Building Rings and Measuring Things

Construction and material measurements for the ATLAS ITk Pixel Outer Endcaps

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Instrumentation Seminar, LBNL

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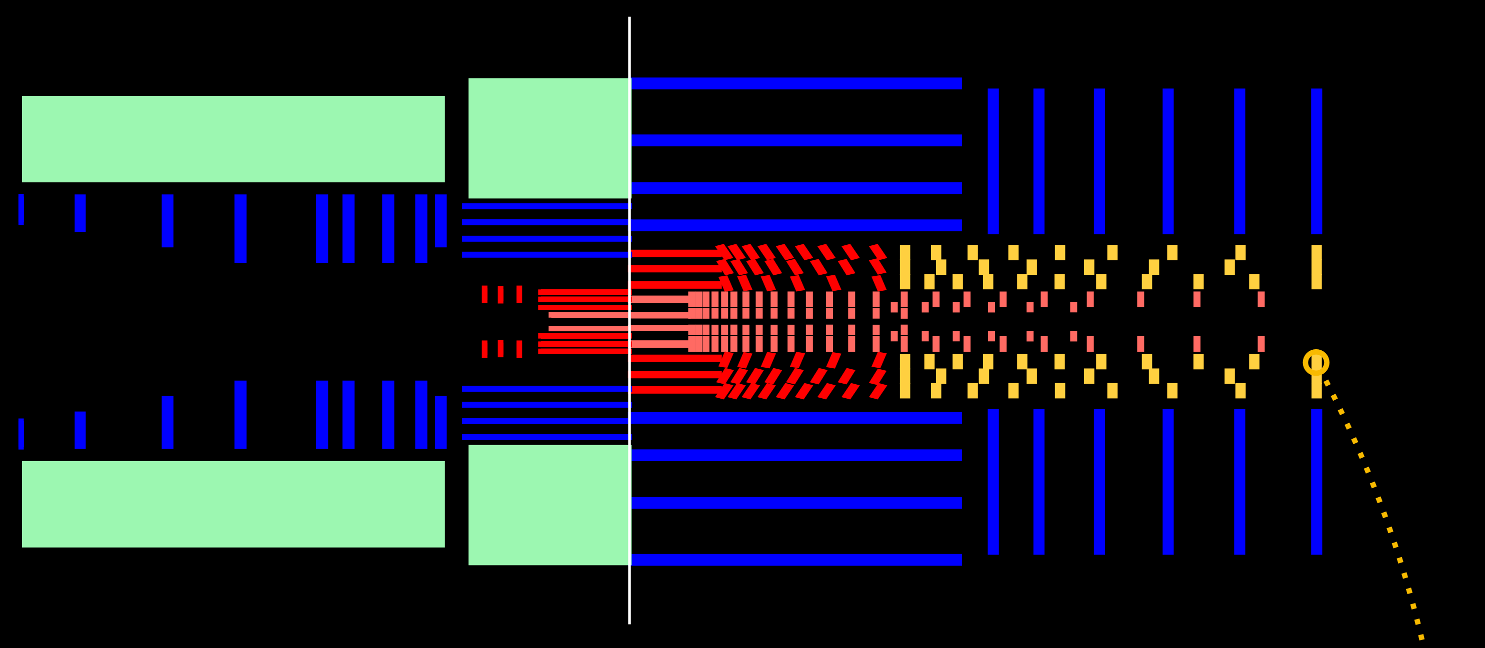
Date: 2022-11-03 11:15:47 CET

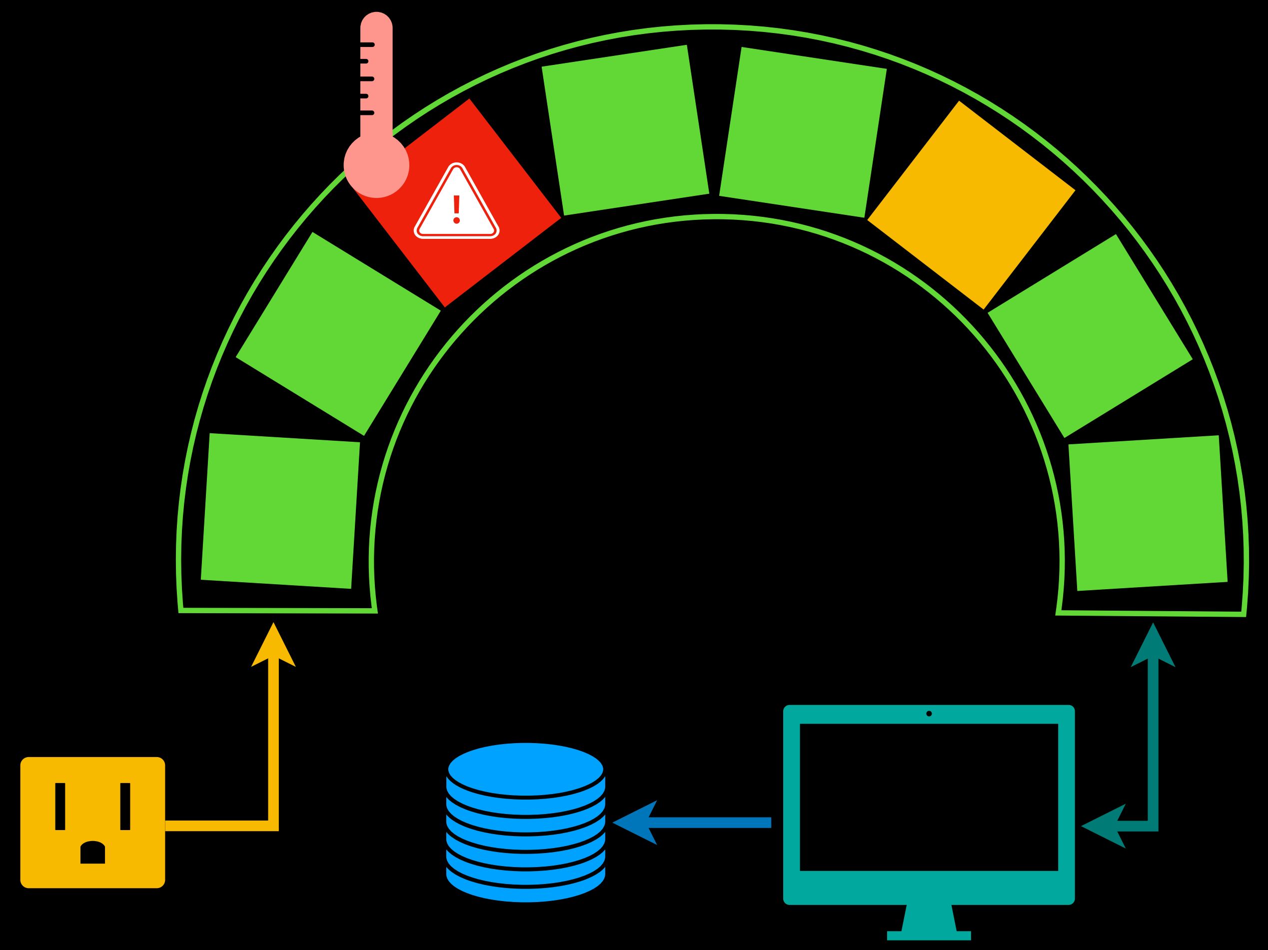
Snapshot of a proton collision
directly from the ATLAS experiment

Outline

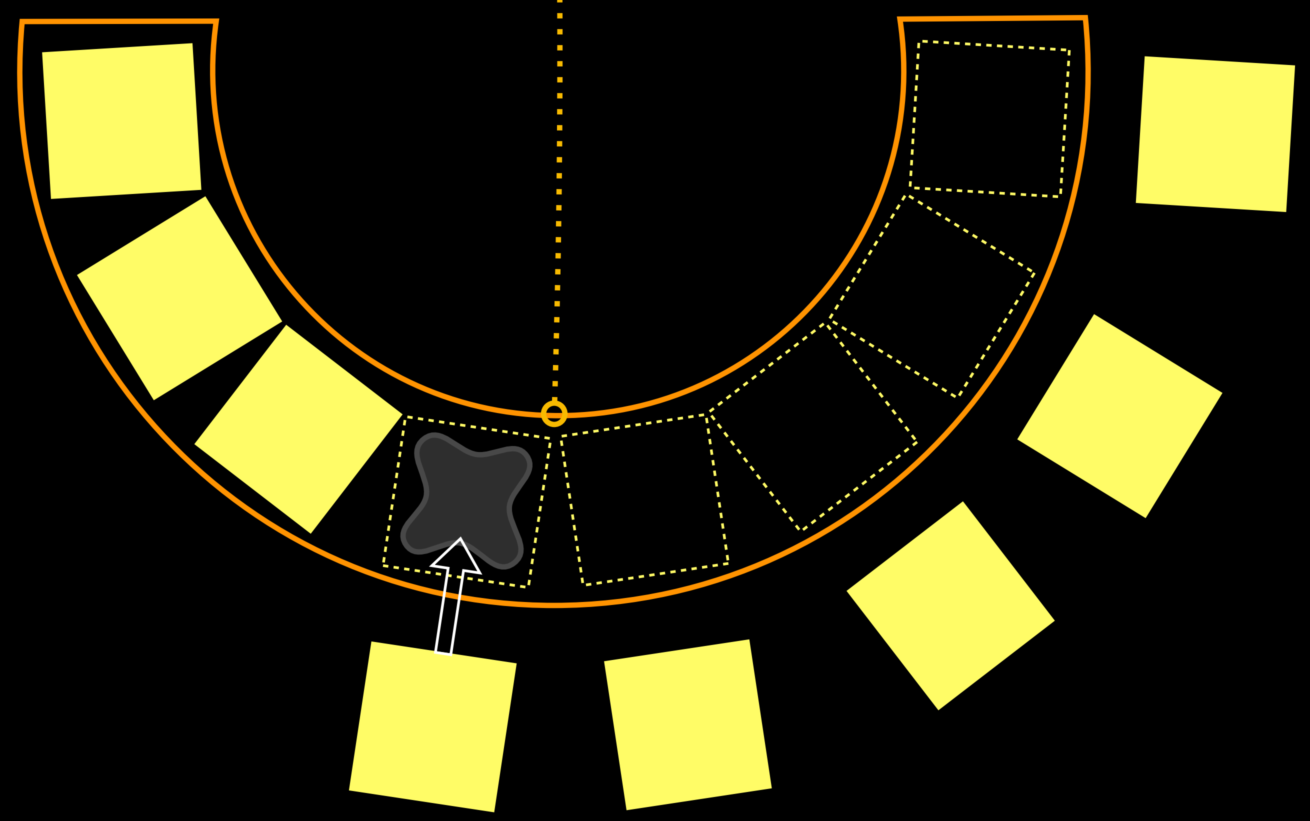
Prologue: ITk Pixels and Oxford



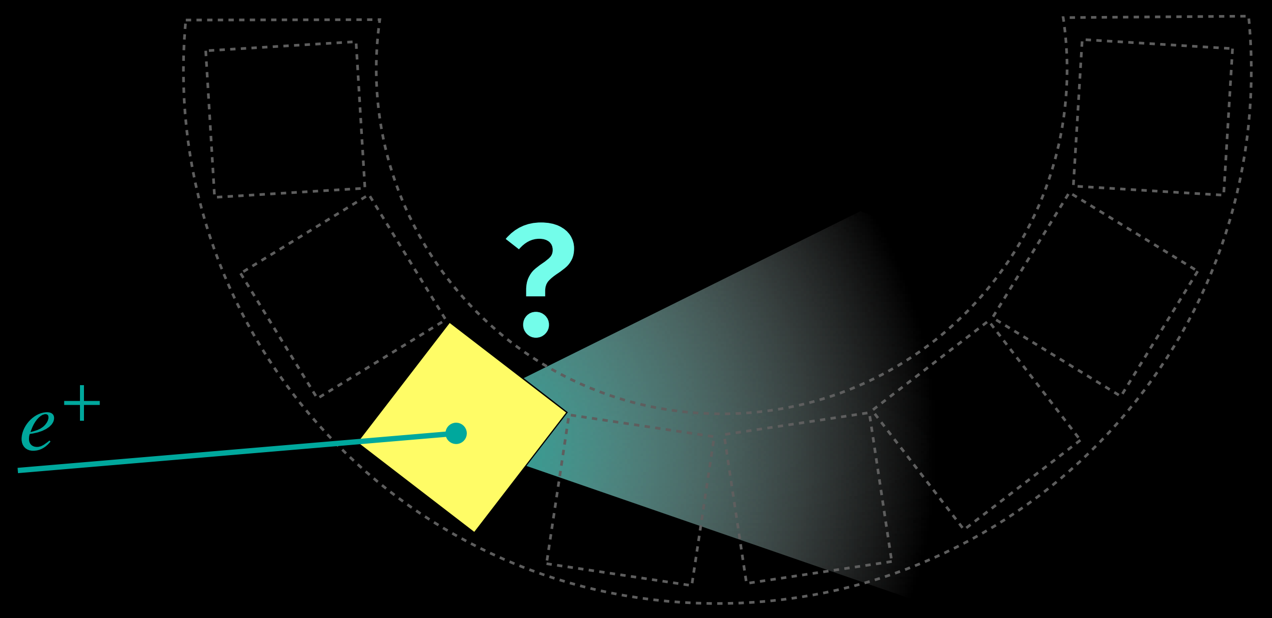
Step 2: Testing the ITk



Step 1: Building the ITk



Step 3: Measuring the ITk



Prologue: ITk Pixels and Oxford

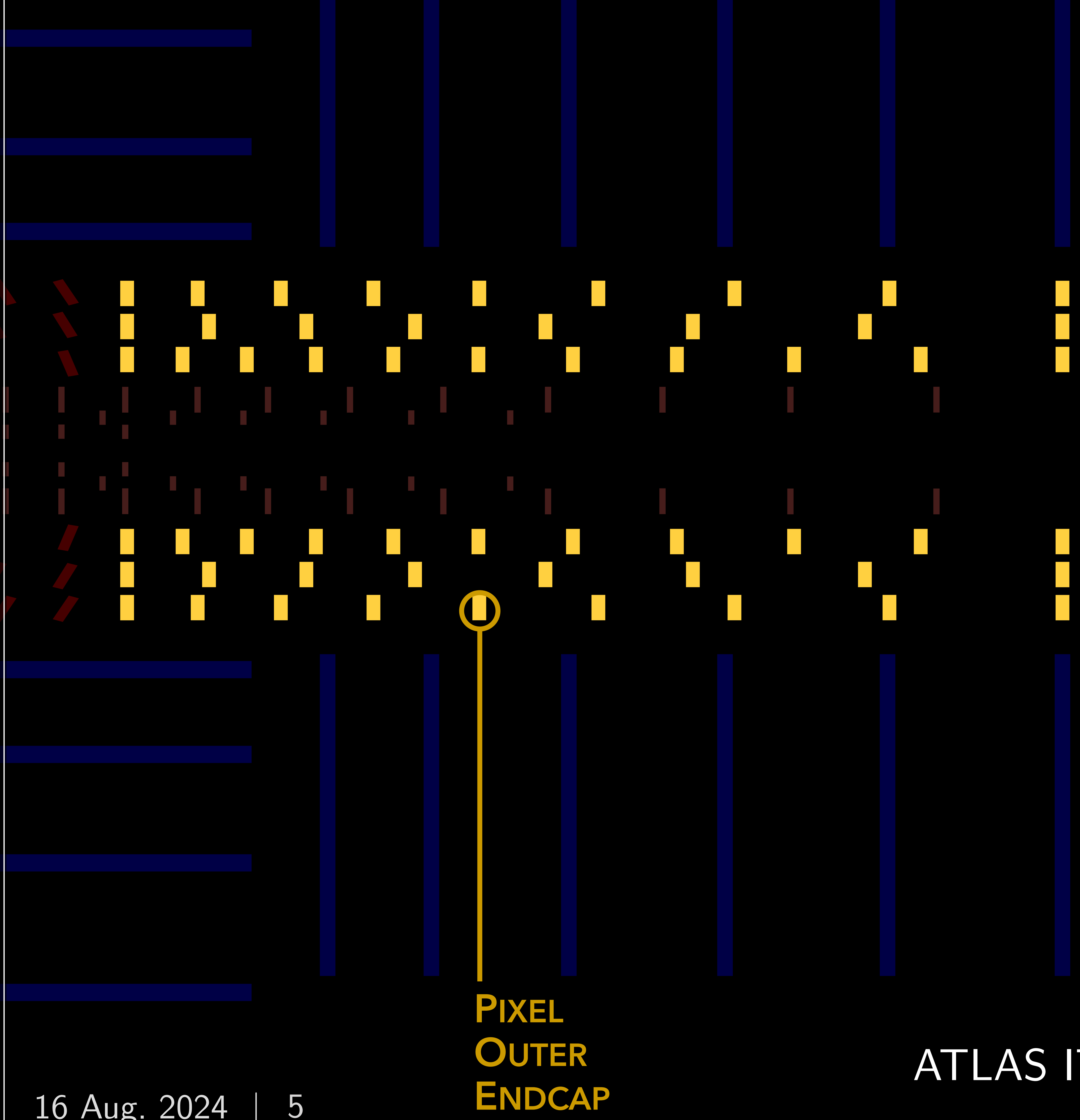
The ITk Upgrade

Outer Endcap

- Three radial layers, 8-11 disks each, covering outer forward region along beam pipe

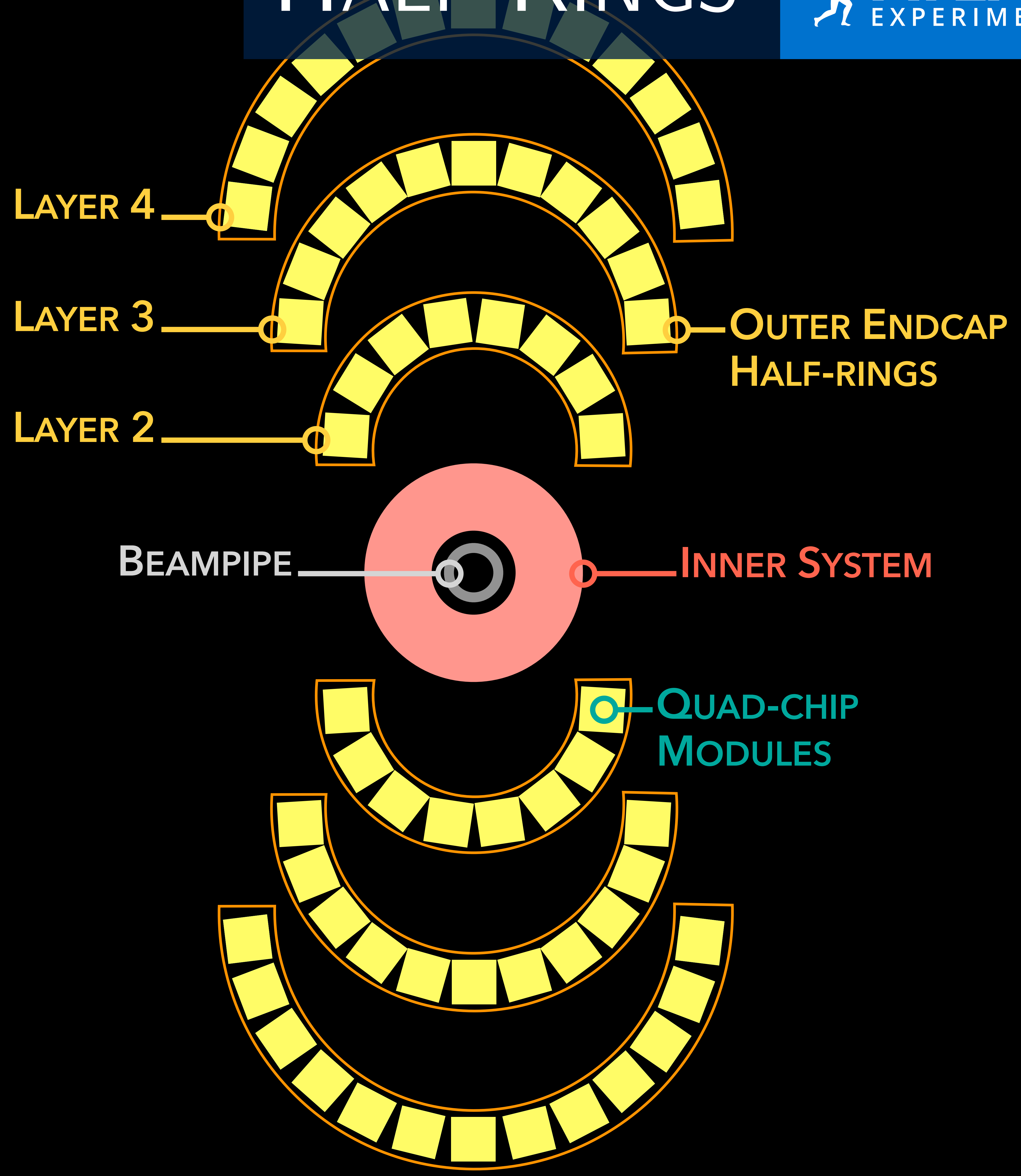
- One endcap will be built in the UK, the other in Italy
  - Construction split between four total **ring-loading sites**, and many **module production sites**

- Endcaps built as half-rings, then assembled into half-shells before integration at CERN SR1 laboratory



Half-Rings

- Each half-ring consists of 8-13 quad modules per side, plus services
  - Both sides populated for 100% coverage
- **OPMD** at Oxford is involved in both **quad module construction** *and* **half-ring loading**, a unique position
- OPMD focuses on automated, reliable, repeatable production processes using a **robotic gantry system**
- In addition, a comprehensive suite of QA/QC tests for modules and rings is performed post-construction

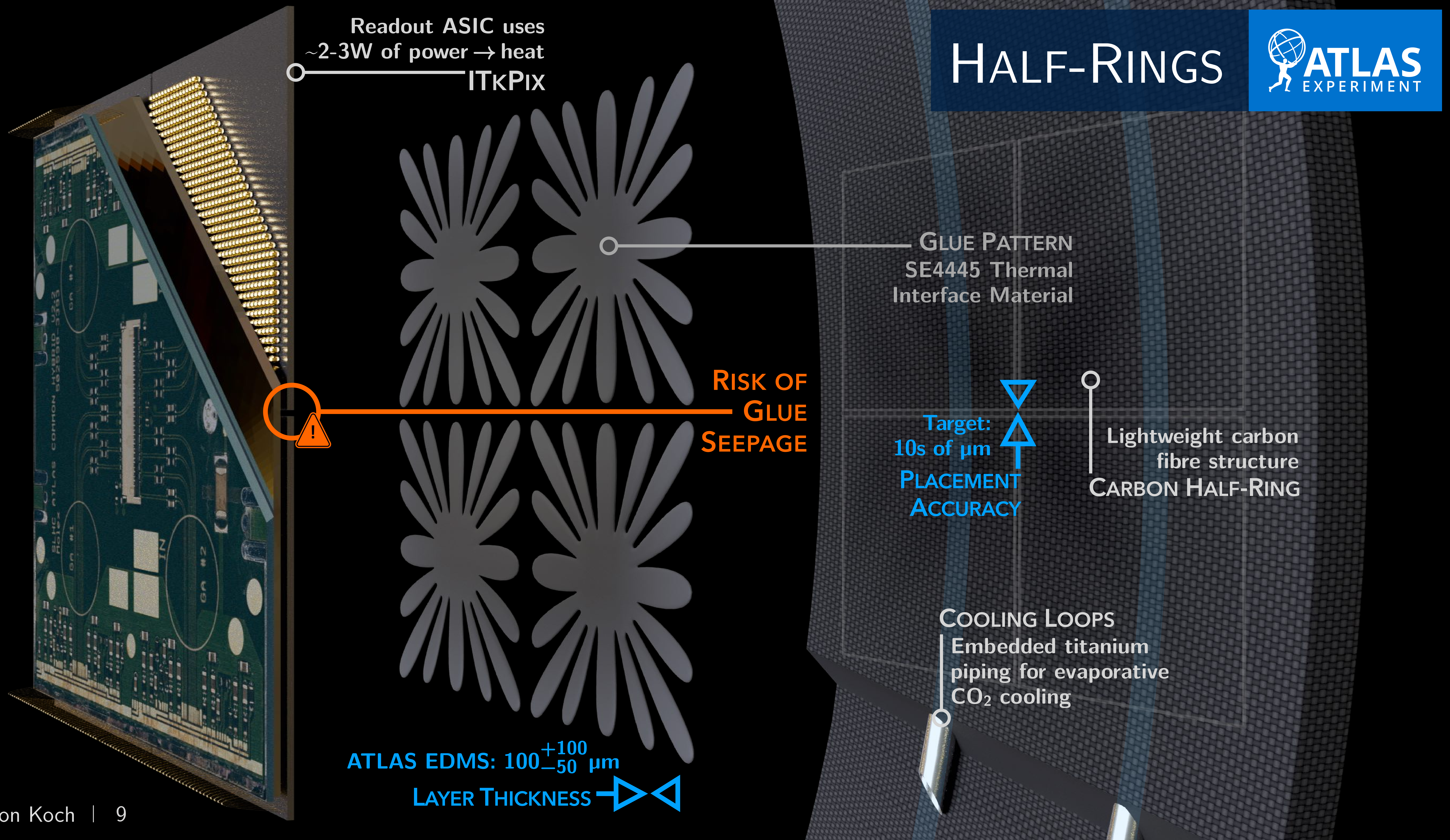


Half-Rings


Wirebonds
Readout ASIC
ITkPix
Glue
Sensor
Bump Bonds
Flex PCB
Module
ATLAS
EXPERIMENT
Carbon Half-Ring
Cooling
Local Support

Step 1: Building The ITk

Half-Rings



Readout ASIC uses
~2-3W of power → heat
ITkPix
Glue Pattern
SE4445 Thermal
Interface Material
Risk of
Glue
Seepage
Target:
10s of μm
Placement
Accuracy
Lightweight carbon
fibre structure
Carbon Half-Ring
Cooling Loops
Embedded titanium
piping for evaporative
CO_2 cooling
ATLAS EDMS: 100^{+100}_{-50} μm
Layer Thickness

GLUE DEPOSITION

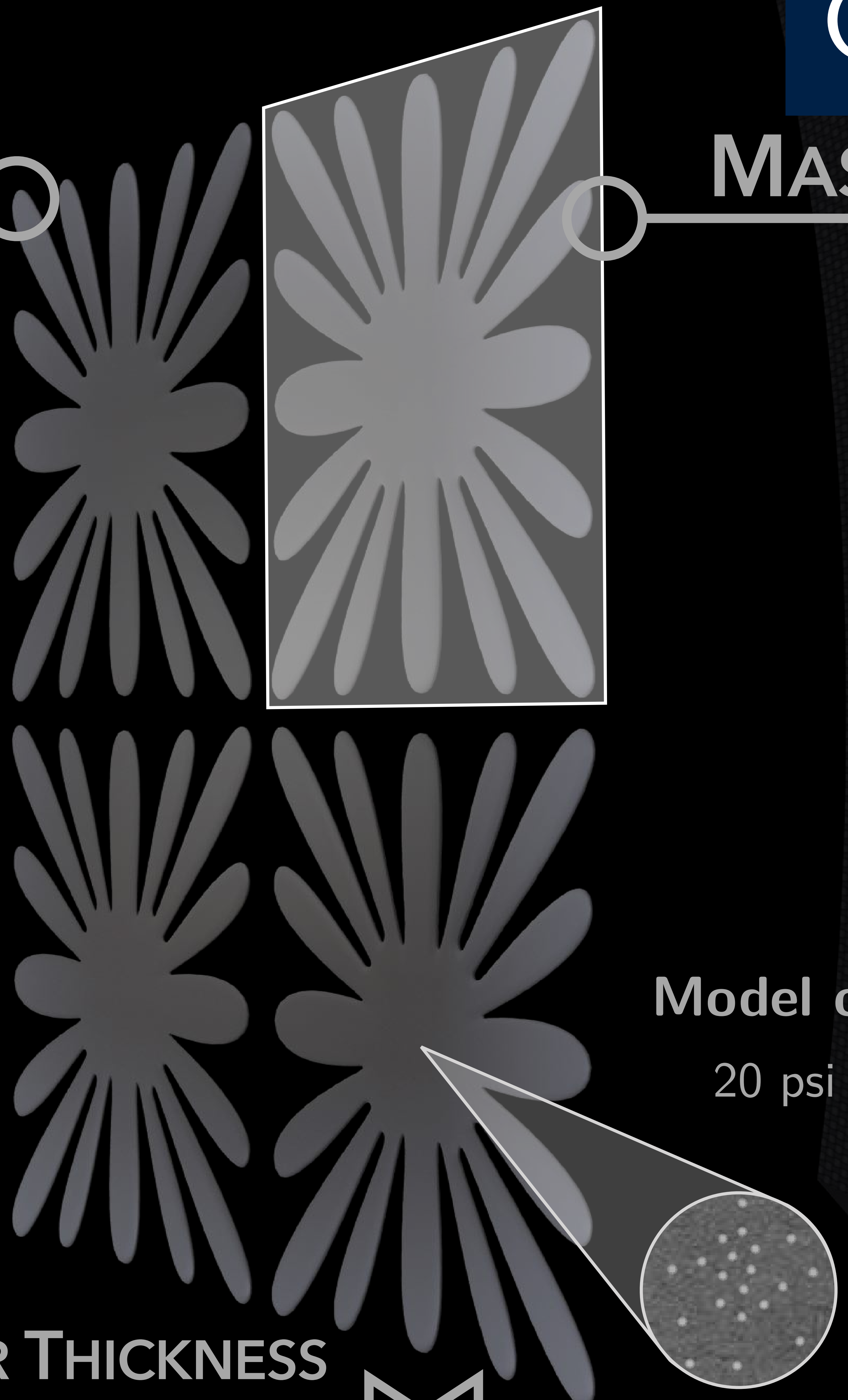
ATLAS EXPERIMENT

LINEAR MODEL FOR GLUE DEPOSITION

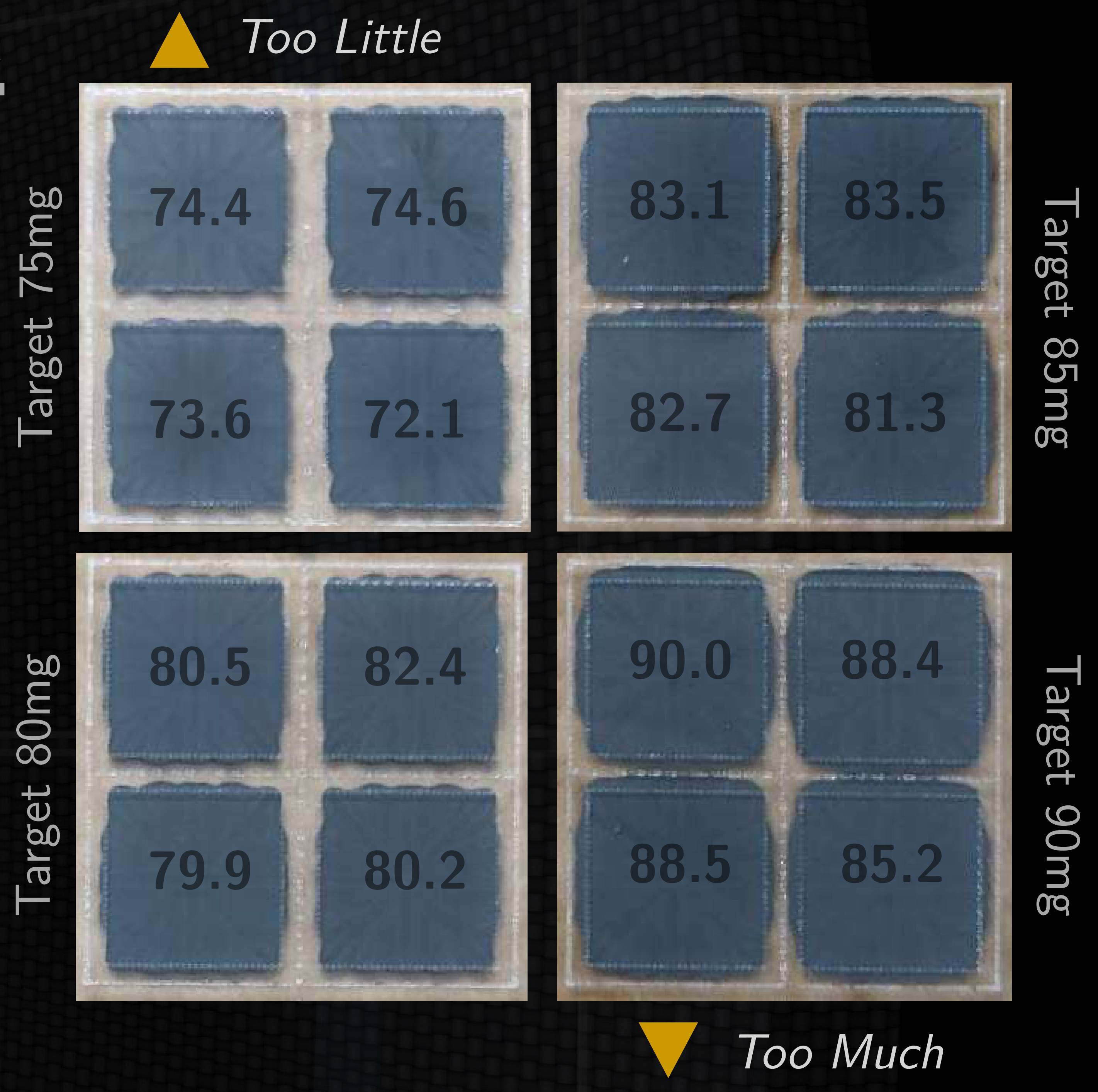
total line length, mass flow rate, robot line speed, target mass:

$$v = \frac{l\,f}{m}$$

flow rate change over time correction: $\frac{\partial v}{\partial t} \approx \frac{l\,\frac{\partial f}{\partial t}}{m}$

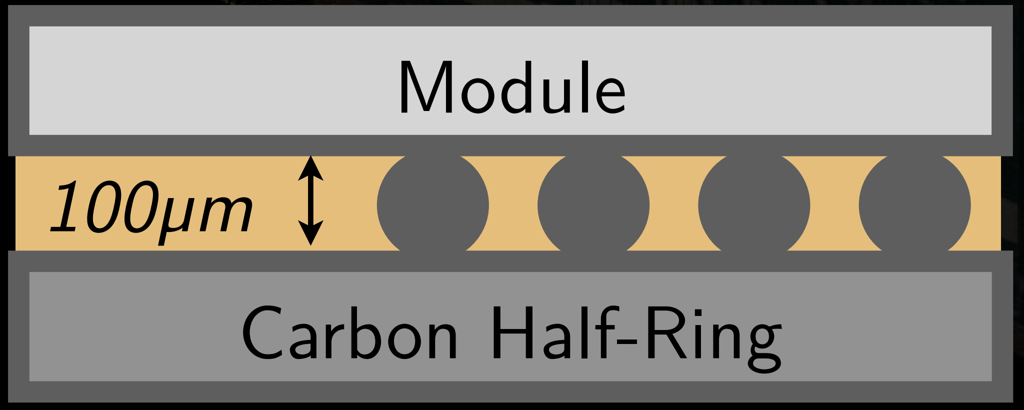


MASS VS AREA



Model only valid in certain phase space:

20 psi ≤ p ≤ 30 psi, 23 AWG needle | other settings



LAYER THICKNESS VIA SPACER SPHERES

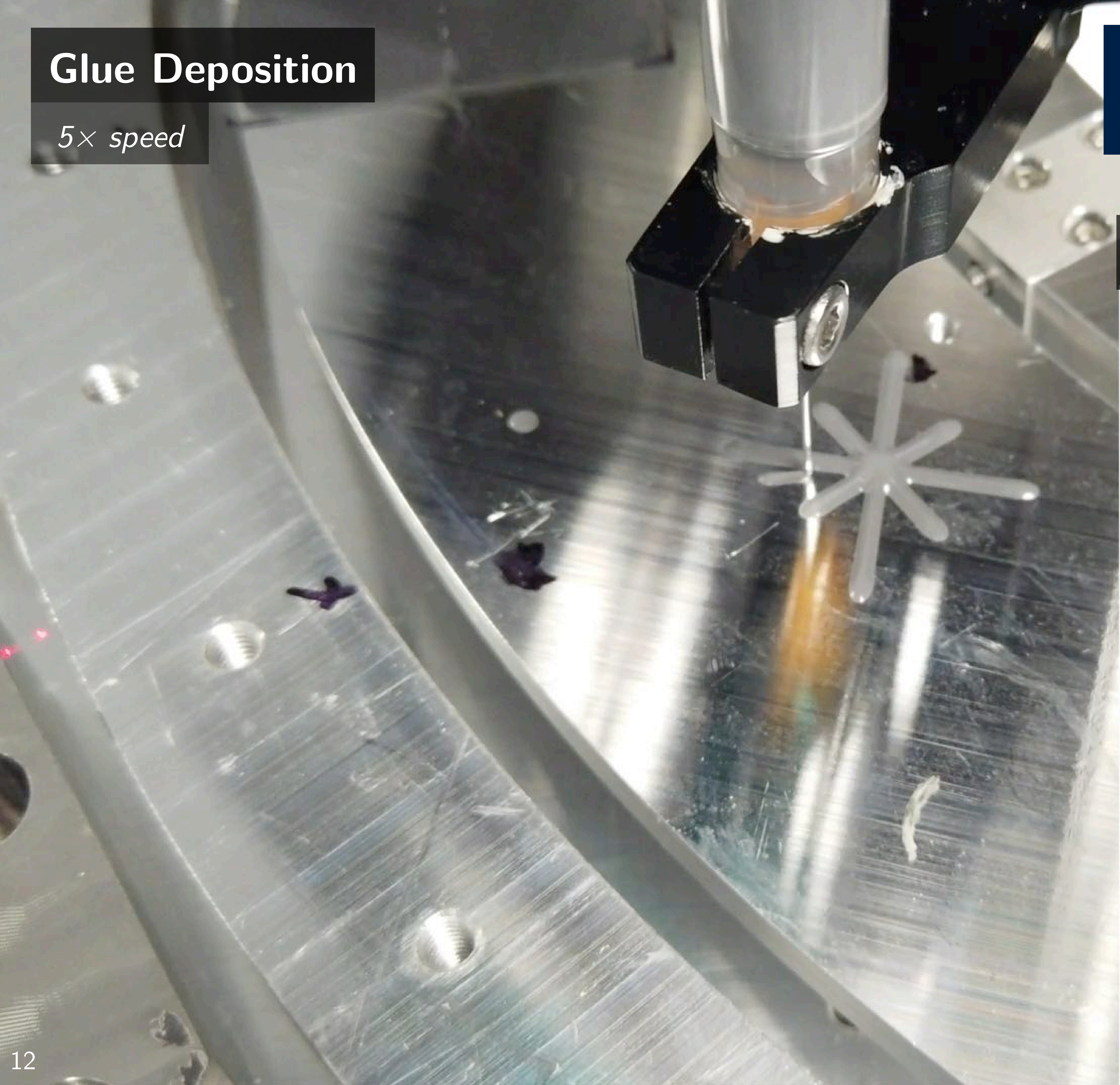
0.25% w/w, [SLAC, RAL]

