Cosmic-ray physics at CERN (LEP and LHC experiments)

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Plan of this talk

a. Introduction

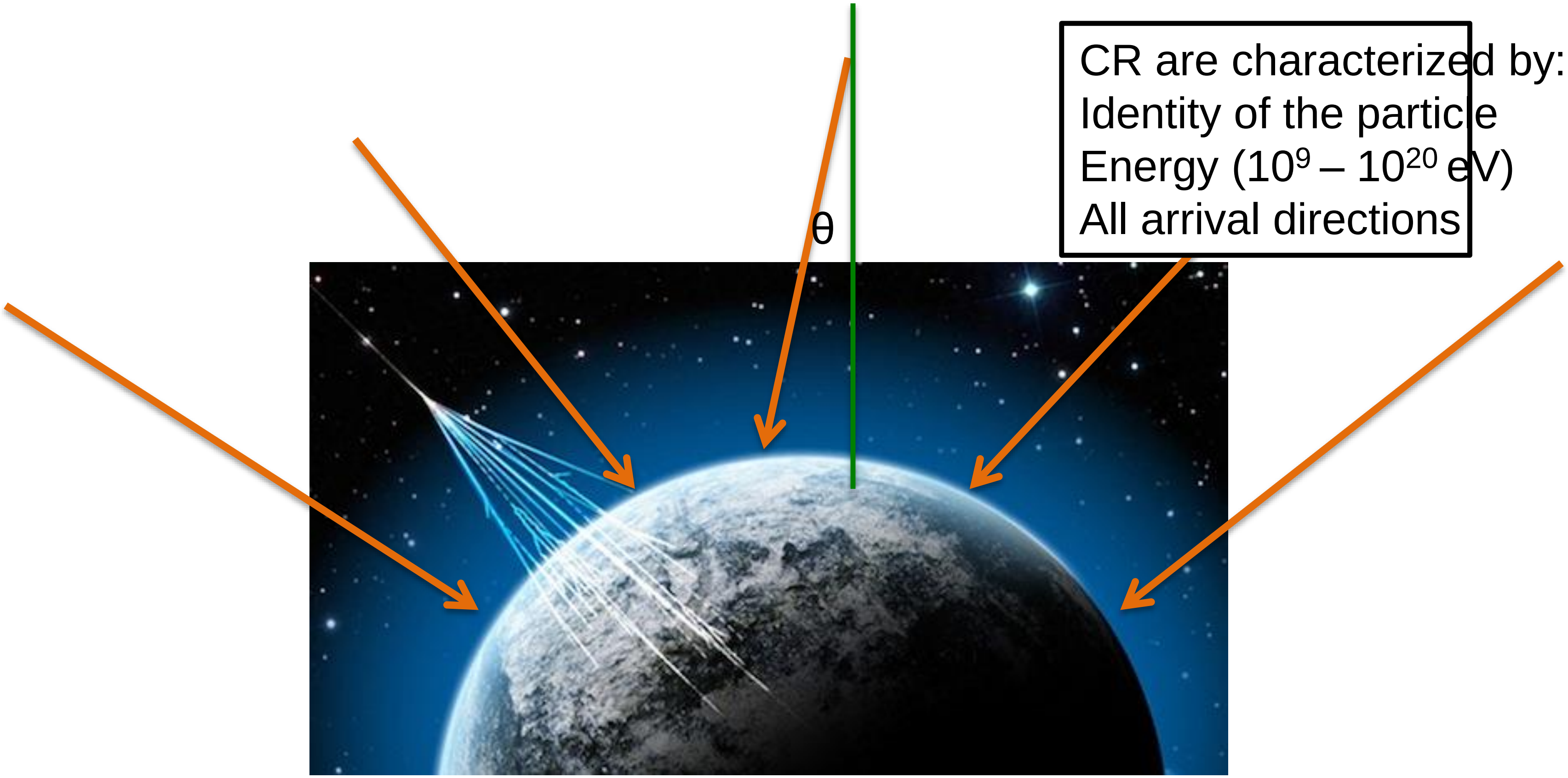
a. Results from LEP

a. Results from LHC

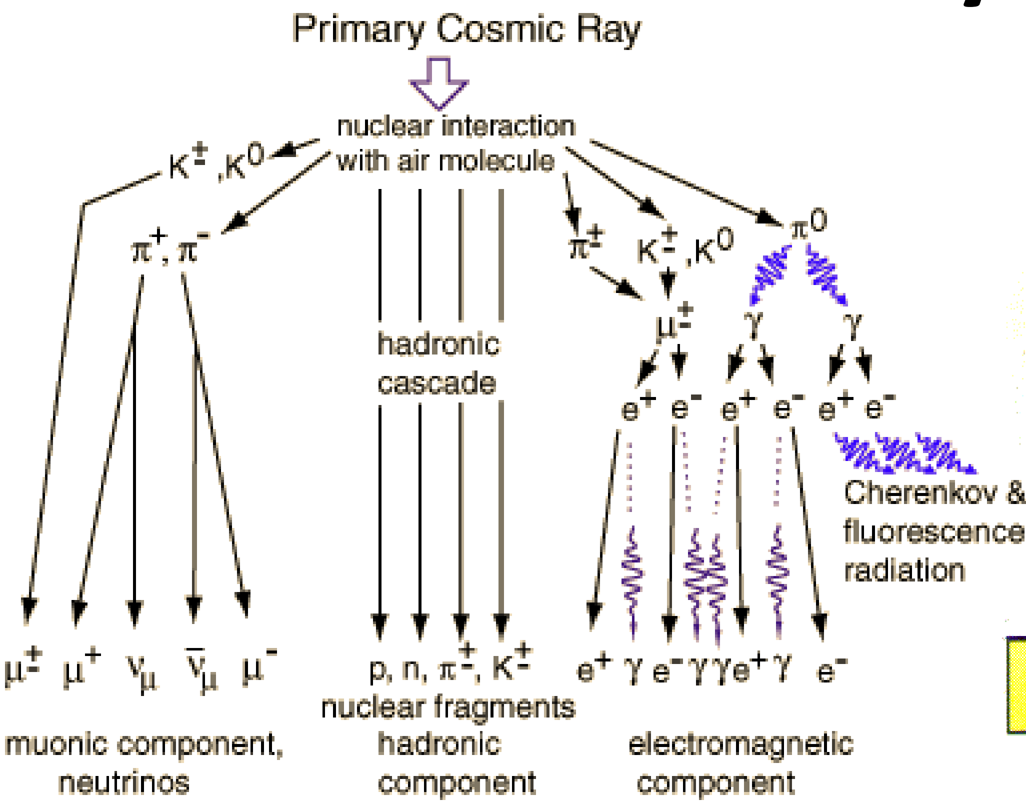
a. Outlook

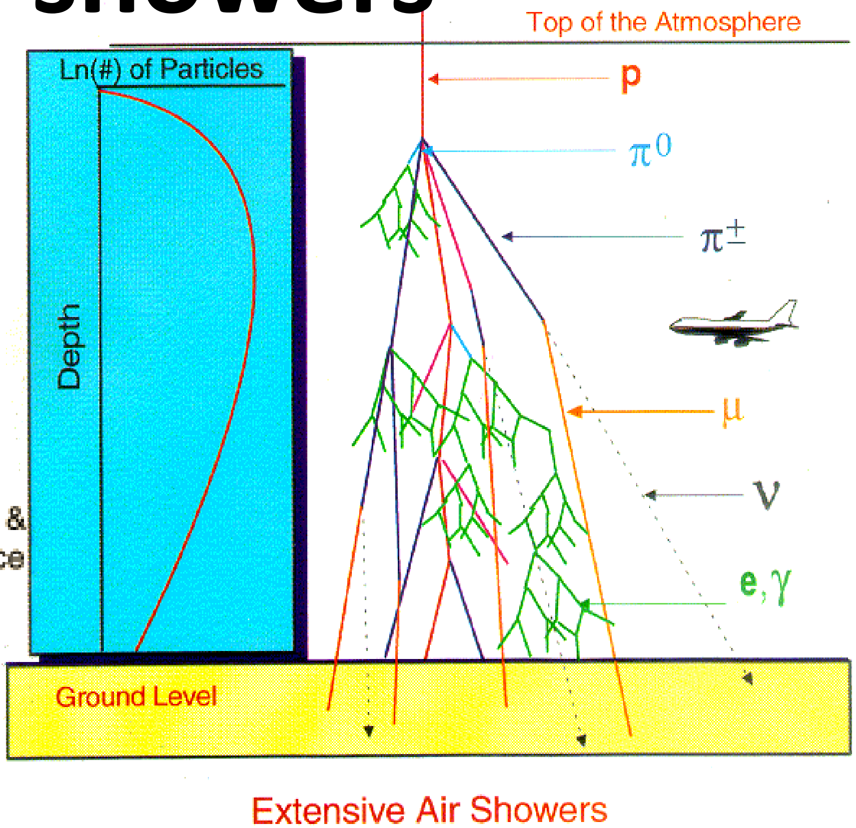
Introduction

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



Cosmic ray showers



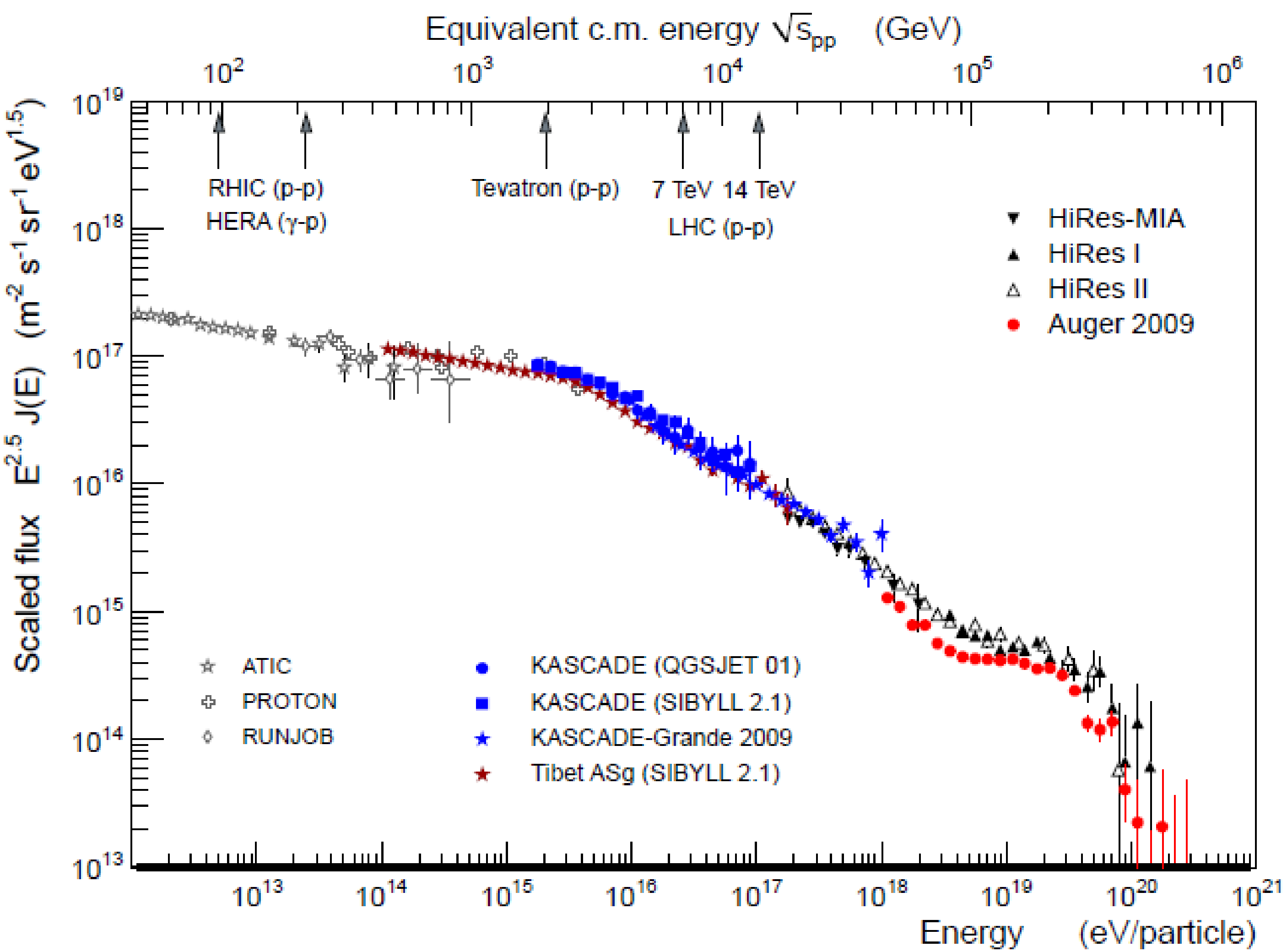


p,n,π → near the shower axis
μ, e, γ → widely spread
e, γ → from π^0 , μ decays (10 MeV)
μ → from $\pi^\pm$, K decays (1 GeV)

Details depend on

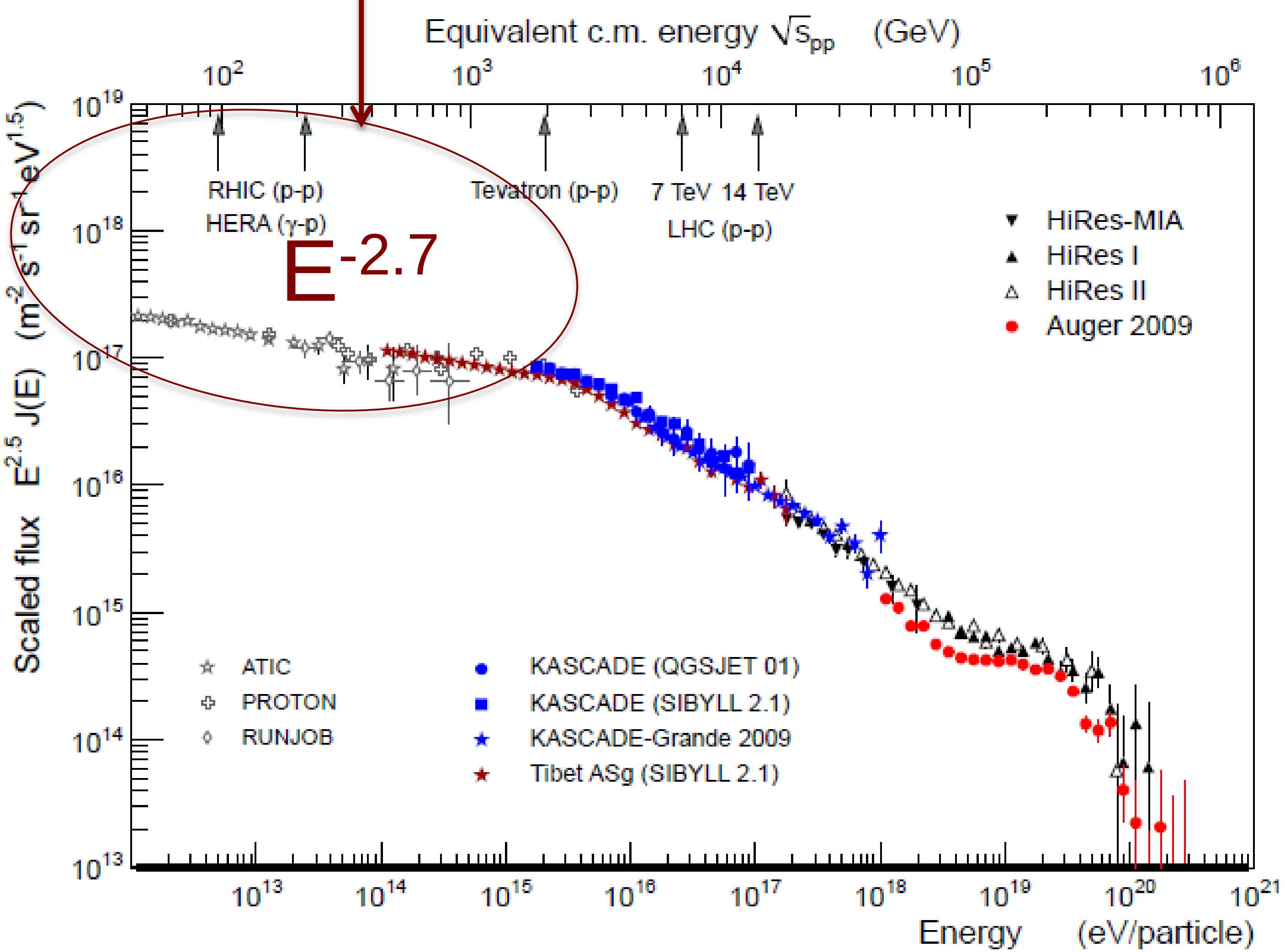
- Interaction cross sections
- Hadronic and electromagnetic particle production
- Decays, transport of particles at energies from MeV's to 10^{20} eV (above accelerators e

