Summary of 2017 beam test results with BTL sensors

Timing days

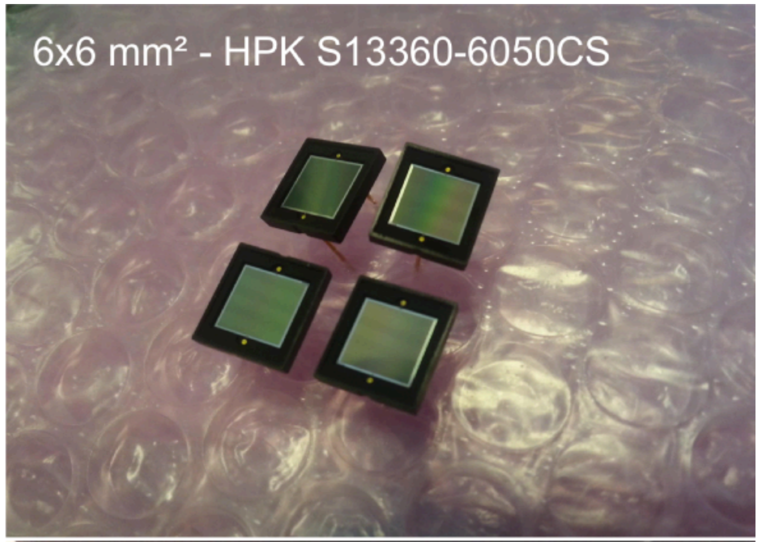
October 31st, 2017

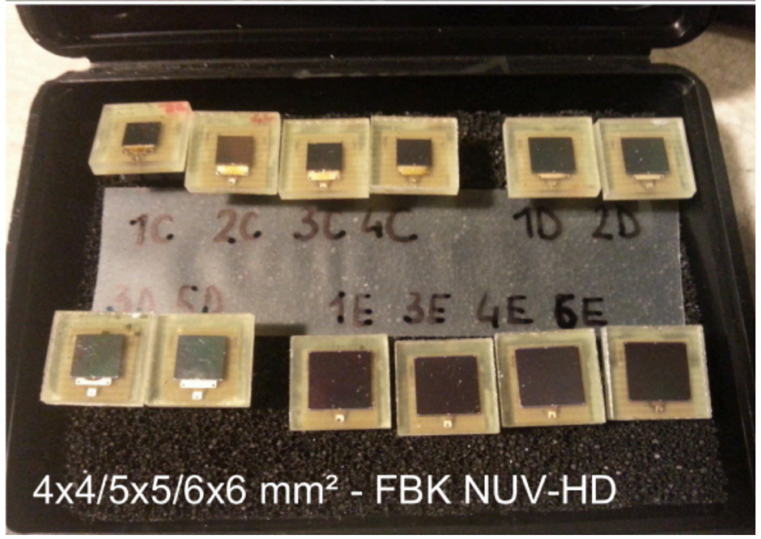
A. Benaglia, with the contribution of many
INFN Milano-Bicocca

The 2017 beam tests

- Three beam test campaigns in 2017:
  - T9 beam line (May)
  - H4 beam line (July)
  - H6 beam line (August)

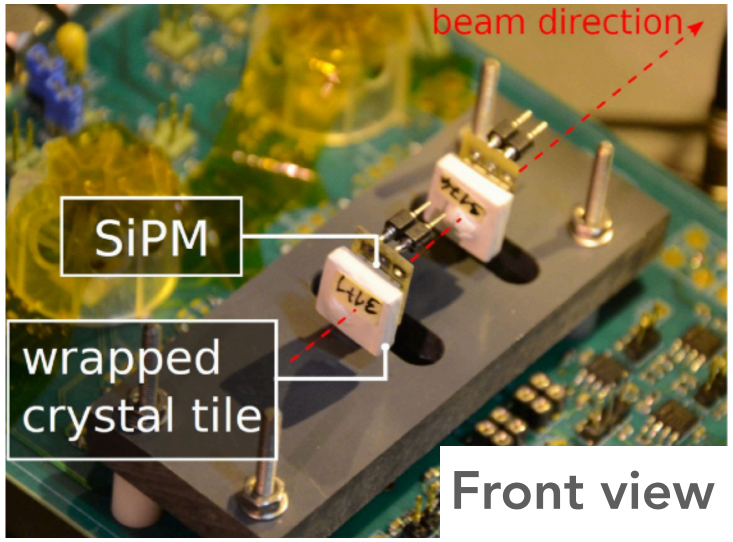
- Purpose: optimization of the individual sensors
  - systematic study of several **LYSO tile geometries; $11 \times 11 \times 3.75$ mm^3** is the current default in the TP
    - different crystal surfaces (5.6×5.6 mm^2, 10×10 mm^2, and 12×12 mm^2 also tested)
    - different thickness tested too (2, 3, 4 mm)
  - systematic study and **characterization of SiPMs** (in terms of active surface, PDE, cell size);
    a sensor with **4×4 mm^2** total surface, **$\lesssim$ 15 μm cell size**, and operated at **1-2 V** above breakdown is the current default
    - many different devices from different vendors tested



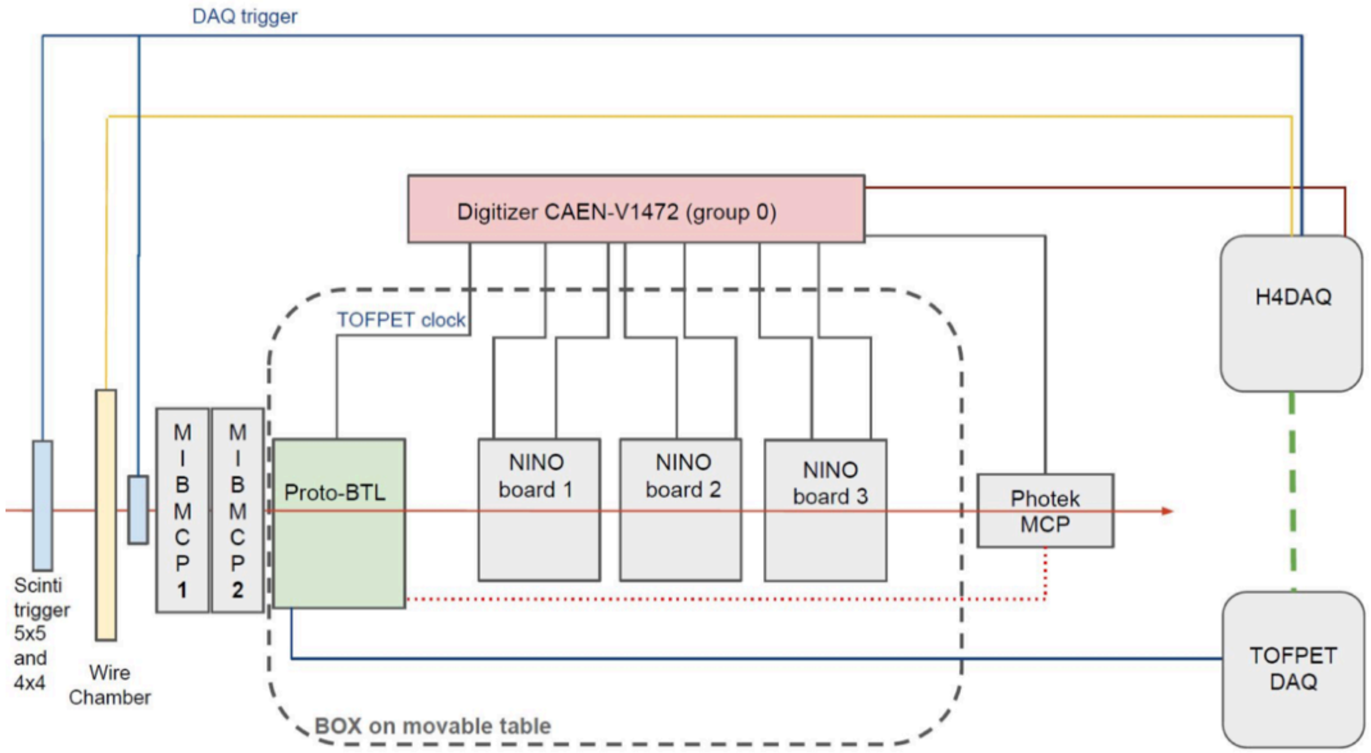


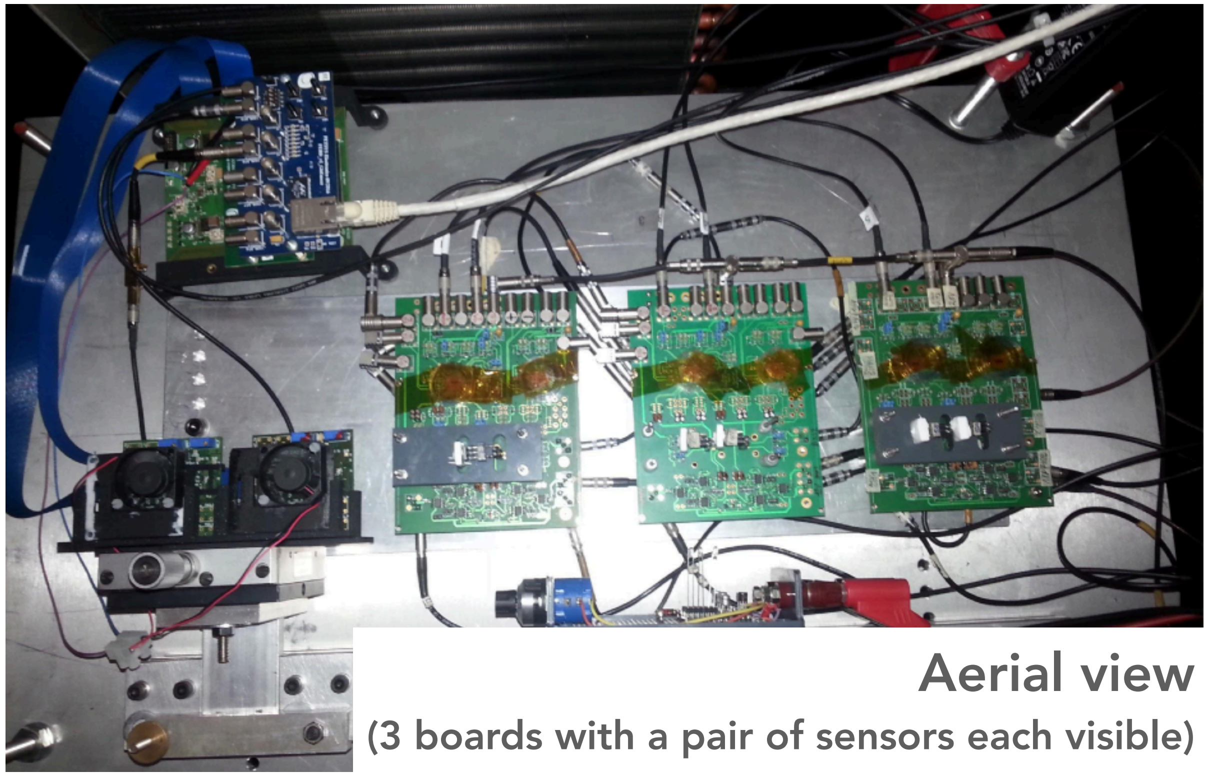
The typical beam test setup

- **Time** from LYSO+SiPM extracted with a **dedicated ASIC** providing **leading edge** discriminator (a.k.a. NINO)
- **Analog SiPM signal** also extracted for **amplitude** measurement
- **External precise time** reference provided by one or multiple **MCPs** (not present in all beam tests)
- All signals **digitized** with CAEN-V1742



