

# *Building Rings and Measuring Things*

Construction and material measurements for the ATLAS ITk  
Pixel Outer Endcaps

Simon Koch

Instrumentation Seminar, LBNL

23 Oct 2024

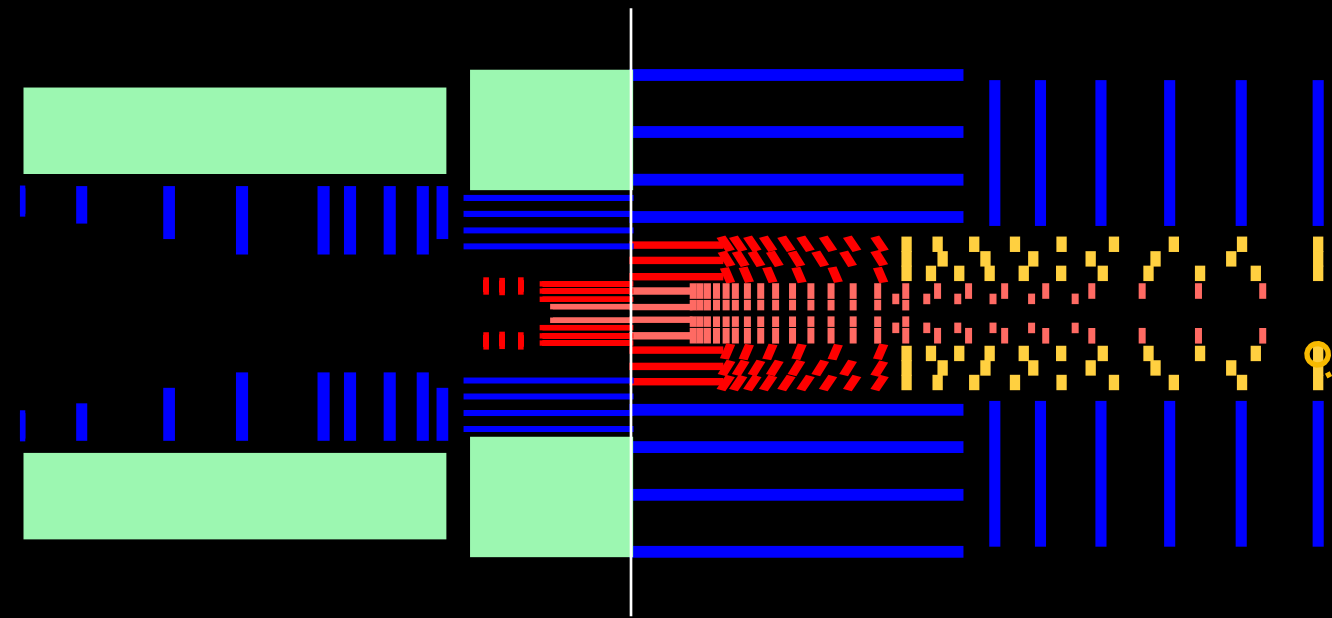
Run Number: 438532, Event Number: 2501374315

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

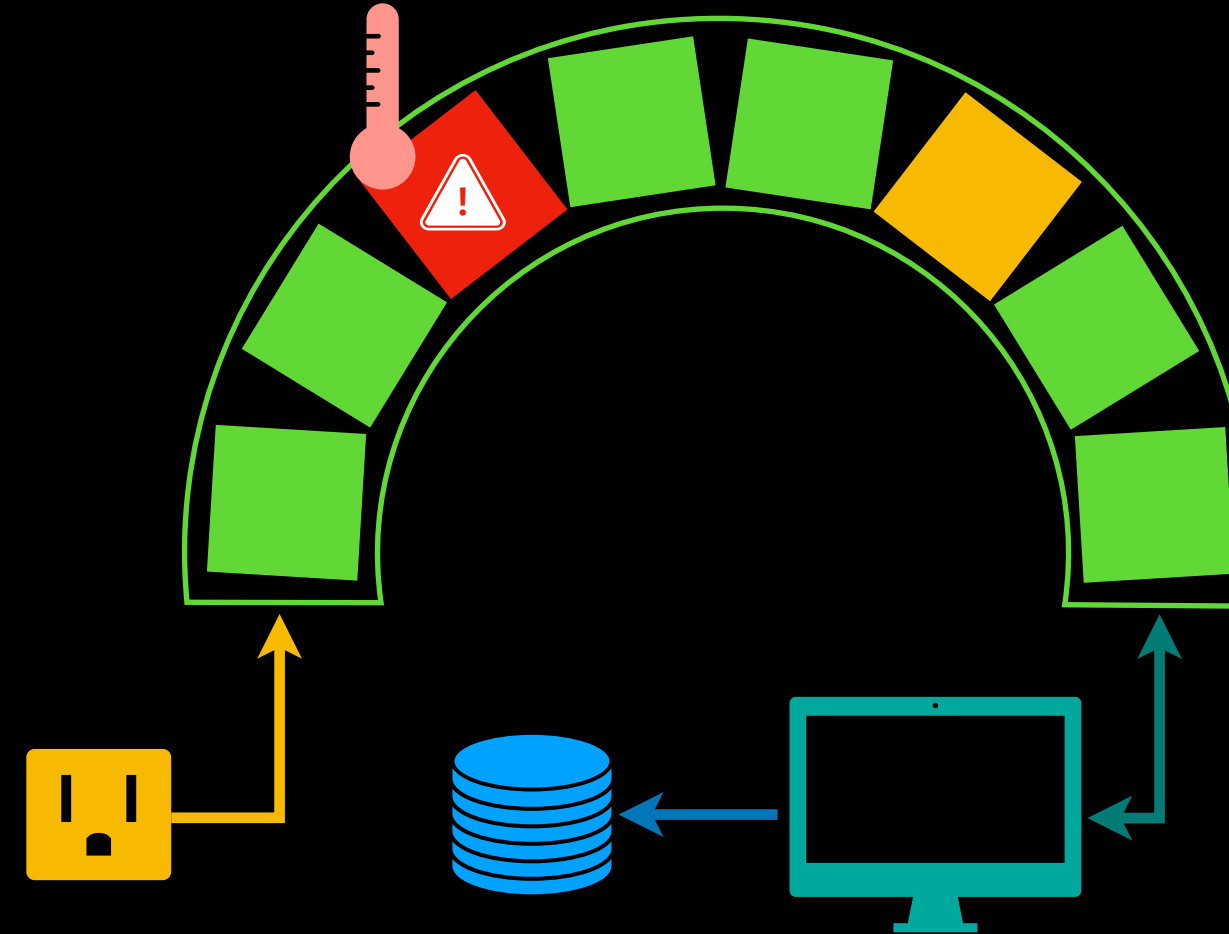
Snapshot of a proton collision  
directly from the ATLAS experiment



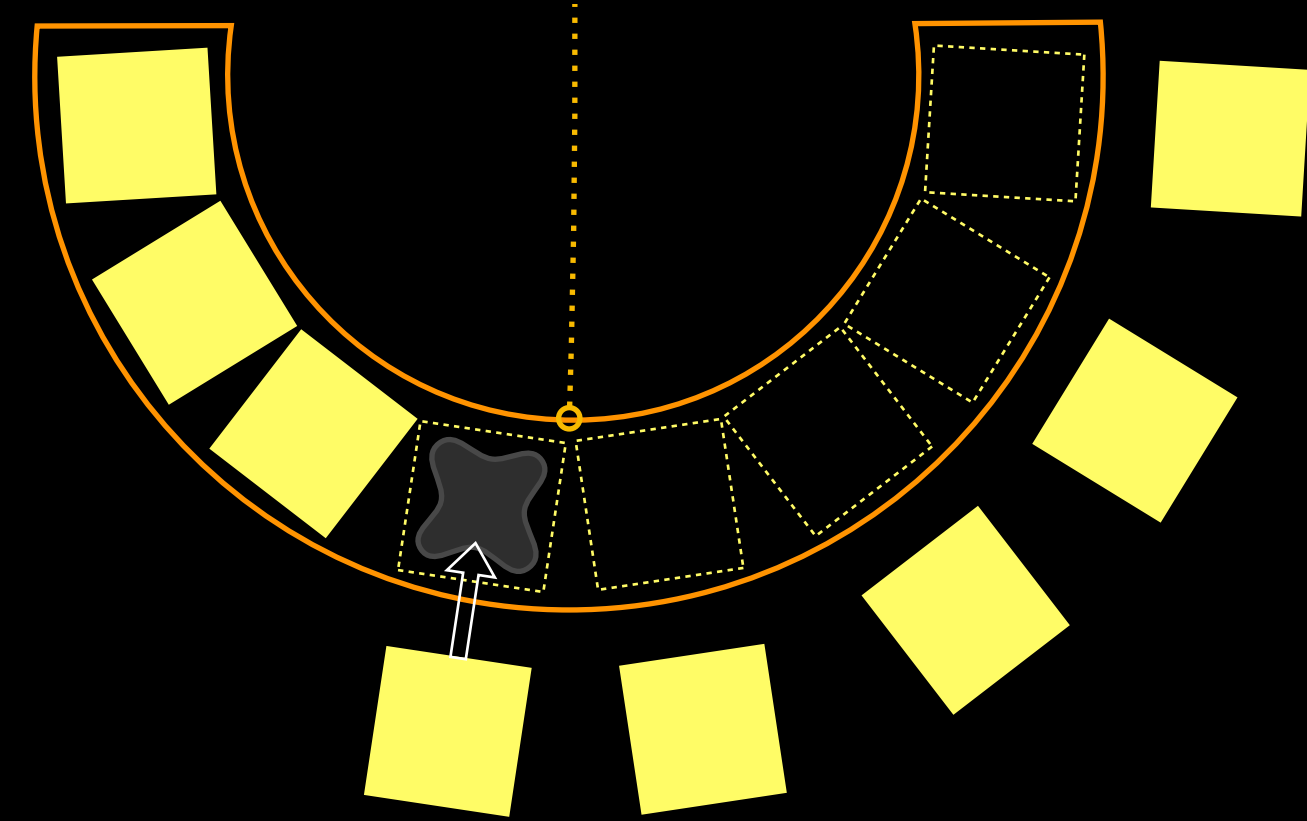
## PROLOGUE: ITK PIXELS AND OXFORD



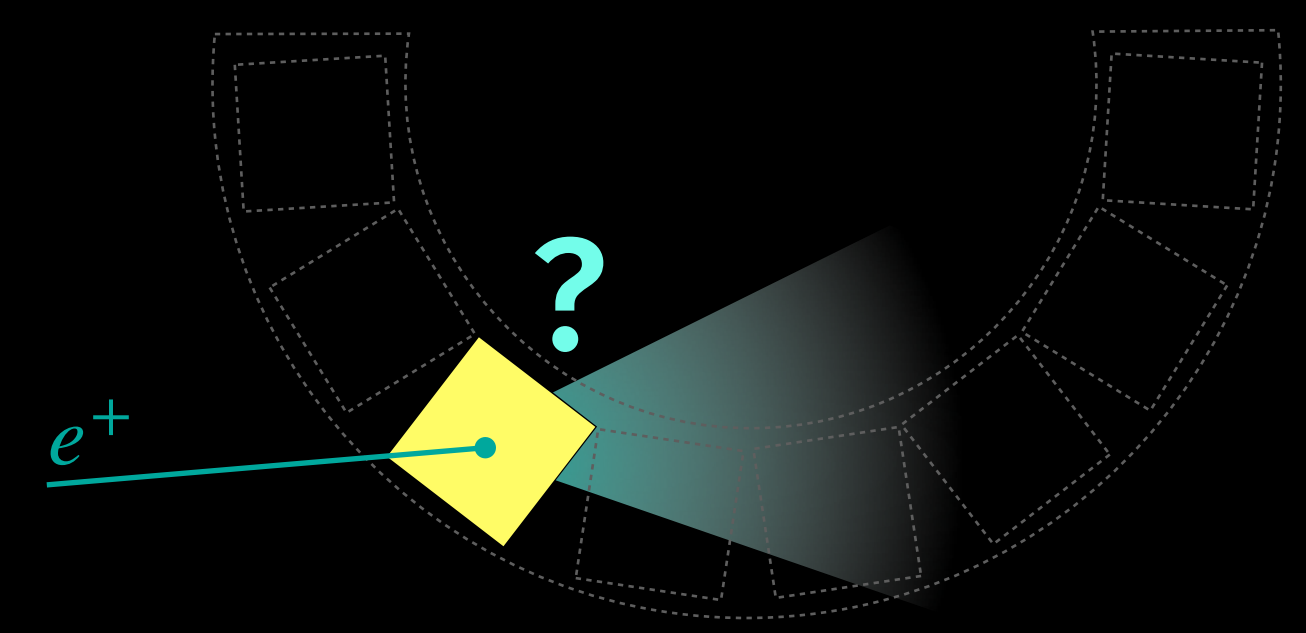
## STEP 2: TESTING THE ITK



## STEP 1: BUILDING THE ITK



## STEP 3: MEASURING THE ITK





# PROLOGUE: ITk PIXELS AND OXFORD



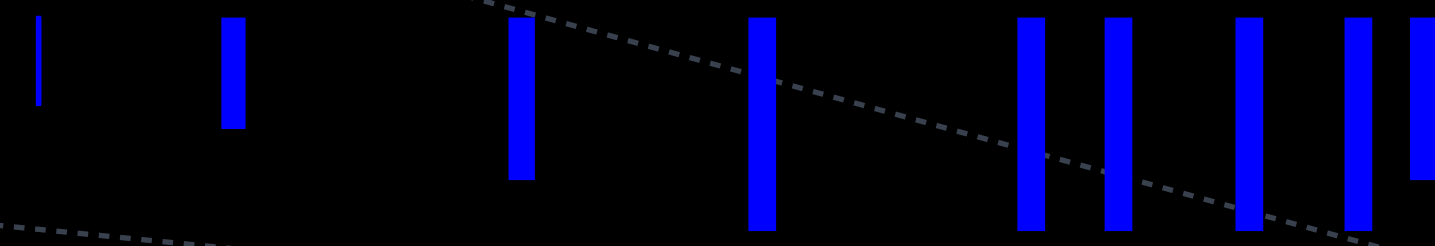
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# THE ITk UPGRADE



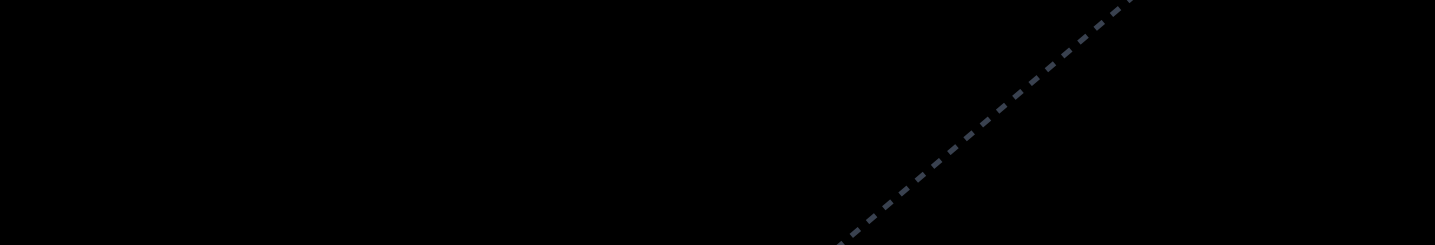
TRANSITION RADIATION TRACKER



STRIPS



PIXELS



$\eta=1$

STRIPS



$\eta=2$

PIXELS



$\eta=3$

$\eta=4$

PIXEL  
OUTER  
ENDCAP

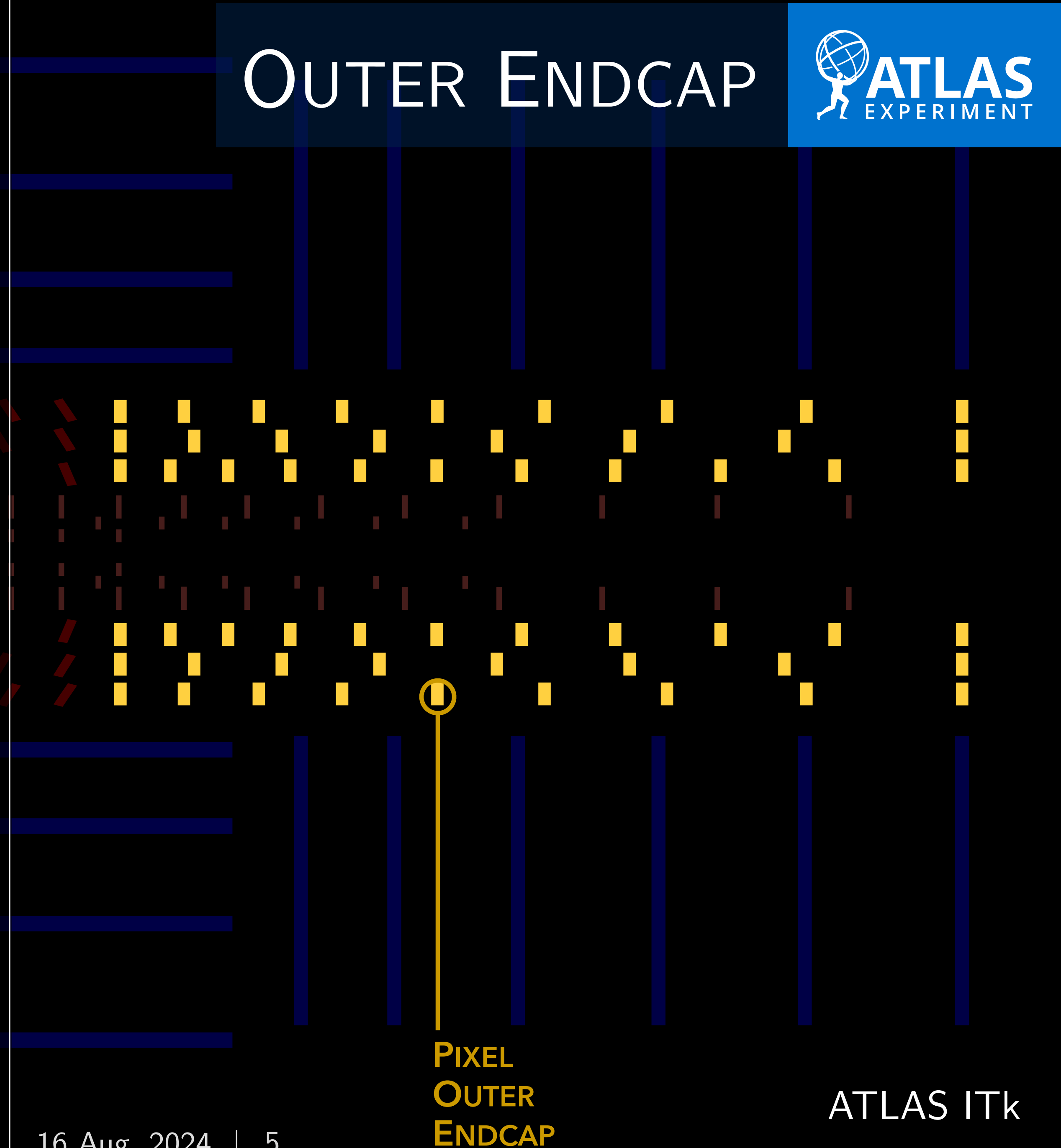


ATLAS ID

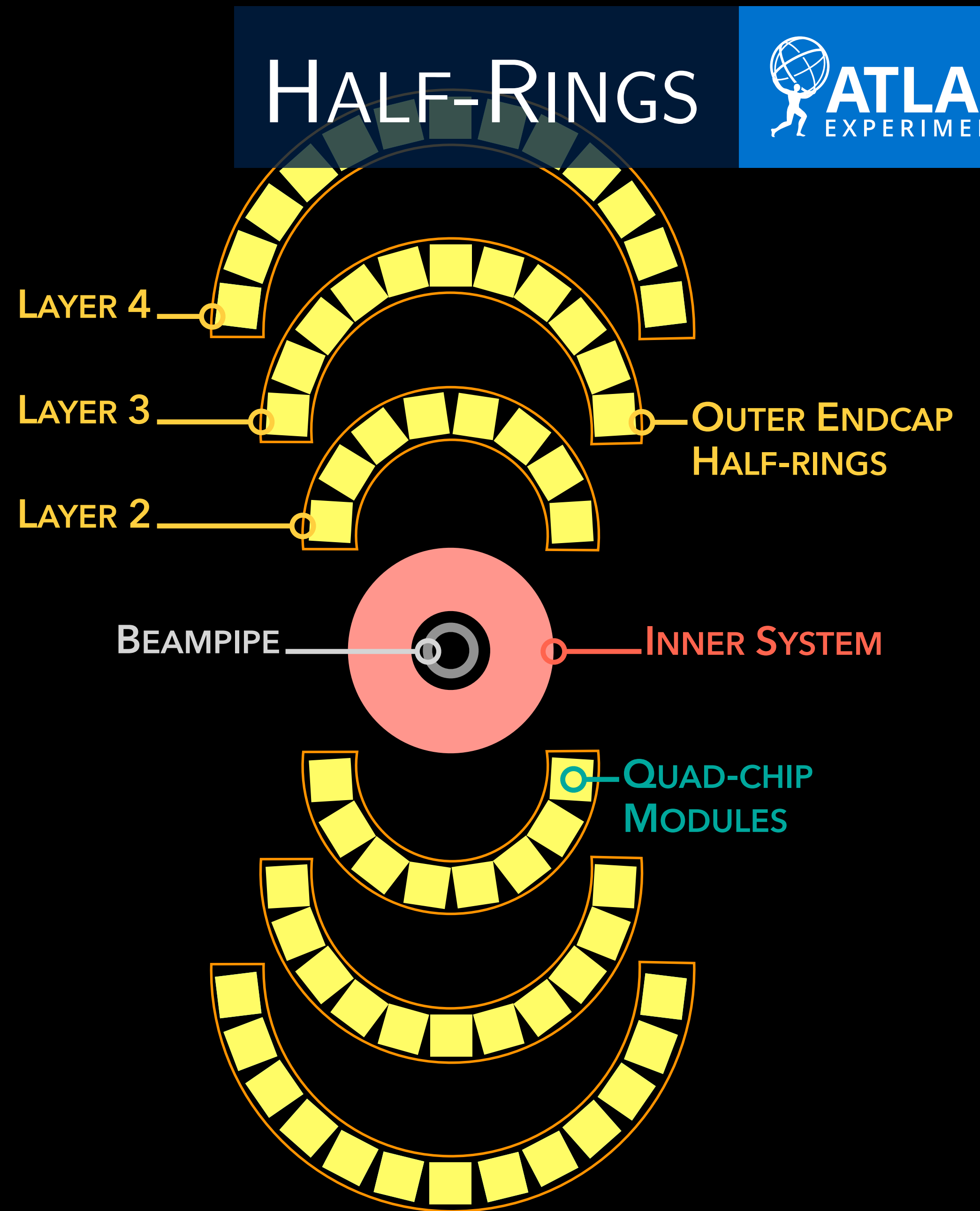
ATLAS ITk

# 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



- ▶ 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





WIREBONDS

Readout ASIC  
ITkPIX

# HALF-RINGS



GLUE

CARBON HALF-RING

COOLING

LOCAL SUPPORT

MODULE

SENSOR

BUMP BONDS

FLEX PCB



# STEP 1: BUILDING THE ITK



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# HALF-RINGS



Readout ASIC uses  
~2-3W of power → heat  
ITkPIX

GLUE PATTERN  
SE4445 Thermal  
Interface Material

RISK OF  
GLUE  
SEEPAGE

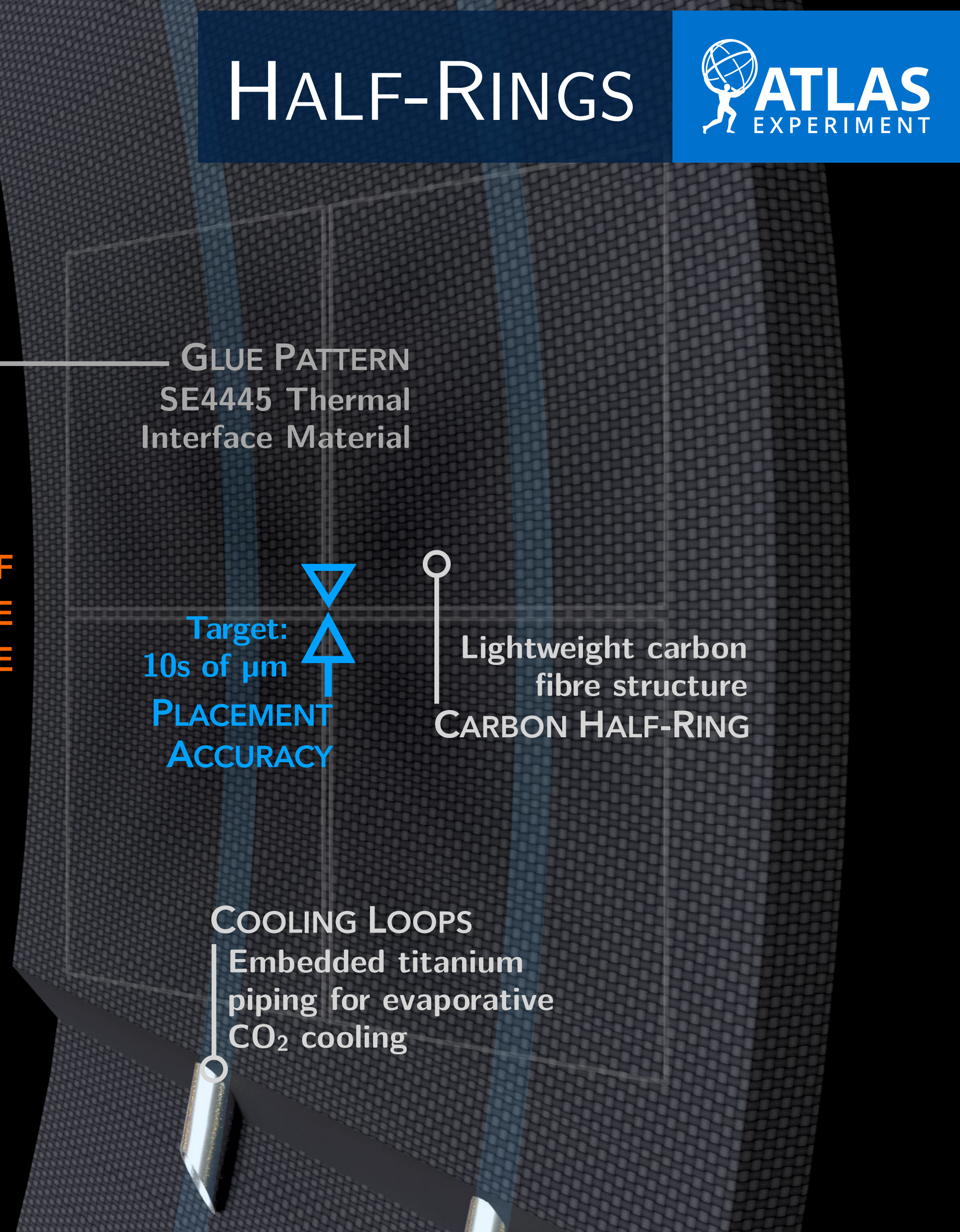
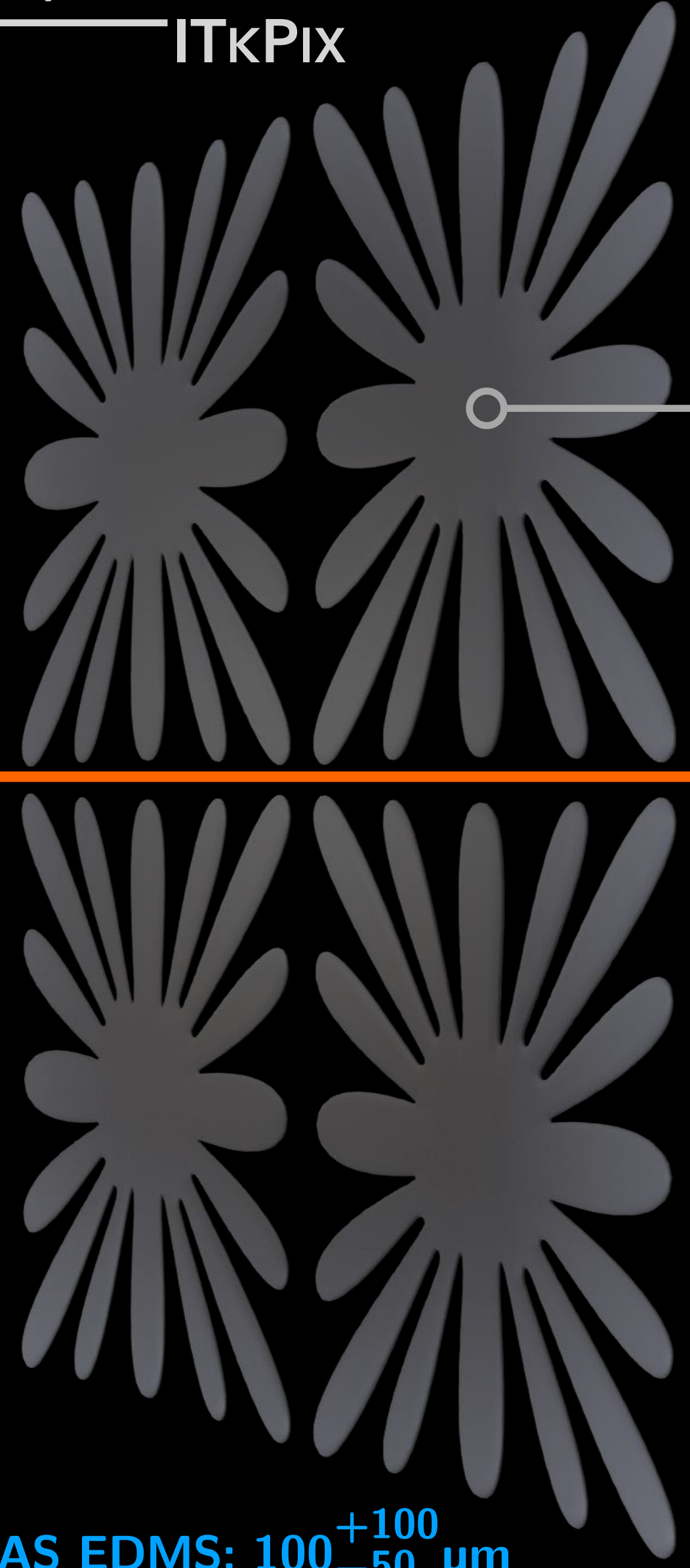
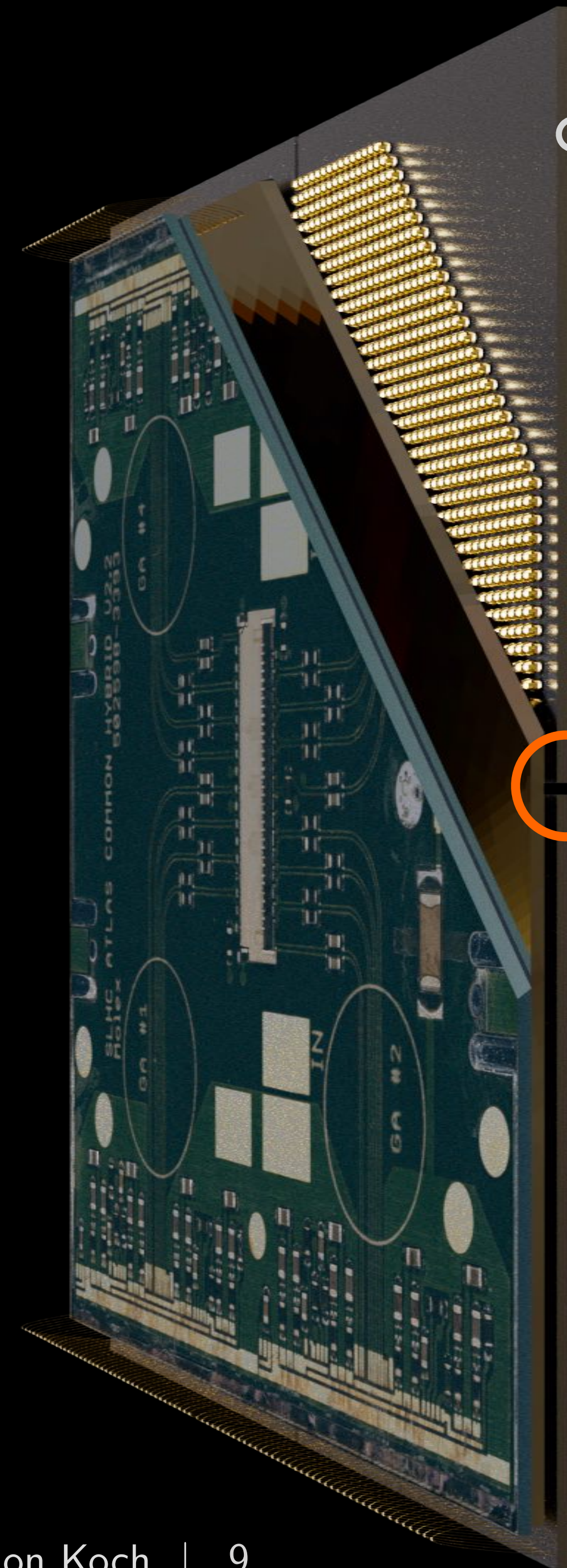
Target:  
10s of  $\mu\text{m}$   
PLACEMENT  
ACCURACY

Lightweight carbon  
fibre structure  
CARBON HALF-RING

COOLING LOOPS  
Embedded titanium  
piping for evaporative  
CO<sub>2</sub> cooling

ATLAS EDMS:  $100^{+100}_{-50}$   $\mu\text{m}$

LAYER THICKNESS



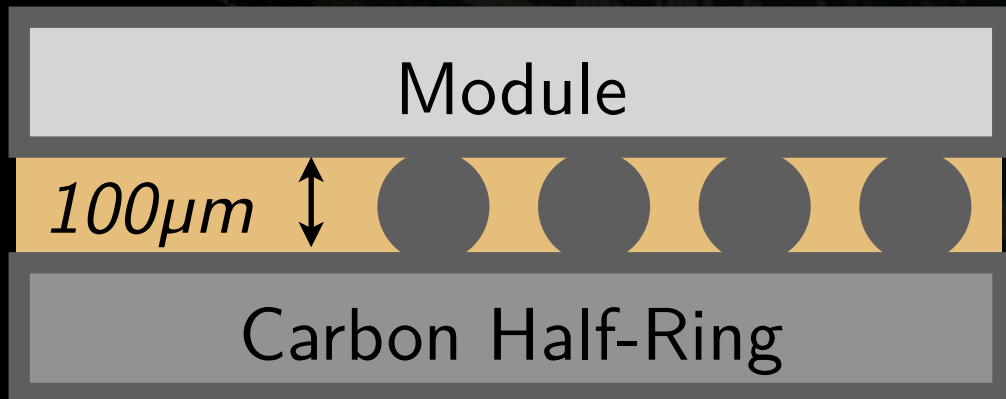


## LINEAR MODEL FOR GLUE DEPOSITION

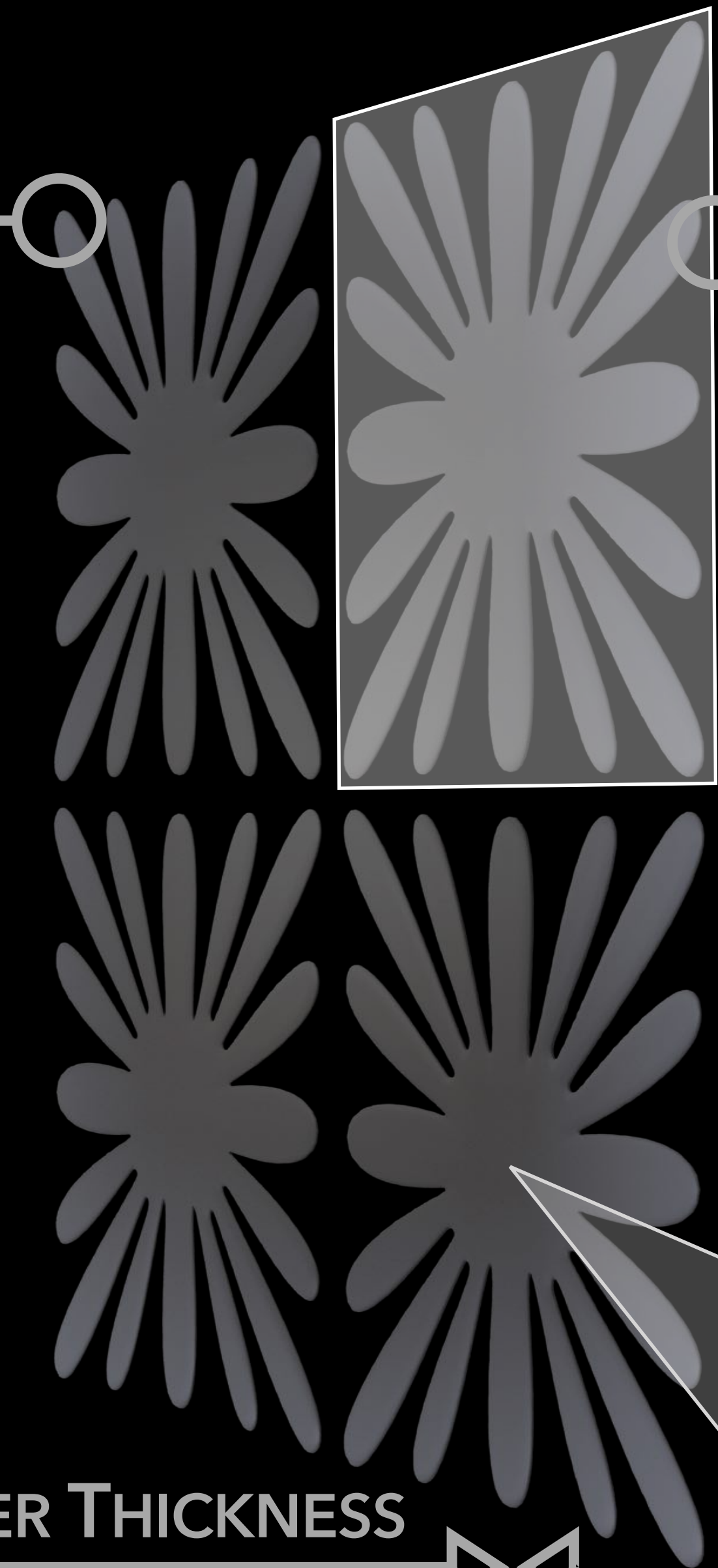
$$\text{robot line speed } v = \frac{\text{total mass flow } l f}{\text{target mass } m}$$

flow rate change over time correction:

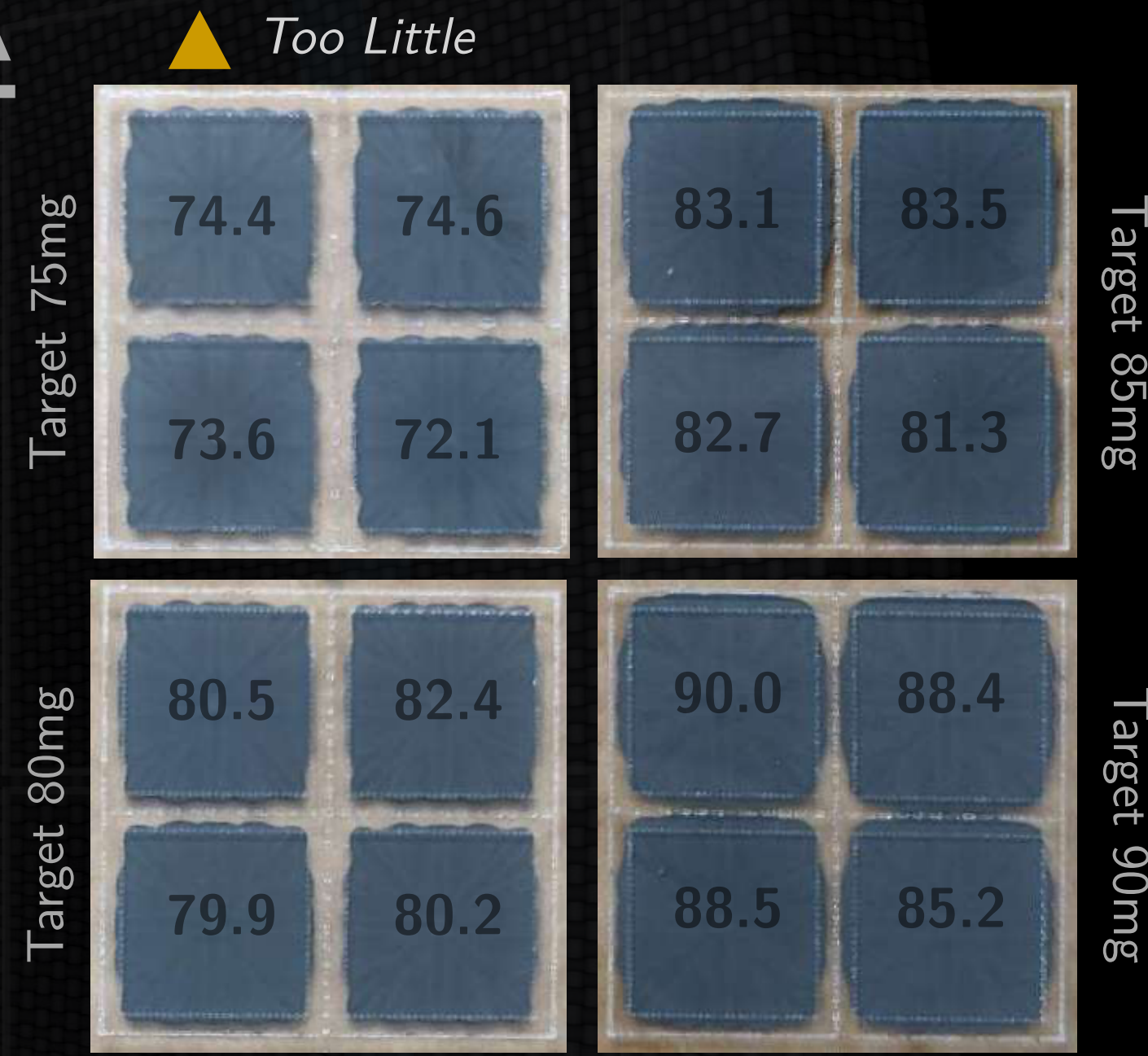
$$\frac{\partial v}{\partial t} \approx \frac{l \frac{\partial f}{\partial t}}{m}$$



**LAYER THICKNESS**  
**VIA SPACER SPHERES**  
 0.25% w/w, [SLAC, RAL]



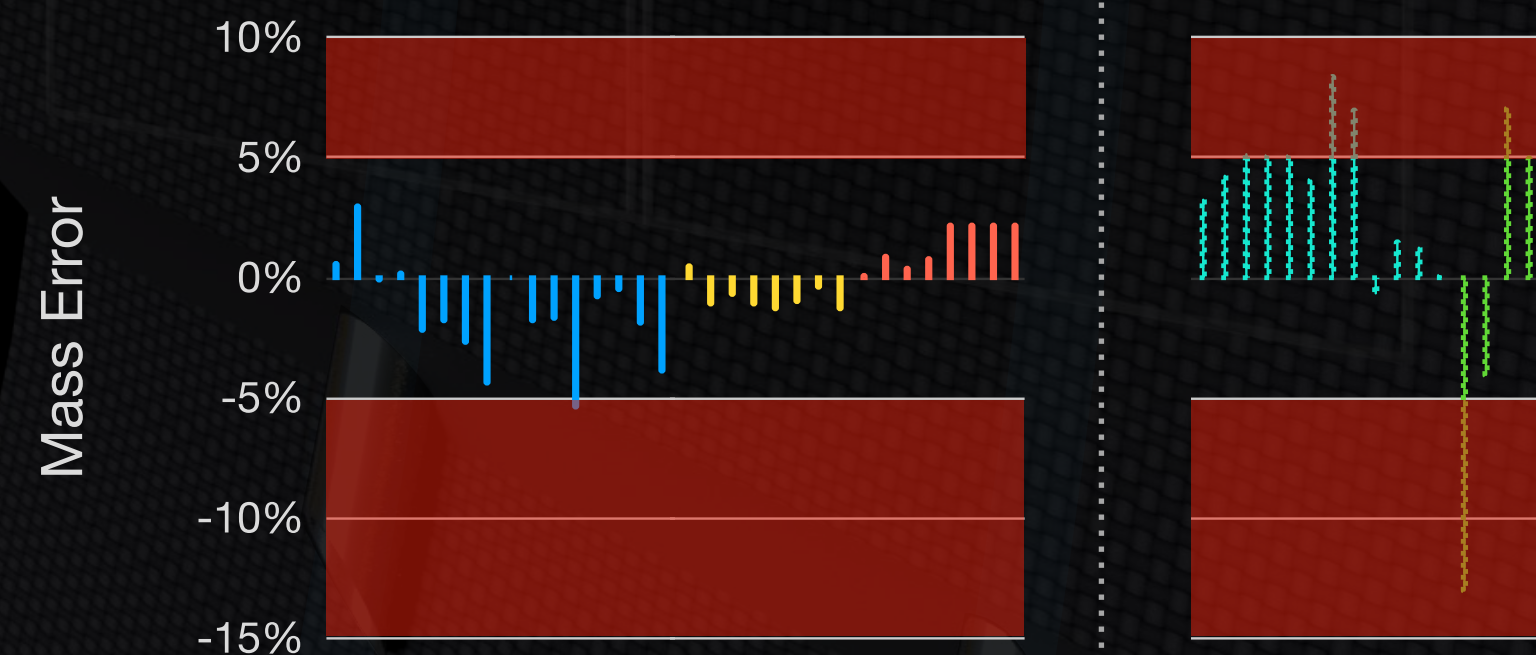
## MASS VS AREA



Model only valid in certain phase space:

20 psi ≤ p ≤ 30 psi, 23 AWG needle

other settings





# LOADING GANTRY



SPREADER TOOL

GLUE SYRINGE

BRIDGE TOOL

MODULE TRAY

HALF-RING



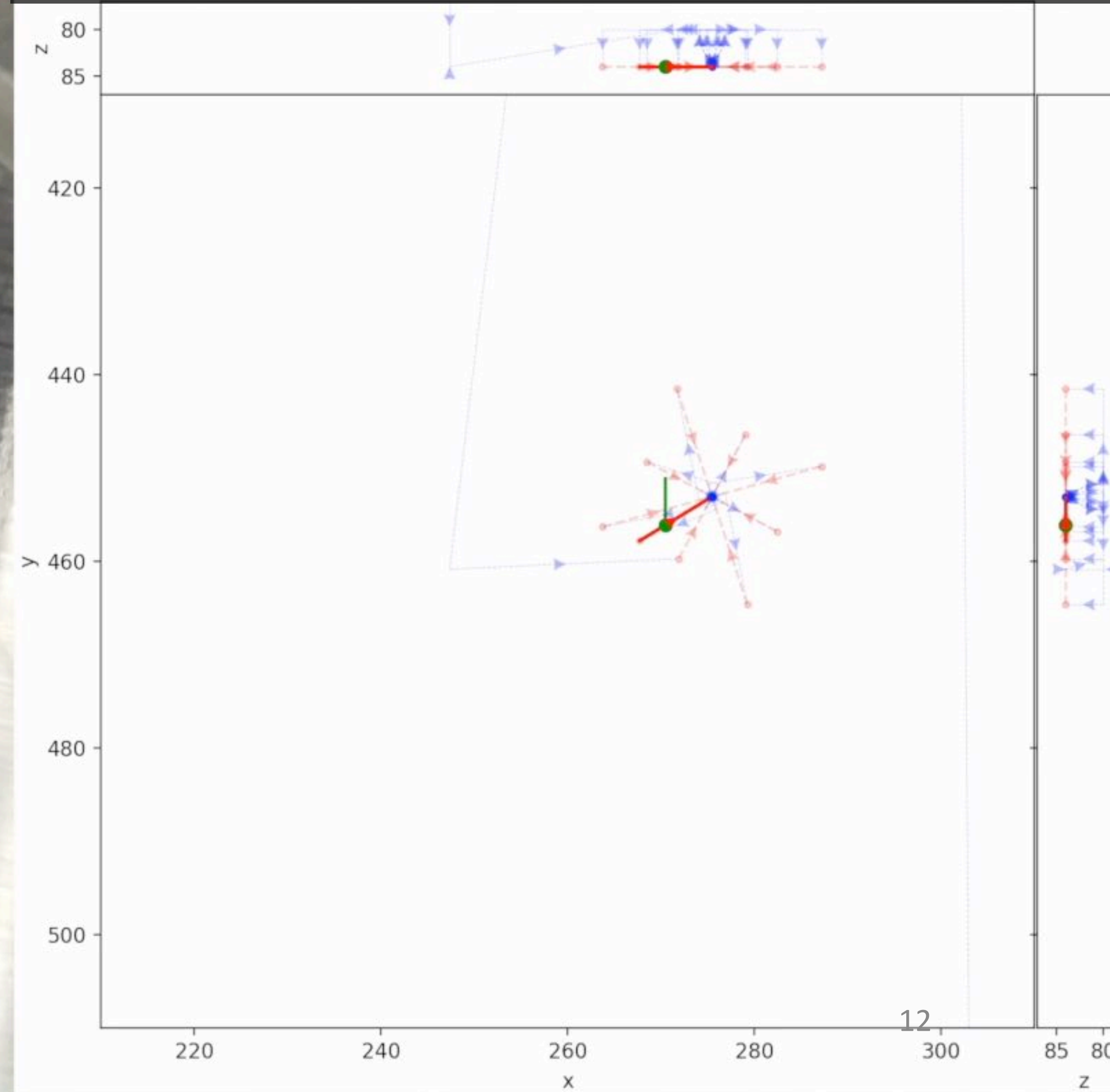
# Glue Deposition

5× speed

# GLUE DEPOSITION



## Gantry Program Visualiser





# Module Placement

2x speed

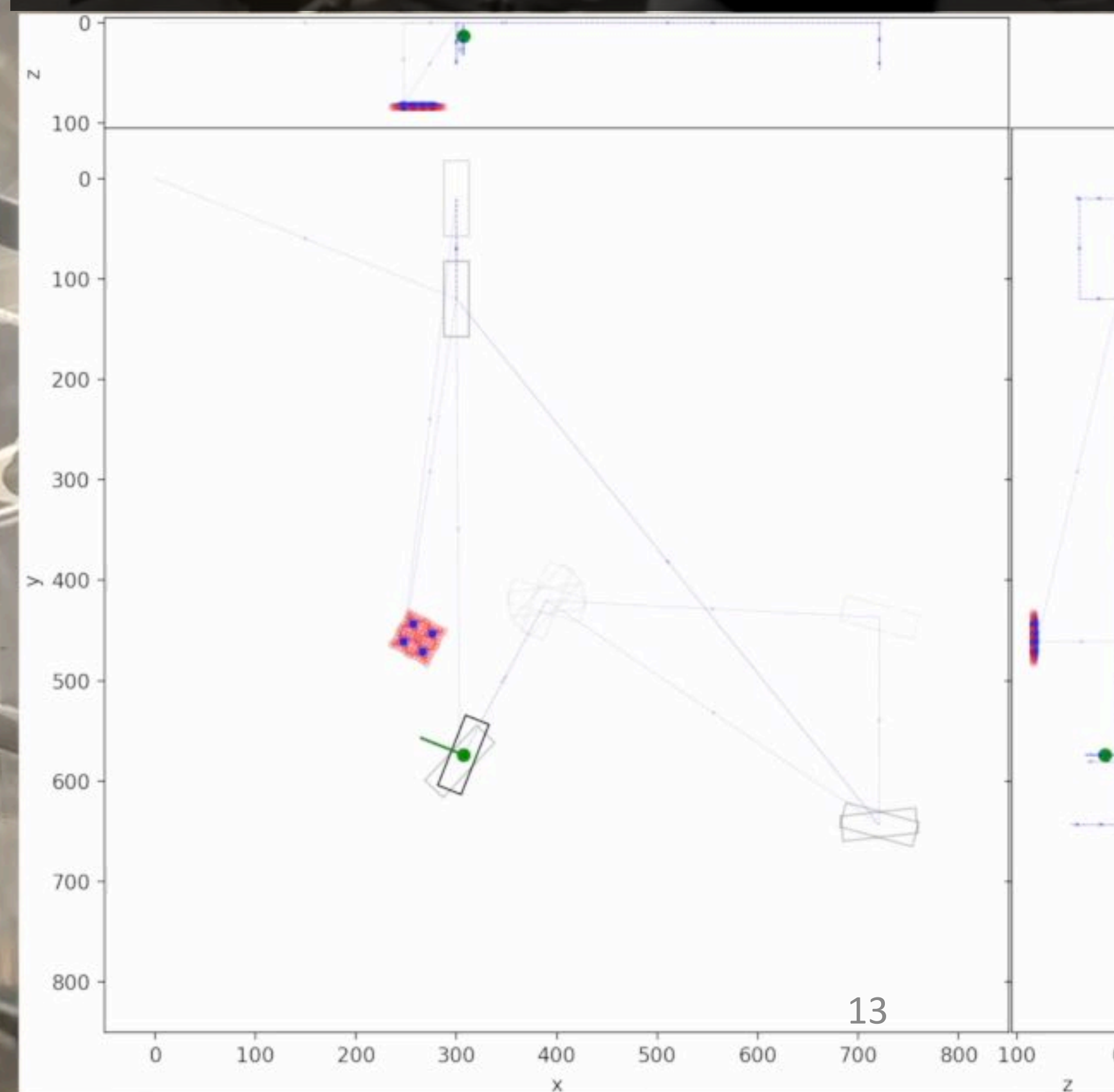
SPREADER TOOL

BRIDGE TOOL

LOADING



## Gantry Program Visualiser

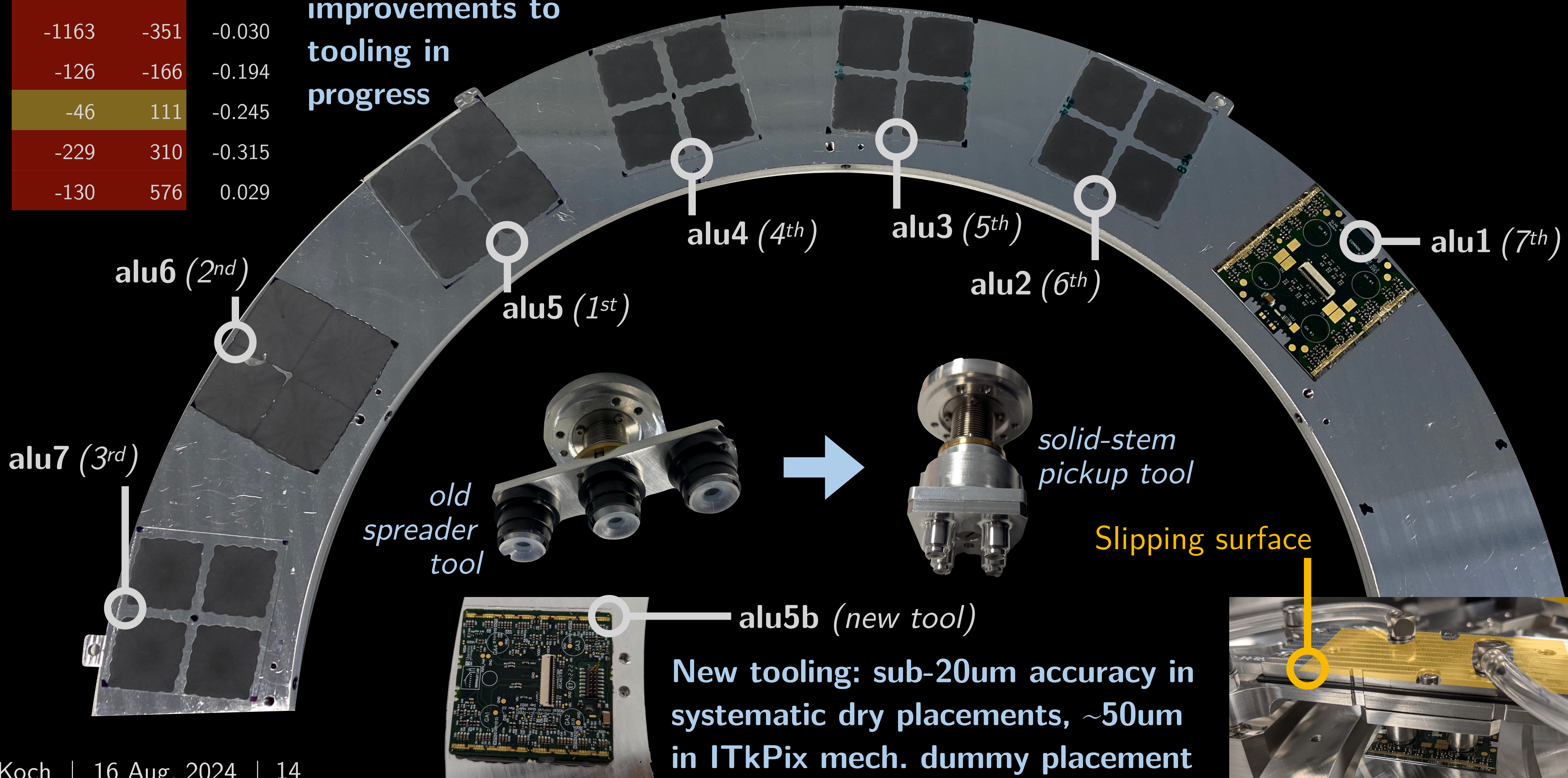




Offset from Nominal

	X ( $\mu\text{m}$ )	Y ( $\mu\text{m}$ )	Phi ( $^\circ$ )
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





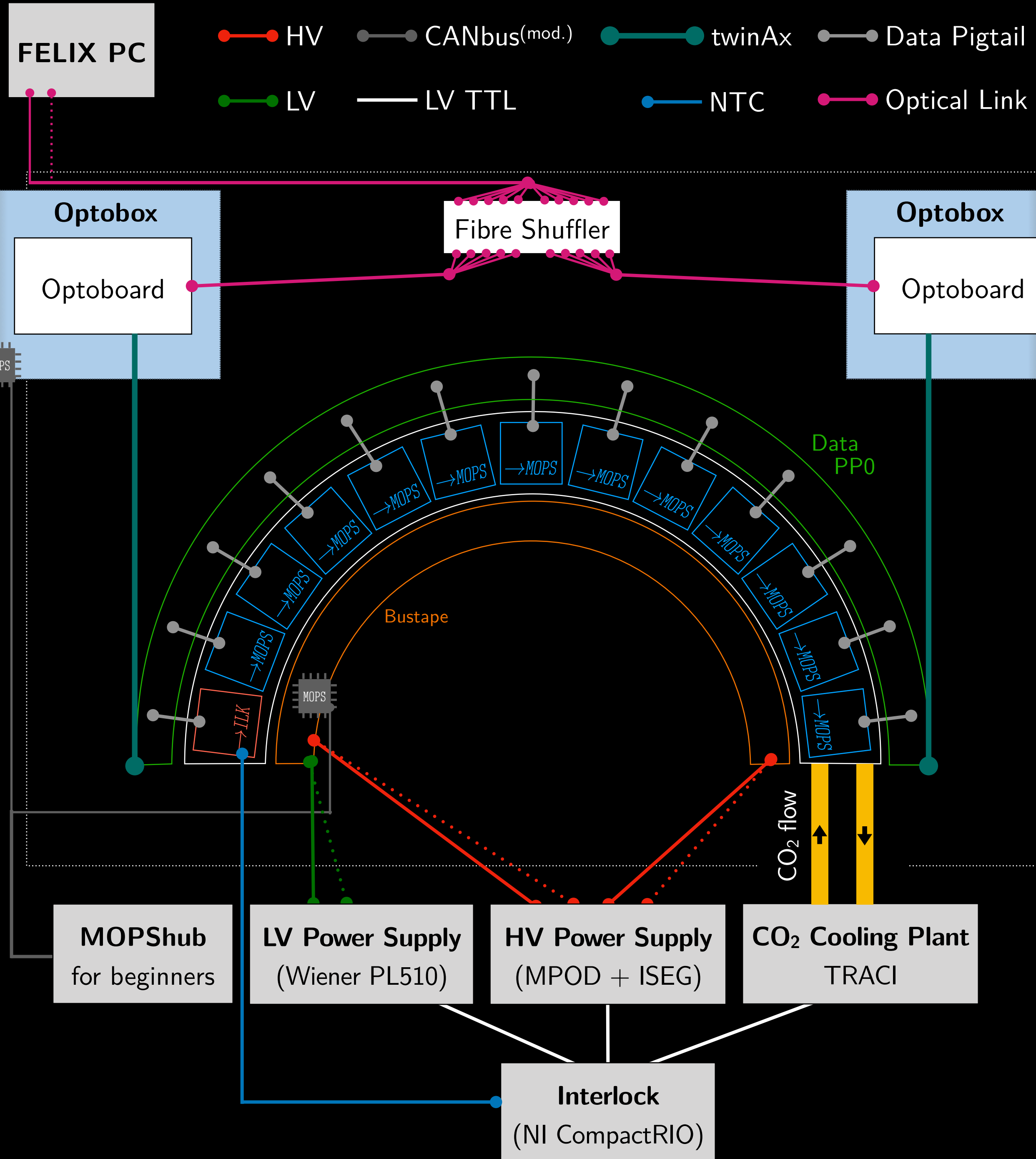
# STEP 2: TESTING THE ITK



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# HALF-RING TESTING



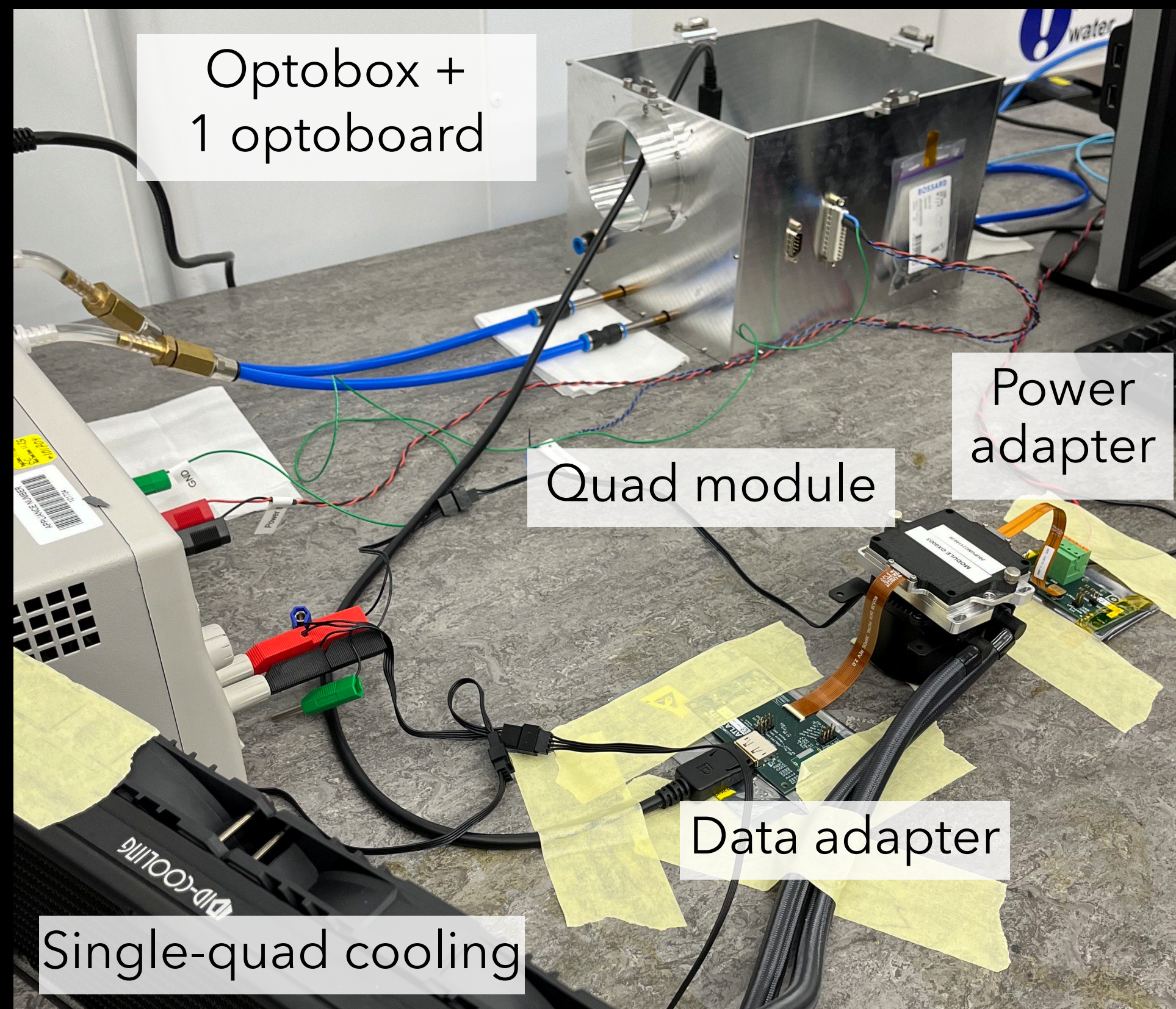
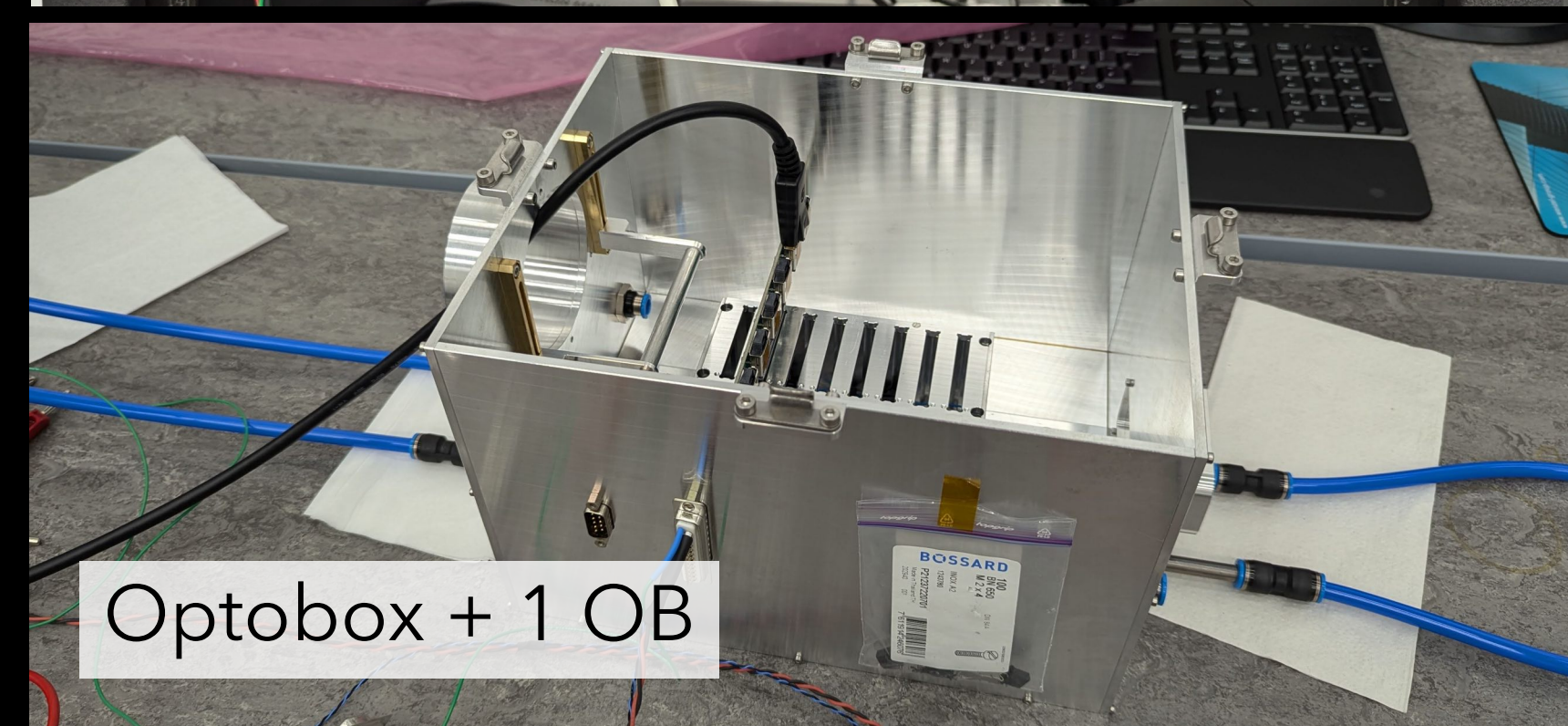
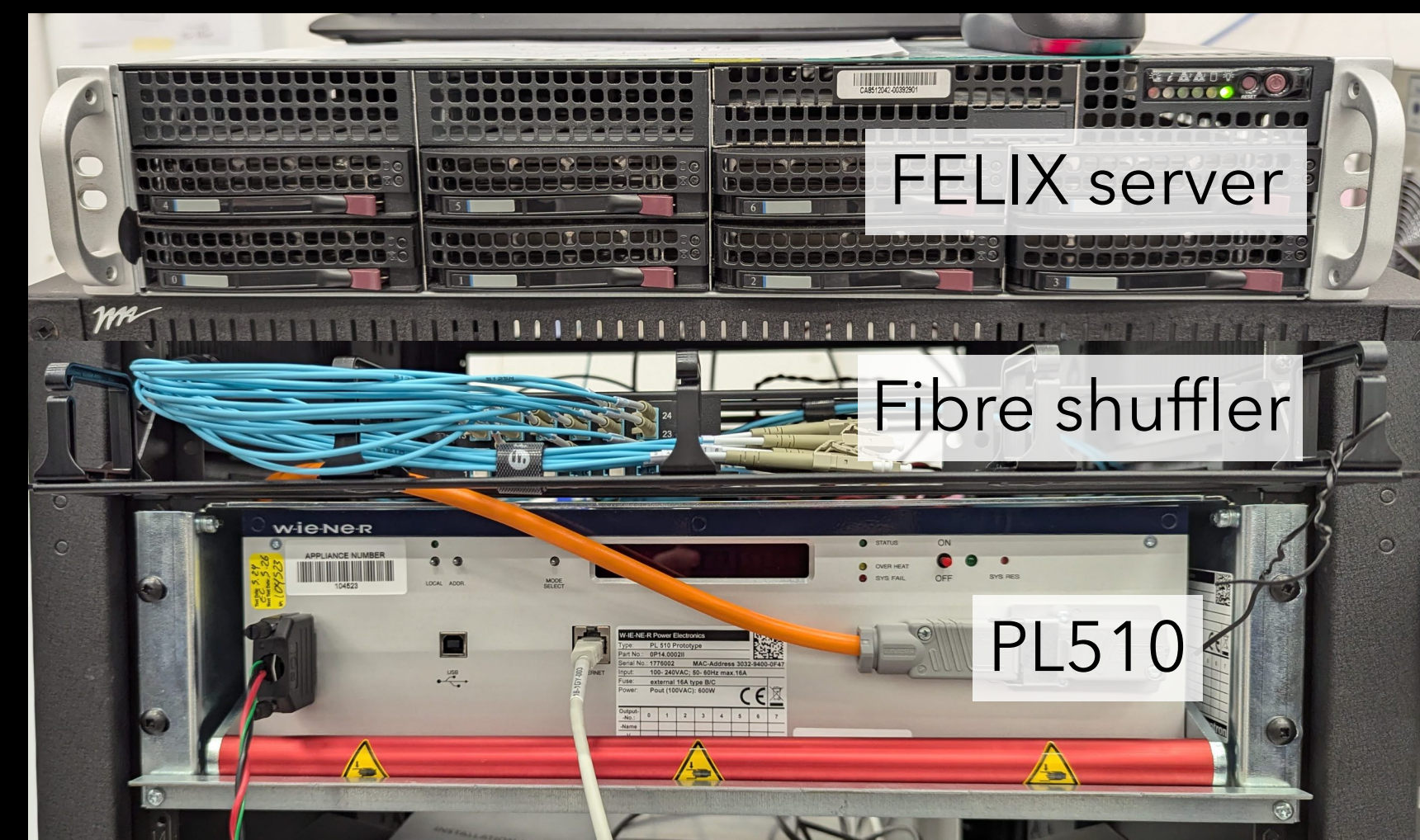
- ▶ We use the FELIX optical readout system, in a setup similar to that used for system tests in SR1 at CERN
- ▶ Other challenges include cooling  $O(20)$  modules - requires CO<sub>2</sub> plant
- ▶ Optical readout elements have so far been tested with a single module and adapter cards



# HALF-RING TESTING



- ▶ 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

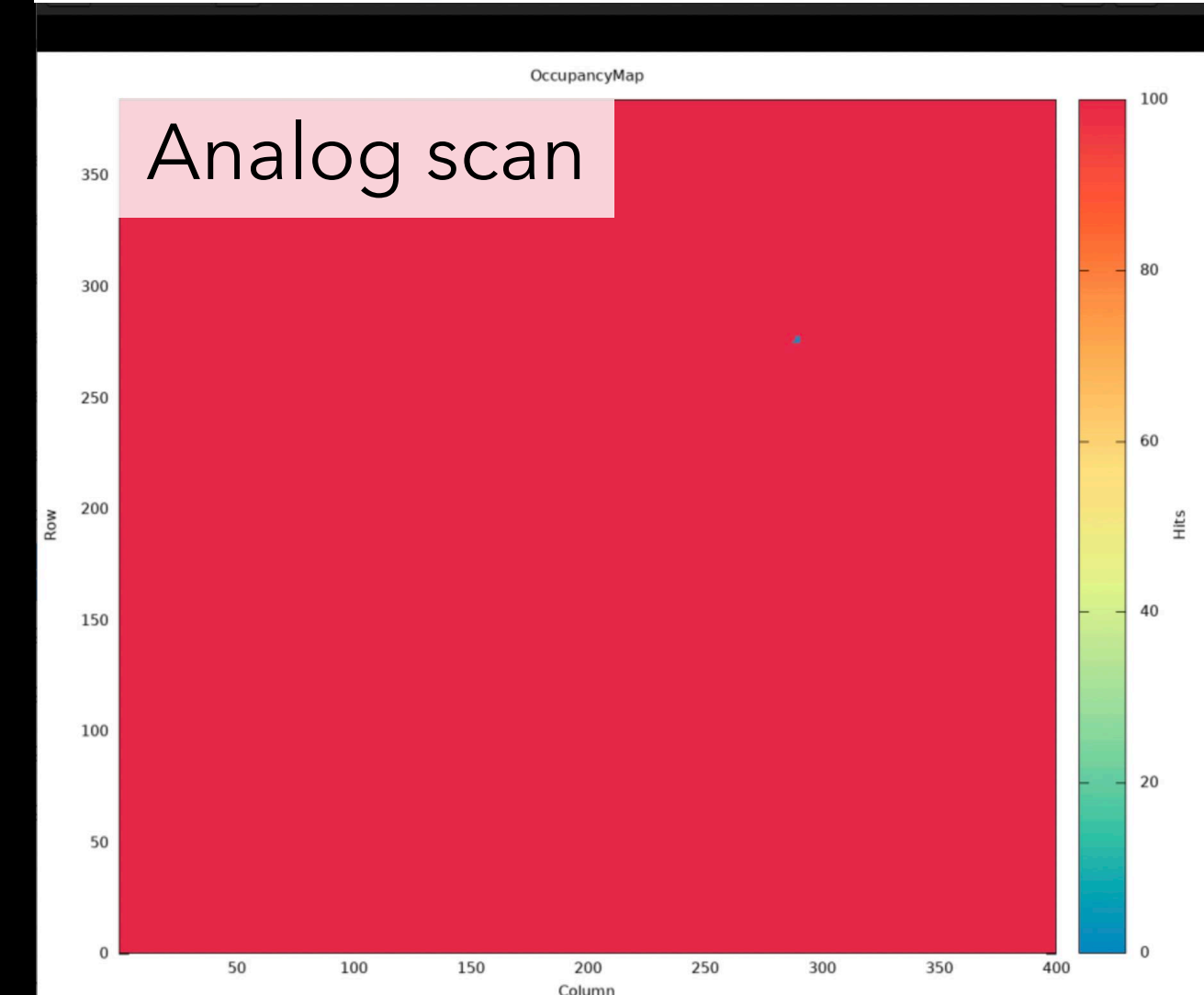


Microservices

### FELIX API - itk-felix-sw

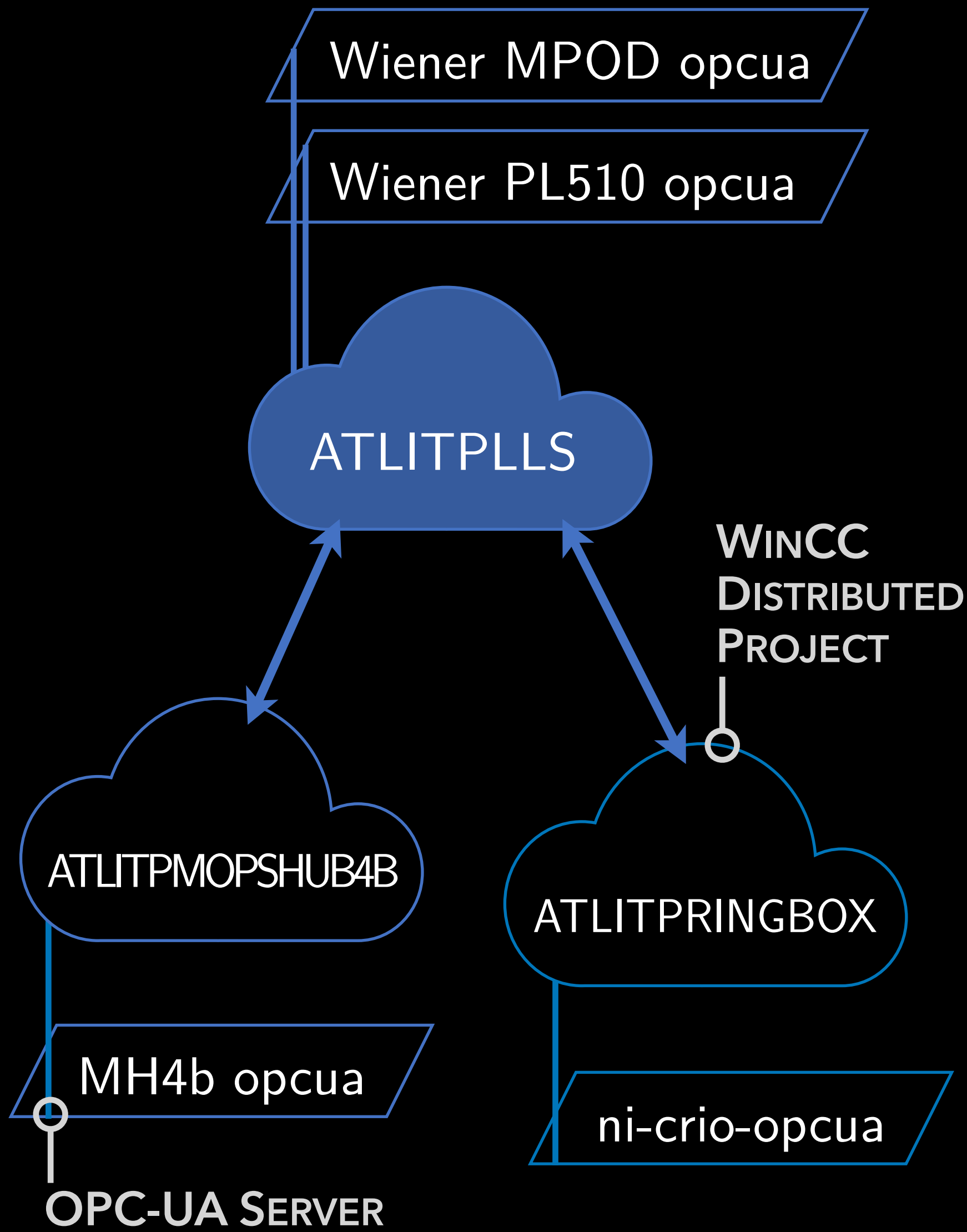
Home Monitoring FelixOff

Links :	0	1	2	3	4	5	6	7	8	9	10	11	12	13
Optical Power														
Read														
Advanced														
Optical link alignment														
Read														
0 :														





