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MTD BTL
Sensor Module Assembly and Tests

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01 MTD BTL

Physics motivation of MTD BTL

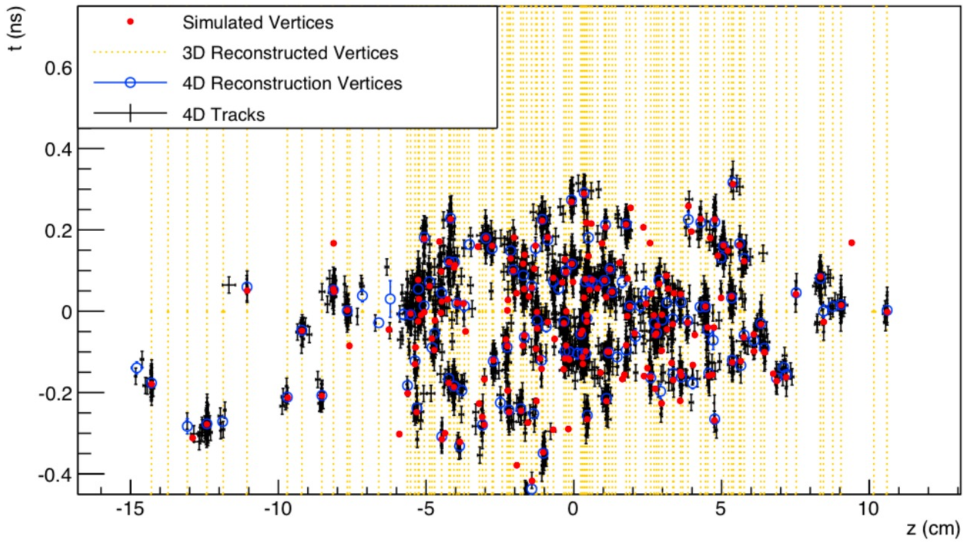
High luminosity → high pileup

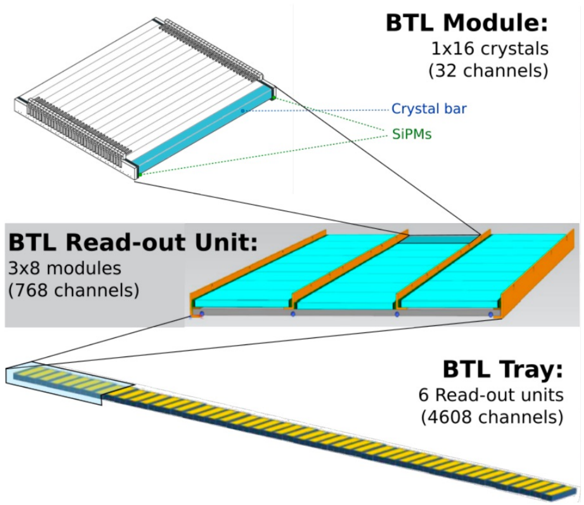
The MTD will be added to CMS to help meet the challenge of high luminosity.

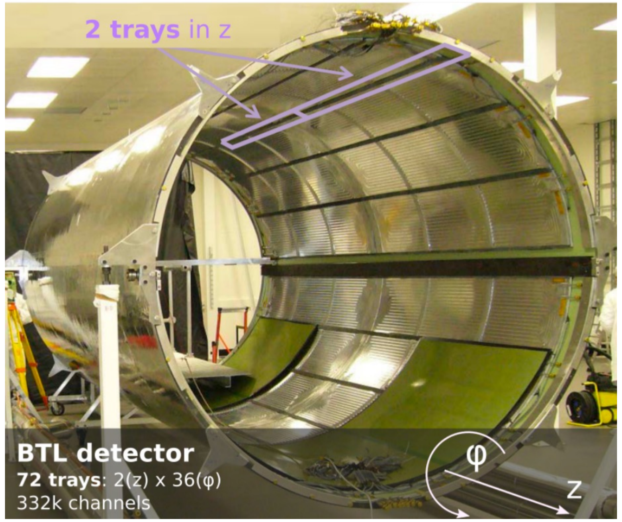
- offset fully degradation from 140 to 200 pileup recover the effective background conditions close to Phase-1 operations.

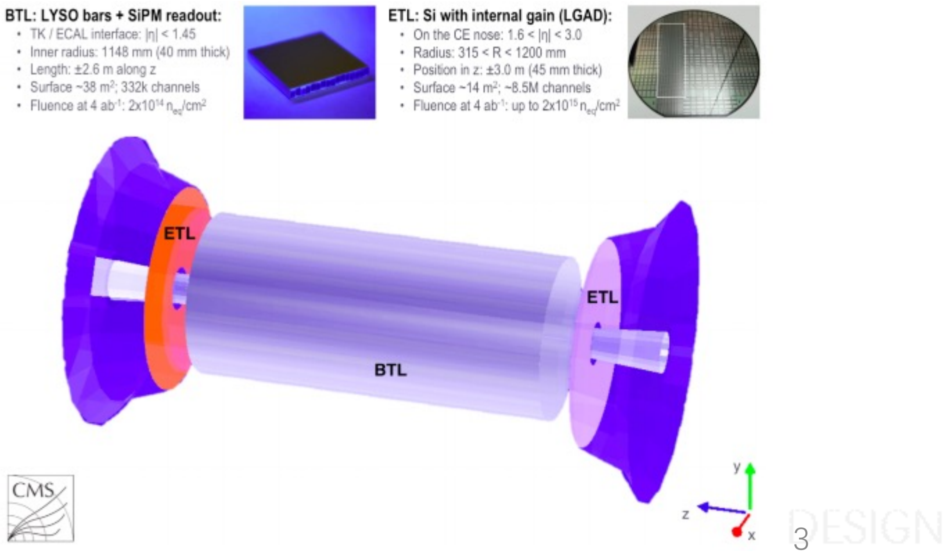
The BTL is a thin, cylindrical detector

- BTL Module, Read-out Unit, Tray, BTL detector









Schedule of MTD BTL

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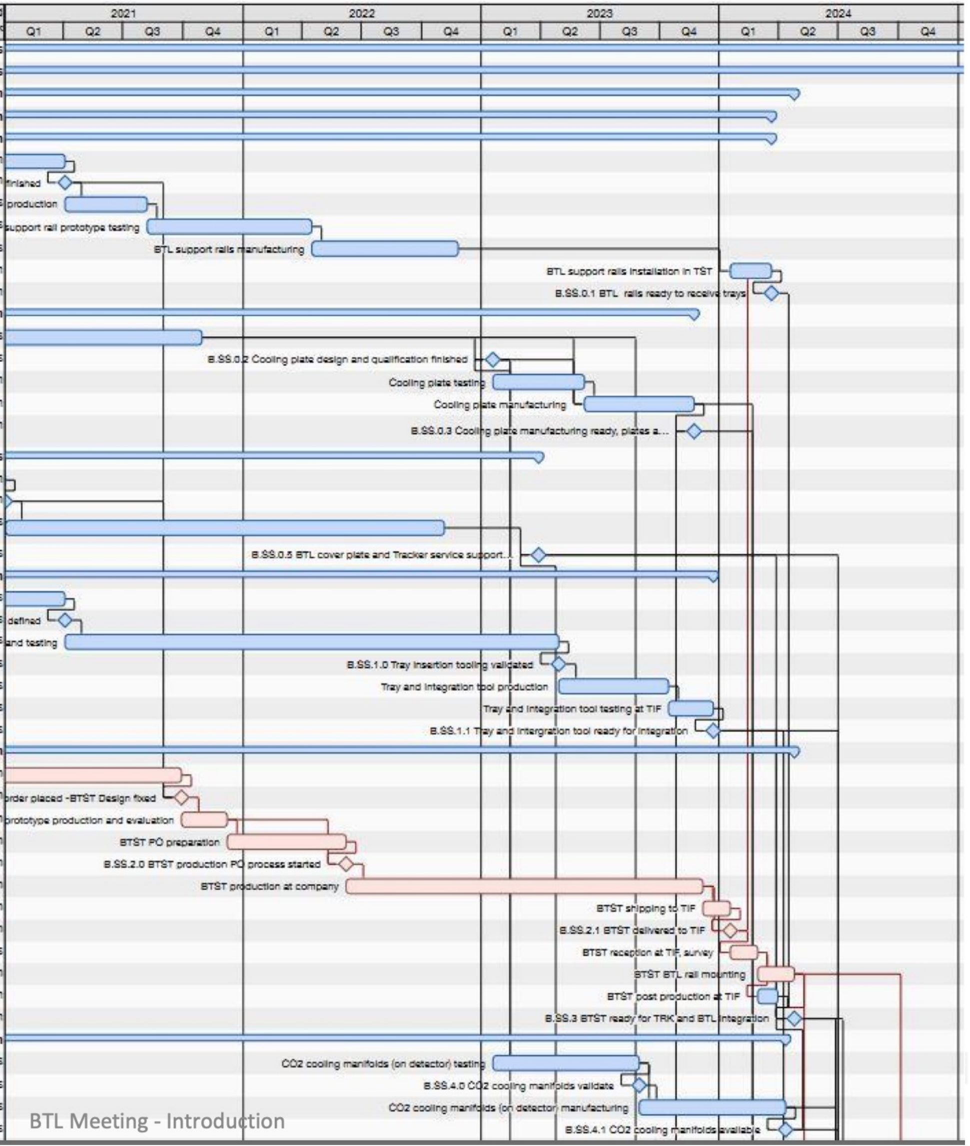
PKU Assembly timeline

- Improve the assembly and QA/QC in the summer of 2023
- Assembly Center Certification in the autumn of 2023
- Start batch assembly in early 2024
- End assembly in the summer of 2026
- Installed in the autumn of 2026

#	Title	Expected Start	Expected End	Expected End Slack
0	**BTL_CS_schedule_V35.1**	**Jan 1, 2018**	**Mar 8, 2028**	**0 days**
1	**BTL**	**Jan 1, 2018**	**Mar 8, 2028**	**0 days**
2	**Mechanical Systems**	**Jan 1, 2018**	**April 24, 2024**	**3.2m**
3	**Mechanical Structures**	**Jan 1, 2018**	**Mar 20, 2024**	**4.6m**
4	**BTL support rails (BTL-Tracker mechanical interface)**	**Jan 1, 2018**	**Mar 20, 2024**	**4.6m**
5	BTL support rails design	January 1, 2018	April 2, 2021	6.4m
6	B.SS.0.0 BTL rail design and qualification finished	April 2, 2021	April 2, 2021	6.4m
7	BTL support rail prototype production	April 5, 2021	Aug 6, 2021	1.61 years
8	BTL support rail prototype testing	August 9, 2021	April 15, 2022	1.61 years
9	BTL support rails manufacturing	April 18, 2022	Nov 25, 2022	1.61 years
10	BTL support rails installation in TST	Jan 17, 2024	Mar 20, 2024	4.6m
11	B.SS.0.1 BTL rails ready to receive trays	Mar 20, 2024	Mar 20, 2024	4.6m
12	**Cooling Plates and Tray Mechanics**	**Jan 1, 2018**	**Nov 22, 2023**	**4.2m**
15	Cooling plate preproduction and qualification	Oct 2, 2020	Oct 29, 2021	1.63 years
16	B.SS.0.2 Cooling plate design and qualification finished	Jan 18, 2023	Jan 18, 2023	3.7 months
17	Cooling plate testing	Jan 19, 2023	June 7, 2023	4.2m
18	Cooling plate manufacturing	June 8, 2023	Nov 22, 2023	4.2m
19	B.SS.0.3 Cooling plate manufacturing ready, plates available for tray assembly	Nov 22, 2023	Nov 22, 2023	4.2m
20	**BTL cover plates - Tracker responsibility**	**Jan 1, 2018**	**Mar 29, 2023**	**1.43 years**
21	BTL cover plate and Tracker service supports design	January 1, 2018	Jan 1, 2021	9.6m
22	B.SS.0.4 BTL cover plate design defined	January 1, 2021	Jan 1, 2021	9.6m
23	BTL cover plate and Tracker service supports, prototyping, testing and manufacturing	Jan 1, 2021	Nov 4, 2022	1.86 years
24	B.SS.0.5 BTL cover plate and Tracker service supports ready	Mar 29, 2023	Mar 29, 2023	1.43 years
25	**Trays and Integration Tools**	**Jan 1, 2018**	**Dec 21, 2023**	**4.4m**
26	Trays and Integration Tool design	January 1, 2018	April 2, 2021	4.4 months
27	B.SS.1 Tray insertion tooling process defined	April 2, 2021	April 2, 2021	4.4 months
28	Tray insertion tooling prototyping and testing	April 5, 2021	April 28, 2023	4.4 months
29	B.SS.1.0 Tray insertion tooling validated	April 28, 2023	April 28, 2023	4.4 months
30	Tray and integration tool production	May 1, 2023	Oct 13, 2023	4.4 months
31	Tray and integration tool testing at TIF	Oct 16, 2023	Dec 21, 2023	4.4 months
32	B.SS.1.1 Tray and intergration tool ready for integration	Dec 21, 2023	Dec 21, 2023	4.4 months
33	**BTST - Not official BTST schedule**	**Jan 1, 2018**	**April 24, 2024**	**3.2m**
35	BTST conduct tender process	August 7, 2020	Sep 29, 2021	-4.2h
36	B.SS.2 BTST order placed -BTST Design fixed	Sep 29, 2021	Sep 29, 2021	-4.2h
37	BTST prototype production and evaluation	Sep 29, 2021	Dec 8, 2021	-4.2h
38	BTST PO preparation	Dec 8, 2021	June 8, 2022	-4.2h
39	B.SS.2.0 BTST production PO process started	June 8, 2022	June 8, 2022	-4.2h
40	BTST production at company	June 8, 2022	Dec 6, 2023	-4.2h
41	BTST shipping to TIF	Dec 6, 2023	Jan 17, 2024	-4.2h
42	B.SS.2.1 BTST delivered to TIF	Jan 17, 2024	Jan 17, 2024	-4.2h
43	BTST reception at TIF, survey	Jan 17, 2024	Feb 28, 2024	-4.23 hours
44	BTST BTL rail mounting	Feb 28, 2024	April 24, 2024	-4.2h
45	BTST post production at TIF	Feb 28, 2024	Mar 29, 2024	4.1m
46	B.SS.3 BTST ready for TRK and BTL integration	April 24, 2024	April 24, 2024	3.2m
47	**CO2 Cooling**	**Jan 1, 2018**	**April 10, 2024**	**3.7m**
49	CO2 cooling manifolds (on detector) testing	Jan 19, 2023	Aug 30, 2023	3.7 months
50	B.SS.4.0 CO2 cooling manifolds validate	Aug 30, 2023	Aug 30, 2023	3.7 months
51	CO2 cooling manifolds (on detector) manufacturing	Aug 31, 2023	April 10, 2024	3.7 months
52	B.SS.4.1 CO2 cooling manifolds available	April 10, 2024	April 10, 2024	3.7 months



