Resistive Plate Chambers for High-energy Physics

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Resistive Plate Chambers (particle triggers and TOF)

RPCs, gaseous detector, are typically used **for triggers of high-energy particles** in high-energy and nuclear physics experiments. In many large scale experiments, RPCs are installed inside the magnetic field to measure the hit and time information and the rough positions of particle tracks for the momentum selection.

→ **Like plastic scintillators**

What to detect? → All high-energy charged particles **(but also neutrons and gammas for other purposes)**
RPCs are composed of thick detector materials. Therefore, RPCs are not sensitive to low-energy charged particles or X-rays.

Provides fast time information in time
→ Best time resolution in the world (σ ~ 40 ps for TOF and ~ 1 ns for trigger RPCs)

Provides rough positions in space
→ Position resolution depends of the strip width and the electronics In trigger RPCs, σ ~ a few mm ~ a few cm But it could be ~ 0.2 mm if ADCs are used.

In general, we use RPCs for particle triggers.

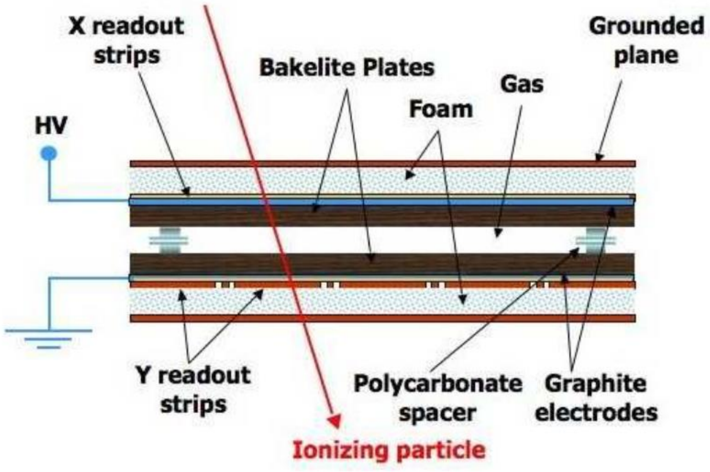
No role for tracking in large scale experiment.
So, a relatively poor position is accepted and used for momentum selection of particles.

In 1981, by R. Santonico (Italy) {NIMA 187 377 (1981)}
- RPCs were designed by a modification of **Parallel Plate Chambers** (equipped with a spark-gap and trigger scintillators).

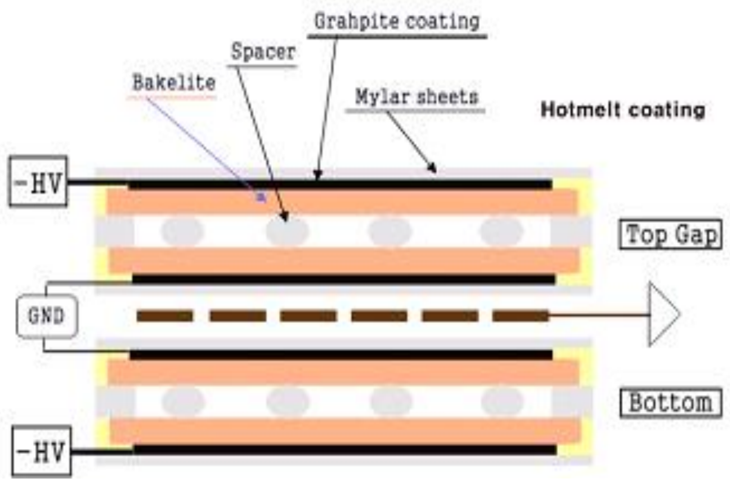
The RPCs were originally operated in a spark mode.
- But, the avalanche-mode operation was adopted to obtain the higher particle-detection capability. (LHC experiments NIMA 315 92 (1992))

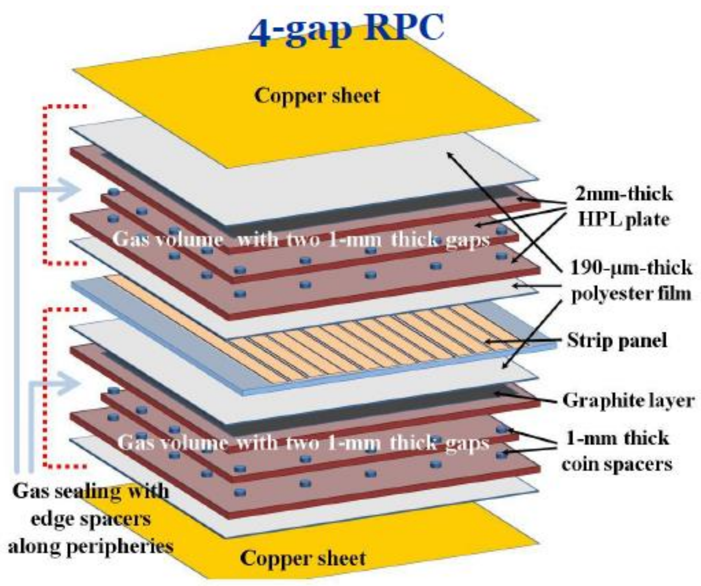
RPCs

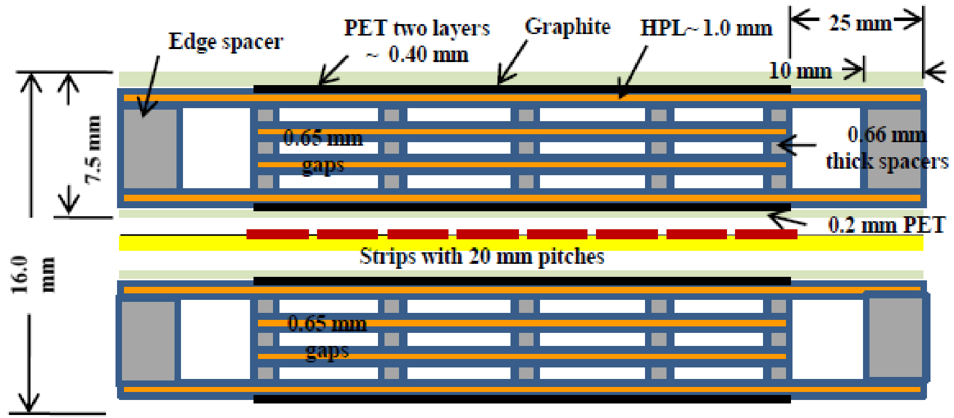
Single-gap RPC



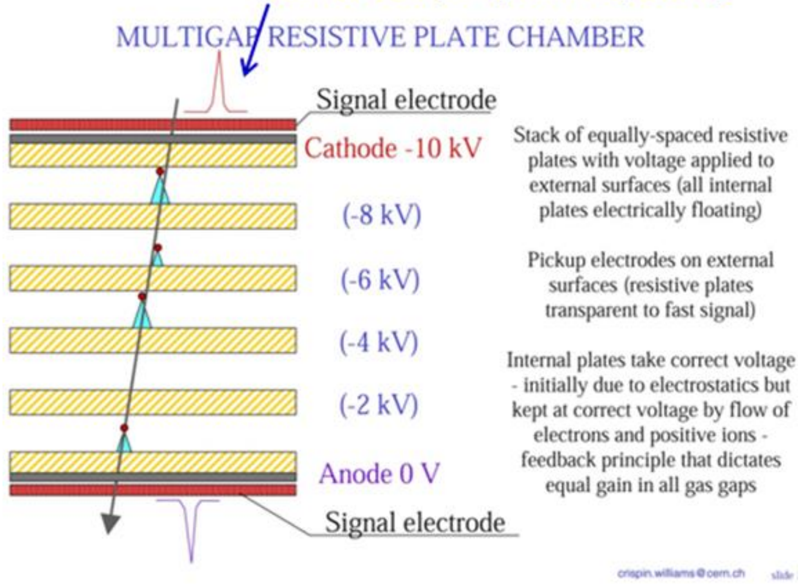
Double-gap RPC







Cathode strips : positive polarity



Anode strip : negative polarity

The role of the resistive plates of RPCs

Effectively suppress spontaneous discharges from the surfaces of the conductive electrode to the gas volume due to the high electric field intensity.

What to use?

Historically, **phenol plates** (called Bakelite: phenol resin + paper layers) have been used for the resistive plate of the RPCs.

- ✓ The bulk resistivity ranges from 10^{10} to 10^{12}. (CMS, ATLAS, LHC-b, PHENIX etc…)
- ✓ Cheep but we have to apply water vapor to suppress further polymerization.

Glass plates: often used to build trigger RPCs and multigap (timing) RPCs (time resolution as low as 40 ps).

- ✓ The bulk resistivity of the typical floating glass plates lies between 10^{11} and 10^{13}. (BELLE, ALICE, FOPI, INO, CBM etc…)
- ✓ Poor rete capability due to the high resistivity. Moreover, Freon can not be used due to aging.

Low resistive glass: amorphous mixture of floating glass + iron oxide (with mixture of ?)

- ✓ The bulk resistivity ~ 10^{10} (CBM/FAIR)
- ✓ Too expansive!

Ceramic plates for high particle rate

- ✓ The bulk resistivity ~ 10^{10}
- ✓ Too expansive!

Gas mixture:

In the beginning, Ar + iC_4H_{10} (for instant, 50:50) for the typical gas mixture for the RPCs

In many large scale experiments like LHC and PHENIX experiments, a tetrafluoroethane-based (TFE, R134 Freon) gas mixtures are open used. There are two advantage of using Freon: first the gas gain of the Freon mixture is larger than the Ar mixture due to the higher gas density. The other advantage is that the portion of use of the flammable quencher is relatively much smaller than the Ar mixture, which ensures the safety for many underground experiments.

Trigger RPCs (TFE): 95.2% $C_2H_2F_4$ + 4.5% iC_4H_{10} + 0.3% SF_6.

Multigap RPCs (TFE) ~ 90.0% $C_2H_2F_4$ + 5.0% iC_4H_{10} + 5.0% SF_6.

Eco gas mixture using HFO1234ze: The global warming potential (GWP) for this new Freon gas (GWP=6) is significantly lower than the conventional TFE (GWP=1430).

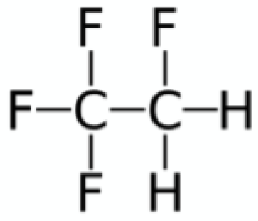
For instant, 95.0% HFO1234ze + 4.5% iC_4H_{10} + 0.5% SF_6.

JINST 11 C07016 (2016)

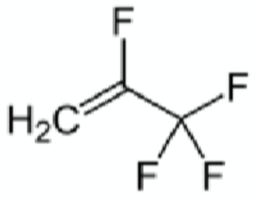
Other Freon gases to try; HFO1234yf, HFC-245fa, HFC-32, HFC-152a

Gas	Atmospheric lifetime (years)	GWP (100 years)
R-134A	13.8	1430
Isobutane	774	3.3
SF_6	3200	22300
Argon	87	0
CO_2	variable	1 (reference)

TFE $C_2H_2F_4$



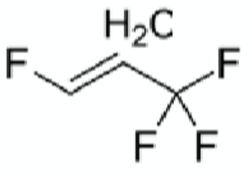
GWP 1430



HFO-1234yf (flam)

($C_3H_2F_4$)

GWP 4



HFO-1234ze

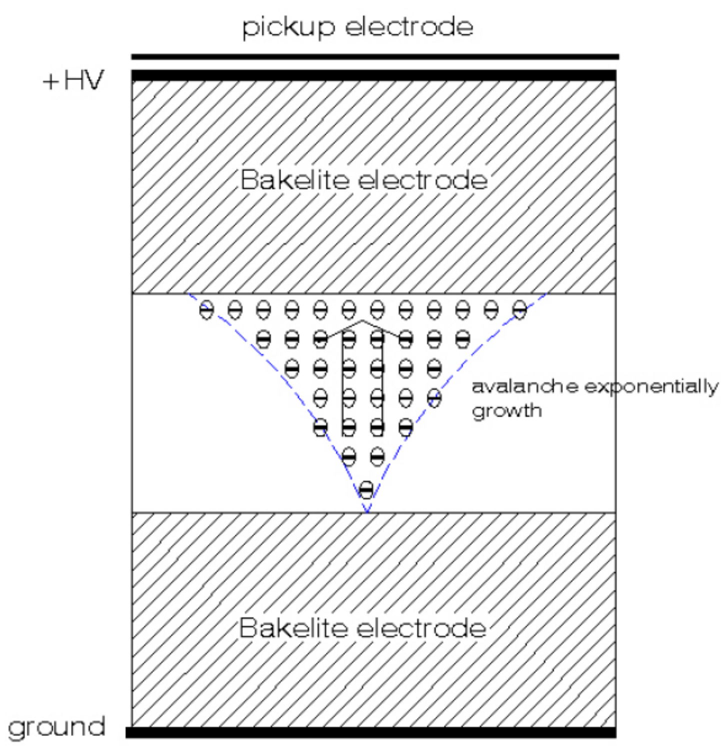
($C_3H_2F_4$)

GWP 6

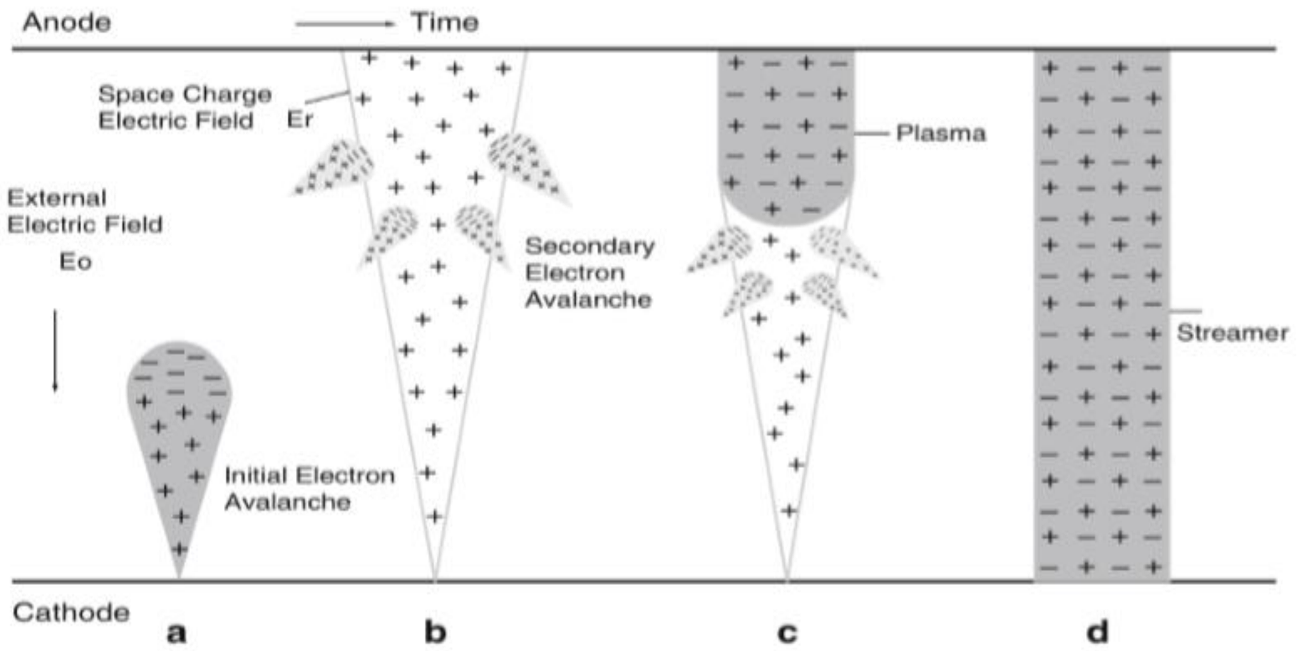
Operation modes:

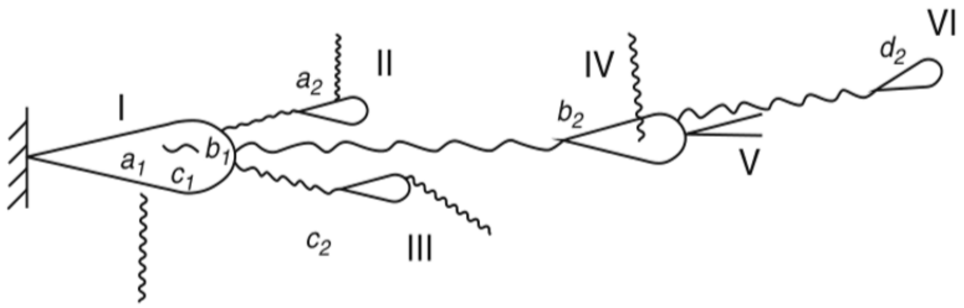
RPCs were originally designed for the **Geiger-Muller mode operation (streamer mode)**. But a limited proportional mode operation has been accepted to enhance rate capability of particle detection. We called this operation mode the **'avalanche mode' (limited proportional mode)**.

The avalanche mode has been firstly adopted in many large scale experiments.



How streamers are developed when the electric field is strong enough.





Operation modes for gaseous detectors

1) Recombination region (region I in the figure)

If the applied voltage is not strong enough, the electrons and positive ions, created by a radiation will be recombined and be neutralized, before they arrive to the electrodes.

→ No ionization current or signal (useless)

2) Ionization region (region II in the figure)

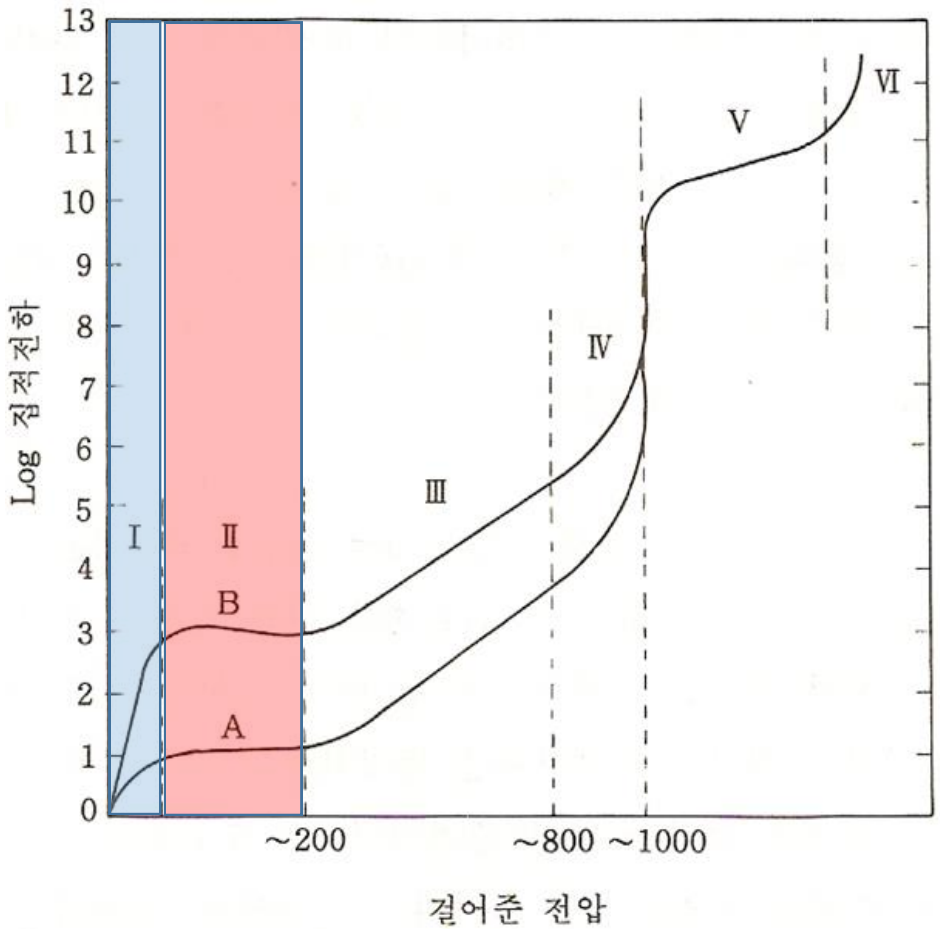
If the applied voltage is strong enough to prevent the recombination, the electrons and positive ions arrive to the electrodes and create ionization current.

The amount of the radiation-induced current represents the number of positive ions or electrons

→ Number of incident radiations

In the detector working in the ionization mode, the detector current is independent to the applied voltage.

→ The current can be read by an electronics to measure the amount of the radiation.



3) Proportional region (region III + IV in the figure)

If the electric field intensity is strong enough, the primary electrons are accelerated and drifting along the electric field provided by the applied voltage, and collide the atoms in the gas, creating secondary electrons and positive ions.

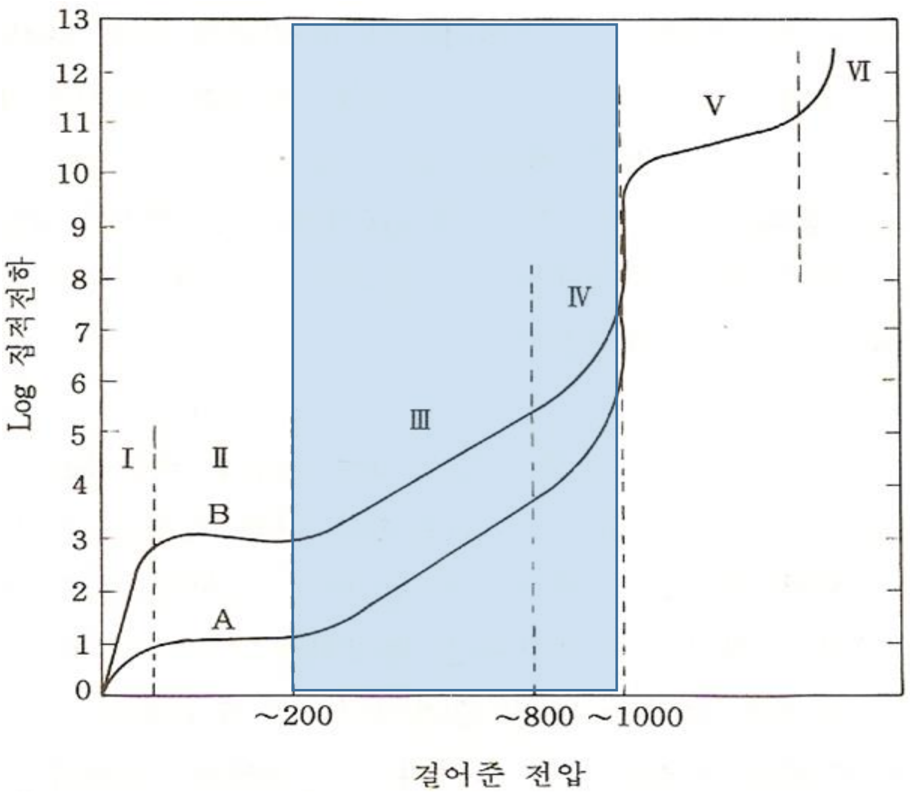
The secondary ionization process keeps going on

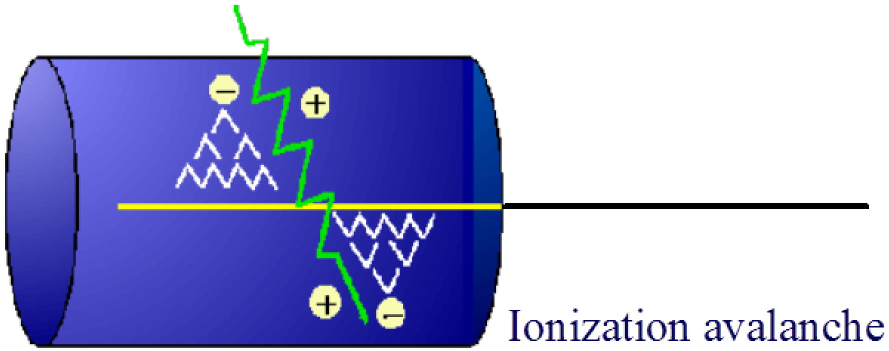
→ Ionization avalanche and cause an amplification for the radiation signal.

The typical gain of amplification in the detectors working in the proportional region is **10^4 < Gain < 10^6**. But the gain increases as the applied voltage.

The integration of the charges induced by the avalanche process of the radiations is proportional to the energy deposit in the detector by the incident radiation. Therefore, we call this operation mode

→ 'Proportional mode' → Proportional counters





Ionization avalanche

4) Limited proportional mode

At the region V in the figure, **the gain reaches ~ 10^7** before entering a Geiger-Muller mode. In this region, the size of a pulse is NOT proportional to the deposited energy by the incident radiation any more. The limited proportional mode is often used in the high-position resolution drift chambers in virtue of the large gas gain.

→ Thin drift chambers in precision spectrometers

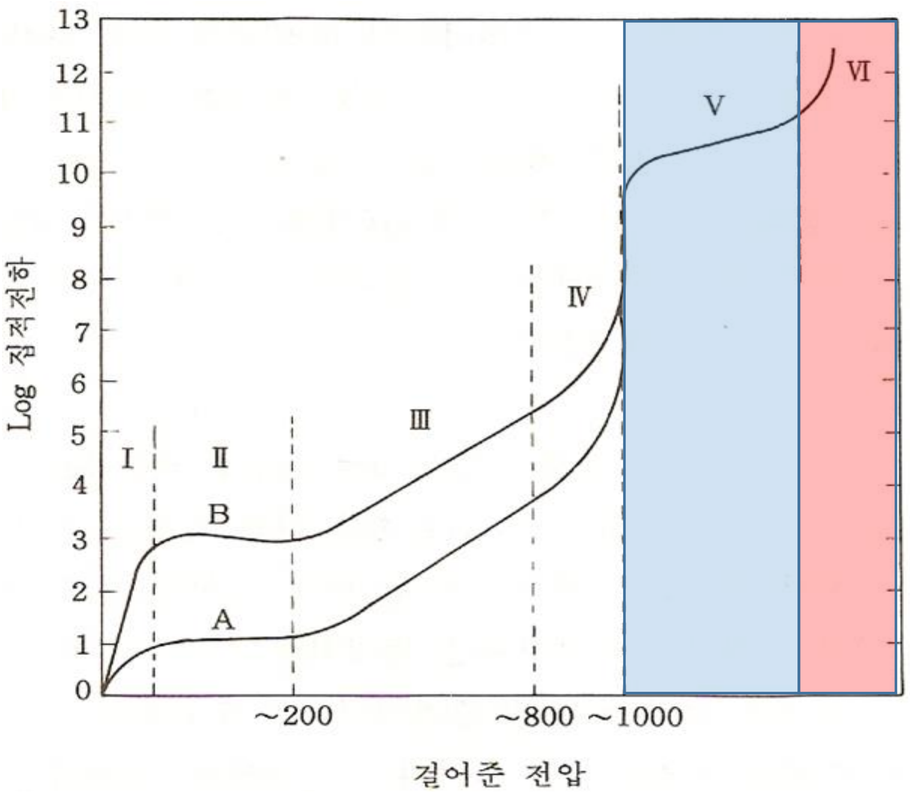
→ Resistive plate chambers in avalanche mode

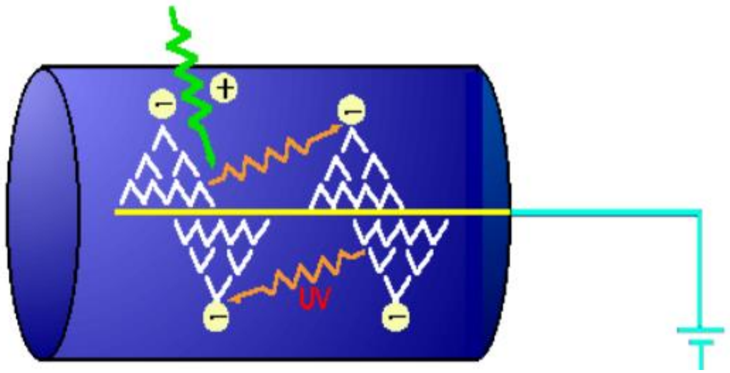
5) Geiger-Muller region (for GM counter, region VI in the figure)

If the applied voltage is strong enough, the ionization avalanche by the incident radiation can create a series of secondary avalanches right after.

