Current Resistive Plate Chambers experiments

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(Cern, INFN and Politecnico of Bari)

First International RPC School,
Mexico City,
23-26 February 2018

Operating (or almost) Resistive Plate Chambers in the world

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RPC are gaseous detectors used as counters or trackers of charged particles in several experiments:

- At CERN: **ATLAS, CMS & ALICE**
- In Tibet: **ARGO**
- In Beijing: **BESIII**
- In Italy: **EEE project**

The Large Hadron Collider

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- The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator.
- Installed 100 m underground, it consists of a 27km ring of superconducting magnets with a number of accelerating structures to boost the energy of the particles along the way.
- Two high-energy particle beams travel in opposite direction at close to the speed of light before they are made to collide.
- **It started on 10 September 2008**

The LHC numbers

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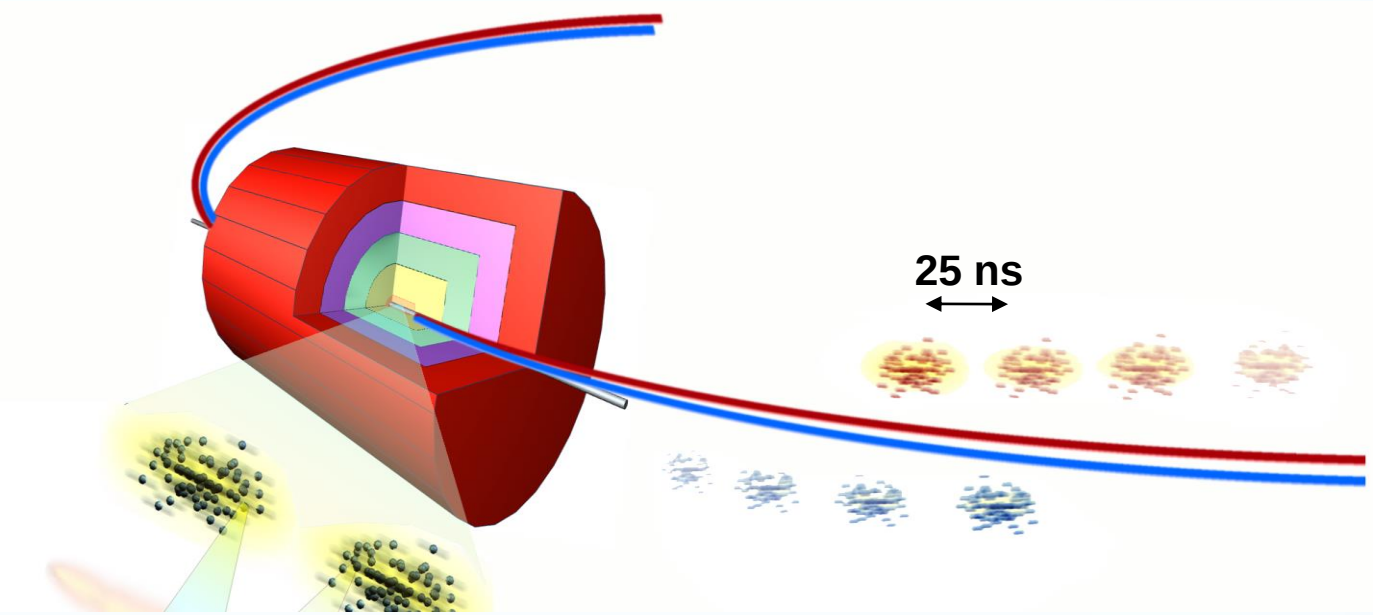

Nominal settings	
Beam energy (TeV)	7.0
Number of particles per bunch	1.15 10^{11}
Number of bunches per beam	2808

It is a Discovery Machine

Proton-proton collider

- ✧ **CM Energy = 14 TeV (up to today 13 TeV)**
- ✧ **L=2 10^{34} cm^{-2}s^{-1} (designed for L~10^{34} cm^{-2} s^{-1})**
- ✧ **Bunch Spacing: 25ns**

The LHC Physics Programme

- ✓ Origin of the particle masses
- ➢ Nature of Dark Matter
- ➢ Matter versus antimatter
- ➢ New physics beyond the SM

July 4, 2012: Higgs Boson Discovery

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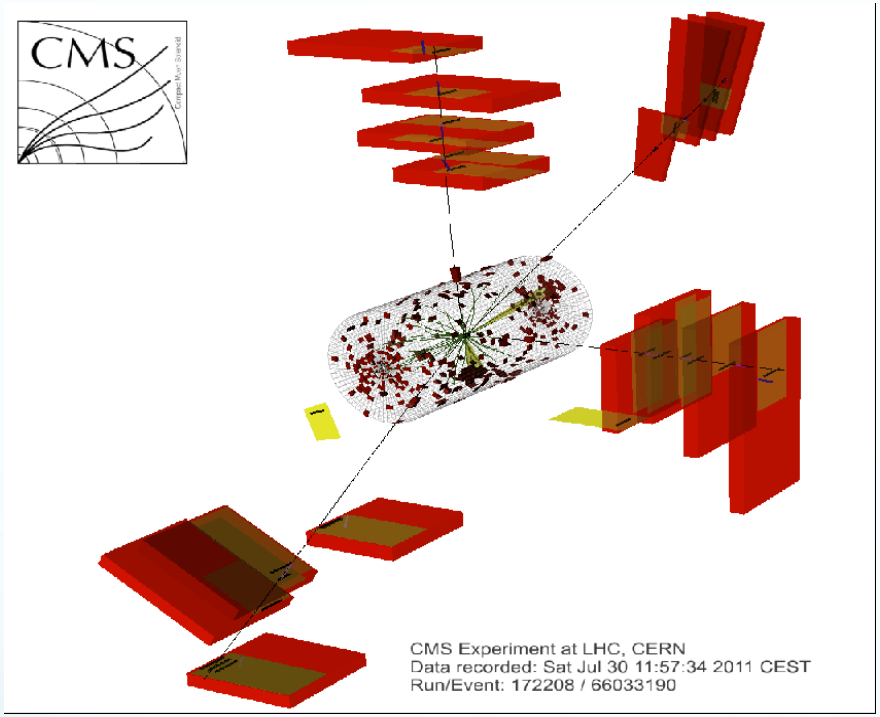
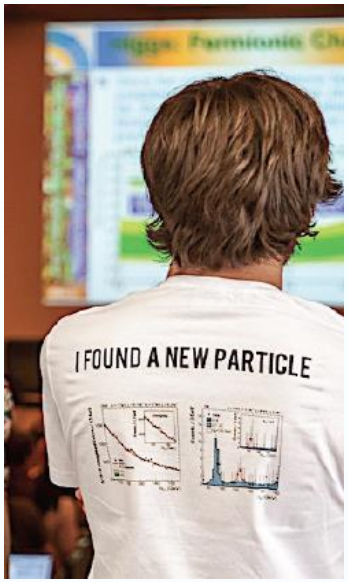
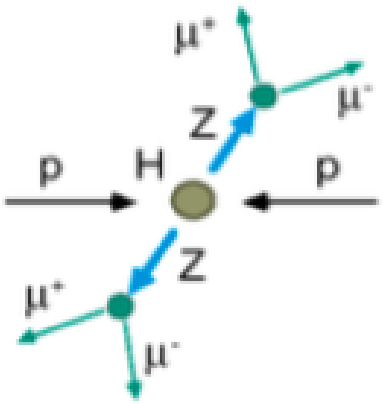
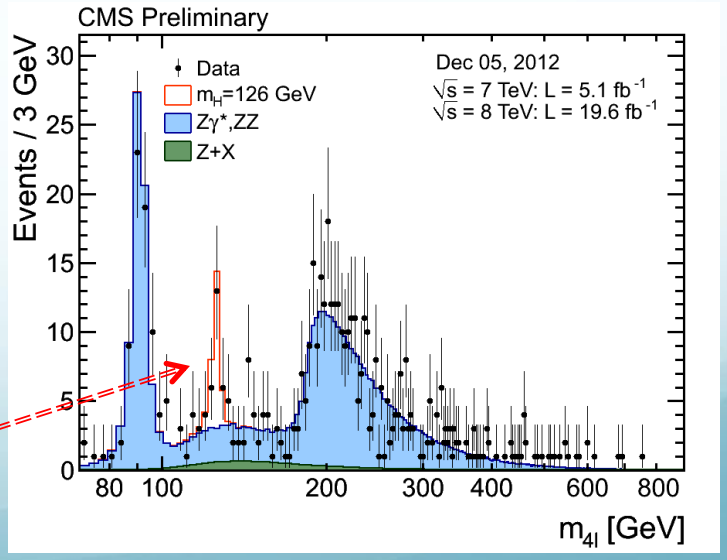


CMS event with 4 muons
(RPC hits are in black)





Important discovery for the foundamental understanding of our universe!!



Four-lepton mass spectrum:
clean signal peak at ~126 GeV

The 2013 Nobel Prize in physics

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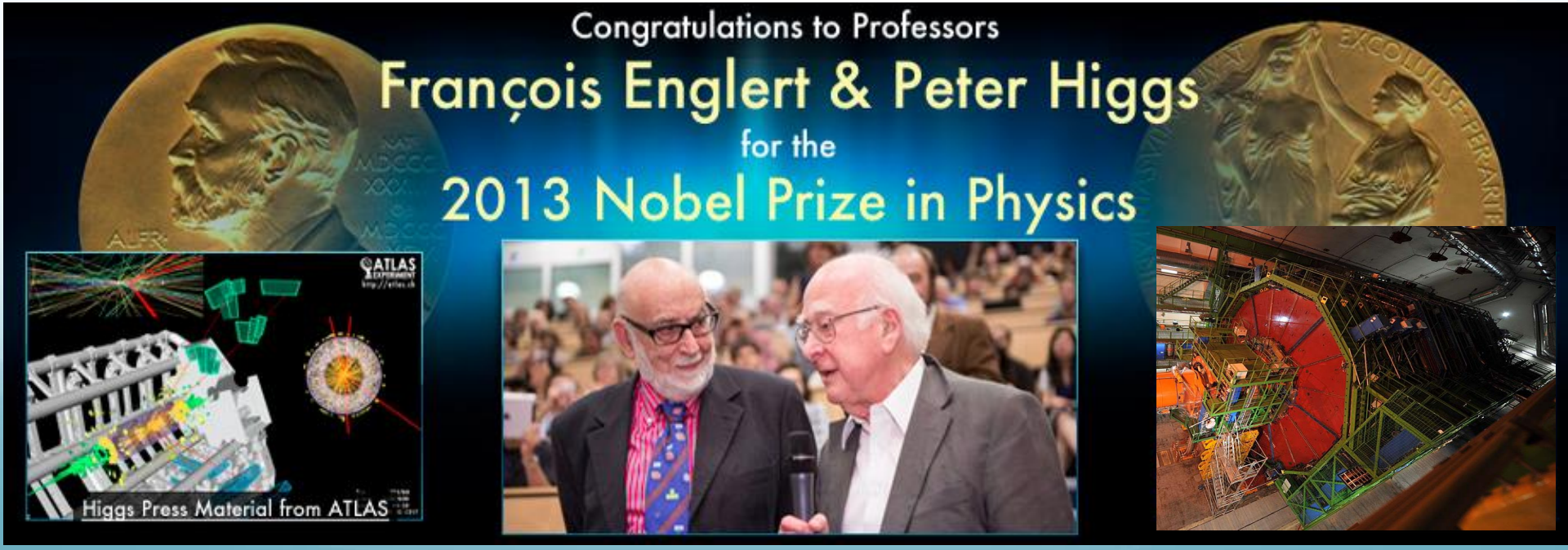
The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert
Université Libre de Bruxelles, Brussels, Belgium

Peter W. Higgs
University of Edinburgh, UK

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"



ATLAS and CMS experiments in numbers

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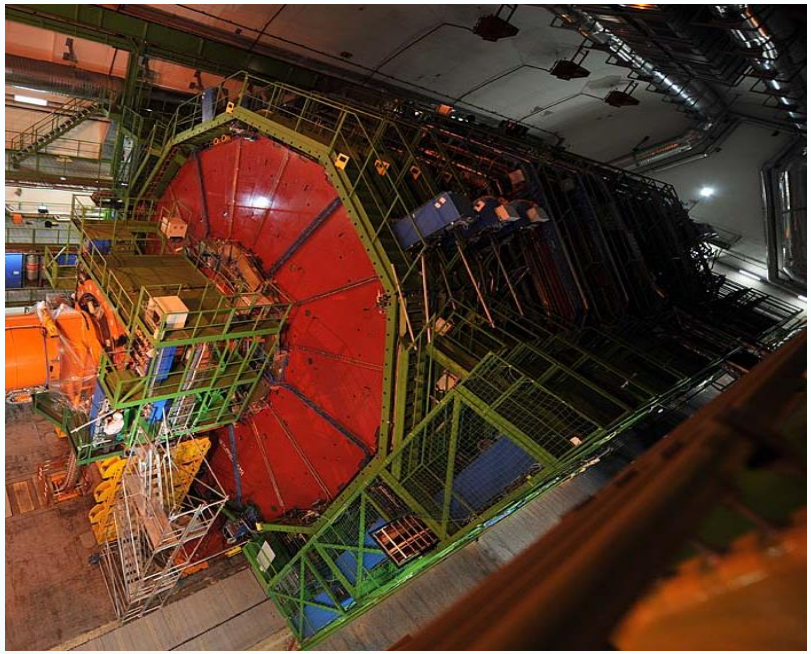

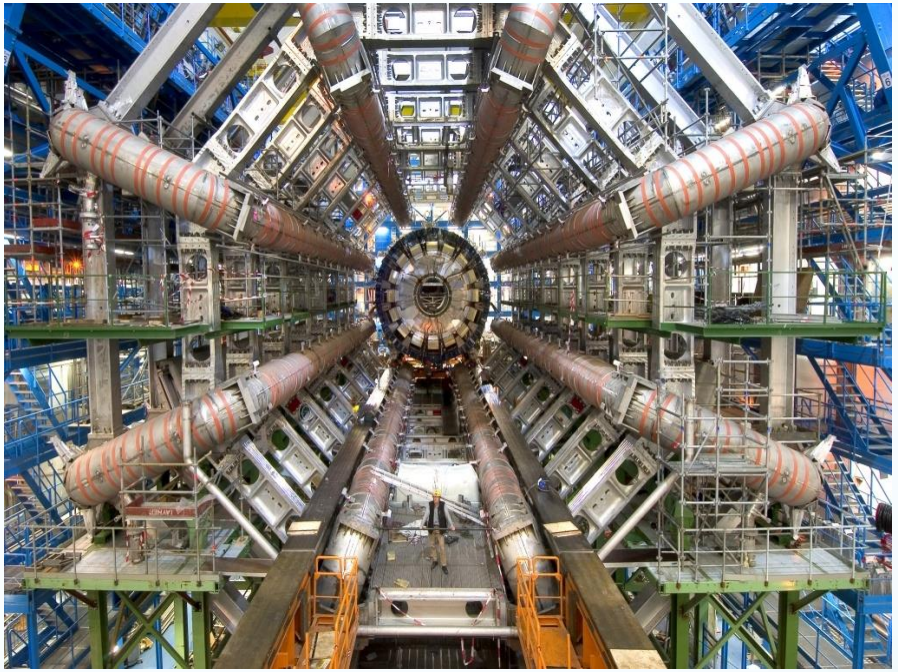

Compact Muon Solenoid

- **15 m wide** and **28.7 meters long**
- **Weighs:14000 t** (twice as much as the Eiffel Tower)
- **Solenoid magnet field: 3.8 T**
- Scientists and engineers: ~2000

