ANALYSIS OF COSMIC EVENTS WITH THE ALICE-LHC

Mario Rodríguez Cahuantzi

Departamento de Física - CINVESTAV

Seminario del Cuerpo Académico de Partículas, Campos y Relatividad General
FCFM-BUAP, 2/10/2013

Plan of this talk

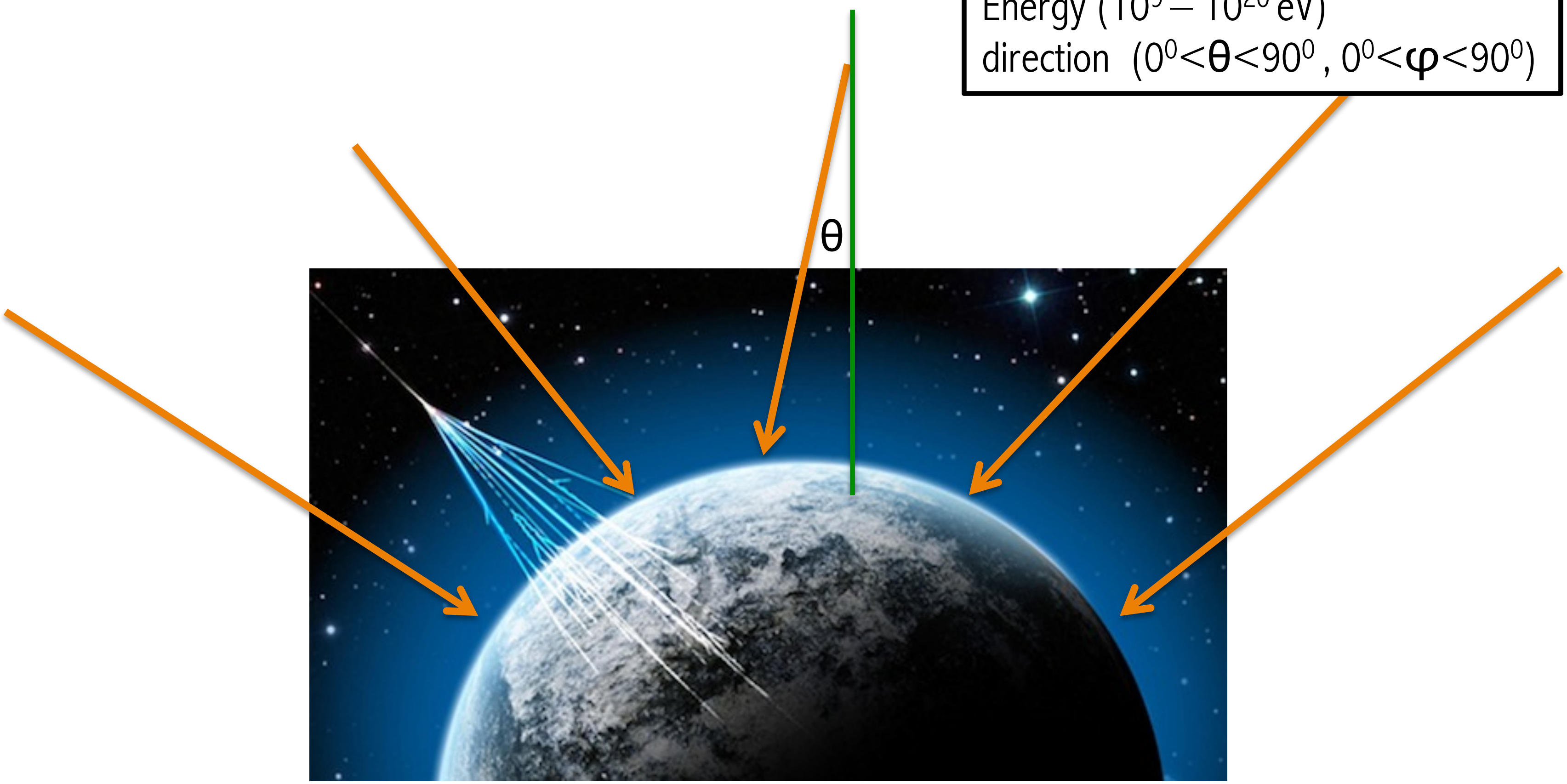
- Introduction
- ALICE Experiment: trigger and tracking detectors for cosmics
- Atmospheric Muon Multiplicity Distribution (MMD)
- Monte Carlo to study High Atmospheric Muons Events (HME)
- Final comments

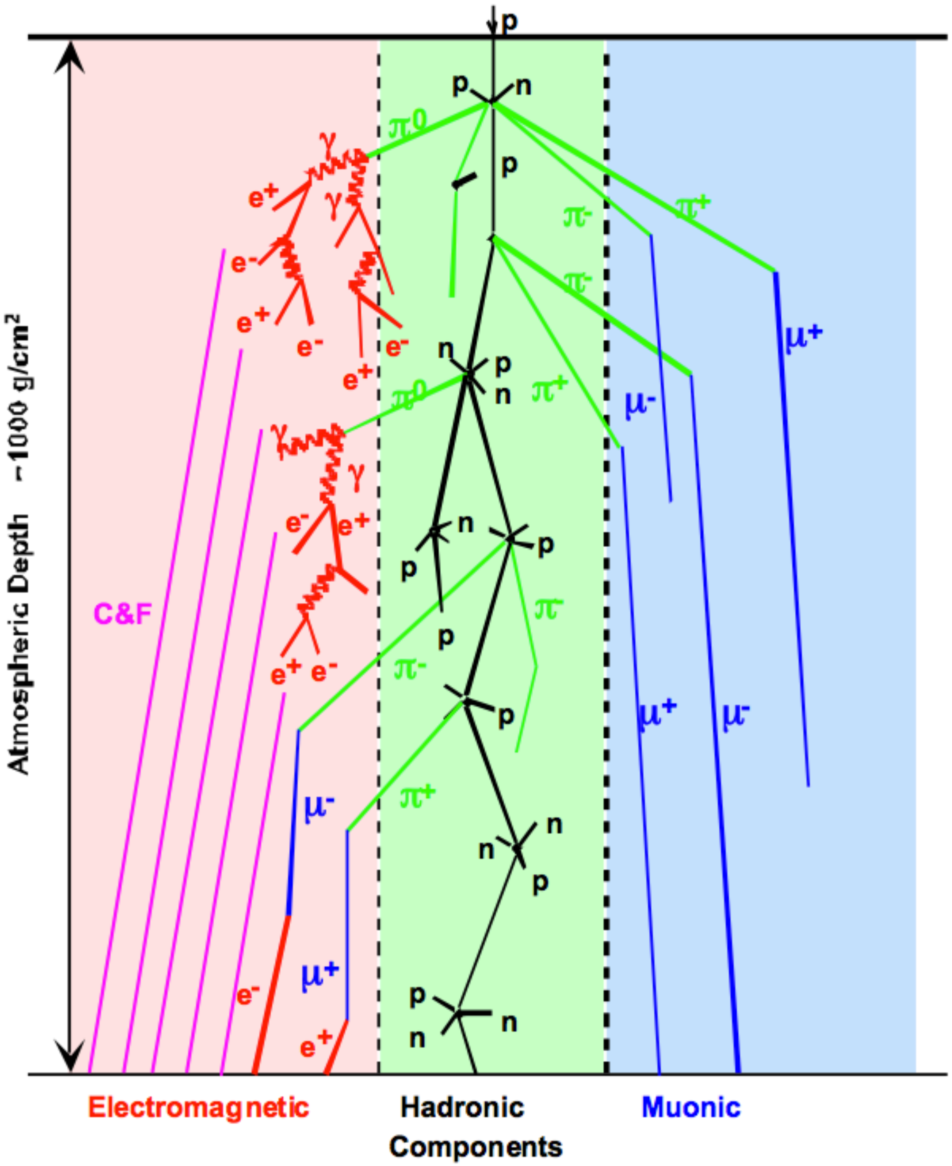
Introduction

What are cosmic rays?

- ✓ Cosmic rays (CR) are particles coming from galaxy or outside the galaxy reaching the Earth's atmosphere.
- ✓ 90% protons, 9% He nuclei, 1% heavier nuclei
- ✓ Gammas , neutrinos
- ✓ Rate ~ 1000 particles hits the atmosphere per m^2s

CR are characterized by:
Identity of the particle
Energy ($10^9 - 10^{20}$ eV)
direction ($0^0<\theta<90^0$, $0^0<\varphi<90^0$)





p, n, π : near shower axis

μ, e, γ : widely spread

e, γ : from π^0, μ decays ~ 10 MeV

μ : from $\pi^\pm$, K, ... decays ~ 1 GeV

$N_{e,\gamma}$: N_μ ~ 10 ... 100 varying with core distance, energy, mass, Θ, ...

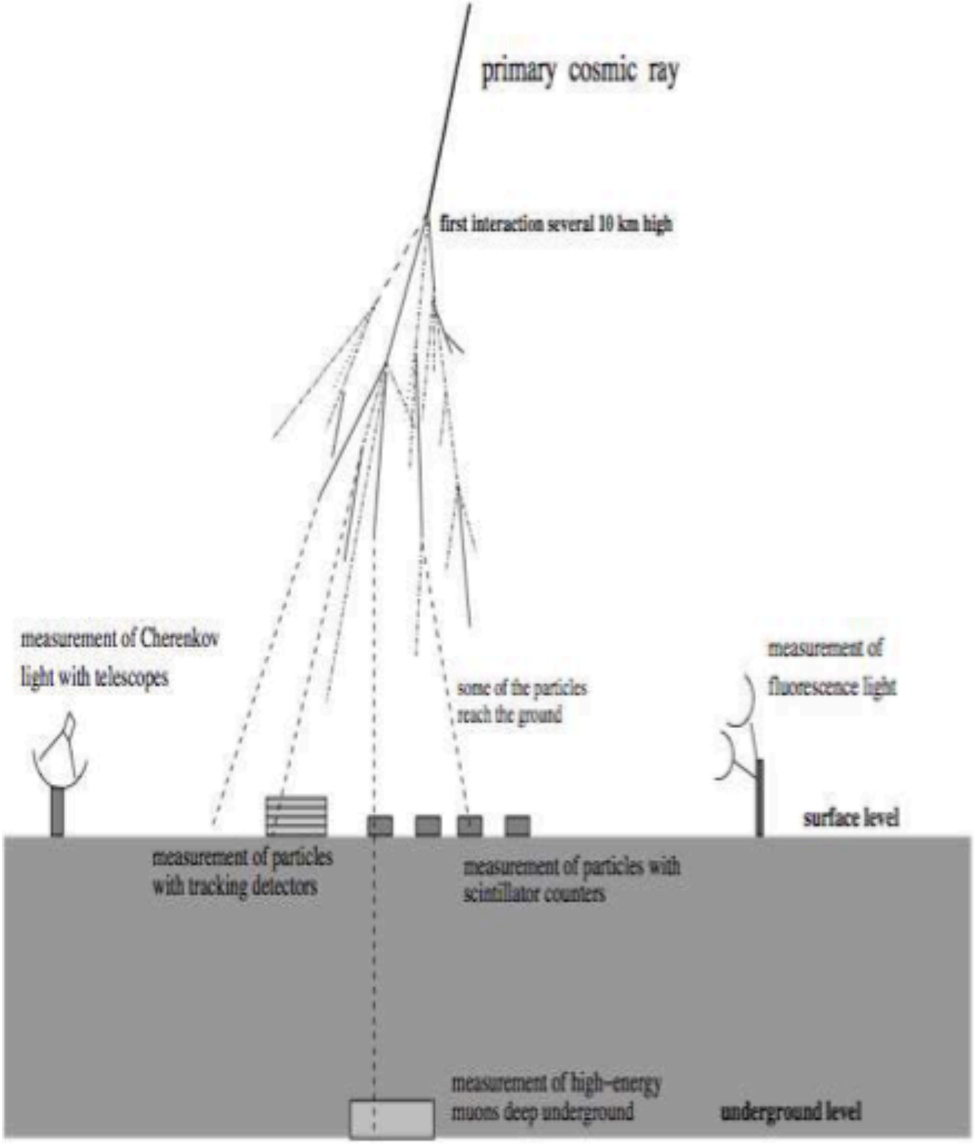
Details depend on:

- interaction cross-sections,
- hadronic and el.mag. particle production,
- decays, transport, ...

at energies of MeV to 10^{20} eV
(well above man-made accelerators.)

Complex interplay with many correlations
requires MC simulations

Introduction



p, n, π : near shower axis
μ, e, γ : widely spread

e, γ : from π^0, μ decays ~ 10 MeV
μ : from $\pi^{\pm}$, K, ... decays ~ 1 GeV

$N_{e,\gamma}$: N_μ ~ 10 ... 100 varying with core distance, energy, mass, Θ, ...

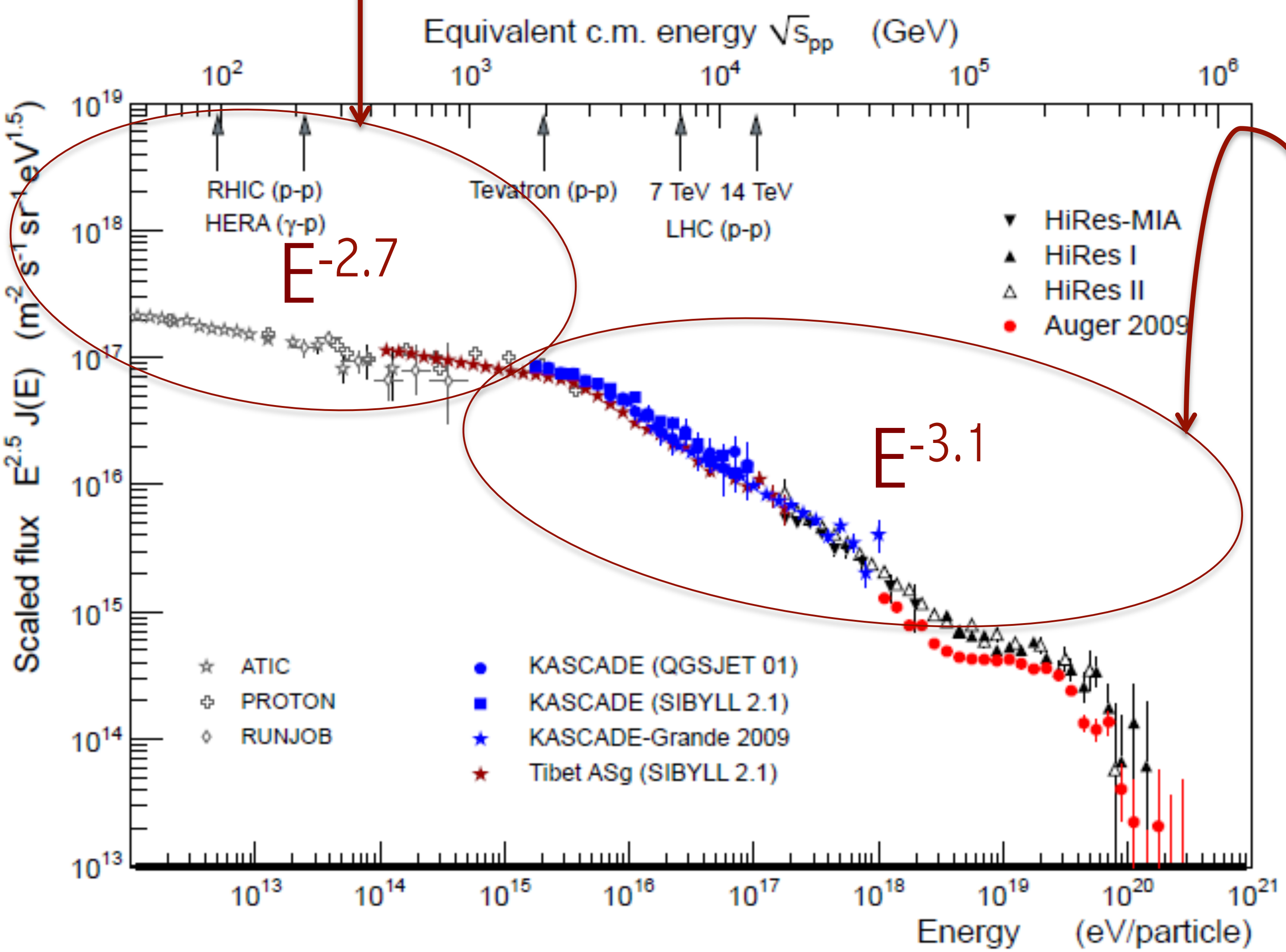
Details depend on:
- interaction cross-sections,
- hadronic and el.mag. particle production,
- decays, transport, ...

at energies of MeV to 10^{20} eV
(well above man-made accelerators.)

Complex interplay with many correlations
requires MC simulations

Introduction

Direct measurements up to E ~ 10^{14} eV → Primary particles (balloons, satellites)

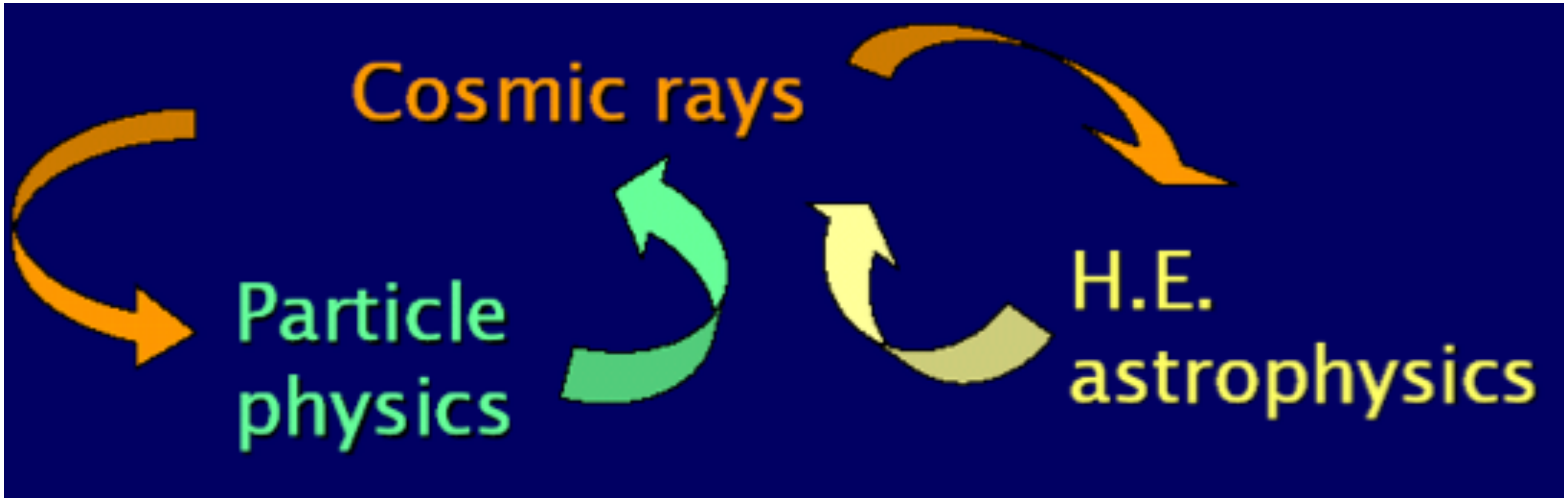


Indirect measurements E > 10^{14} eV → Secondary particles ([under]ground experiments)

Direct measurements up to E ~ 10^{14} eV → Primary particles (balloons, satellites)

Indirect measurements with (under)ground experiments to E > 10^{14} eV

- ✓ Cosmic ray interactions with atmosphere and Extensive Air Showers (EAS)
- ✓ Measurements around the knee (Eas-Top, Kaskade, Casa …) and beyond (Kaskade-Grande)
- ✓ Ultra high energy cosmic rays (Auger, HiRes)
- ✓ Underground experiments (Macro, Emma)
- ✓ COSMIC RAY PHYSICS AT CERN (LEP: L3+C, ALEPH, DELPHI; LHC: CMS, ALICE)



