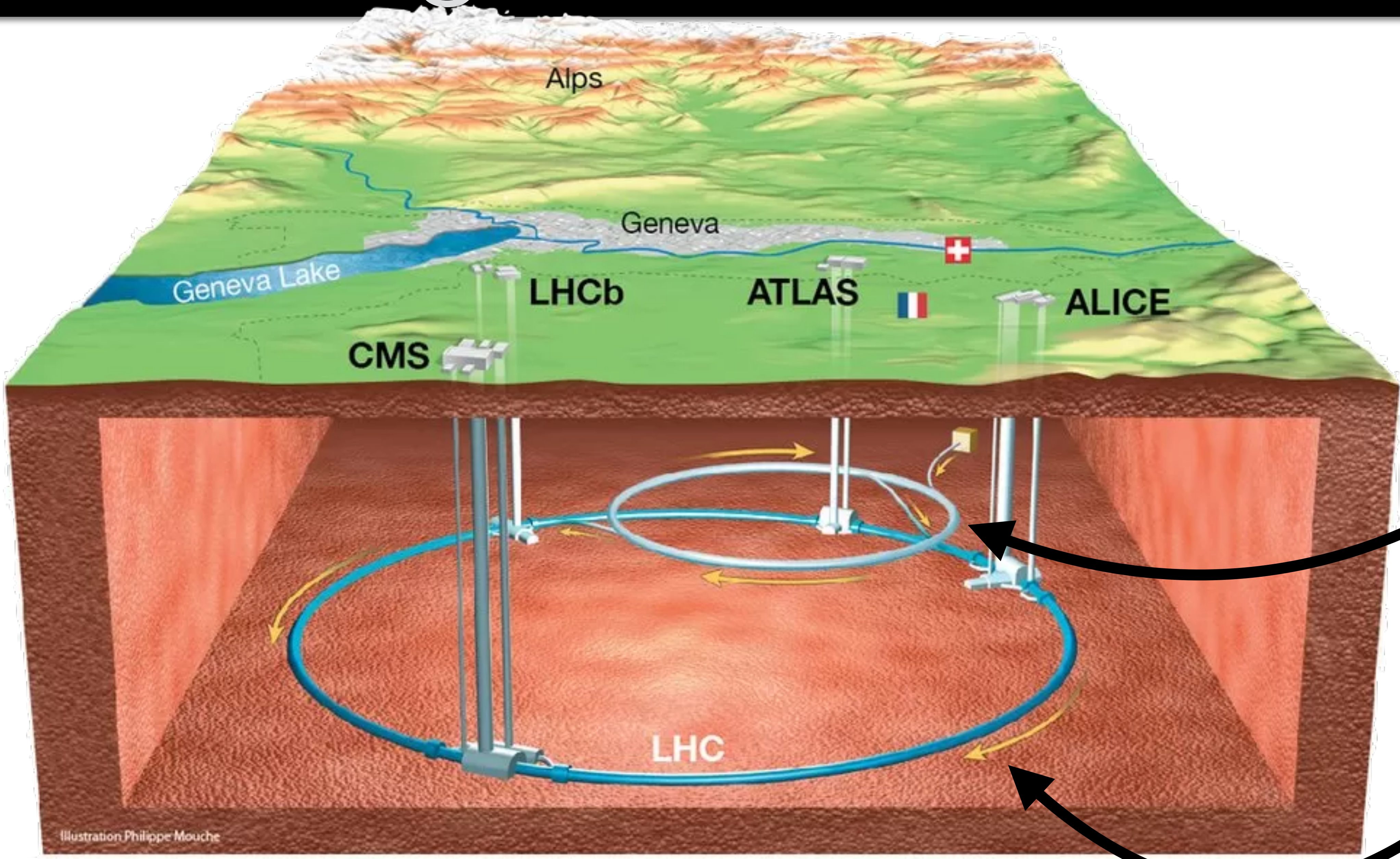
ATLAS Upgrades for the HL-LHC

Jeff Dandoy
on behalf of the ATLAS Collaboration

2024 CAP Congress
Western University
30 May 2024

The Large Hadron Collider



$Sp\bar{p}S$ discovered W & Z in 1980's

LHC built to find Higgs (+ more)

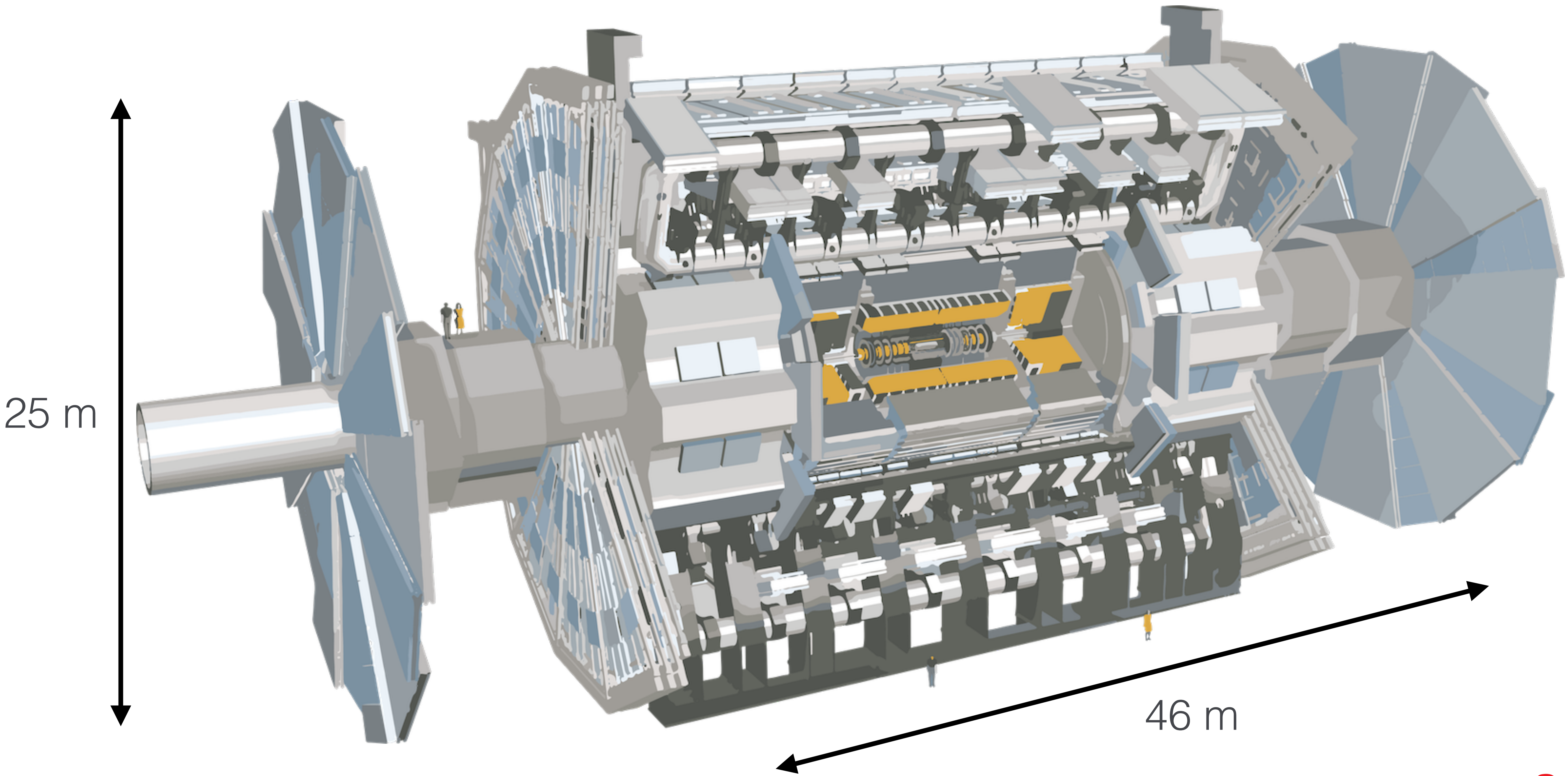
Discovering massive particles requires *high energy* & *high luminosity* accelerators

= many interesting collisions

The ATLAS Detector

Observing energetic particles require *large* & *highly granular* detectors

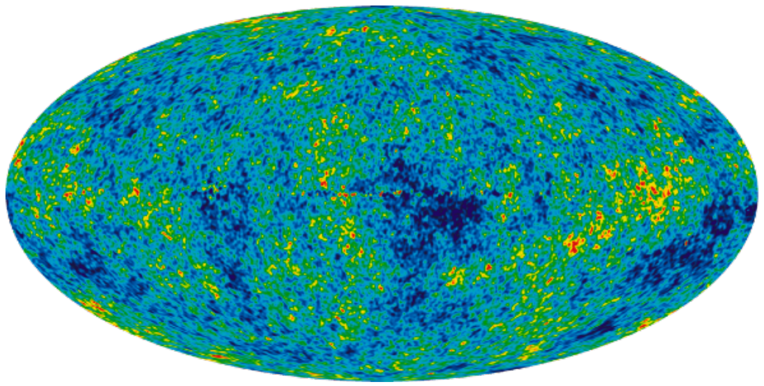
$\mathcal{O}$(100 million) channels → 1 petabyte / s



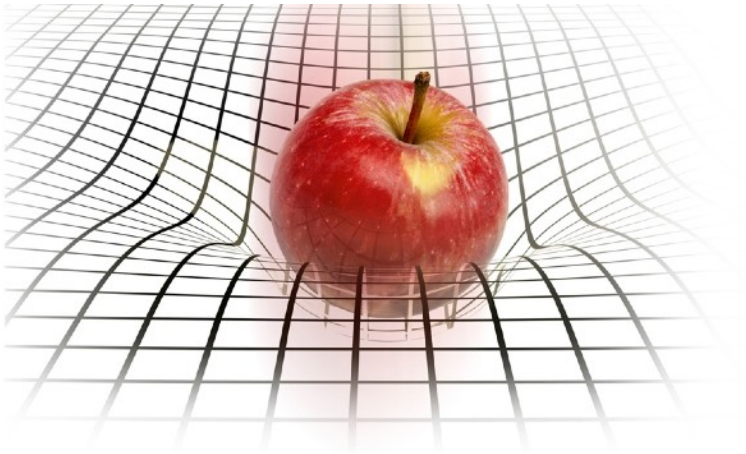
University College’s Middlesex Memorial Tower

The Standard Model still doesn't explain...

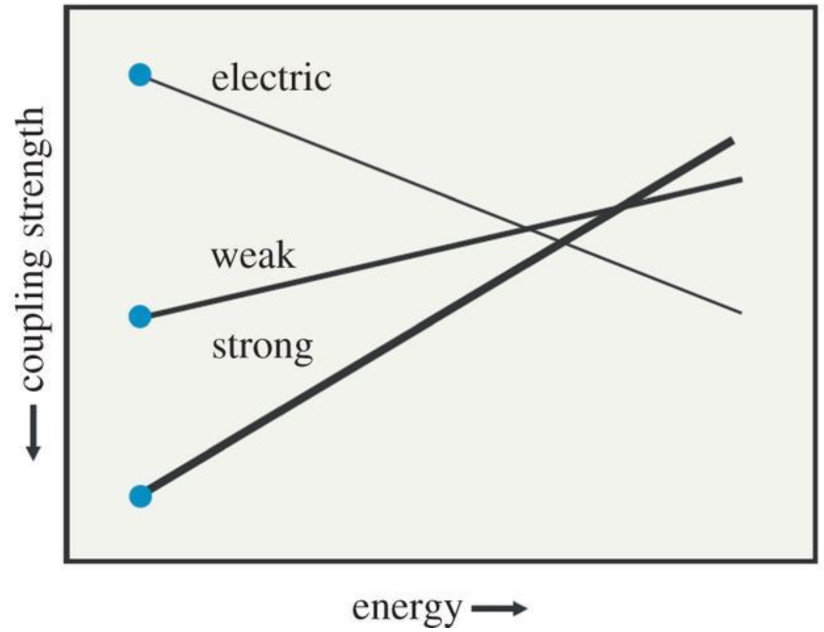
Dark Matter



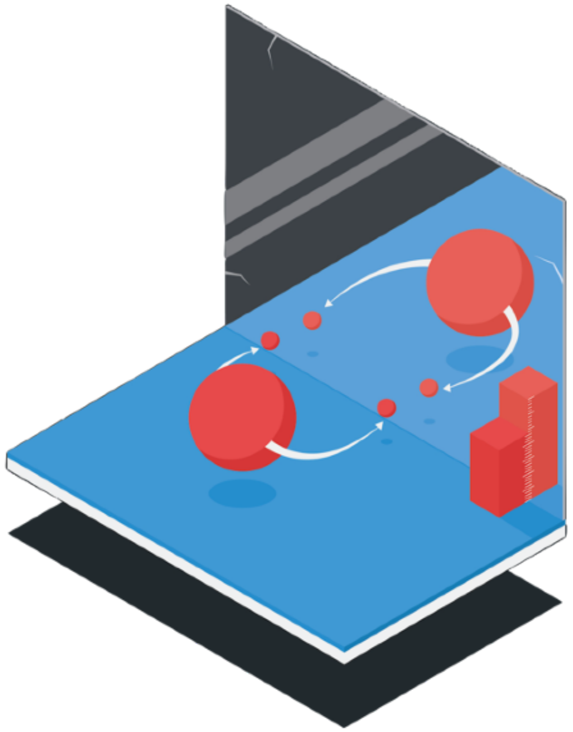
Gravity



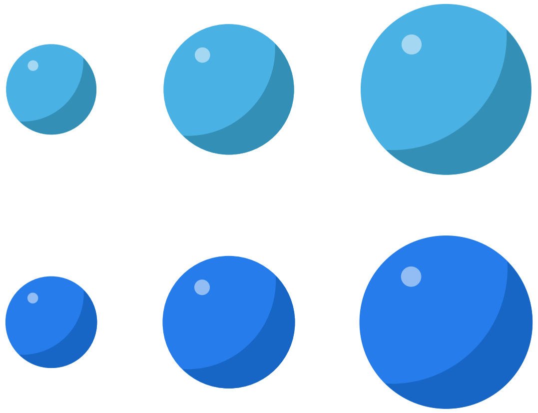
Barely no force unification?



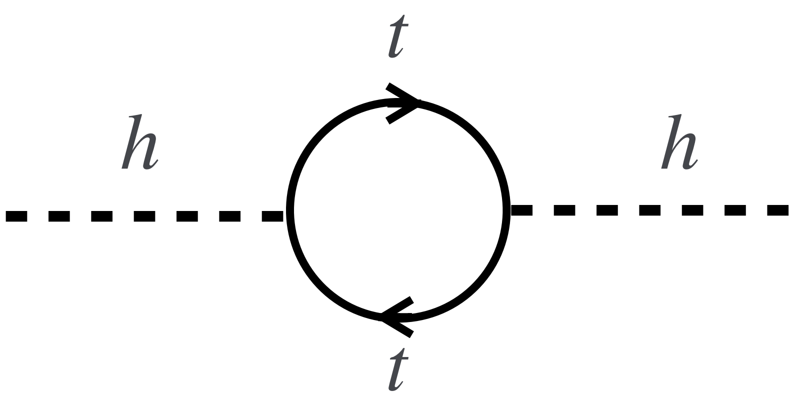
Matter-antimatter asymmetry?



3 particle generations



Unexplainably small Higgs mass?



- Answers & hints to these questions may be found at the LHC - at the ***energy frontier***
- Signatures will be rare, hard to reconstruct, & hidden among immense Standard Model backgrounds

LHC Schedule

2009-2012

Run 1

1 square = 30 fb^{-1}

LHC Schedule

2009-2012

Run 1

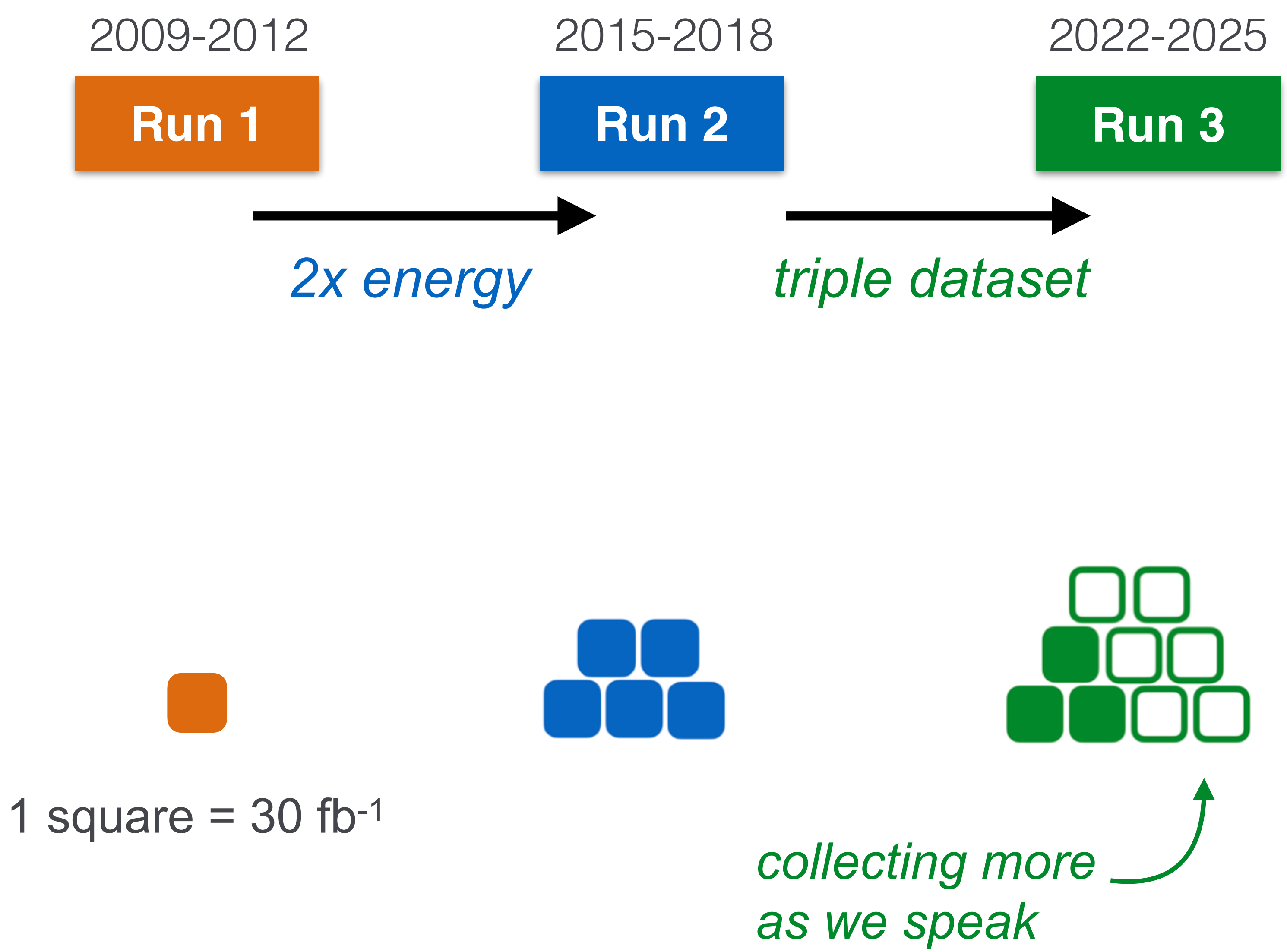
2015-2018

Run 2

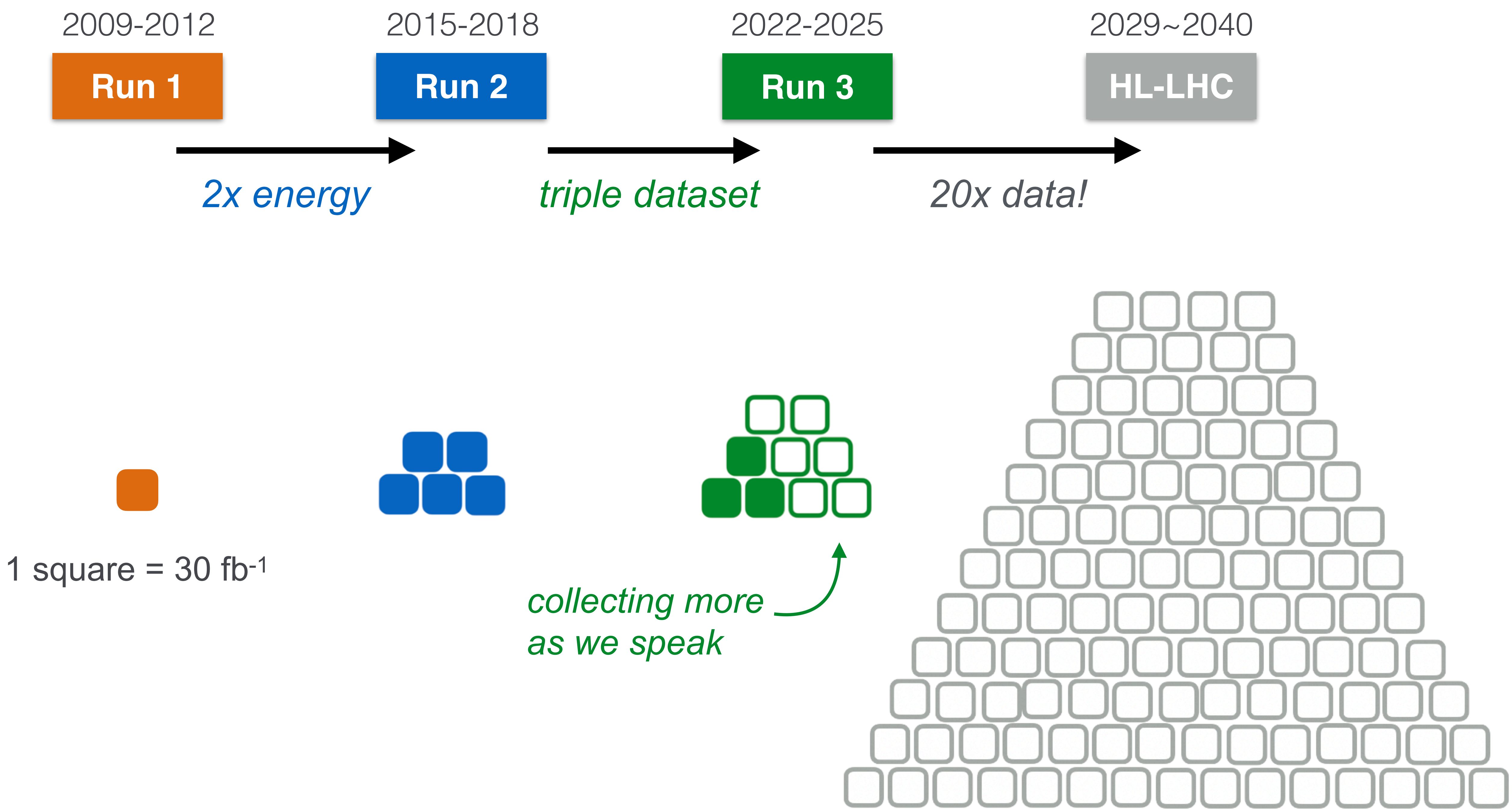
2x energy

1 square = 30 fb^{-1}

LHC Schedule



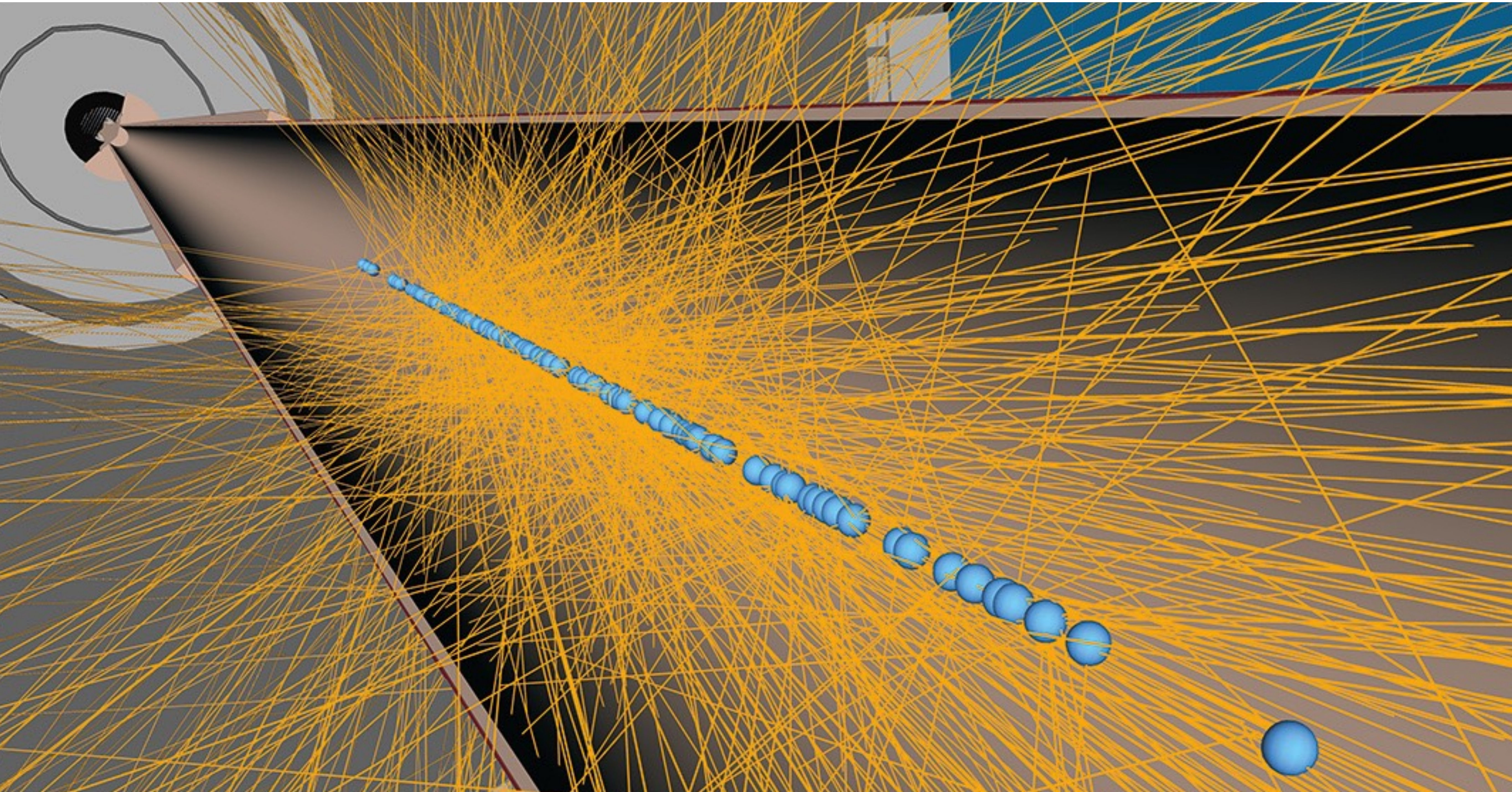
LHC Schedule



~4000 fb^{-1} of data to access rare unseen processes, such as Higgs self-coupling!

