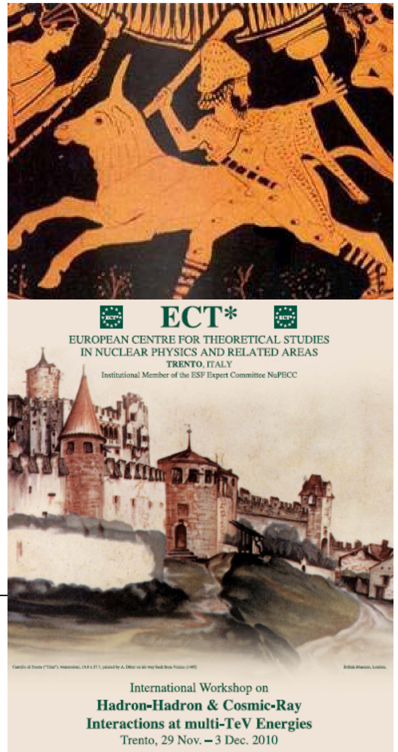
Hadronic Interaction Studies with ARGO-YBJ



Ivan De Mitri

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Istituto Nazionale di Fisica Nucleare
Lecce, Italy

On behalf of the ARGO-YBJ Collaboration

Hadron-Hadron & Cosmic Ray Interactions at multi-TeV Energies
ECT*, Trento, Nov 29-Dec 3, 2010

The ARGO-YBJ experiment

High Altitude Cosmic Ray Observatory @ YangBaJing,Tibet, China

Site Altitude: 4,300 m a.s.l. , ~ 600 g/cm^2

ARGO-YBJ physics goals

- **Cosmic ray physics**:
  spectrum and composition (E_{th} few TeV),
  <u>study of the shower space-time structure</u>,
  <u>p-Air cross section measurement and hadint studies</u>
  anti-p / p ratio at TeV energies,
  …..

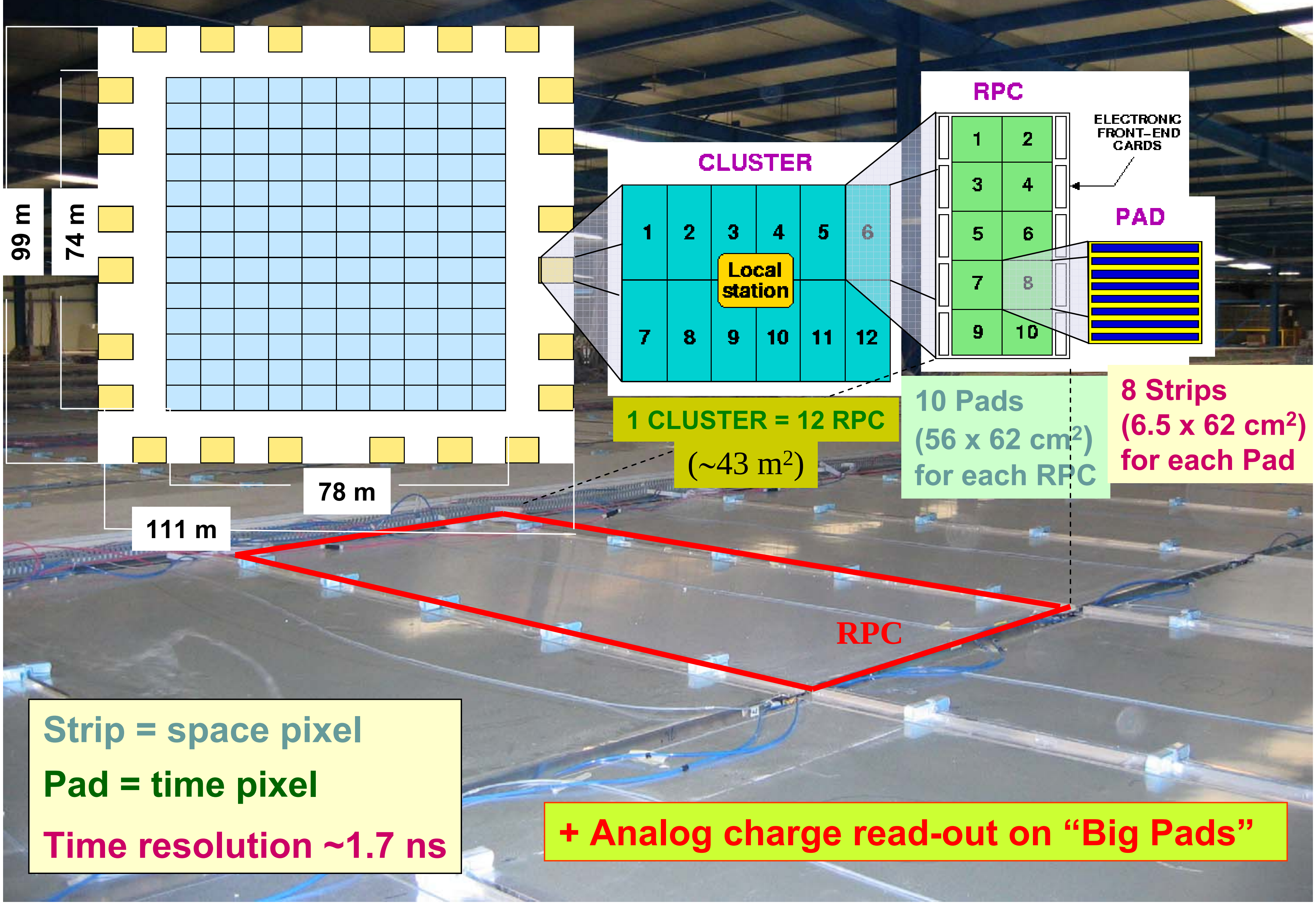
- **VHE γ-Ray Astronomy**:
  (search for)/(study of) point-like (and diffuse) galactic and extra-galactic sources at few hundreds GeV energy threshold

- **Search for GRB's** (full GeV / TeV energy range)
- …

through the…

Observation of *Extensive Air Showers* produced in the atmosphere by primary γ's and nuclei

The ARGO-YBJ detector



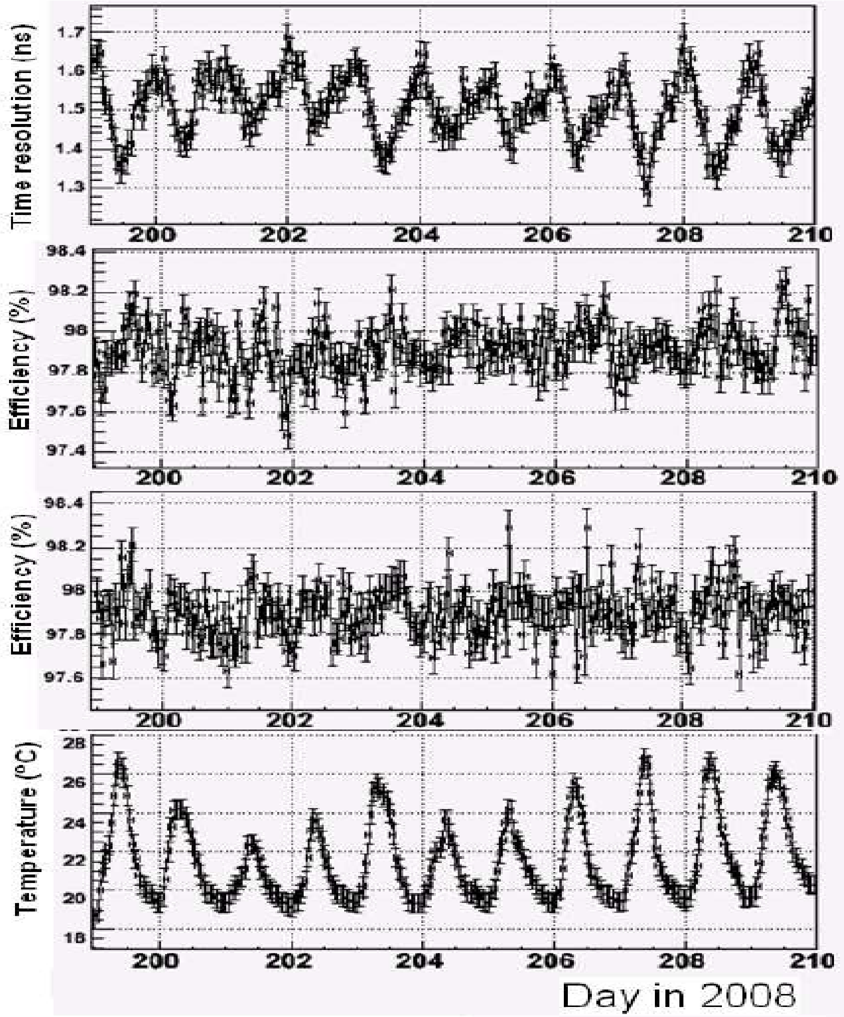
Strip = space pixel

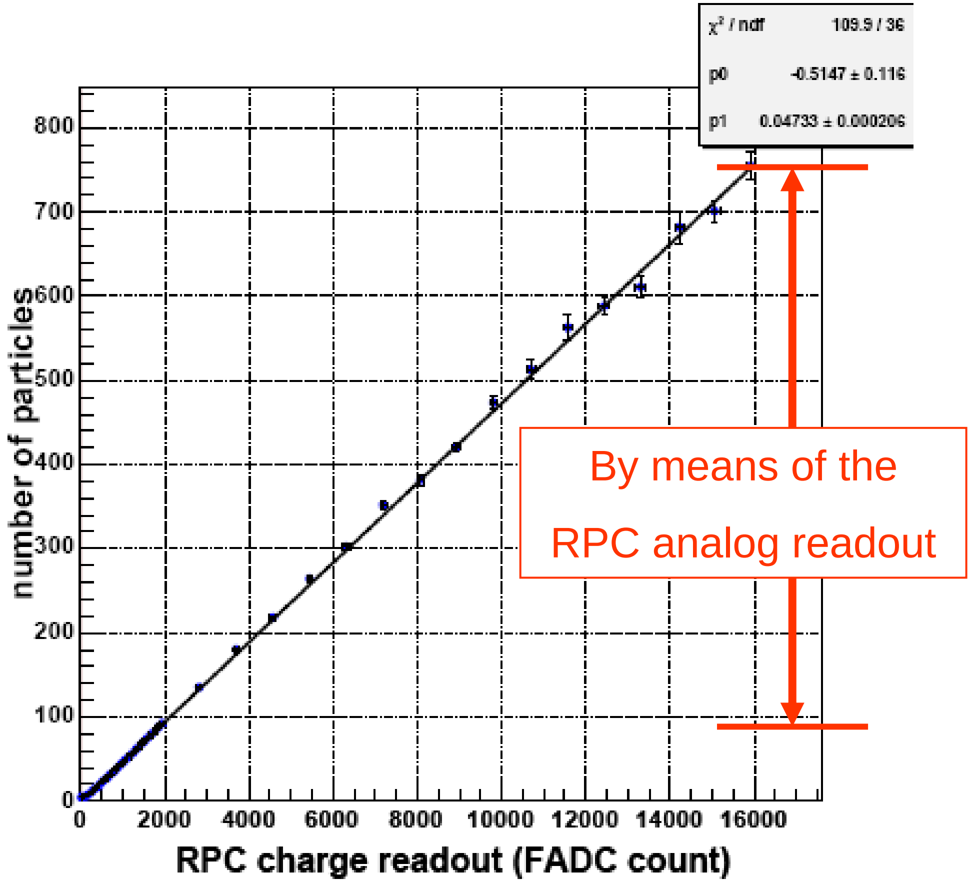
Pad = time pixel

Time resolution ~1.7 ns

+ Analog charge read-out on "Big Pads"

RPC performance and linearity range





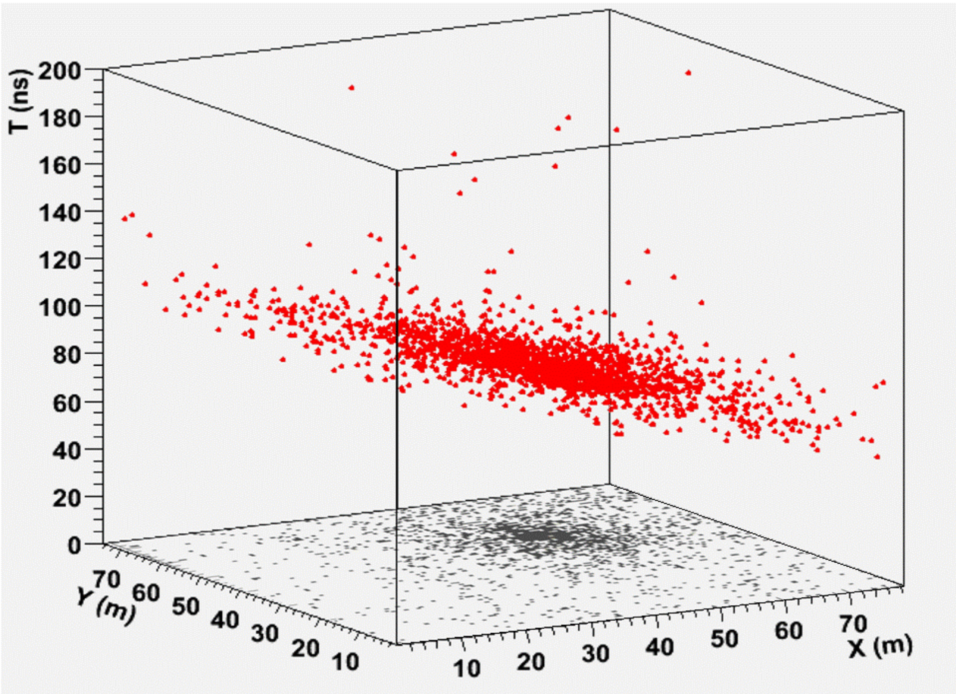
EAS reconstruction

Event Rate ~ 3.6 kHz for N_{hit} >20

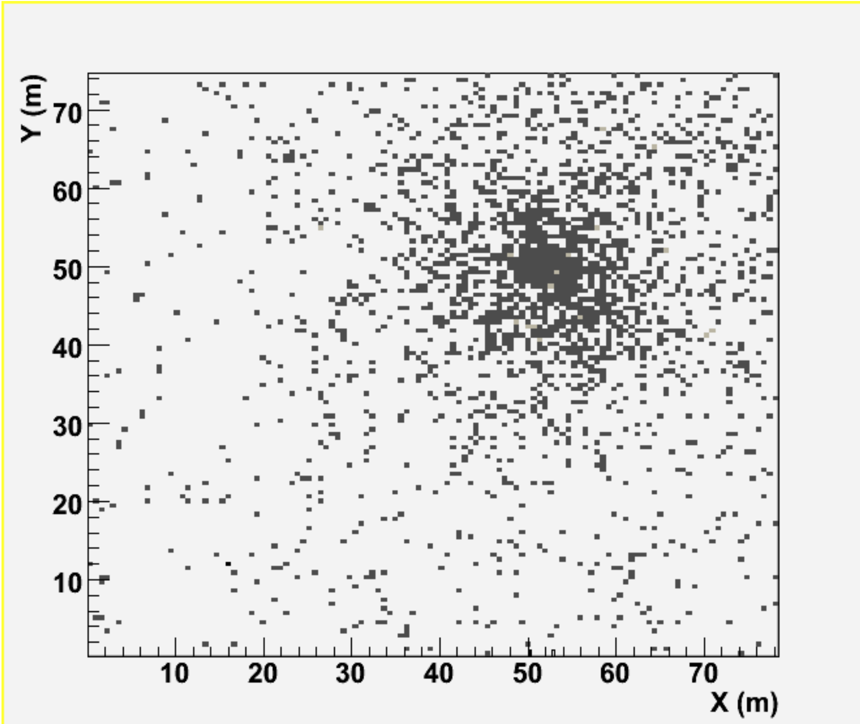
High space/time granularity
+ Full coverage
+ High altitude

