New RPCs for High-Energy Physics Experiments and for Applications to Nuclear Science

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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

RPCs are the detectors for both tracking and triggering with a best time resolution of less than 1 ns

Tracking & trigger RPCs where not so high position (not better than 1 mm) is not required.

↔ 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

→ Various applications like muon radiography and medical purpose

SHiP experiment to address beyond Standard Model Physics

To search for 'hidden particles' in theoretically 'hidden sectors'

Searching for new particles in a mass range from sub-GeV to *O*(10) GeV

- Dark photons (vector portal)
- HNLs (neutrino portal)
- Scalar portal: hidden sector interacting with a known sector of SM Higgs fields
- Light SUSY particles decaying into a light neutralino $\tilde{\chi}^0 \rightarrow K + l$
- Axion like Particle

Tau neutrino physics measuring tau-neutrino cross section

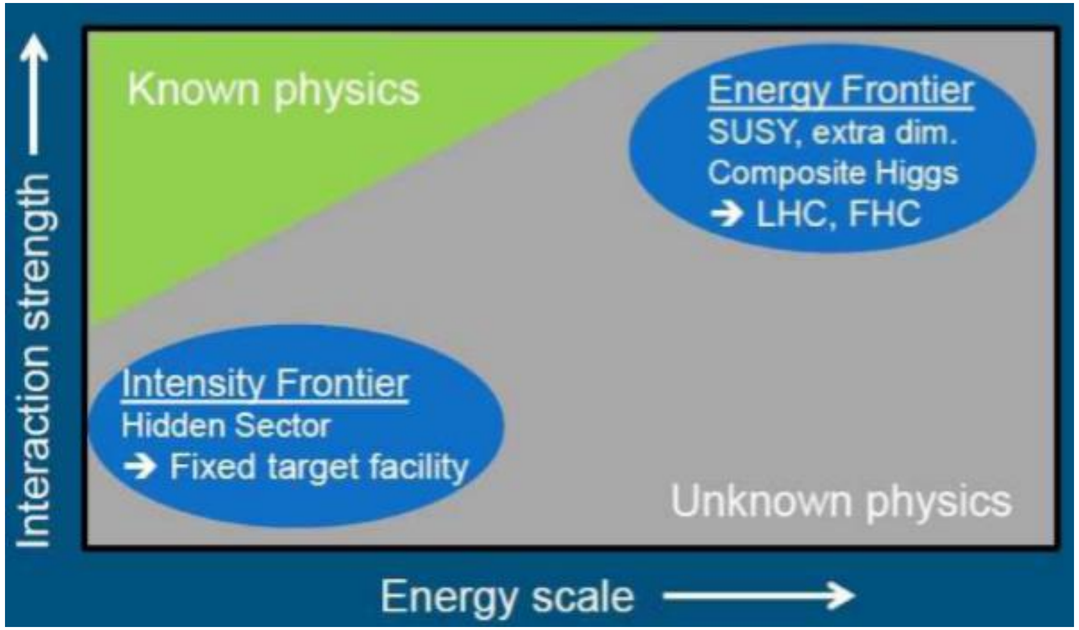
→ Structure functions F_4 & F_5

RPC system will differentiate tau and anti-tau reactions requiring a position resolution of ~ 4 mm.

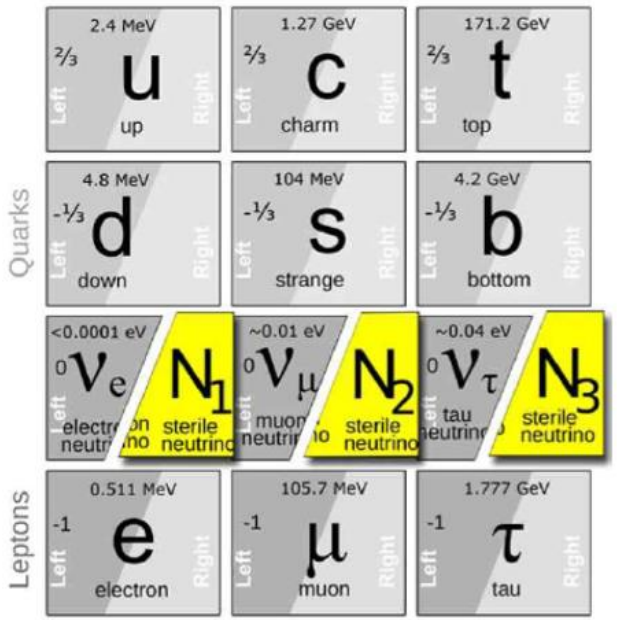
SHiP: Dump experiment for 5 years using 2×10^{20} protons of 400 GeV

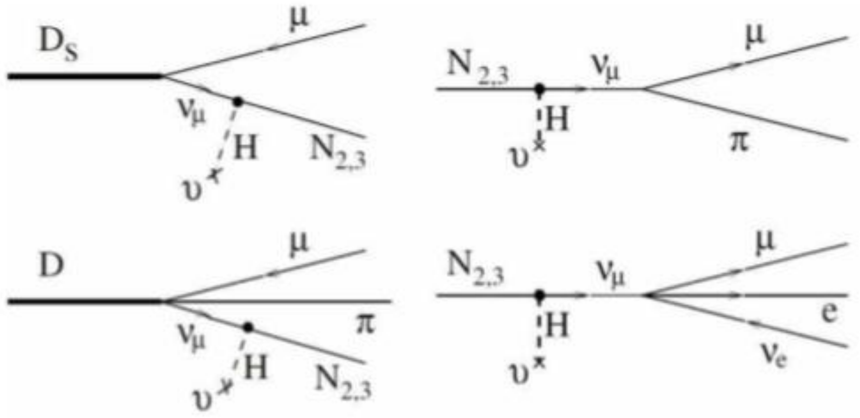
- Called an intensive frontier experiments
- Collider experiments -> energy frontier experiments

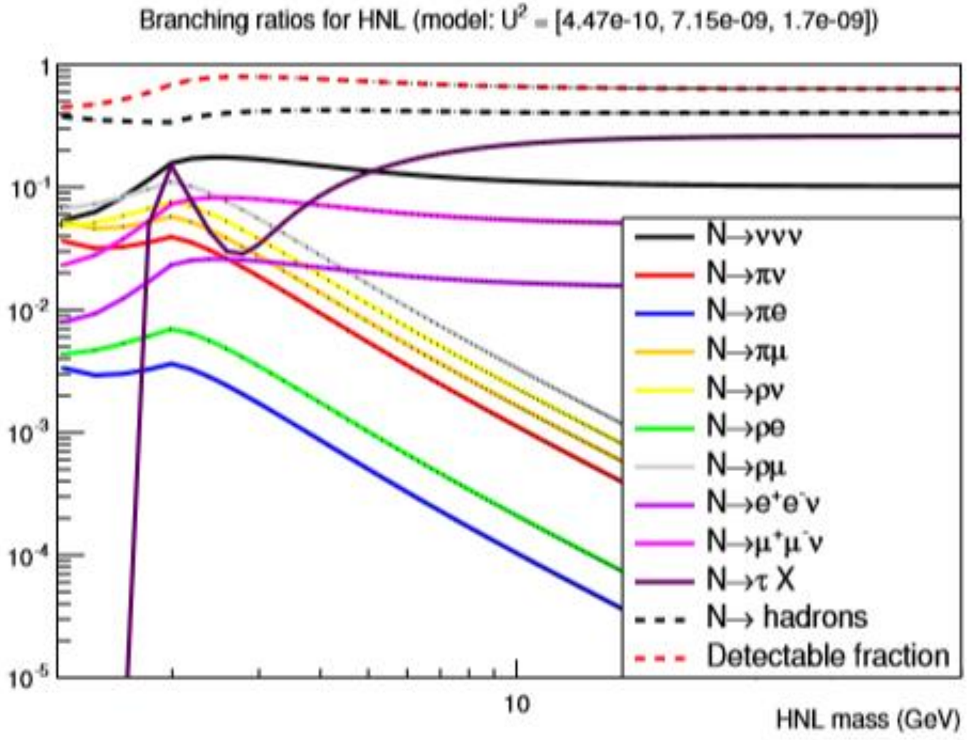
Unfortunately, European strategy meeting (ESPPU) prefers e^+e^- Higgs factory and ILC support in future.



Heavy neutral leptons (sterile neutrinos, neutrino portal)







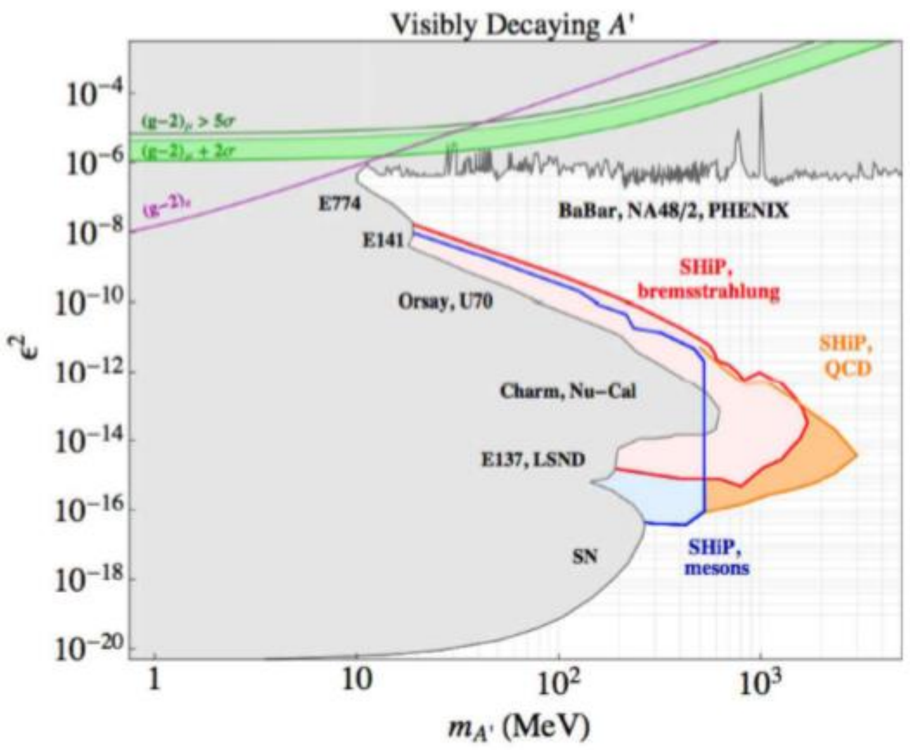
$$D \to K\ell + HNL$$
$$D_s \to \ell + HNL$$
$$D_s \to \tau\nu_\tau \text{ followed by } \tau \to \ell\nu + HNL \text{ or } \tau \to \pi + HNL$$
$$B \to \ell + HNL$$
$$B \to D\ell + HNL$$
$$B_s \to D_s\ell + HNL$$

Dark photon (Vector portal assuming a new U1 symmetry) to be produced via

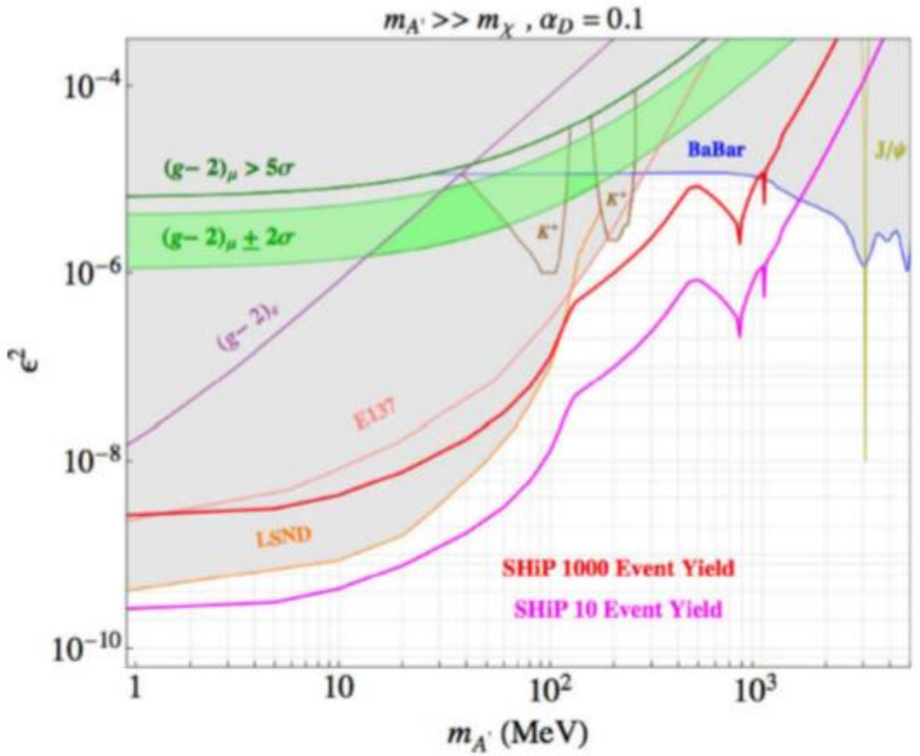
- Mesons (π^0, K, D) produced by 400 GeV proton beam
  i.e., $\pi^0 \rightarrow \gamma A'$ via mixing proportional to ε^2 (ε: mixing between gauge particles of $U(1)$ and $U(1)'$)
- Dark photon via Bremsstrahung processes
- QCD process: $q + \bar{q} \rightarrow A'$, $g + g \rightarrow g + A'$

$A' \rightarrow \chi\tilde{\chi}$, $A' \rightarrow l^+l^-$, $A' \rightarrow$ hadronic decays

