Rivelatori di tracciamento a gas per CMS e LHCb

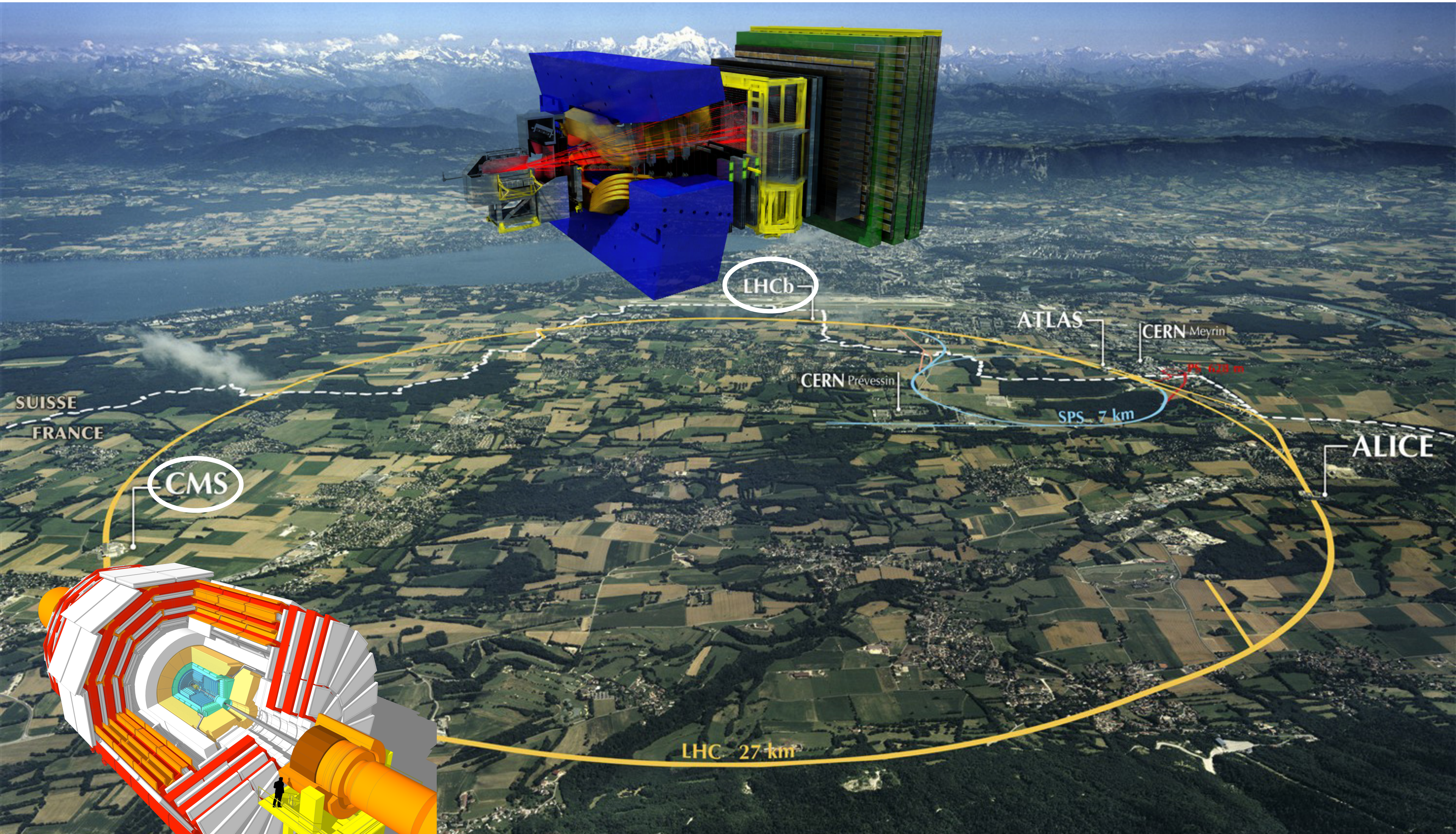
2° Congresso della Sezione INFN
e del Dipartimento di Fisica di Bari
Feb 3-4 2022

Alessandra Pastore, Piet Verwilligen
for INFN & Uni/Poli-BA LHCb & CMS groups

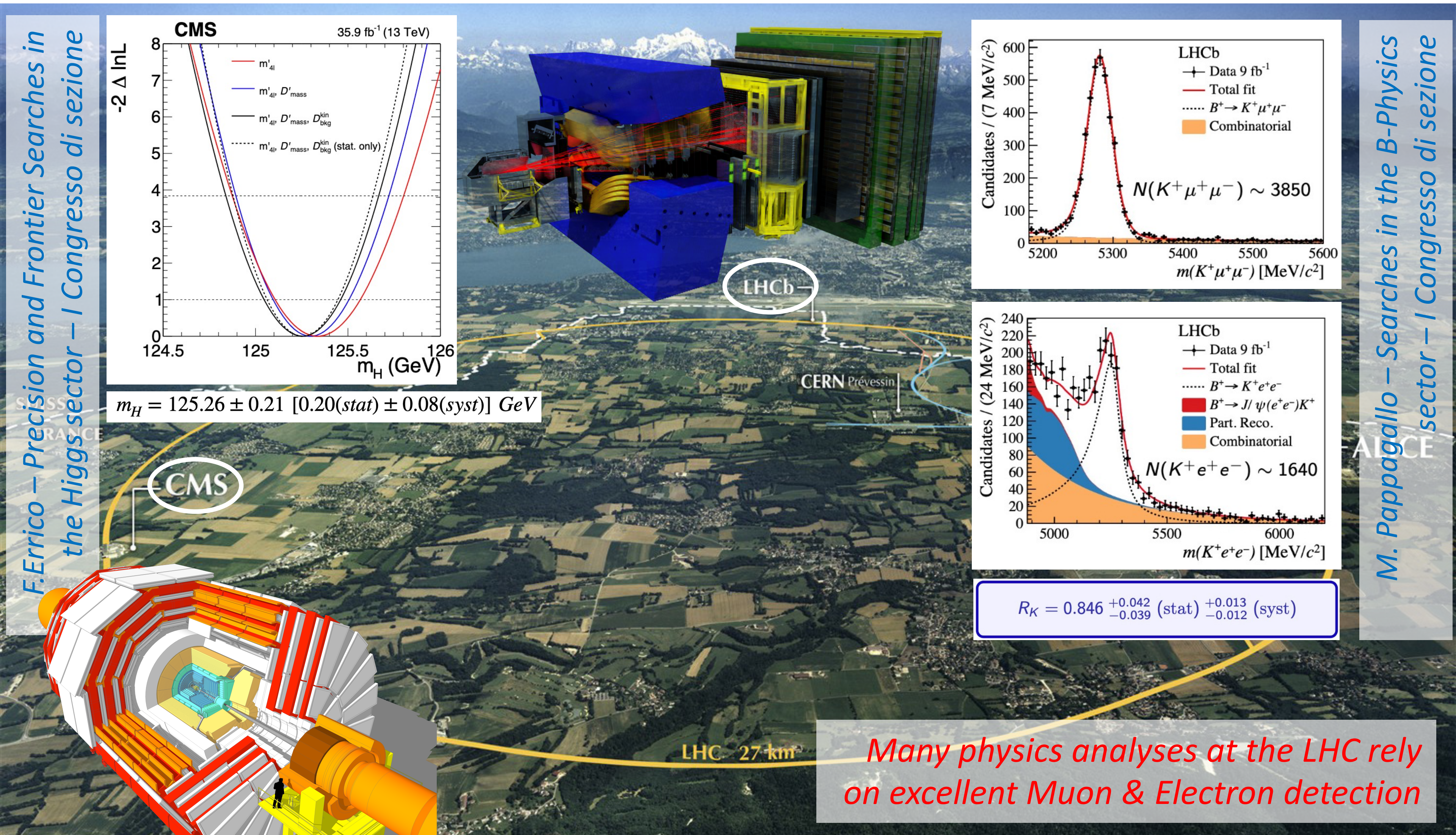
Bari, Feb 3rd 2022

CMS & LHCb experiments

Setting the scene



CMS & LHCb experiments
Setting the scene



F.Errico – Precision and Frontier Searches in the Higgs sector – I Congresso di sezione

$m_H = 125.26 \pm 0.21\ [0.20(stat) \pm 0.08(syst)]\ GeV$

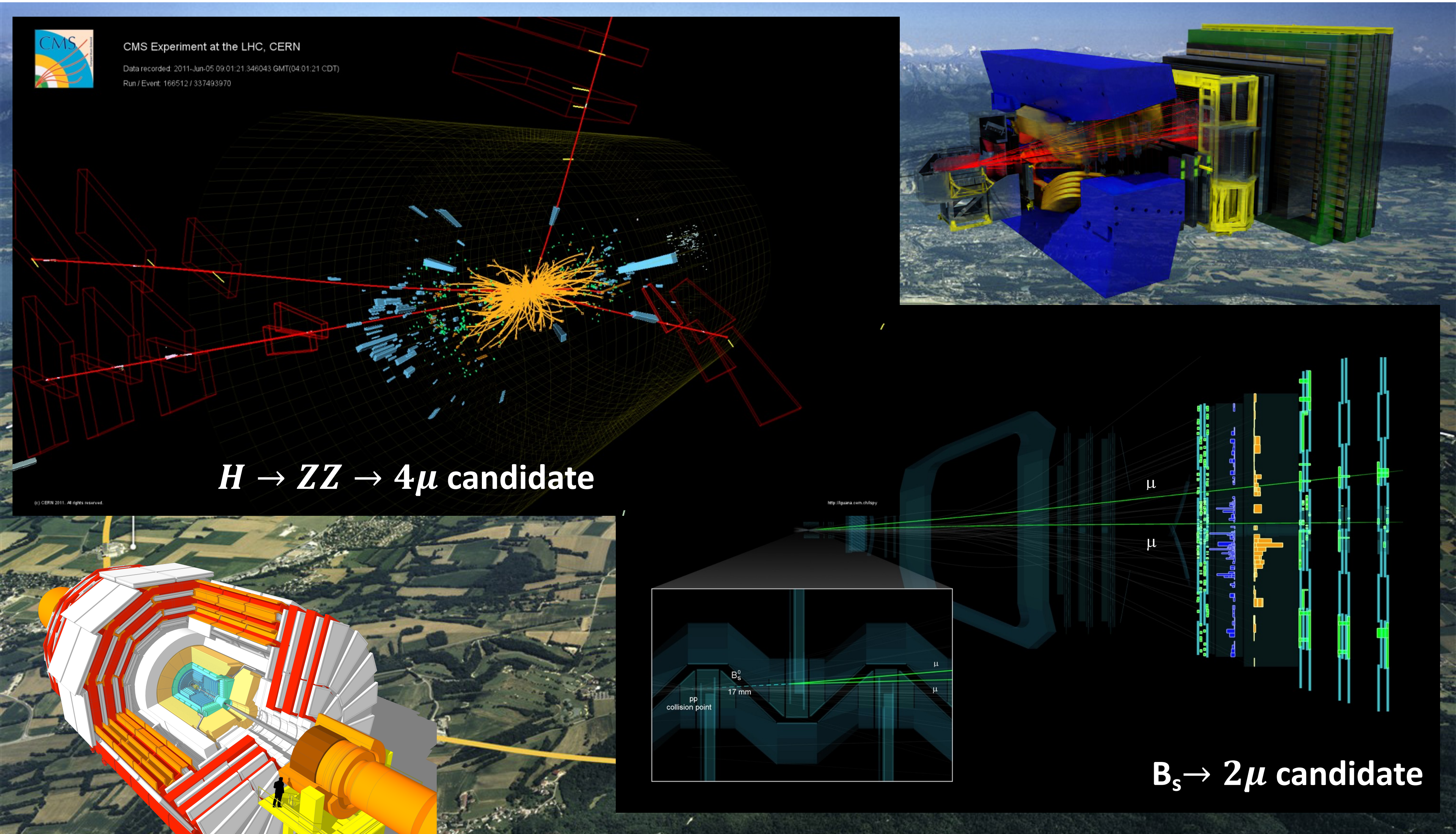
M. Pappagallo – Searches in the B-Physics sector – I Congresso di sezione

$R_K = 0.846\ ^{+0.042}_{-0.039}\ (\mathrm{stat})\ ^{+0.013}_{-0.012}\ (\mathrm{syst})$

