2D single-gap trigger RPCs for high-energy physics experiments

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1. Motivation of R&D
2. Fundamental R&D on 2-mm single-gap RPCs for SHiP
3. 1-mm single-gap RPC: time resolution ~ 500 ps
4. 1.6-mm single-gap RPC: to lower the WP 9.6 kV -> 8.2 kV

Traditional role of trigger RPCs

Provide fast trigger signals with a time resolution of ~ 1 ns and a position resolution of ~ 1 cm

Time resolutions

- ✓ Trigger RPCs (panel shape) ~ 1 ns
- ✓ Timing RPCs (bar shape) ~ 50 ps

Goal of the present R&D

On multi-layer **trigger RPCs whose required position and time resolutions are NOT so high.**

↔ Single-gap trigger RPCs with 2D tracking capability with a sub ns time and a sub-cm position resolutions

→ Muon trigger RPC systems for accelerator-based experiments like CMS and ATLAS

→ Large-scale accelerator-based experiments pursuing New Physics (BSM, Dark matters…) like SHiP and Matshula

→ Neutrino-physics experiments

- ➢ Fundamental detector R&D for 2-mm thick single gap RPCs
- ➢ Time measurements for 1-mm and 1.6-mm thick single-gap RPCs

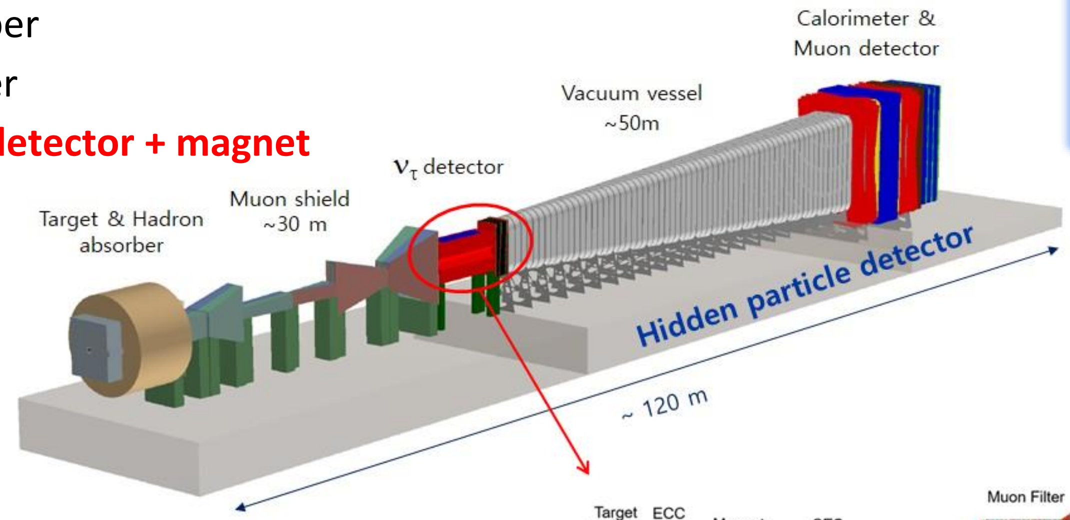
R&D target: SHiP tau neutrino RPCs

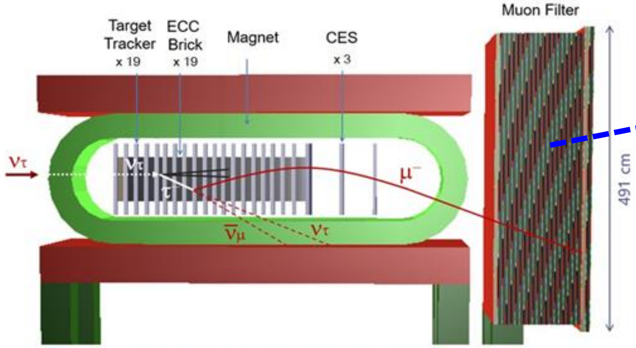
- SHiP detector system
- Target
- Hadron absorber
- Muon Absorber
- **Tau neutrino detector + magnet**

Better triggers for tau associated muons

Better VETO for neutrino associated muons impinging the decay vessel

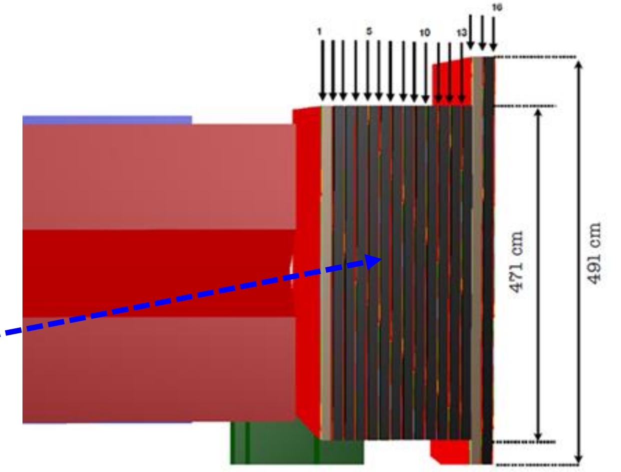
In RPC2020, "RPCs and readout system for the neutrino detector of the SHiP experiment" by Liliana Congedo
RPCs dedicated to Scattering Neutrino Detector (SND)





Neutrino & LDM detector

MUON FILTER



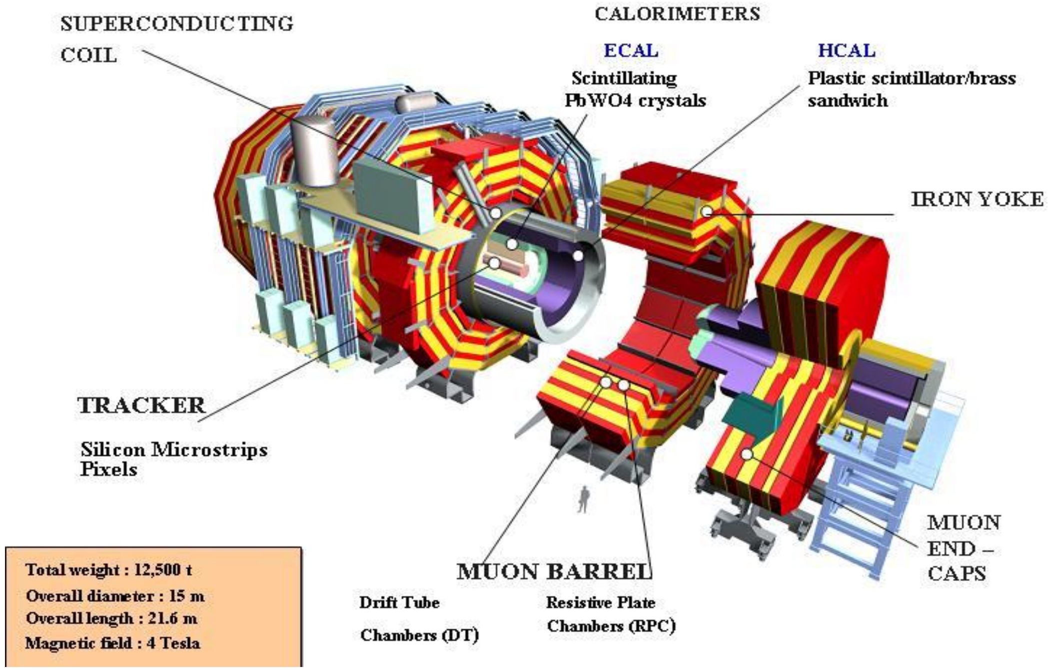
STRUCTURE
16 Rpc (3 cm) / 15 Fe layers (10 cm)
Frontal size:
(upstream: 13 RPC) 200 x 471 cm²
(downstream: 2 RPC) 210 x 491 cm²

- Decay vacuum vessel
- Muon veto detectors
- Downstream detectors
  - ✓ ECAL
  - ✓ HCAL
  - ✓ TOF RPC

Collaboration of ~ 250 members from 52 institutes, 17 countries

Technical Proposal: *arXiv:1504.04956* (2015)

Adding new RPCs (iRPCs) to the Compact Muon Solenoid

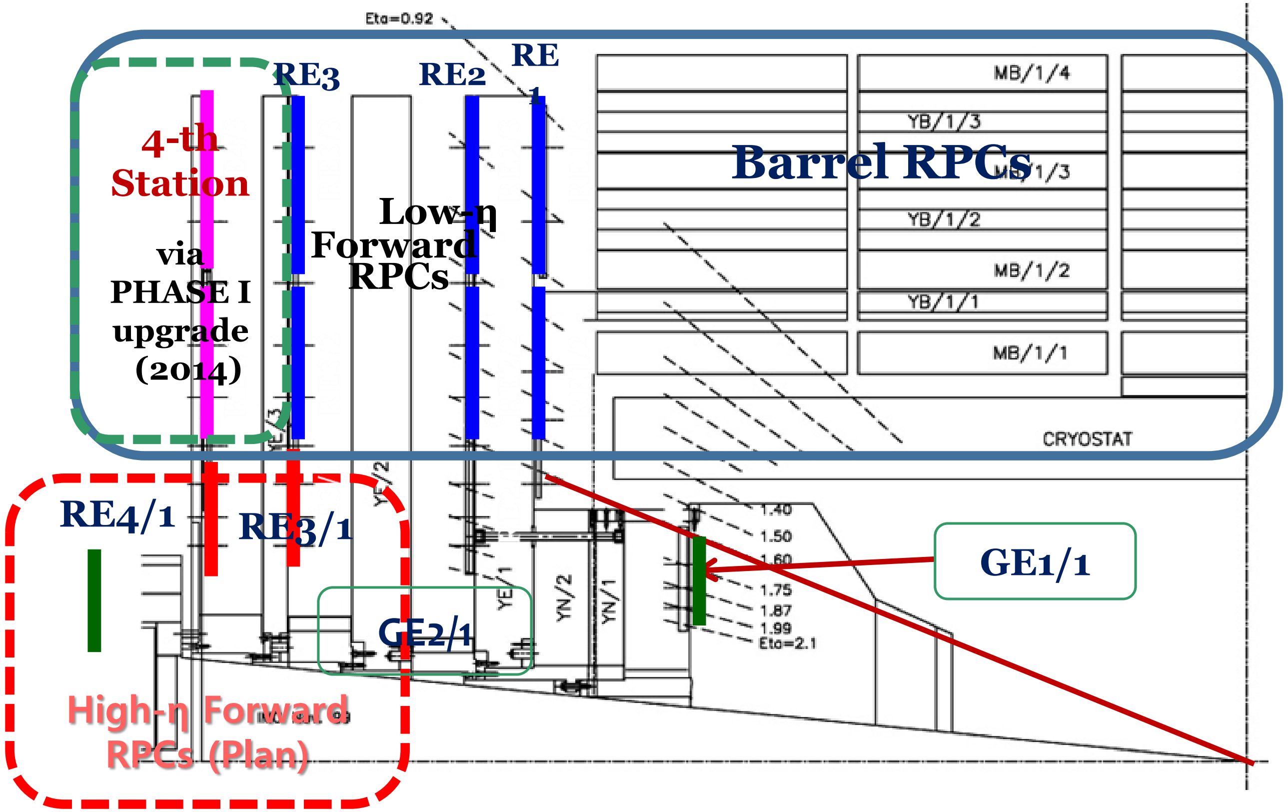


Barrel RPCs

- 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 (RE1, RE2, RE3, RE4) in each wing
- Covering 0.92 < η <2.1



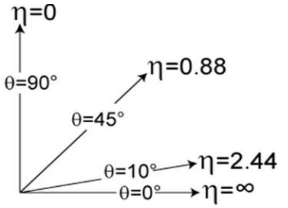
Backup solution for CMS iRPCs

Here, 2D double-gap RPCs

"Towards a two-dimensional readout of the improved CMS Resistive Plate Chamber with a new Front End electronics" **by Sabino Meola**

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

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

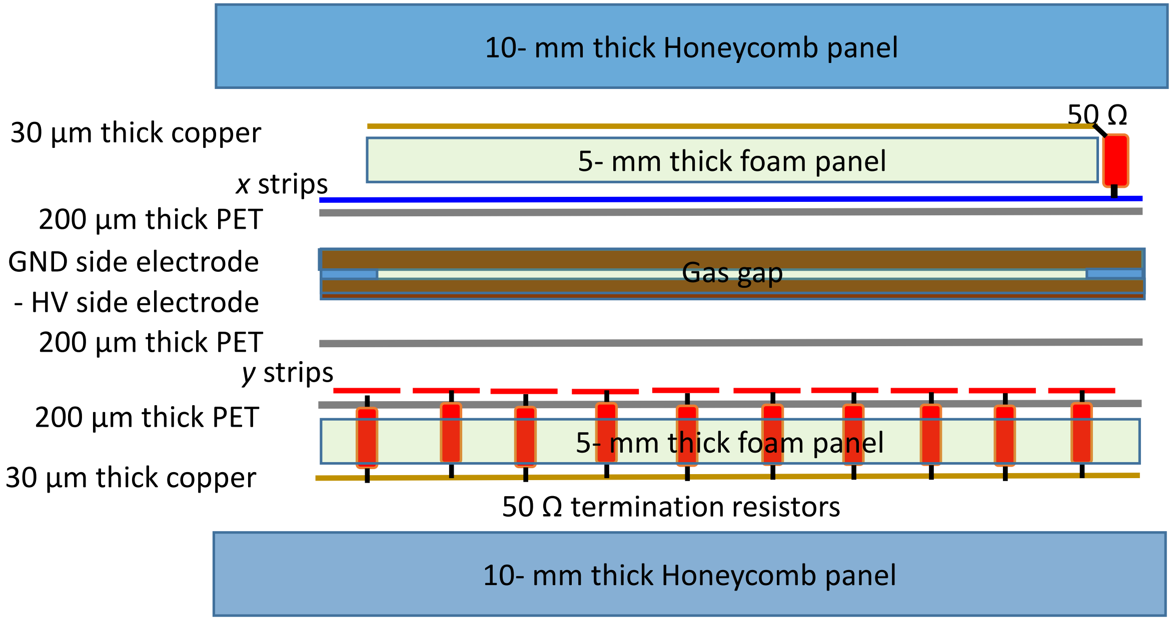


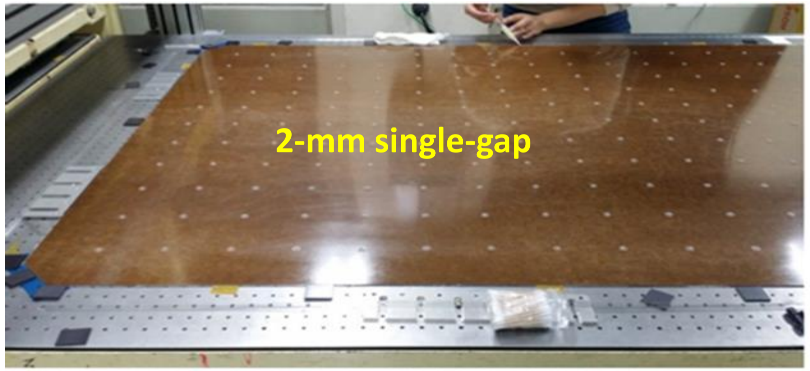
In 2018, 1st prototype: 2-mm single-gap 2D RPCs

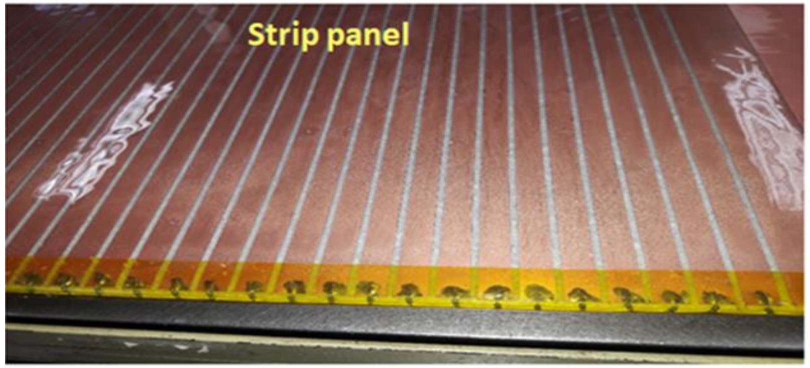
Baseline structure for SHiP RPCs

One of the backup designs for CMS iRPCs

- ✓ **Cathode + anode strips (orthogonal)**
  - Cathode signals: positive polarity
  - Anode signals: negative polarity
- ✓ **Avalanche mode**
- ✓ **2 orthogonal strip readouts for 2D trigger measurements**
  - Strip pitch = 10.625 mm for both coordinates







