Study of extensive air shower structure around the axis with ARGO-YBJ experiment

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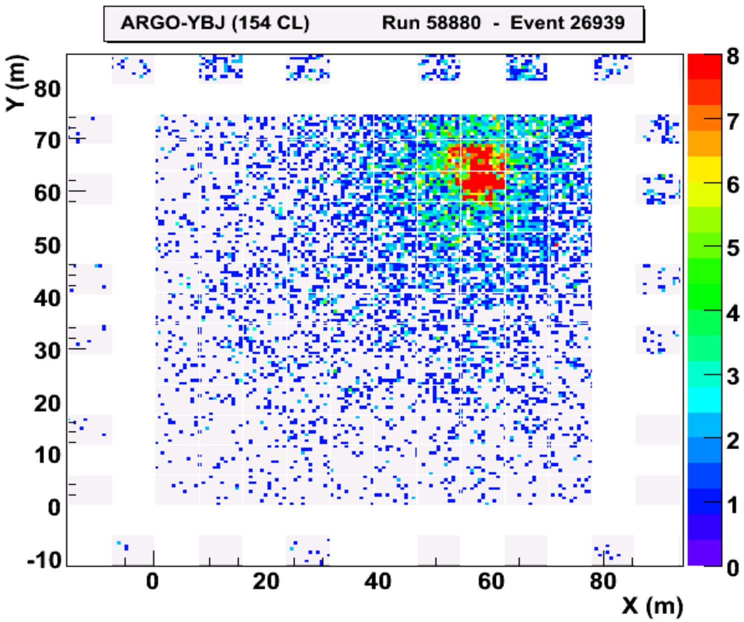
Shower detection by ARGO-YBJ:

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

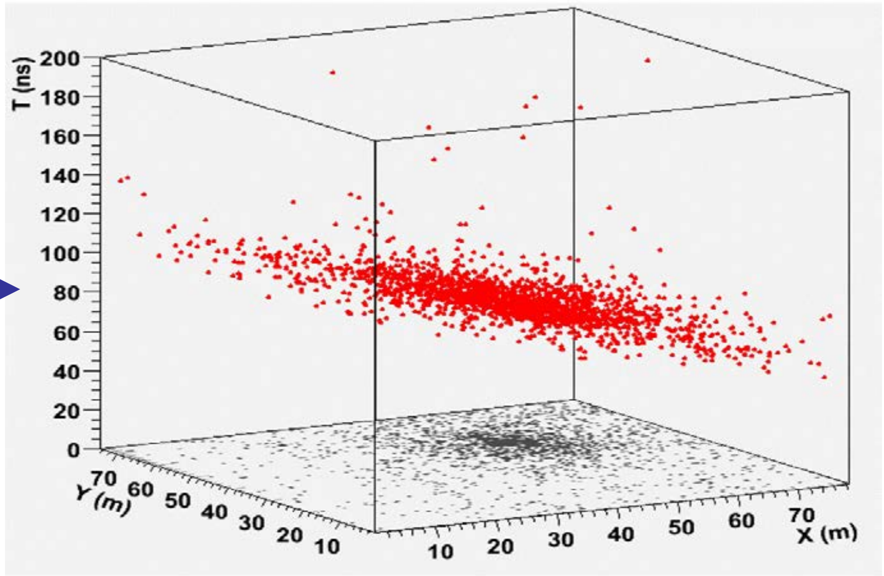
Time resolution: ≈ 1 ns

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

A real event from digital information



Number of fired Strips

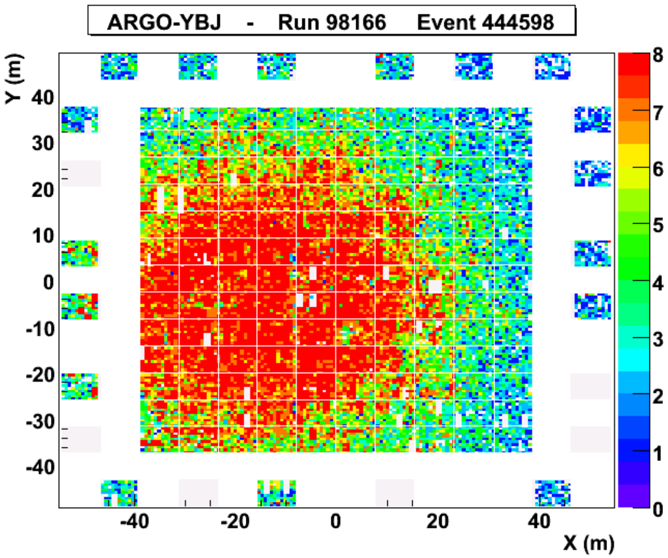


Analog charge readout system

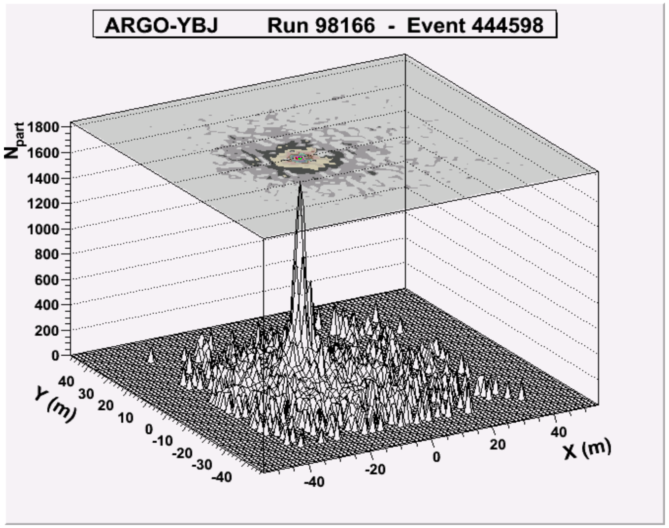
- ⇒ **extending the explorable energy range of showers above 100 TeV**
- ⇒ **accessing values of local particle densities up to ~$10^4/m^2$ (where digital information from strips is saturated)**

The system implements several electronics Gain Scales (i.e. particle density ranges). Data from scales G4 and G1 are used in this analysis.