→ Streamer tubes for particle trigger and ID

→ Resistive plate chambers in avalanche mode



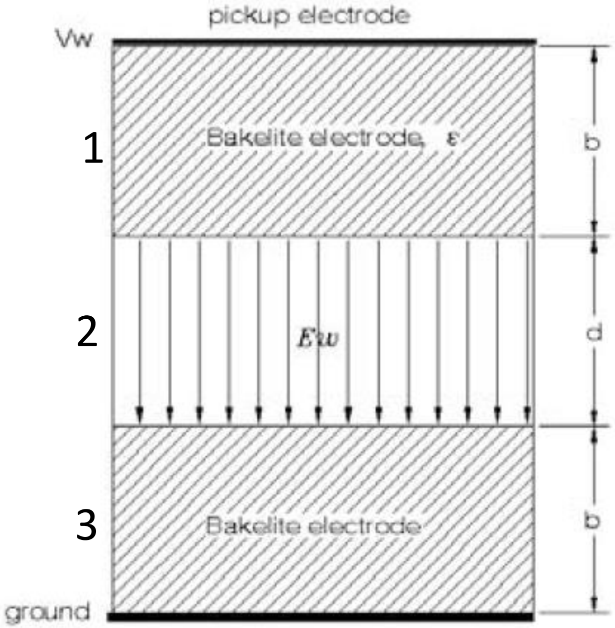


How we get pulses in the RPCs?

The **Shockley–Ramo theorem** allows one to easily calculate the instantaneous electric current induced by a charge moving in the vicinity of an electrode. It is based on the concept that current induced in the electrode is due to the **instantaneous change of electrostatic flux lines** which end on the electrode, ***not*** the amount of charge received by the electrode per second.

$$i(t) = \frac{E_w}{V_w} v e_0 N(t)$$

e_0: electrons charge,
$N(t)$: number of electrons presented at time t
v: electron drift velocity
E_w (weighting field): the electric field in the gap when V_w is set the pickup electrode

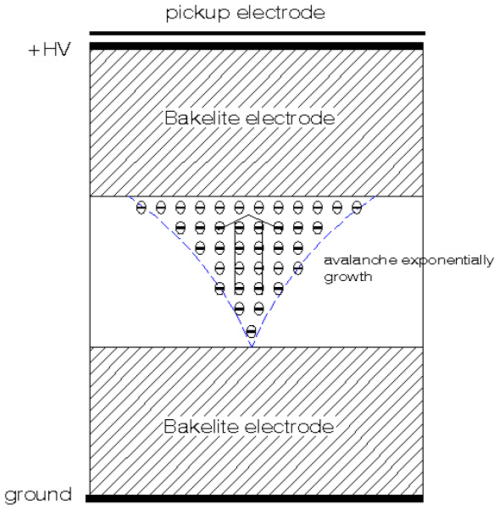


$$V_w = bE_1 + dE_2(=E_w) + bE_3(=E_1) \qquad \varepsilon E_1 = E_2(=E_w) = \varepsilon E_3\,(=E_1)$$

Then, we get $\dfrac{E_w}{V_w} = \dfrac{\varepsilon}{2b + d\varepsilon}$

The Ramo theorem gives us

$$i(t,x) = \frac{E_w}{V_w} e_0 v e^{(\alpha-\eta)vt} \Theta\left(\frac{d-x}{v} - t\right)$$



$\Theta(x)$ is the step function, it indicates when the electrons reach Bakelite surface and then, the induced current suddenly stopped.

Assuming an ideal Townsand avalanche (exponential growth with the drifting path length), the induced charge

$$Q^{ind}(d-x)=\int_0^\infty i(t,x)dt=\left[\frac{E_w}{V_w(\alpha-\eta)}\right]e_0(e^{(\alpha-\eta)(d-x)}-1)$$

α: Townsand coefficient
η: attachment coefficient
α – η: effective Townsand coefficient

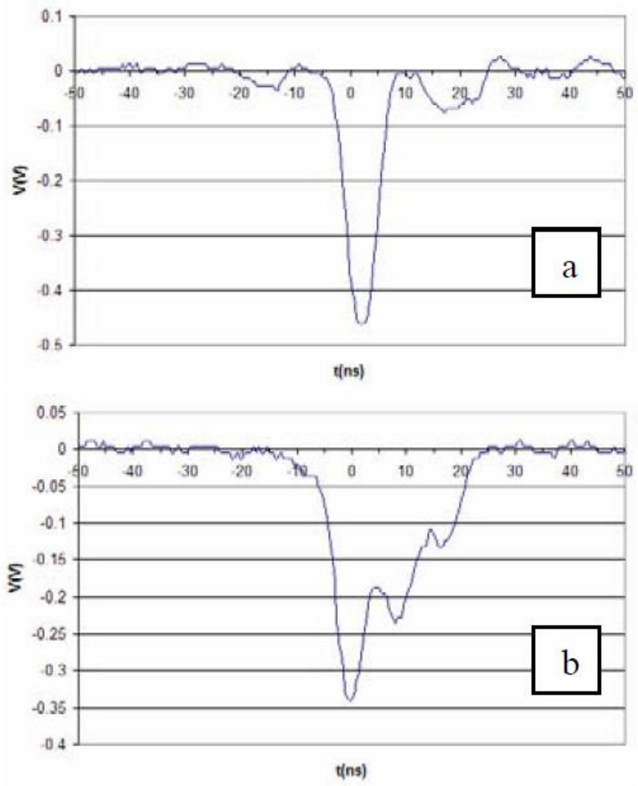
$$Q_{tot}=e_0\,(e^{(\alpha-\eta)(d-x)}-1) \qquad \frac{Q_{ind}}{Q_{tot}}=\frac{\varepsilon}{(2b+d\varepsilon)(\alpha-\eta)}$$

For instant in a typical avalanche mode using the typical TFE based gas,
$\varepsilon \sim 4$, $\alpha-\eta \sim 95$, and $b = d = 2$ mm for current CMS RPCs → $Q_{ind}/Q_{tot} = 0.0351$
$Q_{ind} \sim 2.5$ pC at WP (Th = 150 fC)
→ $Q_{tot} \sim 70$ pC

$\varepsilon \sim 4$, $\alpha-\eta \sim 130$, and $b = d = 1.4$ mm for new CMS iRPCs → $Q_{ind}/Q_{tot} = 0.0366$
$Q_{ind} \sim 0.6$ pC at WP (Th ~ 20 fC)
→ $Q_{tot} \sim 16$ pC

For typical streamer pulses, $Q_{ind}/Q_{tot} > 0.5$

Avalanche pulses



Drift ion molecules in gas

Charges produced by an ionizing particle event quickly lose their energy in multiple scattering (collisions) with gas molecules in the chamber gas and are thermalized with a Maxwell distribution in energy.

For molecule ions (not electrons) in a Maxwell distribution,

$$F(\epsilon) = C\sqrt{\epsilon}\, e^{-(\epsilon/kT)} \qquad \frac{dN}{N} = \frac{1}{\sqrt{4\pi Dt}} e^{-(x^2/4Dt)} dx$$

$$\sigma_x = \sqrt{2Dt}\ ,\ \sigma_V = \sqrt{6\,Dt}$$

Drift velocity of ion molecules

$$\mu^+ = \frac{w^+}{E}, \quad \Rightarrow \quad w^+ = \mu^+ \frac{E}{P}$$

The quantity, diffusion coefficient divided by mobility is proportional to *kT*,

$$\frac{D^+}{\mu^+} = \frac{kT}{e} \quad \Rightarrow \quad \sigma_x = \sqrt{2Dt} = \sqrt{\frac{2kTw^+t}{e\,E}} = \sqrt{\frac{2k\,Tx}{eE}}$$

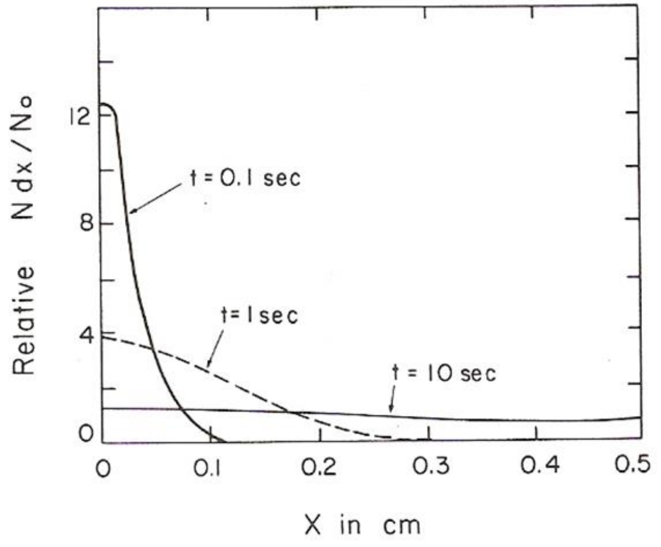
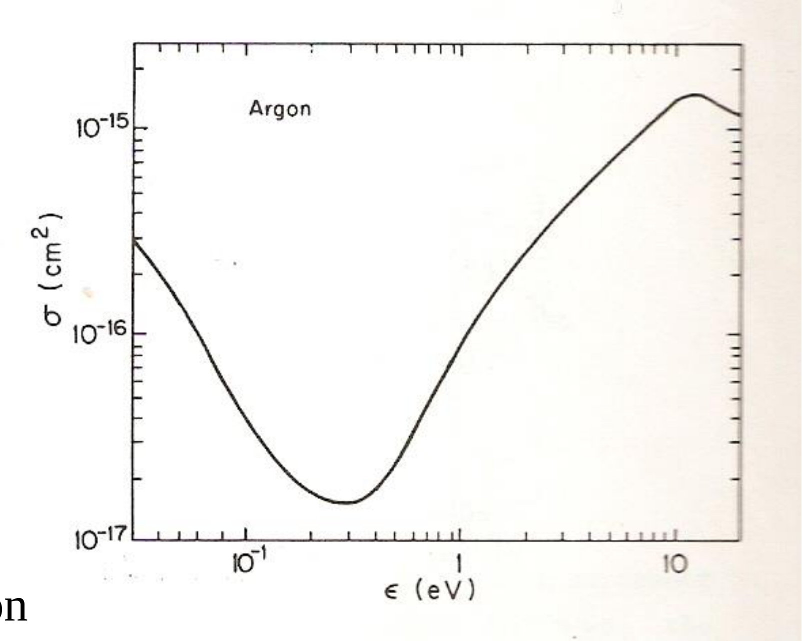


Fig. 20 Space distribution of ions produced in air, at normal conditions, after different time intervals[18)]

Classical mean free path, velocity, diffusion coefficients, and mobility for molecules, under normal conditions[18-21)]

Gas	λ (cm)	u (cm/sec)	D^+ (cm^2/sec)	μ^+ ($cm^2\ sec^{-1}\ V^{-1}$)
H_2	1.8×10^{-5}	2×10^5	0.34	13.0
He	2.8×10^{-5}	1.4×10^5	0.26	10.2
Ar	1.0×10^{-5}	4.4×10^4	0.04	1.7
O_2	1.0×10^{-5}	5.0×10^4	0.06	2.2
H_2O	1.0×10^{-5}	7.1×10^4	0.02	0.7

Drift of electrons in gas



In contrast to positive ions, the mobility is not simple except for very low electric field. Because of their small mass, the electrons quickly obtain kinetic energies by acceleration in electric field and lose the energies by collisions with gas molecules. A simple formula for the drift velocity of electrons is

$$w = \frac{e}{2m} E\tau$$

where, τ is the mean time between collisions and is, in general, a sensitive function of the electric field E. The collision cross section of the electrons with gas molecules is very sensitively varies with their kinetic energy. We call this effect '**Ramsauer effect**'.

τ is a sensitive function of E (so, kinetic energy). This is the reason why drift velocity of the ionized electrons is very sensitive to the particular choice of gas mixture.

In a high electric field (in general we use an electric field intensity of 1 kV/cm for drift chambers and MWPCs used in nuclear and particle physics experiments), the typical drift velocity **50 mm/μs at 1 atm.**

For typical trigger RPCs working with the TFE base gas, the **drift velocity ~ 0.1 mm/ns**

The time resolution for RPCs depends on the diffusion of the drift electrons in the gas. If you wish to get a high time resolution, you need short drift times in the gap → Multigap (timing) RPCs

$$\sigma_x = \sqrt{2Dt}\ , \ \sigma_V = \sqrt{6\,Dt}$$

RPC pulses

For a typical double-gap RPC, the induced charge on the strips is the addition of the pickup charges from two independent gaps.

The $(\alpha - \eta)d$ for the avalanche mode lies just below the Rather condition (20). So, actually, the pulse height developed in an avalanche in the RPC gaps does not follow the **exponential growth** with E field because of space charges formed during the dense ionization (limited proportional mode).

→ The model using a **logistic function**, *i.e.*,

$$Q_{tot} = K \ln(1 + e^{a(V_w - V_0)})$$

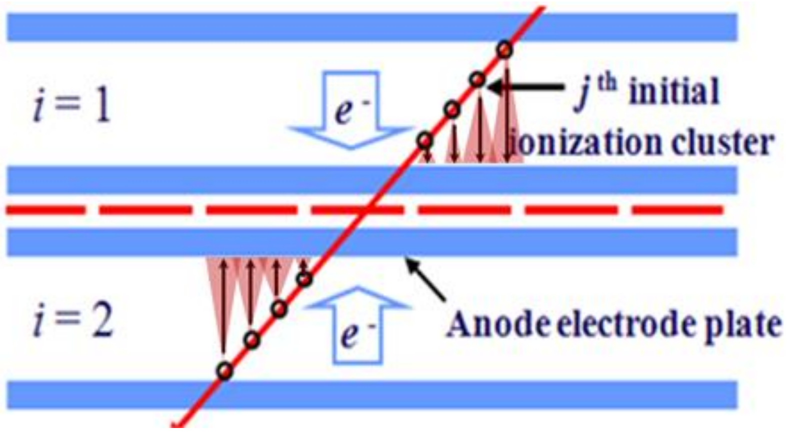
NIMA 508 6 (2003)

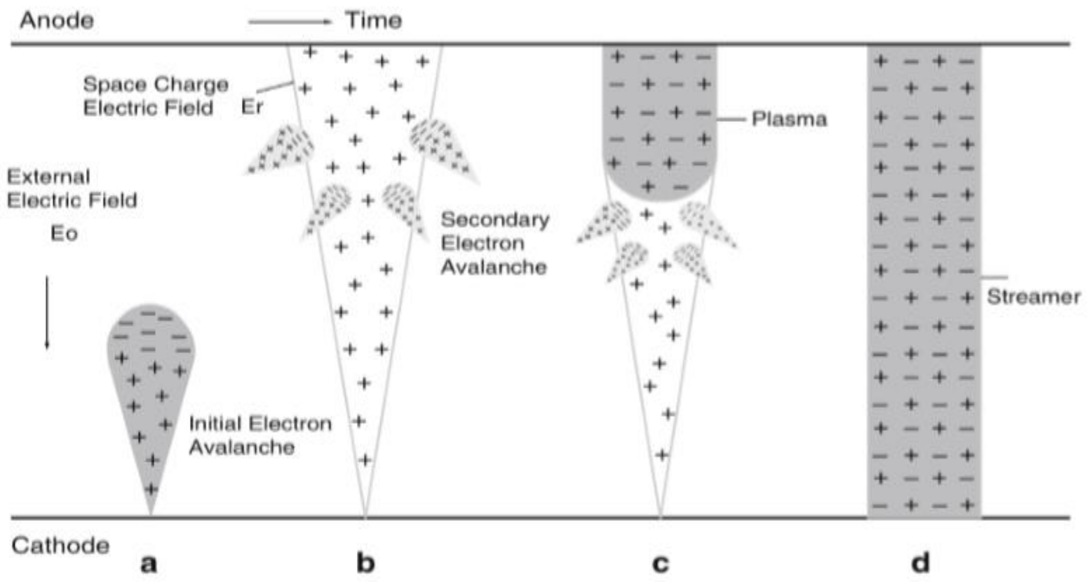
Previously by assuming the exponential growth (valid only for low *E* field)

$$Q_{tot} = e_0 \left(e^{(\alpha-\eta)(d-x)} - 1\right) \rightarrow \quad Q_{tot} \sim K\, e^{b\,(V_w - V_o)}$$

$$\frac{Q_{ind}}{Q_{tot}} = \frac{\varepsilon}{(2b + d\varepsilon)(\alpha - \eta)}$$

Actually this is not a constant, but a function of *E* field





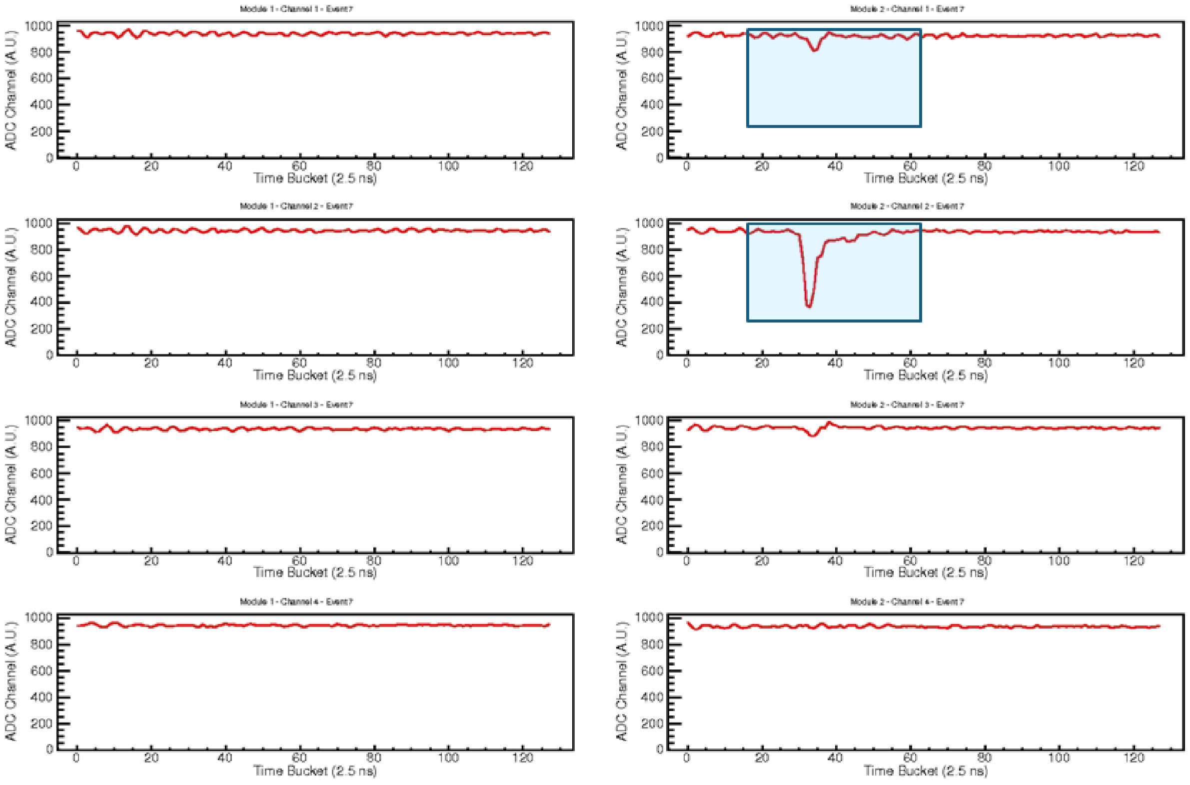
Rather condition: transition from an avalanche mode to a streamer mode: $(\alpha-\eta)\, d \ \sim 20$

In the avalanche mode for the present CMS RPCs we use $(\alpha-\eta)\, d \sim 19.5$.

For CMS iRPCs, it would be ~ 18 (?) → $(\alpha-\eta) \sim 130$ / cm

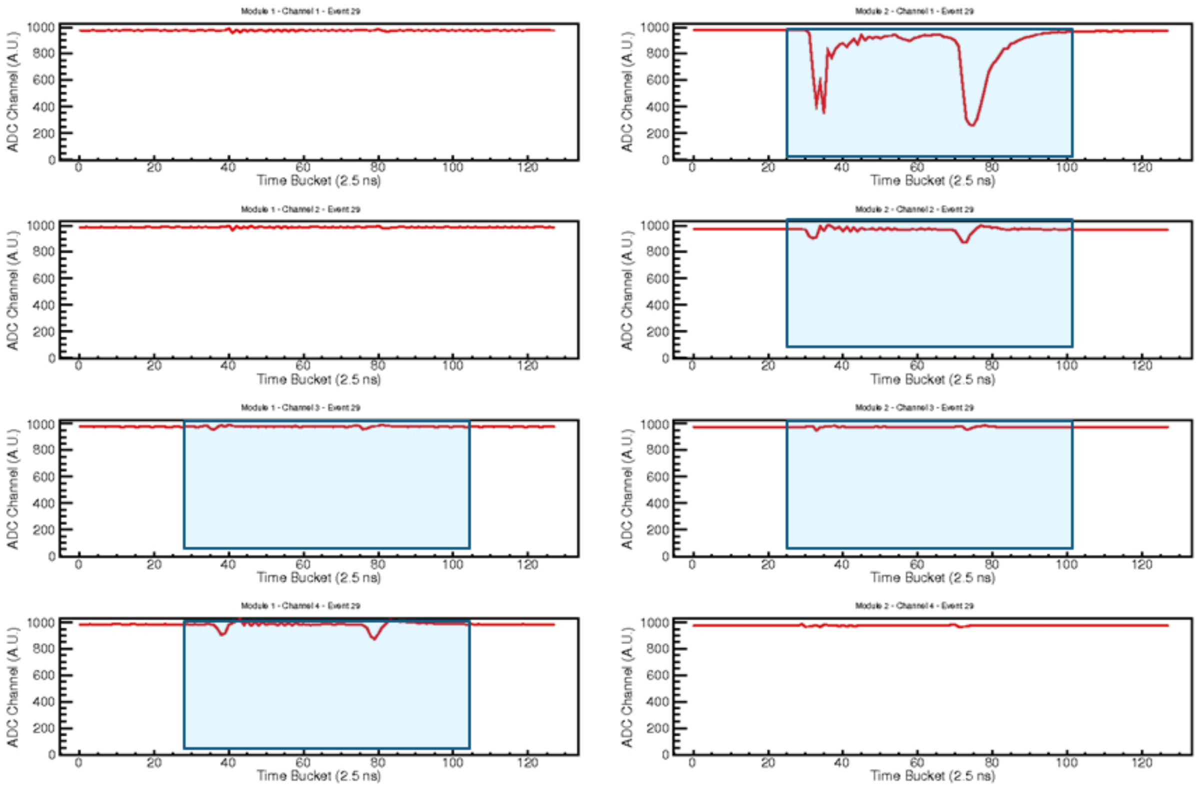
Avalanche pulse at FADC

$q_e \sim 1$ pC



Streamer pulse at FADC

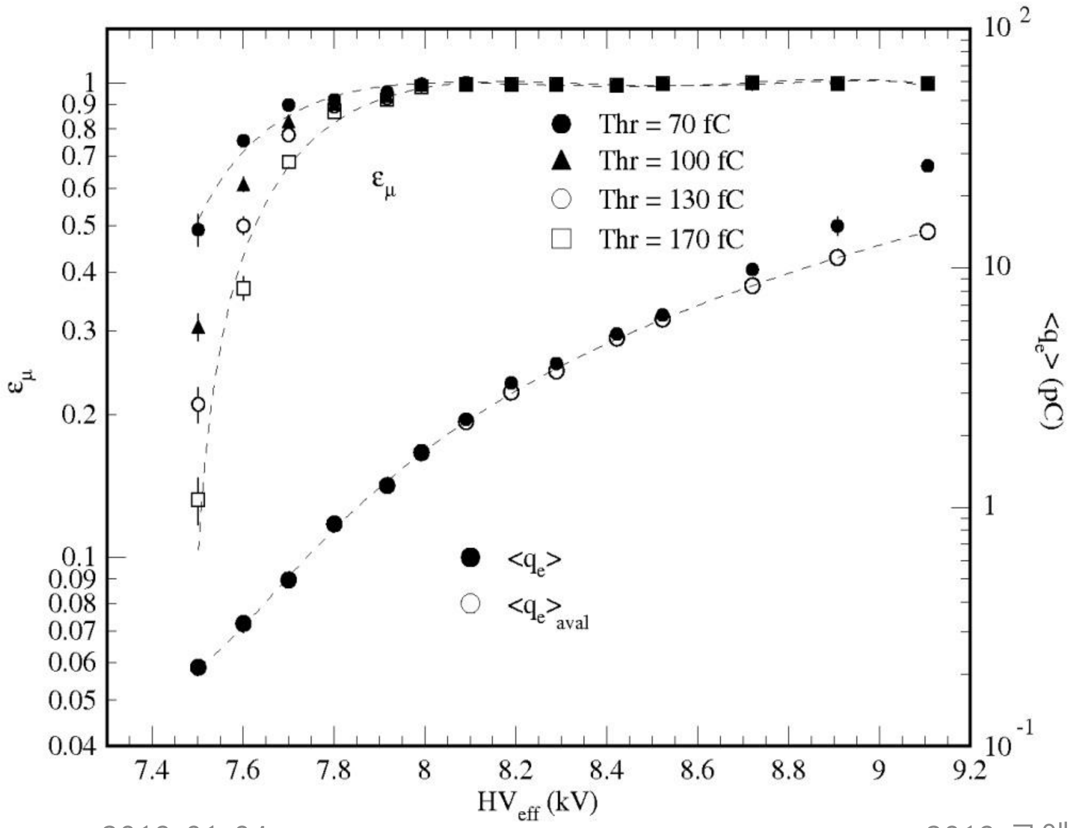
$q_e \sim 60$ pC → the precursor pulse is comparable to the secondary pulse.

