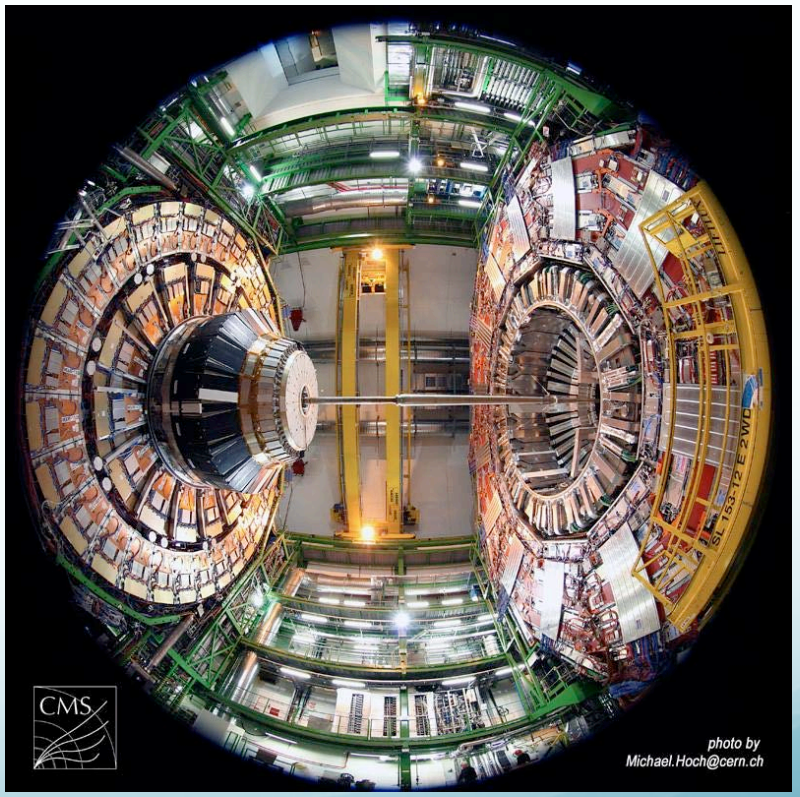
3th RPC generation: Future applications in HEP and life

G. M. I. Pugliese

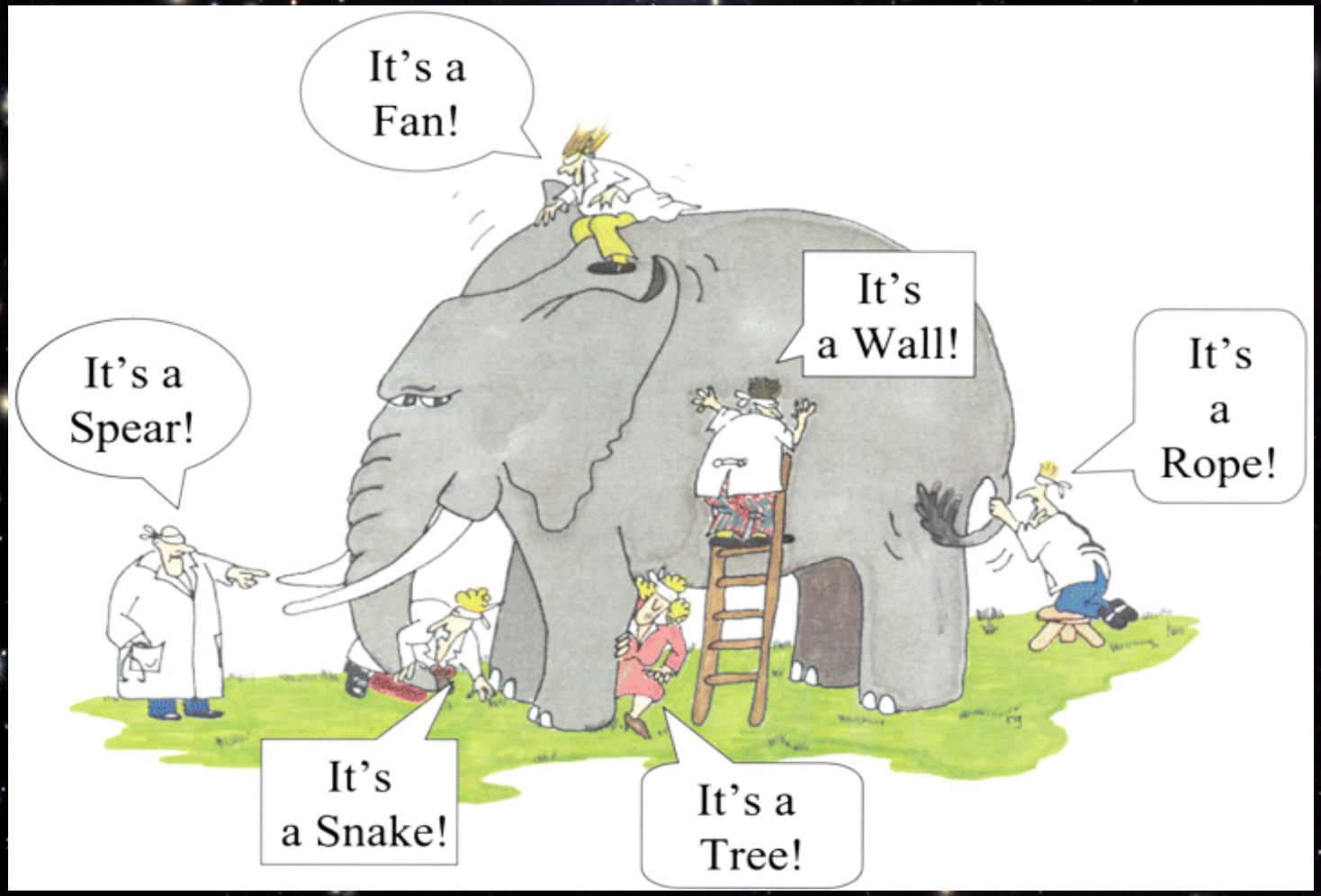
(Cern, INFN and Politecnico of Bari)

The 2nd Omani School of High Energy Physics

28 March – April 4th, 2018



We have only just started to understand the Higgs boson… and we need to look from every angle



The HL-LHC

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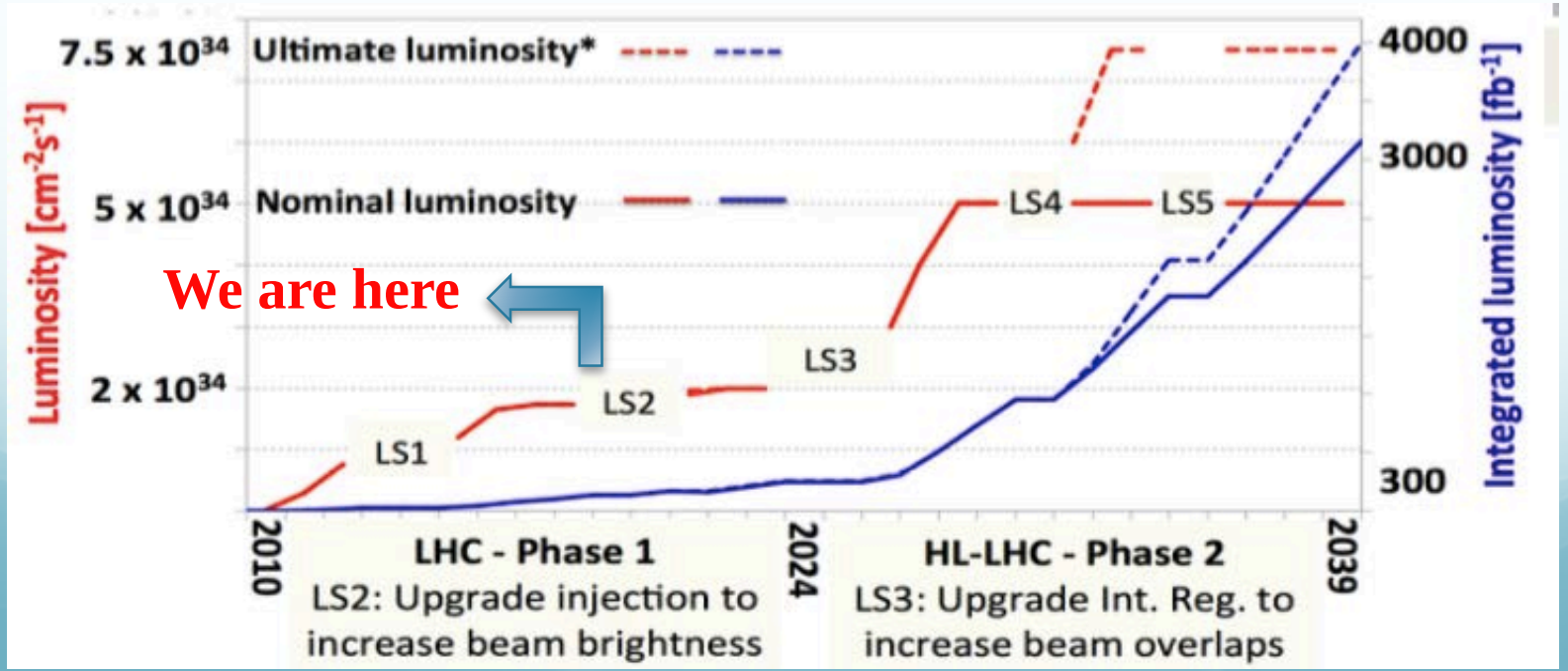
		LHC	HL-LHC	ultimate HL-LHC
Collider	instantaneous luminosity ($cm^{-2}s^{-1}$)	10^{34}	5×10^{34}	7.5×10^{34}
	pileup collisions	30	150	200
	integrated luminosity (fb^{-1})	500	3000	4000
CMS	L1 trigger (kHz)	100	500	750
	L1 trigger latency (μs)	3.6	12.5	



Challenges for the RPC systems in the LHC experiments

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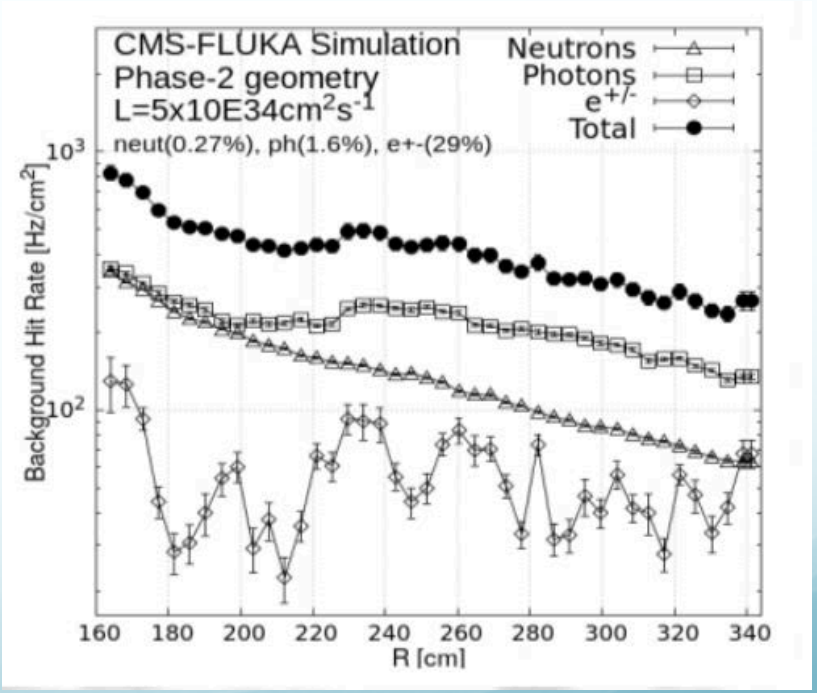
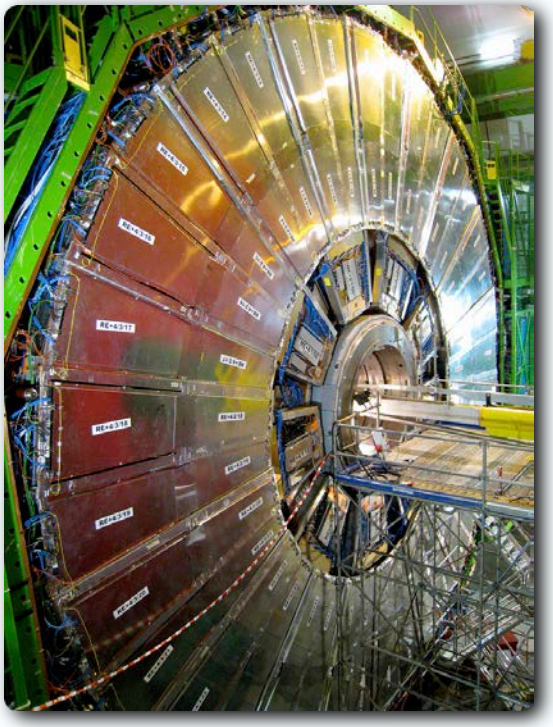
1. Confirm muon system performance at HL-LHC conditions: the RPC systems have to run at **5 times the expected LHC intensity** and for **30 years (instead of 10).**