02 Test Beam

SiPM cell-size: introduction and setup

章立诚（PKU）

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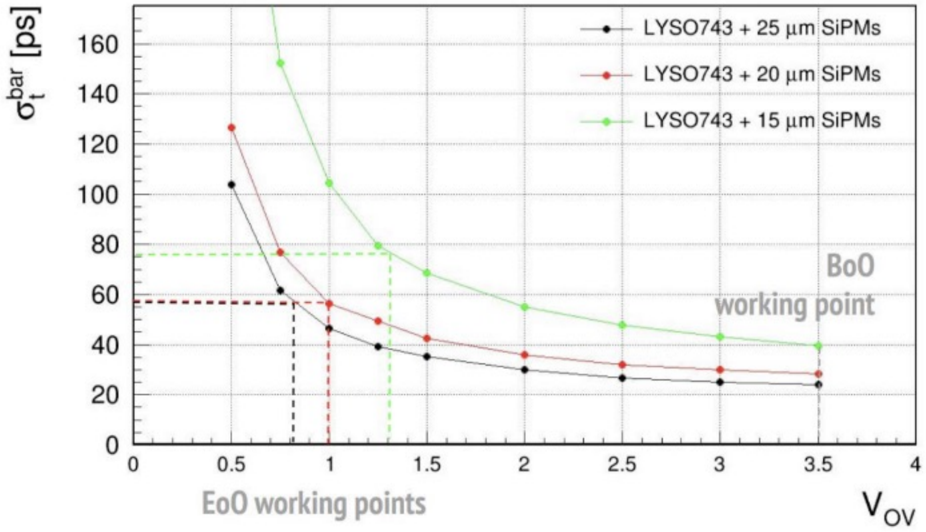
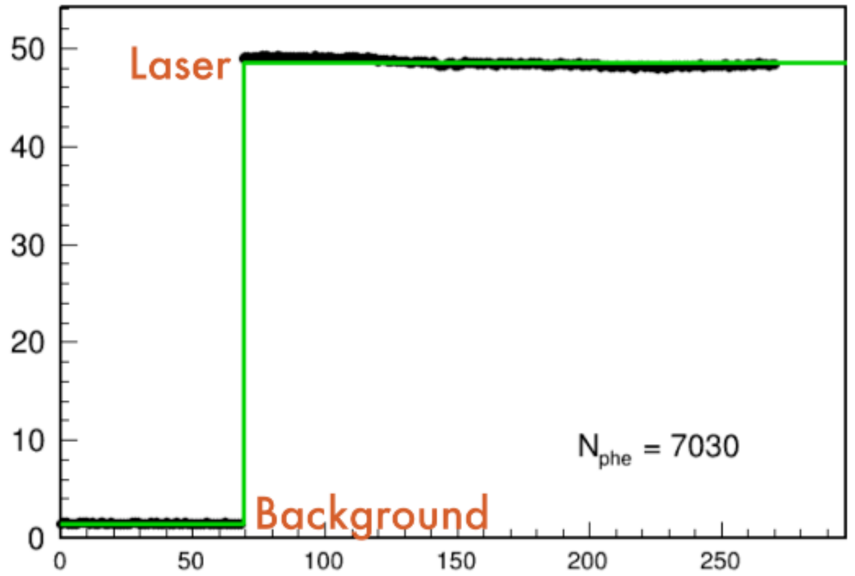
Motivation

- The cell size of SiPM has a significant impact on the time resolution

Setup

- LYSO array (#743, LYSO MS from prod 3) grease-coupled to HPK SiPM arrays with different cell-sizes (15 , 20, 25 μm - all type 2)
- Time resolution measured with TOFHIR2X and UV-induced scintillation
    - ➢ vs overvoltage, threshold
    - ➢ vs Npe (tuning the laser intensity)

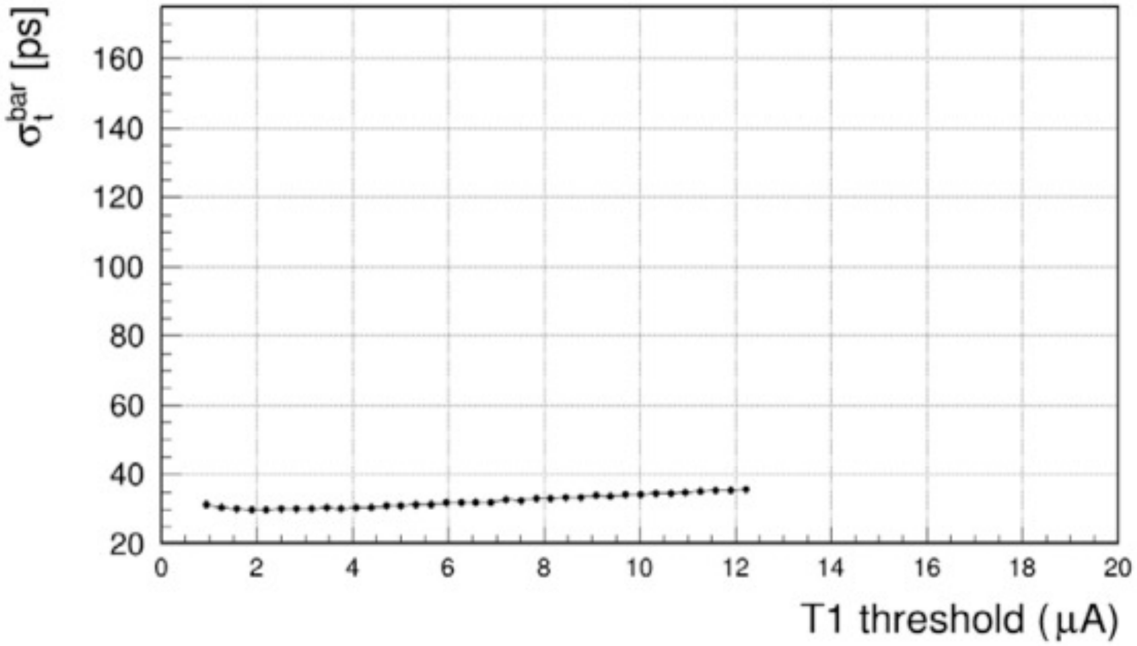


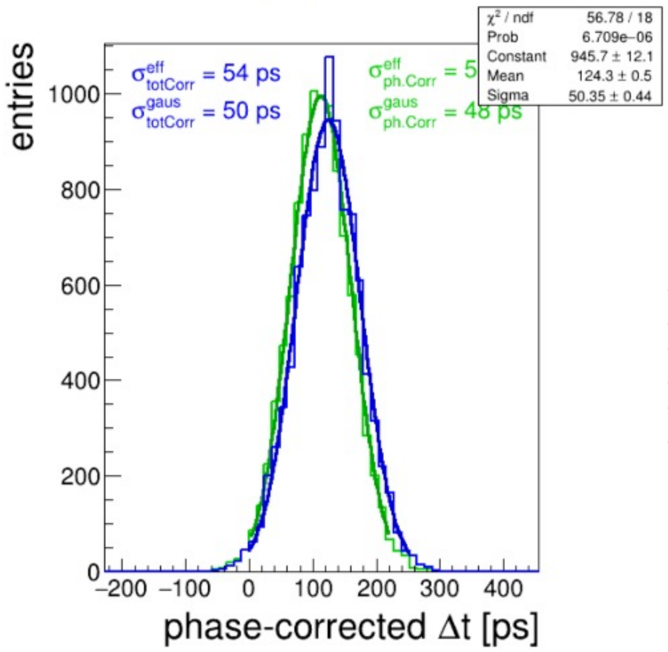


SiPM cell-size: optimization and correction

Pulse Shapes

- Find the threshold that can minimize the time resolution





- Correction over energy difference
- Correction over ToT
- Should be highly correlated

- Correction of the starting point in the triggering window
- Secrets in electronics

SiPM cell-size: summary and understanding

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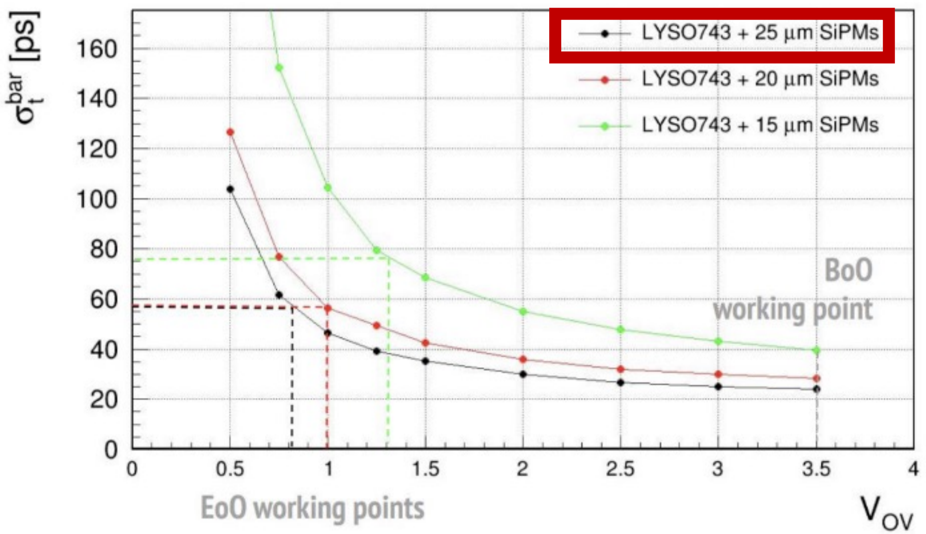
Summary

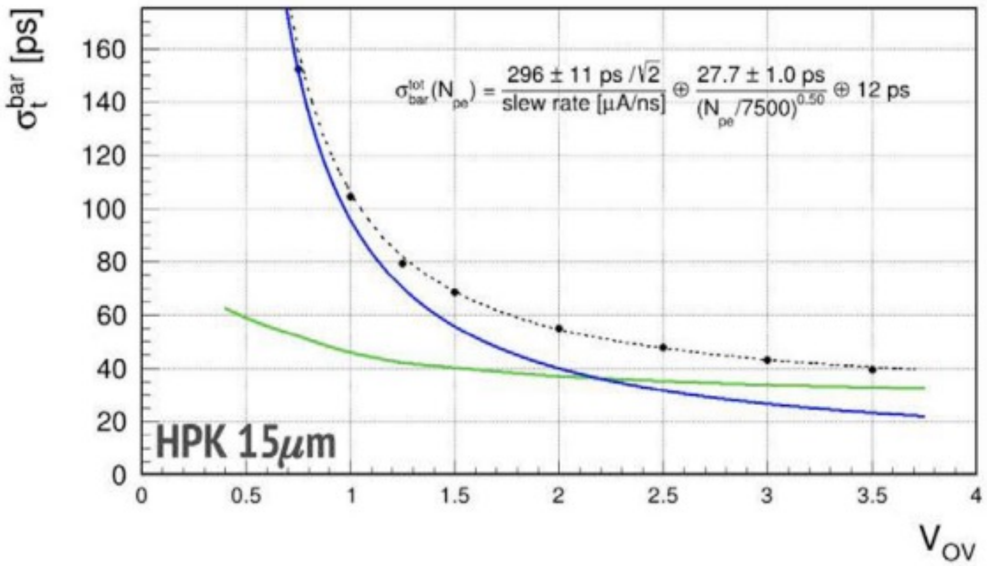
- First lab measurements of modules with new SiPMs with larger cells
- Improved performance for larger cells SiPMs (25 µm)



