CMS Barrel Timing Detector Beam Tests and Low Temperature Tests

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CLHCP 2025, Xinxiang, Henan

30/10/2025

Outline

- Brief introduction to MTD barrel timing detector (BTL)
- Preliminary results of MTD BTL 2025 test beam (TB)
- Tray test at low temperature
- Summary and Plan

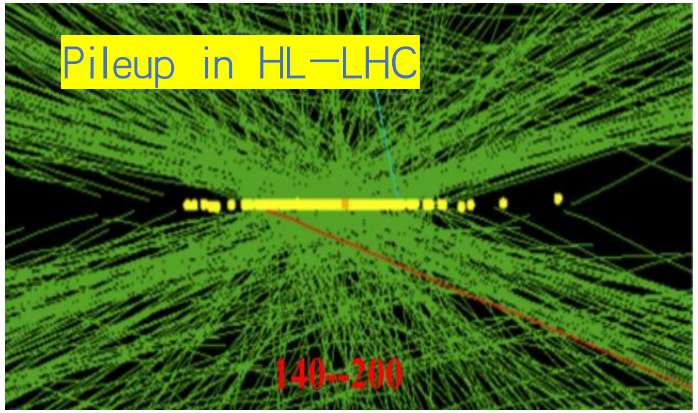
Brief introduction to MTD barrel timing detector (BTL)

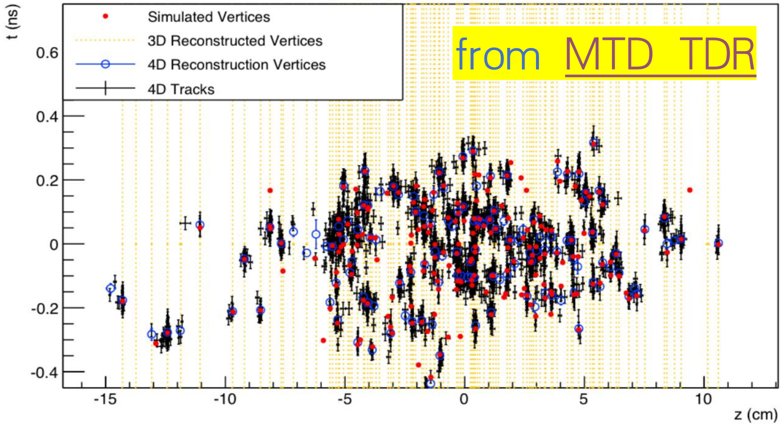
Brief Introduction to MTD BTL

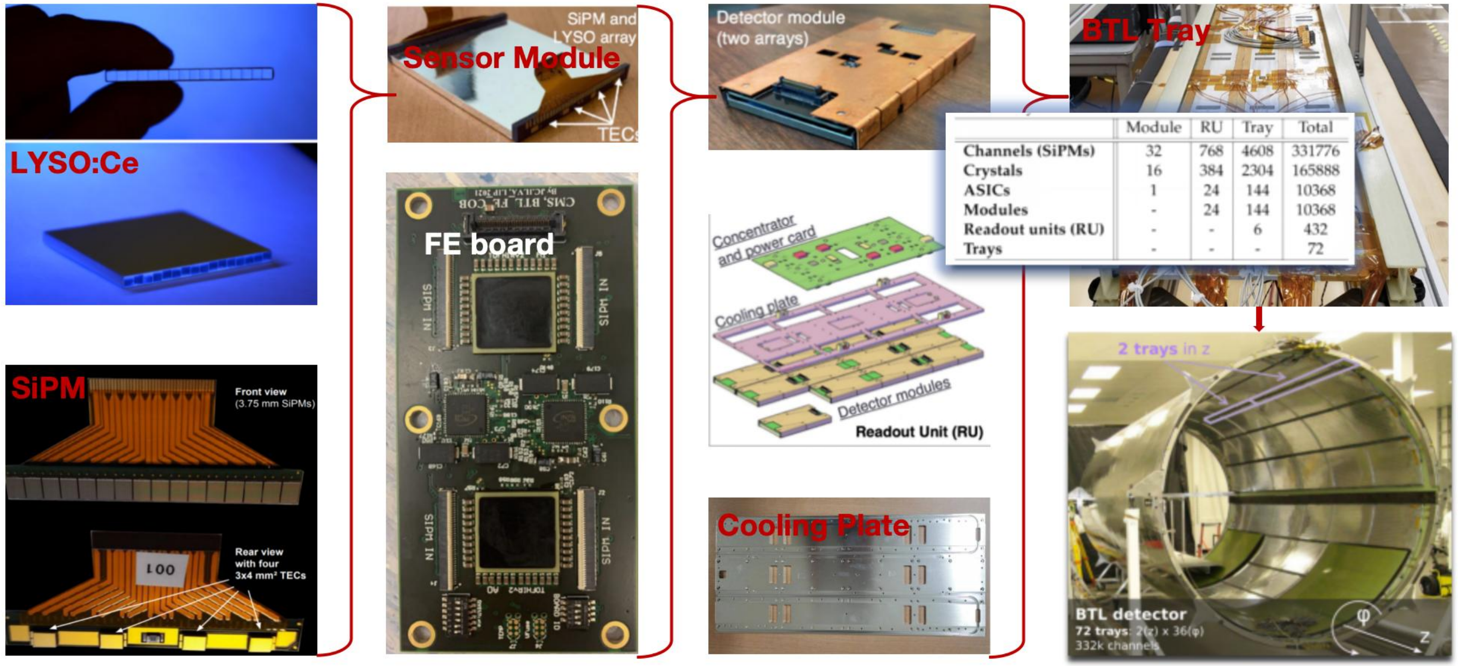
- The HL-LHC challenge
  - 3-4 times higher instantaneous luminosity;
  - Higher Pile-Up (40-60 → 140-200 events) and radiation damage.

- The MIP Timing Detector (MTD)
  - Reduce effective PU at HL-LHC using timing information;
  - Time measurement of min.-ionizing (charged) particles (MIP) with time resolution of 30-60 ps.

- The MTD Barrel Timing Layer (BTL)
  - Radiation hardness
  - Negligible impact on calorimeter performance (small energy absorption)
  - Mechanics, service, cost and schedule compatible with existing upgrades
  - … …







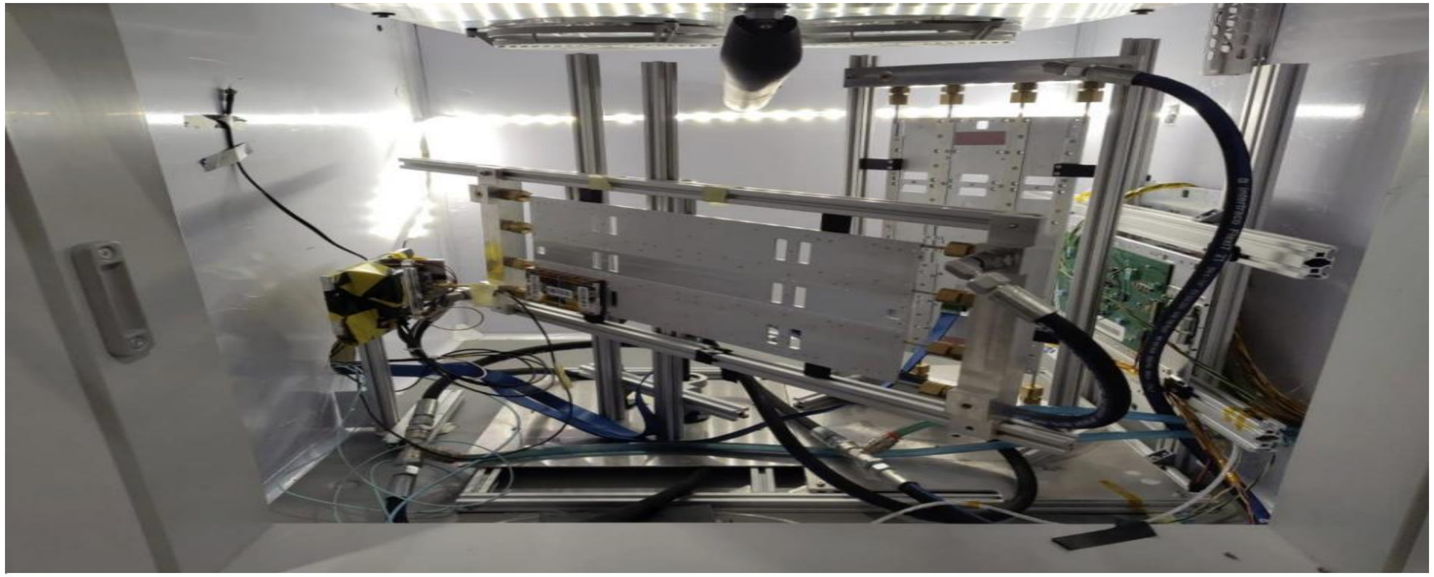
	Module	RU	Tray	Total
Channels (SiPMs)	32	768	4608	331776
Crystals	16	384	2304	165888
ASICs	1	24	144	10368
Modules	-	24	144	10368
Readout units (RU)	-	-	6	432
Trays	-	-	-	72