- ✓ DETECTION AND STUDY OF COSMIC RAY PHYSICS
- ✓ STUDY OF HIGH ENERGY INTERACTIONS IN p-p, Pb-Pb COLLISIONS TO EXTRAPOLATE INFORMATION FOR COSMIC RAY PHYSICS

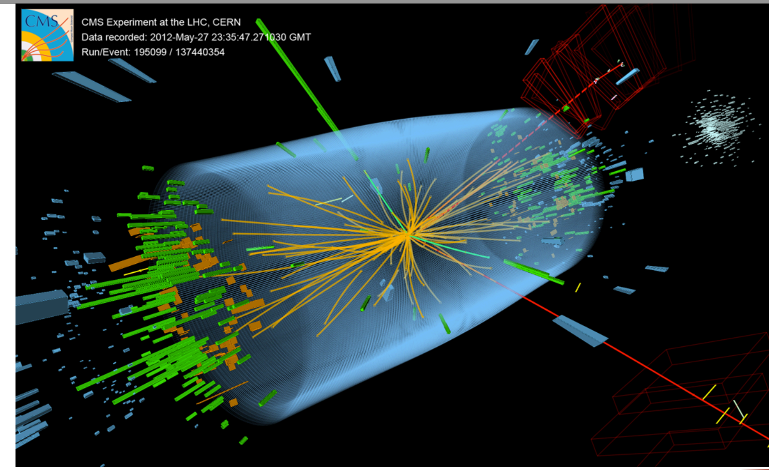
Table 1. Discovery of elementary particles

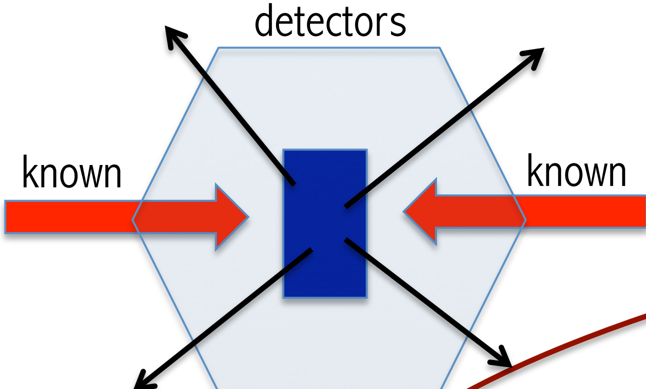
Particle	Year	Discoverer (Nobel Prize)	Method
e^-	1897	Thomson (1906)	Discharges in gases
p	1919	Rutherford	Natural radioactivity
n	1932	Chadwik (1935)	Natural radioactivity
e^+	1933	Anderson (1936)	Cosmic Rays
$\mu^\pm$	1937	Neddermeyer, Anderson	Cosmic Rays
$\pi^\pm$	1947	Powell (1950) , Occhialini	Cosmic Rays
$K^\pm$	1949	Powell (1950)	Cosmic Rays
π^0	1949	Bjorklund	Accelerator
K^0	1951	Armenteros	Cosmic Rays
Λ^0	1951	Armenteros	Cosmic Rays
Δ	1932	Anderson	Cosmic Rays
Ξ^-	1932	Armenteros	Cosmic Rays
$\Sigma^\pm$	1953	Bonetti	Cosmic Rays
p^-	1955	Chamberlain, Segre' (1959)	Accelerators
anything else	1955 $\Longrightarrow$ today	various groups	Accelerators
$m_\nu \neq 0$	2000	KAMIOKANDE	Cosmic rays

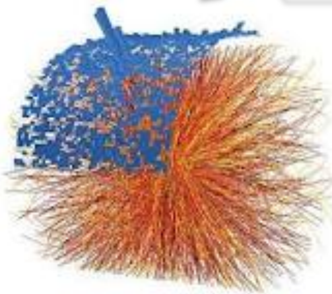
Introduction

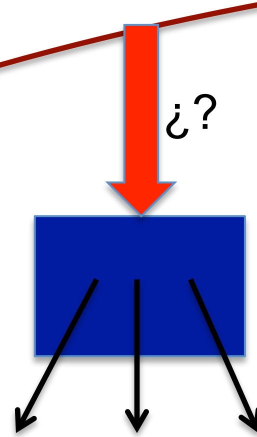
ACCELERATOR PHYSICS:

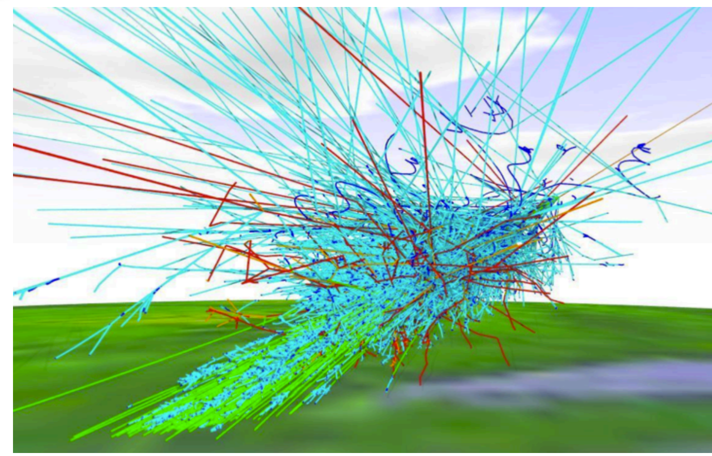
BEAM KNOWN → DETECTION OF THE SECONDARIES
→ STUDY OF THE INTERACTIONS











COSMIC RAY PHYSICS WITH EAS:

BEAM UNKNOWN → DETECTION OF THE SECONDARIES ARRIVING AT GROUND
→ STUDY OF THE BEAM

Introduction

Cosmic rays with the accelerator apparata

- ✧ Small apparata
- ✧ Low underground
- ✧ Detection of muons crossing the rock

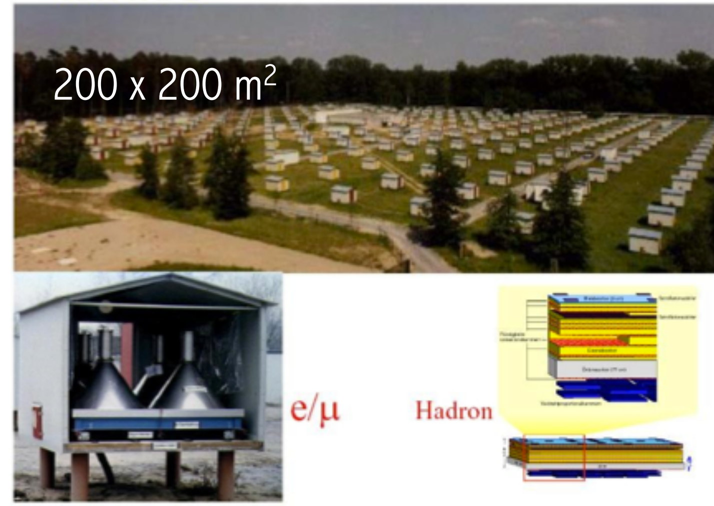
★ These apparata are not designed for cosmic ray physics:

❑ Small detectors compared with the standard cosmic ray apparata:

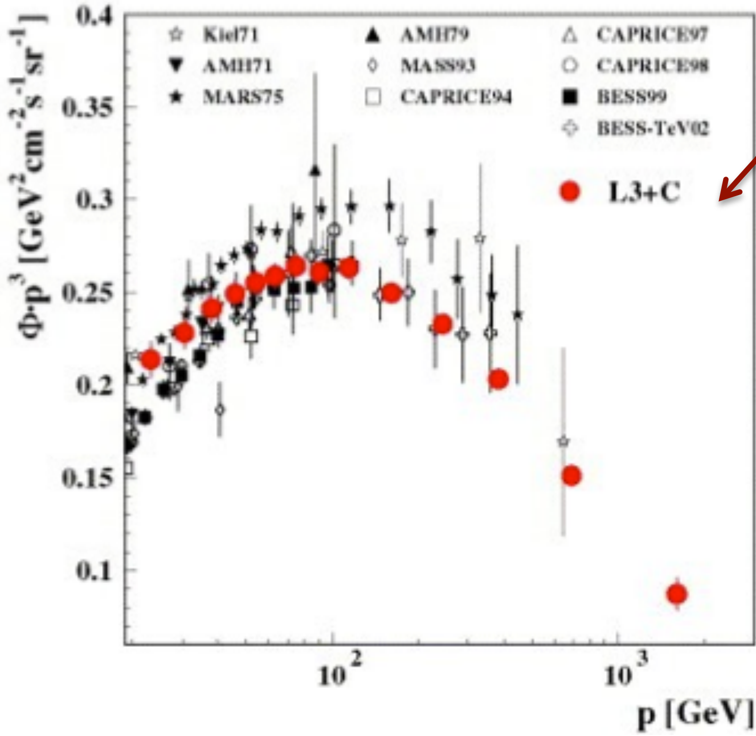
- ✧ Only muons are detected
- ✧ Short live time of data taking

✓ Advantage: detectors with very high performances, presence of magnetic field

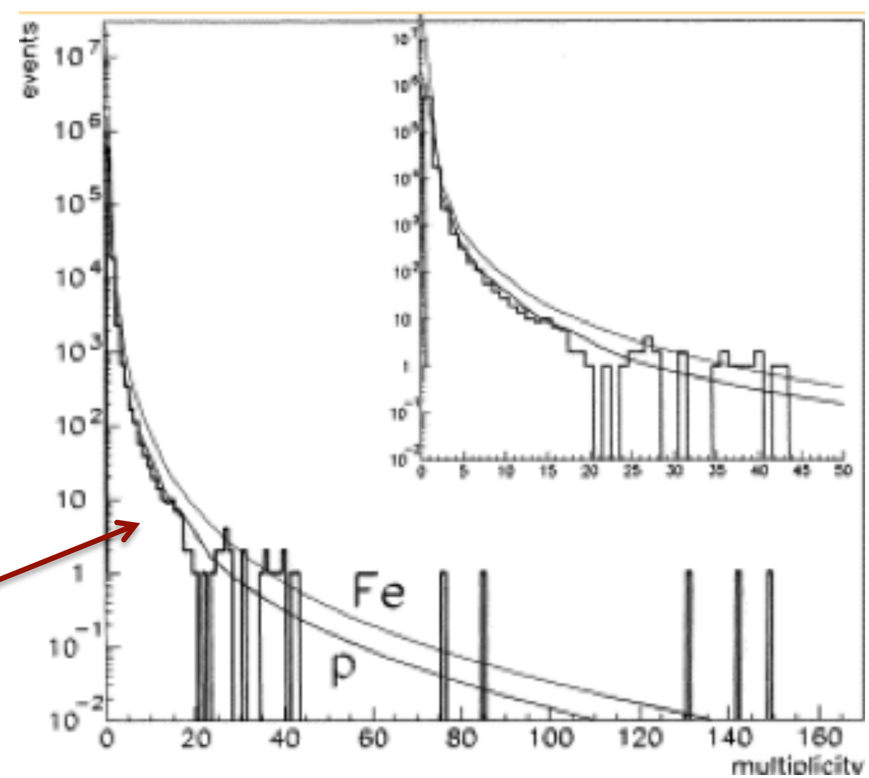
KASCADE



Main topic with accelerator apparata

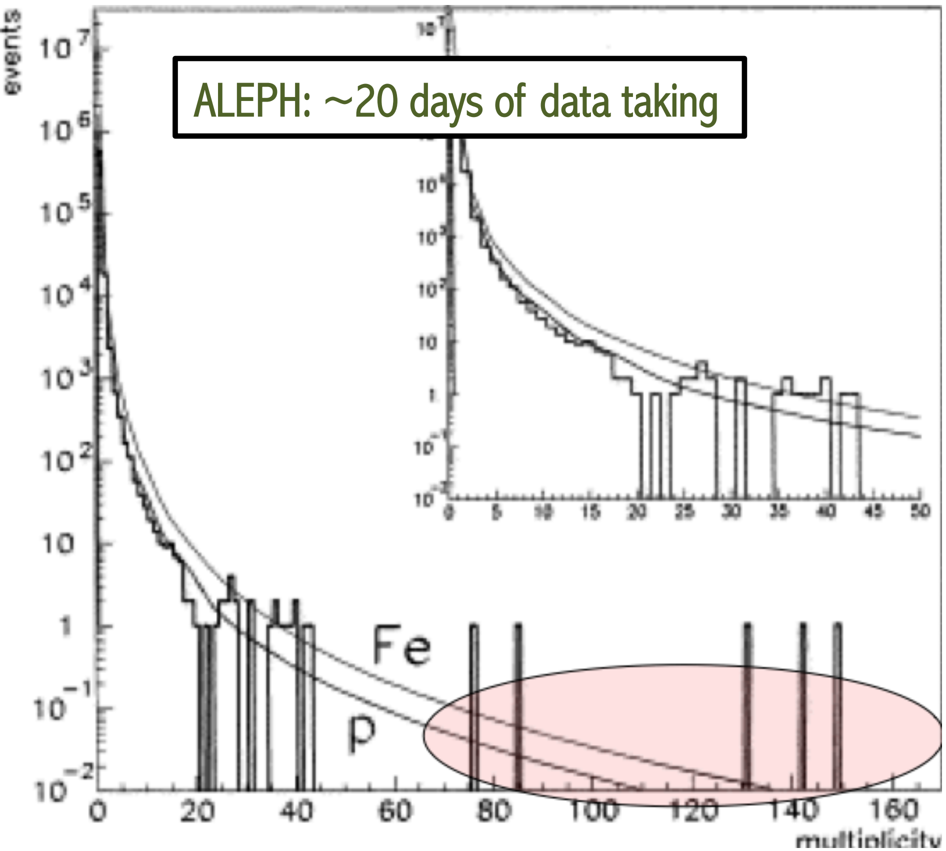


- Magnetic field + Precise momentum measurement
- Muon momentum spectrum and charge ratio (L3)
  Charge ratio (CMS)



- High tracking capabilities
- Muon-bundles (high muon density): Aleph, Delphi, L3 and Alice

Introduction

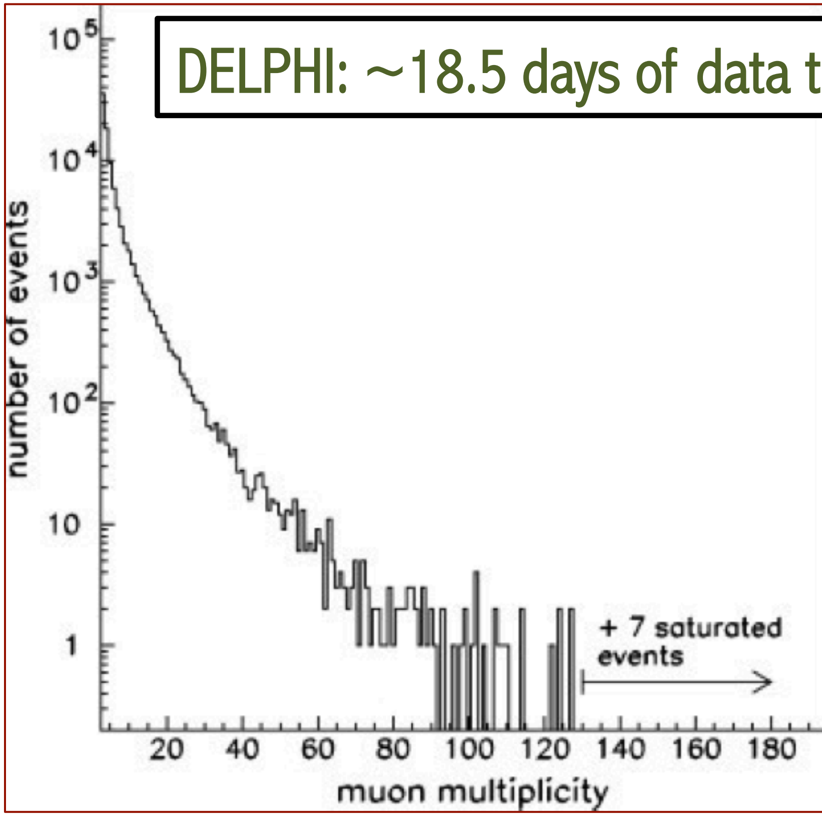


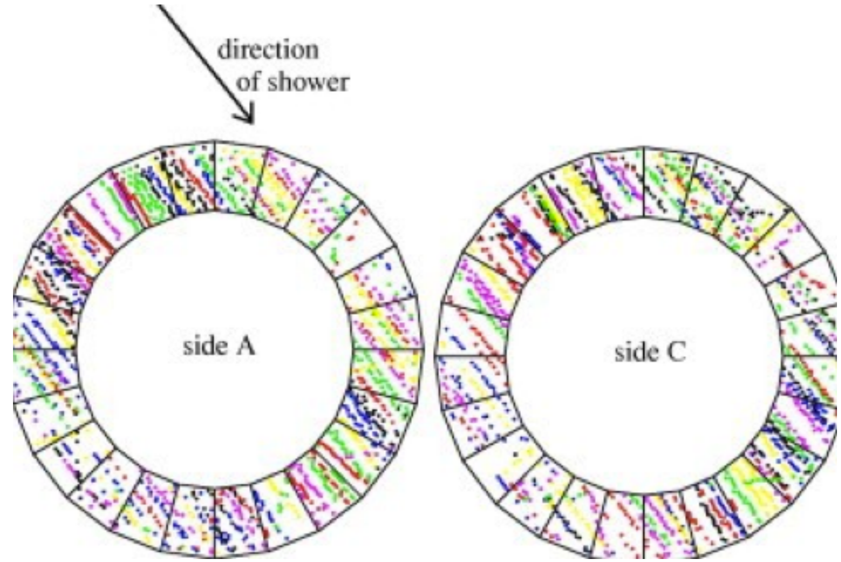
1) 4.75 μ/m^2 Zenith=40.8^0
   Primary energy = 3 x 10^{16} eV
2) 5.3 μ/m^2 Zenith=37.7^0
   Primary energy = 3 x 10^{16} eV
3) 8.9 μ/m^2 Zenith=40^0
   Primary energy = 6 x 10^{16} eV
4) 8.2 μ/m^2 Zenith=48.6^0
   Primary energy = 7 x 10^{16} eV
5) 18.6 μ/m^2 Zenith=27^0
   Primary energy = 10^{17} eV

Astroparticle Physics 19 (2003) 513–523

The five highest multiplicity events, with up to 150 muons within an area of 8 m^2, occur with a frequency which is almost an order of magnitude above the simulation.

