Inner tracking for inner beauty

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Tuesday, 2 April 2024
SLAC: Fundamental Physics Directorate seminar

ATLAS EXPERIMENT

Brookhaven National Laboratory

Who am I?

- Abraham (Abe) Tishelman-Charny
- 1994: Born in **Manhattan, NY**
- 2016: B.S. in Physics:
  Stony Brook University
- 2022: PhD from **Northeastern University** on the CMS experiment (Boston, then 4 years at CERN)
- 2022: Started as a postdoc at **Brookhaven National Laboratory**:
  - **Experimental particle physics**

Outline

I. The SM and Higgs boson
II. The ITk strips detector
III. Future prospects

Next section

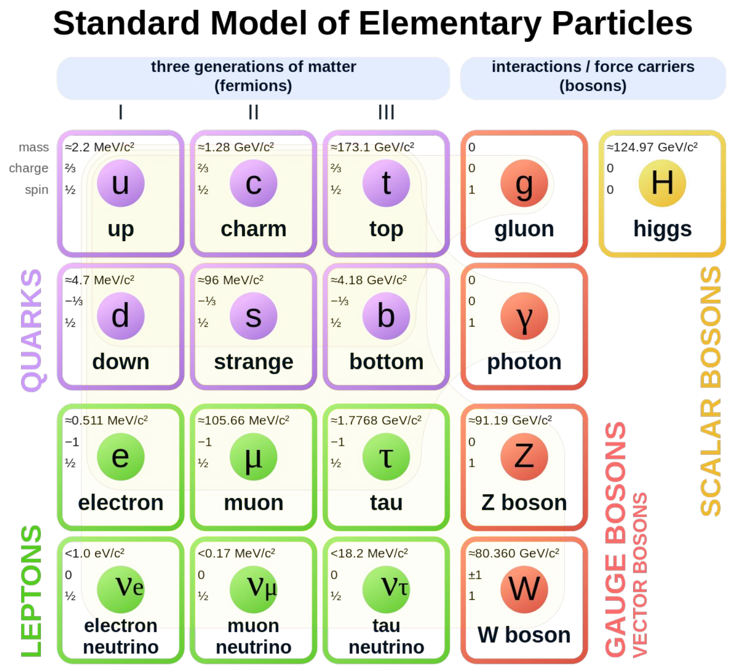
I. **The SM and Higgs boson**

II. The ITk strips detector

III. Future prospects

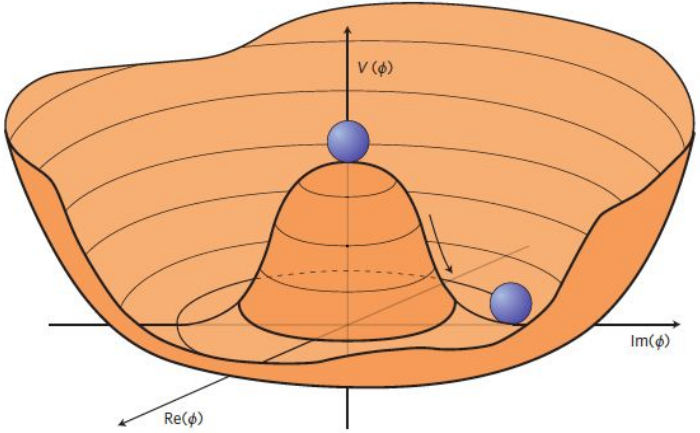
The standard model

- What do we know? What is our theoretical basis?
- The **Standard Model** (SM) of particle physics:
    - Defines elementary **particles**, and their **interactions**
- Extremely successful! Predicts **vast majority** of observed phenomena



The Higgs boson

- **Higgs potential** determines nature of Higgs interactions with **other particles**
- Intertwined with **electroweak symmetry breaking** - process by which particles acquire **mass**
- Coupling lacking a precise measurement: **Higgs self-coupling (λ)**
  - Determines magnitude of Higgs interaction with itself, shape of the **Higgs potential**
- **<u>Has SM prediction we can compare to</u>**



Higgs potential and mechanism

$$V(h) = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \ldots$$

The Higgs boson

- The **Higgs boson**: Theorized in the **1960s**
- Experimentally observed in 2012!
- Made expected splash in the **scientific** community
- Also made **international** news!

The New York Times

Physicists Find Elusive Particle Seen as Key to Universe

Share full article 122

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson. Pool photo by Denis Balibouse

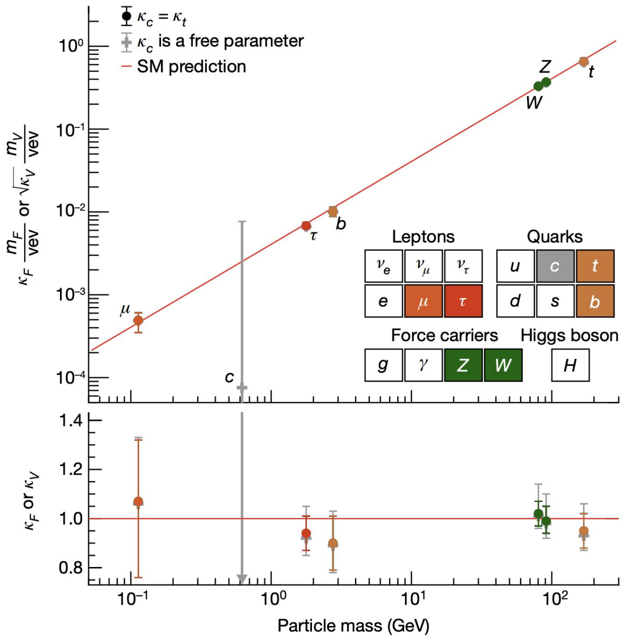
By Dennis Overbye

July 4, 2012

Characterizing the Higgs

- What do you do after observing a new particle?
- You **<u>characterize</u>** it, and compare to **theory**
- Since 2012, precise measurements of couplings, mass, spin, width, CP
- Came a long way, but want to:
  - Measure more, e.g. the Higgs self-coupling
  - **<u>Improve precision on all measurements</u>**

= Measurement
= Standard Model



Nature 607, 52-59 (2022)

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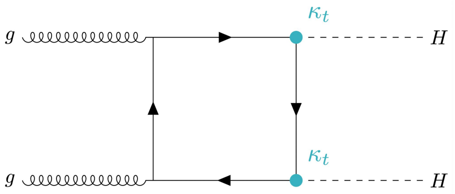
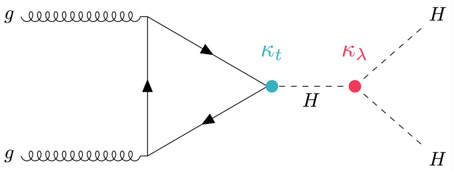
Higgs pair production

Can directly access Higgs self-coupling via **Higgs pair production (HH)**:

Gluon fusion:

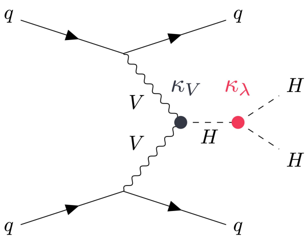
- **Leading** production mode
- Access to **self-coupling**
- $\sigma_{\text{NNLO, FTapprox}}$ ~ **31.05 fb** @ 13 TeV, m_H = 125.0 GeV [1803.02463]

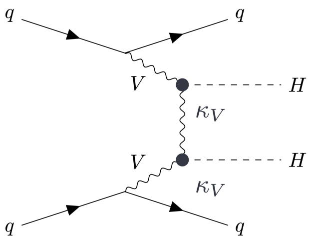


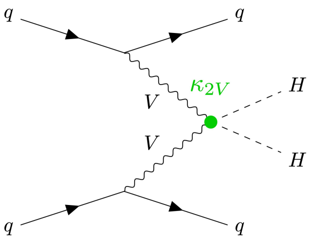


Vector boson fusion:

- **Subleading** production mode
- Access to self-coupling, κ_{2V}, κ_V
- **Quarks** in final state
- σ_{N3LO} QCD ~ **1.73 fb** @ 13 TeV, m_H = 125.0 GeV [1811.07906]







- Self-coupling affects **cross-section** and **differential distributions**
- **Rare processes** - need **final states** with good signal to background. Would benefit from more data!

HH final states

- **Higgs boson** has many decay modes
- Therefore, many **HH** decay modes
- Most common: H→bb (and HH→bbbb) (~58% at 125 GeV)
- Final states have different **likelihoods**, leave different **detector signatures**

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

= Existing results

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Next section

I. The SM and Higgs boson

II. The ITk strips detector

III. Future prospects

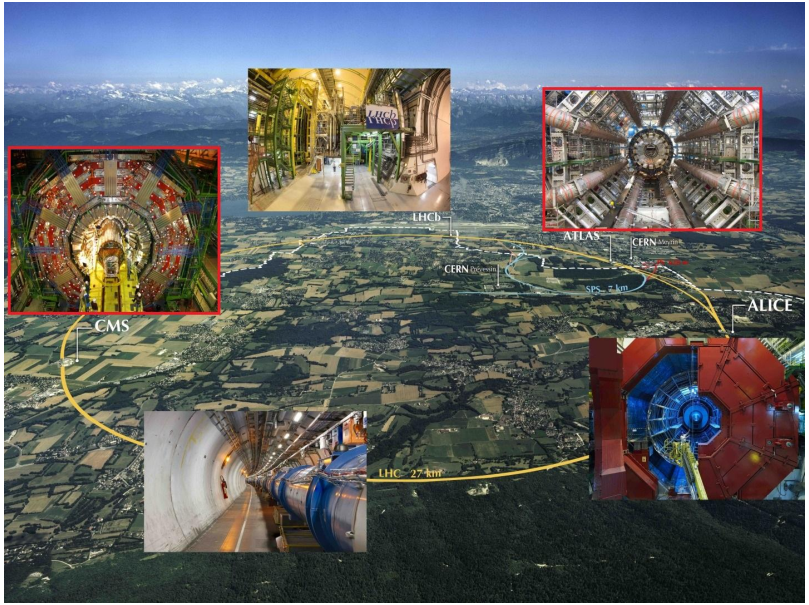
LHC

- Need **machine** capable of producing particles we want to study **in abundance**:

- Collides **protons**, heavy ions. pp collisions at 7, 8, 13, now **13.6 TeV**

- Has **four detectors** stationed: ALICE, ATLAS, CMS, LHCb

  (only **ATLAS & CMS** geared towards Higgs physics)

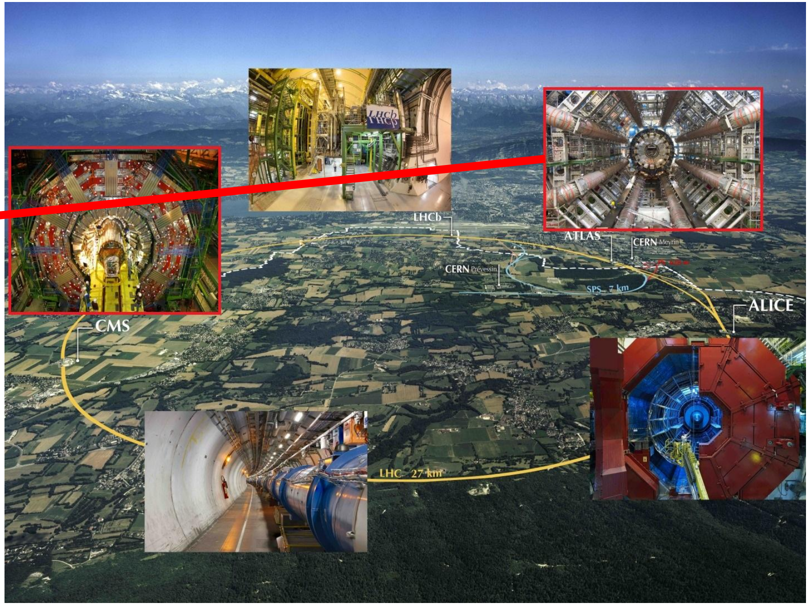


The Large Hadron Collider

LHC

- Need **machine** capable of producing particles we want to study **in abundance**:

January 2024



The Large Hadron Collider

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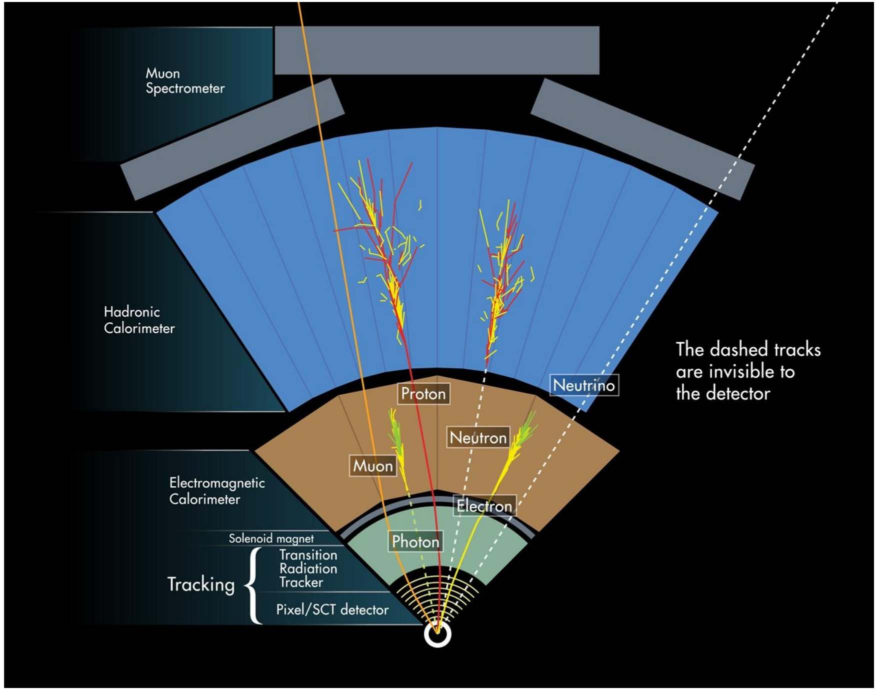
ATLAS

- Different **layers** detect different **particles** (needed for different final states!)

- Requires use of different detector **technologies** → Need to choose wisely considering **cost** and **size**

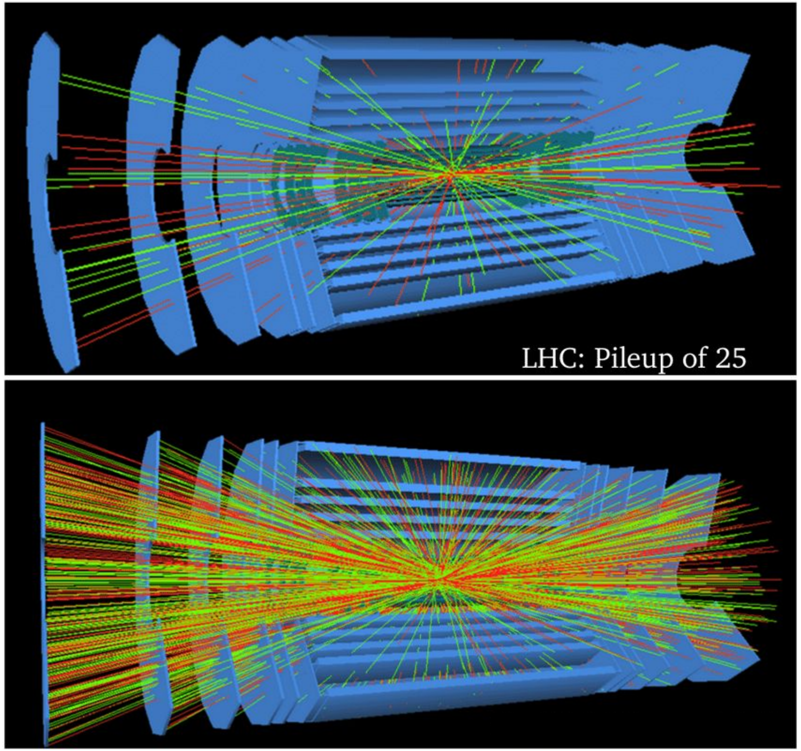
- **Reconstruct** physics **event** by working backwards from detector information

- Need almost **hermetic** detector to reconstruct all final states, gets stats for rare processes



High-Luminosity LHC

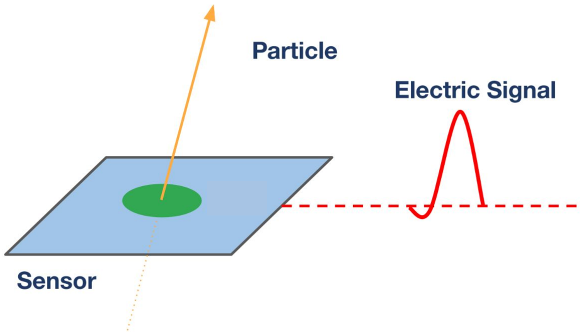
- 2029: LHC will finish upgrade to **High Luminosity LHC** - ready to **deliver collisions** to experiments
- **Pro:** Will increase ATLAS + CMS datasets by ~ factor of 20
- **Con:** Extremely challenging data-taking environment
    - Extensive **detector upgrades** in progress to handle this