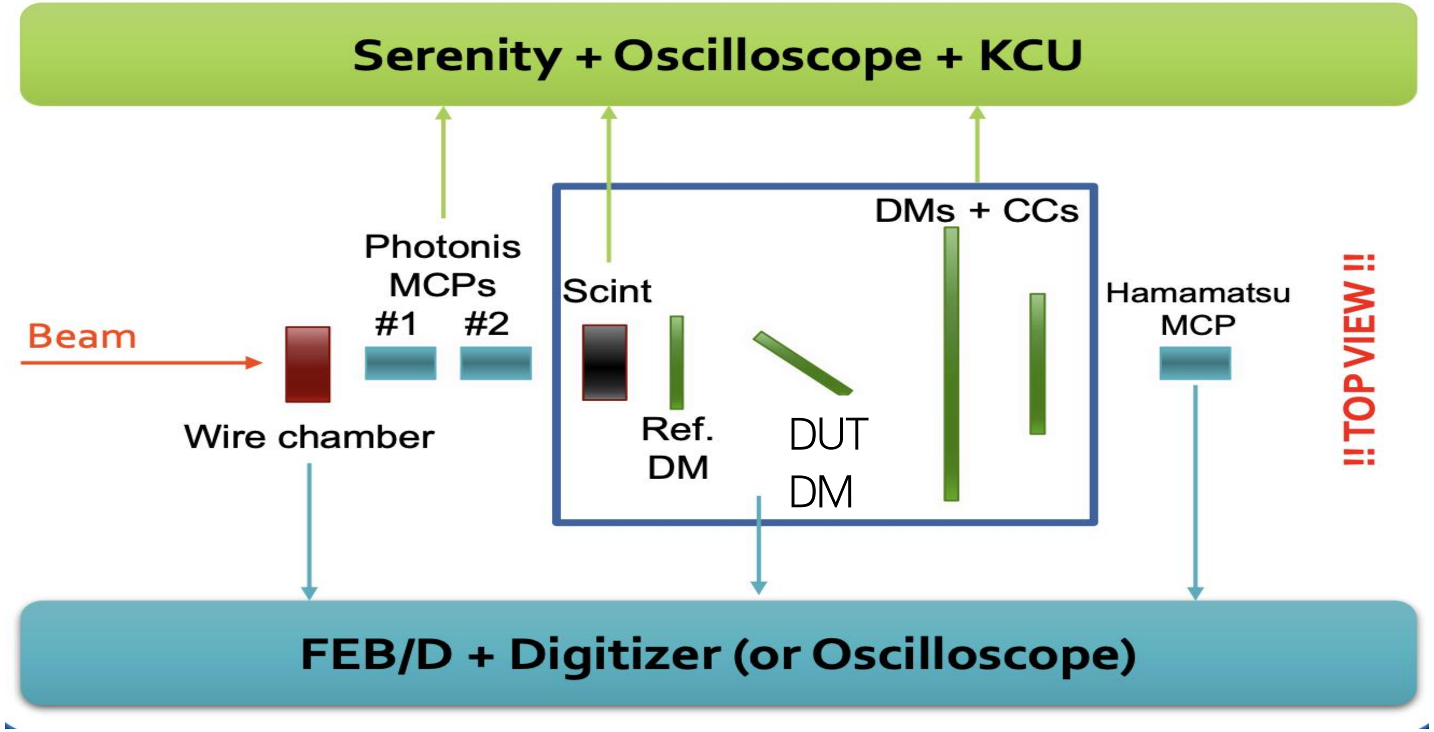
Elements of MTD BTL

Preliminary results of MTD BTL 2025 test beam (TB)

TB Preparation

- TB setups
  - FEB/D setup
    - Pair of DMs, LYSO crystals oriented vertically (horizontally) for upstream (downstream) module;
    - New: Oscilloscope for MCP digitization as alternative to CAEN Digitizer → higher acquisition rate
  - Serenity setup
    - Pair of CCs mounted on cooling plates;
    - Oscilloscope + KCU for MCP digitisation and signal optical conversion





TB Preparation

- Modules tested
  - Modules in Cat. A are used as the reference ones and do some research, such as energy sharing;
  - The modules in Class D and R are used to do some research, such as uniformity;
  - Parameters (delayE, attGain) calibrated for all DMs involved.

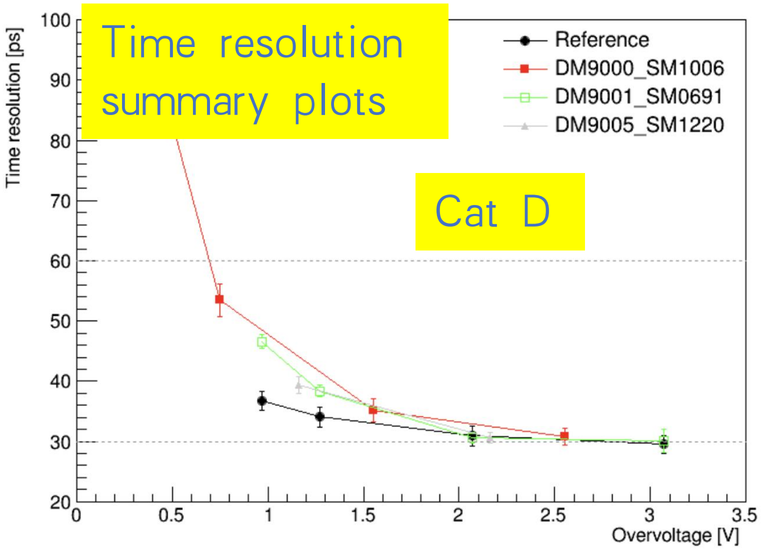
Category	Description
A	No bad bar in it, and no spe issue
B	1 bad bar in it, and no spe issue
C	2 bad bar in it, and no spe issue
D	more than 2 bad bars, and no spe issue, mainly due to energy resolution
R	more than 2 bad bars, mainly due to gluing issue (large asymmetry between left and right)

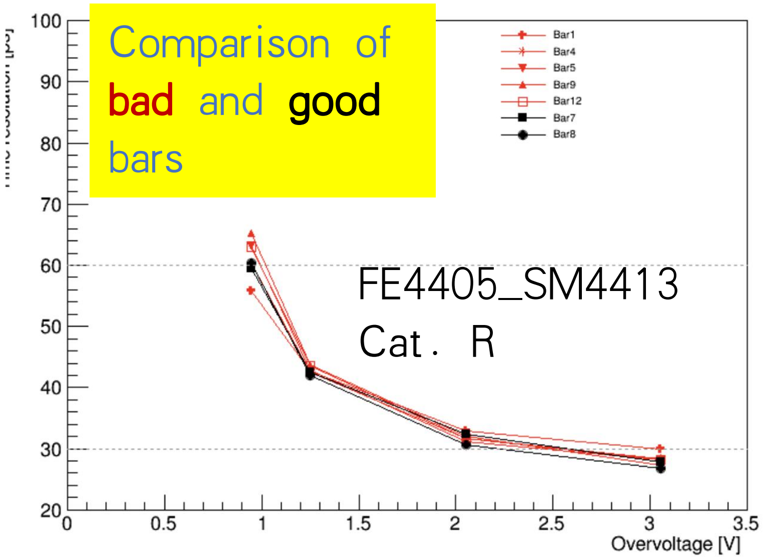
*bad bar: bar with energy resolution larger than threshold, asymmetry larger than threshold, or light yield lower than threshold

