Cosmic-ray studies using the ALICE detector at LHC

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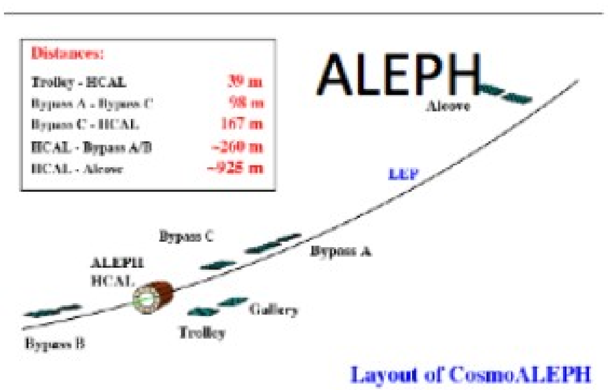
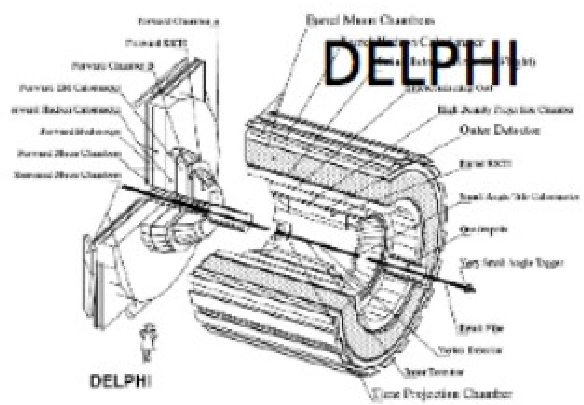
Outline

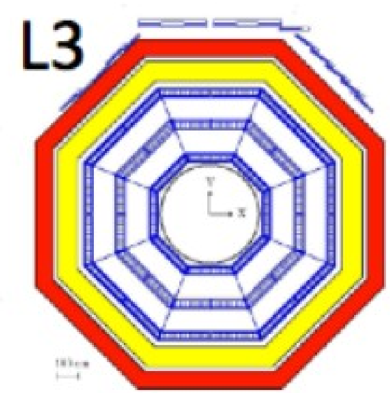
- Motivations
- Detecting atmospheric muons with the ALICE experiment
- The Muon Multiplicity Distribution
- High Muon Multiplicity events
- Monte Carlo and data comparison
- Conclusions

Motivations

- Use of collider detectors for cosmic-ray studies was pioneered by LEP experiments ALEPH, DELPHI and L3







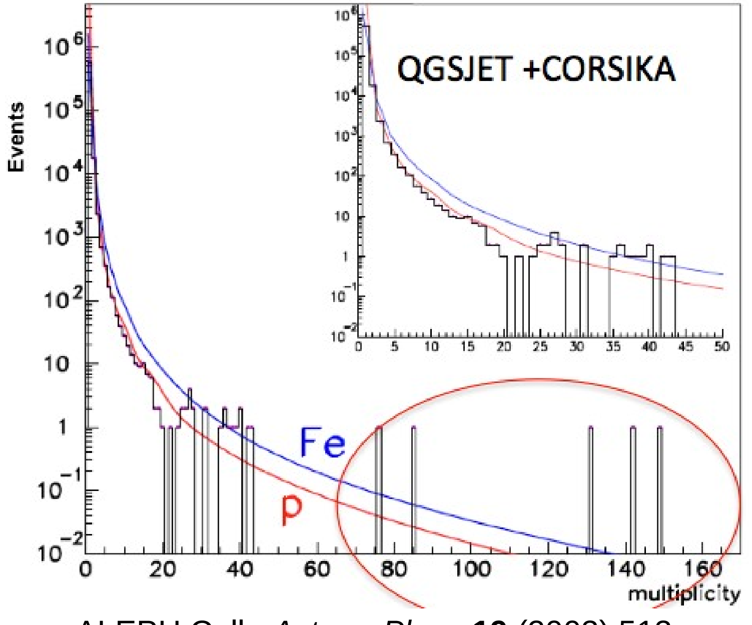
✗ Small apparatuses

✗ Muons crossing the rock

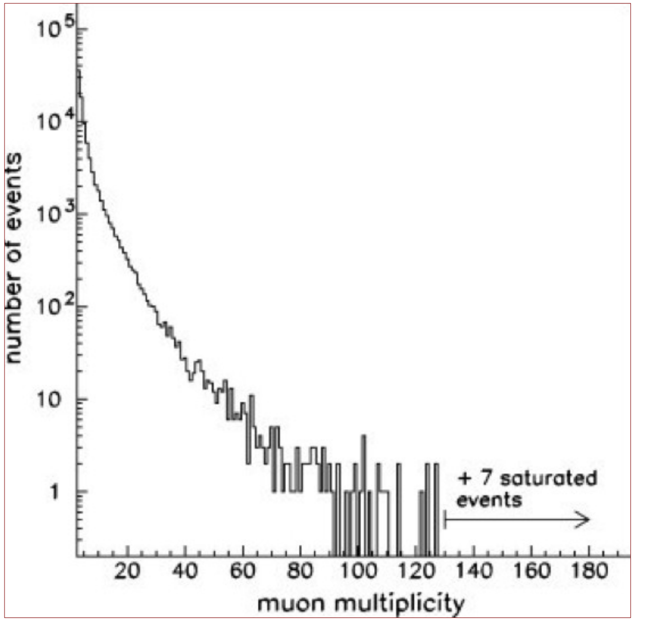
✔ High performance detectors
- tracking
- magnetic field