# DETECTOR CONTROL SYSTEM



- ▶ 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

**PL512 Channel Operation**

Channel Name: ATLITPLSDCS:Wiener/LLSQC\_PL512I01/Channel4 Model: PL512 Channel (TCP/IP)

Description: ATLITPLSDCS:Wiener/LLSQC\_PL512I01/Channel4. Position: 4

Channel Name: U4

Status:  Power OFF  STABLE VOLTAGE

Channel Inhibit: INACTIVE

Error Flags: Sense Voltage: OK, Terminal Voltage, Current, Temperature, Power Output, Communication Timeout

Measurements: Sense Voltage: 0.000 V, Terminal Voltage: 0.000 V, Current: 0.000 A, Temperature: 27 °C

Settings: Nominal Voltage: 3.000 V, Current Limit: 5.800 A, Voltage Rise Rate: 10000.000 V/s, Voltage Fall Rate: 10000.000 V/s, Regulation Mode: 0: Fast

Limit Settings: Minimum Sense Voltage: 0.000 V, Maximum Sense Voltage: 3.500 V, Maximum Terminal Voltage: 3.500 V, Maximum Current: 6.000 A, Maximum Power: 300.000 W, Maximum Temp: 90

Commands: Power: On Off

Last Voltage Update: 2024.05.26 15:48:43.640

Channel Group: 0 1 (1..127)

Load Settings From Hardware

**POWER SUPPLY**

**Mops Panel (ATLITPMOPSHUB4B - ATLITPMOPSHUB4B; #1)**

ADC Channels	Value	Status
Ch3	0.00	OK
Ch4	0.00	OK
Ch5	0.00	OK
Ch6	0.00	OK
Ch7	0.00	OK
Ch8	0.00	OK
Ch9	0.00	OK
Ch10	0.00	OK
Ch11	0.00	OK
Ch12	0.00	OK
Ch13	0.00	OK
Ch14	0.00	OK
Ch15	0.00	OK
Ch16	0.00	OK
Ch17	0.00	OK
Ch18	0.00	OK
Ch19	0.00	OK
Ch20	0.00	OK
Ch21	0.00	OK
Ch22	0.00	OK
Ch23	0.00	OK
Ch24	0.00	OK
Ch25	0.00	OK
Ch26	0.00	OK
Ch27	0.00	OK
Ch28	0.00	OK
Ch29	0.00	OK
Ch30	0.00	OK
Ch31	0.00	OK
Ch32	0.00	OK
Ch33	0.00	OK
Ch34	0.00	OK

Info: Node ID 1, Location Crate:0, CIC: 26, Port 26

Configuration values: Device Typ 0, Error Register 0, COB-ID SYNC 0, COB-ID EMCY 0, Number of entr 0, Vendor ID 0, ADC Trimming 0