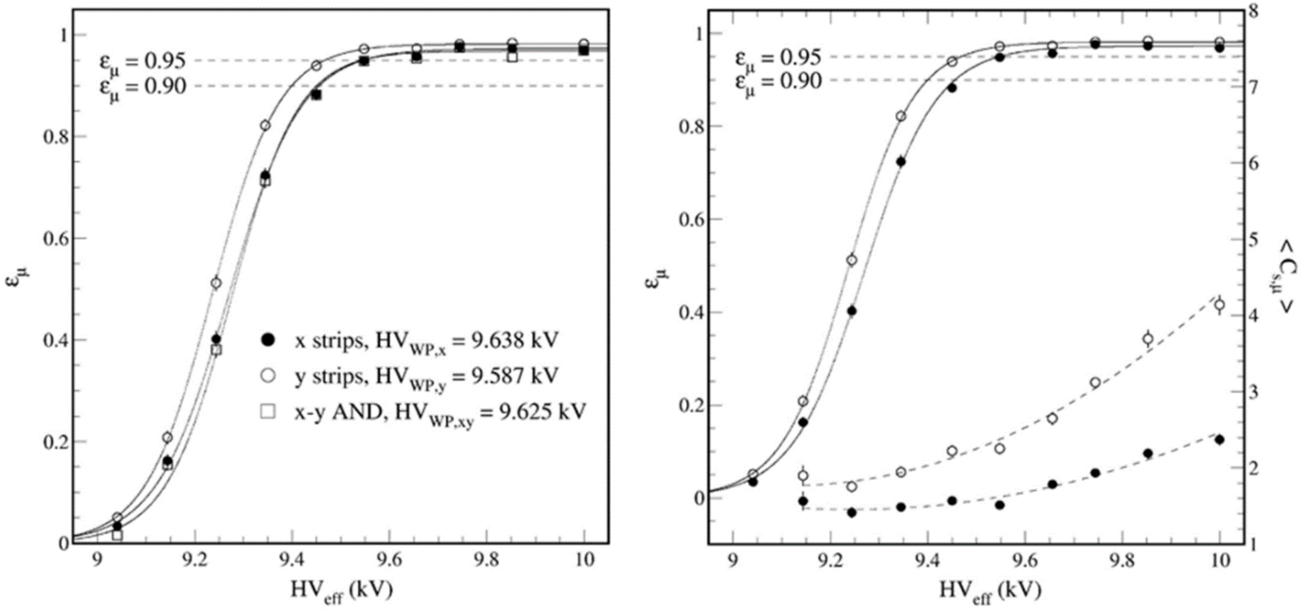
Cosmic-muon tests for the first small prototype

- Working point HV = 9.63 kV / 9.82 kV with low/high threshold setups, respectively.
- **Working point efficiency requiring both *x* and *y* signals > 95 %.**
- Mean cluster sizes at the WP: 1.8 for anode (*x*) and 2.5 for cathode (*y*) strips
- Probability of large pulses (defined by cluster size > 6) at the WP ~ 1%
- **Noise rate at the WP in coincidence of *x* and *y*: < 1 k Hz m^{-2}**

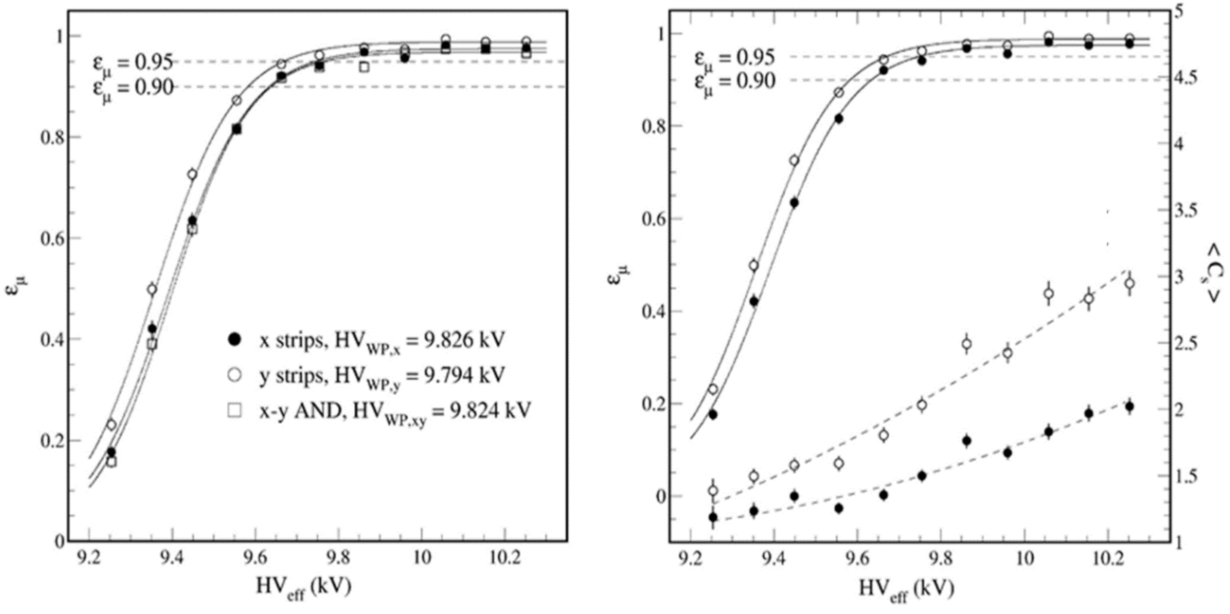
Used current sensitive mode FEBs

Test gas = 95.2% TFE + 4.5% iC_4H_{10} + 0.3% SF_6

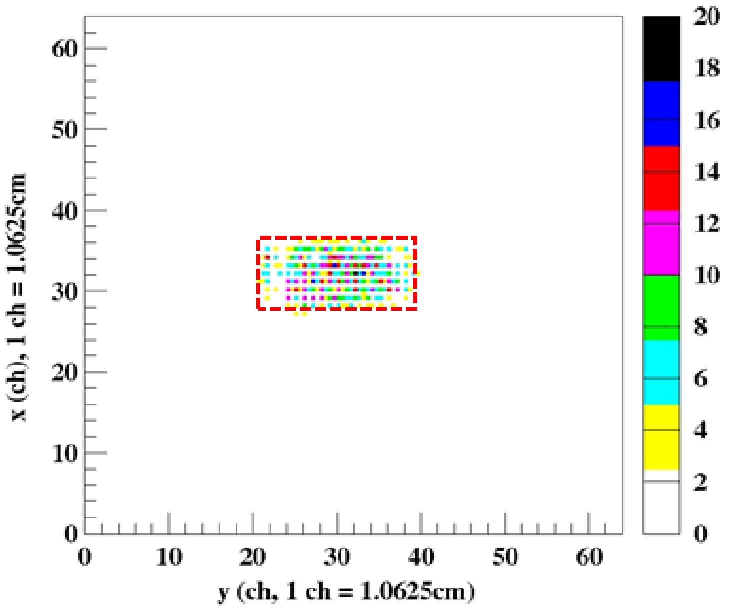
Th = 0.33 mV (~ 50 fC) for *x* (anode strip, negative)
Th = 0.40 mV (~ 60 fC)for *y* (cathode strips, positive)

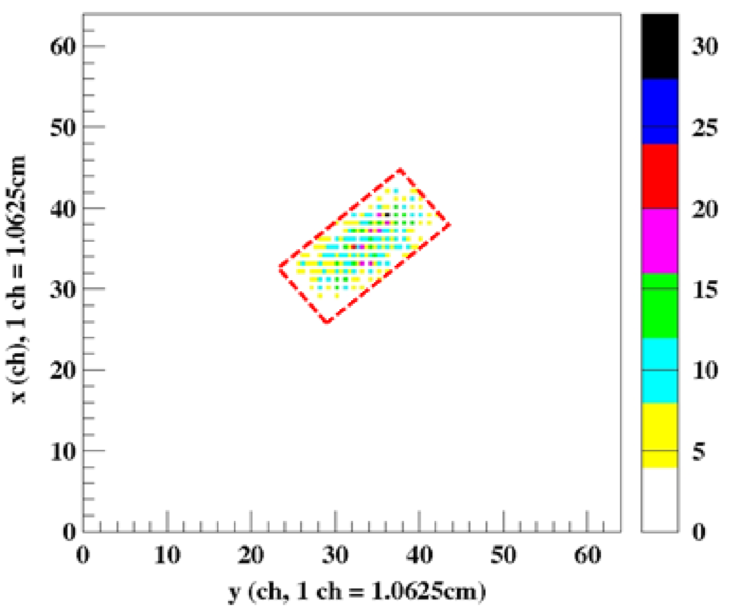


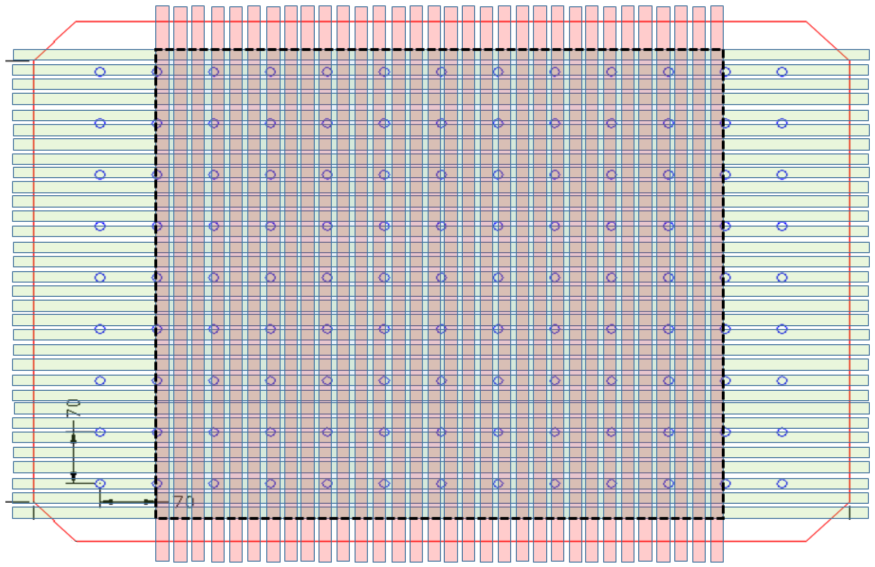
Th = 0.80 mV (~ 120 fC) for *x* (anode strip, negative)
Th = 1.00 mV (~ 150 fC) for *y* (cathode strips, positive)

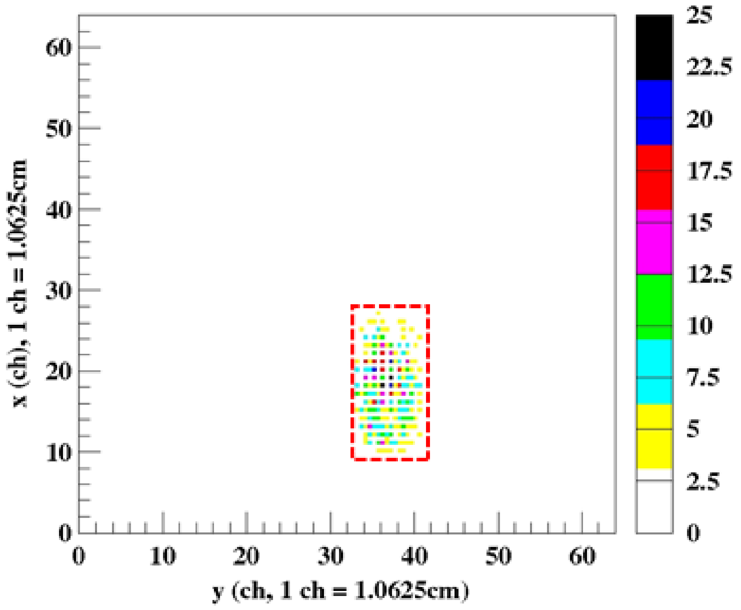


Reconstructed 2D images of cosmic muons
(tagged by plastic scintillators)







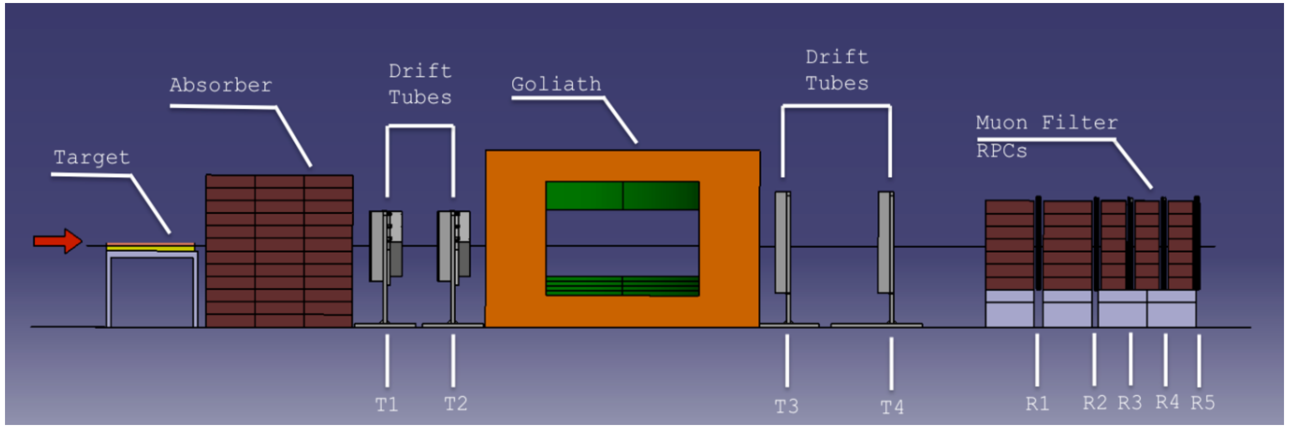


In July 2018, KODEL provided RPC electrodes and strips for beam tests with CERN SPS 400 GeV/c proton beam at H4 area

KODEL provided RPC gaps and strips.

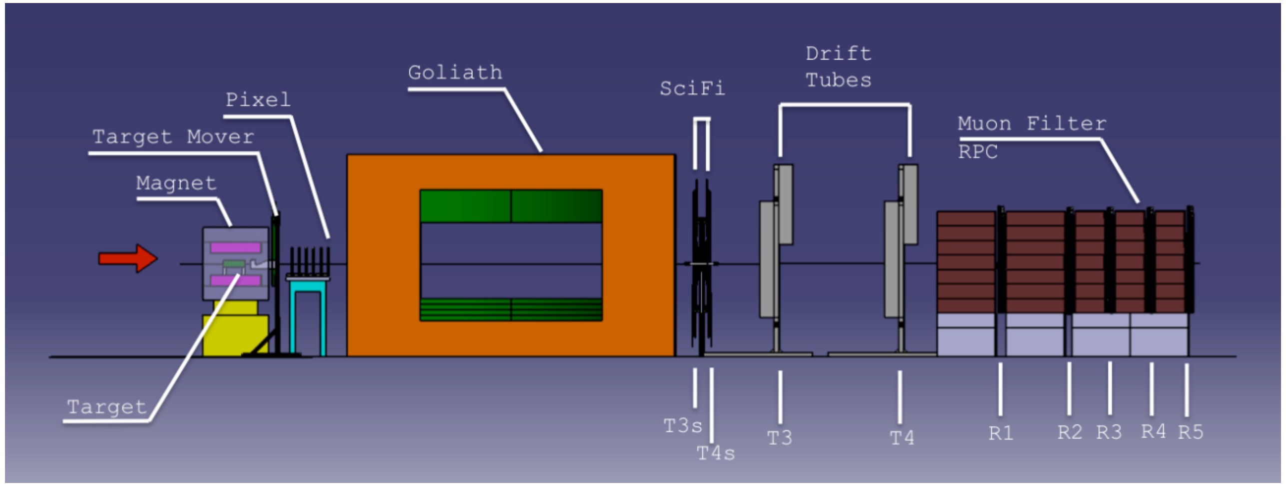
Measurement of muon flux

- ✓ **SHIP target replica:** TZM 58 cm-thick + Tungsten 58 cm-thick
- ✓ **Spectrometer (Goliath+DTs)** to measure momentum and charge of the muons
- ✓ **Muon tagger (RPCs)** to identify muons



Inclusive charm cross section measurements

- ✓ **ECC (Emulsion Cloud Chamber) target**: 12.5×10 cm^2 lead plates interleaved with emulsion films to detect both production and decay of the charmed hadrons
- ✓ **Spectrometer (Goliath+DTs)** to measure momentum & charge of charm daughters
- ✓ **Muon tagger (RPCs)** to identify muons

