ATLAS Phase II Upgrade

How did we end up with this?

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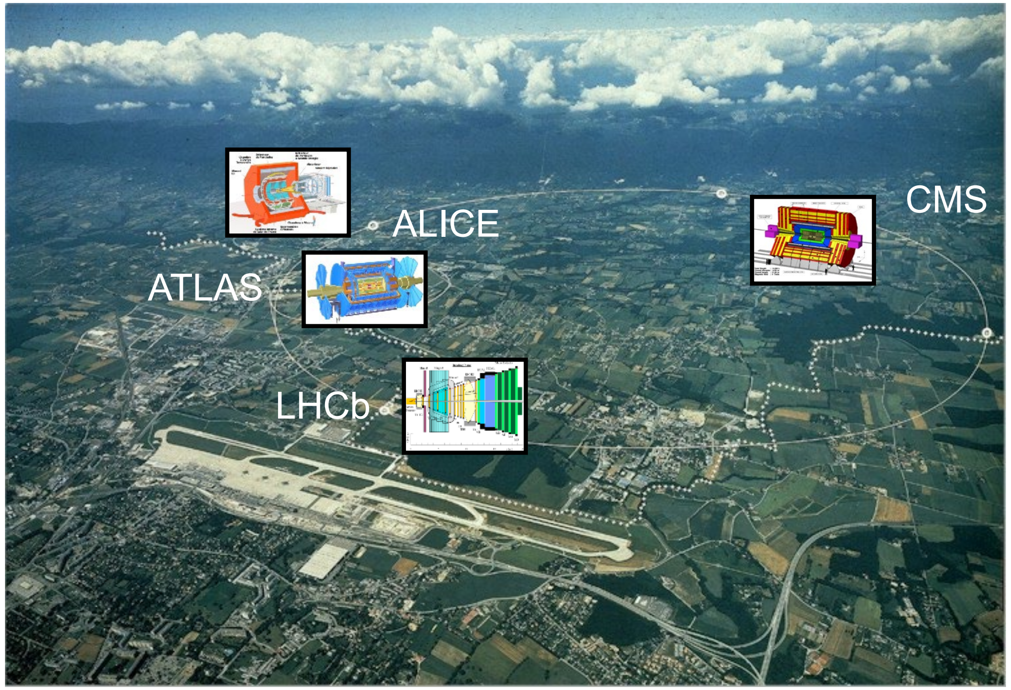
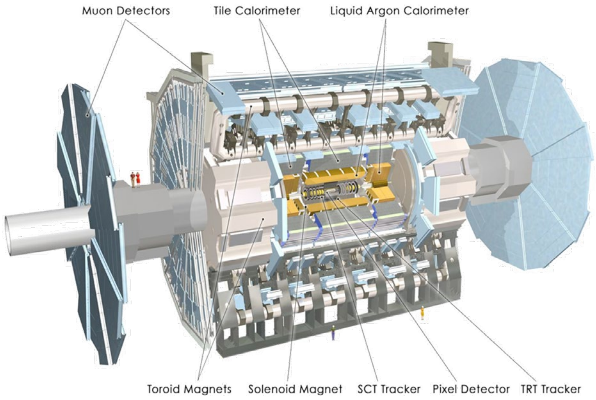
Birmingham Particle Physics Group Seminar

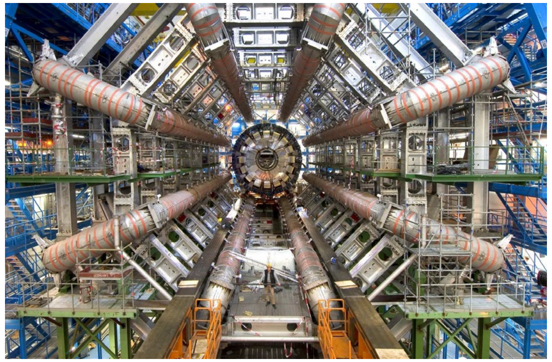
27th April 2022

ATLAS & the LHC

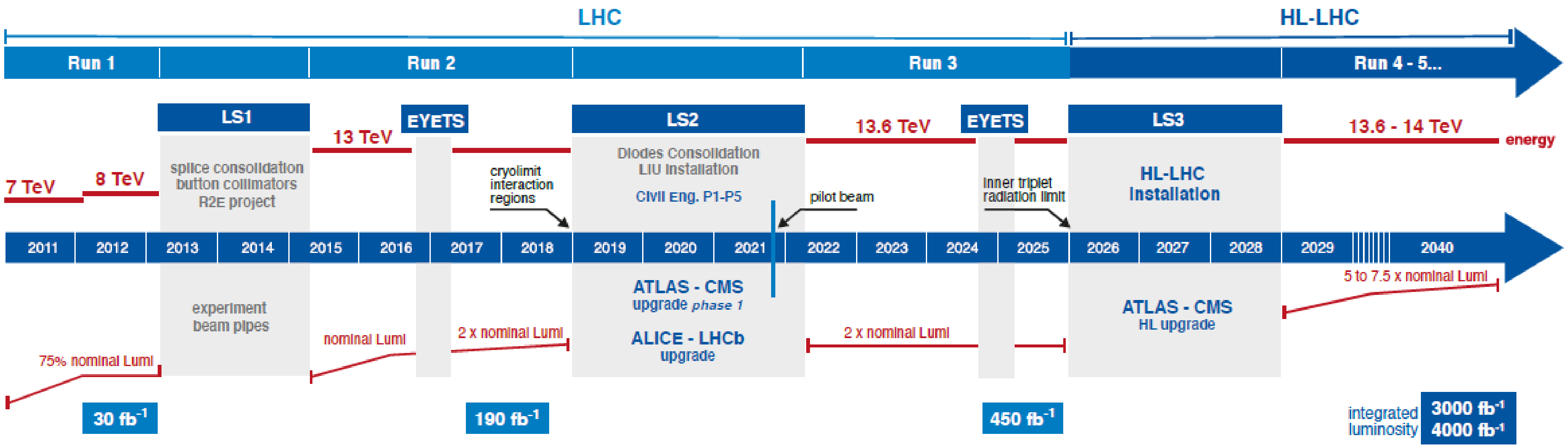
- Large Hadron Collider (LHC)
  - Circumference: 27 km
  - 1600 super conducting magnets
  - Center-of-mass energy: 13.6 TeV
- ATLAS experiment is a 4π coverage, "general-purpose" detector
  - Discovery + precision physics





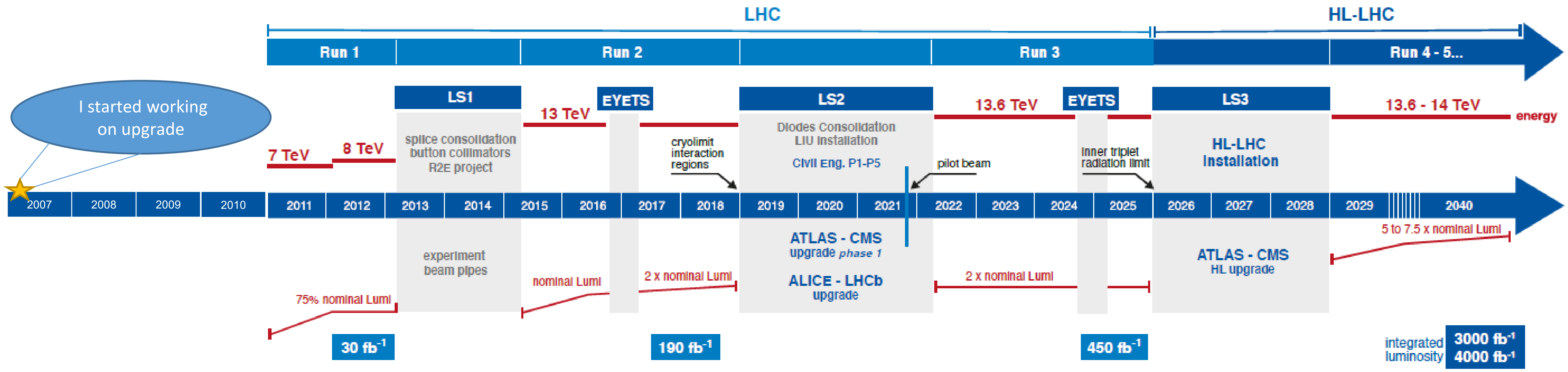


HL-LHC



- HL-LHC will provide a 10-fold in increase of integrated luminosity, enabling a broad program covering all areas of hadron collider physics of ATLAS
  - Installation of upgrade begins in 2026
  - Operations commence in late-2029 for about ten years
- Involves upgrades to the accelerator complex as well as all experiments

HL-LHC



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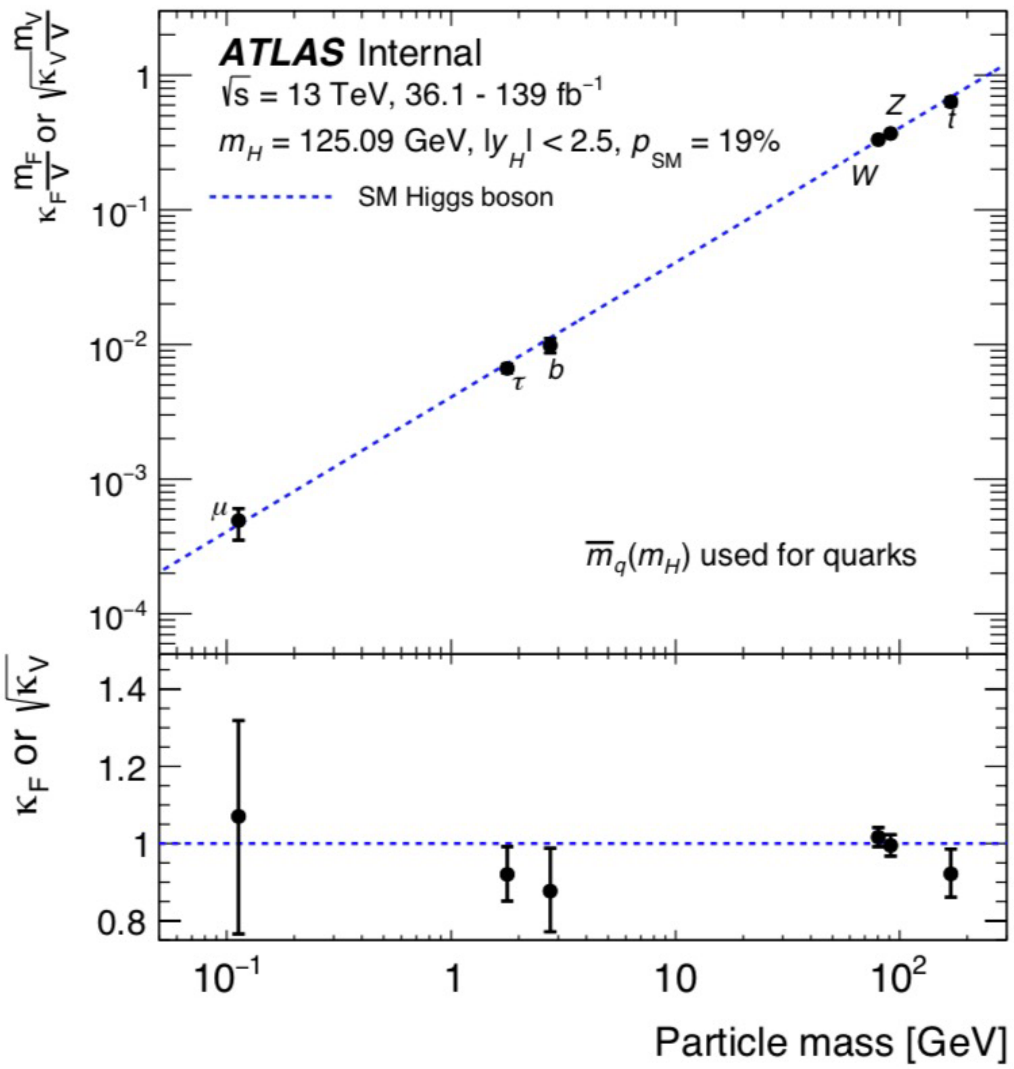
ATLAS HL-LHC Physics Program

- Highlights include:
  - Measurement of Higgs boson properties: couplings, mass, width, self-coupling
  - Precision electroweak measurements: vector boson scattering, triboson couplings, rare processes
  - Searches for Beyond Standard Model physics: SUSY, dark matter, new resonances, long-lived particles
  - Flavor physics studies: rare bottom and top decays, constraints on CKM
- Recent public studies:
  - Sensitivity to H -> bb and cc in VH production [ATL-PHYS-PUB-2021-039]
  - Sensitivity to WW production in photon-photon scattering [ATL-PHYS-PUB-2021-026]



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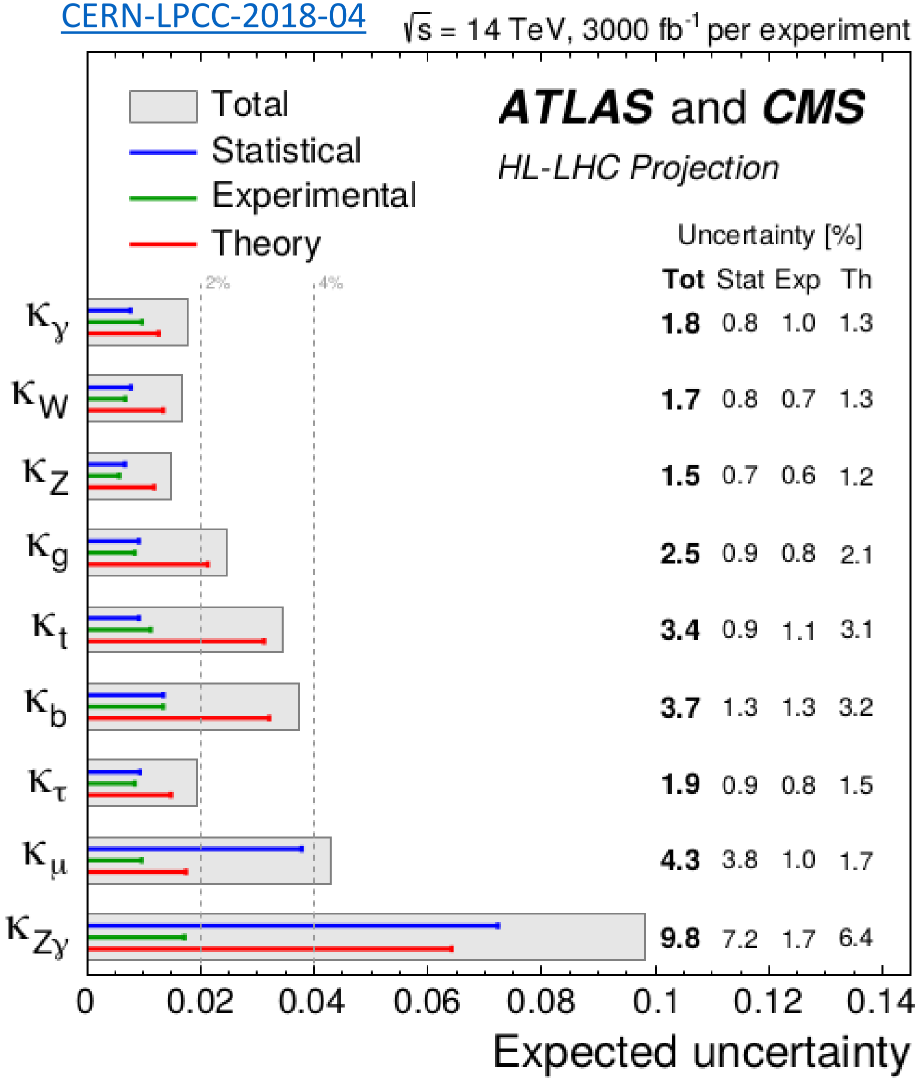
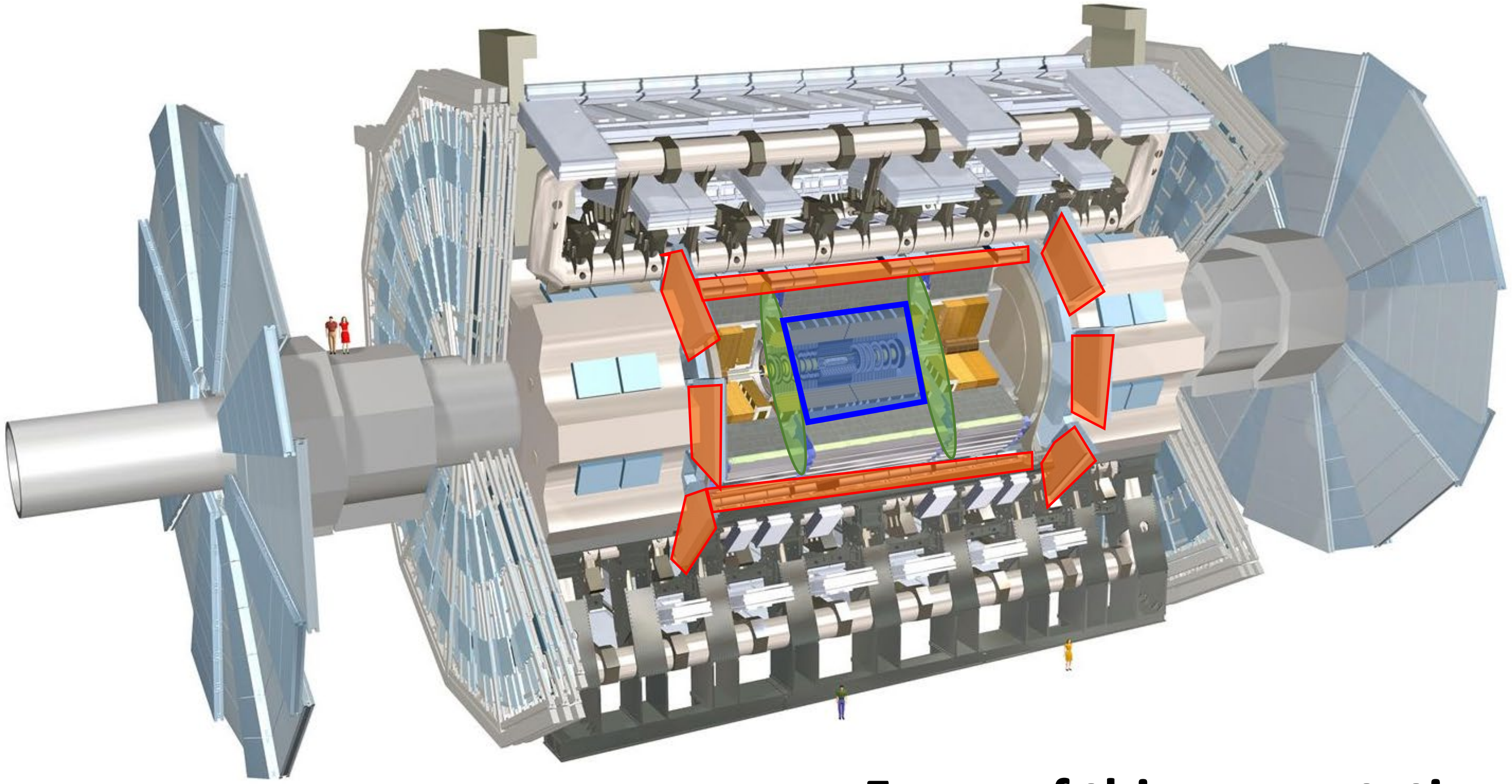
CERN-LPCC-2018-04



ATLAS Phase-2 Upgrade



Upgraded Trigger and Data Acquisition System

- Single Level Trigger with 1 MHz output
- Improved 10 kHz Event Farm

Electronics Upgrades

- On-detector/off-detector electronics upgrades of LAr Calorimeter, Tile Calorimeter & Muon Detectors
- 40 MHz continuous readout with finer segmentation to trigger

High Granularity Timing Detector (HGTD)

- Precision time reconstruction (30 ps) with Low-Gain Avalanche Detectors (LGAD)
- Improved pile-up separation and bunch-by-bunch luminosity

Focus of this presentation

New Muon Chambers

- Inner barrel region with new RPCs, sMDTs, and TGCs
- Improved trigger efficiency/momentum resolution, reduced fake rate

New Inner Tracking Detector (ITk)

- All silicon with at least 9 layers up to $|\eta| = 4$
- Less material, finer segmentation