Motivations

- 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

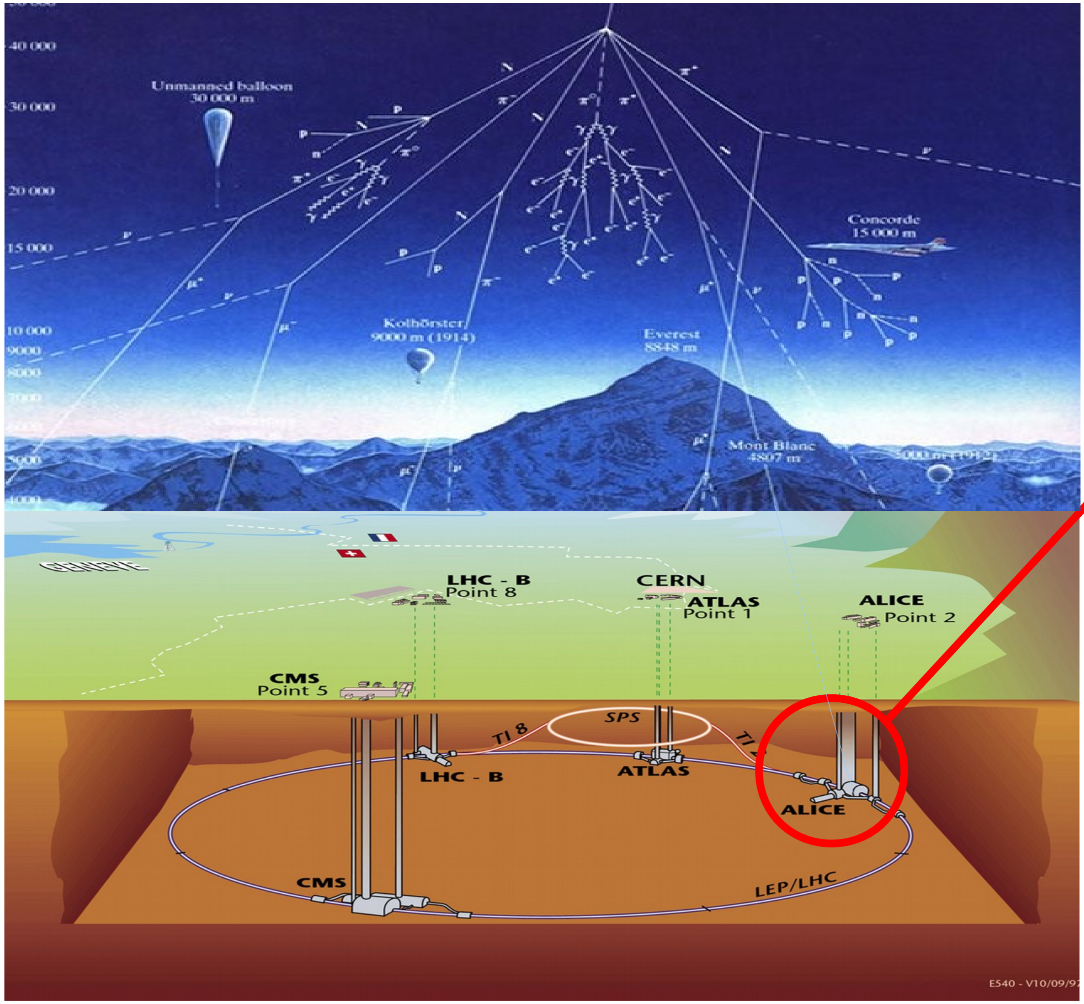


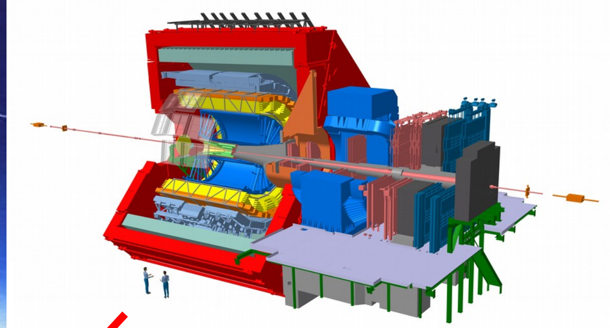
ALEPH Coll., *Astrop. Phys.* **19** (2003) 513



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

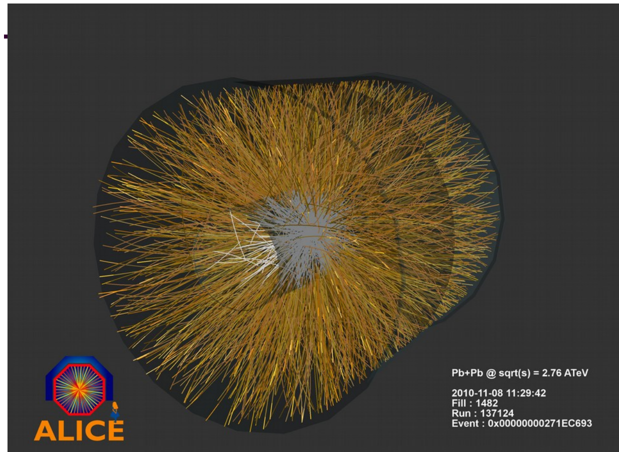
Detection of cosmic muons at LHC



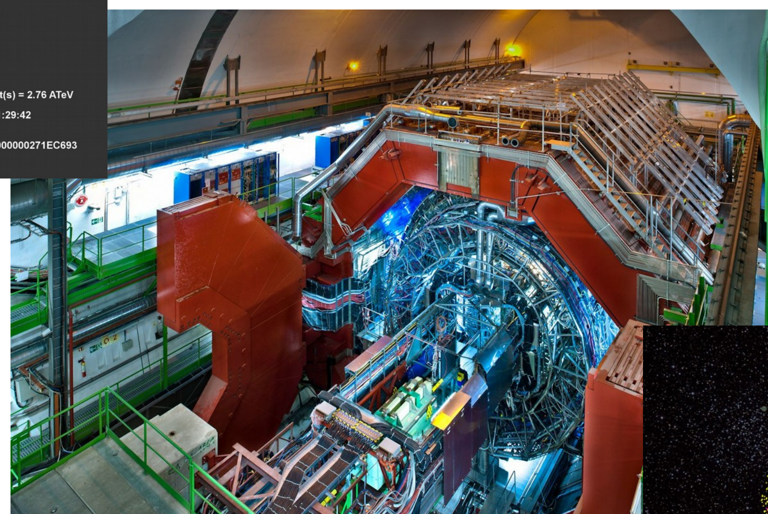


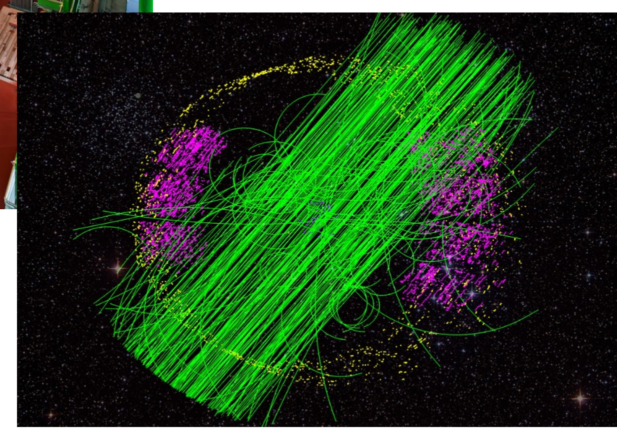
- ALICE is located at LHC Point2 52m underground (28m rock above)
- Muon energy threshold ~16 GeV

