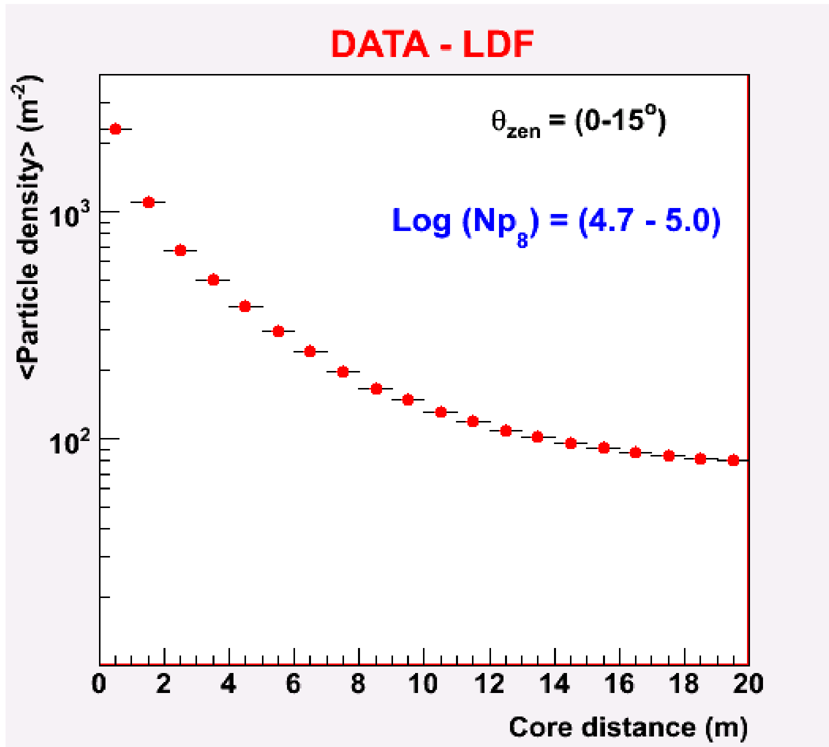
The LDF slope very near the core (1m of distance) offers a possible way to constrain X_{dm}:



Data: LDF for different Np_8 intervals



LDF for Log(Np_8) = (3.7-4.0)



LDF for Log(Np_8) = (4.7-5.0)

The study of the whole lateral distribution could provide information on X_{max} position and primary mass → fit LDF through a proper function

MC: LDF fit for different primaries

Several function used to fit the LDF shape in the range 0.5 m < R < 15.5 m of core distance (p, He and Fe primaries)

A NKG-like function found to reasonably reproduce the LDF shape in the above distance interval, with some modifications/re-interpretations of the parameters

$$\boxed{\rho'_{NKG} = A \cdot \left(\frac{r}{r_M}\right)^{s'-2} \cdot \left(1 + \frac{r}{r_M}\right)^{s'-4.5}}$$

$r_M = r_M^{(YBJ)}/4 = 30.3$m: fixed

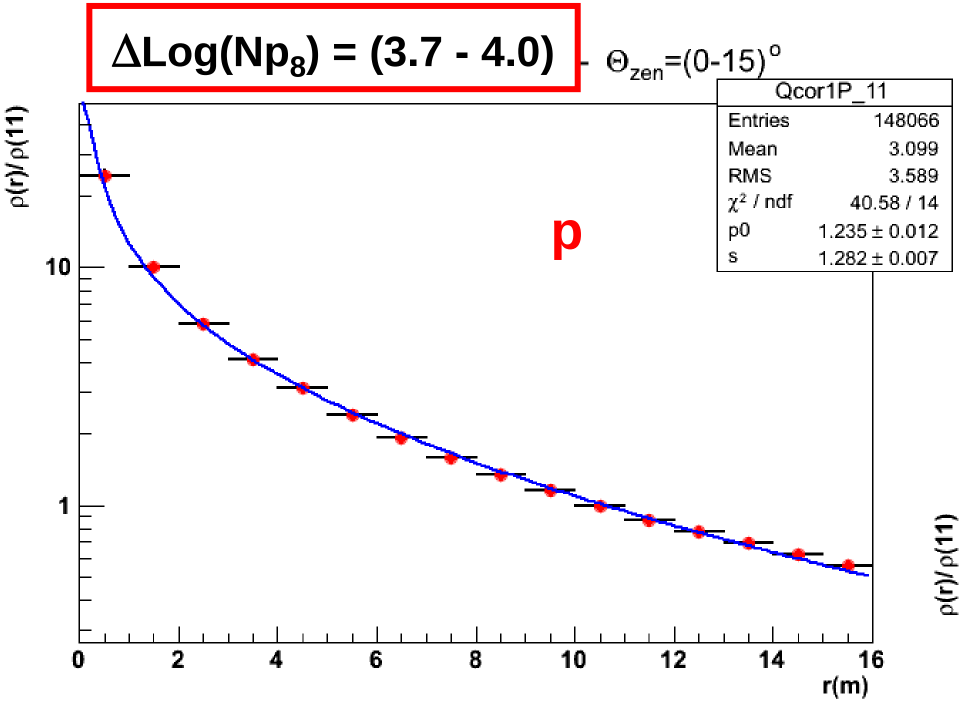
Normalization factor *A* and *s'*: free parameters