Cosmic ray energy spectrum



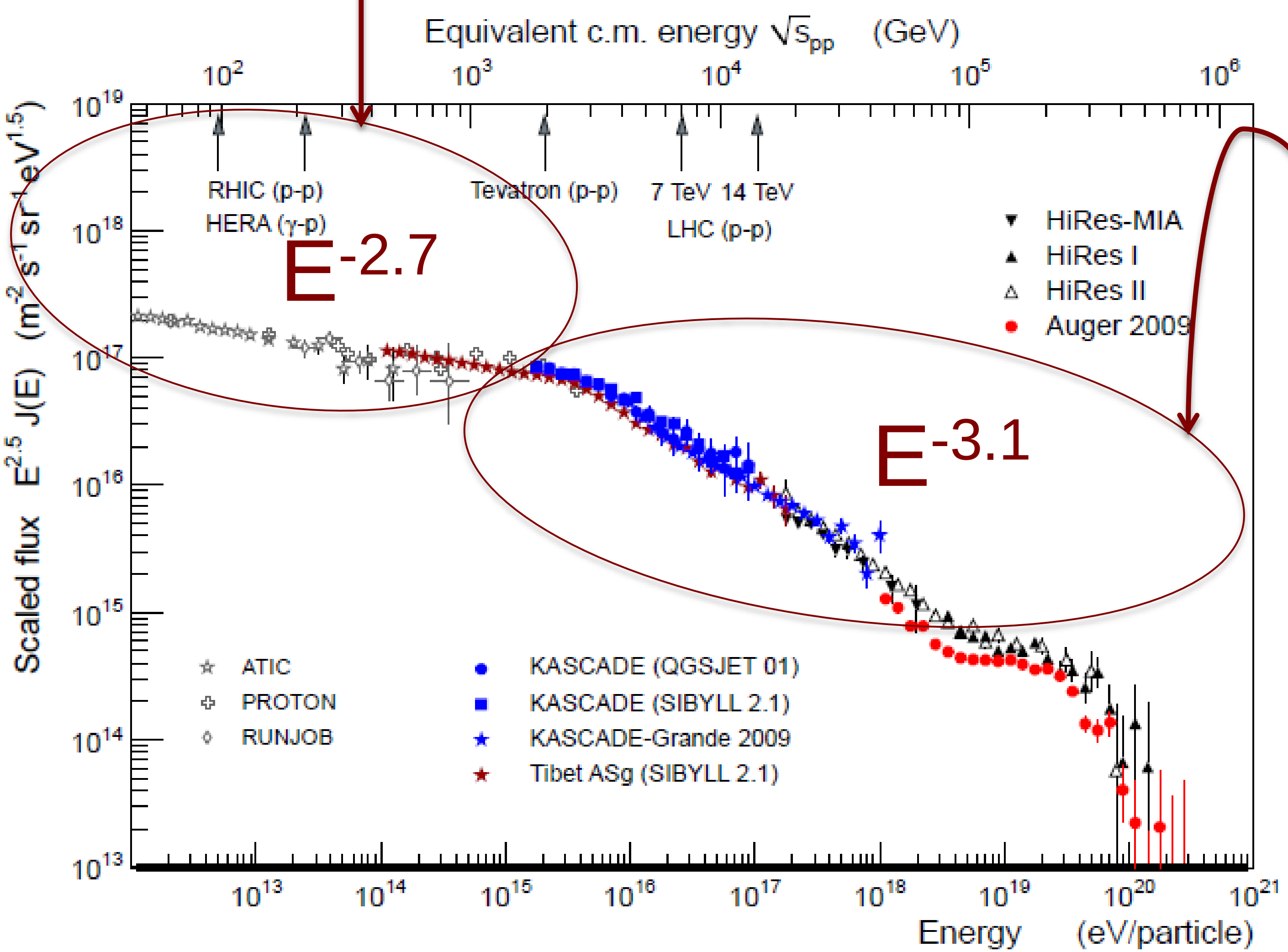
Cosmic ray energy spectrum

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



Cosmic ray energy spectrum

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



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

Direct and indirect measuremets

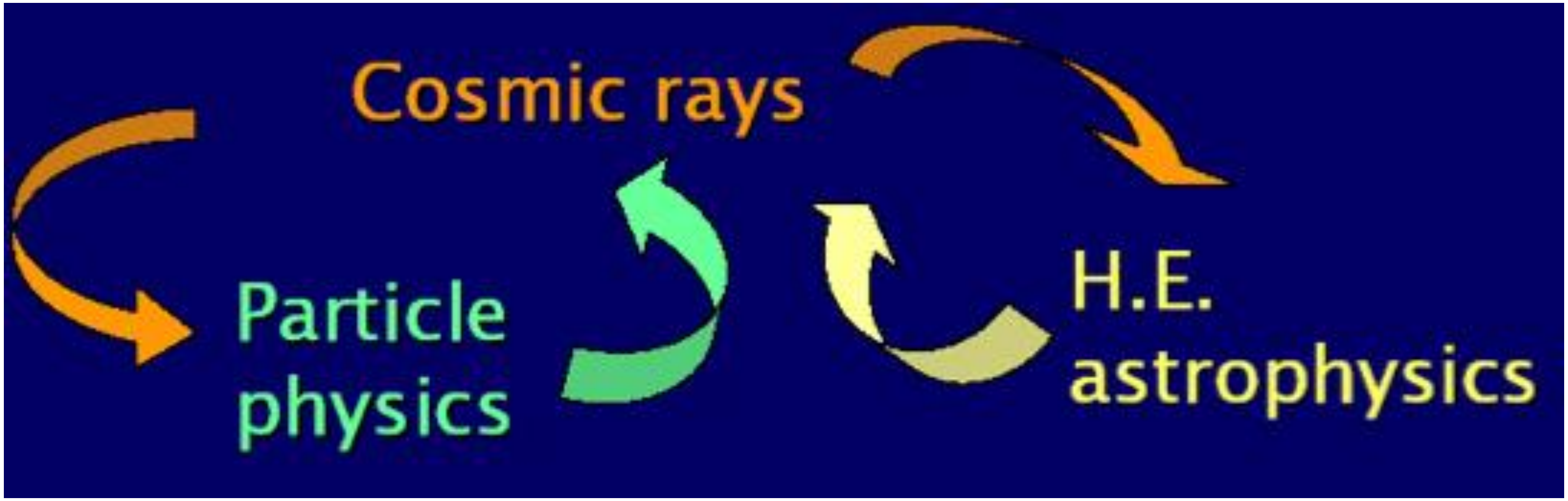
Direct measurements up to E ~ 10^{14} eV

→ Primary particles (balloons, satellites)

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

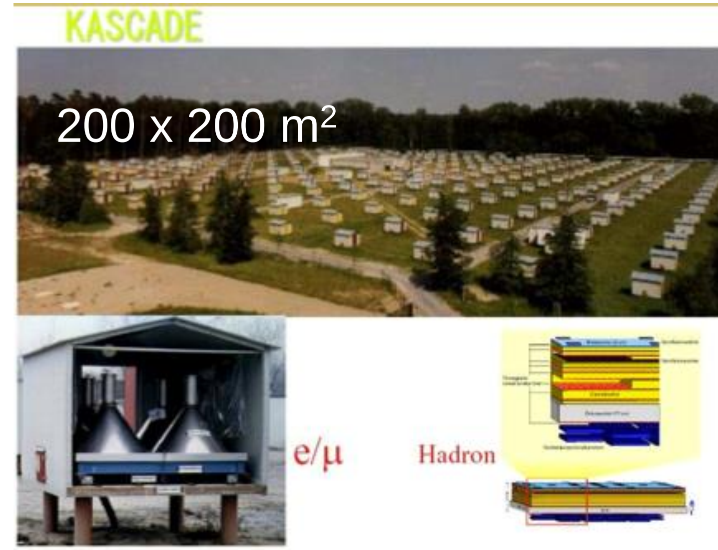
- ✓ Cosmic ray interactions with atmosphere and Extensive Air Showers (EAS)
- ✓ Measurements around the knee (Eas-Top, Kaskade, Casa …) and beyond (Kaskade-Grande)
- ✓ Ultra high energy cosmic rays (Auger, HiRes)
- ✓ Underground experiments (Macro, Emma)
- ✓ COSMIC RAY PHYSICS AT CERN (LEP: L3+C, ALEPH,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

Astroparticle physics



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

CR PHYSICS WITH HEP APPARATA



- ✧ Small apparatus (with respect to EAS experiments)
- ✧ Low underground
- ✧ Detection of muons crossing the rock

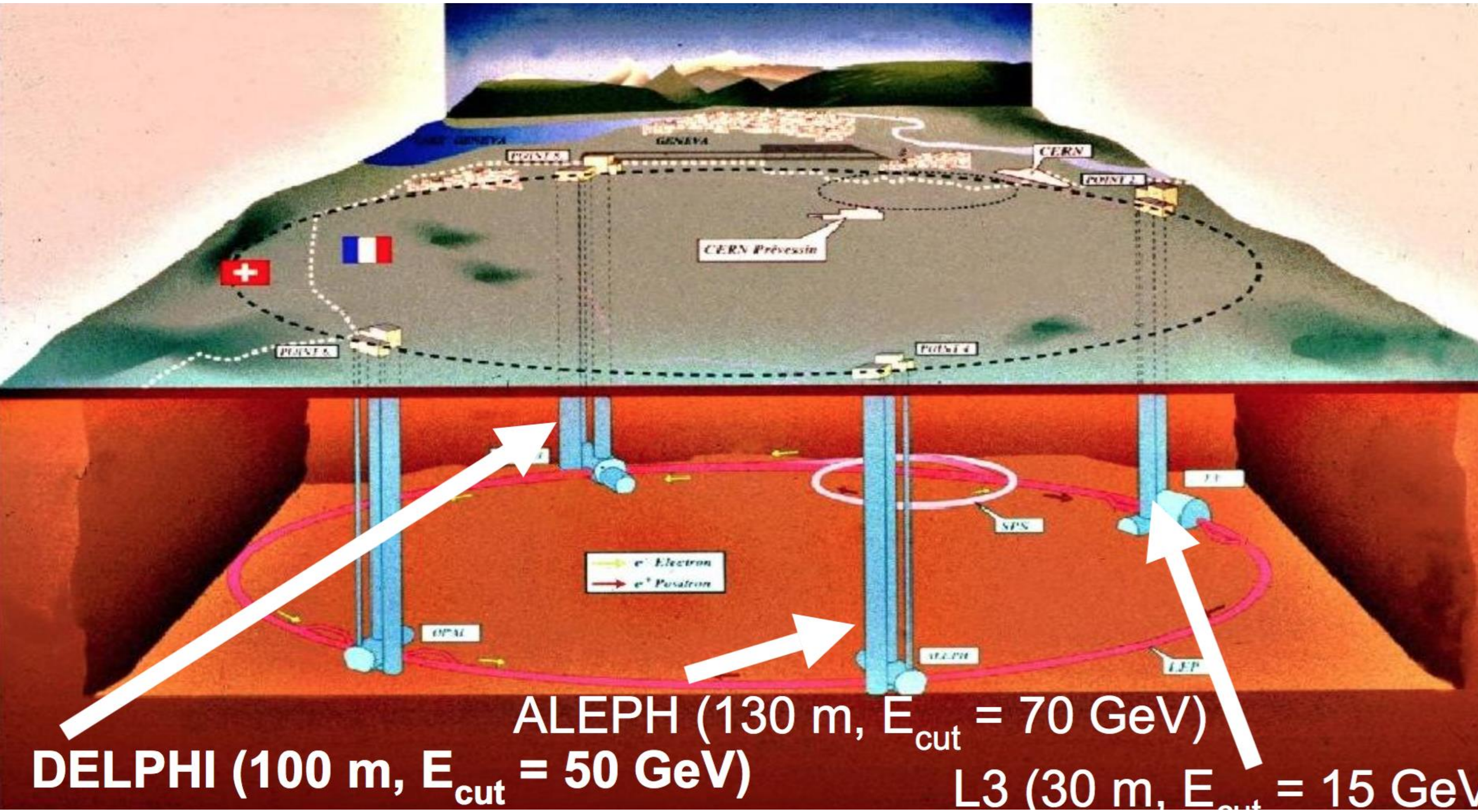
★ These apparatus are not designed for cosmic ray physics ☹ :

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

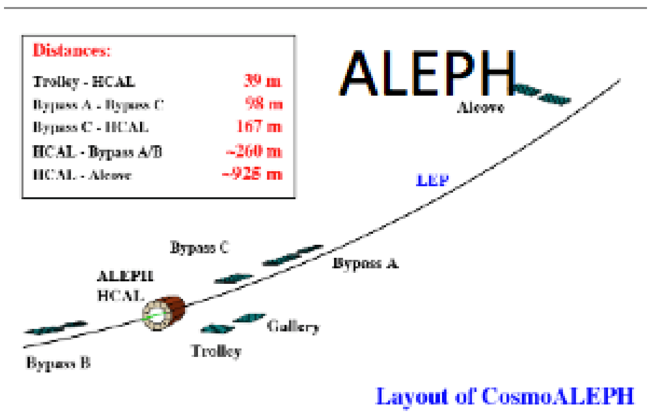
✓ Advantage: detectors with very high performances, presence of magnetic field ☺

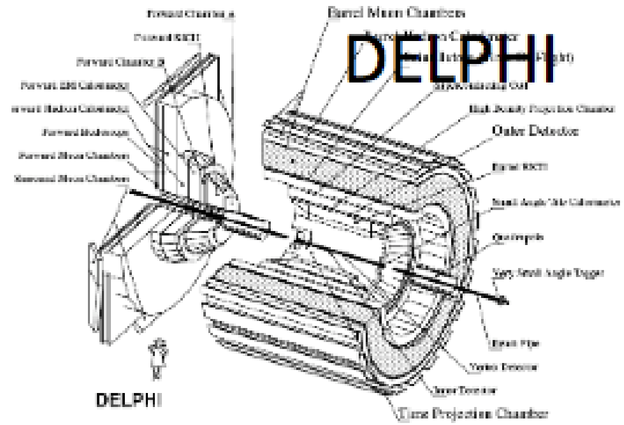
✓ Remember that the only one result from LEP that did not agree "perfectly" with the Standard Model was the observation of high multiplicity muon in cosmic events (muon bundles).