ALICE Experiment



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



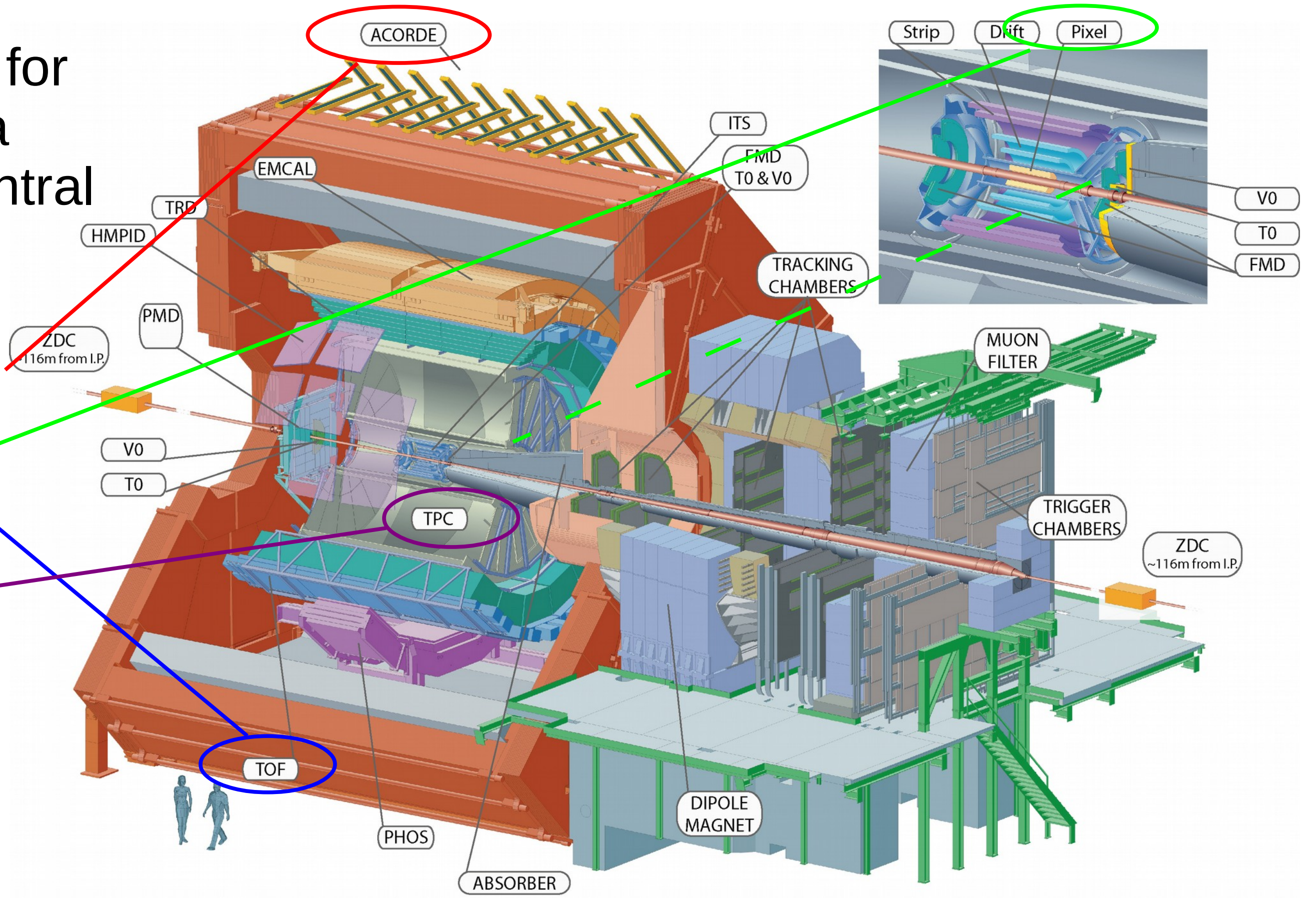


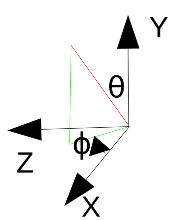
Besides the Heavy-Ion Physics program, ALICE has a dedicated physics group devoted to cosmic-ray studies

The ALICE detectors

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

- Trigger
  - ACORDE
  - TOF
  - SPD
- Tracking
  - TPC

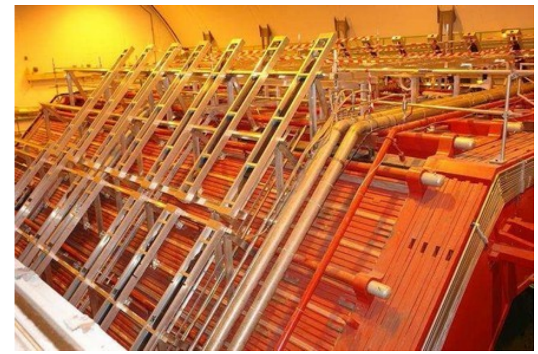




Trigger detectors for cosmic muons

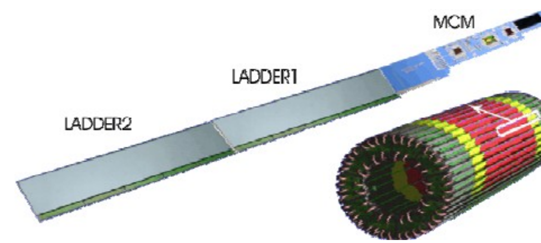
ACORDE

Array of 60 scintillator modules located in the three top octants of the magnet
Each module is made of two plastic scintillators with effective area of 0.38 m^2.
Configurable from 2-fold coincidence (1Hz) onward.



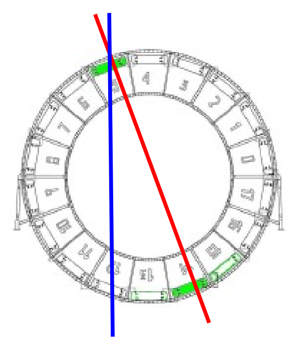
SPD

Two innermost coaxial cylinders of ITS, around the beam pipe.
1200 FastOr chips (for a total of 10 M pixels) provide the trigger.

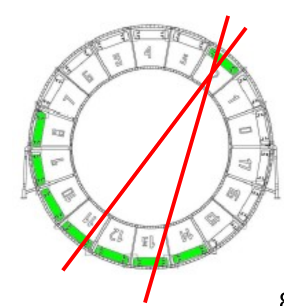


TOF

Array of 1638 MRPC pads (18 φ sectors with 5 modules each) around TPC.
Full φ coverage, $45° < \theta < 135°$, time resolution 100ps, ~95% efficiency