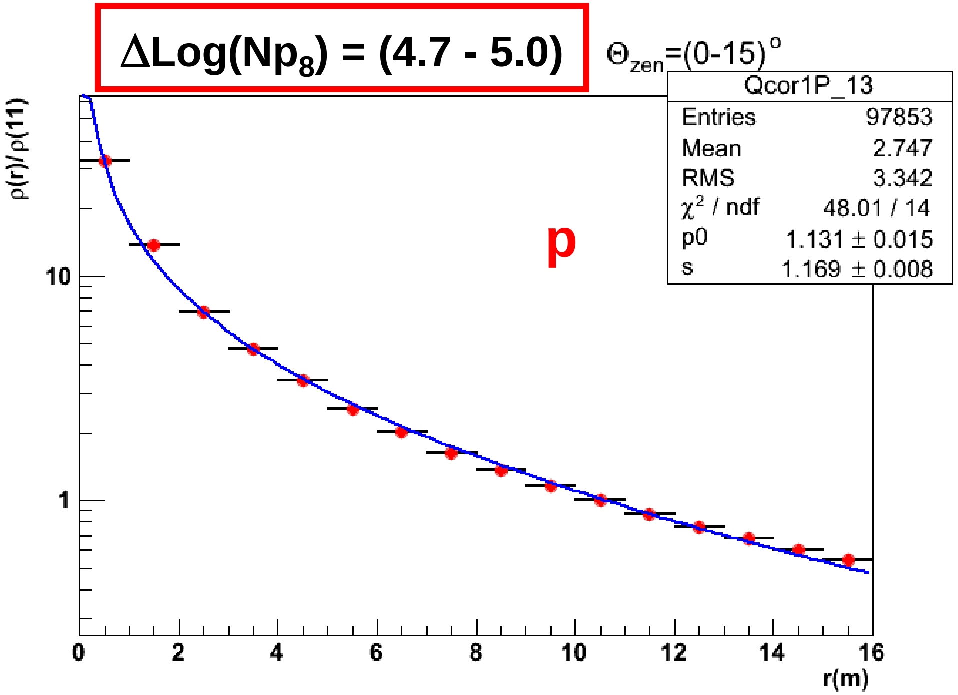
(Fit distribution normalized to ρ_{11})

<u>Remarks</u>:

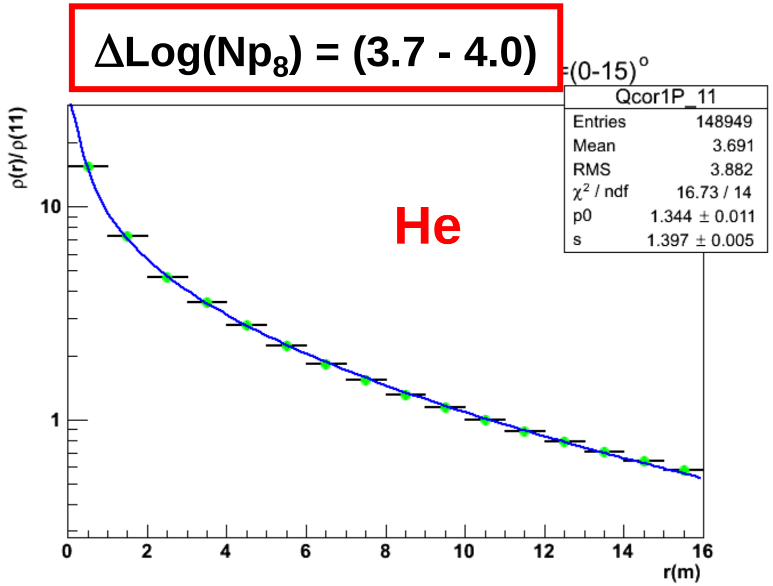
- ***s'***: **'lateral shower age', describing the slope of the radial distribution of charged particles**
- **In principle, *s'* coincides with 'longitudinal age' *s* (reflecting the longitudinal shower development)**
- **In practice *s'* differs from *s*, altough they must be related ...**