Monitoring values: Number of entr 0.001, VBANDGAP 0.48, VCANSEN 0.564, VGNDSEN 0

**MOPS READOUT** Snapshot Save data

CIC 3

CAN Bus 26

Power Status Bus 26  ON  OFF

ADC CANBus 26

Vmon[V]	Imon[A]	VCAN[V]	TEMP[°C]
-1	0	0	23.733

Connected MOPS:  MOPS  MOPS  MOPS  MOPS



# INTERLOCK AND SAFETY



**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
    
```

**WINCC PROJECT**

Alert actions... Matrix Setup Show/Hide Dependencies

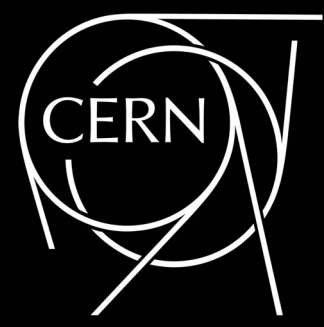
Test Signals	Interlock	IN_S7_C5	NTC_S3_C6	IN_S7_C6	NTC_S4_C1	NTC_S4_C2	IN_S7_C1
Input		BoxSwitches	SP2/Tilock	Lightinterlock	Optobox_Powerboard	Optobox_Conboard	CO2Plant_S
Dep 1		FALSE	-4.211	FALSE	-4.153	-4.106	FALSE
Dep 2			-4.211		-4.153	-4.106	
OUT_S9_C5	OB/L3/R01/T/A/SP2/LV/CH/ILK	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
OUT_S12_C9	OB/L3/R01/T/A/SP2/HV/CH1/ILK	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
OUT_S12_C10	OB/L3/R01/T/A/SP2/HV/CH2/ILK	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
OUT_S15_C12	INFRA/MOPSSYS/CRATE01/VCANPSU/ILK	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
OUT_S15_C1	OB/L3/R01/T/A/SP2/OPTO/CH/ILK	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>

Interlock active  
  Interlock inactive  
  undefined (0.1<V<3.2)  
  stale



- ▶ 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



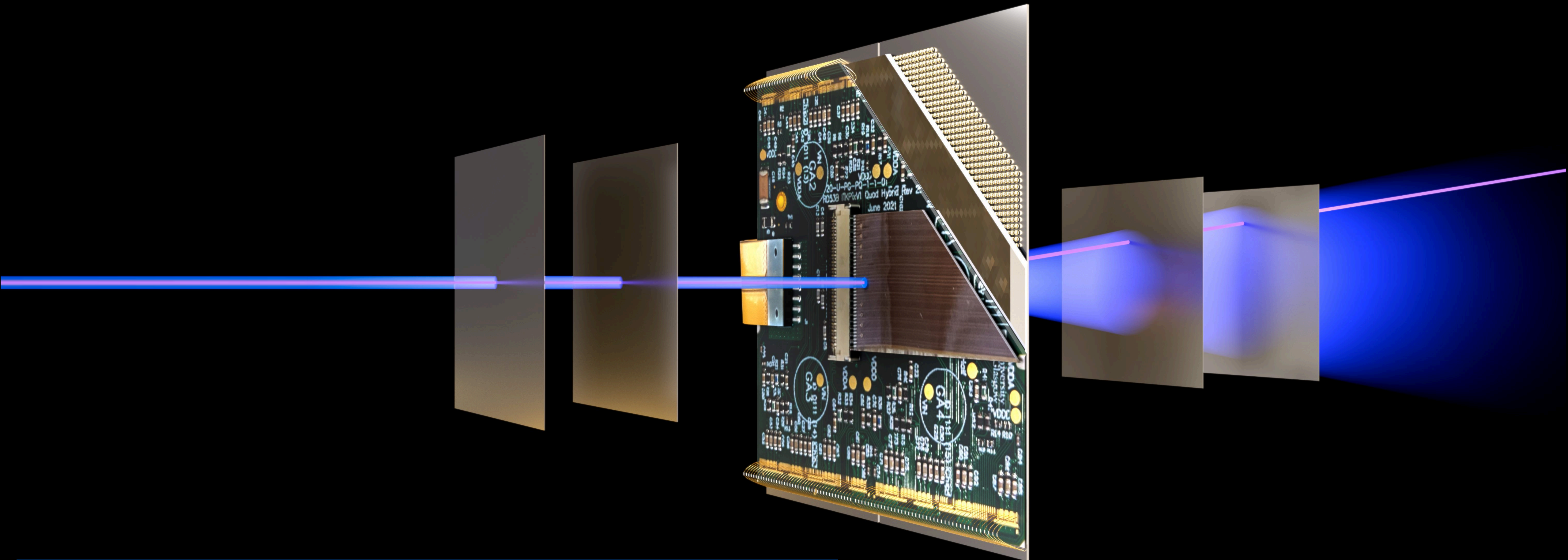


**MALTA**  
#not-a-real-detector

**MONSTAR**  
MULTIPLE OR NEGLIGIBLE SCATTERING TELESCOPE AS REQUIRED



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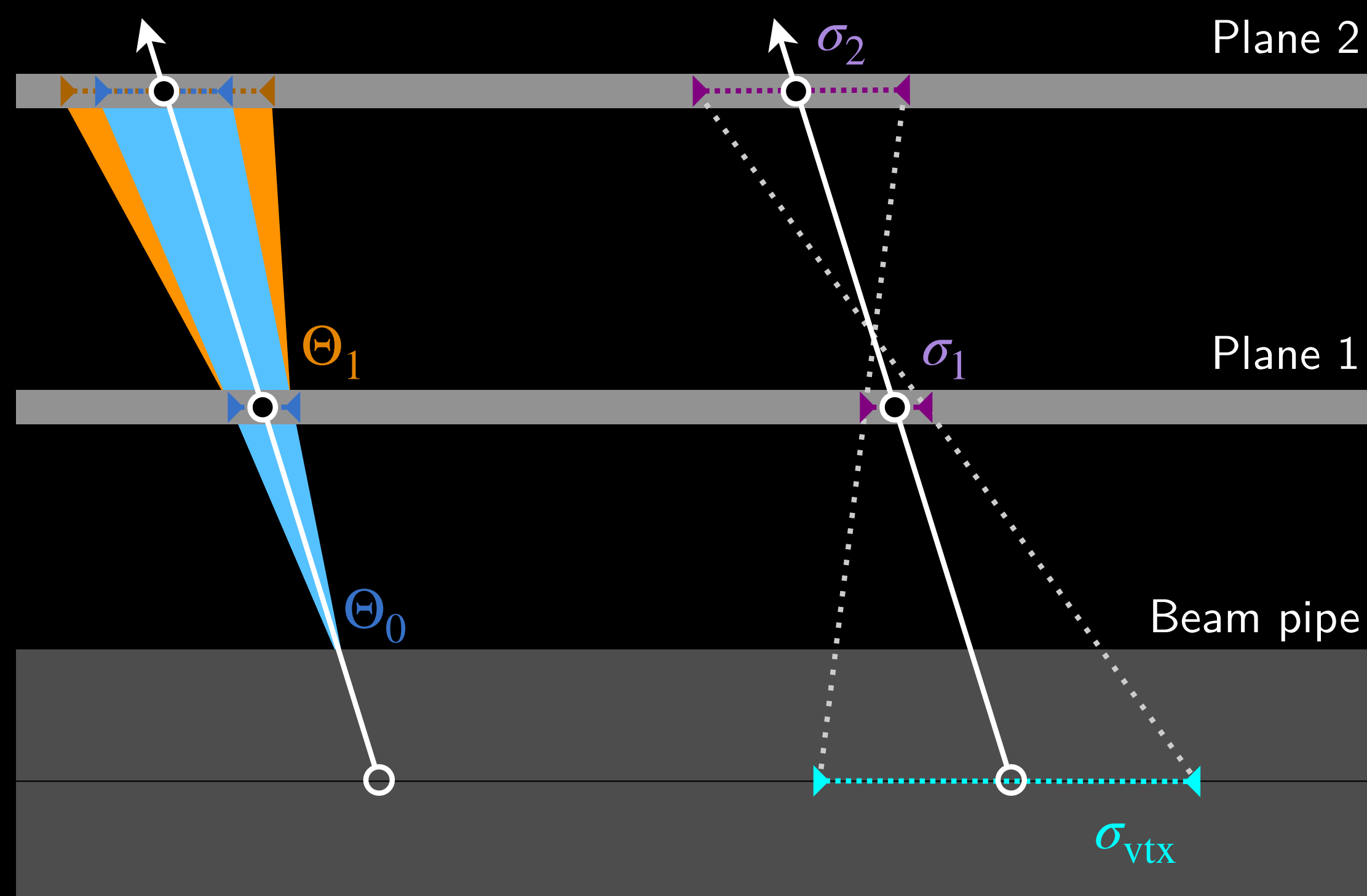


# STEP 3: MEASURING THE ITK

*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]:

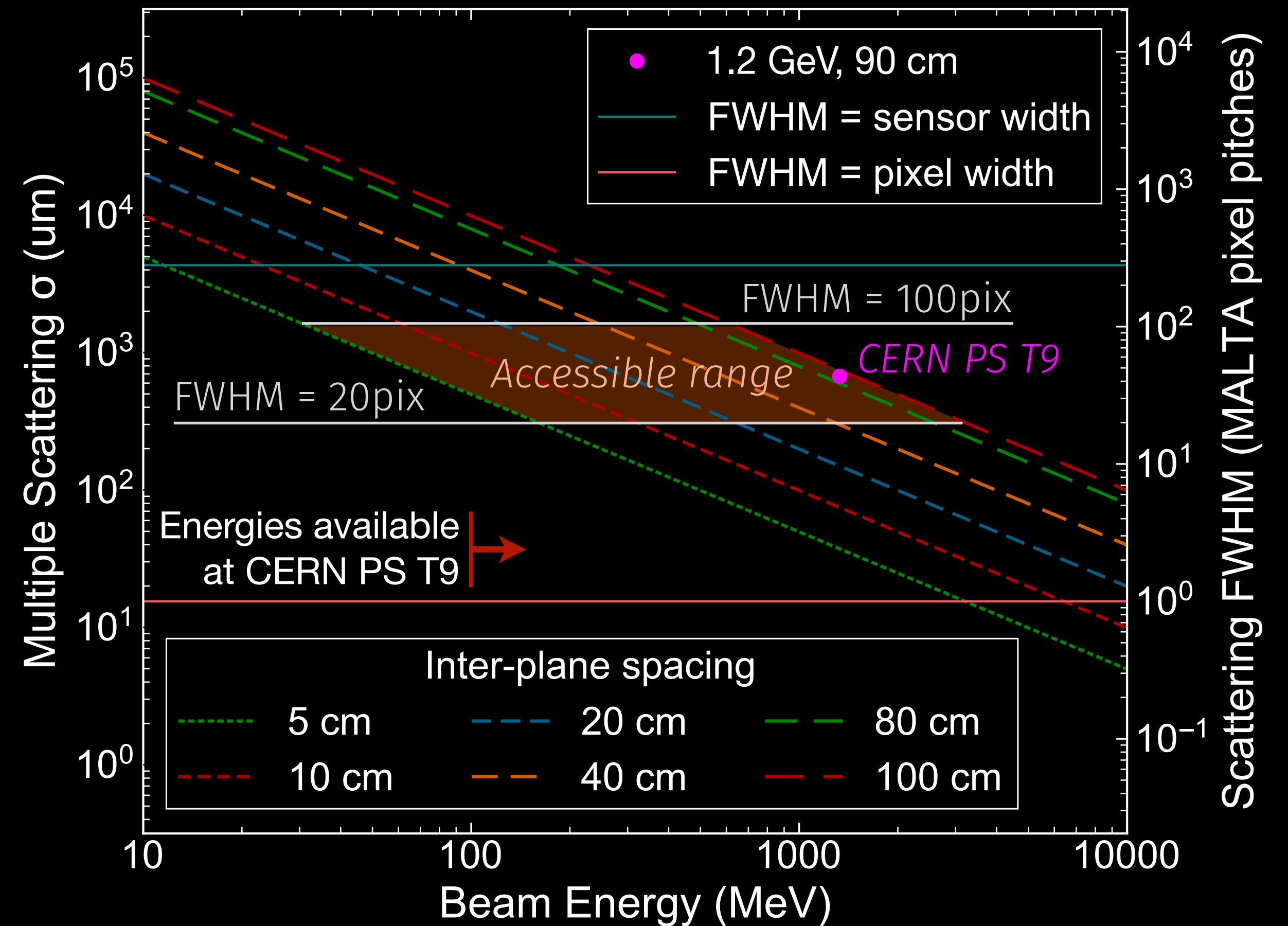
$$\theta_{\text{rms plane}} = \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{x/X_0} (1 + 0.038 \ln(x/X_0))$$

[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

Scattering behaviour for  $x/X_0 = 0.80\%$



# MEASURING RADIATION LENGTH

▶ Use a low- $X_0$  telescope to measure multiple scattering of  $e^+$  at  $O(1 \text{ GeV})$  at CERN PS

▶ MS is gaussian with “single-hard-scatter” Rutherford tail ( $\sim \theta^{-4}$ )  
- fit with Double-sided Crystal Ball<sup>[1]</sup>

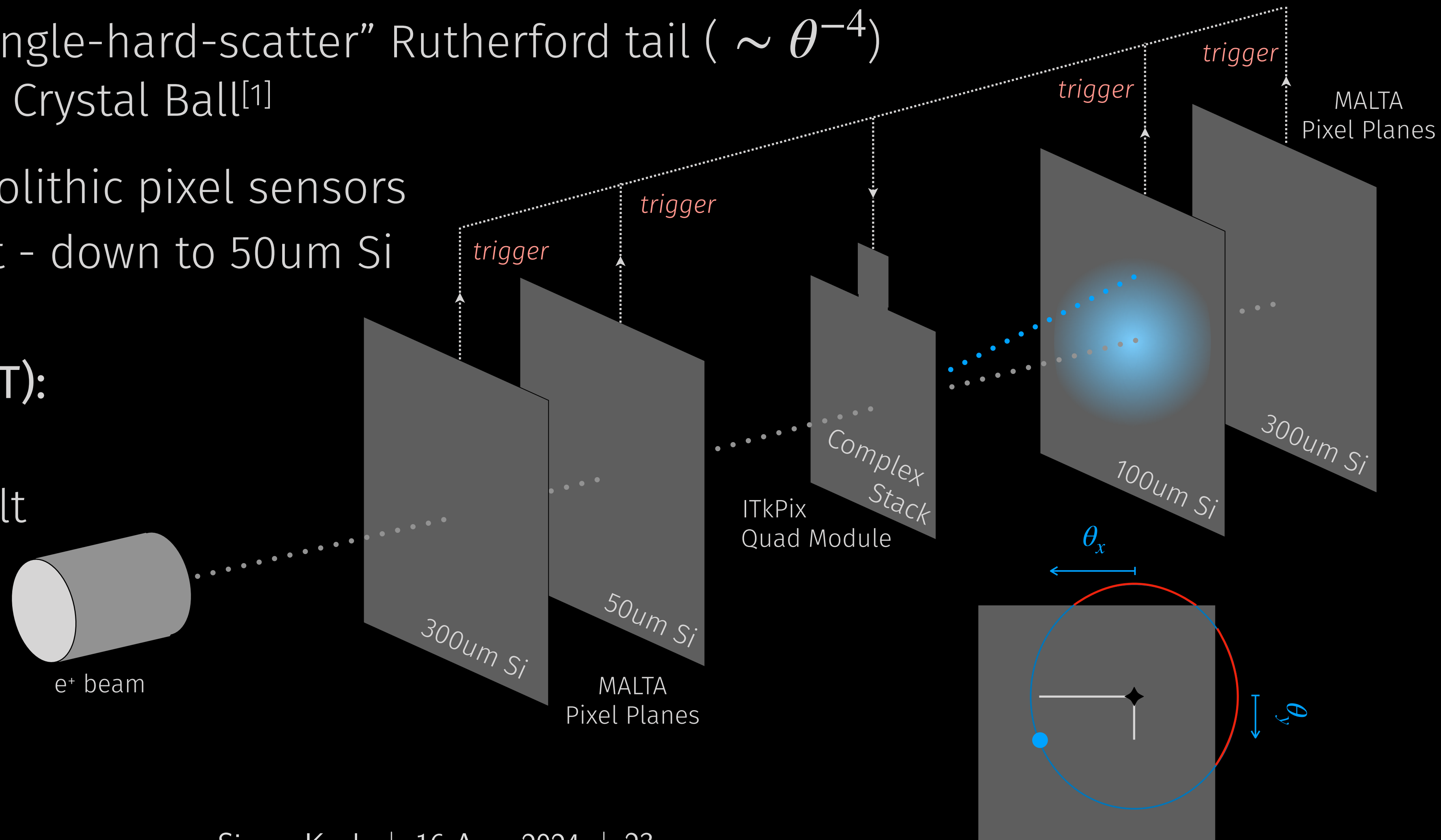
▶ **Telescope:** MALTA Monolithic pixel sensors

- Low material content - down to 50 $\mu\text{m}$  Si

▶ **Device Under Test (DUT):**

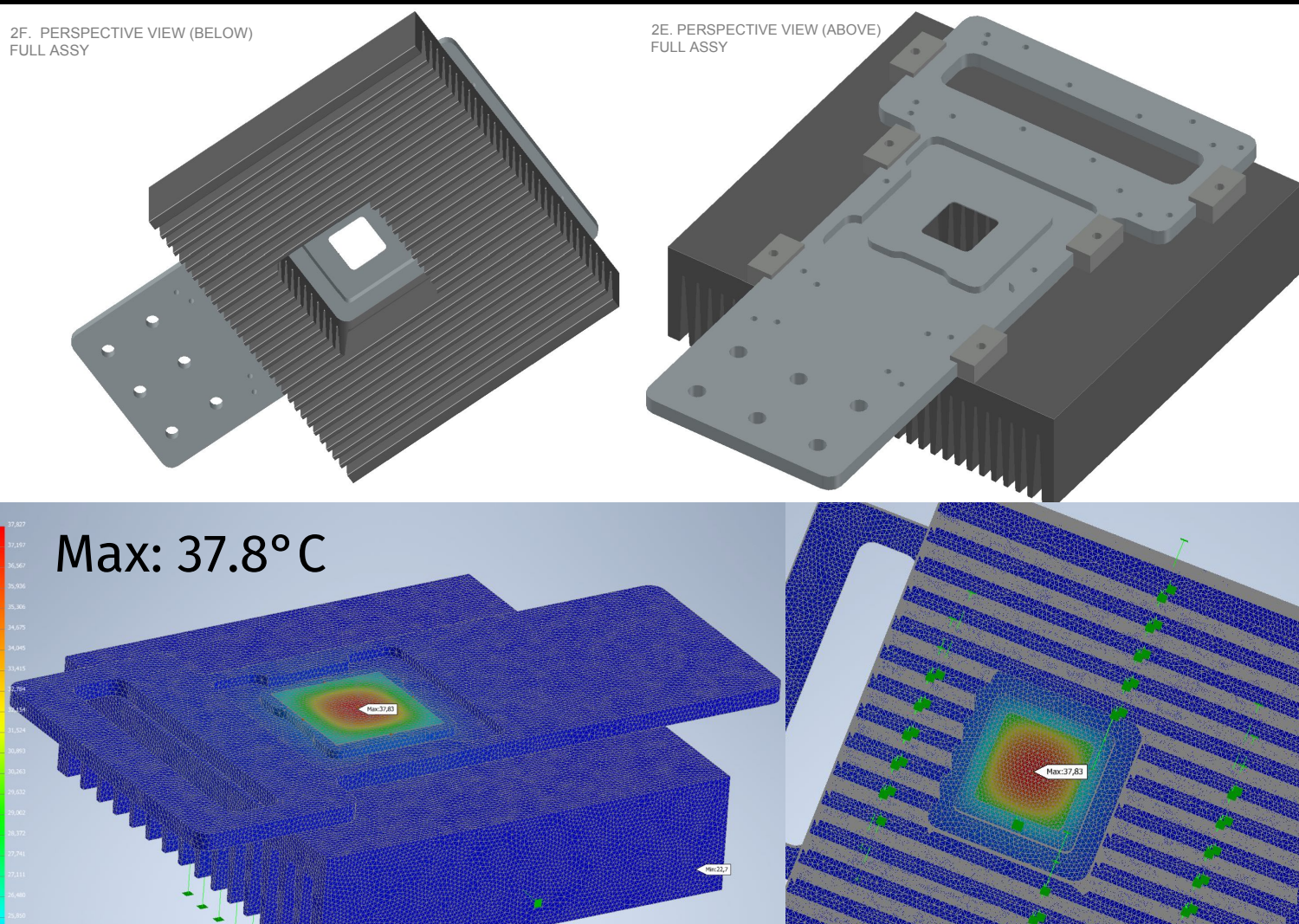
ITkPix Quad Module

- Hybrid design difficult to get a clean rad. length estimate for
- FELIX readout chain



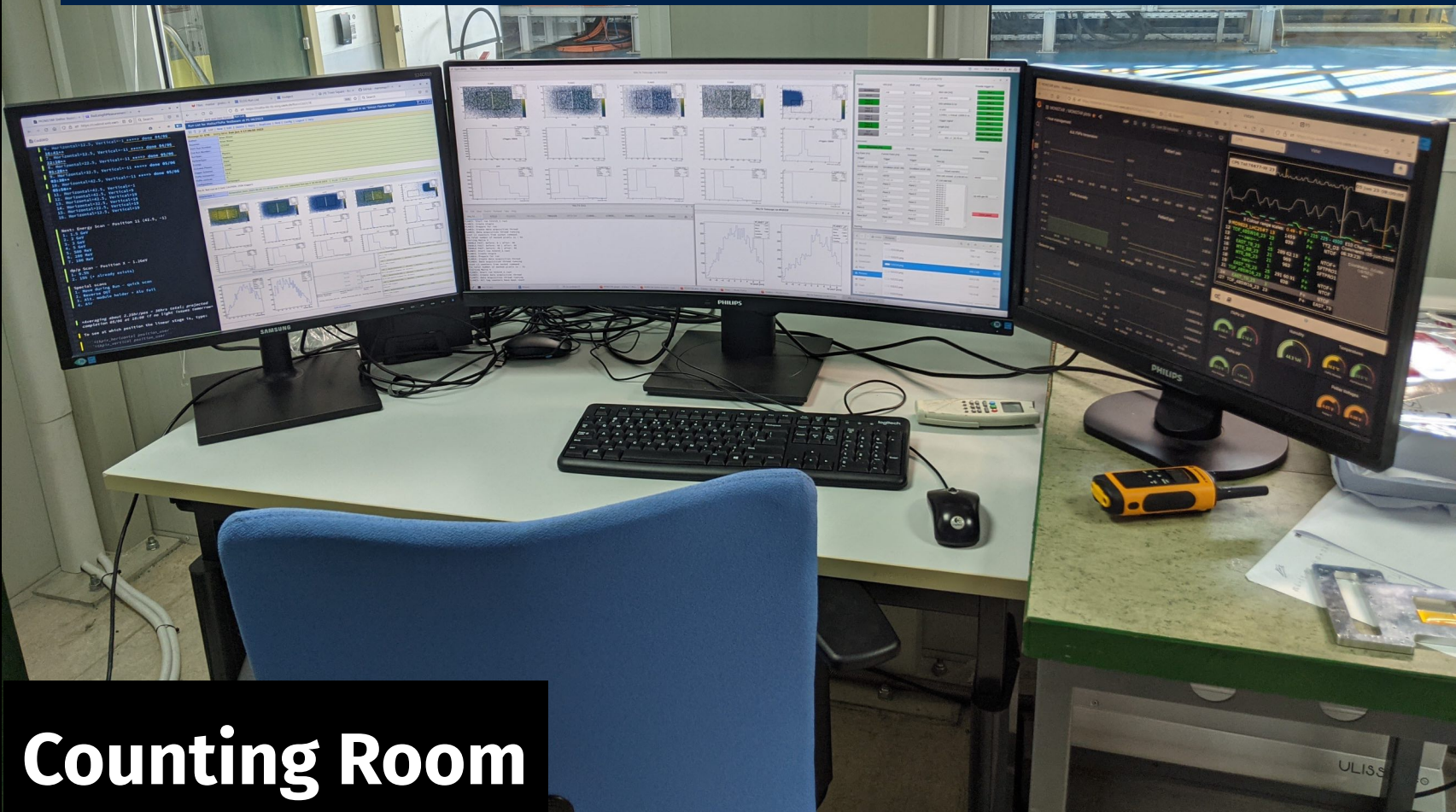
[1] double-sided crystal ball function ([link](#))



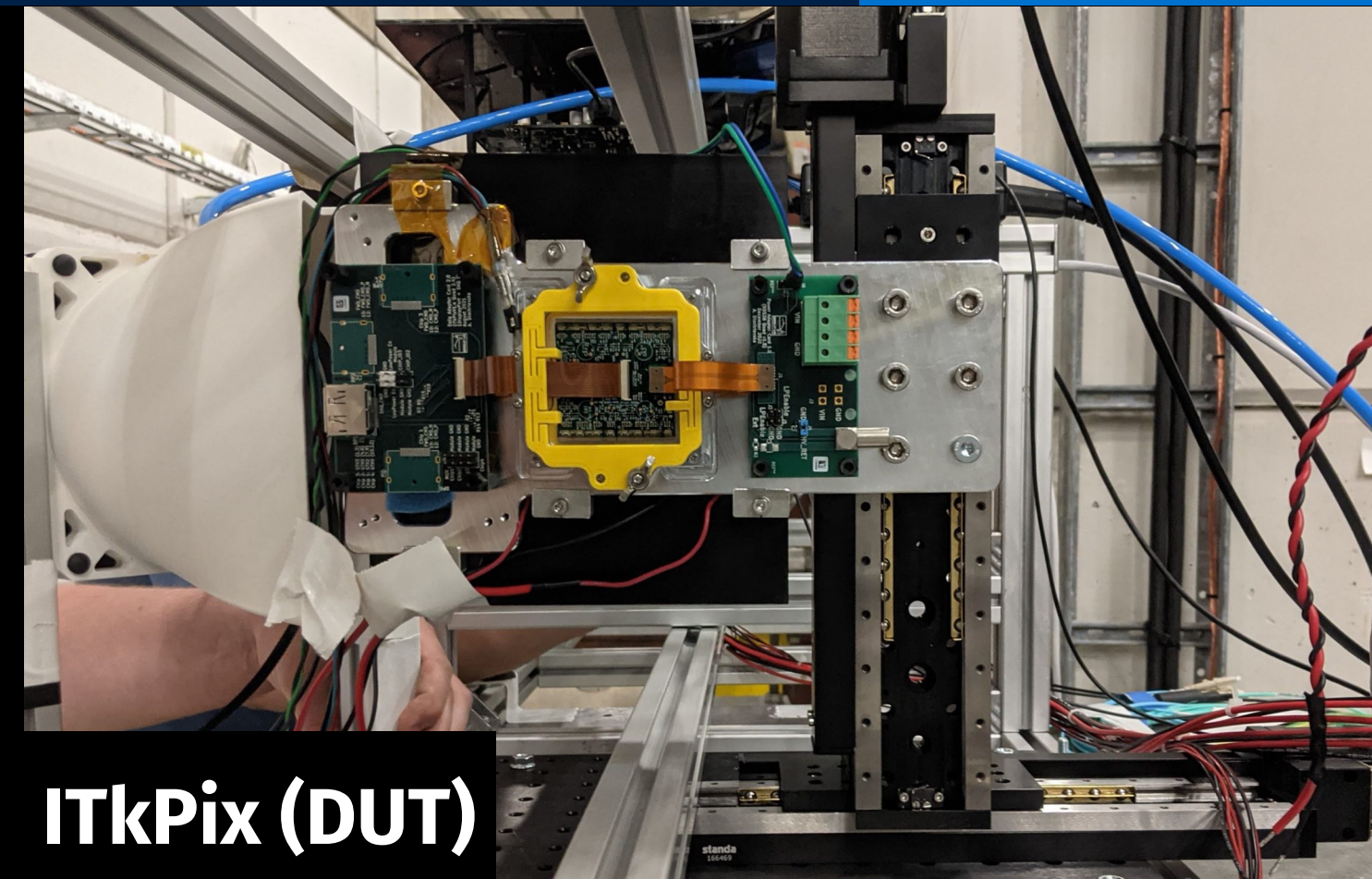


**ITkPix Cooling + Mechanics (Oxford)**

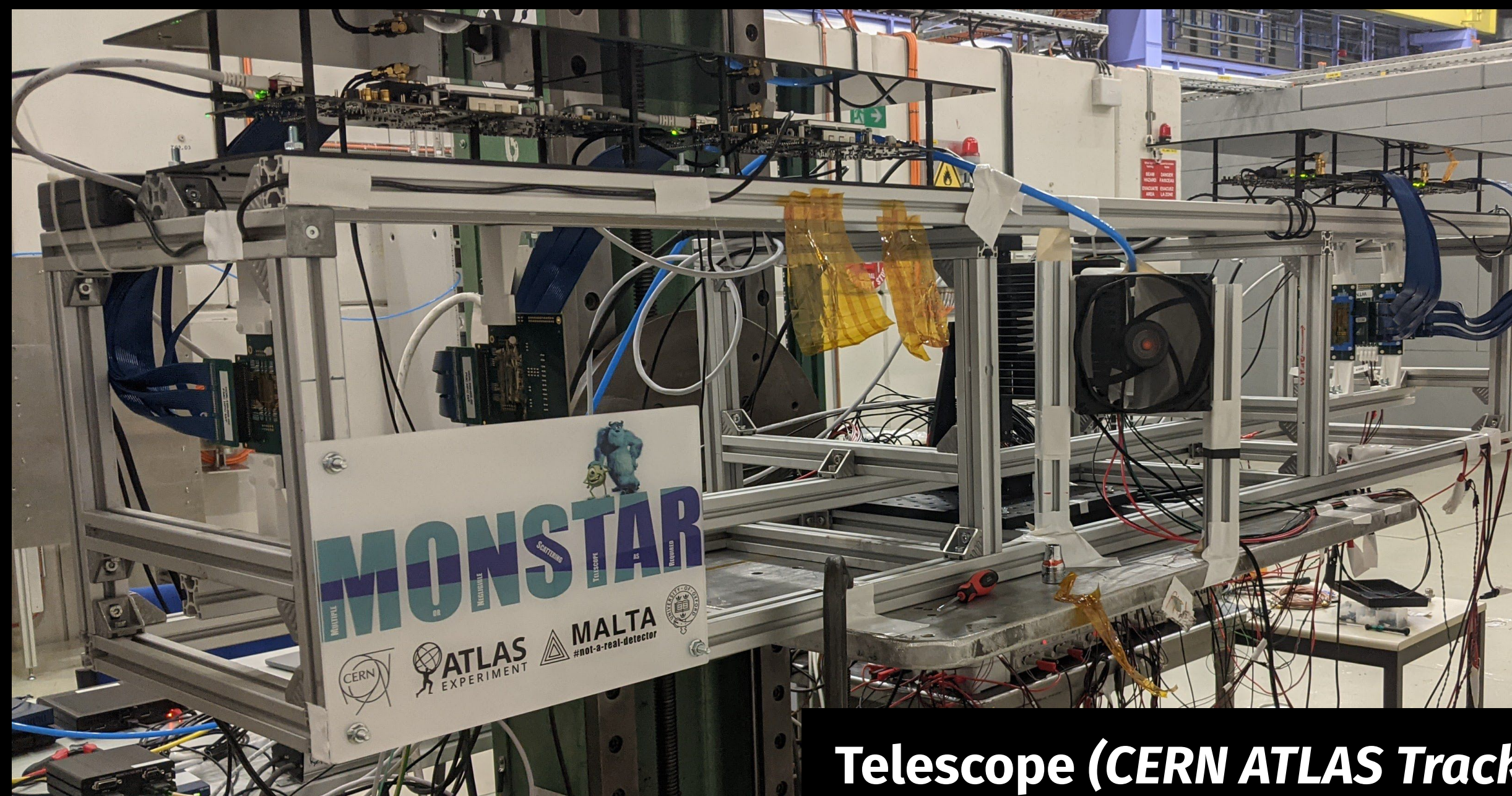
# THE SETUP AT THE CERN PS



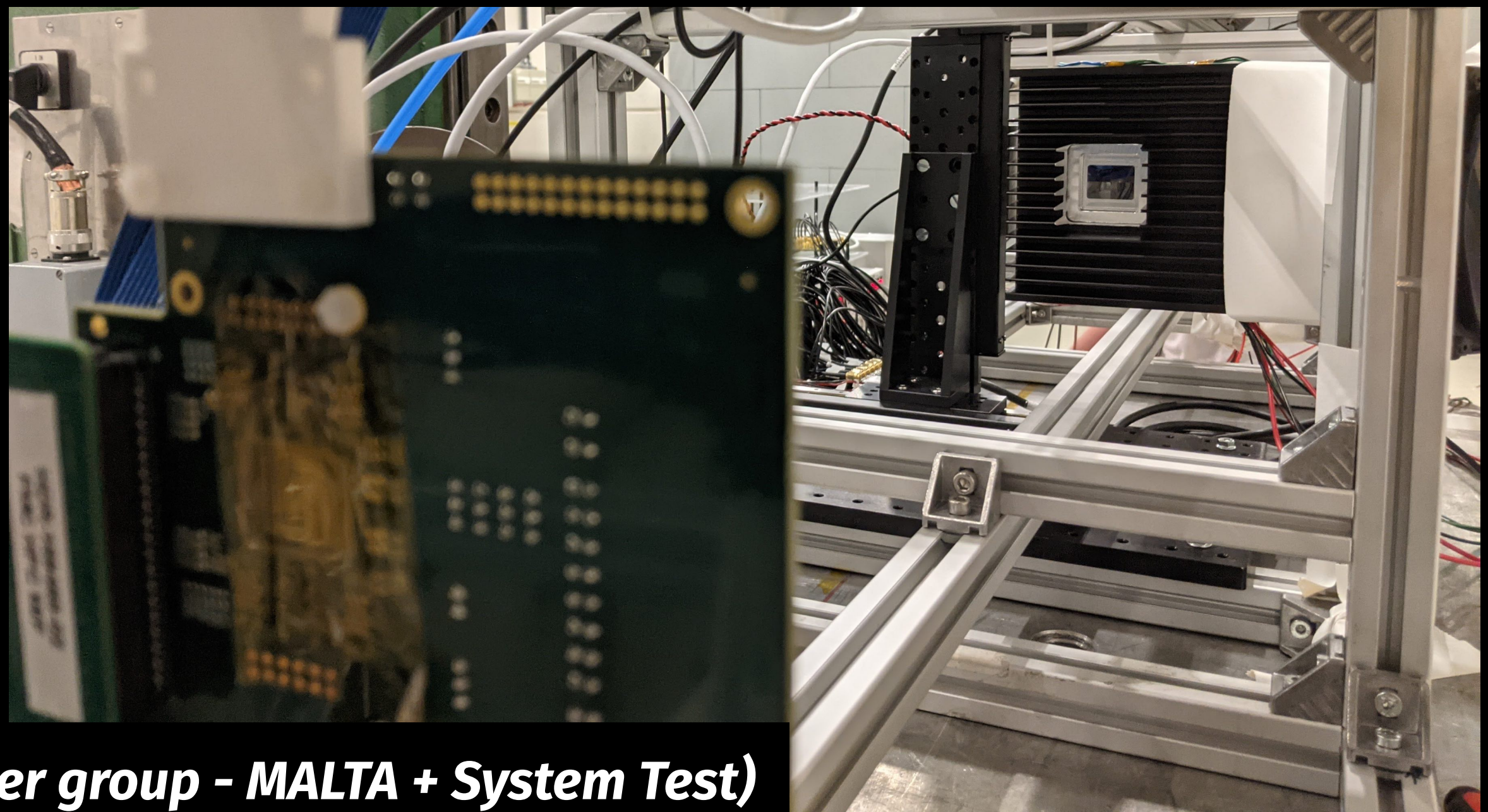
**Counting Room**



**ITkPix (DUT)**



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

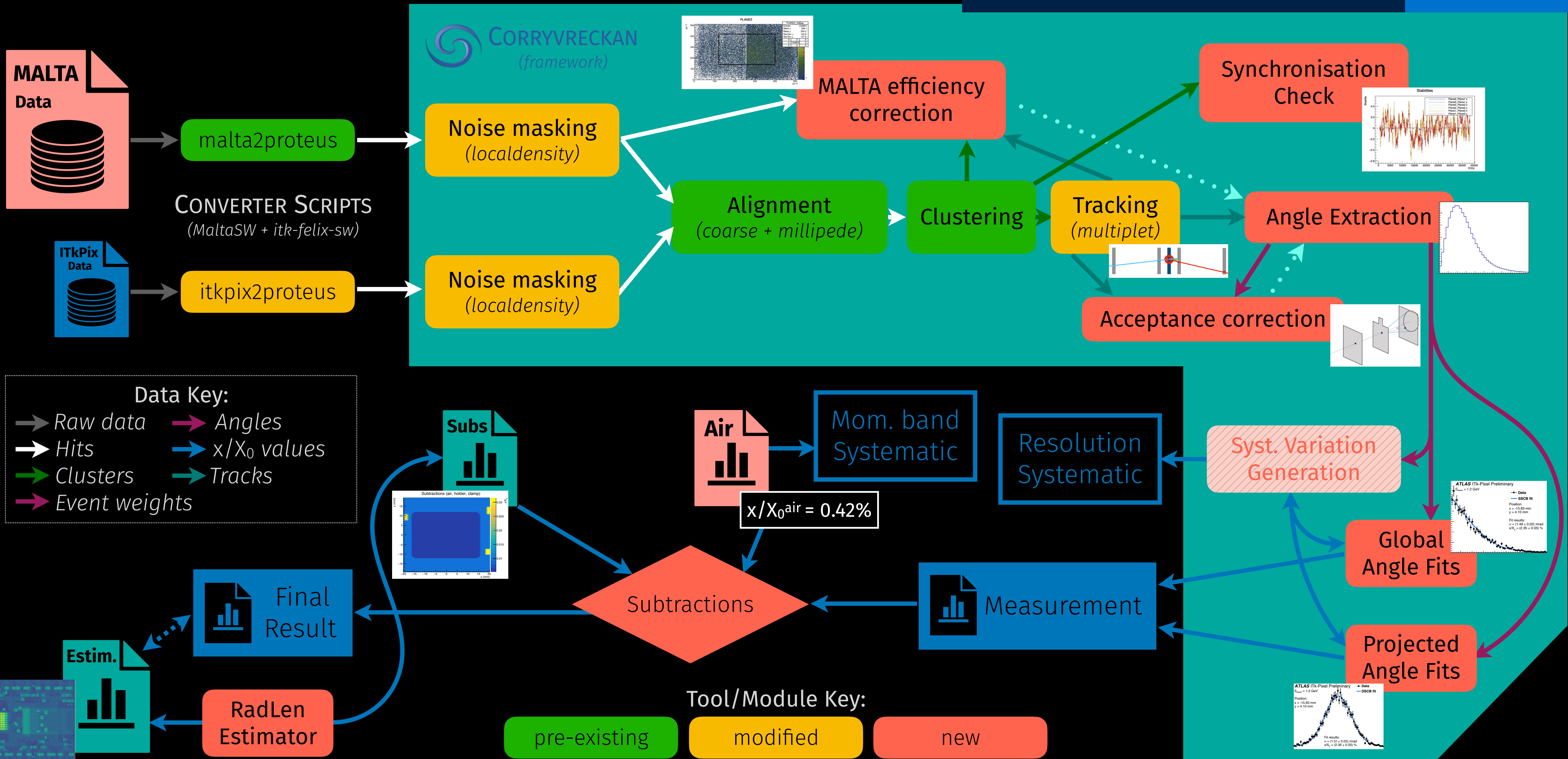




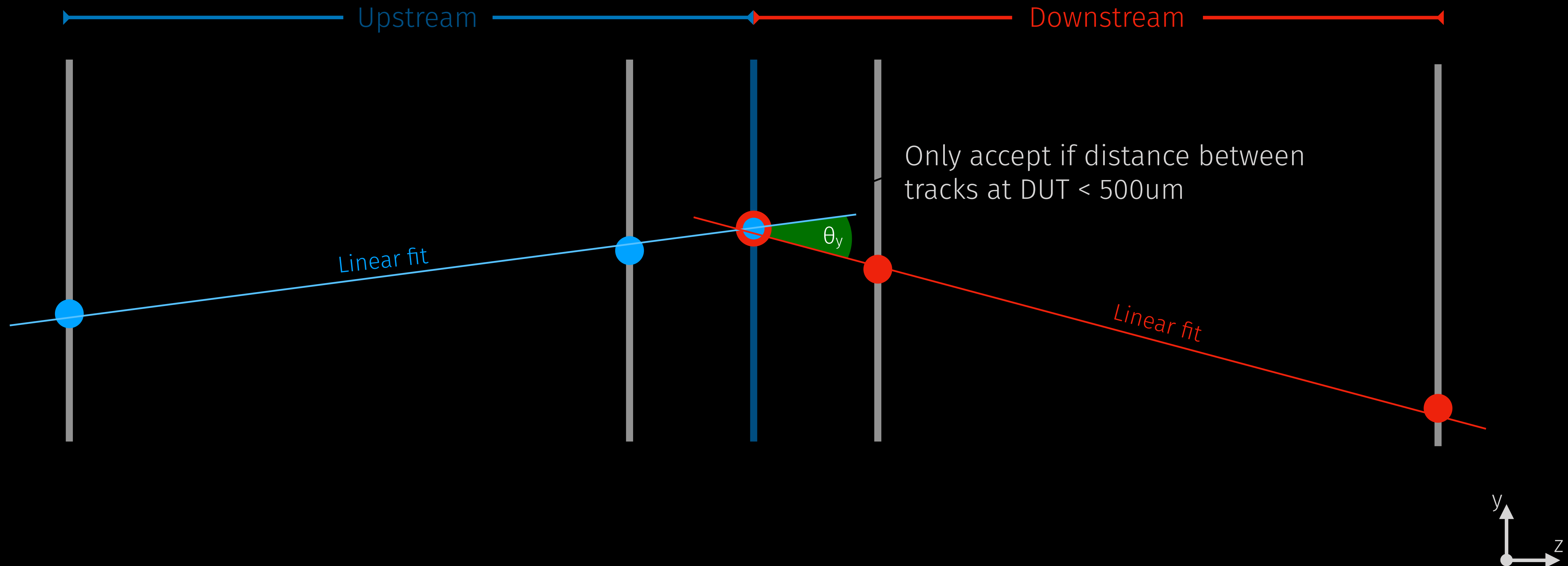
Almost entire analysis chain uses:  
(or implemented as new modules for)

 Corryvreckan testbeam  
analysis framework

# ANALYSIS CHAIN



We require 3 hits per track on both upstream and downstream