Many physics analyses at the LHC rely on excellent Muon & Electron detection

CMS & LHCb experiments

Setting the scene

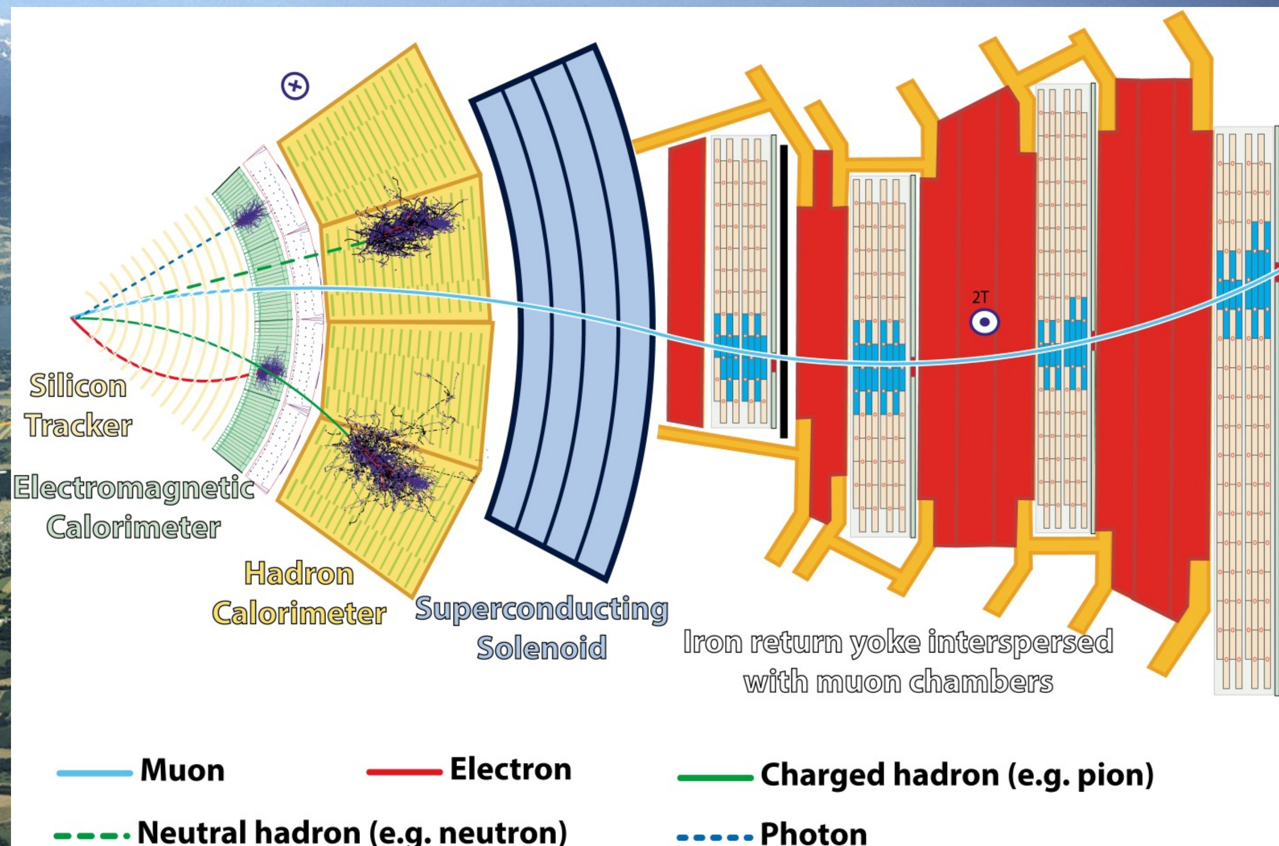


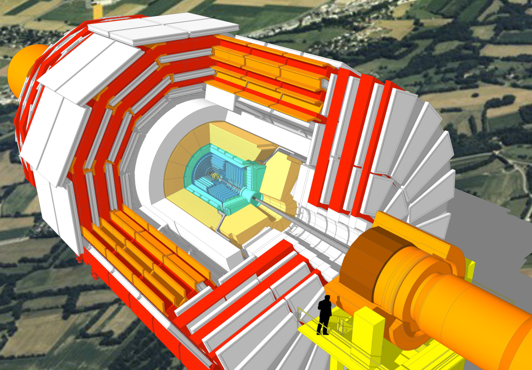
CMS & LHCb experiments

Setting the scene for gaseous detectors

High-energy muons are not stopped in the calorimeters and require tracking detectors outside the magnetic coil for precise particle identification

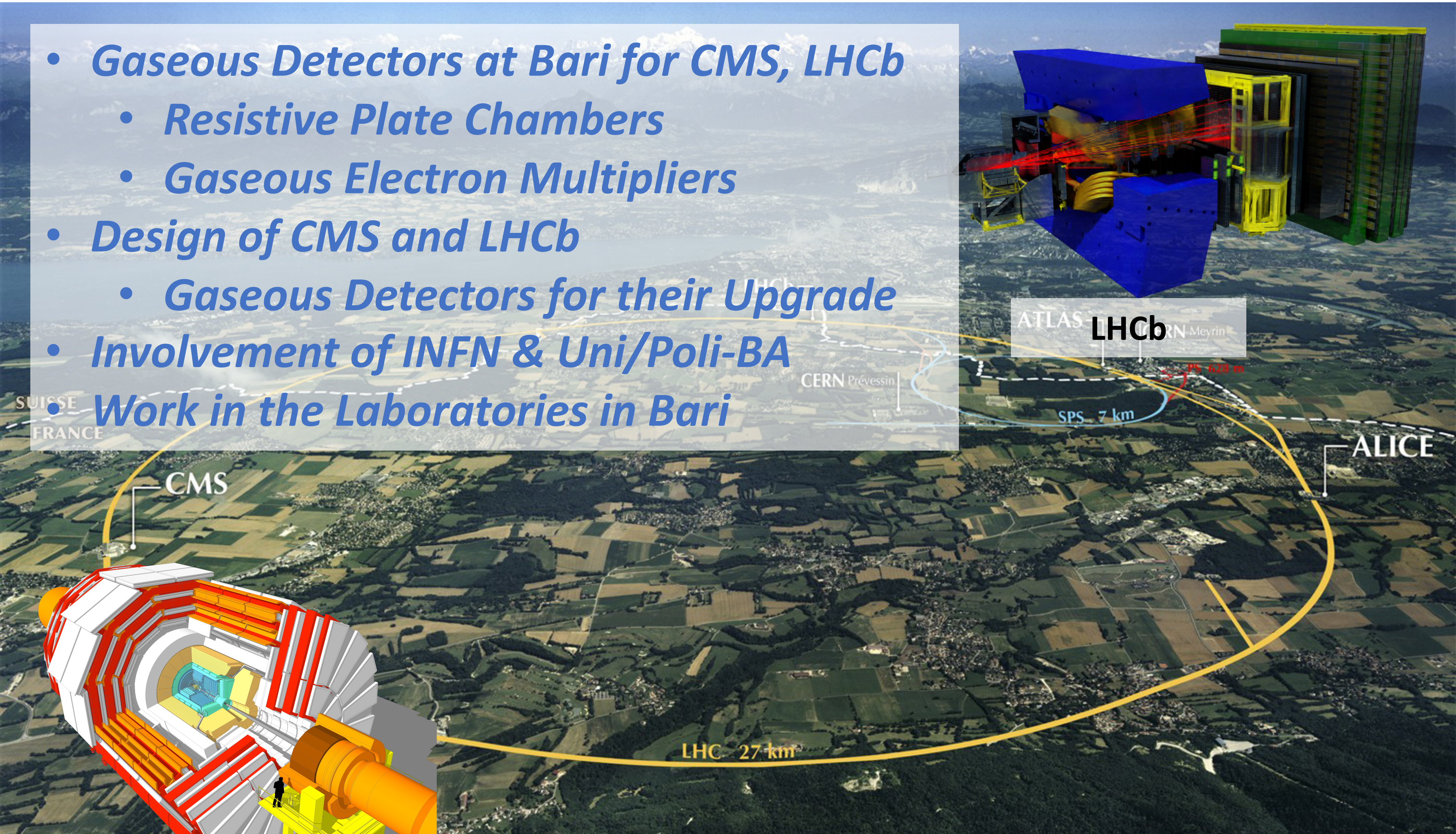
Muon detectors need to cover several 1000 m² and ***Gaseous Detectors are therefore the first choice***



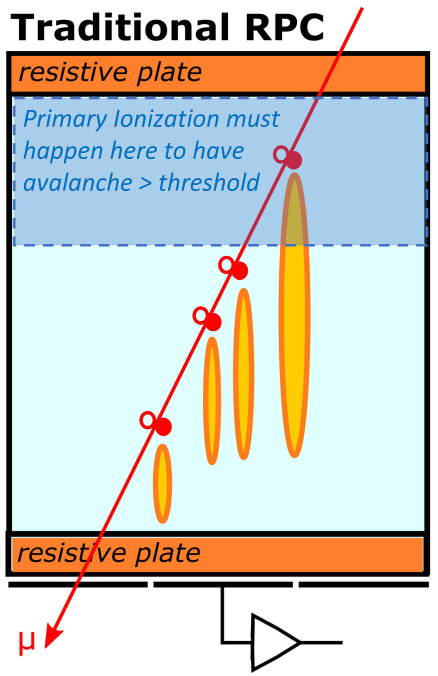


Outline
of this talk

- *Gaseous Detectors at Bari for CMS, LHCb*
  - *Resistive Plate Chambers*
  - *Gaseous Electron Multipliers*
- *Design of CMS and LHCb*
  - *Gaseous Detectors for their Upgrade*
- *Involvement of INFN & Uni/Poli-BA*
- *Work in the Laboratories in Bari*



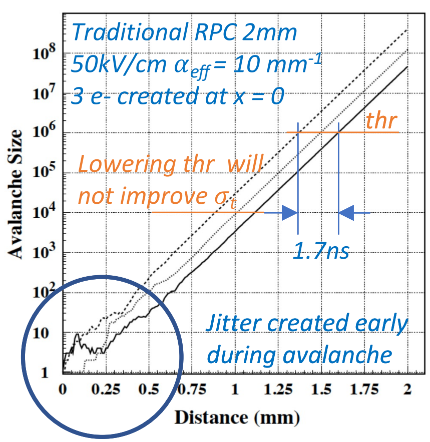
Resistive Plate Chambers
working principle

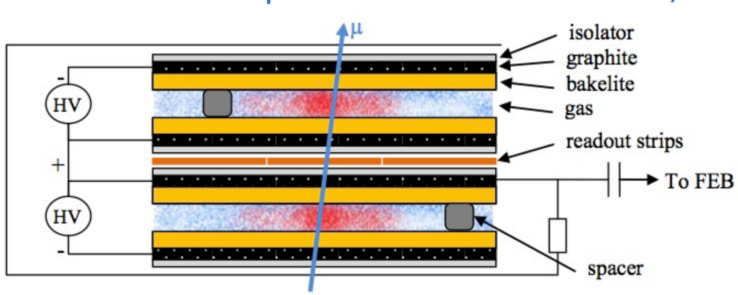


- Ionizing particle passing through gas gap (1-2mm) creates primary electrons that start immediately an avalanche in the uniform high Electric field (~50kV/cm) applied between two resistive electrodes
- Avalanche is quenched by voltage drop on resistive plates
- Avalanche signal is induced on external pickup electrodes
- Time res (1-1.5ns) is driven by fluctuations early in avalanche
  - Need gas with high primary ionization yield (R134a – $C_2H_2F_4$)
- Resistivity of electrodes drives recharge time and Rate-Capability
- Rate-cap ≤ 1kHz/cm^2 (R&D for ATLAS & CMS '90 also INFN Bari)
- Improved $\sigma_t \approx$ 30- 50ps with Multi-Gap RPC
- However: EU phasing-out use of Gas with high GWP (R134a, SF_6)

Main Challenges / Ongoing & Future R&D:

- Find new gas mixture with similar properties and lower GWP
- Improve Rate-Capability (lower bulk-resistivity ρ & lower charge Q), reduce Gap & Electrode thickness, sensitive Electr , Improve $\sigma_t \leq 0.5$ns

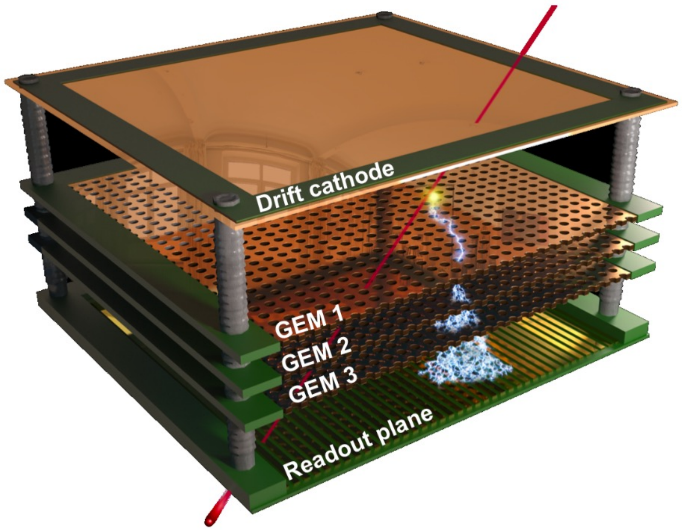




Design CMS RPC:

- Double gap, strips@center
- 2mm gas, 2mm HPL 1-6 $10^{10}\Omega cm$
- Graphite coating 10^5 Ω/■
- 95.2% R134a 4.5% iC_4H_{10}0.3% SF_6

Gaseous Electron Multipliers
working principle

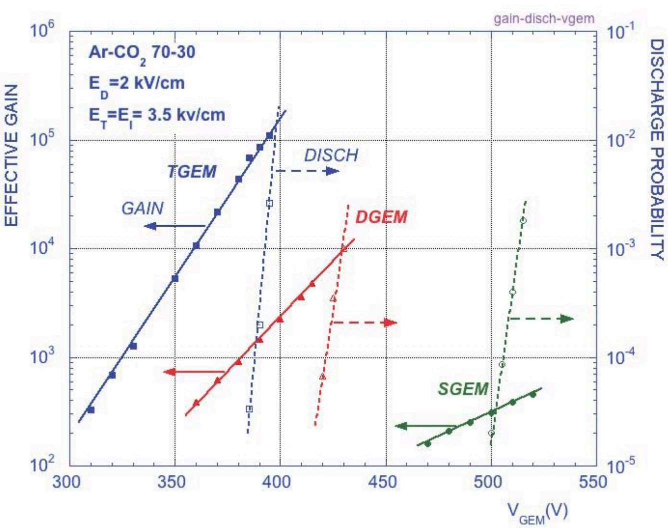


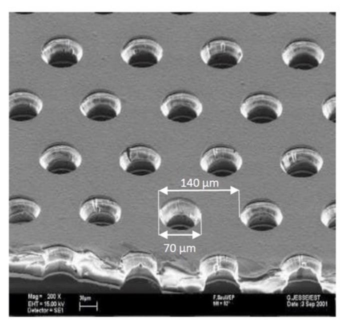
GEM is a Micro-Pattern Gaseous Detector (MPGD):

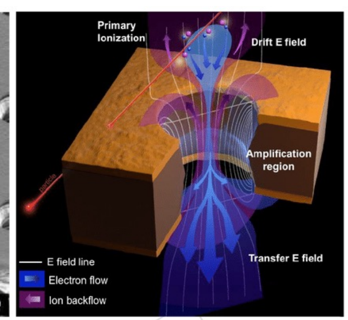
- Ionizing particle passing through drift volume (3mm) creates primary electrons that drift inside E-field to kapton foil with ~6000 holes/cm^2 (50um diam, 140um pitch)
- Electrons are multiplied inside intense E-field (50kV – 90kV/cm) inside hole: typical gain G = 20 / foil
- 3 subsequent amplification foils: total gain G= 8000
  - Advantage: multiplication split over several holes
  - Reduction of discharge prob to $\lesssim 10^{-10}$ @ G=10^4
- $\sigma_x \approx 50\mu m$, $\sigma_t \approx$ 5- 7ns ($ArCO_2$), Rate > MHz, radhard