Delayed decay up to $m_A \sim 2$ GeV



Prompt decay $A \rightarrow \chi\tilde{\chi}$



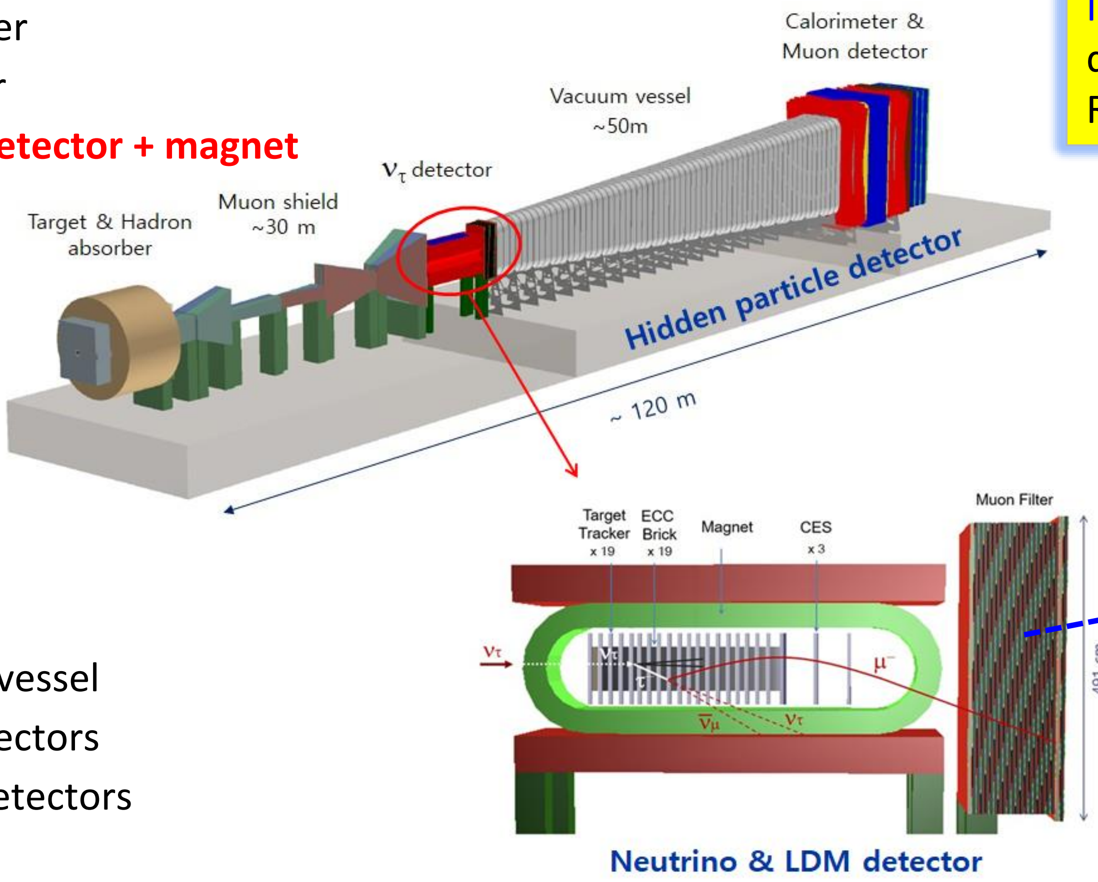
R&D target: SHiP tau neutrino RPCs

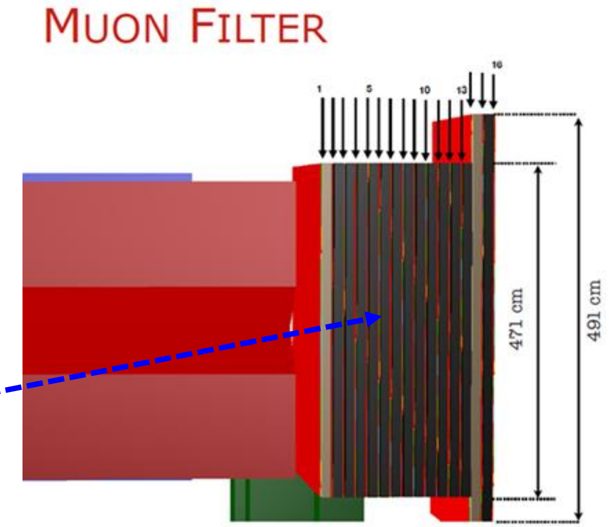
Better triggers for tau associated muons

Better VETO for neutrino associated muons impinging the decay vessel

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

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





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

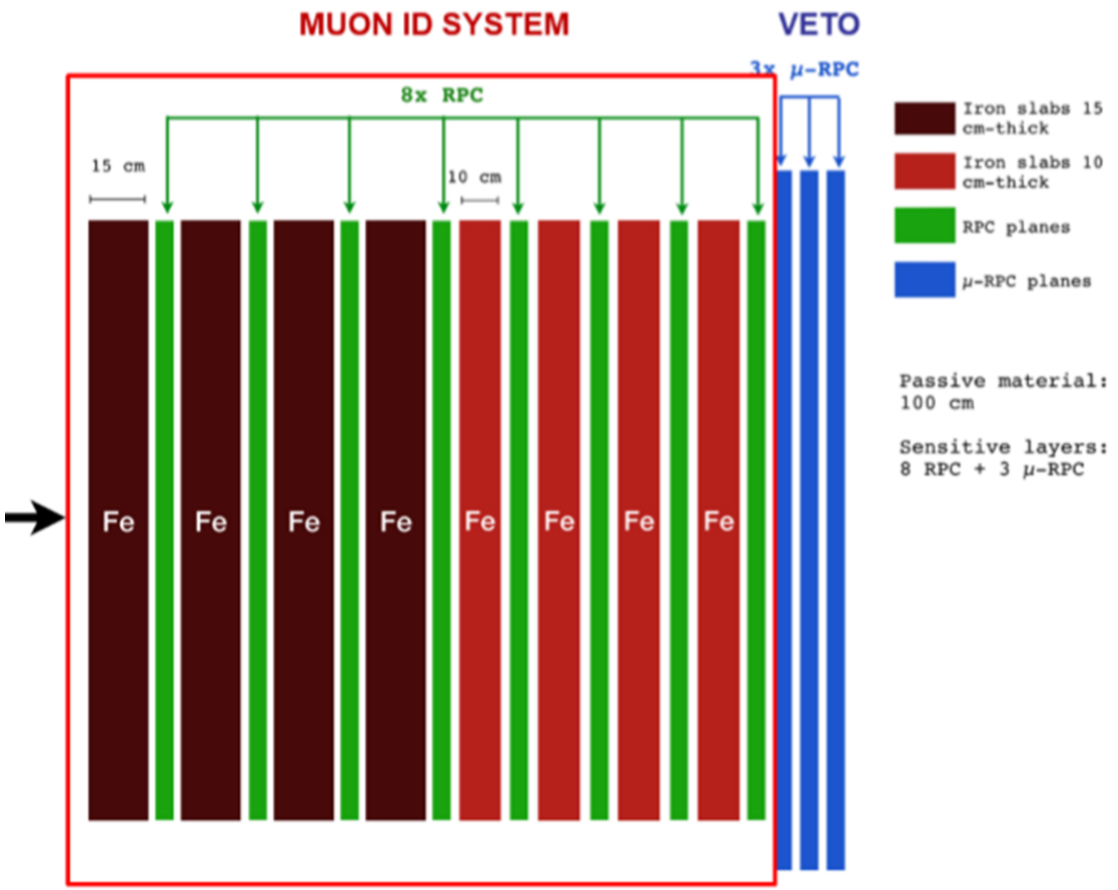
Technical Proposal: *arXiv:1504.04956* (2015)

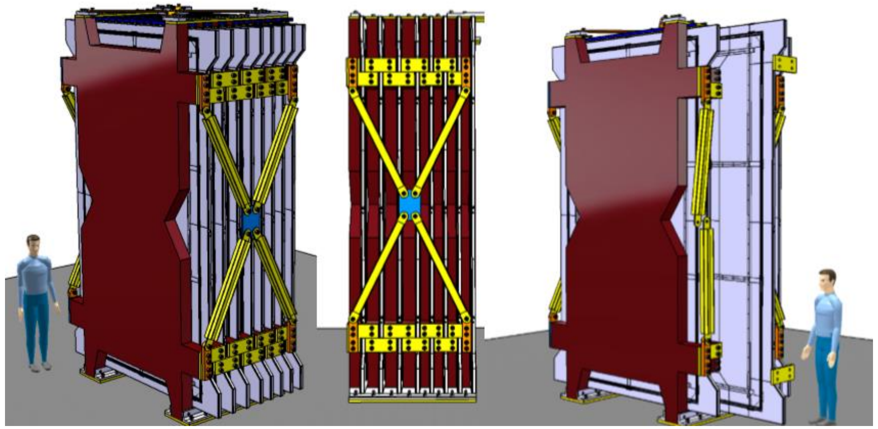
Muon tagger

11 layers of RPC planes and Fe absorbers

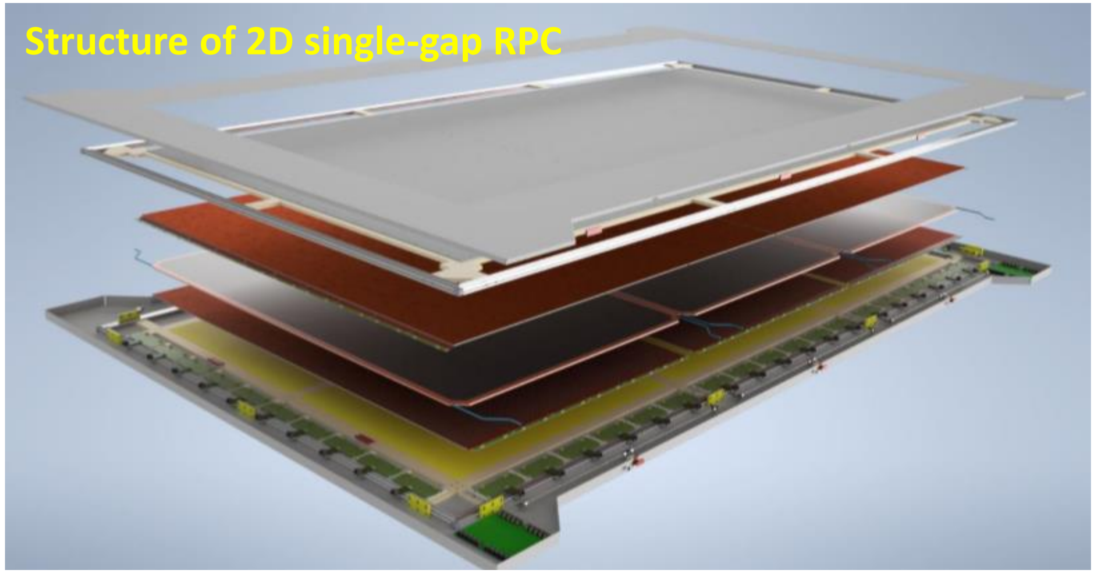
Tagging tau-decayed muons and VETO of neutrino associate muons

- 8 layers of muon tagging RPCs (σ ~ 1 ns) also used for muon VETO
- 3 layers of TOFs (σ < 300 ps) for muon VETO





RPCs for muon tagger requiring 3 ~ 4 mm resolution → able to differentiate muon charges from the tau neutrino interactions ($\nu_\tau \rightarrow \tau^- \rightarrow \mu^-$, $\nu_\tau \rightarrow \tau^+ \rightarrow \mu^+$)



For SHiP: in 2018, 1st prototype: 2-mm single-gap 2D RPCs

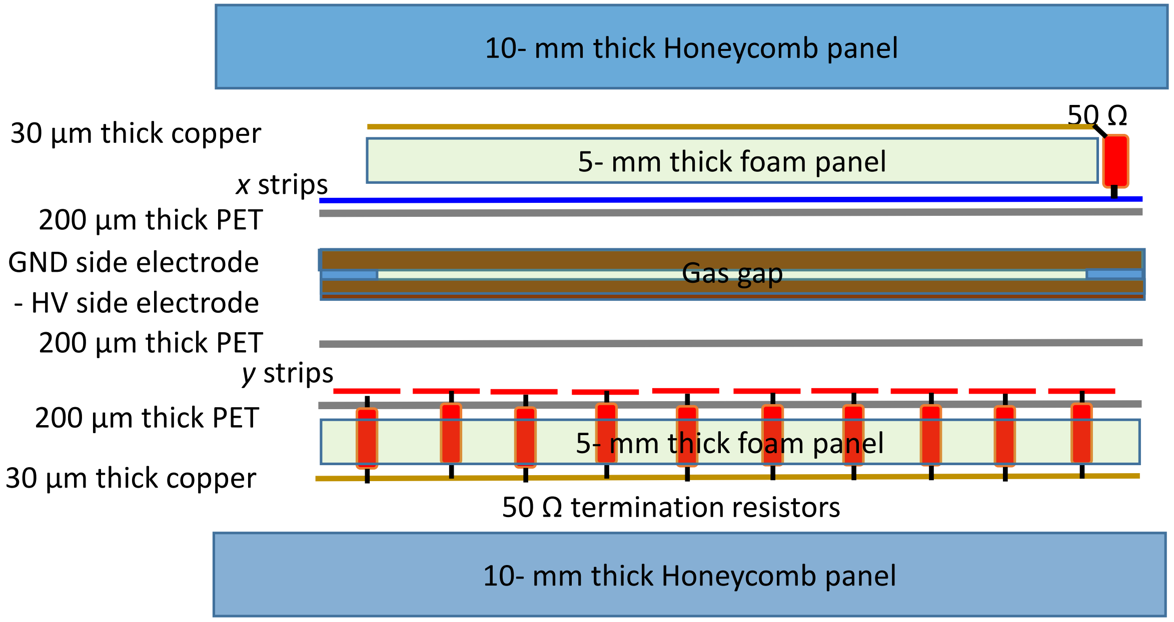
Baseline structure for SHiP RPCs

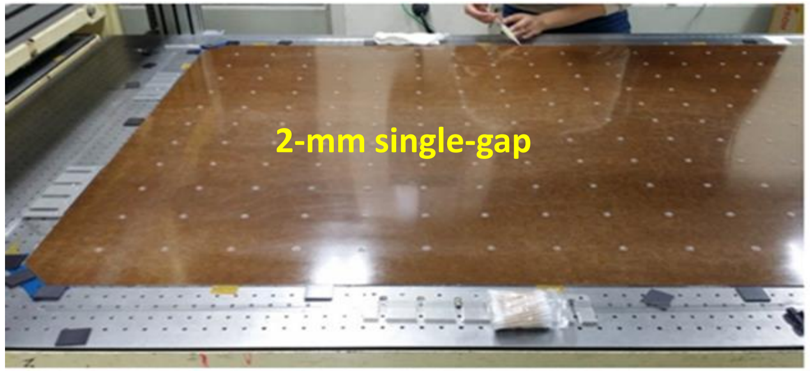
One of the backup designs for CMS iRPCs

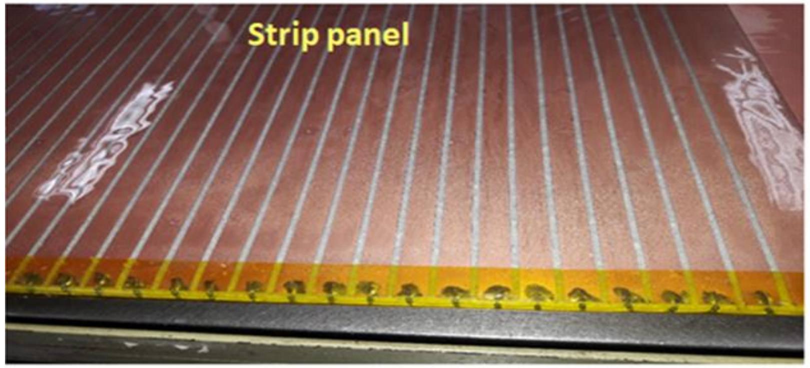
✓ **Cathode + anode strips (orthogonal)**
- Cathode signals: positive polarity
- Anode signals: negative polarity

✓ **Avalanche mode**

✓ **2 orthogonal strip readouts for 2D trigger measurements**
- Strip pitch = 10.625 mm for both coordinates





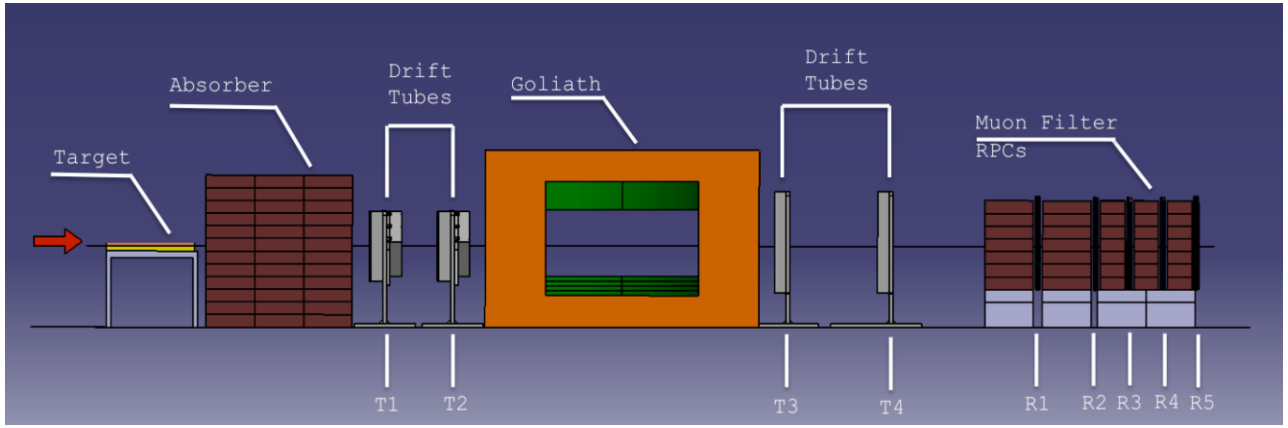


In July 2018, KODEL provided RPC electrodes and strips for an experiments using CERN SPS 400 GeV/c proton beam at H4 area

KODEL provided RPC gaps and strips.