Development and Evaluation of Novel, Large Area, Radiation Hard Silicon Microstrip Sensors for the ATLAS ITk Experiment at the HL-LHC

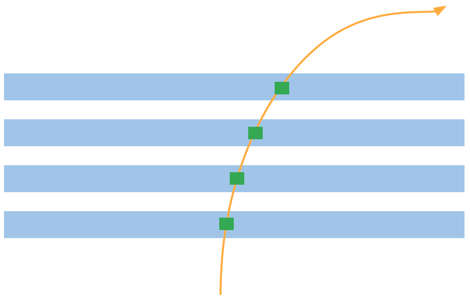
Silicon based tracking

- Particle hits silicon
- Electric signal read out
- Series of hits forms a **track**
- Use radius to measure **particle momentum**
- Orient geometry based on magnetic field



G. D'amen - BNL physics seminar series

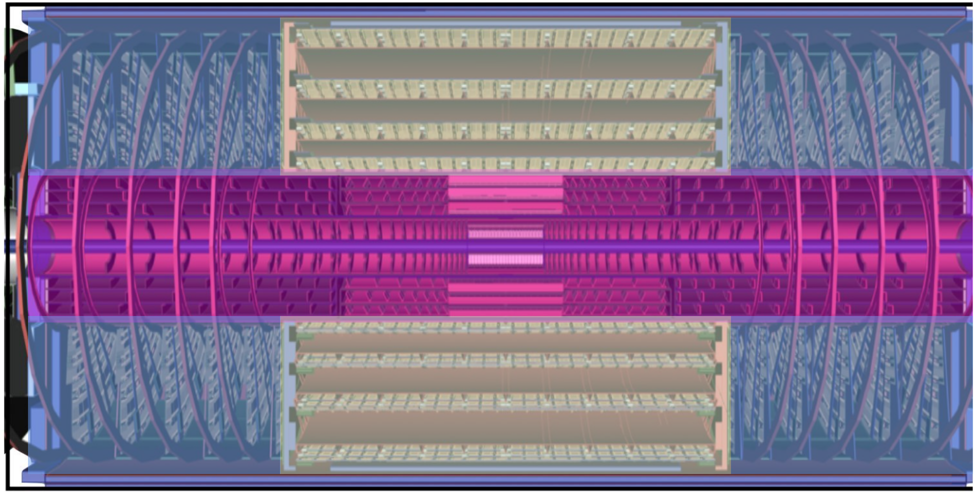
Silicon trackers actively used by ATLAS and CMS!



The ATLAS ITk Layout

- Part of ATLAS **upgrade**: Replace tracker with **full silicon pixel** and **strip** sub-detectors - **The ITk** (Inner Tracker):

~ **6 meters**



~ **2 meters**

ITk pixels

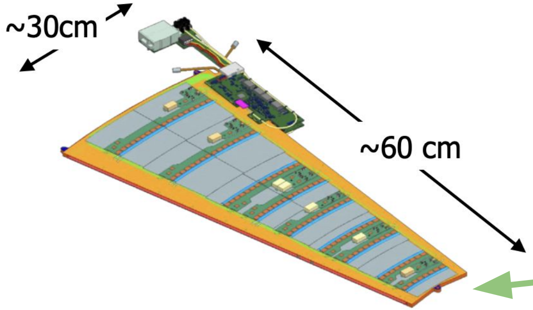
ITk strips endcap

ITk strips barrel

~ 100 m^2 area covered!

ITk strips layout

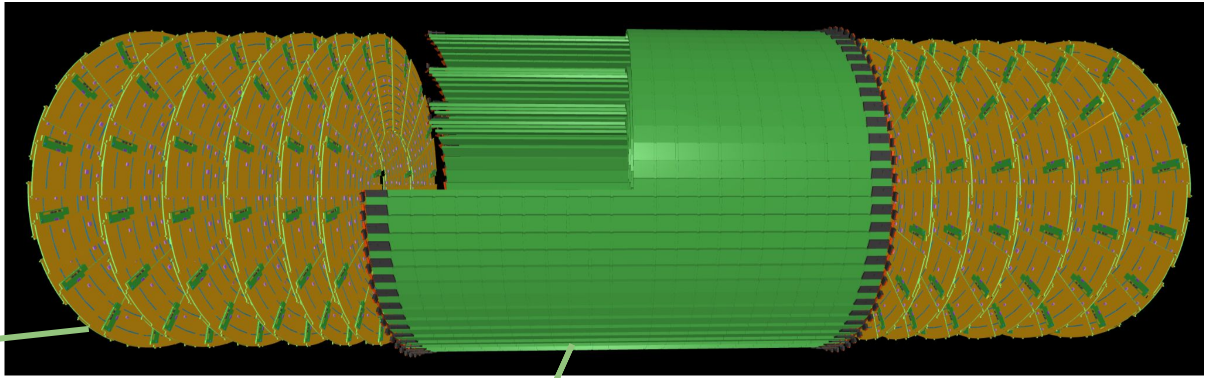
1 Disk = 32 **Petals**



Endcap
6 disks

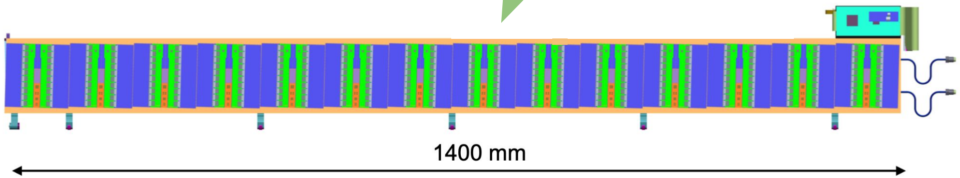
Barrel
4 layers

Endcap
6 disks



[ITk viewer]

1 Barrel layer = 56-144 **Staves**



Sensors

Detect particles at the **strip level**. Two flavors of **barrel** sensors:

| = 1 strip

Short strip (SS)

97 mm

97 mm

Long strip (LS)

Technology:
- p-type w/ n-type implants
- Radiation hard
- AC-coupled

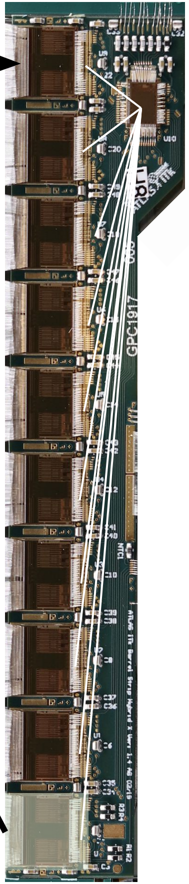
Eventually operate **cold (-35°C)** to account for radiation damage

- SS/LS: 4/2 rows of 1280 strips in same amount of area.

Hybrids

- Need to **<u>read out each strip</u>**
- **Hybrid: Flex PCB** glued onto sensors
- **Hosts ASICs**, called the **ABCStar**:
  - Hybrid hosts **7-12** ABCStars, depending on hybrid/sensor flavor - read out in **star configuration**
- Wire-bonded to strips for **individual readout!**

ABCStar chip
(x10 for this type)



Powerboards

- Need to power ASICs on hybrid
- Accomplished via a **powerboard** PCB housing various components:

<u>DC-DC converter</u>

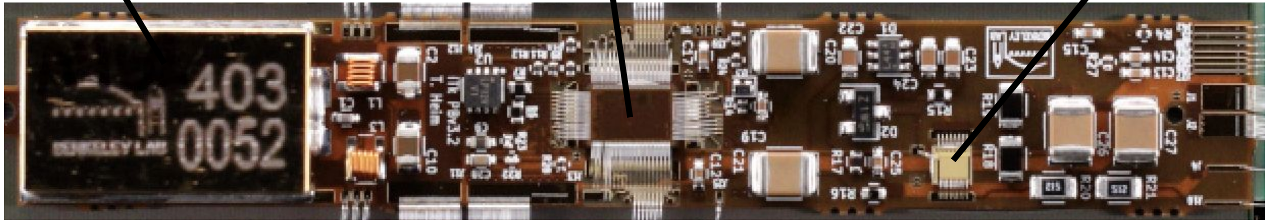
- 11V input, 1.5V output
- 110 μm Al shield to prevent EM noise leakage

<u>Measurement and control</u>

- Autonomous Monitoring and Control (AMAC) chip
- Enable/Disable DCDC
- Measure voltage, current, temperature

<u>HV filter</u>

- Includes a GanFET (Gallium Nitride Front End Transistor)
- Allows **isolation** of failed sensor in breakdown connected to the same HV line

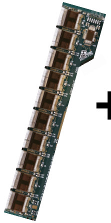


Modules

- Let’s put it all together! Define this as a **module:**

<u>Long strip **sensor**</u>

\+



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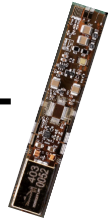

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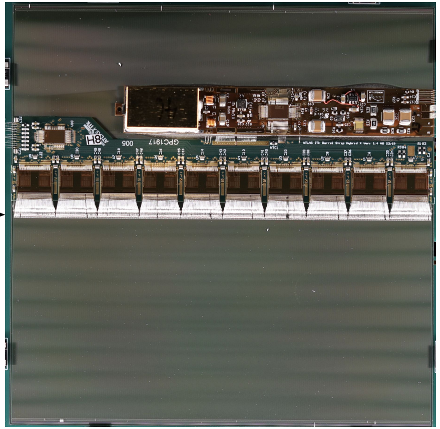
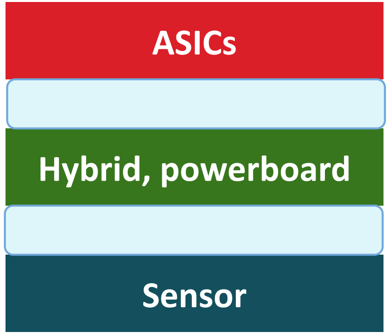
<u>Long strip **module**</u>



Birds-eye view

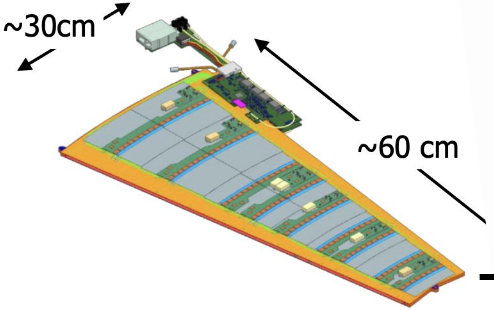


Side view

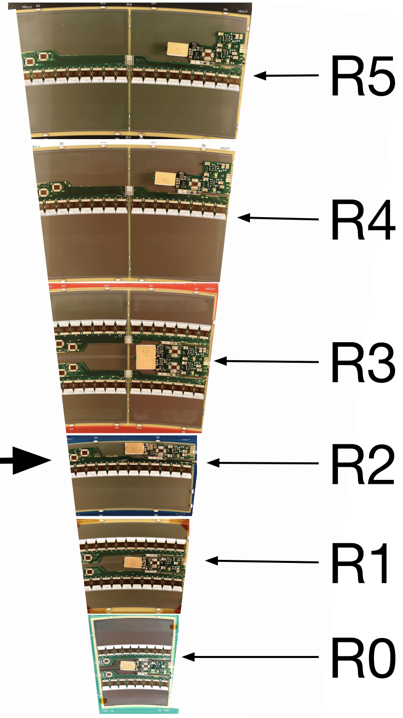
All module flavors

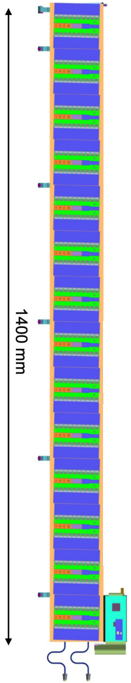
- Need appropriate module geometries to make up **petals (endcap) and staves (barrel):**

6 endcap module types
to make one petal



All petals identical: R0-5 modules on each side





Each stave has **14 modules per side**

Long strip stave:
14 long strip modules per side

Short strip stave:
14 short strip modules per side

Module QC

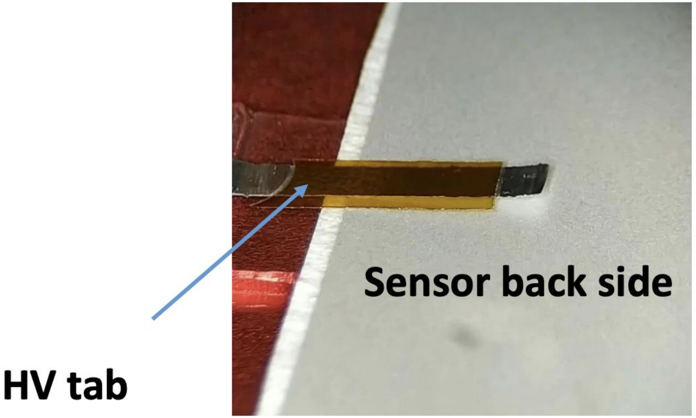
- Module QC tests are performed after **each assembly step**:

Module QC

- Module QC tests are performed after **each assembly step**:

HV-Tab attached

- **IV**
- **Visual inspection**

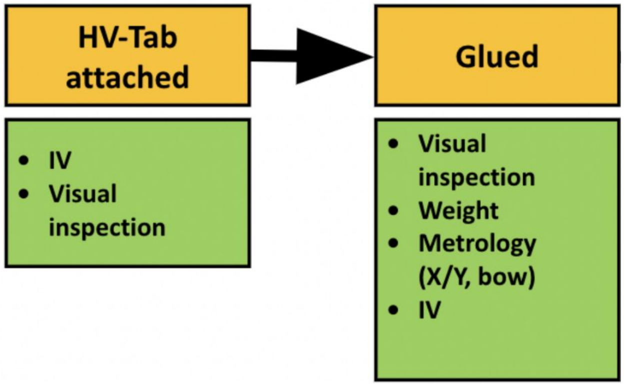


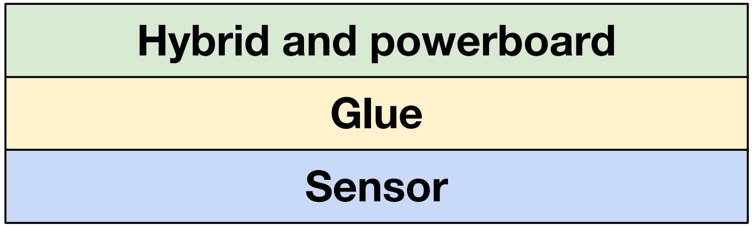
I. Mandić

Aluminum strip attached to metal backplane

Module QC

- Module QC tests are performed after **each assembly step**:





Module QC

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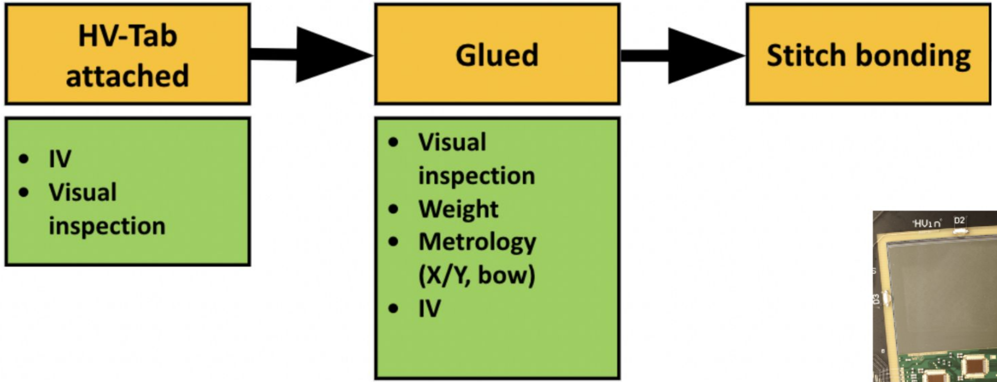
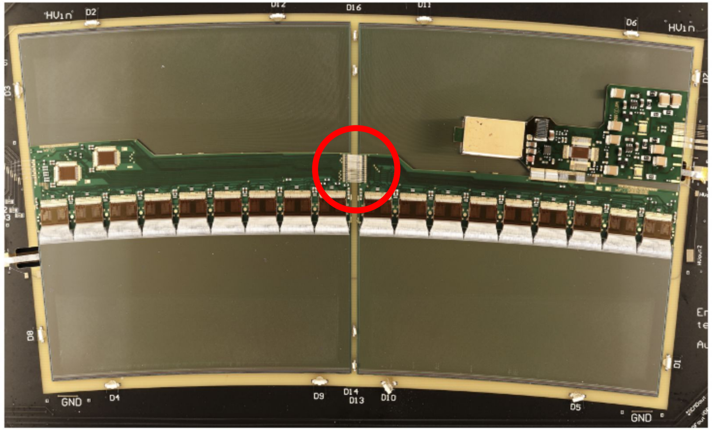


