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Cosmic-ray physics at CERN

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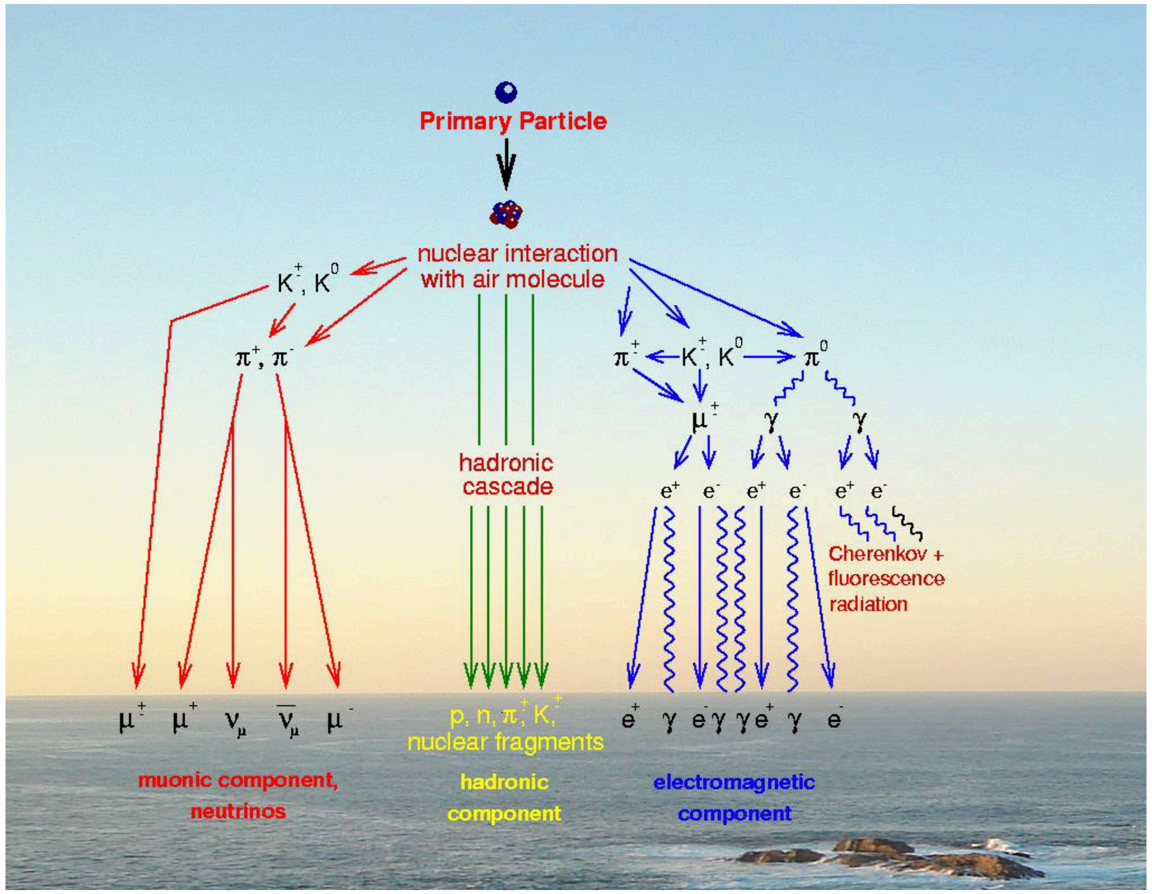
Outline

- Introduction
- Cosmic-ray physics at CERN
  - LEP
  - CMS
  - ALICE
  - MATHUSLA
- Final comments

Cosmic ray known properties

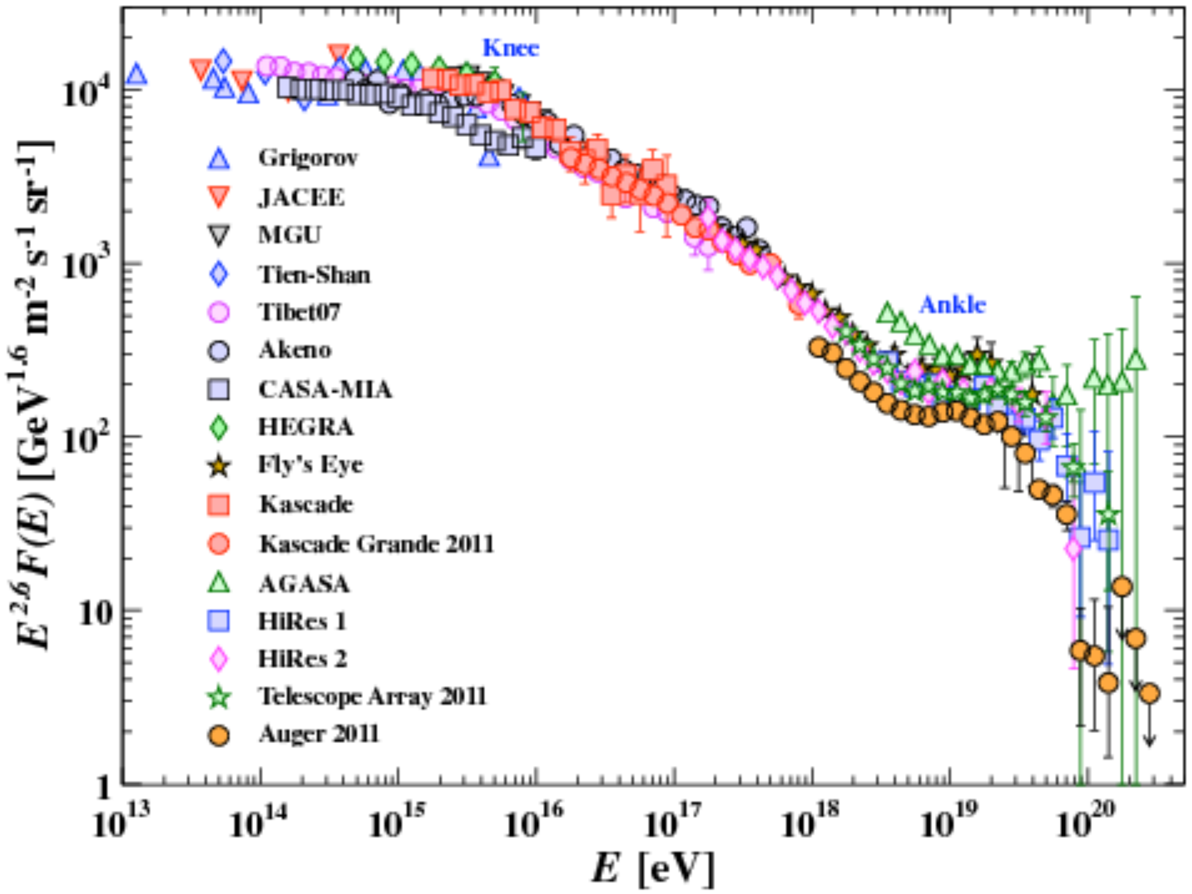


http://inspirehep.net/record/1365207/plots

- **Mainly composed** by atomic nuclei
- **Energy** ranges from 10^8eV to 10^{20} eV
- **Spectrum** follows roughly a power law

- **Origin** is galactic and extragalactic:
- Sun (E < 10 GeV),
- Supernova remnants (E~TeV),
- Extragalactic sources (E > 1 EeV).

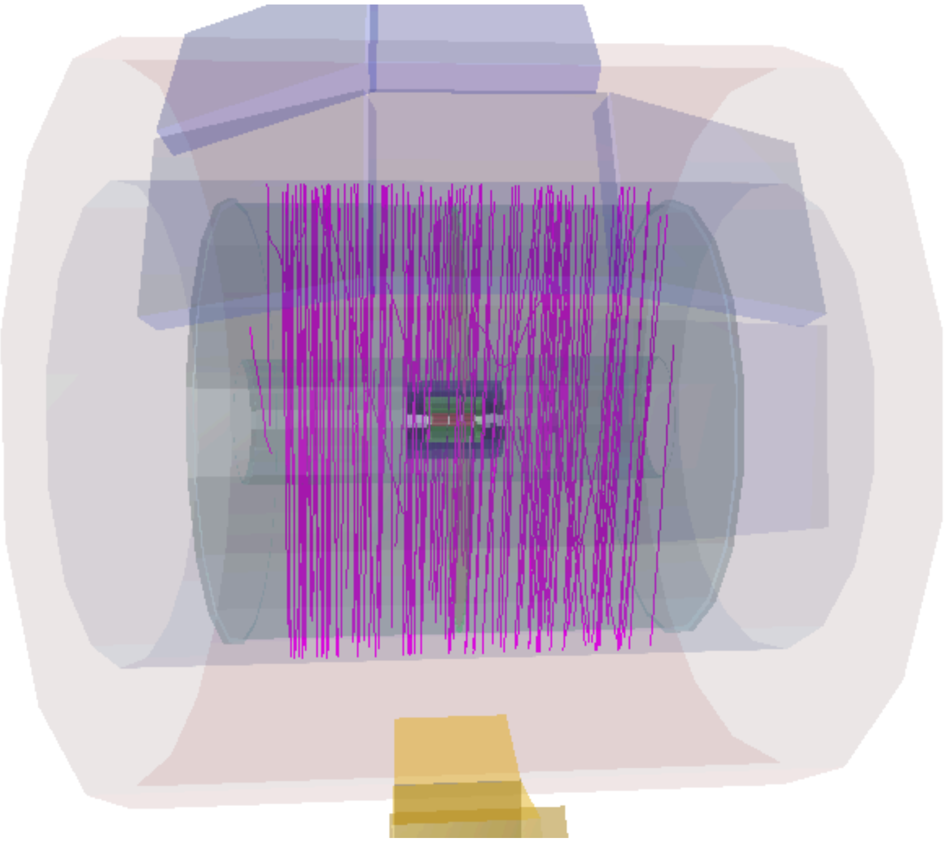
The backbone of an air shower is the hadronic component of nucleons, pions and more exotic hadronic particles



DOI: 10.1103/PhysRevD.98.030001

Muon multiplicity distribution

- The **muon multiplicity distribution** carries information on the chemical composition of primary cosmic rays and their interactions in the atmosphere.

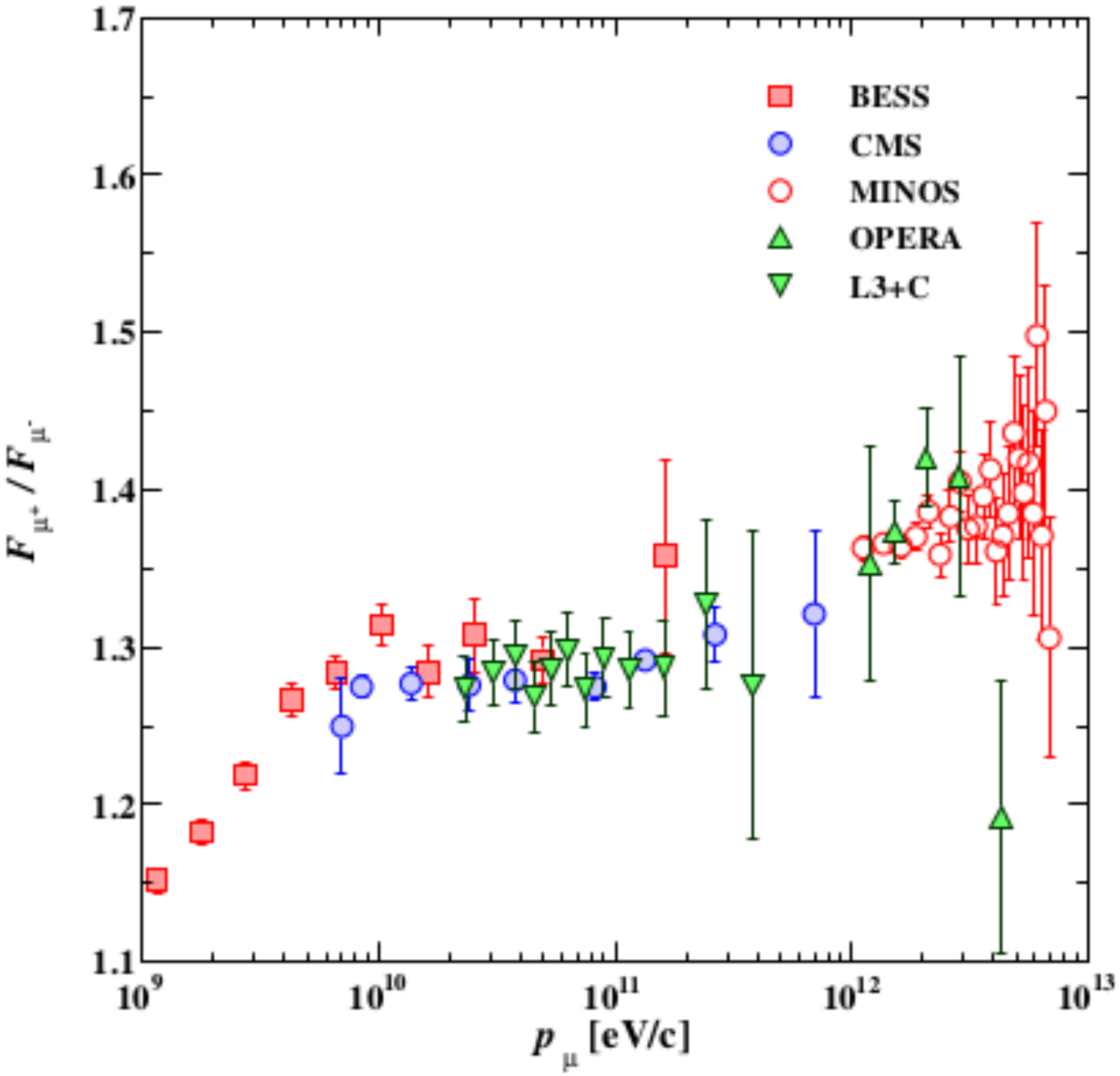


- Lighter elements will on average produce smaller multiplicities than heavier elements.