Loading Gantry

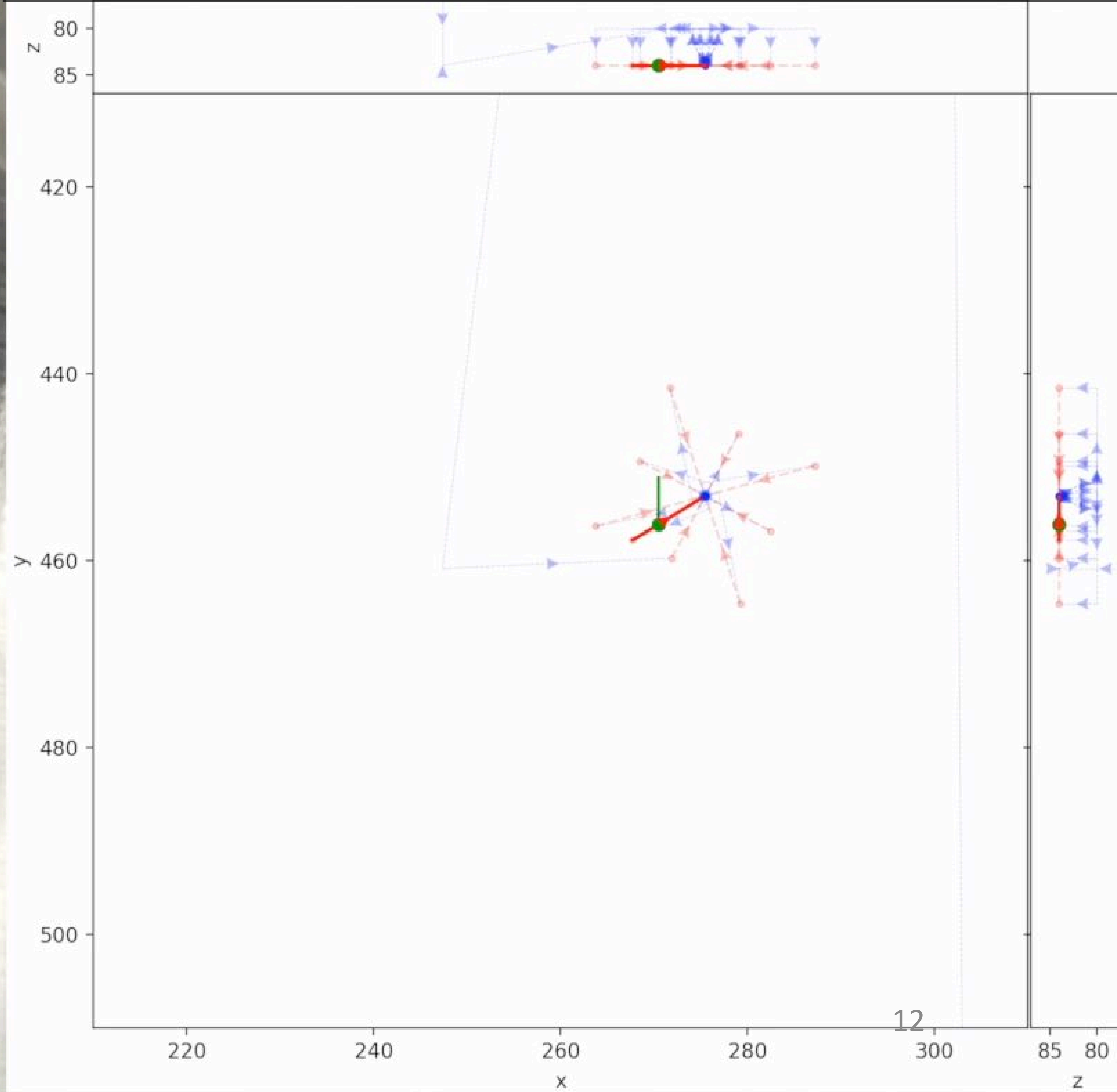
Glue Deposition

Glue Deposition

5× speed



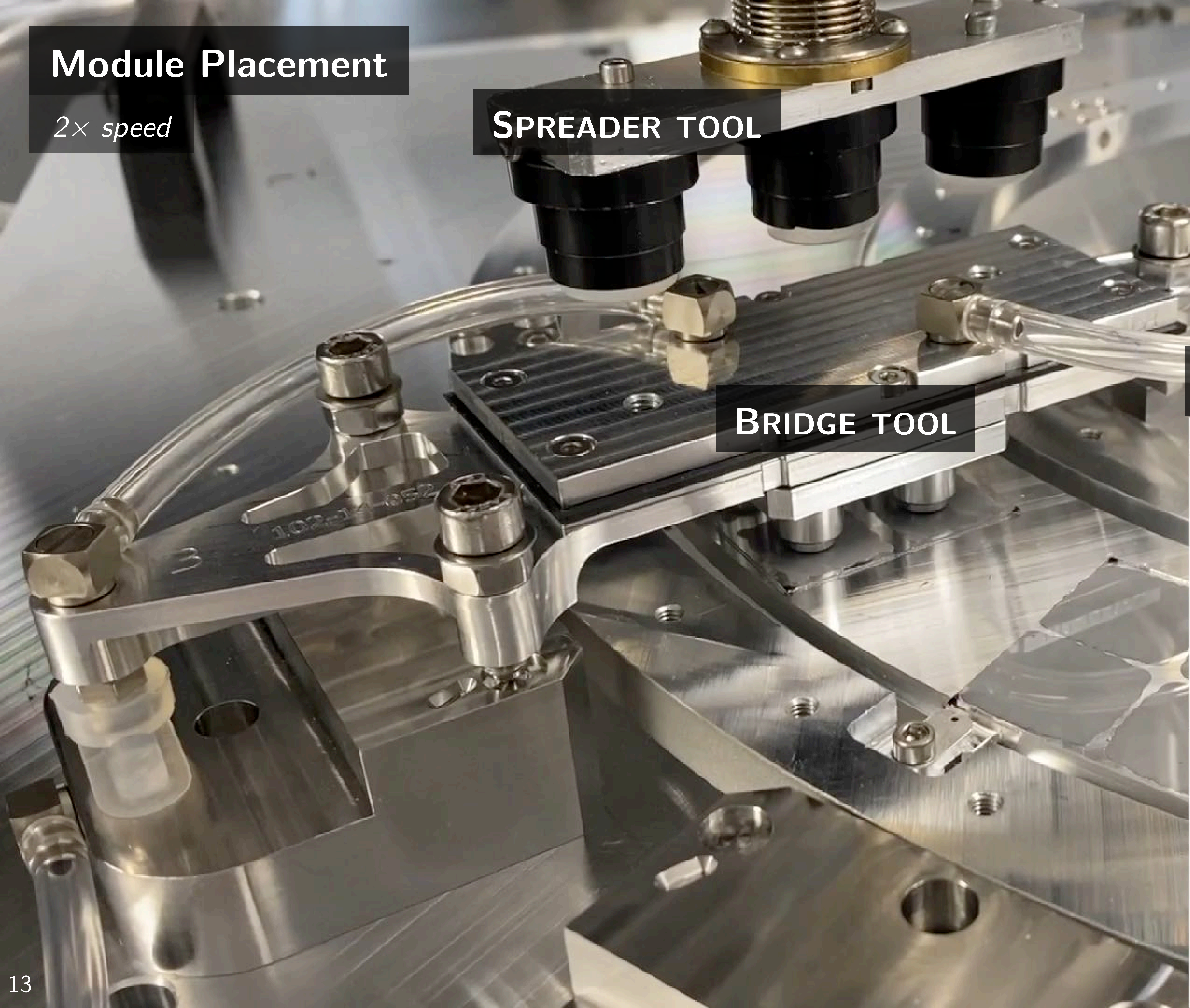
Gantry Program Visualiser



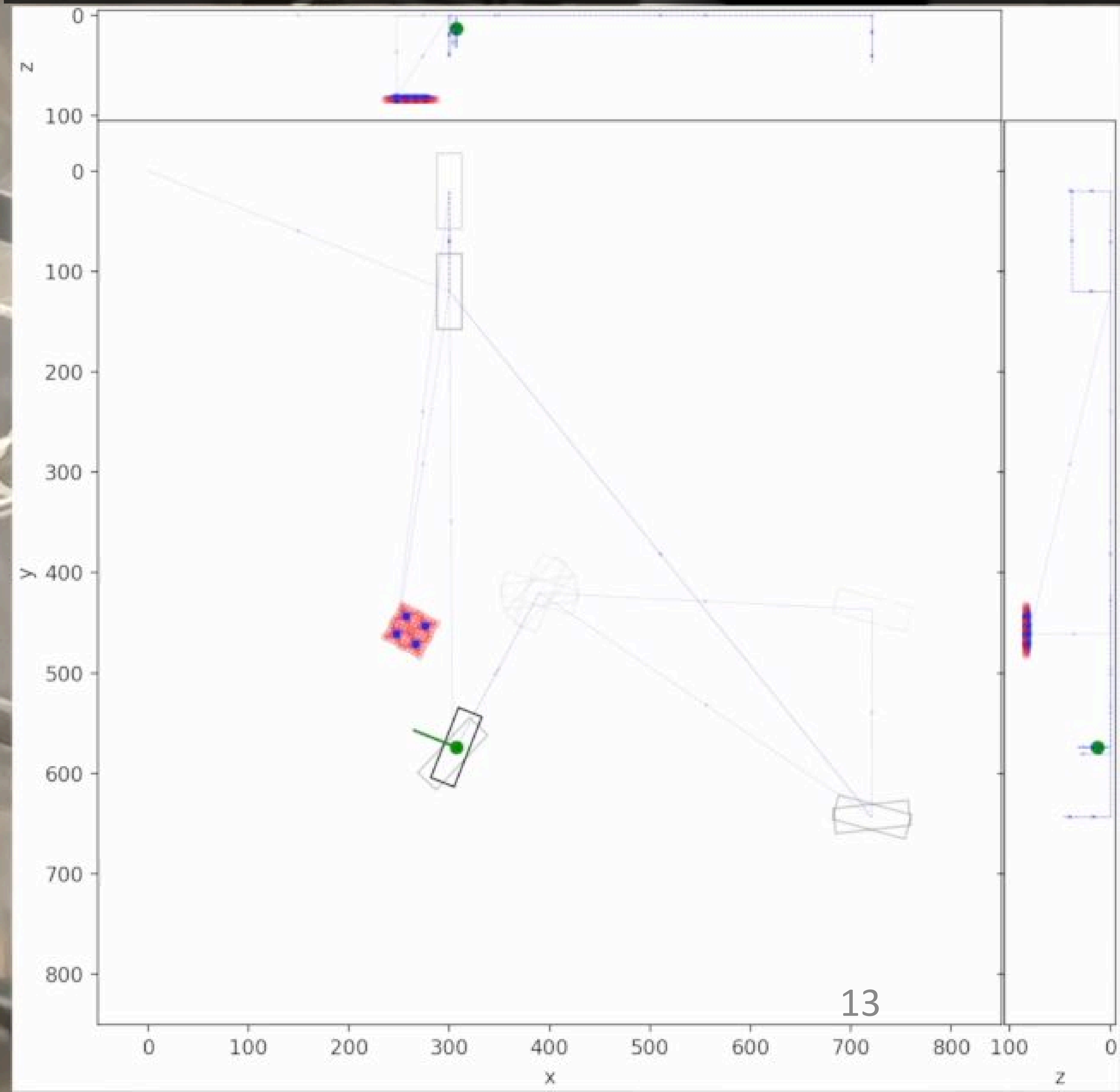
Module Placement

2× speed

Loading



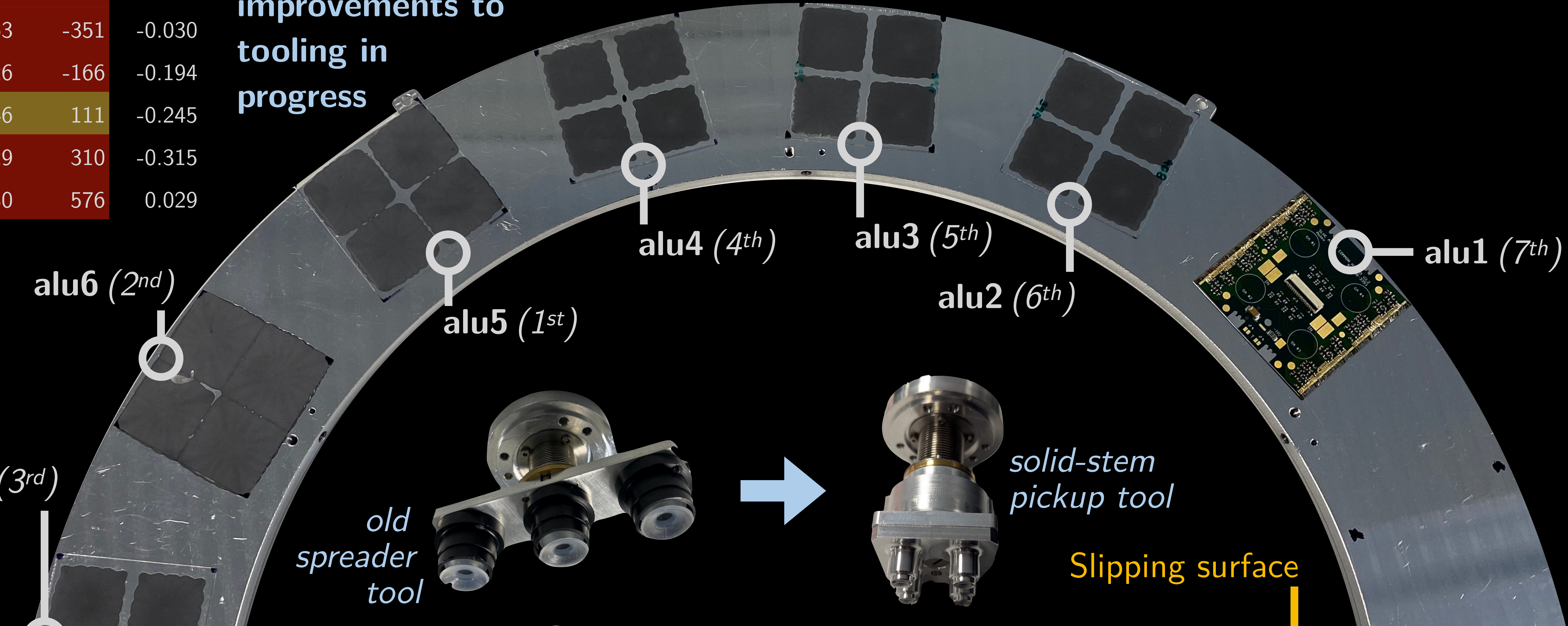
Gantry Program Visualiser

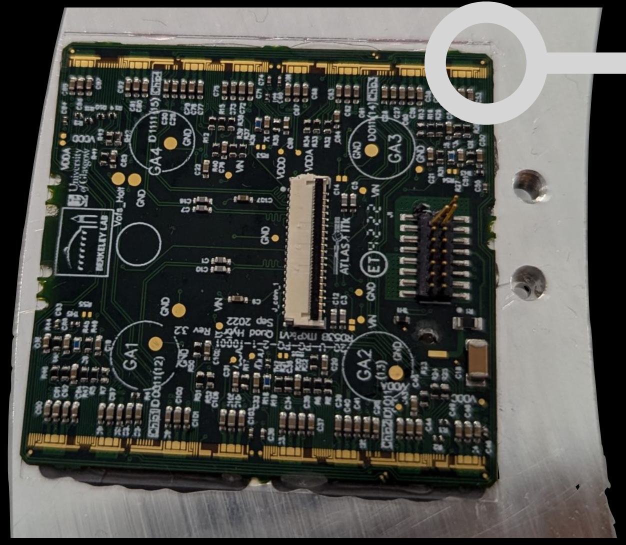


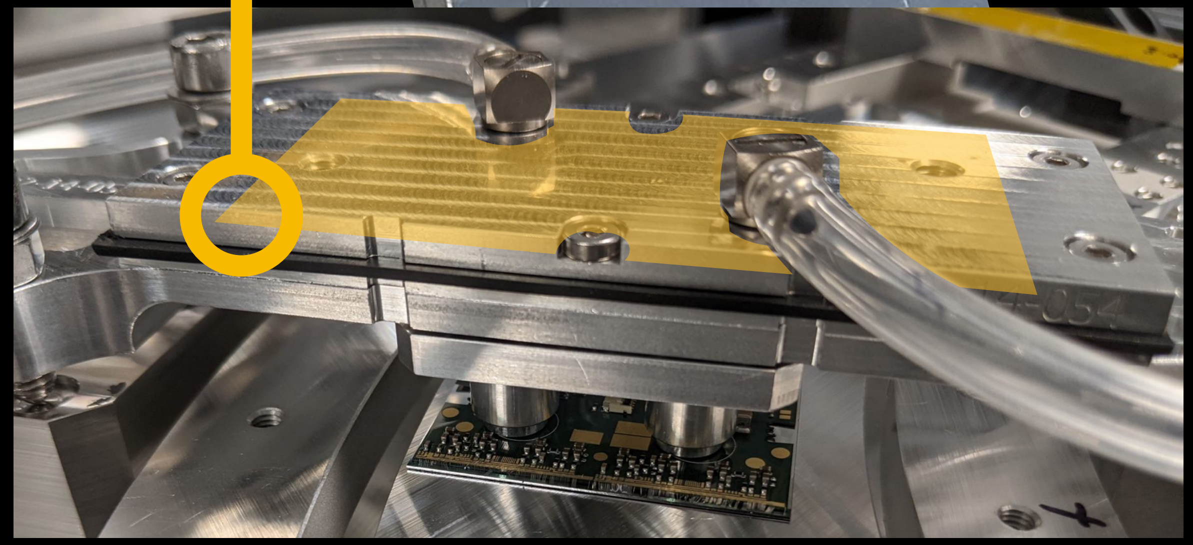
Initial Loading Tests

	Offset from Nominal		
	X (µm)	Y (µm)	Phi (°)
alu5	-2085	-102	89.733
alu6	-743	-694	0.217
alu7	-1163	-351	-0.030
alu4	-126	-166	-0.194
alu3	-46	111	-0.245
alu2	-229	310	-0.315
alu1	-130	576	0.029

Issues with *slippage* in tooling identified, issues identified and improvements to tooling in progress

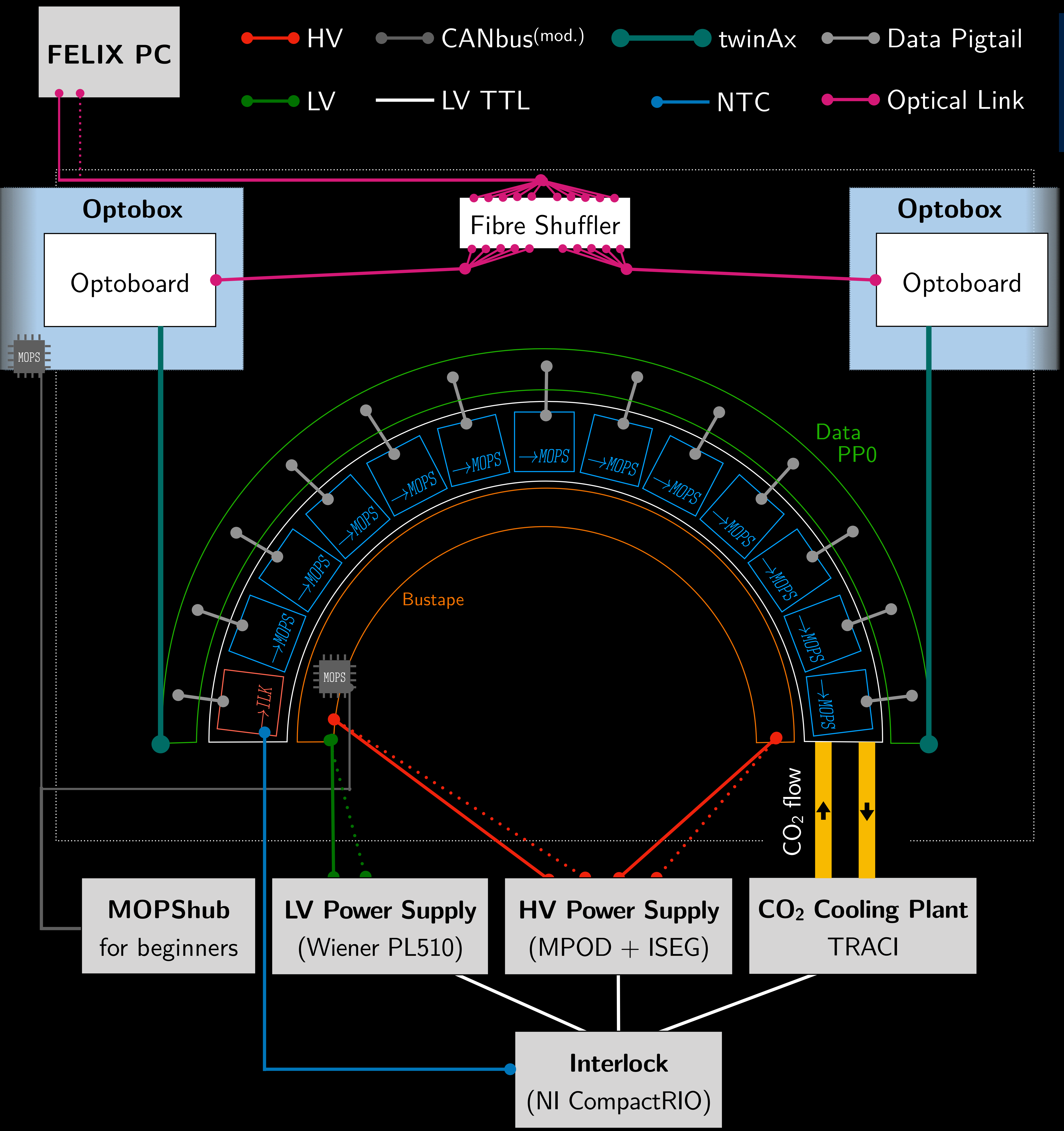






New tooling: sub-20um accuracy in systematic dry placements, ~50um in ITkPix mech. dummy placement

Step 2: Testing The ITk



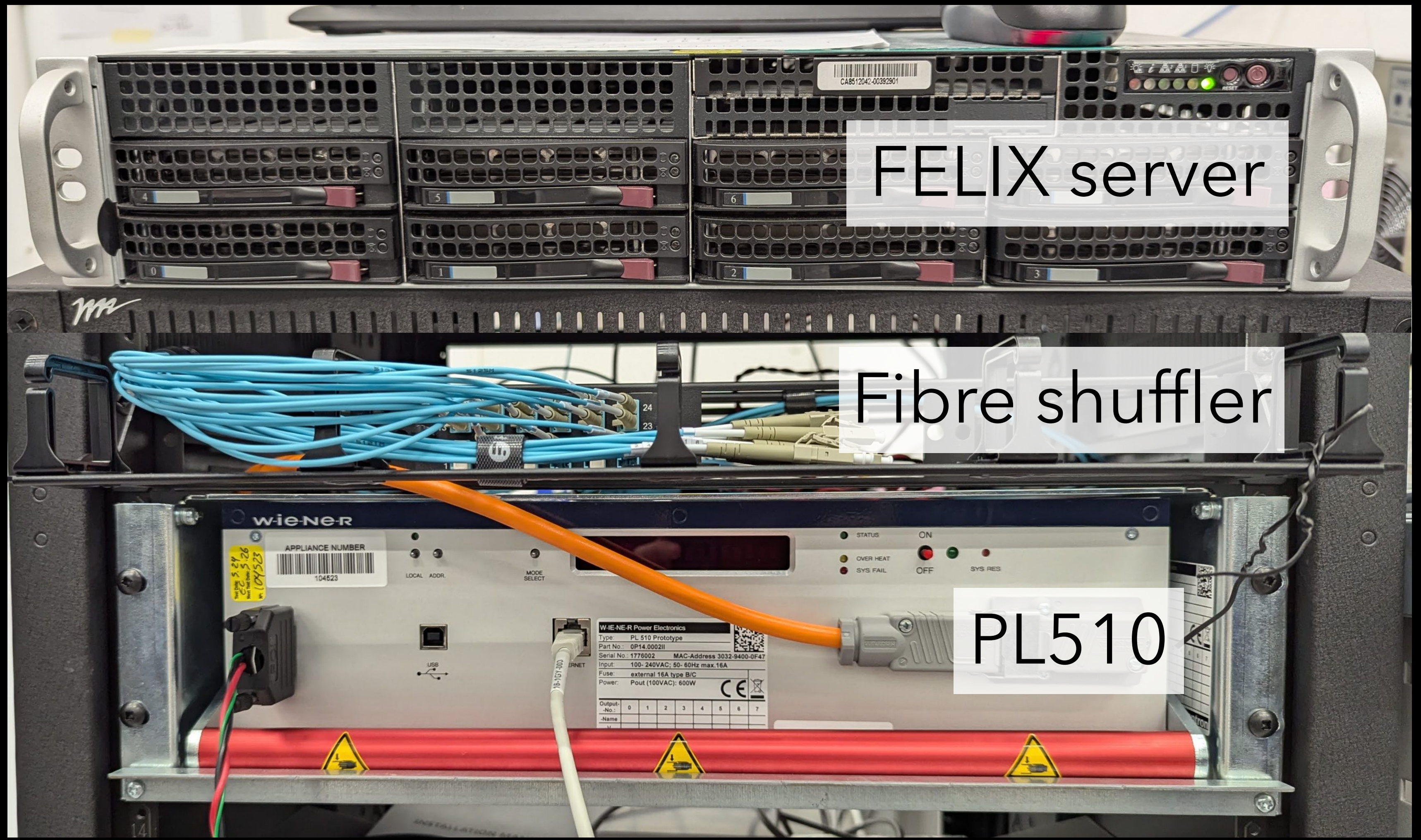
Half-Ring Testing

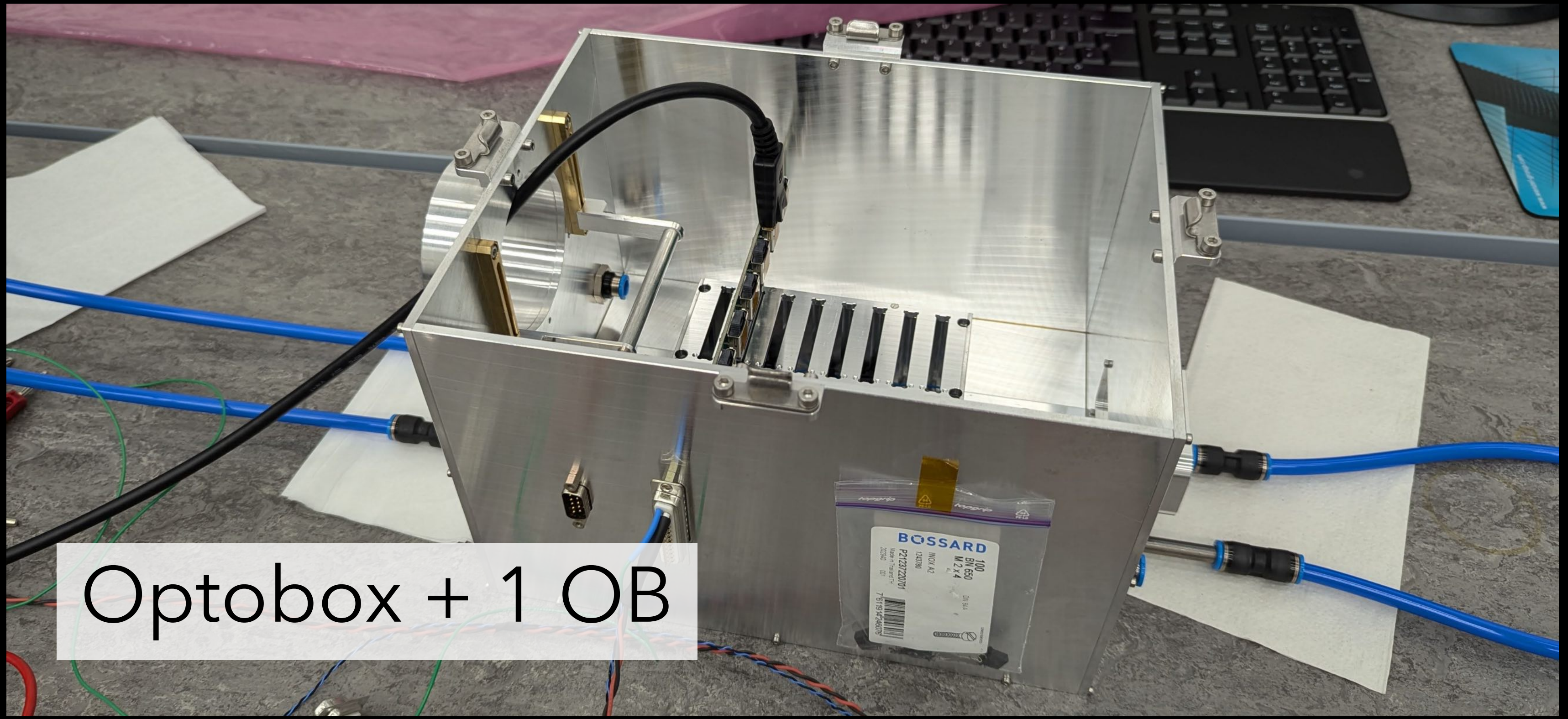
- We use the **FELIX optical readout system**, in a setup similar to that used for system tests in SR1 at CERN
- Other challenges include cooling ***O***(20) modules - requires CO_2 plant
- Optical readout elements have so far been tested with a single module and adapter cards

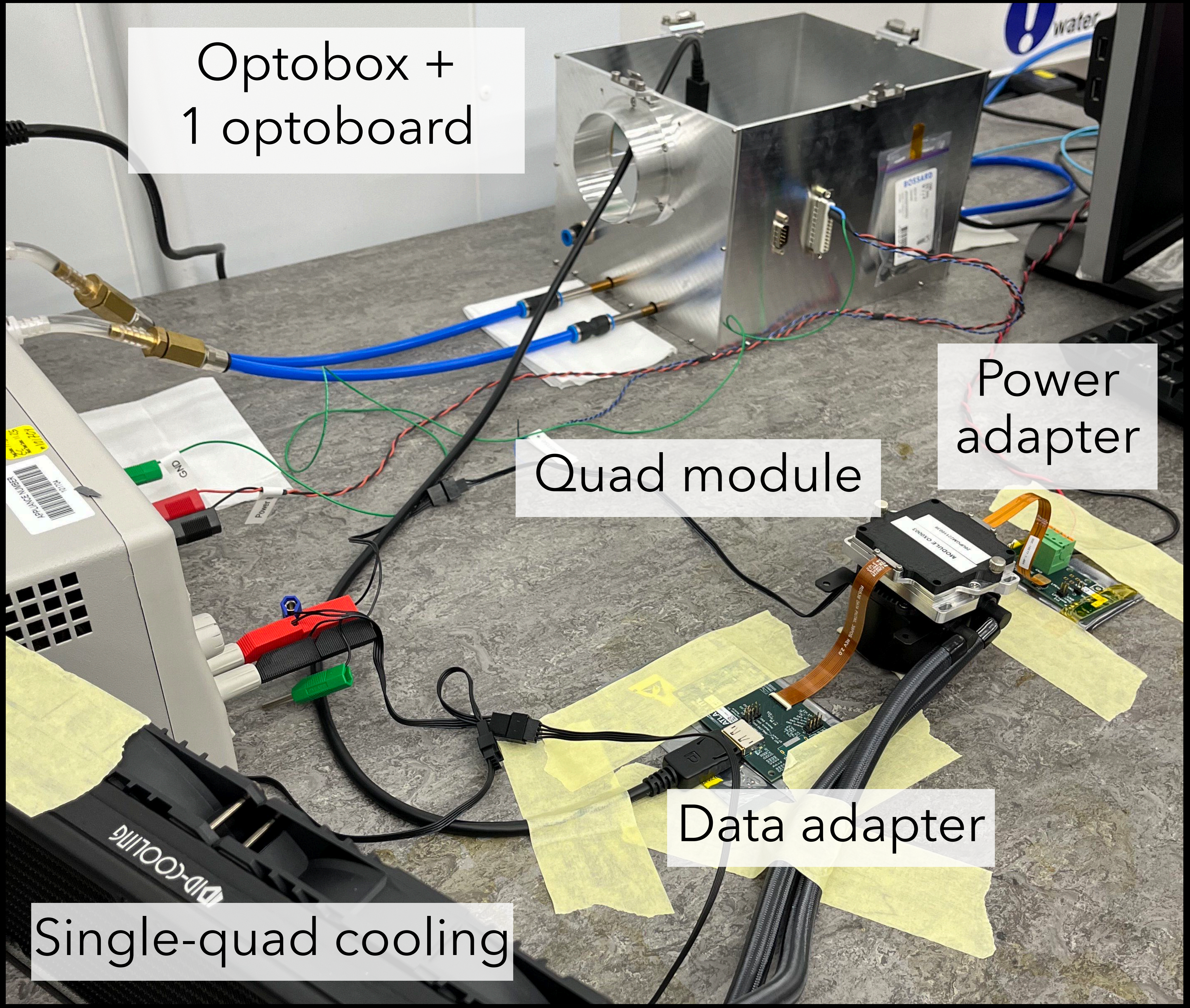
Half-Ring Testing

ATLAS EXPERIMENT

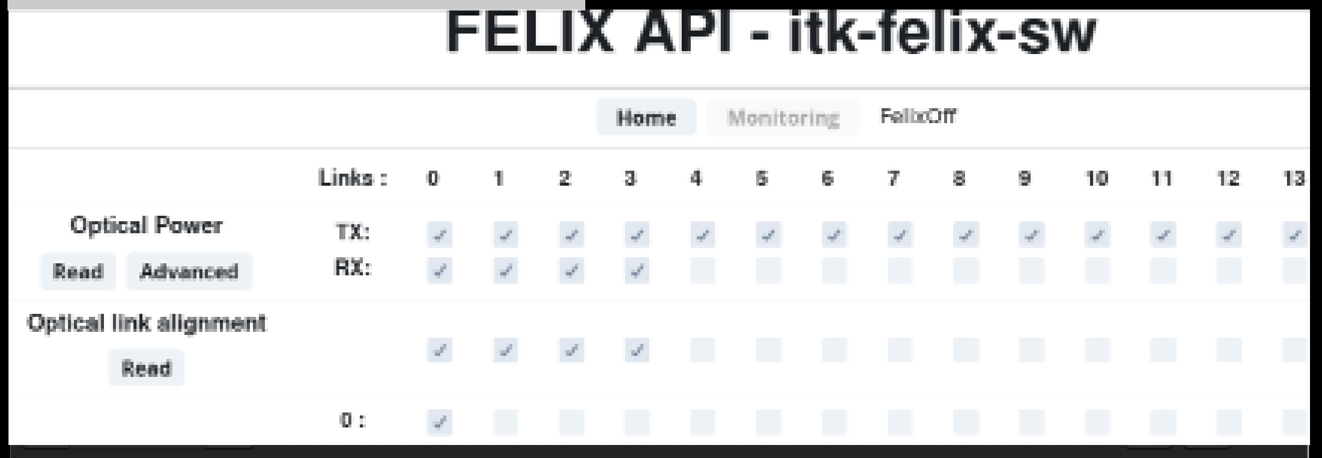
- We have demonstrated readout of an ITkPix v1.1 Quad,
- and of several MOPS monitoring chips (v1 and v2), including one mounted on a bustape,
- ...but still waiting for parts to build a first ring