A Toroidal LHC ApparatuS

- **25 wide** and **46 meters long**
- Weighs: 7000 t
- Toroidal Magnet: 1 T (in the muon chambers)
- Scientists and engineers: ~3000

Basic trigger concepts for LHC experiments

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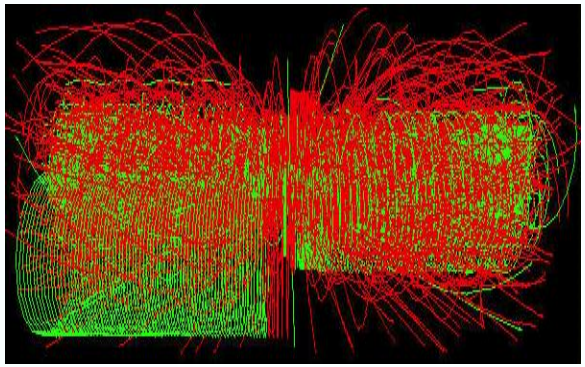

Interaction rate 1 GHz (bunch crossing rate 40 MHz) → Mass storage 100 Hz

ATLAS / CMS	
Event Rates:	**~ 10^9 Hz**
Event size:	**~ 1 MB**
Mass storage	**~10^2 Hz**

- The role of the **trigger** is to make the **selection** of particle collisions potentially containing interesting physics
- It must be:
  - **Efficient** for selecting processes of interest for physics analysis
  - **Able to have a large reduction of rate**
  - **Fast..**limits complexity of algorithms that can be used

It not easy to achieve all the above simultaneously! And never forget that **an event rejected by the Trigger is lost for ever!**

- **In CMS and ATLAS, multi level triggers have been implemented (2 levels and 3 levels)**

L1 Muon ATLAS Trigger

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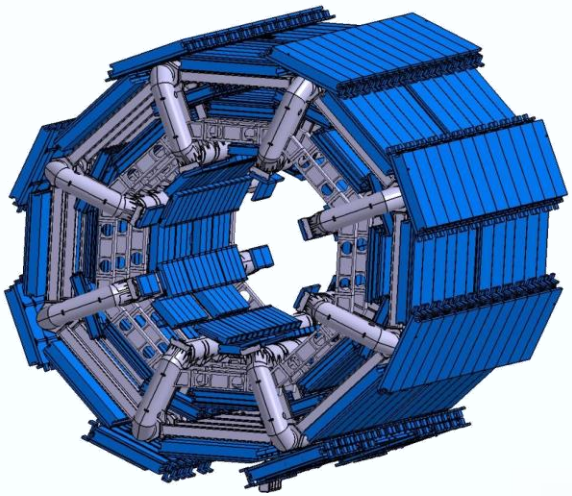

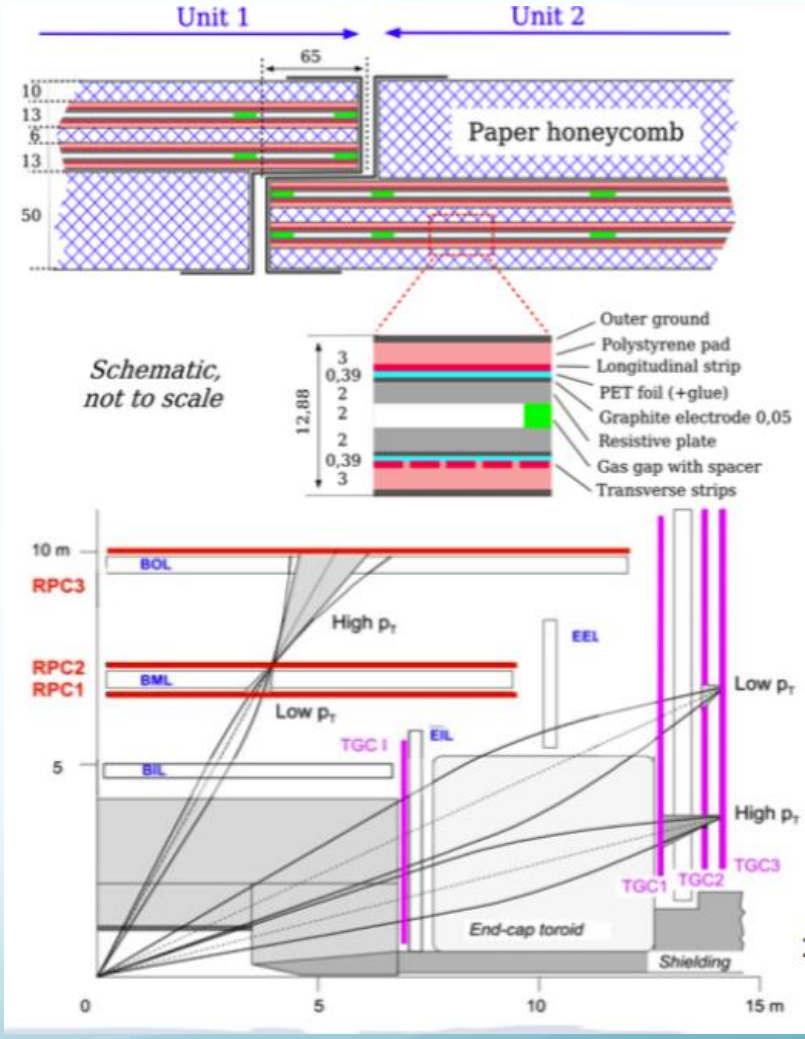

- **In the Barrel region, the ATLAS LV1 muon trigger** is based ONLY on RPCs (η **coverage < 1)**
- **3 layers (**each equipped with a doublet of RPCs)
- **Two kind of triggers:**
  - Low-p_T (2-stations coincidence, 3/4)
  - High-p_T (3-stations coincidence, 4/6)

L1 Muon CMS Trigger

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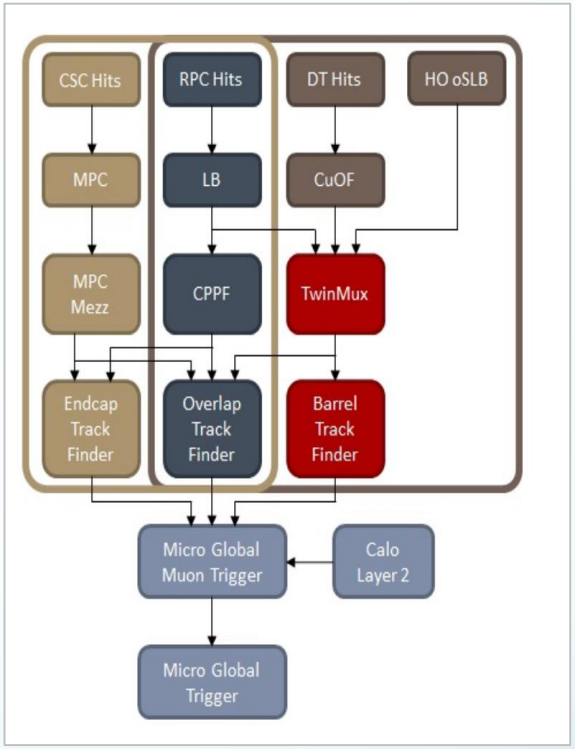
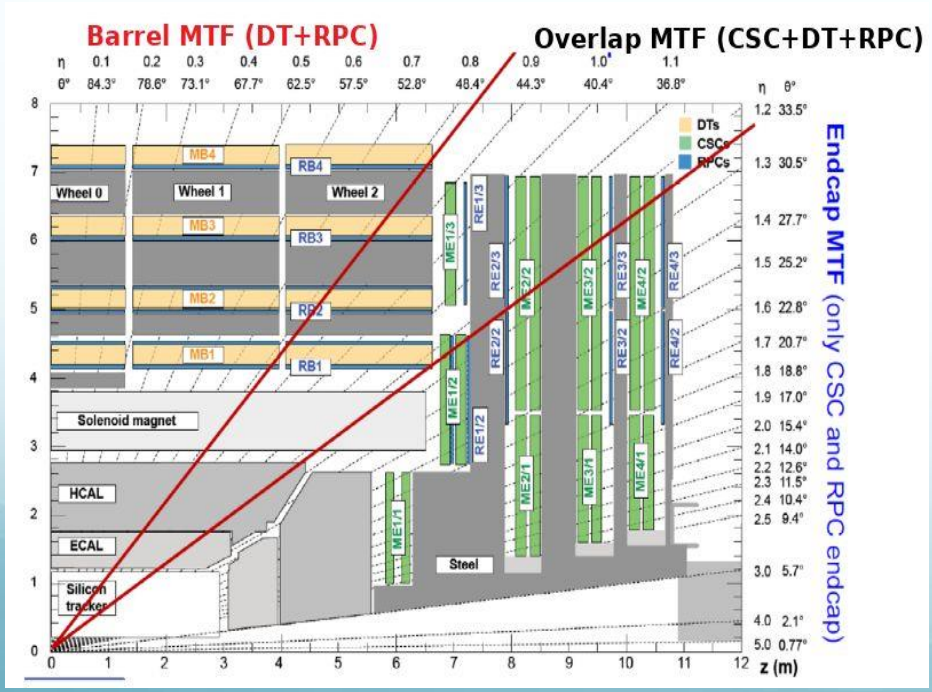
- The CMS L1 muon trigger system combines the information from three muon detectors (Drift Tube, RPC, Cathode Strip Chambers): **it is a redundant system.**
- It is divided in 3region: Barrel, Overlap and Endcap





Requirement of μ system:

- identification of μ
- measurement of μ p_t
- bunch crossing (BX) assignment

ATLAS and CMS RPCs

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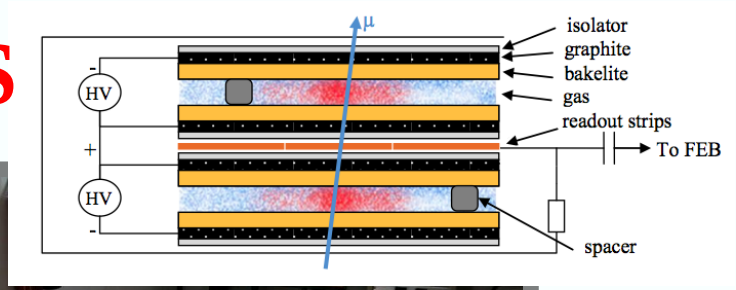
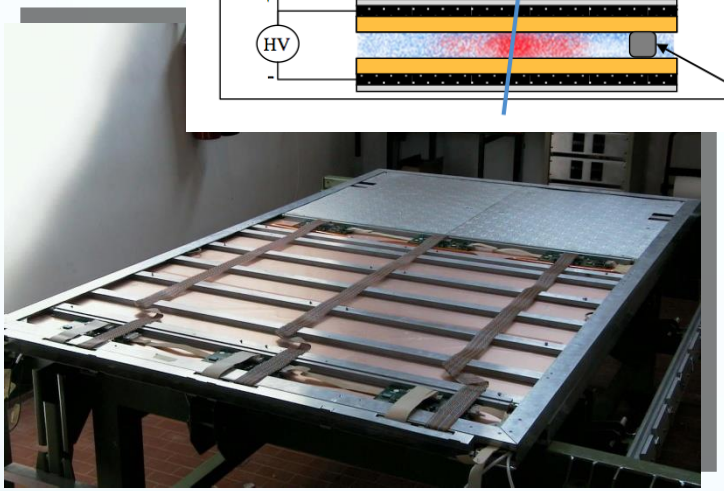
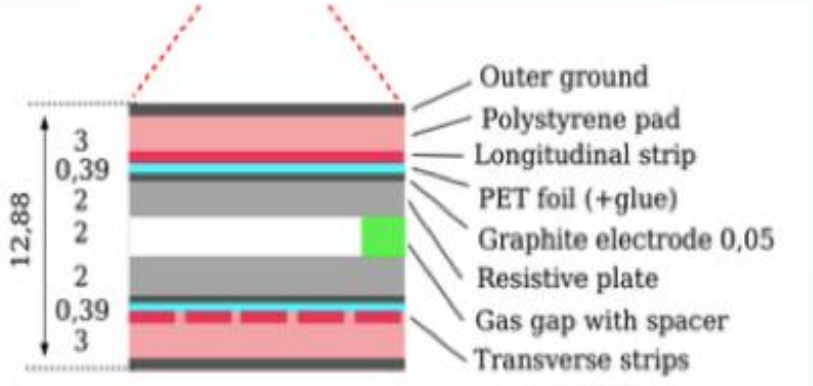
CMS





- **1056** chambers
- Sensitive layers area: **3.200 m²**
- **Double gaps: 2mm gas gap width**
- **Working in avalanche mode**
- **Bakelite** bulk resistivity: $\rho = 2 - 5 \times 10^{10}\ \Omega$cm
- **Gas Mixture** 95.2% $C_2H_2F_4$+4.5% i-C_4H_{10}+ 0.3%SF_6
- **Strip read-out:** 2 ÷ 4 cm
- **Charge per hit ≈ 20-30 pC**

ATLAS



- **600** chambers
- Sensitive layers area: **7000 m²**
- **Single gap: 2mm gas gap**
- **Working in avalanche mode**
- **Bakelite bulk resistivity:** $\rho = 2 - 5 \times 10^{10}\ \Omega$cm
- **Gas Mixture** 94.7% $C_2H_2F_4$+5.0% i-C_4H_{10}+ 0.3%SF_6
- **Strip read-out in η and φ:** 2.3-3.5 cm
- **Charge per hit ≈ 20- 30 pC**

The CMS and ATLAS RPC mass production

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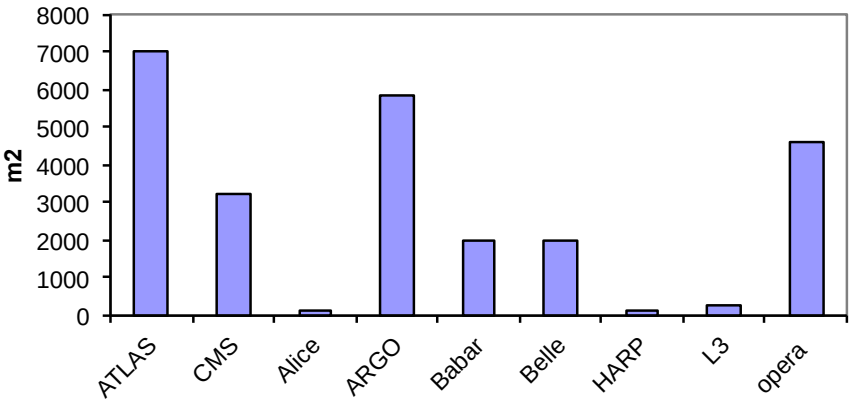
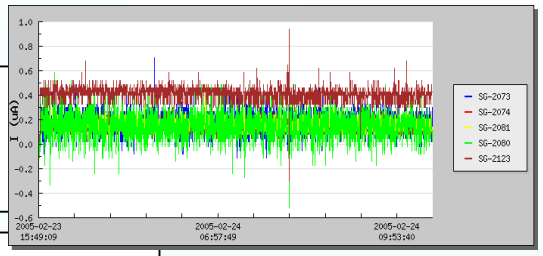
- CMS and ATLAS are very large experiments equipped with RPC.
- RPC mass production started in early 2002 and it required extensive control quality test at each production step.