Understanding

- Splitting noise and stochastic contributions

$$\sigma_t^{noise} = \frac{\sigma_N}{dA/dt} \qquad \sigma_t^{pe} = \frac{A}{\sqrt{N_{pe}}}$$



LYSO selection

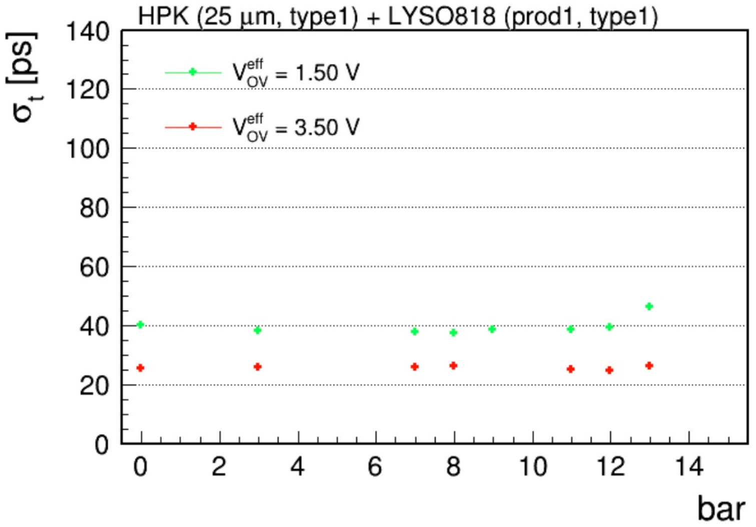
张铭滔（PKU）

Comparison between vendor 1 (LYSO818) and vendor 5 (LYSO828)

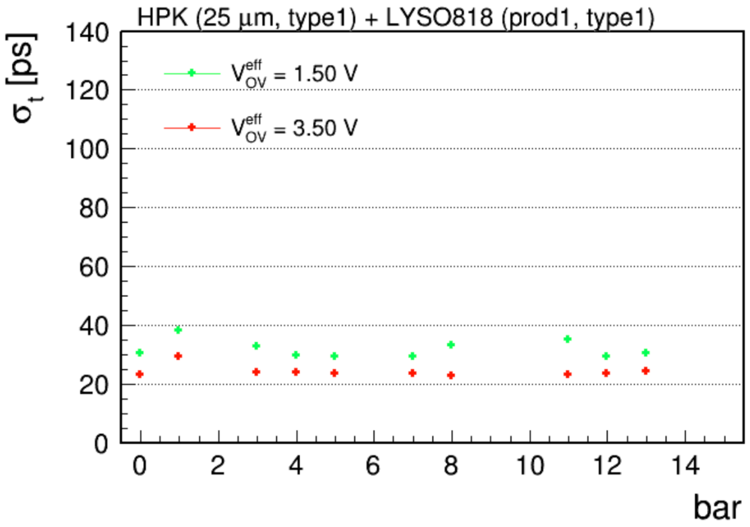
Measurement of time resolution (σ_tdiff)

- Compare the time resolution (σ_tdiff) given by the two modules under different **angles** and **Vov.**

prod1 32deg



prod1 64deg



Results are measured at the optimal threshold

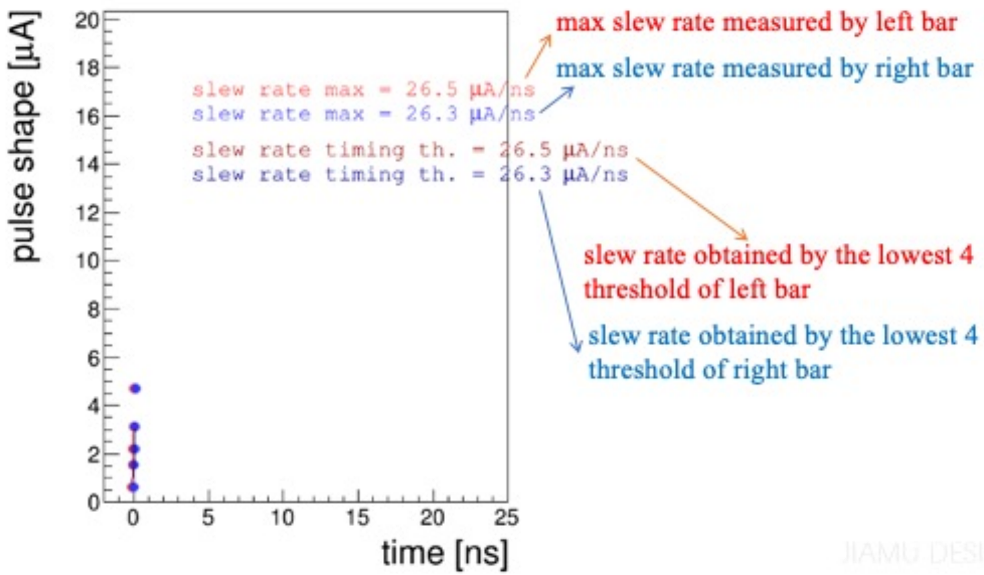
LYSO	Vov/V	angle/deg	t_{Res}/ps	error/%
prod1	1.50	32	38.2	6.9
		52	**32.2**	3.1
		64	30.9	9.0
	3.50	32	25.7	2.1
		52	**23.5**	1.2
		64	23.6	7.2
prod5	1.50	52	**35.1**	4.3
	3.50		**24.6**	4.0

- Due to the influence of noise, the resolution of 3.50V is generally better than 1.50V. Moreover, the signal increases when the angle to the beam increases, which is beneficial to distinguish the MIP peak from the noise peak, so the resolution is better;
- Time resolution of **prod1 is better than prod5**.

LYSO selection

Slew rate

➢ Plot the relation between Amplitude and time, and Compare the maximum slope of each module.



LYSO	Vov/V	angle/deg	SR/(μA/ps)
prod1	1.50	32	16.7
		52	18.7
		64	16.9
	3.50	32	33.6
		52	33.3
		64	57.9
prod5	3.50	52	44.6

- With the increase of Vov and angle to the beam, the signal amplitude increases, so SR is generally larger;
- The slew rate of **prod5 is better than prod1**;
- In the data of prod5, there are only 4 points when Vov=1.50V, so it cannot be compared together.

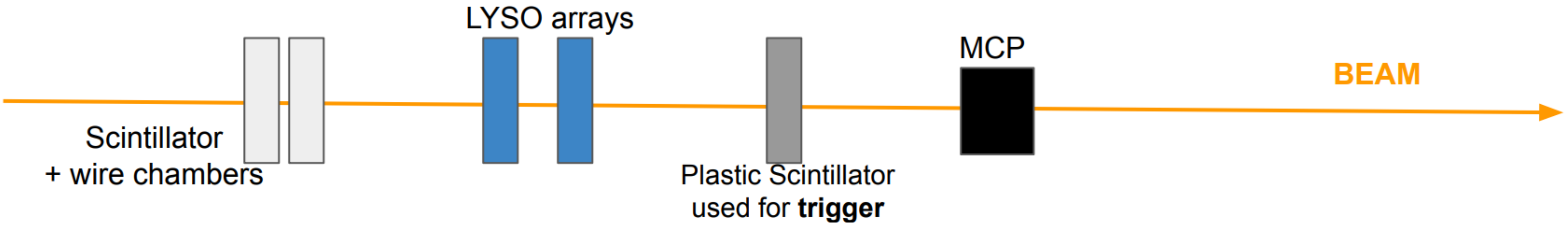
Energy linearization: setup

张铭滔（PKU）

- Measurement of LYSO arrays, irradiated and non-irradiated SiPMs using TOFHIR2B
- Configuration:
  - LYSO arrays + SiPMs & TECs
  - TOFHIR2B
- Temperature: +10℃, -33℃
- Beam: Pions wide beam(~70% pions, ~15% protons, ~5% electrons and ~10% others)

- Test irradiated SiPMs (HPK) with TECs:
  - 0, 1e14, 2e14 irradiated fluence

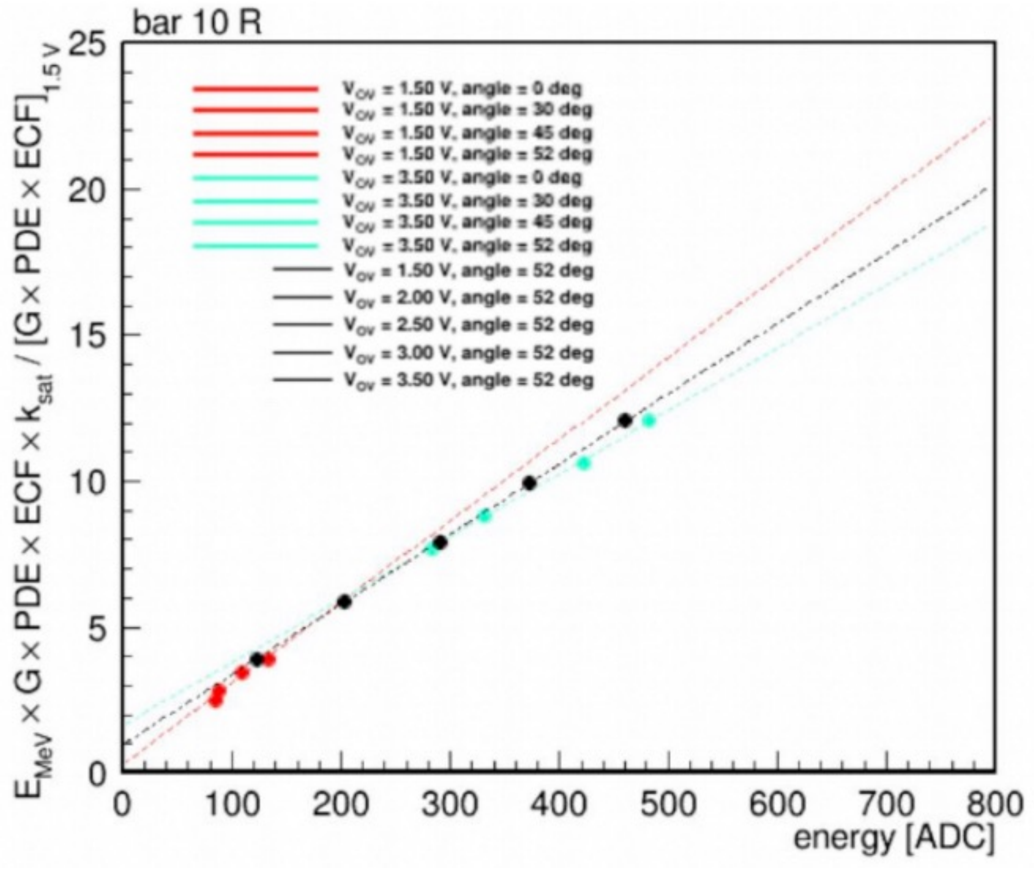
- HPK:
  - non-irr: LYSO528 type2 15um
  - 2e14: LYSO796 type2 15um
  - 1e14: LYSO802 type2 15um
- FBK:
  - 1e14: LYSO803 type2 15um
  - 2e14: LYSO797 type2 15um



- Set up in CERN

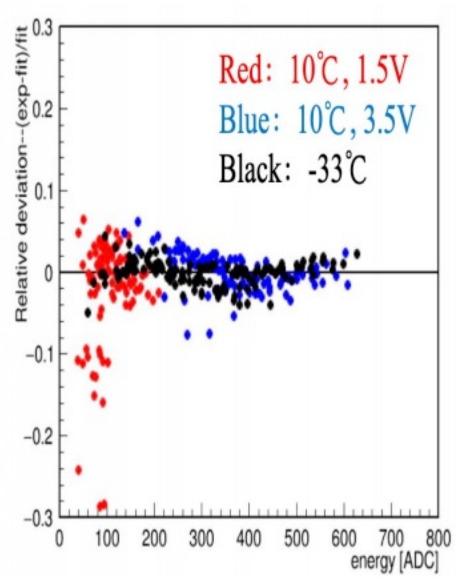
Energy linearization: results

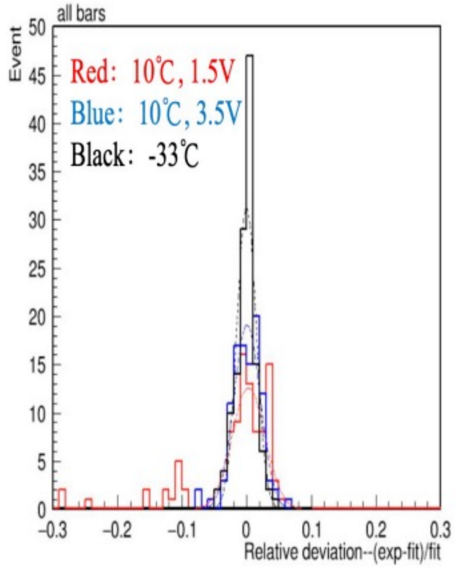
- At the same temperature, the linearity is relatively high, and energy spread is about 1.5%~2.5%



$f(x) = ae^{-\frac{(x-b)^2}{2c^2}}$	b	c
10℃, 1.5V	0.0026	0.0257
10℃, 3.5V	0.0004	0.0205
-33℃	-0.0004	0.0149