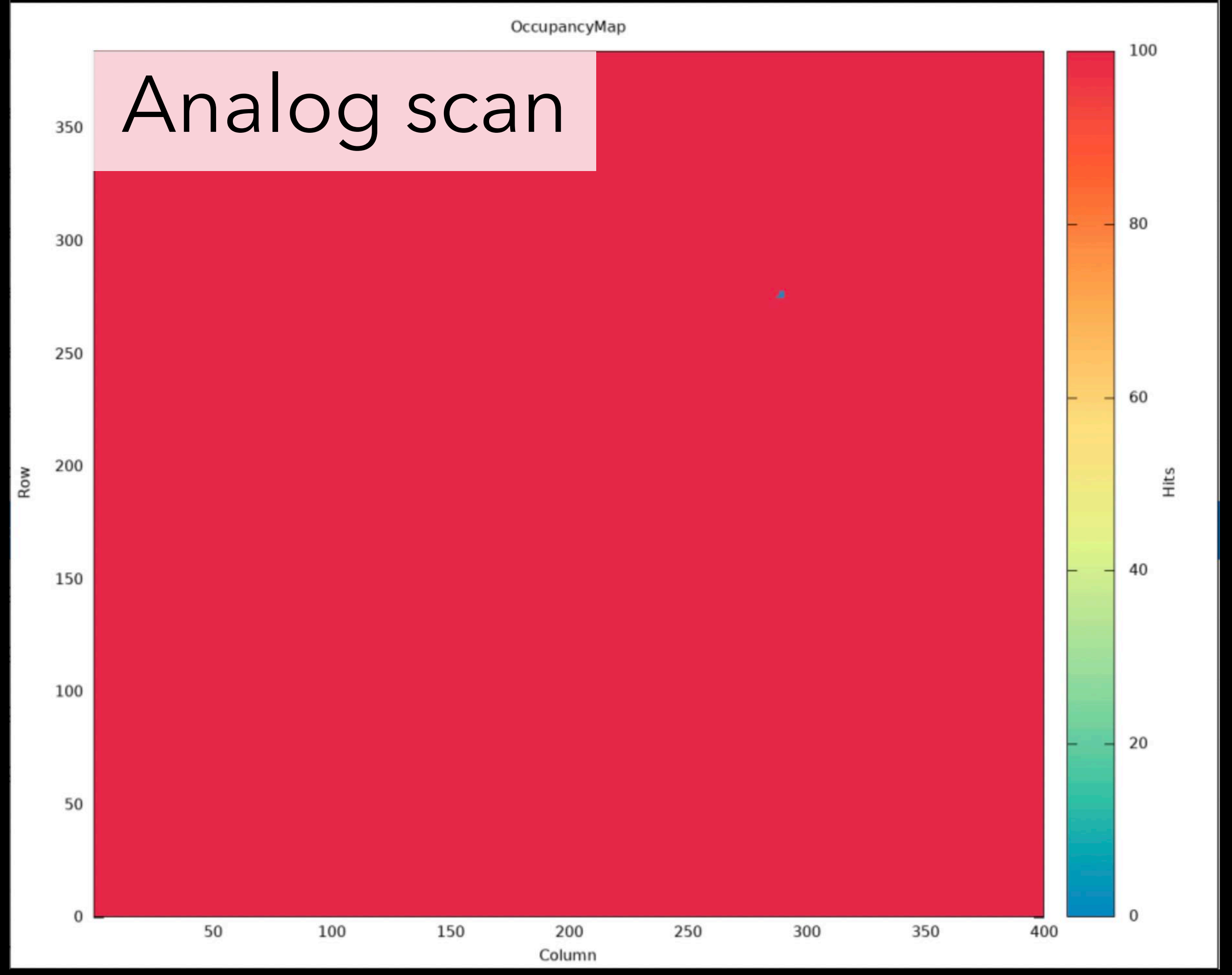






Microservices

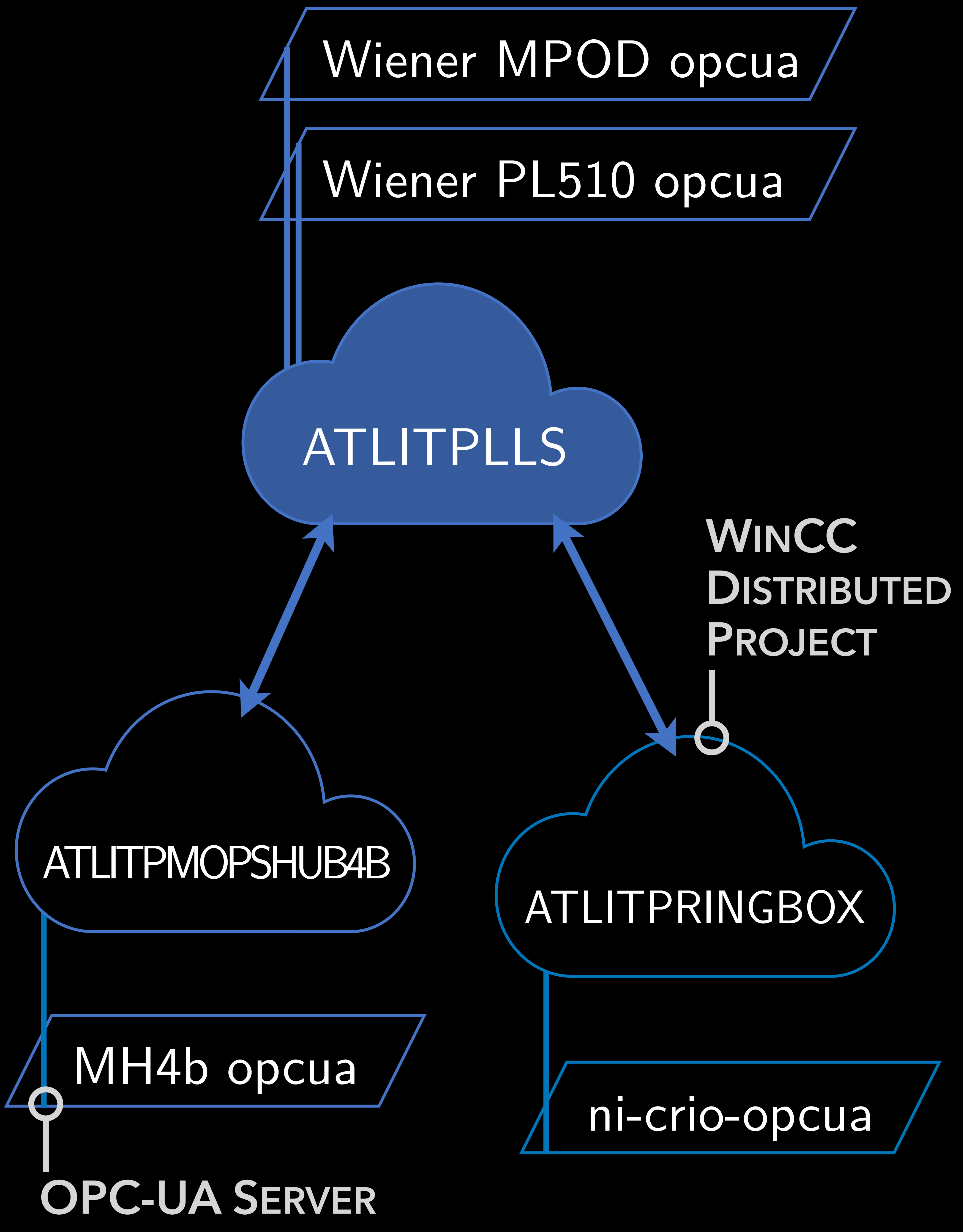


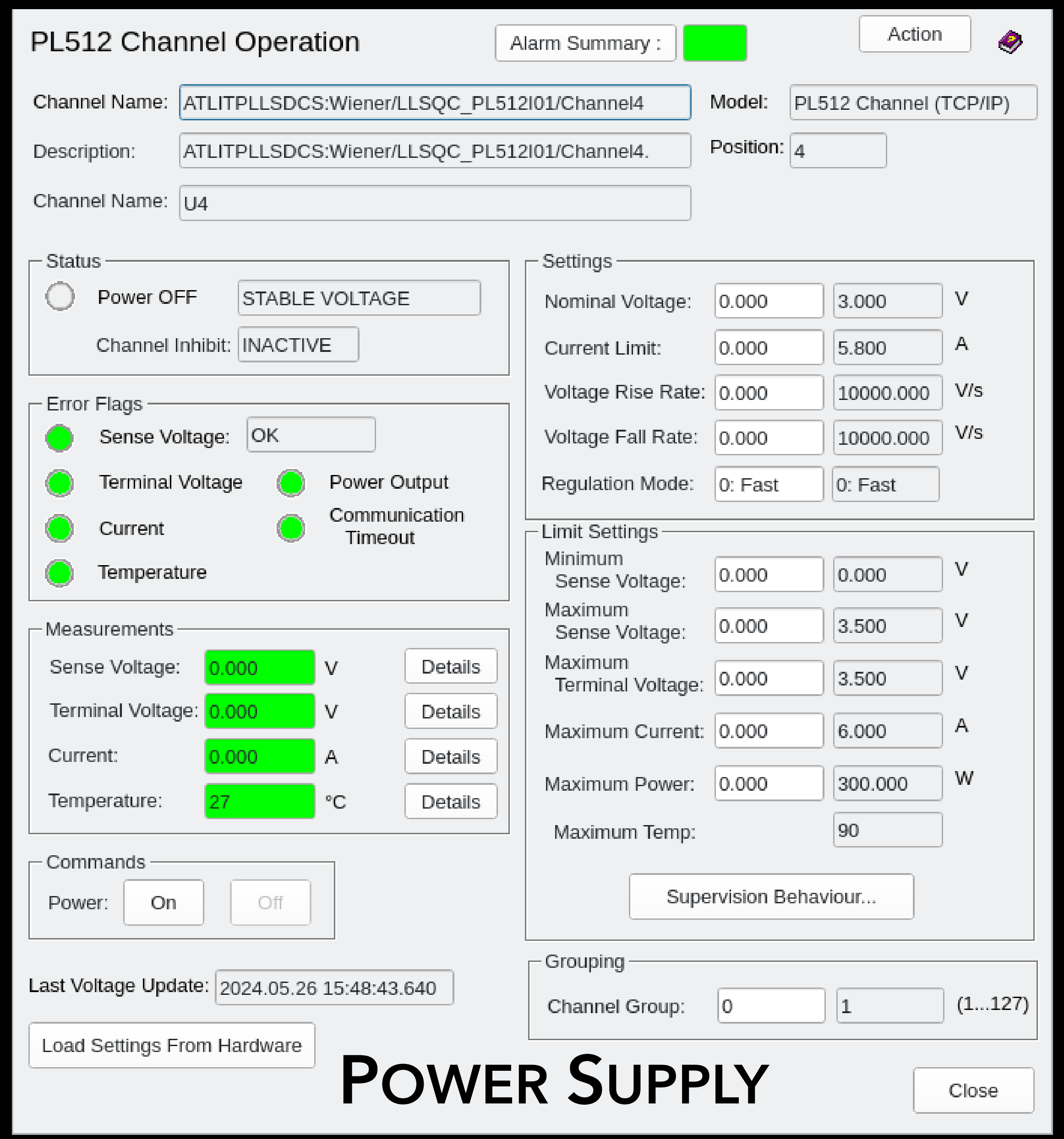


Detector Control System

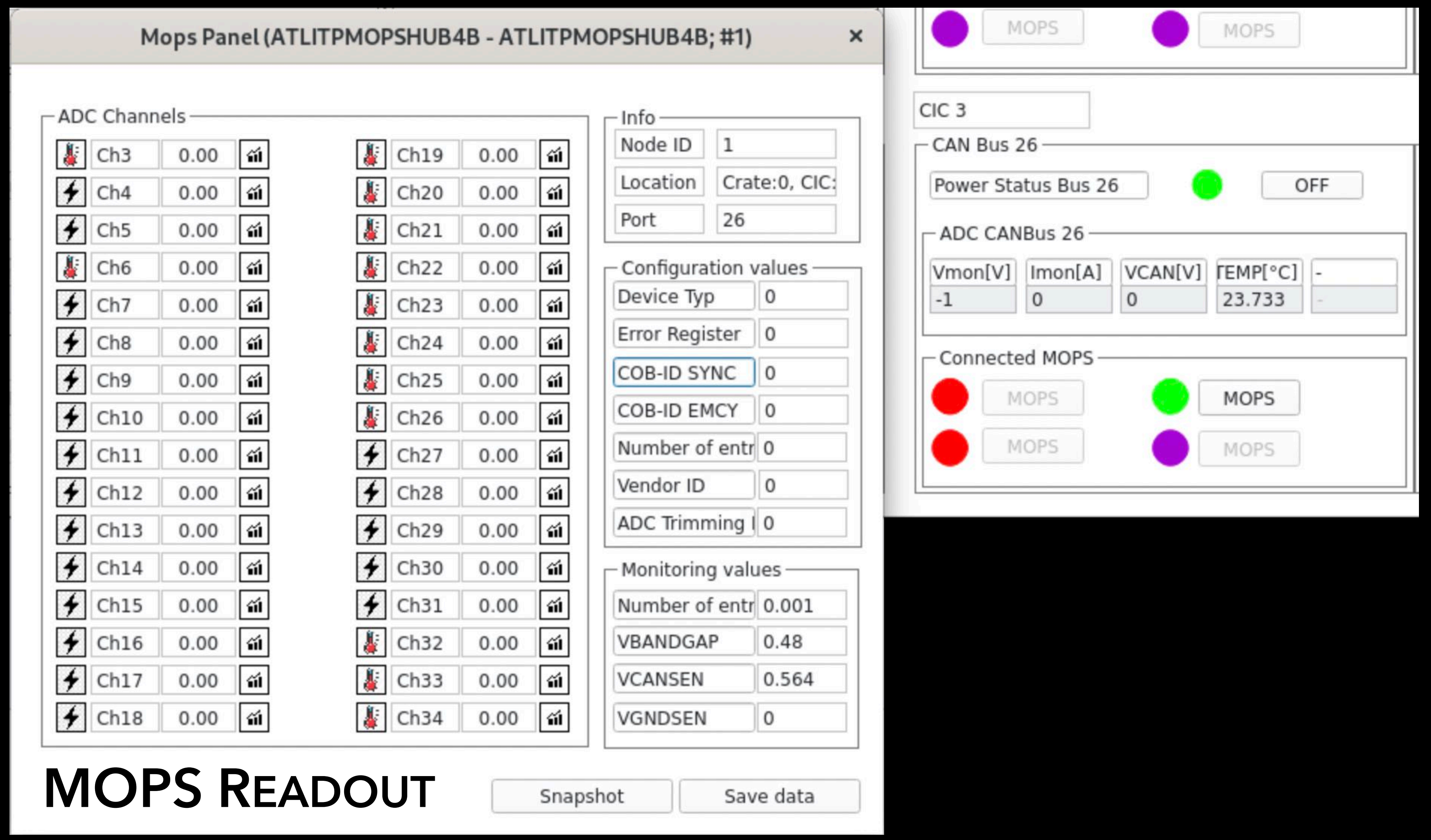
ATLAS EXPERIMENT

- WinCC-OA is the DCS solution used in the ATLAS control room, and the SR1 system test at CERN
  - Power supply control and MOPS readout have been demonstrated, hardware interlock is in development
  - Will eventually commission full DCS scheme used in SR1 in Oxford for ring-testing setup





Power Supply



MOPS Readout

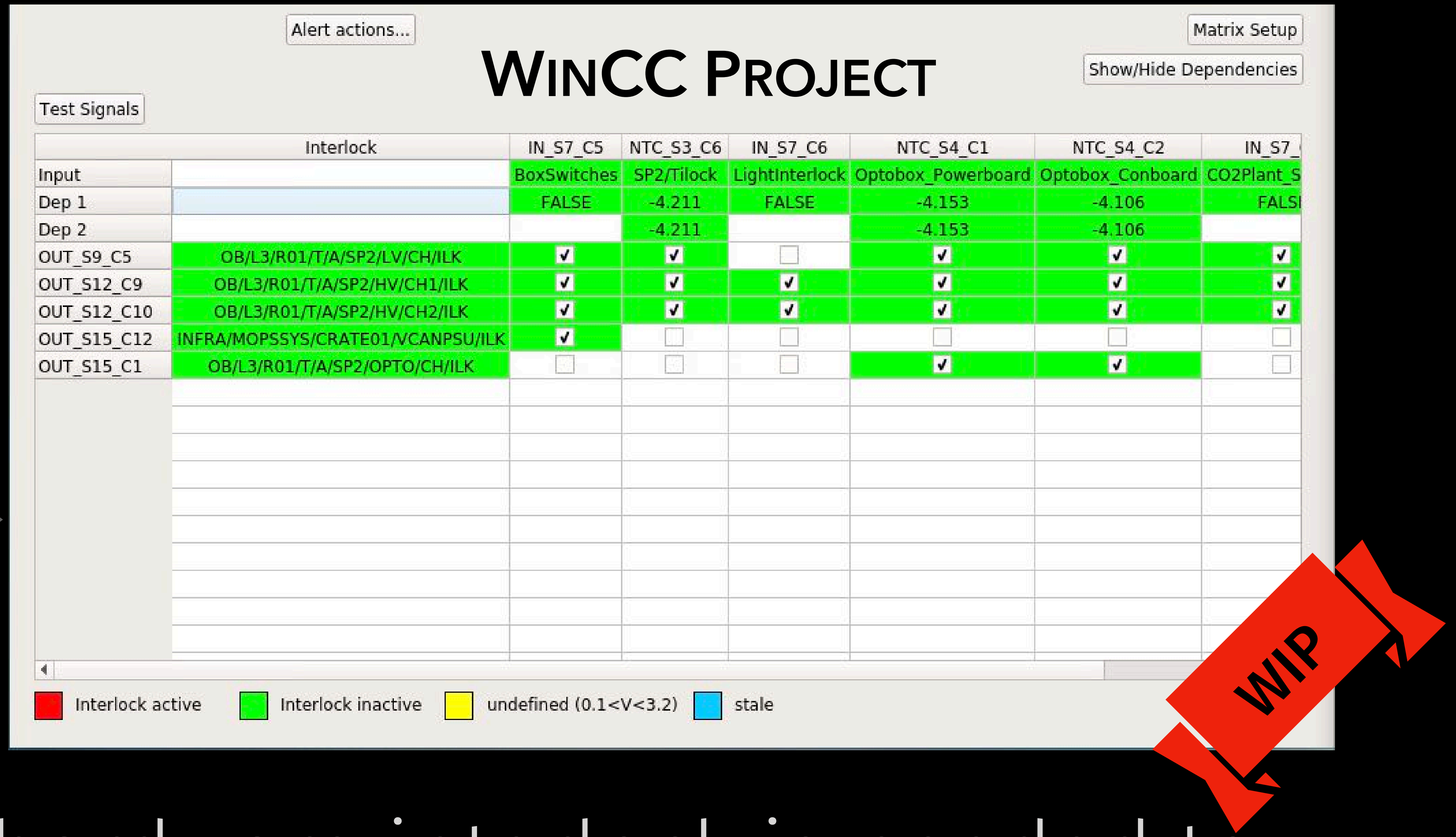
Interlock and Safety

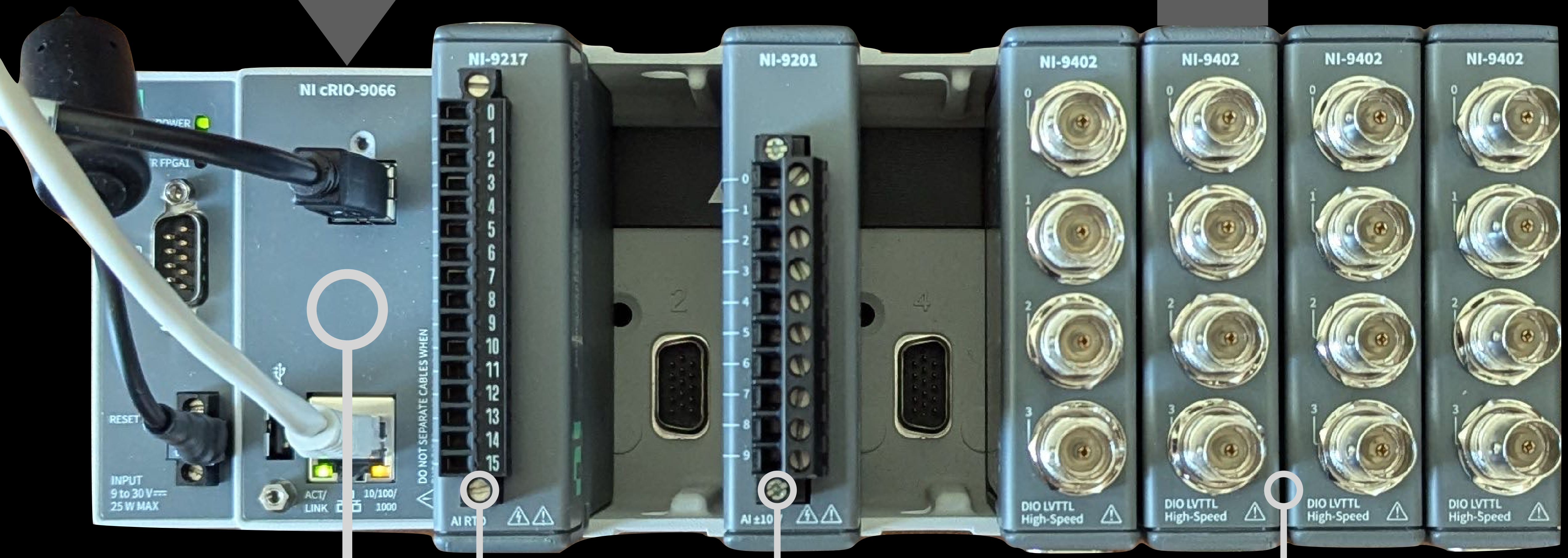
ATLAS EXPERIMENT

Interlock Matrix OX-EC-LLS v0.1 KEY: X: interlocked THRESHOLDS: SP NTCs: 40°C OPTO NTCs: 35°C Dewpoint: -40°C	cRIO Slot/Channel	SP1 LV PSU CH	SP1A HV PSU CH	SP1B HV PSU CH	SP2 LV PSU CH	SP2A HV PSU CH	SP2A LV PSU CH	OPTOBOX PSU GRP	MOPSH-CIC PSU GRP	TRACI Go-to-Warm
cRIO Slot/Channel		S3.1	S2.1	S2.2	S3.2	S2.3	S2.4	S3.3	S3.4	S4.1
SP1 NTC	S1.1	X	X	X						
SP2 NTC	S1.2				X	X	X			
OPTOB-CB NTC	S1.3	X	X	X	X	X	X	X		
OPTOB-PB NTC	S1.4	X	X	X	X	X	X	X		
- unused -	S1.5-8									
PT100 1	S5.1	X	X	X	X	X	X			X
PT100 2	S5.2	X	X	X	X	X	X			X
PT100 3	S5.3	X	X	X	X	X	X			X
PT100 4	S5.4	X	X	X	X	X	X			X
Door Switch 1 (F)	S4.2								X	
Door Switch 2 (B)	S4.3								X	
Emergency Stop	S4.4	X	X	X	X	X	X	X	X	X
Light sensor (F)	S1.5		X	X		X	X			
Light sensor (B)	S1.6		X	X		X	X			

OPC-UA Server

17	NS2|String|itk-lls-interlock.PT100Inputs.1.value	499.73828125
18	NS2|String|itk-lls-interlock.PT100Inputs.2.value	499.84942627
19	NS2|String|itk-lls-interlock.PT100Inputs.3.value	499.808898926
20	NS2|String|itk-lls-interlock.PT100Inputs.4.value	499.778381348
21	NS2|String|itk-lls-interlock.PT100Inputs.5.value	0
22	NS2|String|itk-lls-interlock.PT100Inputs.6.value	0
23	NS2|String|itk-lls-interlock.PT100Inputs.7.value	0
24	NS2|String|itk-lls-interlock.PT100Inputs.8.value	0

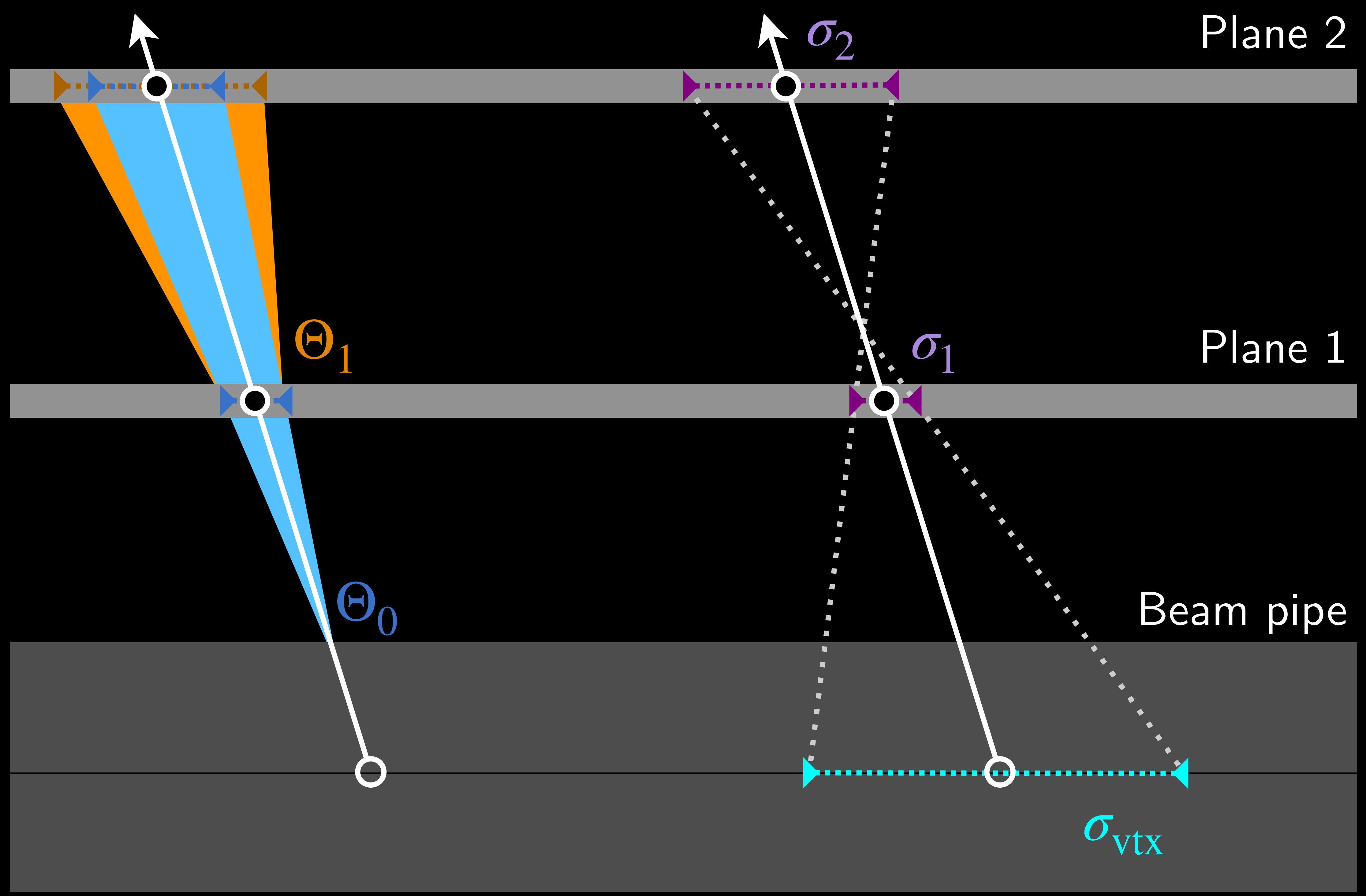




- A hardware interlock is needed to prevent damage or unsafe operation
  - Custom interlock solution for half-ring testing based on NI CompactRIO crate, FPGA-controlled with LabView firmware
  - An OPC-UA server has been implemented to allow for seamless communication with WinCC-OA-based DCS project

Step 3: Measuring the ITk

Plots public as ITK-2023-002



Detector Material

- Detector effects have a significant impact on our analyses - **minimisation of material** and **precise simulations** (i.e. knowledge of detector makeup) are critical for success
- Material thickness of innermost pixel layers is **critical for b-tagging** (light-jet rejection)**, vertexing resolution**, due to multiple scattering, hadronic interactions

- Material **usually only estimated (from limited information) during R&D phase**, measured in dedicated runs and analyses (e.g. photon conversion) post-commissioning

- Many tracking-limited analyses derive “material model” uncertainties by adding +10% on innermost pixel layers; +30% on services in simulations

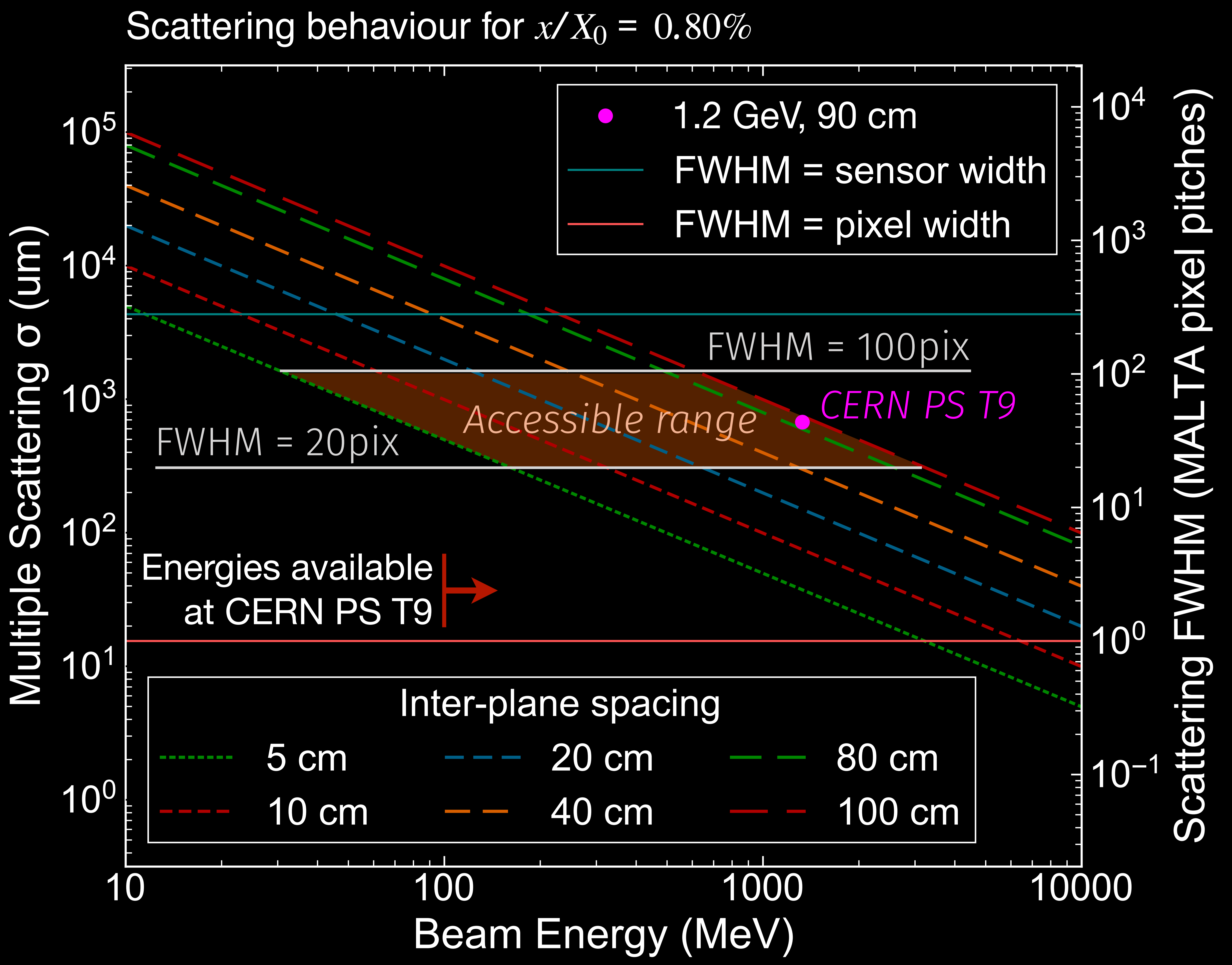
- **Multiple Scattering of low-energy EM particles** provides direct link between material budget (in radiation lengths X_0) and an observable - distribution of scattering angles projected on a plane

Highland formula [1,2]:

$$\theta^{\mathrm{rms}}_{\mathrm{plane}} = \frac{13.6\,\mathrm{MeV}}{\beta c p} z \sqrt{x/X_0}\left(1 + 0.038 \ln(x/X_0)\right)$$

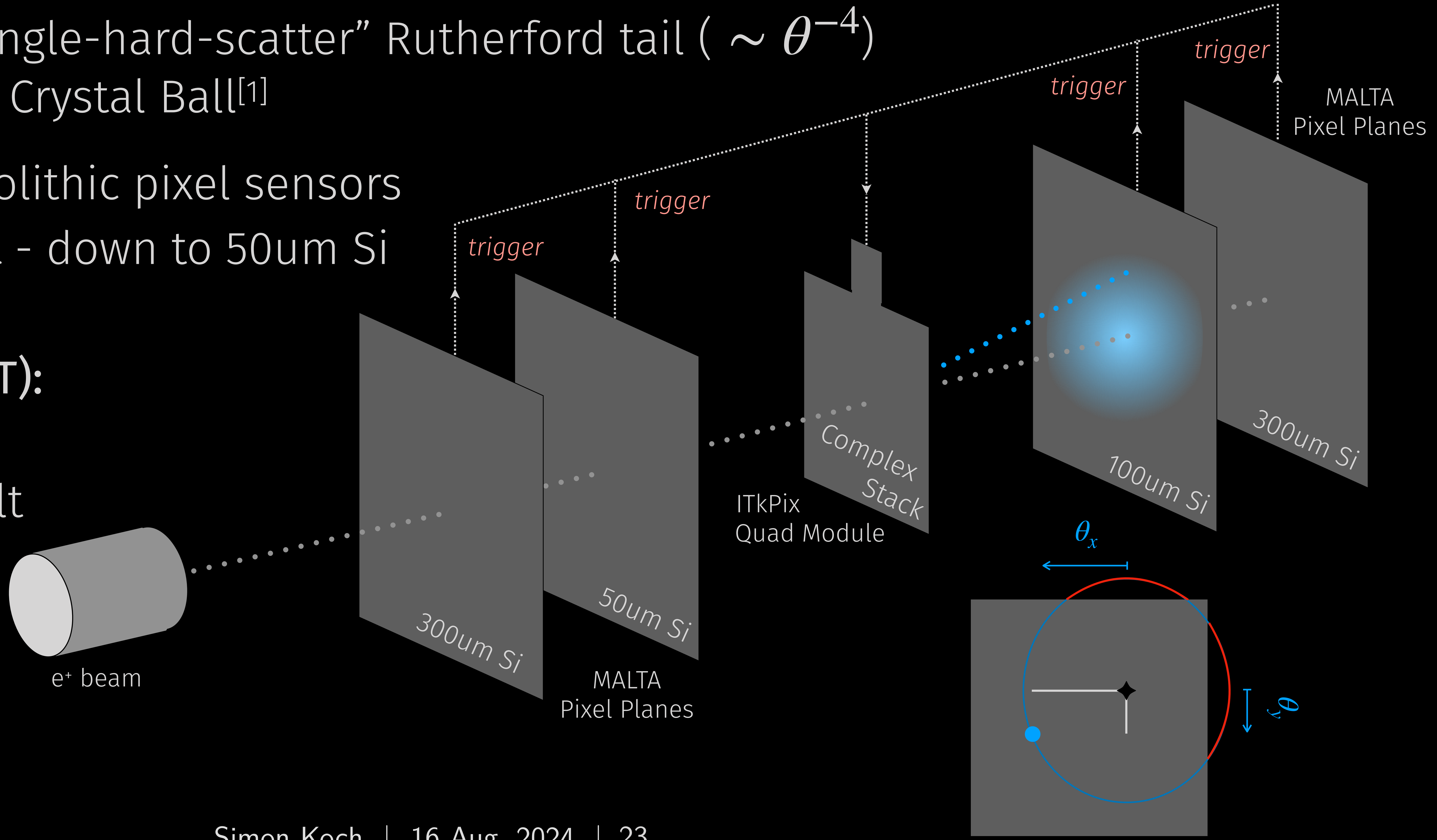
[1] PDG rev. 27
[2] Highland et. al.

- Testbeam measurements have been attempted before at DESY, Göttingen, ETH Zürich, but concentrated on thicker slabs of single materials, and/or inactive material



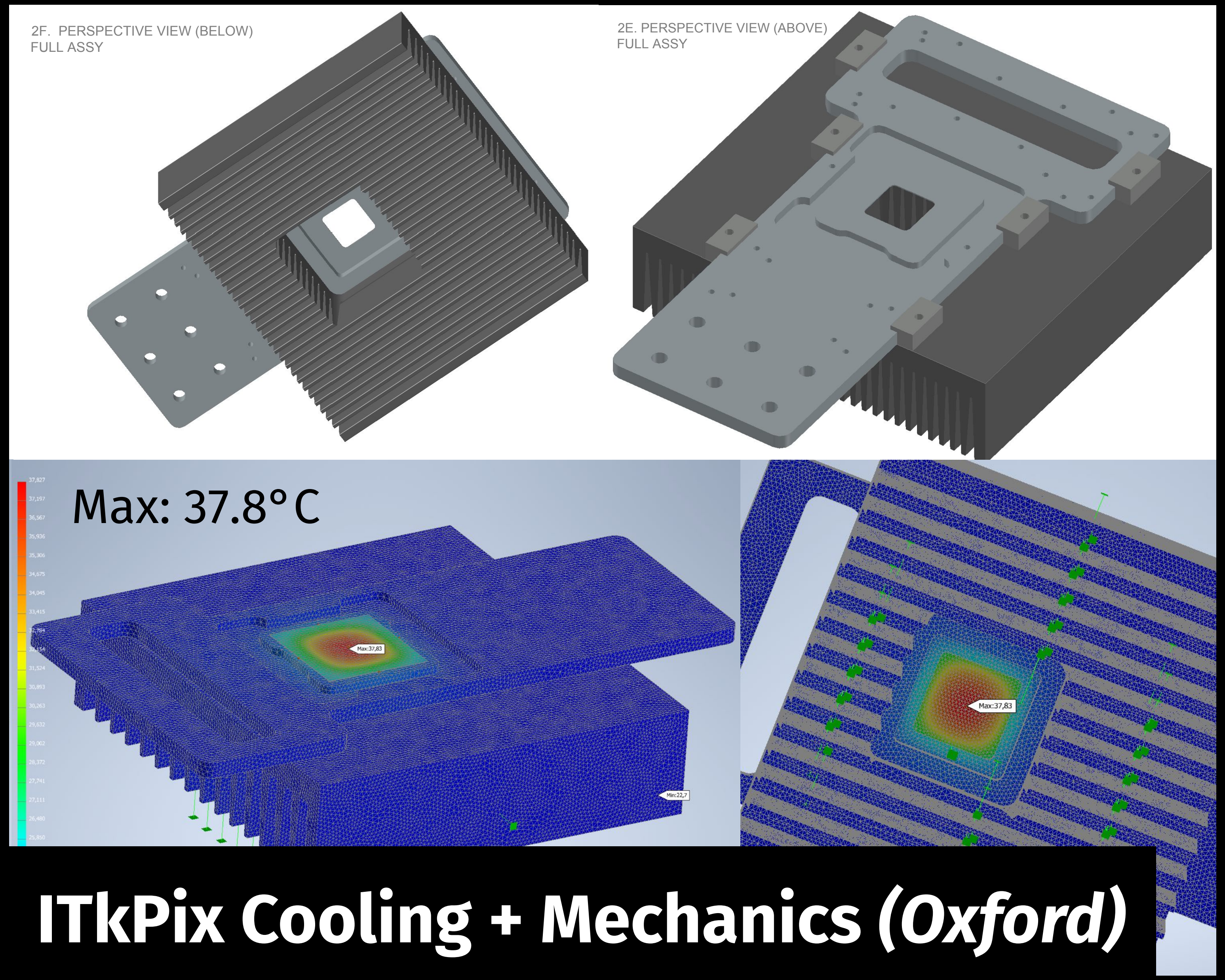
MEASURING RADIATION LENGTH

- Use a low-X_0 telescope to measure multiple scattering of e^+ at O(1 GeV) at CERN PS
- MS is gaussian with "single-hard-scatter" Rutherford tail ($\sim \theta^{-4}$)
  - fit with Double-sided Crystal Ball[1]
- **Telescope:** MALTA Monolithic pixel sensors
  - Low material content - down to 50um Si
- **Device Under Test (DUT):** ITkPix Quad Module
  - Hybrid design difficult to get a clean rad. length estimate for
  - FELIX readout chain



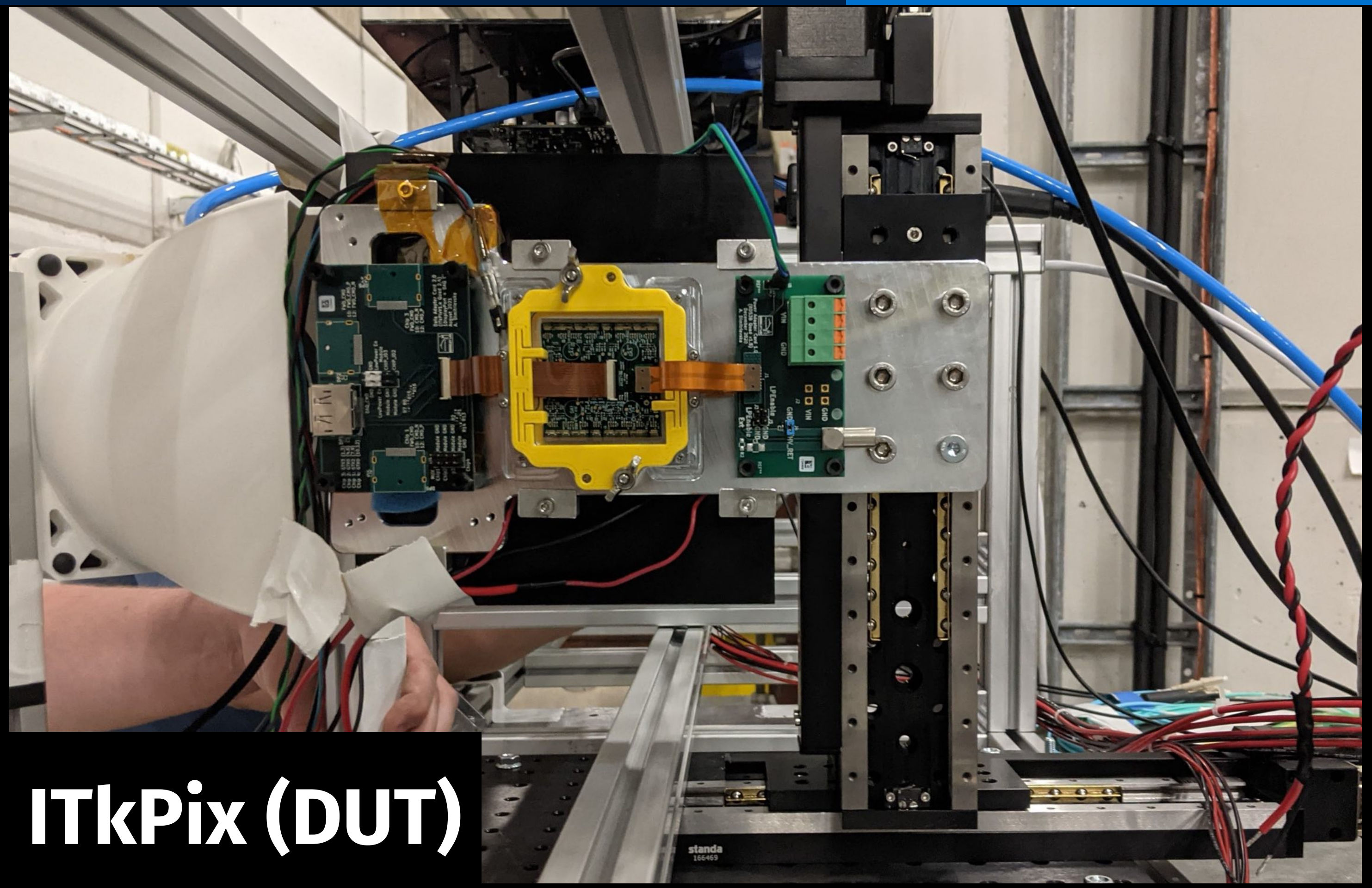
[1] double-sided crystal ball function (link)