Additional small upgrades

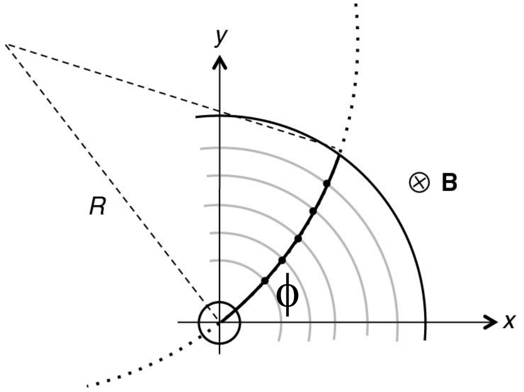
- Luminosity detectors (1% precision)
- HL-ZDC (Heavy Ion physics)

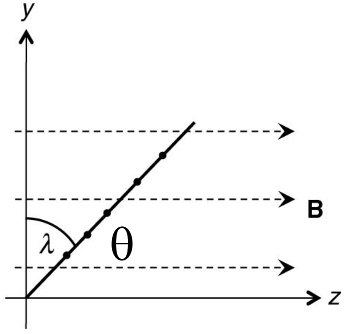
Disclaimer

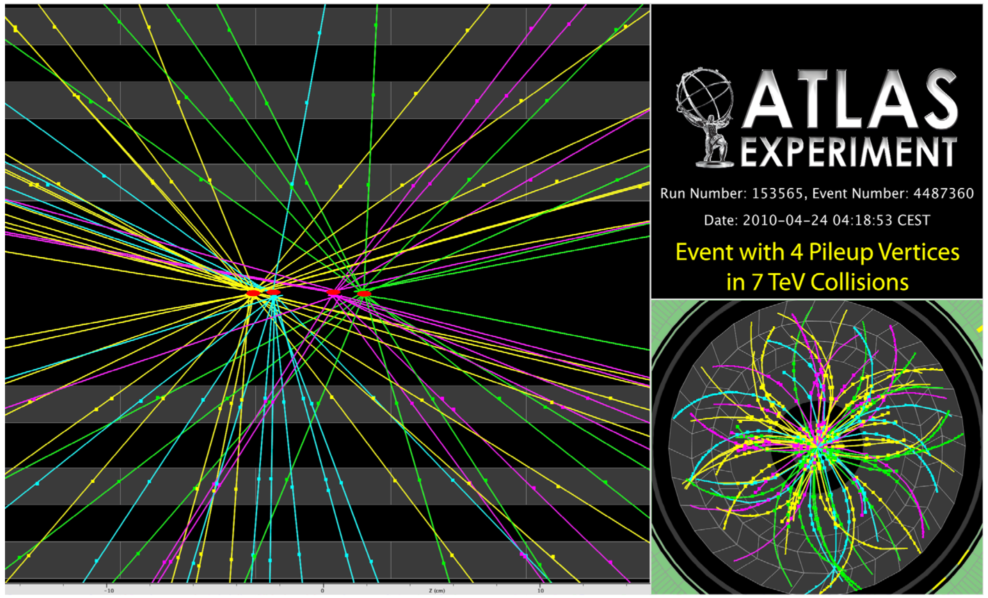
- I am a detector nomad - going to where the next big build is:
  - KTeV ⇨ CDF ⇨ CMS ⇨ LHCb ⇨ ATLAS
- I am interested (love) the technology which enables particle physics, in particular trackers.
  - I care about physics outcomes, but really not an expert in data analysis
- This talk will align strongly to my specialties: sensors, readout electronics, modules (packaging)
  - Many, many more interesting technologies and issues than I can cover here
- And this is all been extremely simplified
  - We could have spent a whole seminar on each slide
- The goal of this seminar to is cover the main enabling technologies of the ATLAS upgrade tracker (ITk), describe the drivers for the layout and the issues we had to solve.
  - And a short look to the future

What does a tracking detector do?

- Tracking detectors
  - Measure position and momentum of charged particles
    - Transverse momentum (p_T) – From curvature of track
    - Impact Parameter (d_0) – x-y distance of closest approach of beam approach
    - Z_0 – Location along beam of closest approach point
    - ϕ and η ($-\ln \tan(\theta/2)$) – Angles of track in x-y plane and along z respectively
- A track is the reconstructed trajectory of a charged particle made by connecting hits from various layers
  - Pattern recognition is figuring out which hits go to what tracks (charged particles)

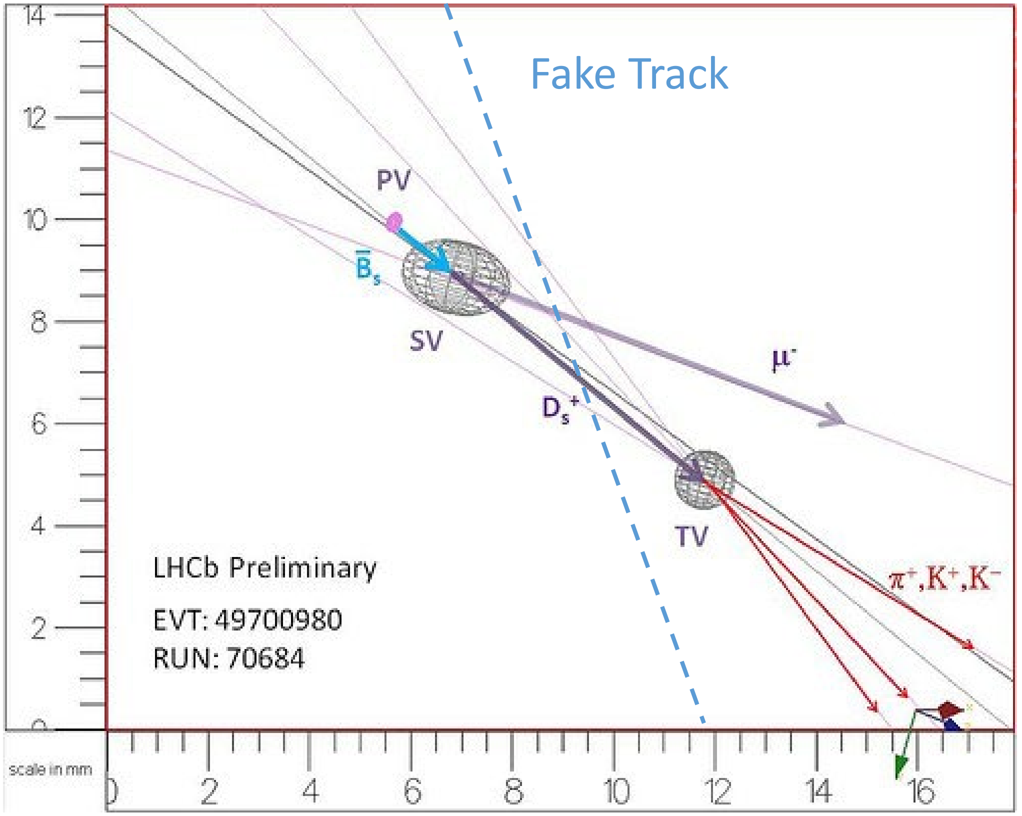




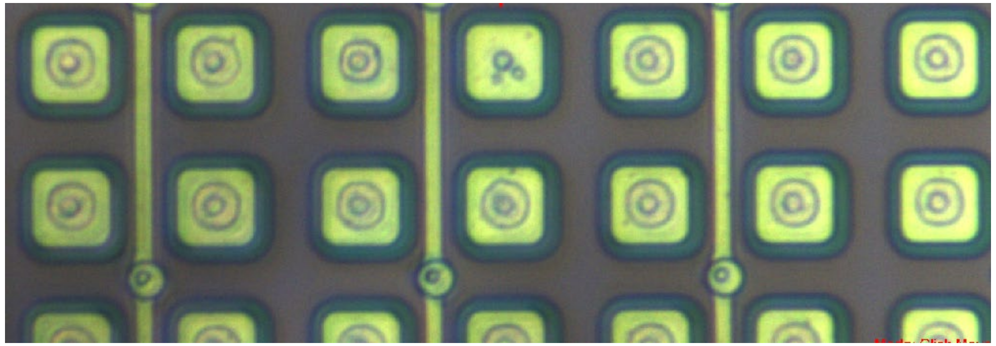


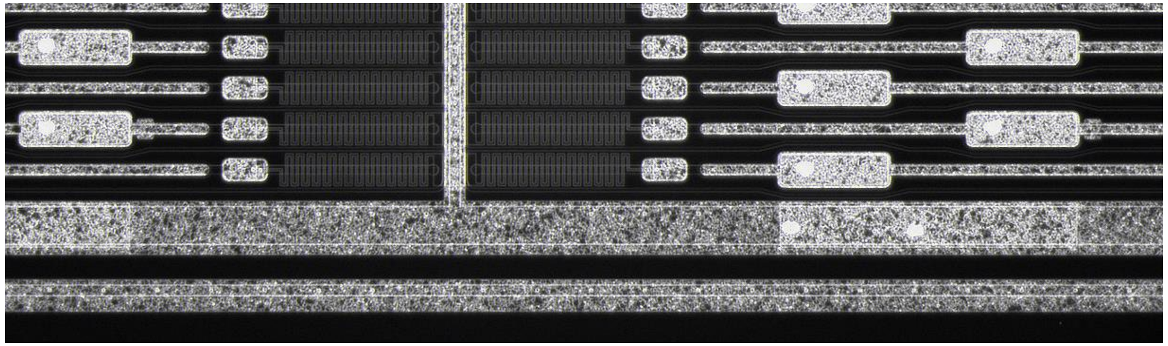
Fake Tracks and Vertices

- Vertexes
  - Location of Collisions (Primary)
  - Decay of Particles with Lifetime (Secondary/Tertiary)
- In search for new physics, reconstructing particles with bottom and charm quarks and τ mesons are critical
- Fake tracks (fakes) are a track that is a mis-constructed particle trajectory. Either from:
  - Merging two tracks
  - Mis-assigning some hits
  - Random combination of hits (unlikely)
- Fakes can have surprisingly large impact on the ability to reconstruct displaced vertices from decays of charm, bottom and tau particles



What are pixels and strips?

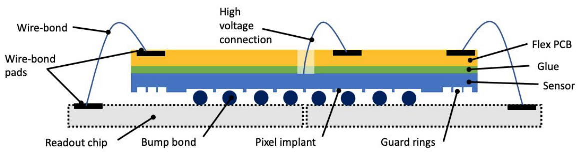


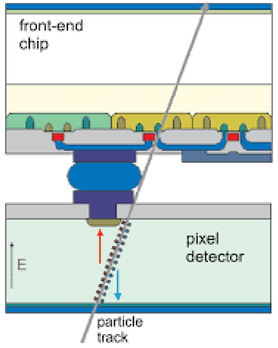


- Pixel Systems
  - Sensitive silicon sensor elements (nearly) square
    - 50×50 μm^2 (some 25×100 μm^2)
  - Near beam where finer segmentation needed to separate tracks
    - Drives d_0 and z_0 resolutions

- Strip System
  - Sensitive silicon sensor elements long and skinny
    - 75.5 μm x 2-6 cm
  - Covers larger area, further from beam
    - Drives momentum and η resolutions

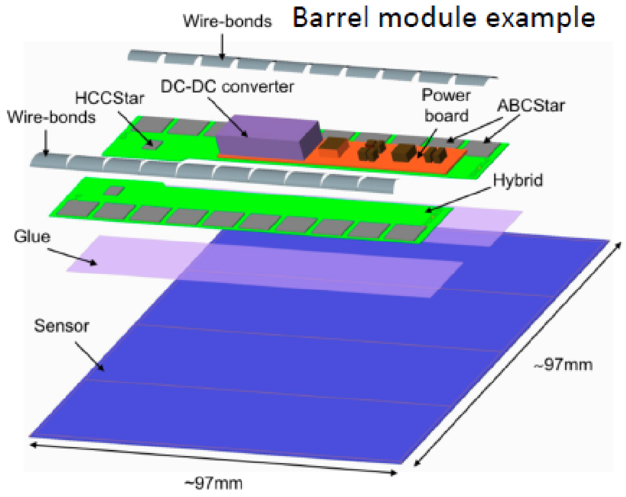
Hybrids and Modules

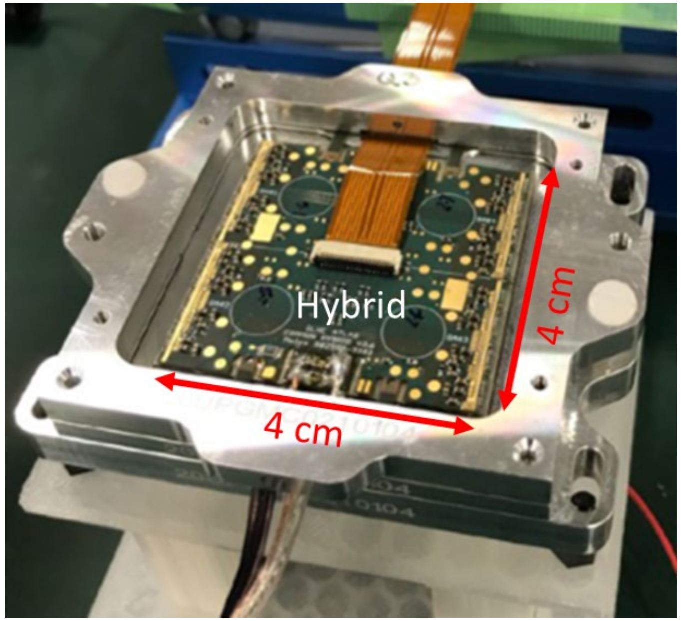




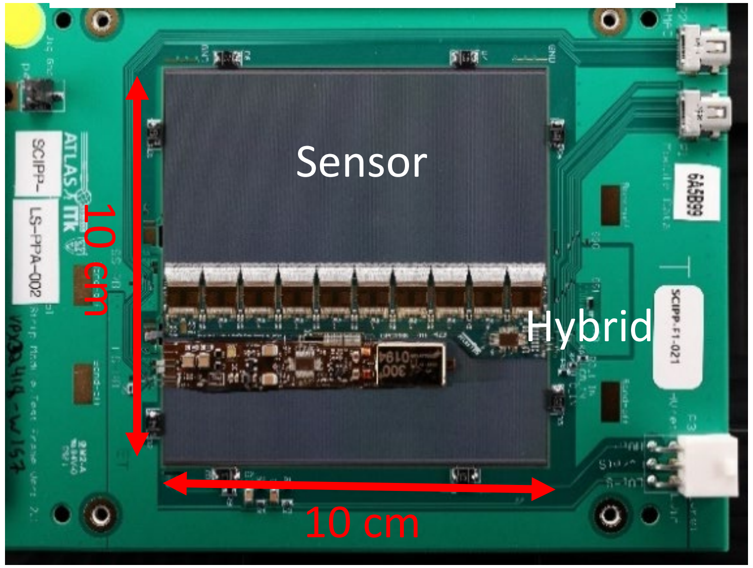
- Hybrid: Polyimide-Copper flexible circuit which can hold multiple custom ASICs and SMDs

- Module: smallest sensitive unit of a tracker. Consists of sensor, hybrid(s), support circuits





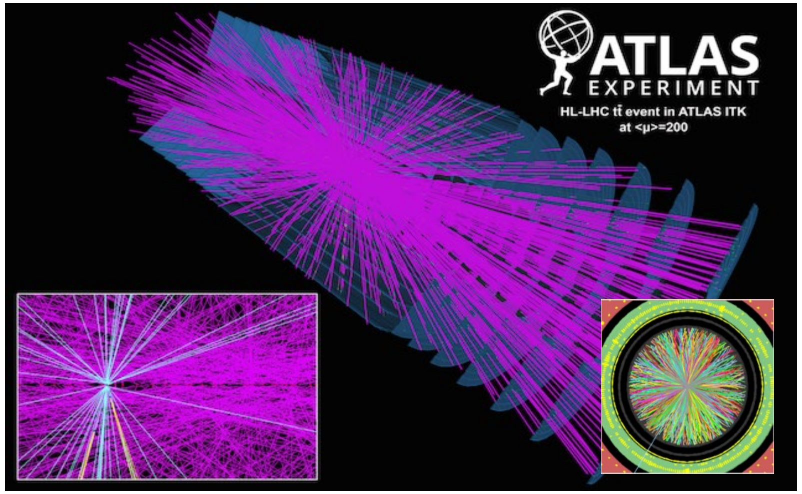
Pixel Quad Module

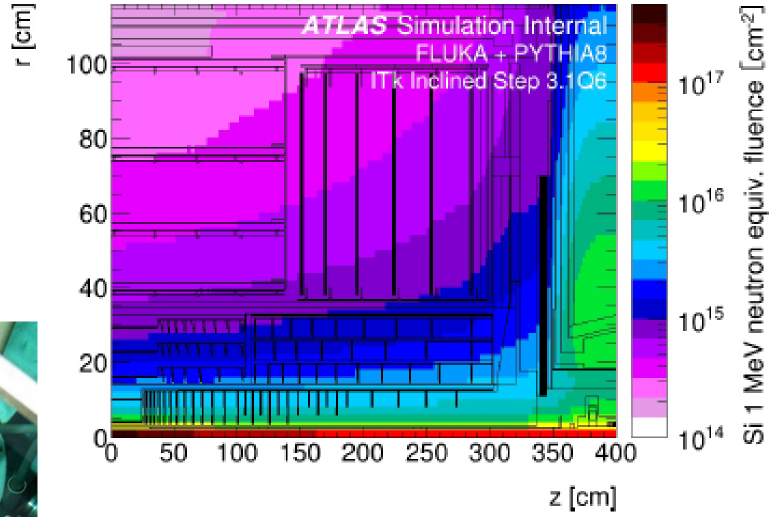


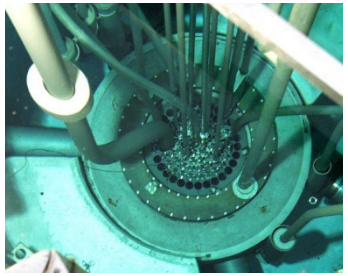
Strip Long Strip Module

Challenges

- Peak Luminosity: 7×10^{34} cm^{-2} s^{-1} (x7 now)
- Average Pile-Up:
  - Number of collisions per bunch crossing (every 40 ns)
  - HL-LHC: 200 (x5)
    - Compromises ability to assign hits to tracks
- Total Fluence: up to 2×10^{16} n_{eq} cm^2 (~x10)
  - Number of 1 MeV Neutron Equivalent Particles
    - Insert into TRIGA test nuclear reactor 50 minutes to reach dose

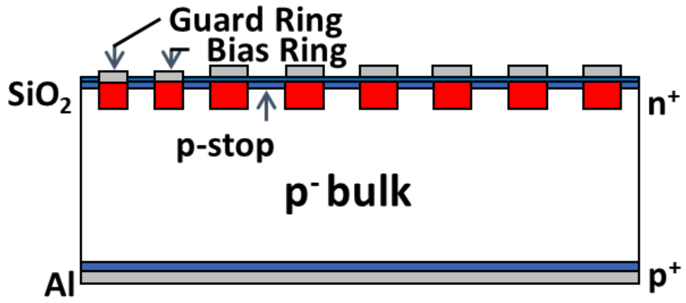


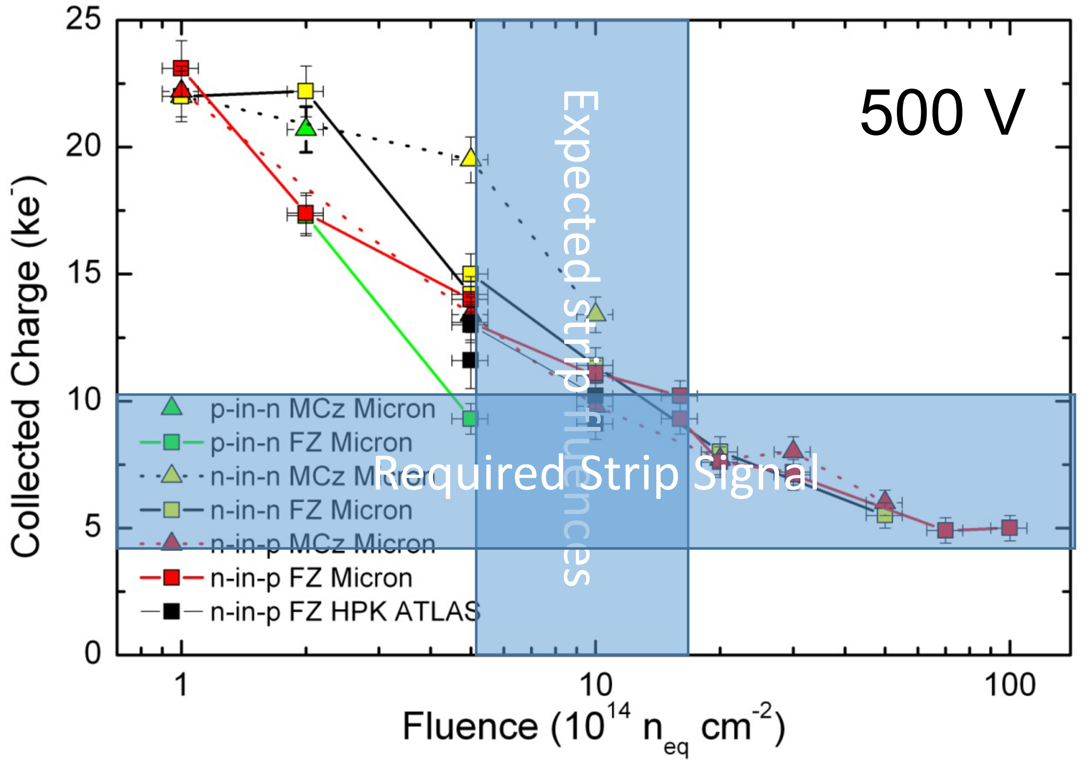




Enabling Technologies (RD50)