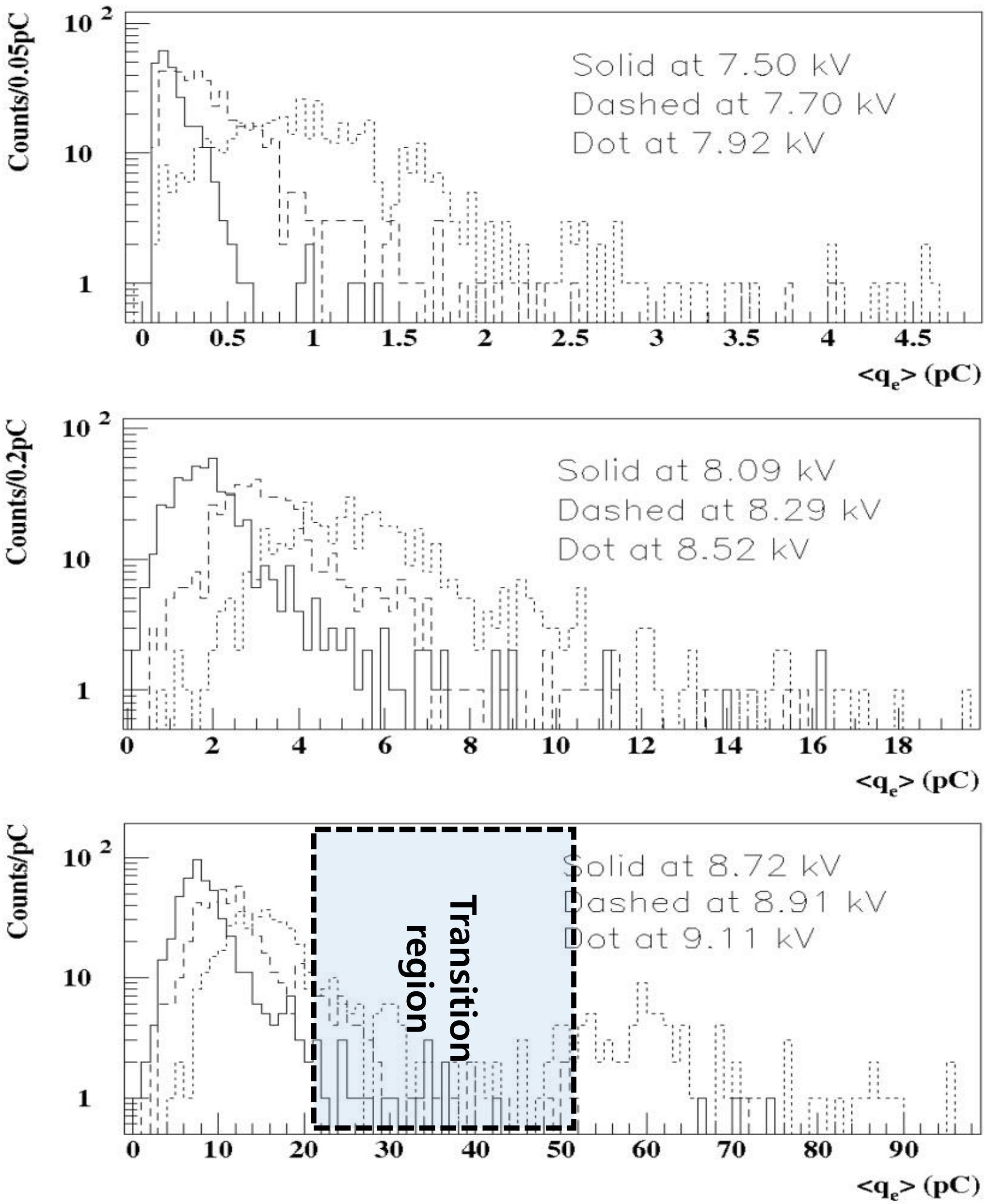


For a 1.6-mm double-gap RPC

- ✓ Gas = 95.1% TFE + 4.5% iC_4H_{10} + 0.4% SF_6
- ✓ Measured with no zero-suppression

- q_e = 20 pC → limit of the avalanche mode
- Transition region between the avalanche and streamer regions lying in **20 pC < q_e < 50 pC.**





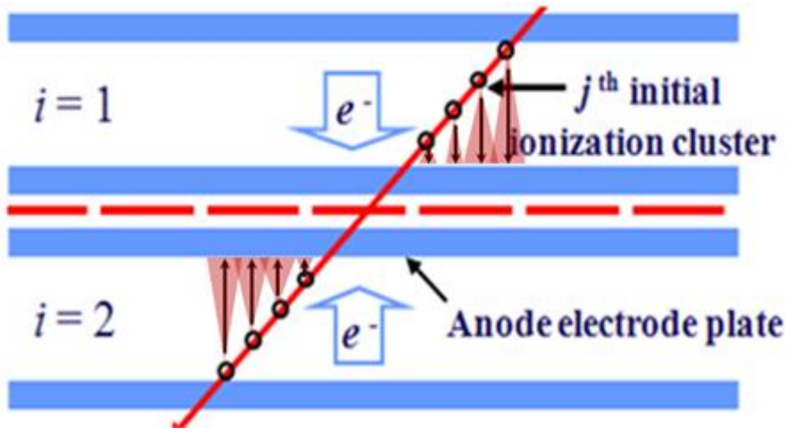
RPCs can be used for many different purposes

1. Trigger RPCs

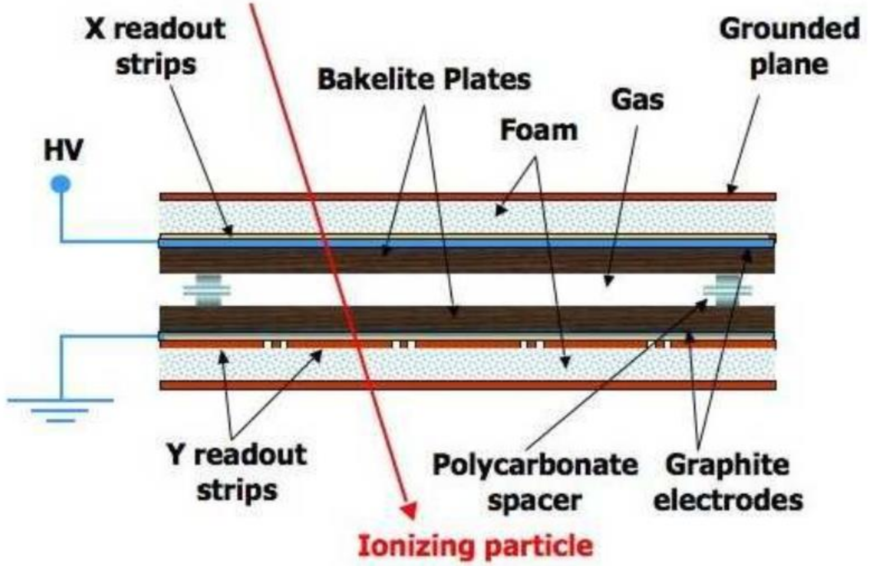
Fast data for high-energy particles (tracking provided by tracker like DTs, CSCs, etc..)

- ✓ Time resolution ~ 1ns
- ✓ Position resolution ~ 1 cm
- ✓ In general, provide 1 dimensional data (now 2D for iRPCs for CMS and ATLAS)

CMS RPC system (double-gap 1D RPCs)



ATALS RPC system (single-gap 2D RPCs)



2. Timing RPCs

Timing RPCs : highest time resolution $\sigma \leq 50$ ps

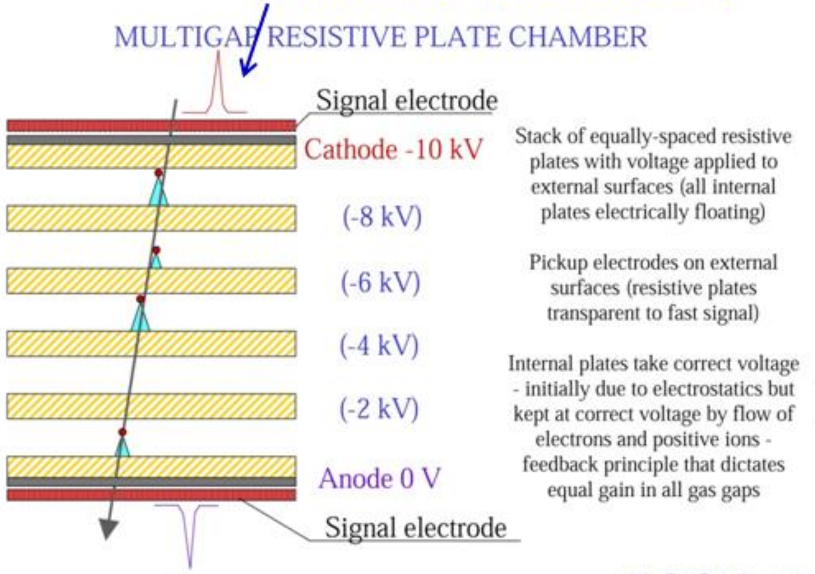
→ TOF measurements and particle ID in high-energy and nuclear physics .

$\sigma \sim 1/d$, d: thickness of each micro-gap

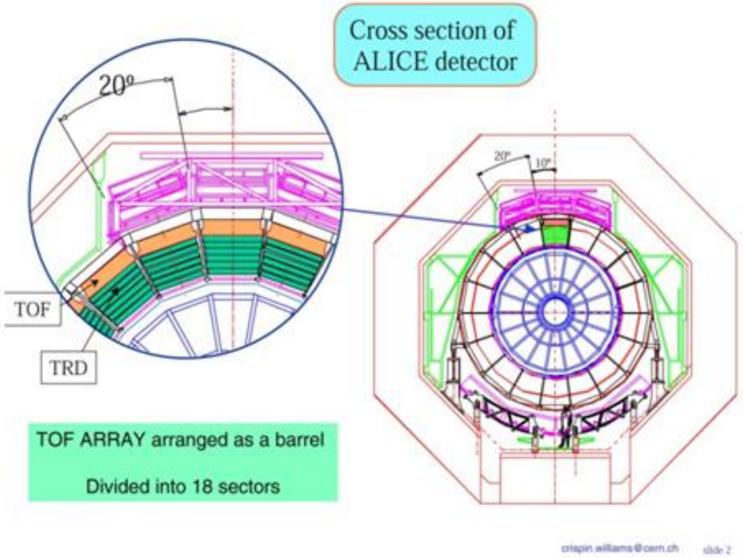
For CMS RPCs, $d = 2$ mm → $\sigma \sim 500$ ps (intrinsic resolution)

For $d = 0.2$ mm → $\sigma \sim 50$ ps

Cathode strips : positive polarity

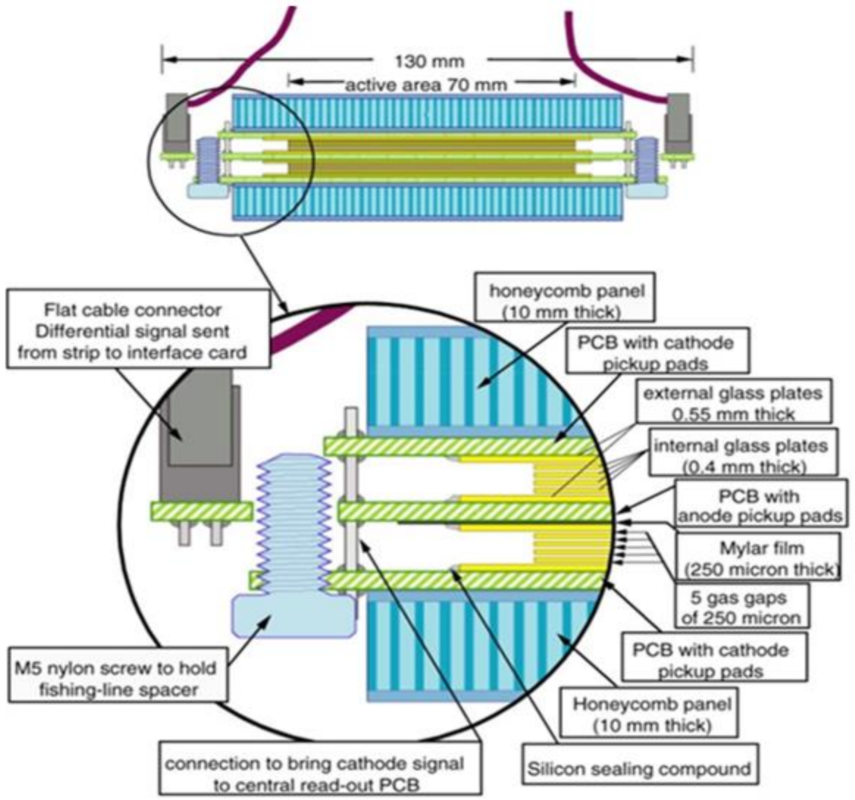


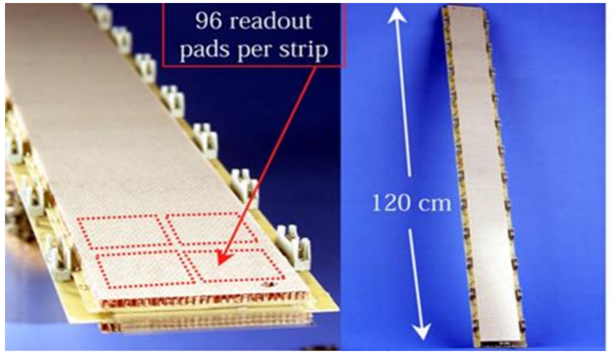
Anode strip : negative polarity



ALICE TOF

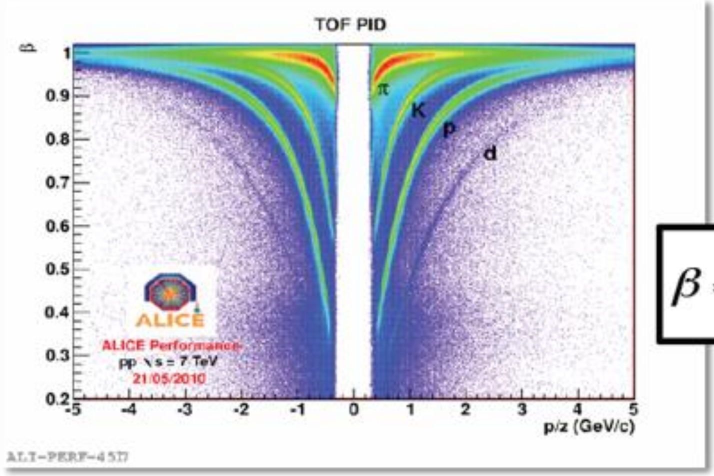
Cross section of double-stack MRPC - ALICE





TOF Performance - PID

pp collisions



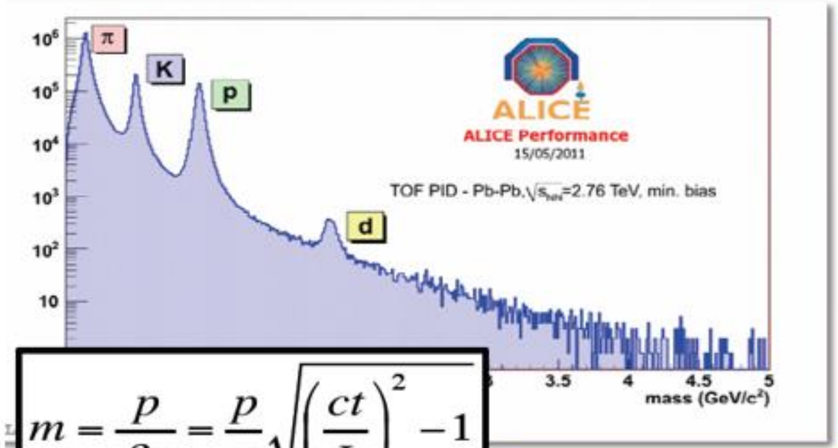
TOF measured particle β vs. signed momentum in pp collisions @ 7TeV

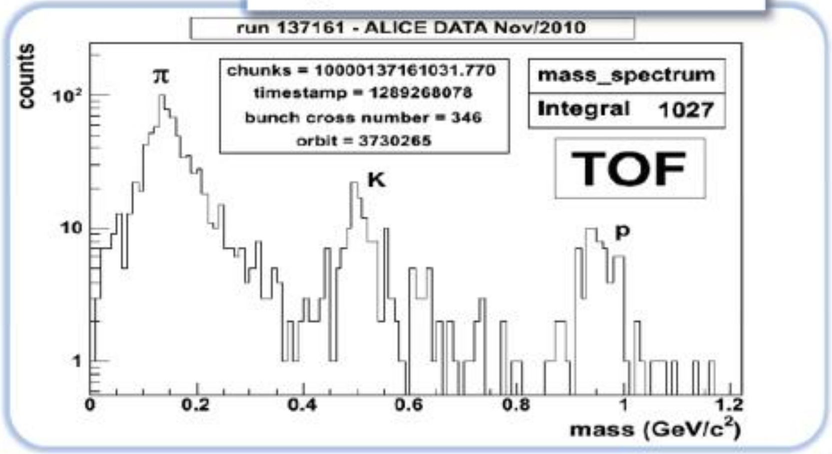
$$\beta = \frac{L}{tc}$$

Different species are clearly visible

PbPb collisions

Mass distribution in one single PbPb collision!





$$m = \frac{p}{\beta\gamma} = \frac{p}{c}\sqrt{\left(\frac{ct}{L}\right)^2 - 1}$$

Mass spectra from TOF in Pb-Pb collisions @ 2.76 TeV

6/02/2012 RPC2012 - XI Workshop on Resistive Plate Chambers and Related Detectors

3. Trigger/Tracking RPCs

Proposal: arXiv:1504.04956 (2015)

Trigger RPCs for SHiP

SHiP (Search for Hidden Particle) experiment

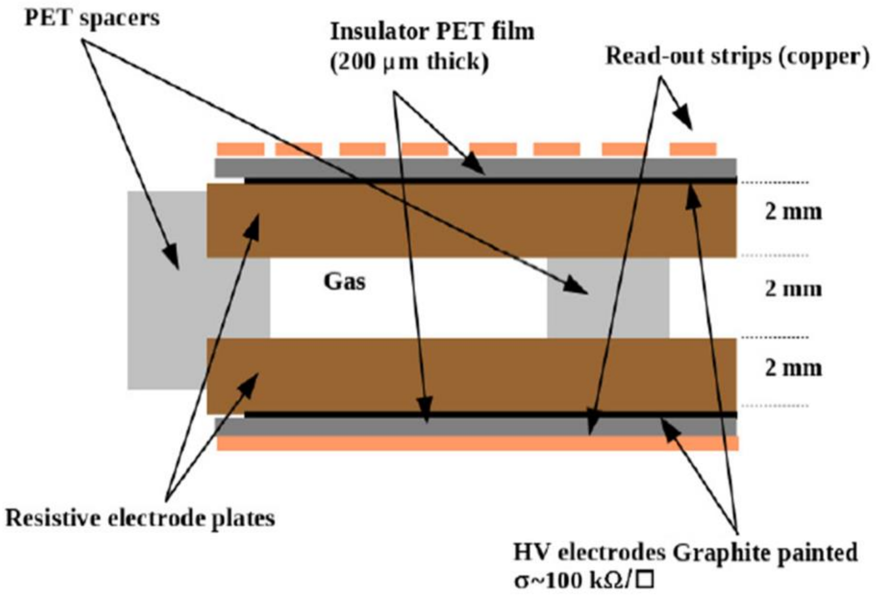
CERN beam dump experiment to search **BSM** HNL, dark photons, Axino, etc…

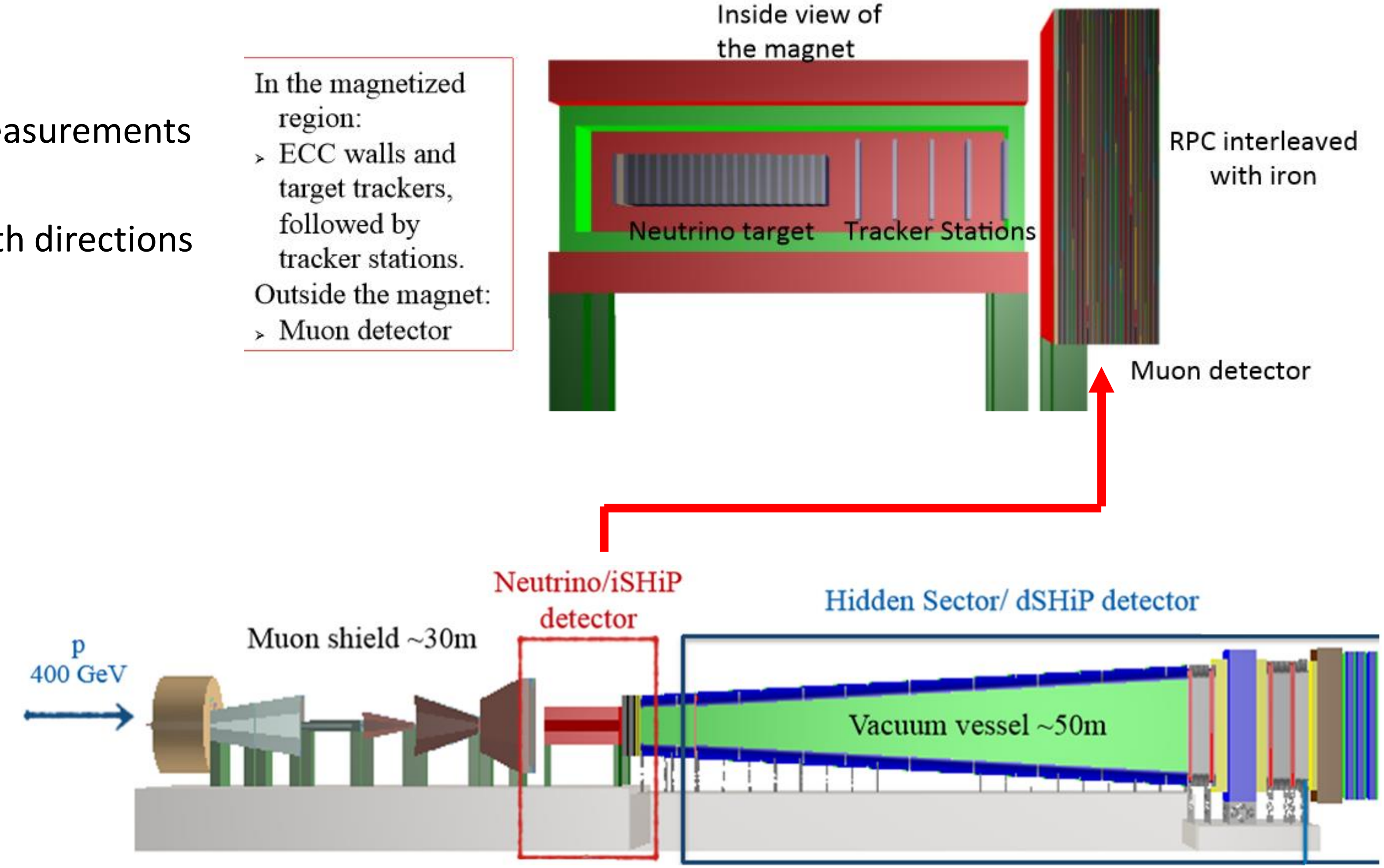
Cathode + anode strip RPC

- Cathode signals: positive
- Anode signals: negative

Two orthogonal strip readouts for 2D trigger measurements (anode strips for *x* and cathode strips for *y*)

