Time and Space Measurements with Silicon Detectors

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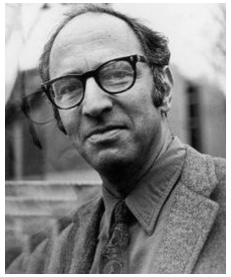
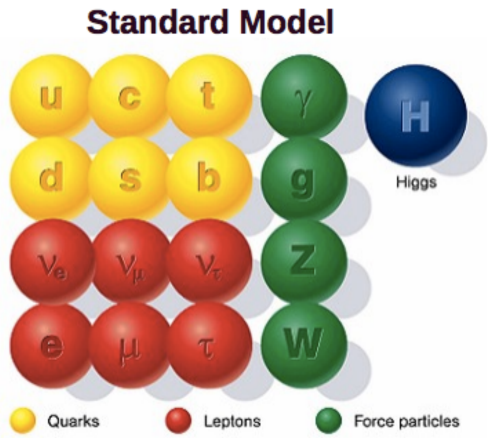
Guidance towards the Next Revolution

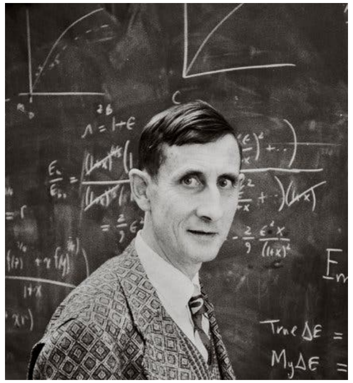
"[Science is] a series of peaceful interludes punctuated by intellectually violent revolutions"
T. Khun, "The Structure of Scientific Revolutions", 1962



- HEP is in an interlude period, awaiting for the next revolution
- The Higgs boson discovery consolidated the Standard Model (SM) paradigm
- So far direct searches of new physics beyond the SM have failed to bring the next revolution in HEP, but several *anomalies* have appeared
- Cross fertilization between different fields: intensity frontier, cosmic frontier, nuclear physics, etc.
- Theory cannot provide concrete directions on the energy scale at which the SM breaks down
  - ➔New experimental results will provide necessary guidance

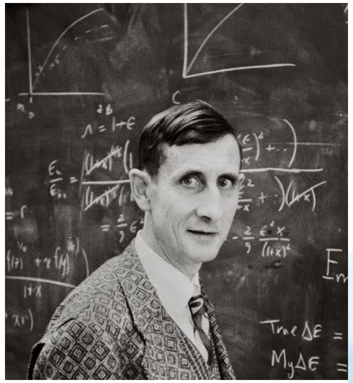


Experimental Guidance



"New directions in science are launched by new tools much more often than by new concepts"
Freeman Dyson

Experimental Guidance



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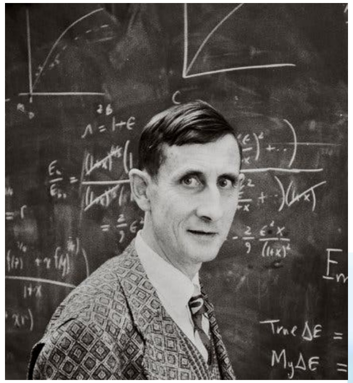
Experimental Guidance

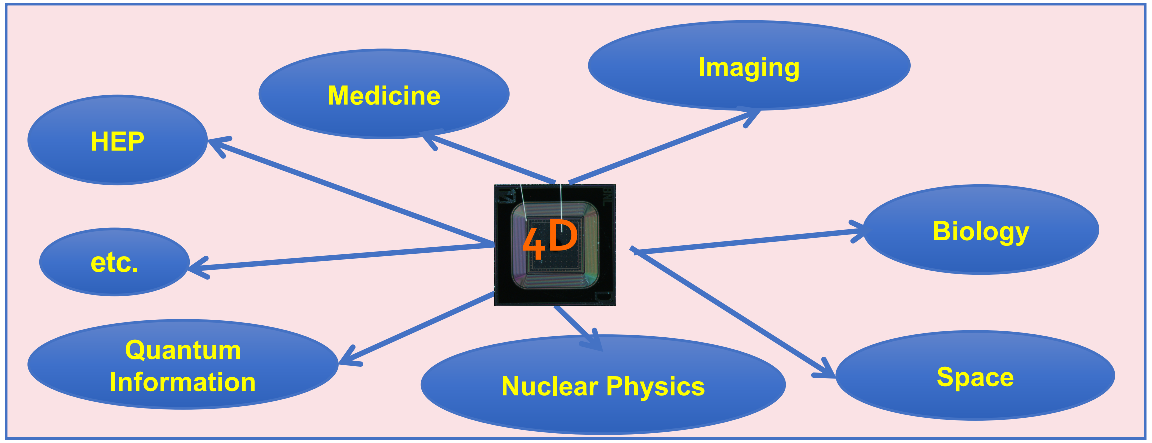


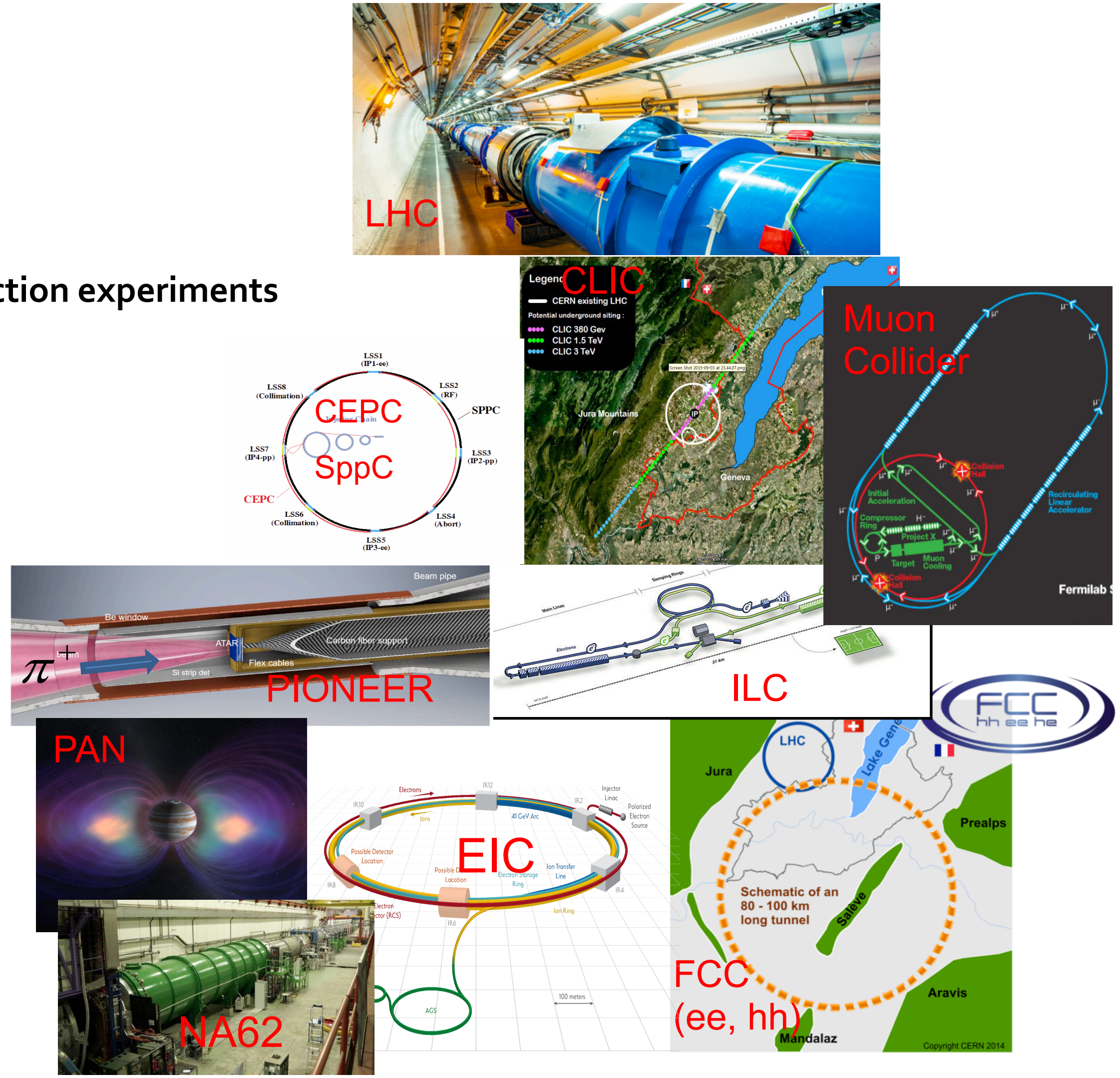
"New directions in science are launched by new tools much more often than by new concepts"
Freeman Dyson

- New methodologies and technologies are critical
- HEP experiments are no longer table-top, preparation for the next generation of experiments must start decades ahead of time
  - A long term vision and planning is critical
- Impact of novel technologies extends beyond HEP

Need for Time & Space (4D) detectors

- Particle Tracking at **collider experiments**
- Pileup mitigation at **hadron colliders**
- Forward proton tagging at **hadron colliders** and **EIC**
- Particle identification at **e+e- colliders, nuclear physics** and **rare process detection experiments**
- Beam background mitigation at **muon collider**
- **Beam monitoring** at colliders
- **Space** applications, **Photons science, QIS, Biology etc.**

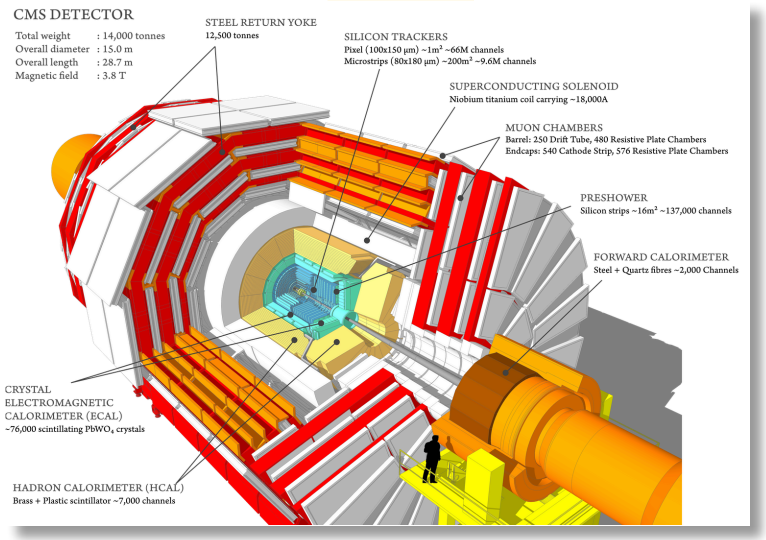




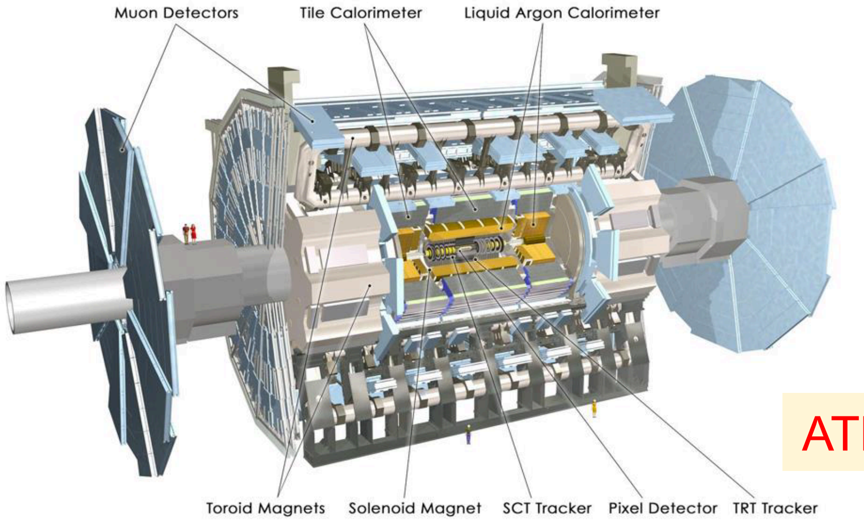
Silicon Trackers (ATLAS, CMS,…)

Large Hadron Collider

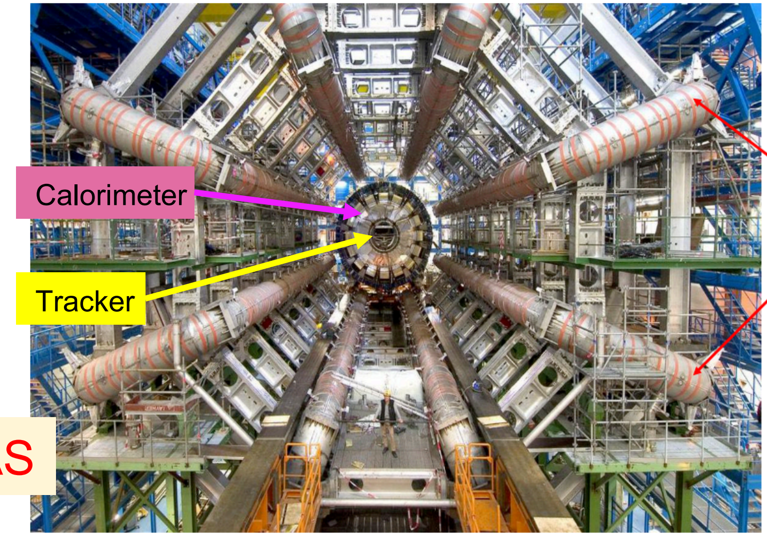
CMS



Pixel and Strip Silicon sensors are key components of **Tracking Systems** in modern particle detectors and at the LHC

