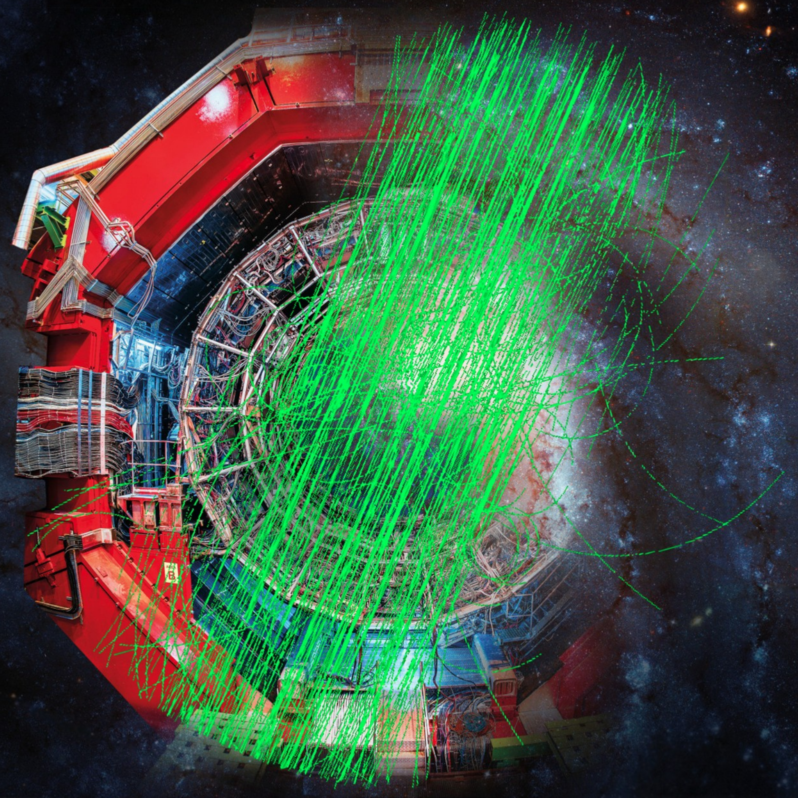
Multimuon events from cosmic rays with the ALICE detector



Mario Sitta
for the ALICE Collaboration
Università del Piemonte Orientale & INFN Torino
Alessandria
Italy

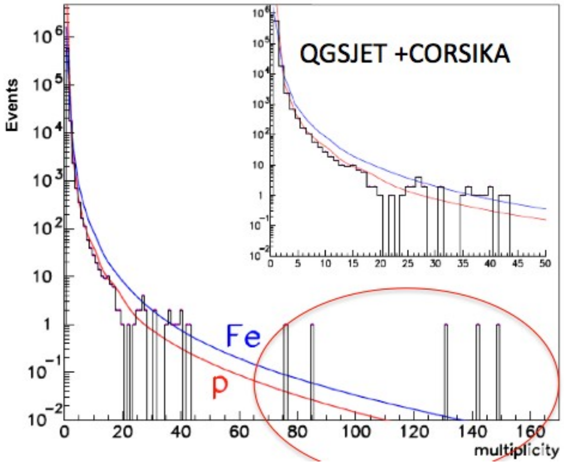
Outline

- Motivations
- Detecting atmospheric muons with the ALICE experiment
- The Muon Multiplicity Distribution (MMD)
- The High Muon Multiplicity (HMM) events
- Monte Carlo and data comparison
- Conclusions

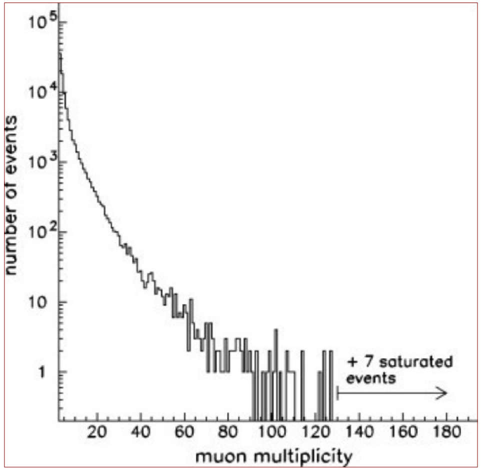
Motivations

- Use of collider detectors for cosmic-ray studies was pioneered by LEP experiments ALEPH, DELPHI and L3
- All LEP results were consistent with standard hadronic interaction models except for the observation of high multiplicity muon bundles
  - even under the assumption of highest measured flux and pure iron spectrum