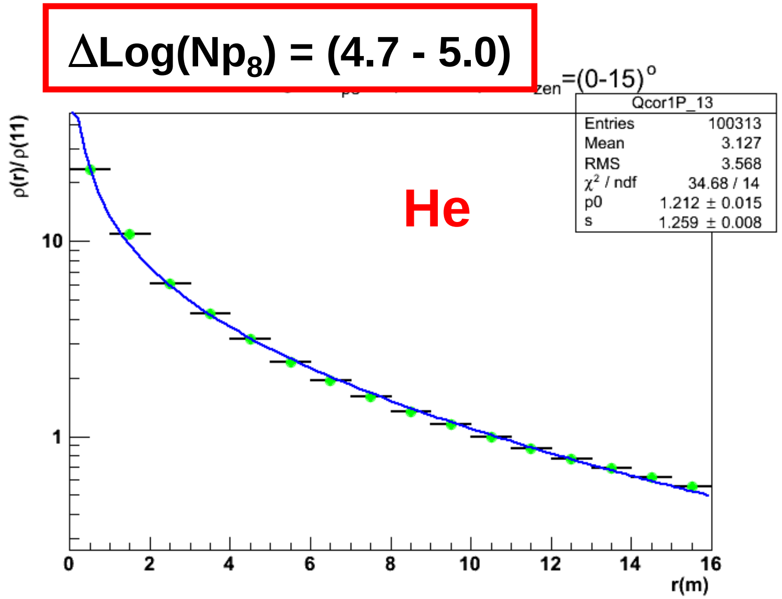
LDF fit: p primaries

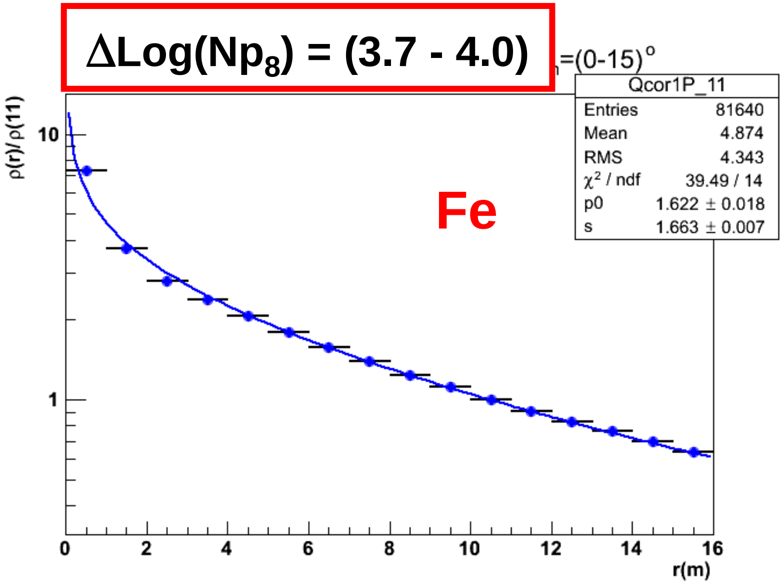


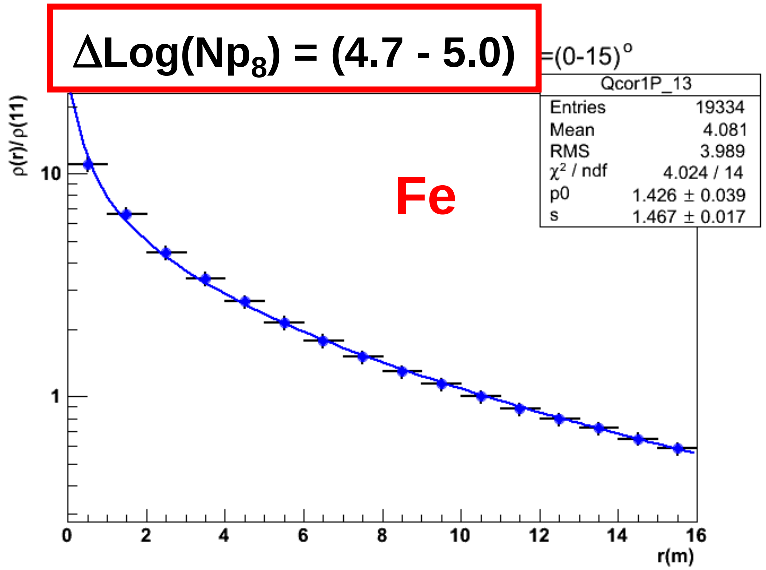


LDF fit: He and Fe primaries





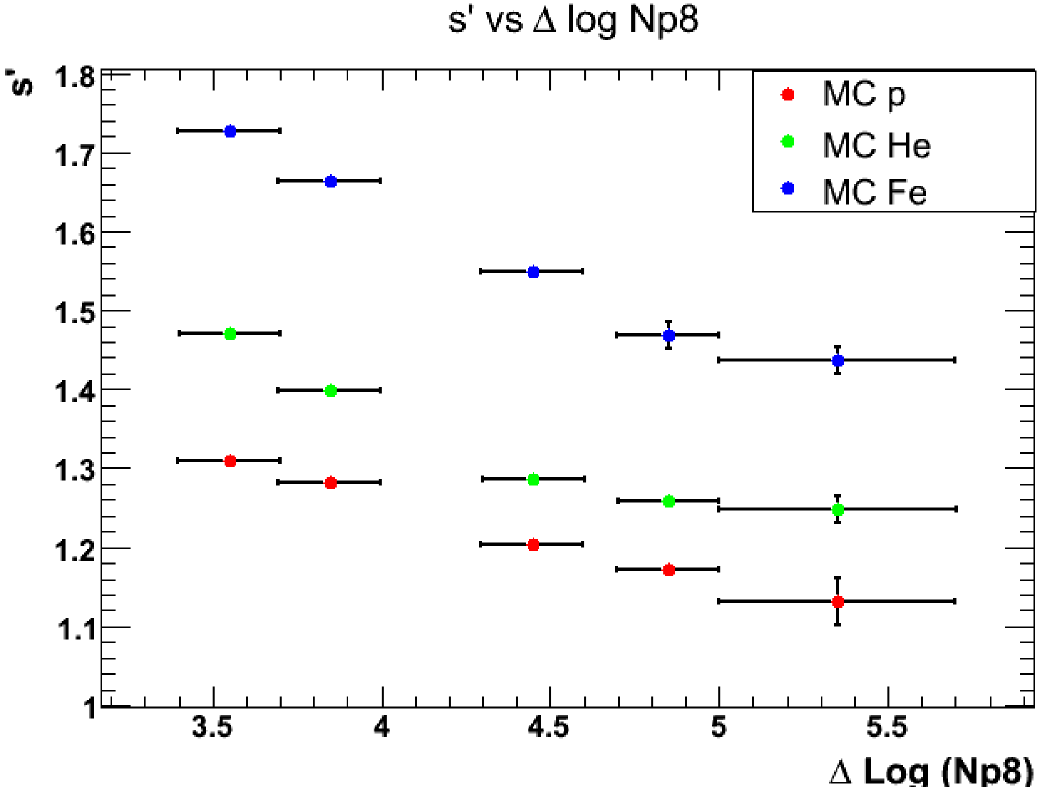




Fit results: summary table

Energy (TeV)	$\Delta Log(Np_8)$	Protons s'	He s'	Fe s'
(p) ~70 (He) ~100 (Fe) ~300	3.7-4	1.282 ±0.007	1.397 ±0.005	1.663 ±0.007
(p) ~200 (He) ~300 (Fe) ~750	4.3-4.6	1.202 ±0.006	1.287 ±0.006	1.549 ±0.007
(p) ~400 (He) ~750 (Fe) ~1400	4.7-5	1.170 ±0.008	1.259 ±0.008	1.467 ±0.017