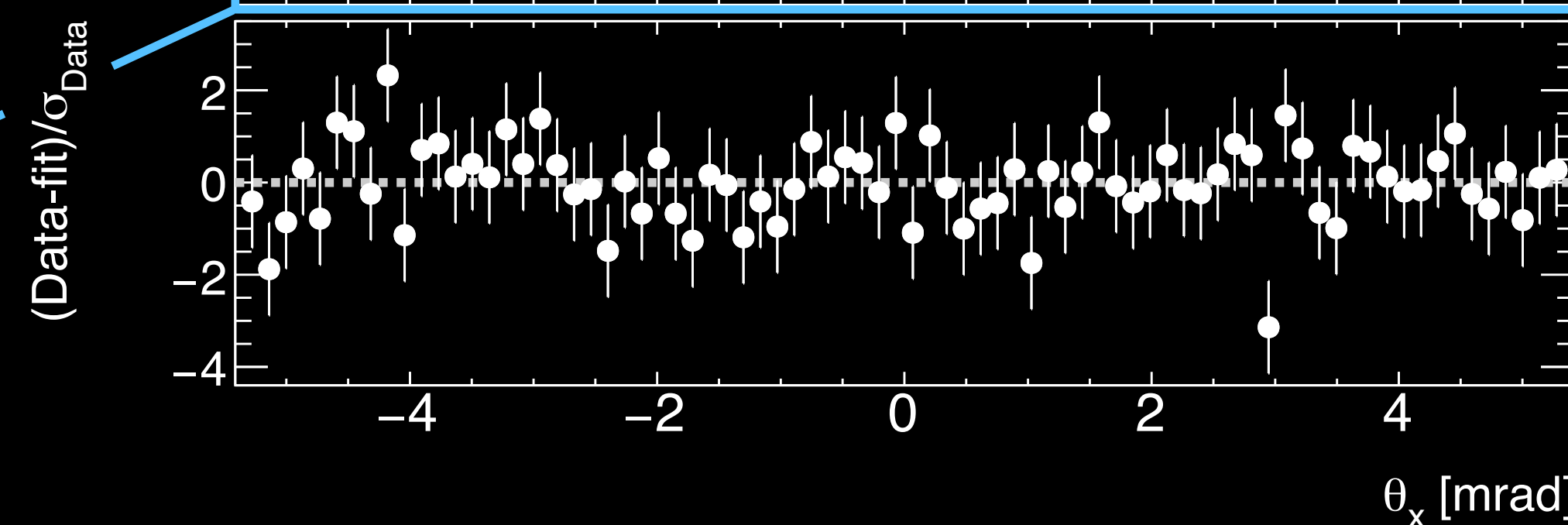
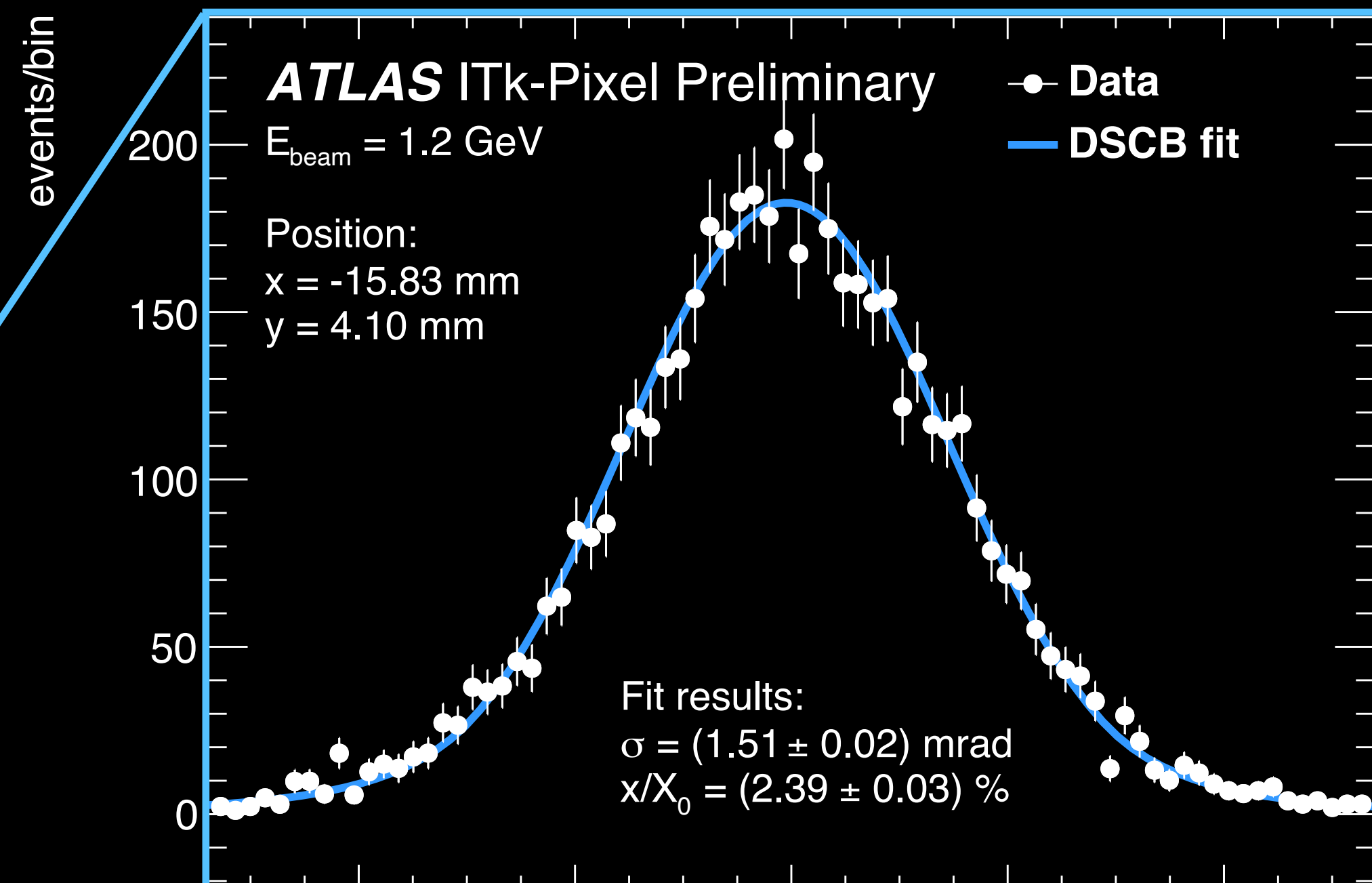


# ANGLE DISTRIBUTION FITS



- ▶  $\theta_x, \theta_y$  (projected distributions) fitted by double-sided crystal ball function (DSCB)
- ▶ Fit performed unbinned directly on angle data using RooFit

1.5	5.1	9	8.8	2.1	1	0.9	0.8	0.56	0.52	0.53	0.55	0.58	0.53	0.56	0.59	0.57	0.7	0.58	0.59	
+0.2	+0.6	+1	+1	+0.3	+0.1	+0.1	+0.1	+0.1	+0.09	+0.09	+0.1	+0.1	+0.09	+0.09	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1
1.7	5.5	9	9	2.5	1	1	0.8	0.44	0.48	0.41	0.4	0.51	0.47	0.59	0.6	0.56	0.6	0.61	0.62	
+0.2	+0.6	+0.9	+0.9	+0.3	+0.1	+0.1	+0.1	+0.1	+0.08	+0.09	+0.08	+0.08	+0.09	+0.09	+0.1	+0.1	+0.09	+0.1	+0.1	+0.1
1.6	5.8	9	9.1	2.3	1	0.9	0.7	0.7	0.52	0.46	0.51	0.47	0.54	0.6	0.6	0.6	0.57	0.7	0.7	
+0.2	+0.9	+0.9	+0.9	+0.3	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.08	+0.08	+0.09	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1
1.6	7.4	9.1	9.2	2.4	1.1	1	0.41	0.4	0	0.43	0.47	0.51	0.53	0.6	0.7	0.62	0.52	0.58	0.58	
+0.2	+0.9	+0.9	+0.9	+0.3	+0.1	+0.1	+0.1	+0.1	+0.08	+0.08	+0.1	+0.08	+0.1	+0.09	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1
1.3	1.7	2.4	2.5	1.4	1.1	1	0.5	0.43	0.61	0.44	0.46	0.54	0.53	0.57	0.58	0.7	0.6	0.6	0.6	
+0.2	+0.2	+0.3	+0.3	+0.2	+0.1	+0.1	+0.1	+0.1	+0.1	+0.09	+0.1	+0.1	+0.08	+0.08	+0.09	+0.1	+0.1	+0.1	+0.1	+0.1
1.1	1.1	1.1	1.1	1.1	1.1	1	0.8	0.6	0	0.51	0.45	0.47	0.43	0.52	0.56	0.6	0.6	0.55	0.57	
+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.08	+0.08	+0.08	+0.08	+0.09	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1
1.1	1.2	1.1	1.1	1.4	1.2	0.7	0.48	0.46	0.38	0.55	0.45	0.55	0.53	0.57	0.57	0.61	0.6	0.5	0.5	
+0.1	+0.1	+0.2	+0.1	+0.2	+0.2	+0.1	+0.1	+0.1	+0.1	+0.08	+0.08	+0.08	+0.08	+0.09	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1
1.1	1.2	1.6	1.6	1.8	1.4	0.9	0	0.51	0.54	0.55	0.51	0.54	0.55	0.61	0.54	0.59	0.6	0.58	0.56	
+0.1	+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.1	+0.09	+0.09	+0.09	+0.09	+0.09	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1
1.2	1.1	1.1	1.1	1.1	1.1	1	0.9	0	0.52	0.51	0.6	0.7	0.7	0.48	0.4	0.55	0.51	0.48	0.6	
+0.2	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.08	+0.09	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1
1.3	1.2	1.2	1.1	1.1	1.1	1.1	0.9	0.61	0.6	0.7	0.55	0.56	0.6	0.55	0.47	0.47	0.47	0.47	0.52	
+0.2	+0.2	+0.2	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.09	+0.1	+0.1	+0.08	+0.08	+0.08	+0.09	+0.1	+0.1	+0.1
1.2	1.2	1.7	1.5	1.7	1.9	1.1	1.7	1.9	2.1	2.2	2.1	1.5	1.4	1	0.58	0.61	0.51	0.48	0.6	
+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1
1.8	1.5	1.6	1.7	1.8	2.6	4.7	4.3	4.9	7.1	2.1	3.2	5.3	4.4	3.1	1.6	0.7	0.8	0.53	0.47	
+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.5	+0.5	+0.5	+0.8	+0.2	+0.4	+0.6	+0.5	+0.4	+0.2	+0.1	+0.1	+0.1	+0.1	+0.1
1.8	1.6	1.7	1.7	1.7	2.1	2.4	3.3	2.6	2.9	2.1	2.6	3.3	2.2	1.8	1.1	0.7	0.7	0.61	0.5	
+0.2	+0.2	+0.2	+0.2	+0.2	+0.3	+0.3	+0.3	+0.3	+0.3	+0.2	+0.3	+0.3	+0.2	+0.2	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1
1.7	1.6	1.7	1.7	1.7	1.9	2.7	2.7	3.7	5.2	2.2	4	4.7	3.2	2.5	1.5	0.7	0.7	0.61	0.47	
+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.3	+0.3	+0.4	+0.5	+0.3	+0.4	+0.5	+0.4	+0.3	+0.2	+0.1	+0.1	+0.1	+0.1	+0.1