- The multiplicity of high-energy secondary muons is one of the characteristics of the Extensive Air Showers, that depends on the composition and energy of primary particles

Cosmic ray known properties

❖ μ+/μ- charge ratio measureent

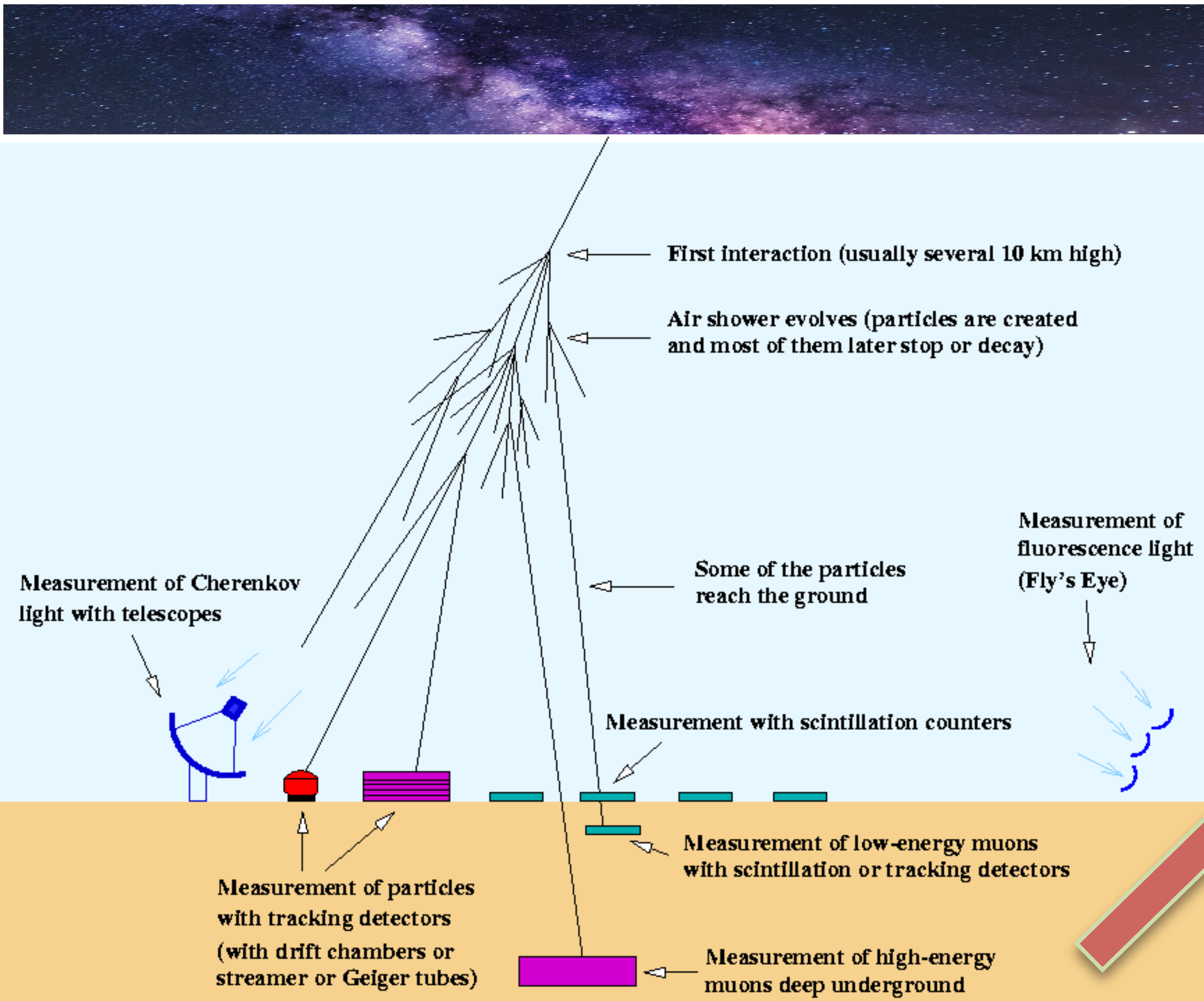


Several contributions

- ✓ Composition of the primary cosmic ray (ratio protons over heavy component).
- ✓ Hadronic interactions features
- ✓ Atmospheric conditions (low energy, below few GeV) .
- ✓ Contribution of muons from charmed particle decays (prompt muons, very high energy) .

DOI: 10.1103/PhysRevD.98.030001

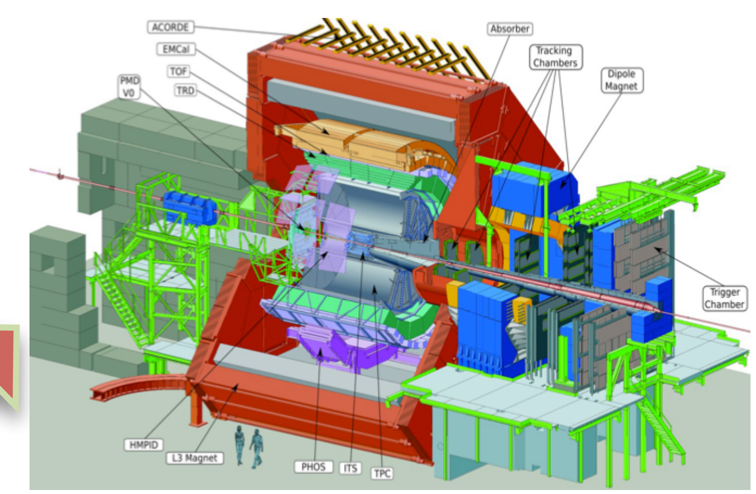
Underground experiments: Ice Cube, Macro, LEP & LHC



Cosmic-ray physics at CERN

LEP: L3+C, ALEPH, DELPHI

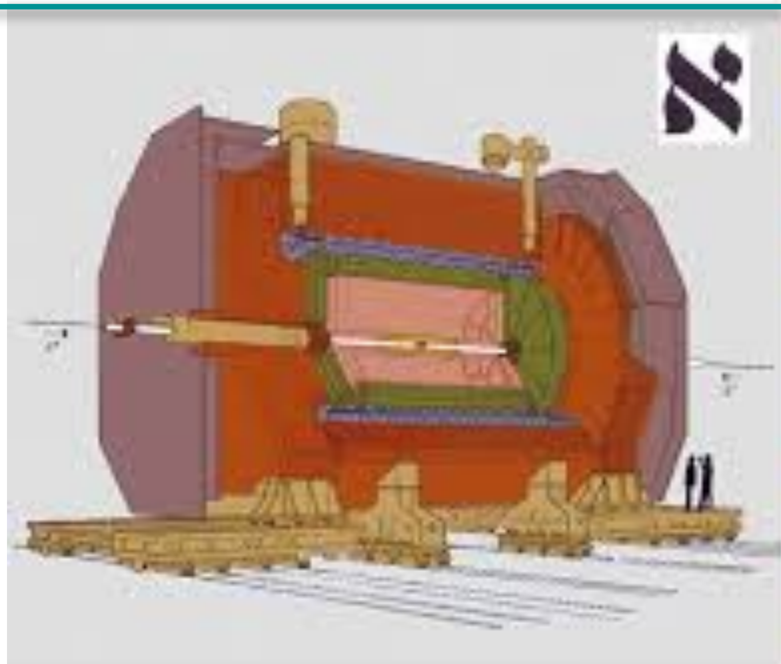
LHC: CMS, ALICE

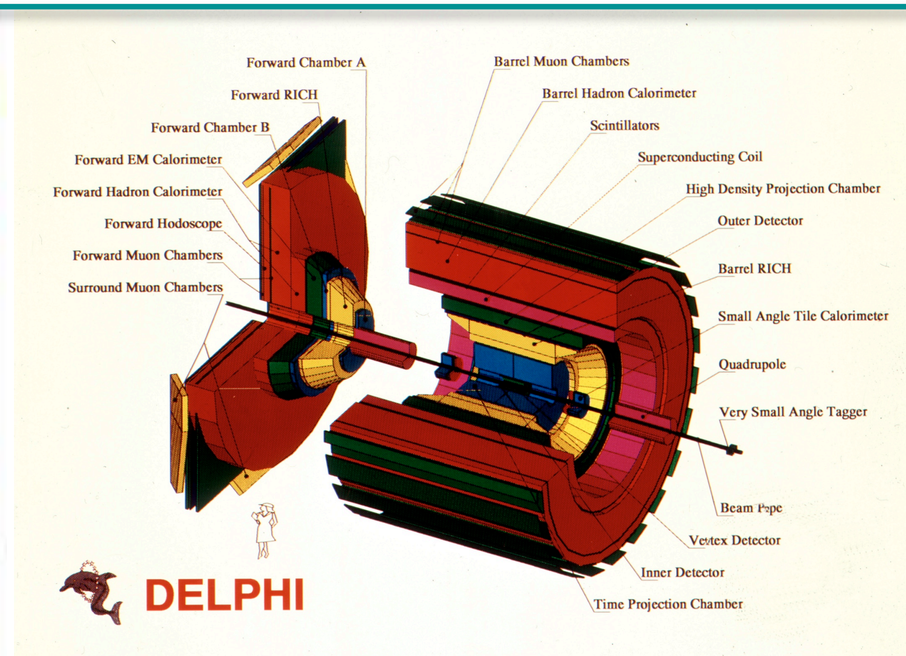


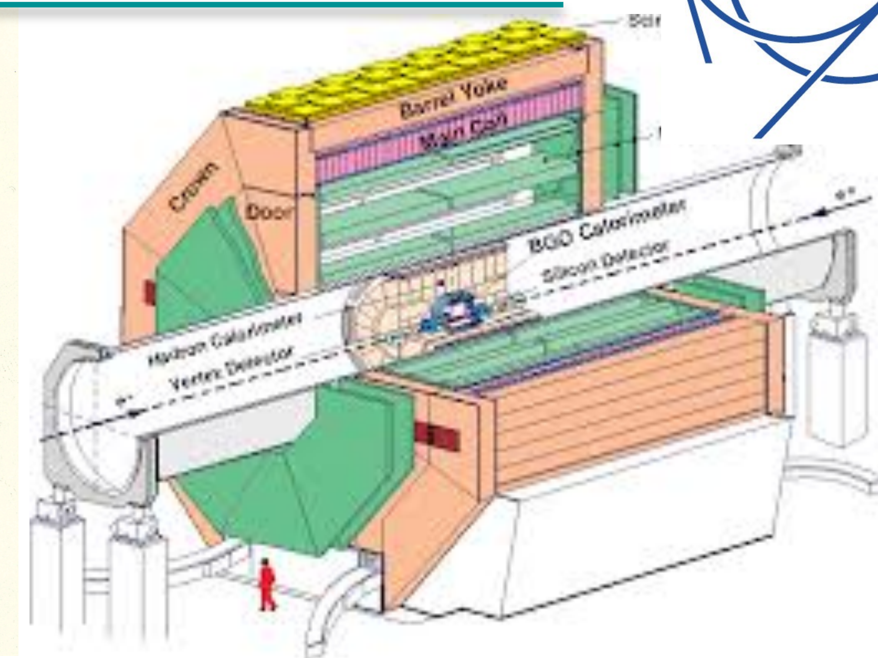
https://astroparticle.online/experiments/