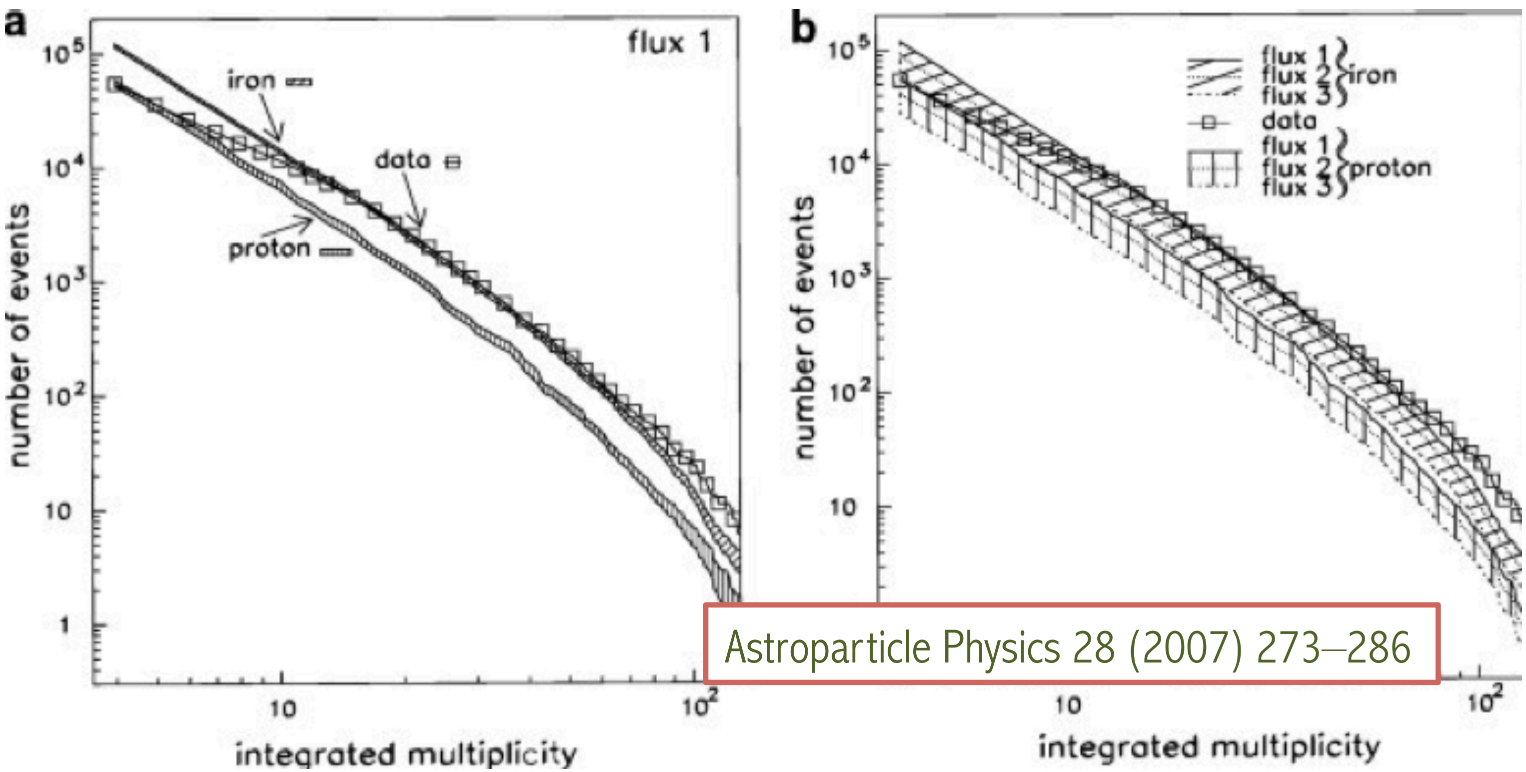
DELPHI: ~18.5 days of data taking





7 high multiplicity events that saturate the detector

Astroparticle Physics 28 (2007) 273–286

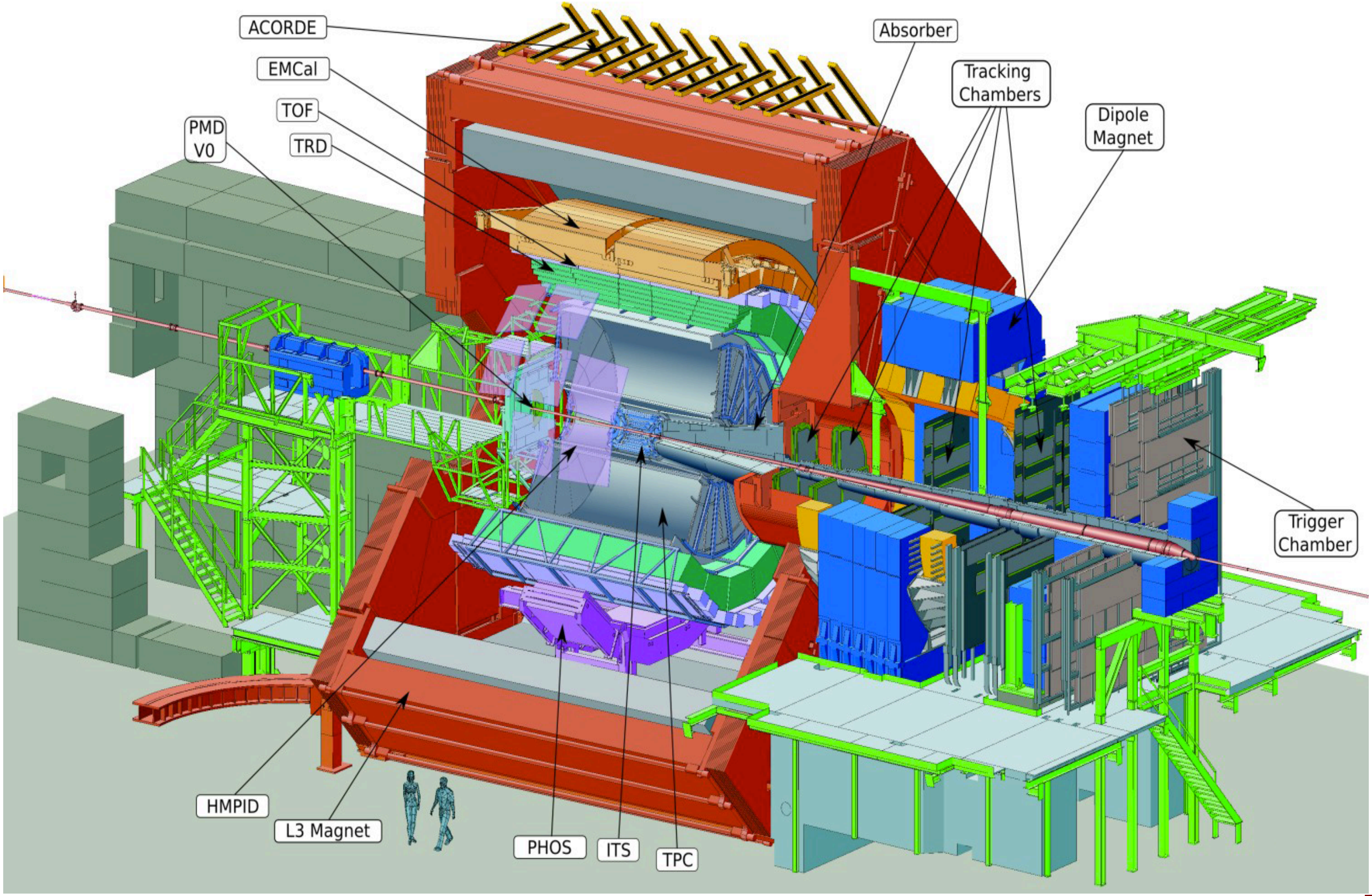


Astroparticle Physics 28 (2007) 273–286

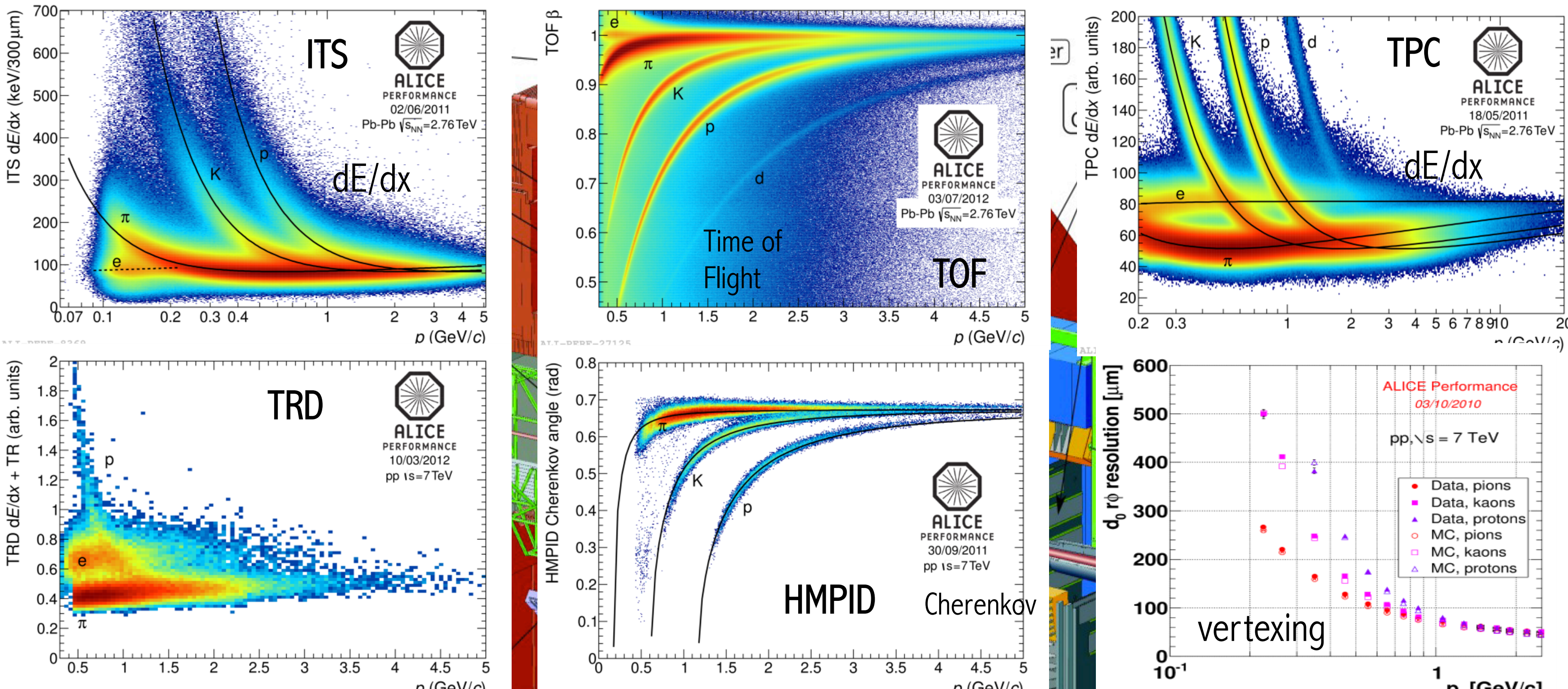
The conclusion is similar to Aleph :

However, even the combination of extreme assumptions of highest measured flux value and pure iron spectrum fails to describe the abundance of high multiplicity events. Let's see the ALICE results

ALICE Experiment: trigger and detection for cosmics



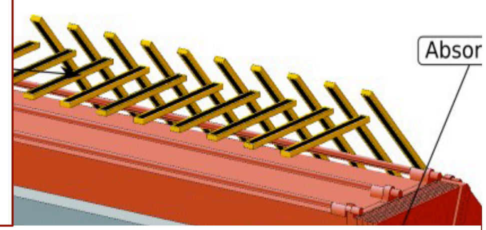
ALICE Experiment: trigger and detection for cosmics

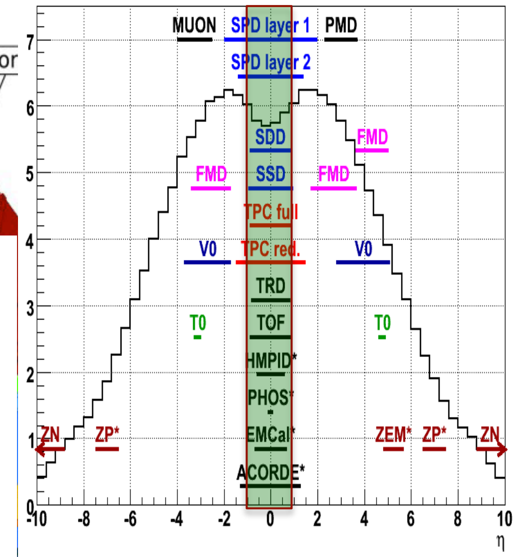


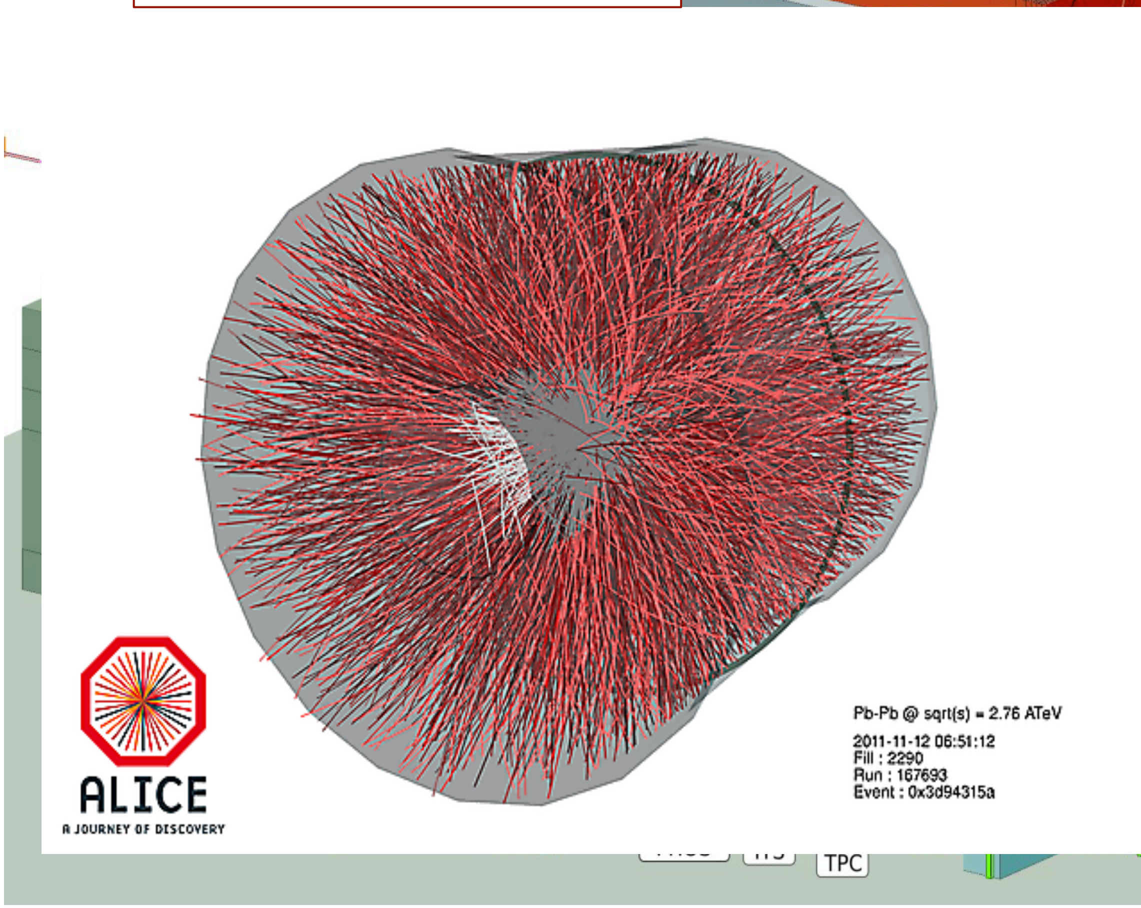
The design is optimized for reconstruction and identification of particles in a wide range of transverse momentum

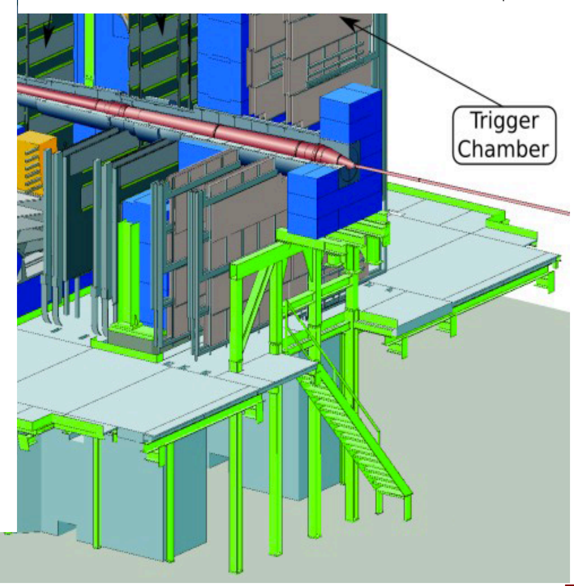
- particle identification (practically all known techniques)
- extremely low-mass tracker ~ 10% of *X0*
- excellent vertexing capability
- efficient low-momentum tracking – down to ~ 100 MeV/*c*

Central detectors
Inner tracking system (ITS)
Time Projection Chamber (TPC)
$|\eta| < 0.9$

