XV MEXICAN WORKSHOP ON PARTICLES AND FIELDS

2-6 November 2015 *Playa Mazatlán Beach Hotel*
Mexico/BajaSur timezone

Cosmic-ray physics with LEP and LHC experiments

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XV Mexican Workshop on Particles and Fields
Mazatlán, Sinaloa - México

Plan of this talk

a. Introduction

b. Results from LEP

c. Results from LHC

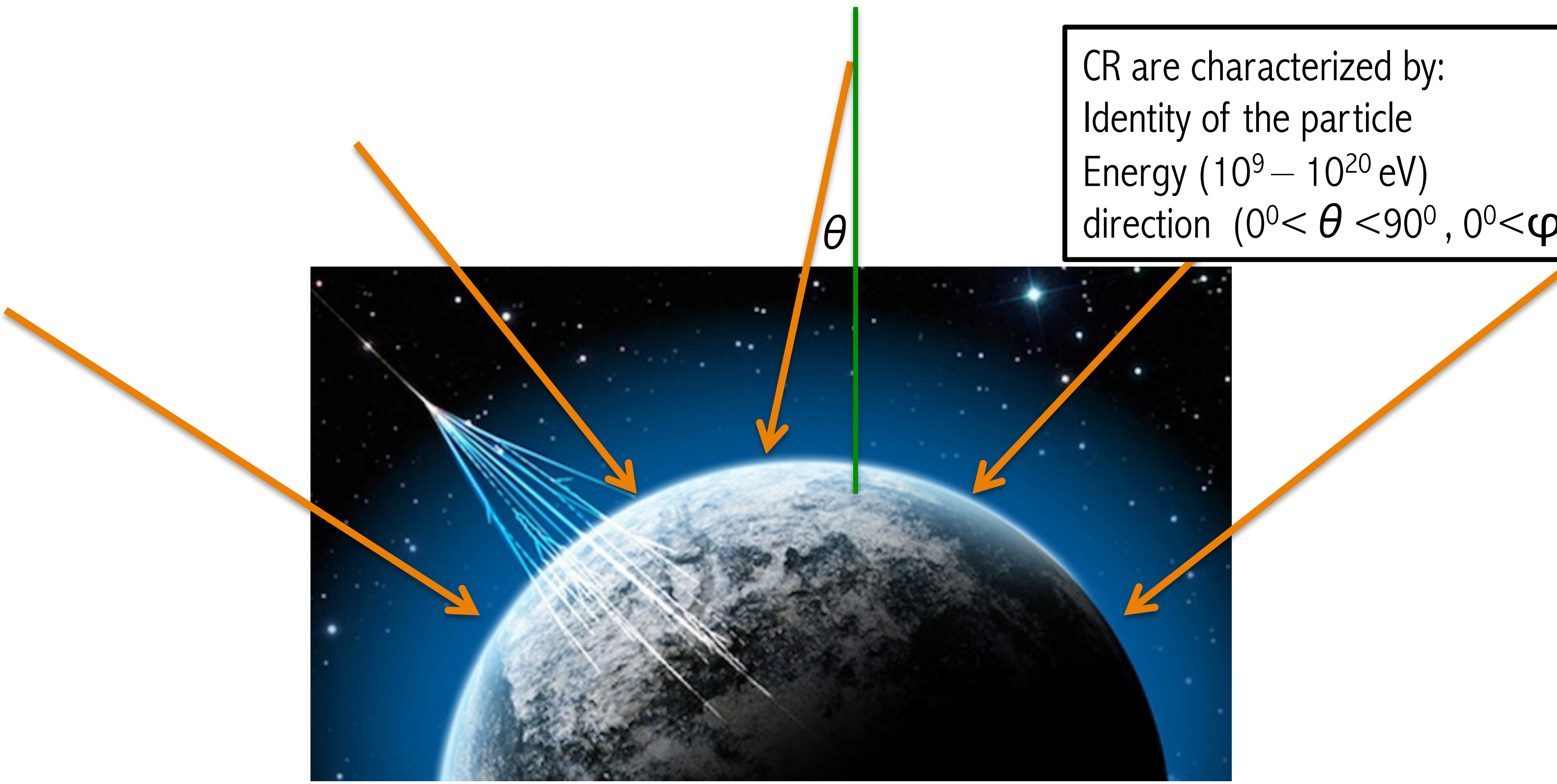
d. Outlook

Introduction

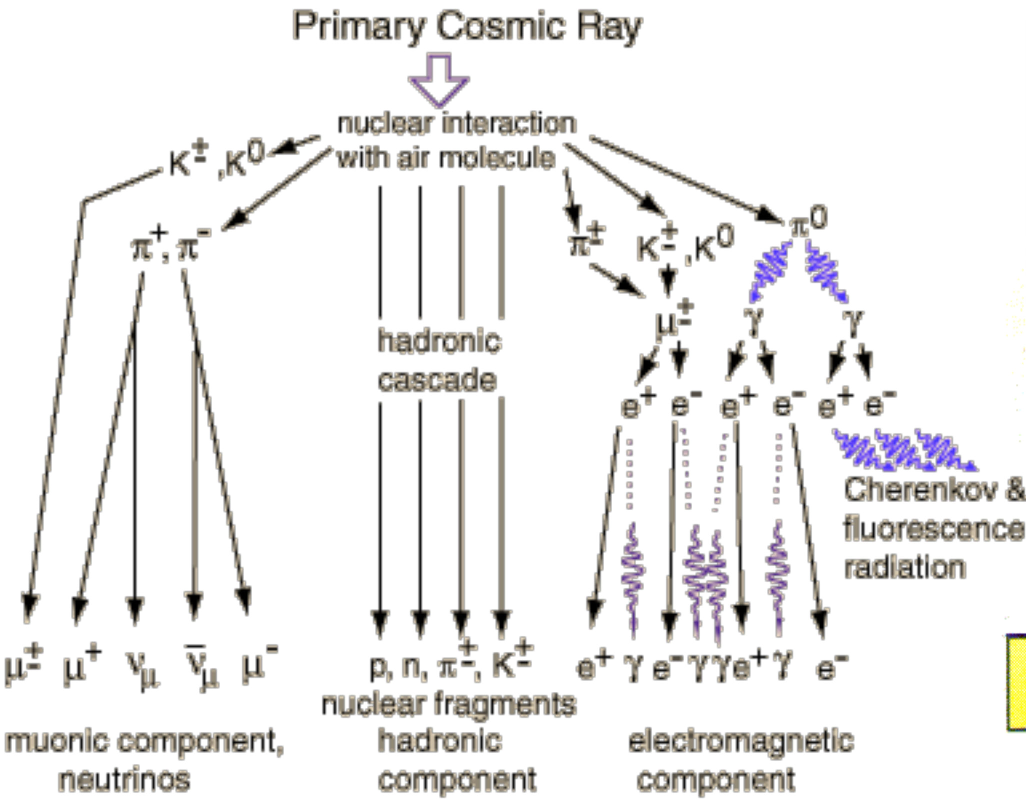
What are cosmic rays?

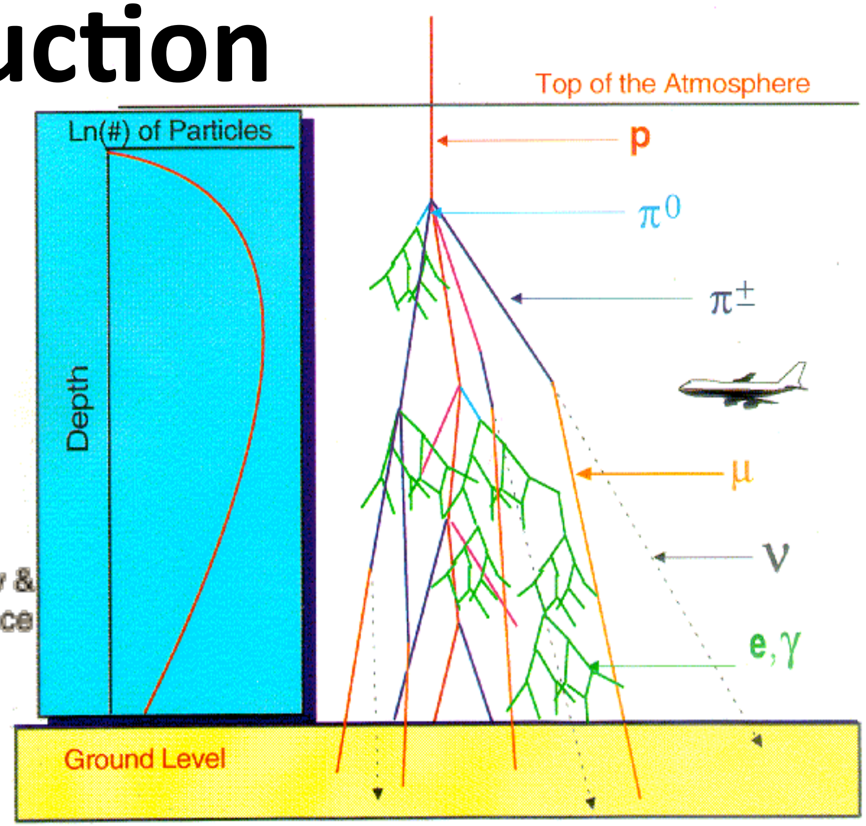
- ✓ Cosmic rays (CR) are particles coming from galaxy or outside the galaxy reaching the Earth's atmosphere.
- ✓ 90% protons, 9% He nuclei, 1% heavier nuclei
- ✓ Gammas , neutrinos
- ✓ Rate ~ 1000 particles hits the atmosphere per m^2s

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



Introduction





Extensive Air Showers

p,n,π → near the shower axis

μ , e, γ → widely spread

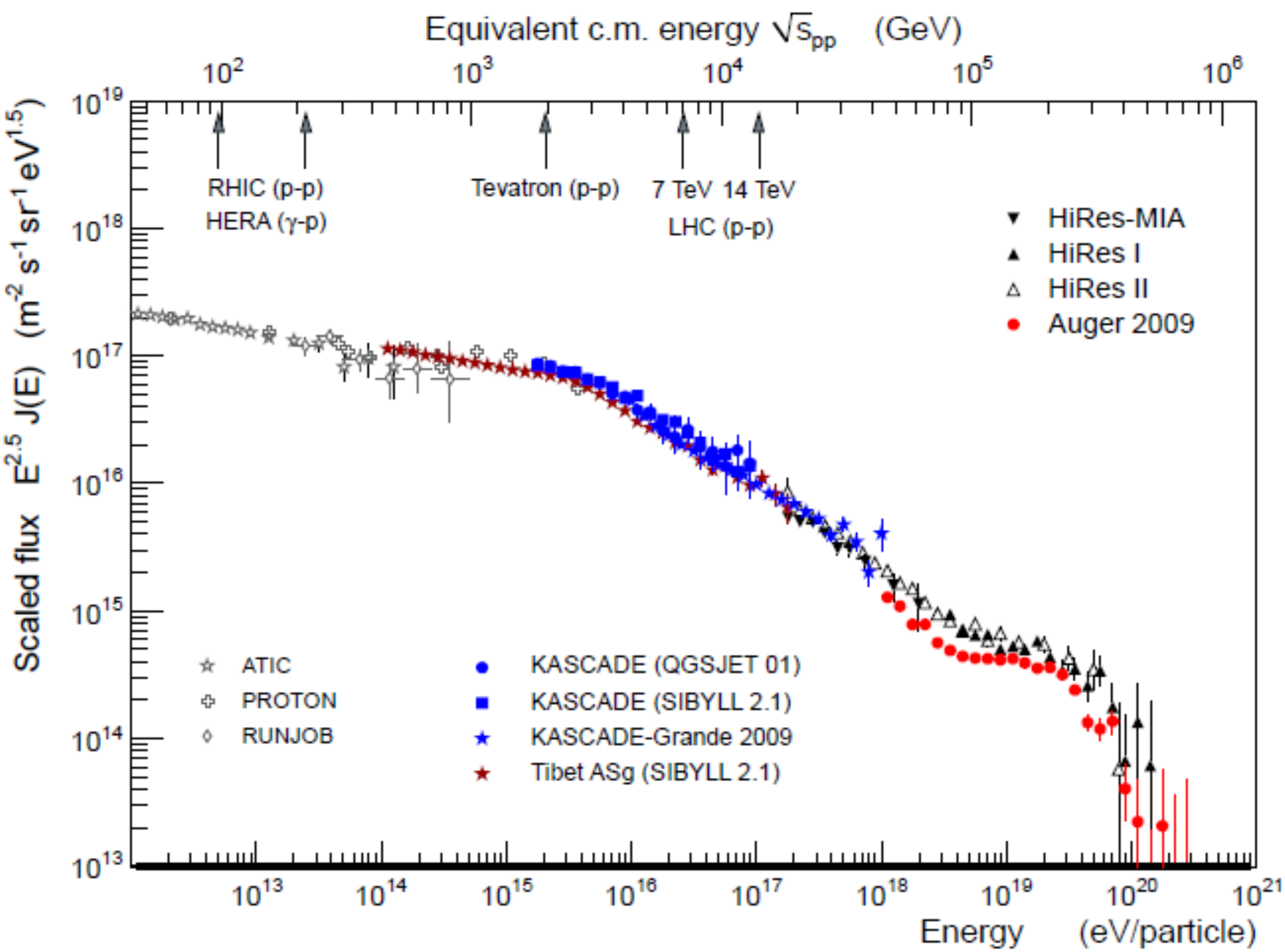
e, γ → from π^0 , μ decays (10 MeV)

μ → from $\pi^{\pm}$, K decays (1 GeV)

Details depend on

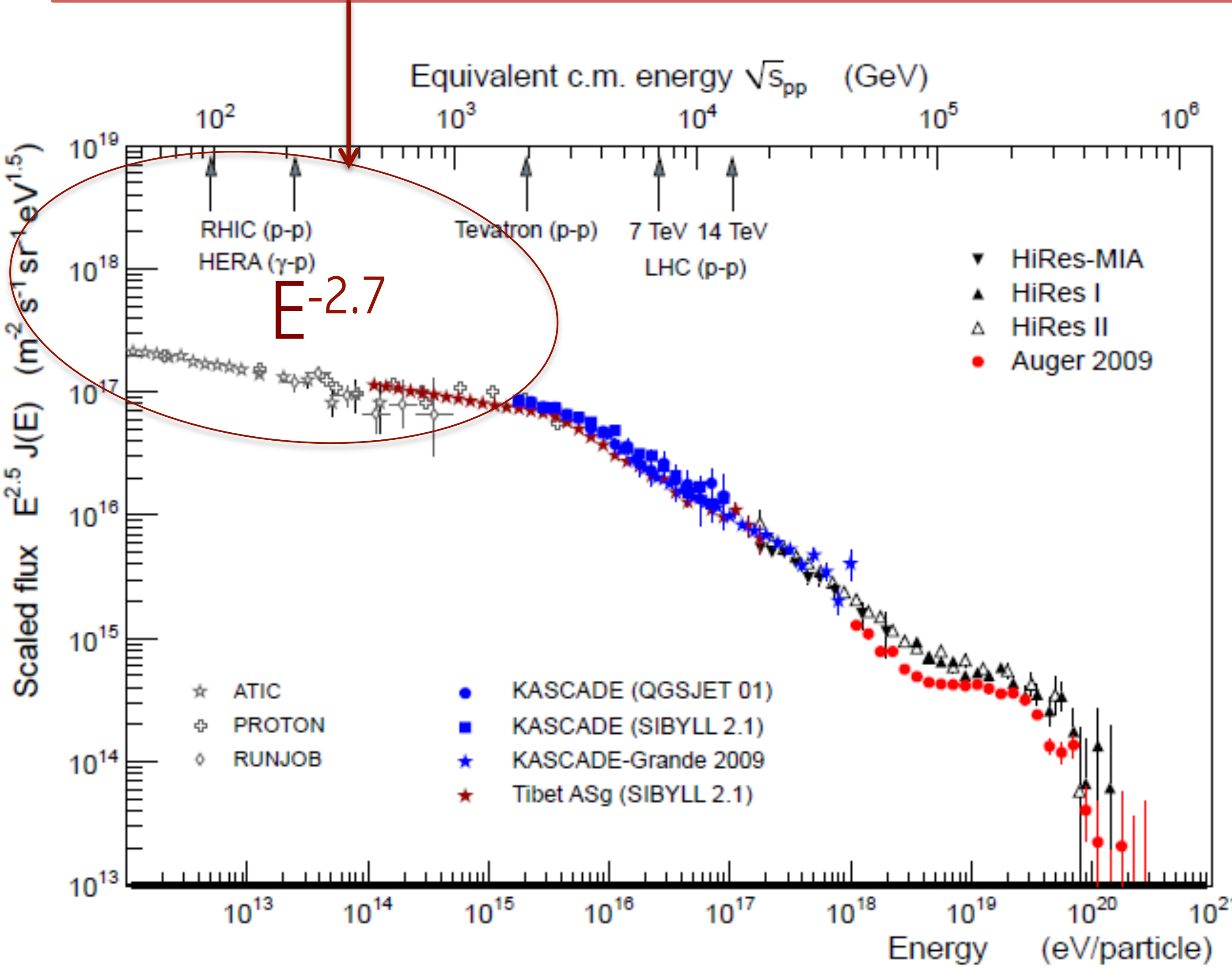
- Interaction cross sections
- Hadronic and electromagnetic particle production
- Decays, transport of particles at energies from MeV's to 10^{20} eV (above accelerators energy)