Unparalleled challenges

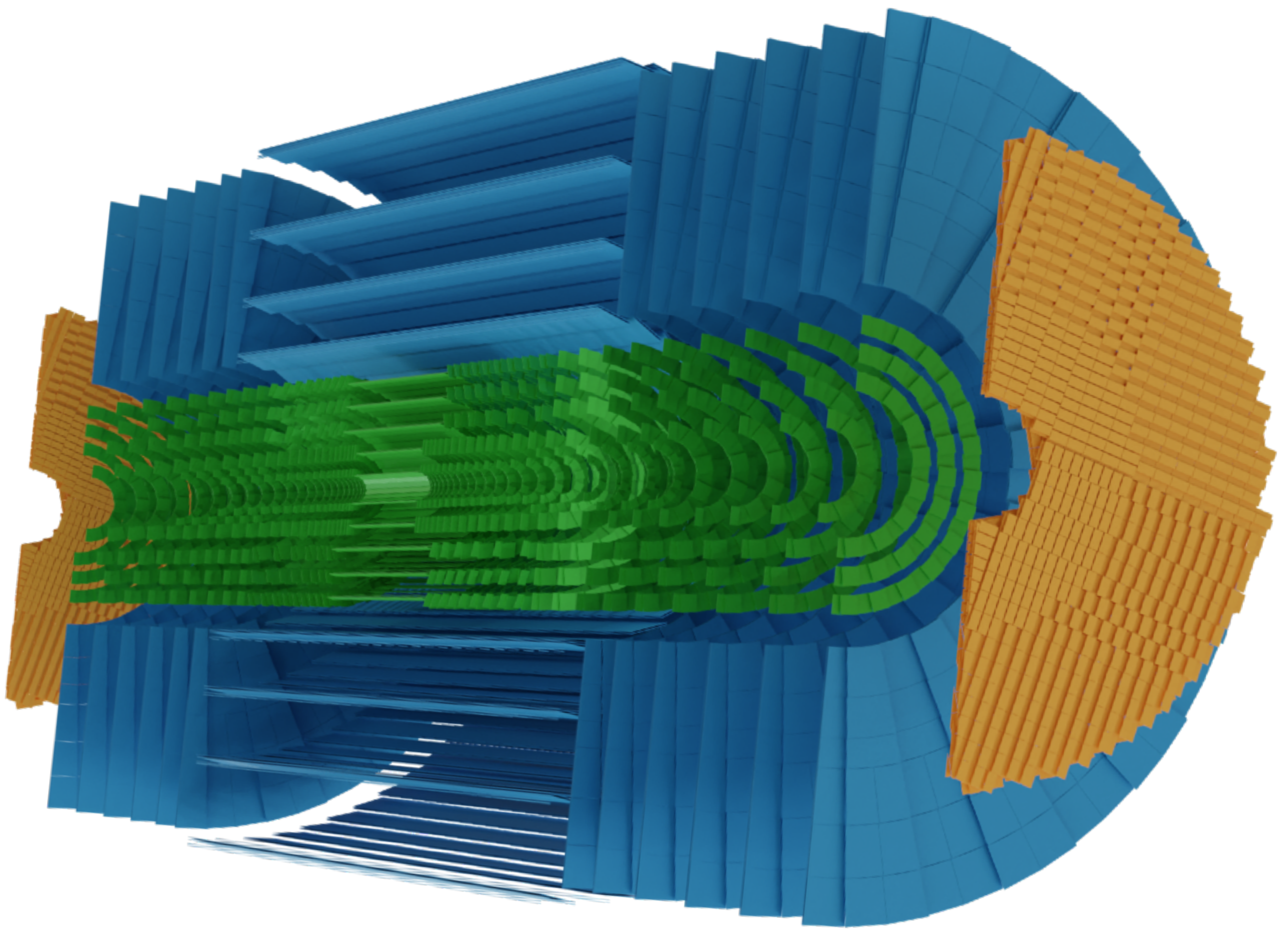
- 5x as many simultaneous collisions requires new detector technologies to untangle & understand
- The very particles we seek to observe also cause damaging radiation
  - HL-LHC ATLAS must withstand up to **1.7 Grad**!



HL-LHC Upgrades

New detector technologies will give access to currently unattainable physics!

Canadian institutes driving major contributions to these efforts



- New Inner Tracker - Full silicon replacement with **Pixel** & **Strip** tech
- **High Granularity Timing Detector** for 30 ps resolution

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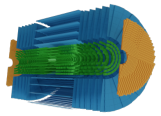
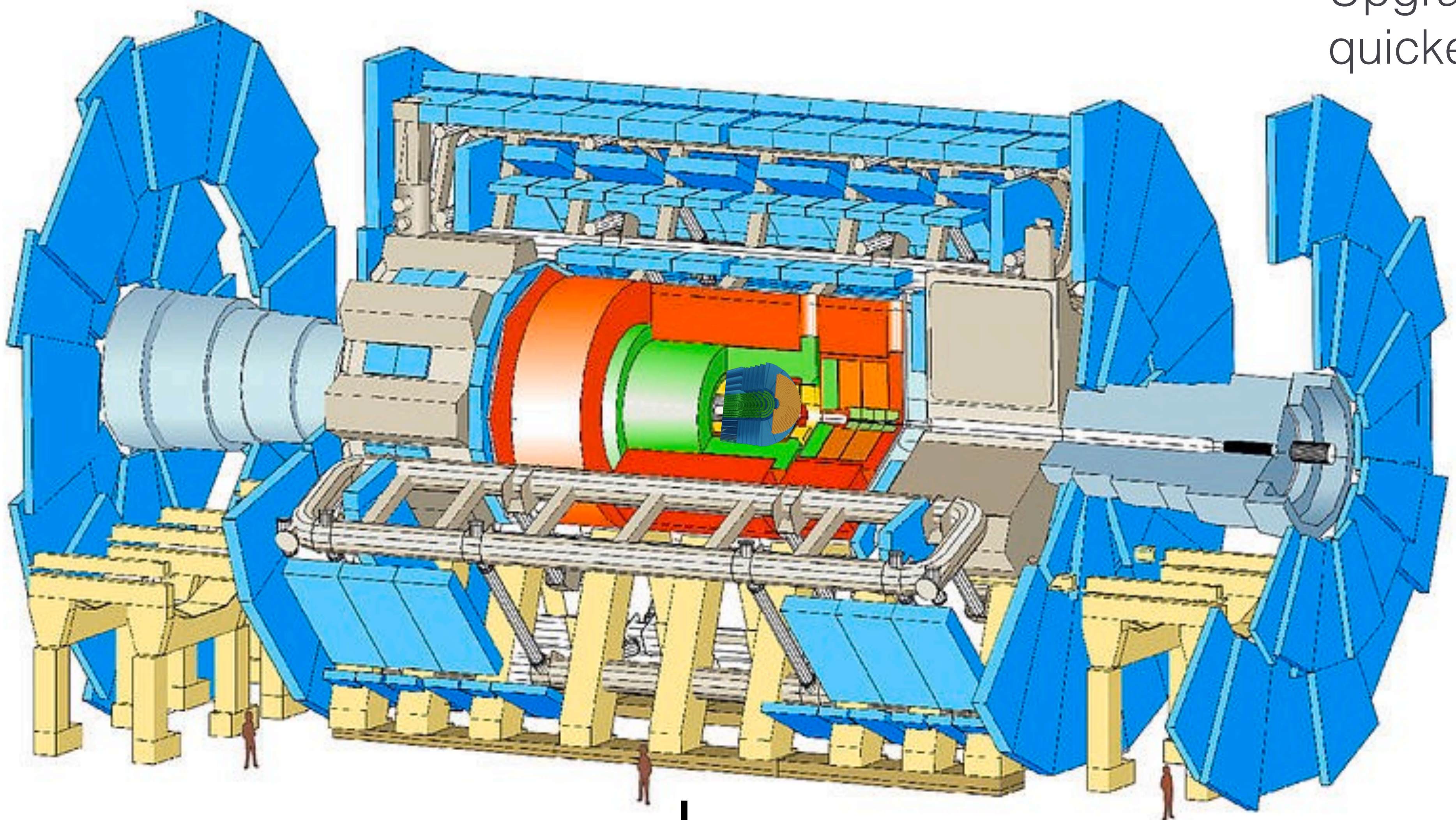


HL-LHC Upgrades

New detector technologies will give access to currently unattainable physics!

Canadian institutes driving major contributions to these efforts

- New Inner Tracker - Full silicon replacement with Pixel & Strip tech
- High Granularity Timing Detector for 30 ps resolution
- Upgraded **Muon Spectrometer** for quicker & precise muon tracking



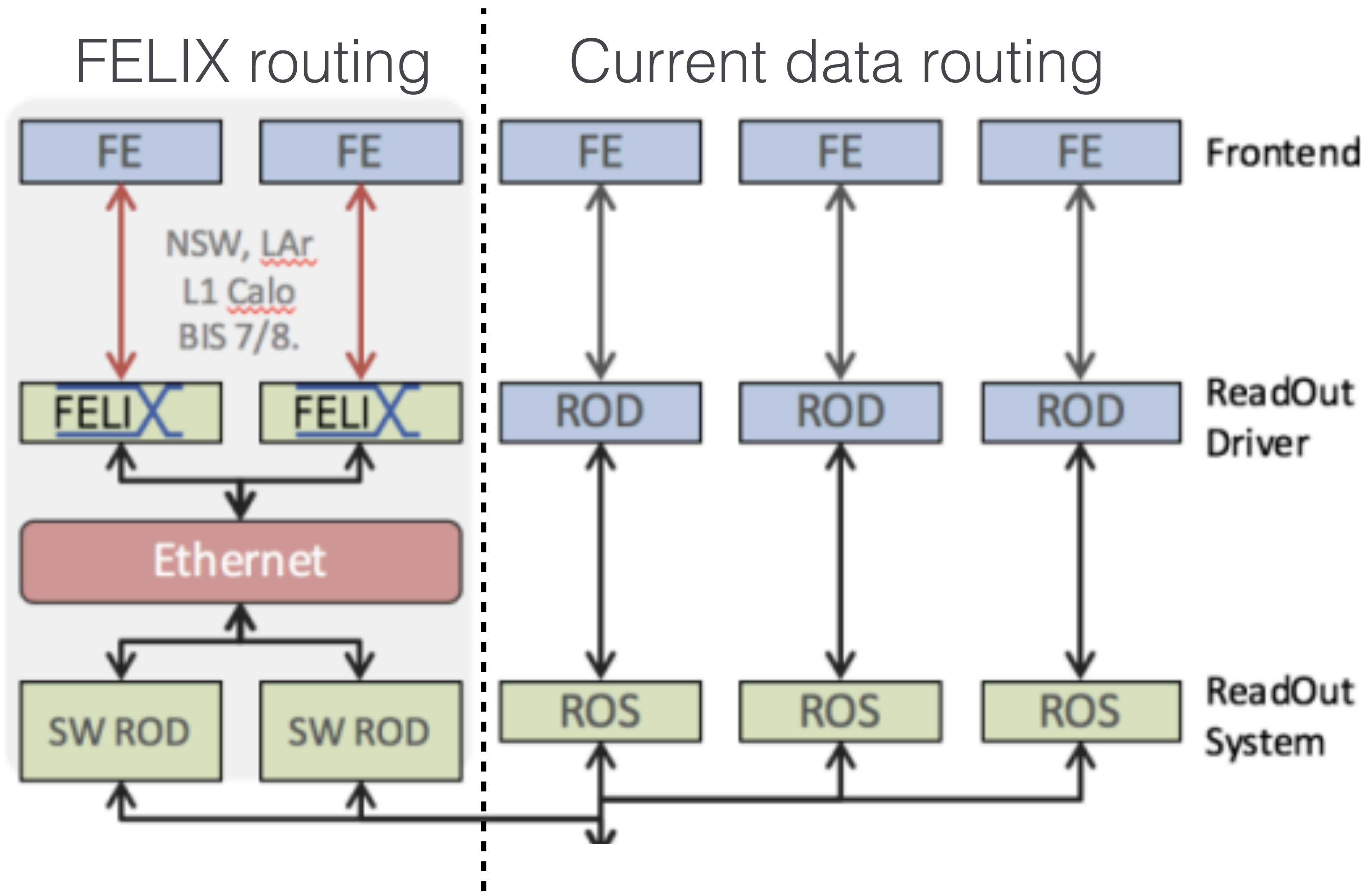
Off-detector computing

- Unifying off-detector data transfer between subdetectors
- Full 40 MHz readout of **LAr** & **Tile** Calorimeters & **Muon** systems

Unifying Detector Data Streams

- Standardizing connection between on-detector electronics & off-detector commodity computing
  - **GBTx**: on-detector rad-hard ASIC for aggregating data streams
  - **FELIX**: off-detector data router (Xilinx Ultrascale FPGA) interfacing subdetectors with ATLAS readout & timing / trigger / control (TTC) systems
- Reduces complexity & costs from custom components, de-duplicates design+maintenance
  - Scalable! Will ultimately route 4.6 TB/s through ~30,000 links
- Adopted beyond ATLAS (ProtoDUNE, sPHENIX, NA62, …)

FELIX being utilized now for select Run 3 detectors



[FELIX: the Detector Interface for the ATLAS Experiment at CERN]

Upgraded Muon Detector

- New Small Wheel is first new detector designed for HL-LHC rates
  - Two innovative gaseous detectors for fast & precise muon tracking & triggering
- Installed in 2021 before Run 3, public followed videos of the journey

The New Small Wheel Upgrade Project of the ATLAS Experiment

Small-strip Thin Gap Chambers ¼ made in Canada!

Meeting, Unboxing, & Installing the NSW

Upgraded Muon Detector

[The New Small Wheel Upgrade Project of the ATLAS Experiment]

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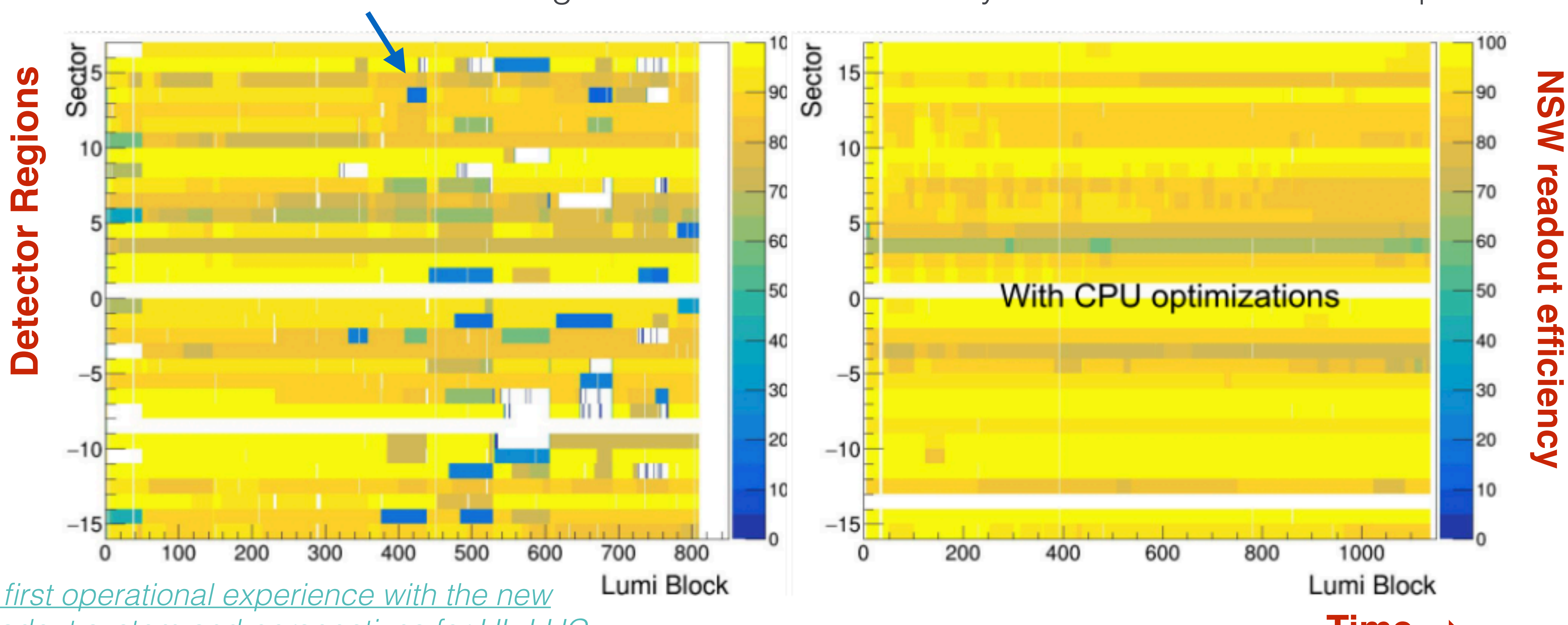
  - Two innovative gaseous detectors for fast & precise muon tracking & triggering
- Installed in 2021 before Run 3, public followed videos of the journey

- Most data links yet → essential feedback on GBTx/FELIX in saturated conditions
  - Rare issues found & solved, new performance optimizations investigated & deployed

= Smoother start to HL-LHC!

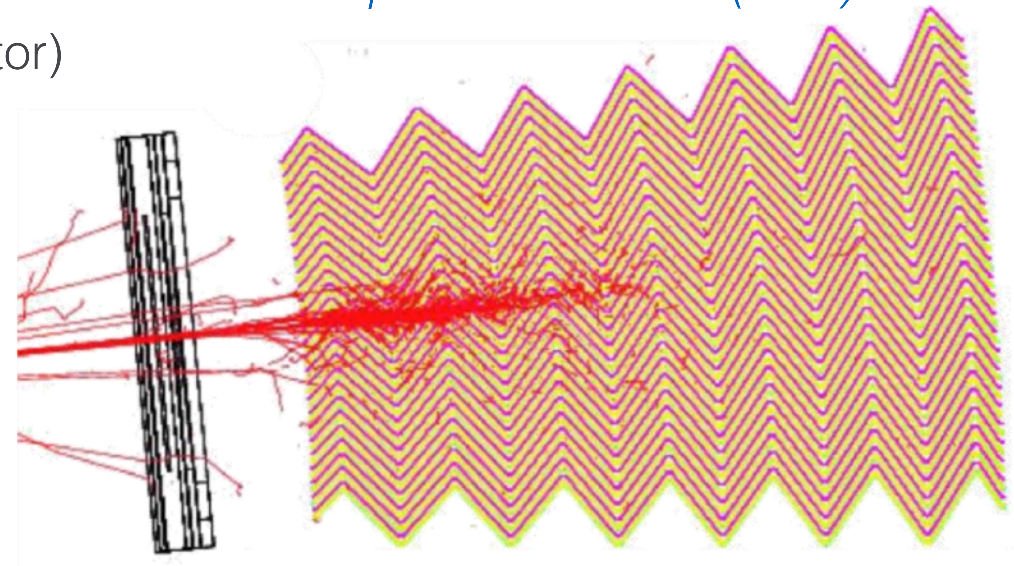
Readout becomes **stuck** due to long latencies | Efficiency recovered with software optimizations



[FELIX: first operational experience with the new ATLAS readout system and perspectives for HL-LHC]

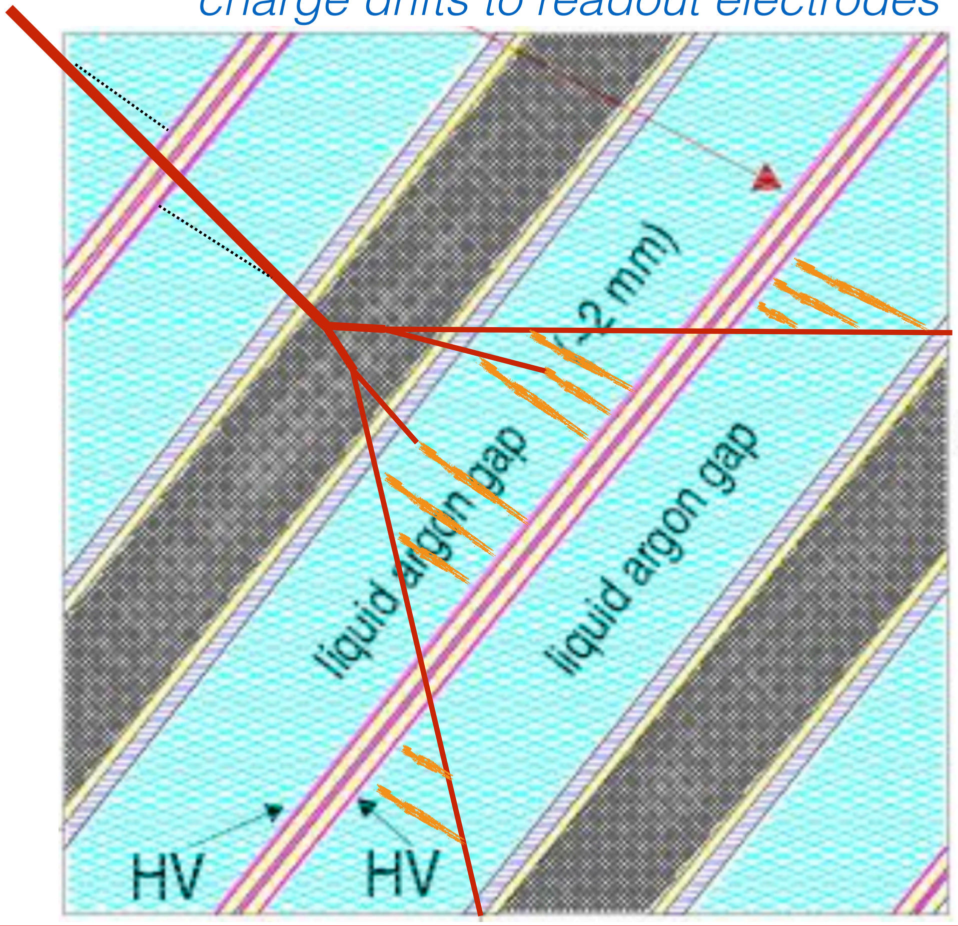
Calorimeter upgrades

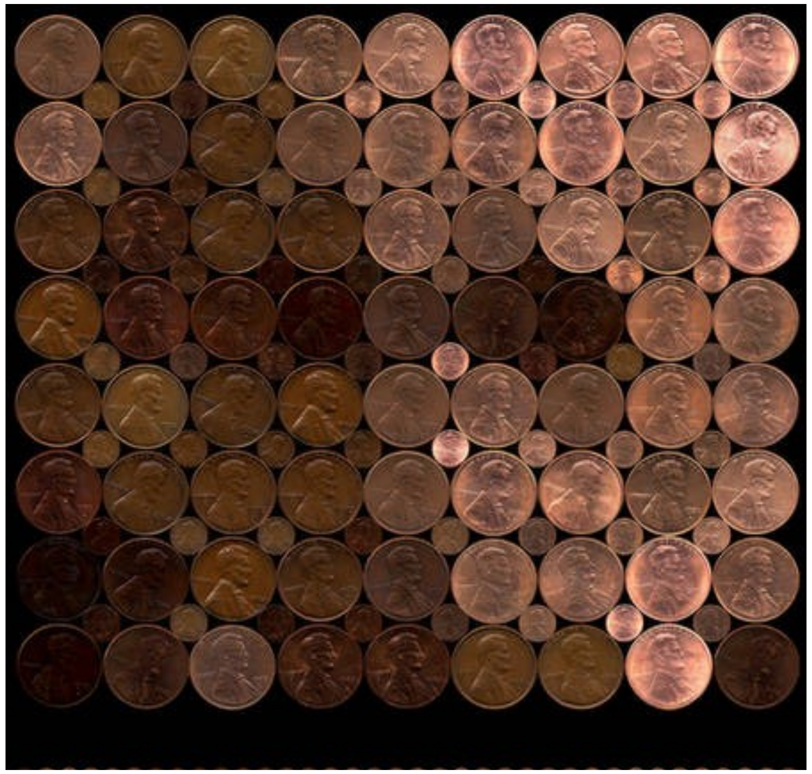
High-energy charged particles shower in dense passive material (lead)



- Sampling calorimeters use rad-hard materials (liquid argon, plastic scintillator)
  - No full replacement necessary for HL-LHC
- Current electronics bandwidth limited, cannot send all info off-detector
  - Must sum into granular towers for trigger decision