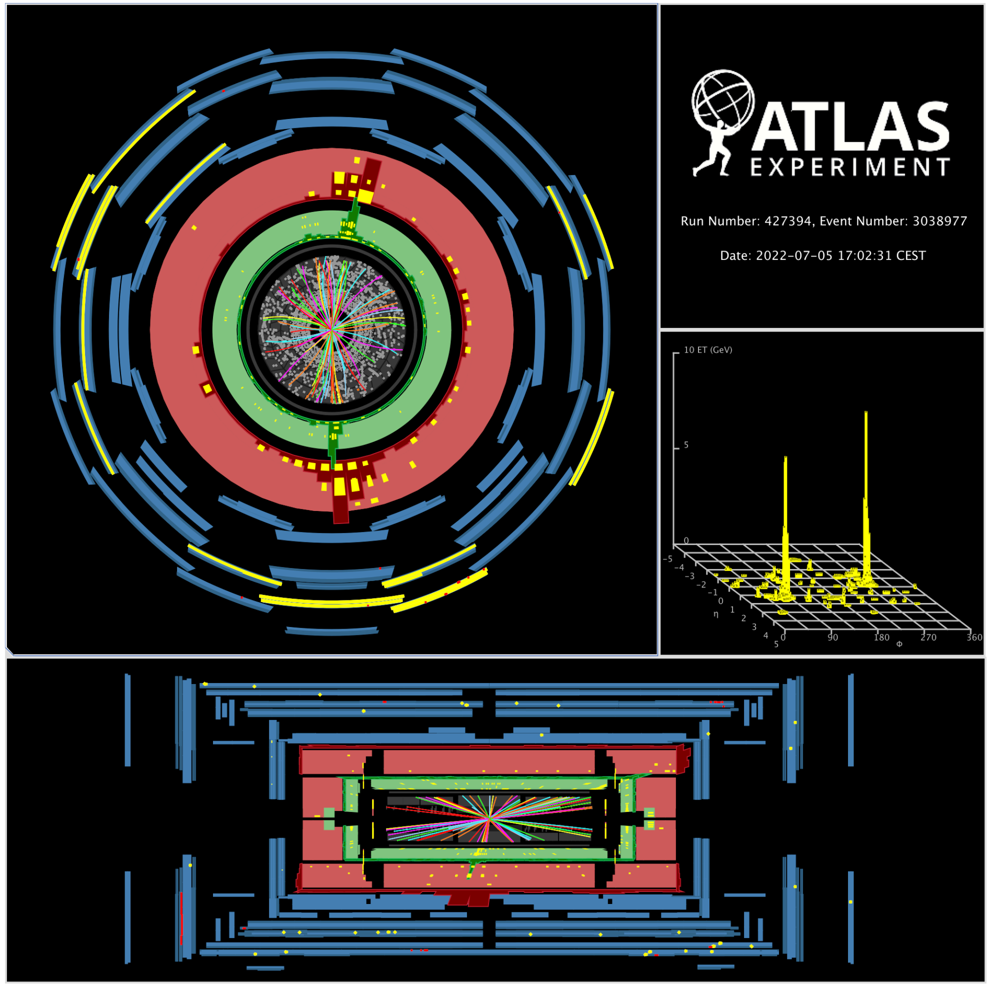


ATLAS

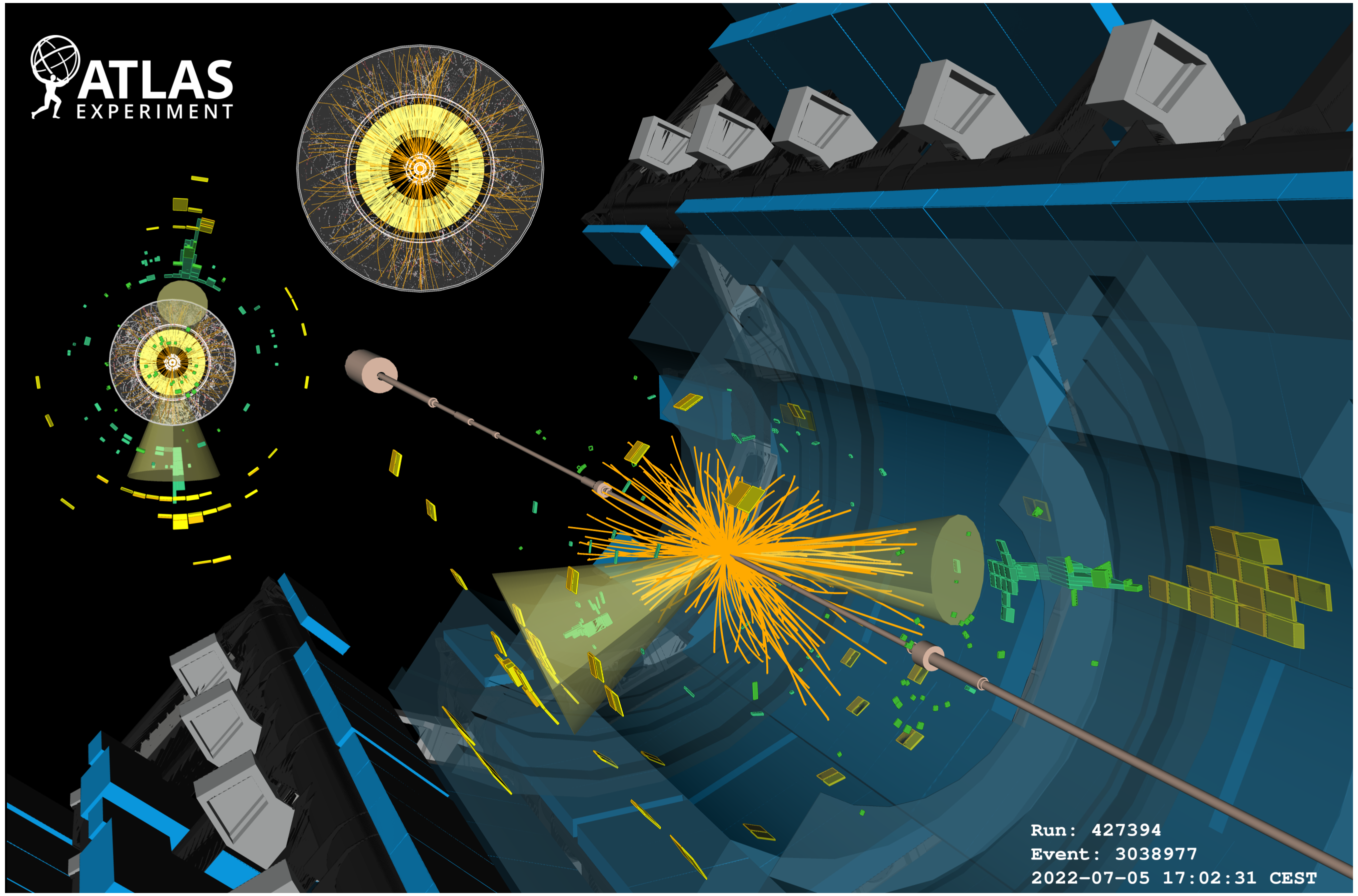


Toroid magnets

ATLAS Data in Run-3

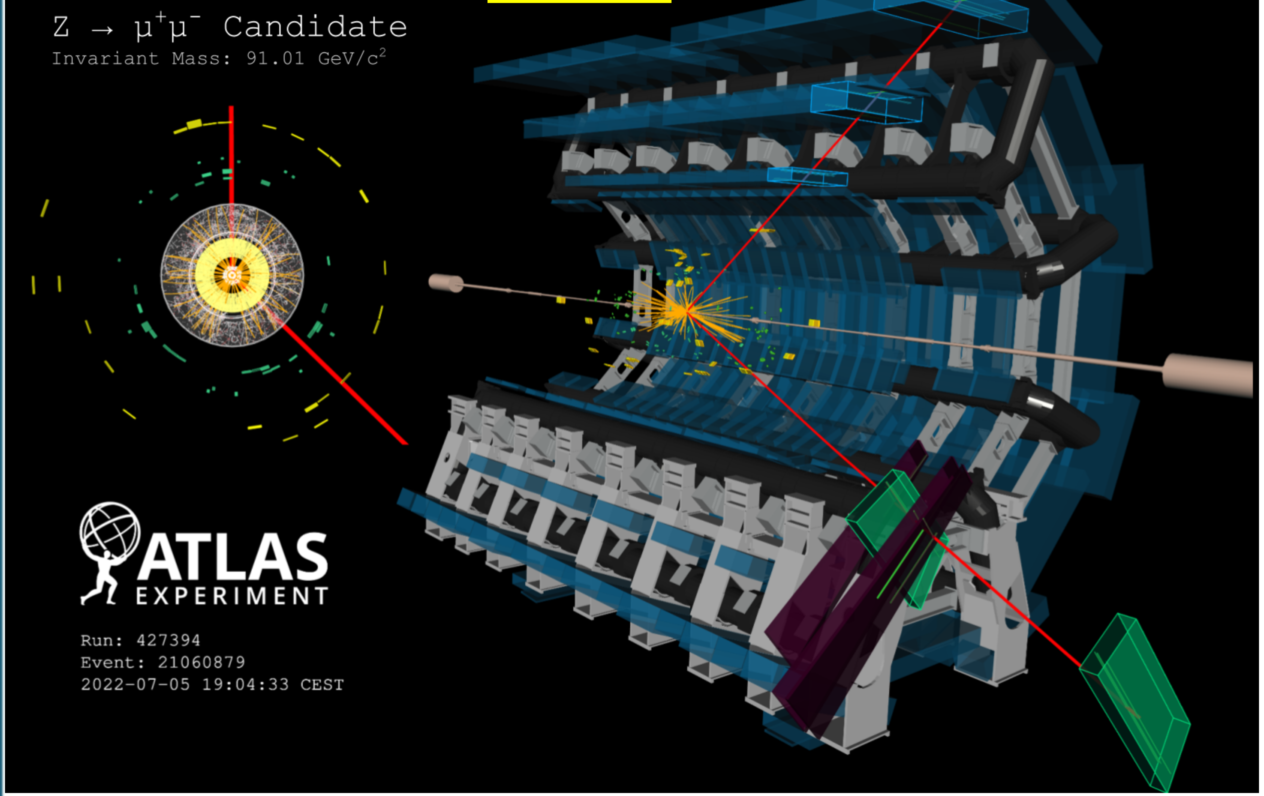


Particle reconstruction from tracks in Run-3 data

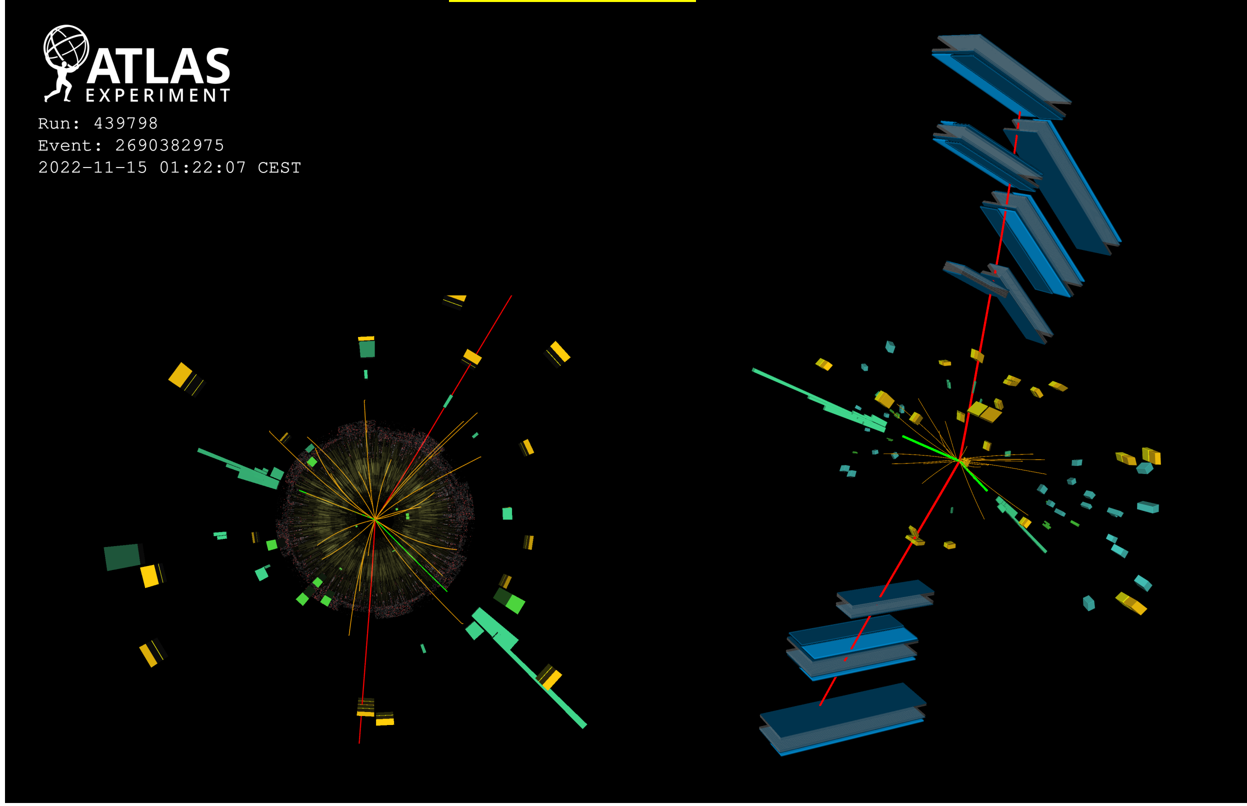


ATLAS Data in Run-3

Z→μμ



H→2e2μ



Particle reconstruction from tracks in Run-3 data

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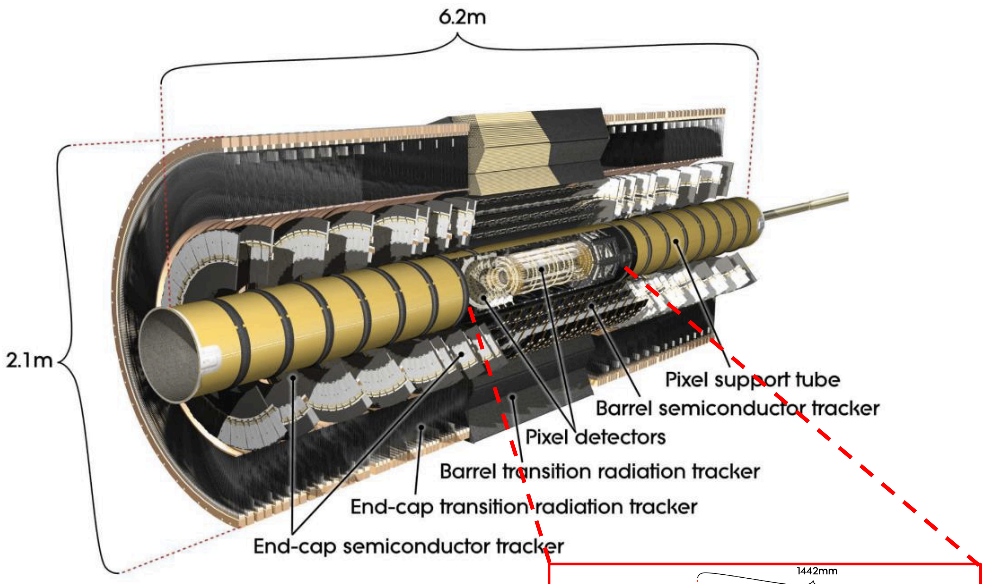
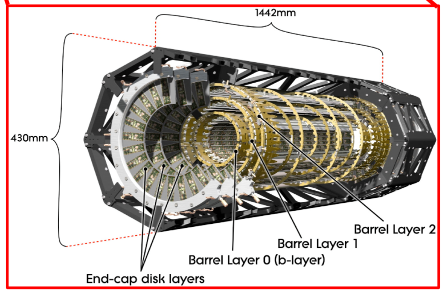
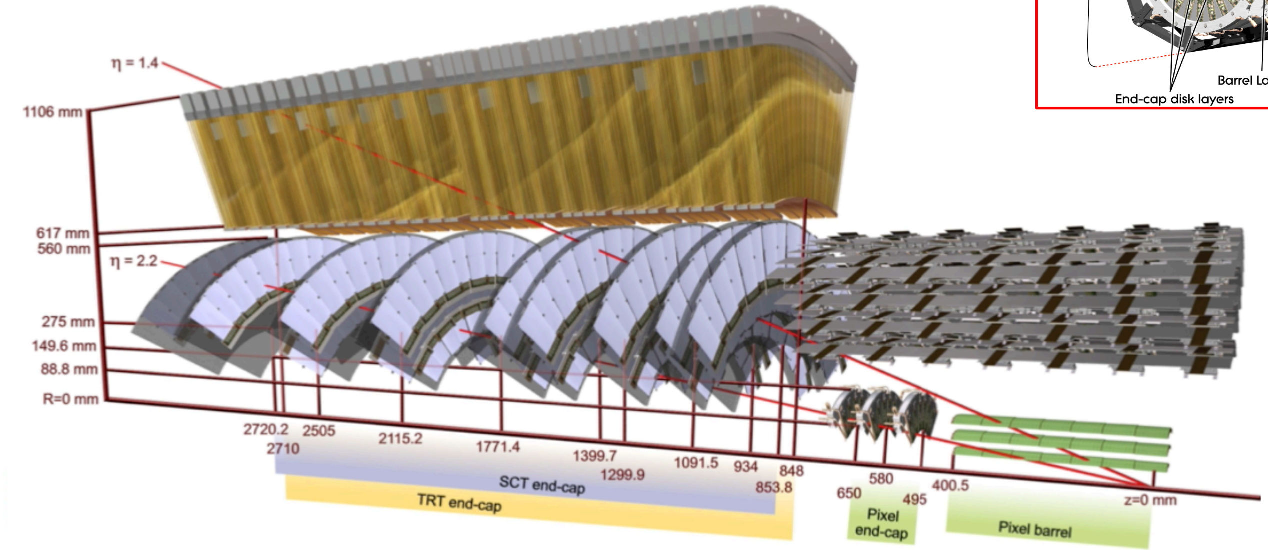
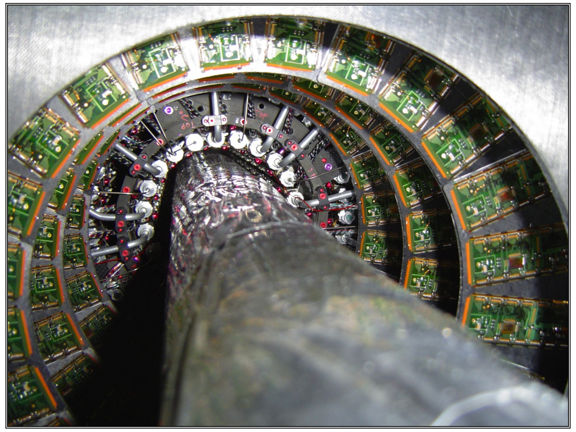
ATLAS Tracker

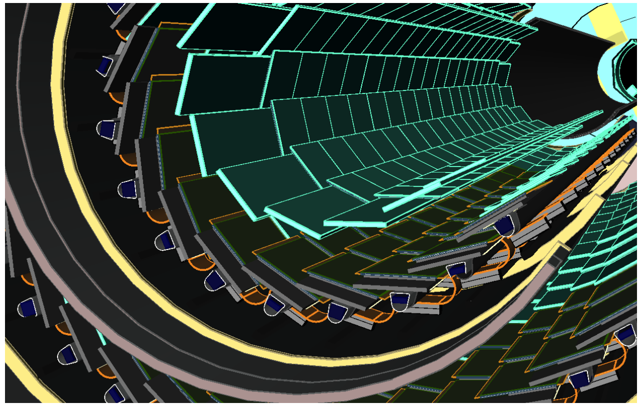


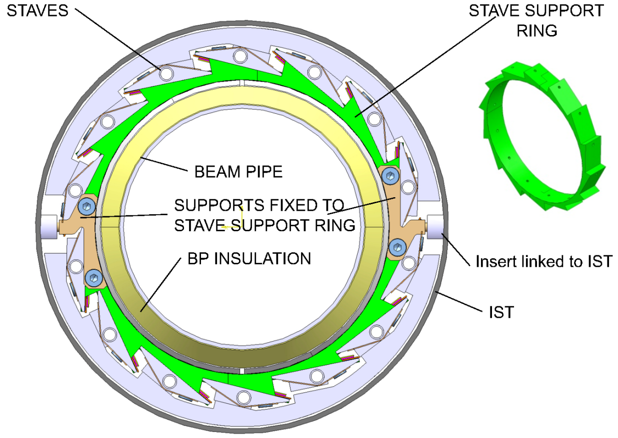




Insertable B-Layer (IBL)

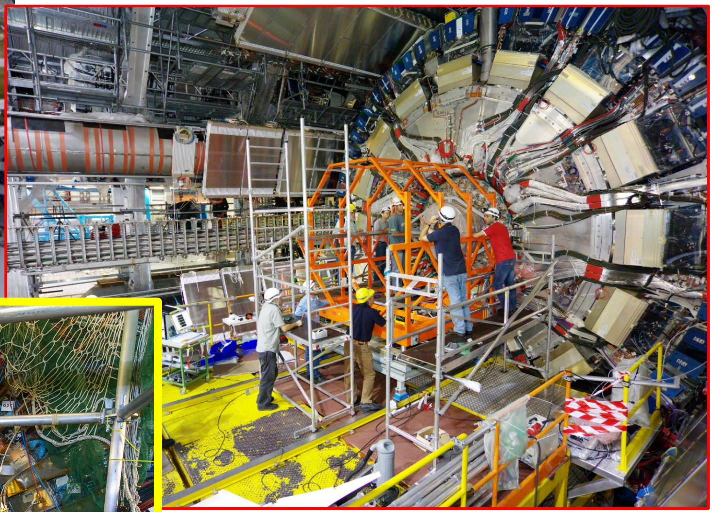


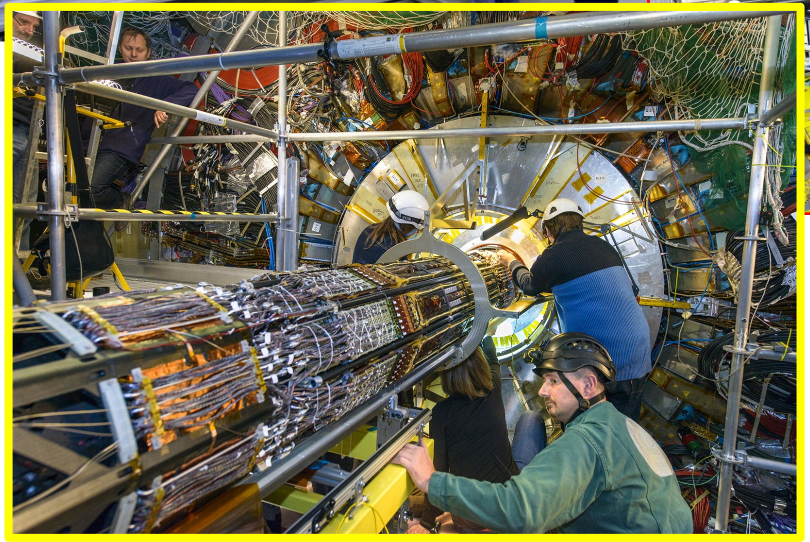




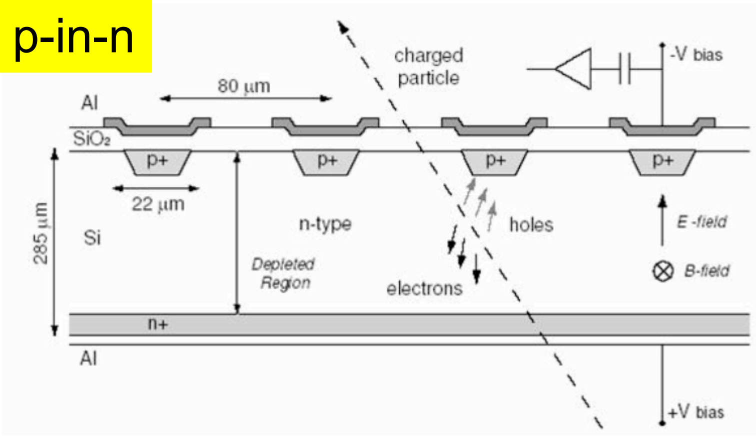
ATLAS Silicon Strip Detector

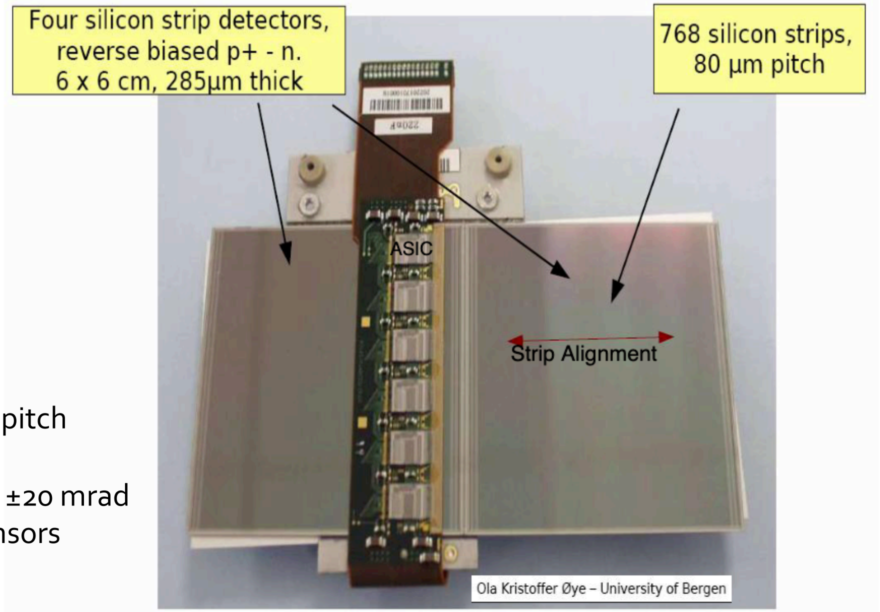
Inner Detector installation in cryostat





p-in-n





- The 2112 barrel SCT modules use 80 μm pitch micro-strip sensors
- Four sensors (2 each side) are rotated by ±20 mrad around the geometrical center of the sensors