Stitch bonding step for **R3-5** modules only:



Module QC

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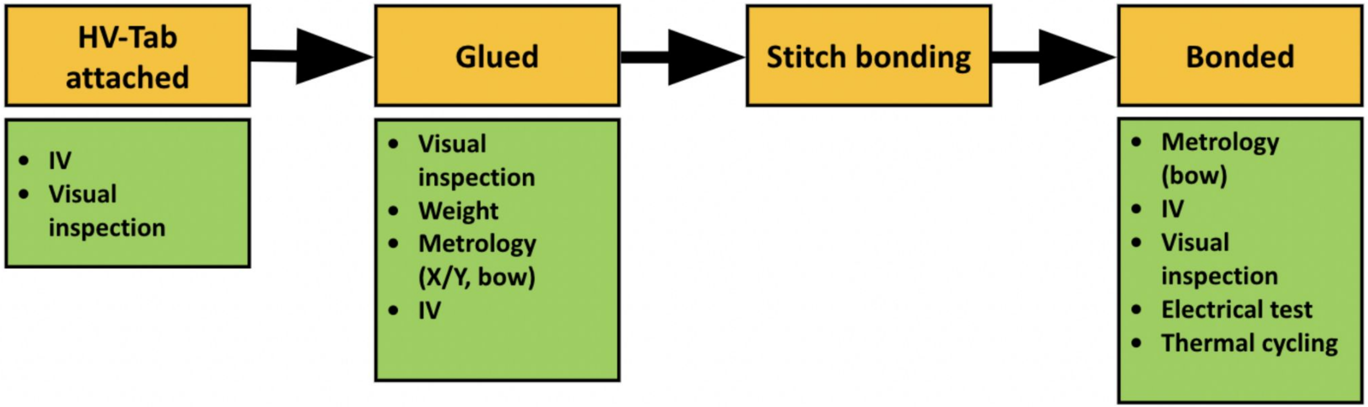
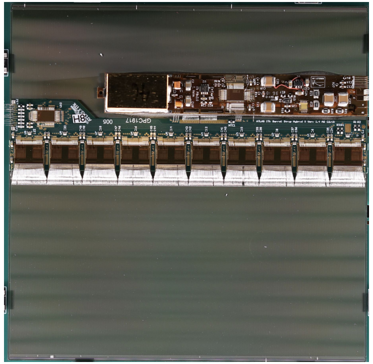


[2024 JINST 15 P09004](#) [[arXiv:2401.17054]](#)



Completed module!

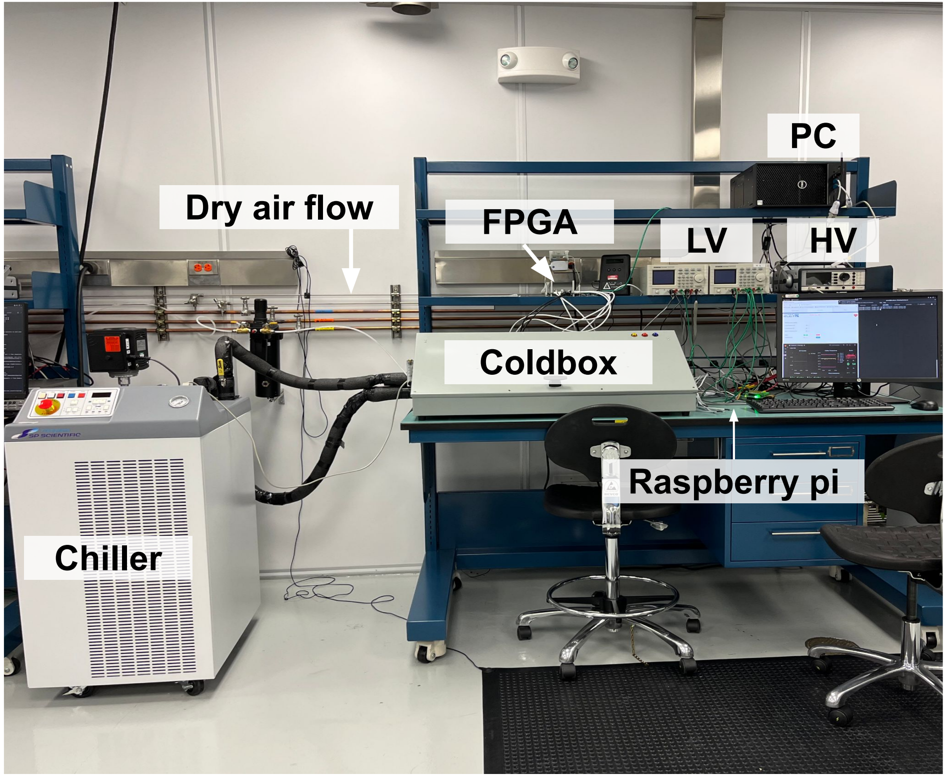
Module QC setup

- To perform these steps, need a robust and complete setup!

Example module testing setup

- Coldbox (Modules go in here)
- Chiller (temp control)
- Dry air flow (humidity control)
- Power supplies to power electronics, bias sensors
- FPGA + PC for DAQ
- Raspberry pi: Environment monitoring

BNL setup



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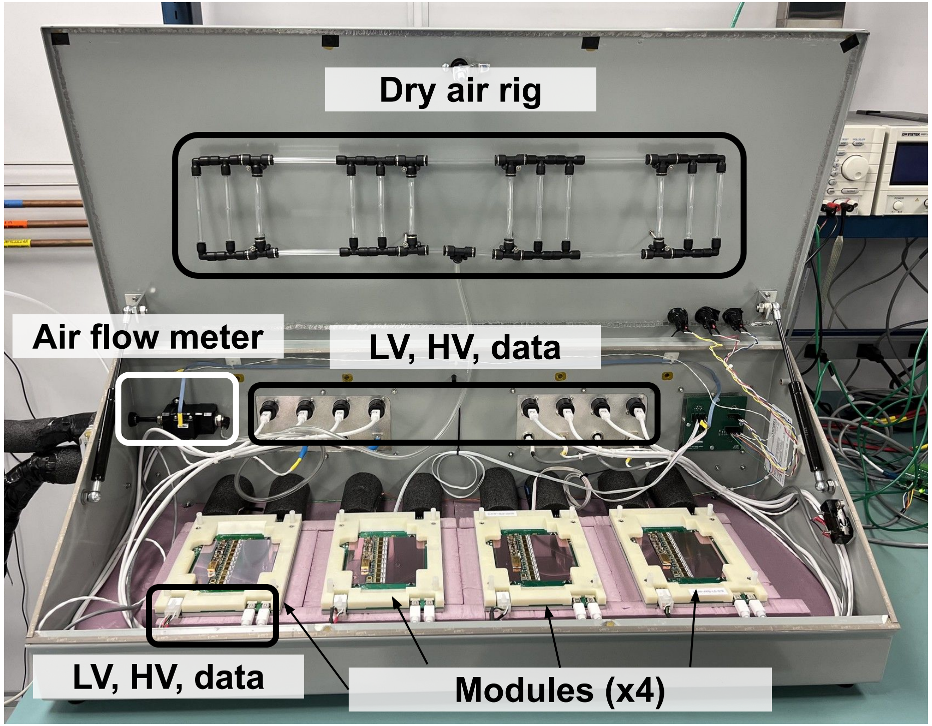
Module QC coldbox at BNL

Inside the coldbox:

- Up to **four modules**
- **Dry air rig** (minimize humidity)
- Air flow meter (monitor)
- Module side LV, HV, data lines
- Box side LV, HV, data lines

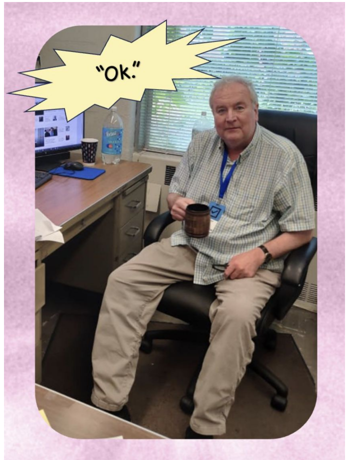


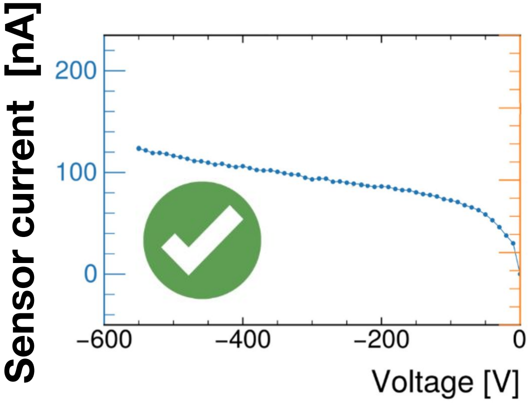
Module IV

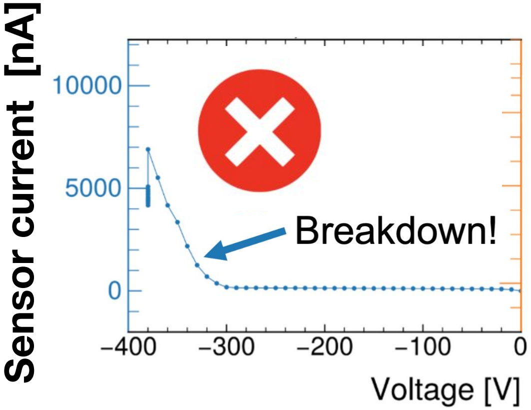
- Modules must be operational up to **-500 volts**
- First electrical test of a module: **IV curve**
    - Increase voltage in steps of -10V, measure sensor current

Bonded

- Metrology (bow)
- **IV**
- Visual inspection
- Electrical test
- Thermal cycling

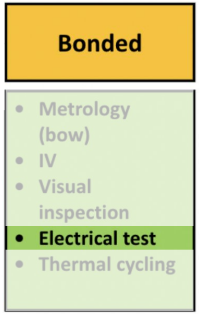


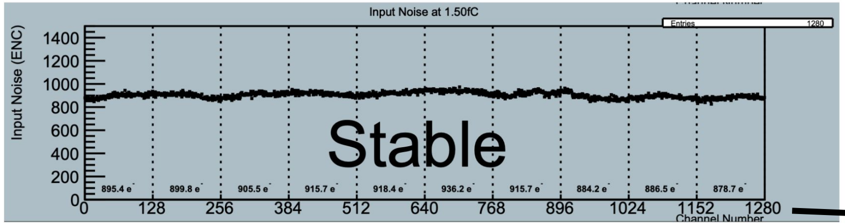


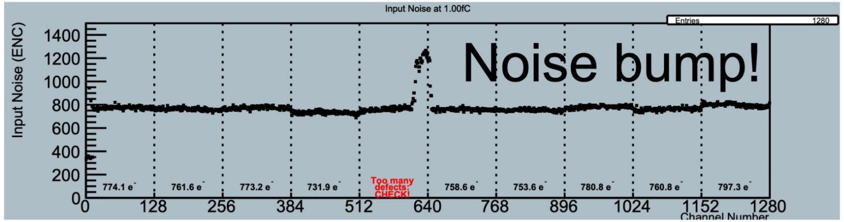


Module electrical test

- Modules must exhibit **acceptable noise**
- Bias sensor at **-350V**, inject **test charges**, measure gain, noise



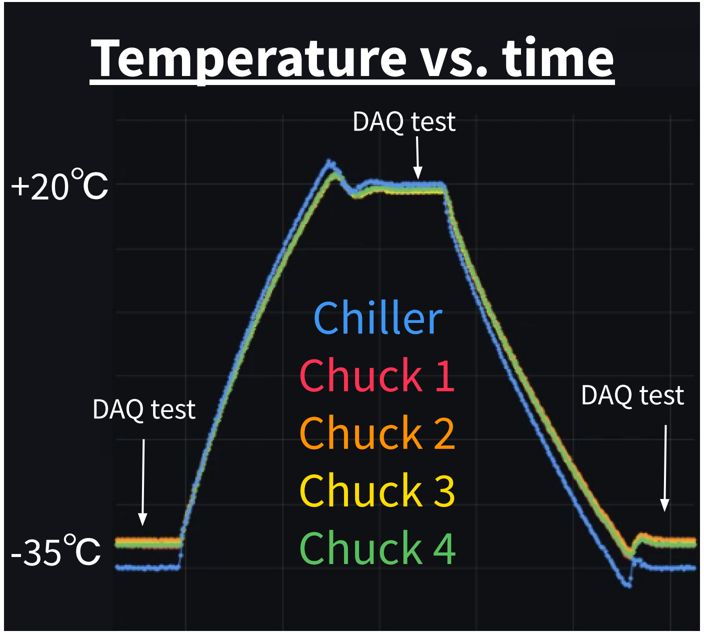




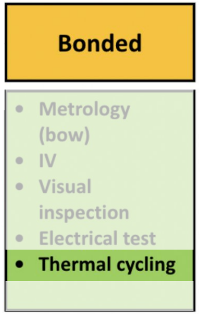
Can accept module with max **2%** of channels failed

Module thermal cycling

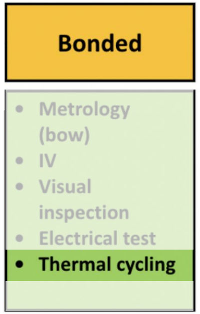
- Expect modules to experience **temperature changes** during operation (~ 1 expected time per year from **year end shutdown**)
- Emulate this effect with **thermal cycling**
- Define **one thermal cycle** as:
  - Start cold
  - Take noise measurement
  - Go warm
  - Take noise measurement
  - Go cold
  - Take noise measurement
- Module must undergo **10 thermal cycles** and have passing **noise and IV** afterwards



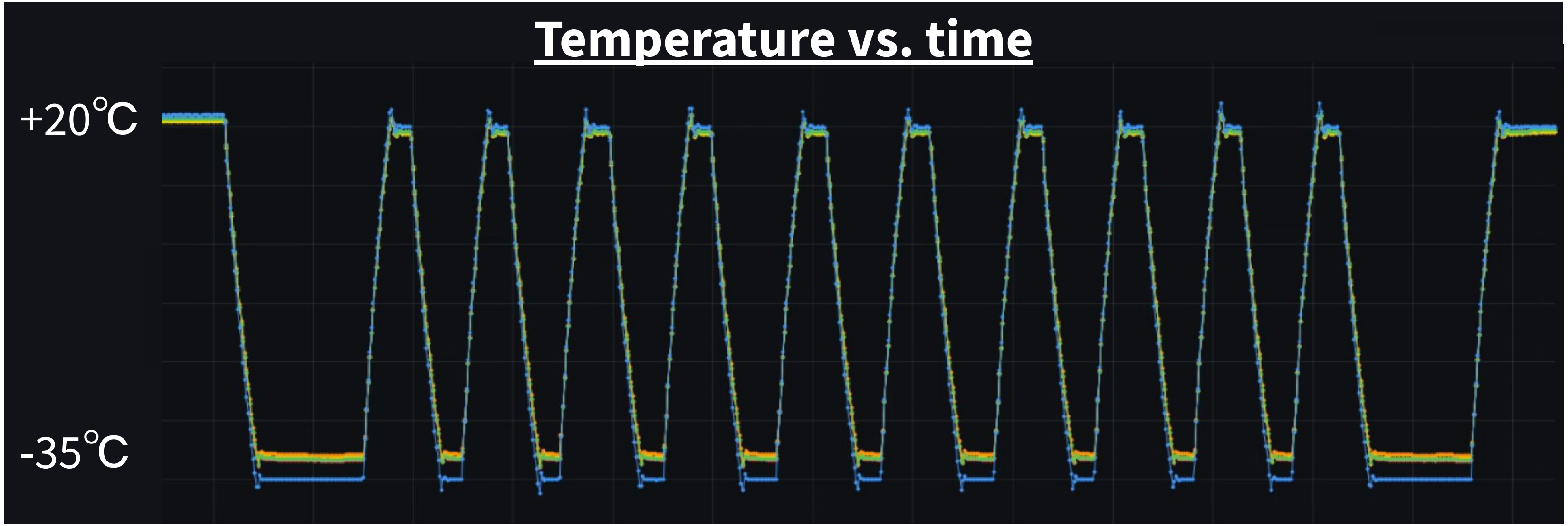
X 10



Module thermal cycling example



- Example set of **ten thermal cycles**
- Cycled **four modules simultaneously**
- Noise and IVs after TC looked good



Extreme thermal cycling

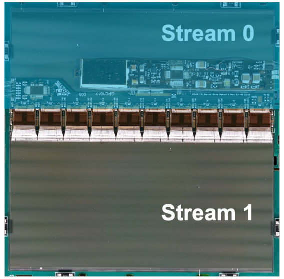
- Say modules good after 10 TCs. **How much headroom do we have?** Were they going to fail on the **11th cycle**?