Showering particles ionize LAr, charge drifts to readout electrodes





Coarse trigger readout can remove relevant details from event

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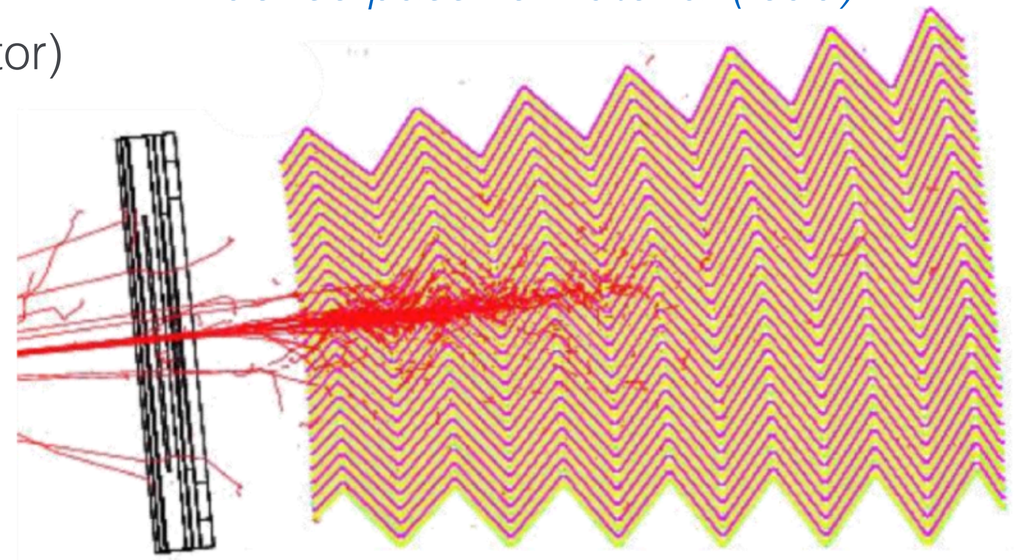
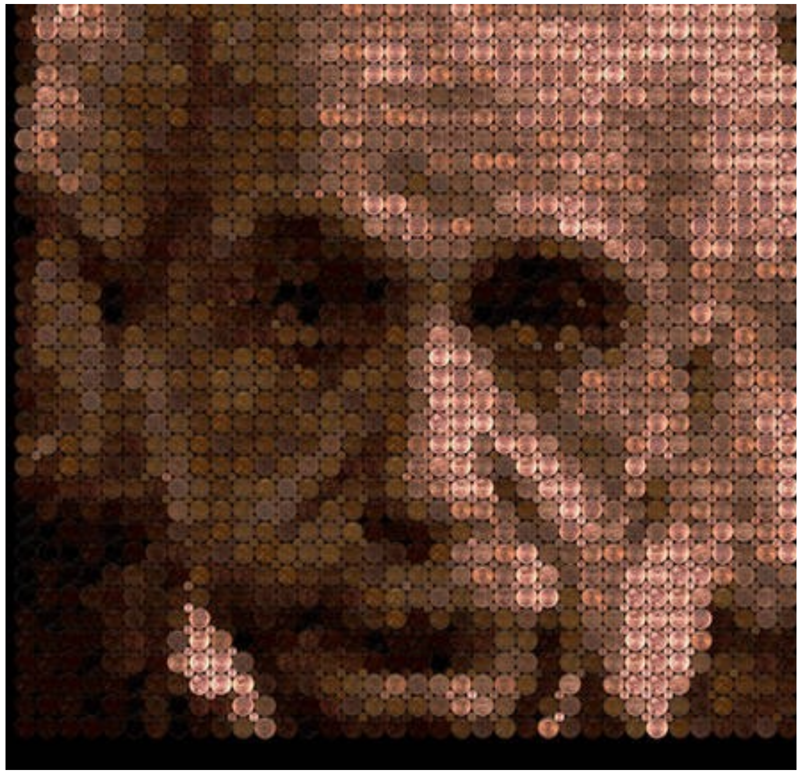
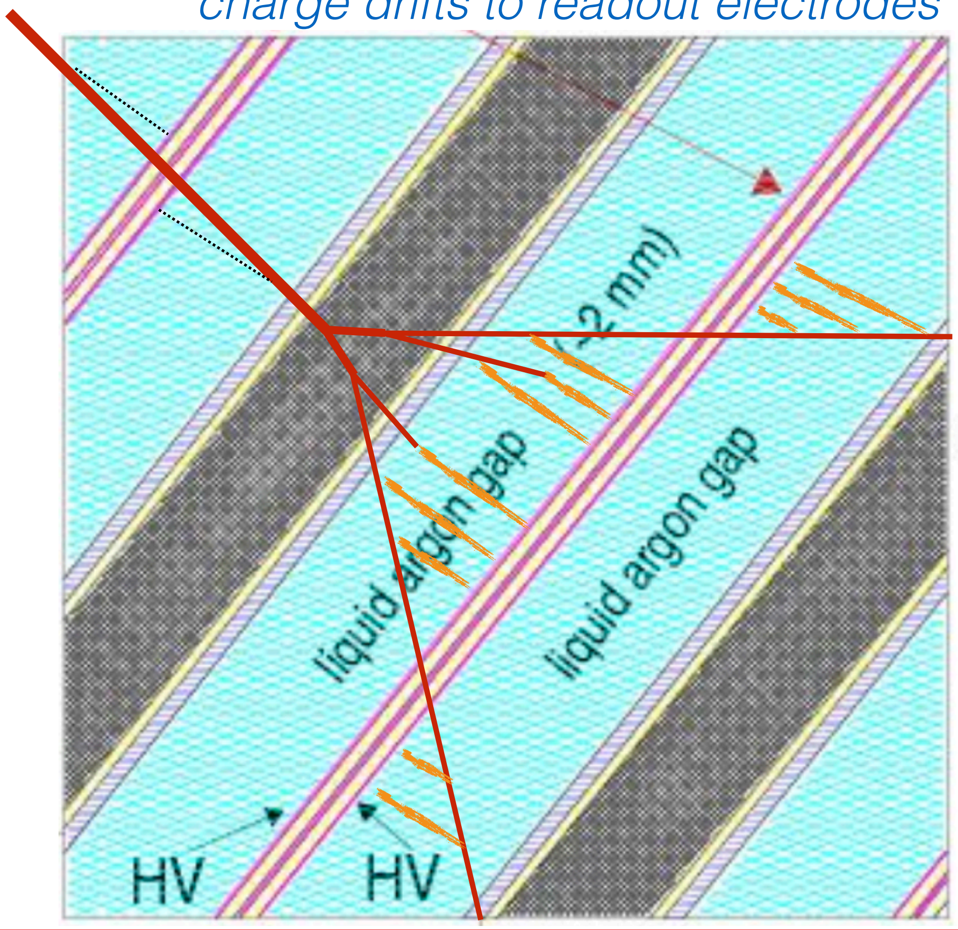


- Current electronics bandwidth limited, cannot send all info off-detector
    - Must sum into granular towers for trigger decision
- Electronics redesign to allow for full granularity, *triggerless* 40 MHz readout



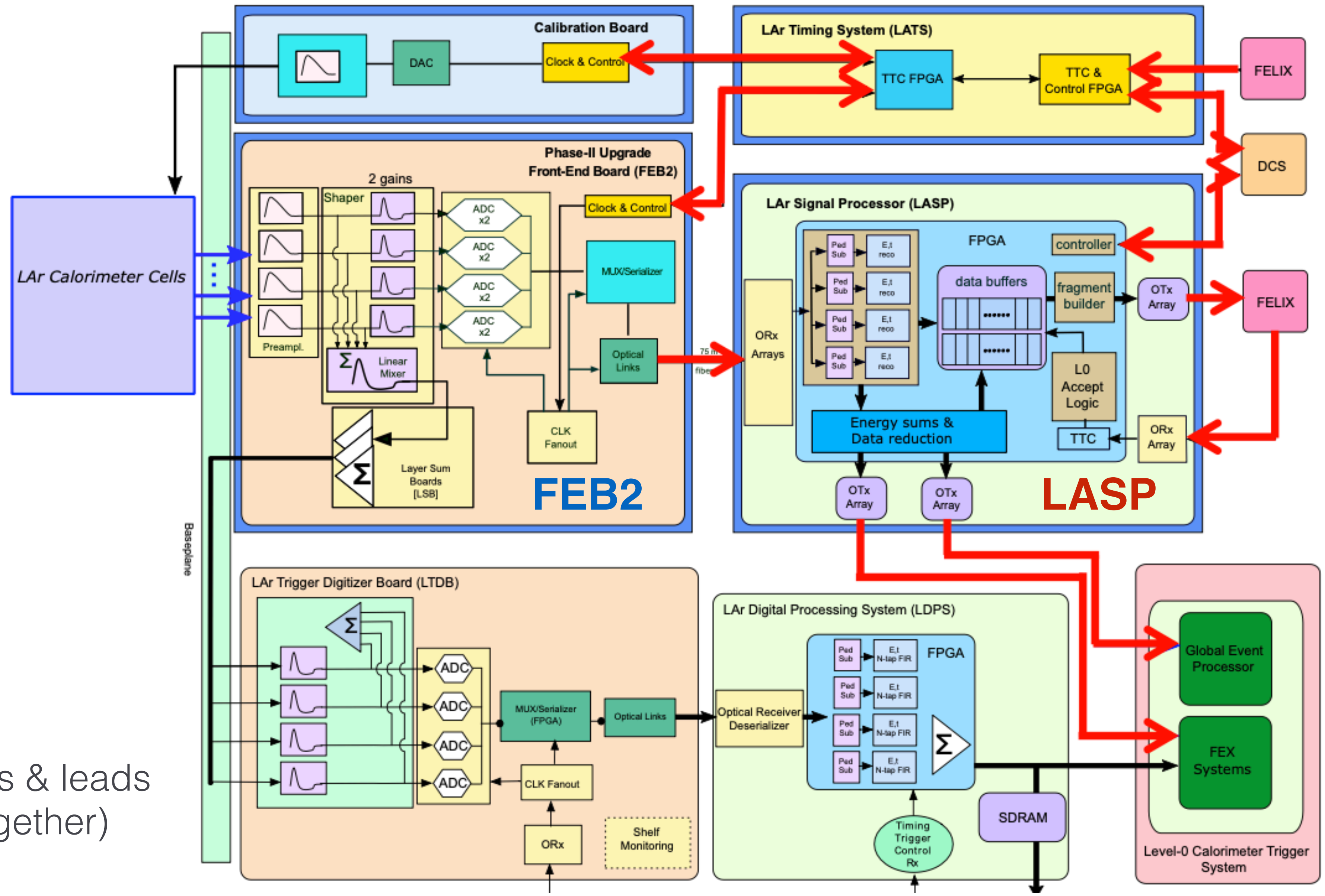
HL-LHC full readout will give clearer picture!

Showering particles ionize LAr, charge drifts to readout electrodes



LAr Upgrade Integration

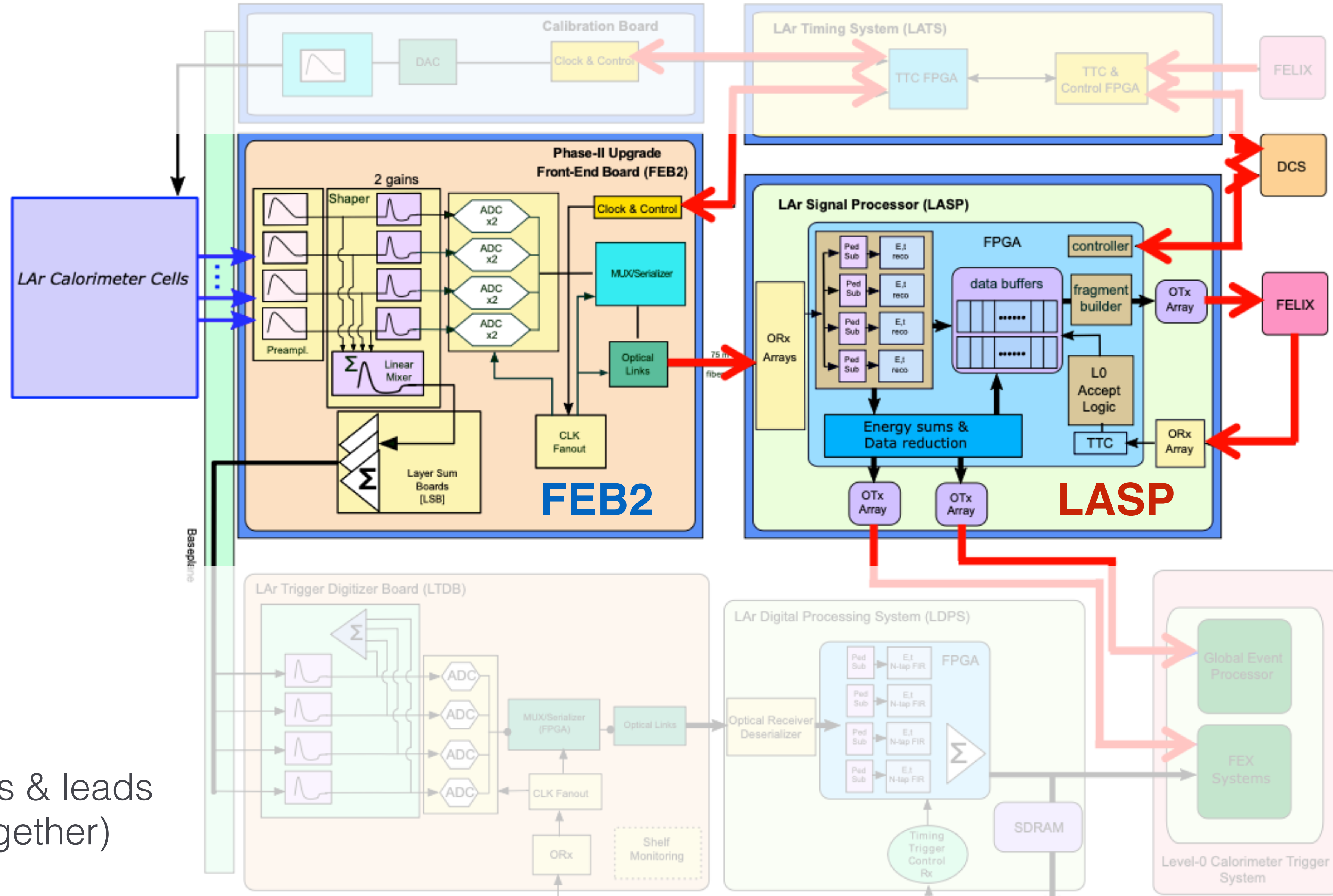
Schematic of LAr Phase-2 upgrade



- Huge project with many pieces independently developed worldwide
- Canada develops several components & leads integration efforts (prove they work together)

LAr Upgrade Integration

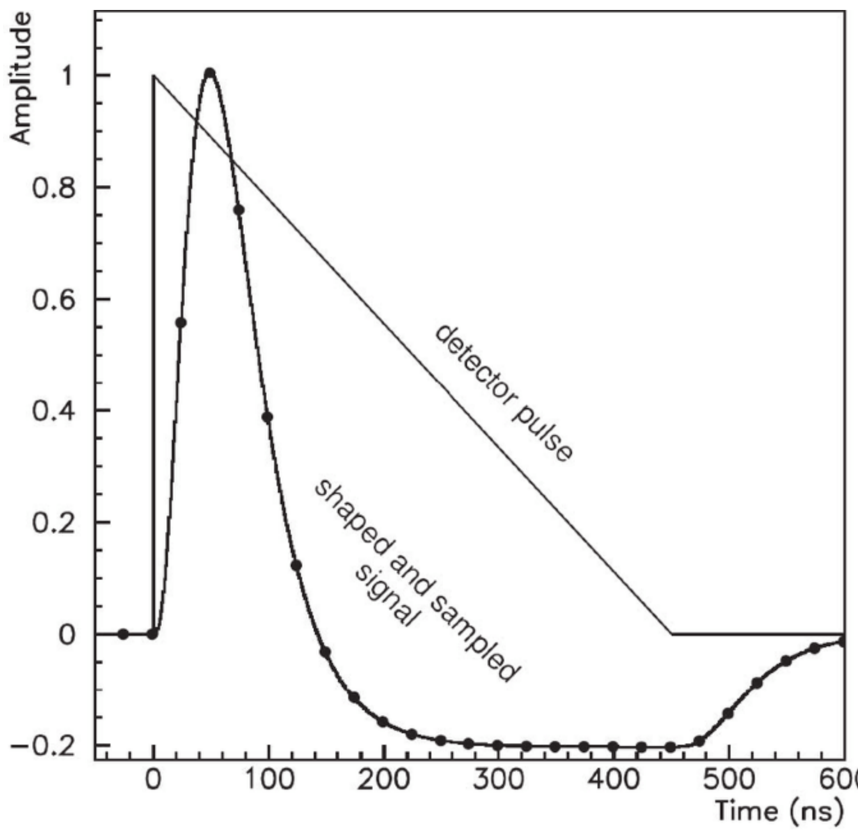
Schematic of LAr Phase-2 upgrade



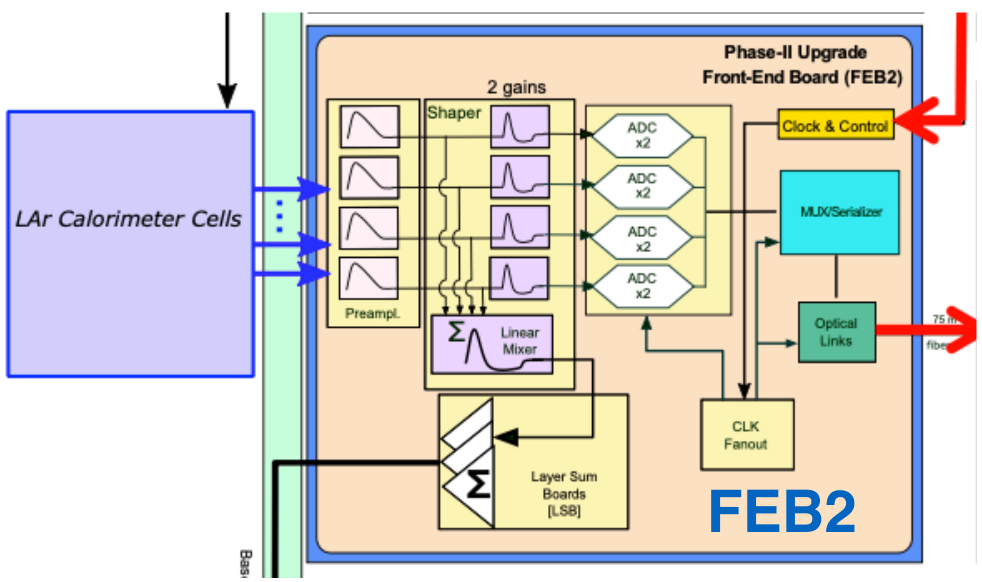
- Huge project with many pieces independently developed worldwide
- Canada develops several components & leads integration efforts (prove they work together)
  - Have achieved system configuration & demonstrated data flow

from front-end boards (**FEB2**) ⟶ to LAr Signal Processor (**LASP**) ⟶ and out to **FELIX**

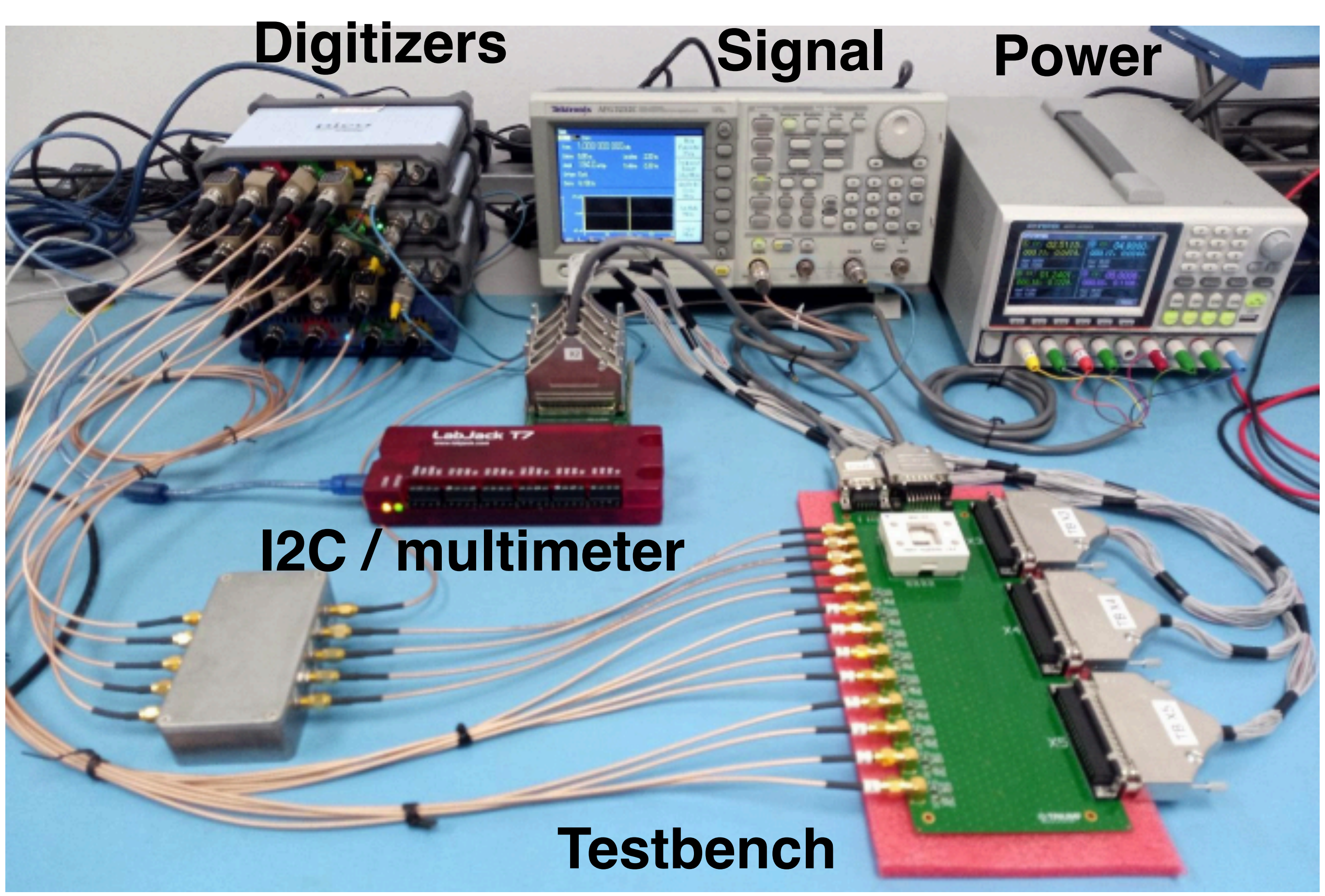
LAr Upgrade Integration



1524x on detector



HPS testbench at TRIUMF

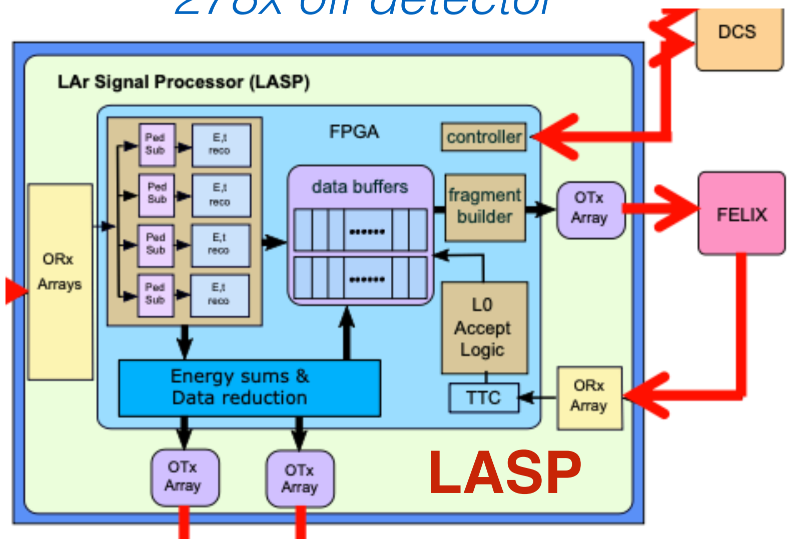


- Hadronic Endcap preshaper (HPS): on-detector ASIC shapes raw signals and applies gain on-detector
- Recently developed quality testing program, inspected 200 preproduction ASICs

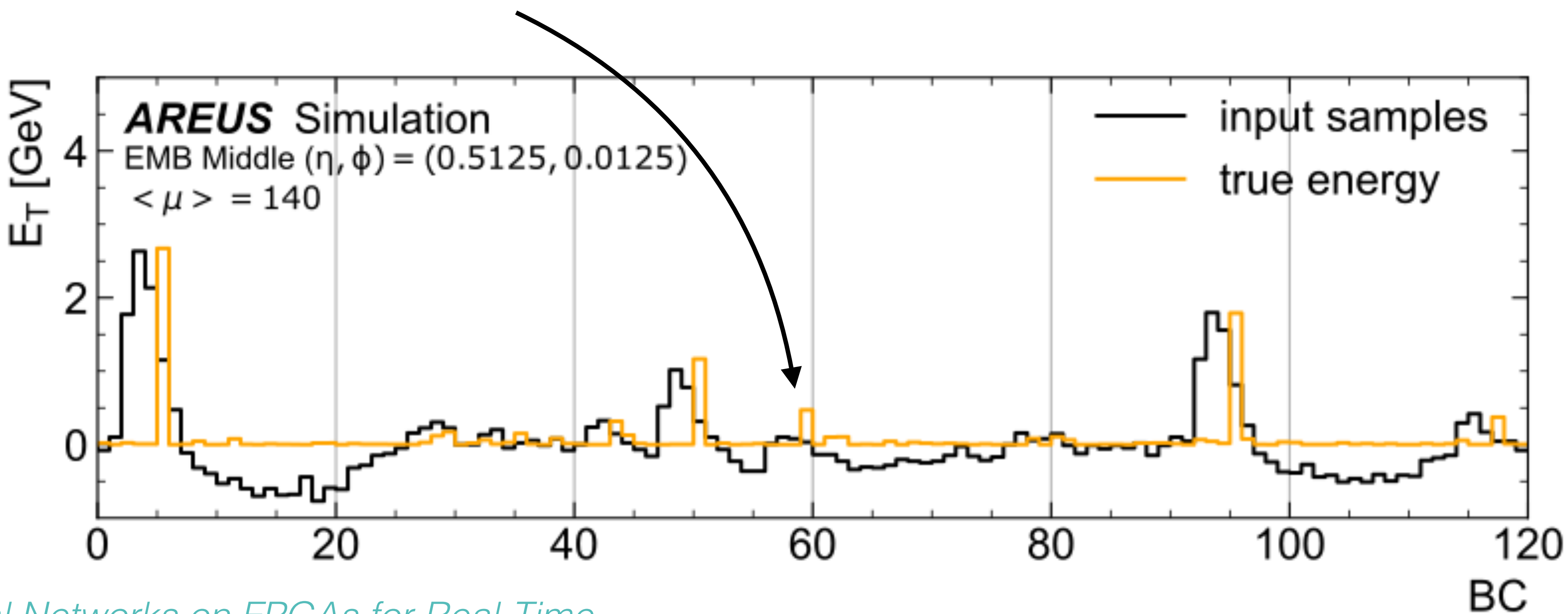
LAr Upgrade Integration

- LAr Signal Processor (LASP): Off-detector FPGA boards (2 Intel Agilex)
  - Will handle 250 Tbps of data from 36k optical fibers
  - Clean signals of pileup contamination, computes cell energy & timing