Front view





Aerial view
(3 boards with a pair of sensors each visible)

See Adi's talk for a discussion on proto-MTD module data acquired with TOFPET-2 ASIC

Time response dependence on impact point

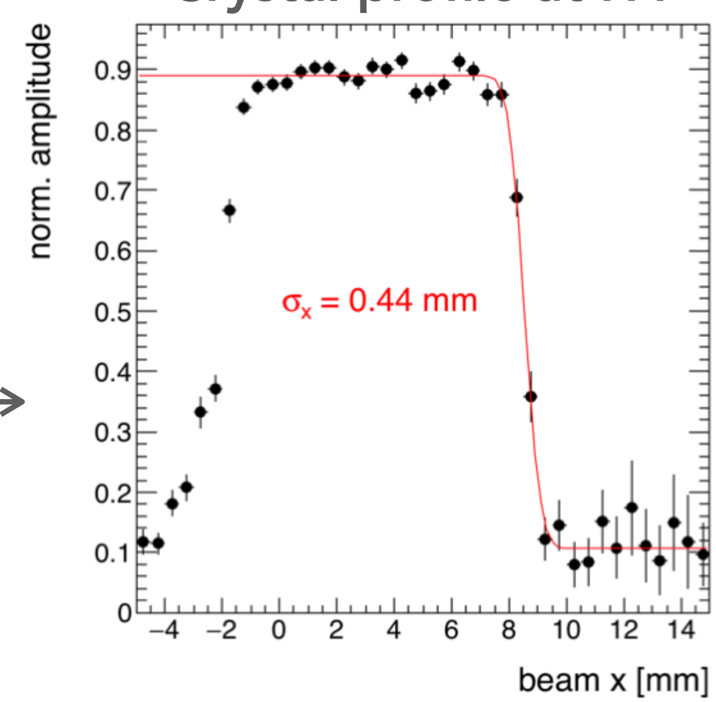
- A most important result of the beam tests was the study of the time response **dependence** on the **impact point position** on the crystal surface
- Two conditions are necessary for this measurement:
  - presence of an **external time reference** ($\Delta t = t_{LYSO+SiPM} - t_{MCP}$), as opposed to comparing two aligned crystals ($\Delta t = t_{LYSO+SiPM1} - t_{LYSO+SiPM2}$)
  - particle tracking with **good spatial resolution** and **parallel beam**
  - the combination of both was not always realized at TB

- MCP not well aligned with sensors at H4

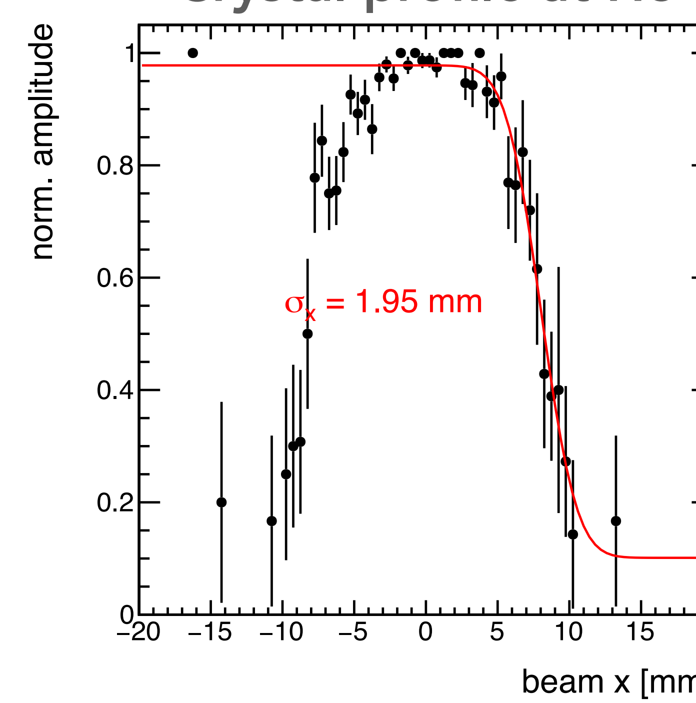
- no position information at T9
- divergent beam at **H6 (~2 mm res.)**

- H4 experimental setup was good enough to allow the uniformity study
  - MIP impact point position resolution at **H4 ~0.5 mm**

Crystal profile at H4



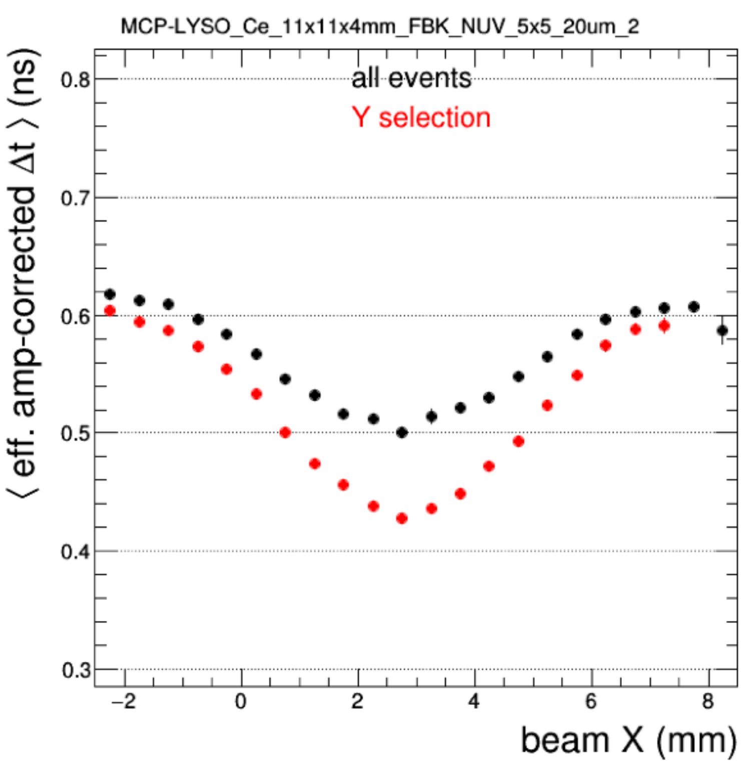
Crystal profile at H6

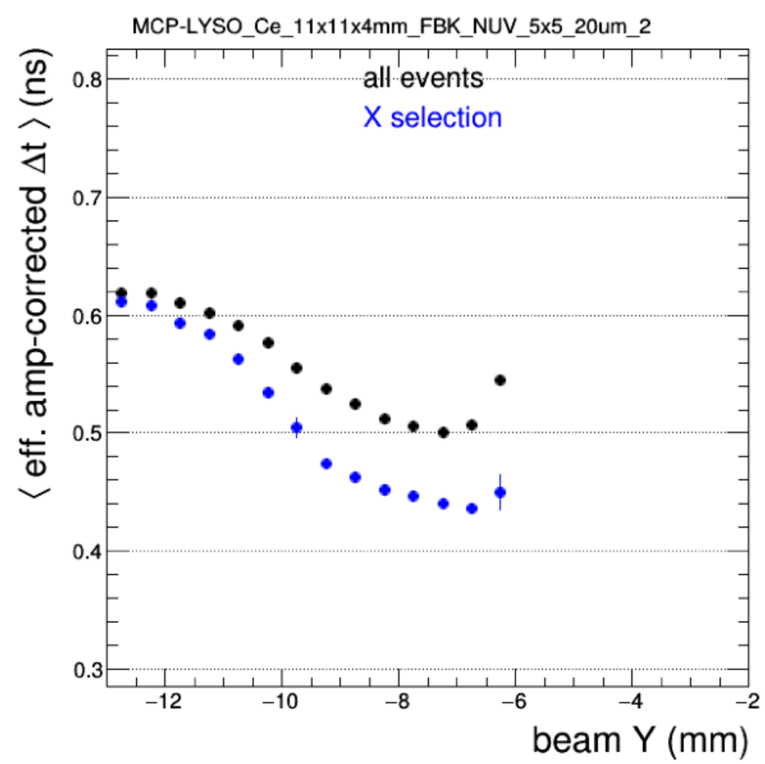


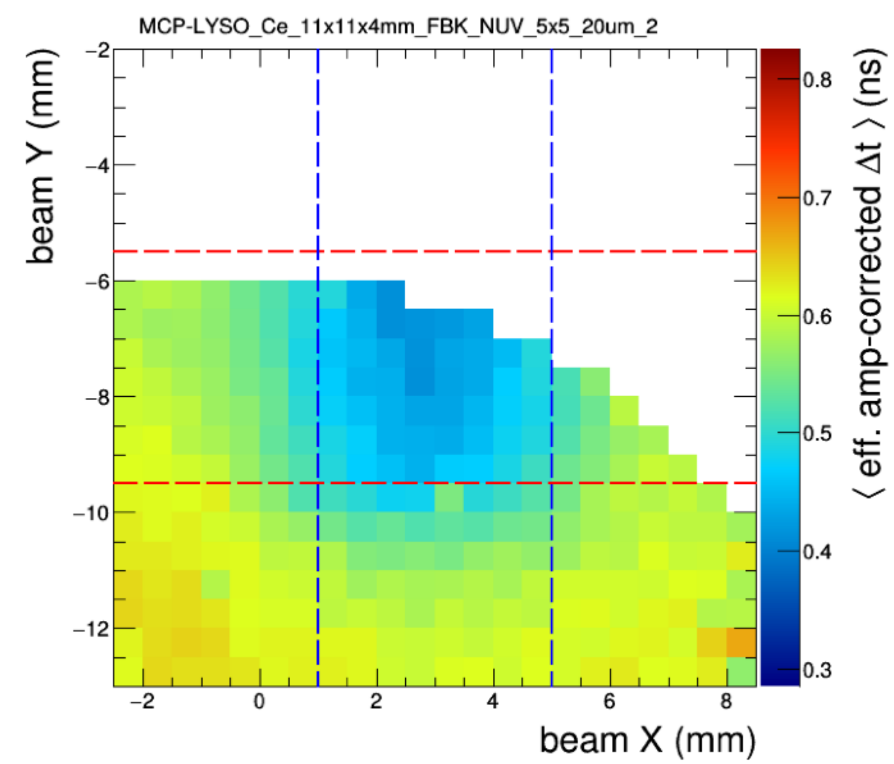
Time response dependence on impact point