2. Install new RPC chambers to extend CMS muon coverage up to $|\eta| < 2.8$ or to improve the trigger perfomance in the case of ATLAS
Chamber requirements: rate capability ≈ 1-2 kHz/cm^2

3. Search for an **"ecological"** gas mixture





RPC longevity

Accelerated longevity tests: detectors and electronics are being exposed to irradiation and neutron irradiation facilities

Irradiation tests @ GIF++

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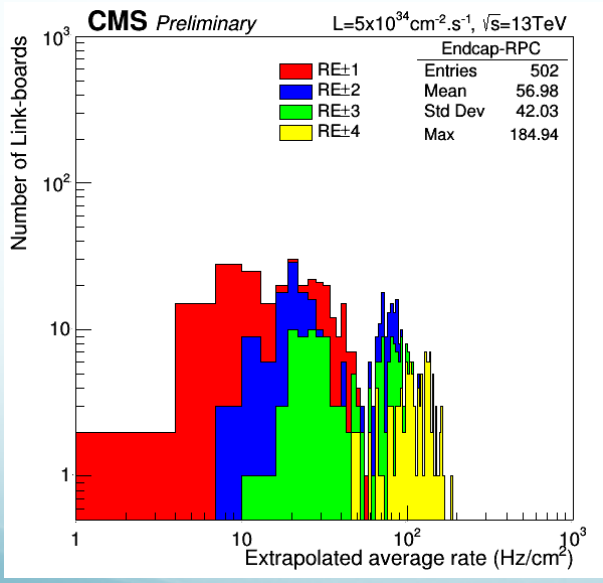
- The CMS RPC system has been certified for 10 years of LHC (at nominal luminosity of 10^{34} cm^{2}s) to maximum rate of **300 Hz/cm^2**.
- At HL-LHC, the RPCs will be required to operate beyond the design specification: the maximum expected **background rate ≈ 600 Hz/cm^2** (with safety factor of 3)



To certify the RPC system at HL-LHC conditions an irradiation test started @ the CERN Gamma Irradiation Facility in July 2016.

Source: 13.7 TBq Cs^{137} gamma source

The Irradiation test

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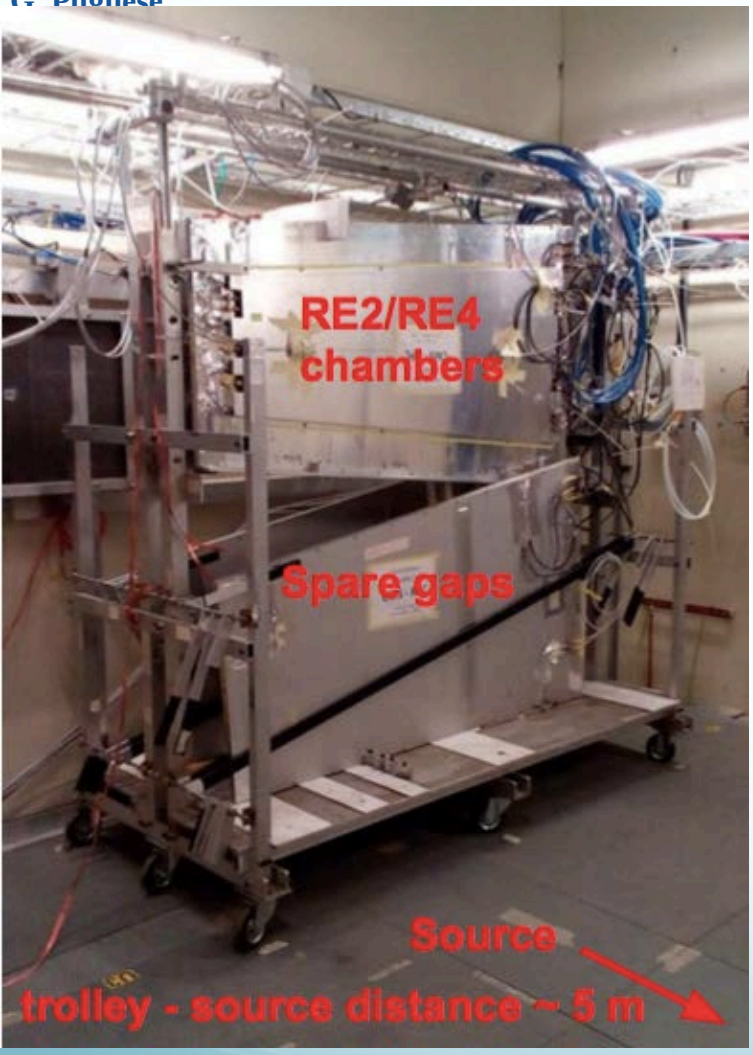

RPC Set-up:

- four fully equipped spare chambers
  - one RE4 and one RE2 at HV ON "irradiated"
  - one RE4 and one RE2 at HV OFF "reference"

RPC Gas system:

- CMS Humidified gas mixture

Environmental condition controlled:

Temperature ~21°C, RH ~ 45 %

Parameters monitored:

- Currents and rates continuously
- Detector performance 3-4 times/year

- The GOAL is to integrate the **expected integrated charge ≈ 840 mC/cm^2** (with safety factor of 3) after collecting 3000 fb^{-1} of HL-LHC data

Irradiated RPC: results (not final)

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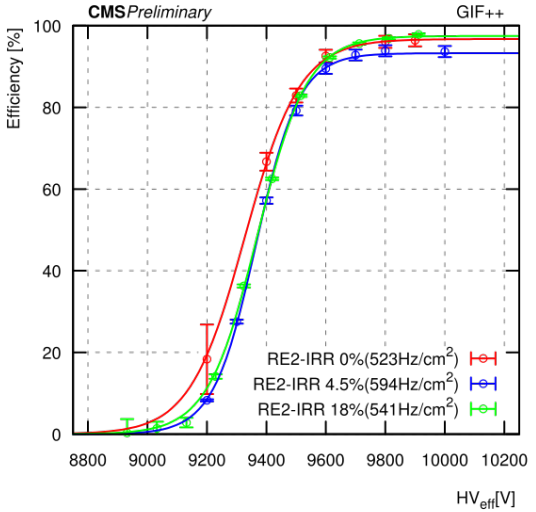
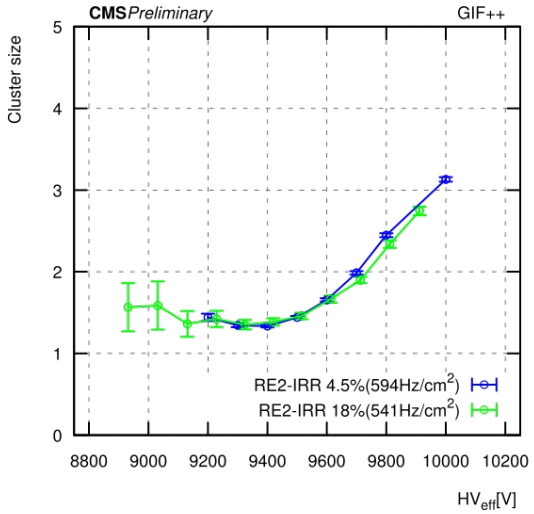
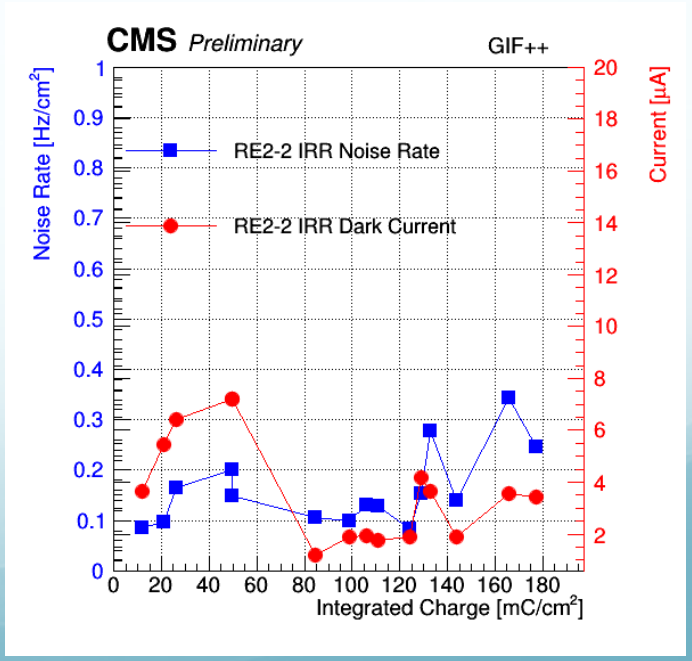




RPC performance with muon beam:

1. RPC can sustain the maximum expected rate ≈ 600 Hz/cm^2
2. performance stable up to 18% of the expected HL-LHC integrated charge.

Dark current and **noise rate** at WP **stable so far.**



3th generation of RPC for HL-LHC

Goal: rate capability 1-2 kHz/cm^2 and longevity

ATLAS RPC Upgrade: a new layer

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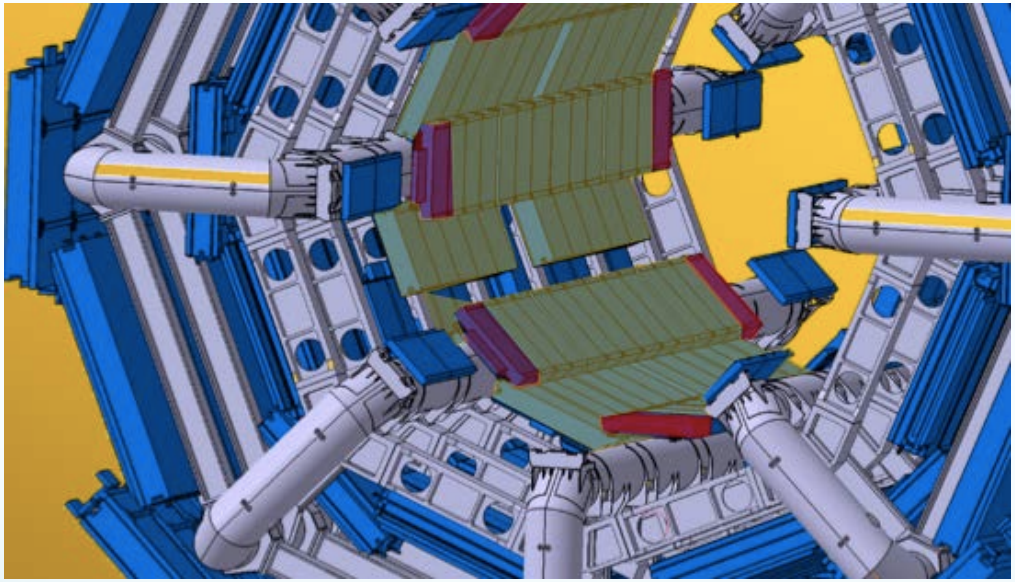
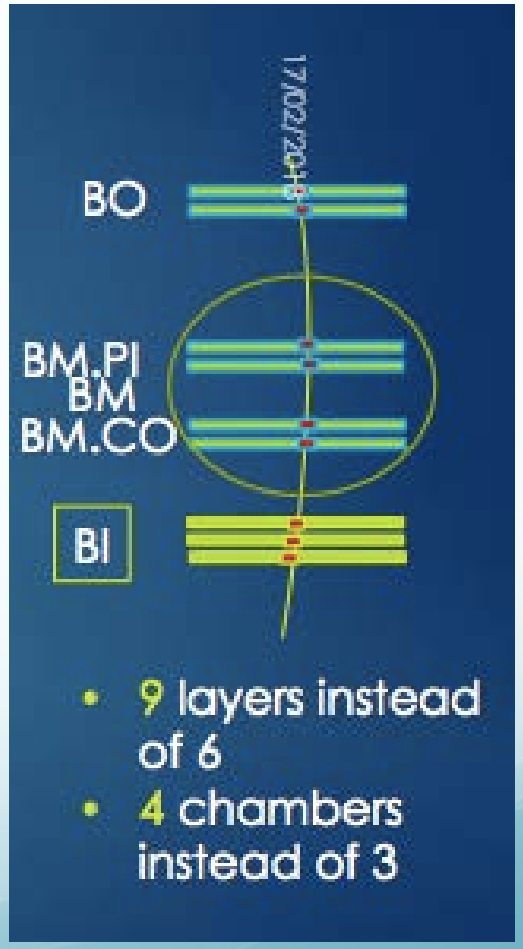
Increase the redundancy by adding a new RPC inner layer