Example of events imaged by the analog readout:



Strip pattern



Particle distribution from analog charge

Shower front structure around the core

Full-coverage + Charge readout segmentation + dynamical range

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

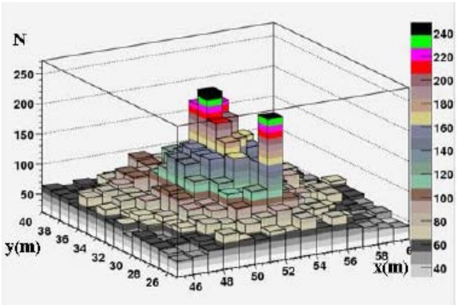
Several observables considered:

- **particle concentration parameters Rp_{70}, Rp_{50}, ..**
- **steepness parameter $Log(N_{max}/Rp_{50})$**
- **conical front shape parameter (α) $\rightarrow$ related to particle arrival times**
- **LDF-Slope near the core (ρ_0-ρ_1)**
- ***lateral age* parameter from LDF fit in the most significant range of core distances**

with the aim of:

(a) studying the detailed features of the shower front around the core
(b) extracting any interaction model peculiarity
(c) investigating the sensitivity to the primary mass composition

Possibility to study "exotic" topologies, i.e. multi-core events, …



MC simulation

- **Simulated air shower samples:**

  (a) p showers (1- 10,000)TeV, Theta<45°
  (b) He showers " "
  (c) CNO showers " "
  (d) Fe showers " "

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

- **Also p and He showers (1- 3000)TeV, Theta<45°**

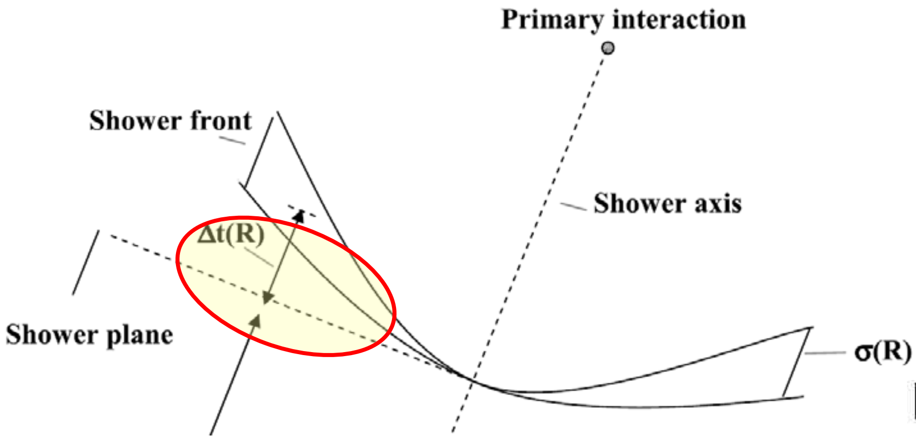
  produced using *a different hadronic model: SIBYLL-2.1 (+ Fluka*)

- **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)**

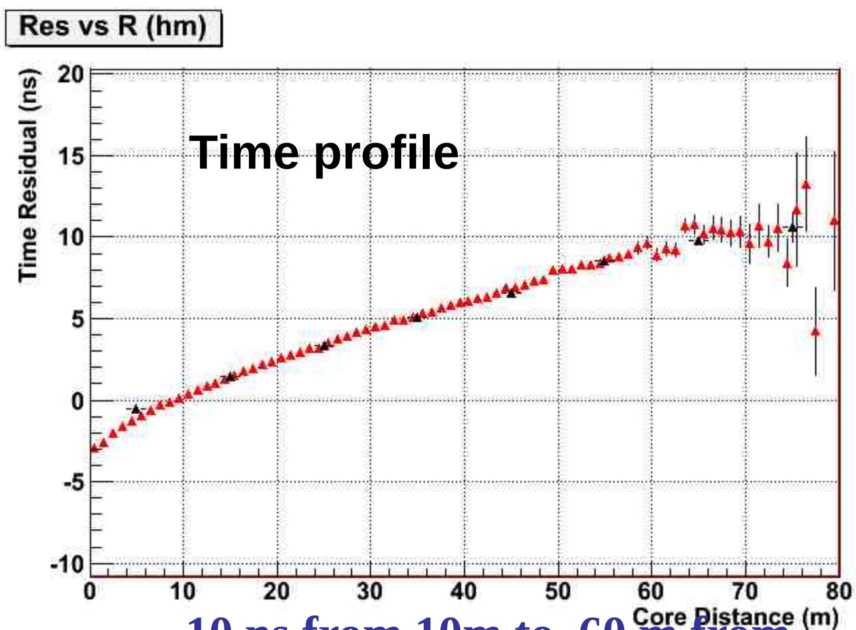
- **MC data reconstructed by using the same program as for real data.**

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

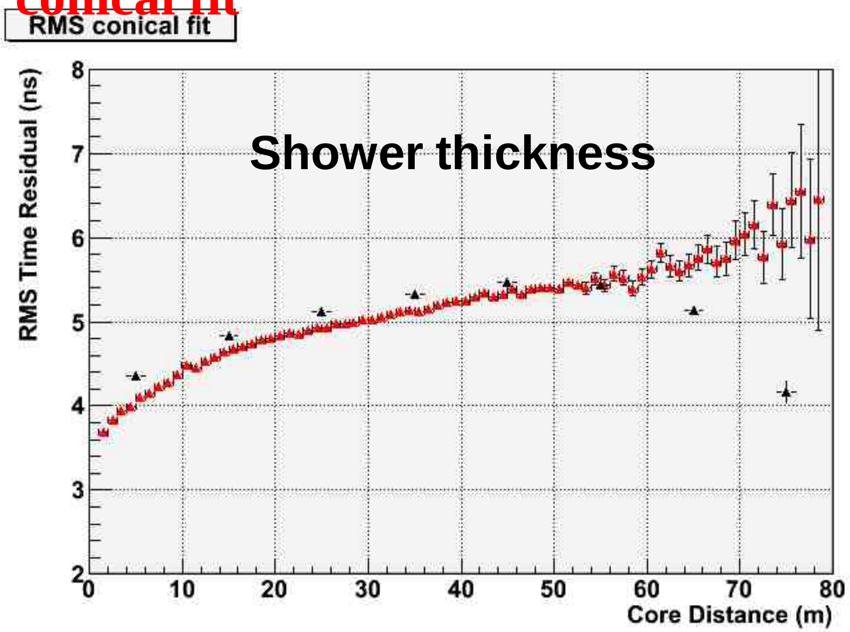
Time profile of shower front



Average Curvature: the mean of time residuals **Δt(R)** with respect to a **plane fit**