CMS example

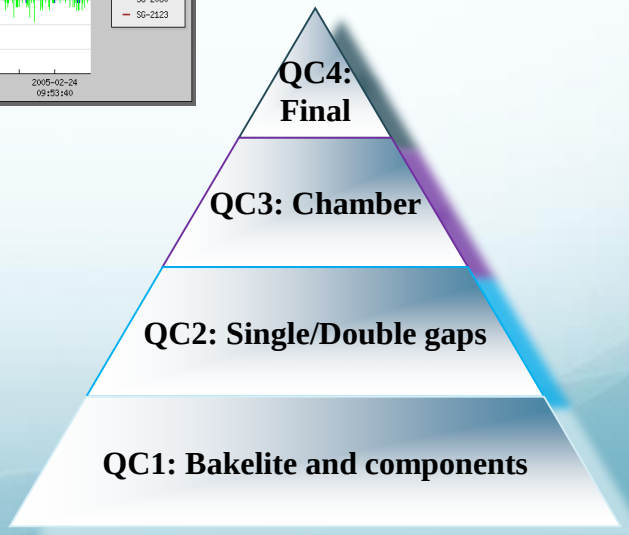


Final chamber tests:
- Gas leak, connectivity, dark current tests
- Long term detector stability test

Chamber Assembly and tests
- Visual inspection, gas tightness, dark current test, connectivity test
- Performance study with cosmic muons

Gaps and Double production test
- Visual inspection, gas tightness and spacer test
- Electrical and dark current, resistivity measurement

HPL production test: surface inspection, HPL resistivity
FEB test: PCB electrical integrity, FEB calibration, FEB +PCB calibration



World Wide RPC production (CMS example)

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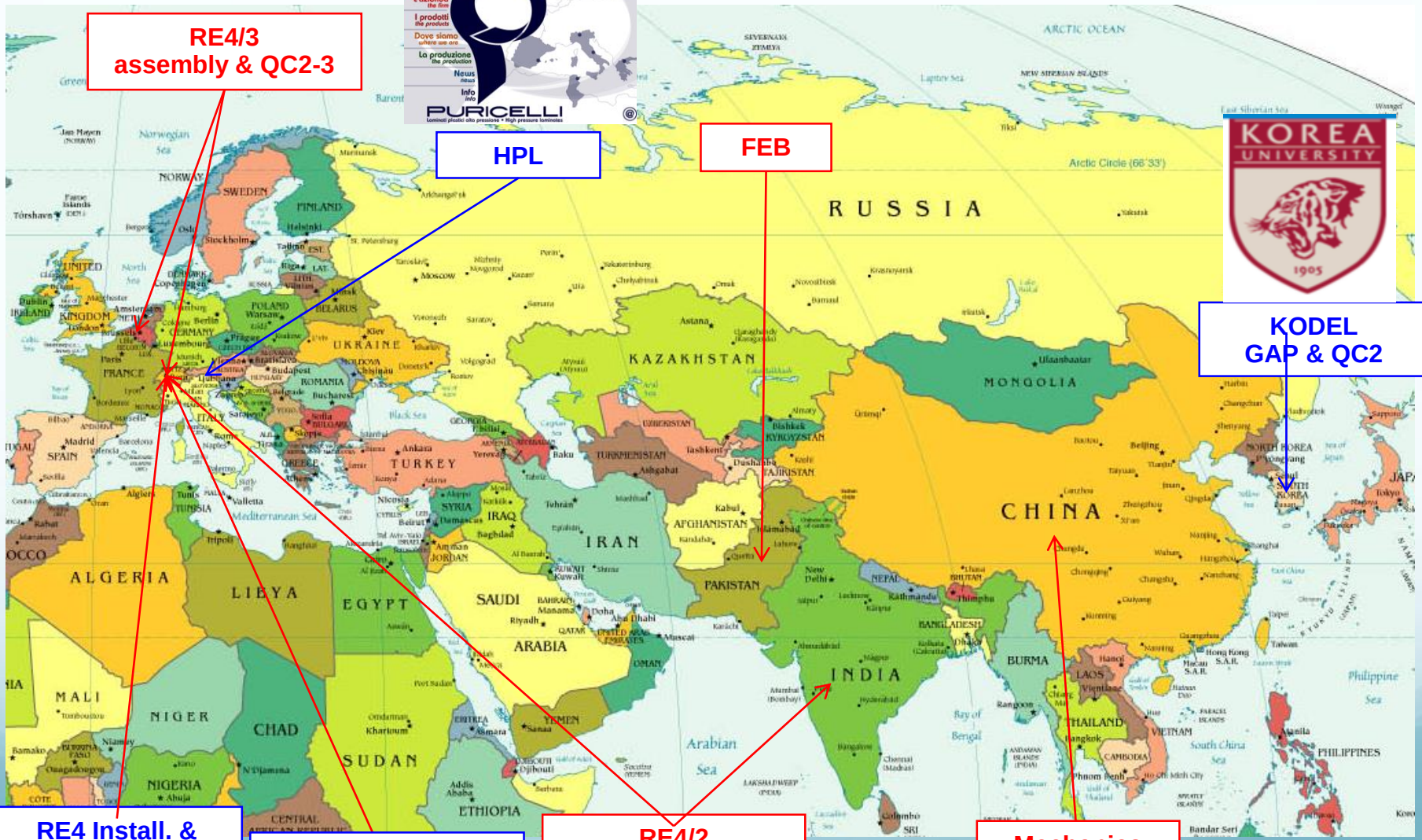

From the production to the installation and commissioning (CMS example)

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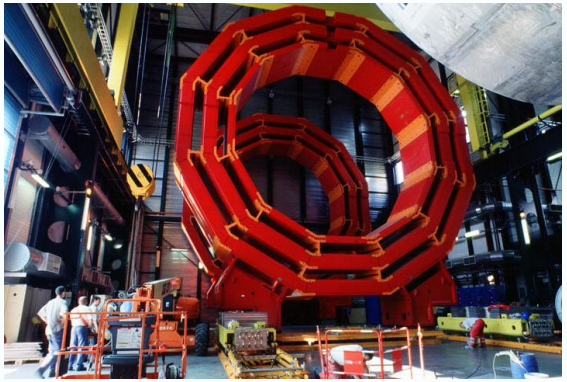
CMS RPCs mass production started in 2002 in Italy for the Barrel chambers (as for ATLAS chambers) and Korea University for Endcap chambers.



Commissioning

Lowering into the cavern

Endcap Installation

ATLAS and CMS RPC system performance (1)

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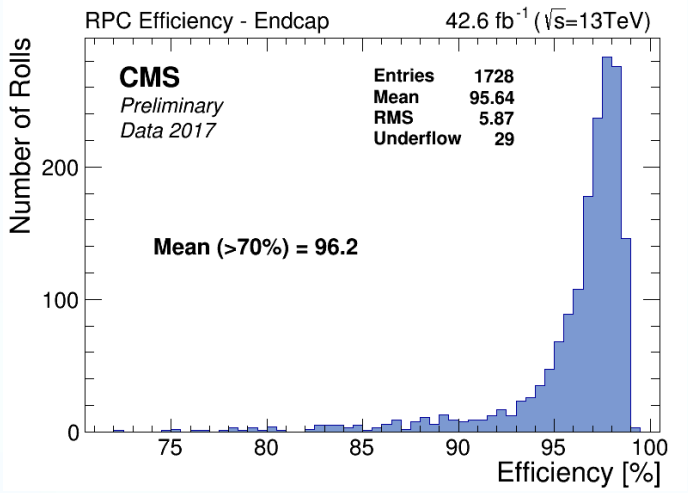

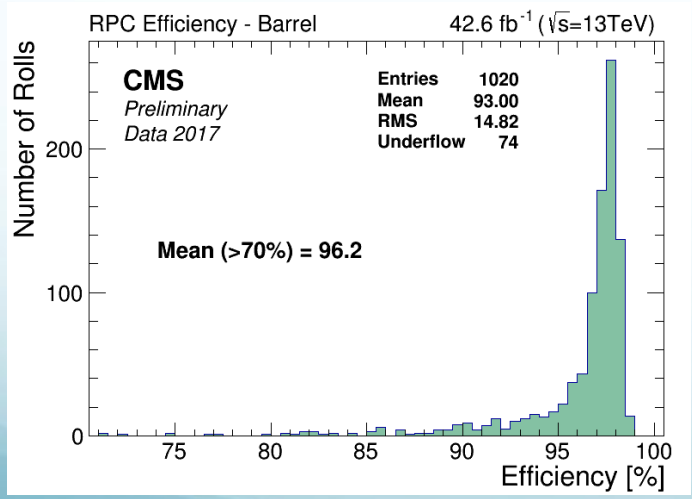

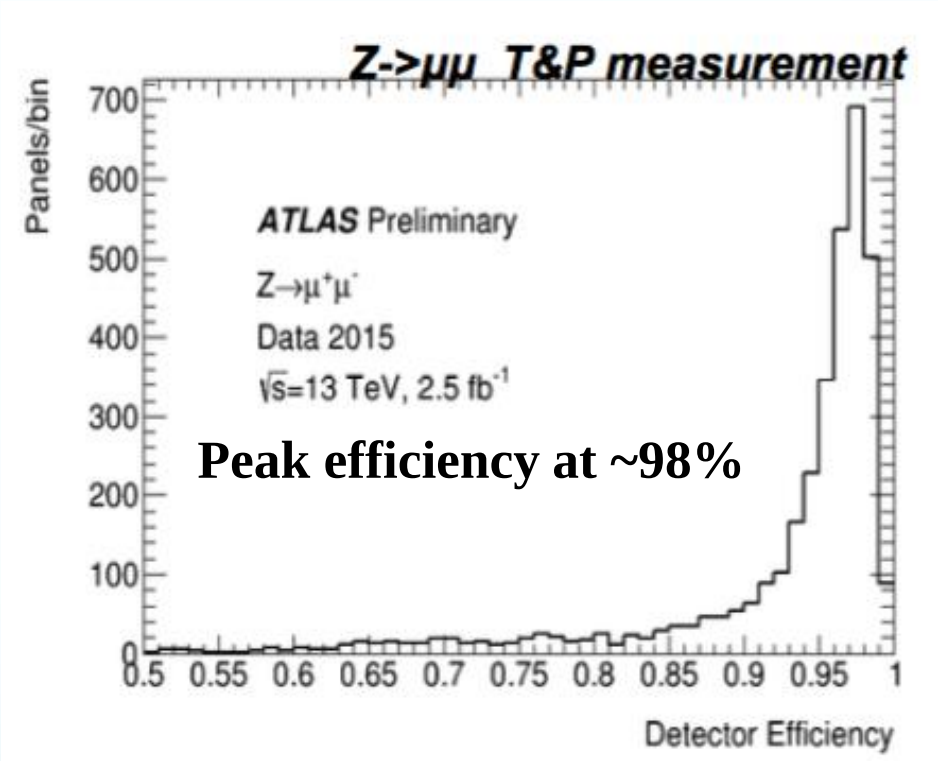

Although the complexity of the two systems, the CMS and Atlas chambers are very efficient!

All hardware problems are included in the distributions

ATLAS & CMS RPC system performance (2)

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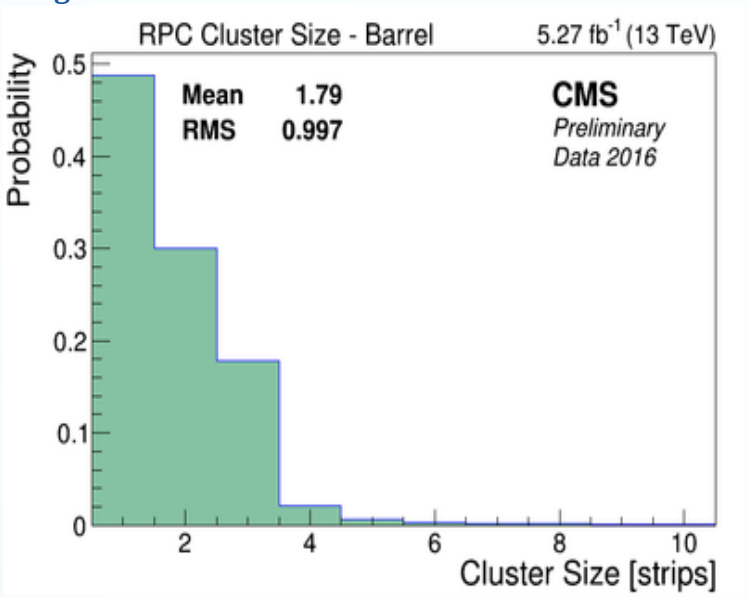

