Test-beam qualification of the PS modules for the CMS Phase-2 Outer Tracker

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HELMHOLTZ

Overview of the Phase-2 CMS Outer Tracker Modules

Phase-2 CMS Outer Tracker

Harder, better, faster, stronger

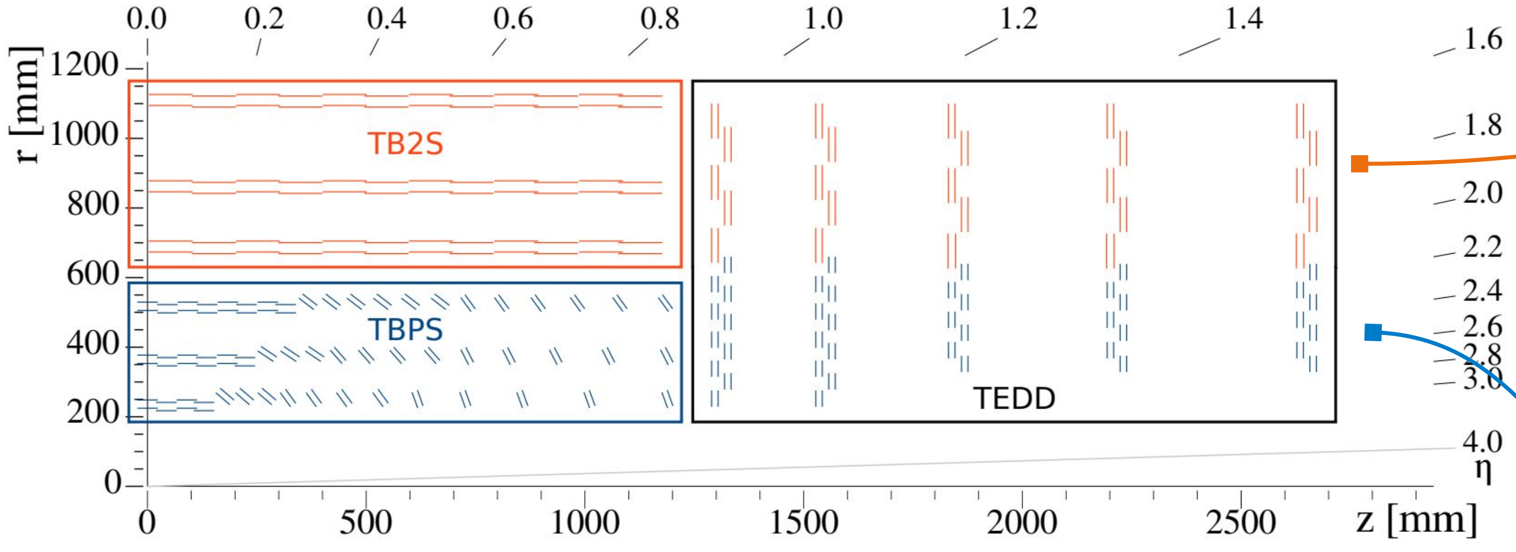
HL-LHC upgrade:

- Instantaneous luminosity up to **$7.5 \cdot 10^{34}$ cm^{-2}s^{-1}**
- pile-up up to **200**

The all-new Outer Tracker, improved in every aspect:

- Higher granularity
- Higher radiation hardness
- Higher data rate
- Contribution to the fast hardware (L1) trigger by track p_T discrimination

Built of **two types** of **double sensor** layer modules:



Cross-section of one quarter of the Phase-2 Outer Tracker

Strip-strip (2S)
7680 pcs.

- 10×10 cm^2
- 2 strip layers

Pixel-strip (PS)
5616 pcs.

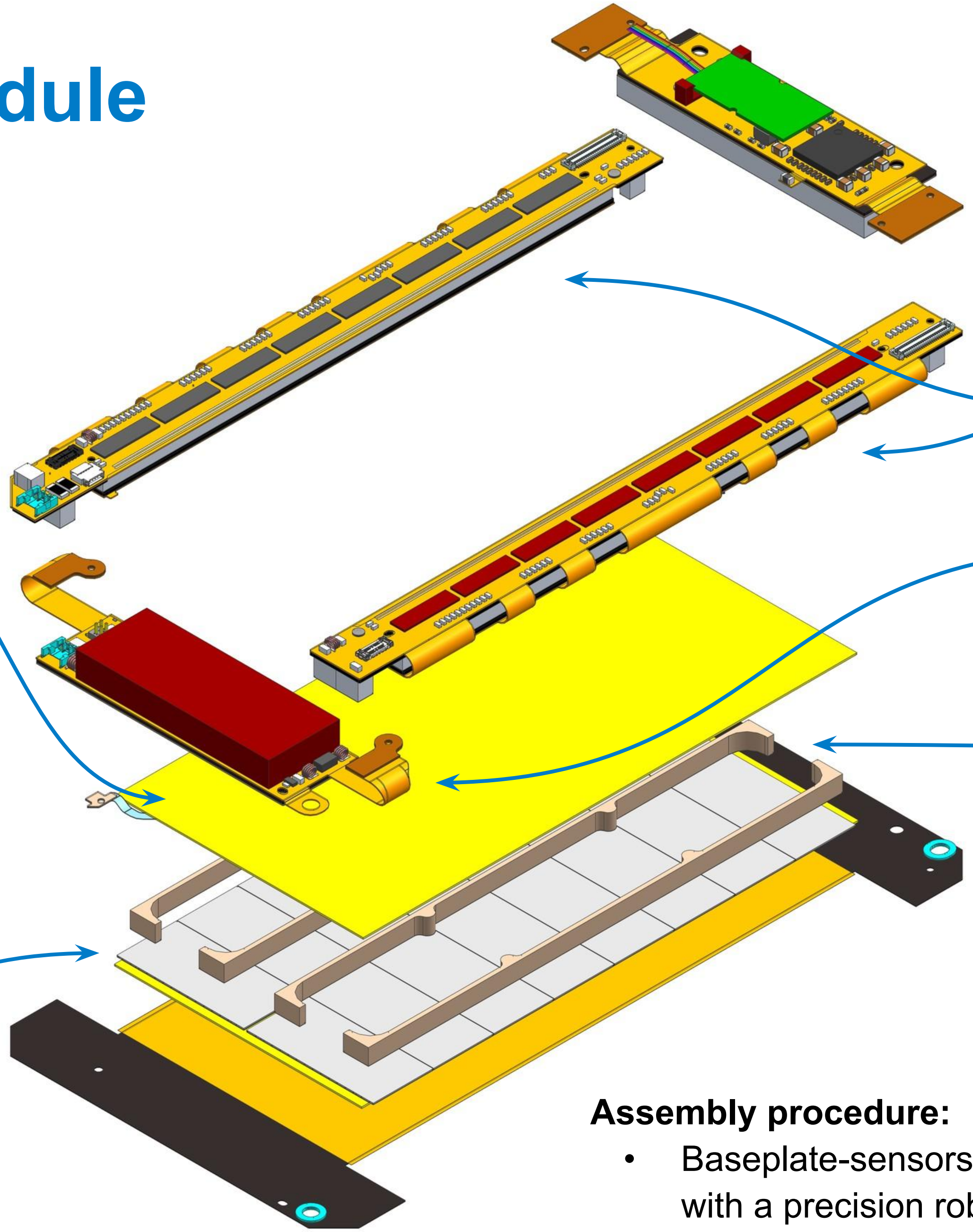
- 10×5 cm^2
- 1 macro-pixel layer
- 1 strip layer