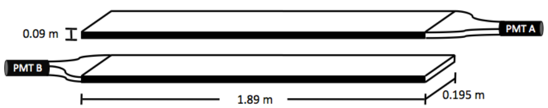


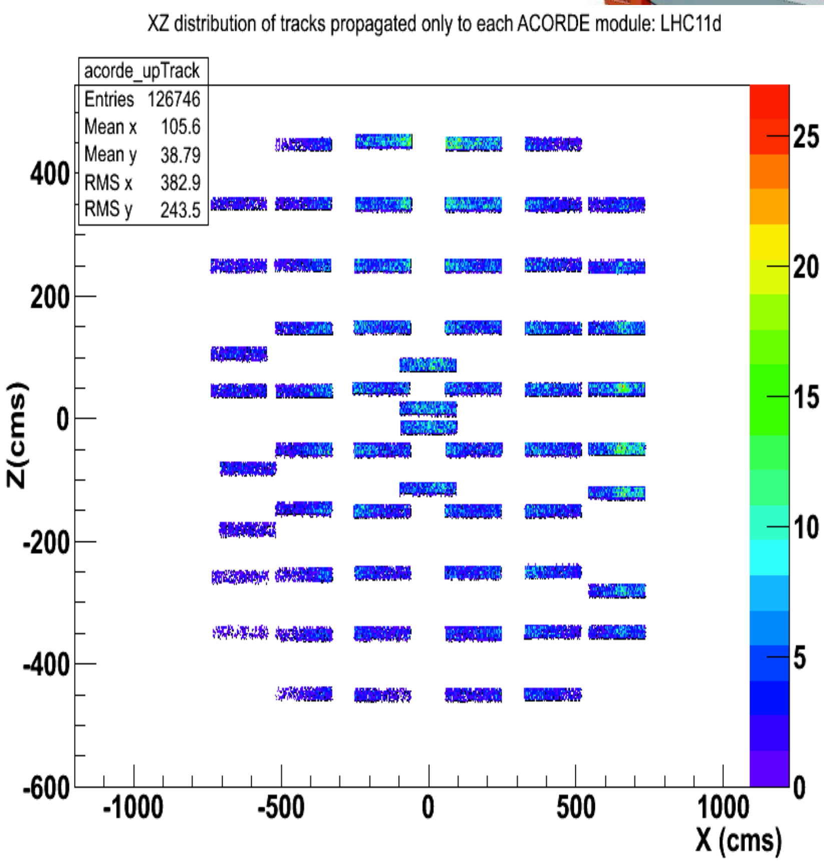


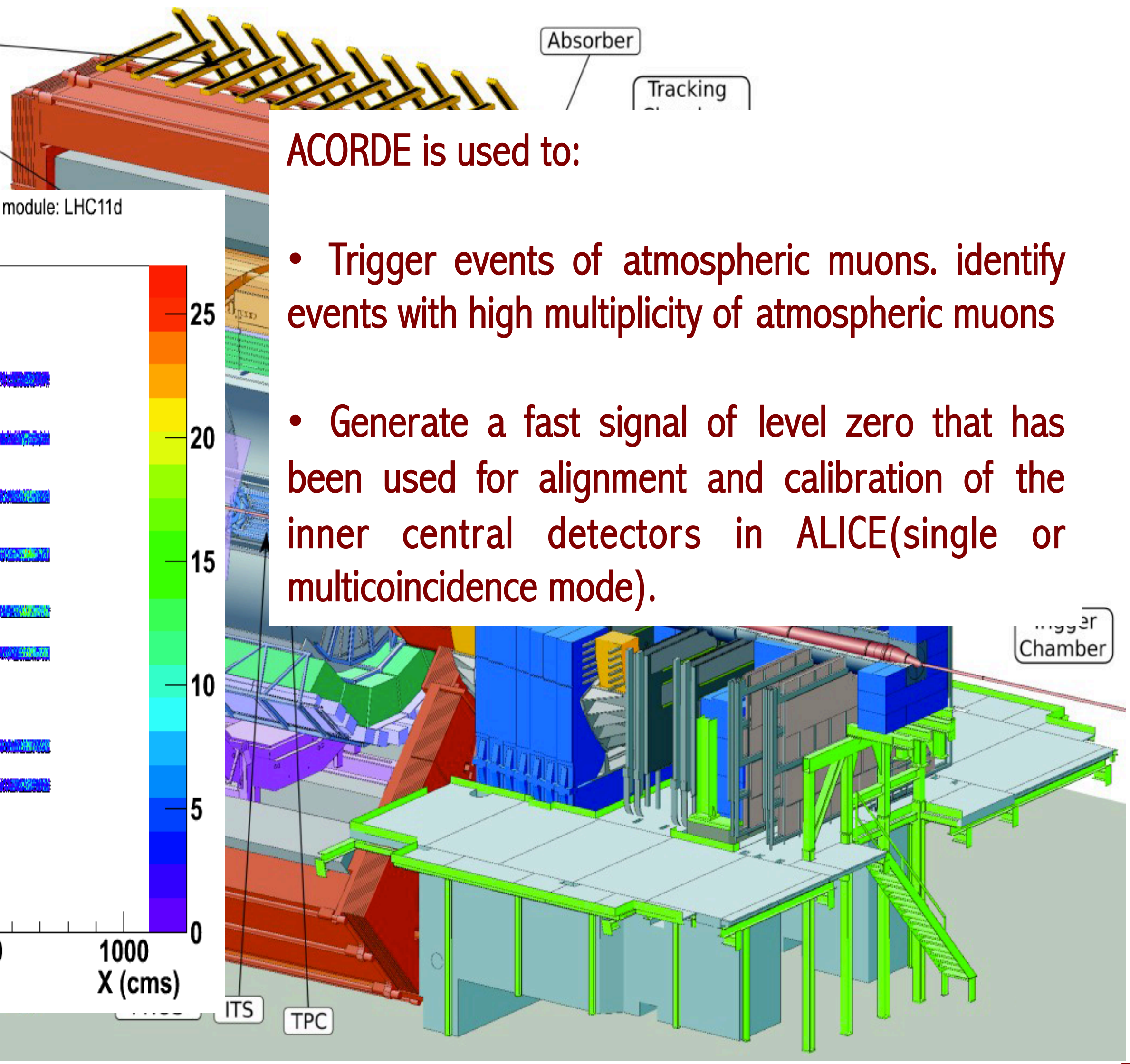




ALICE Experiment: trigger and detection for cosmics





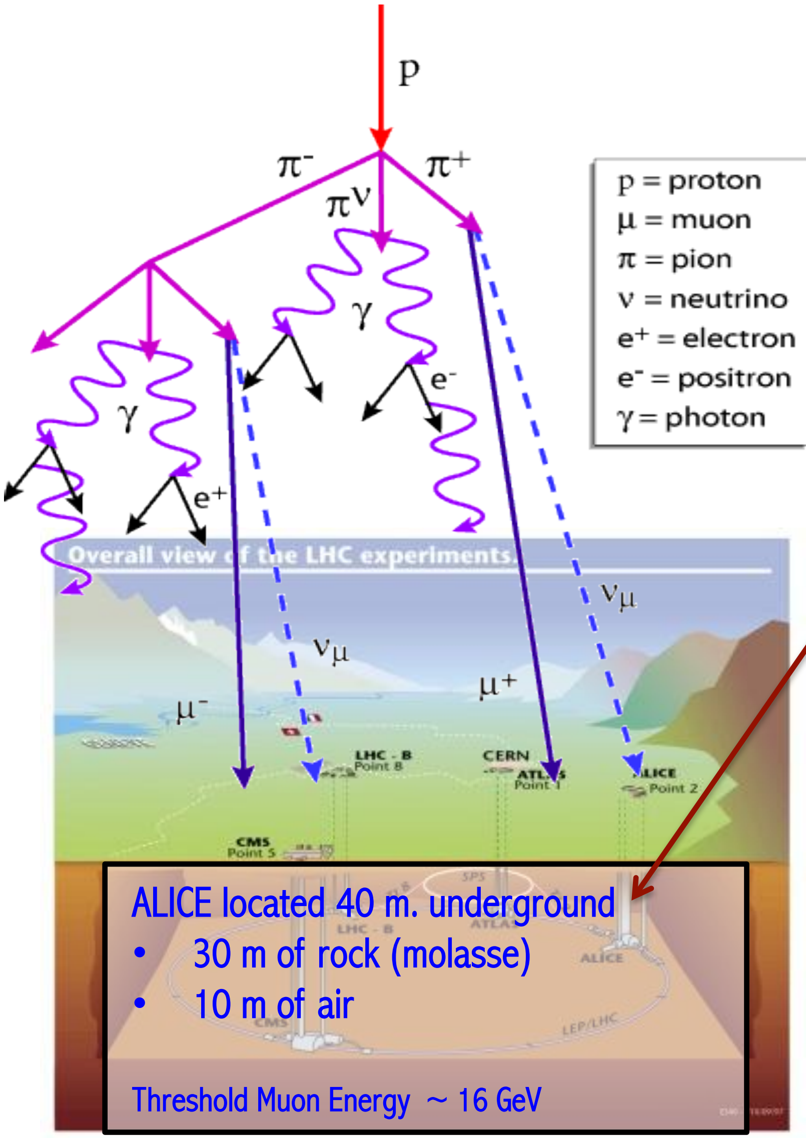


ACORDE is used to:

- Trigger events of atmospheric muons. identify events with high multiplicity of atmospheric muons

- Generate a fast signal of level zero that has been used for alignment and calibration of the inner central detectors in ALICE(single or multicoincidence mode).

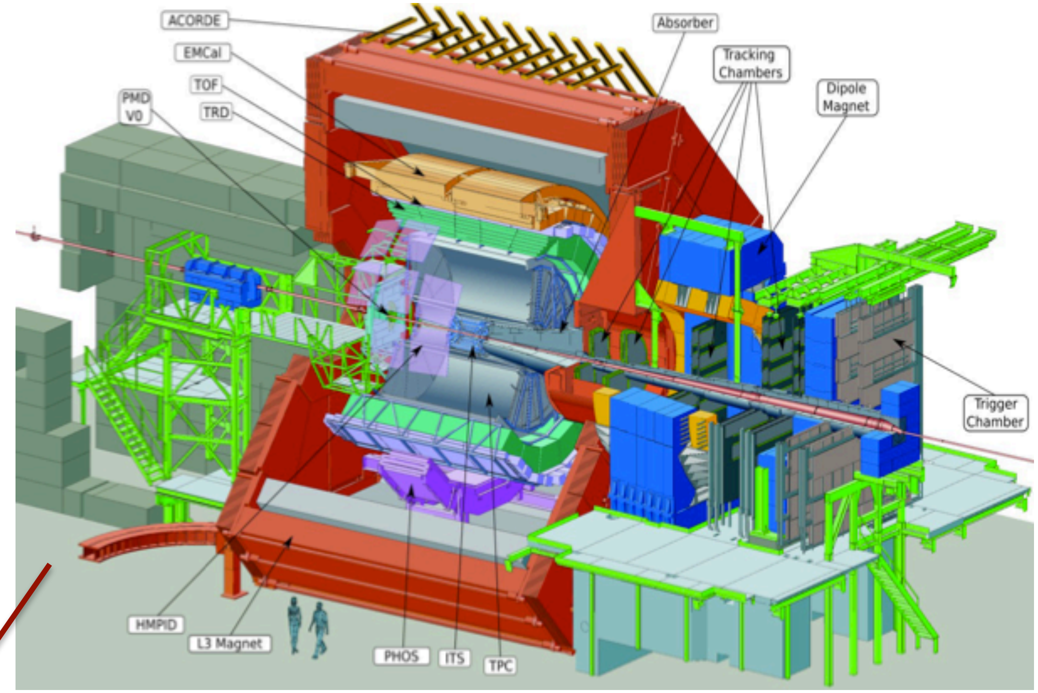
ALICE Experiment: trigger and detection for cosmics



ALICE located 40 m. underground

- 30 m of rock (molasse)
- 10 m of air

Threshold Muon Energy ~ 16 GeV



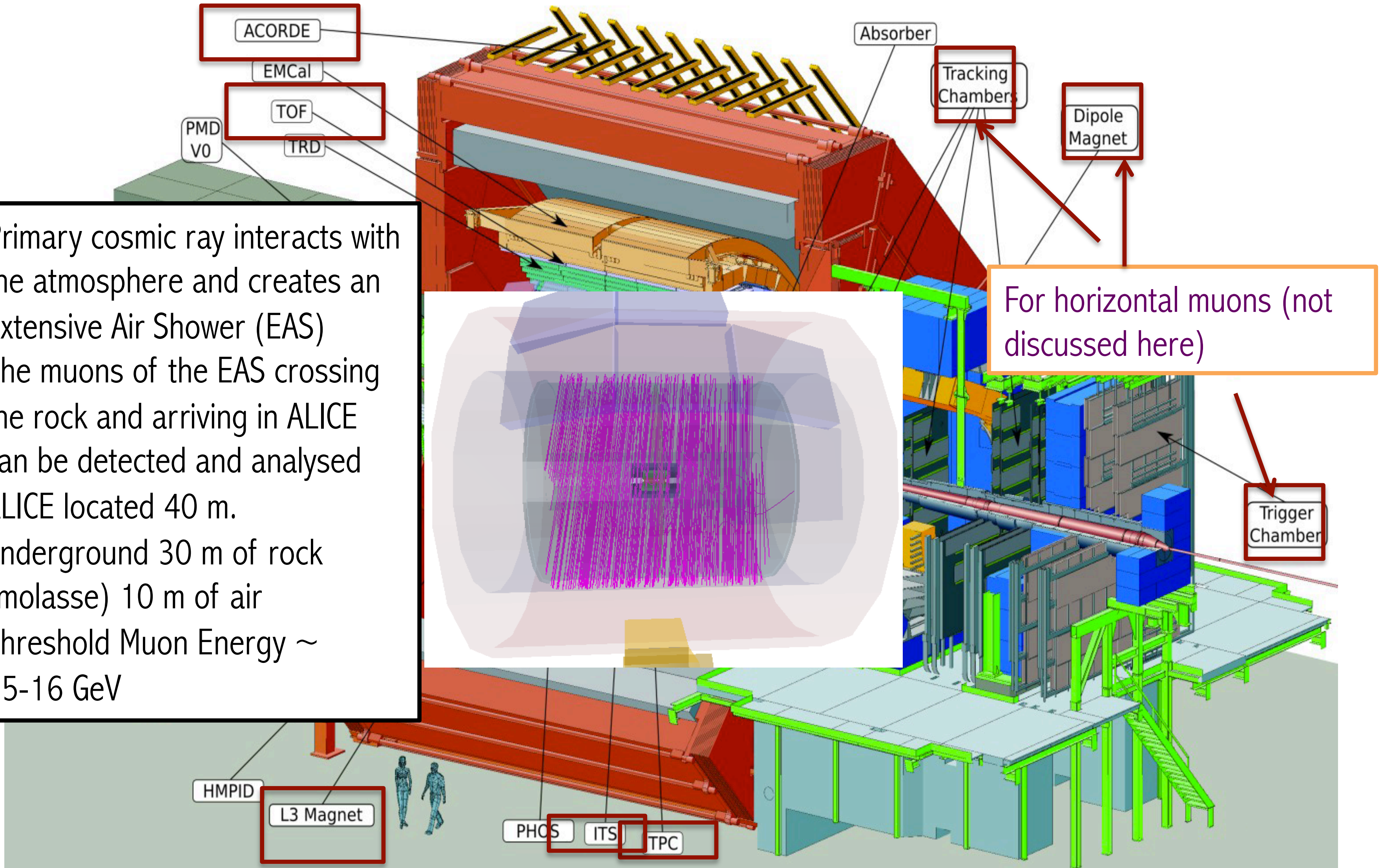
Topics of interest in Cosmic ray analysis in ALICE:

- ❑ Muon multiplicity distribution
  - ❑ Study of cosmic muon bundles
- ❑ μ^+/μ^- charge ratio measurement
- ❑ Study of cosmic horizontal muons

YEAR	DAYS OF DATA TAKING	TYPE OF RUN
2010	4.41	NO BEAM RUNS
2011	13.37	NO BEAM RUNS
2012	10.97	NO BEAM RUNS
	18.60*	BEAM RUNS*
2013	2.55	NO BEAM RUNS
TOTAL	49.9	NO BEAM/BEAM RUNS

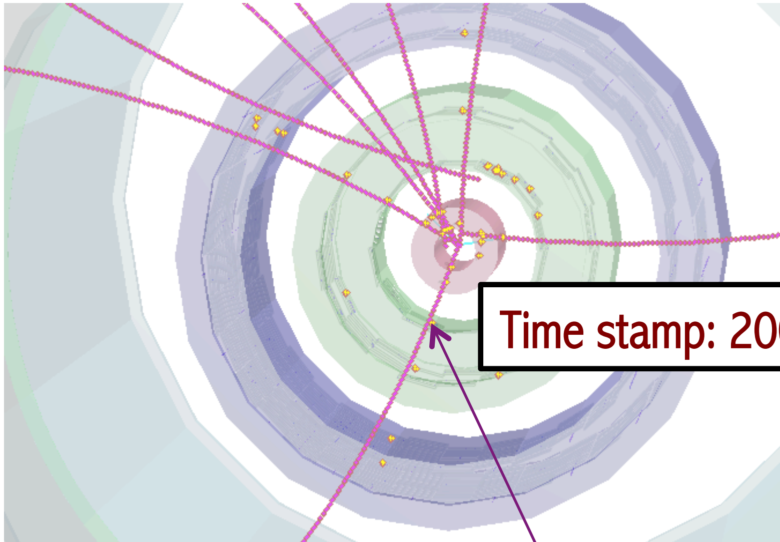
* Not discussed in this talk

ALICE Experiment: trigger and detection for cosmics

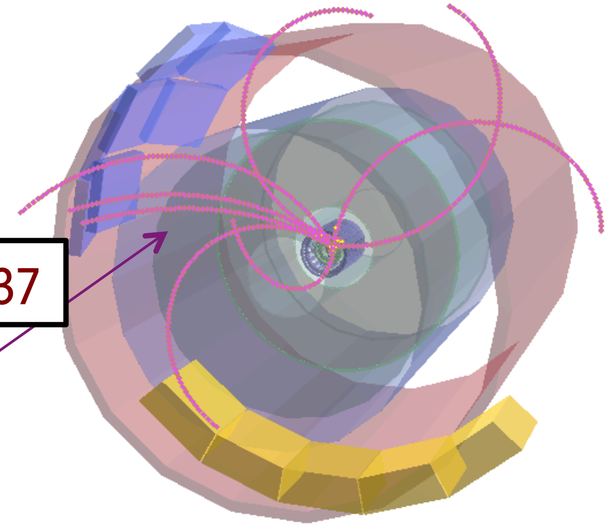


1. Primary cosmic ray interacts with the atmosphere and creates an Extensive Air Shower (EAS)
2. The muons of the EAS crossing the rock and arriving in ALICE can be detected and analysed
3. ALICE located 40 m. underground 30 m of rock (molasse) 10 m of air
4. Threshold Muon Energy ~ 15-16 GeV

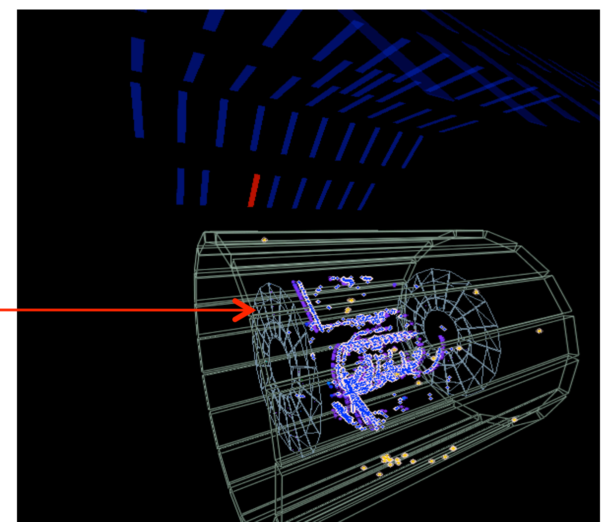
ALICE Experiment: trigger and detection for cosmics



Time stamp: 2009-11-23 16:13:37



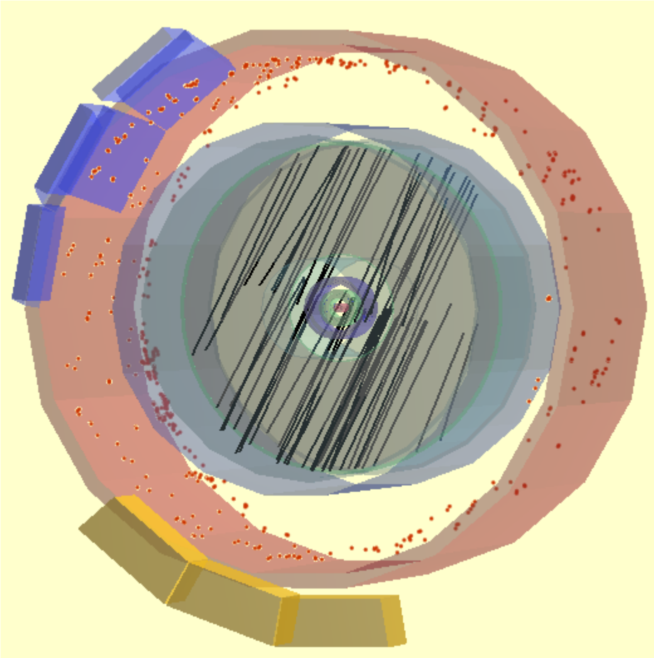
The algorithmes for reconstruction of tracks in the TPC have been created mainly for protons and heavy ions collisions.
These methods have been adapted and improved continuously during the analysis of CR – events which have a completely different topology.