The Setup at the CERN PS

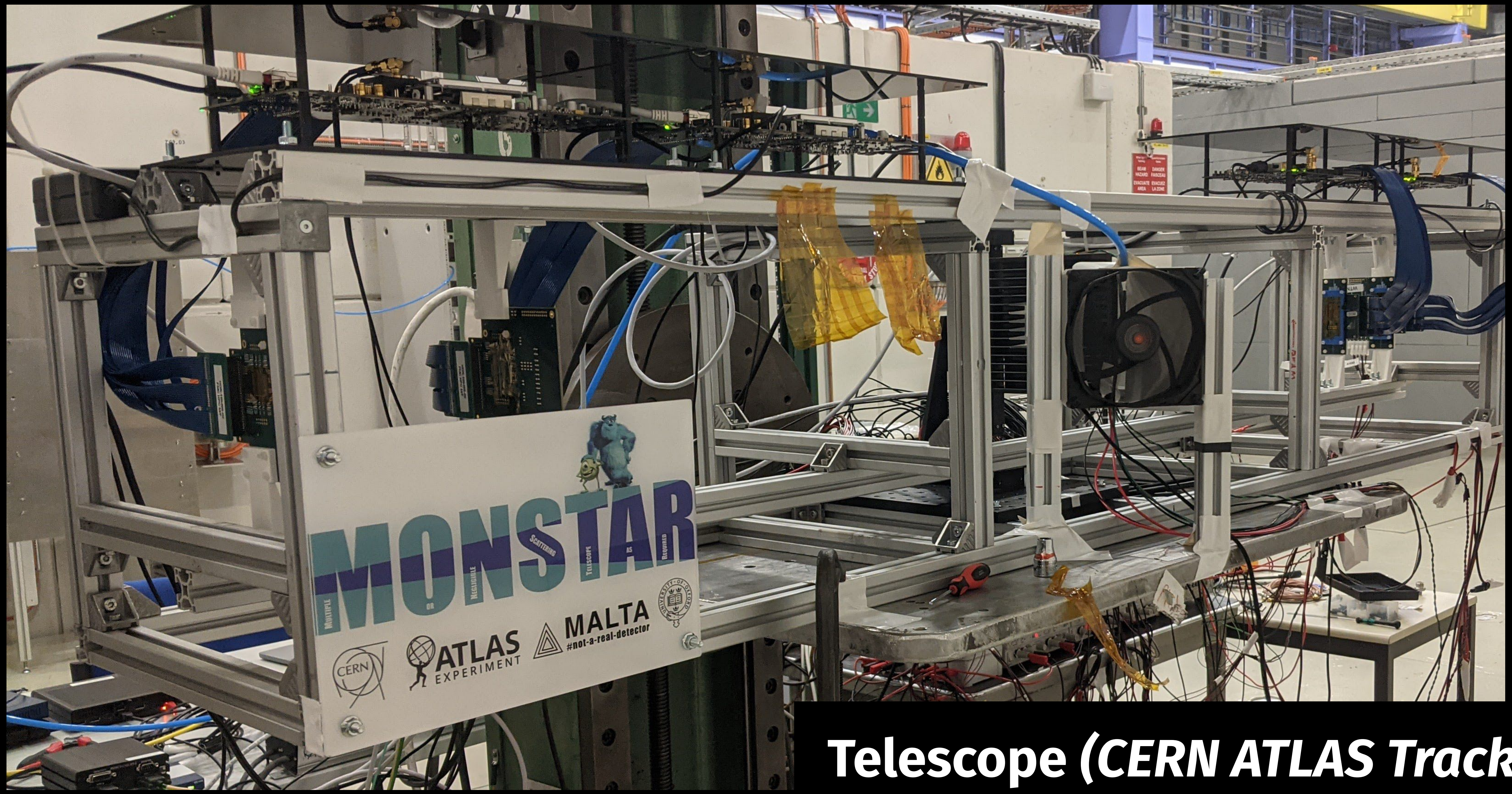


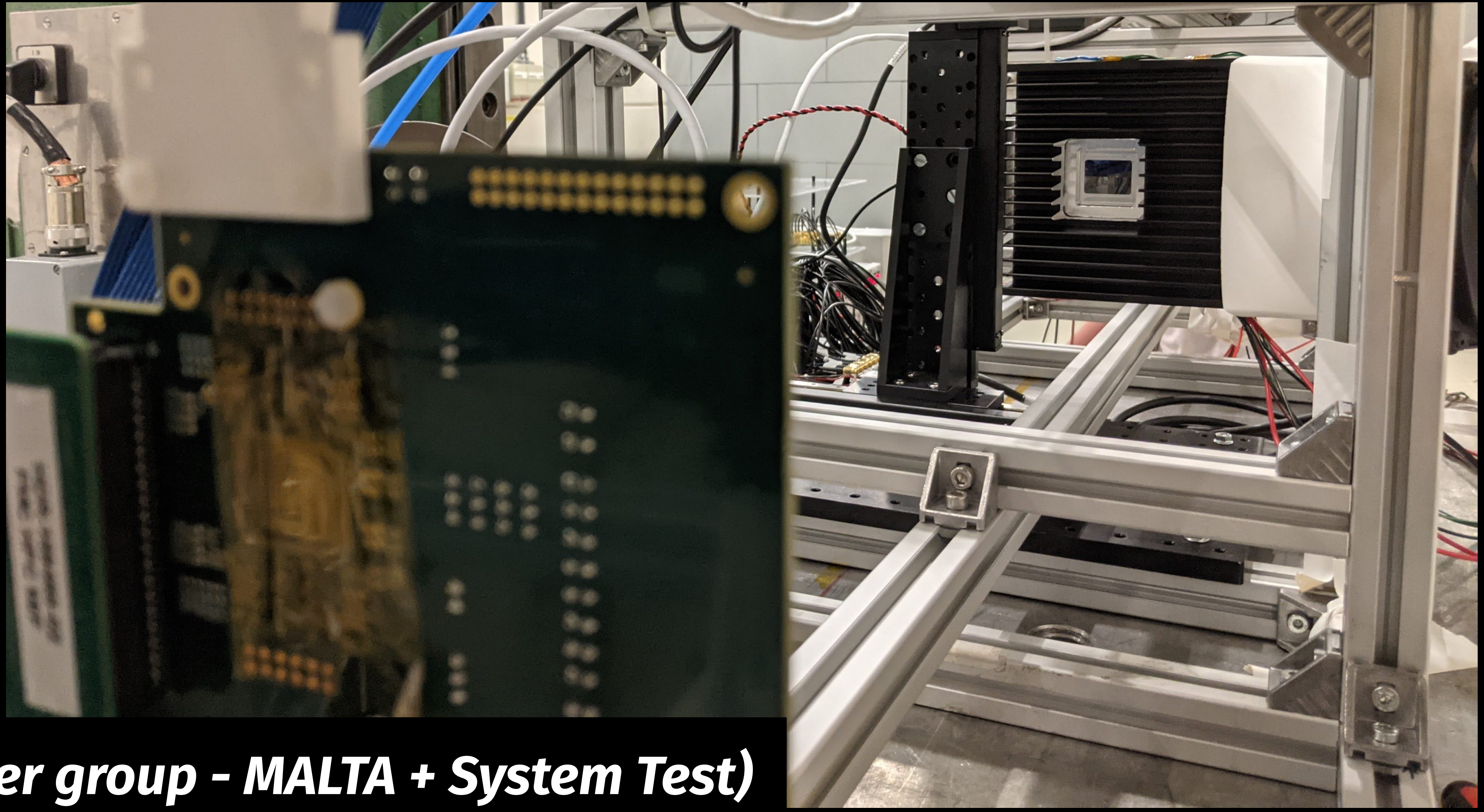
ITkPix Cooling + Mechanics *(Oxford)*

Counting Room



ITkPix (DUT)





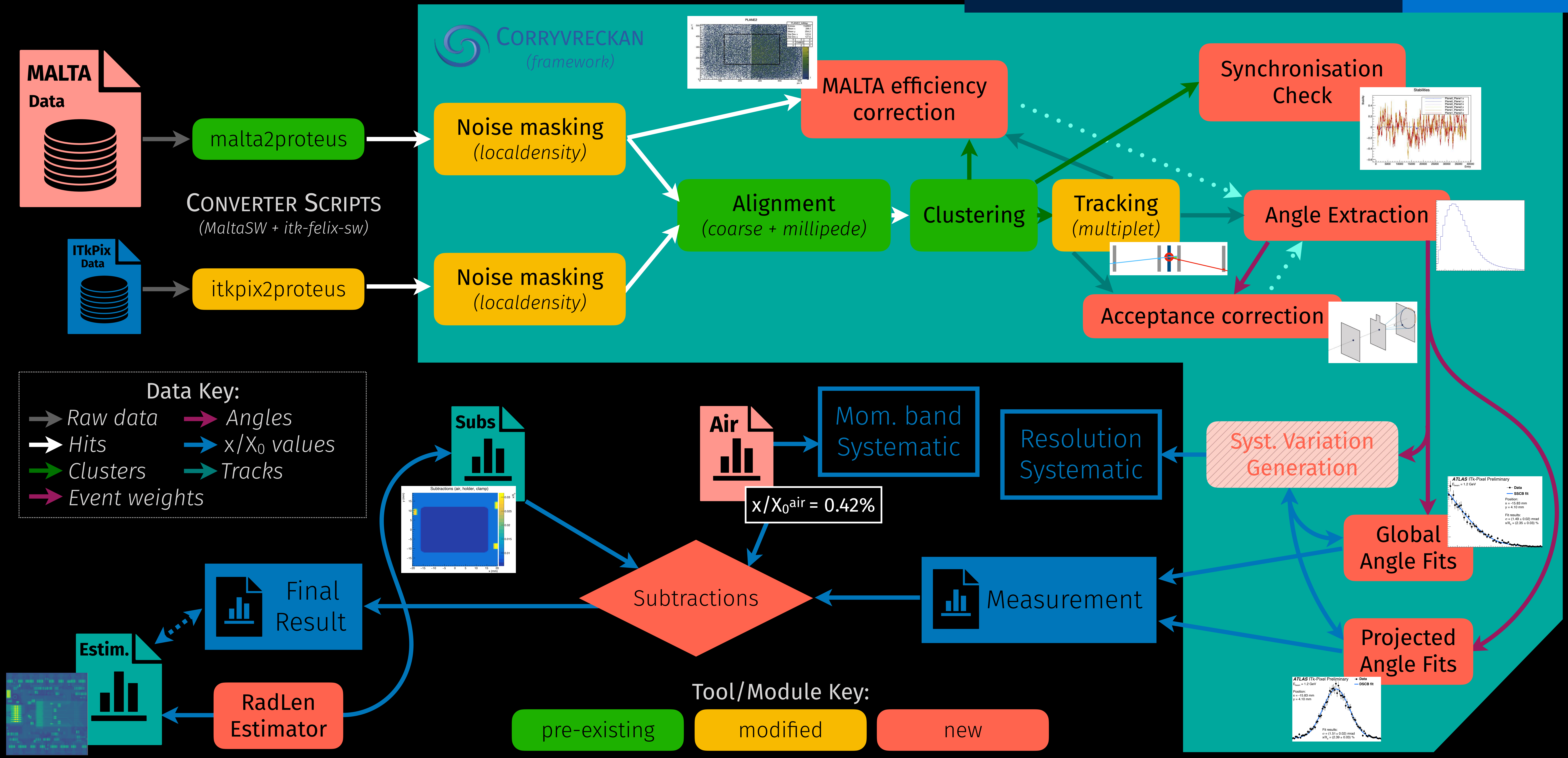
Telescope *(CERN ATLAS Tracker group - MALTA + System Test)*

Analysis Chain

Almost entire analysis chain uses:
(or implemented as new modules for)

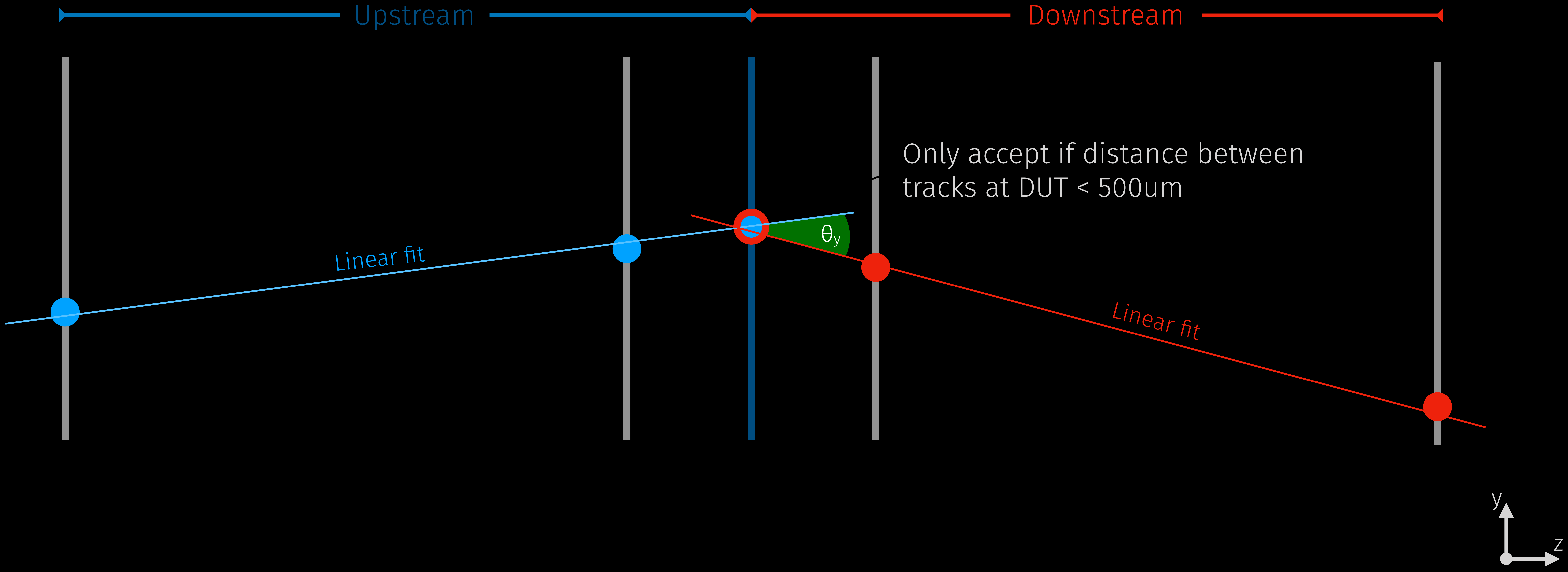
Corryvreckan testbeam analysis framework

ATLAS EXPERIMENT

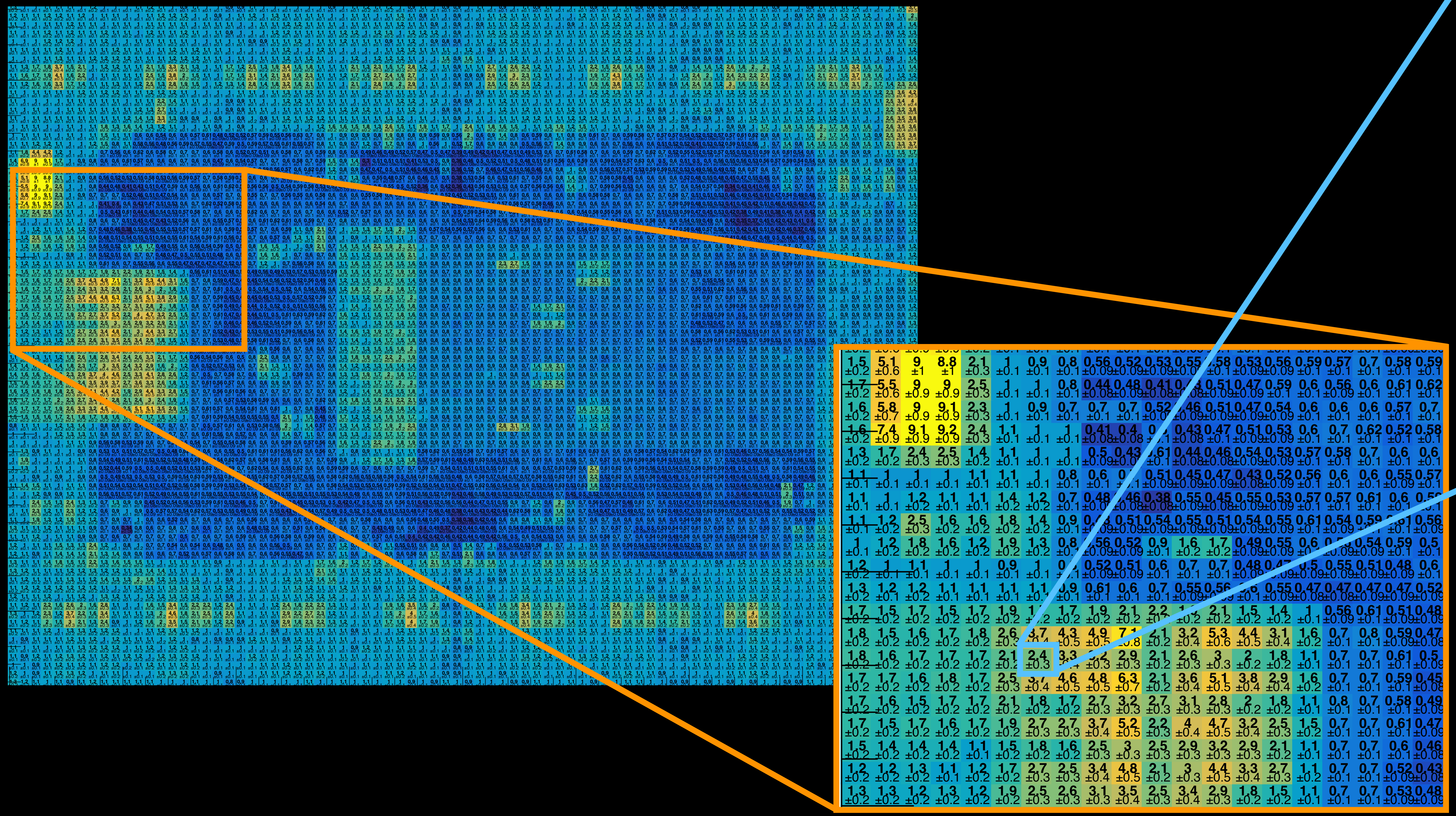


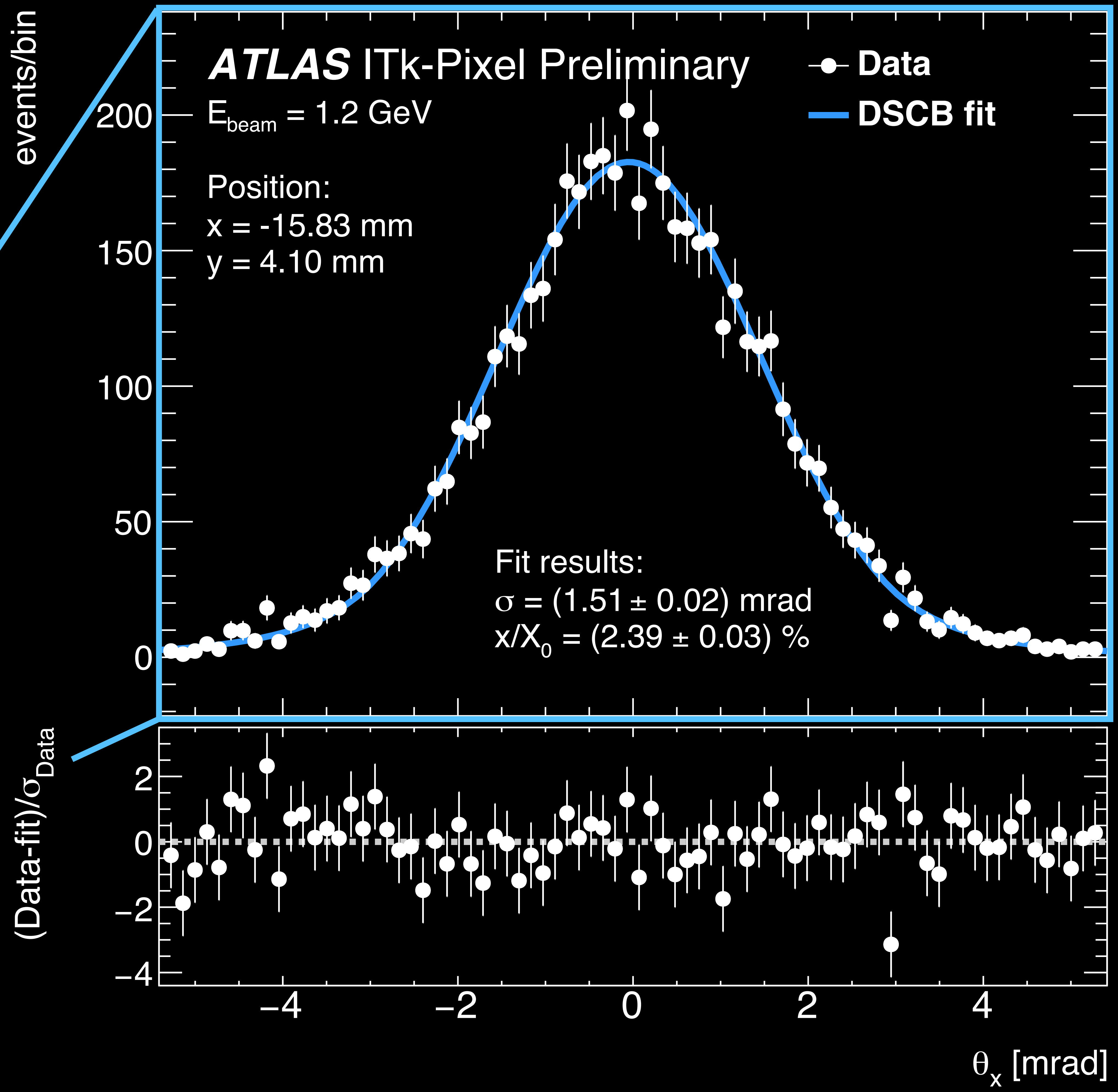
Multiplet Tracking

We require 3 hits per track on both upstream and downstream

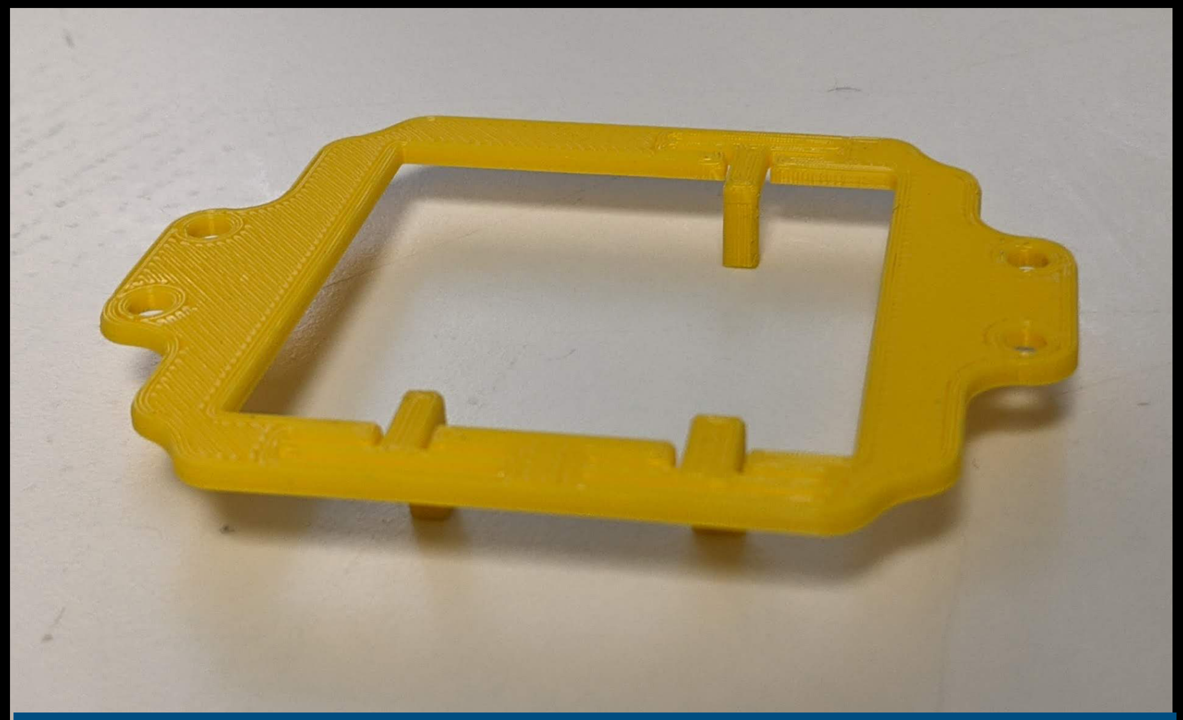


- θ_x, θ_y (projected distributions) fitted by **double-sided crystal ball function (DSCB)**
- Fit performed unbinned directly on angle data using RooFit



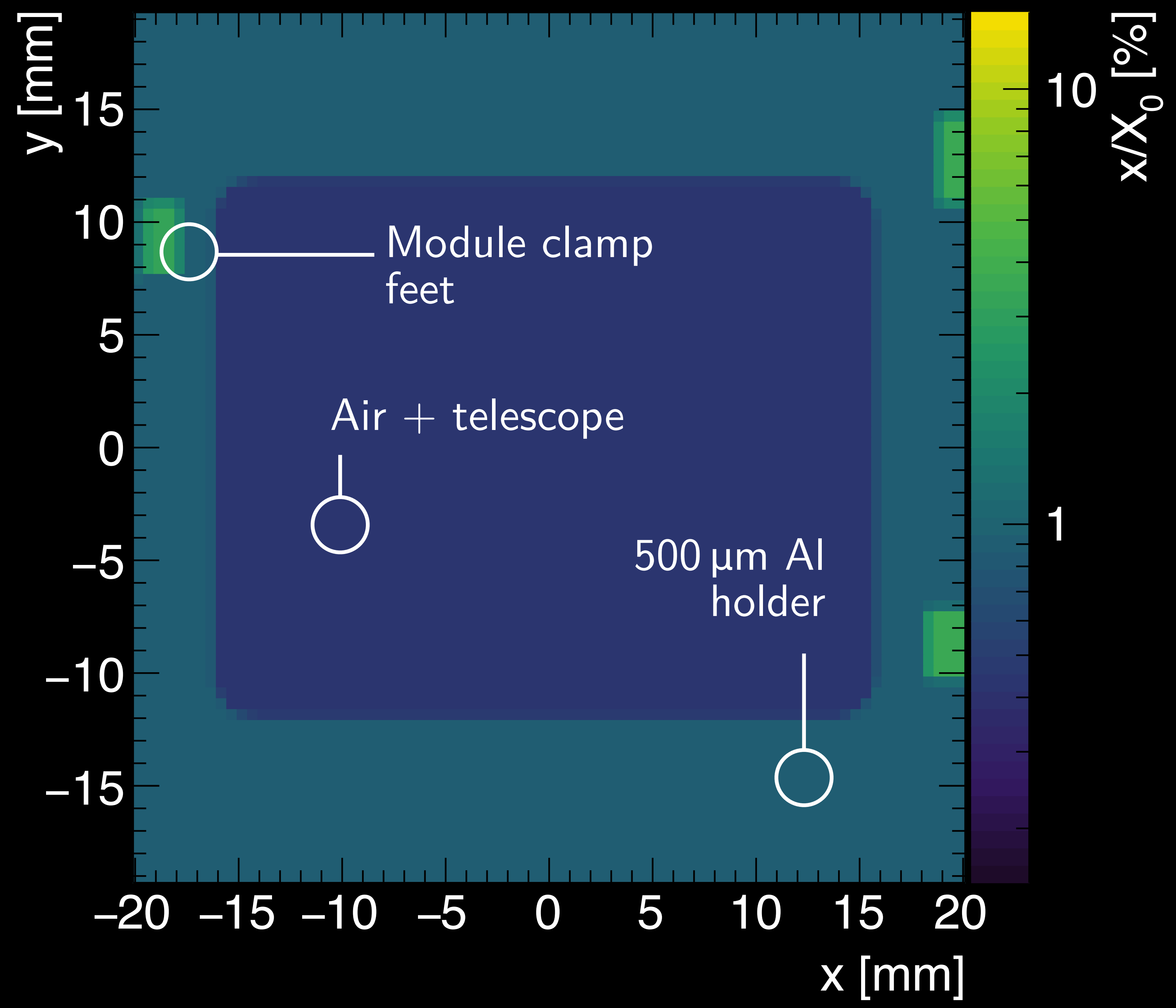


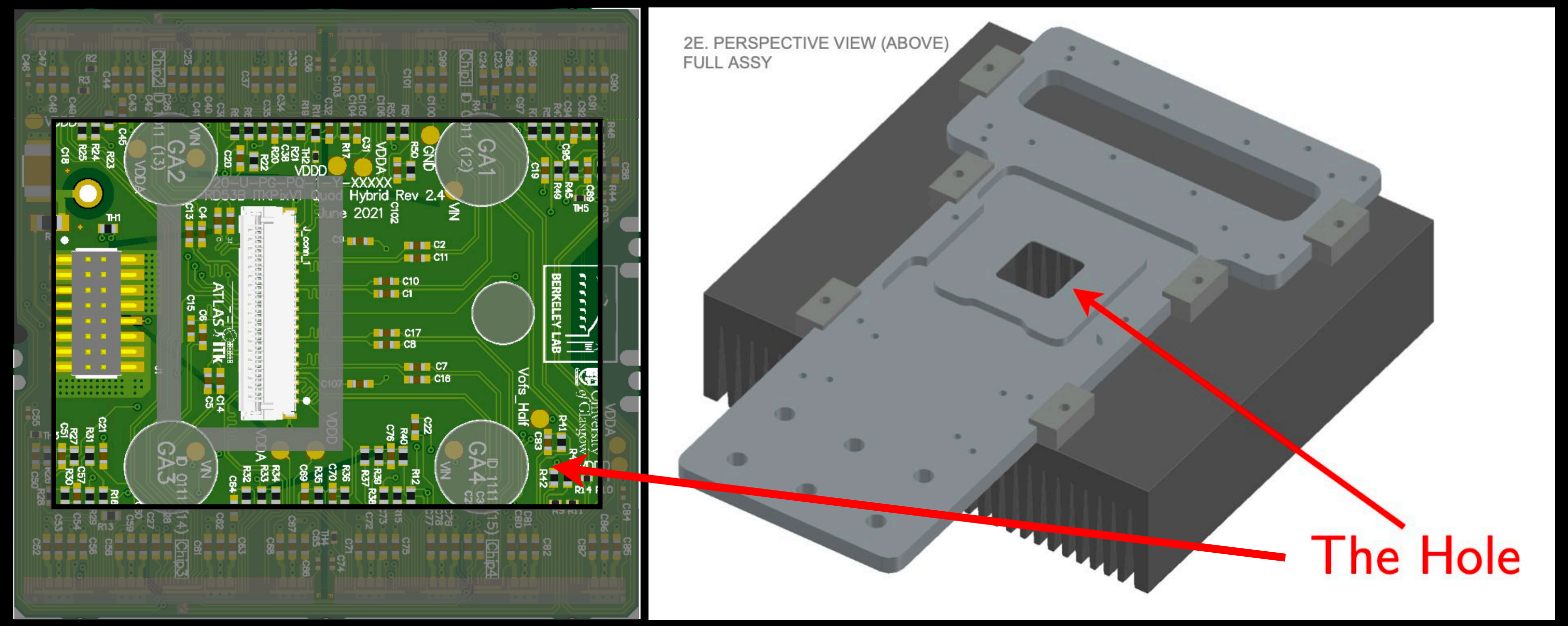
- Need to model and **subtract** auxiliary contributions to x/X_0
  - **Metal module holder** (500um Al nominal)
    - Performed metrology on SmartScope at OPMD
  - **3D-printed Clamp**
    - Dissected and weighed for density measurement

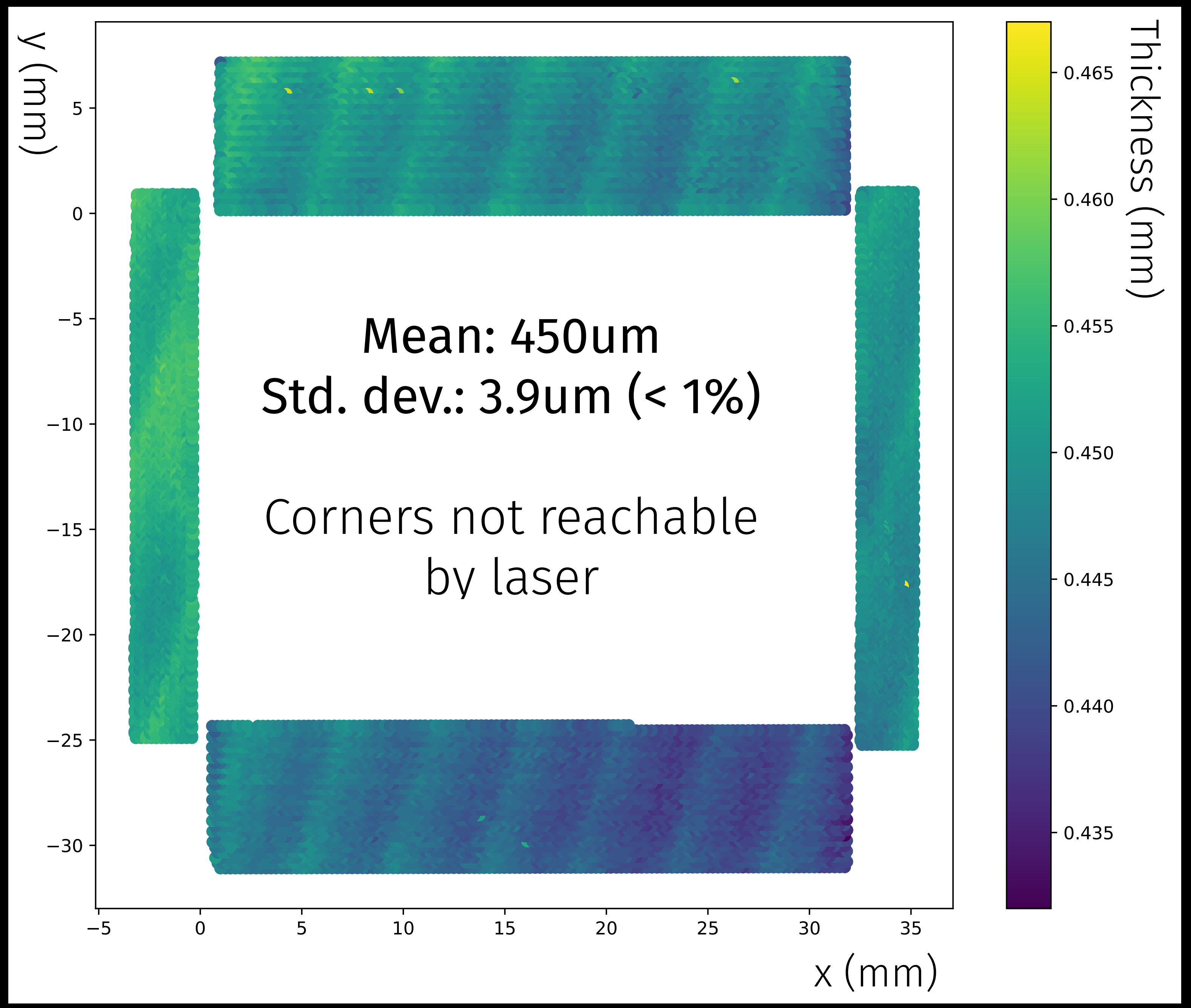


	M (g)	ρ (g/cm^3)	x/X_0
top left hv cap leg	0.045	1.096	2.24%
bot left rect leg	0.069	1.046	2.63%
bot right square leg	0.097	1.052	2.64%
top left hv cap arm	0.037	1.038	0.47%
bot left rect arm	0.038	0.958	0.45%
bot right square arm*	0.021	0.963	0.43%

Estimated air and telescope contributions



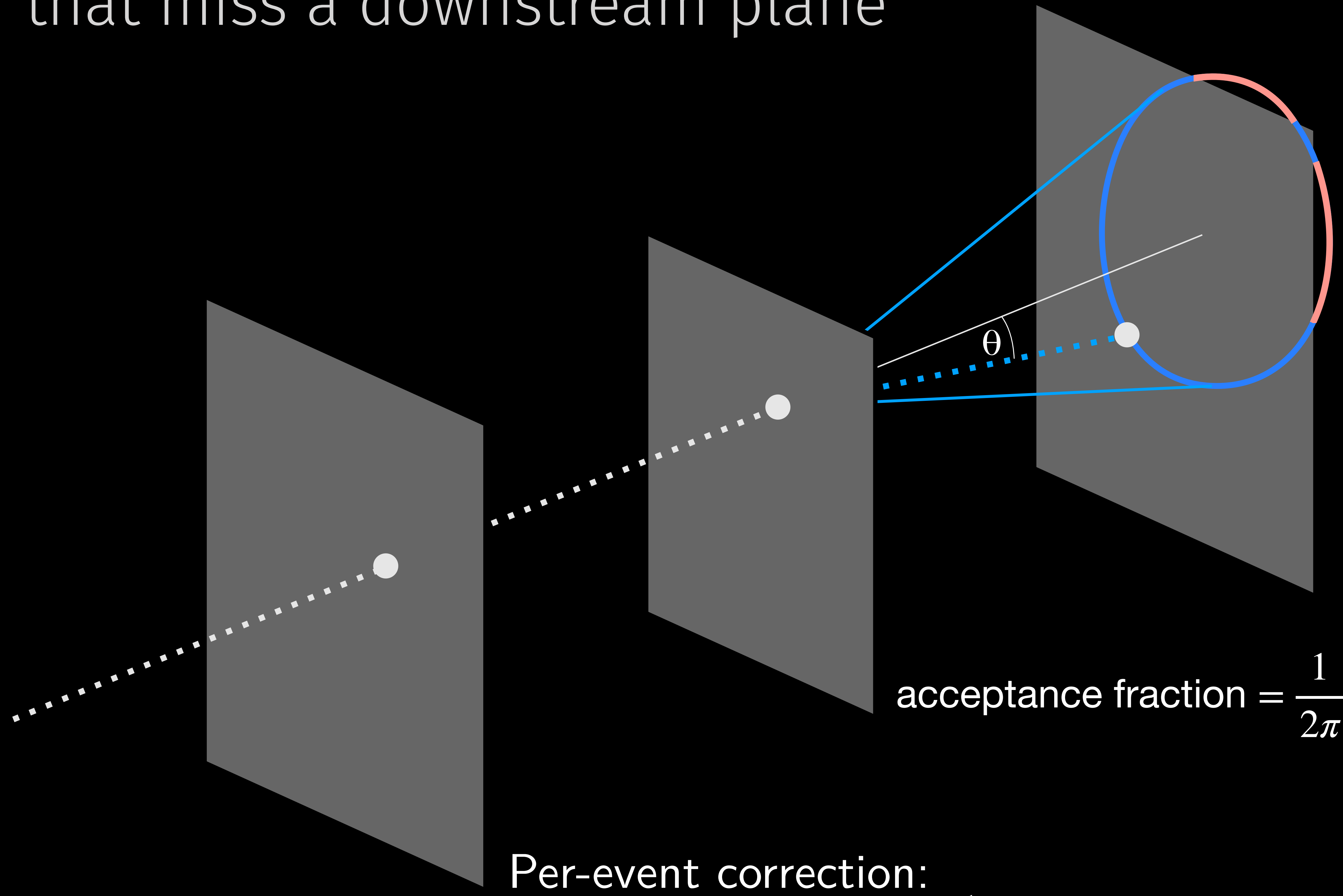




TELESCOPE ACCEPTANCE

ATLAS EXPERIMENT

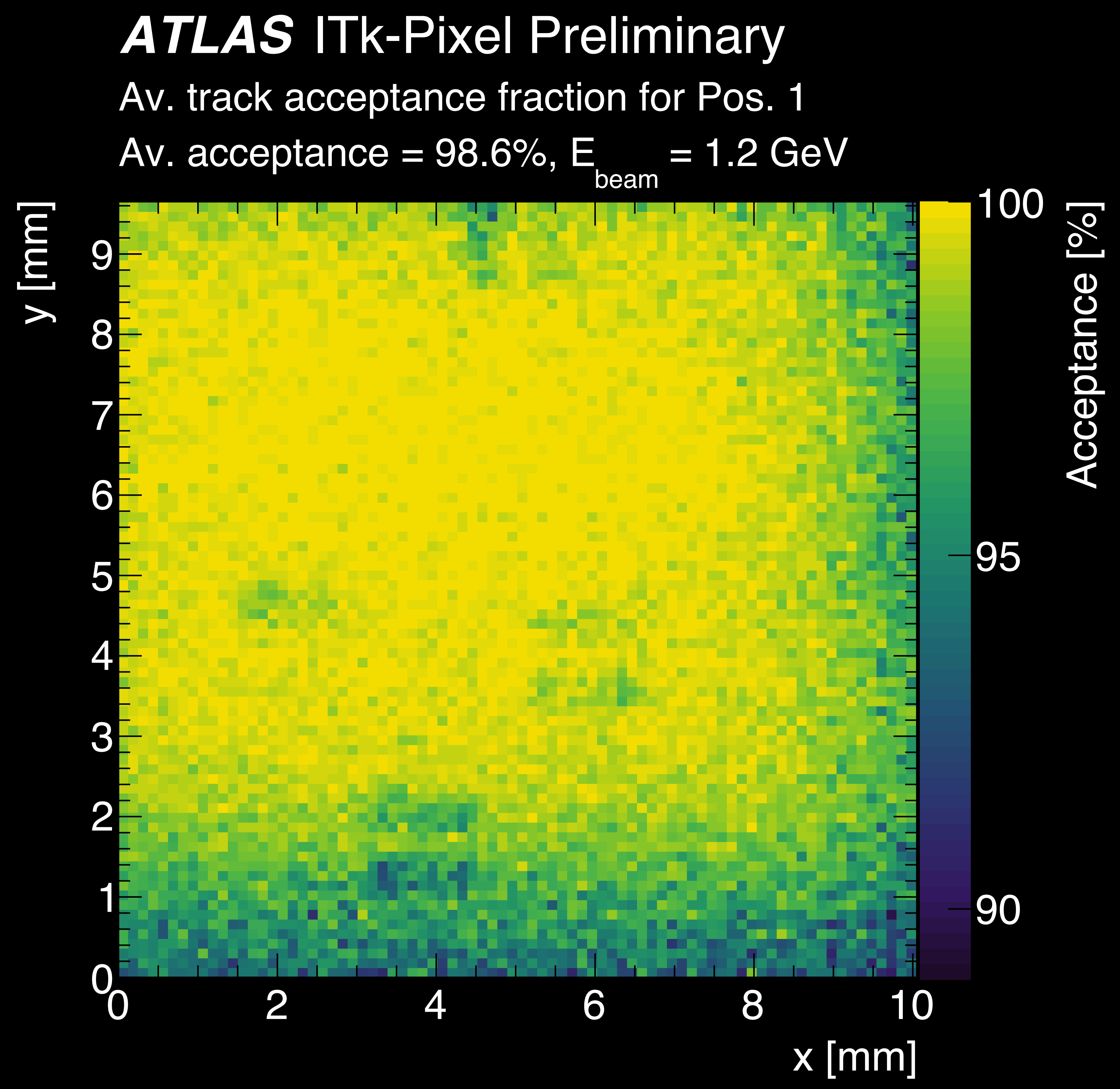
- Acceptance estimated per-track
  - fraction of all possible tracks with the same upstream vector and opening angle that miss a downstream plane



$$\text{acceptance fraction} = \frac{1}{2\pi}\sum\left(\angle^{\text{inside}}_{\text{subtended}}\right)$$