Design of a PS module

Strip layer (PS-s):
- 960 × 2 strips
- 100 μm pitch

Double sensor for angle discrimination

Macro-pixel layer (PS-p):
- 960 × 32 macro-pixels
- 100 × 1467 μm^2 pitch
- 16 ASICs on top



Transceiver

Strip front-end x2

Power supply

Spacers x4
different thicknesses for modules at different *rz* positions

CFRP baseplate

Assembly procedure:
- Baseplate-sensors-spacers subassembly built with a precision robot
- Hybrids are glued with jigs and wire-bonded to sensors and ASICs

On-module p_T discrimination

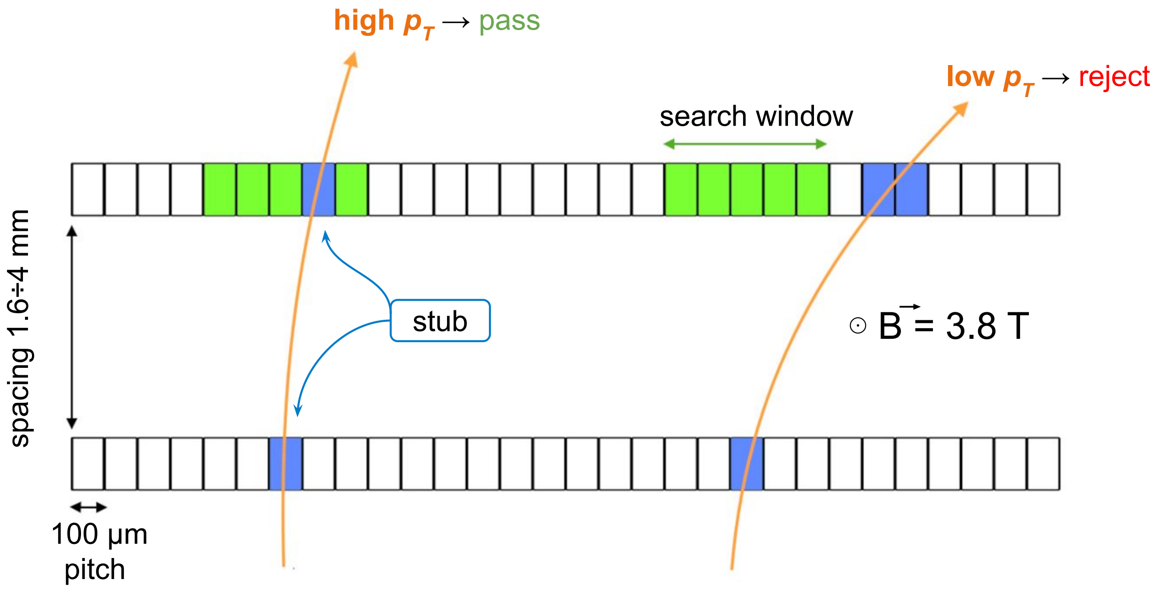
How the modules contribute to the L1 trigger

Modules are able to spot **high p_T tracks (> 2 GeV)** = candidates for interesting events:

- high p_T → ~perpendicular traverse
- low p_T → traverse at an angle

A **stub** is a special data instance, produced by the module as a response to a high p_T track
→ contains position and bend angle

Modules are designed to produce and send out **stubs** at the BX rate (40 MHz) and with low latency
→ to be used in the fast hardware (Level-1) trigger



Stub pipeline, run on the module onboard ASICs:

Clustering → Correlation between two planes → Discrimination by a given window → if passed: a **stub** is generated → Stubs are sent out via dedicated low-latency data path

Test-beam campaign

Test beam campaign

DESY-II, Feb 5th – Feb 18th 2024

The list of modules tested:

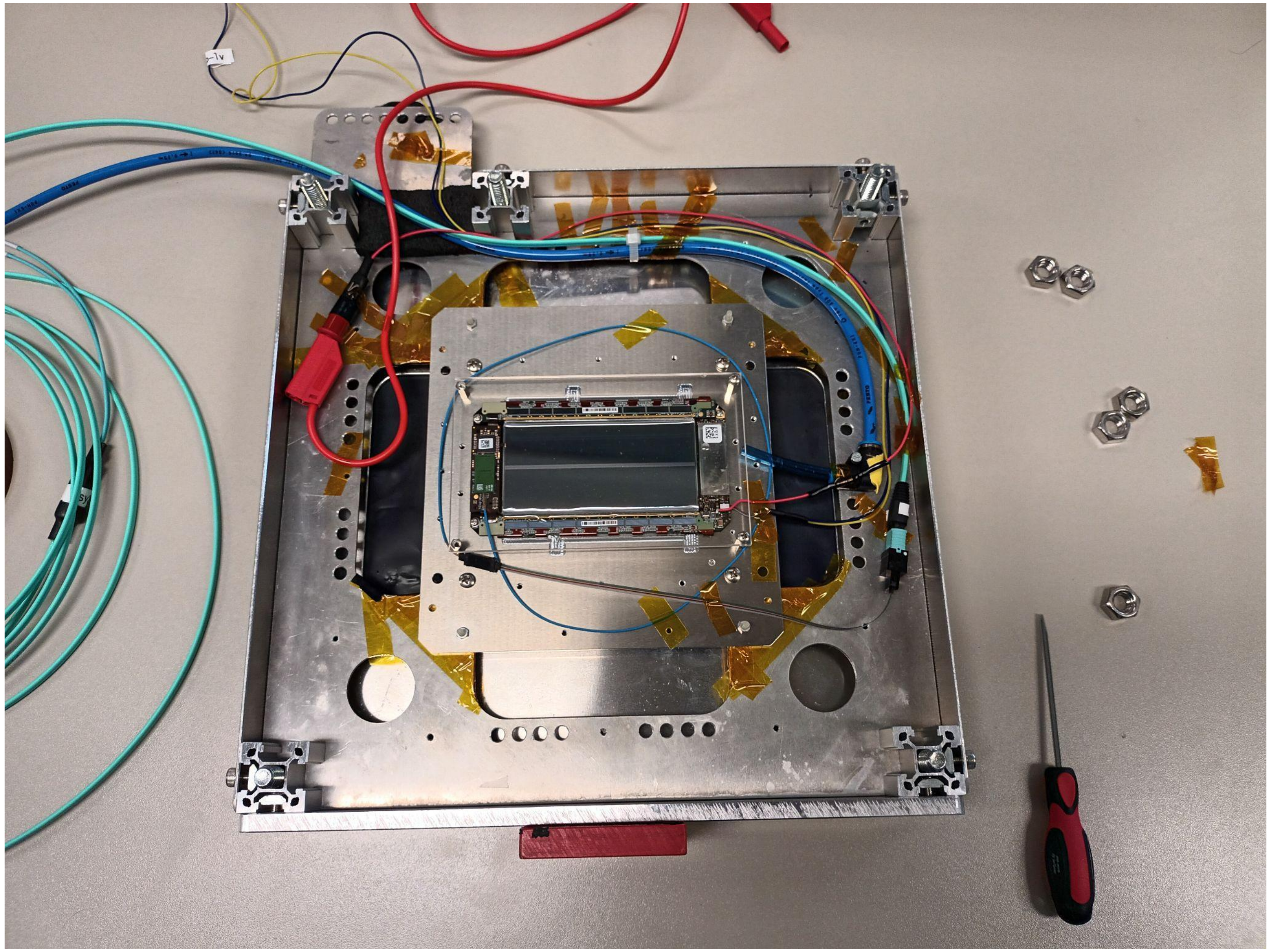
PS kick-off, DESY, 2.6 mm
- validation of kick-off components

this talk

PS kick-off, Perugia, 2.6 mm, 10 Gbps
- tests of 10 Gbps readout

PS prototype, US East, 1.6 mm, irrad. strips
- tests of an irradiated PS-s sensor

3x. 2S kick-off, KIT
- validation of kick-off components
- simultaneous readout of 3 modules

