R&D on high timing performance RPCs

On behalf of RPC R&D groups from I KODEL and NFN-Ba-To

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RPC R&D

High timing performance RPC for future accelerators (DRD1-WP7b)

Some tasks:

- Development and performance study of small RPC prototype with time resolution of O(200 ps)
- Production of large area RPC keeping the timing performance

Performance study:

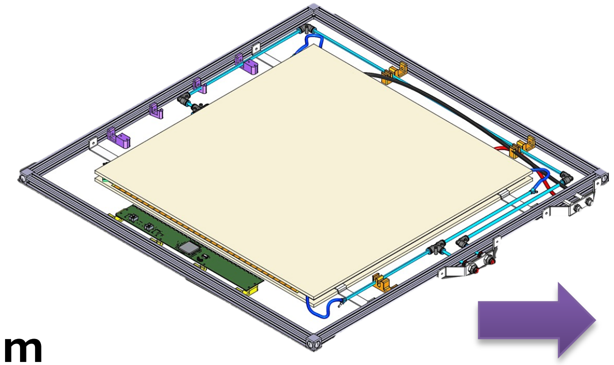
- Characterization with cosmics: signal study with different gaseous mixtures

- Performance on beam tests (efficiency, ..., time and spatial resolution)

FOR Space resolution measurements: **Readout the prototype with VMM-3a FEE integrated in GDD beam telescope**

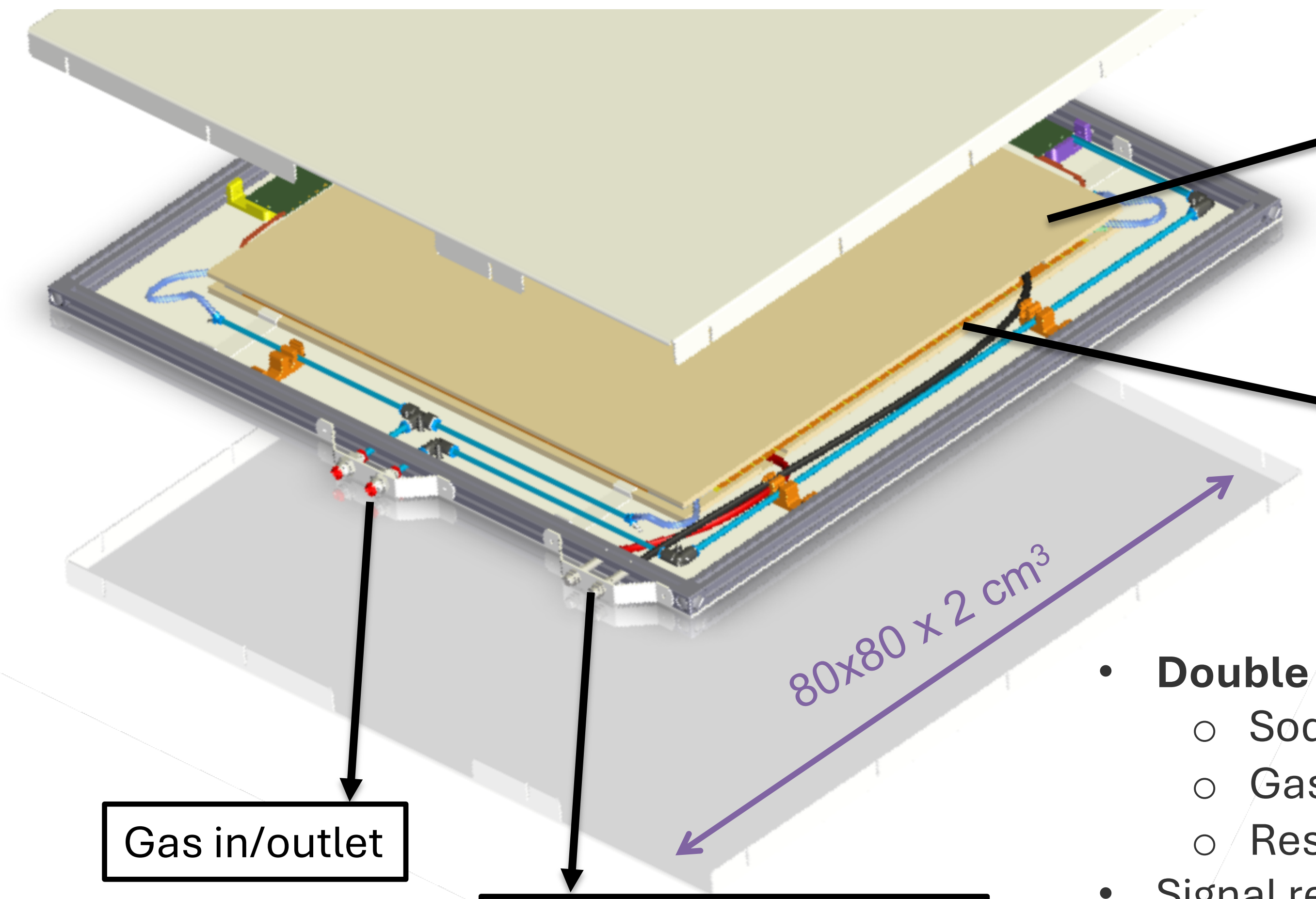
→ Possible of RPC into GDD beam telescope providing time stamp with resolution of 2 ns

- (...)

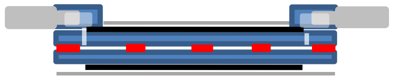


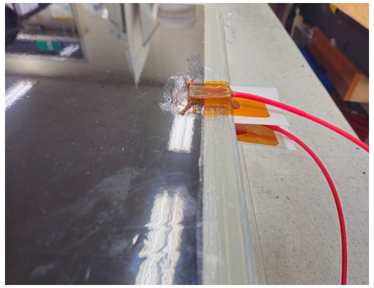
GDD beam monitoring tracker

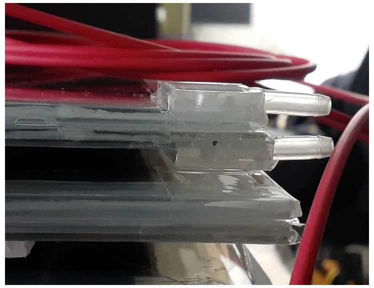
Thin-RPC prototype



thin gaps built in KODEL laboratory







Strip panel - pitch 5 mm - single readout (strips terminated with 50 Ω)

Gas in/outlet

HV connectors (1x gap)

- **Double gap** with strip readout panel in between
  - Soda-lime glass electrodes: 1.1 mm thickness
  - Gas gap: 500 um thickness
  - Resistivity: $10^{12}\ \Omega\cdot$cm at 20 C
- Signal readout: [CAEN Digitizer DT5742]() for signal detector study
  - 16 Ch + Fast trigger @ 5Gs/s
  - Active area: ~10 x 50 cm2

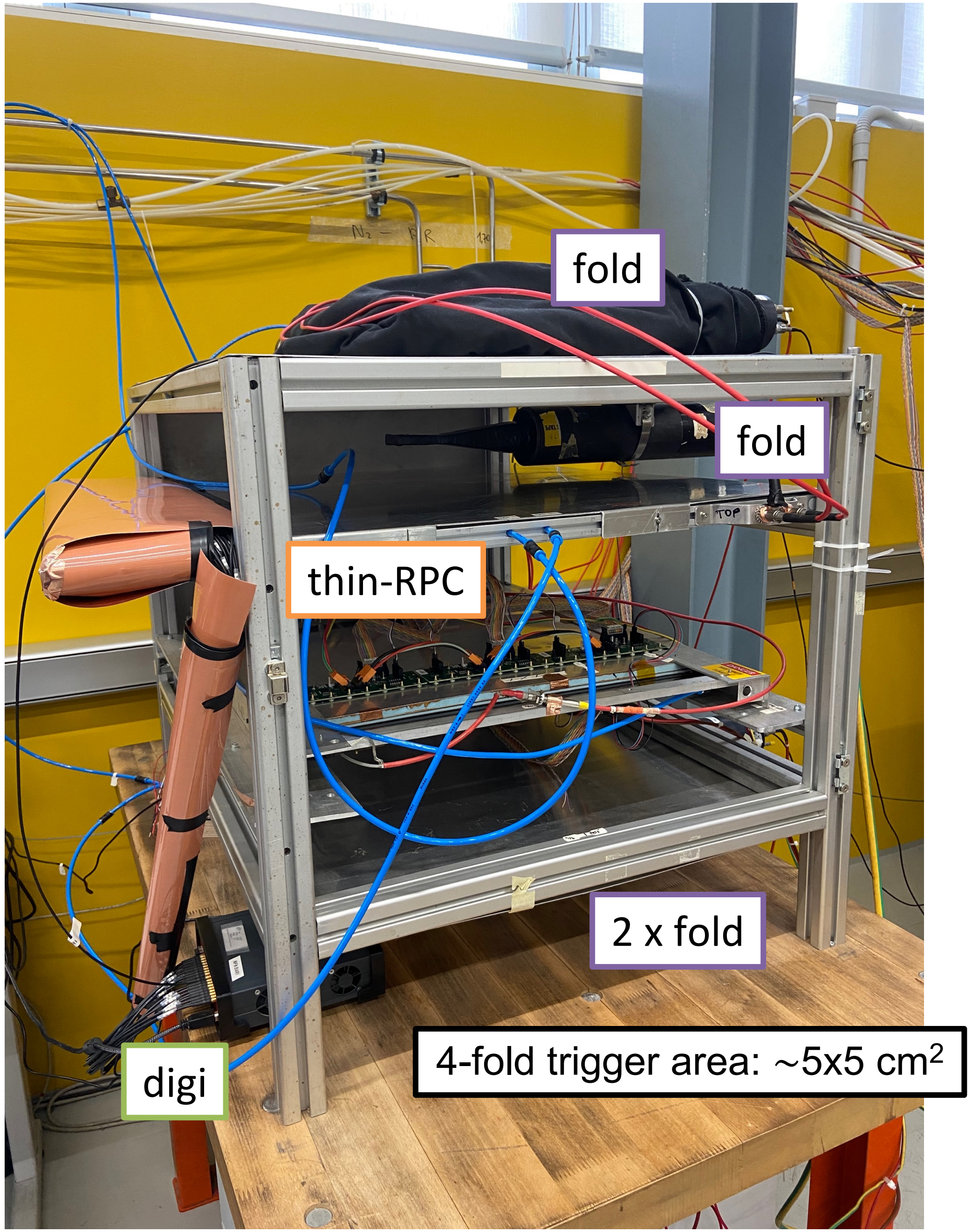
Setup @INFN-To

Cosmic setup → performance study with several mixture:

- Explore the possibility of operation with simplest mixture
- Timing study

Mixtag	TFE (%)	HFO-1234ze (%)	CO_2 (%)	iC_4H_{10} (%)	SF6 (%)
STD	95.2	-	-	4.5	0.3
STD2ISO	97.7	-	-	2	0.3
STD0ISO	99.7	-	-	-	0.3
STD30CO2	65	-	30	4	1
ECO65	-	65	30	4	1
TFEISO	95	-	-	5	-
TFE	100	-	-	-	-
Density (g/l)	4.68	5.26	1.98	2.69	6.61
GWP	1430	7	1	3	22800

test for integration at GDD lab

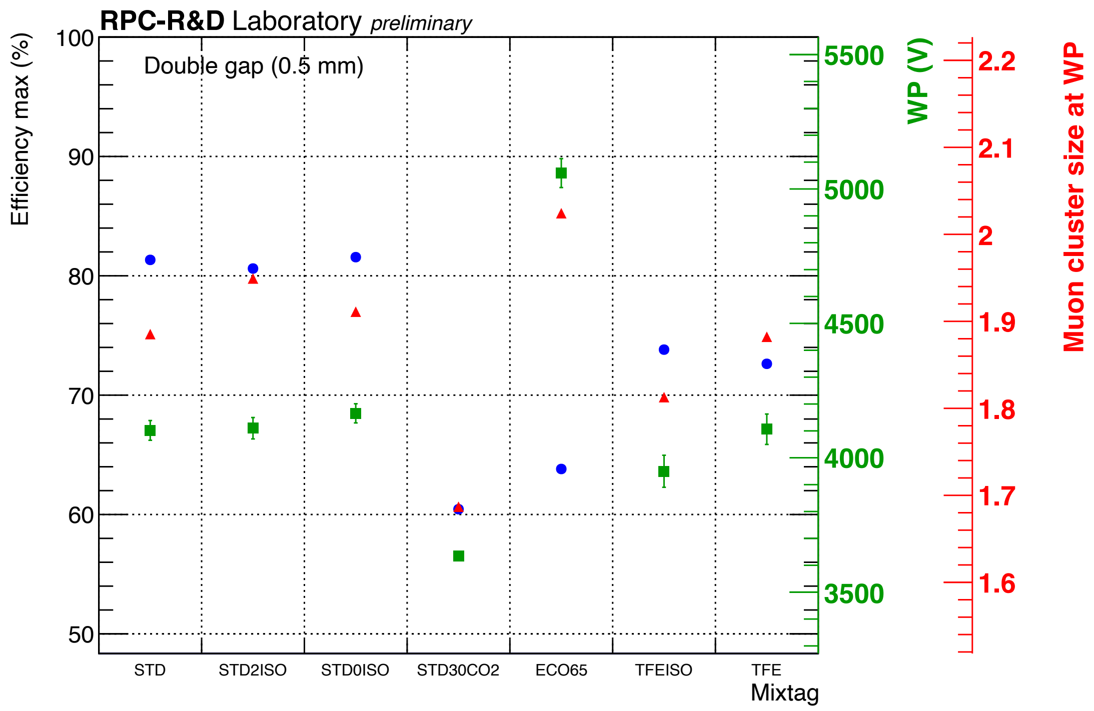


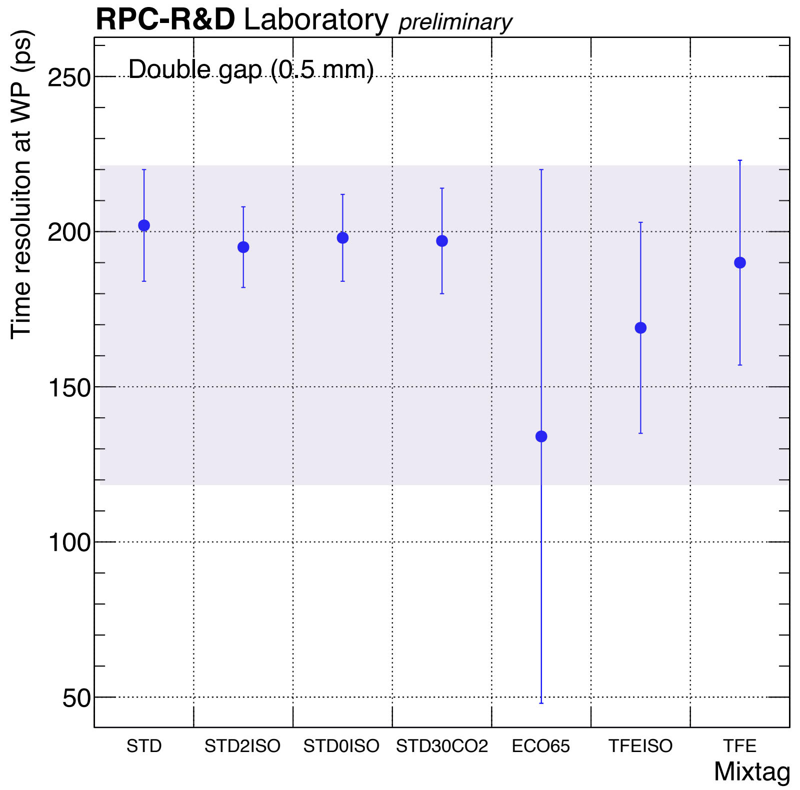
Preliminary results

Efficiency and Working Point (operation voltage)

$$\varepsilon(HV) = \frac{\varepsilon_{max}}{1 + e^{-\beta(HV - HV_{50})}}$$

$$WP = \frac{\log 19}{\beta} + HV_{50} + 150\ V$$





- Low efficiency at WP, roughly 70-80% (without FEE/preamlification)
- WP ~ 4 kV, around +1kV for ECO65
- Chamber time resolution ~ 200 ps for all mixtures