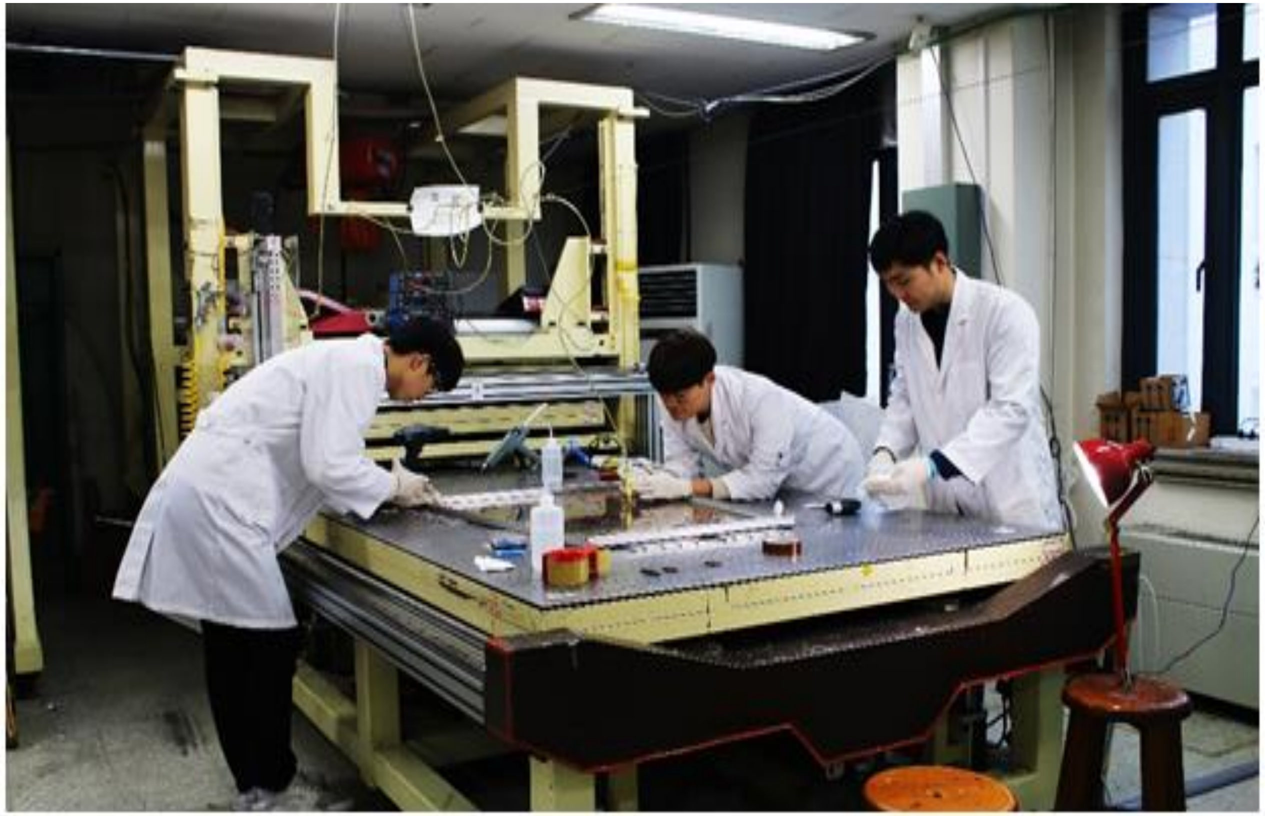


In 2019, R&D with a 1-mm single-gap 2D RPC

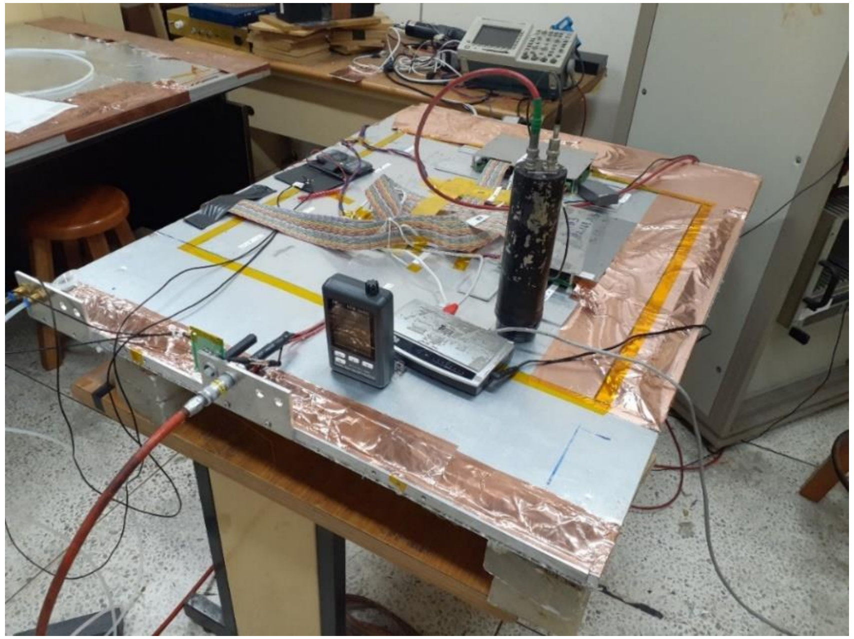
Same structure but with a narrower gap thickness

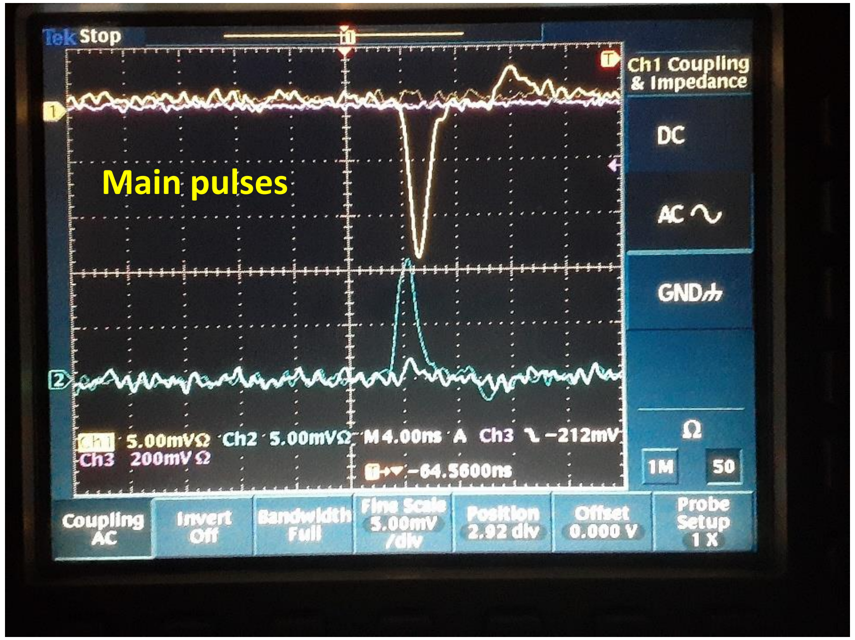
- ✓ Aiming for faster time response < 10 ns and a time resolution ~ 500 ps for the trigger system
- ✓ 2 orthogonal strip readouts for 2D trigger measurements + a time resolution mush better than 1 ns

Thickness of Bakelite = 1.4 mm
Thickness of gap = 1.0 mm
Strip pitch for both x and y = 20 mm

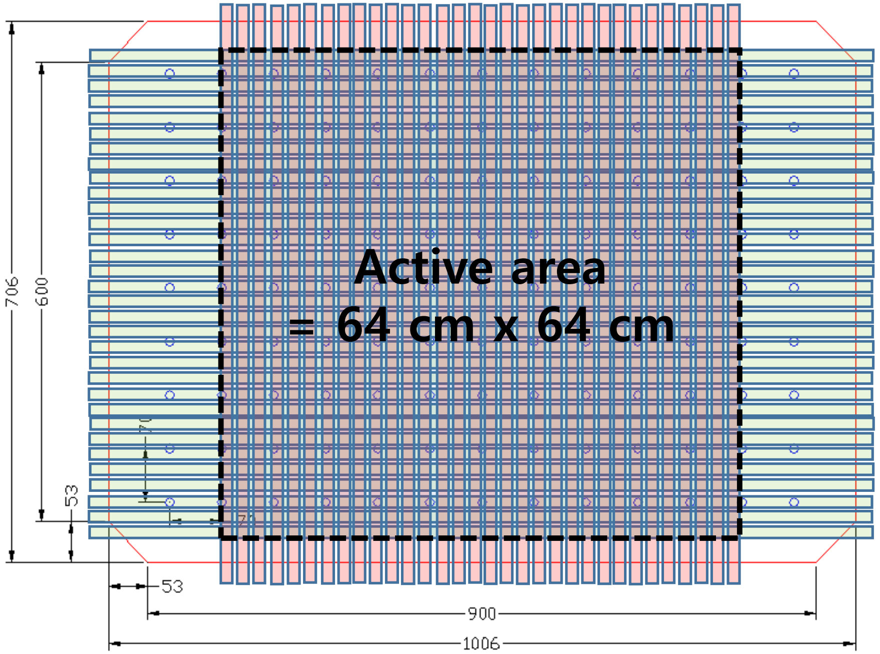


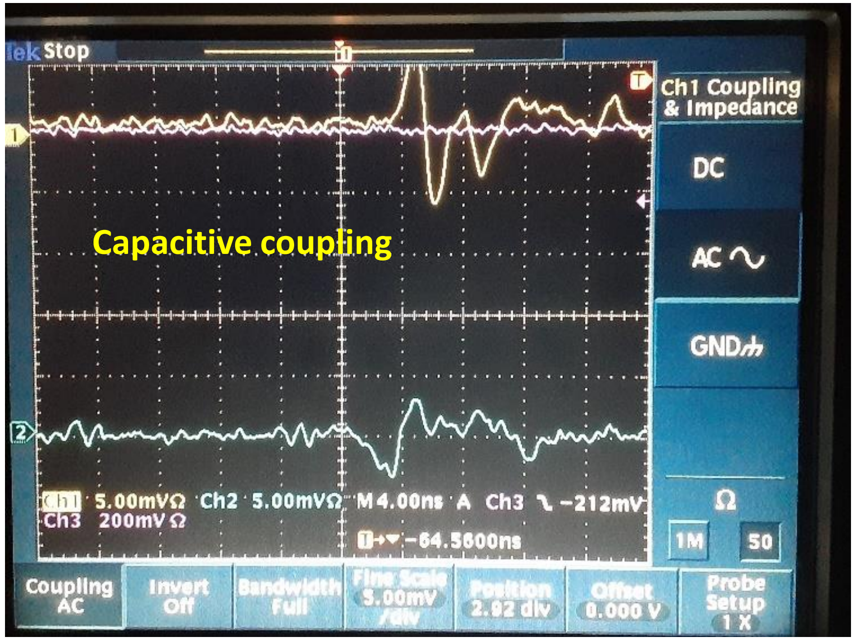
A small prototype using a 100 cm x 70 cm 1-mm single gap





64 cm x 64 cm active area using two orthogonal strips





Tests with cosmic muons

- ✓ **Gas: 95.2% TFE + 4.5% i-C_4H_{10} + 0.3% SF_6**
- ✓ Used 1.0m-mm thick 1.2-cm diameter spacers
  - -> Efficiency loss due to spacers ~ 3%
  - -> Maximum efficiency is at best ~ 0.96
  - -> Typical WP efficiency = 0.942 @ HV_{eff} = 5.85 kV
  - -> Strip pitch for both *x* and *y* = 20 mm
  - -> Position resolution ~ 7 mm in both directions

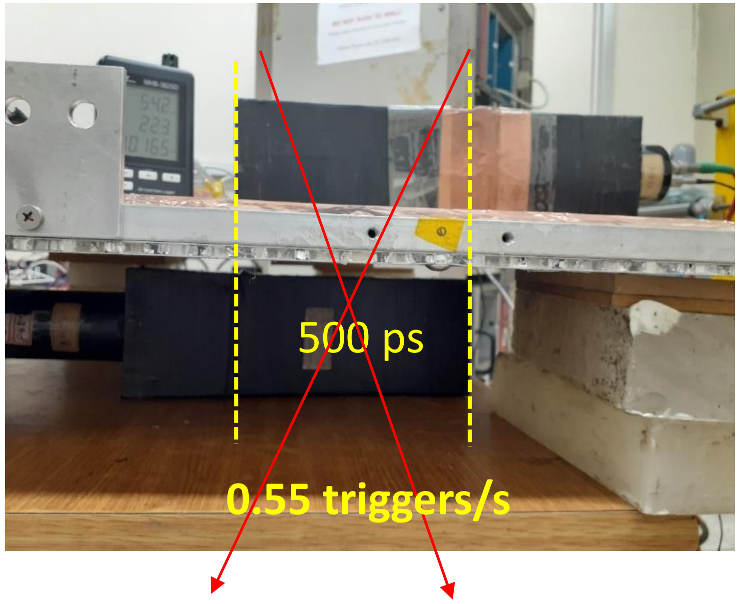
Estimated time resolution for KODEL FEBs ~ 390 ps

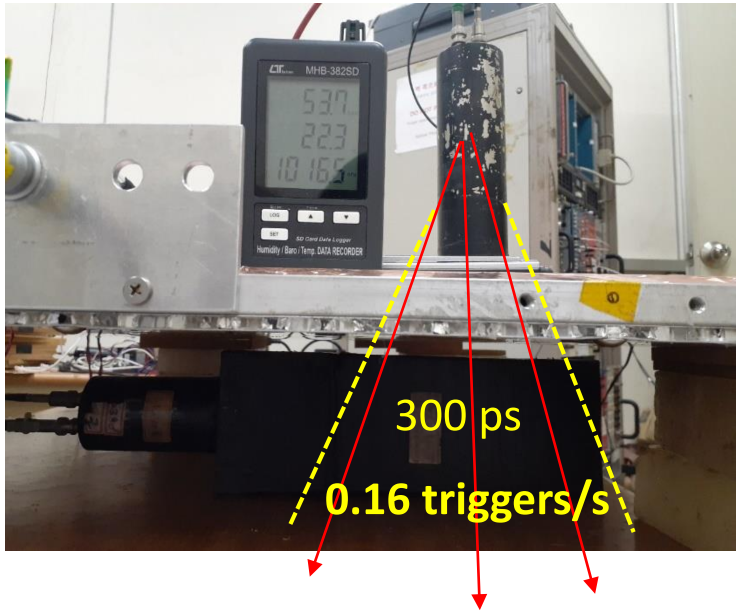
Time resolution for triggers

Using two block scintillators ~ 500 ps

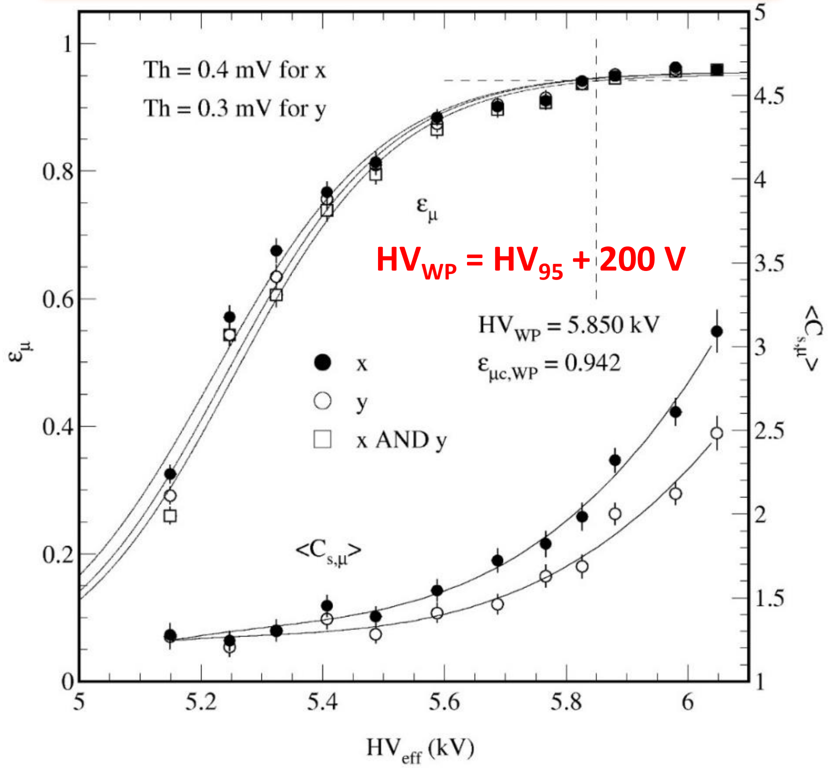
Using a block + a disc scintillators = 300 ps

- ✓ Threshold for *x* = 0.4/1.0 mV (~ 60 fC/150 fC)
- ✓ Threshold for *y* = 0.3/0.8 mV (~ 45 fC/120 fC)