ALEPH: ~320 mwe, ~70 GeV threshold
DELPHI: ~286 mwe, ~52 GeV threshold

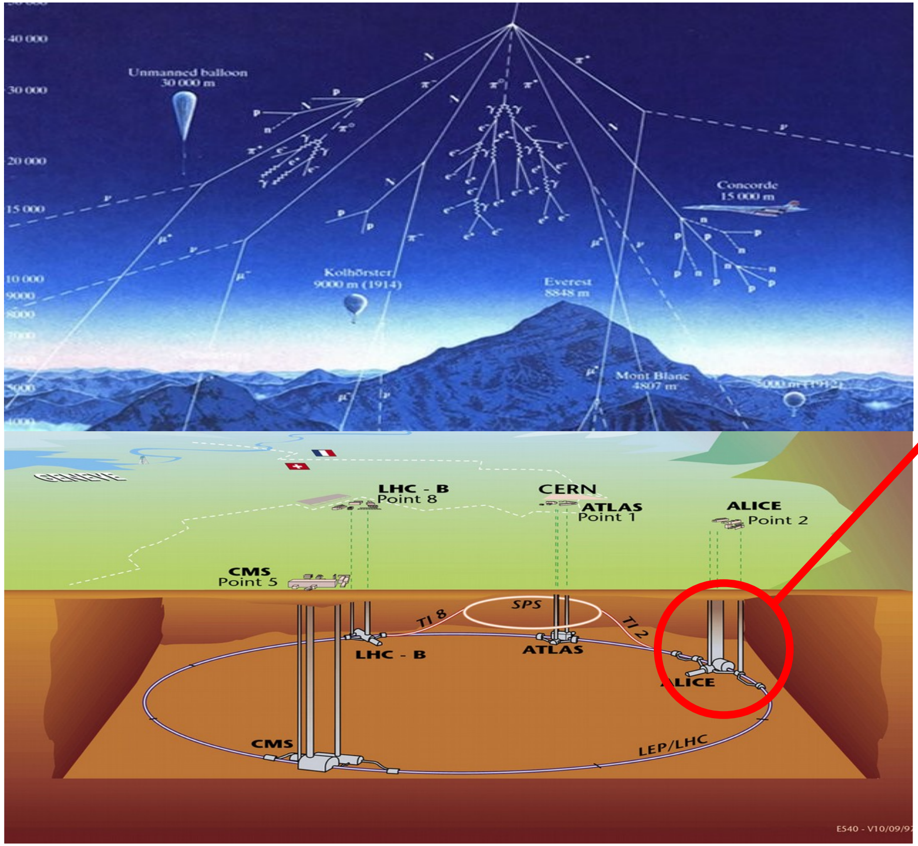


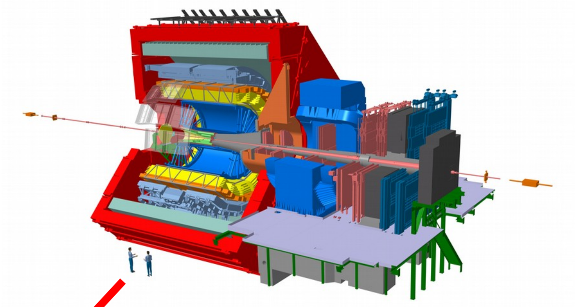
ALEPH Coll., *Astrop. Phys.* **19** (2003) 513



DELPHI Coll., *Astrop. Phys.* **28** (2007) 273

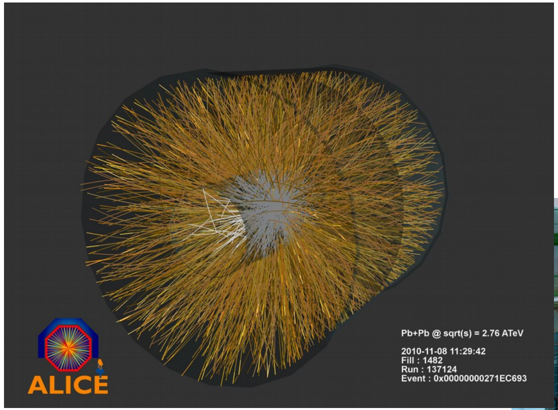
Detection of cosmic muons at LHC



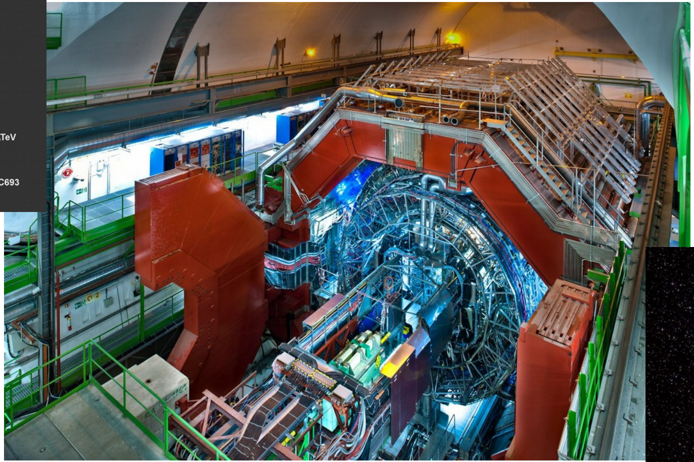


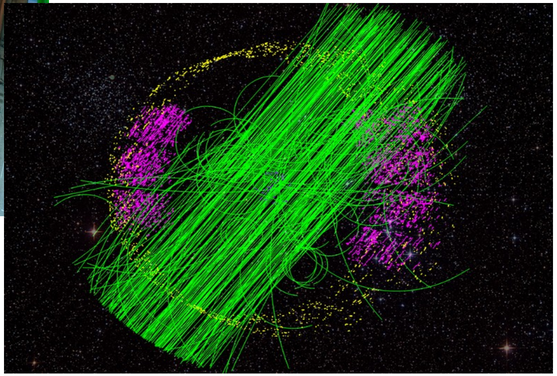
- ALICE is located at LHC Point2 52 m underground (28 m rock above, ~80 mwe)
- Muon energy threshold ~16 GeV

The ALICE Experiment



ALICE is mainly devoted to the study of strongly interacting matter in *pp*, *p*A and AA collisions at ultra-relativistic energies