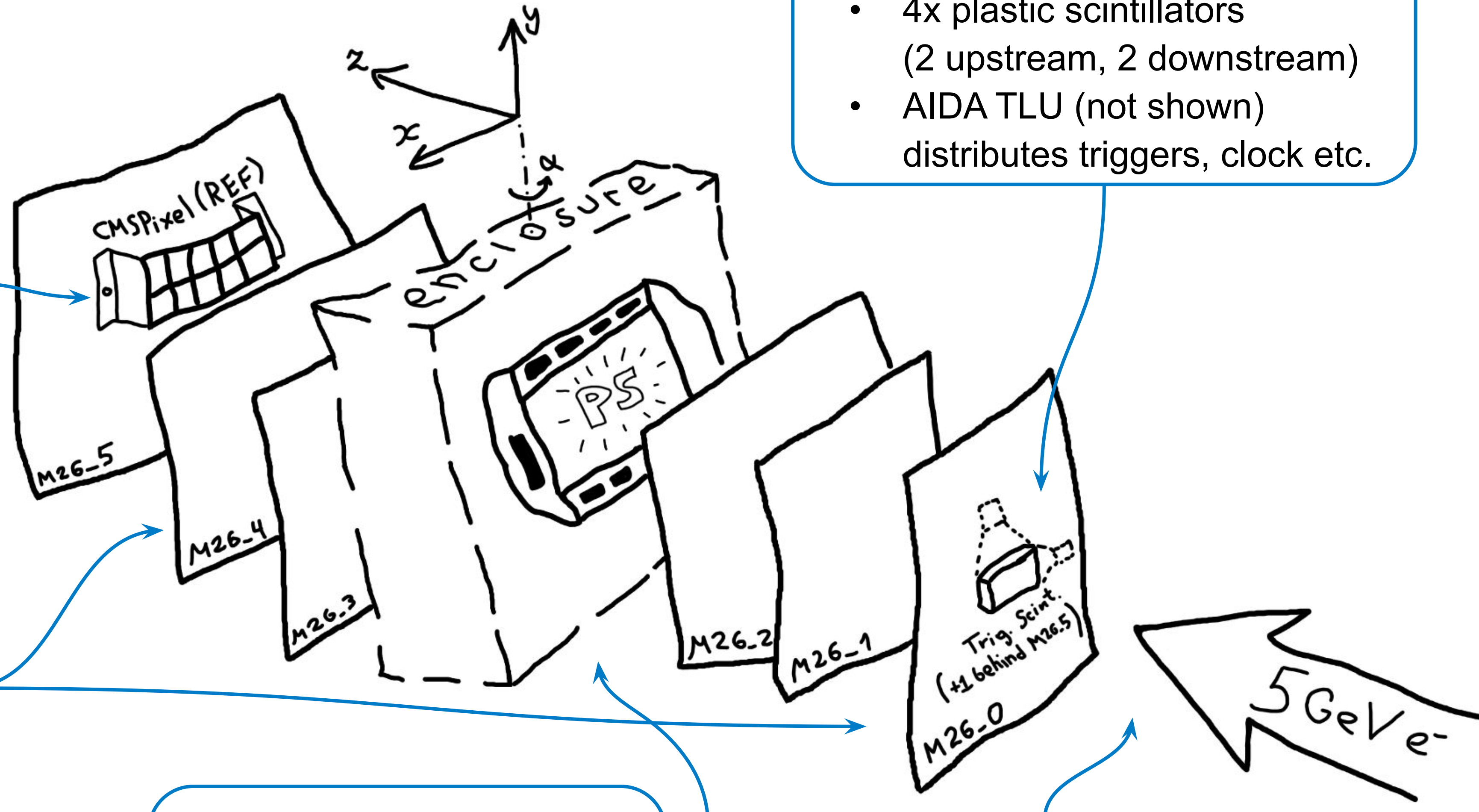


PS module on a carrier plate inside of a test box

Test beam setup trivia

Reference plane
- CMS Phase-1 pixel module
- 150✕100 μm^2 pitch
- to spatially select tracks within a given time window

DATURA beam telescope
- 6x MIMOSA26 planes
- 18.4 μm pitch
- 115 μs time frame
- O(μm) tracking resolution



Trigger logic
- 4x plastic scintillators (2 upstream, 2 downstream)
- AIDA TLU (not shown) distributes triggers, clock etc.

DUT enclosure
- on a rotation stage
- nitrogen/cooling
- holds module(s) inside

DESY-II beamline 21
- adjustable energy (5 GeV used)
- O(kHz) rate

Observable quantities

Definitions of detector performance FOMs

Reconstruction performed with Corryvreckan

$$\text{Residuals}_x = \{x_{\text{track}} - x_{\text{cluster}}\}_{\text{tracks}}$$

$$\text{Resolution}_x = \text{RMS}(\text{Residuals}) \ominus \sigma_{\text{telescope}}$$

Fit with a Gaussian and take its RMS instead
→ more robust

$$\mathcal{E}(\text{DUT}) = \frac{\text{Tracks} \cap \text{Matched REF} \cap \text{Matched DUT}}{\text{Tracks} \cap \text{Matched REF}}$$

Efficiency = chance for the DUT to *properly respond* to a *good track*

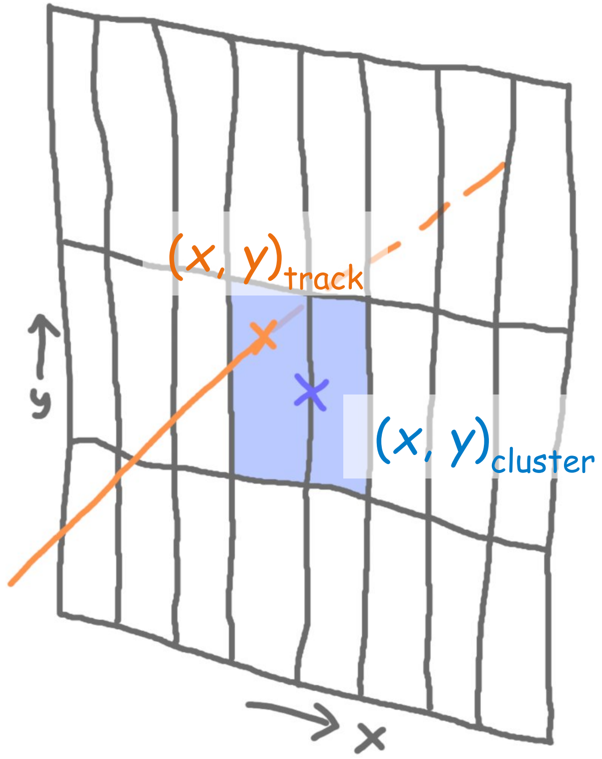
Criteria for track matching:

PS-p: $|x_{\text{track}} - x_{\text{cluster}}| \leq 200\mu\text{m}$, $|y_{\text{track}} - y_{\text{cluster}}| \leq 2\text{mm}$

PS-s: $|x_{\text{track}} - x_{\text{cluster}}| \leq 200\mu\text{m}$, $|y_{\text{track}} - y_{\text{cluster}}| \leq 26\text{mm}$

REF: $|x_{\text{track}} - x_{\text{cluster}}| \leq 300\mu\text{m}$, $|y_{\text{track}} - y_{\text{cluster}}| \leq 200\mu\text{m}$

→ distance(hit↔track) ≲ 2x pitch



Sensor efficiency

Determining working points

For non-irradiated sensors,
the working point was determined as follows:

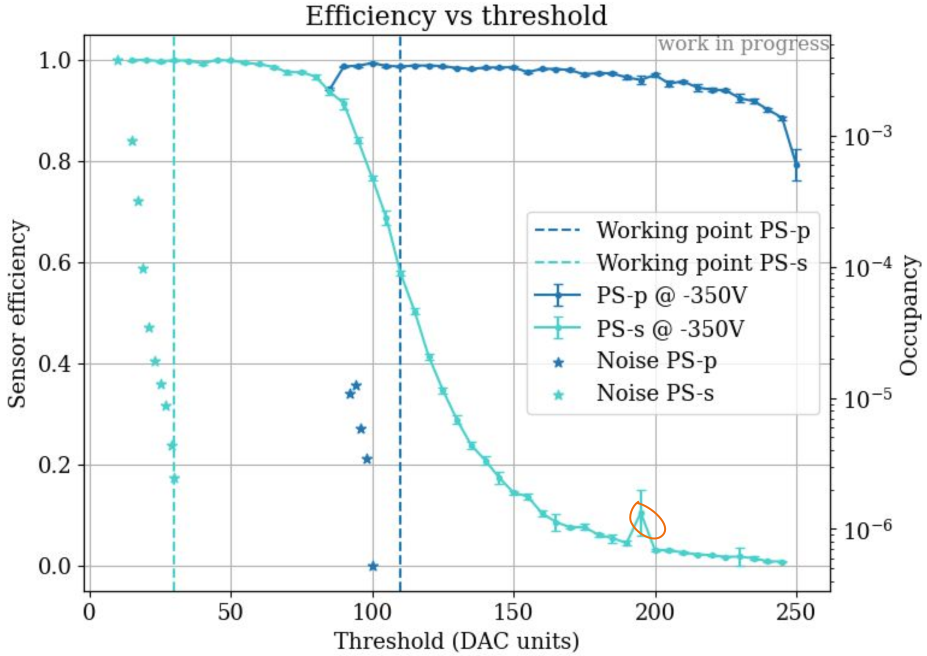
- Threshold MPA = **110 DAC units**
- Threshold SSA = **30 DAC units**
- Bias = **– 350 V**