Back to back

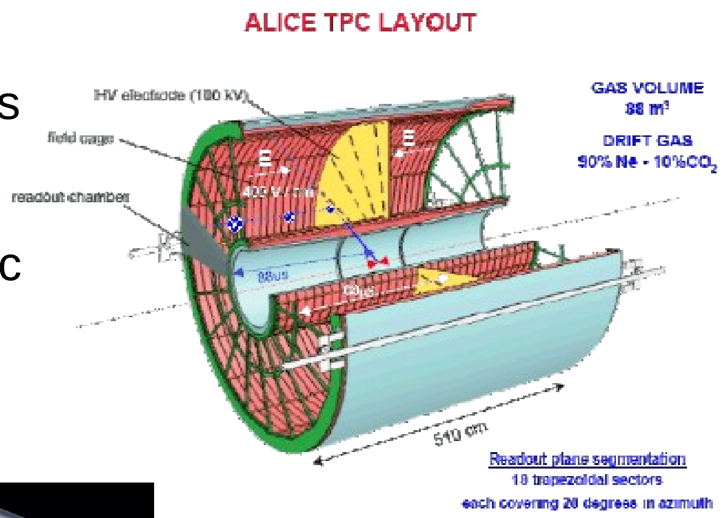


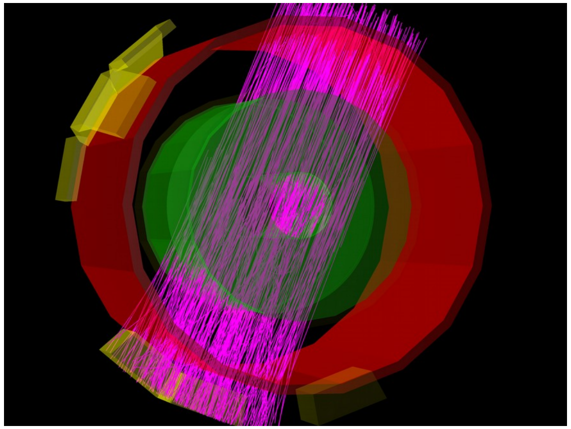
Back to back ± 3 pads

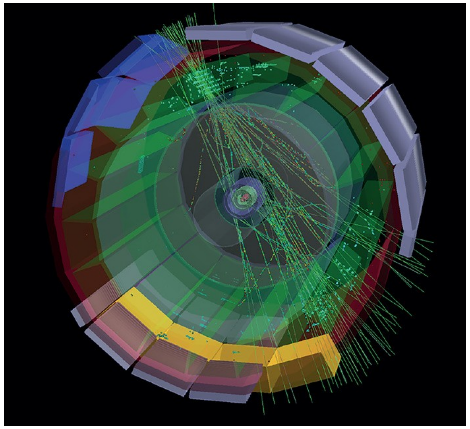
Tracking detector for cosmic muons

TPC

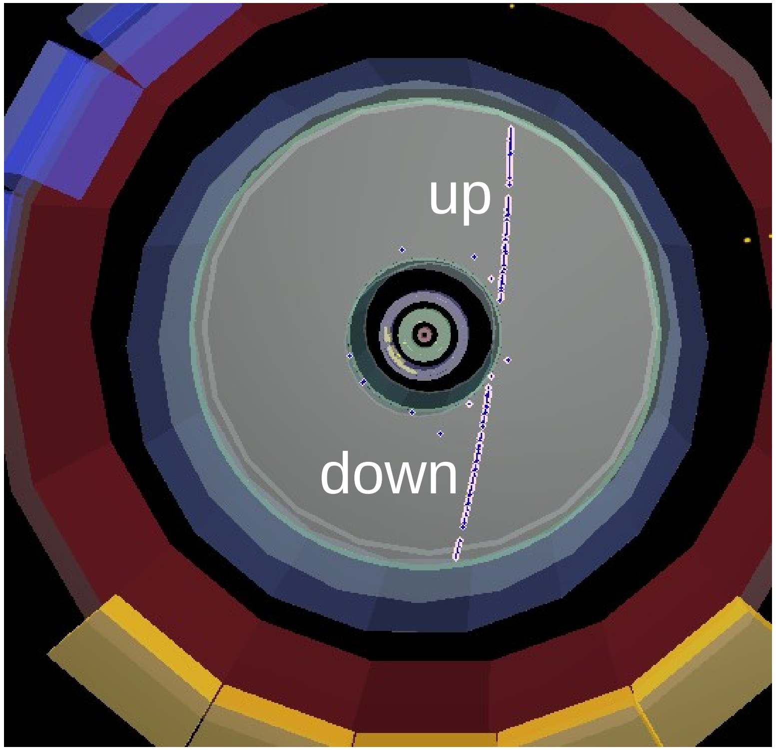
- Main tracking device with excellent capabilities for high-track density
- 557k readout channels
- Momentum resolution ~10% for p = 100 GeV/c for cosmic muons
- Tracking efficiency 98% for N_{μ} = 100







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

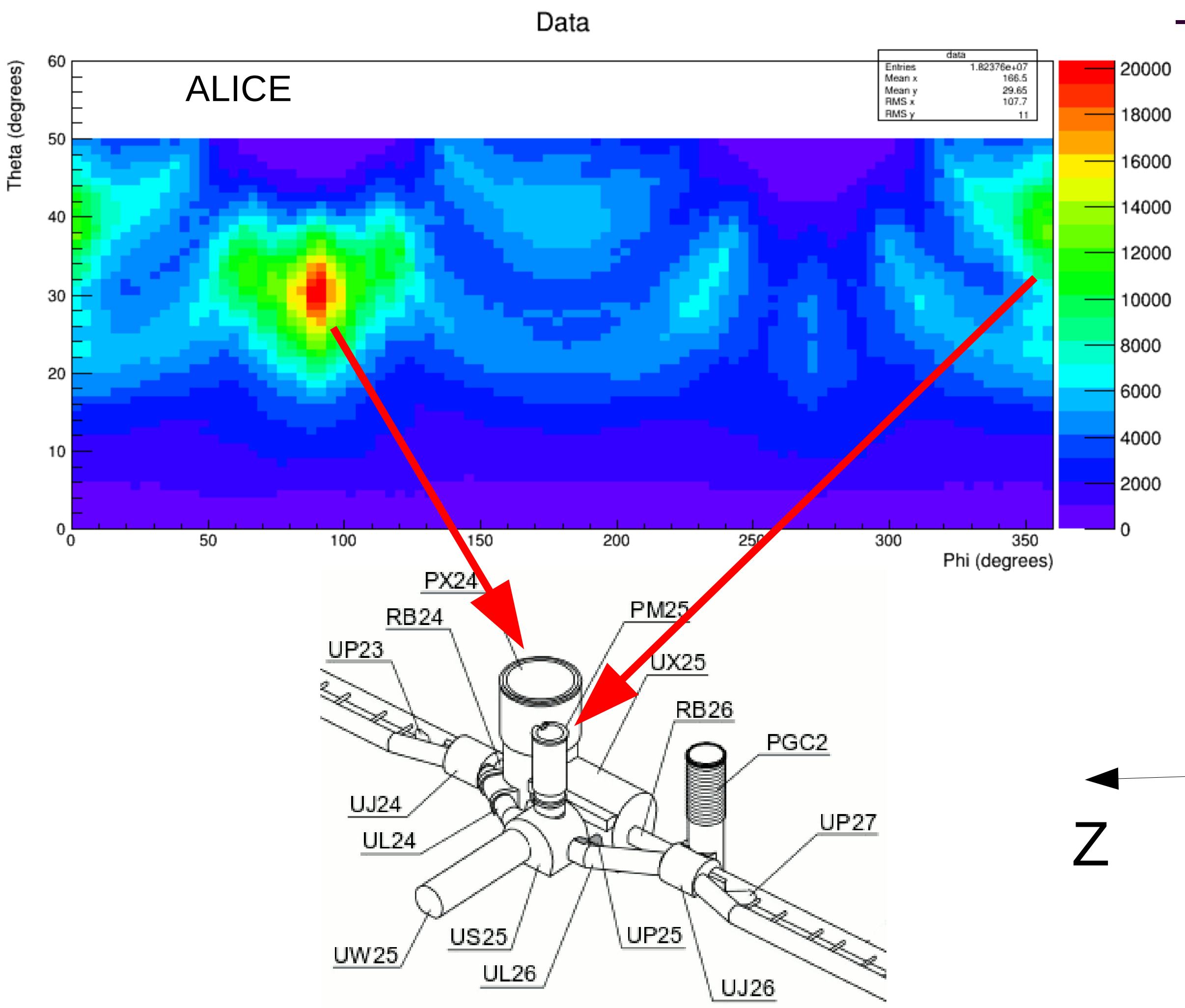
Analysis cuts

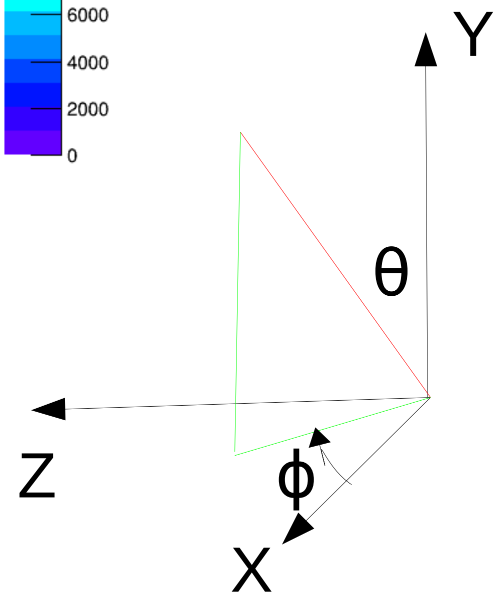
- To accept a track
  - > 50 space points in the TPC (out of a maximum of 159)
  - $p > 0.5$ GeV/c
  - if multi-muon, parallelism cut $cos(\Delta\Psi) > 0.990$
- To match an up track with a down track
  - $d_{ca} < 3$cm in the mid horizontal TPC plane
- Matched muon: up and down tracks matched
- Single-track muon: a track satisfying all cuts but distance d_{ca}
- Cut efficiency checked with MC simulations

Data sample for cosmic-ray studies

- Data taken between 2010 and 2013 during no-beam periods
  - OR of ACORDE, TOF and SPD triggers
  - with and without magnetic field (0.5 T)
  - integrated live time 30.8 days
  - ~ 22.6M events with at least 1 reconstructed muon in TPC
- Multi-muon event: $N_\mu > 4$ in TPC
  - 7487 multi-muon events
- All events with a zenith angle $\theta<50°$ are kept for further analyses

Muon angular distribution





Muon multiplicity distribution (MMD)