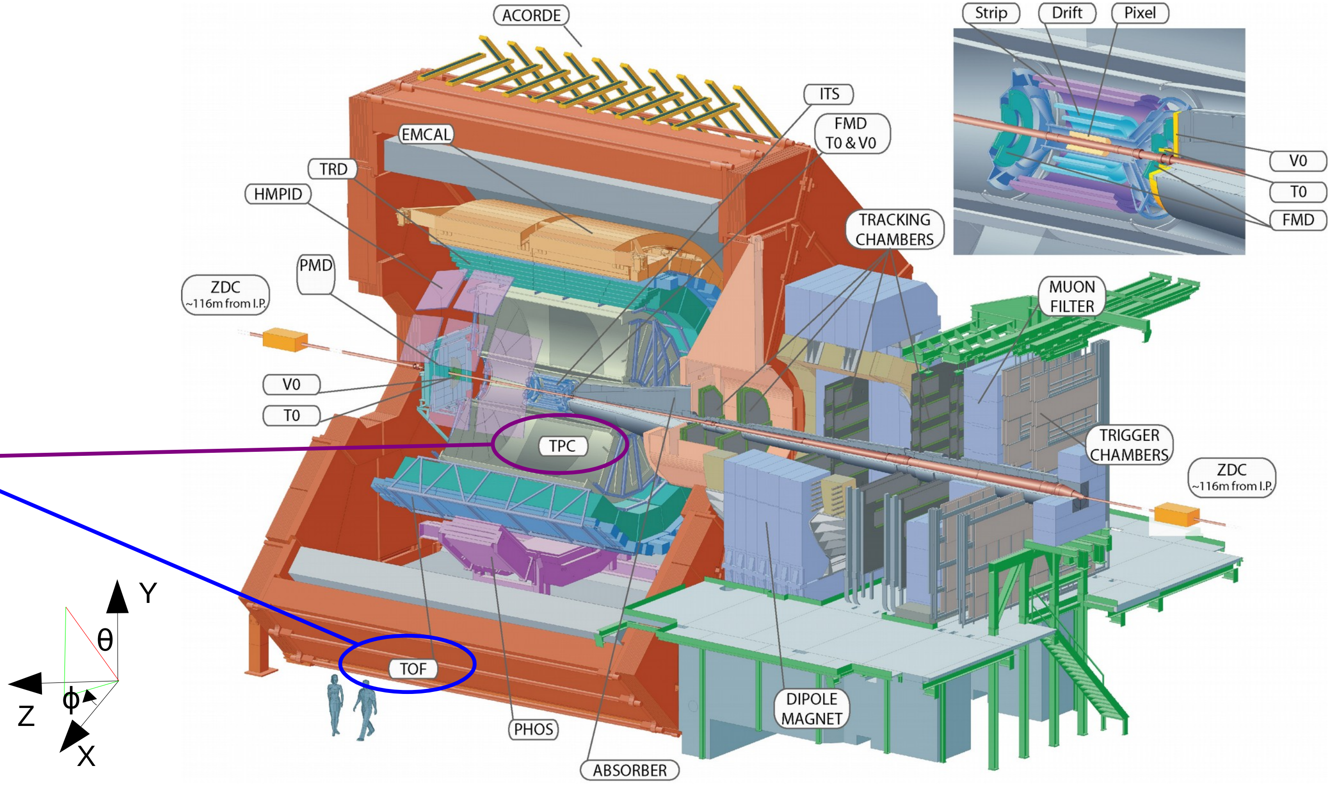


Besides the Heavy-Ion Physics program, during Run1 and Run2 ALICE had a dedicated physics group devoted to cosmic-ray studies

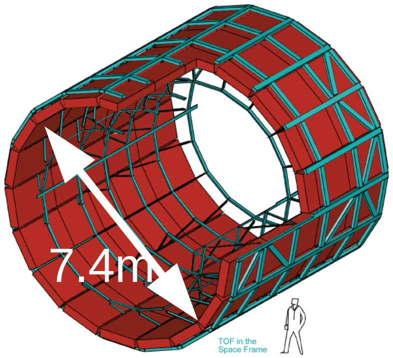
The ALICE detectors

Detectors used for cosmic-ray data taking in the central barrel:

- TOF
  - for trigger
- TPC
  - for tracking



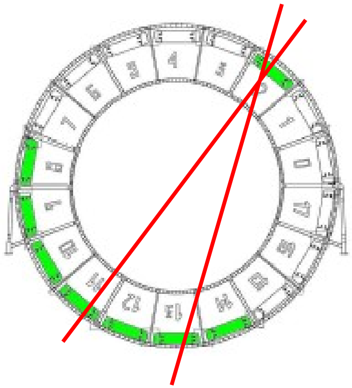
Time-Of-Flight (TOF)



TOF

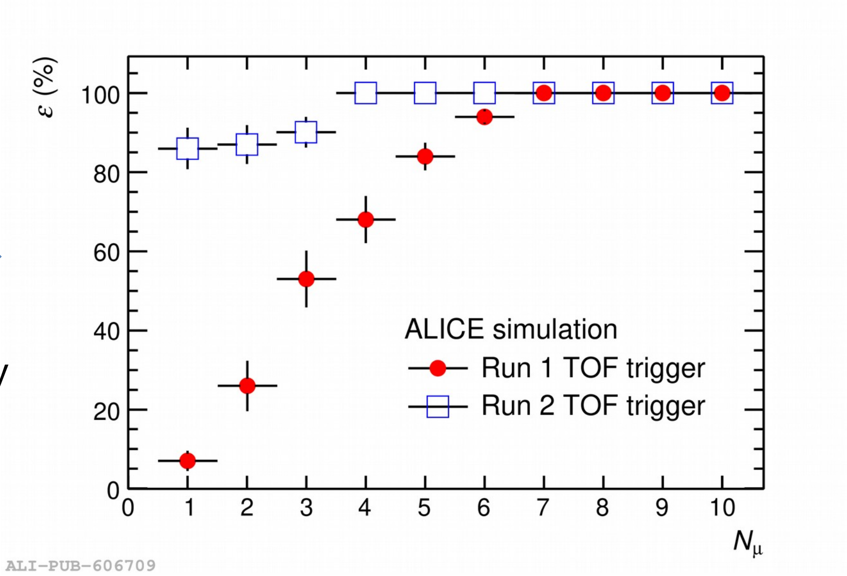
Array of 1638 MRPC pads (18 φ sectors with 5 modules each) around TPC

Full φ coverage, 45° < θ < 135°, time resolution 100ps



Back to back ± 3 pads

Trigger efficiency



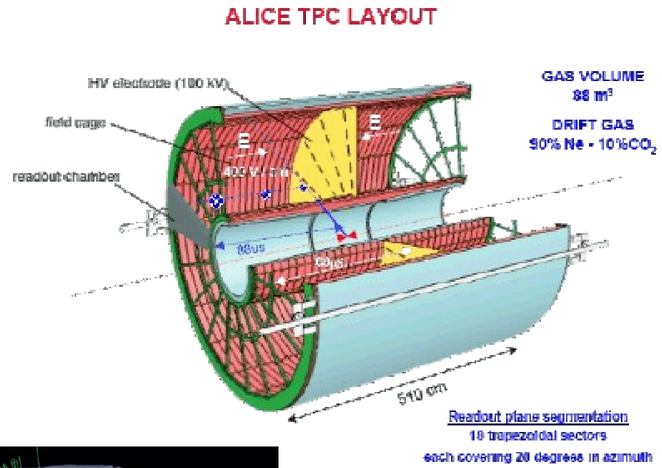
Time Projection Chamber (TPC)