Preliminar

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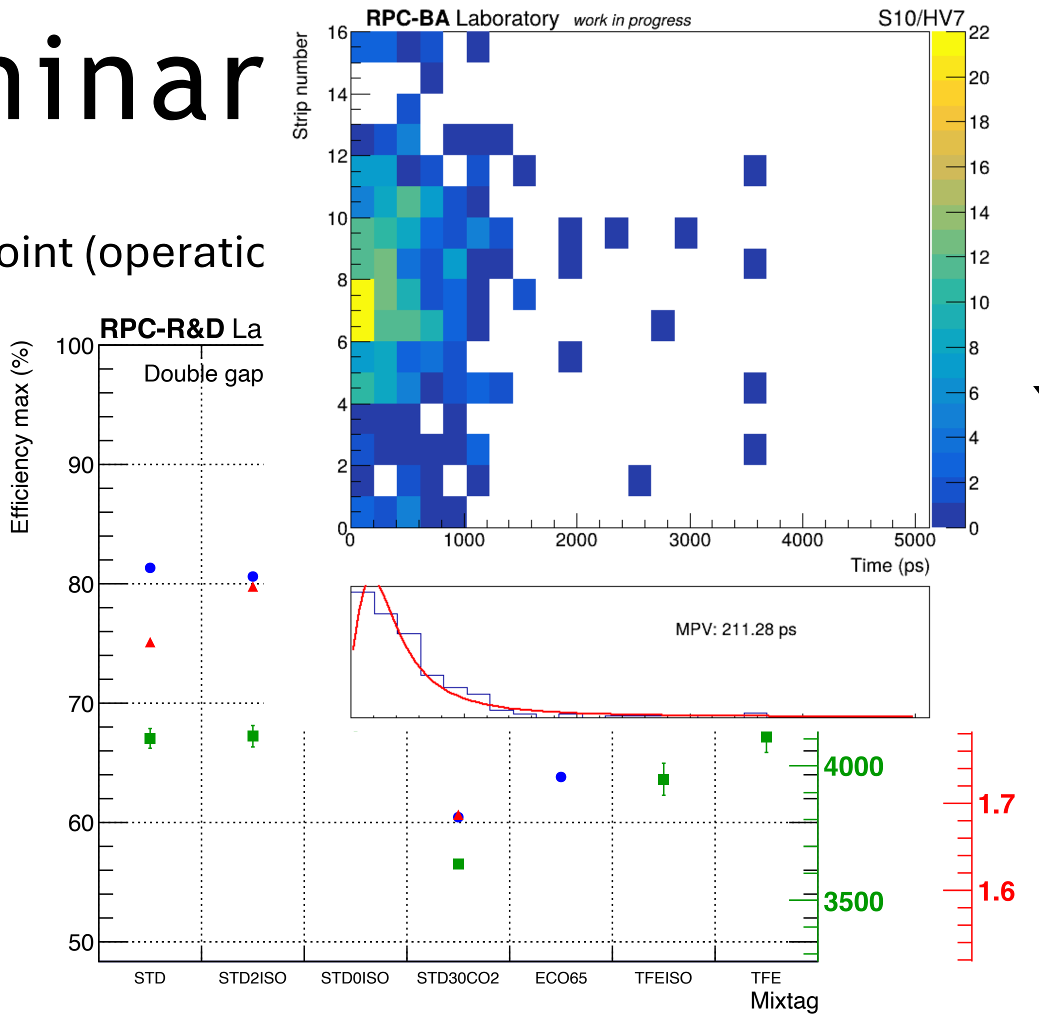

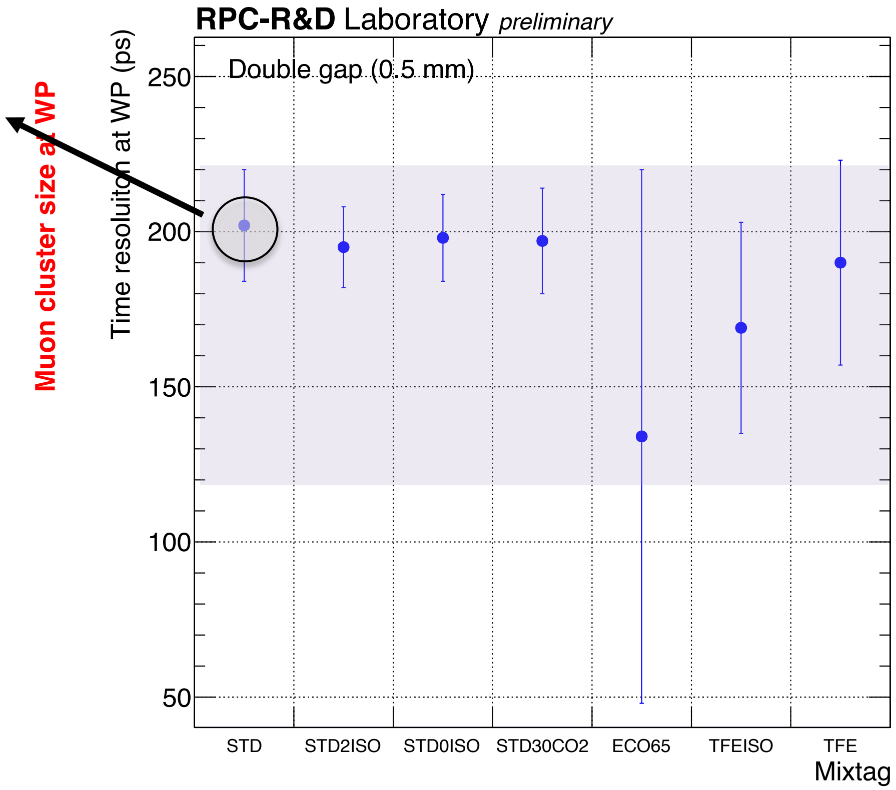

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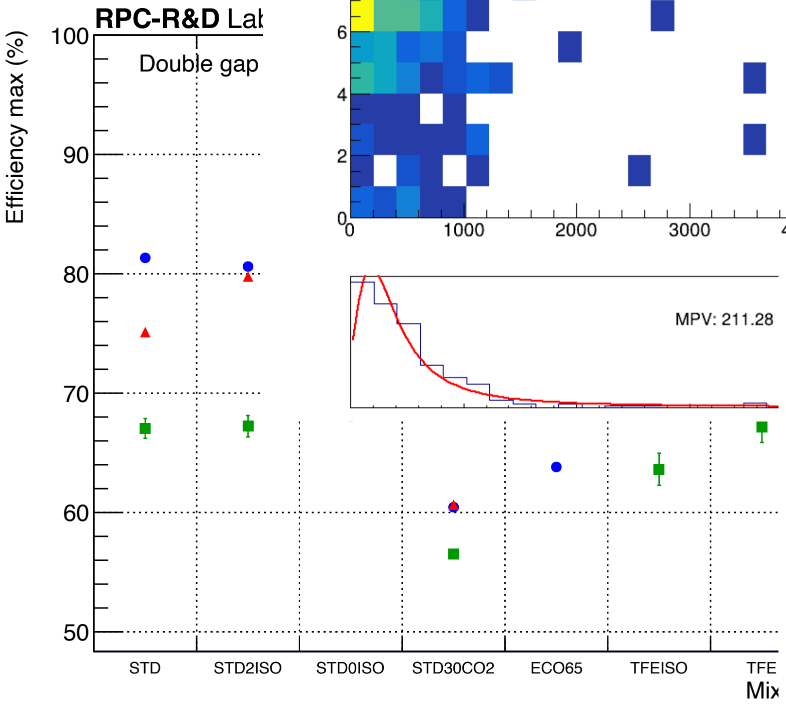
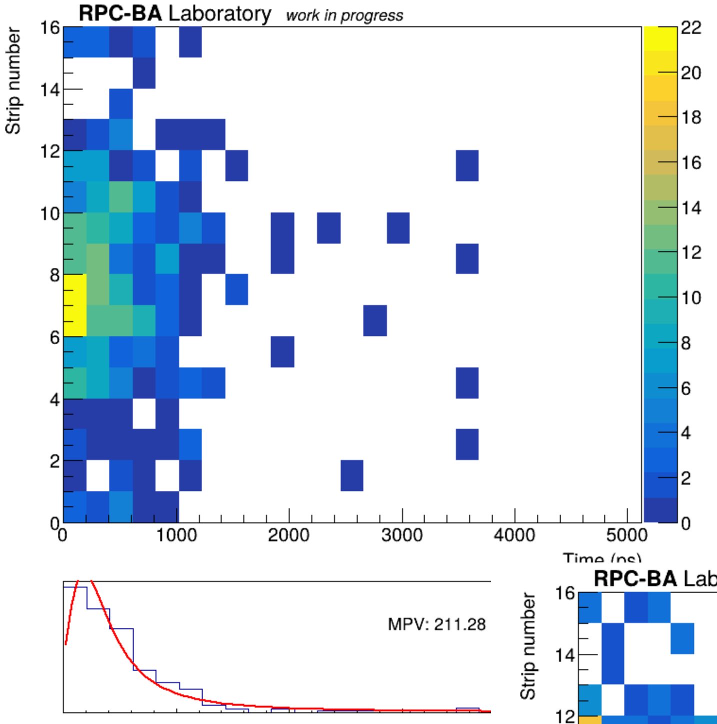
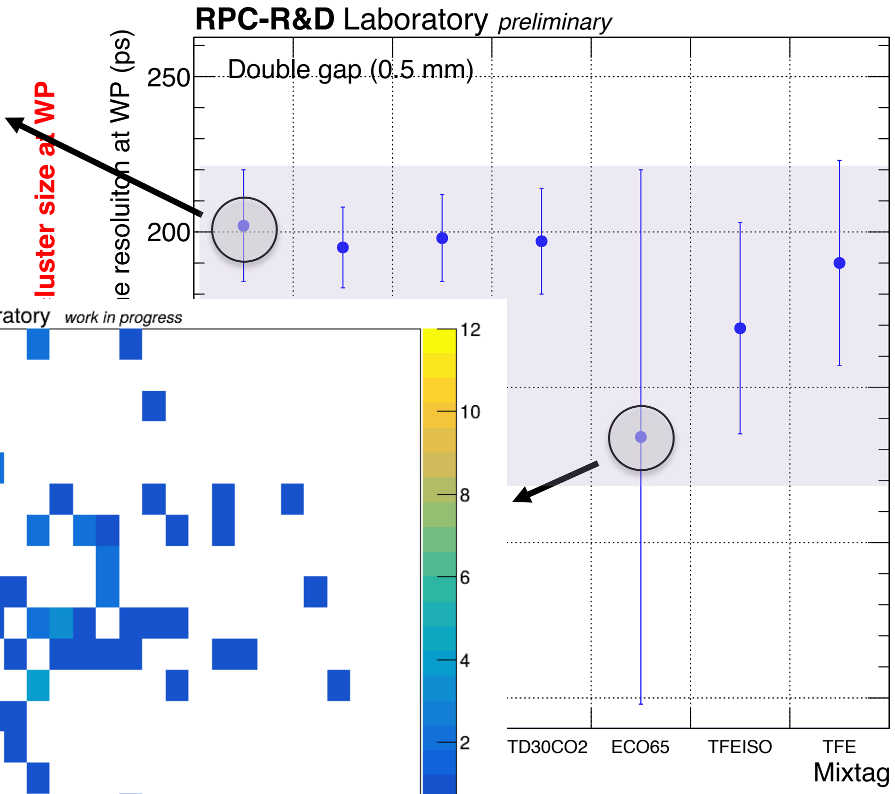
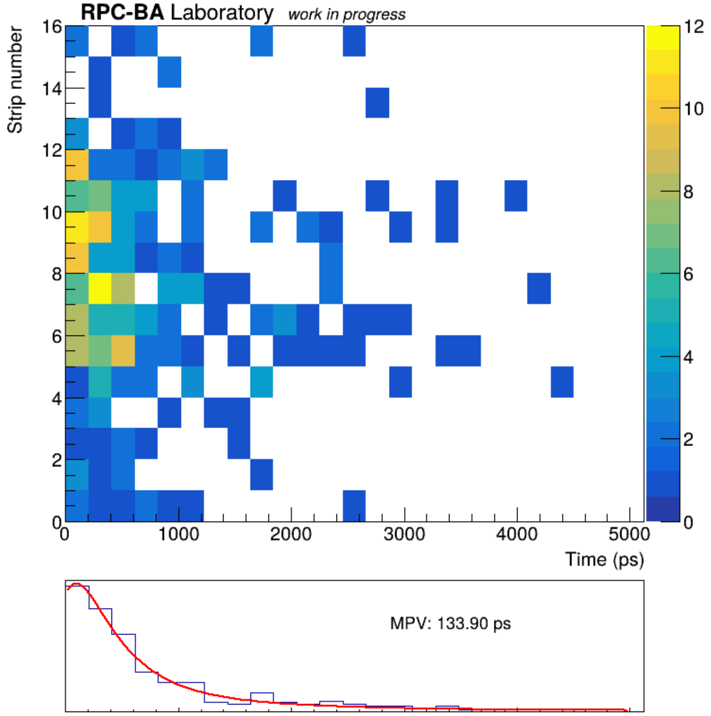




