ANALYSIS OF HIGH MUON MULTIPLICITY COSMIC EVENTS WITH THE ALICE EXPERIMENT

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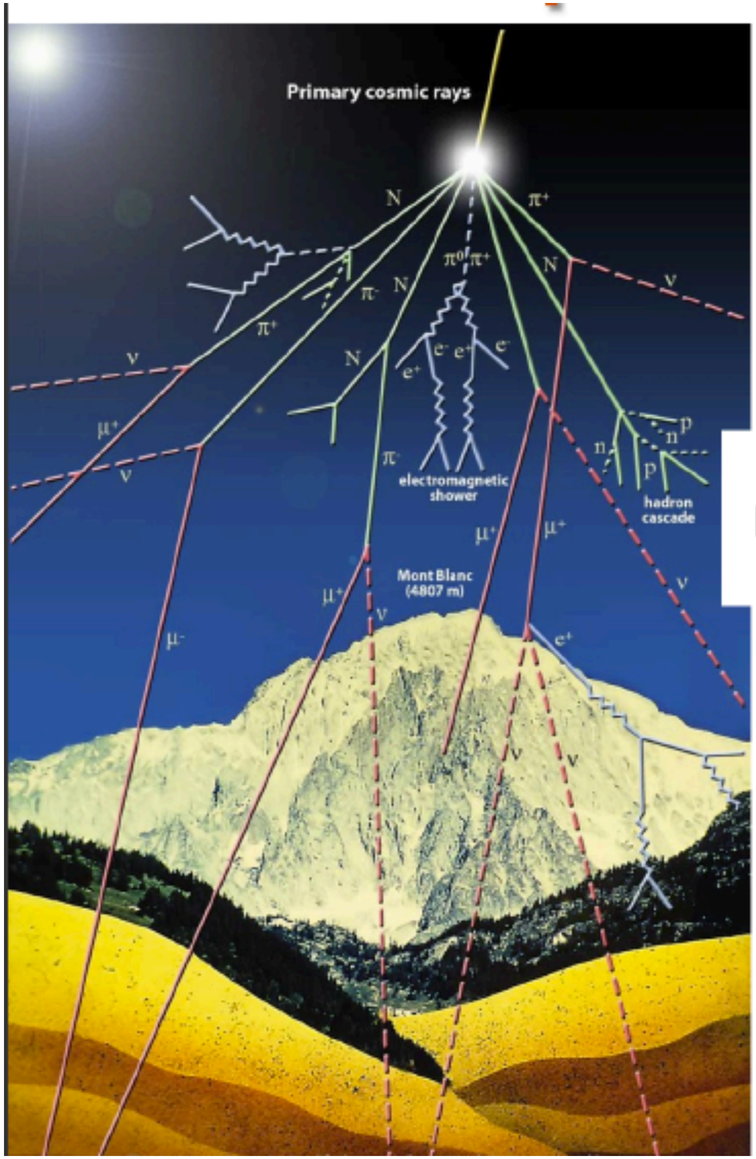
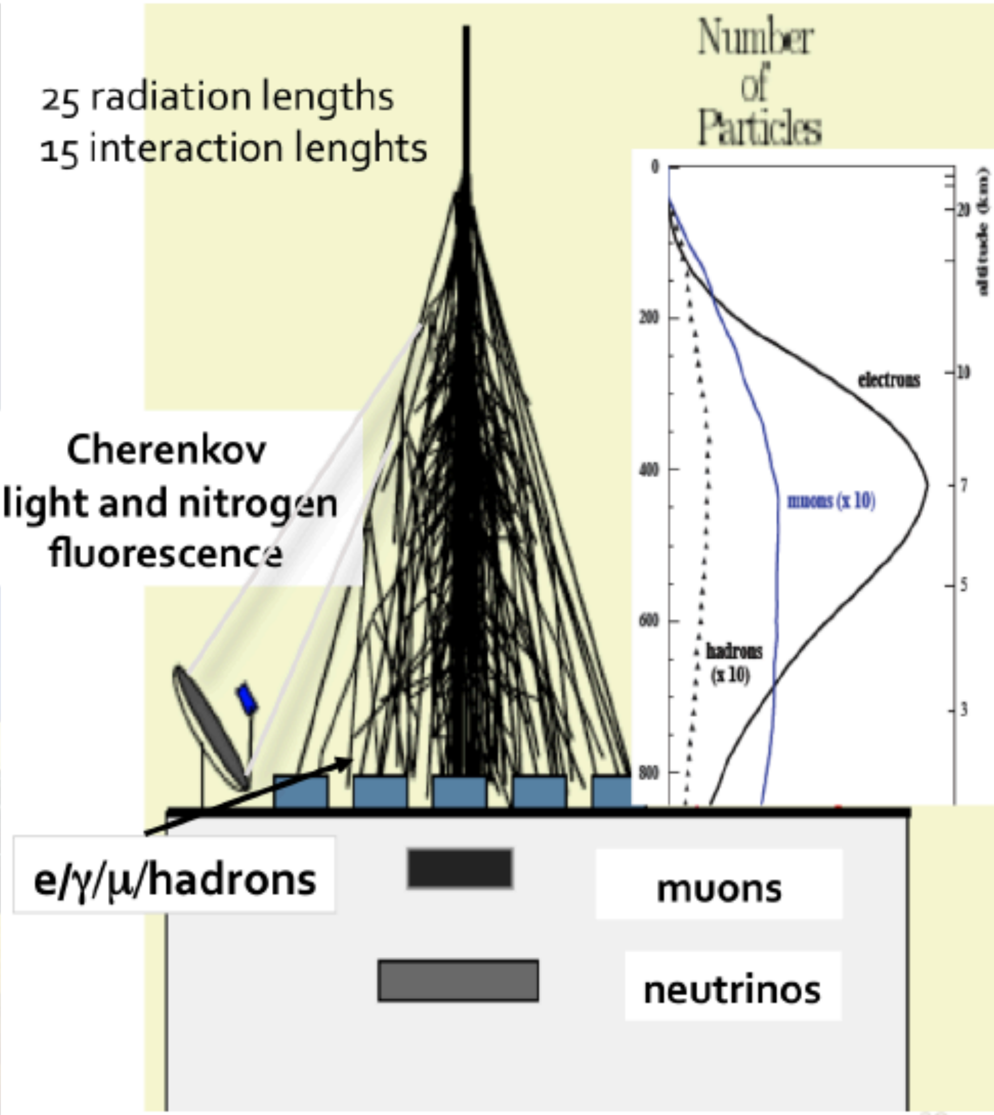
Plan of this talk

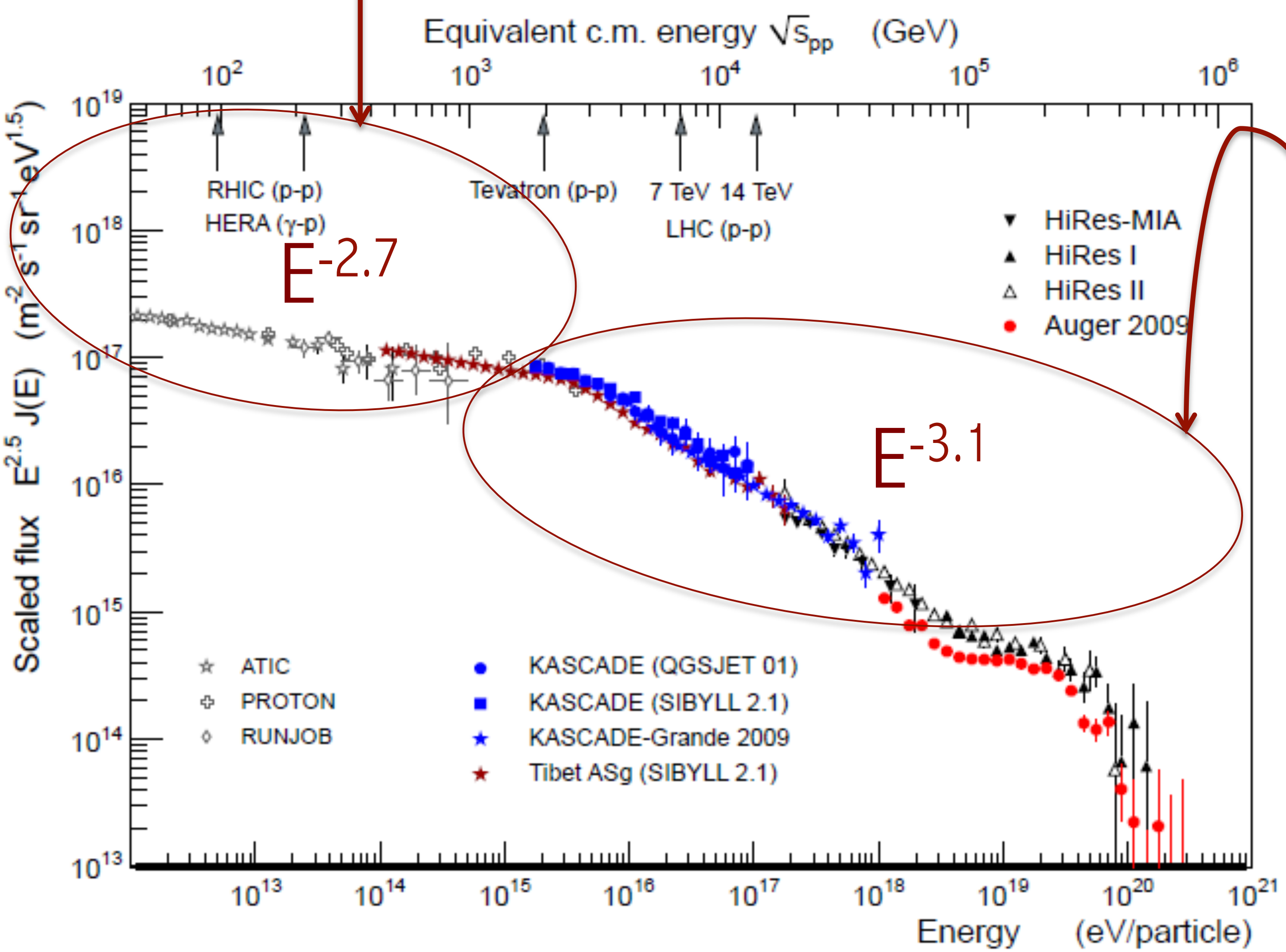
- Introduction
- ALICE Experiment: trigger and tracking detectors for cosmics
- Atmospheric Muon Multiplicity Distribution (MMD)
- Monte Carlo to study High Atmospheric Muons Events (HME)
- Final remarks


Primary cosmic rays
electromagnetic shower
hadron cascade
Mont Blanc (4807 m)
N
π+
π-
π0
e-
e+
μ+
μ-
ν
p
n


25 radiation lengths
15 interaction lenghts
Cherenkov light and nitrogen fluorescence
e/γ/μ/hadrons
muons
neutrinos
Number of Particles
electrons
muons (x 10)
hadrons (x 10)
altitude (km)
0
200
400
600
800
20
10
7
5
3