Introduction



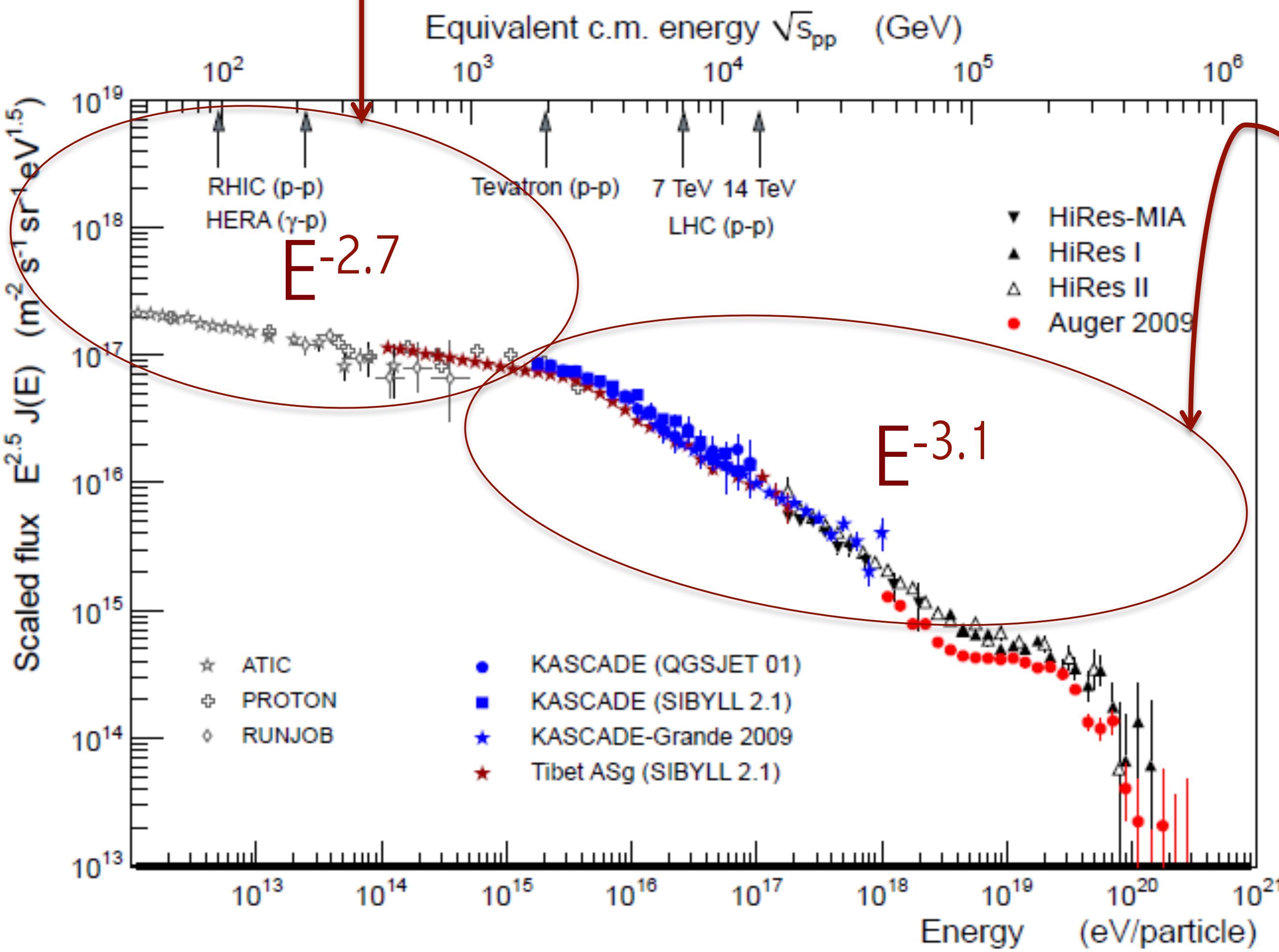
Introduction

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



Introduction

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



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

Introduction

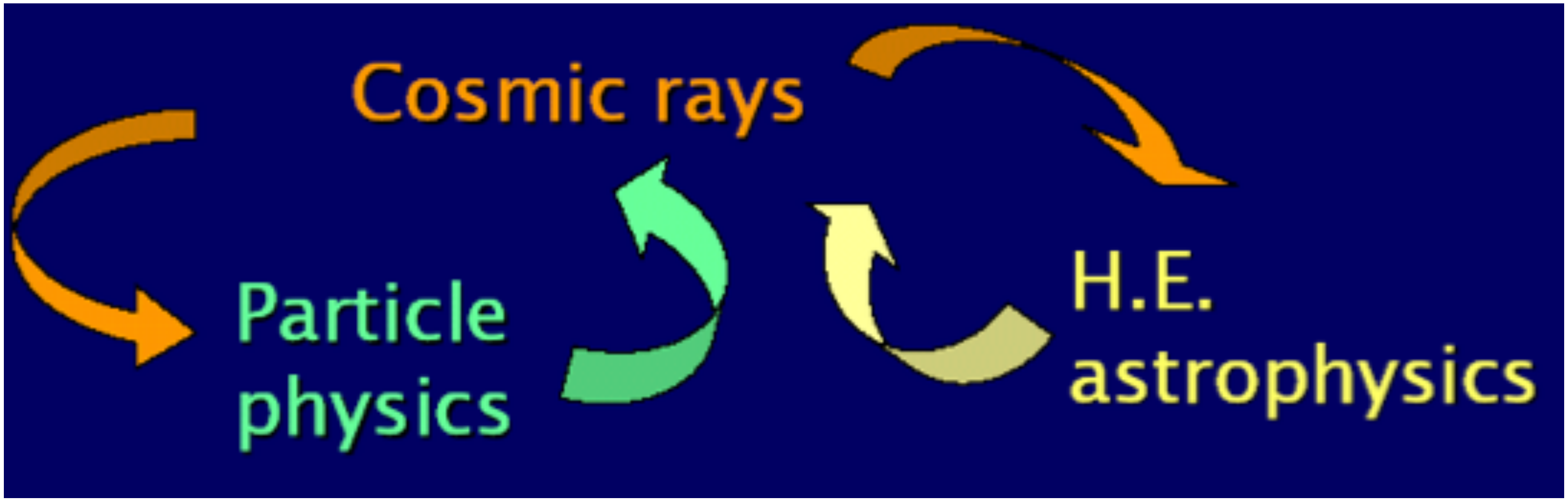
Direct measurements up to E ~ 10^{14} eV

→ 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)

Introduction



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

Introduction

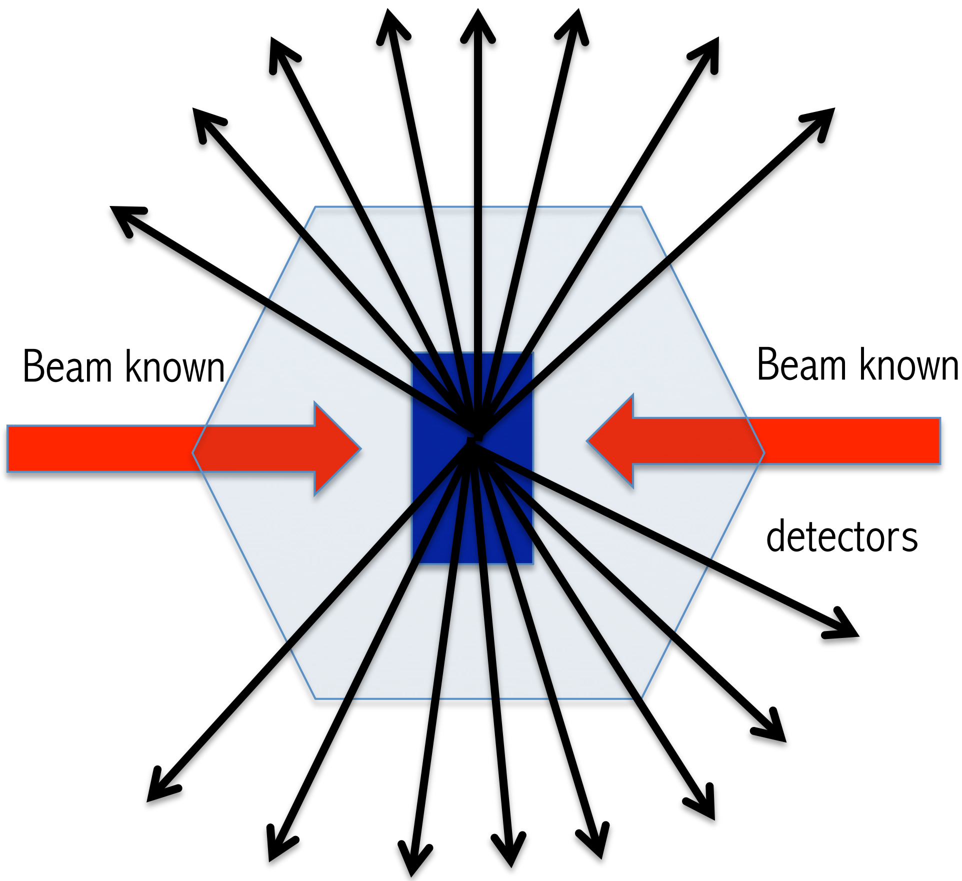
Table 1. Discovery of elementary particles

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
H^0	**2012**	**ATLAS/CMS**	**Accelerators (LHC)**

Introduction

ACCELERATOR PHYSICS:

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



Introduction

ACCELERATOR PHYSICS:

BEAM KNOWN → DETECTION OF THE SECONDARIES
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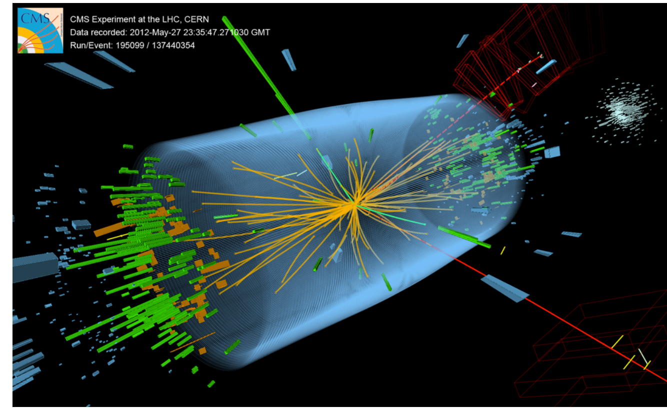
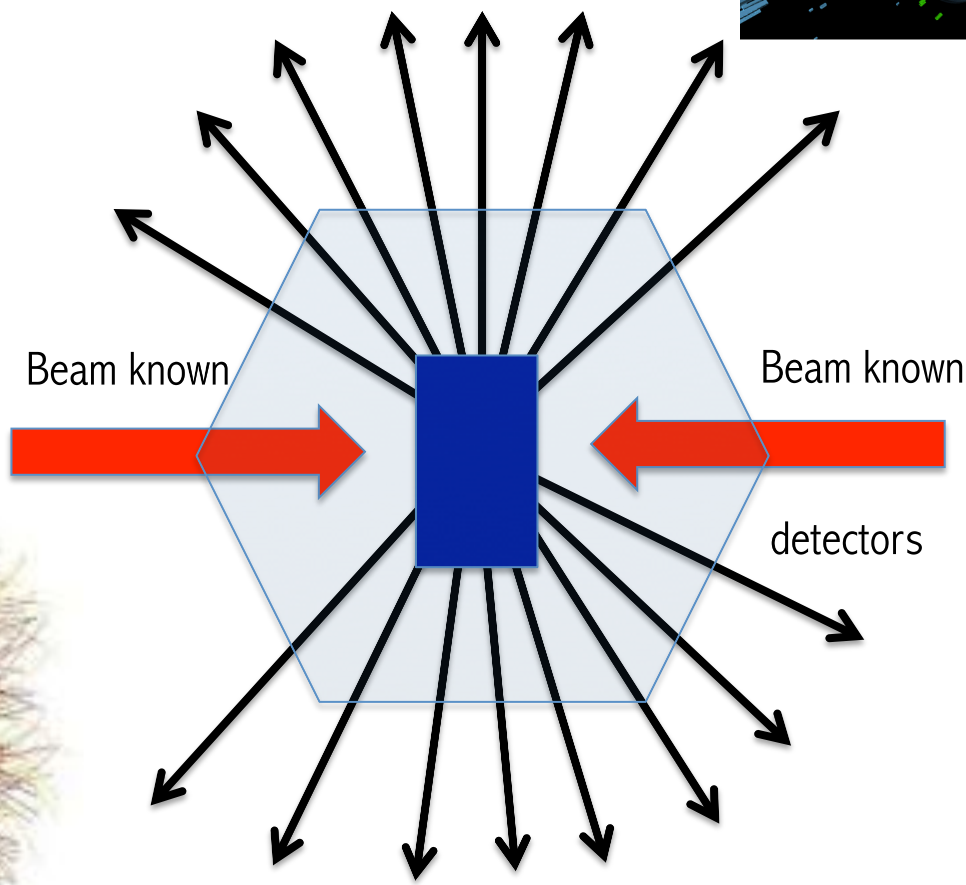
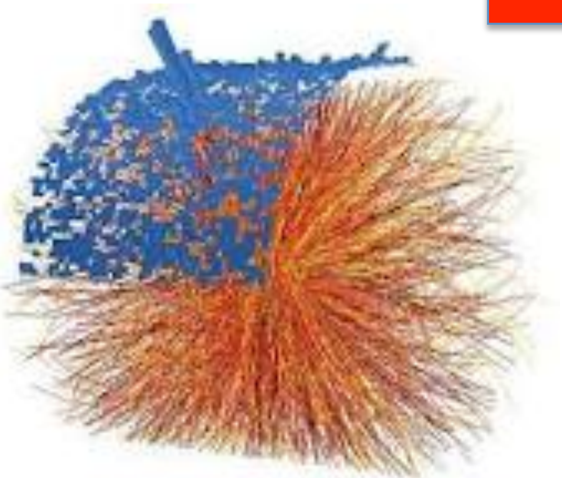




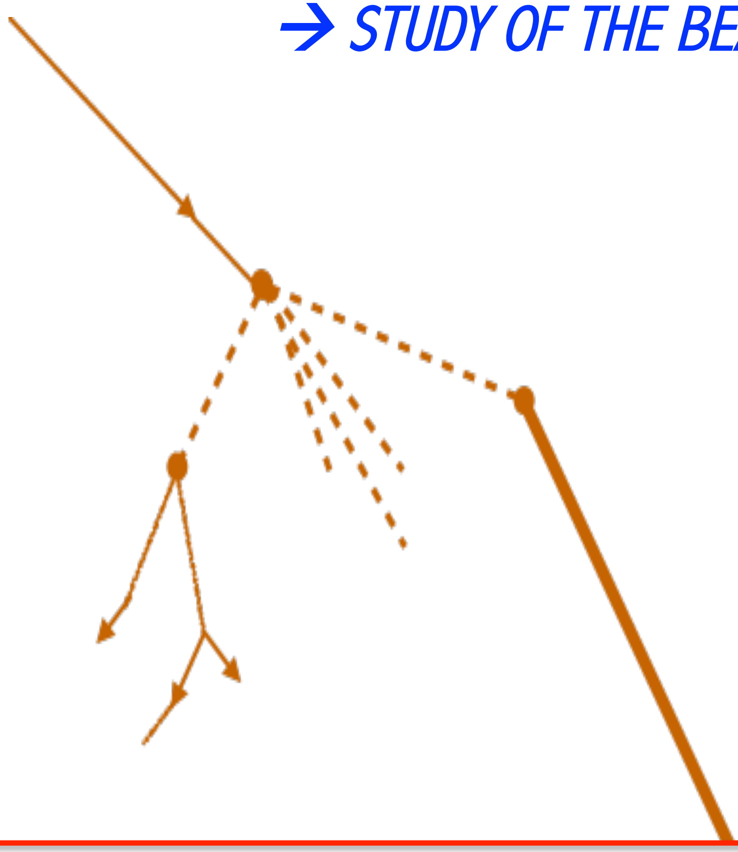


Introduction

COSMIC RAY PHYSICS WITH EAS:

BEAM UNKNOWN → DETECTION OF THE SECONDARIES ARRIVING AT GROUND

→ *STUDY OF THE BEAM*



Level of observation

AMS, PAMELA, Fermi

Balloons

High altitude detectors:
HAWC, Tibet

Ground experiments: Pierre Auger, Kaskade-Grande

Under-ground experiments:
Ice cube, Macro, LEP&LHC experiments

Introduction

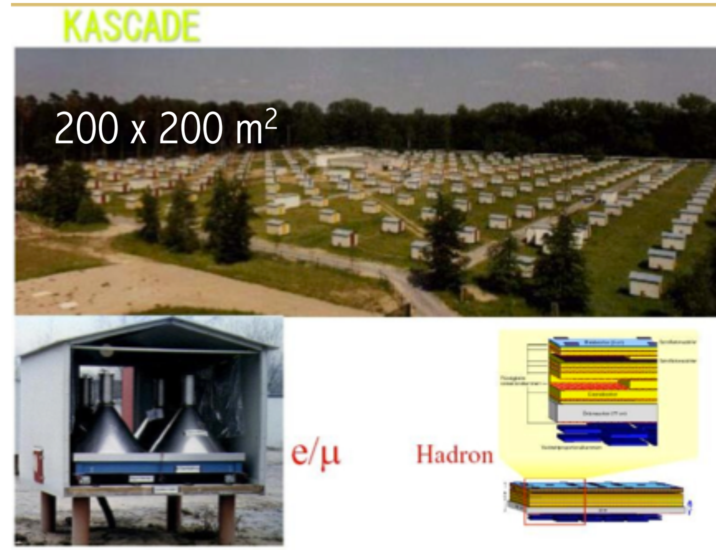
Cosmic rays with the accelerator apparatus