The fraction of red point in (-0.1, 0.1) is 91/104





Energy linearization: summary

Performed test beam analysis to study the energy response of MTD BTL sensor modules with the data taken from June22nd

- Found good linearization of the energy digitized by TOFHIR2B ASIC
- Observed radiation effects rougly consistent with expectations

Temperatures: Calculating

张铭滔
（PKU）

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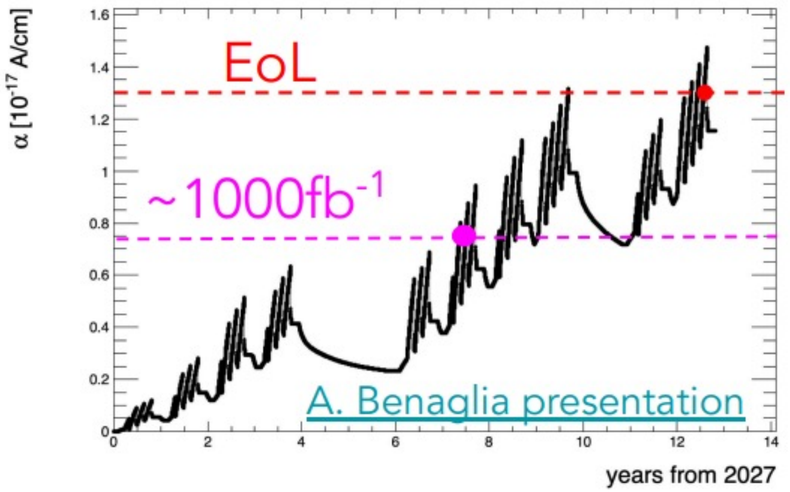
- Annealing factor evolution for irradiated SiPMs during HL-LHC (-45℃)
  - The expected value of damage rate parameter α is 1.3E-17 A/cm

- PDE(photon detection efficiency), Gain losses and DCR(dark count rate) vs Vov caused by irradiation are not considered:
  - $I_{dark}/I_0 \sim (1.9)^{dT/10}$

✓ 2E14 → T(EoL) = 10log1.9(1.3/0.68)+(-45)°C = -35°C
✓ 1E14 → T(EoL) = 10log1.9(1.3/0.34)+(-45)°C = -24.2°C
✓ 1E13 → T(EoL) = 10log1.9(1.3/0.034)+(-45)°C = +11.7°C

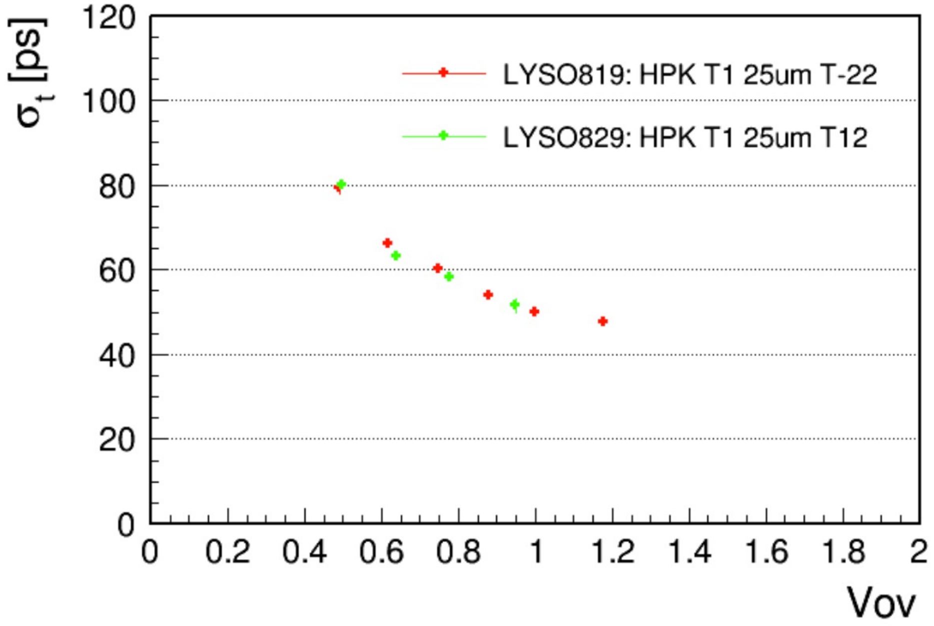
✓ 2E14 → T(mid-life) = 10log1.9(0.8/0.68)+(-45)°C = -42°C
✓ 1E14 → T(mid-life) = 10log1.9(0.8/0.34)+(-45)°C = -32°C
✓ 1E13 → T(mid-life) = 10log1.9(0.8/0.034)+(-45)°C = +4°C



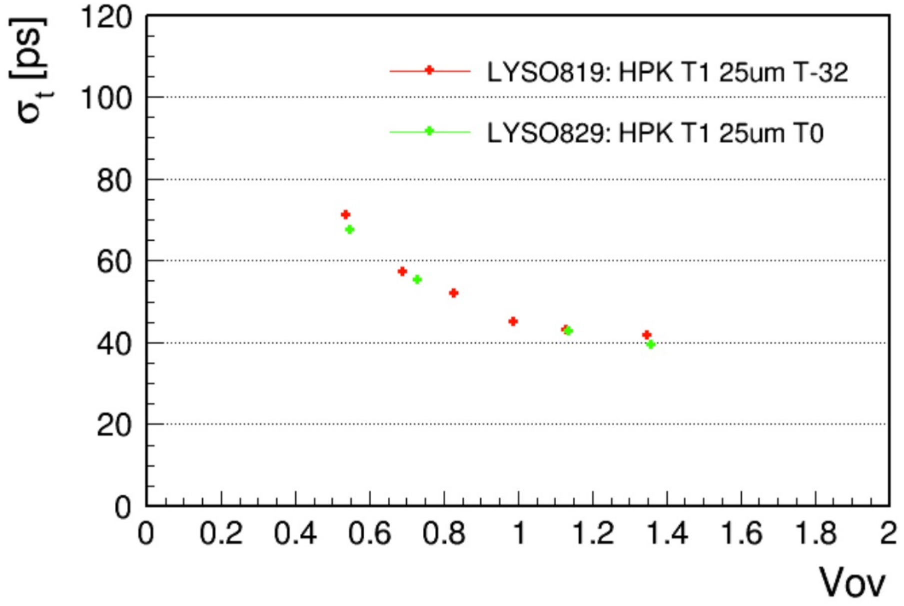
Temperatures: time resolution

➢ Comparison of time resolution(1E14 vs. 1E13)

- in EoL condition



- in mid-life condition



- The time resolution for both configuration both go better when Vov increasing;
- The performance of two configuration meet very well.
- Time resolution ~ 50ps

- The time resolution for both configuration both go better when Vov increasing;
- The performance of two configuration meet very well;
- Time resolution ~ 40ps.

Temperatures: Summary

- With the assumption of α(EoL) = 1.3E-17 A/cm and α(mid-life) = 0.8E-17 A/cm, the temperatures to emulate the two conditions under 1E14 and 1E13 fluence are calculated;

- The time resolutions of the two set of configuration are very close to each other. Both the two configurations can be used to emulate EoL condition and mid-life condition.

- The time resolution for EoL emulation can reach about 50 ps. The time resolution for mid-life condition emulation can reach about 40 ps.

03 Coupling and QA/QC

Gluing Work and QA/QC Test

王 锦
（PKU）
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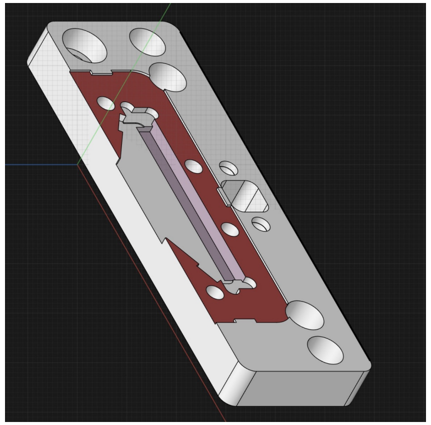
Based on the original LYSO+SiPM gluing tool designed by UVA

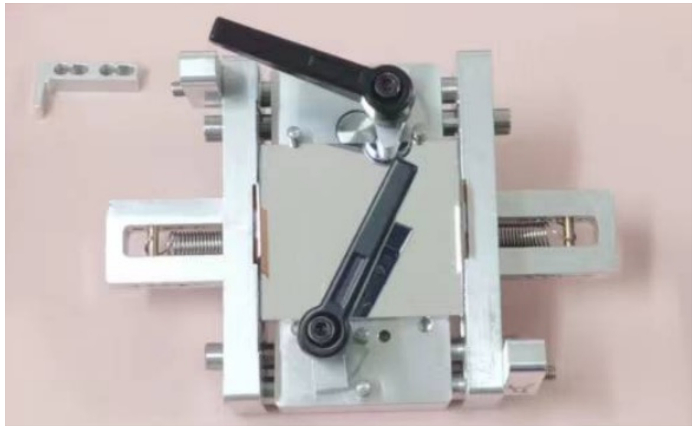
modified the SiPM cups：

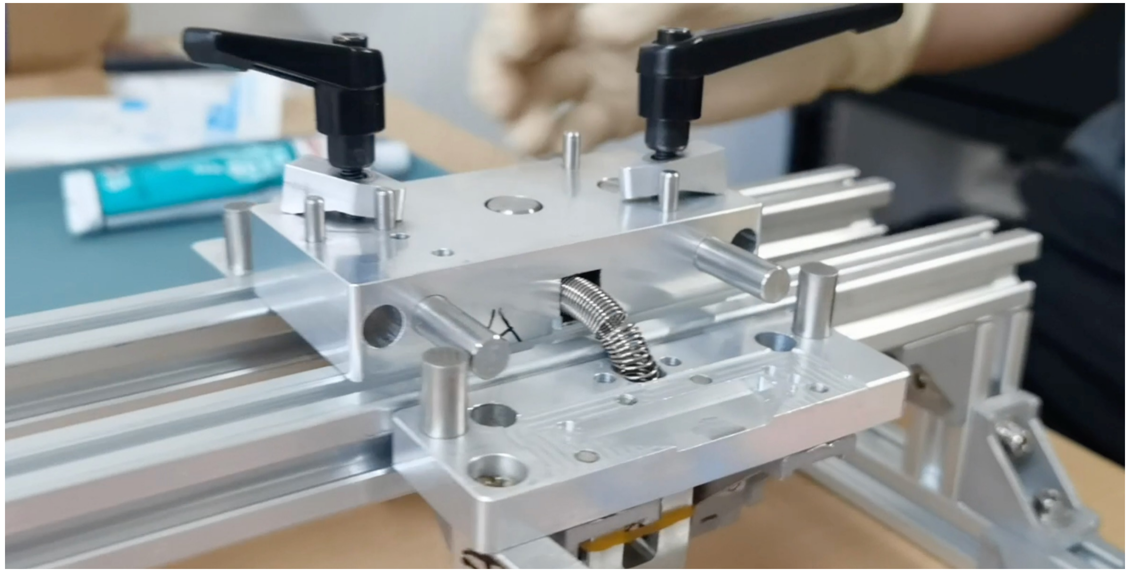
- Magnets used to fix mask
- The shape and depth can hold a mask
- The groove matches the TECs

A simple shelf is made to hold the gluing tool

- Open the SiPM cups and place them on the shelf for the preparation of glue and the gluing process
- Given the springs, the two cups cannot stay horizontally. Thus, a rubber band is introduced to balance the spring

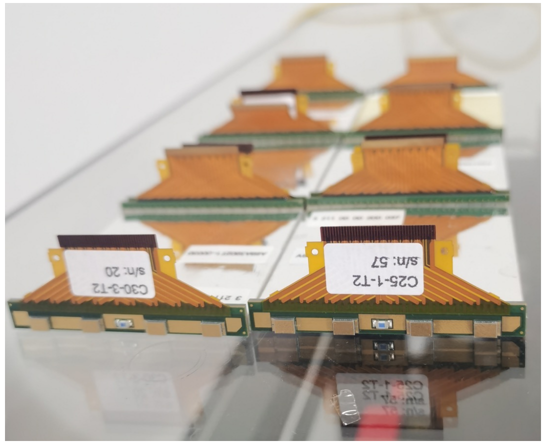


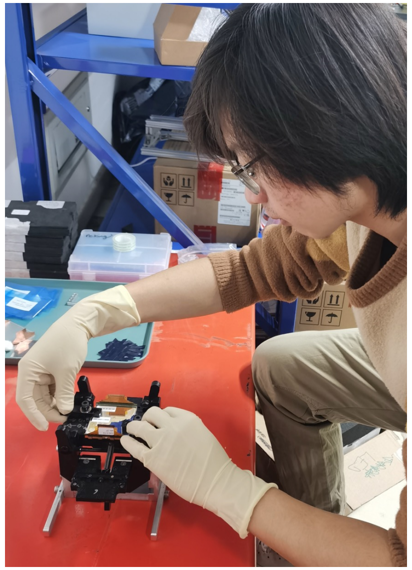


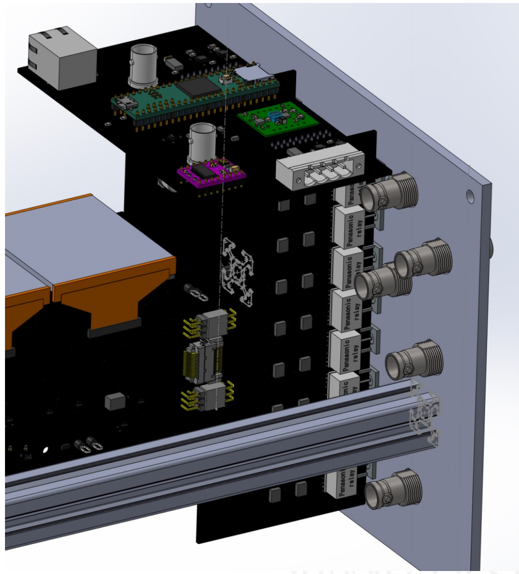


Gluing Work and QA/QC Test

- Some advantages of the coupling workplates
  - Simplify the coupling steps (the preparation of glue and the gluing process)
  - Effectively reducing the time the adhesive is exposed to the air after gluing; reducing the probability of SiPM falling off the workpiece
  - Improve reliability in multiple ways
- Using a new gluing tool with similar design for gluing small batch modules for test
- Further tests will be conducted afterwards
  - QA/QC test is an important method for checking the gluing effect