Introduction

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



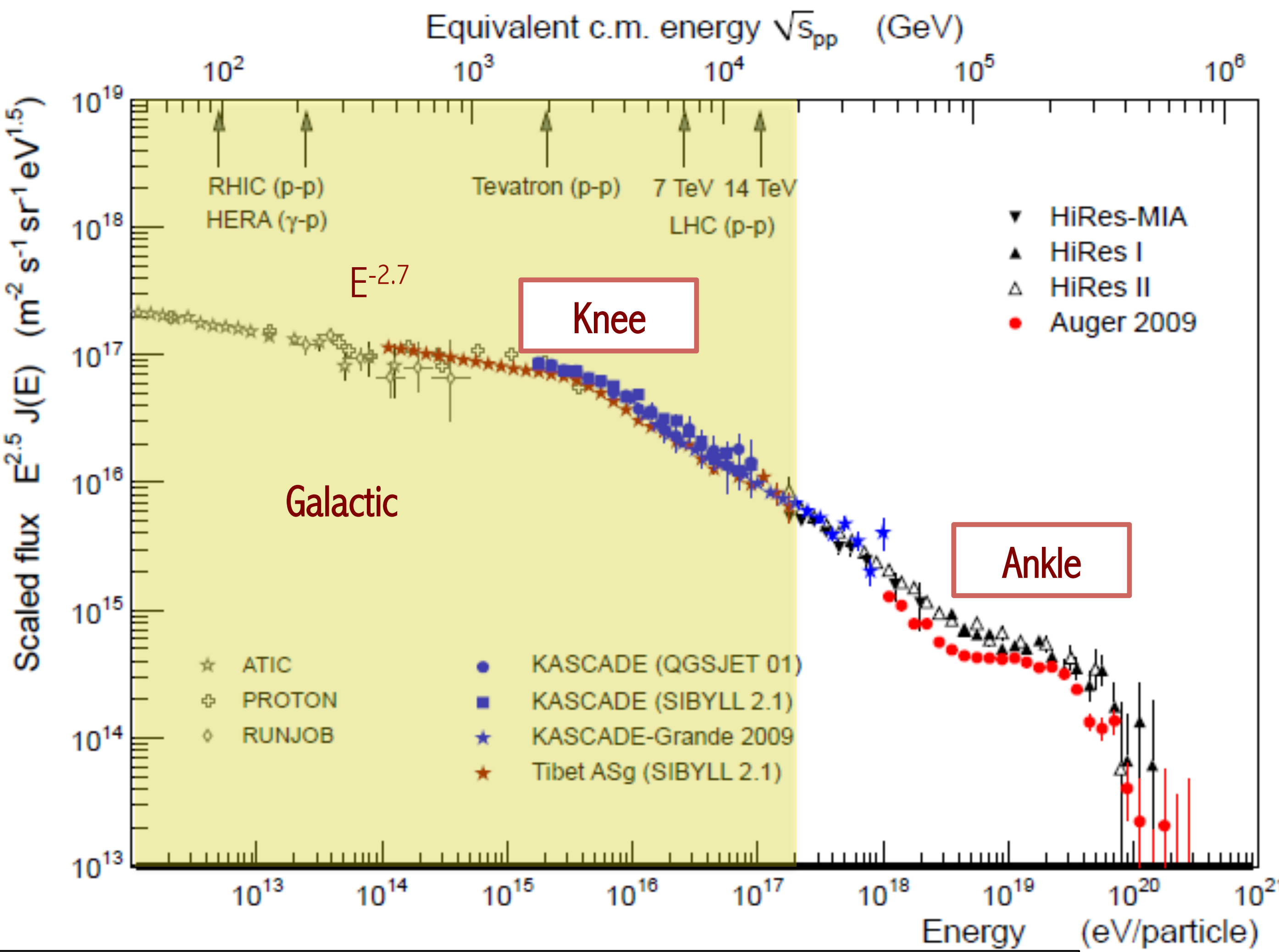
Indirect measurements E > 10^{14} eV → Secondary particles

Around the knee: Kaskade, Casa, EAS-Top, ..

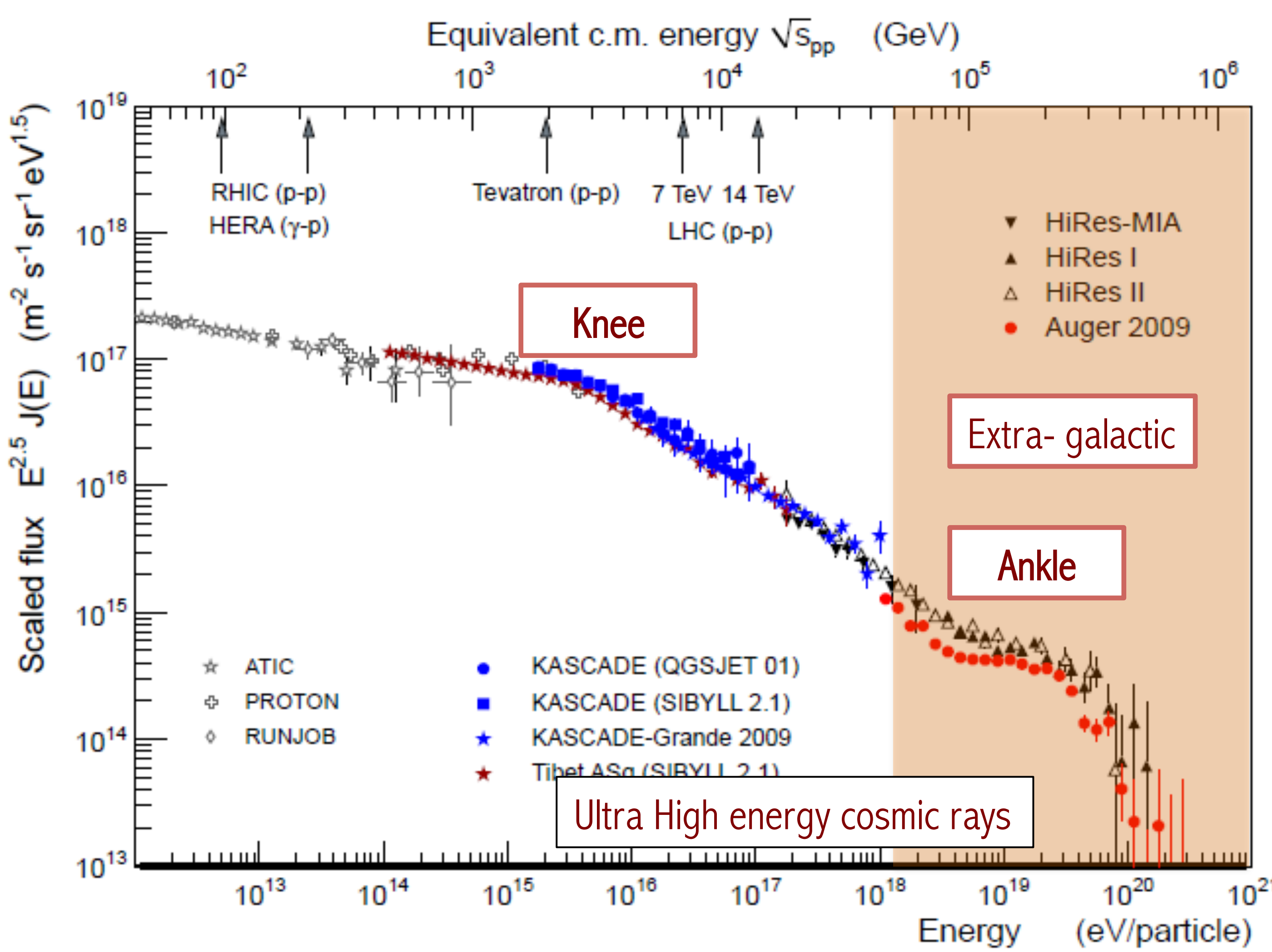
Ultra High Energy cosmic rays: Auger, Hires

Underground experiments: MACRO, EMMA

Cosmic Ray Physics at CERN: LEP (L3+C, ALEPH, DELPHI), LHC (CMS, ALICE)