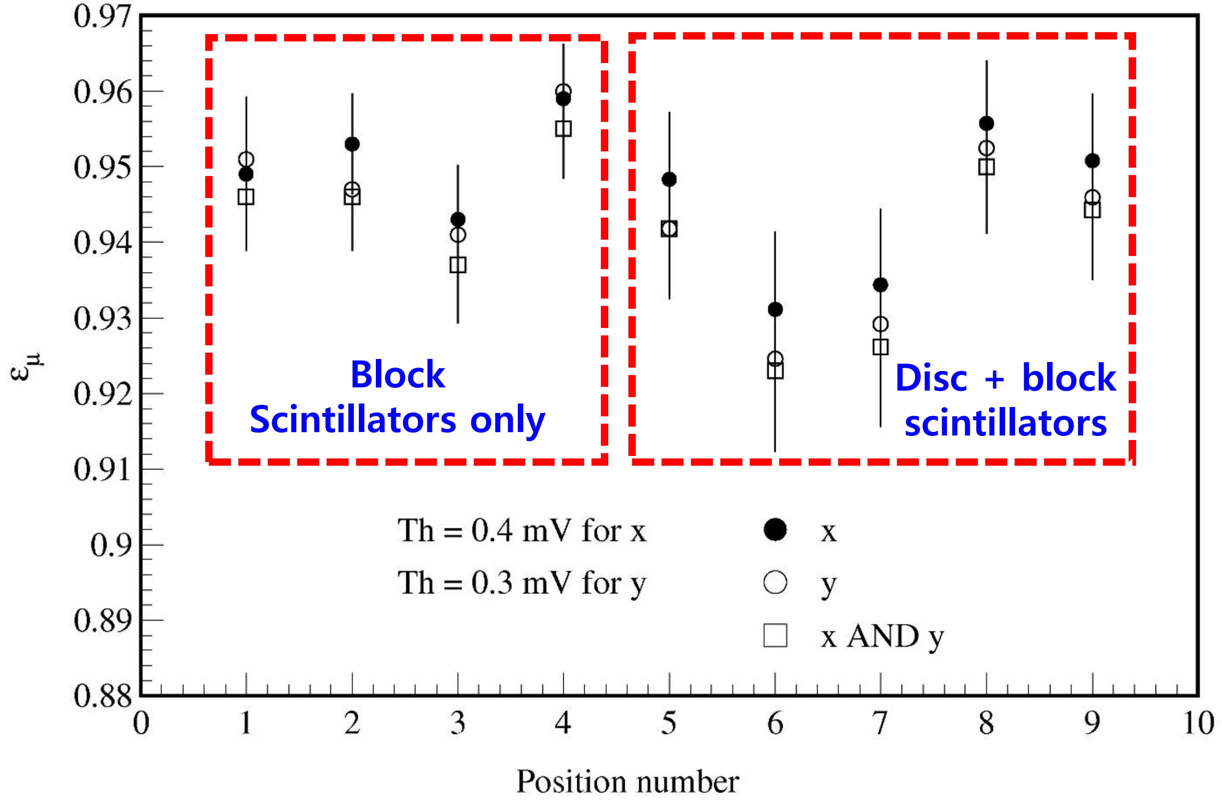


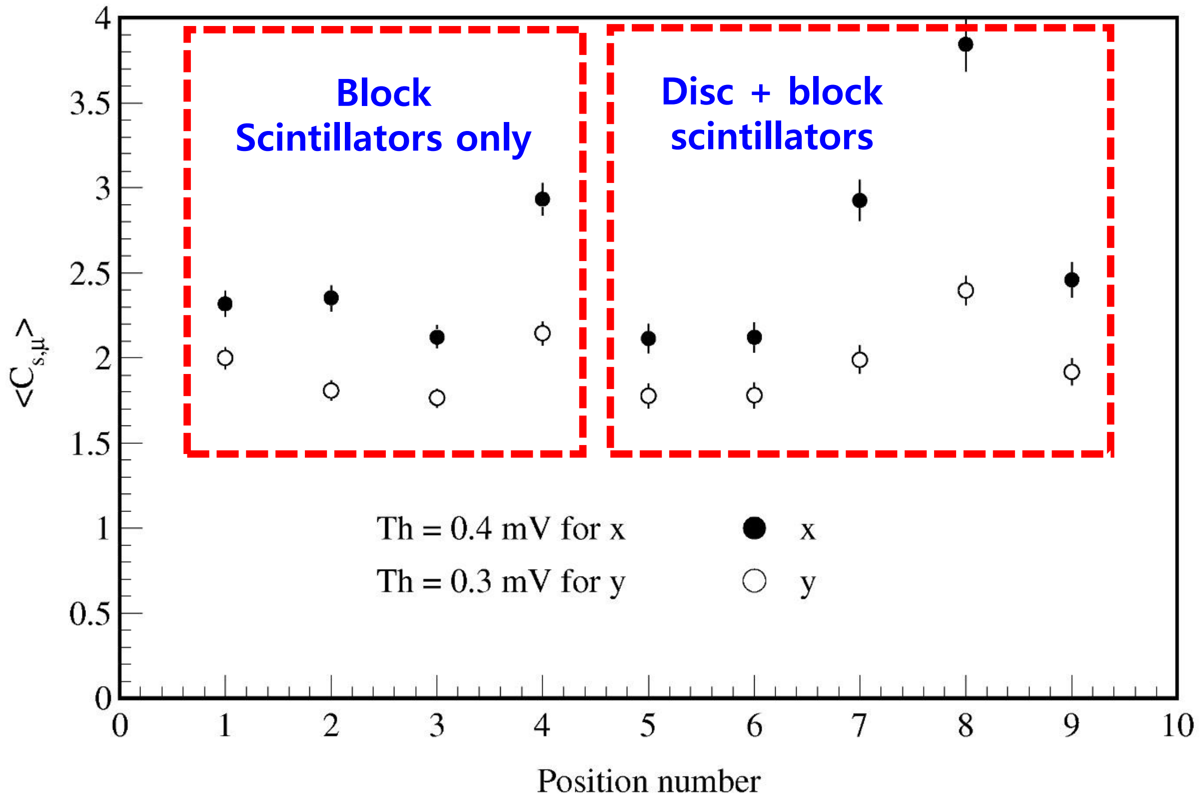


Test gas = 95.2% TFE + 4.5% iC_4H_{10} + 0.3% SF_6



Th = 0.4 mV (~ 60 fC) for x strips
= 0.3 mV (~ 45 fC) for y strips





Time measurement and corrections for *x*-strip signals using *y*-strip positions

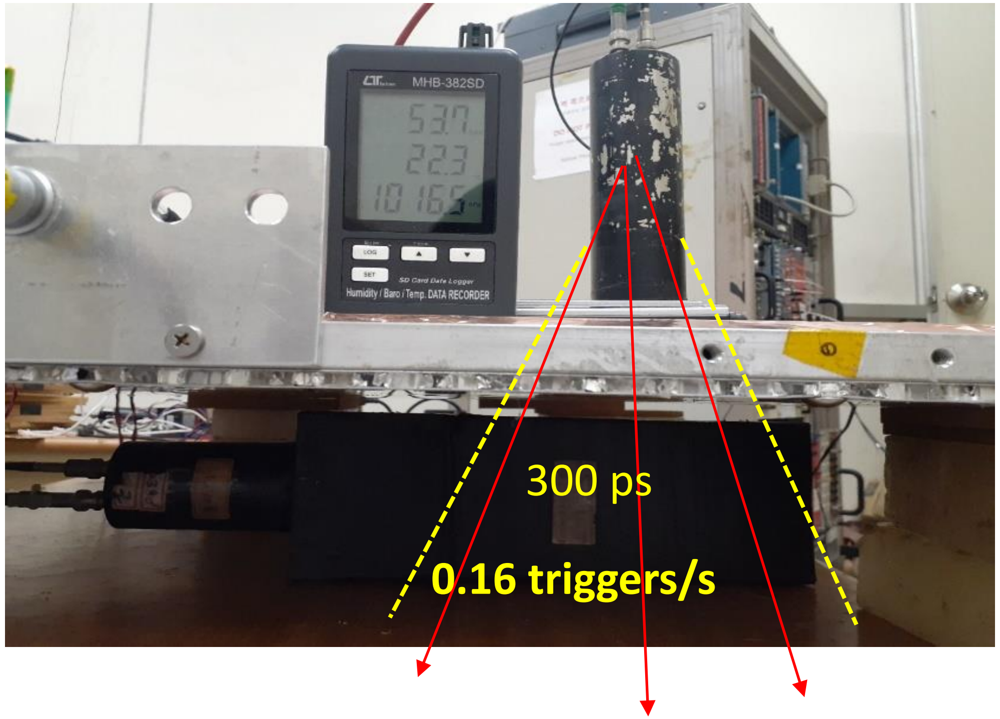
Signal arrival times vary position by the position on the strips
Can apply time corrections for *x* strip signals using *y* strip positions using a speed of **signal transfers of ~ 19.2 cm/ns** (valid when impedance ~ a few 10s Ω)

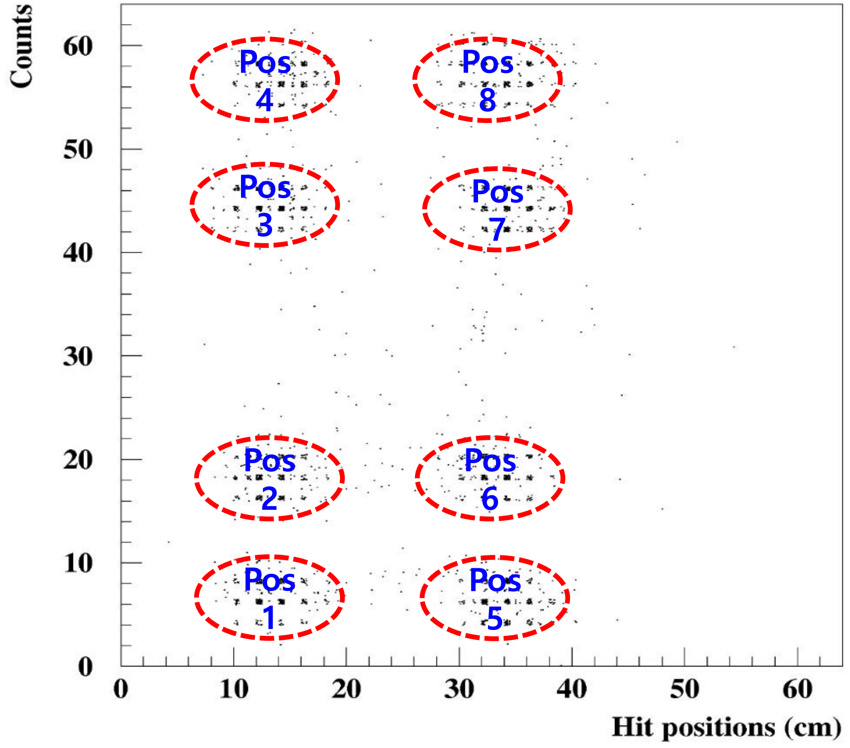
Position corrected anode time → $t_x^c = t_x + 52.08\ \mathrm{ps\ cm^{-1}} \times y$

→ Hit-position corrected time distribution of the anode (*x*) strip times using vertical y-strip positions

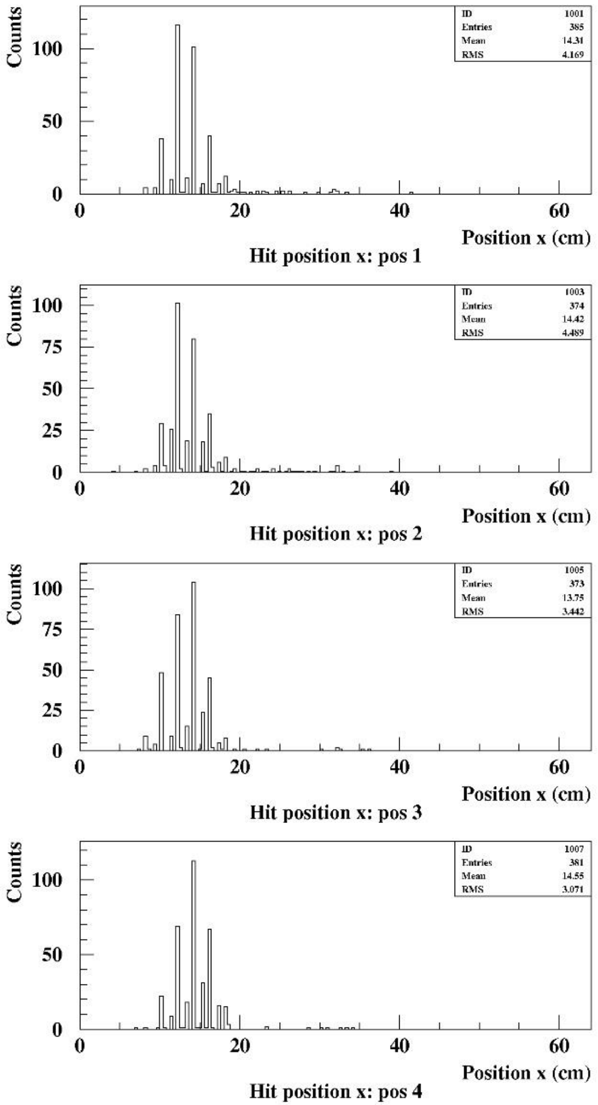
$\sigma_{trigger}$ ~ 300 ps
σ_{FEB} ~ 390 ps