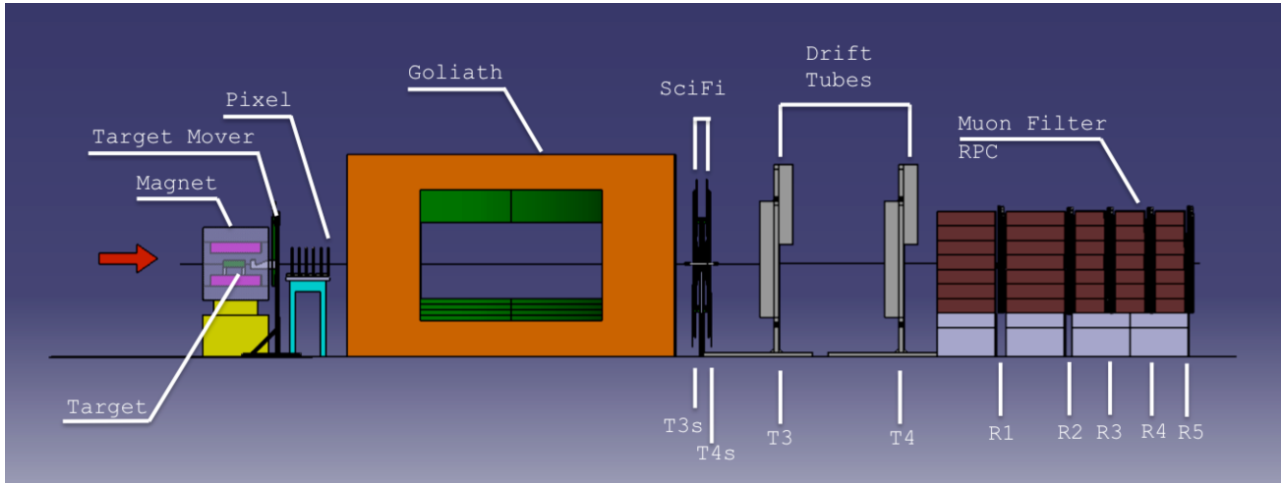
Measurement of muon flux

- ✓ **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

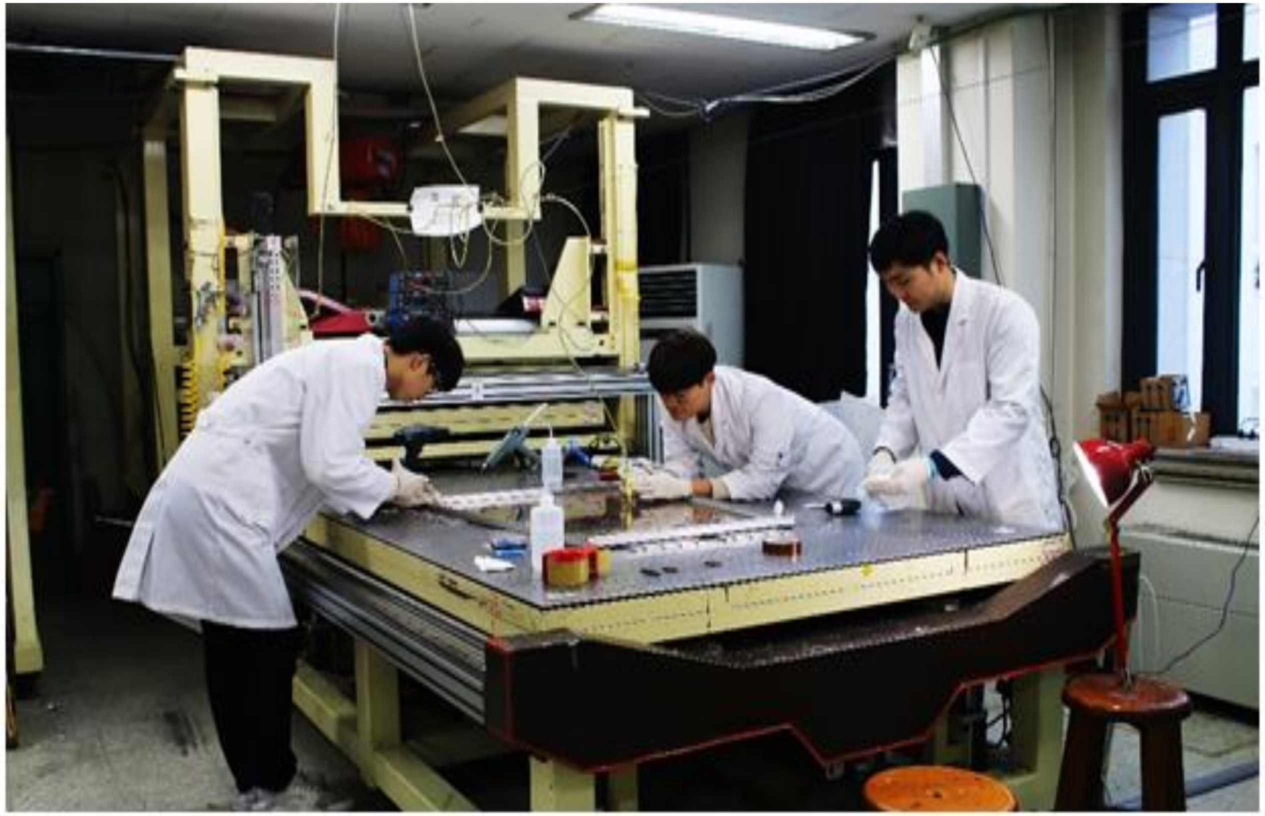


In 2019, R&D on 1-mm single-gap 2D RPCs

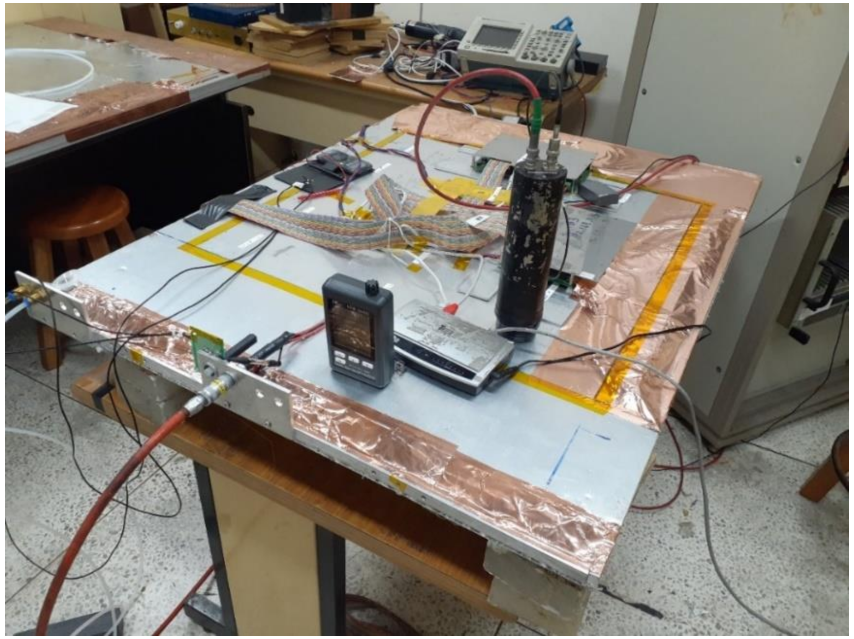
Same structure but with a narrower gap thickness

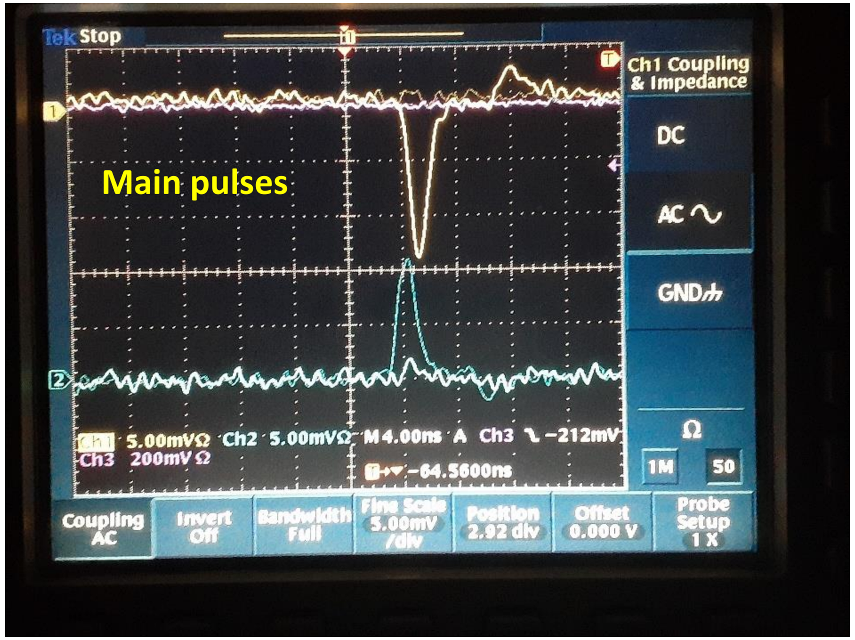
- ✓ Aiming for faster time response < 10 ns and a time resolution ~ 500 ps for the trigger system
- ✓ 2 orthogonal strip readouts for 2D trigger measurements + a time resolution mush better than 1 ns

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

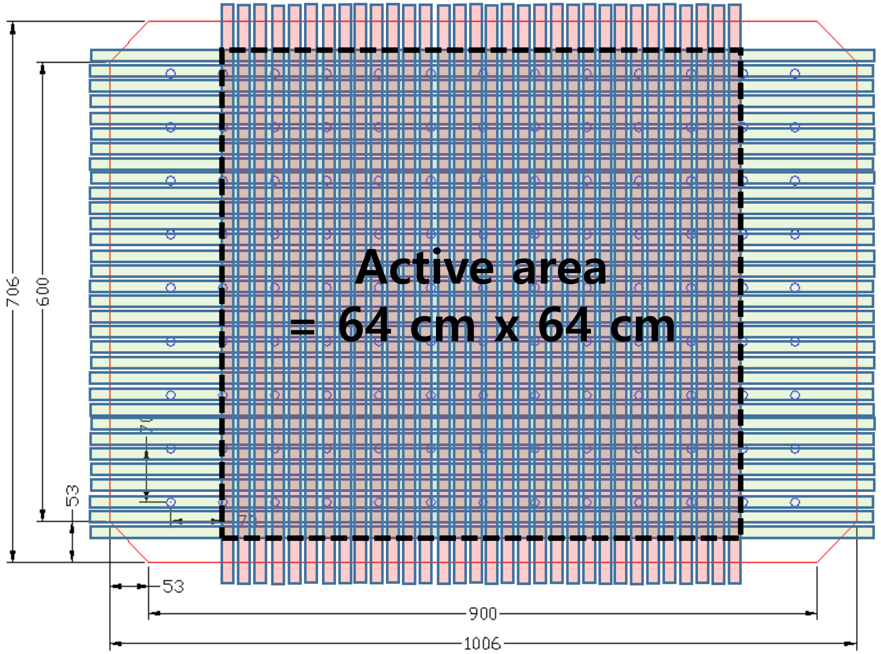


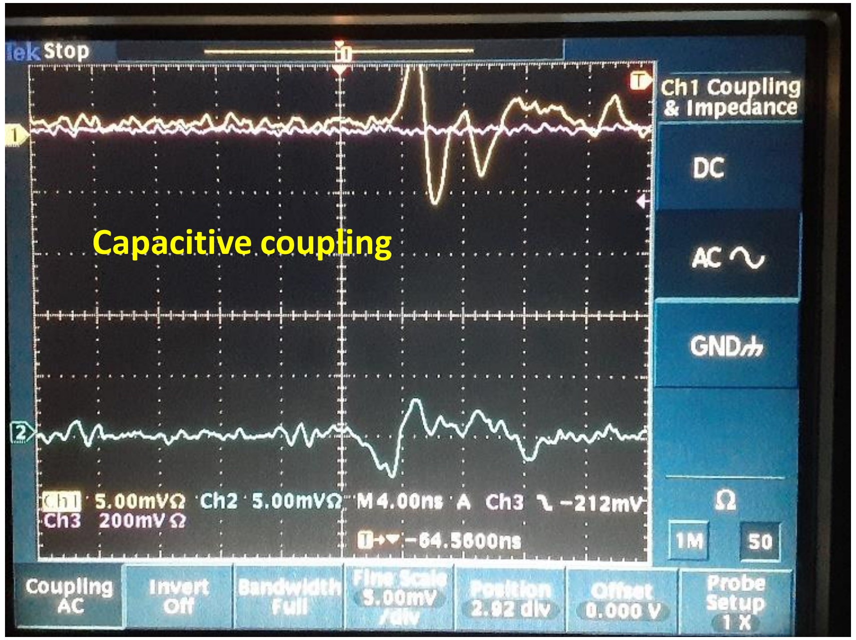
A small prototype using a 100 cm x 70 cm 1-mm single gap