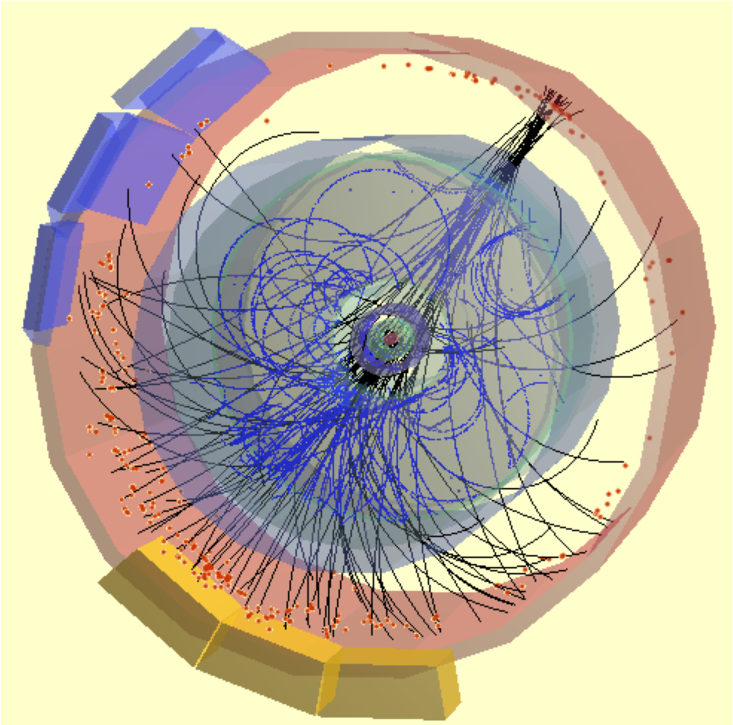
TIME PROJECTION CHAMBER (TPC) :

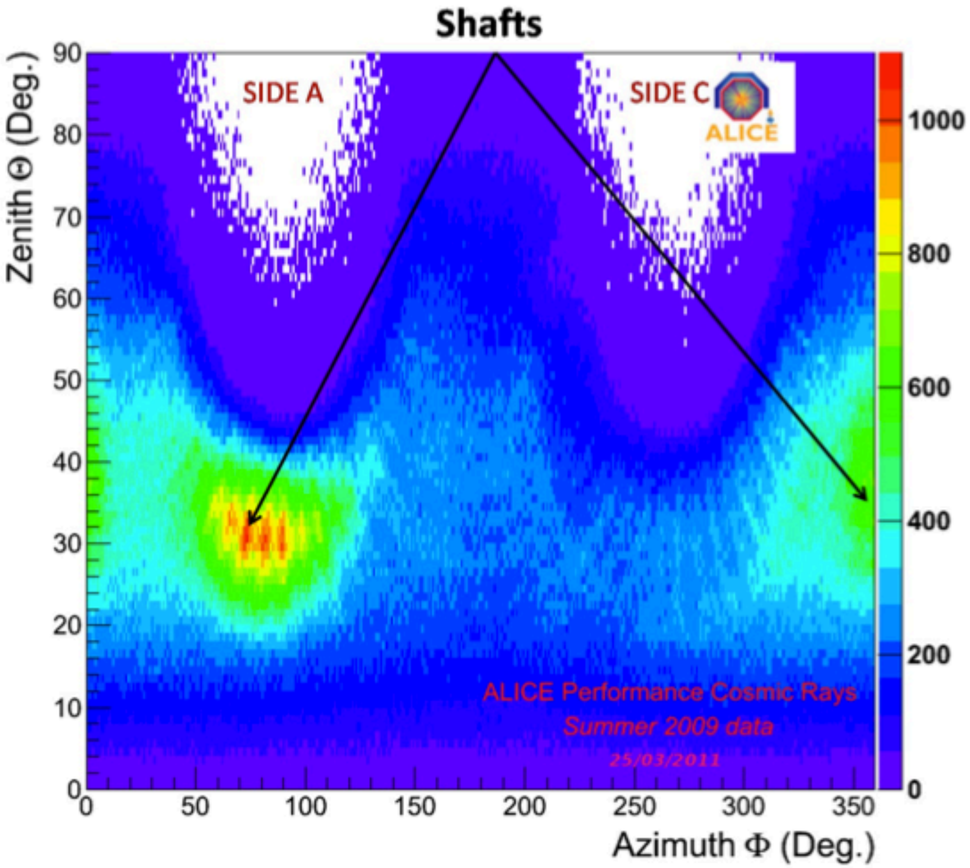
ALICE TPC Collaboration, J. Alme et al., "The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events.", Physics. Ins-Det/ 10011950 (2010).

Muon Interaction Event



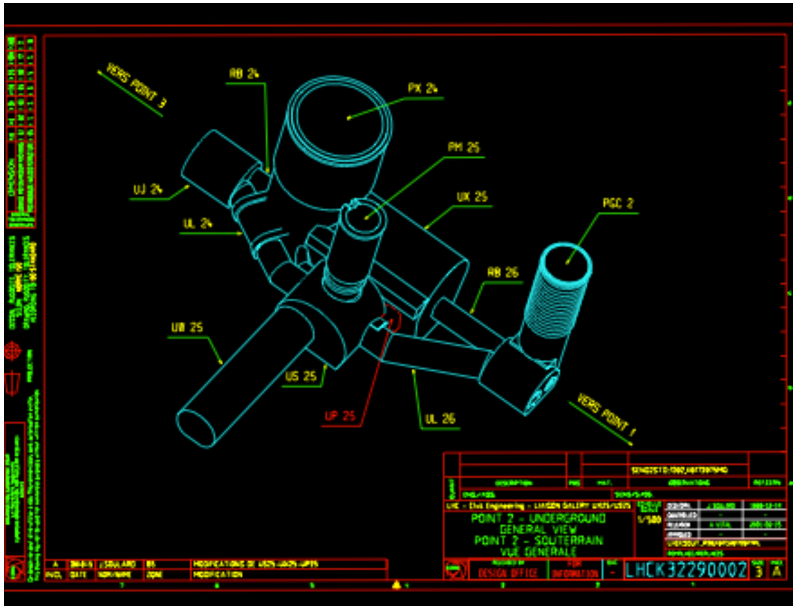
Standard Muon Event (multimuon)



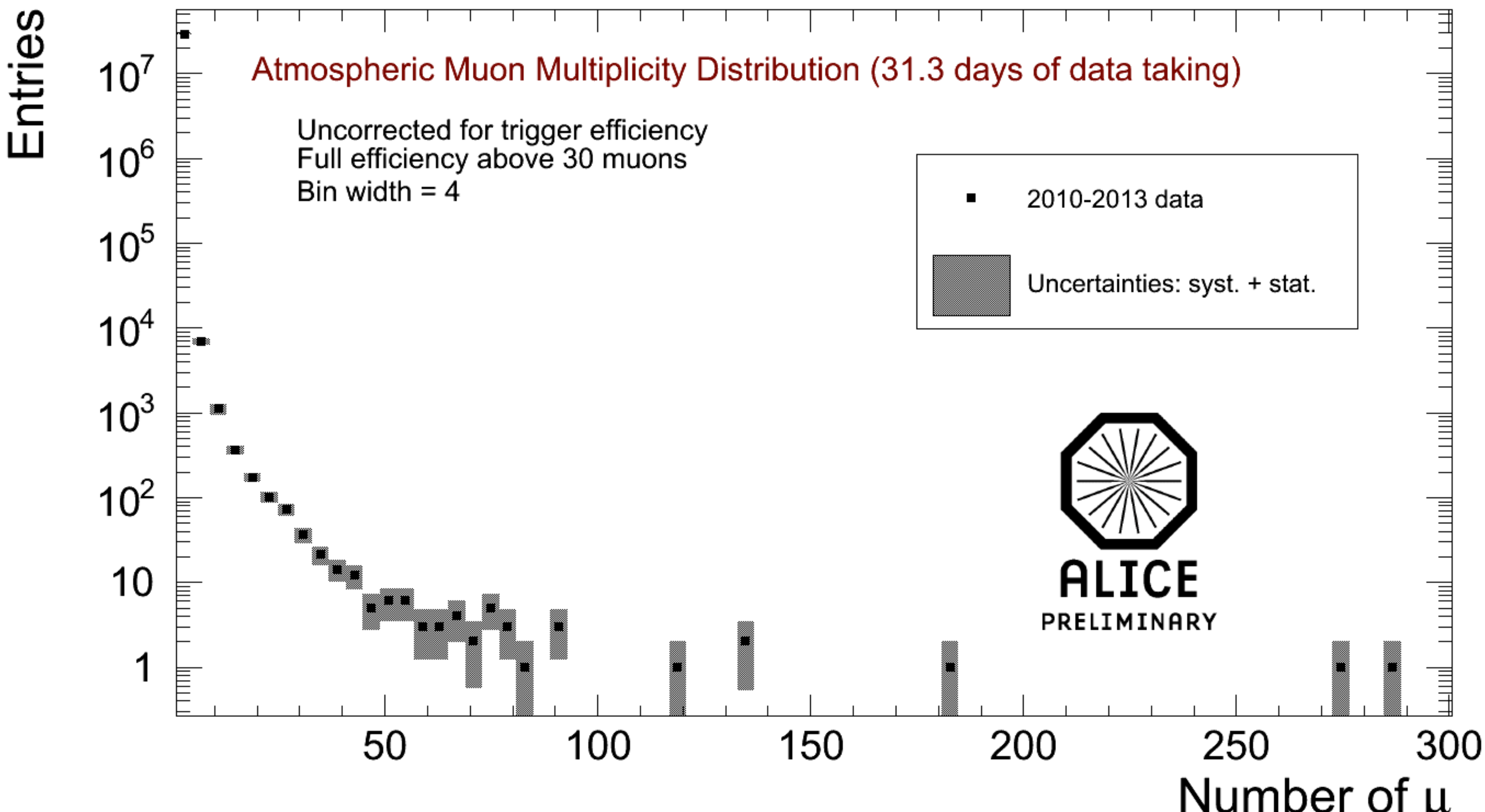


The muons crossing the shafts have a lower energy cut-off.

A larger number of muons arrive at the experiment in the directions of the shafts



ALICE Experiment: trigger and detection for cosmics



ALICE collected 6 events with more than 100 atmospheric muons during 31.3 days of data taking.

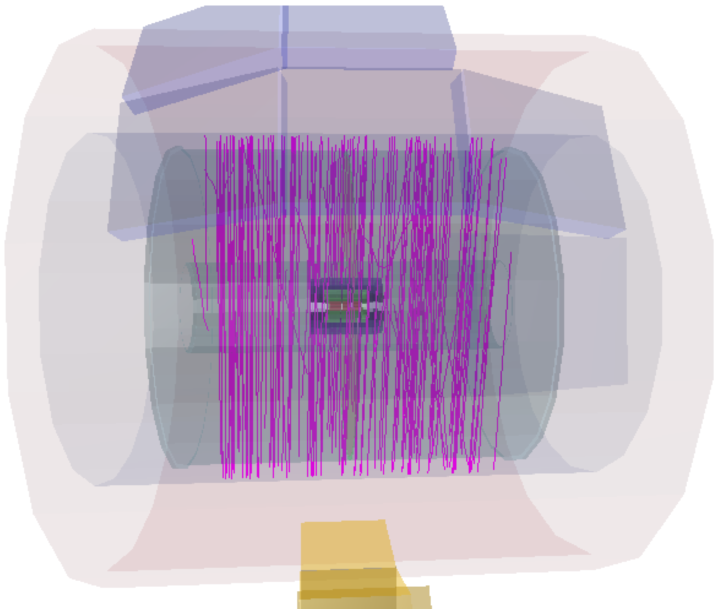
ALICE Experiment: trigger and detection for cosmics

Number of atm. muons	Run	Period	Trigger	B (T)	Zenith angle(^{0})	Azimuth angle (^{0})	Density of #muons/ m^2
136	111689	LHC10a	TOF	0	16.65	170.2	9
136	179742	LHC12c	TOF	0.5	2.60	264.8	9
181	110519	LHC10a	SPD	-0.5	40.39	212.4	12
276	152599	LHC11c	ACORDE	-0.5	26.02	192.9	18
288	179090	LHC12b	TOF	0	23.55	235.7	19

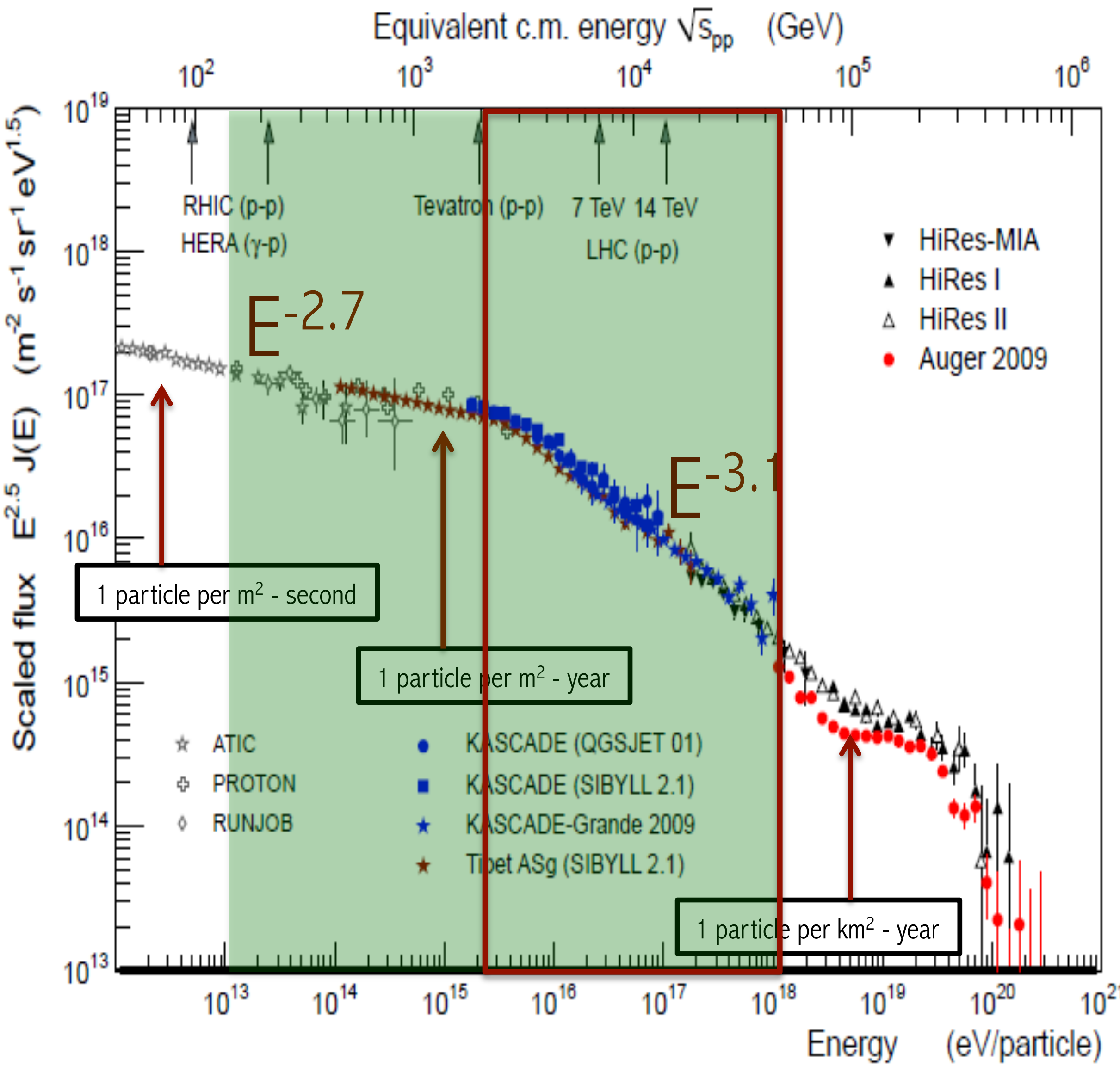
Applying the cut: zenith θ angle $\leq 50^0$, we obtain 5 hmm events.

QUESTION:

Is it possible to explain these high muon multiplicity events with a standard composition of primary cosmic rays and actual hadronic interaction model ?



Monte Carlo to study HME



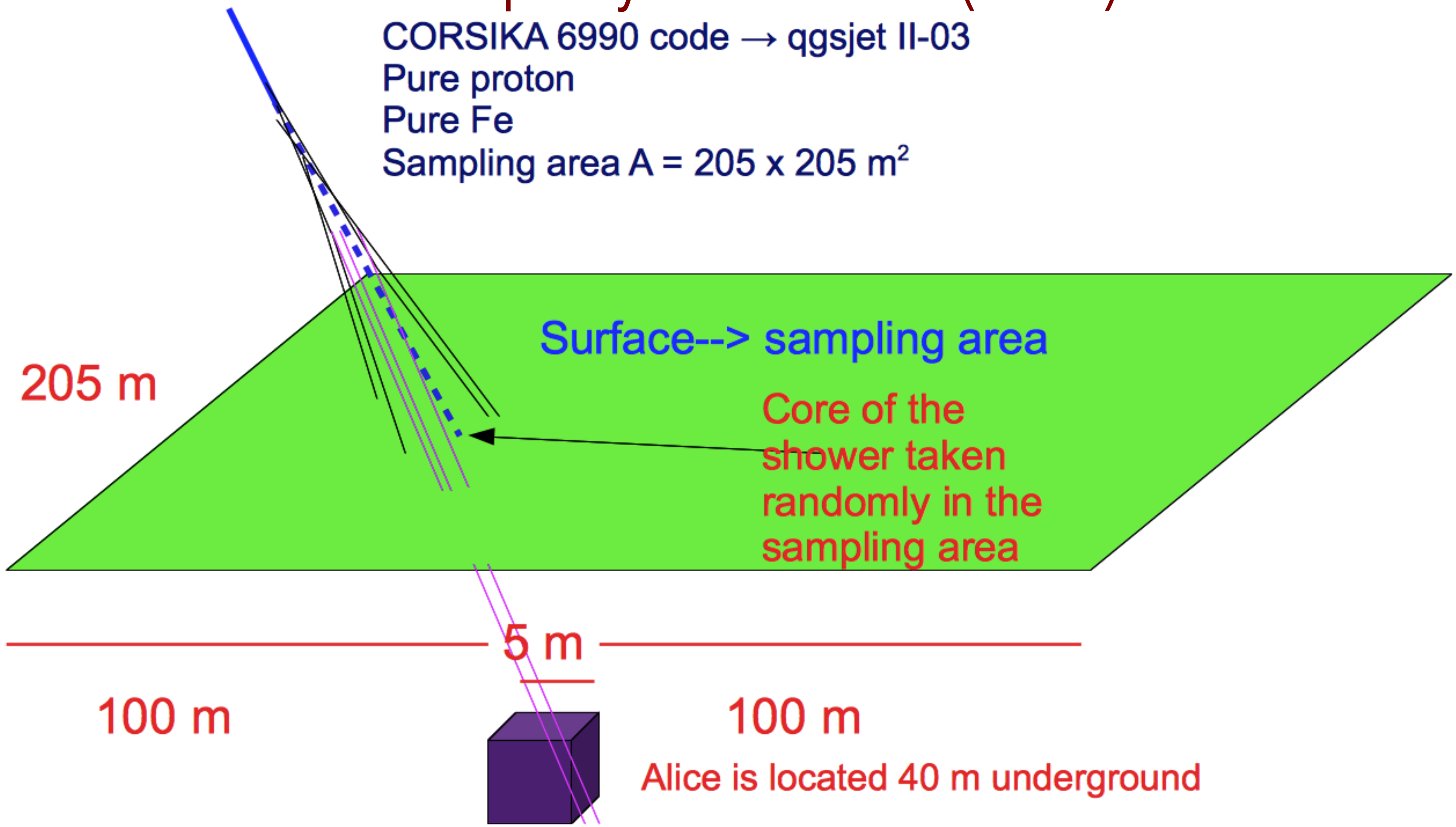
Primary Energy in Alice : $10^{13} < E < 10^{18}$ eV

To study high multiplicity events
Restrict the energy range above the knee :
$3 \times 10^{15} < E < 10^{18}$ eV

Flux of the all-particles extrapolated from J. Horandel, Astrop.Phys. 19 (2003) 193-220

Monte Carlo simulations to study the muon multiplicity distribution (mmd)

CORSIKA 6990 code → qgsjet II-03
Pure proton
Pure Fe
Sampling area A = 205 x 205 m^2