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

★ These apparatus are not designed for cosmic ray physics ☹ :

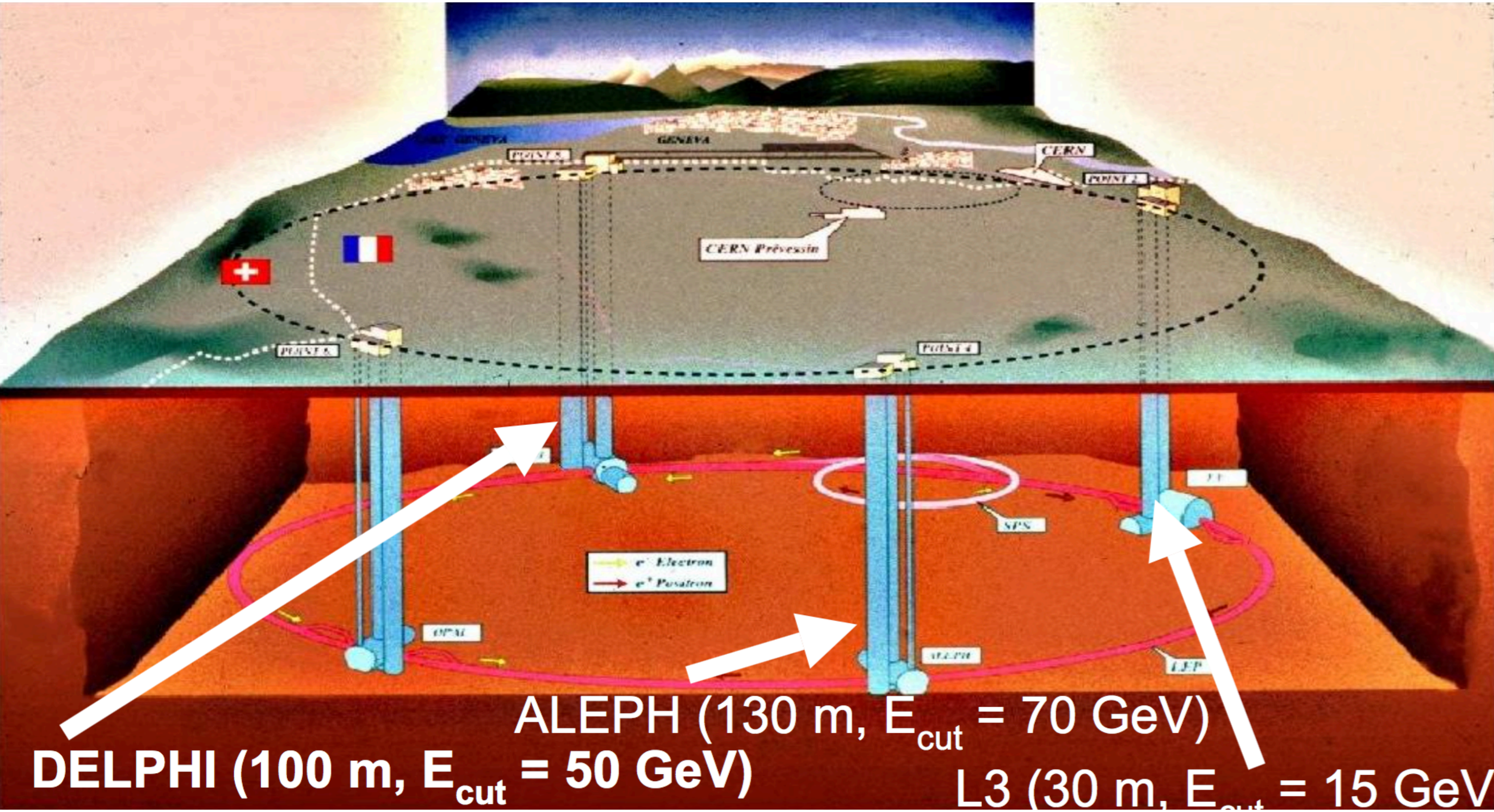
❑ Small detectors compared with the standard cosmic ray apparatus:

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

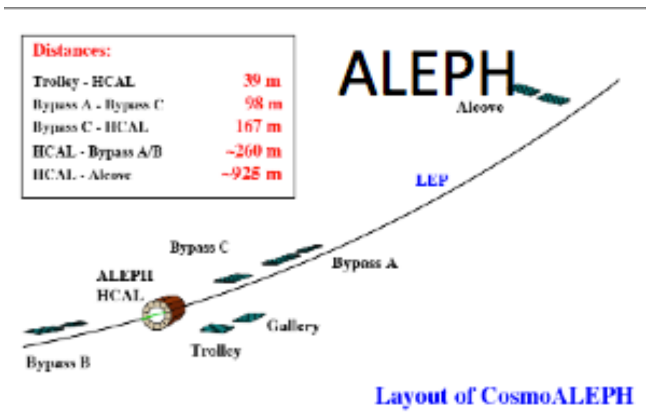


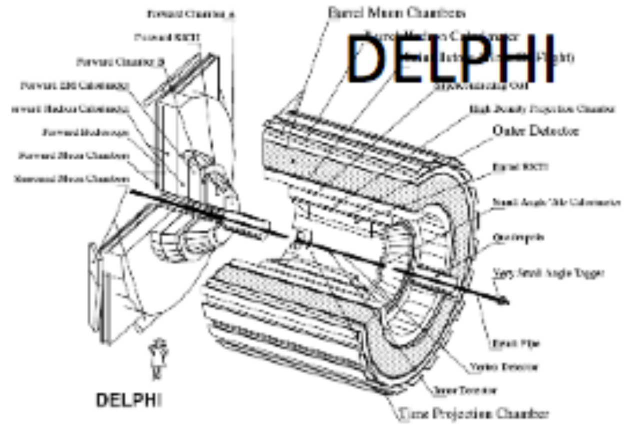
- ✓ Advantage: detectors with very high performances, presence of magnetic field ☺
- ✓ Why to study cosmic ray events with dedicated accelerator experiments? → remember that the only result out of LEP that did not agree "perfectly" with the Standard Model was the observation of too many multiplicity muon bundles.

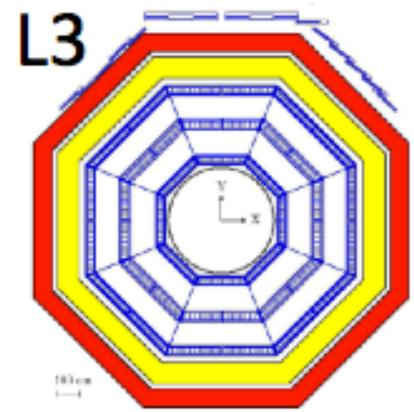
LEP results


GENEVA
CERN
POINT 2
POINT 8
POINT 4
CERN Prévessin
SPS
LEP
OPAL
ALEPH
e⁻ Electron
e⁺ Positron
ALEPH (130 m, E_{cut} = 70 GeV)
DELPHI (100 m, E_{cut} = 50 GeV)
L3 (30 m, E_{cut} = 15 GeV

LEP results





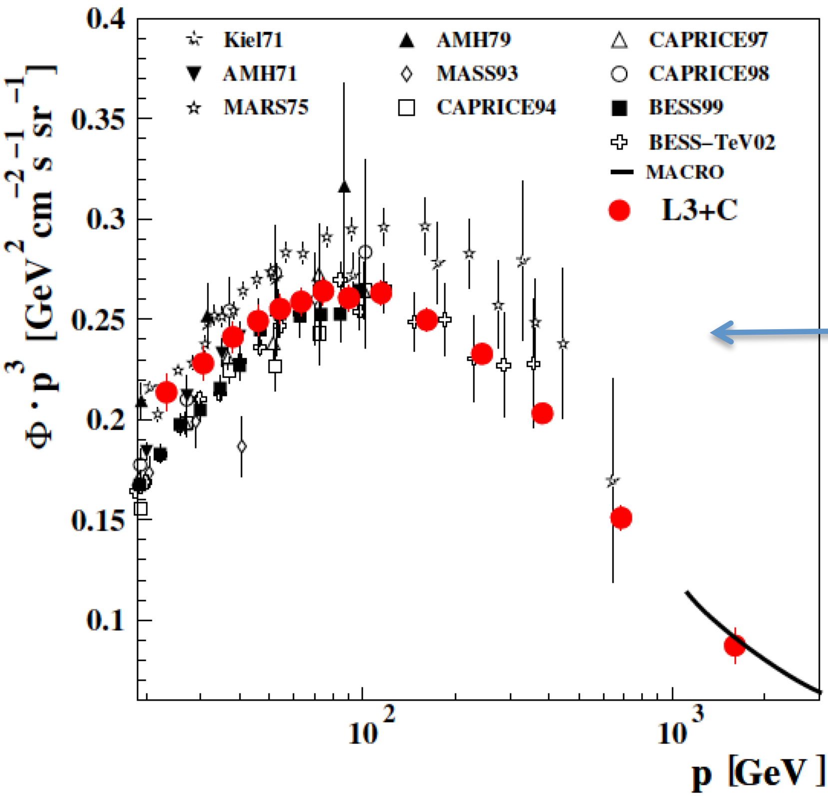


- ✧ ALEPH: 140 m of rock, momentum muon threshold p > 70/cos θ
  - ✓ underground scintillators, HCAL (horizontal area ~ 50 m^2), TPC projected area ~ 16 m^2
- ✧ DELPHI: 100 m of rock, momentum muon threshold p > 52/cos θ
  - ✓ Hadron calorimeter (horizontal area ~ 75 m^2), muon barrel, TPC, ToF and outer detectors
- ✧ L3+C: 30 m of rock, momentum muon threshold p > 20/cos θ + surface array
  - ✓ Scintillator surface array (200 m^2), trigger, muon barrel (100 m^2), hadron calorimeter, etc.

COSMIC RAY ENERGY COVERAGE FROM $10^{14} - 10^{18}$ eV

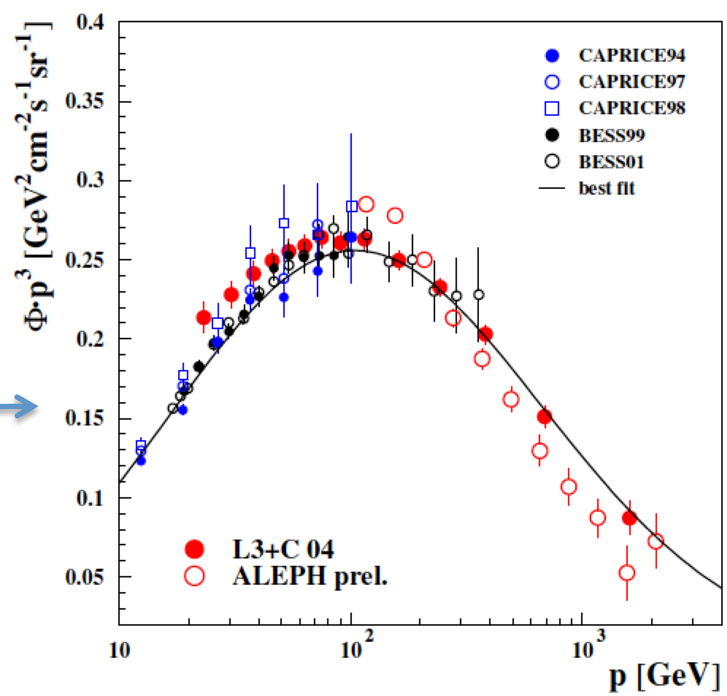
LEP results

29th International Cosmic Ray Conference Pune (2005) 10, 137.150



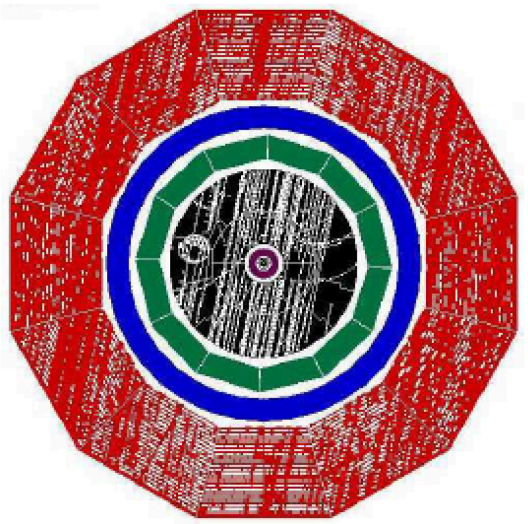
The flux is multiplied with 3rd power of momentum to see details along the steep spectrum.
Best agreement with BESS (also with CAPRICE)
Kiel agrees in shape but records systematically higher flux
MACRO agrees at high energy end of the spectrum.

Fit of BESS, CAPRICE and L3+C data gives z chi^2/Ndf = 1.2 taking into account the systematic momentum scale and normalization uncertainties quoted by the collaborations

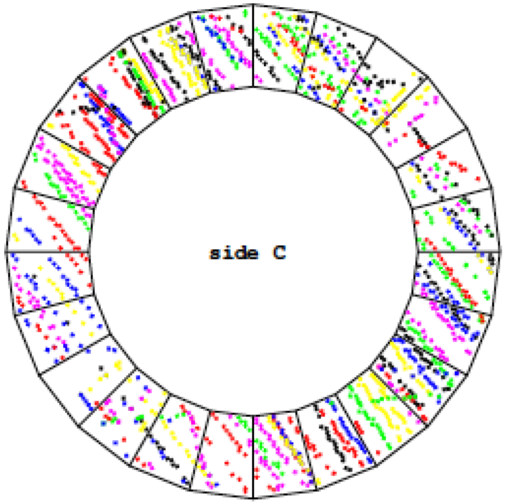


LEP results

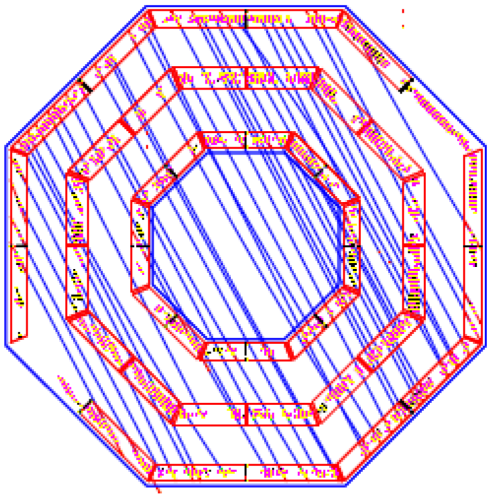
Muon bundles at LEP



ALEPH



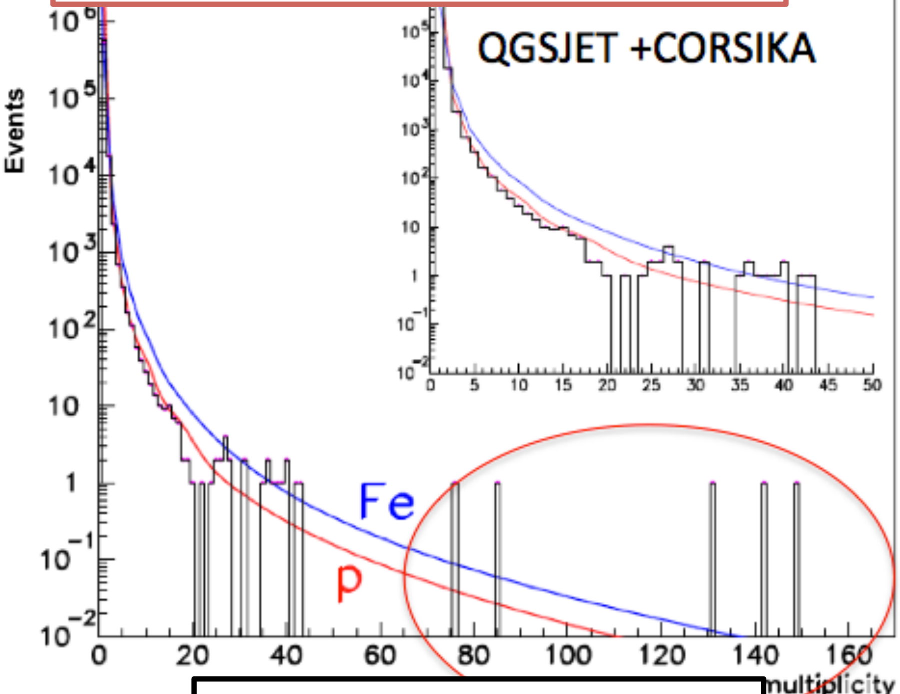
DELPHI



L3+C

LEP results

Astroparticle Physics 19 (2003) 513–523

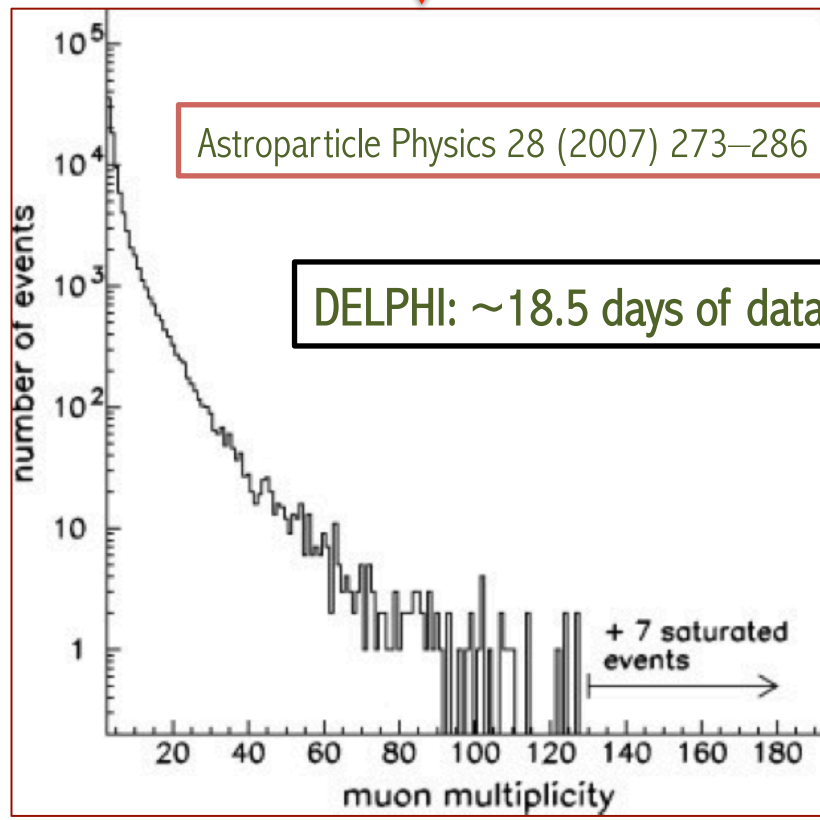


ALEPH: ~20 days of data taking

Data indicate that heavier component is needed to explain higher multiplicity muon bundles
These muon bundles are not well described (almost an order of magnitude above the simulation)