➡

detailed study on the EAS space/time structure with unique capabilities

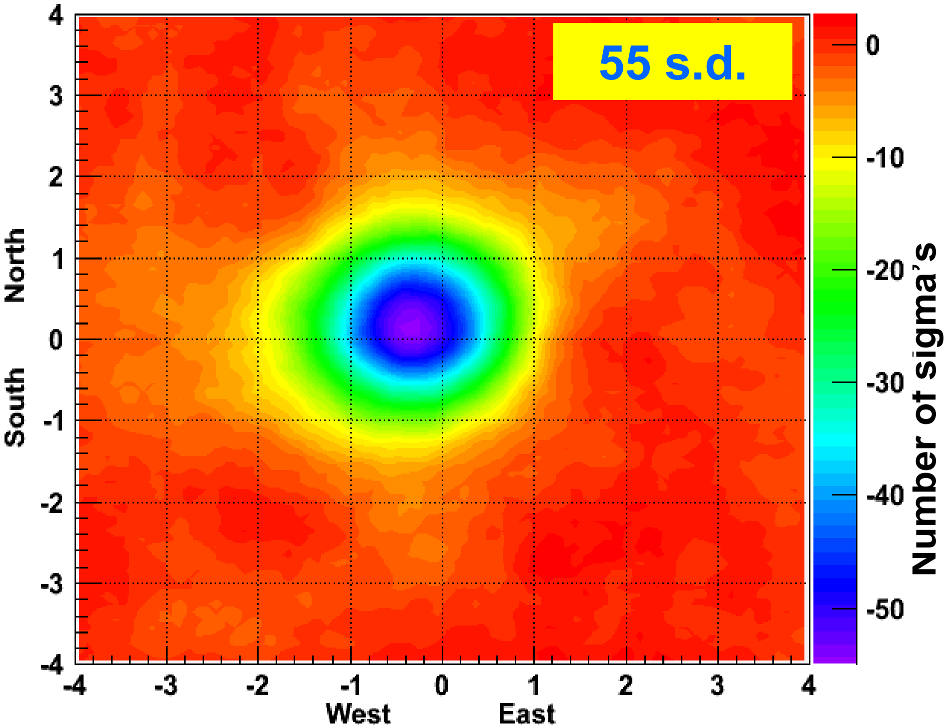


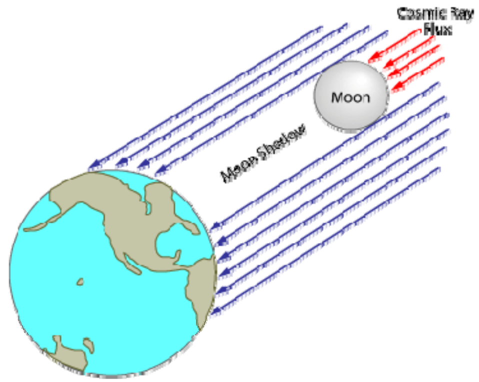
3-D view of a detected shower

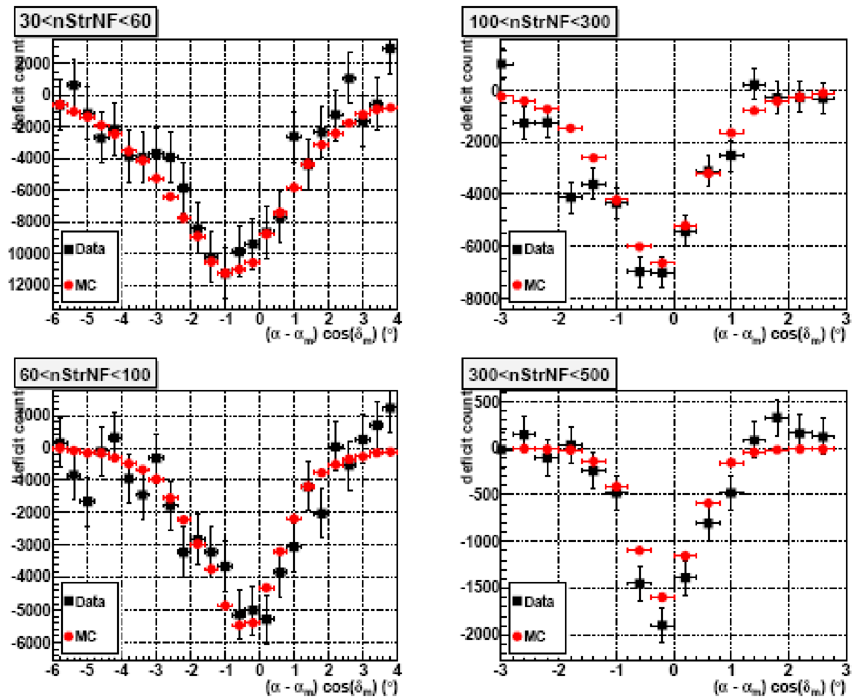


Top view of the same shower

The Moon Shadow







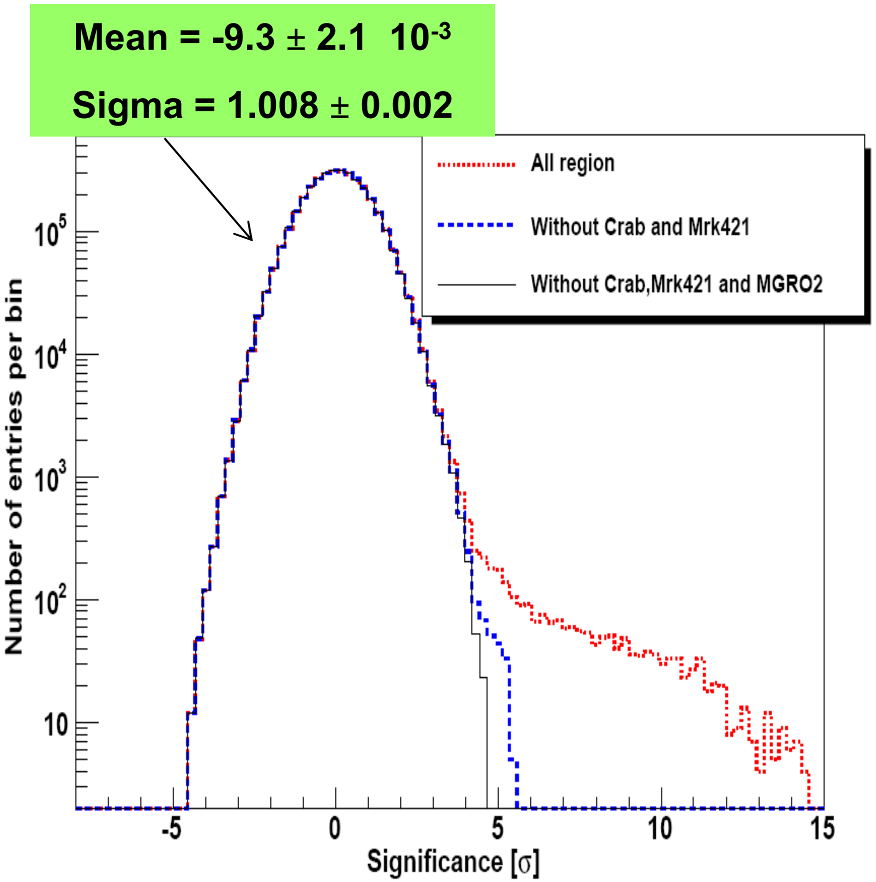
3200 hours on-source

- Size of the deficit ⇒ **angular resolution**
- Position ⇒ **pointing accuracy**
- West displacement ⇒ **Energy calibration** (Geomagnetic bending ≈ 1.57° / E (TeV))
- **Antiprotons** should give a shadow on the opposite side ⇒ Upper limit

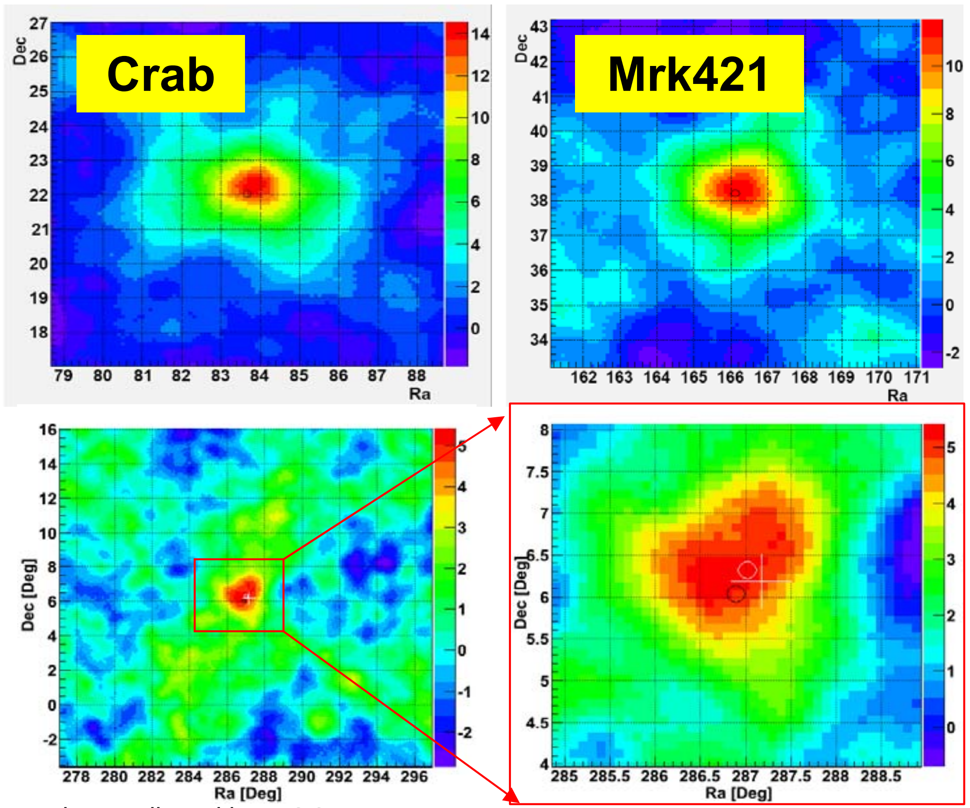
VHE gamma-ray astronomy

All sky survey in the 1 – 30 TeV energy band

- 3 sources with significance >5 σ in ~800 days (July 06 – Dec. 09)
- Crab 14 σ, Mrk421 12 σ, MGRO J1908+06 6 σ
- Interesting results on long term variabilities, correlation with Xrays, spectra,….

