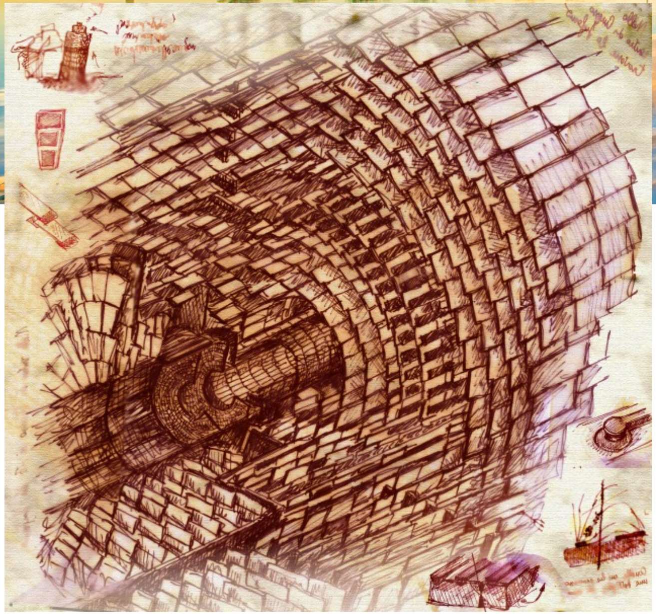


Silicon detectors & the CMS tracker

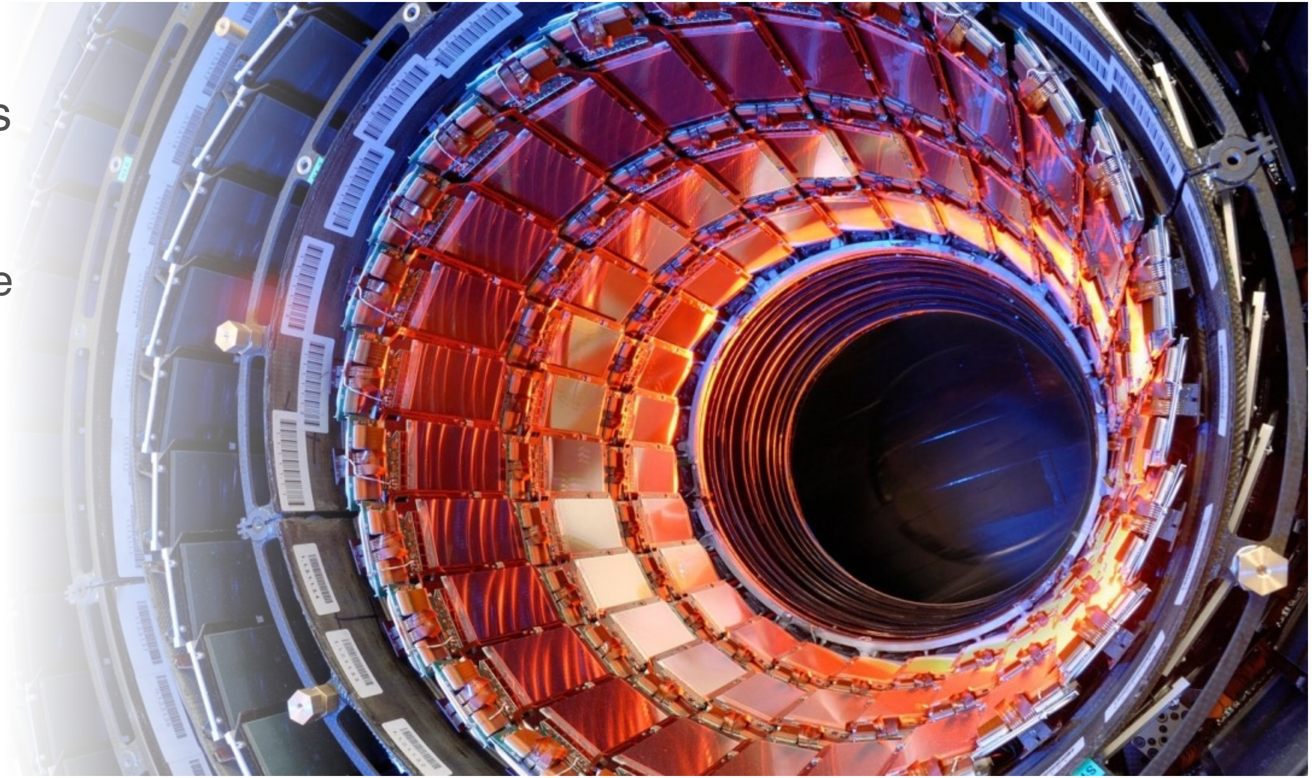
Jennet Dickinson

June 15, 2023

Outline

- Hello
- Silicon detector basics
- The CMS tracker

  Past, present, and future



Silicon is a semiconductor

- In an atom, electrons have discrete energy levels
- In solid state material, the atomic levels merge into energy bands

The energy difference between valence and conduction bands determines whether a material is an insulator, semiconductor or conductor

Fermilab

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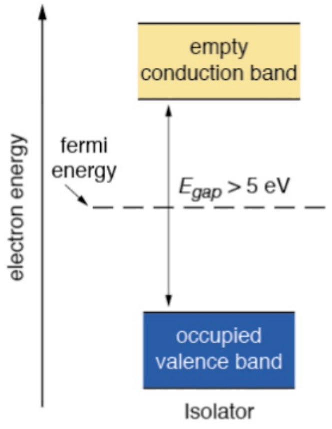