- A critical dependence of the time response on the impact point position on the crystal surface was revealed
  - **O(200 ps) response delay** for events impinging outside the SiPM region w.r.t. central events
- The effect is cancelled (to a certain extent) when two aligned crystals are compared for the measurement

SiPM: FBK-NUV 5×5 mm^2
Crystal: LYSO 11×11×4 mm^3



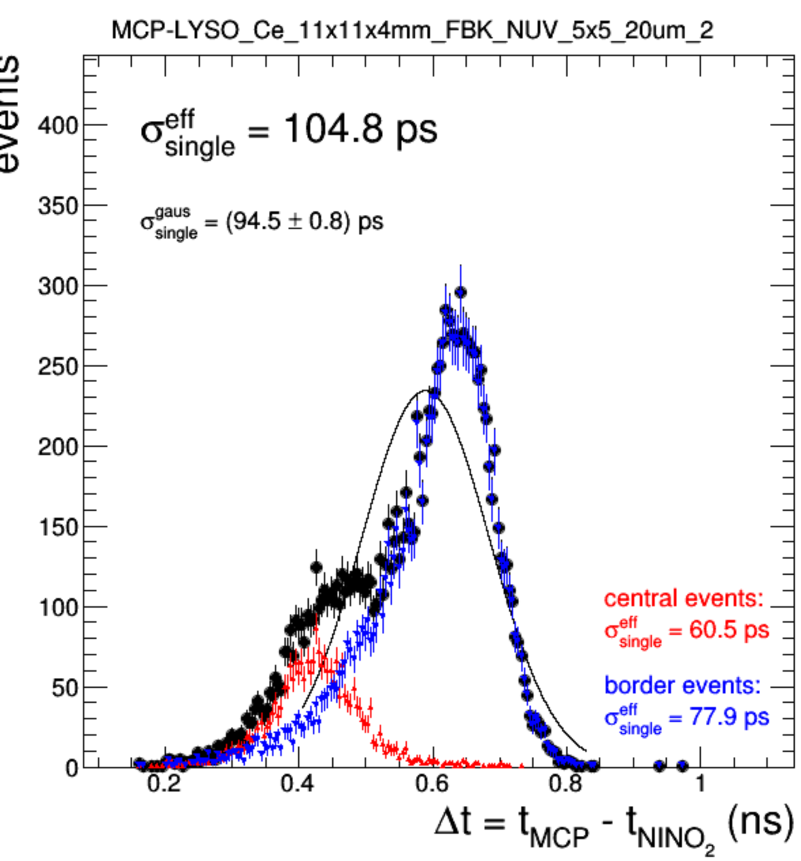


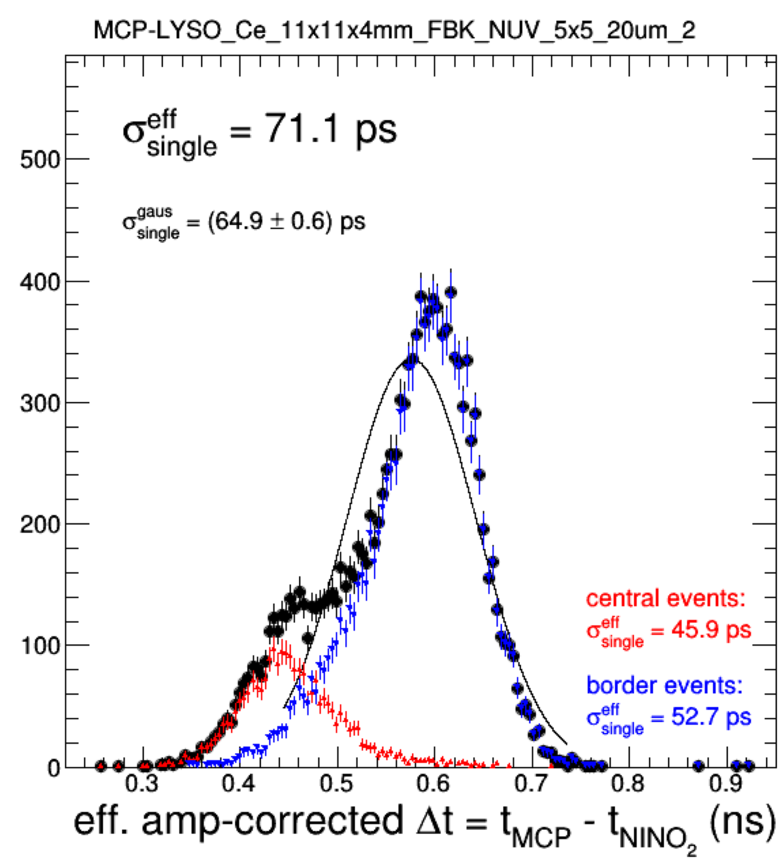


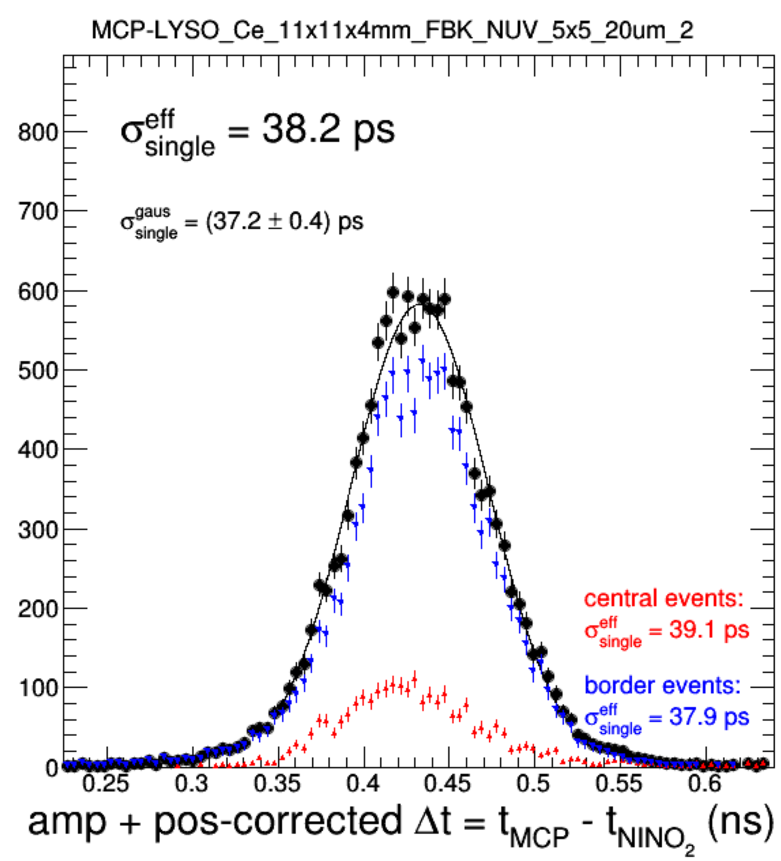
Time response dependence on impact point

- If not accounted for, the response non uniformity has a critical effect on time resolution
  - no position correction ⇒ O(60 ps) added in quadrature

SiPM: FBK-NUV 5×5 mm² 20 μm, 33 V (6 OV)
Crystal: LYSO 11×11×4 mm³







no corrections

two populations visible
(central-border events)

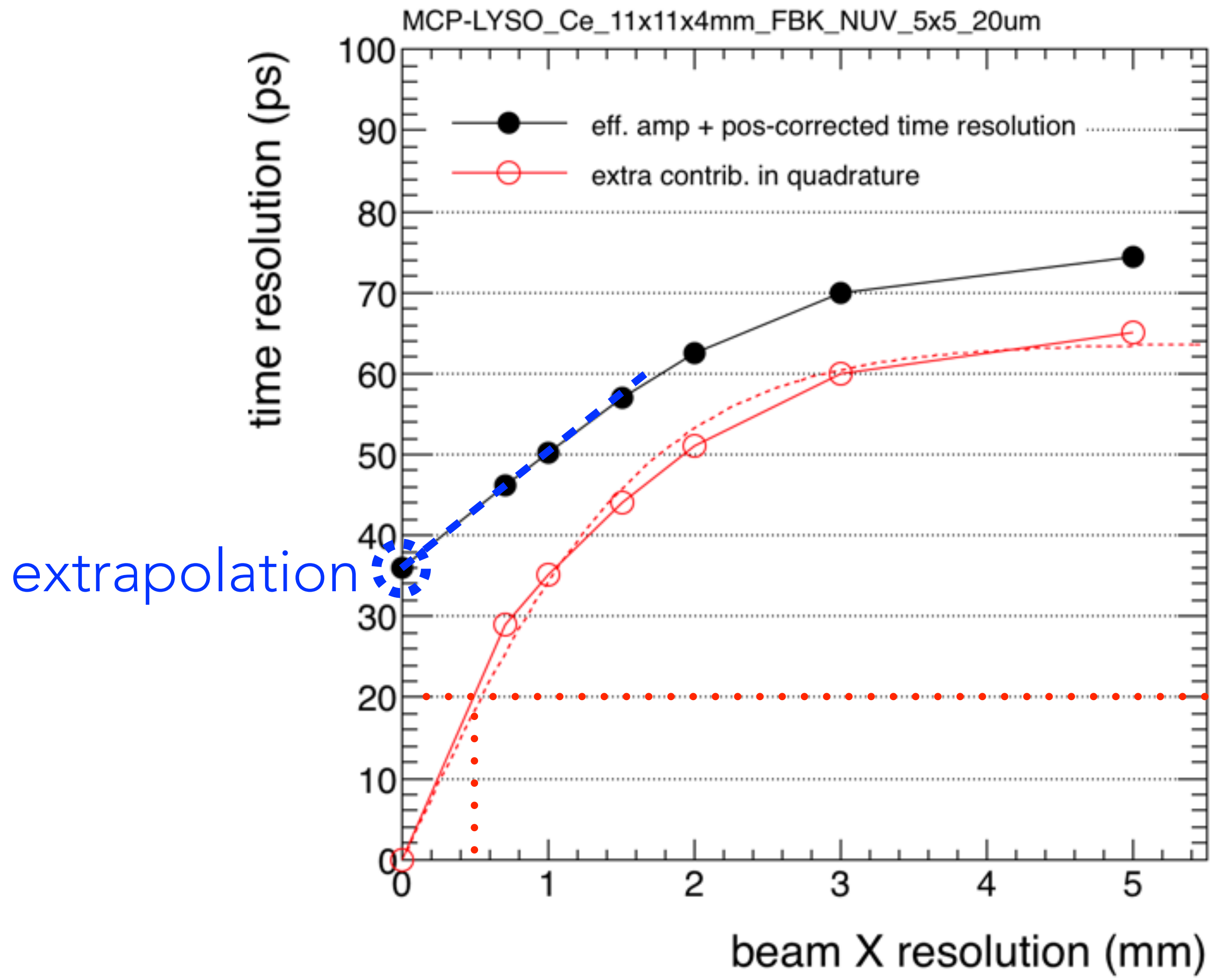
time-walk corrections

two populations visible
(central-border events)

time-walk + position corrections

Position resolution required

- MIP impact point position smeared in TB data to assess the level of precision required
  - N.B. position resolution at H4 was ~0.5 mm
  - time resolution for 0 position resolution extrapolated from nearby points