64 cm x 64 cm active area using two orthogonal strips



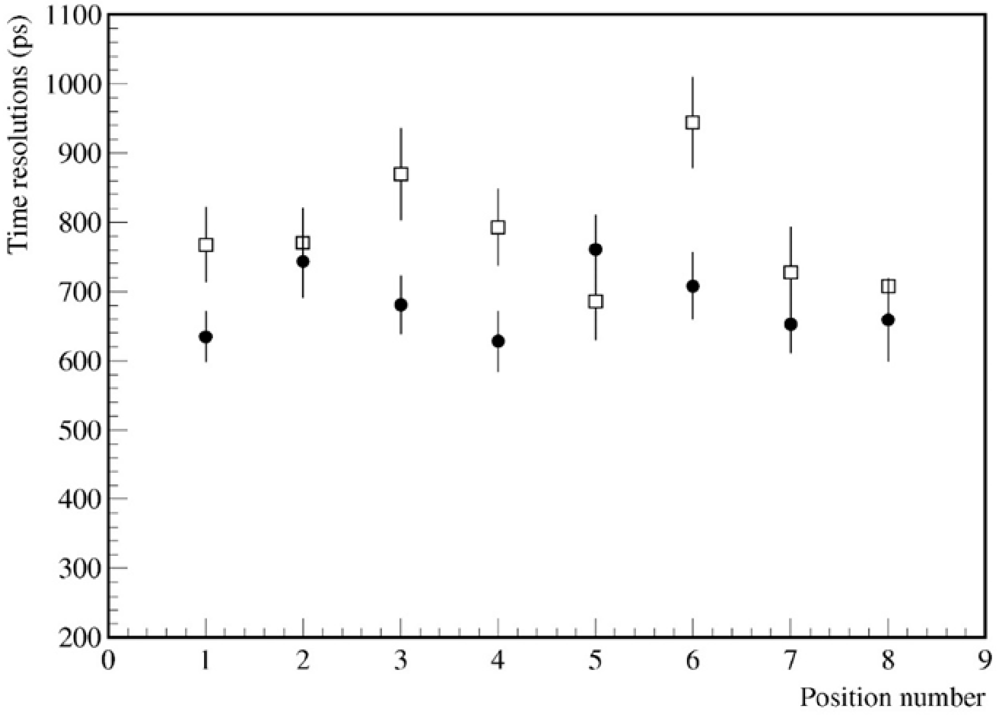


Intrinsic time resolution of 1-mm single-gap RPCs

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

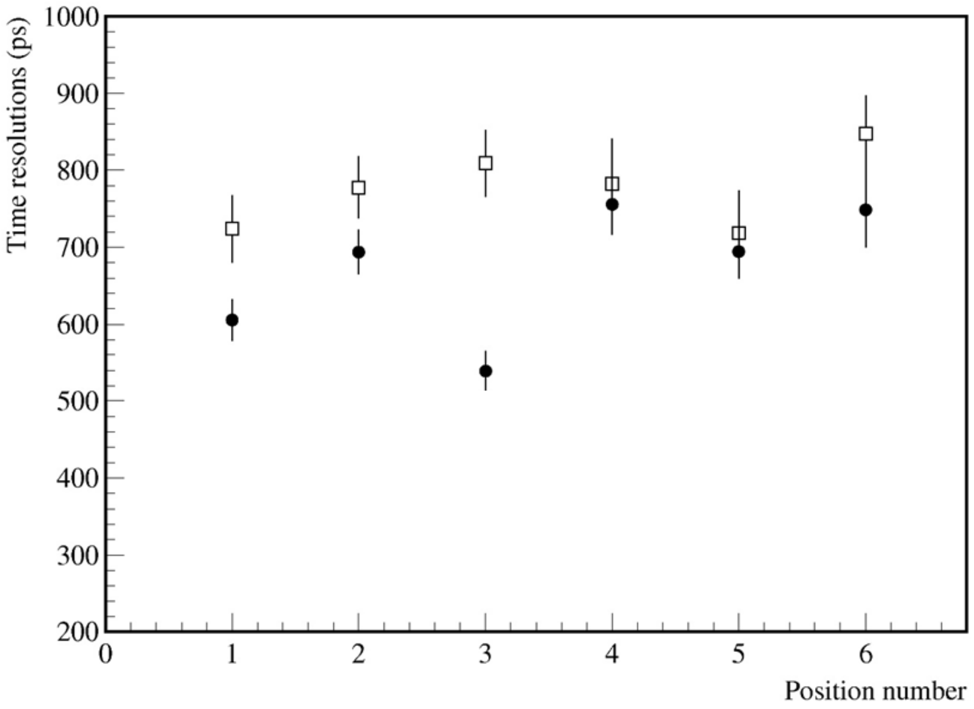
Th = 0.4 mV (~ 60 fC) for *x* strips
= 0.3 mV (~ 45 fC) for *y* strips

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



Time measurement and corrections for *x* strips using a *y* strip position

Signal arrival times vary position by the position on the strips
Can apply time corrections for *x* strips 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 → $t_x^c = t_x + 52.08 \text{ ps cm}^{-1} \times y$

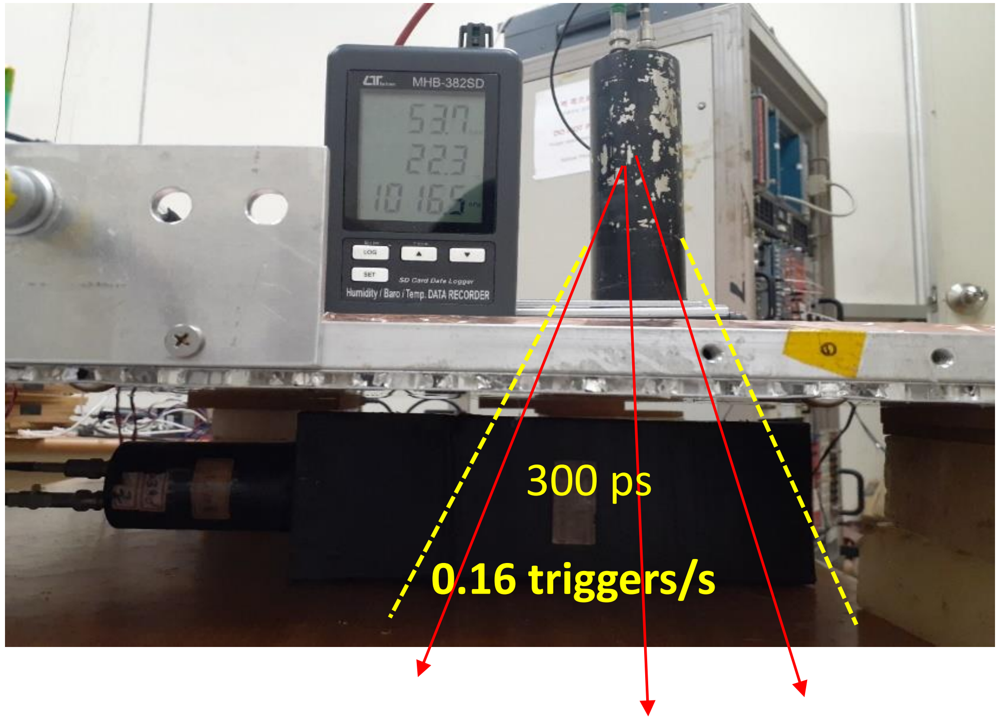
→ Hit-position corrected time distribution of the anode (*x*) strip times using vertical y-strip positions

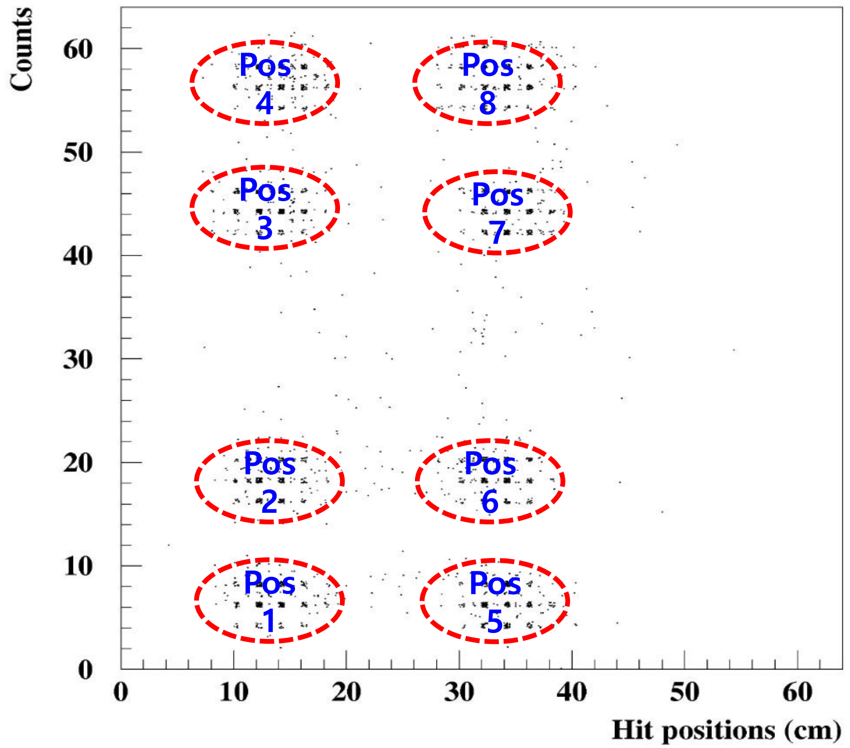
$\sigma_{trigger}$ ~ 300 ps

σ_{FEB} ~ 390 ps

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

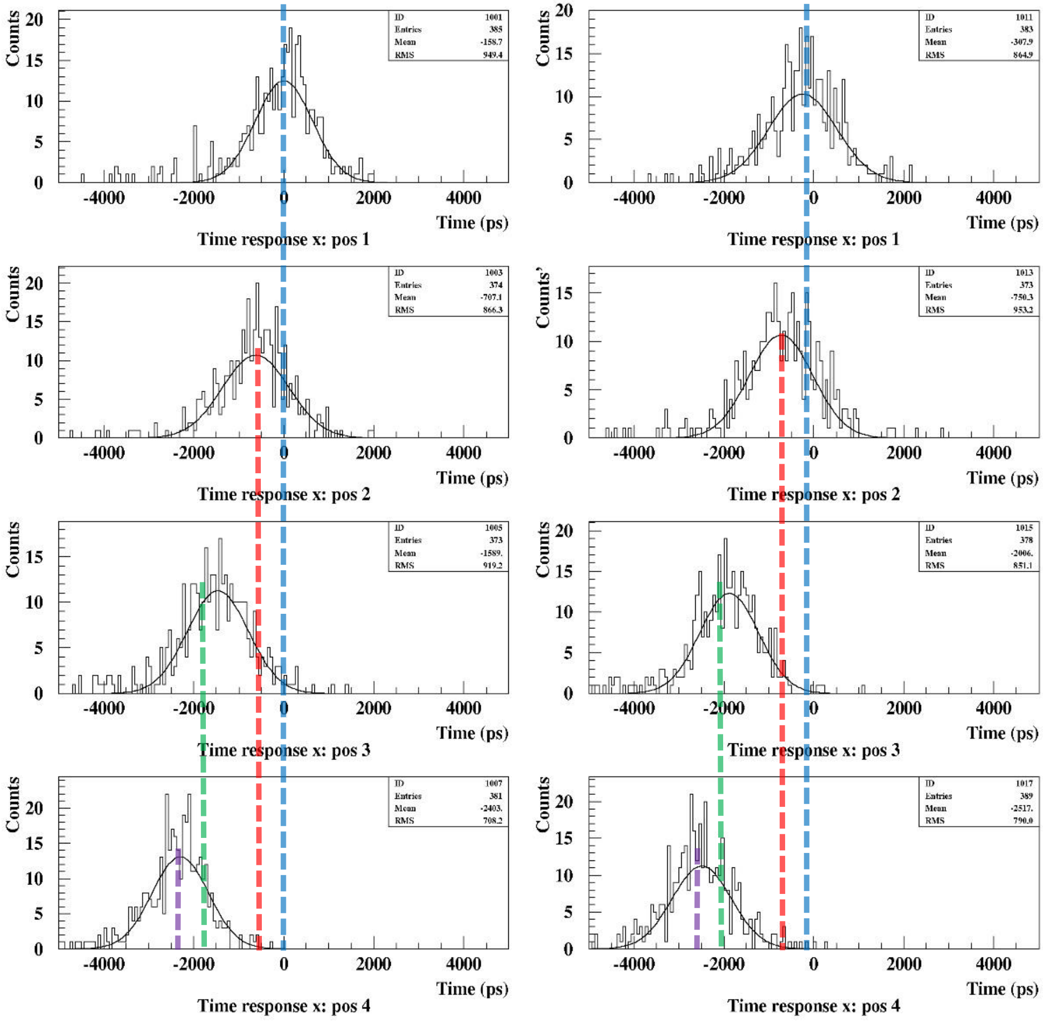
= 0.3 mV (~ 45 fC) for y strips





Corrections for signal arrival times on *x* strips

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

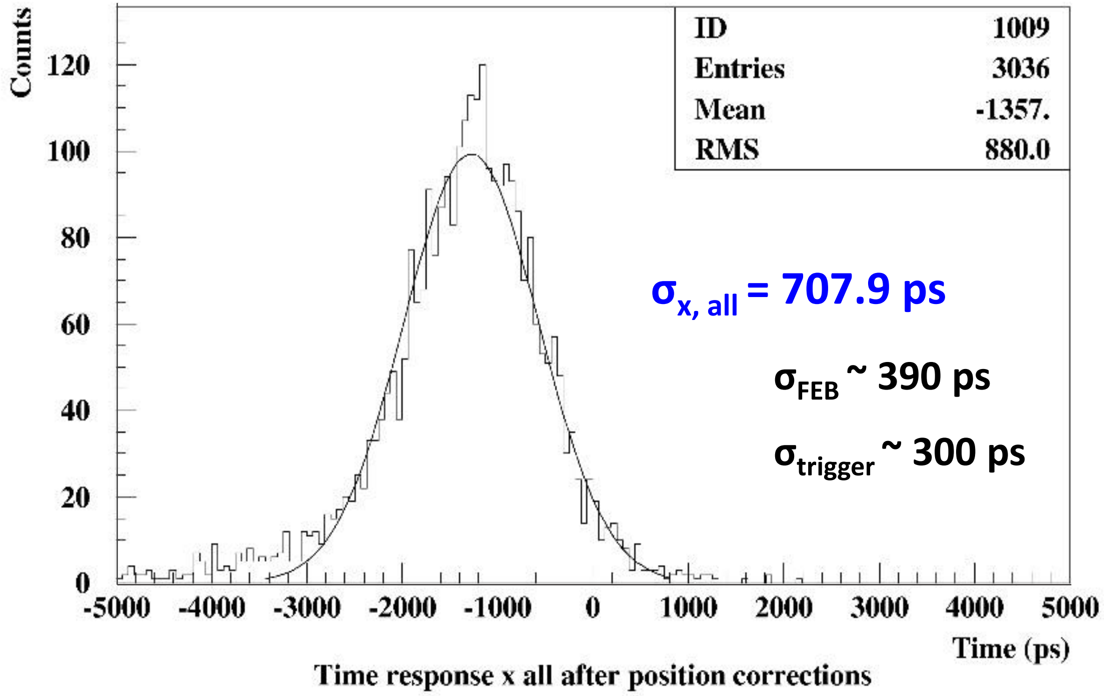


After the hit-position corrections, the signal arrival time on anode strips are corrected for a reference position of the detector layer.