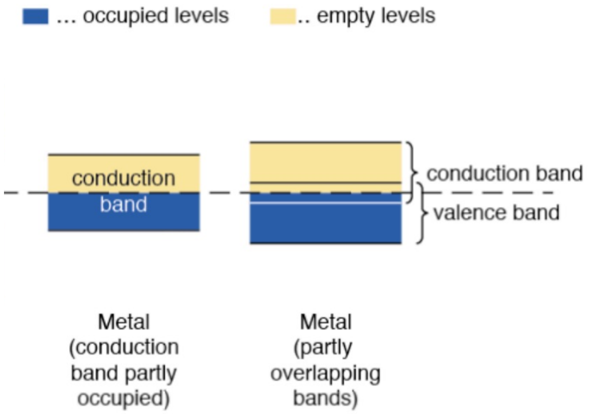

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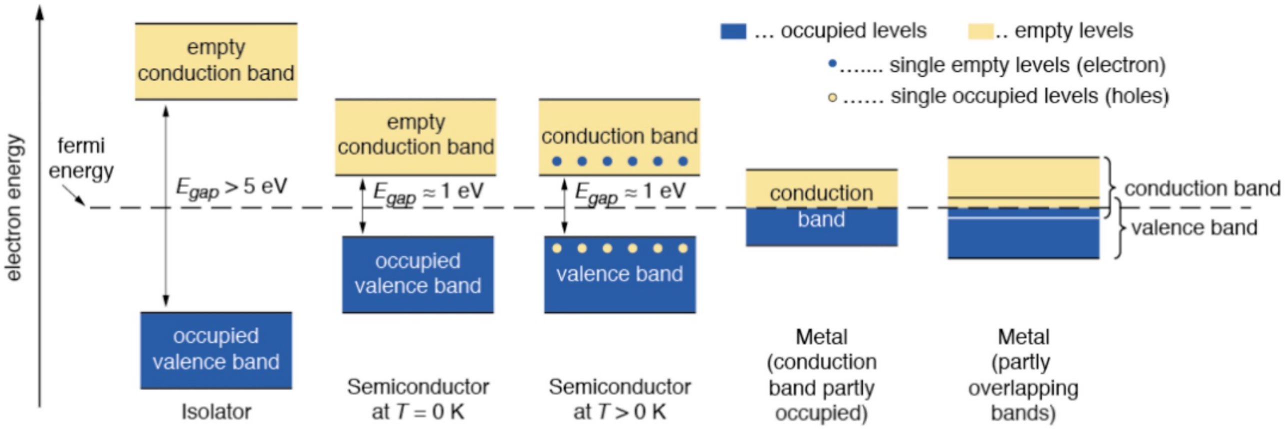
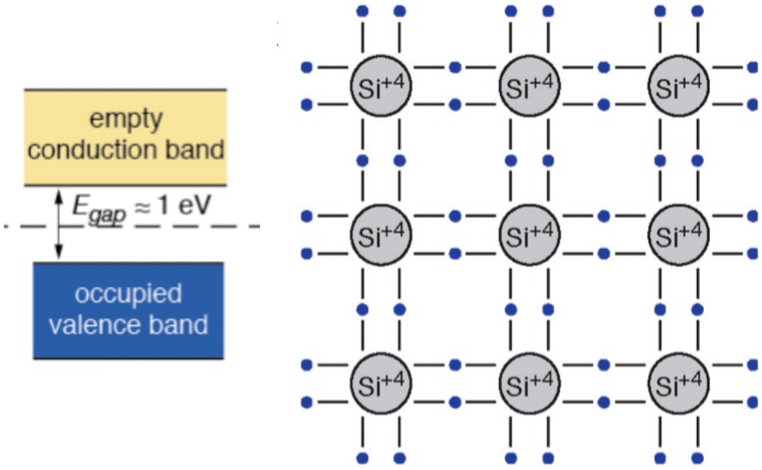


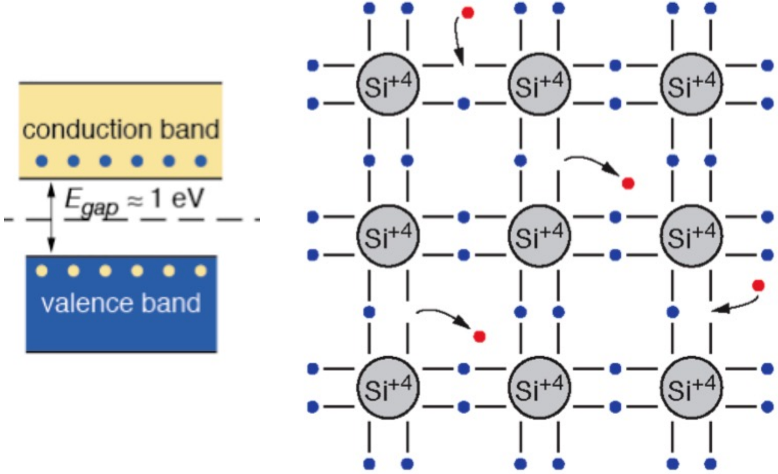
Silicon lattice

- What does this look like microscopically?

Temperature = 0 K
All electrons are bound



Room temperature
Conduction electrons: 1.45 x 10^{10} / cm^3
(electron-hole pairs)



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- What does this look like microscopically?

Noise

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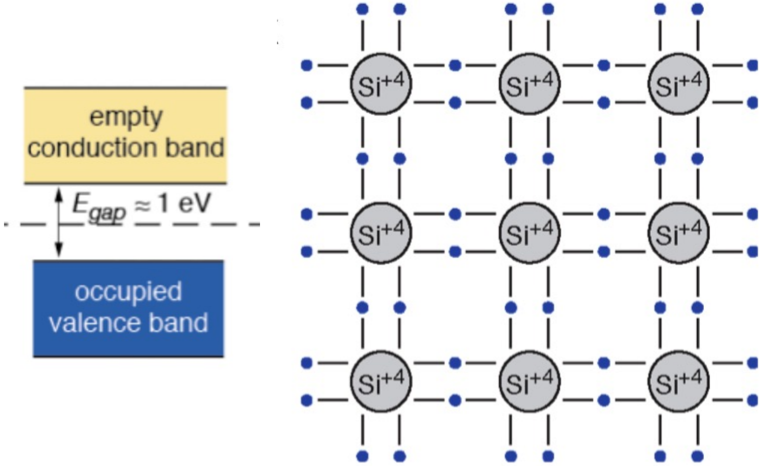

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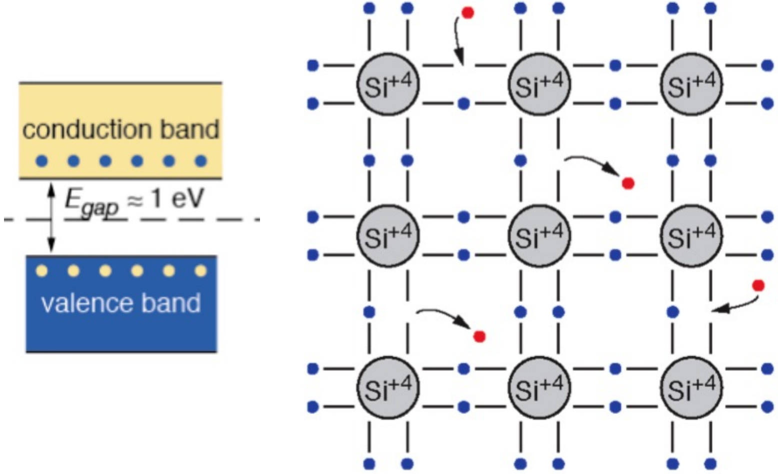

Signal and noise

- Let's say we have a sensor d = 300 μm thick and area A = 1 cm^2
- How much noise do we see?

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  Mean ionization energy 3.62 eV

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Noise >> signal!

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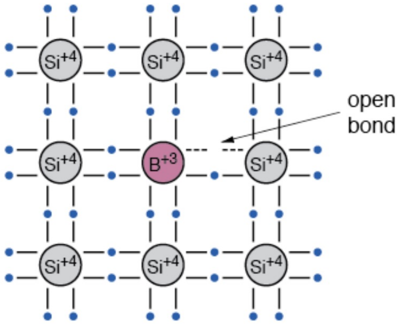
Removing charge carriers

- In an extrinsic semiconductor, there is an excess of electrons or holes

p-doped
(acceptor)



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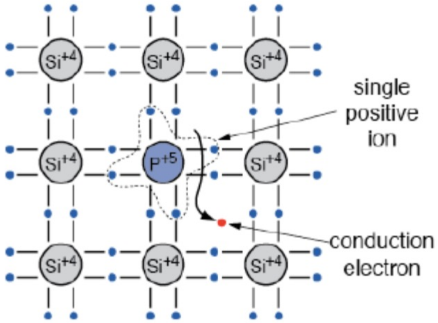

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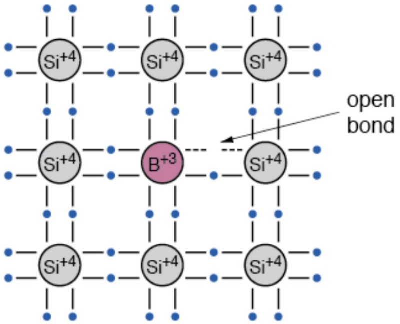

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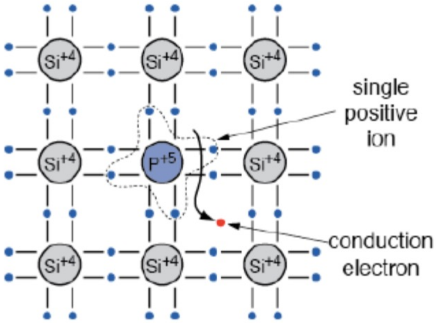