Expected position resolution of 3 ~ 4 mm in both directions





4. Muon radiography

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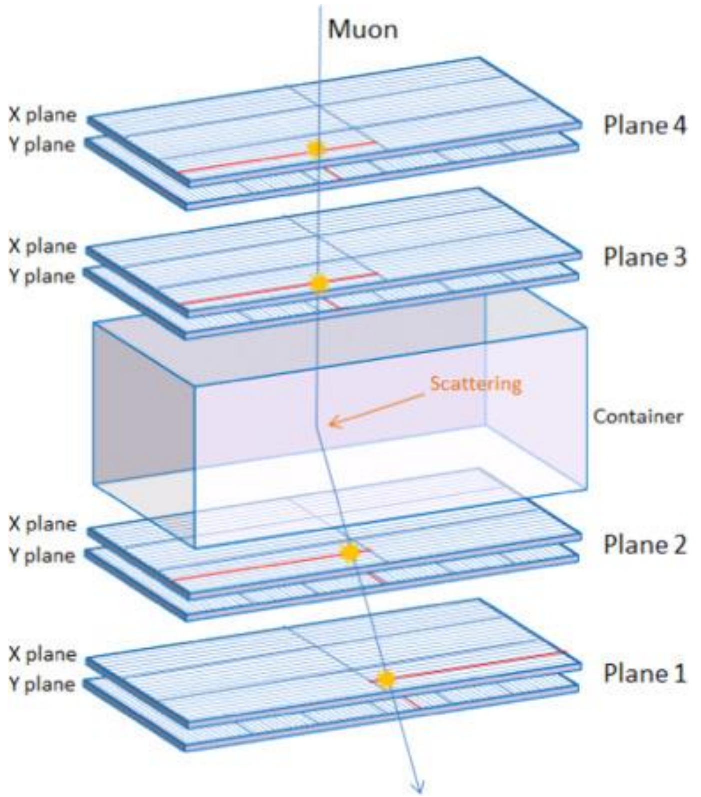
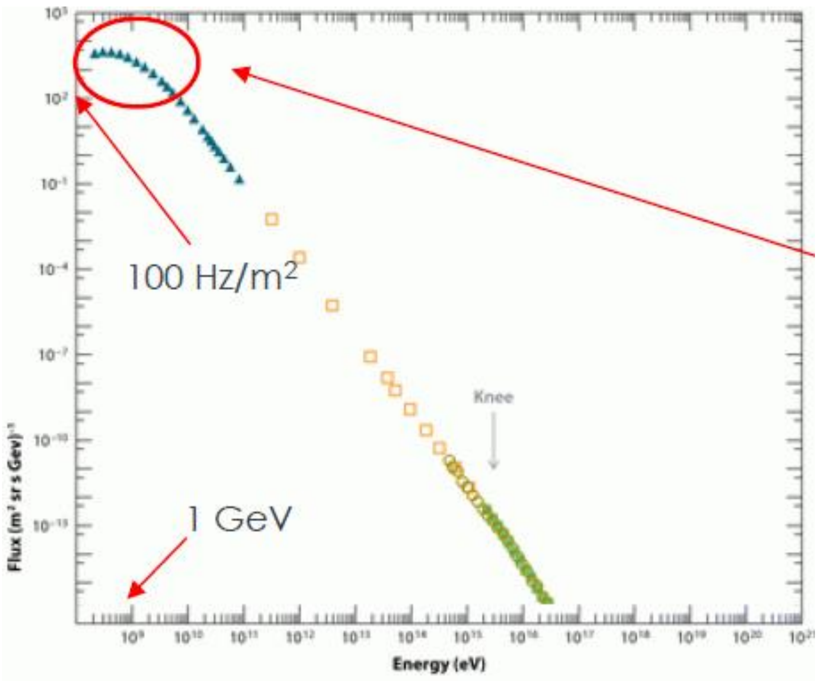
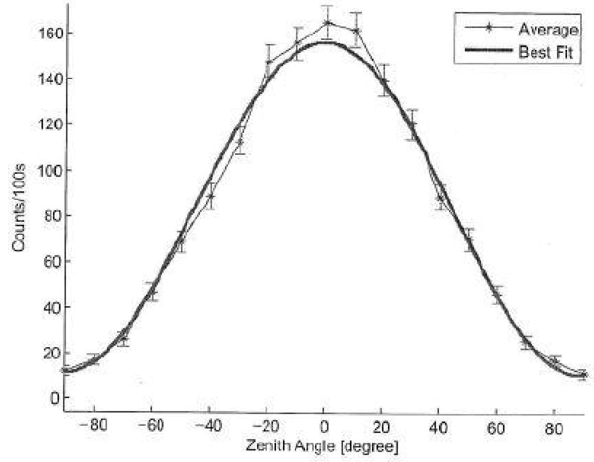
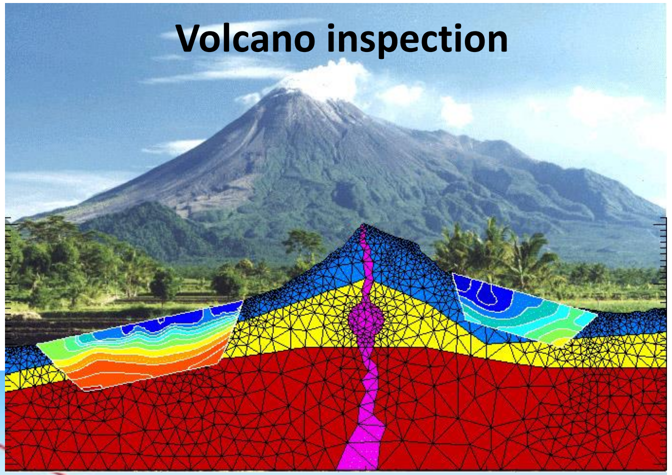
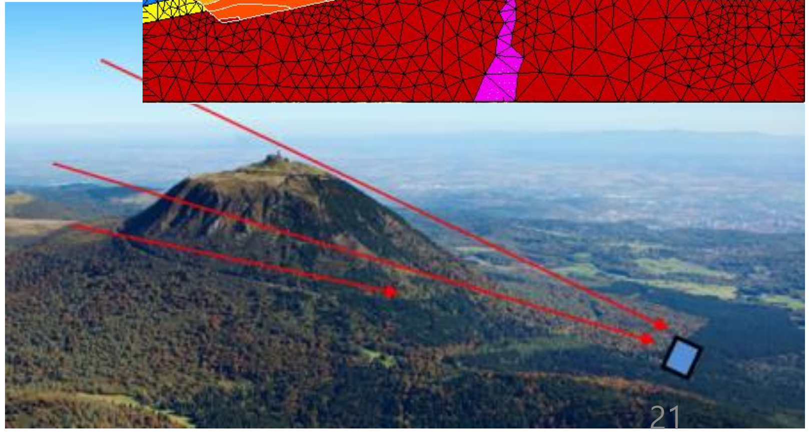




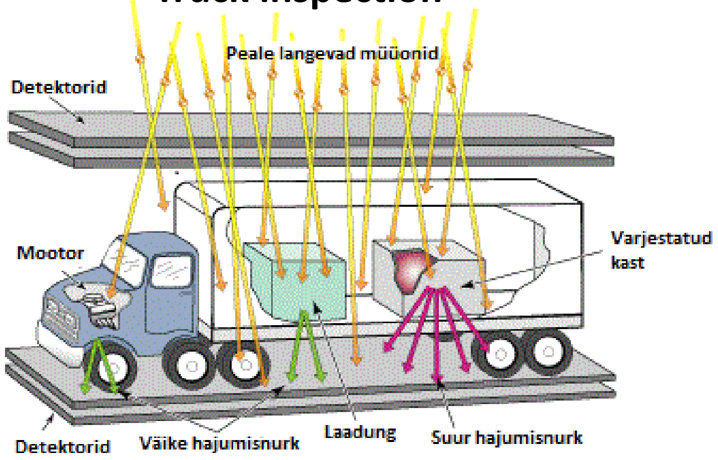
Beatty JJ, Westerhoff S. 2009.
Annu. Rev. Nucl. Part. Sci. 59:319–45

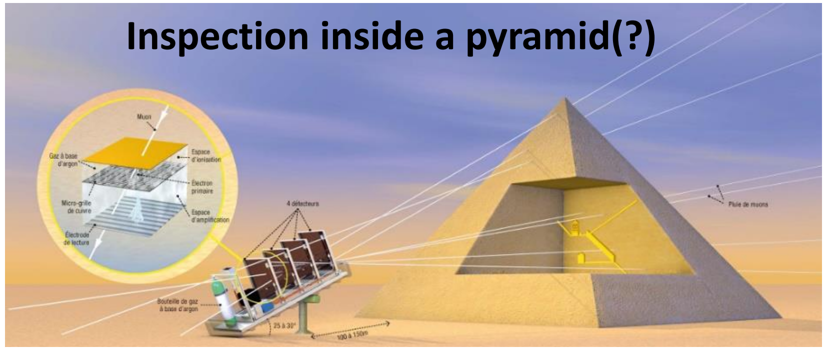




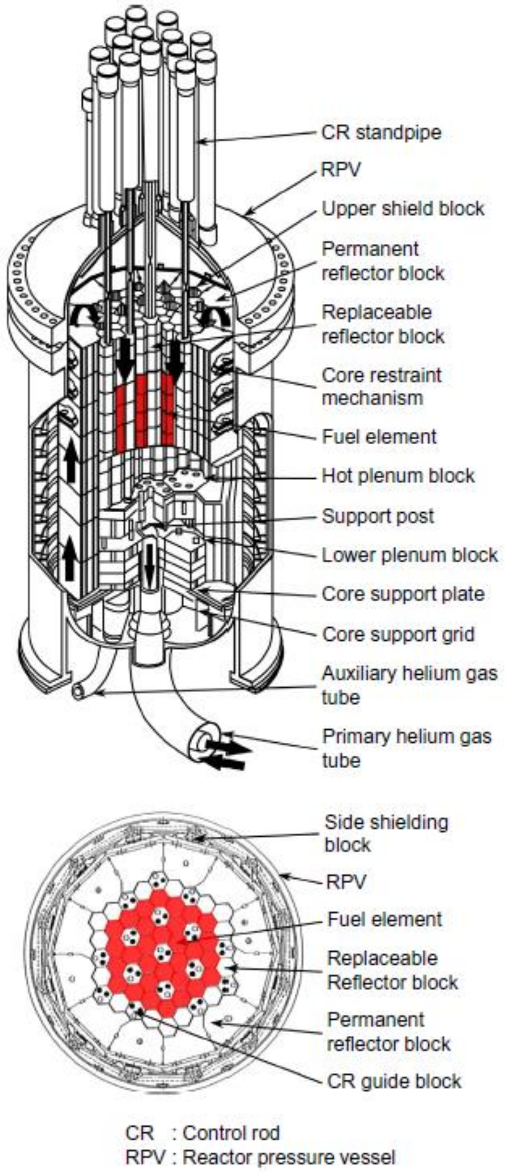


Truck inspection





Inspection of reactor cores



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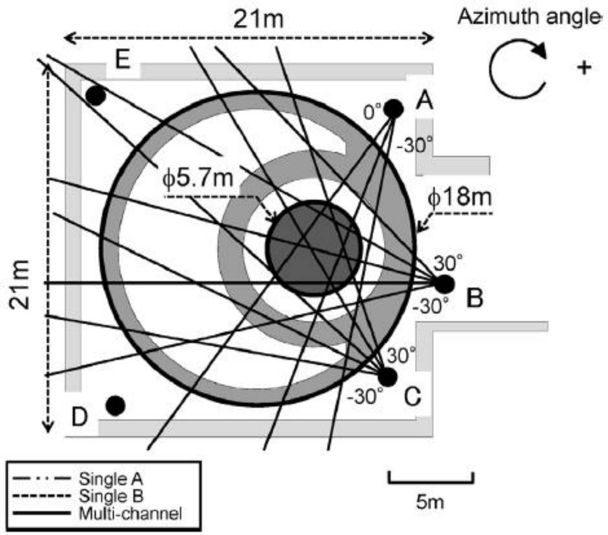
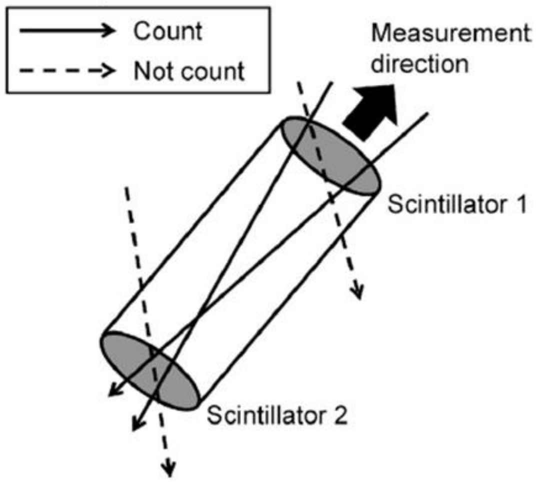
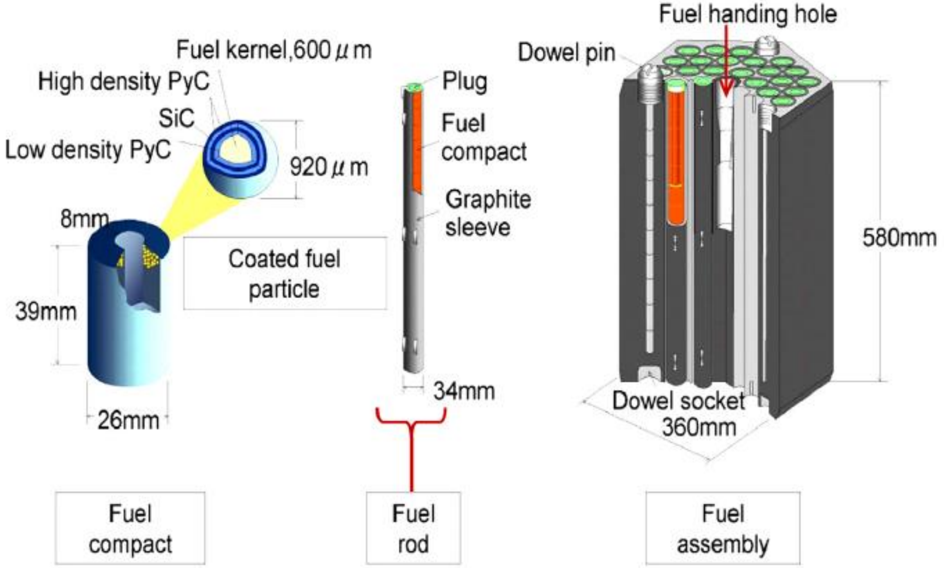
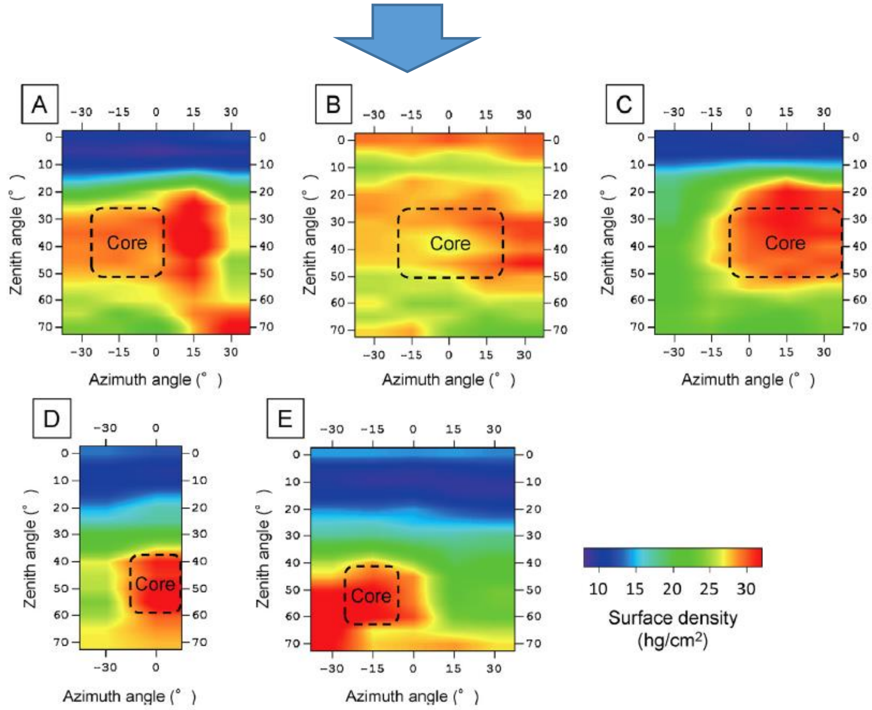
Used plastics scintillators.

The coincidence detector system should be relatively handy and movable.







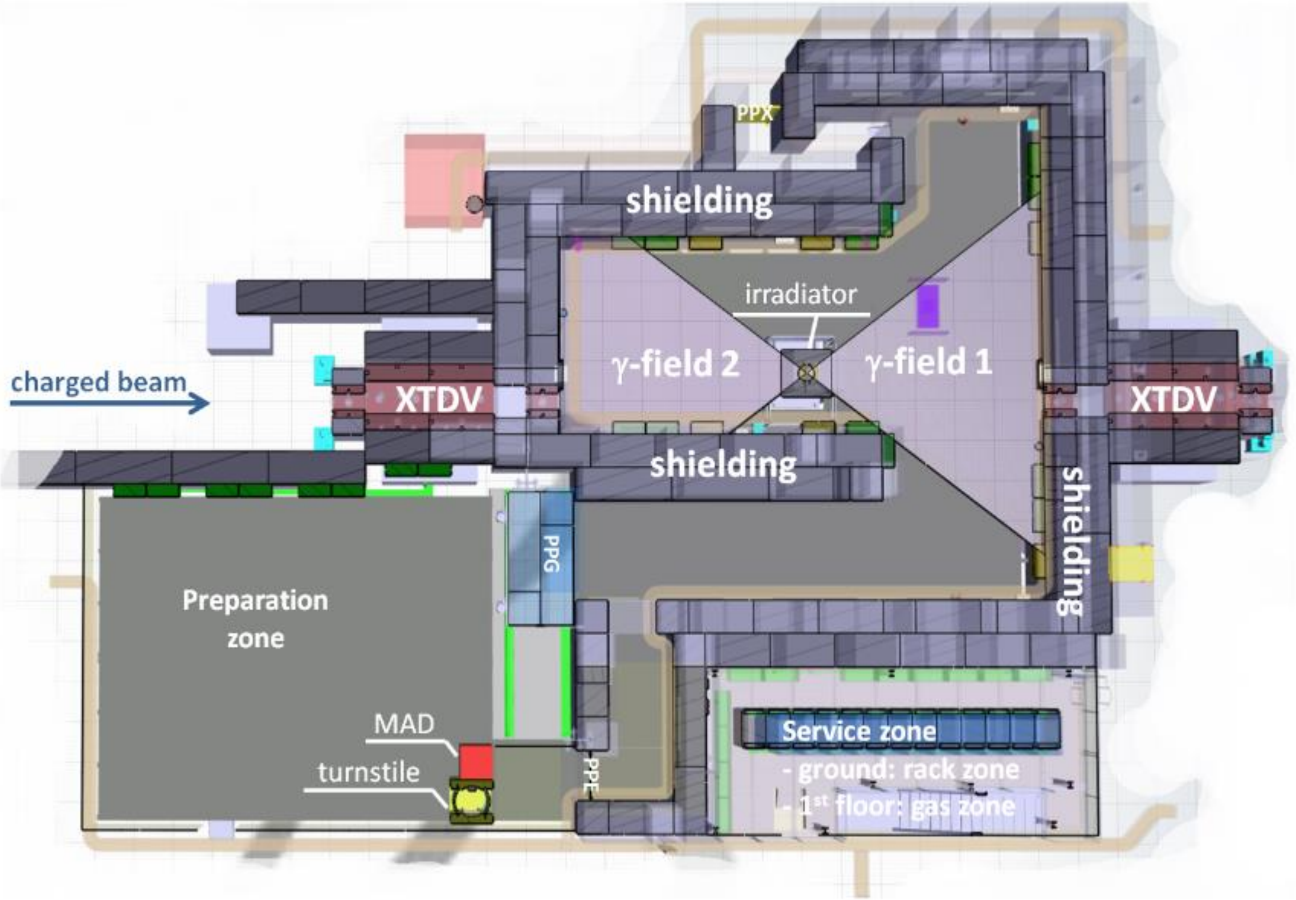


What do we need for the RPC R&D?

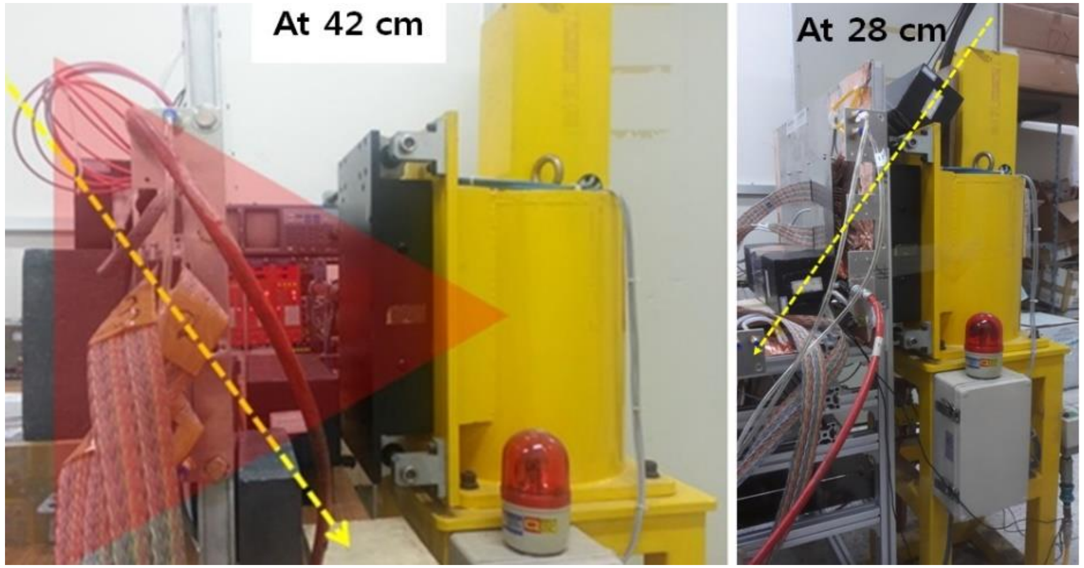
1. Radiation sources

- ✓ Muon beams (~ 100 GeV at CERN H4)
- ✓ Cosmic muons (~ 1 GeV)
- ✓ ^{137}Cs gamma sources