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

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

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

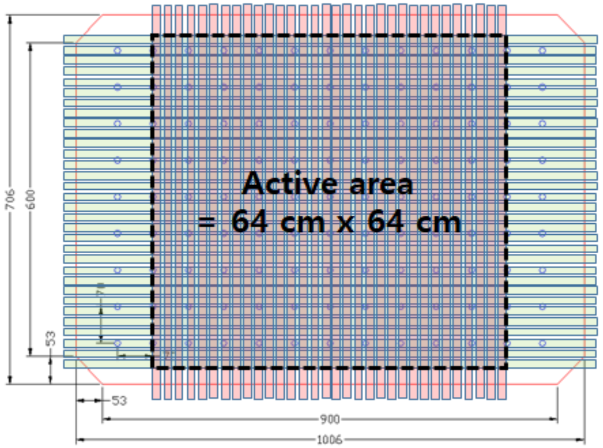


In 2019, R&D on 1.6-mm single-gap 2D RPC

Same detector structure but with a 1.6 mm gap

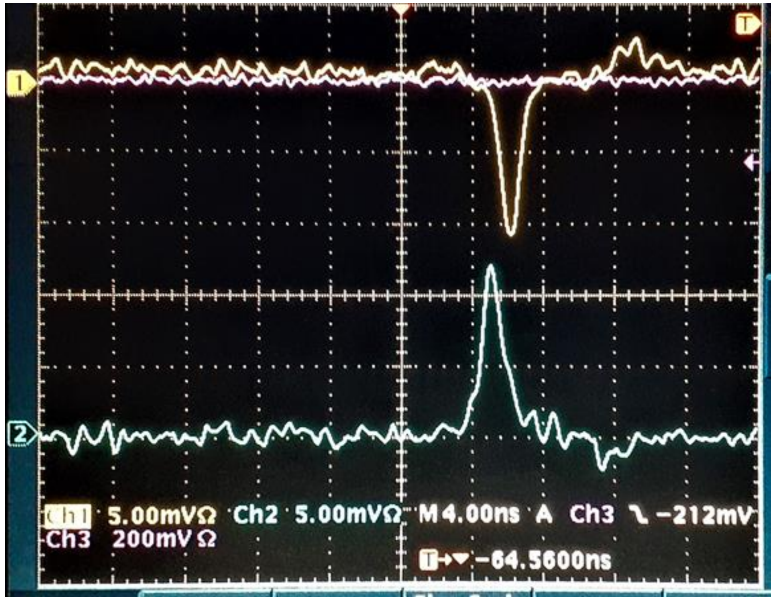
- ✓ The WP HV (~ 8.2 kV) is lower compared to 2-mm gap RPCs (~ 9.6 kV)
  → WP HV < 11 kV when using a new HFO1234a based eco gas
- ✓ Applied 2 orthogonal strip readouts for 2D trigger measurements with a time resolution better than 1 ns
- ✓ The intrinsic time resolution is relatively poor compared to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

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

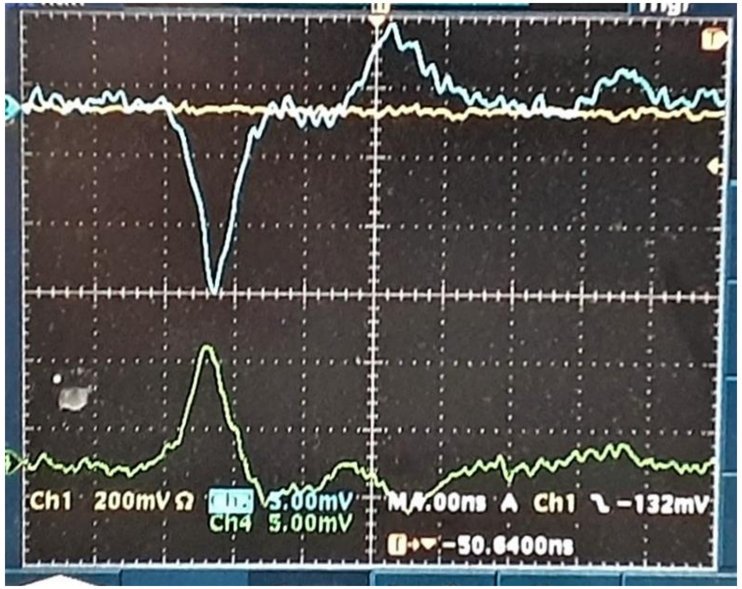


Test gas = 95.2% TFE + 4.5% iC_4H_{10} + 0.3% SF_6

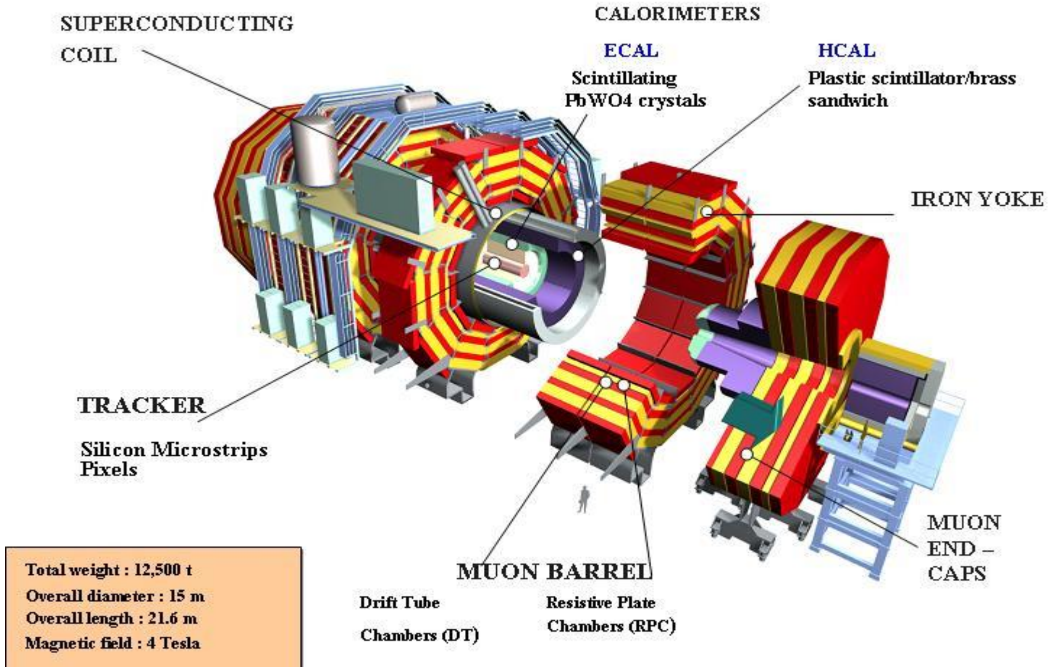
1.0-mm single-gap 2D RPC



1.6-mm single-gap 2D RPC



Adding new RPCs to the Compact Muon Solenoid

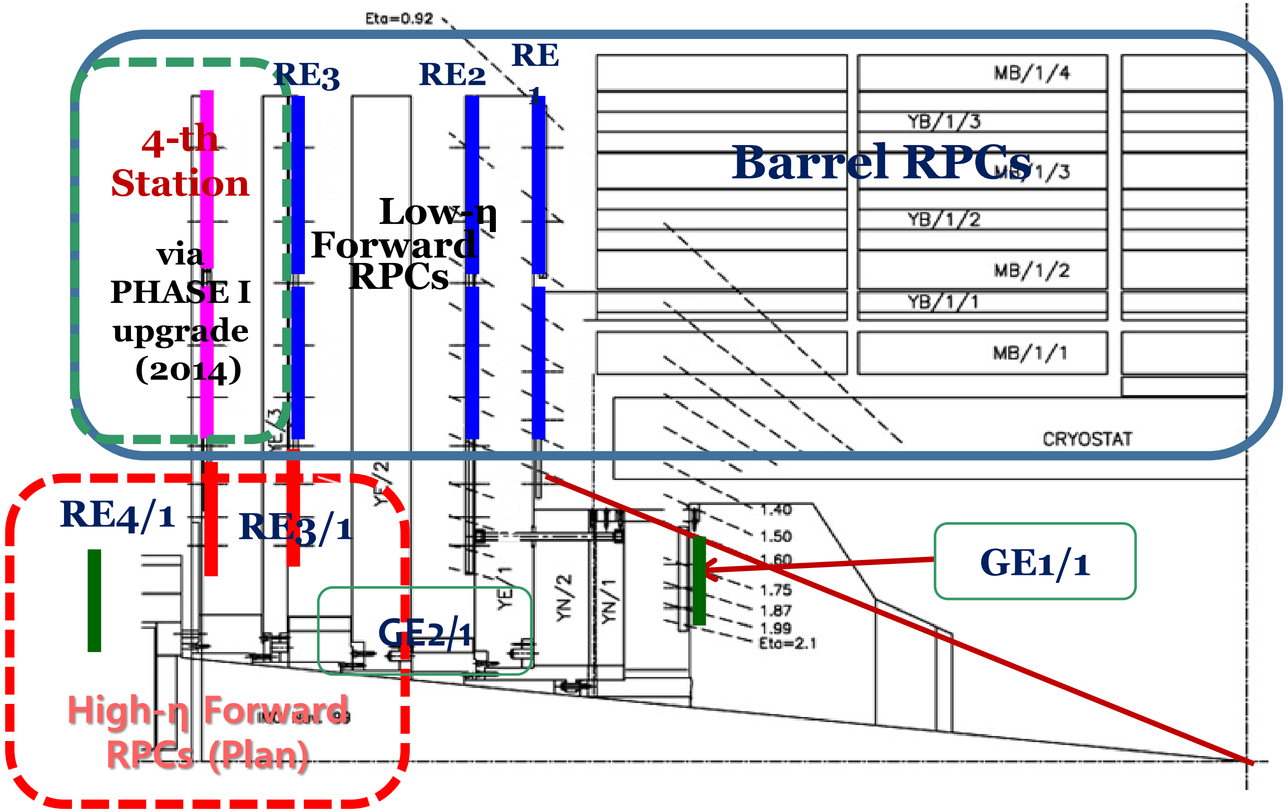


Barrel RPCs

- 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

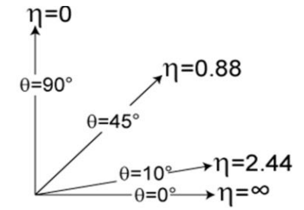


Backup solution for CMS iRPCs

2D double-gap RPCs

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

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



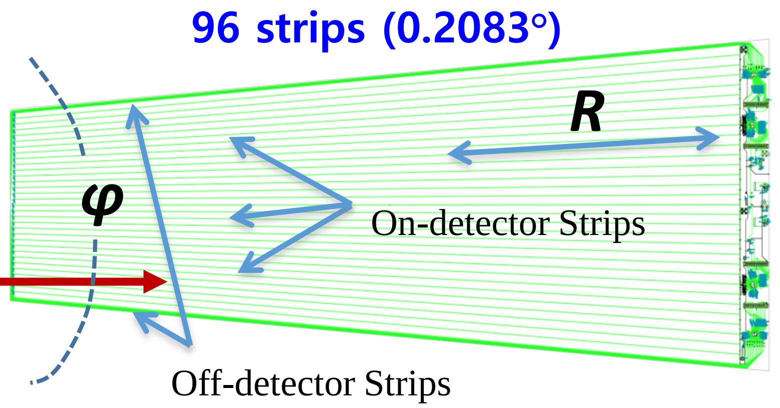
Baseline design for CMS iRPCs

Reading ***φ-r*** **positions (2-dimensional tracking)**

- Position resolutions: ~ 3 mm for φ and ~ 20 mm for r
- 1.4-mm thick double-gap RPCs
  - ✓ WP efficiency > 0.97 @ HV=7.3 kV
  - ✓ Mean C_s at WP ~ 2.2 @WP
- Reading signals from both ends of strips

  Signal propagation speed in the strips

  = 18.4 cm/ns @ strip 30 Ω < Z < 70 Ω



96 strips (0.2083°)
φ resolution ~ 3 mm

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

$$\sigma(R) = v\ (19.2\ \text{cm/ns}) \times \sigma_{(tL - tR)} / 2\ (\text{ns}) \sim 2.0\ \text{cm}$$

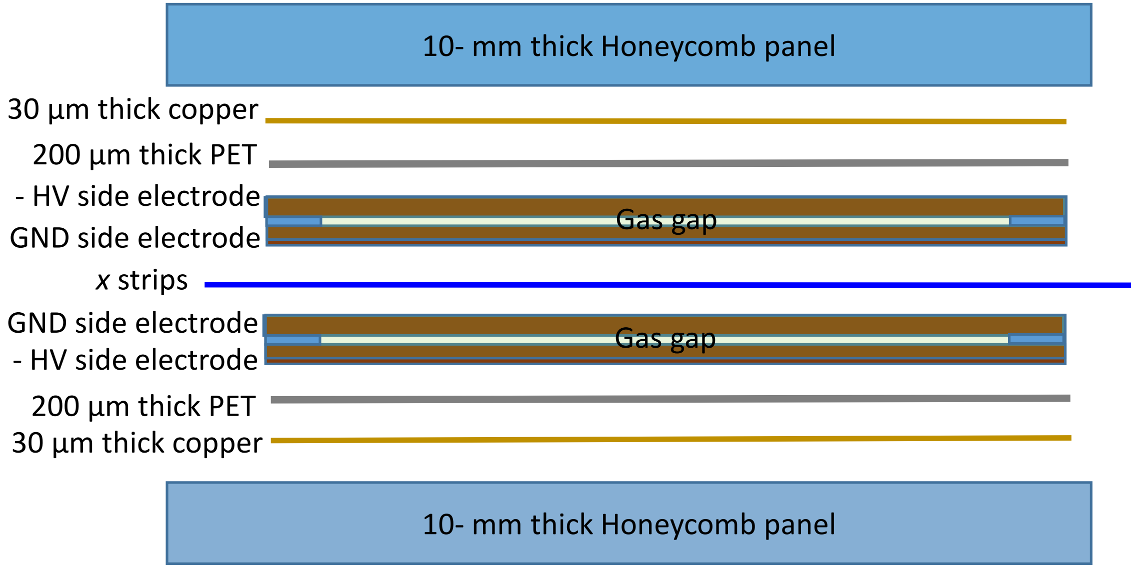
Front-end electronics: **PETIROC ASIC + TDC**