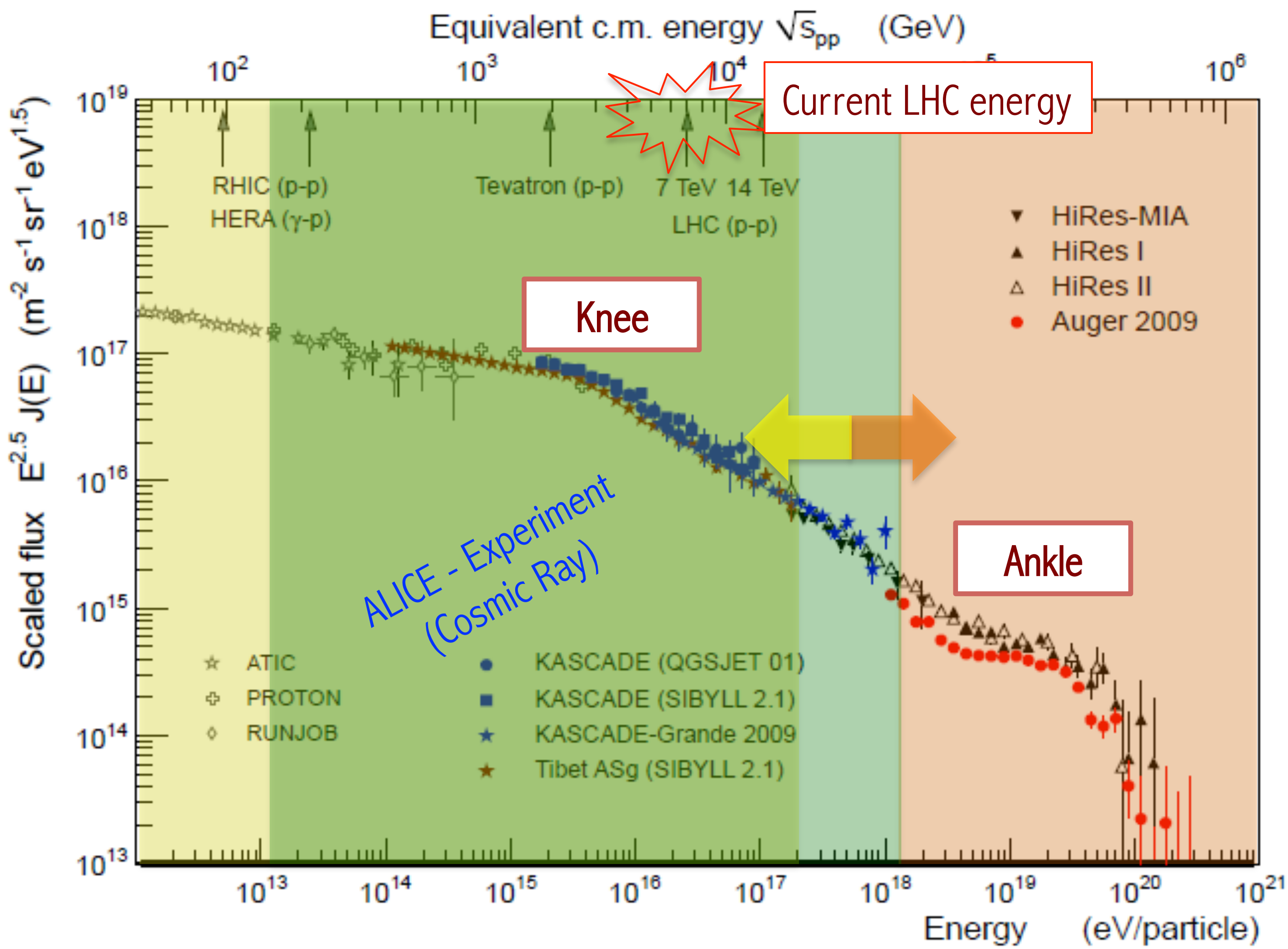


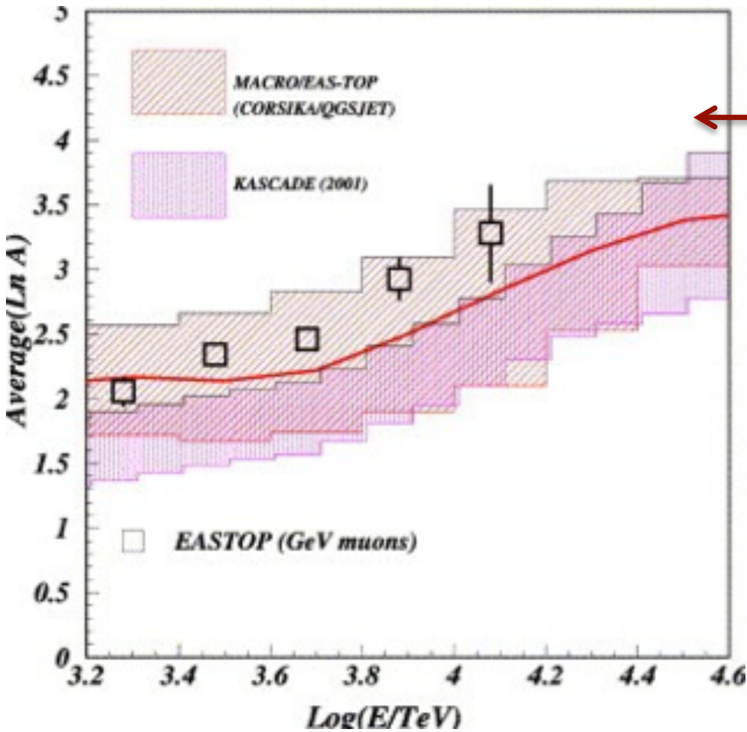
- Density of the galactic primary cosmic ray: ~ 1 eV/cm^3
- Protons for energies below 10^{16} eV
- Heavy nuclei composition: ~ $8*10^{16}$ eV (**Phys. Rev. Lett. 107, 171104 (2011)**)



Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2
10^3
10^4
10^5
10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
Knee
HiRes-MIA
HiRes I
HiRes II
Auger 2009
Extra- galactic
Ankle
Scaled flux $E^{2.5}$ J(E) ($m^{-2} s^{-1} sr^{-1} eV^{1.5}$)
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2009
Tibet ASγ (SIBYLL 2.1)
Ultra High energy cosmic rays
Energy (eV/particle)

Introduction



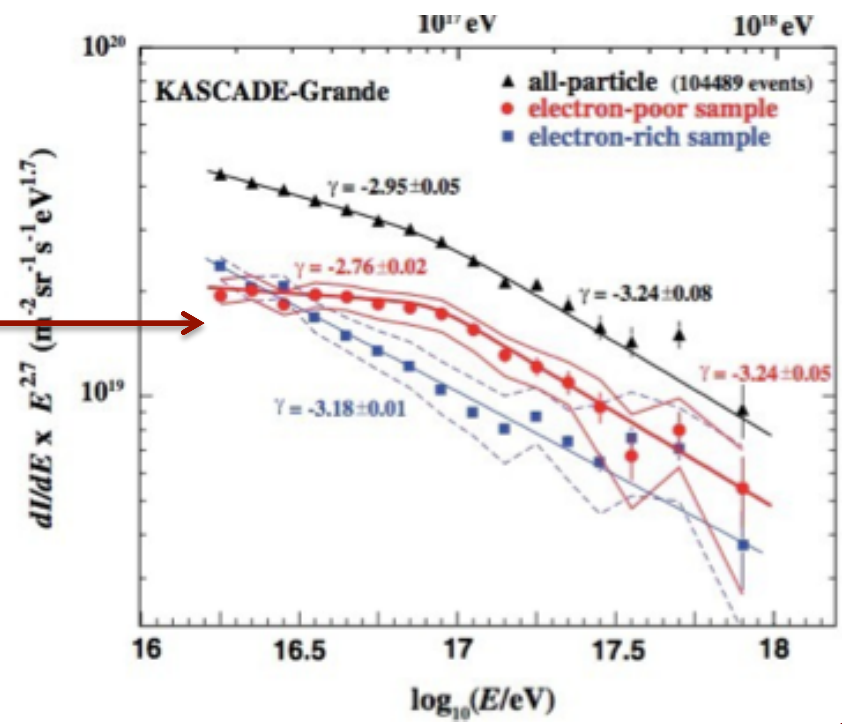


MACRO-EASTOP KASCADE :

- 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

Cosmic rays with the accelerator apparata

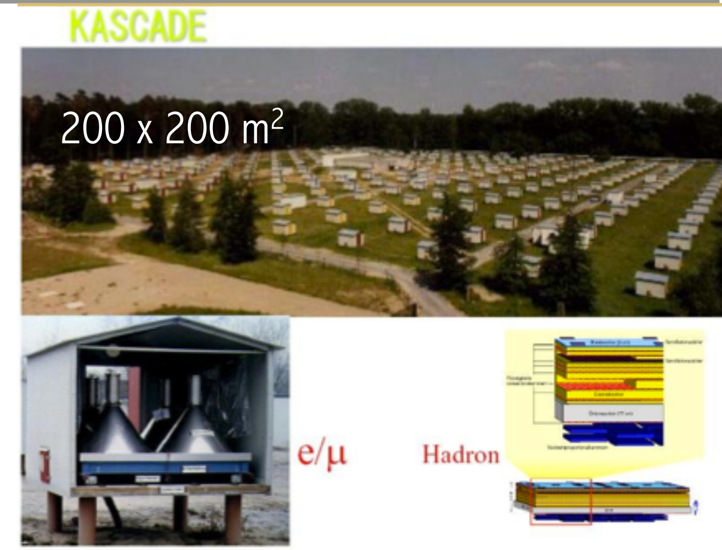
- ✧ Small apparata
- ✧ Low underground
- ✧ Detection of muons crossing the rock

★ These apparata are not designed for cosmic ray physics:

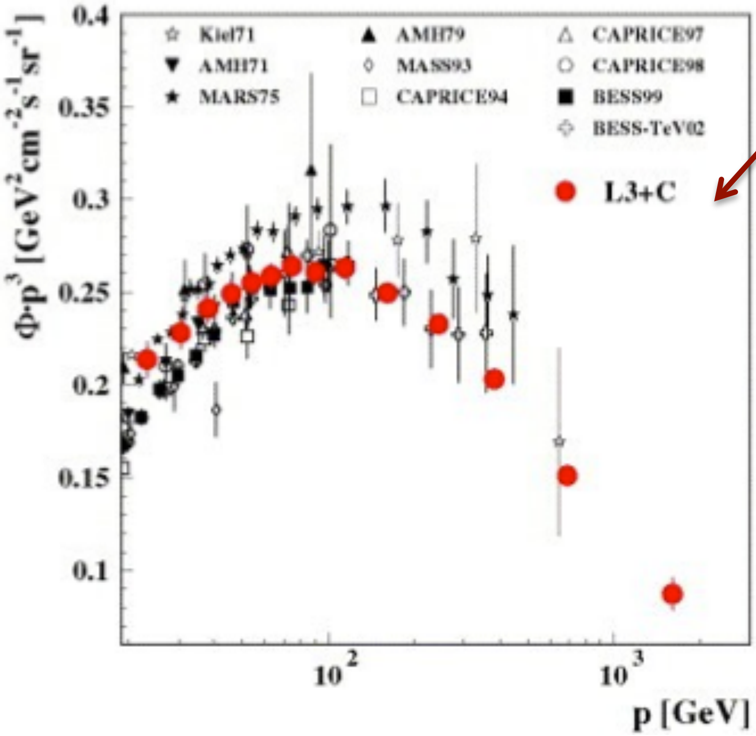
❑ Small detectors compared with the standard cosmic ray apparata:

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

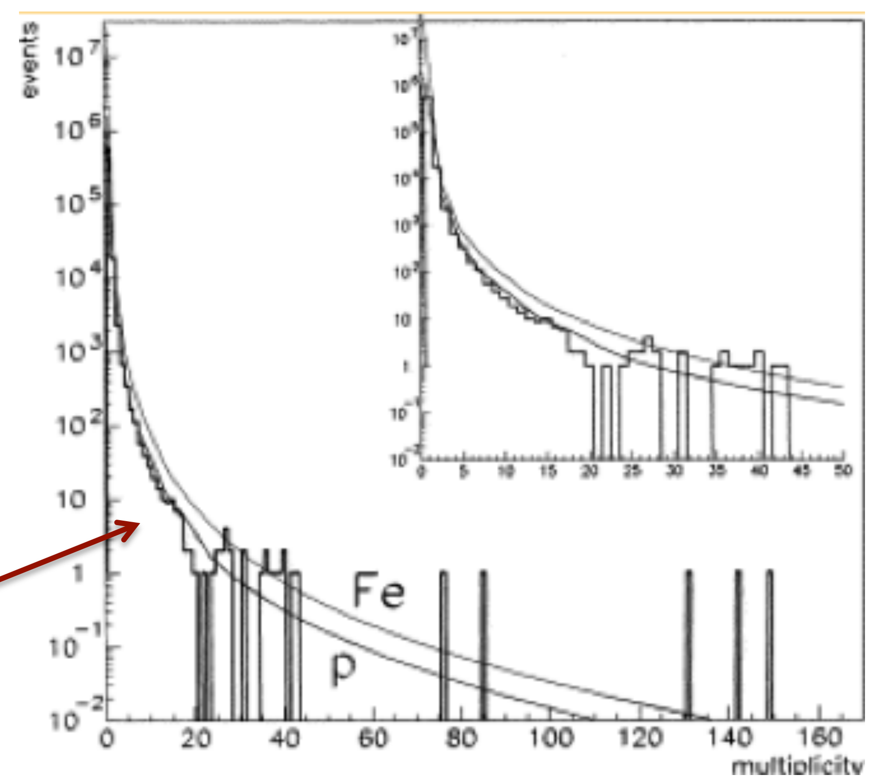
✓ Advantage: detectors with very high performances, presence of magnetic field