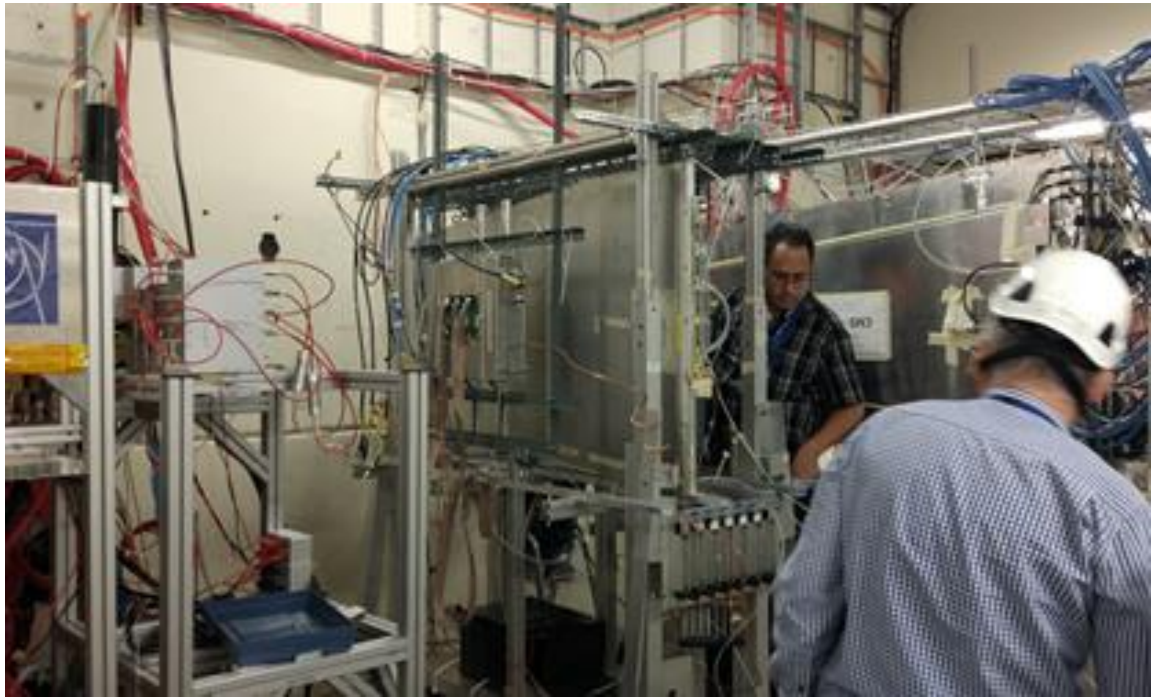
13.9 TBq CERN GIF++ at H4 beam line



~ 5.0 GBq at B117 Korea U



Installation of iRPCs in the GIF zone



2. Reference detectors

Triggers: **Plastic scintillators**

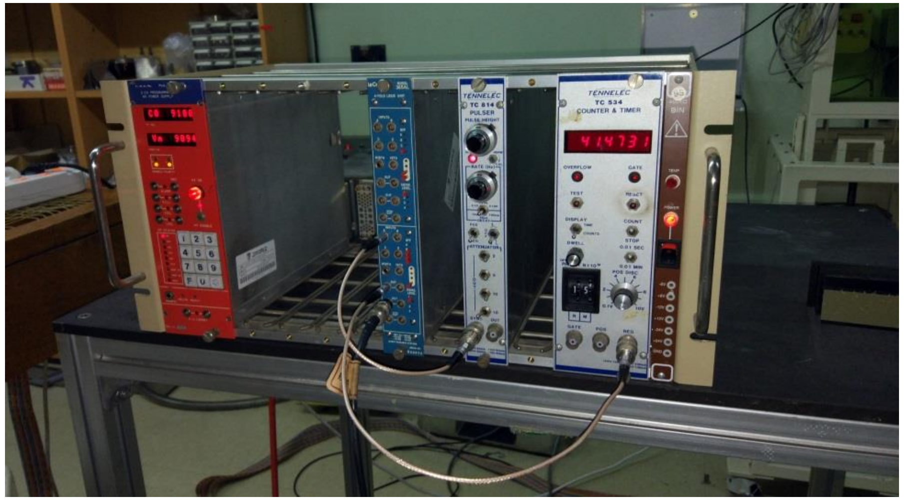
Positioning: Pad chambers

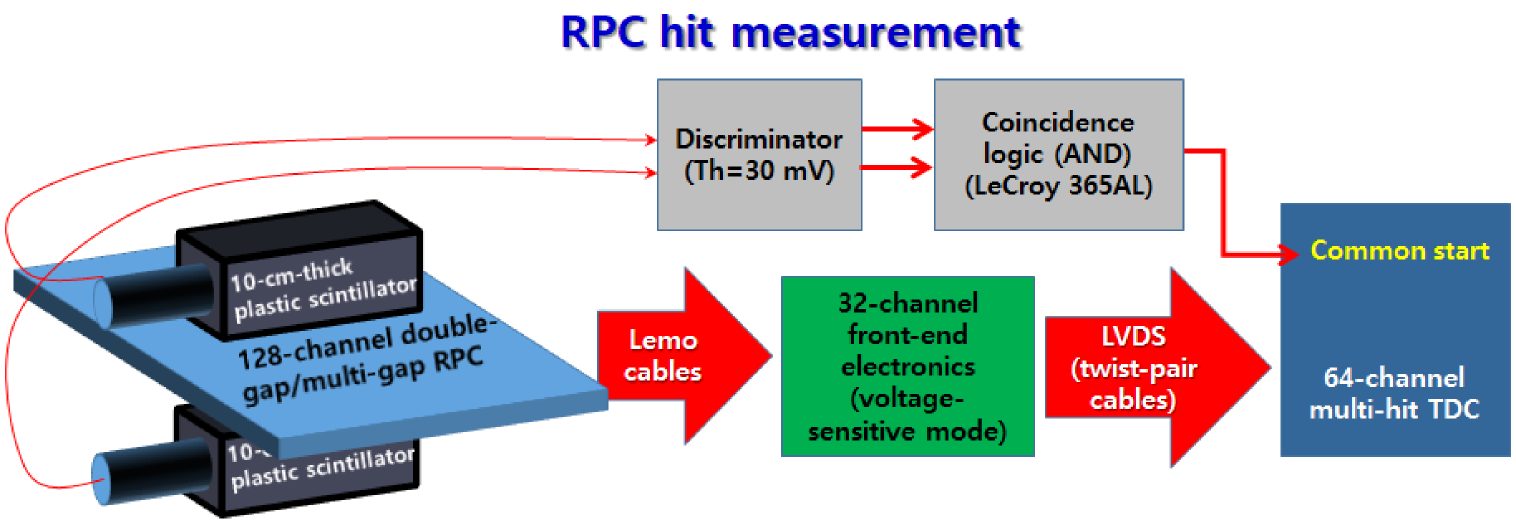
3. Electronics

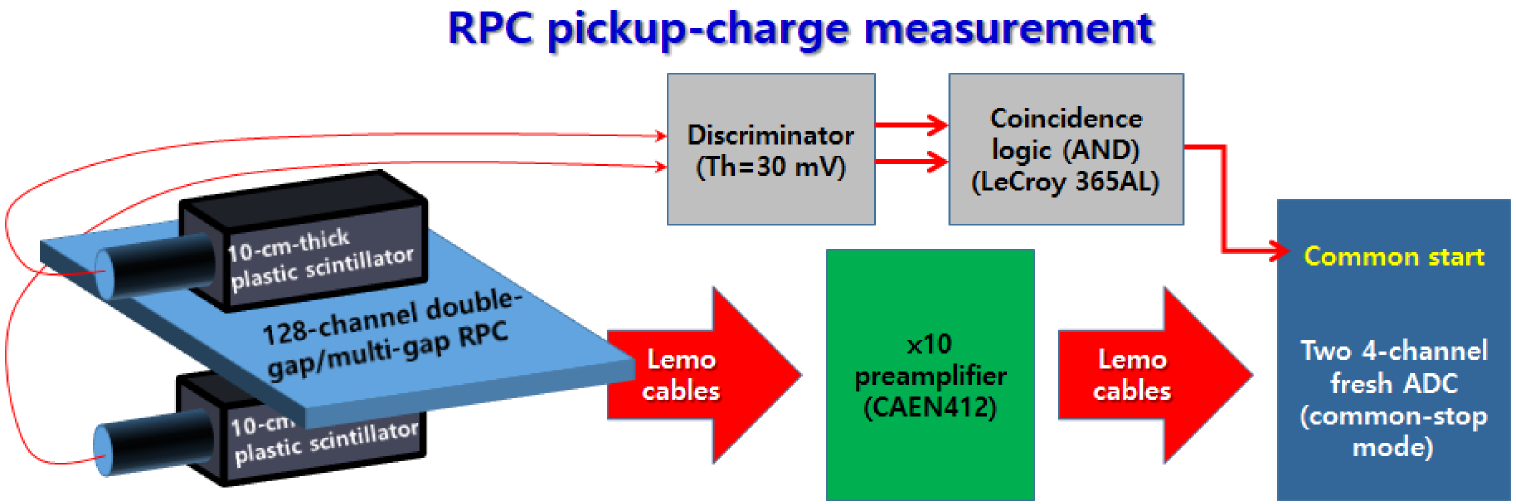
Multi-hit TDCs and ADCs

Coincidence logics

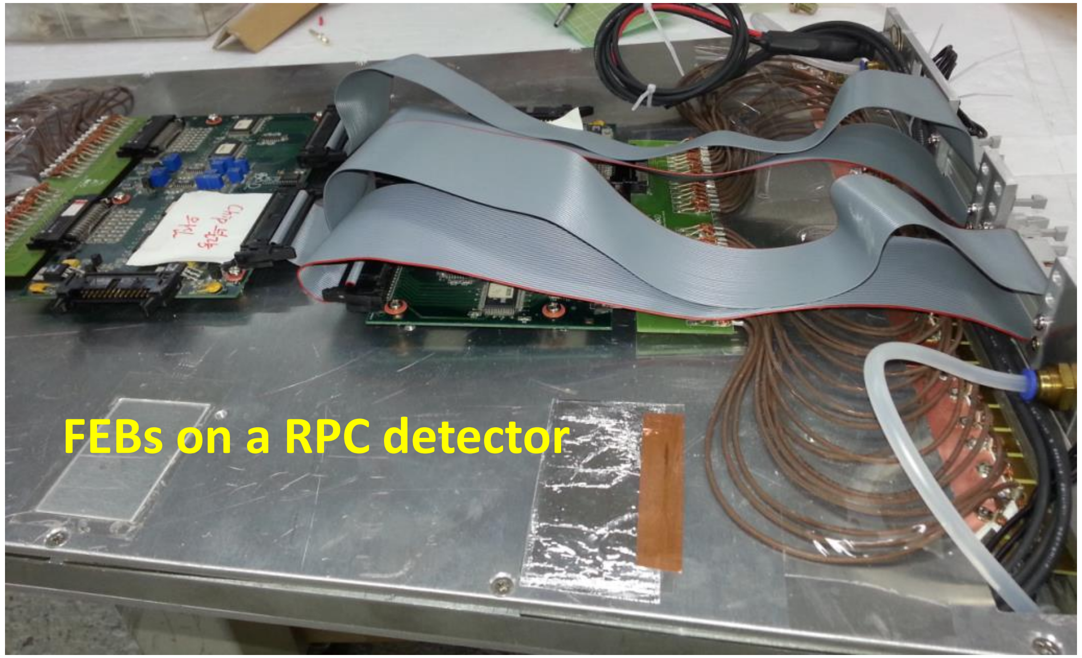
HV power supplies (~10 kV)

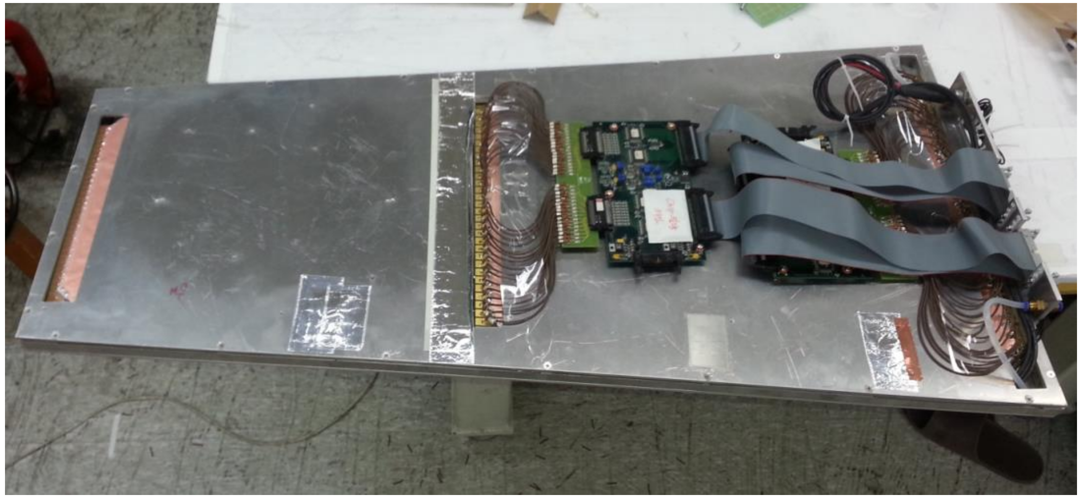






4. Gas systems





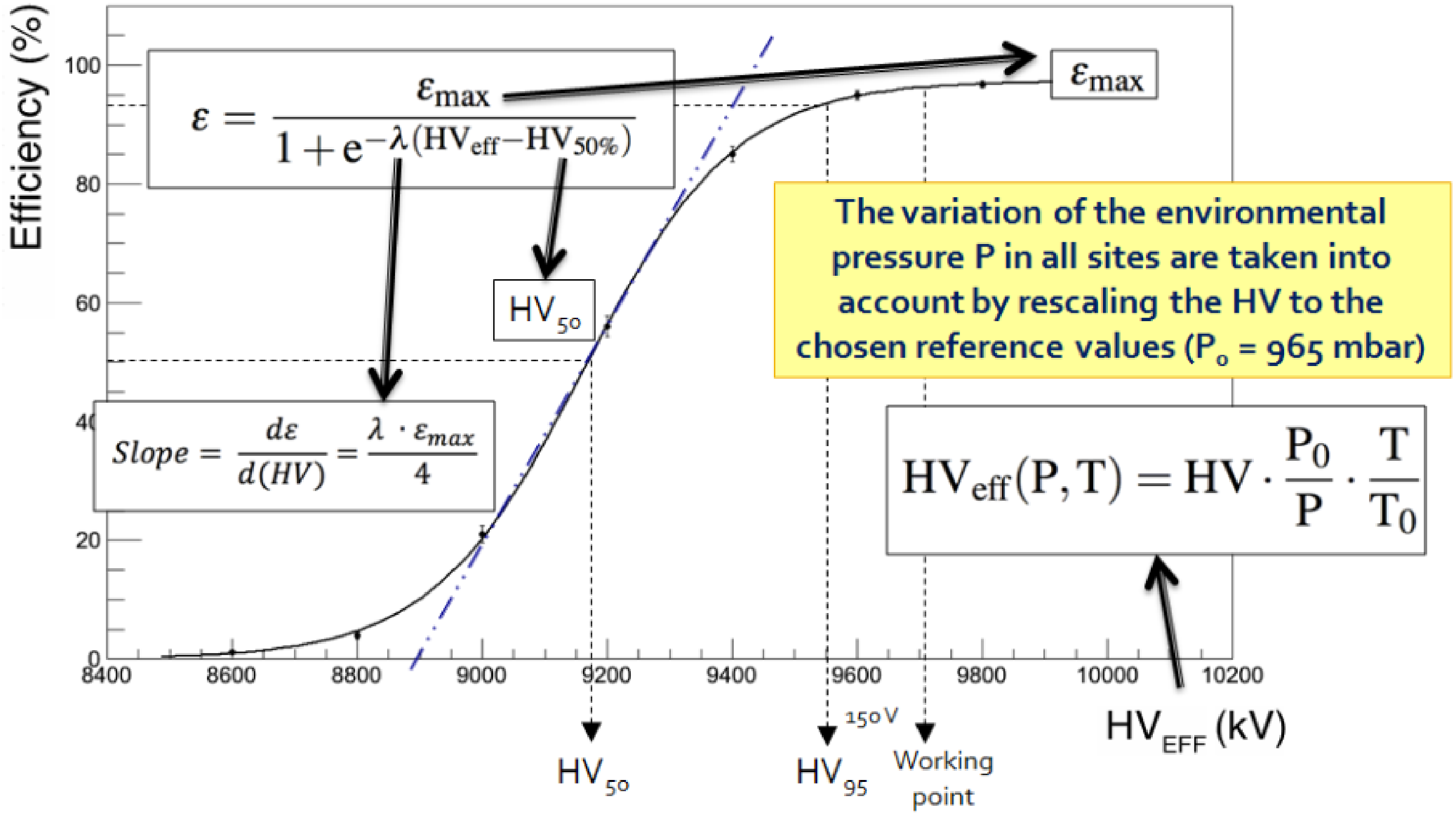
What to do on R&Ds for trigger RPCs?

The detector will be designed to fit the physics requirement.

Tests of detector performance using radiation source

Efficiency and the uniformity, strip multiplicity, rate capability, noise, current stability

Time resolution, position resolution (1D or 2D)



The operational high voltage can be found using a **sigmoidal function.**

$$\varepsilon_{\mu} = \frac{\varepsilon_m}{1+e^{-\lambda(HV_{eff}-HV_{50})}}$$

ε_m : maximum efficiency

HV_{50} : HV_{eff} yielding a 50% efficiency

λ : slope parameter of the sigmoidal response function at HV_{50}.

We define Working Point HV = HV_{95} + 150 V

WP efficiency ~ 97%

Strip multiplicity at WP ~ 2

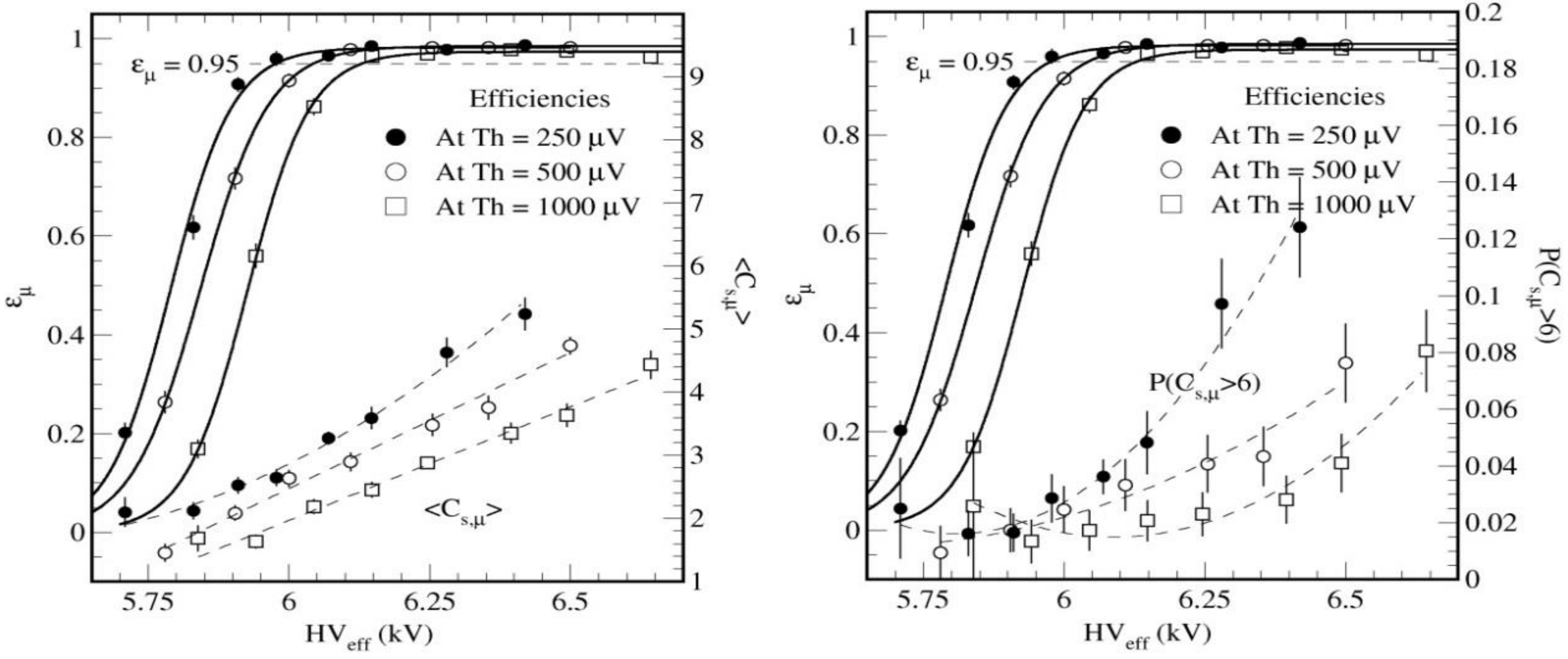
Threshold dependence of Efficiency

Measured for a 1.2-mm double-gap RPC using current sensitive FEBs

Threshold 0.25 mV ~ 45 fC

Threshold 1 mV ~ 180 fC

in a charge sensitive mode FEB

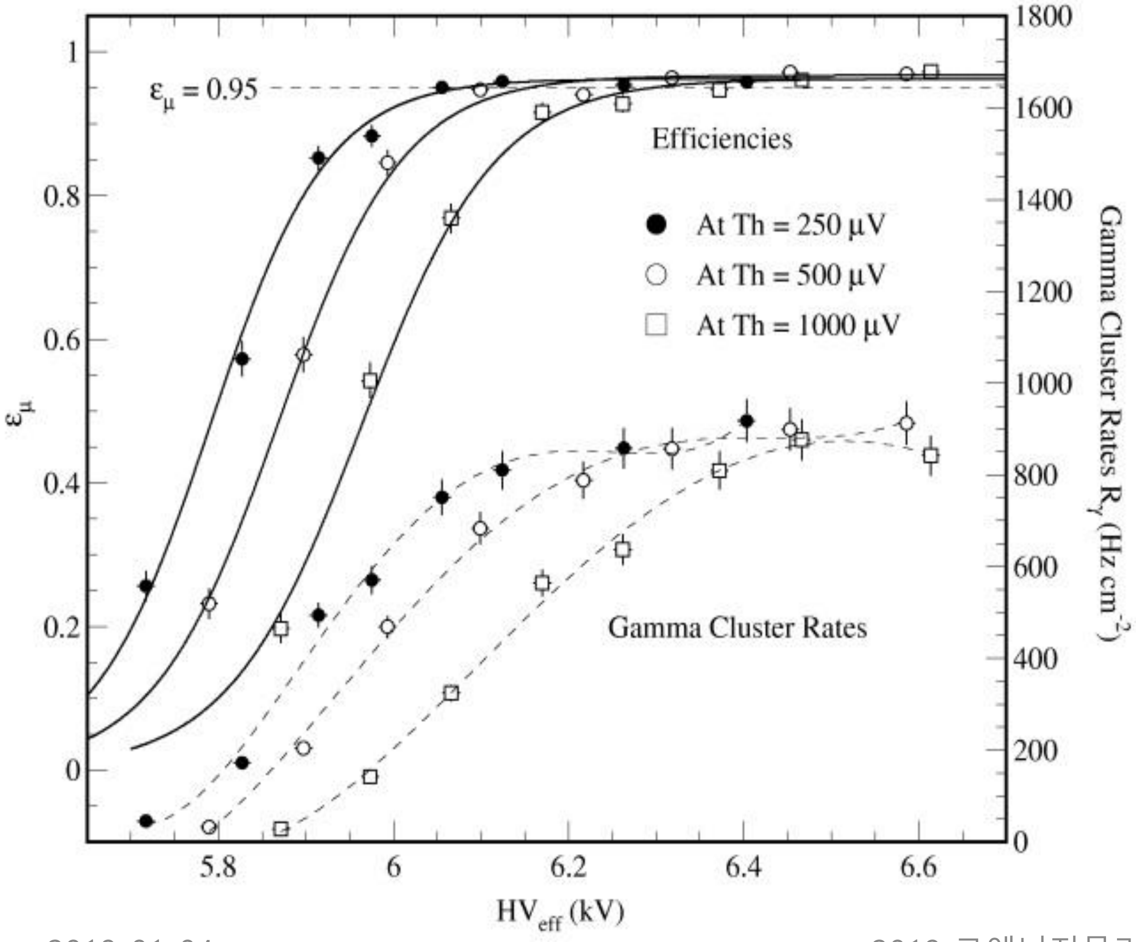


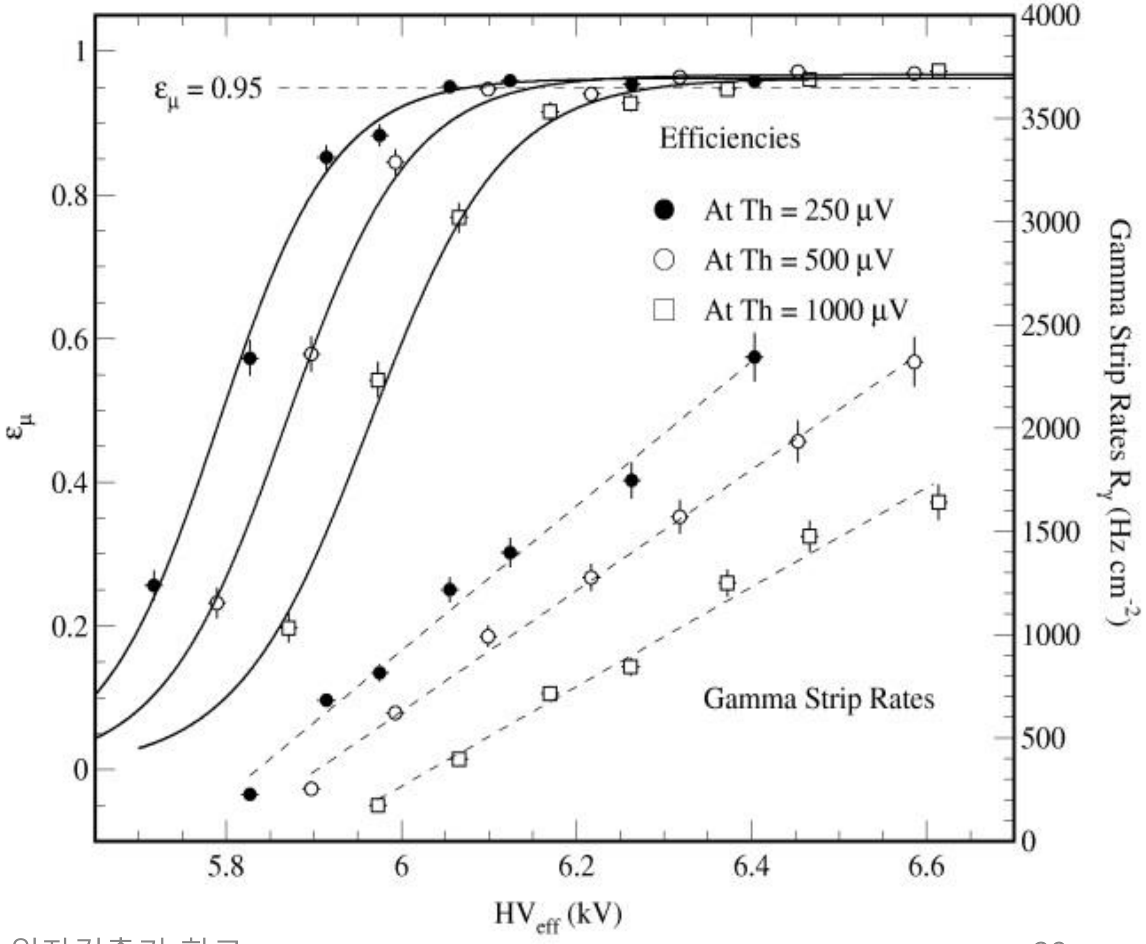
Threshold dependence of efficiency with presence of gamma background

Measured for a 1.2-mm double-gap RPC using current sensitive FEBs

Threshold 0.25 mV ~ 45 fC   in a charge sensitive mode FEB

Threshold 1 mV ~ 180 fC





Threshold dependence of efficiency with presence of gamma background

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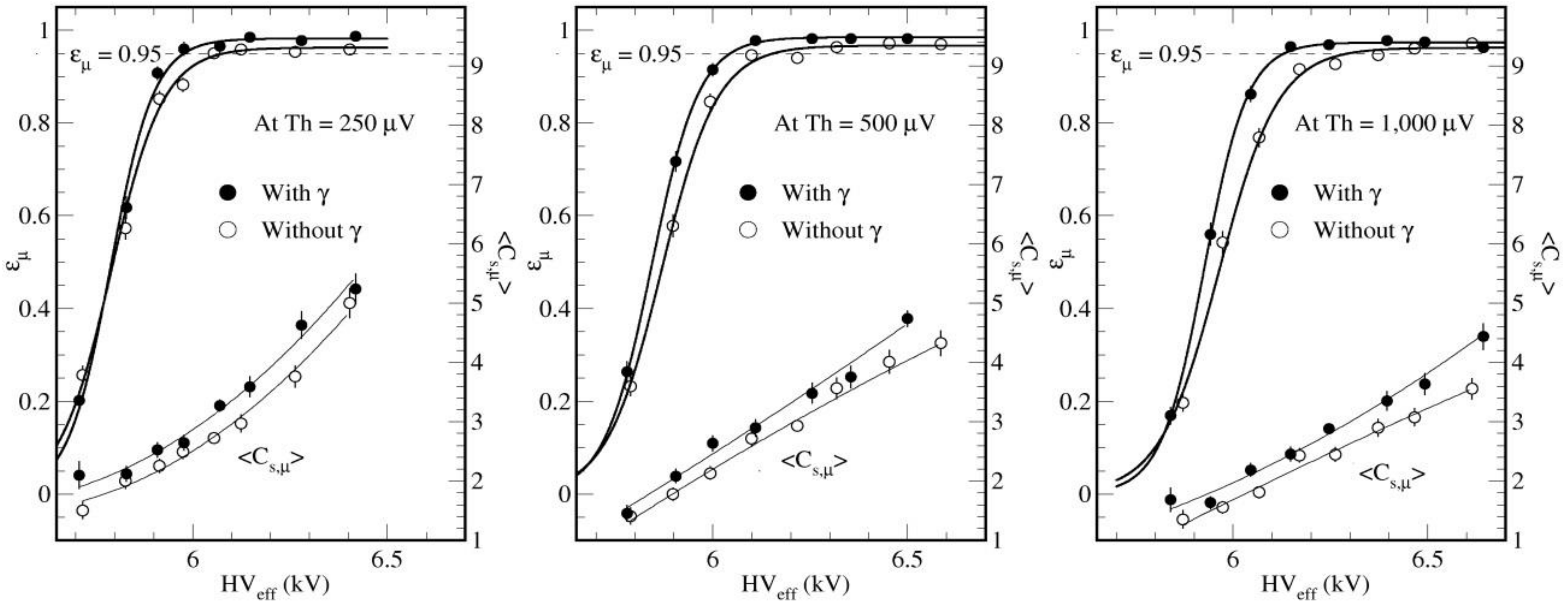
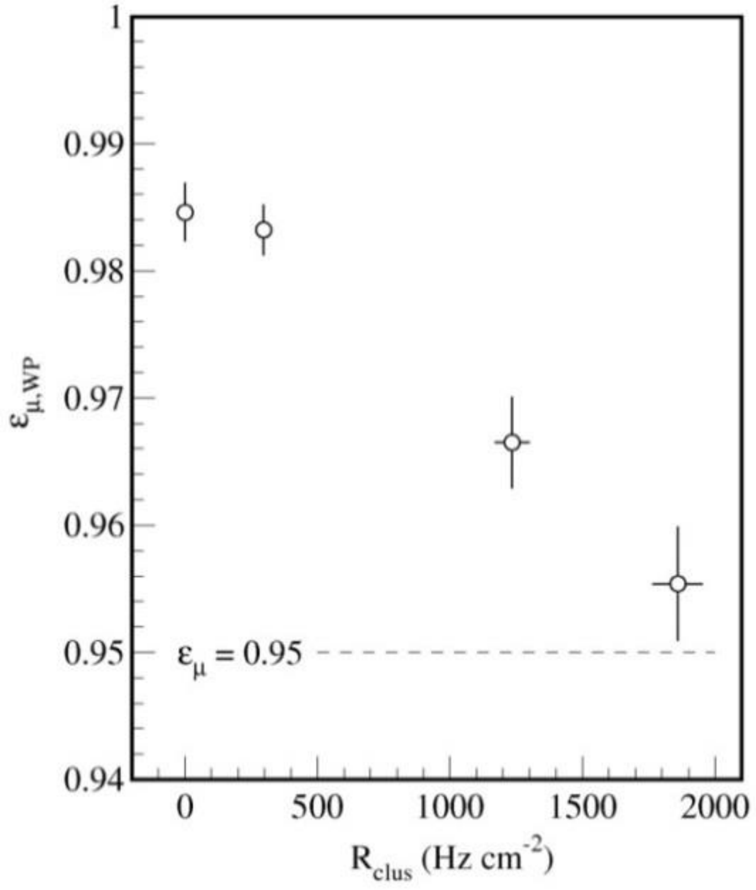
Threshold 1 mV ~ 180 fC