278x off detector



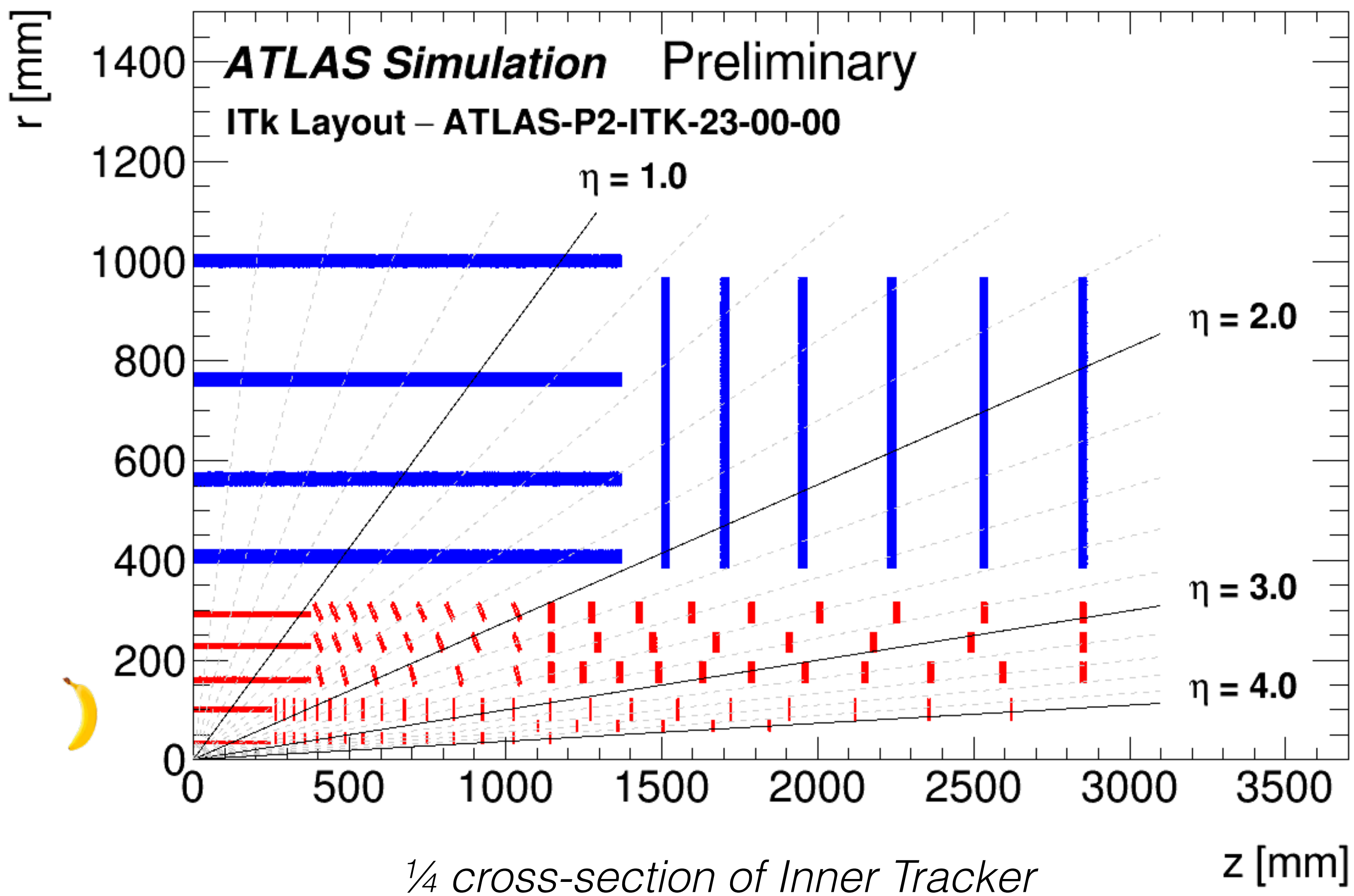
- Exploring AI integrations in FPGAs for advanced signal filtering
- CNNs & RNNs to detangle overlapping signals for better signal-vs-background efficiency (80%→95%)



[Artificial Neural Networks on FPGAs for Real-Time Energy Reconstruction of the ATLAS LAr Calorimeters]

New ITk detector

Moving to all-silicon charged-particle tracker with
cutting-edge technologies for inner Pixel and outer Strip layers



¼ cross-section of Inner Tracker

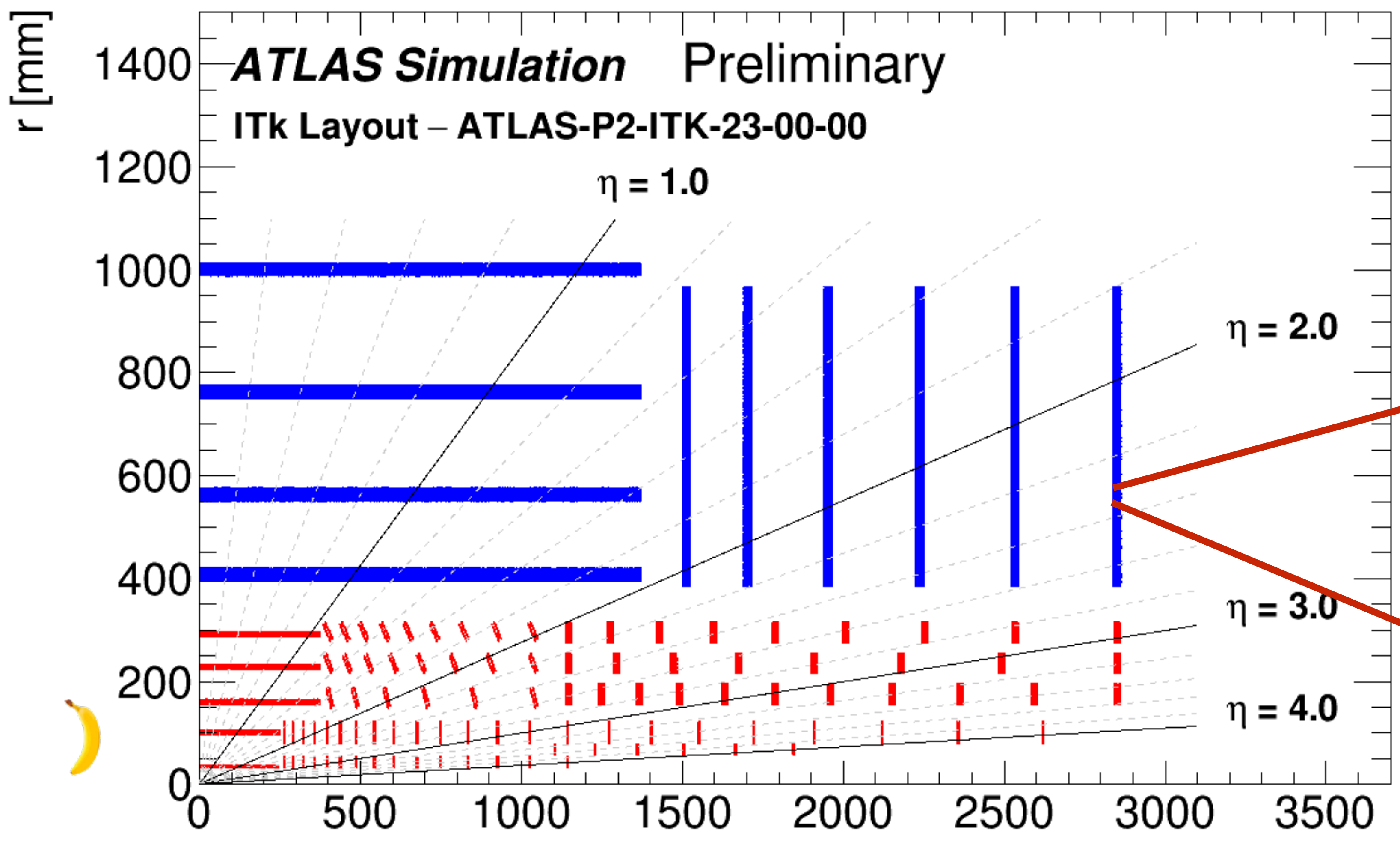
- ✔ Withstand 1.7 Grad of radiation
- ✔ 10x faster readout (1 MHz)
- ✔ Expanded detector coverage
- ✔ Improved physics performance

Canada deeply involved in design & construction of **Outer Strip tracker**

165 m^2 of silicon, split into **60 million** channels, read by **300,000** on-detector ASICs

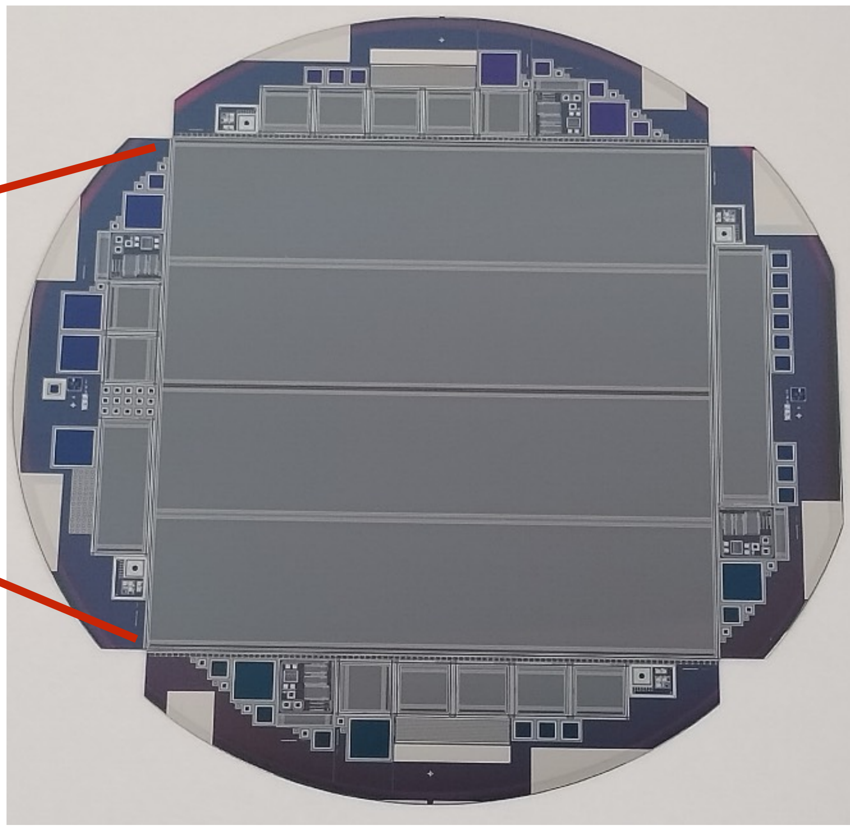
Zooming in on strip sensors

Moving to all-silicon charged-particle tracker with cutting-edge technologies for inner Pixel and outer Strip layers



¼ cross-section of Inner Tracker

silicon sensor wafer



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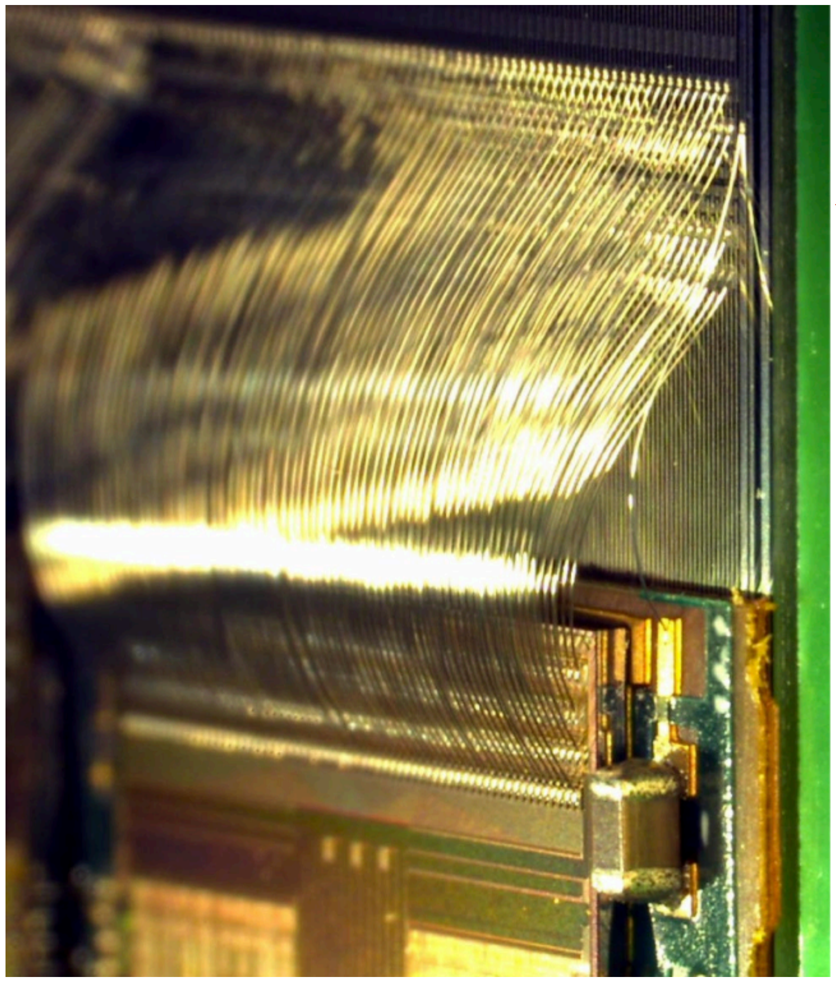
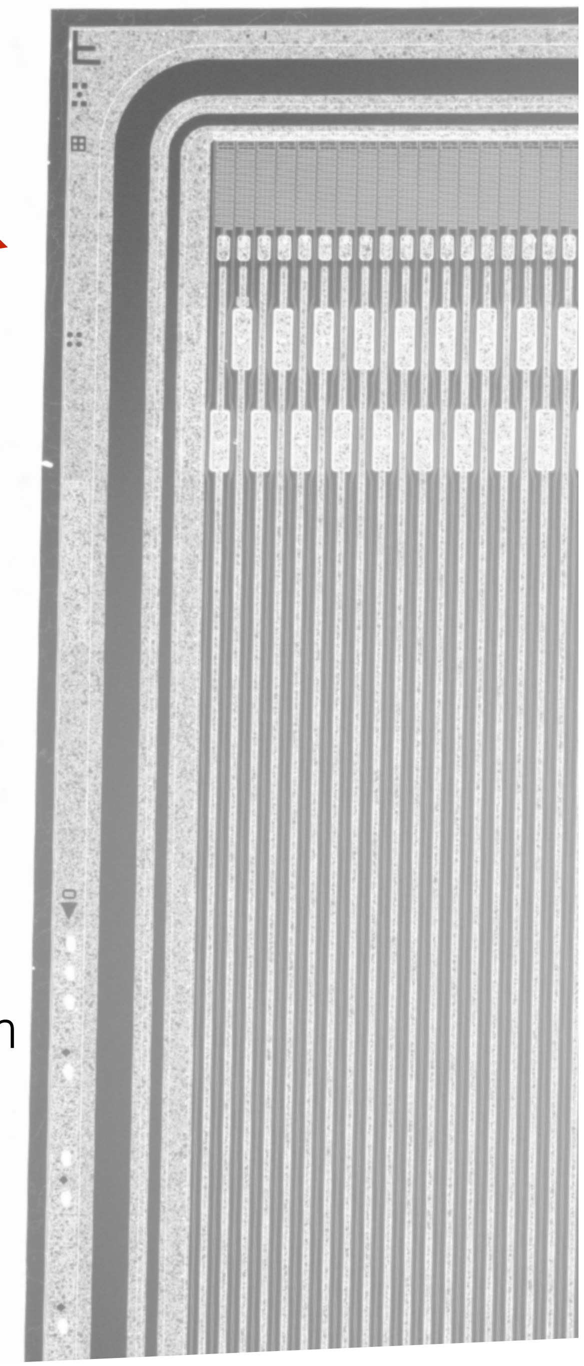
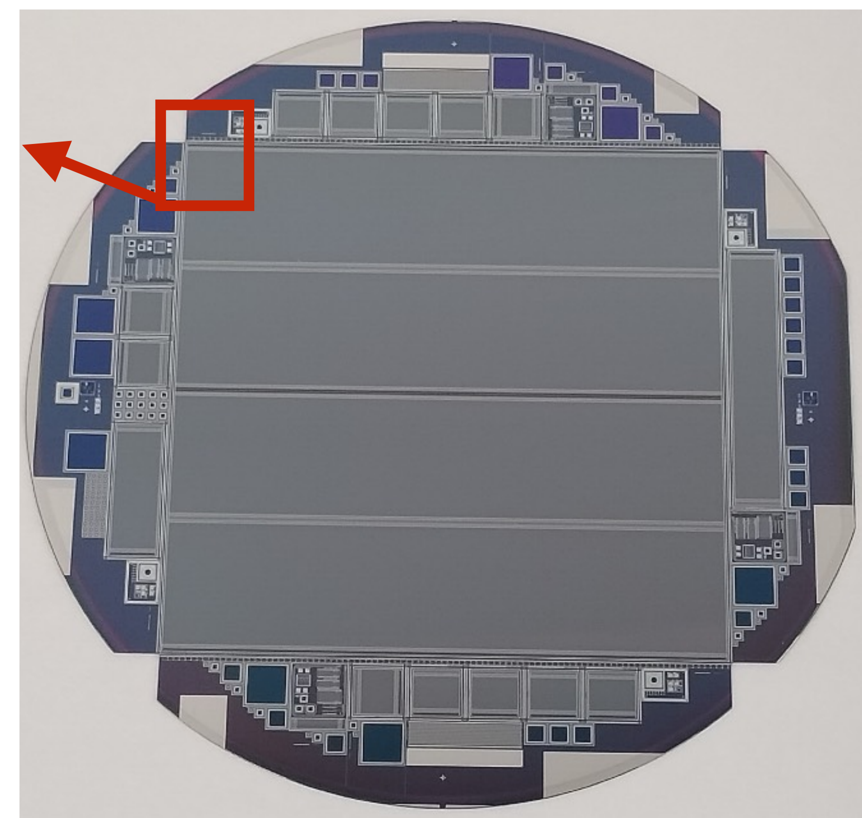


silicon sensor strips



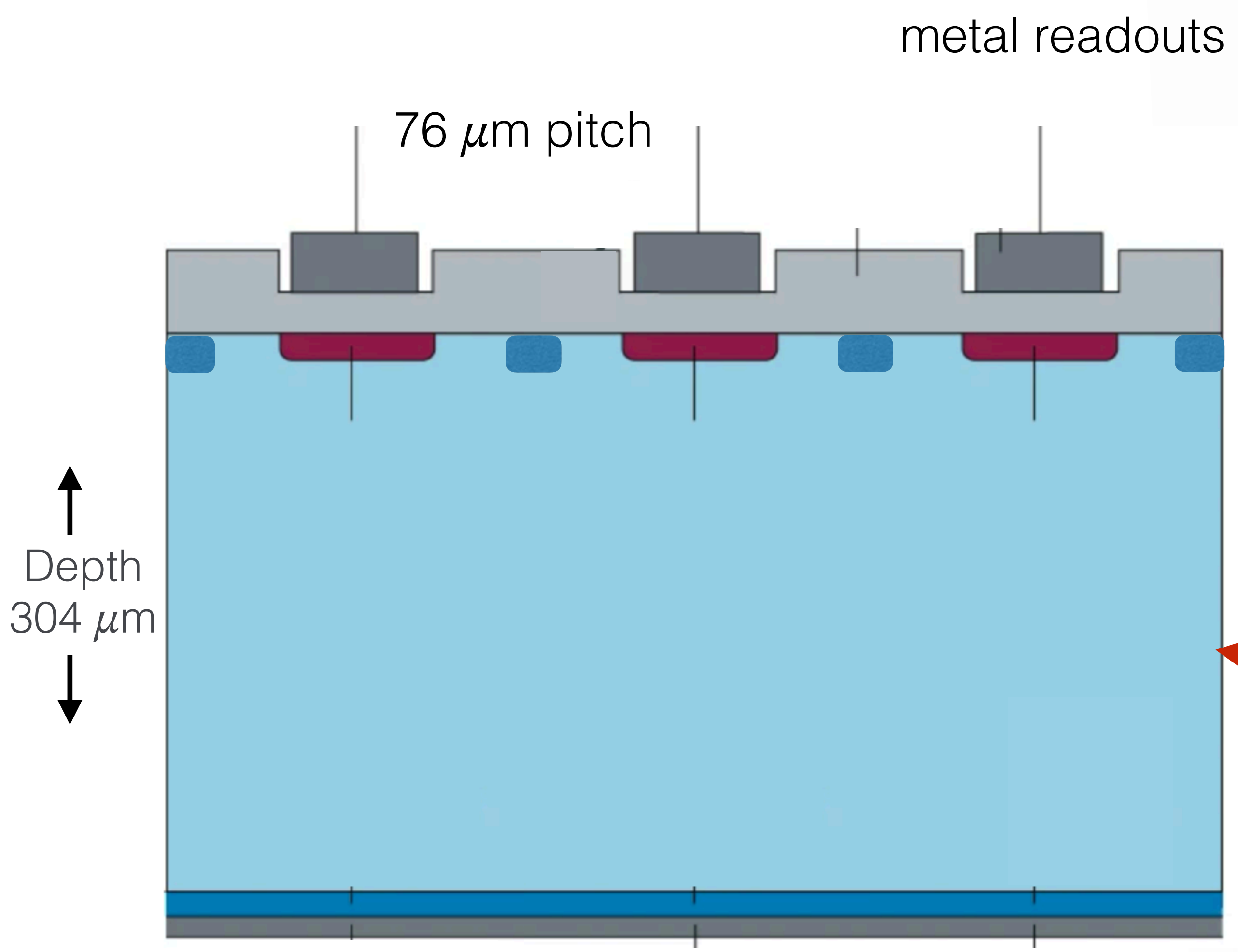
2.4 - 4.8 cm
length

silicon sensor wafer

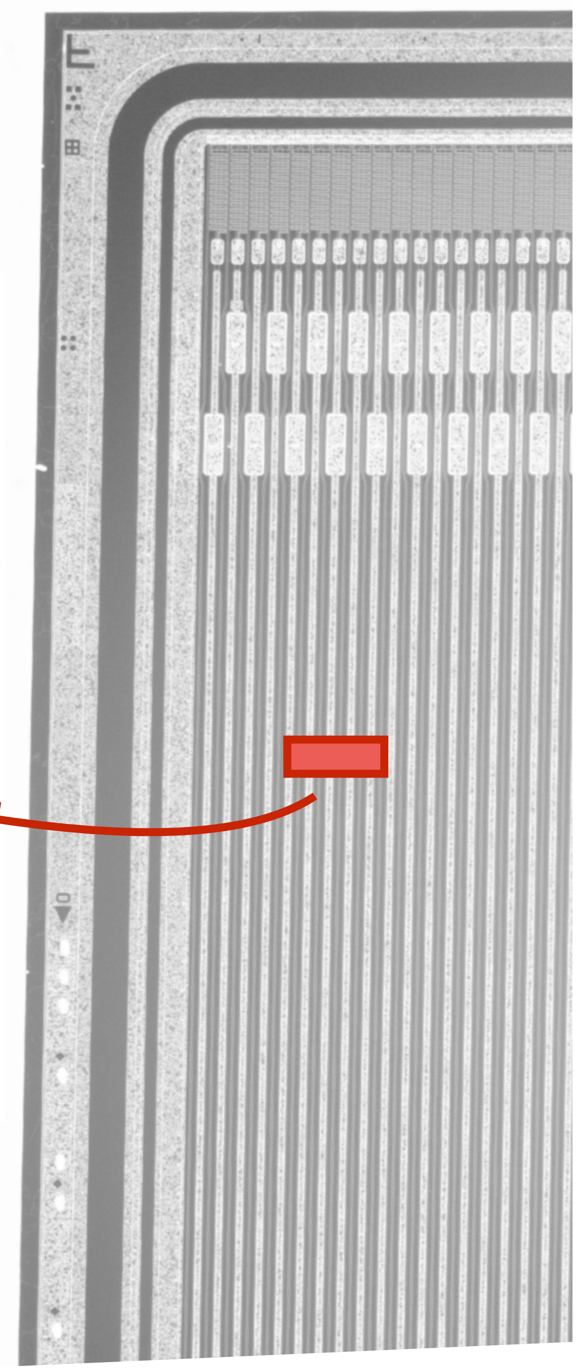


Zooming in on strip sensors

cross-section of silicon sensor strips



silicon sensor strips



silicon sensor wafer

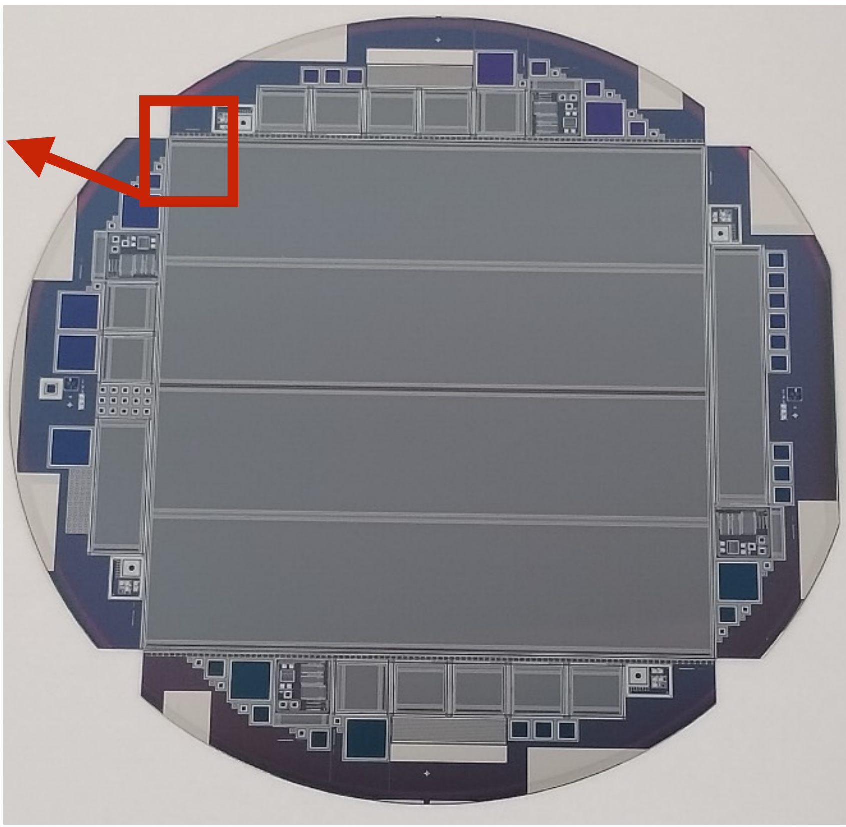
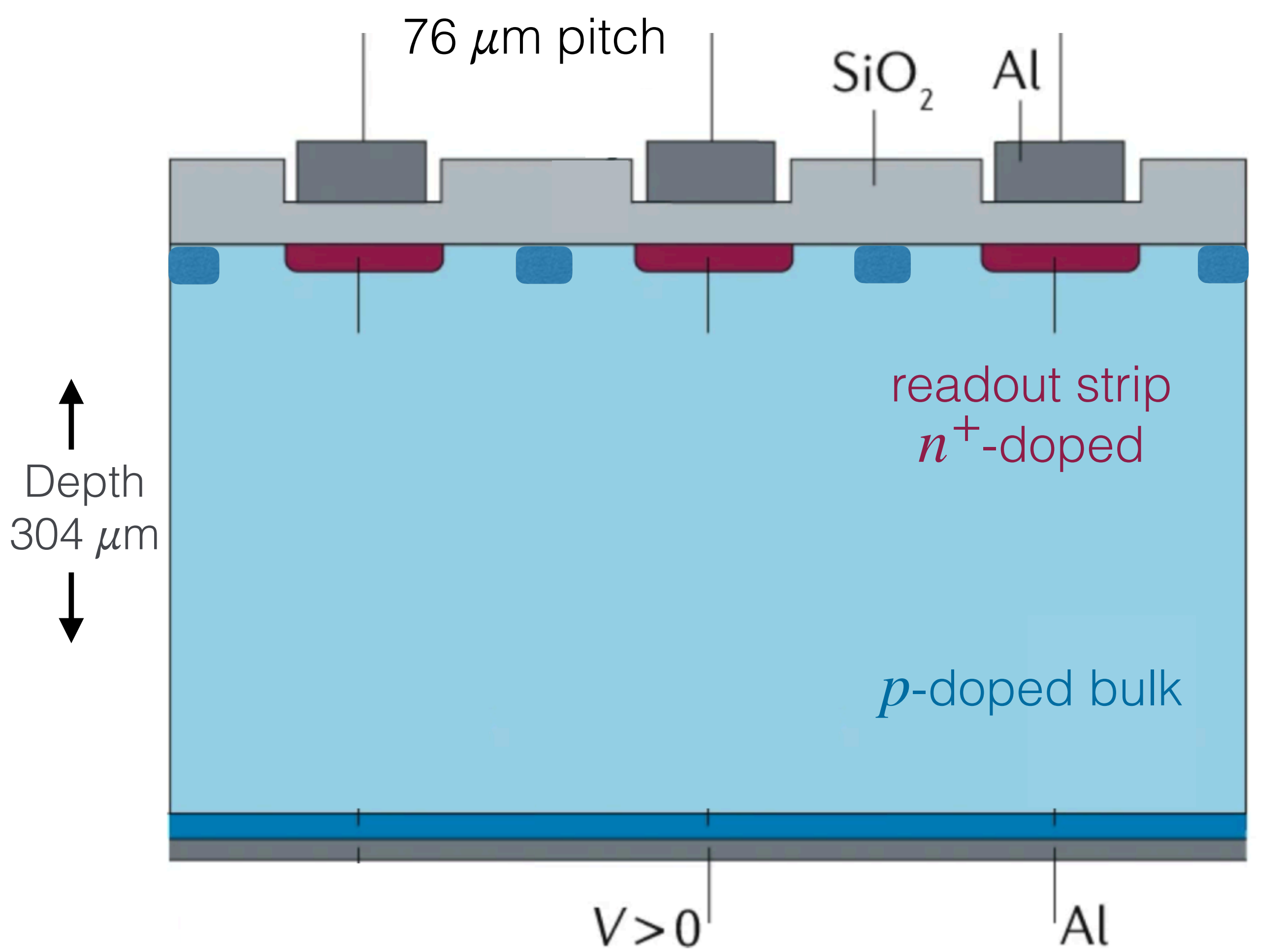