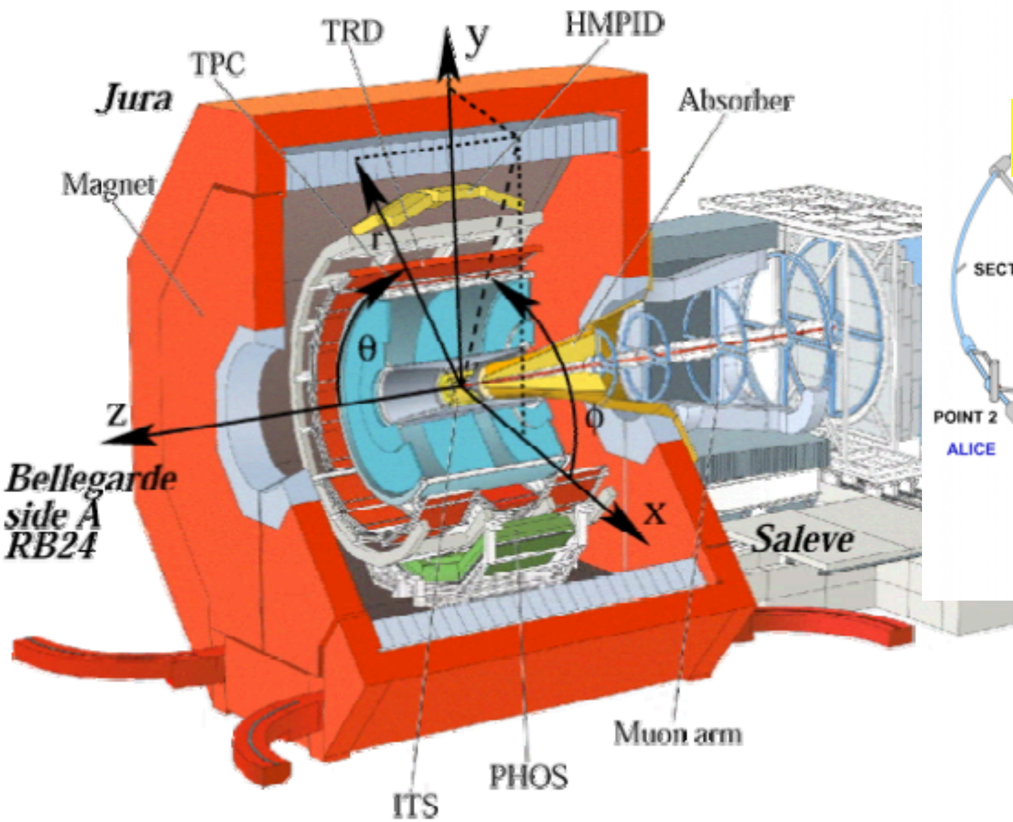
Monte Carlo to study HME

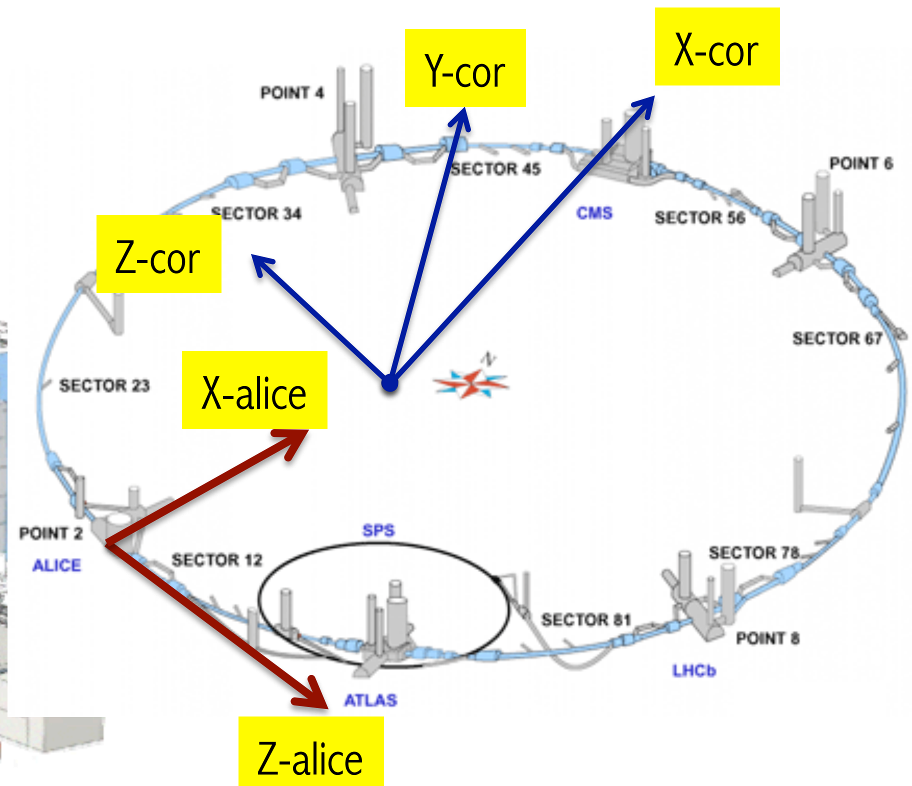
General: All ALICE sub-detector components are to be numbered starting from zero.

Rotational Numbering: Counter-clockwise (coinciding with the direction of increase of the angle φ) on the side ***A*** of the detector with the observer looking toward side ***C*** and clockwise on side ***C*** of the detector with the observer looking toward side ***A***. This way, sub-detectors which have mirror symmetry with respect to the x,y plane will have the same part numbers facing each other on the two sides of the detector. If a sub-detector part is sectioned by the x axis, it will be number 0, otherwise the first sub-detector part at positive y will be number 0.

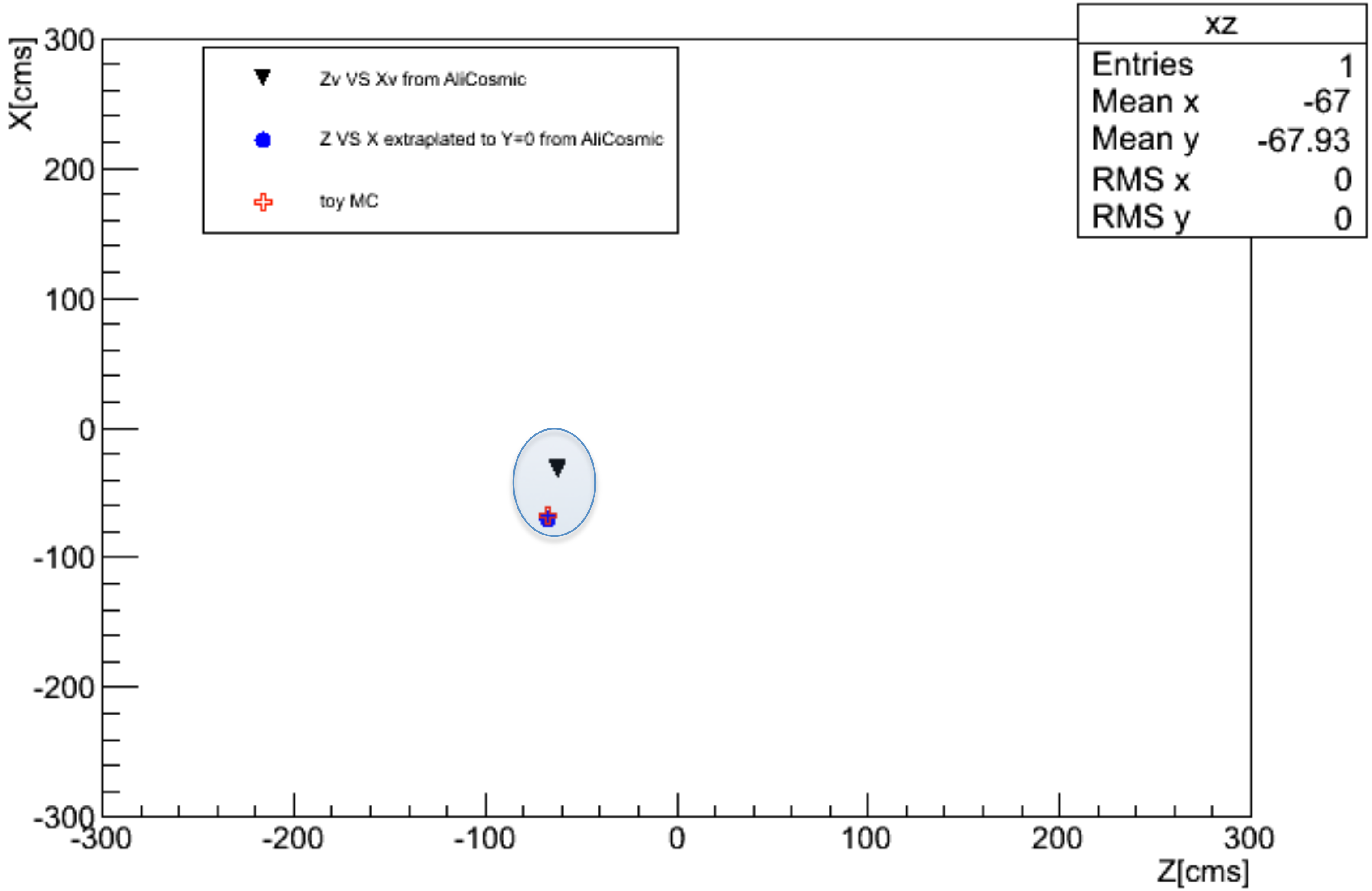
Linear Numbering: The counting increases from side ***A*** to side ***C***, opposite to the z axis direction, without interruption in the middle at z = 0.

Radial Numbering: The counting increases with increasing radius.



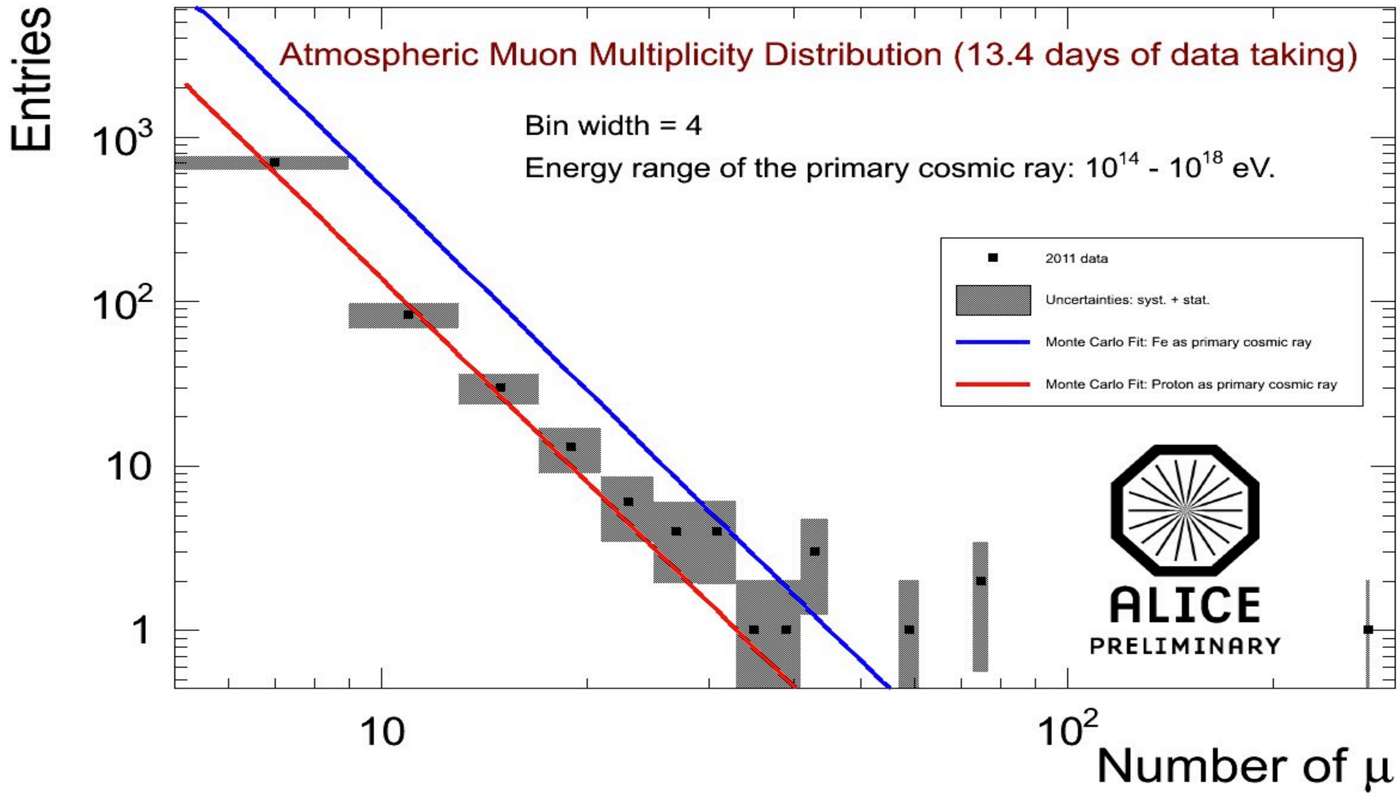


Monte Carlo to study HME



Monte Carlo to study HME

MMD at low muon multiplicity (Nmu>=4) with and absolute normalization for 13.4 days (2011 data)



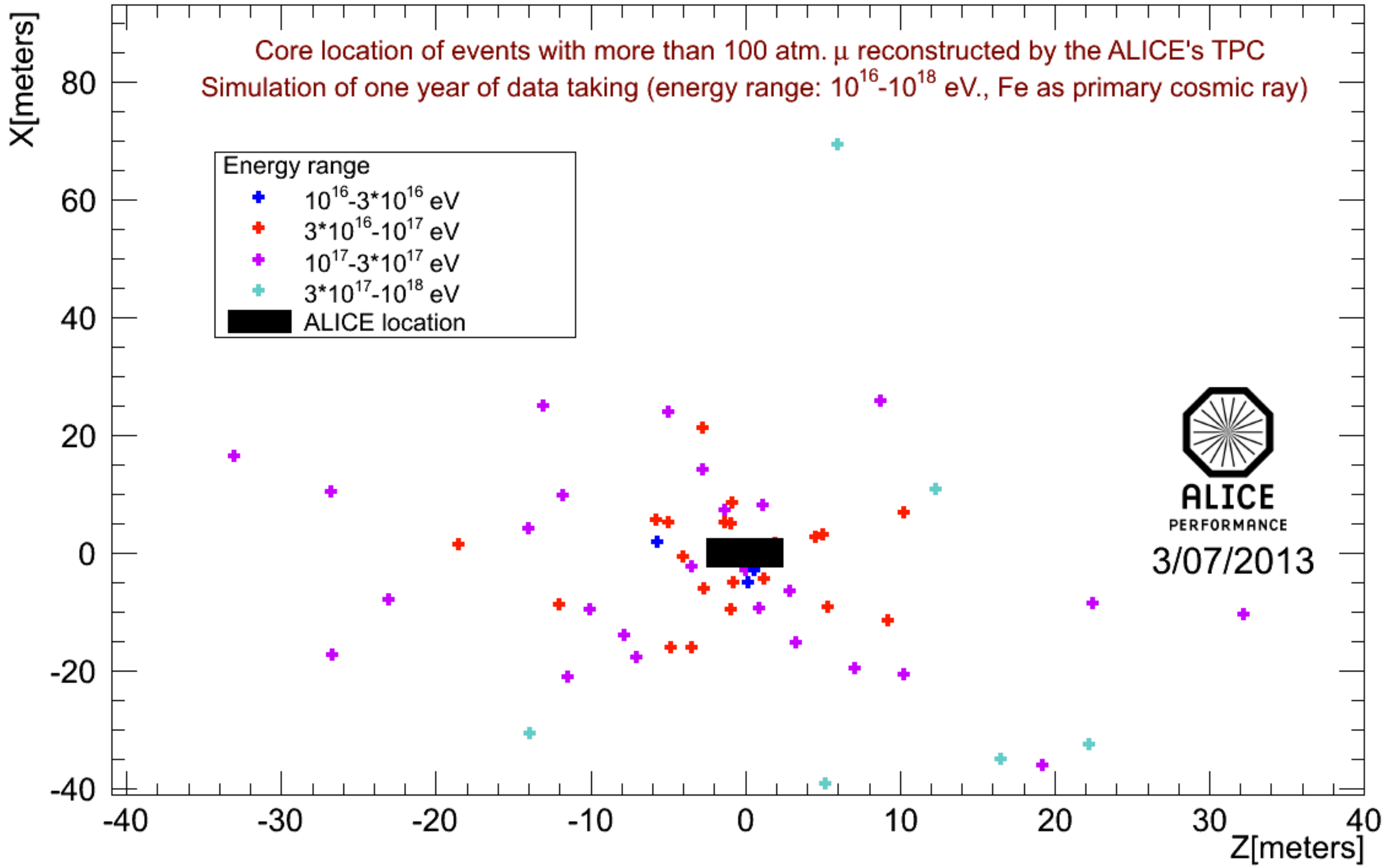
- Primary energy range of the simulation : $10^{14} < E < 10^{18}$ eV
- The data are, as expected, in between the pure Proton composition (light elements) and pure Fe (heavy elements).
- The lower multiplicities (lower primary energies) are closer to pure Proton as expected.

We want to measure the rate of the hmm events.

To reduce the fluctuations, we simulate 1 year of data
(Corsika 6990-Corsika 73500, QGSJET II-03, QGSJET II-04)

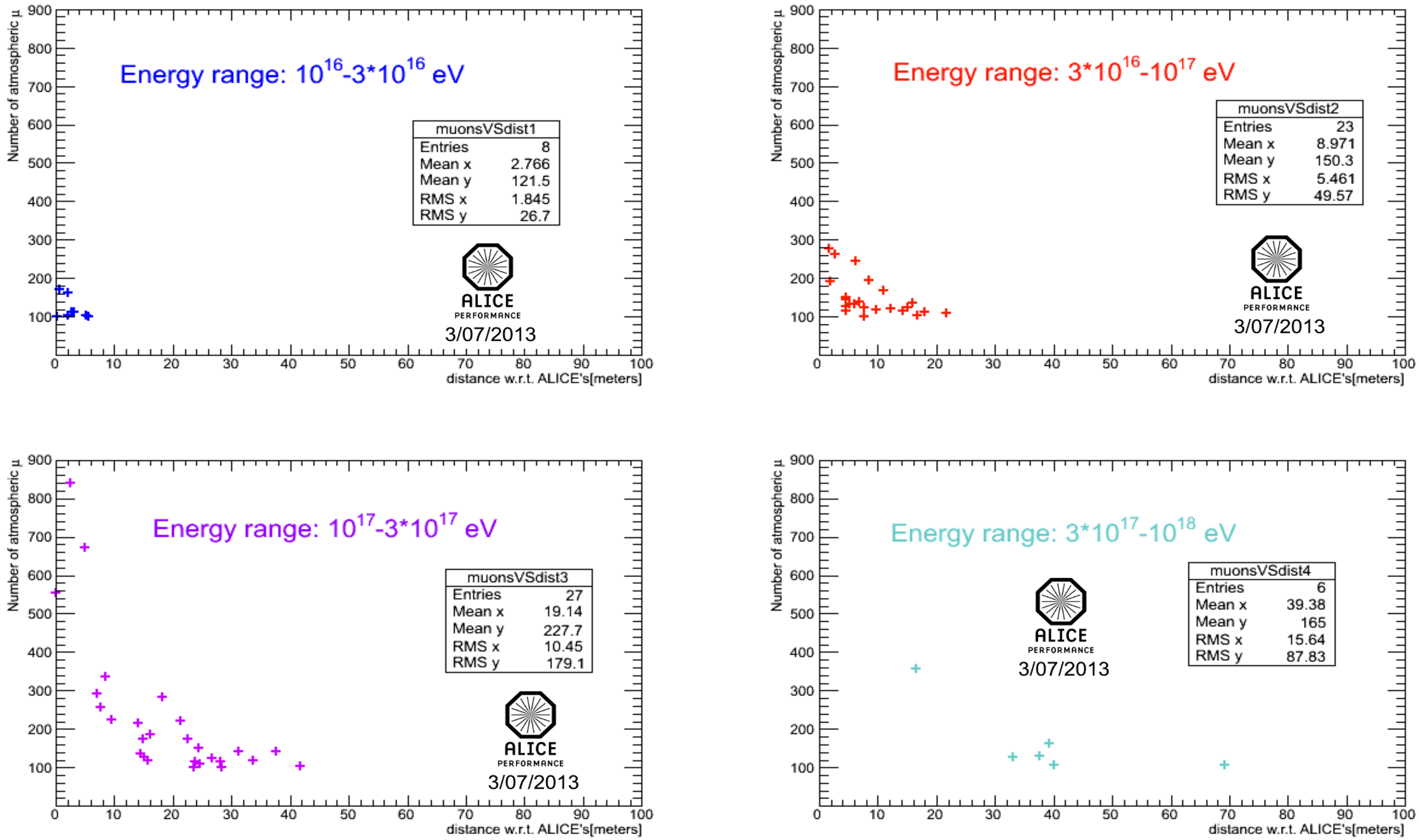
- Energy range: $10^{16} - 10^{18}$ eV
- Primary cosmic ray composition: proton, Fe nuclei
- Theta <= 50^0