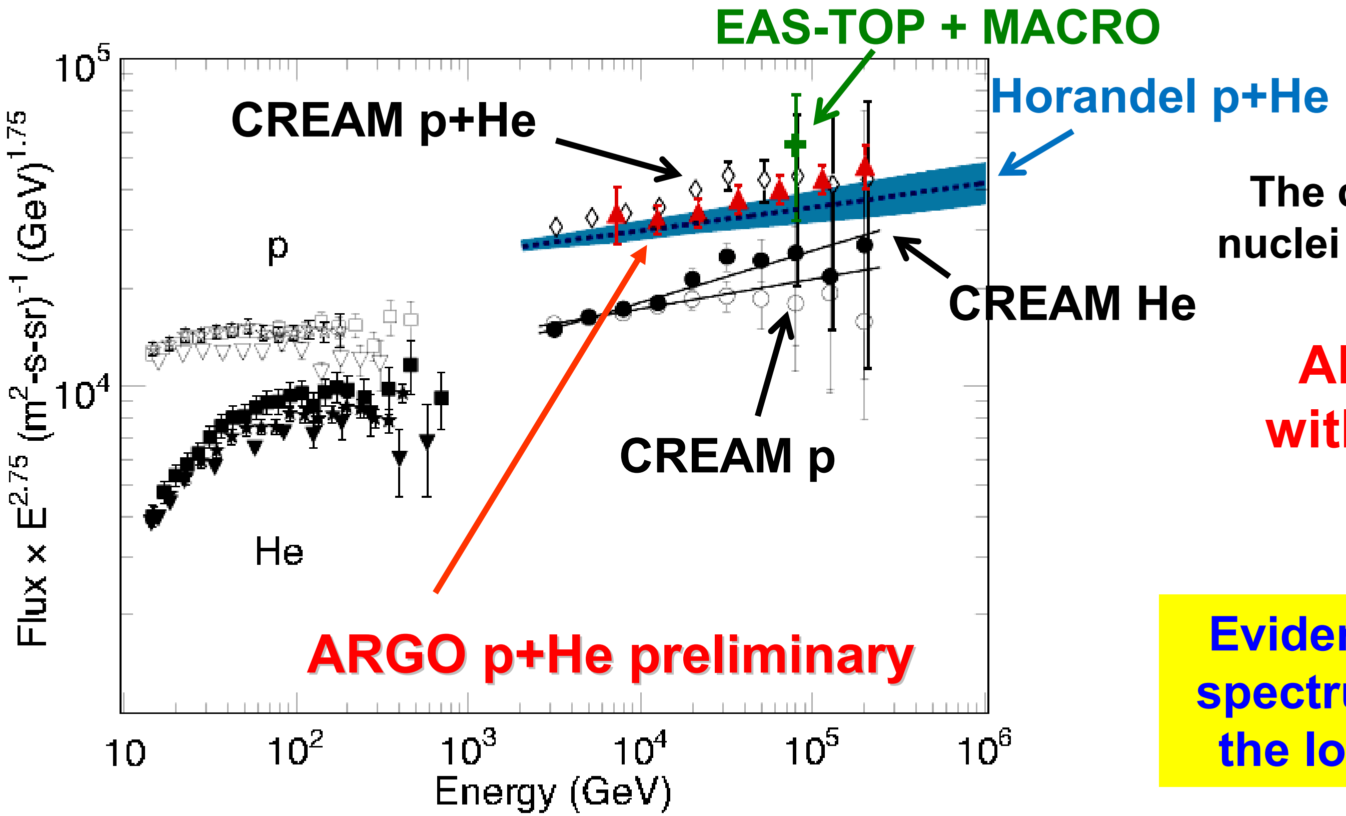


Evidence for a signal at ≈4 s.d. from the MGRO J2031+41 region.



Light-component spectrum of CRs

Measurement of the *light-component* (p+He) spectrum of primary CRs in the energy region (5 – 250) TeV via a Bayesian unfolding procedure.



The contribution of heavier nuclei to the trigger is a few %

ARGO data agree with CREAM results

Evidence that the proton spectrum is flatter than in the lower energy region

For the first time direct and ground-based measurements overlap for a wide energy range thus making possible the cross-calibration of the experiments.

Proton-air cross section measurement

Use the shower frequency vs (secθ -1)

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

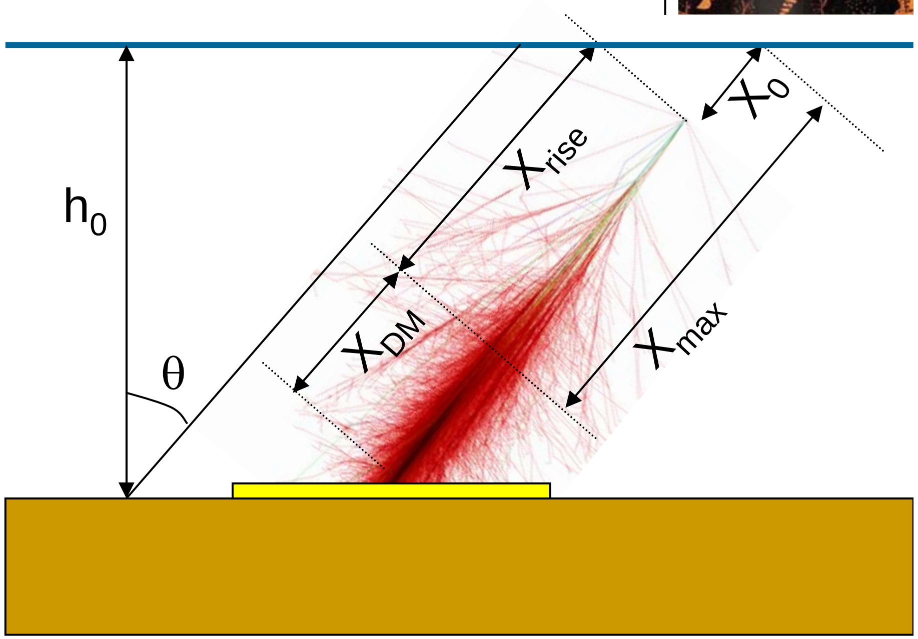
for fixed energy and shower age.

The lenght Λ is not the p interaction lenght mainly because of collision inelasticity, shower fluctuations and detector resolution.

It has been shown that **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)**

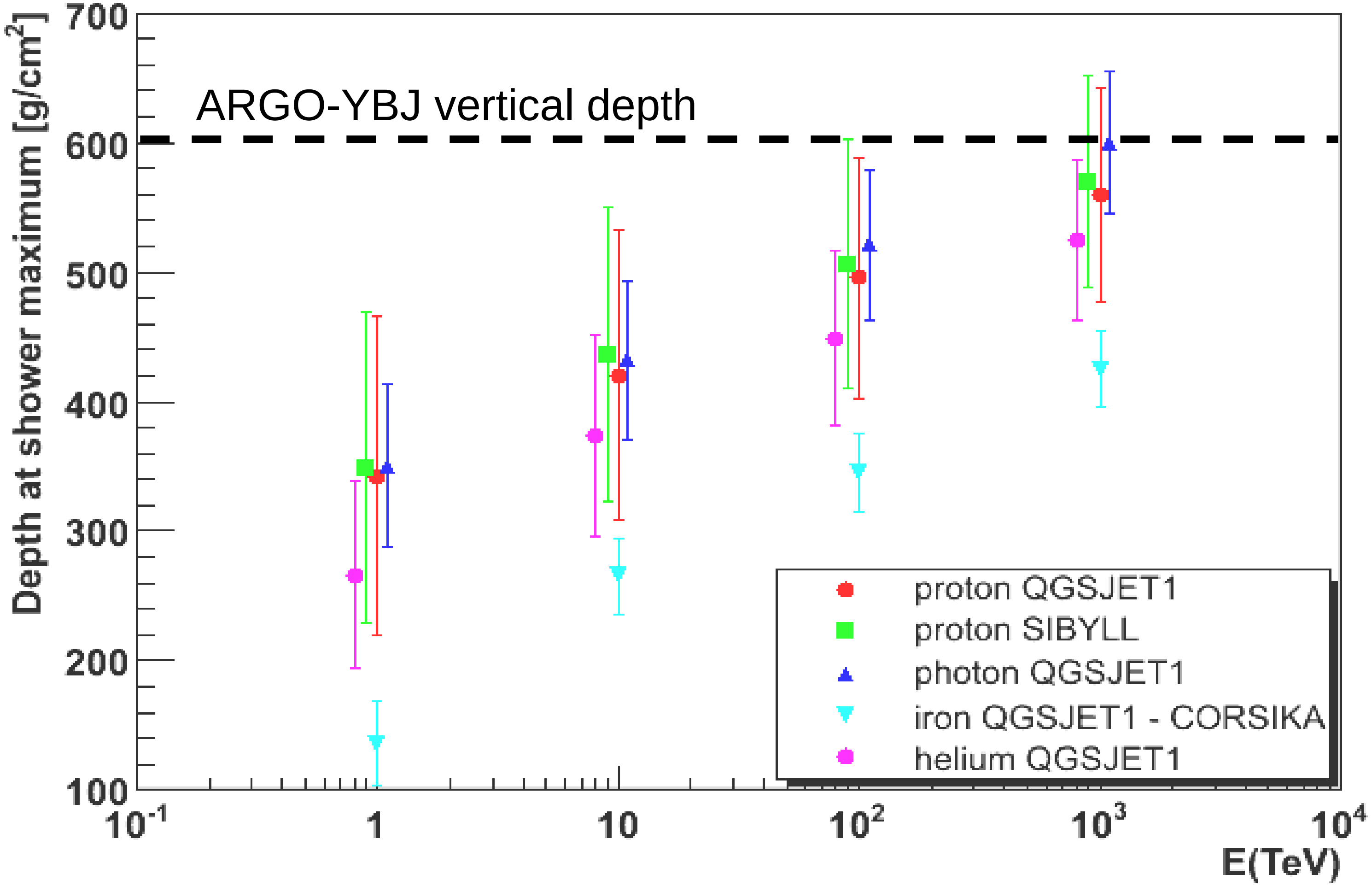


Take care of shower fluctuations

- **Constrain** $X_{DO} = X_{det} - X_0$ or

  $X_{DM} = X_{det} - X_{max}$
- **Select** deep showers (large X_{max}, i.e. small X_{DM})
- **Exploit** detector features (space-time pattern) and location (depth).

The position of the shower maximum (and its rms)



Data selection

- **Event selection based on:**

  (a) **"shower size" on detector, N_{strip} (strip multiplicity)**

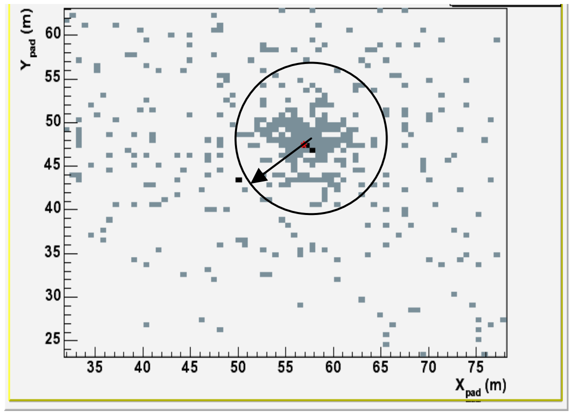
  (b) **core reconstructed in a fiducial area (64 x 64 m^2)**

  (c) **constraints on Strip density (> 0.2/m^2** within R_{70} **)**

  and shower extension (R_{70} < 30m)

N_{strip} is used to get different E sub-samples

R_{70}: radius of circle including 70% of hits

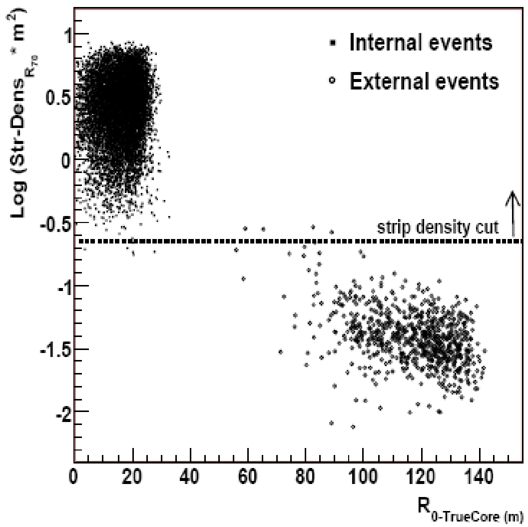


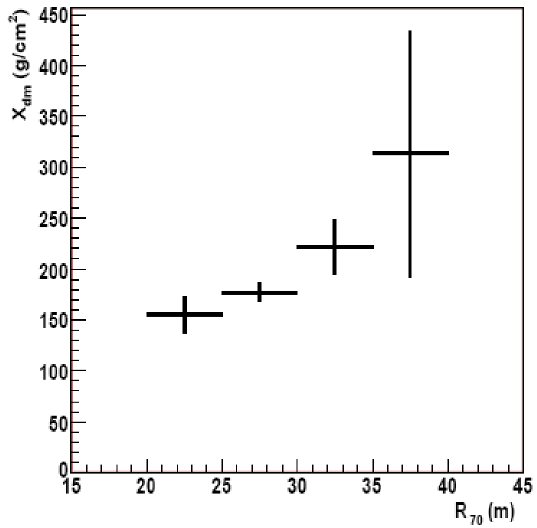
Full Monte Carlo simulation:

Corsika showers

QGSJET-I and **QGSJET-II**, **SYBILL** int. models

GEANT detector simulation

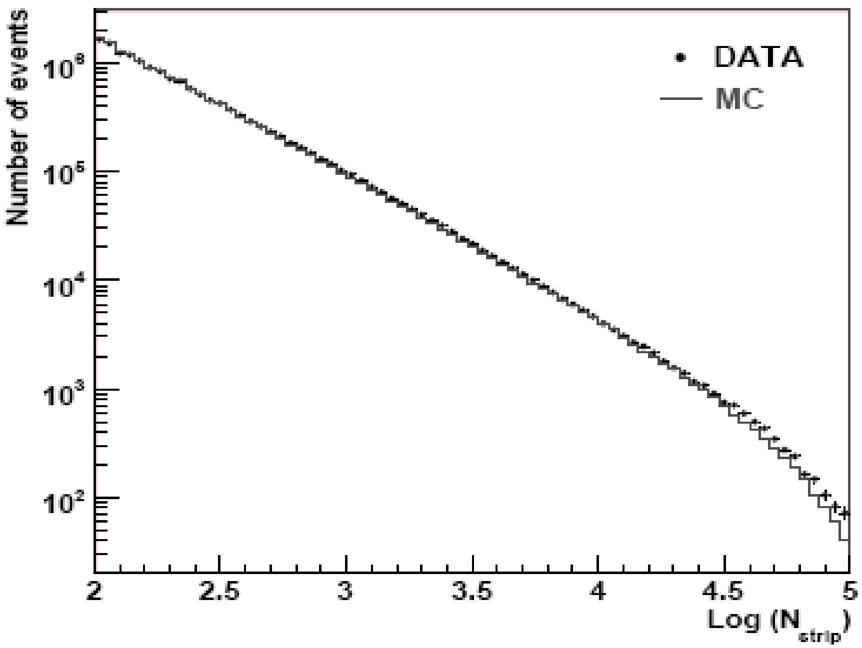


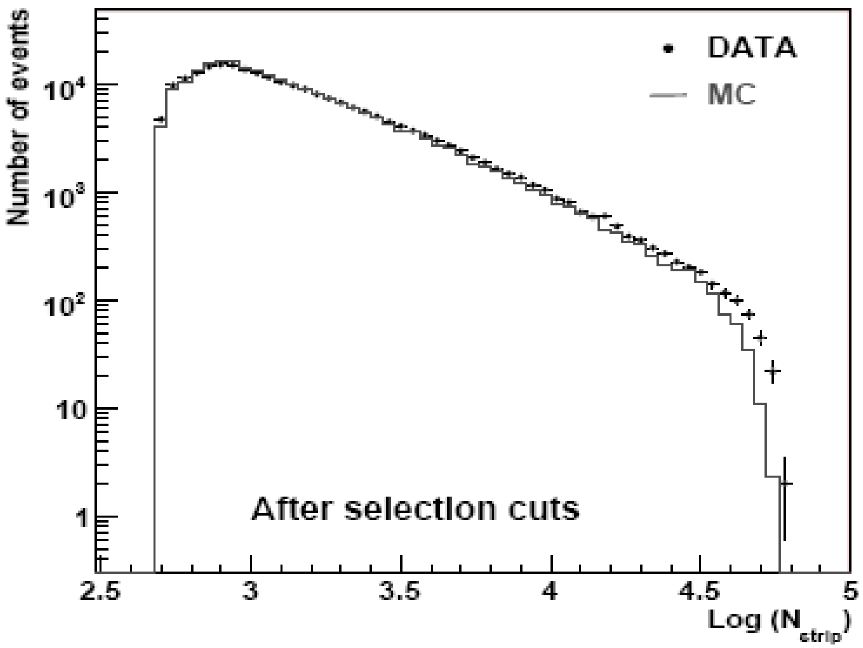


MC vs DATA

The distribution of the observable quantities **before and after the analysis cuts** are in **good agreement** with the MC data