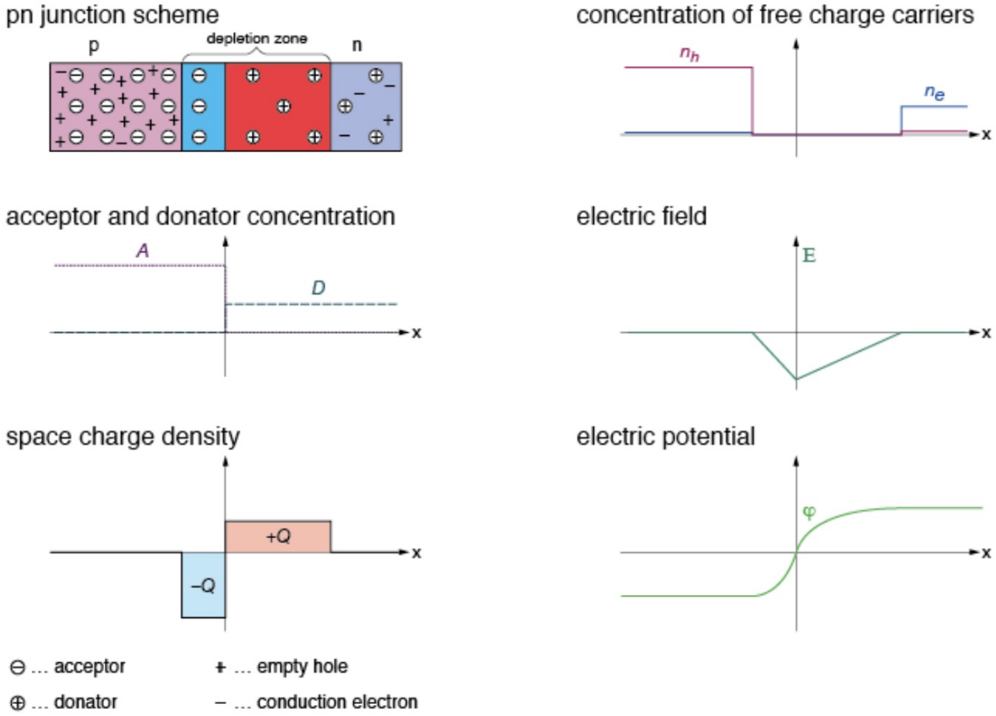

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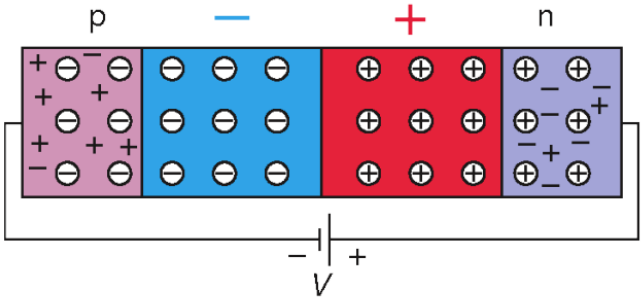
Depletion zone



- The region without charge carriers is called the **depletion zone**
- Maximize the size of the depletion zone by applying a high **bias voltage** (HV)
- Thermal electron-hole pairs are separated by the applied electric field, creating a small **leakage current** across the junction

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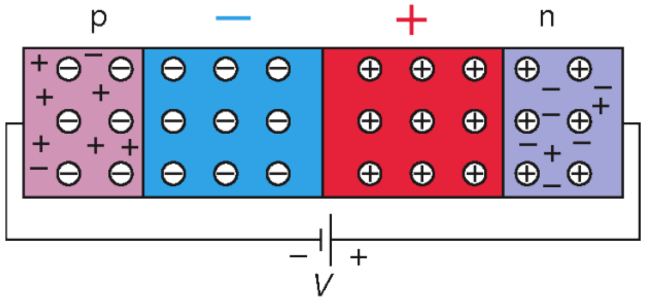
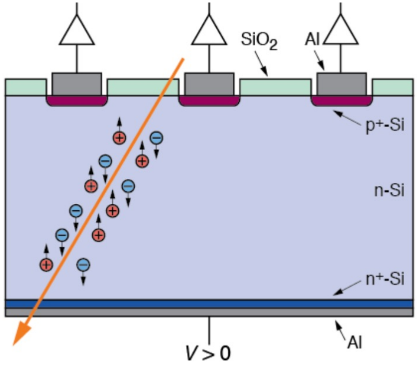


- Thermal electron-hole pairs are separated by the applied electric field, creating a small **leakage current** across the junction

A more realistic picture

Silicon detectors in HEP typically have a bulk region of n-type silicon and heavily doped p-type implants

Pixels: the implants are placed in a grid pattern
Strips: the implants are places in long, thin strips



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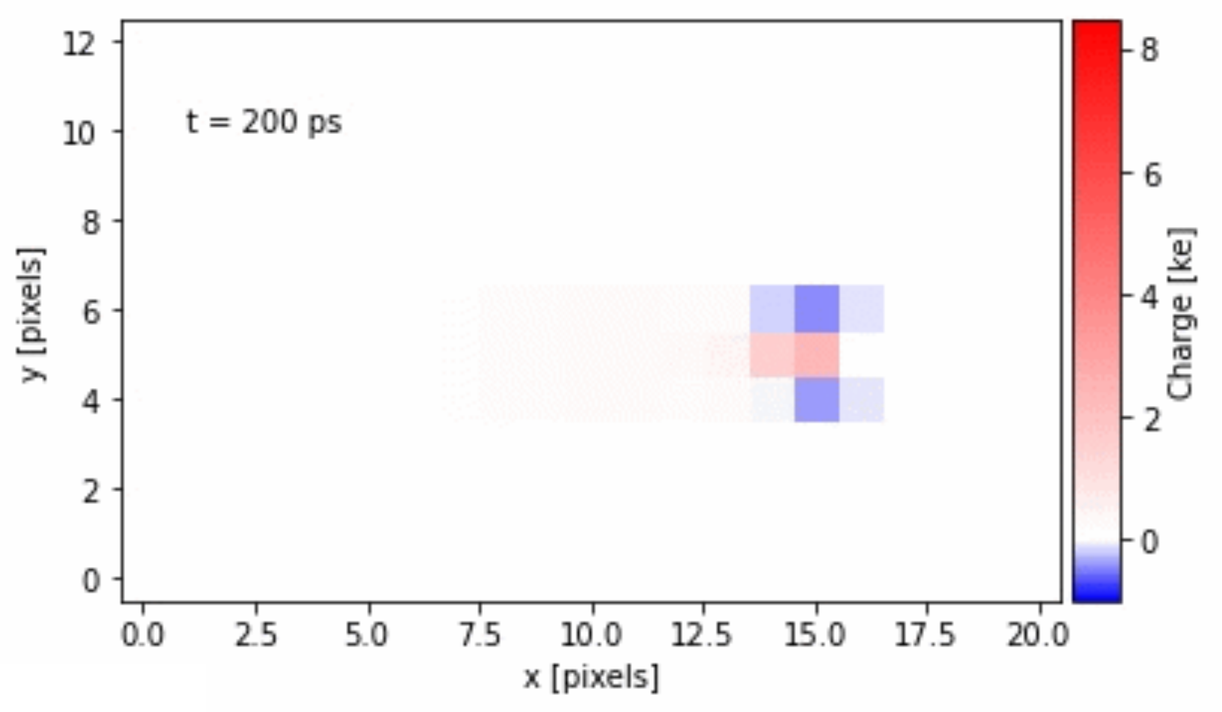
Development of a charge cluster