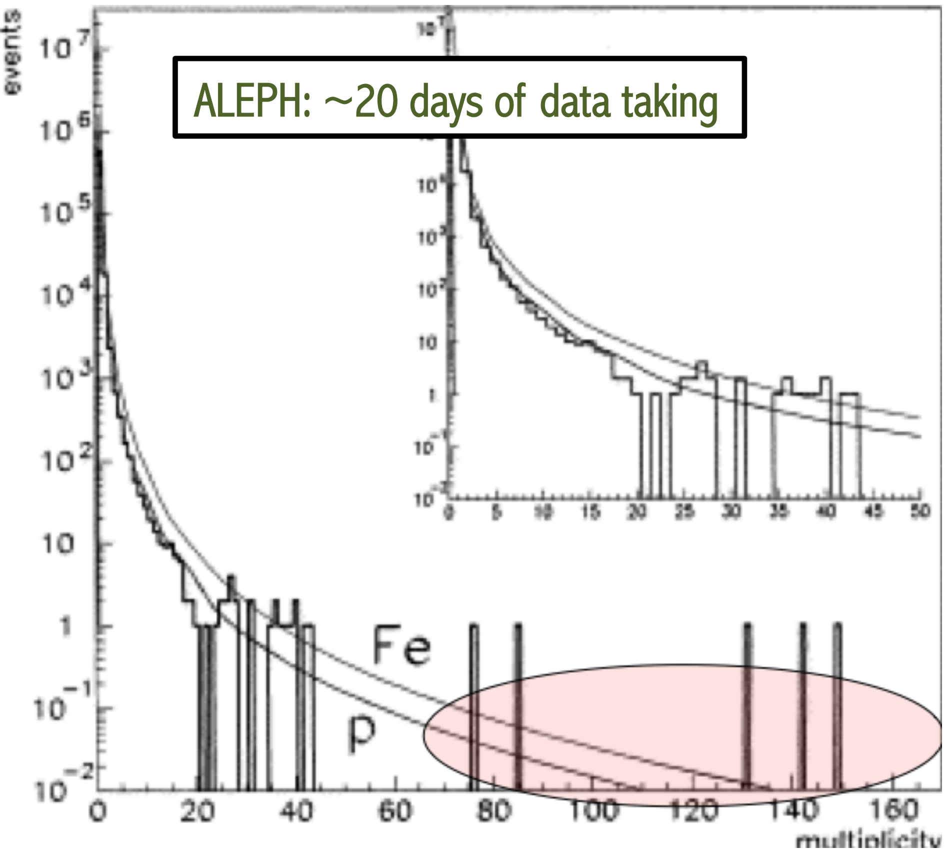
Main topic with accelerator apparata



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



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

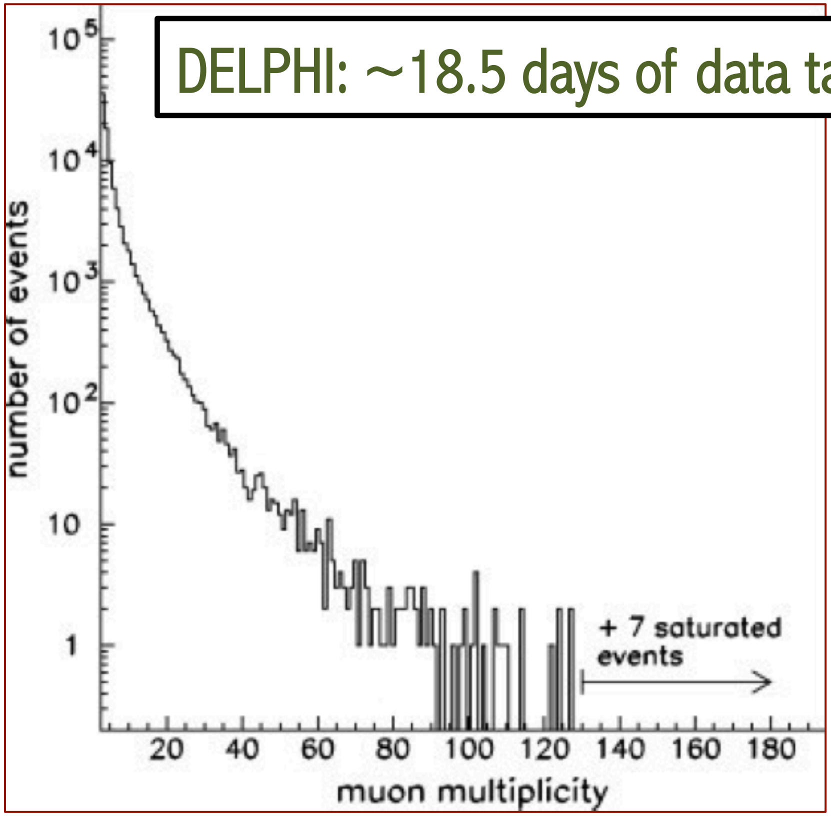


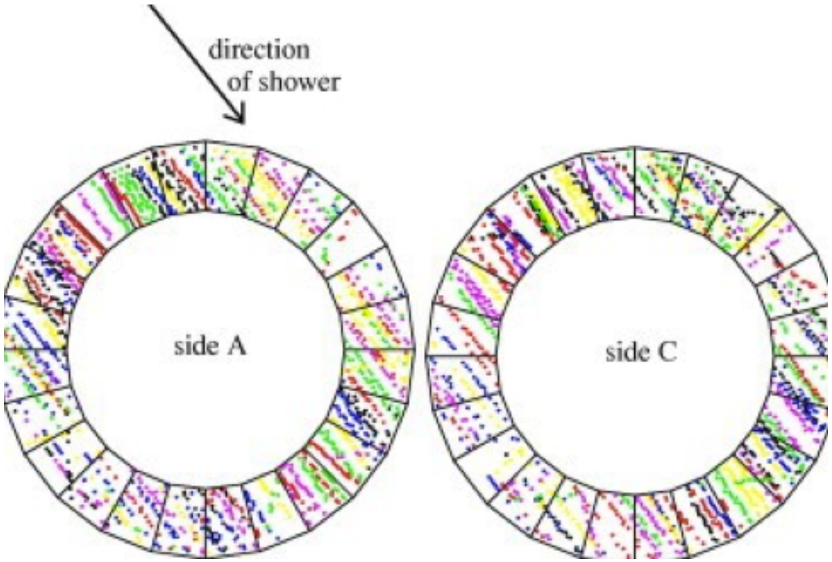
1) 4.75 μ/m^2 Zenith=40.8^0
Primary energy = 3 x 10^{16} eV
2) 5.3 μ/m^2 Zenith=37.7^0
Primary energy = 3 x 10^{16} eV
3) 8.9 μ/m^2 Zenith=40^0
Primary energy = 6 x 10^{16} eV
4) 8.2 μ/m^2 Zenith=48.6^0
Primary energy = 7 x 10^{16} eV
5) 18.6 μ/m^2 Zenith=27^0
Primary energy = 10^{17} eV

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.

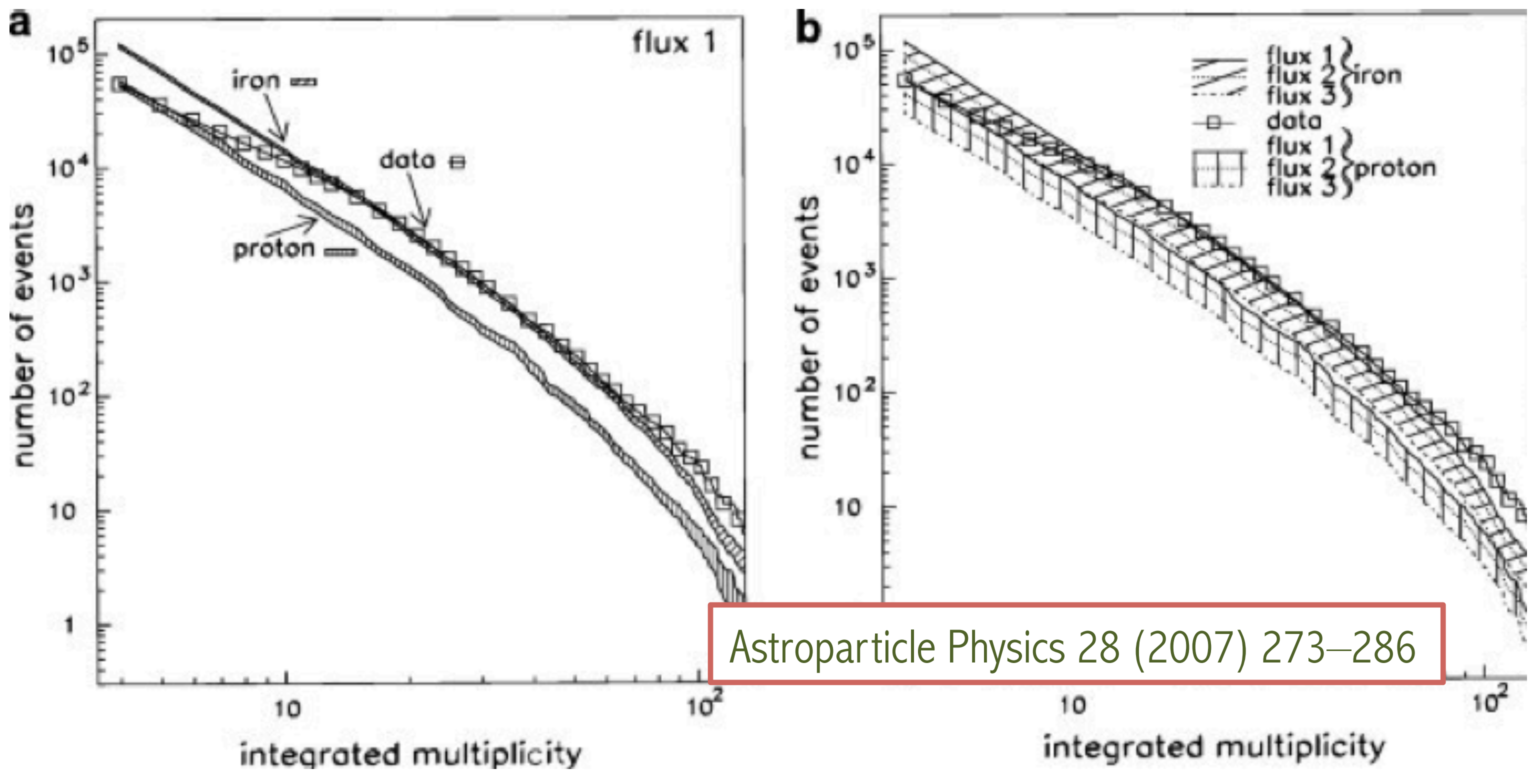
DELPHI: ~18.5 days of data taking





7 high multiplicity events that saturate the detector

Astroparticle Physics 28 (2007) 273–286

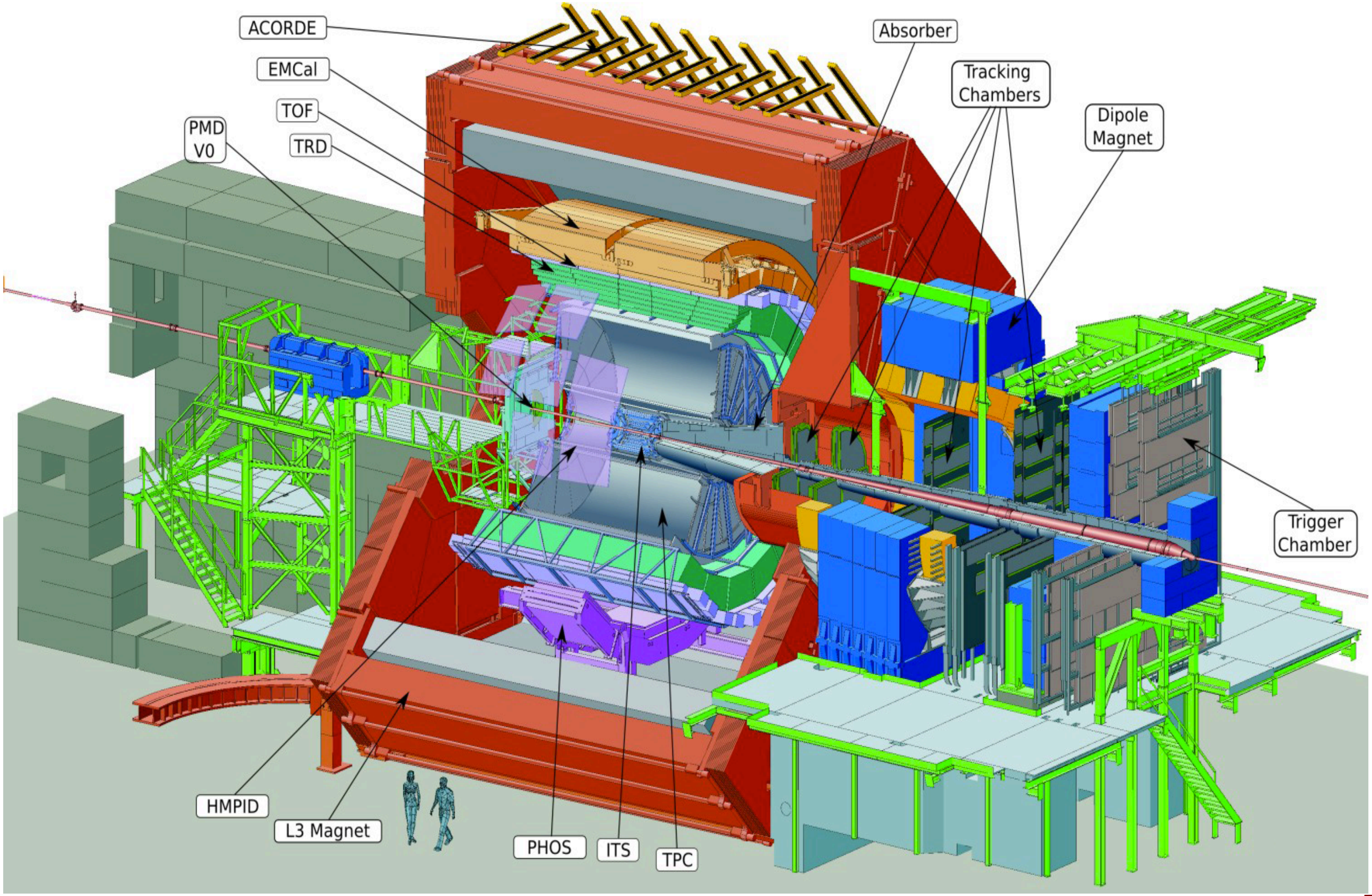


Astroparticle Physics 28 (2007) 273–286

The conclusion is similar to Aleph :