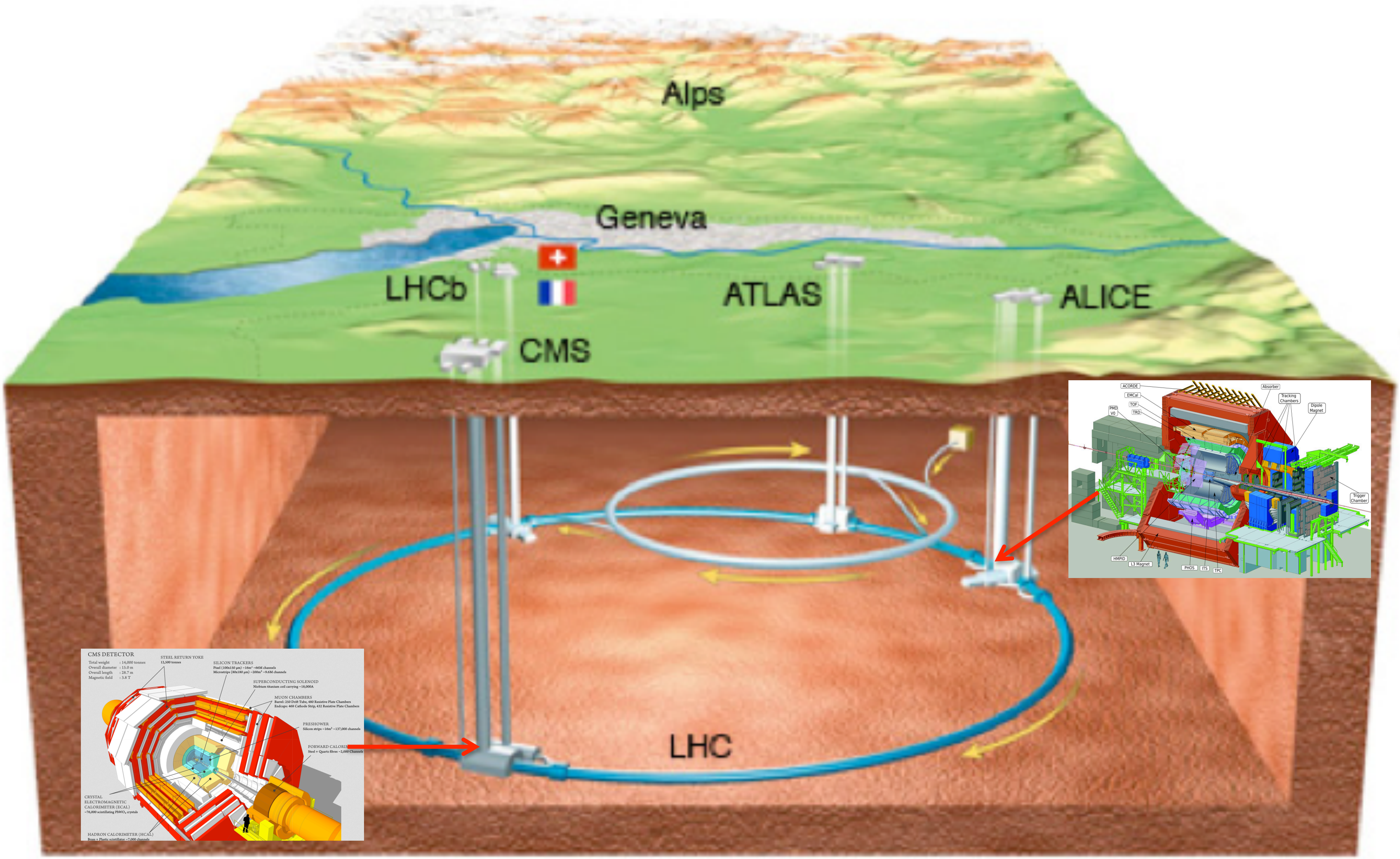
The conclusion is similar to Aleph :
However, even the combination of extreme assumptions of highest measured flux value and pure iron spectrum fails to describe the abundance of high multiplicity events.