- To start answering this question, TC'd
3 modules 101 times

- Varied number of cycles per day, in total **16 days of cycling**

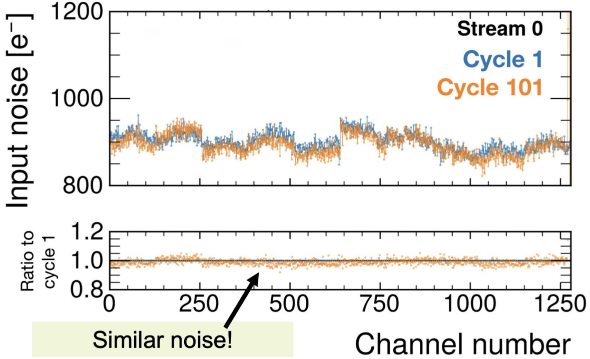
Day	Module 1	Module 2	Module 3
1	0	4	4
2	6	6	6
3	8.5	8.5	8.5
4	8.5	8.5	8.5
5	7.5	7.5	7.5
6	6	6	6
7	4	4	4
8	9.5	9.5	9.5
9	5.5	5.5	5.5
10	2	2	2
11	7	7	7
12	6	6	6
13	10	10	10
14	8.5	8.5	8.5
15	7	7	7
16	5	5	5
Total thermal cycles	**101**	**105**	**105**

Extreme TC: Noise

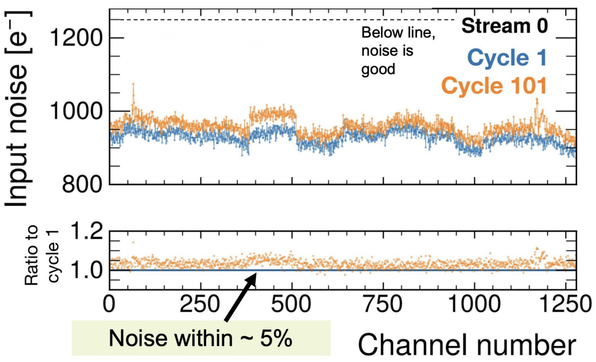


- Input noise (intrinsic to **sensor**) measured at **first** and **final** **cold** DAQ tests:

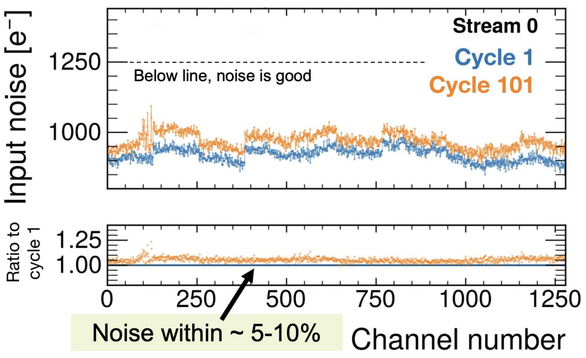
Module 1



Module 2



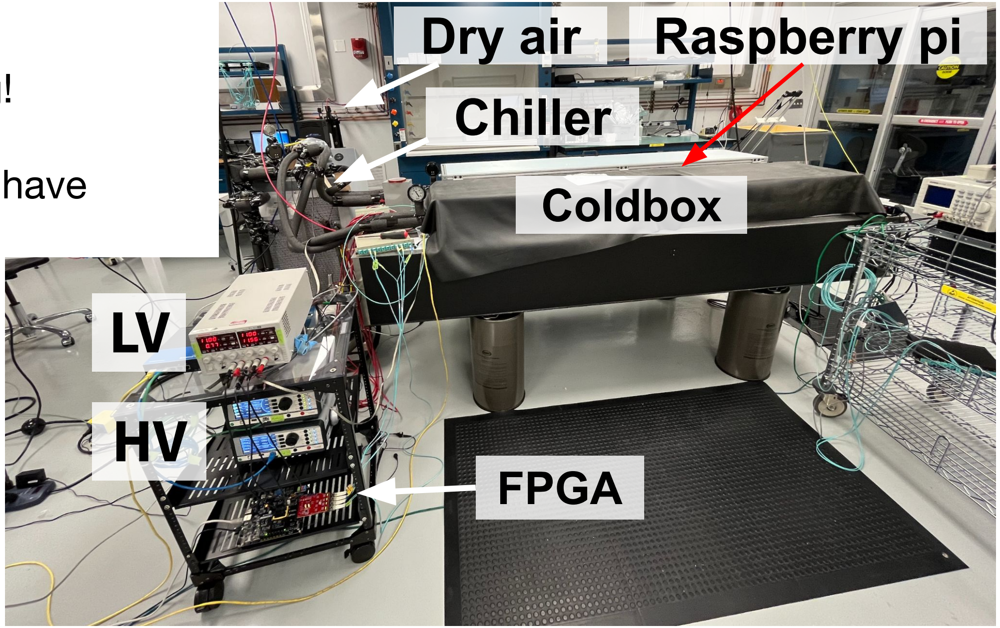
Module 3



- Noise a bit above **room temperature target** during first **cold** tests (target of 824 e^-)
- After cycling, almost all channels within **~5%** of initial noise
- A few noisy strips on Module 1 edge and certain Module 2/3 regions
  - Modules are mostly **operational**

Stave testing setup at BNL

- After passing, **load** onto **stave/petal**
- Need to check **unaffected** from **loading**!
- No well-defined **QC procedure** yet, but have setup



<u>**Example stave testing setup**</u>

- Coldbox (Stave inside)
- Chiller (temp control)
- Dry air (humidity control)
- Power supplies to power electronics, bias sensors
- FPGA for DAQ
- Raspberry pi: Environment monitoring

Stave coldbox

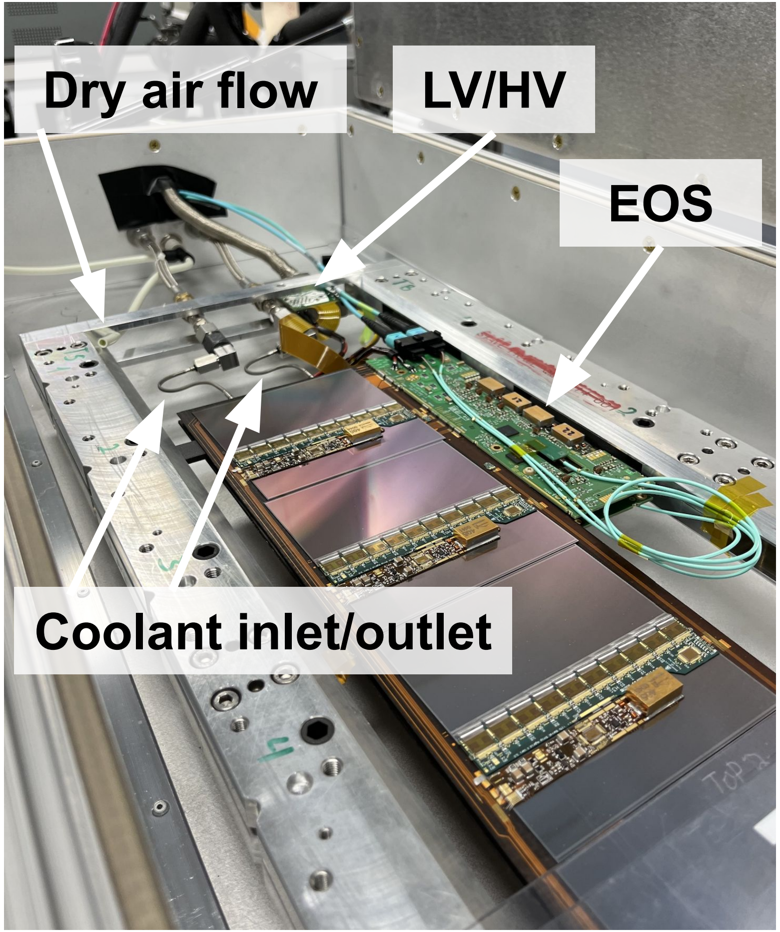
Inside the coldbox:

- One stave

Stave coldbox

<u>Inside the coldbox:</u>

- One stave
- **Dry air flow** (minimize humidity)
- Coolant inlet/outlet (temperature control)
- LV/HV connector
- **End Of Substructure (EOS) card** for data readout



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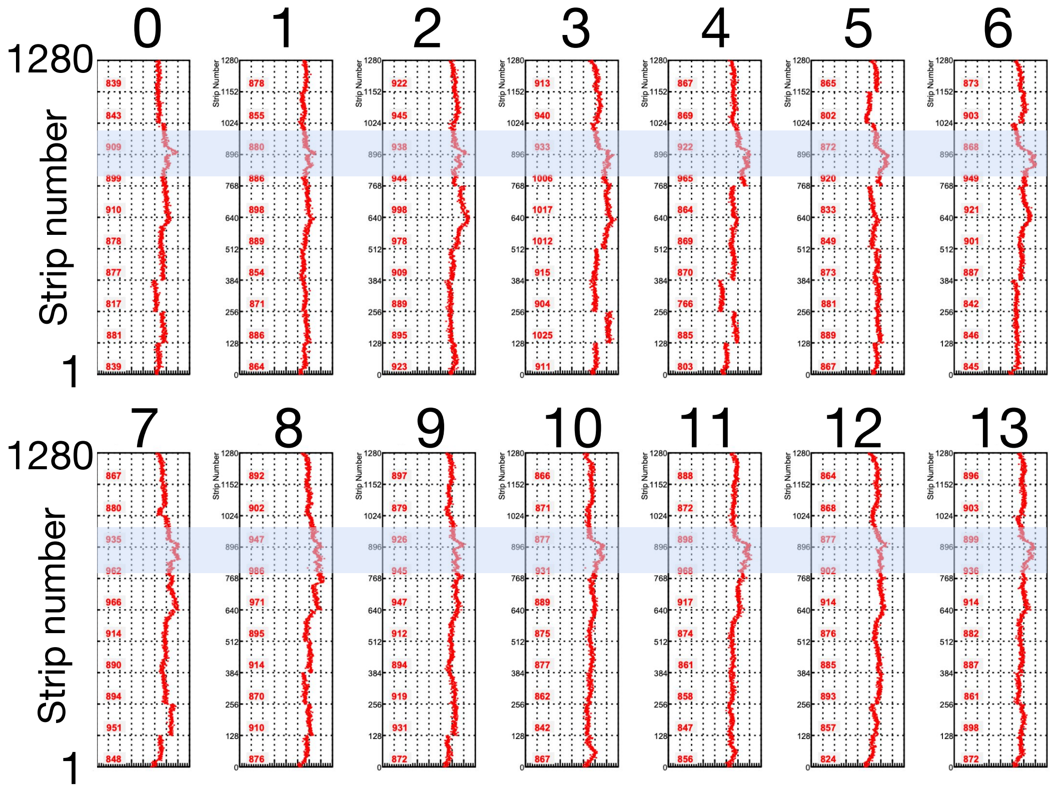
Stave electrical test

- Can take noise measurement of **all modules simultaneously**
- Example noise measurement for **one stave side** (14 modules)
- X-axis ranges: 300-1100 ENC
- Expected shape near DCDC coil
- Flat, ~ 900 ENC. Considered **healthy noise** for **Long Strip stave** based on expected signal to noise

Module Number:

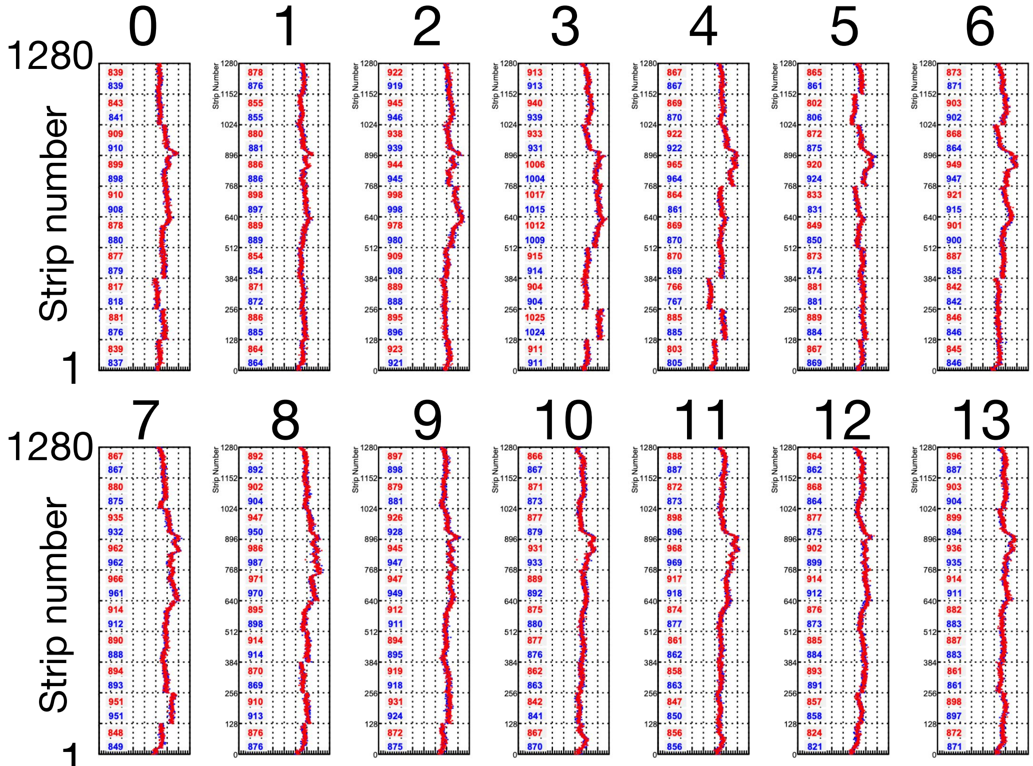


Noise [ENC] xmin/max of each: **300/1100**

Stave TC

- Also plan to **thermal cycle** staves a number of times (number undefined, at least **once**)
- Will compare noise **before** and **after** thermal cycling, just like for module TC
- In this example, TCd stave to inlet/outlet avg. temperature = -35°C **5 times**
- Noise looks **very similar** before/after

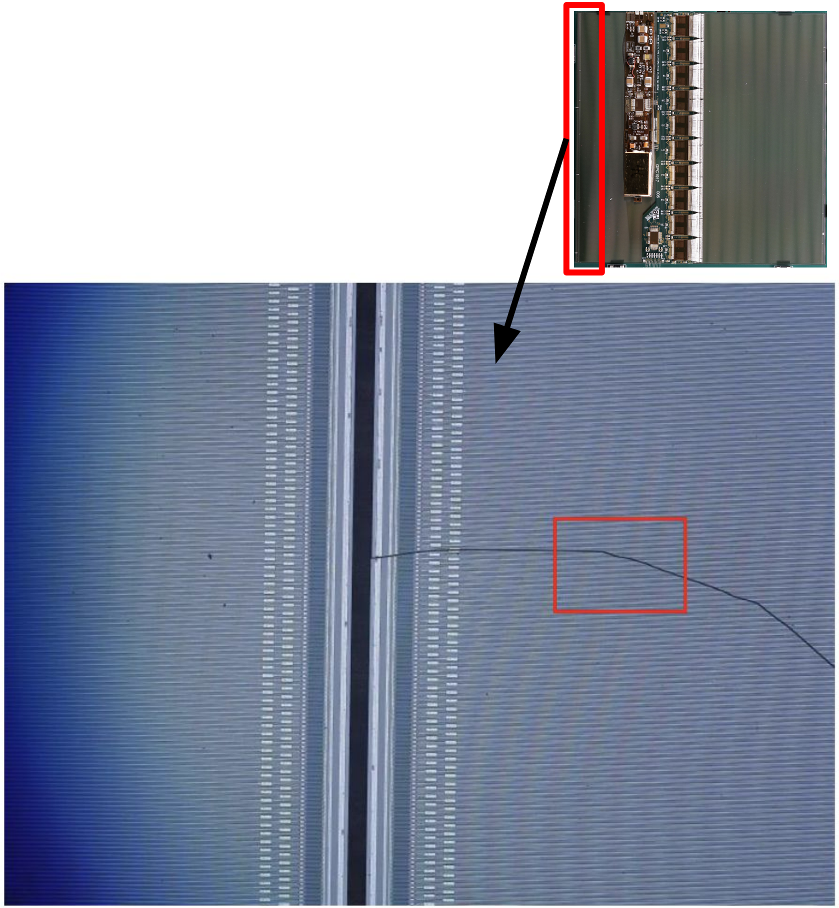
Module Number:



Noise [ENC] xmin/max of each: **300/1100**

Production status

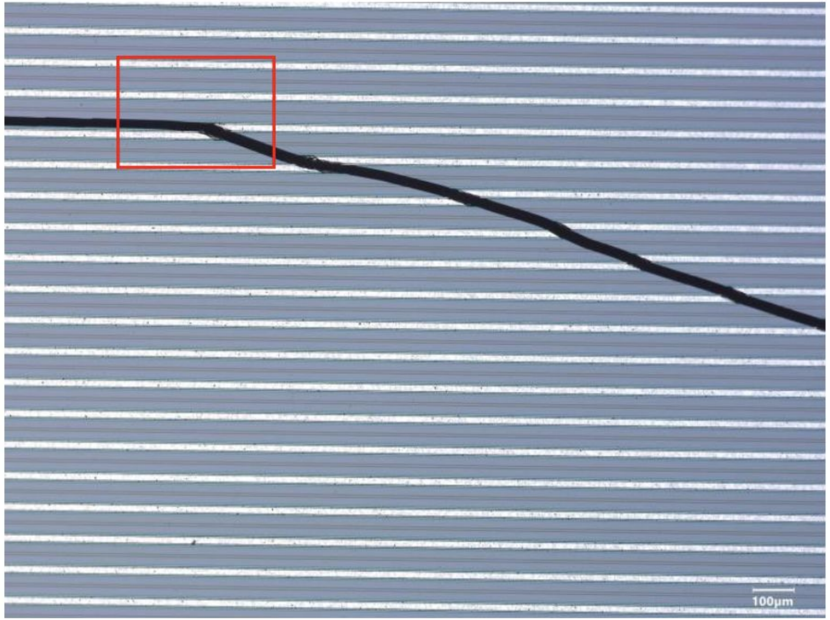
- During pre-production, module I-Vs with **breakdown on staves** (Not off stave!)
- Upon investigation, found sensors **fracturing** during stave TC



Production status

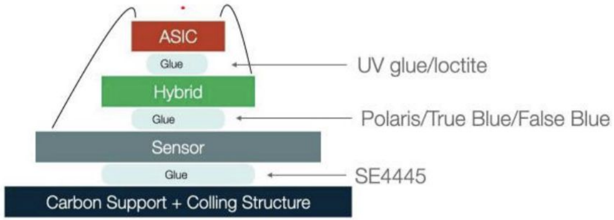
- During pre-production, module I-Vs with **breakdown on staves** (Not off stave!)

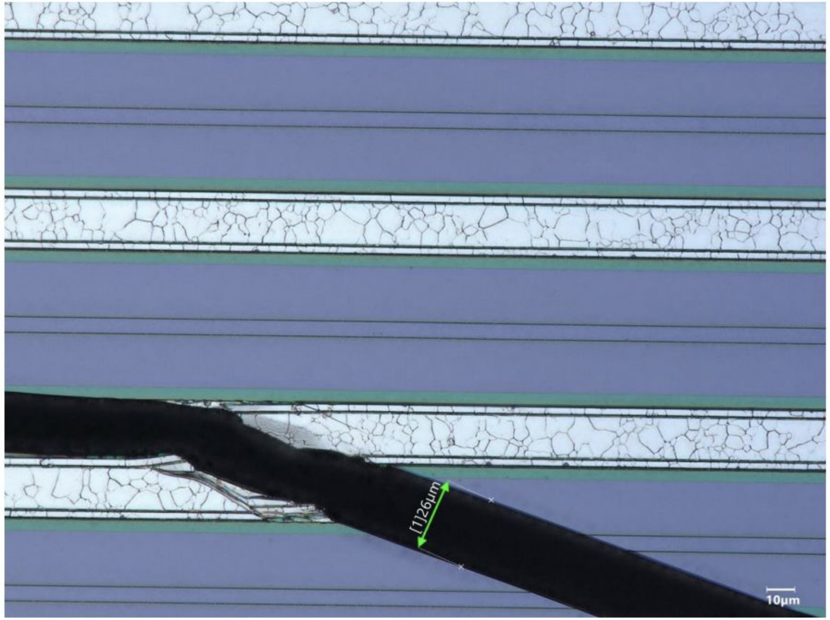
- Upon investigation, found sensors **fracturing** during stave TC



Production status

- During pre-production, module I-Vs with **breakdown on staves** (Not off stave!)
- Upon investigation, found sensors **fracturing** during stave TC
- Understanding: Due to **CTE mismatch**, close proximity of **hybrid** and **powerboard**.
- Module production **halted** while we try mitigation strategies, possible solutions





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Next section

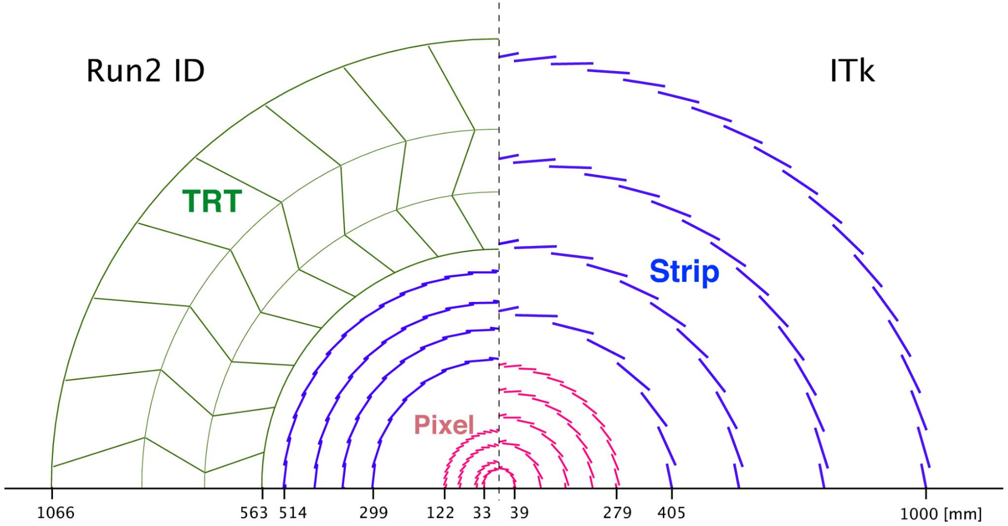
I. The SM and Higgs boson

II. The ITk strips detector

III. Future prospects

Comparison to Run 2 tracker

- How does ITk compare to current tracker?
- All silicon tracker
- Extend pseudorapidity range from $|\eta| = \pm 2.5$ to $|\eta| = \pm 4$!



ATL-PHYS-PUB-2018-033

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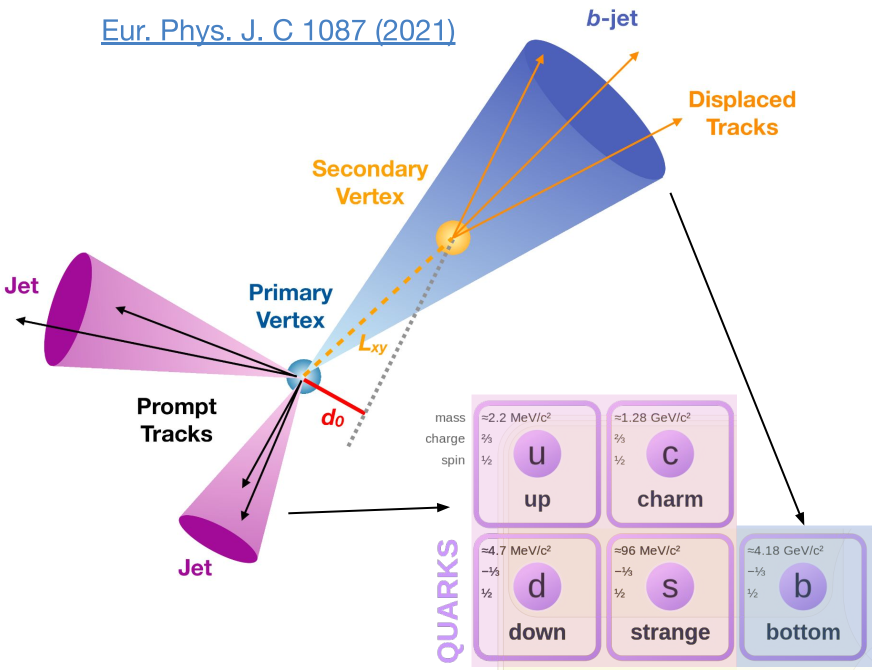
Review: Bottom quarks

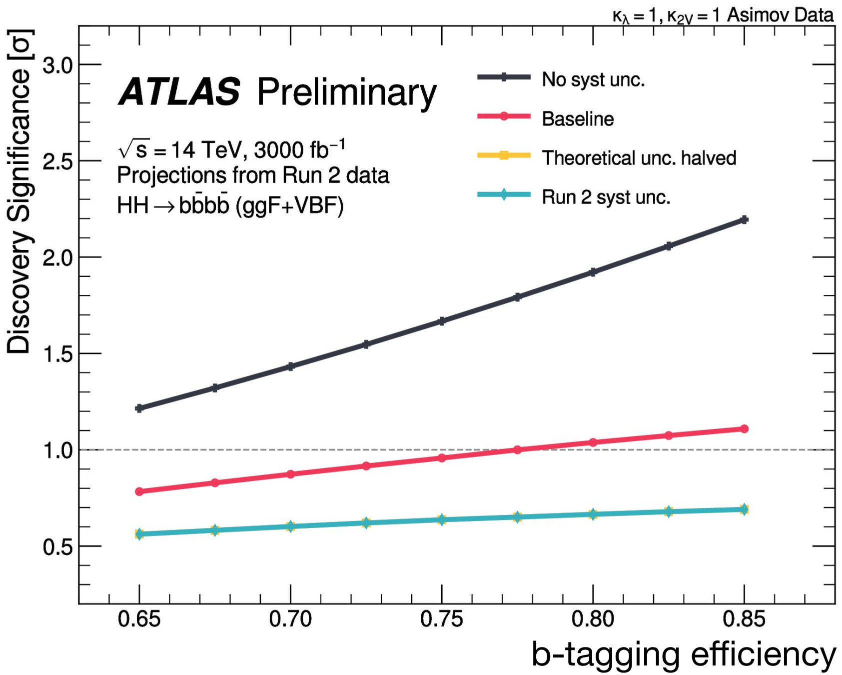
- The **bottom** (or **beauty**) quark: Relatively **heavy**
- Propagates before hadronization: **b-jet**
- **Distinctly different** signature! Can use to differentiate from **“lighter”** jets

Eur. Phys. J. C 1087 (2021)



Projected HH→bbbb

- **Why did we do all of this work to upgrade the tracker?**
- Projected significance of HH→bbbb channel **as function of b-tagging efficiency**
- If we can improve b-tagging, combine with other H(bb) channels, can increase HH discovery chances
- **<u>This depends on a robust ITk!</u>**



ATL-PHYS-PUB-2023-023

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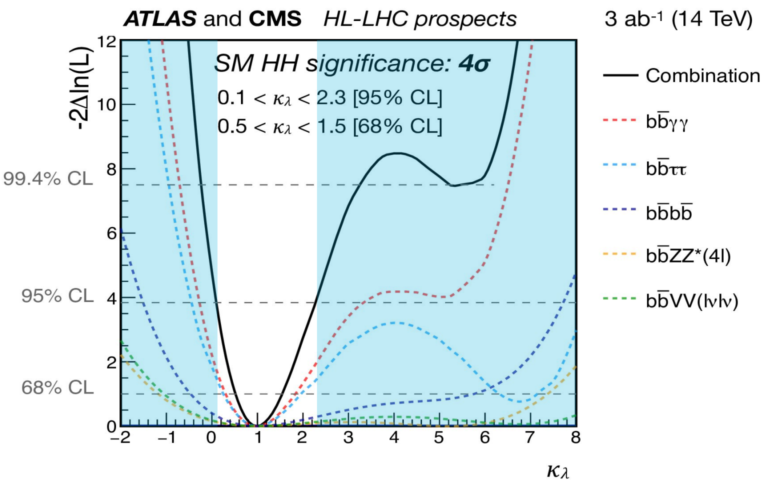
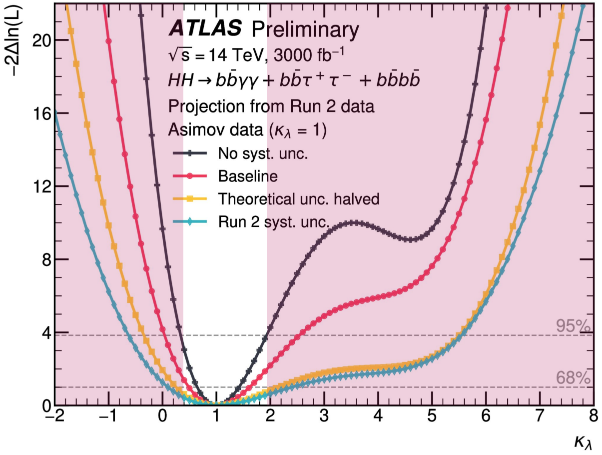
Projected HH combination

- And if we combine HH channels with b-quarks? (All rely on an excellent detector!)



CERN-2019-007



ATL-PHYS-PUB-2022-053

European Strategy (2018)

- Combination of 5 HH channels, many based on partial Run 2 analysis strategy
- 50% precision on self-coupling
- **4σ SM HH significance** (ATLAS+CMS)

Recent ATLAS update (2022)

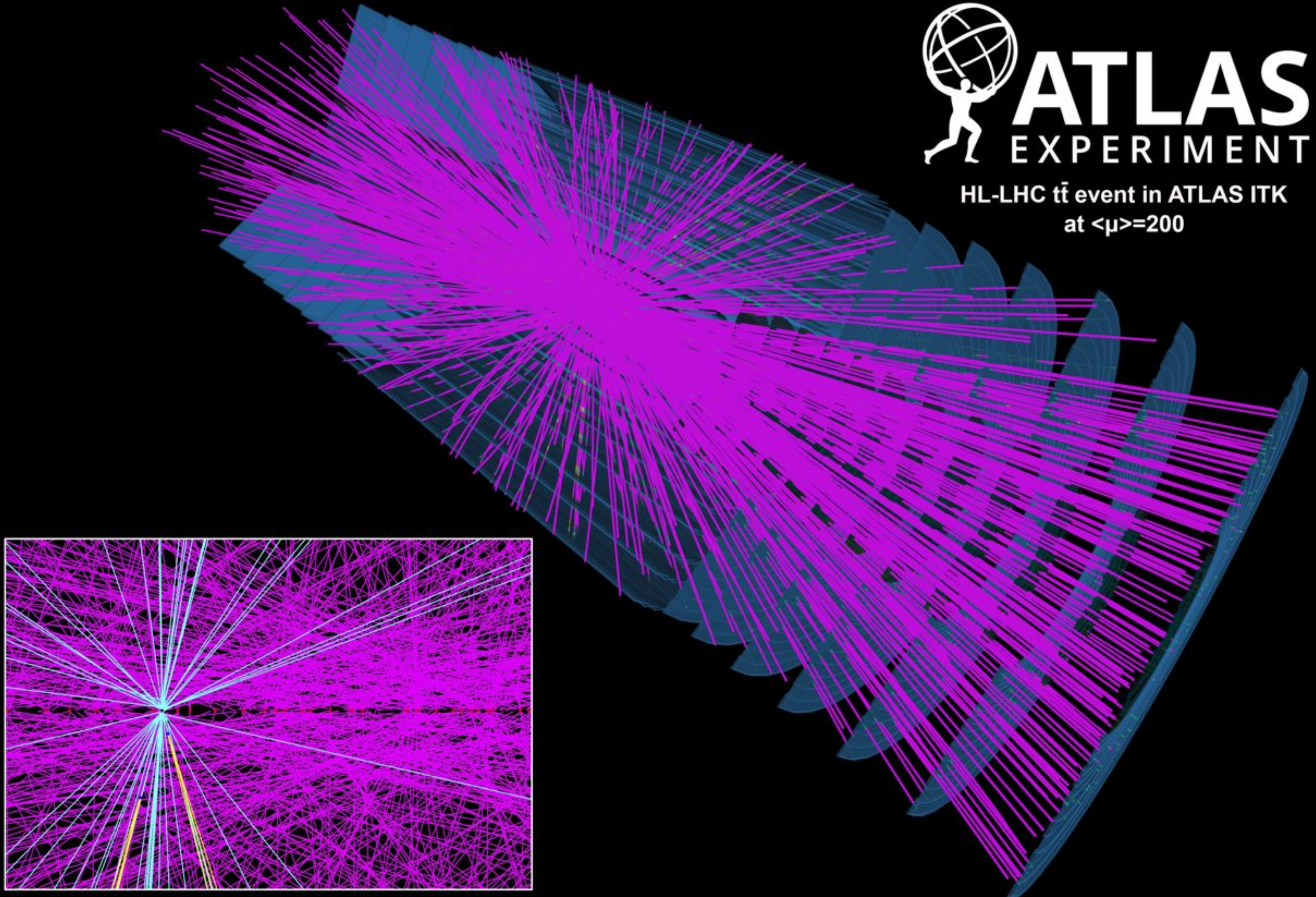
- 50% precision on the self-coupling with just ATLAS!
- Assuming Run 2-level b-tagging