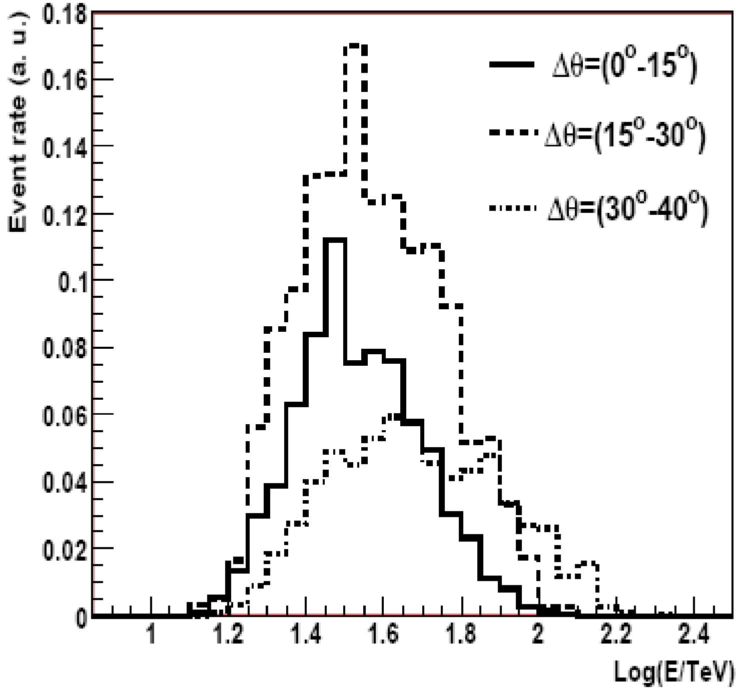
The **fraction of events** passing the analysis cut is consistent (at each step) with the correponding MC estimate



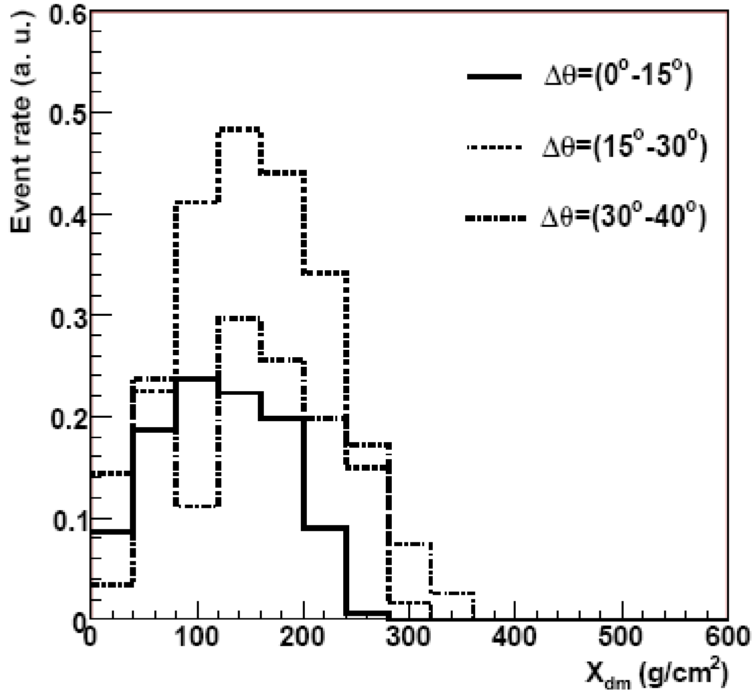


Cuts in-dependence on the zenith angle

Energy



$X_{det} – X_{max}$

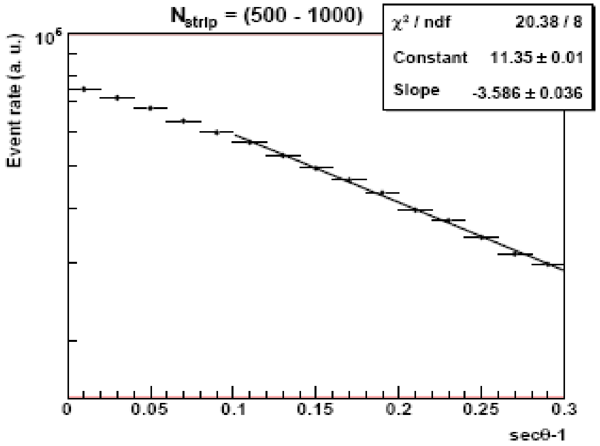


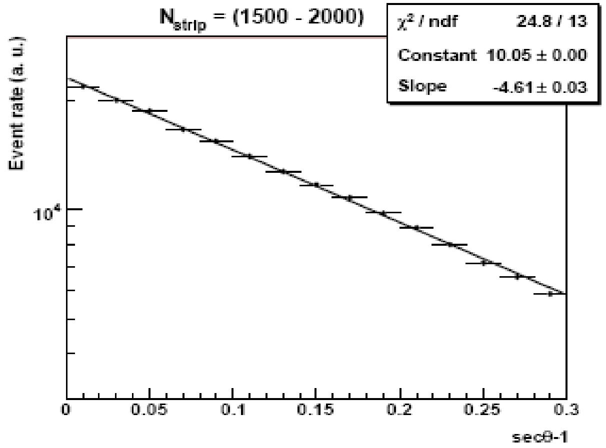
No significant zenith angle dependence below 30 degrees.

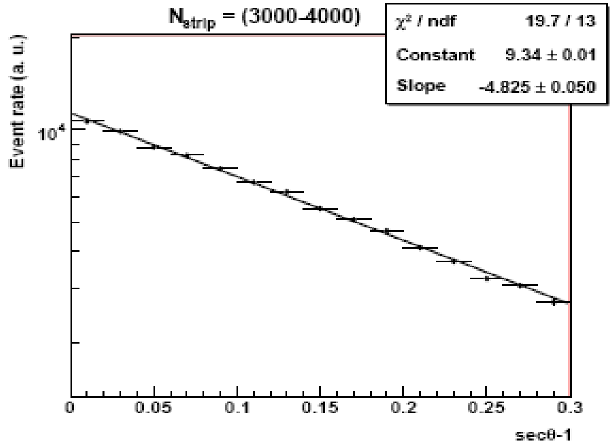
A slight shift might be seen above 40 degrees.

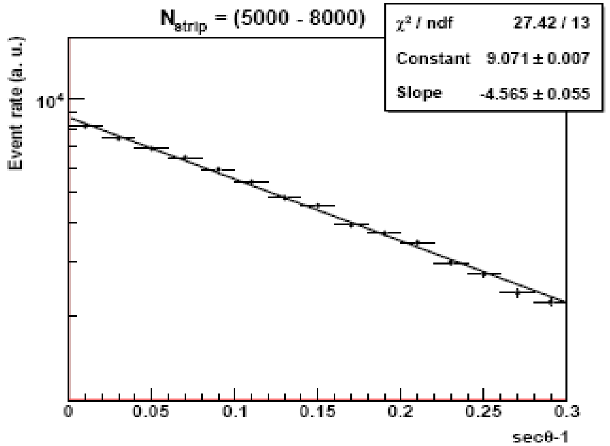
In this analysis we stop at 40 degrees

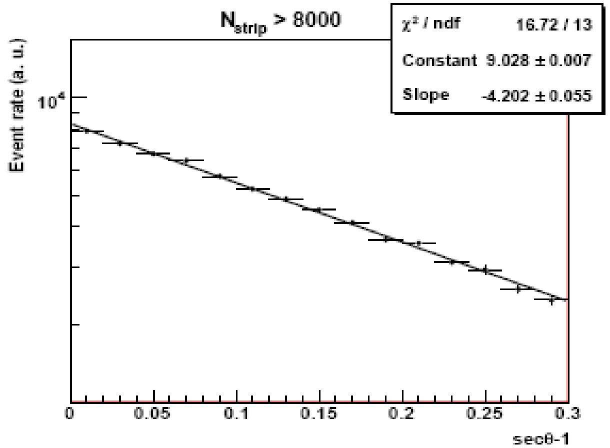
Experimental data











Clear exponential behaviour

Full consistency with MC simulation at each selection step

Weather effects, namely the atmospheric pressure dependence on time, have been shown to be at the level of 1 %

h_0^{MC} = 606.7 g/cm² (4300m a.s.l. standard atm.)

$h_0^{MC} / h_0 = 0.988 \pm 0.007$

Heavy primaries contribution

Hoerandel AP 19 (2003) 193 taken as reference.

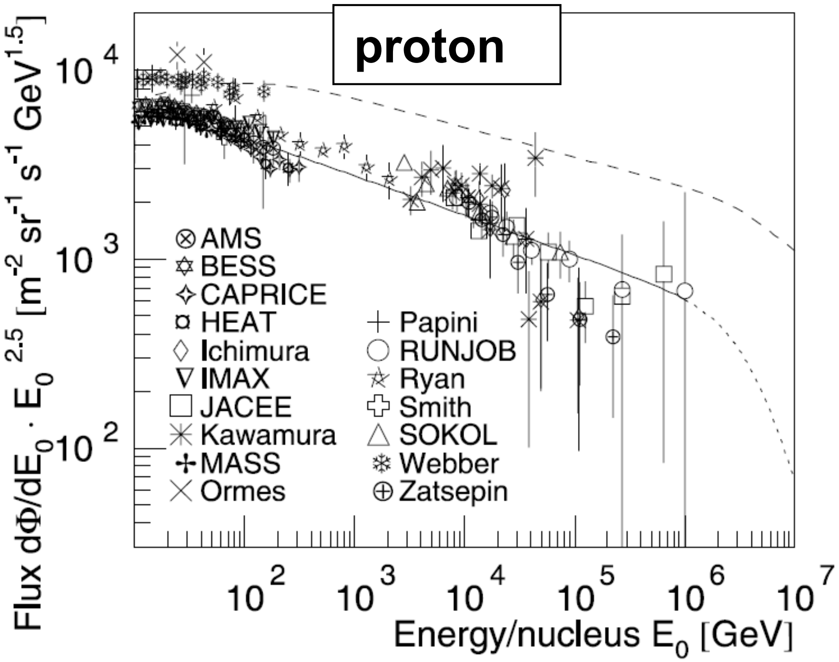
JACEE and RUNJOB for the evaluation of systematic error

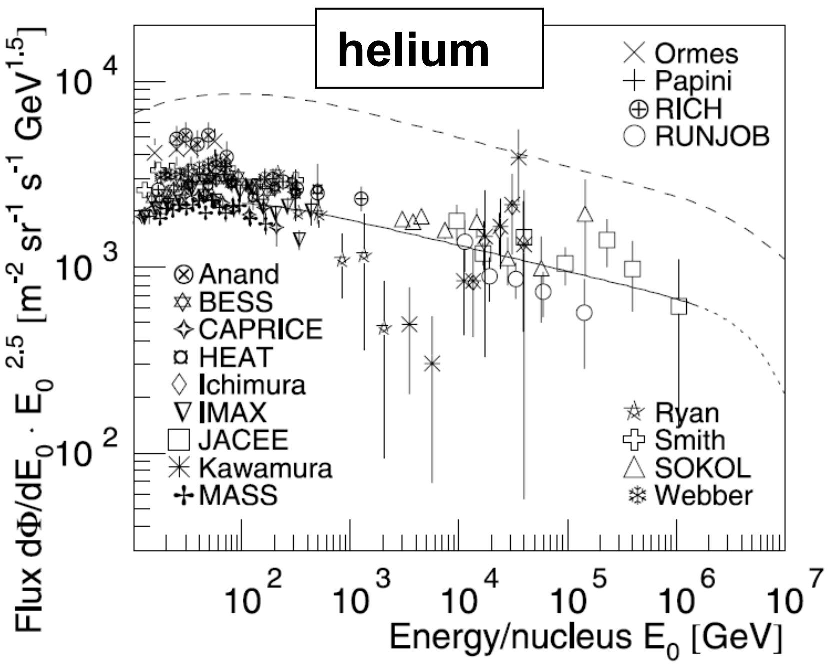
$$\frac{dN}{dE} = \Phi(E) = \Phi_Z^0 \cdot \left(\frac{E}{TeV}\right)^{-\gamma_Z}$$

198 *J.R. Hörandel / Astroparticle Physics 19 (2003) 193–220*

Table 1
Absolute flux Φ_Z^0 ((m^2 sr s TeV)$^{-1}$) at $E_0 = 1$ TeV/nucleus and spectral index γ_Z of cosmic-ray elements