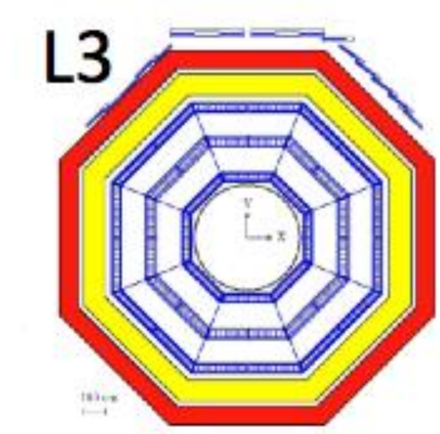
LEP results


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

LEP experiments with CR physics program





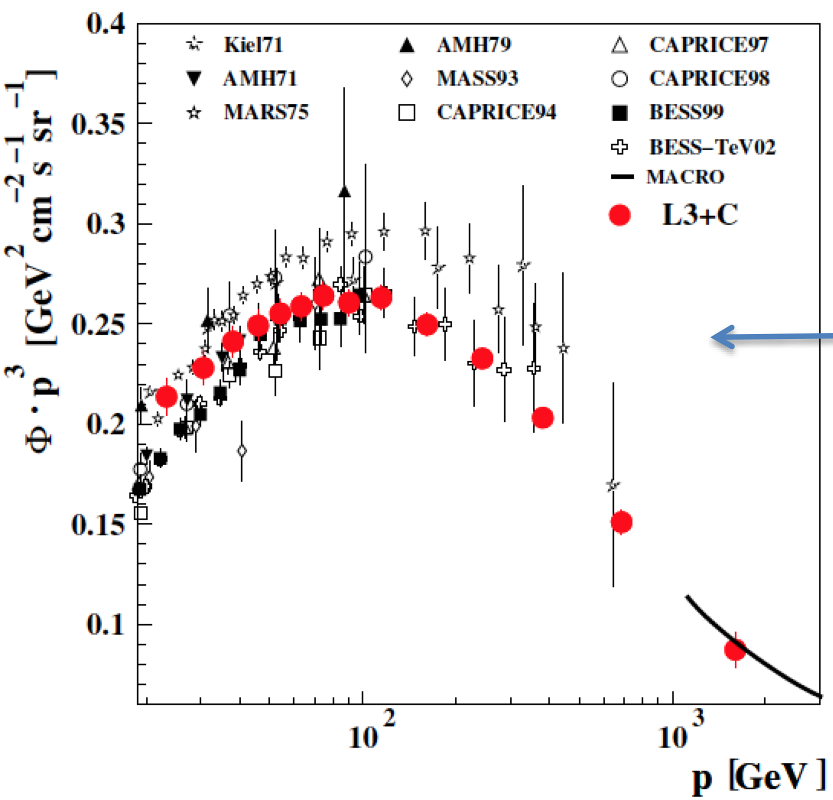


- ✧ **ALEPH: 140 m of rock, momentum muon threshold p > 70/cosθ**
  - ✓ underground scintillators, HCAL (horizontal area ~ 50 m^2), TPC project
- ✧ **DELPHI: 100 m of rock, momentum muon threshold p > 52/cosθ**
  - ✓ Hadron calorimeter (horizontal area ~ 75 m^2), muon barrel, TPC, ToF ar
- ✧ **L3+C: 30 m of rock, momentum muon threshold p > 20/cosθ + surface**
  - ✓ Scintillator surface array (200 m^2), trigger, muon barrel (100 m^2), hadror

COSMIC RAY ENERGY COVERAGE FROM 10^1

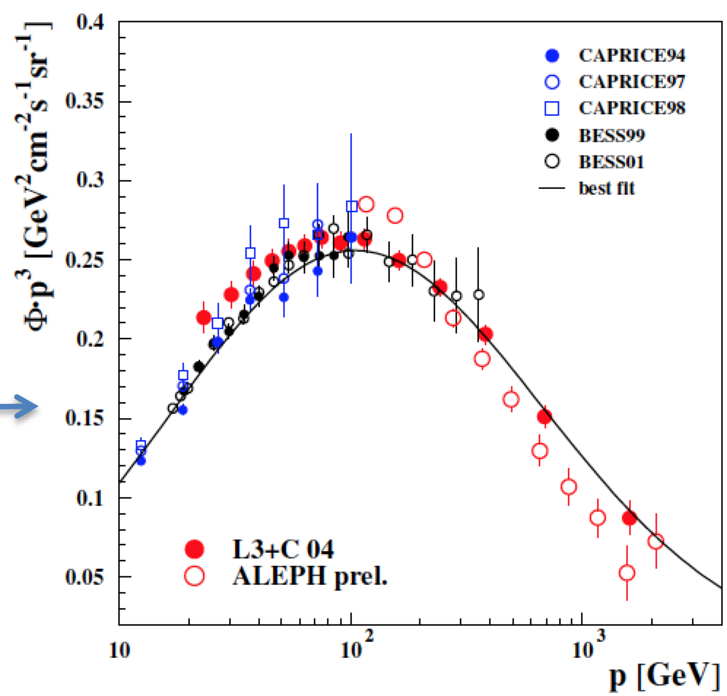
LEP results

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



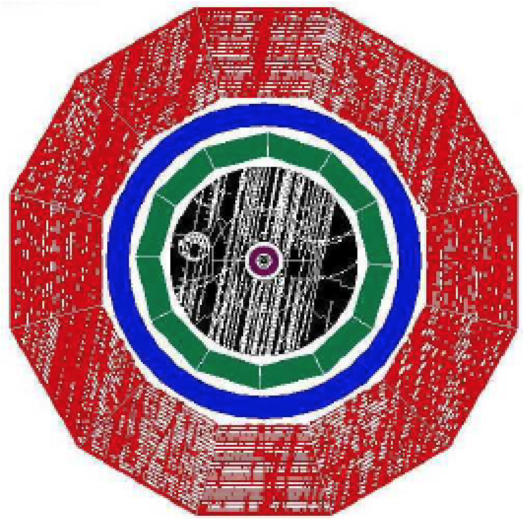
The flux is multiplied with 3rd power of momentum to see details along the steep spectrum.
Best agreement with BESS (also with CAPRICE)
Kiel agrees in shape but records systematically higher flux
MACRO agrees at high energy end of the spectrum.

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

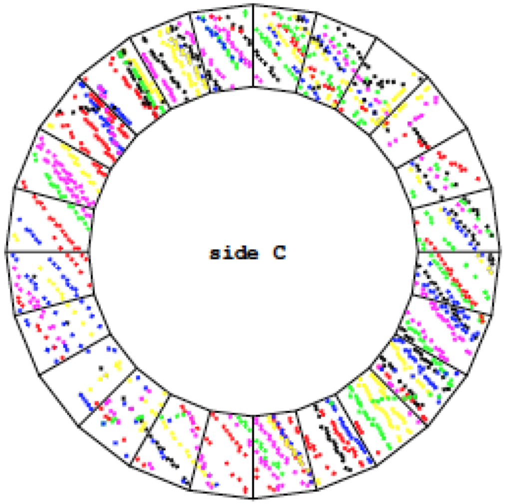


LEP results: Muon Bundles

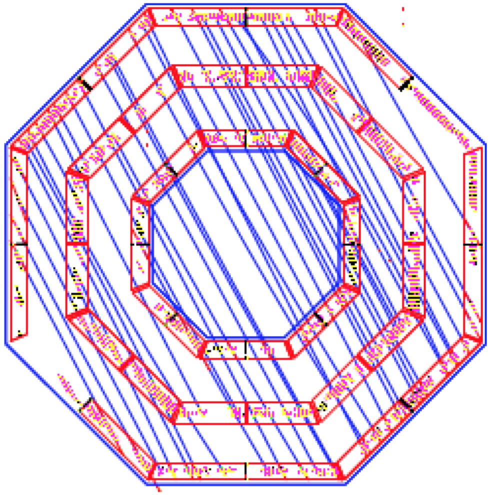
Muon bundles at LEP



ALEPH



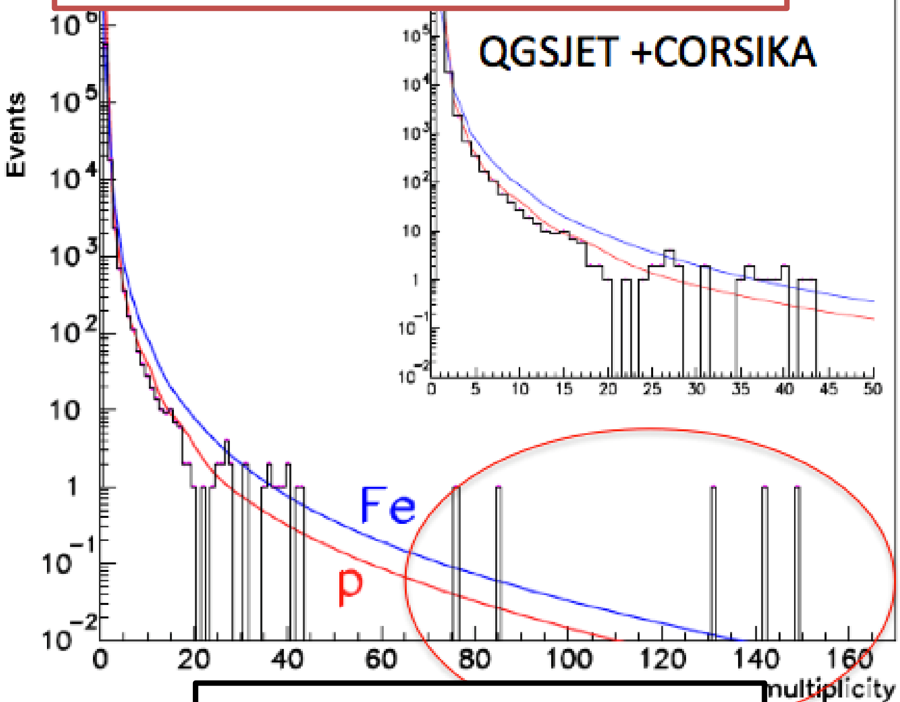
DELPHI



L3+C

LEP: Muon Multiplicity spectrum

Astroparticle Physics 19 (2003) 513–523



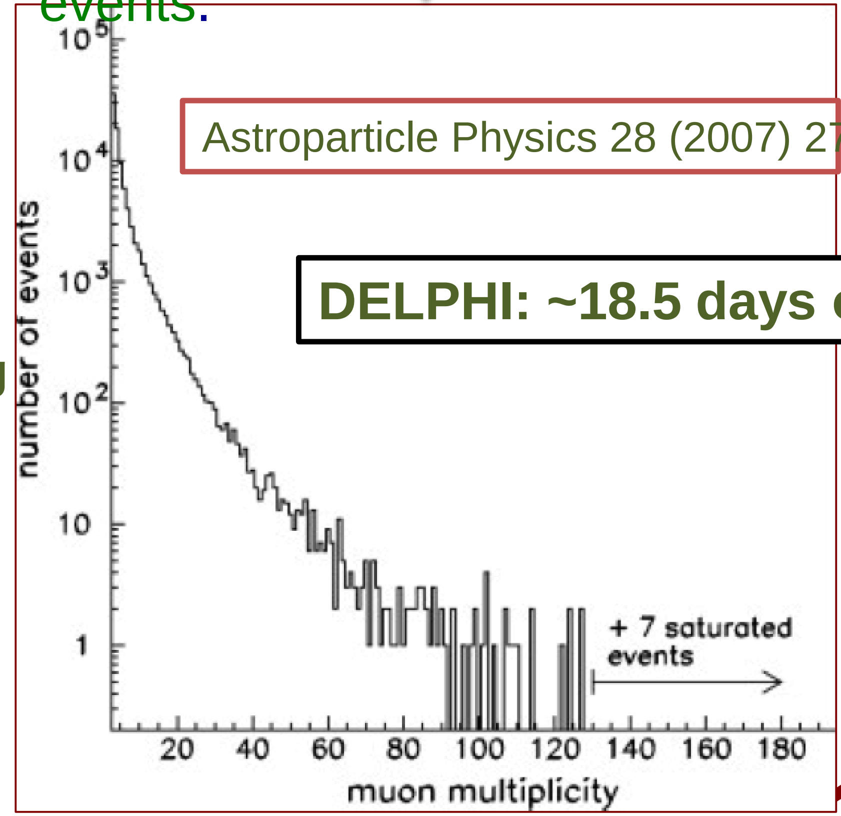
ALEPH: ~20 days of data taking

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 :