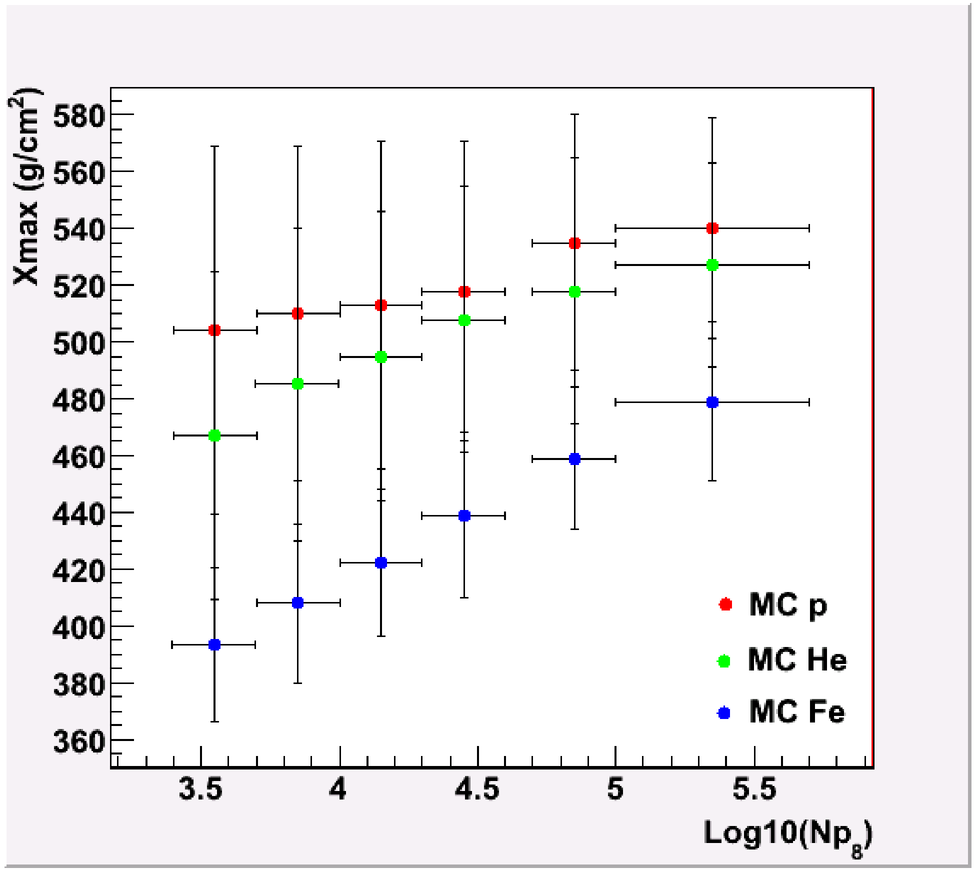
s’ values from LDF fits
(different primaries and energies)



s’ **behaviour is the expected one when describing the longitudinal shower development as a function of primary Energy and Mass**

⇒ **Possibility to get hints on (a) X_{max} position and (b) primary nature**

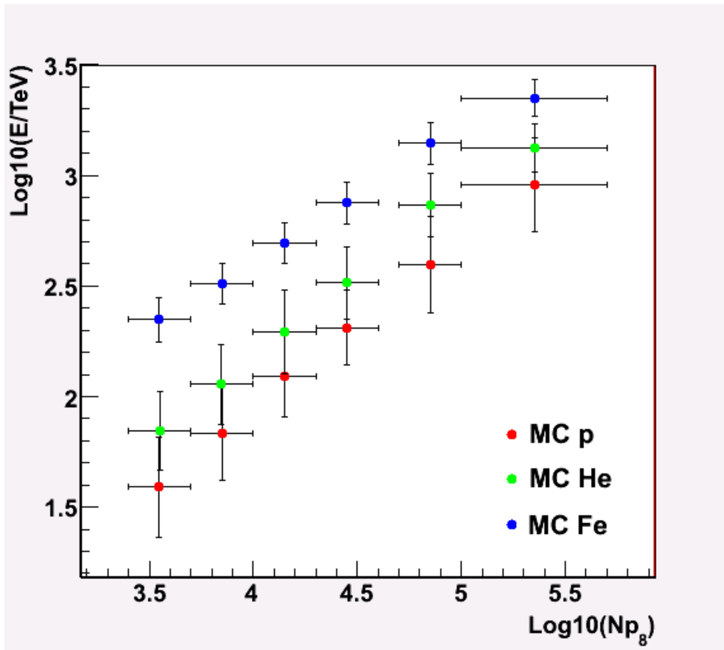
$\langle X_{max} \rangle$ vs Np_8 (i.e. energy) for p, He and Fe



Vertical error bars: RMS (X_{max})

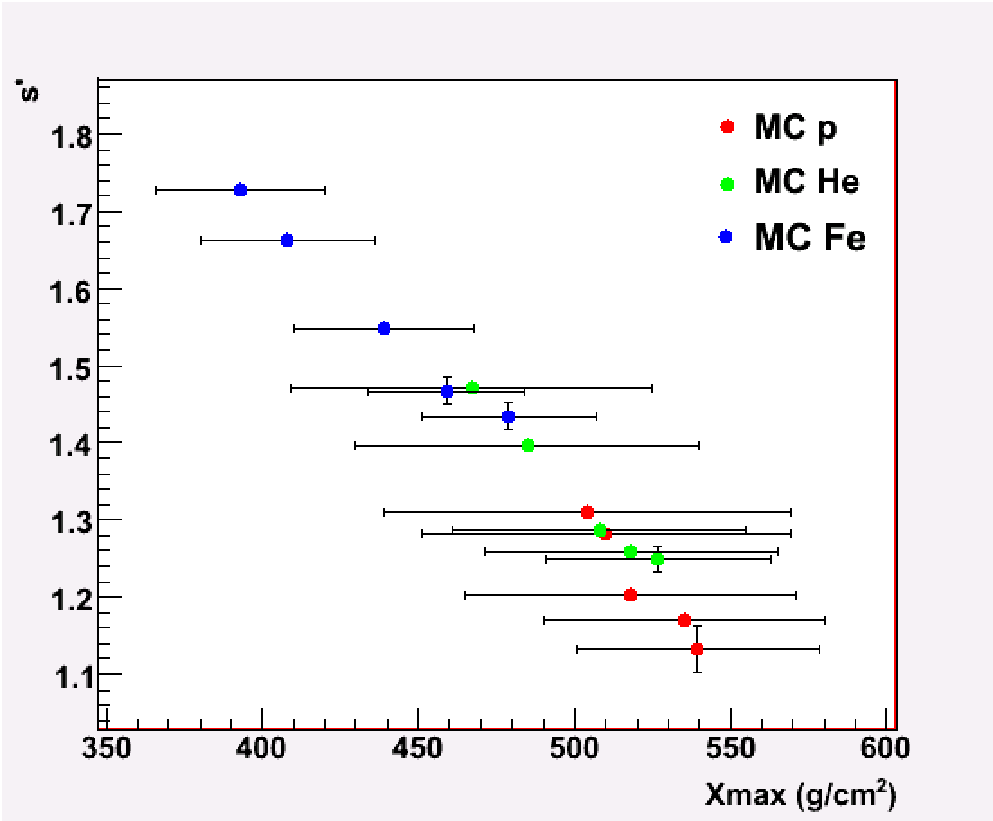
X_{max} as a funtion of Np_8

(which is our $E_{primary}$ estimator)