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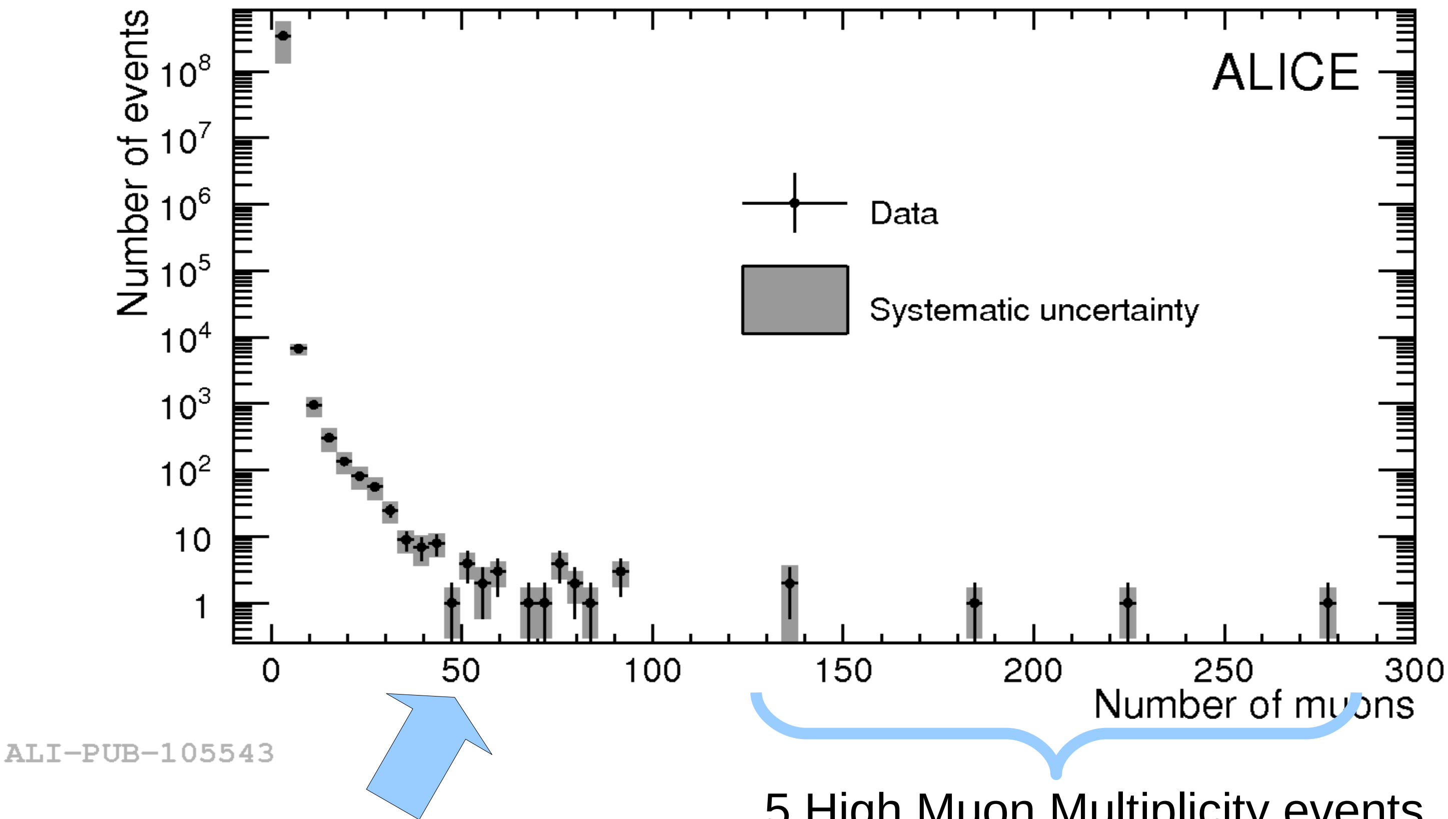

Smooth distribution up to N_μ ~70

5 High Muon Multiplicity events (defined when N_μ >100)

High Muon Multiplicity event display

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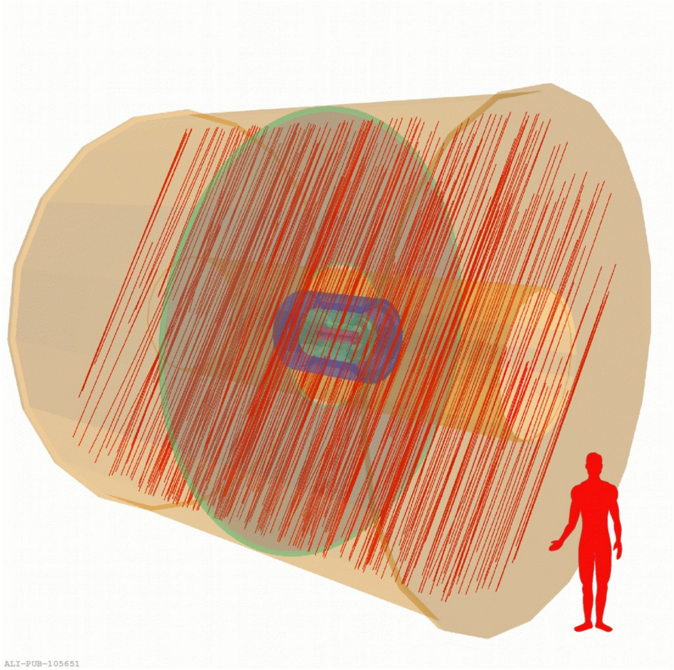
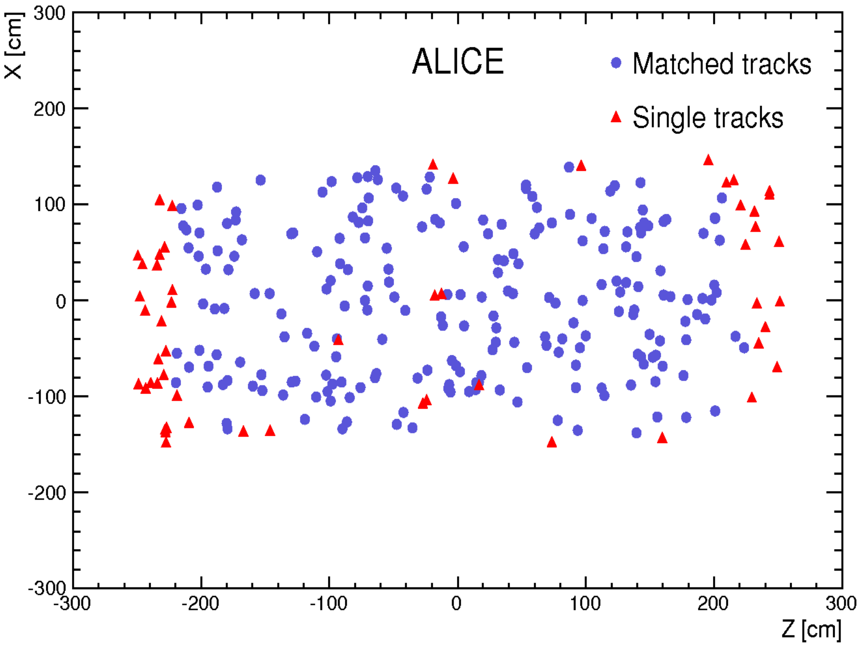