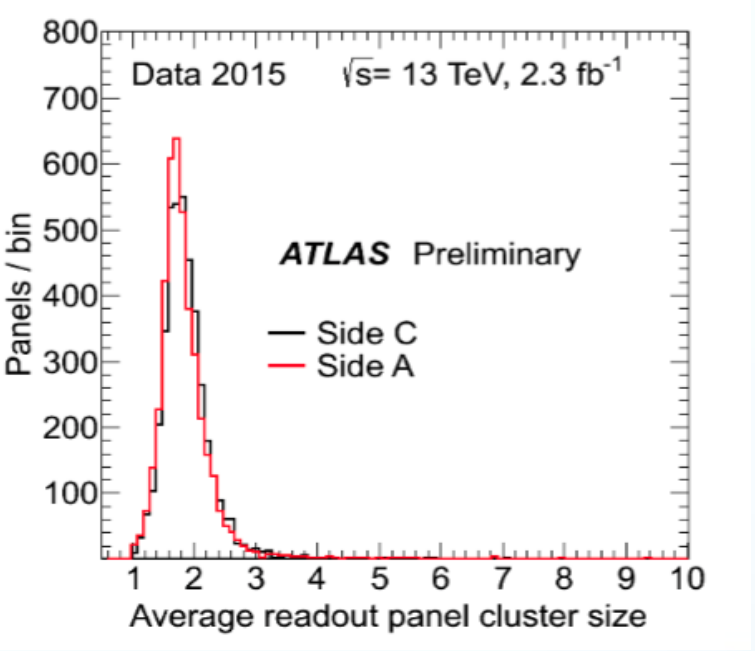

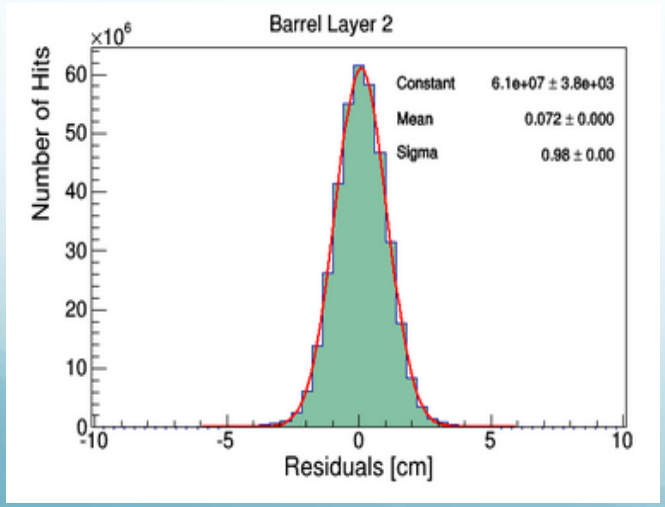

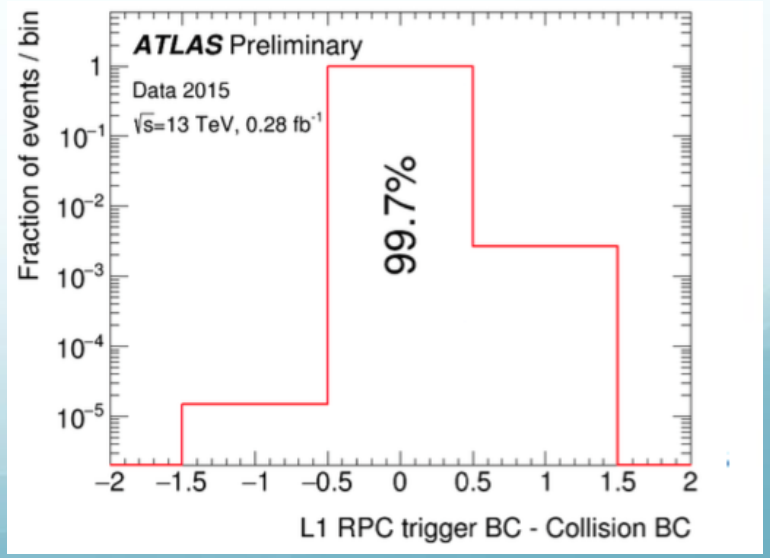

RPC Hit Resolutions

CMS and ATLAS L1 muon performance

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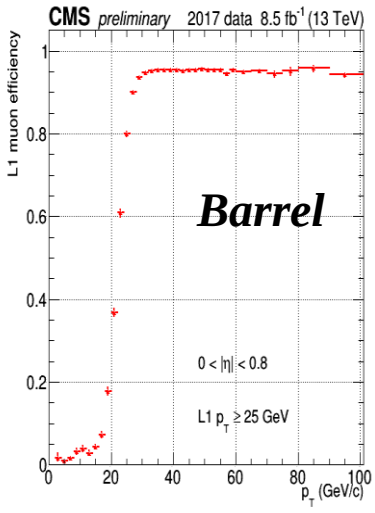

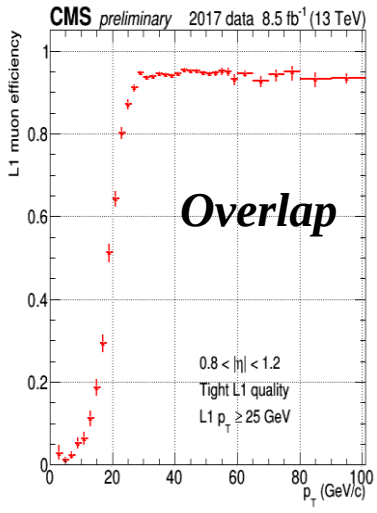

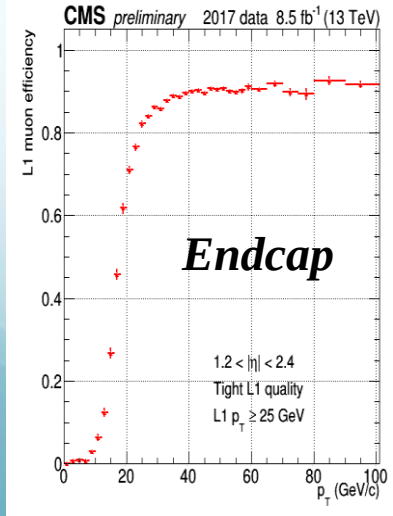

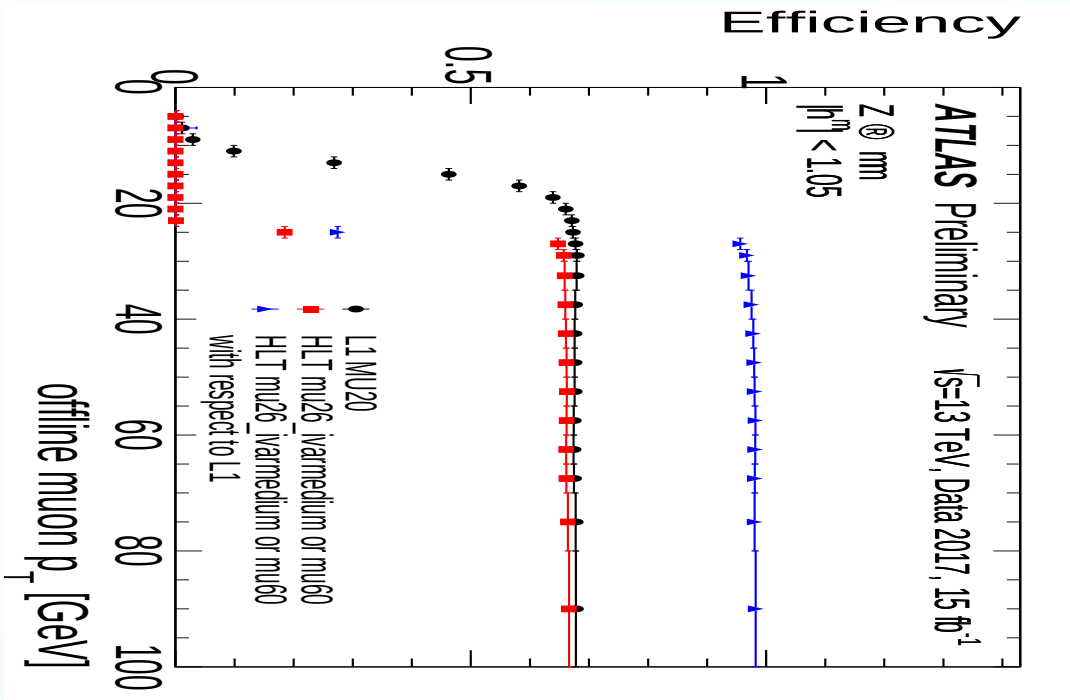

CMS and ATLAS L1 efficiency vs p_T curves

ALICE

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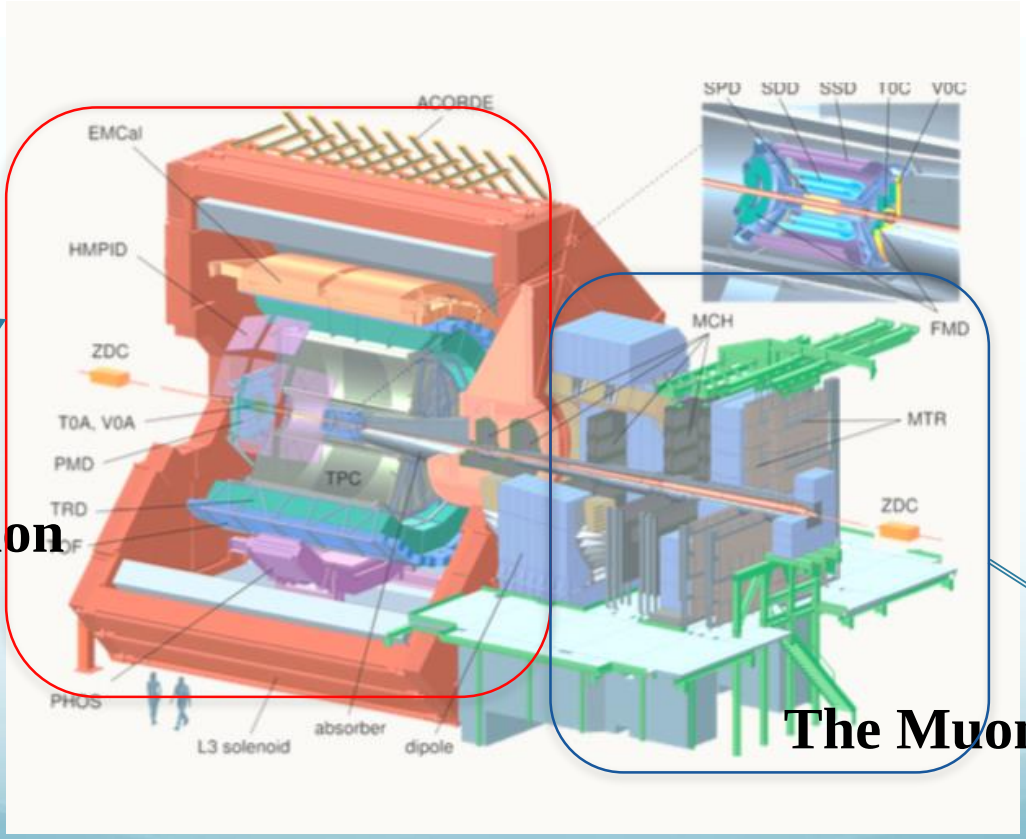
ALICE (A Large Ion Collider Experiment) is specialized in the detection of signatures of the Quark-Gluon Plasma state @ Heavy-ion collisions at ultra-relativistic energies (5.5 GeV). It is composed by two groups of detectors:



The Barrel region

The Muon Spectrometer

The Barrel region: ALICE TOF

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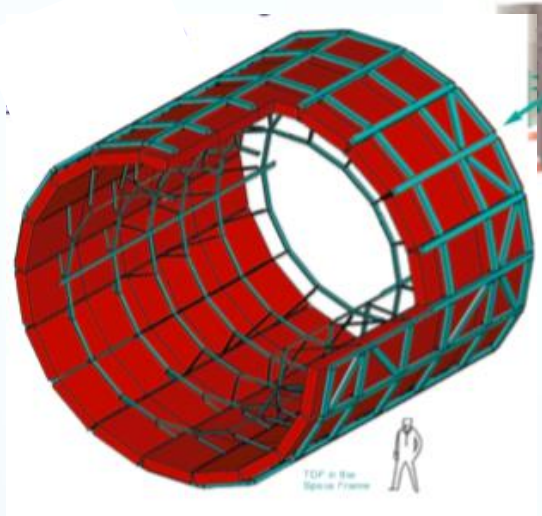


In the barrel region, charged particles in the intermediate momentum range (from 1 GeV/c to a few GeV/c) are identified by the **Time Of Flight (TOF) detector.**

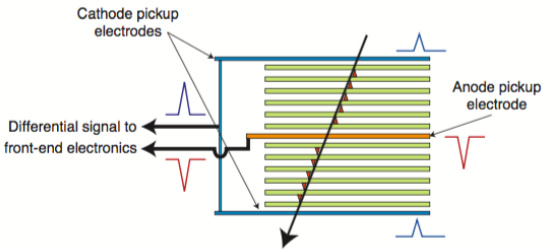
- The TOF s a large area detector covering a cylindrical surface of 141 m^2 with an inner radius of 3.7 m, a pseudo-rapidity interval [-0.9,+0.9] and full azimuthal coverage.
- **The time measurement with the TOF,** in conjunction with the **momentum and track length** measured by the **tracking detectors** is used to calculate the particle mass.
- **A time resolution of 100 ps** is required to provide 3σ π/K separation up to 2.2 GeV/c and K/p separation up to 4 GeV/c.

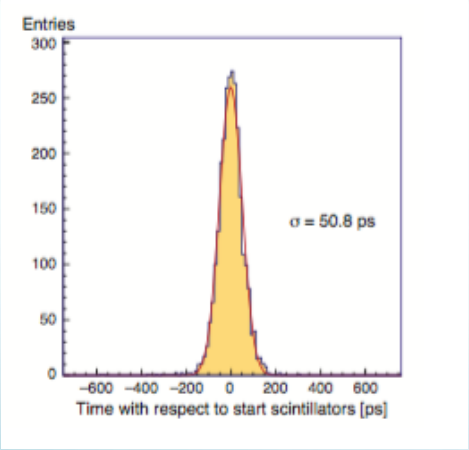
MRPC for ALICE TOF

G. Pugliese

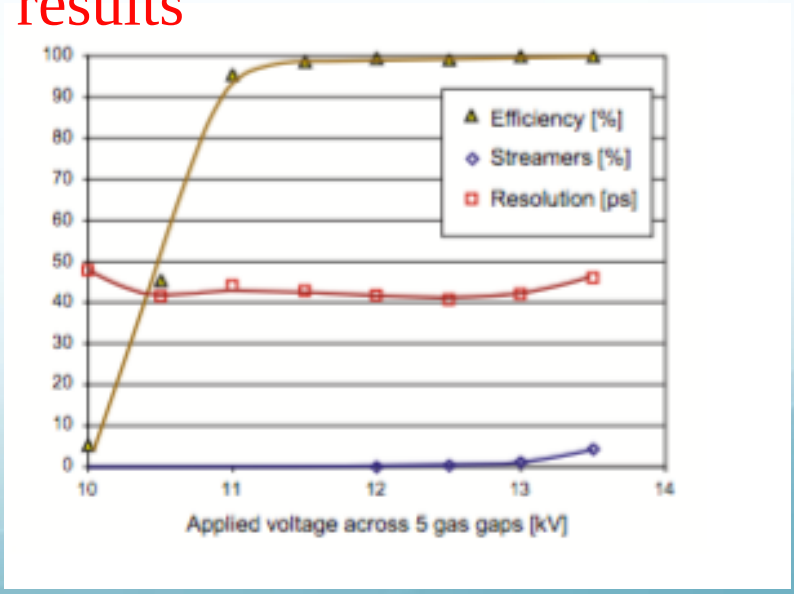
The TOF system is made of 1593 Multigap Resistive Plate Chamber (MRPC)

- Each MRPC consists of 2 stacks of glass, each with 5 gas gaps of 250 μm; with an active area of 7.4×120 cm^2
- Electrodes: high resistivity (≈10^{13} Ωcm) float glass, 0.4 mm thick
- 96 readout pads of 2.5 × 3.5 cm^2





Performance results



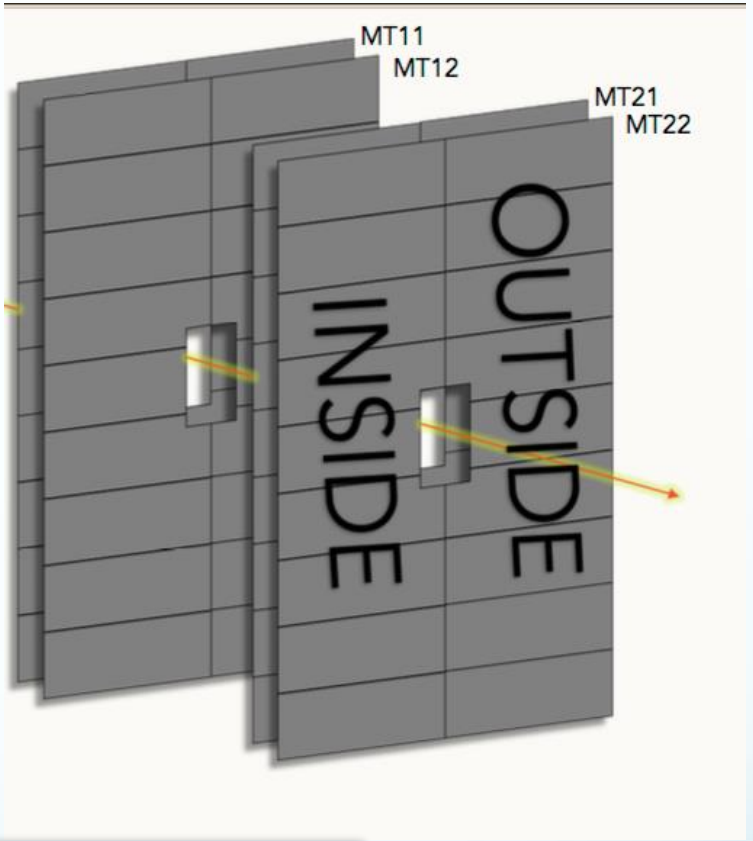
The time resolution of the TOF MRPC is in the 50 ps range. A typical efficiency and time resolution plateau as a function of the high voltage is more than 2 kV long before the onset of streamers, with efficiency reaching 99.9 %.