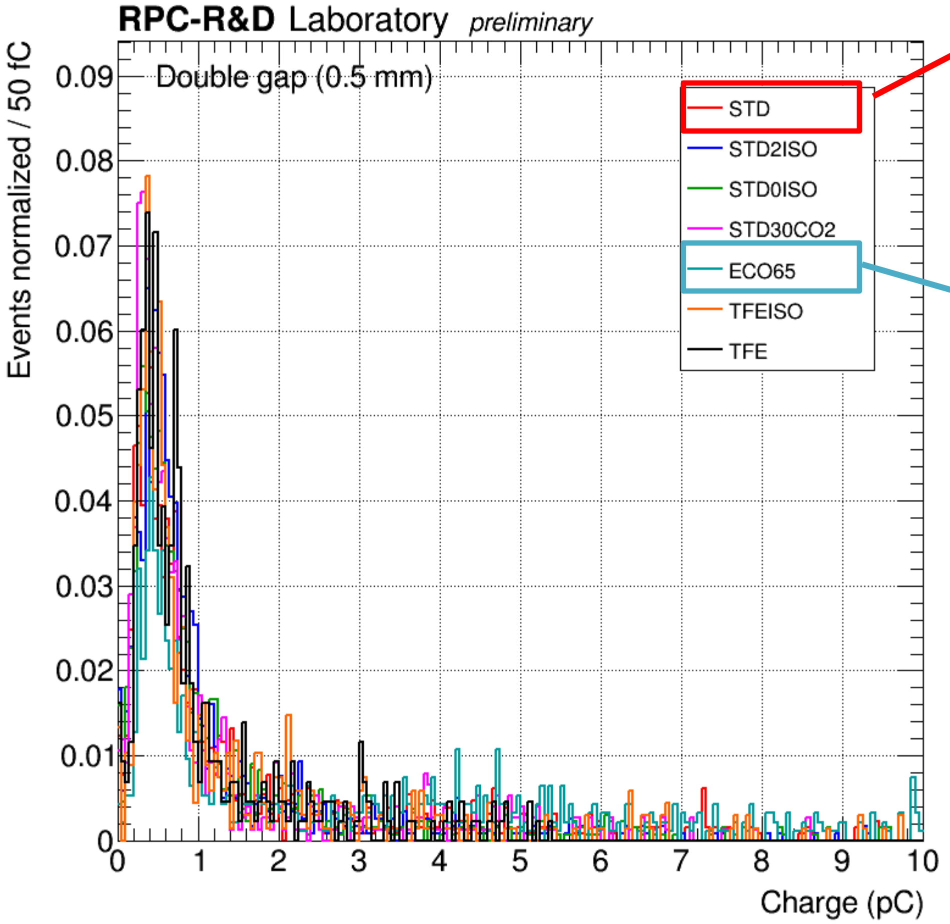


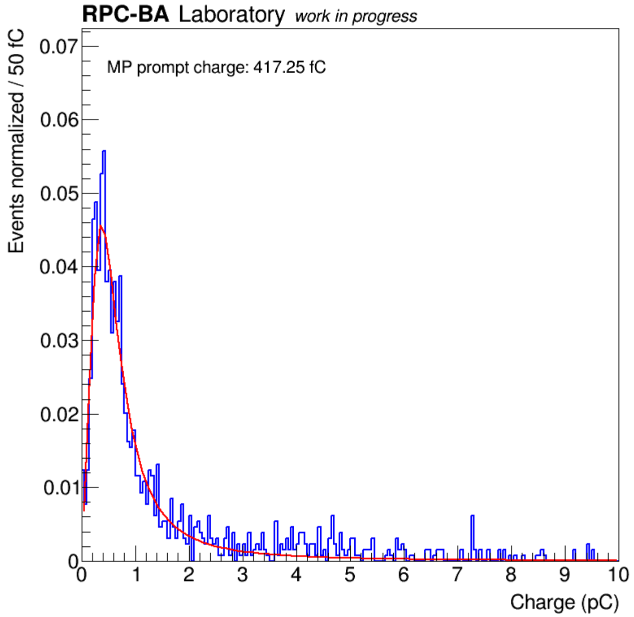


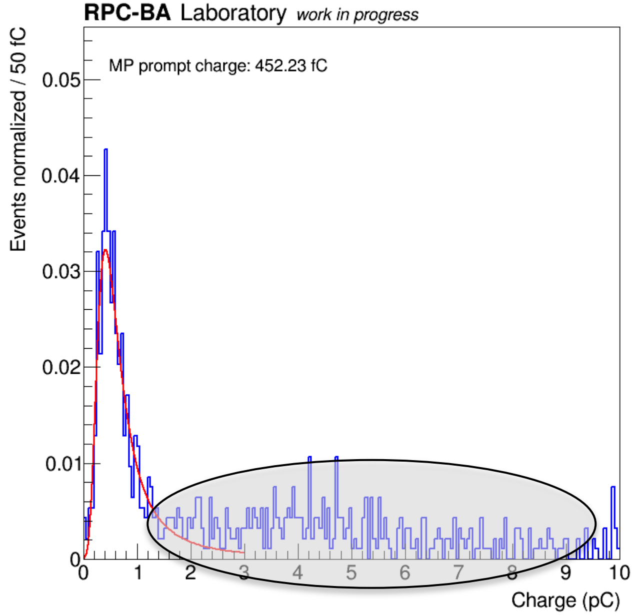
- Low efficiency at WP, roughly 70-80% (without FEE/preamlifi
- WP ~ 4 kV, around +1kV for ECO65
- Chamber time resolution ~ 200 ps for all mixtures

Preliminary results

- Prompt charge populated at ~420 fC for all mixtures
- Larger signal contribution with ECO65



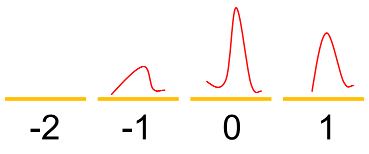


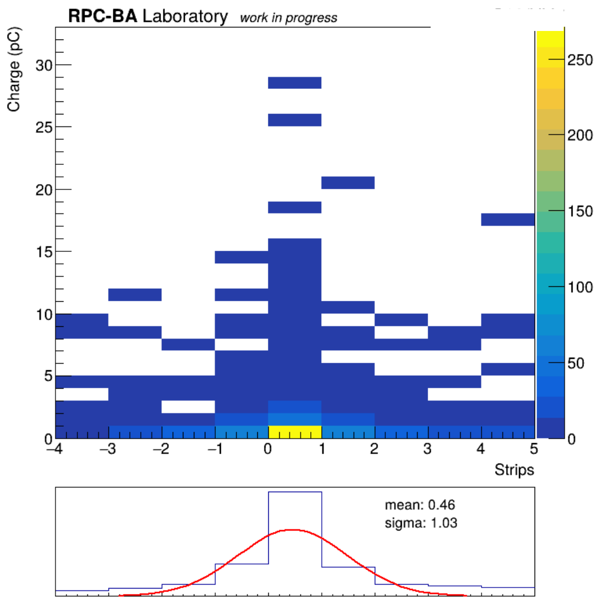


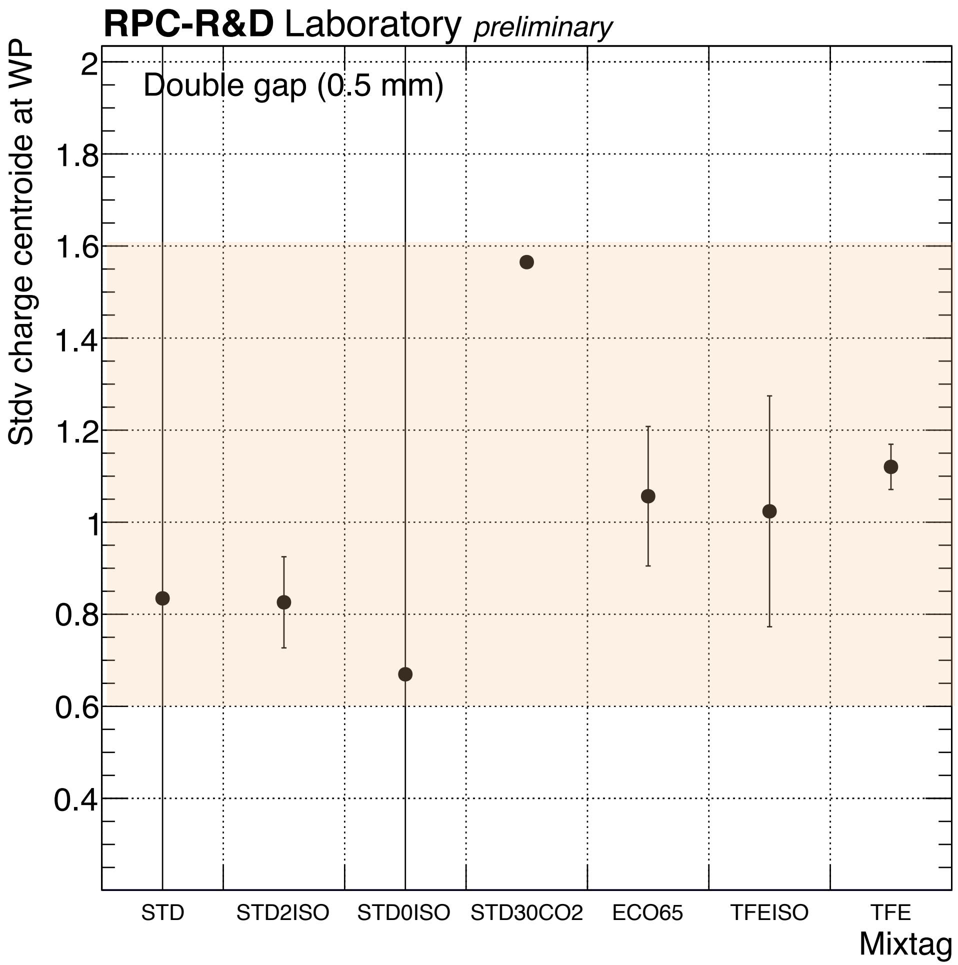
Preliminary results

- charge centroid analysis

Cluster charge defined:





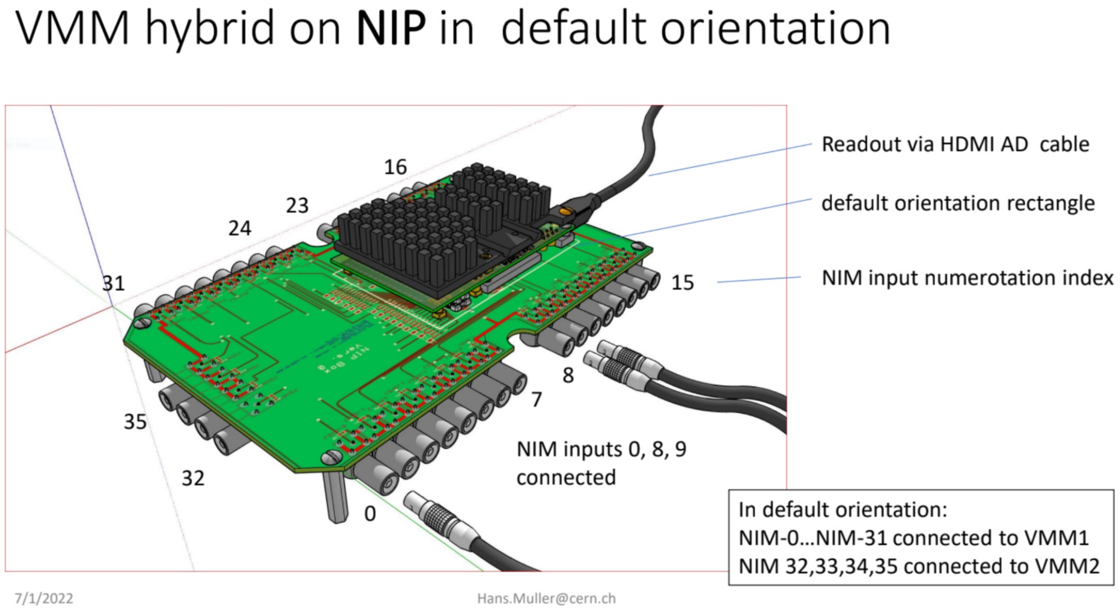


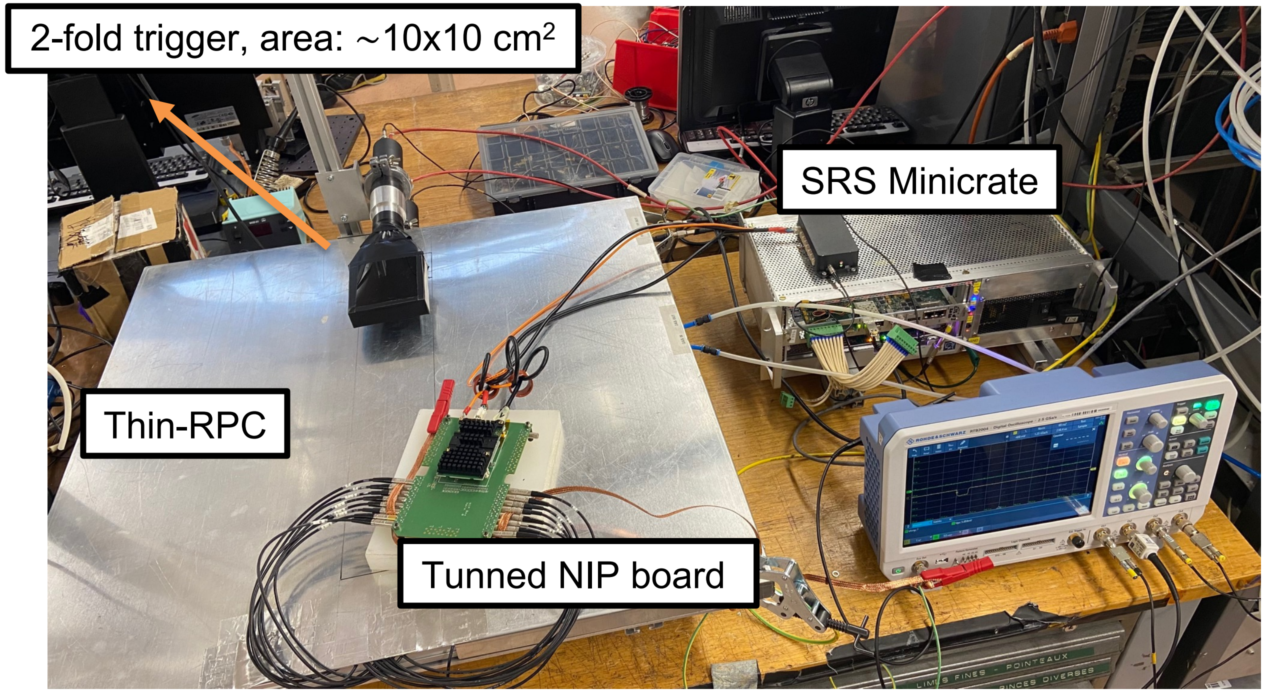
5mm strip pitch single side readout

- σ clus. charge centroid ~1 strip → **potentially improved space resolution**

VMM-3a – RPC coupling study

NIM Pattern Injector box for the VMM frontend
→ modified by removing C, direct RPC signal