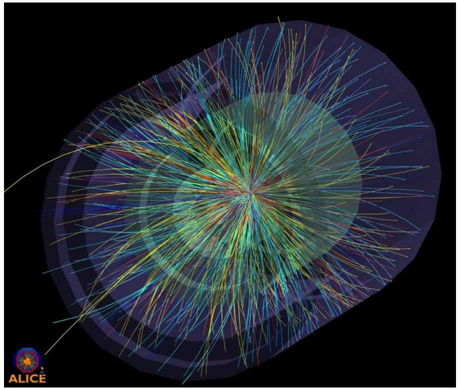
TPC

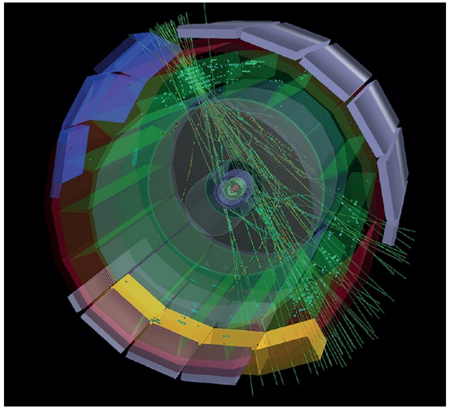
Main tracking device with excellent capabilities for high-track density, 557k readout channels

Momentum resolution ~1% for $p_t < 2$ GeV/c ~20% for $p_t = 100$ GeV/c in HI collisions

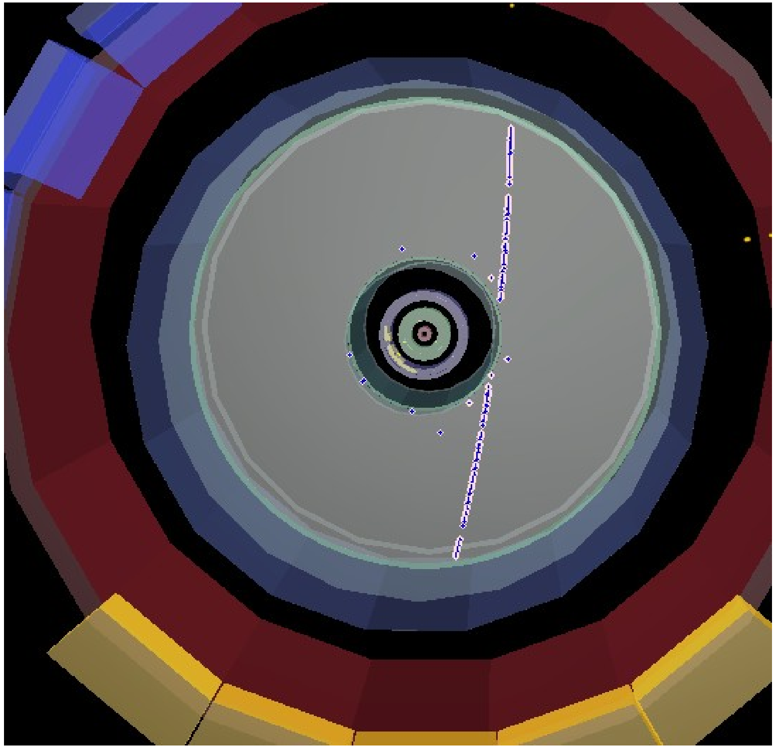
dE/dx resolution < 10%







Atmospheric muon reconstruction



- The TPC reconstructs a single muon as two tracks (up and down)
- A specific algorithm was worked out to match the two tracks as a single one
- Monte Carlo events and data of high multiplicity have been used to optimize the parameters of the matching algorithm

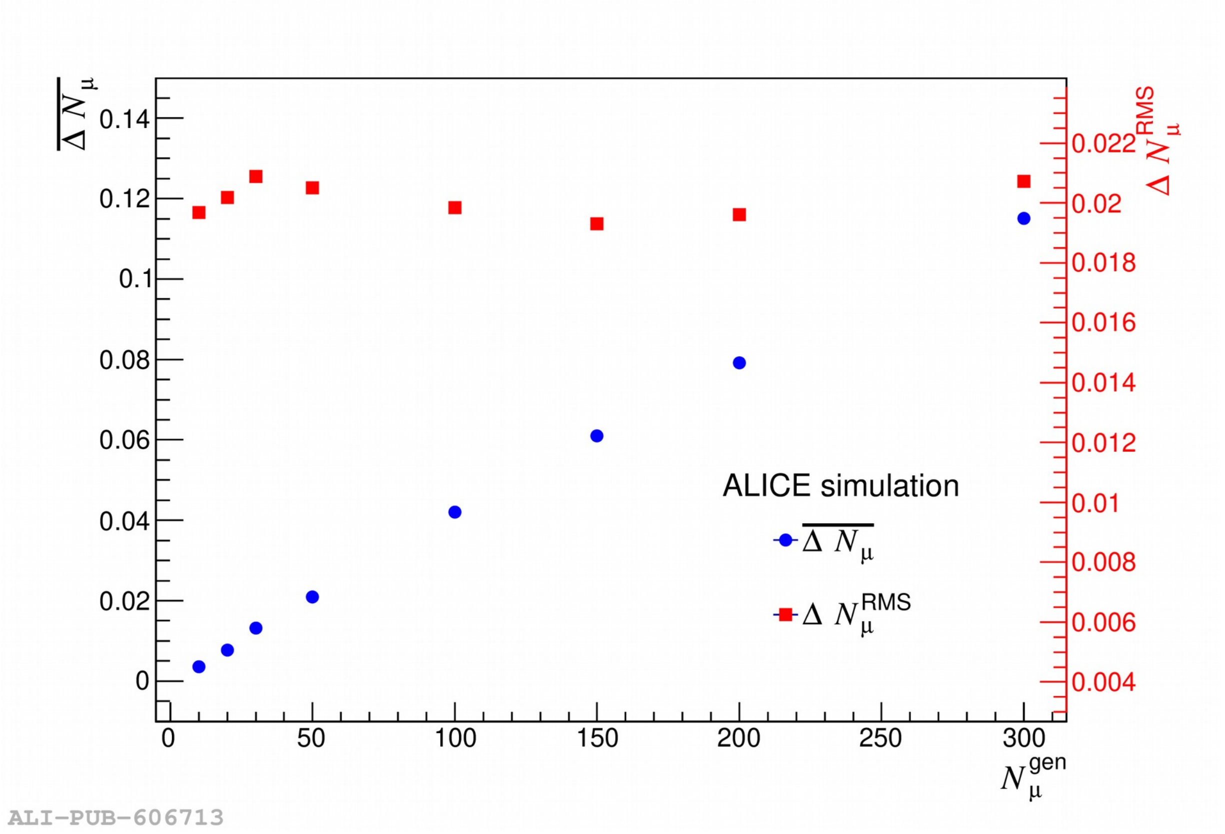
Analysis cuts

- To accept a track
  - ≥ 50 space points in the TPC (out of a maximum of 159)
  - $p > 0.5$ GeV/c
  - if multi-muon, parallelism cut $cos(\Delta\Psi) > 0.990$
- To match an up track with a down track
  - $d_{xz} < 6$ cm in the mid horizontal TPC plane
- Matched muon: up and down tracks matched
- Single-track muon: a track satisfying all cuts but distance d_{xz}
- Cut efficiency checked with MC simulation