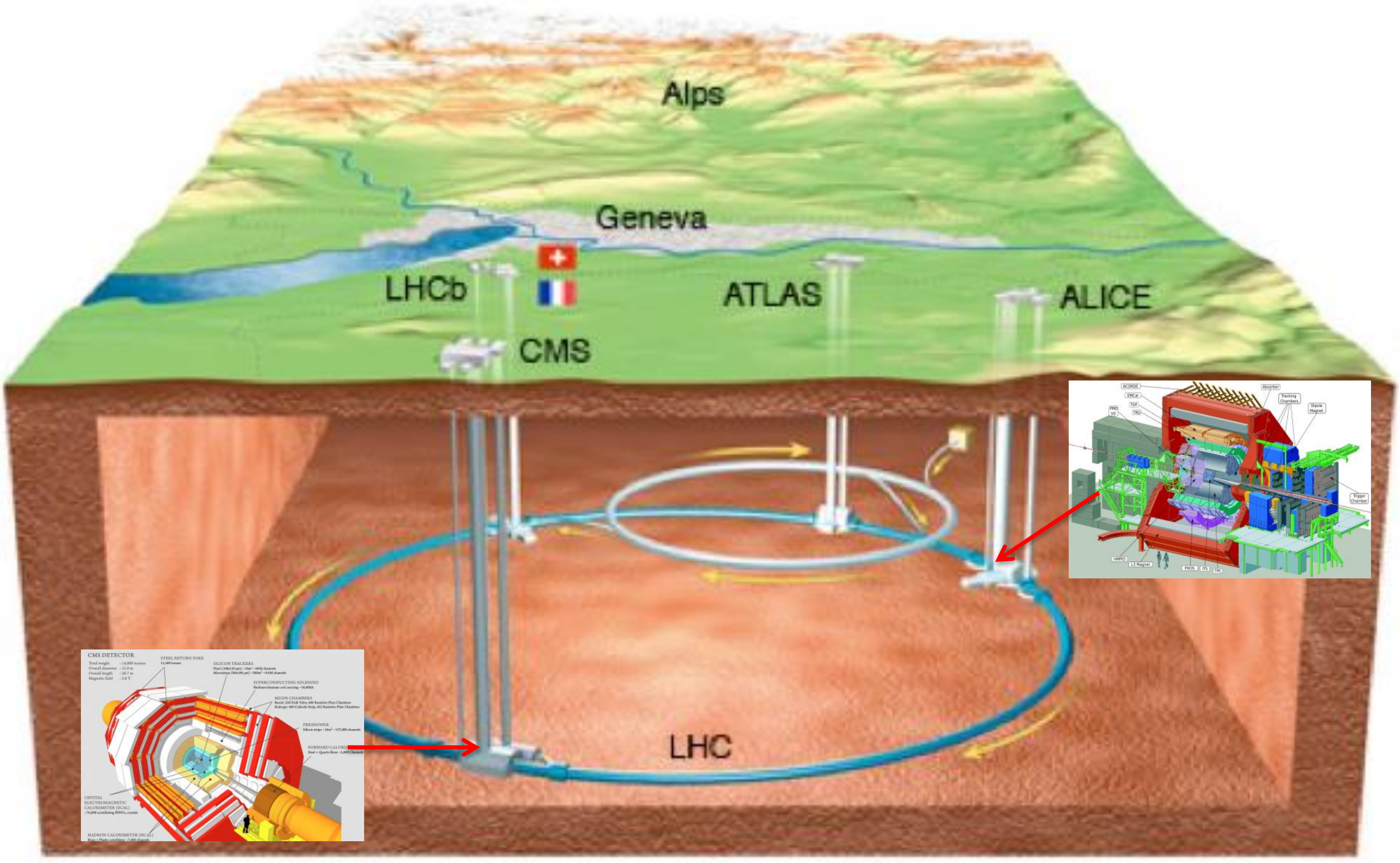
However, even the combination of extreme assumptions of highest measured flux value and pure iron spectrum fails to describe the abundance of high multiplicity events.

Astroparticle Physics 28 (2007) 273–286



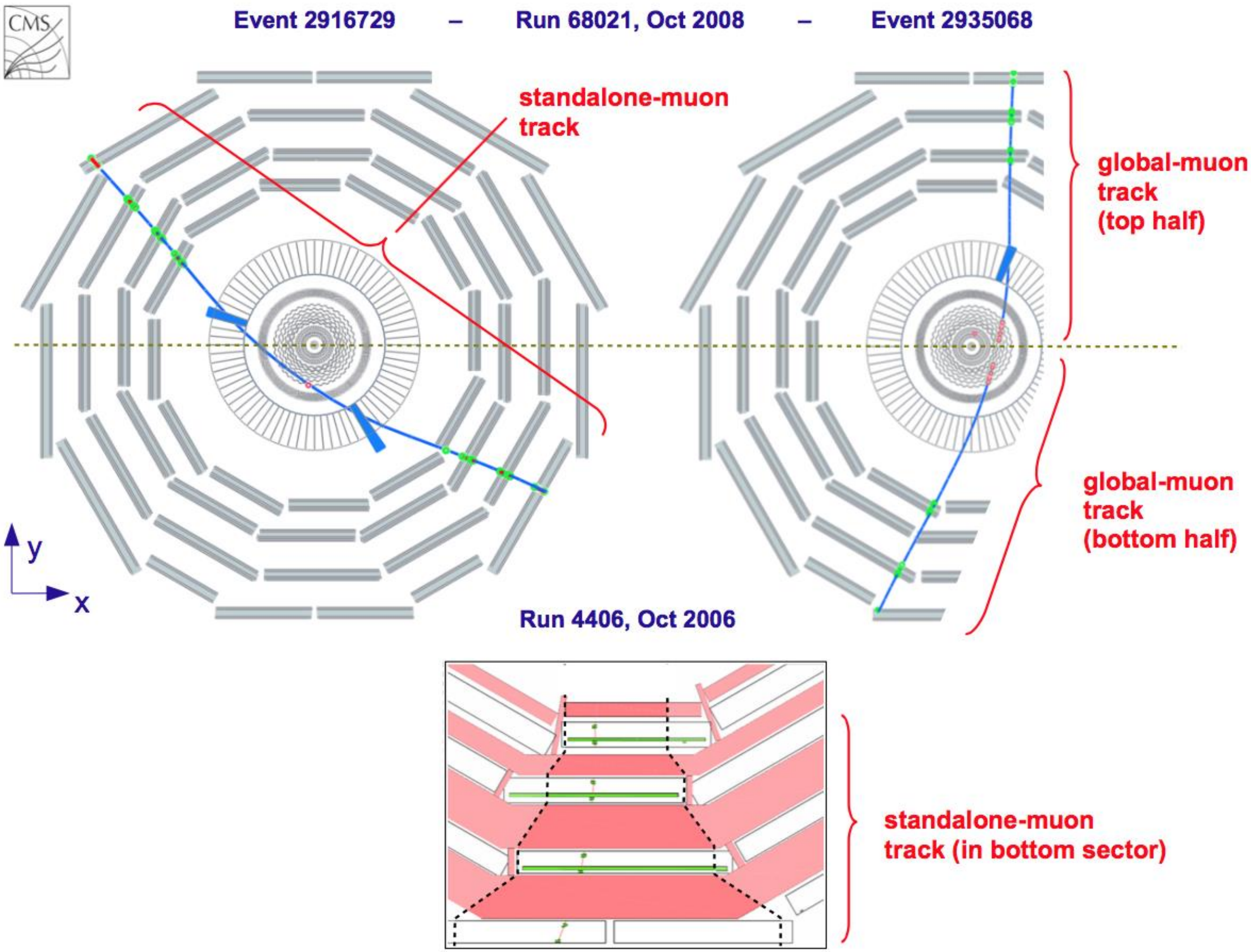
DELPHI: ~18.5 days of dat

LHC experiment with CR Physics program



Atmospheric muon reconstruction at CMS

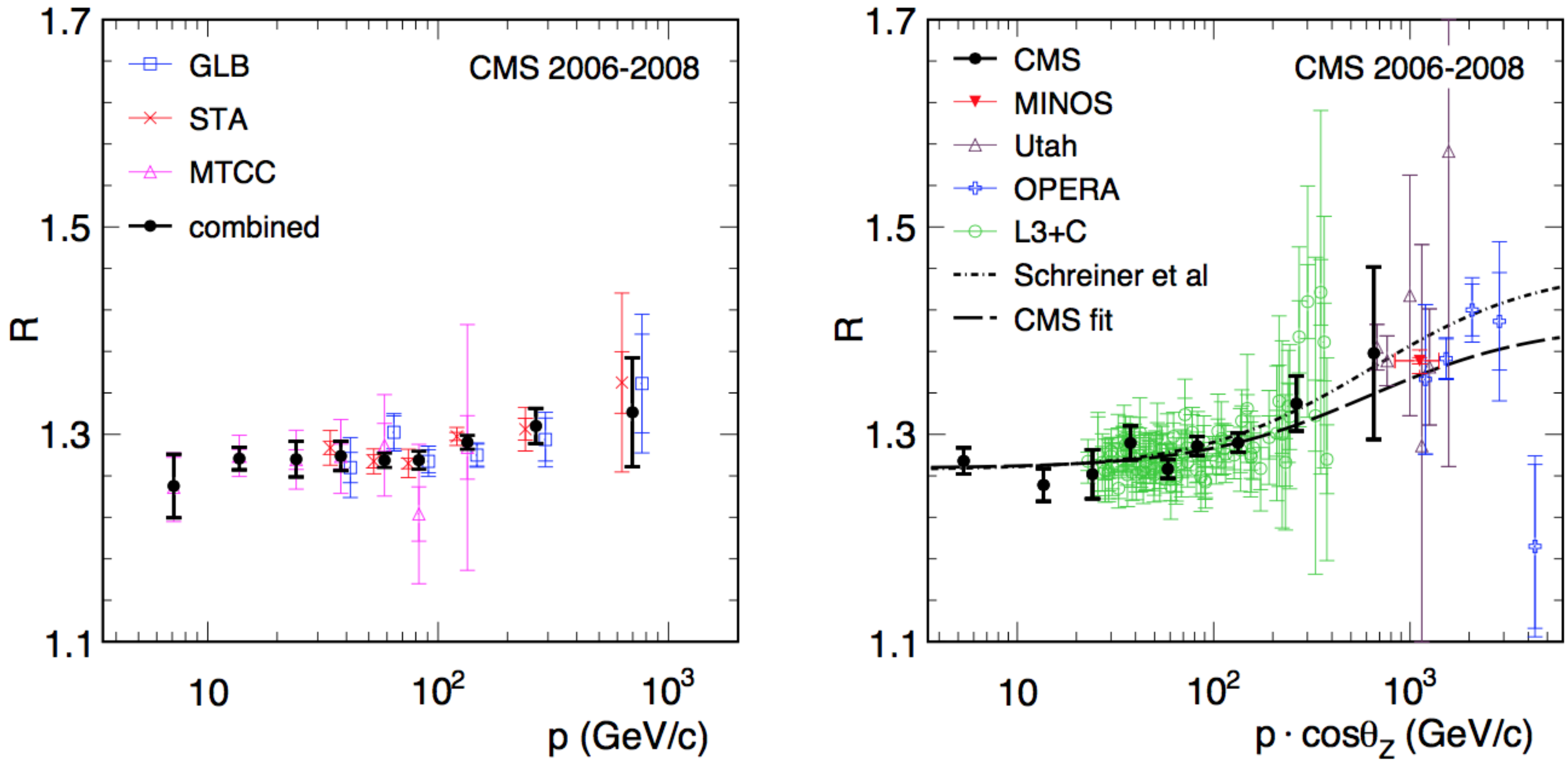
CERN-PH-EP-2010-011 2010/05/31



mu+/mu- Ratio (R)