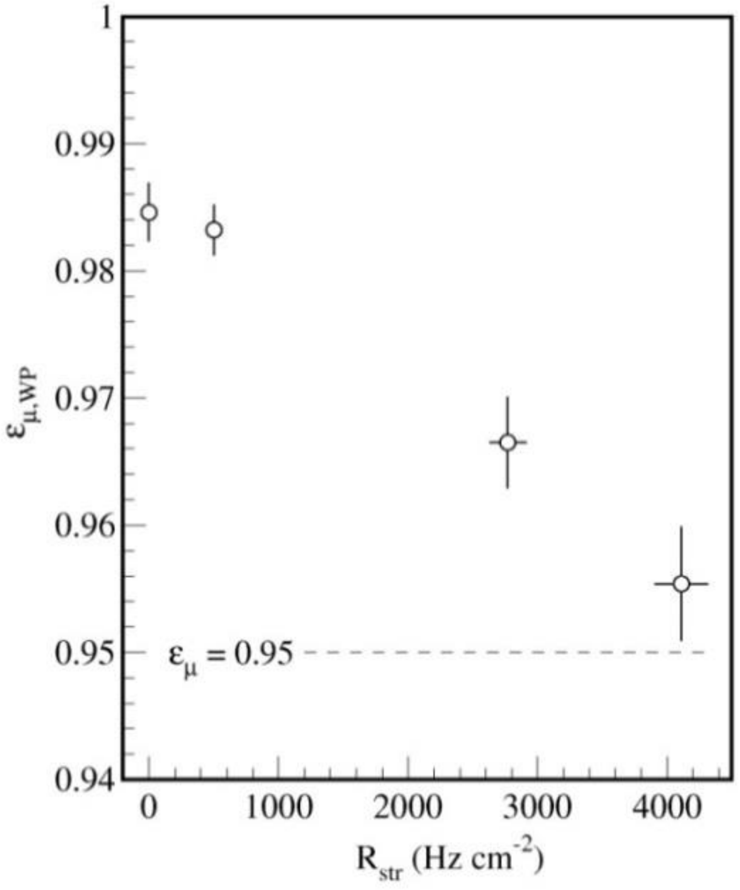


Variation of WP efficiency with gamma background

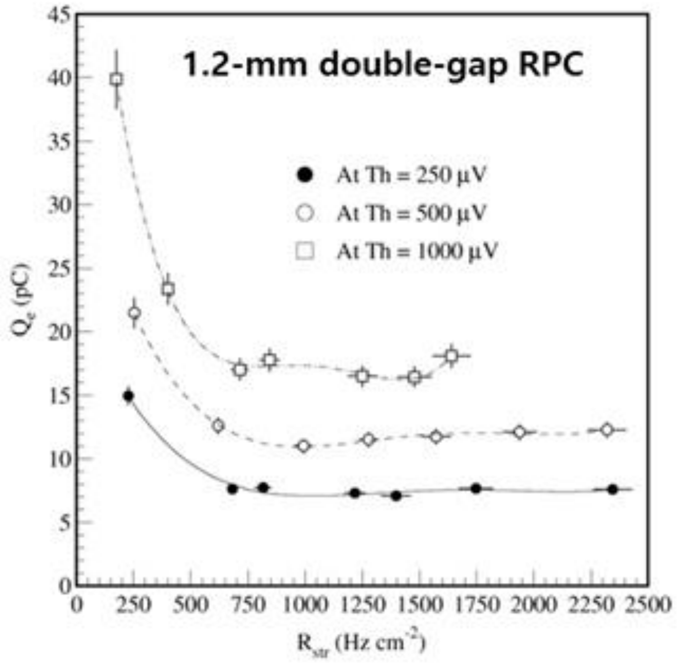
Measured for a 1.4-mm double-gap RPC using current sensitive FEBs

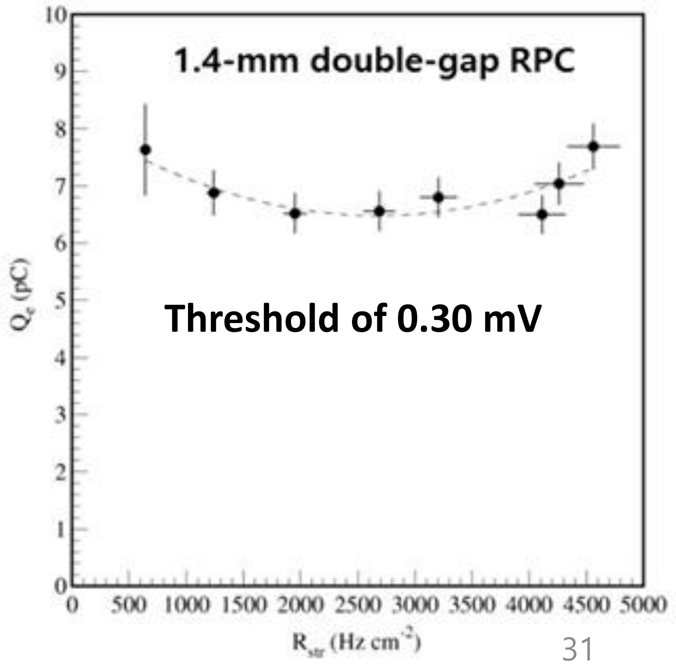
Threshold of 0.30 mV ~ 50 fC



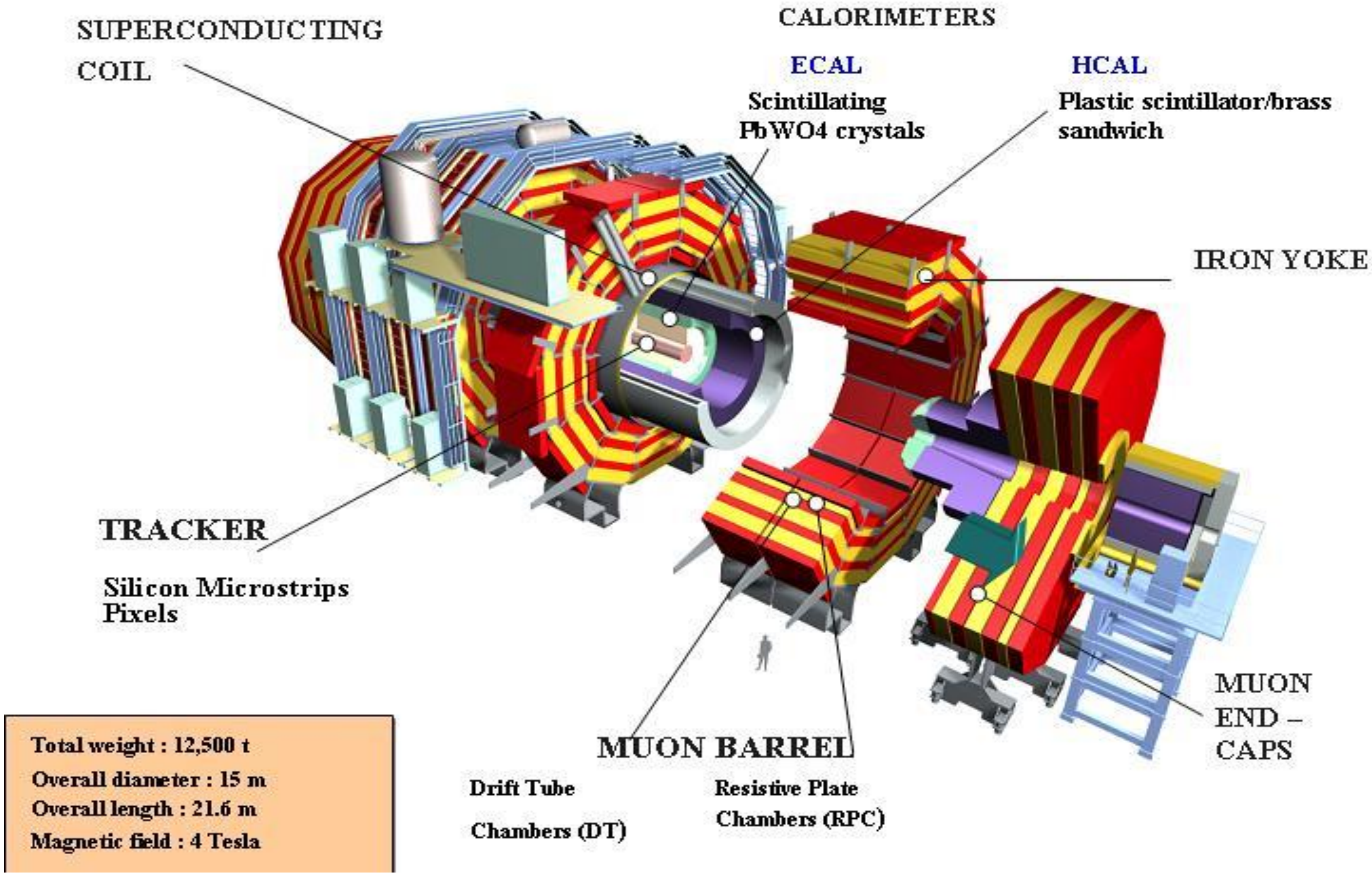


Avalanche charge Q_γ measured for 1.2- and 1.4-mm Double gap RPCs





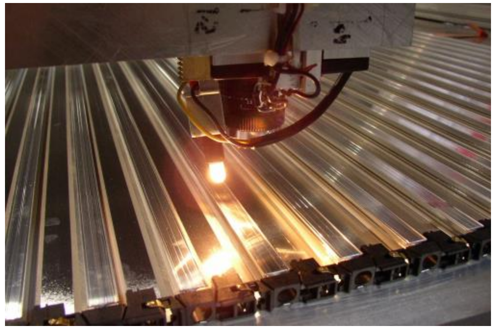
CMS RPC system

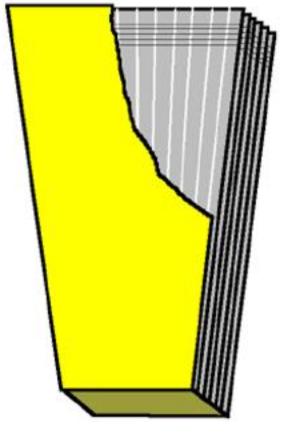


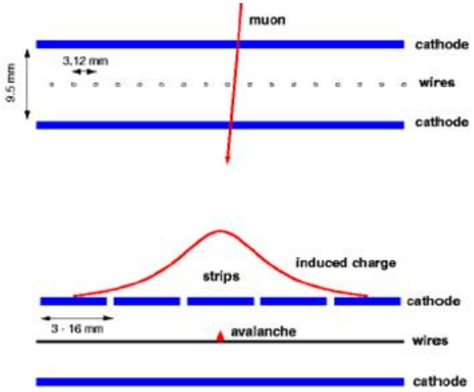
In the muon detector section

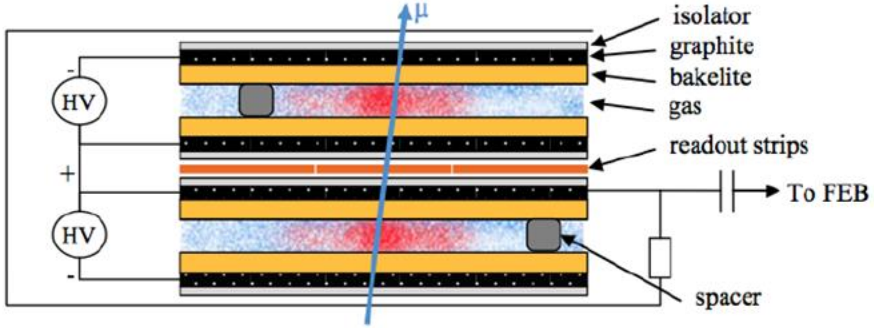
DTs and CSCs for tracking

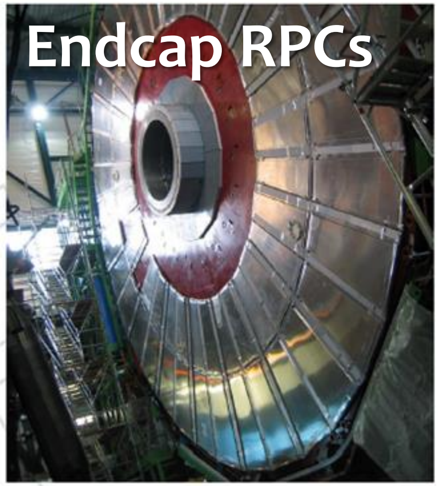
RPCs for triggers







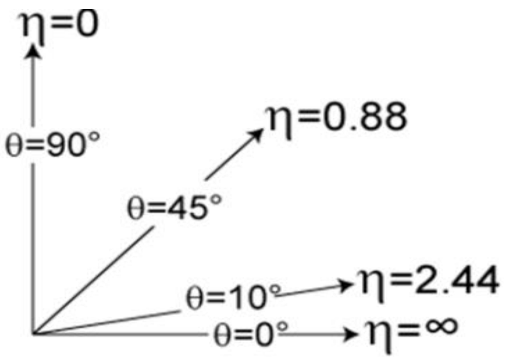




Current RPCs System in the CMS

$$\eta = \frac{1}{2}\ln\left(\frac{|\mathbf{p}| + p_L}{|\mathbf{p}| - p_L}\right)$$

$$v \rightarrow c \quad \eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

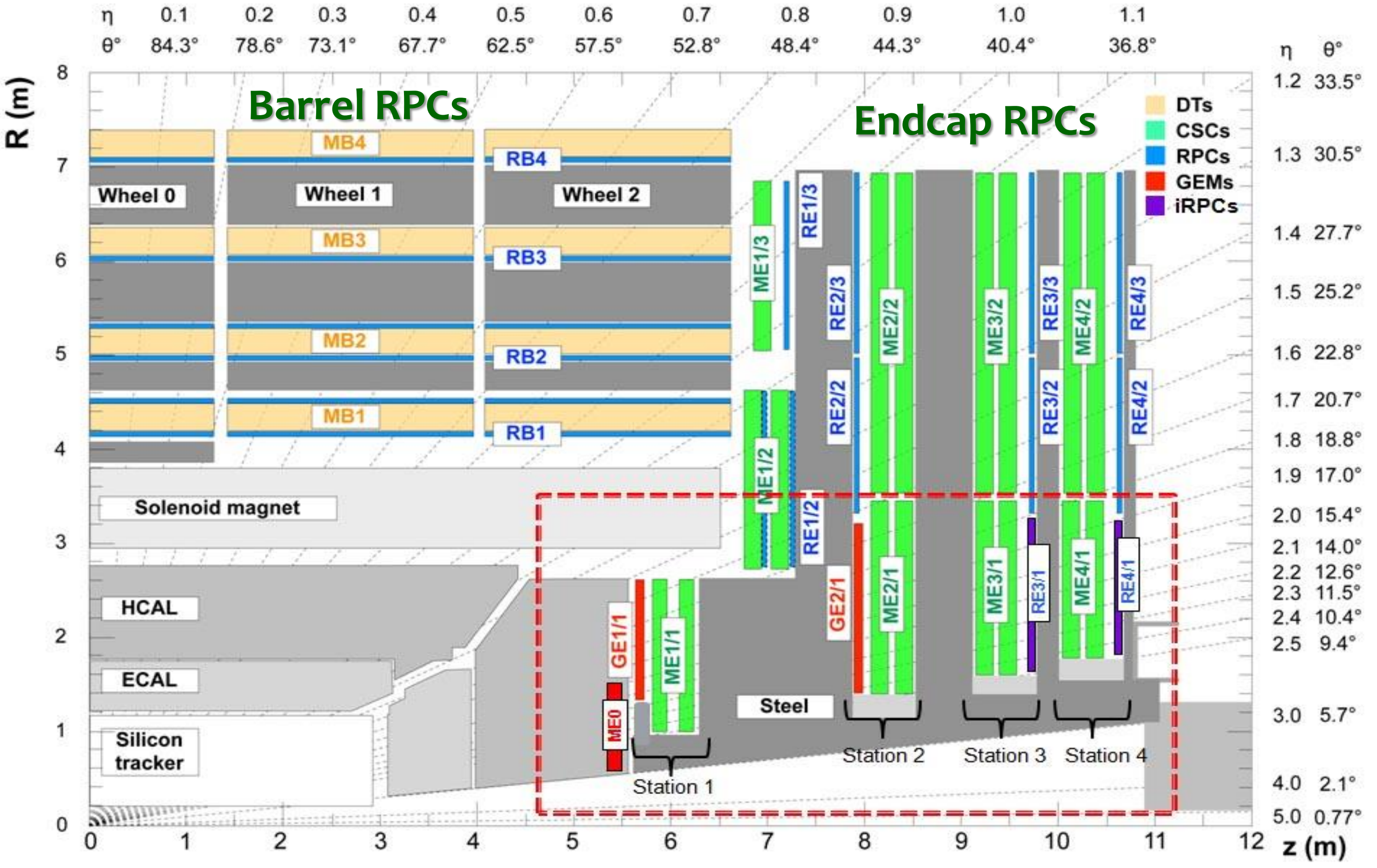


Barrel RPCs

- 6 stations (layers)
- Fully covering up to η = 0.8
- Partially covering up to η ~ 1.2

Endcap RPCs

- 2 wings (RE+, RE-)
- 4 stations in each wing
- Covering 0.92 < η <2.4(5)



What data do we need for the RPC trigger?

In the typical large-scale experiment, The pulses are just digitized to provide logic pulses (LVDS) in front-end-electronics (<- threshold).

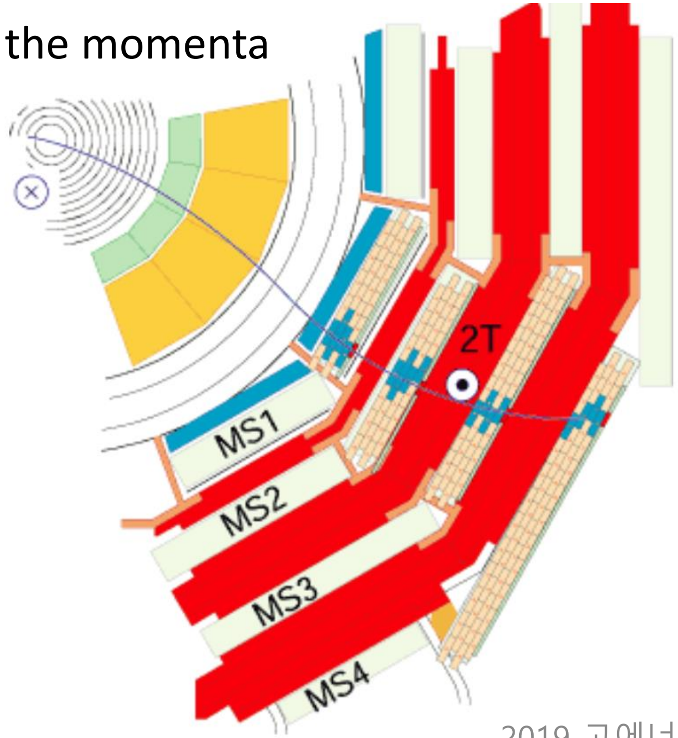
→ Times and rough Hit positions to reconstruct the particle tracks

For CMS (as well as in many other experiments), the RPCs find important muon tracks among high-level background hits

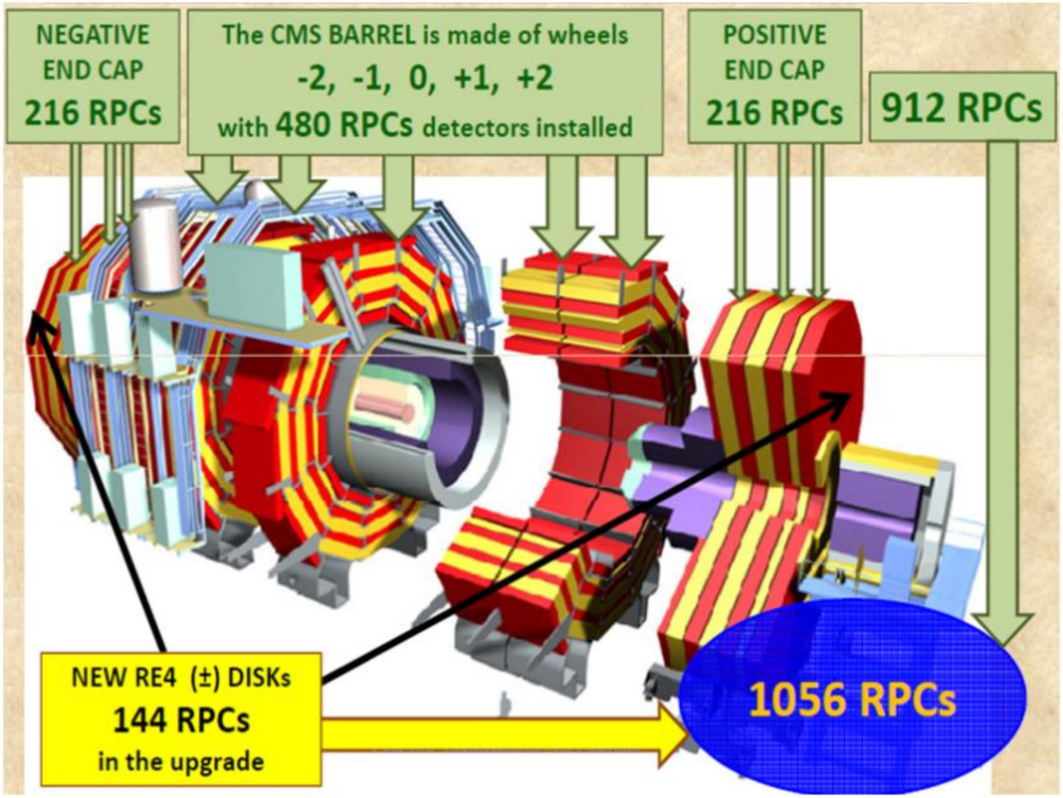
→ **Pattern Comparator Trigger (PACT)** using PAttern Comparator ASIC