Cosmic setup @ GDD Lab

Remarks

Pros

- Double gap thin-RPC equipped prototype have demonstrate time resolutions around 200 ps
- Reduced cluster sizes ($\sim$ 2 strips) and charge centroid ($\sigma \sim$ 1 strip) rely on improvement in space resolution
- All mixture can be operated at lower Working Points, roughly 4 kV

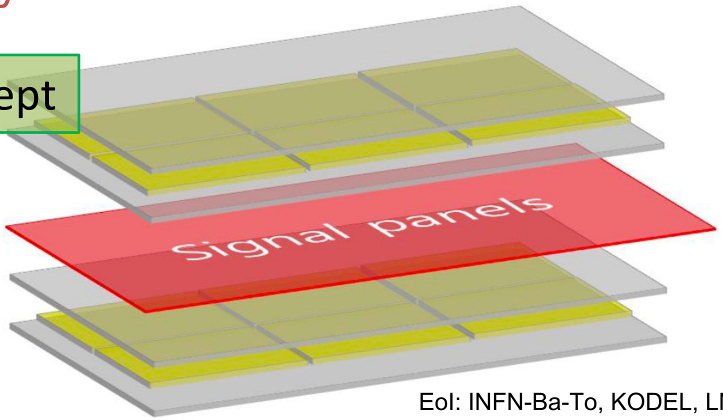
Cons

- Low efficiency without amplification

Foreseen steps

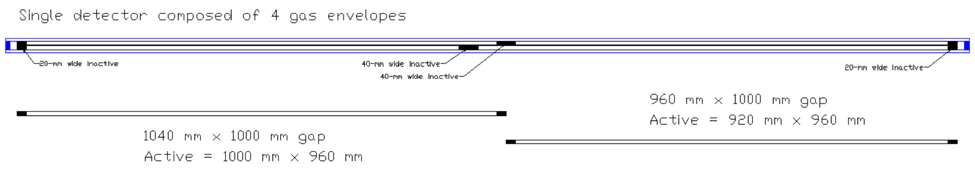
- New layout

Bi-gap concept

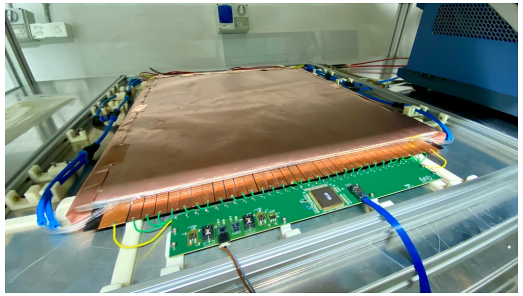


EoI: INFN-Ba-To, KODEL, LNF, MPI

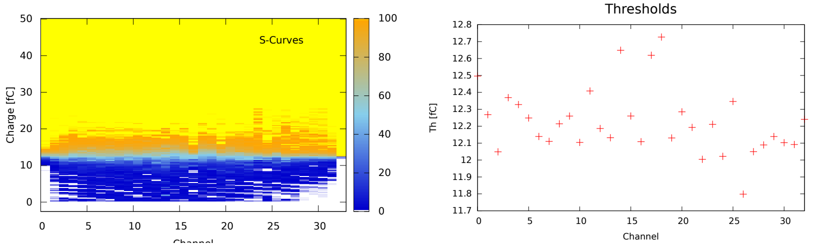
- 1 mm **RPC segmented** by a thin layer of a floating dielectric electrode, in two 0.5 mm sub-gaps
- Expected: 100-200 ps time resolution spatial resolution better than 1 mm with 3 mm wide pick-up strips



- FEE – low charge operation
  Tests with FATIC3-RPC version



Pre: FATIC2 on double gap glass RPC



- Improve granularity and charge centroid algorithm
  DRD1 test beams (July and November)

- Sustainability test: Low flux RPC operation

Thanks!

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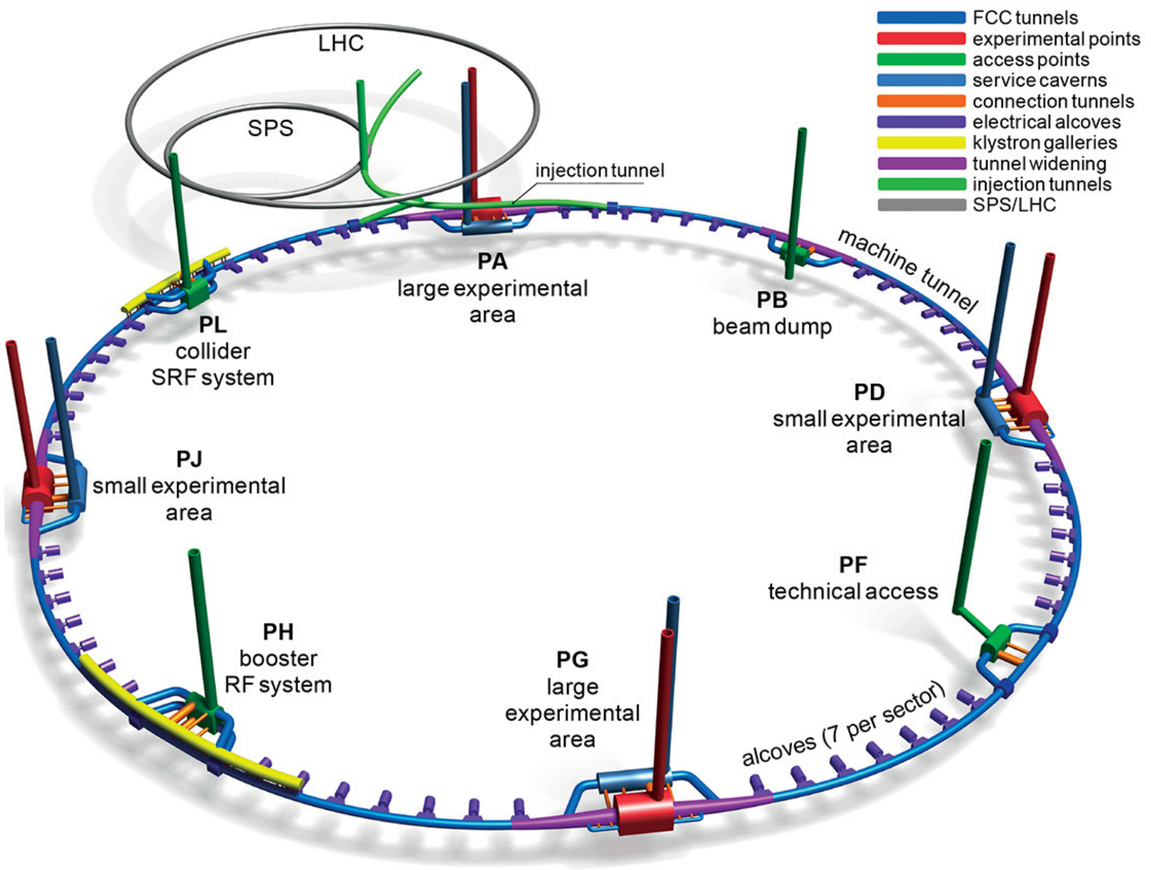
Backup

FCC-ee

- FCC-ee [1] will operate at 4 different center-of-mass energies:
  - Z pole (90 GeV)
  - WW pairs production (160 GeV)
  - HZ events production (240 GeV)
  - $t\bar{t}$ events production threshold (365 GeV)

- High Luminosity (~ **10^{34}-10^{35} cm^{-2}s^{-1}**) while lower rate environment than HL-LHC
- Maximum **muon momentum roughly 180 GeV/c**
- Isolated muons detection similar to LEP. Identification of non-isolated muons from hadron decays inside jets needs more stringent measures for precision flavor physics [2]
- High statistic of inelastic electron-positron collisions → rare processes production of feebly-interacting and slow particles



[1] https://indico.fnal.gov/event/64626/contributions/293153/attachments/179640/245471/fnaluec-fccee.pdf
[2] S. Monteil and G. Wilkinson, Heavy-quark opportunities and challenges at FCC-ee, Eur. Phys. J. Plus 136, 837 (2021), 2106.01259.

Challenges for Muon detectors

At the moment, only educated guess for Muon detection

- **High efficiency** muon identification **> 98%** (momentum measured by tracking system)
- Serving as tail-catcher for the hadron showers not fully contained in the calorimeter (discrimination/separation efficiency lower than 1%)
- Standalone momentum measurement for long-lived particles (**space resolution below 500 μm and time resolution better 200 ps**)
- **Rate capability << 1kHZ/cm^2**
- Environmentally sustainable

Most of the detectors rely on instrumenting the return yoke outside the coil

Scintillator bars

RPCs

Micro-pattern Gaseous Detector (MPGD) technologies

such as μ-RWELL, Micromegas, etc.,

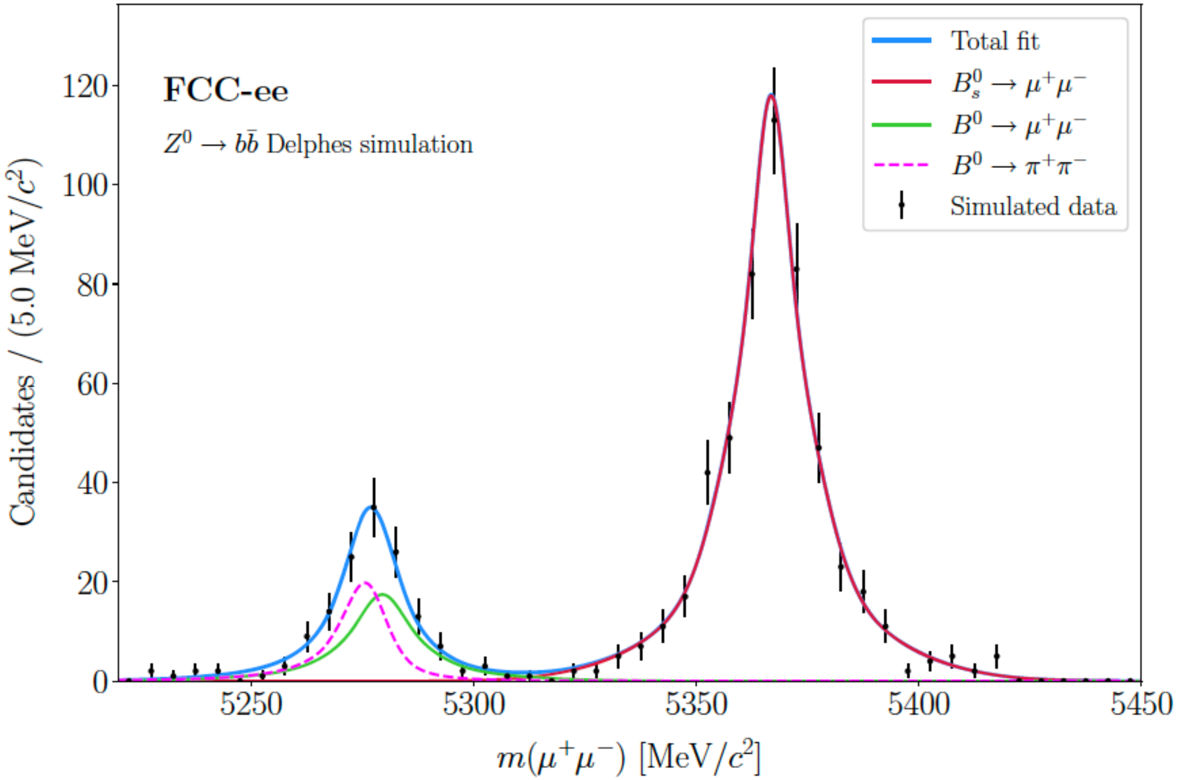
[1] J. Zhu, FCC-ee Detector Requirements and Benchmarks

Muon physics at FCC-ee

Heavy-quark opportunities

- **Rare flavor-changing neutral currents** sensitive to **new physics** effects
- **Mass resolution** and **muon identification** at FCC-ee → crucial for separating close-in-mass states like B_s^0 and B^0

$$B_s^0 \rightarrow \mu^+\mu^- \quad (5366\ \text{MeV/c}^2)$$
$$B^0 \rightarrow \mu^+\mu^- \quad (5279\ \text{MeV/c}^2)$$