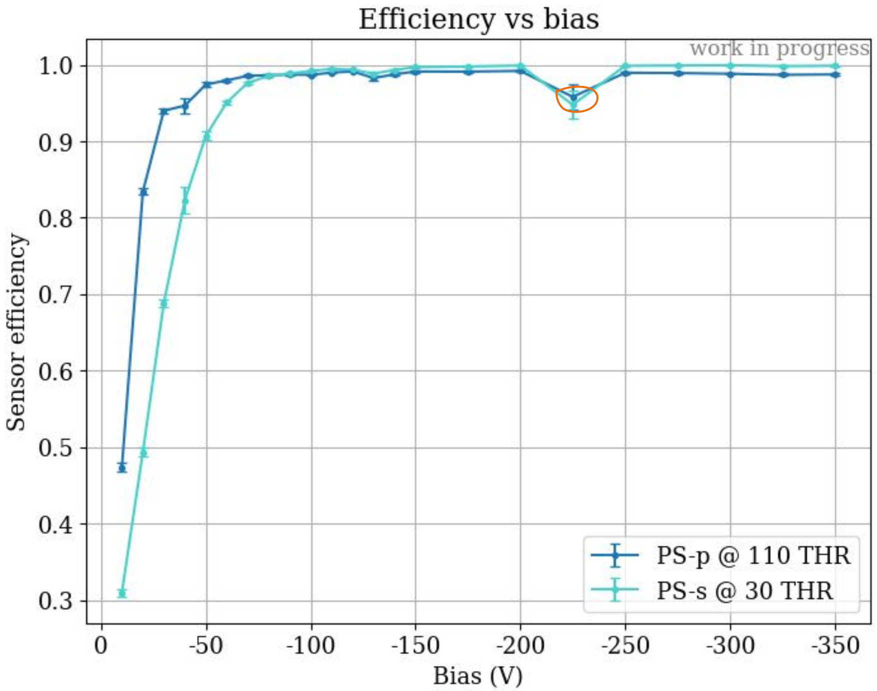
This yields efficiencies:

- ε(PS-p) = **98.7±0.1%**
- ε(PS-s) = **99.7±0.1%**

NB: results shown are work in progress

- outliers in plots → corrupted data points with unphysical monitoring values
- under investigation
- suspected REF malfunction





Angular calibration of the setup

by cluster size vs angle dependency

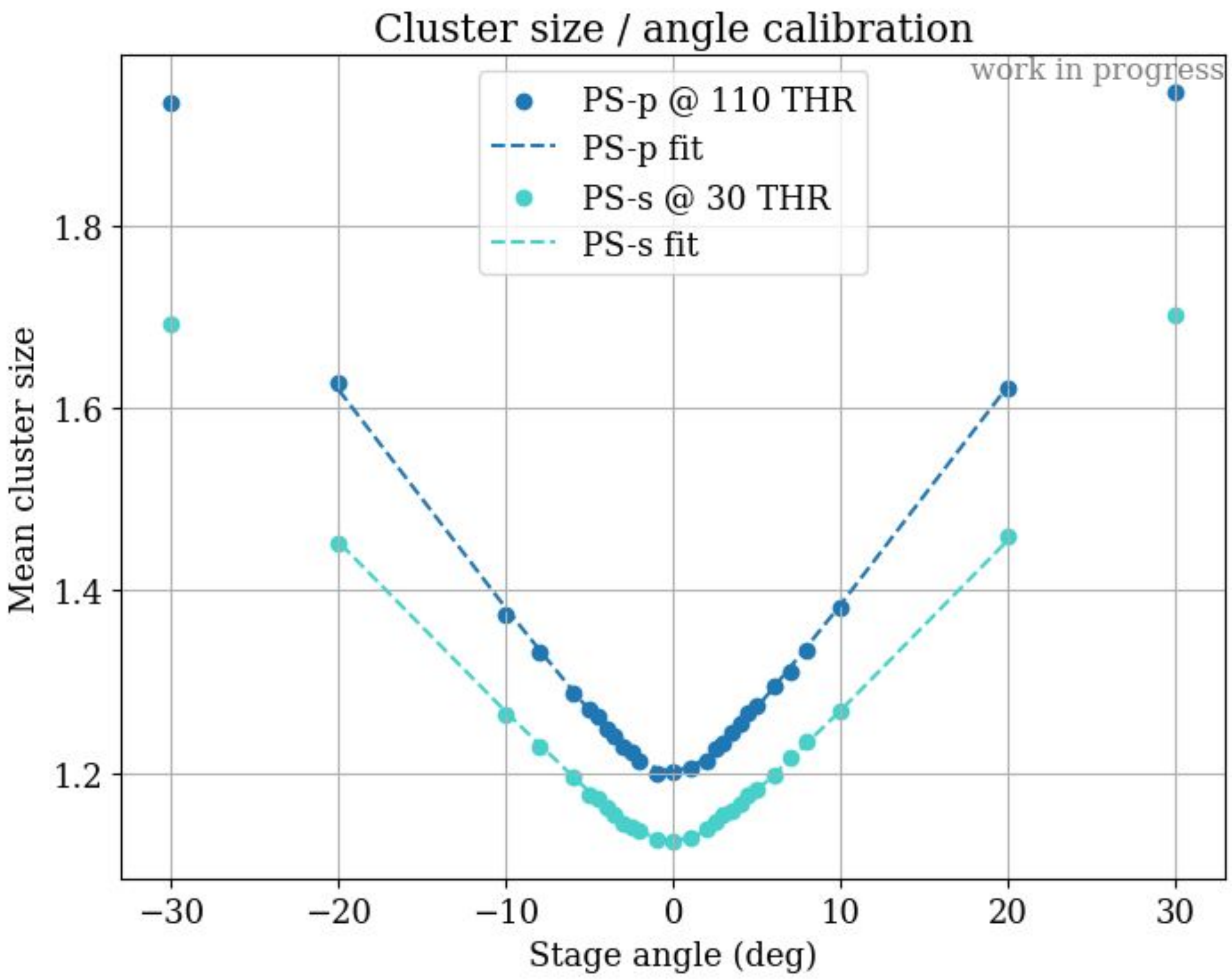
Cluster size vs. incidence angle
is a precise way of zeroing of the rotation stage:

- independent of tracking/reconstruction
- strongly dependent on the angle

convolution

$$\mathrm{size}(\alpha) = s_0 + k \cdot \langle \tan|x - \alpha_0| * \exp -\frac{y^2}{\sigma^2} \rangle(\alpha)$$

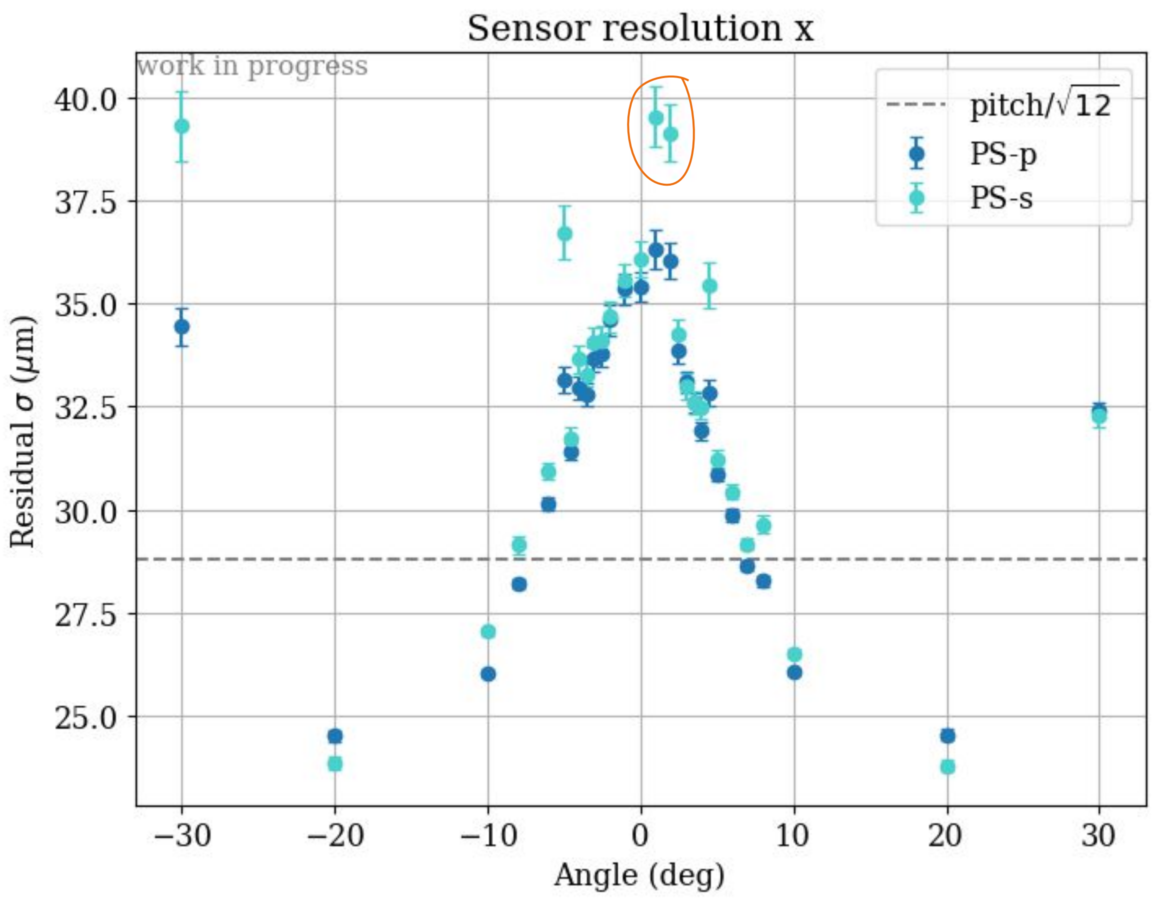
→ angular offset α_0=−0.15° extracted from the fit and applied to all angle readings from the rotational stage

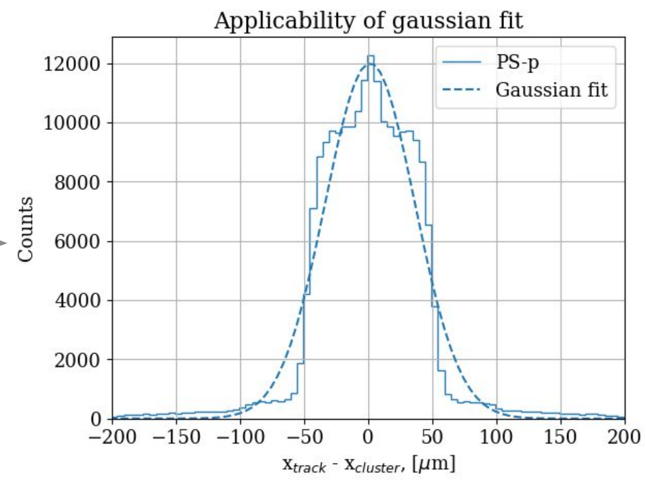


Spatial resolution

and its angular dependence

Coordinate resolution quantified by fitting a **Gaussian** to the distribution of *local* residuals





Worst case
(*least Gaussian distribution*)

For both sensors,

- Residual width of **~35 μm** for perpendicular incidence
- This improves with incidence angle, **overcoming binary limit** due to increasing cluster size