Th = 0.4 mV (~ 60 fC) for x strips
= 0.3 mV (~ 45 fC) for y strips

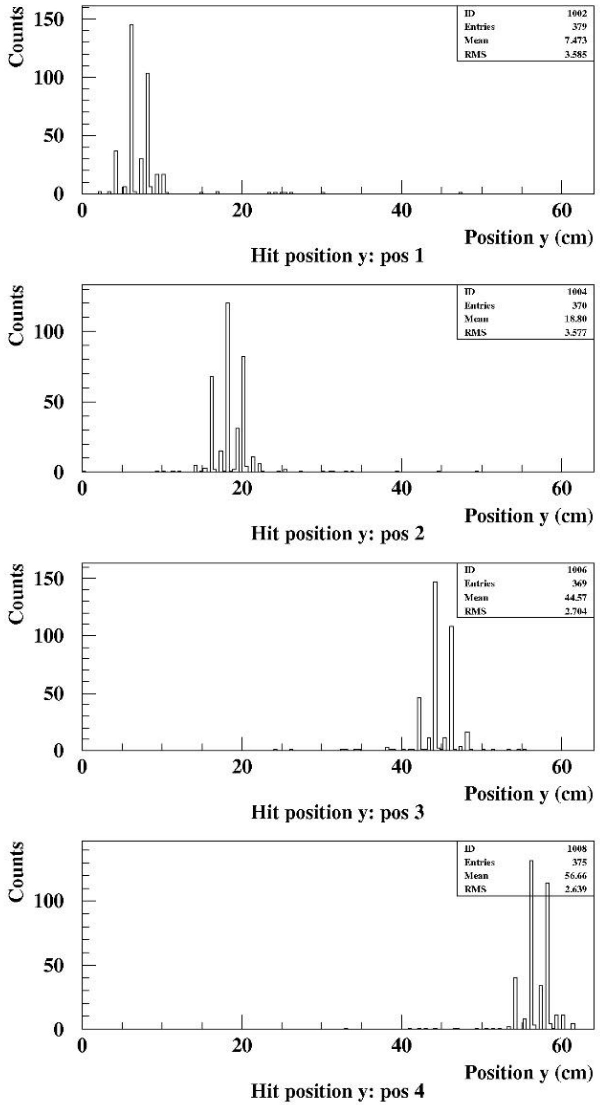




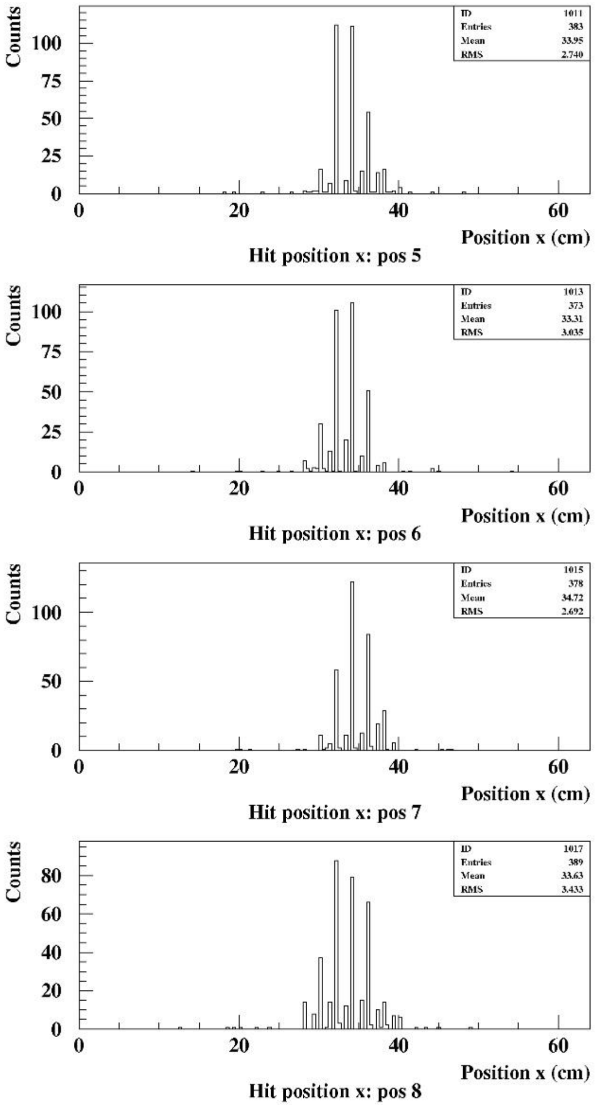
Hit positions on x strips



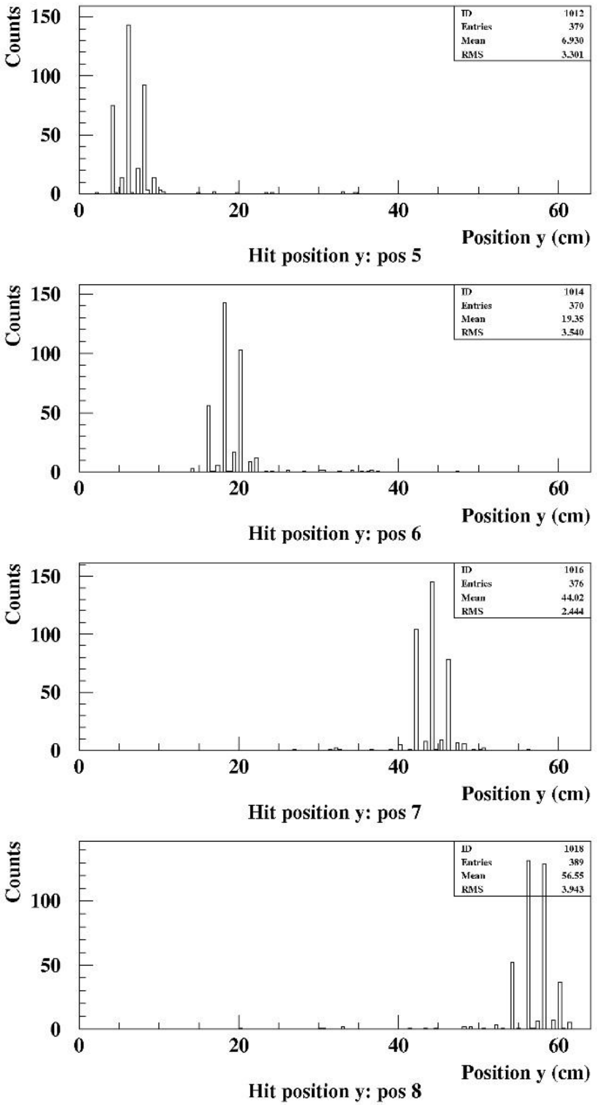
Hit positions on y strips



Hit positions on x strips



Hit positions on y strips

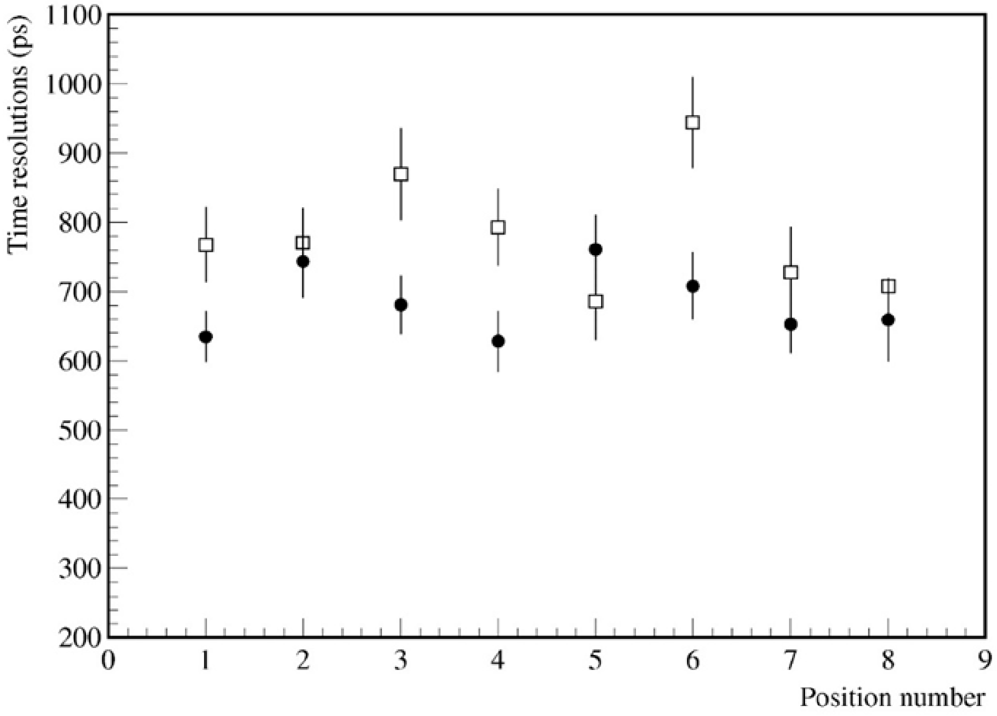


Intrinsic time resolution of 1-mm single-gap RPCs

σ_{FEB} ~ 390 ps $\sigma_{trigger}$ ~ 300 ps

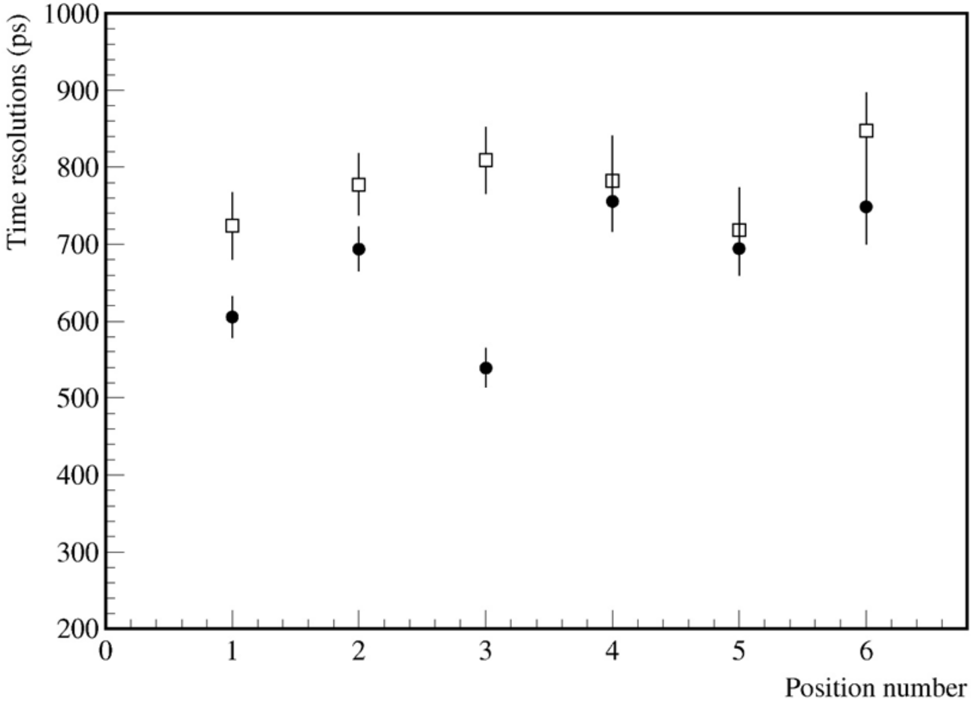
Th = 0.4 mV (~ 60 fC) for *x* strips
= 0.3 mV (~ 45 fC) for *y* strips

$\sigma_{x,\,int} = \text{sqrt}\,(684.4^2 - 390^2 - 300^2) = 475.7$ ps
$\sigma_{y,\,int} = \text{sqrt}\,(787.5^2 - 390^2 - 300^2) = 614.9$ ps



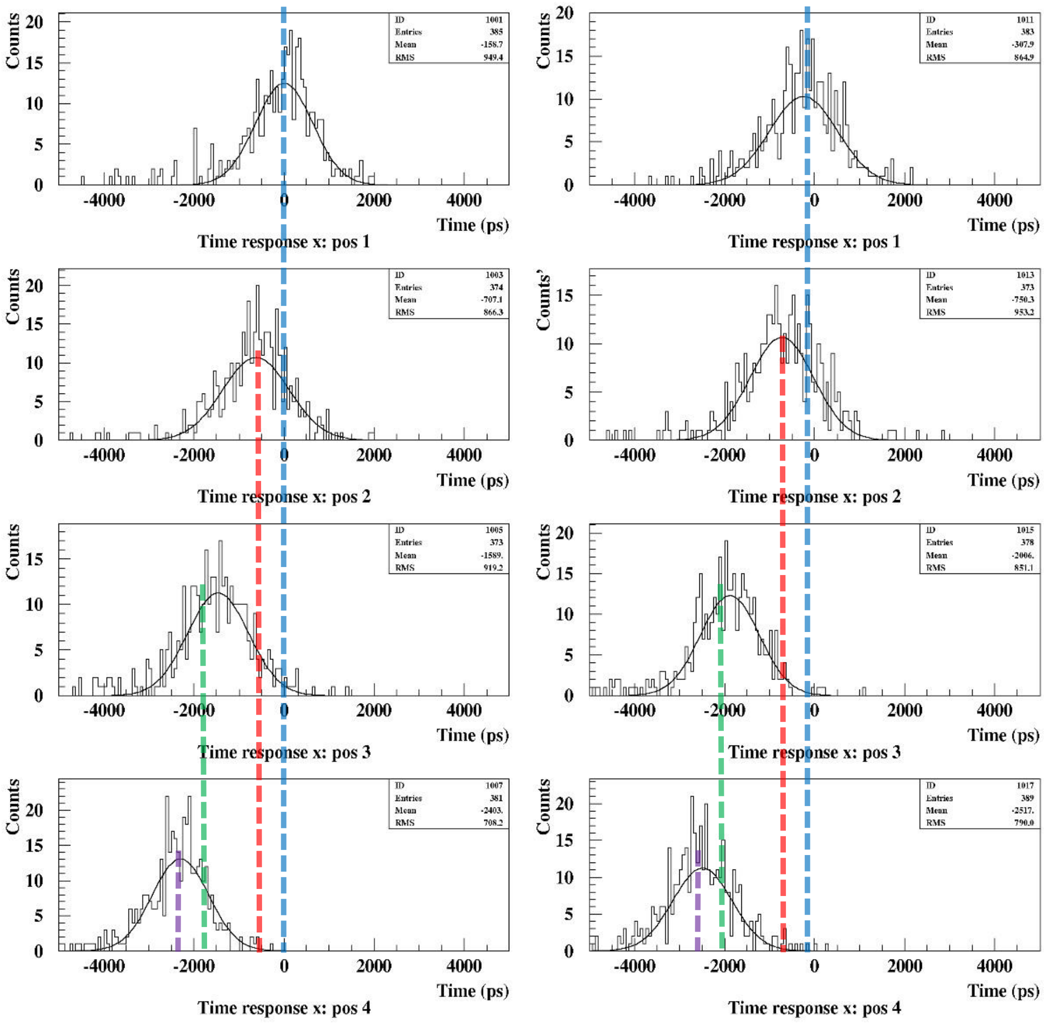
Th = 1.0 mV (~ 150 fC) for *x* strips
= 0.8 mV (~ 120 fC) for *y* strips

$\sigma_{x,\,int} = \text{sqrt}\,(672.7^2 - 390^2 - 300^2) = 458.7$ ps
$\sigma_{y,\,int} = \text{sqrt}\,(777.5^2 - 390^2 - 300^2) = 602.0$ ps



Corrections for signal arrival times for *x* strips

$$t_x^c = t_x + 52.08 \text{ ps cm}^{-1} \times y$$

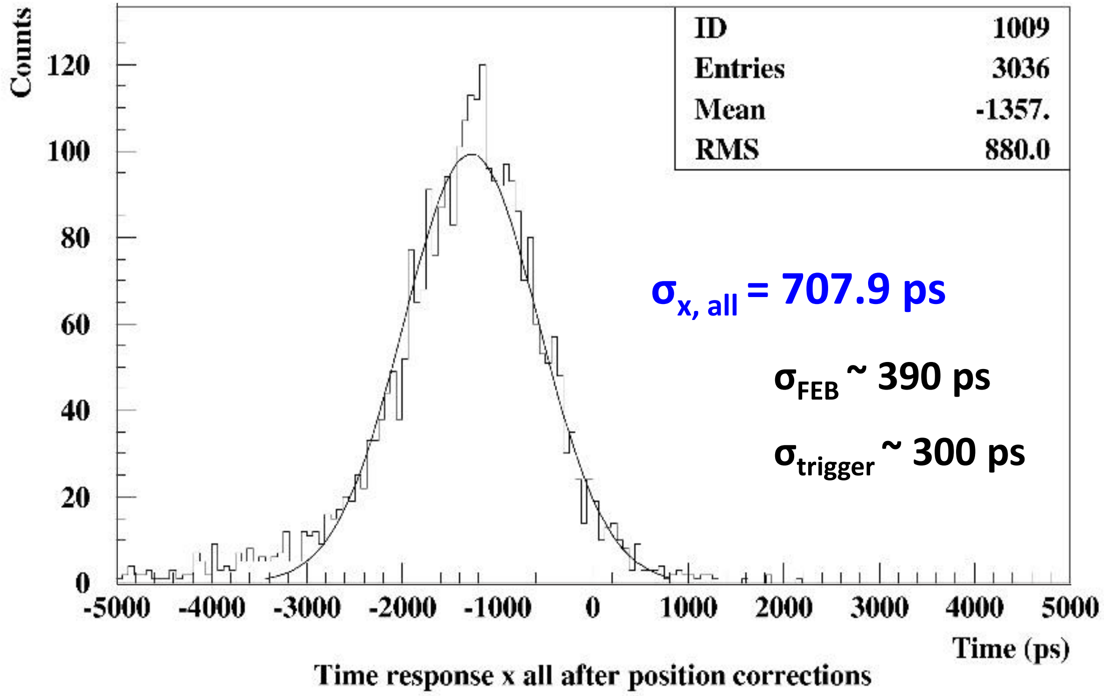


After the hit-position corrections, the signal arrival times on anode strips are corrected for a reference position of the detector layer.

Adding all the time data measured at 8 positions after the position-time corrections

→ $\sigma_{x,\text{ all}}$ = 707.9 ps, then,

$\sigma_{x,\text{ all int}}$ = sqrt $(707.9^2 - 390^2 - 300^2)$ = 508.4 ps

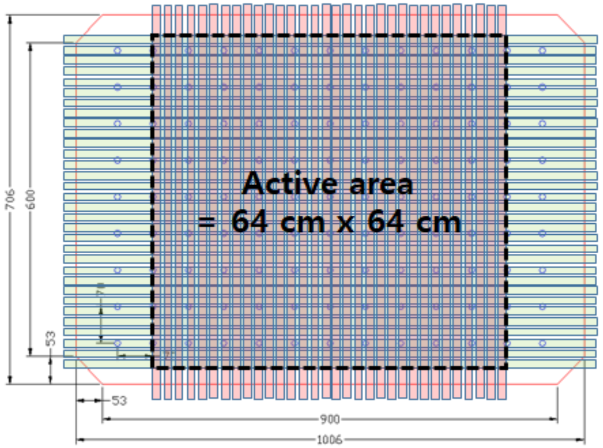


In 2019, R&D for a 1.6-mm single-gap 2D RPC

Same detector structure but with a 1.6 mm gap

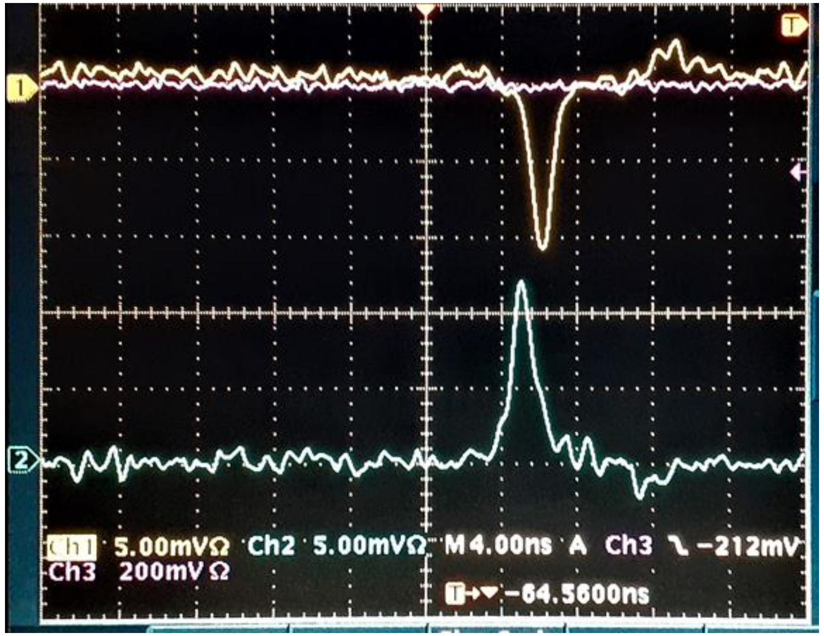
- ✓ The WP HV (~ 8.2 kV) is 1.4 kV lower compared to 2-mm gap RPCs (~ 9.6 kV)
  → WP HV < 11 kV when using a new HFO1234a based eco gas
- ✓ Also applied 2 orthogonal strip readouts for 2D trigger measurements
- ✓ The intrinsic time resolution is relatively poor compared to the 1.0-mm case, but the time resolution is still better than 1 ns

Thickness of Bakelite = 2.0 mm
Thickness of gap = 1.6 mm
Strip pitch for both *x* and *y* = 20 mm