$B \to \mu\mu$ with an assumption of a π/μ misidentification rate of 2×10^{-5}

[1] Heavy-quark opportunities and challenges at FCC-ee

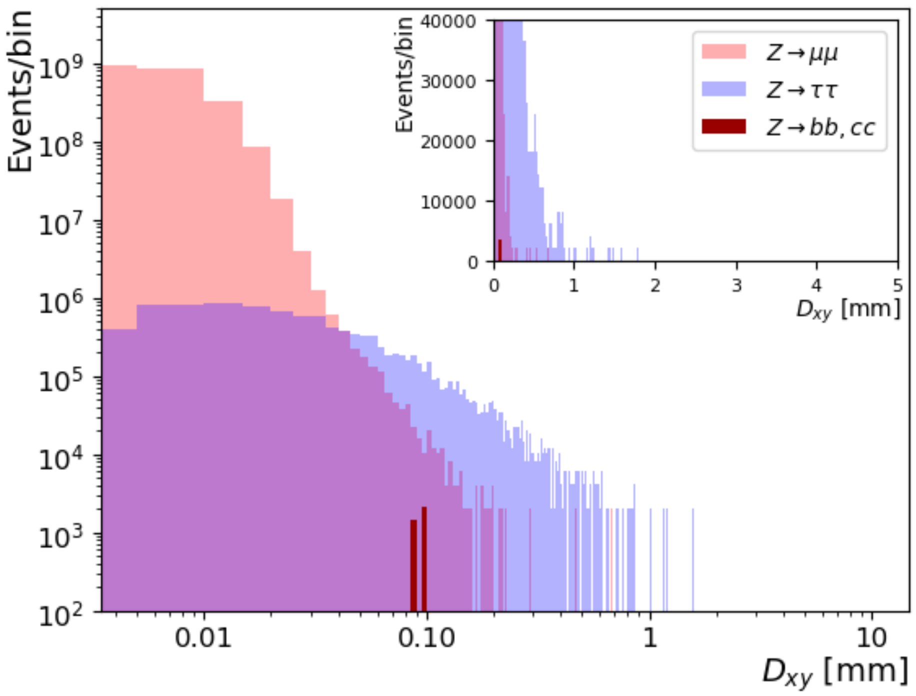
Muon physics at FCC-ee

Heavy Neutral Leptons searches

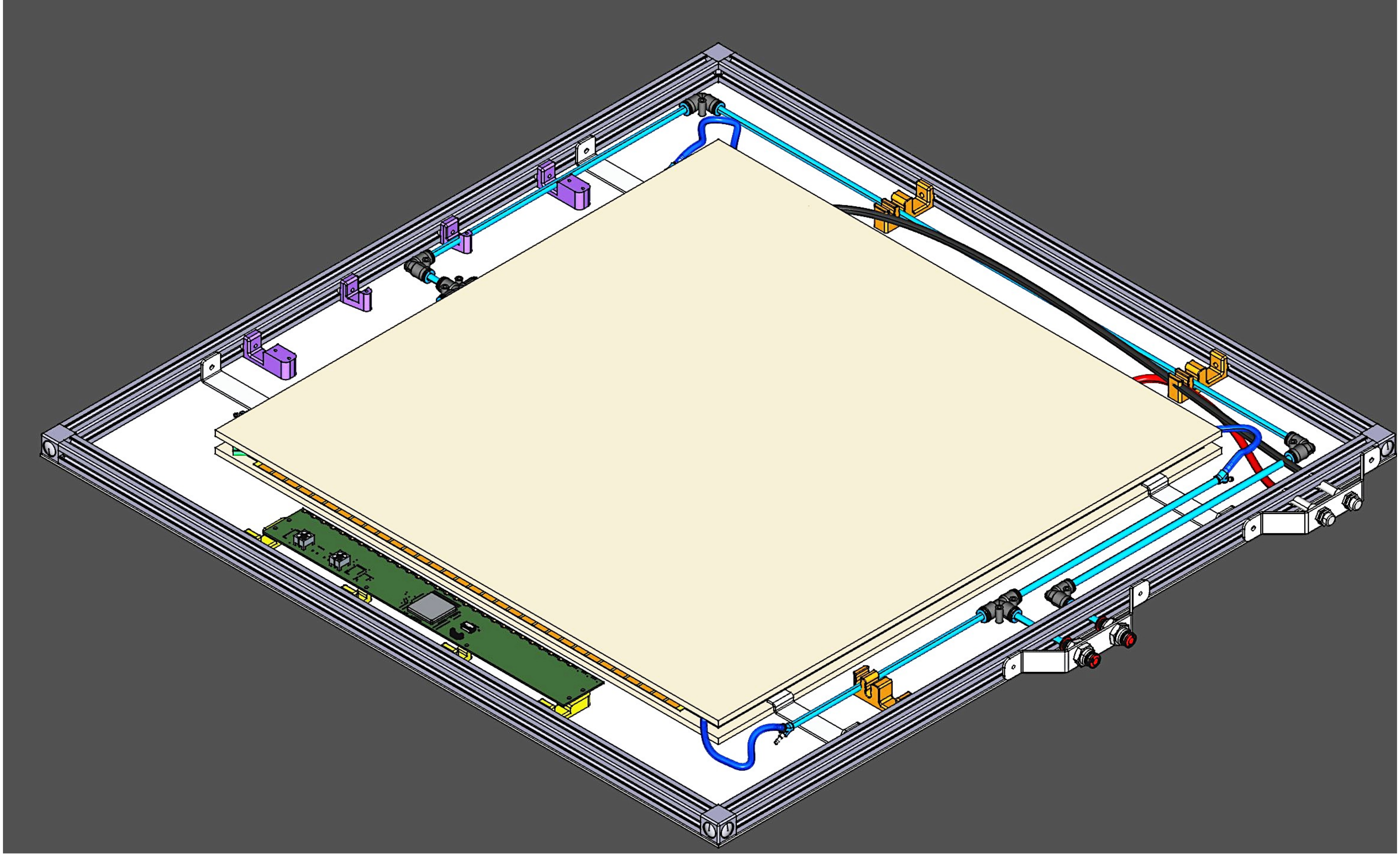
FCC-ee for Detecting HNLs

- **Clean background** → better LLP signature discrimination
- **Precise tracking and vertexing** → key for reconstructing displaced decays
- Sensitivity to **low-mass HNLs** (few GeV) via rare Z or B decays
    - a **fully leptonic final state $\mu^+\mu^-\nu$** → discrimination by *reconstructed transverse distance Dxy*
    - **semileptonic decay into μjj**, where js are hadronic jets

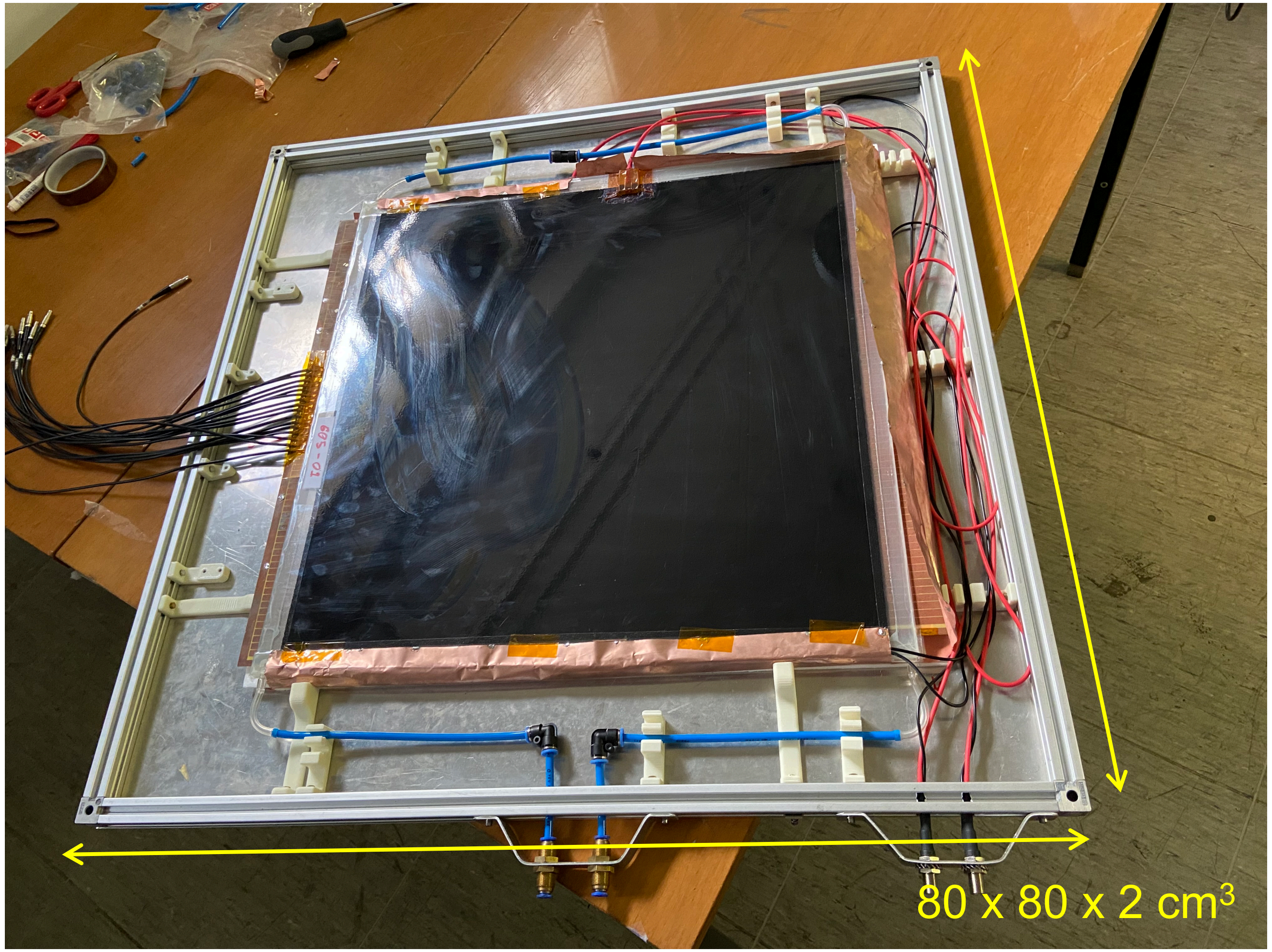
D_{xy} distribution for Z → μμ, Z → τ τ and Z → bb/cc

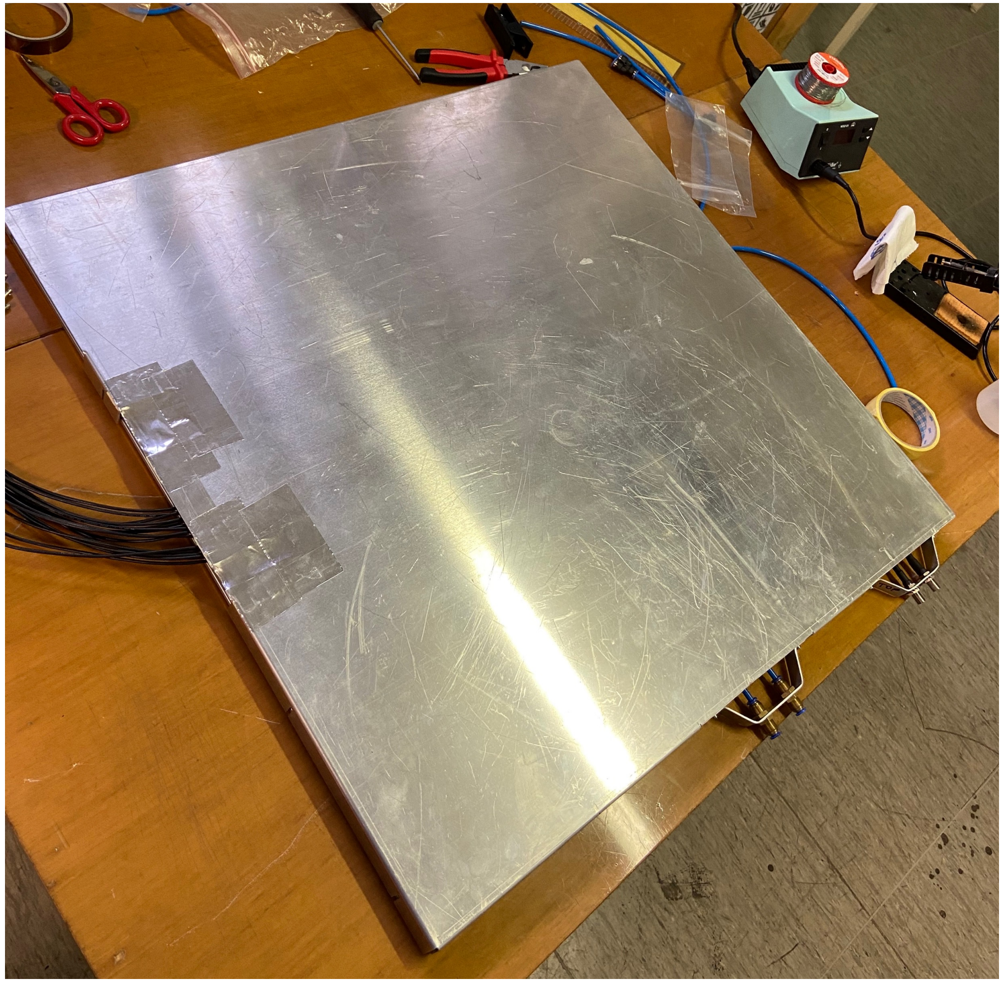


[1] Searches for Heavy Neutral Leptons at FCC-ee in final states including a muon