About **96 BIS** and **150 BIL** RPC triplet UNITS installed in the INNER LAYER

- 3 independent layers measuring Eta and Phi
- Total surface **1400** m^2

ATLAS RPC: Trigger motivation

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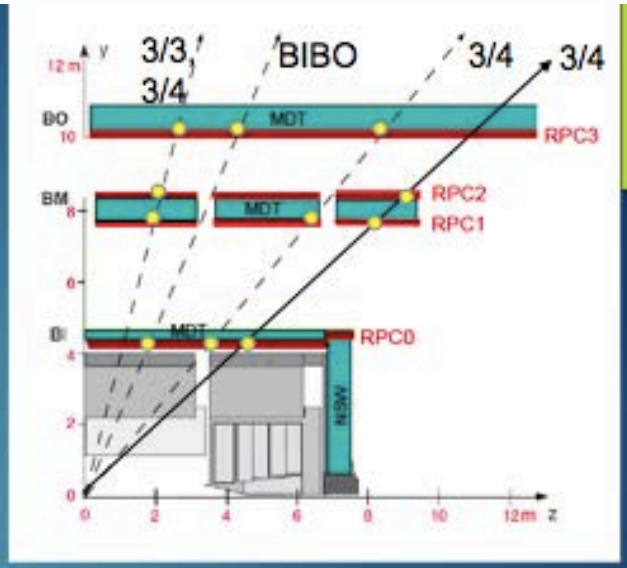
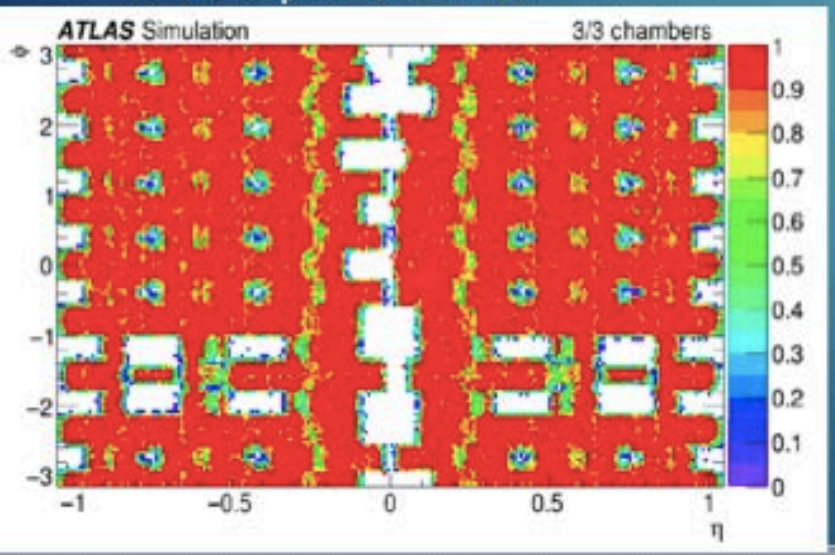
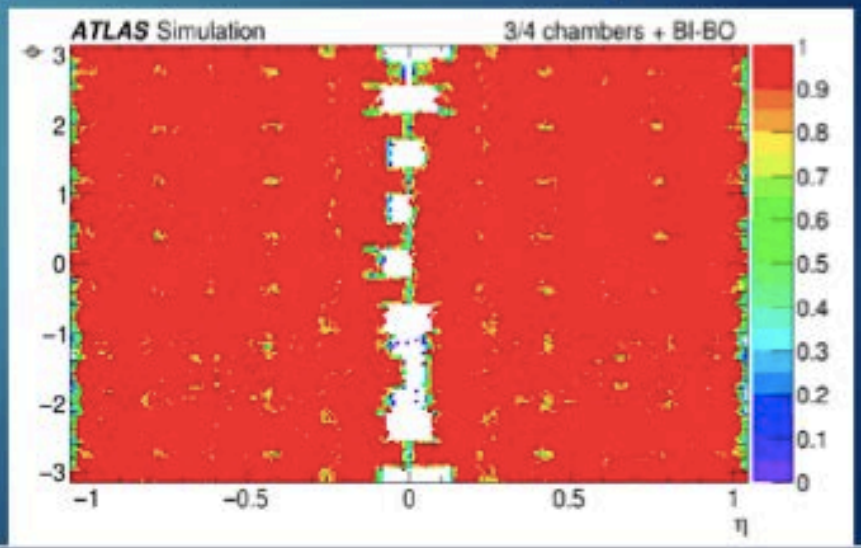
Improving trigger acceptance

The acceptance limitation is recovered introducing the BI RPC layer and a new flexible trigger logic:

- Replace "3-out-of-3 chambers" requirement with "3-out-of-4 chambers"
  - Acceptance 78% → 92%
- Adding BI-BO two-chambers coincidences
  - Acceptance → 96%







CMS RPC Upgrade: high eta completion

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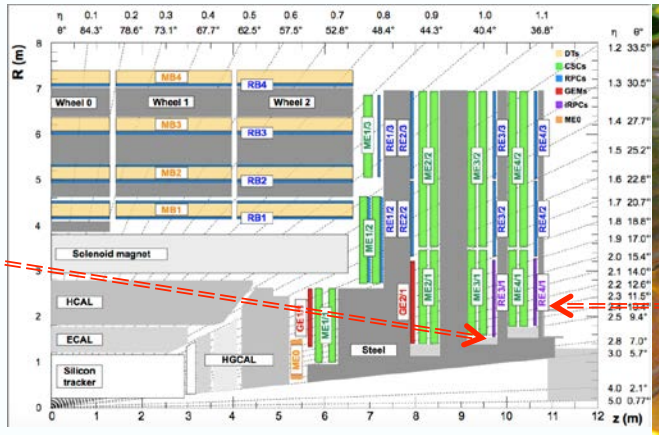
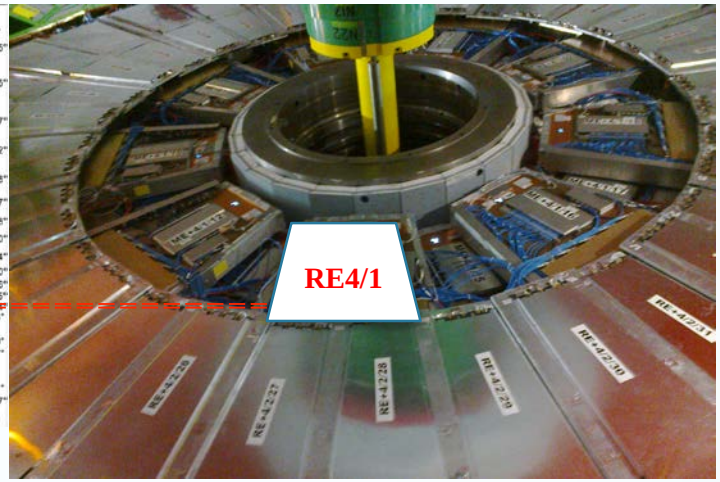
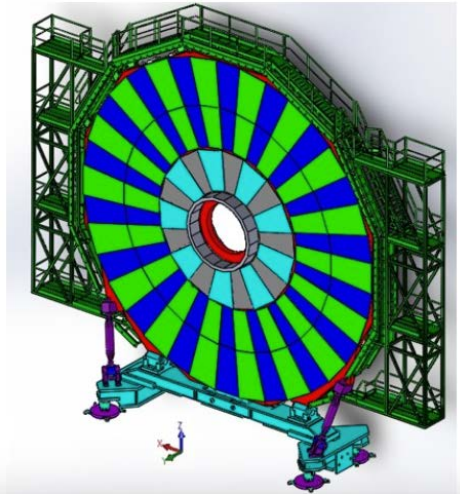
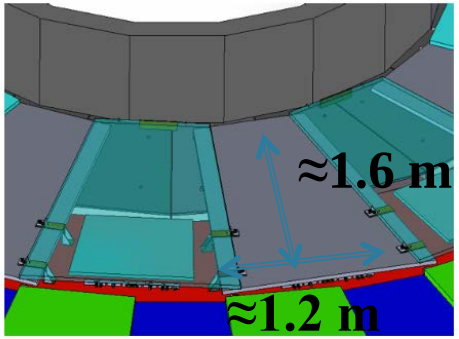




The 3th and 4th stations will be equipped with a new generation of RPC with improved performance, capable of handling the challenging conditions expected at the HL-LHC:

- 72 iRPC chambers
- trapezoidal shape chamber
- 20° in φ





CMS RPC Upgrade motivation

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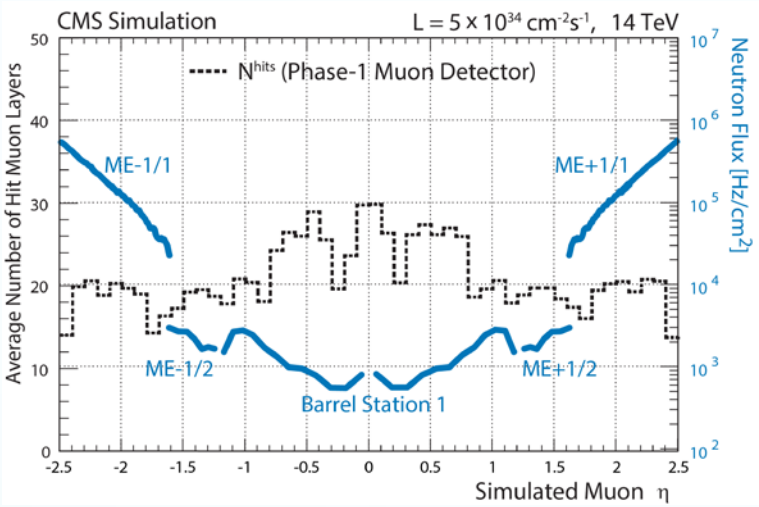
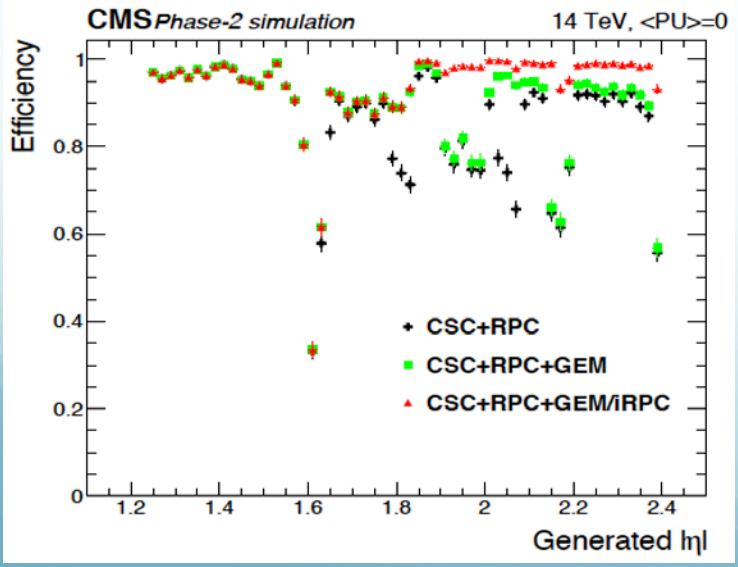
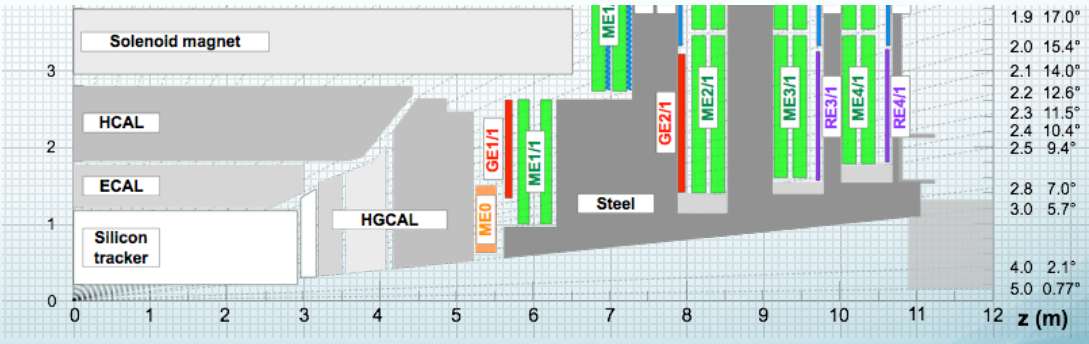


VERY CHALLENGING REGION, both for trigger and offline reconstruction

- **high rates due to n/γ-induced background, punchthrough and muons**
- **small bending of muons by magnetic field**
- **small number of measurements per muon in forward direction (present system); smaller than in the barrel**





L1 muon trigger **efficiency** will benefit from the addition of iRPC in the high η region.