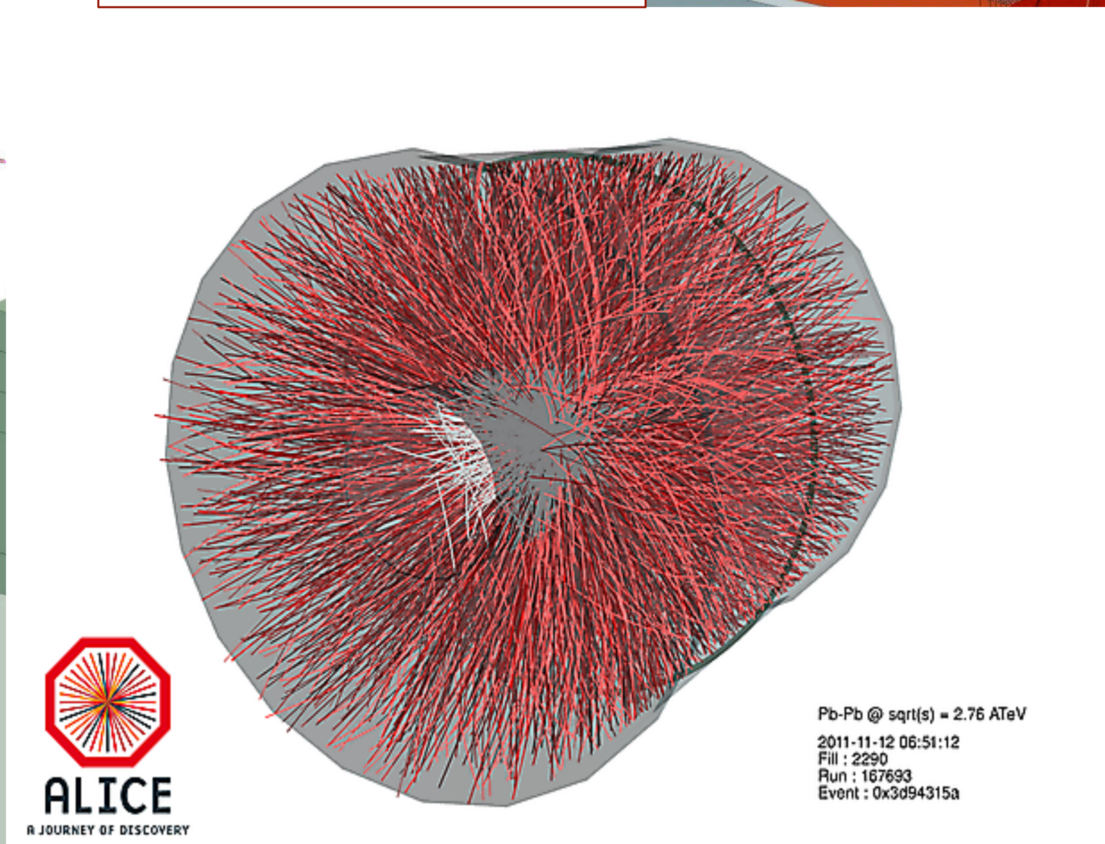
However, even the combination of extreme assumptions of highest measured flux value and pure iron spectrum fails to describe the abundance of high multiplicity events. Let's see the ALICE results

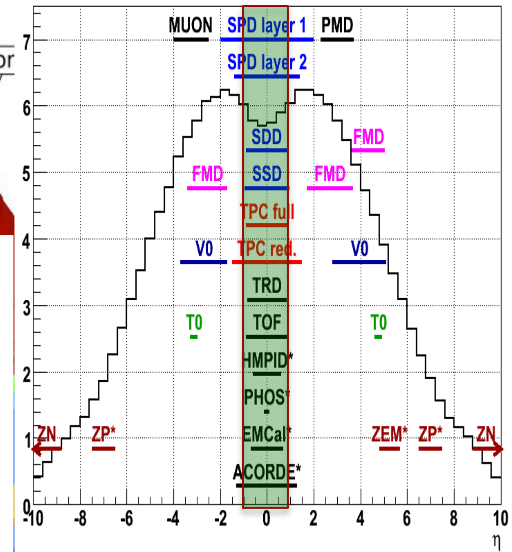
ALICE Experiment: trigger and detection for cosmics

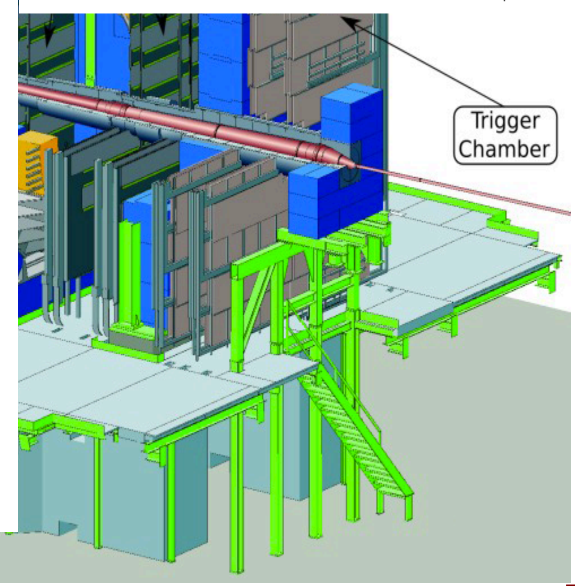


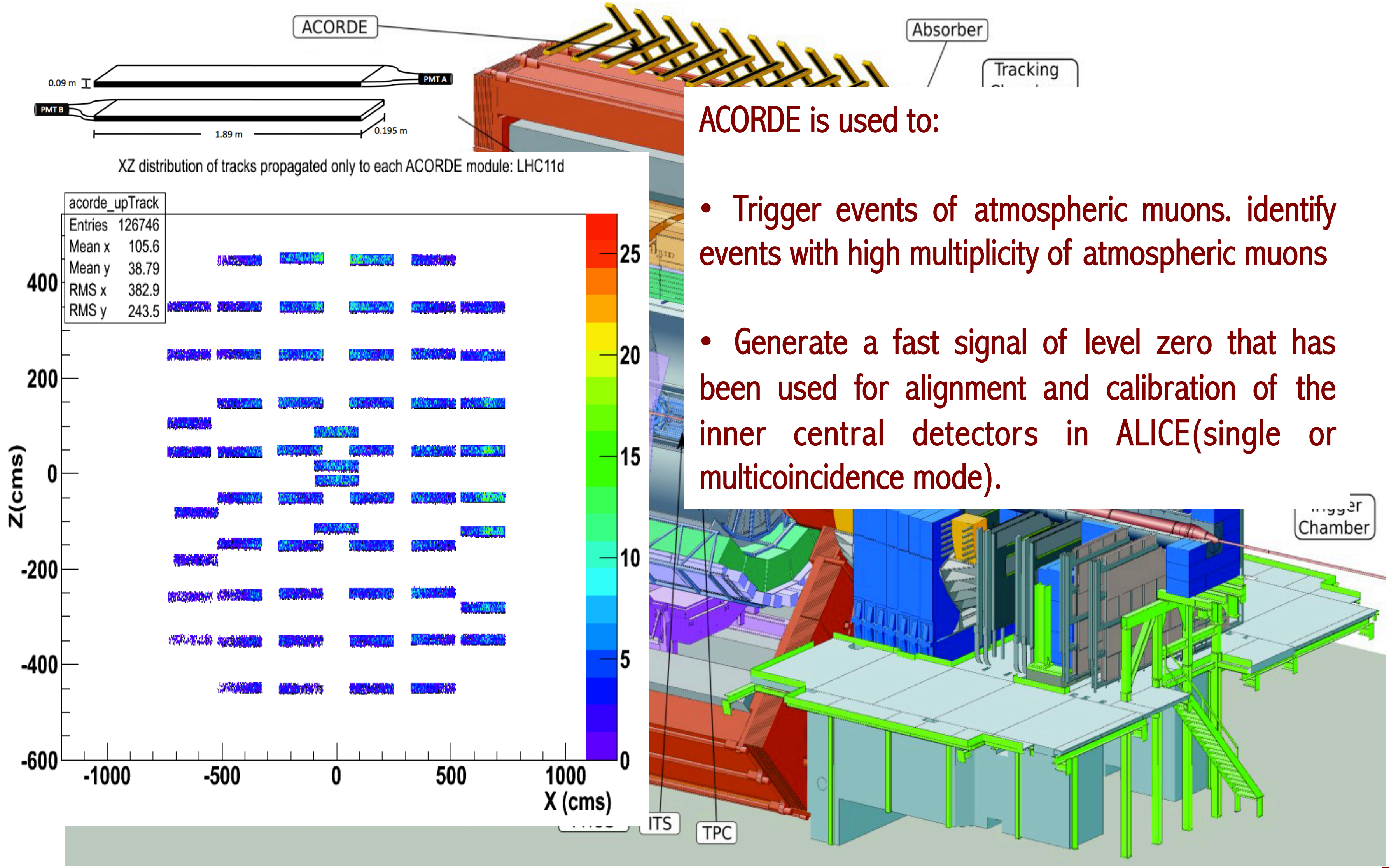
ALICE Experiment: trigger and detection for cosmics