Z		Φ_Z^0	$-\gamma_Z$	Z		Φ_Z^0
1[a]	H	8.73×10^{-2}	2.71	47[c]	Ag	4.54
2[a]	He	5.71×10^{-2}	2.64	48[c]	Cd	6.30
3[b]	Li	2.08×10^{-3}	2.54	49[c]	In	1.61
4[b]	Be	4.74×10^{-4}	2.75	50[c]	Sn	7.15
5[b]	B	8.95×10^{-4}	2.95	51[c]	Sb	2.03
6[b]	C	1.06×10^{-2}	2.66	52[c]	Te	9.10
7[b]	N	2.35×10^{-3}	2.72	53[c]	I	1.34
8[b]	O	1.57×10^{-2}	2.68	54[c]	Xe	5.74
9[b]	F	3.28×10^{-4}	2.69	55[c]	Cs	2.79
10[b]	Ne	4.60×10^{-3}	2.64	56[c]	Ba	1.23





QGSJET-I

QGSJET-II.03

SIBYLL 2.1

The spread among the models has been used in order to have a conservative estimate of the associated systematic uncertainties

ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS TRENTO, ITALY

$k = k_0$(inelasticity,CR spectrum, …)$\times k_{det}$ (det. Features,, analysis, …)

ΔN_{strip}	$\mathrm{Log}(E/\mathrm{eV})$	$k_{QGSJET-I}$	$k_{QGSJET-II.03}$	$k_{SIBYLL-2.1}$	k
$500 \div 1000$	12.6 ± 0.3	$1.98 \pm 0.06 \pm 0.05$	$1.84 \pm 0.14 \pm 0.05$	$1.87 \pm 0.08 \pm 0.04$	$1.93 \pm 0.05 \pm 0.06$
$1500 \div 2000$	13.0 ± 0.2	$1.59 \pm 0.03 \pm 0.04$	$1.75 \pm 0.12 \pm 0.04$	$1.76 \pm 0.06 \pm 0.04$	$1.63 \pm 0.03 \pm 0.08$
$3000 \div 4000$	13.3 ± 0.2	$1.69 \pm 0.05 \pm 0.03$	$1.63 \pm 0.13 \pm 0.03$	$1.72 \pm 0.05 \pm 0.03$	$1.70 \pm 0.03 \pm 0.04$
$5000 \div 8000$	13.6 ± 0.2	$1.74 \pm 0.05 \pm 0.03$	$1.97 \pm 0.17 \pm 0.04$	$1.91 \pm 0.05 \pm 0.03$	$1.84 \pm 0.03 \pm 0.10$
> 8000	13.9 ± 0.3	$2.04 \pm 0.06 \pm 0.05$	$2.23 \pm 0.19 \pm 0.05$	$2.01 \pm 0.05 \pm 0.05$	$2.03 \pm 0.04 \pm 0.10$

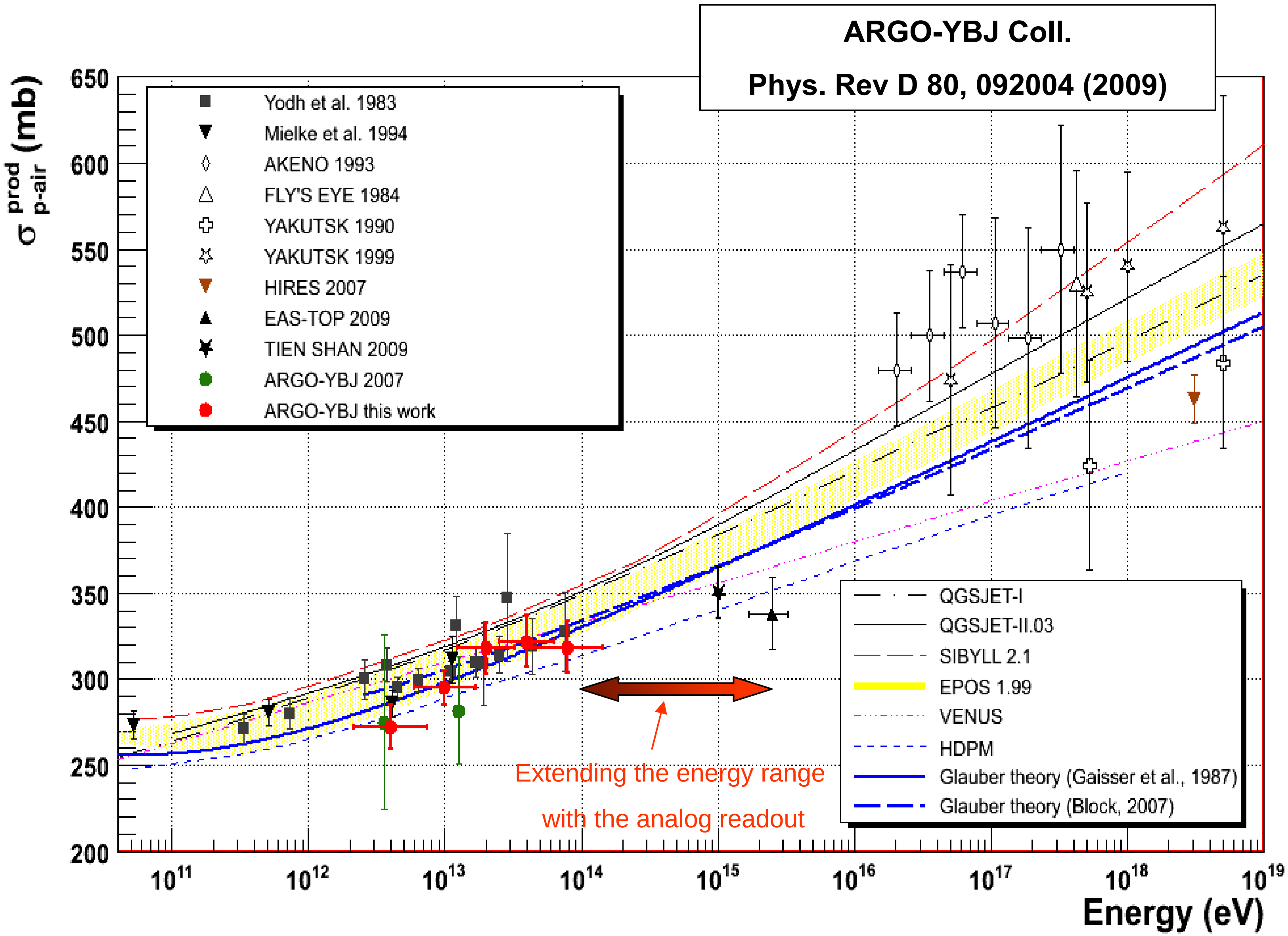
Correction factor for heavier primaries

Glauber theory applied

(model differences contribute in the sys error)

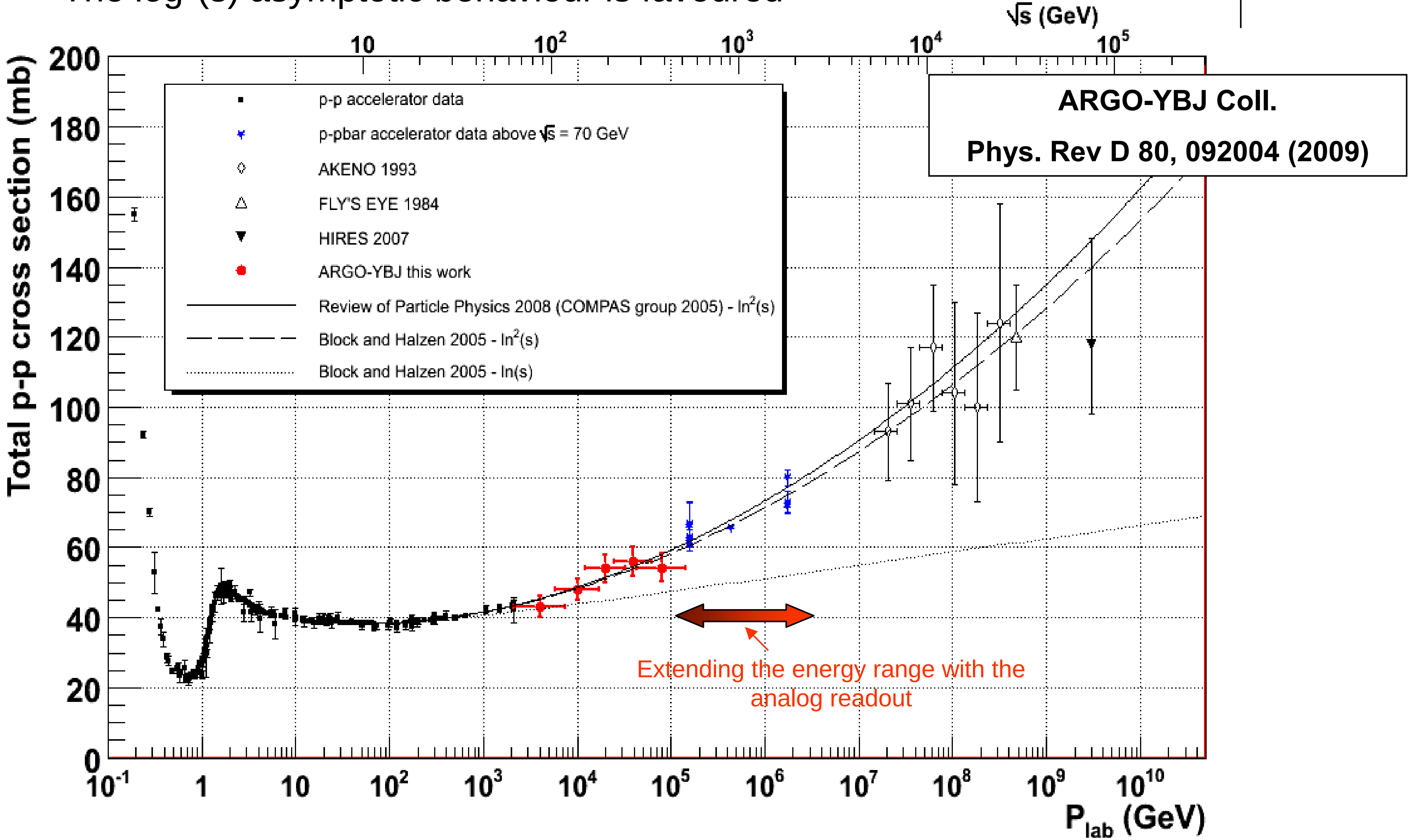
ΔN_{strip}	η	σ_{p-air} (mb)	σ_{p-p} (mb)
$500 \div 1000$	$1.00 \pm 0.04 \pm 0.01$	$272 \pm 13 \pm 9$	$43 \pm 3 \pm 5$
$1500 \div 2000$	$1.00 \pm 0.03 \pm 0.01$	$295 \pm 10 \pm 14$	$48 \pm 3 \pm 6$
$3000 \div 4000$	$0.99 \pm 0.04 \pm 0.01$	$318 \pm 15 \pm 8$	$54 \pm 4 \pm 6$
$5000 \div 8000$	$0.98 \pm 0.04 \pm 0.03$	$322 \pm 15 \pm 20$	$56 \pm 4 \pm 7$
> 8000	$0.95 \pm 0.04 \pm 0.04$	$318 \pm 15 \pm 21$	$54 \pm 4 \pm 8$

The proton-air cross section



The total p-p cross section

- No p-p (and pbar-p) accelerator data available at these energies
- The $\log^2(s)$ asymptotic behaviour is favoured



Physics History Corner

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY

Zeitschrift für Physik, Bd. 133, S. 65—79 (1952).

Mesonenerzeugung als Stoßwellenproblem.

Von
W. HEISENBERG.

Mit 6 Figuren im Text.

(Eingegangen am 5. Mai 1952.)

Die Erzeugung vieler Mesonen beim Zusammenstoß zweier Nukleonen wird als ein Stoßwellenvorgang beschrieben, der von einer nichtlinearen Wellengleichung dargestellt wird. Die quantentheoretischen Züge des Vorgangs können dabei näherungsweise nach dem Korrespondenzprinzip berücksichtigt werden, da es sich um einen „Vorgang hoher Quantenzahl" handelt. Aus der Diskussion der Lösungen der nichtlinearen Wellengleichung ergeben sich Aussagen über die Energie- und Winkelverteilung der verschiedenen Mesonensorten.