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3th generation of RPC

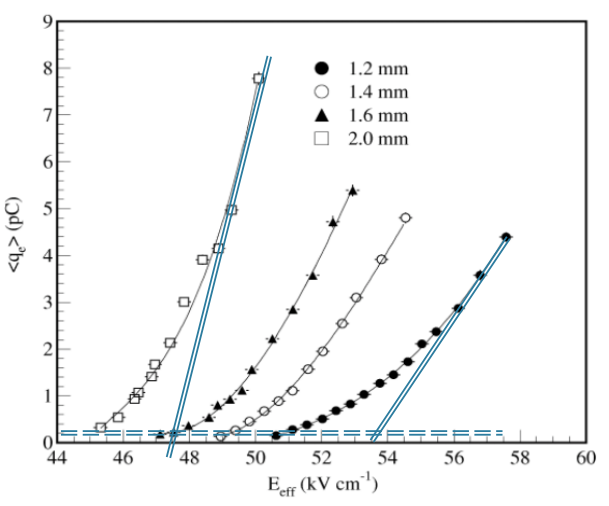
All relevant detector improvement factors have been investigated **to improve rate capability:**

- Reduced electrode resistivity
- **New detector geometry: gas gap and electrodes thickness**
- New Front-End electronics

The key points is to reduce:

- the charge
  - thinner gas gaps: from 2 mm to 1 mm
  - lower electronics threshold

- Thinner electrodes: from 2 mm to 1mm



$$\Delta V_{el} = \rho \, d \, \Phi \, \langle Q \rangle$$

The role of the electrodes thickness

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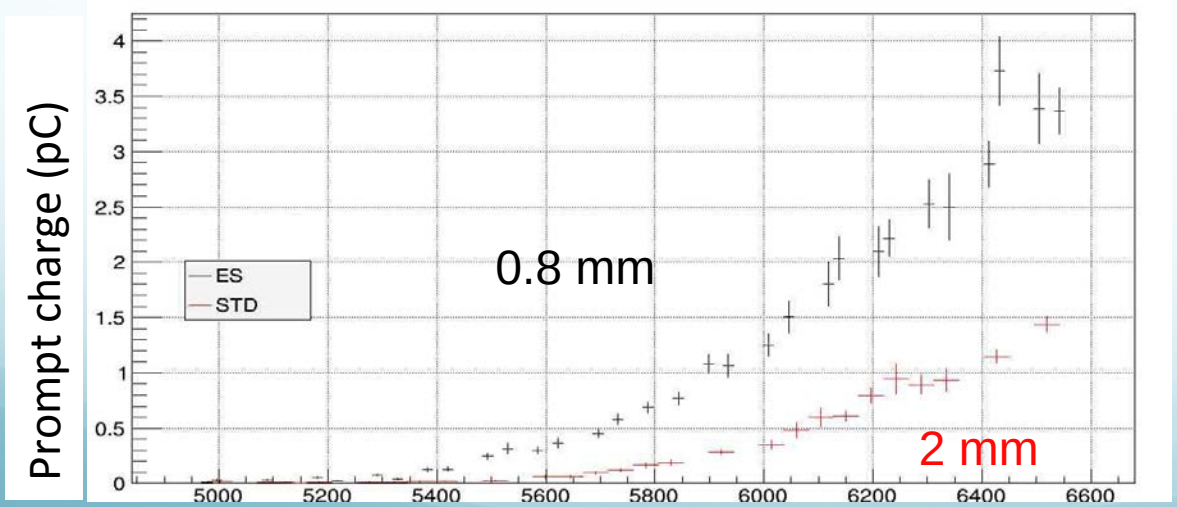

Increase of more than a factor of 2 of collected signal.

$$q_e(x) \cong \frac{Q_{ele}^{tot}}{\eta d} \frac{\varepsilon_r d / s}{2 + \varepsilon_r d / s}$$

The CMS RPC solution

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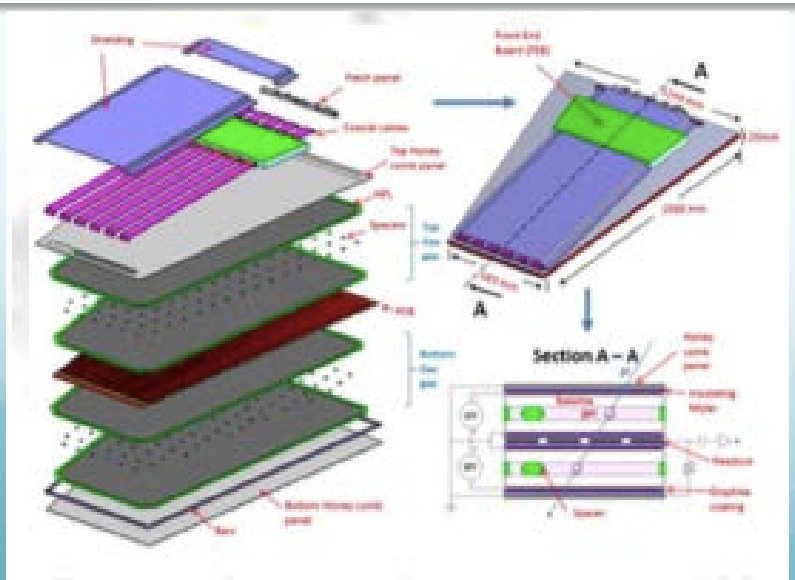
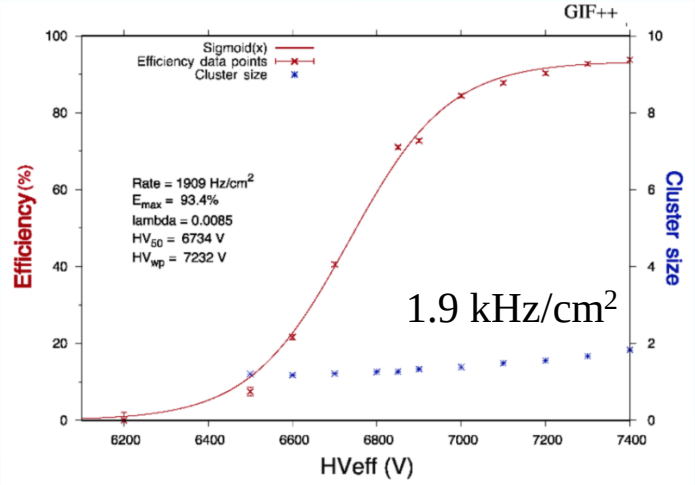
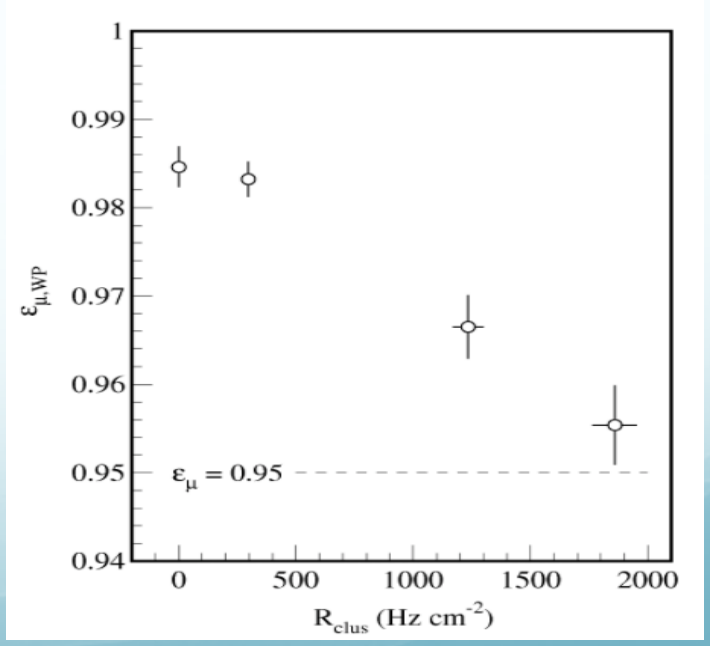
	New RPC	RPC
High Pressure Laminate thickness	1.4 mm	2 mm
Num. of Gas Gap	2	2
Gas Gap width	1.4 mm	2 mm
Resistivity (Ωcm)	0.9 - 3 x 10^{10}	1 - 6 x 10^{10}
Charge threshold	50 fC	150 fC
η segmentation	2D readout	3 η partitions







New generation of multi-gap GRPC

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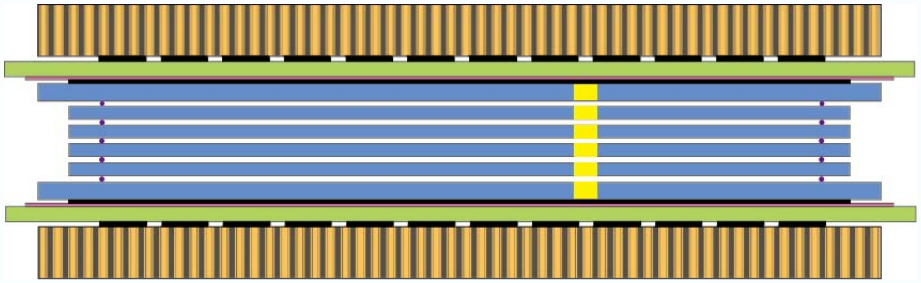
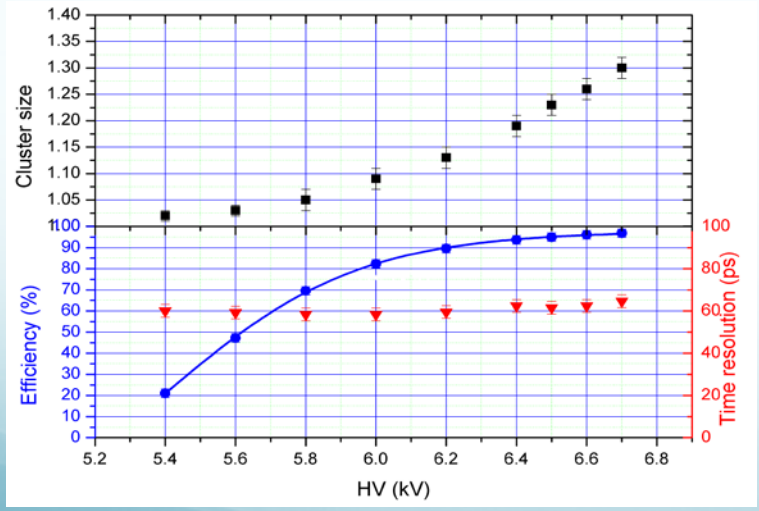
New Multi-gap GRPC build using
low resistive glasses (~ 10^{10} Ωcm)

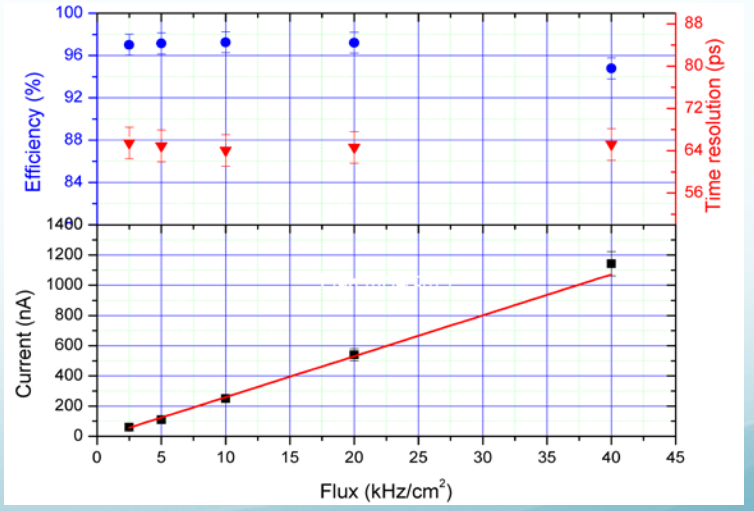


Rate capability: Eff ~95% up to 20 kHz/cm^2
Time resolution ~60 ps

Thickness electrode: 0.7 mm
Gap geometry: 5 gas gaps with width of 250 μm
Gas Mixture: 90% TFE + 5% isoC_4H_{10} + 5% SF_6



Cluster size, efficiency and time resolution as function of the applied HV.



Efficiency, time resolution and current as function of the beam flux.