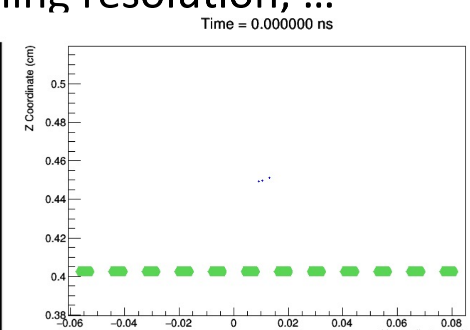
Main Challenges / Ongoing & Future R&D:

- Reduce damage of discharges with Resistive materials
- Ensure large rate capability over large area detectors
- Improve spatial resolution, timing resolution, …



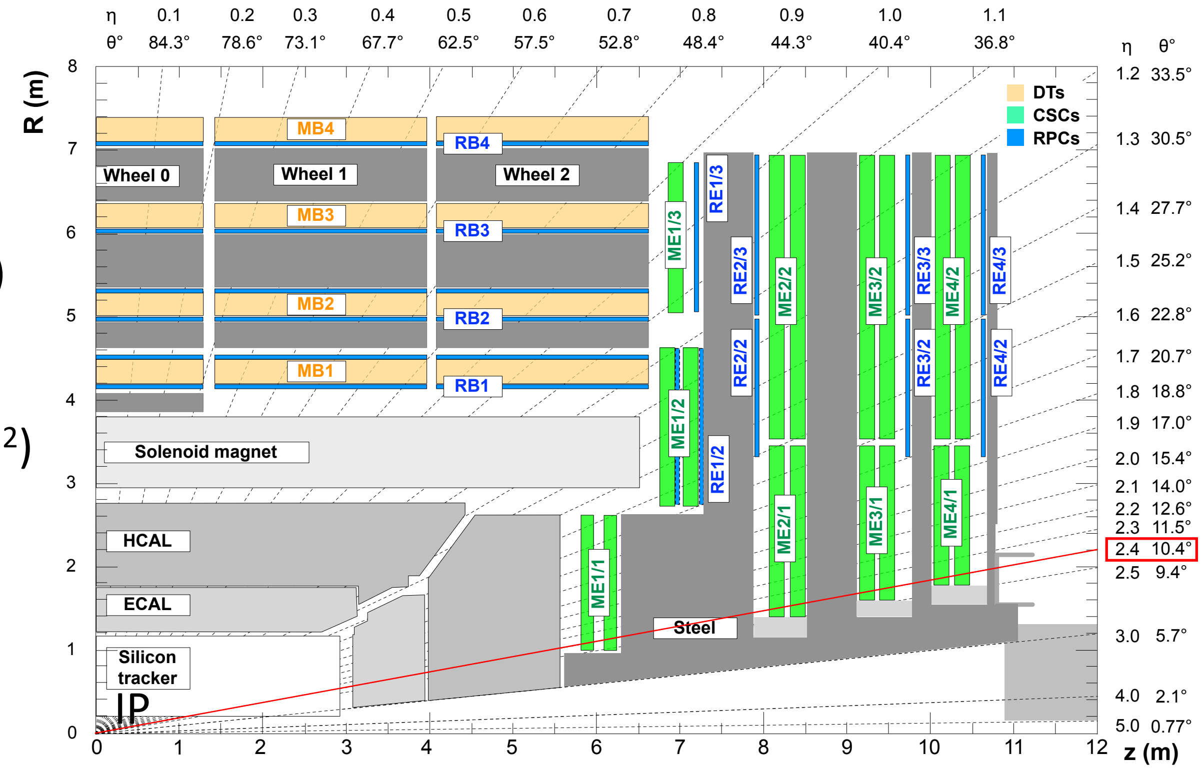






Design of CMS Muon System

Phase 1



Muon System consists of:

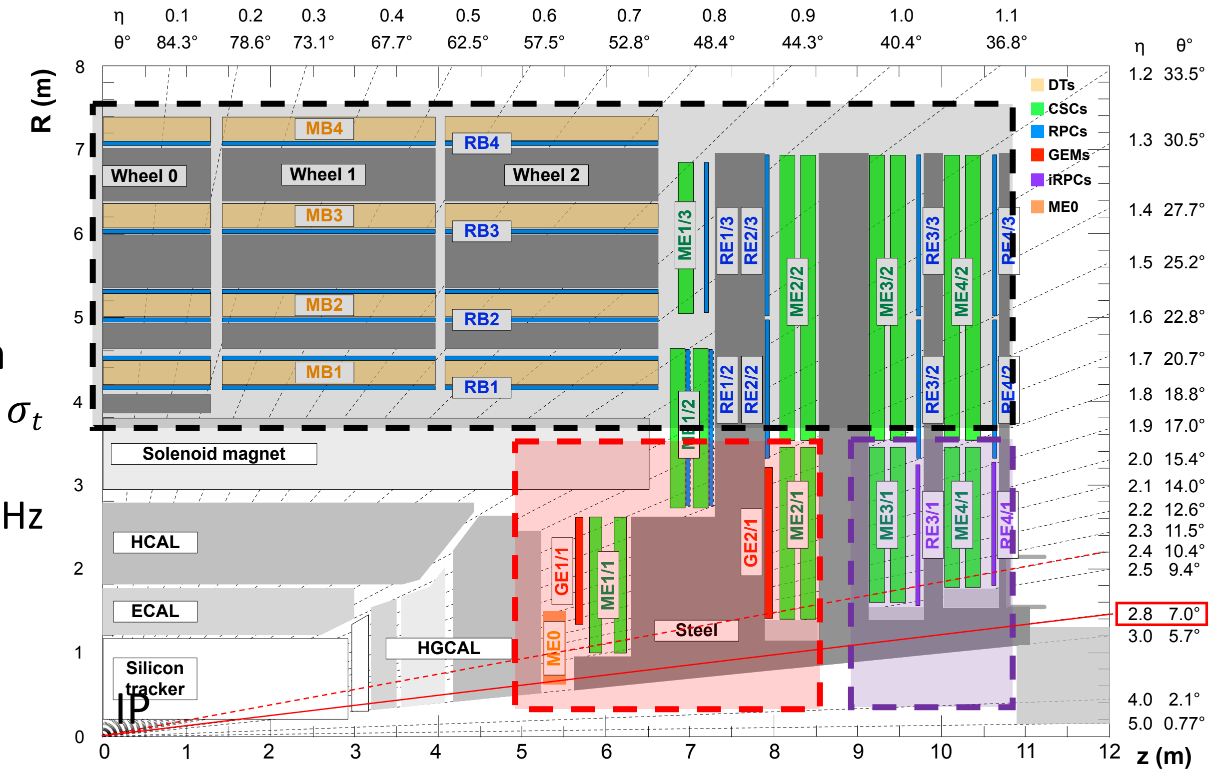
- **Multi-layer Drift Tube (DT)** detectors for precise (100um) muon reconstruction and triggering in low B-field and low-background (<100Hz/cm^2)
    - $0.0 \le \eta \le 1.2$
    - 250 chambers
    - 18 000 m^2
    - 172k channels
- **Cathode Strip Chambers (CSC)** for precise (50-150um) muon reconstruction and triggering in B-field and relative high background (few kHz/cm^2 rate)
    - $0.9 \le \eta \le 2.4$
    - 7000 m2
    - 577k channels
- **Resistive Plate Chambers (RPC)** for fast triggering (1.5-2ns) and redundant tracking (~1cm) in low-to-medium background (< $\sim$300Hz/cm^2)
    - $0.0 \le \eta \le 1.9$
    - 3200 m2
    - 123k channels
    - INFN & Uni/Poli-BA involved in R&D, Construction & Operation since ~1994

Upgrade of CMS Muon System

Phase 2

For the High-Luminosity Phase of the LHC (2029-2042) the Muon System will be upgraded with:

- **Improved electronics for the existing CSC, DT & RPC system**
  - Readout w/ high BW, exploit σ_t
  - Longer trigger Latency 12us
  - Higher L1A rate: 100 → 750kHz
- **Gaseous Electron Multiplier (GEM) detectors** for precise (150um) muon reconstruction and triggering in B-field and high background (few – 100 kHz/cm² rate)
  - GEx/1 : $1.6 \leq \eta \leq 2.4$
  - ME0: $2.0 \leq \eta \leq 2.8$
  - 432 chambers, ~150 m²
  - 1.2M channels
  - 18 GE1/1 built in Bari (2018)
  - FE-chip designed in Bari

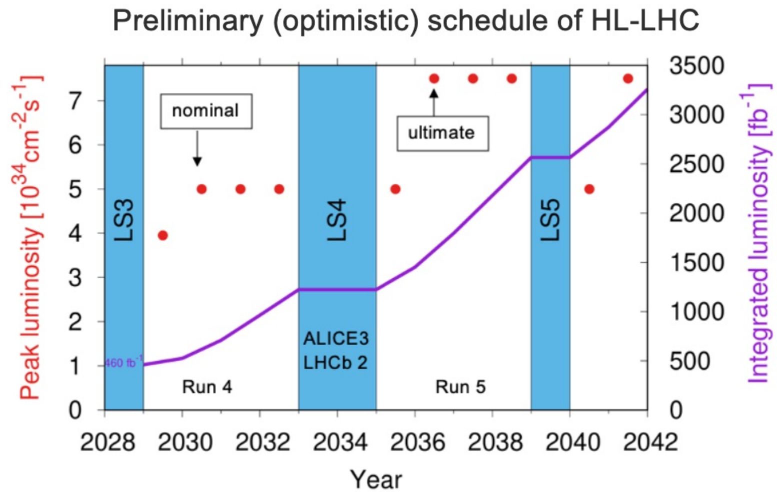


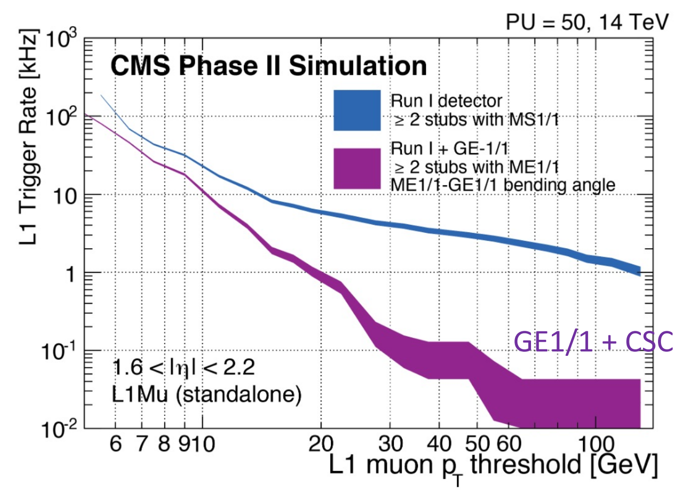
- **Improved Resistive Plate Chambers (iRPC)** for fast triggering (1.5-2ns) and redundant tracking (<1cm) in medium background (< ~1kHz/cm²)
  - RE3/1 and RE4/1: $1.8 \leq \eta \leq 2.4$
  - 72 chambers, ~100 m²
  - 7k channels
- **Gas recuperation plants + search for more GWP friendly gasmixtures for future (for operation > 2033)**

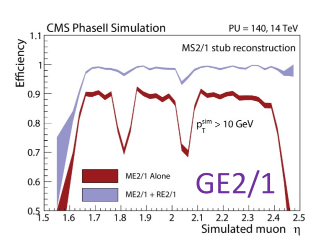
Upgrade of CMS Muon System

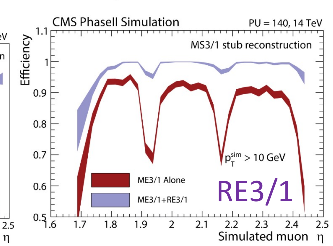
motivation

- During Run 2 operated at 2 10^{34} $cm^{-2}s^{-1}$, 193.2fb^{-1} integrated, expect 460 fb^{-1}
- Evidence for Vector Boson Scattering, HH-production, %-level measurement of Higgs-boson couplings,… requires dataset ~3 ab^{-1}
- Enter High-Lumi LHC (5-7.5 1034 cm-2 s-1 in 10 year increase data x 10 (300fb^{-1} →3ab^{-1})
- At cost for detectors to efficienty take high-quality data at 140-200 PU
- Huge upgrade program for CMS (~300 MEur)
    - New Tracker and new Endcap Calorimeter
    - Replace electronics most other detectors
    - Reinforce CMS with new technologies
- **New Muon Detectors**
    - GE1/1 is early Phase-2 upgrade: reduce Trigger rate by using $\Delta\phi$(GEM,CSC) before track trigger becomes available in Run 4
    - GE2/1 + CSC → displaced muon triggering
    - GE2/1, RE3/1, RE4/1 improve Muon Track Finder Trigger in combination with CSCs