Gluing Work and QA/QC Test

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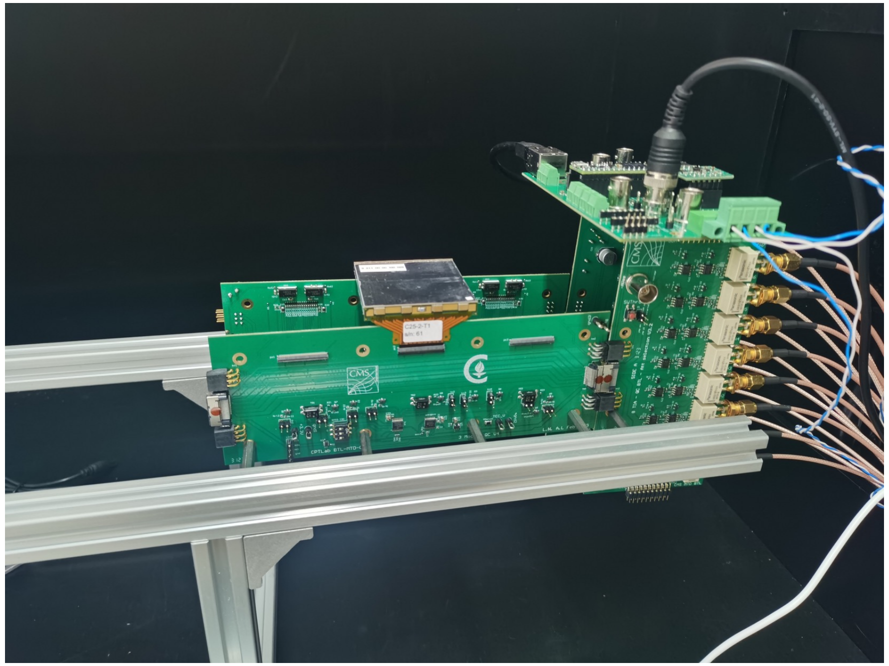
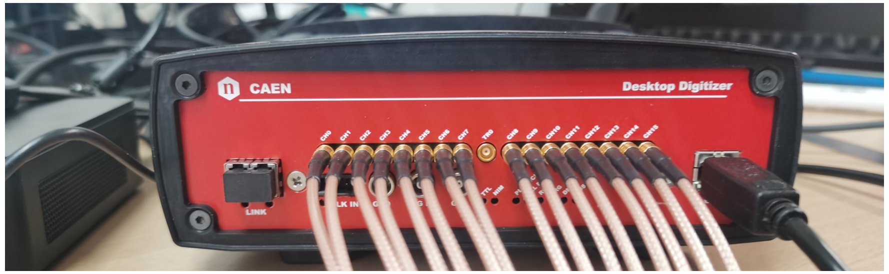
The BTL QA/QC jig :

- Designed to test up to 12 LYSO arrays at a time for quality assurance during gluing procedure.

- Hardware organization and theory of operation:
  - 3 Module Boards: connecting to the actual modules and controlling the HV relay
  - Amplifier boards: taking 8 analog signals from the SiPMs and amplifying them to be able to read out by the CAEN digitizer
  - Control Board (with teensy 4.1): talking to the other boards to control the HV relays, attenuation relays, as well as to read out the RTD and thermistor temperatures, etc
  - DT5742 CAEN digitizer: Obtaining 16 channels at a time
  - Dark Box, support and cooling system: Providing a constant temperature dark environment and easy control of experiments

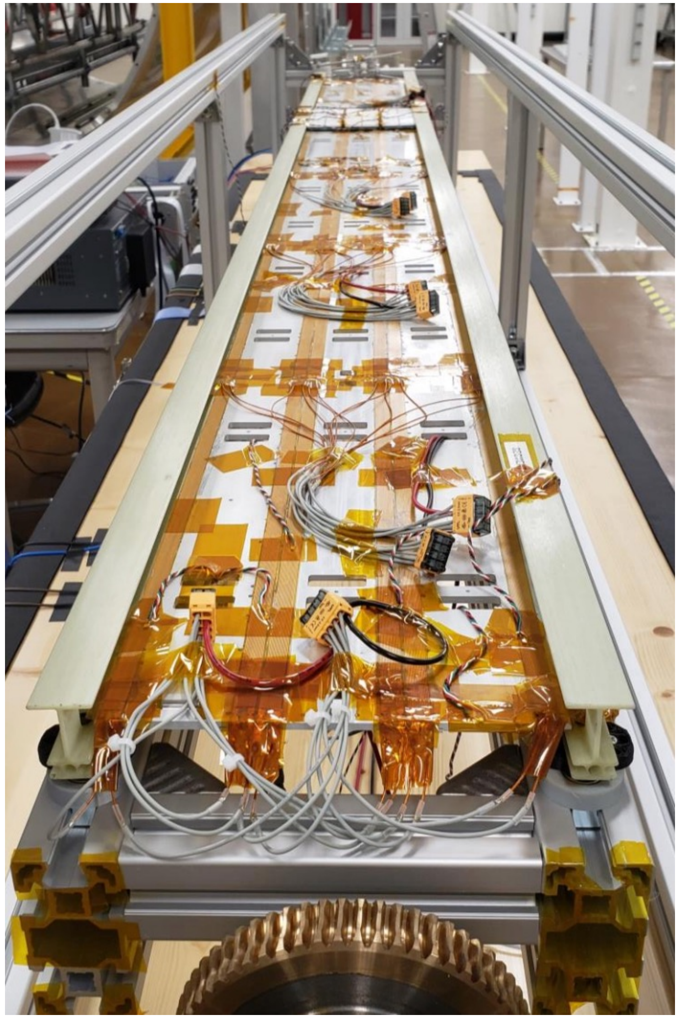




04 Cooling Plates and Thermal Test

Cooling plates and Spitroast

王锦（PKU）



Structure

- 2.5×0.2×0.03m Aluminum plate with 2 embedded cooling loops.
  - ➢ Plate segmented in 6 pieces (RUs).
- Thermal paste between cooling plate and cooling loops.
- Cooling loops are held in place with laminas that are attached with screws to the cold plate.

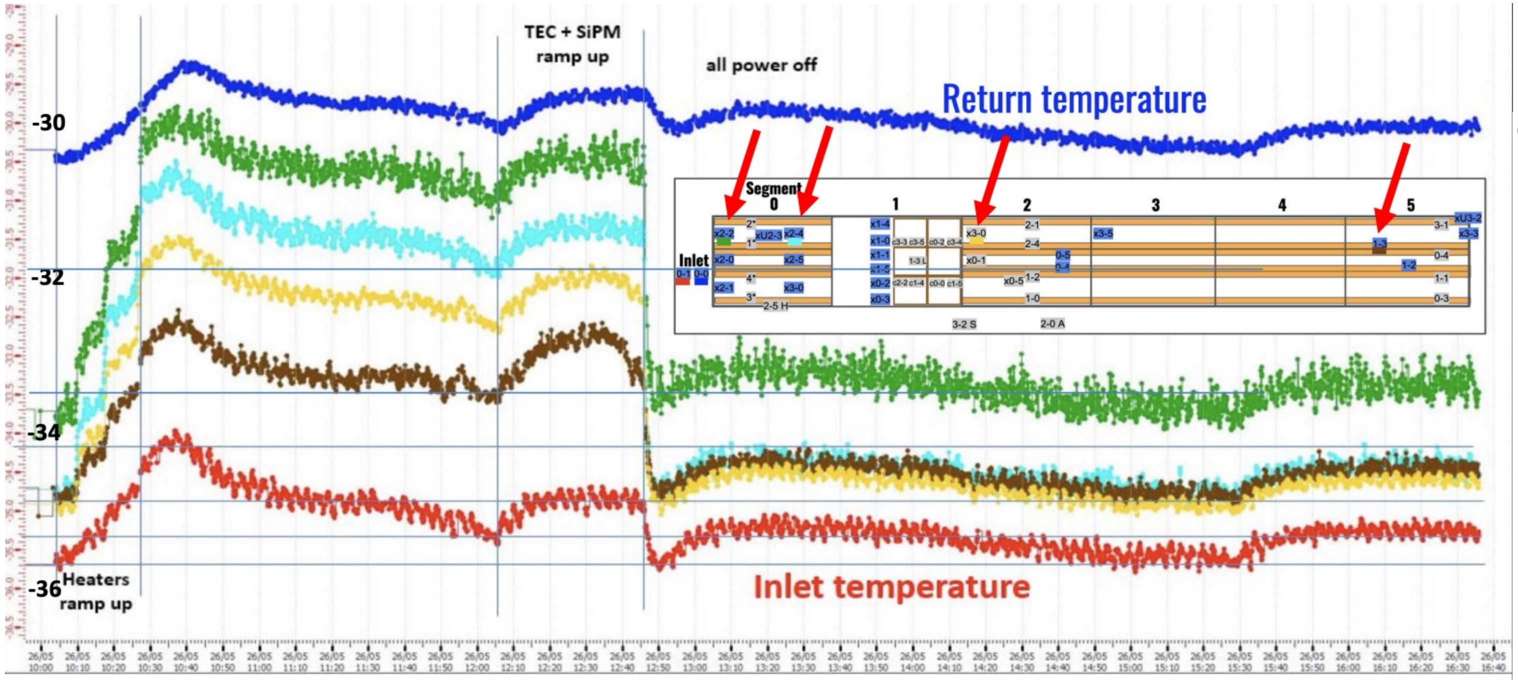
- At Peking University, we have produced a batch of cooling plates(5 sets) for test
- The rotating bracket "spitroast" has also been put into use,
  - ➢ making it more convenient to carry out on the front and back sides of the plates and assist in transportation

Cooling plates: Thermal test

张铭滔
（PKU）

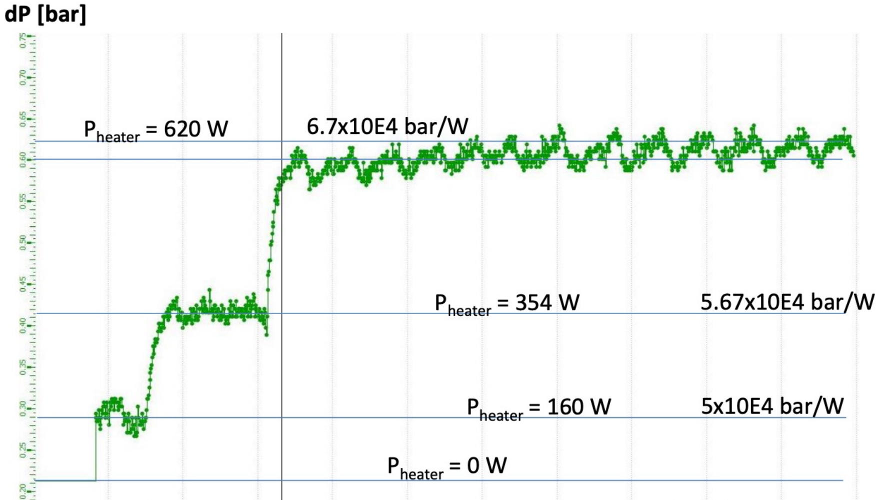
Tray cold test

- dP capillary ~ 21.2 bar, T ~ -34 °C, CO_2 flow ~ 6 g/s.
- Measurement on the tray:
  - ➢ Inlet ~ -36 °C; Outlet ~ -30 °C; dT along the tray ~ 2 °C (somewhat larger than expected 1 °C)
- Plan
  - ➢ Add a loop for the dry air; Add insulating material to the surface of tray; Attach more temperature sensors to the inlet/outlet.



Environment loss:

dP in BTL loops vs Heater Power



@5x10E4 bar/W, **0.2 bar pressure drop corresponds to 400 W heat loss to environment**

Cooling plates: Thermal test

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CO_2 cooling and tray thermal management meet expectation.

- Thermal gradient along the tray larger than expected.
- Plan: Add a loop for the dry air; Add insulating material to the surface of tray; Attach more temperature sensors to the inlet/outlet.