New RPC ecological gas-mixture

Eco-friendlier gas

New regulation: *in 2014, the European Commission adopted a new regulation limiting the total amount of* ***fluorinated greenhouse gases (F-gases)*** *that can be sold in the EU from 2015 onward and phasing them down in steps to* ***one-fifth of 2014 sales in 2030. Recently CERN is committed to reducing greenhouse gas emissiosn to 30%of the 2016 level in Run3)***

RPCs use **95.2% $C_2H_2F_4$** and **0.3% SF_6**:

1440 m^3/hr of CO_2 equivalent **(yearly, ≈10K cars)**

F-gases used by RPCs prevent aging and ensure reliable operation

Solutions

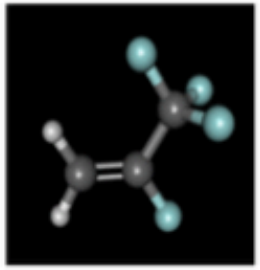
1. **Replace the old with a new eco-friendlier gas**
2. **Other measures being explored:**
   - Add a recuperation system
   - add an “abatement” system to burn off F-gases on the exhaust into harmless compounds

Eco gas possible candidates

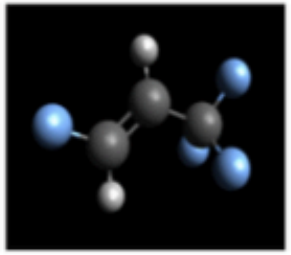
Tetrafluorepropene ($C_3H_2F_4$)

It cames in two allotropic forms

HFO-1234ze



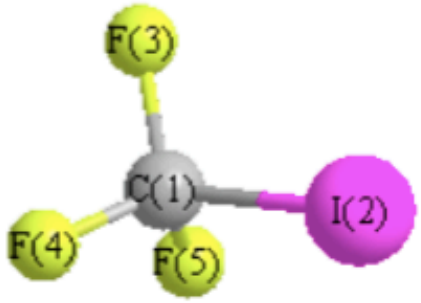
HFO-1234yf



Molecule	CCl_2F2	CF_4	R134a
Ionization energy (eV)	10.24	12.81	12.40
Molecule	R152a	HFO1234ze	HFO1234yf
Ionization energy (eV)	10.78	9.34	9.37

Molecule similar to R134a ($C_2H_2F_4$) BUT
HFO-1234ze GWP=6, HFO-1234yf GWP=4
R134a GWP = 1430
HFO-1234yf HMIS code =2
(moderate flammability)

Trifluoroiodomethane (CF_3I)



GWP and ODP close to 0

High quenching power
Very expansive ! We were able to buy just a small bottle of 0.5 kg for very few preliminary tests

Global Warming Potential (GWP)

Preliminary results

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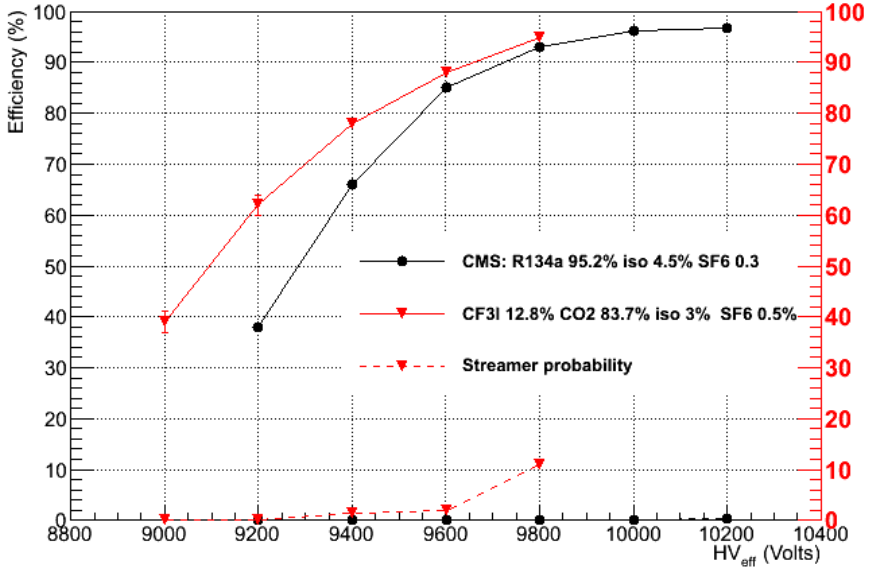


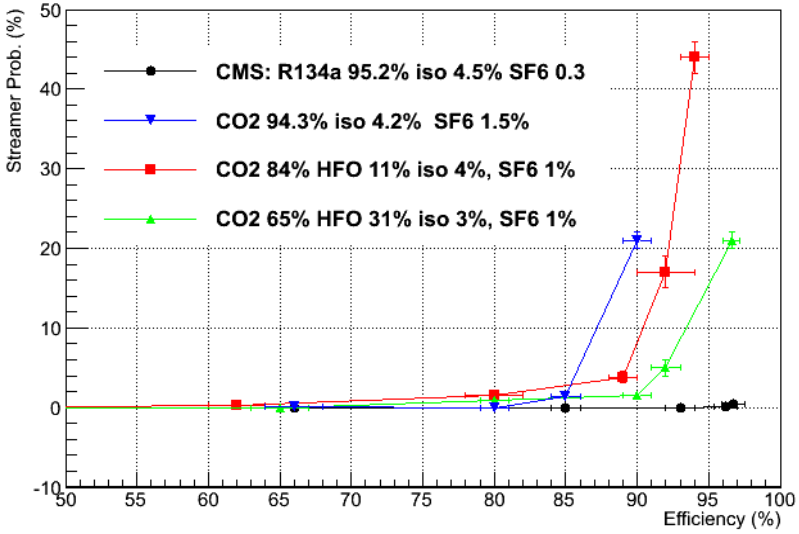
Eco-Gas mixture:

CF_3I	CO_2	iso-C_4H_{10}	SF6
12.8 %	83.7 %	3 %	0.5 %

Efficiency at HV Working Point similar to that of the CMS gas mixture but with higher streamer probability

Eco-gas mixture with 31% of HFO & 65% of CO_2

It showed promising results: at 90% of efficiency the streamer probability about 2%.



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Recap… the RPC from 1981 to nowadays

- **Rate capability** from 10 Hz/cm^2 to 30000 Hz/cm^2
- **Time resolution** from 1 ns to 60 ps
- **Space resolution** from 1 cm to 0.01cm
- But performance is not all: the increase is obtained while keeping the same simple structure which always allowed to scale the detector to large surfaces

The Secret?

- Simple physics laws and right choice of materials do most of the job
- The physical event is very local in space-time. A discharge (local) can never evolve in spark (global)
- Better electronics → better performance → widely span over the avalanche dynamical range

Future not Hl-LHC experiments..

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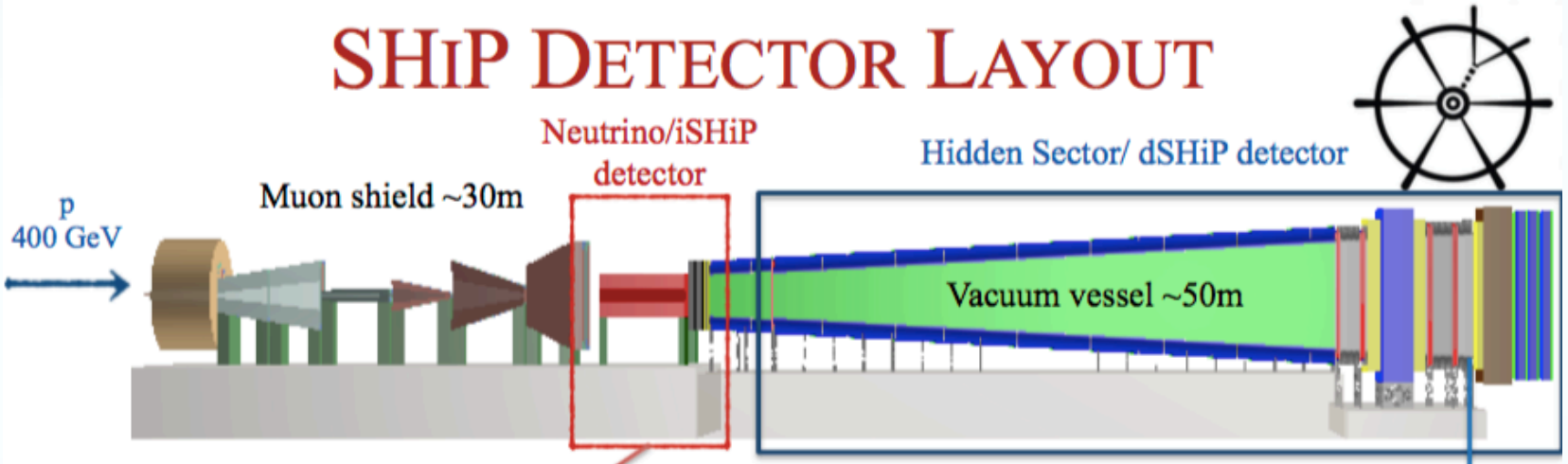
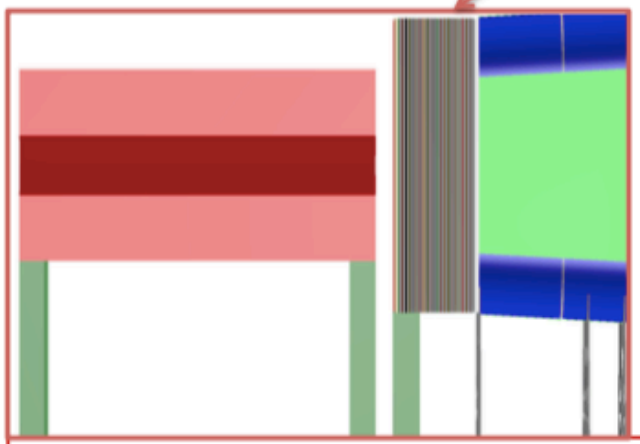
SHiP Detector Layout





24 RPC planes 214 x 490 cm^2
Acting as:
- Muon Tagger for iSHiP detector
- Upsteam Veto System for dSHiP detector

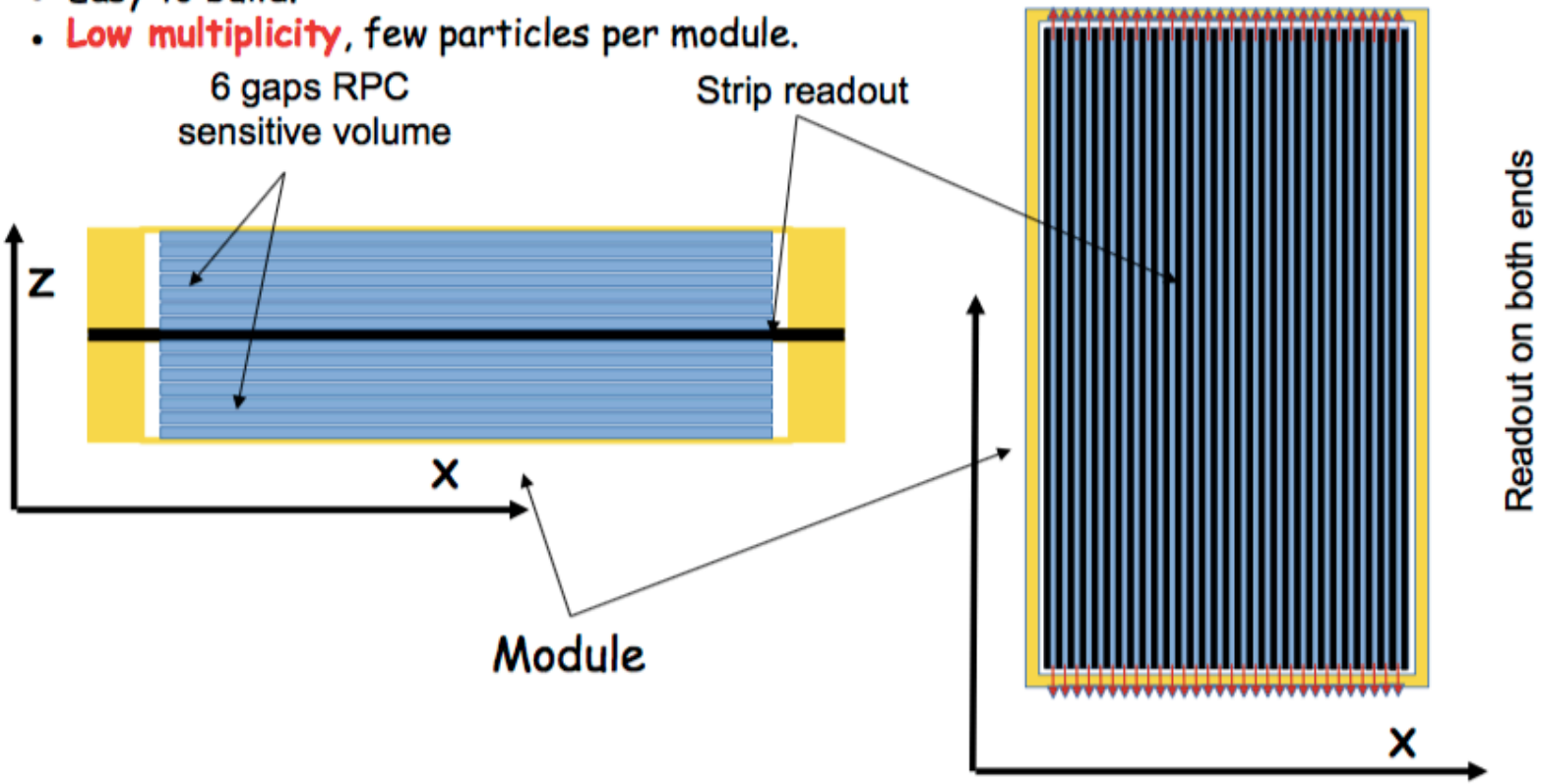
Multigap Resistive Plate Chambers
- possible option for dSHiP Timing Detector
- Required time resolution: <100 ps
- Transverse size: 5x10 m^2

4

The Timing Detector implementation based on MRPCs.