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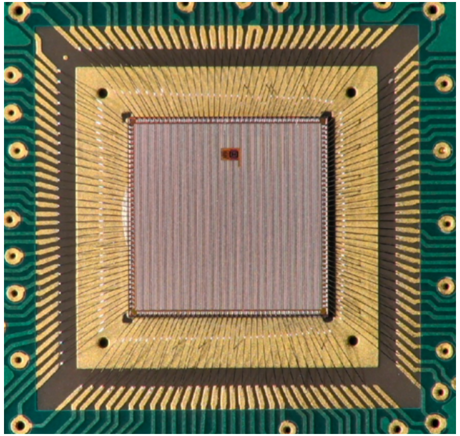
Reading out the charge

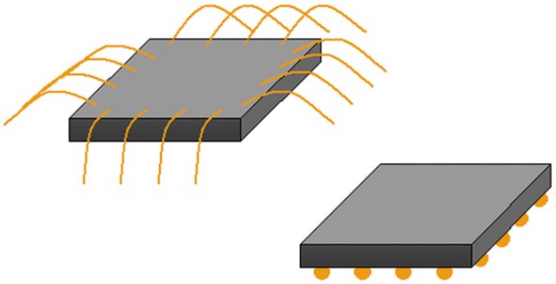
- Readout chip = Application Specific Integrated Circuit (ASIC)

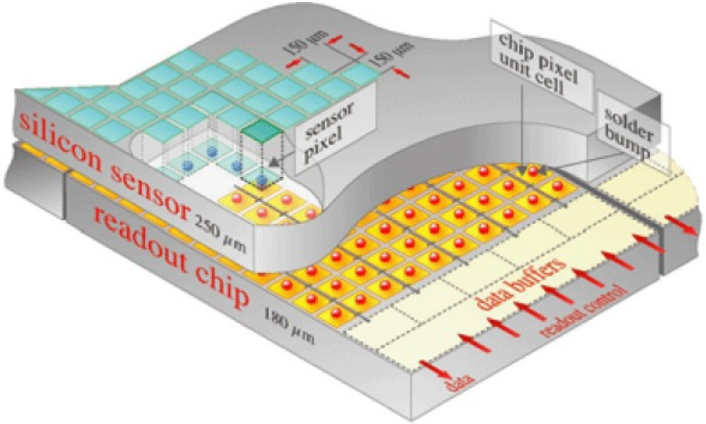
  Also made mostly of silicon

  Powered by low voltage (LV)

  Connected to the sensor via wire bonds or bump bonds







Reading out the charge

- At minimum, the ASIC must:

Amplify	Amplify charge signal
Digitize	Digitize the signal
Store	Store the signal
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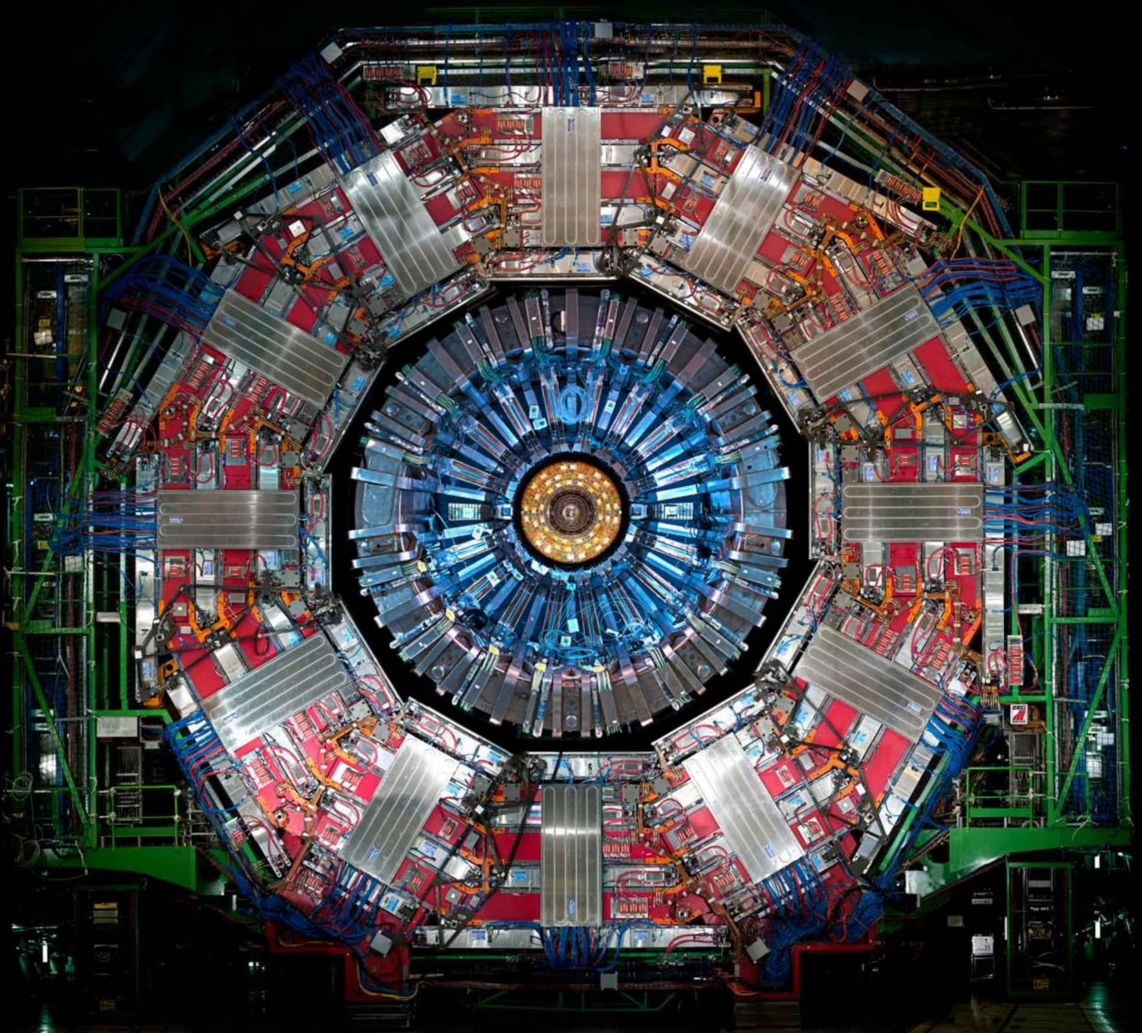
- The future of ASICs: can some physics analysis already happen here?