Experiments at LEP

Previous experiments



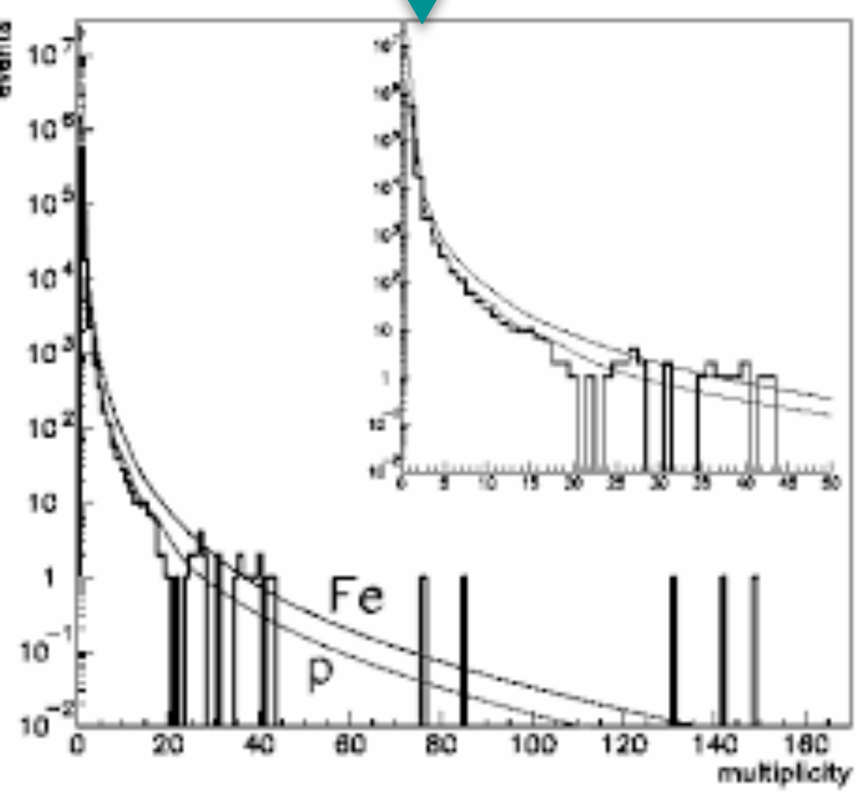


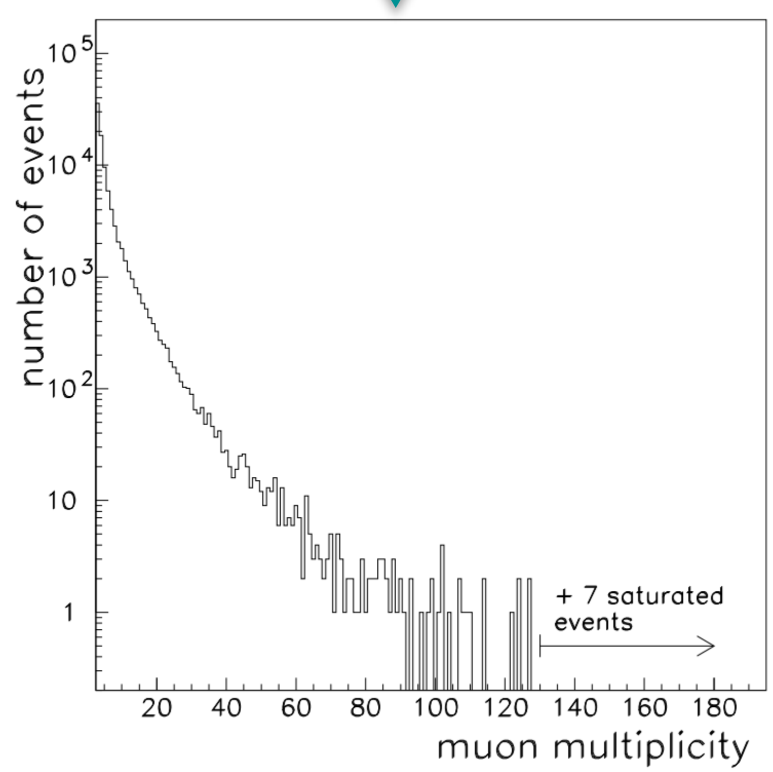


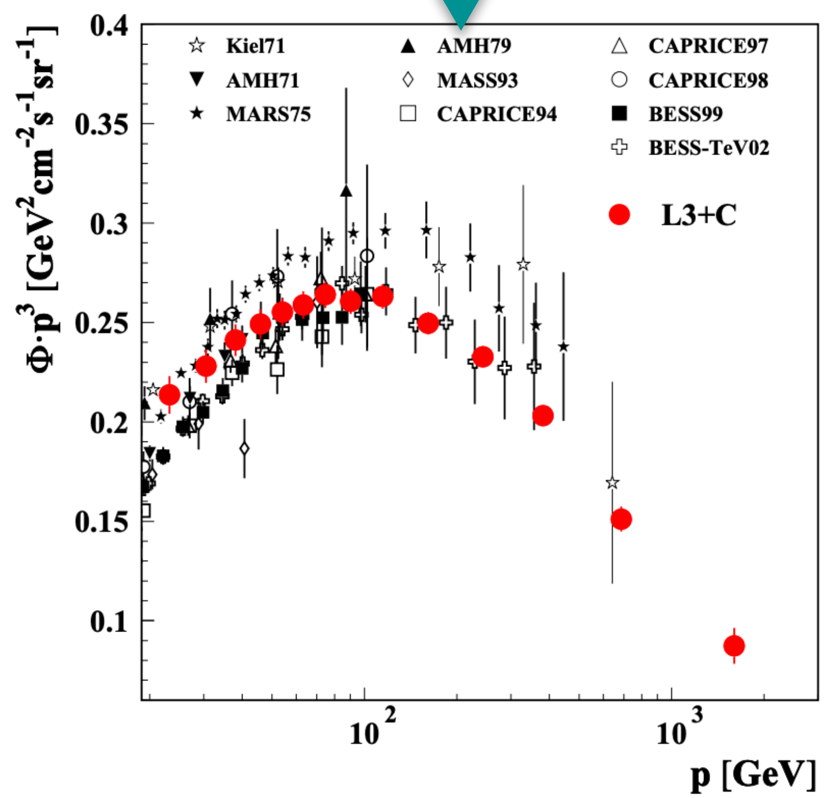
Astroparticle Physics 19 (2003) 513–523

Astroparticle Physics 28 (2007) 273–286

Phys.Lett.B598(2004) 15–32

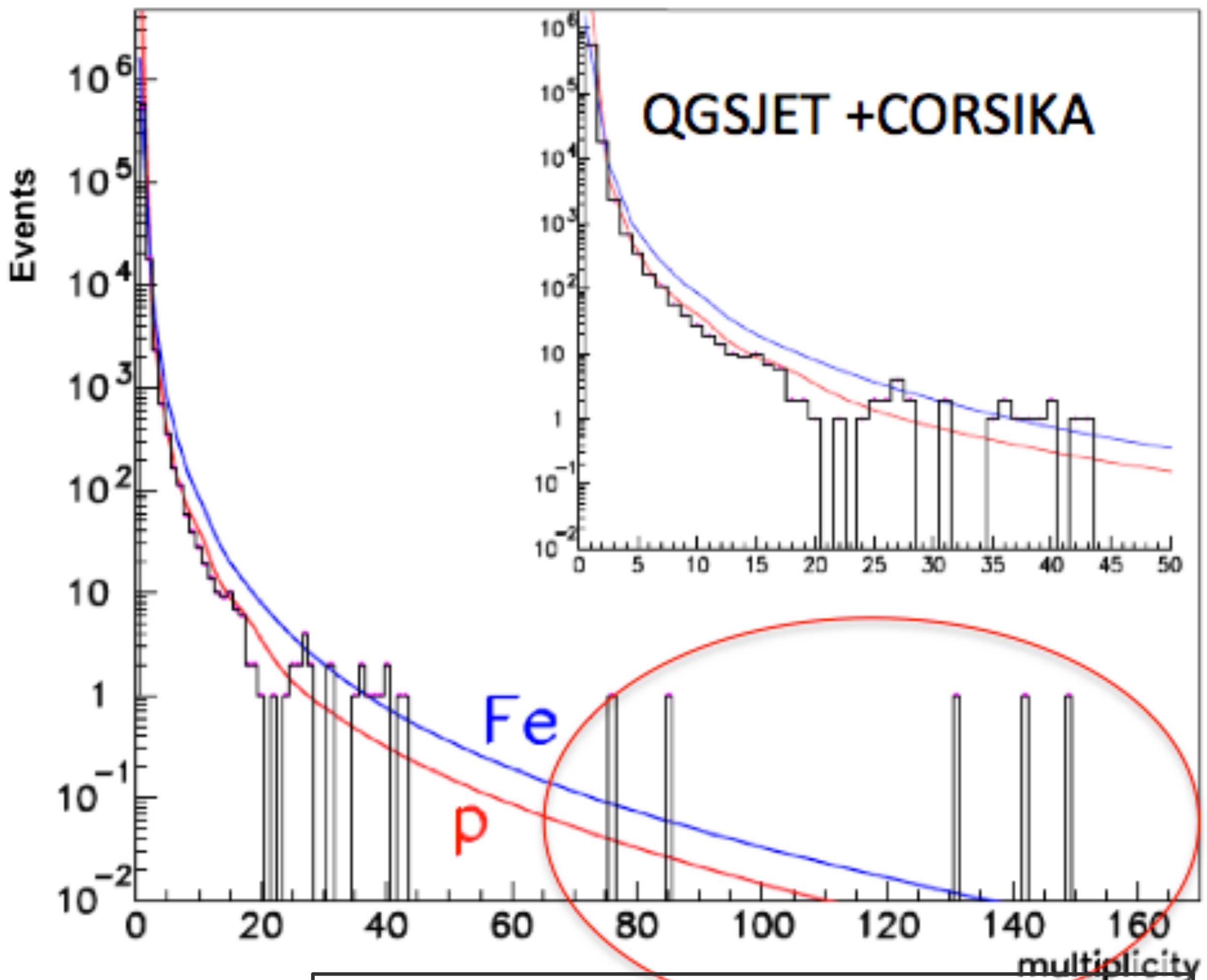






Previous experiments

LEP experiments were pioneers in the study of atmospheric muon bundles with underground apparatus used in particle accelerators:



ALEPH: ≈20 days of data taking

ALEPH conclusion *(Astroparticle Physics 19 (2003) 513 - 523)*:

"While the simulation agrees with the data over a wide multiplicity range, it fails to describe the highest multiplicities, even under the extreme assumption of a pure iron composition".

DELPHI conclusion *(Astroparticle Physics 28 (2007) 273 - 286)*:

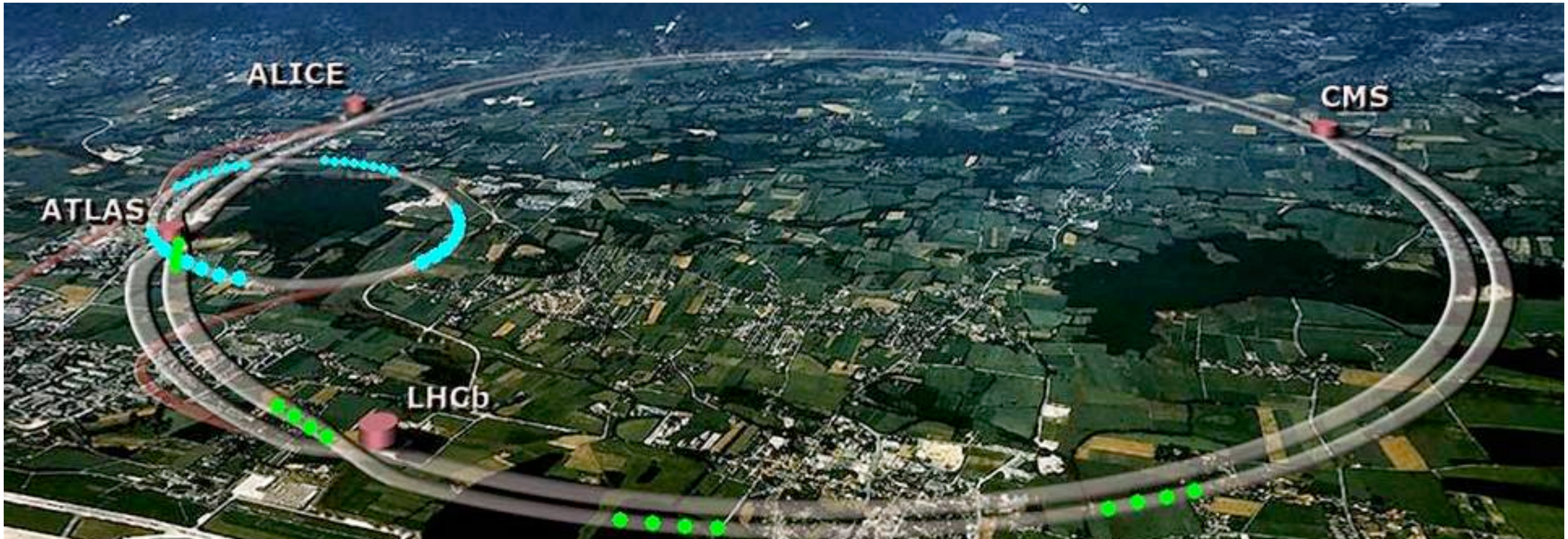
"However, even the combination of extreme assumptions of highest measured flux value and pure iron spectrum, fails to describe the abundance of high multiplicity events".