Environmental losses are important in our test setup – more refinements needed making it more similar to final layout in CMS.

- At 5×10^{-4} bar/W, 0.2 bar pressure drop corresponds to 400 W heat loss to environment.

05 Summary

Summary

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Summary

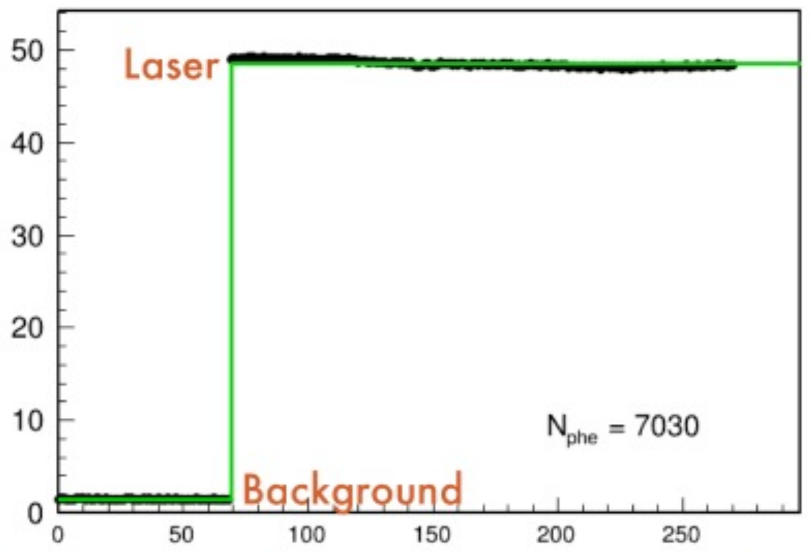
- Optimized sensor design through test beam(Energy linearization, LYSO, SiPM, Temperature), finalize plan, and pass CMS review
- Improved the coupling work of LYSO SiPM, simplify the scheme and improve system reliability
- Completed the construction of the sensor module QA/QC and conduct small-scale module tests
- The thermal test of the cooling system show that the cooling plates and TEC design scheme meet the requirements

Plan

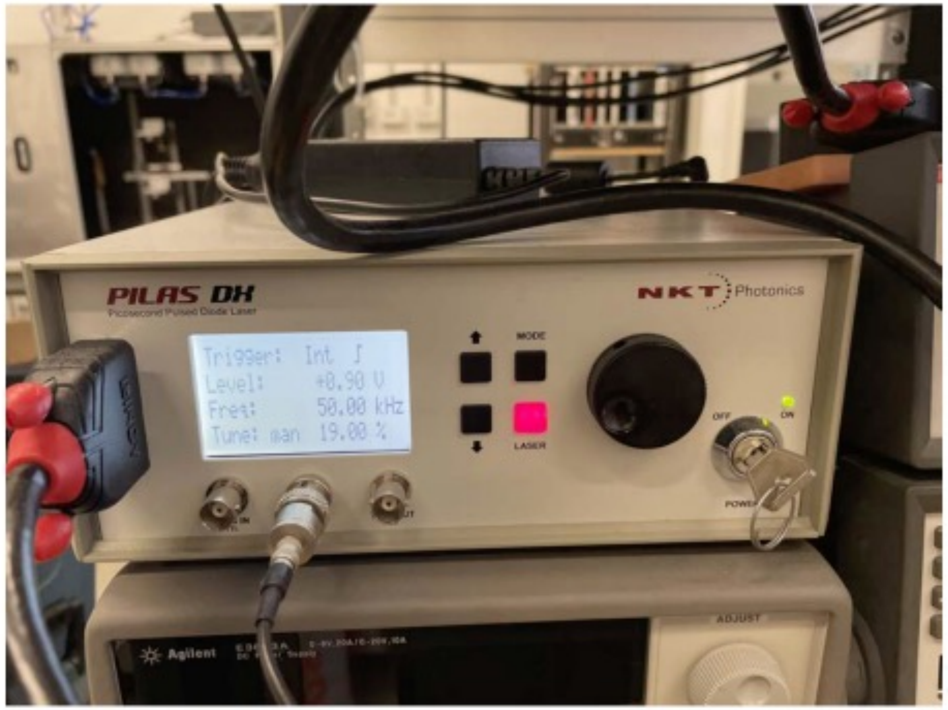
- Continue with TB analysis for comparion of different SiPM vendors
- Improve the design of LYSO+SiPM coupling work
- Further tests of the cooling plates system
- Start assembling the sensor module
- Improve sensor module QA/QC and conduct large-scale tests

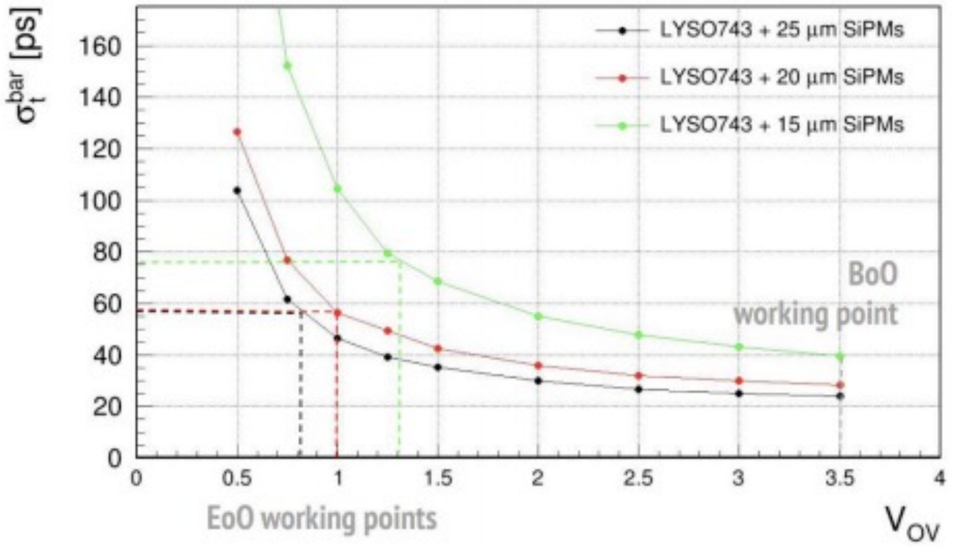
Thanks for your attention!

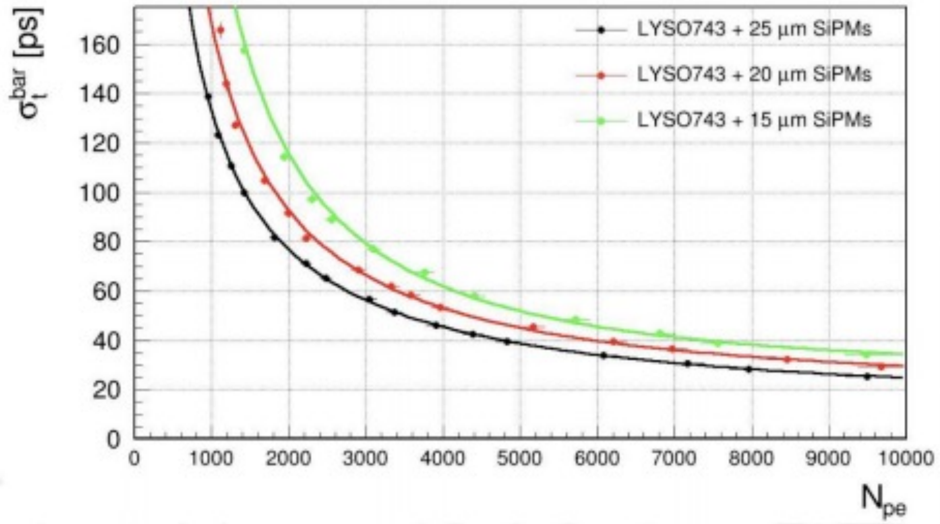
Back up

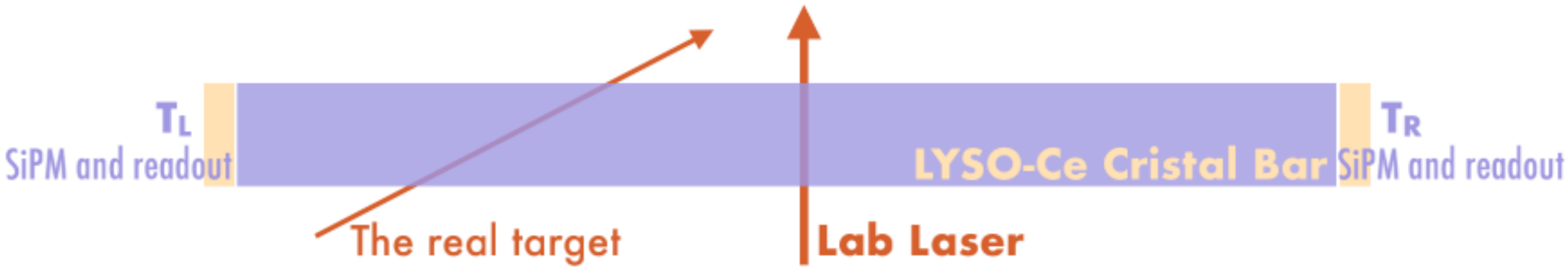


- Laser intensity tuned to reproduce the expected Npe at 3.5 V (LO~1250 pe/MeV for optimized LYSO+15μm SiPMs)
  - Npe = 4.2 MeV x 1250 pe/MeV = 5250 pe for 15μm
  - Npe = 4.2 MeV x 1250 pe/MeV x $PDE_{20\mu m}/PDE_{15\mu m}$ = 7950 pe for 20μm
  - Npe = 4.2 MeV x 1250 pe/MeV x $PDE_{25\mu m}/PDE_{15\mu m}$ = 8900 pe for 25μm





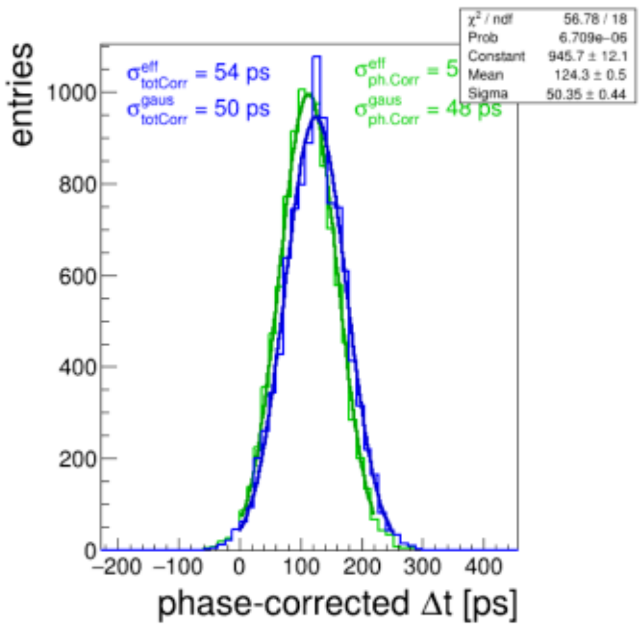


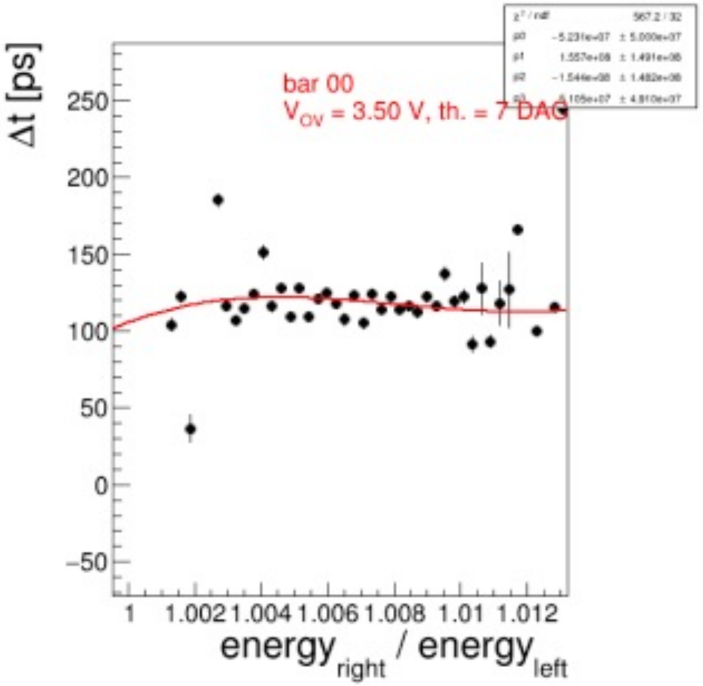


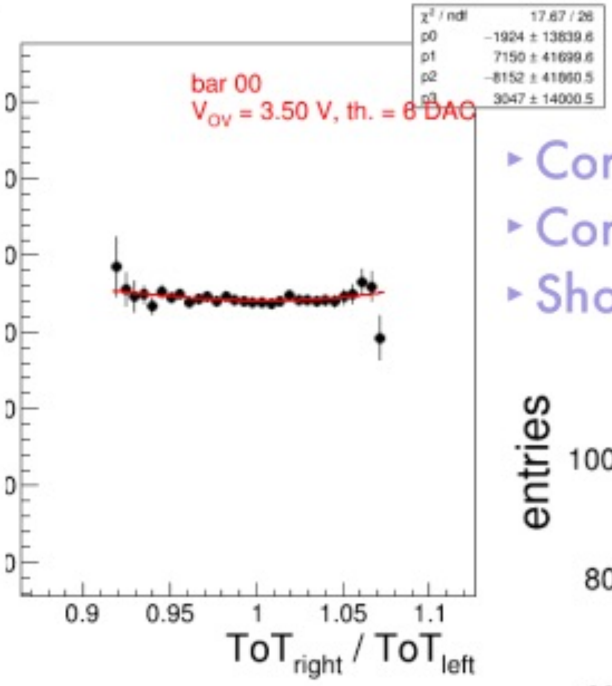
$$T_{ave} = 1/2(T_L + T_R) \qquad \sigma_{ave} = 1/2\sqrt{\sigma_L^2 + \sigma_R^2}$$