The ALICE muon spectrometer

G. Pugliese

It consists of:

- **4 detection planes** organized in two stations (@ 16 m and 17 m from IP)
- Each plane equipped with **18 RPCs** (72 RPCs in total), for a total of active area per detection plane **5.5 x 6.5 m^2**
- RPC planes are read out on both sides with a strip pitches follow projective geometry



RPC geometry

- Single gap (2mm thickness)
- HPL resistivity $10^9 \div 10^{10}$ Ωcm
- **Maxi-Avalanche working mode**
- Gas mixture 89.7 % $C_2H_2F_4$ +10 % i-C_4H_{10} + 0.3 % SF_6
- **Charge per hit ≈ 100 pC**

Alice RPC Performance

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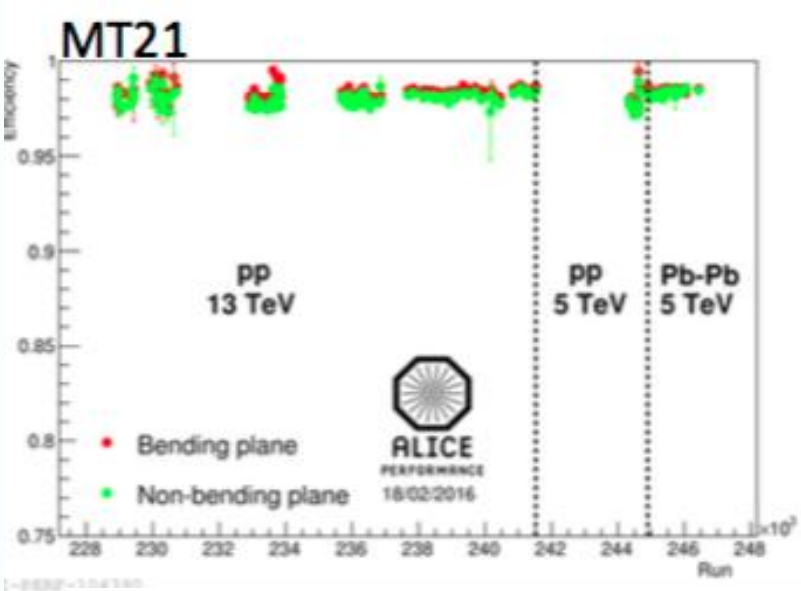
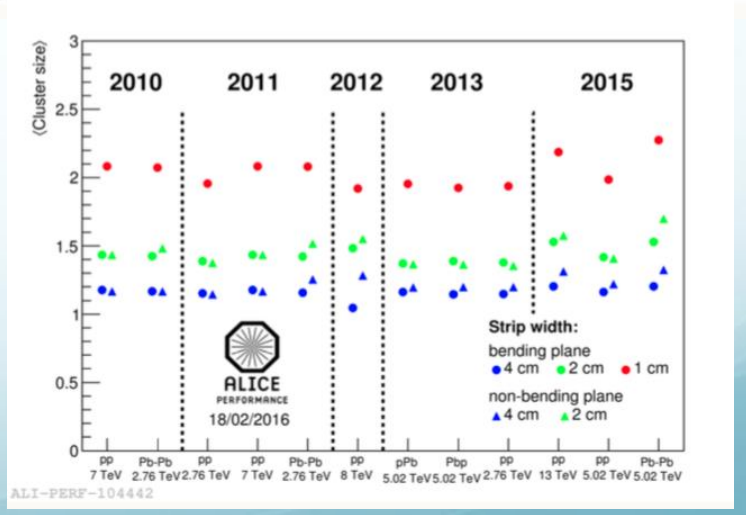
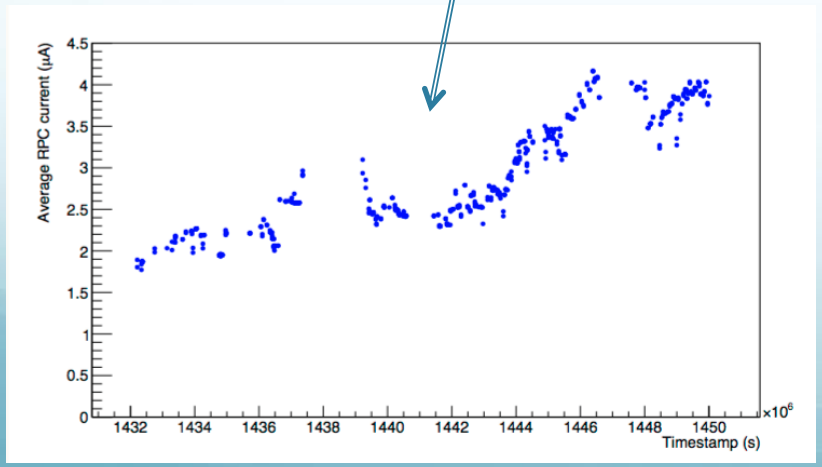
For all 4 detection planes, the efficiency is > 95% and stable in time.

Cluster size stable in time and almost independent of collision system

Increasing trend for dark current and rate, under monitoring…







The RPC in ARGO experiment

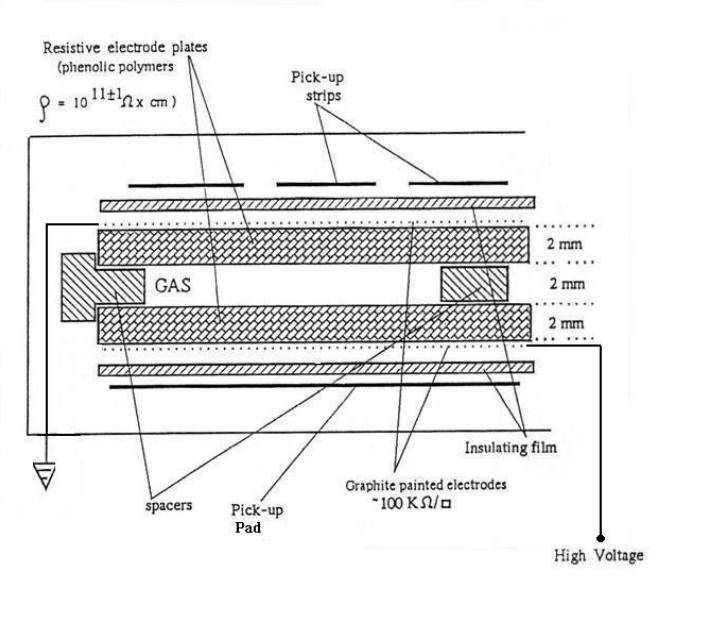
G. Pugliese

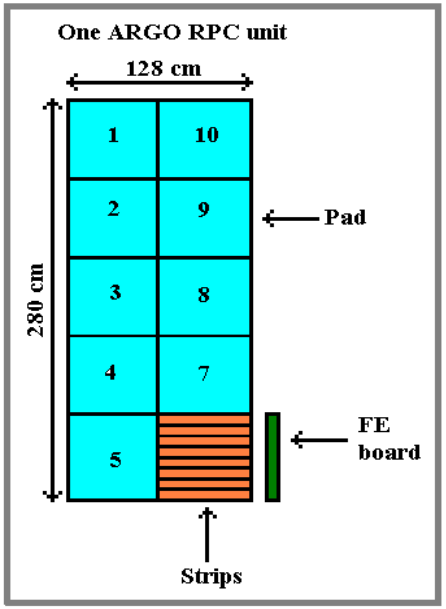
ARGO is an Extensive Air Showers detector being installed in YBJ laboratories (4300 m a.s.l., Tibet)

- The **energy** is reconstructed from hit multiplicity (in the range 100 GeV to several TeV for γ astrophysics)
- The **direction** of primaries is reconstructed from the time profile of the shower front **(time resolution ~ ns required)**
- The discrimination γ/p done from the particle density
- **Low energy threshold for an EAS detector is obtained with: high altitude and full coverage over 74×78 m²**

Argo experiment

G. Pugliese



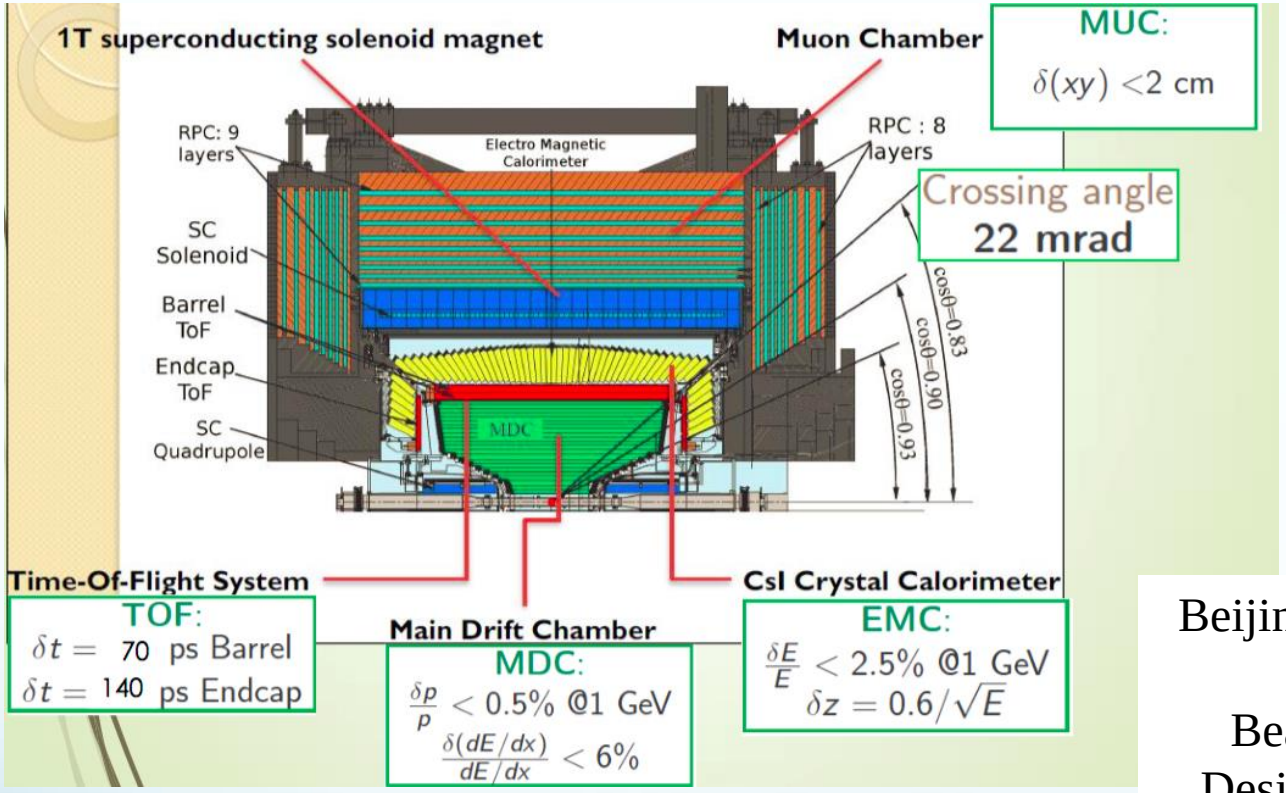


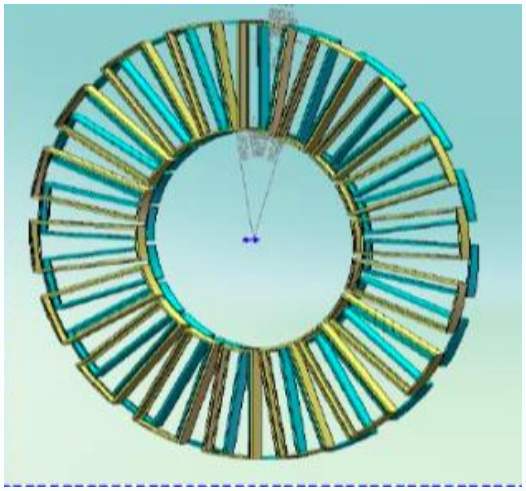
Layer of Resistive Plate Chambers (RPC), covering a large area (5850 m²)

- Gas gap thickness: 2 mm (single gap)
- HPL Electrodes are 2 mm thick
- Gas mixture: C2H2F4 /Ar/i-C4H10=75/15/10 (to be operated at 600 mbar)
- Signal picked up with strips 6 x 62 cm² or pads

Beijing Spectrometer III (BESIII)

G. Pugliese





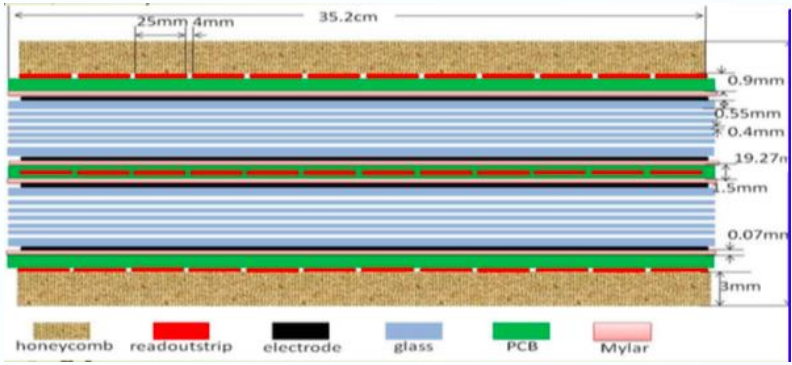
Beijing Electron-Positron Collider II (BEPCII)
Beam Energy: 1.0 – 2.3 GeV
Design Luminosity: 10^{33} $cm^{-2}s^{-1}$

- TOF system in the endcap region is equipped with 36 overlapping MRPCs replacing scintillators (EJ204) due to high resolution to pion (138 ps)
- Mass production started in 2014-2015
- Installation and commissioning in 2015 -2016