- 16 channels
- Gain 25: lowest digitization threshold ~ 80 fC

  → The minimum threshold < 20 fC in a new version

  essential for rate capability & longevity (chemical hardness)
- Fast pre-amplifier and fast discriminator in SiGe technology → time resolution (jitter) <100 ps

  essential for HSCP



Another 2D RPC model with double gaps

Asymmetric detector structure for the signal readout

- ✓ Anode signals from double gaps
- ✓ Cathode signals from top single gap

Anode side efficiency @WP ~ 0.98

Cathode side efficiency @WP ~ 0.96

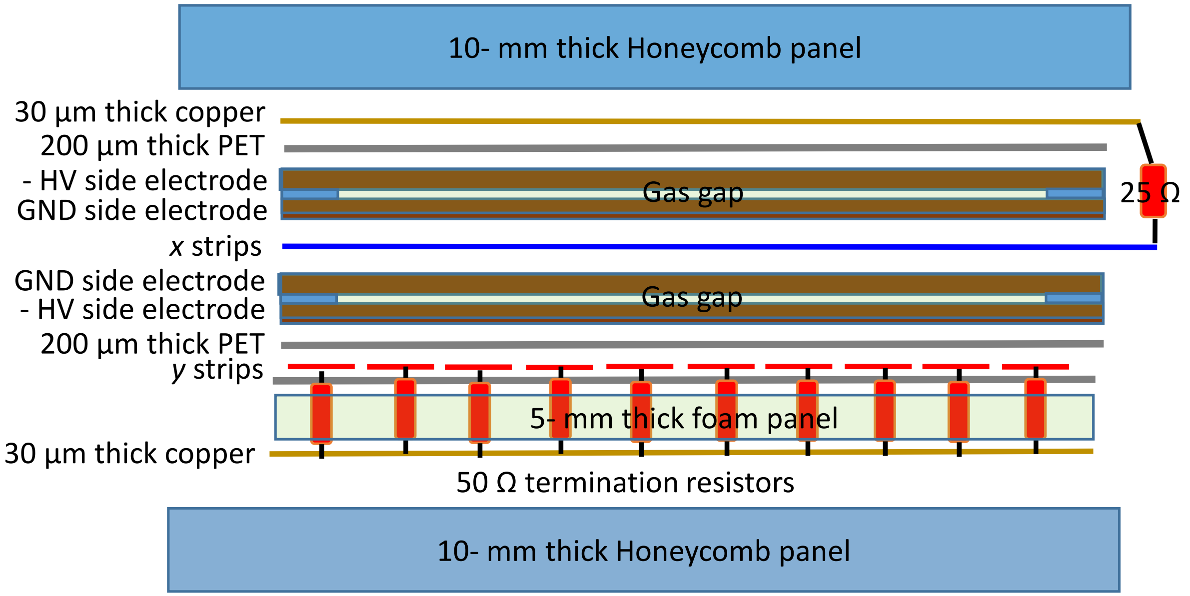
Coincidence efficiency @ WP ~ 0.96

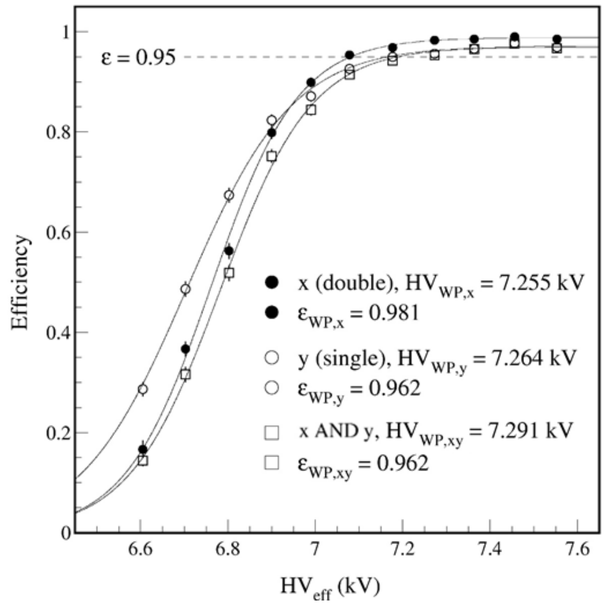
Merit:

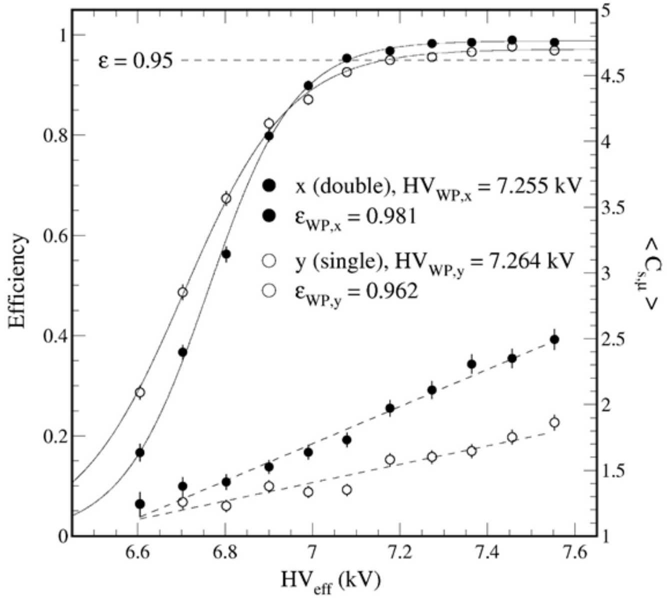
- ✓ higher anode side efficiency compared to the single-gap case
- ✓ Thin 2D double-gap detectors for the CMS RPC system

Drawback:

- ✓ Operational complexity. Have to make the WPs matching as close as possible by adjusting the thresholds
- ✓ Cathode strips are the lower part of the reference ground. They affect to the impedance for the anode strips







Conclusions

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

→ successfully tested for 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 < 11 kV

1.4-mm asymmetric double-gap RPCs: thin detector structure -> nice candidate for a backup solution for CMS iRPCs

The present model RPCs with better time & position resolutions

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

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

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

Milestones

CMS iRPCs

2020 07: Completion of production facilities for gap electrodes and the QC

2020 09 - 2021 03: Preproduction for gap electrode and first RE4.1 prototypes

2021 06: Final version Front-end electronics (digitization + TDC)

2021 08: Final version Back-end electronics

2021 04 - 2022 06: Main production of gap electrodes for iRPCs (during preproduction period)

2022 12: 1st 4 ~ 6 RE3.1 or RE4.1 iRPCs

2021 10 - 2023 04: Production of iRPCs and completion of installations.

SHiP SND RPCs

2020 11: Delivery of 3 ~ 4 gap electrodes to CERN (the 1.6-mm 2D single-gap model is the final.)

New detector R&Ds to produce a few real size prototypes

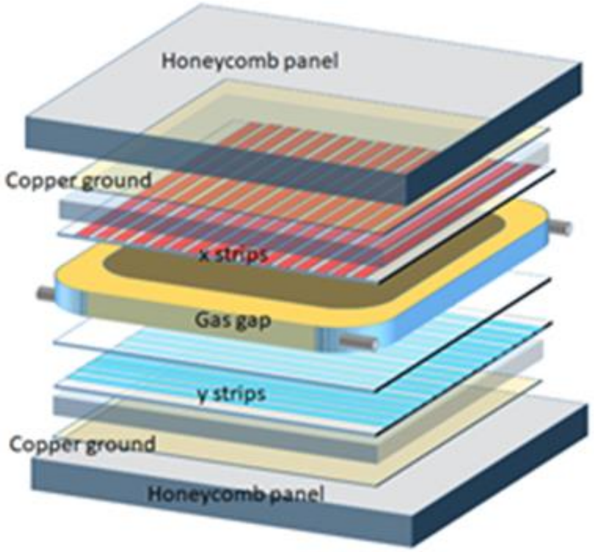
The final model will provide the solution for the use of the environmental friendly gas mixture.

Muon radiography

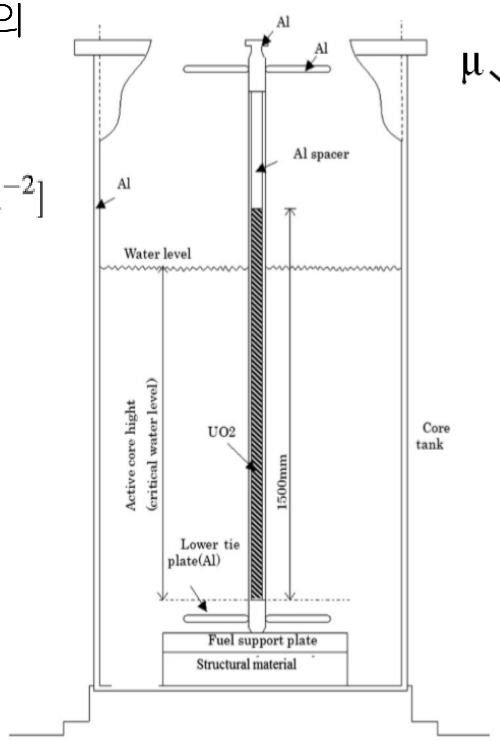
유온 래디오그래피는 방사선이 물질에 흡수되지 않고 약하게 쿨롱 산란되는 원리(주된 산란이 한번일 확률이 높아야 무거운 대상 물질에서의 반응 위치를 찾아냄)를 이용하여 투과된 뮤온의 궤적 추적으로부터 투시 대상을 영상화하는 기술.

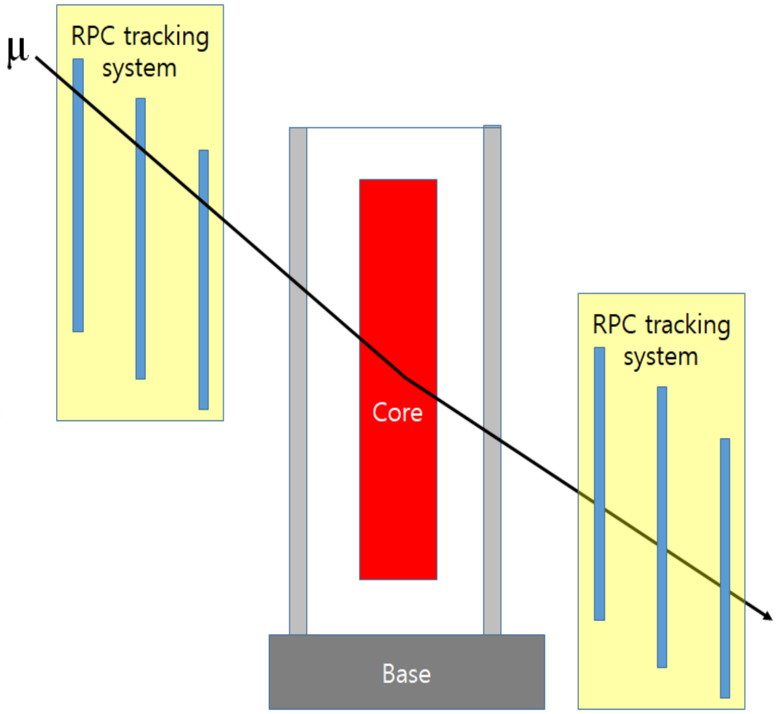
두께가 T, (단위 g cm^{-2}) 전하량이 Z, 질량수가 A인 물체를 대전입자가 투과 할 때 쿨롱 산란에 의한 산란각 분포(가우스)의 편차를 나타낸 식. X_0는 radiation length

$$\sigma_\theta \approx \frac{13.6\,MeV}{pc\beta}\sqrt{\frac{T}{X_0}}\left[1+0.038\,ln\left(\frac{T}{X_0}\right)\right] \qquad X_0 \approx \frac{716.4A}{Z(Z+1)\ln\left(\frac{287}{\sqrt{Z}}\right)} \quad [\mathrm{g\cdot cm^{-2}}]$$



핵반응로 내에 존재할 물, 콘크리트, 철, 우라늄 등에 대한 radiation length는 각각 36.08, 26.57, 13.84, 6.00 g cm^{-2}



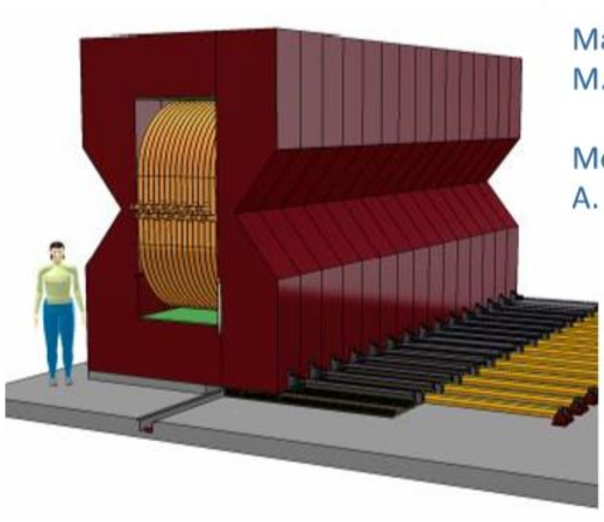


BACKUPS

Scattering and Neutrino Detector

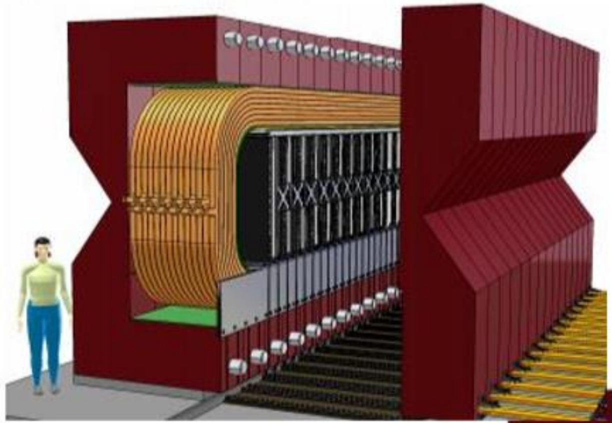
- Warm magnet
- Target system
- Muon system

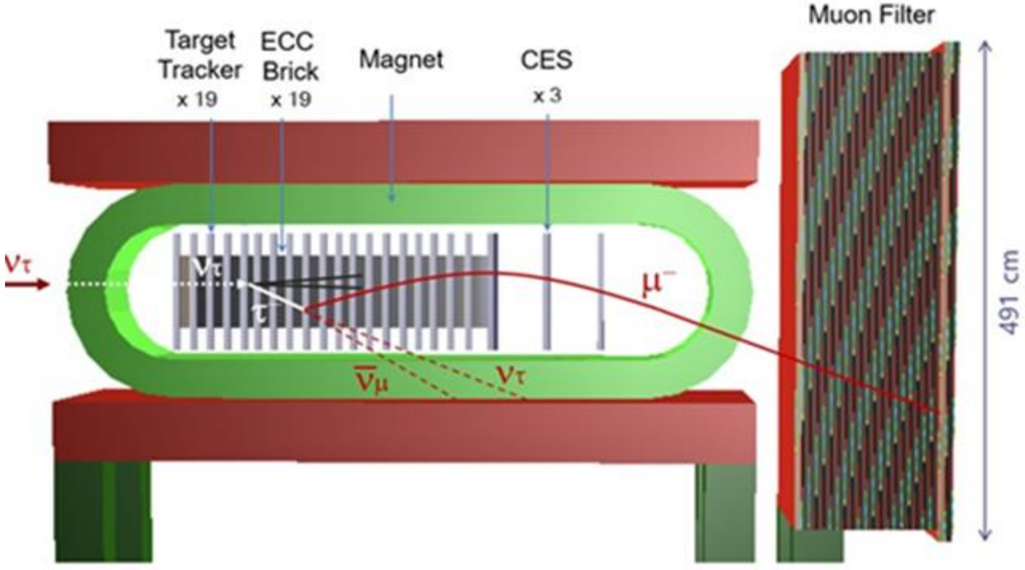
M. De Serio (University of Bari and INFN Bari)
SHiP Collaboration Meeting, 2 April 2020



Magnet design*:
M. de Magistris (Electrical engineering group of Napoli Univ.)