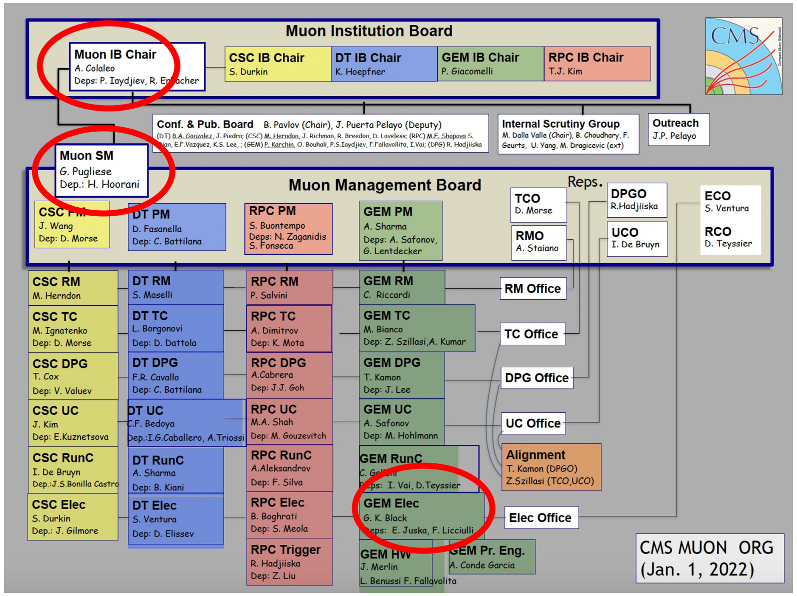
Involvement INFN & Uni/Poli-BA

and the global context

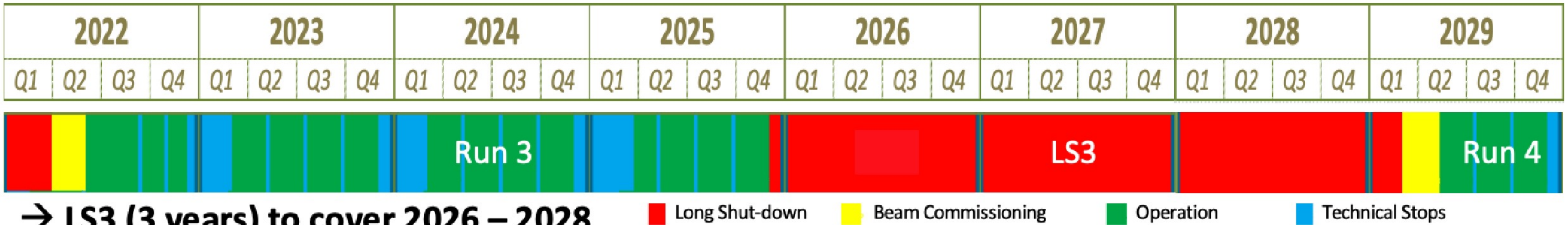
Researchers & Technicians Bari active in

- *Muon Management* *(System Manager + IB Chair)*
- *Detector Operations* *(data certification)*
- *Detector Maintenance* *(gas leak repair)*
- *Detector R&D @ CERN* *(GIF++ longevity)*
- *Detector Quality Tests @ CERN* *(Cosmics)*
- *Detector Commissioning* *(GE11 Eff analysis)*

Many interesting and important work, however ***in this presentation I will mostly concentrate on work done at home lab (BA)***



What drives the work in the lab & at CERN is the global schedule for LS3*:



→ LS3 (3 years) to cover 2026 – 2028

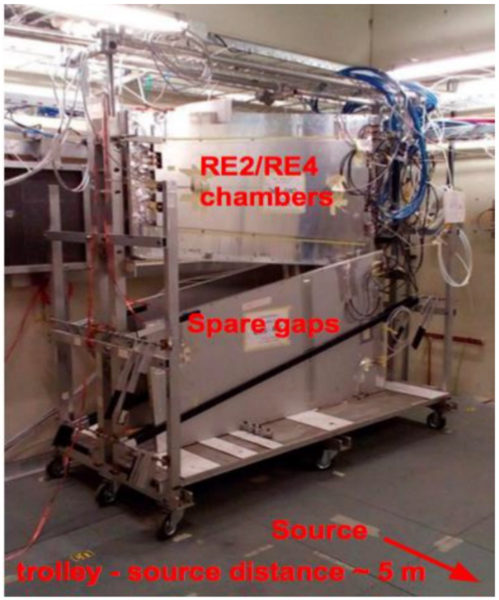
Long Shutdown 3 is devoted to Tracker & High Granularity Calorimeter Upgrade

iRPC & GEM Upgrades must go before in End-of-Year Technical stops 2023 and 2024

* No further extension or delay of LS3 possible due to radiation damage to focussing triplets

Activities @ INFN & Uni/Poli-BA

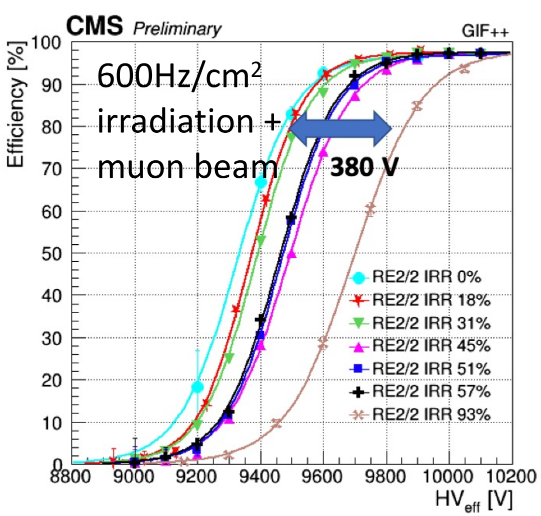
RPC longevity

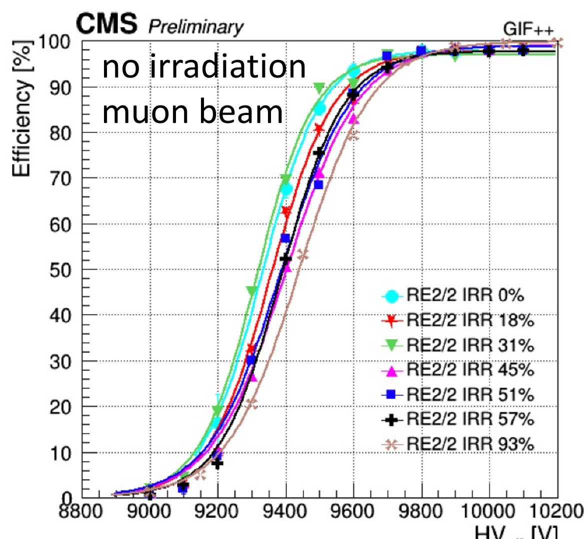


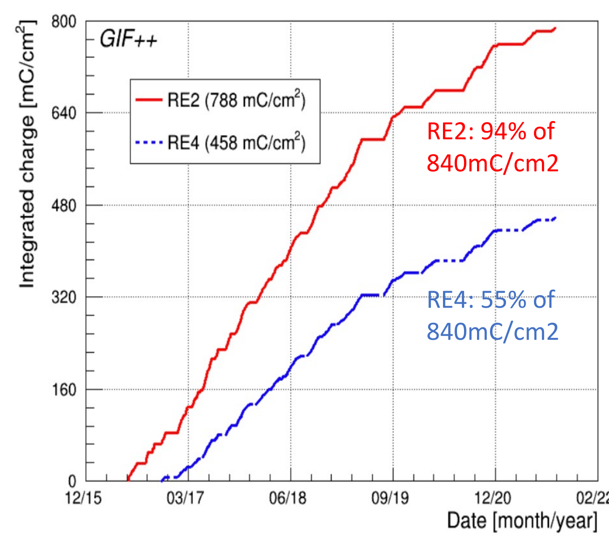
GIF++ is unique irradiation infrastructure in the world

Combines high energy μ/π beams with 14 TBq ^{137}Cs source

- Validate existing RPC for HL-LHC
- Irradiate chambers ≥ expected dose @ HL
  - So far no ageing detected (same efficiency turn-on)
  - Under 600 Hz/cm^2 (SF 3 w.r.t. 200Hz): 380V shift of WP
- **GIF++ also good place to evaluate new Eco-Gas mixtures**
  - Evaluate Efficiency, Working Point Shift, charge/hit, Clustersize, production of HF, …
- Joint effort ATLAS CMS LHCb/Ship ALICE CERN
  - Increase exchange of expertise and use of common tools

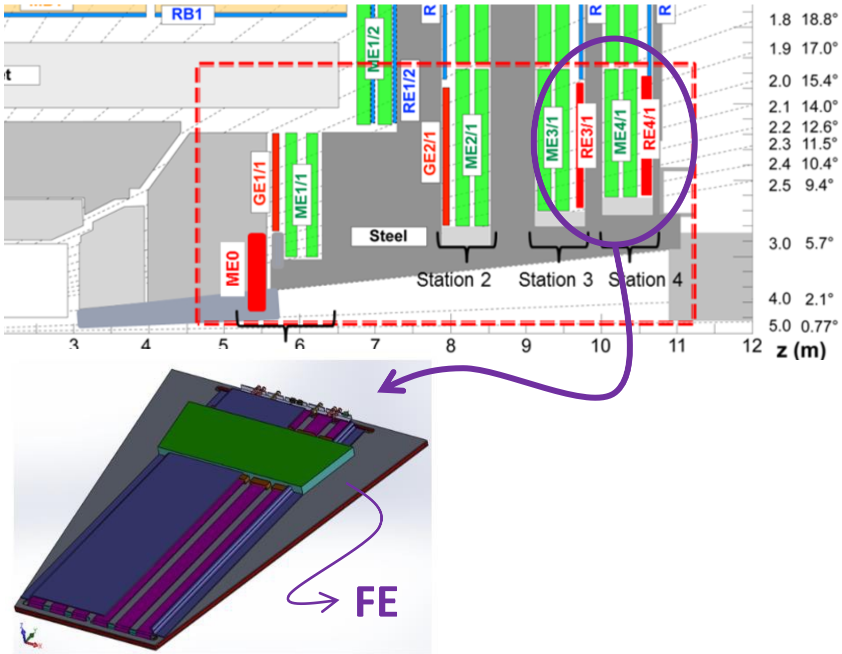






Activities @ INFN & Uni/Poli-BA

irradiation studies iRPC



	Existing RPC	Improved RPC
HPL thickness	2 mm	1.4 mm
Gas gap width	2 mm	2 mm
# Gas gap	2	2
Resistivity [Ωcm]	1 – 6 10^{10}	0.9 – 3 10^{10}
Threshold (typ)	150 fC	50 fC
Readout	3 η partitions	2D readout

Improved RPC (iRPC) for high rate environment

- reduced gap thickness → reduced charge
- reduced HPL thickness → improve signal ind
- More sensitive front-end electronics
- Reduced charge/hit → improved rate-cap

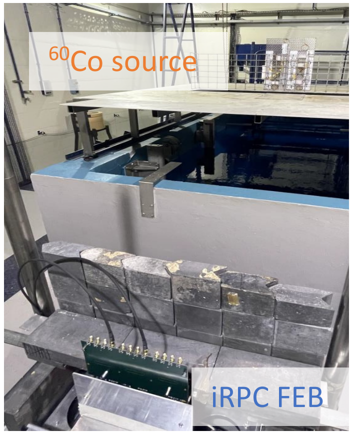
iRPC irradiation tests at GIF++

- 2kHz/cm^2 – WP 7.2kV – 90mC/cm^2 integrated

iRPC front-end electronics irradiated at ENEA

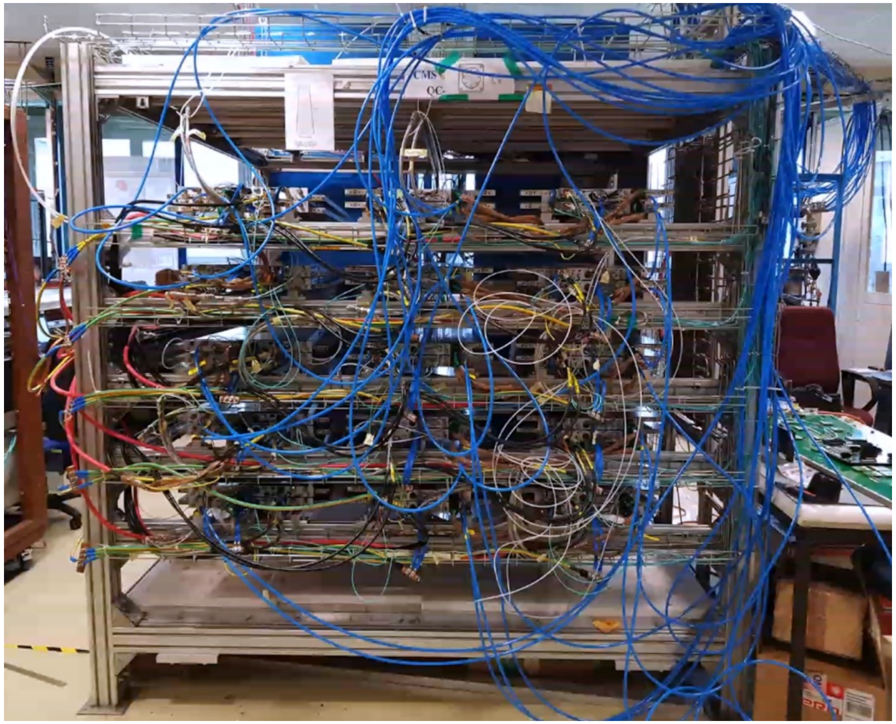
- ^{60}Co source – 160Gy on asic – 50 Gy on FPGA

iRPC Testing continues at RPC Lab Bari



Activities @ INFN & Uni/Poli-BA

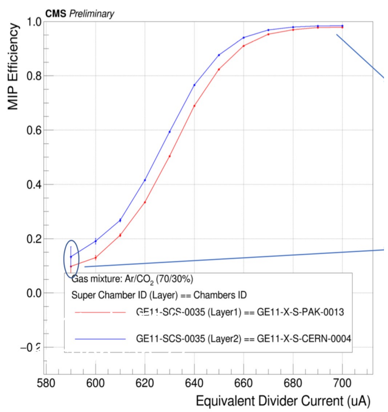
GE1/1 Construction

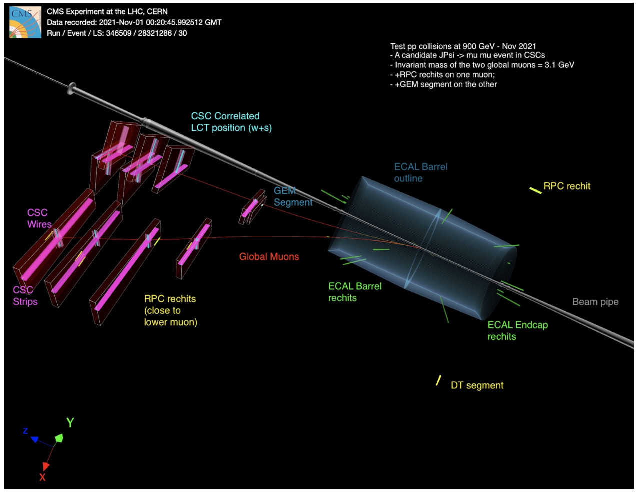


GE1/1: 160 chambers
- ”Early” Phase-2 upgrade to help trigger in Run 3
- 18 chambers constructed & Qualified at Bari
- QC2-5 in Bari + QC6-8 at CERN