  Can use ML to extract particle properties from charge cluster

CMS
Compact Muon Solenoid

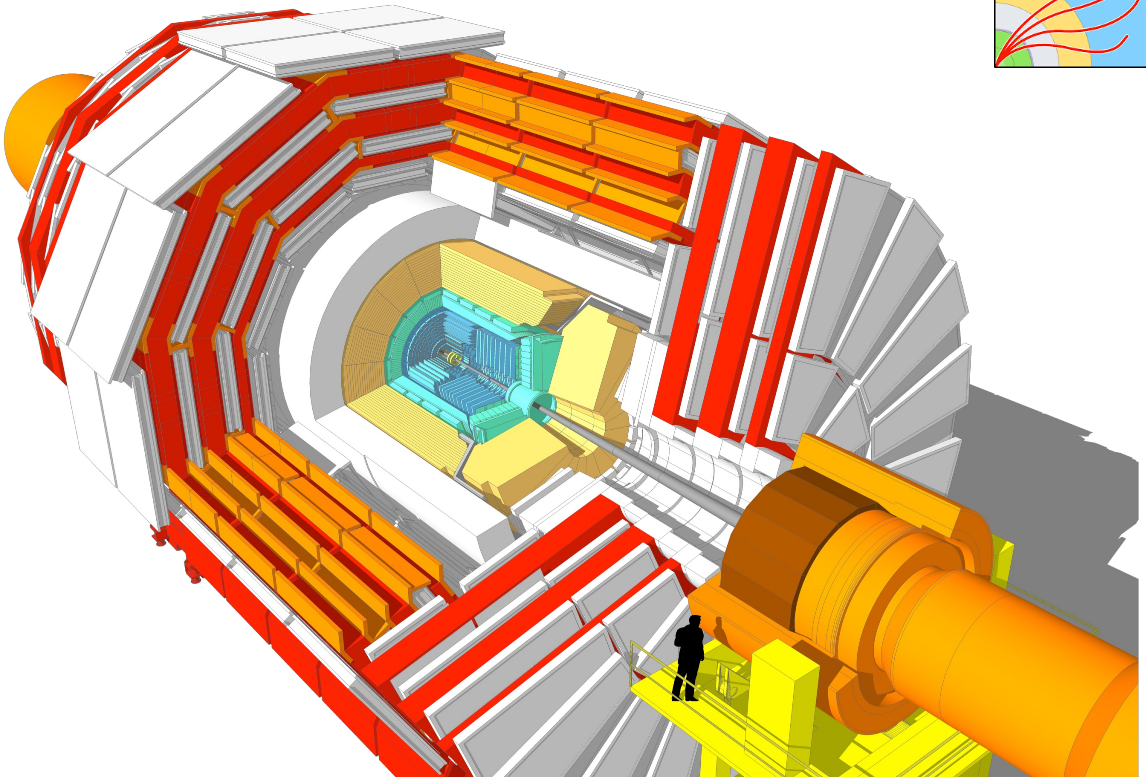


A look at the detector layers

Inside: Trackers

Middle: Calorimeters

Outside: Muon system



The inside: tracker

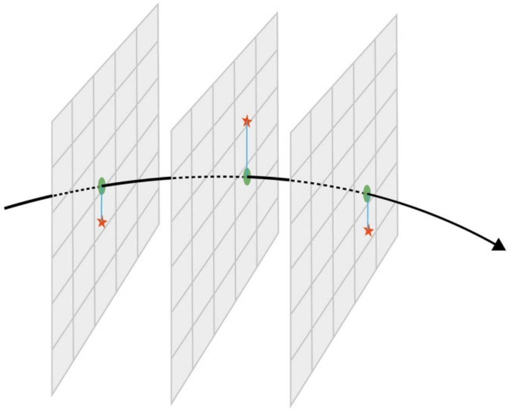
- Measure a particle's spatial trajectory

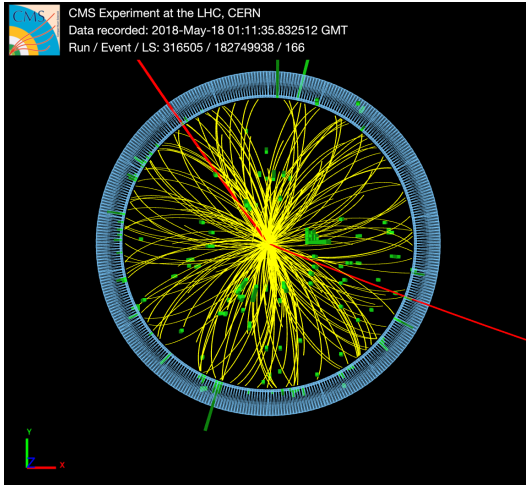
  Connect the dots between hit pixels to create a **track**

  Must be lightweight

- **Solenoid magnet** provides a magnetic field in the tracker, causing particle tracks to curve

  Radius tells you the **momentum**





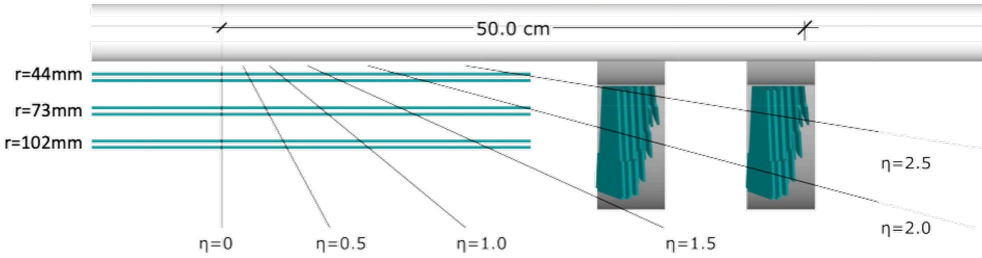
$$\frac{mv^2}{r} = qvB$$

Very curved → low momentum
Almost straight → high momentum

The CMS pixel detector

- Original (2011): 3 barrel layers + 2 endcap disks

  Pixel area 100 x 150 μm^2, thickness 320 μm



The CMS pixel detector

- Original (2011): 3 barrel layers + 2 endcap disks

  Pixel area 100 x 150 μm^2, thickness 320 μm

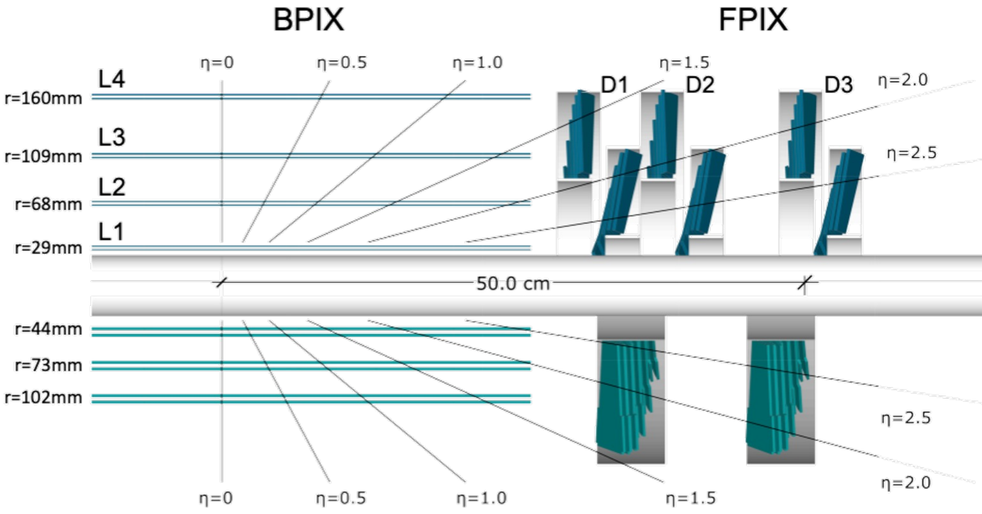
- Phase 1 upgrade (2017): 4 barrel layers + 3 endcap disks

  Innermost layer closer to collision

  Pixel area same, thickness 285-300 μm

  Less material in the forward region (carbon-fiber mechanics, CO_2 cooling)

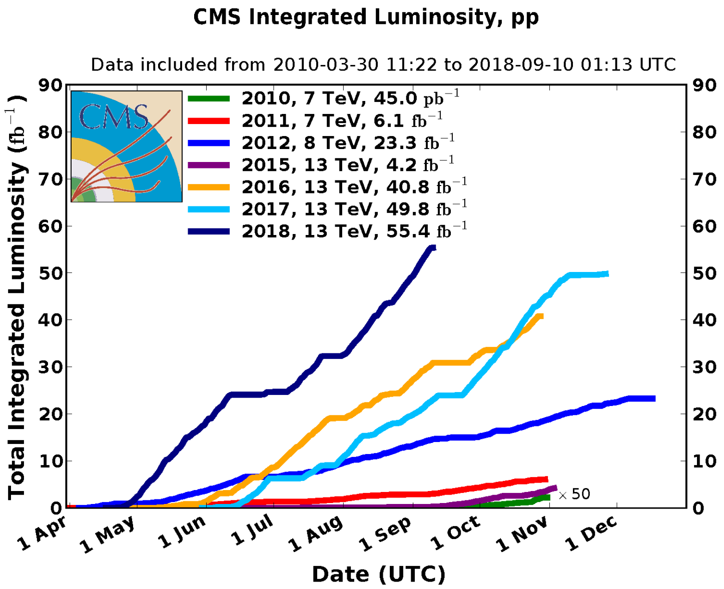
  [A short video]



Why the Phase 1 upgrade?