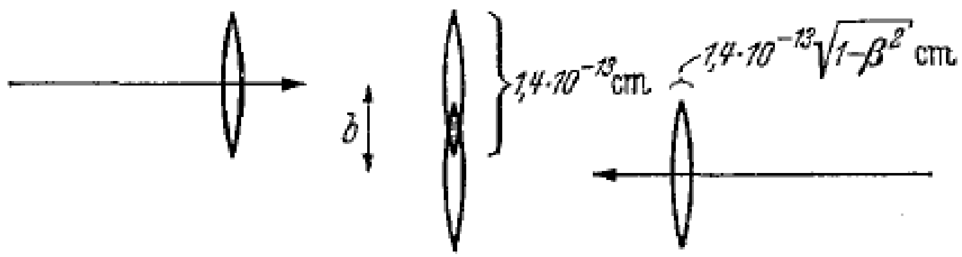


Fig. 1.

$$\sigma = \frac{\pi}{\varkappa^2} \lg^2 \gamma_{\min}$$

The reaction can occur only if the energy density in the overlap region is high enough to produce at least a pion pair

Then

$$\sigma \rightarrow k \cdot \ln^2(s)$$

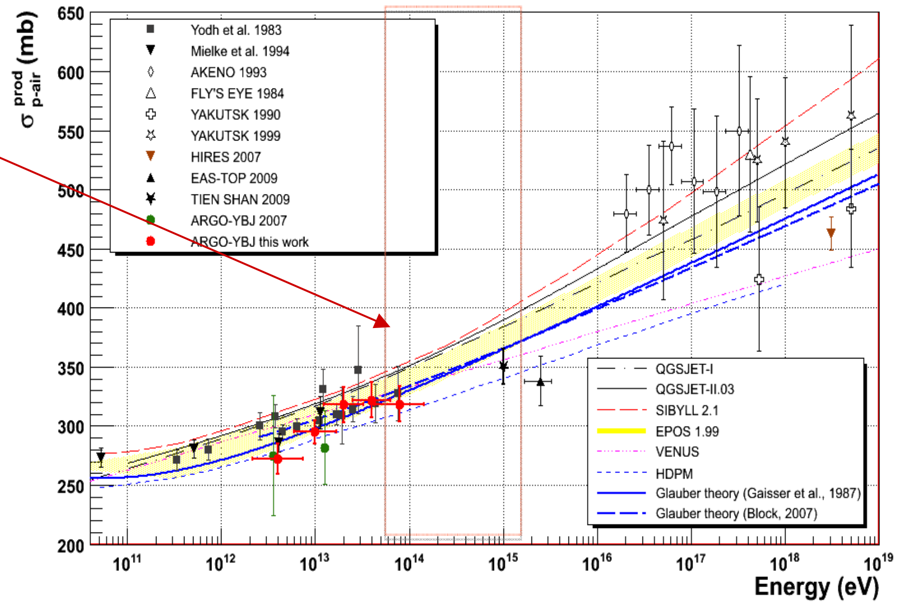
As

$$s \rightarrow \infty$$

Next steps in the cross section analysis

- **Use the analog RPC charge readout to extend the Energy range**

- **Better estimate of systematics**



Improvements are expected from:

(a) More detailed informations on the shower time structure, longitudinal development and lateral density profile (LDF)

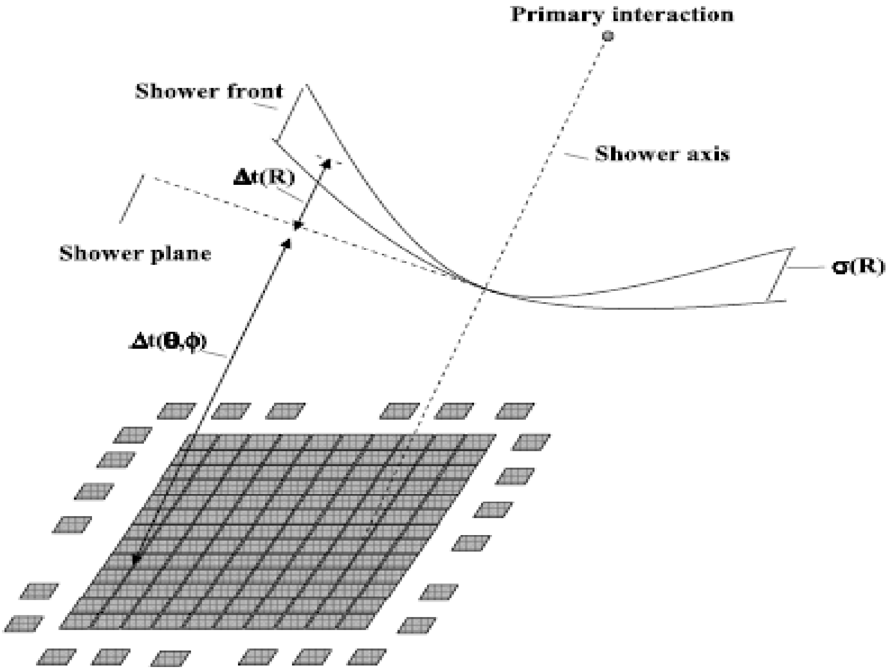
(b) Better constraints on shower Xmax ($\rightarrow$ lower systematics)

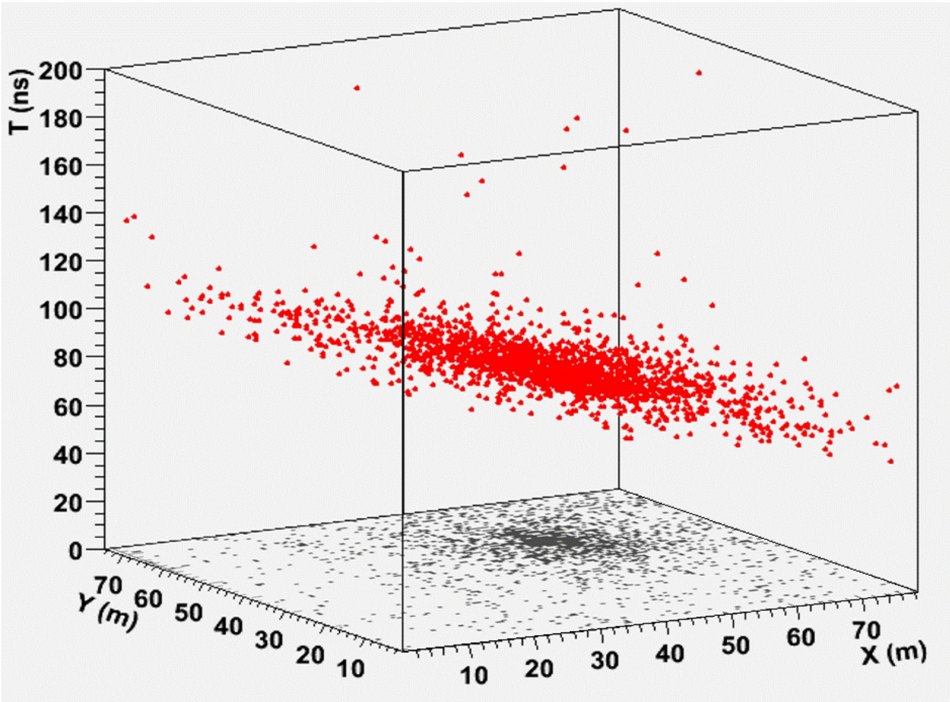
... also given by the RPC charge information