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From LHC to HL-LHC

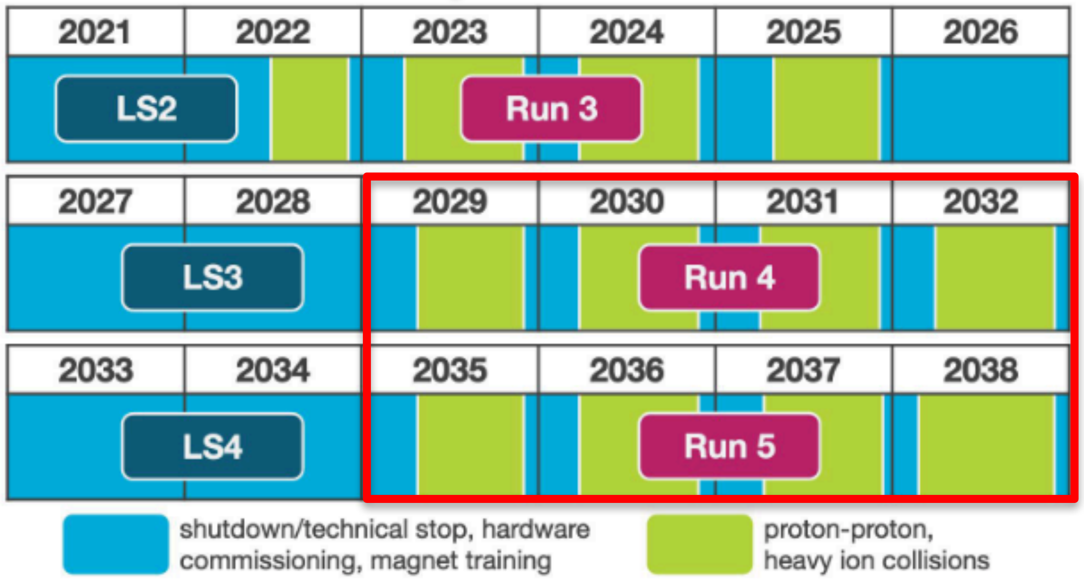
- We are only at the beginning of the LHC program!
  - We only accumulated 5% of the total expected LHC data
  - Extensive and exciting physics program at High-Luminosity LHC (HL-LHC) thanks to the 20x increase in data statistics

#events = L * σ

Luminosity
→beam dependent
[to be maximized at expenses of pileup]

Cross section
→process dependent

We are HERE



HL-LHC

LHC in Run-2/3 (so far):
- p-p collision energy: 13.6 TeV
- Peak luminosity: 2 x 10^{34} $cm^{-2}s^{-1}$
- Int. luminosity/exp.: 11 fb^{-1} Run-3 (156 fb^{-1} Run-2)
- **Average Pileup in Run-2: 34 (peak ~70)**

HL-LHC key numbers:
- p-p collision energy: 14 TeV
- Peak luminosity: 5-7.5 x 10^{34} $cm^{-2}s^{-1}$
- Int. luminosity: 3,000 fb^{-1}
- **Average Pileup: 200**

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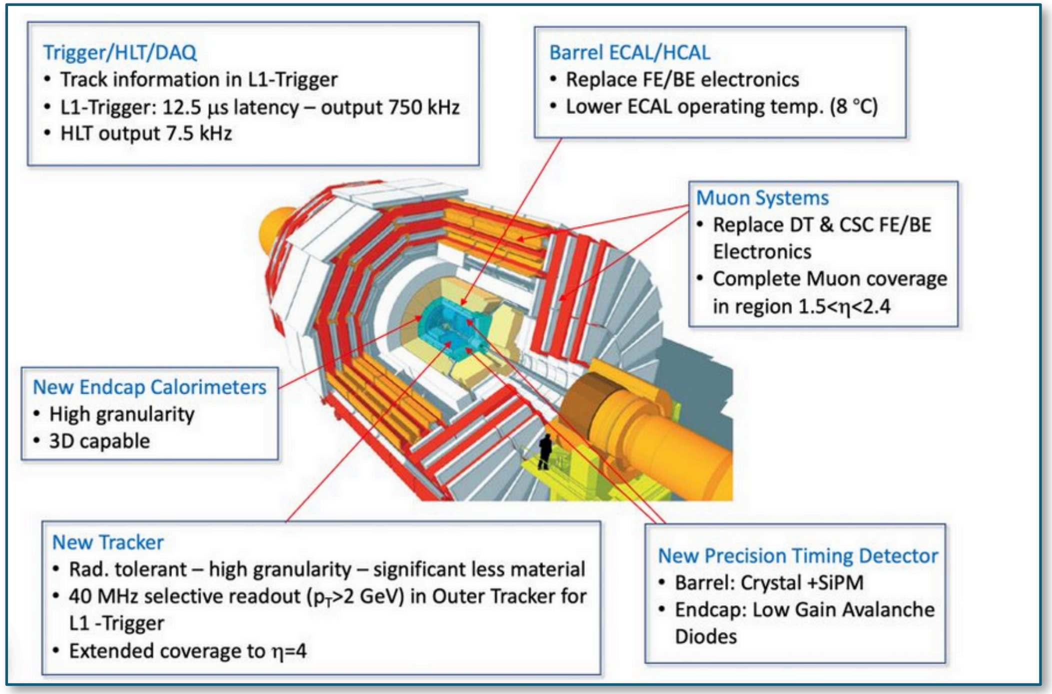
ATLAS and CMS Upgrades at HL-LHC

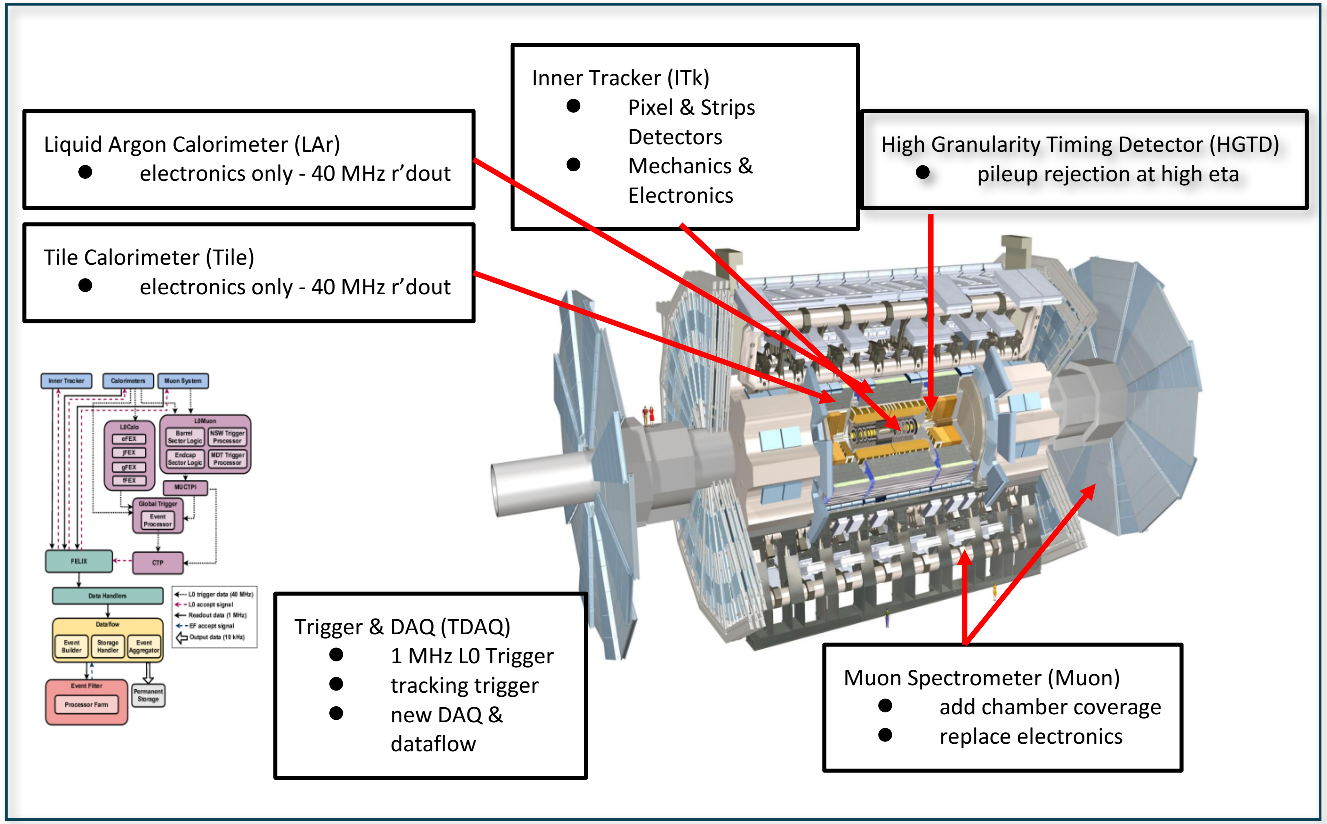
Major Detector Upgrades for HL-LHC

- Protect against high radiation
- Mitigate pileup rates and occupancy
- Keep low p_T requirements for main triggers
- Precise measurements up to large rapidity
- Lighten the detector, dropping material

CMS



ATLAS



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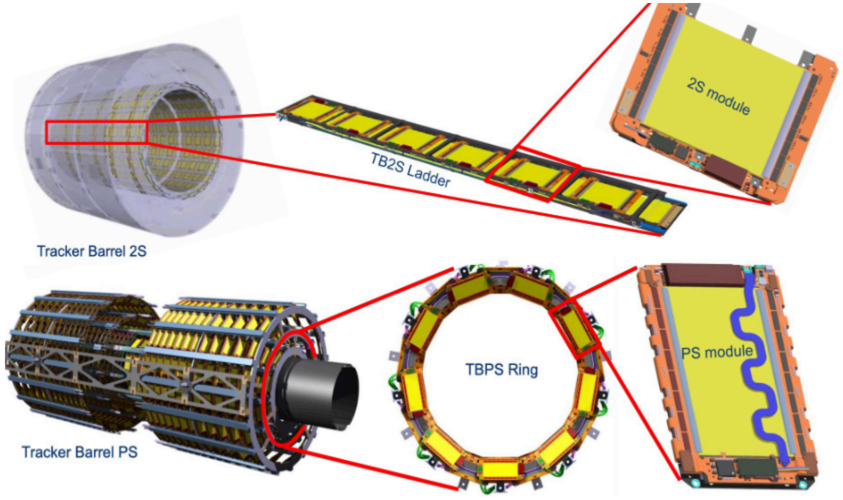
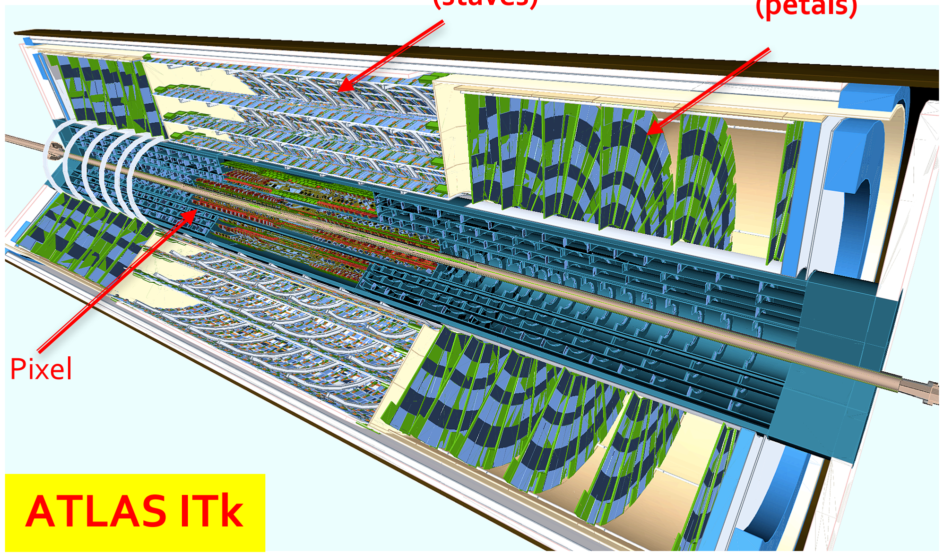
ATLAS, CMS Tracker Upgrades at HL-LHC

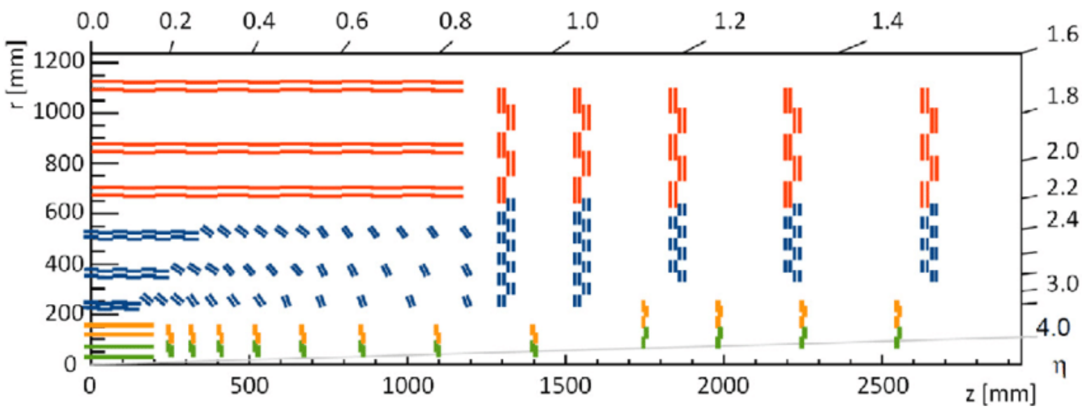


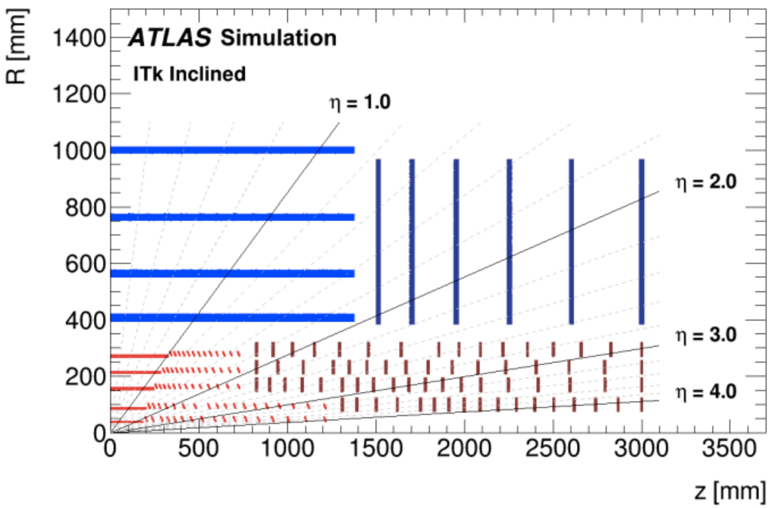
CMS Outer Tracker

New silicon trackers with greater granularity and coverage



ATLAS ITk





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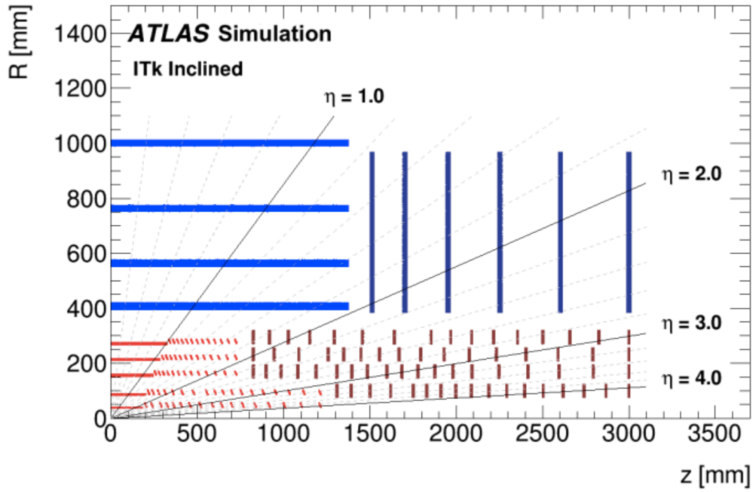
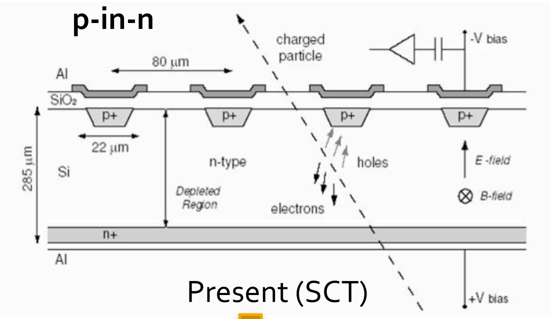
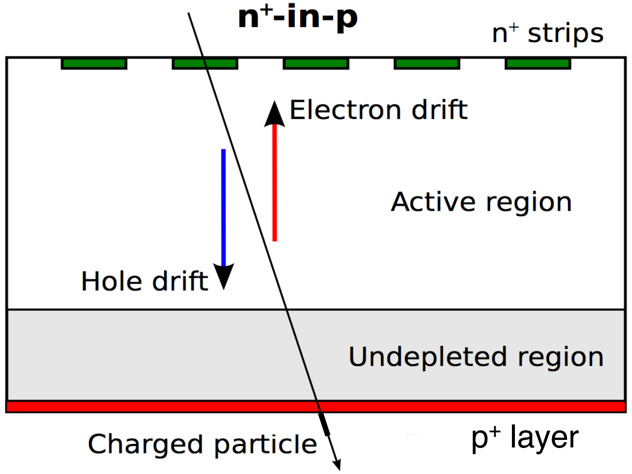
ATLAS Tracker (ITk) at HL-LHC

- **New All-Silicon tracker**
  - ~180 m^2 of silicon: strips (outer) + pixel (inner)
  - Extended coverage up to forward region $|\eta|=4$
  - Higher granularity
  - Less material

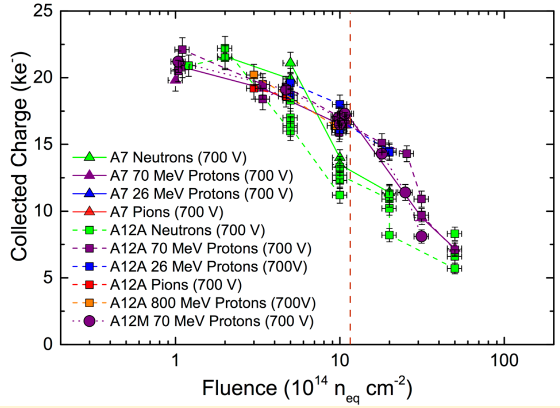
- **Pixel**
  - 5 barrel layers and several end-cap rings
- **Strips**
  - 4 barrel layers and 6 end-cap rings







Future (ITk)



- **Strips are AC-coupled with n-type implants in a p-type silicon bulk (n^+-in-p)**
  - Deliver a factor of two more charge wrt the current ATLAS SCT (p-in-n)
  - Collect electrons (faster so less charge trapping)
  - No radiation-induced type inversion
  - Can be operated in partially depleted state - high radiation tolerant
  - Cheaper than other technologies (e.g. double-sided lithography for n-in-n)

- **Radiation tolerance as key requirement**
  - Expected maximum fluence of 8-10 × 10^{14} $neutron_{eq}/cm^2$
  - Ionizing dose of 33.3 MRad
  - Operate up to 700 V
  - 300-320 µm target thickness