- Every year, CMS collects MORE integrated luminosity in THE SAME amount of time

How?



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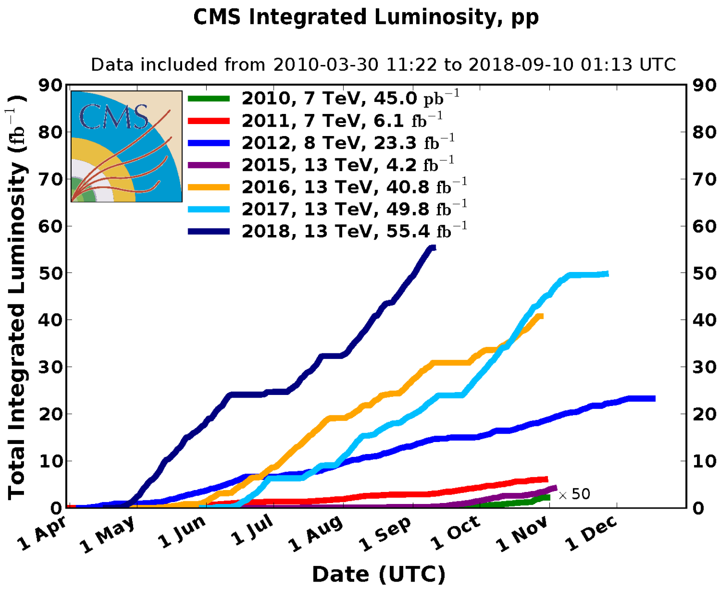
- Every year, CMS collects MORE integrated luminosity in THE SAME amount of time
- Upgrades to the LHC accelerator give higher **instantaneous luminosity** $\mathcal{L}$

More collisions at the same time (**pileup**)

$$\mathcal{L} = \frac{n_p^2 n_b f}{4\pi\sigma_x\sigma_y}$$



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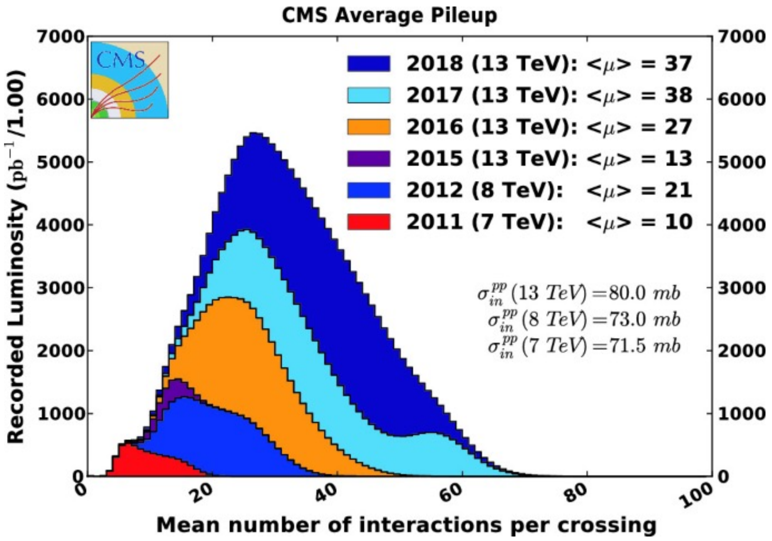
  More collisions at the same time (**pileup**)
- Levels of $\mathcal{L}$ exceeded design expectations

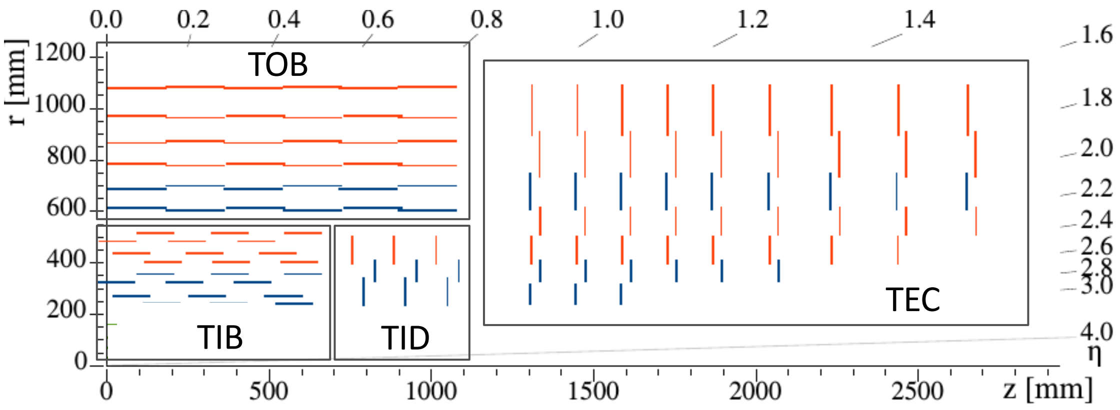
  Original pixel detector electronics could not cope!

  Upgrade gave higher data output, larger buffers for data storage, etc.



The CMS strip tracker

- Two types of modules: **single-sided** and **double-sided** divided into four regions:
  - Tracker inner barrel (TIB)
  - Tracker outer barrel (TOB)
  - Tracker inner disks (TID)
  - Tracker end-caps (TEC)
- 80-120 μm pitch
- Length 8.5-20 cm
- 320-500 μm sensor thickness
- This sub-detector is still the original!
  - Farther from the interaction point ⟶ effects of pileup are less extreme



The HL-LHC

- By Run 3, we will have collected ~ 450 fb^{-1} in 11 years
- The **High Luminosity LHC (HL-LHC)** collider upgrade will provide 3000 fb^{-1} to CMS in 11 years

Up to 20x more integrated luminosity than we have now

100x more than we had at the time of the Higgs discovery

How?

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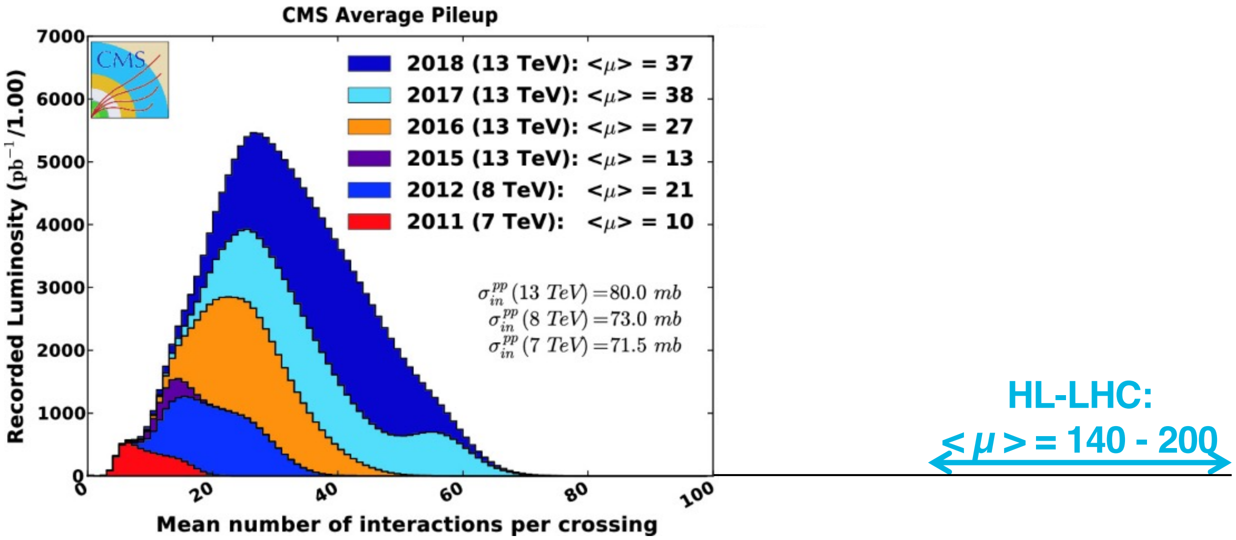