HMM: ≈ an order of magnitude above the simulation

LHC

The Large Hadron Collider (LHC):

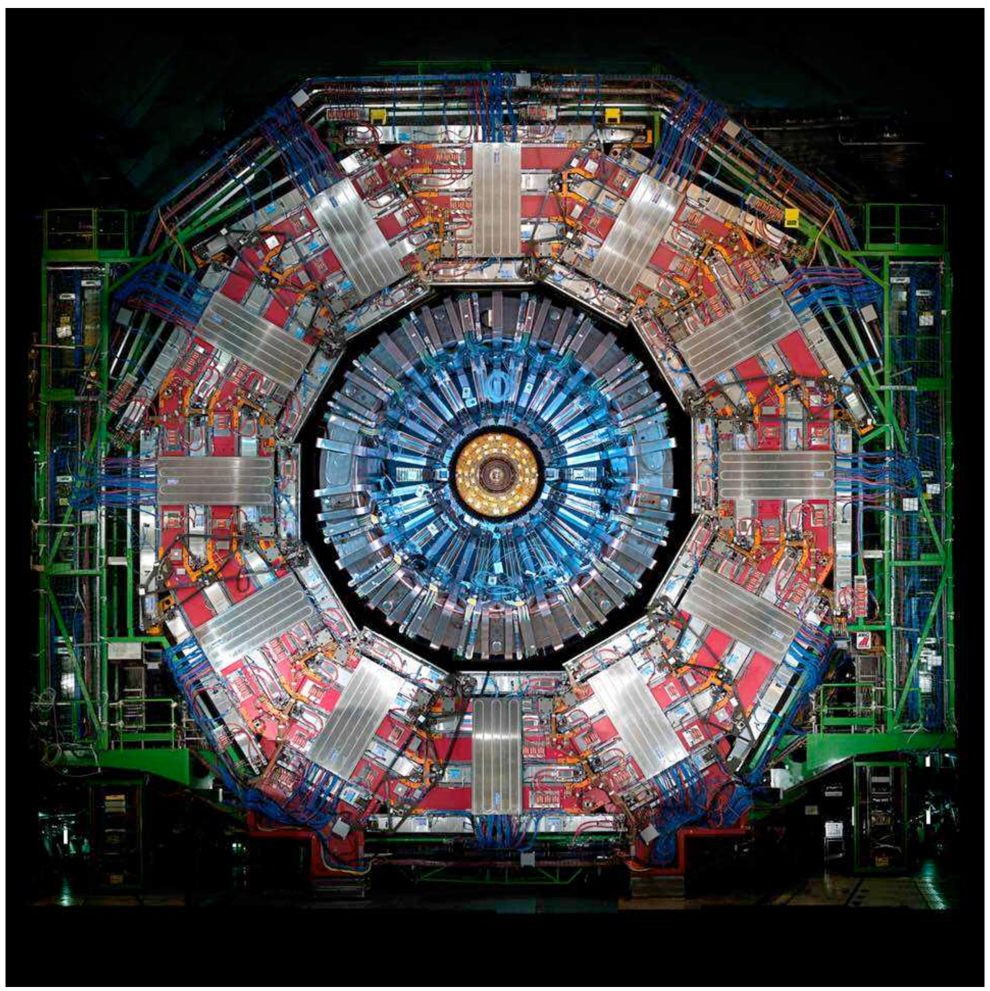
- 27 km circumference
- 100m underground
- 9,300 superconducting magnets.
- -270 degrees Celsius.
- Temperatures 100,000 times hotter than the interior of the Sun are generated.
- 2015- 14 TeV

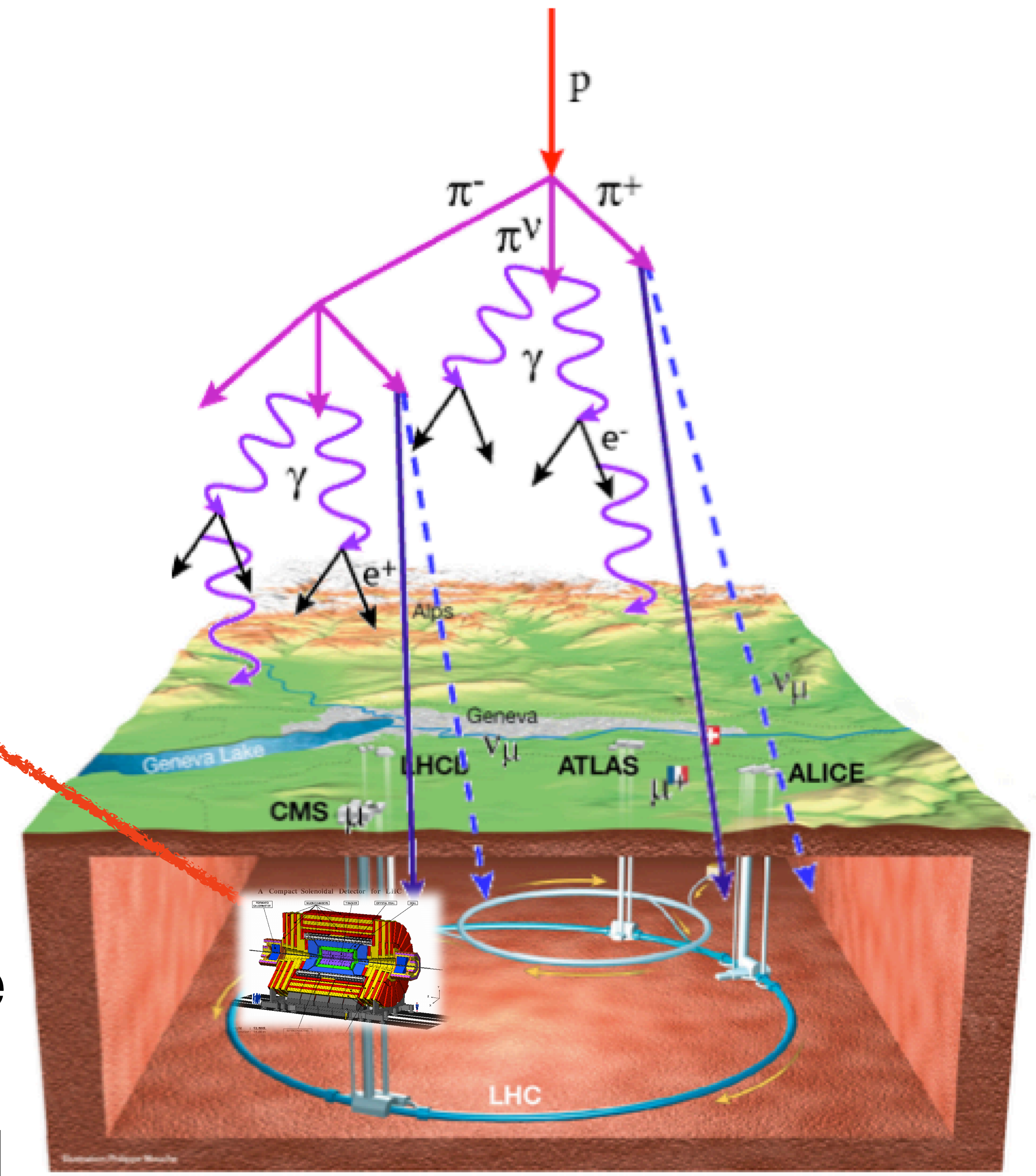


Compact Muon Solenoid

CMS

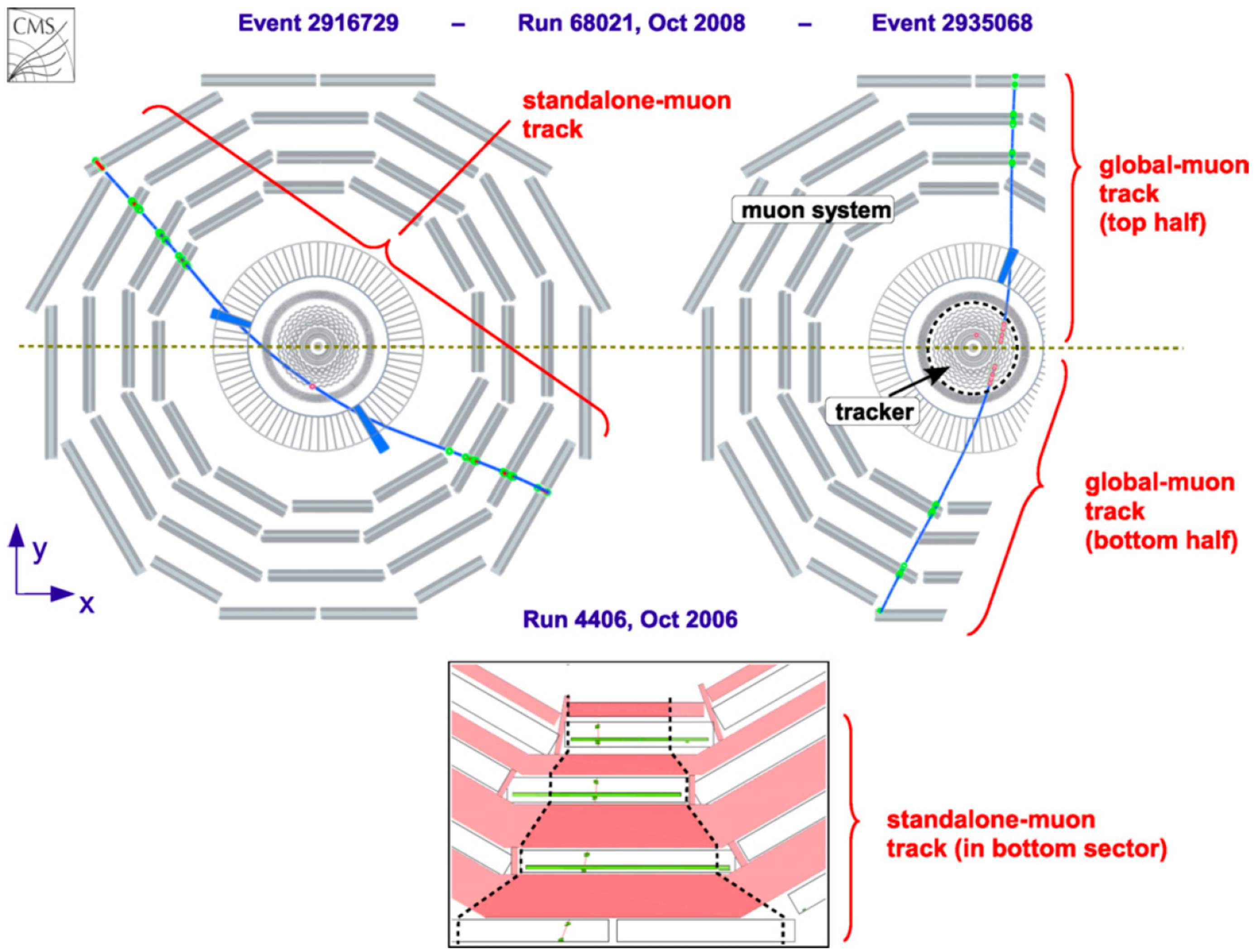
It has a broad physics programme ranging from studying the Standard Model (including the Higgs boson) to searching for extra dimensions and particles that could make up dark matter.

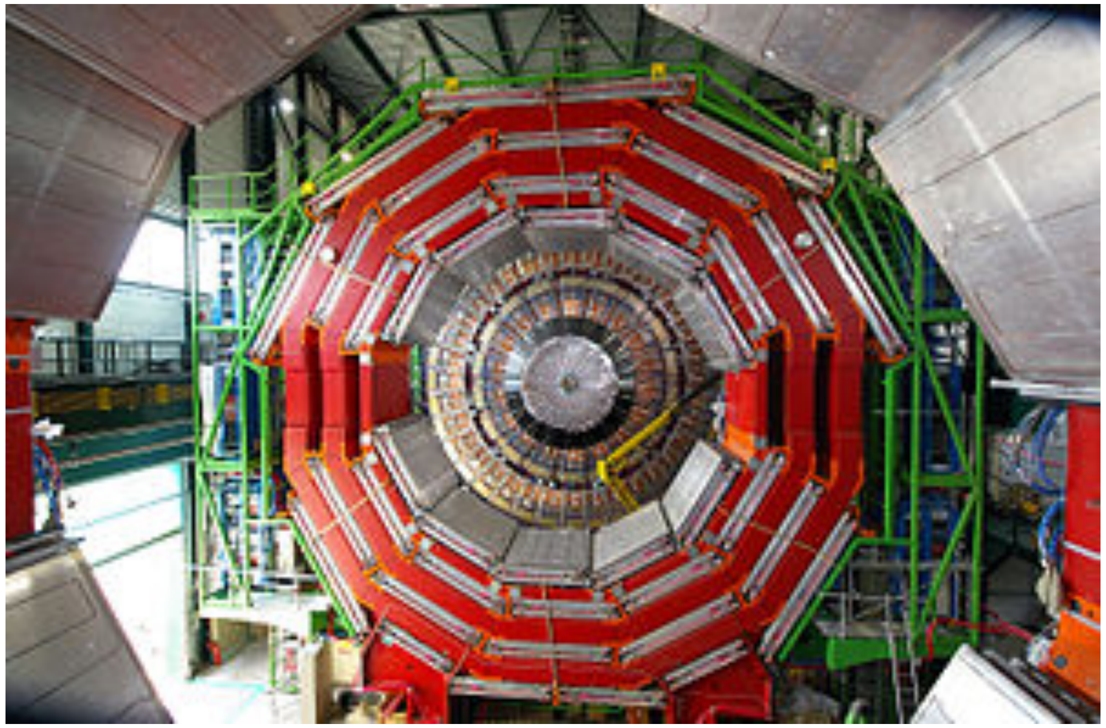




About 25 million cosmic-muon events were recorded during the first phase of the MTCC with the magnet at a number of field values ranging from 3.67 to 4.00 T.