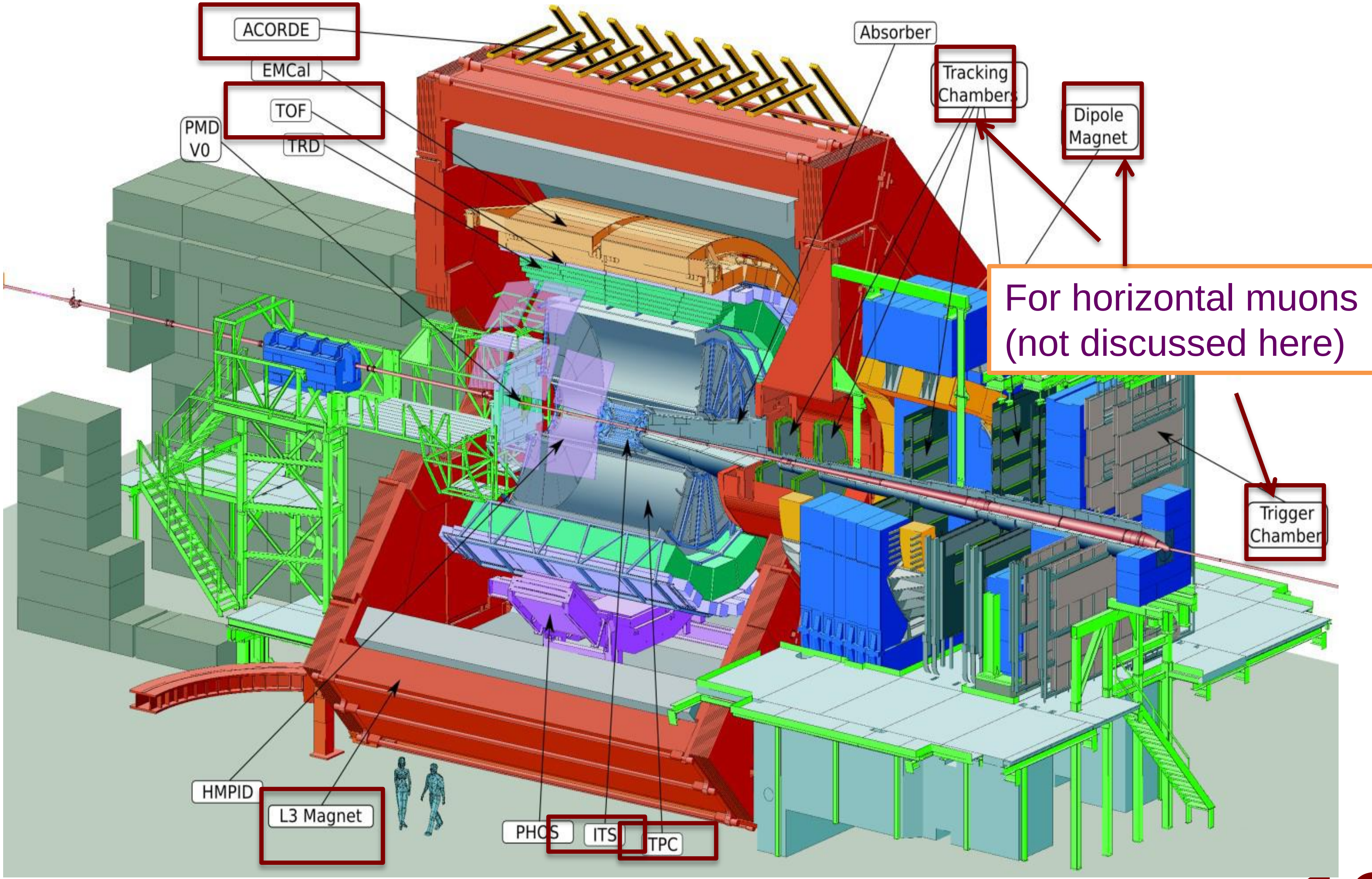
CMS

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



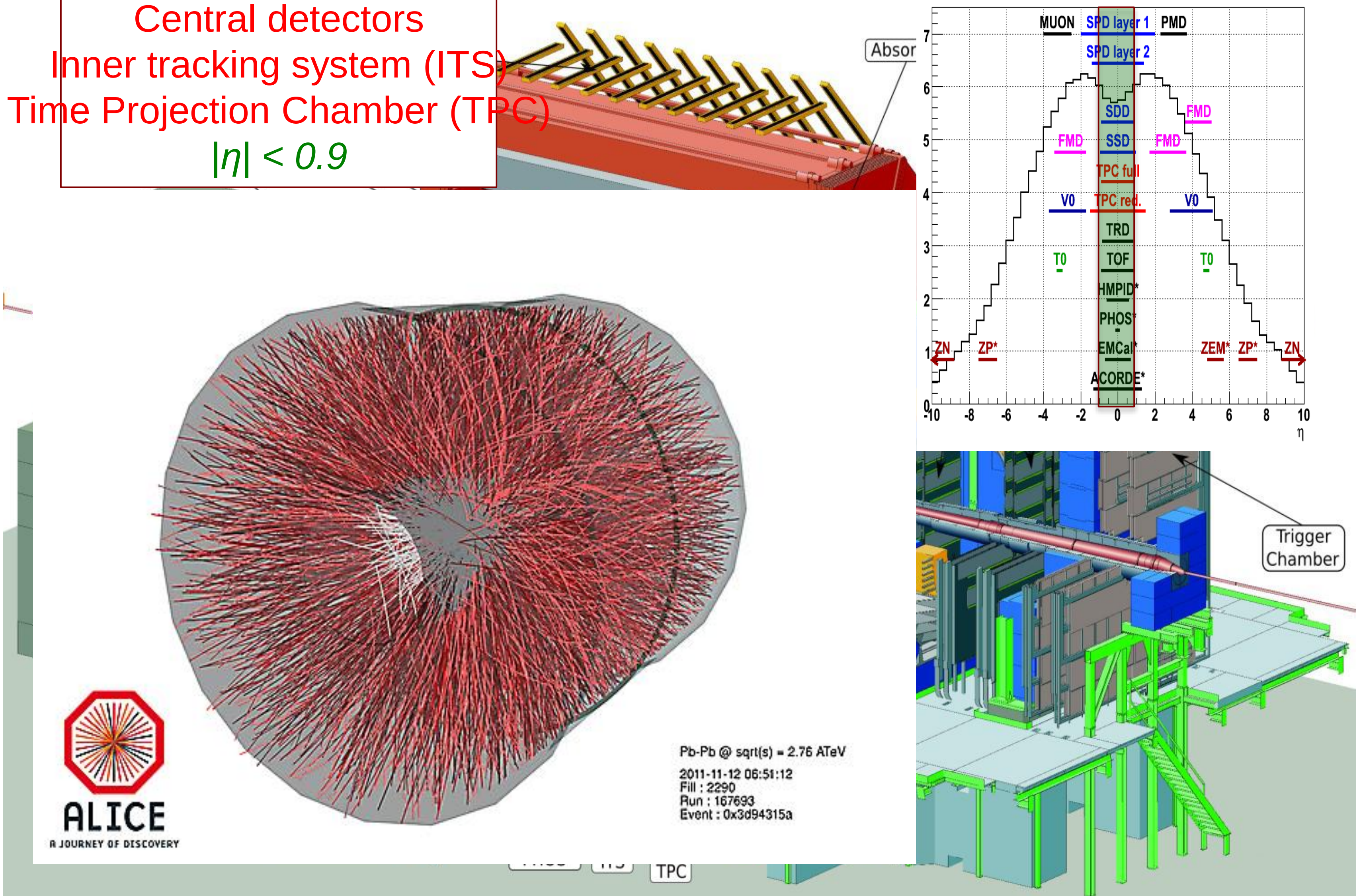
CMS has measured the flux ratio of positive- to negative-charge cosmic ray muons, as a function of the muon momentum and its vertical component. The result is in agreement with previous measurements by underground experiments. This is the most precise measurement of the charge ratio in the momentum region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

ALICE spectrometer



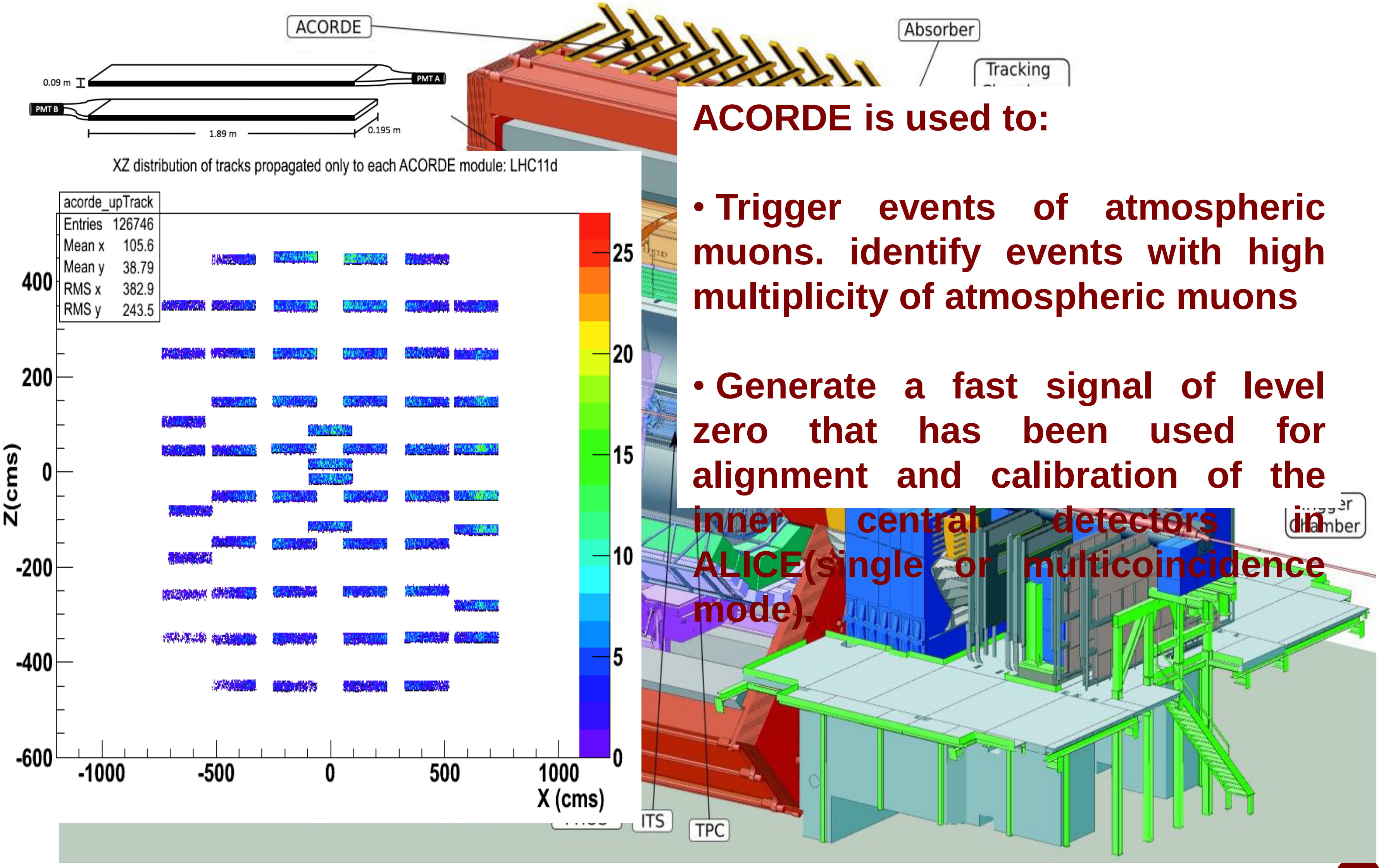
ALICE Central tracking system

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



ALICE Cosmic ray detector

ACORDE

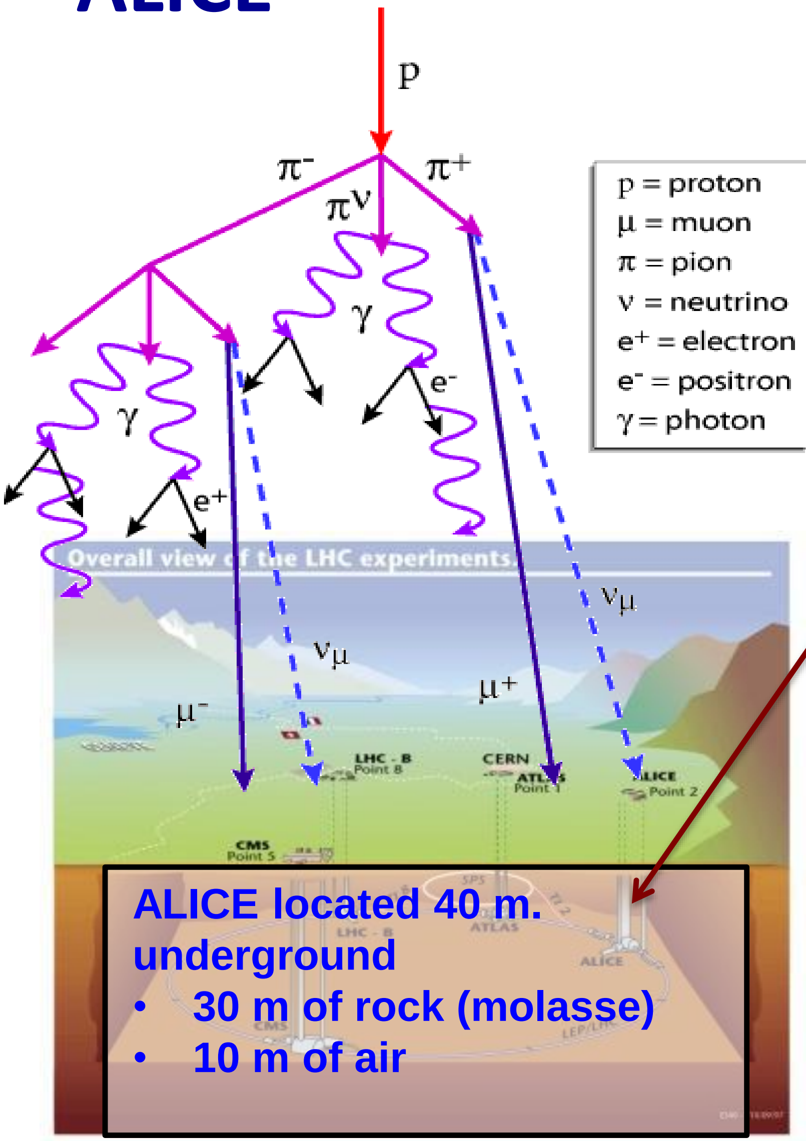


ACORDE is used to:

- 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).

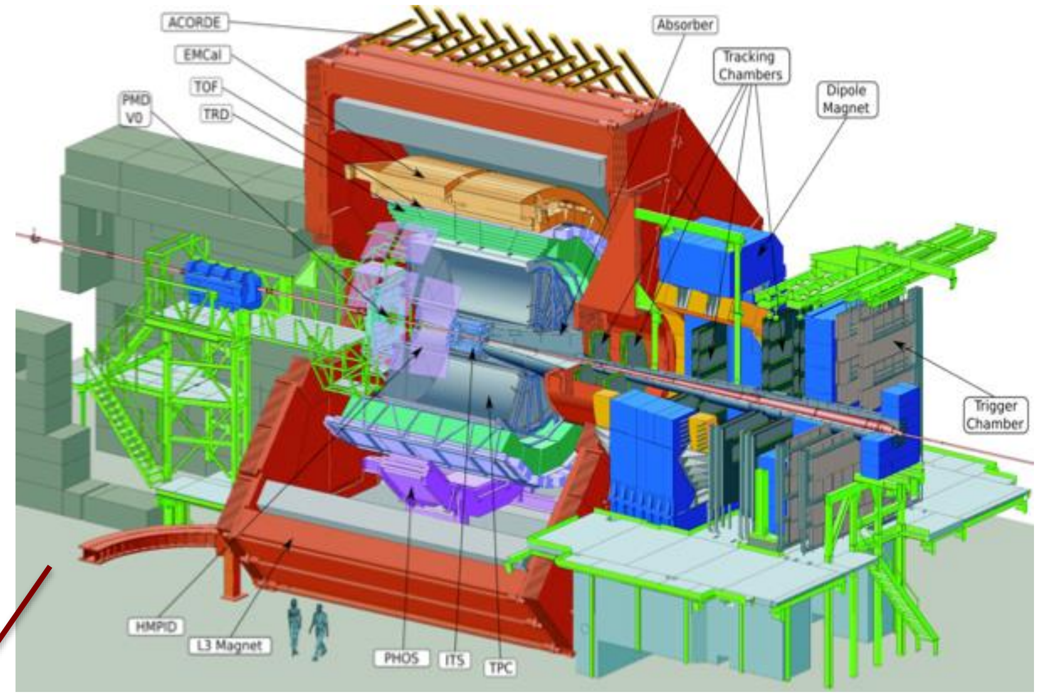
Cosmic ray Physics topics in ALICE

ALICE



ALICE located 40 m. underground
- 30 m of rock (molasse)
- 10 m of air

Threshold Muon Energy ~ 16 GeV



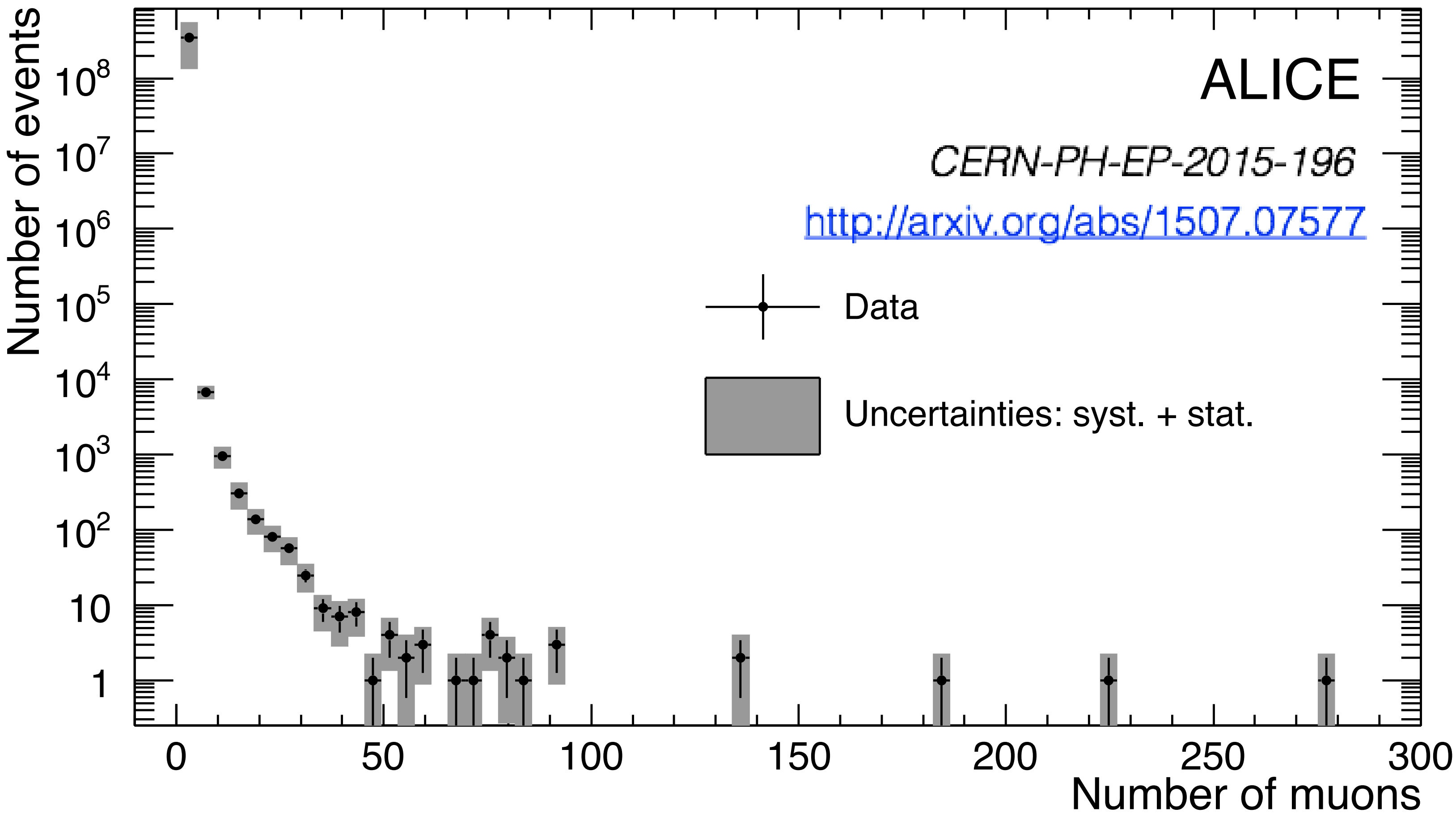
Topics of interest in Cosmic ray analysis in ALICE:

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

LHC ALICE results

ALICE

Presented last week at ICRC-2015

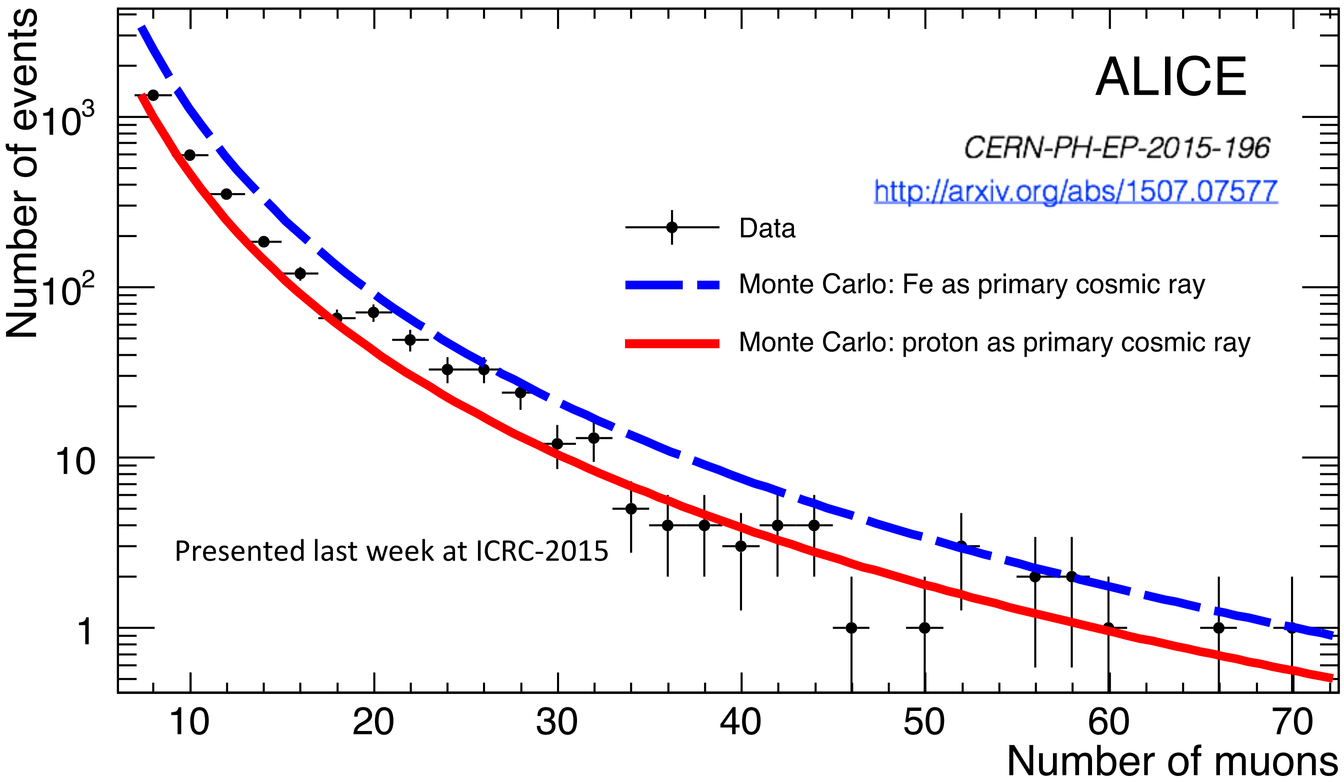


ALICE found a smooth distribution up to #μ < 70 and 5 events with more than 100 atmospheric muons (HMM)

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.



High muon multiplicity rates

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 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 (1)

Accelerator apparatus can be suitable for cosmic-ray physics : LEP experiments were the pioneers on this topic. LHC (ALICE and CMS) have some results i, 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 (2)

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

LHC

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

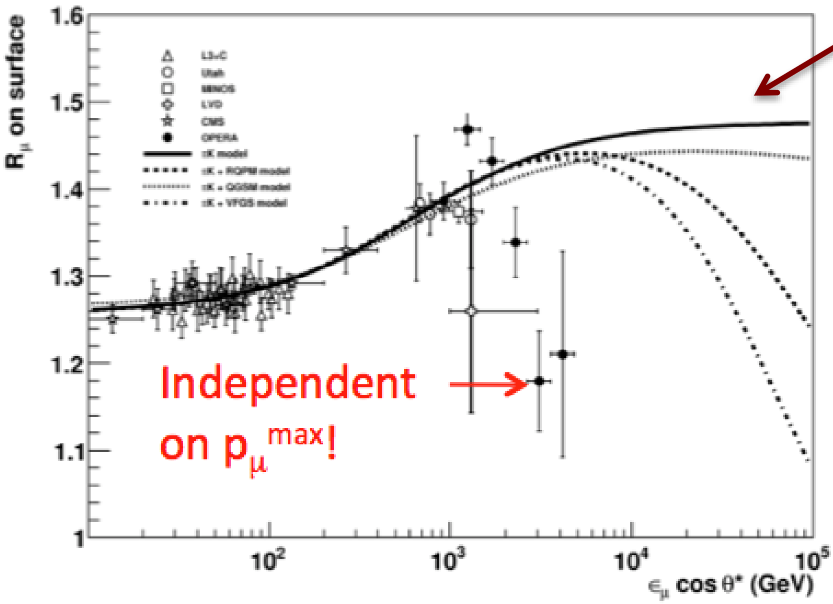
For more details please check:
"Study of cosmic ray events with high muon multiplicity using the ALICE detector at the CERN Large Hadron Collider", ALICE Collaborarion (CERN-PH-EP-2015-196, arXiv:1507.07577)

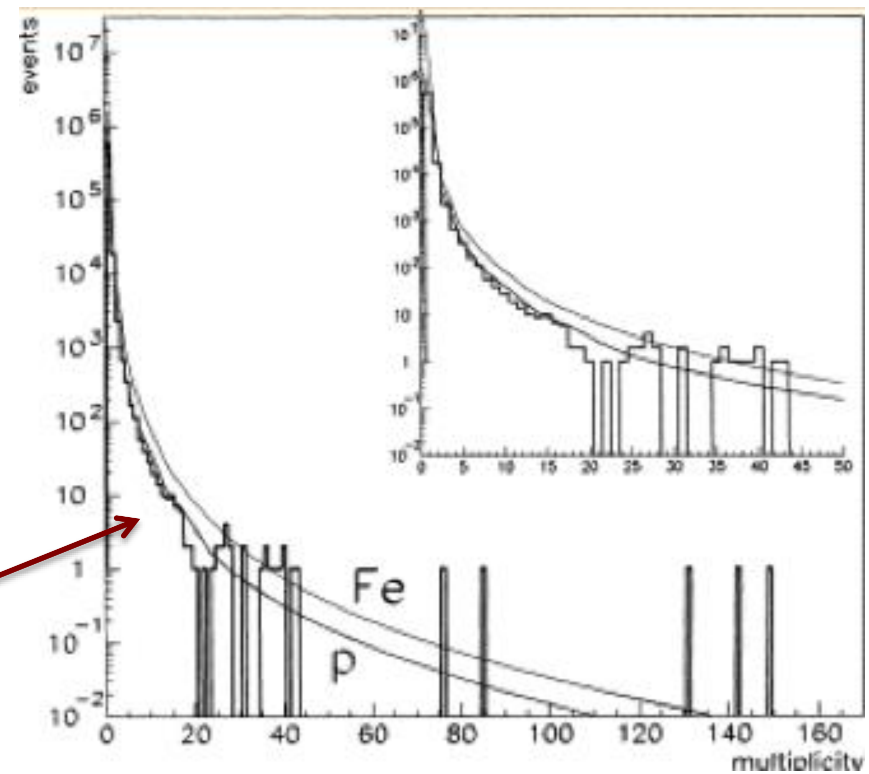
Backup

Backup slides

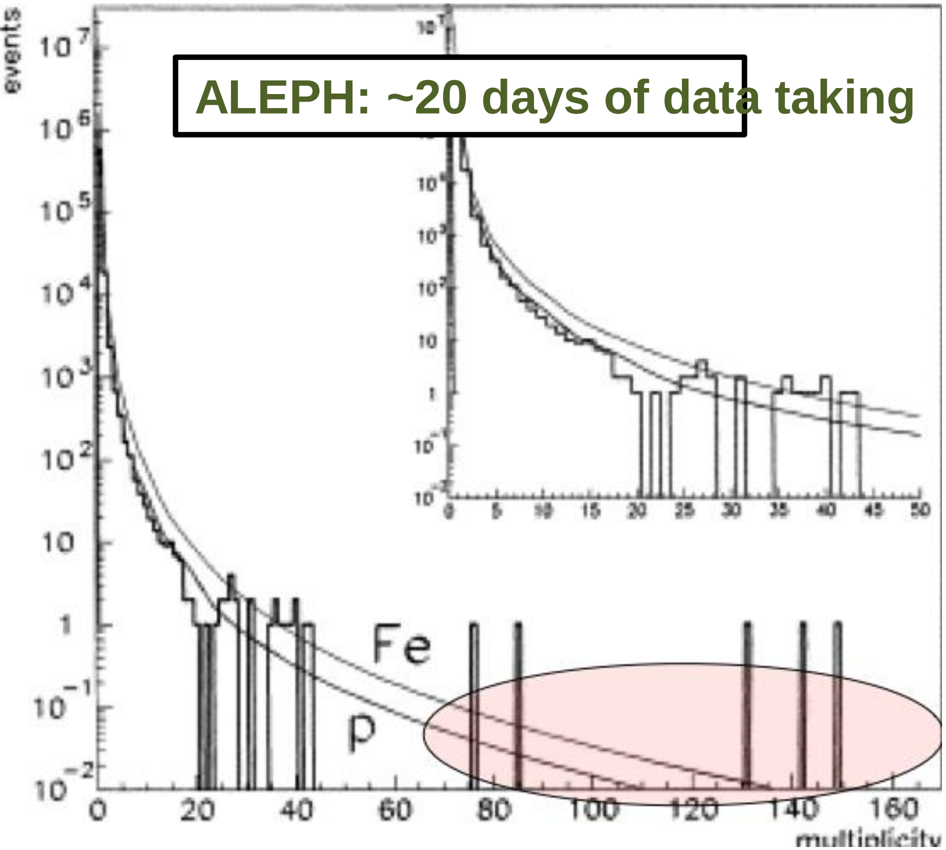
Main topic with accelerator apparatus

- **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) 513–52

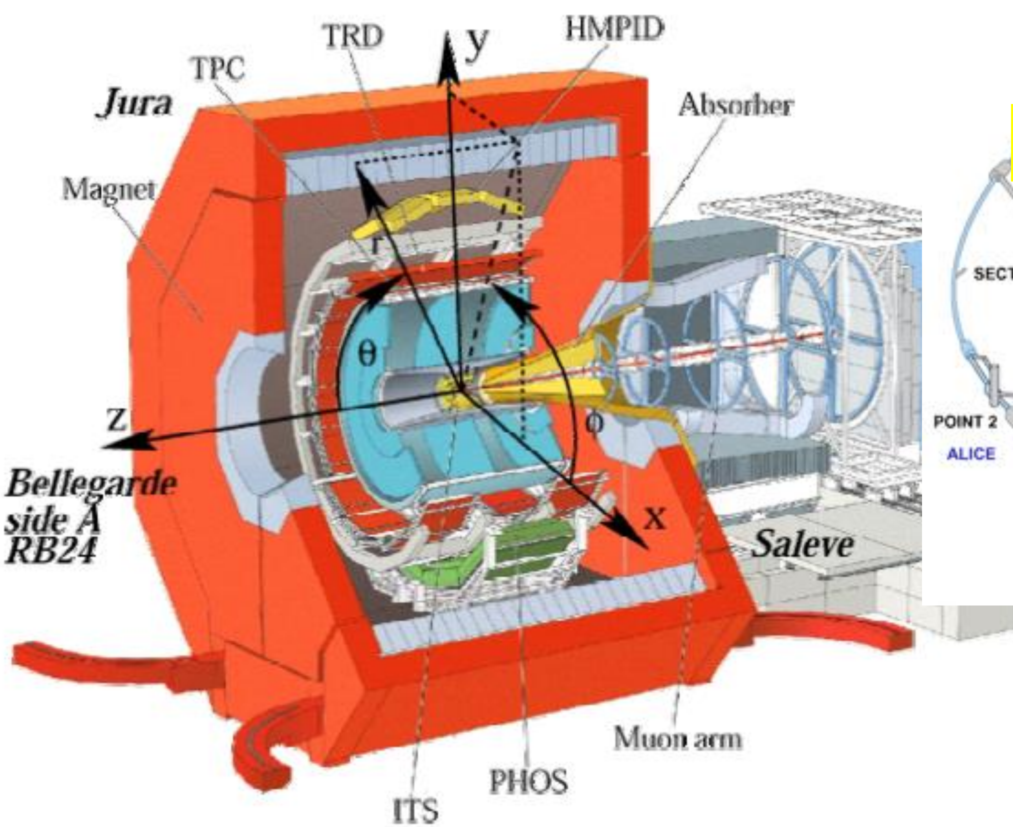
The five highest multiplicity events, with up to 150 muons within an area of 8 m^2, occur with a frequency which is almost an order of magnitude above the simulation.