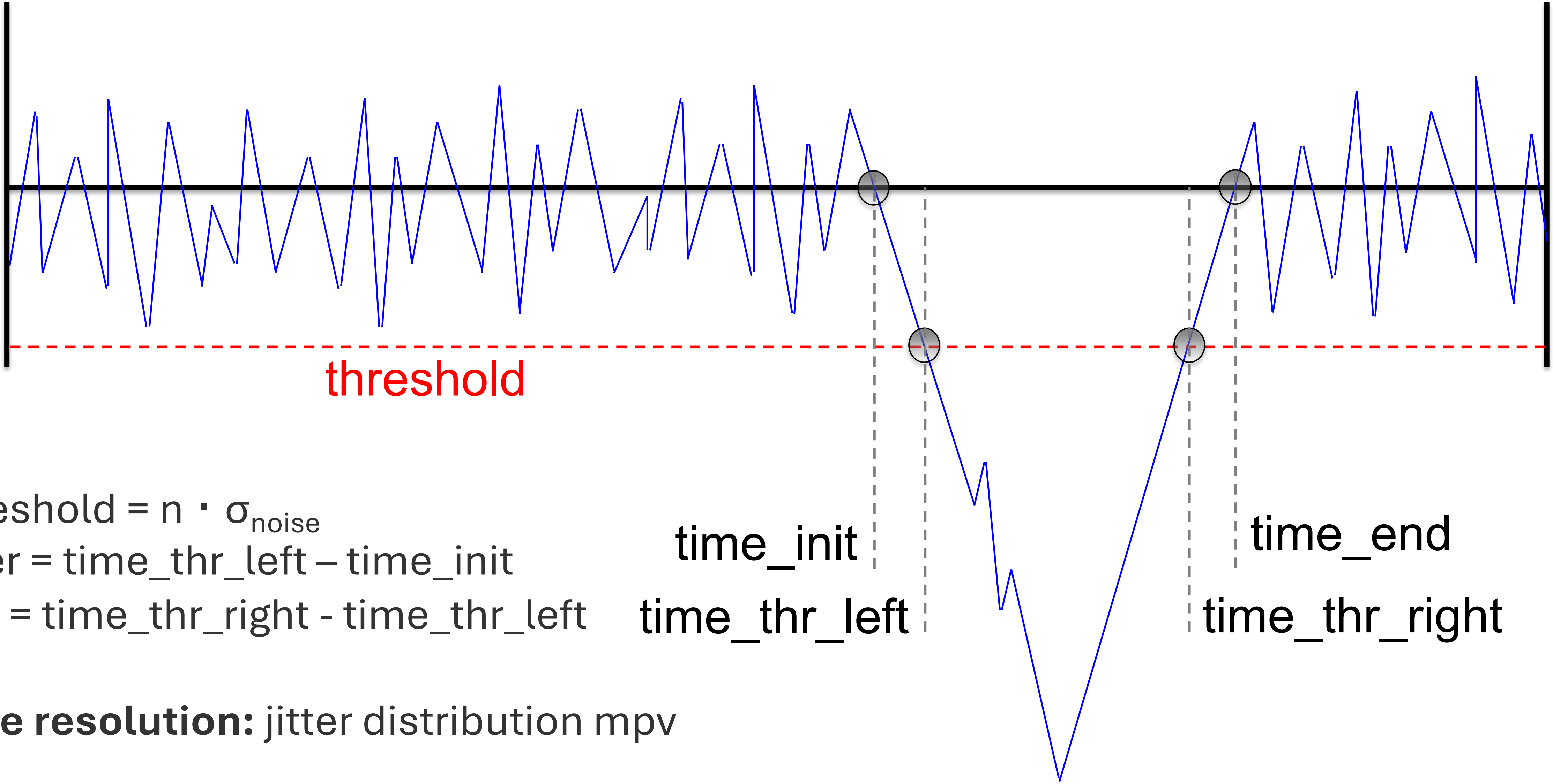


Thin-RPC KRONOS



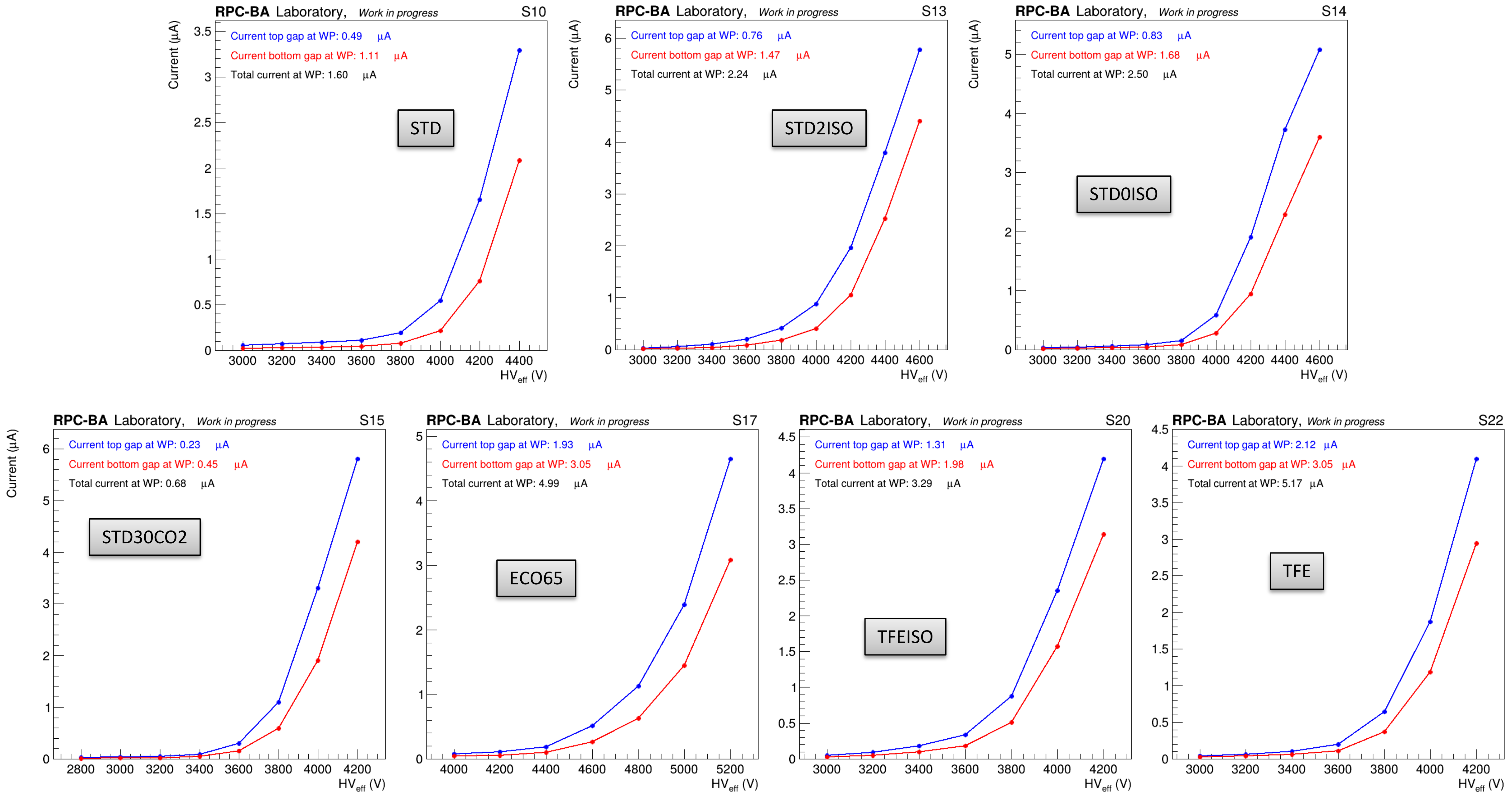


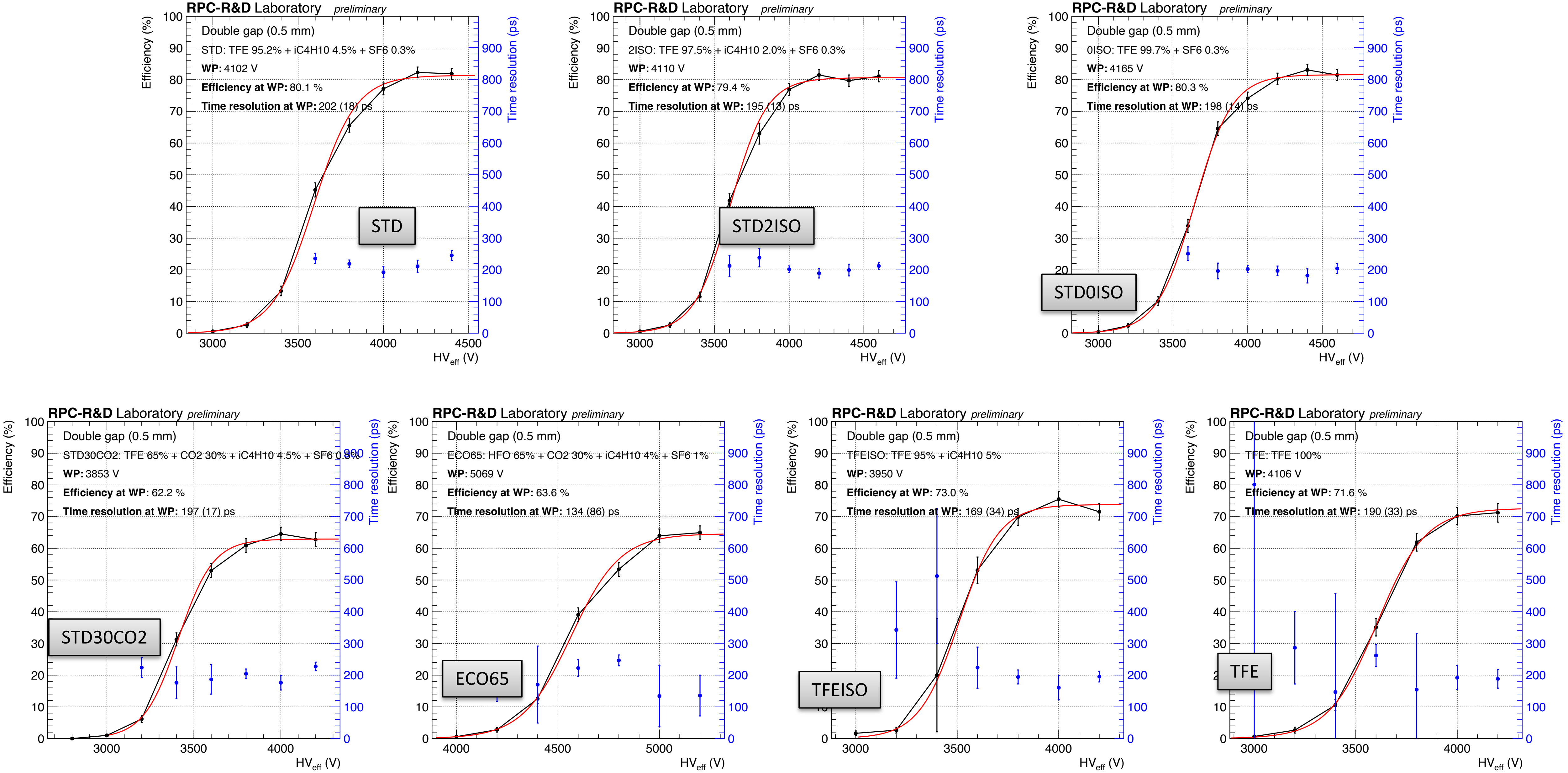
Signal analysis



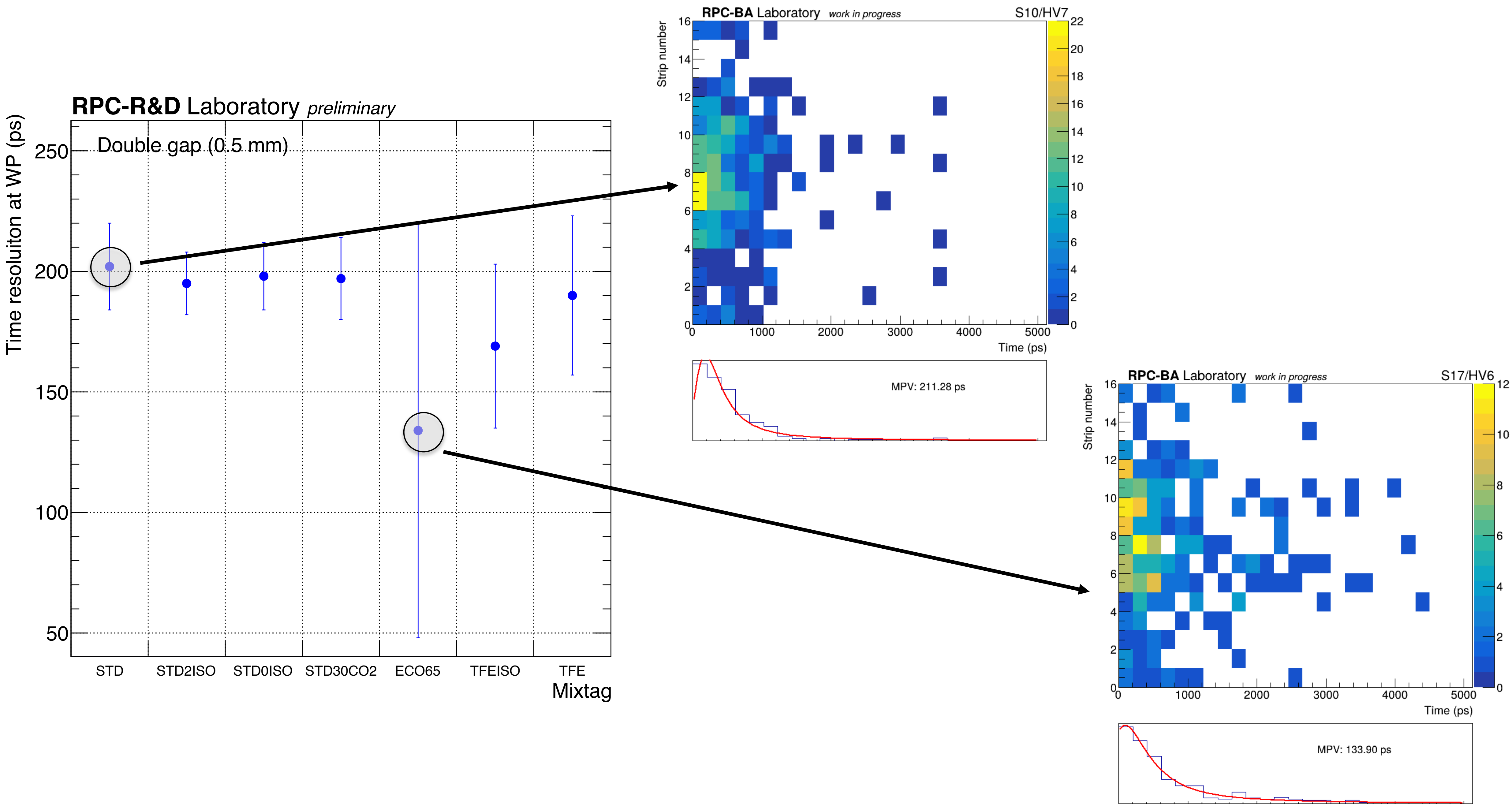
- threshold = n · σ_{noise}
- jitter = time_thr_left – time_init
- ToT = time_thr_right - time_thr_left