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





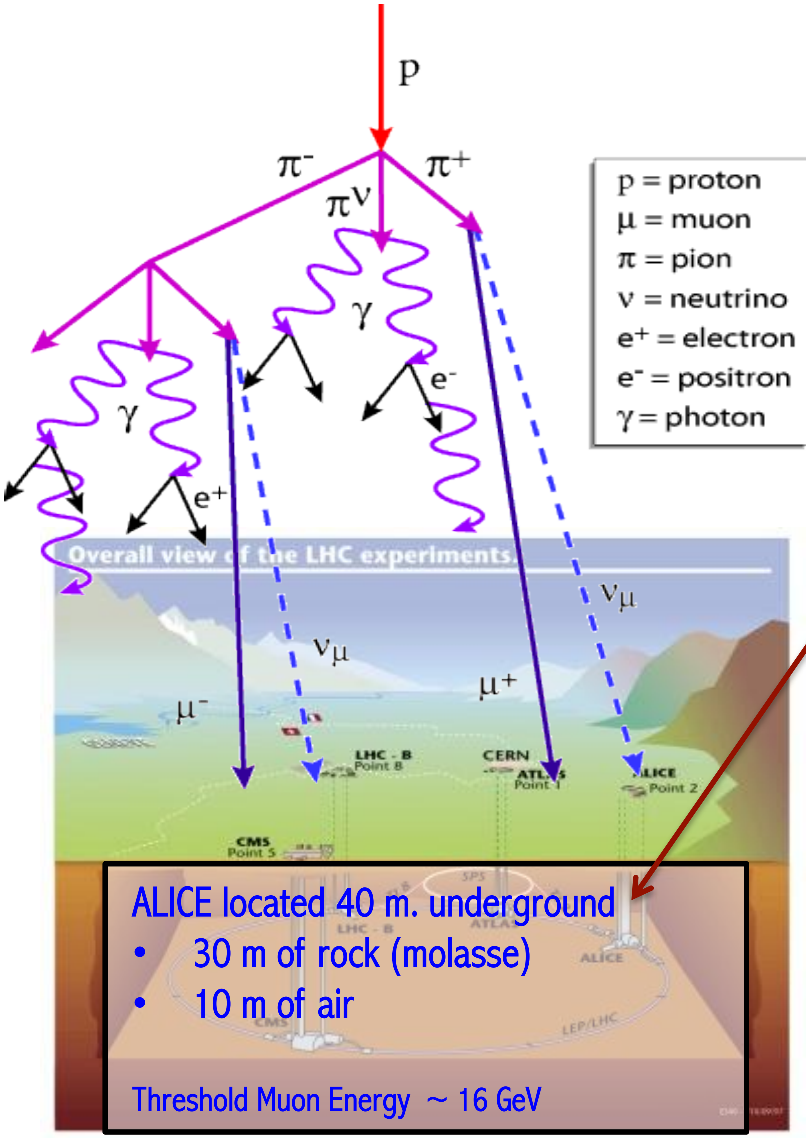




ACORDE is used to:

- 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).

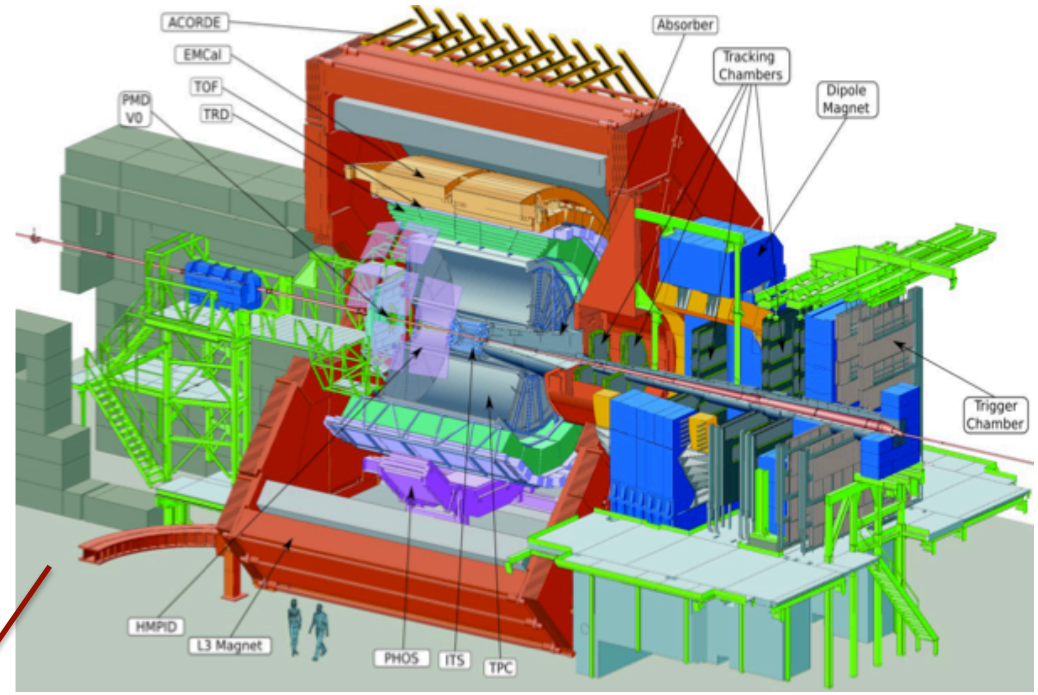
ALICE Experiment: trigger and detection for cosmics



ALICE located 40 m. underground

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

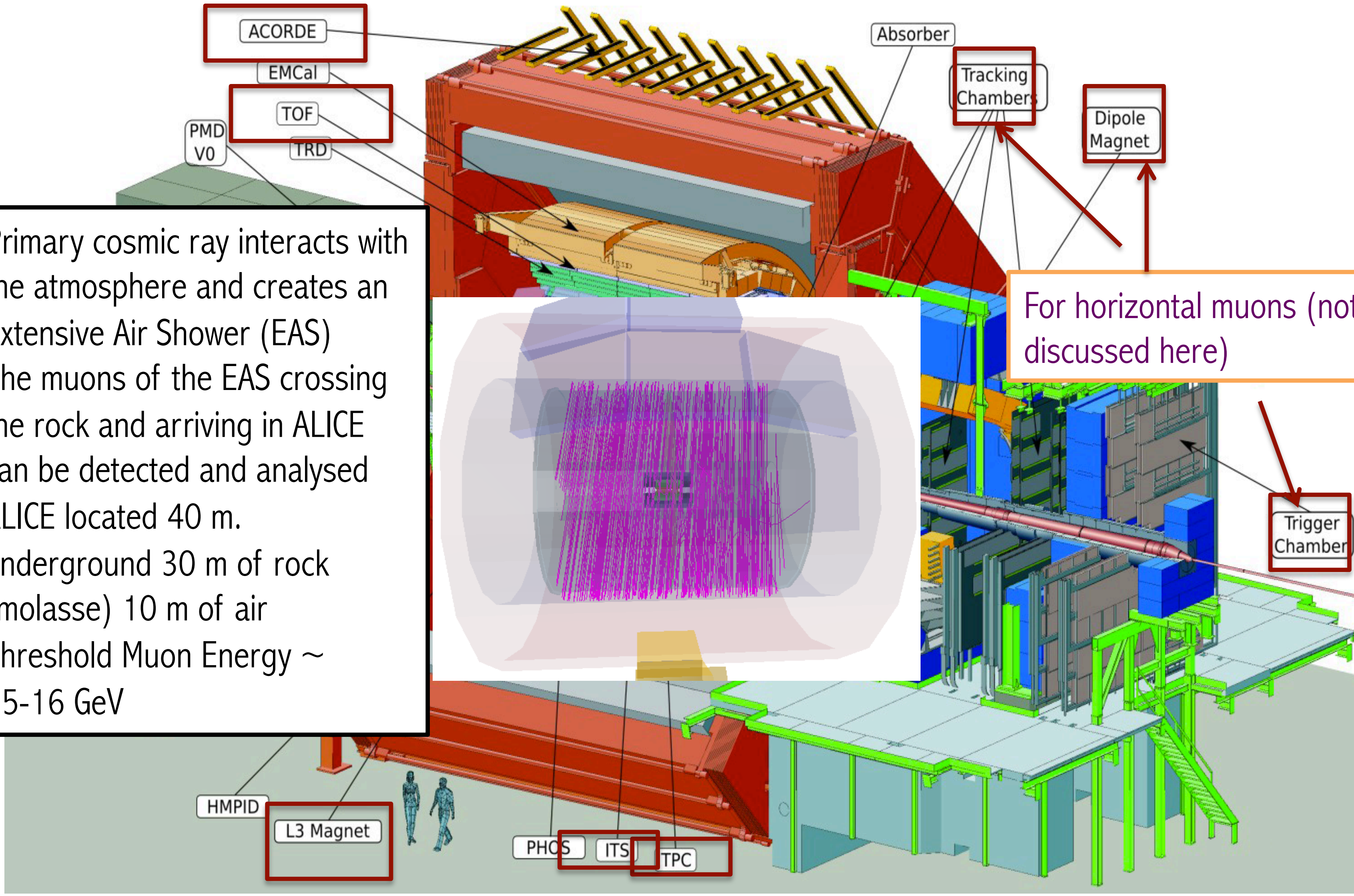
Threshold Muon Energy ~ 16 GeV



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

ALICE Experiment: trigger and detection for cosmics



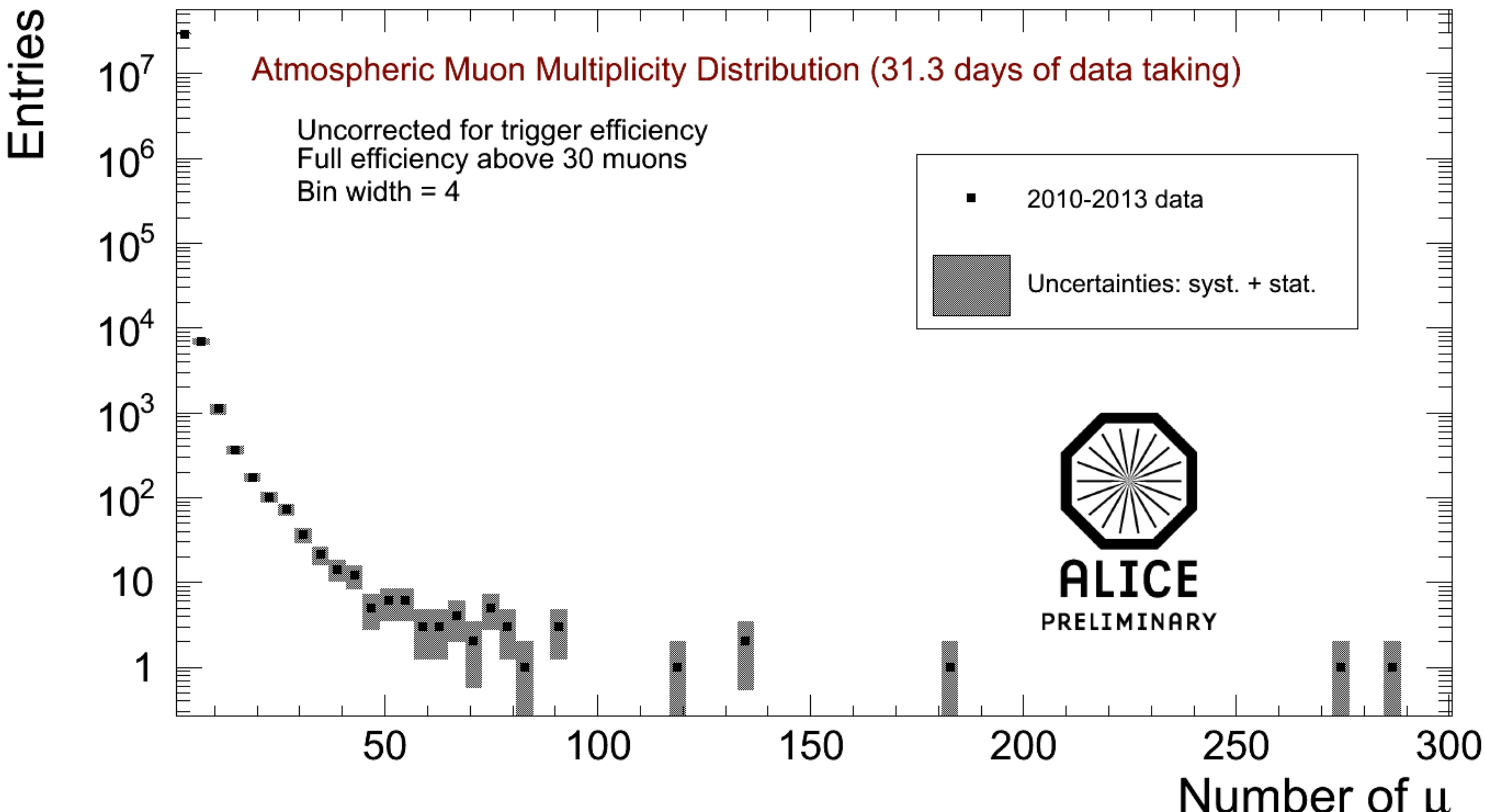
① Primary cosmic ray interacts with the atmosphere and creates an Extensive Air Shower (EAS)
② The muons of the EAS crossing the rock and arriving in ALICE can be detected and analysed
③ ALICE located 40 m. underground 30 m of rock (molasse) 10 m of air
④ Threshold Muon Energy ~ 15-16 GeV