s' vs X_{max}

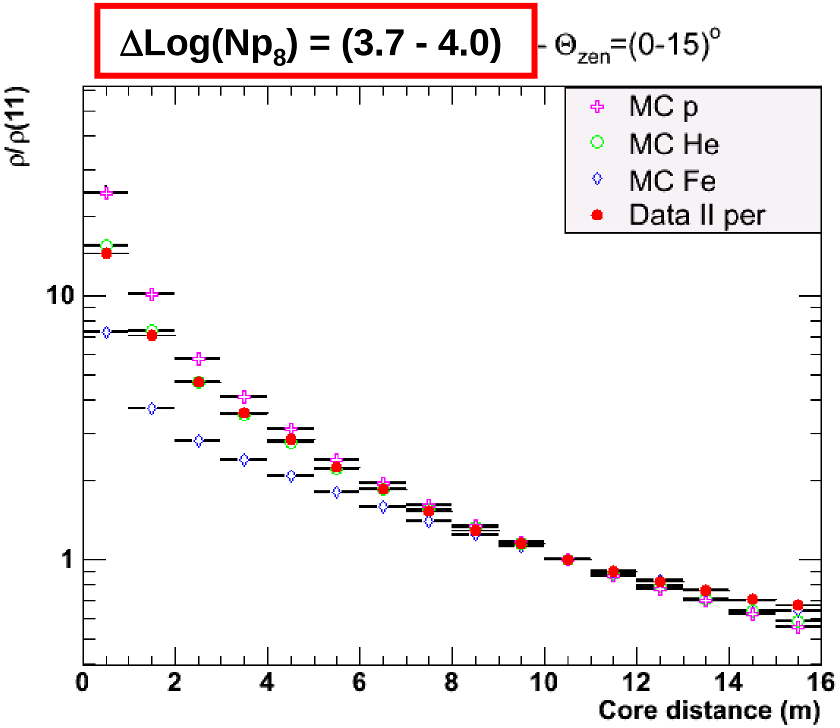
s' from LDF fit on simulated showers 'observed' by ARGO- YBJ ...

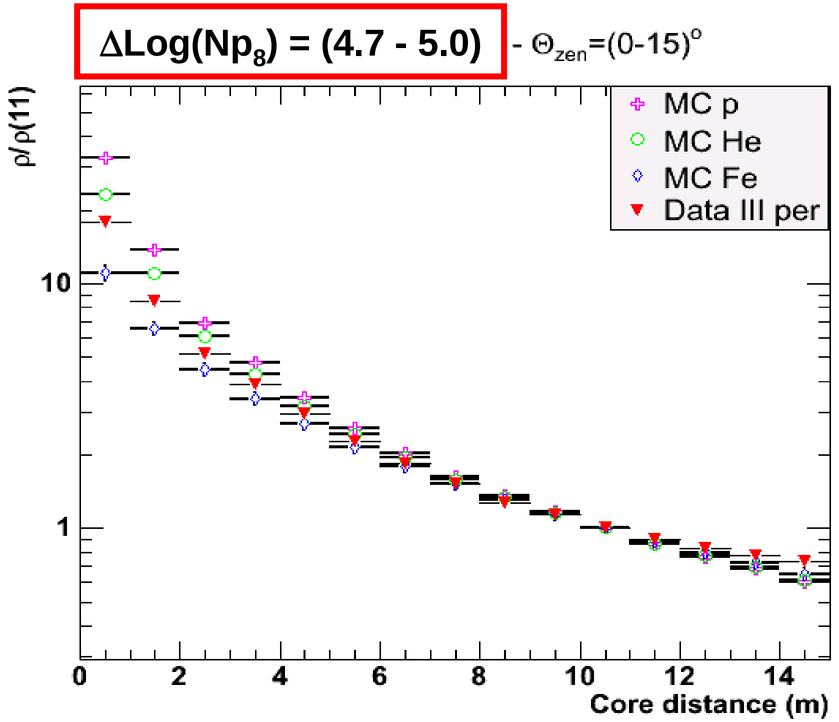


Error bars: RMS(X_{max})

⇒ **s' is clearly related to the X_{max} position (whatever the primary is) and can be used to select the shower development stage**