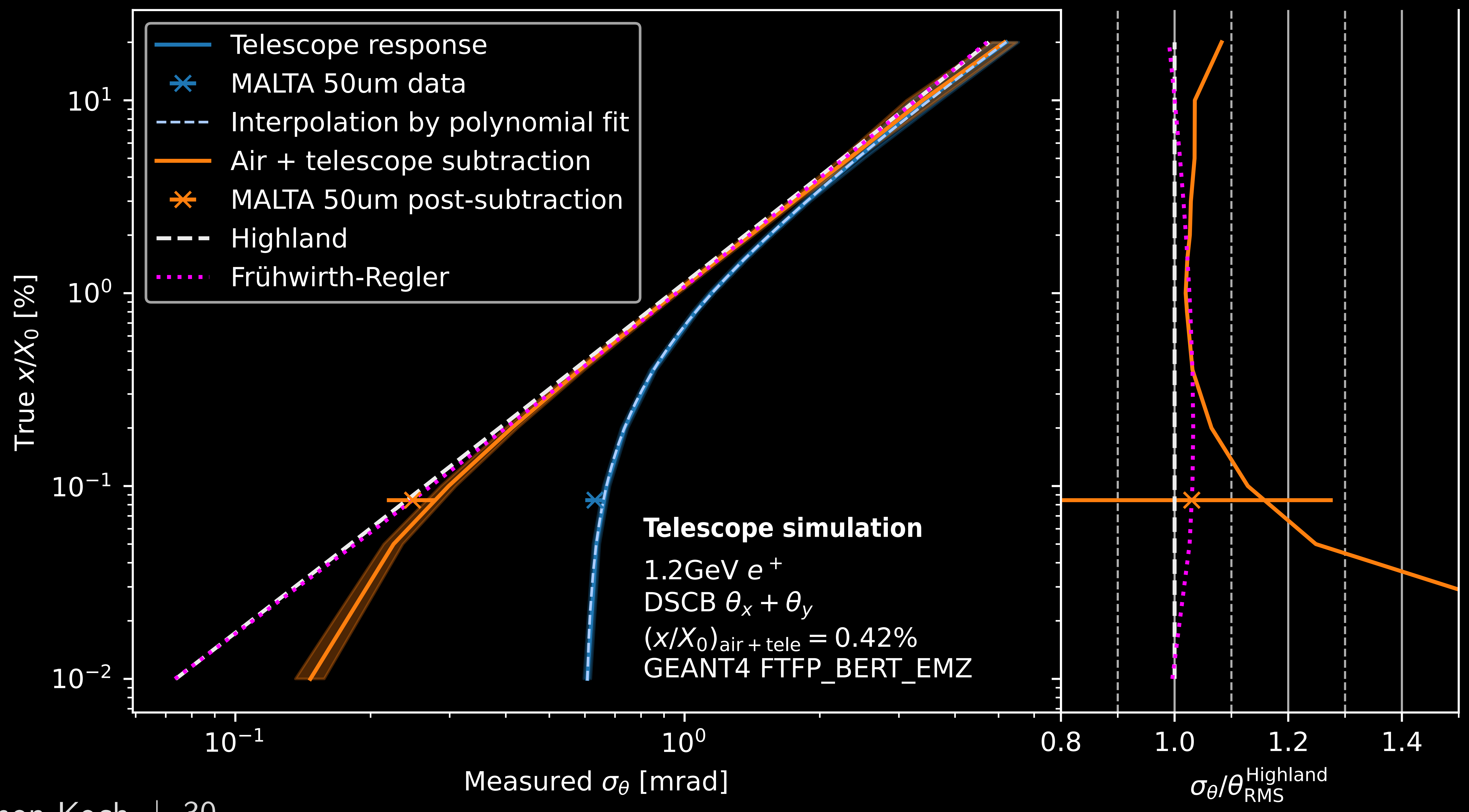
Per-event correction:

$$w_{\text{correction}} = \frac{1}{\text{acceptance fraction}}$$



Av. telescope acceptance *> 98%*

- Developed simulation model in **Geant4** (using **AllPix²**)
  - Physics list: FTFP_BERT_EMZ (best EM models for MS)
  - Complete description of telescope geometry (sensors, PCBs, tape, …)
- Simulated with and without air and telescope contributions to scattering, across range of target x/X_0 values



- Theory models:

  Highland (1970): industry-standard rule-of-thumb fit to Moliére theory

  $$\mathcal{O}\left(\sqrt{x(1 + ln^2 x)}\right)$$

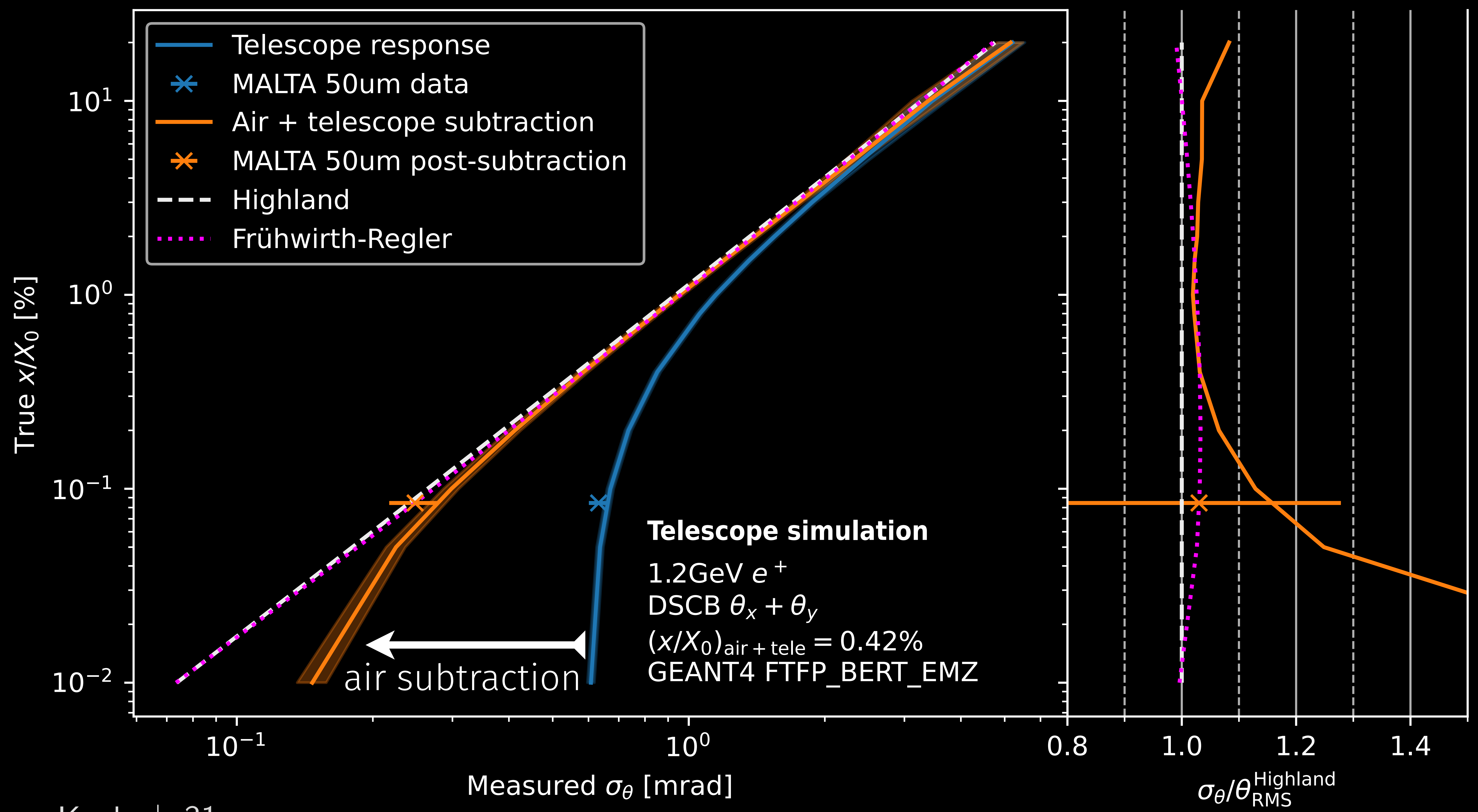
  Frühwirth-Regler (2001): fit to up to 2^{30} convolutions of single-scattering formula

  $$\mathcal{O}\left(\sqrt{x(1 + ln x + ln^2 x)}\right)$$

- $\Delta_{\text{models}} \leq 3\%$

Simulations

- Developed simulation model in **Geant4** (using **AllPix²**)
  - Physics list: `FTFP_BERT_EMZ` (best EM models for MS)
  - Complete description of telescope geometry (sensors, PCBs, tape, …)
- Simulated with and without air and telescope contributions to scattering, across range of target x/X_0 values

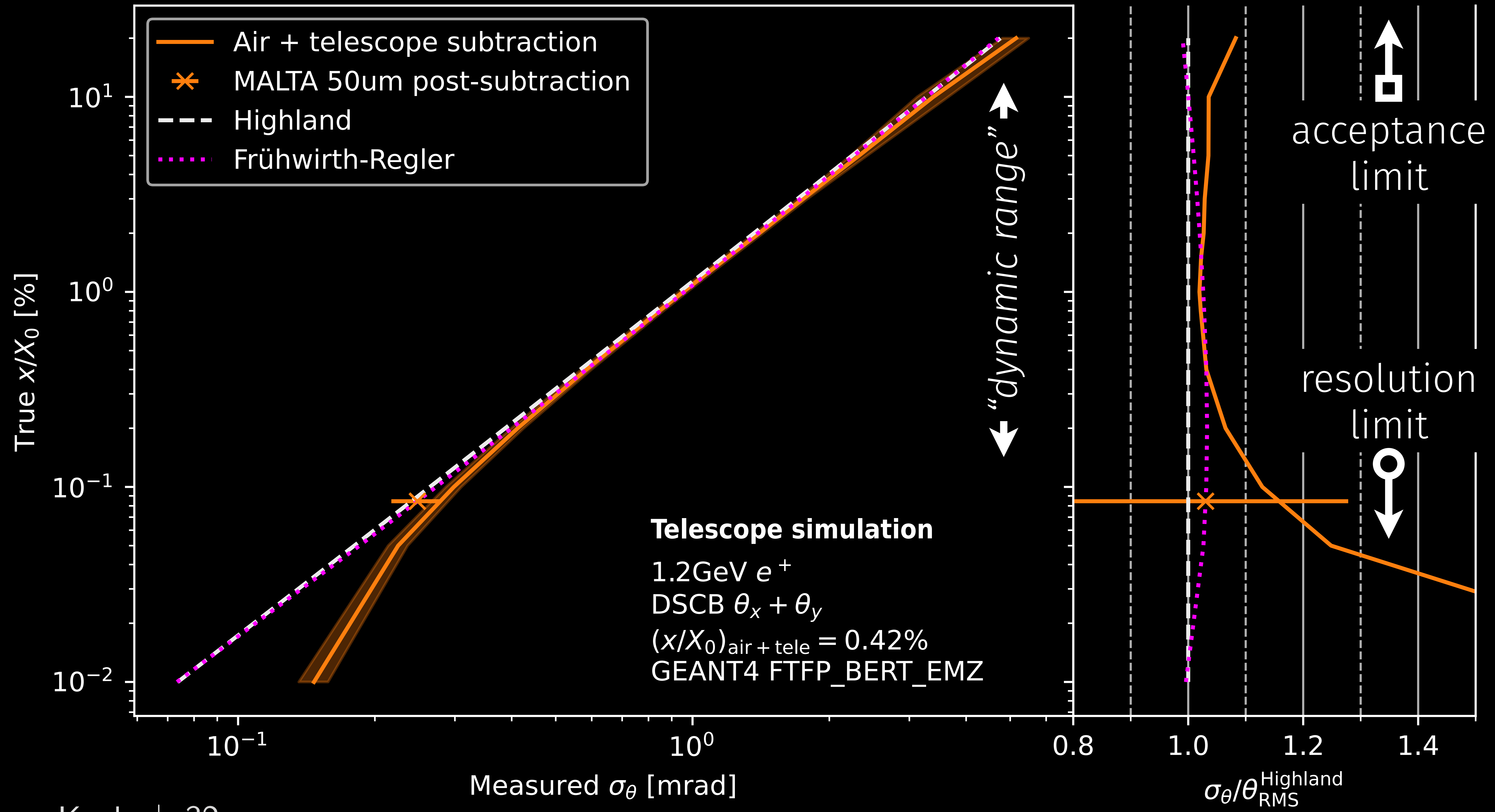


- Subtracting $(x/X_0)_{\text{air,tele}} = 0.42\,\%$ from response curve gives back curve close to model-only result
- Value derived from reference dataset (MALTA 50µm), cross-checked in simulations

Breakdown: **0.22%** from telescope, **0.2%** from 2m air

Simulations

- Developed simulation model in **Geant4** (using **AllPix²**)
  - Physics list: `FTFP_BERT_EMZ` (best EM models for MS)
  - Complete description of telescope geometry (sensors, PCBs, tape, …)
- Simulated with and without air and telescope contributions to scattering, across range of target x/X_0 values



- Dynamic range: ~ **0.1%** to **15%** of an X_0

  (with 1.2 GeV e^+, 2m tele)

SIMULATIONS

- Developed simulation model in **Geant4** (using **AllPix²**)
  - Physics list: `FTFP_BERT_EMZ` (best EM models for MS)
  - Complete description of telescope geometry (sensors, PCBs, tape, …)
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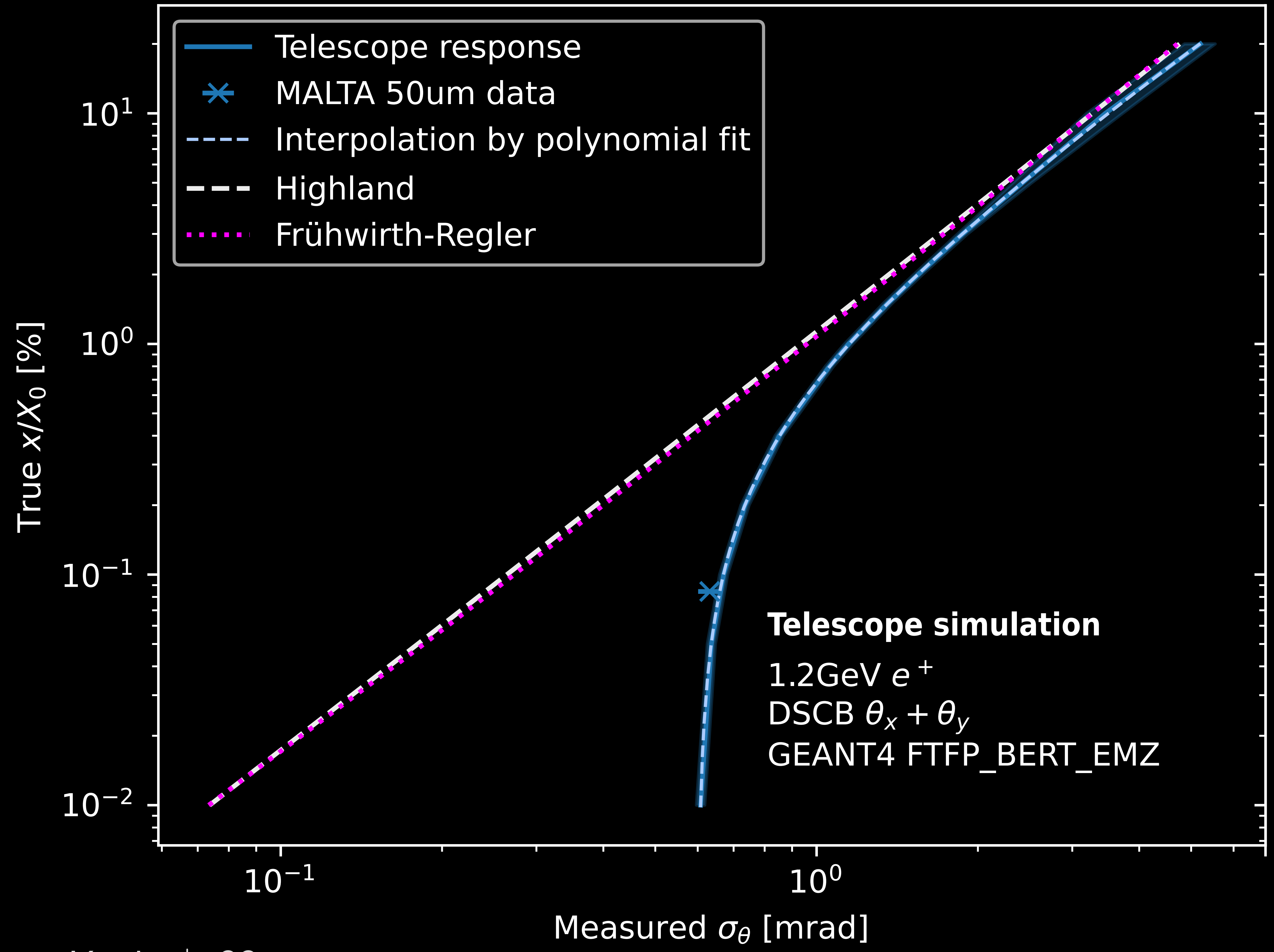
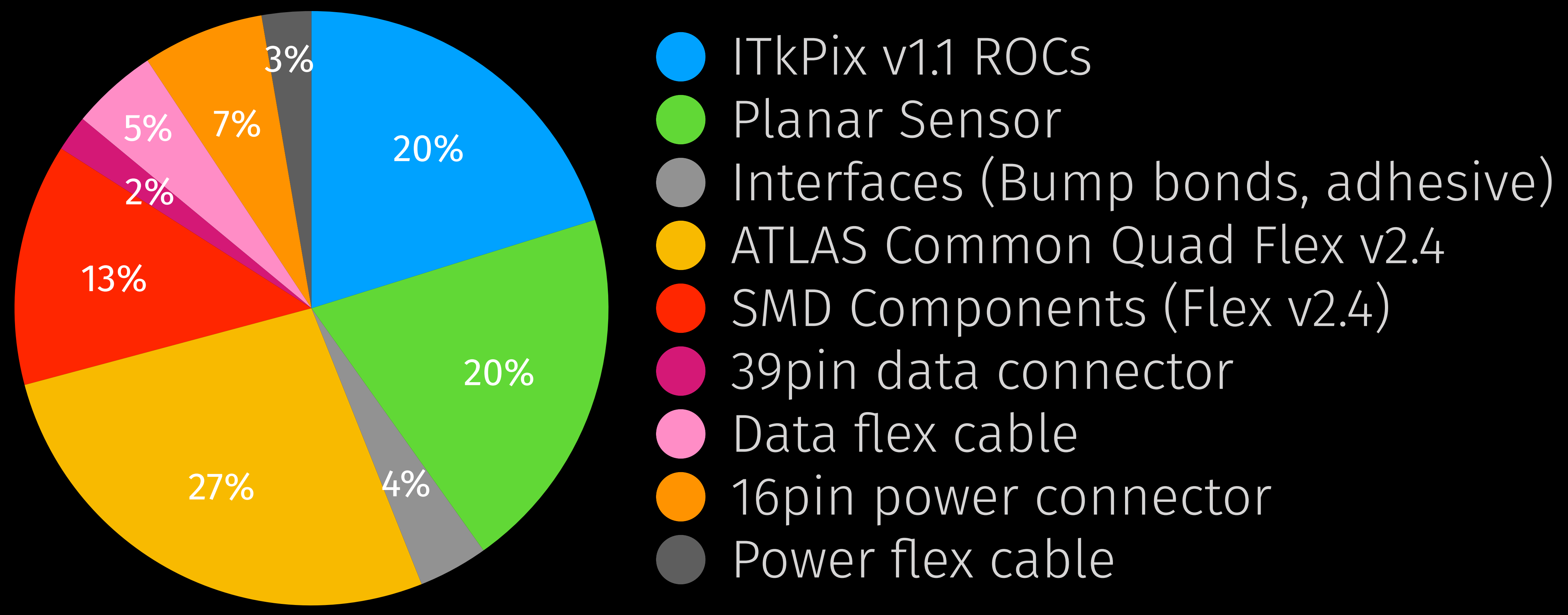
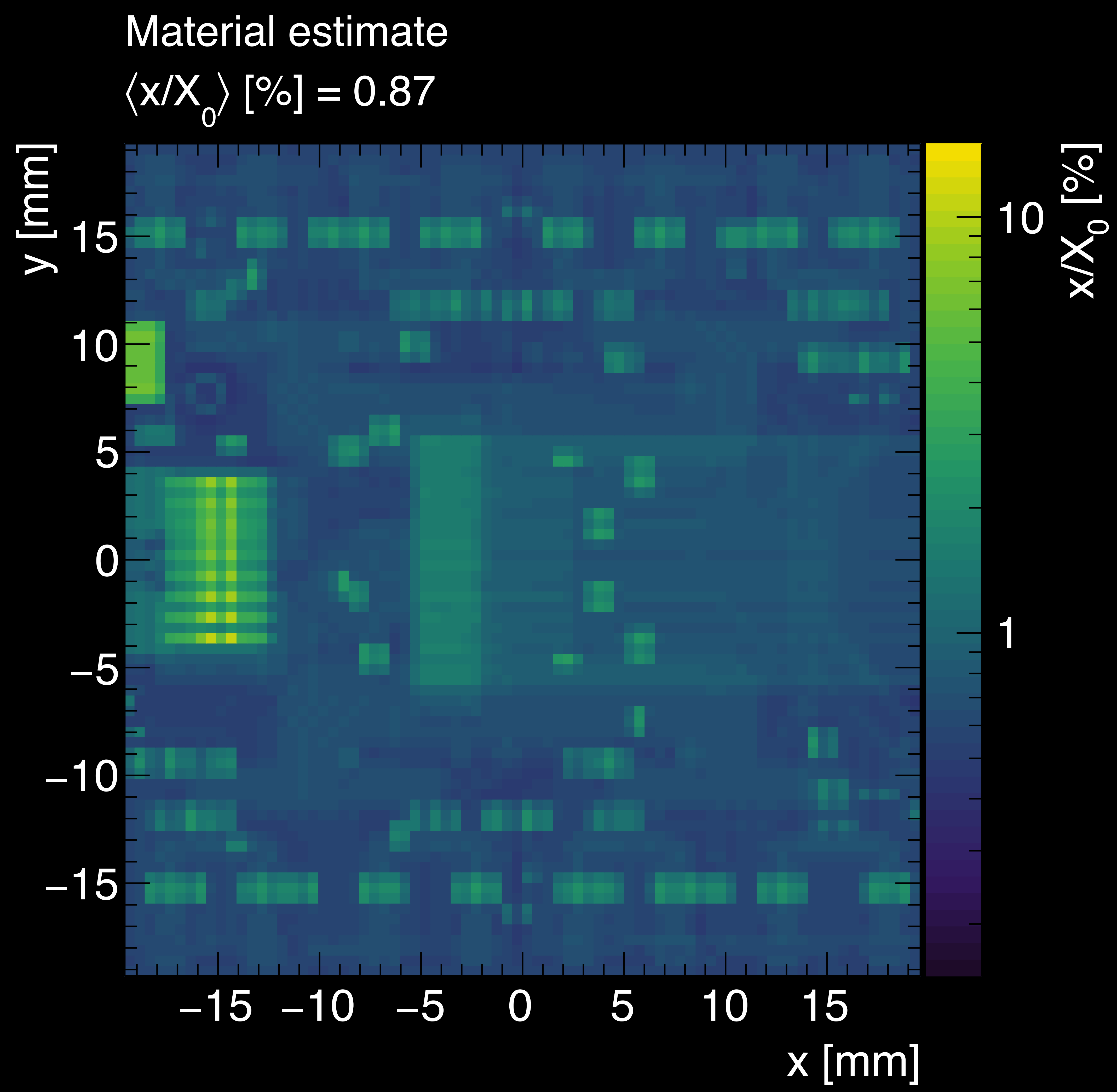


- Can **"unfold"** telescope response curve (pre-air-subtraction)
- "Smart interpolation" with 3rd or 4th-order **polynomial fit**
- *Alternative to/cross-check on interpretation via theory models*

Material Estimate

- Estimate built directly from PCB design files and product data-sheets
  - 57 "layers" of contributions
  - X/X_0 values taken from closest known material (e.g. Kapton®/PI for DuPont®), or estimated as mixture if possible (e.g. phosphor bronze, PLA)
  - SMD components and connectors estimated from available manufacturer data - these values are a *best-guess*, and difficult to determine precisely



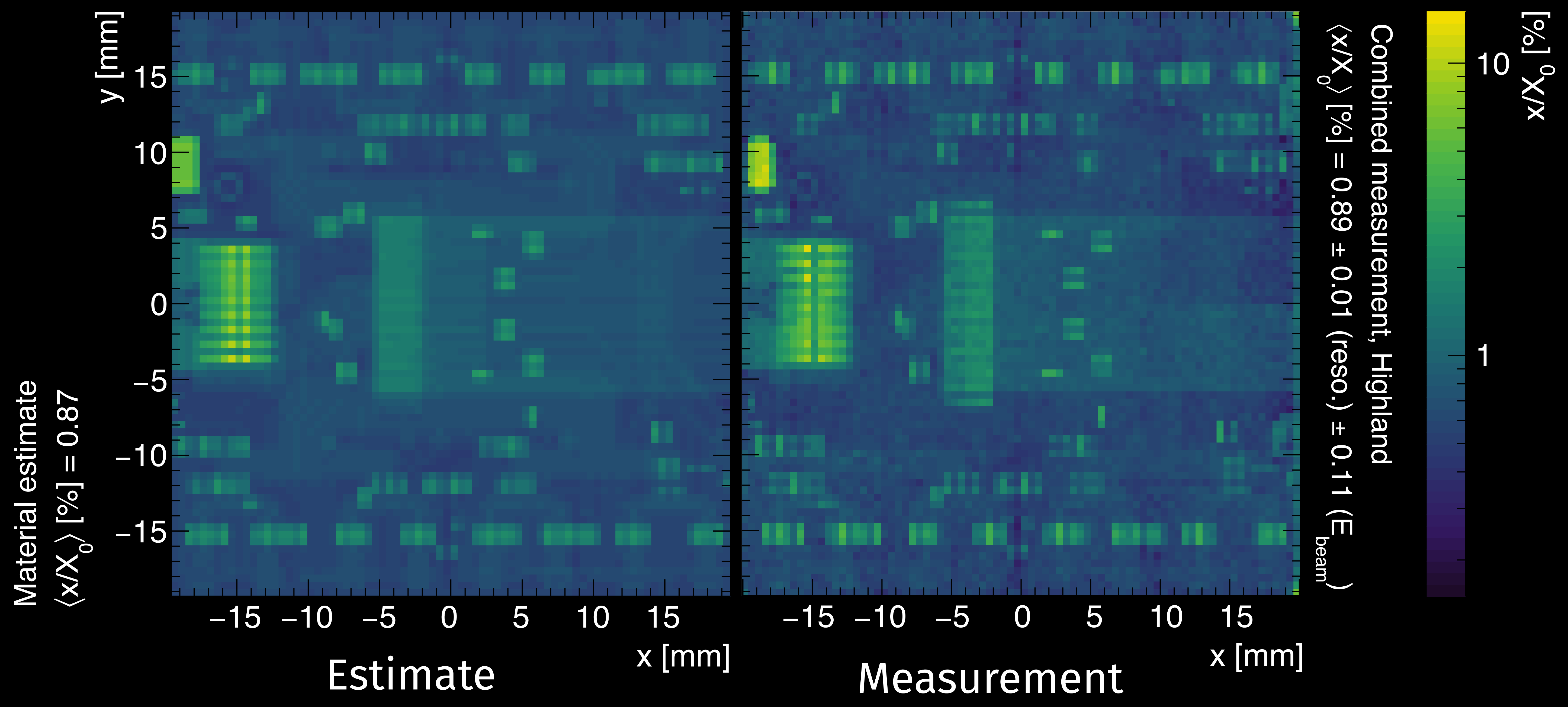


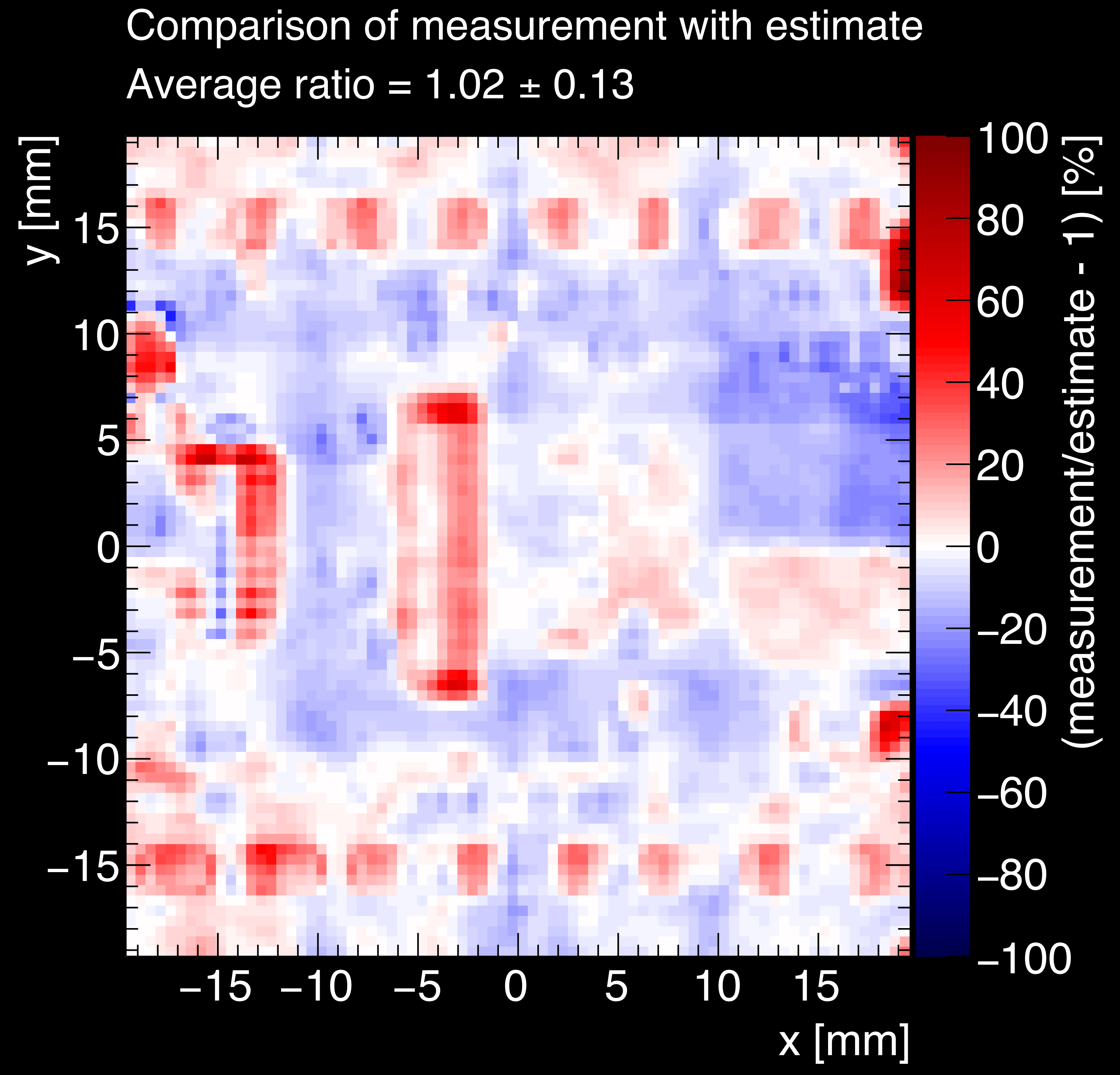
Results and Comparison to Estimate

- Result with subtractions shows **good agreement** with estimate, mean agrees within uncertainties

$$\left\langle \frac{x}{X_0} \right\rangle_{\text{meas}} [\,\%\,] = 0.89 \pm 0.01 \ (\text{reso.+sub.}) \pm 0.08 \ (E_{\text{beam}})$$

- Dominant uncertainty: **beam momentum band** *(5% FWHM)*

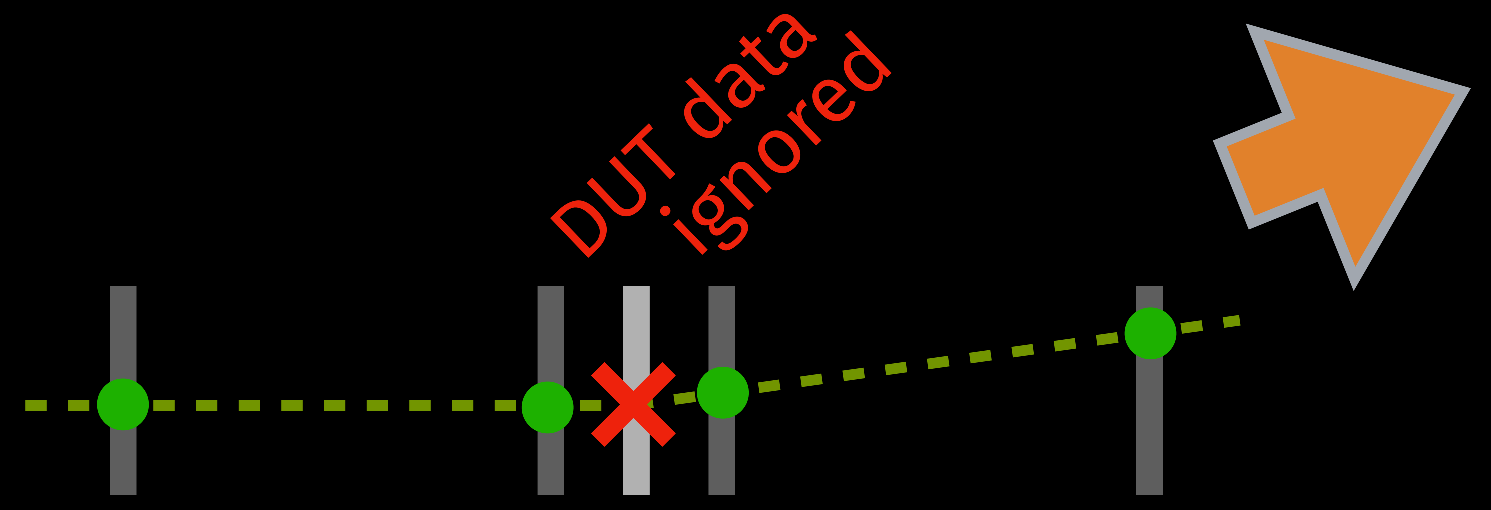


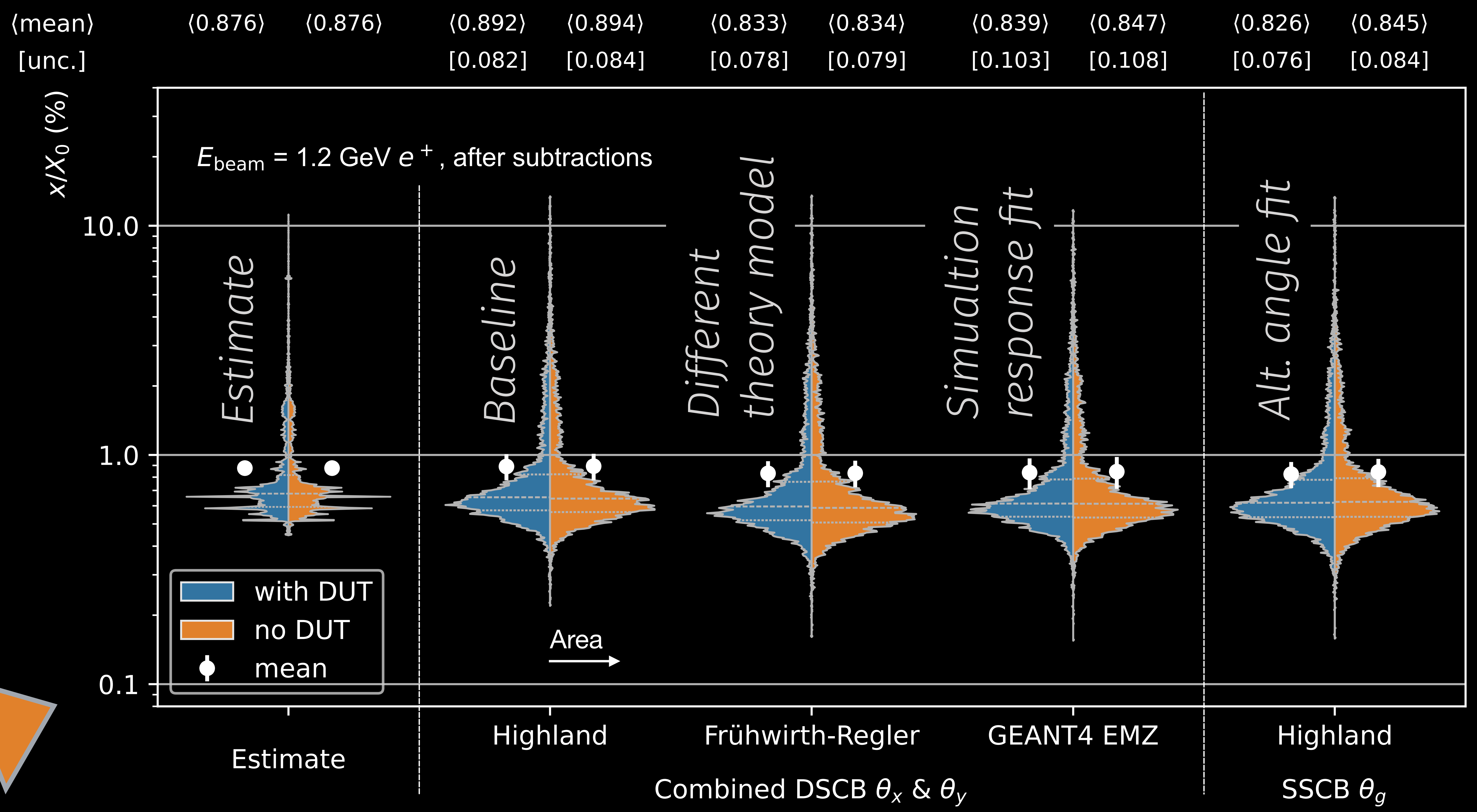


- SMD components, connectors appear to be main points of contention - likely caused by imprecision in estimate

Comparing Interpretations

- Highland, Frühwirth-Regler, Geant4 (response curve fit) agree within uncertainties
  - Highland estimates 6% higher x/X_0 values than FR or G4
- Spectrum of x/X_0 values match estimate (with unc. smearing) very well
- Spectra without DUT info are good match for with DUT - don't need the DUT hit in future