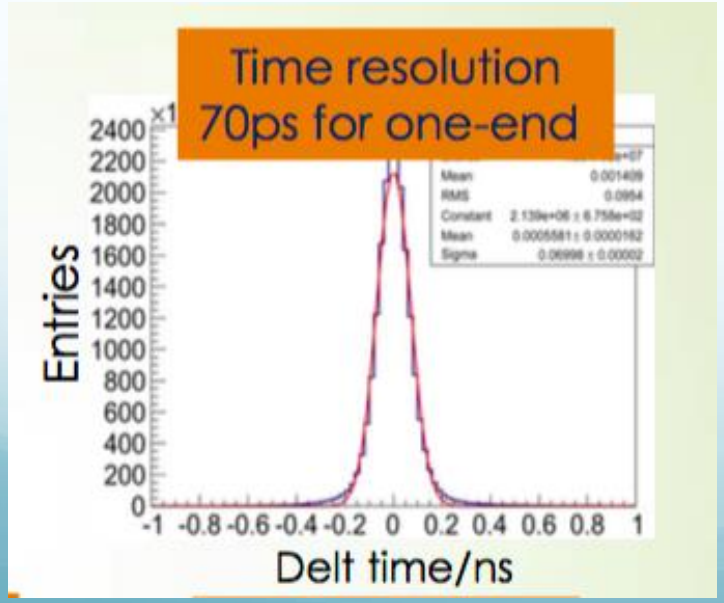
ETOF @ BESIII

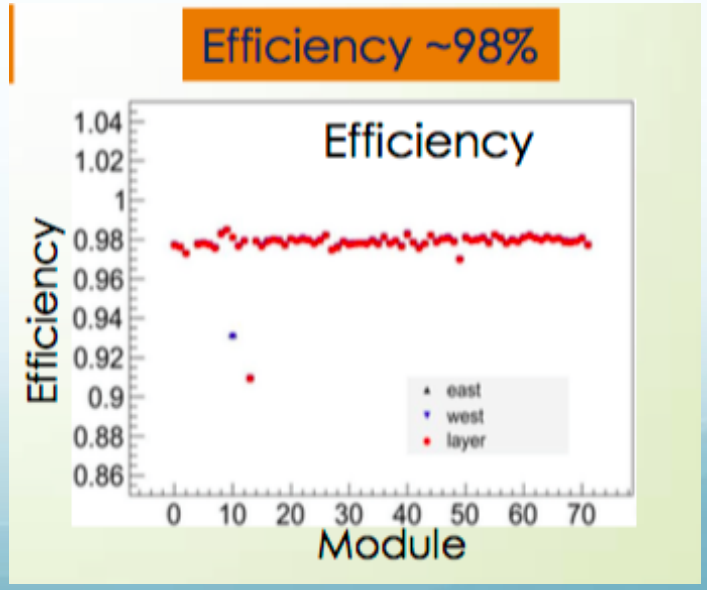
G. Pugliese

Electrodes: Resistive plate: floating glass
Number of gas gap: 2 x 6
Gap size: 0.22 mm
Readout strip: 2.4 cm x 9.1-14.1 cm
Gas mixture: 90%R134a+5%C4H10+5%SF6.



Preliminary results with collision data





MRPC module mass production

11

Production processes and quality control
Details in Zhen Liu's Poster

Materials Test
Cleaning
Assemble
Quality Inspection
Box Package
Leak detection
Cosmic-ray Test
finished

Materials Testing

Assembling

Finish production

Production record

80 MRPC modules is produced

G. Pugliese

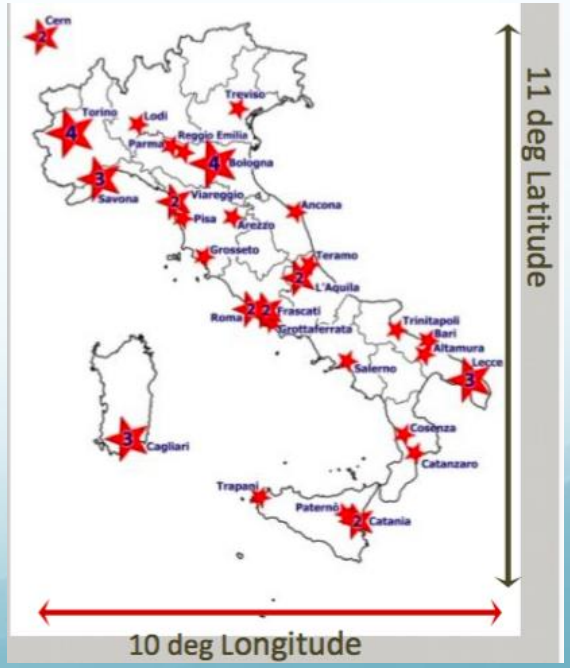
The EEE project

- The **Extreme Energy Events (EEE) Project** is an experiment for the detection of Extensive Air Showers (EAS).
- It is a joint scientific and educational initiative by CENTRO FERMI in collaboration with INFN and CERN.

- **Physics goal** is to reveal EAS of very high/extreme energy coming from very high energy primary cosmic rays ($> 10^{18}$ eV).

- The detection of an EAS is achieved by measuring the coincidences of secondary muon on ground recorded at the different sites of the **EEE Telescopes Array.**

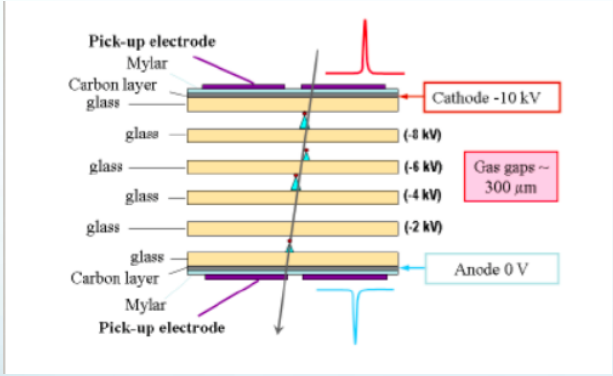
- More then **50 EEE telescopes across** an overall area of ~ 0.5 x 10^6 km^2 are hosted in High Schools spread on the Italian territory

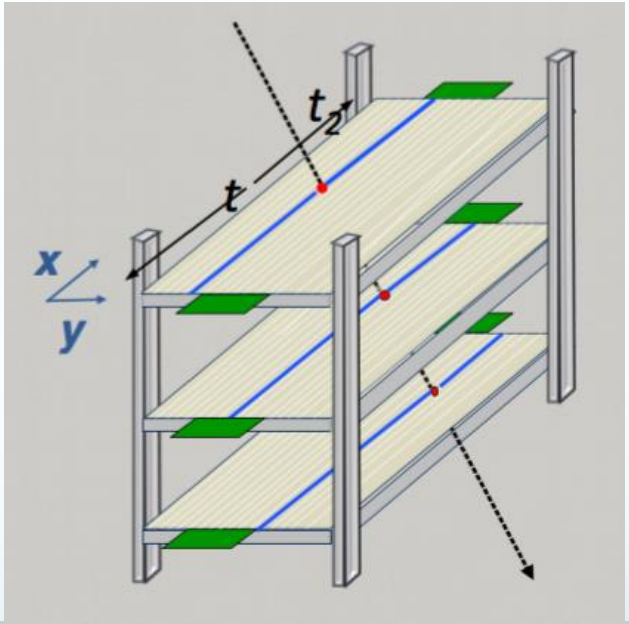


The EEE Telescope

G. Pugliese

- Three Multi-Gap Resistive Plate Chambers (MRPCs) of 1.60 x0.80 m^2, with similar operation characteristics to the ones built for the ALICE TOF.
  - 6 Gas Gaps
  - Gas mixture 98 % $C_2H_2F_4$ + 2 % SF_6
  - 24 readout copper strips as electrodes, pitch of 3.2 cm, on both glass plates
  - ~10^{13} Ωcm volume resistivity





The impact time in each MRPC is reconstructed as the average of signal arrival times at the strip ends (*RIGHT* and *LEFT SIDE*)

$$T_{Hit} = \frac{T_{RIGH} + T_{LEFT}}{2}$$

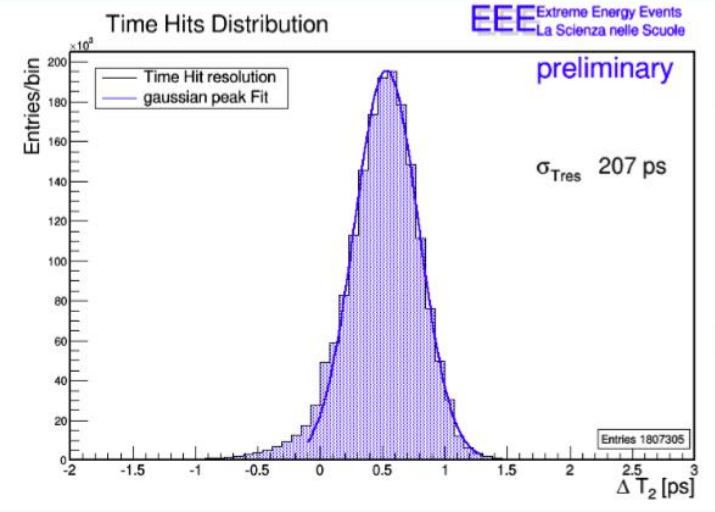
The particle impact point is reconstructed by :

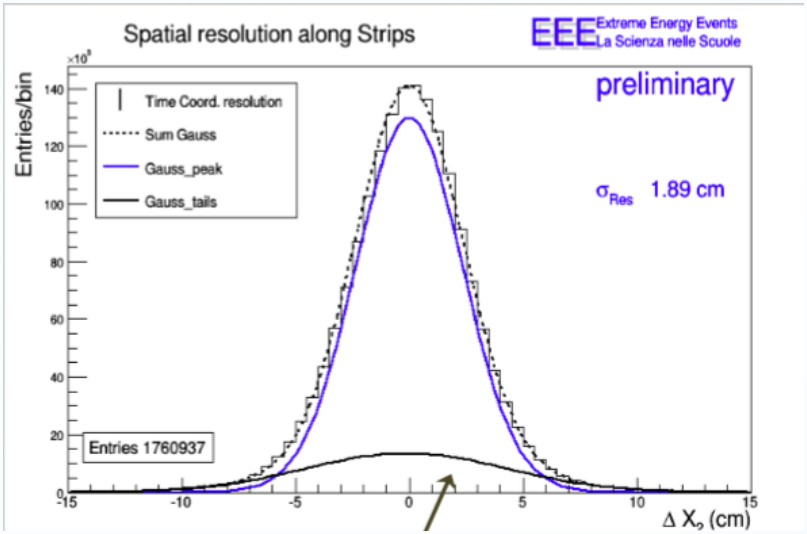
- the fired strip (y)
- the difference of signal arrival times at the strip ends measured by TDCs (x)

$$x = \frac{L - |t_2 - t_1| v_e}{2}$$

EEE Telescopes performance

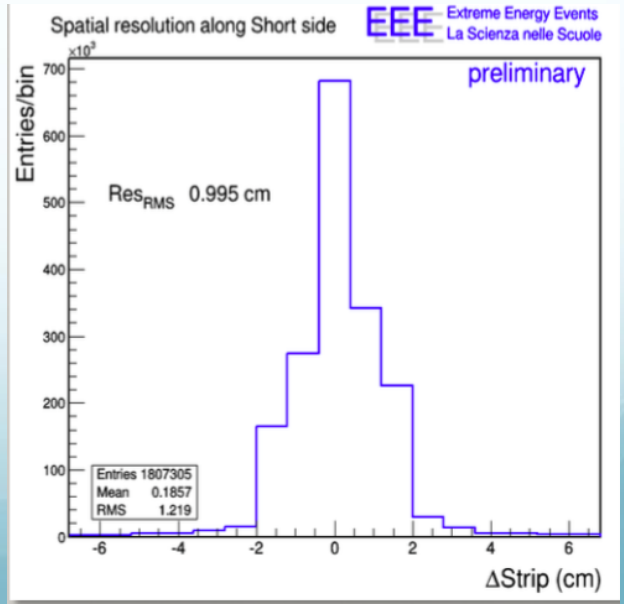
G. Pugliese





Time resolution for the 3 MRPCs

X-Y Spatial resolution



Conclusions

The RPC are gas detector are extensively used in several experiments for precise time and spatial measurements. High detection efficiency, the relative low production cost and simple structure are the most attractive futures of the RPCs as many modern detector systems require the coverage of large areas.

Currently they are used as trigger detector at the Large Hadron Collider in the experiments **ATLAS, CMS & ALICE**, and for Extensive Air Shower experiments, **ARGO** in Tibet and the EEE project in Italy.

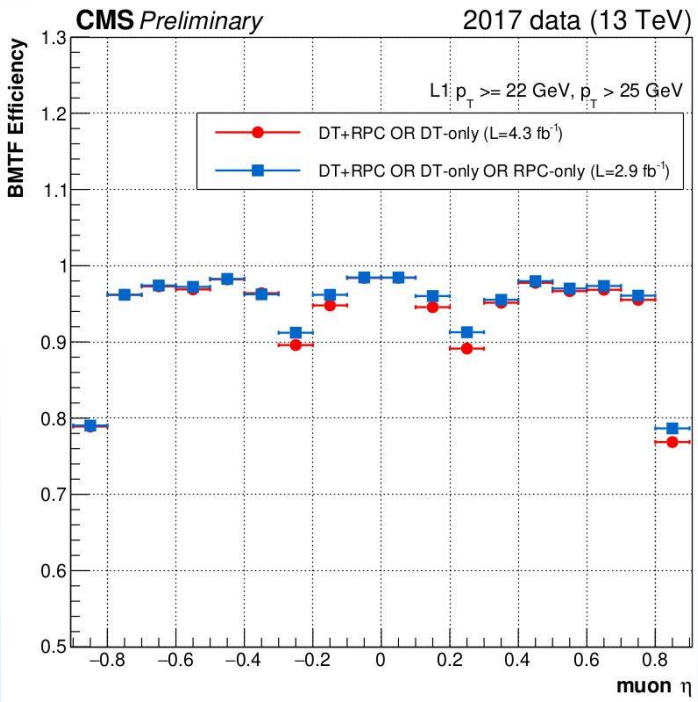
They are also used as TOF detector at BEPCII for **BESIII experiments** and at LHC in **ALICE.**

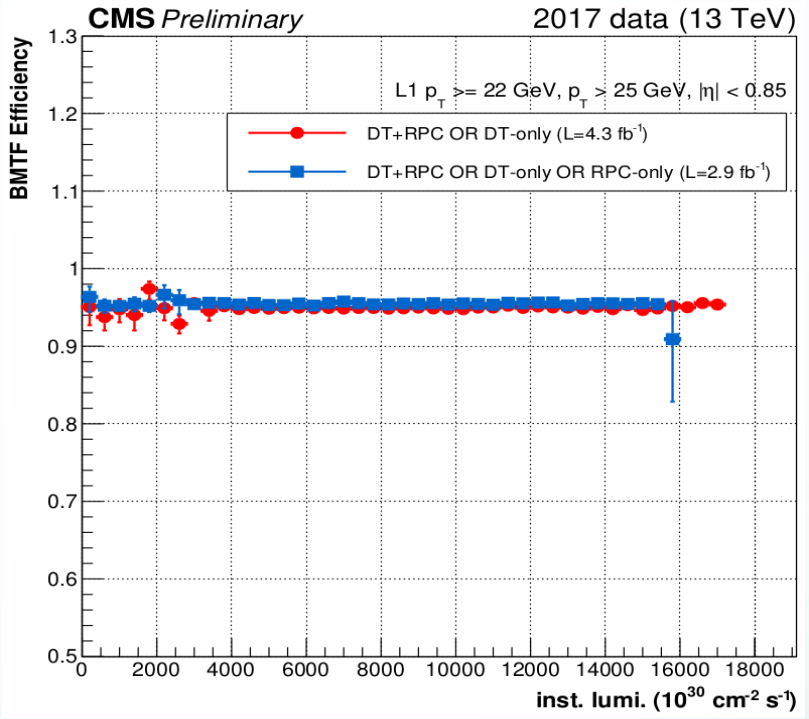
Looking forward for future applications....