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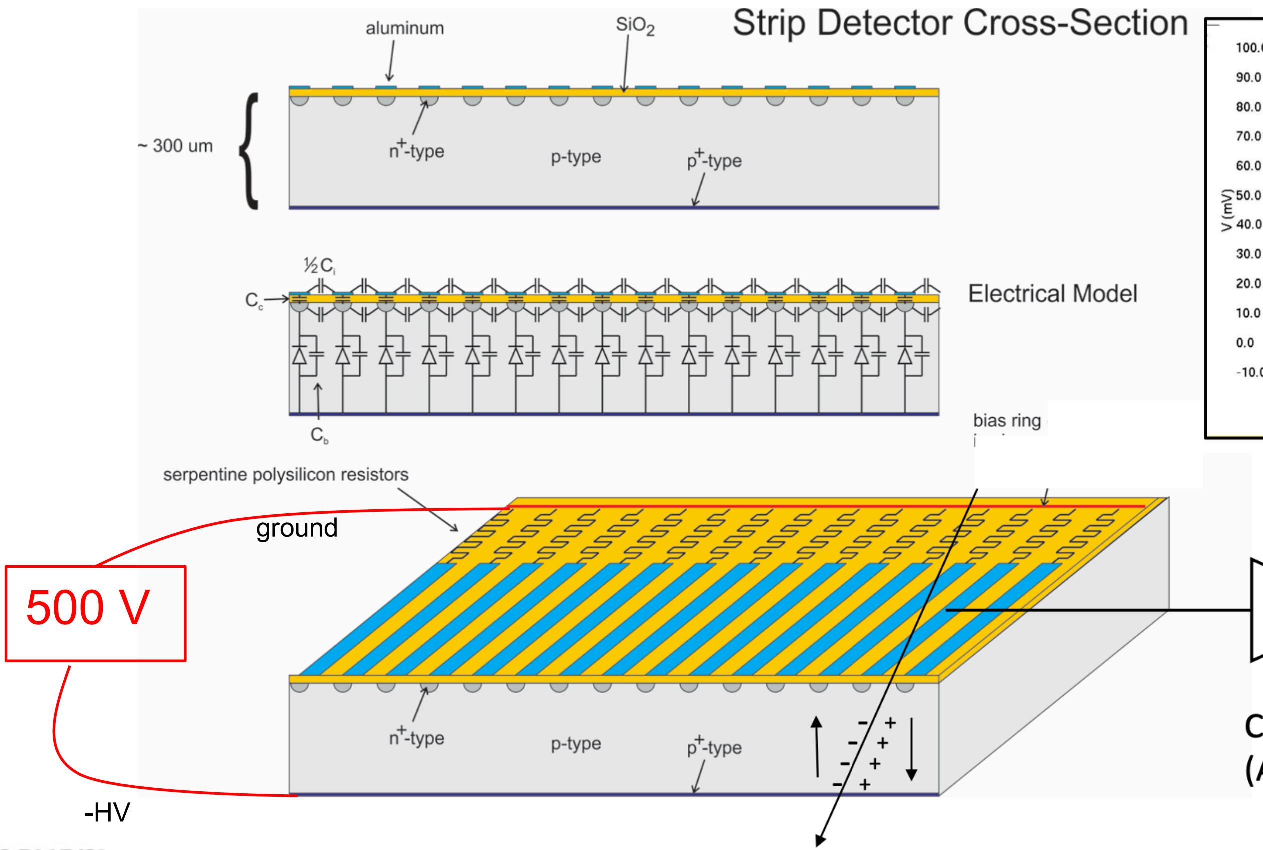
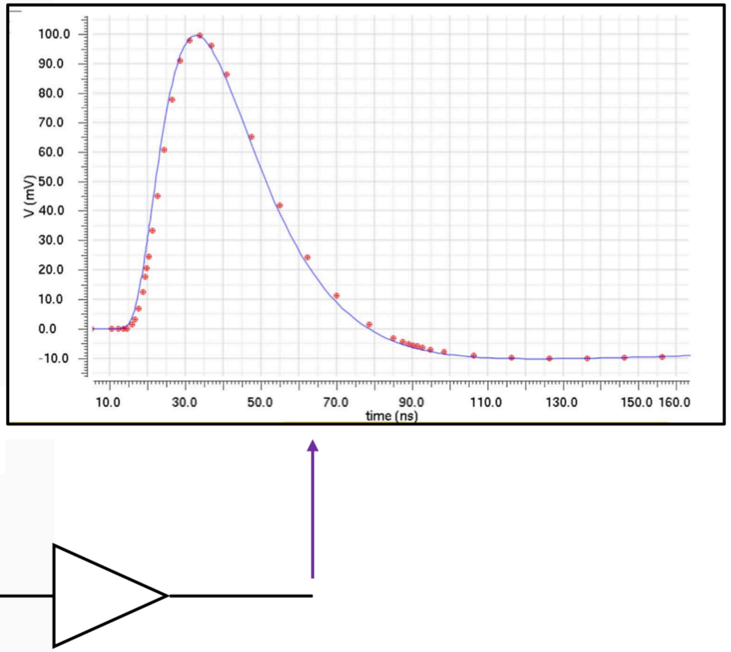
ITk Strip Sensors

- 2 rows of 1,280 diode strips (detecting element)
- Spaced 75.5 μm
- Overall size of a single sensor 98 mm x 98 mm x 0.3 mm (very thin and fragile)

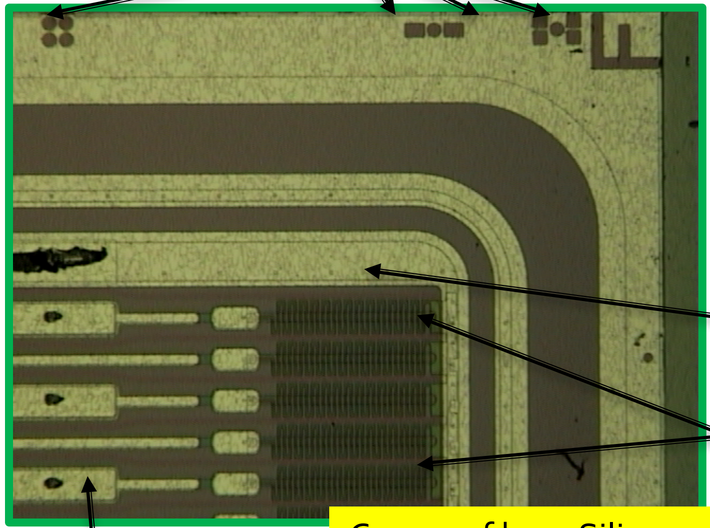
Each Strip is a reverse bias **diode**





ITk Barrel Strip Module

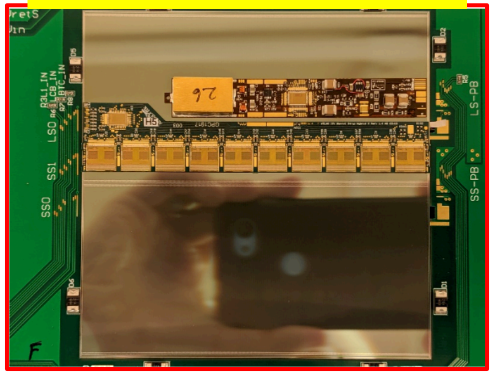
- **Strip Barrel sensors:**
  - Active area of ~98 ×98 mm²
  - 1,280 channels, strip pitch 75.5 µm
  - Strips parallel to the edge of the sensor
  - 2 Module types:
    - 4 rows of Short Strips (24.10 mm)
    - 2 rows of Long Strips (48.20 mm)



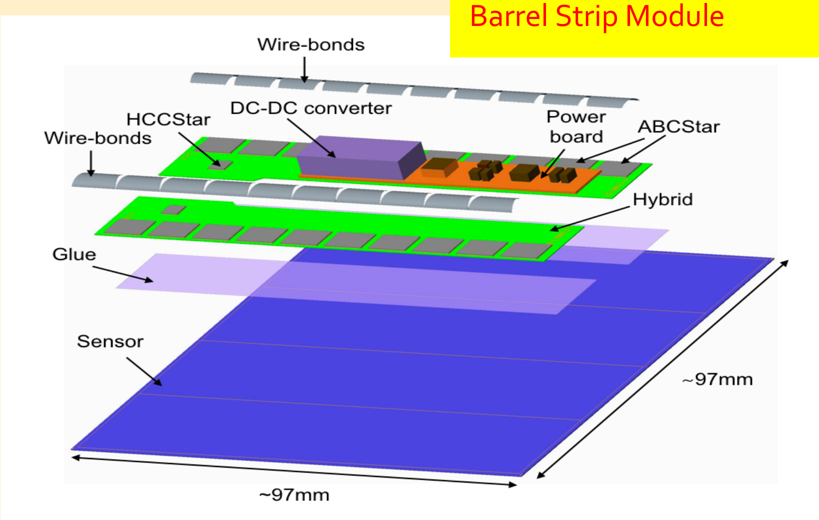
Corner of bare Silicon

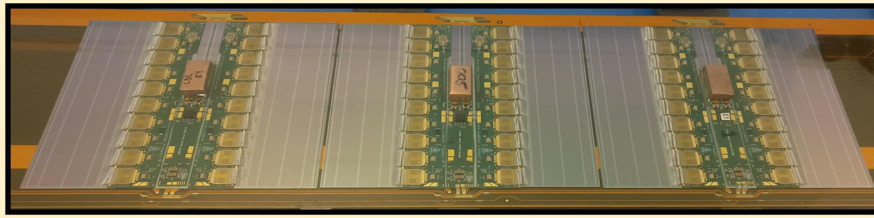
Metalised n+ type implant (Strip with pad for wire-bonding)

Silicon + Hybrids= Module

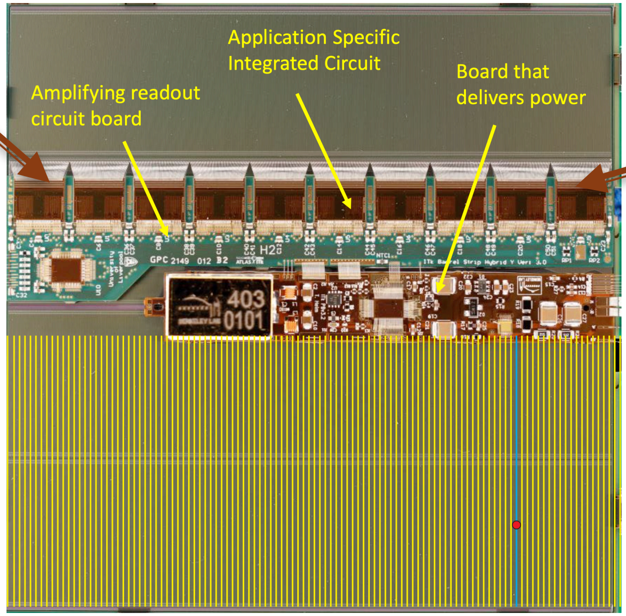


Barrel Strip Module





Controller ASIC (HCC)



Each *Application Specific Integrated Circuit* (**ABC* ASIC**) contains 256 amplifiers

Silicon Strip Module:

- Sensor
- Amplifying circuit flex board (*hybrid*)
  - each supporting 10 readout ASIC (*ABC**) + 1 controller ASIC (*HCC*)
- Board that provides electrical power (Powerboard)

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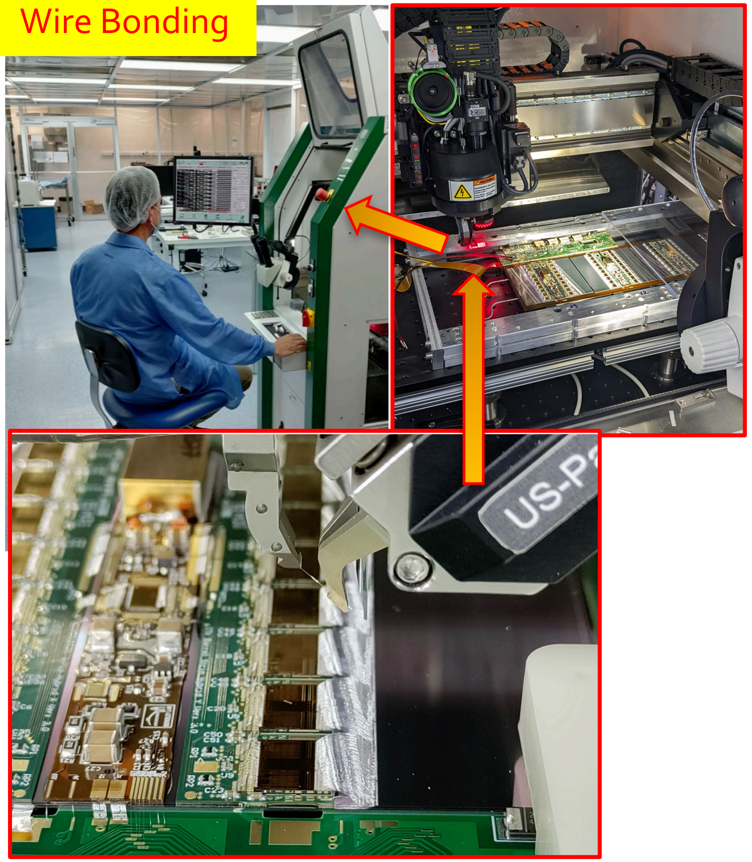
ITk Interconnections

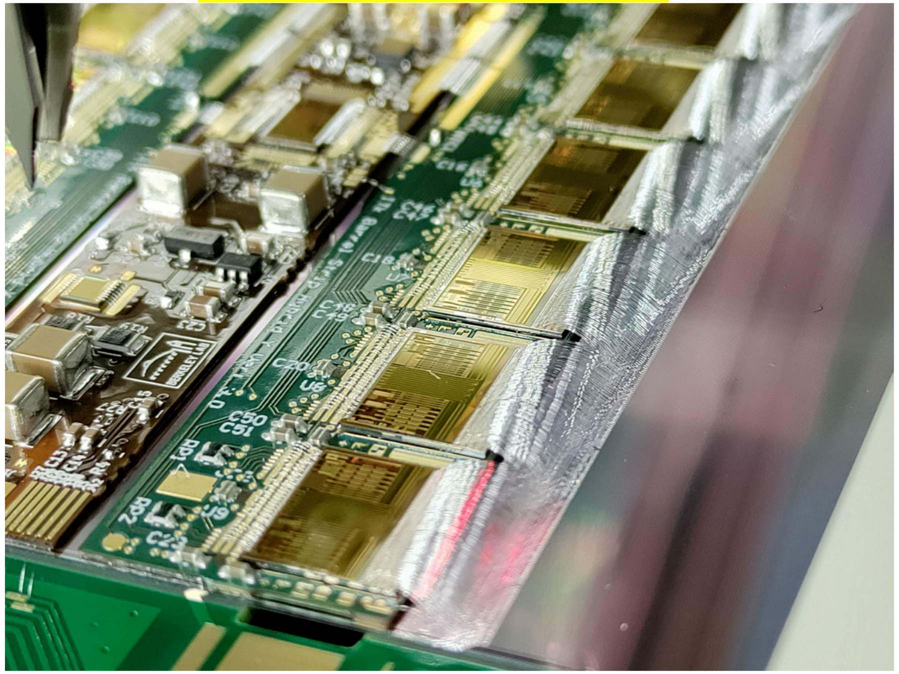
Wire Bonding



Aluminum Ultrasonic
Wedge Bonding

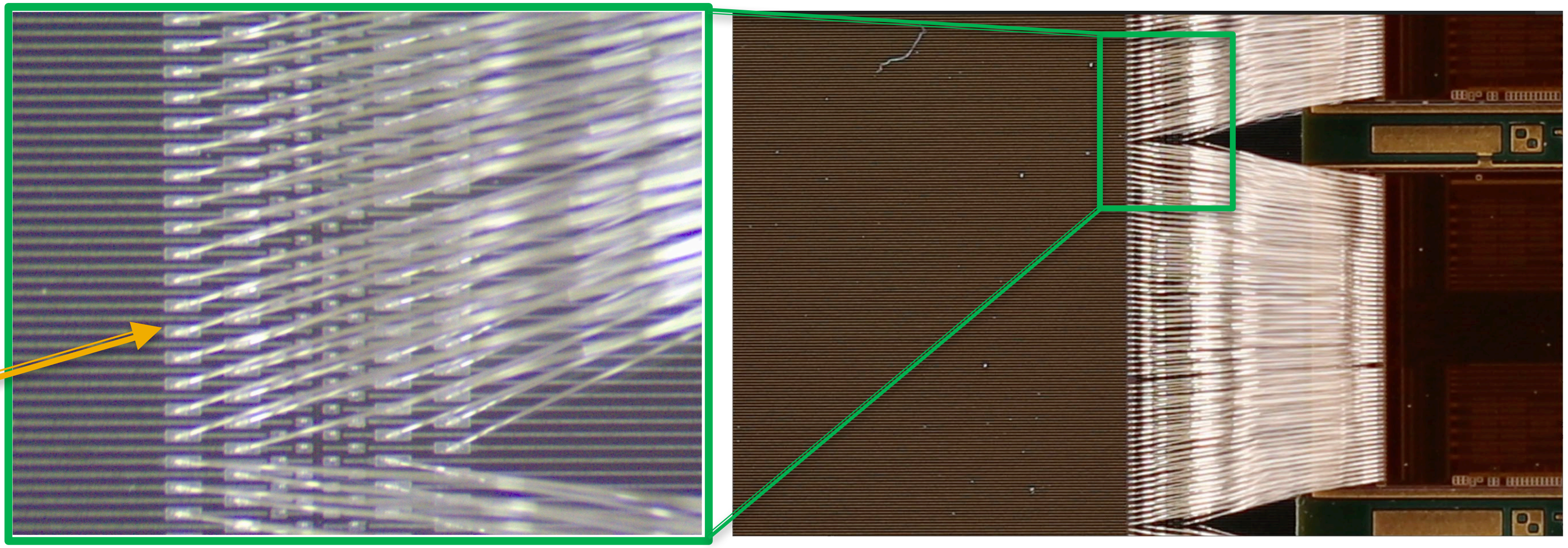
- **Up to ~6000 wire-bonds per module**
  - **1-2hours/module**
  - **2.5 modules per day**

ASIC bonded to strips



Several wire-bonds per sec!

25 um (1/1000th inch)
diameter aluminum wires



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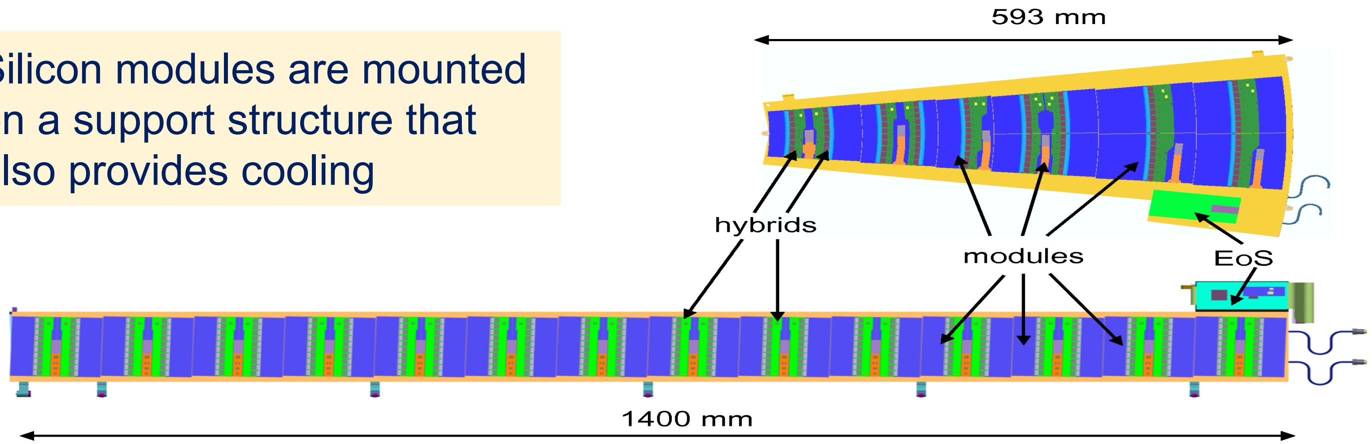
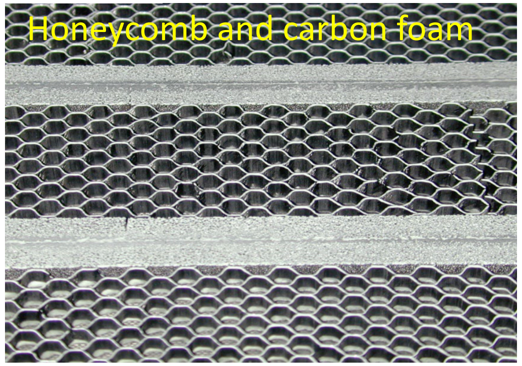
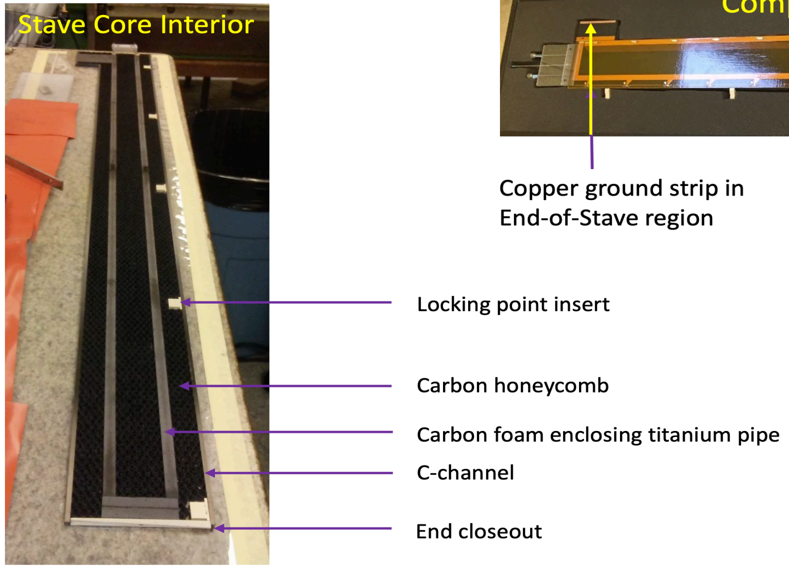
ITk Support Structures (Staves and Petals)