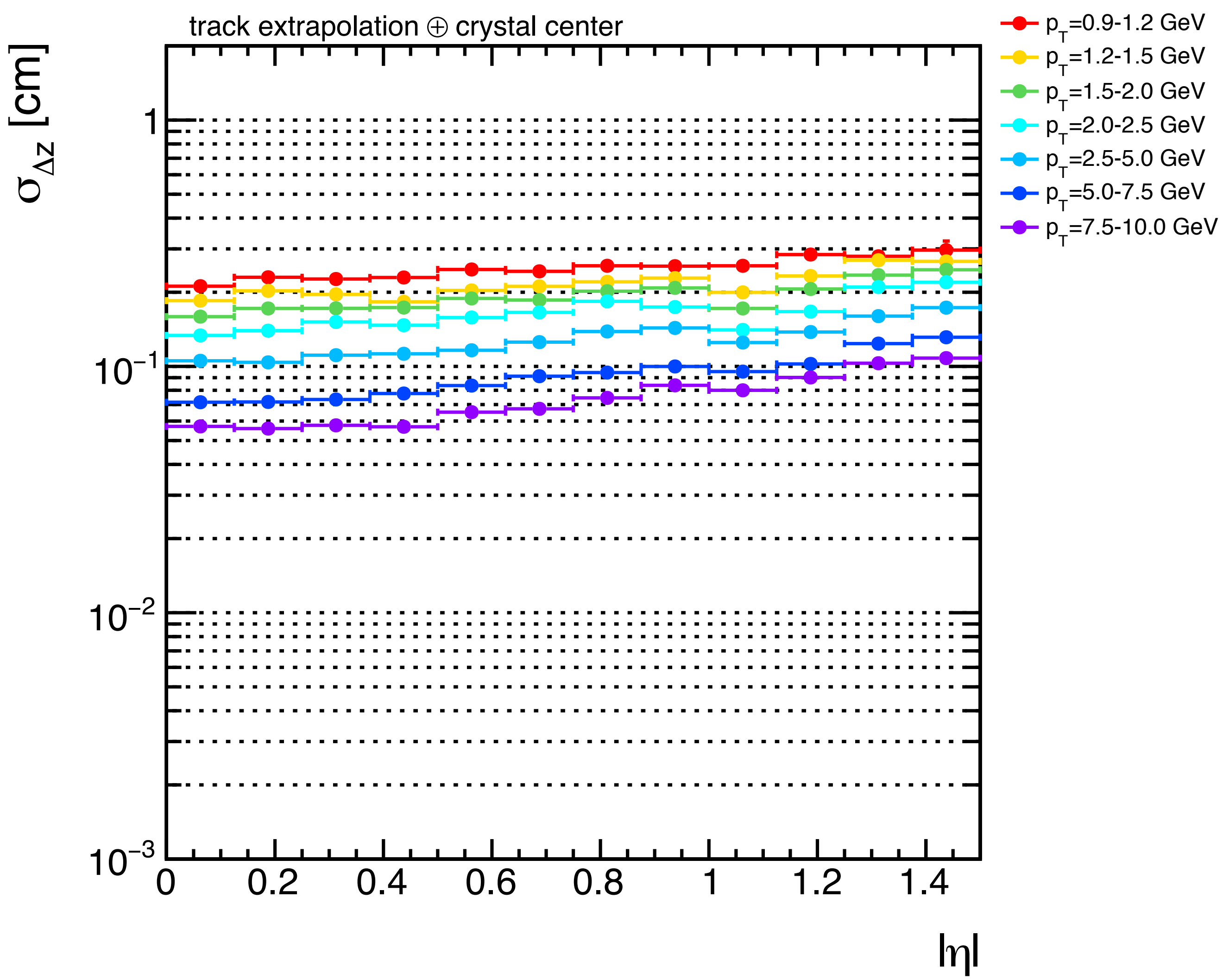


sub-millimiter precision needed to limit the extra-smearing from non-uniformity below 30 ps

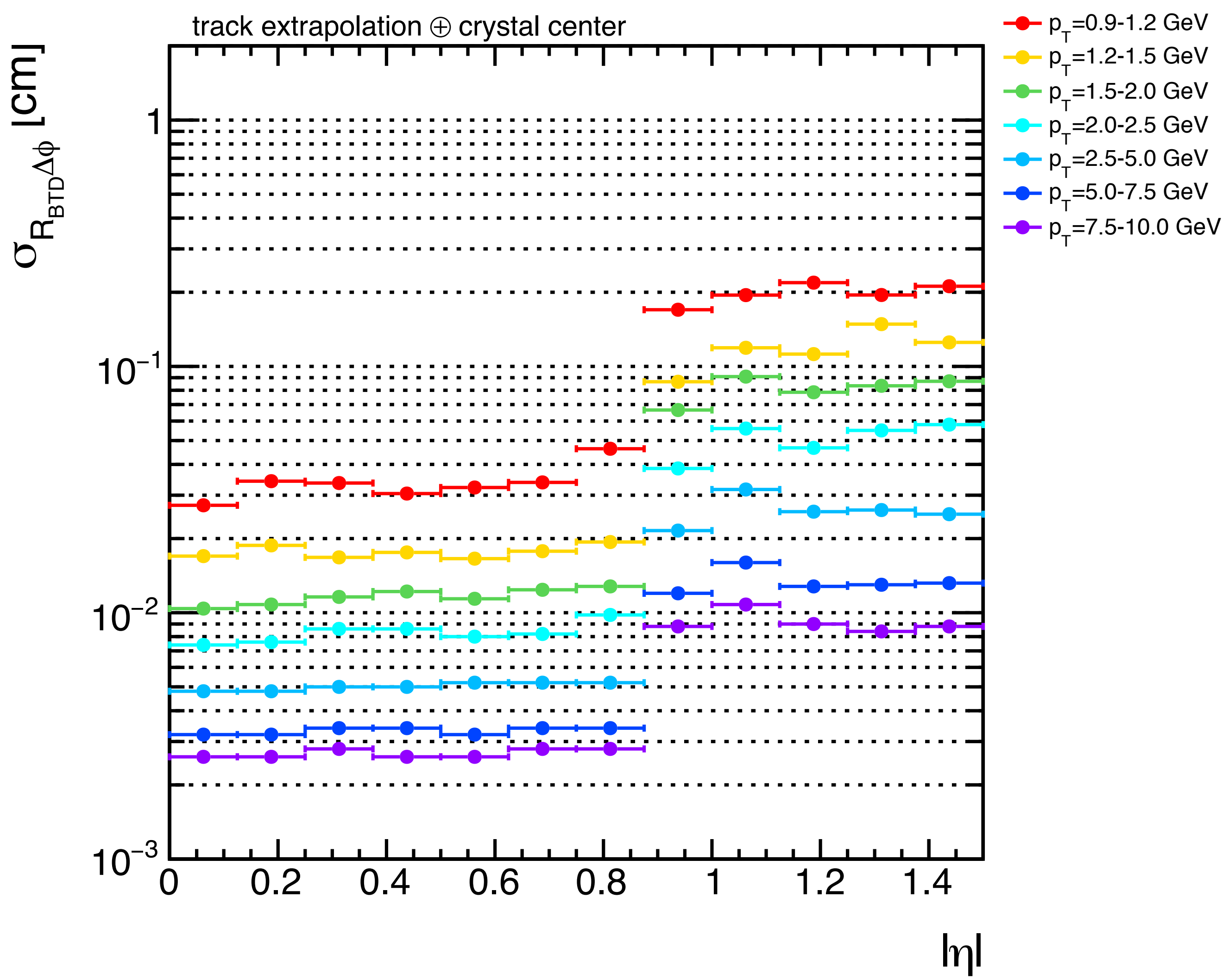
Impact point resolution in the MTD

- Resolution on track extrapolation from the outermost hit to the MTD ⊕ crystal center position (CMS PhaseII geometry simulation)
  - combination with crystal center recovers resolution when tracker only is worse than crystal size / √12 = ~3 mm