ALI-PUB-105555

High Muon Multiplicity (HMM) event with 276 muons

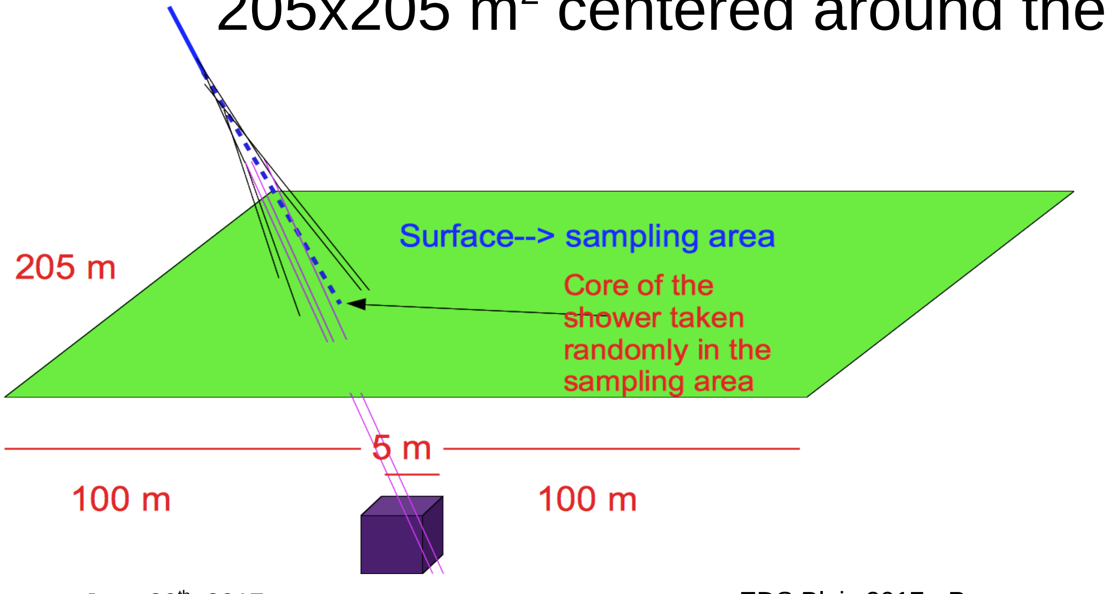
Monte Carlo simulation

- Simulated events equivalent to 30.8 days live time were generated
  - CORSIKA* 6990* and QGSJET** II-03 were used to model low-intermediate MMD and study HMM events
  - CORSIKA* 7350 and QGSJET** II-04 were used to check and confirm results for HMM events
  - two samples: pure *p* (light composition) and pure Fe (extremely heavy composition)
  - primary cosmic-ray energy $10^{14} < E < 10^{18}$ eV
  - usual power law energy spectrum $E^{-\gamma}$ with $\gamma = 2.7$ below the knee (3×10^{15} eV) and $\gamma = 3.0$ above

* FZKA-6019 (1998) ** Phys. Rev. D83 (2011) 014018

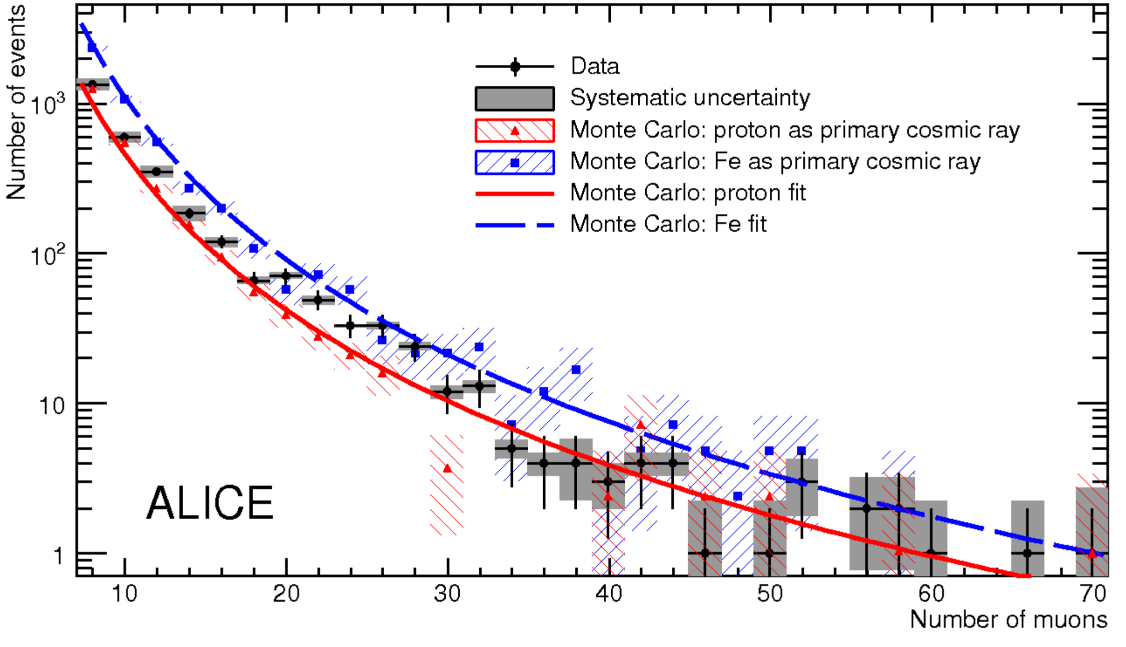
Monte Carlo simulation

- the total (all-particle) absolute flux of cosmic rays was extracted from J. R. Hörandel, *Astrop. Phys.* **19** (2003) 193-220
- 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



Comparison Data-MonteCarlo

Compare the MMD in the range $7 < N_\mu < 70$ with the simulated distributions fitted with a power-law function



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ALI-PUB-105547

As expected the data are between the pure *p* composition (approaching it at low multiplicity) and the pure Fe composition (at higher multiplicity)

Monte Carlo study of HMM events

- In 30.8 days, 5 HMM events were recorded, corresponding to a rate of 1.9×10^{-6} Hz
- To estimate the rate of these events
  - a simulation of 1 year of live time was perfomed
  - simplified Monte Carlo simulations show that only primaries with $E > 10^{16}$ eV contribute to HMM events reconstructed in the ALICE TPC
  - so only primaries with $10^{16} < E < 10^{18}$ eV are generated
  - samples for both *p* and Fe primaries

HMM: comparison data-MC

HMM events	CORSIKA 6990		CORSIKA 7350		Data
	QGSJET II-03		QGSJET II-04		
	p	Fe	*p*	Fe	
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) (%)	25	25	22	28	49

- The rate of HMM events can be reproduced using the latest hadronic interaction models and a reasonable CR primary flux
- Pure Fe primary composition (i.e. heavy nuclei composition) seems to better reproduce the rate of HMM events
  - though the large uncertainty in the measured rate prevents a firm conclusion about the origin of these events
- Consistent with the fact that HMM events are generated by primaries with E > 10^{16} where the composition is dominated by heavier elements

Conclusions – I

- In 2010-2013 ALICE took 30.8 days of cosmic-ray data
- The MMD at low and intermediate multiplicity is well reproduced by Monte Carlo simulations using CORSIKA 6990 with QGSJET II-30 model
- ALICE results suggest a mixed ion primary CR composition with an average mass increasing with energy

Conclusions – II

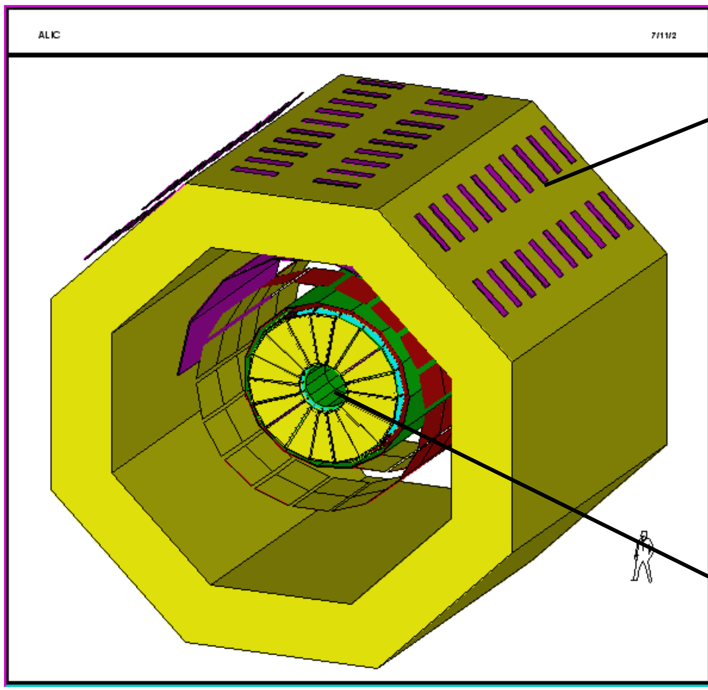
- 5 HMM events (N_μ > 100) were recorded in the same 30.8 days data taking period
- The observed rate is consistent with the predictions of CORSIKA 7350 with QGSJET II-04 model using a pure Fe primary composition and energy > 10^{16} eV
- For the first time the rate of HMM events has been well reproduced using conventional hadronic interaction models