Mechanical structure and integration:
A. Crupano (INFN Napoli)

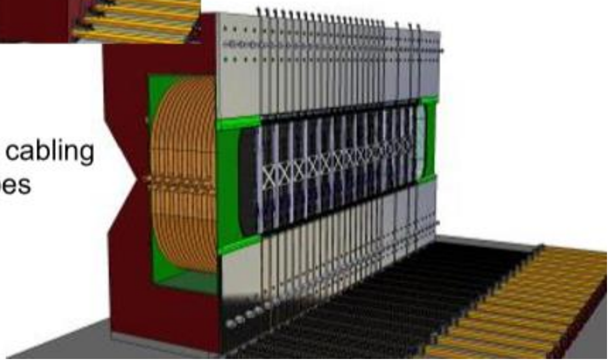




Neutrino & LDM detector

JINST 15 P01027 (2020)

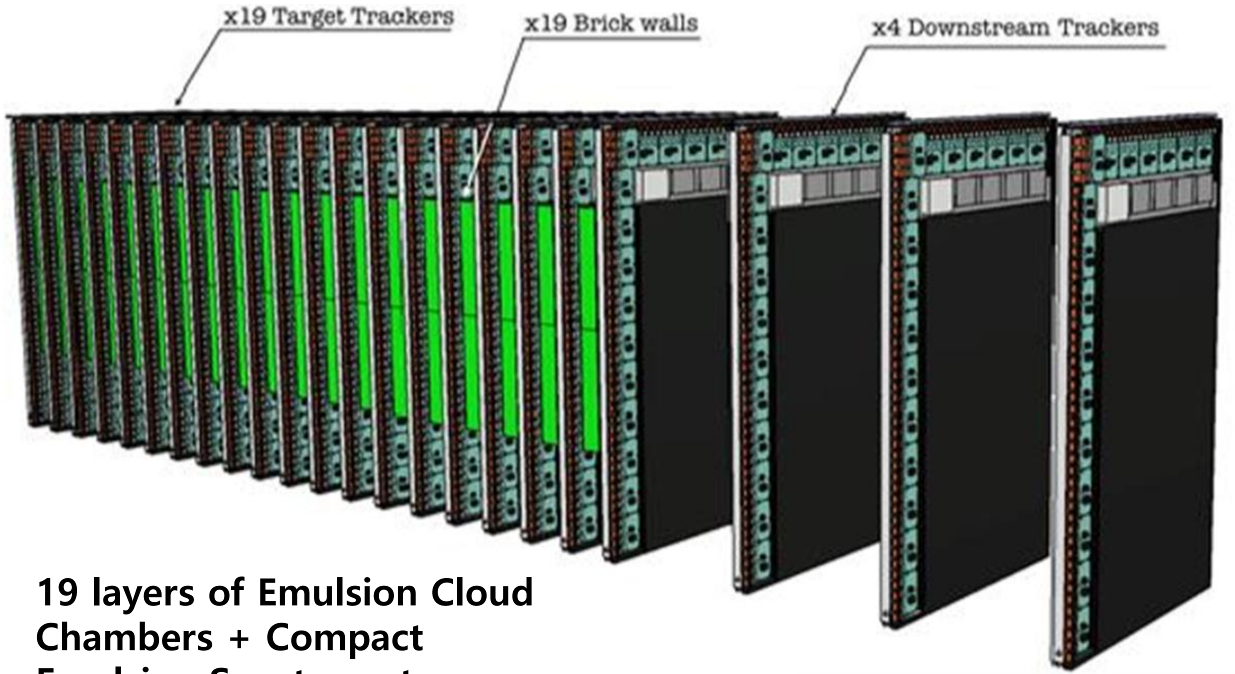
Integration of SciFi cabling and water pipes



Target System

To allow neutrino interactions and potential detection of light dark matter

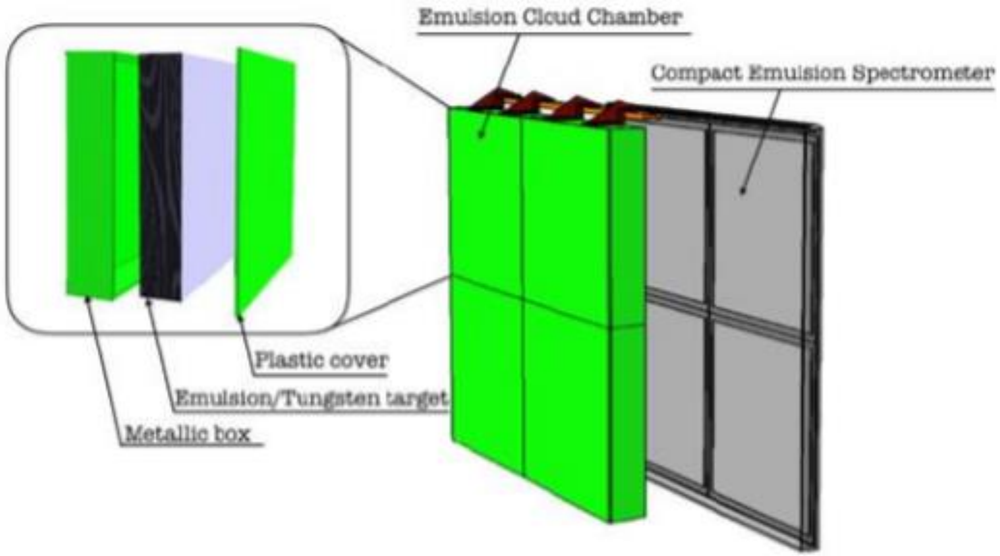
19 layers of Emulsion Cloud Chambers + Compact Emulsion Spectrometer
Four 2D TT planes compose of scintillation fibers equipped with SiPMs

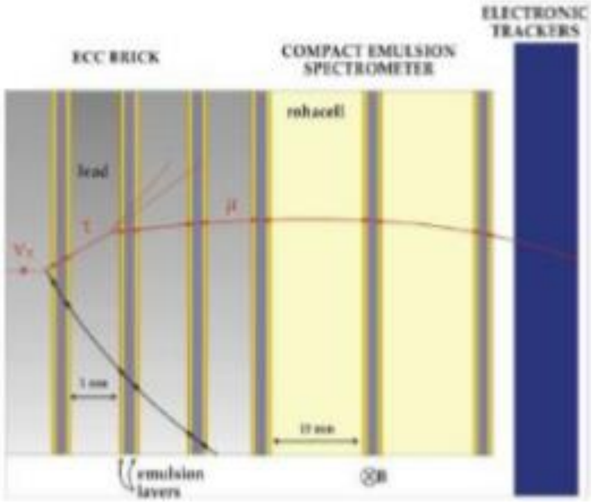


19 layers of Emulsion Cloud Chambers + Compact Emulsion Spectrometer

TT planes (917 x 1440mm^2)
- Provide event time stamp
- ECC/CES track matching
- Energy measurement

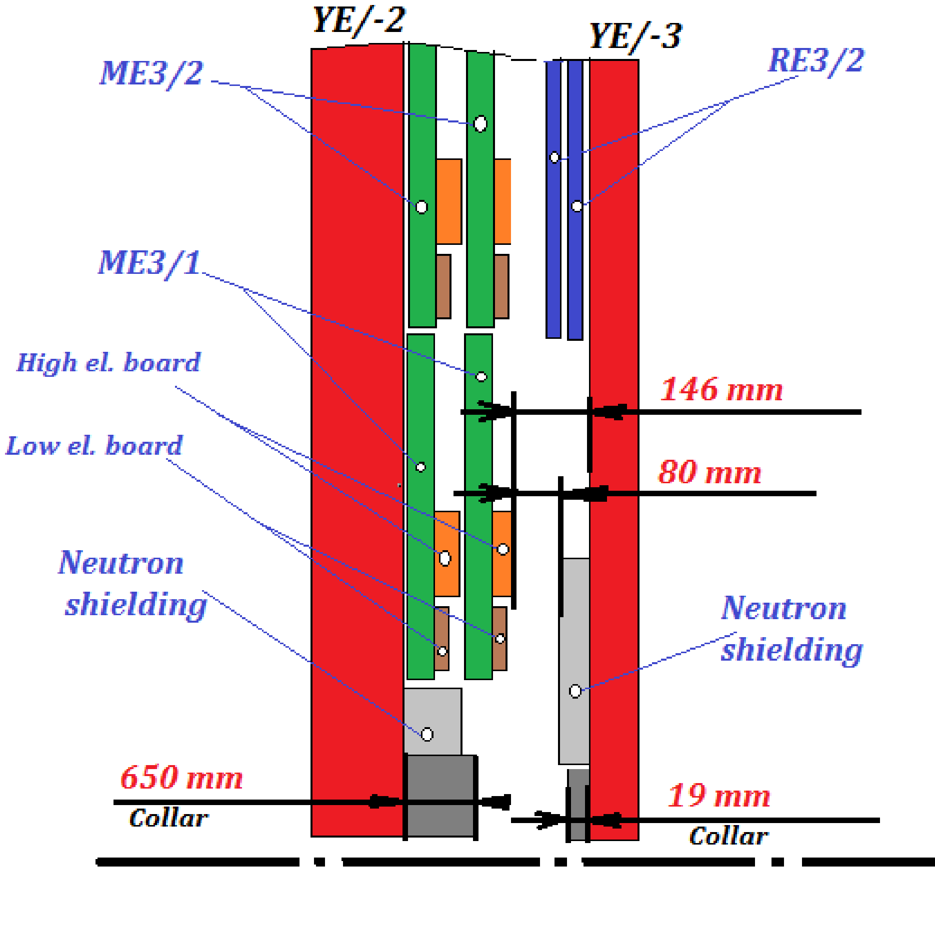
ECC + CES

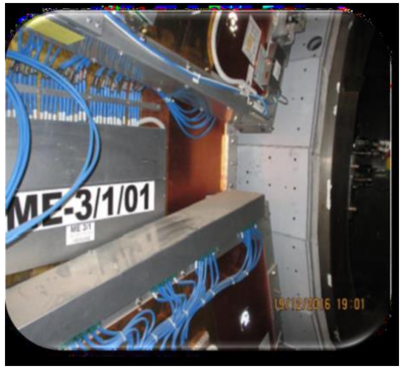




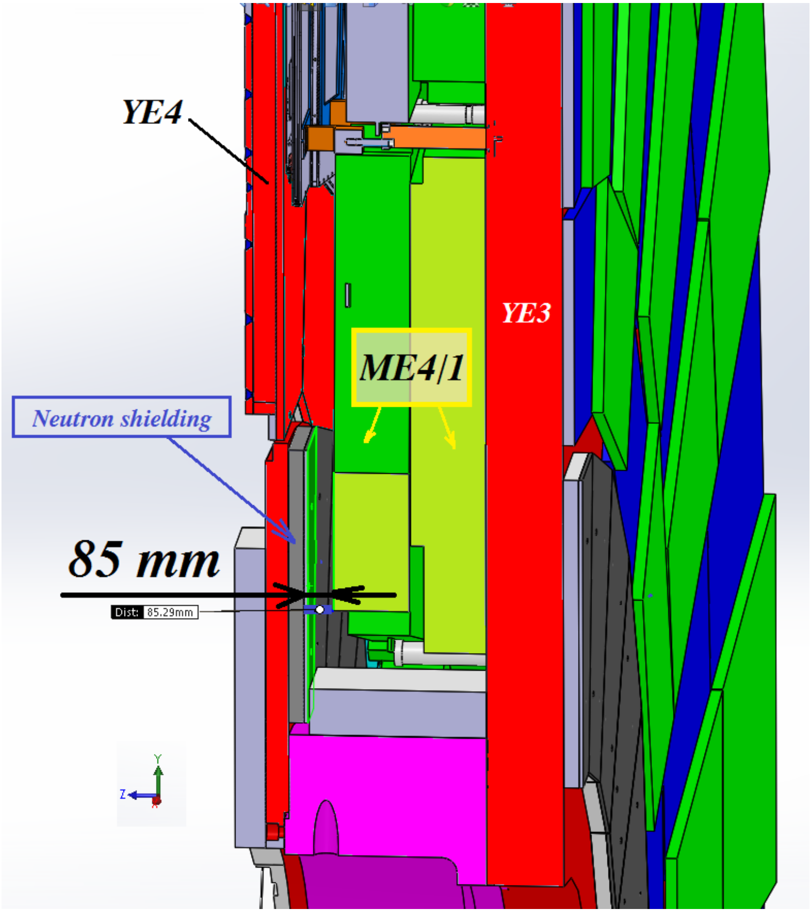
New iRPCs in the RE3/1 and RE4/1 stations with the improved technology