Schematic drawing (Alberto Blanco and Paulo Fonte)

- **Modules composed of two 6 gaps RPCs** sensitive volumes.
- Strip (placed in the middle of two sensitive volumes) readout in both sides.
- Active **area of 1500x1200 mm² = 1,8 m²**
- **Good time resolution,** < 100 ps σ.
- **Good efficiency,** > 95 %
- Easy to build.
- **Low multiplicity**, few particles per module.



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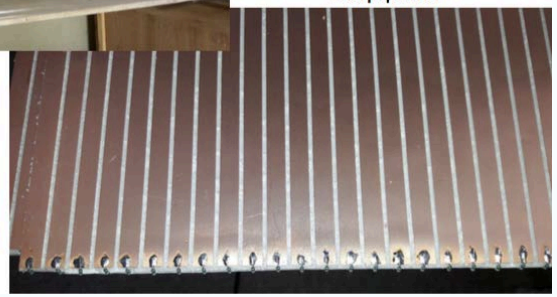
Status of RPC production (KODEL)

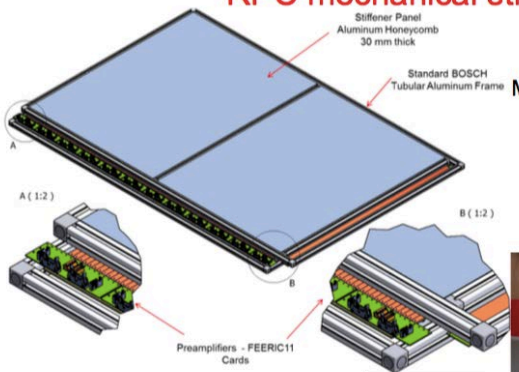
Sung Park
Kyong Sei Lee

Gaps at CERN

Strip panel

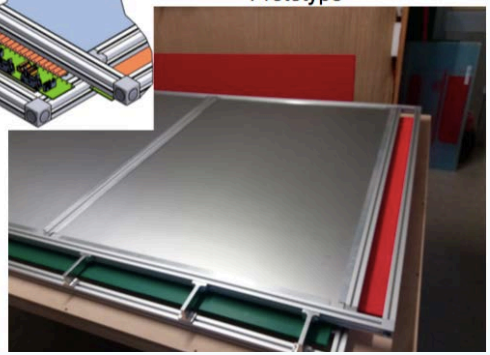


RPC mechanical structure

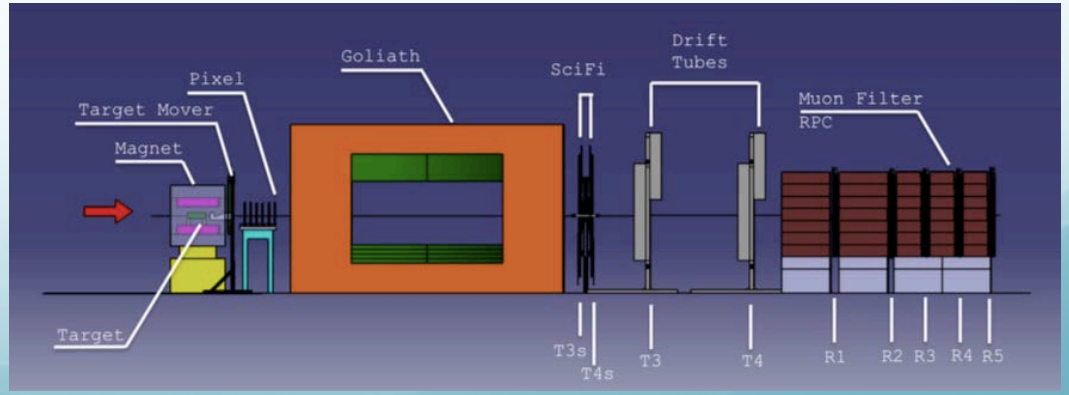


Mechanics Service INFN - Bari

Prototype



4 chambers will be built in April at CERN (in 904) to be tested at TB in July

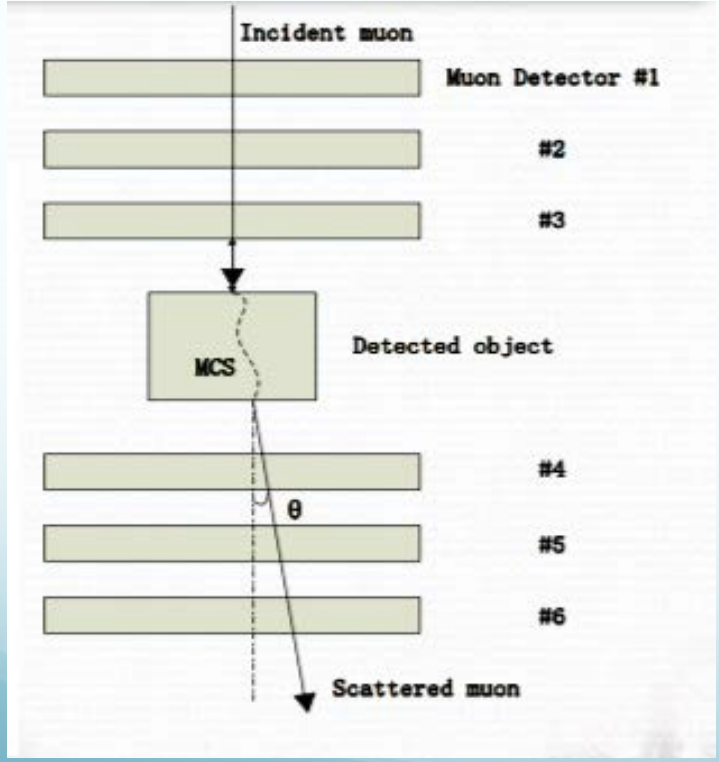


Some Applications for life

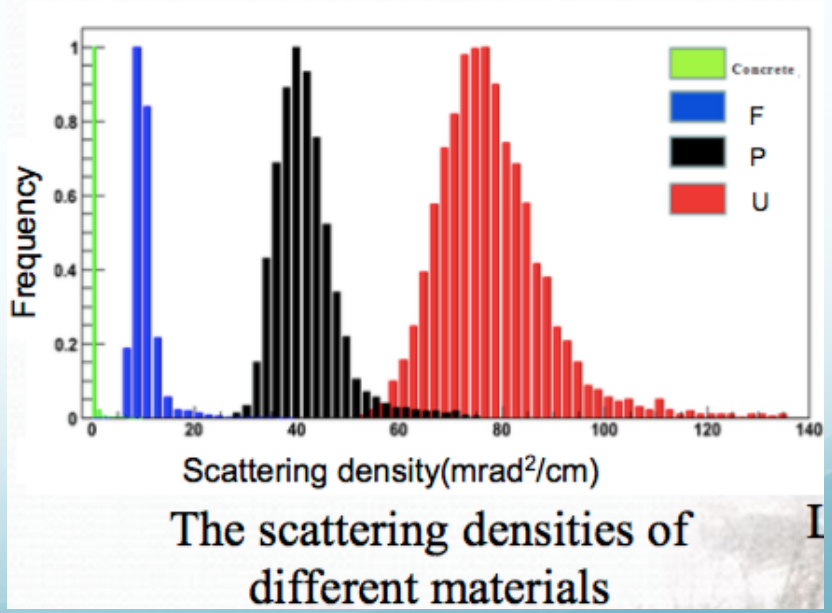
The Muon Tomography

G. Pugliese

Cosmic ray muon tomography is a newly developed method based on scattering theory which can be applied in nuclear material discrimination because of its sensitivity to high Z material.



Muon undergo multiple scattering on nuclei while passing through matter depending by their atomic number z



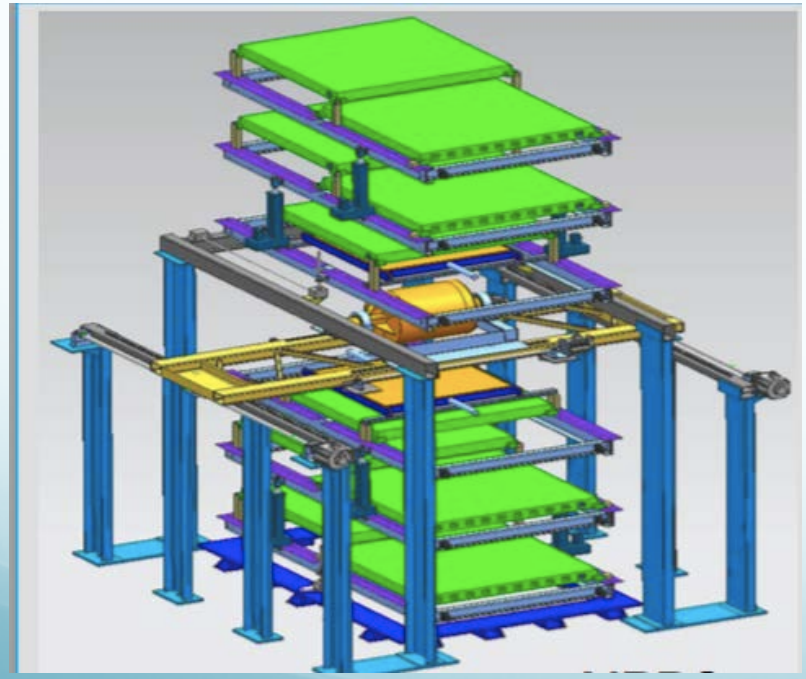
Rate: □ 1/cm^2 min continuously bombard the Earth

Application: Cargo Inspection

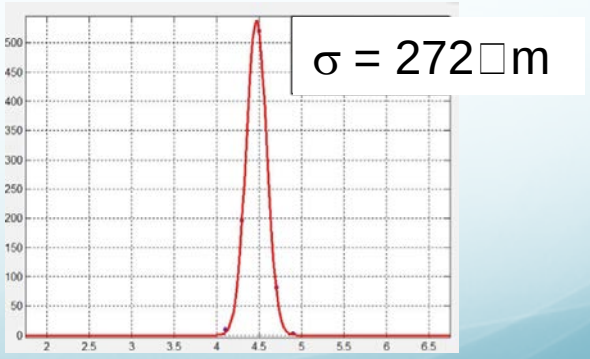
G. Pugliese

typically takes 2–10 min.

Prototype developed at Tsinghua Univ.
Detector: MRPC
Strip pitch 1.44 mm
Sensitive area: 720mm×720mm



Requirements: sub-mm spatial resolution to achieve an angular resolution in the order of micro-rad .



Under study the MRPC performance in sealed gas (flush gas intermittently) in order to fit industrial applications

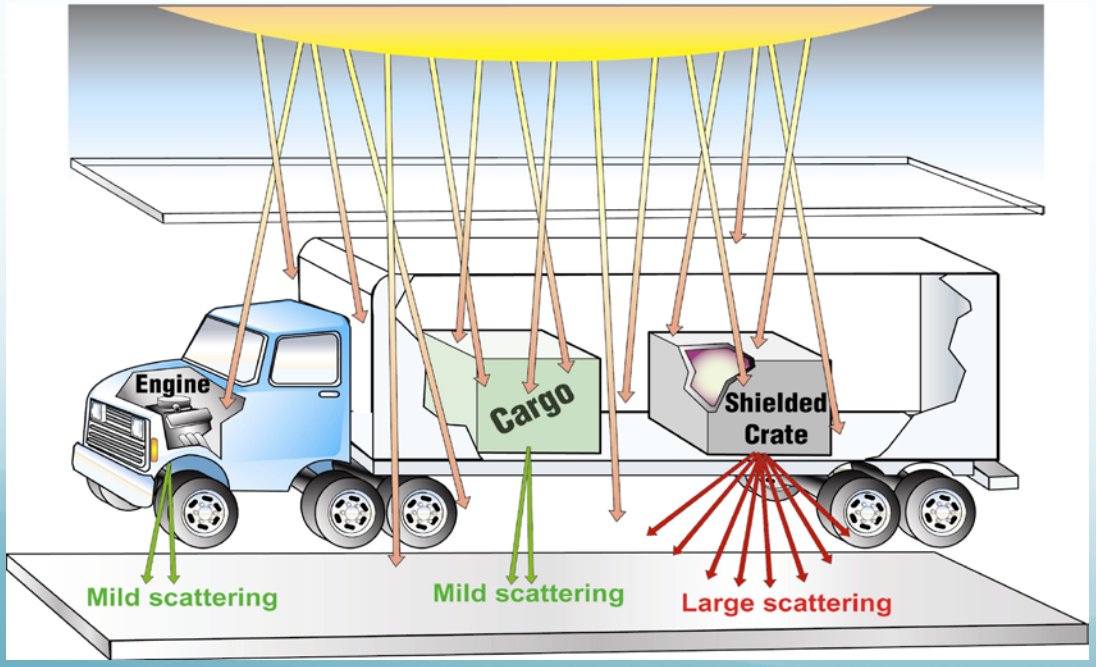
Flawless vehicles control – the muon tunnel