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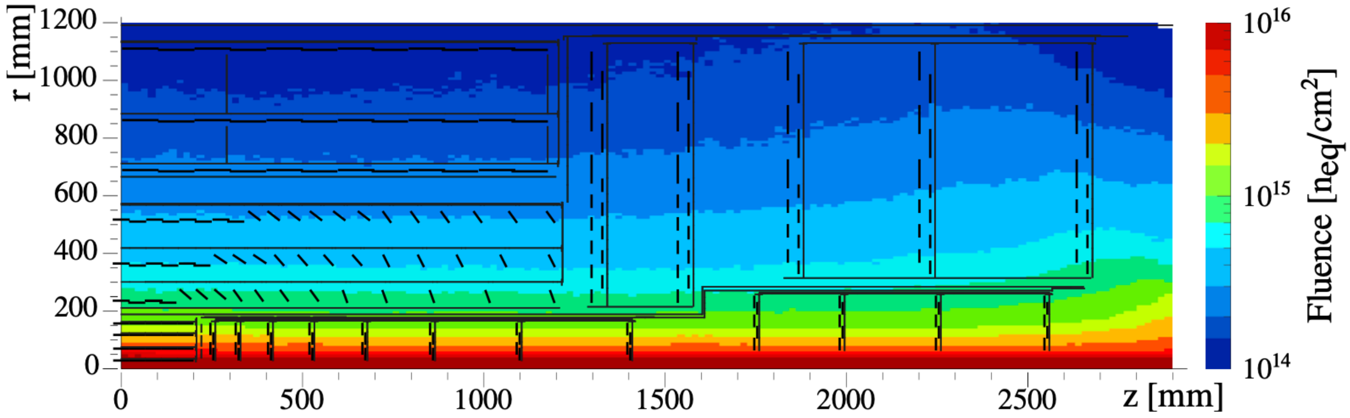
Running conditions at the HL-LHC

- Large doses of non-ionizing radiation, or **fluence**, cause damage to silicon sensors by disrupting the lattice
- **Fluence ∝ integrated luminosity**

If we want more data, we have to deal with more damage.

Projected fluence in the tracker volume at 3000 fb^{-1}



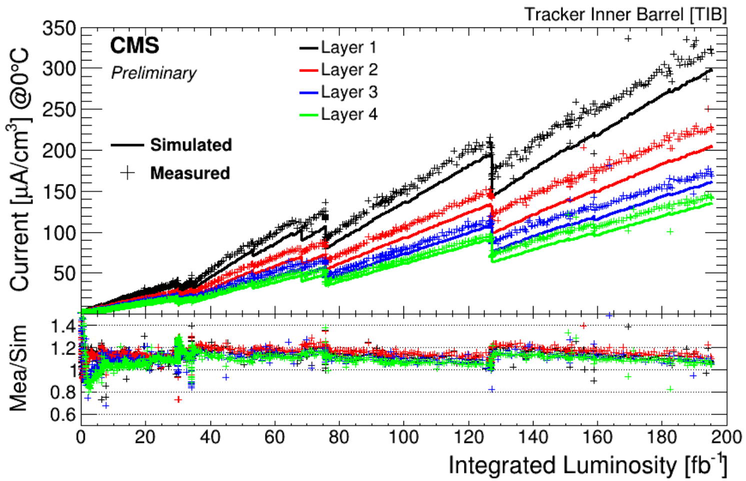
Signs of wear in the tracker

- Increasing **leakage current** due to damage to the silicon lattice

  Periods of **annealing** when the detector is at room temperature

- Shown here for strip modules at different layers

  Closer to the interaction point ⟶ more radiation damage ⟶ higher leakage current



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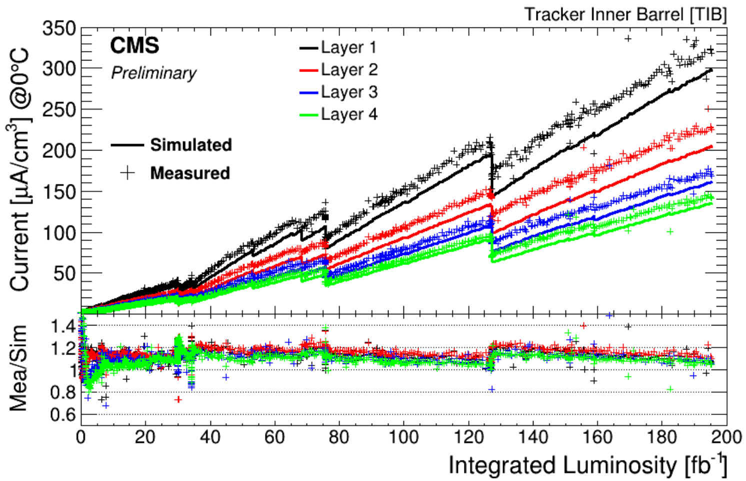


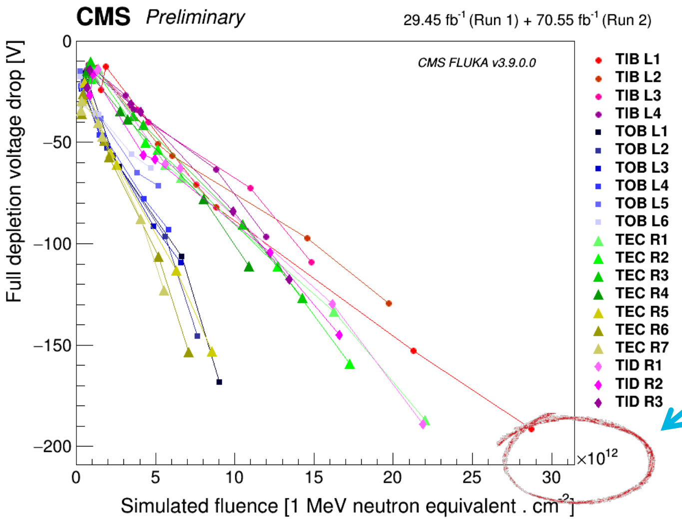
- Without sufficient cooling, will experience **thermal runaway**

  Higher I_{leak} increases temperature, which increases I_{leak}, etc.