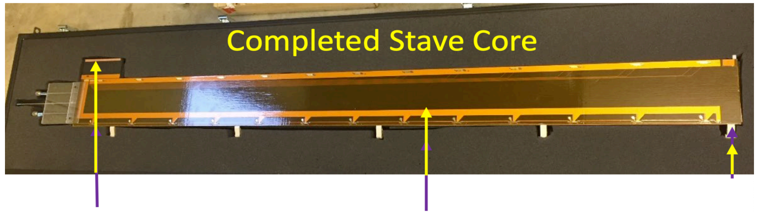
- **Staves (for barrel) and Petals (for endcap) provide support structures to modules, cooling lines, power distribution and electrical signal transmission**
- **28 Barrel modules on each stave (14 mod. per side)**
- **18 End-caps modules on each petal (9 mod. per side)**

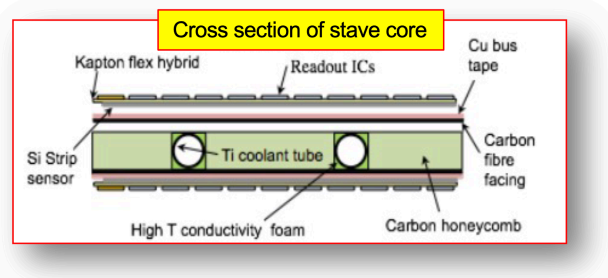
Silicon modules are mounted on a support structure that also provides cooling











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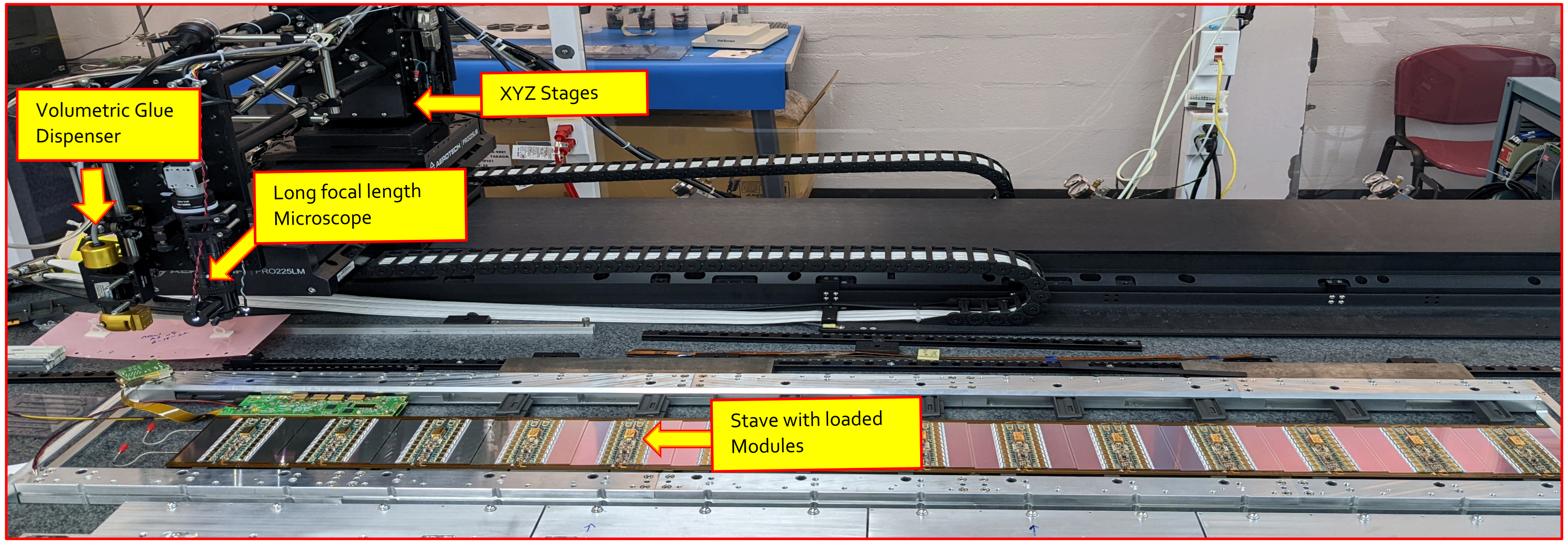
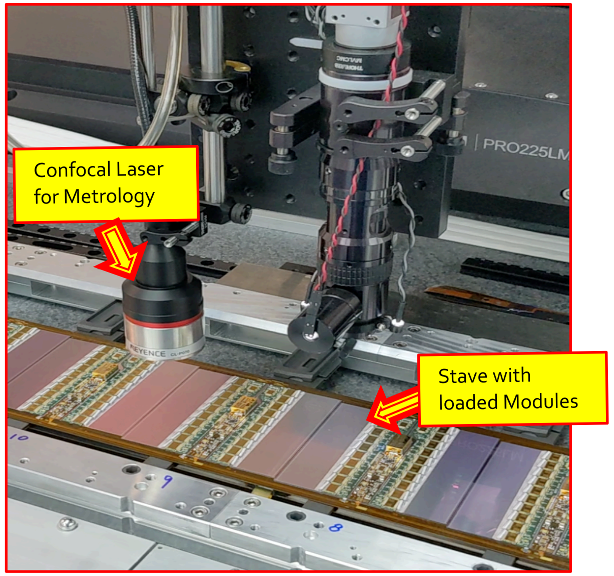
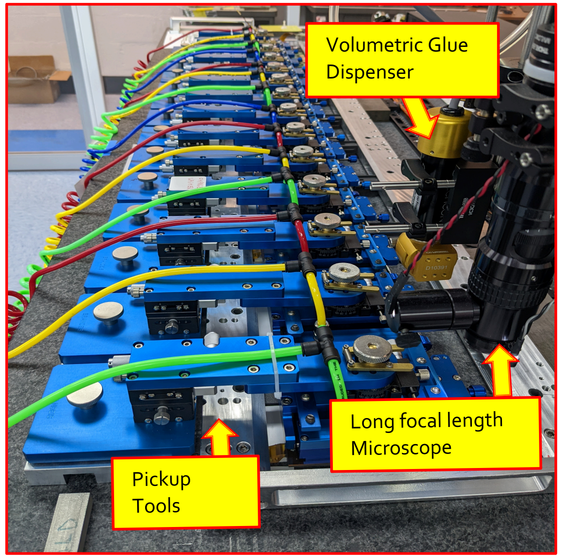
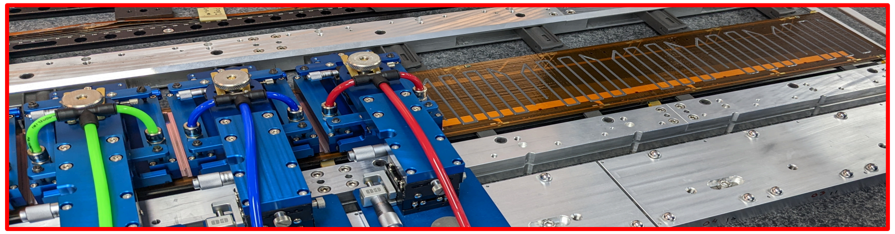
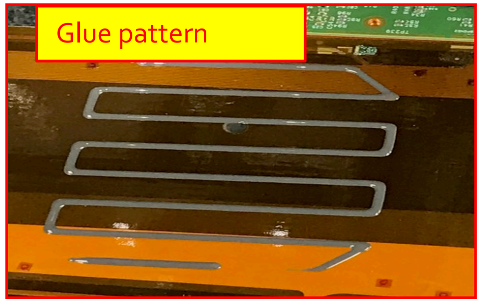
ITk Module Loading on Staves









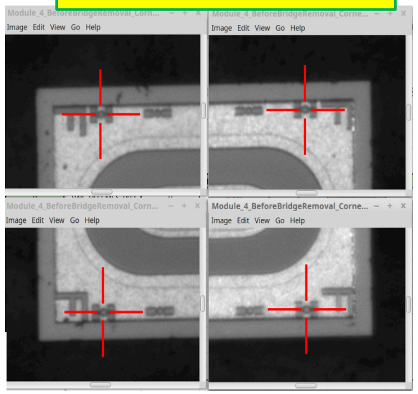


Gluing module to carbon support structure.
Modules must be placed to within 50 micron accuracy.

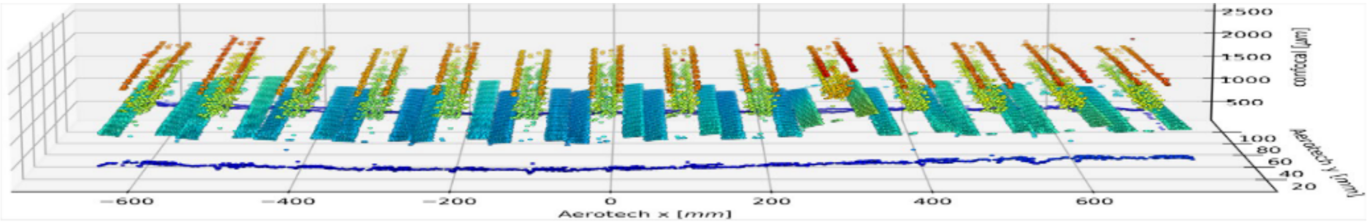
Quality Control and Assurance on Staves

- Visual inspection: before/after bonding and electrical tests
- Metrology: inspect module positions and glue thickness
- Mechanical Tests: envelope test and glue weight, wire pull tests
- Electrical and Functional Tests: ensure functioning of all channels at room temp. and cold (-40 C) conditions

Visual Inspection



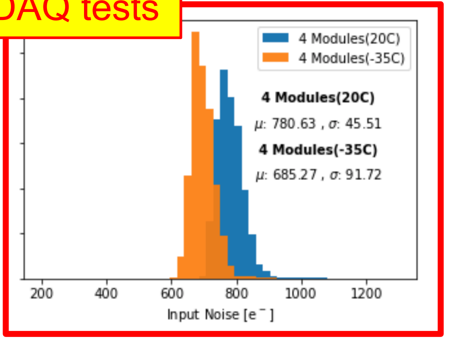
Metrology with confocal laser: assess accuracy of loading process



- Testing of final stave is done at cold temperature (~ -40 °C) inside a "coldbox"
- Detectors will run cold in experiment to reduce current in sensor that is due to radiation damage

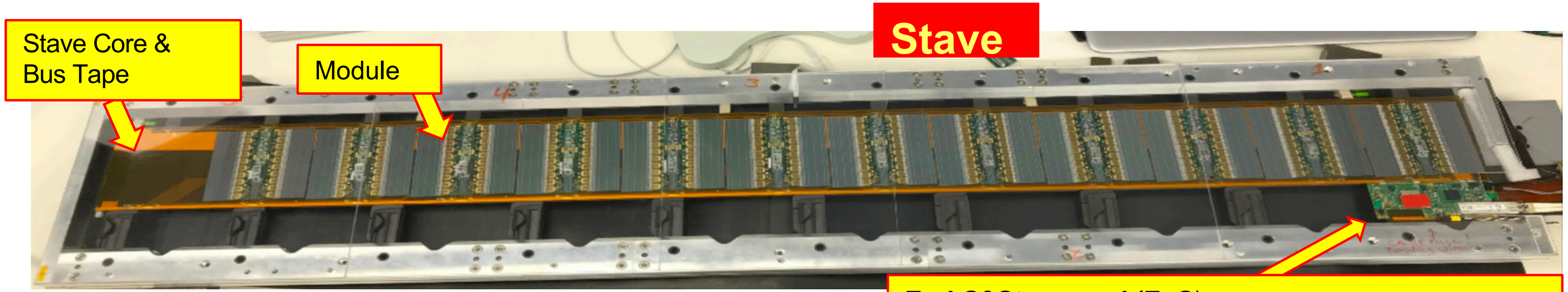
Insulated/Dry Cold Boxes

DAQ tests

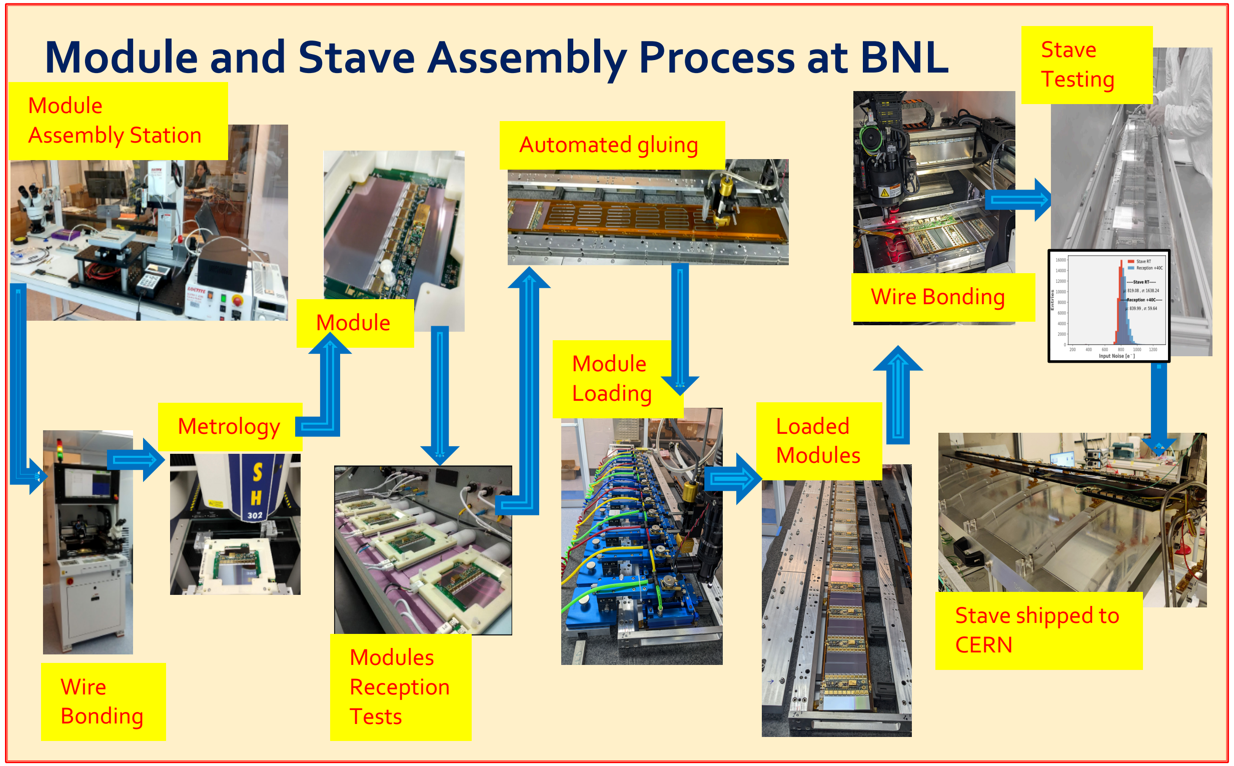


Electrical and DAQ tests at room and cold conditions are compared with module results prior to stave loading

ITk Project



End Of Stave card (EoS): interface between a stave and upstream ATLAS: connections for data and command lines, and it houses lpGBT chip set and the VTRx optical link.



International Strip ITk

Layer	Radius	staves per layer	# of modules	# of hybrids	# of ABC130	# of channels	m²
0	405	28	784	1568	15680	4,01	7,45
1	562	40	1120	2240	22400	5,73	10,53
2	762	56	1568	1568	15680	4,01	14,75
3	1000	72	2016	2016	20160	5,16	18,96
Total full barrel		392	10976	14784	147840	37,85	103,43
Disk	**z-position**	**petals per disk**	**#modules**	**# of hybrids**	**# of ABC130**	**# of channels**	**m²**
0	1512	32	576	832	7168	1,83	5,03
1	1702	32	576	832	7168	1,83	5,03
2	1952	32	576	832	7168	1,83	5,03
3	2252	32	576	832	7168	1,83	5,03
4	2602	32	576	832	7168	1,83	5,03
5	3000	32	576	832	7168	1,83	5,03
Total end-caps		384	6912	9984	86016	11 Mio	60,39
Total total			17888	24768	233856	48,9 Mio	163,82

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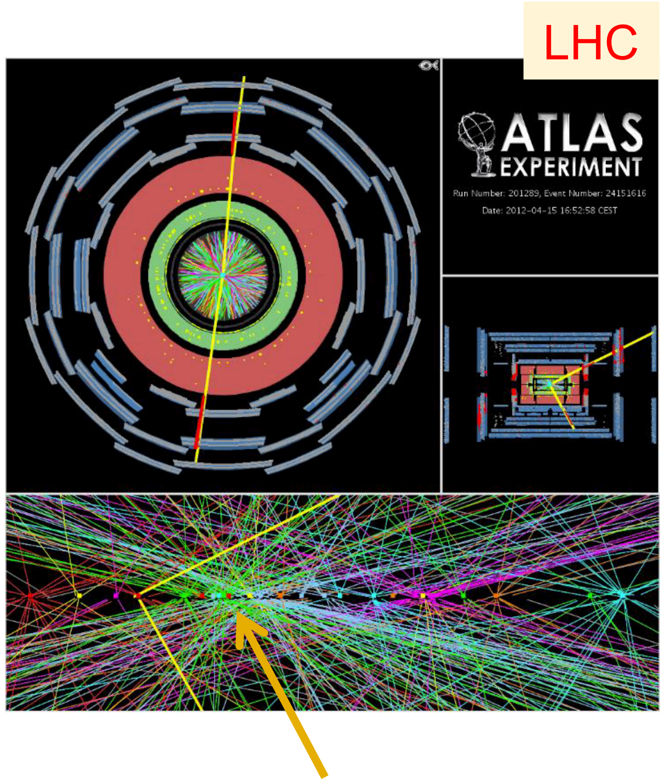
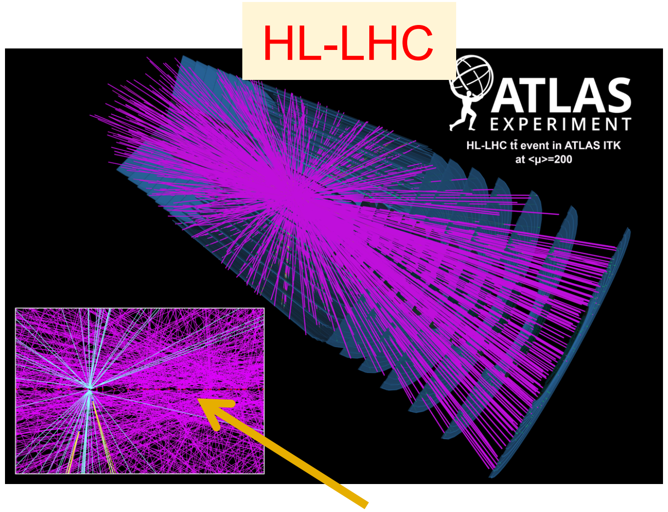
Pile-up challenge from LHC to HL-LHC



Pileup:
~50 interactions/bunch crossing at LHC

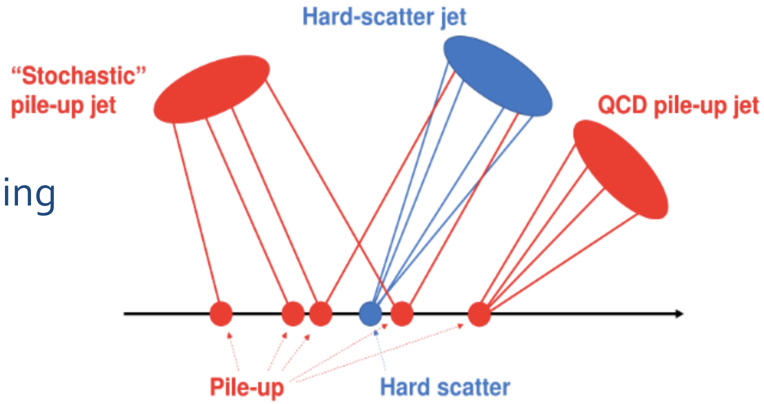


Pileup:
~200 interactions/bunch crossing at HL-LHC

Pile-up: number of concurrent scattering processes (140 – 200).