Figure Adapted from M. Krammer

Strip Sensor

- Semiconductors: doping impurities into silicon creates electric field with no mobile charge carriers



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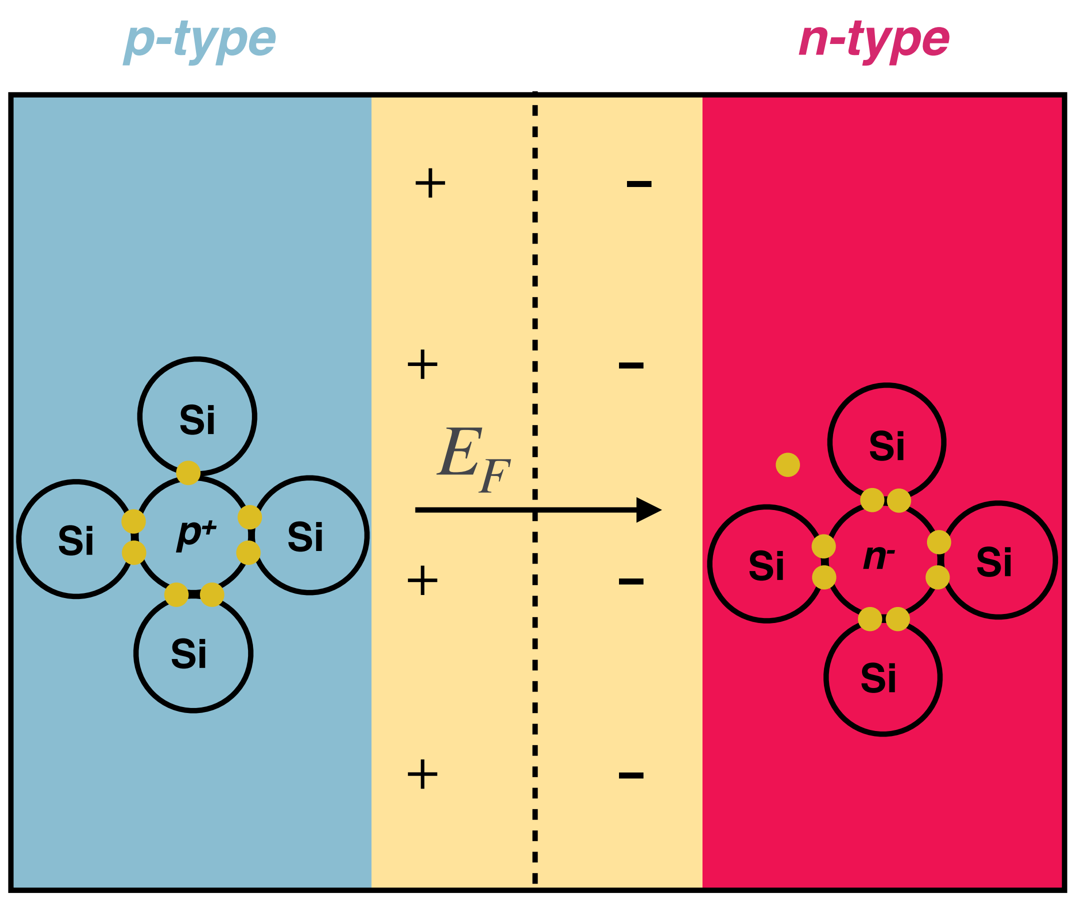
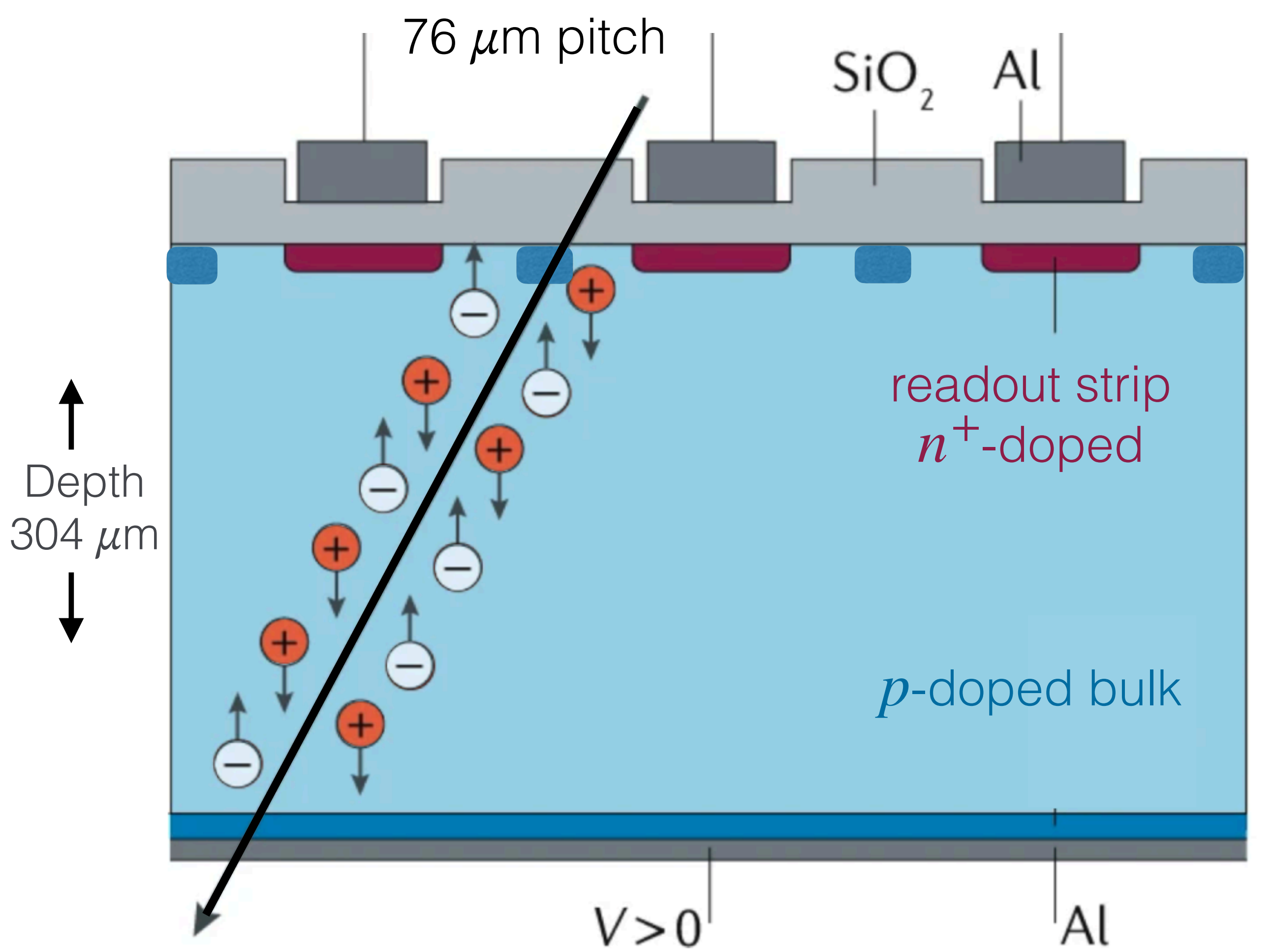


Region with space charge but no free charge carriers

Strip Sensor

- Semiconductors: doping impurities into silicon creates electric field with no mobile charge carriers
  - Adapted into sensors: ionizing particles will free electrons & holes, drift to readout



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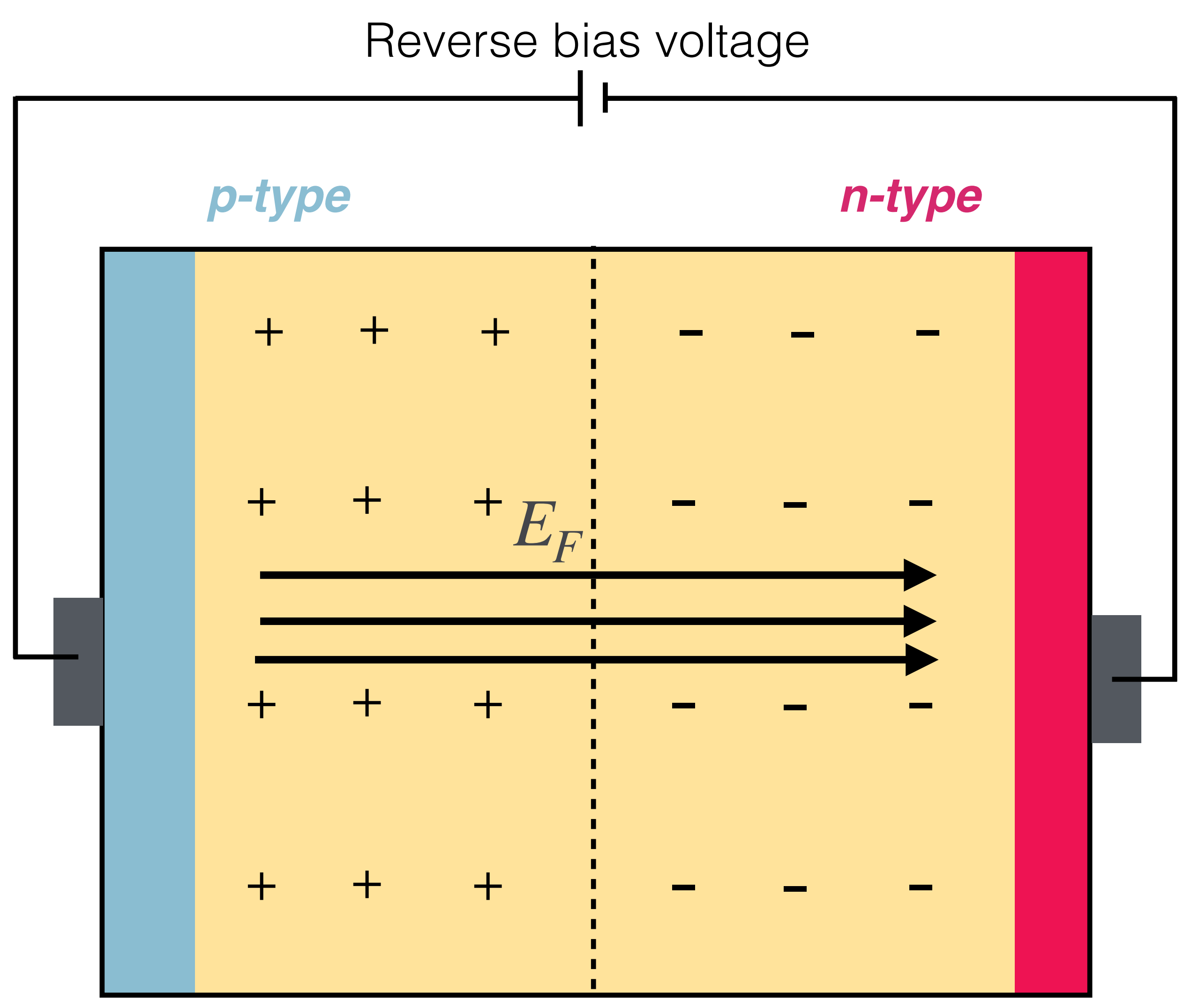


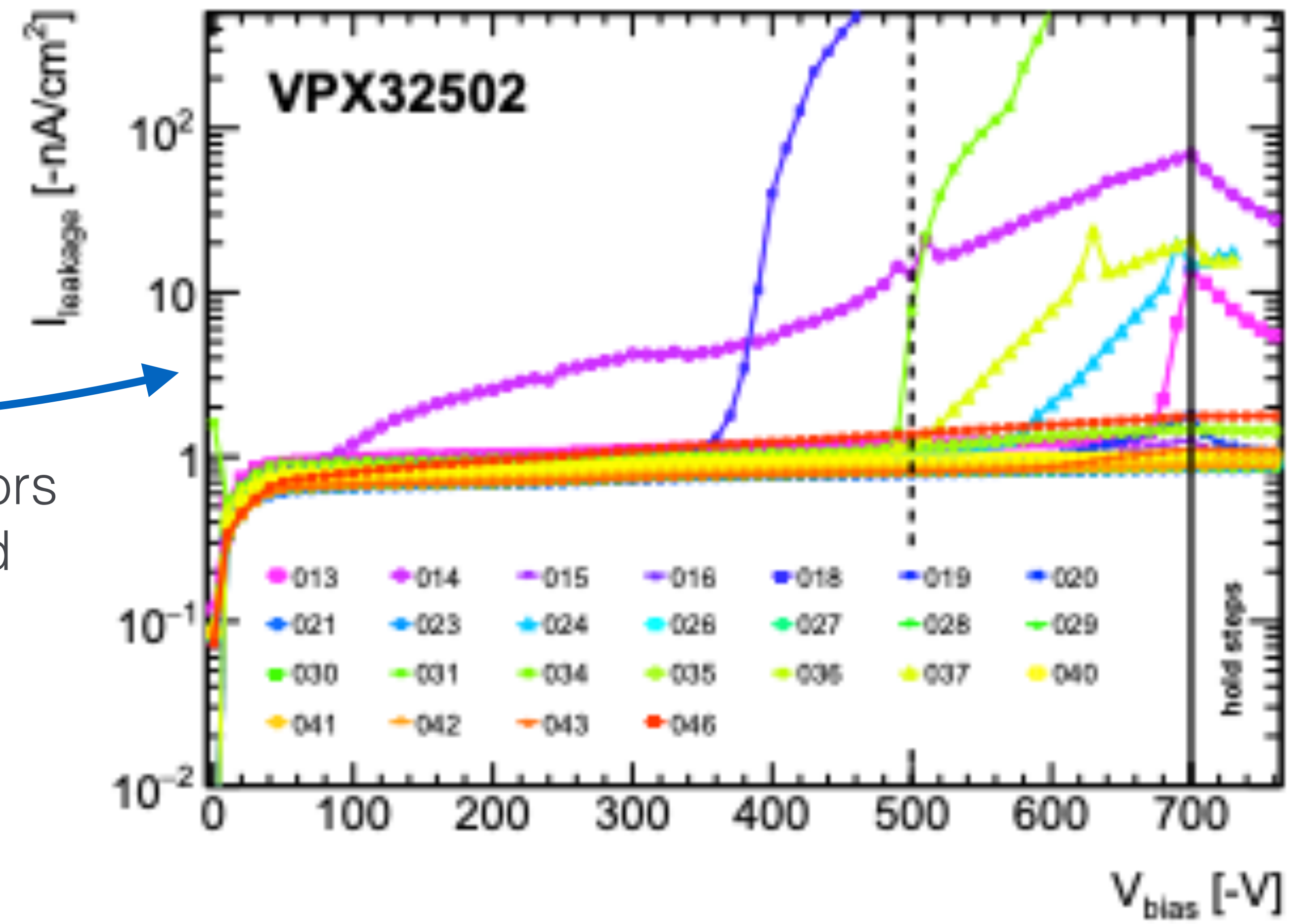
Region with space charge but no free charge carriers

n+-in-p technologies only recently possible thanks to work of RD50 collaboration that includes Canada!

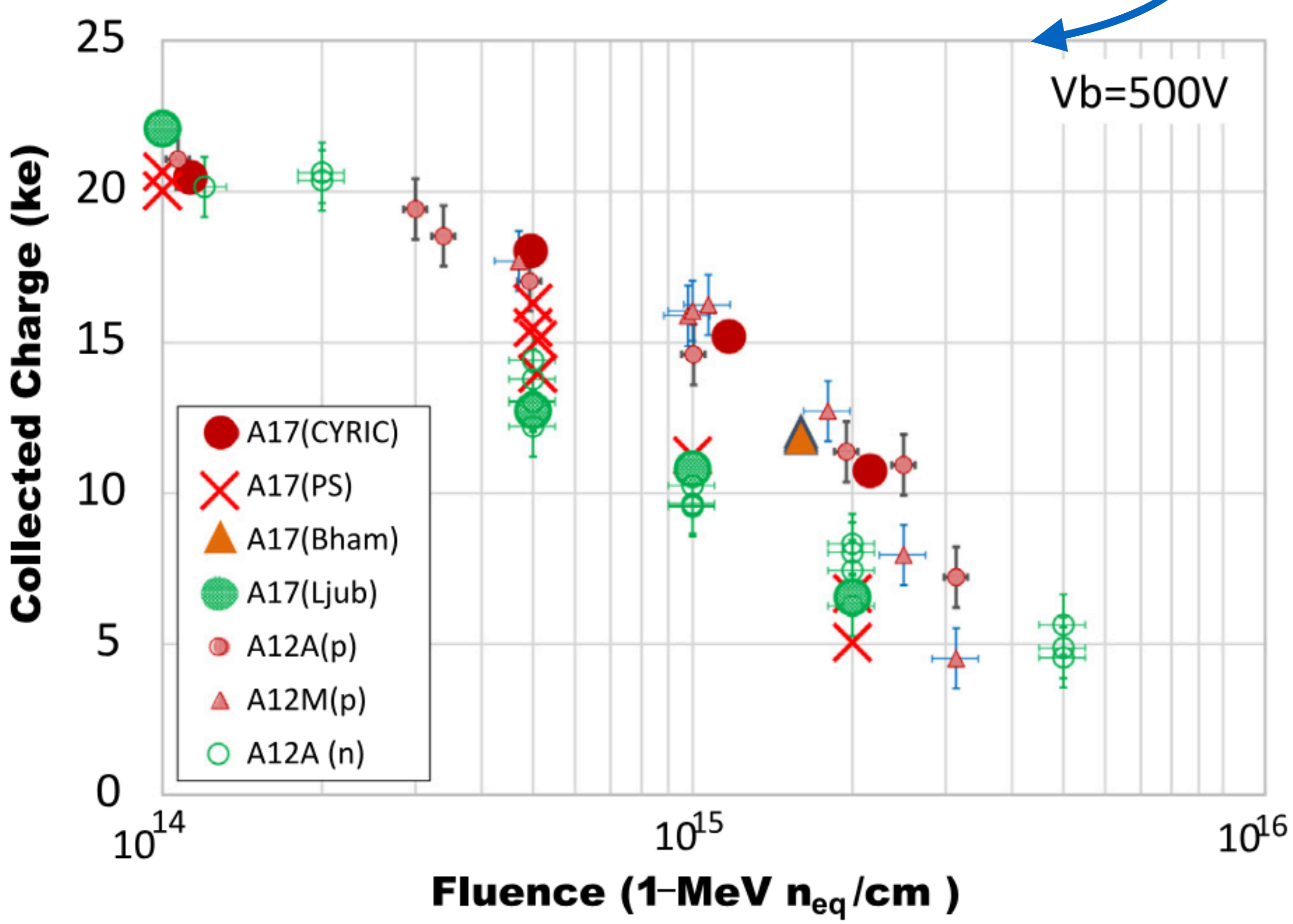
Sensor QC & QA

- Over 20,000 sensors to be produced, must ensure every sensor installed is working
- **Quality Control**: Non-destructive tests of *every* sensor ensure baseline behavior
- **Quality Assurance**: Destructive tests of a few sensors per-batch to ensure robust operation while irradiated

I-V curves identifying sensor breakdown



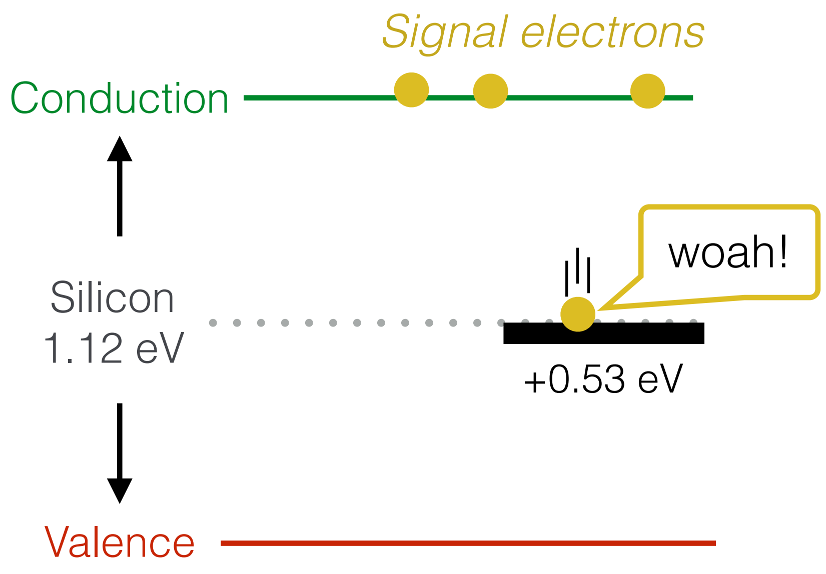
[ATLAS ITk Strip Sensor Quality Control and Review of ATLAS18 Pre-Production Sensor Results]



- low-E proton
- high-E proton
- low-E proton
- neutron

[Charge collection study with the ATLAS ITk prototype silicon strip sensors ATLAS17LS]

Sensor Modeling: Electric Field



- Simulate sensor behavior using **industry tool TCAD**
- Inject traps into Silicon bandgap to model radiation damage

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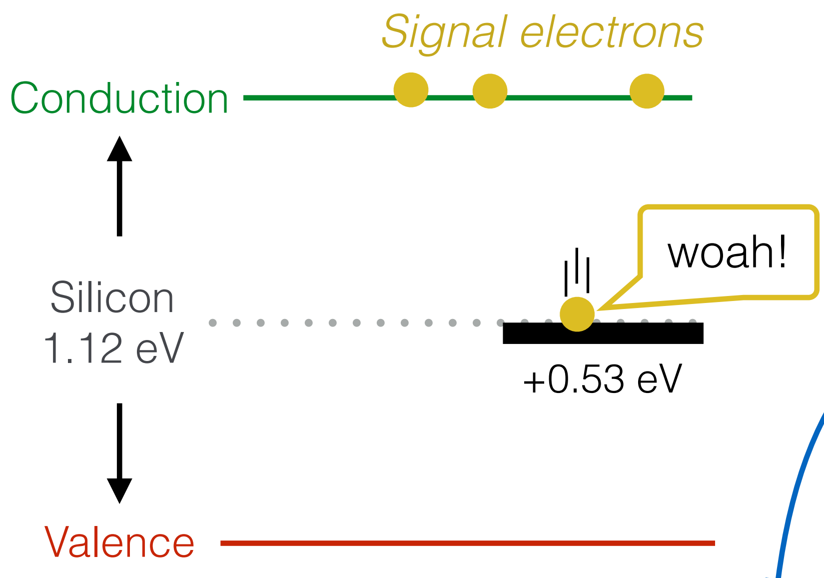
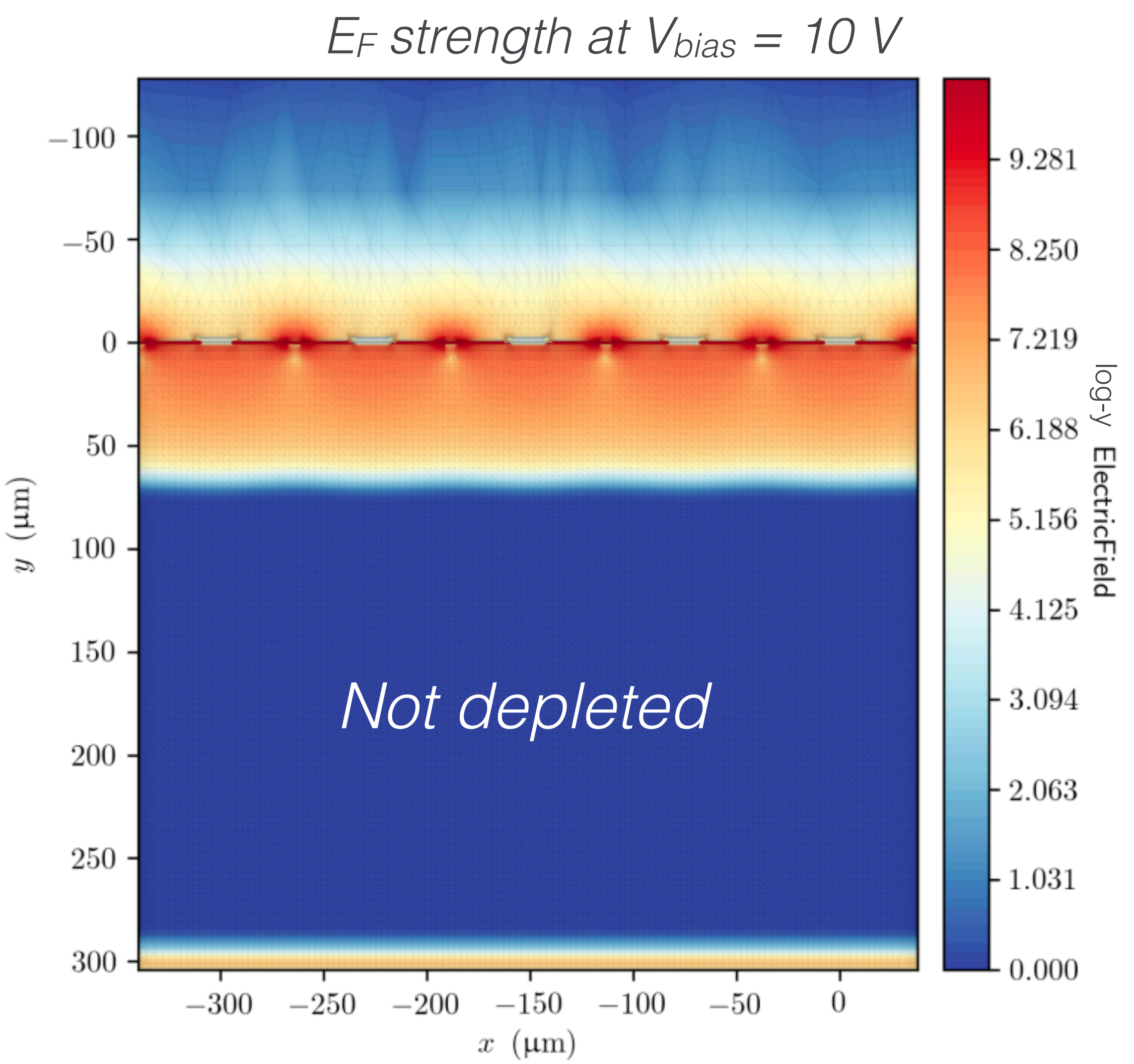