Astroparticle Physics 28 (2007) 273–286



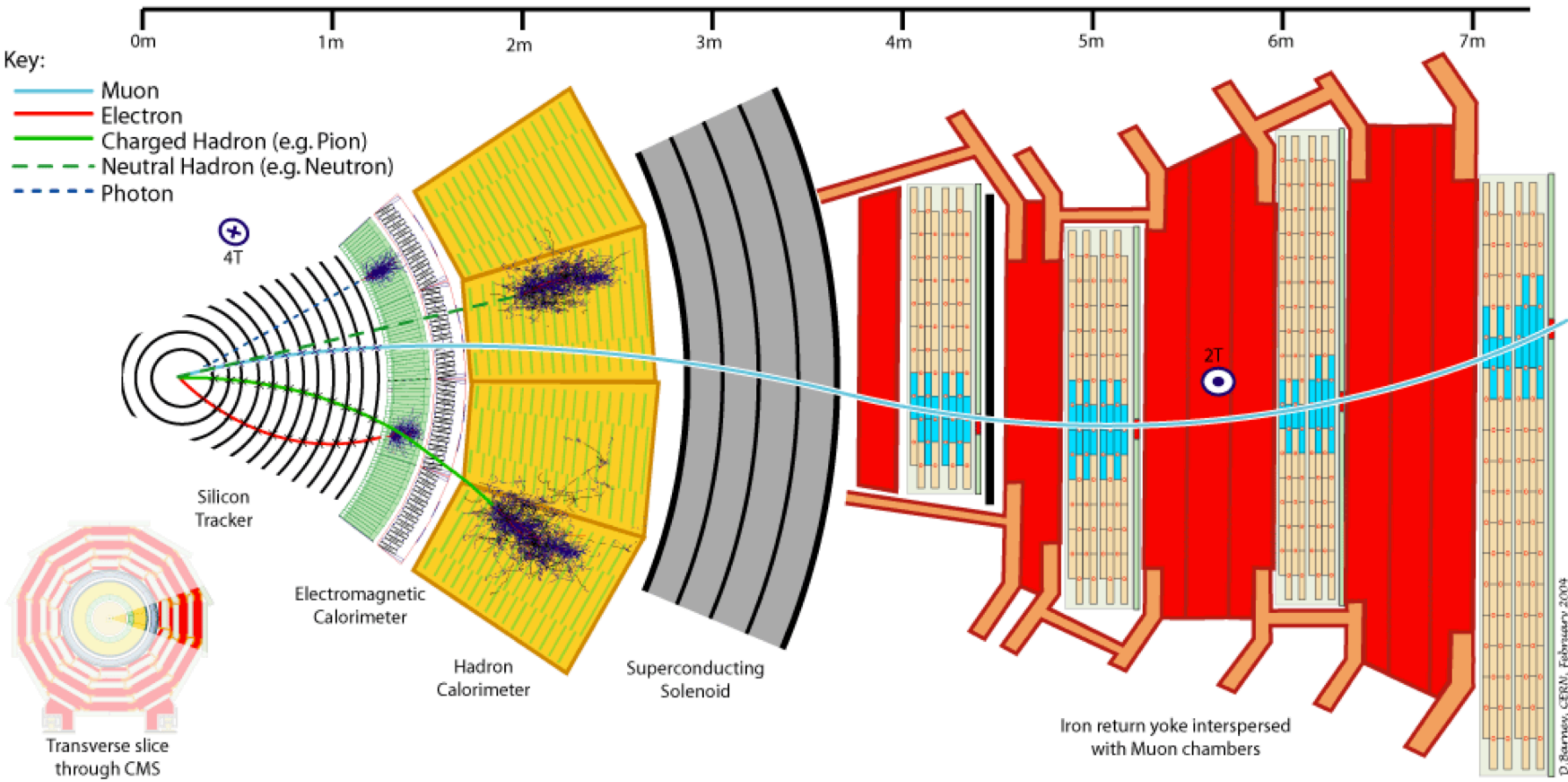
DELPHI: ~18.5 days of data taking

LHC results



LHC results

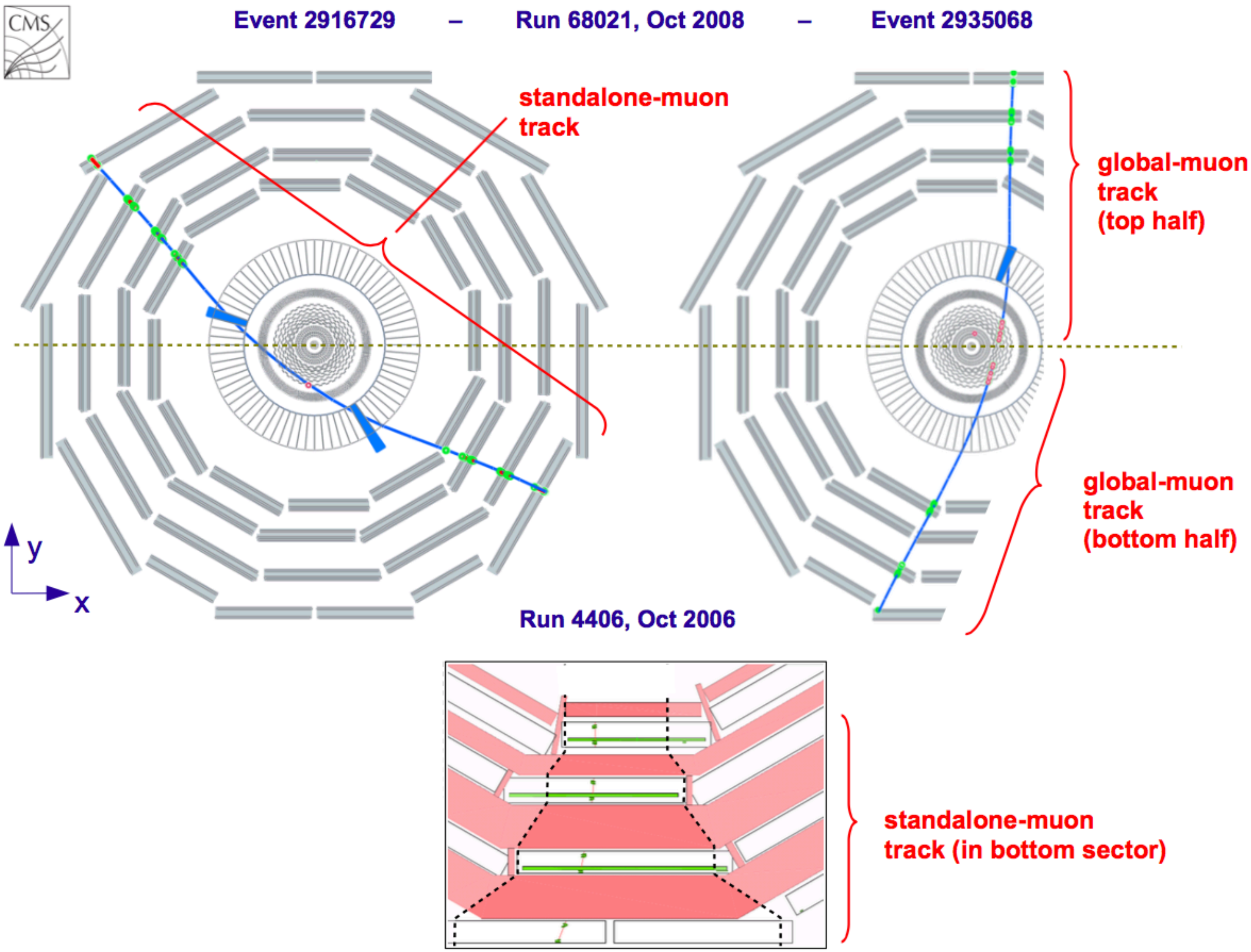
CMS



LHC results

CMS

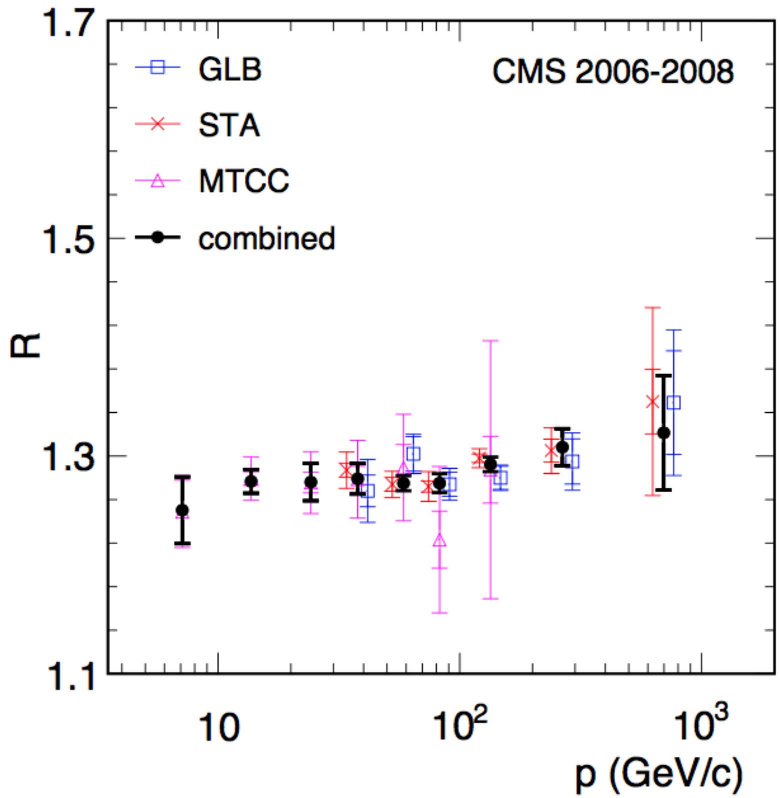
CERN-PH-EP-2010-011 2010/05/31

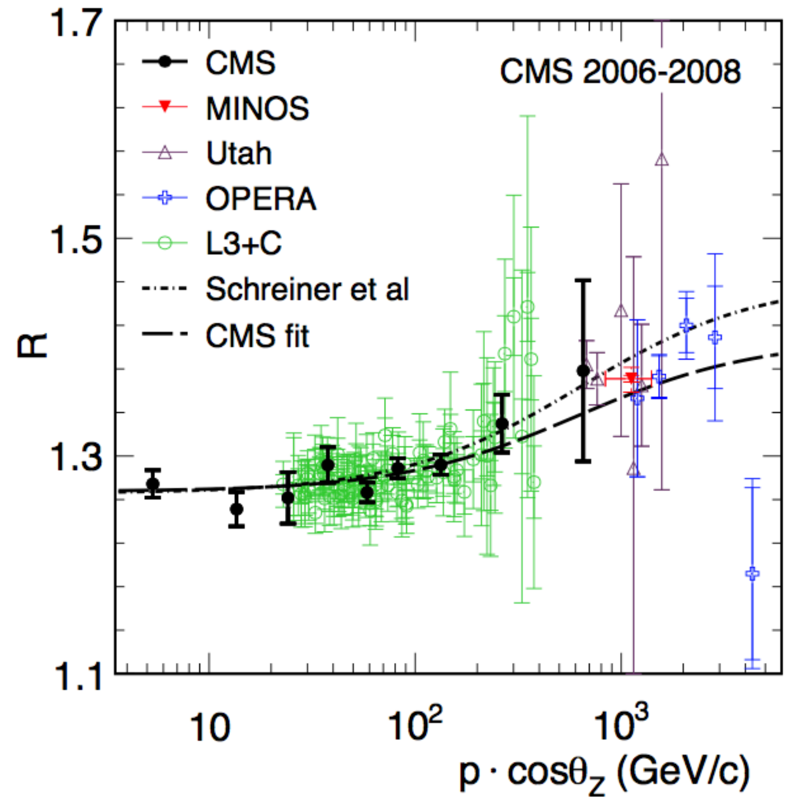


LHC results

CMS

CERN-PH-EP-2010-011 2010/05/31

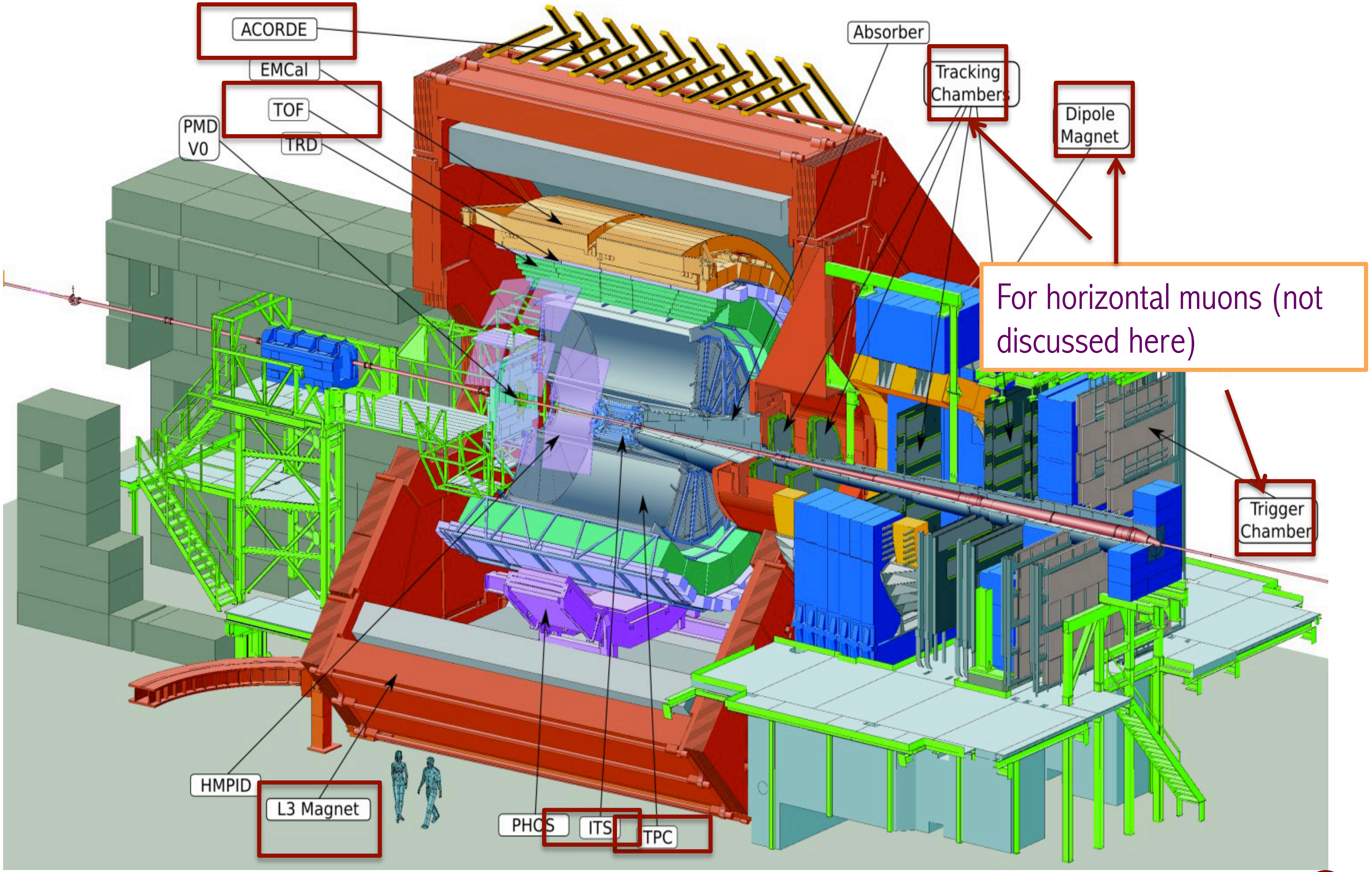




CMS has measured the flux ratio of positive- to negative-charge cosmic ray muons, as a function of the muon momentum and its vertical component. The result is in agreement with previous measurements by underground experiments. This is the most precise measurement of the charge ratio in the momentum region below 0.5 TeV/c. It is also the first physics measurement using muons with the complete CMS detector.

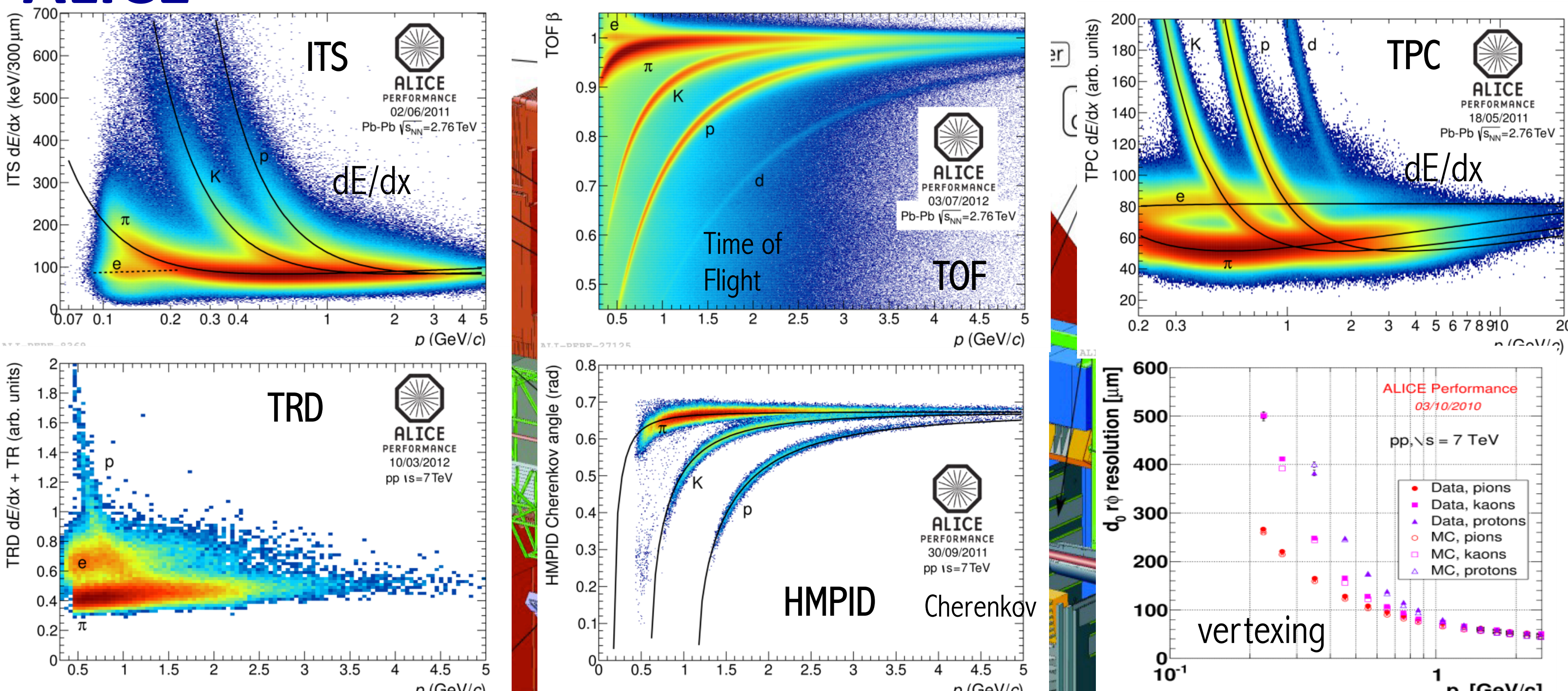
LHC results

ALICE



LHC results

ALICE



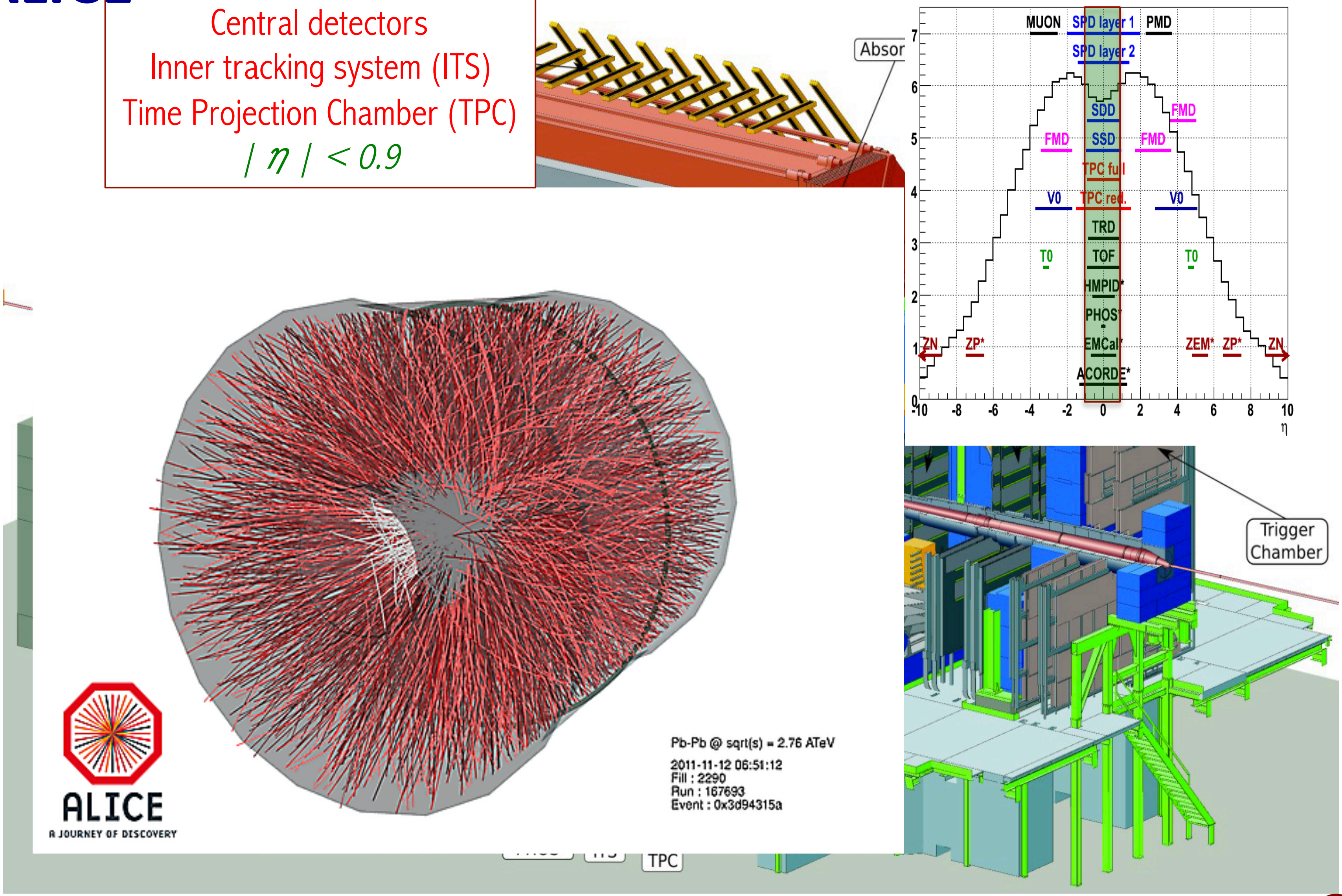
The design is optimized for reconstruction and identification of particles in a wide range of transverse momentum