1.7	1.6	1.8	1.7	1.7	2.3	3.4	4.6	4.8	6.3	2.1	3.6	5.1	3.8	2.9	1.6	0.7	0.7	0.59	0.48	
+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.3	+0.4	+0.4	+0.5	+0.3	+0.3	+0.3	+0.3	+0.3	+0.2	+0.1	+0.1	+0.1	+0.1	+0.1
1.7	1.5	1.7	1.6	1.7	1.9	2.7	2.7	3.7	5.2	2.2	4	4.7	3.2	2.5	1.5	0.7	0.7	0.61	0.47	
+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.3	+0.3	+0.4	+0.5	+0.3	+0.4	+0.5	+0.4	+0.3	+0.2	+0.1	+0.1	+0.1	+0.1	+0.1
1.2	1.2	1.3	1.4	1.1	1.2	1.3	1.6	1.6	2.3	1.3	1.9	1.6	2.3	1.3	1.1	0.7	0.7	0.6	0.48	
+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.3	+0.3	+0.3	+0.3	+0.3	+0.2	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1
1.2	1.2	1.3	1.1	1.2	1.7	2.7	2.5	3.4	4.8	2.1	3	4.4	3.3	2.7	1.1	0.7	0.7	0.52	0.43	
+0.2	+0.2	+0.2	+0.2	+0.2	+0.3	+0.3	+0.4	+0.5	+0.2	+0.3	+0.5	+0.4	+0.3	+0.2	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1
1.3	1.3	1.2	1.3	1.2	1.9	2.5	2.6	3.1	3.5	2.5	3.4	2.9	1.8	1.5	1.1	0.7	0.7	0.53	0.48	
+0.2	+0.2	+0.2	+0.2	+0.2	+0.3	+0.3	+0.3	+0.4	+0.3	+0.3	+0.4	+0.3	+0.2	+0.2	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1

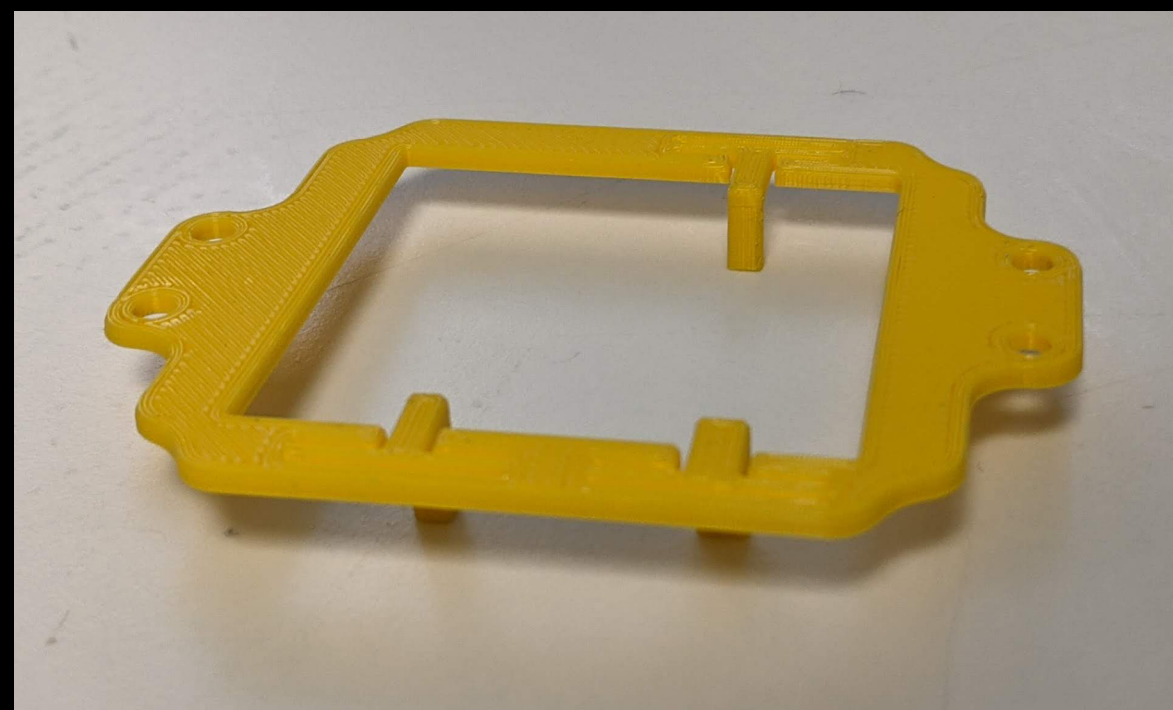
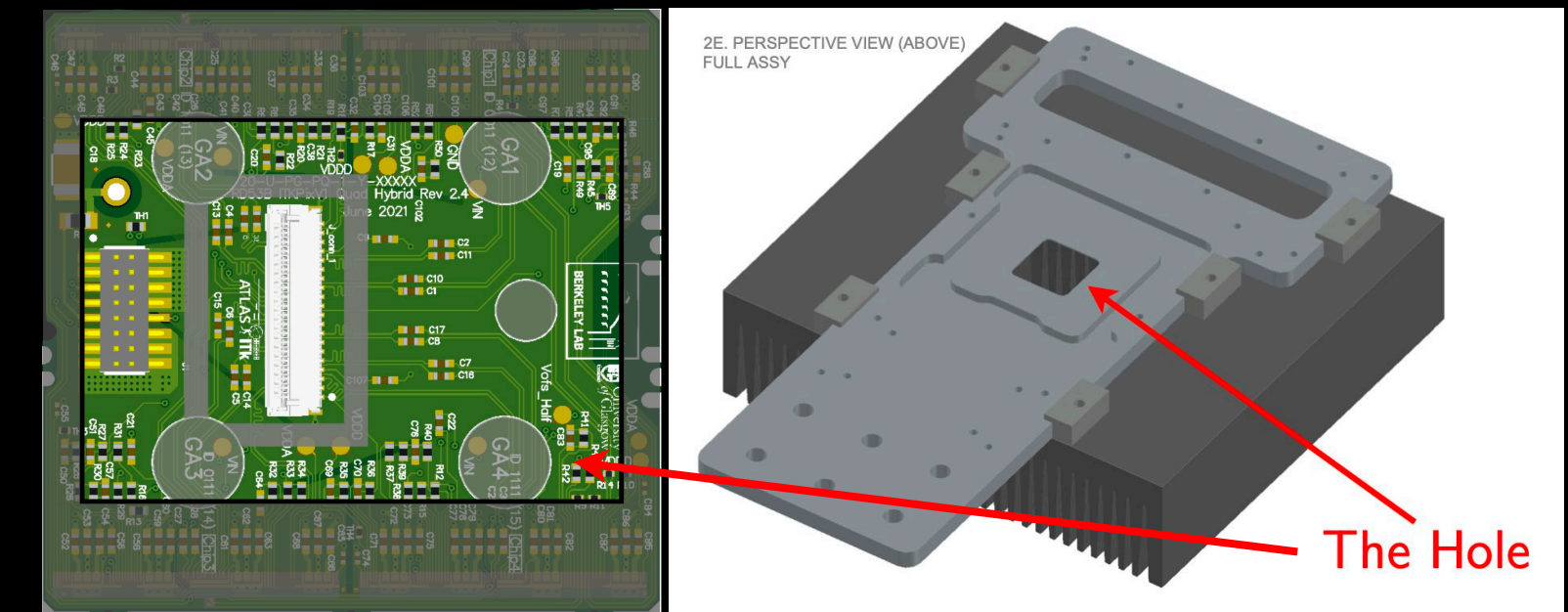




# SUBTRACTIONS

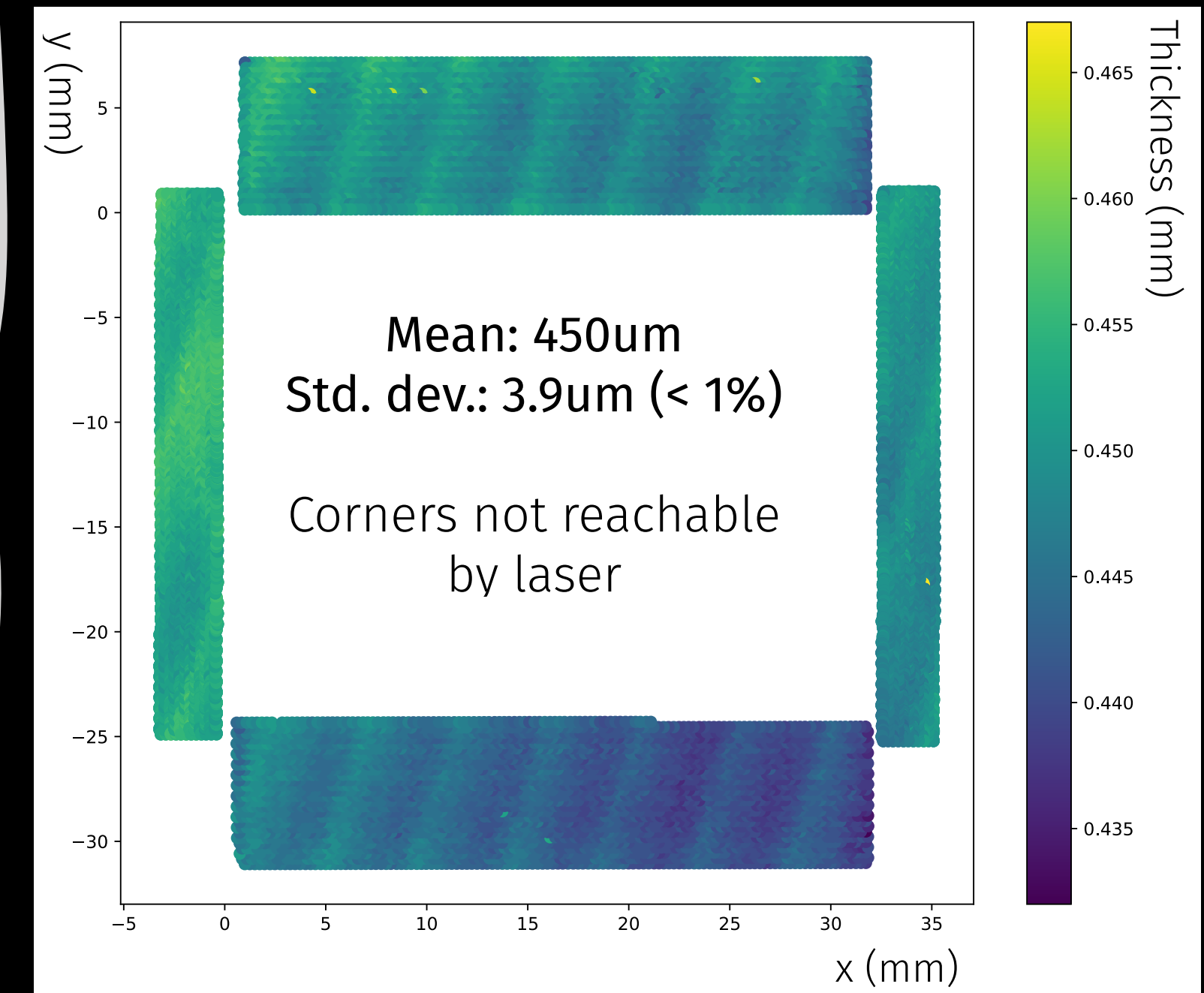
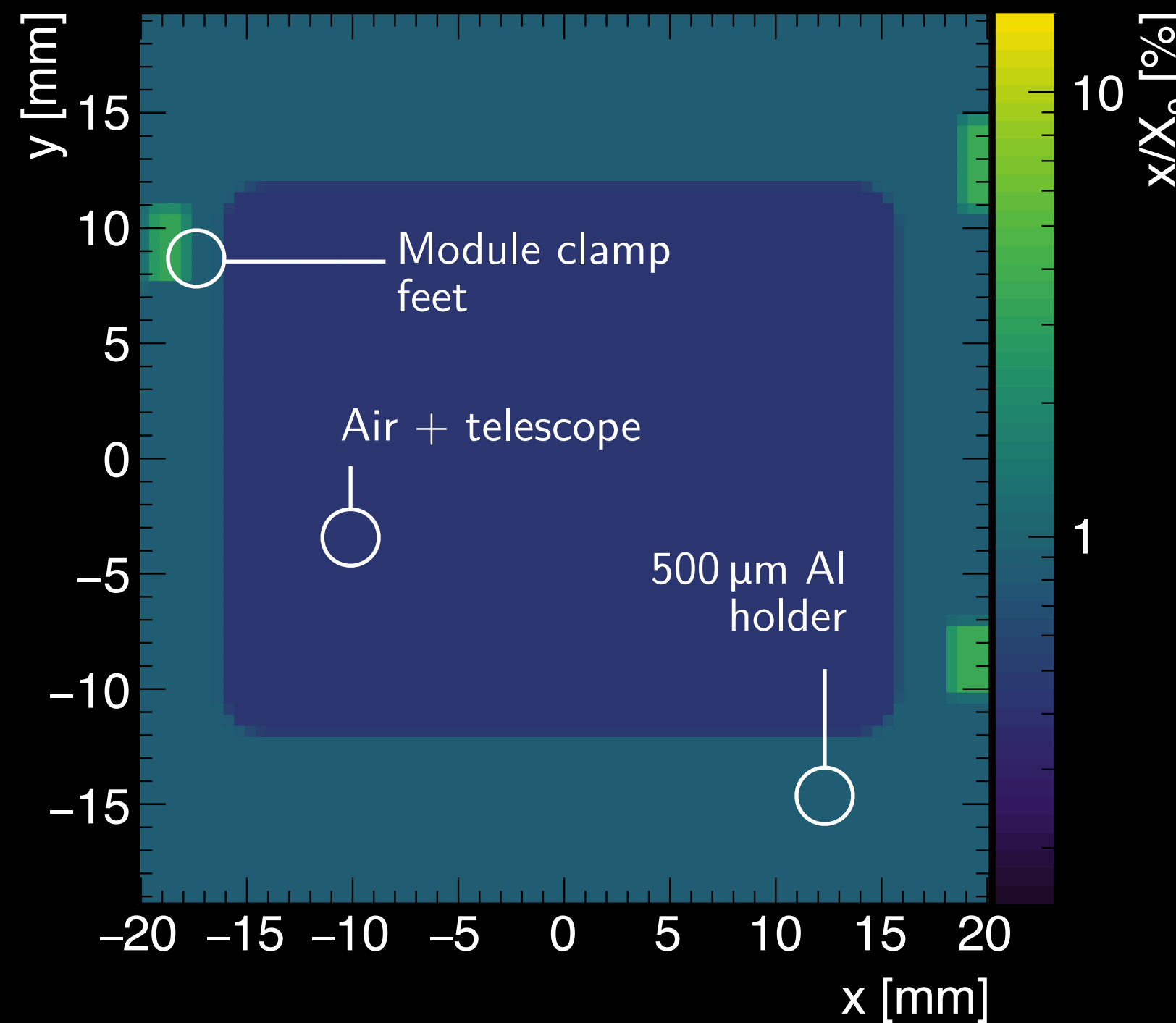


- ▶ Need to model and subtract auxiliary contributions to  $x/X_0$ 
  - Metal module holder (500um Al nominal)
    - Performed metrology on SmartScope at OPMD
  - 3D-printed Clamp
    - Dissected and weighed for density measurement



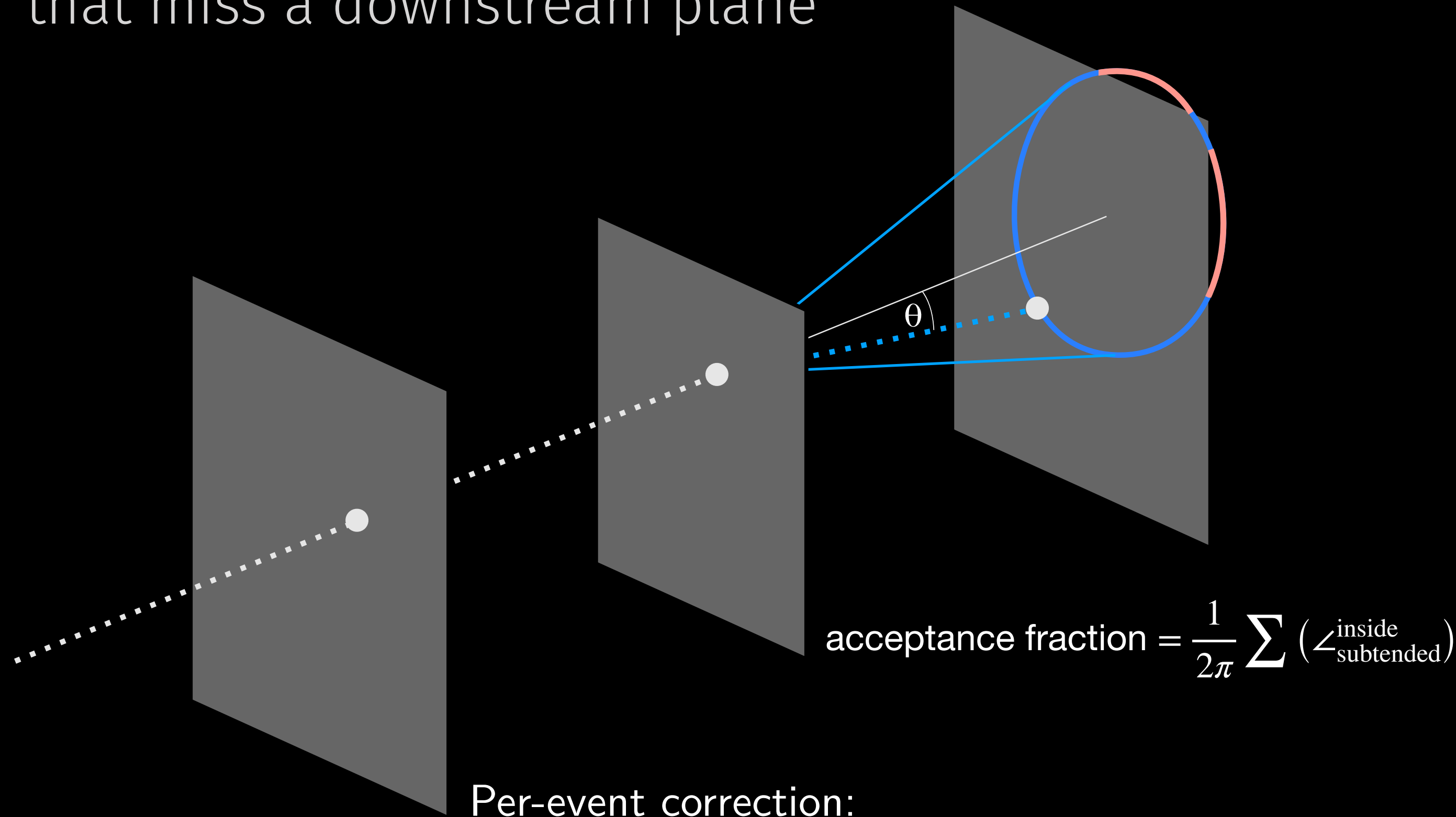
	M (g)	$\rho$ (g/cm <sup>3</sup> )	$x/X_0$
top left hv cap leg	0.045	1.096	2.24%
bot left rect leg	0.069	1.046	2.63%
bot right square leg	0.097	1.052	2.64%
top left hv cap arm	0.037	1.038	0.47%
bot left rect arm	0.038	0.958	0.45%
bot right square arm*	0.021	0.963	0.43%

Estimated air and telescope contributions





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



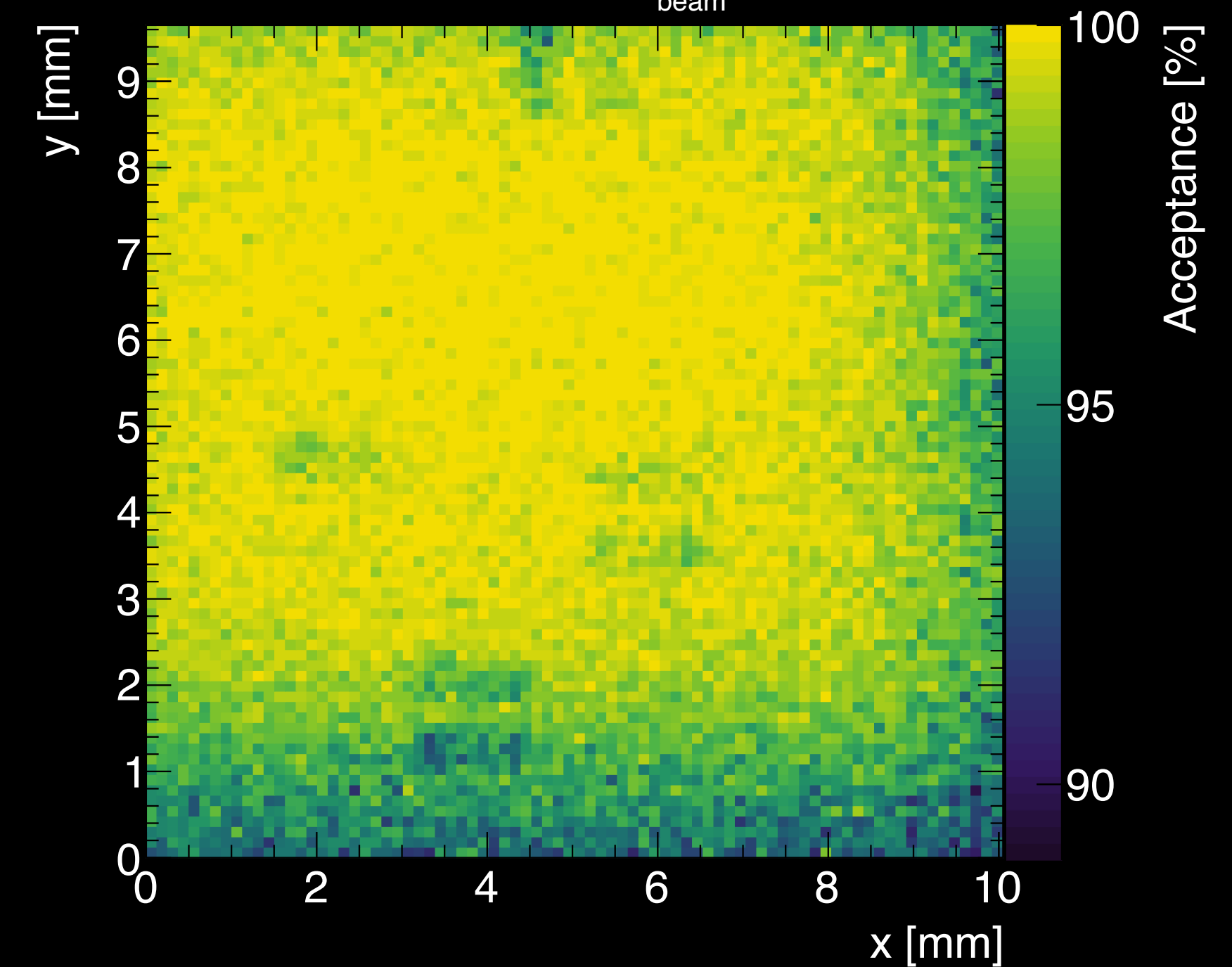
Per-event correction:

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

## ATLAS ITk-Pixel Preliminary

Av. track acceptance fraction for Pos. 1

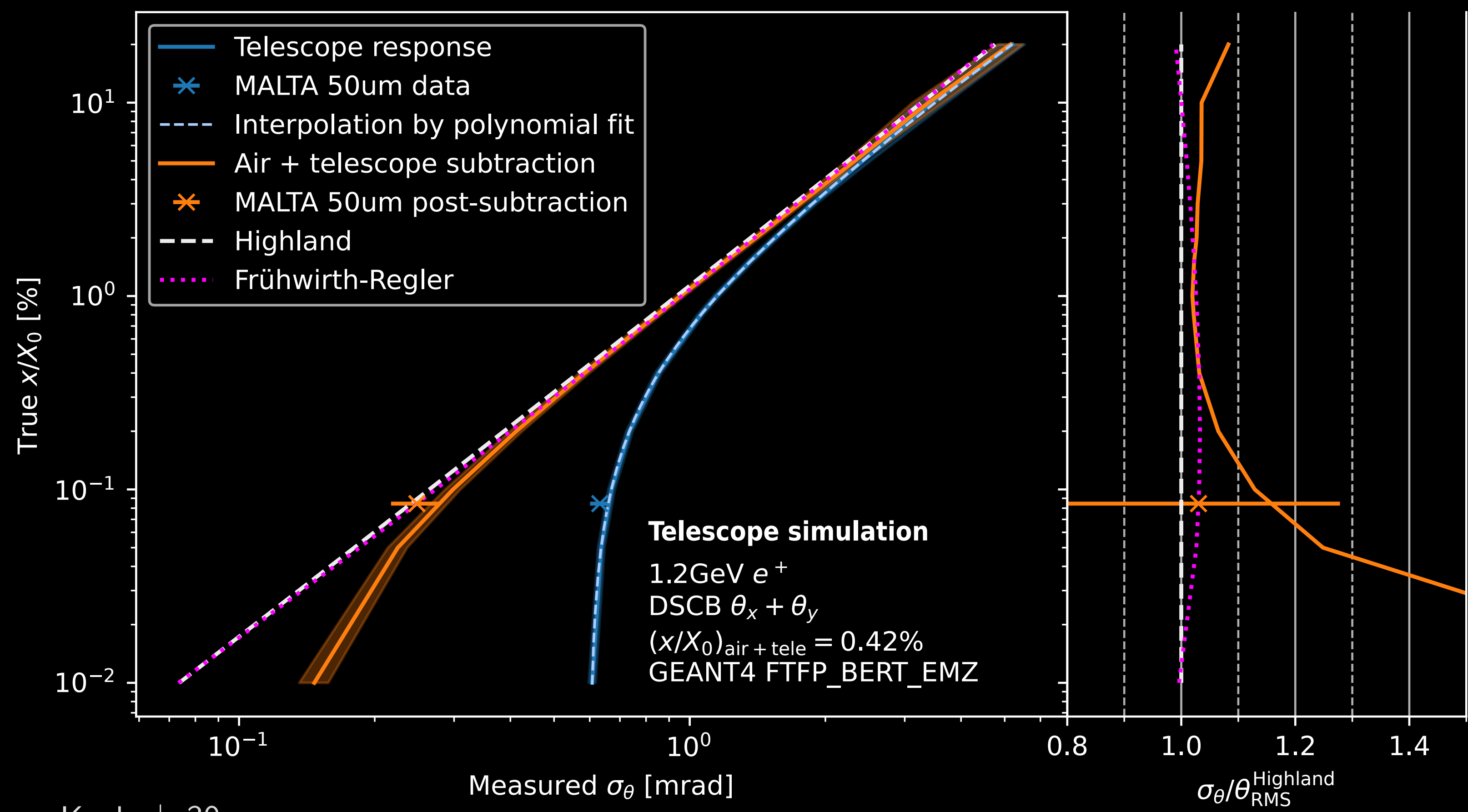
Av. acceptance = 98.6%,  $E_{\text{beam}} = 1.2 \text{ GeV}$



**Av. telescope acceptance > 98%**



- ▶ Developed simulation model in **Geant4** (using **AllPix<sup>2</sup>**)
  - 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



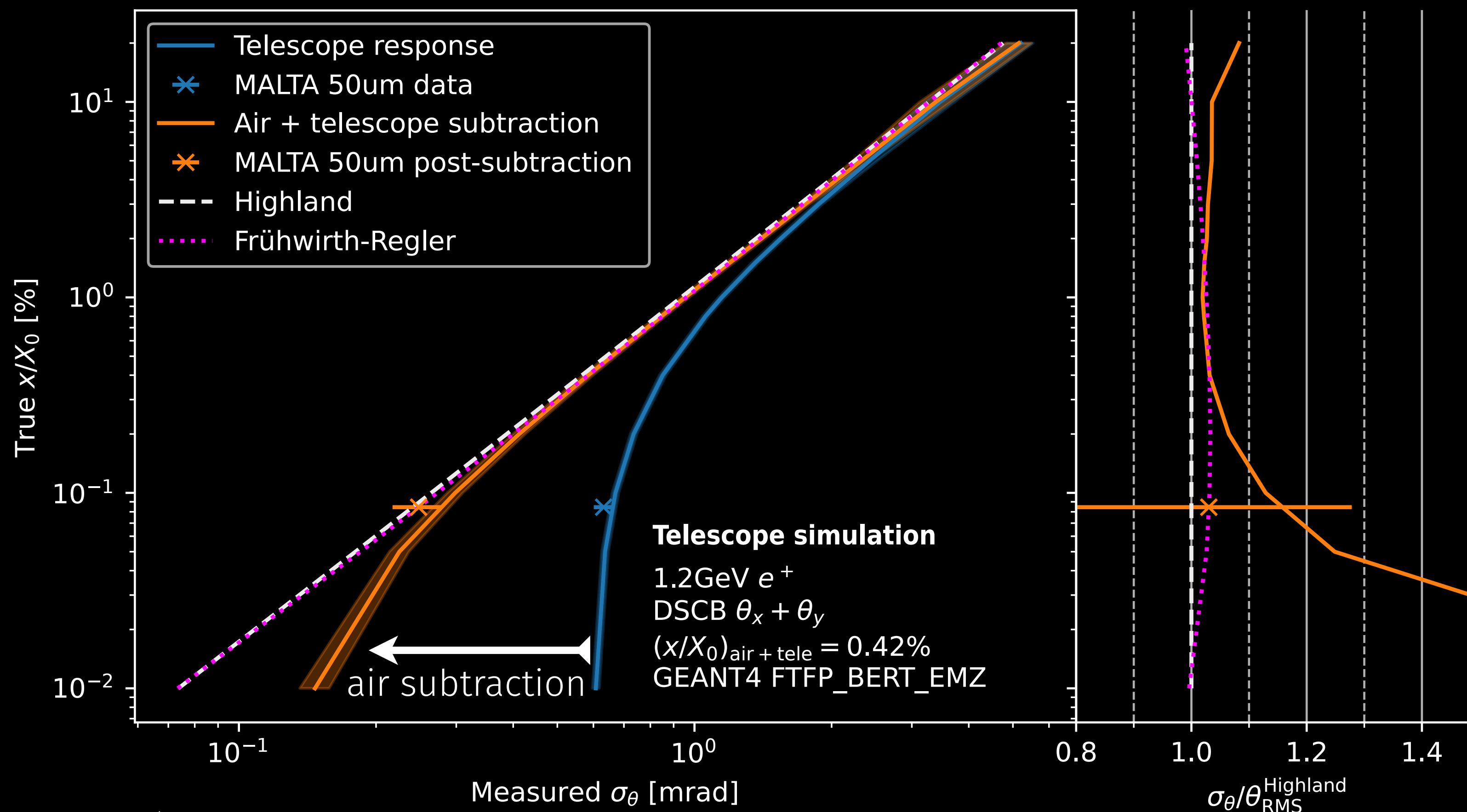
- ▶ Theory models:
  - Highland (1970):**  
 industry-standard rule-of-thumb fit to Molière theory  

$$\mathcal{O} \left( \sqrt{x(1 + \ln^2 x)} \right)$$
  - Frühwirth-Regler (2001):**  
 fit to up to  $2^{30}$  convolutions of single-scattering formula  

$$\mathcal{O} \left( \sqrt{x(1 + \ln x + \ln^2 x)} \right)$$
- ▶  $\Delta_{\text{models}} \leq 3\%$



- ▶ Developed simulation model in **Geant4** (using **AllPix<sup>2</sup>**)
  - 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

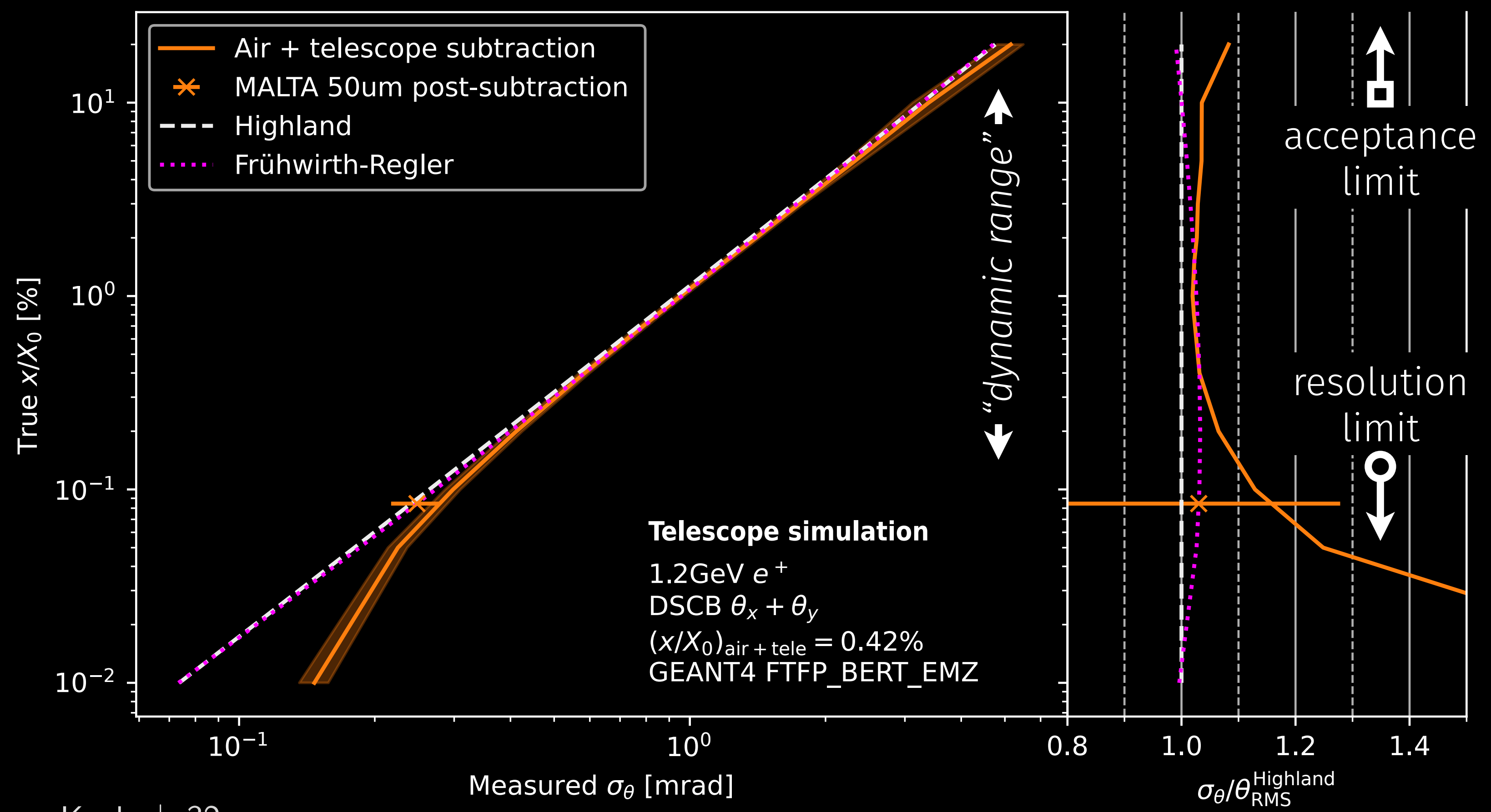


- ▶ Subtracting  $(x/X_0)_{\text{air,tele}} = 0.42\%$  from response curve gives back curve close to model-only result
- ▶ Value derived from reference dataset (MALTA 50  $\mu\text{m}$ ), cross-checked in simulations