Efficiency in multiplicity measurement

- Generate 8 samples 1000 events each with N_μ from 10 to 300 (all parallel)
- Reconstruct with same algorithm as real data
- Study mean and RMS of

$$\Delta N_\mu = \frac{N_\mu^{gen} - N_\mu^{rec}}{N_\mu^{gen}}$$

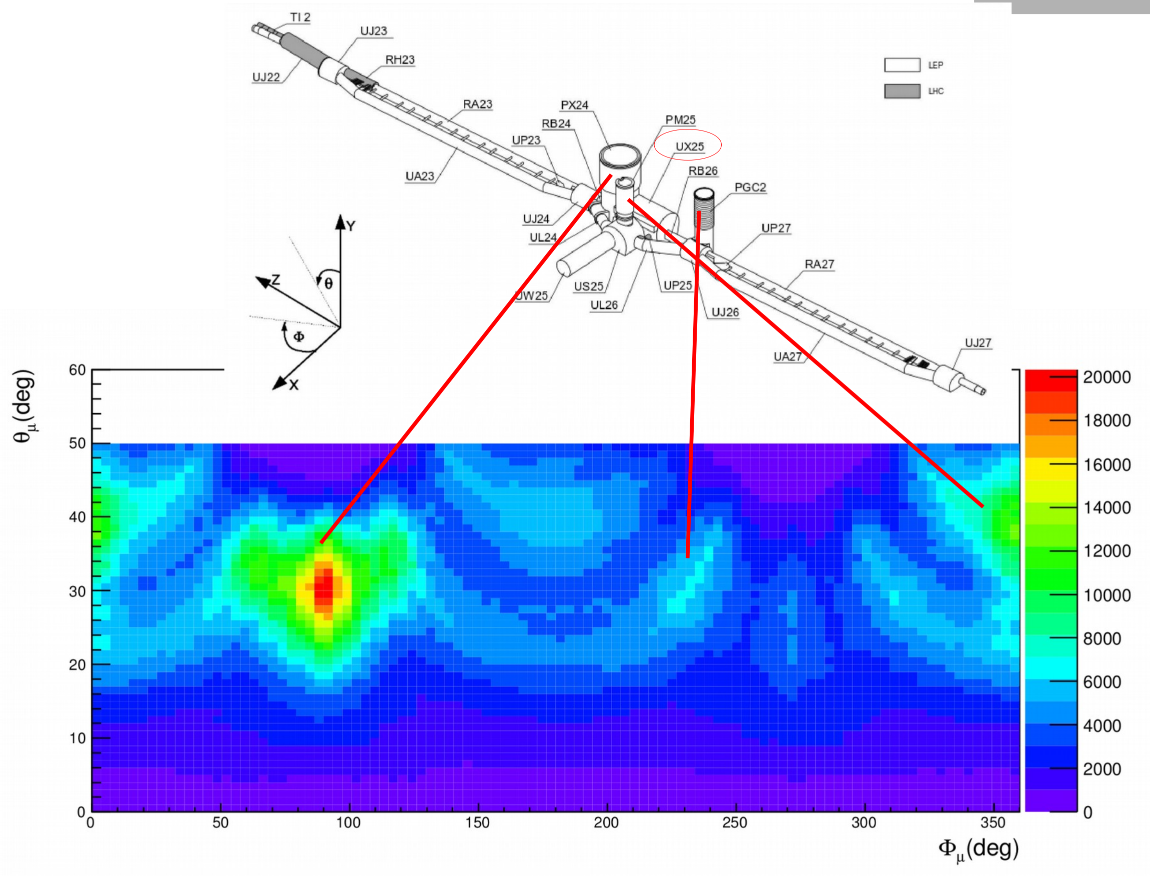


Data sample for cosmic-ray studies

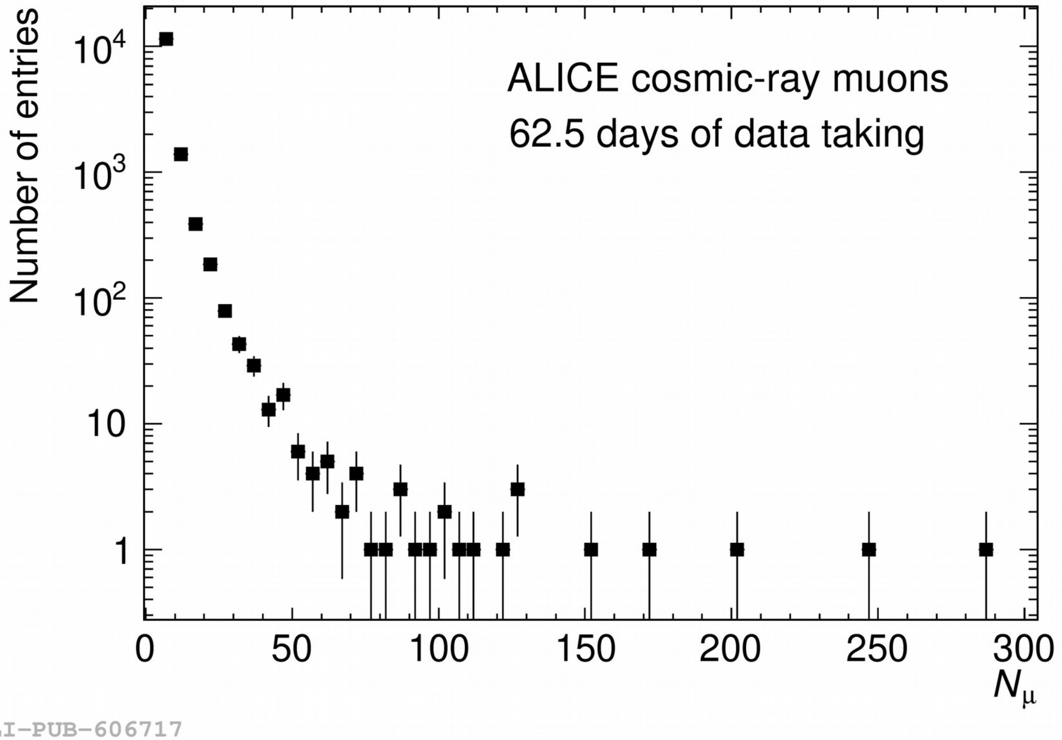
- Data taken during Run2 (2015 – 2018) during no-beam periods
  - with TOF trigger
  - with full magnetic field (0.5 T)
- Integrated live time: 62.5 days
  - > 165 million events with at least 1 reconstructed muon in TPC
  - 15702 multimuon ($N_\mu > 4$) events
  - 13570 multimuon events with zenith angle $\theta < 50°$ kept for further analyses