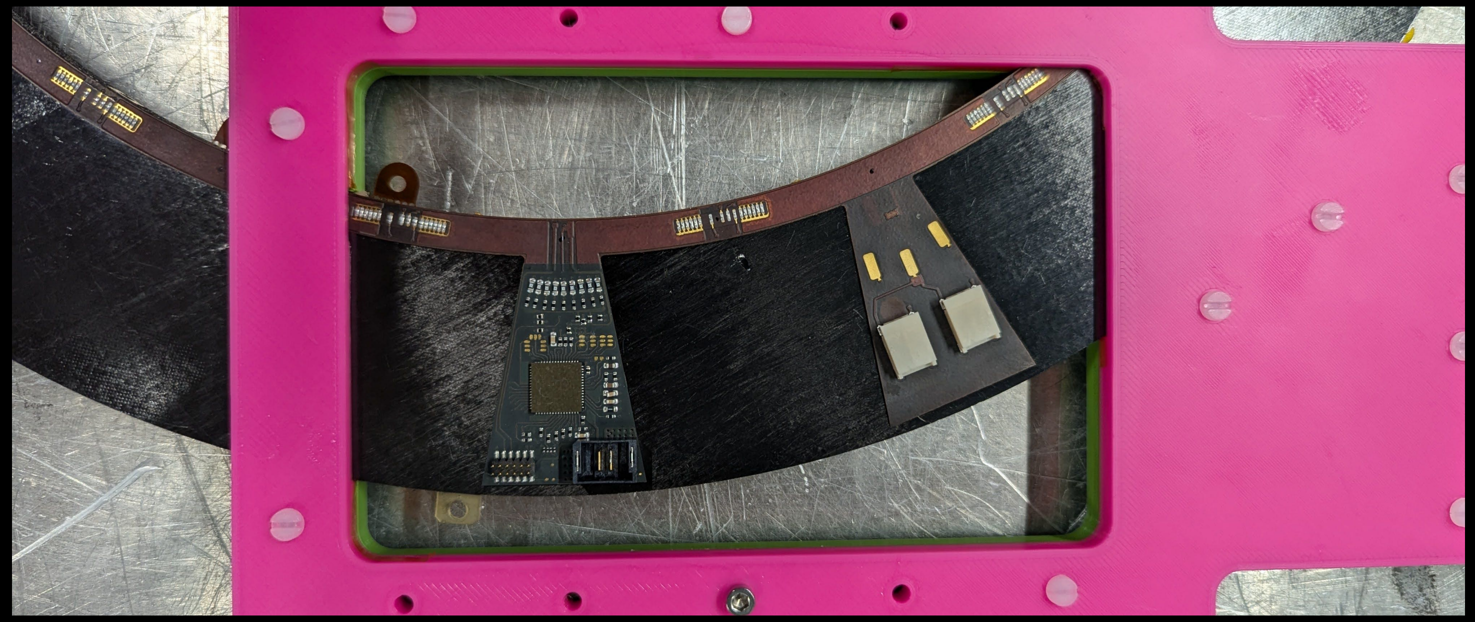




Recent Measurement at PSI

- Identified low positron rate (and beam energy spread of 5%) as limiting factors
  → **1 week of beamtime in Oct. at PSI PiM1** (in collaboration with CMS and Mu3e)
- Measured >550 cm2 of PP0s, modules, calibration samples, *without DUT hit*
- **New challenge:** mixed beam (π/μ contamination)
  → solved by measuring time-of-flight (ToF) of particles using a TimePix4 plane behind telescope
- **Full analysis in-progress**

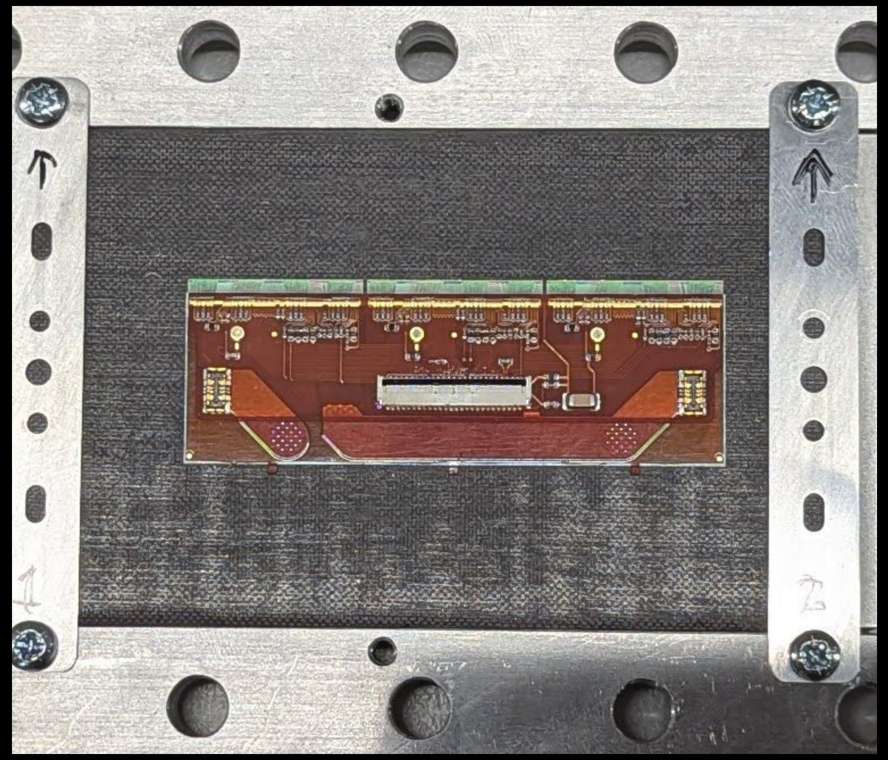
Outer Endcap Half-ring



Inner System PP0

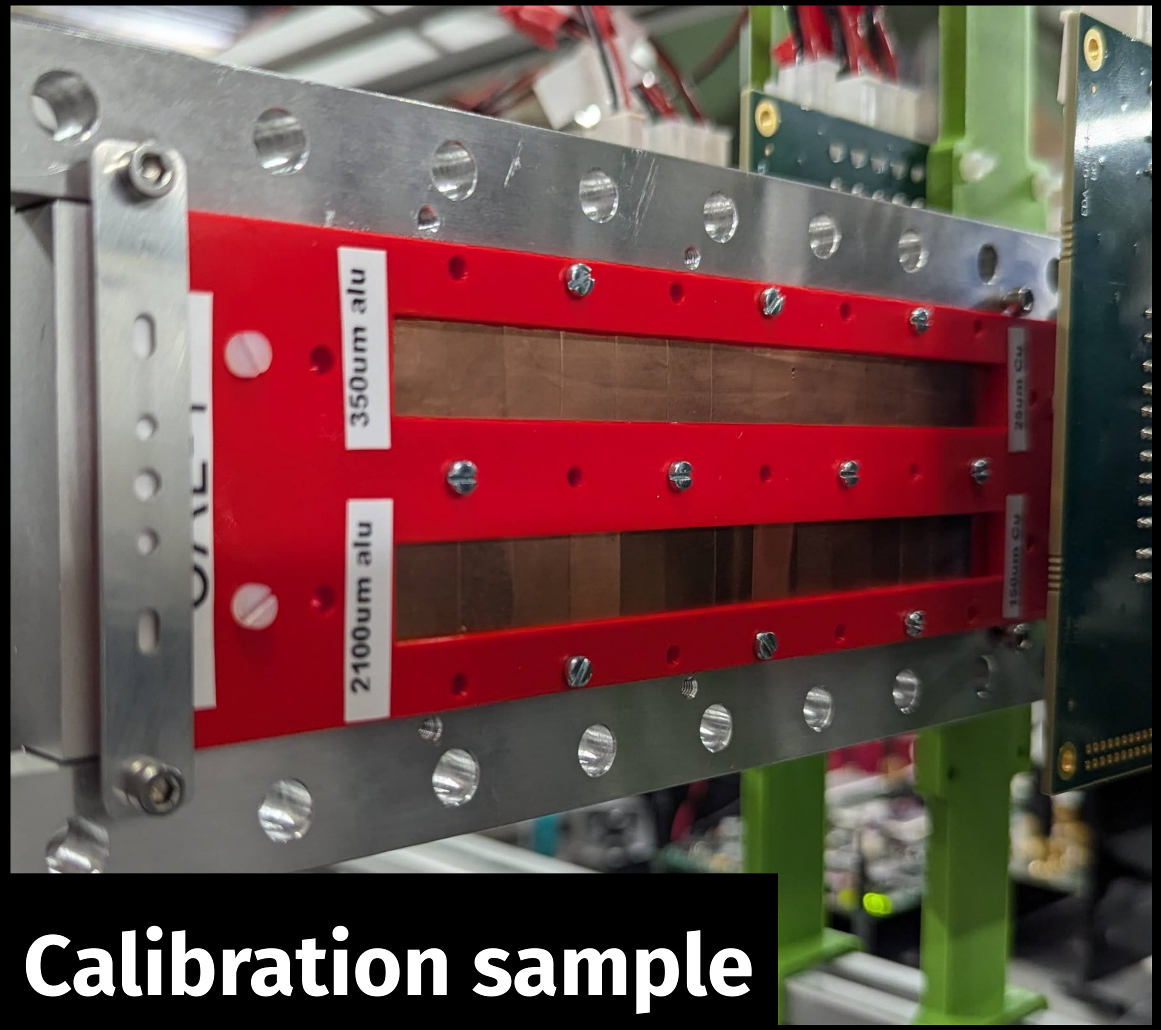
Outer Barrel Flat PP0

Inner System Triplet Module

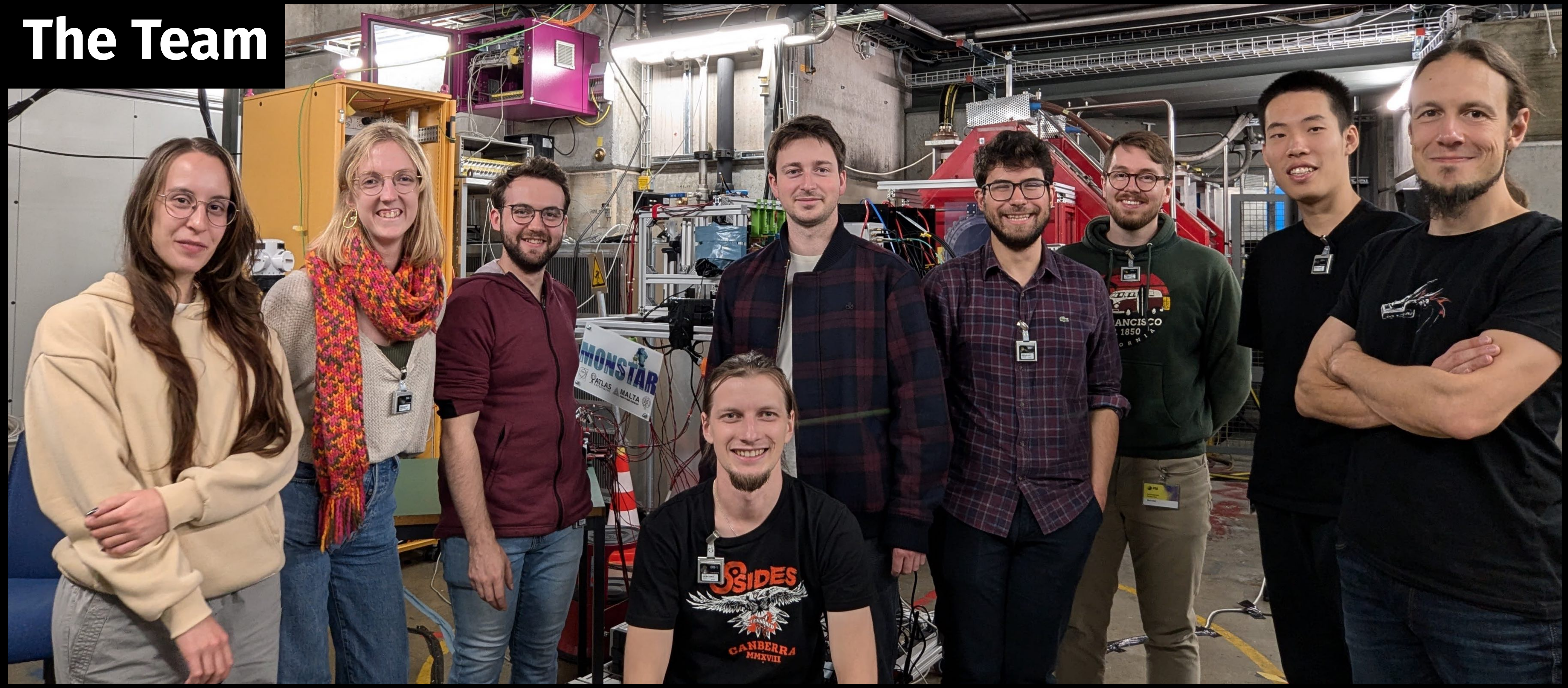


This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101057511.
EURO-LABS

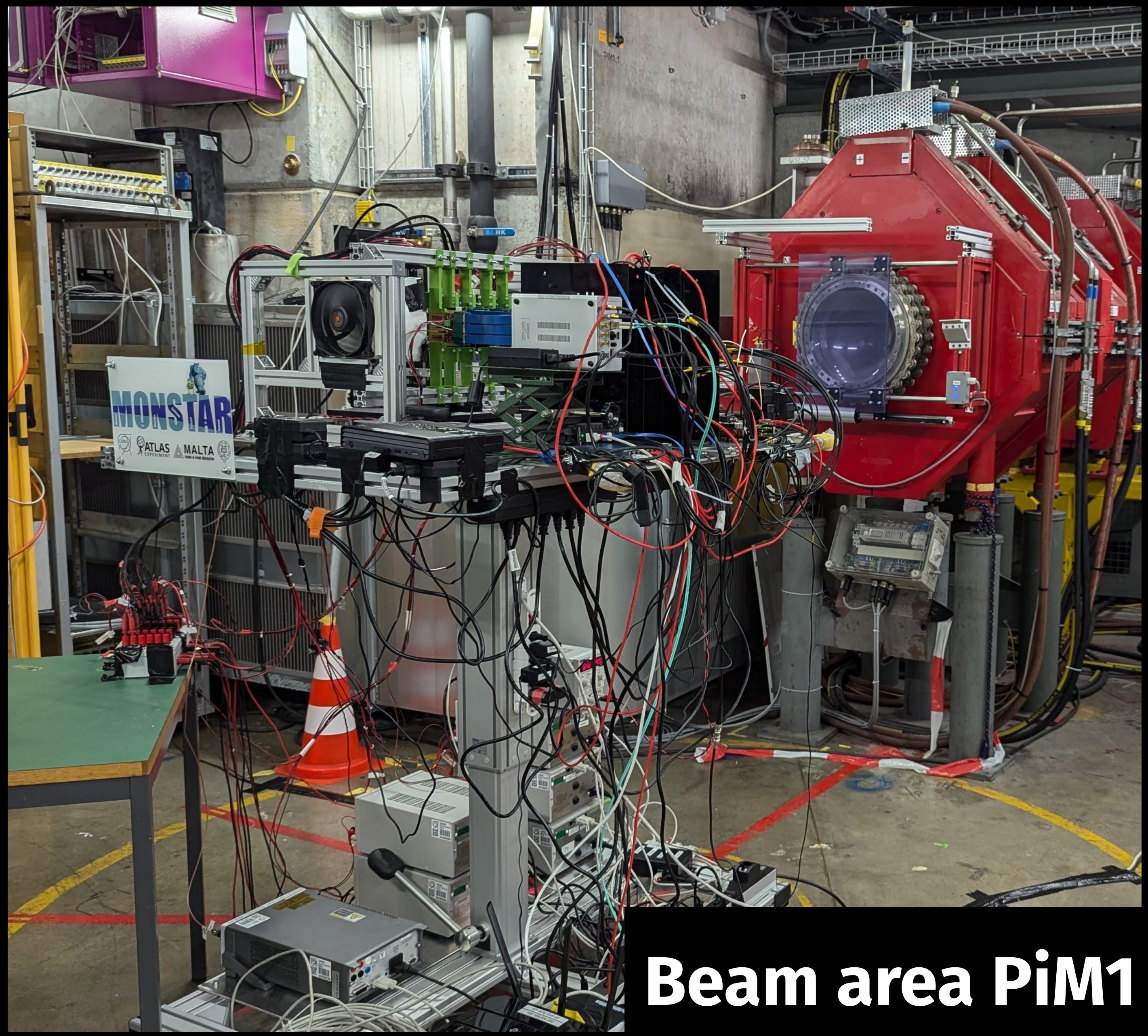
Recent Measurement at PSI



Calibration sample

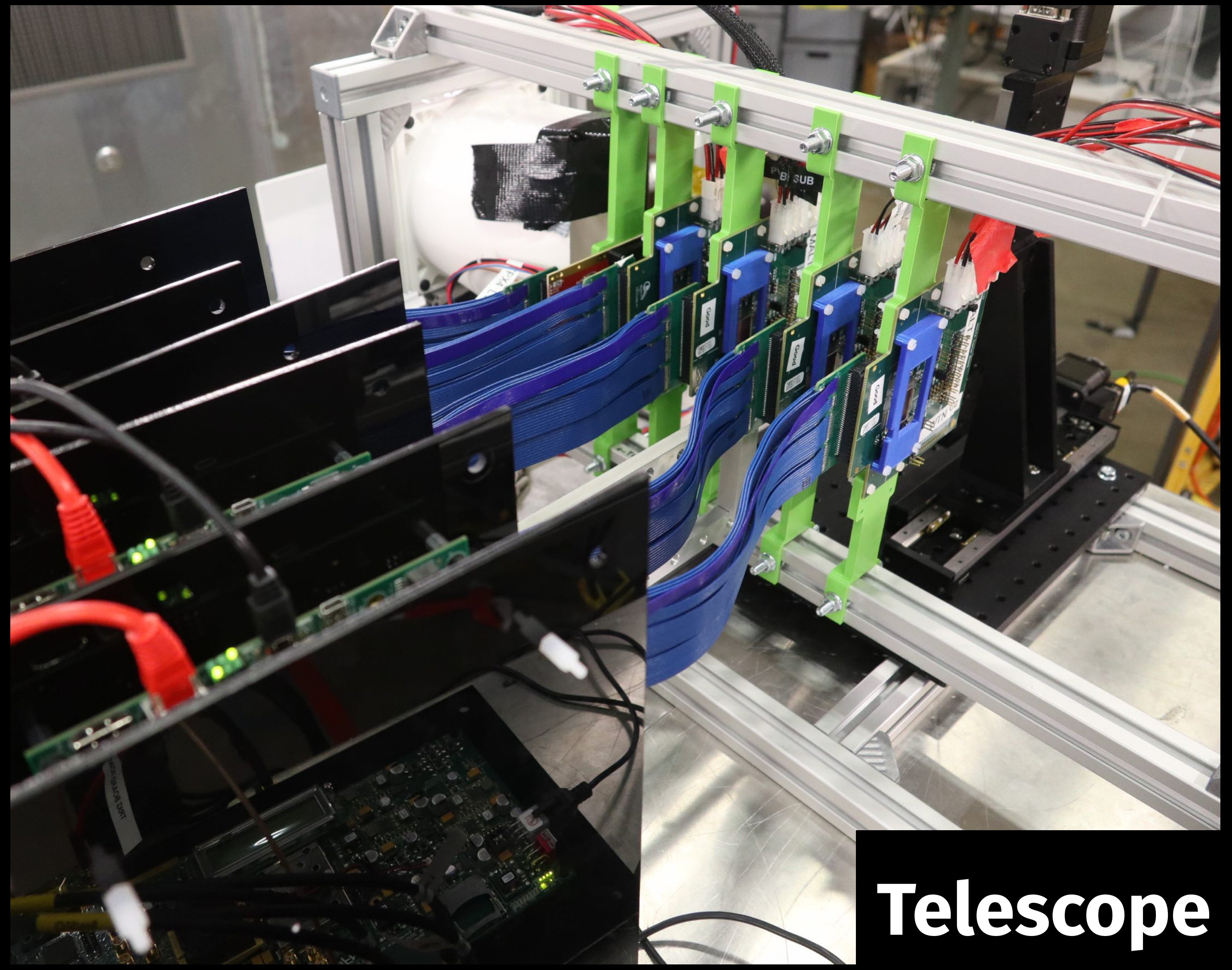

The Team


XY-stage, sample harness



Beam area PiM1

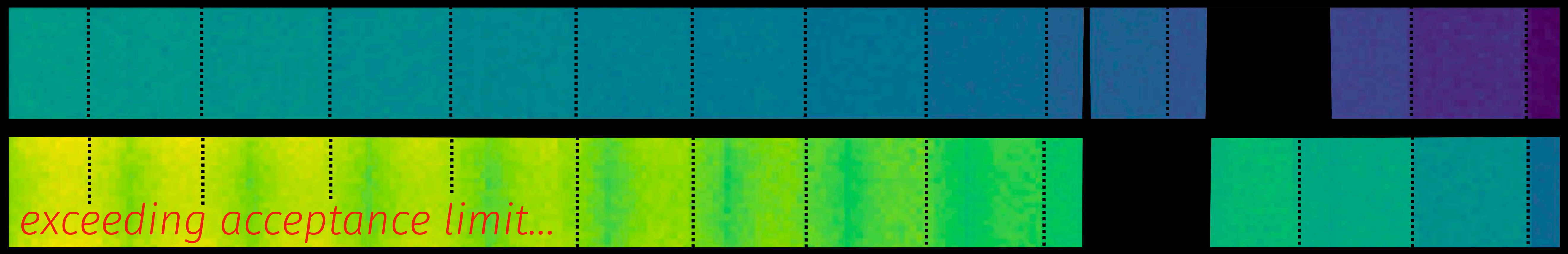
Monitoring/webcam

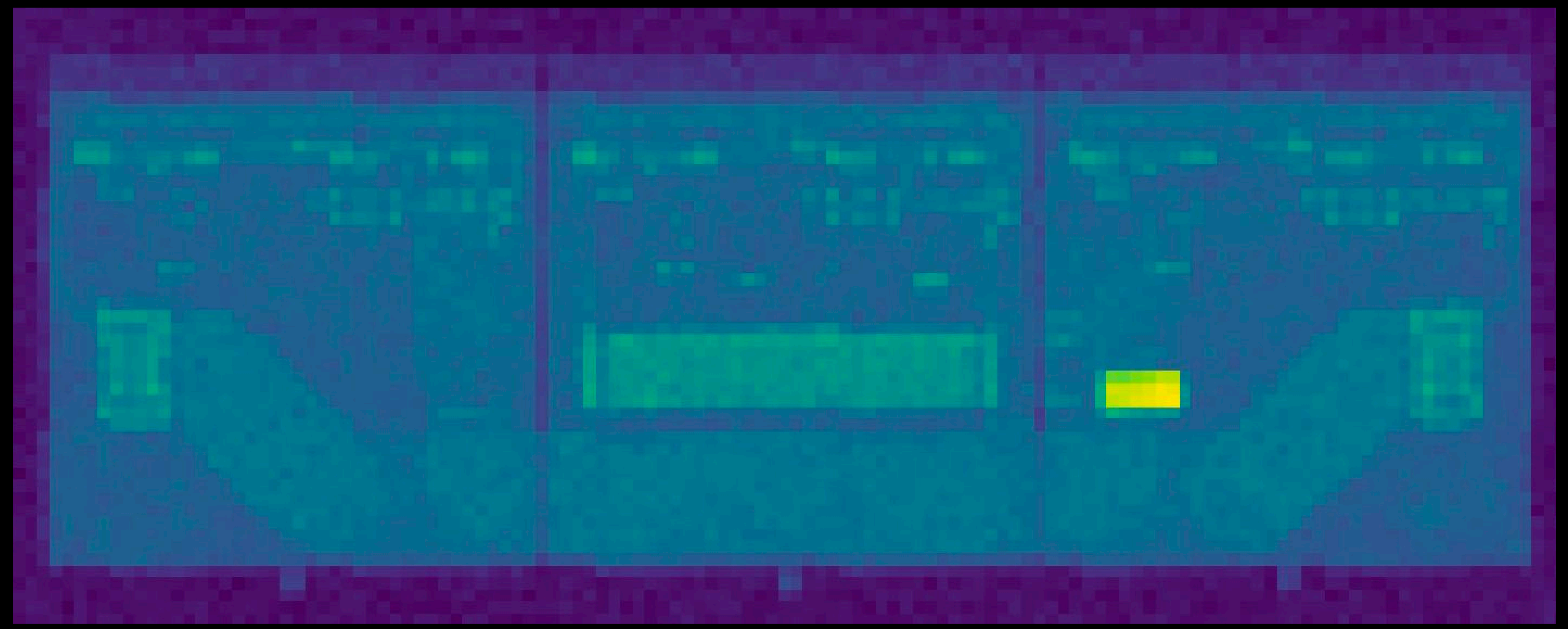

Telescope

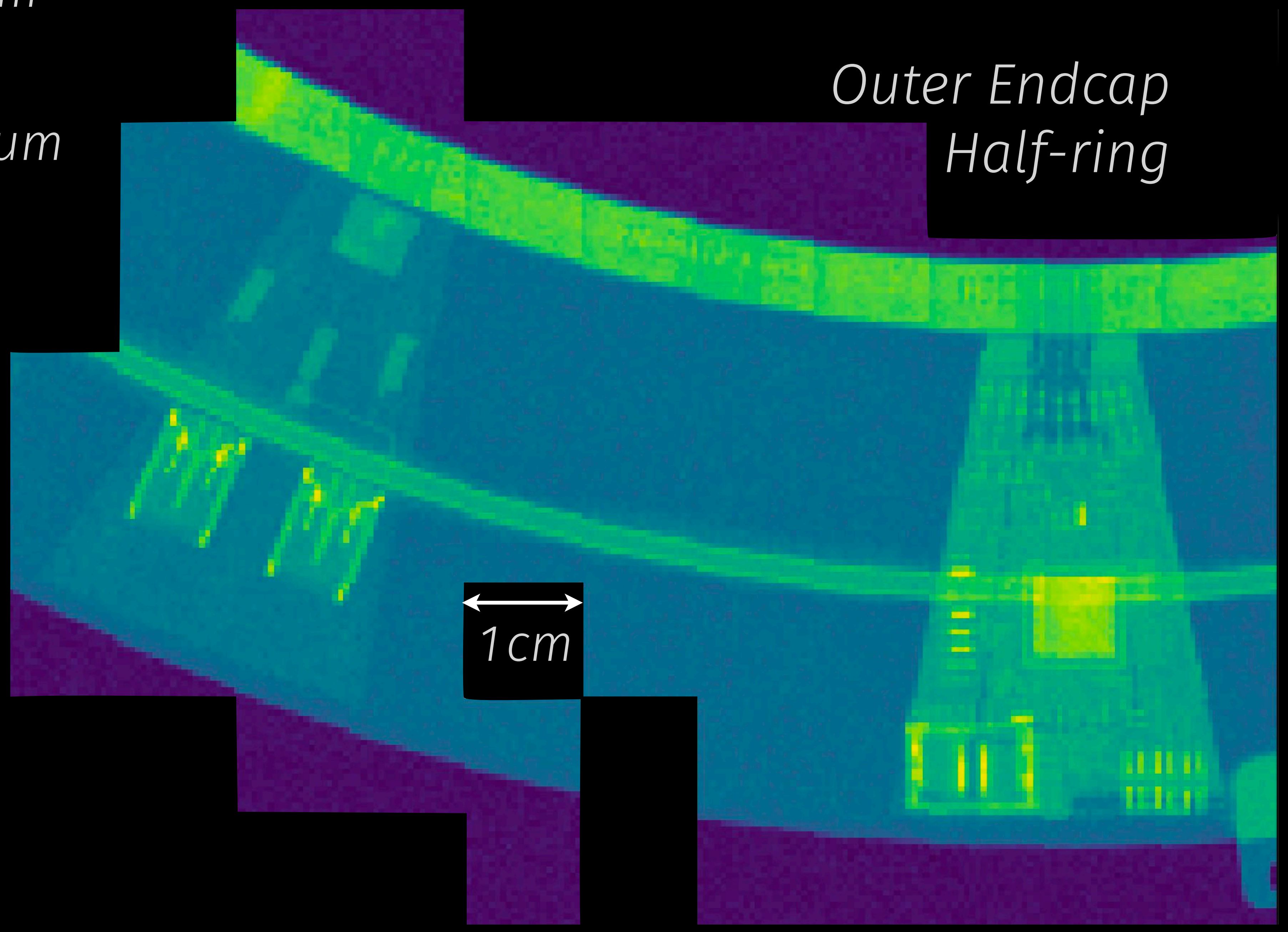
Sneak Peek - Prelim. Results

- Initial coarsely-binned analysis was performed almost real-time for most samples (without full set of subtractions and ToF information/Particle ID)
  - x/X_0 *axis removed - “blinded” for now - but features clearly visible in map*

Cu calibration sample







all images in (not the same) log scale

Where next for Material?

ATLAS EXPERIMENT

MONSTAR
Multiple Or Negligible Scattering Telescope As Required

Demonstrated ability to measure large areas in short times (130 cm^2/day) to high reso. (sub-mm)

Template fits of multi-layer x/X_0 estimates to TB data

- Develop framework to "tune" 2d-resolved estimates to data
- Should help produce accurate estimates with only small sample areas measured

Migrate to low-X_0 sensor that can handle rates > 15kHz

- e.g. ALPIDE, MuPix11, ITkPix+thin film
- Even higher measurement rates
- PSI can probably reach 50+kHz

Database of industry components

- Systematic study of common SMDs, connectors, glues, support materials
- Establish a database to help guide design choices for future experiments

Attempt equivalent measurement in ATLAS Data

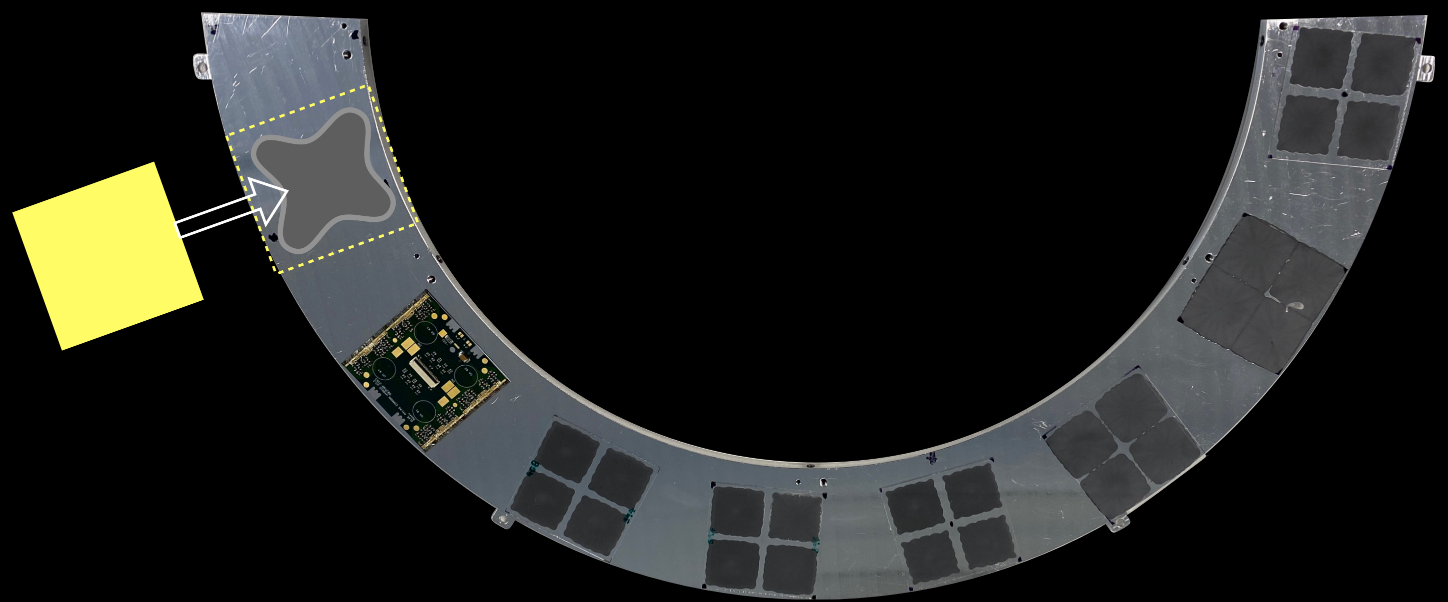
- Rebuild tracks as broken-line-fits in subsequent pixel layers (or prim. vtx.)
- Does not rely on simulation, more fine-grained than usual tuning of material model (e.g. entire IBL +10%)

The ITk is one of the largest, most complex, and most ambitious silicon detector projects ever attempted...

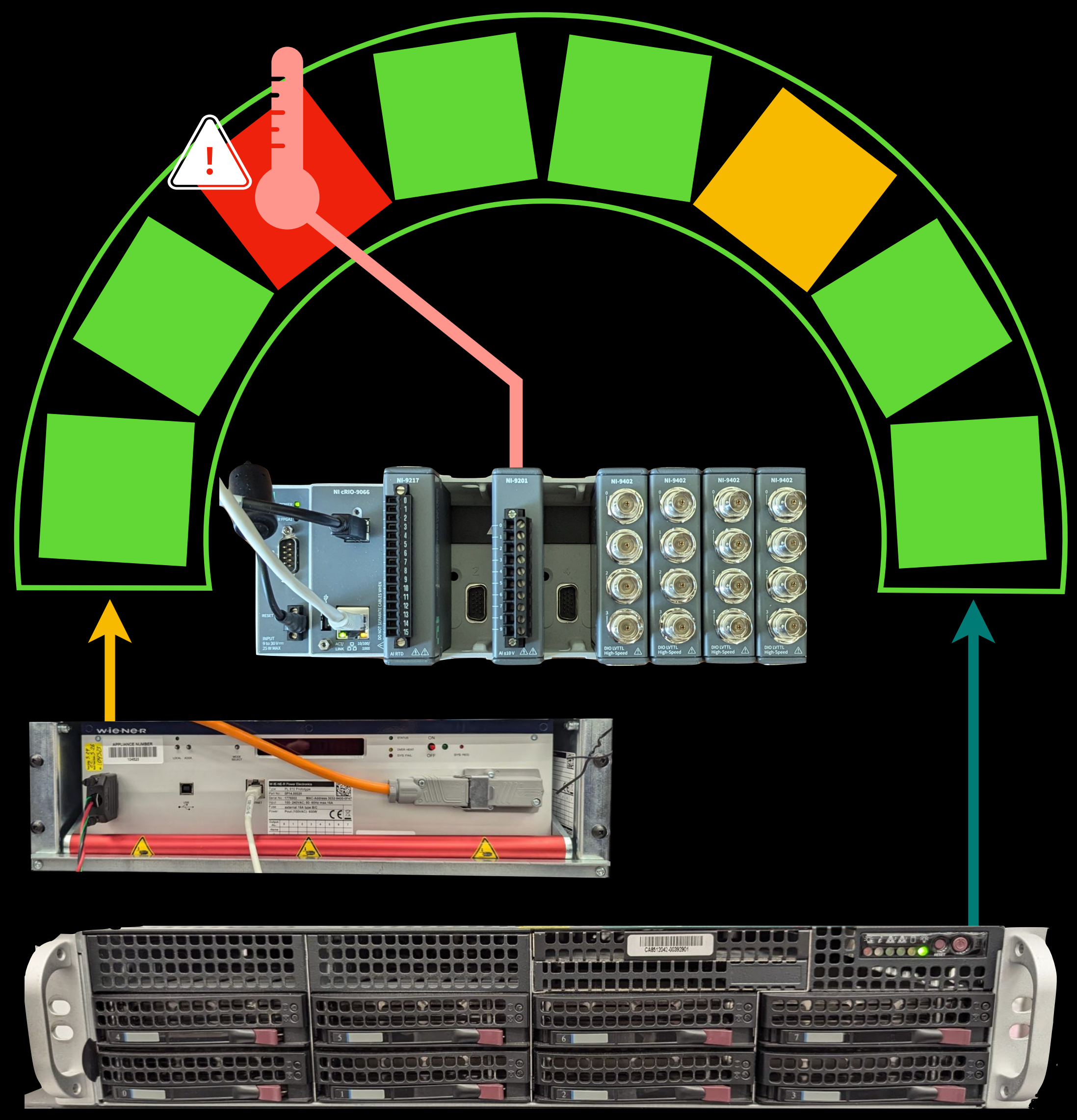
Summary

- Module+ring construction processes in Oxford have been developed and are being fine-tuned
- Some work still to go, but close to ready to begin with pre-production

Step 1: Building the ITk



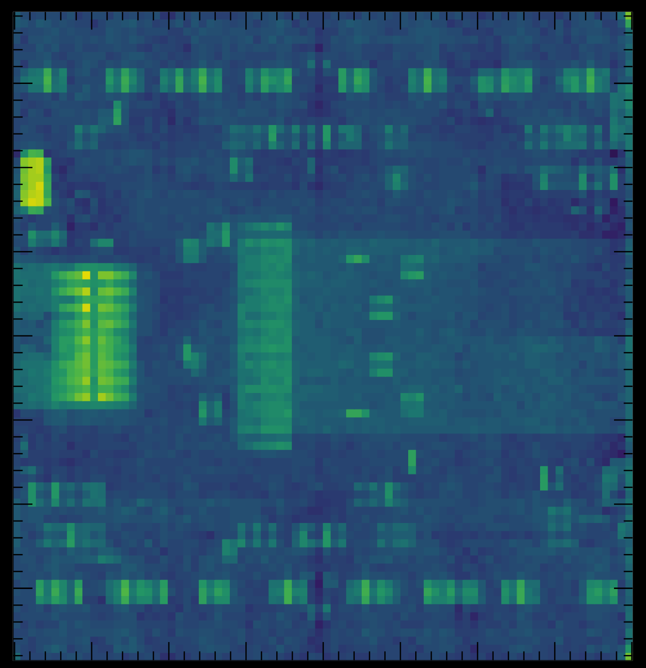
Step 2: Testing the ITk



- **Ring-testing setup** well-advanced, preparing to test first pre-production rings

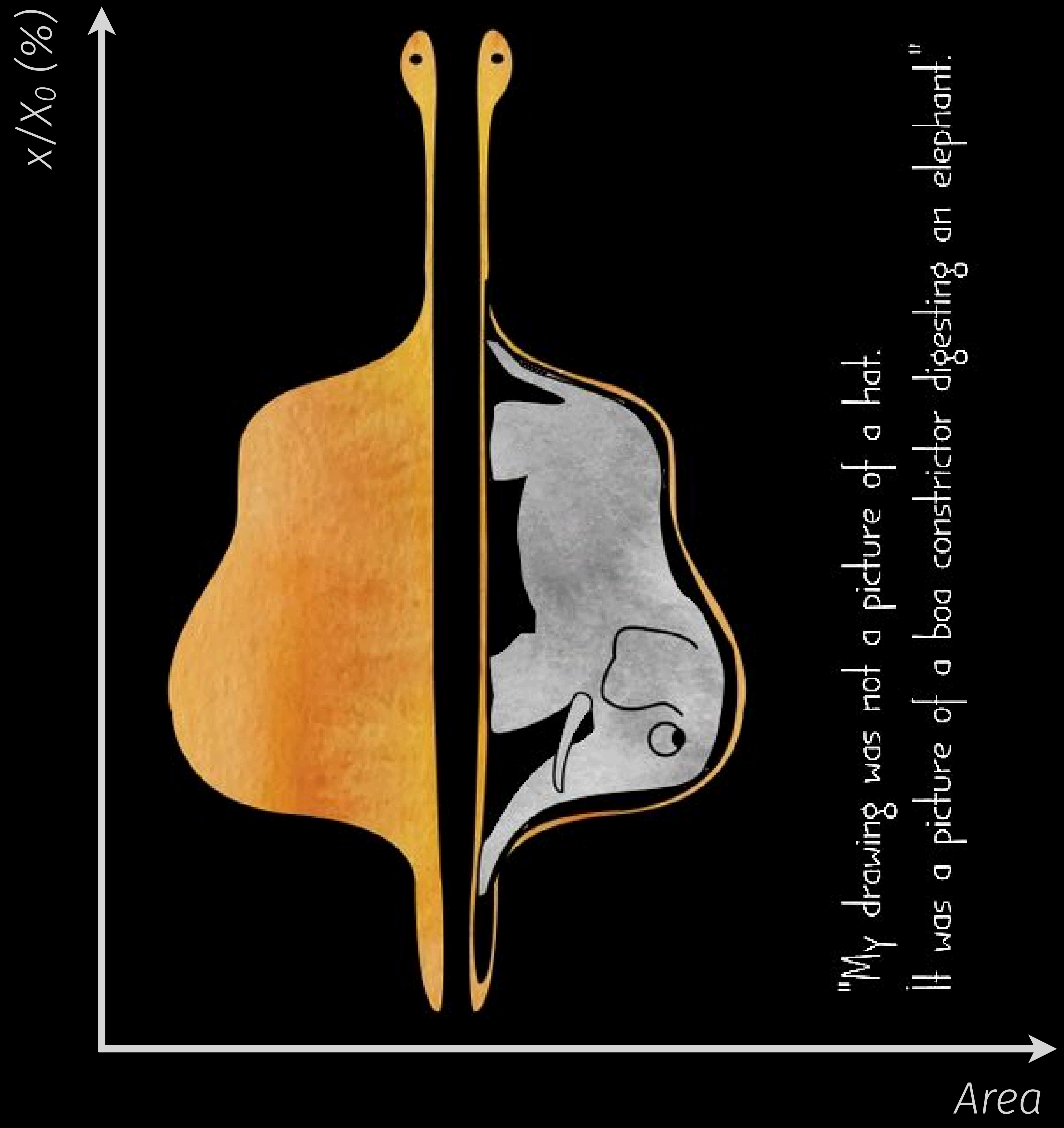
- Material content is critical for the performance of tracking detectors
- We have measured x/X0 for a quad module, and are continuing with services and mechanics

Step 3: Measuring the ITk



Thank you!