- 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

LHC results

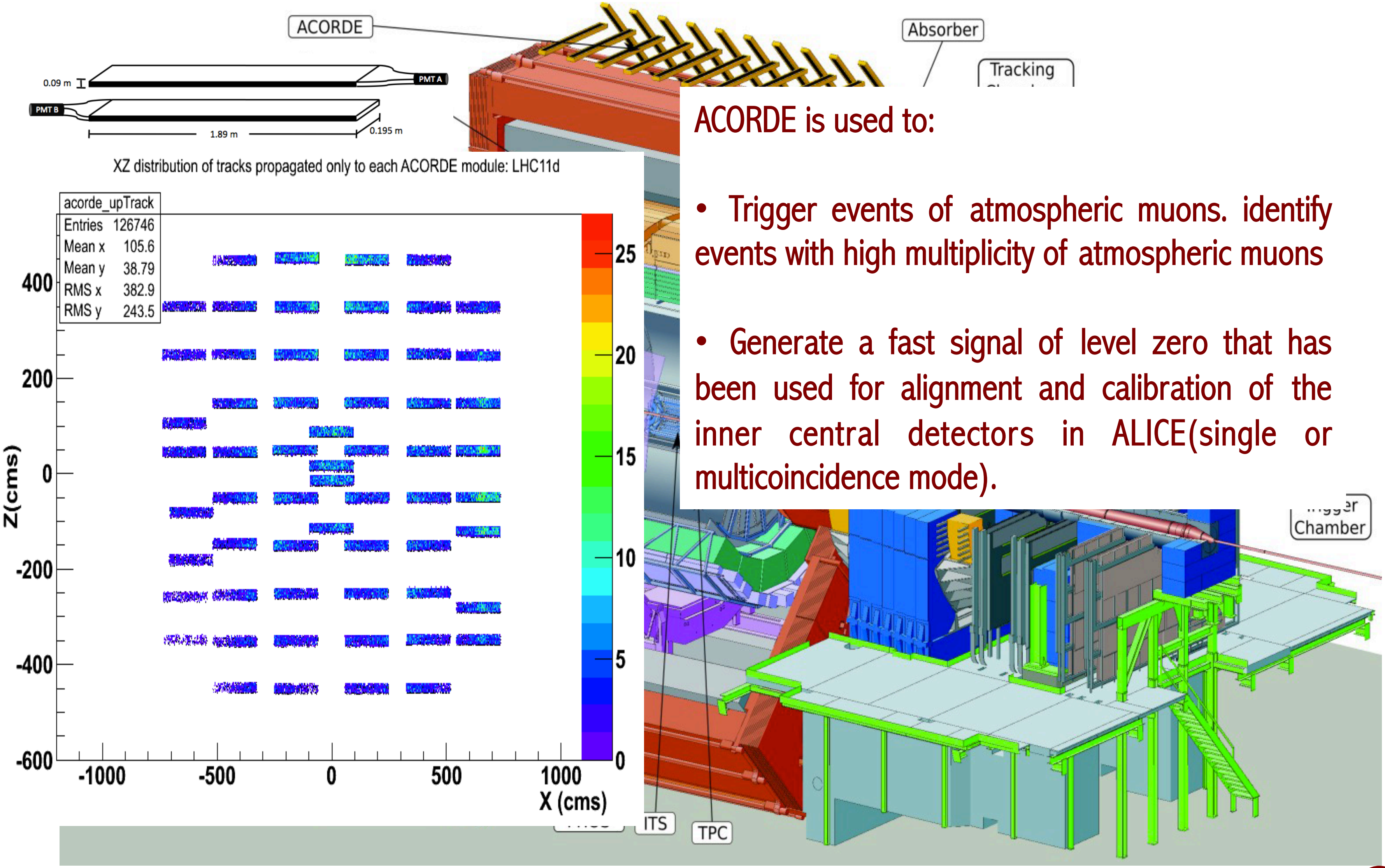
ALICE

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



LHC results

ALICE

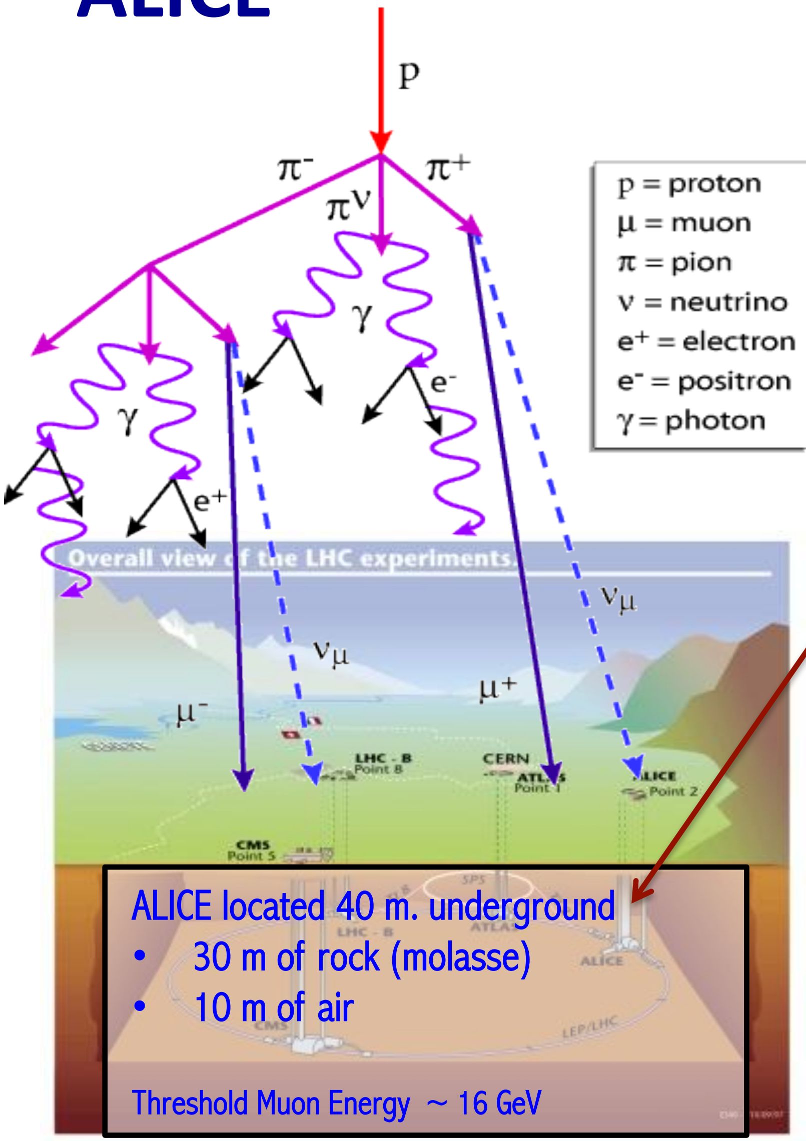


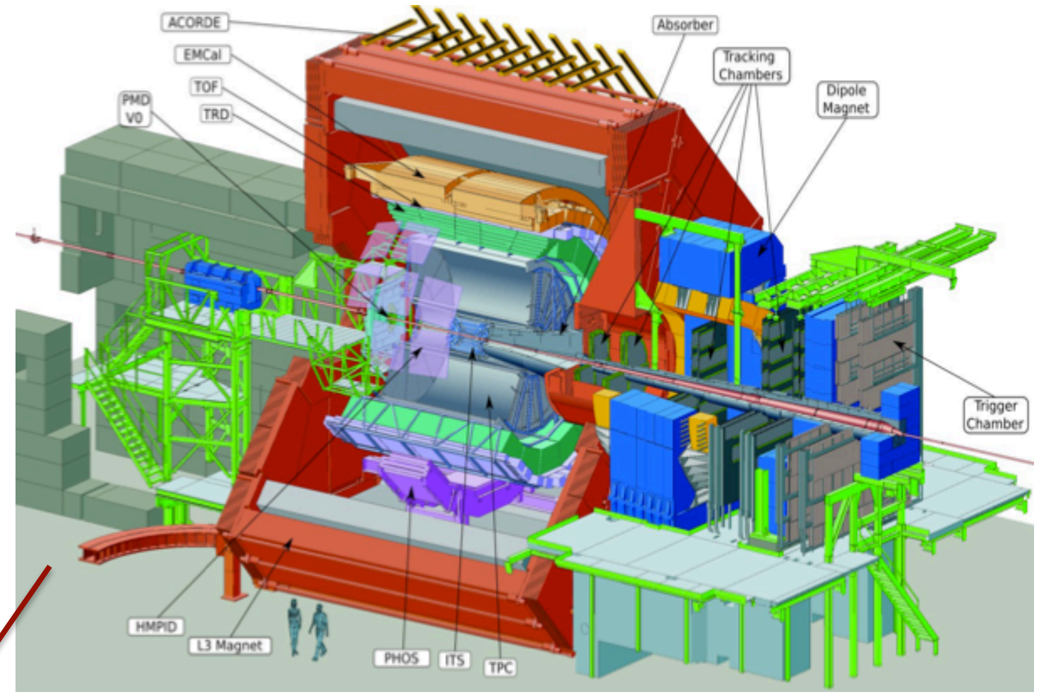
ACORDE is used to:

- 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).

LHC results

ALICE





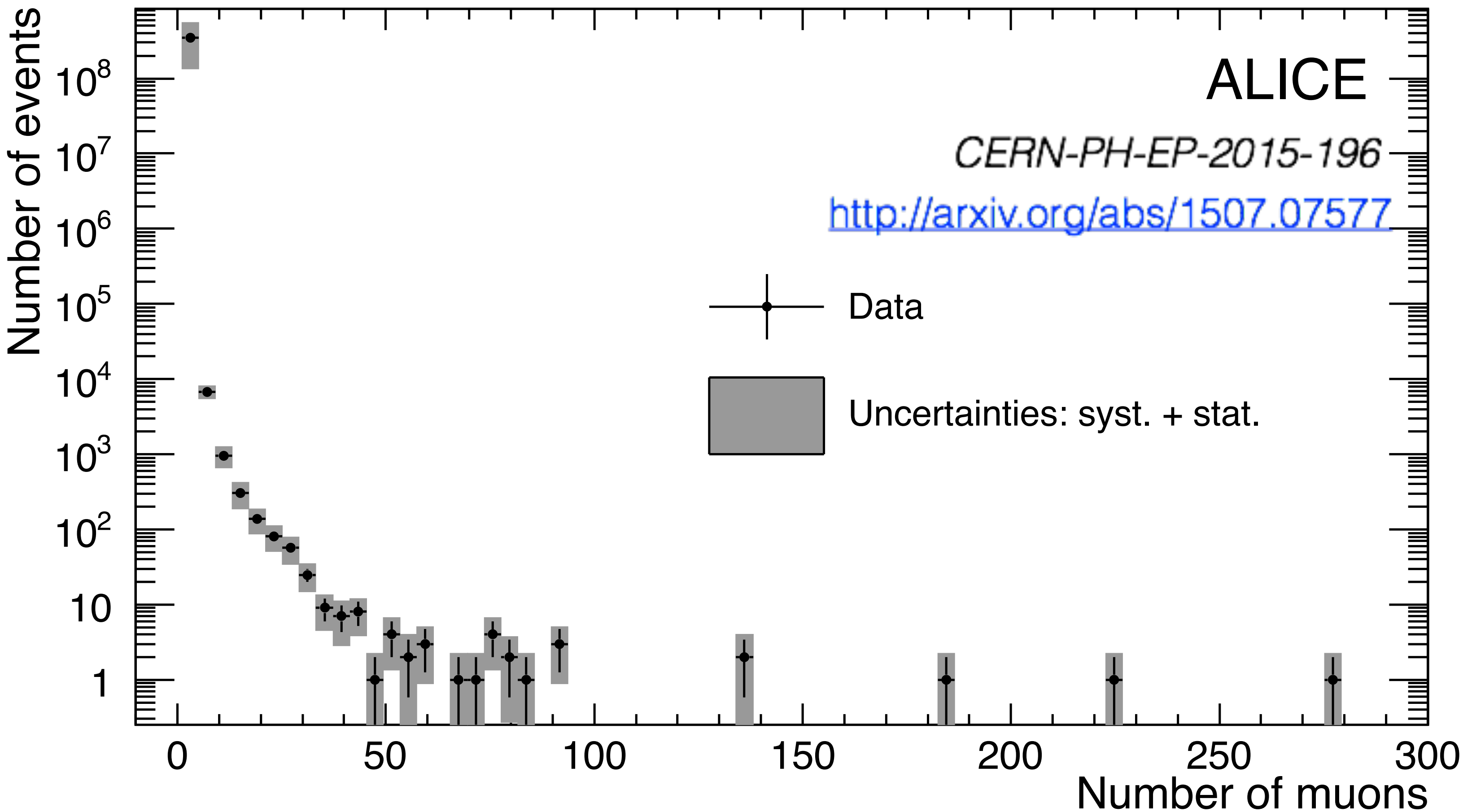
Topics of interest in Cosmic ray analysis in ALICE:

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

LHC results

ALICE

Presented last week at ICRC-2015

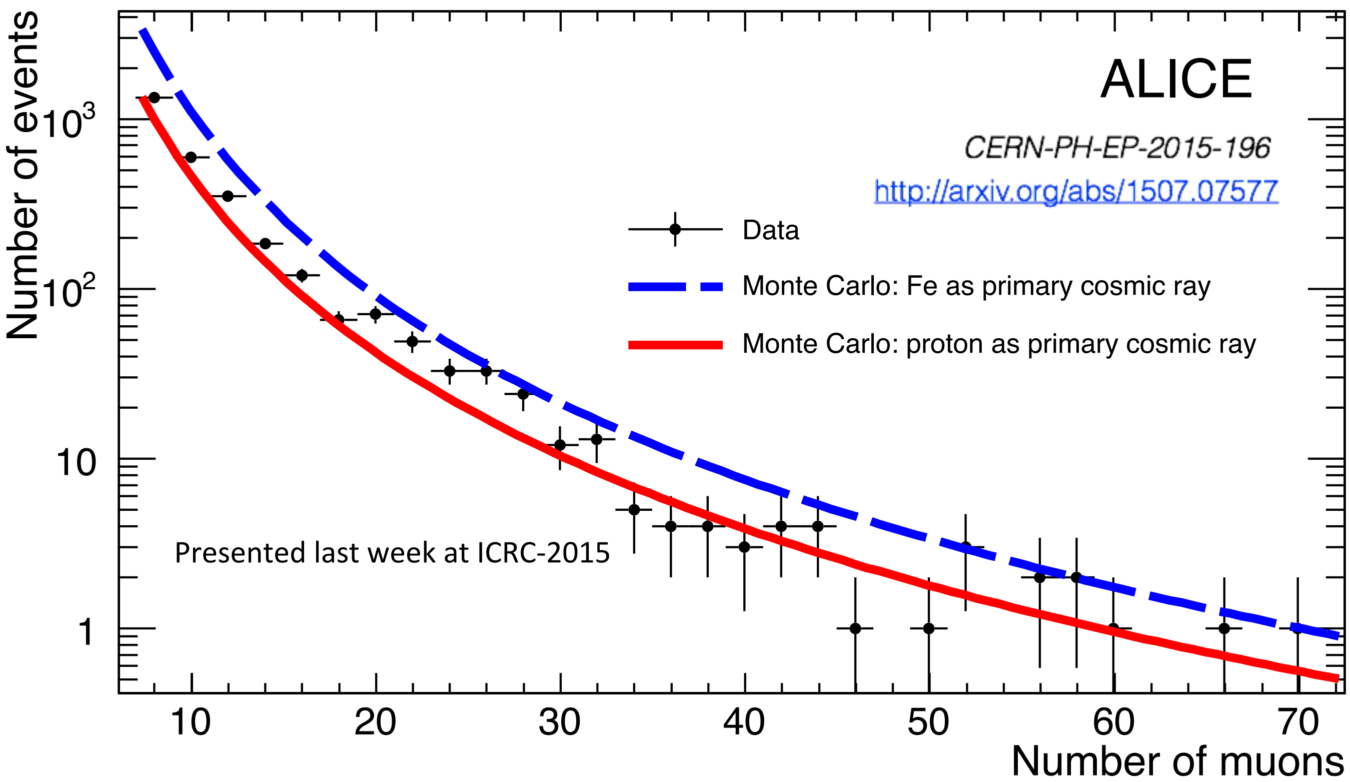


ALICE found a smooth distribution up to #μ < 70 and 5 events with more than 100 atmospheric muons (HMM)

LHC results

ALICE

The data approach the proton curve (low multiplicities). High multiplicity data lie closer to the iron curve. This suggests that the average mass of the primary cosmic-ray flux increases with increasing energy.



LHC results

ALICE

CERN-PH-EP-2015-196
http://arxiv.org/abs/1507.07577

Presented last week at ICRC-2015

HMM events	CORSIKA 6990 QGSJET II-03 proton	CORSIKA 6990 QGSJET II-03 iron	CORSIKA 7350 QGSJET II-04 proton	CORSIKA 7350 QGSJET II-04 iron	Data
Period [days per event]	15.5	8.6	11.6	6.0	6.2
Rate [$\times 10^{-6}$ Hz]	0.8	1.3	1.0	1.9	1.9
Uncertainty (%) (syst + stat)	13	16	8	20	49

Pure iron sample simulated with QGSJET II-04 model reproduces HMM event rate in close agreement with the measured value.

Independent of the version model, the rate of HMM events with pure proton cosmic-ray composition is more difficult to reproduce.

This result is compatible with recent measurements which suggest that the composition of the primary cosmic-ray spectrum with energies larger than 1016 eV is dominated by heavier elements: Phys. Rev. Lett. 107 (2011) 171104.

Summary

Accelerator apparatus can be suitable for cosmic-ray physics (CRP): LEP experiments were the pioneers on this topic. LHC (ALICE and CMS) have some results in CRP (apart from the global physics studies used in model tuning of hadronic interactions)

LEP

LEP experiments provided important results in the field of cosmic ray physics (HE interactions, source searches, composition …)

Atmospheric muon energy spectrum, charge ratio (and angular dependencies of both items)

- Hadronic interaction models cannot describe observed muon spectrum and charge ratio (for given CR composition)

Muon bundles

- Low multiplicities favor light nuclei as primaries, median multiplicities show trend to heavier primaries

- At high multiplicities the interaction models probably fail to describe hard muon bundles

Summary

First measurement of LHC era → Cosmic charge ratio by CMS (excellent tracking capabilities)

ALICE MMD is similar to the LEP previous measurements. For the first time the rate of HMM events have been satisfactory reproduced using conventional hadron interaction models (QGSJET II-04 tuned with LHC data) → test of the LHC results with hadronic models OK

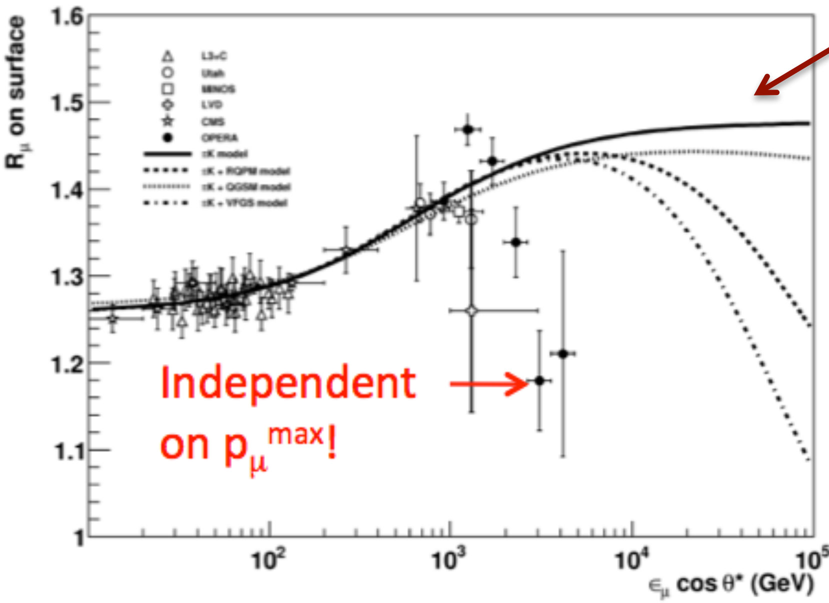
ALICE observation places significant constraints on alternative, more exotic, production mechanisms)