- **time resolution:** jitter distribution mpv

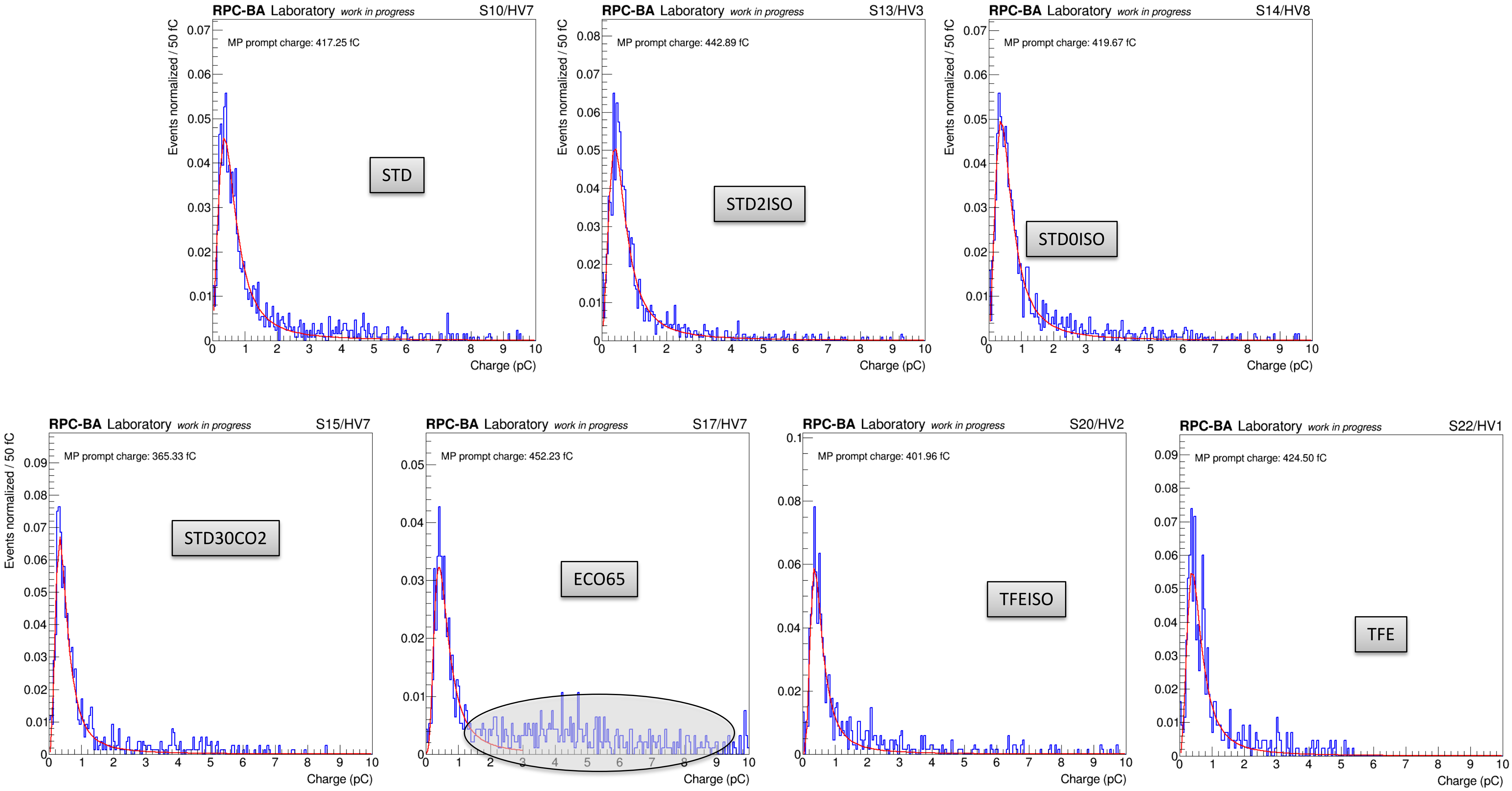

RPC-BA Laboratory, Work in progress S10
Current top gap at WP: 0.49 µA
Current bottom gap at WP: 1.11 µA
Total current at WP: 1.60 µA
STD
RPC-BA Laboratory, Work in progress S13
Current top gap at WP: 0.76 µA
Current bottom gap at WP: 1.47 µA
Total current at WP: 2.24 µA
STD2ISO
RPC-BA Laboratory, Work in progress S14
Current top gap at WP: 0.83 µA
Current bottom gap at WP: 1.68 µA
Total current at WP: 2.50 µA
STD0ISO
RPC-BA Laboratory, Work in progress S15
Current top gap at WP: 0.23 µA
Current bottom gap at WP: 0.45 µA
Total current at WP: 0.68 µA
STD30CO2
RPC-BA Laboratory, Work in progress S17
Current top gap at WP: 1.93 µA
Current bottom gap at WP: 3.05 µA
Total current at WP: 4.99 µA
ECO65
RPC-BA Laboratory, Work in progress S20
Current top gap at WP: 1.31 µA
Current bottom gap at WP: 1.98 µA
Total current at WP: 3.29 µA
TFEISO
RPC-BA Laboratory, Work in progress S22
Current top gap at WP: 2.12 µA
Current bottom gap at WP: 3.05 µA
Total current at WP: 5.17 µA
TFE
Current (µA)
HVeff (V)

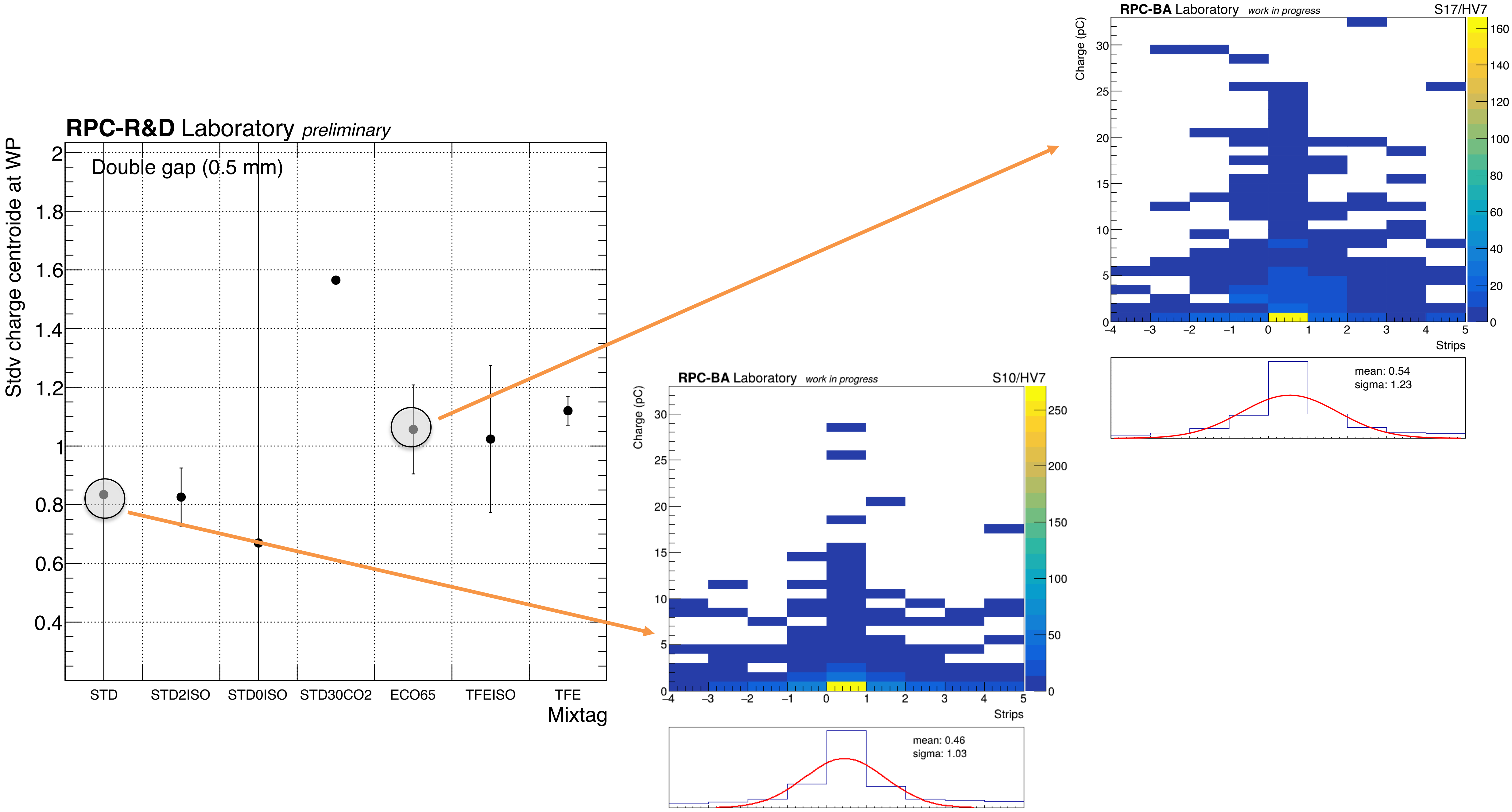


RPC-R&D Laboratory preliminary
Double gap (0.5 mm)
STD: TFE 95.2% + iC4H10 4.5% + SF6 0.3%
WP: 4102 V
Efficiency at WP: 80.1 %
Time resolution at WP: 202 (18) ps
STD
RPC-R&D Laboratory preliminary
Double gap (0.5 mm)
2ISO: TFE 97.5% + iC4H10 2.0% + SF6 0.3%
WP: 4110 V
Efficiency at WP: 79.4 %
Time resolution at WP: 195 (13) ps
STD2ISO
RPC-R&D Laboratory preliminary
Double gap (0.5 mm)
0ISO: TFE 99.7% + SF6 0.3%
WP: 4165 V
Efficiency at WP: 80.3 %
Time resolution at WP: 198 (14) ps
STD0ISO
RPC-R&D Laboratory preliminary
Double gap (0.5 mm)
STD30CO2: TFE 65% + CO2 30% + iC4H10 4.5% + SF6 0.5%
WP: 3853 V
Efficiency at WP: 62.2 %
Time resolution at WP: 197 (17) ps
STD30CO2
RPC-R&D Laboratory preliminary
Double gap (0.5 mm)
ECO65: HFO 65% + CO2 30% + iC4H10 4% + SF6 1%
WP: 5069 V
Efficiency at WP: 63.6 %
Time resolution at WP: 134 (86) ps
ECO65
RPC-R&D Laboratory preliminary
Double gap (0.5 mm)
TFEISO: TFE 95% + iC4H10 5%
WP: 3950 V
Efficiency at WP: 73.0 %
Time resolution at WP: 169 (34) ps
TFEISO
RPC-R&D Laboratory preliminary
Double gap (0.5 mm)
TFE: TFE 100%
WP: 4106 V
Efficiency at WP: 71.6 %
Time resolution at WP: 190 (33) ps
TFE
Efficiency (%)
Time resolution (ps)
HVeff (V)



RPC-R&D Laboratory preliminary
Double gap (0.5 mm)
Time resoluiton at WP (ps)
250
200
150
100
50
STD
STD2ISO
STD0ISO
STD30CO2
ECO65
TFEISO
TFE
Mixtag
RPC-BA Laboratory work in progress
S10/HV7
Strip number
Time (ps)
MPV: 211.28 ps
RPC-BA Laboratory work in progress
S17/HV6
Strip number
Time (ps)
MPV: 133.90 ps

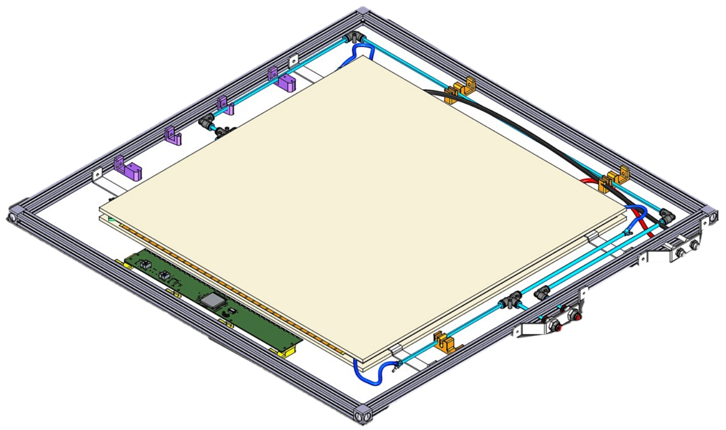

RPC-BA Laboratory work in progress
S10/HV7
MP prompt charge: 417.25 fC
STD
Events normalized / 50 fC
Charge (pC)
RPC-BA Laboratory work in progress
S13/HV3
MP prompt charge: 442.89 fC
STD2ISO
Events normalized / 50 fC
Charge (pC)
RPC-BA Laboratory work in progress
S14/HV8
MP prompt charge: 419.67 fC
STD0ISO
Events normalized / 50 fC
Charge (pC)
RPC-BA Laboratory work in progress
S15/HV7
MP prompt charge: 365.33 fC
STD30CO2
Events normalized / 50 fC
Charge (pC)
RPC-BA Laboratory work in progress
S17/HV7
MP prompt charge: 452.23 fC
ECO65
Charge (pC)
RPC-BA Laboratory work in progress
S20/HV2
MP prompt charge: 401.96 fC
TFEISO
Charge (pC)
RPC-BA Laboratory work in progress
S22/HV1
MP prompt charge: 424.50 fC
TFE
Charge (pC)


RPC-R&D Laboratory preliminary
Double gap (0.5 mm)
Stdv charge centroide at WP
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
STD
STD2ISO
STD0ISO
STD30CO2
ECO65
TFEISO
TFE
Mixtag
RPC-BA Laboratory work in progress
S17/HV7
Charge (pC)
Strips
mean: 0.54
sigma: 1.23
RPC-BA Laboratory work in progress
S10/HV7
Charge (pC)
Strips
mean: 0.46
sigma: 1.03

RPC readout via VMM3a

Motivation:

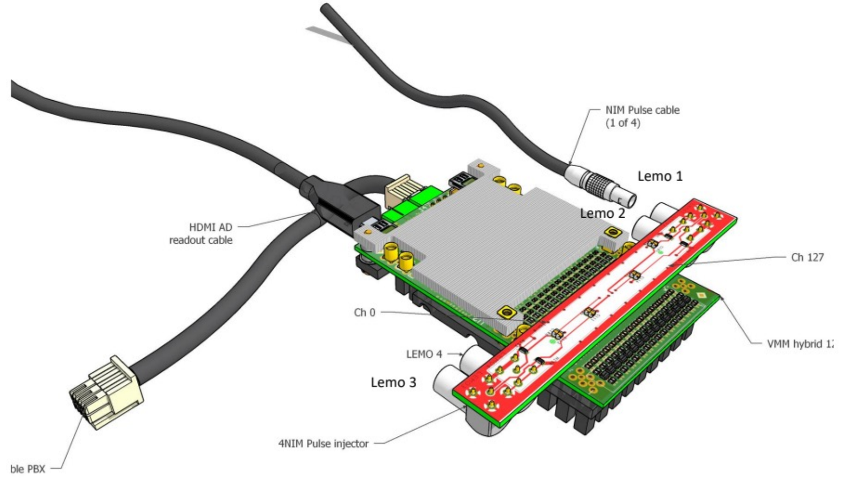
- Space resolution measurements with thin-RPC prototype for high-timing performance applications (DRD1-WP7b) by using GDD beam telescope
- Possible integration of RPC into GDD beam telescope