Single muon angular distribution

Muon tomography of surrounding environment



Muon Multiplicity Distribution (MMD)



- 15702 events with $N_\mu > 4$
  - comparison of muon distribution with MC simulation for $4 < N_\mu < 50$
  - rate measurement and comparison with MC for High Muon Multiplicity Events (HMME) $N_\mu > 100$

Monte Carlo simulation

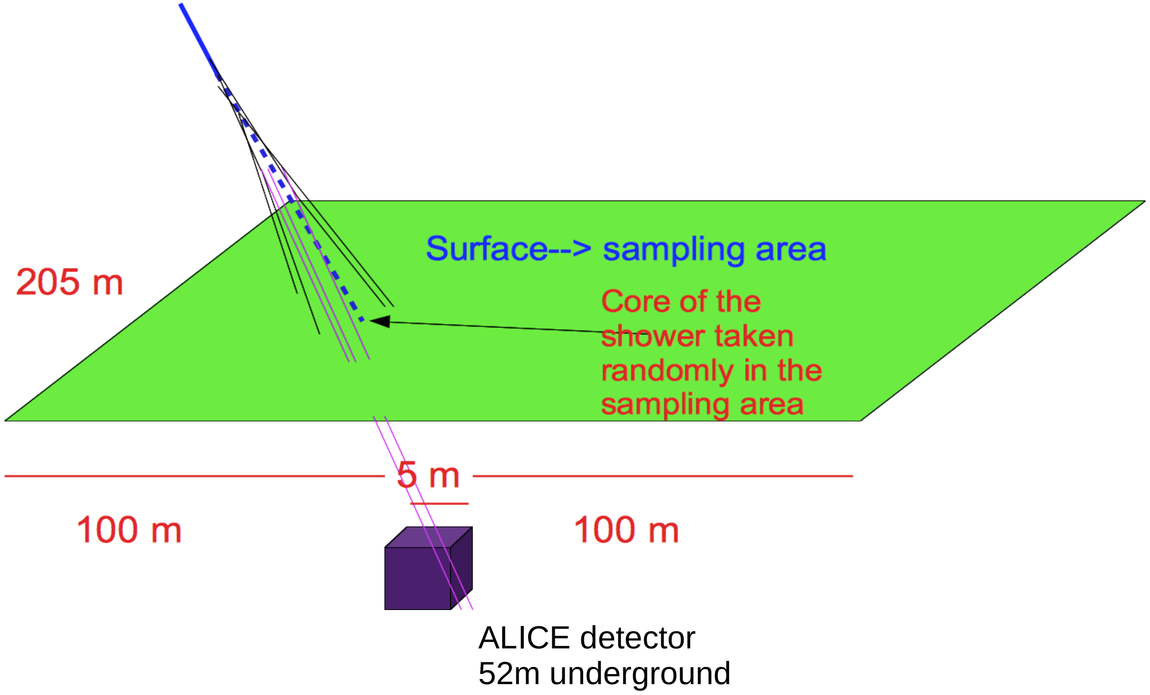
- For MMD studies:
  - $10^{14} < E_p < 10^{18}$ eV
  - pure proton (light composition)
  - pure Iron (heavy composition)
- For HHME studies:
  - $10^{16} < E_p < 10^{18}$ eV
  - pure proton (light composition)
  - pure Iron (heavy composition)
- All-particle flux at 1 TeV: (0.225 ± 0.005) $(m^2\ s\ sr\ TeV)^{-1}$
  - from J. R. Hörandel, *Astrop. Phys.* **19** (2003) 193-220
- Usual power law energy spectrum $dN/dE = K\,E^{-\gamma}$ with
  - $\gamma = 2.70 \pm 0.03$ below the knee ($3 \cdot 10^{15}$ eV)
  - $\gamma = 3.00 \pm 0.03$ above the knee

Monte Carlo simulation

- Simulated events equivalent to 62.5 days live time were generated
  - using CORSIKA as event generator from primary interaction to surface
- Three different hadronic interaction models were used
  - QGSJET-II-04 with CORSIKA 7.74
  - EPOS-LHC with CORSIKA 7.56
  - SYBILL 2.3d with CORSIKA 7.74
- The ALICE experimental hall, the surrounding environment and all the detectors are accurately described
  - using GEANT3 for particle propagation

Monte Carlo simulation

- The core of each shower was scattered at surface level with a flat random distribution in an area of 205x205 m^2 centered around the ALICE apparatus