Shower front time structure

New observables are being studied, mainly shape and width,

and their correlation with the longitudinal shower development

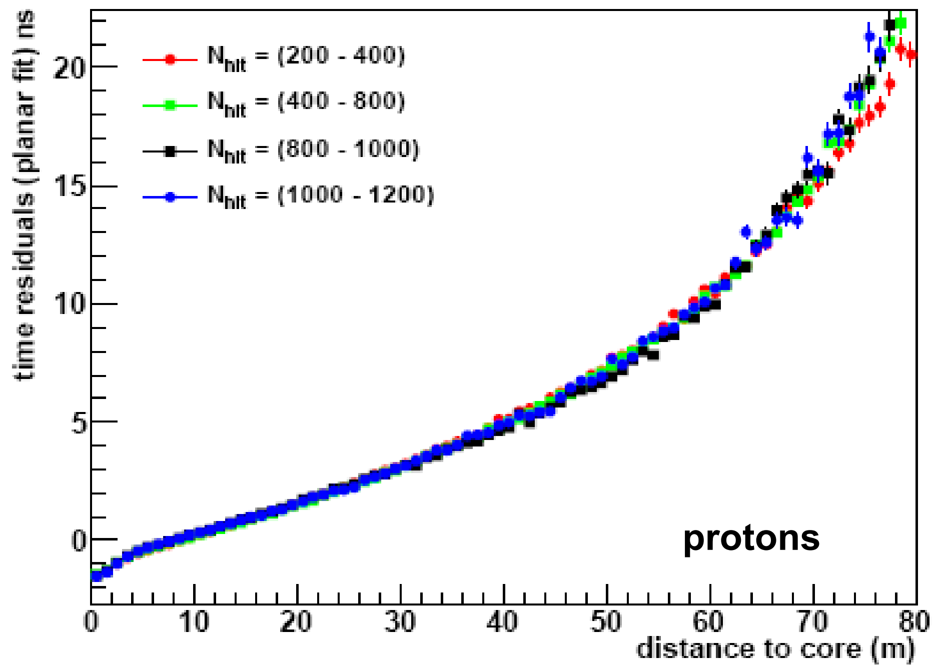


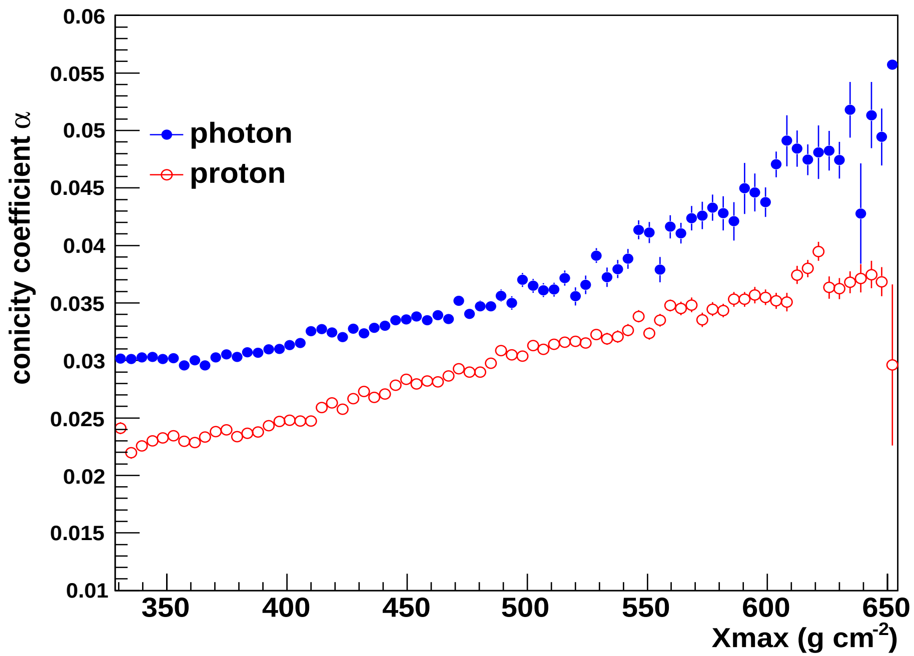


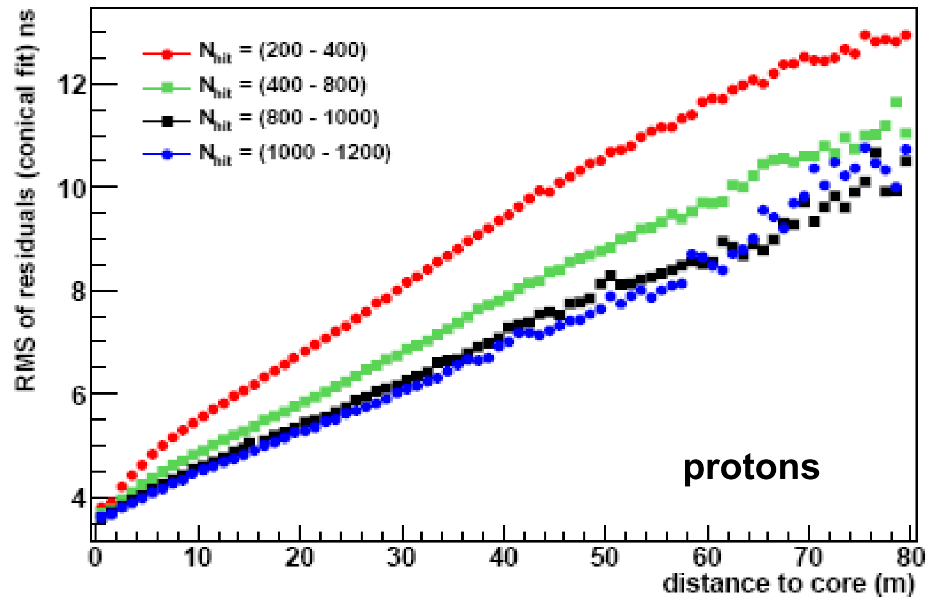
Shower front time structure

Look for detectable differences among various hadint models and data

Look for correlations with Xmax





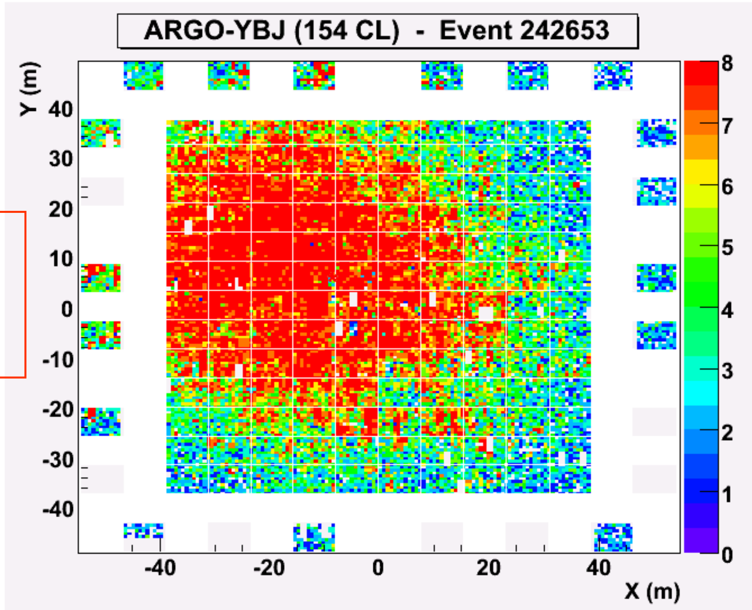


Info from the analog readout

Real event

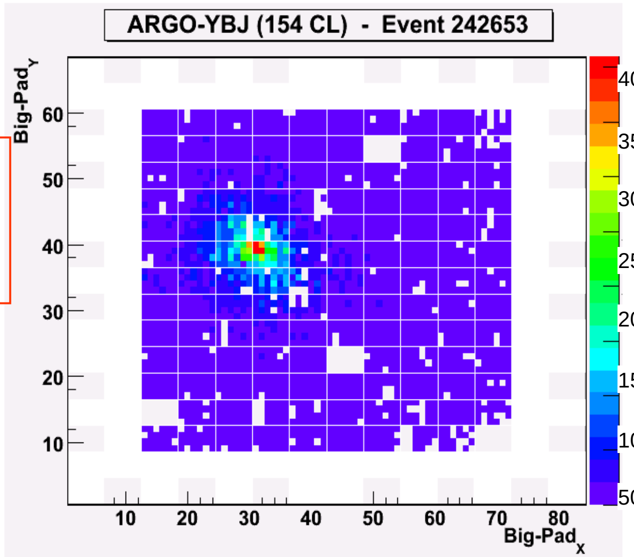
Strips

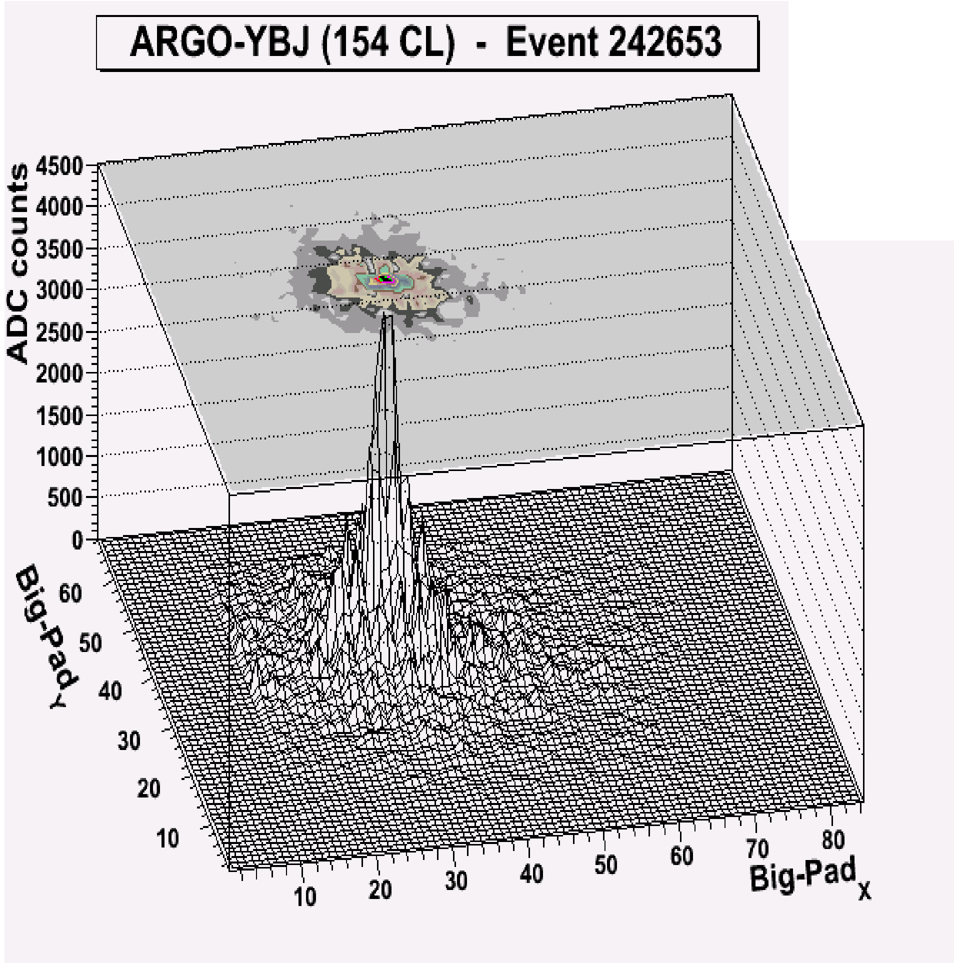
(digital)



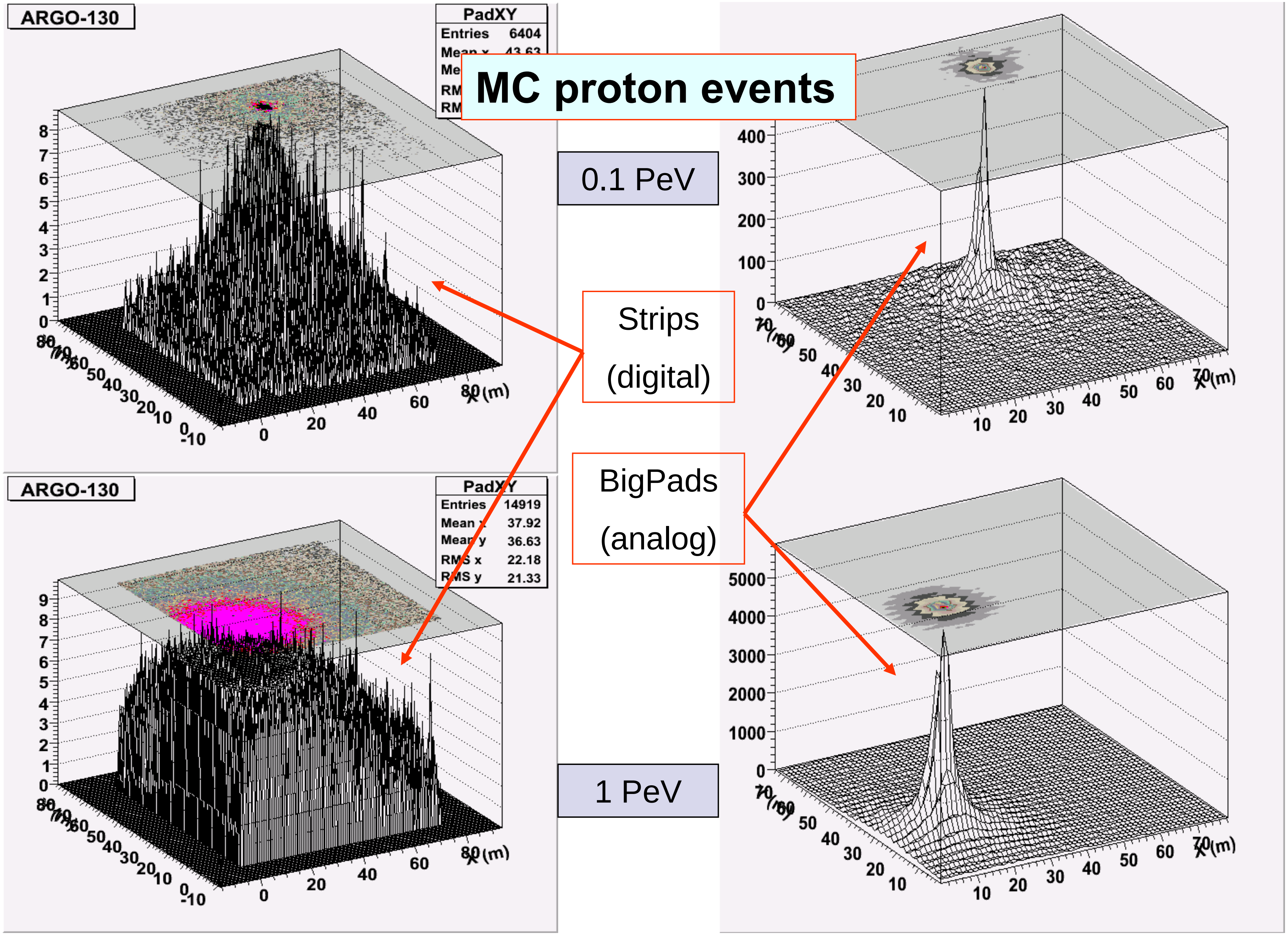
BigPads

(analog)



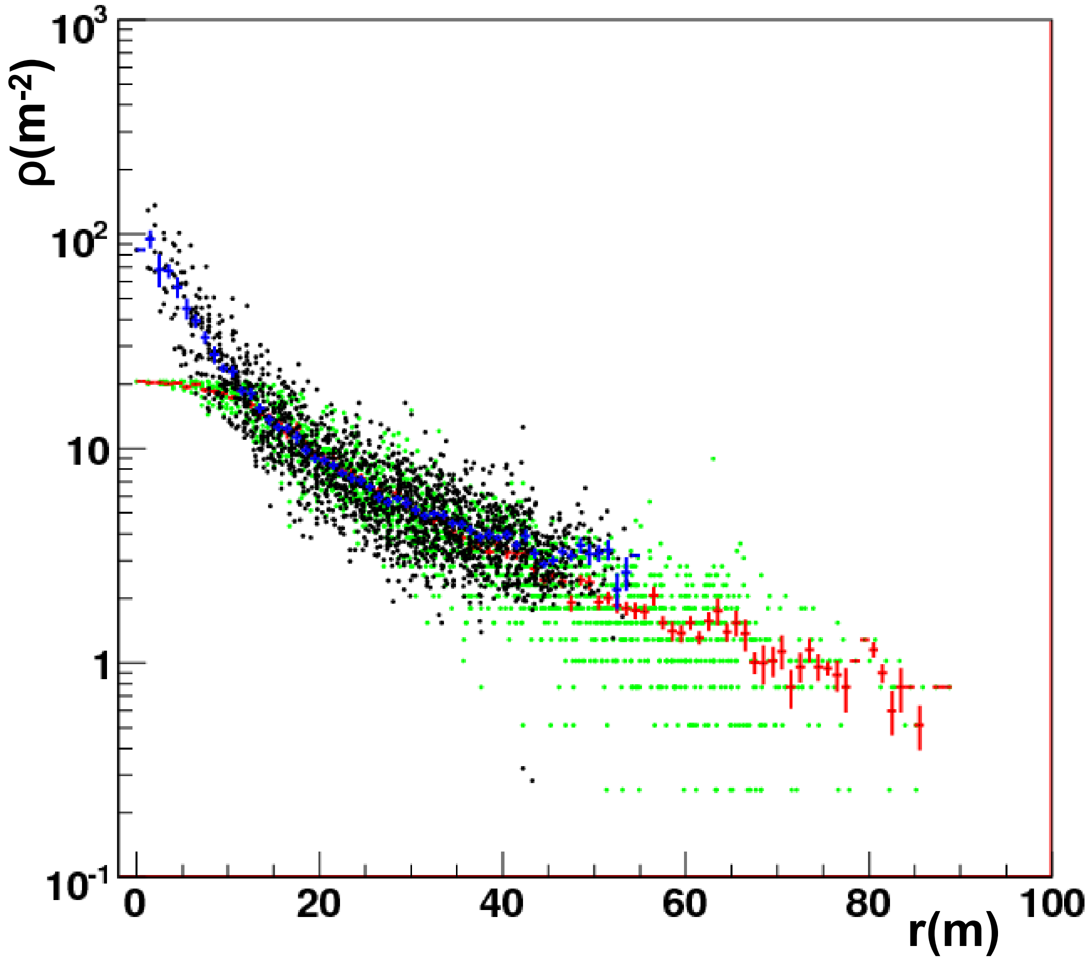


MC proton events



Lateral Distribution Function

With the analog data we can study the LDF without saturating near the core

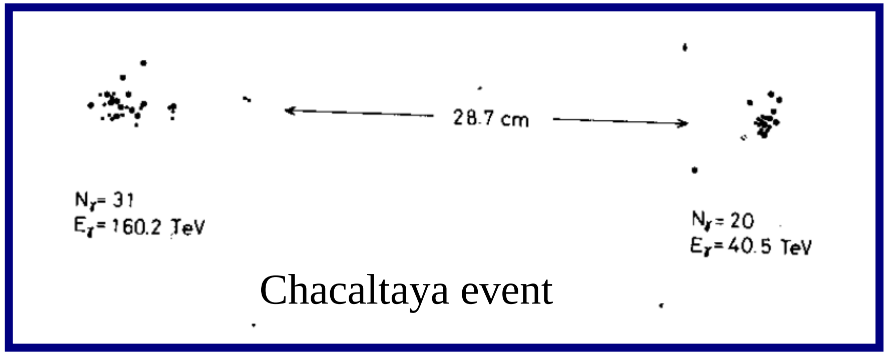


Tests are in progress in order to have:

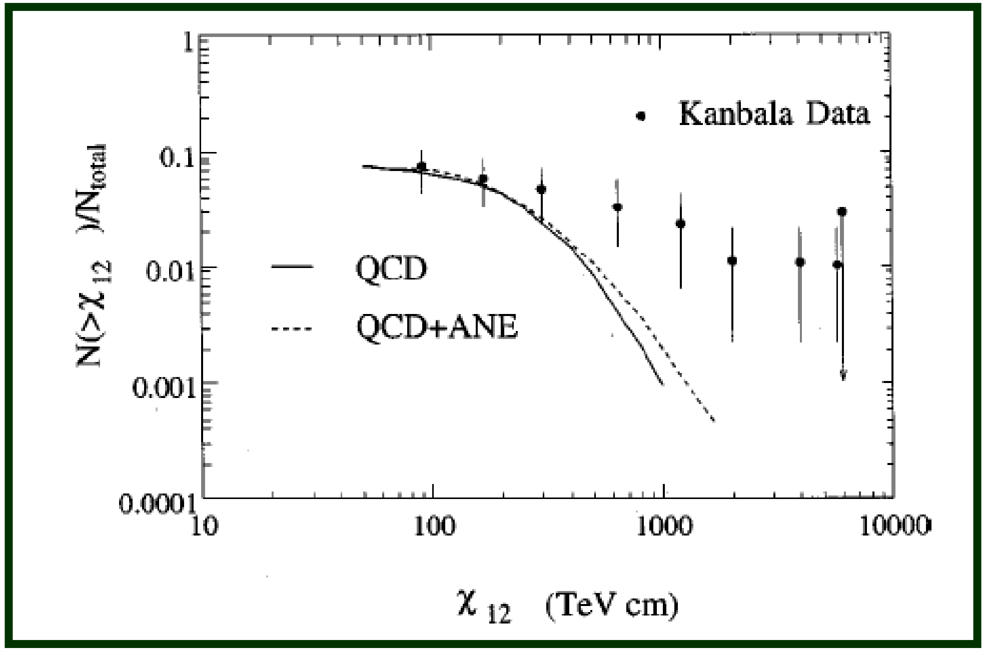
- ✓ **Better resolution on X_{dm} and then lower systematics on the cross section measurement**
- ✓ **Better energy determination / shower reconstruction**
- ✓ **Some sensitivity to the hadronic interaction model**

Multicore events

- They are correlated to large p_T jets
- Multicore γ –hadron family events in mountain emulsion experiments
- Events with $\chi_{12} = \sqrt{E_1 E_2}\, r_{12} \geq 1000 TeVcm$ still not explained by our present knowledge



Pamir Coll., Mt. Fuji Coll. and Chacaltaya Coll., Nucl. Phys. B191(1981)1-25



Z. Cao et al., Phys. Rev. D,v56 1997,7361-7375

Exotic multicore events

PHYSICAL REVIEW D VOLUME 52, NUMBER 5 1 SEPTEMBER 1995

Alignment in γ-hadron families of cosmic rays

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(Received 8 August 1994)

The alignment of the main fluxes of energy in a target plane is found in families of cosmic ray particles detected in deep lead x-ray chambers. The fraction of events with alignment is unexpectedly large for families with high energy and a large number of hadrons. This can be considered as evidence for the existence of coplanar scattering of secondary particles in the interaction of particles with superhigh energy, $E_0 \gtrsim 10^{16}$ eV. Data analysis suggests that the production of most aligned groups occurs slightly above the chamber and is characterized by a coplanar scattering and quasi-scaling spectrum of secondaries in the fragmentation region. The most elaborated hypothesis for the explanation of the alignment is related to the quark-gluon string rupture. However, the problem of the theoretical interpretation of our results still remains open.