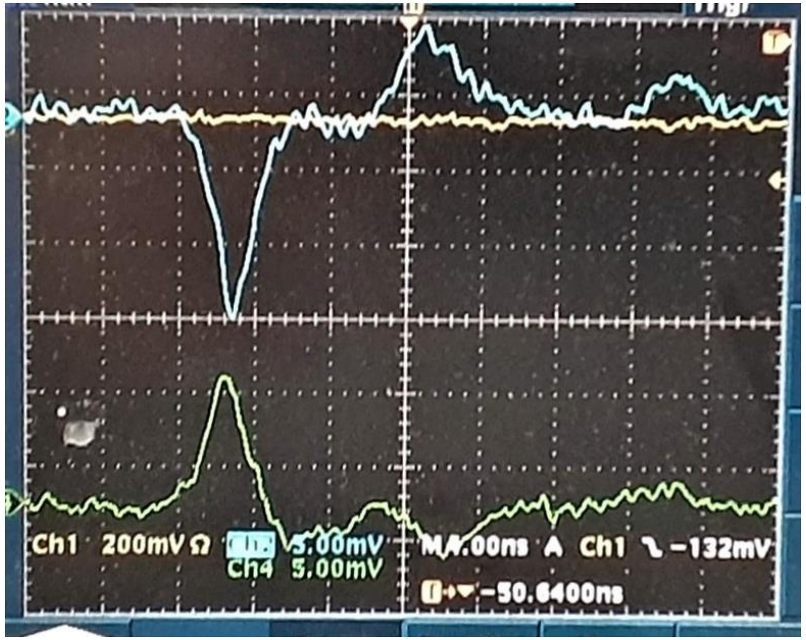


Test gas = 95.2% TFE + 4.5% iC_4H_{10} + 0.3% SF_6

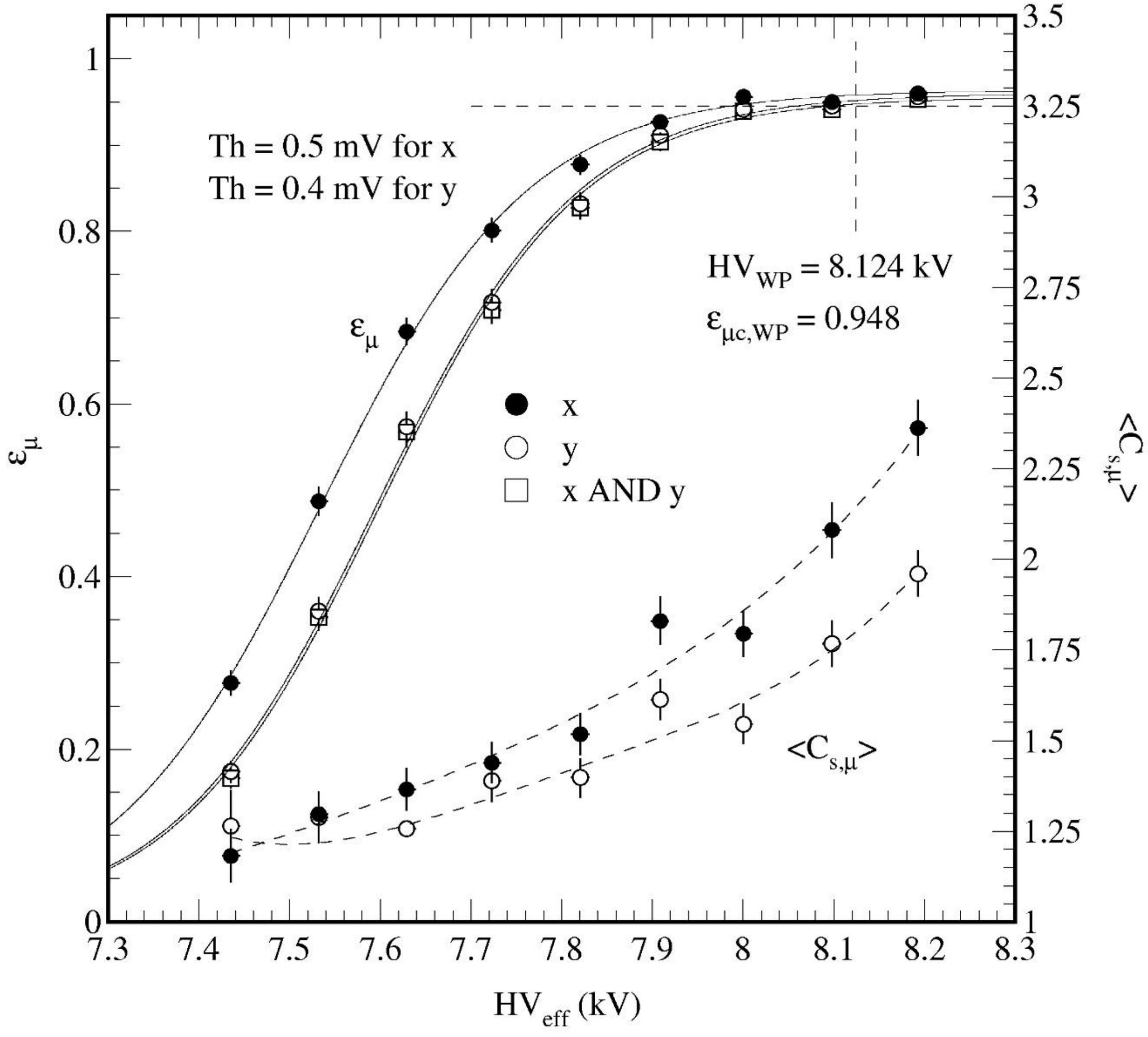
1.0-mm single-gap 2D RPC



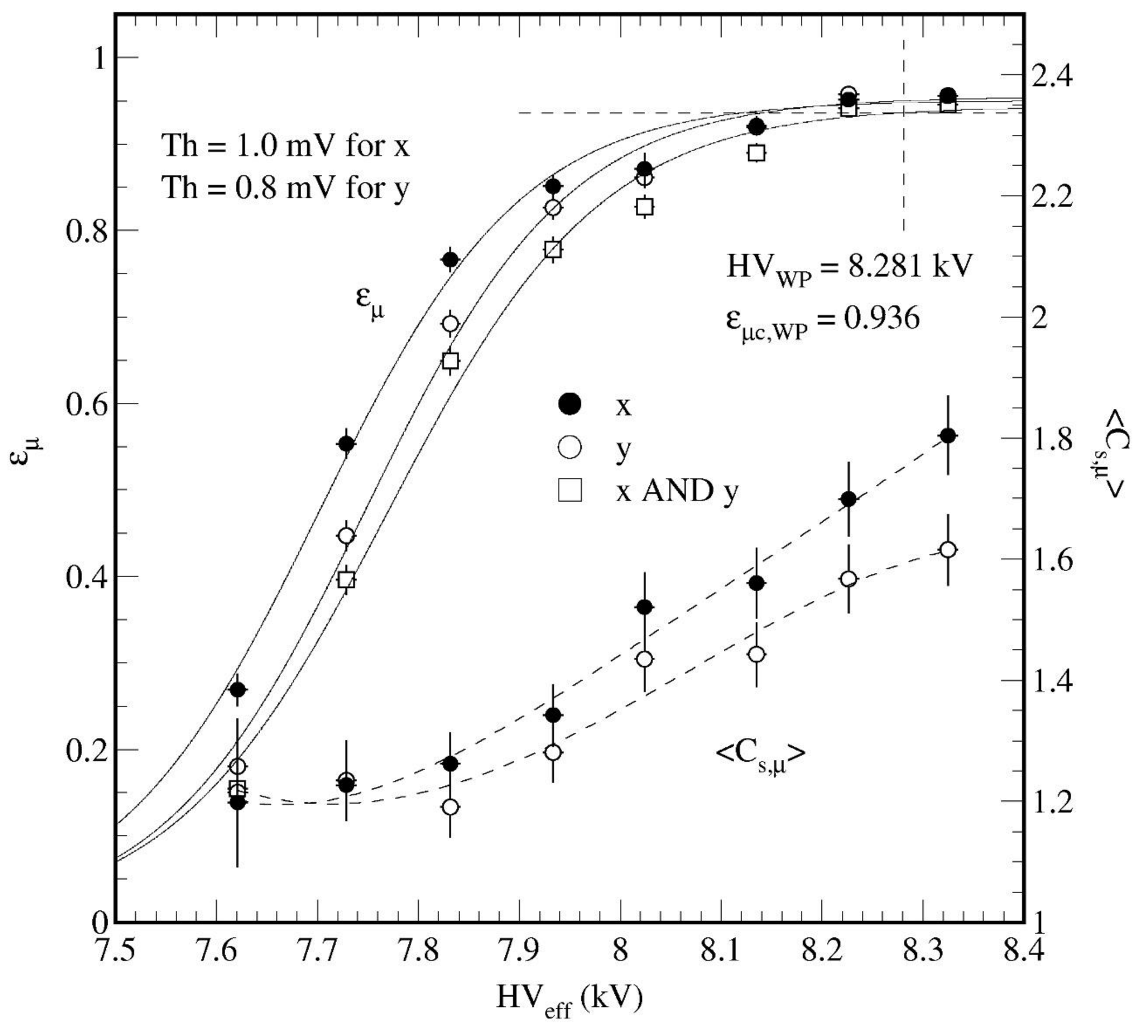
1.6-mm single-gap 2D RPC



Th = 0.5 mV (~ 75 fC) for x strips
= 0.4 mV (~ 60 fC) for y strips



Th = 1.0 mV (~ 150 fC) for x strips
= 0.8 mV (~ 120 fC) for y strips

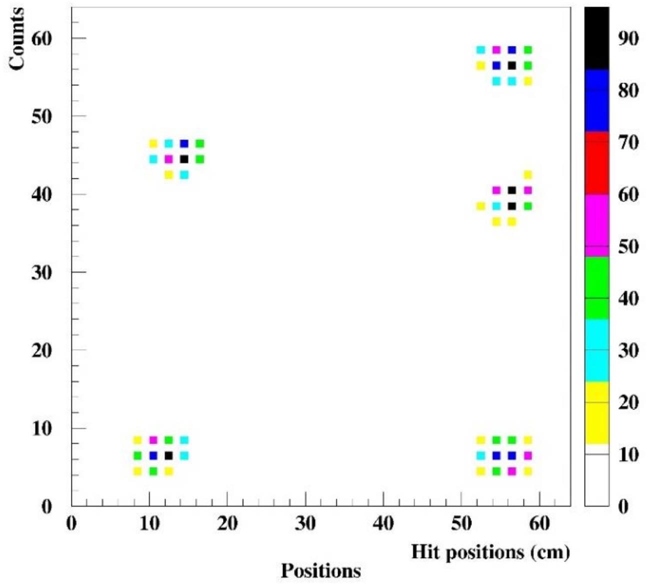


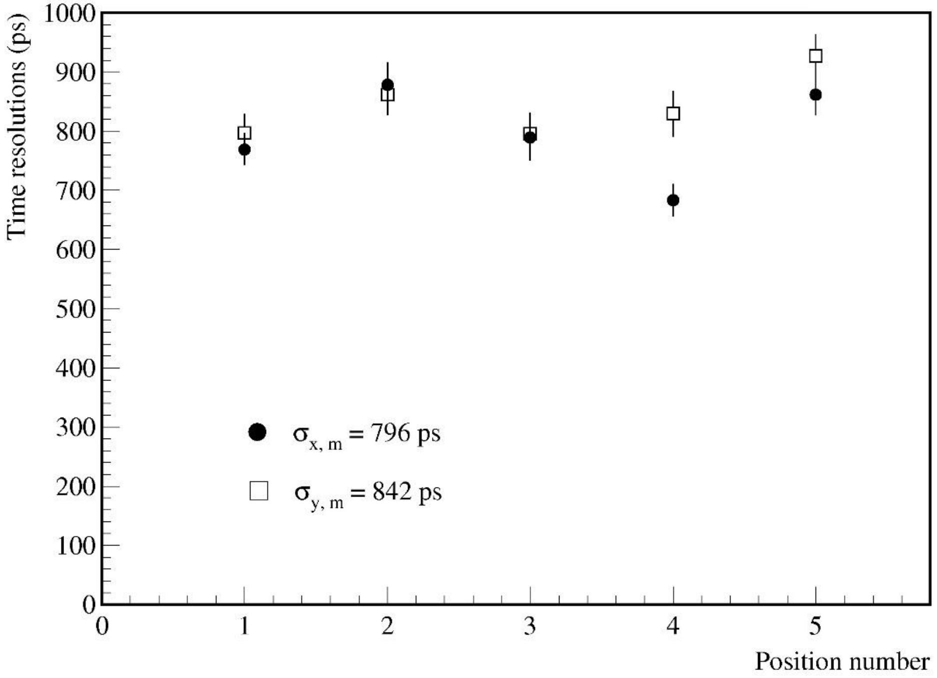
σ_{FEB} ~ 350 ps $\sigma_{trigger}$ ~ 300 ps

Time resolutions for a 1.6-mm 2D RPC

$$\sigma_{x,\,int} = \mathrm{sqrt}\,(796^2 - 350^2 - 300^2) = 649 \text{ ps}$$

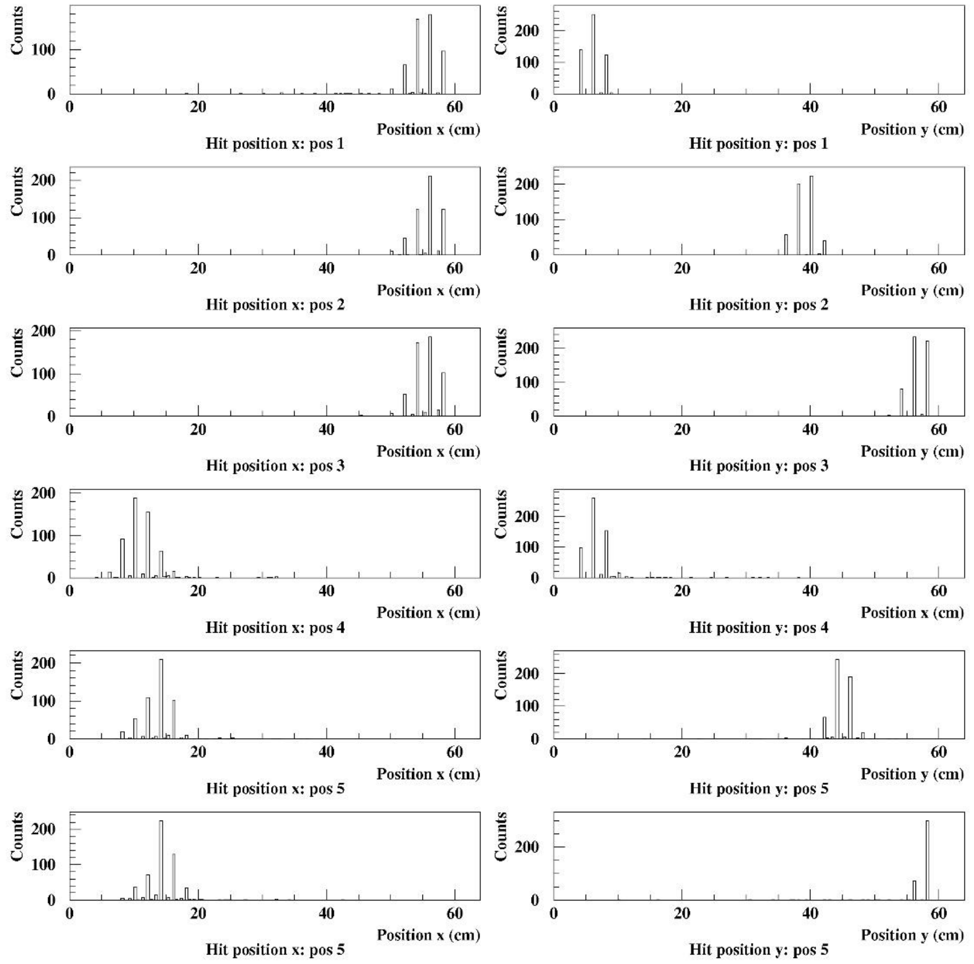
$$\sigma_{y,\,int} = \mathrm{sqrt}\,(842^2 - 350^2 - 300^2) = 705 \text{ ps}$$





x coordinate

y coordinate



Conclusions

2-mm single-gap 2D RPCs: KODEL provided gaps & strips

→ Successfully tested for the beam test at H4 in 2018 and satisfied the SHiP requirement.

1-mm single-gap 2D RPC: capable of 2D tracking with ~ 500-ps time resolution

Applied position corrections to *x*-strip signal arrival times using *y* strip positions

-> Over all time resolution adding all measured data after the position corrections ~ 700 ps

With better front-end-electronics with **σ_{FEB} ~ 100 ps**, then, we expect **σ_{system} ~ 500 ps** for multi-layer RPCs

1.6-mm single-gap 2D RPC: the WP HV can be reduced from 10 kV to ~ 8.2 kV

-> Will provide a good chance for using an eco gas mixture whose WPs ~ 10 kV

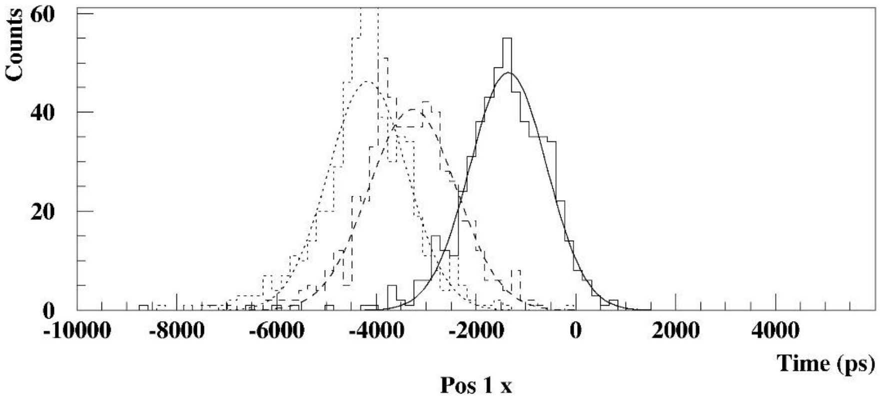
The RPCs construct with thin gaps (< 2.0 mm) provides a better time resolution.