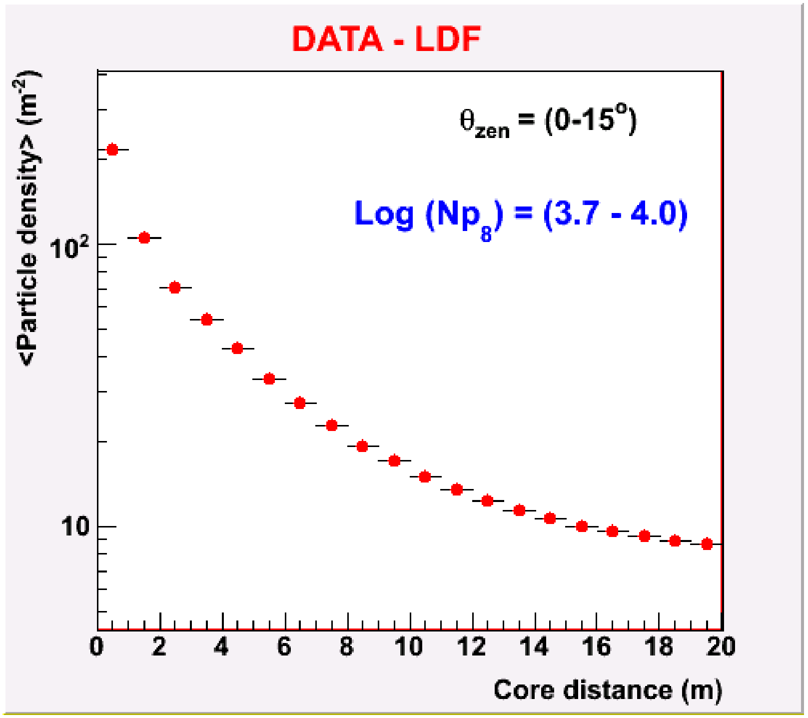
Average Thickness: the RMS of time residuals **σ(R)** with respect to a **conical fit**

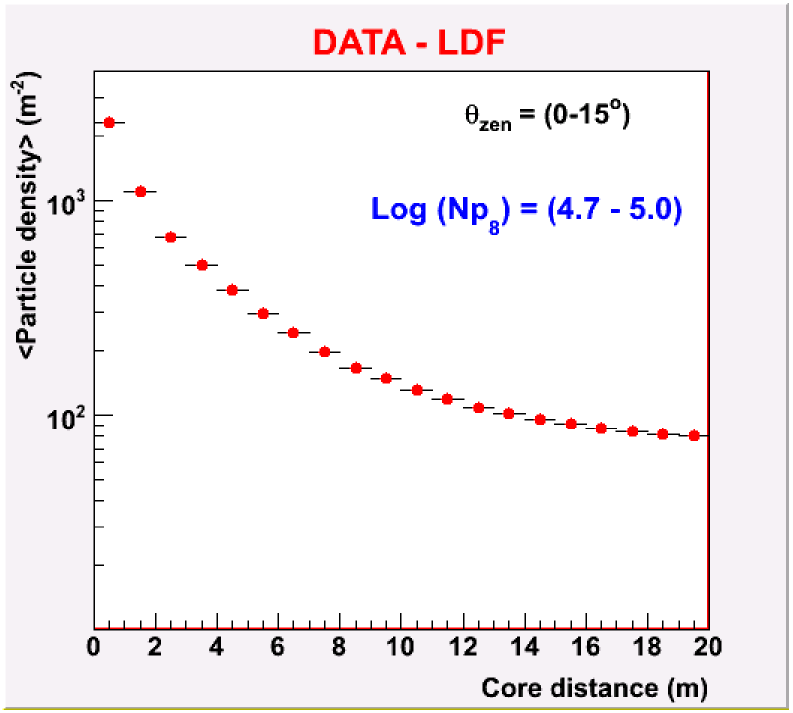


- **10 ns from 10m to 60 m from the core.**

4 ns to 6ns from 10m to 60 m from the core.

Study of the LDF





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

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

(N_{p8} : number of particles within 8m from the shower core)

The study of the lateral distribution provides information on shower age and primary mass

→ fit LDF through a proper function

Best function for LDF fit (MC and DATA)

Several function used to fit the LDF shape in the range 0 < R < 12 m of core distance for different primaries **(see ICRC-2013 paper: *“Study of the shower front structure at few meters from the core with ARGO-YBJ*” for details)**

A NKG-like function found to better reproduce the LDF shape from both experimental data and MC (different primaries) in the above distance interval, with the minimum no. of parameters:

$$\rho'_{NKG} = A \cdot \left(\frac{r}{r_0}\right)^{s'-2} \cdot \left(1+\frac{r}{r_0}\right)^{s'-4.5}$$

r_0 = scale parameter (fixed)

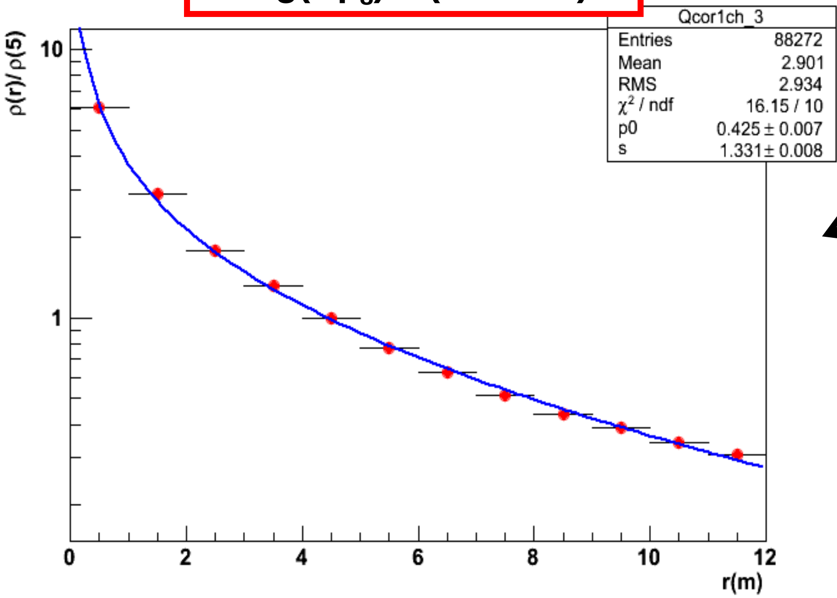
Normalization factor *A* and *s'*: free parameters

<u>Remarks</u>:

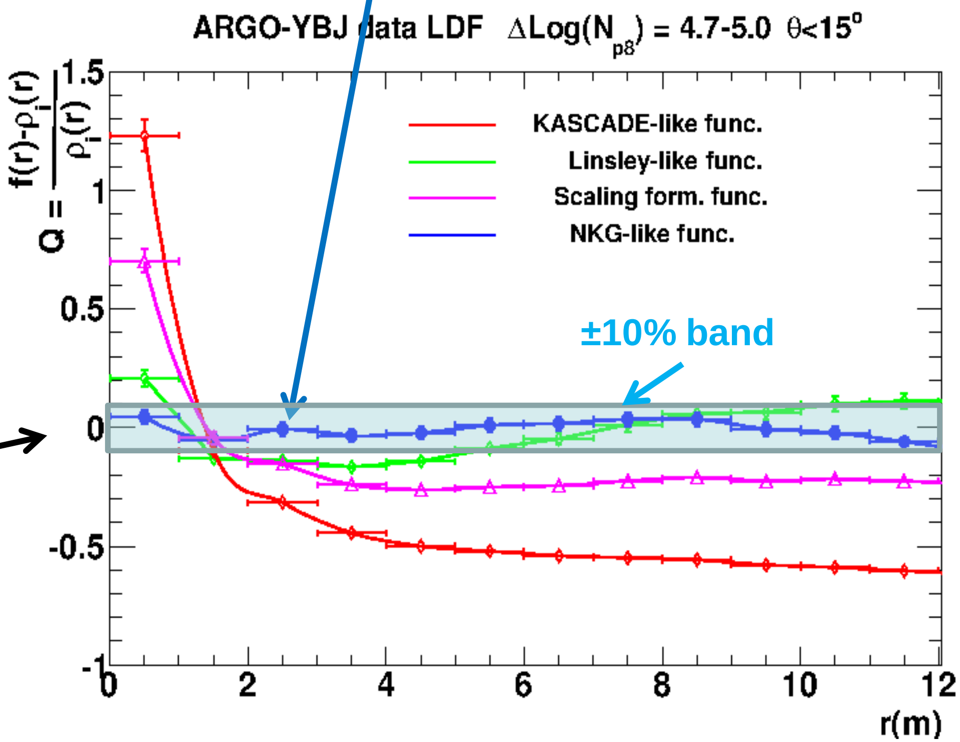
- ***s'*: ‘lateral shower age’, describing the slope of the radial distribution of charged particles**
- ***s'* diferent from ‘longitudinal age’ *s* (reflecting the longitudinal shower development)**
- **BTW *s'* and *s* very well correlated**

ARGO-YBJ data: LDF fits

ΔLog(Np$_8$) = (4.7 - 5.0)

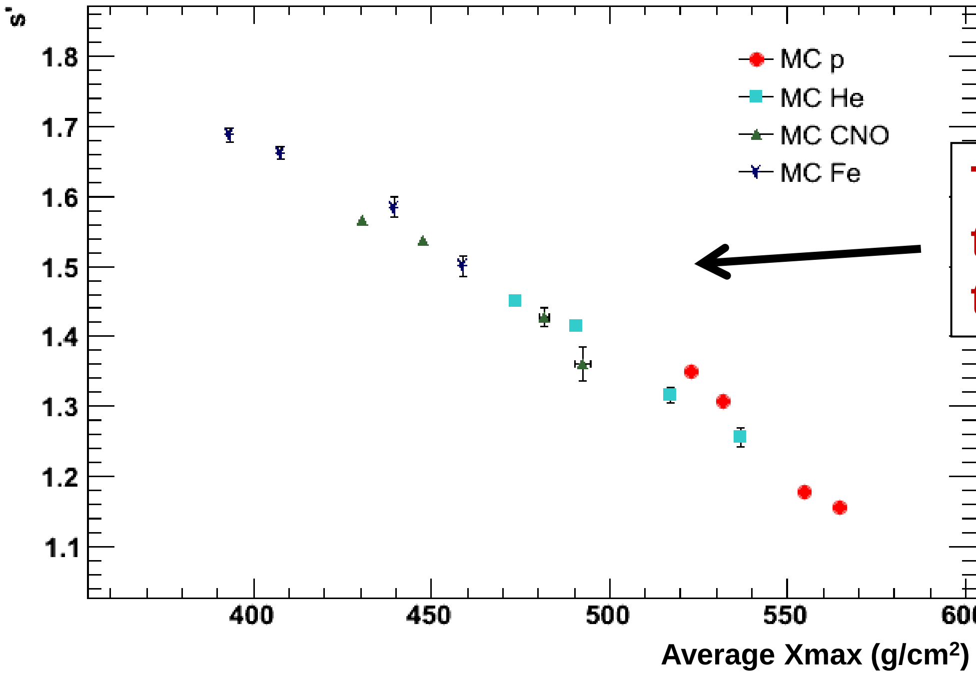


Fit with ρ'$_{NKG}$



Comparison of residuals from different function fits:

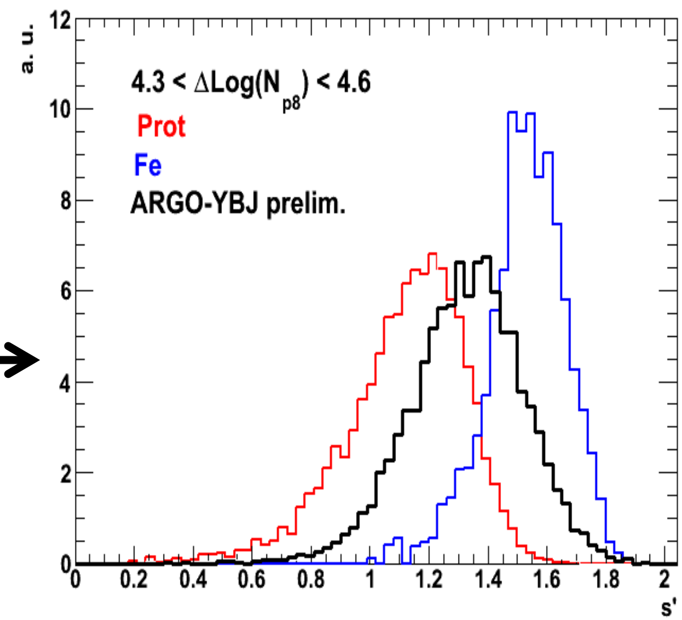
MC: LDF fits for different primaries



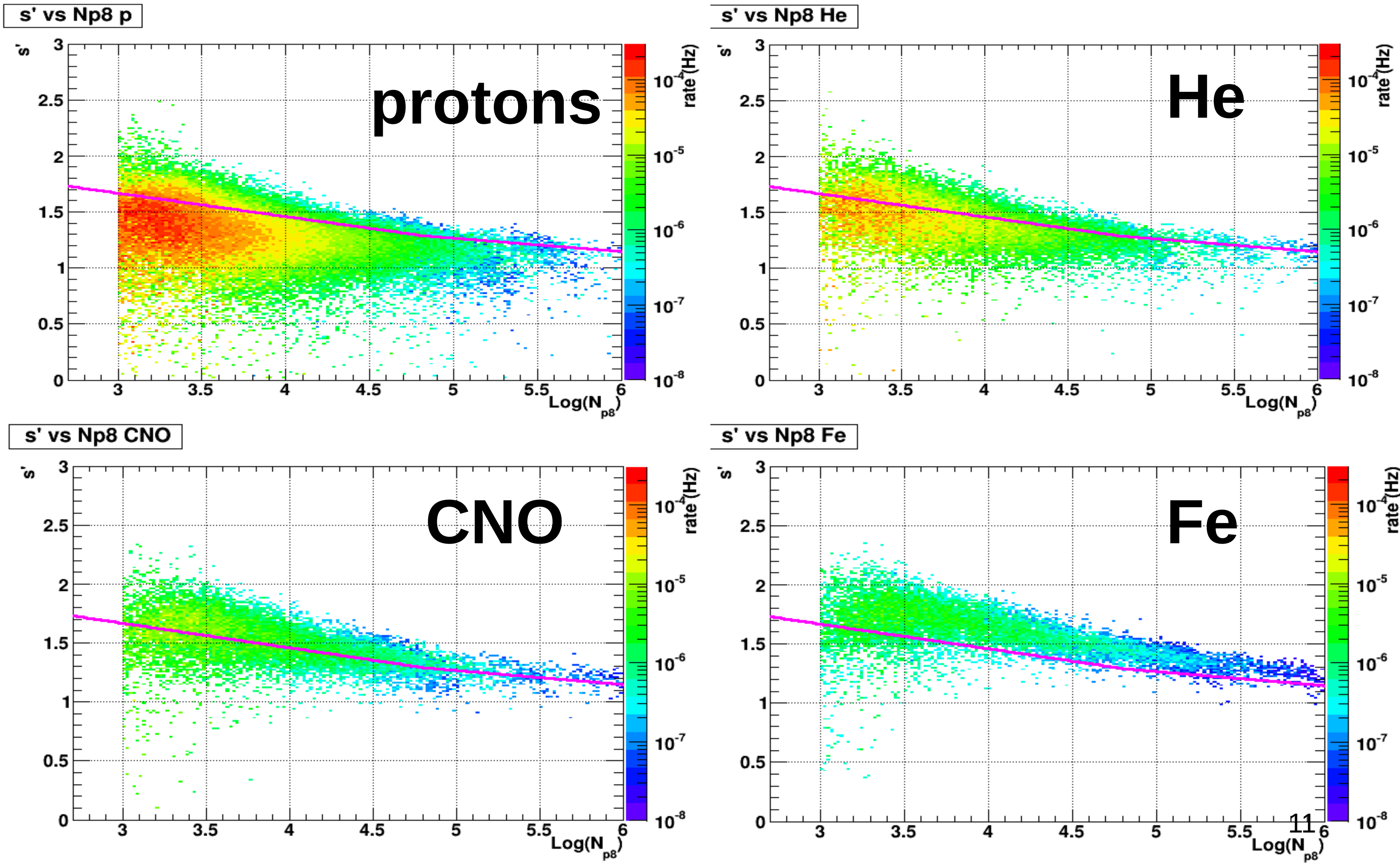
The LDF slope parameter s' is related to the shower age independently on the primary mass

s' values from event-by-event LDF fit in one of the N_{p8} bins, for p and Fe primaries and for experimental data.

→ Mass composition studies



Sensitivity to the primary mass (1)

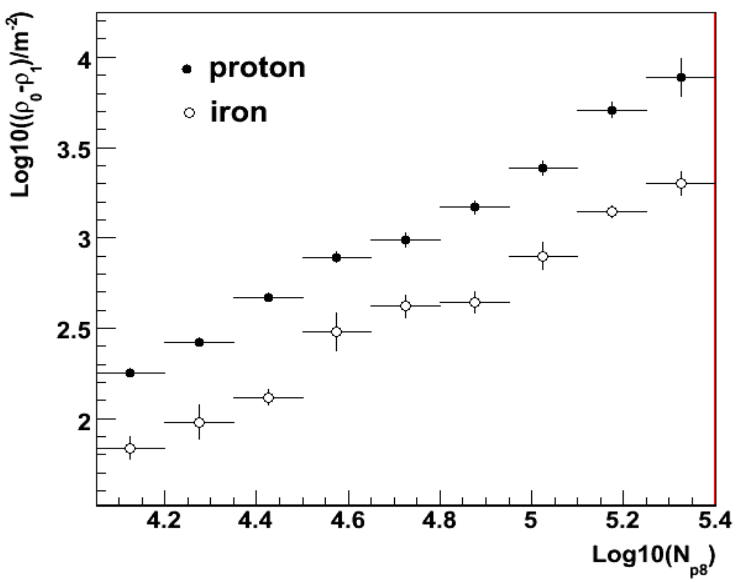


Sensitivity to the primary mass (2)

Slope of particle density distribution just near the core:

MC: (ρ_0-ρ_1) vs N_{p8}

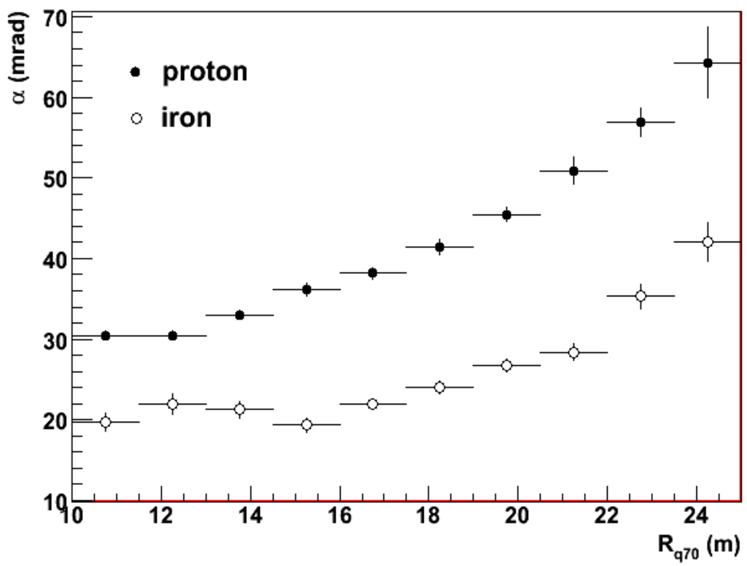
$\rho_0 = \rho_{part}$ on the core
$\rho_1 = \rho_{part}$ 1m from the core