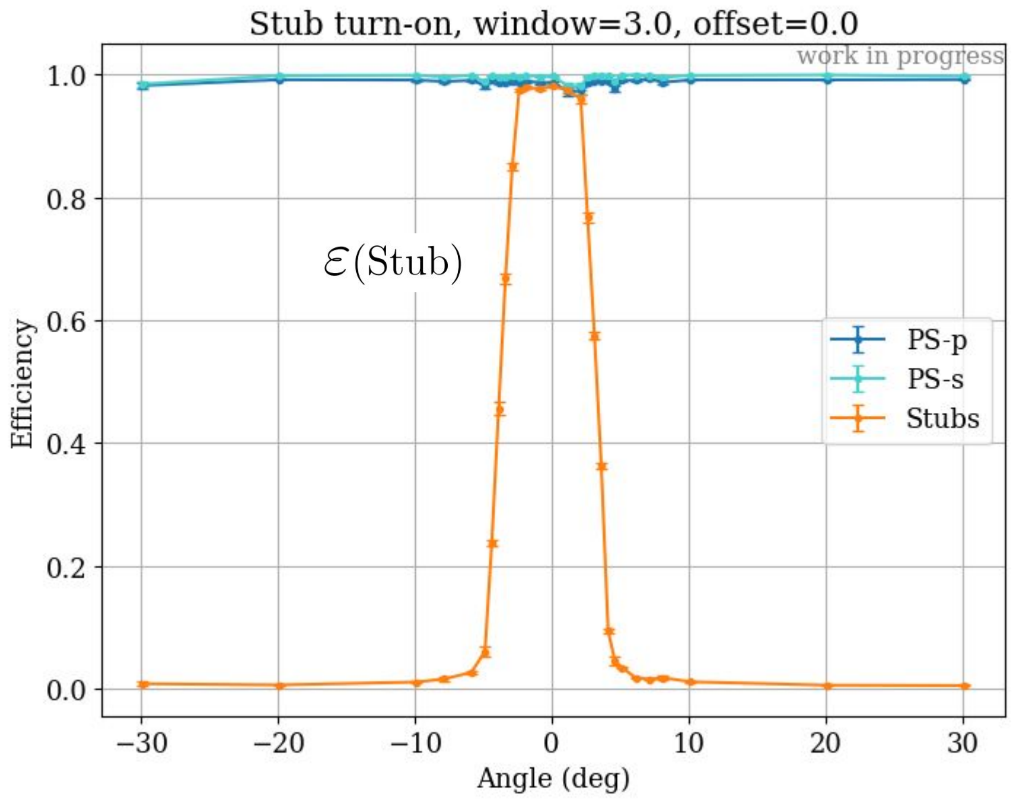
NB: telescope resolution is not taken into account yet

- the actual sensor resolution is 1-2 μm better than the residual width values shown
- fitting strategy to be improved

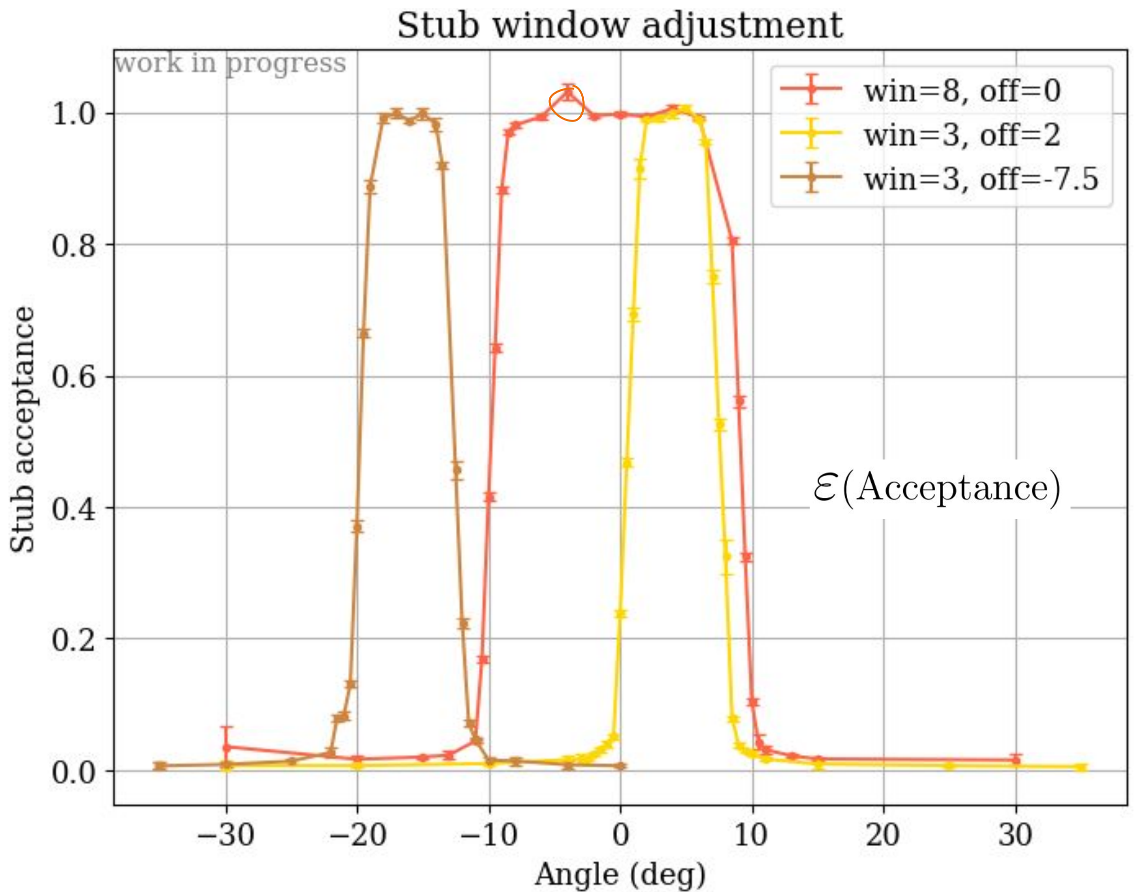
Angle discrimination

and stub acceptance adjustment

Discrimination window width and offset are adjusted to ensure equal p_T cut for different module locations in the Tracker



$$\mathcal{E}(\text{Stub}) = \mathcal{E}(\text{PS-p}) \cdot \mathcal{E}(\text{PS-s}) \cdot \mathcal{E}(\text{Acceptance})$$