Summary

Summary

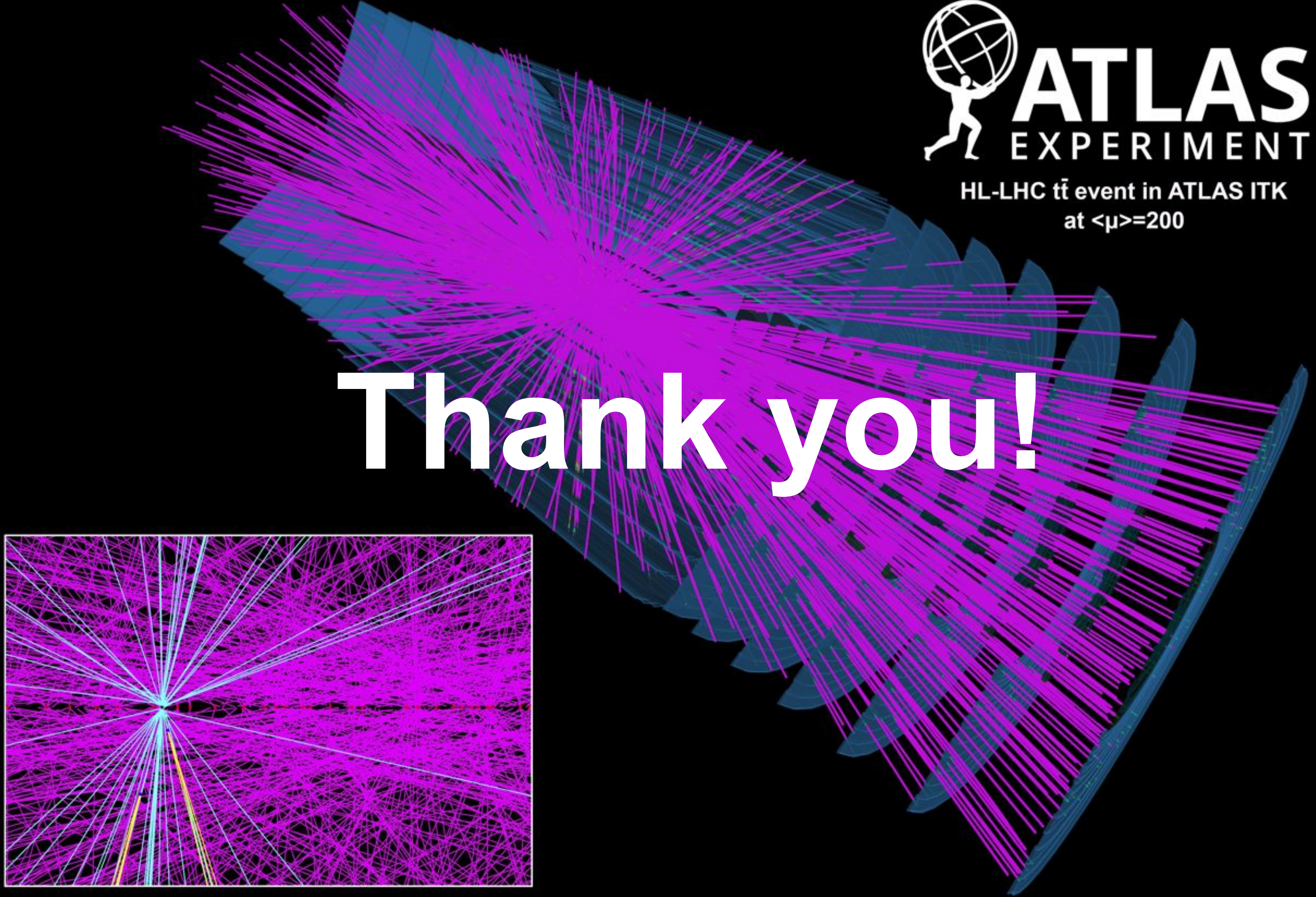
- Since Higgs discovery, extensive studies to **characterize it** - as part of **large ATLAS physics program**
- These studies will greatly benefit from increased dataset at **HL-LHC**
- This will require a **robust, performant detector** that can succeed in a **challenging data-taking environment**
- ITk project ongoing, will be part of **ATLAS at HL-LHC**. Examples shown for **ITk strips**:
  - Well-defined **Quality Control program defined**
  - Excellent **test setups** required to ensure **QC of ITk components**
  - **Extreme reliability tests** also performed to assess **headroom**, including **extreme thermal cycling.** 3 modules cycled **101 times**, still **work** afterwards
- The more **robust** the **ITk**, the **better the chance** of HH discovery at HL-LHC
  - Will give us better b-tagging, object reconstruction in general
  - Expect improvement in all physics analyses from increased dataset

ATLAS EXPERIMENT



HL-LHC $t\bar{t}$ event in ATLAS ITK at $\langle\mu\rangle=200$

Thank you!



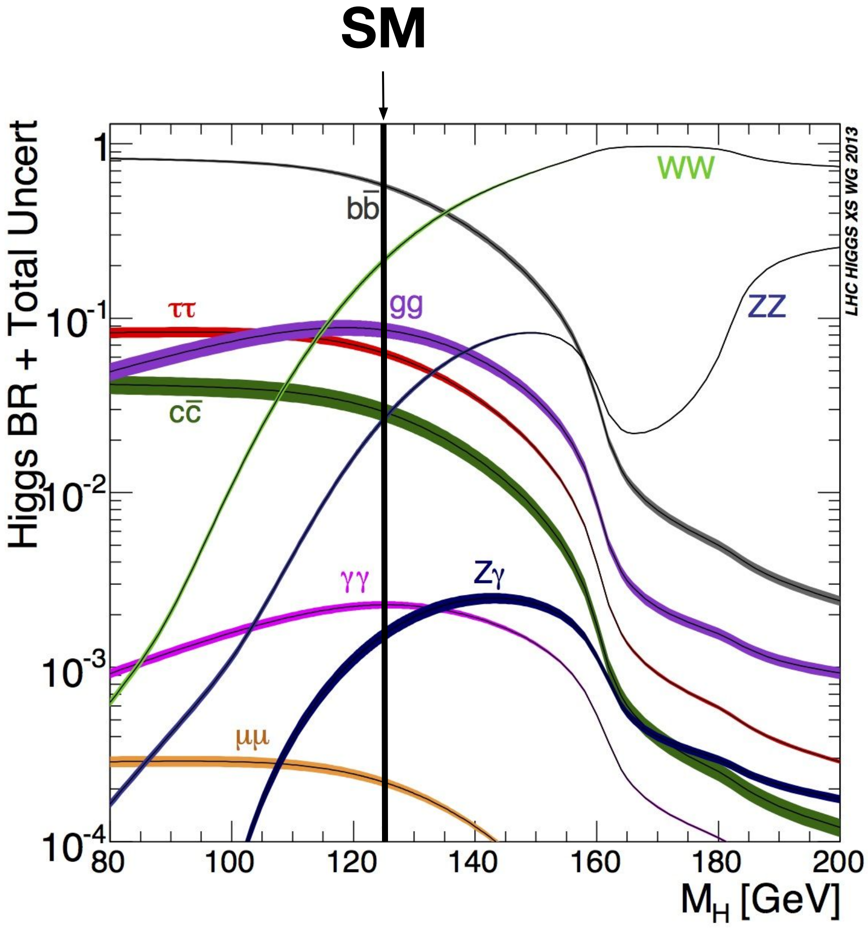
HL-LHC $t\bar{t}$ event in ATLAS ITK at $\langle\mu\rangle=200$

Backup

Theoretical basis

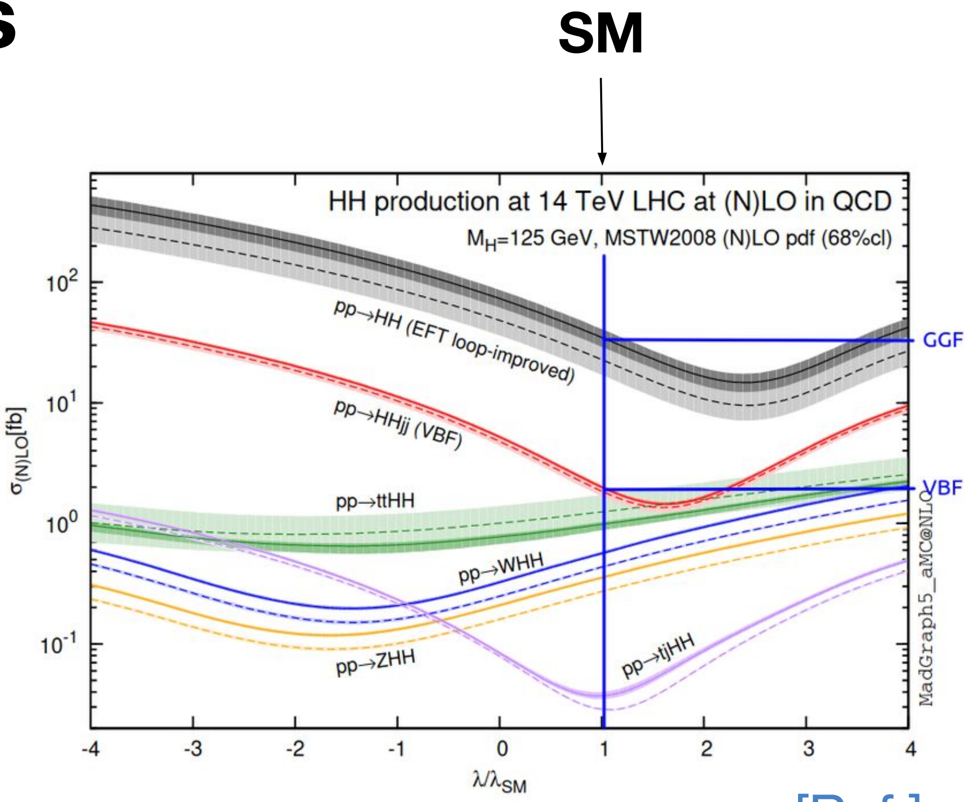
Higgs decays

- Higgs decays as function of mass:



HH cross-sections

- HH cross-sections a function of kl
- GF, VBF leading
- ttHH close to VBF, but much smaller than GF

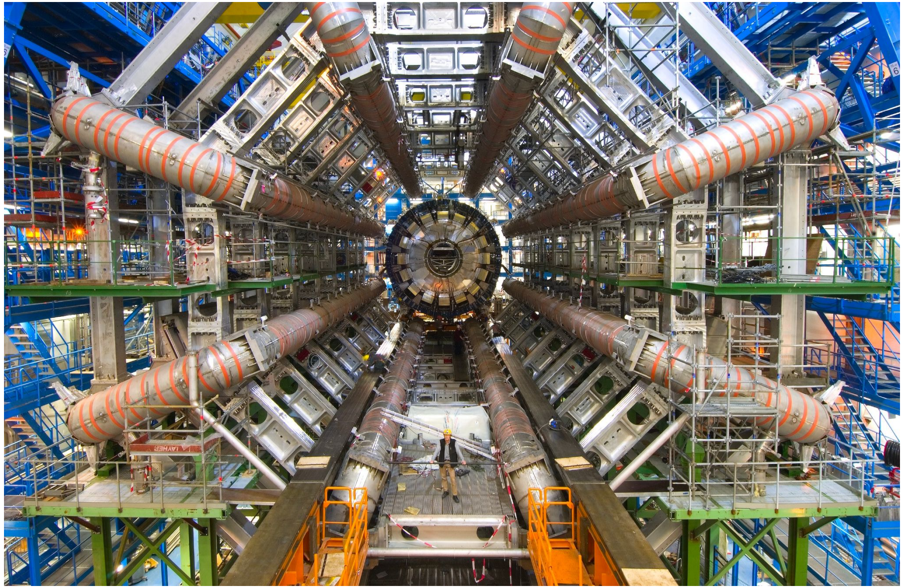


[Ref.]

LHC and ATLAS

ATLAS

- ATLAS detector
- One of two **general purpose** LHC detectors
- Rich physics program:
  - **Higgs**, Dark matter, Electroweak, Supersymmetry, …

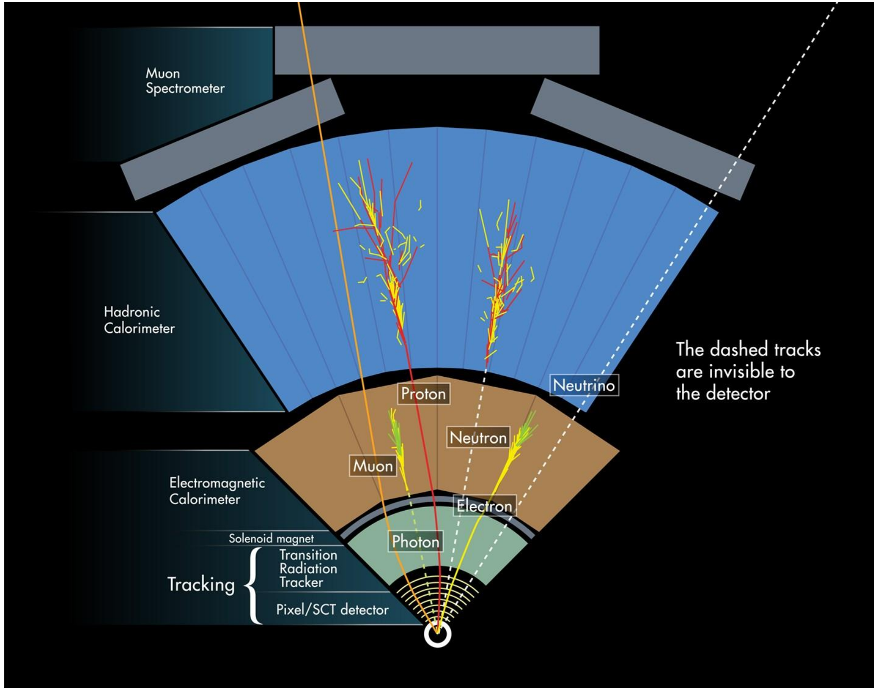


ATLAS

- Different **layers** detect different **particles** (needed for different final states!)

- Requires use of different detector **technologies**

- **Reconstruct** underlying physics **event** by working backwards from detector information



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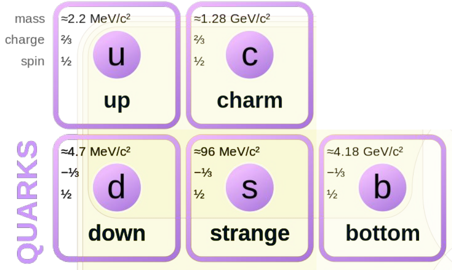
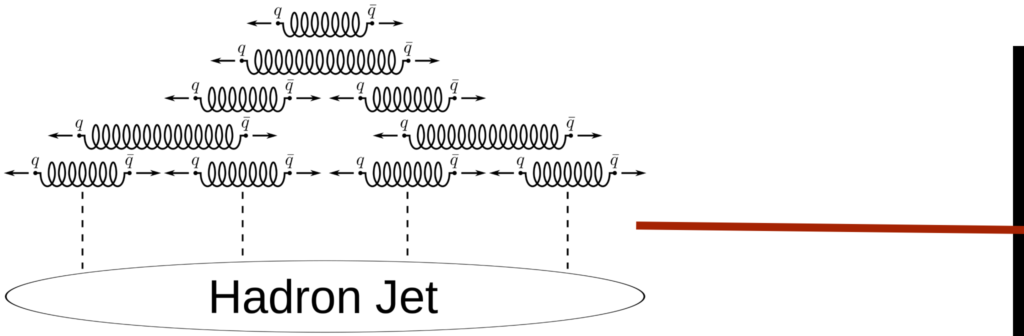
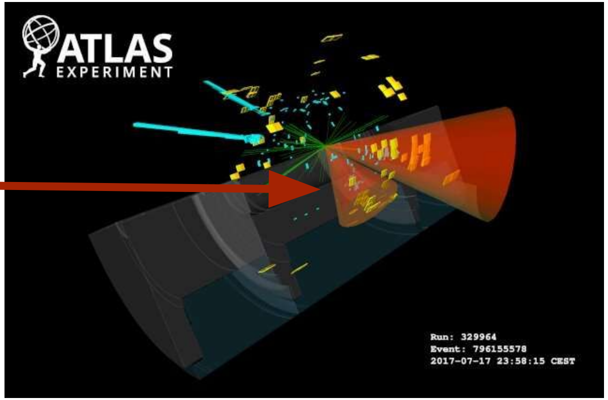
Review: Hadronization

- **Reminder:** In SM, **quarks cannot exist freely.** Must bind with other quarks
- When produced from Higgs decays, quarks separate and form **new pairs**, repeats







ITk

Module, stave distribution

- Barrel strip distributions among LS / SS:

Table 6. Dimensions and component counts for the ITk Barrel Strip Detector.