along z



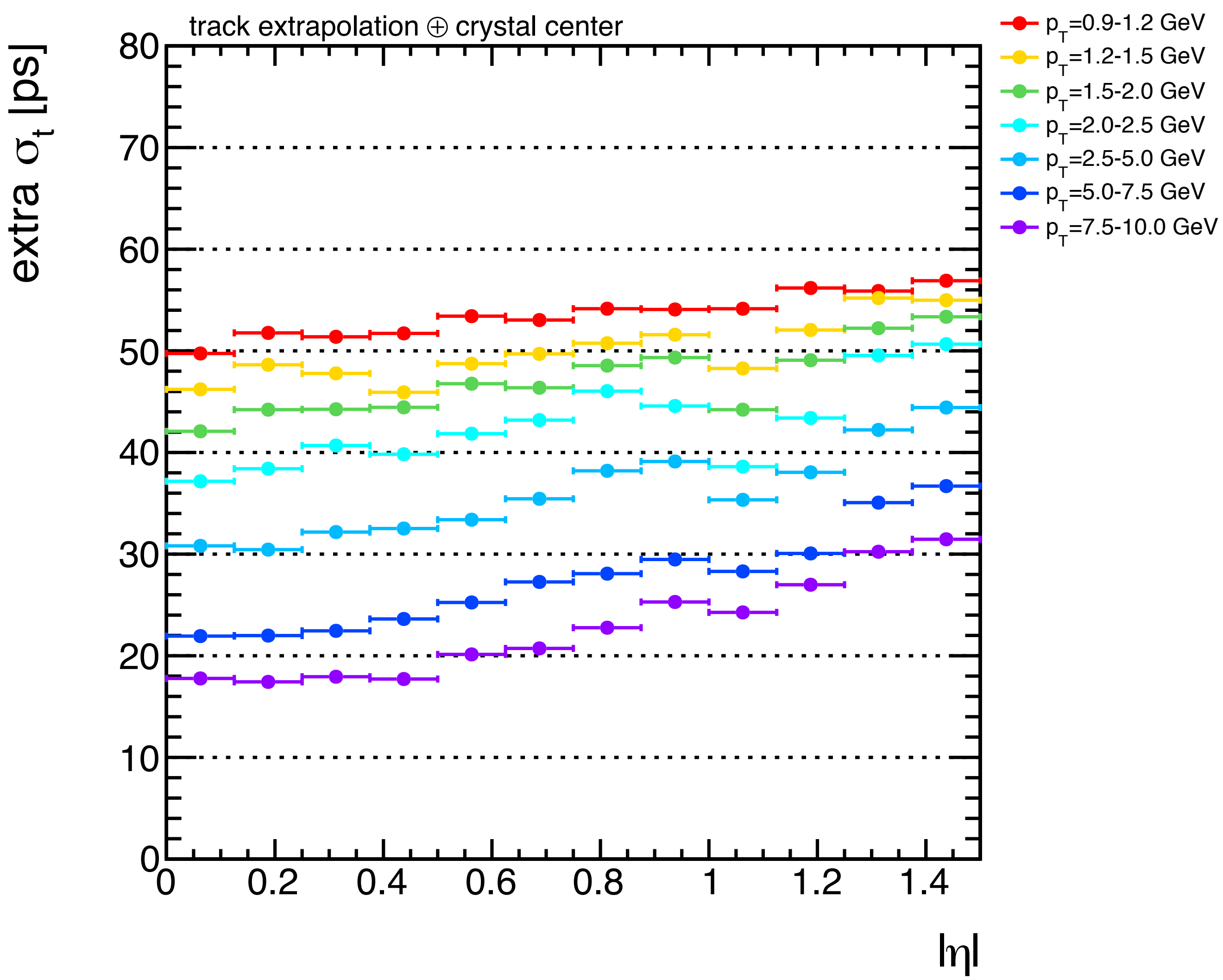
along φ



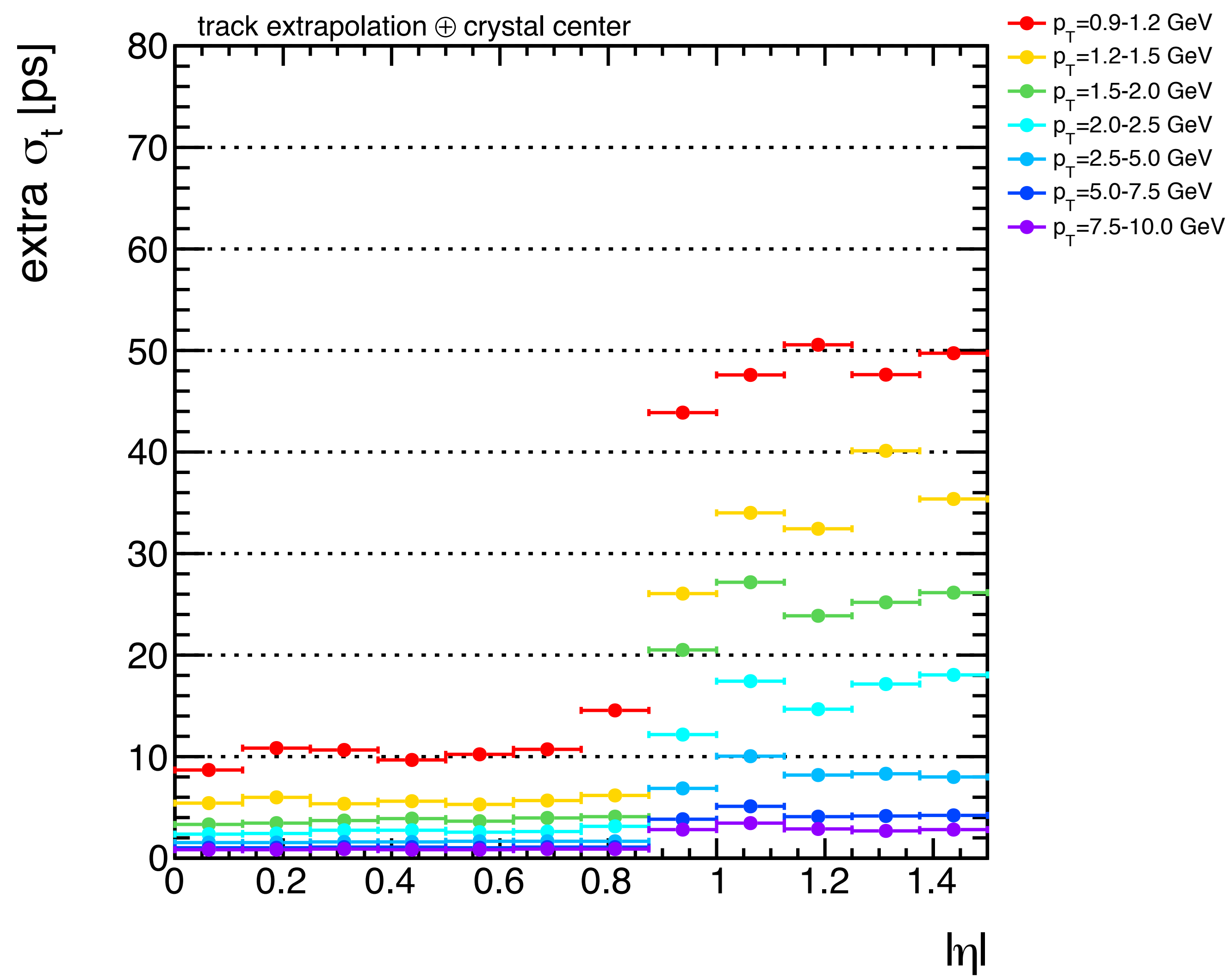
Impact point resolution in the MTD

- Time resolution extra-smearing from limited knowledge of impact point:
  - critical degradation of performance along z
  - critical degradation of performance along **φ** below 2 GeV and for |η| > 1
- This calls for a **robust hardware solution**

along z

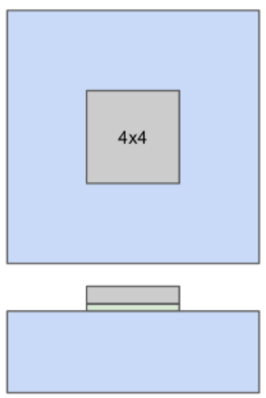


along **φ**



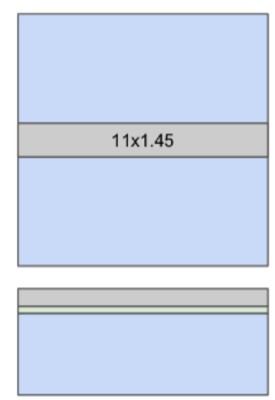
Possible hardware solutions

- Different options being considered to reduce the light collection non-uniformity (won't discuss them extensively here):



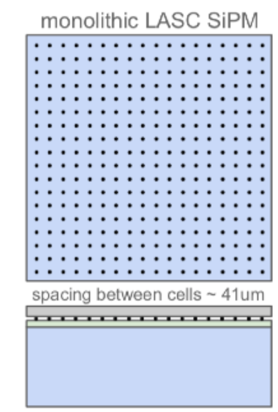
default

1 4×4 mm² in the center



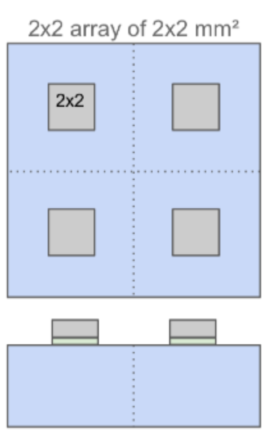
SiPM strip

cancel non-unif. in one direction (z)