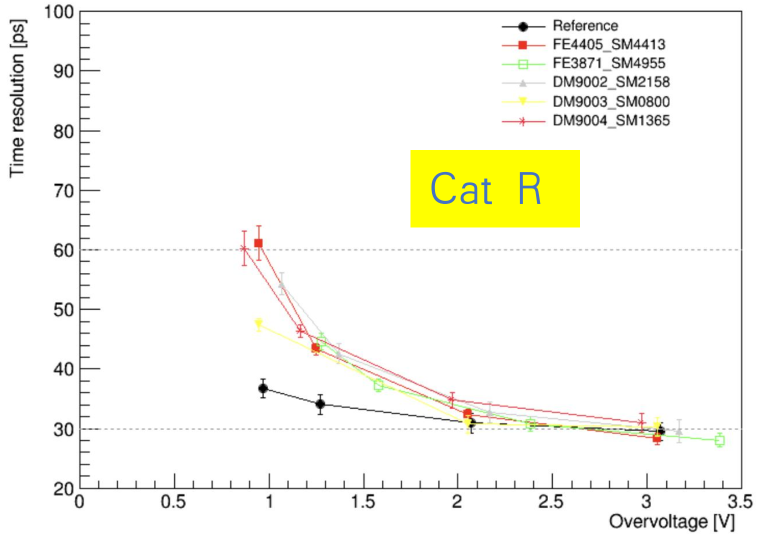
A+B+C will be used in the BTL

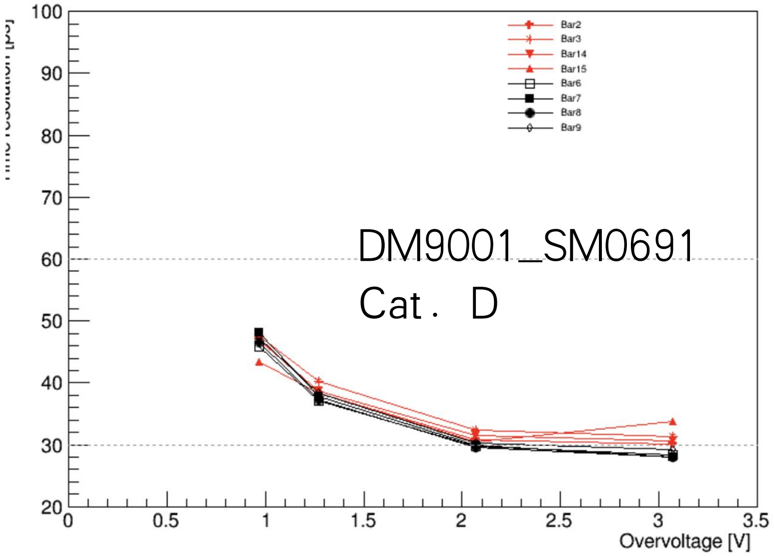
Preliminary results from FEB/D setup

- FEB/D data reconstruction is almost done, and MCP data reconstruction is still on going;
- Uniformity study
  - Get the average time resolution for different SMs at different over voltages;
  - Don't see very bad performance on time resolution in bad bars, but research is still on going;
  - Try to get the time resolution from fitting function, and the function is still under discussion
  - Using MCP as external time reference to do some resarch (not started yet)





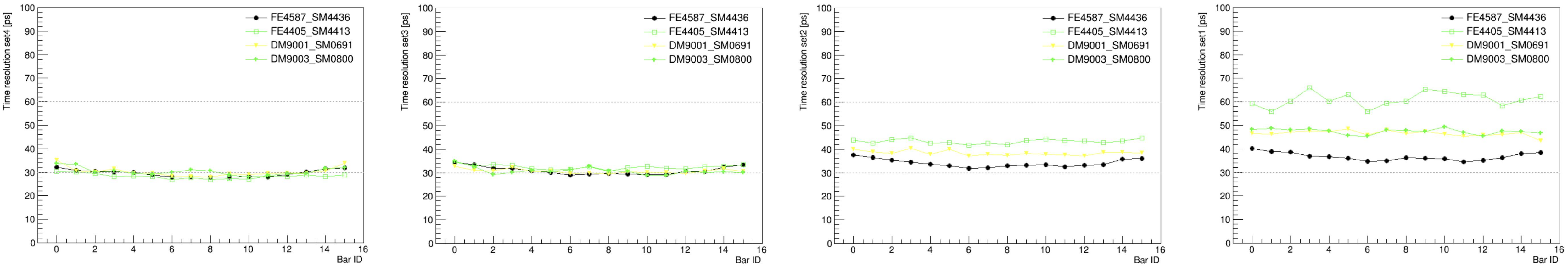




Preliminary results from FEB/D setup

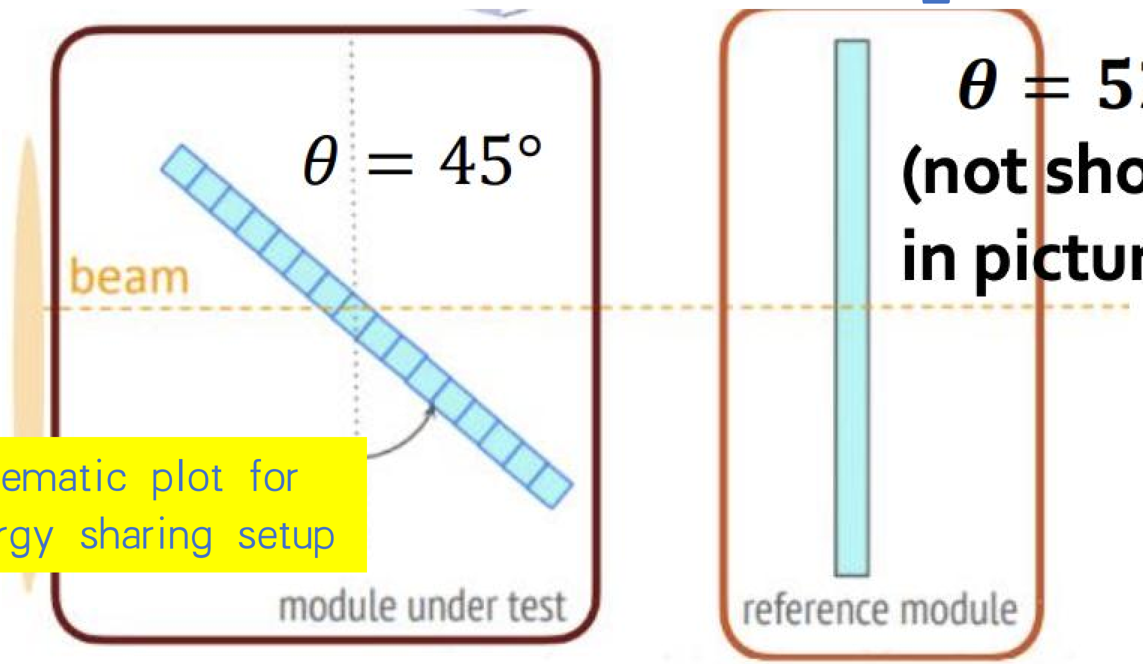
- FEB/D data reconstruction is almost done, and MCP data reconstruction is still on going;
- Uniformity study
  - The performance difference becomes larger when the over voltage becomes lower. The SM with bad bars and lower light yield become worse faster