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



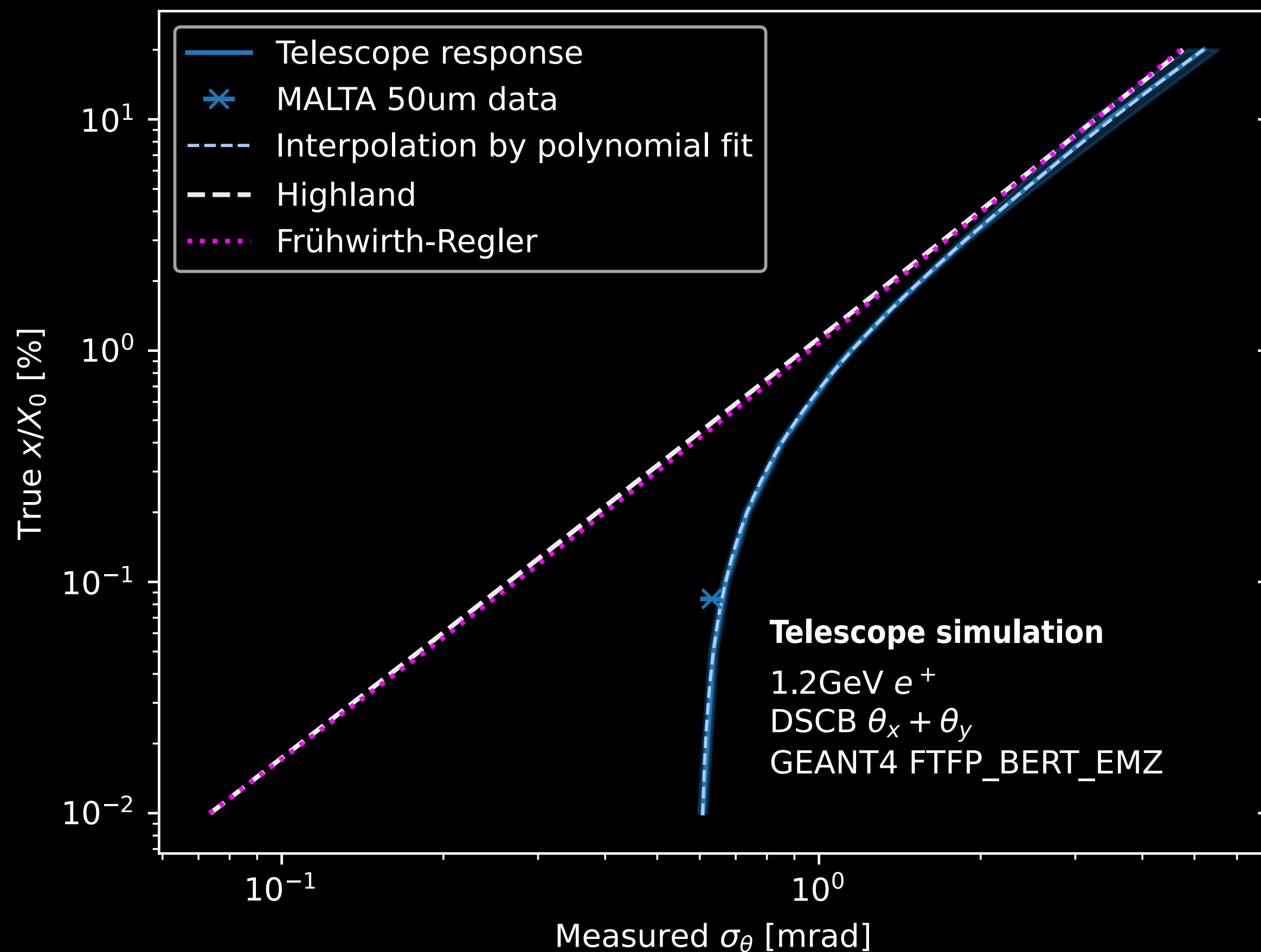
- ▶ Developed simulation model in **Geant4** (using **AllPix<sup>2</sup>**)
  - Physics list: **FTFP\_BERT\_EMZ** (best EM models for MS)
  - Complete description of telescope geometry (sensors, PCBs, tape, ...)
- ▶ Simulated with and without air and telescope contributions to scattering, across range of target  $x/X_0$  values



▶ Dynamic range:  
 ~ **0.1% to 15%** of an  $X_0$   
 (with 1.2 GeV  $e^+$ , 2m tele)



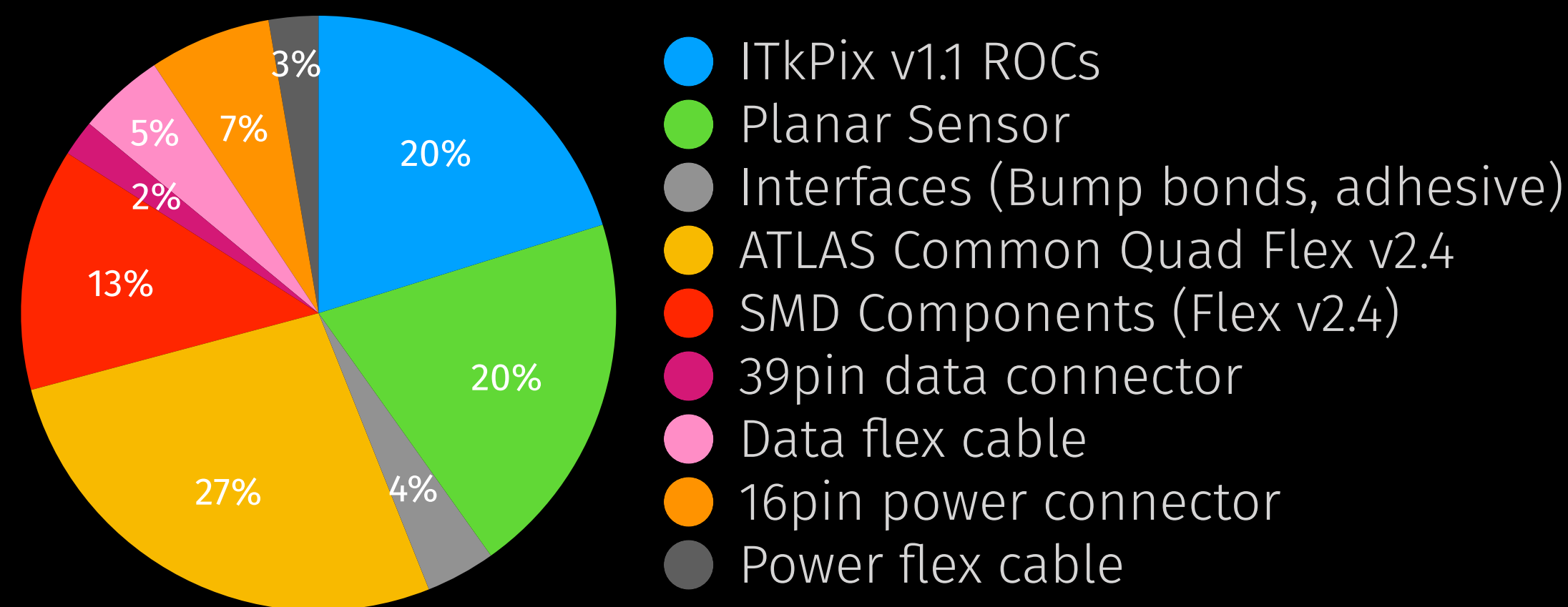
- ▶ Developed simulation model in **Geant4** (using **AllPix<sup>2</sup>**)
  - Physics list: **FTFP\_BERT\_EMZ** (best EM models for MS)
  - Complete description of telescope geometry (sensors, PCBs, tape, ...)
- ▶ Simulated with and without air and telescope contributions to scattering, across range of target  $x/X_0$  values



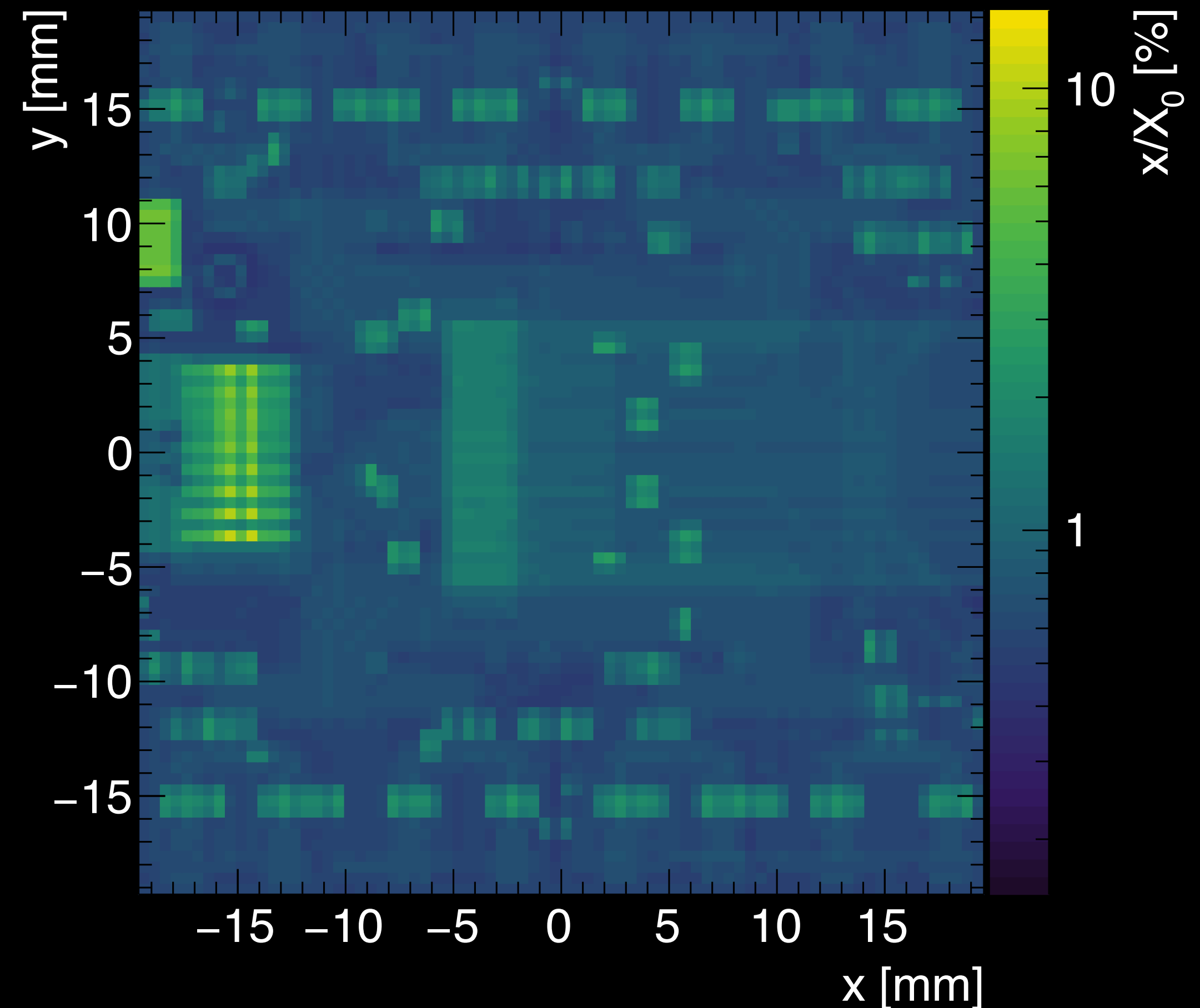
- ▶ Can “**unfold**” telescope response curve (pre-air-subtraction)
- ▶ “Smart interpolation” with 3rd or 4th-order **polynomial fit**
- ▶ *Alternative to/cross-check on interpretation via theory models*



- ▶ 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



Material estimate  
 $\langle x/X_0 \rangle [\%] = 0.87$



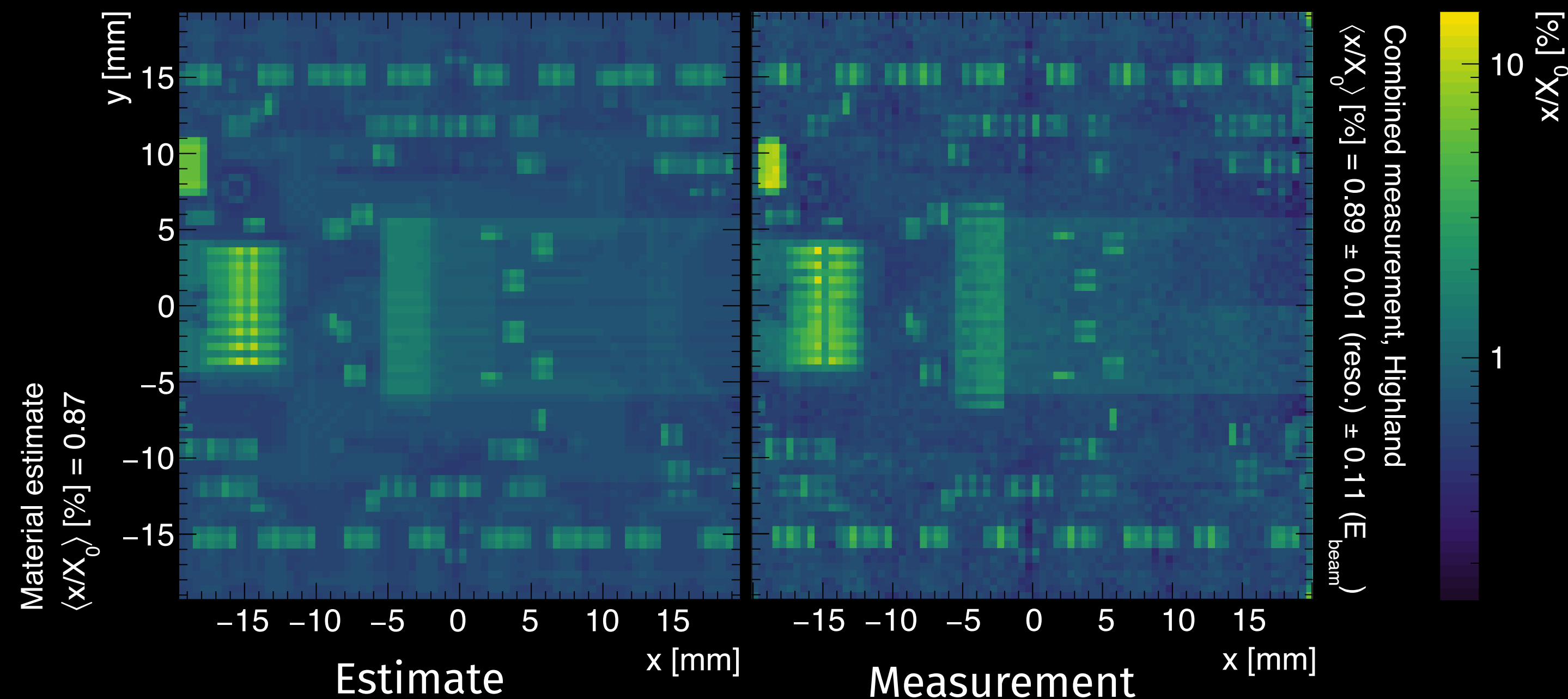


# RESULTS AND COMPARISON TO ESTIMATE

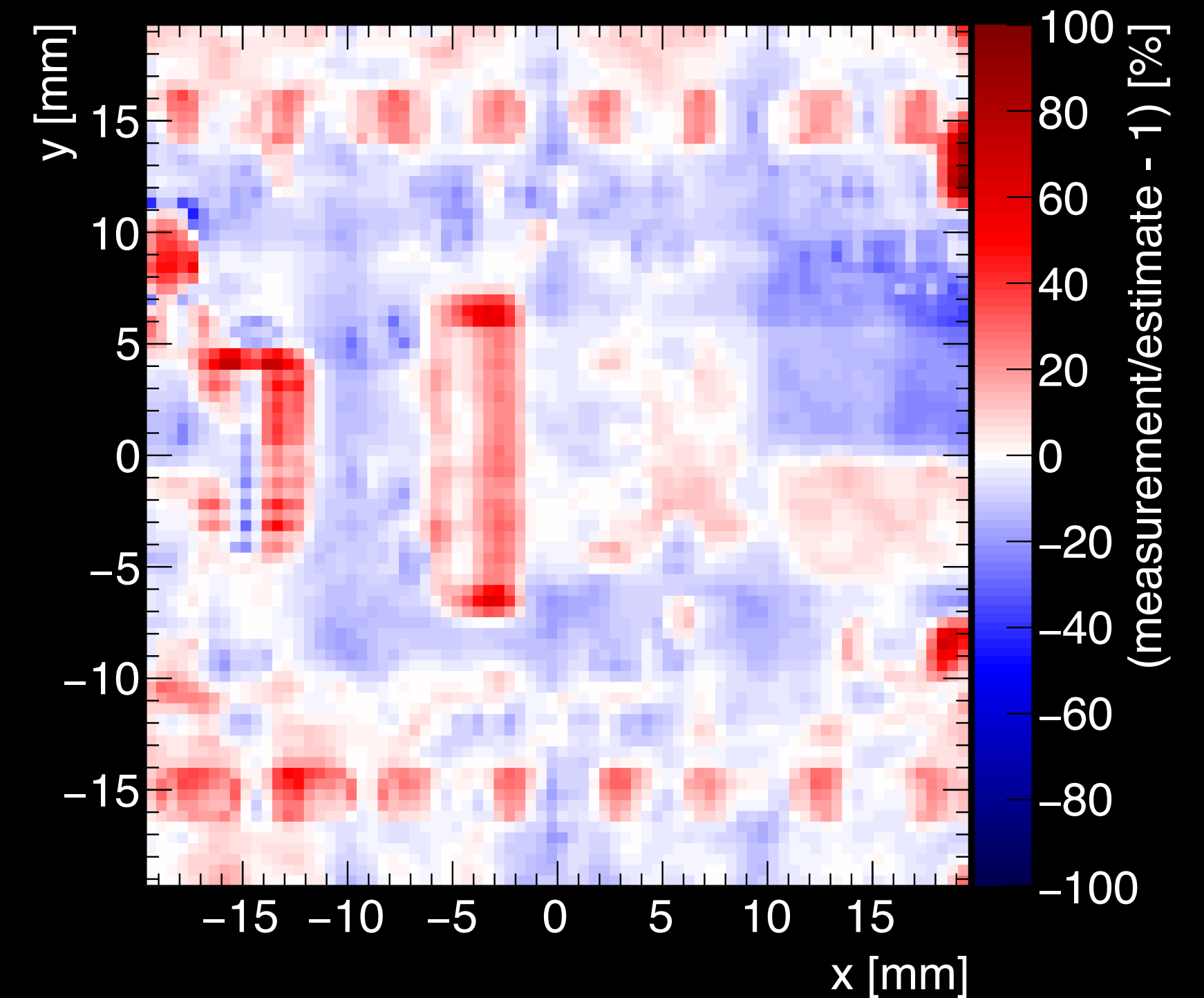
- ▶ Result with subtractions shows **good agreement** with estimate, mean agrees within uncertainties

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

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



Comparison of measurement with estimate  
Average ratio =  $1.02 \pm 0.13$



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



# COMPARING INTERPRETATIONS

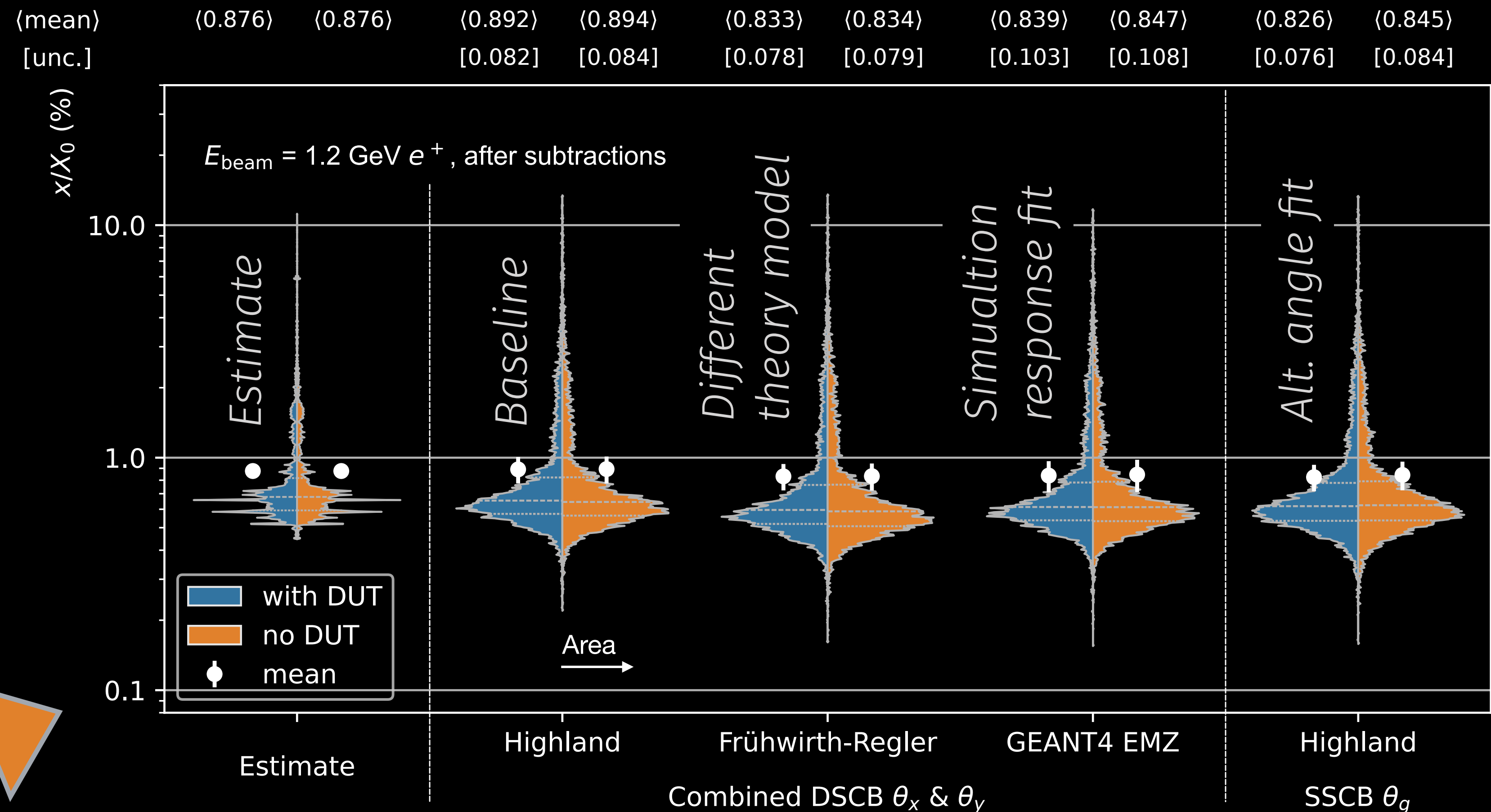
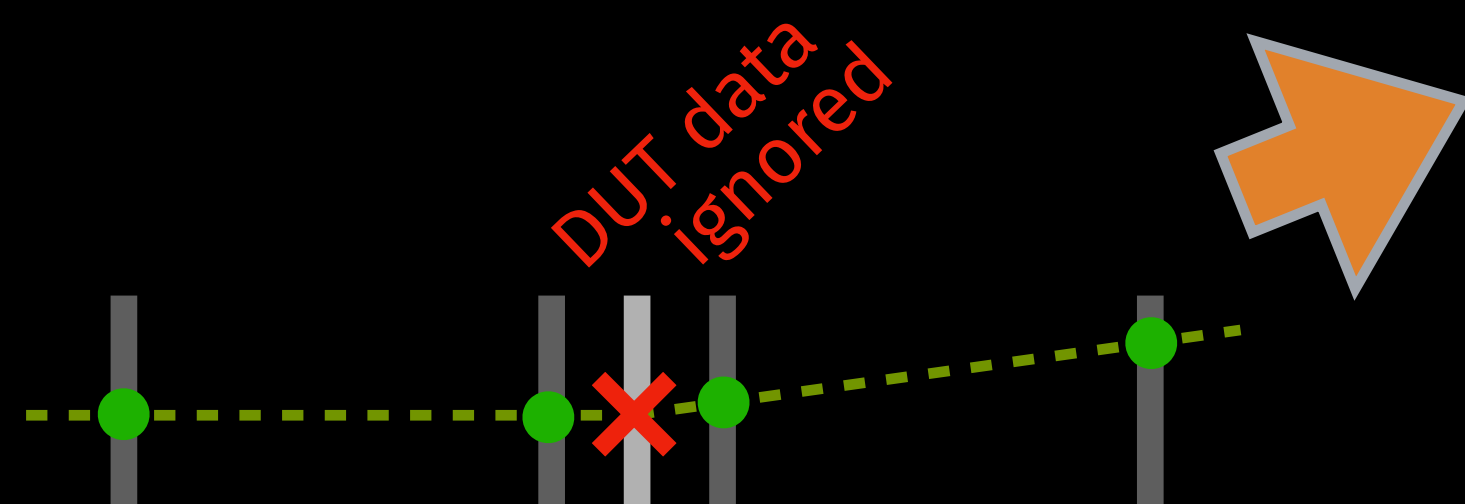


▶ Highland, Frühwirth-Regler, Geant4 (response curve fit) agree within uncertainties

- 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

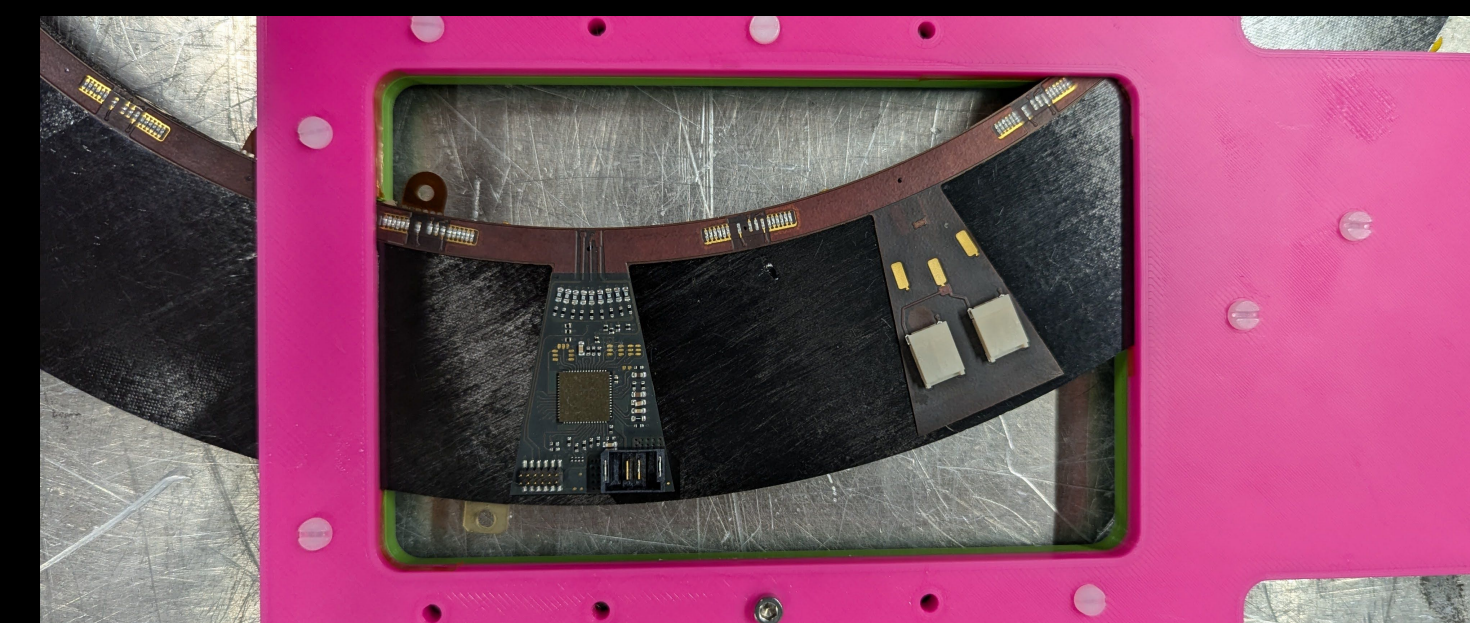
▶ Spectra without DUT info are good match for with DUT - don't need the DUT hit in future





- ▶ 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 cm<sup>2</sup> of PP0s, modules, calibration samples, *without DUT hit*
- ▶ **New challenge:** mixed beam ( $\pi/\mu$  contamination)  
→ solved by measuring time-of-flight (ToF) of particles using a TimePix4 plane behind telescope
- ▶ **Full analysis in-progress**

Outer Endcap Half-ring



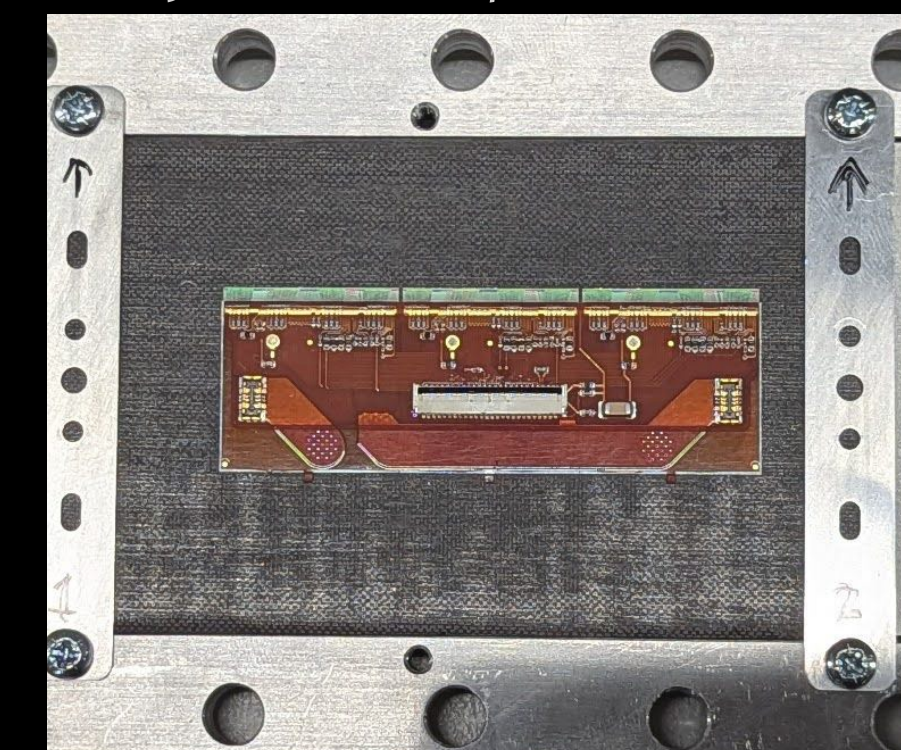
Inner System PP0



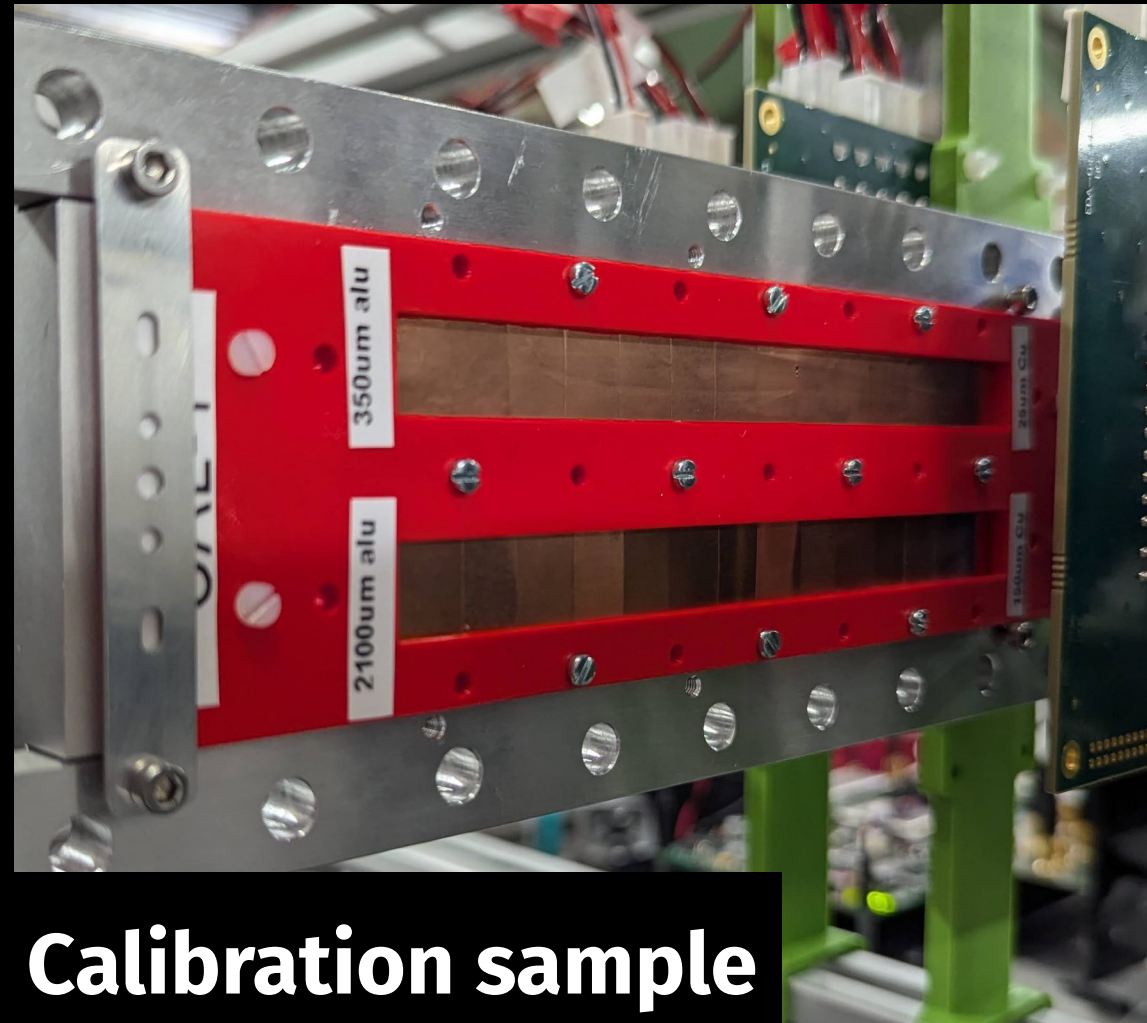
Outer Barrel Flat PP0



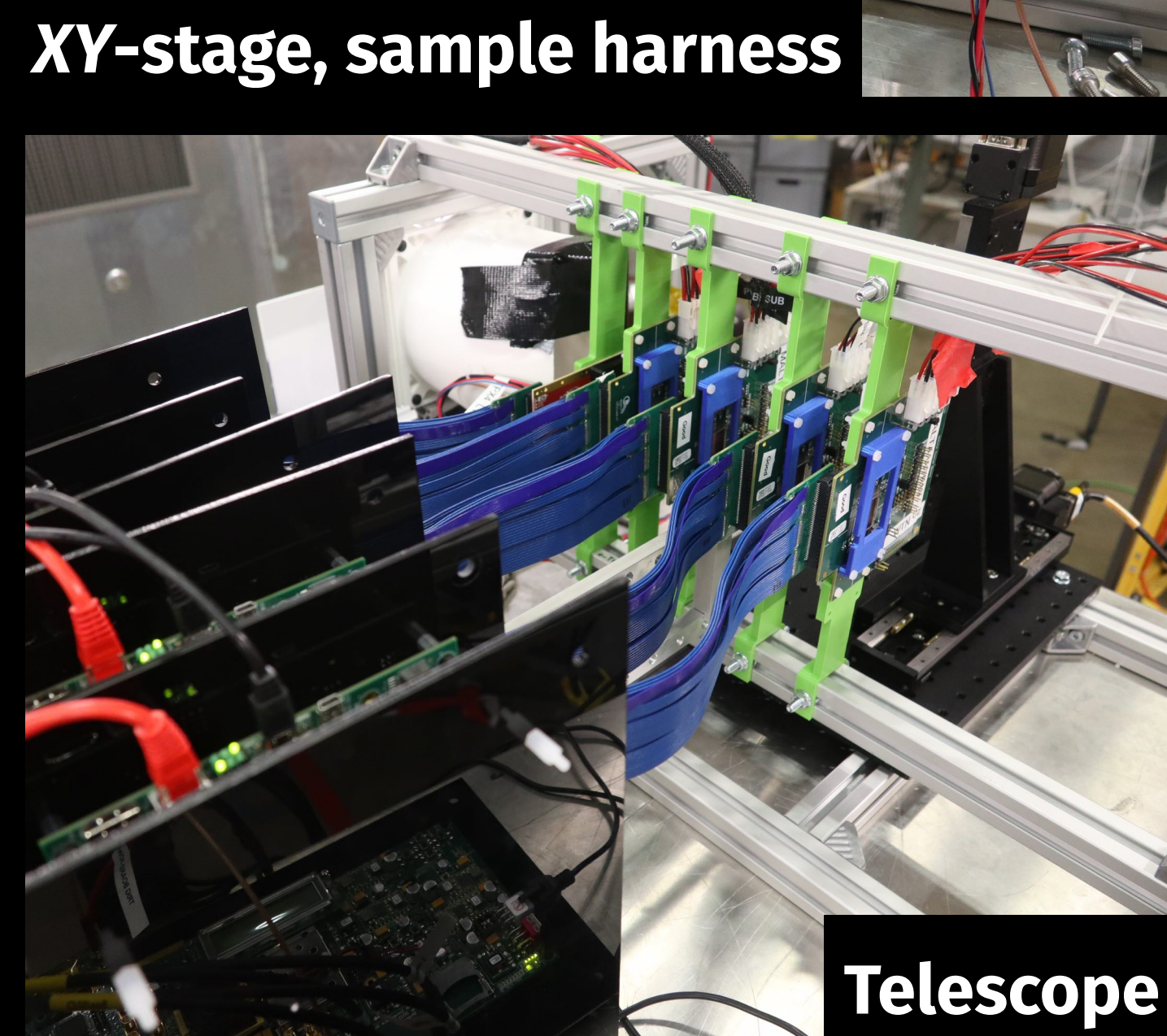
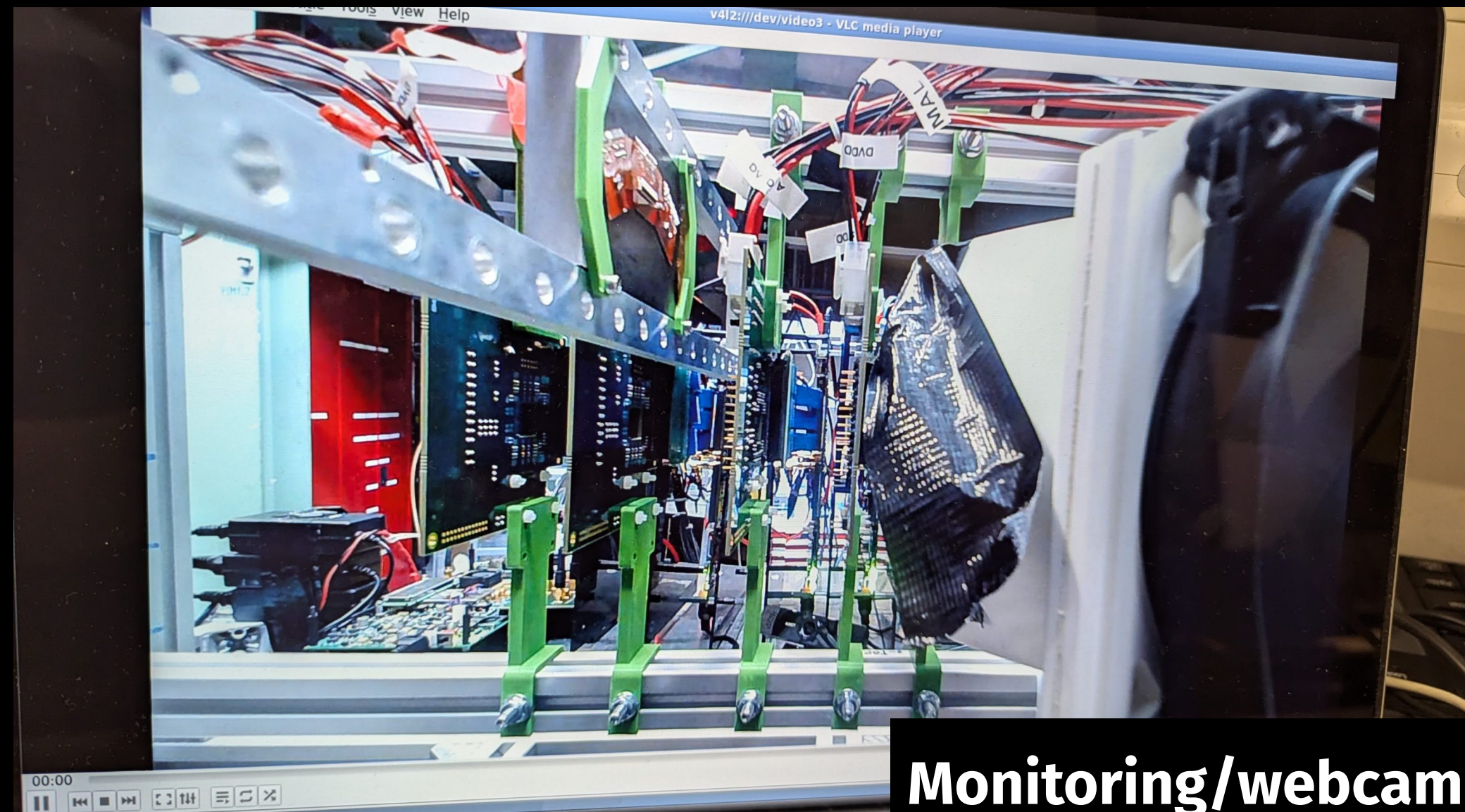
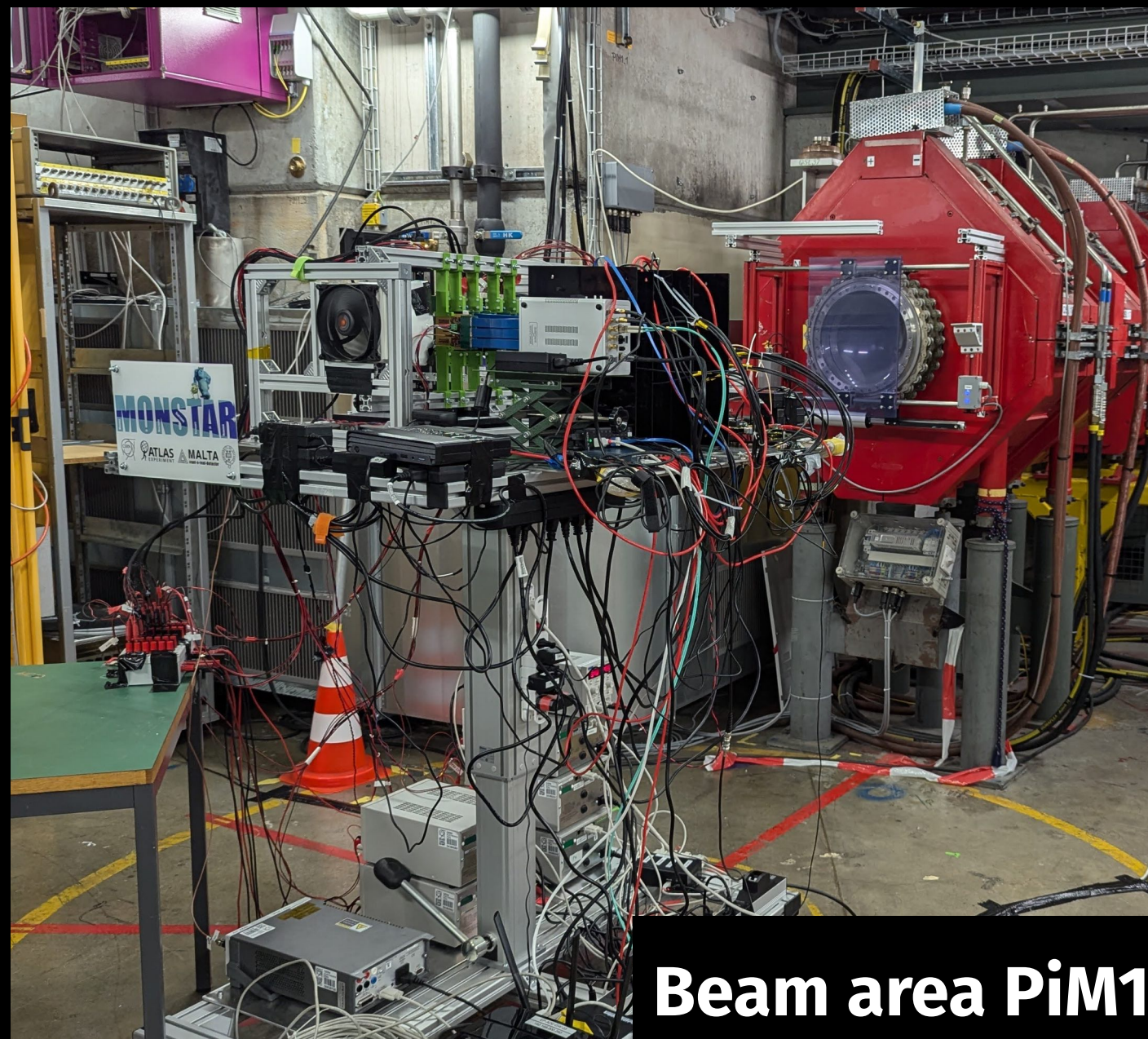
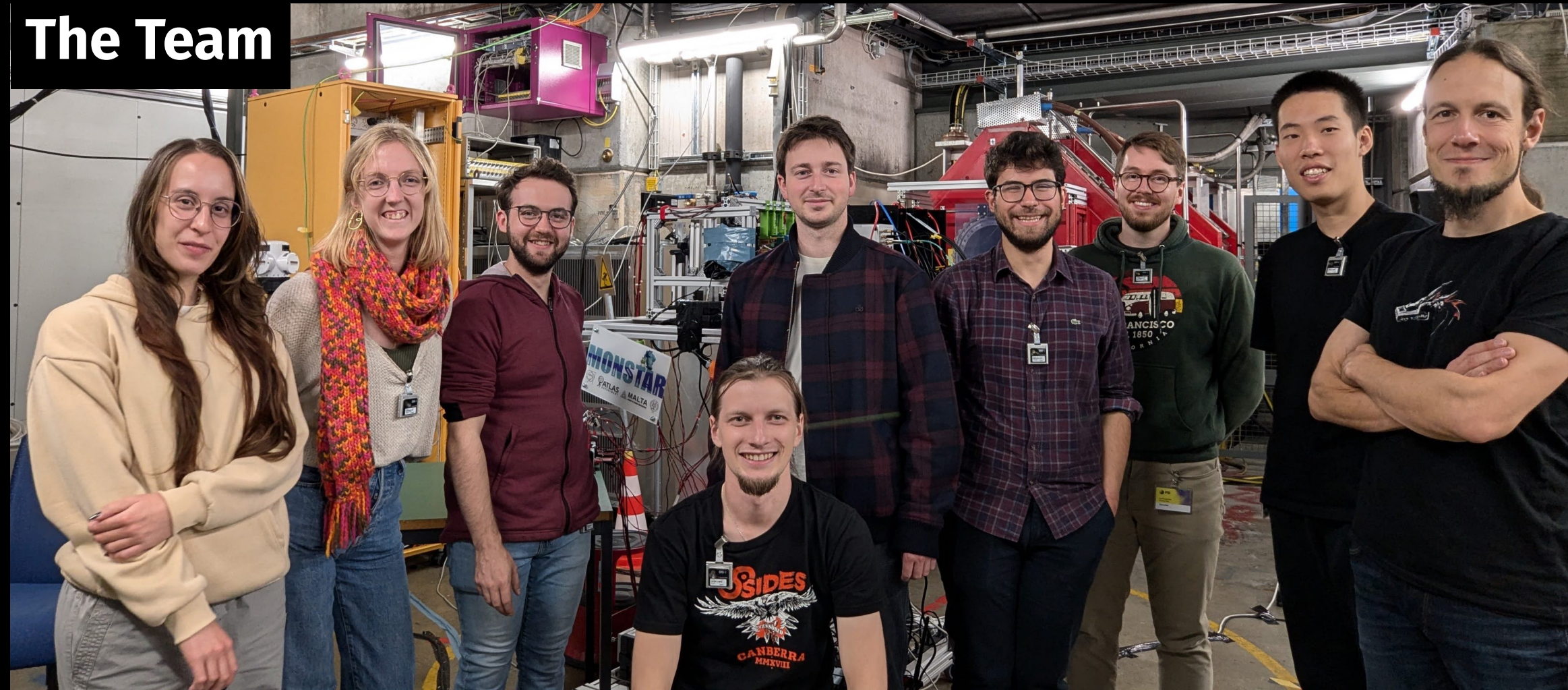
Inner System Triplet Module





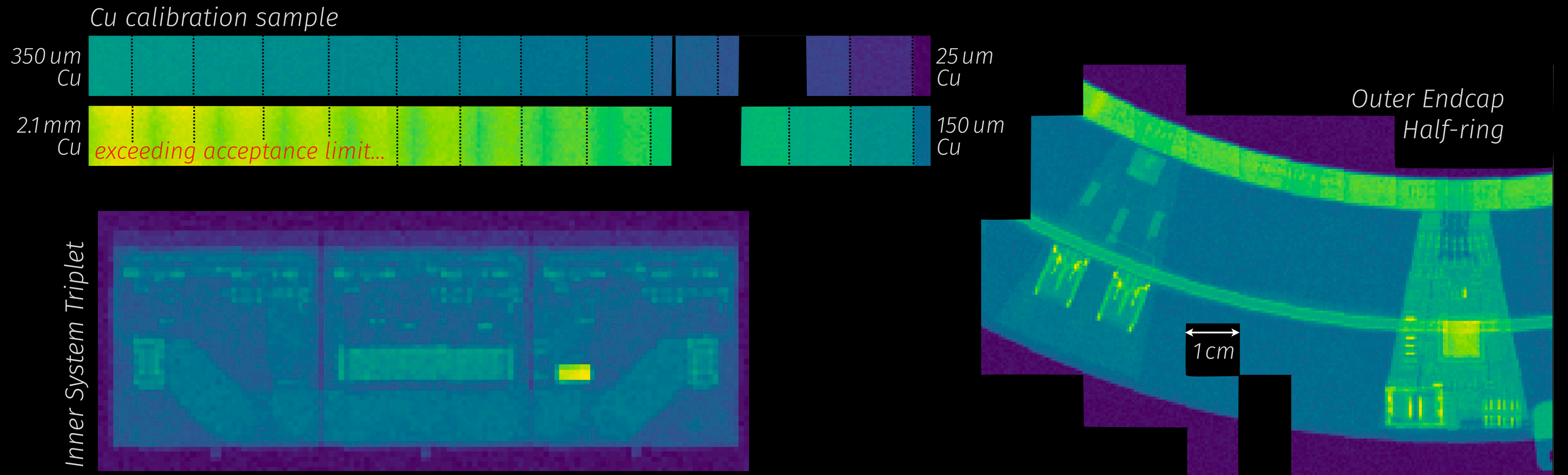


Calibration sample





- ▶ 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





# WHERE NEXT FOR MATERIAL?

## MONSTAR

Demonstrated ability to measure large areas in short times (130 cm<sup>2</sup>/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%)



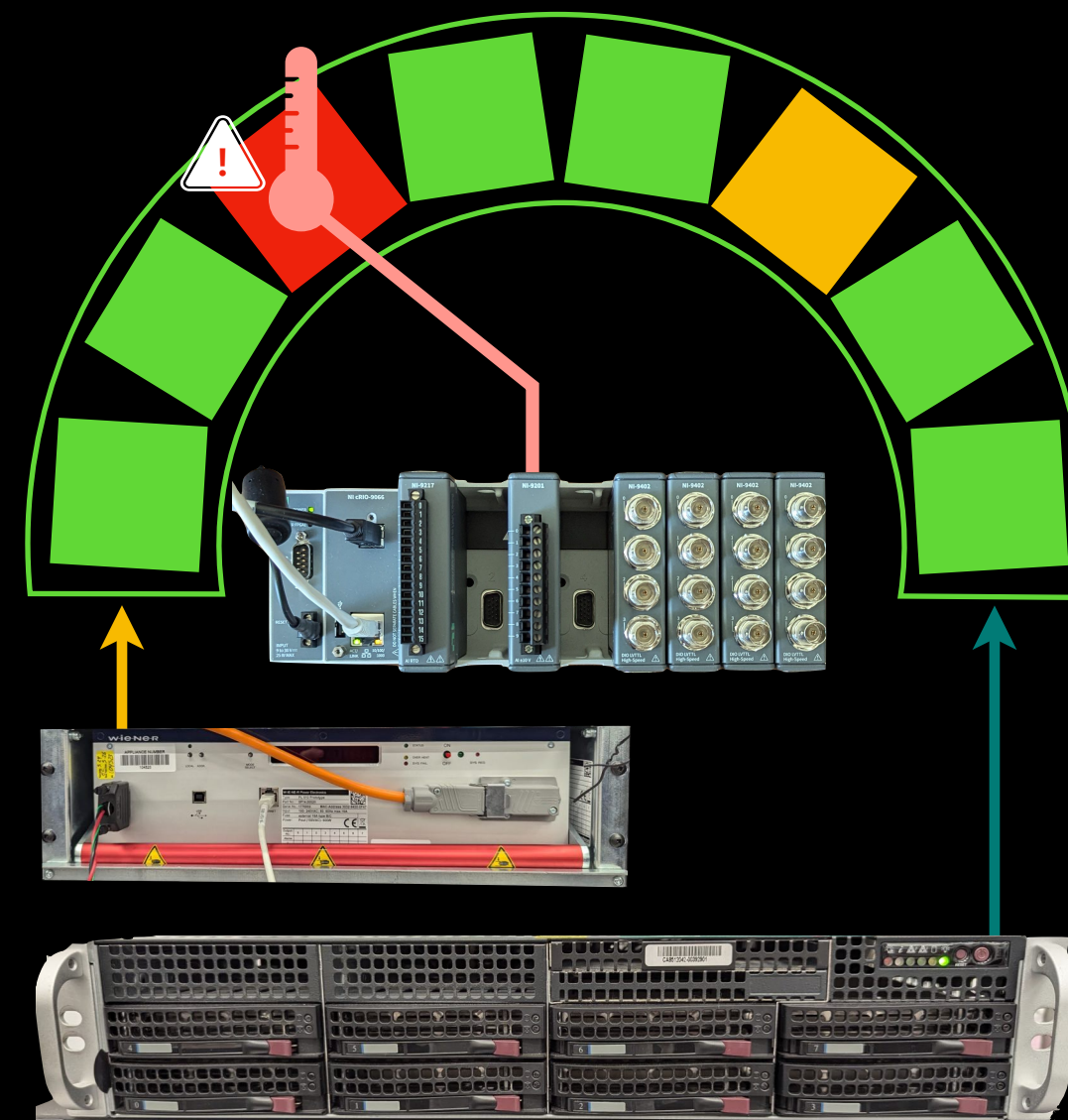