Monte Carlo to study HME



Core's position (ALICE coordinate system reference) w.r.t ALICE for the different energy ranges simulated:
The black rectangle shows the ALICE's surface in the XZ plane.
Most of the hmm events have a core located very close to ALICE (< 30 m),
only some events of very high primary energy have a farther core (cyan markers)

Monte Carlo to study HME



Number of muons VS distance of the CORE of primary cosmic ray, different Intervals of energy ranges

Monte Carlo to study HME

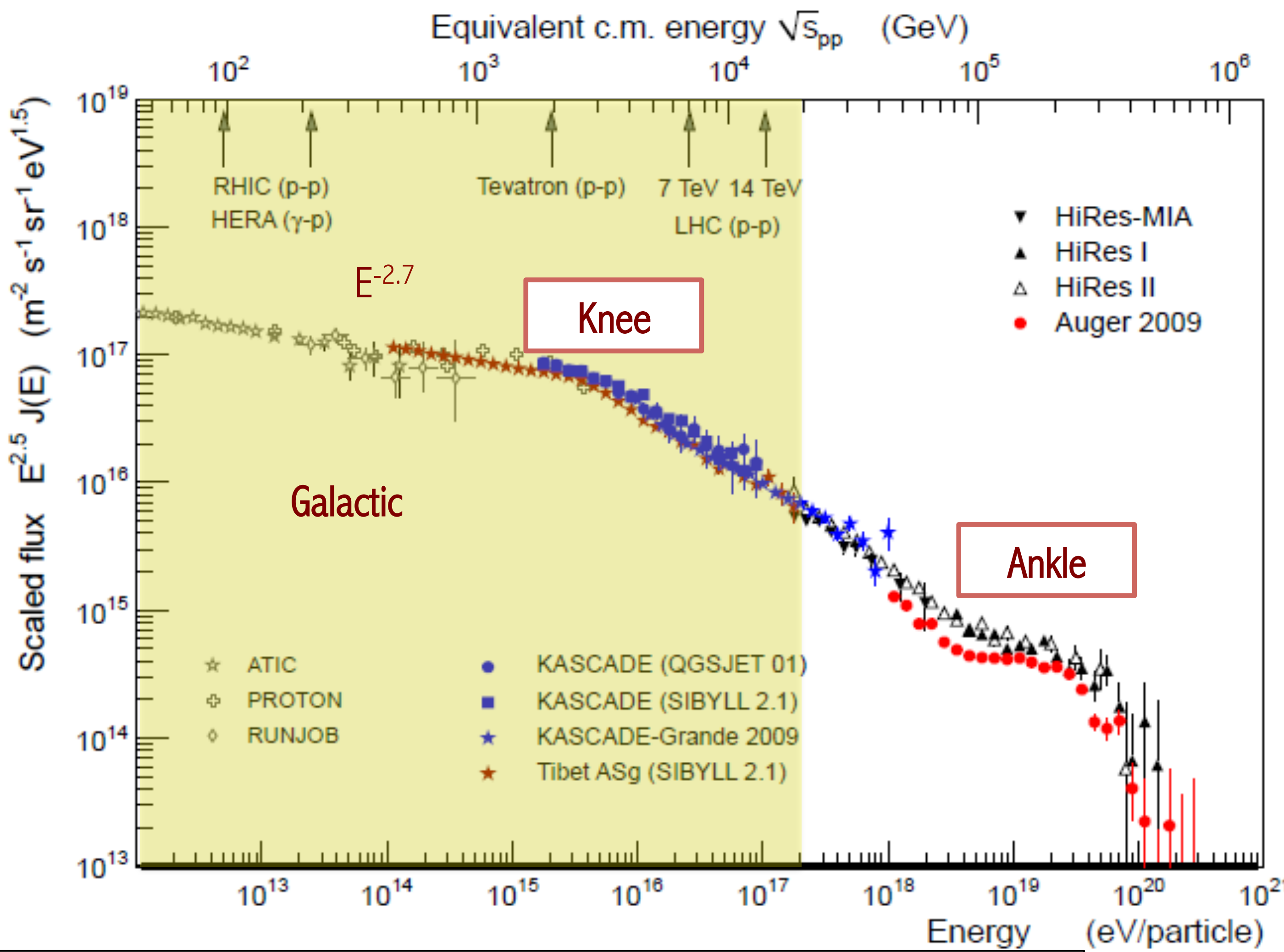
MONTE CARLO				
Model	Primary Cosmic Ray composition in the energy range 10^{16}-10^{18} eV	HME rate (/days)	Rate (Hz)	Syst. Uncertainty (%): syst. + stat.
QGSJET II-03	Fe	1 event each 5.7	2.0×10^{-6}	20
	Proton	1 event each 11.8	9.8×10^{-7}	17
QGSJET II-04	Fe	1 event each 4.9	2.3×10^{-6}	20
	Proton	1 event each 10.7	1.1×10^{-6}	17

DATA		
HME rate (/days)	Rate (Hz)	Syst. Uncertainty (%): syst. + stat.
1 event each 6.3	1.81×10^{-6}	40

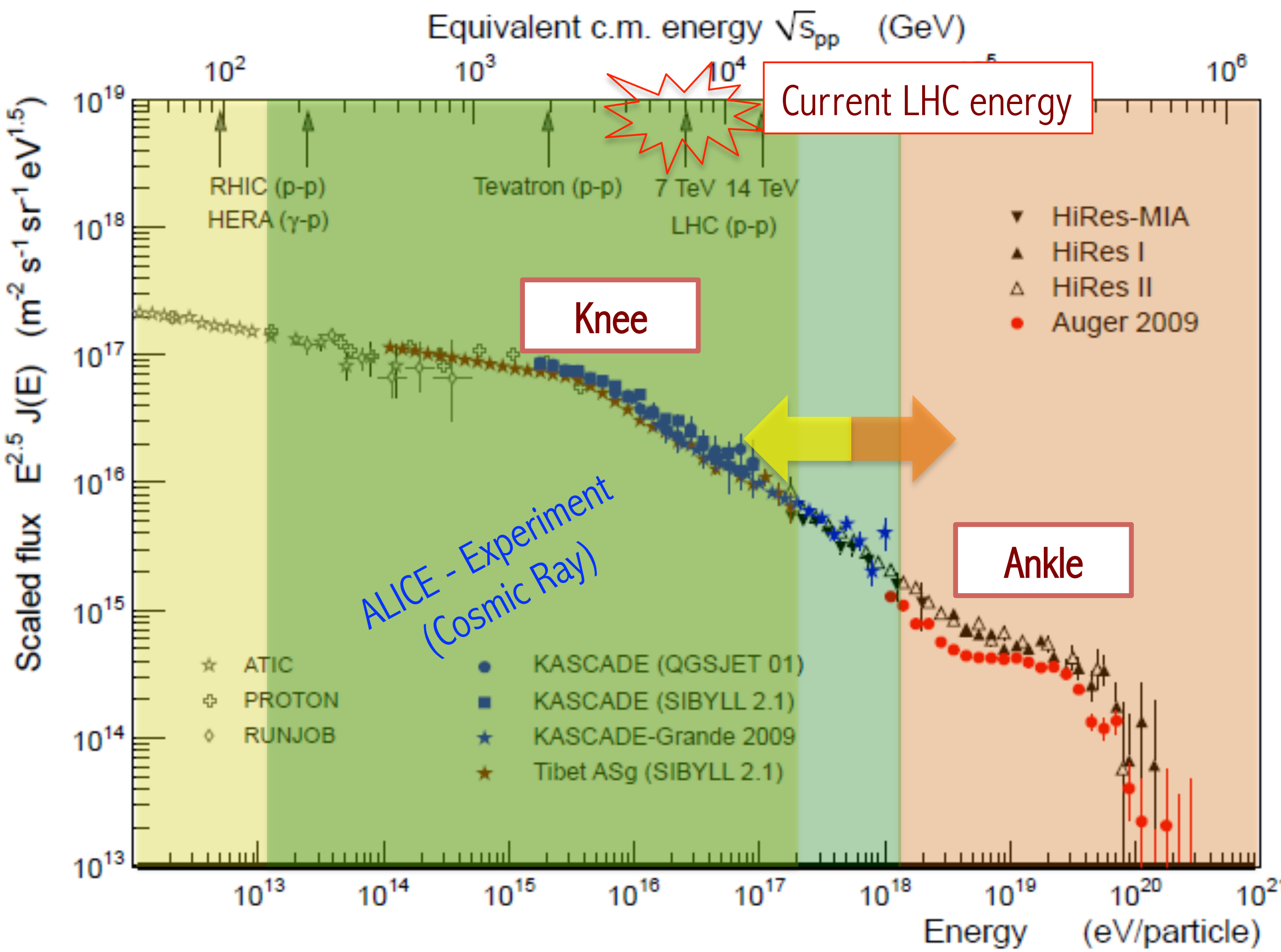
Final comments

- ✓ In the period 2010-2013 ALICE experiment took around 31.3 effective days of dedicated cosmic runs, recording around 35 million trigger events.
- ✓ A mixed composition with an increasing average mass of the primary at higher energies is suggested (MC vs Data).
- ✓ 5 events with more than 100 muons reconstructed in the TPC have been found. These type of high multiplicity events were also found by Aleph and Delphi at LEP.
- ✓ Using CORSIKA (6990 and 7350) with the QGSJET II-03/04 as interaction models we are able to simulate these events and to reproduce the ending tail of the high muon multiplicity spectrum.
- ✓ These events seem mostly due to iron or heavy nuclei with an energy greater than 10^{16} eV and a shower core located near ALICE.

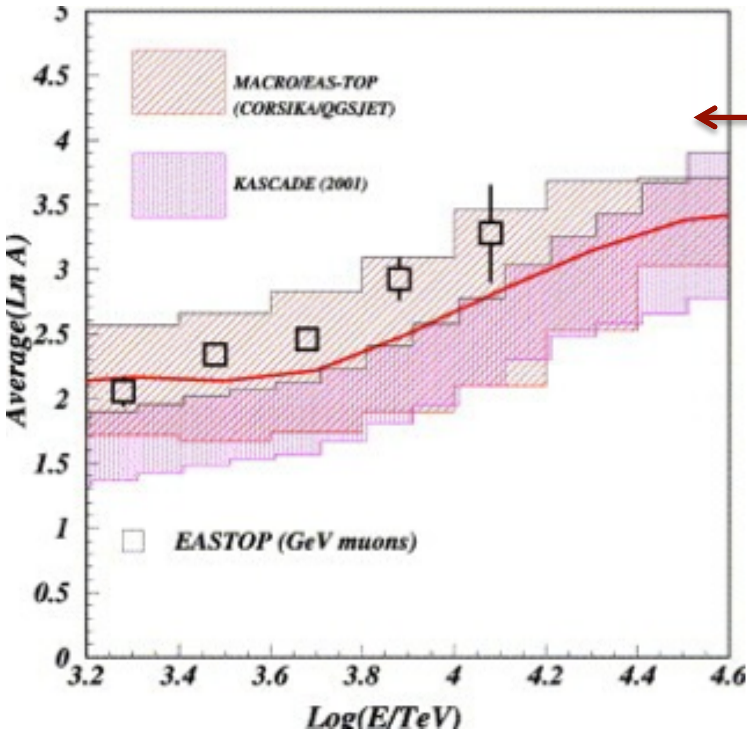
BACKUP



- Density of the galactic primary cosmic ray: ~ 1 eV/cm^3
- Protons for energies below 10^{16} eV
- Heavy nuclei composition: ~ $8*10^{16}$ eV (**Phys. Rev. Lett. 107, 171104 (2011)**)



Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2
10^3
10^4
10^6
Current LHC energy
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
Auger 2009
Knee
Ankle
ALICE - Experiment
(Cosmic Ray)
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2009
Tibet ASg (SIBYLL 2.1)
Scaled flux $E^{2.5}$ J(E) $(m^{-2} s^{-1} sr^{-1} eV^{1.5})$
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
Energy (eV/particle)



MACRO-EASTOP KASCADE :

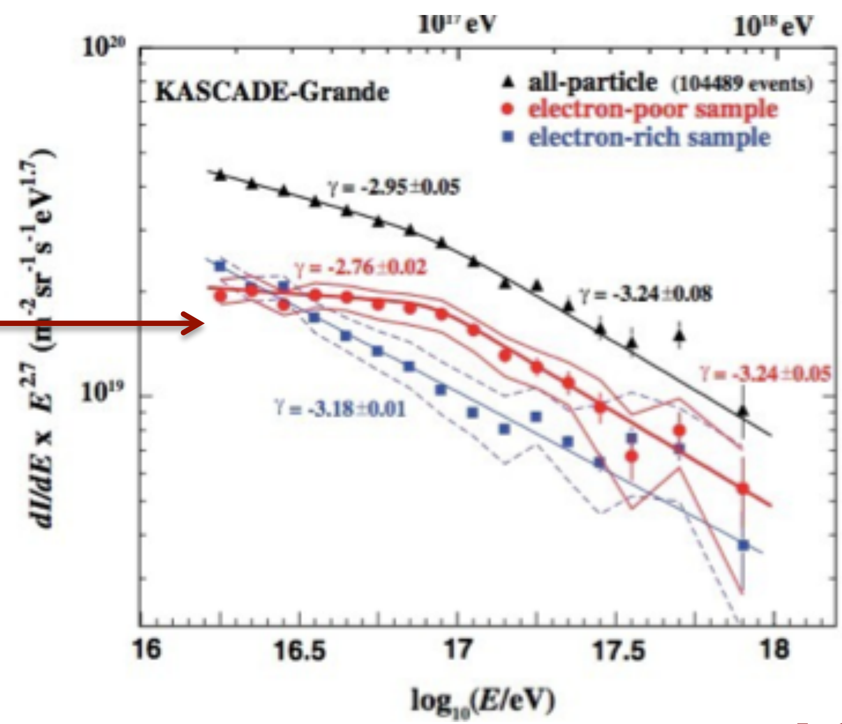
- Primary Composition Ln(A) vs Energy
- A=mass of the primary nucleus

There is an increase of the:

- <A> above the knee
- <A> ~ 8 at 3 x 10^{15} eV
- <A> ~ 30 at 3 x 10^{16} eV

KASCADE-GRANDE :

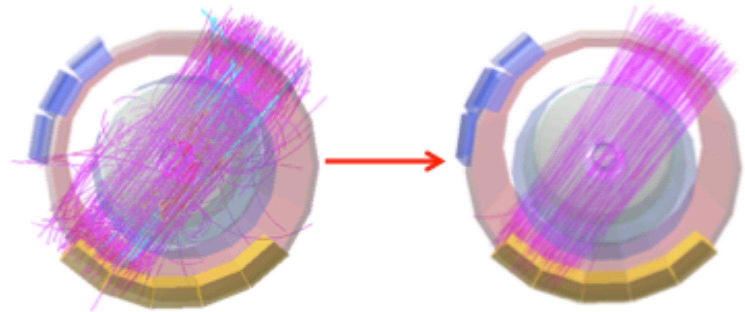
- electron-poor sample selects heavy elements (Fe) and shows a knee at E~ 8 x 10^{16} eV
- electron-rich sample selects light elements and the knee is at lower energy E ~ 3 x 10^{15} eV

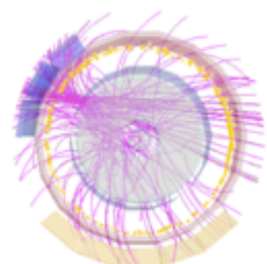


Introduction

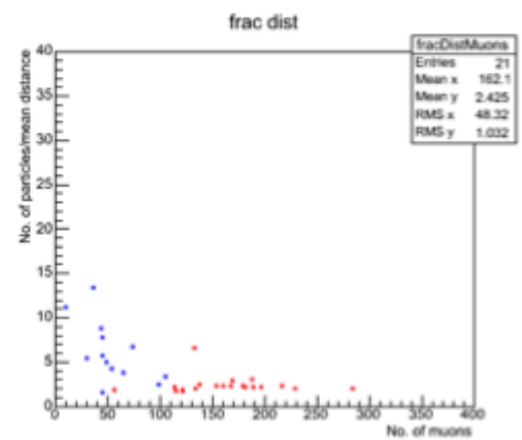
La TPC de ALICE se ha desempeñado con gran eficiencia en la reconstrucción de los datos provenientes de las colisiones p-p y Pb-Pb en el CERN – LHC. Para el estudio de muones atmósfericos, se deben entender sus capacidades en la reconstrucción de las trayectorias de los mismos.

- $p > 0{,}5\ GeV/c$: con esto excluimos del análisis a aquellas trayectorias de baja calidad que no contribuirán significativamente a la identificación de trayectorias paralelas.
- $\Delta dist < 3\ cms$: la distancia entre cada par de trayectorias debe ser menor a 3 cms. para ser consideradas como la misma para una partícula cargada.
- $cos(\Delta\theta) > 0{,}990$: el ángulo entre ambas trayectorias no debe ser aproximadamente de 180^0.
- $cls > 50$ para trayectorias solitarias: se espera que este este tipo de trayectorias atravie-sen al menos el 40 % del área transversal de la TPC.
- $cls > 30$ para cada par de trayectorias correspondientes entre sí: cuando la multiplicidad de partículas es alta, se espera que este tipo de trayectorias atraviesen al menos el 20 % de la sección transversal de la TPC.