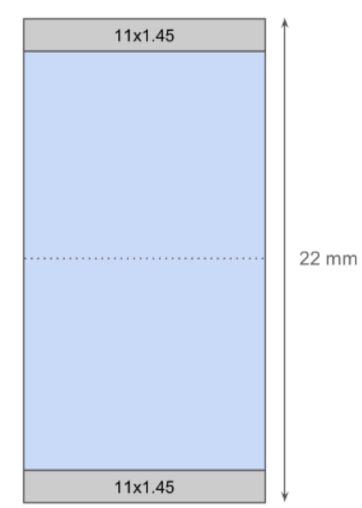
"Final" solution

full tile readout with a sparse cell SiPM



array

multiple smaller SiPMs

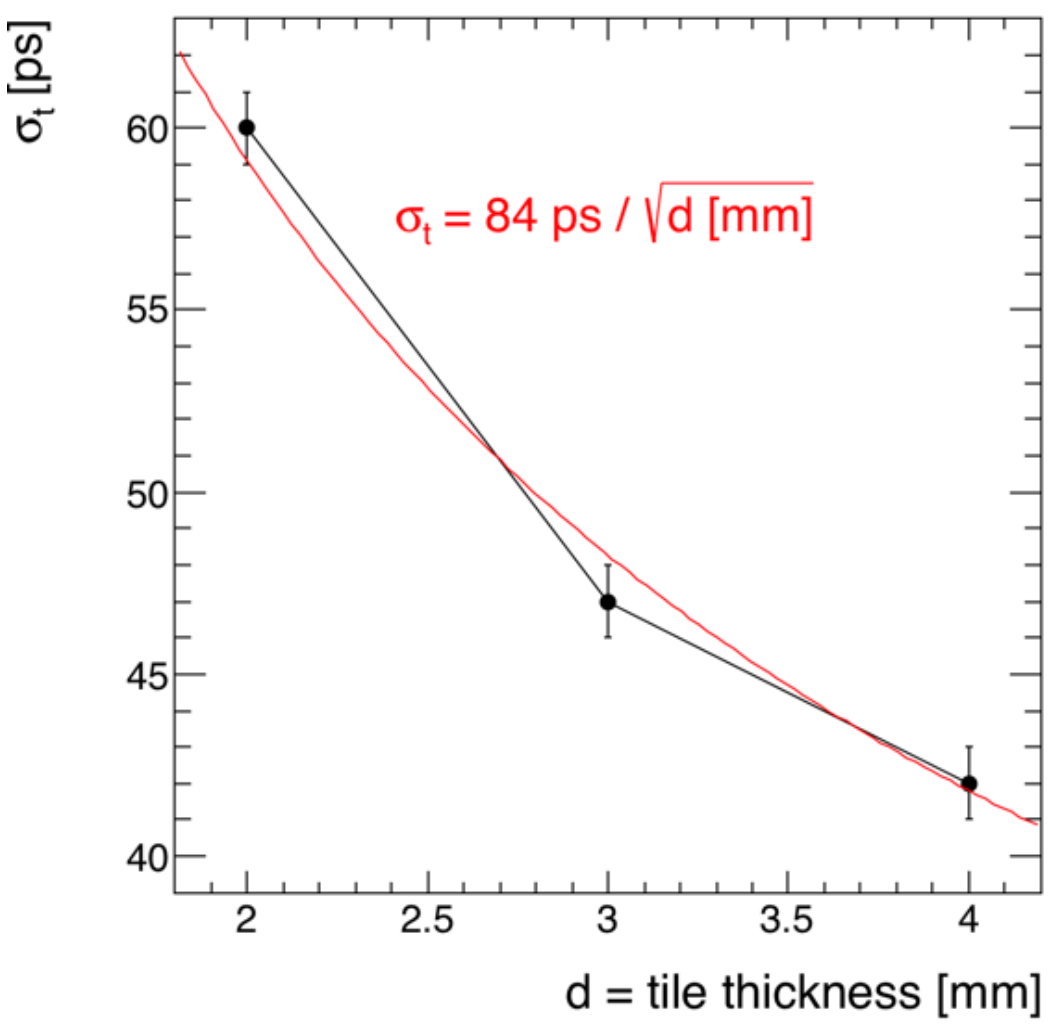


Double readout

time difference at the two ends

Scaling with thickness

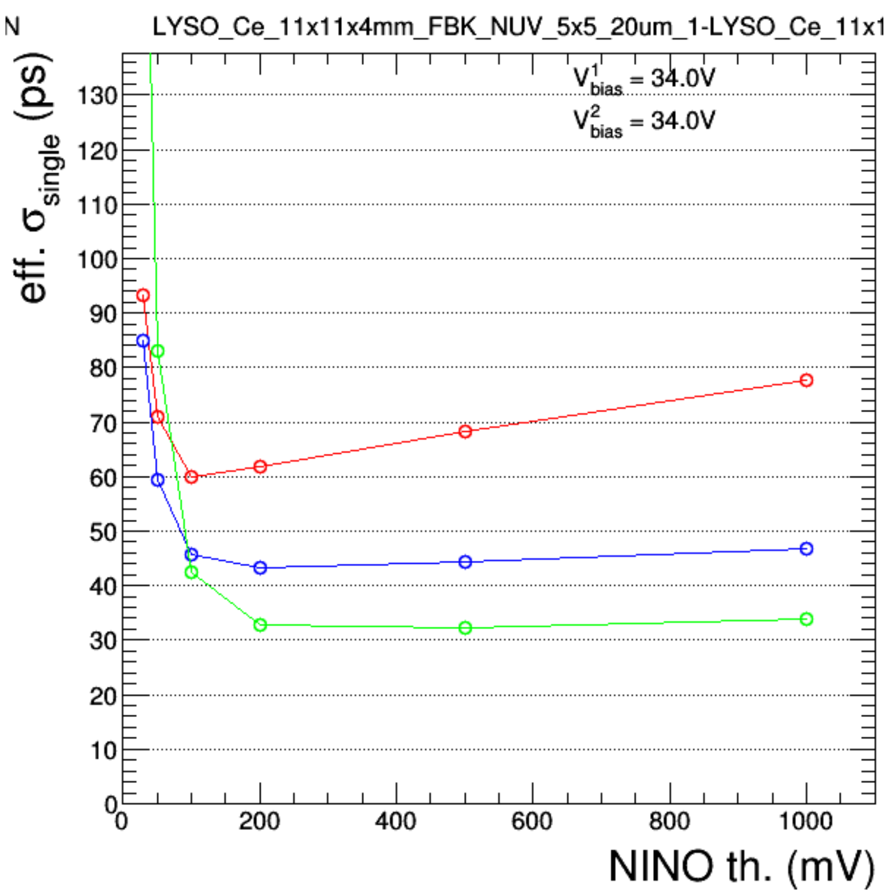
- **[T9 beam test]**
  - LYSO tiles of different **thickness** (**11×11×2 mm³, 11×11×3 mm³, 11×11×4 mm³**) tested
  - SiPM Ketek 3×3 mm² 25 μm
  - time resolution measured **comparing two identical sensors**

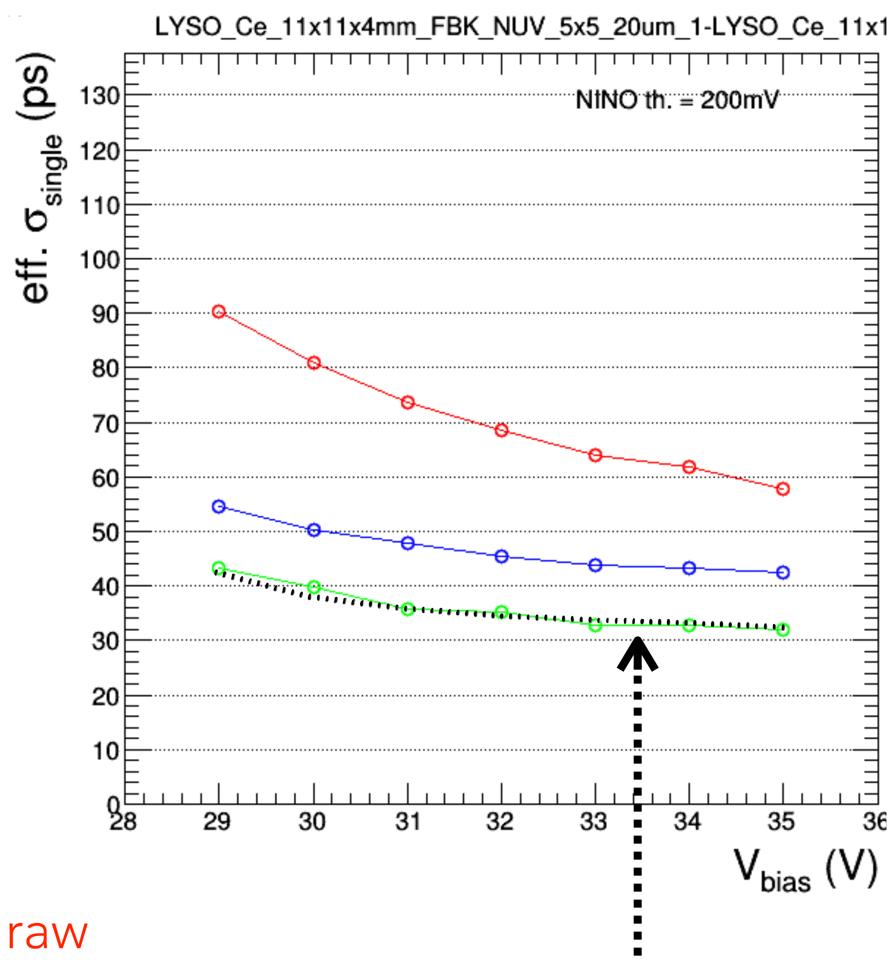


- time resolution scales as $1/\sqrt{d}$, as light output (LO) scales as d
- **40-45 ps** for the nominal MTD thickness

Scaling with PDE

- **[H4 beam test]**
  - 11×11×4 mm³ LYSO tile
  - SiPM FBK-NUV 5×5 mm² 20 µm
  - time resolution measured **comparing two identical sensors**





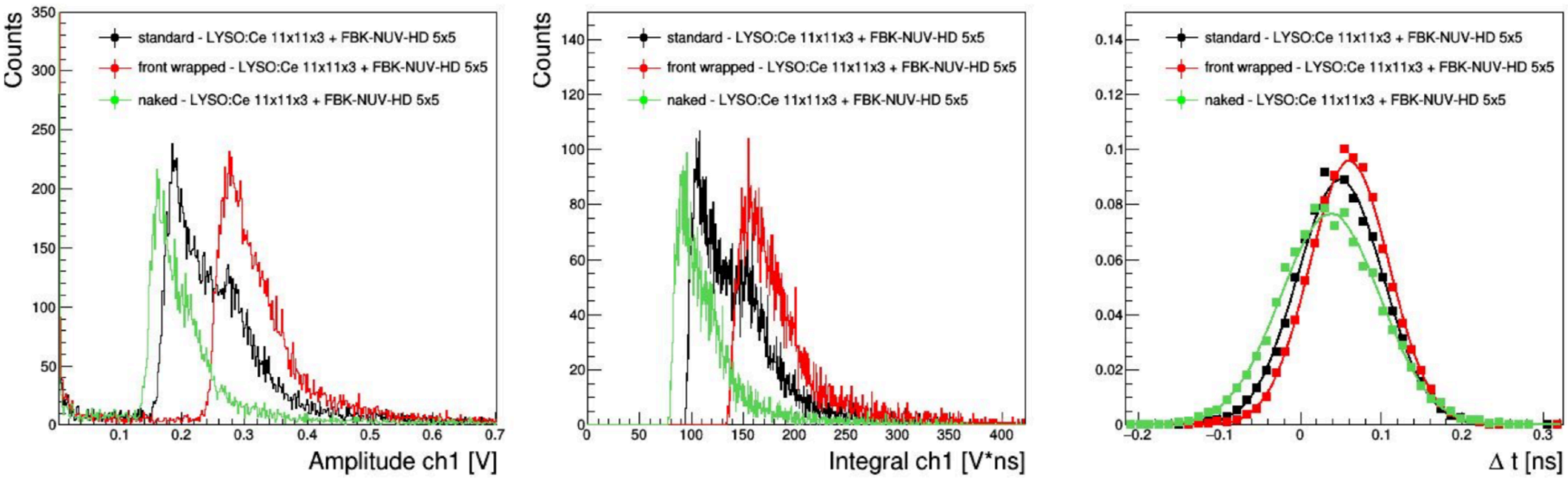
raw
time-walk corrected
time-walk + position corrected

1/√PDE

- fully corrected time resolution flat vs. NINO threshold above 100-200 mV
- time resolutions scales as 1/√PDE
- **30-35 ps** for 4-5 V overvoltage

Effect of wrapping

- **[H4 beam test]**
  - $11\times11\times3$ mm^3 LYSO tile, different **wrappings (no wrapping, rear+lateral sides, all sides)**
  - SiPM FBK-NUV 5×5 mm^2 20 μm
  - time resolution measured **comparing two identical sensors**