G. Pugliese

Tunnel long enough to allow a continuous flow of vehicles:

60 s @ 20 Km/h → ~ 300 m using the present simulated performance

Los Alamos test setup



G. Pugliese

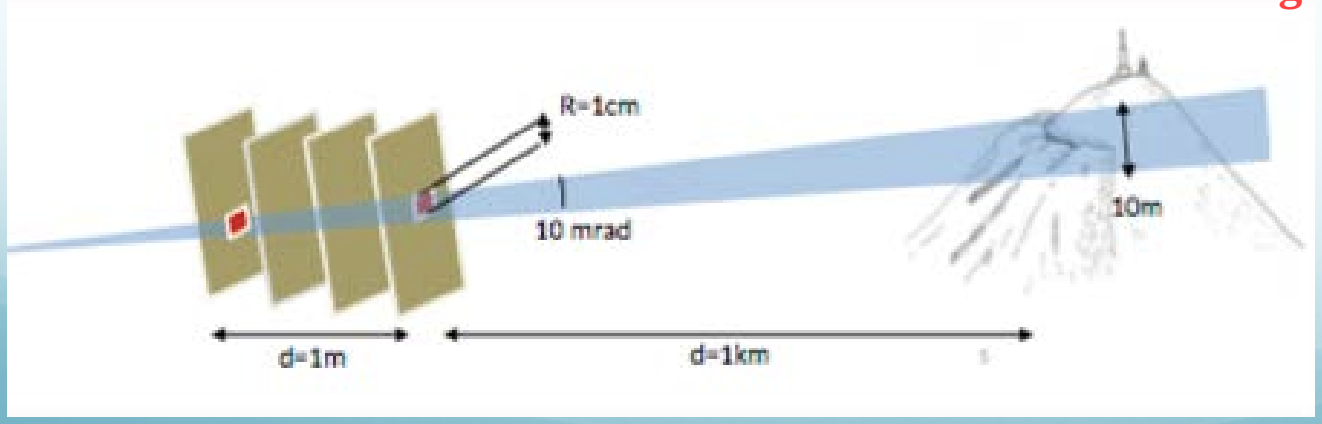
Muography

Muography is an imaging technique for large and dense structures using atmospheric muons.

Principle (same as for radiography): measure the absorption of the atmospheric muons through a target to have an 2D image from its transmission

Vantage of m: Cross kilometers of rock before decaying
Large energy spectrum: 100 MeV → PeV
Simple trackers and no direct measurement of incoming flux

Target → volcano

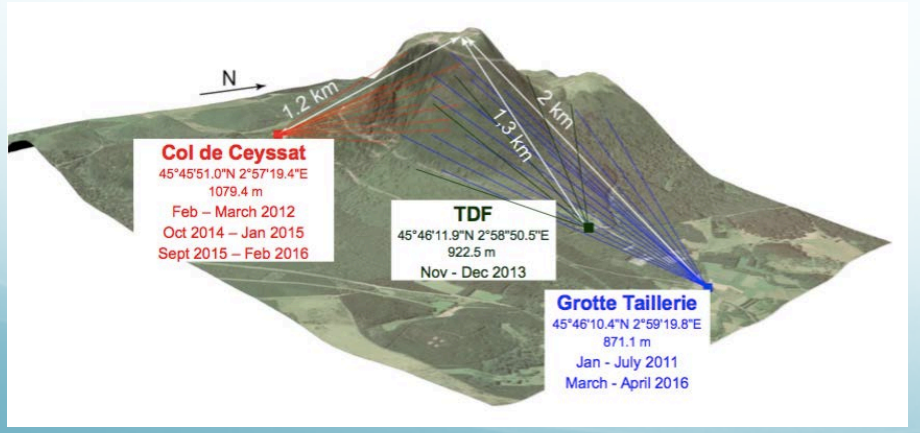


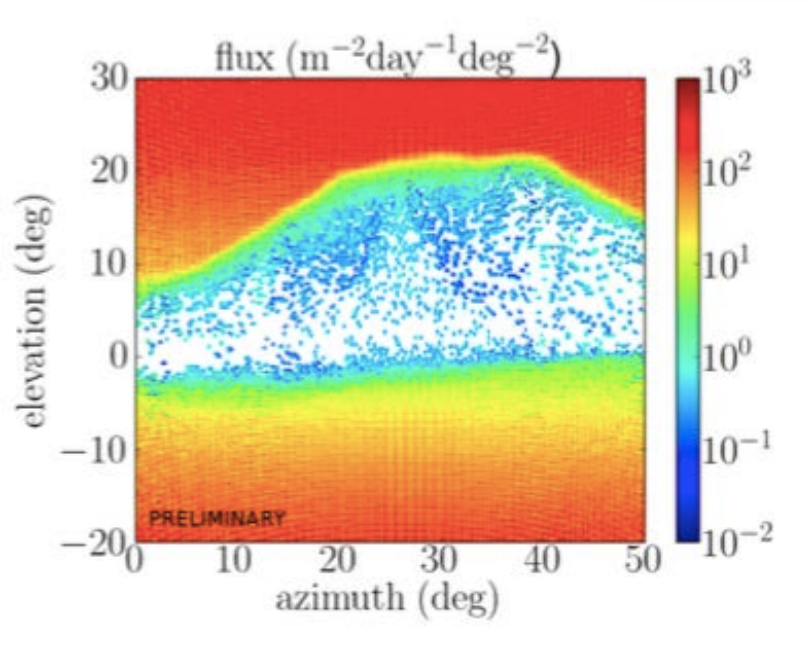
Tomuvol experiment

G. Pugliese

Application: volcanic hazard mitigation by predicting their future behavior from internal structure

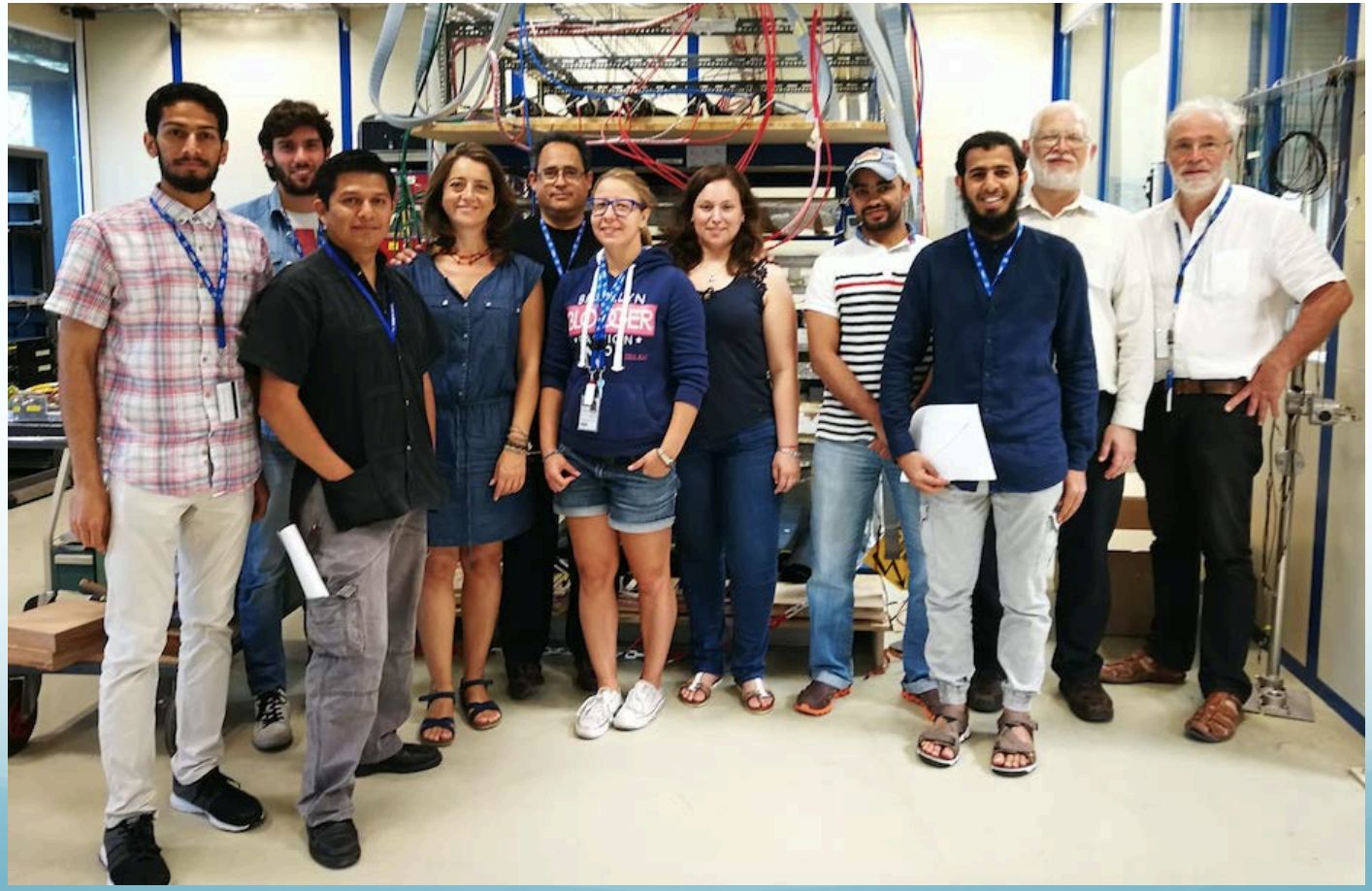
Tested at Puy de Dôme, a volcano 2 km wide close to Clermont-Ferrand, France
3 sites tested
Set-up: 4 layers of single gap glass-RPCs operated in avalanche mode.
Pad of 1 cm2