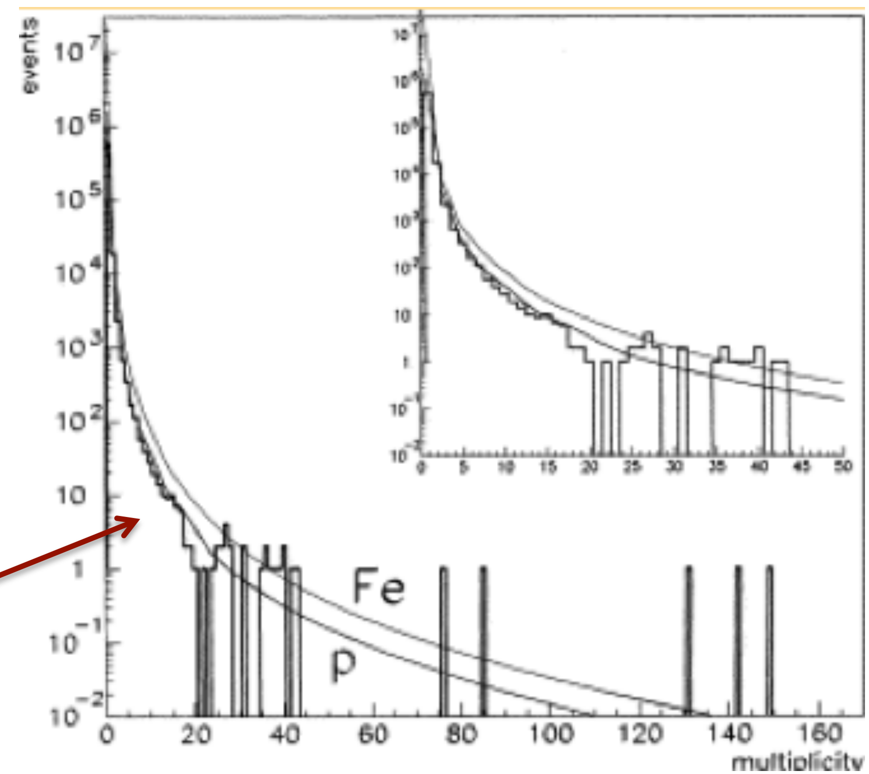
LHC

Backup slides

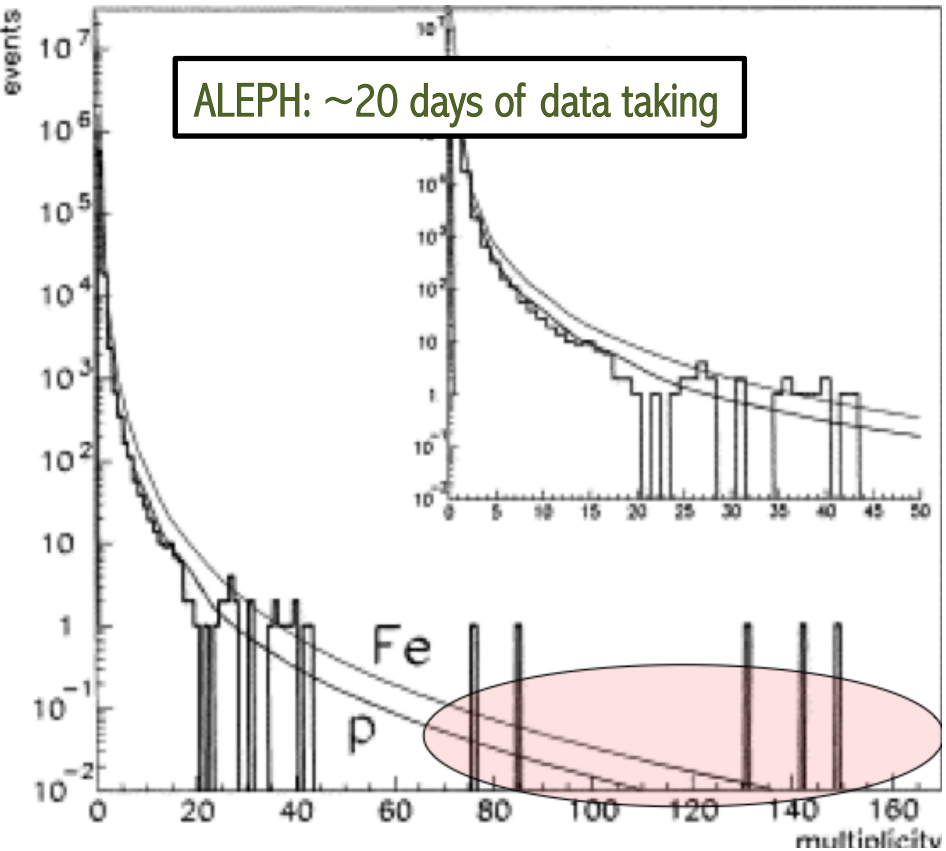
Main topic with accelerator apparatus

- 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



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

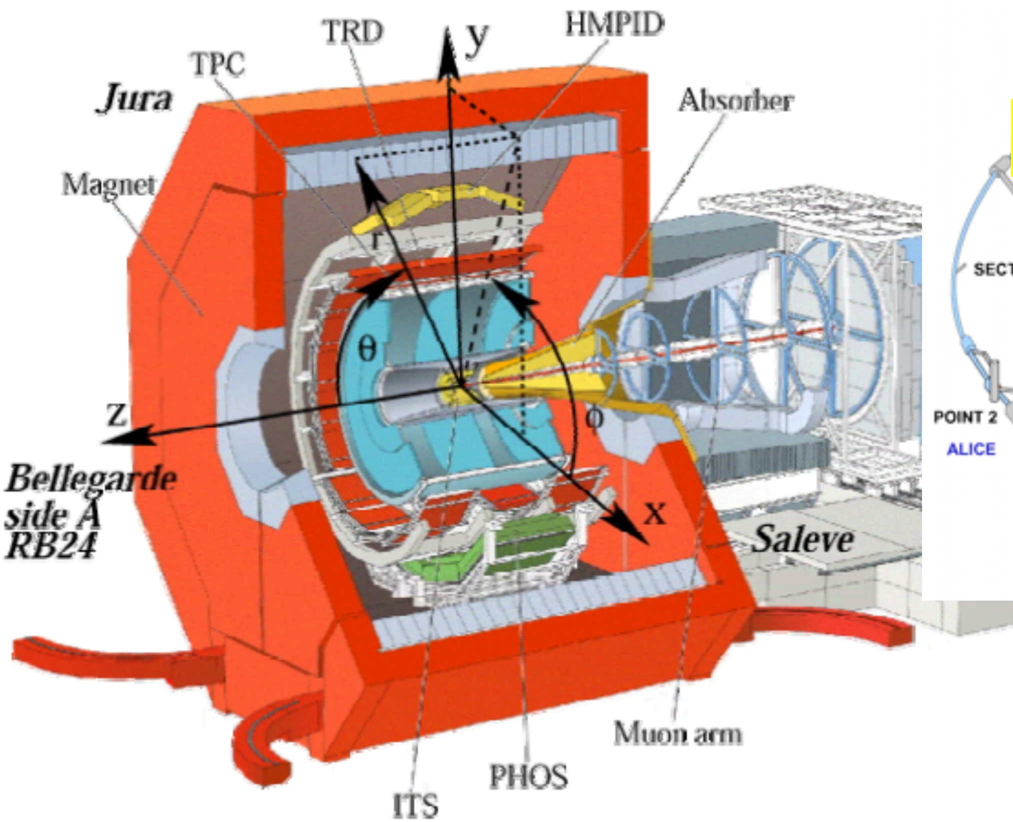
The five highest multiplicity events, with up to 150 muons within an area of 8 m^2, occur with a frequency which is almost an order of magnitude above the simulation.

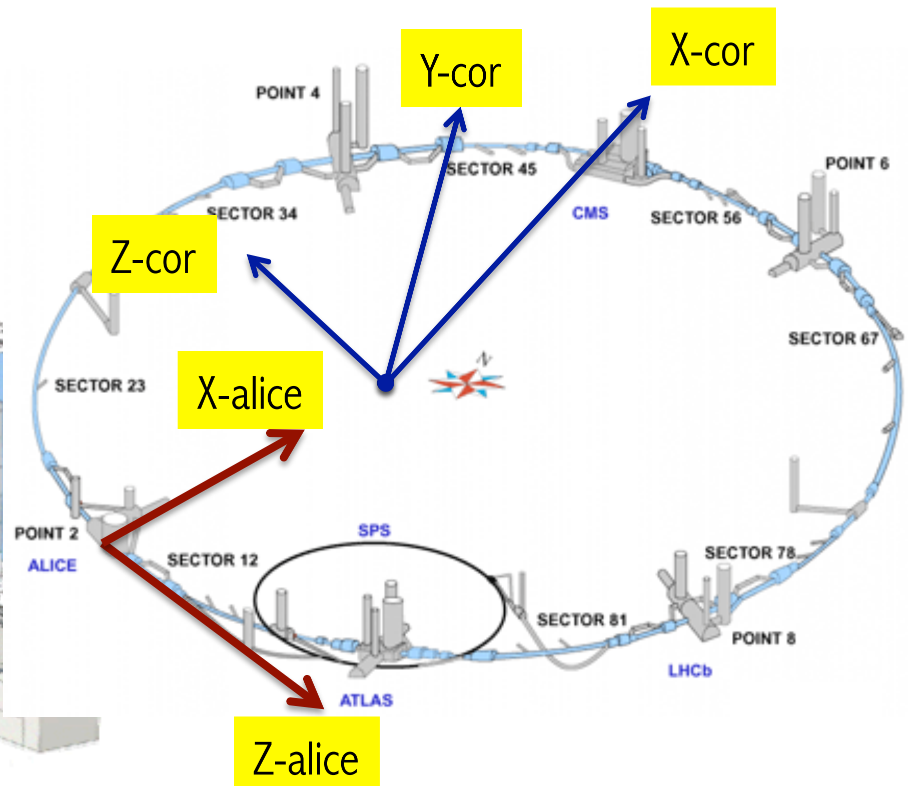
General: All ALICE sub-detector components are to be numbered starting from zero.

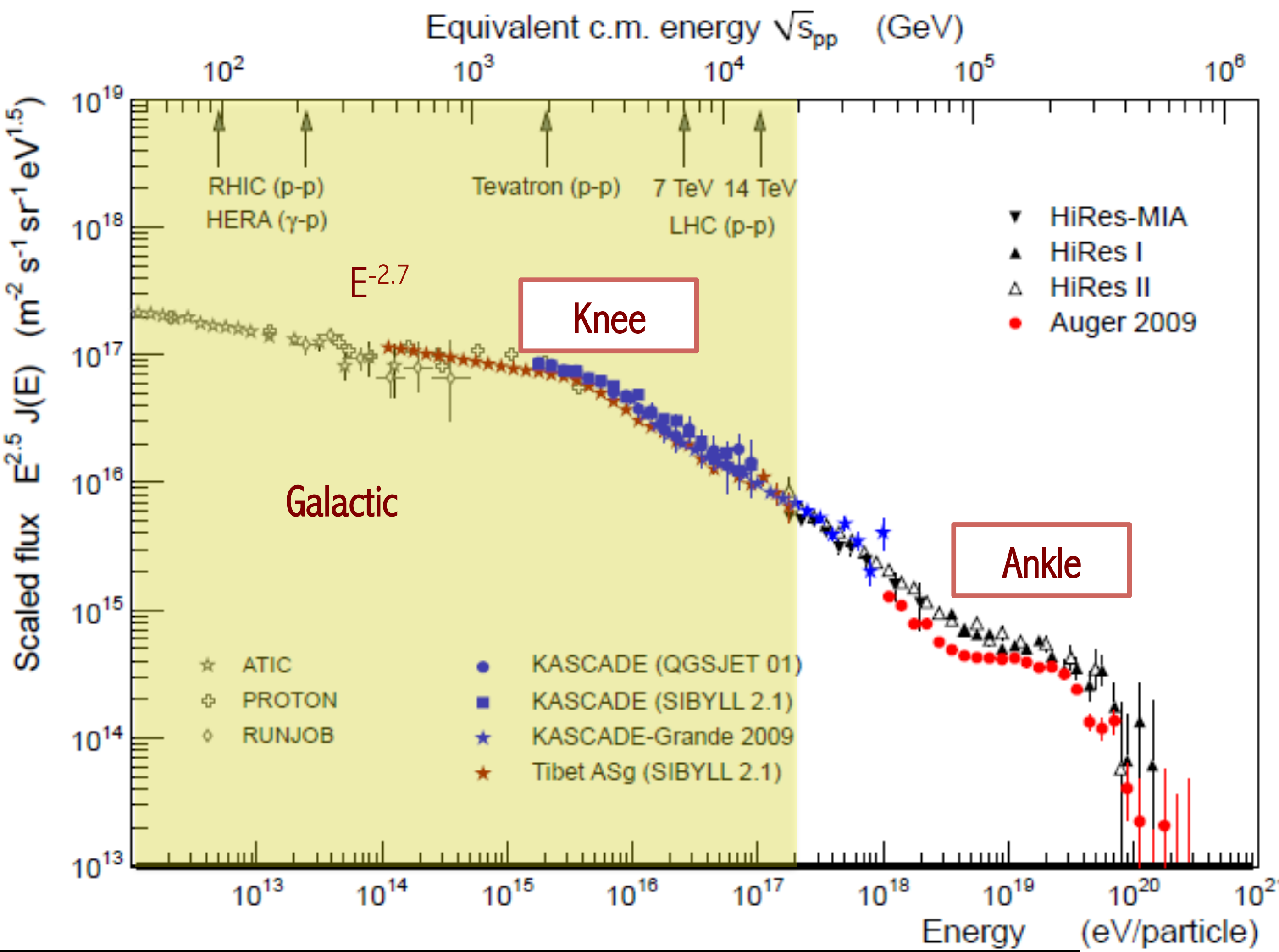
Rotational Numbering: Counter-clockwise (coinciding with the direction of increase of the angle φ) on the side ***A*** of the detector with the observer looking toward side ***C*** and clockwise on side ***C*** of the detector with the observer looking toward side ***A***. This way, sub-detectors which 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.

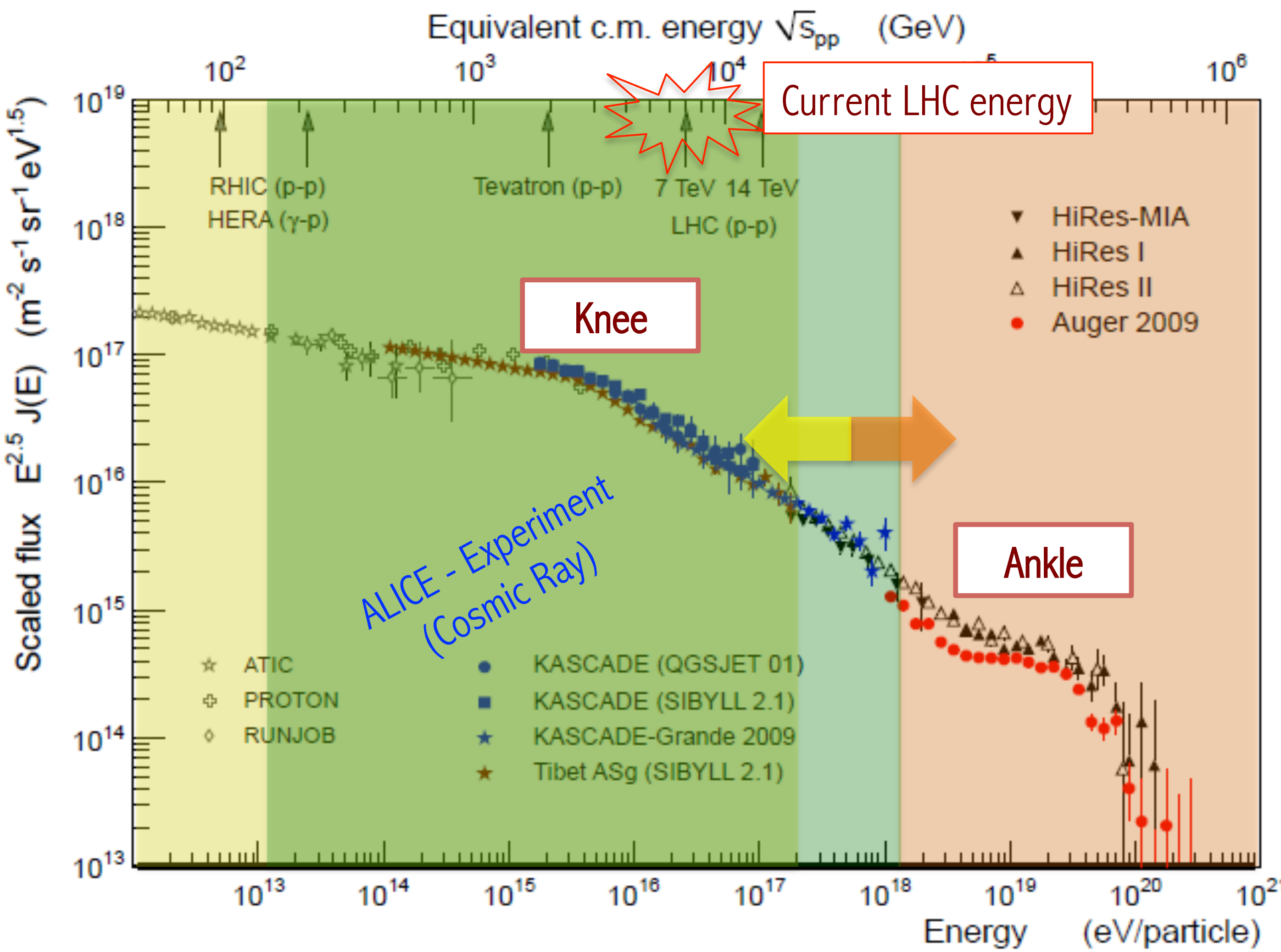
Radial Numbering: The counting increases with increasing radius.