CMS



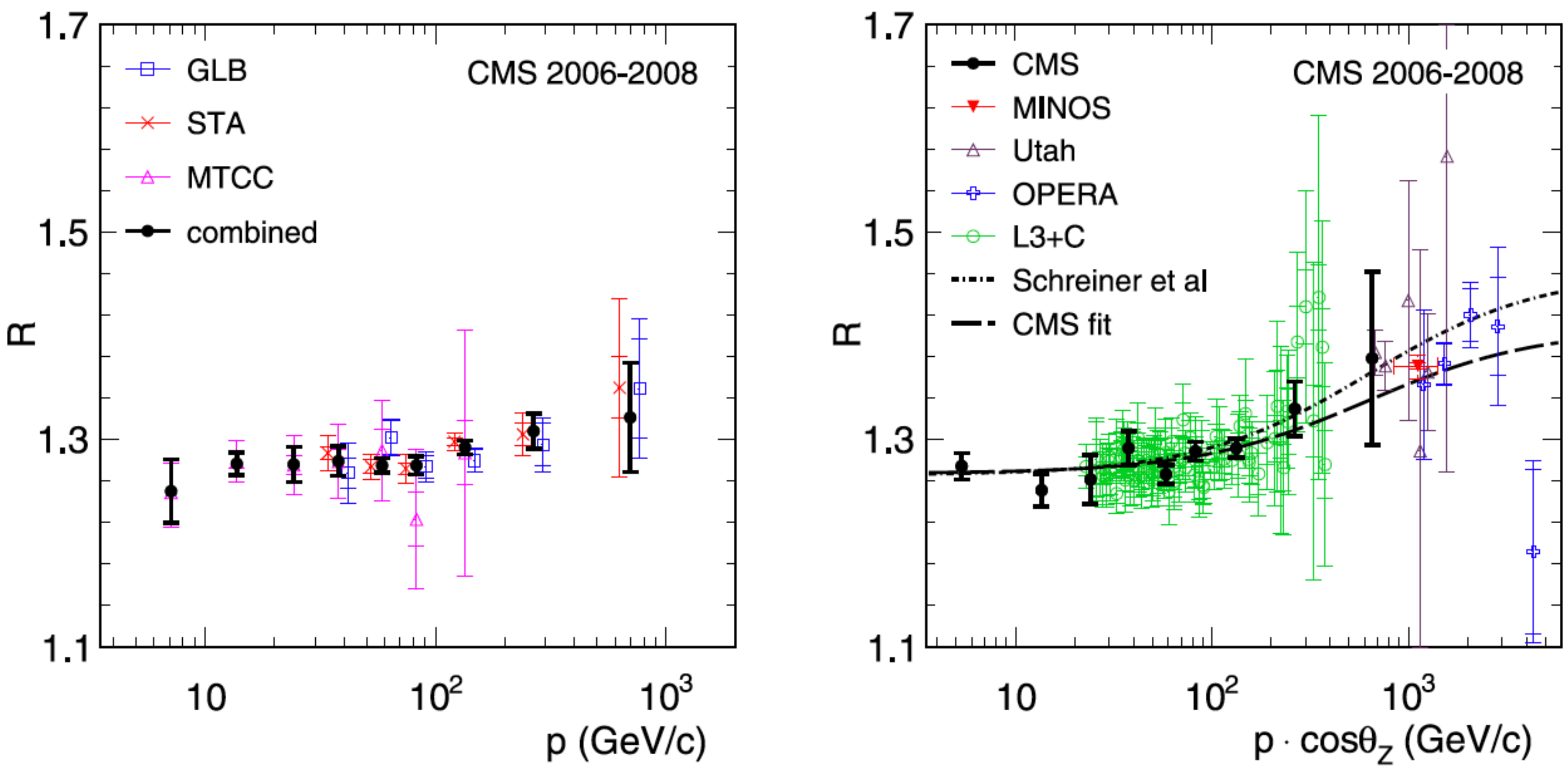


The upper two pictures display muons from 2008 underground data, leaving signals in the muon system, tracking detectors and calorimeters. A standalone track (top left) and a pair of global half-tracks (top right) are shown.

CMS

The muon charge ratio R from the combination of all three CMS analyses, as a function of p and $p\cos\theta_z$, in GeV/c, together with the combined statistical and systematic relative uncertainty, in %.

p range	$\langle p \rangle$	R	Uncertainty	$p\cos\theta_z$ range	$\langle p\cos\theta_z \rangle$	R	Uncertainty
5–10	7.0	1.250	2.45	2.5–10	5.3	1.274	0.99
10–20	13.7	1.277	0.85	10–20	13.6	1.251	1.26
20–30	24.2	1.276	1.34	20–30	24.1	1.262	1.88
30–50	37.8	1.279	1.10	30–50	37.7	1.292	1.27
50–70	58.5	1.275	0.54	50–70	58.4	1.267	0.71
70–100	82.5	1.275	0.68	70–100	82.4	1.289	0.70
100–200	134.0	1.292	0.52	100–200	133.1	1.292	0.72
200–400	265.8	1.308	1.29	200–400	264.0	1.330	1.99
> 400	698.0	1.321	3.98	> 400	654.0	1.378	6.04

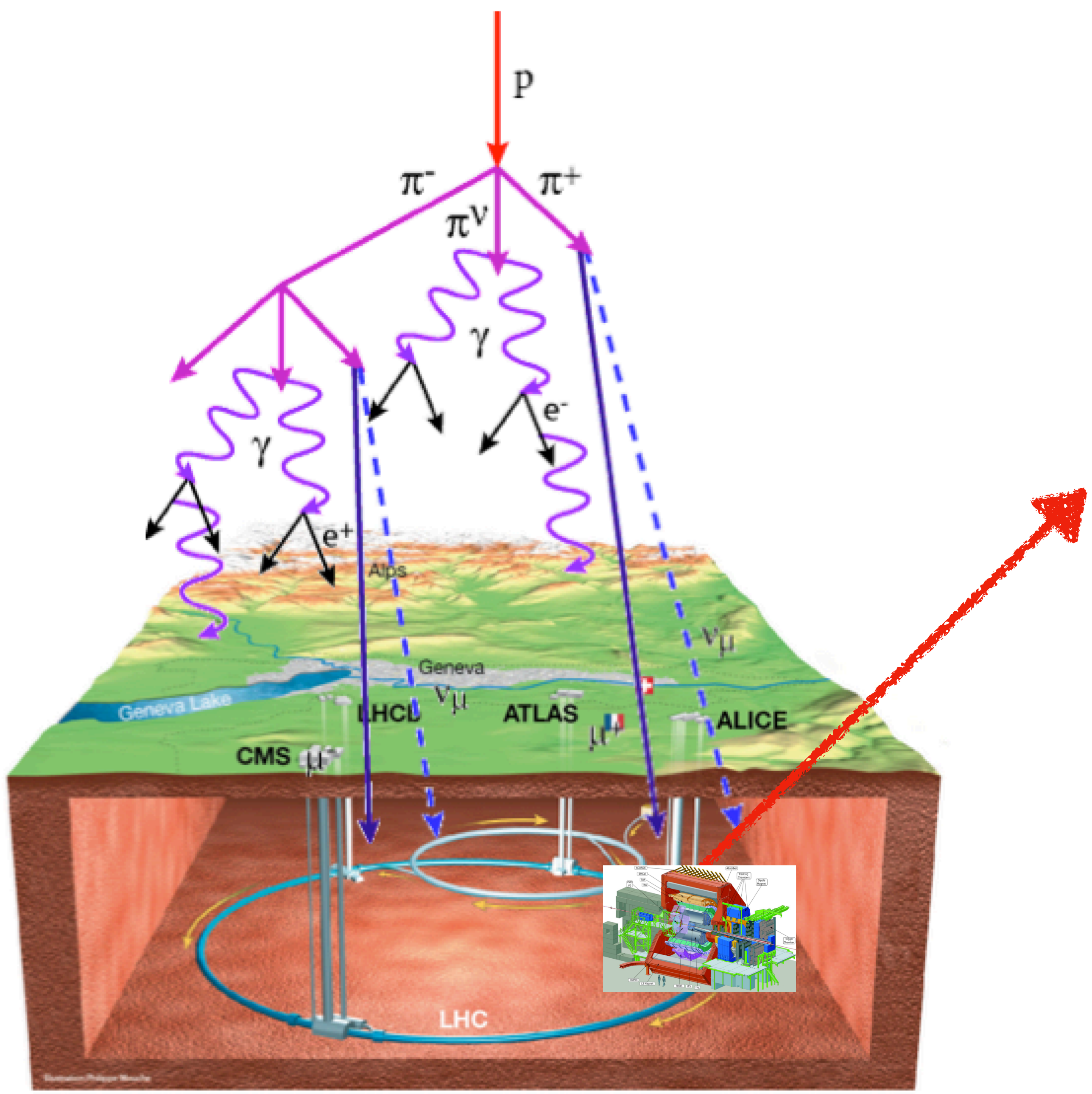


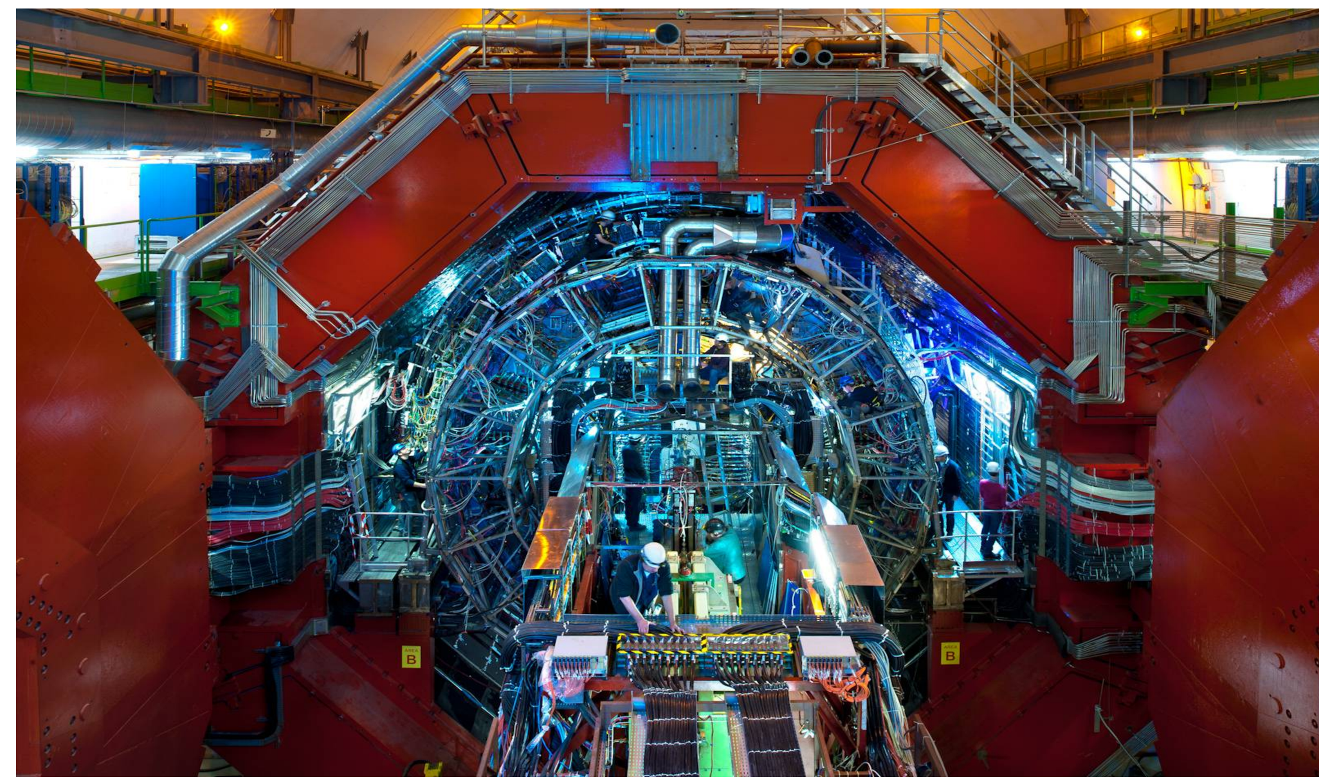
DOI: 10.1016/j.physletb.2010.07.033

A Large Ion Collider Experiment

ALICE

ALICE is designed to study the strongly interacting matter created in ultrarelativistic heavy-ion collisions at the CERN Large Hadron Collider (LHC)