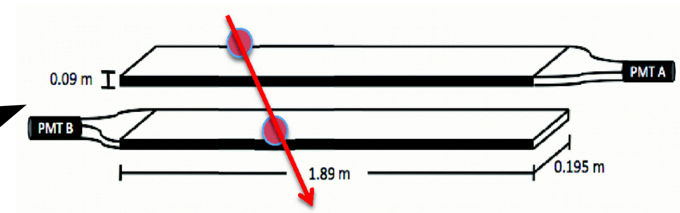
Outlook

- ALICE will continue to take cosmic data during LHC Run2 (2015 onward)
  - during no-beam periods
  - in 2015/16 about 43 days of live time were collected
- The aim is to study HMM events in greater detail; other cosmic-ray topics (e.g. cosmic muon charge ratio) could also be performed with larger statistics
  - analysis in progress

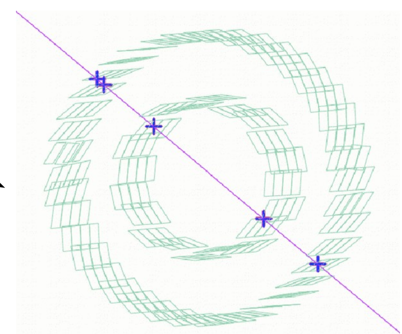
BACKUP

ACORDE and SPD triggers



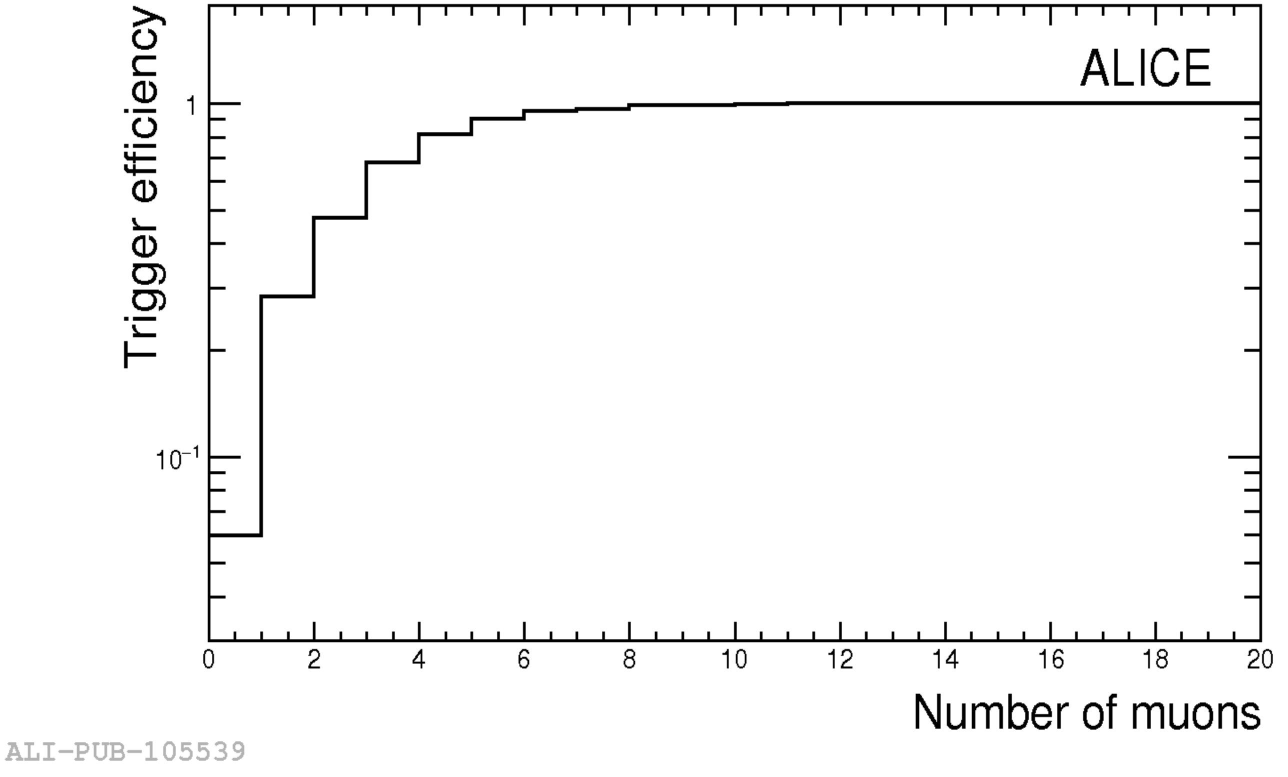


The ACORDE cosmic trigger requires a 4-fold coincidence of modules



The SPD cosmic trigger requires a coincidence between top and bottom halves of outer layer