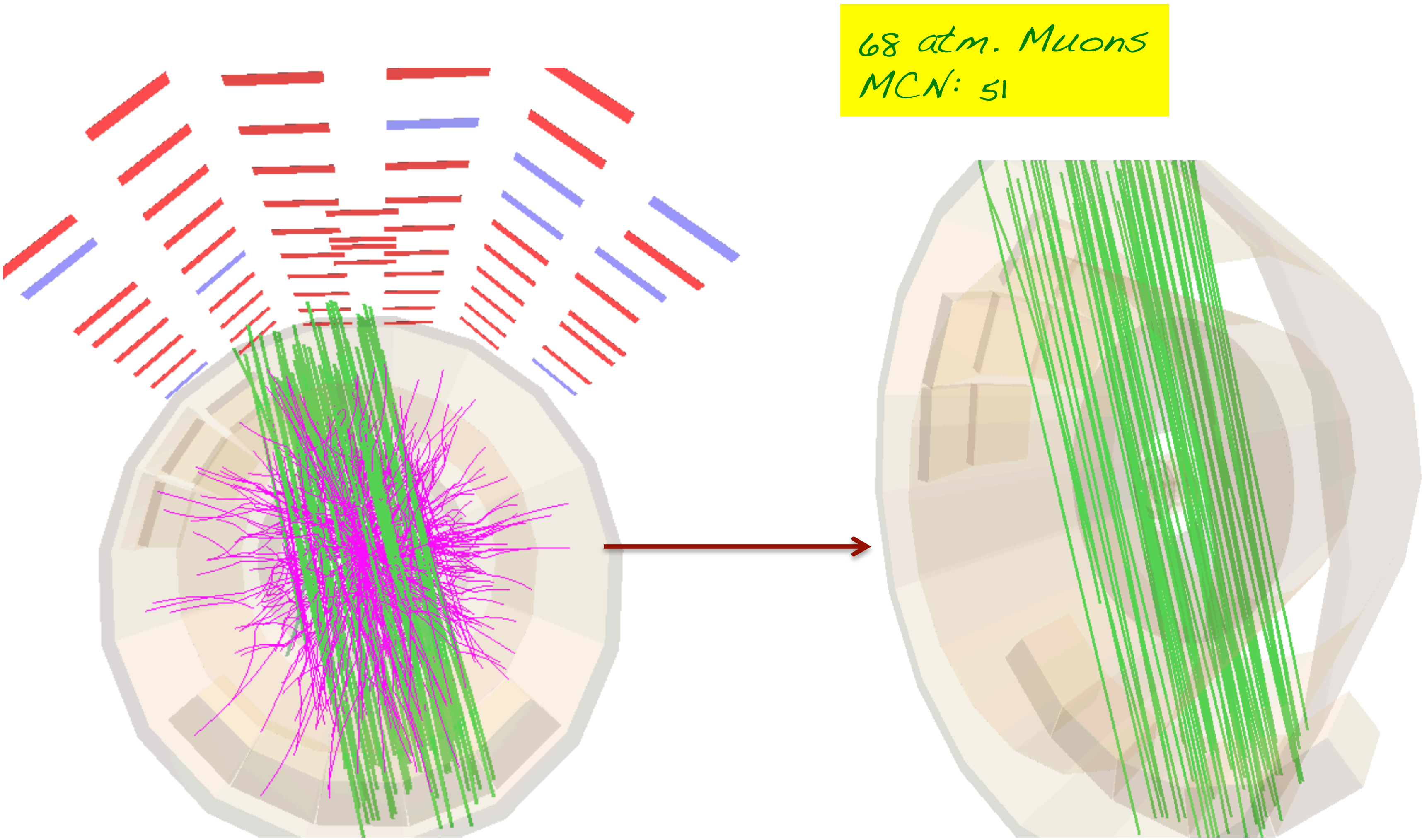


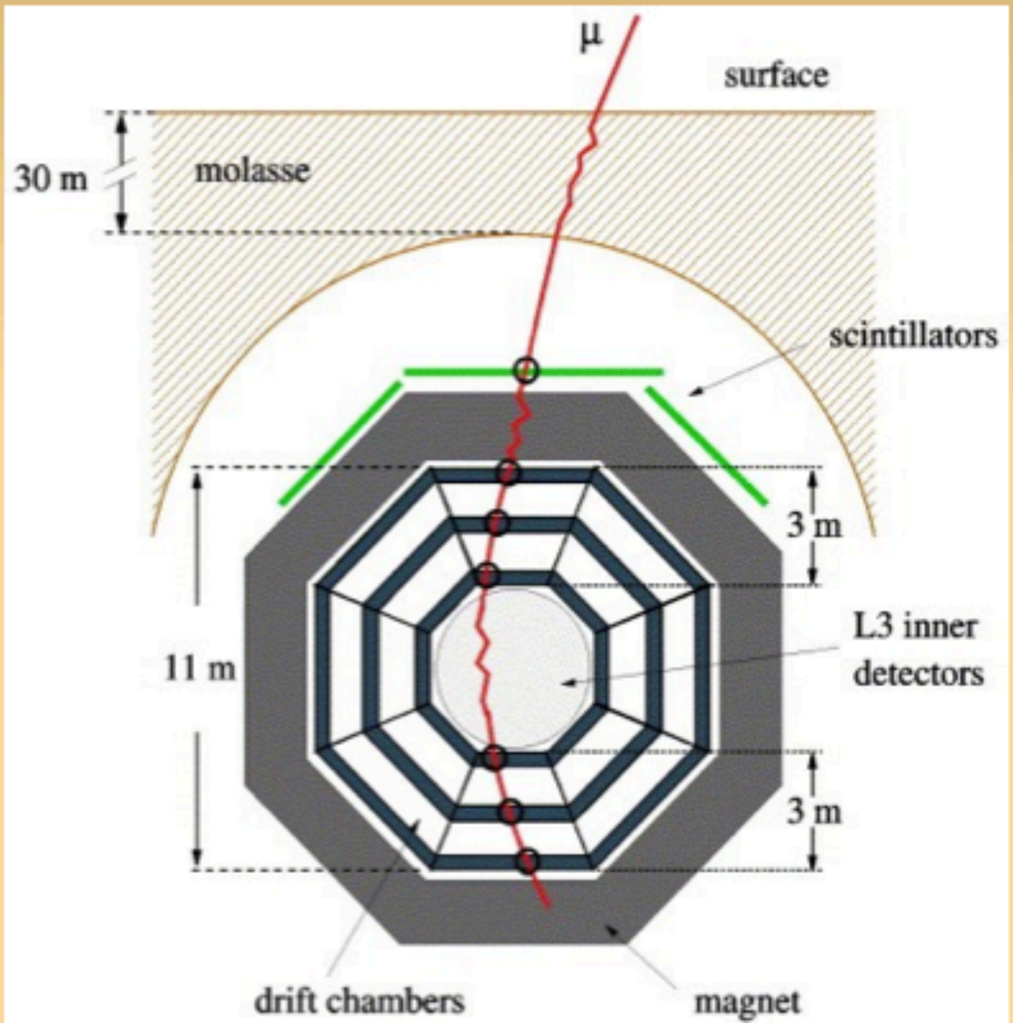


- $mean_{dist} > 47\ cms$: la distancia entre cada par de trayectorias se espera que sea grande comparada con eventos de multi-muones.
- $nTracks/nMuons > 2{,}3$: debido a la topología de las trayectorias reconstruidas, en promedio la TPC reconstruye el 50 % de las mismas como partículas cargadas.

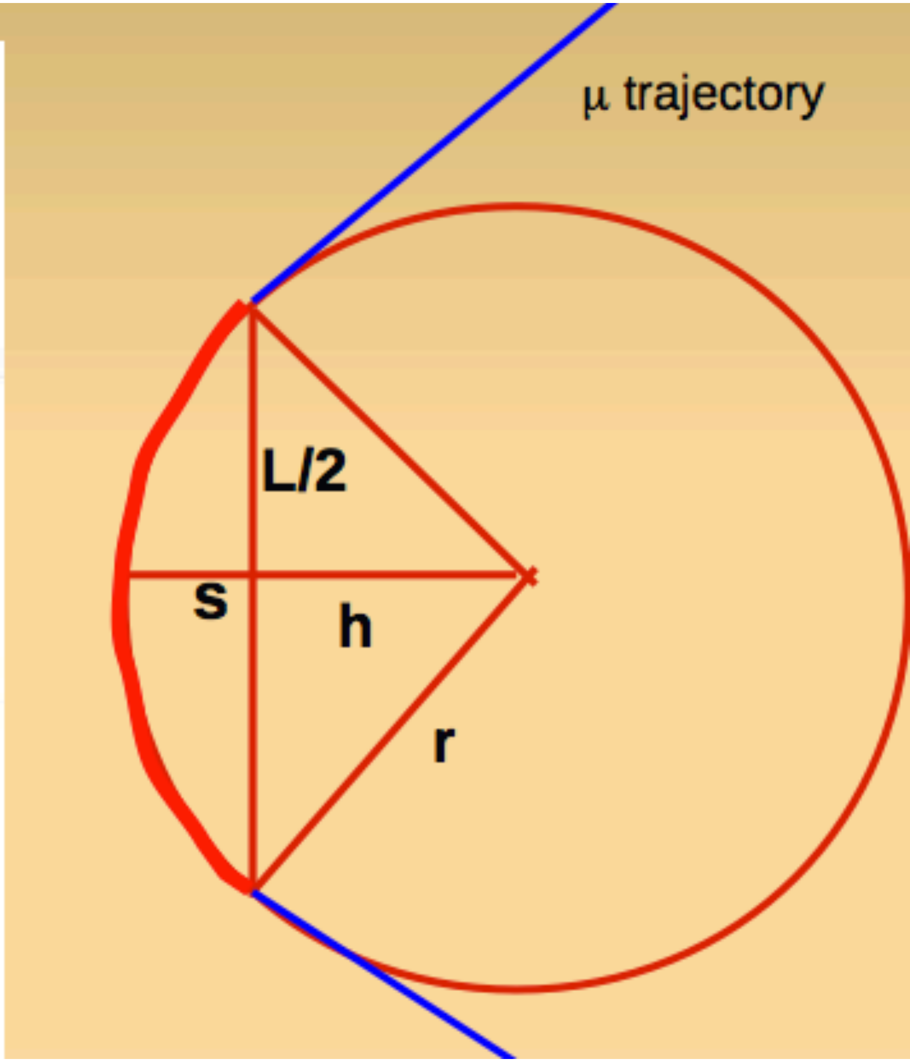


Introduction

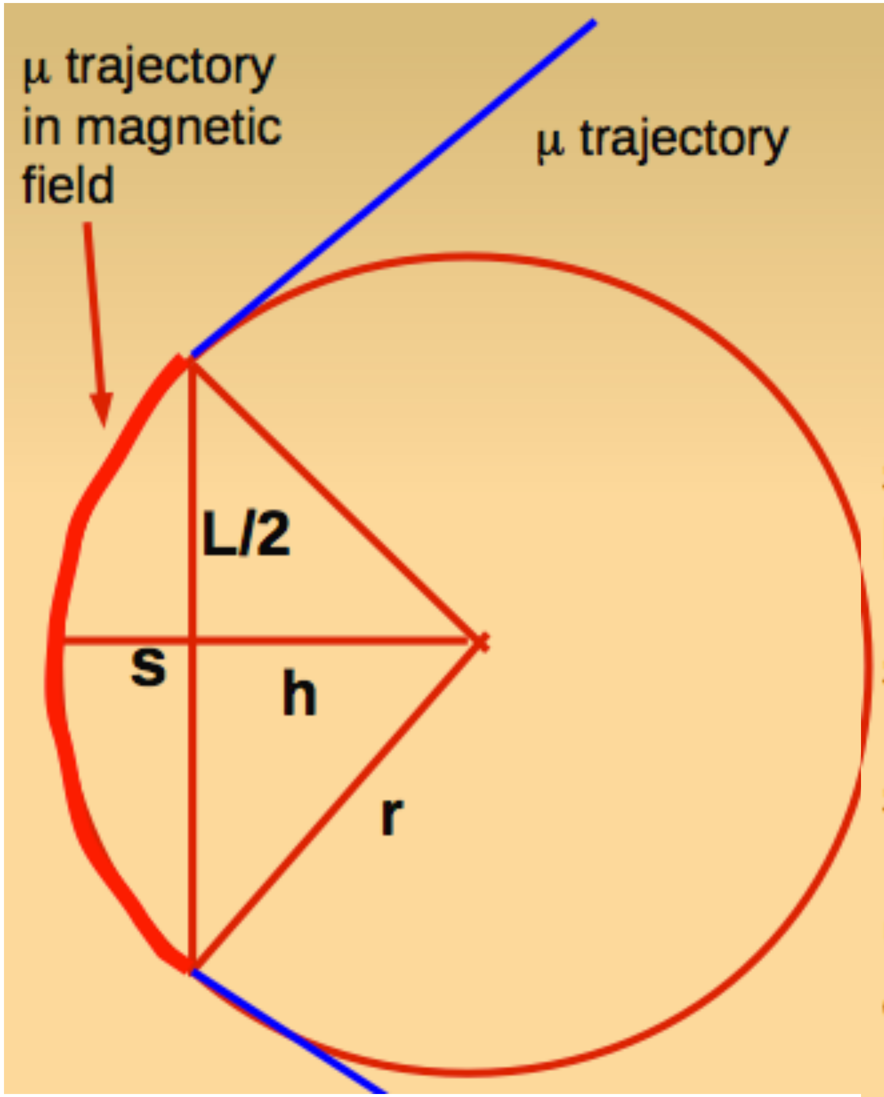




μ
surface
30 m
molasse
scintillators
3 m
11 m
L3 inner
detectors
3 m
drift chambers
magnet



μ trajectory
L/2
s
h
r



v perpendicular B

$F = e\, v\, B$ force in a magnetic field

$F = dp/dt = \gamma\, m\, dv/dt = \gamma\, m\, v^2/r = p\, v/r$

$p\, v/r = e\, v\, B$

$p = e\, B\, r$ [m,T,Gev/c]

v=velocity
p=momentum
s=sagitta
L=length
B=magnetic field
e=charge
r=radius

$s = r - h$

$h^2 = r^2 - L^2/4$

$s = r - \sqrt{r^2 - L^2/4}$

$s = r - r\sqrt{1 - L^2/4r^2}$

$(1+x)^\alpha = 1 + \alpha x$

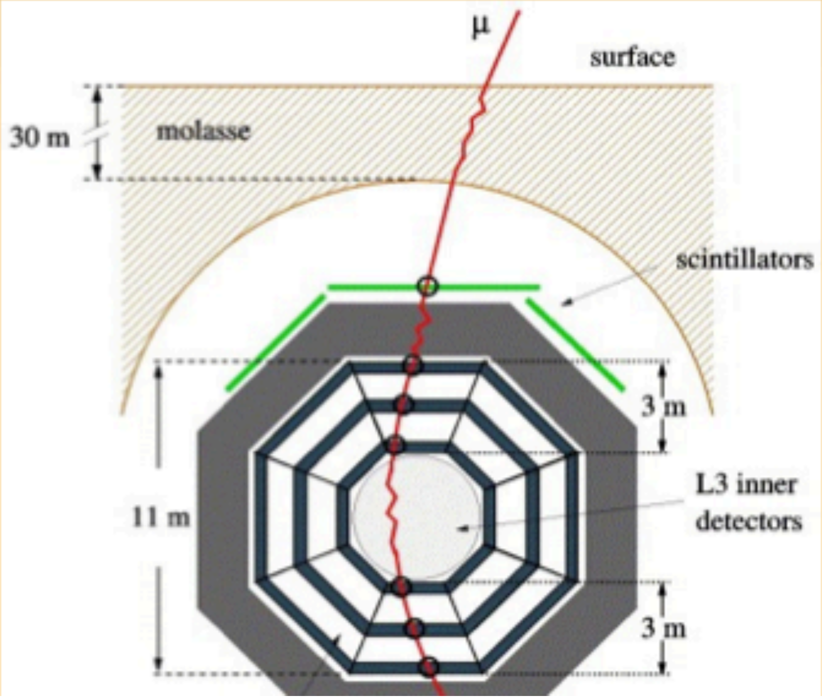
$\alpha = ½ \quad x = -(L^2/4r^2)$

$s \sim L^2/8r$

$$p = \frac{e\, L^2\, B}{8\, s}$$

$$p = \frac{e\,L^2\,B}{8\,s}$$

$$\sigma_p/p = \sigma_s/s = \sigma_s \frac{8\,p}{(e\,L^2\,B)}$$



High magnetic filed
B=0.5 T in L3+C

To have a good resolution it is necessary to have a large lever arm L

Lever arm ~ 11 m in L3+C

$$p = \frac{e\,L^2\,B}{8\,s}$$

$$\sigma_p/p = \sigma_s/s = \sigma_s \frac{8\,p}{(e\,L^2\,B)}$$

We define the Maximum Detectable Momentum (P_{MD}) =
The value of p for which the error is big as the momentum itself

$\sigma_p/p = 1$ $\quad$ $P_{MD} = (e\,L^2\,B)/(8\,\sigma_s)$

Example for L3+C :

$\sigma_s = 1$ mm $= 0.001$ m

$L = 11$ m

$B = 0.5$ T

PMD = $(1*11^2*0.5)/(8*0.001)$ = 7562 GeV/c ~ 7.5 TeV/c

The maximum detectable momentum of the spectrometer, defined as the momentum at which p/p reaches unity, is 0.78 TeV for muons measured in only one octant and about 5 TeV for muons measured in two octants. Phys. Letters B 598 (2004) 15-32

$$p = \frac{e L^2 B}{8 s}$$

$$\sigma p/p = \sigma s/s = \sigma s \frac{8 p}{(e L^2 B)}$$

Example for L3+C :

$\sigma s = 1$ mm

$L = 11$ m

$B = 0.5$ T

p = 100 GeV/c Resolution σp

$\sigma p = (0.001 * 8 * 100^{2)}/(1 * 11^2 * 0.5)$

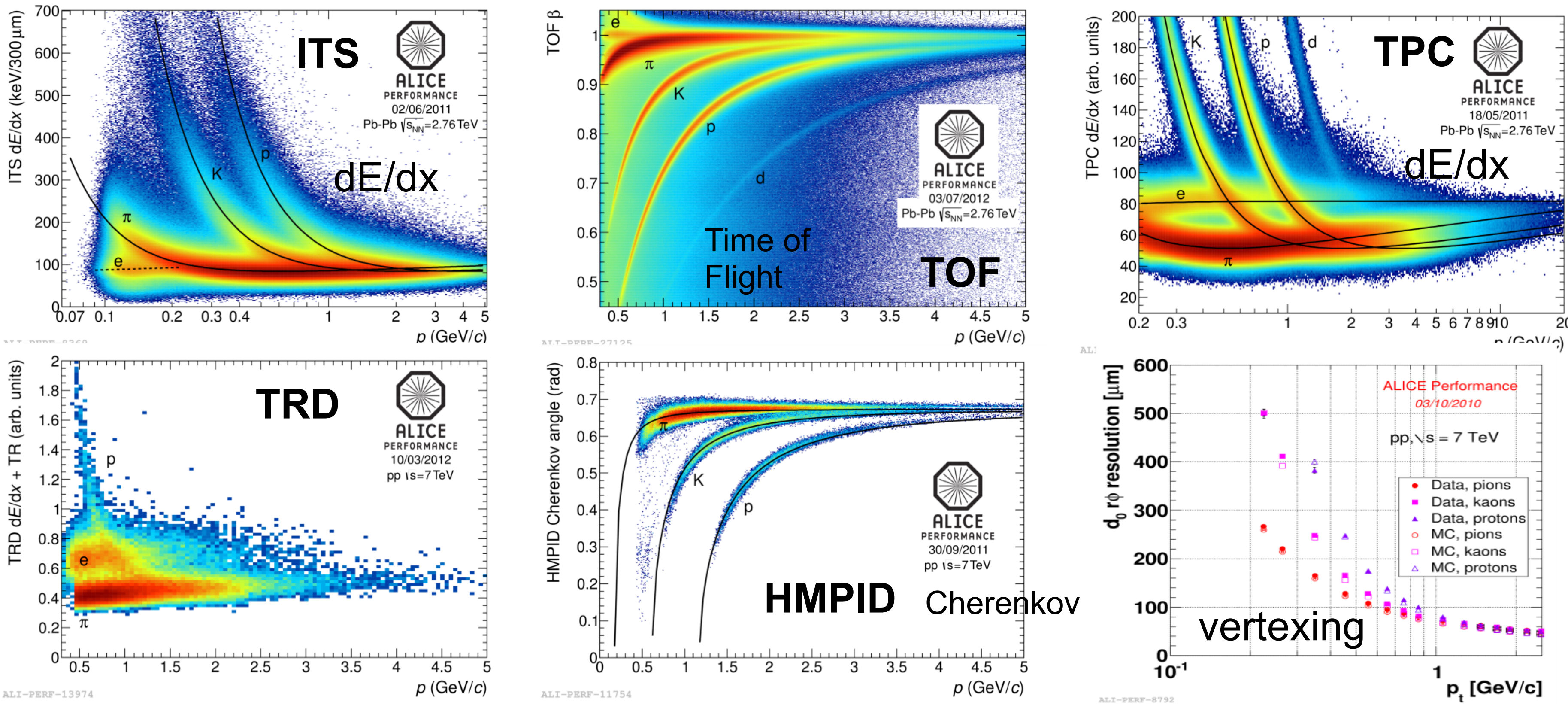
$\sigma p = 1.32$ GeV/c ==> 1.3%

p = 1 TeV/c Resolution σp

$\sigma p = (0.001 * 8 * 1000^{2)}/(1 * 11^2 * 0.5)$

$\sigma p = 132$ GeV/c ==> 13%

Introduction



The design is optimized for reconstruction and identification of particles in a wide range of transverse momentum.

- particle identification (practically all known techniques)
- extremely low-mass tracker ~ 10% of X0
- excellent vertexing capability
- efficient low-momentum tracking - down to ~ 100 MeV/c