Over voltage high -> low



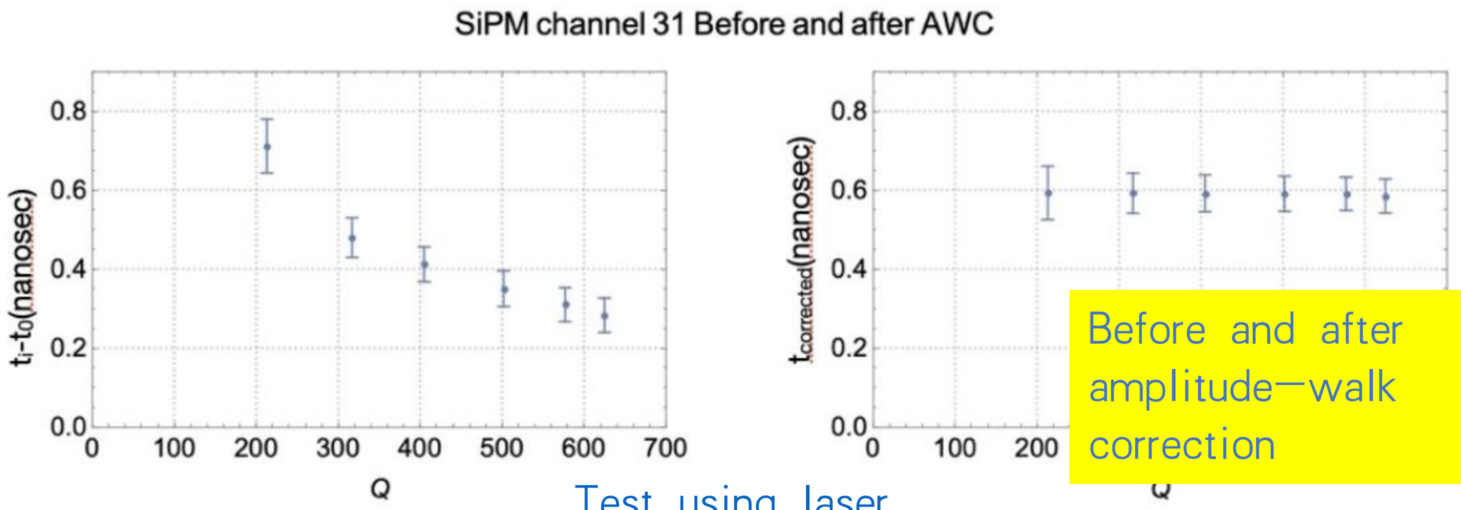
Preliminary results from FEB/D setup

- FEB/D data reconstruction is almost done, and MCP data reconstruction is still on going;
- Uniformity study
- Energy sharing study (not started yet)
  - Upstream module rotated by 45° w.r.t. beam
  - MIP energy deposit shared between 2-3 crystals
  - Estimate time resolution using consecutive bars sharing MIP energy
- Amplitude-walk corrections (not started yet)
  - Use TOFHIR double-time reading to evaluate signal slope and study correlation with time measurement
  - Use MCP to characterize Ref. DM, then use it to test module downstream (increasing data available)



$\theta = 52°$ (not shown in picture)

Schematic plot for energy sharing setup



Before and after amplitude−walk correction

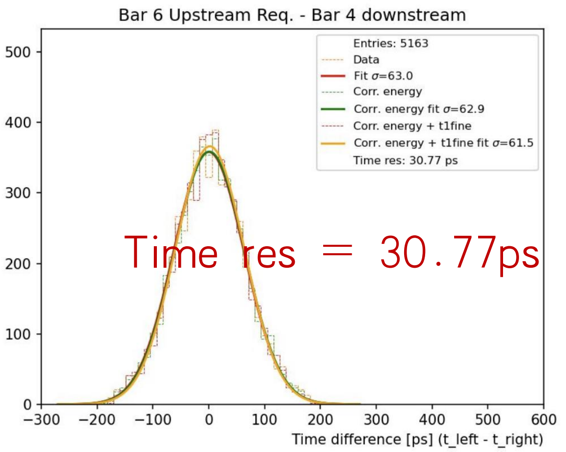
Test using laser

Preliminary results from Serenity setup

- First validation with production components: CC v2 with lpGBT v1, TOFHIR 2C, and Serenity S1.2 with VU13P FPGAs;
- Preliminary results indicate that the readout chain is verified, and time resolution is measured as expected with various settings;
- MCP data reconstruction is still on going, and many things need to be understood;
- MTD DAQ group will repeat these tests with two Serenity S1.2s using laser pulse

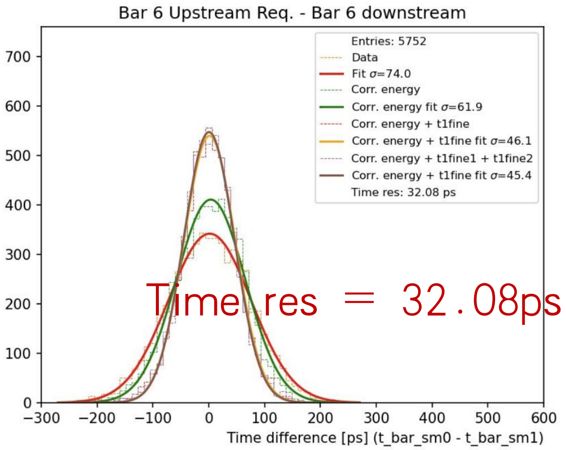
Left vs Right: Time Resolution

- Data with different levels of corrections
- Time res is the final sigma / 2
- Both REF and DUT SM were perpendicular to the beam (0°)



SM0 bar vs SM 1 bar: Time Resolution

- Data with different levels of corrections
- Time res is the final sigma / √2



Tray test at low temperature

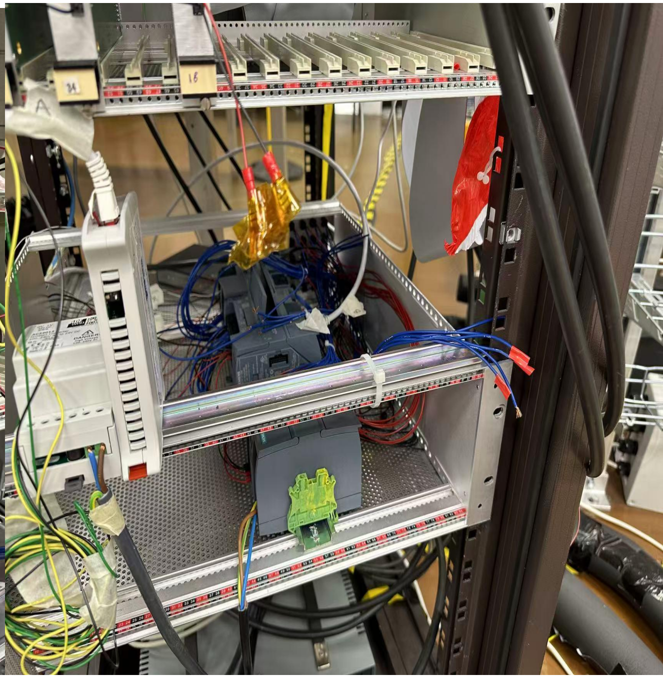
Big-picture goals of the test

- Tests below mainly focus on only one readout unit (RU)

- Demonstrate realistic Tray operations
  - Safe operation with -35℃ CO_2, -45℃ SiPMs
  - Physics results (e.g. LYSO spectra) under these conditions

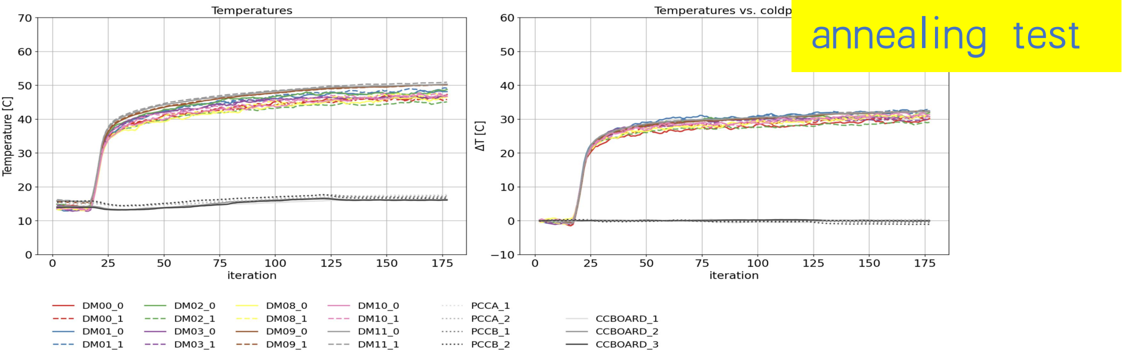
- Use this experience to develop TIF tray checkout procedures and infrastructure