CERN Cosmic Stand
- Simulataneous test of 30 GE1/1 chambers
- 92k readout channels (med-size Experiment!)
- Final electronics, optical fiber readout
- CMS DAQ with uTCA backend, DCS, Database

Installation in CMS
- Good data taking w/cosmics & early collisions
- Prompt analysis & ready for 1st collisions 2022





Activities @ INFN & Uni/Poli-BA

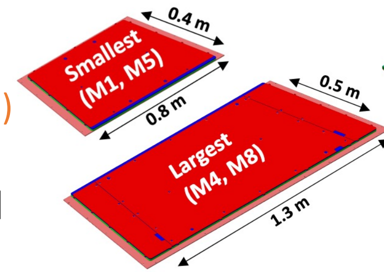
GE2/1 Construction

GE2/1: 300 modules M1-M8

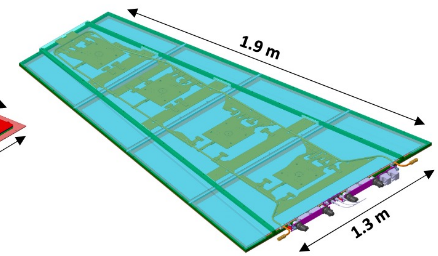
- 36 modules M4 to be constructed & Qualified at Bari (but likely will be more)
- QC2-5 in Bari + QC6-8 at CERN
- First shipment 8 modules M1 arrived

GE2/1 Installation Slot: Dec '23

- Constr & QC of 36 finished by Dec '22
- Thereafter 27 modules ME0 by Dec '24



8 slightly different triple-GEM modules (M1 to M8)



BACK-type (M1 to M4) and FRONT-type (M5 to M8) chambers

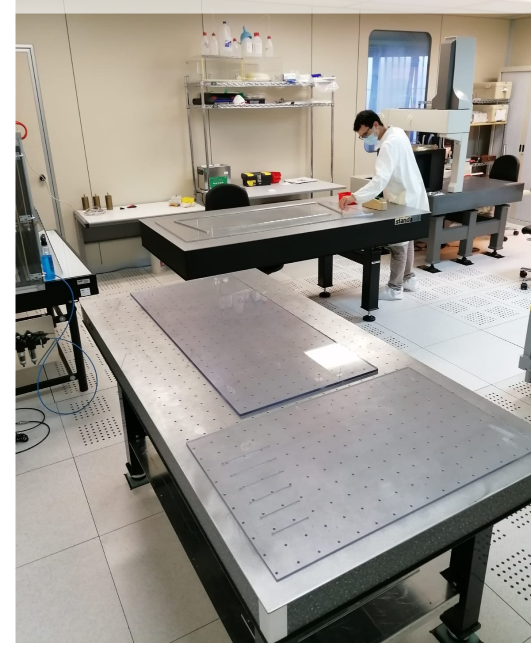
Pseudo-rapidity coverage 1.62 < |η| < 2.43

Assembly Tools designed by CAD INFN BA and used in 8 assembly sites

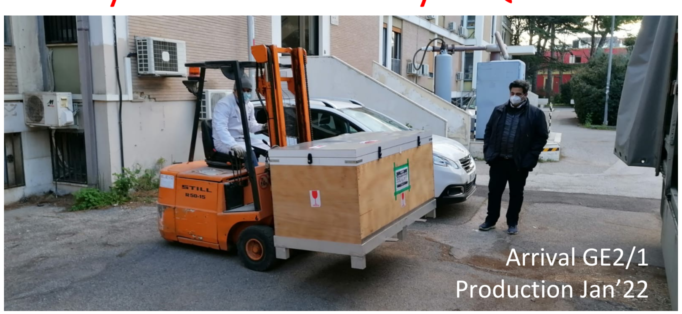
- Assembly jigs for 8 modules
- Plexiglass covers & base plates x 8M
- HV Clips

Construction GE21 prototype Nov'2018

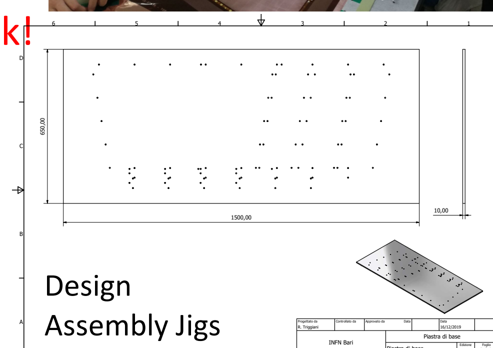
Cleanroom ready to start



Ready to start Assembly & QC Next week!



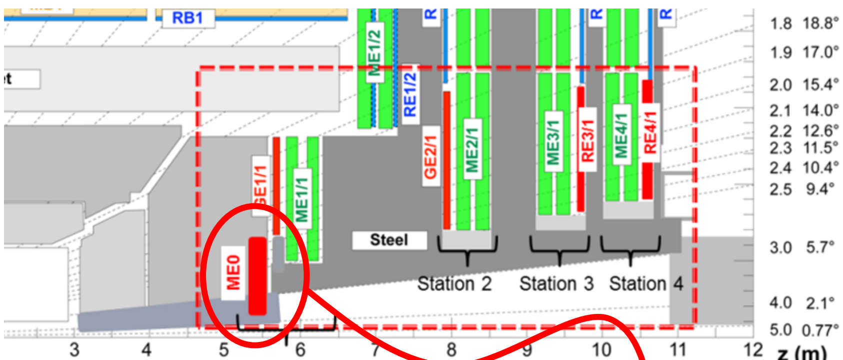
Arrival GE2/1 Production Jan'22

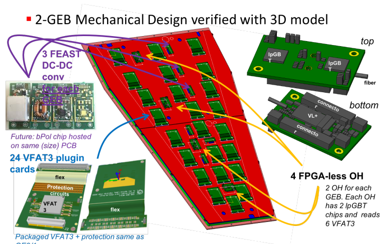


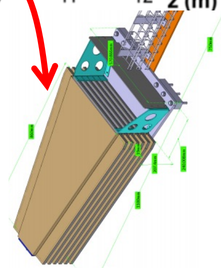
Design Assembly Jigs

Activities @ INFN & Uni/Poli-BA

ME0 Design

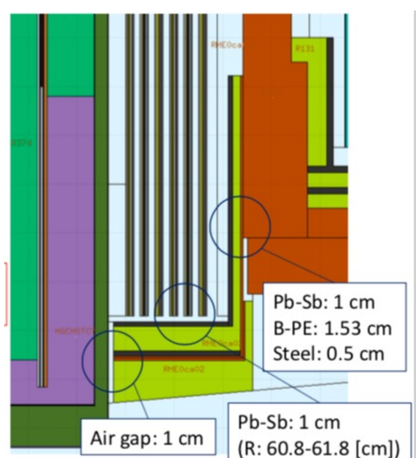


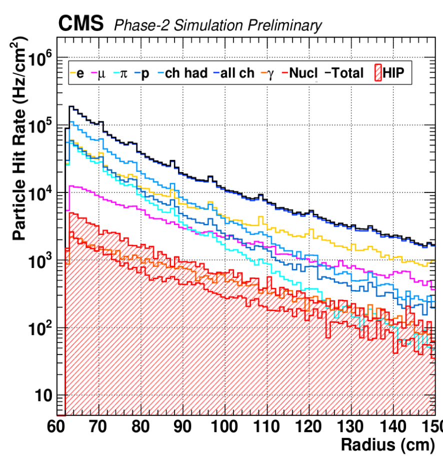


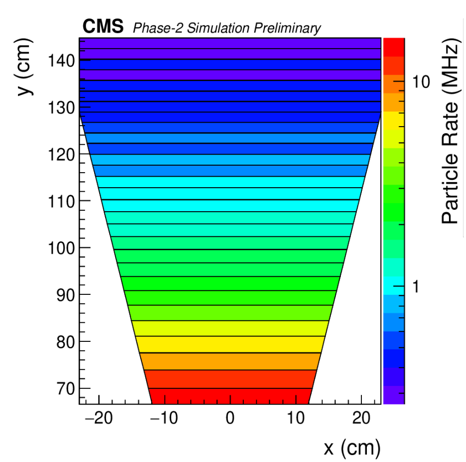


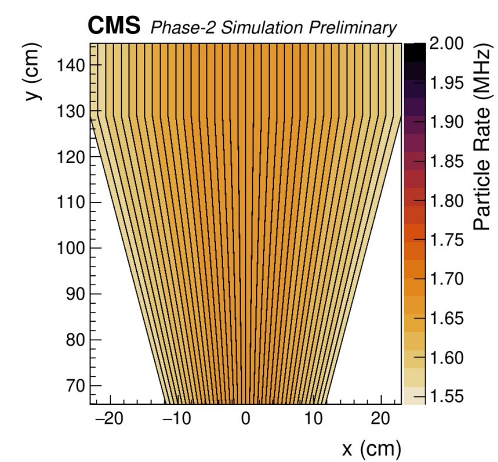
ME0 is a 6-layer Triple-GEM detector behind the High Granularity Calorimeter (radiation!)

- Design of Services layout (reduced area)
- Prototype production & Test
- Optimization & Simulation of Shielding
- Max rate: 150 kHz/cm^2
- Requires design optimization
  - Optimization of shielding
  - Optimization of detector Layout
- Radical change: Horizontal → Vertical Seg
  - Horizontal current evacuation would have led to serious rate capability reduction
- All design work during pandemic done remote







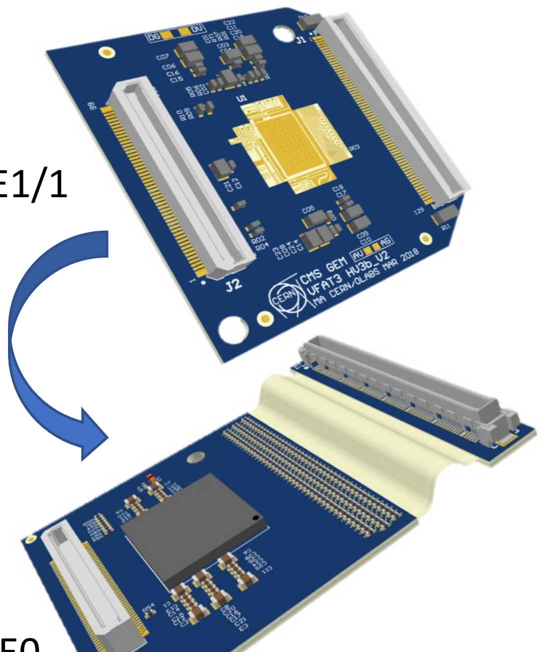


Activities @ INFN & Uni/Poli-BA

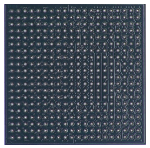
VFAT3 front-end electronics

- **Front-End electronics for Triple-GEM detector** (VFAT3 asic) designed by INFN Bari (F.Loddo, G.De Robertis, F.Licciulli)
- GE1/1: hybrid plugin-card with wire-bounded VFAT3 asic
  - Lessons learnt: difficult to manufacture (small bond pitch)
  - Reduce mechanic stress: flex part for connector to det
  - Extra input protection
- **Test packaged VFAT3 chips with MOSAIC-based setup**
  - Clam shell socket host VFAT3
  - 5 test systems produced
  - 20 different tests
- VFAT3 is INFN Responsibility
- F.Licciulli Electronics coord.

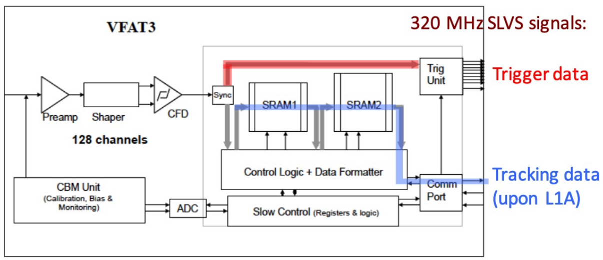
GE1/1



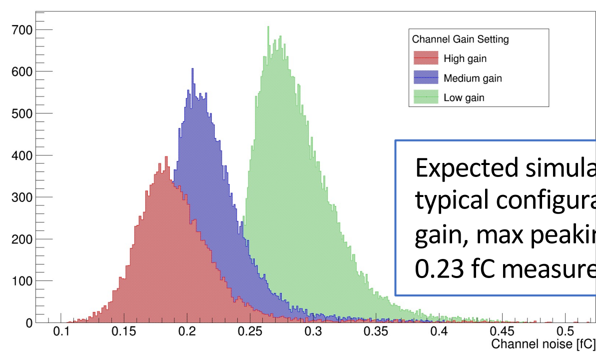
ME0
GE2/1



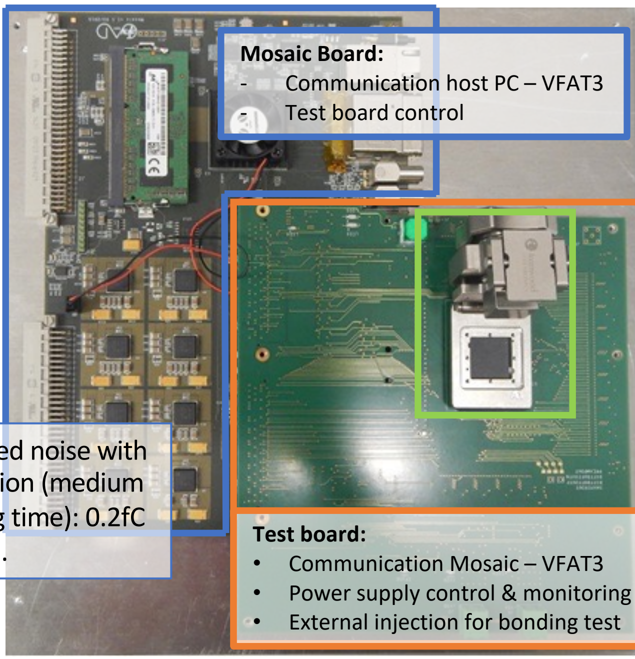
BGA packaging



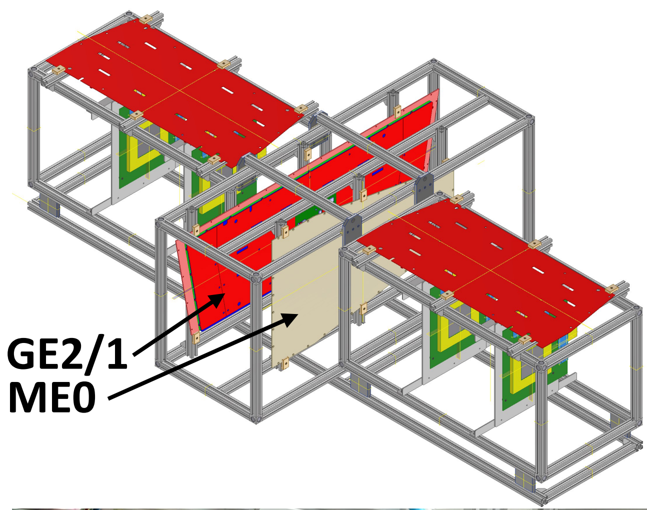
Noise measurement, ~ 110 VFAT3b



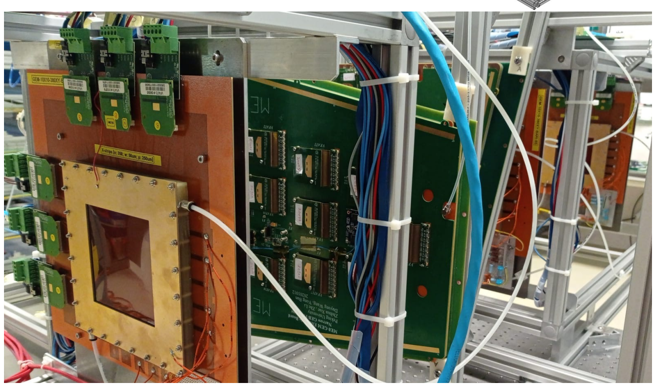
Expected simulated noise with typical configuration (medium gain, max peaking time): 0.2fC
0.23 fC measured.