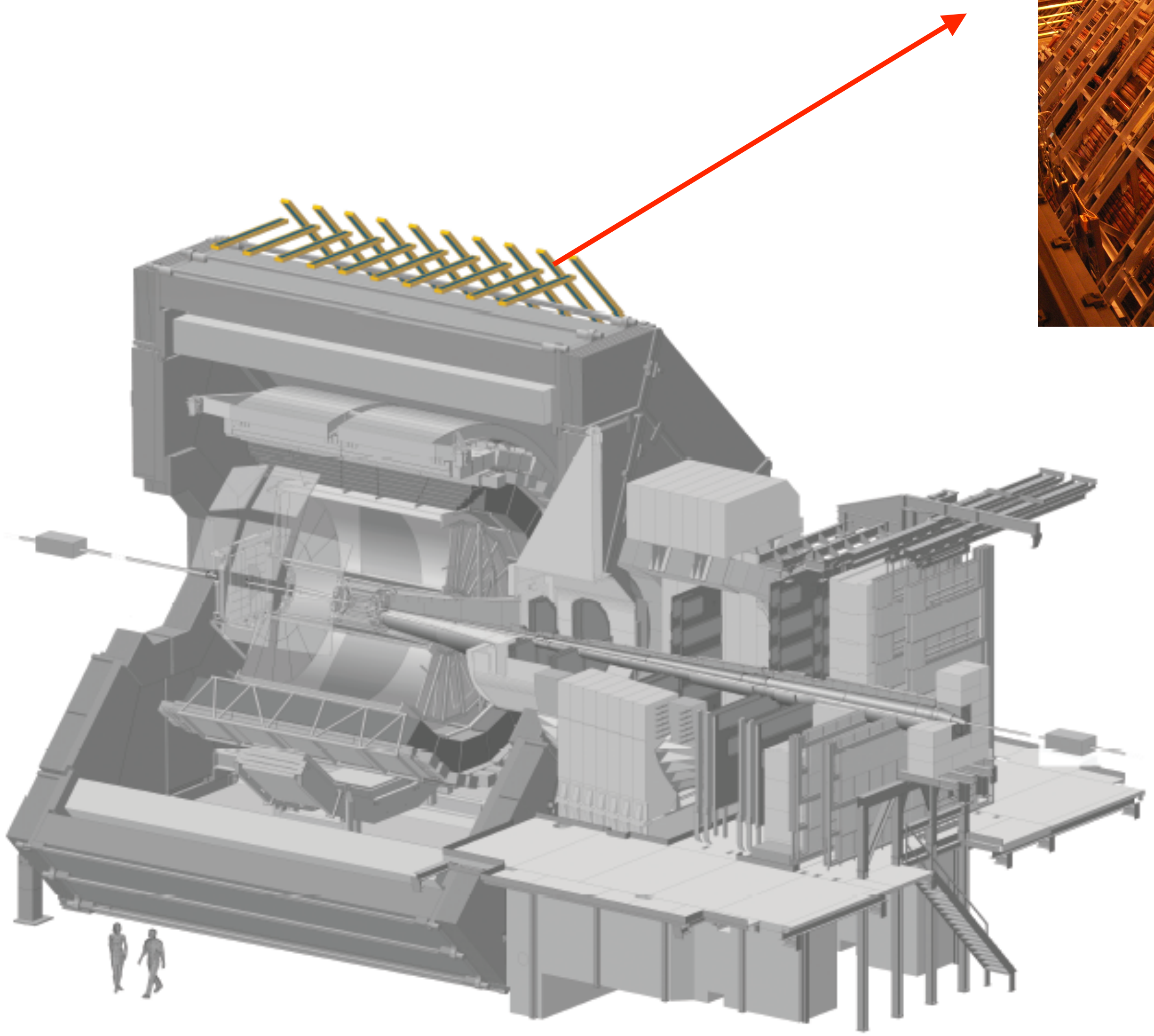


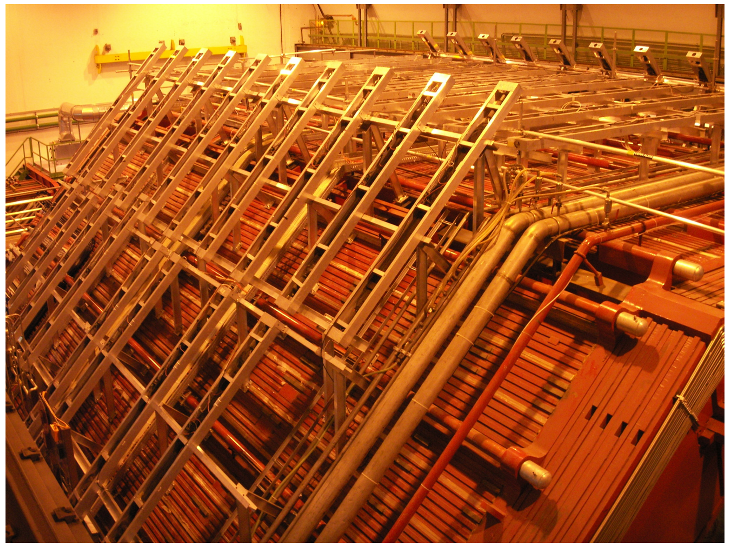
- The muons of the EAS crossing the rock and arriving in ALICE can be detected and analyzed.
- Muon threshold energy ~ 16 GeV

ALICE

Cosmic triggers: ACORDE

- **ACORDE** (ALICE Cosmic Ray Detector): It detects cosmic-ray showers by triggering the arrival of muons to the top of the ALICE magnet.





The **A**lice **CO**smic **R**ay **DE**tector is used to trigger on **atmospheric muons**.

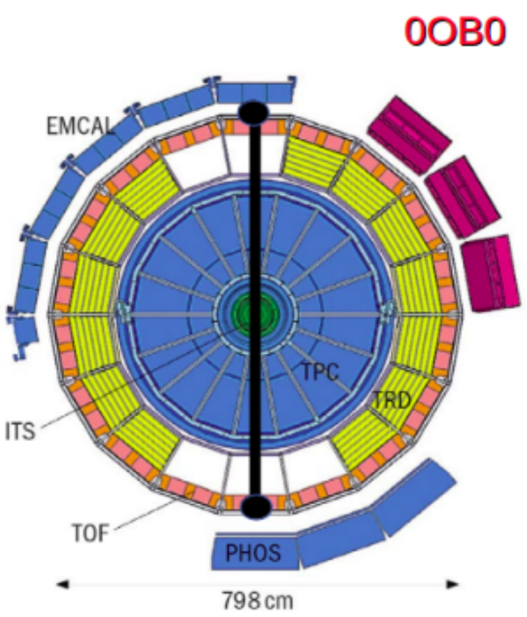
It consists of an array of 60 scintillator modules located on the three top octants of the magnet. Atmospheric muons are also used for calibration & alignment of central barrel detectors.

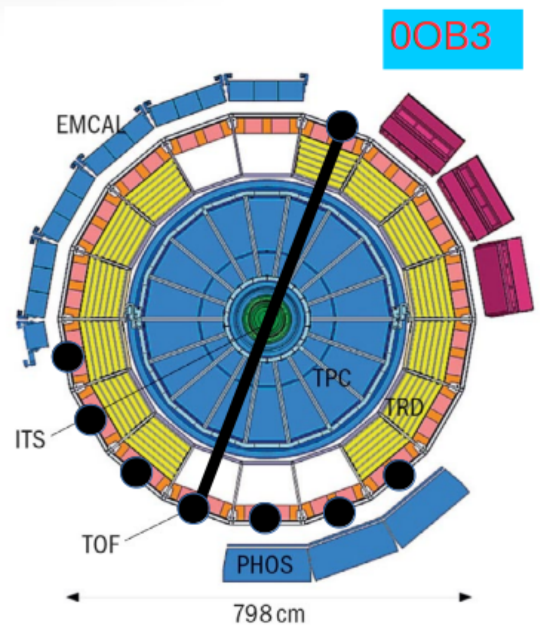
ALICE

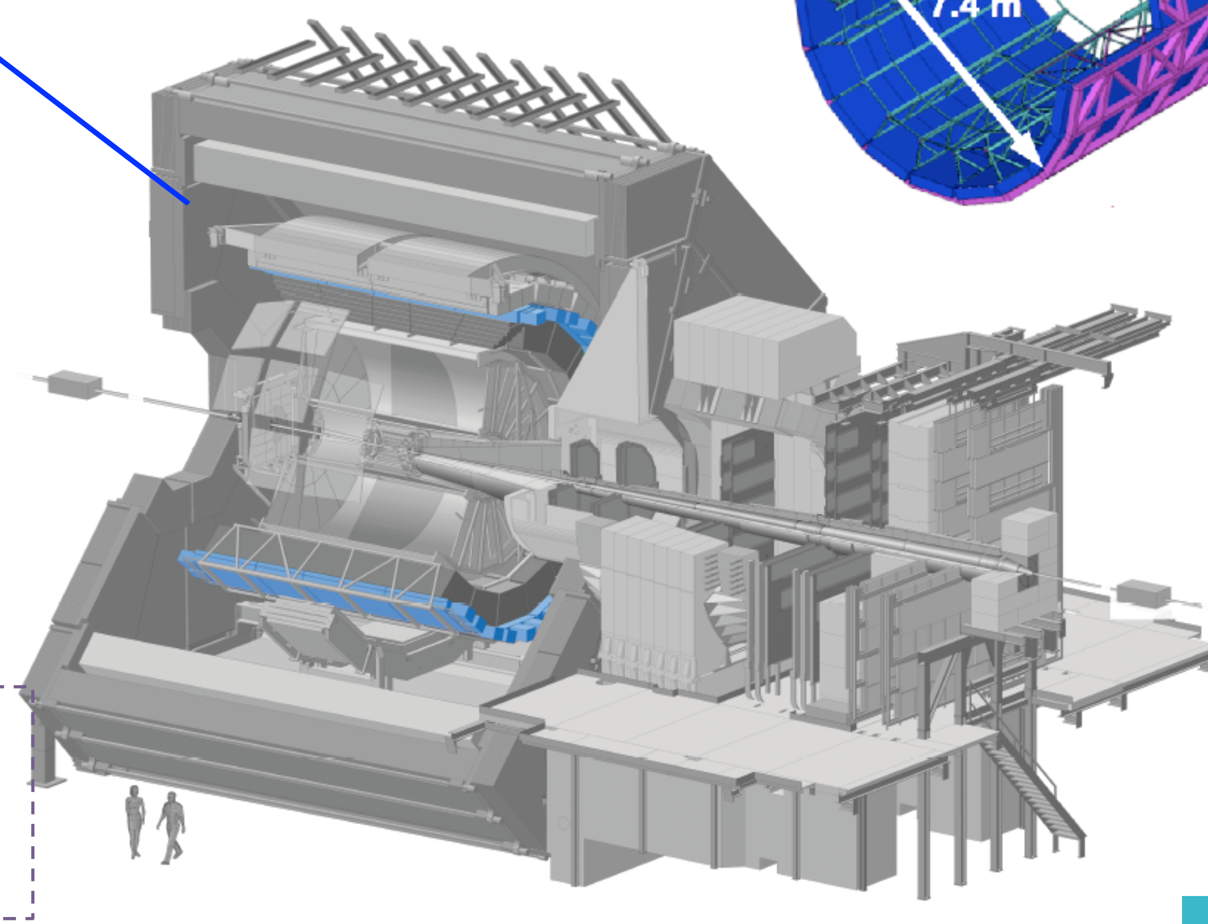
Trigger configuration for cosmic-ray detection:

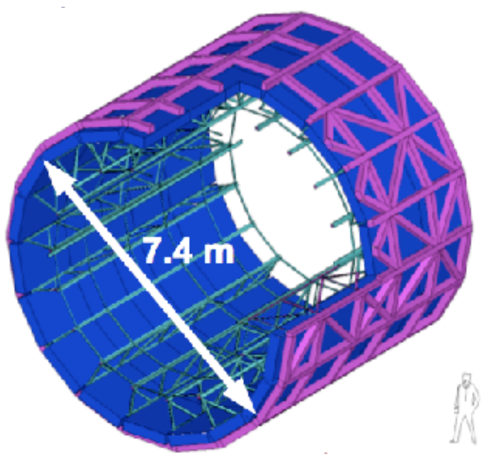
- **TOF**: Time Of Flight .

Is dedicated to charged particle identification over a very large part of the phase space.