Particle arrival time distribution inside the shower front:

MC: α (mrad) vs Rp_{70} (m)

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

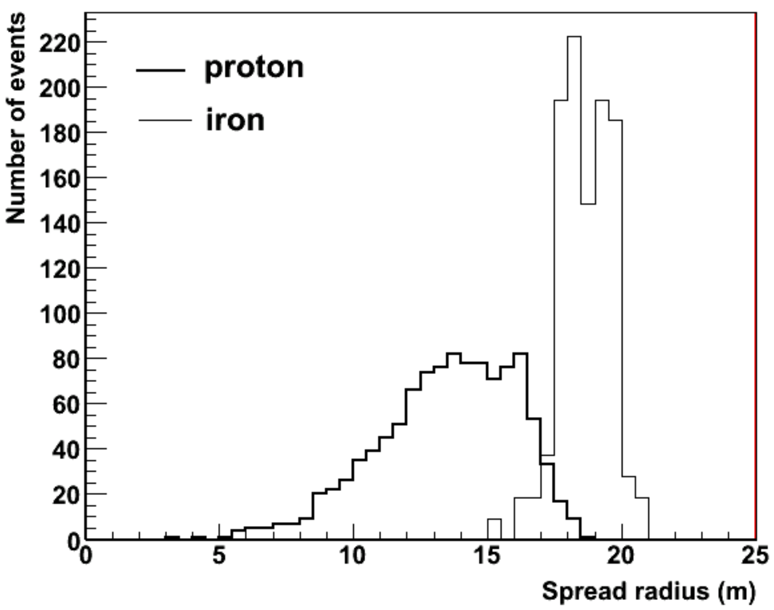


Sensitivity to the primary mass (3)

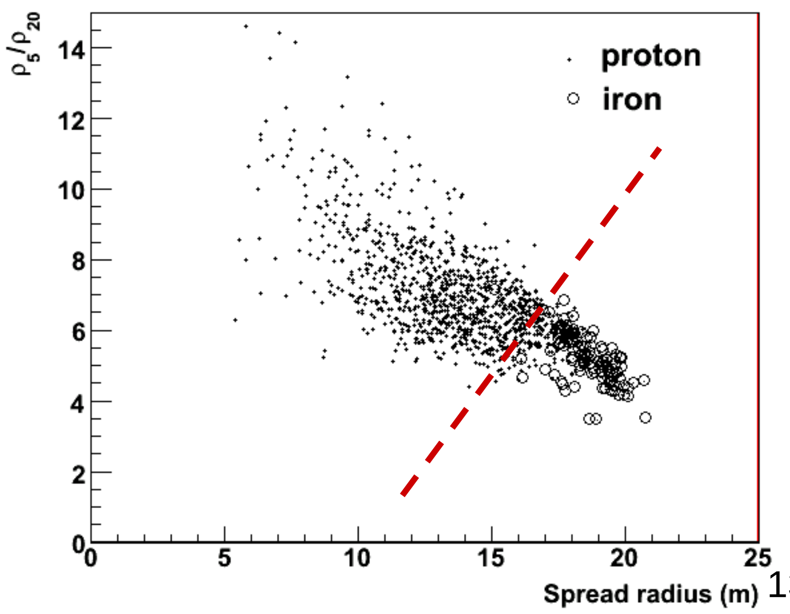
Useful observables:

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

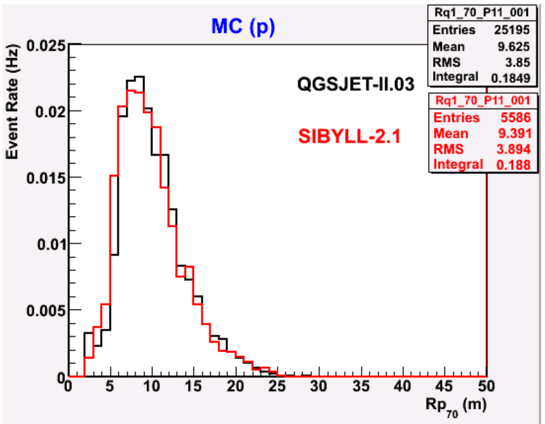
$$R_{spread} = \frac{\sum r_{BigPad_i - Core} \times N_{part_i}}{\sum N_{part_i}}$$

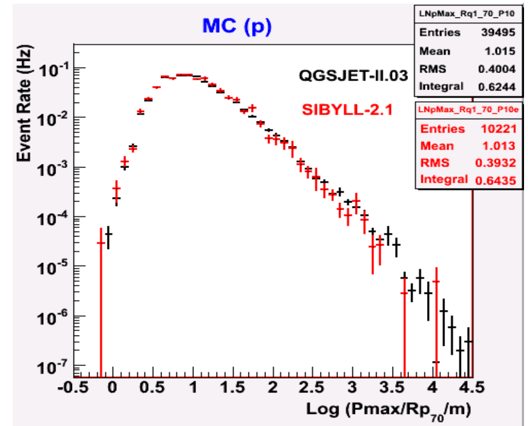


ρ_5/ρ_{20} vs R_{spread}



SIBYLL – QGSJET comparison (I)

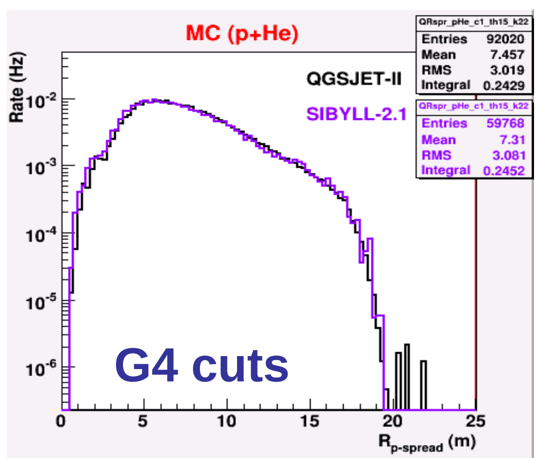


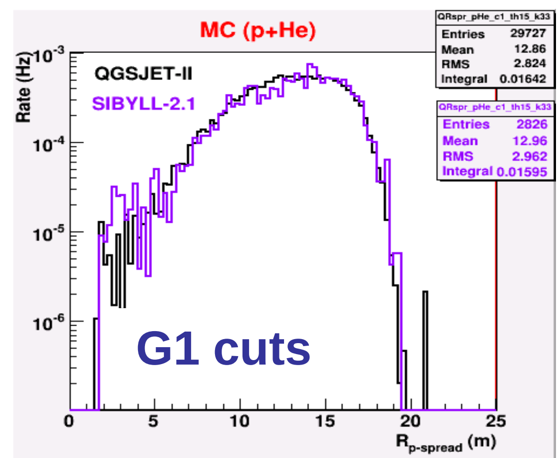


Rp_{70}: radius including 70% of particles

Nmax / Rp_{70} ratio (steepness)