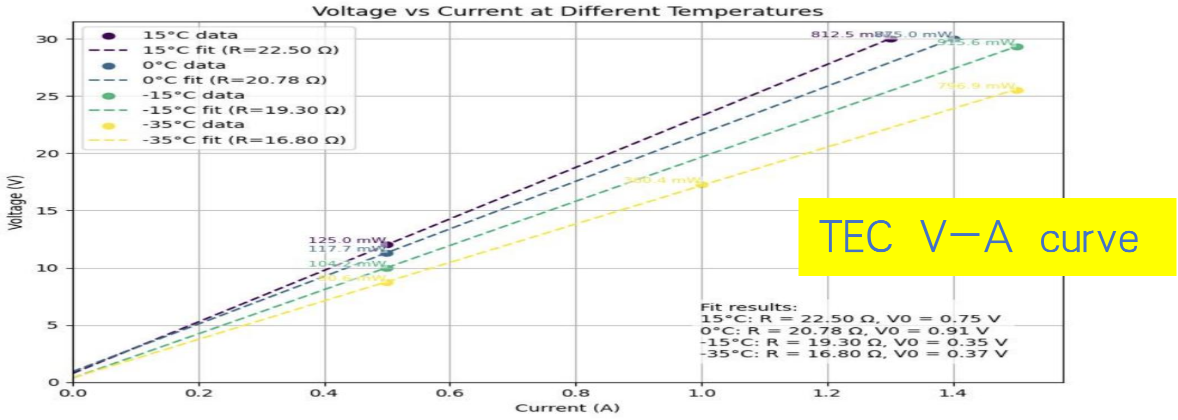


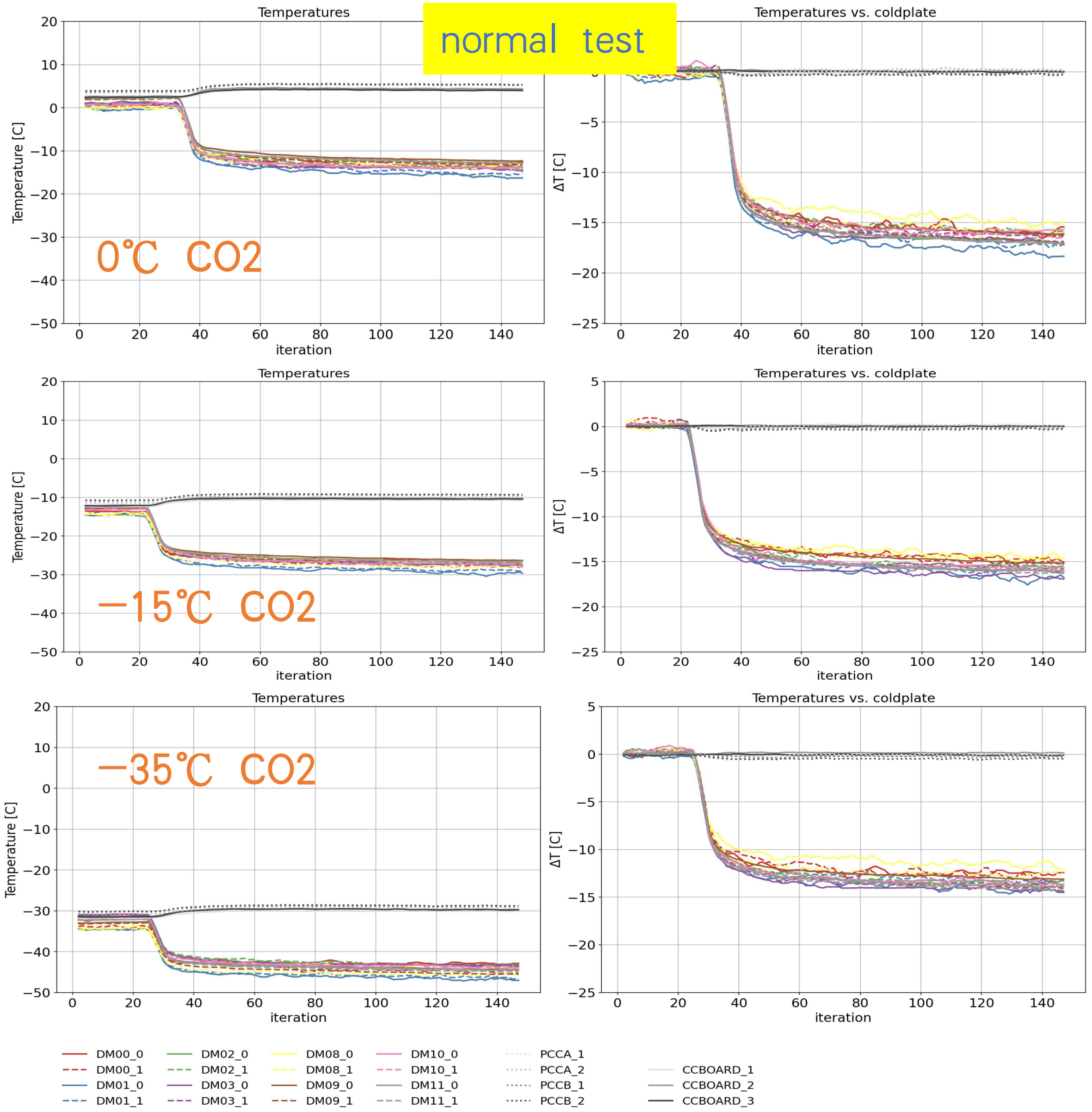


TEC tests at low temperature

- Repeat TEC tests at each CO2 temperature to lower the sipm temperature;
- Repeat annealing test at 10℃ CO2 to make sure it can work and to know the working power