- Simulate sensor behavior using **industry tool TCAD**
  - Inject traps into Silicon bandgap to model radiation damage
  - Visualize Electric Field & more



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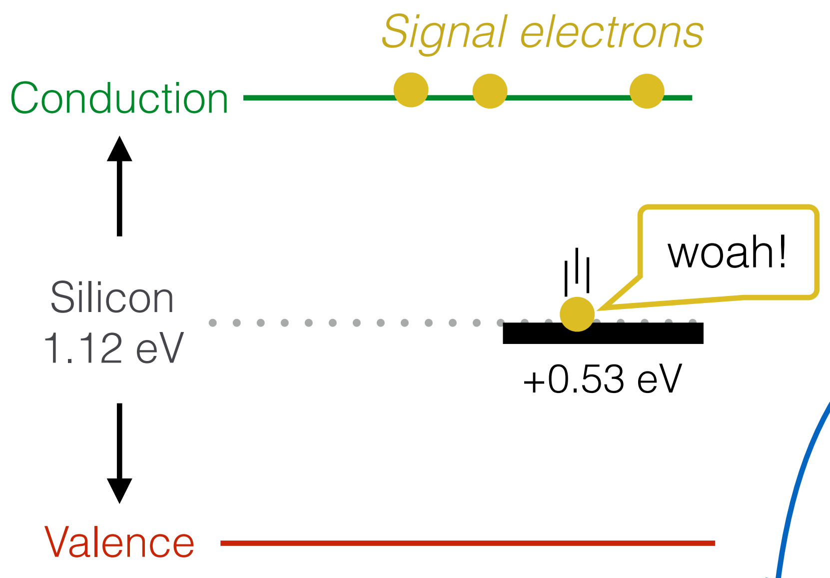

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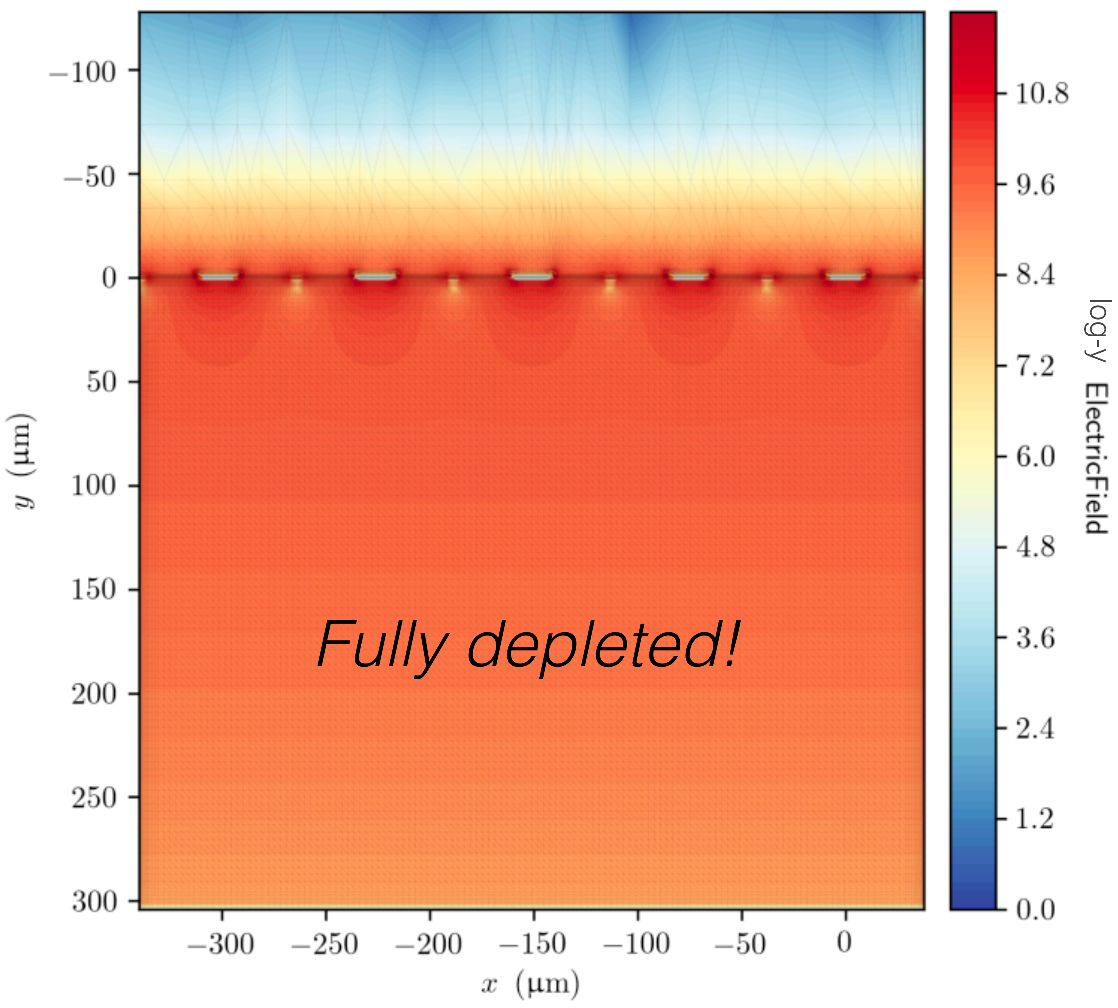
  - Visualize Electric Field & more

E_F strength at V_{bias} = 200 V



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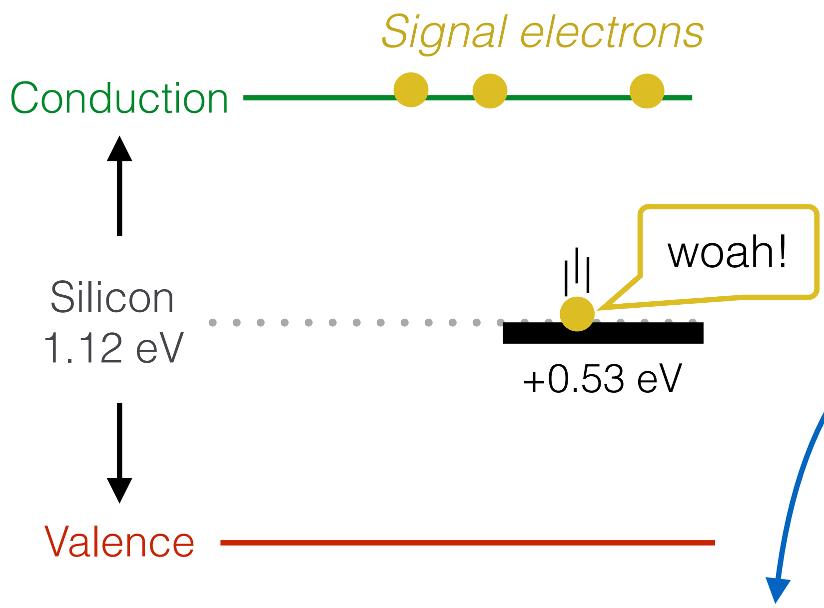
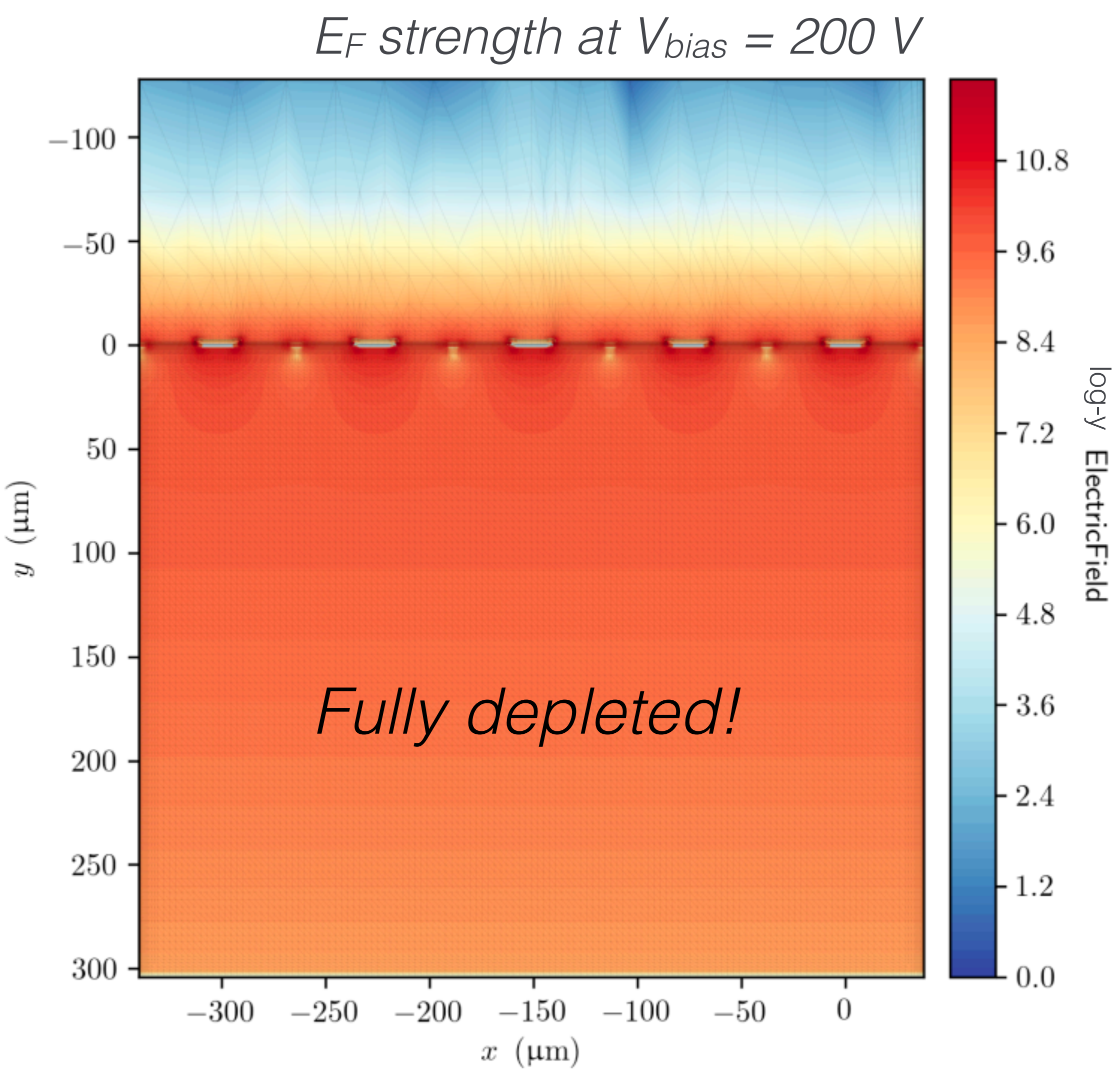
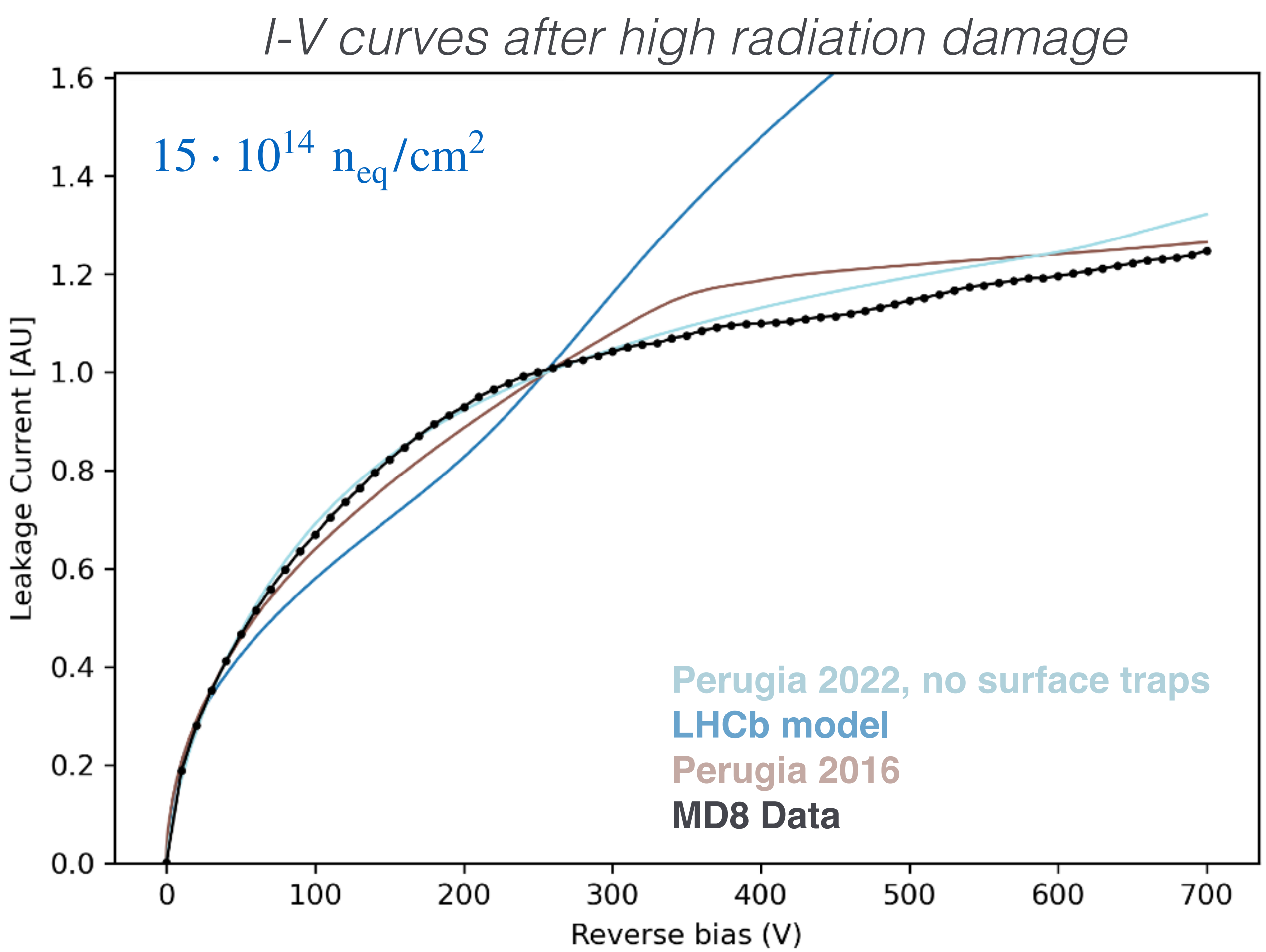


- Simulate sensor behavior using **industry tool TCAD**
  - Inject traps into Silicon bandgap to model radiation damage
  - Visualize Electric Field & more
  - Compare & tune performance against irradiated test devices

Will lead to new models of radiation damage for n+-in-p sensor technologies!





43rd RD50 Collaboration Workshop

Readout ASICs

Three ASIC designs to manage & aggregate data

ATLAS Binary Chip (ABC)
Signal amplification, digitization, compression

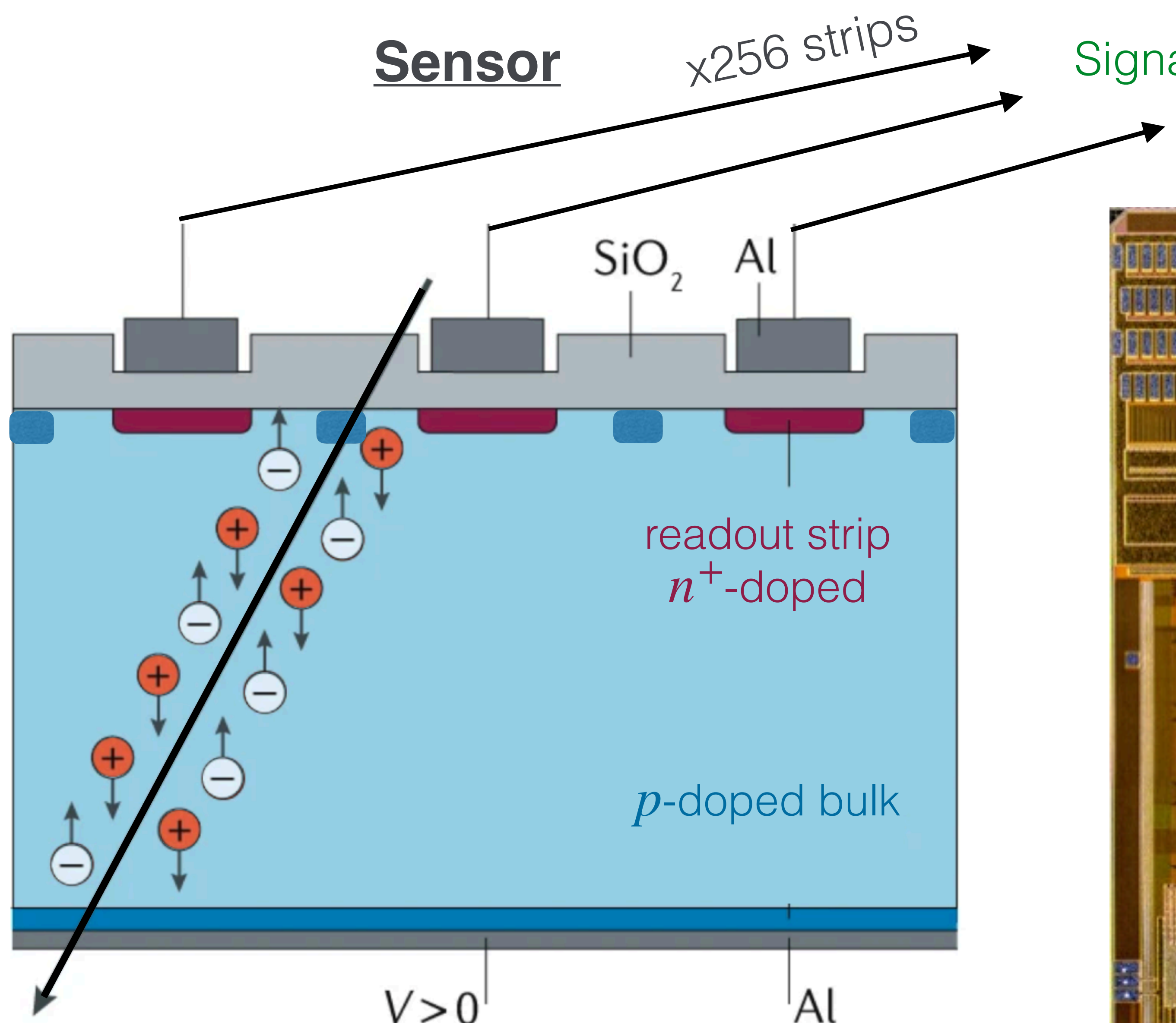
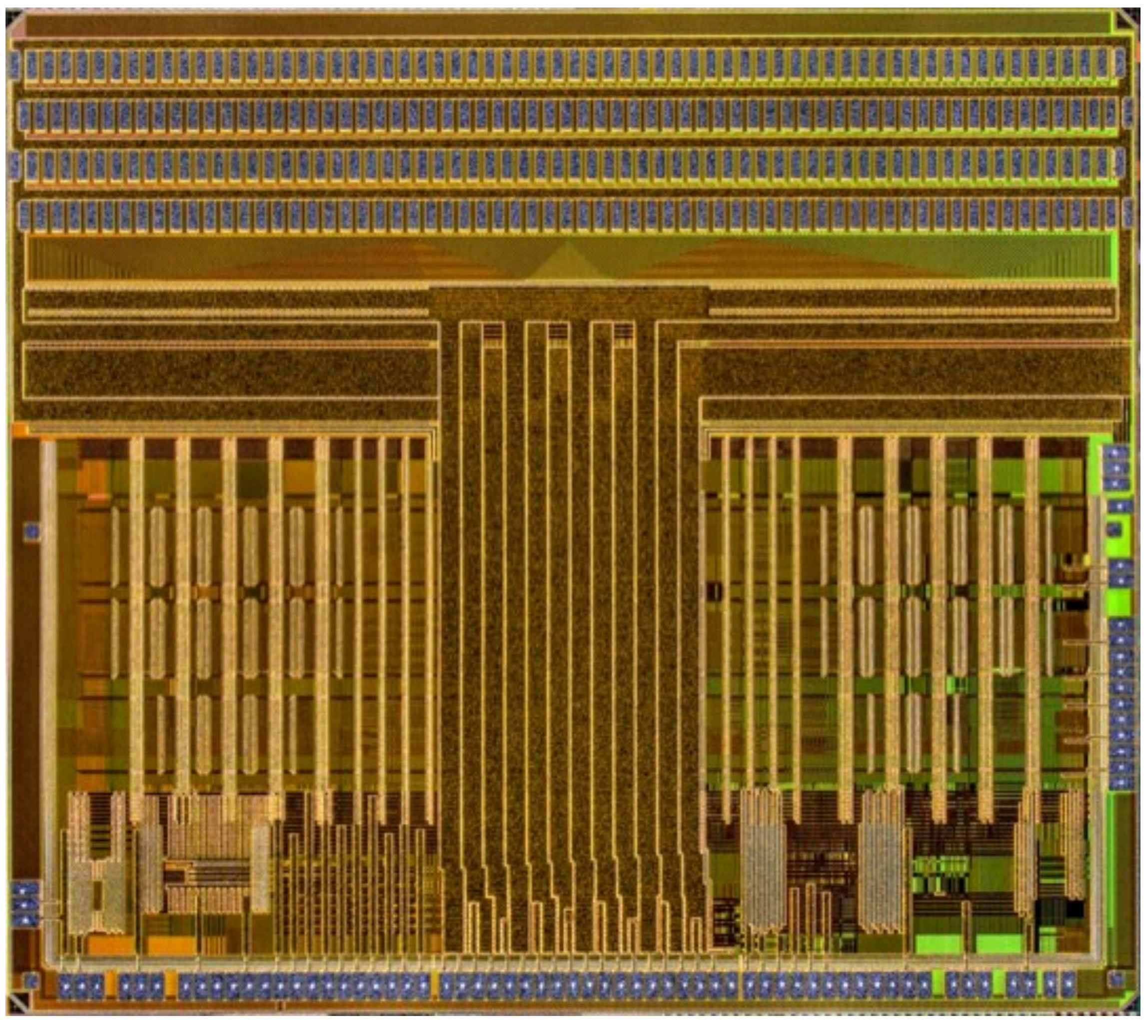
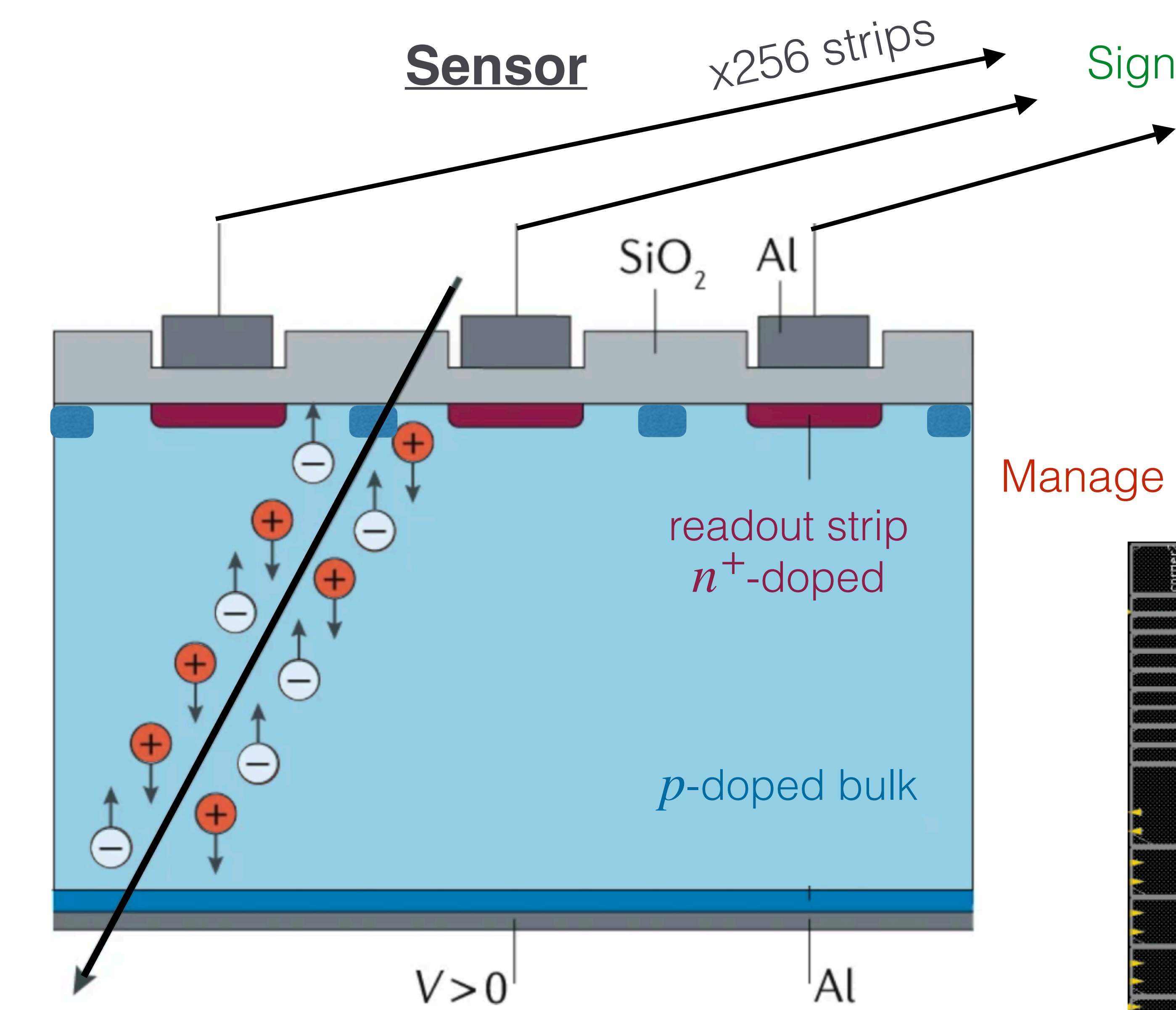