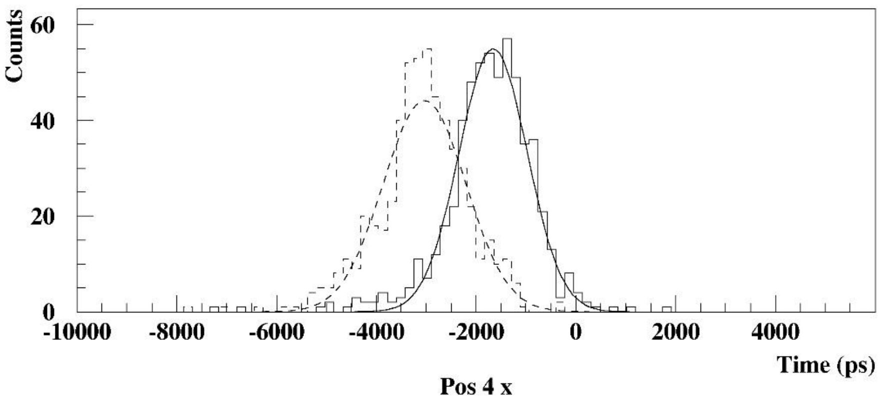
- **Nice to apply to accelerator-based experiments like CMS**

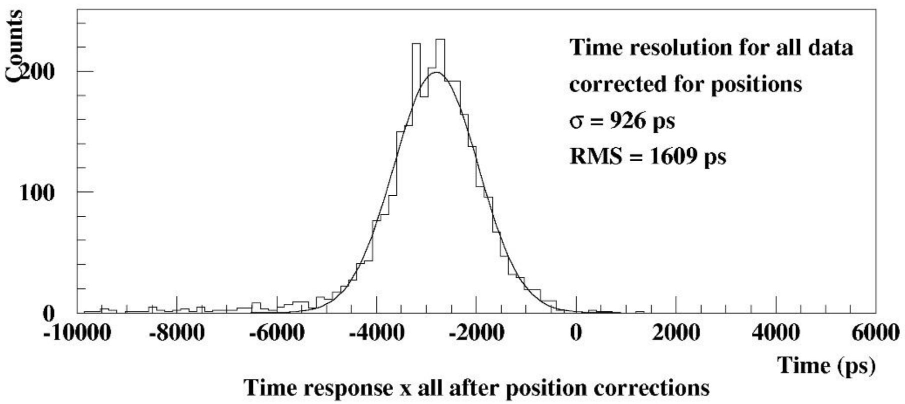
  -> Provides a better condition of selecting heavy slow charge particles **(HSCP)** for CMS

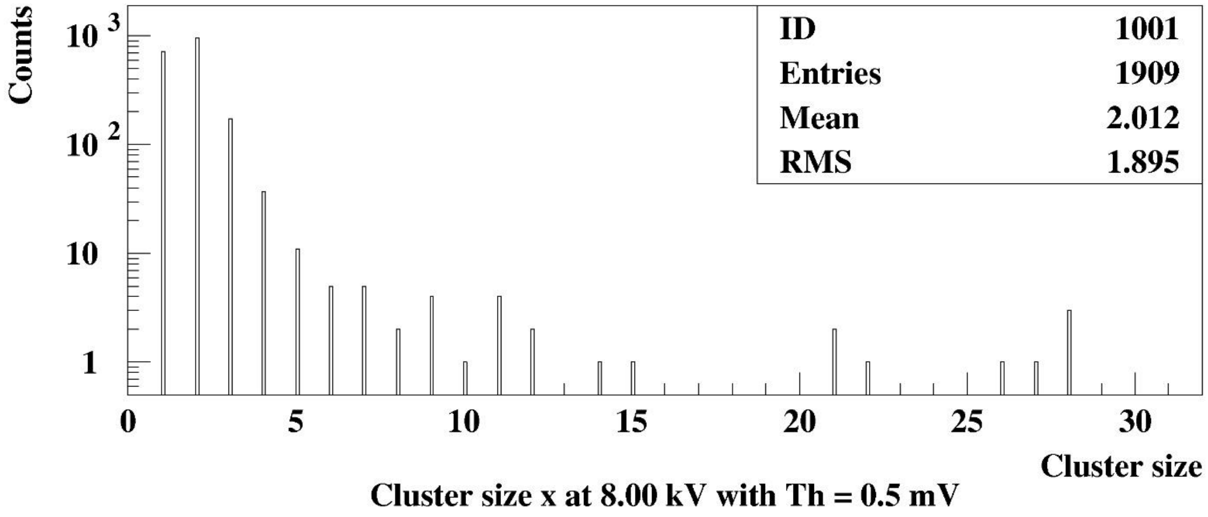
- **Nice apply to intensity frontier experiments pursuing New Physics** (BSM, dark matters, etc…) and neutrino physics that not so high position and time resolutions are required.

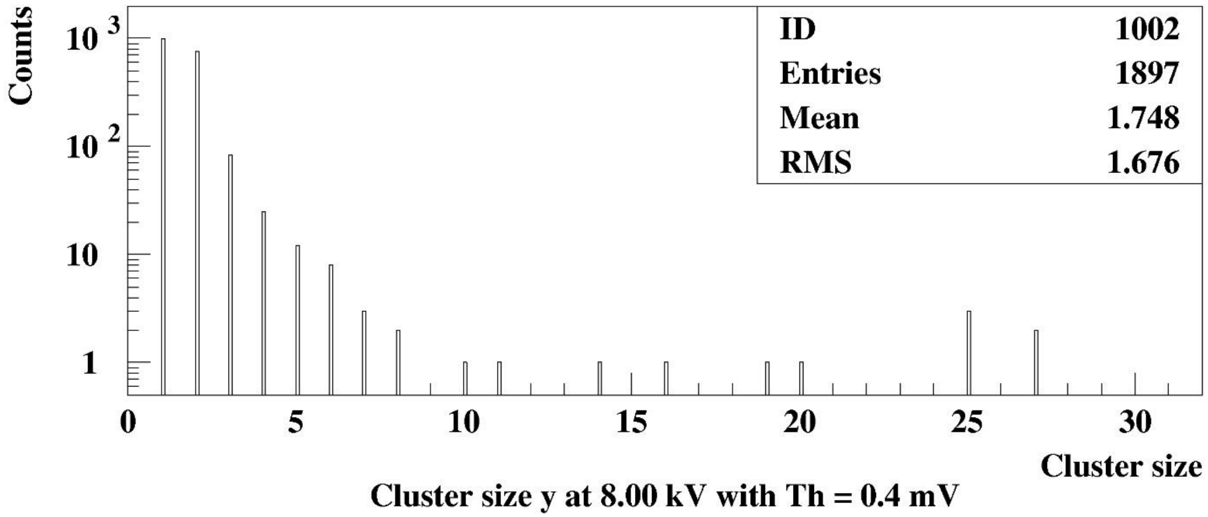
BACKUPS


Counts
Time (ps)
Pos 1 x


Counts
Time (ps)
Pos 4 x


Counts
Time resolution for all data
corrected for positions
σ = 926 ps
RMS = 1609 ps
Time (ps)
Time response x all after position corrections


Counts
ID 1001
Entries 1909
Mean 2.012
RMS 1.895
Cluster size
Cluster size x at 8.00 kV with Th = 0.5 mV

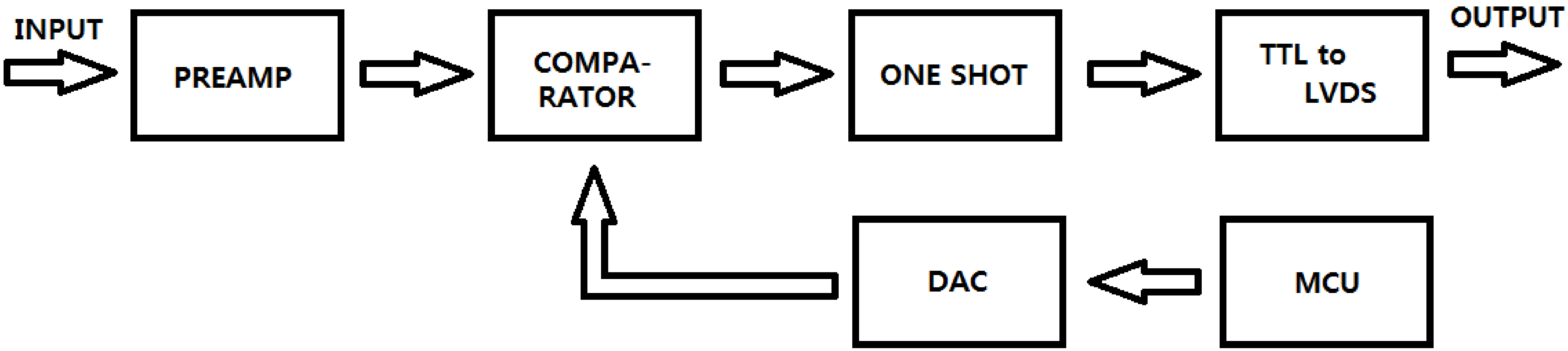

Counts
ID 1002
Entries 1897
Mean 1.748
RMS 1.676
Cluster size
Cluster size y at 8.00 kV with Th = 0.4 mV

KODEL FEBs used in the previous R&Ds

- The gain of the amplification is 200 mV/mV, which roughly corresponds to ~ 2 mV/fC in a typical charge sensitive mode amplification (for the current CMS RPC FEBs, the gain is set to 1.8 mV/fC).
- The digitization threshold value ~ 0.3 mV roughly corresponds to 40 ~ 50 fC for typical RPC pulses of double-gap trigger RPCs.
- RMS noises of the FEB ~ 0.02 mV
- Time jitter at comparators & One shots ~ 200 ps
- Ethernet communication using a web browser and an intranet communication:

i.e. setup in your PC with 192.168.0.1 and

192.168.0.2 ~ 10 in each FEB board



1. Preamplifier (current sensitive mode)
   function = converts current to voltage signal and linearly amplifies the pulse
   gain = 200 mV/mV for an input pulse
   band width = 200 MHz
   input impedance = 20 ohm
   part = ADA4895 (Analog Device)

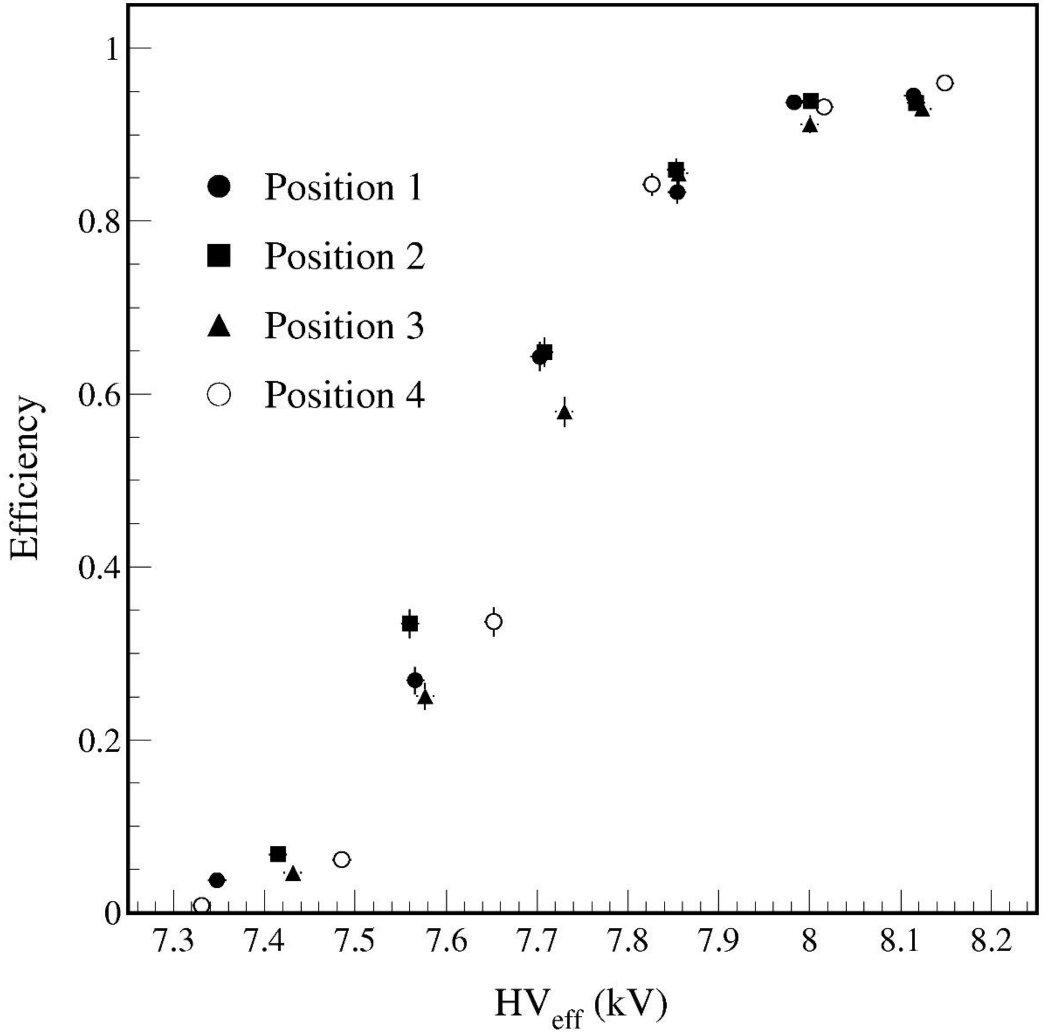
2. Comparator
   function = compares preamplifier's output with a given threshold and generates logic pulse if input signal is larger than the threshold
   threshold voltage = 0 ~ 2,000 mV
   propagation delay = 3.5 ns
   minimum pulse width = 3 ns
   part = ADCMP600 (Analog Device)

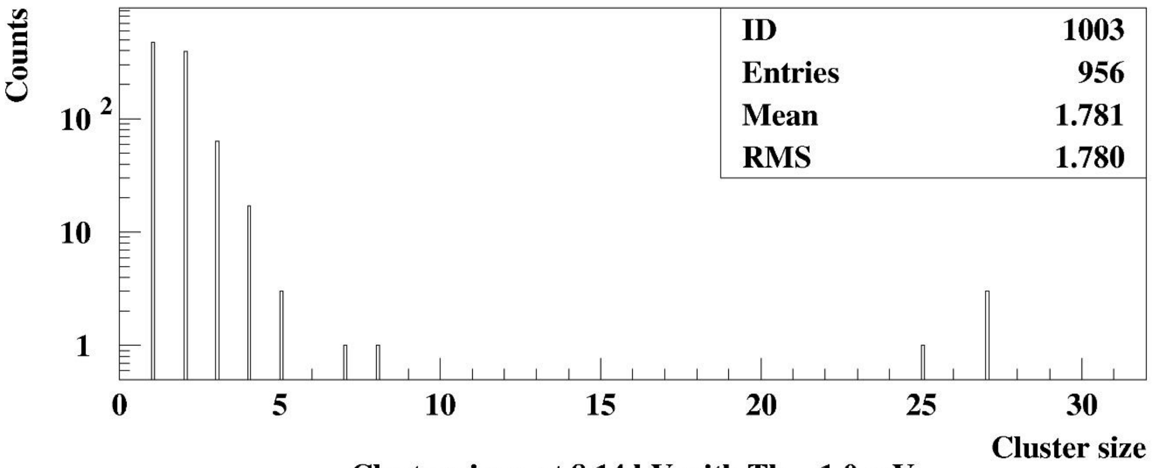
3. One shot
   function = generates a logic pulse with given width regardless of comparator's output width which depends on the pulse shape and amplitude of analog input signal from preamplifier
   pulse width = 30 ~ 500 ns
   propagation delay = 2.2 ns
   minimum pulse width = 2.7 ns
   part = SN74LVC1G74 (Texas Instruments)

4. TTL to LVDS translator
   function = converts LVTTL logic pulse to LVDS logic pulse
   propagation delay = 1.2 ns
   Adjustable width = 20 ns ~ 60 ns
   part = DS90LV047 (Texas Instruments)

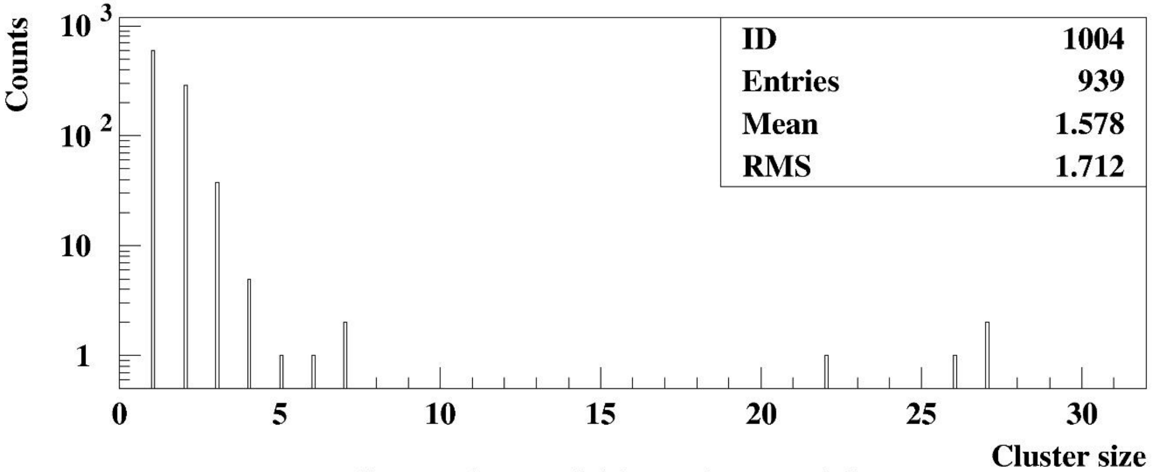
5. Digital to Analog Converter(DAC)
   function = generates threshold voltage to comparator
   threshold voltage = 0 ~ 2,000 mV (0 ~ 10 mV input voltage equivalent)
   resolution = 12 bit (precision = 2.5 us input voltage equivalent)
   part = TLV5630 (Texas Instruments)

6. Micro Controller Unit(MCU)
   function = controls DAC via TCP/IP protocol
   part = ATMEGA64 (Atmel) + TCP/IP interface