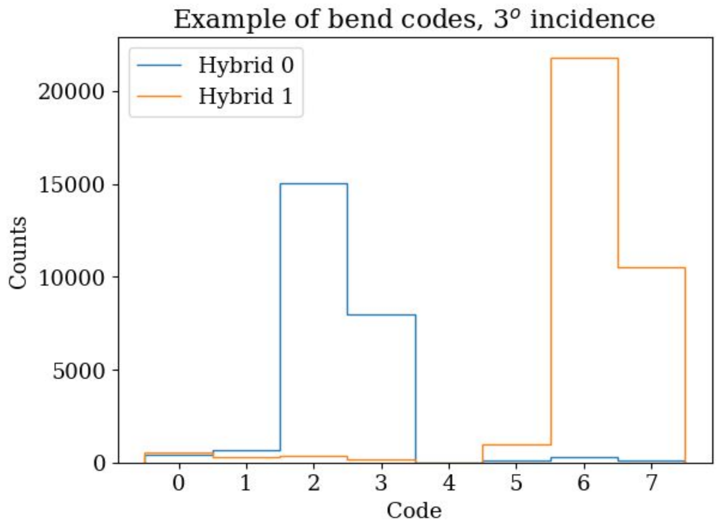


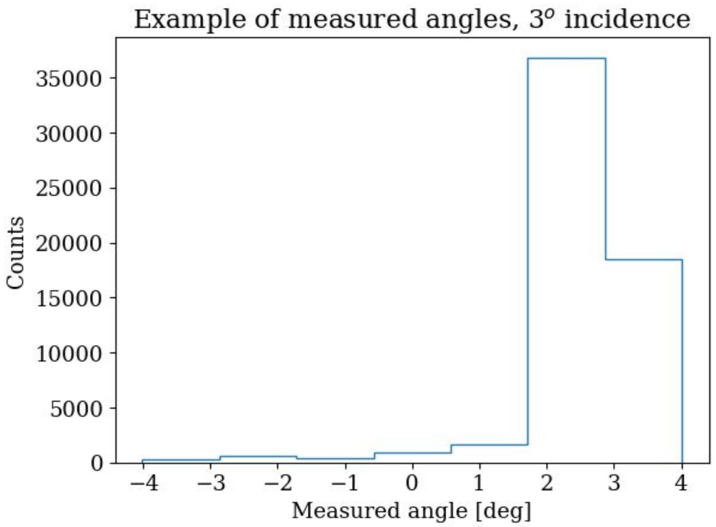
On-module stub angle measurement

via stub bend codes

For each stub, a **bend code** is stored

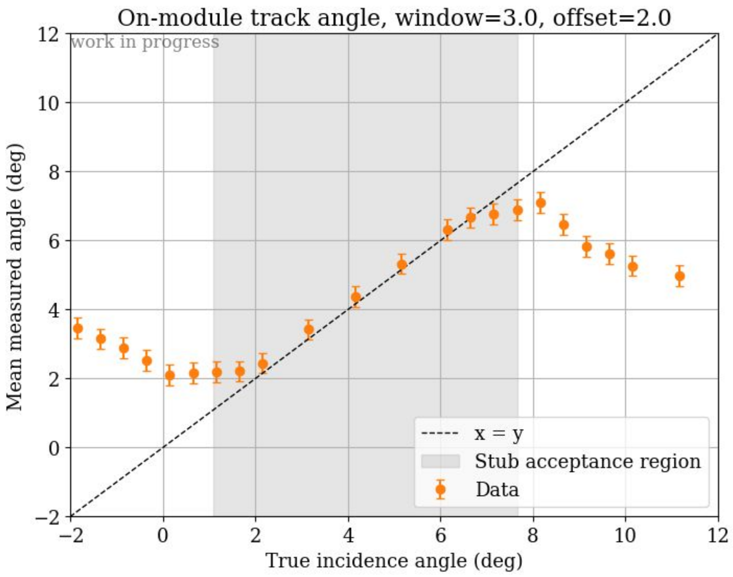
- contains information on track angle
- to be used in Level-1 trigger

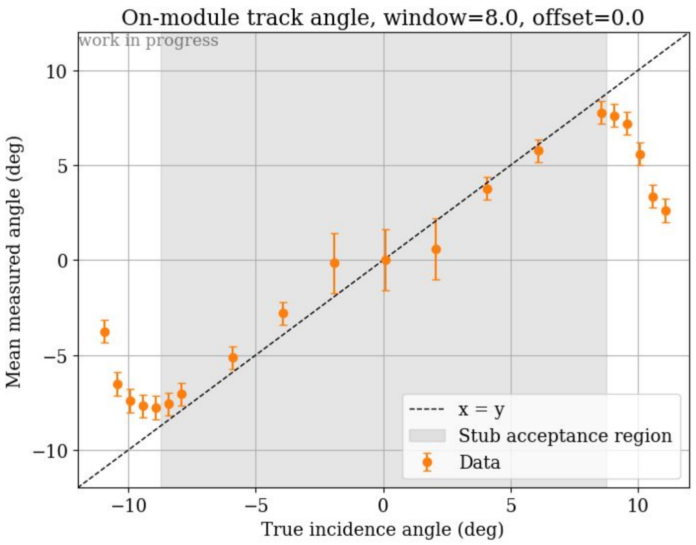




Each stub has a physical bend encoded

Which translates to the track angle:
α=atan((phys_bend+offset) · pitch/(2 · spacing))
~1.15° per half-strip for a 2.6 mm module





NB: error bars represent only encoding/binning errors

Conclusions & outlook

Things are looking good!

- DESY kick-off module is **fully functional**
- The module matches the performance expectations:
  - Basic performance
  - Angular discrimination
- Analysis for the DESY module data mostly complete
- Analysis for the other modules in progress, preliminarily looking promising

The measurements leading to these results have been performed at the
Test Beam Facility at DESY Hamburg (Germany),
a member of the Helmholtz Association (HGF)

That’s it!