Spare

CMS RPC Trigger performance

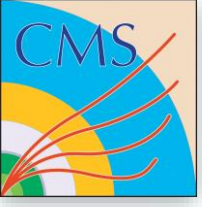
G. Pugliese





No dependence on luminosity is observed for either algorithm and the inclusion of the RPC-only segments.

RPC-only segments were included in the Barrel Trigger primitive algorithm in 2017:
Overall BMTF efficiency improves by ≈ **0.7%**.



G. Pugliese

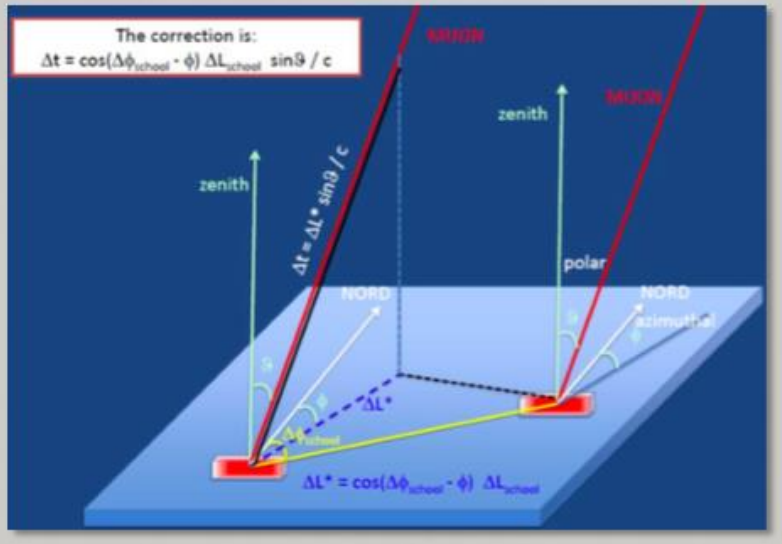
The Muon Tomography

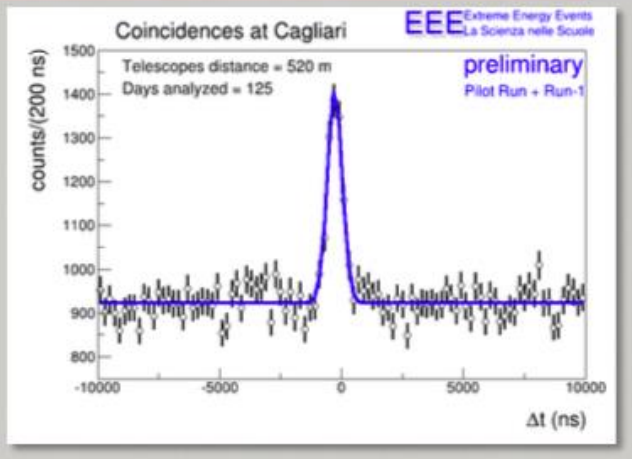
Proton detection of the ToF-RPC at the BGOegg experiment

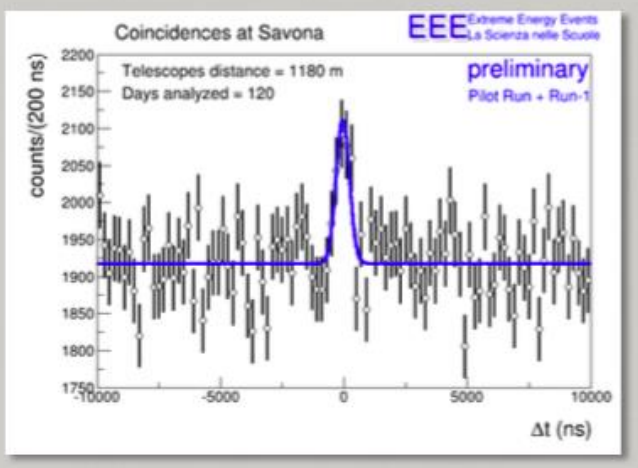
EEE Telescopes Physics results

G. Pugliese

Search for coincidences







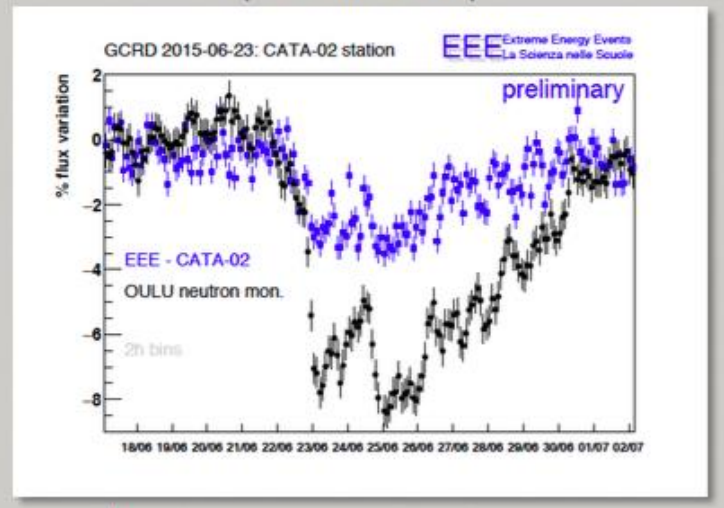
… to more than 1 km at Savona

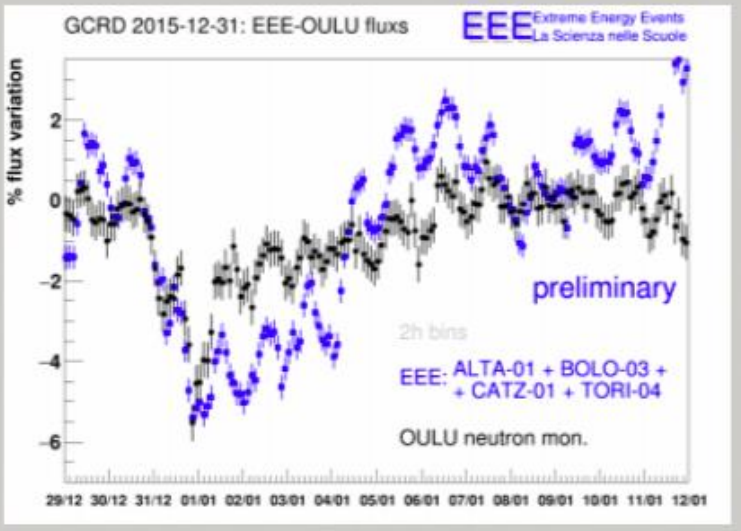
RPC 2016

Study of cosmic ray flux variation

Rapid decreases (Forbush decreases) of the galactic cosmic-ray flux, associated to solar phenomena are detected by the EEE stations in good agreement with neutron monitor stations

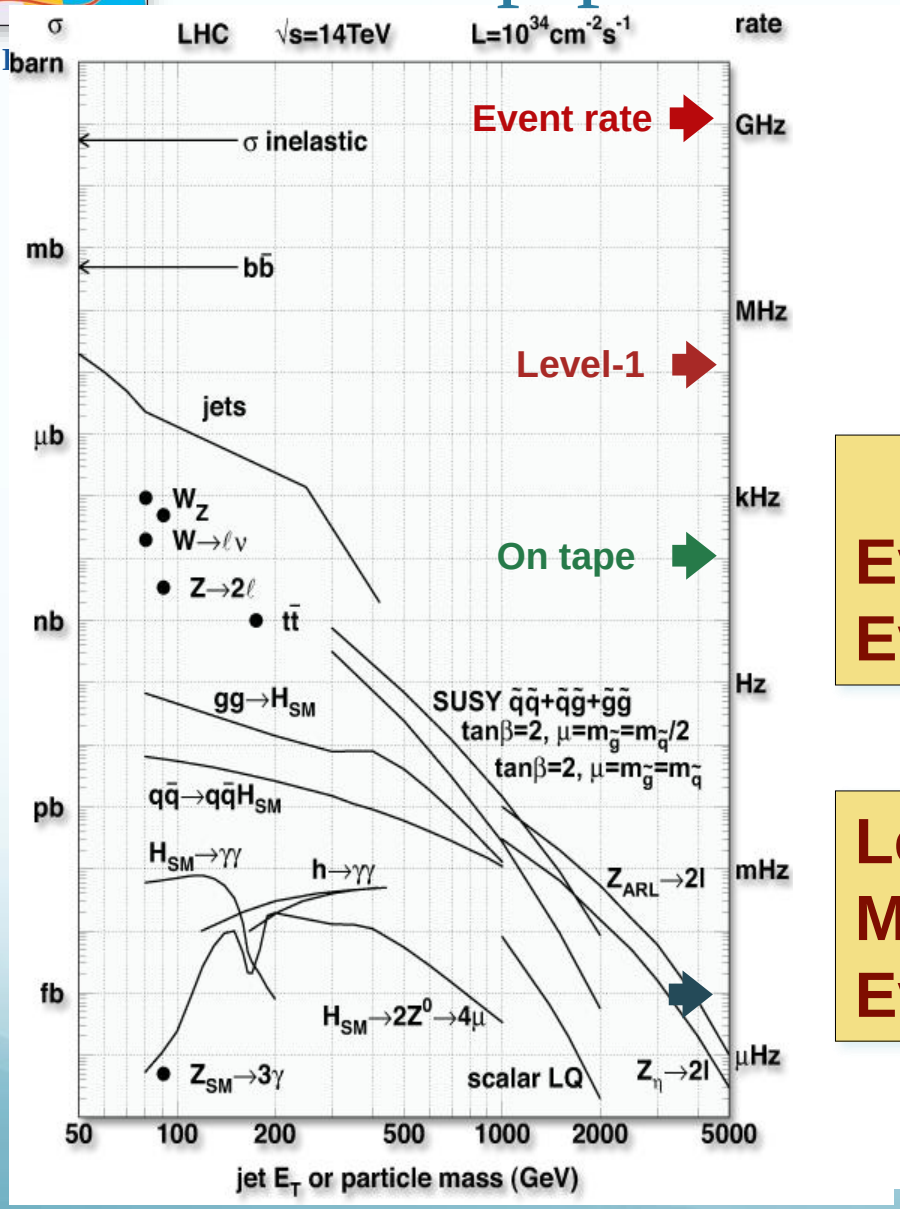
Flux decrease as observed by the CATA-02 station (Forbush June 2015)

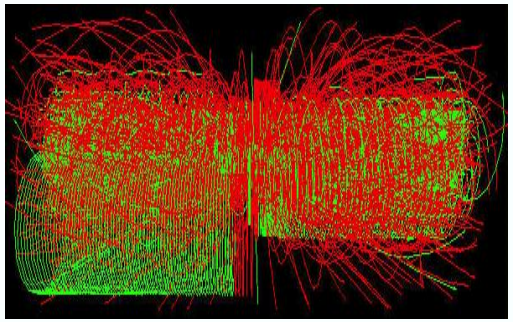




Flux decrease as observed by 6 stations (adding up data set from different stations reduce the signal/noise value)

p-p collisions at LHC





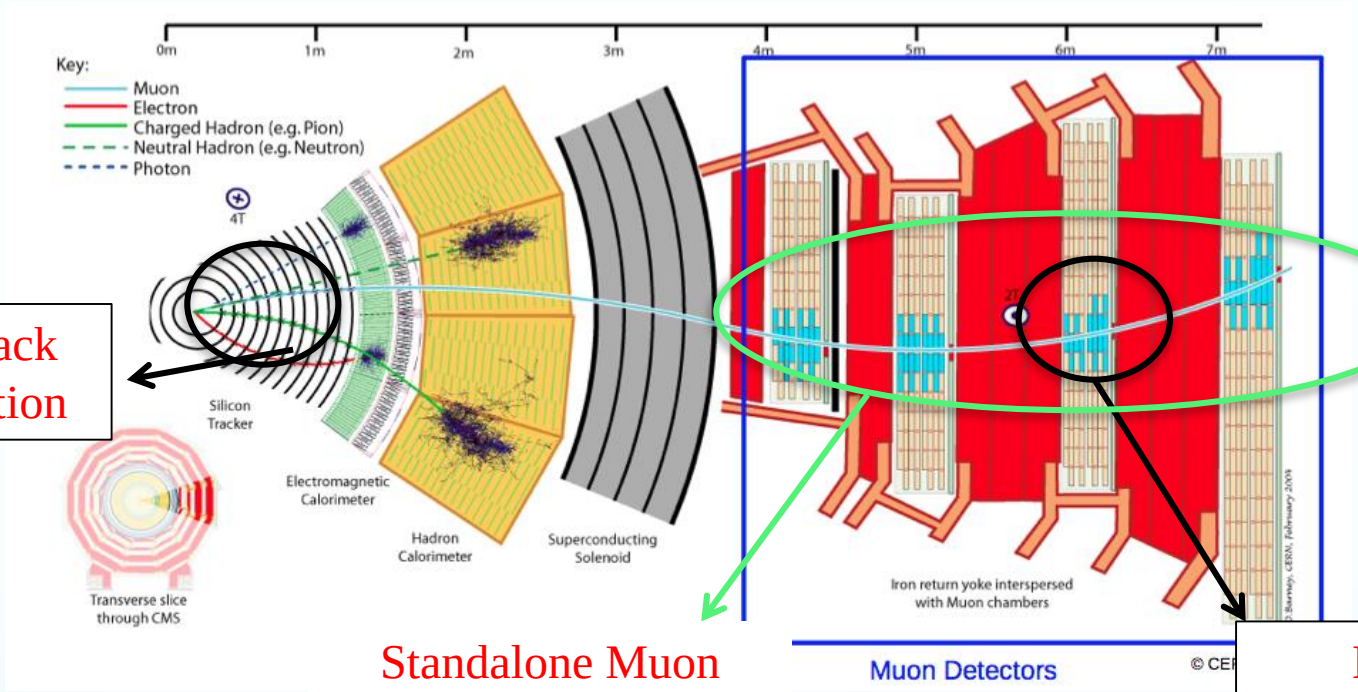
ATLAS / CMS

Event Rates:	**~ 10^9 Hz**
Event size:	**~ 1 MB**

Level-1 Output	**~100 kHz**
Mass storage	**~10^2 Hz**
Event Selection:	**~1/10^{13}**