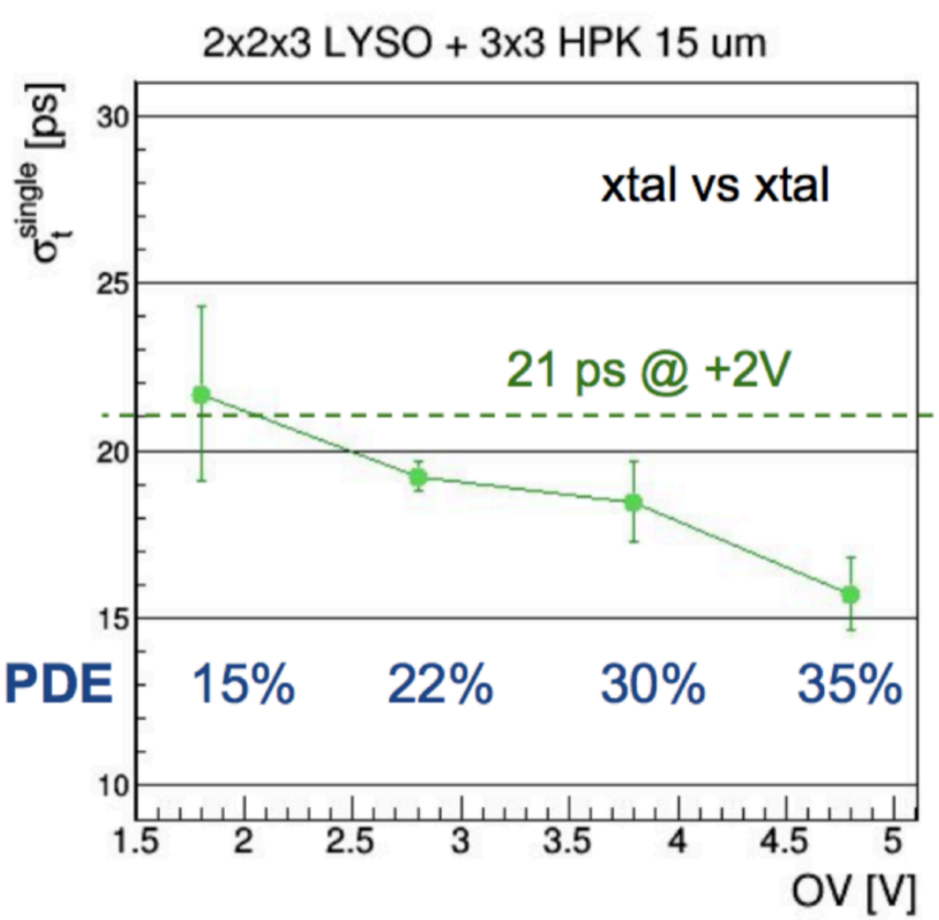


34V/200 mV - no BS selection	Max. Amp. MPV [V]	Pulse Integral MPV [V*ns]	σ_t **single** (uncorr., **corr.**) **[ps]**
no wrapping (ch1/ch2)	0.17 / 0.18	96 / 104	61.9 / **42.9**
rear+side wrapping (ch1/ch2)	0.21 / 0.24	119 / 133	53.5 / **36.6**
full wrapping (ch1/ch2)	0.28 / 0.32	159 / 180	49.9 / **34.4**

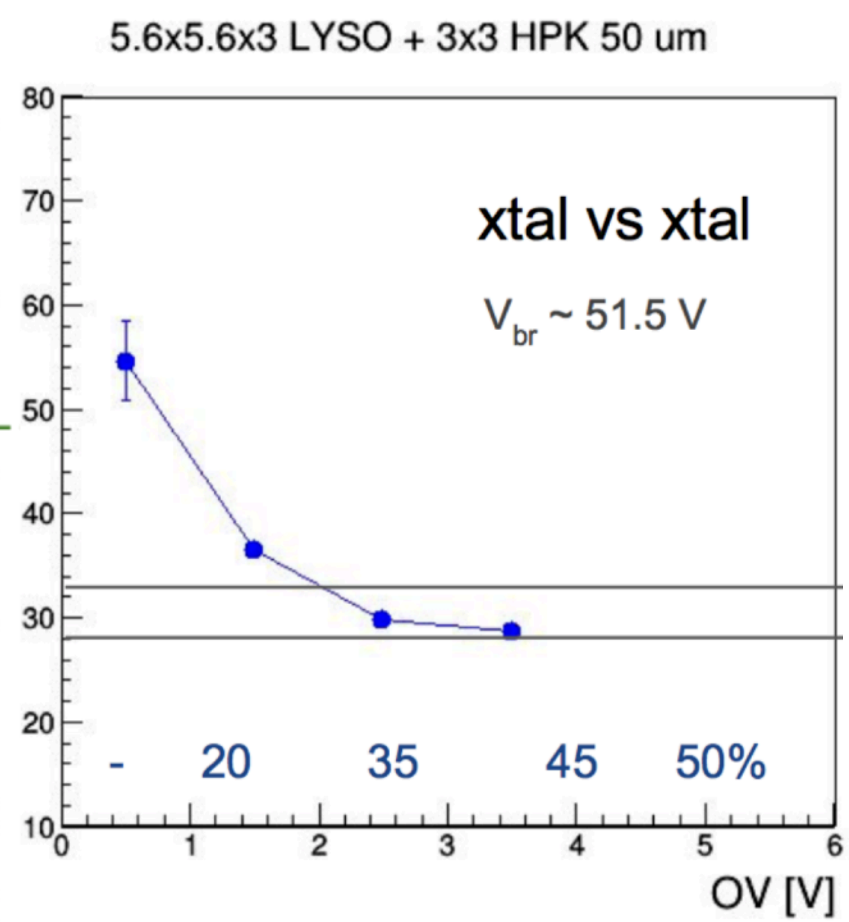
15 µm sensor

- **[H6 beam test]**
  - 2×2×3 mm³ and 5.6×5.6×3 mm³ LYSO tile
  - SiPM HPK 3×3 mm² 15 µm: **first test of a 15 µm sensor**
  - time resolution measured **comparing two identical sensors**

small pixel (full readout)



1/4th of a nominal MTD tile

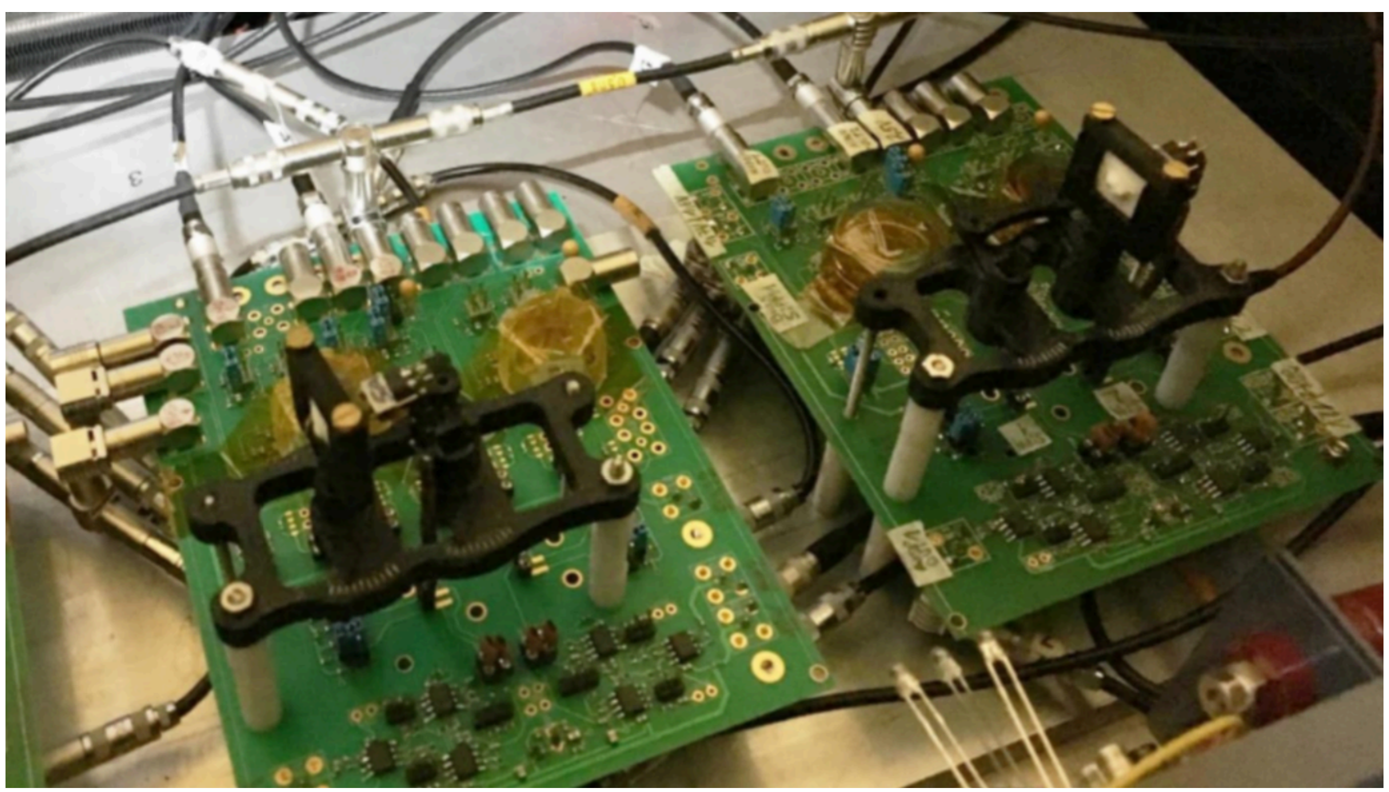


- very good time resolution when full readout of the surface — maximum light output (LO)
- time resolutions scales as $1/\sqrt{PDE}$ and as $1/\sqrt{LO}$
- ~**35 ps** extrapolated for a 2×2 mm² sensor