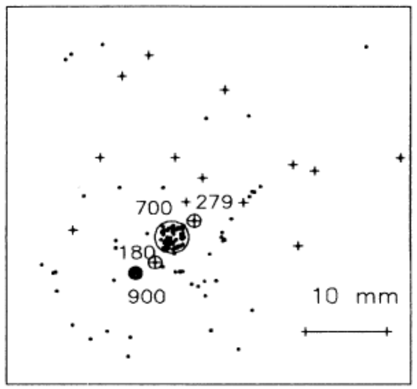


FIG. 2. An example of the target diagram with energy distinguished cores for the event with alignment (the family Pb-6). λ_4=0.95. Figures in the plot stand for energy in TeV (already multiplied by 3 for hadrons). EDC: ☹ is the halo of electromagnetic origin; ● is the hadronic halo; ⊕ are the high energy hadrons; • are the family γ quanta; + are the hadrons of the family.

A.DE Roeck et al., in arXiv:1002.3527

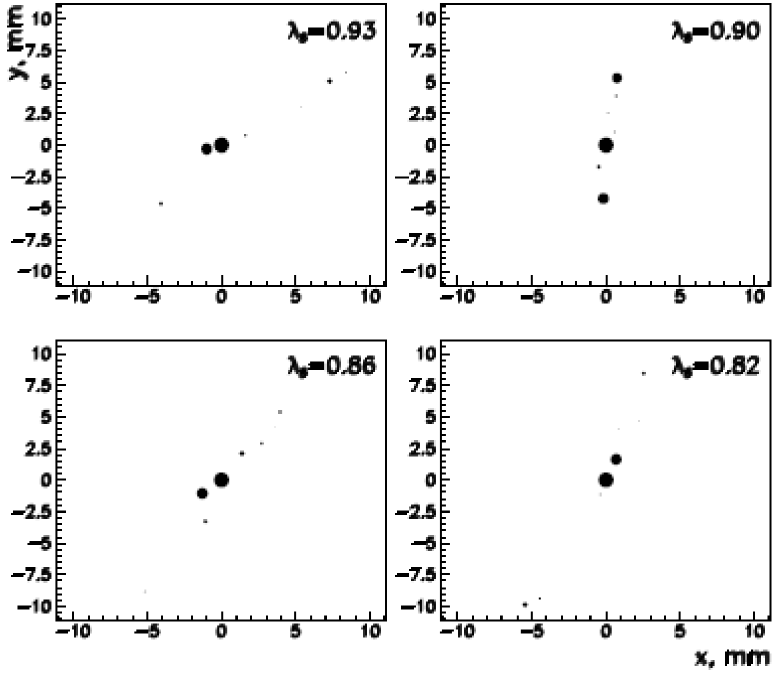
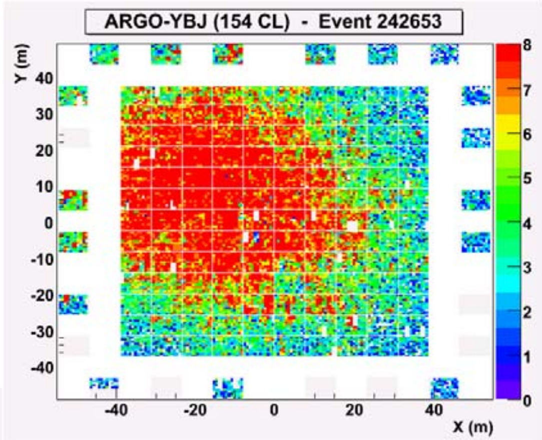


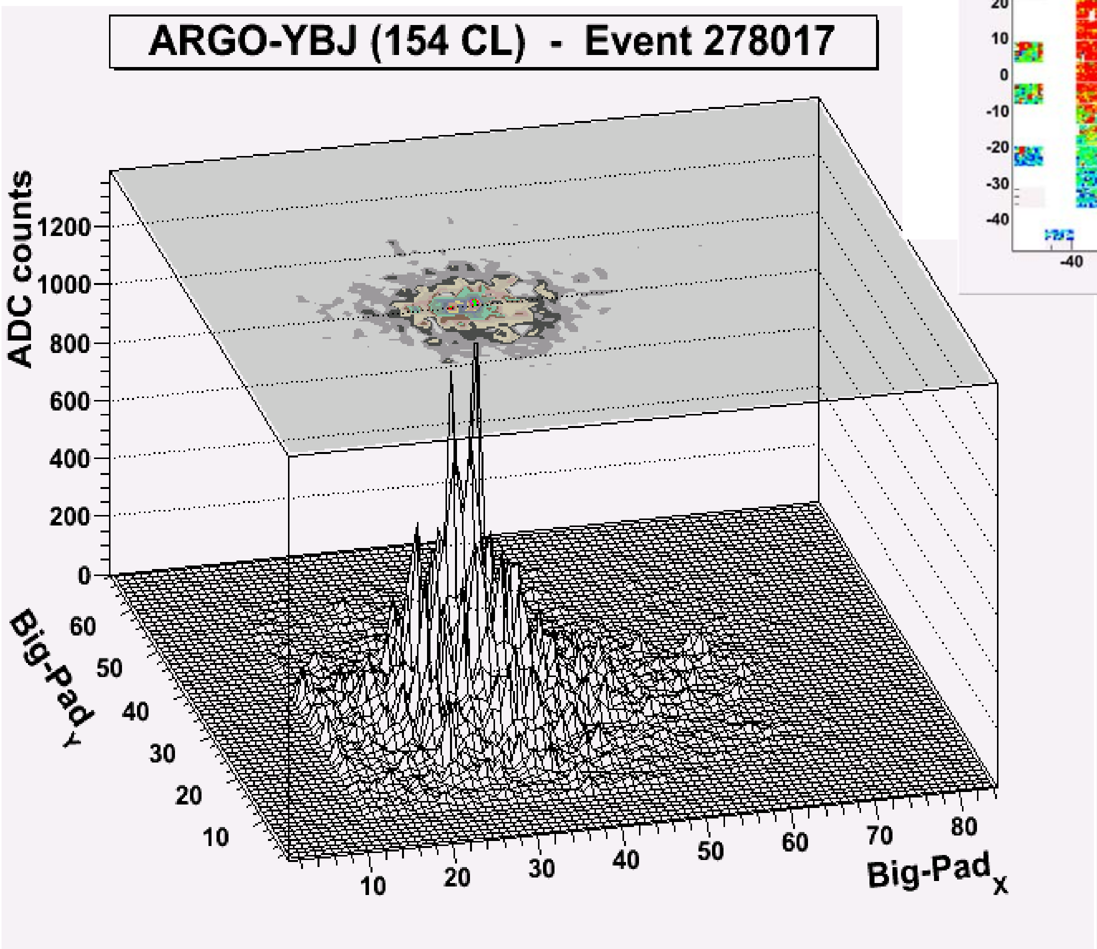
Figure 2: Samples of core distributions for PYTHIA simulated events with $E_{\Sigma}^{\rm thr} = 10$ PeV and $\lambda_8 > 0.8$. The size of spots is proportional to their energy (except for the central spot which is not to scale).

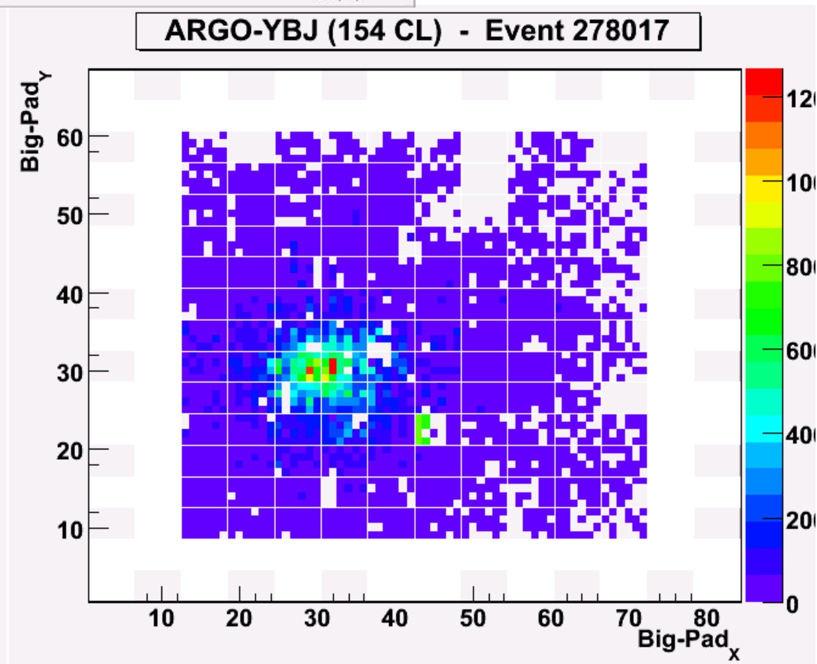
Multicore events with analog data

Preliminary results show the feasibility of these studies.

Analysis is in progress..



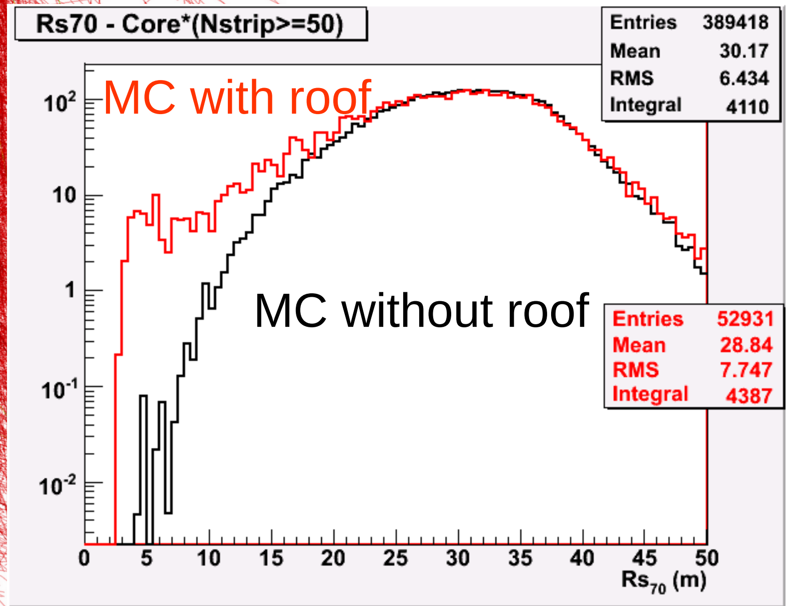


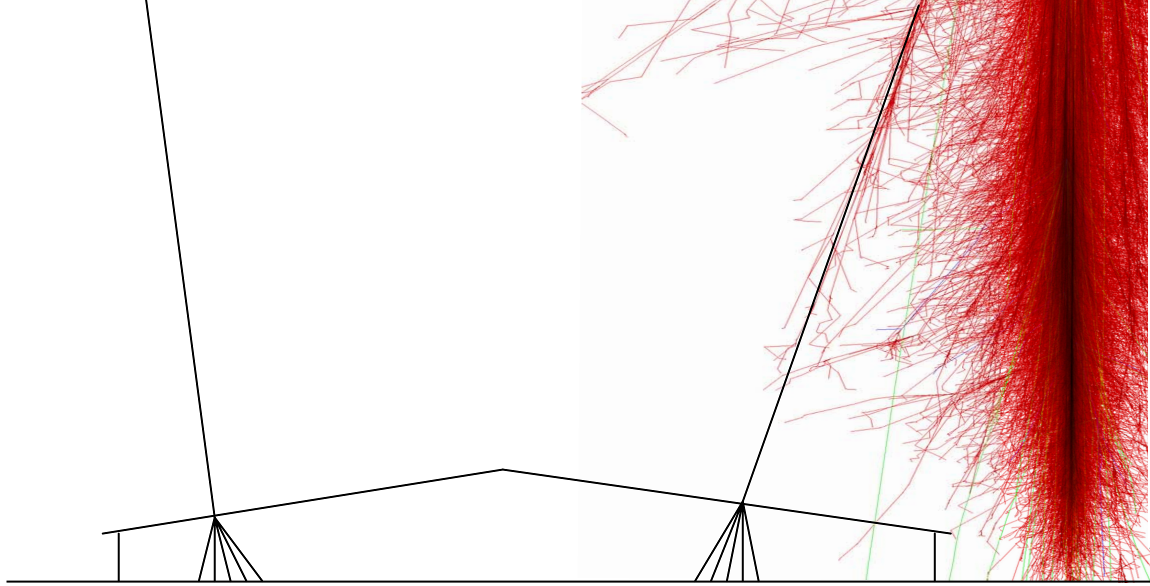


“Hot spots” Events

- Use the roof as an “opportunity”
- It might give info on:
  - low energy primary proton spectrum
  - p-air cross section (with a different technique)
  - test on hadronic interaction models

A background for Multicore event analysis





Summary and Outlook

- The **proton-air cross section** has been measured, giving results in agreement with previous works, done with totally different techniques.

- Results indicates **slightly smaller cross section values** with respect to QGSJET and SYBILL predictions (**definition/simulation/detection of low inelasticity events**)

- More accurate shower age and energy determinations will be performed, by the use of **timing, rise time, front curvature… , and topological information**

- The analysis will be extended to larger energies (**up to the PeV region**), by using the analog RPC readout, now being implemented

- Interesting information on hadronic interactions might come from the study of the **time structure of the front, the LDF, and multicore events**.