LDF: comparison of Data with MC



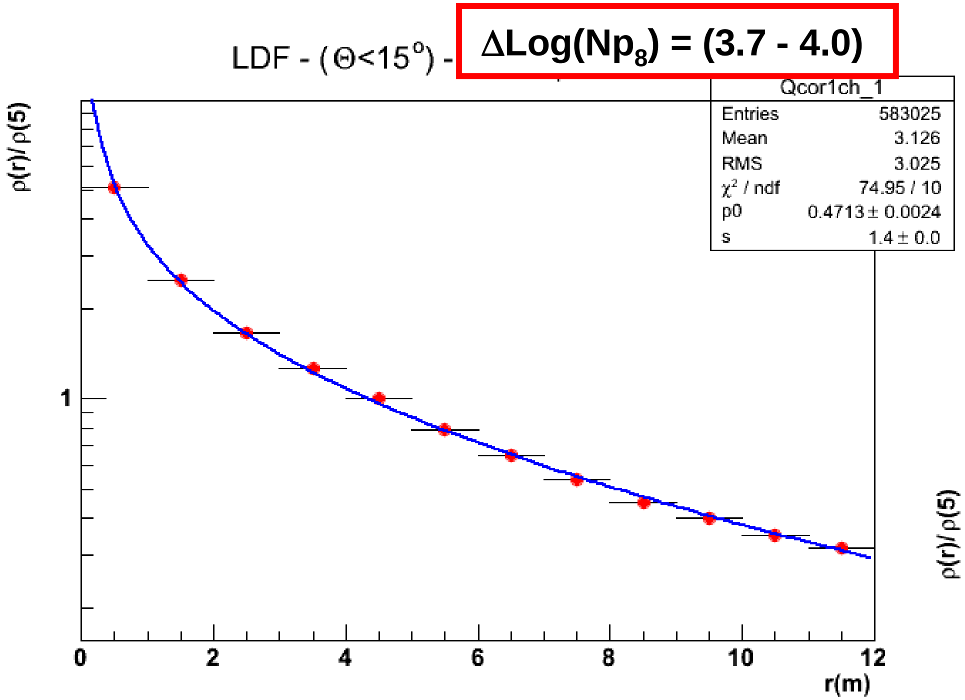


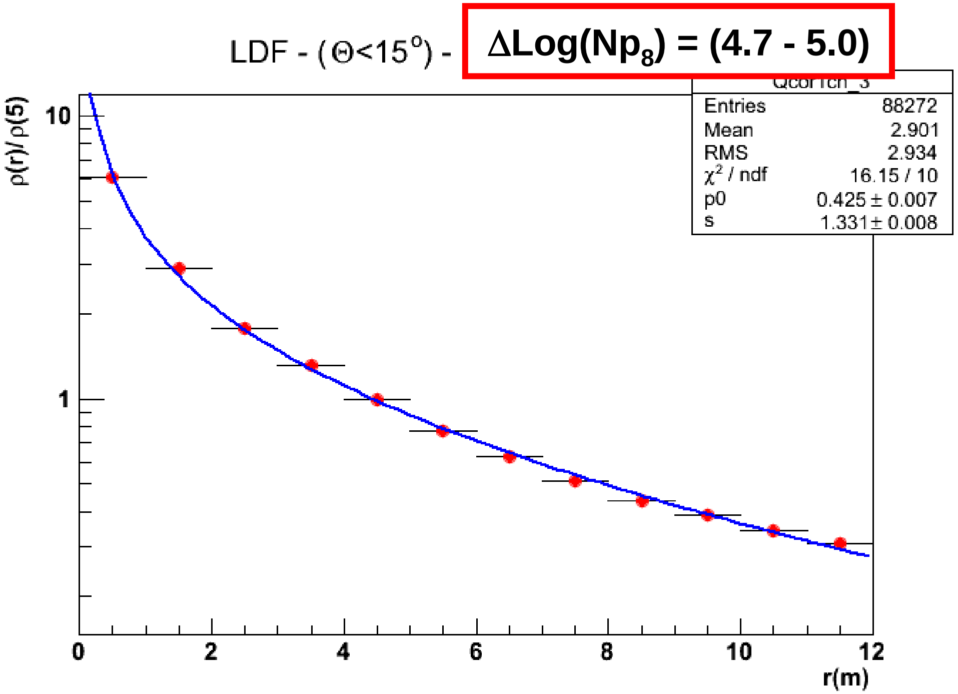
The LDF shapes are compared

(all distributions are normalized to ρ_{11m})

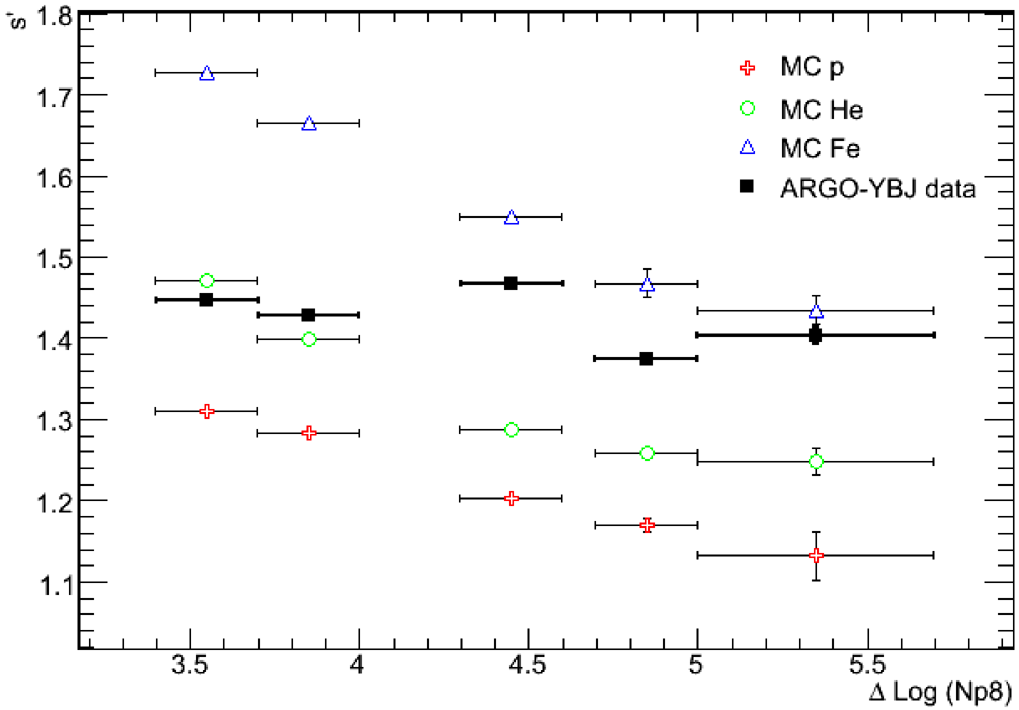
ARGO-YBJ data: LDF fits

Preliminary





s' vs Log(Np_8) for MC and Data



- The ARGO-YBJ data lie between the expectations from extreme pure compositions (p and Fe)
- A trend towards a heavier composition for increasing energy can be envisaged

Conclusions (1)

The ARGO-YBJ features (digital + analog charge readout) allow to:

- measure shower particle densities of ~$10^4/m^2$
- study with unprecedented details the shower core region
- fully inspect the lateral distribution up to few tens of meters

⇒ Possibility to investigate several characteristics of the very high energy hadronic interactions, to extend the p-air cross section measurement up to ~ PeV proton energy, to investigate the primary mass composition

Crucial points for such analyses are:

(a) energy estimate,
(b) discrimination of heavy elements,
(c) selection of the X_{max} (or X_{dm}) range
(d) sensitivity of any observable to the primary nature

Conclusions (2)