For horizontal muons (not discussed here)

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



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

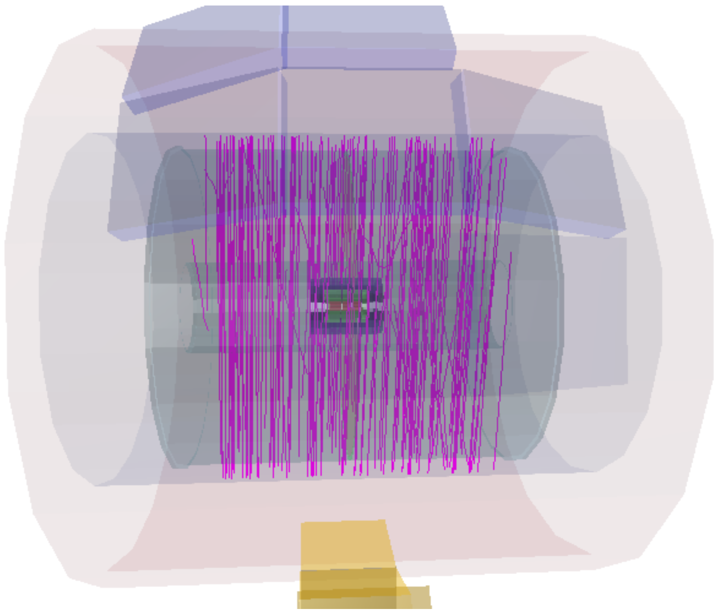
ALICE Experiment: trigger and detection for cosmics

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

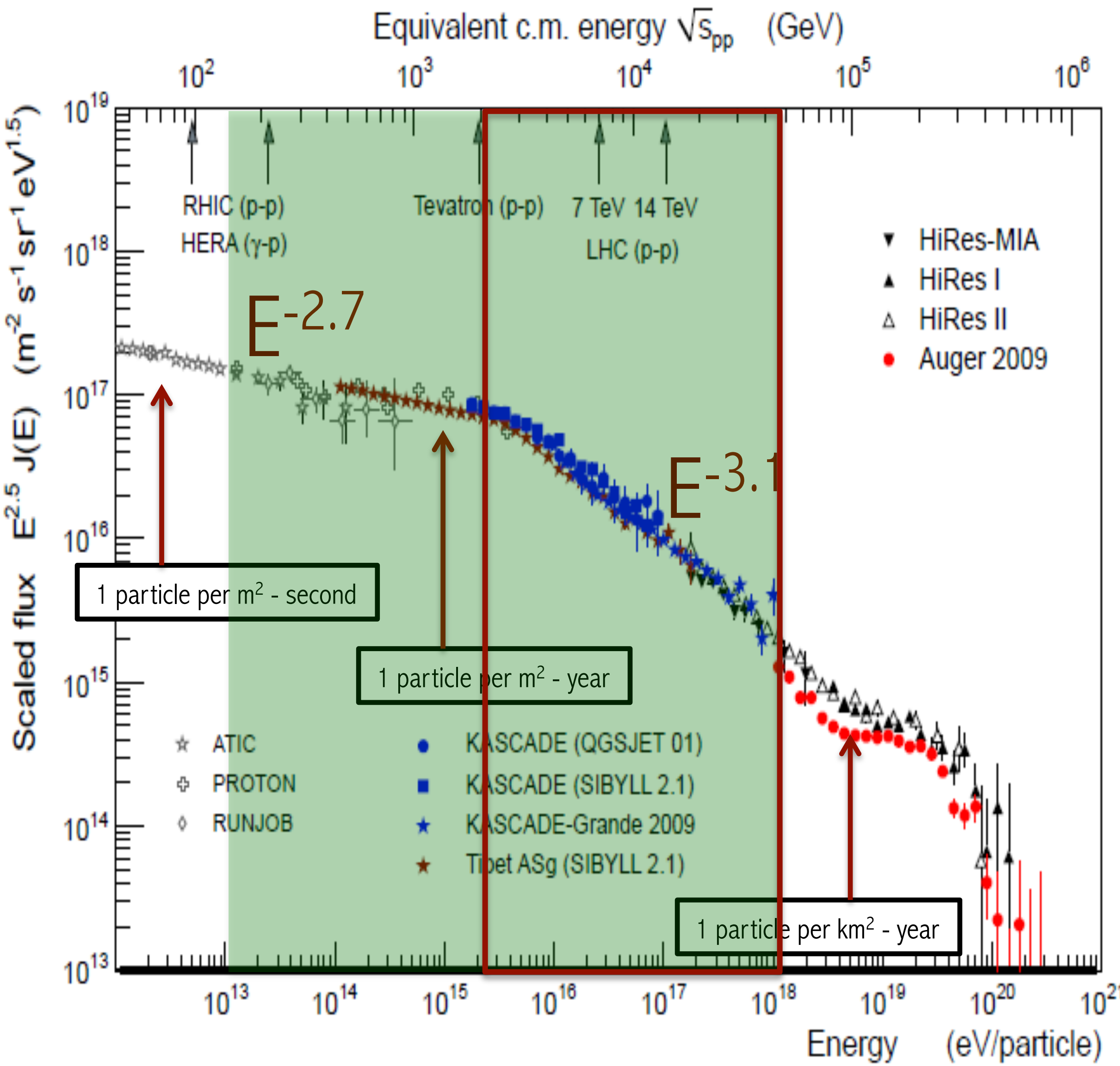
Applying the cut: zenith θ angle $\leq 50^0$, we obtain 5 hmm events.

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



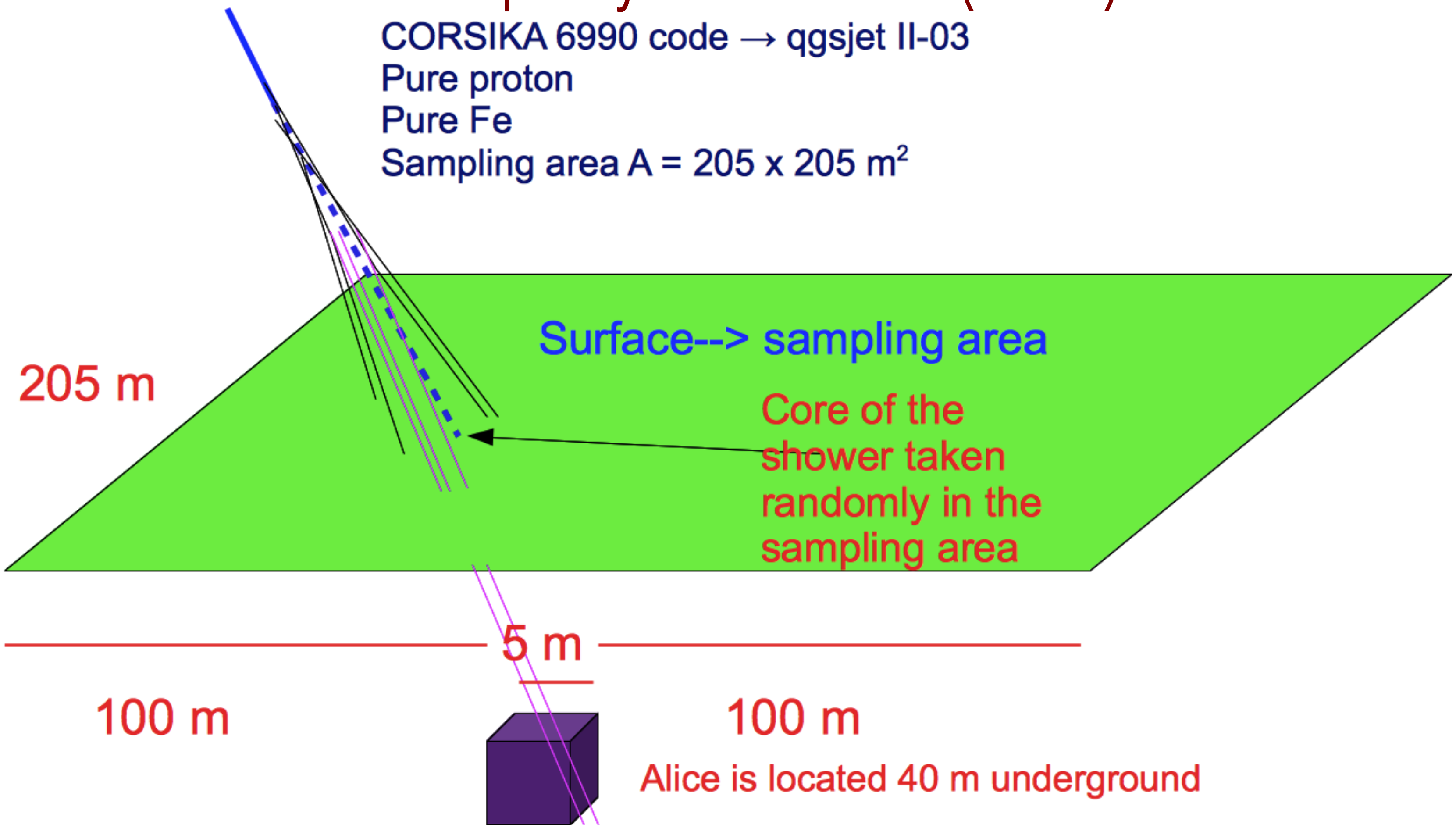
Primary Energy in Alice : $10^{13} < E < 10^{18}$ eV