Density of events: number of events 1 mm (0.2 – 2 event/mm)

- The high number of interactions per bunch crossing (pileup ~200) is a serious challenge for the detectors
  - **Reduced accuracy of particle reconstruction**
  - **One of the key elements to mitigate the effect of pile-up is the precise assignment of tracks to vertices**



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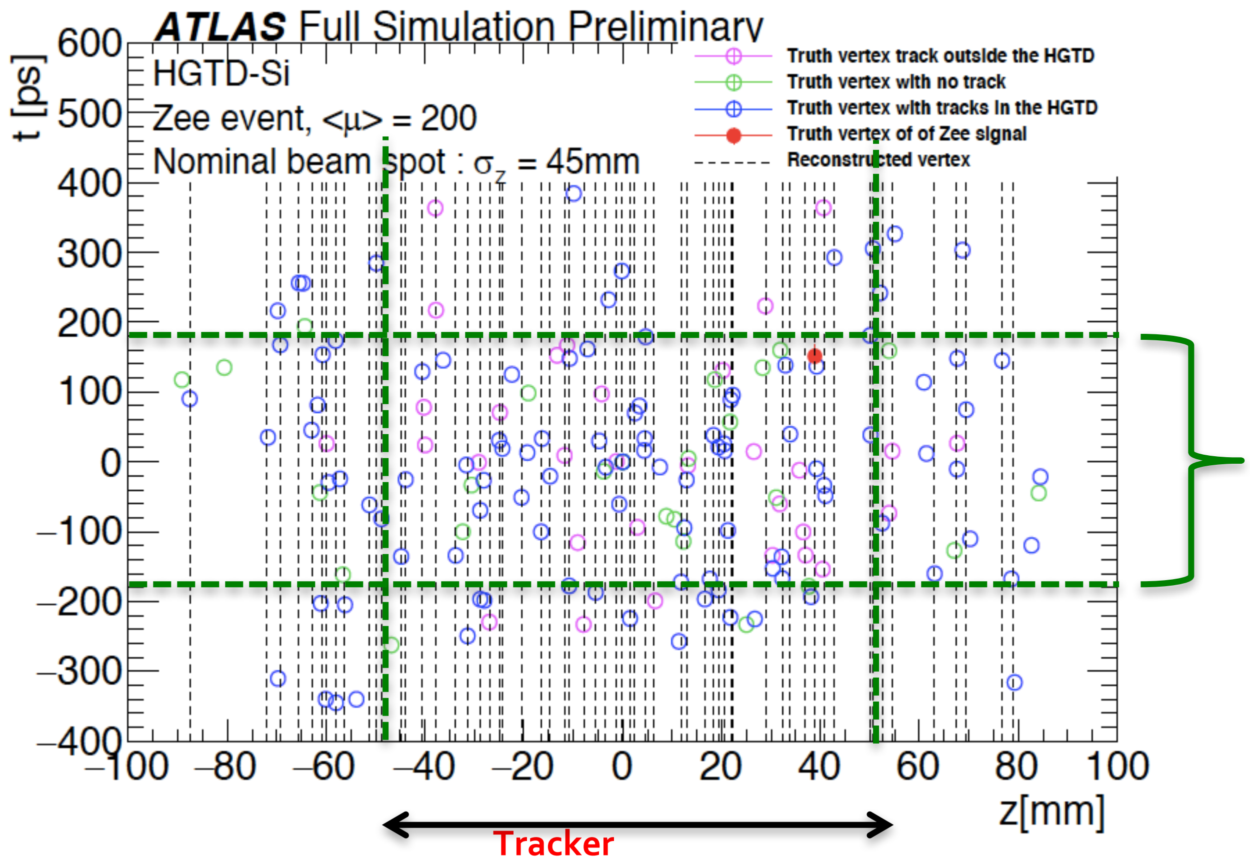
Pile-up Mitigation at HL-LHC

- New technique: measure time
- Timing Detectors complement Tracker by exploiting the time spread of collisions and reduce pile-up contamination



Beamspot size:
z ~50 mm
t ~175 ps

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Pile-up Mitigation at HL-LHC

- New technique: measure time
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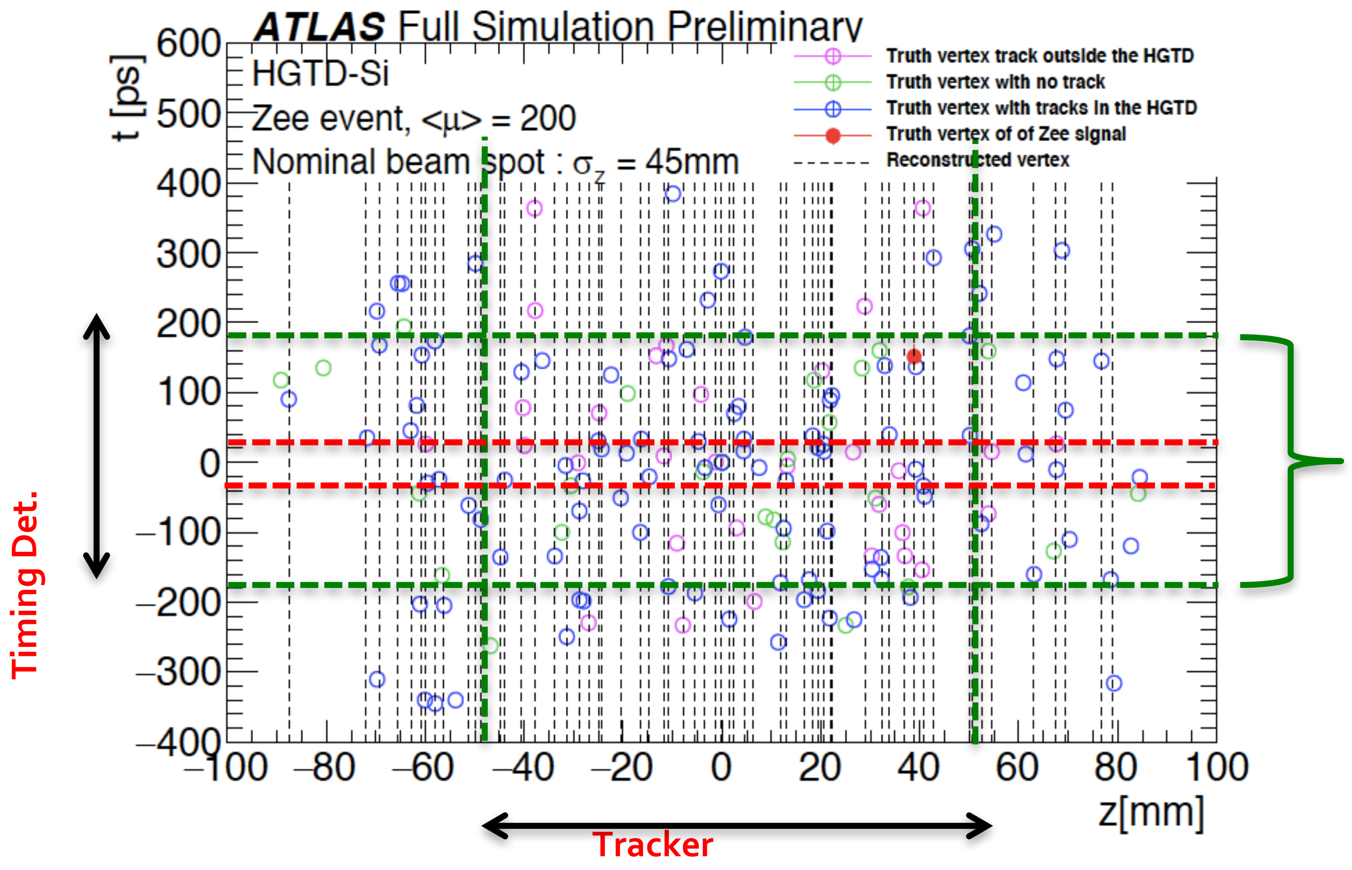

Beamspot size:
z ~50 mm
t ~175 ps

- With 30 ps time resolution
- ➔ 180/30 = 6x pile-up rejection than with tracker alone

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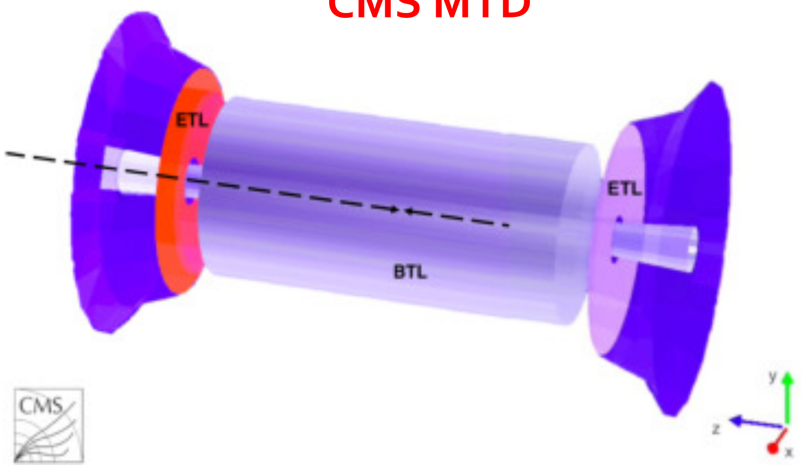
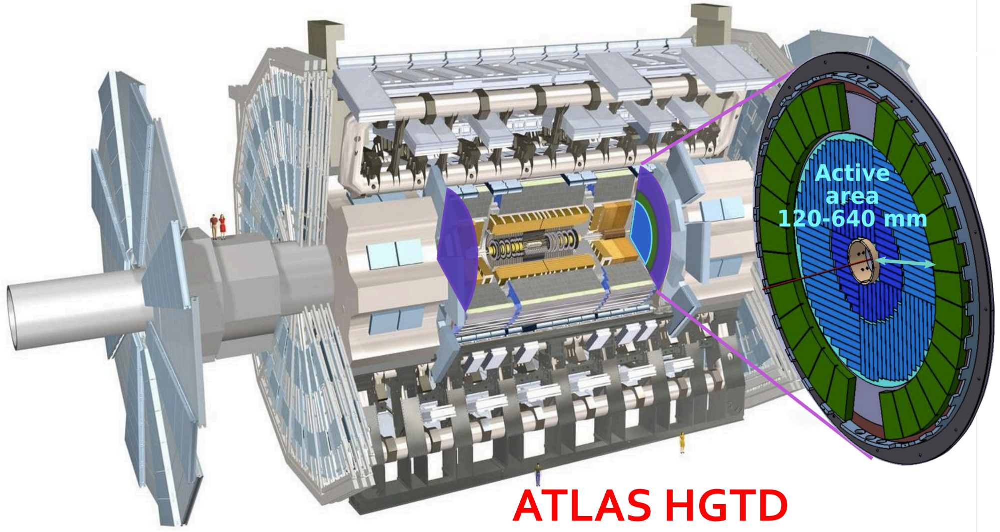
ATLAS, CMS Timing detectors at HL-LHC

- New silicon-based systems for timing to mitigate pileup
  - **Goal: ~30 ps time resolution per hit**
  1. CMS MIP Timing Detector (MTD) in -3 <|η|< +3
     - Barrel: Crystal read out by SiPMs - Endcap: fast-time silicon (**15.6 m²** of **LGADs**)
  2. ATLAS High Granularity Timing Detector (HGTD) in 2.4<|η|< 4.0
     - End-cap only: fast-time silicon (**6.4 m²** of **LGADs**)

→ **LGADs** in endcaps

CMS MTD

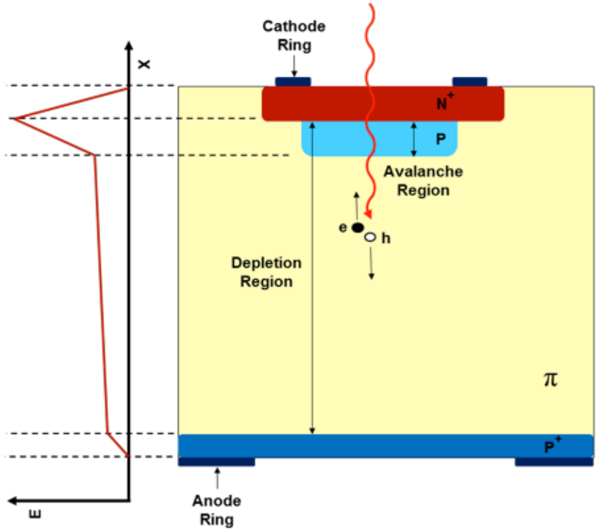


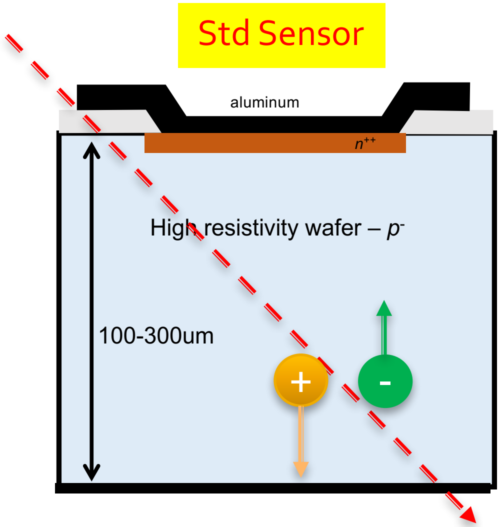


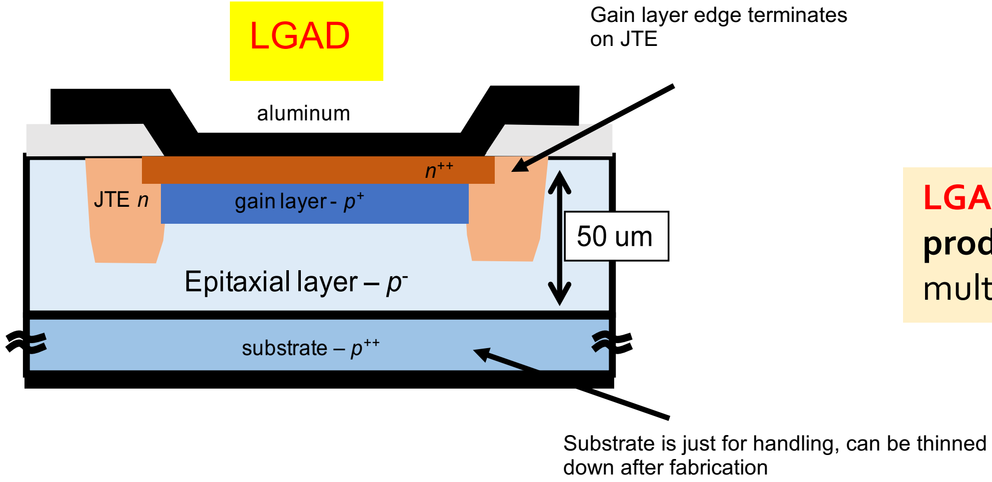
ATLAS HGTD

Fast-Time Silicon Sensors: LGADs

- **Low Gain Avalanche Diode (LGAD) will be used at HL-LHC**
- **Process similar to standard n-in-p sensors + built-in multiplication**
  - High and uniform electric field
    - 300 kV/cm over ~ 1 μm near junction ➔ **Gain Layer**
    - Bulk field ~ 20 kV/cm saturates electron drift velocity (~ 10^7cm/s)
  - High S/N thanks to gain
    - Moderate gain (10-100) through electron impact ionization







LGAD: electrons multiply in gain layer and produce additional e/h pairs (no hole multiplication)

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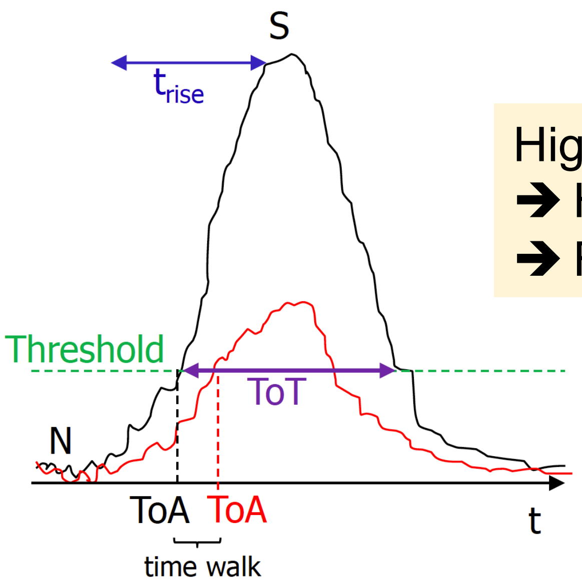
How to measure good time with LGADs

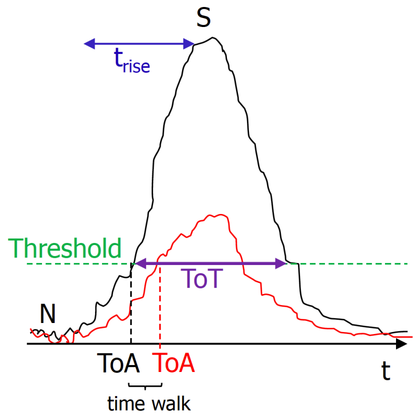
- Time = Threshold Crossing (Time of Arrival)



Higher the gain
➔ Higher the signal amplitude
➔ Faster the signal

How to measure good time with LGADs

- **Time = Threshold Crossing (Time of Arrival)**



Uncertainty

$$\sigma^2_{\mathrm{det}} = \sigma^2_{\mathrm{Landau}} + \sigma^2_{\mathrm{jitter}} + \sigma^2_{\mathrm{TW}} + \sigma^2_{\mathrm{TDC}}$$

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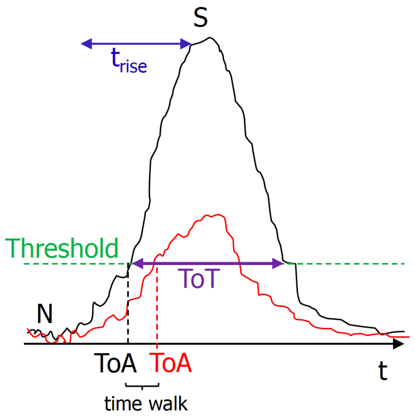
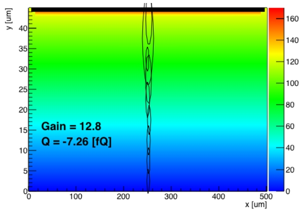


Uncertainty

$$\sigma_{\rm det}^2 = \sigma_{\rm Landau}^2 + \sigma_{\rm jitter}^2 + \sigma_{\rm TW}^2 + \sigma_{\rm TDC}^2$$

  - **Landau fluctuations in the deposited charge in the sensor**



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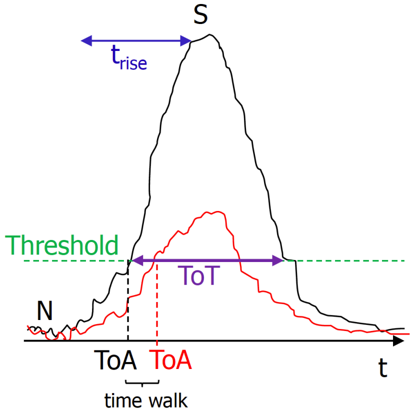

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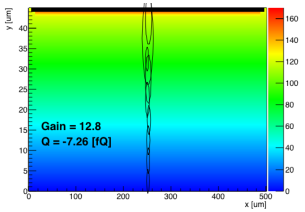
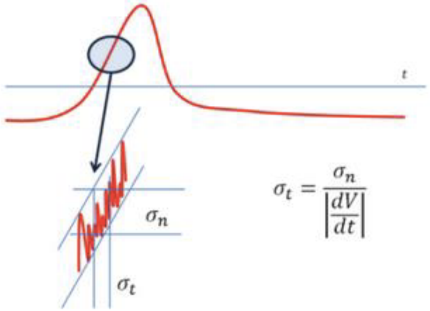


  - **Jitter (noise in signal):**
    ➔ **high S/N and fast rise time**



$$\sigma_{\text{Jitter}} = \frac{N}{(dV/dt)} \simeq \frac{t_{\text{rise}}}{(S/N)}$$

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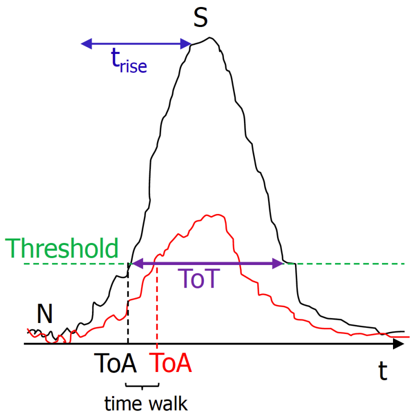
How to measure good time with LGADs