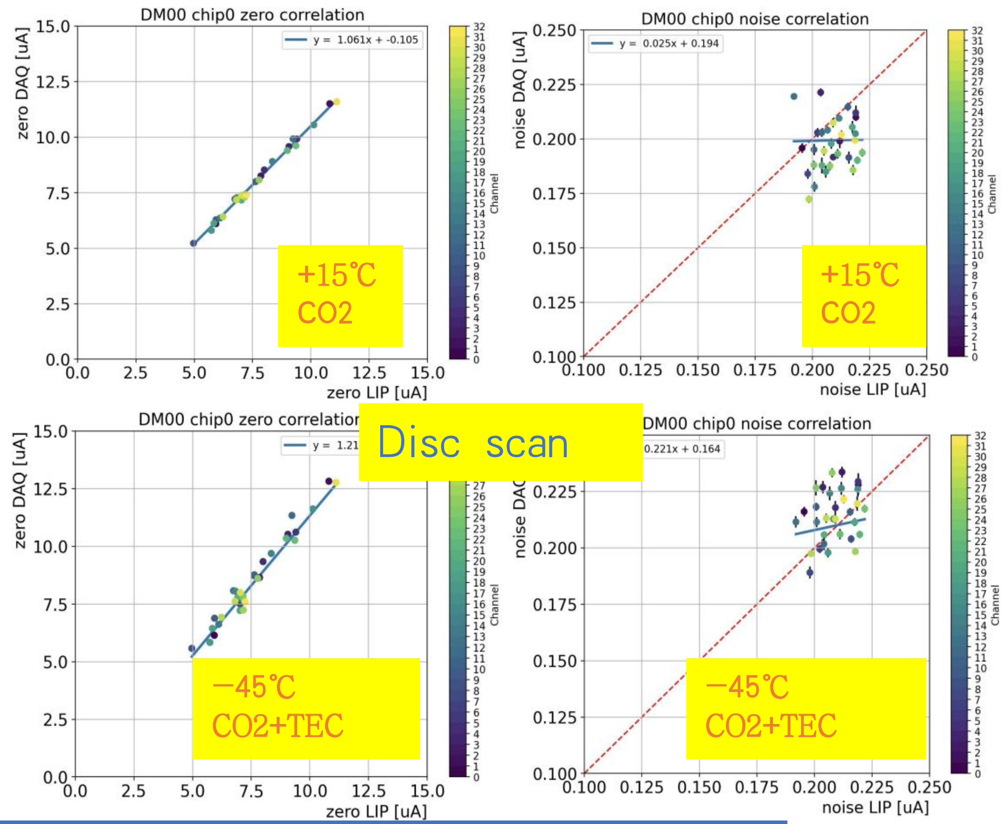


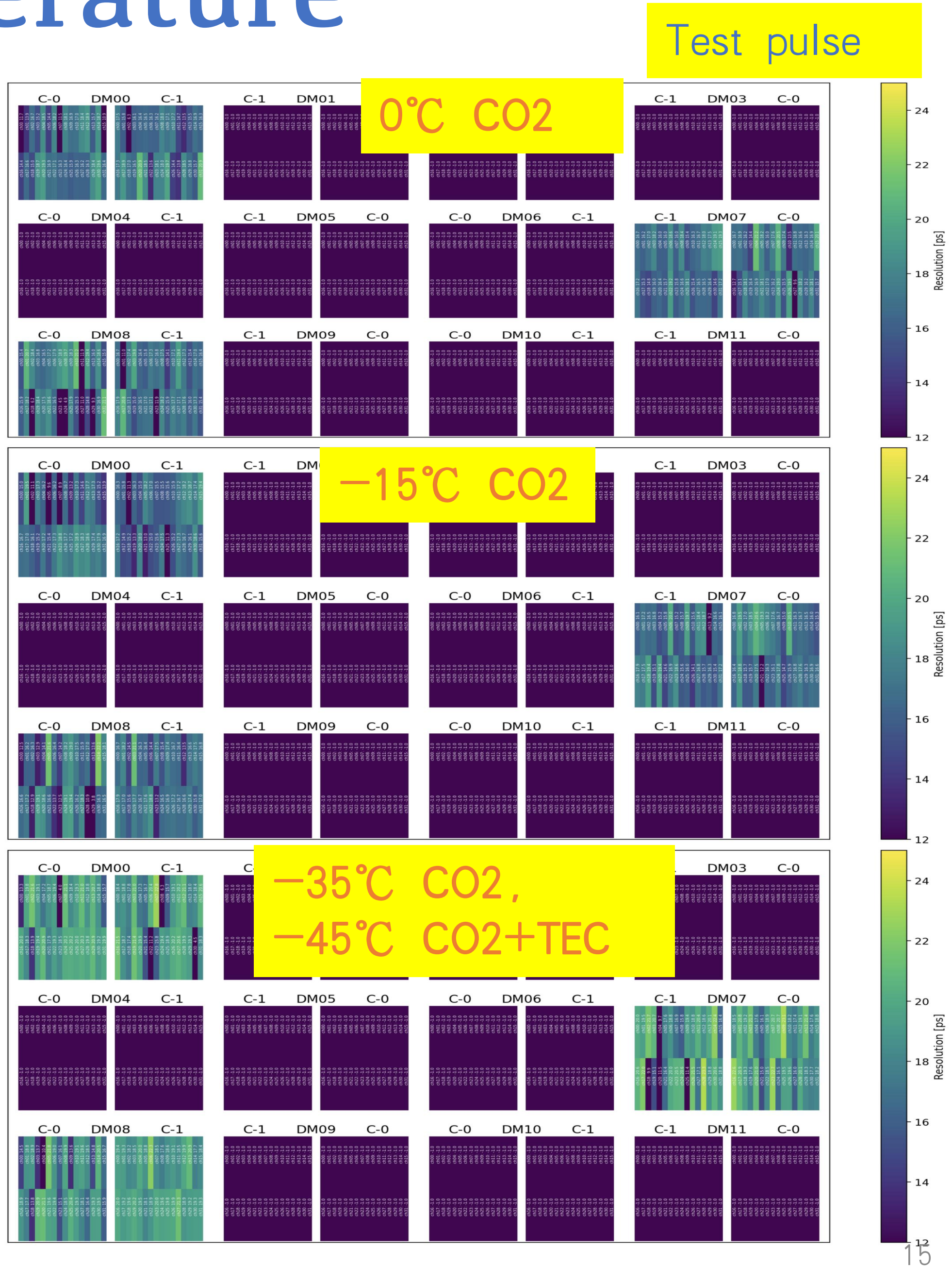




TOFHiR tests at low temperature

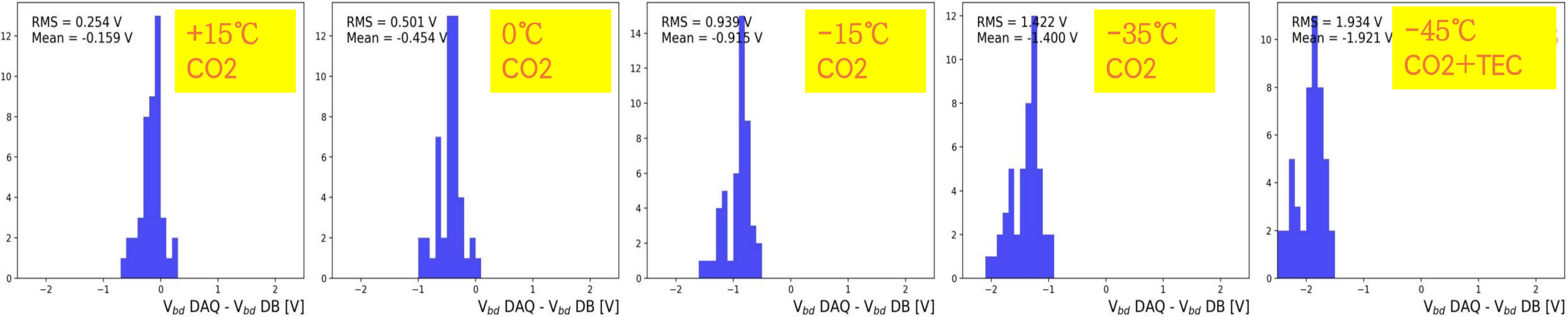
- Test Pulse runs at each temperature
  - Higher TP time resolution at -45℃ needs to be understood...(The purple DMs are masked)
- Disc scan with -45℃ SiPM
  - Slight shift in correlation with LIP, slightly higher noise





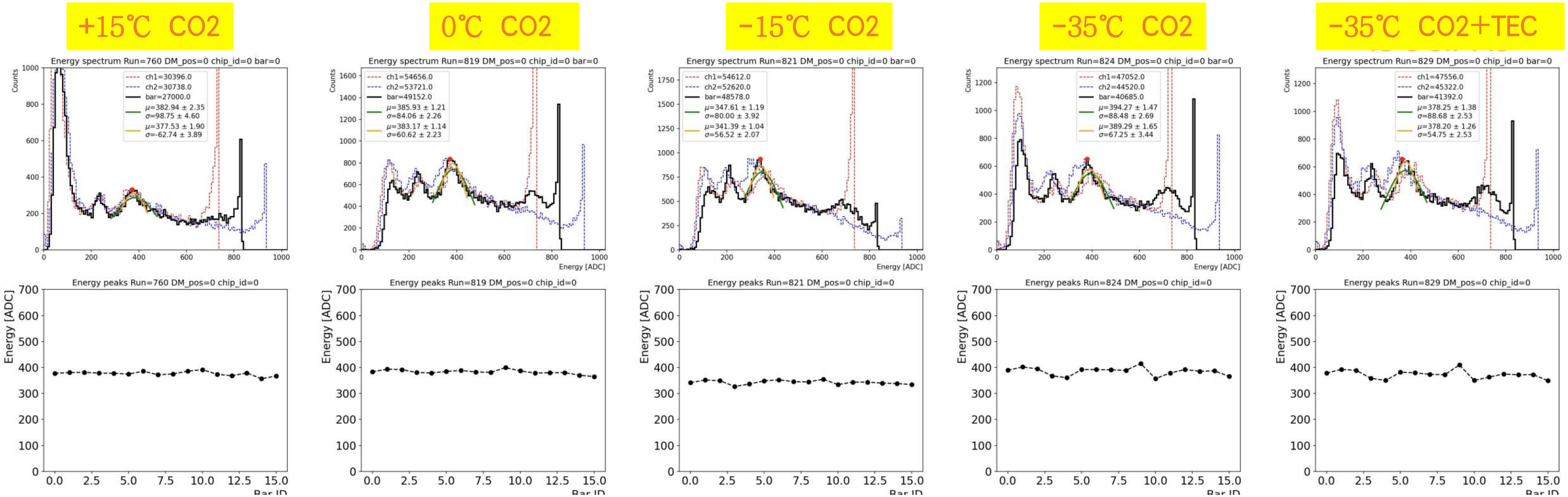
Cold SiPM IV curves

- Take IV curves at each temperature
  - Qualitative behavior of IV curves as expected
  - Measured Vbd shift is not quite as expected from first principles
    - SiPM Vbd will increase 0.0375V per degree from first principles
    - Expect that ALDO calibration is shifting with temperature (still under discussion)
  - Use measured avg Vbd to adjust OV during LYSO runs