	Layer	Radius	Strip pitch × length	Staves	Modules	Hybrids	Channels	Sensor area
Short strip	L0	405 mm	75.5 µm × 24.16 mm	56	1,568	3,136	8.0M	15.0 m^2
	L1	562 mm	75.5 µm × 24.16 mm	80	2,240	4,480	11.5M	21.4 m^2
Long strip	L2	762 mm	75.5 µm × 48.35 mm	112	3,136	3,136	8.0M	30.0 m^2
	L3	1000 mm	75.5 µm × 48.35 mm	144	4,032	4,032	10.3M	38.6 m^2
	Total			392	10,976	14,784	37.8M	105.0 m^2

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ITk components

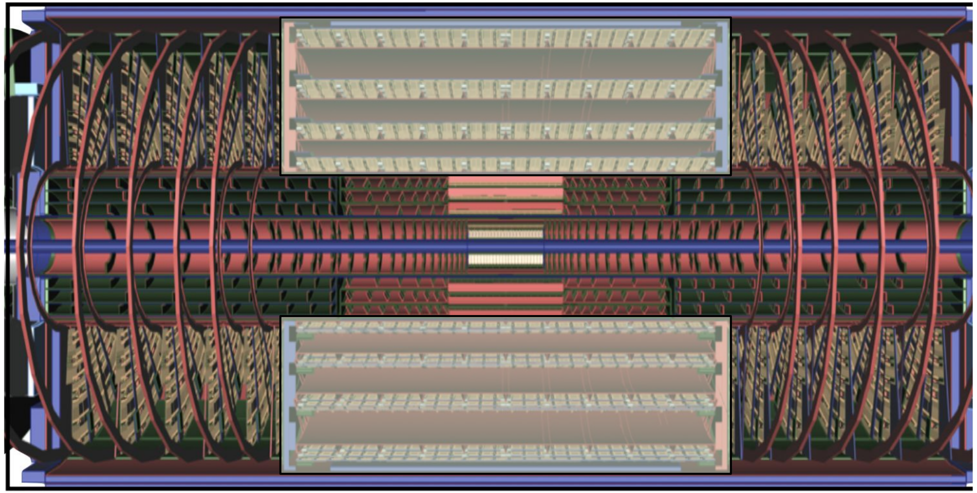
Table 5.1: Number of components for the ITk Strip Detector in barrel (top half) and end-cap (bottom half). The numbers for the barrel are for the full barrel with 2.8 m length. The numbers for the end-caps (EC) are given both for one and both end-caps.

Barrel Layer:	**Radius [mm]**	**# of staves**	**# of modules**	**# of hybrids**	**# of of ABCStar**	**# of channels**	**Area [m^2]**
L0	405	28	784	1568	15680	4.01M	7.49
L1	562	40	1120	2240	22400	5.73M	10.7
L2	762	56	1568	1568	15680	4.01M	14.98
L3	1000	72	2016	2016	20160	5.16M	19.26
Total half barrel		196	5488	7392	73920	18.92M	52.43
Total barrel		392	10976	14784	147840	37.85M	104.86
End-cap Disk:	**z-pos. [mm]**	**# of petals**	**# of modules**	**# of hybrids**	**# of of ABCStar**	**# of channels**	**Area [m^2]**
D0	1512	32	576	832	6336	1.62M	5.03
D1	1702	32	576	832	6336	1.62M	5.03
D2	1952	32	576	832	6336	1.62M	5.03
D3	2252	32	576	832	6336	1.62M	5.03
D4	2602	32	576	832	6336	1.62M	5.03
D5	3000	32	576	832	6336	1.62M	5.03
Total one EC		192	3456	4992	43008	11.01M	30.2
Total ECs		384	6912	9984	86016	22.02M	60.4
Total		**776**	**17888**	**24768**	**233856**	**59.87M**	**165.25**

ATLAS-TDR-025

The ATLAS ITk Layout

- Part of ATLAS **upgrade**: Replacement of tracker with **full silicon pixel** and **strip** subdetectors - **ITk** (Inner Tracker):



ITk strips barrel

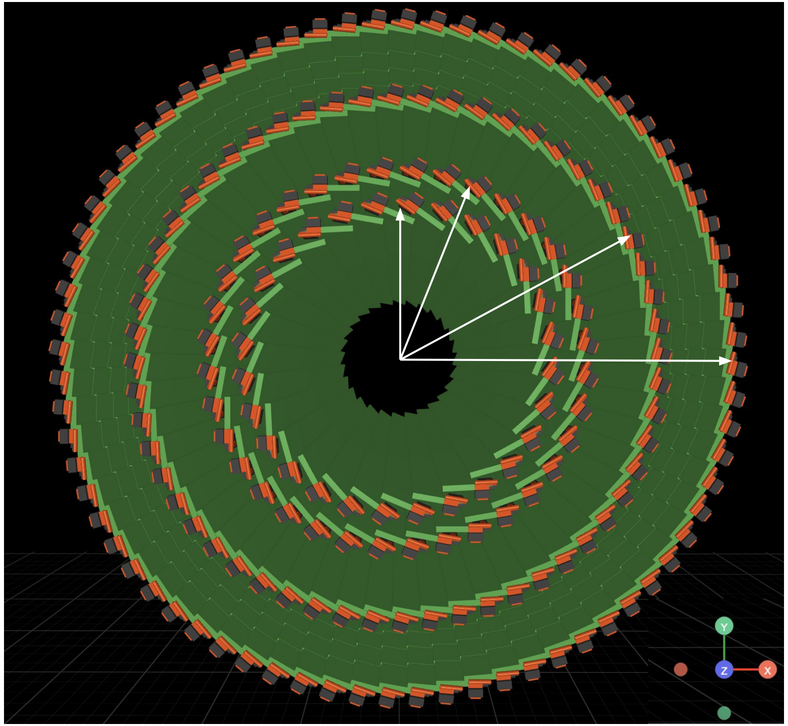
- Will contain 10,976 **modules** (individual detection unit)
- Need to build **robust** modules to last ~**10 years**!

Strips barrel layout

- The ITk strips barrel will be made of **four layers**
- Inner two layers: **Higher granularity sensors**
- Outer two layers: **Lower granularity sensors**

ATLAS-TDR-025

Layer	Radius [mm]	Channels in ϕ	Strip Pitch [μm]	Strip Length [mm]
0	405	28$\times$1280	75.5	24.1
1	562	40$\times$1280	75.5	24.1
2	762	56$\times$1280	75.5	48.2
3	1000	72$\times$1280	75.5	48.2



Cooling setup

- Cooling setup diagrams from [Punit Sharma]()

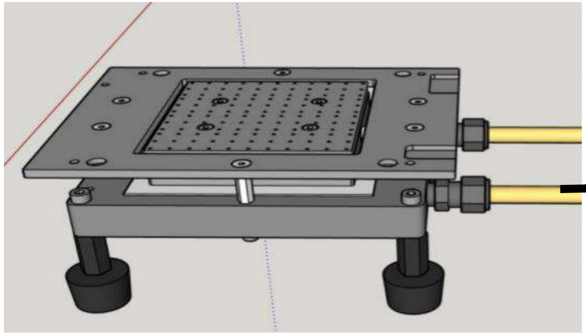


Fig: Drawing of the cooling setup on which modules are held.

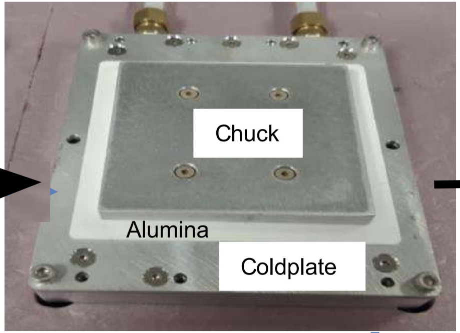


Fig: Image of a cooling setup

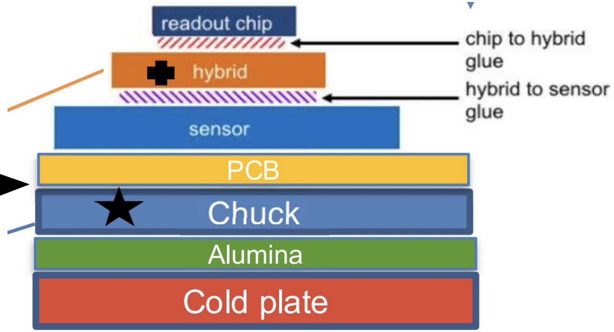


Fig: Drawing of the cooling setup with a module on top

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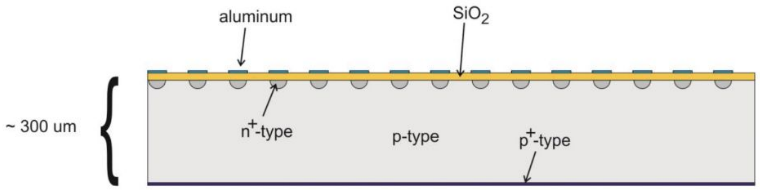
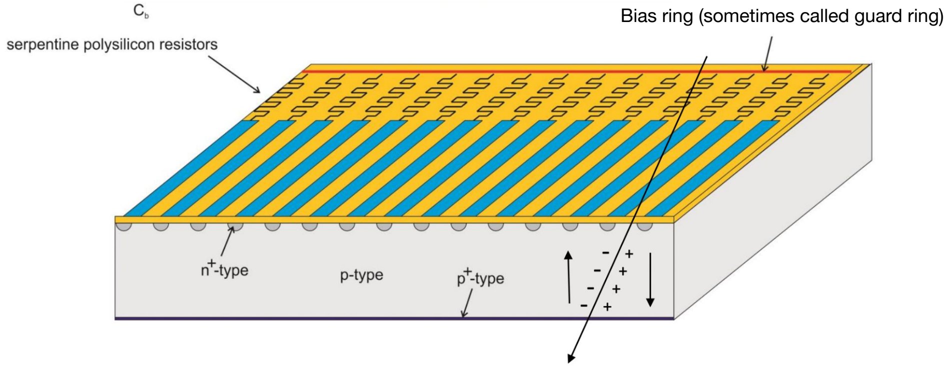
Strip detector sensor

- Example strip detector sensor components
  - (ITk strips barrel sensor thickness is 320 um)

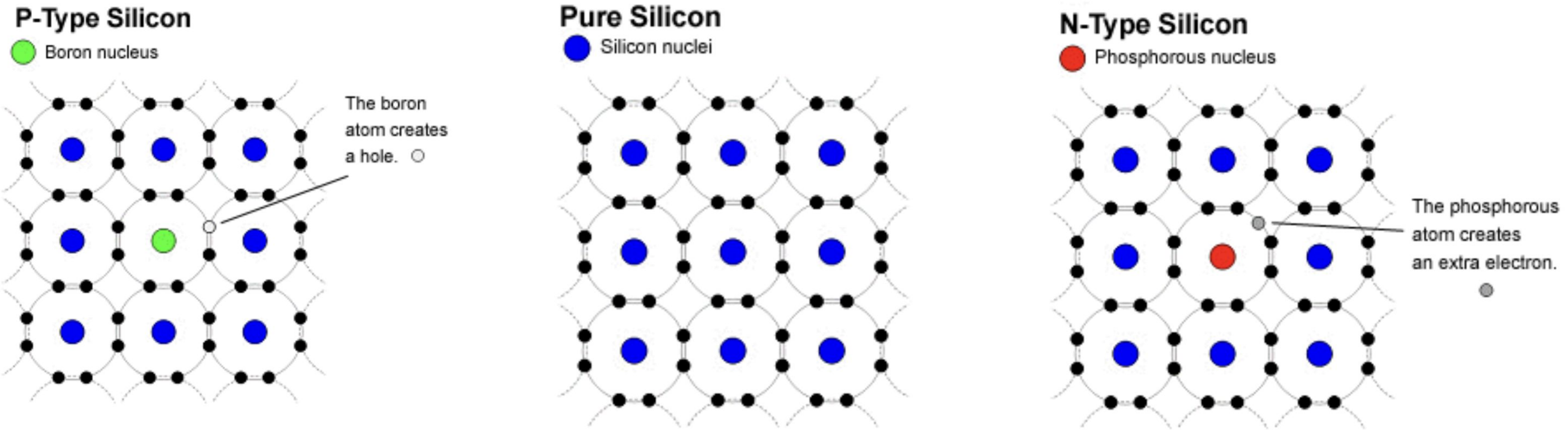
- Active area (depleted region after biasing) ionized by charged particles





Silicon doping types

From: [reference]



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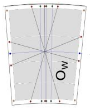
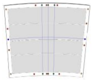
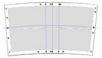
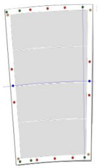
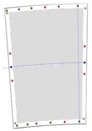
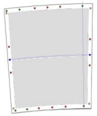
Sensor quantities

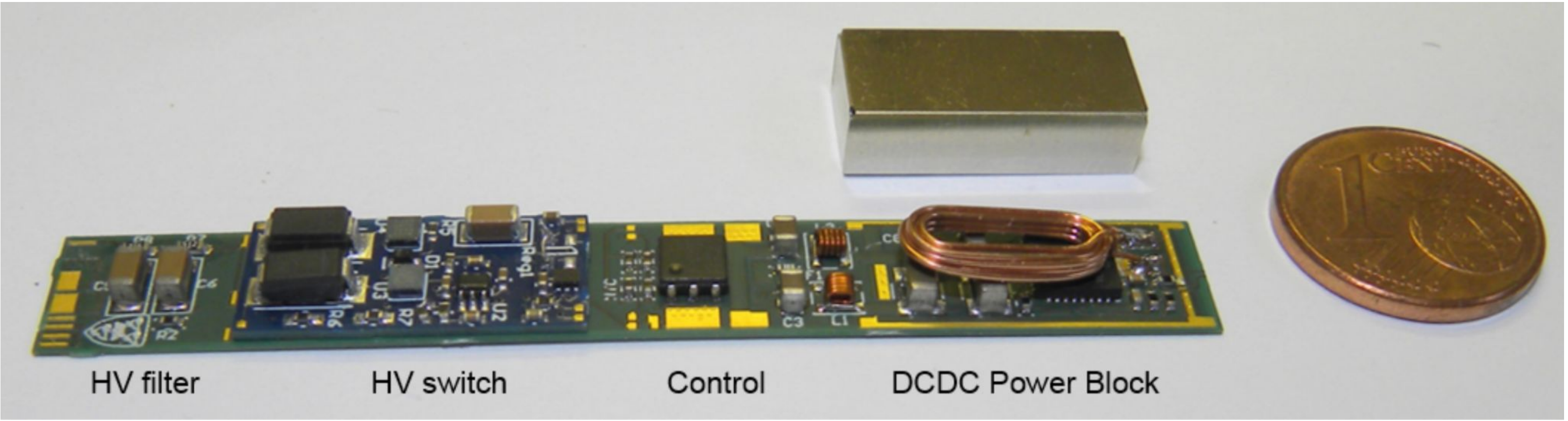
Sensor quantities from TDR

Table 6.2: Overview of the number of silicon strip sensors per required shape with number of strip rows, channels and pitch for the ITk Strip Detector.

Sensor type	Number of sensors	Shape	Number of rows	Channels per sensor	Min/max pitch (μm)
Short-strips	3808	Square	4	5128	75.5
Long-strips	7168	Square	2	2564	75.5
EC Ring 0	768		4	4360	73.5/84
EC Ring 1	768		4	5640	69/81
EC Ring 2	768		2	3076	73.5/84
EC Ring 3	1536		4	3592	70.6/83.5
EC Ring 4	1536		2	2052	73.4/83.9
EC Ring 5	1536		2	2308	74.8/83.6

Powerboards

- Image of powerboard without shield box



ATLAS-TDR-025

Module

- Diagram of a short strip module from the TDR

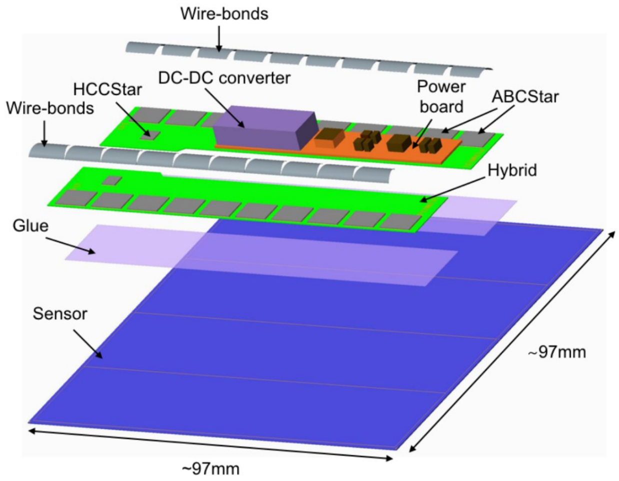


Figure 5.3: Exploded view of a short-strip barrel module with all relevant components. Long-strip modules and end-cap modules feature the same component groups.