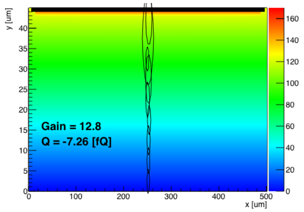
- **Time = Threshold Crossing (Time of Arrival)**



Uncertainty

$$\sigma_{\text{det}}^2 = \sigma_{\text{Landau}}^2 + \sigma_{\text{jitter}}^2 + \sigma_{\text{TW}}^2 + \sigma_{\text{TDC}}^2$$

- **Landau fluctuations in the deposited charge in the sensor**



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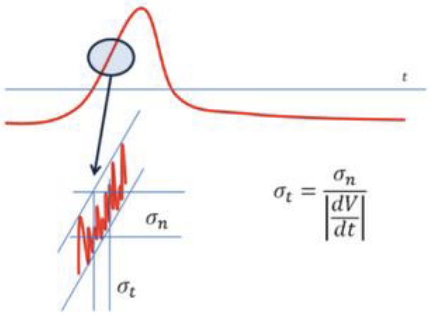

$$\sigma_{\text{Jitter}} = \frac{N}{(dV/dt)} \simeq \frac{t_{\text{rise}}}{(S/N)}$$

- **Time Walk (TW): differences in signal amplitudes**
  - negligible after offline ToT-based correction ➔ critical to correct for radiation damage (lower and lower signal amplitudes)
    - ToT correction to account for TW [t_{corr} = ToA – f(ToT)]

- **Fast/Low noise electronics, precise digitizer (TDC/oscilloscope), stable clock**

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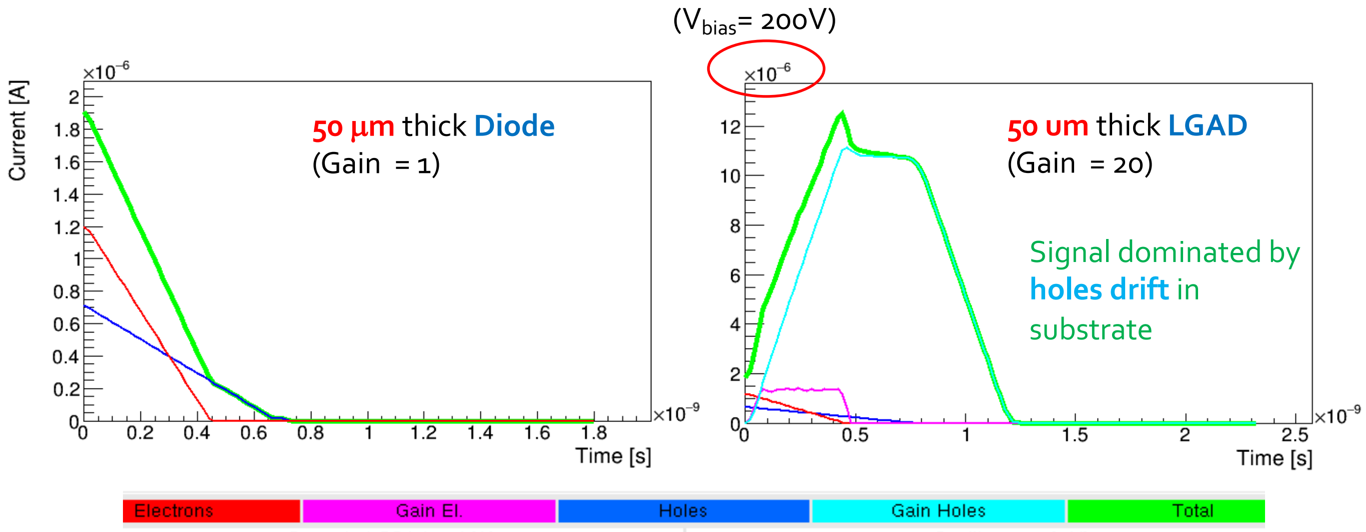
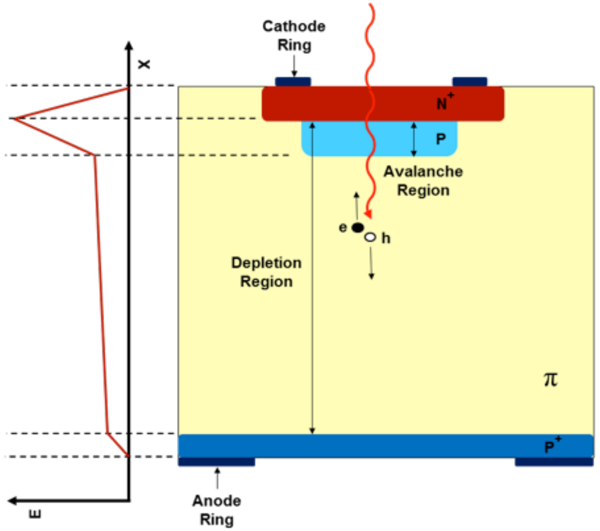
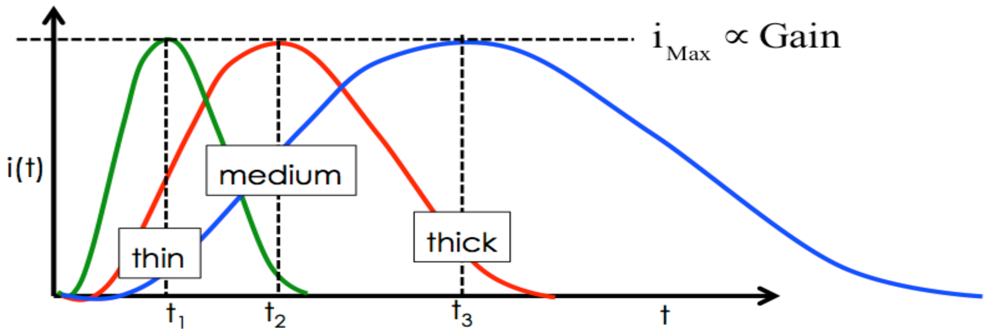
How to measure good time with LGADs



- LGADs have larger amplitudes than Diodes
  - Higher S/N
  - Longer signal ~ 1 ns

- LGAD pulse maximum is determined by the collection time of the last drifting electron
  - Determined by the detector thickness and the (saturated) drift velocity, i.e. providing a fixed time
  - At this point Gain Holes are still drifting





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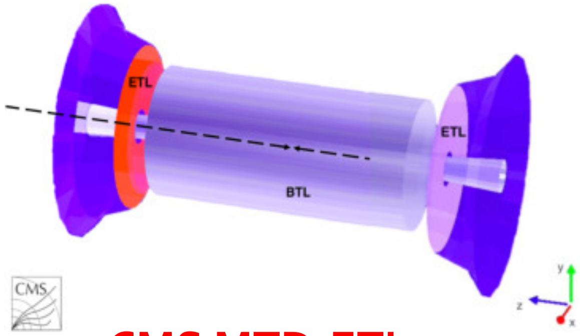
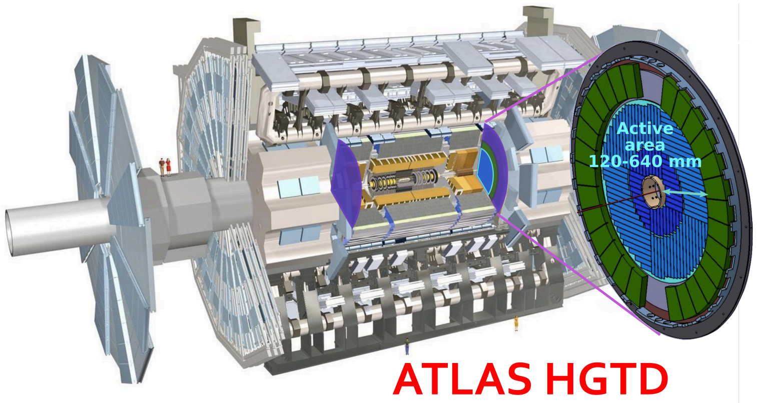
LGADs in ATLAS and CMS

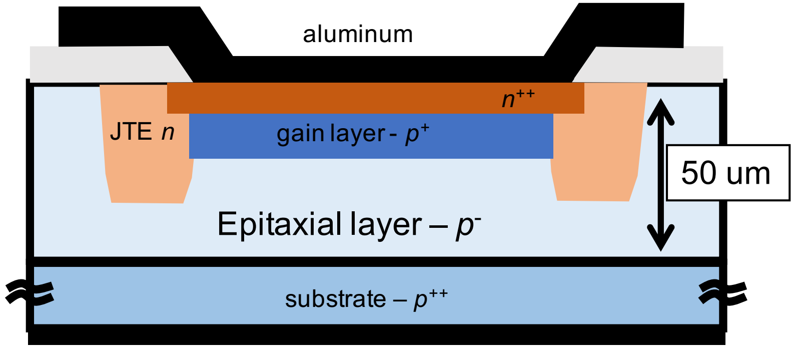
- **LGADs for ATLAS and CMS:**
  - **50 μm thickness**
  - **1.3 mm pixel pitch**
  - **Space resolution is limited by coarse pitch**
  - Several m² of sensors bump-bonded to dedicated ASICs (ALTIROC for ATLAS, ETROC for CMS)
  - **Time resolution pre-irradiation 30-40 ps** per hit



CMS MTD-ETL



ATLAS HGTD



- **Thin LGADs: 50 μm active thickness**
  - Fast charge collection (~1 ns) ← high repetition rate
  - Short rise time (~400 ps) ← minimizes jitter
  - Minimizes Landau fluctuations in charge generation ← faster
  - However, total charge is also small (smaller signal needs low noise electronics), therefore higher gain is advantageous
- **Time resolution: ~25 ps with 50 μm active thickness**
- **Radiation tolerance ~2.5x10^{15} neutrons/cm^2**

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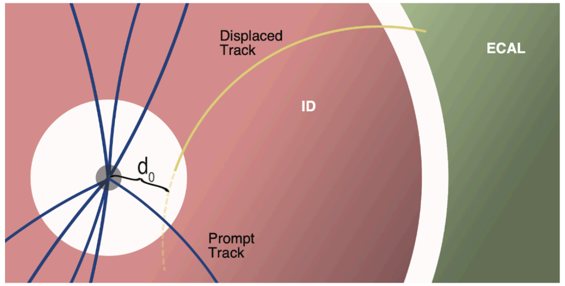
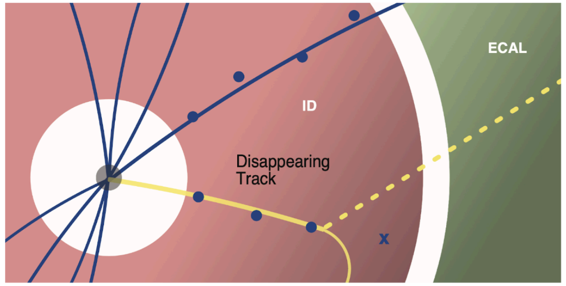
4D Detectors at Future Lepton Colliders

- **4D detectors for particle identification and reconstruction at e^+e^- colliders**
  - Measurements of Higgs boson properties, dark matter searches etc.

    - **Future Linear or Circular e^+e^- colliders**: **low-mass detectors with high position accuracy for precision reconstruction of particle momentum, impact parameter, secondary vertices, and particle identification (Particle Flow)**
      - Space resolution **per track <3-5 μm**
      - Low material budget to minimize multiple scattering ➔ **~100 μm si-tracker thickness**
      - Low power dissipation 0.1-0.2 W/cm²
      - Timing < 1 ns – 100 ns

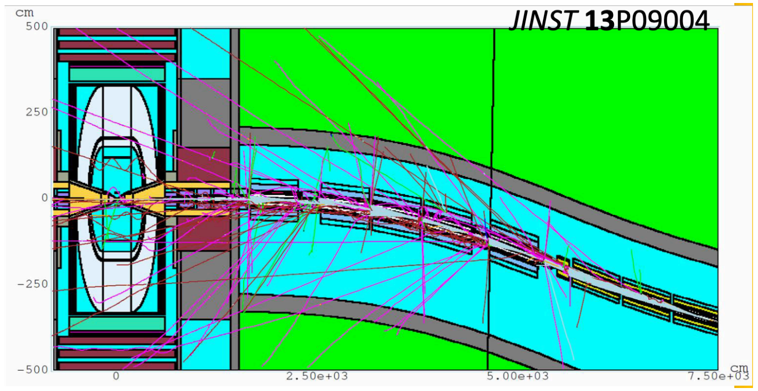
    - **4D tracker could be considered for e+e- if physics gain is significant with respect to increased material budget**





- **Beam Induced background mitigation at Muon Collider**
  - Background from muon decays: multitude of particles from secondary interactions that hit the detectors

    - **Muon Collider Tracker**: **1% occupancy to mitigate Beam Induced Background with high resolution in position and time measurements**
      - No timing in tracker requires 25 x 25 μm pixels ➔ 5 billion channels
      - Tracker with 20-30 ps timing ➔ 1-2 billion channels (similar to CMS at HL-LHC)



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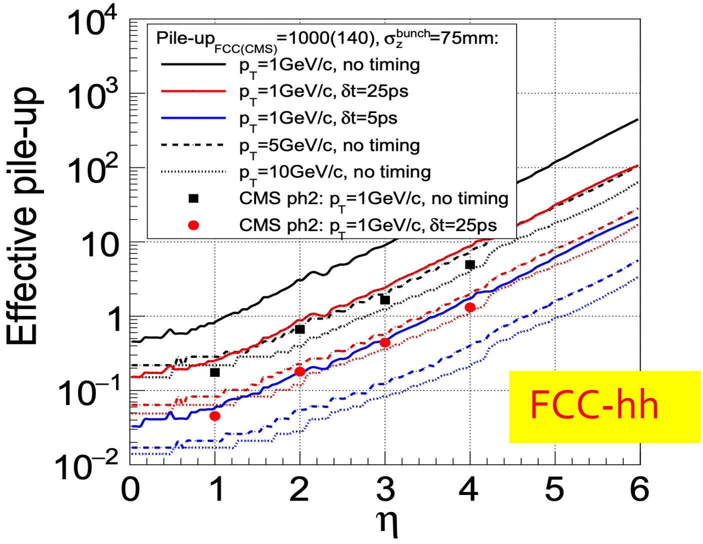
4D Detectors at Future Hadron Colliders

- **Broad physics program at Hadron Colliders**
  - Long-Lived particle detection, Dark Matter searches, Higgs coupling and electroweak measurements etc.

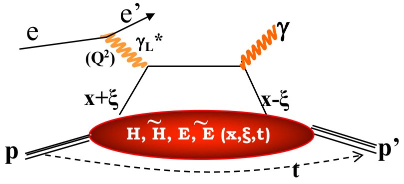
- **Future Hadron colliders (FCC-hh): pileup (~1000), impact parameter resolution, and radiation damage are main concerns as well as cost for a large tracker**
  - **~430 m² of silicon** (250 m² ATLAS/CMS at HL-LHC)
  - **Track resolution < 10 μm per layer**
  - **Radiation levels up to 8 x 10¹⁷ n/cm²**
  - **Timing is necessary to correctly assign tracks to vertices: ~ 5 ps per track**

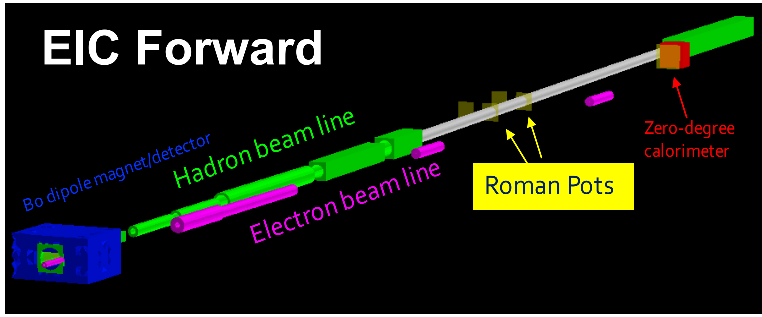


- **Forward proton tagging at hadron or electron-ion colliders**
  - Proton tagging: central diffraction, exclusive γ–γ production, light-by-light scattering etc.

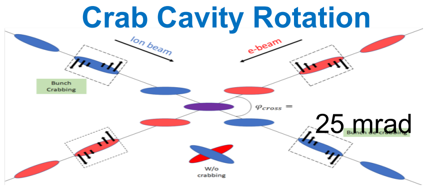
- **Forward Physics at the (HL-)LHC and future hadron collider:**
  - **5 ps** timing to suppress pileup, **5 μm** tracker resolution
  - Radiation hard detector needed

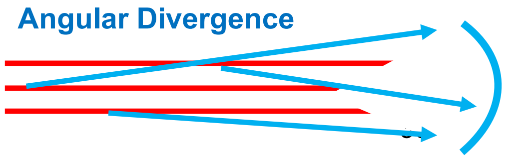
Deeply Virtual Compton Scattering at EIC





- **EIC Roman Pots: physics impacted by smearing of proton momentum**
  - 35 ps timing removes crab cavity rotation effect
  - Fine space resolution (≤500/√12 μm) mitigates angular divergence effect





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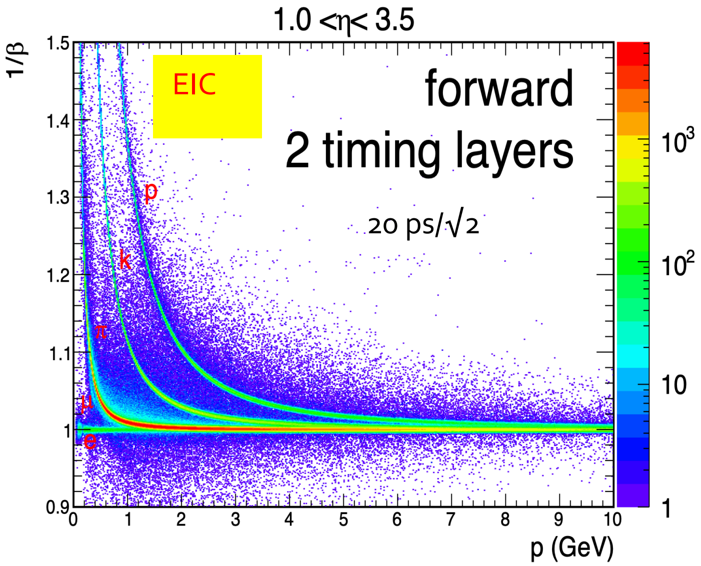
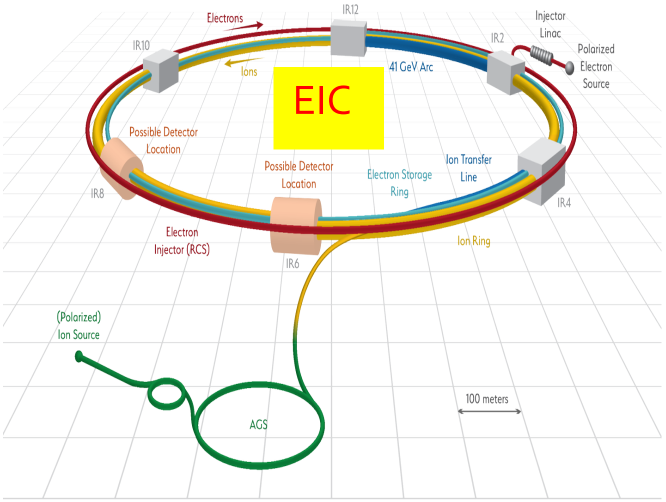
4D detectors for particle identification

- **Particle identification at EIC and rare-process detection experiments**

  - **EIC Time of Flight (ToF): fine time and space resolution needed for p/K/π separation at low/medium momentum**
    - **20-30 ps timing per hit needed**
    - Strip + TOF to improve momentum resolution
    - Low material budget

	Time resolution / hit	Position resolution / hit	Material budget / layer
Barrel ToF (Tracker)	<30 ps	(3-30 μm for Tracker)	$< 0.01\ X_0$
Endcap ToF (Tracker)	<25 ps	(30-50 μm for Tracker)	e-direction $< 0.05X_0$ h-direction $< 0.15X_0$





***π/k separation**: 0.1~4-5 GeV; **k/p separation**: 0.1~7-8 GeV*

by Wei Li (Rice)

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4D Detectors in Space and Imaging