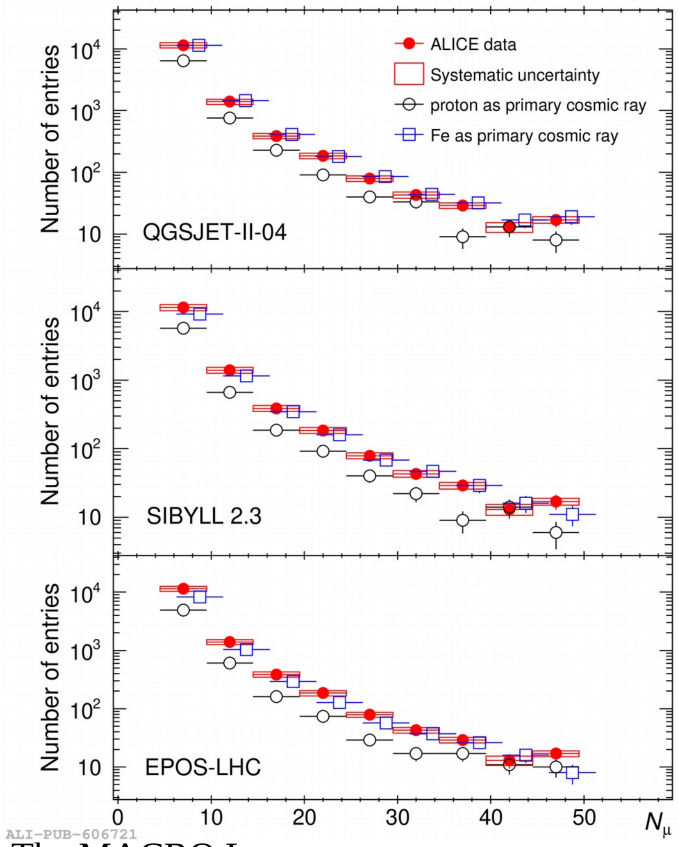


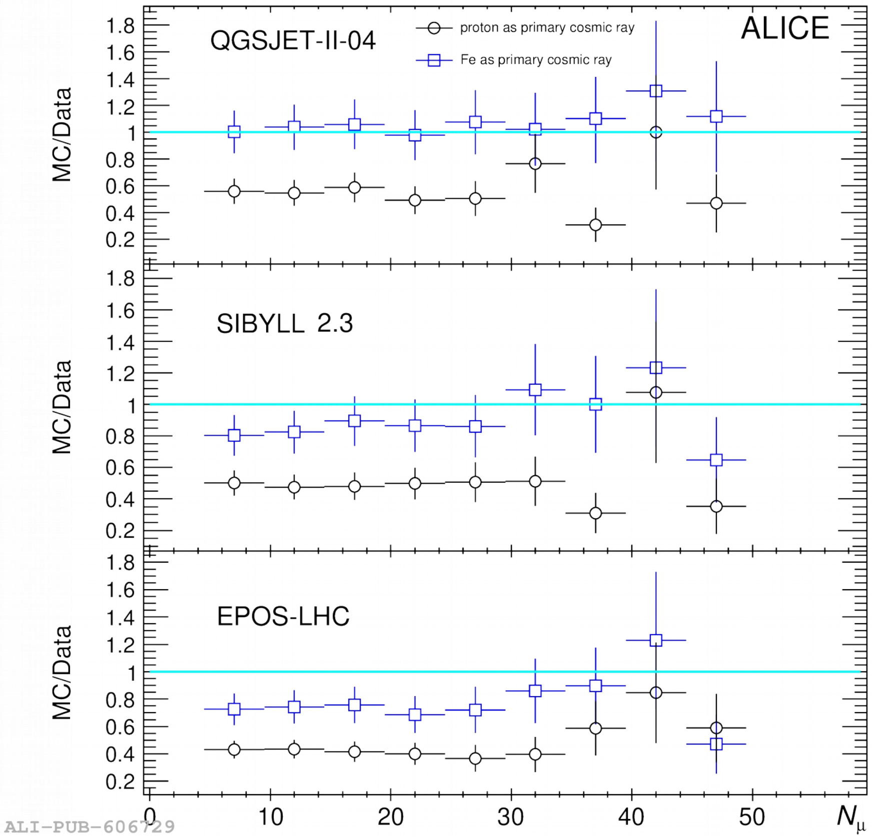
Systematic uncertainties

Data				
N_{cl}^{TPC}	Distance d_{xz}	Momentum p	cos(ΔΨ)	Total
4%	9%	1%	2%	10%

MC simulations							
Model	Element	γ	γ_k	Rock	Flux	Live time	Total
QGSJET-II-04	p	9%	6%	7%	4%	1%	14%
	Fe	8%	6%	5%	3%	1%	12%
SIBYLL 2.3d	p	8%	6%	8%	1%	1%	13%
	Fe	9%	6%	6%	2%	1%	13%
EPOS-LHC	p	8%	4%	6%	2%	0%	11%
	Fe	9%	6%	6%	2%	1%	12%

Comparison Data-MonteCarlo for MMD





QGSJET is the only model able to explain MMD supposing only heavy composition.

SIBYLL and EPOS-LHC show a muon deficit.

None is able to reproduce the expected trend of a mixed composition.

Rate of HMME

- In 62.5 days 13 HMM ($N_{\mu} > 100$) events were recorded
  - corresponding to a rate of $(2.4 \pm 0.7) \cdot 10^{-6}$ Hz
  - i.e. 1 HMM event every (4.8 ± 1.4) days
  - 28% statistical uncertainty, 10% systematic uncertainty