- At the beginning of the proposal for the HL-LHC, it wasn't clear silicon sensors would be radiation hard enough to be used in tracker
  - RD50 collaboration created by CERN to develop required technology
- **Bad news**: most developments in adding controlled contaminants and try different silicon crystal growth/processing didn't do a lot
- **Good news**: n-type silicon used in current pixel systems turned out to be much more radiation tolerant than first thought
  - Rule of thumb (strips): for efficient tracking signal-to-noise > 8-10:1 required
    - Noise: 500-1000 e- (strips)
  - Rule of thumb (pixels): for efficient tracking signal-to-noise > 2.5-4 required
    - Threshold: 600-1200 e- (pixels)





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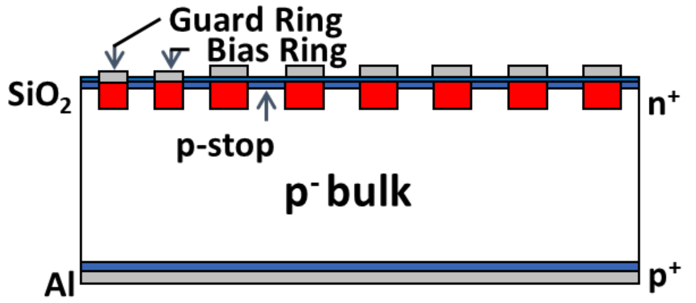
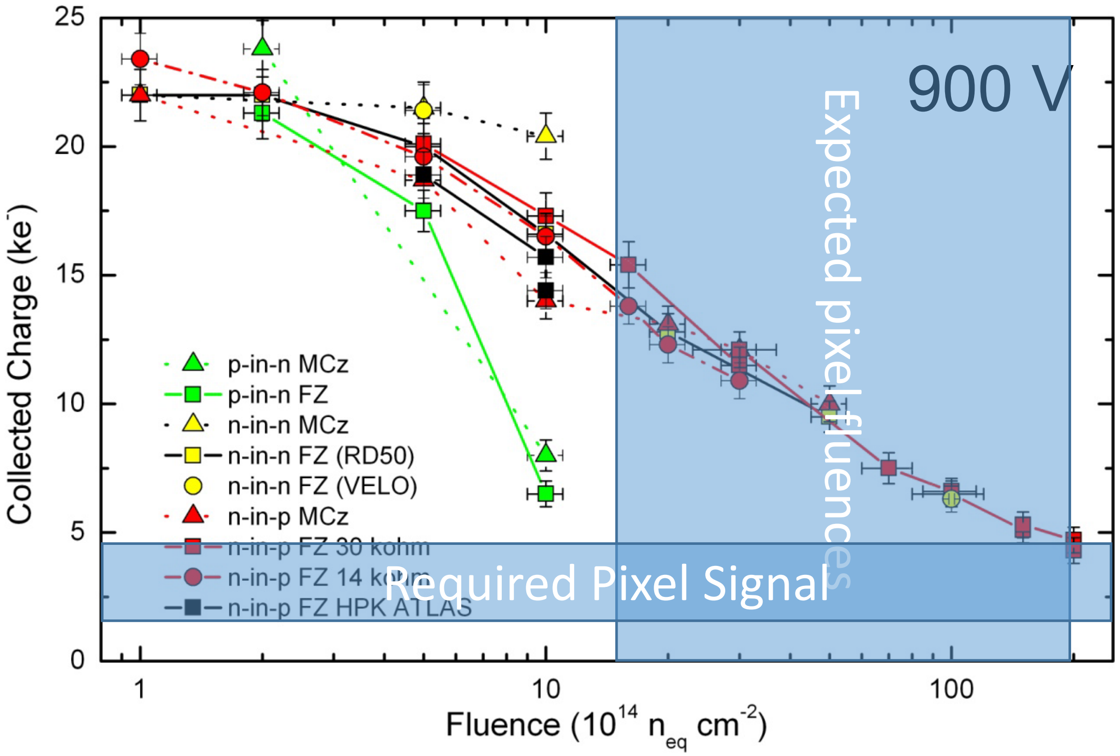
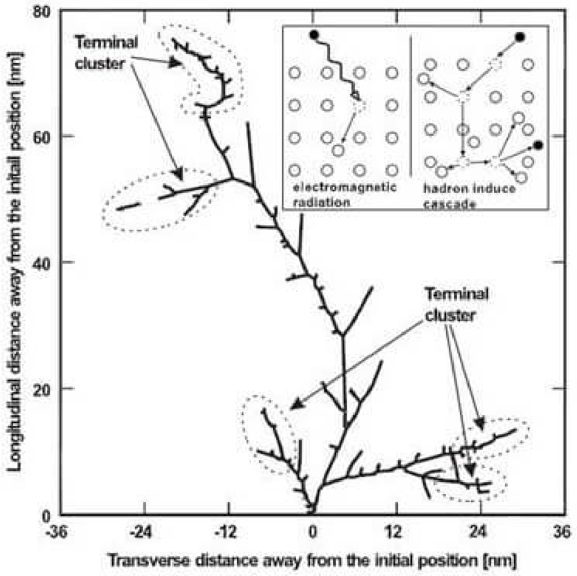
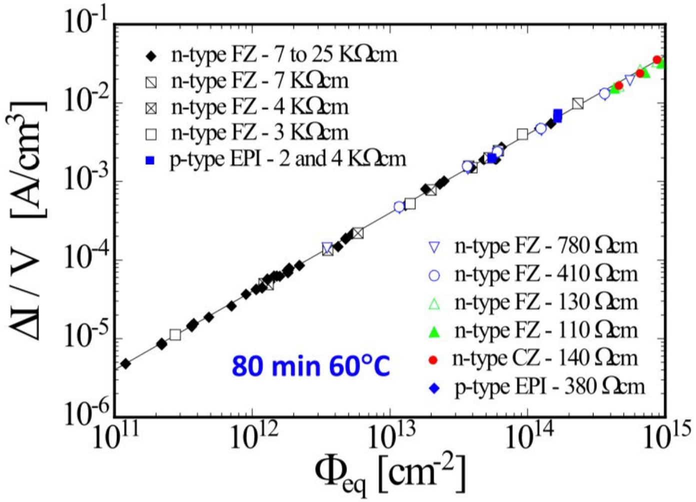




Radiation Impacts

- In addition to lose of signal, radiation has other impacts:
  - Increased leakage current
  - Annealing of damage sites
- Leakage current (power) depends strongly on temperature:
  - Factor of 2 per 7 C°
- Self-heating can lead to thermal runaway
  - Leakage Current heats sensor which increases leakage current…..
- Requires silicon sensors to operate and be kept at -10 to -20 C° for HL-LHC
  - Studies in previous slide all in a -45 C° chest freezer

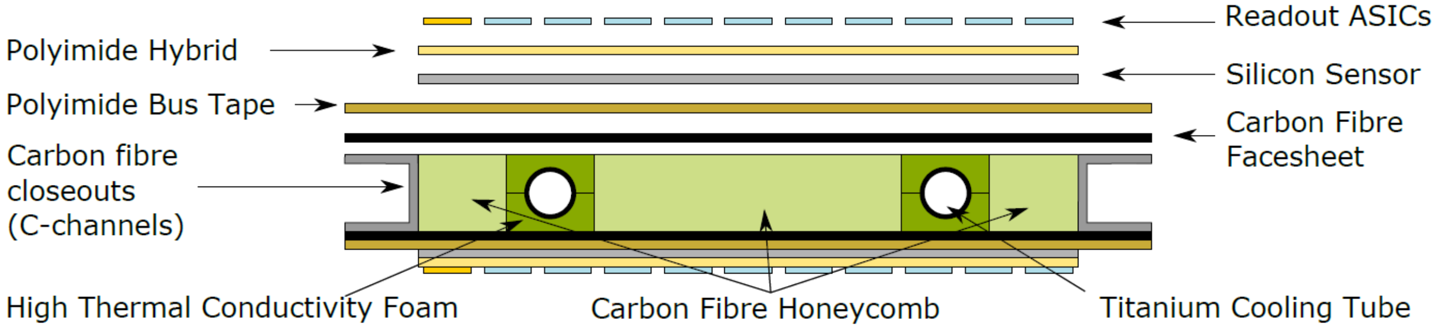




Enabling Technologies (Cooling and Mechanics)

- CO_2 cooling made a comeback
  - First in AMS and LHCb VELO
  - And now all silicon-based upgrades
- Minimum temperature of -45 C° (triple point of CO_2)
- Lightweight structures utilizing thin walled titanium tubes clad in newly developed custom carbon products cools sensors to -15 to -30 C°
  - Pressures up to 143 bar in failure condition
  - Carbon foam, (Thermal) Pyrolytic Graphite

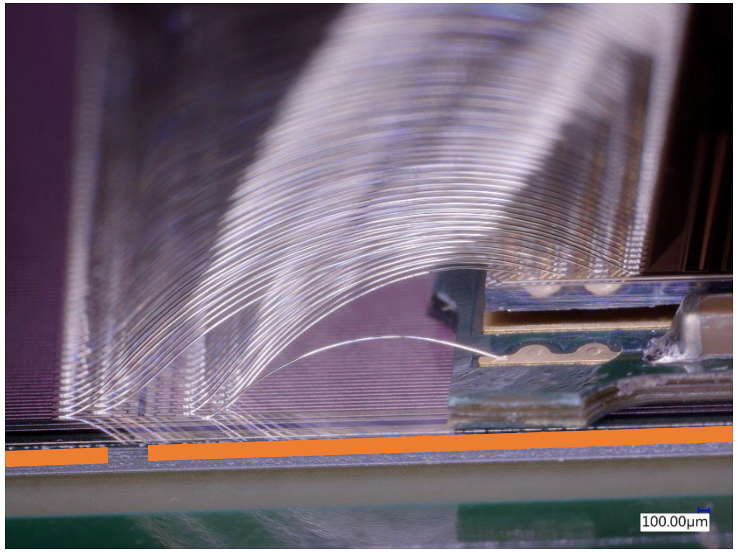
100 kW Demo Plant (Today)



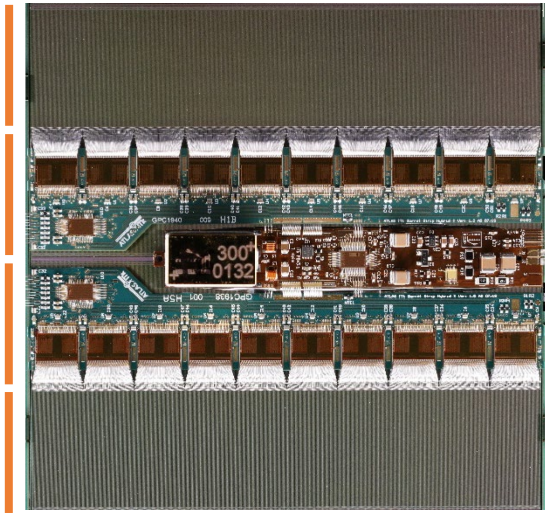
Design Requirements

Occupancy (Strips)

- Occupancy: % of channels with a hit
  - Rule of thumb (Strips): <1% occupancy required for efficient pattern recognition
    - Computing and fake rate
- Current SCT: 80 μm x 12 cm
  - Needed to get to 2-6 cm strip lengths based on peak luminosity
- Solution: 4 row bonding
  - Moved hybrids on top of sensor
    - Connected 2 rows to one set of strips and other 2 row to the next ones
- Made possible by ASIC technology (130 nm CMOS with "thick" metal layers for power)



4 segments of 1280 channels



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- ITk Strip detector at limits of this technology
  - Wire bonding limits pitch to ~60 μm
  - ASIC size and services limit strip lengths to >2 cm
- Need something new for future proton collider experiments!!

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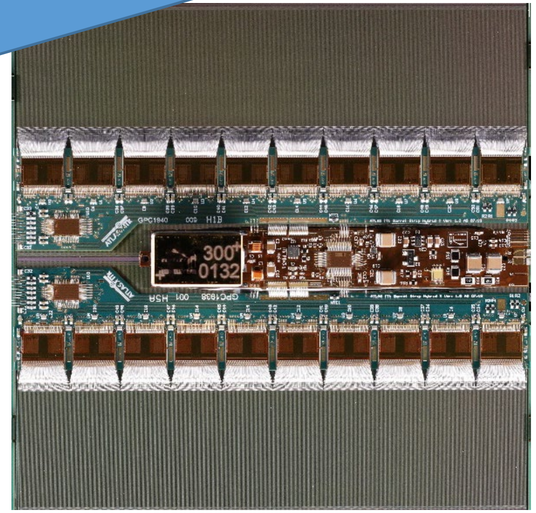
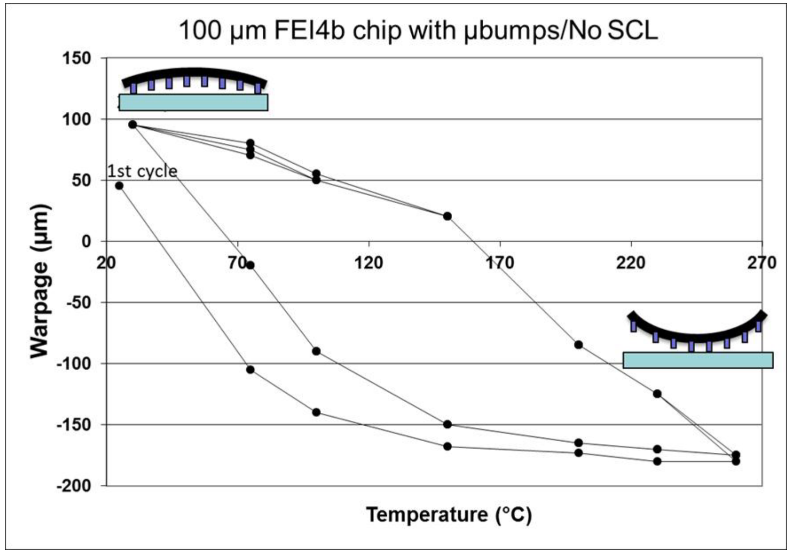
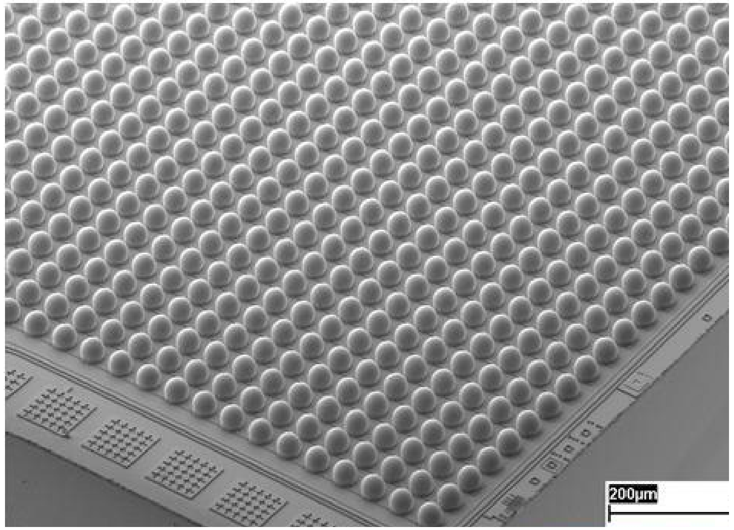


Occupancy (Pixels)

- Occupancy: % of channels with a hit
  - Rule of thumb (Pixels): <0.1% occupancy required for efficient pattern recognition
- Current pixel detector:
  - 50×400 μm^2 (50×250 μm^2 beam layer)
- Developed process to allow for bump bonding in 50×50 μm^2
  - Difficulties included:
    - Alignment of sensor to ASIC
    - Thermal mismatch during bumping process
      - Made worse by thin materials (sensor, ASICs)





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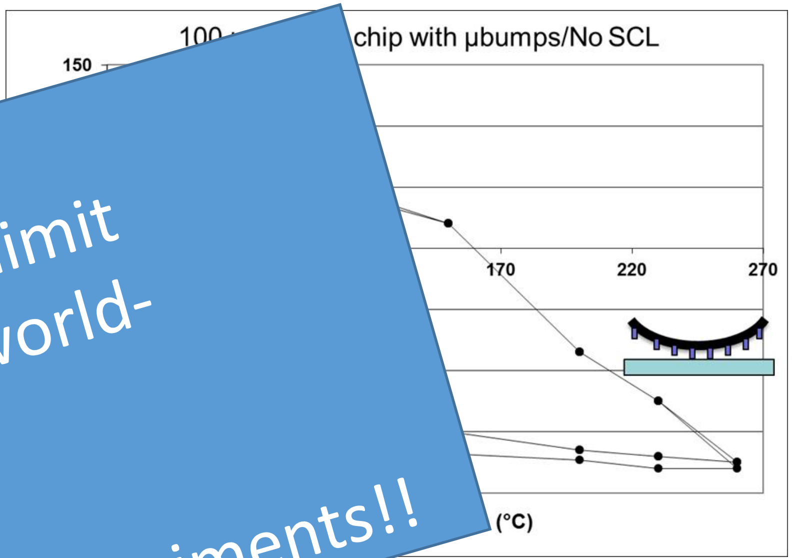
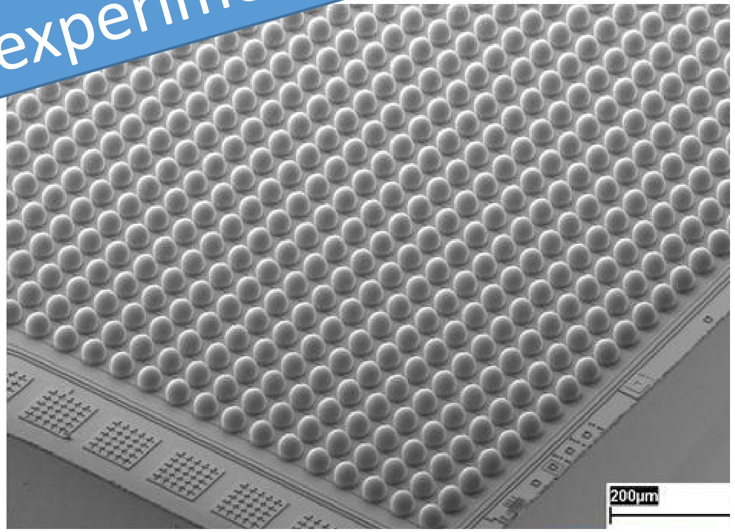
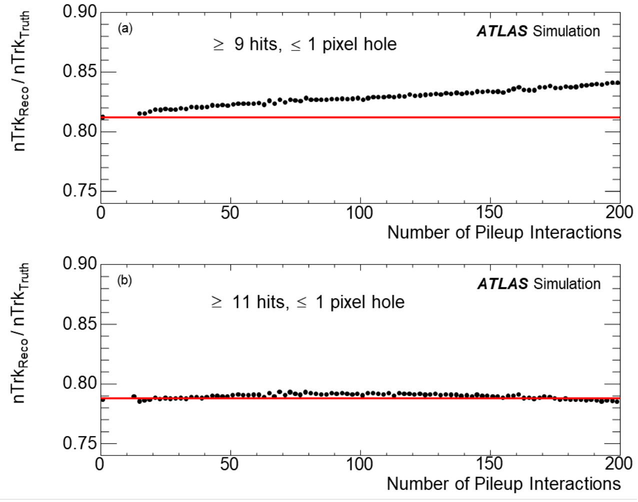


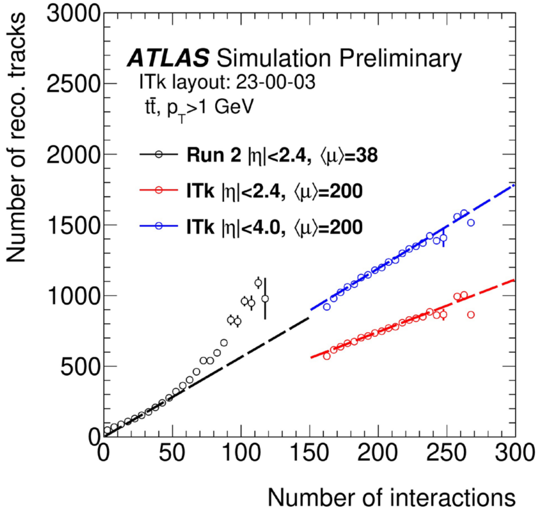


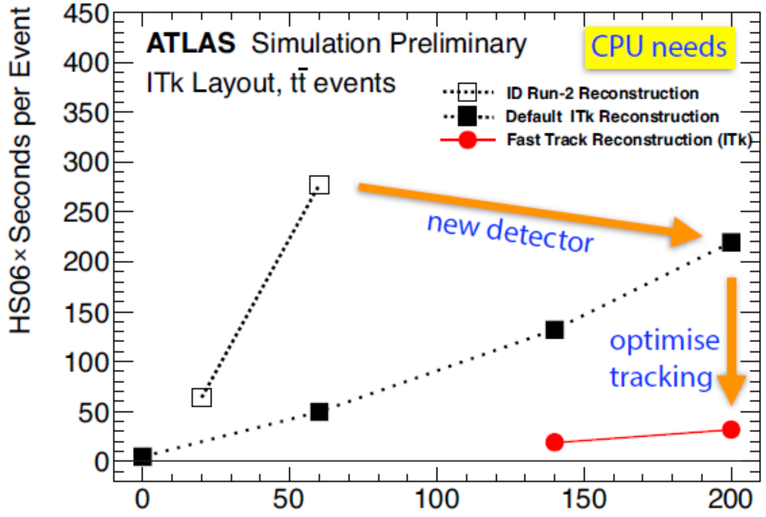
- ITk Pixel detector at limits of this technology
  - With thinned devices, 40x40 μm^2 may be the limit
  - ATLAS+CMS pixel upgrades taking ~100% of world-capability for 2 years
- Need something new for future proton collider experiments!!