Space detectors for charged cosmic ray and γ-ray measurements require solid state tracking based on silicon microstrip sensors

Operating Missions						
	Mission Start	Si-sensor area	Strip-length	Readout channels	Readout pitch	Spatial resolution
Fermi-LAT	2008	$\sim 74\,m^2$	38 cm	$\sim 880 \cdot 10^3$	228 μm	$\sim 66\,\mu m$
AMS-02	2011	$\sim 7\,m^2$	29–62 cm	$\sim 200 \cdot 10^3$	110 μm	$\sim 7\,\mu m$
DAMPE	2015	$\sim 7\,m^2$	38 cm	$\sim 70 \cdot 10^3$	242 μm	$\sim 40\,\mu m$

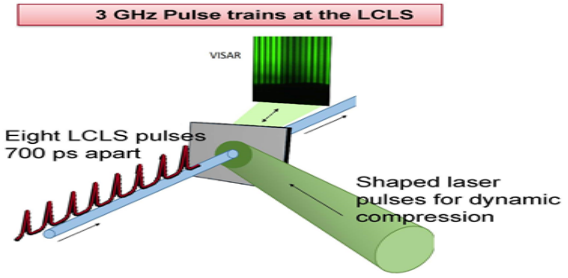
Future Missions						
	Planned operations	Si-sensor area	Strip-length	Readout channels	Readout pitch	Spatial resolution
HERD	2030	$\sim 35\,m^2$	48–67 cm	$\sim 350 \cdot 10^3$	$\sim 242\,\mu m$	$\sim 40\,\mu m$
ALADInO	2050	$\sim$ 80-100 m^2	19–67 cm	$\sim 2.5 \cdot 10^6$	$\sim 100\,\mu m$	$\sim 5\,\mu m$
AMS-100	2050	$\sim$ 180-200 m^2	$\sim$ 100 cm	$\sim 8 \cdot 10^6$	$\sim 100\,\mu m$	$\sim 5\,\mu m$

A. Seiden at TIPP '21

- **Timing for astro-particle detection : <100 ps timing to separate hits from primary particles and secondary backsplash, and for particle spectroscopy via ToF**
  - Radiation hard detectors
  - Low mass and low power electronics
  - Compact detector

4D Photon detectors have multiple applications in visible and X-ray

- Imaging:
  - **Low energy ion mass spectroscopy**
  - **Single photon detection (QIS)**
  - **Medical imaging** (PET): timing improves ToF resolution hence extend application to children
- Biology:
  - **Sub-ns timing allows to study fast evolving samples**
- Soft X-rays for studies of nanoscale dynamics of materials:
  - **Soft-X-rays**: 250 eV - 1.5 keV range is of considerable scientific interest (characteristic energies from Carbon, transition element L-edges, and rare-earth M-edges)



X-ray Detection: speed is the goal

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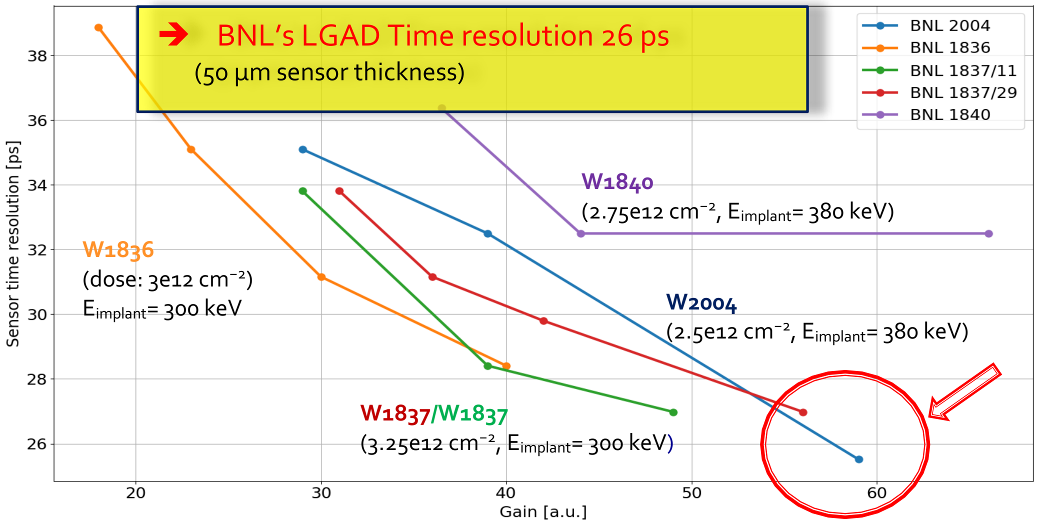
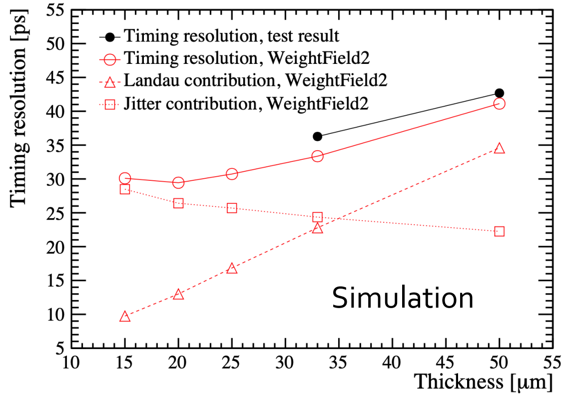
Development towards 4D detectors

- Increasing need to 4D capabilities in a single detecting element
- Several developments needed to meet requirements of future experiments in HEP, Nuclear Physics, Photon Science, Astro-particles, Imaging etc.
  1. Improve time resolution to 10-20 ps per hit
  2. Achieve space resolution of ~1 micron
  3. Reduce power dissipation in readout electronics
  4. Reduce material budget
  5. Improve radiation hardness

Improvements on Time Resolution



- With 50 µm thickness, resolution levels off because of Landau fluctuations at about 30 ps → Thinner sensors
  - Landau fluctuations proportional to the detector thickness
    - Time resolution improves for thinner sensors!
      - 20, 30 micron thick sensors are being produced and tested
- Signal height can be adjusted by changing detector voltage and gain
  - < 20 ps timing resolution with ~20 µm thick LGADs is achievable



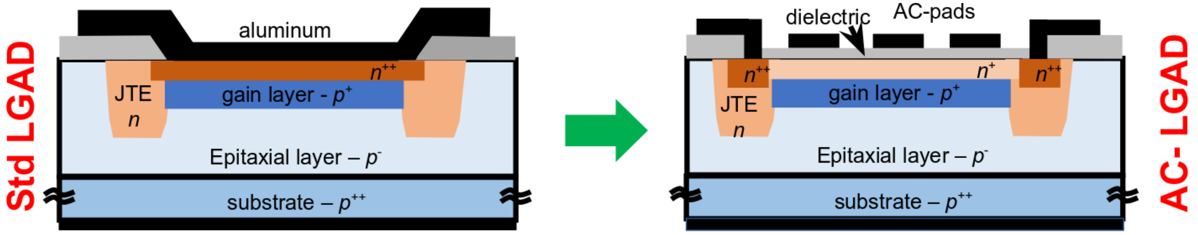
- Jitter dominates in thin detectors
  → to be minimized with low noise electronics and large signal (gain and voltage).

$$\sigma_{\mathrm{Jitter}} = \frac{N}{(dV/dt)} \simeq \frac{t_{\mathrm{rise}}}{(S/N)}$$

M. Li et al. (2021)
doi:10.1109/TNS.2021.3097746.

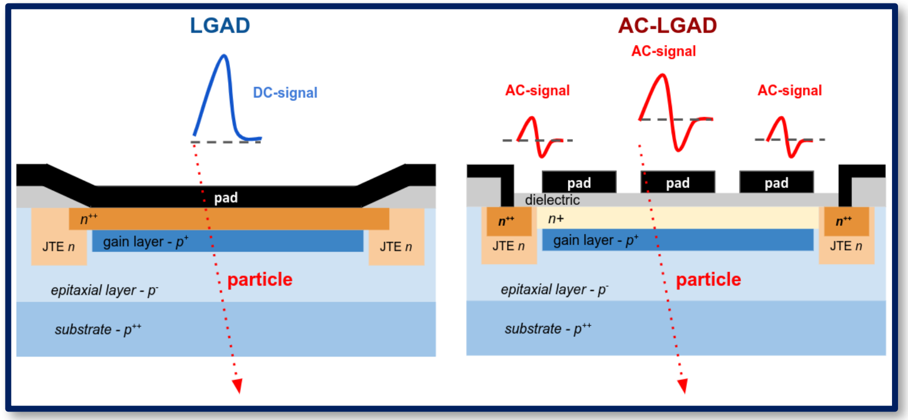
New designs towards 4D det. → AC-LGAD

- LGAD-based technologies have been developed to combine the good timing of LGADs with position resolution.
  - AC-coupled LGAD (AC-LGAD) ← Most advanced
  - Deep Layer AC-LGAD
  - Deep Junction LGAD
  - Trench Isolation LGAD (TI-LGAD)
  - Inverted LGAD (iLGAD)

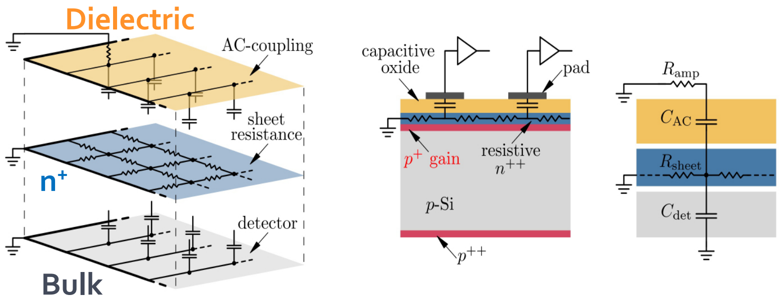


Large pads (~1 mm²) → Timing only

Can be finely pixelated
→ Time+Space (4D)



- One large low-doped / high-ρ n^+ implant over the all active area (instead of a highly doped / low-ρ n^{++})
- A thin insulator over the n^+ where electrodes are placed → AC-coupling
  - **Signal is bipolar,** generated by drift of multiplied holes into the substrate, AC-coupled through dielectric
  - **Signal is shared between multiple electrodes**
  - Electrons collected at the resistive n^+ and then slowly flow to an ohmic contact at the edge (n^{++})
- 100% fill factor and fast timing information at a per-pixel level → 4D



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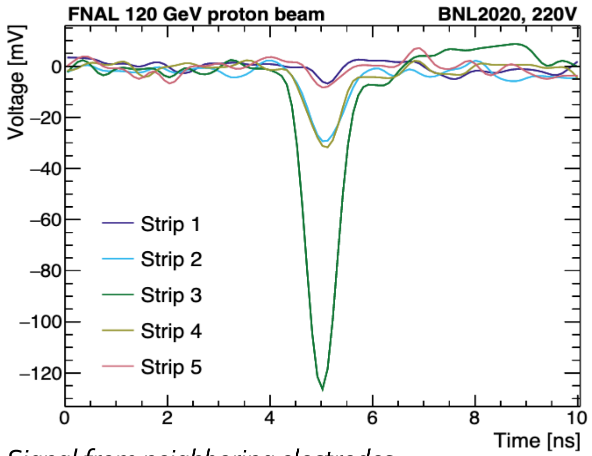
Signal Sharing in AC-LGAD

- Signal sharing depends on electrode geometry (pitch, gap size) and resistivity of n+ layer → tunable

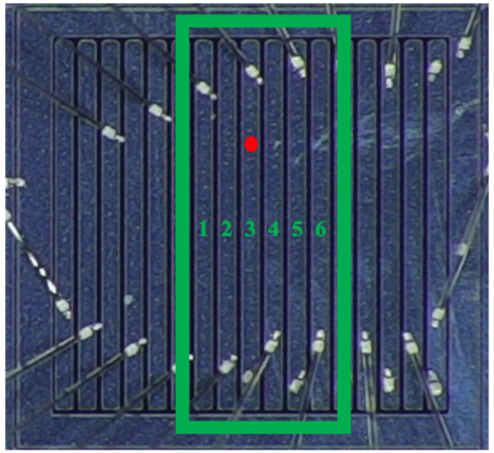
- Signal decreases for electrodes away from hit position
  - It is exploited to improve space/time resolution

- Sparse metallization results in lower capacitance (noise), and lower power by limiting channel count.

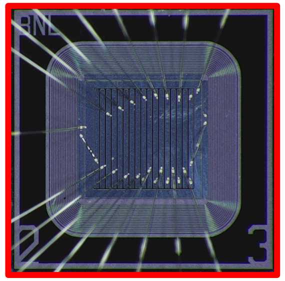


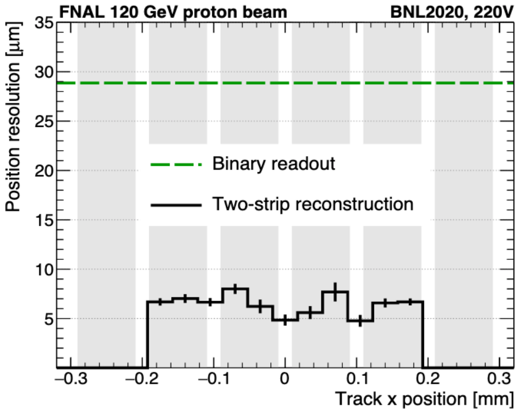
*Signal from neighboring electrodes generated by **120 GeV protons***

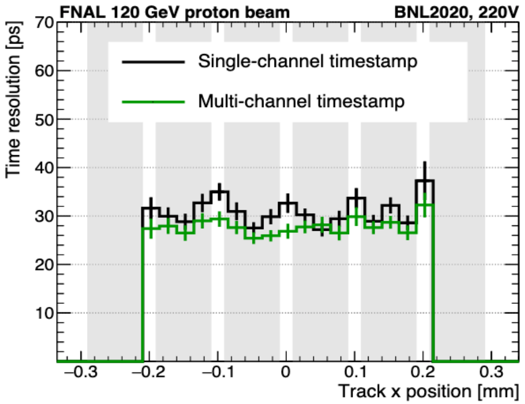
***BNL Strip AC-LGAD**: 100 μm pitch, 20 μm gap, 1.7 mm long strip*



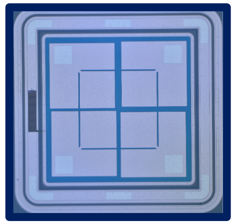
***BNL Strip AC-LGAD**: 100 μm pitch, 80 μm metal width, 1.7 mm long strip*

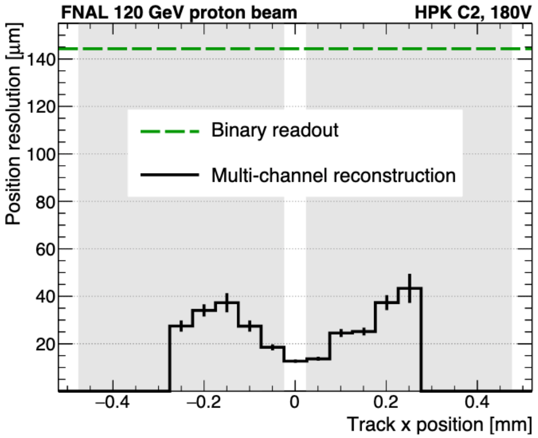






HPK Pixel:
500 x 500 mm^2





~1 μm resolution is at reach with medium-size pixels

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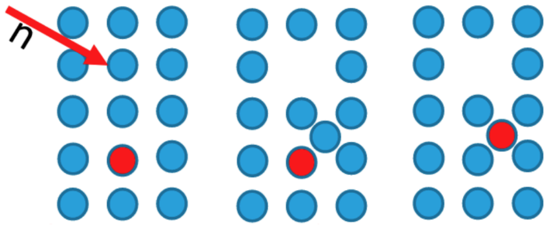
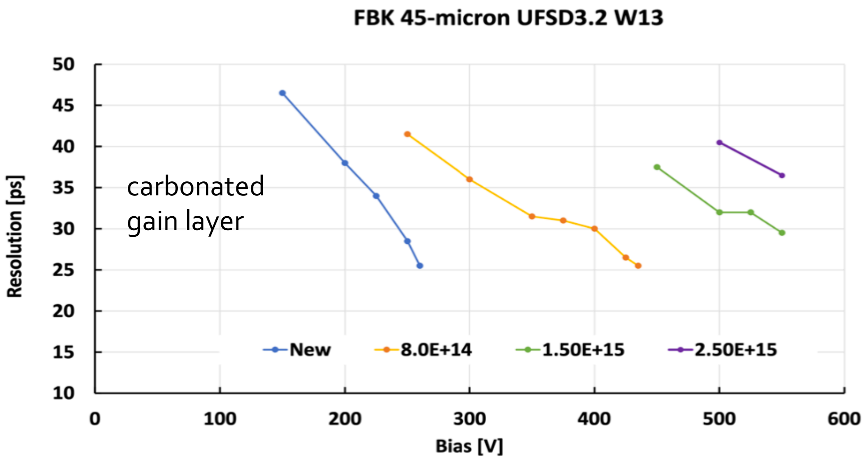
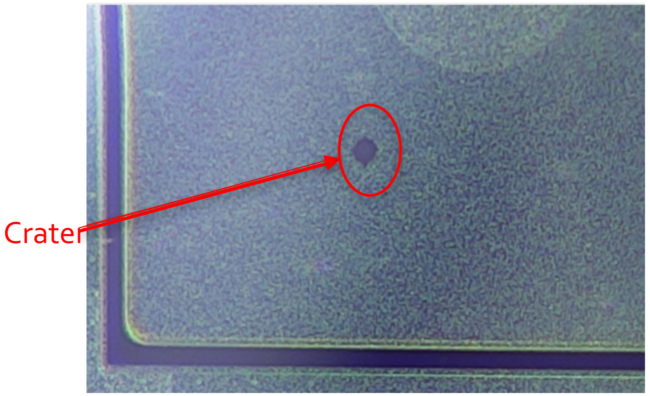
Radiation Hardness in LGADs

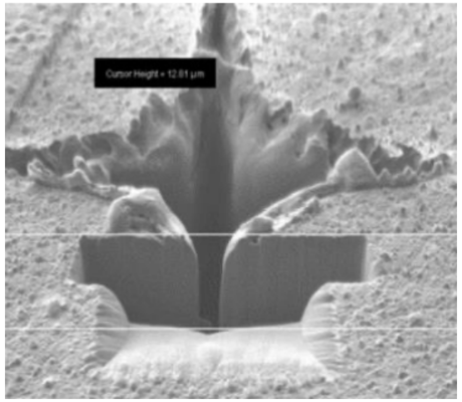
- One of the biggest challenges is radiation hardness at hadron colliders
- LGADs will operate up to $2.5\ 10^{15}\ n/cm^2$ at HL-LHC
- Effective reduction of gain in LGADs at high fluence, and sudden death at high voltages
  - Boron in gain layer loses effectiveness → Acceptor Removal
    → raising the voltage to maintain a large enough net gain layer field
  - Death (crater) in HPK 50 μm LGADs at V_{bias} >600 V ($\gtrsim 10^{15}\ n/cm^2$)



- AC-LGADs are subject to similar radiation damage as LGADs







- Several ideas and ongoing studies to improve radiation hardness
  - **Carbon infusion in gain layer** (carbon ties up defects that otherwise would inactivate Boron)
  - **Thinner gain layer:** damage sites uniformly distributed over the silicon after irradiation → **thin gain layer reduces volume exposed to radiation**
  - **Deep gain layer e.g. ~ 2 μm**: amplification depends not only on the field but also its spatial extent

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Conclusions

"Natural science [...] describes nature exposed to our method of questioning."
W. Heisenberg, "Physics and Philosophy", 1962

- In HEP we are searching for **experimental** guidance for New Physics
  - The LHC and Future Collider experiments aim at pushing further out the boundaries of exploration of HEP landscape
- This exploration needs **novel detectors**
  - **Fast-time silicon technologies** will be the key for coping with the challenging HL-LHC environment (high radiation and pileup) and at future collider experiments (hadron and lepton colliders)
  - Multiple and diverse ideas for **4D silicon detectors** are being studied
- The impact of this **novel silicon technologies** can be vast in many fields
  - Nuclear physics, measurements of rare processes, space science, photon science, imaging etc.
- Detectors have to be designed **holistically** from the start as all parts are interdependent:
  - Coherent design of sensors, front-end electronics, services, cooling, power management, on/off-detector data-reduction, interplay with other subsystems etc.

Questions?