Monte Carlo study of HMM events

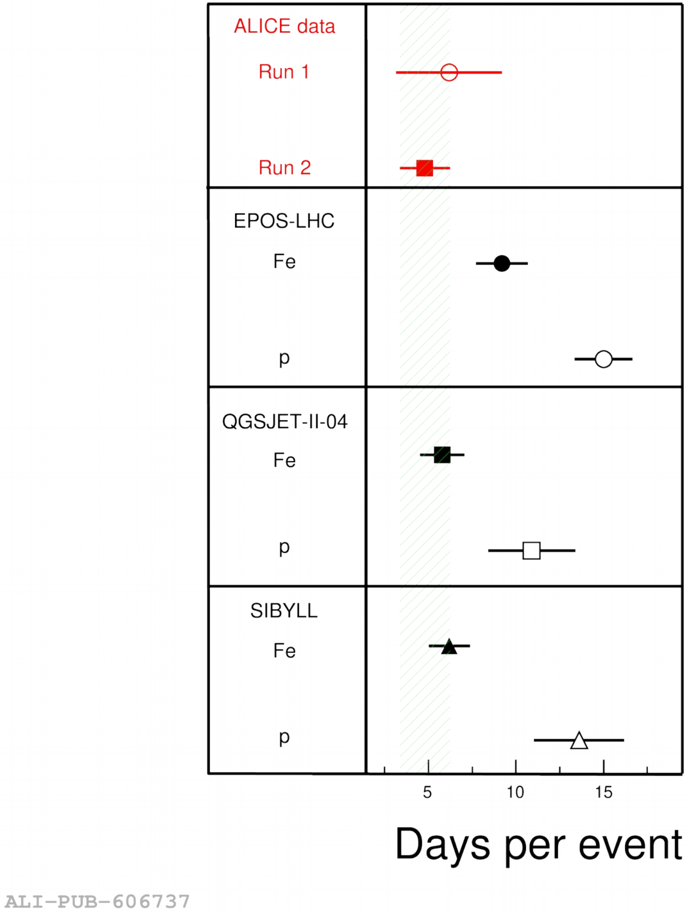
- To estimate the rate of these events
  - a simulation corresponding to 365 days of live time was performed
    - to reduce statistical uncertainties
  - with both p and Fe as primary nuclei
  - for each interaction model (QGSJET, SIBYLL, EPOS-LHC)
  - the counting of HMME in 365 days was repeated 5 times with the same generated sample by randomly assigning the core of each shower in the aforementioned surface area
- Five estimations of the HMME rate
  - the mean value is the computed rate, the standard deviation is the estimated statistical uncertainty

HMME rate: comparison data-MC

HMM events	Data		CORSIKA 7.7400 QGSJET-II-04		CORSIKA 7.5600 EPOS-LHC		CORSIKA 7.7400 SIBYLL 2.3d	
	Run 2	Run 1(*)	p	Fe	p	Fe	p	Fe
Period [days per event]	4.8	6.2	10.9	5.8	15.0	9.2	13.6	6.2
Rate [$\times 10^{-6}$ Hz]	2.4	1.9	1.1	2.0	0.8	1.3	0.9	1.9
Statistical uncertainty	28%	45%	4%	5%	10%	10%	10%	8%
Total uncert. (syst+stat)	30%	49%	23%	22%	11%	16%	19%	19%

(*) For Run 1 (2010–2013): 30.8 days live time, 22.6M muon events, 7487 with $N_\mu > 4$

HMME rate: comparison data-MC



Conclusions

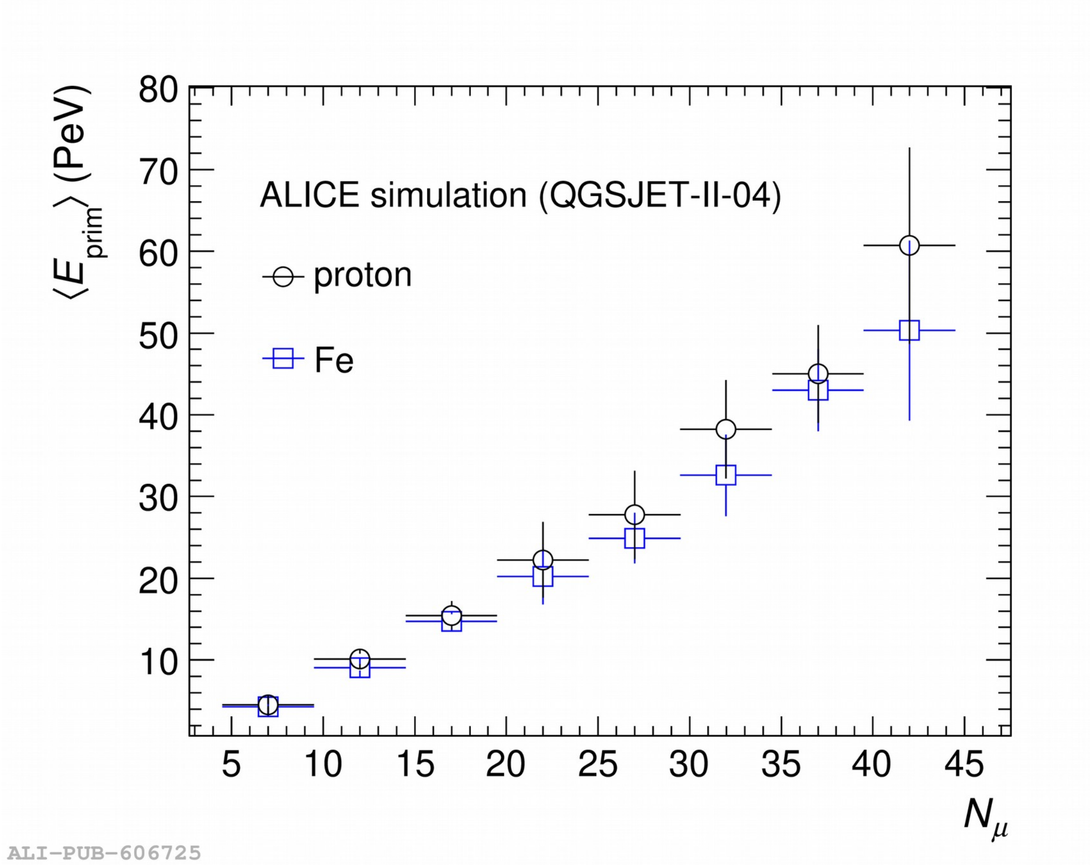
- Analysis of whole Run2 (2015-2018) ALICE cosmics data (62.5 days live time)
- MMD ($4 < N_\mu < 50$) compared with MC with 3 hadronic interaction models
  - only QGSJET-II-04 is able to explain the MMD assuming a pure Fe primary composition – SIBYLL 2.3d and even more EPOS-LHC show a muon deficit
  - anyway none of the three is able to reproduce the expected trend from a mixed primary composition

Conclusions

- The rate of HMME ($N_\mu > 100$) from MC simulation with QGSJET and a heavy primary composition is the closest to the rate measured from real data
  - confirming the results obtained with Run1 data
  - also SYBILL outcome is compatible with real data, while EPOS-LHC gives a definitely lower rate
- An improvement of the hadronic interaction models based on latest LHC results is necessary for a better understanding of cosmic ray data

BACKUP

Primary Energy vs Muon Multiplicity



Primary energy range in Monte Carlo