Figure Adapted from M. Krammer



Readout ASICs

Three ASIC designs to manage & aggregate data



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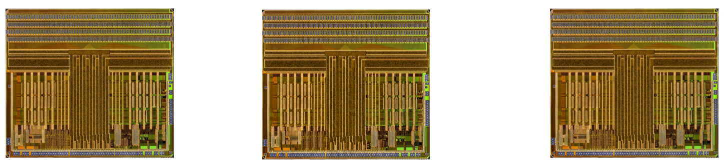
ATLAS Binary Chip (ABC)

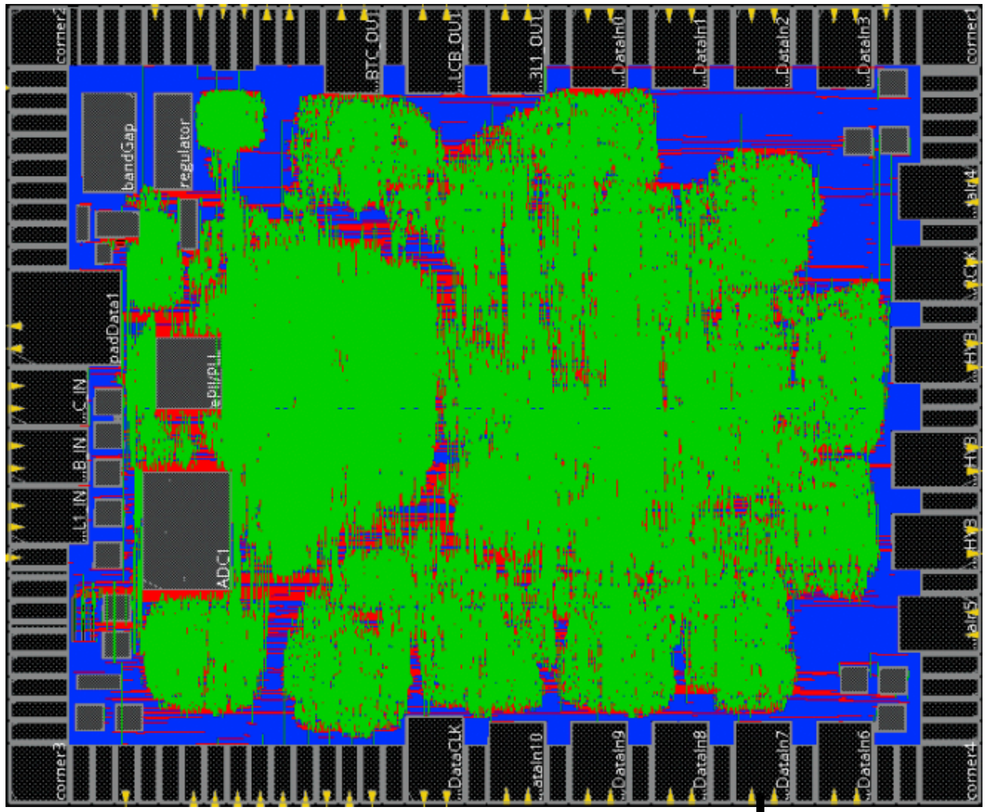
Signal amplification, digitization, compression



x11 ABCs

Hybrid Controller Chip (HCC)

Manage commands & data requests, serialize @ 640 Mbps



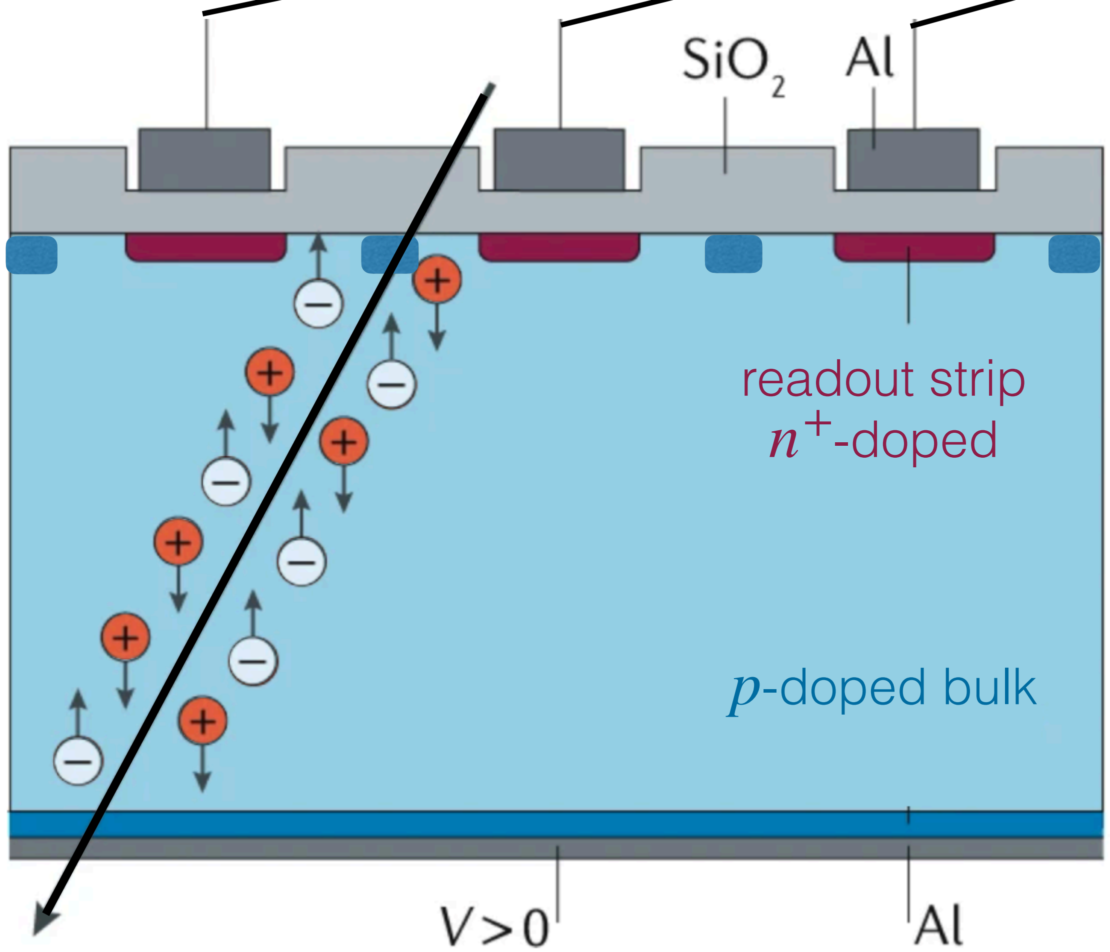
off detector

Readout ASICs

Three ASIC designs to manage & aggregate data

Sensor

x256 strips



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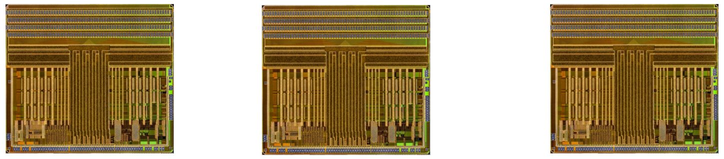

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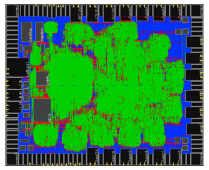
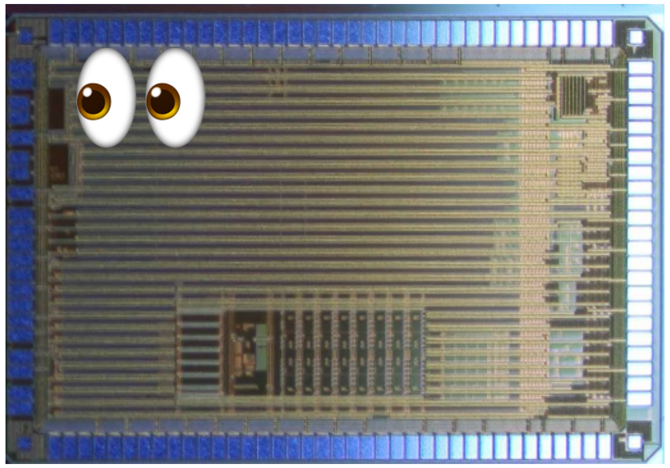


off detector

Autonomous Monitoring And Control (AMAC)

Automatic protections (voltages, currents, temperatures)



Why is verification important?

Recent example: A self-driving car meets a stop sign

Verification ensures working logic with minimal expensive design & testing cycles

Verification strategy

Usually done by big teams of experienced engineers …

- *Industry tools are complex & proprietary*

Typical Intel design team

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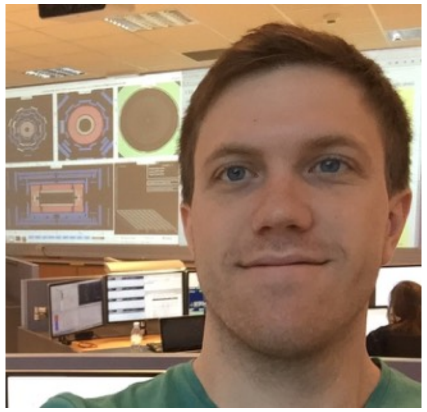
- *Industry tools are complex & proprietary*

Physicists can bring to the table:

- *Physics drives technical requirements*
- *Have operational LHC experience*
- *Data analysis & detector expertise*

Can postdocs and students fill the verification role?



Ben Rosser
(now UChicago)

Typical Intel design team

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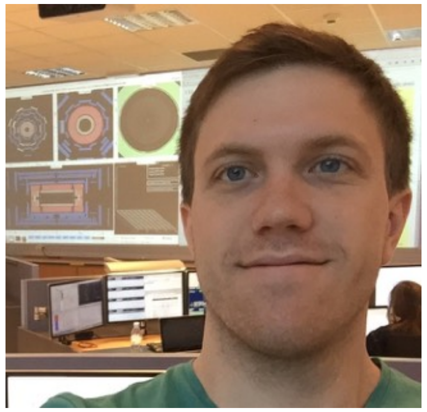


Ben Rosser (now UChicago)

They can if you speak their language!

Typical Intel design team

cocotb

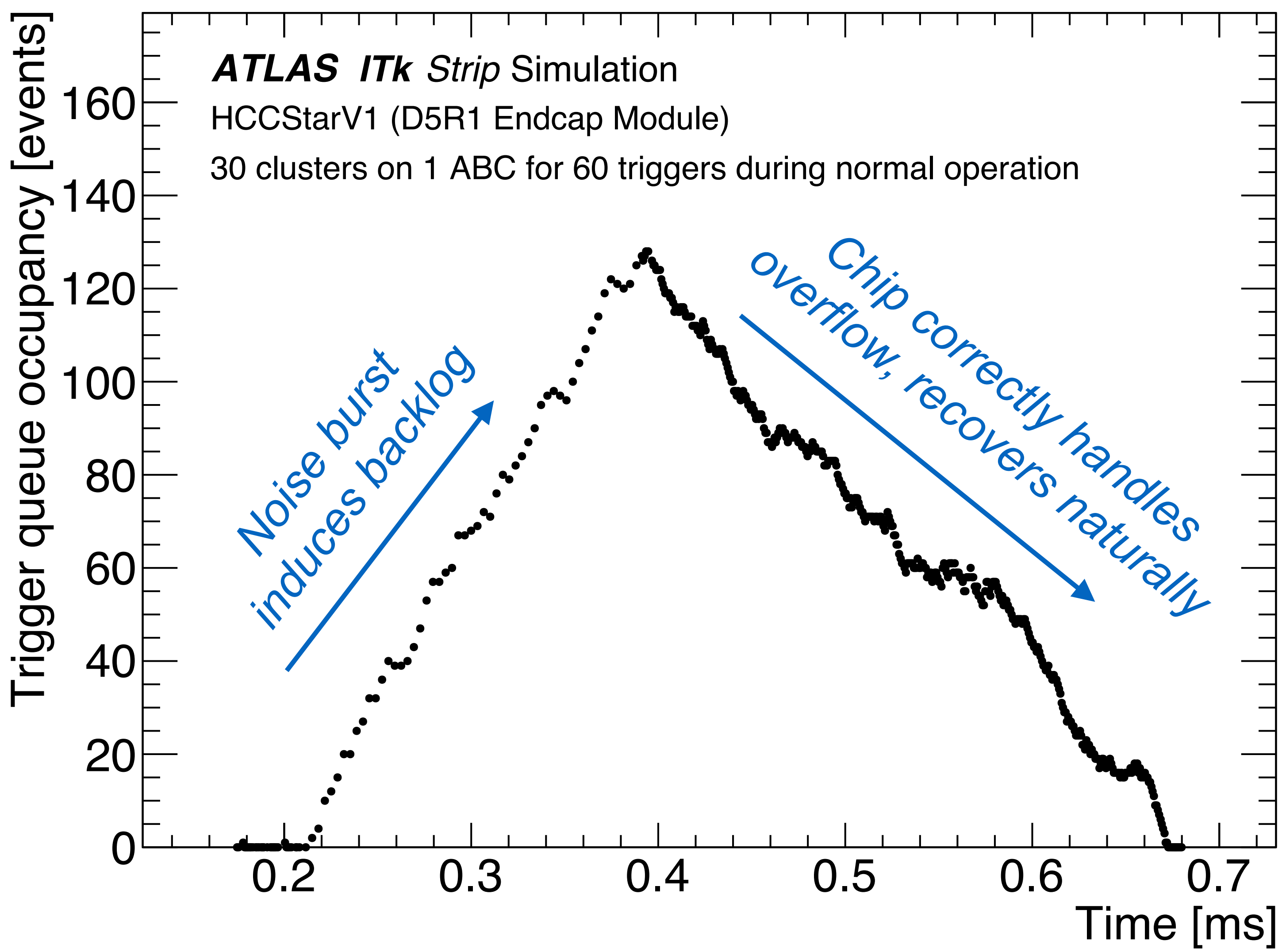
Adopted open-source **python approach** w/ cocotb (coroutine cosimulation testbench)

- Immediate impact by physicists, including *students*
- Realistic LHC dataflow with simulated ASIC interconnectivity (up to 26 ASICs at once)
- Reach *into the ASICs* for data analysis & visualization

A look inside the logic

Simulate all possible scenarios, even unexpected **noise bursts**
hot spot leading to larger data packets than reasonably expected

- During noise burst:
  - Large data packets take longer to process
  - Internal buffer backlog grows with unprocessed requests
  - Excess triggers discarded, no system lockup
- After burst ends, natural recovery
  - Slowly over 1000's of data requests!
    Insight led to operational improvements



Verification of simulated ASIC functionality and radiation tolerance for the HL-LHC ATLAS ITk Strip Detector

A look inside the logic

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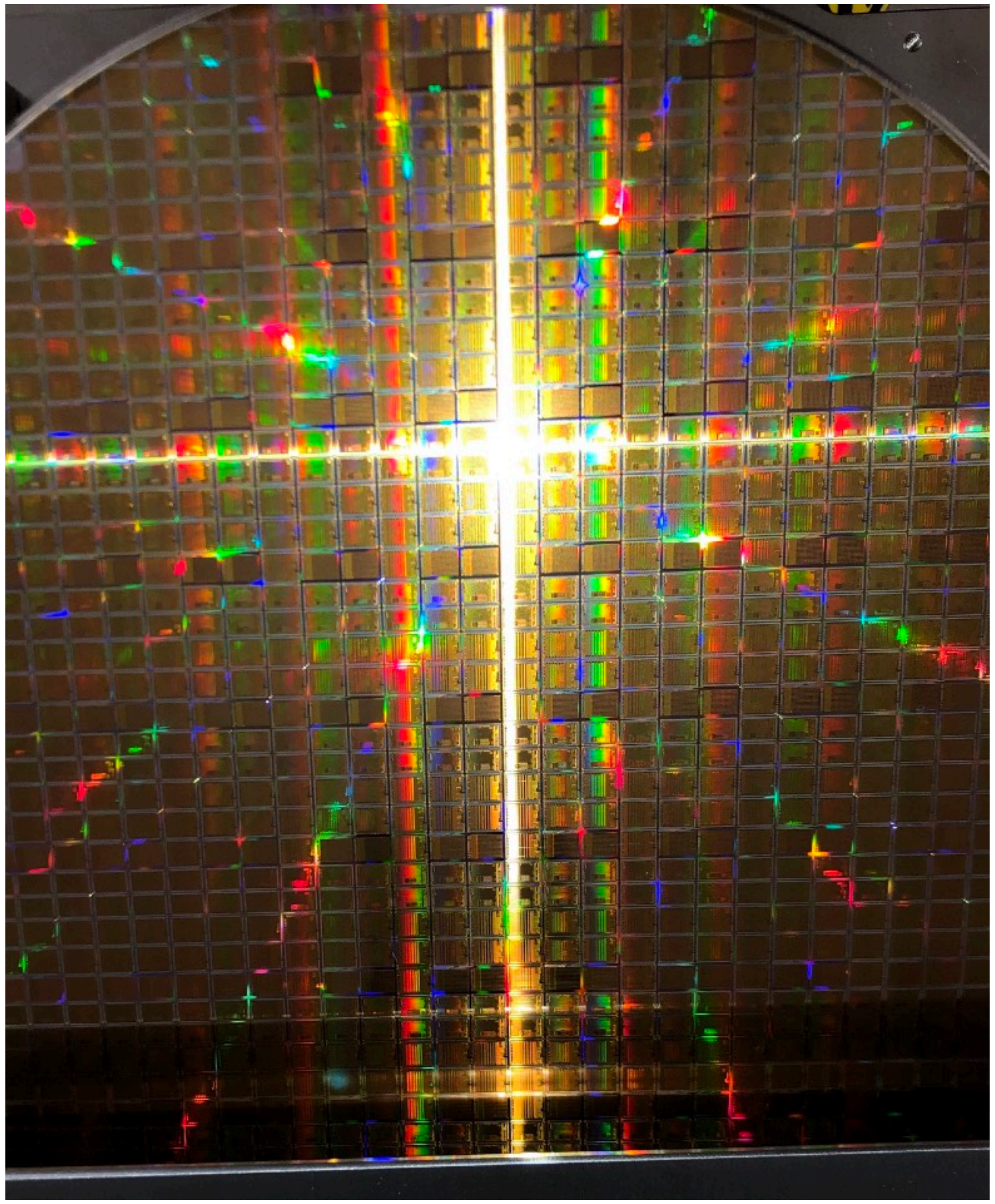
    Insight led to operational improvements

- Knowledge from simulations informed testing procedures on real ASICs
  - >400,000 chips now produced & tested
    thanks to industry partnerships (DA-Integrated)



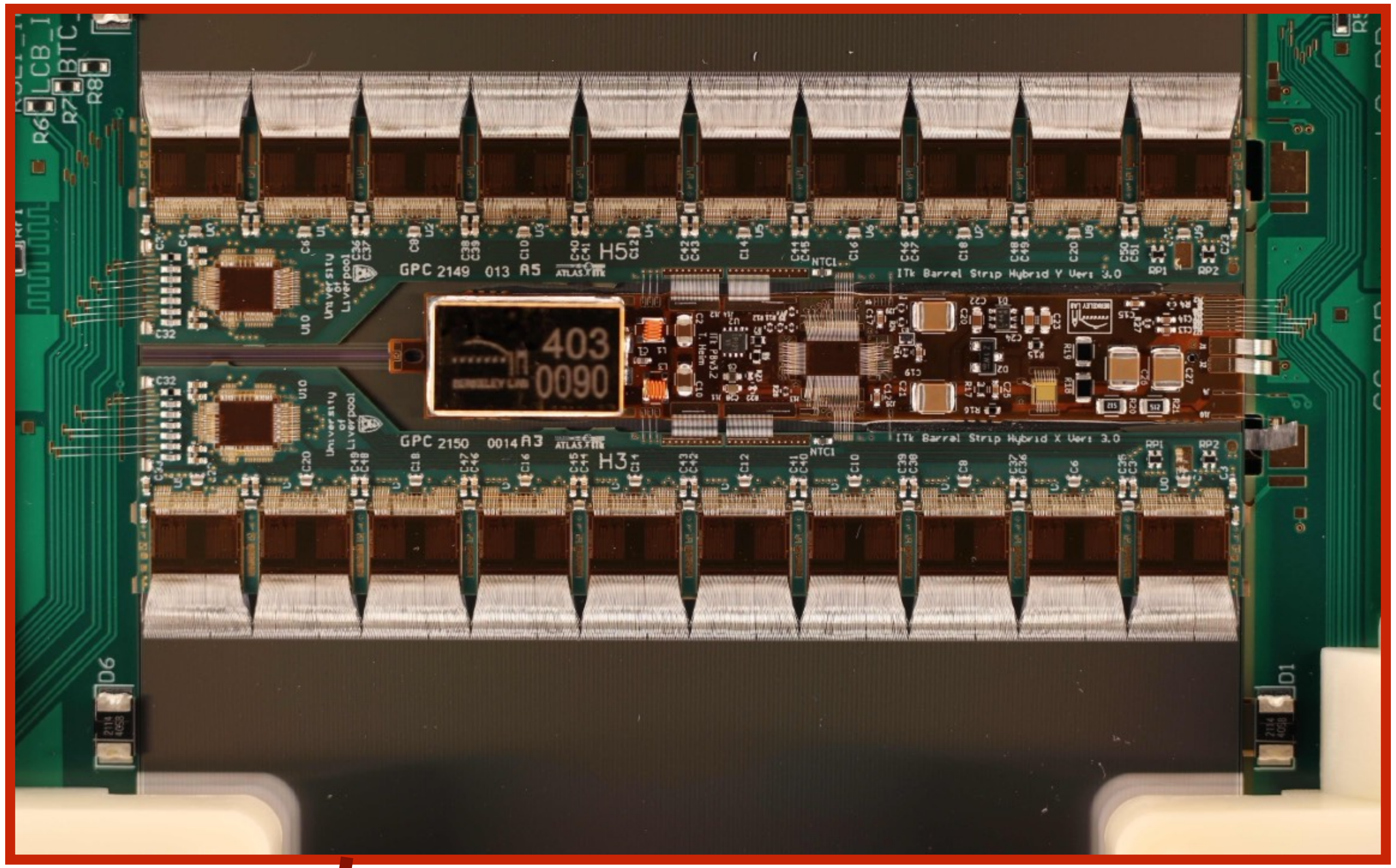
Wafer of ~1000 ASICs as featured on instagram

Quality control testing of the HCC ASIC for the HL-LHC ATLAS ITk Strip Detector

Irradiation testing of ASICs for the ATLAS HL-LHC upgrade

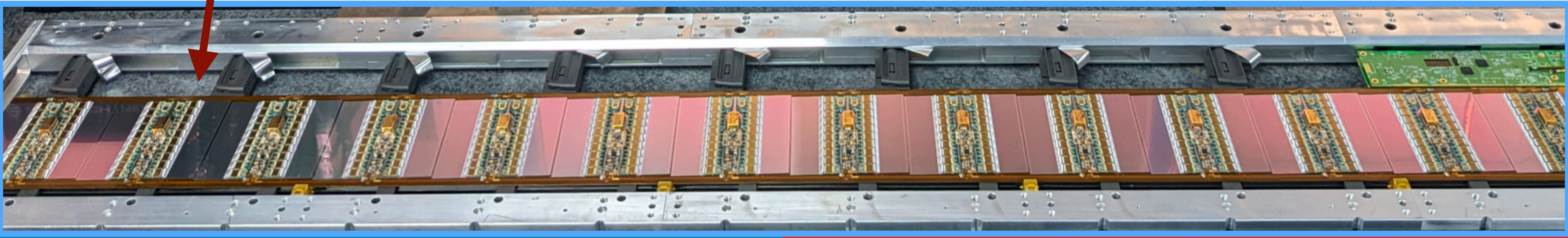
~~Design~~ ~~Test~~ Build it!