RE3/1 in ME3/1

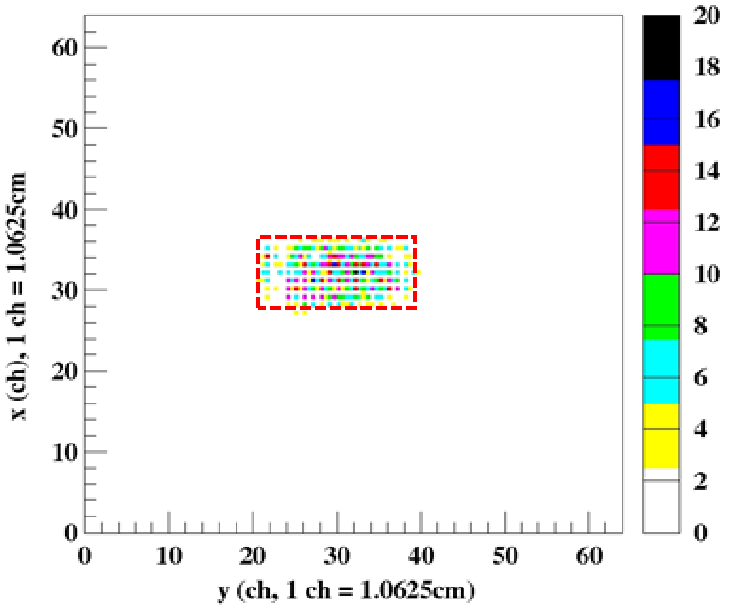


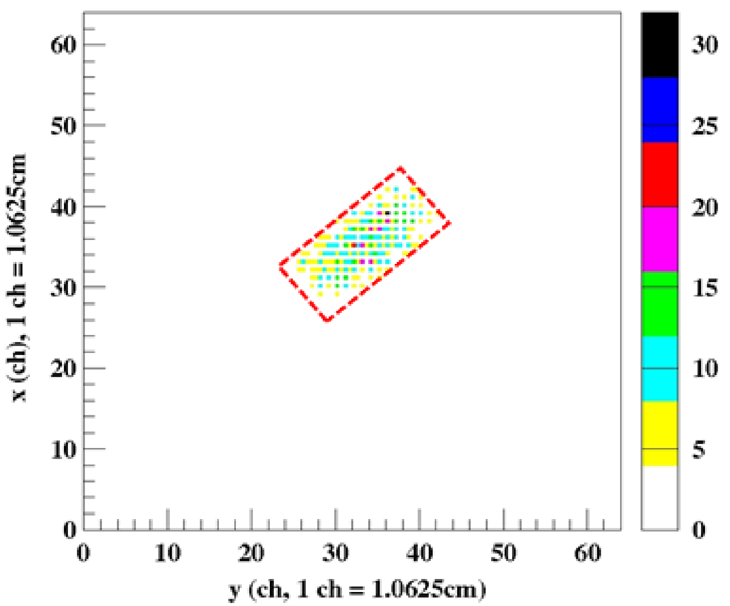


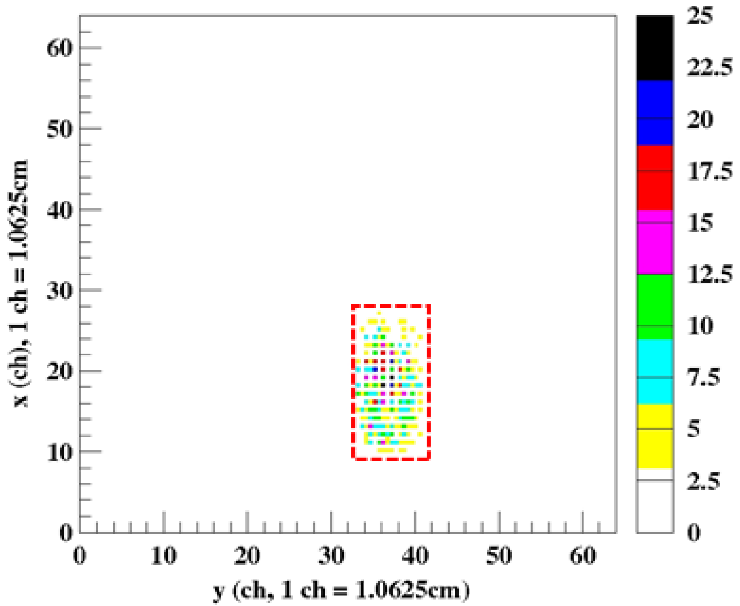
RE4/1 in ME4/1

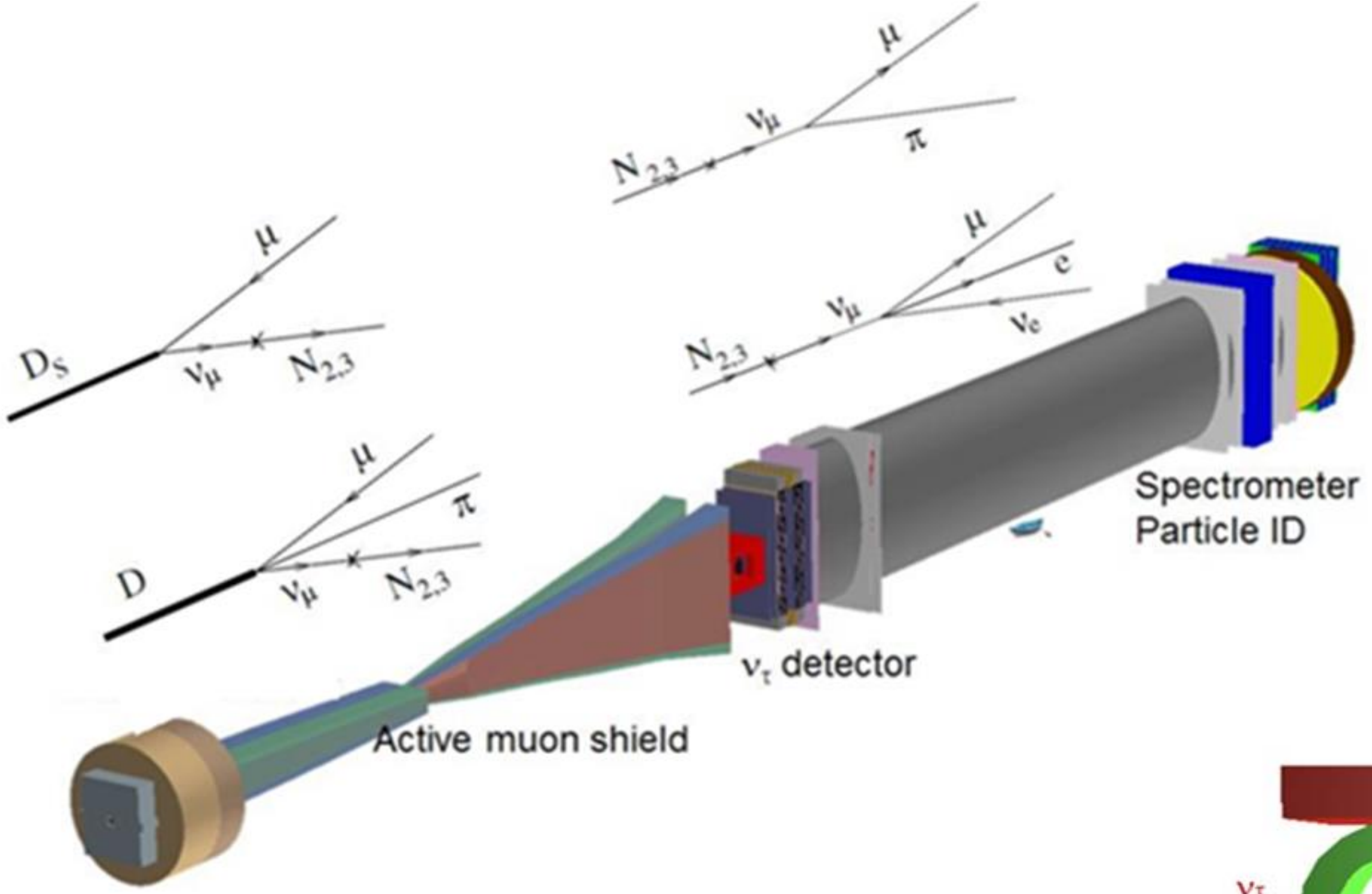


Reconstructed 2D images of cosmic muons (tagged by plastic scintillators)

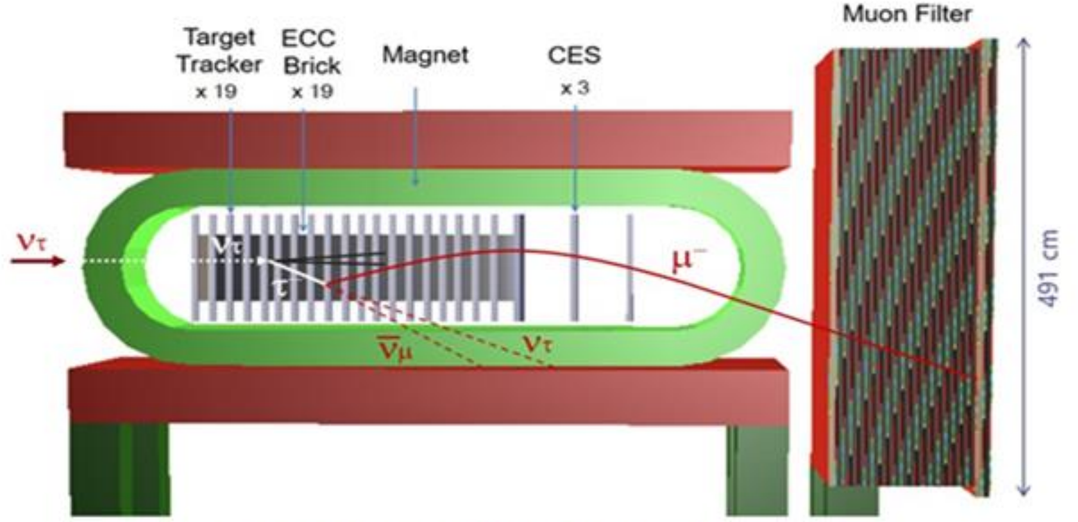








RPC system will be used to reject neutrino associated charged particles coming into decay volume for hidden particles.



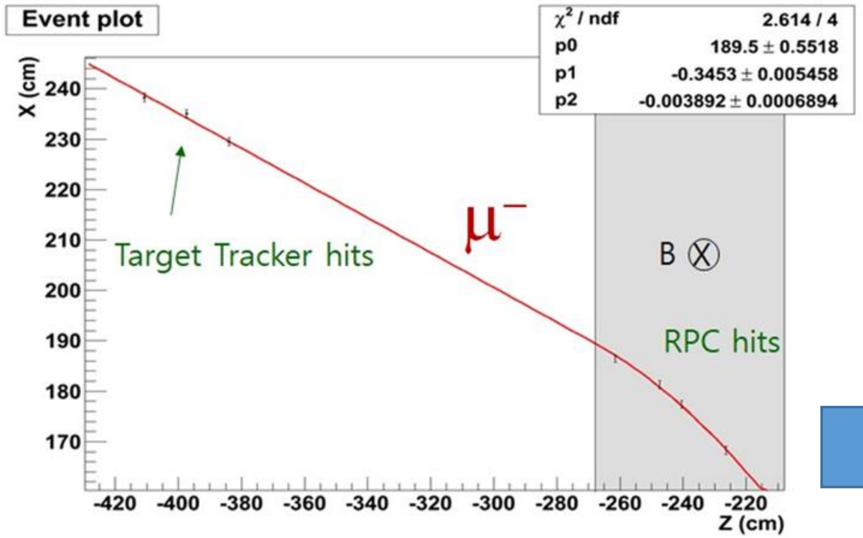
Neutrino & LDM detector

Charm measurement
Sample data

Presented in ShiP-Charm meeting on 2nd October 2018

A. Pastore, INFN Bari and University of Bari

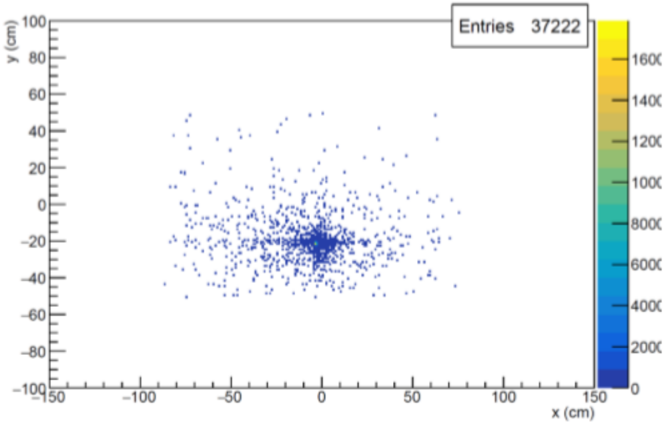
The muon charge was determined to be negative from track curvature in the spectrometer (RPC hits)

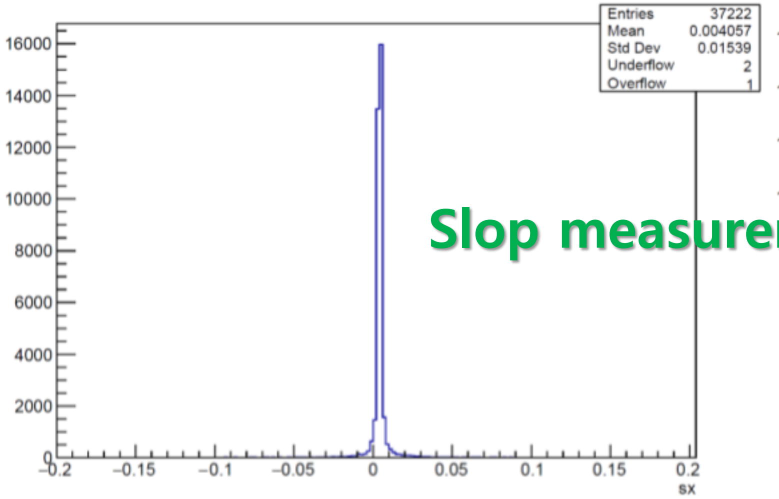


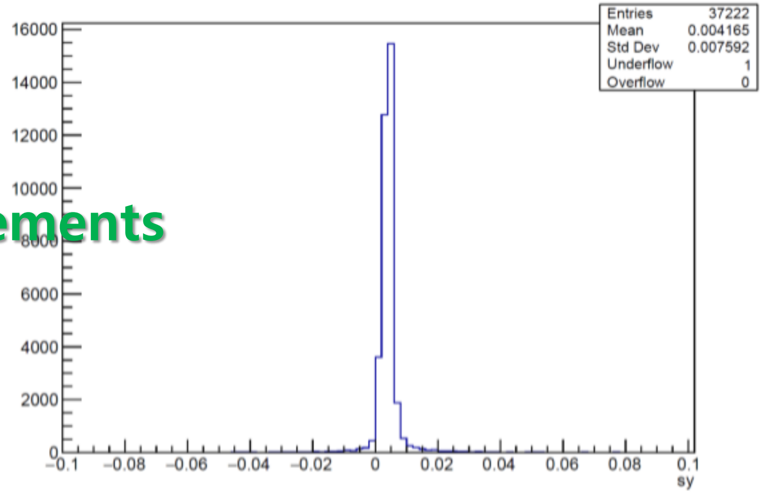
$\nu_\tau \rightarrow \tau^- \rightarrow \mu^-$ ○

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

Reco-tracks in CHARM1-run6, run 2793







Slop measurements

Muon radiography

RPCs system

- Much cheaper to build a large system (detection area 2 m × 2 m)
- RPCs are themselves capable of triggers
- Very low noise

Selection of muons with momentum range larger than 0.5 GeV/c

For typical 1 GeV/c muons, β = 0.995

- ✓ σ_θ ~ 50 mrad in UO2
- ✓ TOF in a 10 m track = 33.49 ns (light = 33.37 ns)

To reject soft muons of 0.5 GeV/c (β = 0.983)

TOF in a 10 m track = 33.88 ns

→ We need a detector system better than a 500 ps time resolution

Assuming 8 2D RPC system,

- 50 cm gap between adjacent layers → total detector thickness < 2 m
- Position resolution of each detector layer ~ 3 mm
- Angle resolution ~ 2 mrad
- Expected position resolution for 'kink' point voxel image ~ 2 cm
- Then, we select muon tracks with deflection angles > 30 mrad