Size/Number of Layers

- Number of layers driven by reconstruction time & resources as well as fake rates
  - Event complexity leads to significant increased to reconstruction time/computing resources
- Adding layers over-constrains track and makes hit linking easier
  - At the cost of efficiency, material and size

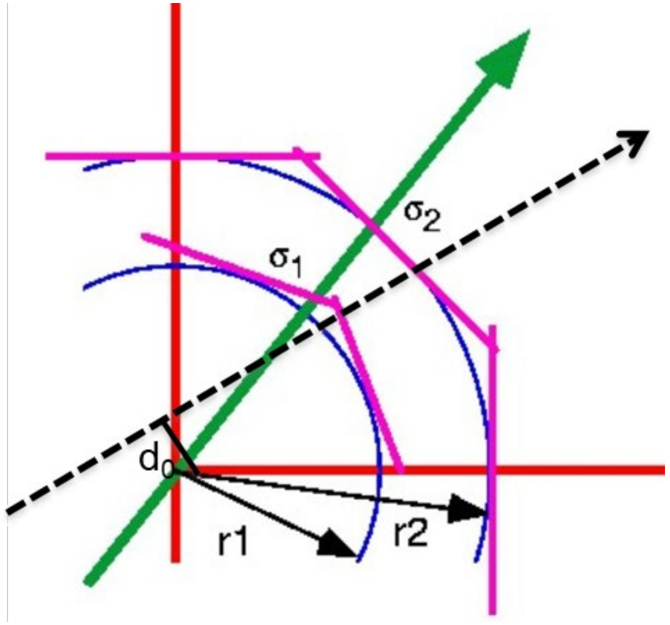






Innermost layer

- Impact parameter resolutions driven by first two layers.
  - Specifically: radii, segmentation, material
- Many constraints:
  - More radiation/track density at lower radius
    - Chip fixed size so overlaps larger at lower radius (higher material)
  - Beam pipe set by CERN
- Pixel cell size (25x100 μm2)
- Innermost radii at 34mm



$$\sigma_{d_0} \approx \sqrt{\frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}} \oplus \frac{r}{p\sin^{3/2}\theta} 13.6\mathrm{MeV}\sqrt{\frac{x}{X_0}}$$

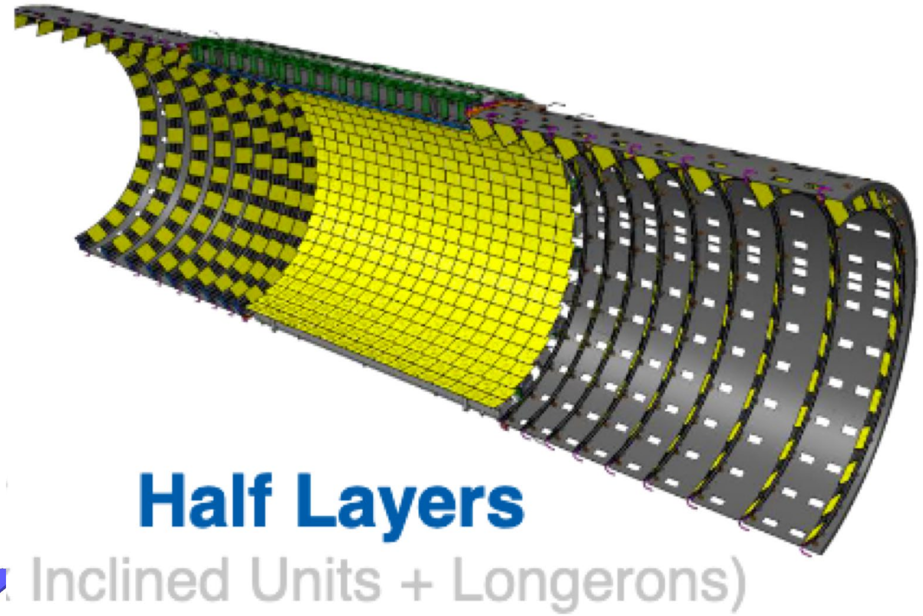
$$\sigma_{d_0} \approx a \oplus \frac{b}{p_T \sin^{1/2}\theta}$$

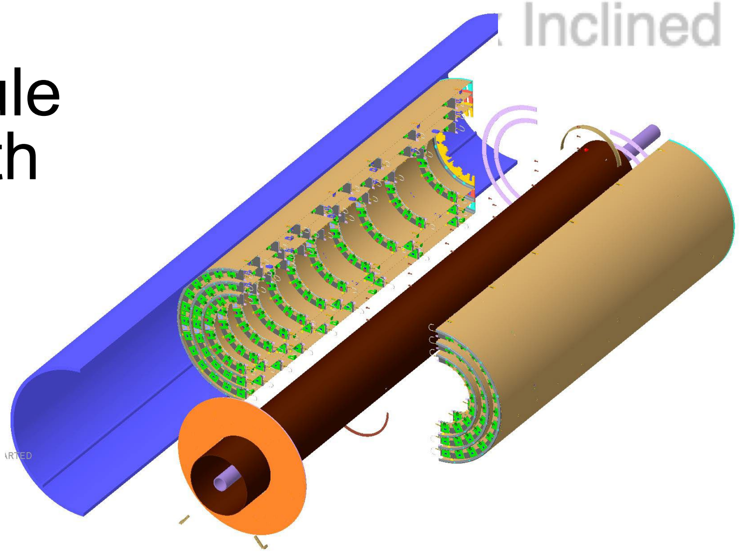
Constant term depending only on geometry

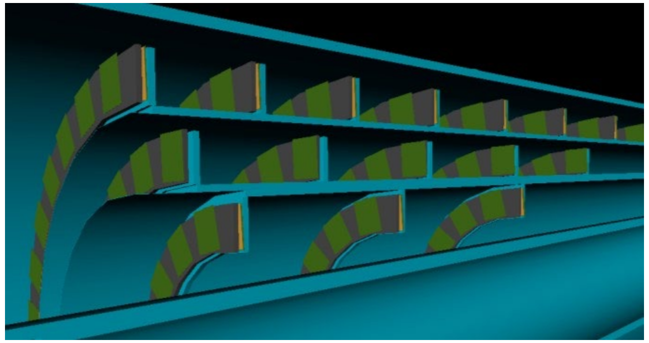
and term depending on material, decreasing with p_T

Pixel Mechanics

- Increasing tracking coverage to $|\eta|<4$ important to physics goals
  - Pile-up rejection, lepton acceptance, E_T miss resolution
  - For pixel only tracking, >9 hits required
- Advance mechanics made this possible
  - Inclined modules: reduce module requirements (30% in layer) with transition gap at $|\eta|>2$
    - At the cost of complexity
  - Rings allow for optimization of coverage

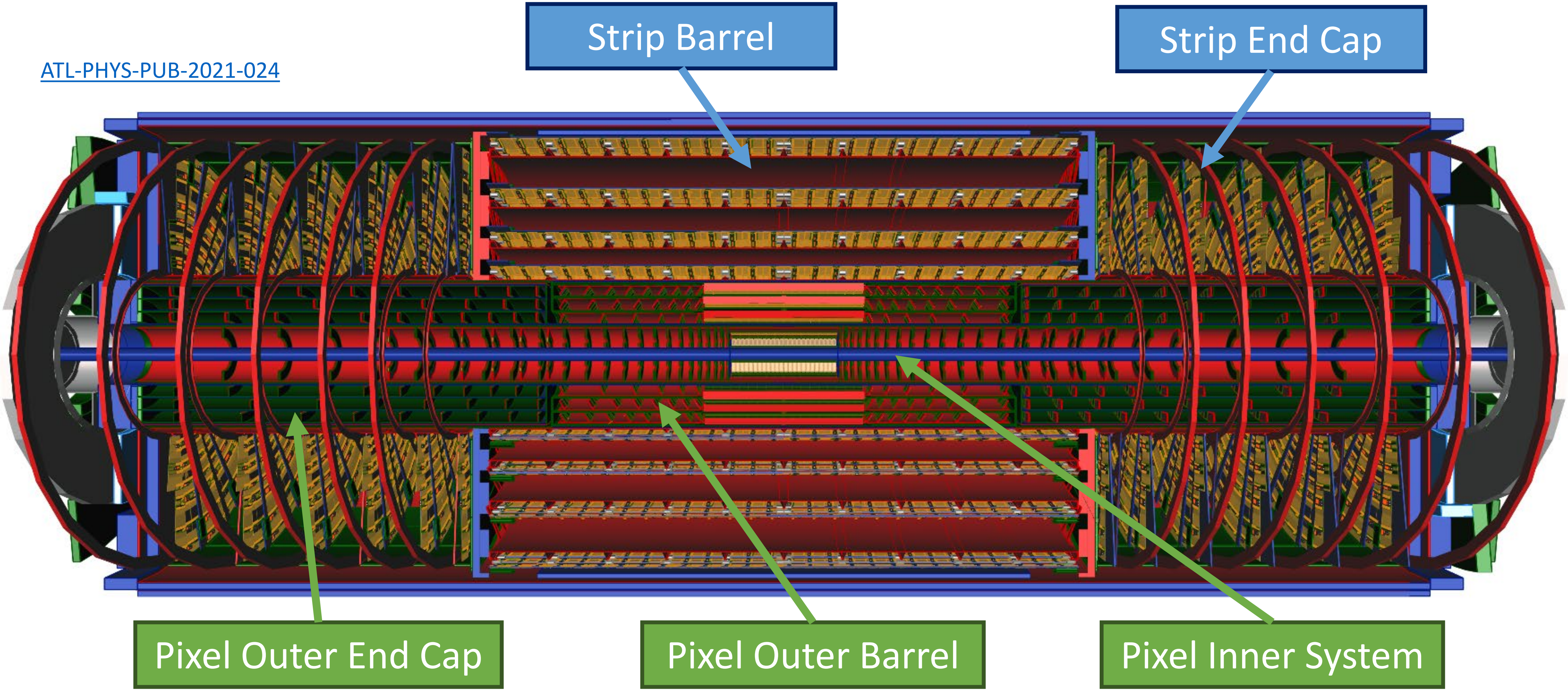




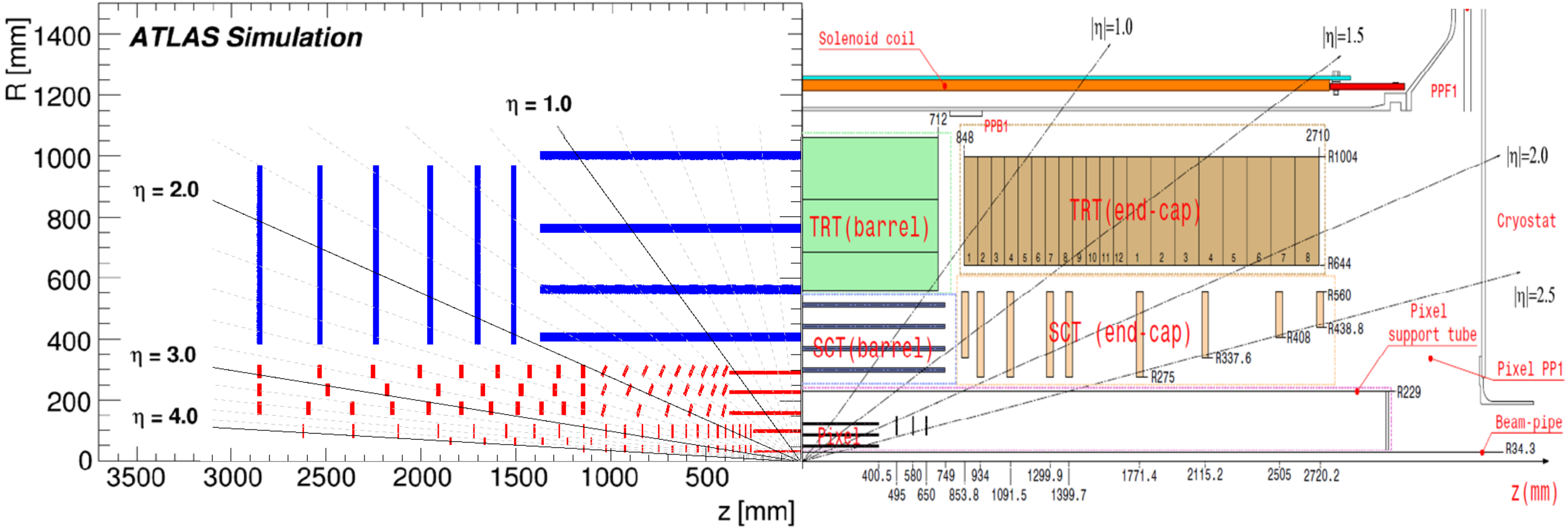


ITk Layout

ATL-PHYS-PUB-2021-024



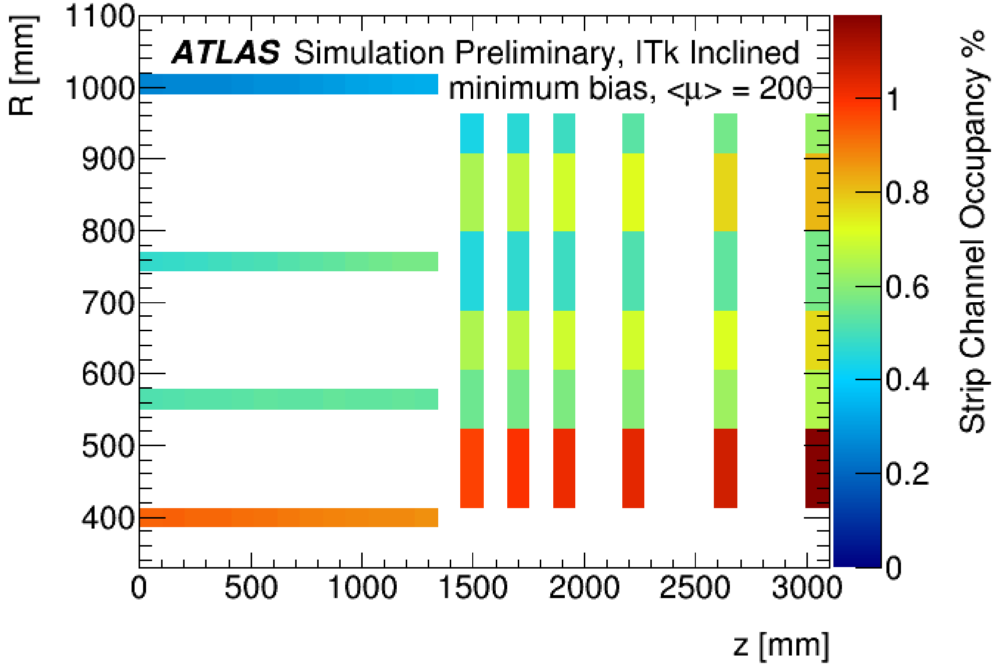
ITk vs ID Layout

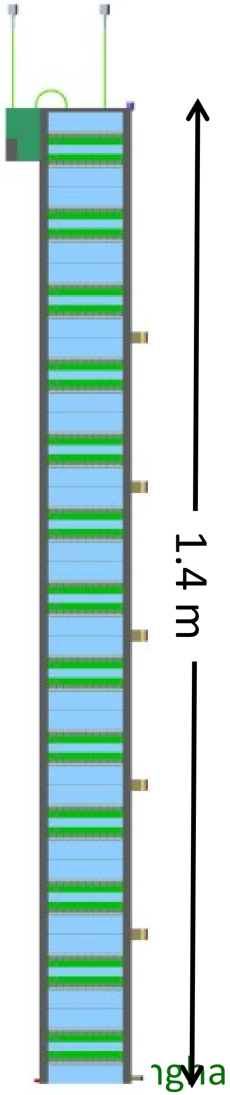


ITk	Pixels	Strips
# Modules	9164	17888
Area (m^2)	13	165
Channels (M)	1400	60

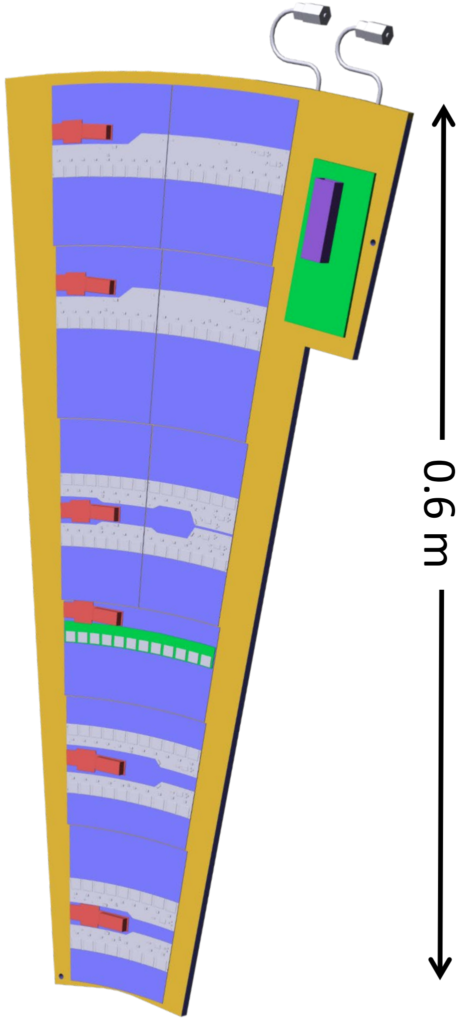
ID (Current)	Pixels	Strips
# Modules	2000	4088
Area (m^2)	1.6	61
Channels (M)	92	6.3

Strip Layout





	Staves	Petals
Modules Per Side	14	9
Module Types	2	9
Hybrids Per Module	1 (B2,3), 2 (B0,1)	1 (R2, 4-5), 2 (R0-1,3)
Hybrid Types	2	13