# THE ITK IS ONE OF THE LARGEST, MOST COMPLEX, AND MOST AMBITIOUS SILICON DETECTOR PROJECTS EVER ATTEMPTED...

## SUMMARY



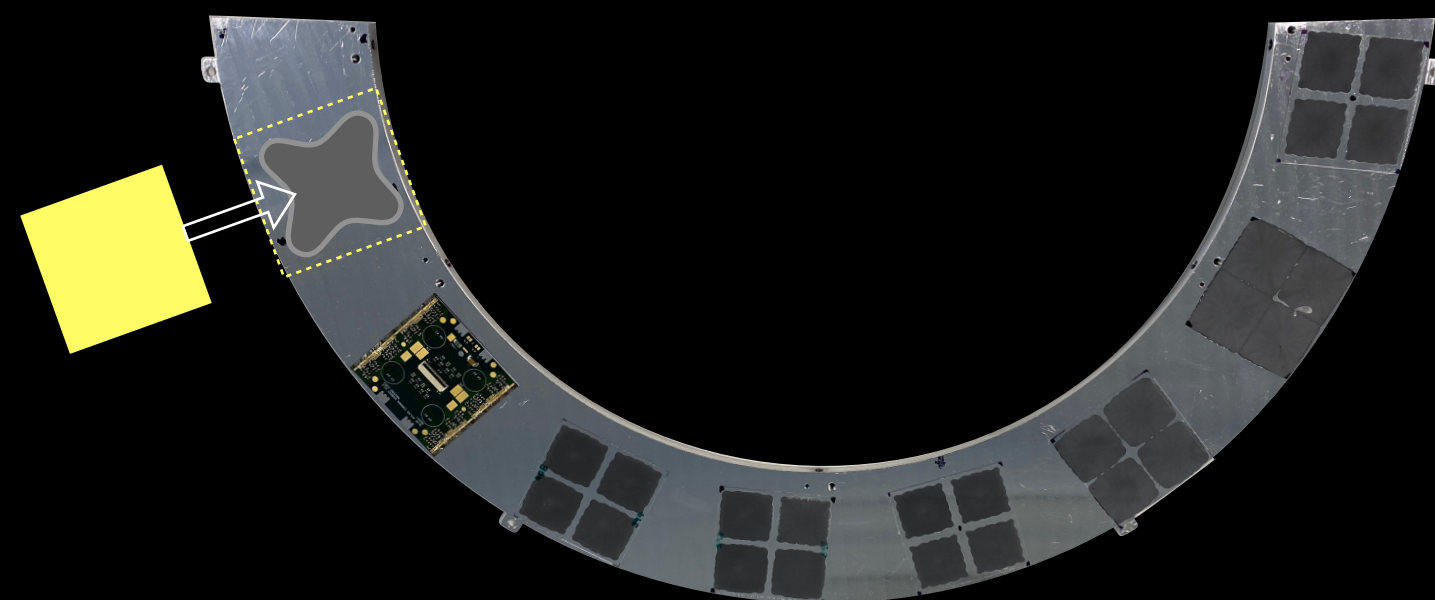
### STEP 2: TESTING THE ITK

- ▶ 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



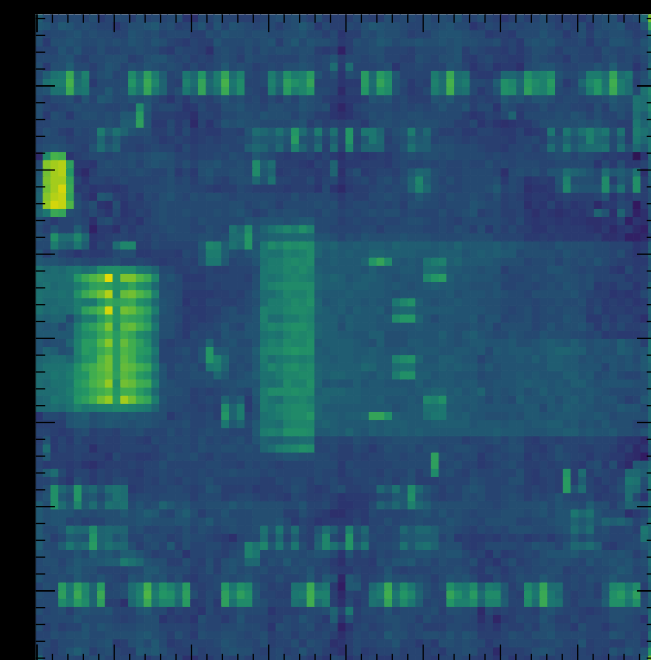
- ▶ Material content is critical for the performance of tracking detectors
- ▶ We have measured  $x/X_0$  for a quad module, and are continuing with services and mechanics

### STEP 1: BUILDING THE ITK



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

### STEP 3: MEASURING THE ITK





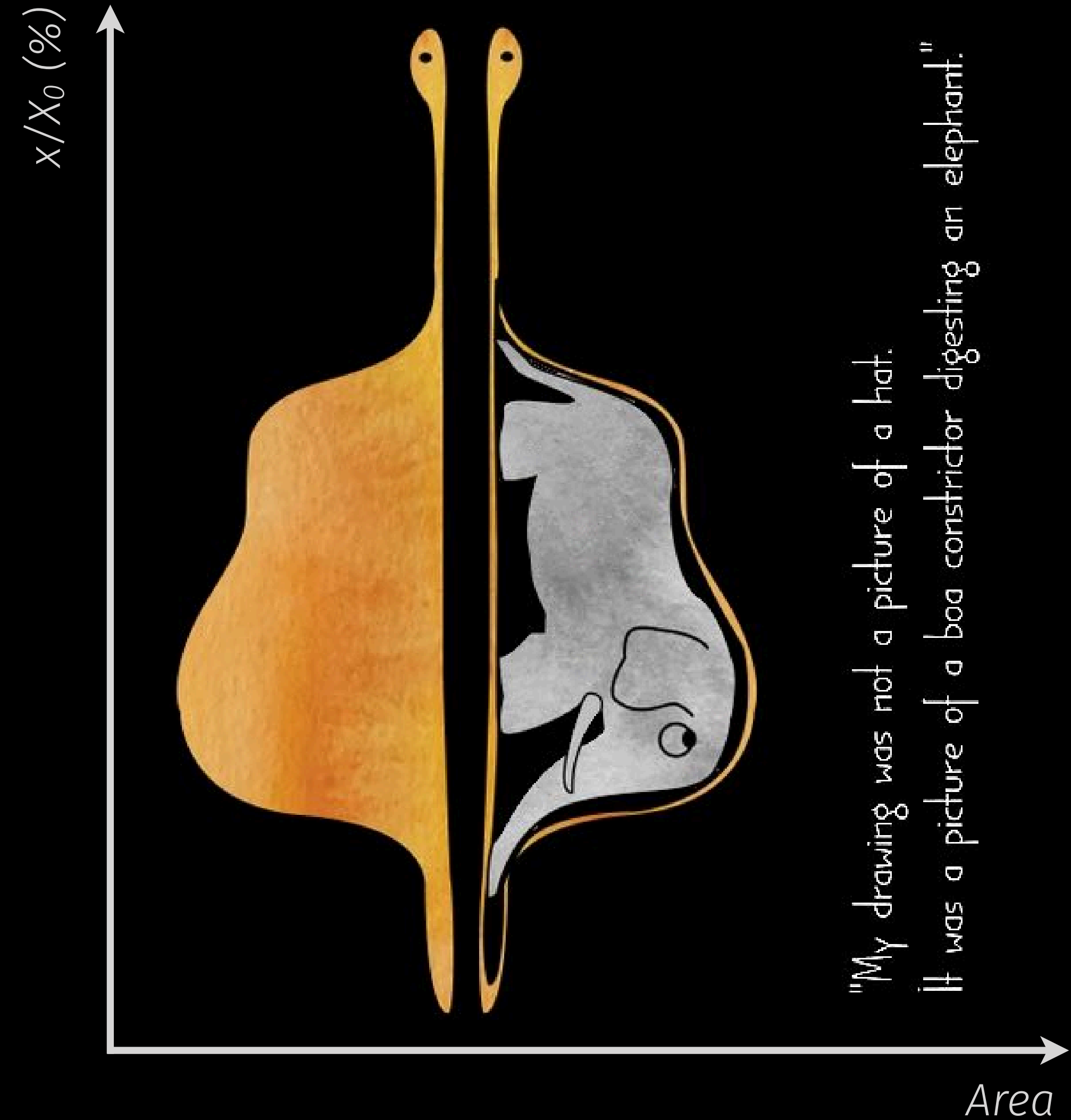
# Thank you!



UNIVERSITY OF  
OXFORD



## Questions?



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





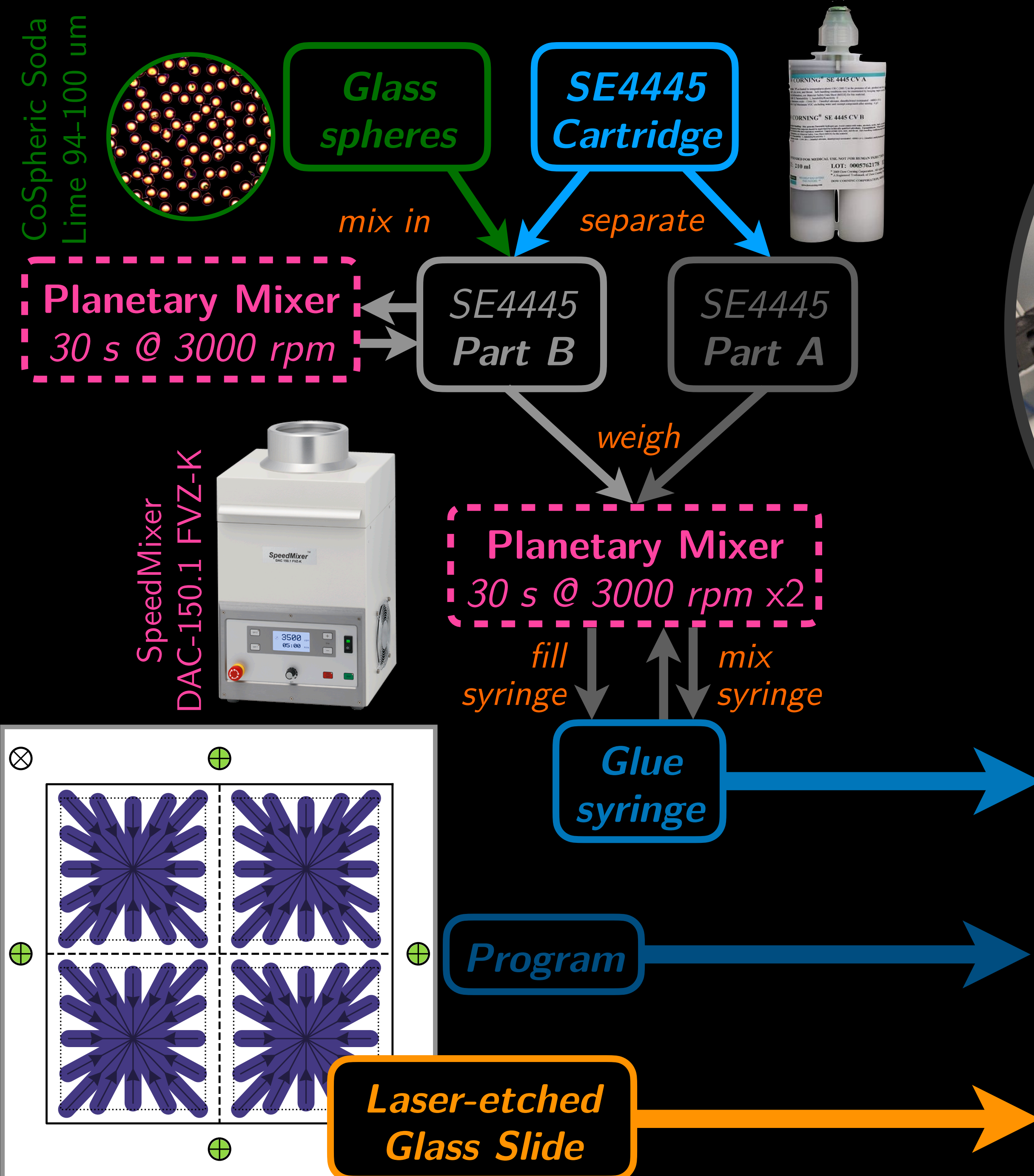
# BACKUP



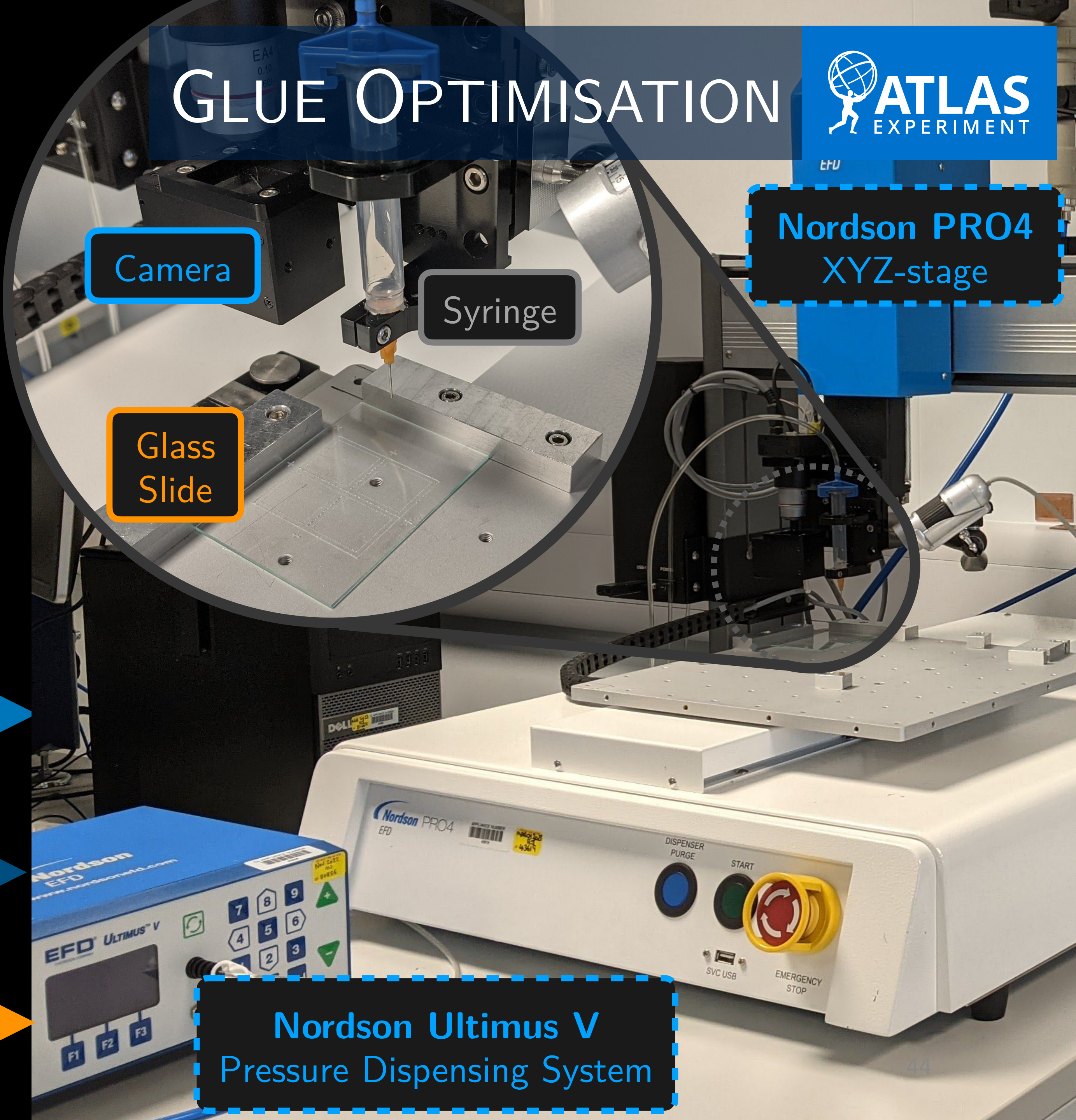
UNIVERSITY OF  
OXFORD







# GLUE OPTIMISATION



Camera

Syringe

Nordson PR04 XYZ-stage

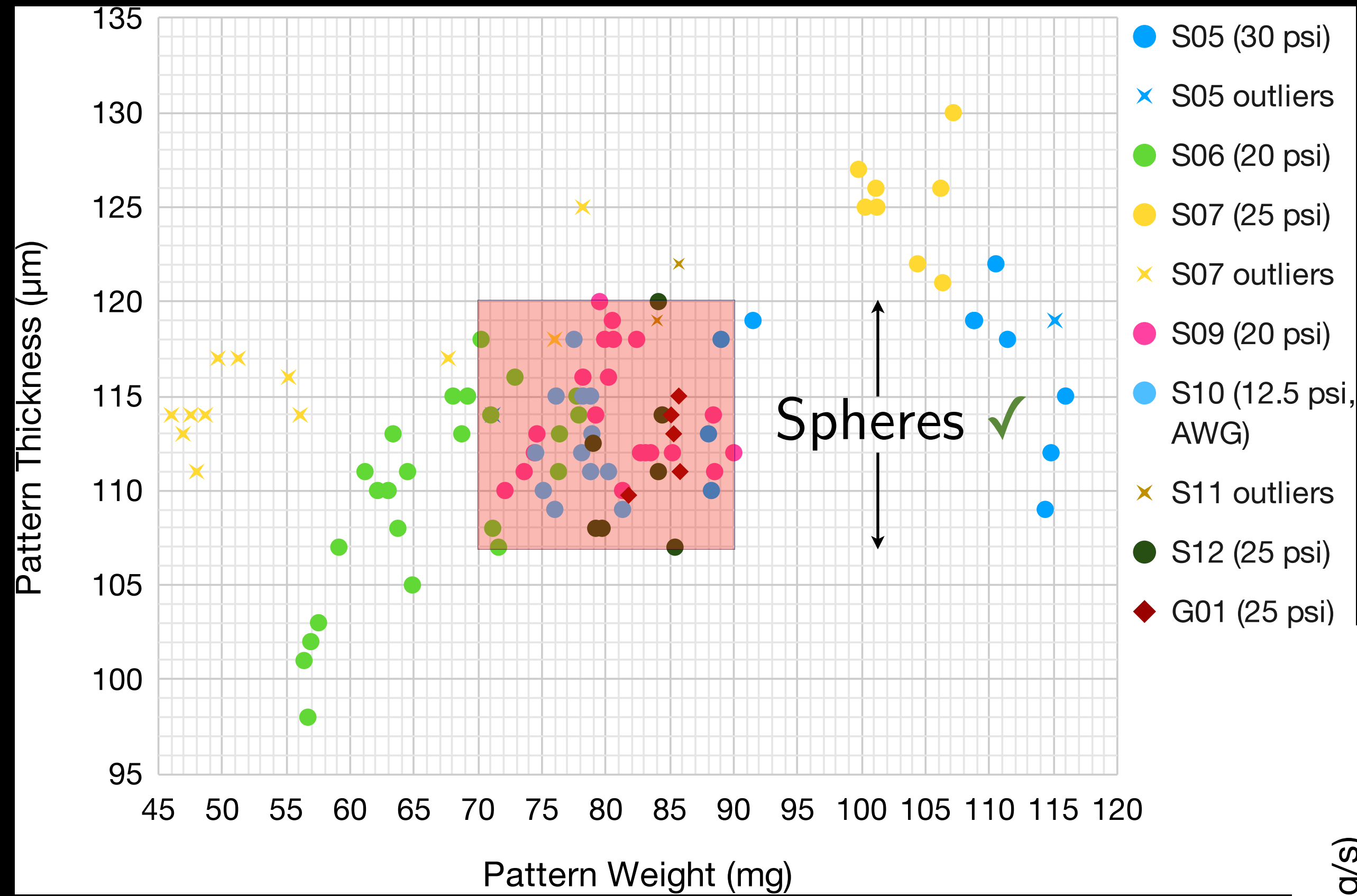
Glass Slide

Nordson Ultimus V Pressure Dispensing System

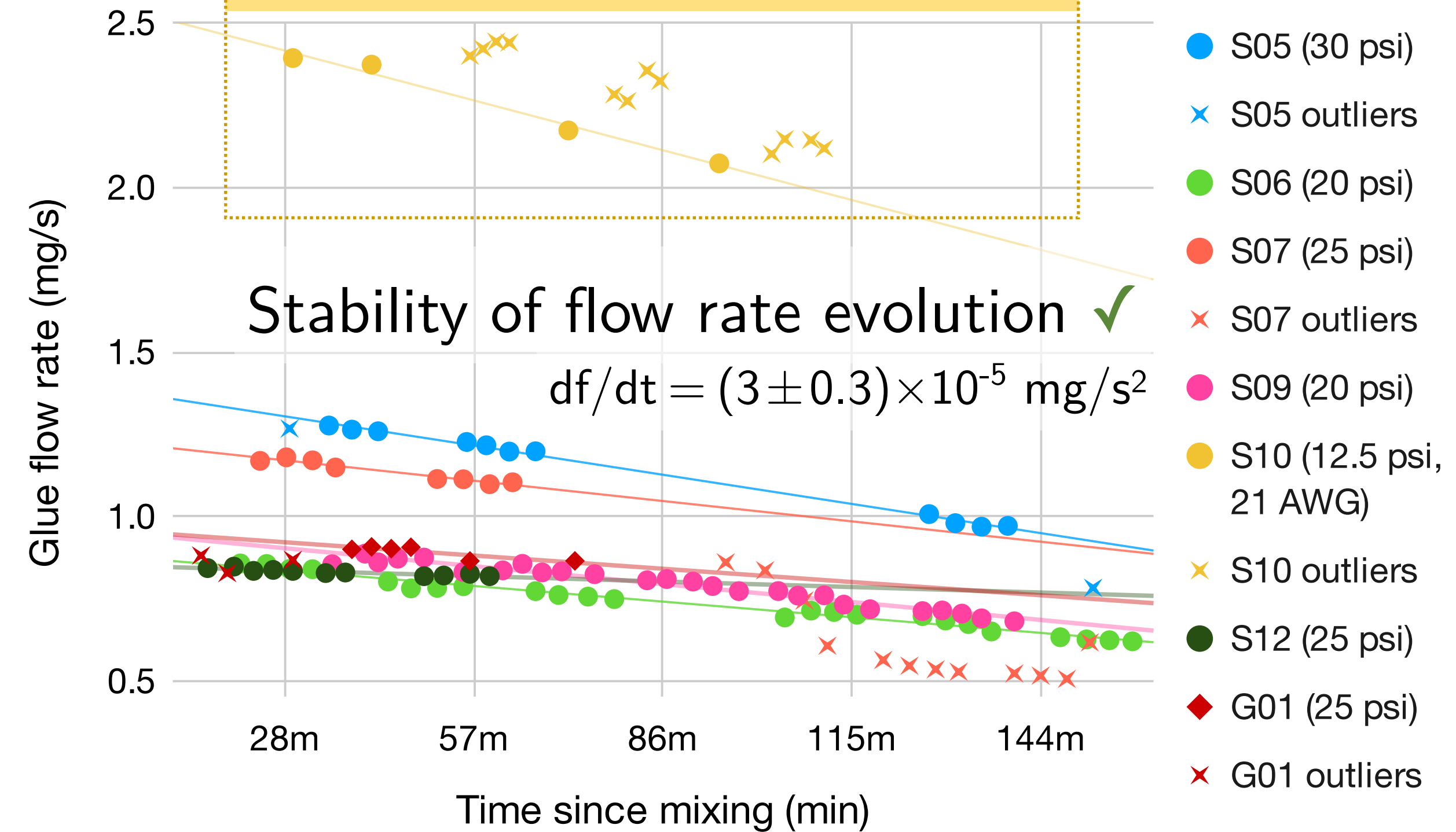
SpeedMixer DAC-150.1 FVZ-K



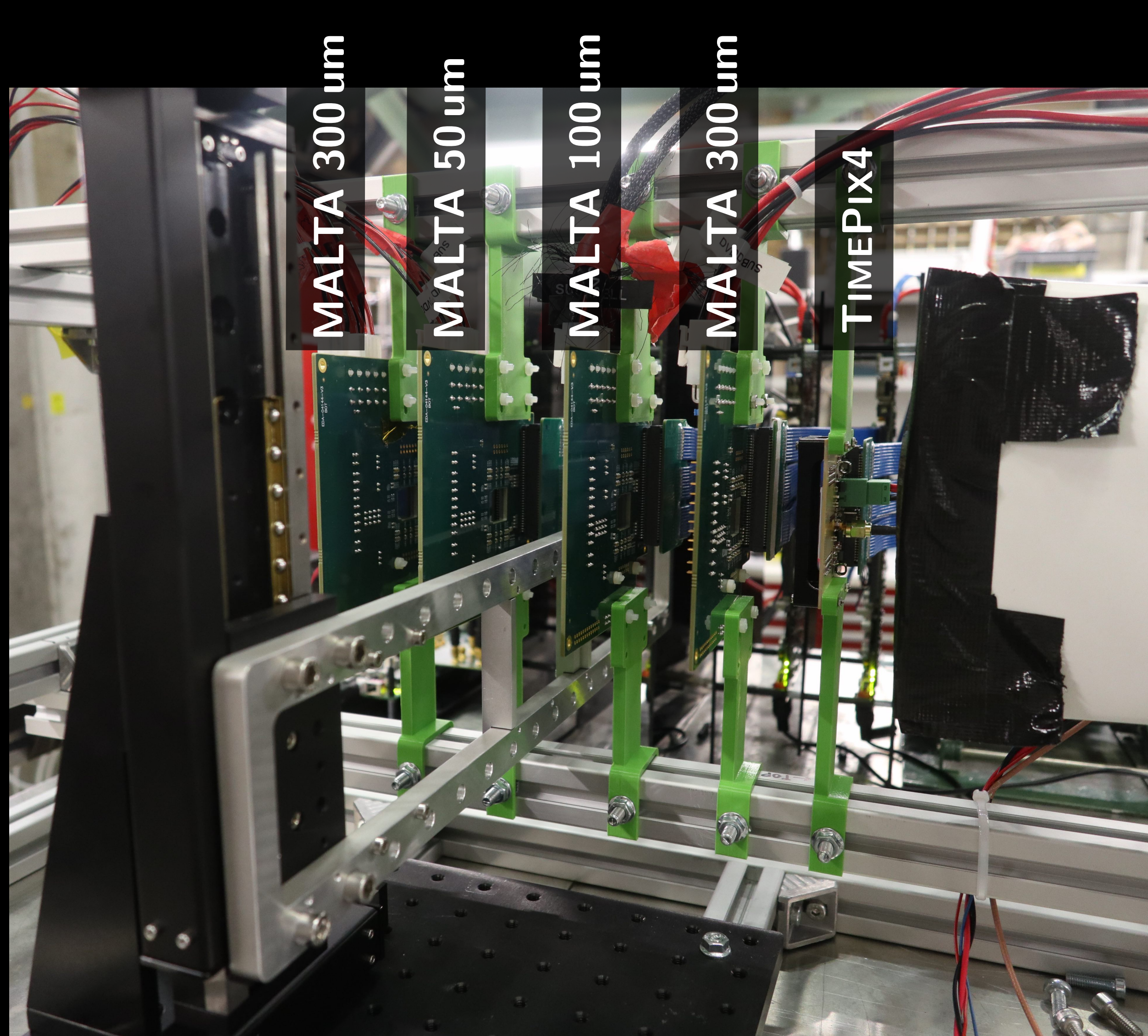
# PERFORMANCE



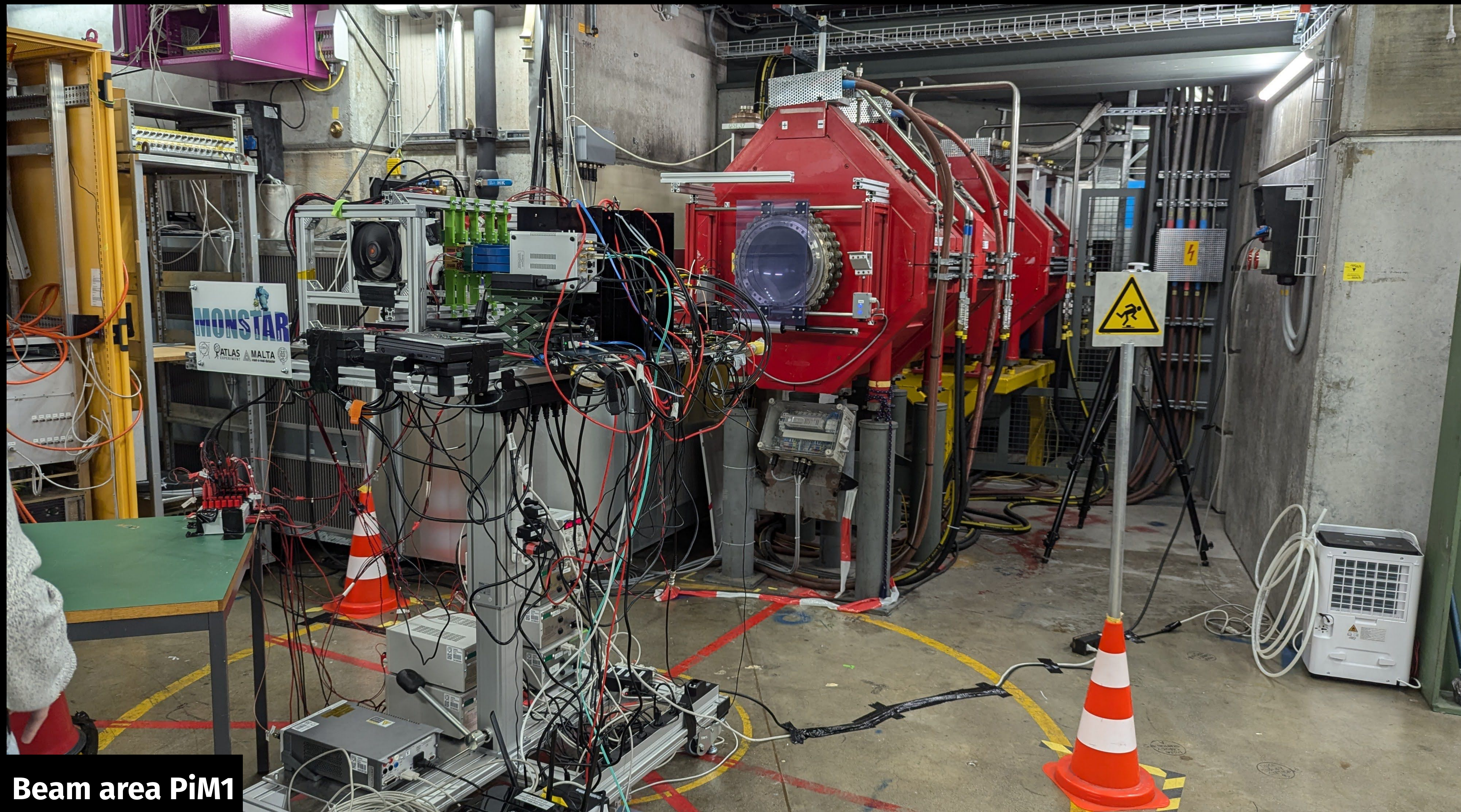
S10 excluded - test run for different needle type









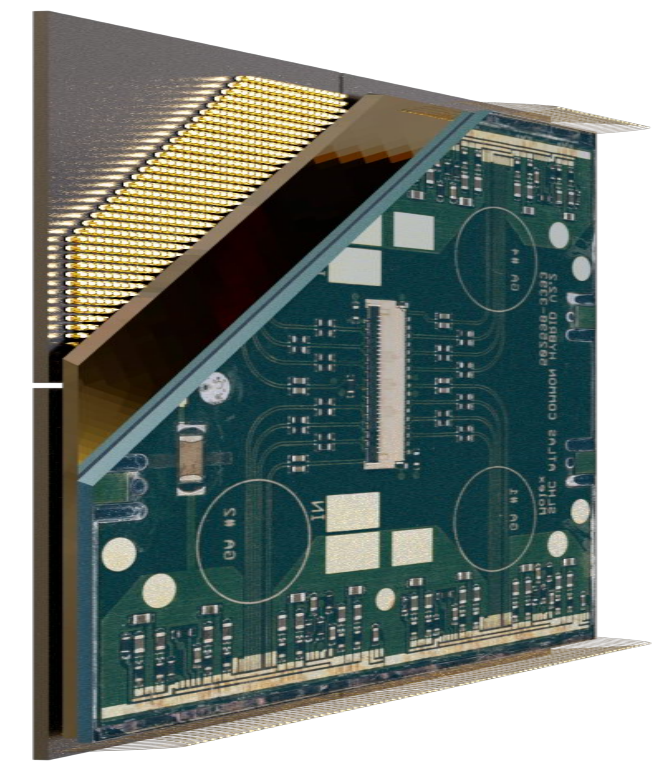


Beam area PiM1



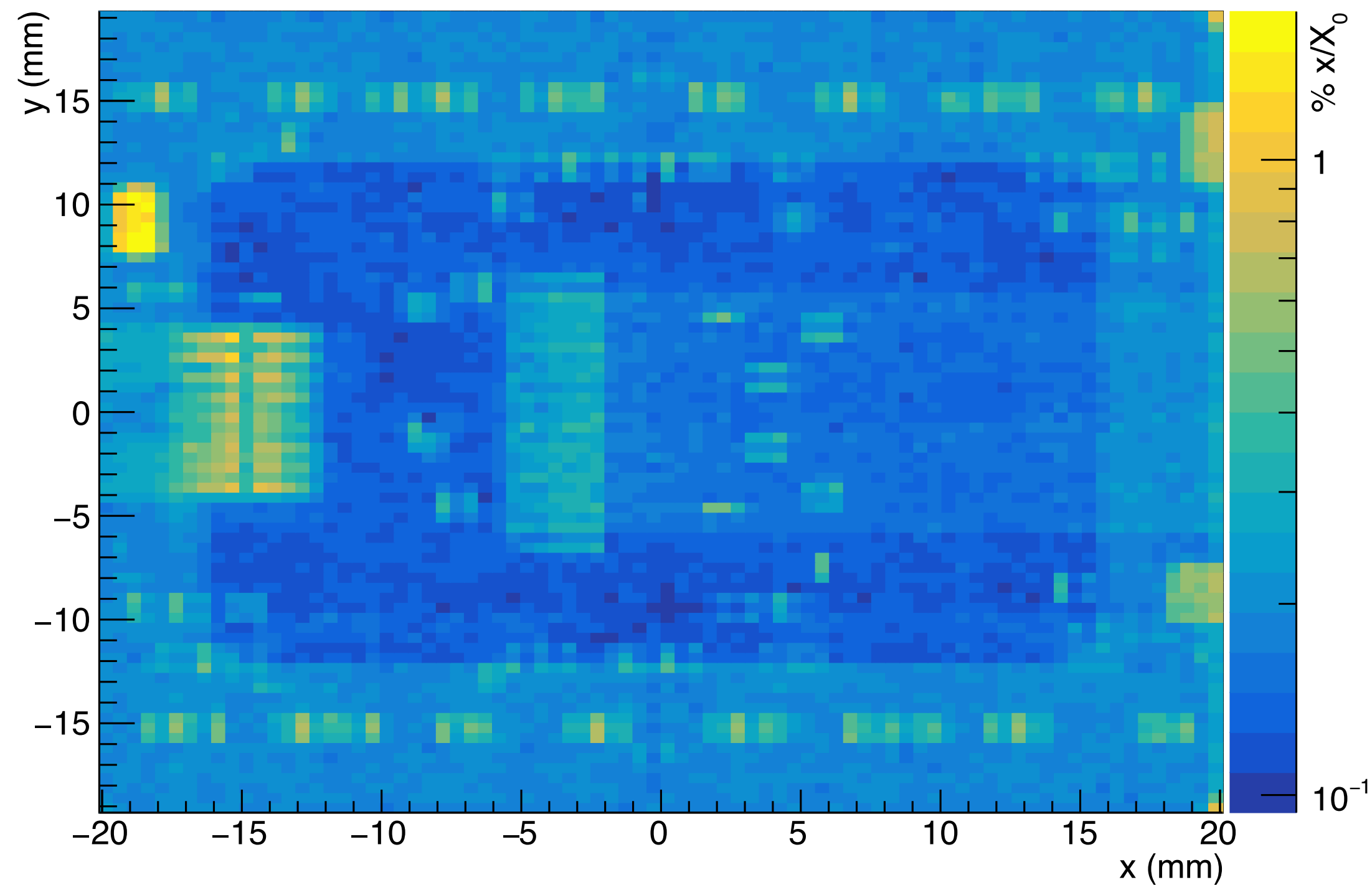
# Momentum band systematic

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

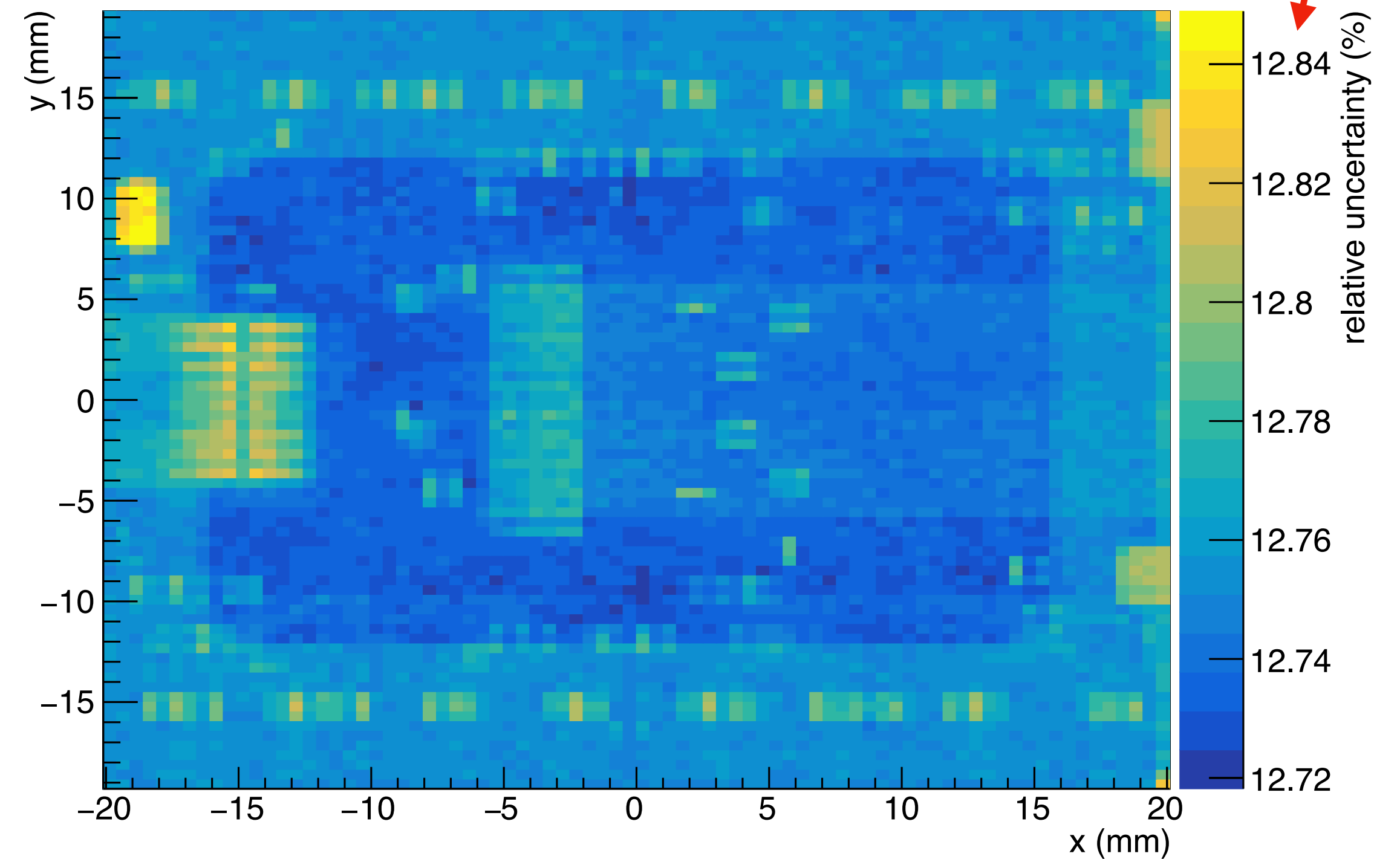


**This axis is completely collapsible**

Momentum Band Systematic (in  $x/X_0$ )



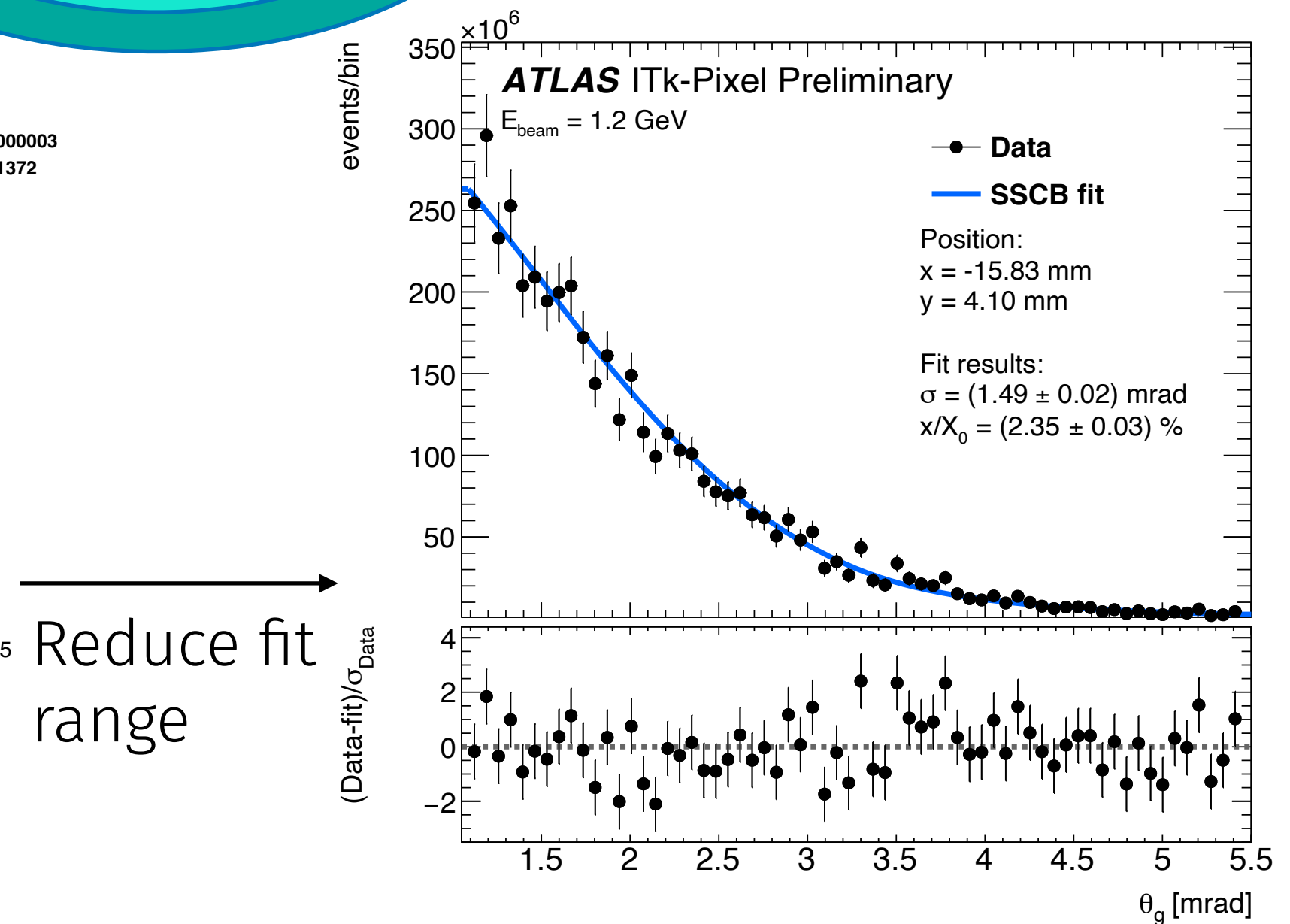
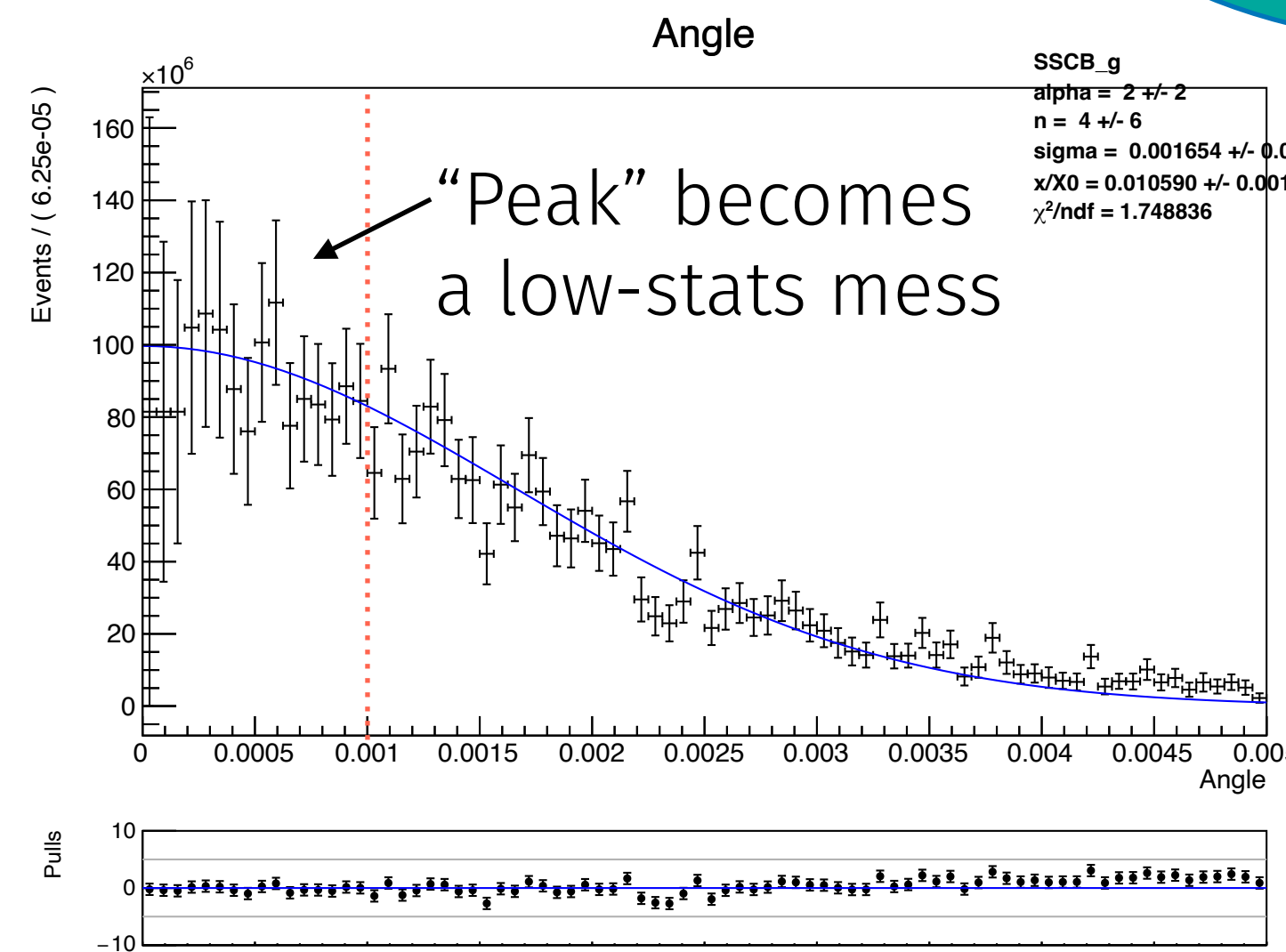
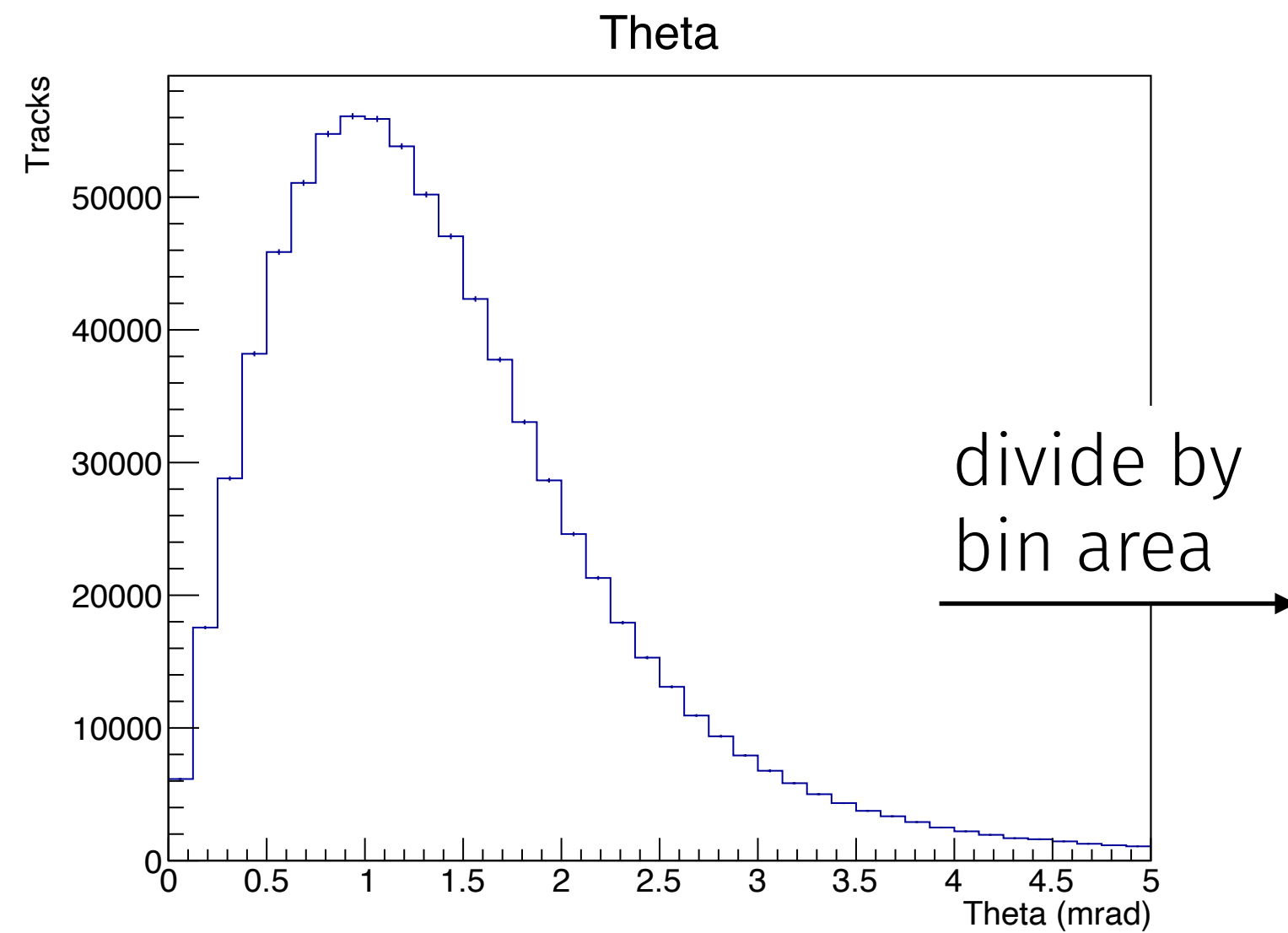
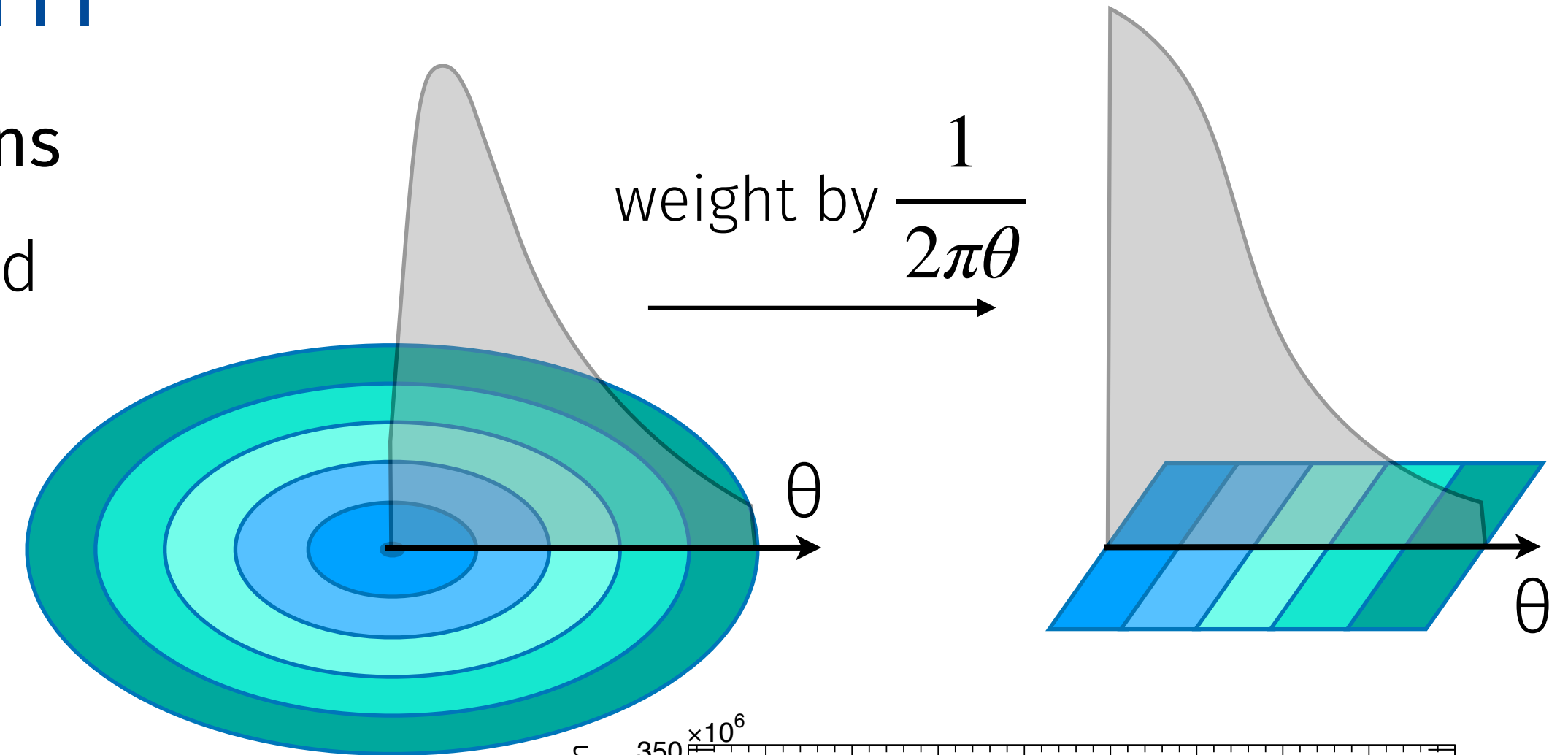
Momentum Band Systematic (in % dev.)





# Global angle coordinate system

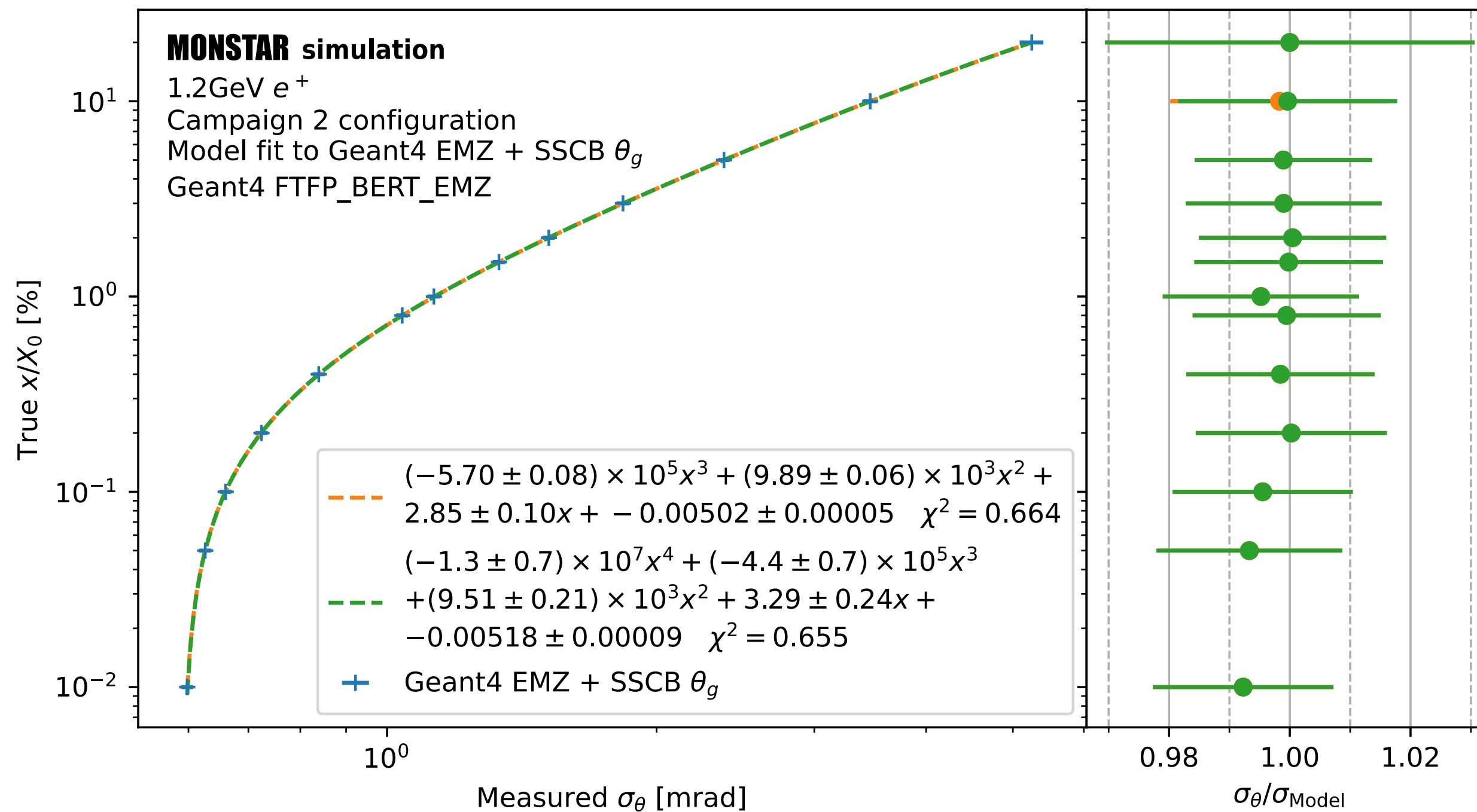
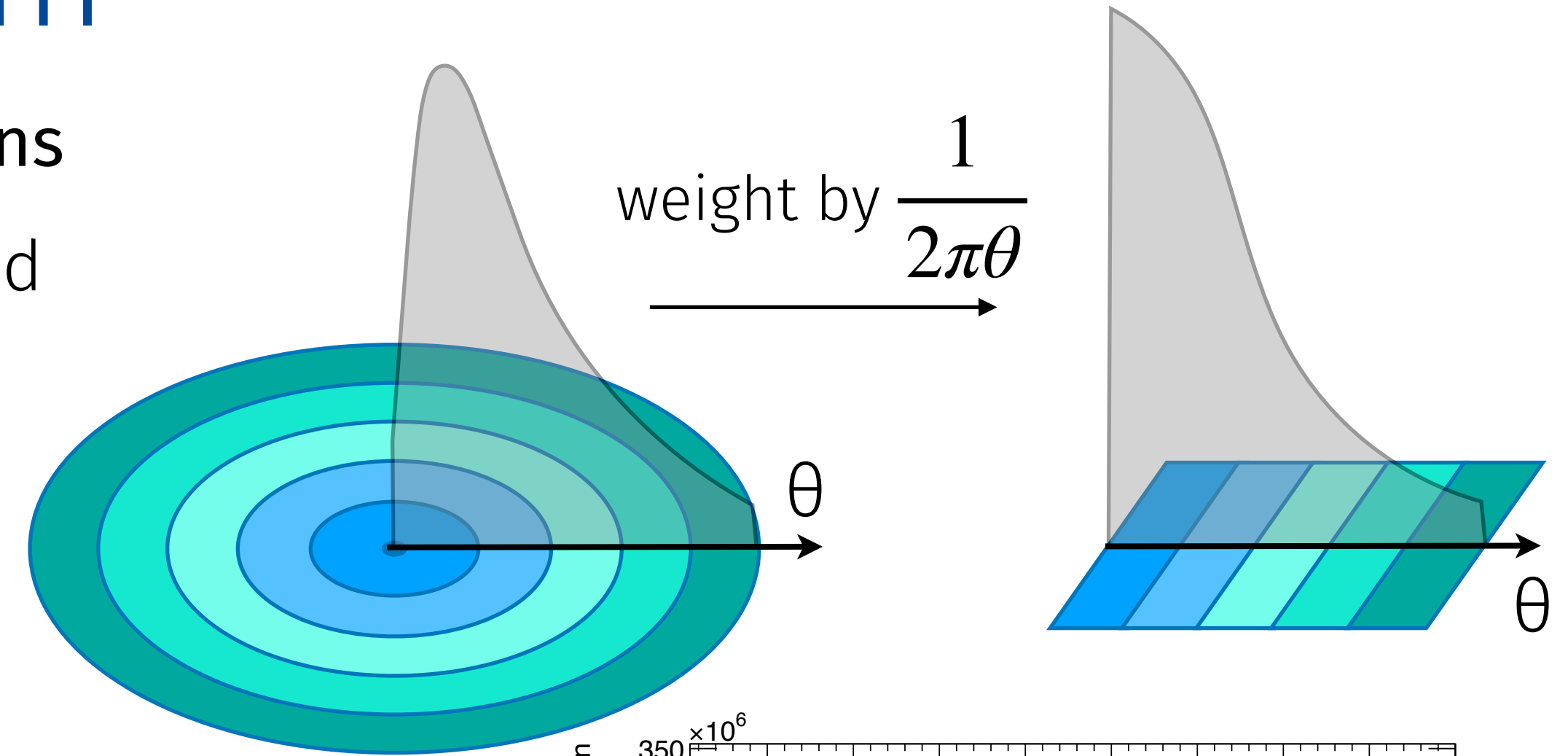
- ▶ Highland formula is derived for **projected angle distributions**
  - These have in inherent directionality (projected plane) and can be sensitive to hard material boundaries
- ▶ Would like to use **phi-invariant “global” angle**, but need to “project” it from a radial bins to a cartesian ones first



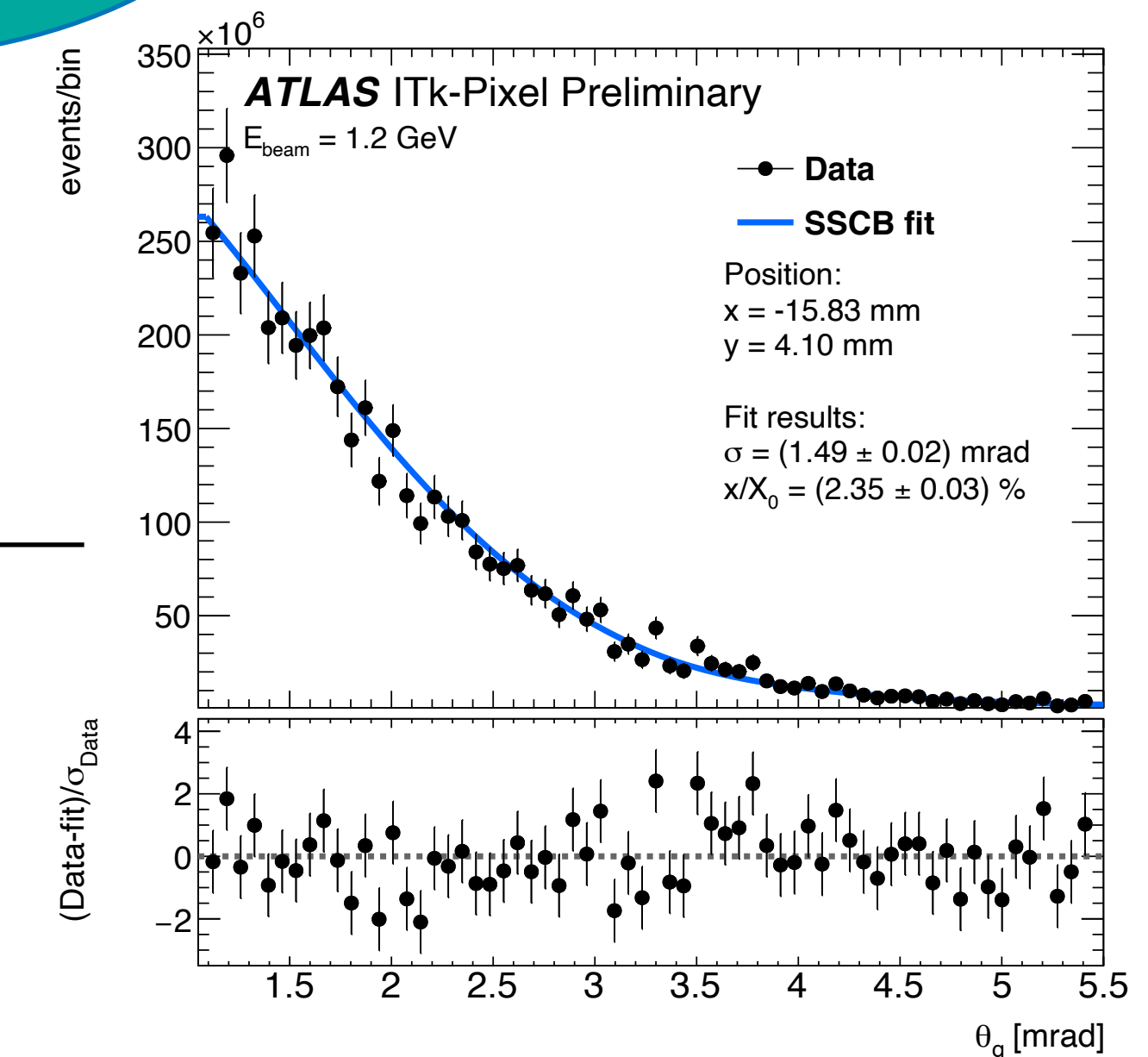


# Global angle coordinate system

- ▶ Highland formula is derived for **projected angle distributions**
  - These have in inherent directionality (projected plane) and can be sensitive to hard material boundaries
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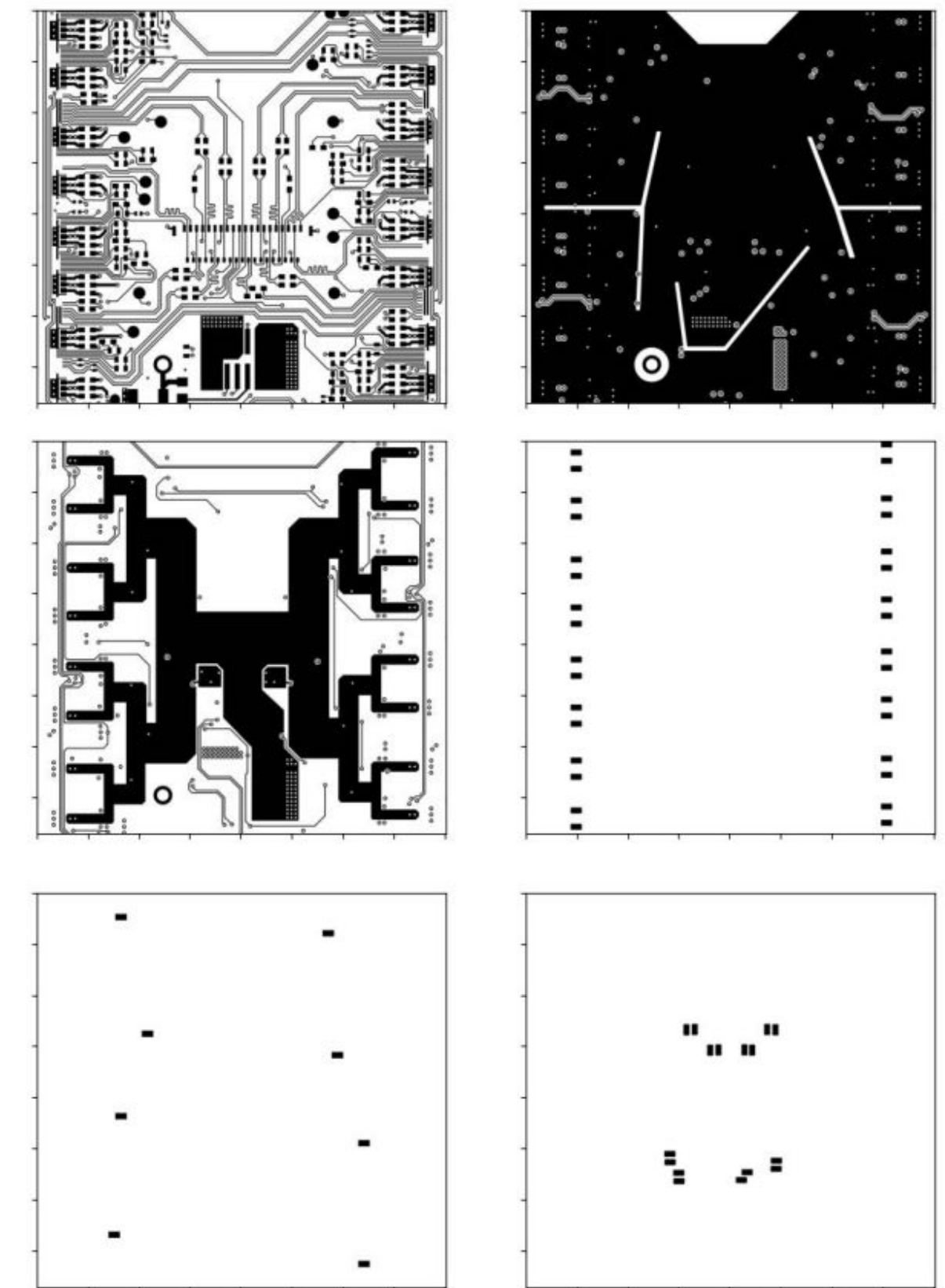
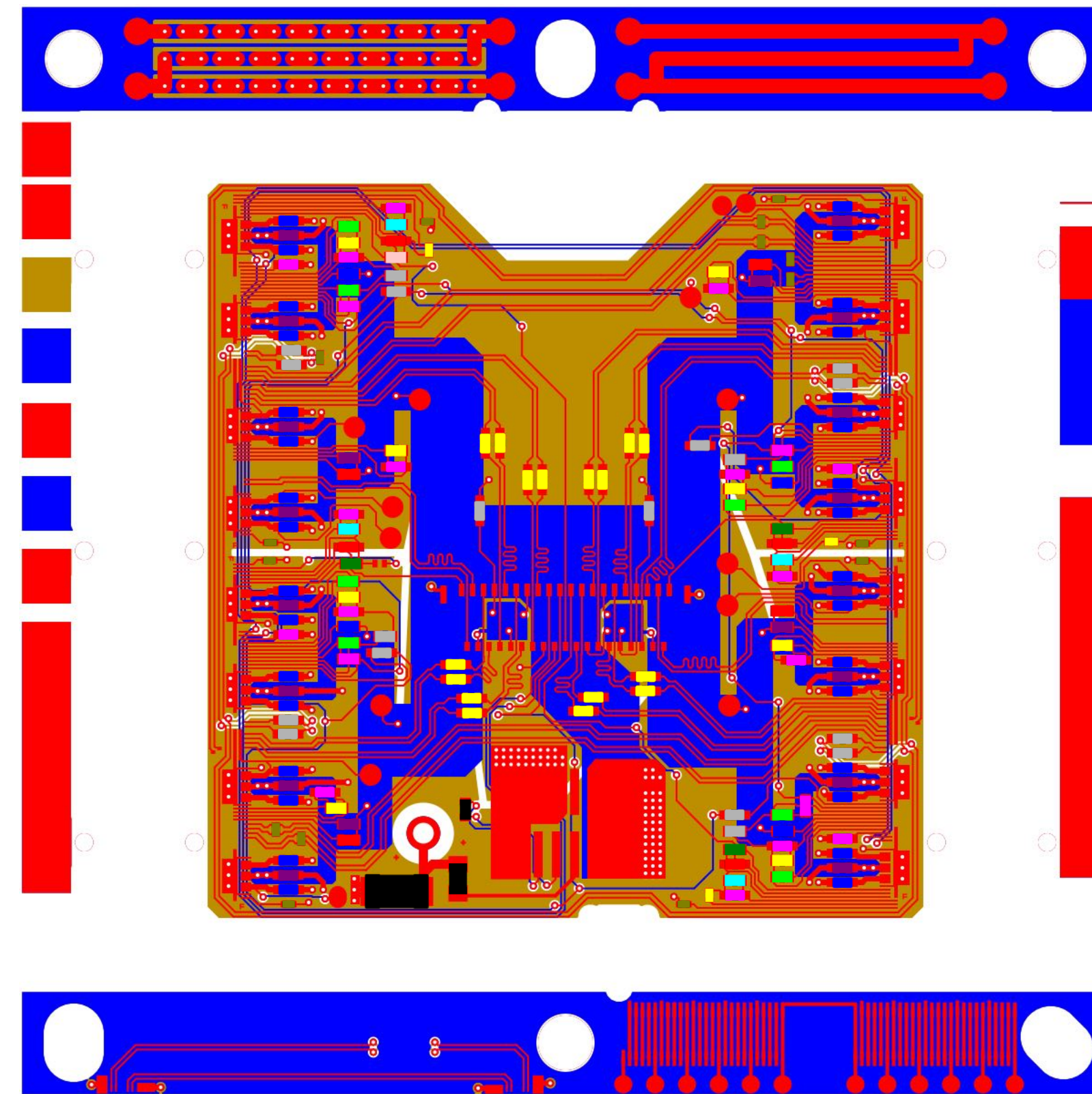
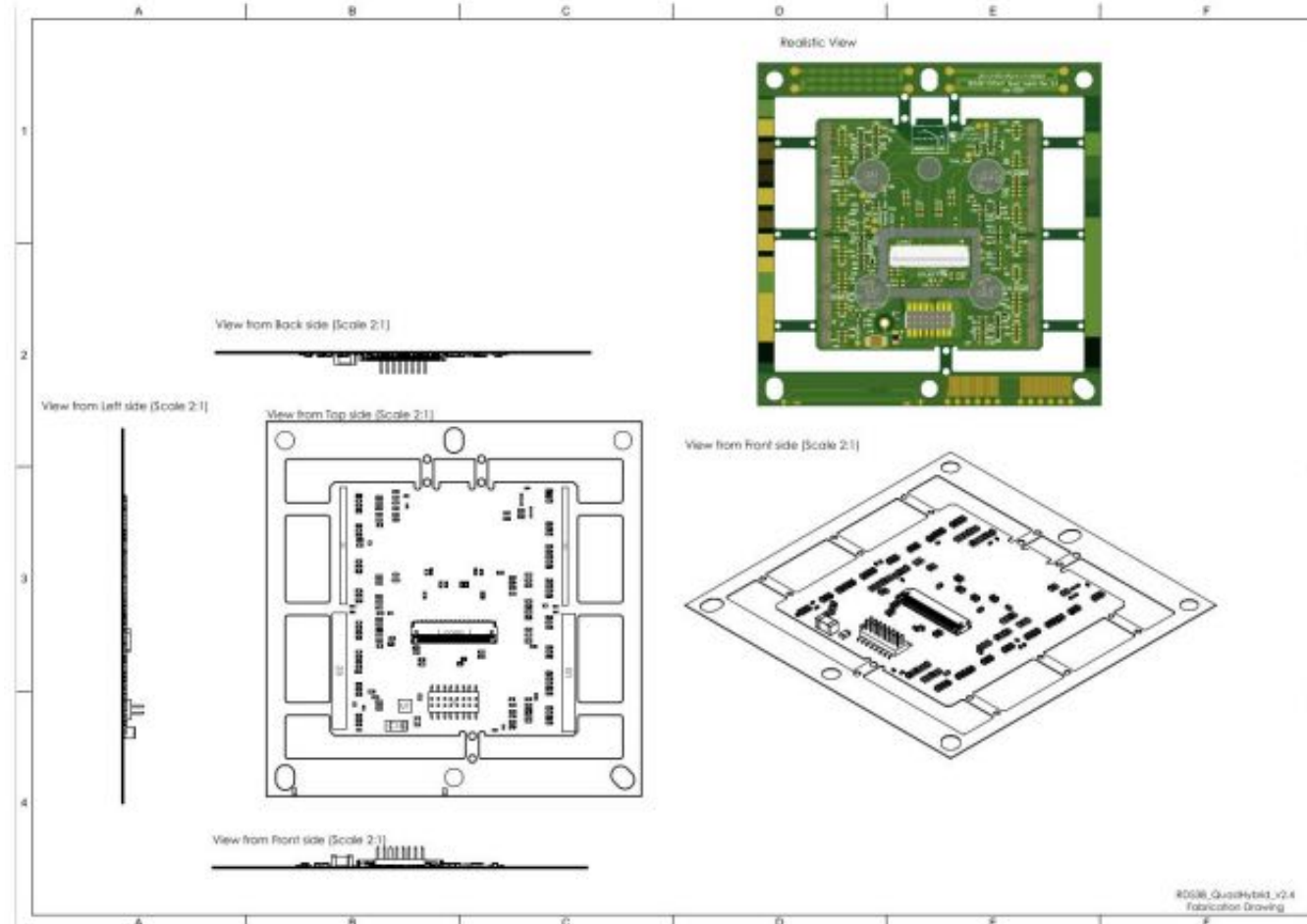
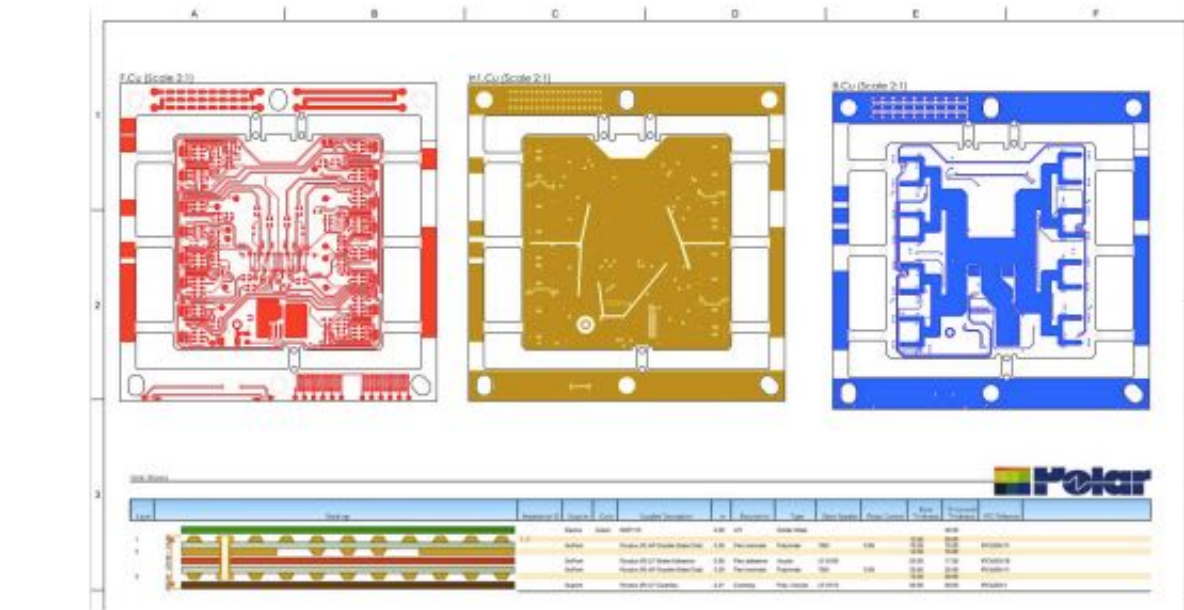
Derive response curve from G4 simulation





# The estimate - more details

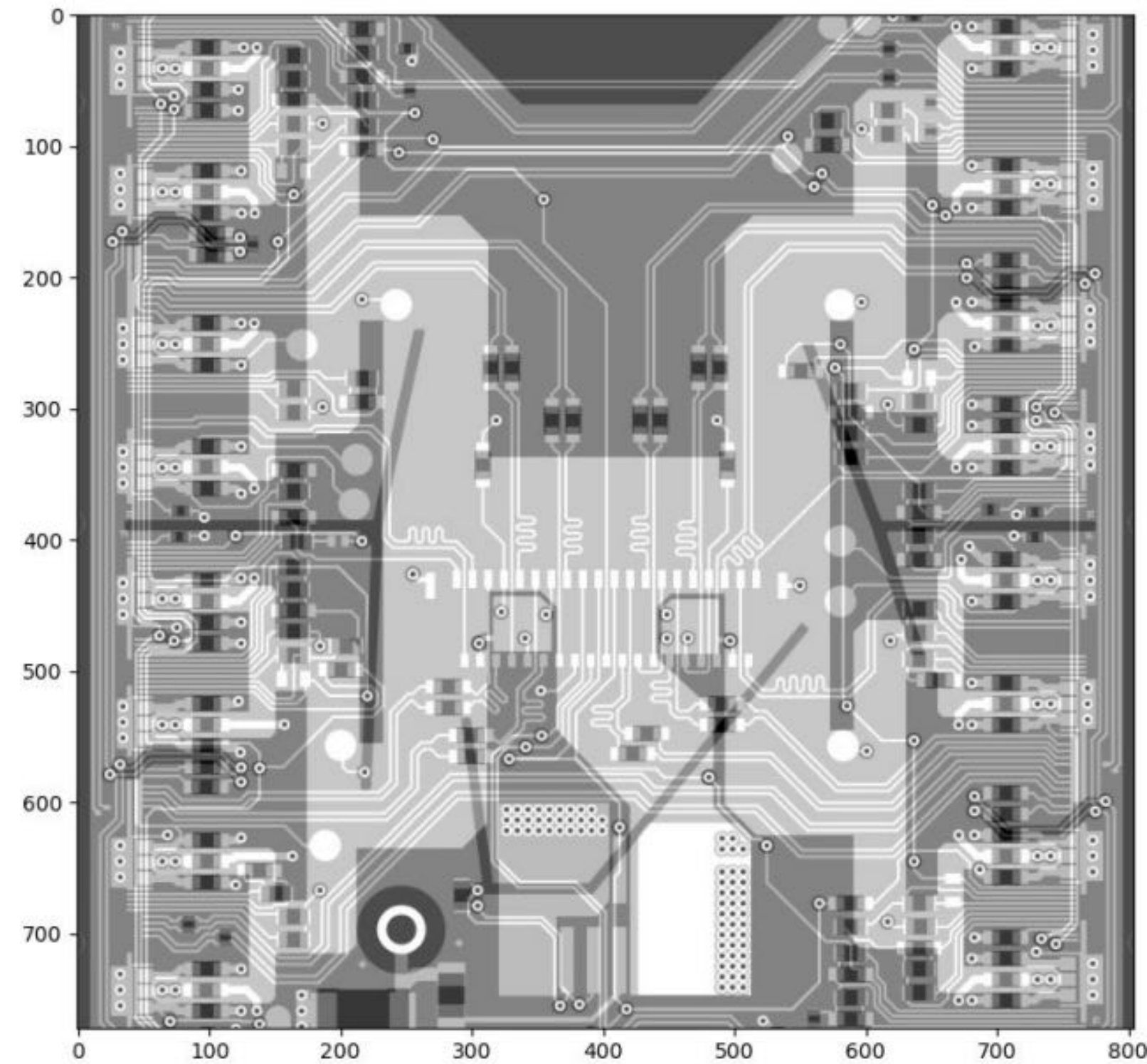
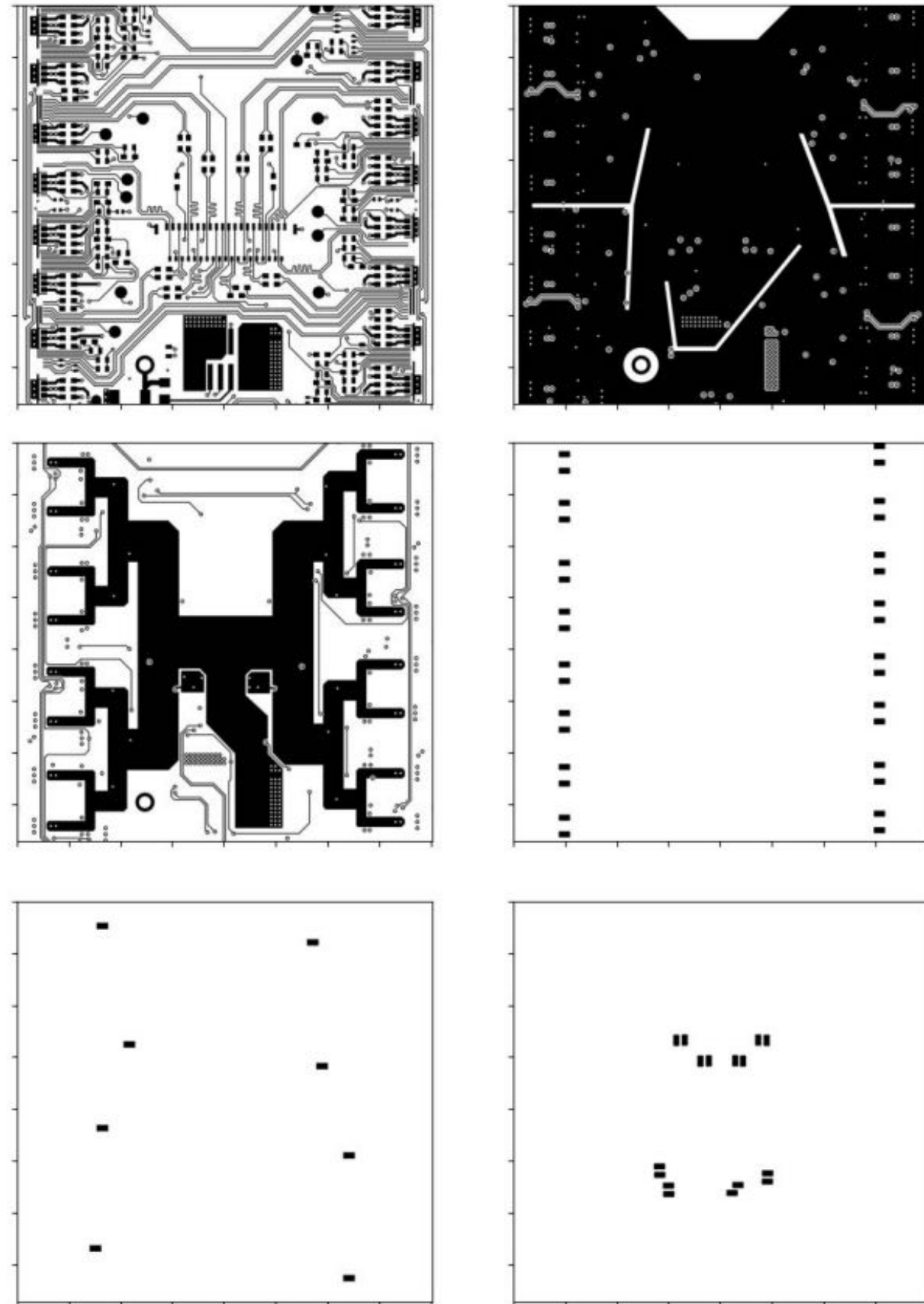
- ▶ The manufacturer drawings of PCB design and SMD layout was exported to .svg
- ▶ Each layer and SMD types were separated to different layers and exported with resolution matching ITkPix detector to .png
- ▶ These masks are then exported to normalised maps, i.e. 2D matrix with values from 0 to 1





# The estimate - more details

- ▶ These maps can be now stacked by adding RL coefficients ( $x/X_0$ ) of each layer



Detail