✓ Searching muon tracks

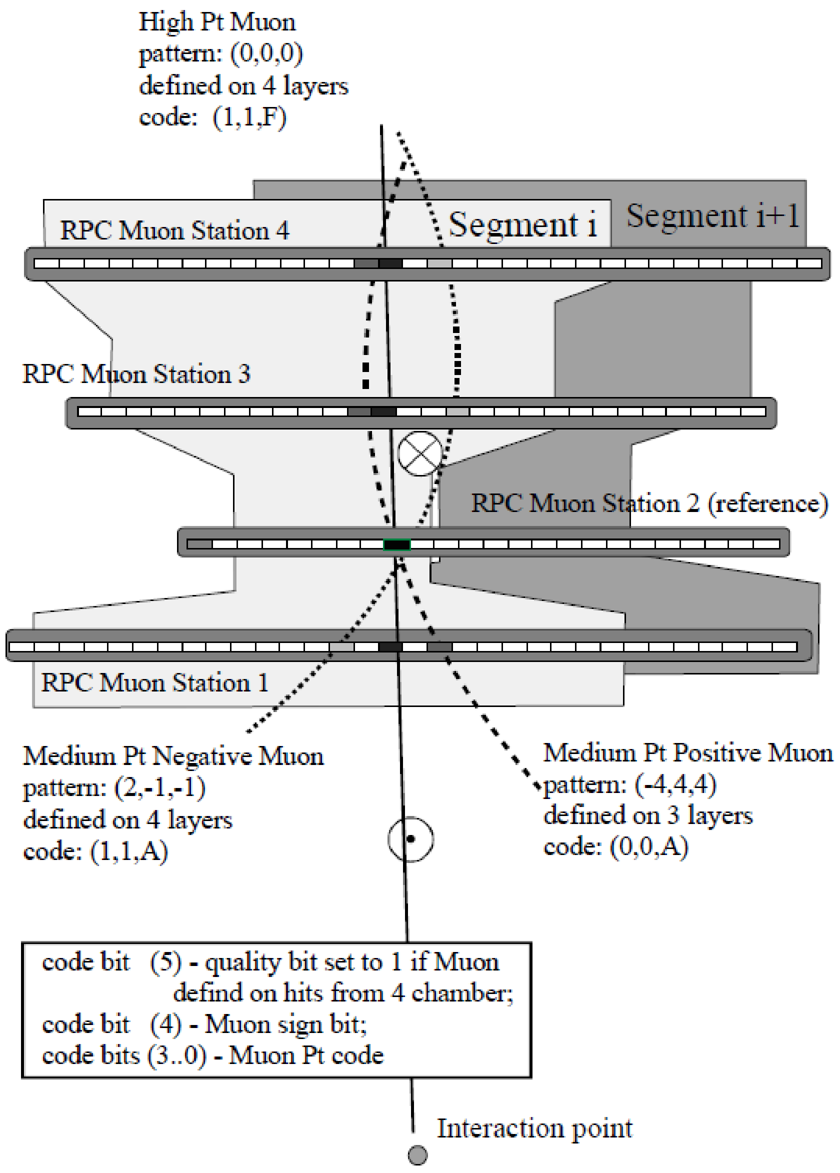
✓ Roughly measuring the momenta

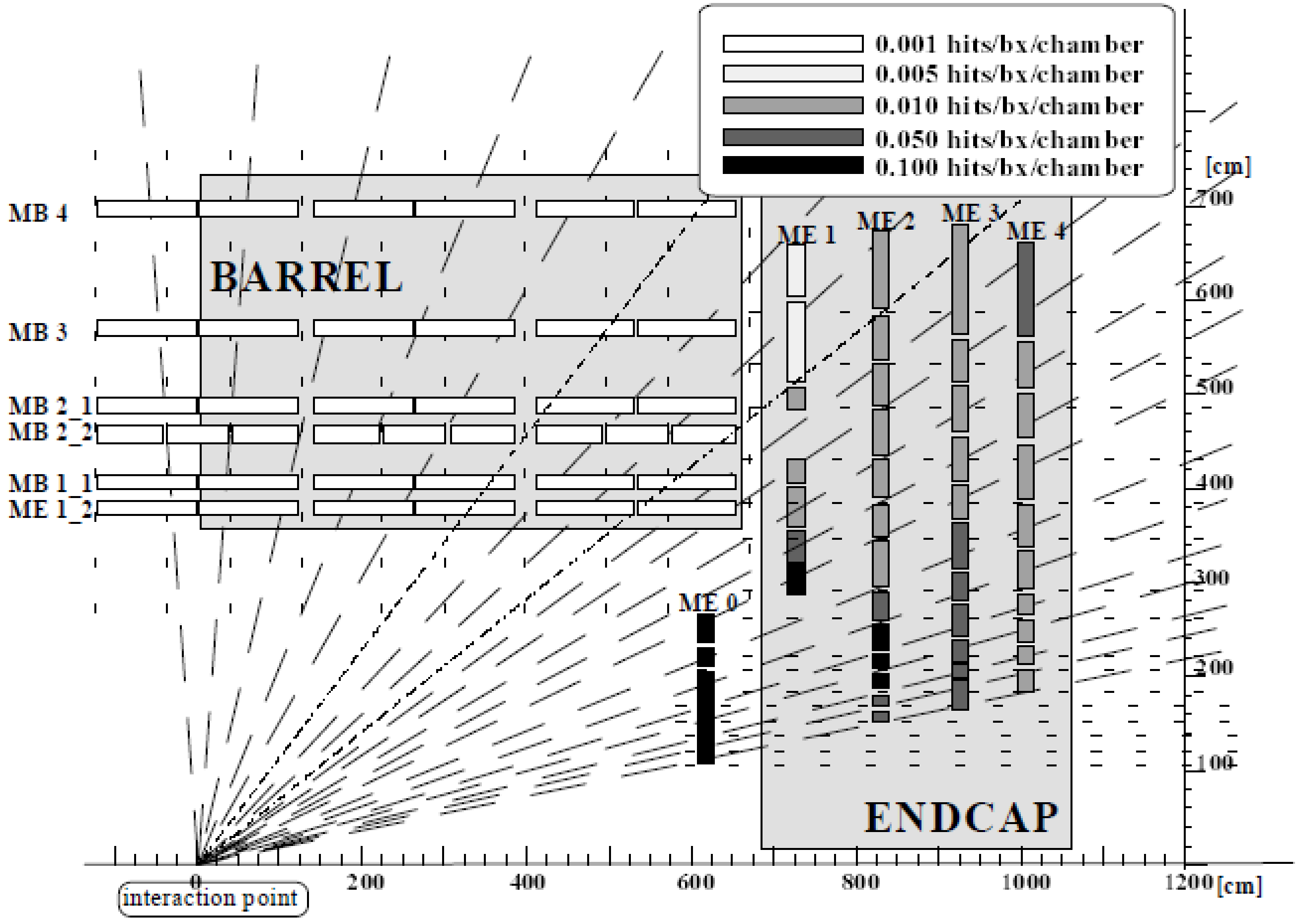


CMS RPC system

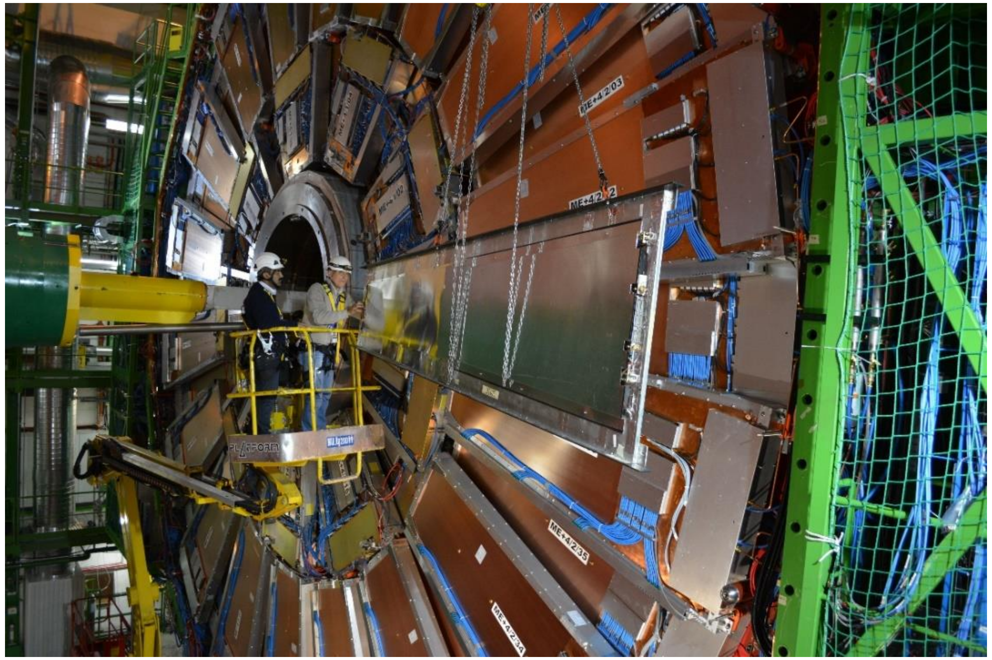


+ 72 iRPC by 2025 = 1128 RPCs up to $\eta = 2.4$


High Pt Muon
pattern: (0,0,0)
defined on 4 layers
code: (1,1,F)
Segment i
Segment i+1
RPC Muon Station 4
RPC Muon Station 3
RPC Muon Station 2 (reference)
RPC Muon Station 1
Medium Pt Negative Muon
pattern: (2,-1,-1)
defined on 4 layers
code: (1,1,A)
Medium Pt Positive Muon
pattern: (-4,4,4)
defined on 3 layers
code: (0,0,A)
code bit (5) - quality bit set to 1 if Muon defind on hits from 4 chamber;
code bit (4) - Muon sign bit;
code bits (3..0) - Muon Pt code
Interaction point


0.001 hits/bx/chamber
0.005 hits/bx/chamber
0.010 hits/bx/chamber
0.050 hits/bx/chamber
0.100 hits/bx/chamber
MB 4
MB 3
MB 2_1
MB 2_2
MB 1_1
ME 1_2
BARREL
ME 1
ME 2
ME 3
ME 4
ME 0
ENDCAP
[cm]
700
600
500
400
300
200
100
0
200
400
600
800
1000
1200
[cm]
interaction point

Installation of RPCs in the CMS



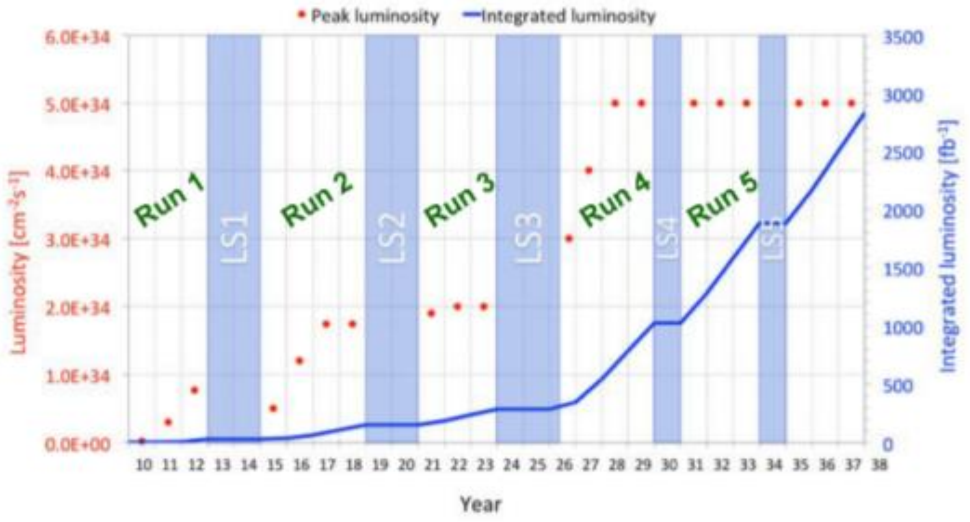
RPC System Upgrade for Phase-2 LHC runs

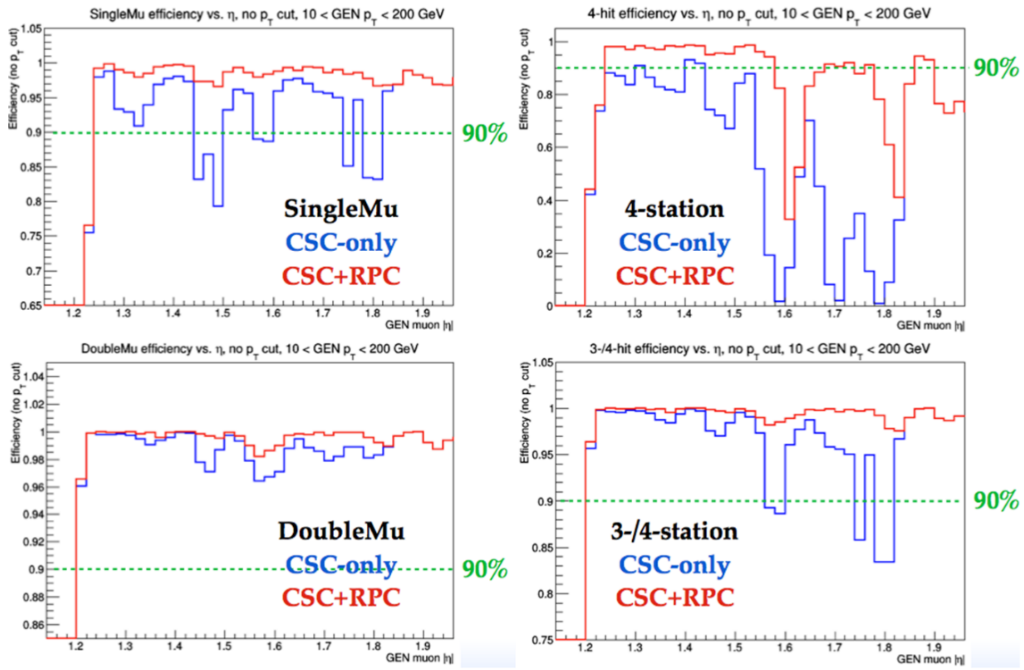
In Phase-2 (2025-), the LHC luminosity up to maximum 5 (7.5) x 10^{34} cm^{-2} s^{-1}

1. **CONSOLIDATION** of the present system
The current RPCs cover $0<|\eta|<1.8$ with 1056 RPCs.
We should maintain the excellent performance of the detector system in the HL-LHC conditions (rates and longevity).

2. **EXTENSION** at high eta ($1.8 < |\eta| < 2.4$)
We improve the CMS RPC system with new 72 RPCs with improved technology.
- ✓ Better position & time resolutions
- ✓ Capable of 2 dimensional measurement
- ✓ Higher rate capability (> 2 k cm^{-2})

3. **ECOGAS**
R&Ds for RPC operation gases with a lower GWP(Global Warming Potential)





The non-exponential nature of the avalanche charges becomes stronger with the higher electric field.

The Rather condition is fixed at ~ 20.

As we decrease the thickness of the gas gap, the operational electric field that allows us the condition, $(\alpha - \eta)\, d < 20$, becomes stronger.

At the higher *E* field, the charge screening effect due to the space charges are stronger.

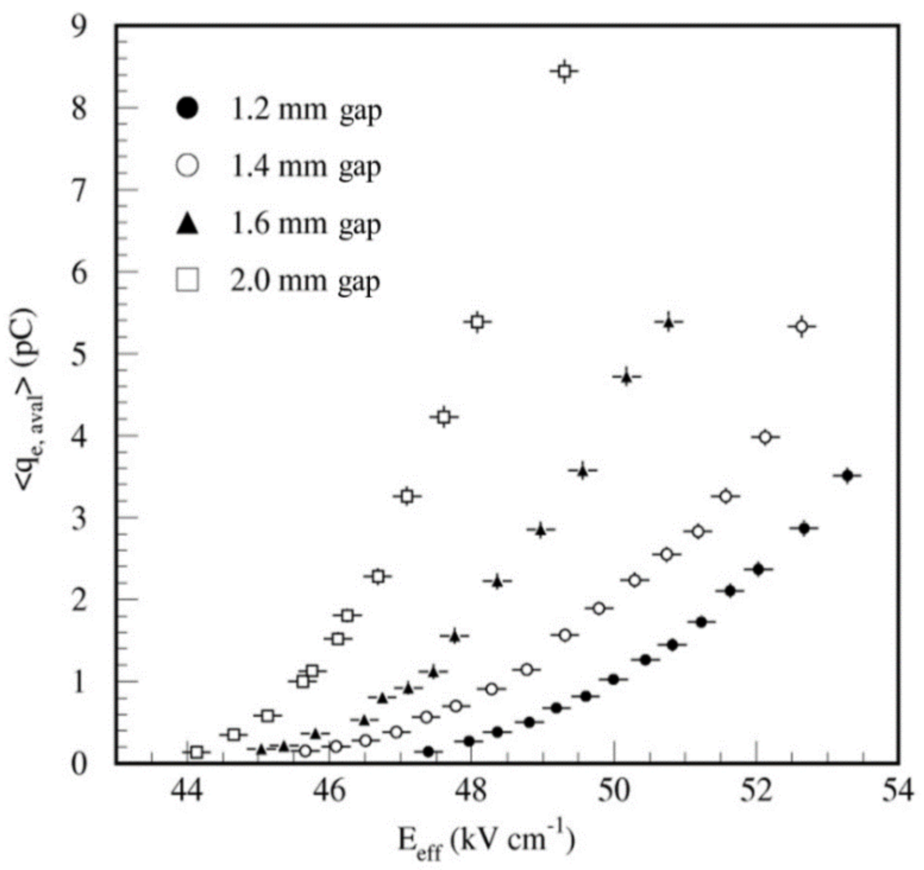
→ Wider operational width in the operational electric field

→ Can choose a lower value of $(\alpha - \eta)\, d \sim 18$ (should be demonstrated) to obtain a lower streamer probability.

→ For CMS, we have chosen 1.4 mm / 1.4 mm electrode / gap for iRPCs instead of 2.0 mm / 2.0 mm because of this reason.

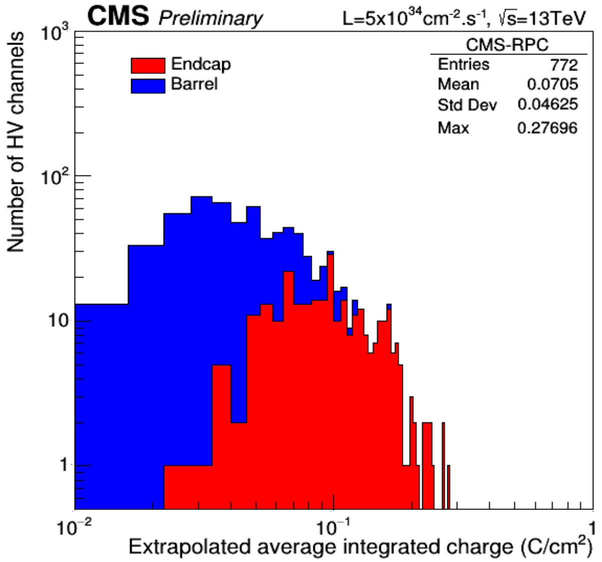
→ We can effectively lower the operational voltage for a better electrical safety for the new CMS iRPCs.

→ **TDR for PHASE-2 CMS muon system**



CONSOLIDATION

The RPC system has been certified for 10 years of LHC (at nominal luminosity of 10^{34} cm^{-2} s^{-1}) at maximum rate of 300 Hz/cm^2 and 50 mC cm^{-2}. The CMS RPC system has to be certified for the future HL-LHC running (luminosity of 5 x10^{34} cm^{-2} s^{-1})



Rate

≈ **600 Hz/cm^2** (safety factor of 3)

➢ Barrel chambers factor 2 less

Int. charge of

≈ **840 mC/cm^2** (safety factor of 3)

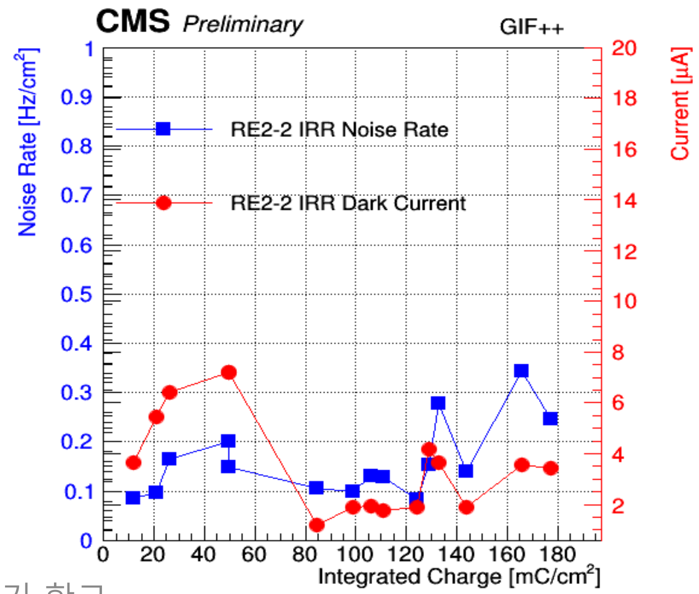
➢ Barrel chambers factor 2 less

A dedicated irradiation test at GIF++ is ongoing since 2016 with four RPC chambers:

➢ One RE4 and one RE2 always at HV on: "irradiated"

➢ One RE4 and one RE2 always off: "reference"

1. **Monitoring detector currents and noise rates**
2. **Detector performance (efficiency, cluster size, etc) measured 3-4 times/year with muon beam with and without presence of gamma background.**

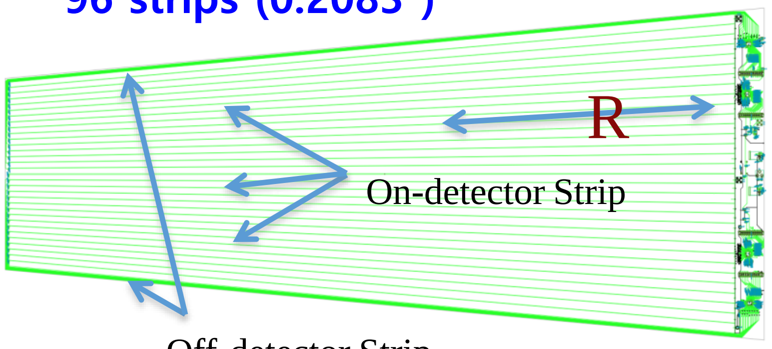


EXTENSION at high eta ($1.8 < |\eta| < 2.4$)

Design #1 for the CMS iRPCs in the Phase-2 LHC runs

Reading ***φ-r*** **position (2D)**

- 1.4-mm thick double-gap RPCs
  WP efficiency ~ 0.97 @ HV=7.3 kV
  Mean C_s at WP ~ 2.5
- Reading signals from both ends of strips
  Signal propagation speed in the strips = 18.4 cm/ns @ Z = 50 Ω

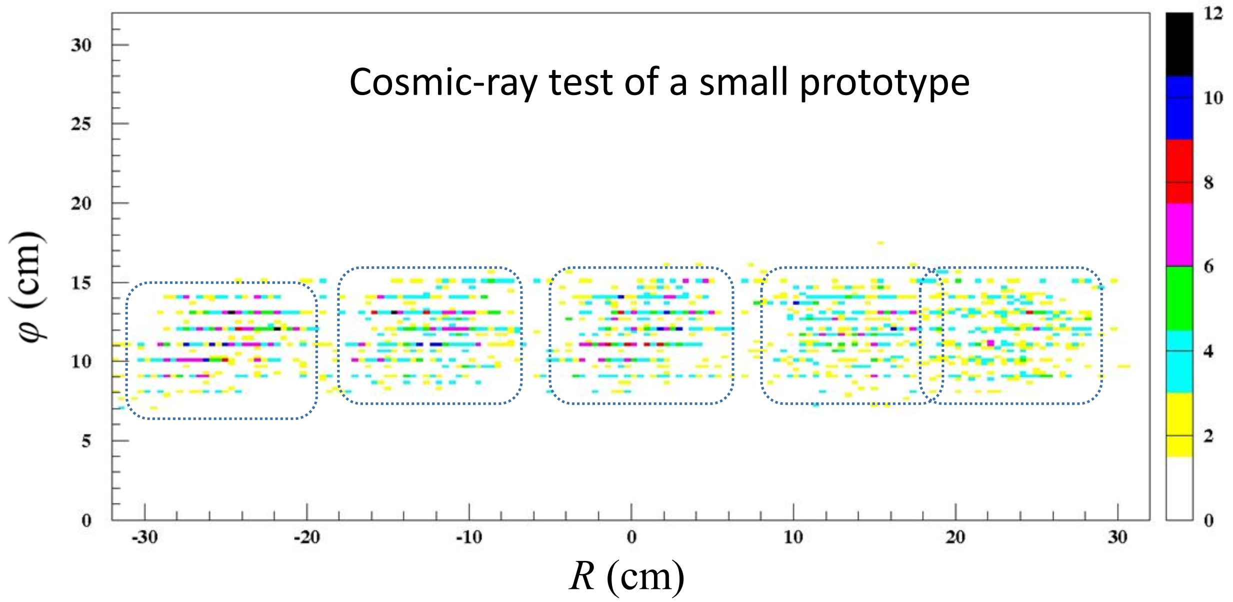


96 strips (0.2083°)
φ resolution ~ 3 mm

$$R = L/2 - v \times (t_L - t_R) / 2$$
$$\sigma(R) = v\ (18.4\ \text{cm/ns}) \times \sigma_{(tL - tR)} / 2\ (\text{ns})$$
~ 2.0 cm

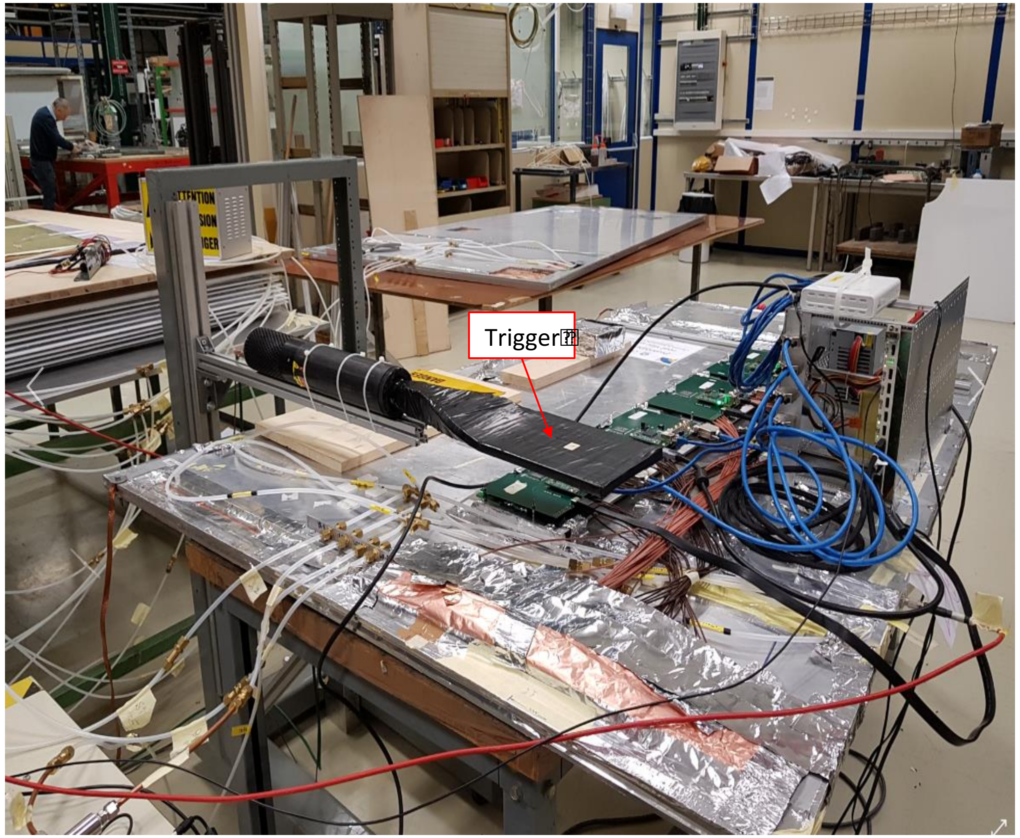
Front-end electronics: **PETIROC ASIC + TDC**

- 32 channels
- low noise
- gain 25 → lowest digitization threshold ~ 80 fC
- fast pre-amplifier and fast discriminator in SiGe technology → time resolution (jitter) <100 ps