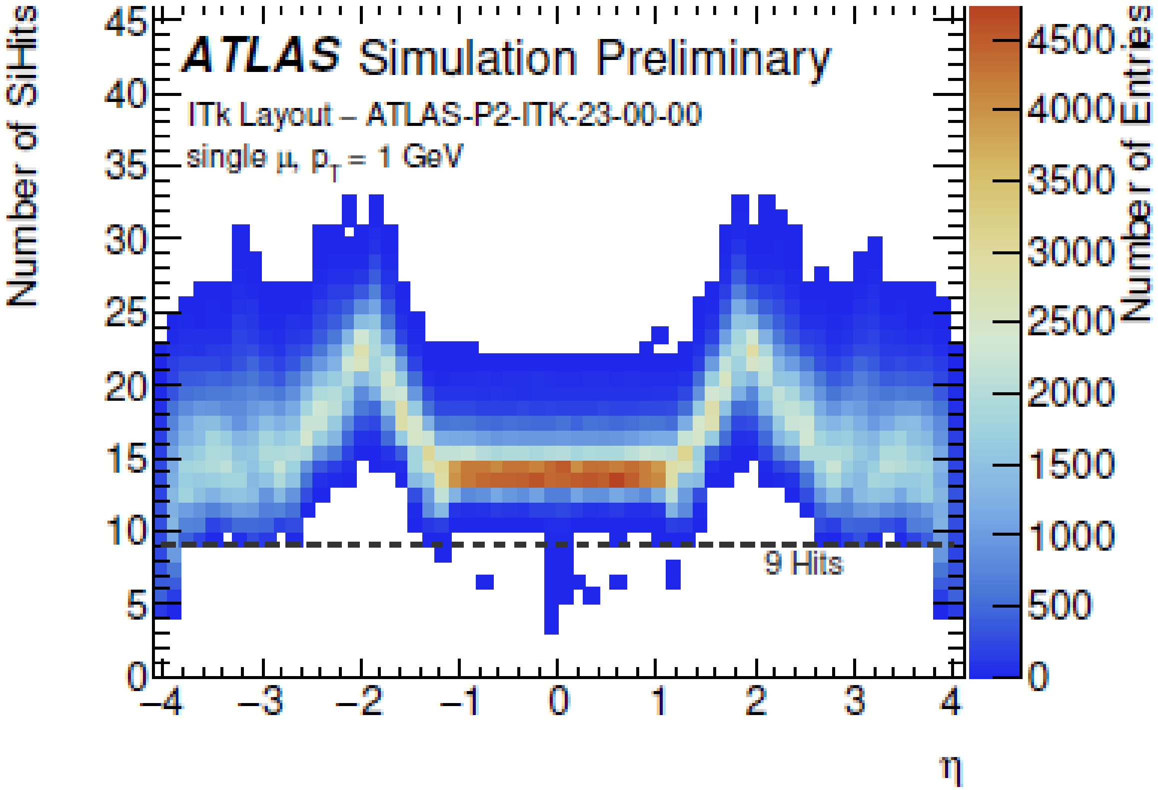
Staves are fairly simple
Petals complicated trapezoidal geometry needed for radial strips without overlap and balance occupancy

ngham
Particle
Physics

Expected Performance

- Layout meets design goals
  - Same or better than current ID even in this extreme environment
    - Meeting Hit Requirements

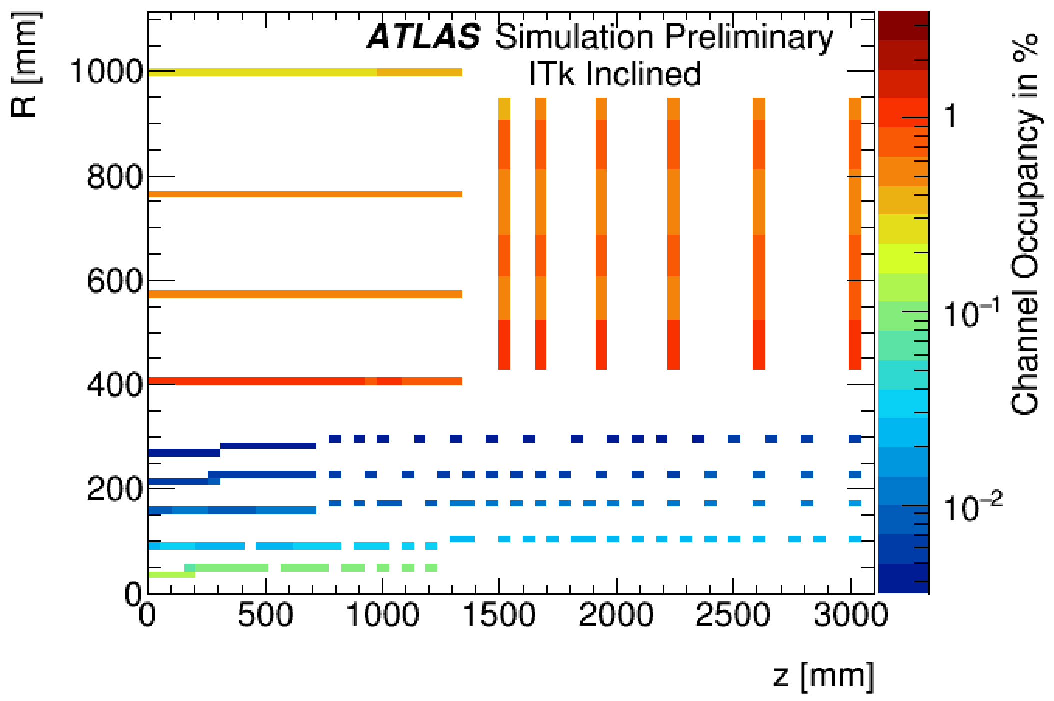
Number of Hits



Expected Performance

- Layout meets design goals
  - Same or better than current ID even in this extreme environment
    - Meeting hit requirements
    - Occupancy

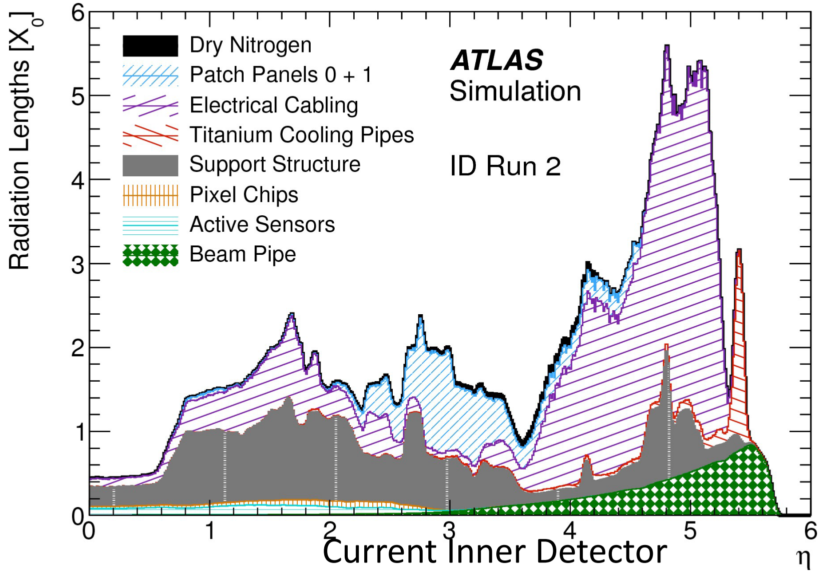
Occupancy



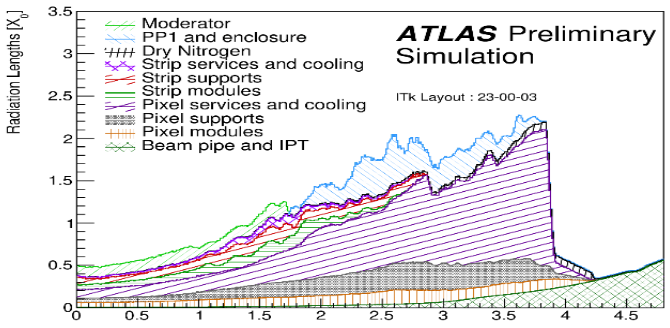
Expected Performance

- Layout meets design goals
  - Same or better than current ID even in this extreme environment
    - Meeting hit requirements
    - Occupancy
    - Material reduction

Material



Current Inner Detector

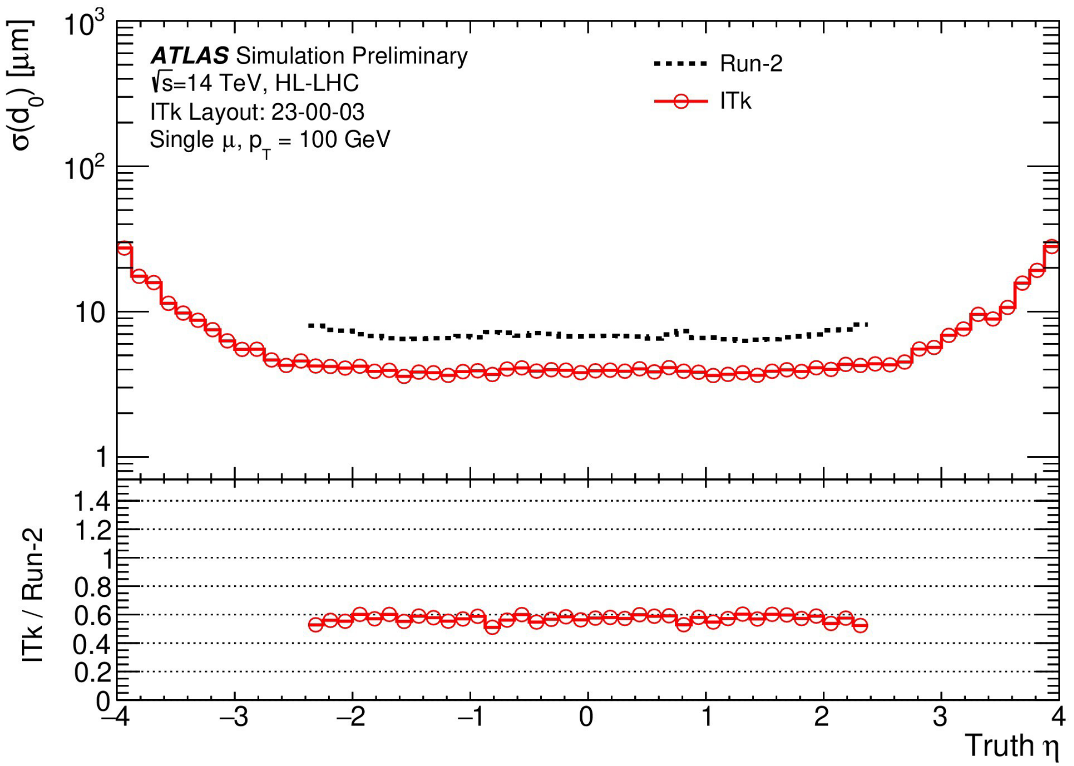


ITk (same scale)

Expected Performance

- Layout meets design goals
  - Same or better than current ID even in this extreme environment
    - Meeting hit requirements
    - Occupancy
    - Material reduction
    - Improved impact parameter

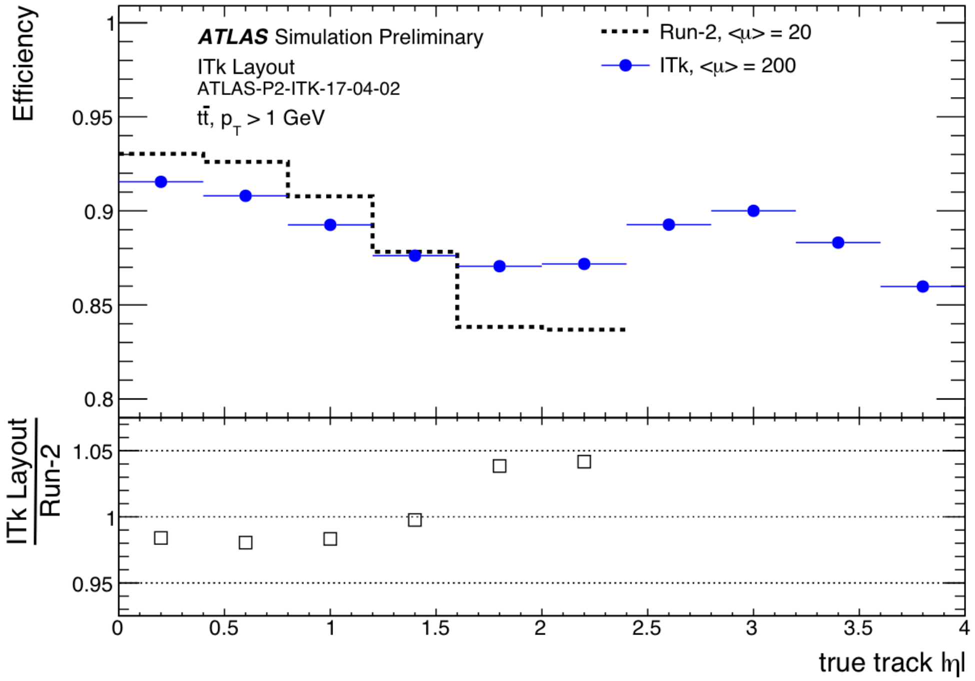
Impact Parameter



Expected Performance

- Layout meets design goals
  - Same or better than current ID even in this extreme environment
    - Meeting hit requirements
    - Occupancy
    - Material reduction
    - Improved impact parameter
    - Increased η coverage

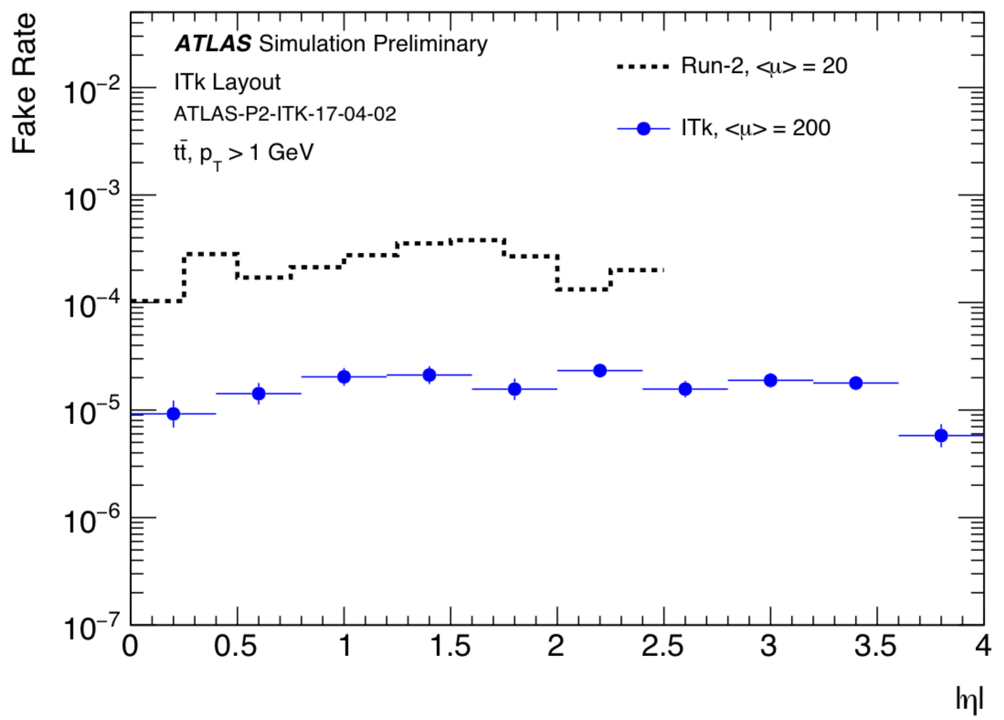
η Coverage



Expected Performance

- Layout meets design goals
  - Same or better than current ID even in this extreme environment
    - Meeting hit requirements
    - Occupancy
    - Material reduction
    - Improved impact parameter
    - Increased η coverage
    - Decreased fake rate
      - Less holes in coverage, more layers

Fake Rate



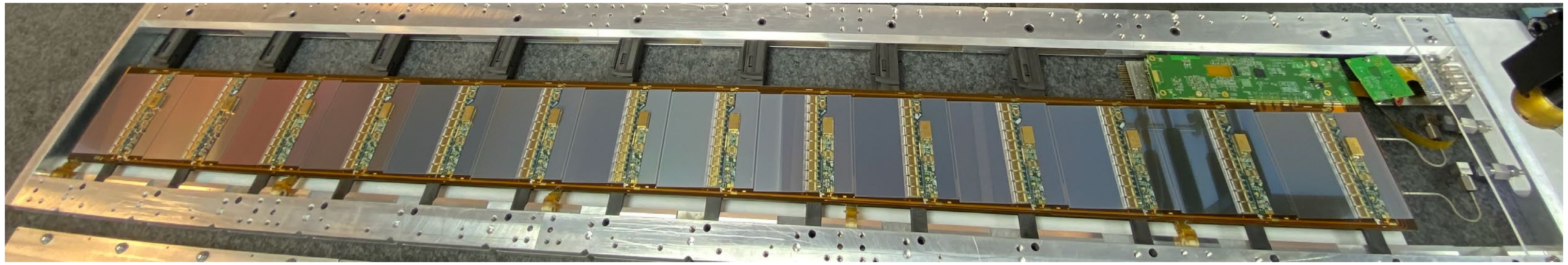
Challenges (Services)

- Current detector has individual power/clock/command services per module
  - Fills all available space
- New detector has many more modules, larger area,….
  - Individual powering cannot fit and would have extremely large power losses in cables
- Services have to be multiplexed or manifolded
  - Pixels/Strips came two different power solutions

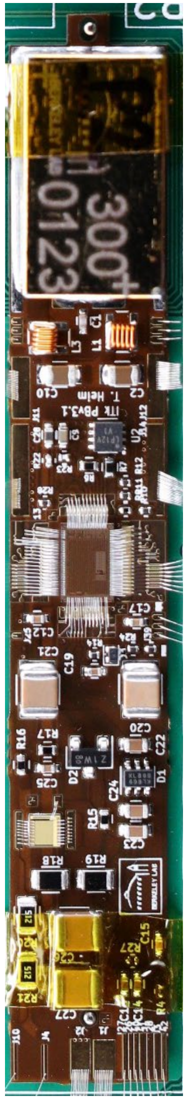
Current Inner Detector Type 2 Services

	Pixels		Strips	
	Power (kW)	Voltage (V)	Power (kW)	Voltage (V)
ID	6.7	2	25	3
ITk	65-90	1.5	100-120	1.5

Strip Powering - DC-DC Converter



- 14 modules powered on a common bus
- bPOL12V converts from delivered 11 V to 1.5 V for module powering
  - Efficiency of 72% at operating point
- Cable plant heat loses go as I^2R
  - Reduction by factor of 28
    - (Conversion ratio × efficiency)^2
- Complications:
  - DC-DC convertors are noisy (high frequency switching)
    - Much development required for light-weight EM shielding and conducted noise reduction.
  - Can not measure V or I per module at power supply
    - Added AMACStar for monitoring
  - As bias on another common bus, developed a custom HV switch to disable individual modules



bPOL12V
- Rad-hard buck converter
- Custom flat air-core coil
- 0.1 mm Al shield-box to prevent EM noise leakage

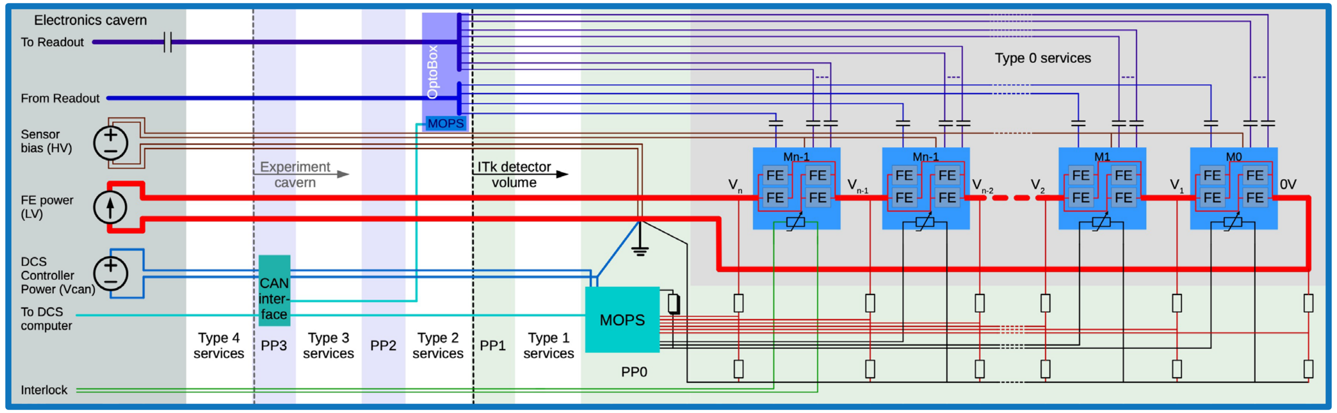
AMACStar
- Control/interlock functionality
- Measurements of temperatures, currents, voltages (LV/HV)