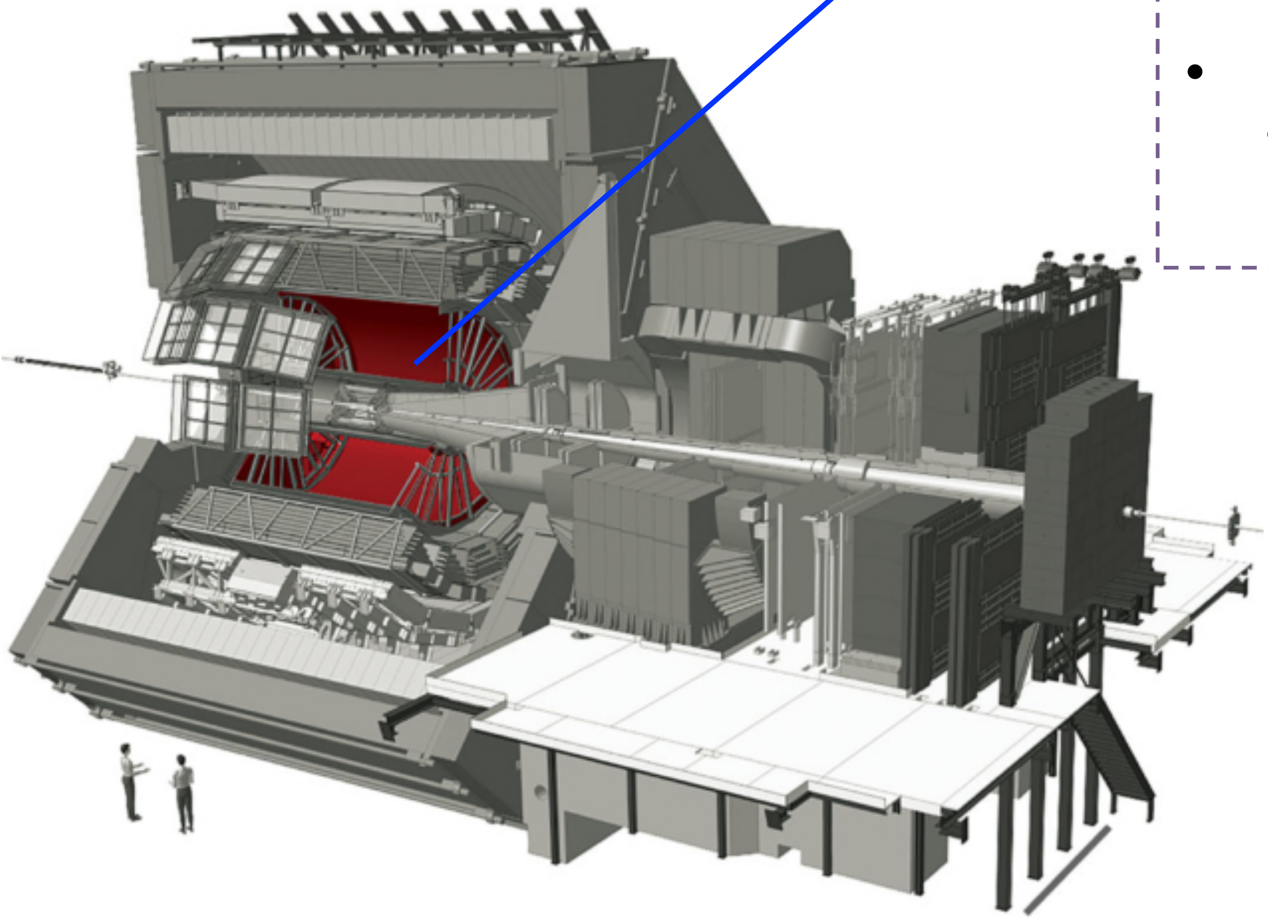


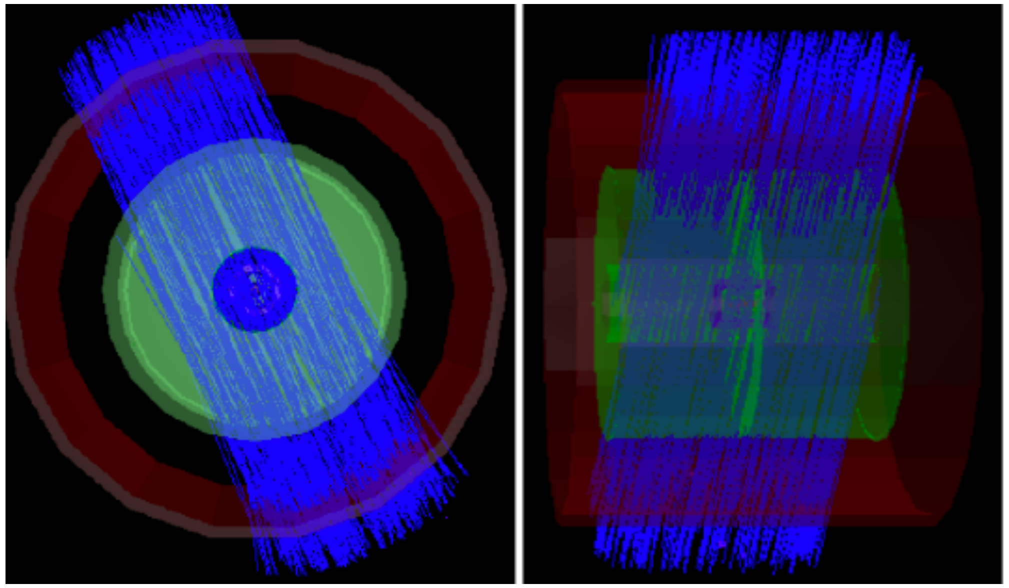
- TOF has an effective area of detection of 160 m^2.
- Full φ and $45^0 \leq \theta \leq 135^0$ coverage.

ALICE

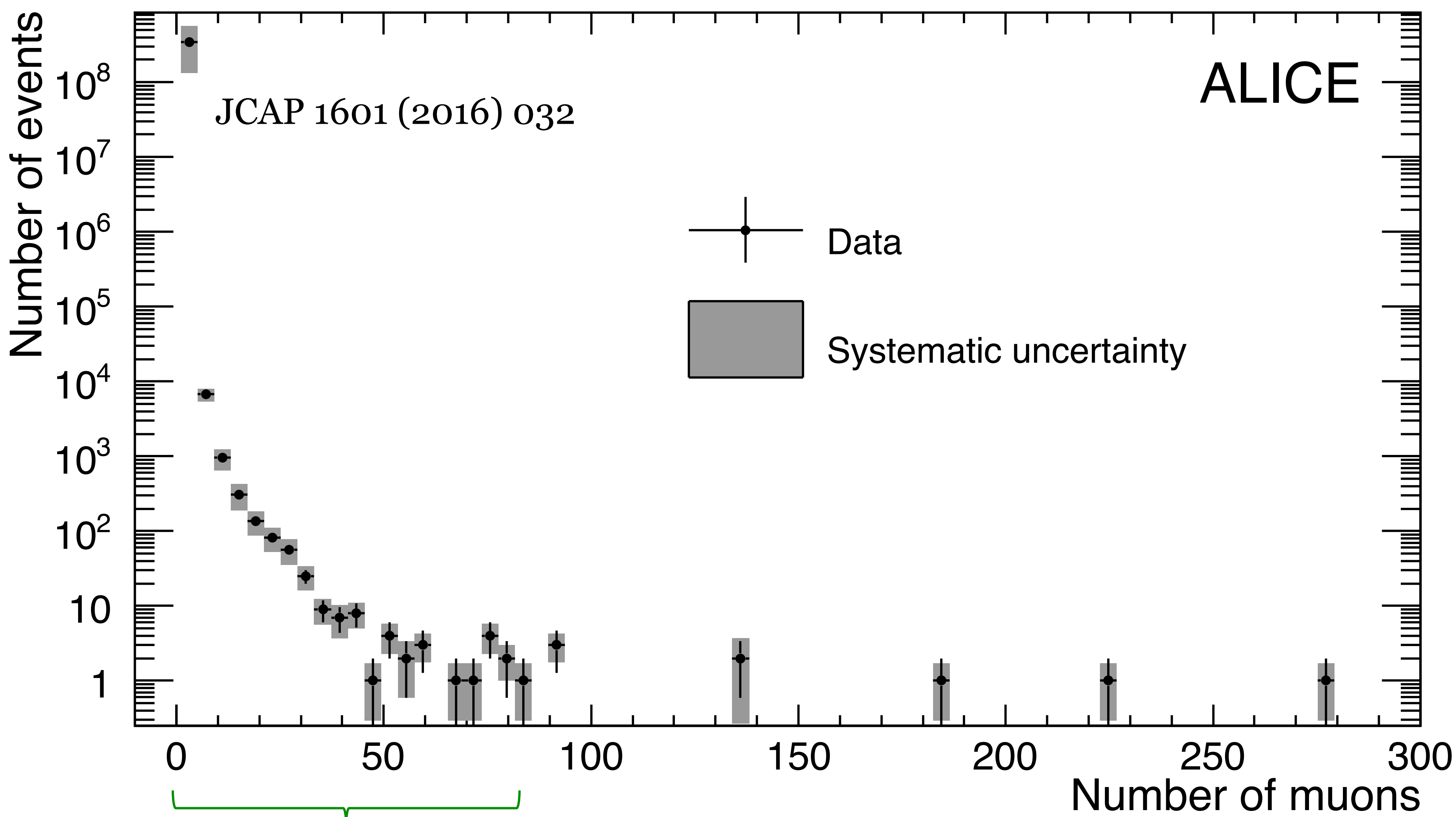
- **TPC**: Time Projection Chamber. Is the main tracking detector of the central barrel

- The atmospheric muons that cross the experiment are reconstructed by the TPC.
- In most cases, the TPC reconstructs two tracks per muon that crosses the central barrel detectors of ALICE.





ALICE results on Cosmic-ray physics



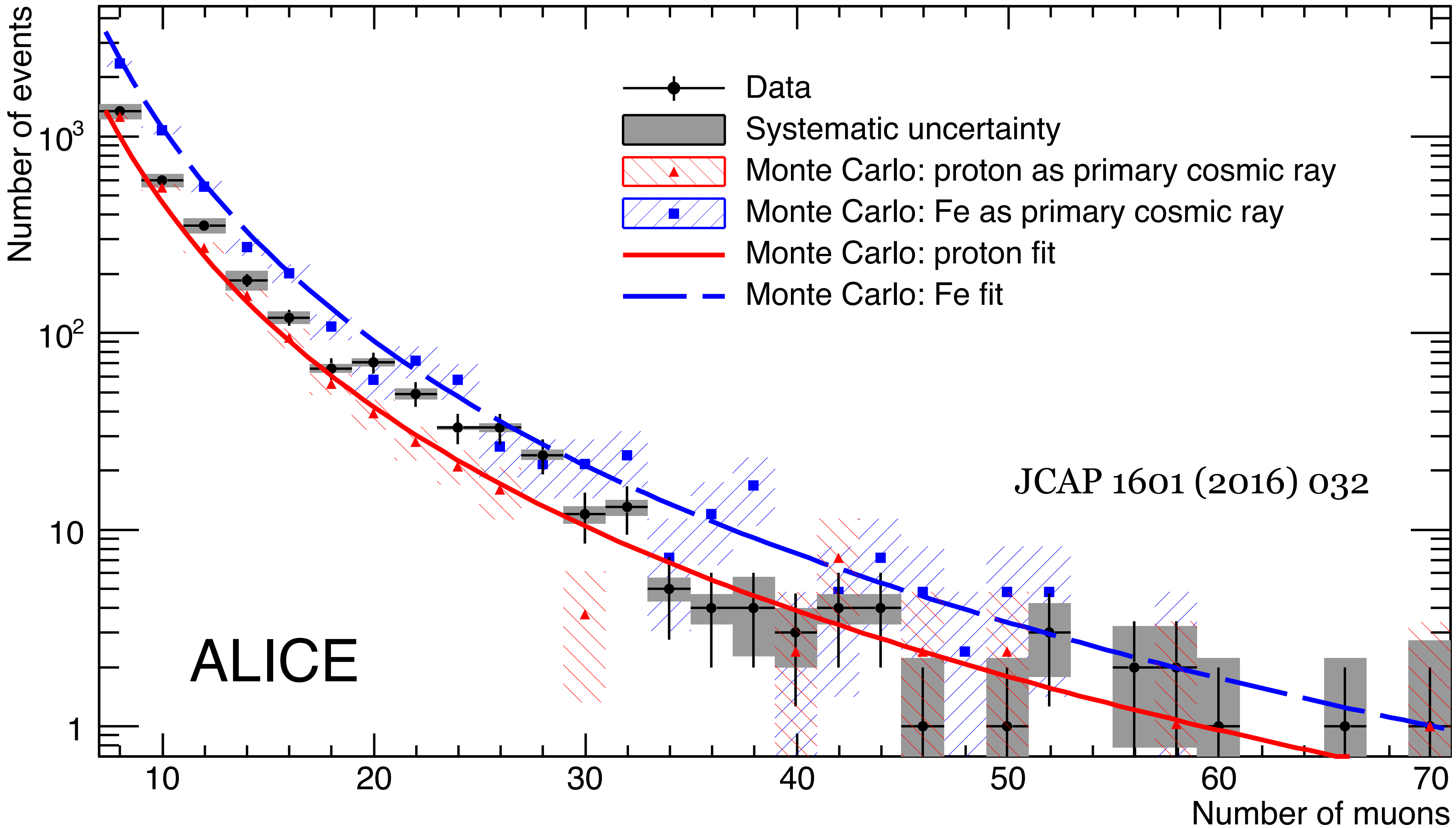
Smooth distribution up to $N_{\mu} \approx 70$