Cluster size x at 8.14 kV with Th = 1.0 mV

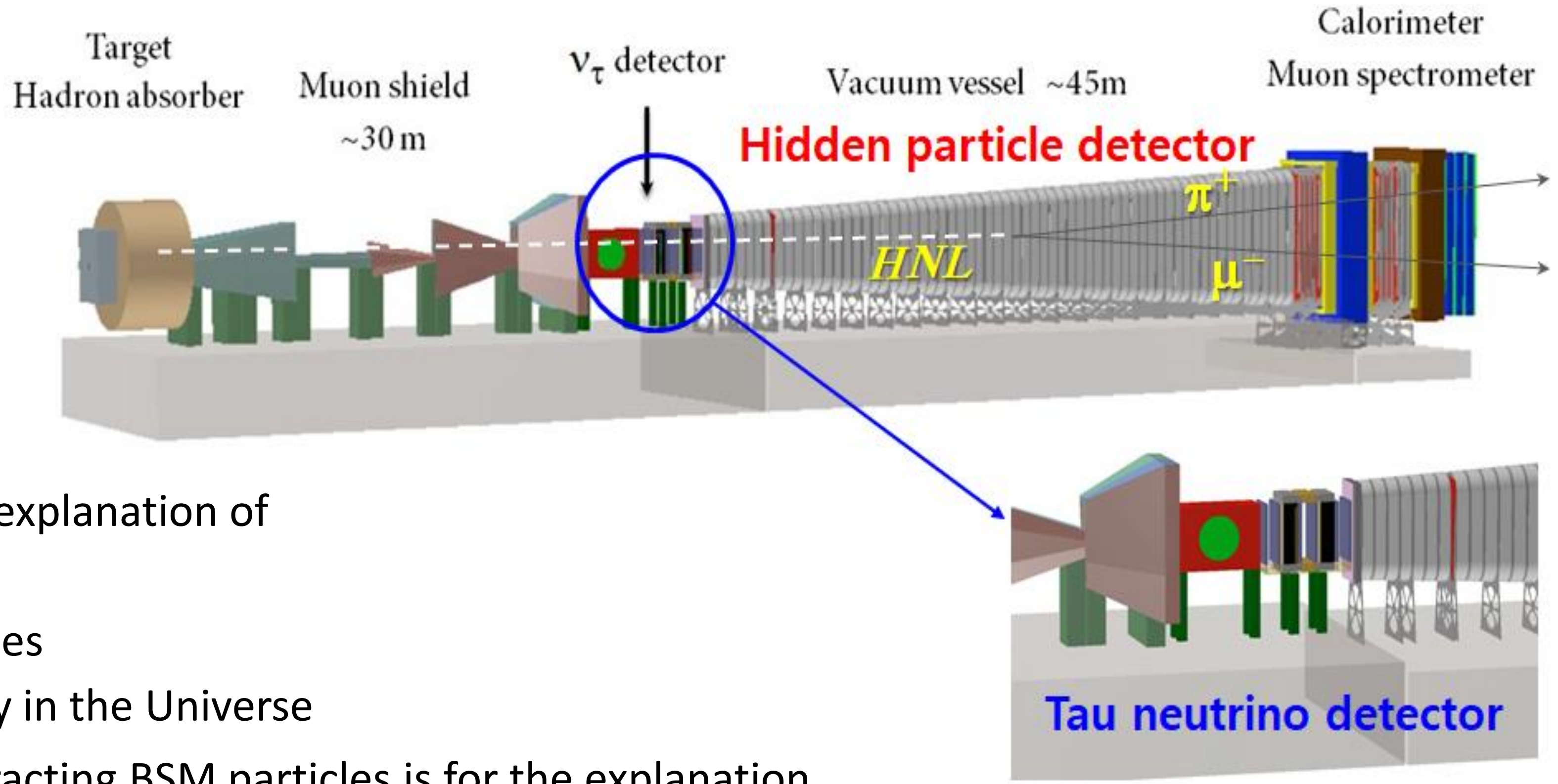


Cluster size y at 8.14 kV with Th = 0.8 mV

Motivation of SHiP

SHiP: a 400-GeV proton-beam dump experiment @SPS CERN starting 2026

Use of SPS protons → Nearly no interference to Phase-2 LHC runs



The current Standard Model fails in explanation of

- ✓ Dark Matter
- ✓ Neutrino oscillation and masses
- ✓ Matter/antimatter asymmetry in the Universe

A Hidden Sector (HS) of weakly interacting BSM particles is for the explanation

Long-lived weakly interacting particles → requires high intensity beams

Collaboration of ~ 250 members from 52 institutes, 17 countries
Technical Proposal: *arXiv:1504.04956* (2015)

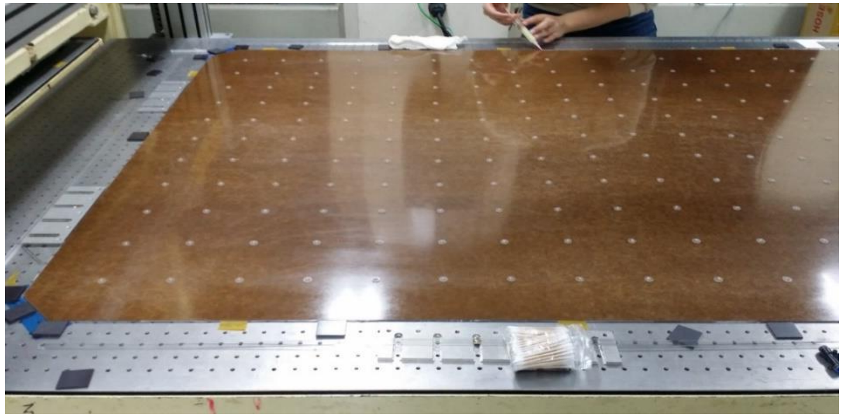
Construction of Trigger RPCs for the 2018 Dump Experiment @ CERN SPS

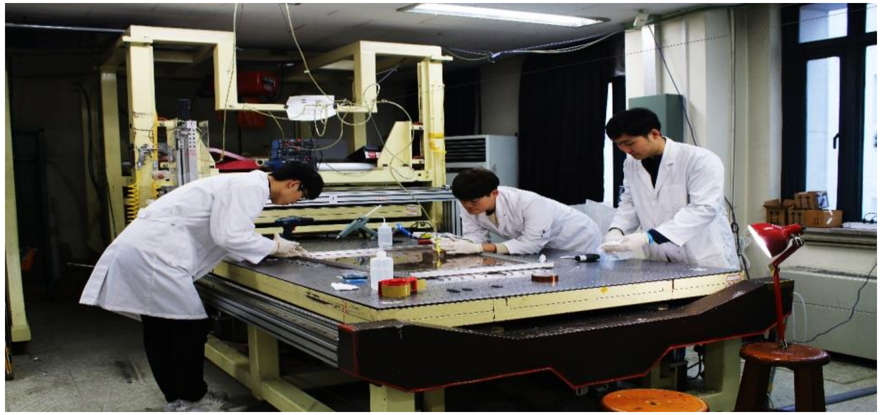
5 RPC modules prepared for a beam-dump measurement at SPS/CERN in July 2018

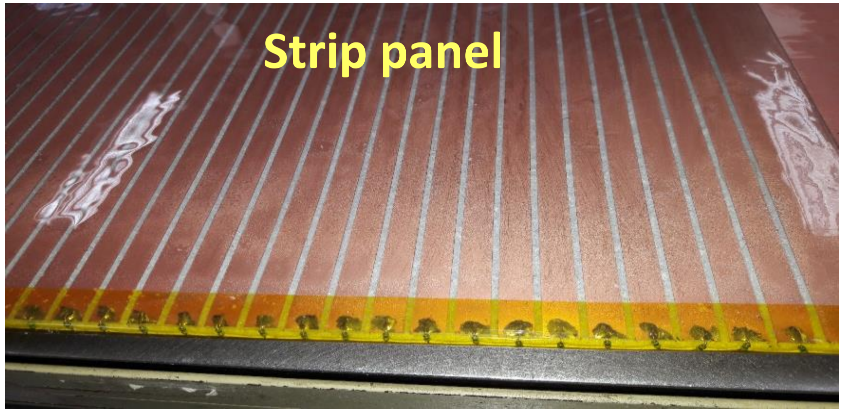
118 horizontal and 184 vertical strips (pitch = 10.625 mm) per RPC

Detector size = 2100 mm x 1350 mm / Active area = 1900 mm x 1200 mm

Gas gaps and strip panels manufactured at Korea University







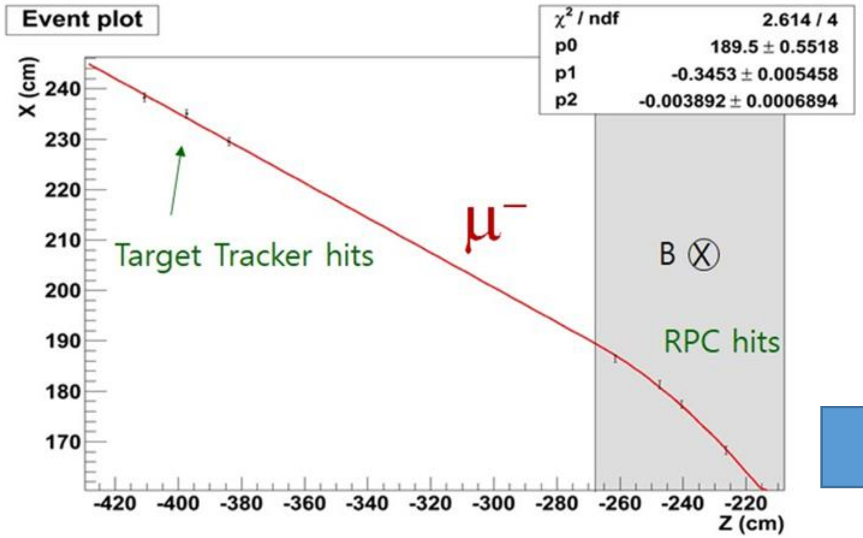
Charm measurement
Sample data

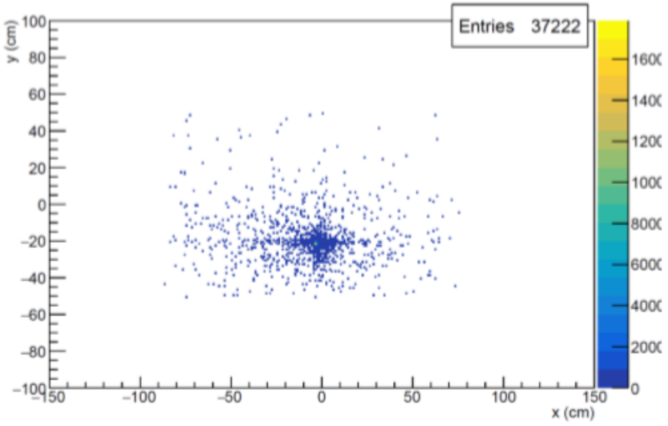
Presented in ShiP-Charm meeting on 2nd October 2018

A. Pastore, INFN Bari and University of Bari

Reco-tracks in CHARM1-run6, run 2793

The muon charge was determined to be negative from track curvature in the spectrometer (RPC hits)

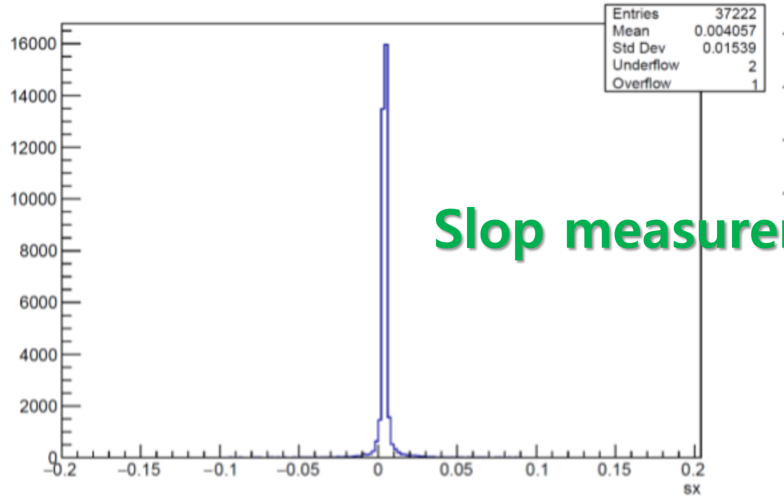


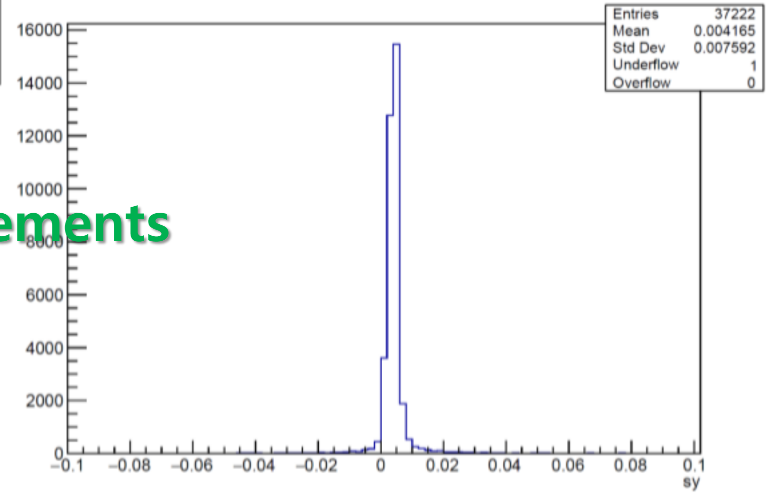


$\nu_\tau \rightarrow \tau^- \rightarrow \mu^-$ ○

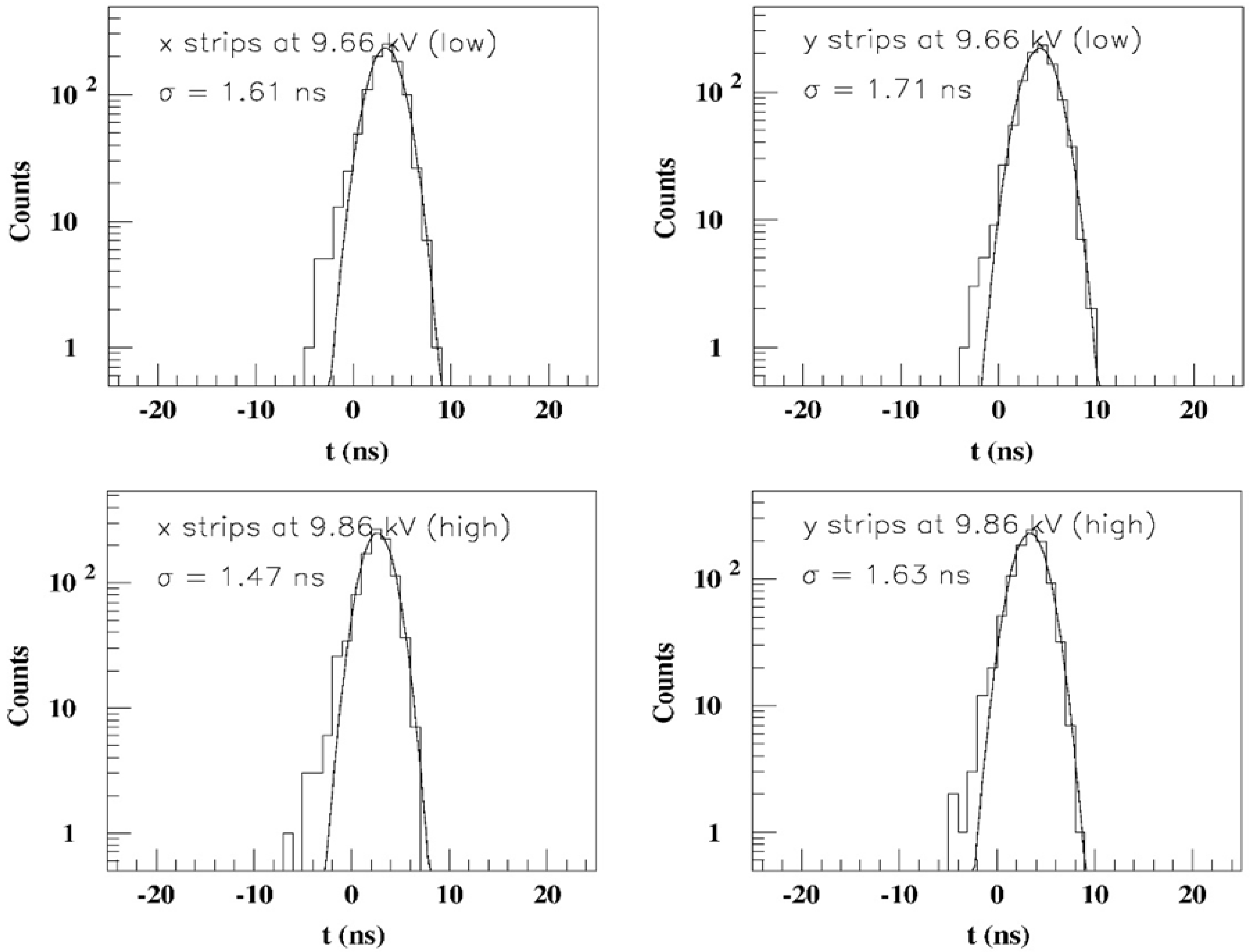
$\bar{\nu}_\tau \rightarrow \tau^+ \rightarrow \mu^+$ ×

Slop measurements





Detector response times and resolutions of the anode (x) & cathode (y) signals are fairly comparable.



With low threshold setup at HV_{eff} = 9.66 kV

With high threshold setup at HV_{eff} = 9.86 kV

Construction & Test of the 1st Prototype RPC module

First prototype manufactured and tested with cosmic muons at Korea University for a technical assurance

- 112 horizontal (*x*) and 80 vertical (*y*) strips (pitch = 10.625 mm)
- Detector size = 1300 mm x 1000 mm / Active area = 1200 mm x 800 mm
- Gas mixture = 95.2% $C_2H_2F_4$ + 4.5% iC_4H_{10} + 0.3% SF_6

Digitization thresholds at Front-end-electronics in a current sensitive mode

Th = 0.33/0.8 mV for *x* (anode strip, negative)

Th = 0.40/1.0 mV for *y* (cathode strips, positive)

Th = 0.4 mV ↔ 60 fC
Th = 1.0 mV ↔ 150 fC