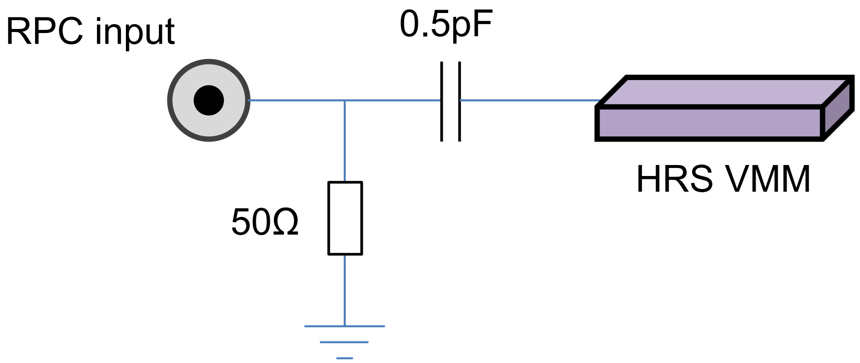


https://vmm-srs.docs.cern.ch

VMM-3a – RPC coupling study

QNI quad NIM injector





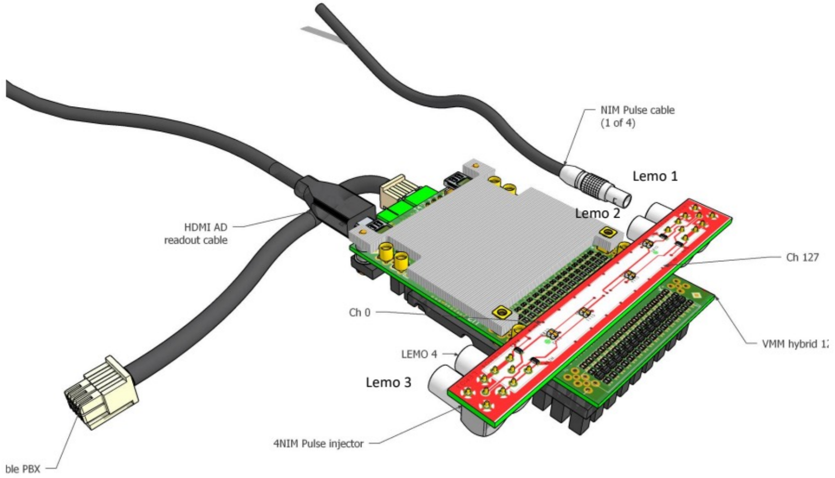
Coupling settings tested:

- Direct RPC signal to HRS VMM
- No C and 50Ω
- 1 pF capacitor without R
- 1 pF capacitor and 50Ω
- 0.5 pF and and 50Ω

All configuration proved with 50Ω terminated/floating strips and several VMM config (gain, st) at fixed detector gain

VMM-3a – RPC coupling study

QNI quad NIM injector



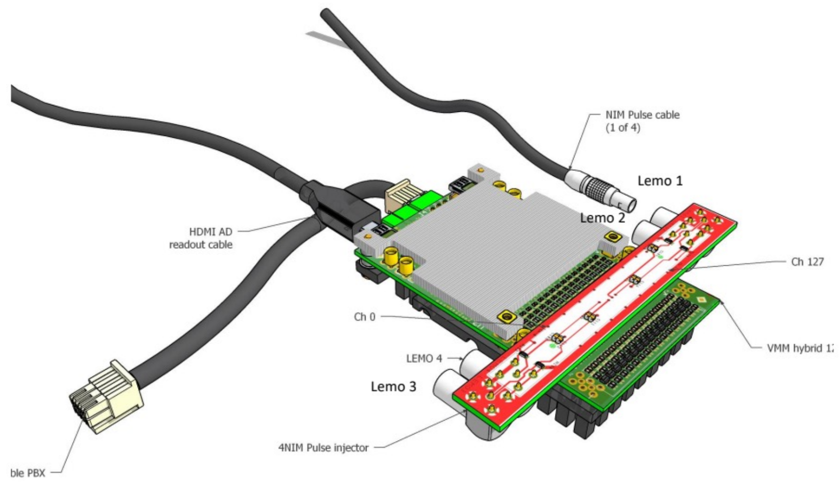
Coupling settings tested:

1. Direct RPC signal to HRS VMM
2. No C and 50Ω
3. 1 pF capacitor without R
4. 1 pF capacitor and 50Ω
5. 0.5 pF and and 50Ω

→ Higher charge amplification (saturation even at lower VMM gain: 0.5 mV/fC)

VMM-3a – RPC coupling study

QNI quad NIM injector

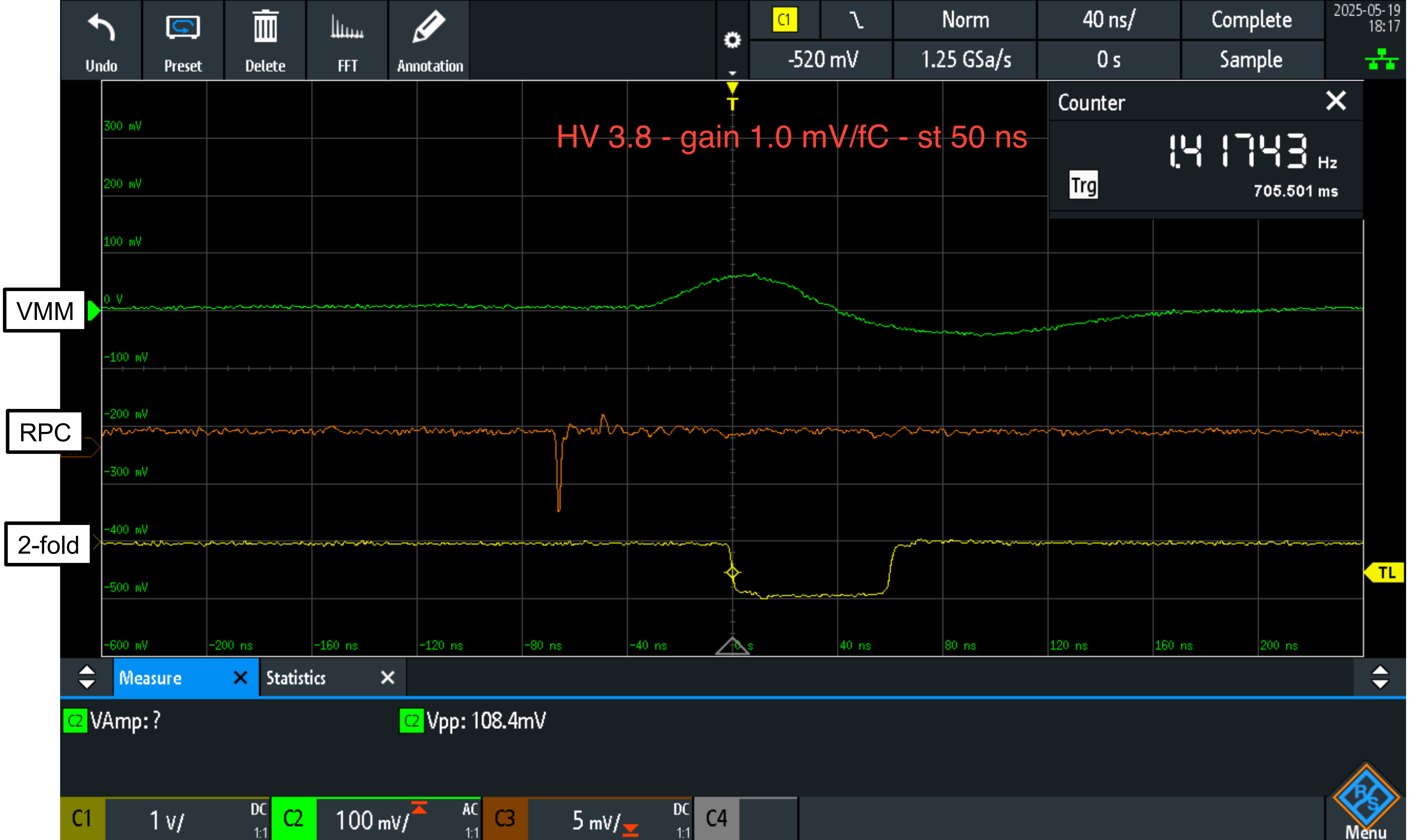


Strip 50Ω terminated

* Floating strip

Coupling settings tested:

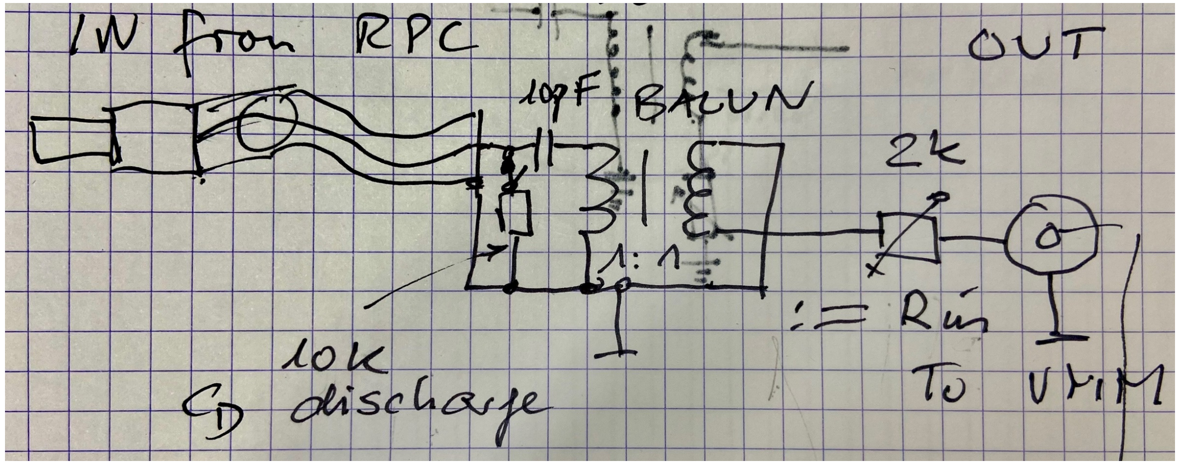
1. Direct RPC signal to HRS VMM
2. No C and 50Ω
3. 1 pF capacitor without R
4. 1 pF capacitor and 50Ω
5. 0.5 pF and and 50Ω

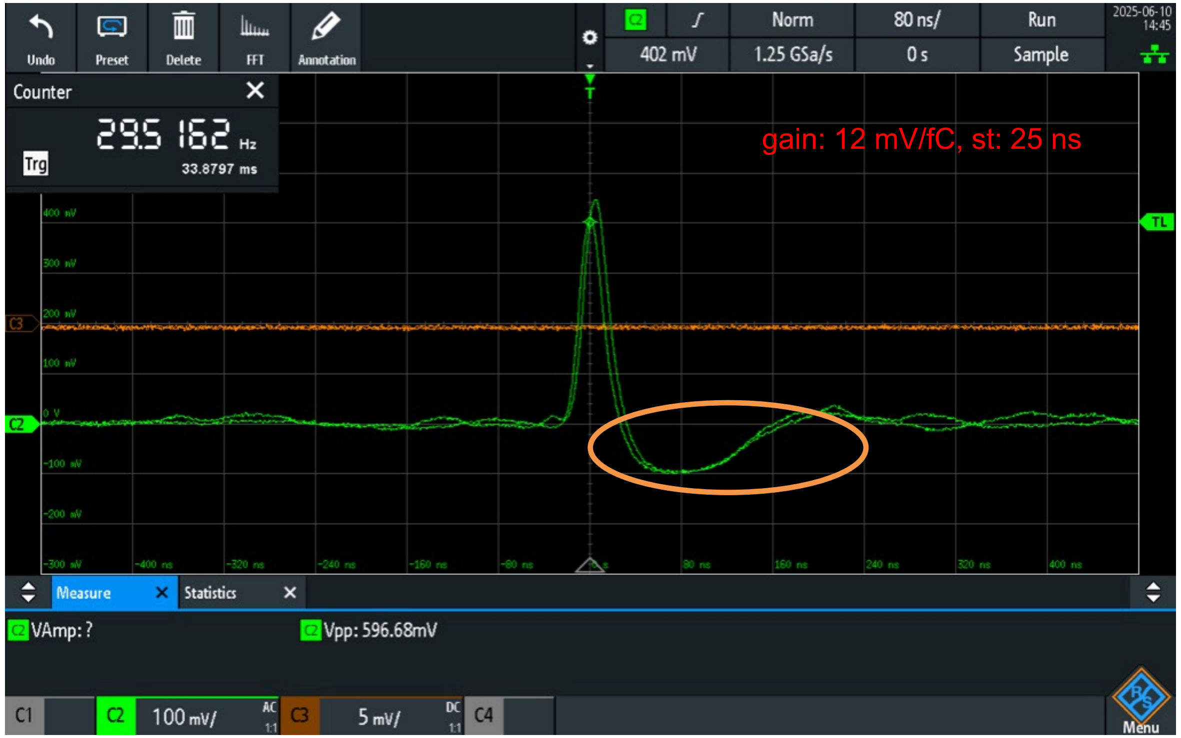


Undo
Preset
Delete
FFT
Annotation
C1
Norm
40 ns/
Complete
2025-05-19
18:17
-520 mV
1.25 GSa/s
0 s
Sample
HV 3.8 - gain 1.0 mV/fC - st 50 ns
Counter
14 1743 Hz
Trg
705.501 ms
VMM
RPC
2-fold
300 mV
200 mV
100 mV
0 V
-100 mV
-200 mV
-300 mV
-400 mV
-500 mV
-600 mV
-200 ns
-160 ns
-120 ns
-80 ns
-40 ns
40 ns
80 ns
120 ns
160 ns
200 ns
TL
Measure
Statistics
C2 VAmp: ?
C2 Vpp: 108.4mV
C1 1 V/ DC 1:1
C2 100 mV/ AC 1:1
C3 5 mV/ DC 1:1
C4
Menu

VMM-3a – RPC coupling study

C_D cancellation search: RPC through BALUN





R210Ω impedance matching VMM side:

- Best operation range (No charge saturation)
- Noise reduction at 25 ns peak time
- Still signal undershoot

Ongoing: match RPC strip impedance and variable capacity