Cold LYSO spectra

- Take LYSO spectra with OV adjusted according to IV scan results and in situ calibrations
  - Overall behavior is as expected
  - Some evidence of FETP (or possibly QDC) calibrations becoming less appropriate at lower temps



Summary and plan

Summary and Plan

- Summary
  - A brief introduction to MTD BTL;
  - Some preliminary results of 2025 TB, and some future analysis;
  - Tray test procedure and results at low temperature;

- Plan:
  - Continue doing and discussing the TB analysis ;
  - Continue doing DM and tray assembly and test;
  - Considering the PKU tray has arrived at CERN safely (the first tray from BACs at CERN🎉), we are trying to setup a whole procedure to checkout the trays at CERN

We’re getting ready for the whole MTD BTL!!!

Thanks

Backup

Time Resolution

- CMS clock distribution: 15 ps;
- Digitization: 7 ps;
- Electronics: 8 ps;
- Photo-statistics: 25–30 ps;
- Noise (SiPM dark counts): negligible at startup, 50 ps after 3000 fb^{-1};

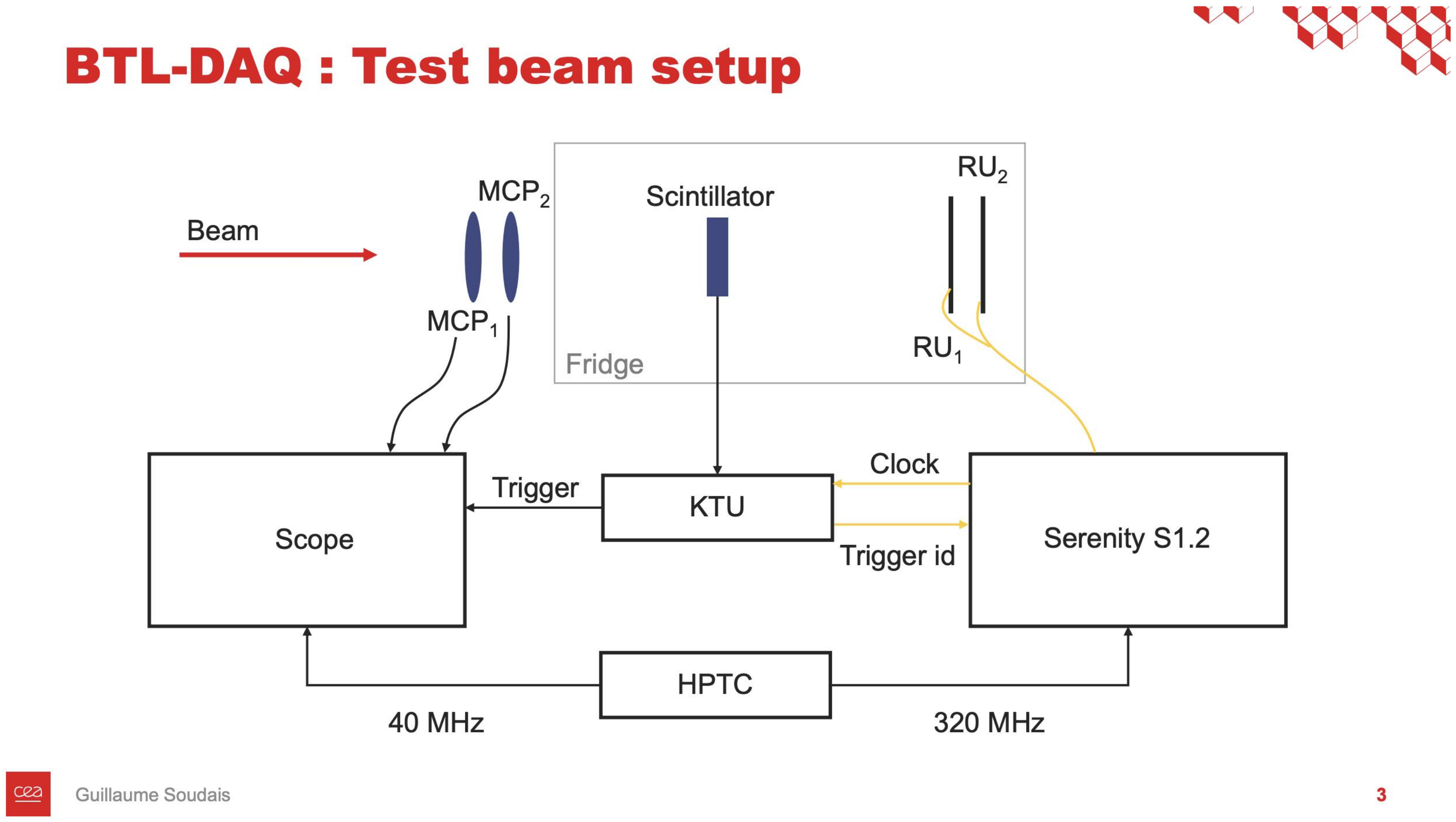
summarized in the equation:

$$\sigma_{\mathrm{t}}^{\mathrm{BTL}} = \sigma_{\mathrm{t}}^{\mathrm{clock}} \oplus \sigma_{\mathrm{t}}^{\mathrm{digi}} \oplus \sigma_{\mathrm{t}}^{\mathrm{ele}} \oplus \sigma_{\mathrm{t}}^{\mathrm{phot}} \oplus \sigma_{\mathrm{t}}^{\mathrm{DCR}} . \tag{2.1}$$

Each of these terms is discussed in more detail in their respective paragraphs, and their relative contributions to the overall time resolution are summarized in Fig. 2.3. Time jitter from the electronics and time digitization effects have a negligible impact on the overall time resolution.

The timing performance drivers are the photo-statistics and the noise term, thus major R&D efforts have been spent on their optimization. The contribution from photo-statistics is related to the stochastic fluctuations in the time-of-arrival of photons detected at the SiPM, and its scaling with respect to key BTL parameters is summarized by the equation:

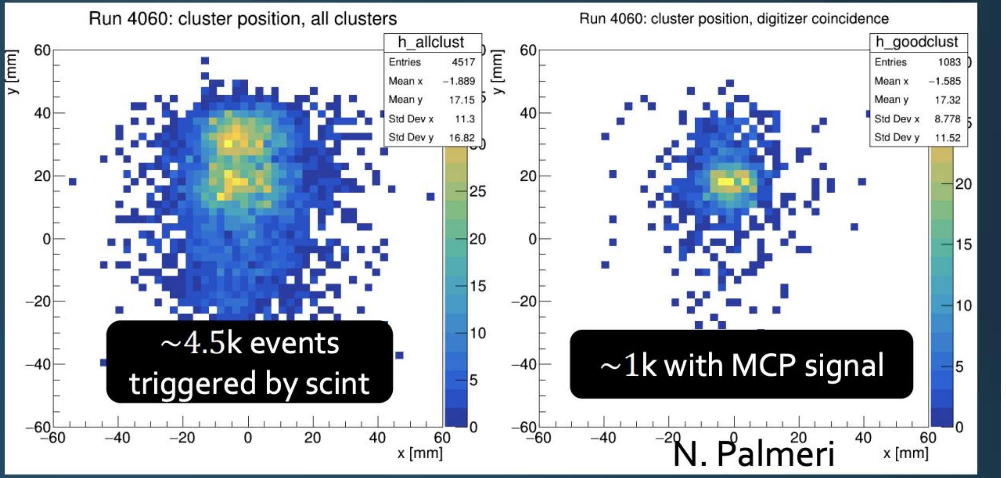
$$\sigma_{\mathrm{t}}^{\mathrm{phot}} \propto \sqrt{\frac{\tau_{\mathrm{r}}\tau_{\mathrm{d}}}{N_{\mathrm{phe}}}} \propto \sqrt{\frac{\tau_{\mathrm{r}}\tau_{\mathrm{d}}}{E_{\mathrm{dep}} \cdot \mathrm{LY} \cdot \mathrm{LCE} \cdot \mathrm{PDE}}} , \tag{2.2}$$