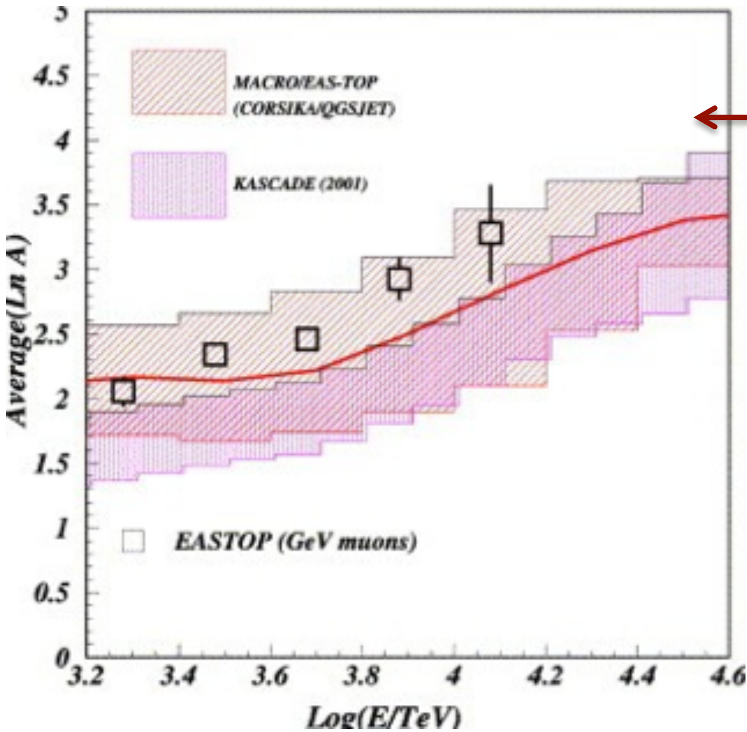






- Density of the galactic primary cosmic ray: ~ 1 eV/cm^3
- Protons for energies below 10^{16} eV
- Heavy nuclei composition: ~ $8*10^{16}$ eV (**Phys. Rev. Lett. 107, 171104 (2011)**)


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)
Knee
Ankle
ALICE - Experiment
(Cosmic Ray)
HiRes-MIA
HiRes I
HiRes II
Auger 2009
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 :

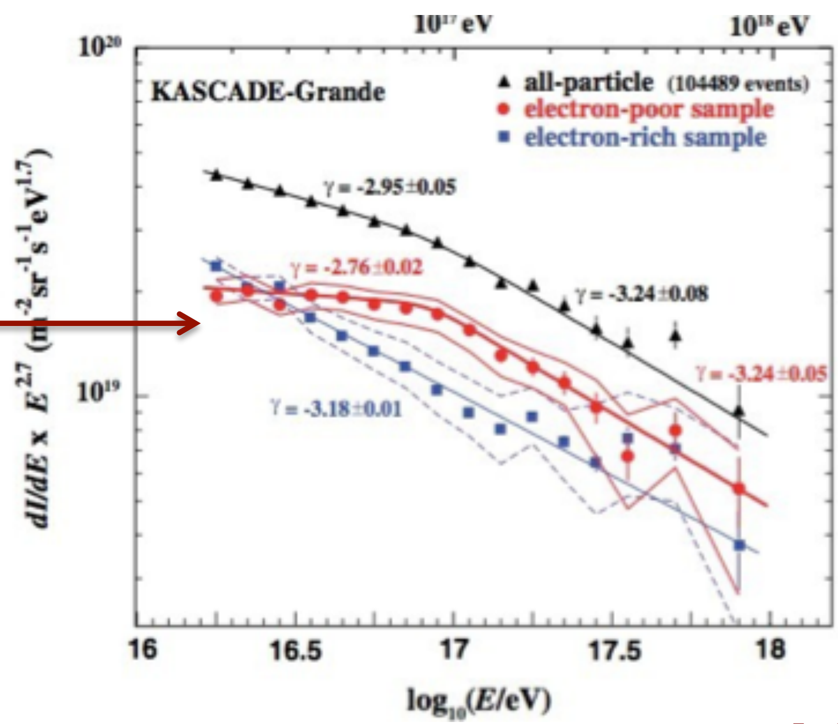
- Primary Composition Ln(A) vs Energy
- A=mass of the primary nucleus

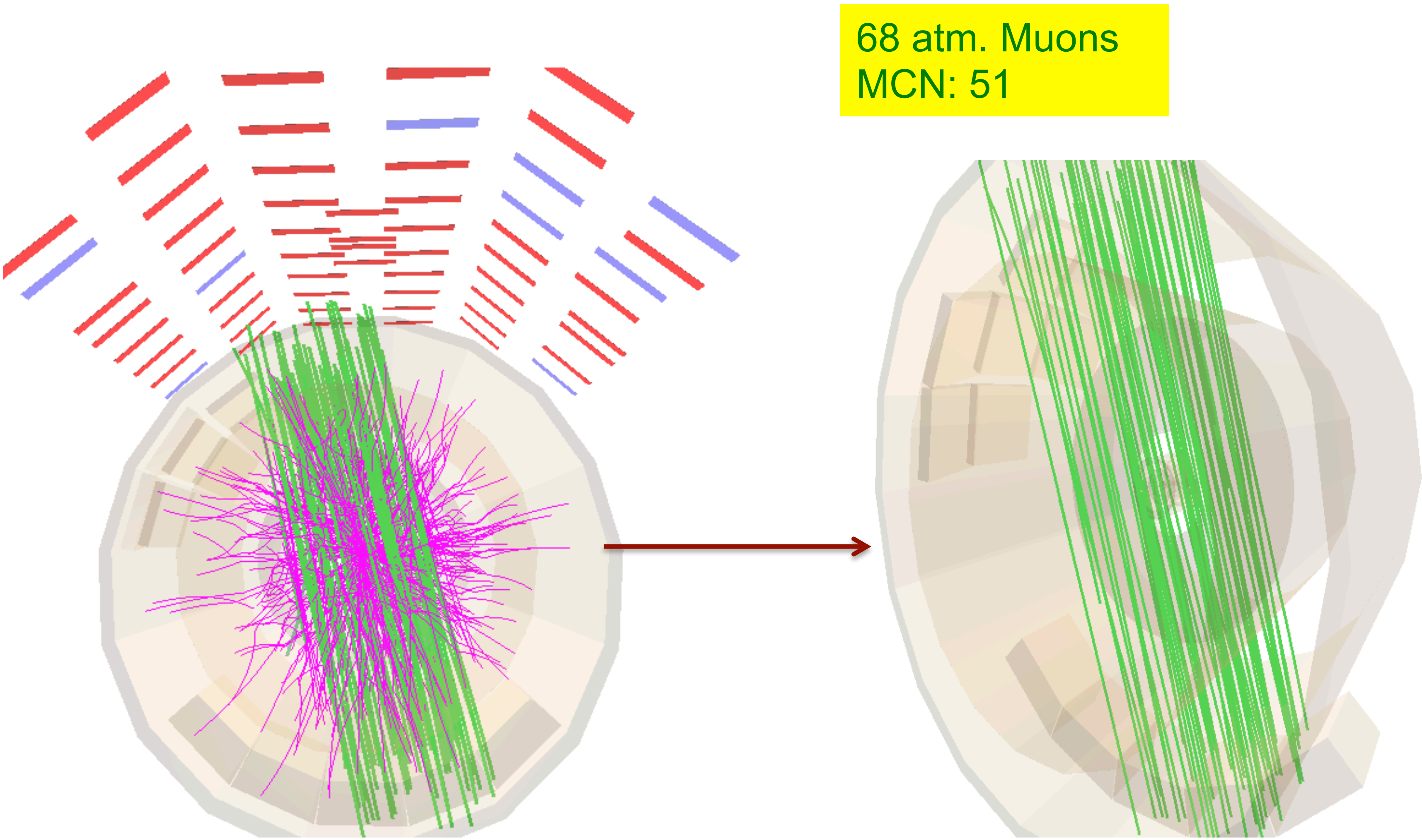
There is an increase of the:

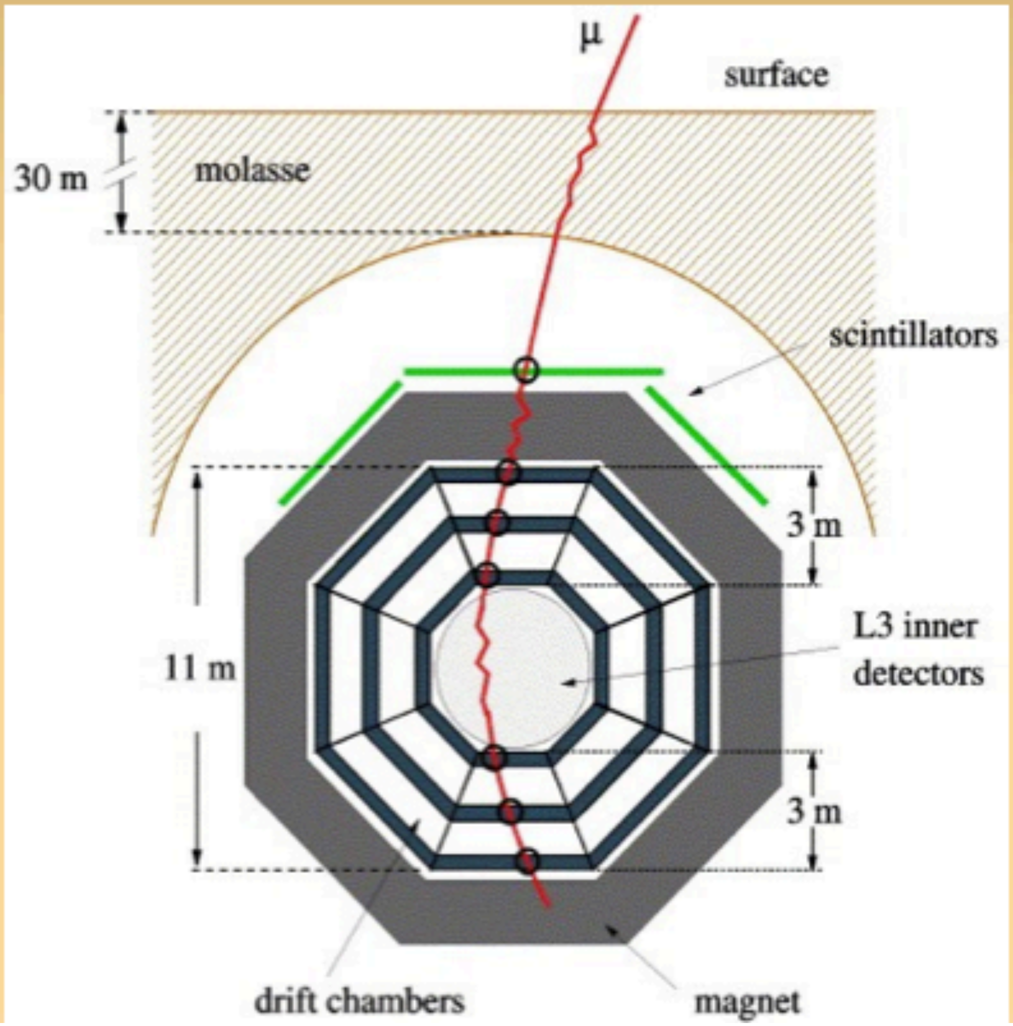
- <A> above the knee
- <A> ~ 8 at 3 x 10^{15} eV
- <A> ~ 30 at 3 x 10^{16} eV

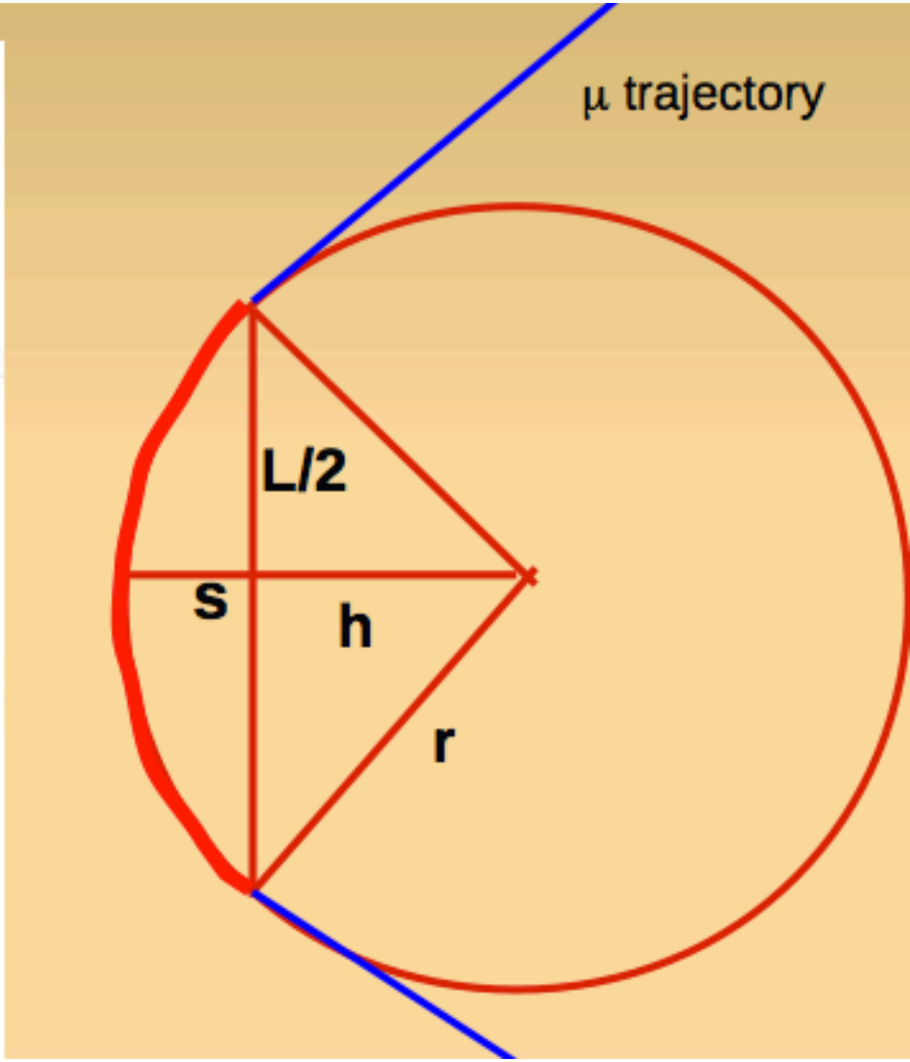
KASCADE-GRANDE :

- 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

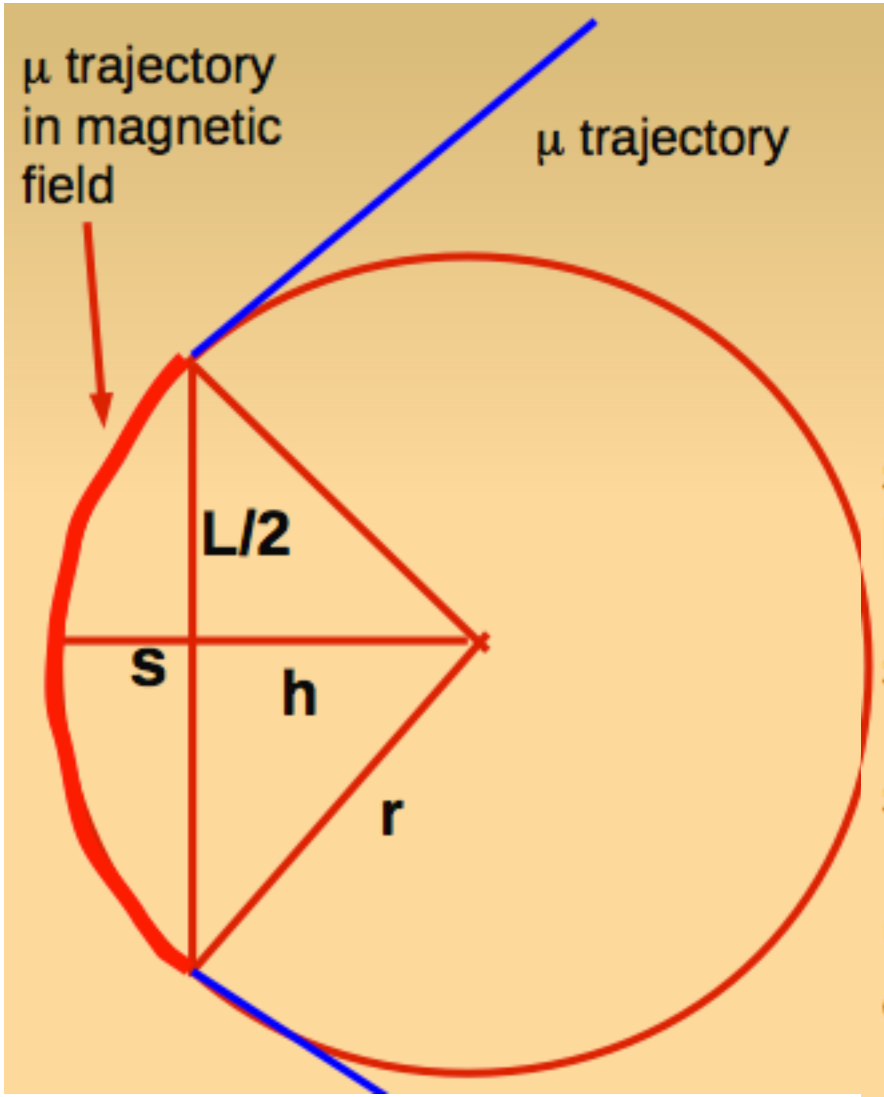



68 atm. Muons
MCN: 51


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

Backup slides



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

$s = r - h$

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

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

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

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

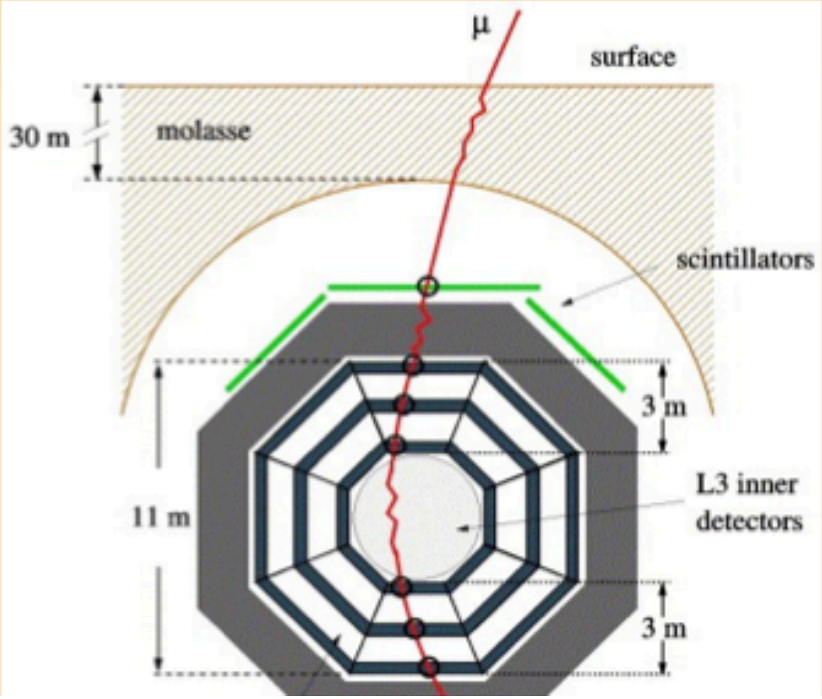
$\alpha = ½ \quad x = -(L^2/4r^2)$

$s \sim L^2/8r$

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

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

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



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 :

σ_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 :

σs = 1 mm

L = 11 m

B = 0.5 T

p = 100 GeV/c Resolution σp

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

σp = 1.32 GeV/c ==> 1.3%

p = 1 TeV/c Resolution σp

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

σp = 132 GeV/c ==> 13%