ATLAS-TDR-025

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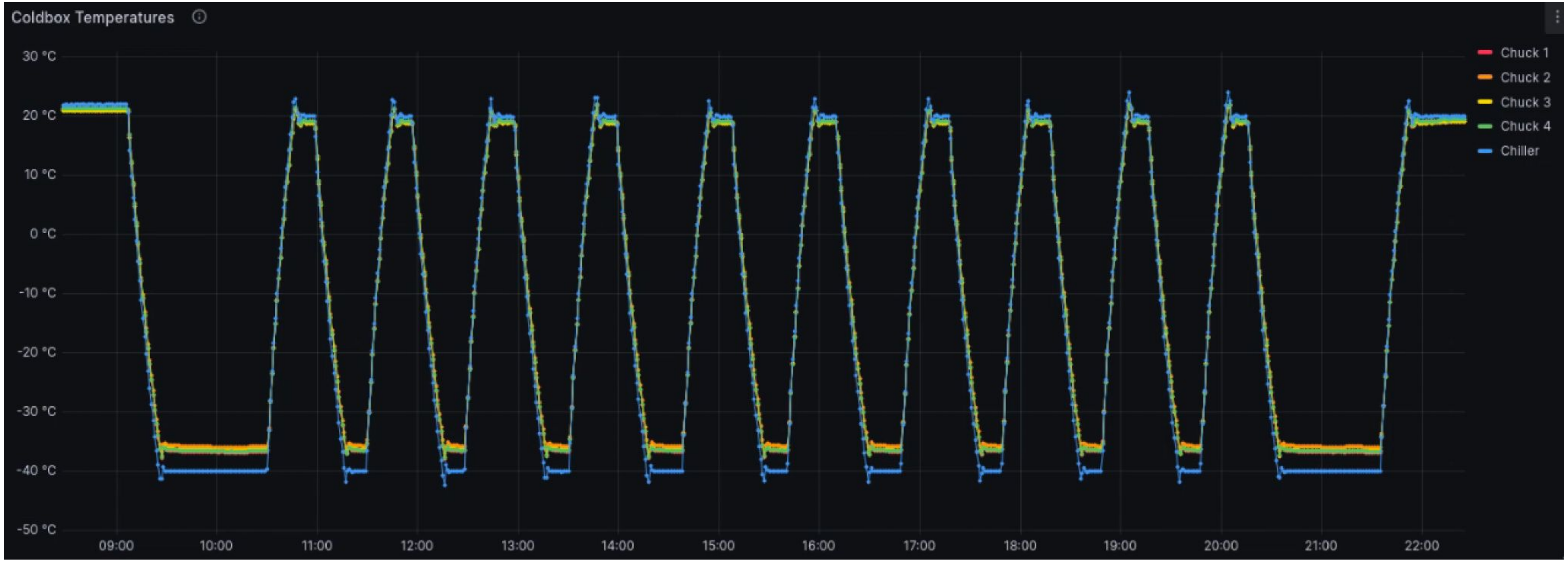
Thermal cycling example

Thermal cycling example:



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TC sequence

	Setup	Pre T/C Test		Initial cool down	Cold turn on			
Chuck Temperature	Room temperature			cool to -35℃	-35℃			
ITSDAQ Testing	PING	IV	TEST	IDLE		IV	TEST	SHUNT
HV Bias	OFF	-550V	-350V	OFF		-550V	-350V	
HYBRID Power	OFF	ON		OFF		ON		
Module LV	OFF	ON			OFF	ON		

	Thermal Cycle 1				Thermal Cycle 2				Thermal Cycle 3				Thermal Cycle 4				Thermal Cycle 5			
Chuck Temperature	heat to +20℃	+20℃	cool to -35℃	-35℃	heat to +20℃	+20℃	cool to -35℃	-35℃	heat to +20℃	+20℃	cool to -35℃	-35℃	heat to +20℃	+20℃	cool to -35℃	-35℃	heat to +20℃	+20℃	cool to -35℃	-35℃
ITSDAQ Testing	IDLE	TEST	IDLE	TEST	IDLE	TEST	IDLE	TEST	IDLE	TEST	IDLE	TEST	IDLE	TEST	IDLE	TEST	IDLE	TEST	IDLE	TEST
HV Bias	OFF	-350V	OFF	-350V	OFF	-350V	OFF	-350V	OFF	-350V	OFF	-350V	OFF	-350V	OFF	-350V	OFF	-350V	OFF	-350V
HYBRID Power	ON																			
Module LV	ON																			

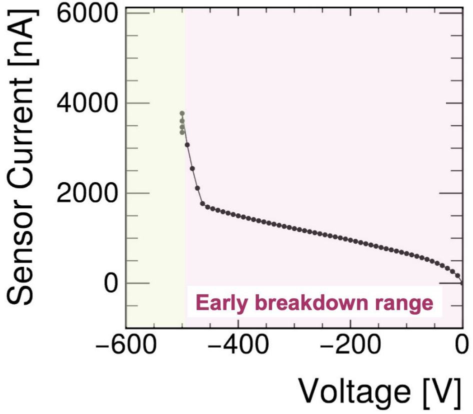
	Thermal Cycle 6				Thermal Cycle 7				Thermal Cycle 8				Thermal Cycle 9			
Chuck Temperature	heat to +20℃	+20℃	cool to -35℃	-35℃	heat to +20℃	+20℃	cool to -35℃	-35℃	heat to +20℃	+20℃	cool to -35℃	-35℃	heat to +20℃	+20℃	cool to -35℃	-35℃
ITSDAQ Testing	IDLE	TEST	IDLE	TEST	IDLE	TEST	IDLE	TEST	IDLE	TEST	IDLE	TEST	IDLE	TEST	IDLE	TEST
HV Bias	OFF	-350V	OFF	-350V	OFF	-350V	OFF	-350V	OFF	-350V	OFF	-350V	OFF	-350V	OFF	-350V
HYBRID Power	ON															
Module LV	ON															

	Thermal Cycle 10						Warm-up	Post T/C Module Test & HV stabilisation				Warm-up	End of Module QC
Chuck Temperature	heat to +20℃	+20℃	cool to -35℃	-35℃			heat to +20℃	+20℃				heat to +22℃	+22℃
ITSDAQ Testing	IDLE	TEST	IDLE	IV	SHUNT	TEST	IDLE	TEST	HV stabilisation		IV	IDLE	
HV Bias	OFF	-350V	OFF	-550V	-350V		OFF	-350V			-550V	OFF	
HYBRID Power	ON												OFF
Module LV	ON												OFF

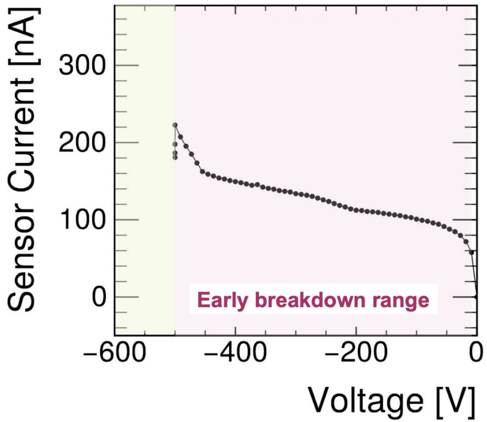
Extreme TC: IV

- IV curves measured **after** 101 thermal cycles:

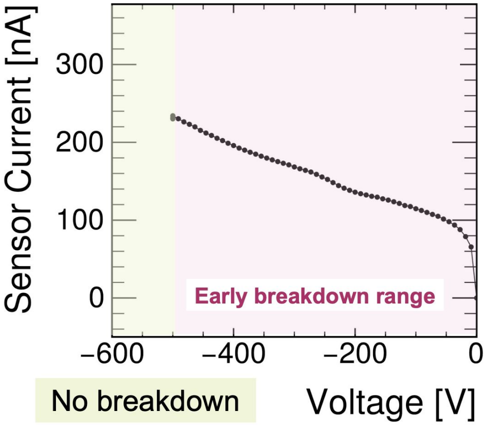
Module 1



Module 2



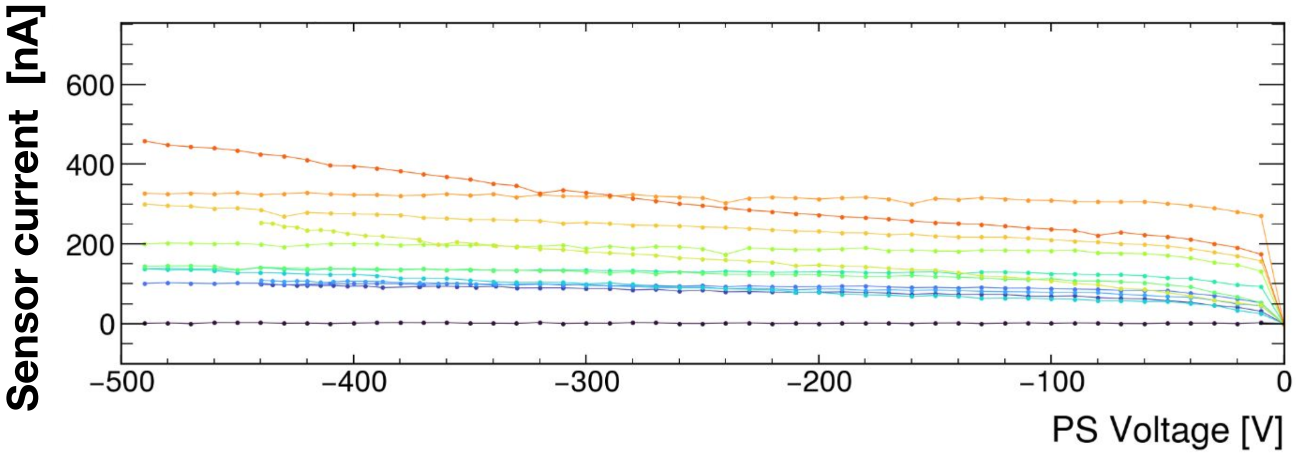
Module 3



- Nominal QC: Require **no breakdown** above **-500V**
- Two sensor current begin to increase before reaching -500V, but have **large operational region**.

Stave IV

- Can take IV of **all modules simultaneously**

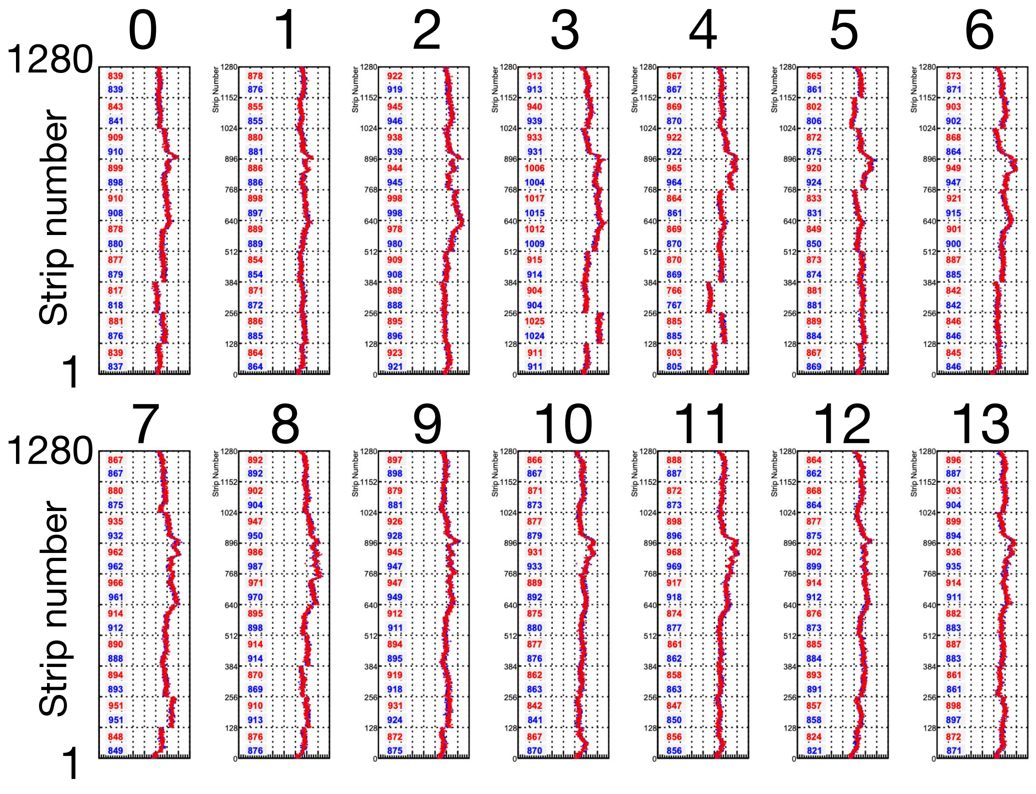


- In this case, **no modules in breakdown**
- Varied current magnitudes among modules, partially expected from **light leakage**

Stave TC

- Also plan to **thermal cycle** staves a number of times (number undefined, at least **once**)
- Will compare noise **before** and **after** thermal cycling, just like for module TC
- In this example, TCd stave to inlet/outlet avg. temperature = -35°C **5 times**
- Noise looks **very similar** before/after

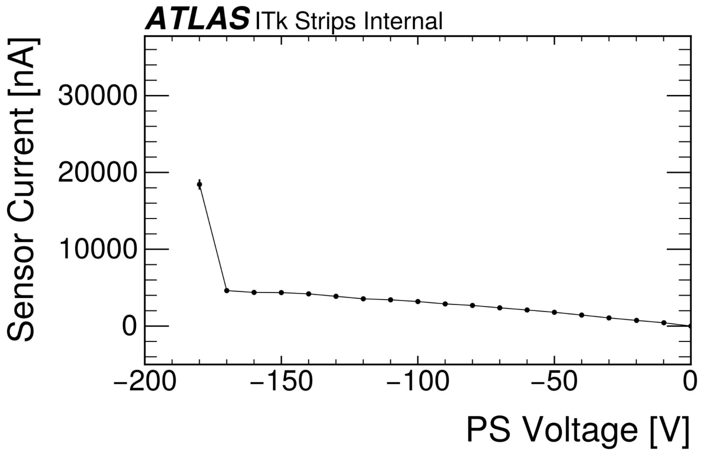
Module Number:

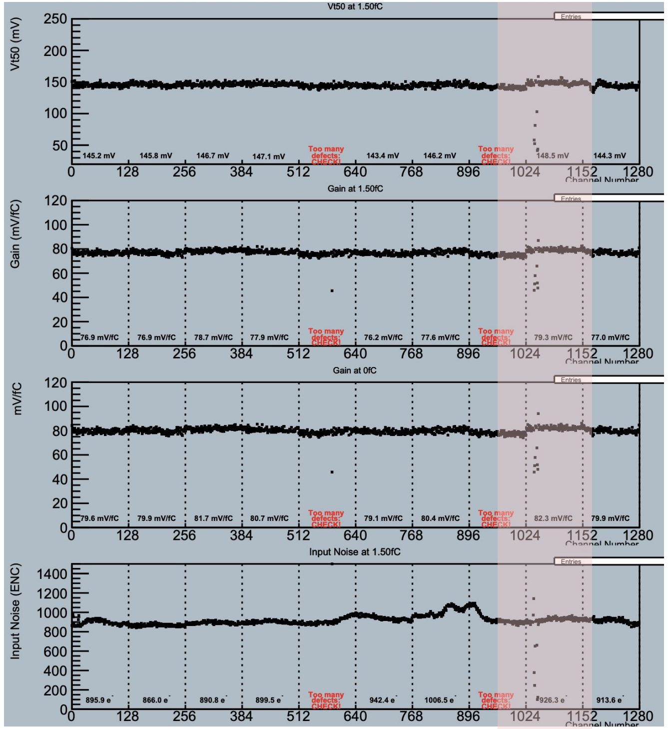


Noise [ENC] xmin/max of each: **300/1100**

Production status

- Electrical test results of suspected cracked module





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