Questions?



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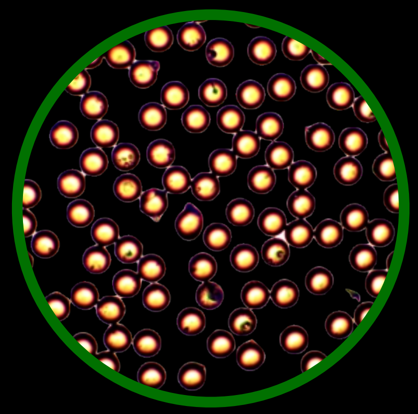
Backup

Glue Optimisation

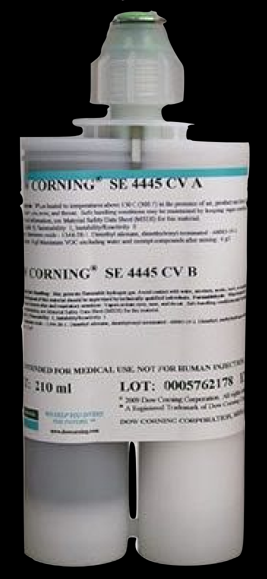
ATLAS EXPERIMENT



CoSpheric Soda Lime 94–100 um

Glass spheres → *mix in*

SE4445 Cartridge → *separate* → SE4445 Part B, SE4445 Part A



Planetary Mixer *30 s @ 3000 rpm* ⇄ SE4445 Part B

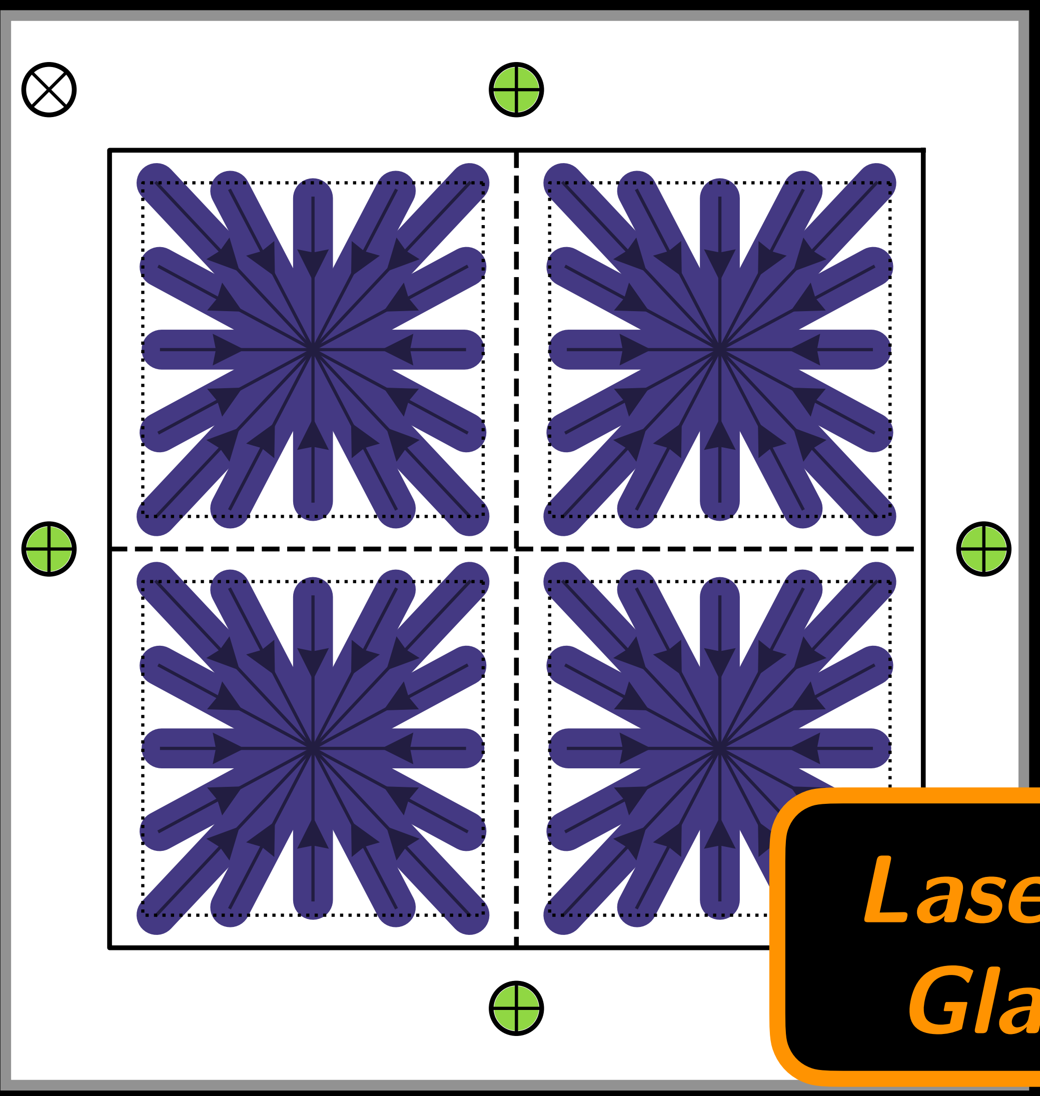
SE4445 Part B, SE4445 Part A → *weigh* → **Planetary Mixer** *30 s @ 3000 rpm x2*

SpeedMixer DAC-150.1 FVZ-K

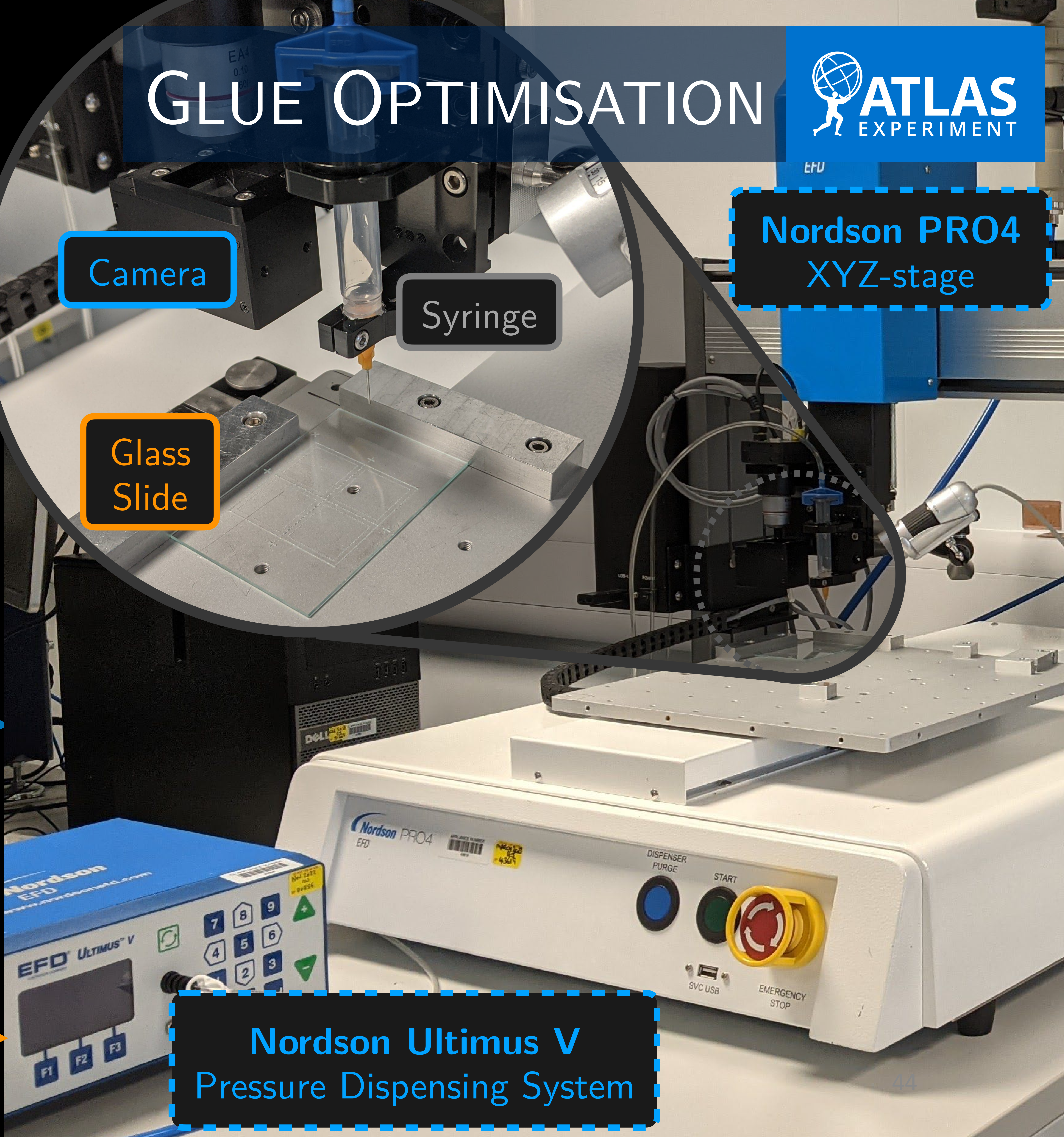
fill syringe / *mix syringe*

Glue syringe →

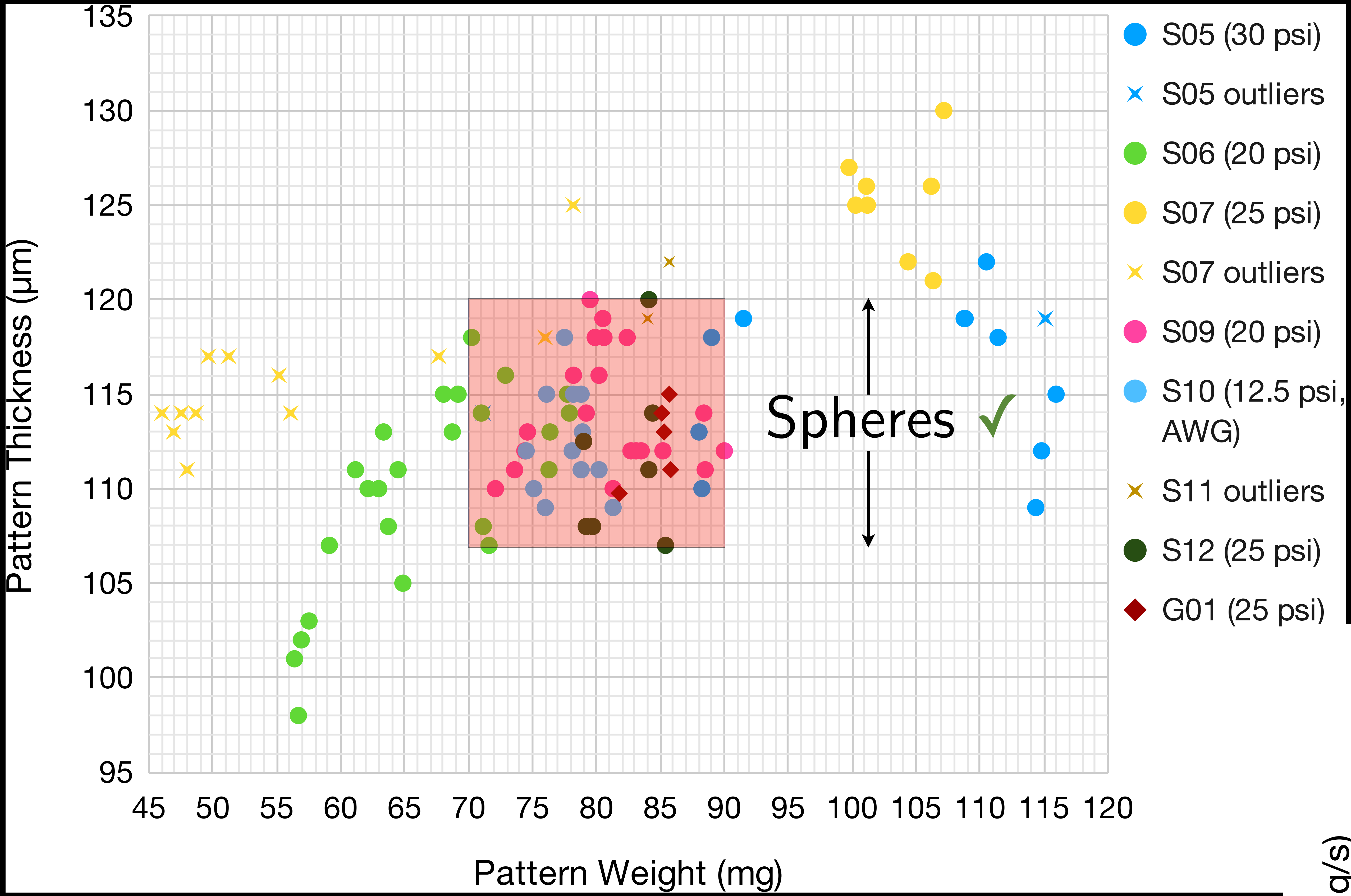
Program →

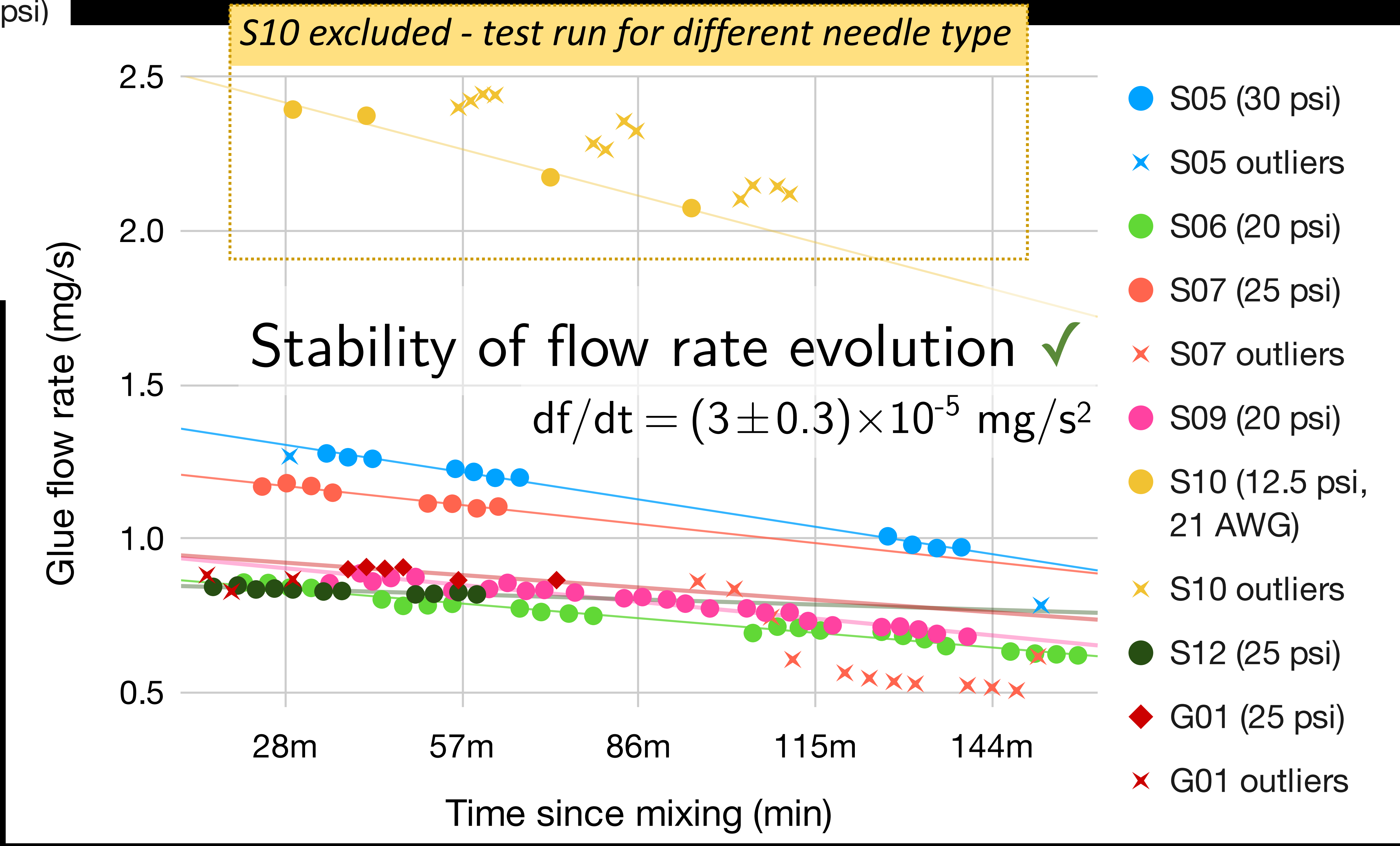


Laser-etched Glass Slide →

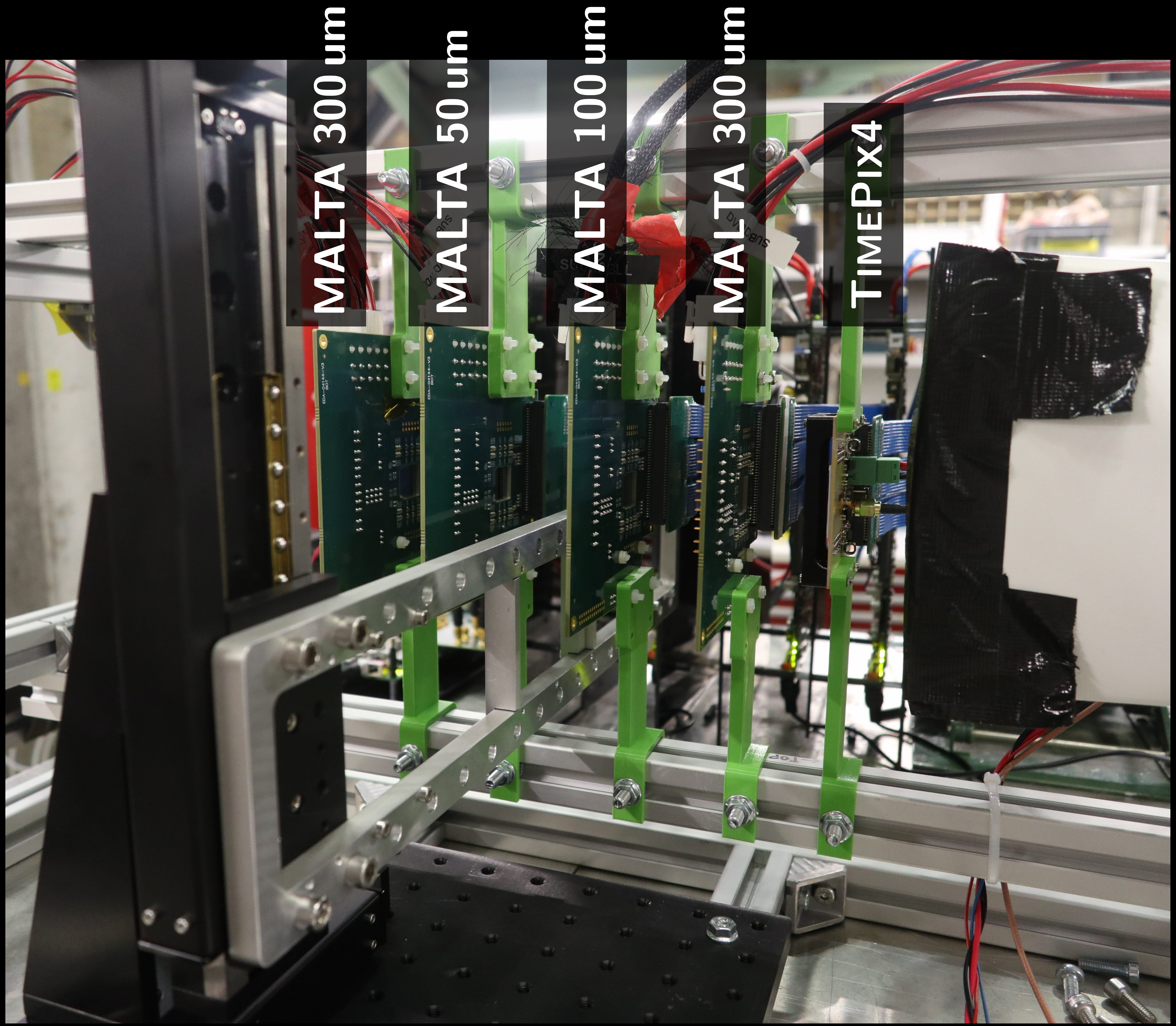


Performance

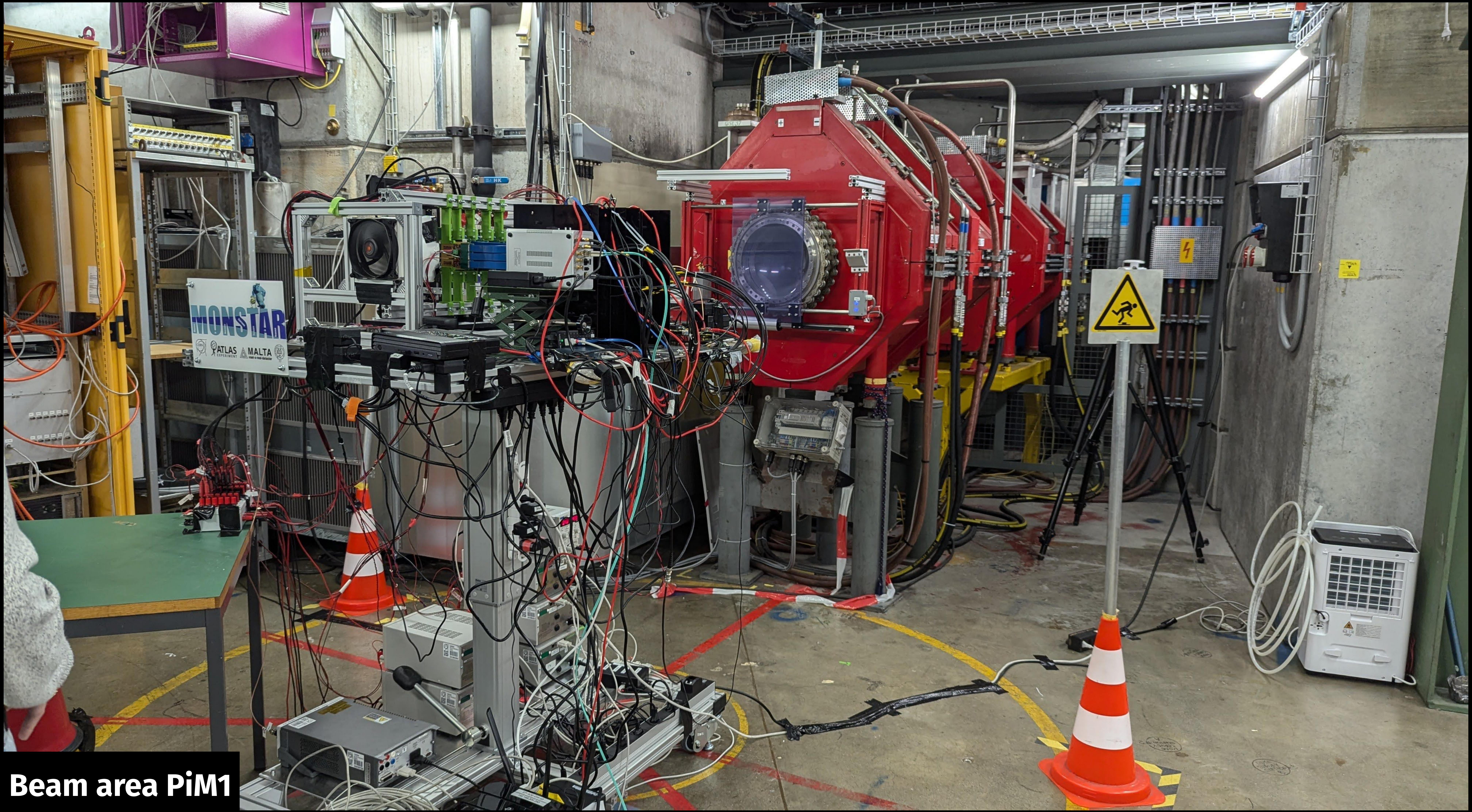




Recent Measurement at PSI

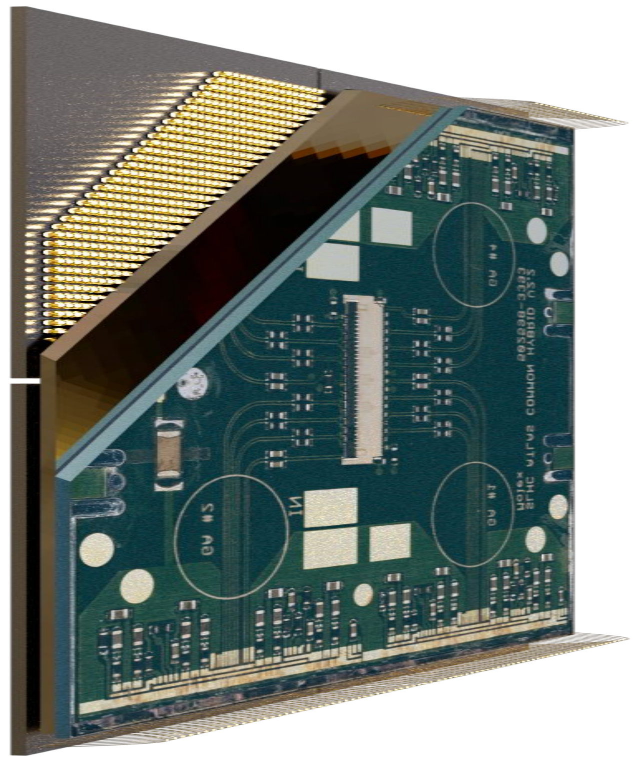


Recent Measurement at PSI

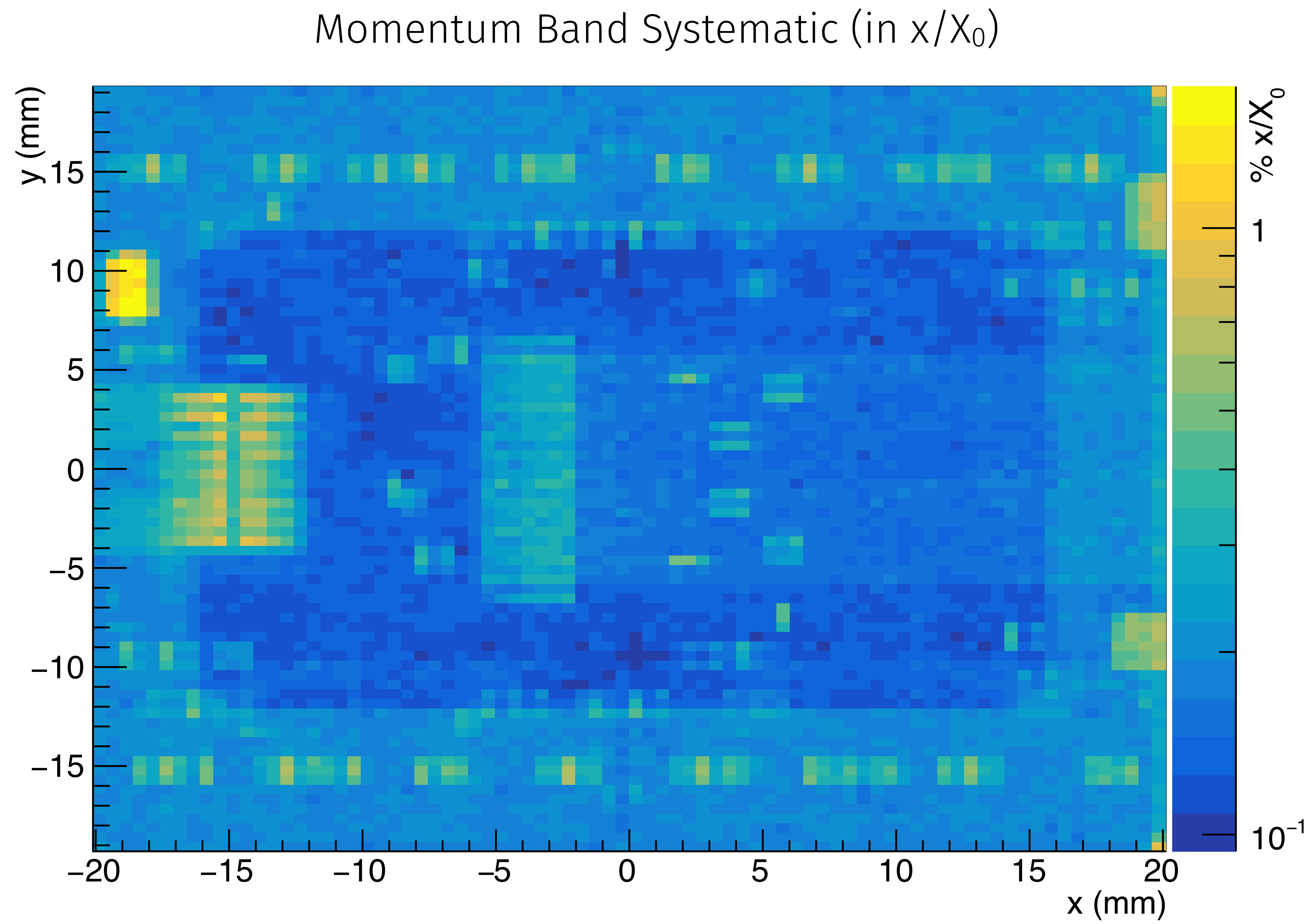


Beam area PiM1

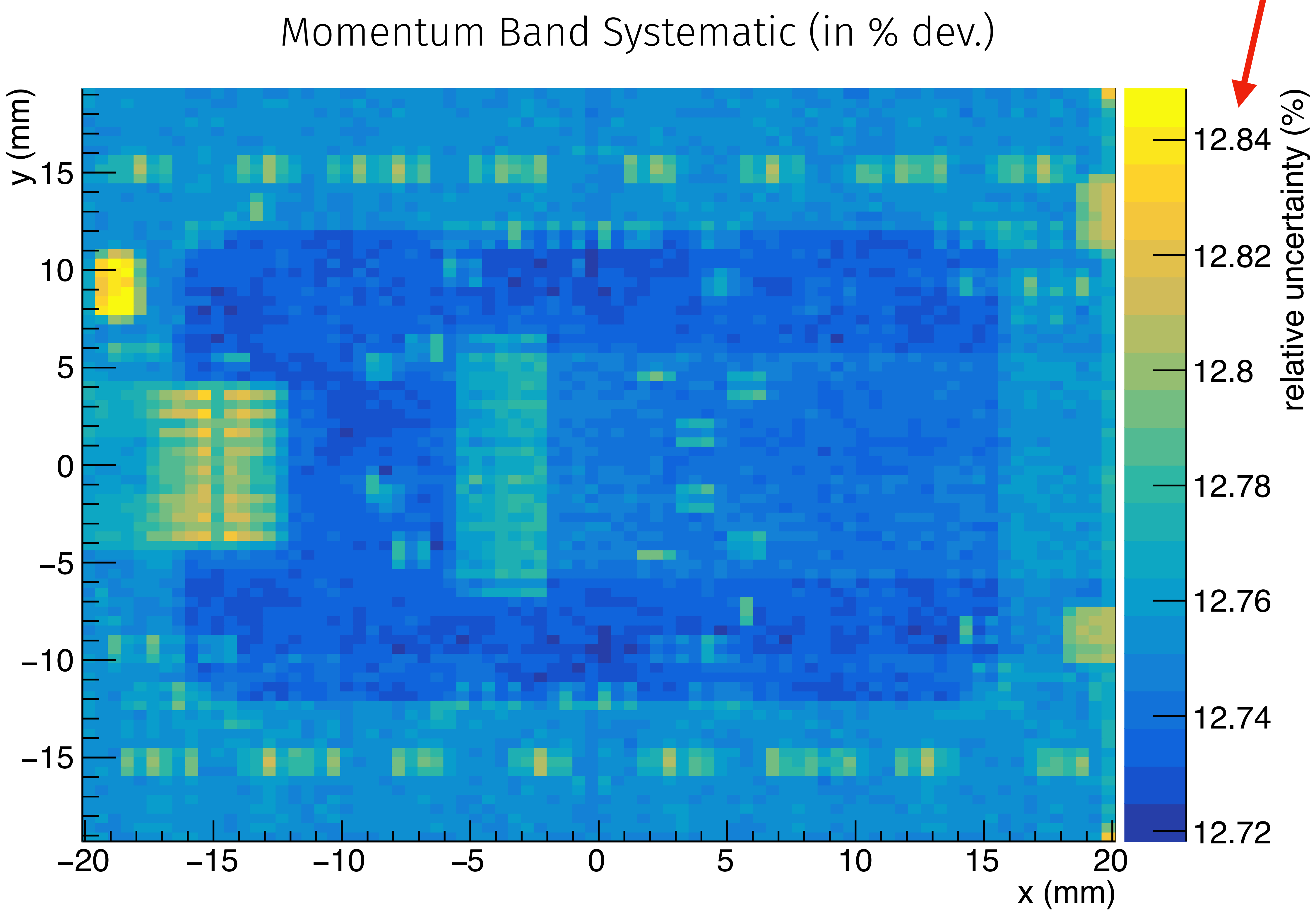
Momentum band systematic



- Air measurement cross-check with MALTA 50um measurement appeared to confirm 5% momentum band - 59 MeV on 1200 MeV beam
- **Global average: 12.79%** - largest systematic in essentially all bins