Found 5 events with more than 100 reconstructed muons

MMD based on the whole data sample and corrected by trigger efficiency

ALICE results on Cosmic-ray physics

The MMD suggests that the average mass of primary cosmic rays increases with the increasing energy



Muon Multiplicity Distribution
$7 \leq N_\mu \leq 70$

ALICE results on Cosmic-ray physics

HMM events	CORSIKA 6.990 QGSJET II-03 proton	iron	CORSIKA 7.350 QGSJET II-04 proton	iron	Data
Period [days per event]	15.5	8.6	11.6	6.0	6.2
Rate [x 10^{-6} Hz]	0.8	1.3	1.0	1.9	1.9
Uncertainty (%) (syst + stat)	25	25	22	28	49

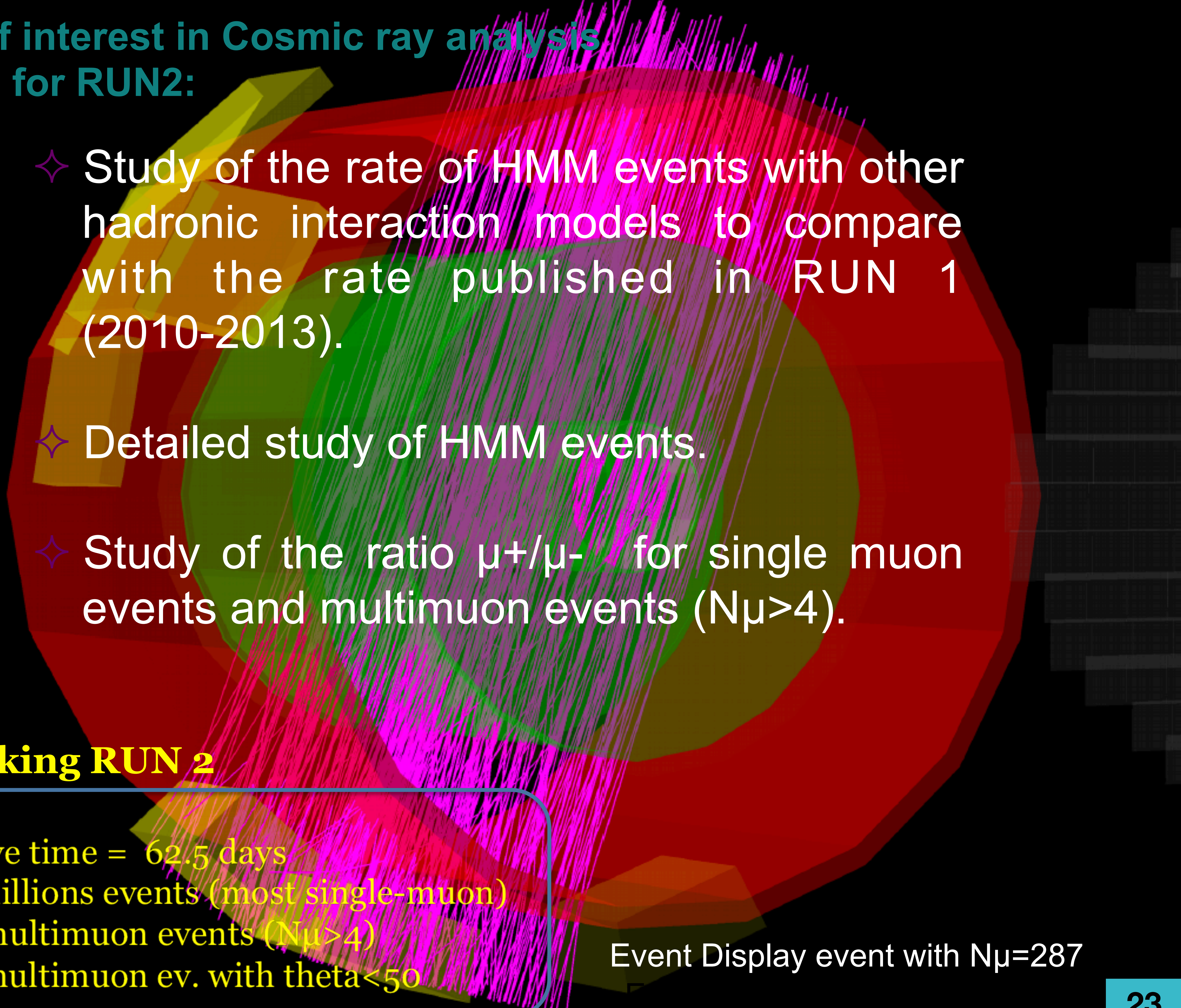
- Independently of the model version, the rate of the HMM events with proton composition have difficulties reproducing the measurement while with iron the rate is close to the data.

Topics of interest in Cosmic ray analysis in ALICE for RUN2:

- Study of the rate of HMM events with other hadronic interaction models to compare with the rate published in RUN 1 (2010-2013).
- Detailed study of HMM events.
- Study of the ratio μ+/μ- for single muon events and multimuon events (Nμ>4).

Data taking RUN 2

Total live time = 62.5 days
> 165 millions events (most single-muon)
15702 multimuon events (Nμ>4)
13570 multimuon ev. with theta<50



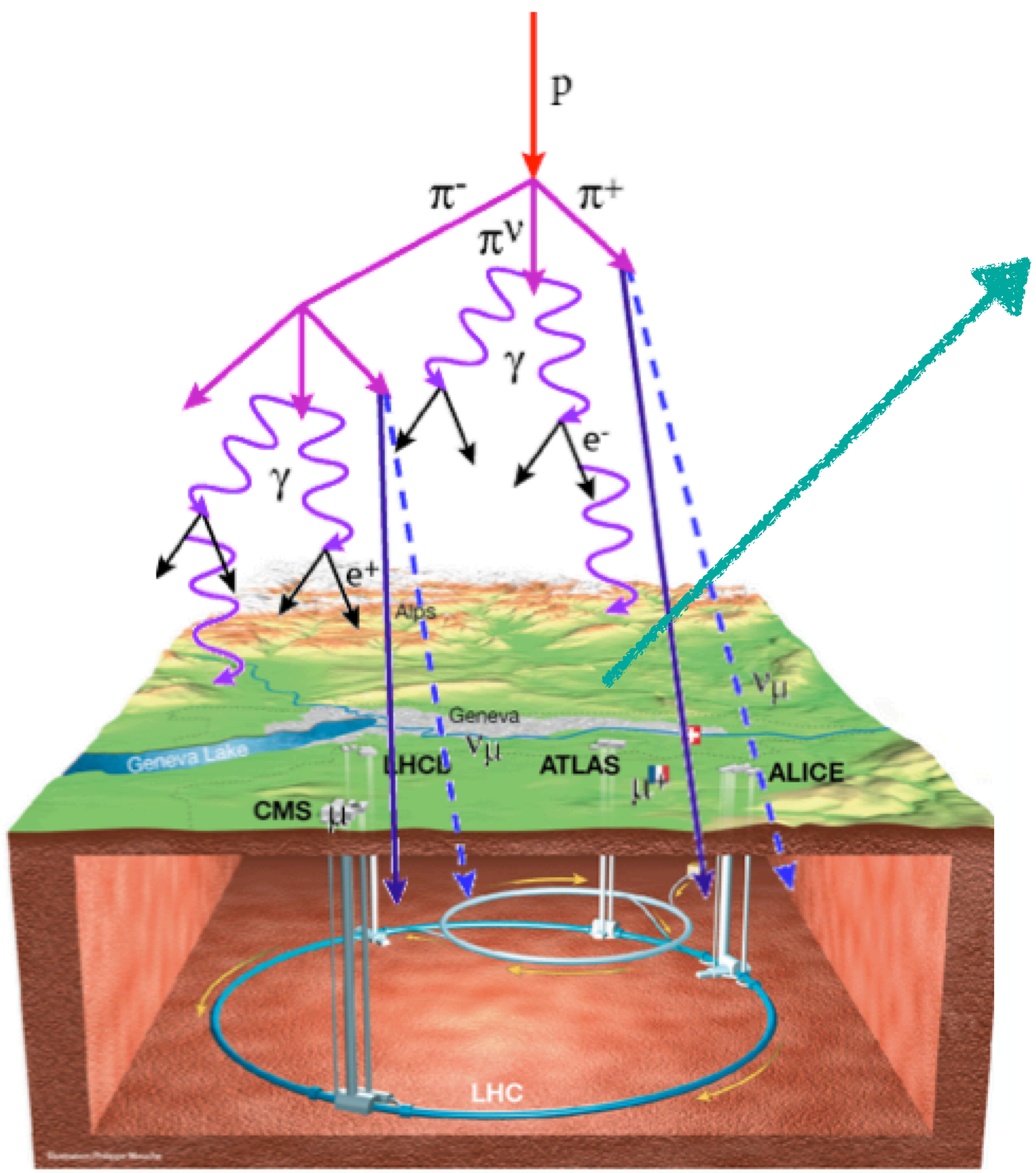
Event Display event with Nμ=287

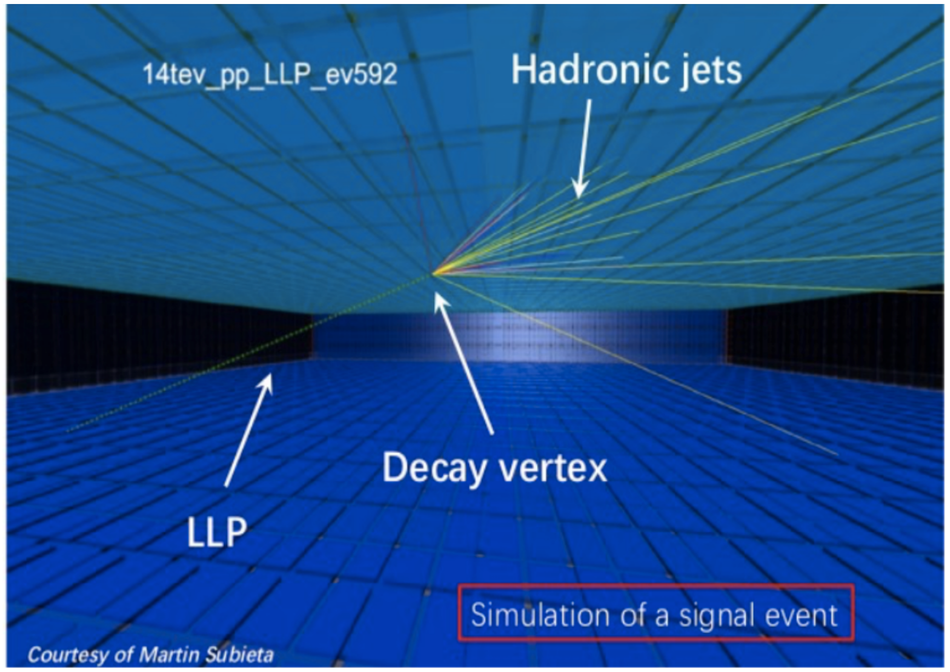
MATHUSLA

MATHUSLA

MATHUSLA detector

(**MA**ssive **T**iming **H**odoscope for **U**ltra **S**table neutral p**A**rticles)





C. Zhang, Pekin University, 2017

1. Purpose:
- Search for ULLPs.
- To complement searches of LLPs at CERN.

2. Description:
- Large volume tracking detector on surface above LHC experiment.

3. Instrumentation:
- RPC tracking layers in building covered by scintillator layers

FINAL COMMENTS

Results from **LEP** and **LHC** have revealed interesting properties of atmospheric muons. This type of studies are useful to test to the interaction hadronic models post-LHC. They have attract the attention from theoretical colleagues to propose alternative interpretations of LEP/LHC data.

New ideas are brewing inside the LHC experiments. Besides ALICE, people from CMS and ATLAS are interested in developing cosmic-ray physics studies:

- Muon multiplicity, study of muon bundles, testing of hadronic interaction models (important input from LHC results to cosmic-ray interaction models).

FINAL COMMENTS

- Charge ratio for single and multi-muon events

- study of horizontal events (not discussed here, but LHC experiments are willing to have a deep look on this data.)

Mathusla project aims to be a project involving ATLAS and CMS experiments searching for LLP particles.


Thank you!