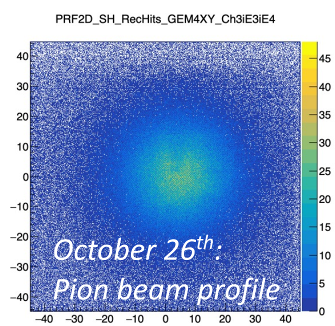
Activities @ INFN & Uni/Poli-BA
beam test of Phase-2 GEM detectors

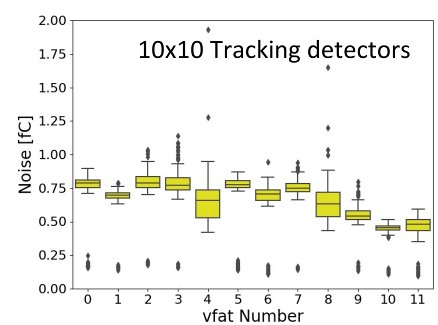


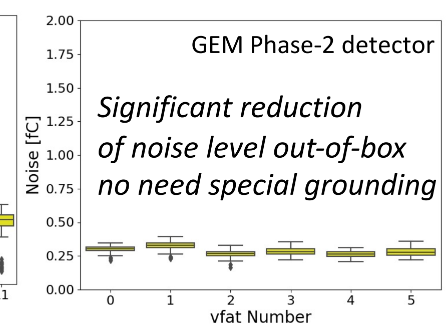
- **GEM Collab has extensive history of TB periods 2010-15**
  - Tested many prototypes, essential for approval TDR
  - With installation of Slice-Test effort was discon'ted
    - However slice test = 1st Final Det x Final Electr
    - Several problems were discovered, no access
    - Problems had to be reproduced in the lab
- **=> Bari pushed for testing GE2/1 dets w/ final electronics**
  - Good opportunity to test ME0 R&D chambers
  - Mechanics: designed by V. Valentino, constructed M.Franco
  - Electronics: VFAT3 adapters (G.De Robertis, F.Licciulli, M.Rizzi)
  - High-Resolution Triple-GEM detectors for Tracking
  - Final Electronics: FE, Opto-hybrids with GBTx, fibers
  - CMS DAQ run on FPGA board (CVP-13)
  - 100 kHz data taking! >120h - 2G evts - 1TB data



Period	Time	Muon Beam		Pion Beam	
First Period	9 days	90h - 700M	377 GB	4:50h - 400M	180 GB
2nd Period	5 days	35h - 900M	500 GB	1:20h - 70M	51 GB

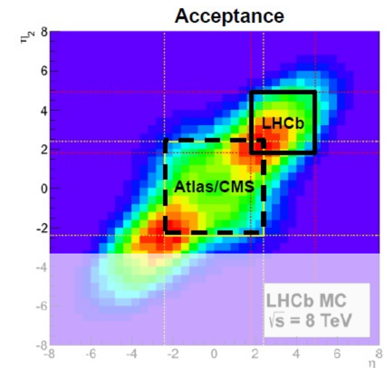






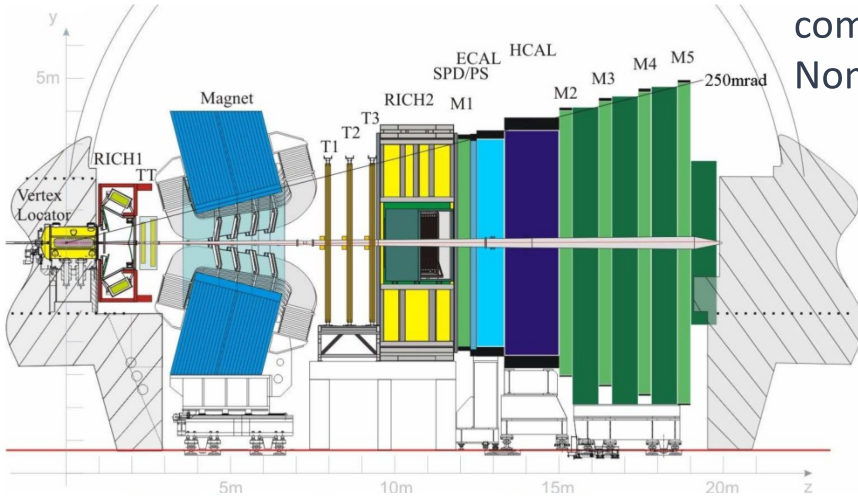
Design of the LHCb Muon detector

2008-2018



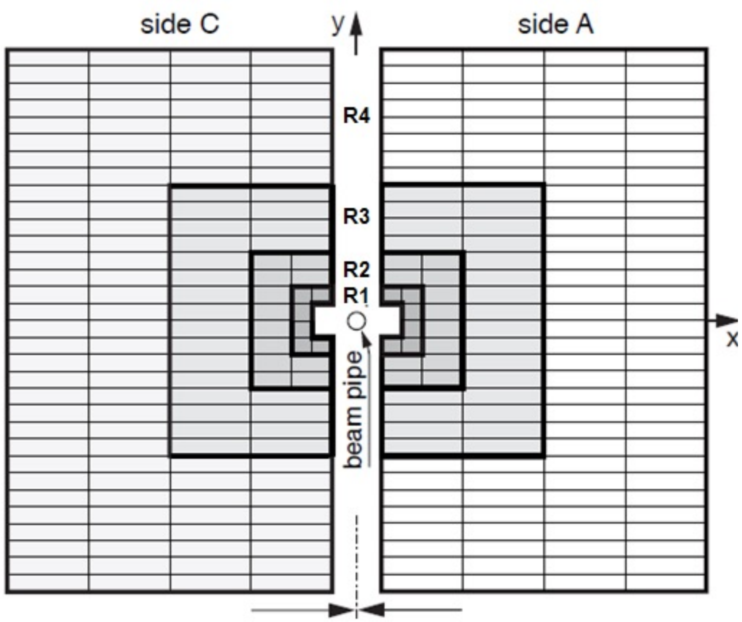
Single-arm forward spectrometer

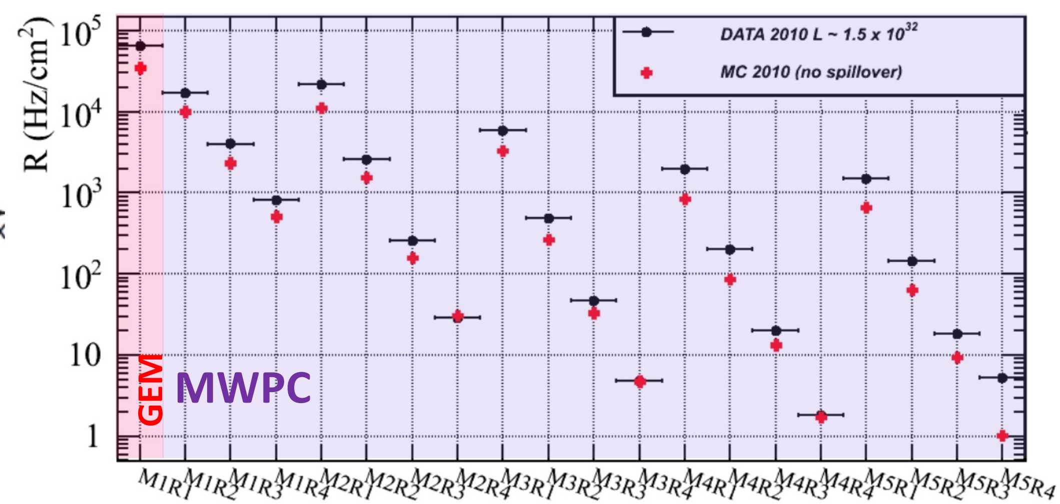
pseudorapidity coverage $2 < \eta < 5$,
complements CMS ($0 < |\eta| < 2.5$)
Nominal luminosity: $2\ 10^{32}\ cm^{-2}s^{-1}$



muon detector: 5 stations + 80 cm Fe absorbers

- Each station (M2-M5) has 276 MWPC
- Station M1 has 12 GEM + 264 MWPC
- M1 removed for Run ≥ 3 (2022 – 2025)
- 122k channels, 435 m^2
- Rates: 1 – 10^5 Hz/cm^2
- Gas mixture: Ar:CO_2:CF4
  - 40:55:5 for MWPC and 45:15:40 for GEM

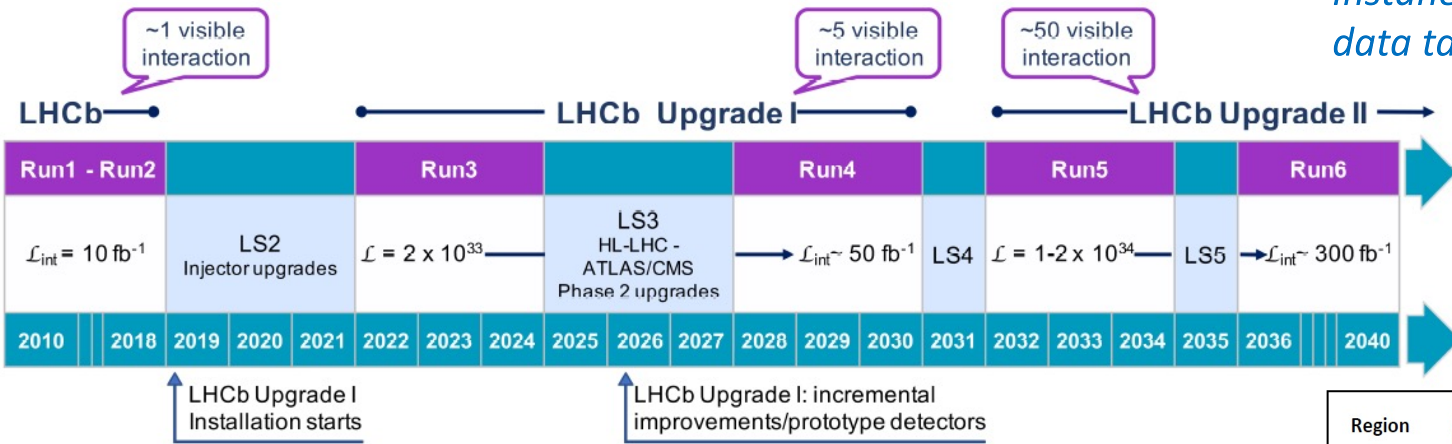




LHCb Muon detector upgrade

2035-2042

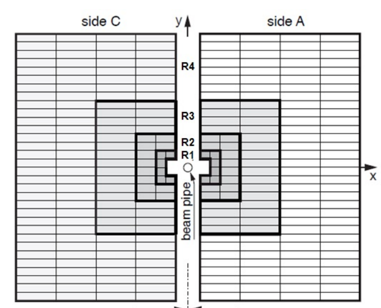
Factor 100 increase in Instaneous Luminosity, data target: 300 fb^{-1}



Upgrade II

Region		Max rate [kHz/cm^2]	MWPC
M2	R1	998	to be replaced
	R2	98	to be replaced
	R3	13	replaced/reused
	R4	10	replaced/reused
M3	R1	575	to be replaced
	R2	72	to be replaced
	R3	8	replaced/reused
	R4	3	replaced/reused
M4	R1	211	to be replaced
	R2	30	to be replaced
	R3	5	reused
	R4	2	reused
M5	R1	179	to be replaced
	R2	20	to be replaced
	R3	4	reused
	R4	2	reused

- **LHCb Upgrade 1 (Run 3-4 :: 2022 – 2031)**
  - Major upgrades installed in LS 2 (SciFi, RICH2, VELO)
  - Removal of muon station in front of ECAL, HCAL
- **LHCb Upgrade 2 (Run 5-6 :: 2035-2042)**
  - uRWELL for R1-R2
    - INFN Ba + LNF are in charge of testing new FE (FATIC2)
  - Reuse of MWPCs for some R3/R4
  - RPC is option for R4 (alt: Scintillating Tiles) *investigating possible timing advantages*
    - INFN & Uni-Ba (≤ 10 kHz/cm^2)



Bari RPC Lab

new generation of RPCs for low rate

Activities on RPC detectors started for NESSiE and SHiP proposals, for rates *O*(10^2) Hz/cm^2

- Synergy with CMS RPC team

Cosmic test stand:

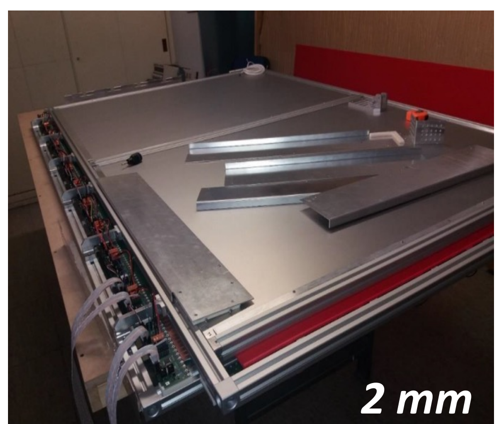
- 12 chambers (~3x1 m^2) - streamer mode – trig & tracking
- 1 avalanche RPC (~2x1 m^2), under test

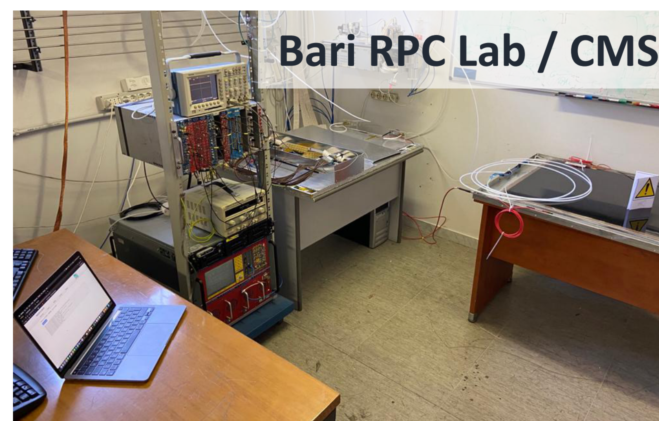
Gas distribution systems:

- 3 gas distribution systems, detectors can be tested with different gas mix and/or premixed gas

Current studies:

- large gaps (2 mm and 1.6 mm) operated with Freon and Freon-free gas mixtures in Bari and at CERN GIF++

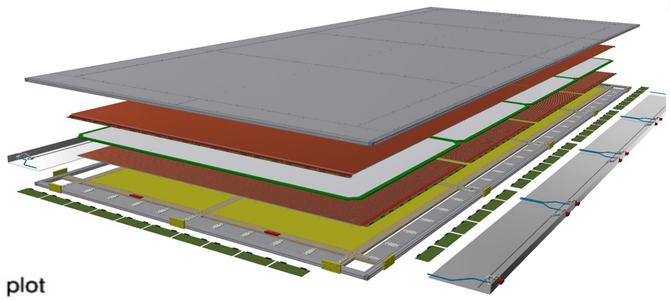


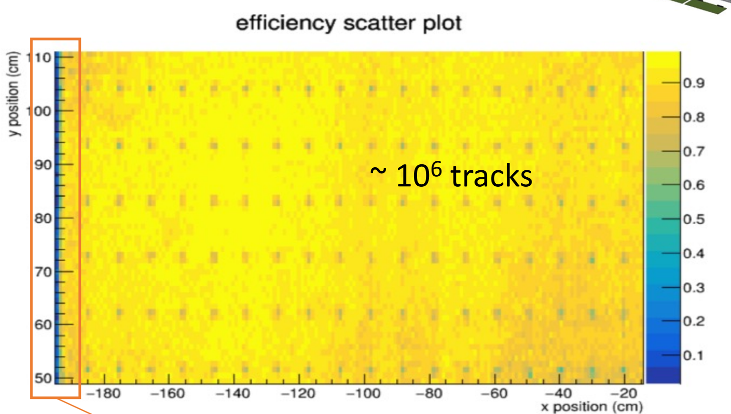


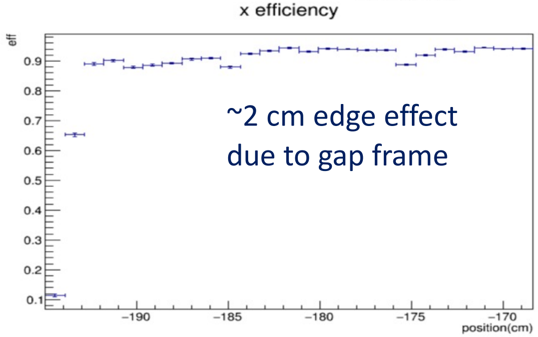
Performance 2 mm gap RPC

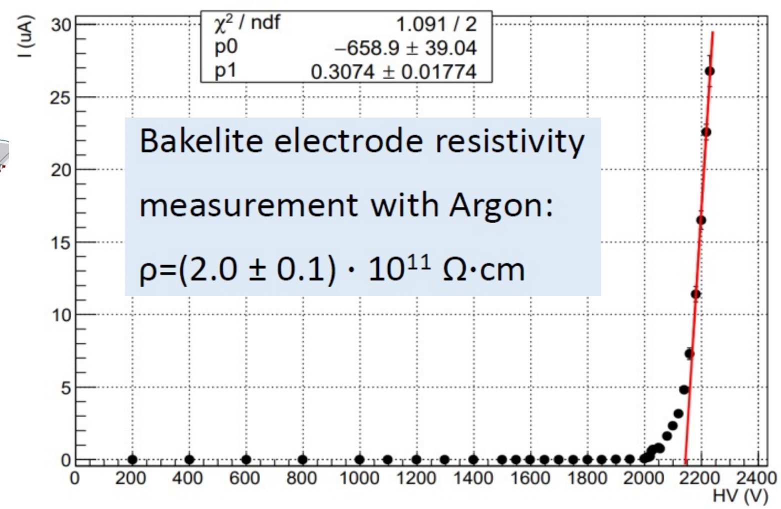
Large single gap RPC: ~(1.9 x 1.2) m^2

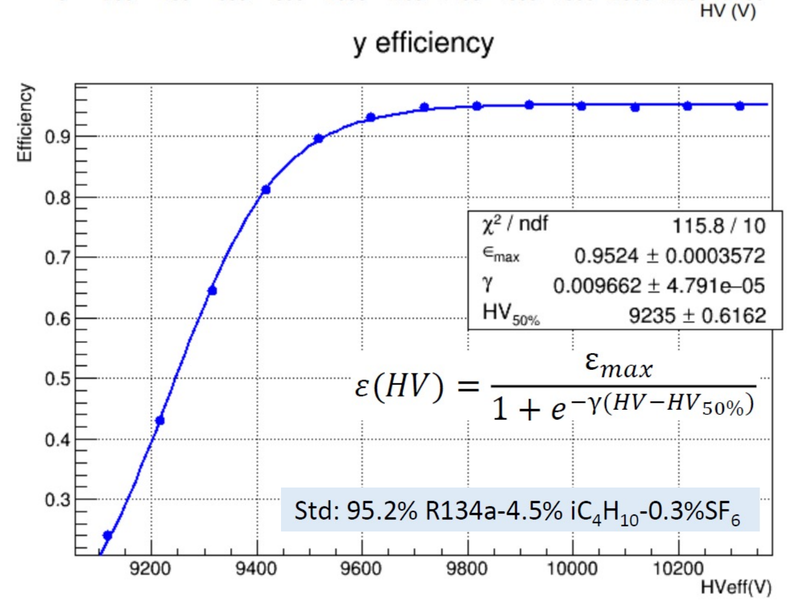
- 2 mm gap width; 2 mm HPL thickness
- 2D readout with 2 pannels of orthogonal strips ~1cm pitch







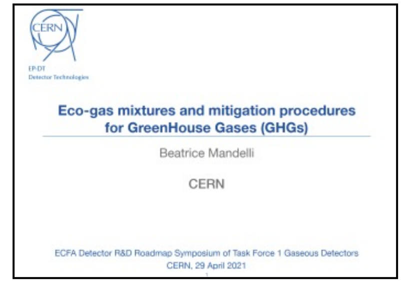




Eco-friendly gas mixtures for RPC

Fluorinated greenhouse gases (GHGs) with high **Global Warming Potential (GWP)** have been recently limited in the EU (EI regulation 517/2014)

- *GWP quantifies the contribution of a gas to the greenhouse effect, normalized to the effect of CO_2*
- *CERN is committed to reducing its direct GHG emissions*


EP-DT Detector Technologies

Eco-gas mixtures and mitigation procedures for GreenHouse Gases (GHGs)

Beatrice Mandelli

CERN

ECFA Detector R&D Roadmap Symposium of Task Force 1 Gaseous Detectors
CERN, 29 April 2021

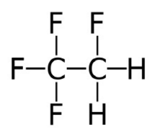

Environment Report

2019 - 2020

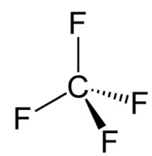
https://e-publishing.cern.ch/index.php/CERN_Environment_Report/index

Alternative eco-friendly gas mixtures for RPCs under study. Requirements:

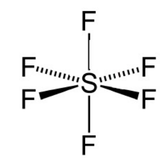
- low toxicity;
- not flammable;
- detector performance comparable with standard gas mixture.



R134a
($C_2H_2F_4$)
GWP 1430



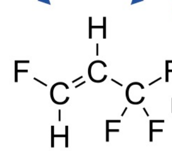
R14
(CF_4)
GWP 5700



SF_6
GWP 23900

EcoGas collaboration

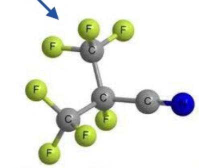
Not in industry
(tried by CSC)



Hydro-Fluoro-Olefin (HFO)
C=C double bond
fluorine-containing
hydrogen-containing

HFO-1234ze
($C_3H_2F_4$)
GWP 6

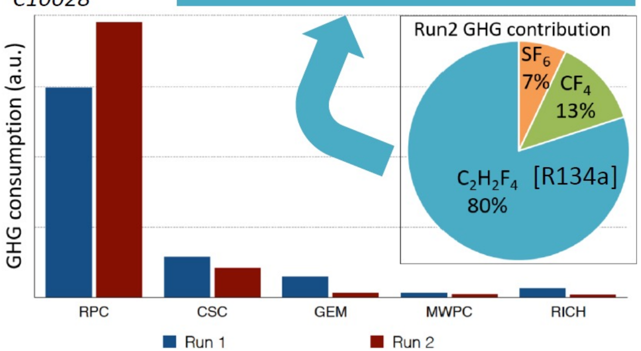
3M™ Novec™ 5110
($CF_3C(O)CF(CF_3)_2$)
GWP <1



3M™ Novec™ 4710
($(CF_3)_2CFCN$)
GWP 2100

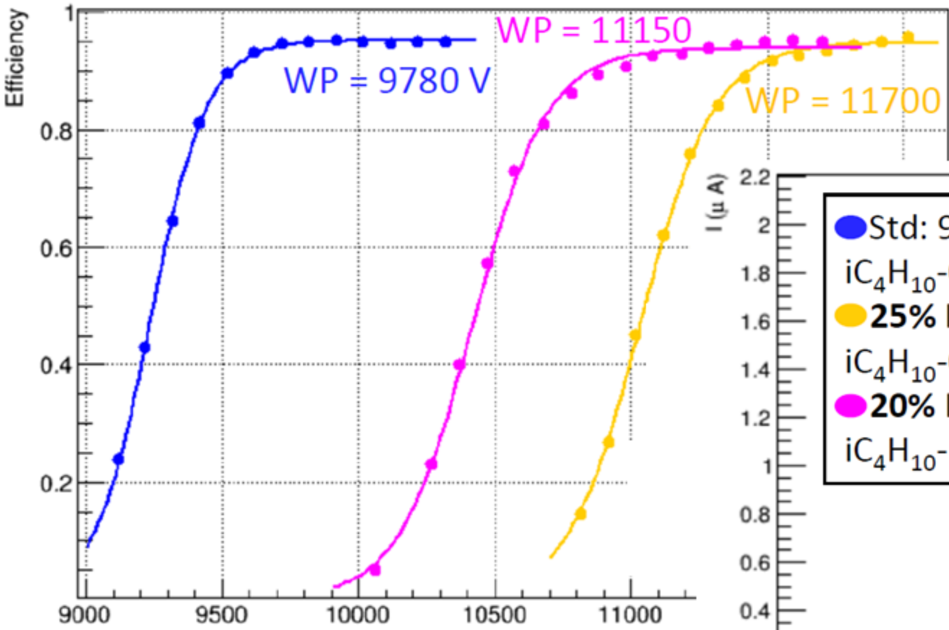
R134a: standard gas mixture main component, GWP=1430