$$\sigma_{diff} = 2 \times \sigma_{ave}$$

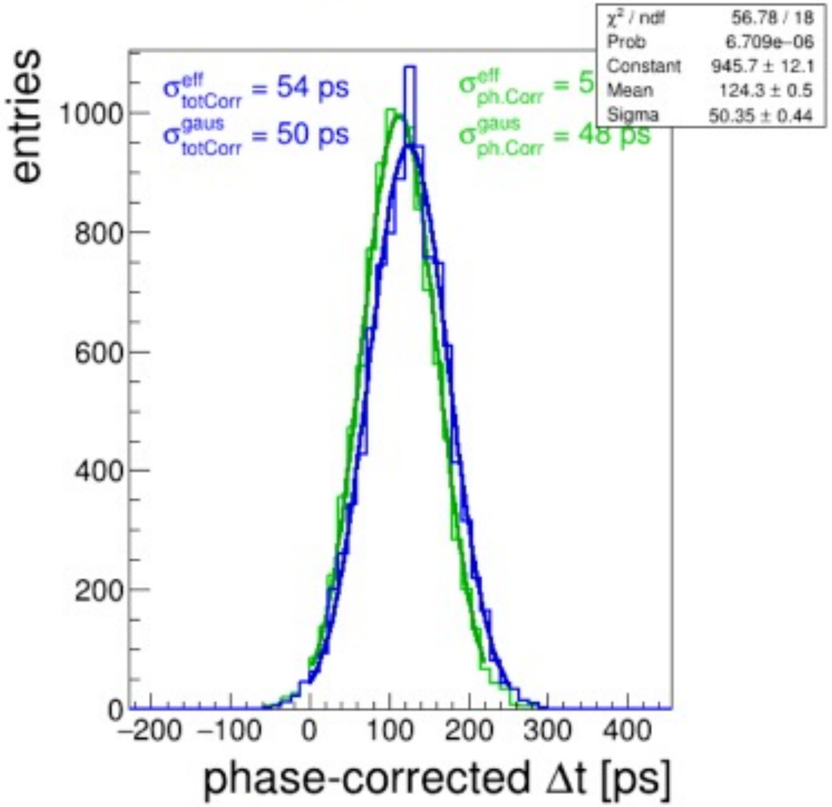
$$T_{diff} = T_L - T_R \qquad \sigma_{diff} = \sqrt{\sigma_L^2 + \sigma_R^2}$$

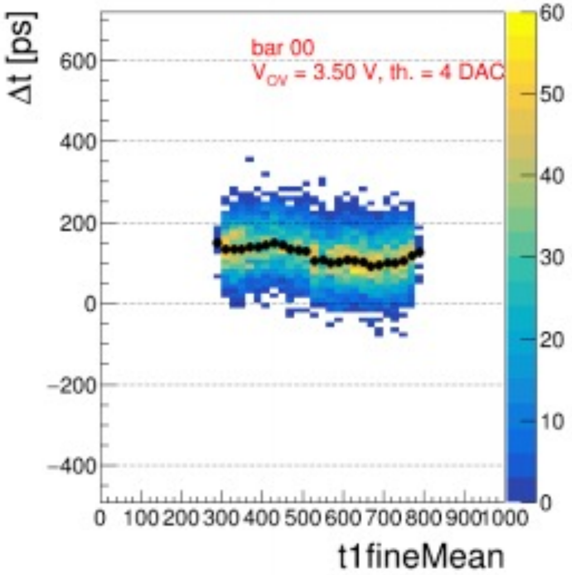






- Correction over energy difference
- Correction over ToT
- Should be highly correlated

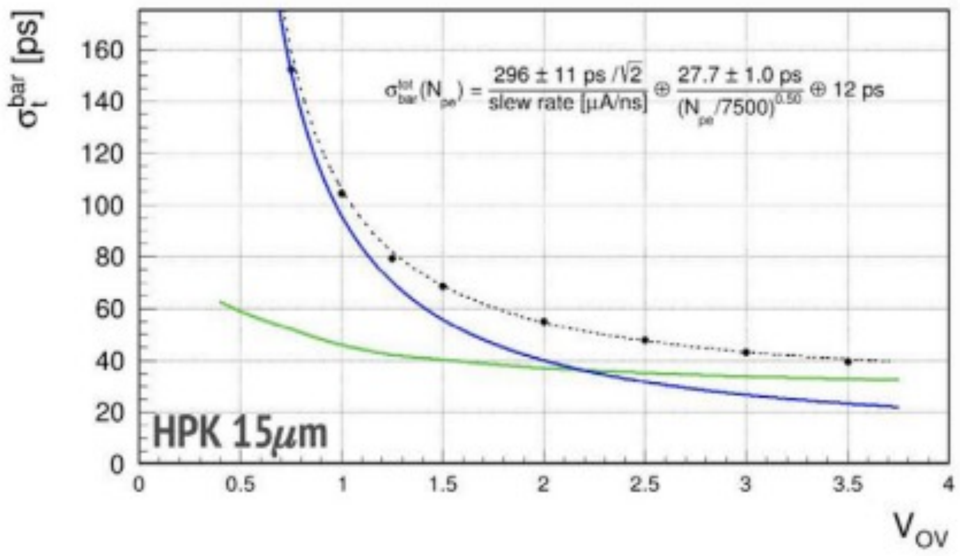


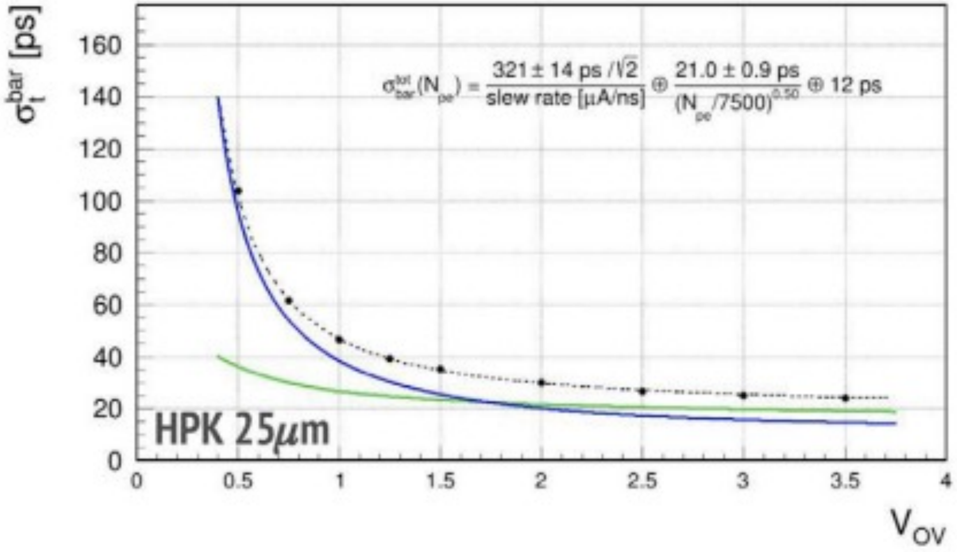


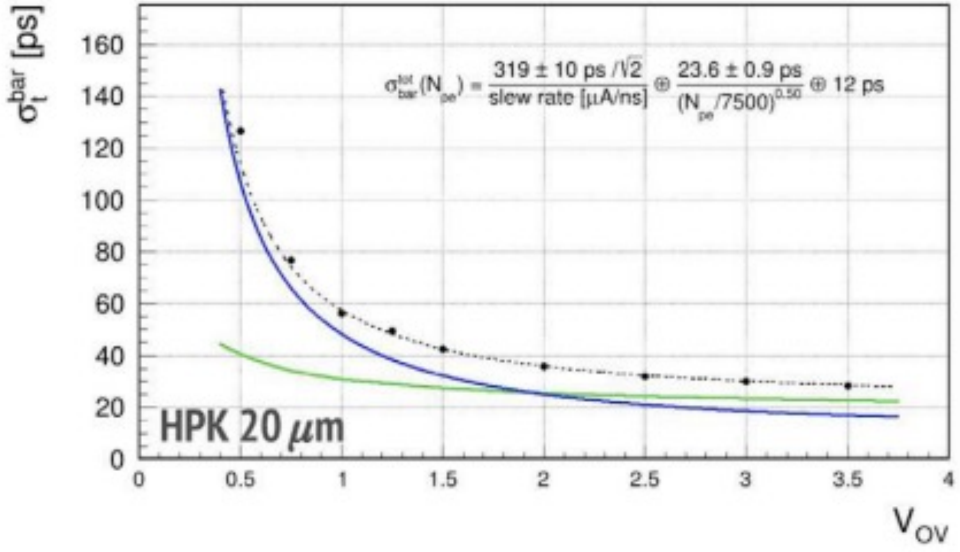
- Correction of the starting point in the triggering window
- Secrets in electronics

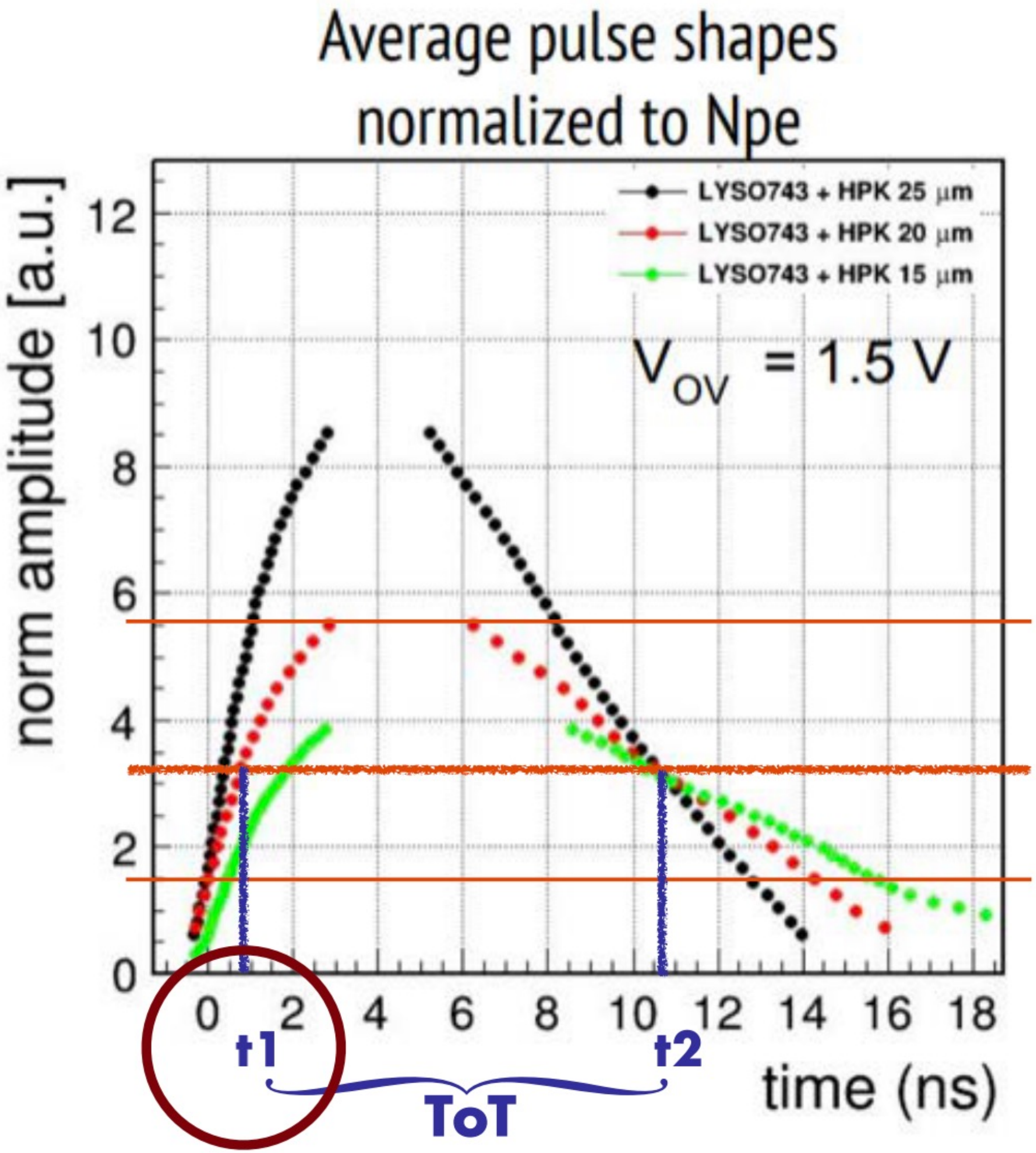
Splitting noise and stochastic contributions