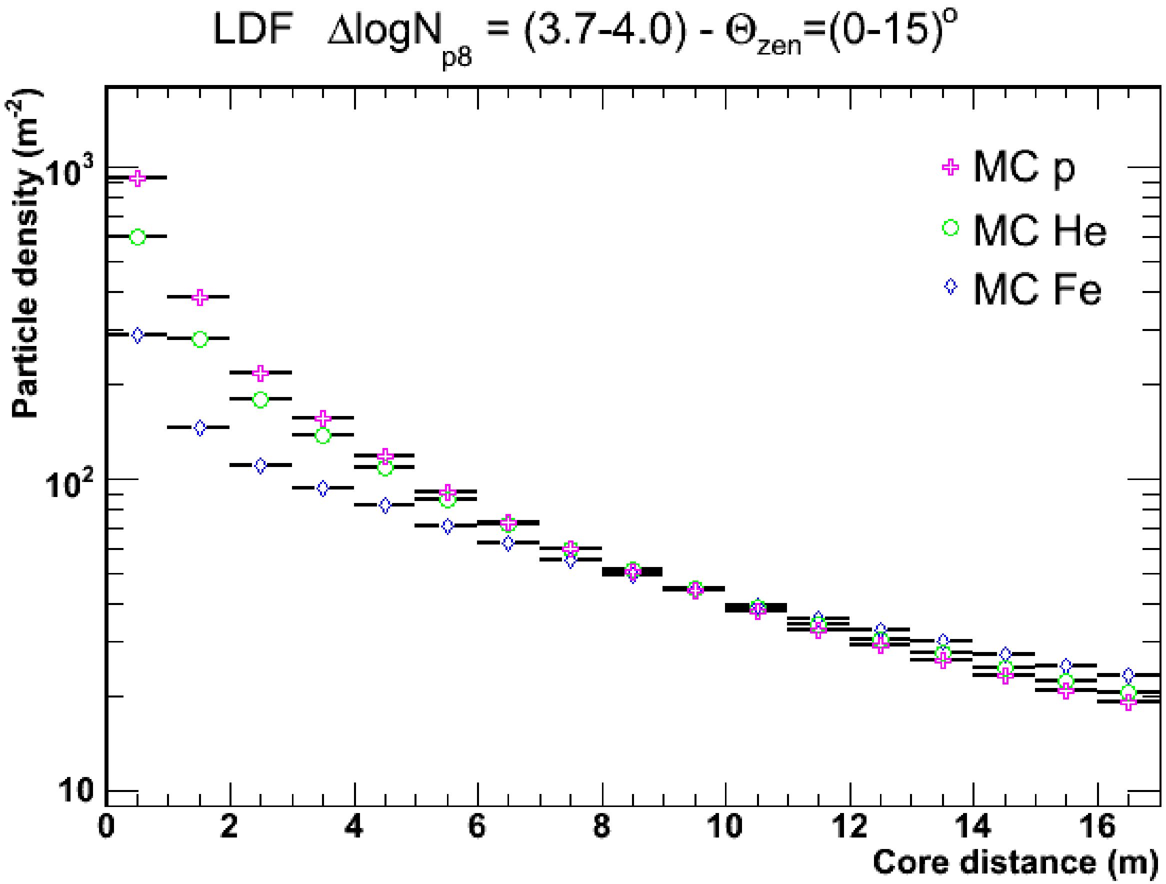
Preliminary results from analog data analysis indicate the capability of ARGO-YBJ to:

- **reliably estimate the primary energy (by means of Np_8)**
- **select proton enriched data samples by exploiting several shower features, like the front curvature, the particle spread, the Rp_{70} parameter, some local particle densities, ...**
- **put constraints on X_{max} position from the particle distribution structure, namely the density slope near the core and, mainly, the s' parameter from the LDF fit**

- **The s' parameter is also sensitive to the primary composition, even if its fluctuations, possible dependence from r and correlations with the other quantities have to be carefully studied**

- **preliminary s' values from LDF fits on ARGO-YBJ data lie between predictions from extreme pure compositions, with a trend towards a heavier composition when the energy increases**

MC: LDFs from different primaries

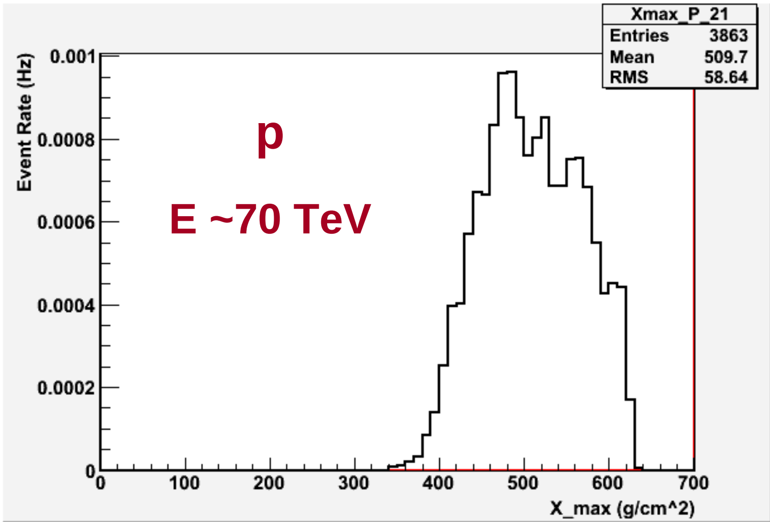


$\Rightarrow$ Fit to distributions normalized to ρ (11m)

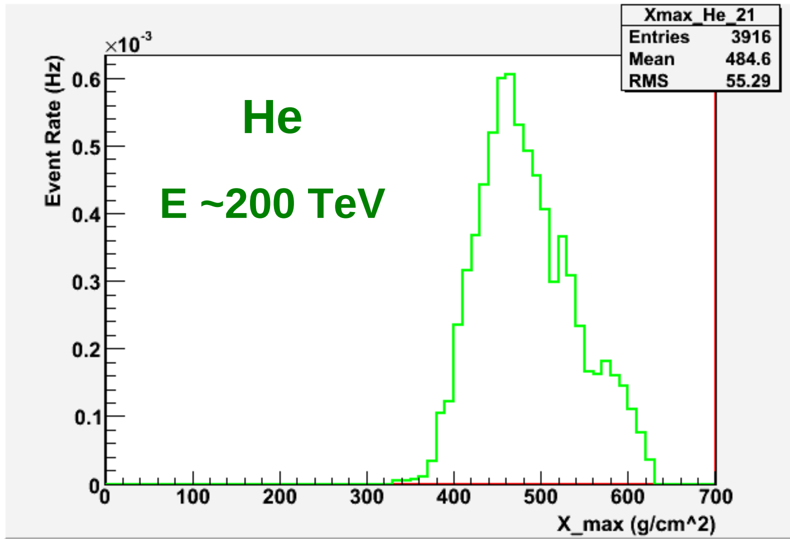
Same results if a different distance (f.i. 5m) is used as reference