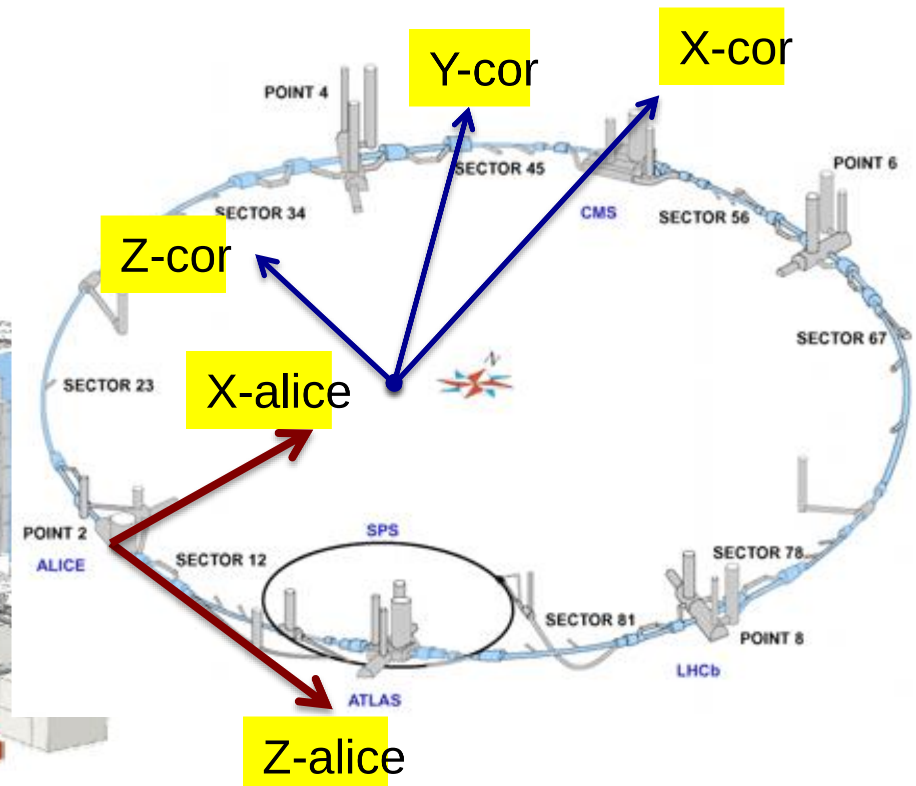
General: All ALICE sub-detector components are to be numbered starting from zero.

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.

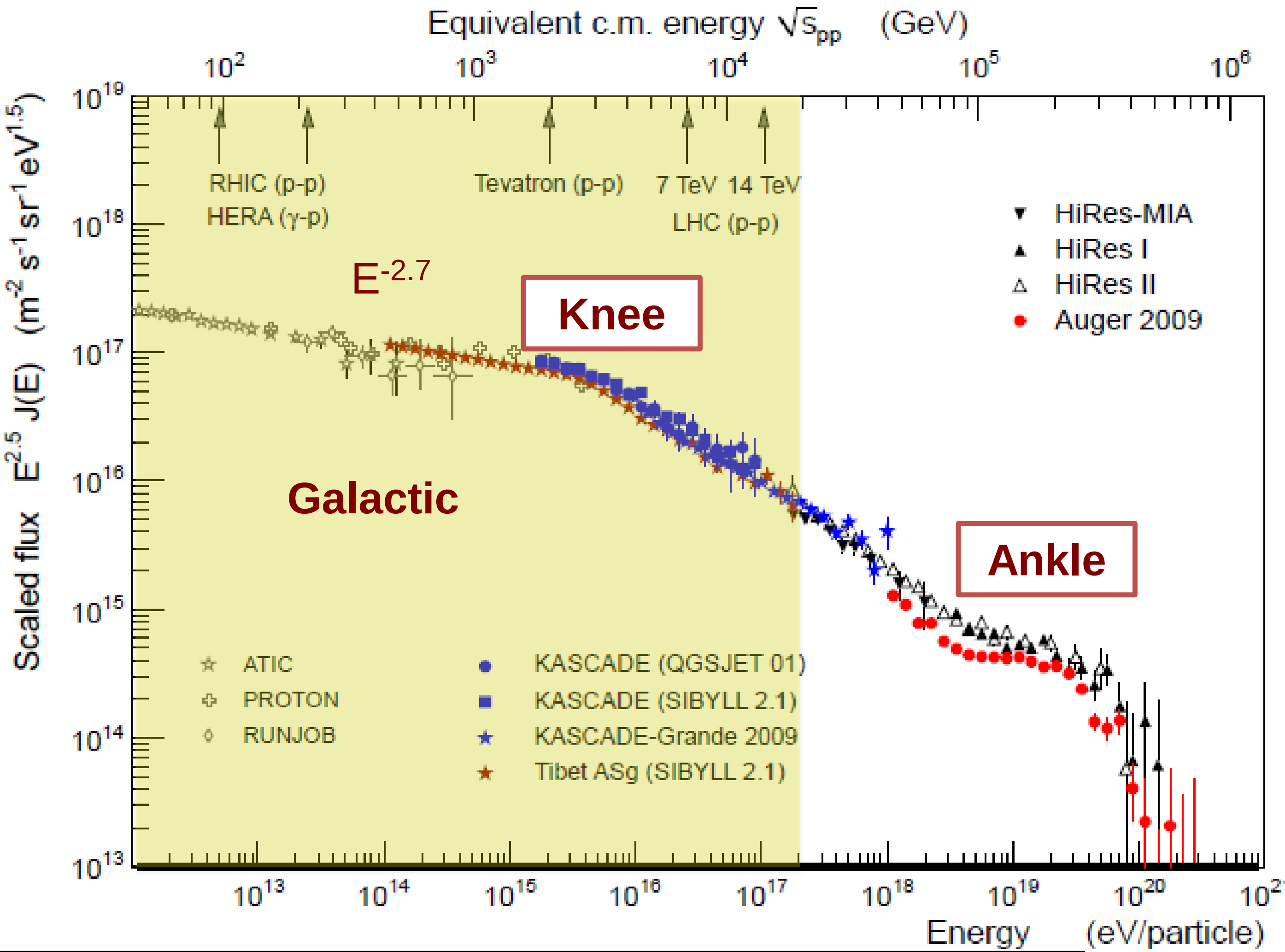
Linear Numbering: The counting increases from side ***A*** to side ***C,*** opposite to the z axis direction, without interruption in the middle at z = 0.

Radial Numbering: The counting increases with increasing radius.



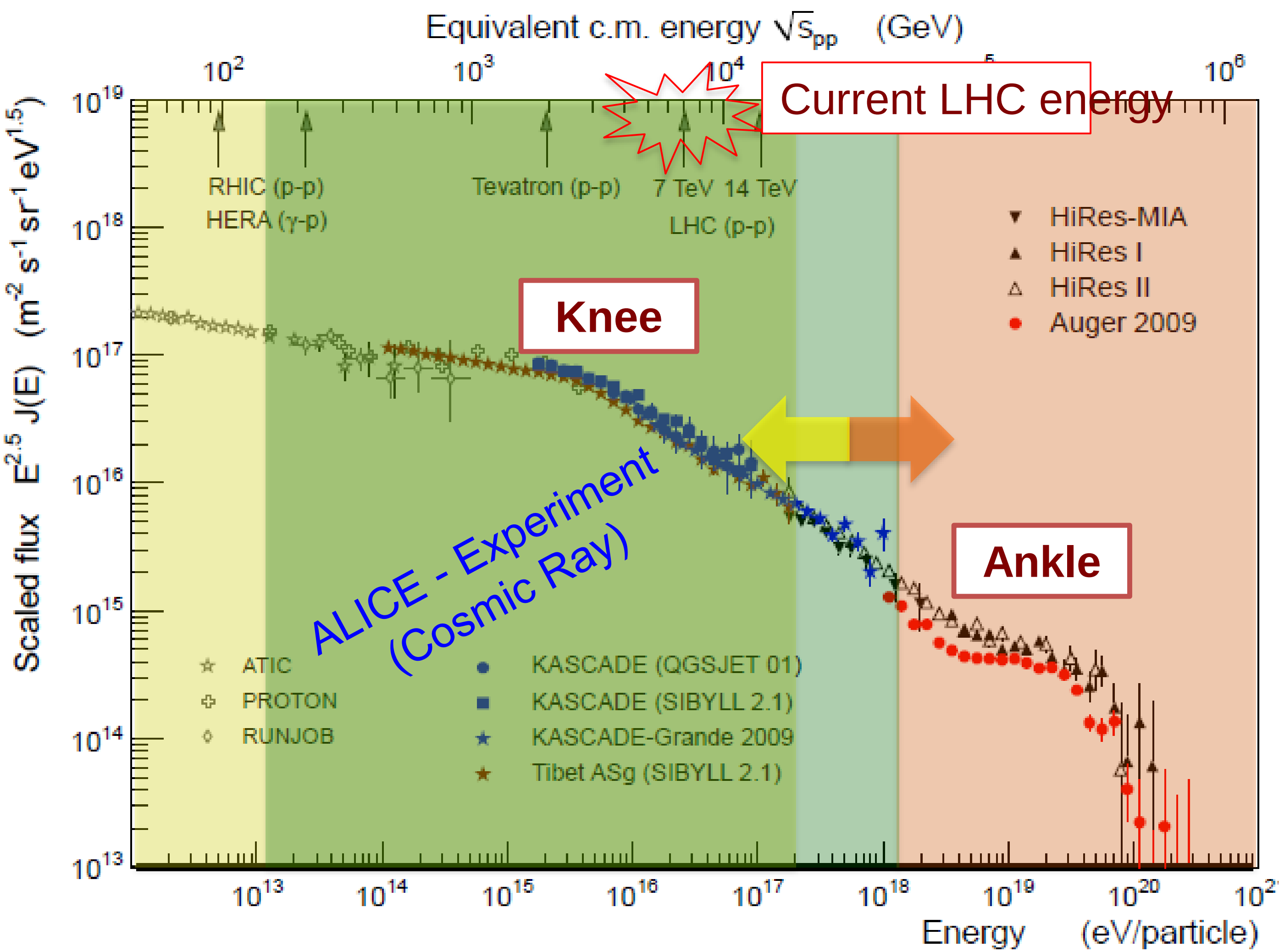


Backup slides

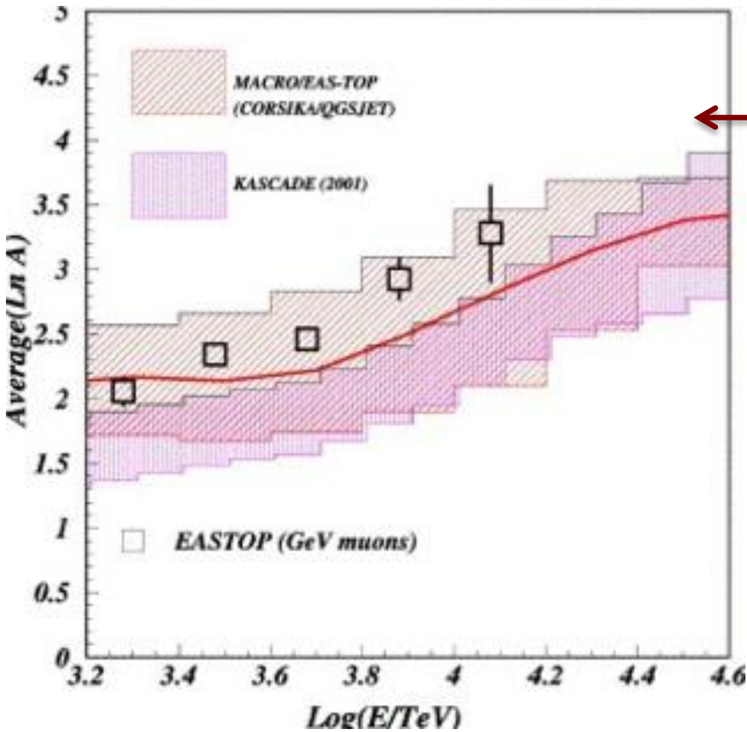


- Density of the galactic primary cosmic ray: ~ 1 eV/cm^3
- Protons for energies below 10^{16} eV
- Heavy nuclei composition: ~ 8*10^{16} eV (**Phys. Rev. Lett. 107, 171104 (2011)**)

Backup slides



Backup slides

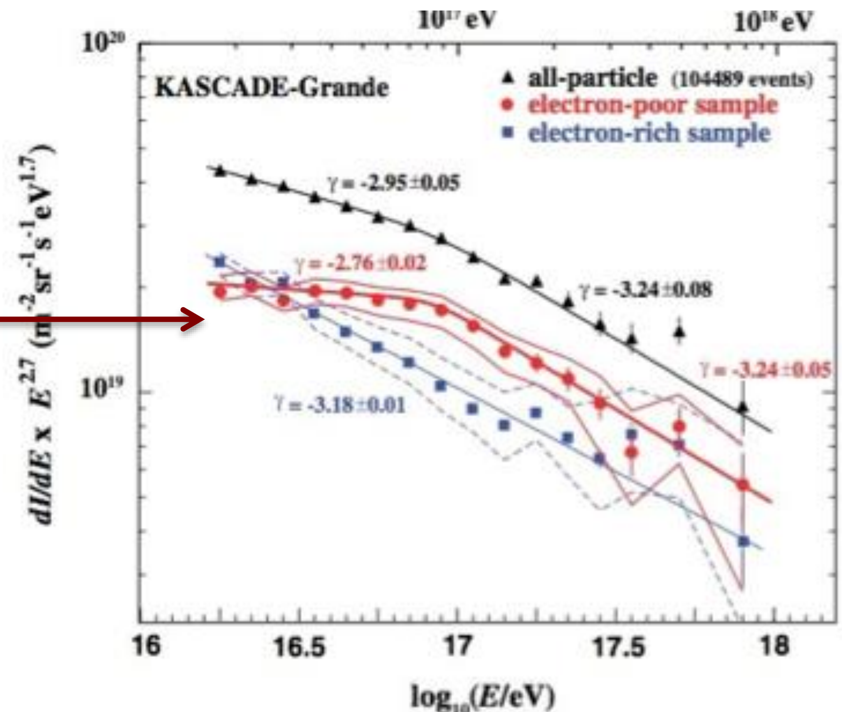


MACRO-EASTOP KASCADE :