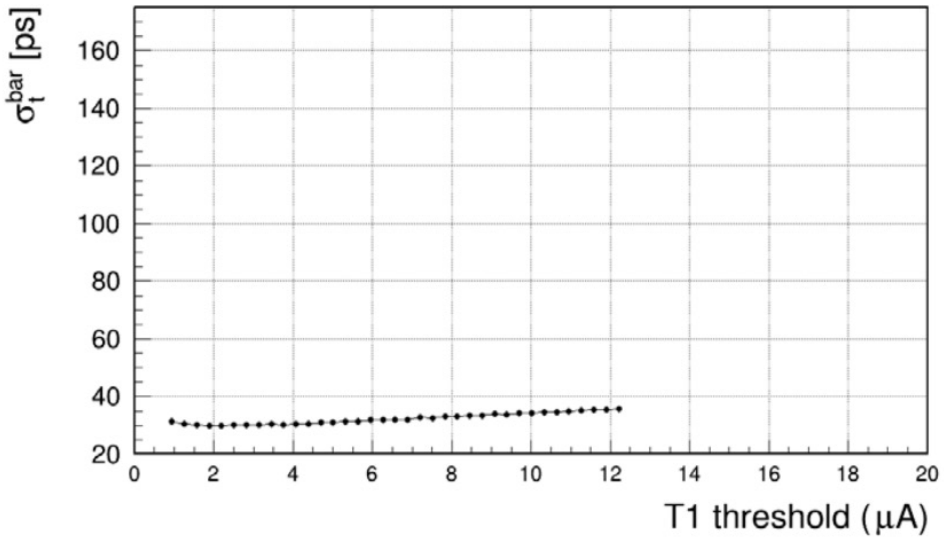
- Fit total time resolution vs Vov with sum in quadrature of stochastic and noise terms
- Stochastic term ~ 28 ps for 15 um, compatible with previous estimations
- Stochastic term for 20, 25 um smaller (thresholds effect?)
- Noise term smaller than measured in the past (420 nA)
  - however, we are using a different board (T2TB v2)





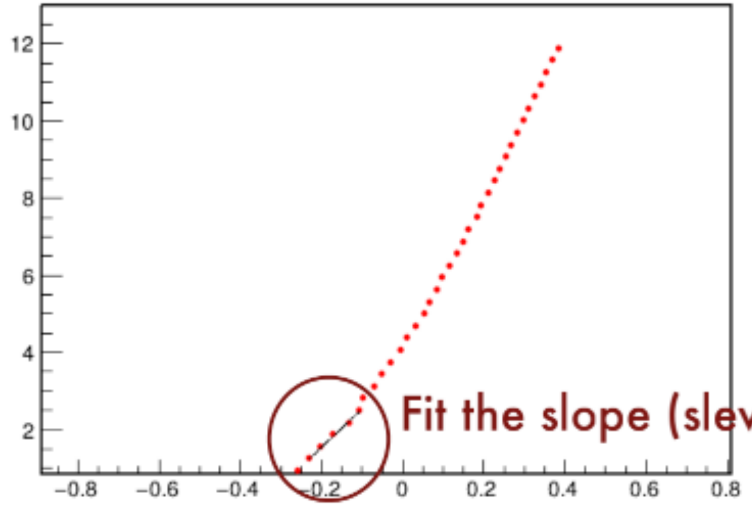






Thresholds

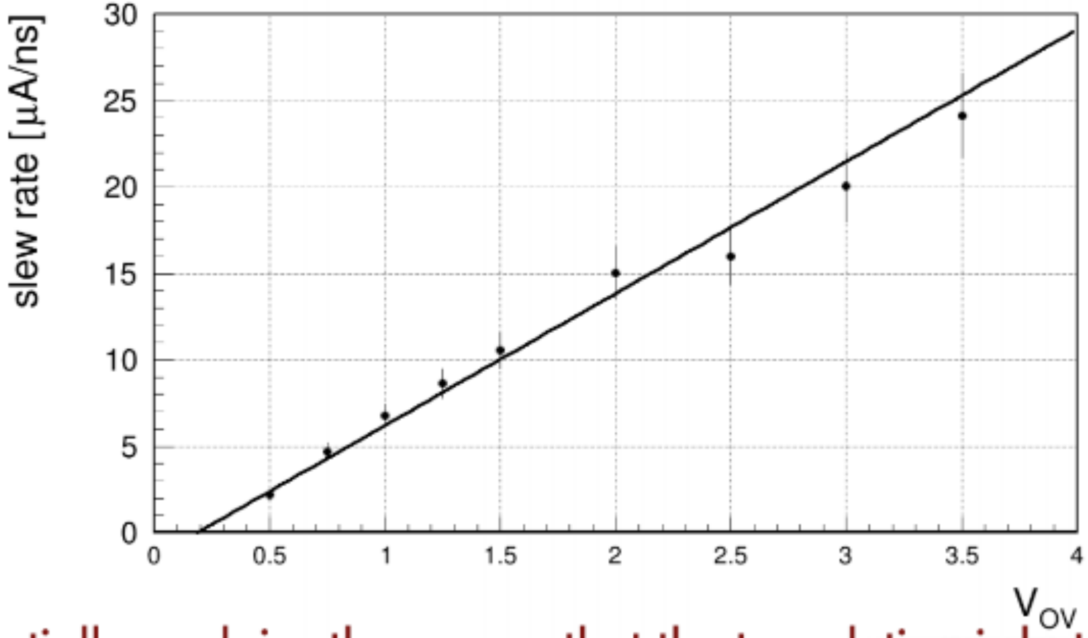
- Find the threshold that can minimize the t-resolution
- Understand how performances are effected



Fit the slope (slew rate)

$$\sigma_t^{pe} = \frac{A}{\sqrt{N_{pe}}}$$

At the beginning of the pulse shapes (near the optimized threshold)



$$\sigma_t^{noise} = \frac{\sigma_N}{dA/dt}$$

Partially explains the reason that the t-resolution is better at higher Vov

LYSO selection

■ Plot the "expected energy" vs. the measured MIP Landau MPV in ADC, as measured by the TOFHIR2B

- energy [ADC] (x-axis):
  MIP peak obtained by Landau fitting

- "expected energy" (y-axis):
  E_{dep} [MeV] × G × PDE × ECF × $k_{saturation}$ / Norm

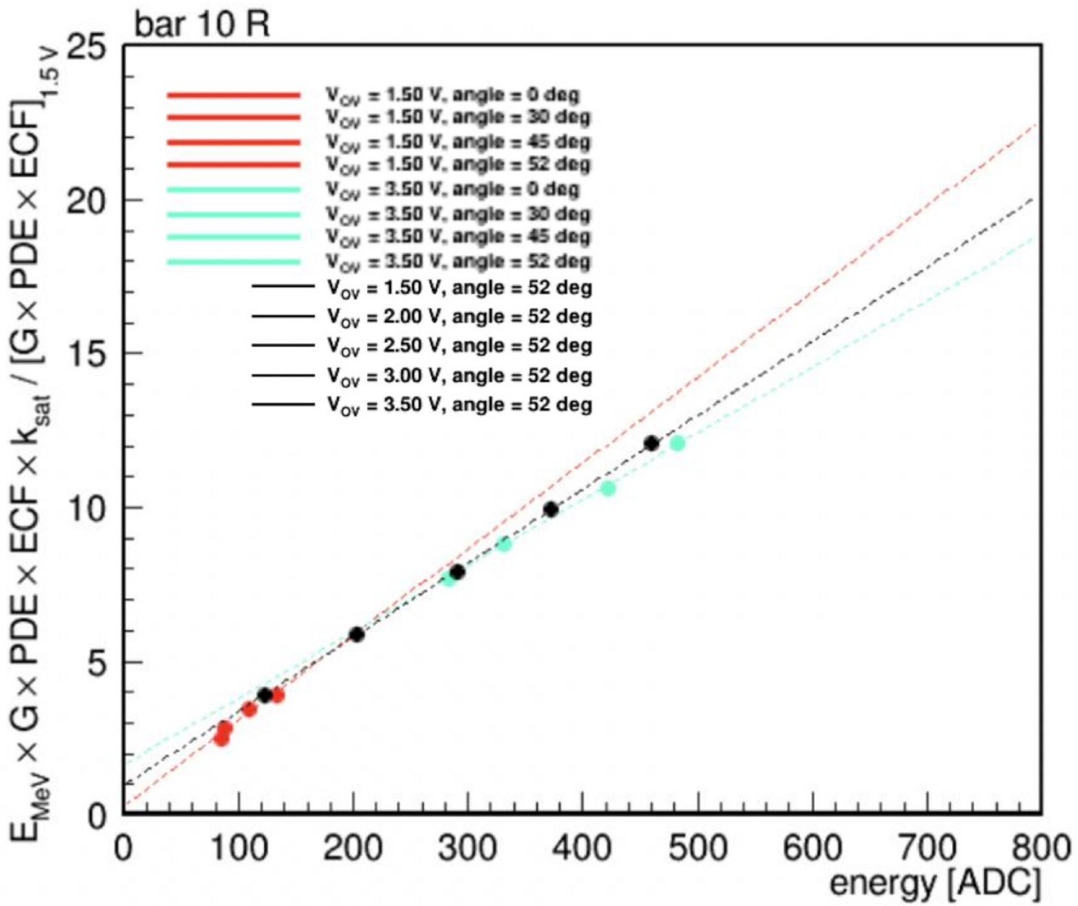
E_{dep} = 0.86 MeV/mm * 3 mm / cos(angle)

G = sipm Gain

PDE = photon detection efficiency

ECF = excess charge factor

$k_{saturation} = N_{pixels} \times [1 - \exp(-N_{pe} / N_{pixels})] / N_{pe}$ (with Npixels = 40000)

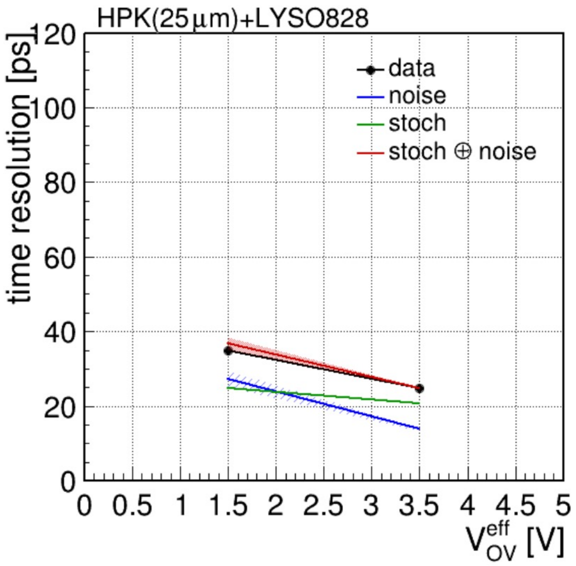


LYSO selection

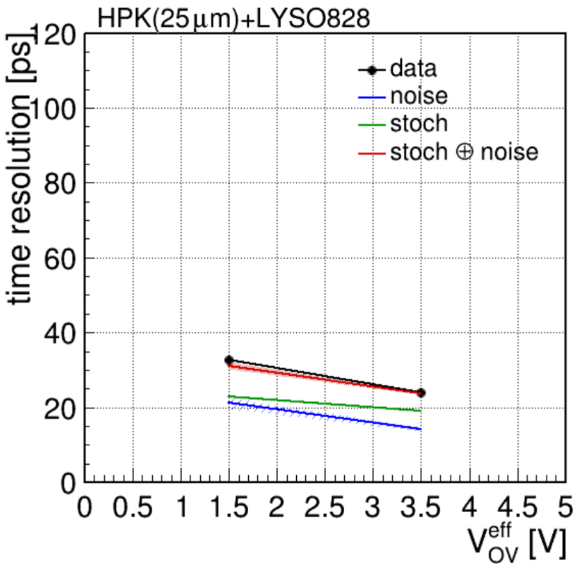
Breakdown of uncertainties

➢ Experience formula is used to decompose the time resolution into noise ⊕ stochastic.

prod5, 52deg



prod1, 52deg



- So far, there is no experimental formula of Npe, so Vov = 3.50V is used as a reference, and the formula of PDE is used to estimate the stoch part.
- **With the increase of Vov, the noise contribution decreases faster**. This is because SR is more sensitive to Vov than PDE.

Damage rate parameter

北京大学

Annealing of α at fixed temperature

(Alexander Ledovskoy's talk)

Damage rate parameter α for silicon devices describes change of leakage current with fluence

$$\Delta I = \alpha \cdot \Phi_{eq} \cdot M$$

Measurements described in M. Moll, *"Radiation damage in silicon particle detectors: Microscopic defects and macroscopic properties"*, Ph.D. thesis, Hamburg U. (1999) [Moll99]

Plot from [Moll99] (page 100)