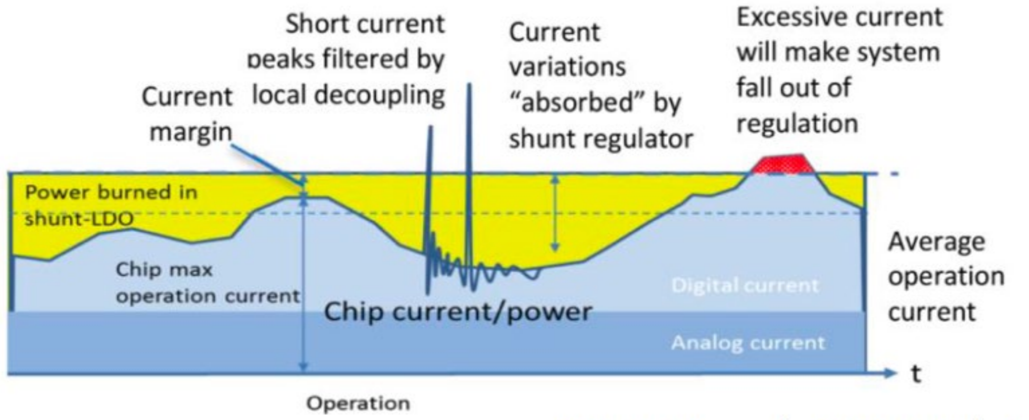
HV Switch
- Connect/disconnect HV to sensor (in case of faulty sensor)
- GaNFET with 600 V rating

Pixel Serial Powering

aka “Fancy Christmas Lights”

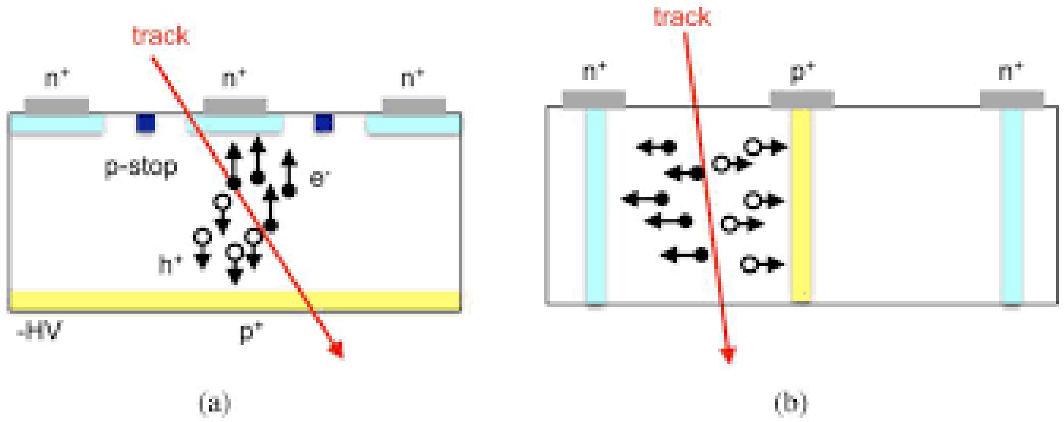
- Powering modules serially with around 1000 chains from 3-14 modules
  - Current flows from one module to next
    - Reduced number of supply lines, less material
    - Chips on a module powered in parallel
  - Power dissipation in services less in services than with parallel powering (30 kW vs 250 kW)
  - Radiation hard on-chip shuntLDO allows regulation of voltage on chip
    - Excess current needs to be supply to accommodate variation due to chip activity (hits)
- Complications
  - Each module on different potential → AC coupling of data lines
  - HV reduces down the chain by the LV voltage drop per module
  - Need to add monitoring chip to measure voltage drops and temperature of individual modules





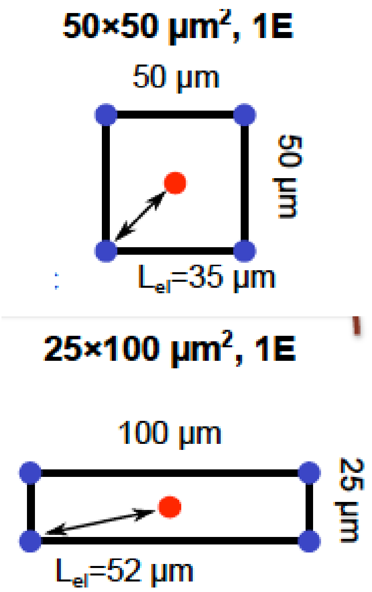
3D Pixel Sensors

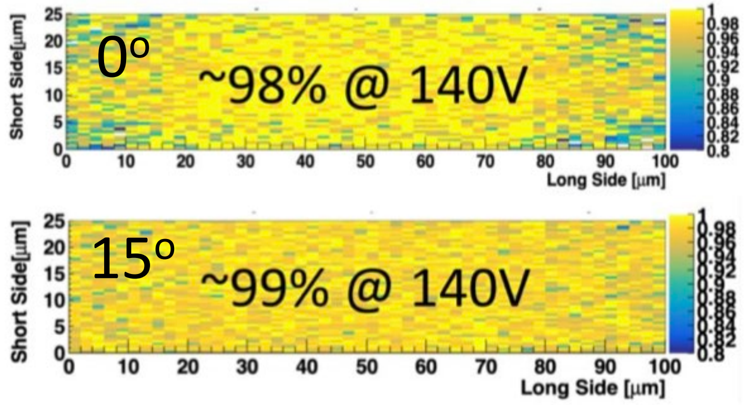
- 3d sensors have columns etched through sensors for implants
  - Allows for lower bias voltage for same collected charge
    - Thin active substrate (150 μm)
  - Factor of 9 power advantage relative to planar
    - < 10 mW cm^{-2} (3d)
    - ~90 mW cm^{-2} (planar)
- 25x100 μm^2 for L0 barrel and 50x50 μm^2 for L0 rings
- Much more difficult to manufacture (reactive ion etching)
  - Columns make sensors fragile
    - Requires inactive, carry wafer of 100 μm
- Greater than 99% efficiency at end-of-lifetime



planar-sensor

3D-sensor





Test Beam at $10^{16} n_{eq}$ cm^{-2}

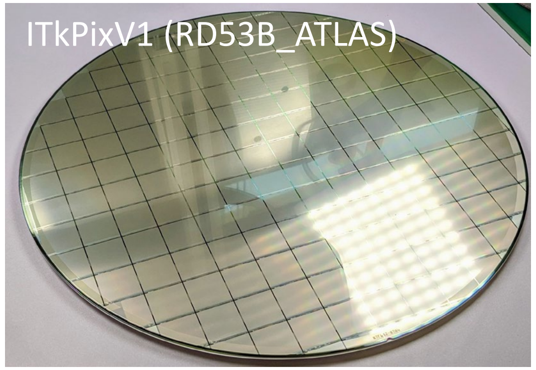
Current Status

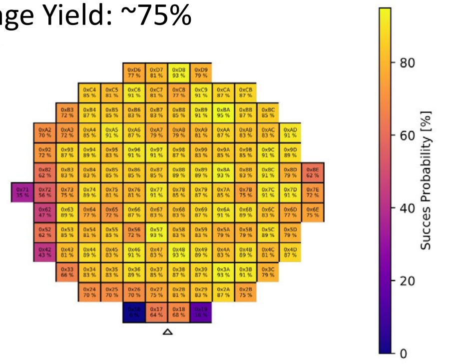
Pixel Sensors and FE Electronics

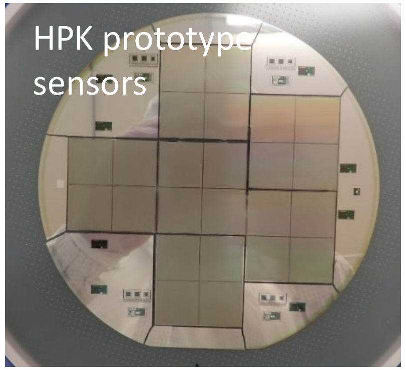
- ITkPixV1 pixel FE chip: Joint ATLAS-CMS effort (RD53) using TSMC 65 nm
  - Full-size prototype ASICs (2×2.2 cm^2)
  - 153,600 pixels per chip
    - 1 MHz readout
    - Low threshold: ~600 e^-
  - Performs well after irradiation.
    - Average chip yield of 75%

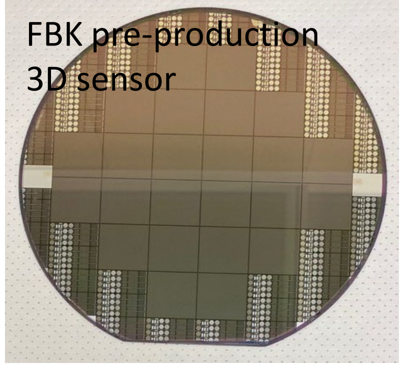
- Sensors with 50×50 μm^2 pixels in 3D and planar technologies (25×100 μm^2 3D inner barrel layer)
  - Pre-production 3D sensors in hand (67% yield)
  - Pre-production planar sensors order being finalized

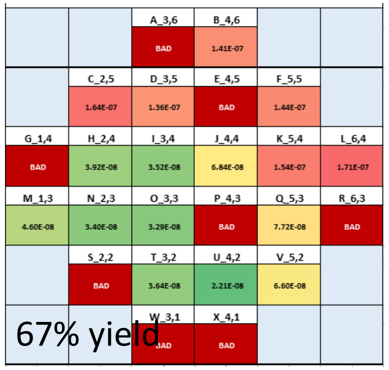
- First RD53A and ITkPixV1 electrical modules assembled and under-test

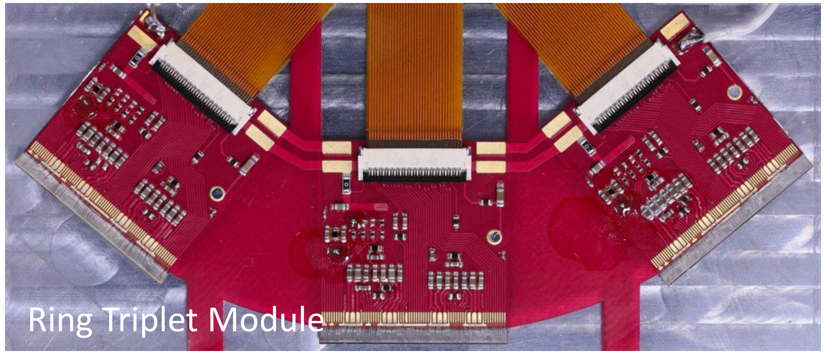


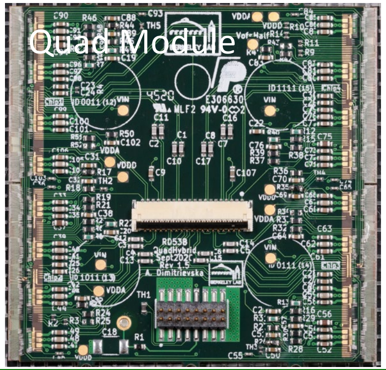






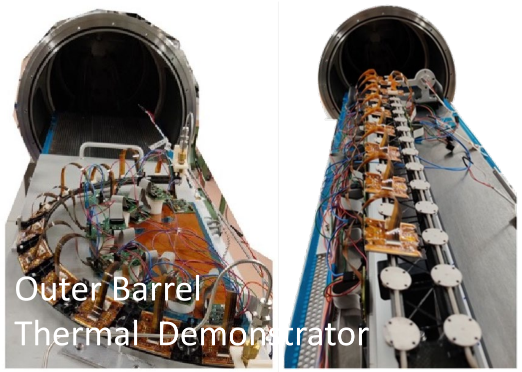


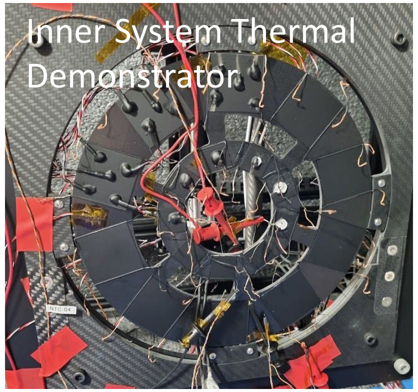


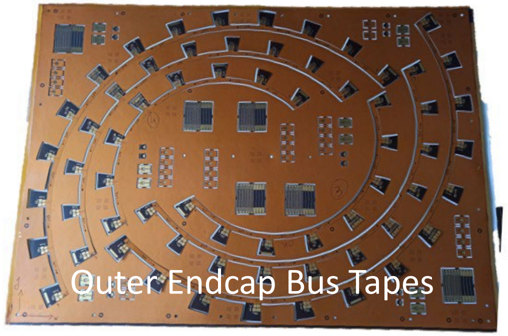


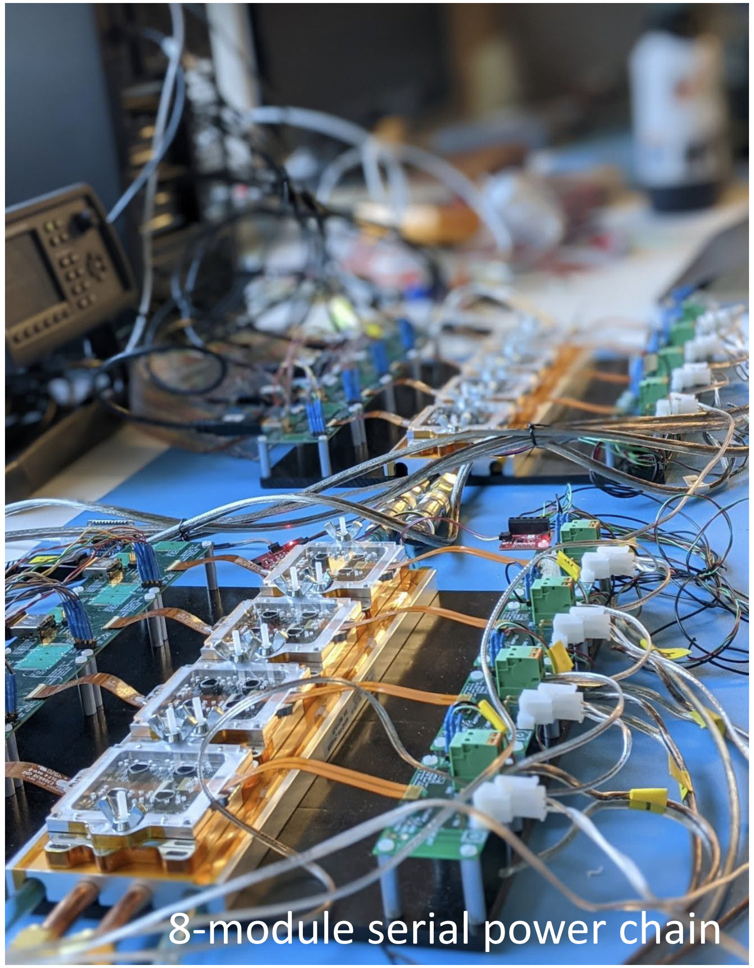
Pixel Mechanics/Systems

- Much progress has been made of mechanics and services
  - Full-scale thermal test of local mechanics met specifications
    - Pre-production of local-mechanics starting
  - 8 quad-module long serial-power chain under test
  - First prototype services/cables of final design in hand

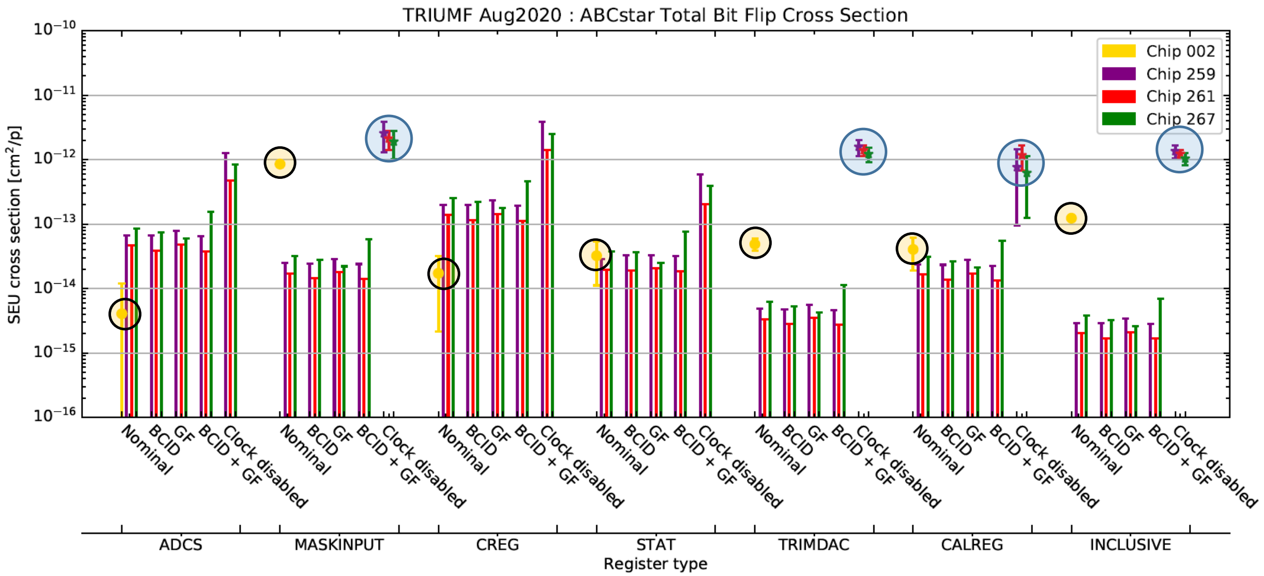

Outer Barrel Thermal Demonstrator


Inner System Thermal Demonstrator


Outer Endcap Bus Tapes


8-module serial power chain

Strip ASICs



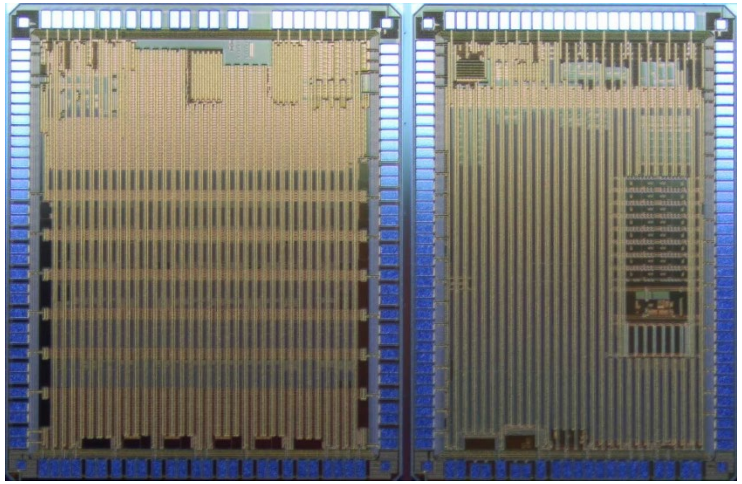
Prototype ABCStar without enhanced triplication

Pre-production ABCStar with triplication disabled

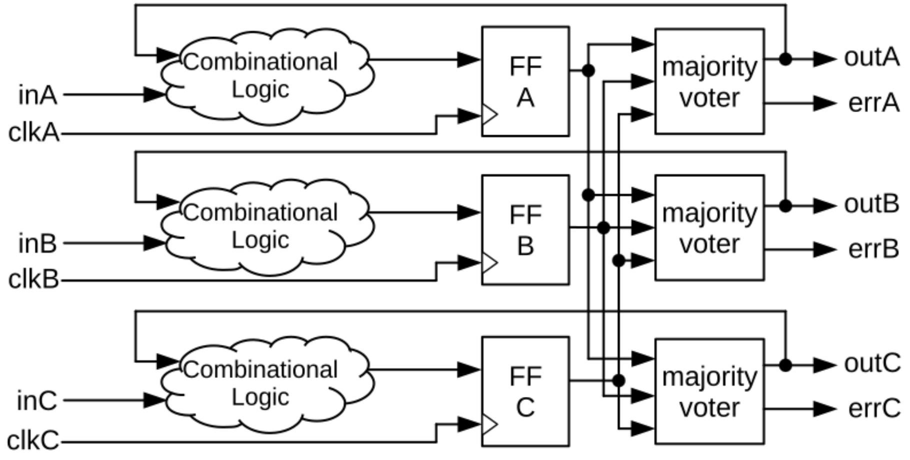
Pre-production ABCStar with triplication enabled had no measured SEUs