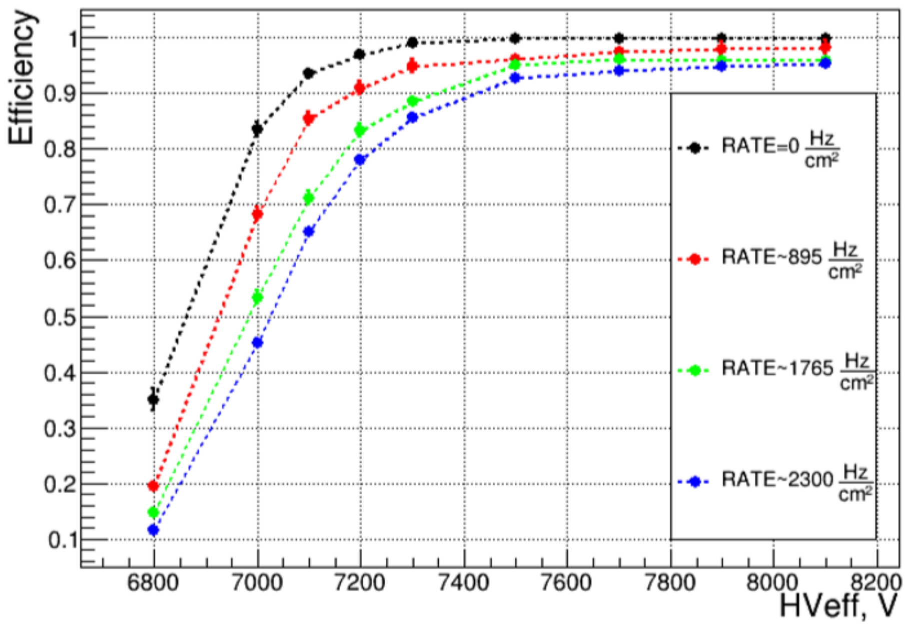


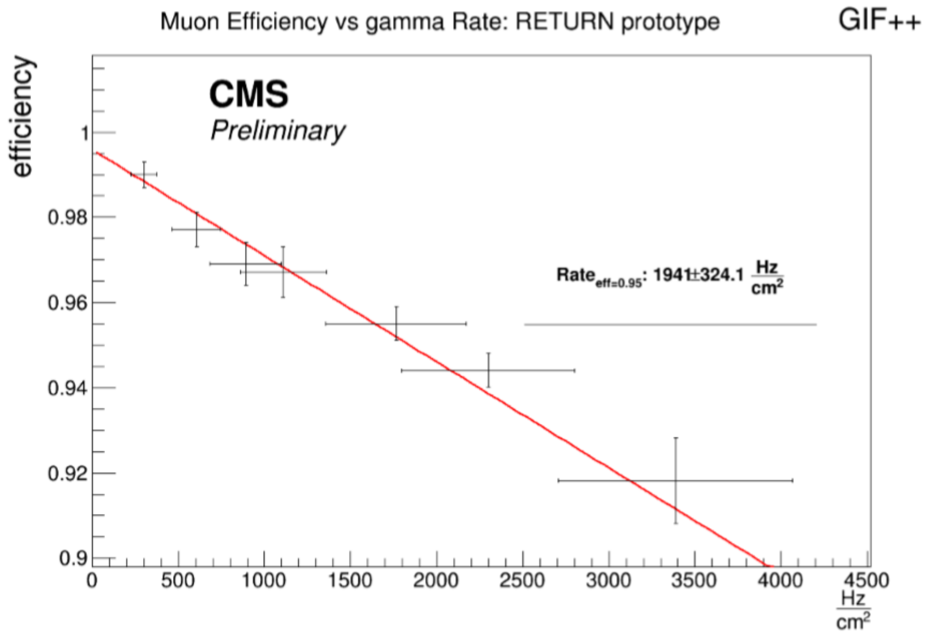
Test of real-sized prototype iRPCs CERN @H4/SPS

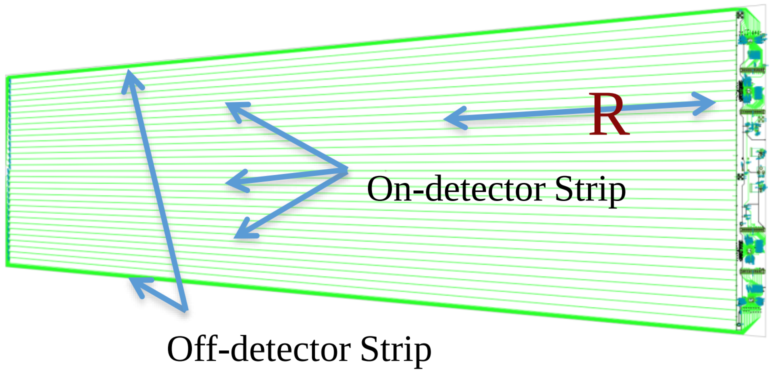
Test with cosmic muons

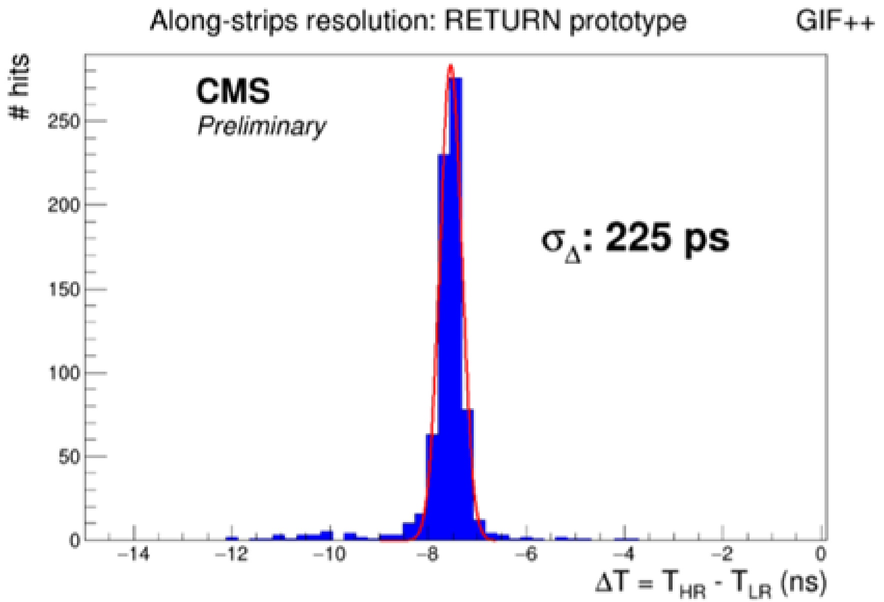


Test with muon beams @H4 beam line of SPS/CERN









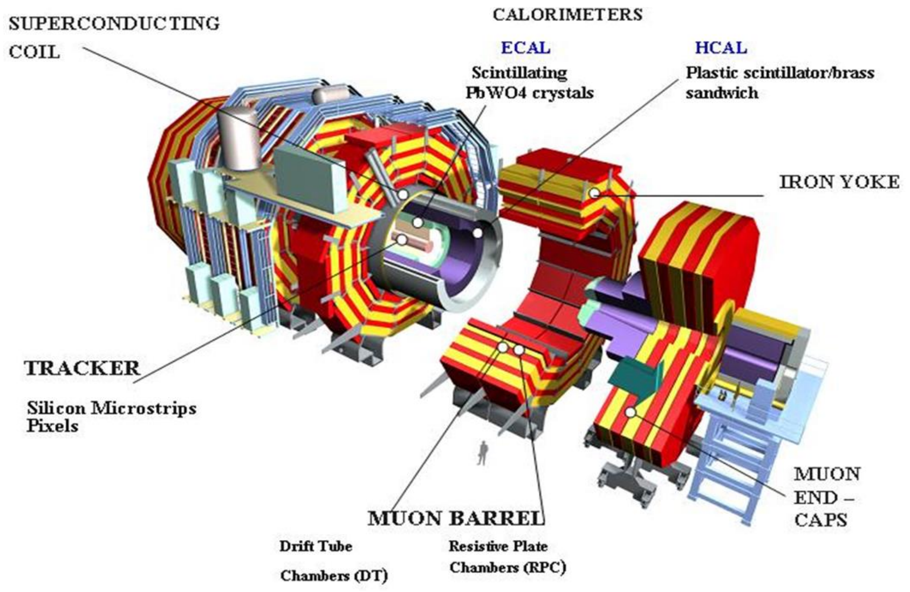
$$R = L/2 - v \times (t_L - t_R) / 2$$

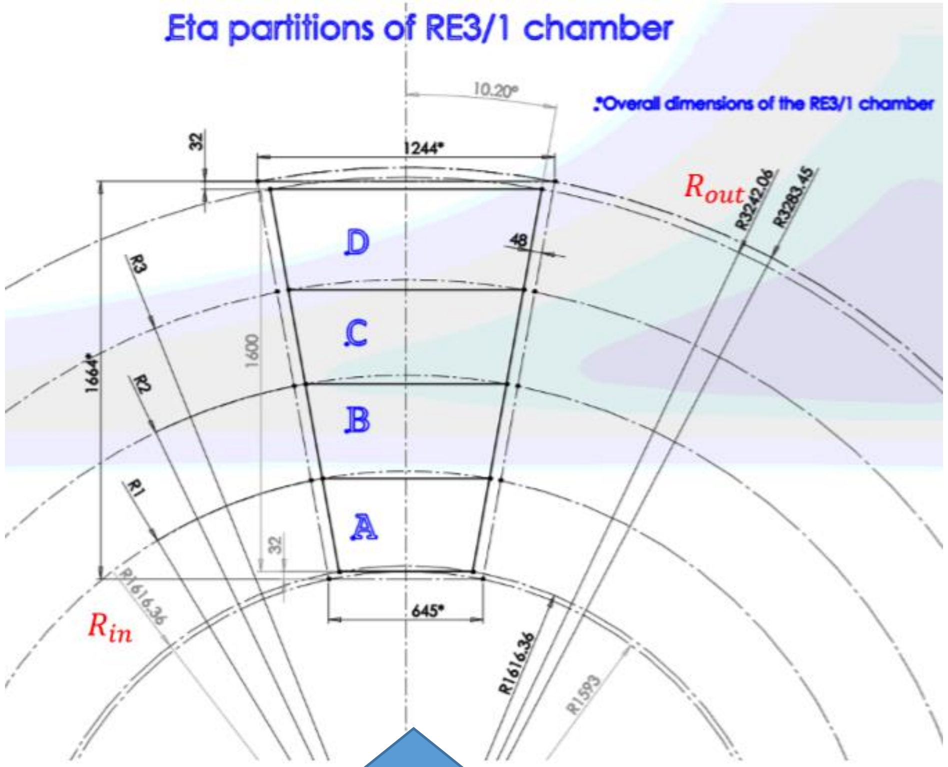
$$\sigma(R) = v\ (18.4\ \mathrm{cm/ns}) \times \sigma_{(tL - tR)} / 2\ (\mathrm{ns}) \sim 2.0\ \mathrm{cm}$$

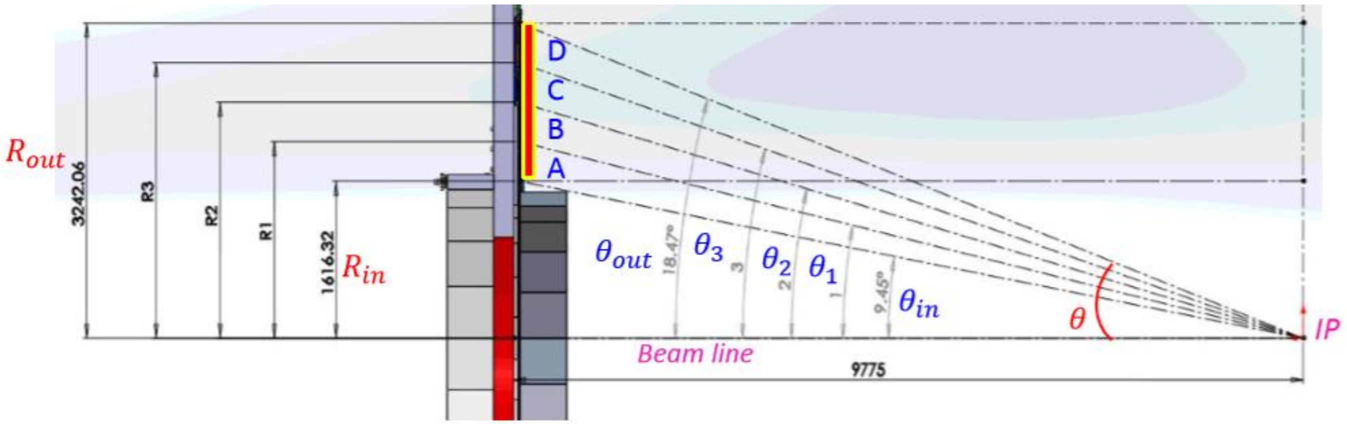
Design #2 for the CMS *i*RPCs in the Phase-2 LHC runs

Reading ***φ* coordinate only (1D) but there are 4 strip sectors in *r***
→ Structure-wise same with the existing CMS RPCs

- 1.4-mm thick double-gap RPCs
  WP efficiency ~ 0.97 @ HV=6.9 kV
  Mean C_s at WP ~ 2.5
- Reading signals from one ends of the strips in each strip sector





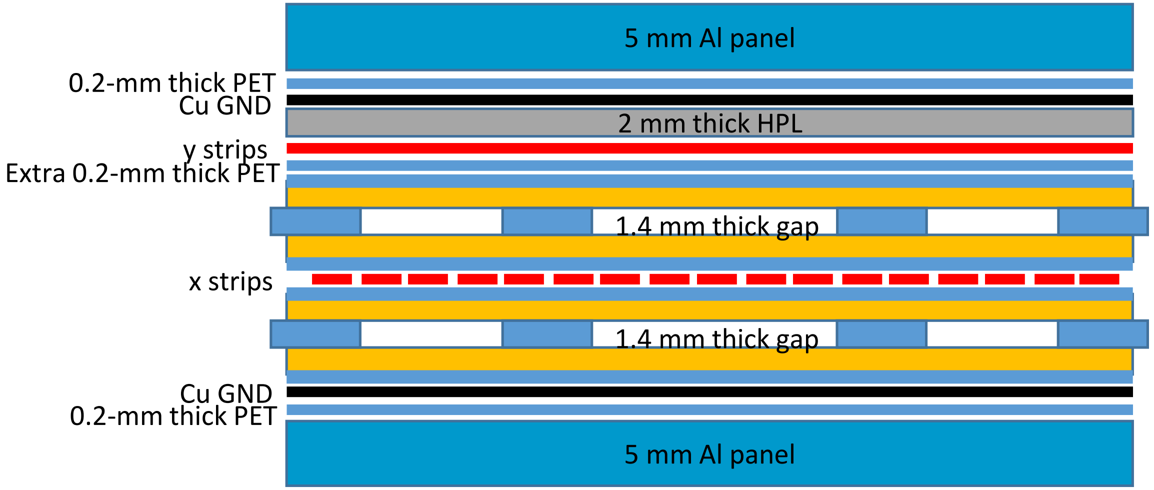


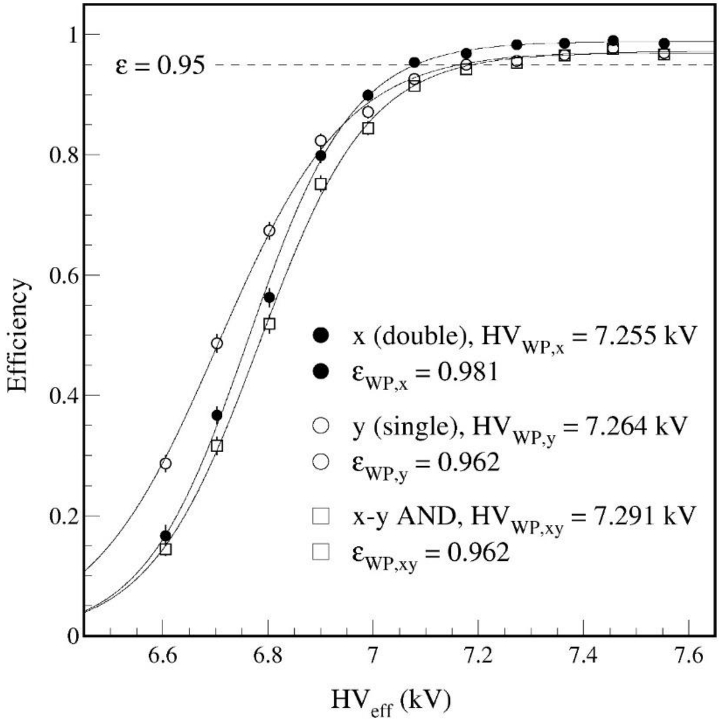
Design #3 for the CMS iRPCs in the Phase-2 LHC runs

ATALS & SHiP–like design but with a double-gap model

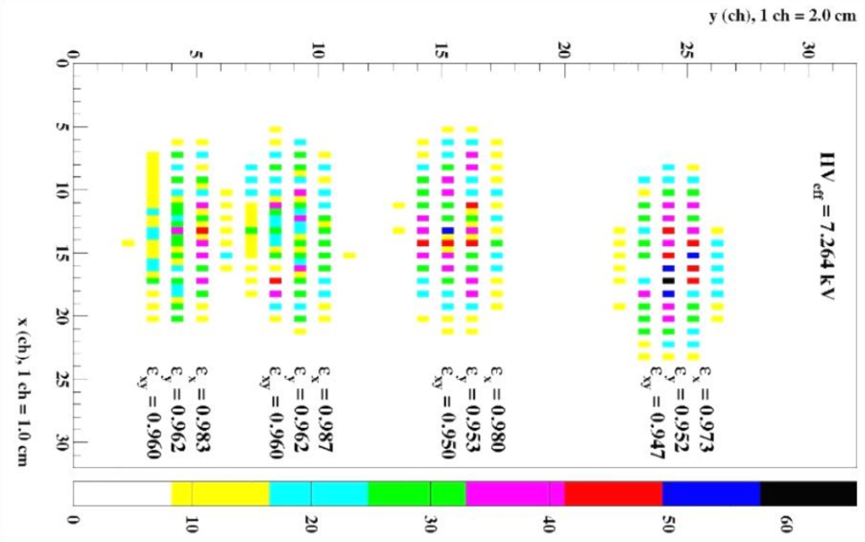
Anode strips for ***x*** and **cathode strips** for ***r*** **(2D)**

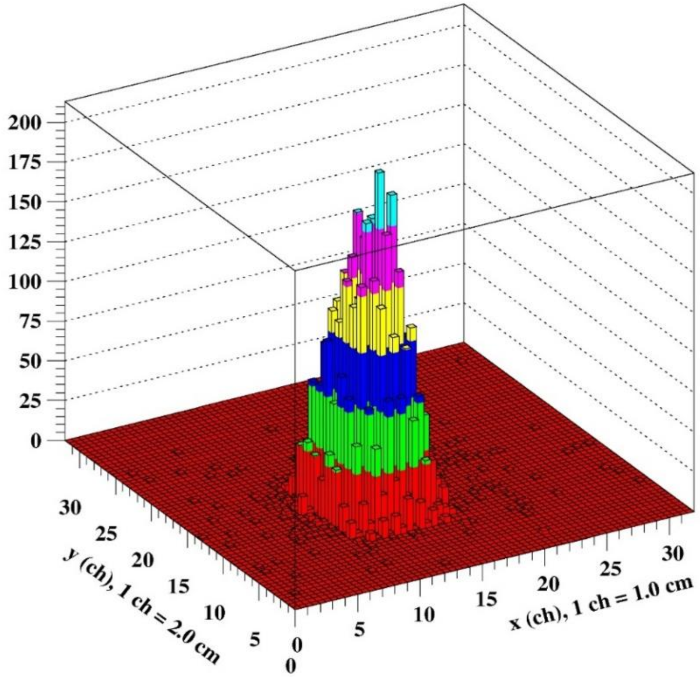
- 1.4-mm thick double-gap RPCs
  WP efficiency requiring both x (φ) and y (r) strip signals > 0.95
- At the WP, mean C_s ~ 2.5 for φ and ~ 1.5 for r
- Position resolutions: 4 mm for φ and ~ 7 mm for r





Cosmic muon test with a small prototype





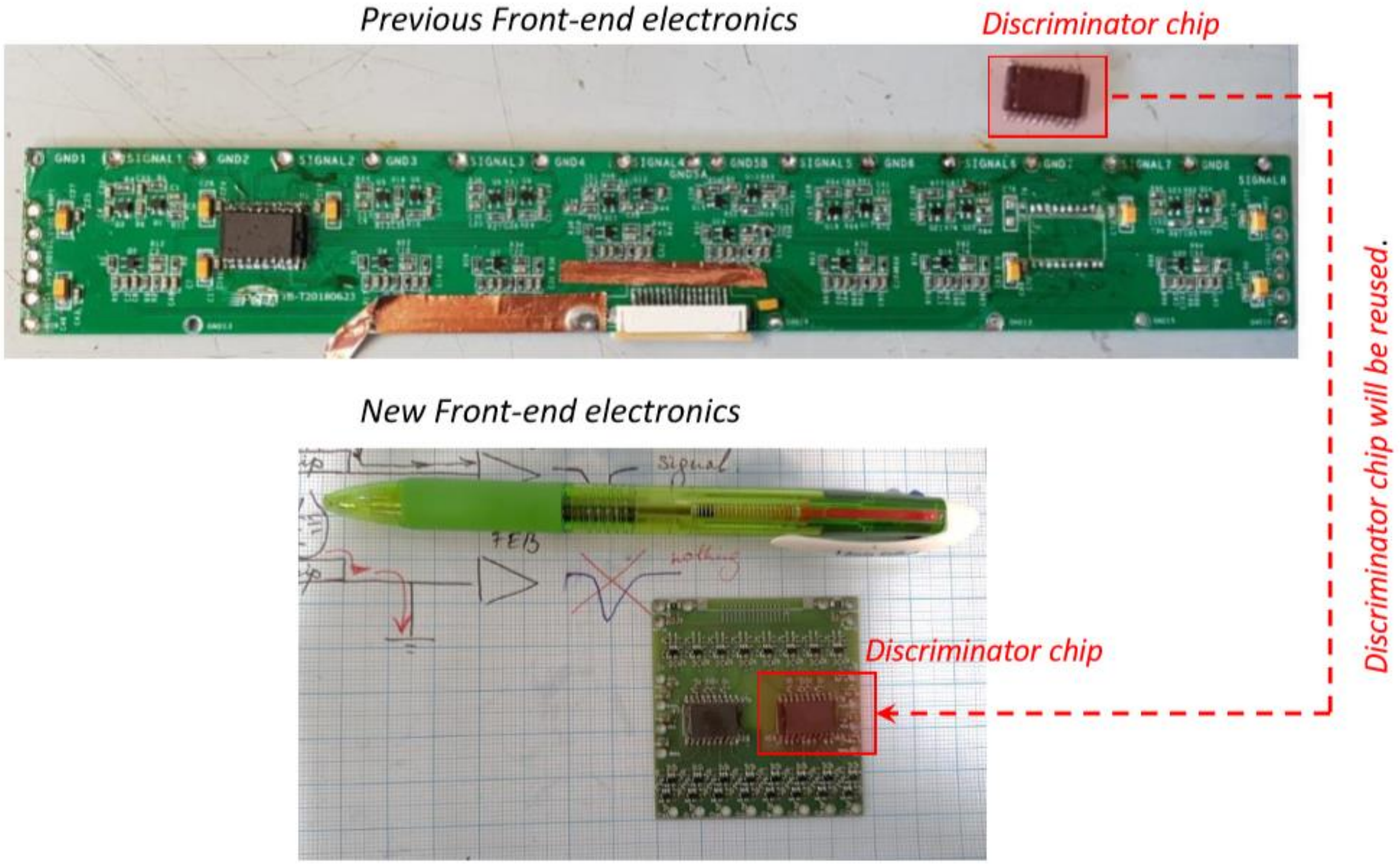
- Proposed to use **sensitive INFN FE electronics**

  Gain 2 mV/fC in a charge sensitive mode

  → lowest digitization threshold ~ 1 fC (~ 0.015 mV)

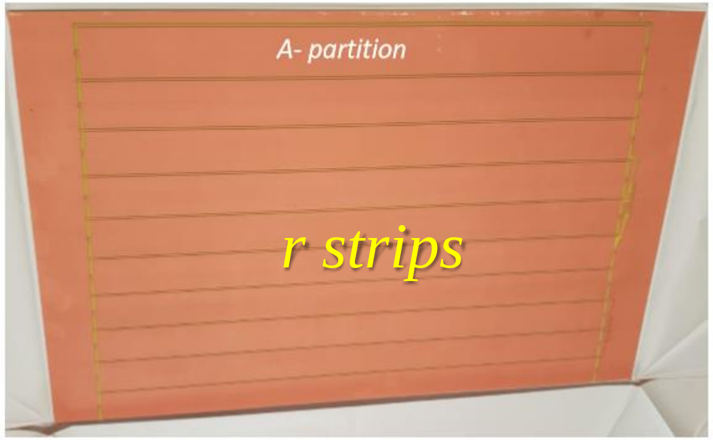
  Optimal threshold for CMS iRPCs = 10 ~ 20 fC

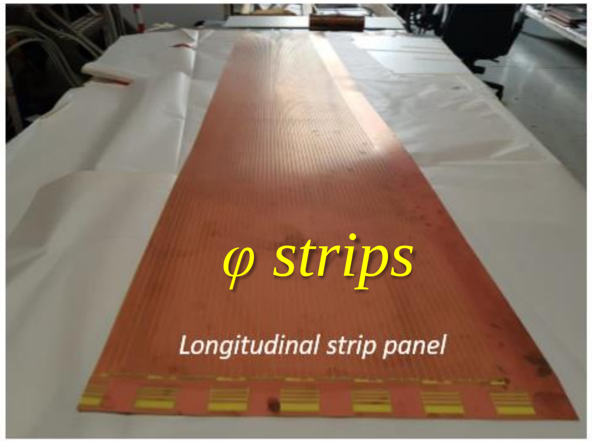
  → Time resolution (jitter) < 200 ps for 100 fC signals



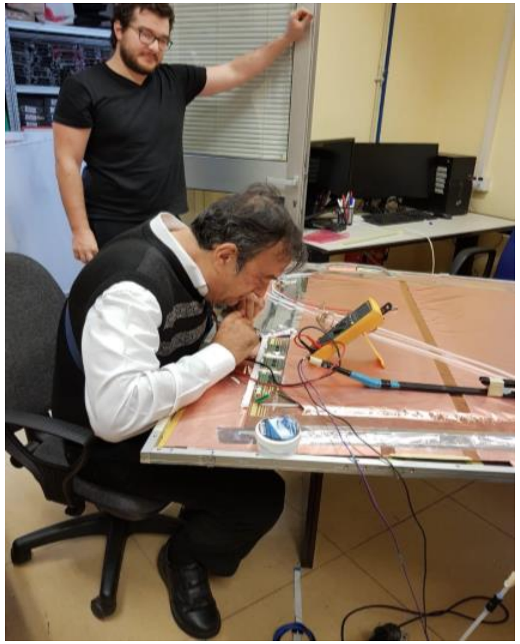
Construction of Real-sized iRPC for a November beam test @H4 beam line at SPS/CERN

Readout strip panels for 2D readout logic





iRPC gas gaps during the services preparation



Conclusions

In high-energy physics, RPCs are essential for particle measurements.

- RPCs are capable of providing data in 4D space-time coordinates.
- RPCs are trigger detectors with a reasonable spatial resolution (a few mm) and with a best time resolution.
- RPCs are relatively less expensive

  → **the best solution for large scale collider experiments, and experiments for hidden sectors and cosmic rays**.
- RPCs are gaseous detectors also sensitive to high-energy gamma rays.
- Keeping the base technology and the facilities is advantageous to Korean high-energy society because of many reasons discussed in this talks.

R&Ds of iRPCs for the Phase-2 CMS/LHC

- A new detector technology has been adopted to achieve the goal of iRPCs

  → a bit **challenging and provocative to the existing society**
- But, the CMS RPCs group has a confidence for the new development.
  - ✓ Have increased the detector sensitivity by a factor 8
  - ✓ Have applied the 2D signal readout to the detectors
  - ✓ A better time resolution by factor 3 (~ 500 ps)
- Construction of RE3/1 and RE4/1 iRPCs from January 2020.