Muon Reconstruction

G. Pugliese



Tracker track reconstruction

Standalone Muon reconstruction

Performed using DT/CSC segments & RPC hits

Local reconstruction

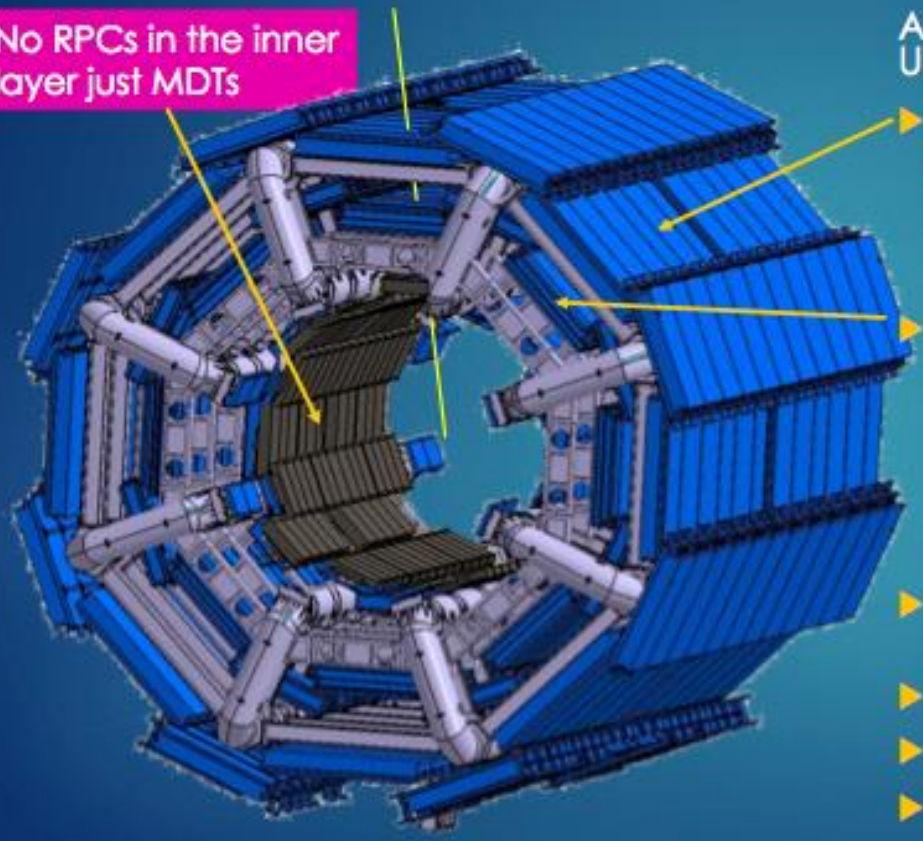
Performed within single chamber

Global muon reconstruction (out side –in): a standalone muon is propagated to match a tracker track. If matching is positive a global fitting is performed.

Tracker Muon (inside – outside): a tracker track is propagated to muon system and qualified as muon if matching with standalone or one segment.

The ATLAS RPC System in numbers

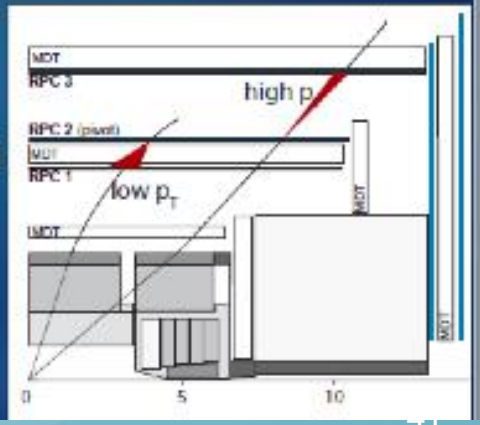
No RPCs in the inner layer just MDTs



About **1000** RPC doublet UNITS

- OUTER LAYER for High pT trigger
  - **400** BO units arranged in **200** chambers
- MIDDLE LAYER for Low pT trigger
  - **600** BM units arranged in **400** chambers (PI+CO coupled in 200 BM stations)
- 6 independent layers measuring Eta and Phi
- Total surface **7000** m^2
- **370000** FE channels
- **800** trigger PADs hard wired to the detector

G. Aielli - RPC Seminar - USTC, Hefei 09/02/18



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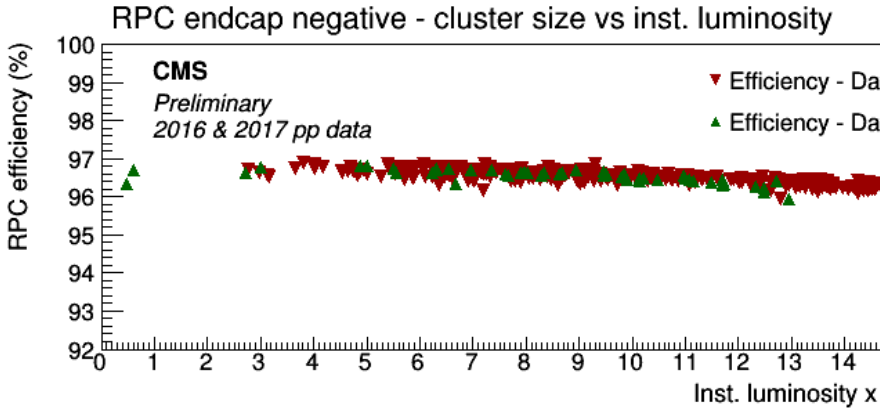
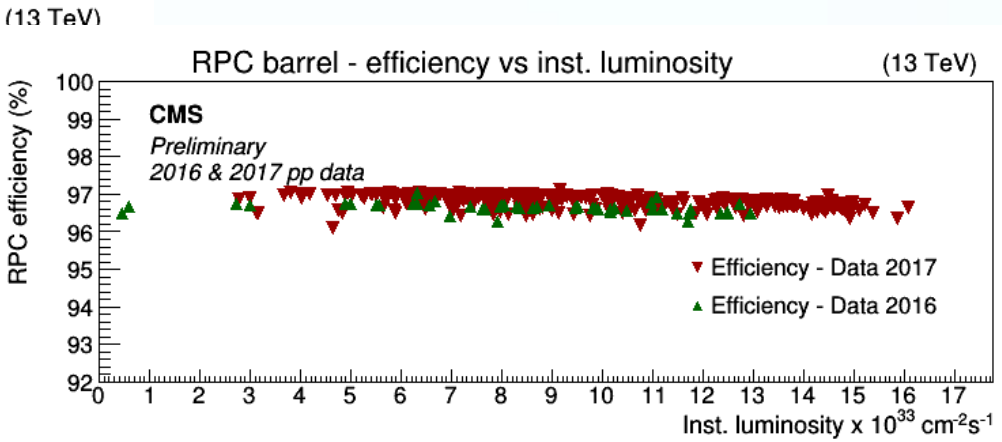
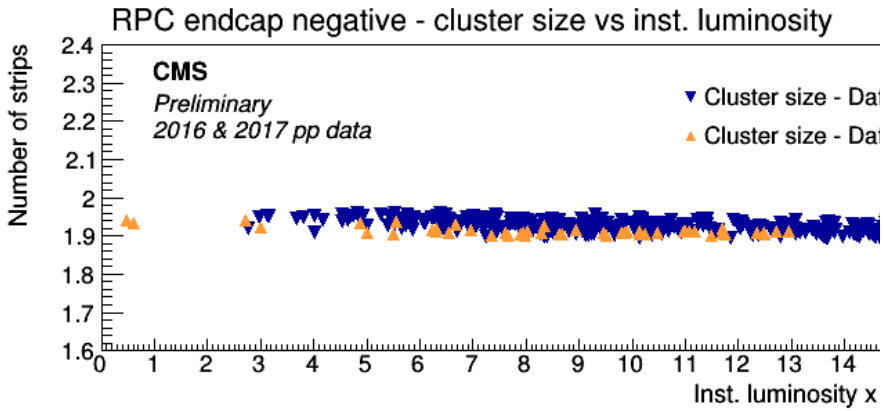
At $L = 5*10^{34}\ cm^{-2}s^{-1}$ **(HL-LHC)**

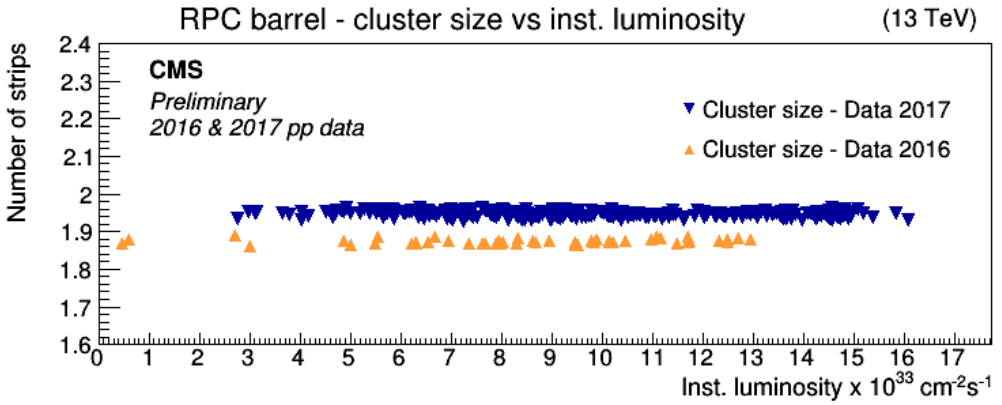
Extrapolated efficiency reduction

~ 0.8 % in barrel **& ~ 2 % in** endcap









G. Pugliese

The Large Hadron Collider

Large Hadron Collider is a proton-proton collider, with center of mass collision energies of up **to 14 TeV.** Installed 100 m underground in a tunnel 27 km long. Two high luminosity experiments, ATLAS and CMS, aiming at a peak luminosity of **10^{34} $cm^{-2}s^{-1}$**.

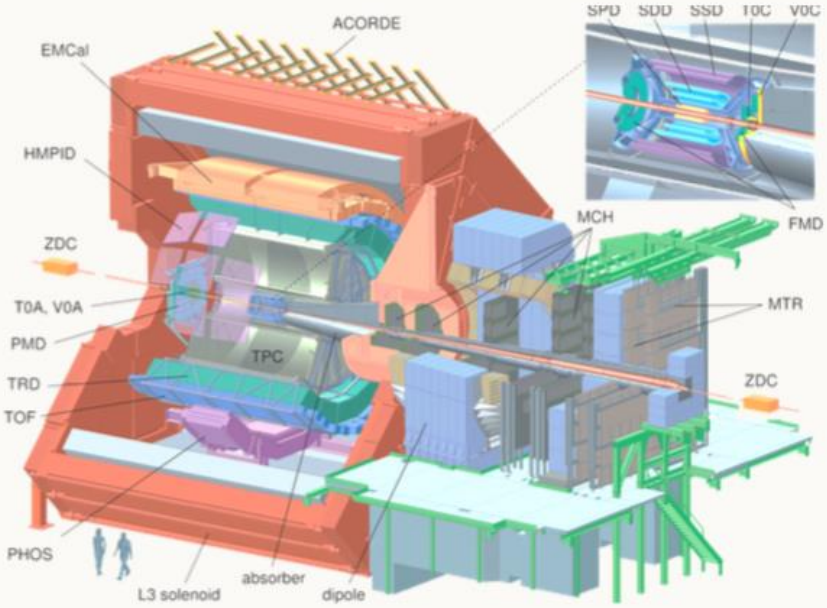
	2010	2011	2012
Lumi Recorded	43.17 pb^{-1}	5.561 fb^{-1}	6.15 fb^{-1}
Max lumi	2 x10^{32} Hz/cm^2	3.5x10^{33} Hz/cm^2	6.64x$10^{33}$$Hz/cm^2$
□s	7	7	8
Bunches spacing	75 ns	50 ns	50 ns

The RPC in ALICE

G. Pugliese

ALICE (A Large Ion Collider Experiment) is specialized in the detection of signatures of the Quark-Gluon Plasma state @ Heavy-ion collisions at ultra-relativistic energies.
It is composed by two groups of detectors:

- The Barrel region
- The Muon Spectrometer

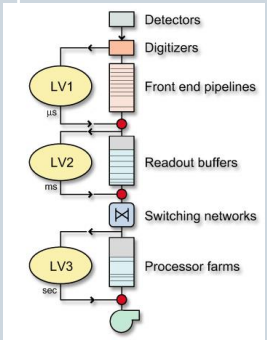
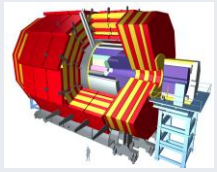
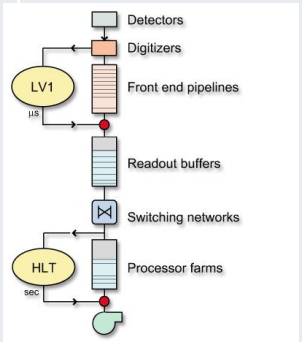


The **Barrel**

The **Muon Spectrometer** performs muon identification and detection at forward rapidity ($-4 < \eta < -2.5$), in order to measure heavy flavour and quarkonia production. The muon trigger, composed by 4 layers of RPC detectors, allows for the online event selection as well as for the offline muon identification.

Trigger system in ATLAS and CMS

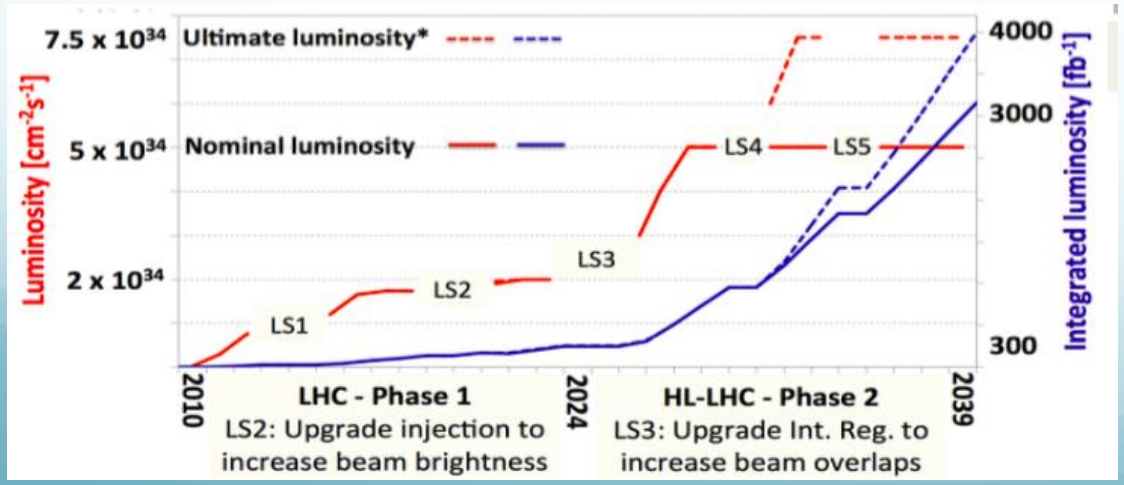
G. Pugliese

	N. of level Trigger	L1 Rate (Hz)	Event storage (Hz)	
ATLAS 		10^5	100	
 CMS		10^5	100	

Expected HL-LHC & CMS conditions

G. Pugliese

		LHC	HL-LHC	ultimate HL-LHC
Collider	instantaneous luminosity ($cm^{-2}s^{-1}$)	10^{34}	5×10^{34}	7.5×10^{34}
	pileup collisions	30	150	200
	integrated luminosity (fb^{-1})	500	3000	4000
CMS	L1 trigger (kHz)	100	500	750
	L1 trigger latency (μs)	3.6	12.5	



The challenging conditions require the muon system upgrade