- Construction sites finalizing qualification for building components→modules, and modules→staves
- Assembly to begin at CERN this year towards installation in 2027/2028



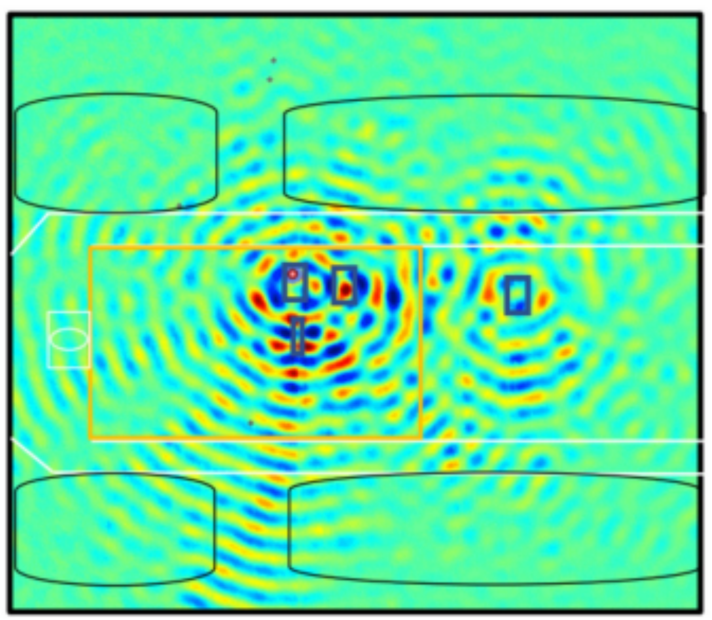
Module of ASICs

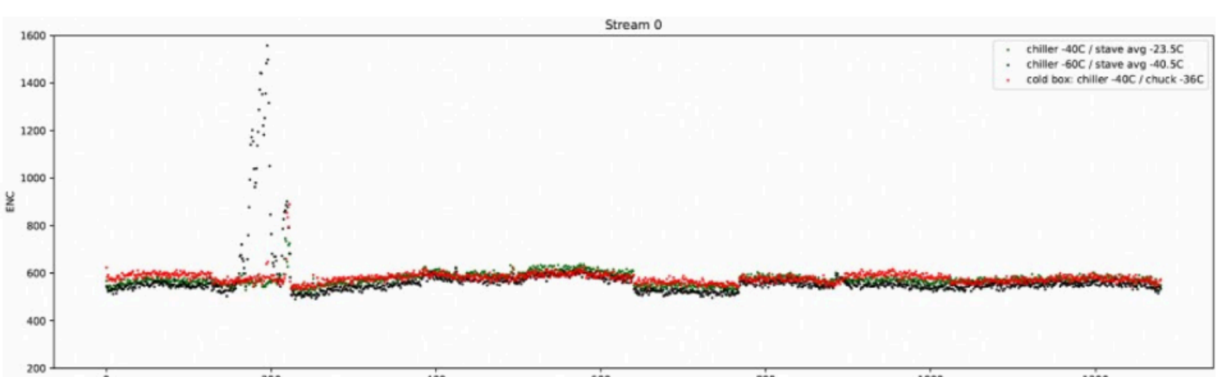
Stave of Modules



Tackling unexpected challenges

- Issues *will* emerge aggregating individual pieces into larger systems
- Last year Luise Poley discussed “cold noise” - noise spikes when operating modules cold
- Major progress since in understanding link between 2 MHz capacitor vibrations & sensor signals

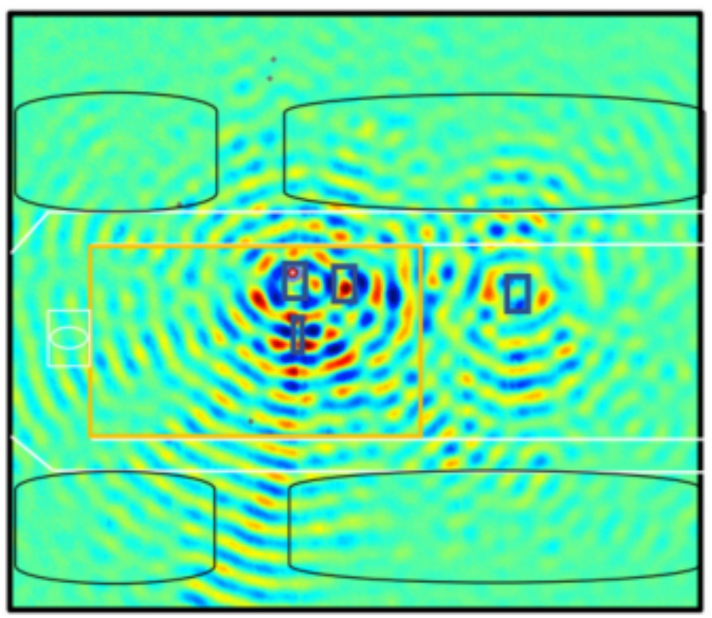


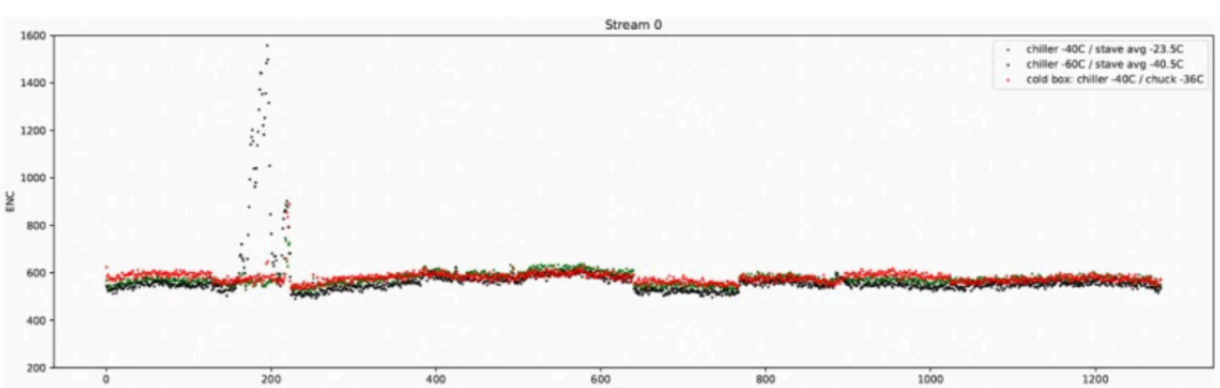


From last year: vibrations travel across sensor and couple to outputs, inducing noise in some channels

Tackling unexpected challenges

- Issues *will* emerge aggregating individual pieces into larger systems
- Last year Luise Poley discussed “cold noise” - noise spikes when operating modules cold
- Major progress since in understanding link between 2 MHz capacitor vibrations & sensor signals
  - Leading theory: Stress in glue adhesion → vibrating glue contact → variable surface charge
  - Mitigated with new glue, ongoing exploration of anchoring glue edges
- Tackling additional issues as they arise, such as sporadic sensor cracking due to CTE mismatches





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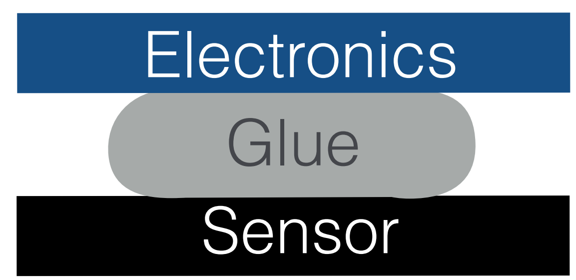
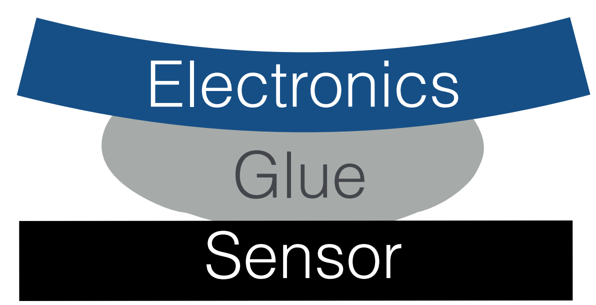


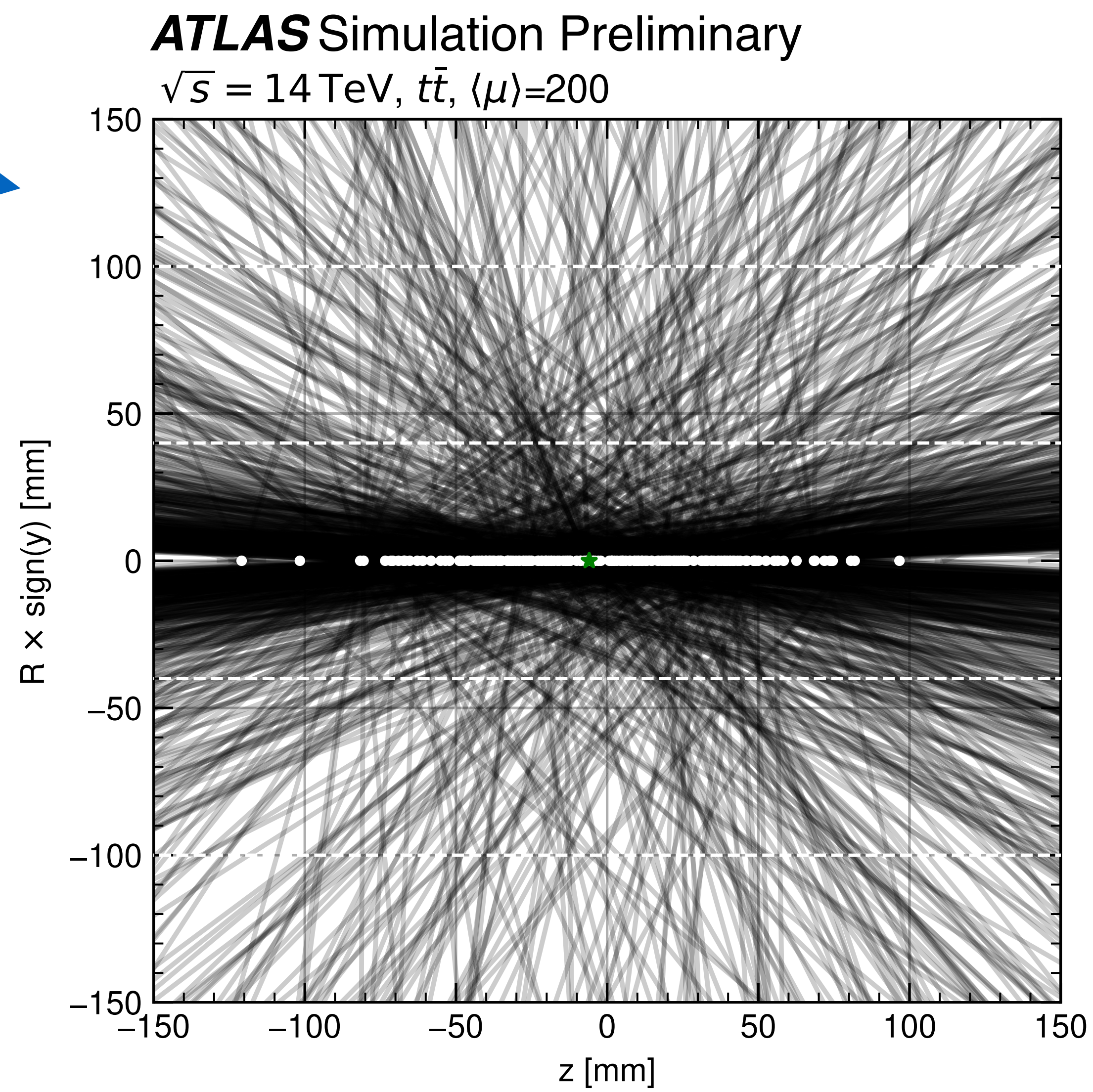
Glue applied in warm conditions



Mismatch in coefficient of thermal expansion (CTE) induces stress & edge peeling

Rethinking Particle Reconstruction

- Adopting **open-source** solutions to do more with less, such as for track reconstruction (ACTS)
- Porting CPU-intensive tasks to **GPUs** for tracking (Traccc) and calorimeter clustering (TopoAutomaton)
- Integrating **machine-learning** methods for better particle reconstruction (Graph Neural Networks for tracking)
- **Industry partnerships** to advance machine learning, quantum algorithms, high-perf computing (NextGen Trigger project)
- Utilizing **new dimensions of information** in our data (30 ps timing resolution of HGTD)



Overlapping particle tracks in a 200 collision event without timing

Investigating the impact of 4D Tracking in ATLAS Beyond Run 4

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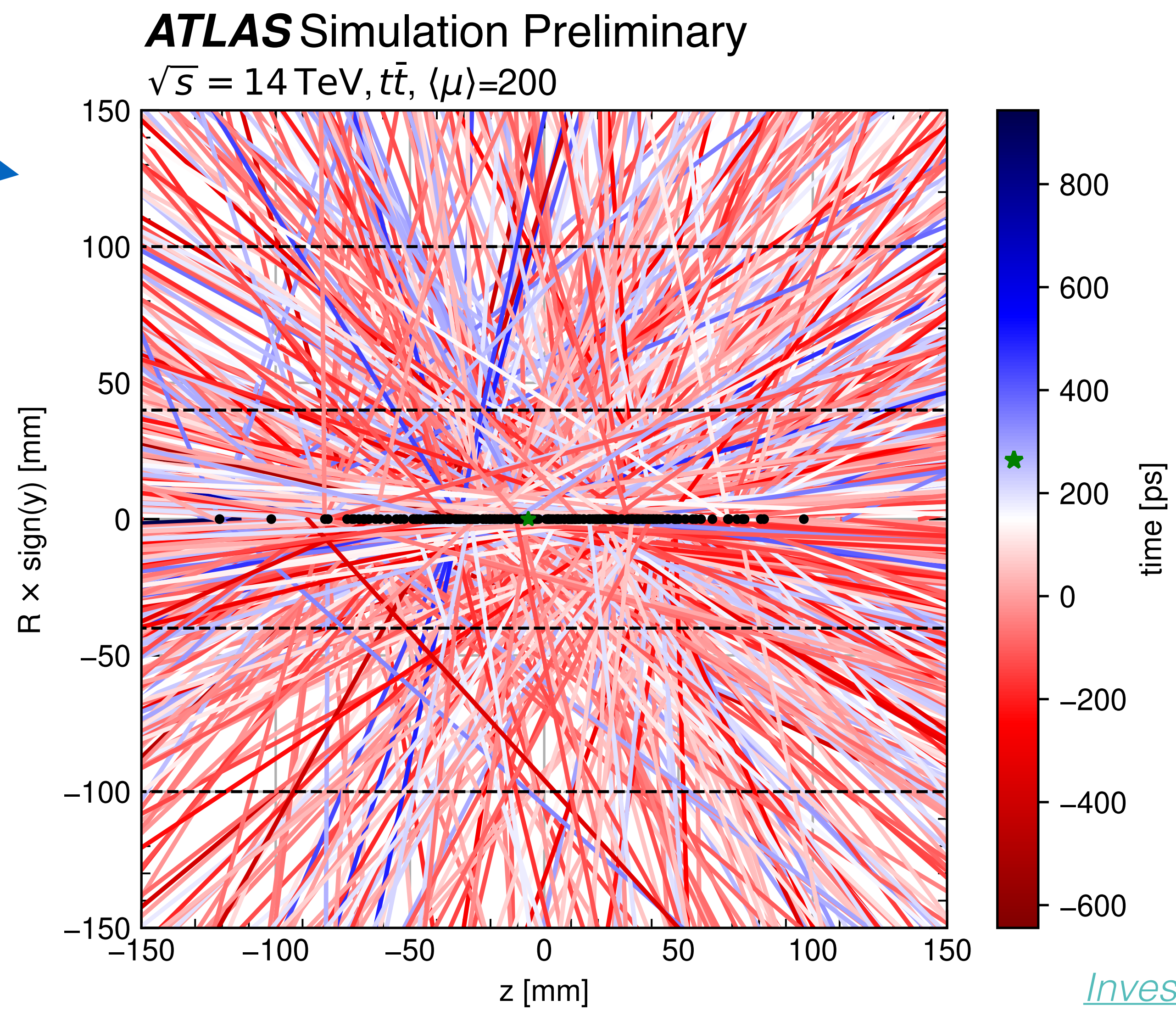

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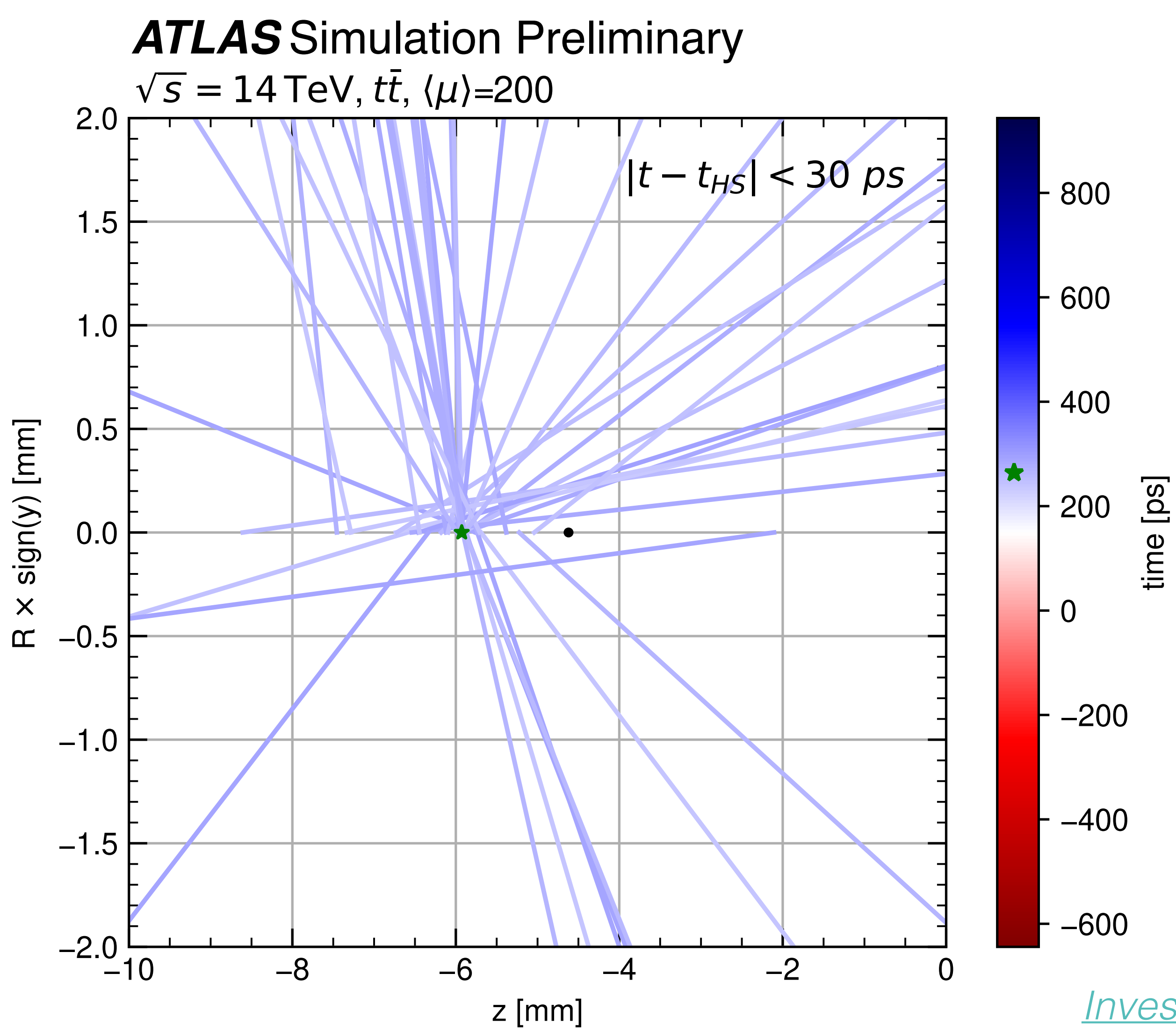


*Overlapping particle tracks in a 200 collision event **with timing***

Canada building the software & algorithms to utilize new timing tech!

Investigating the impact of 4D Tracking in ATLAS Beyond Run 4

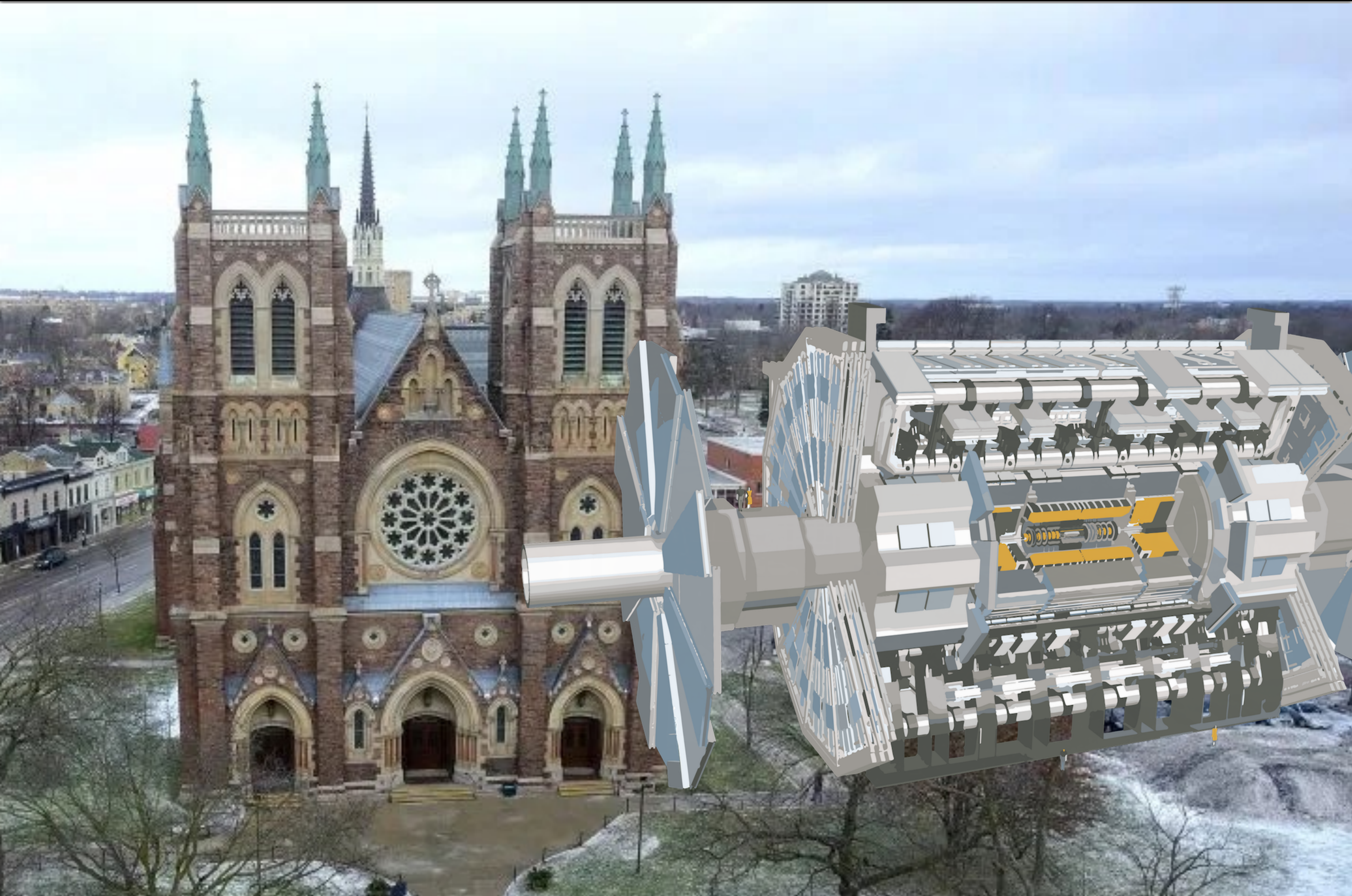
Conclusion

- Significant progress on ATLAS detector upgrades, will enable unparalleled physics program at HL-LHC
  - Unifying and accelerating streaming of data off-detector
  - New Inner Tracker with cutting-edge silicon technologies & robust readout ASICs for high radiation
  - Updating particle reconstruction with new detectors and modern technologies

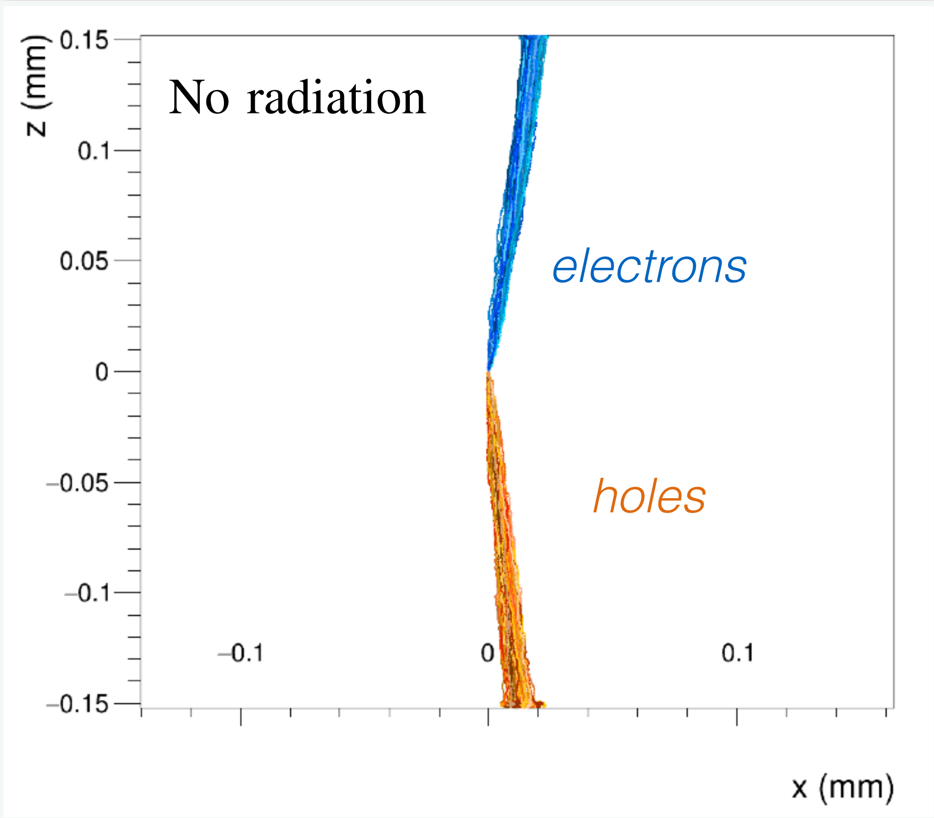
Canadian institutes driving all these efforts!

Backup

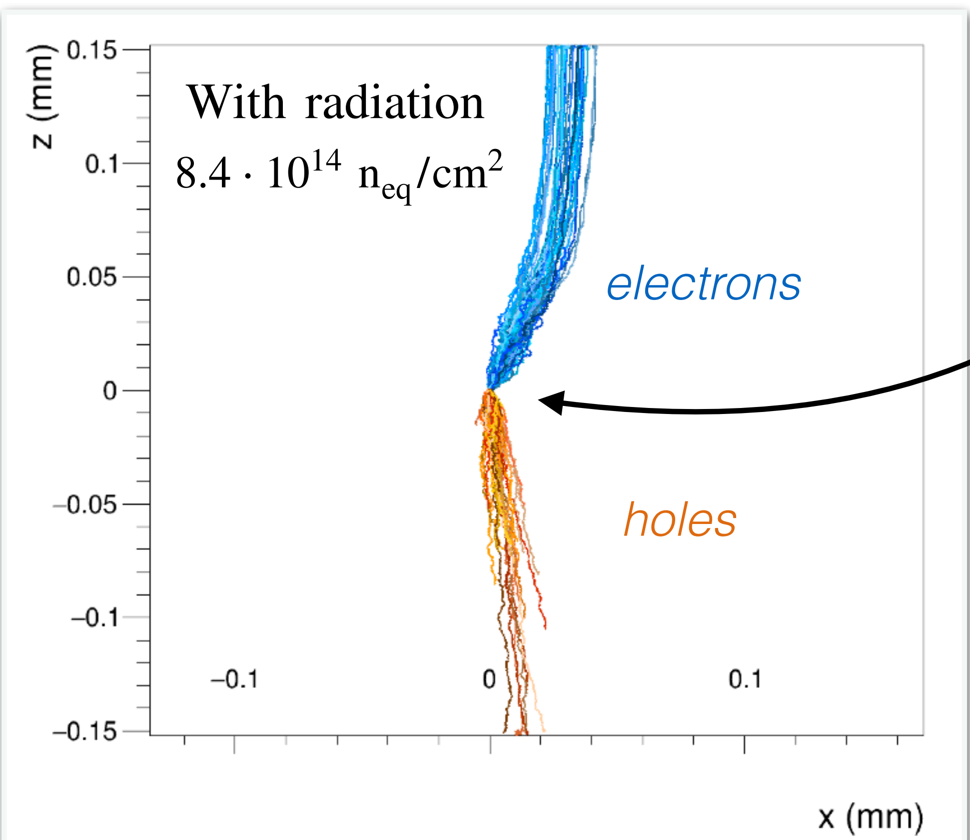
St. Peter's Cathedral Basilica



Sensor Modeling: Charge Propagation



- Adopting open-source AllPix2 for simulating charge collection efficiency
  - Critical for building an accurate model of how radiation damage will effect the tracker performance
- Parameterizing results into look-up tables for a faster simulation of many trillions of particles



Charge deposited in center & propagates to readout electrodes