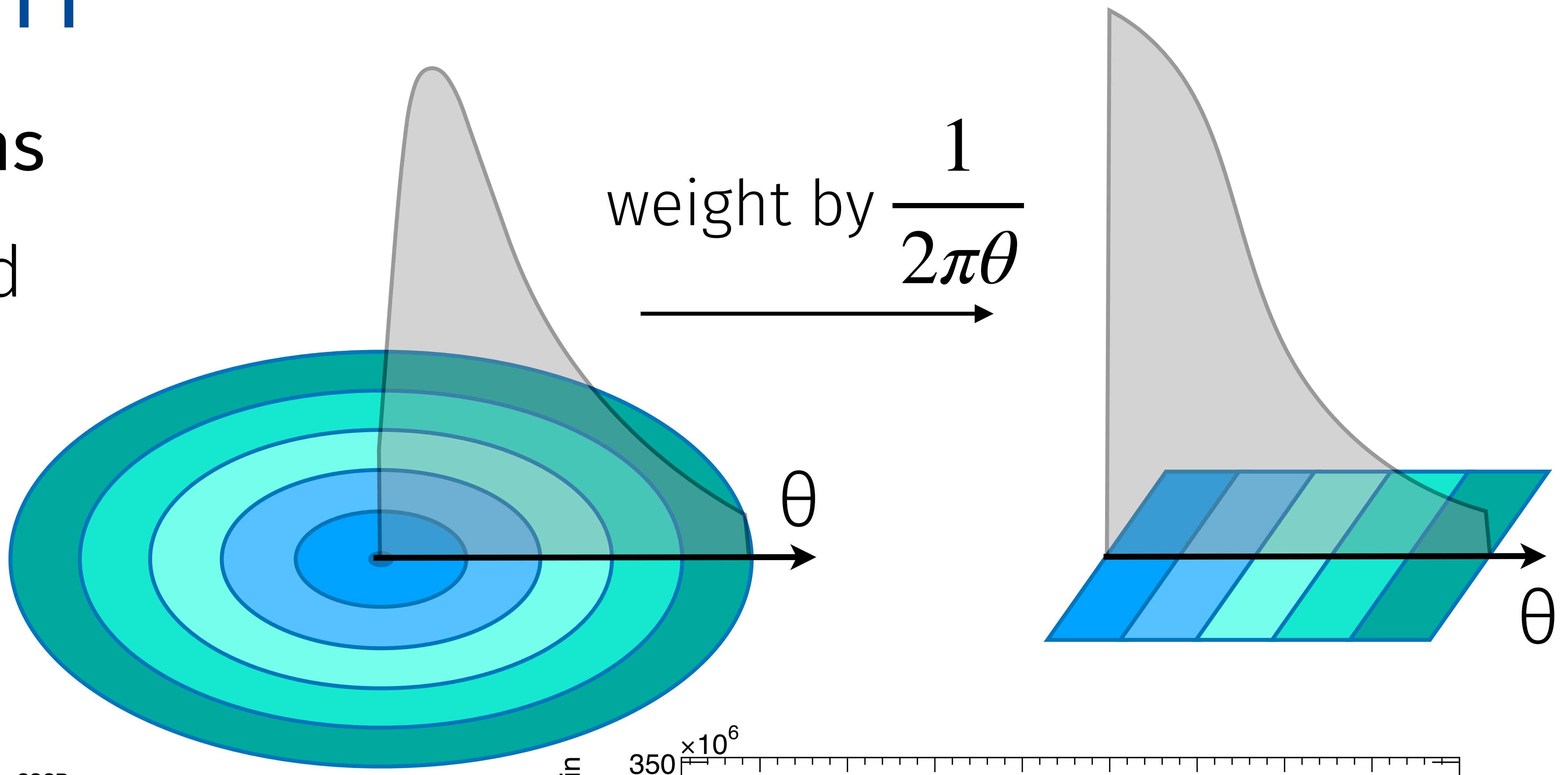


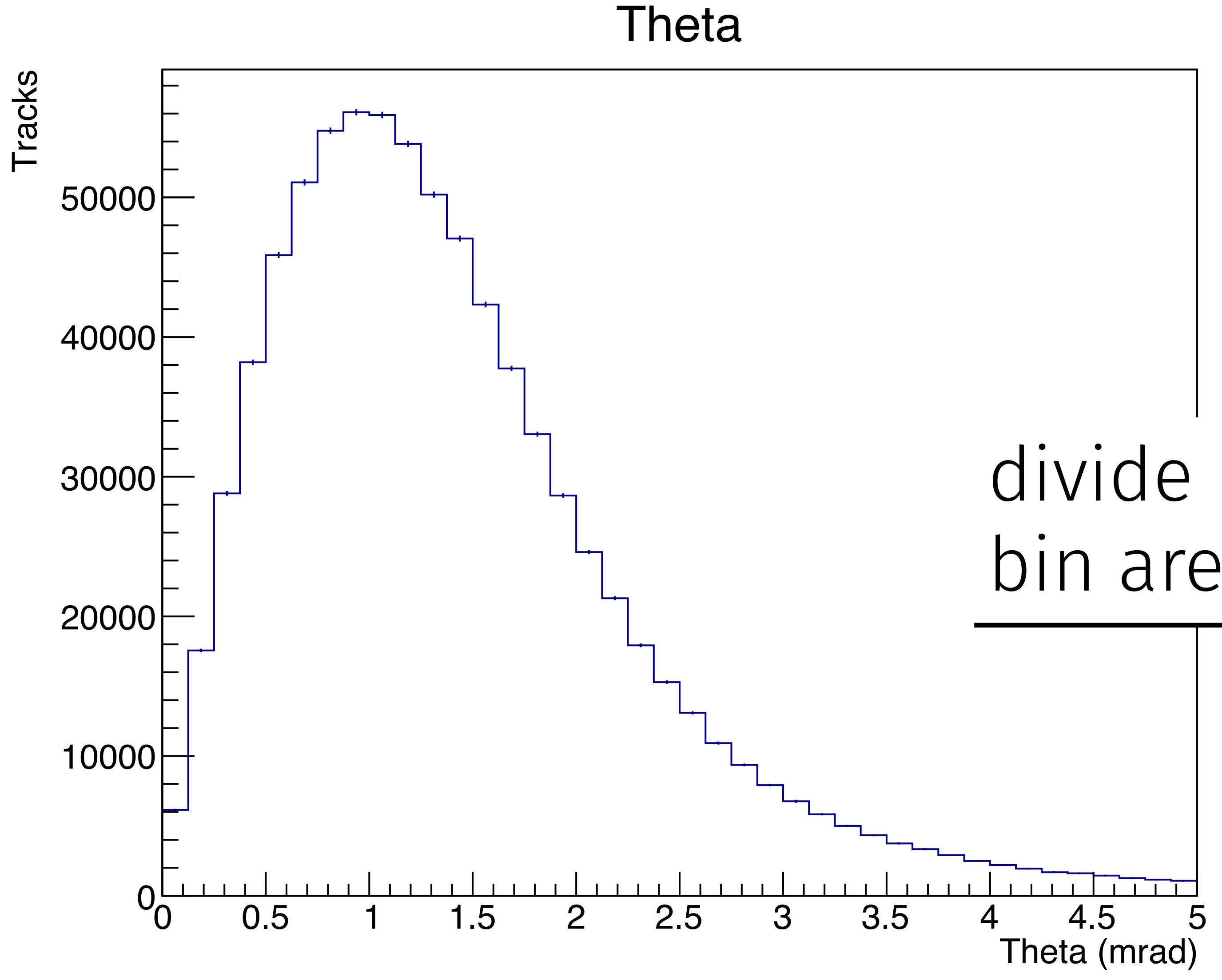
This axis is completely collapsible



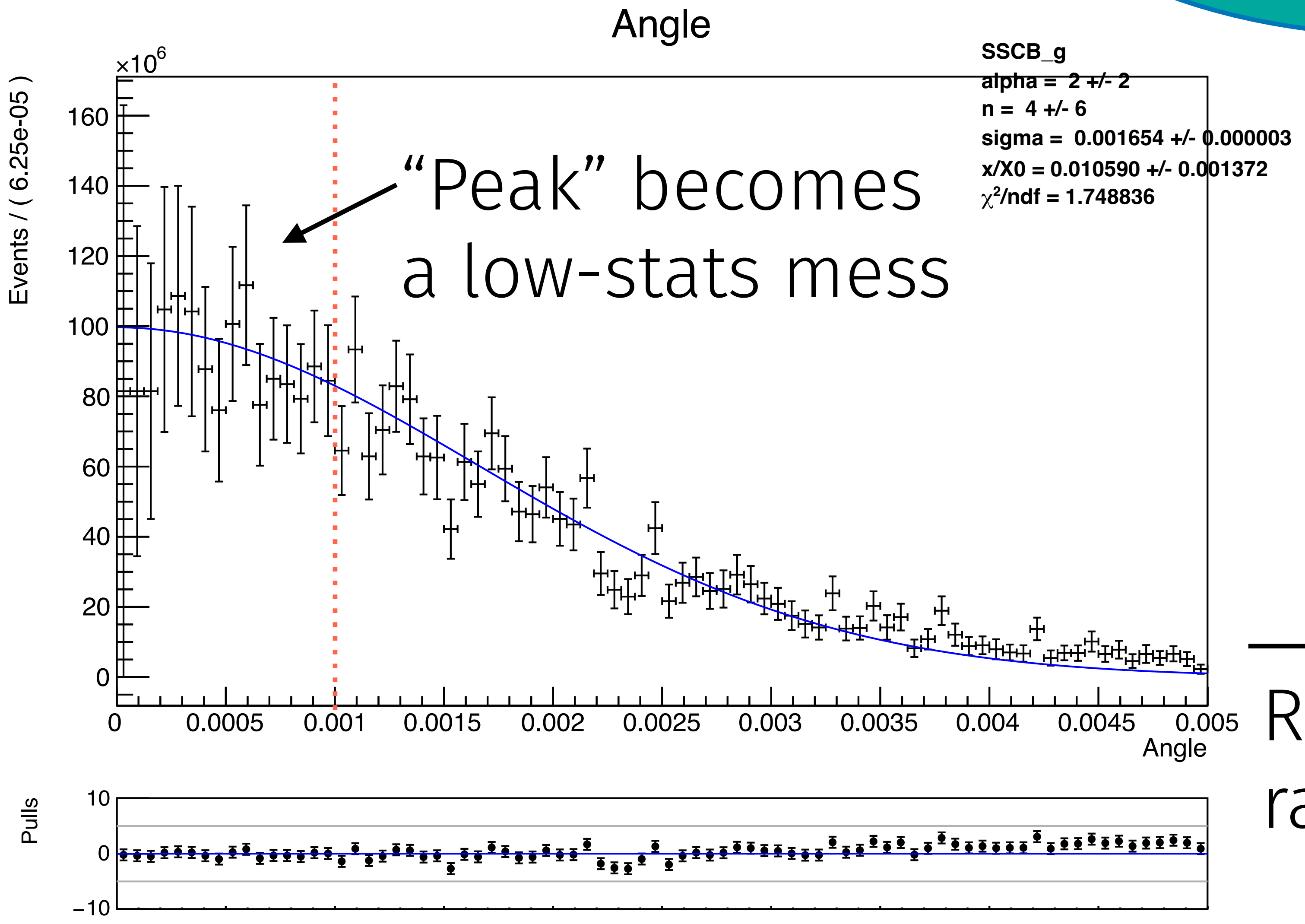
Global angle coordinate system

- Highland formula is derived for **projected angle distributions**
  - These have in inherent directionality (projected plane) and can be sensitive to hard material boundaries
- Would like to use **phi-invariant “global” angle**, but need to “project” it from a radial bins to a cartesian ones first

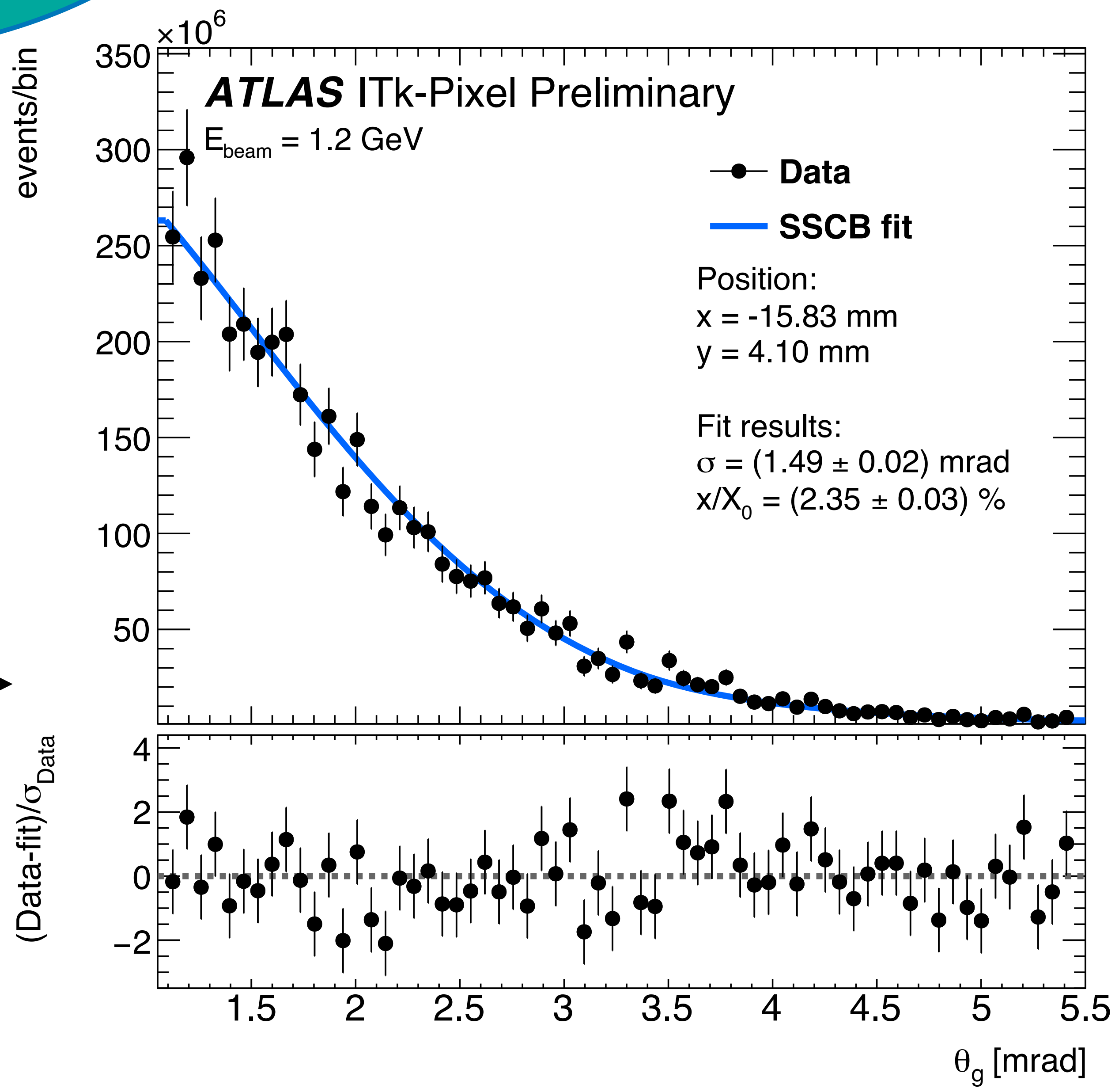




divide by bin area



Reduce fit range



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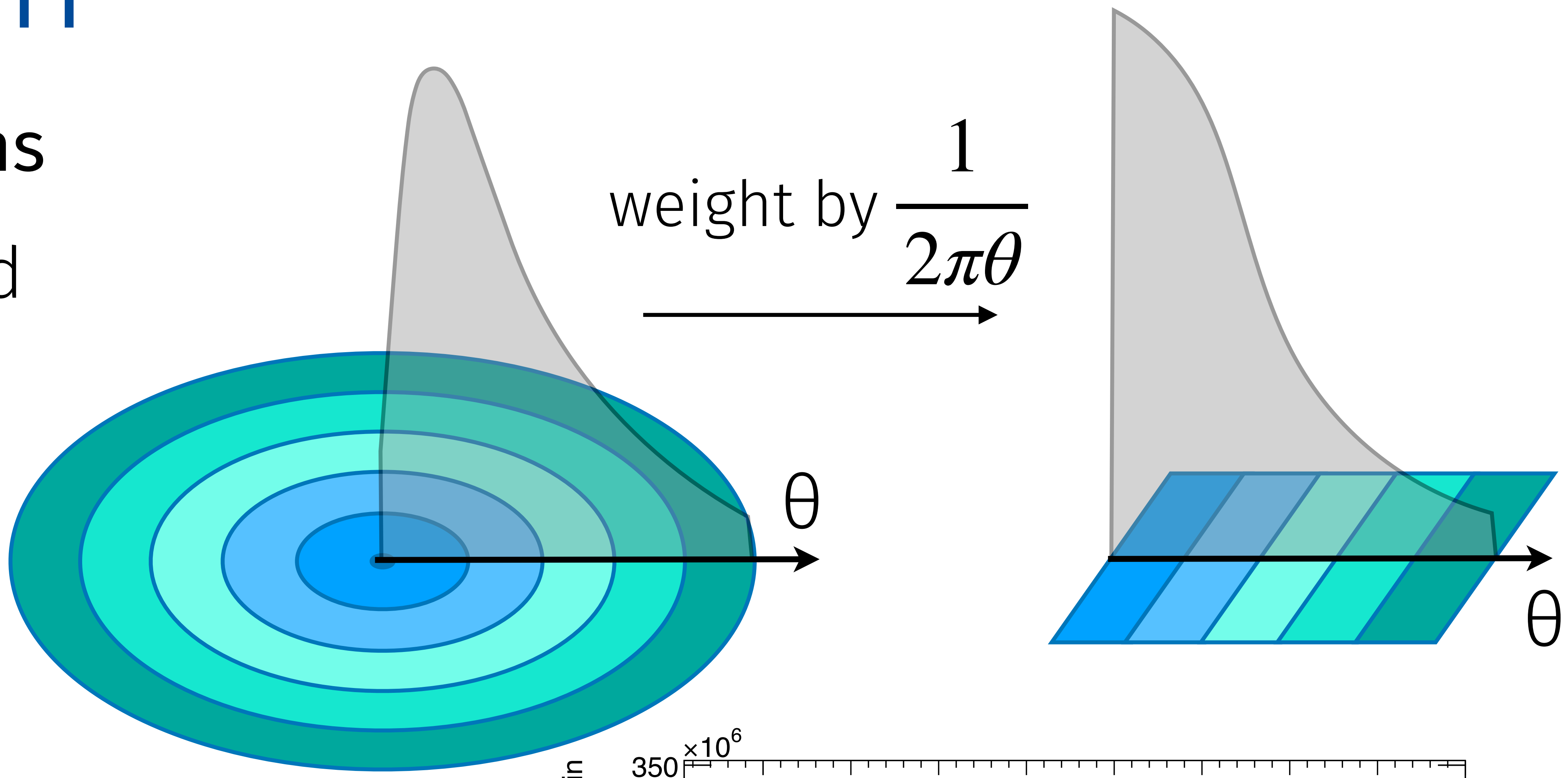
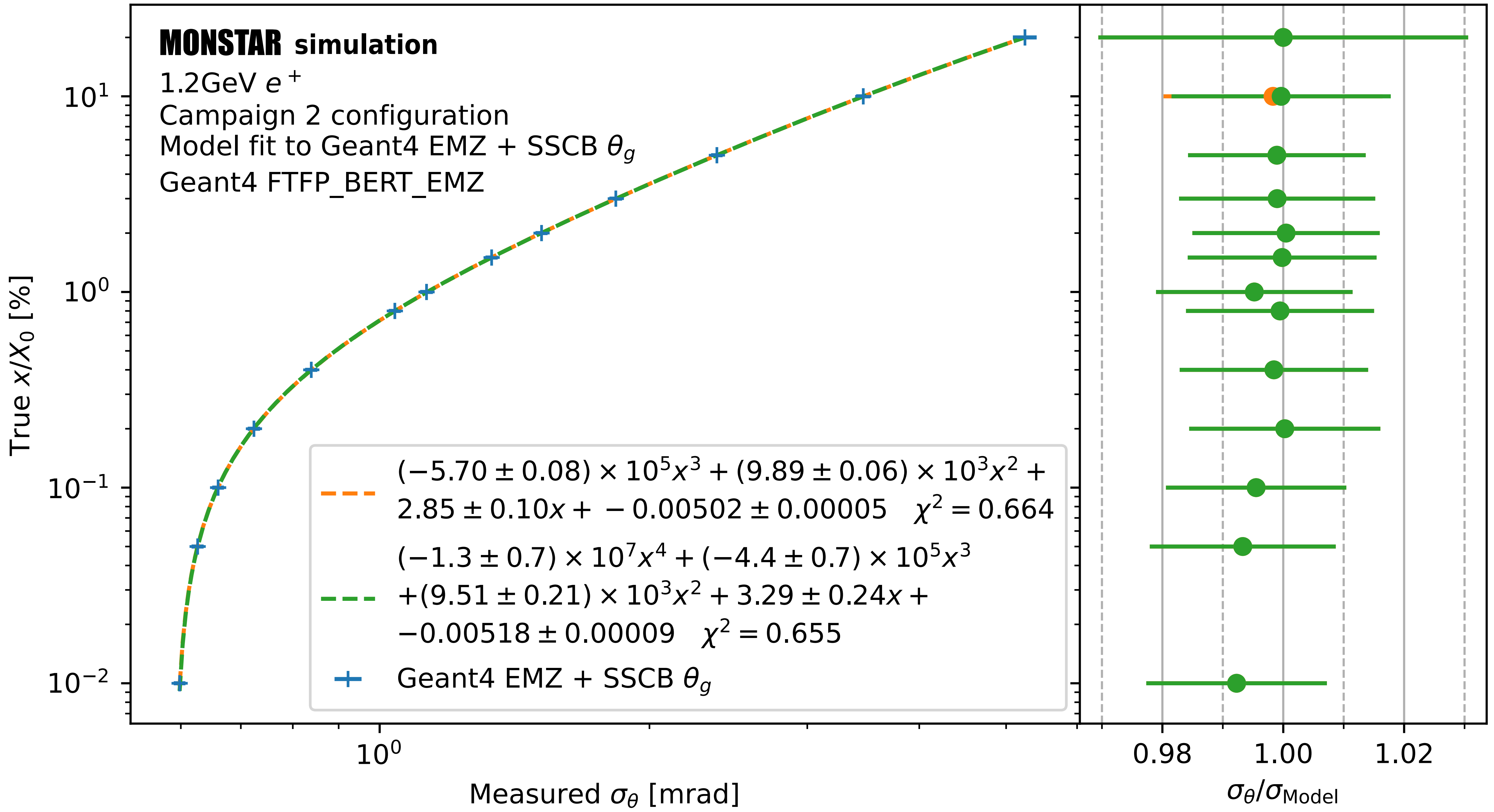
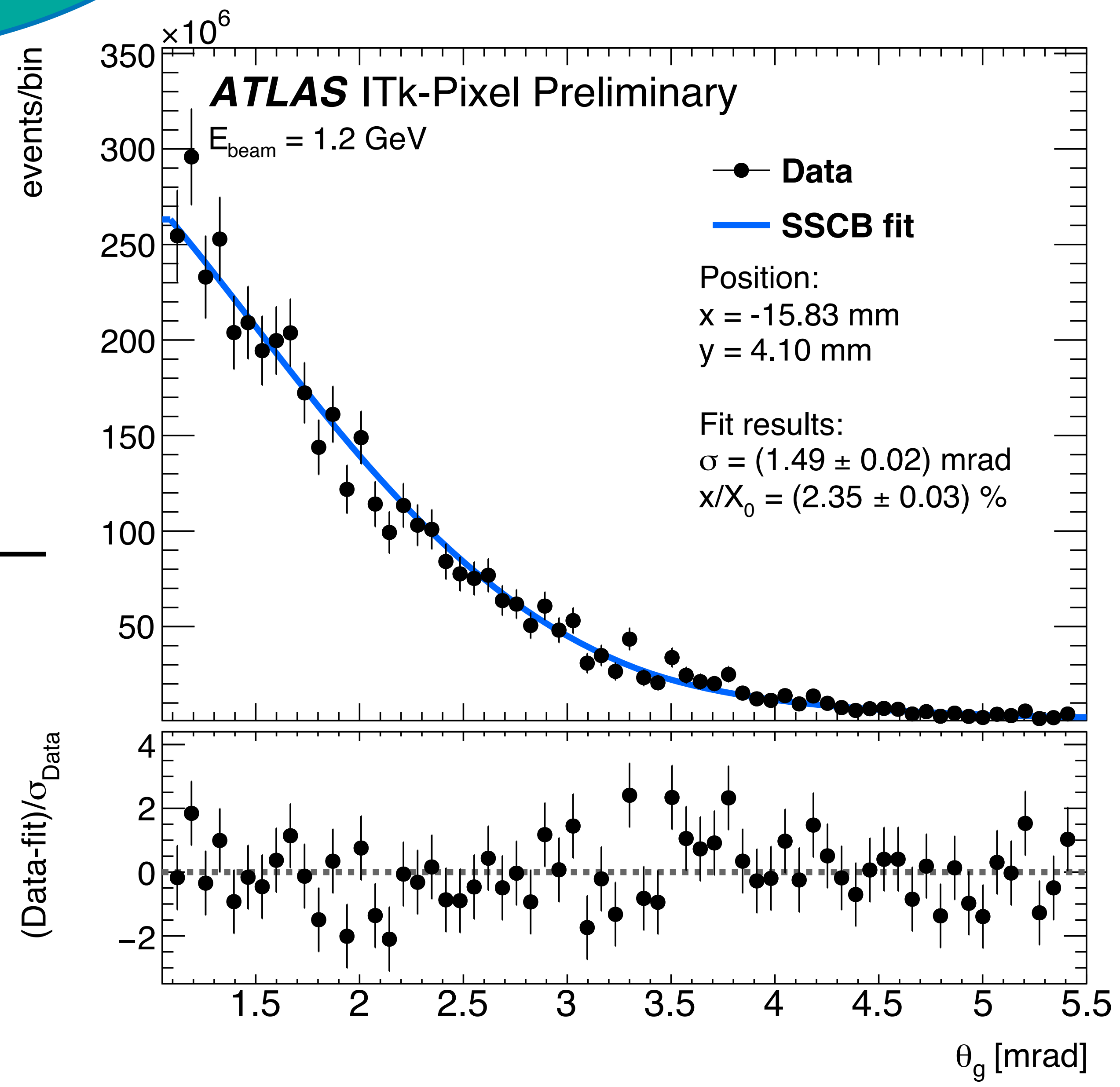


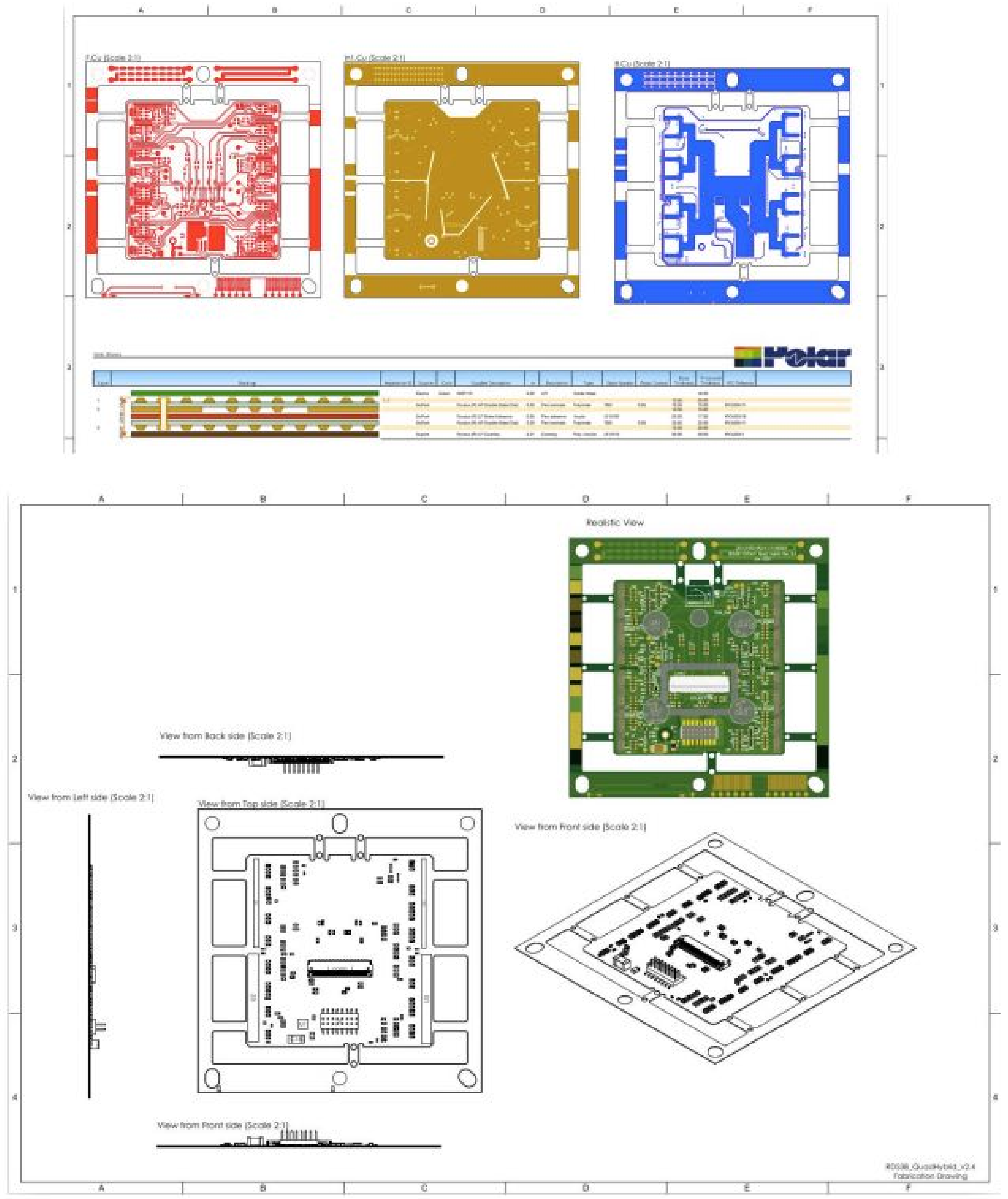


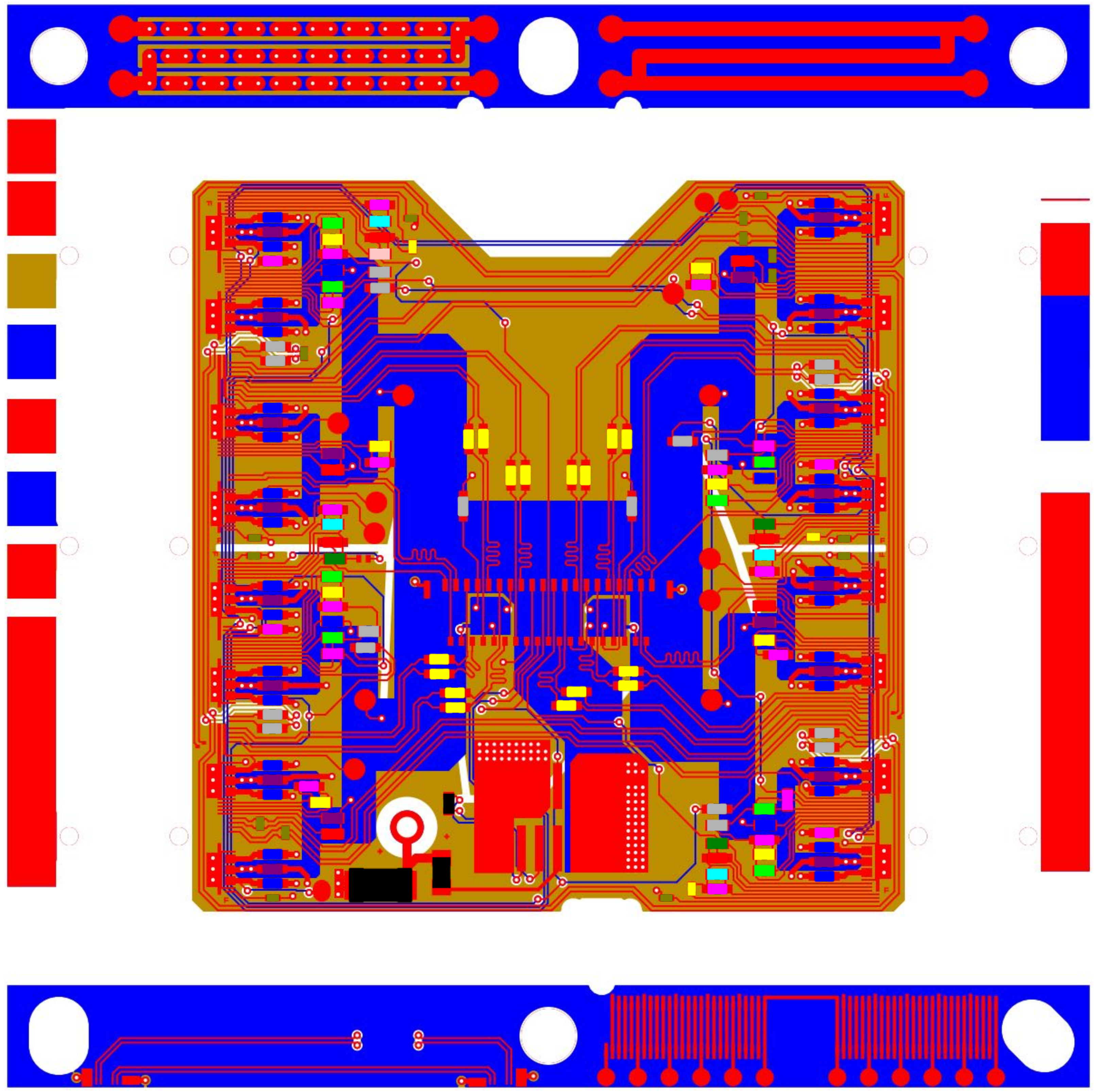
Derive response curve from G4 simulation

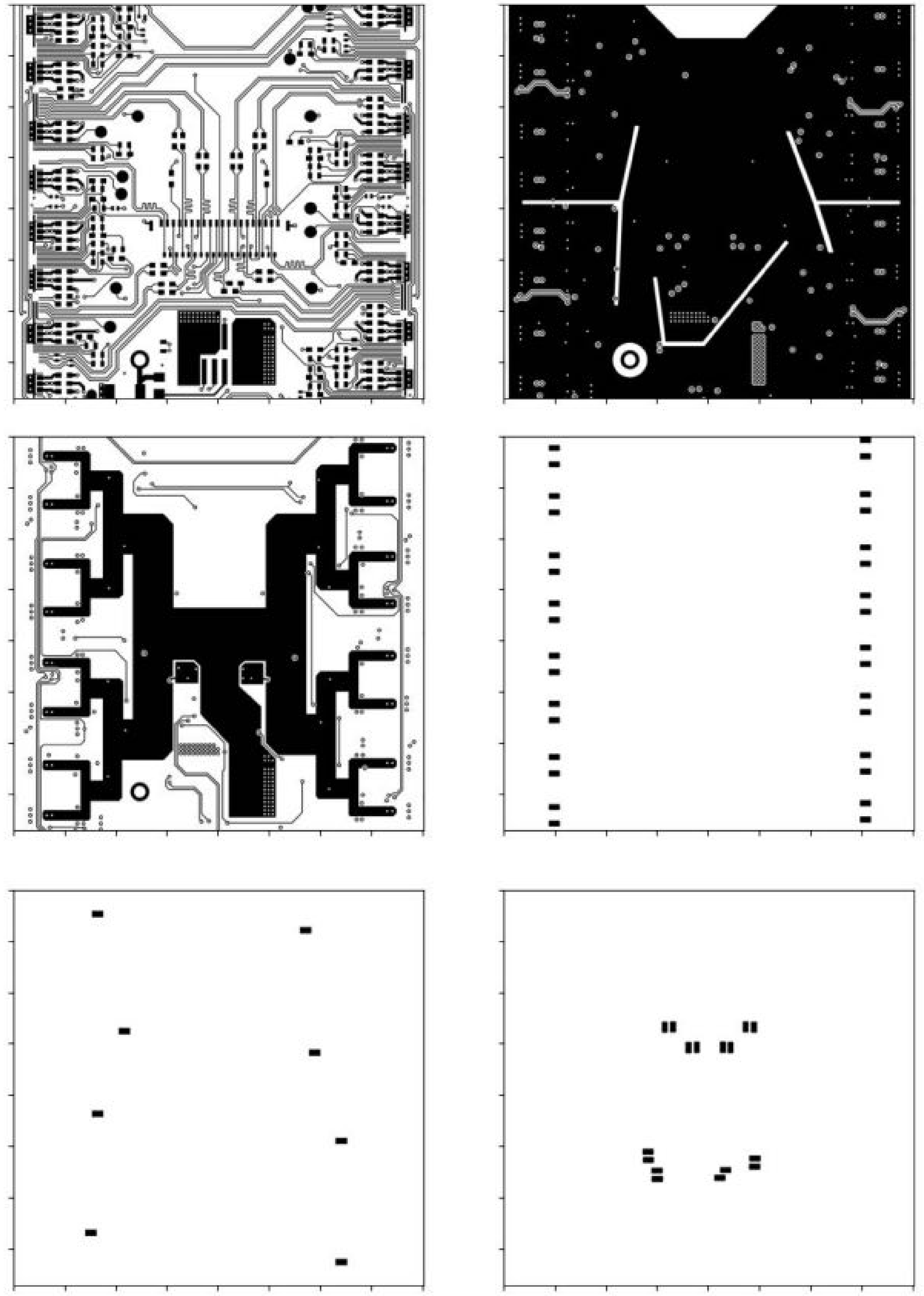


The estimate - more details

- The manufacturer drawings of PCB design and SMD layout was exported to .svg
- Each layer and SMD types were separated to different layers and exported with resolution matching ITkPix detector to .png
- These masks are than exported to normalised maps, i.e. 2D matrix with values from 0 to 1

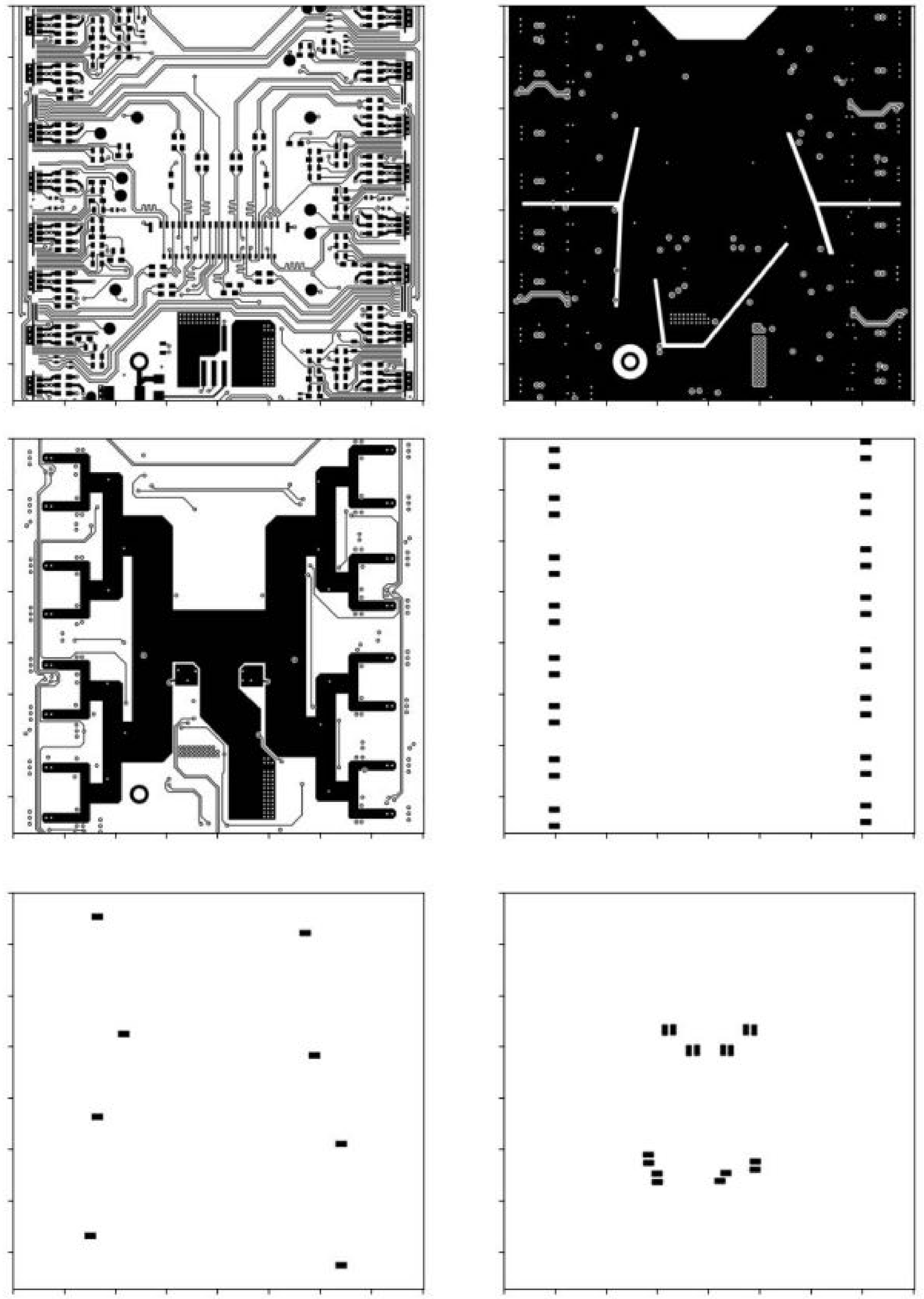


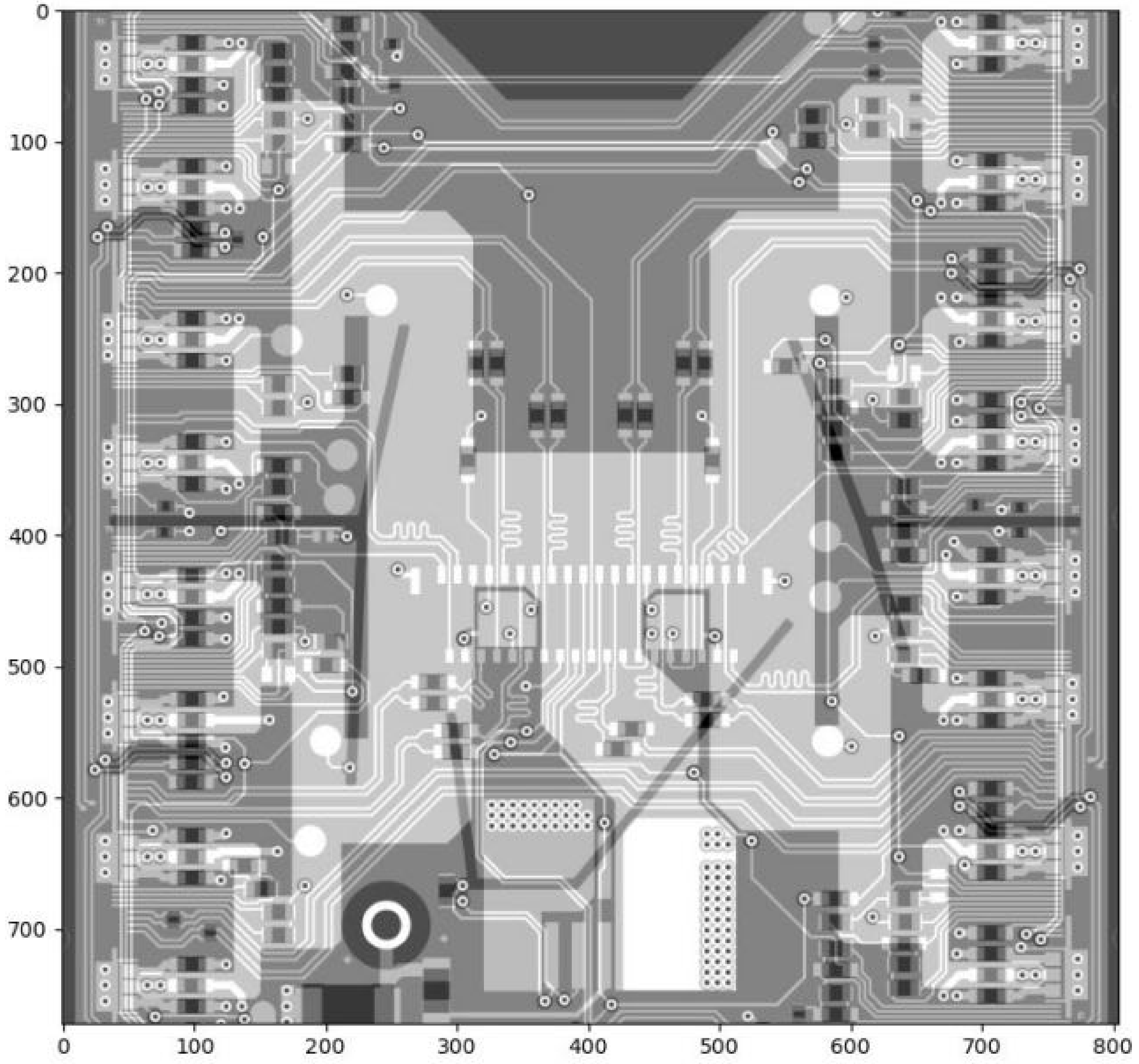




The estimate - more details

- These maps can be now stacked by adding RL coefficients (x/X0) of each layer





Detail