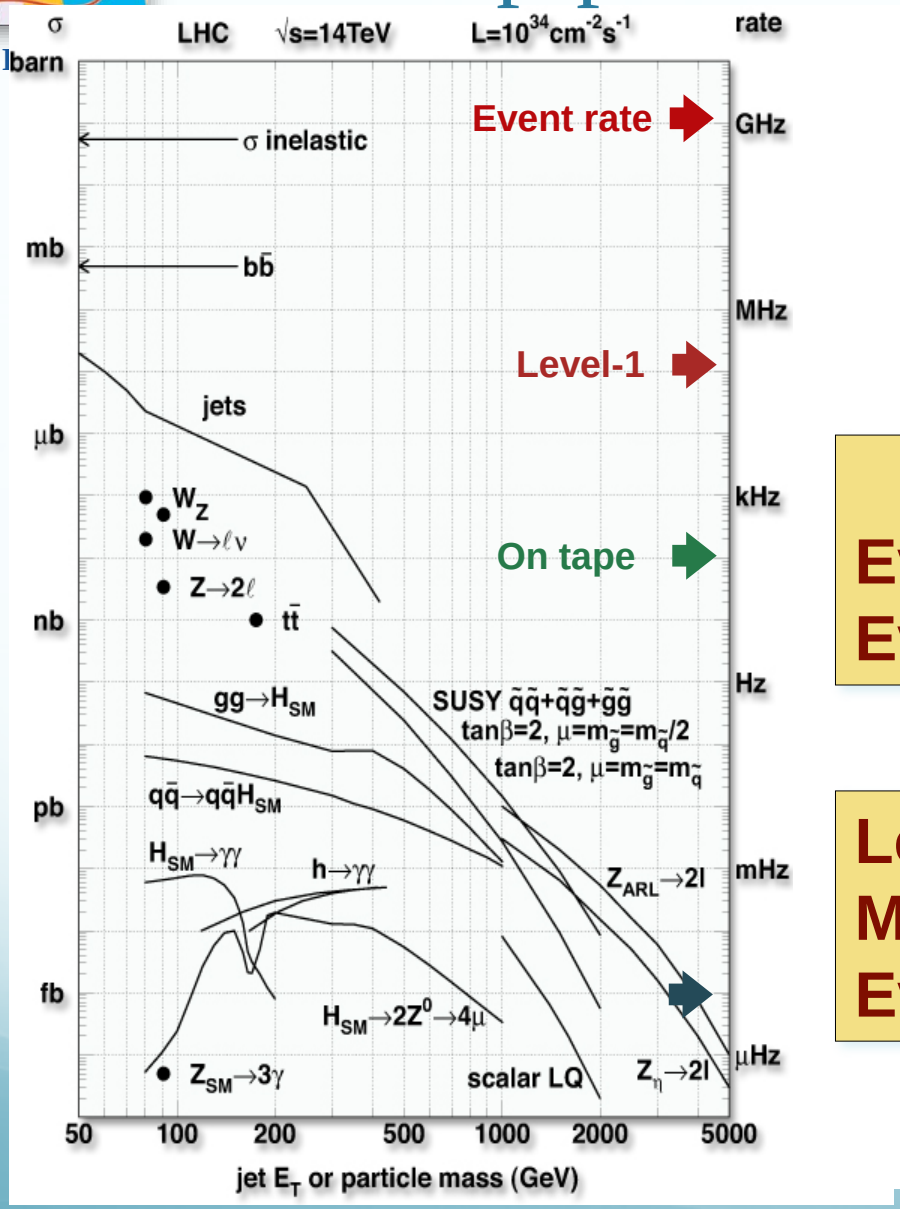
Flux through the Puy de Dôme

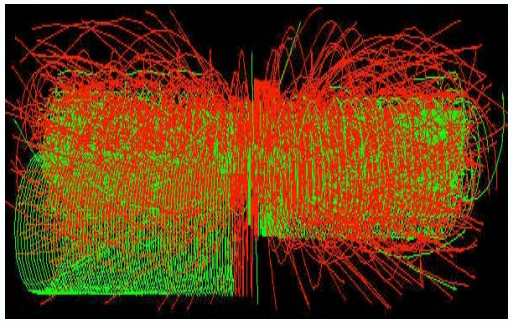
Thanks,
waiting for you at CERN



Spare

p-p collisions at LHC





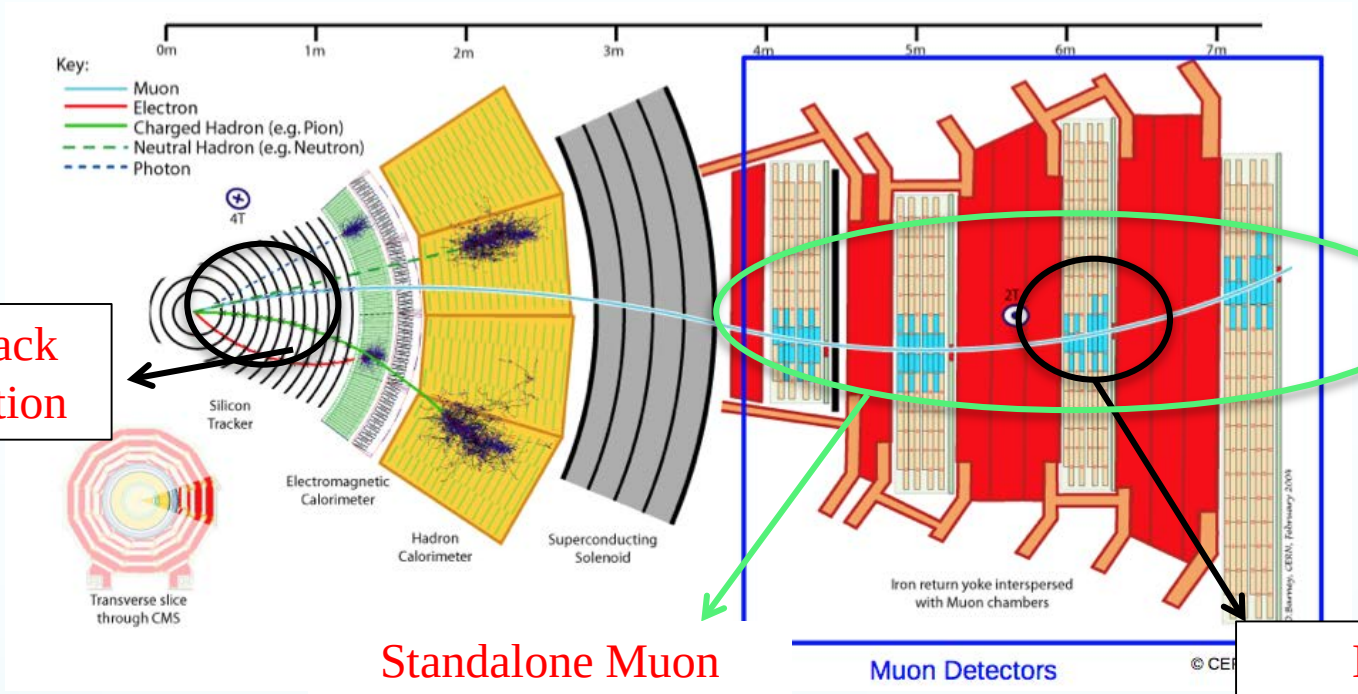
ATLAS / CMS

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.

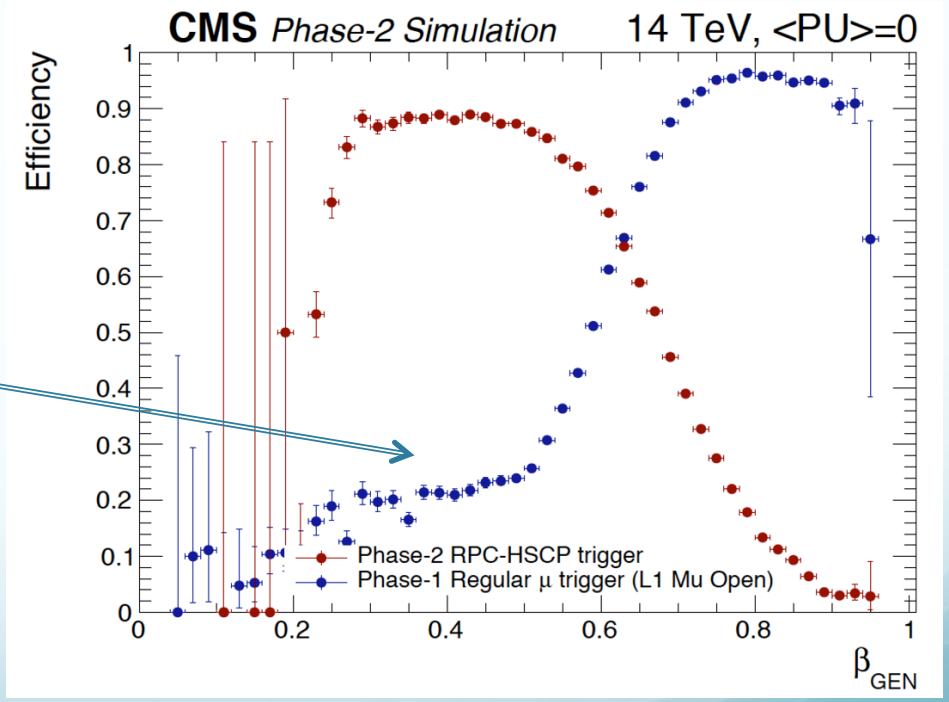
New Physics opportunities

G. Pugliese

The upgrade of the RPC Link System will allow us to explore the RPC intrinsic time resolution ≈ 1.5 ns (from the present 25 ns readout window).

- A new **RPC trigger (RPC-HSCP)** will be devoted to identify very slow "Heavy Stable Charged Particle (HSCP)"
- It will be based on TOF technic to identify the slow particle and to measure the β
- The efficiency of the present muon trigger drops for particle with β < 0.6
- The RPC HSCP trigger capabilities will be extended up to β ~ 0.2.

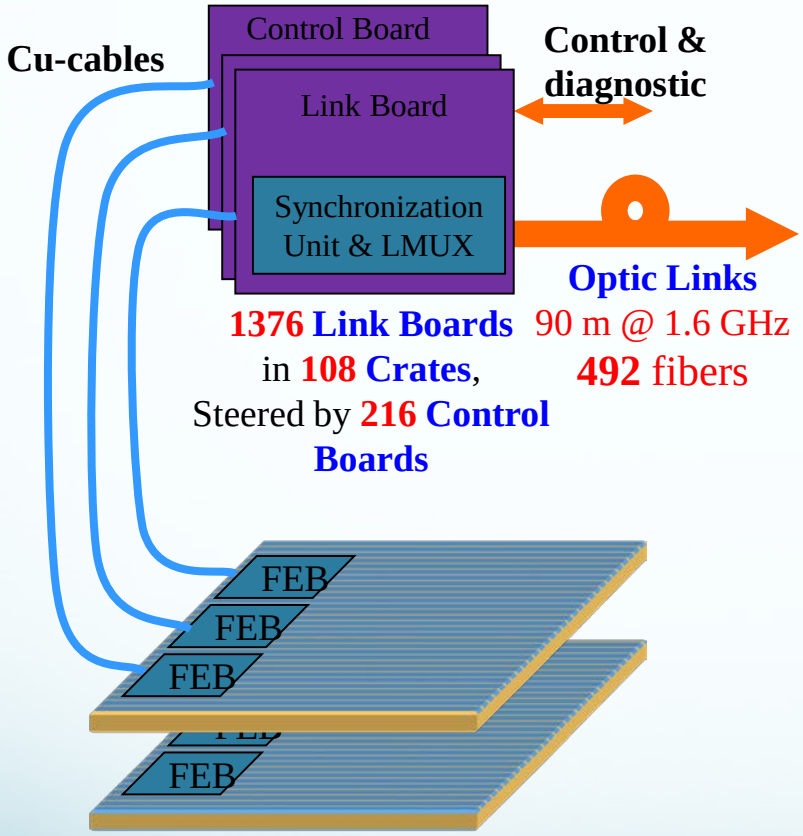
Factor of 4-5 improvement



L1 Trigger efficiency as a function of an HSCP velocity β for the 'regular' muon trigger (in blue) and a dedicated HSCP trigger (red points)

RPC Link System Upgrade: motivation

G. Pugliese



Resistive Plate Chambers
Up to 6 layers of detectors.
480 chambers in Barrel, 648 in Endcap

Off-detector electronics: consists of Link and Control Boards ("Link System") and is located in crates on the balconies around CMS

Motivation for Upgrade:

- **Operation issues:**
  - the CBs are connected into token ring configuration. If one CB fails then the entire ring does not work, leading to a loss of 6 % of the system
- **Maintenance:** it is a custom electronics. Not enough LB/CB spares available (rely on old ASICs)
- **Low speed data transmission links (**1.6 Gbps)

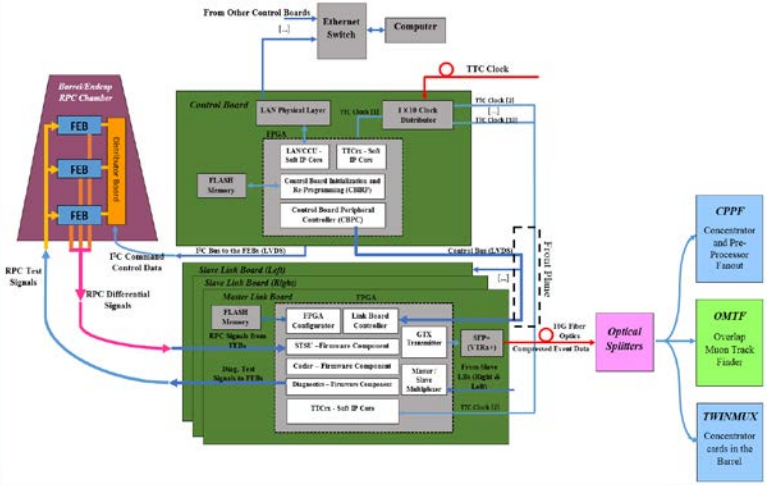
Electronics will be replaced during Long Shutdown3

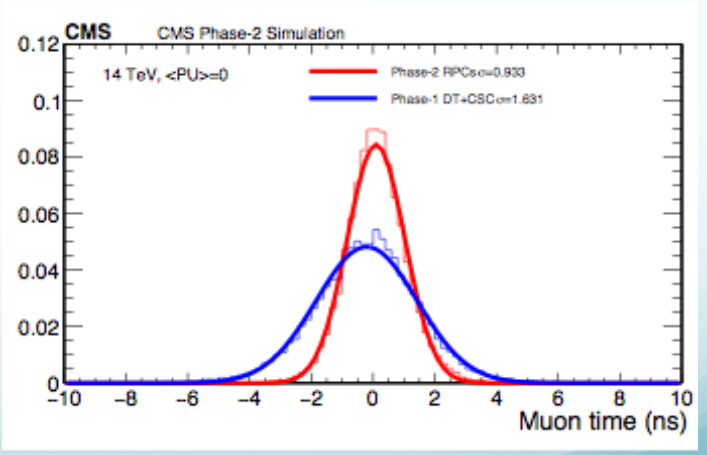
RPC New Link System Design

G. Pugliese

New LB and CB will be produced by the IPM group in Tehran.

- Back compatible with the present Link Boxes. Signal cables from the chambers will be not removed.
- Based on Xilinx 7 FPGAs (replace ASICs)
- RPC signal sampling frequency will be 640 MHz clock from the present 40 MHz clock
  - **Time resolution will be improved: from 25 ns to 1.6 ns. Impact on muon trigger and offline reconstruction.**
- More robust: Ethernet switch board replaces token ring
- Higher bandwidth (10 Gbps output)





See B. Boghrati's talk on Link System Upgrade overview