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

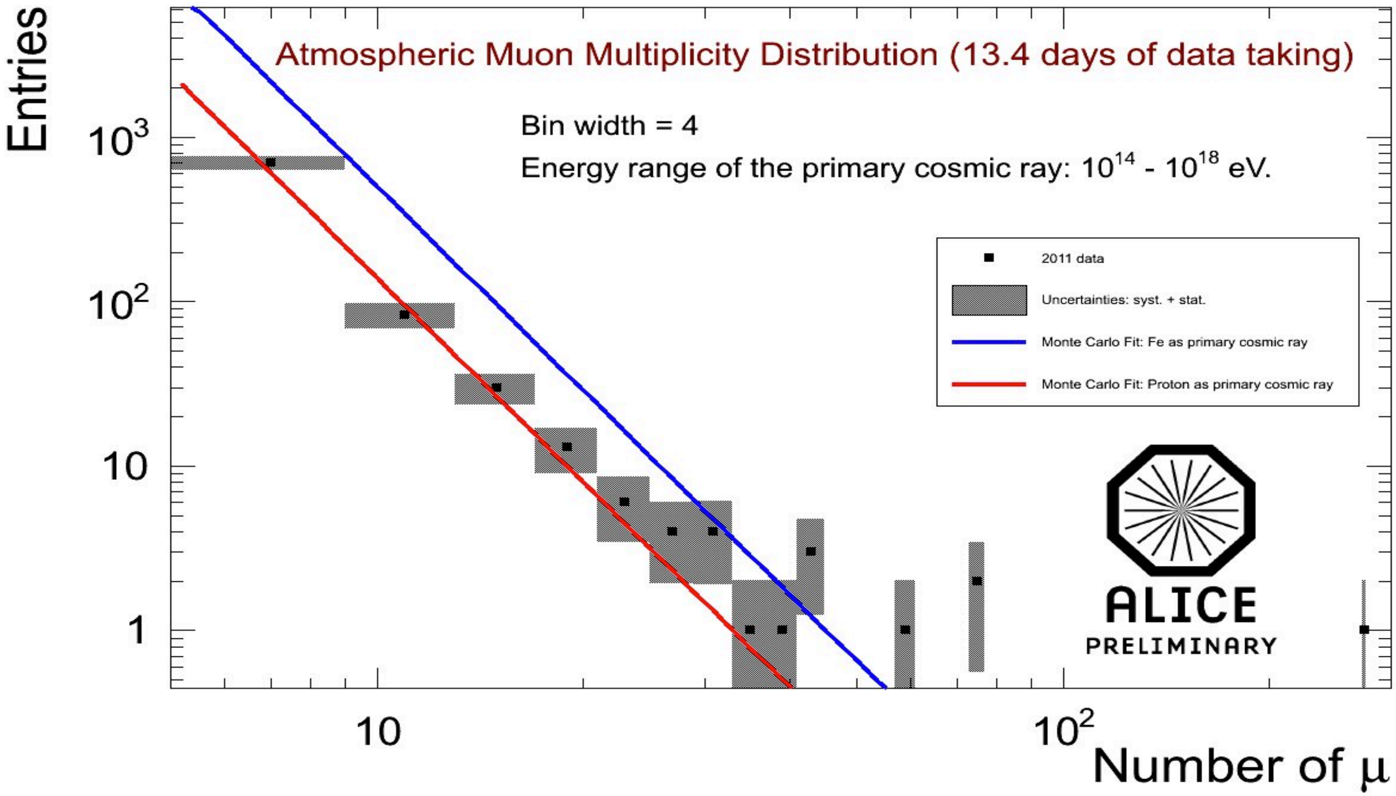
Monte Carlo simulations to study the muon multiplicity distribution (mmd)

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



Monte Carlo to study HME

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



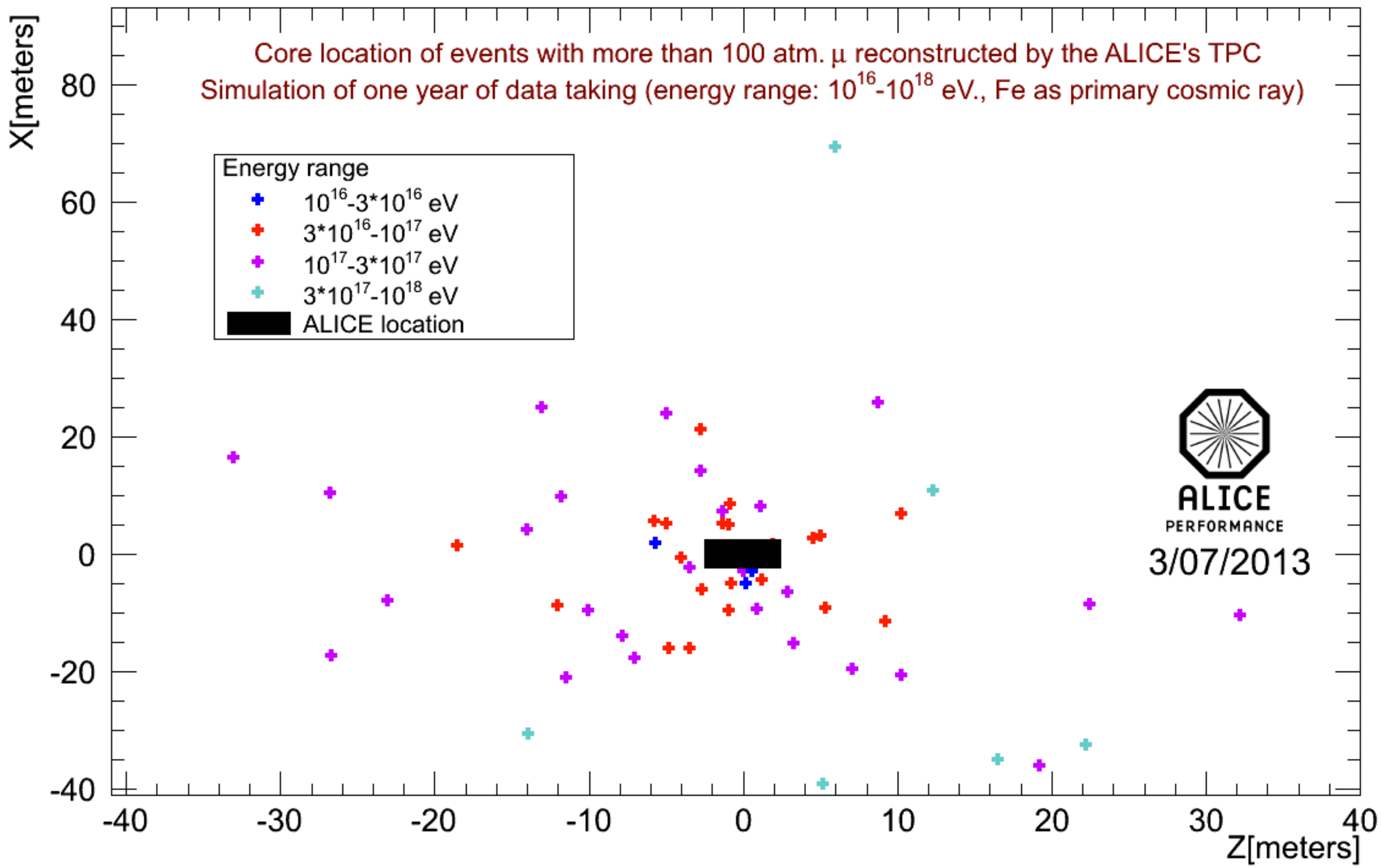
- Primary energy range of the simulation : $10^{14} < E < 10^{18}$ eV
- The data are, as expected, in between the pure Proton composition (light elements) and pure Fe (heavy elements).
- The lower multiplicities (lower primary energies) are closer to pure Proton as expected.

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)

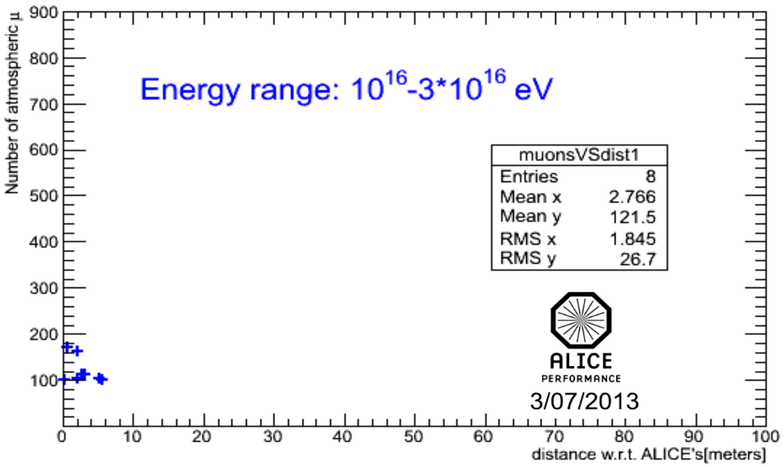
- Energy range: $10^{16} - 10^{18}$ eV
- Primary cosmic ray composition: proton, Fe nuclei
- Theta <= 50^0

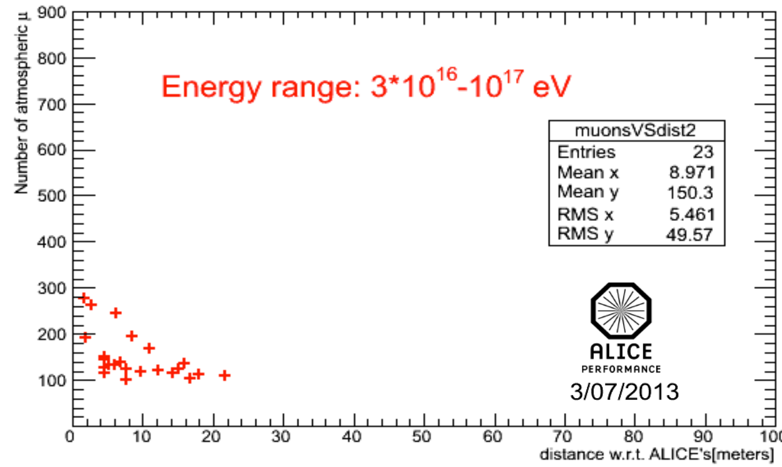
Monte Carlo to study HME

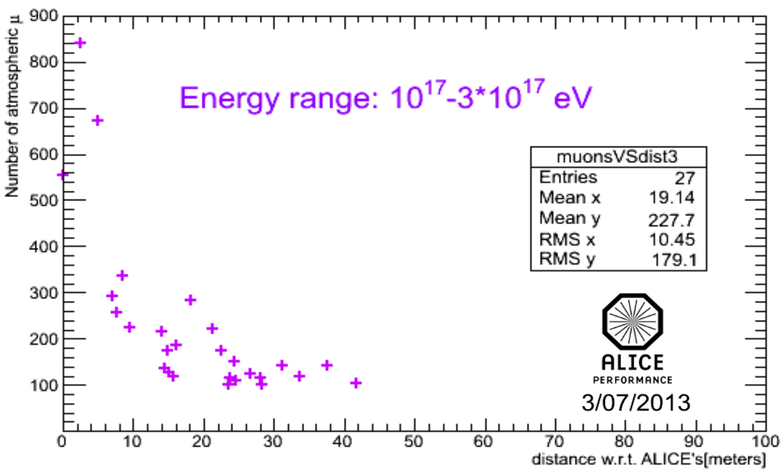


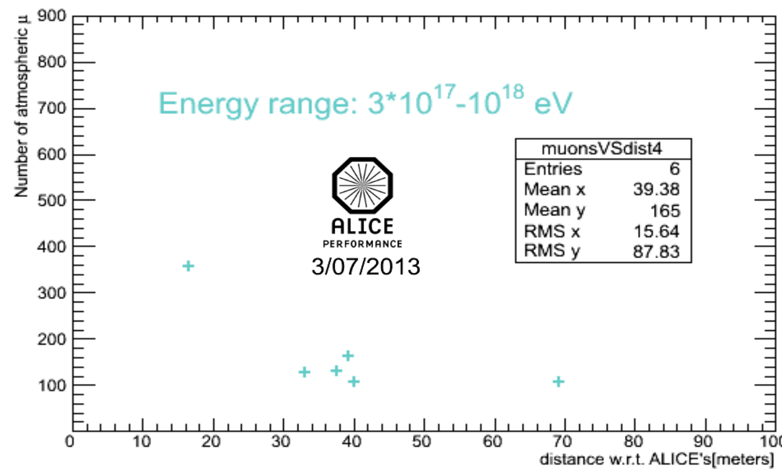
Core's position (ALICE coordinate system reference) w.r.t ALICE for the different energy ranges simulated:
The black rectangle shows the ALICE's surface in the XZ plane.
Most of the hmm events have a core located very close to ALICE (< 30 m),
only some events of very high primary energy have a farther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