Examples of X_{max} distributions

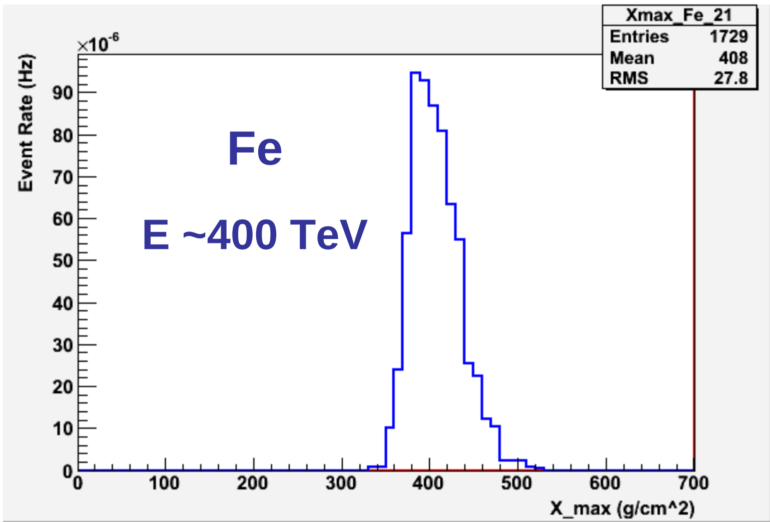
$\Delta Log(Np_8) = (3.7 - 4.0)$



$<X_{max}>_p = 510 \pm 59$

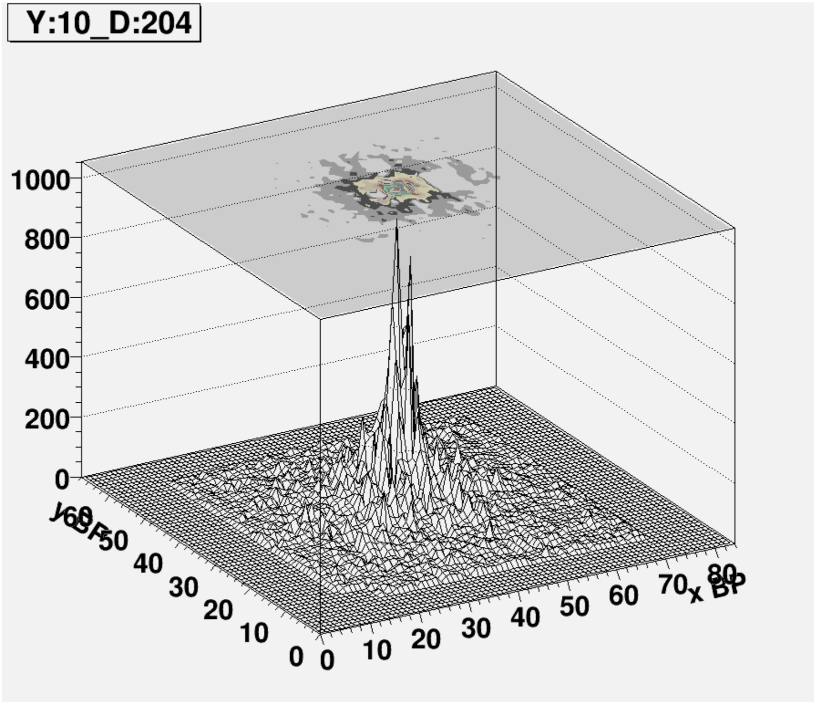


$<X_{max}>_{He} = 485 \pm 55$



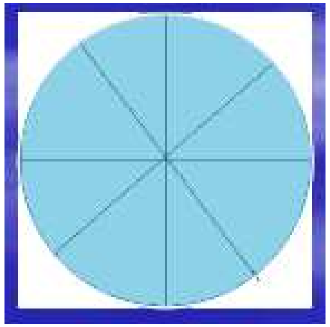
$<X_{max}>_{Fe} = 408 \pm 28$

• Event Asymmetry parameter:

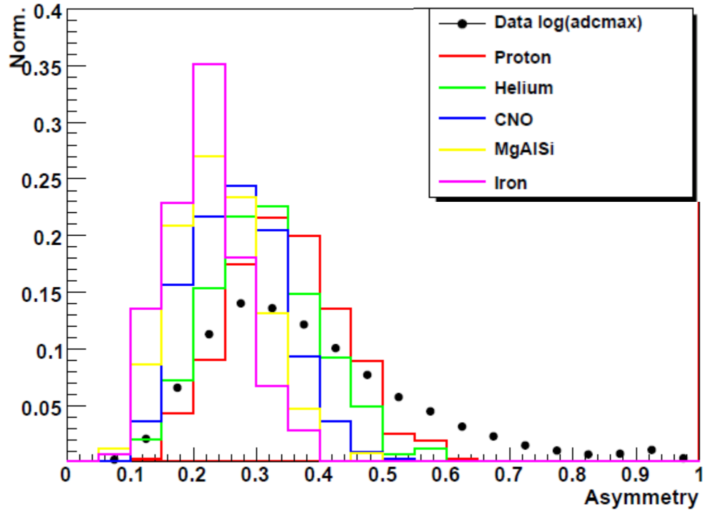


Events are selected by requiring:

- The reconstructed zenith angle < 15◦;.
- core inside the internal detector Afid
- log of the maximum density in 2.5 to 3
- data set of Dec. 2010
- comparison with MC events generated according to Horandel model



$$\xi = \frac{(Q_{max} - Q_{min})}{(Q_{max} + Q_{min})}$$



Asymmetry distribution:
comparison of data and MC events

M. ZHA-ARGO-YBJ Coll., HE1.1 n.242