Particle spread parameter



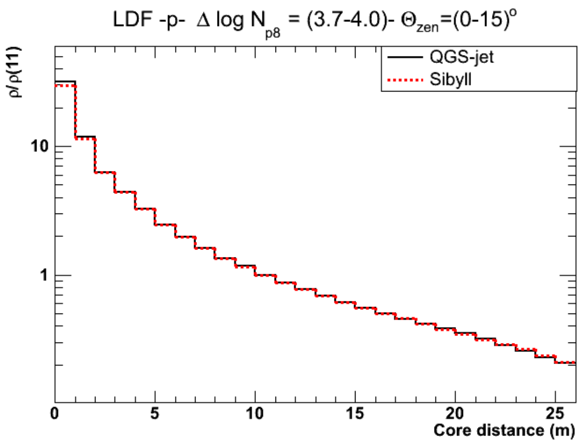


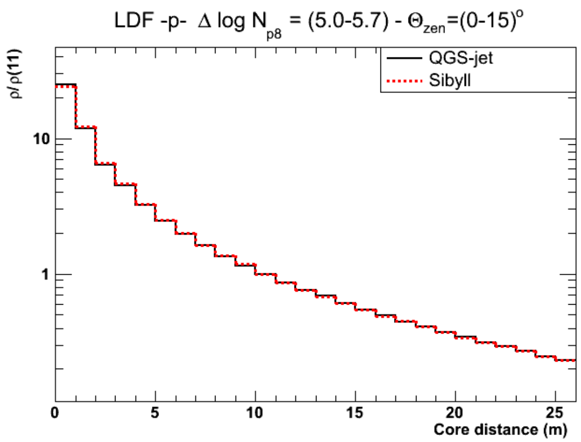
No relevant differences arise from the different hadronic models for such parameters (in the considered energy range)

SIBYLL – QGSJET comparison (II)

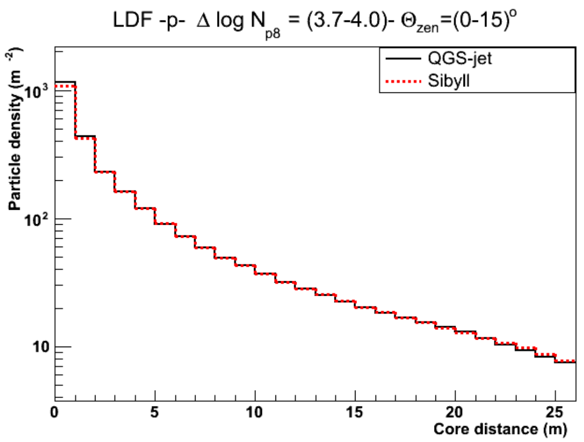
The differences of the two models LDFs are within few percent

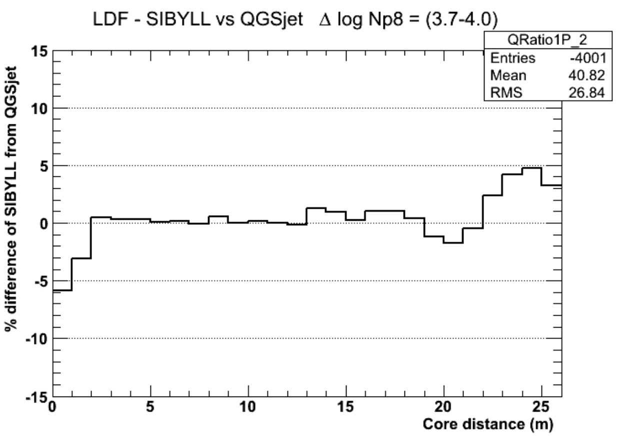
Shape comparison:





Absolute comparison:





Conclusions

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

This impies the capability of ARGO-YBJ to:

- **reliably estimate the primary energy**
- **exploit several shower features to discriminate primary masses**
- **estimate the shower age on the basis of the s' parameter value from the LDF fit**

(see contribution on "*CR spectrum measurement*", this Conference).

MORE STUFF

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)

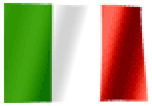
4300 m above the sea level
(606 g/cm^2 vertical depth)

High Altitude Cosmic Ray Observatory @ YangBaJing

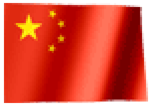
ARGO-YBJ collaboration

International Collaboration:

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

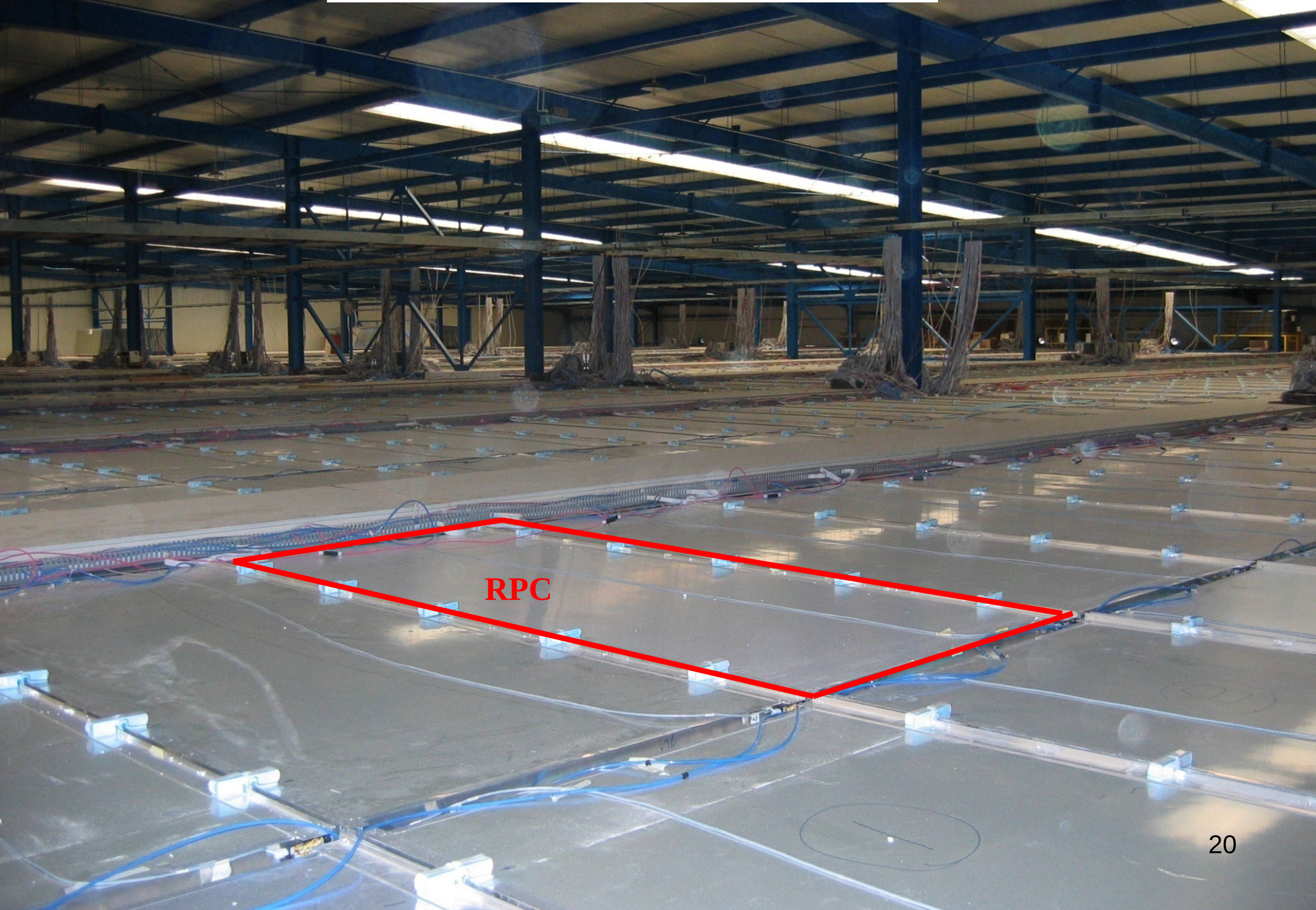


INFN and Dpt. di Fisica Università, Lecce
INFN and Dpt. di Fisica Universita', Napoli
INFN and Dpt. di Fisica Universita', Pavia
INFN and Dpt di Fisica Università "Roma Tre", Roma
INFN and Dpt. di Fisica Univesità "Tor Vergata", Roma
INAF/IFSI and INFN, Torino
INAF/IASF, Palermo and INFN, Catania

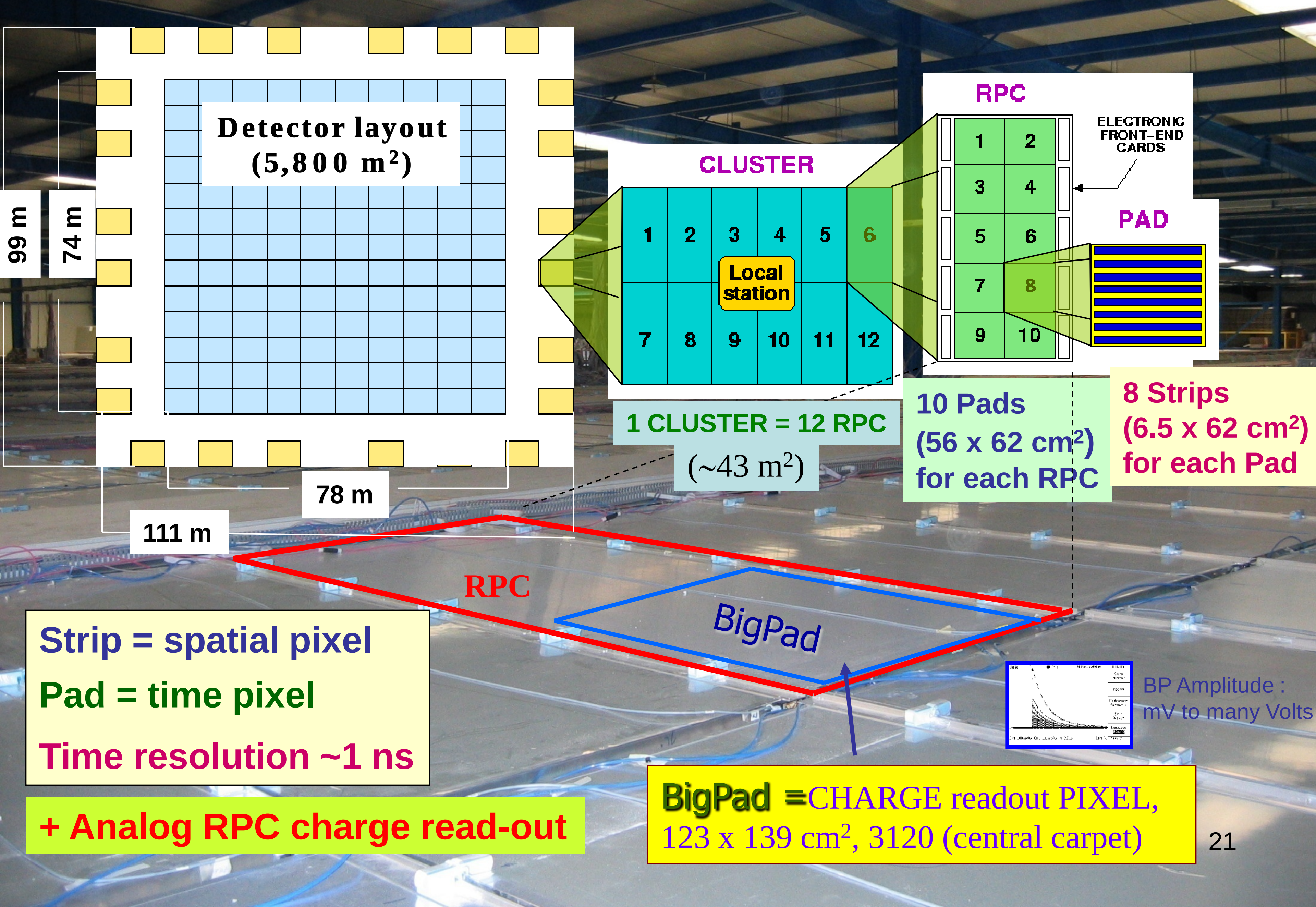


HeBei Normal Unversity, Shijiazhuang
IHEP, Beijing
Shandong University, Jinan
South West Jiaotong University, Chengdu
Tibet University, Lhasa
Yunnan University, Kunming

ARGO-YBJ detector



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)