ITK-2021-002

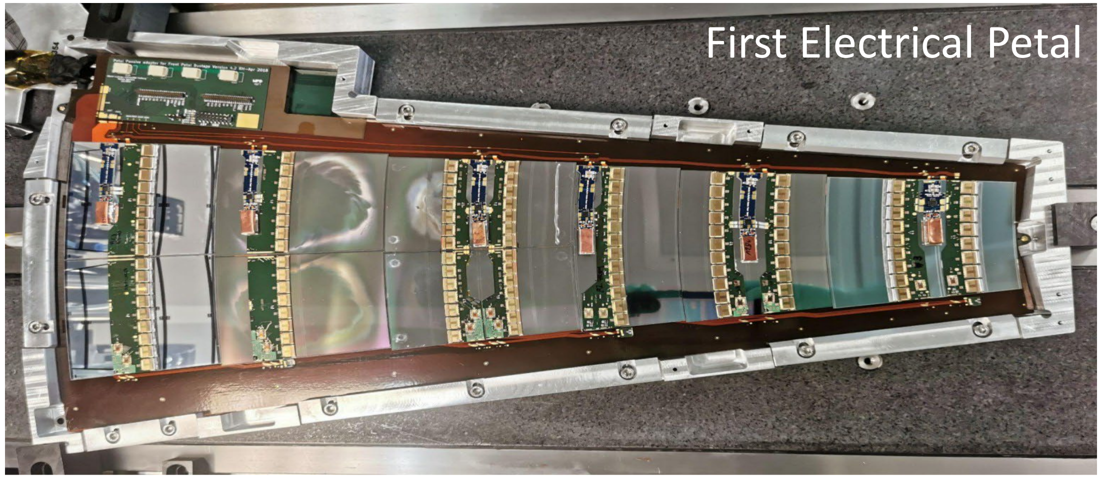
Pre-production HCCStar & AMACStar

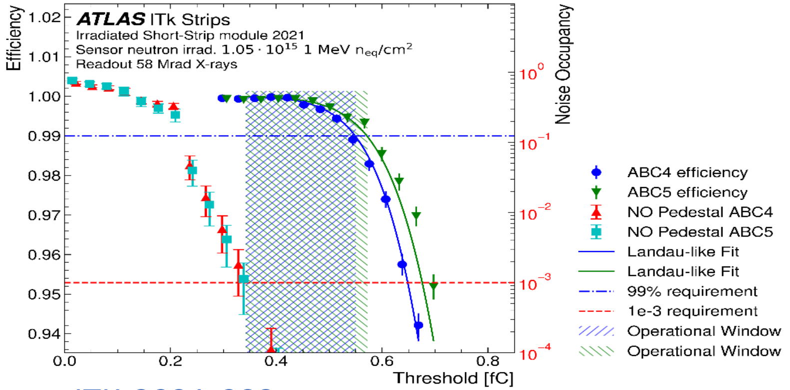


- The three Strip ASICs went through extensive re-design to significantly increase triplication of logic/controls/clocks:
  - Protection against Single Event Effects (SEE): SE Upsets, SE Threshold, SE Latch-up
    - Effects from ionizing particles passing through ASICS
  - ABCStar (front end), HCCStar (hybrid controller), AMACStar (analog monitor & control)
- All three ASICs has been SEE tested in heavy-ions and protons with excellent performance
  - Superb yield in pre-production: 92% (ABCStar), 95+% (HCCStar, AMACStar)
  - ABCStar production order placed

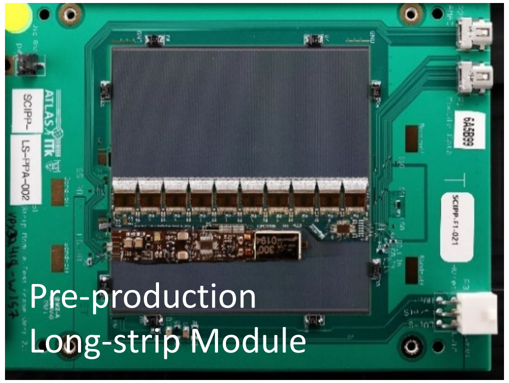


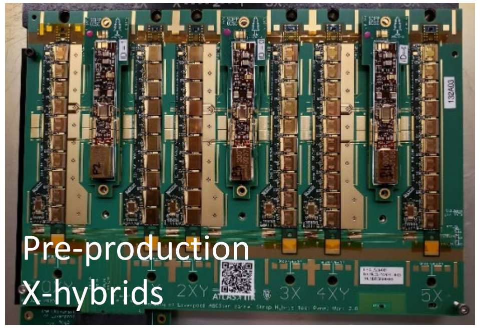
Strip Modules/Mechanics





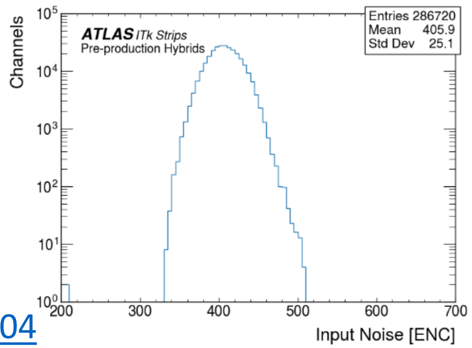
ITK-2021-003





- 20% of production sensors in hand and tested
- Huge amount of progress in modules & mechanics
  - First electrical petal complete (13 hybrid, 9 module types)
  - Irradiated short-strip modules with production ABCStar had wide operating window after 150% maximum fluence
- Hybrid and modules in pre-production
  - Performance, yields and throughput as expected
- Local mechanics also in pre-production
  - Endcap petal cores assembled successfully in industry
- Global mechanics are in production
  - Most elements nearing completion in end-cap

ITK-2021-004



What's Next

For next hadron collider, we will need another factor of 10 radiation hardness, increased segmentation, larger size,…

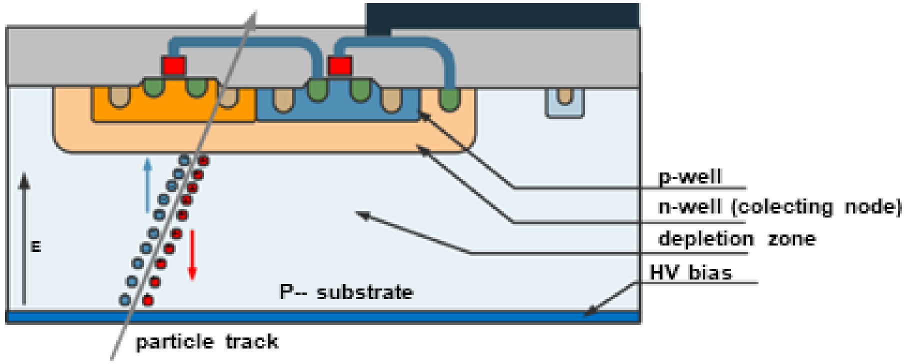
- ITk Strip detector at limits of technology
  - Segmentation
  - Noise
    - Smaller feature size CMOS has worse analogue performance
  - Radiation tolerance
  - Size: Takes a collaboration of 20+ institutes 3 years to build
- ITk Pixel detector at limits of technology
  - Segmentation
  - Radiation tolerance of readout ASICs
  - Cooling (CO_2)
  - Size: take world-wide capacity of bump bonding of thinned devices for 2 years

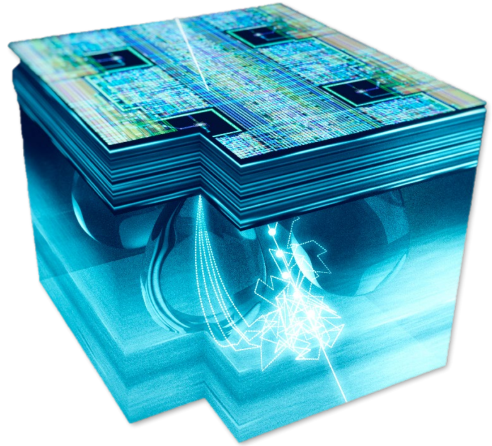
Need to get started on the next 20 year cycle of technology development

Potential Solutions-MAP

- Monolithic Active Pixels (MAPs) could be the solution
  - Sensors and readout electronics produced in one device using commercial CMOS process
  - Driven by consumer and industrial imaging market
  - Devices can be thinned to 25-100 μm.
  - Segmentation as fine as 20×20 μm^2
- Biggest current system: ALICE ITS2
  - 10 m^2 active silicon area, 12.5×10^9 pixels
- Development of this technology for future electron and proton colliders a priority of the particle physics community
  - 2021 ECFA Detector Research and Development Roadmap, DOE Basic Research Needs for High Energy Physics Detector Research & Development and 2021 DOE "Snowmass" Particle Physics Community Planning Exercise

Depleted MAPS (DMAPS) detector

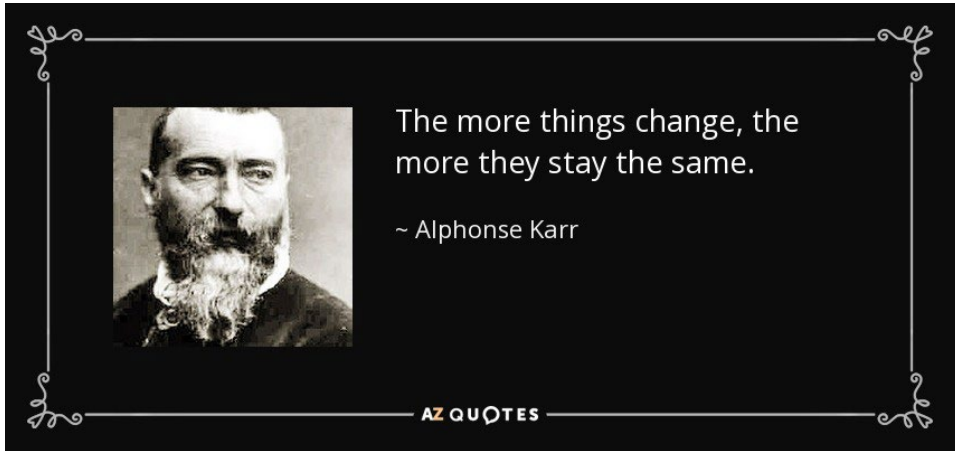




Artistic view of a SEM picture of ALPIDE cross section

Issues to address- MAPs

- Issues to address similar to beginning of HL-LHC technology development
  - Radiation tolerance: currently demonstrated to 2×10^{15} n_{eq} cm^2
    - Need another factor of 2-20
  - Current devices reticle size (~2x2 cm^2)
    - Need to figure out how to package and provide power, clock & data services for 100s of m^2 of detectors
  - Need to find solution to balance segmentation and readout bandwidth

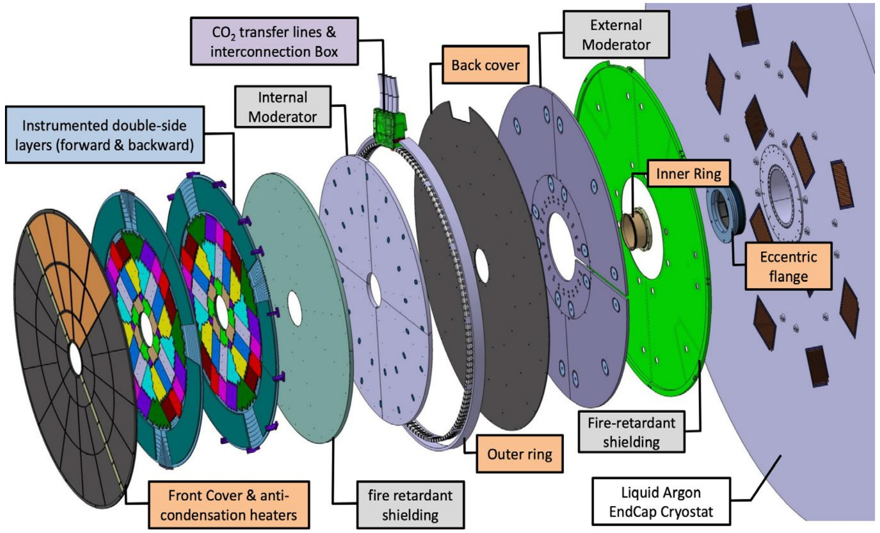


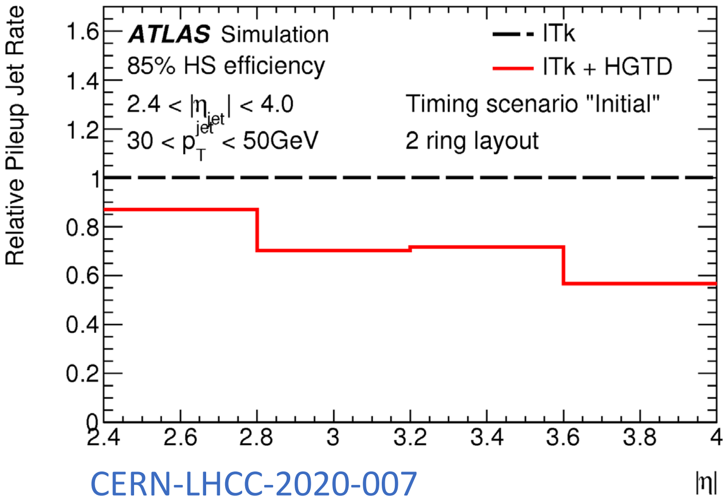
Conclusion

- ATLAS is making a significant upgrade to its detector to cope and thrive in the HL-LHC environment.
  - Made possible by two decades of technology development
  - New silicon inner tracker (ITk) will maintain or improve on the performance of the current detector (with 200 pile-up collision)
- The ITk is beginning pre-production phase
  - Production will be completed in the next 4 years.
- This successful upgrade will enable us to maximize the physics potential from the HL-LHC dataset

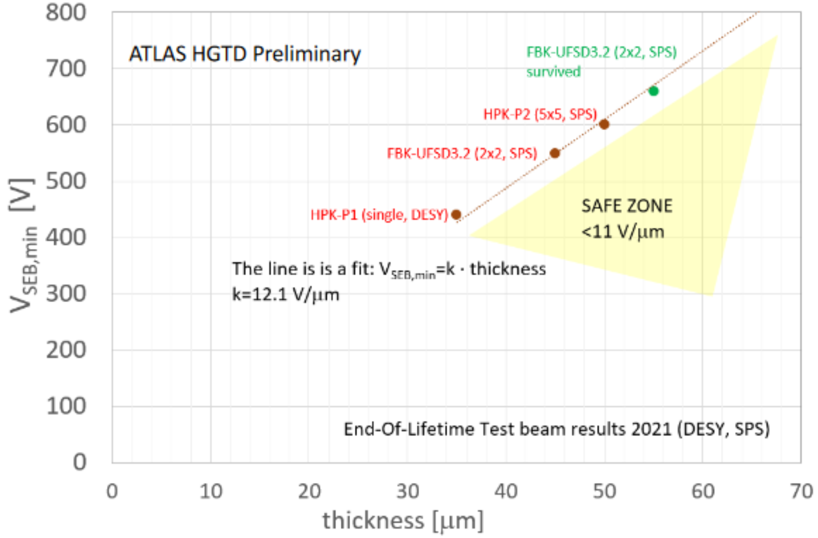
Backup

High-Granularity Timing Detector

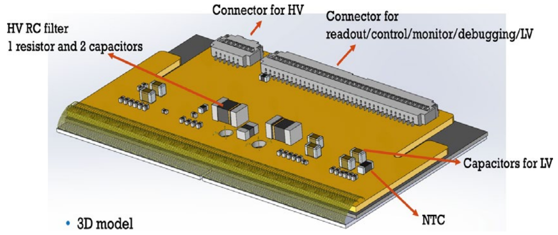


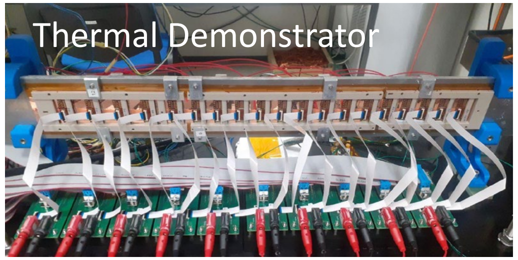


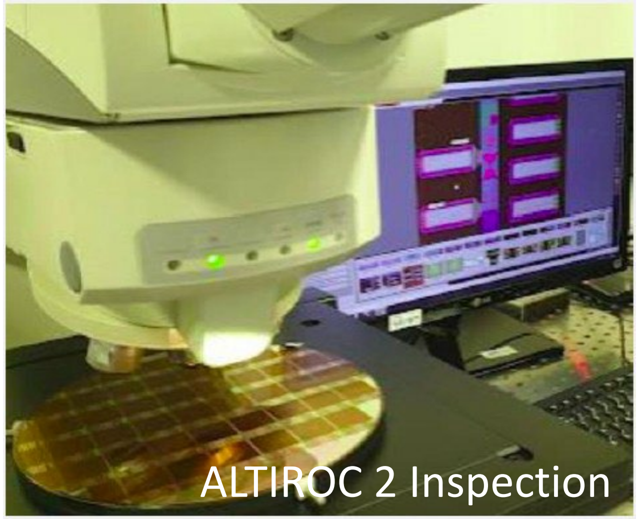
ATL-COM-HGTD-2021--028



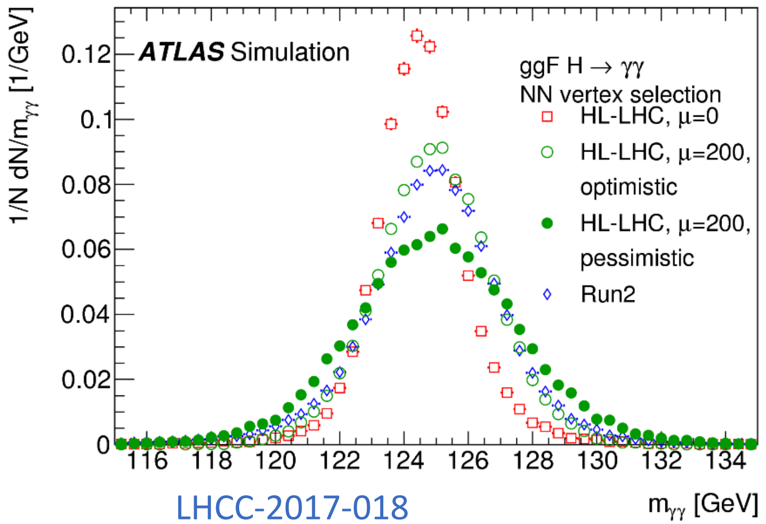
- New HGTD detector (based on LGAD) in 2.4<|η|<4.0 to disentangle pile-up by using timing information
  - <70 ps resolution per hit, 4 layers of silicon modules, at least 2 hits per track
  - Provides bunch-by-bunch luminosity
- Current Status:
  - First tests of full-size FE ASIC (ALTIROC 2) with LGAD sensors demonstrate required resolution
  - Single-event burst events seen in sensor test beam
    - Established maximum field per sensor thickness
    - Prototype sensors met radiation tolerance requirements below this critical field
  - Design of modules, services, mechanics progressing