JINST 15 (2020) C10028

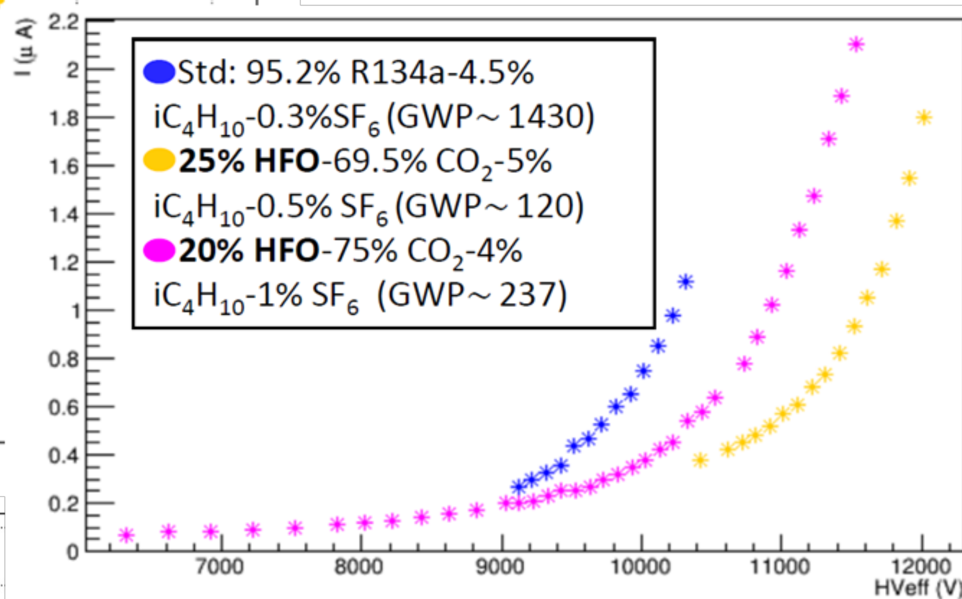


Mixtures based on HFO-CO_2 currently under study

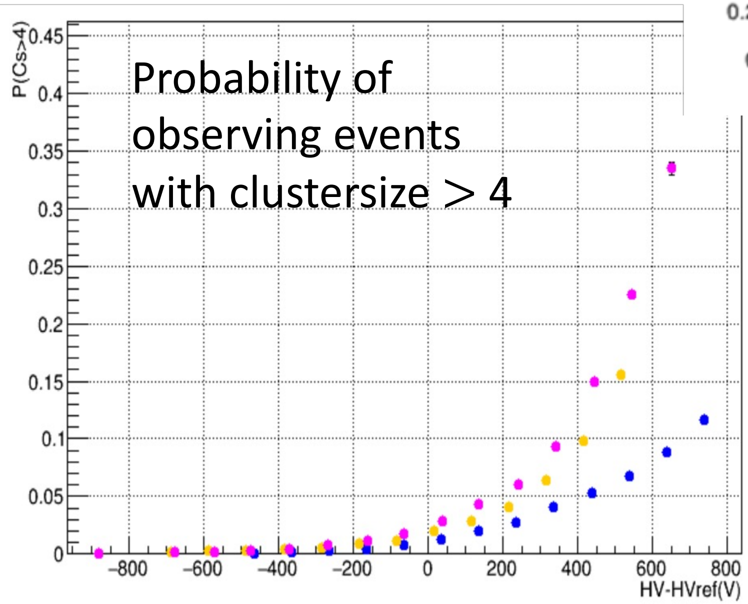
RPC performance with Ecogas



Few examples of HFO-CO_2 eco-friendly gas mix



Probability of observing events with clustersize > 4



Similar performance with shifted WP

Reduced gap thickness RPC

towards new gen RPC for LHCb Upgrade II

Gas mixtures tested @ GIF++

-std: 95.2% $C_2H_2F_4$, 4.5% i-C_4H_{10}, 0.3% SF_6 [GWP ~ 1430]
-eco2: 35% HFO, 60% CO_2, 4% i-C_4H_{10}, 1% SF_6 [GWP ~ 230]
-eco3: 25% HFO, 69% CO_2, 5% i-C_4H_{10}, 1% SF_6 [GWP ~ 230]

Single gap RPC with reduced gap thickness

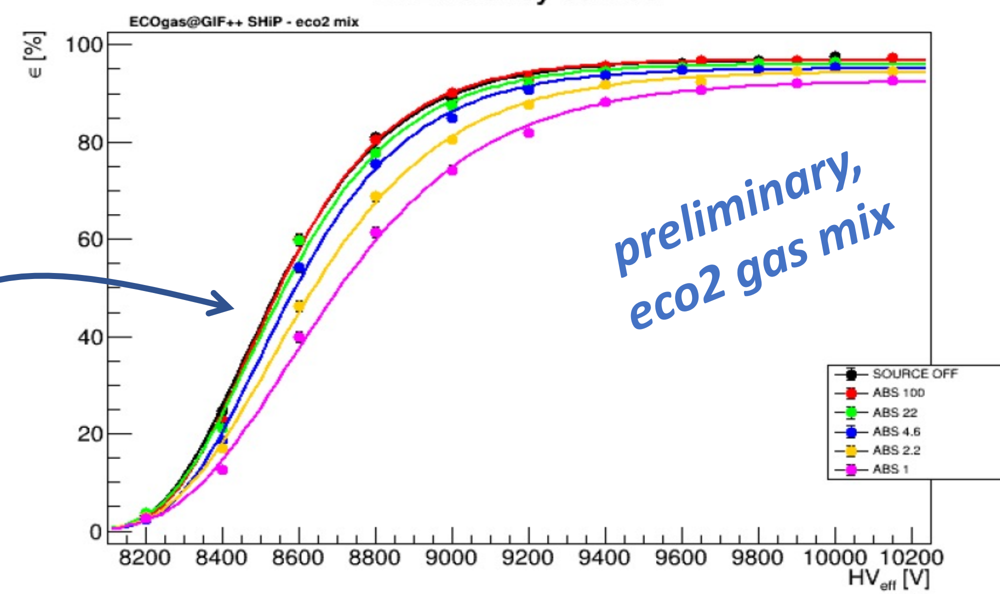
- Decreased average charge / hit
- Improved RPC performance with eco-gas
- Higher rate capability
- Improved detector longevity

Prototype: 70 x 100 cm²

- 1.6 mm HPL electrodes
- 1.6 mm single gas gap
- 2D readout, 32 strips per plane
- 1cm strip pitch

Next:
Further improve longevity & rate capability; new FE; …

X Efficiency curves



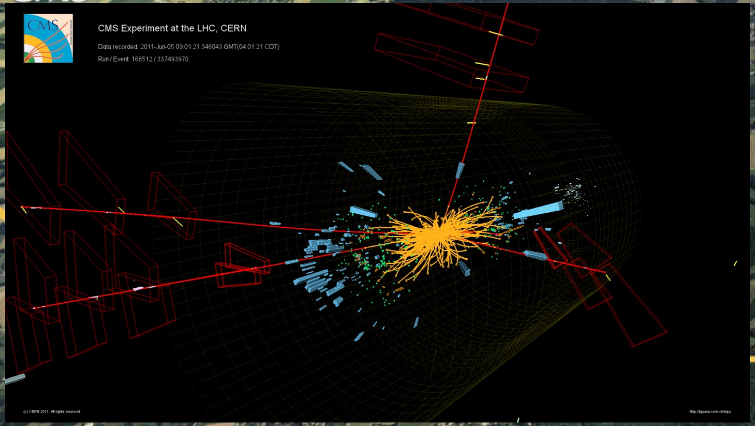
Gaseous Detectors for CMS & LHCb

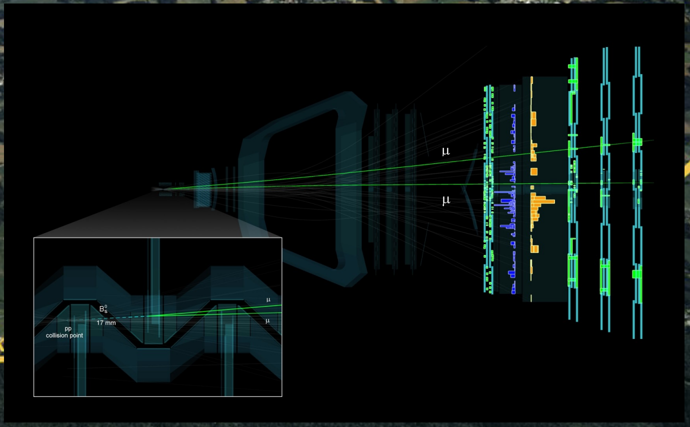
Constructing, testing, learning a lot

Gaseous Detectors for CMS & LHCb
Conclusions

I discussed:

- *Why lepton triggering and detection at hadron colliders is important*
- *For tracking over several 1000m^2 gaseous detectors are indispensable*
- *Current & future gaseous detectors LHCb & CMS with Bari involvement*
- *Needs to develop these detectors further to satisfy Experiment' needs*
- *Specific activities within the global context where Bari is key player*
- *Research & Development on detector technology is exiting and can be done locally in our laboratories, with low prerequisites*

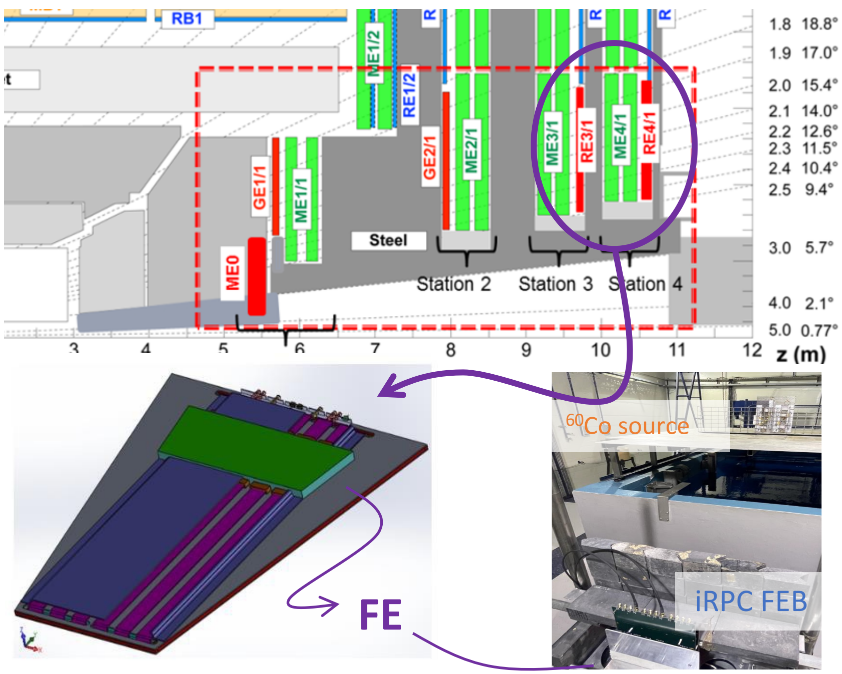




Backup

Activities @ INFN & Uni/Poli-BA

RPC longevity & irradiation studies iRPC

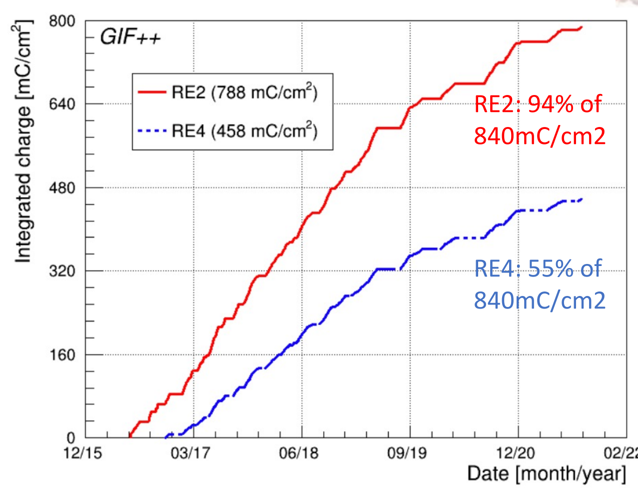


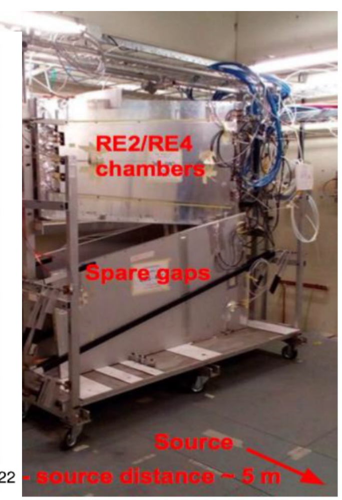
Irradiation FE at CALLIOPE (ENEA)

	Existing RPC	Improved RPC
HPL thickness	2 mm	1.4 mm
Gas gap width	2 mm	2 mm
# Gas gap	2	2
Resistivity [Ωcm]	1 – 6 10^{10}	0.9 – 3 10^{10}
Threshold (typ)	150 fC	50 fC
Readout	3 η partitions	2D readout

Irradiation studies at GIF++

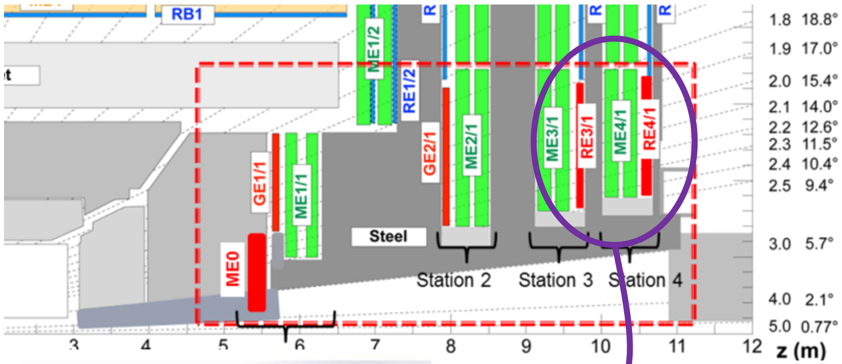
- Validate existing RPC and iRPC for HL-LHC
- Irradiate chambers ≥ expected dose @ HL
- GIF++ also interesting place to evaluate new Eco-Gas mixtures (see later)
  - Evaluate Efficiency, Working Point Shift, charge/hit, Clustersize, production of HF, …
- Joint effort ATLAS CMS LHCb/Ship ALICE CERN
  - Increase exchange of expertise and use of common tools

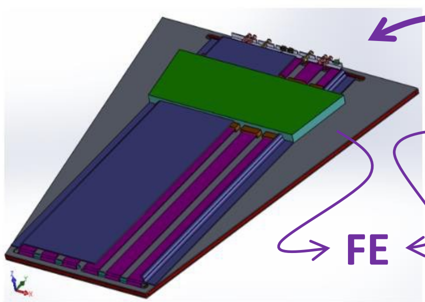


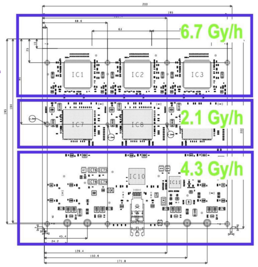


Activities @ INFN & Uni/Poli-BA

RPC longevity & irradiation studies iRPC







ASICs: TID 160Gy

FPGAs: TID 50Gy

Irradiation studies at GIF++

- Validate existing RPC and iRPC for HL-LHC
- Irradiate chambers ≥ expected dose @ HL
- GIF++ also interesting place to evaluate new Eco-Gas mixtures (see later)
  - Evaluate Efficiency, Working Point Shift, charge/hit, Clustersize, production of HF, …
- Joint effort ATLAS CMS LHCb/Ship ALICE CERN
  - Increase exchange of expertise and use of common tools

Irradiation at CALLIOPE (ENEA)

- Irradiation of Front-End Electronics (FPGA)

	Existing RPC	Improved RPC
HPL thickness	2 mm	1.4 mm
Gas gap width	2 mm	2 mm
# Gas gap	2	2
Resistivity [Ωcm]	1 – 6 10^{10}	0.9 – 3 10^{10}
Threshold (typ)	150 fC	50 fC
Readout	3 η partitions	2D readout