- 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

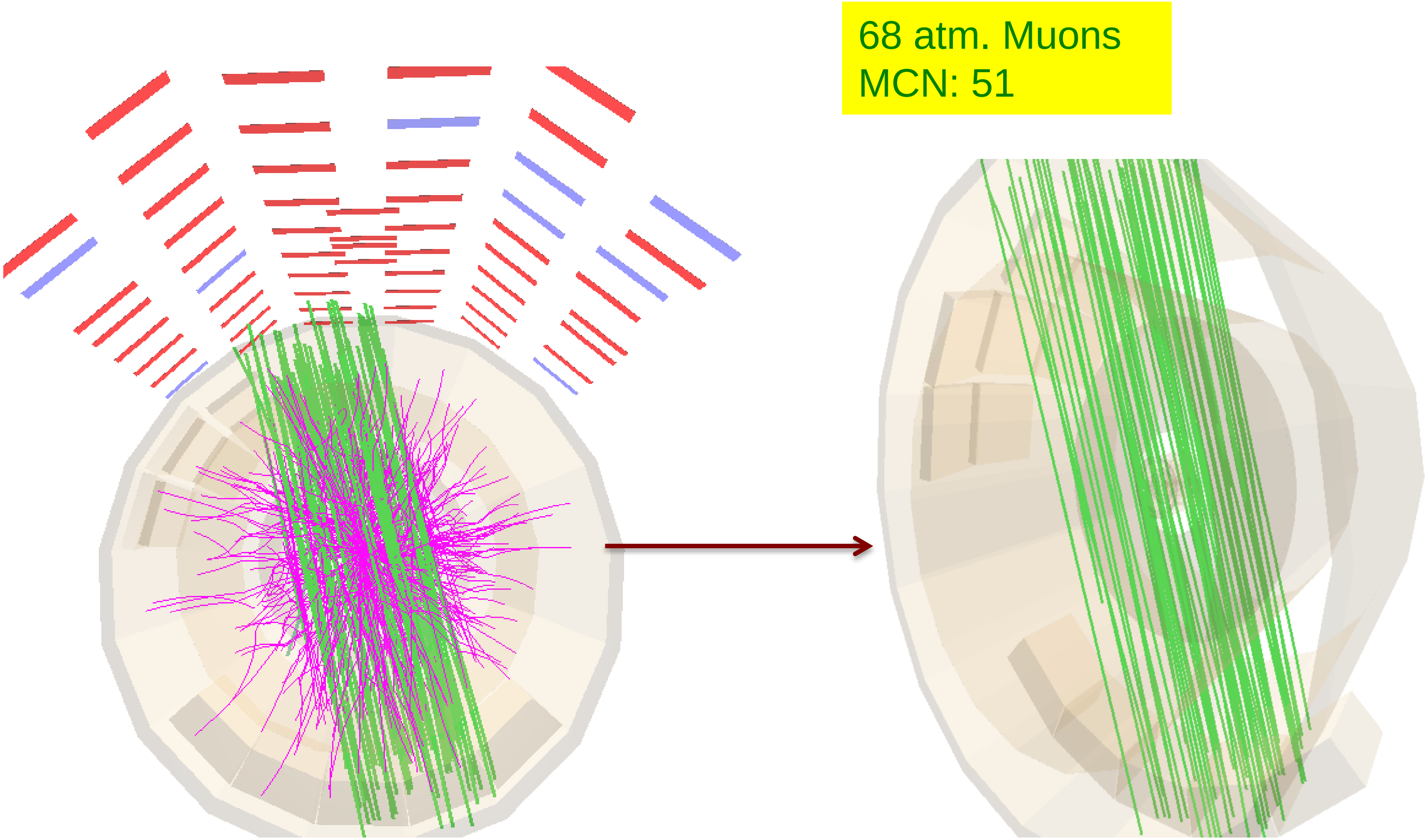


KASCADE-GRANDE :

- 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

Backup slides



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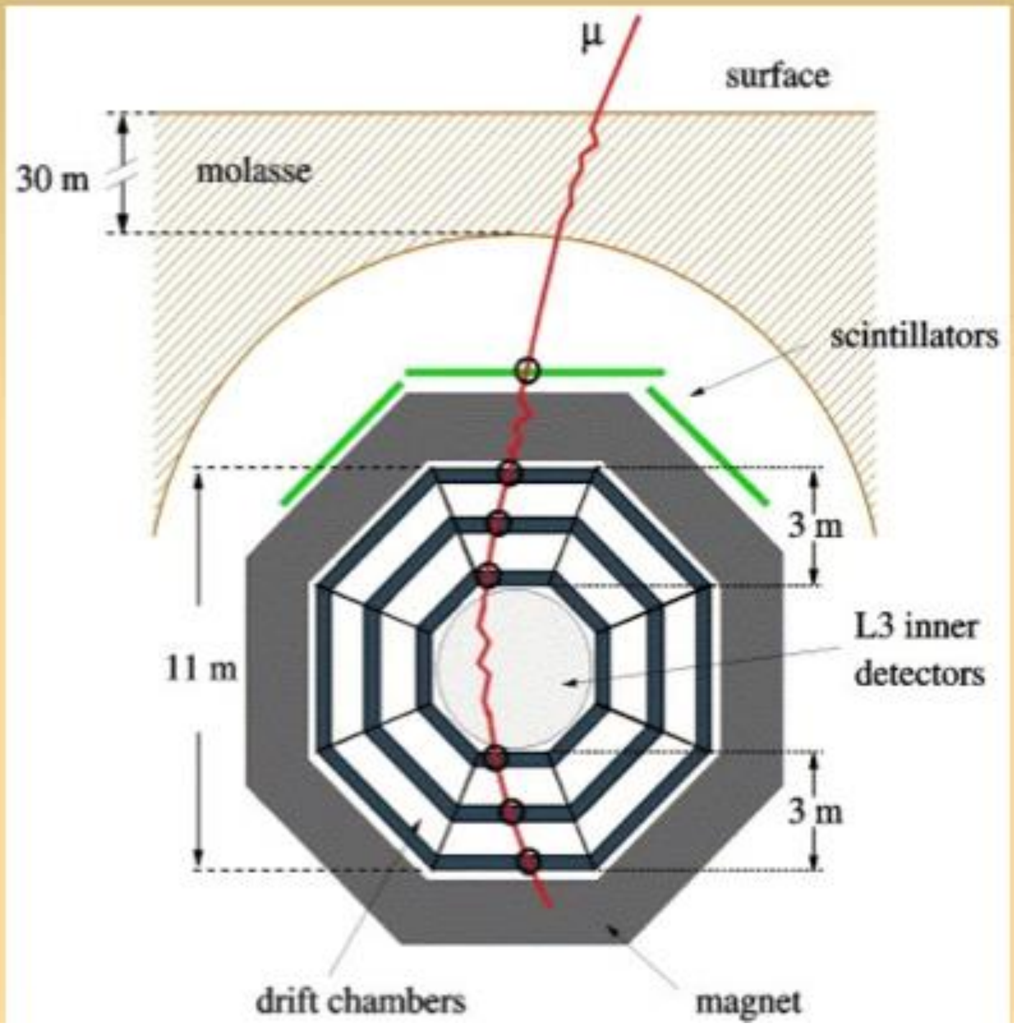
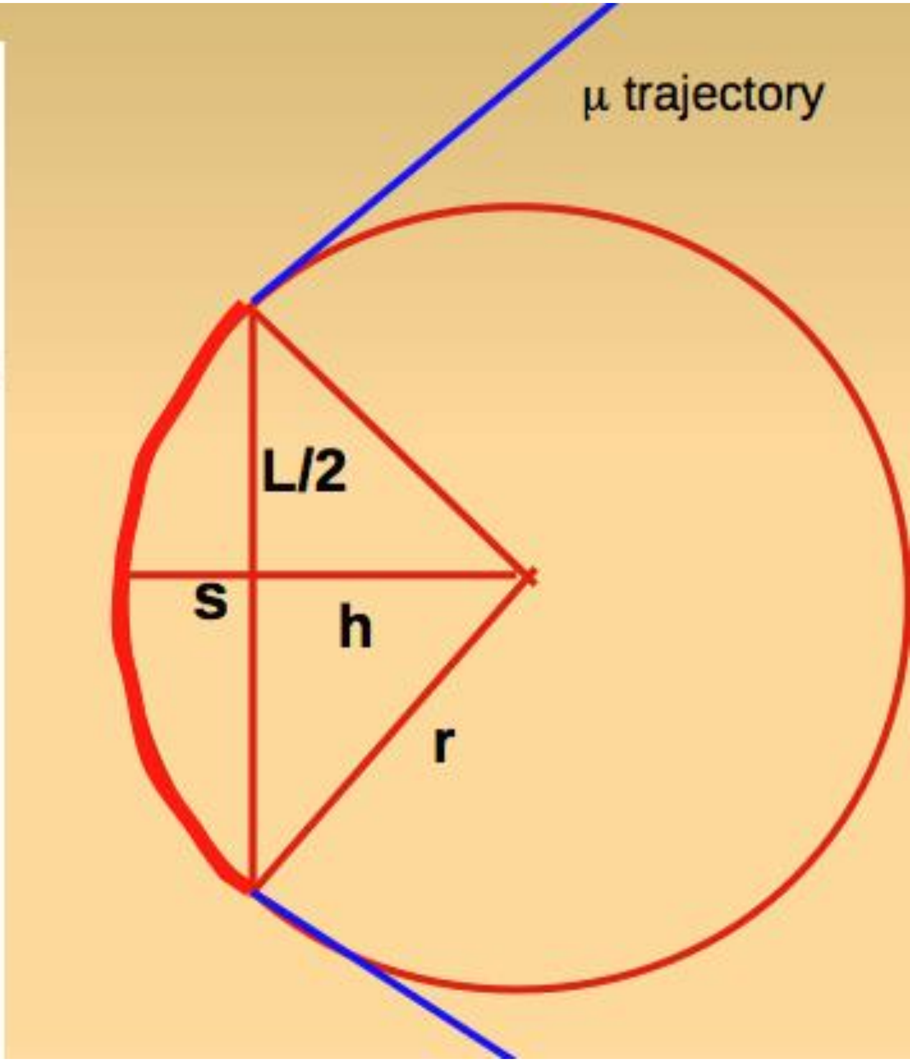
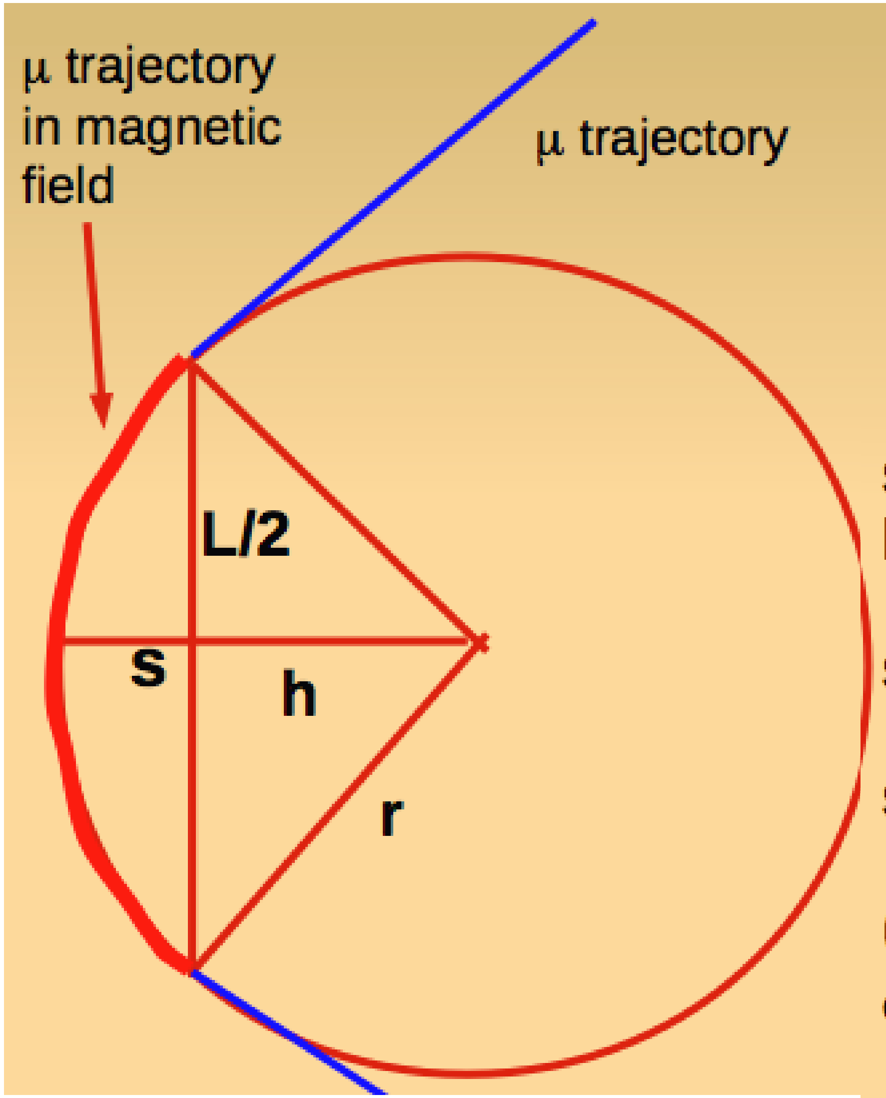






v perpendicular B

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

$s = r - h$

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

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

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

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

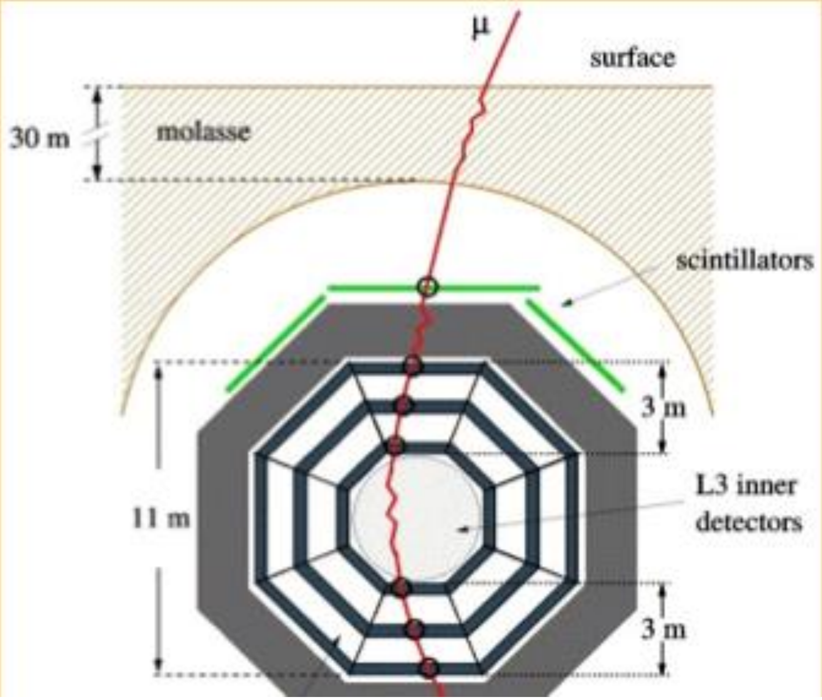
$\alpha = ½ \quad x = -(L^2/4r^2)$

$s \sim L^2/8r$

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

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

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



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

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

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

Example for L3+C :

σ_s = 1 mm

L = 11 m

B = 0.5 T

p = 100 GeV/c   Resolution σ_p

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

σ_p = 1.32 GeV/c ==> 1.3%

p = 1 TeV/c   Resolution σ_p

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

σ_p = 132 GeV/c ==> 13%