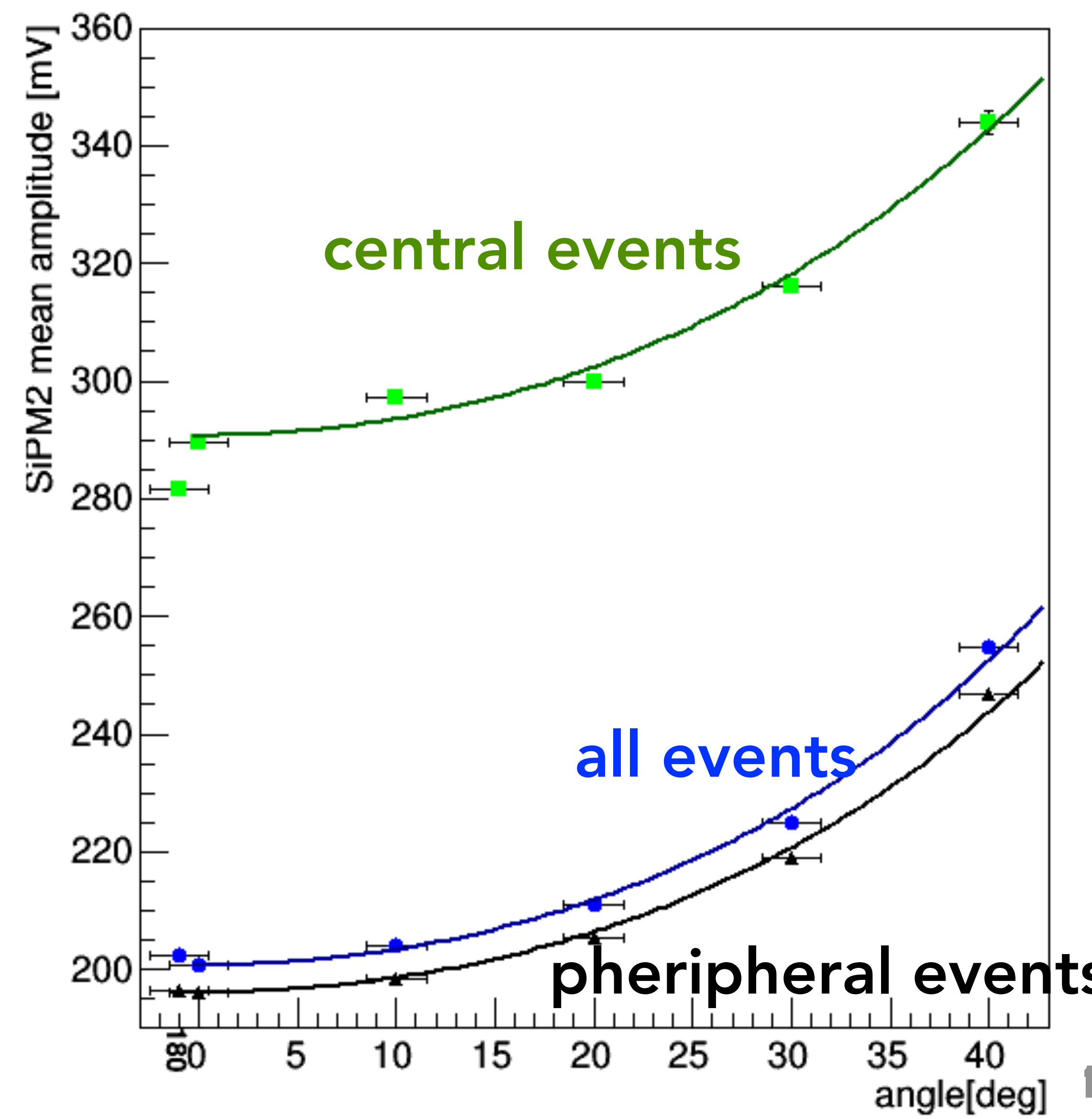
Study at different angles of incidence

- The energy deposited in the crystals by MIPs has a d/cosθ dependence, as expected
  - this supports the η-dependent material leveling being considered in the TP

crystals tilted along x from 0 to 40°



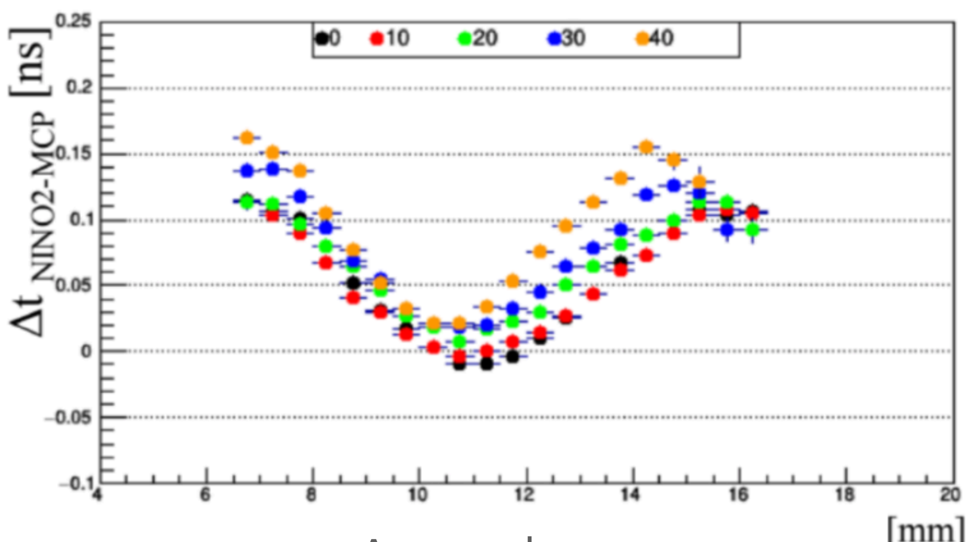
Signal amplitude variation with slant thickness



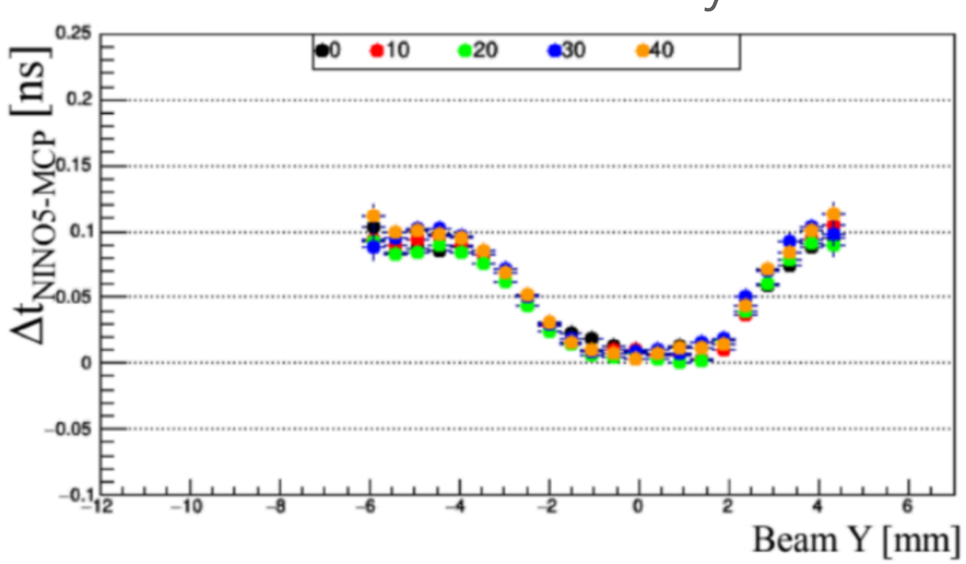
Study at different angles of incidence

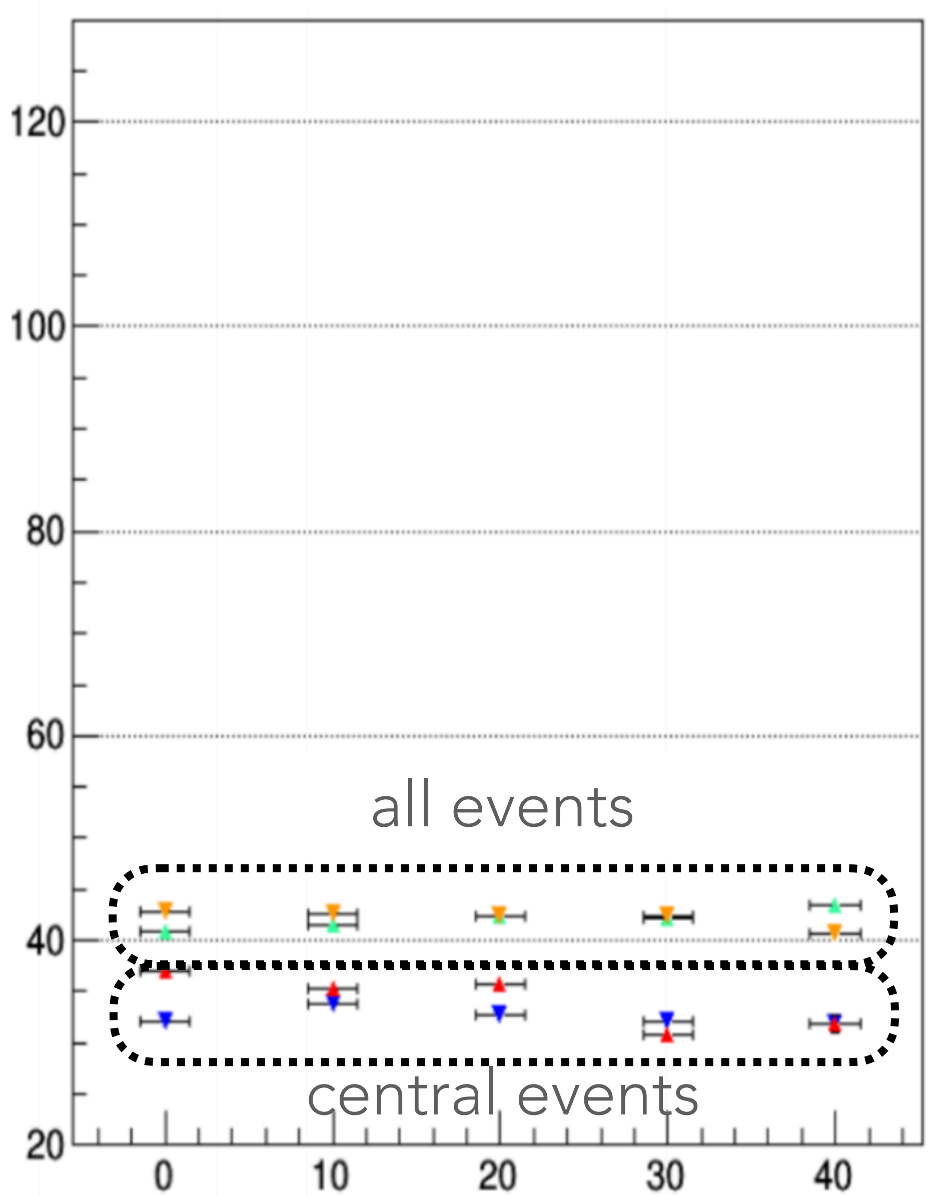
- Time resolution (measured vs. MCP) not influenced (neither negatively nor positively) by incidence angle
  - cannot exclude a residual contribution from non-uniformity
  - should plan a **test of tilted tiles of reduced thickness** in the future (as in the TP)

Δt vs. beam x



Δt vs. beam y





Summary

- 2017 beam tests have been a big effort in terms of organization, setup and data analysis. A lot of important information was collected to help steer the R&D for the next year
  - (re)discovered that performance is dominated by **light collection:**
    - **non-uniformities** in light collection induces a **large dependence on the impact point** — a 60 ps effect if not accounted for
    - scaling as a function of SiPM PDE, crystal thickness and fraction of crystal surface coverage confirm this
  - options to improve uniformity of light collection at the hardware level being worked on
  - optimize wrapping
  - for **future** beam tests, we need to **equip ourselves** with **instrumentation** to allow precise **particle tracking** (e.g. a pair of hodoscopes in our usual experimental box)

  - baseline result: **FBK-NUV 5×5 mm^2, 20 μm, 4-5 V OV** on **LYSO 11×11×4 mm^3**
    ~33 ps (crystal-vs-crystal) / **~40 ps (MCP-vs-crystal)**
    consistent with O(20 ps) extra-smearing from $\sigma_{position}$ ~0.5 mm