TOF trigger efficiency



Efficiency of analysis cuts

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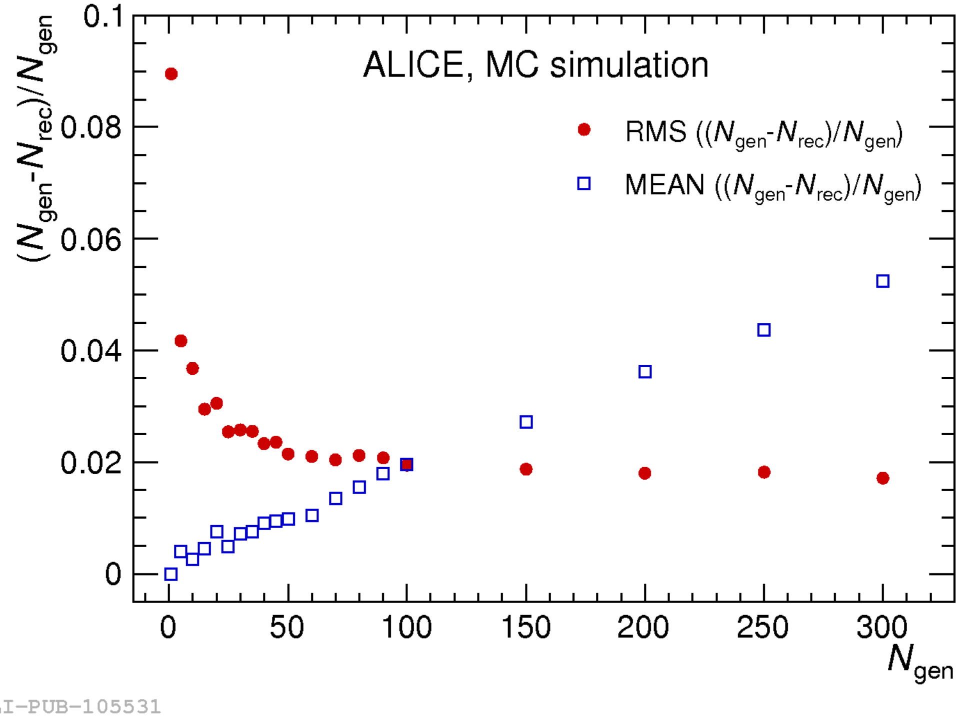
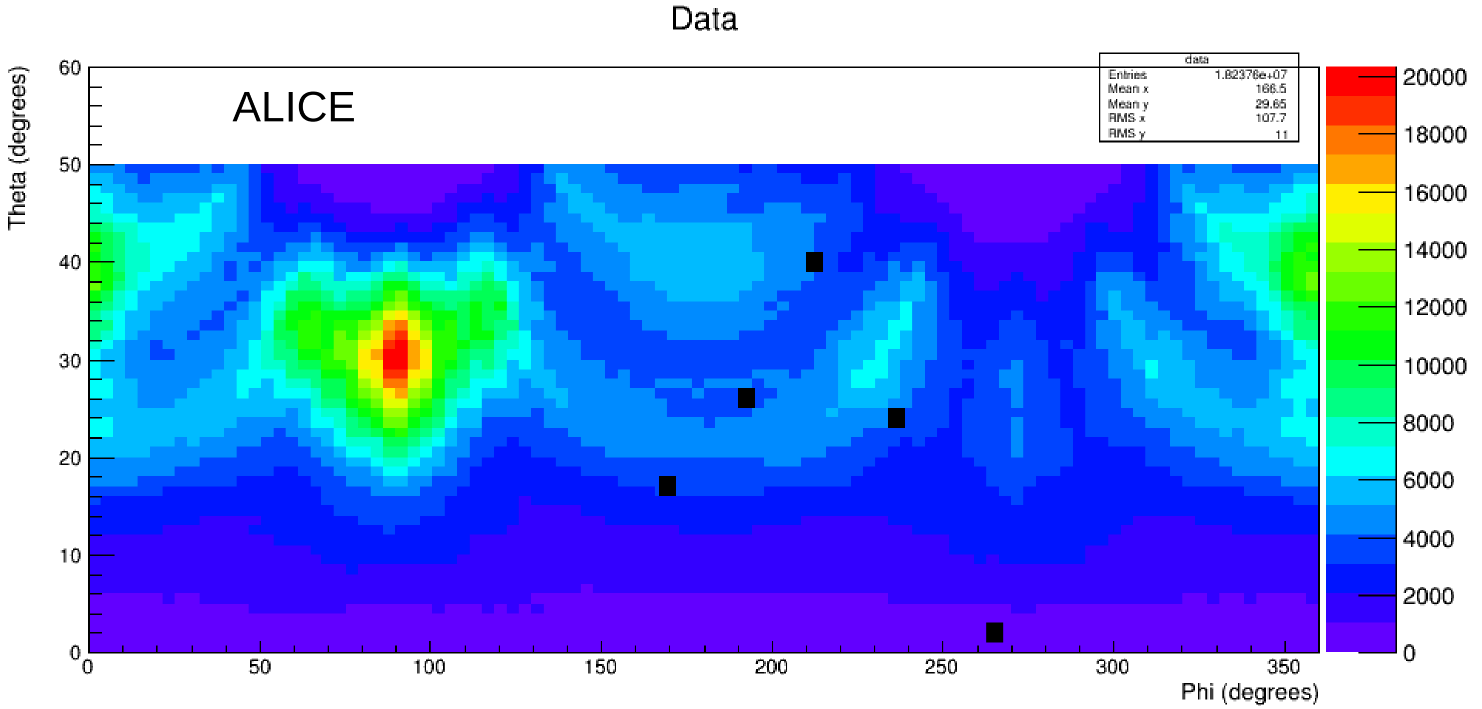


- generate 1000 events for 20 different muon multiplicities (1 to 300)
- reconstruct with same algorithm as real data
- plot mean and RMS of

(# generated μ – # reconstructed μ) / (# generated μ)

Location of HMM events



Monte Carlo results

Number of HMM events in 365 days of data taking

	Simplified MC		Full MC	
	proton	iron	proton	iron
CORSIKA 6990 QGSJET II-03	40	61	27	51
CORSIKA 7350 QGSJET II-04	41	72	30	52

- To reduce the statistical fluctuations, four additional simulations were performed, reusing the EAS sample and randomly assigning the core of each shower over the 205x205 m^2 area

Monte Carlo results

- Averaging the 5 samples
  - estimate the number of HMM in 1 year
  - reduce the statistical fluctuations
- Uncertainties are dominated by
  - statistical errors on real data
  - systematic errors on MC data
- Two sources of systematic errors in MC
  - the uncertainties in the generation parameters
  - the muon reconstruction algorithm

Core location of MC HMM events

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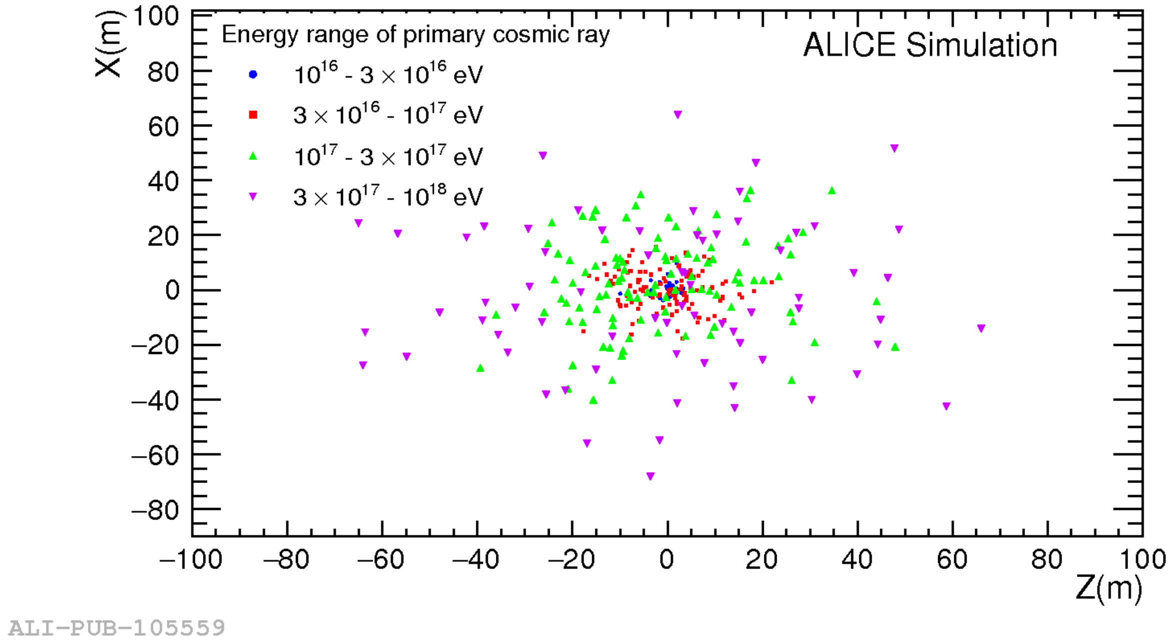

Core location of simulated EAS giving > 100 muons in the ALICE TPC, for Fe primaries with $10^{16} < E < 10^{18}$ eV corresponding to 5 years of data taking

on average shower core falls farther from ALICE location for E > $3\text{x}10^{17}$ eV

Monte Carlo results

Number of HMM events in 365 days of data taking

Run	CORSIKA 6990 QGSJET II-03				CORSIKA 7350 QGSJET II-04			
	Simple MC		Full MC		Simple MC		Full MC	
	p	Fe	*p*	Fe	*p*	Fe	*p*	Fe
1	40	51	27	51	41	72	30	52
2	40	64	24	42	42	88	32	71
3	31	43	25	31	48	78	29	62
4	26	52	20	34	46	84	35	61
5	33	64	22	53	36	83	31	58

Two sources of systematic errors:

- the muon reconstruction algorithm
- the uncertainties in the generation parameters