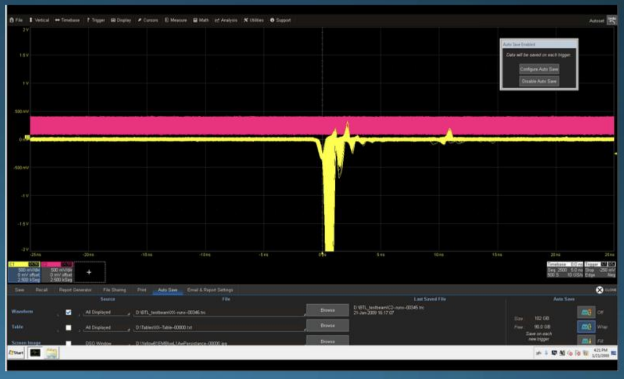
BTL DAQ talk at MTD Days

MCP digitisation (FEB/D setup)

Approach #1:
- Use $7 \times 7\ \mathrm{cm}^2$ scintillator to trigger the event
- Wire Chambers to TDC
- MCP to CAEN digitizer
- Pro: syncronization of time information from MCP + coordinates from WC
- Con:
  - acquisition rate limited by digitizer to $\sim 7 - 800\ \mathrm{Hz}$
  - MCP active area ($\emptyset\ 1\ \mathrm{cm}$) smaller than digitizer



Approach #2:
- Use oscilloscope to acquire MCP signals
- Pro: signal rate increased to 7.5 evt/spill (all with MCP signal)
- Con: lost synchronization with Wire Chambers (no spatial info)



Used both approaches balancing higher MCP statistics with need for position information

Claudio's talk at MTD Days

SM Cat

```yaml
# For e.g.: a metric {key} needs to be defined under the "metrics" block as key: expression
categories:
  A: ({spe_high_nch} + {spe_low_nch}) == 0 and (not {lo_asymm_avg_high}) and {bad_nbar} == 0
  B: ({spe_high_nch} + {spe_low_nch}) == 0 and (not {lo_asymm_avg_high}) and {bad_nbar} == 1
  C: ({spe_high_nch} + {spe_low_nch}) == 0 and (not {lo_asymm_avg_high}) and {bad_nbar} == 2
  D: ({spe_high_nch} + {spe_low_nch}) == 0 and (not {lo_asymm_avg_high}) and {bad_nbar} > 2 and {bad_nbar_lo} <= 2 and {res_high_nbar} > 0
  R: not ({A} or {B} or {C} or {D})

# Define metrics in terms of objects (like tgraphs) read from files
# Python expressions will be evaluated
# For e.g.: an object {key} needs to be defined under "read" block as key: object_name
# The "pairing" key needs to be defined if modules are to be paired
# Can define your favorite metrics here
# All metrics will be stored in the categorization output file
metrics:
  lo_low_nbar: "numpy.count_nonzero(get_gry({lo_bar}) < {lo_bar_min})"
  lo_low_nch: "numpy.count_nonzero(get_gry({lo_ch}) < {lo_ch_min})"
  lo_asymm_nbar: "numpy.count_nonzero(numpy.abs(get_gry({lo_asymm_bar})) > {lo_asymm_bar_max})"
  res_high_nbar: "numpy.count_nonzero(get_gry({res_bar}) > {res_bar_max})"
  spe_high_nch: "numpy.count_nonzero(get_gry({spe_ch}) > {spe_ch_max})"
  spe_low_nch: "numpy.count_nonzero(get_gry({spe_ch}) < {spe_ch_min})"

  lo_asymm_avg_high: "bool(numpy.mean(get_gry({lo_asymm_bar})) > {lo_asymm_avg_max})"

  bad_nbar_lo: >-
    numpy.count_nonzero(
      (get_gry({lo_barL}) < {lo_ch_min})
    + (get_gry({lo_barR}) < {lo_ch_min})
    + (get_gry({lo_bar}) < {lo_bar_min})
    + (numpy.abs(get_gry({lo_asymm_bar})) > {lo_asymm_bar_max})
    )

  bad_nbar: >-
    numpy.count_nonzero(
      (get_gry({lo_barL}) < {lo_ch_min})
    + (get_gry({lo_barR}) < {lo_ch_min})
    + (get_gry({lo_bar}) < {lo_bar_min})
    + (numpy.abs(get_gry({lo_asymm_bar})) > {lo_asymm_bar_max})
    + (get_gry({res_bar}) > {res_bar_max})
    )

  lo_bar_avg: "float(numpy.mean(get_gry({lo_bar})))"
```

```yaml
# Define values
# Python expressions will be evaluated
values:
  lo_bar_min: "(0.85*3150)"
  lo_ch_min: "(0.80*3150)"
  lo_asymm_bar_max: 0.2
  lo_asymm_avg_max: 0.08
  res_bar_max: 0.06
  spe_ch_max: "4.4"
  spe_ch_min: "3.4"
```

```yaml
categories:
  A: "(not {deltaT_high}) and (not {deltaT_avg_high}) and ('R' not in '{sm_cat}')"
  R: "not {A}"


metrics:

  deltaT_high: "bool(max([{tL}.Eval(4), {tR}.Eval(4), {bL}.Eval(4), {bR}.Eval(4)]) > {deltaT_avg_max})"
  deltaT_avg_high: "bool(numpy.mean([{tL}.Eval(4), {tR}.Eval(4), {bL}.Eval(4), {bR}.Eval(4)]) > {deltaT_avg_max})"

  sm_cat: "str({sm1}['results']['category']+{sm2}['results']['category'])"

  deltaT_avg: "float(numpy.mean([{tL}.Eval(4), {tR}.Eval(4), {bL}.Eval(4), {bR}.Eval(4)]))"
  tec_sum: "float(numpy.sum([{sm1}['sipm1']['tec_res'], {sm1}['sipm2']['tec_res'], {sm2}['sipm1']['tec_res'], {sm2}['sipm2']['tec_res']]))"
  tec_std: "float(numpy.std([{sm1}['sipm1']['tec_res'], {sm1}['sipm2']['tec_res'], {sm2}['sipm1']['tec_res'], {sm2}['sipm2']['tec_res']]))"

  lo_avg: "-0.5*({sm1}['results']['lo_bar_avg'] + {sm2}['results']['lo_bar_avg'])"

  # Negative for reverse sorting
  grouping: "-0.5*({sm1}['results']['lo_bar_avg'] + {sm2}['results']['lo_bar_avg'])"
```

```yaml
values:
  deltaT_max: -18
  deltaT_avg_max: -18
```

Signal	Physics measurement	MTD impact
$H \to \gamma\gamma$ and H→4 leptons	+15–25% (statistical) precision on the cross section → Improve coupling measurements	Isolation and Vertex identification
VBF→H→ $\tau\tau$	+30% (statistical) precision on cross section → Improve coupling measurements	Isolation VBF tagging, p_T^{miss}
HH	+20% gain in signal yield → Consolidate searches	Isolation b-tagging
EWK SUSY	+40% background reduction → 150 GeV increase in mass reach	MET b-tagging
Long-lived particles (LLP)	Peaking mass reconstruction → Unique discovery potential	β_{LLP} from timing of displaced vertices