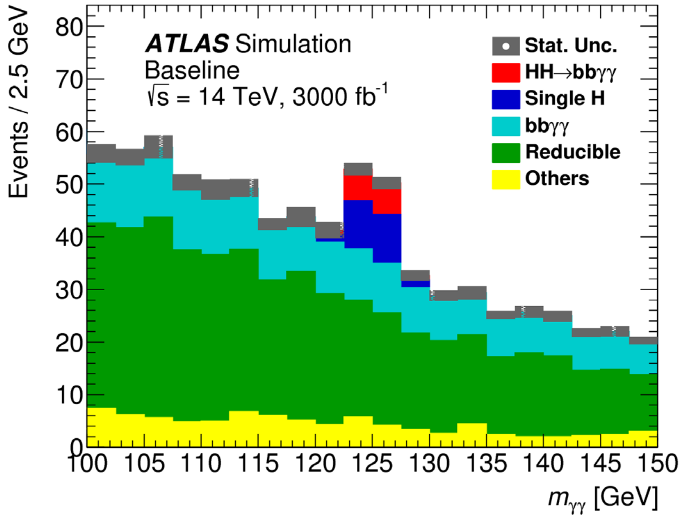




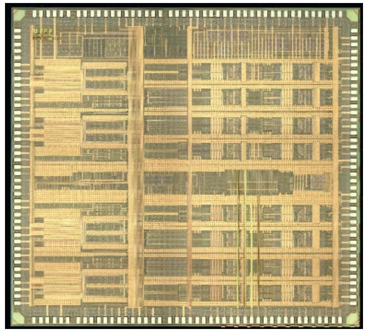
Liquid Argon Calorimeter (LAr)

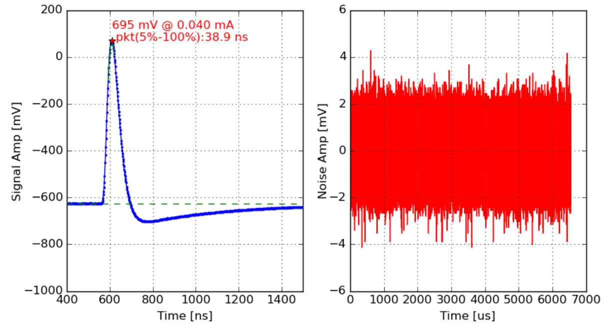


LHCC-2017-018

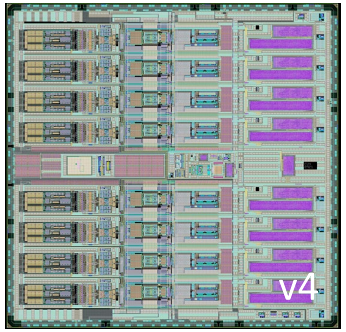


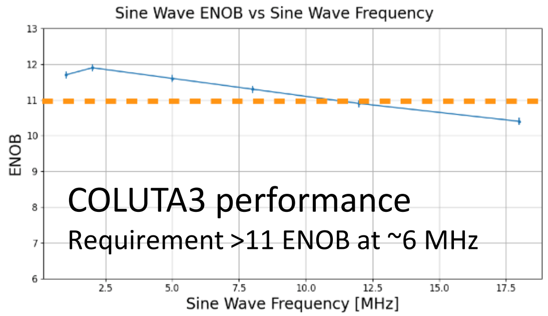
Prototype Pre-amp/Shaper (ALFE2- TSMC 130 nm)



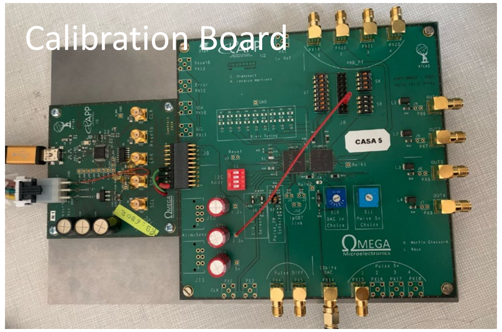


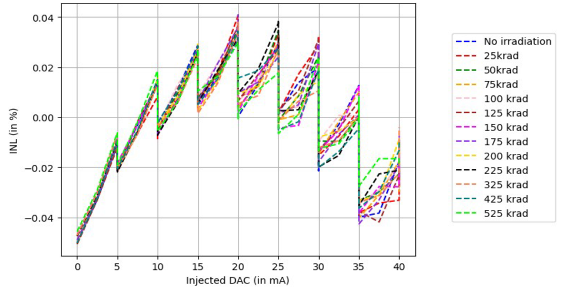
Prototype 14 bit ADC (COLUTA- TSMC 65 nm)



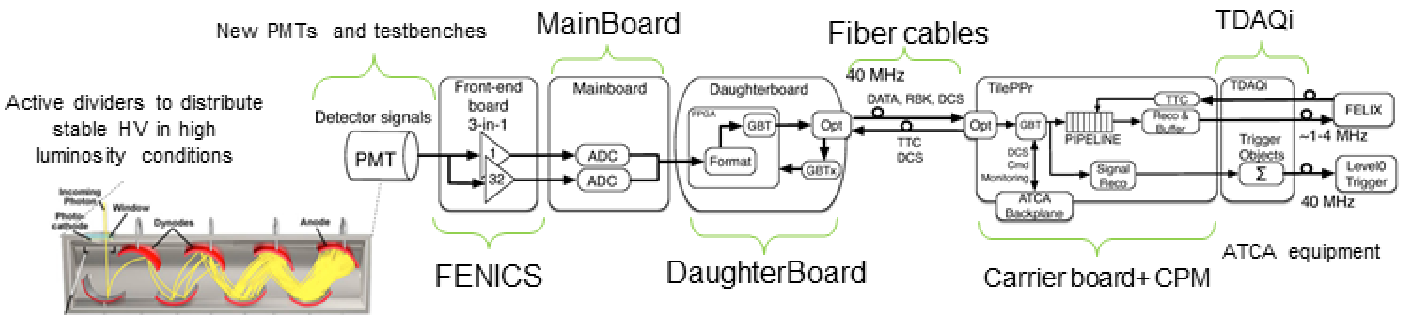


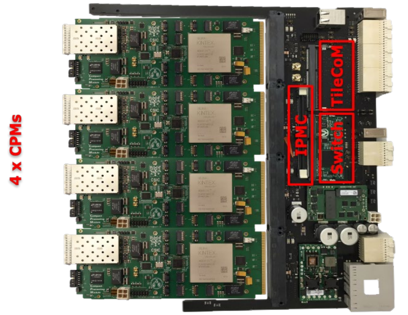
- New on-detector and off-detector electronics
  - 40 MHz continuous readout
    - Pre-amp/shaper: 16-bit dynamic range (from 50 MeV to 3 TeV) with 11-bit precision
    - ADC: 2 overlapping 14-bit gains (12-bits SAR + DRE)
  - Improved radiation hardness
- New LV power supplies in radiation zone for on-detector electronics
- Major technical progress in all areas
  - Last on-detector ASIC prototypes in hand and testing well
    - Building toward ¼ loaded FEB2 in 2022
  - Prototype off-detector elements proceeding



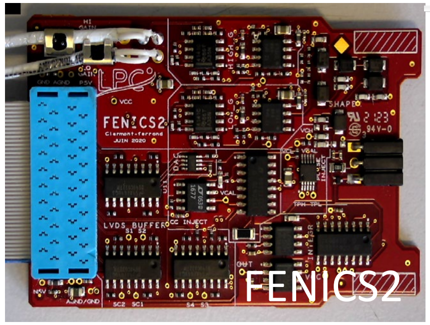


Hadron Calorimeter (Tile)

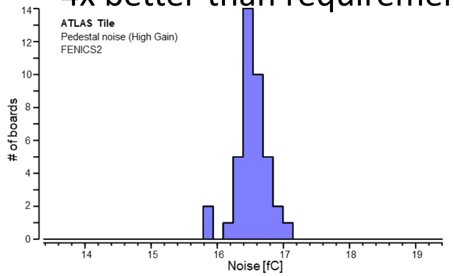


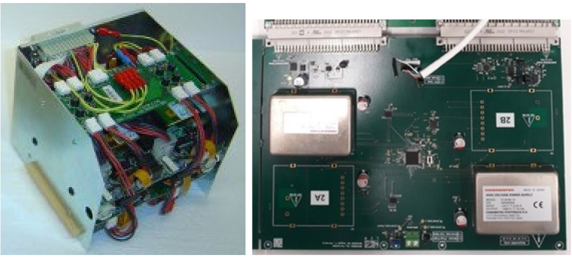


Carrier Board + CPM



4x better than requirement

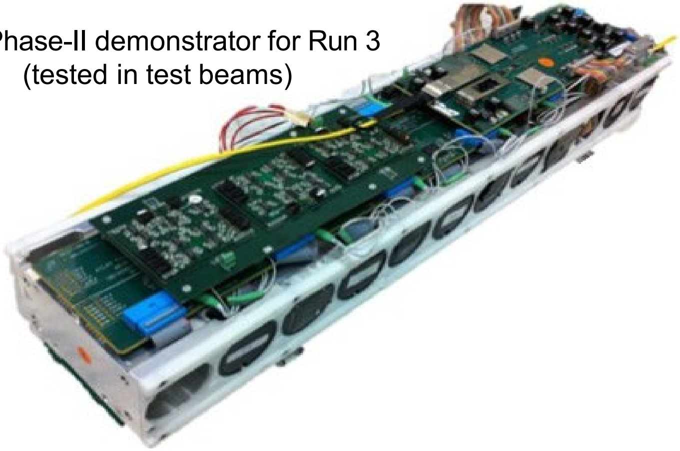


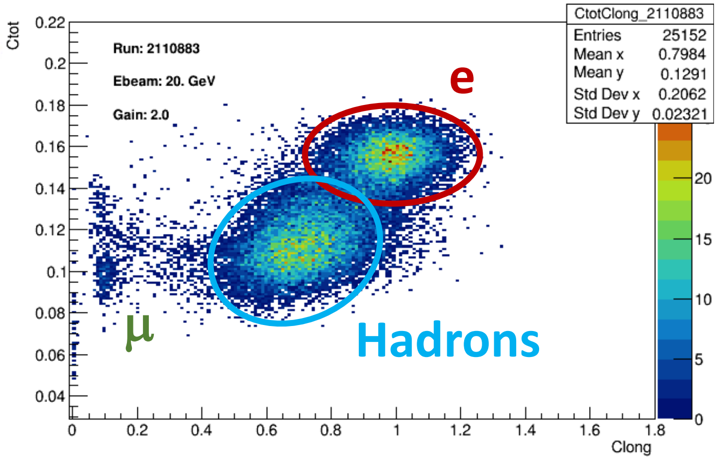


LV/HV Power Supplies

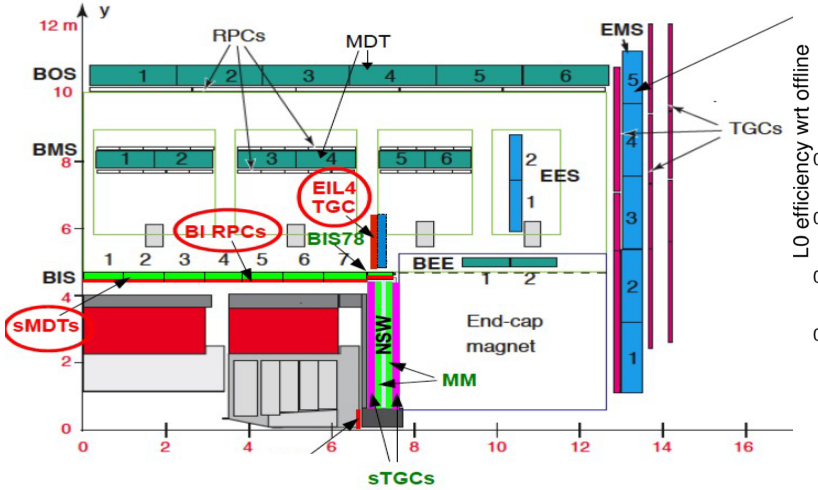
- Upgrade of electronics for 40 MHz output
  - Modified mechanics for easier access/maintainability
  - Replacement of 10% of the PMTs
- Most on-detector items are in pre-production
  - Daughter board prototype evaluation nearly complete
  - Mini-Drawer Mechanics well into production
- Pre-production electronics operated together at SPS test-beam
  - And performs as expected
- Off-detector electronics prototype under evaluation

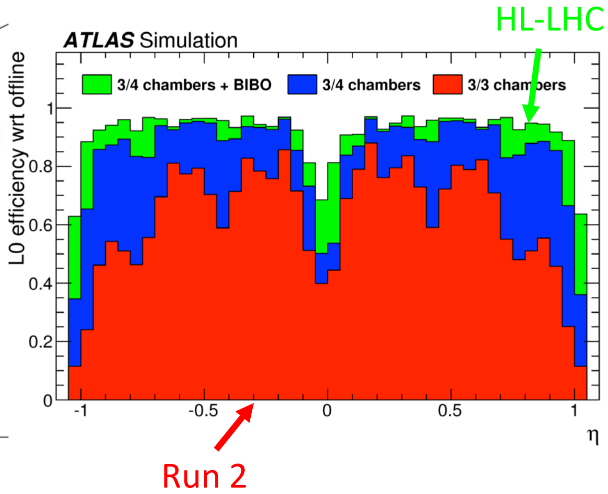
Tile Phase-II demonstrator for Run 3 (tested in test beams)

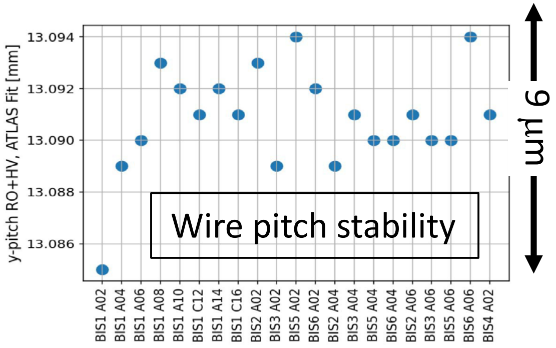


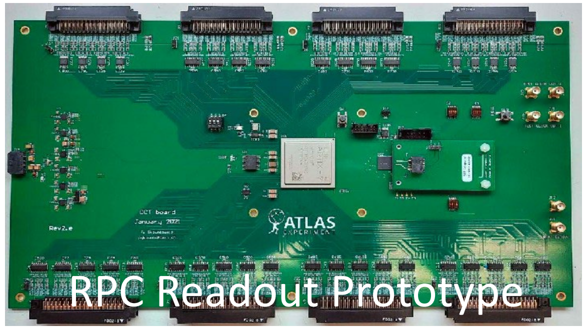


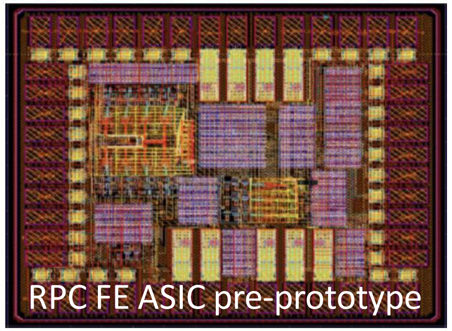
Muons



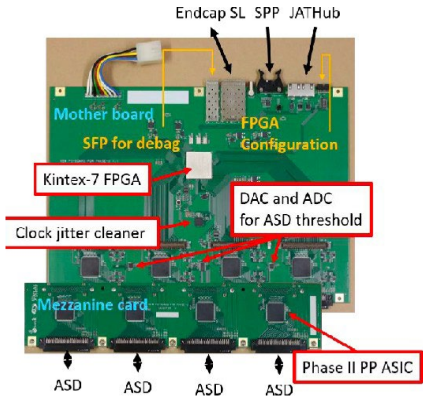


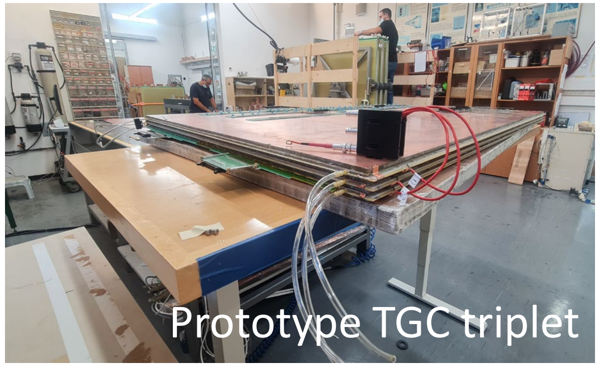




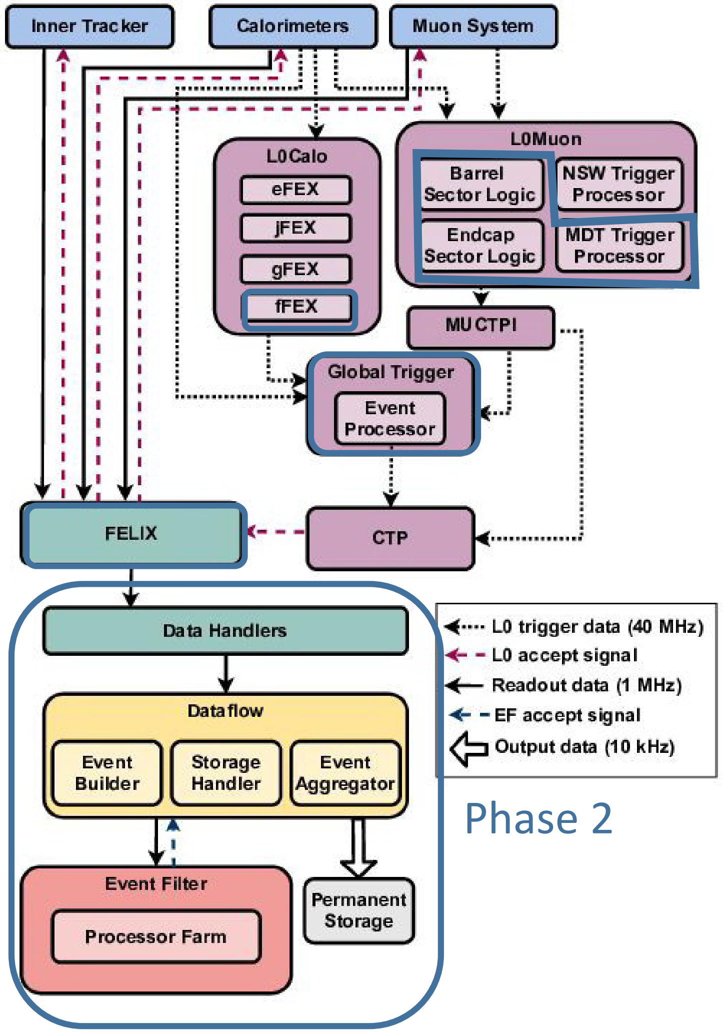


- Updated readout/trigger electronics to 40 MHz
- Addition layers of sMDT, RPC, and TGC to improve coverage, trigger uniformity & momentum resolution, fake rates
- Current status
  - <u>sMDT:</u> chambers in production, electronics near pre-production
  - <u>RPC:</u> FE prototypes submitted, prototype chamber nearly complete
  - <u>TGC:</u> Triplet prototype completed, FE ASIC production complete





TDAQ



Phase 2

Upgrade trigger and data acquisition to allow efficient selection of events

- Exploits full detector granularity in single level trigger
- Improved muon trigger efficiency
- Benefits from extended tracking coverage

Connection between FE electronics and data acquisition via FELIX

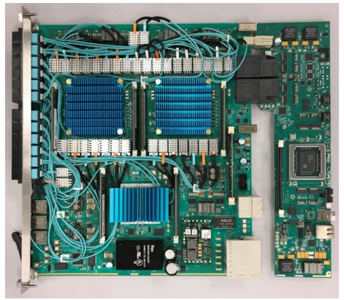
- Custom-designed PCIe I/O cards in a commodity server with up to 100 Gbps bandwidth

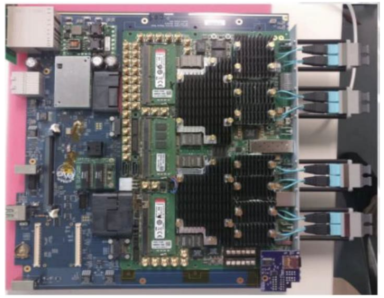
Data rate achievable

- Level 0: 1 MHz, ~5.2 TB/s, latency 10 μs
  - LHC: 100 kHz, ~290 GB/s, latency 2.5 μs
- Event Farm: 10 kHz, ~52 GB/s
  - LHC: 1 kHz, ~2.9 GB/s

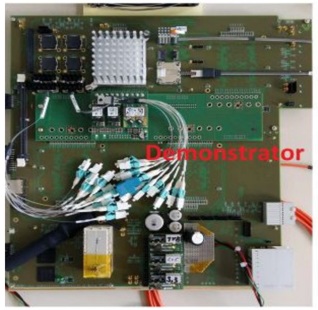
Current Status:

- Prototypes of FELIX, fFEX, L0Muon Trigger, & Global Trigger under evaluation


GCM/GRM prototype


L0 muon trigger prototype


FELIX Phase-II prototype



fFEX prototype v2b