  Current tracker cooling system is limited to -20°C

Signs of wear in the tracker

- Higher bias voltage is required to deplete strip sensors
- At the HL-LHC, bias voltage is expected to go from ~ **-250 to -800 V** by end of data-taking



At the HL-LHC, fluence is projected to reach up to **10^{15} MeV n_{eq} / cm^2** in some parts of the strip tracker

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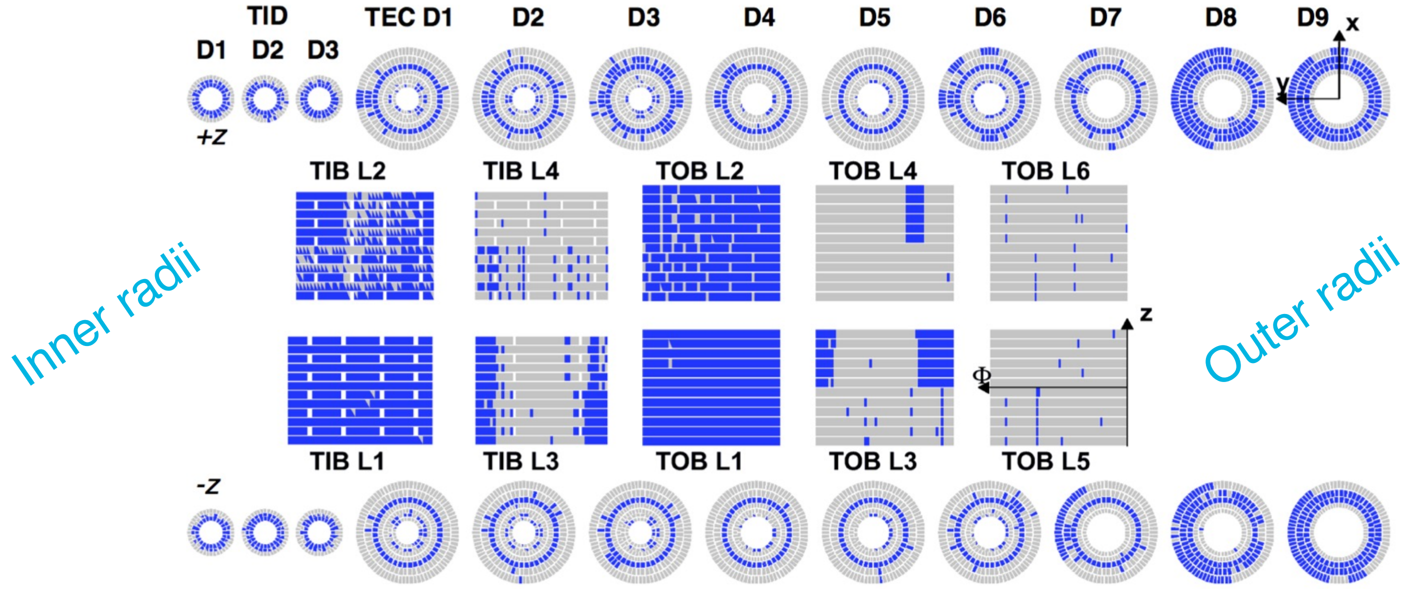
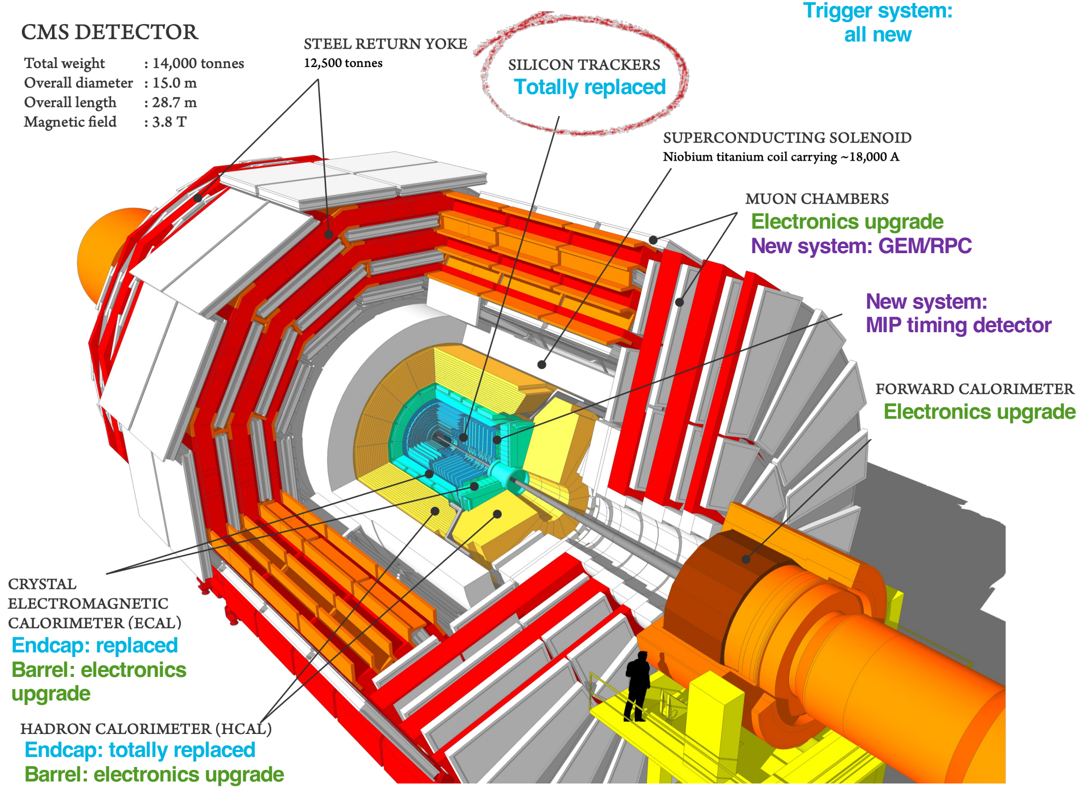
What will the HL-LHC do to our tracker?

- After collecting only 1000 fb^{-1}, the blue modules in the current tracker become completely **in-operable**!



Phase 2 upgrade of the CMS tracker

Upgrading CMS for the HL-LHC



Priorities of the tracker upgrade

🐾 Robust **tracking** in high pile-up conditions

Fine granularity, less material

👵 **Built to last** for a decade or more

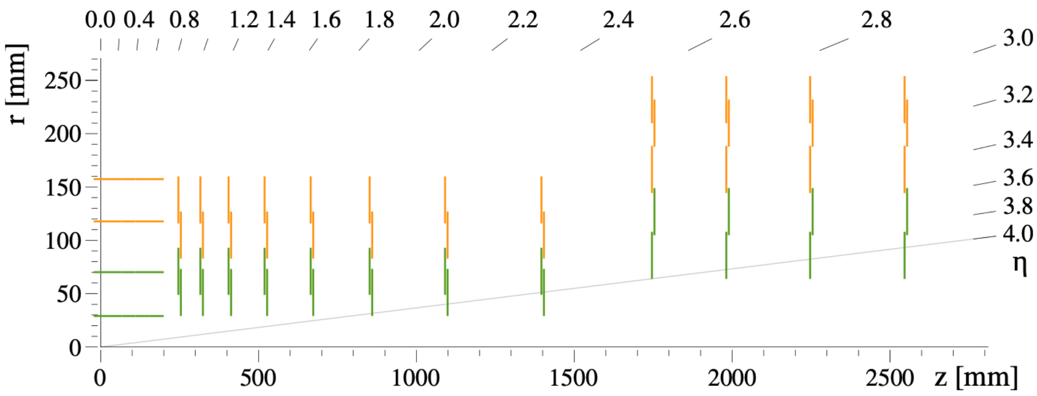
Radiation tolerance is critical

💿 Pass track info to the **hardware-level trigger** (L1) – Outer Tracker only

Using tracks to decide whether to read out data

Phase 2 inner tracker (pixel)

- Consists of 4 barrel layers (TBPX) + 8 small and 4 large double-disks (TFPX)
  - 👵 Thinner sensors: 100-150 μm (compared to 285-300μm)
  - 🐾 Smaller pixel size: 25 x 100 μm^2 or 50 x 50 μm^2
  - 🐾 Coverage up to |η| < 4.0 (compared to 2.5)



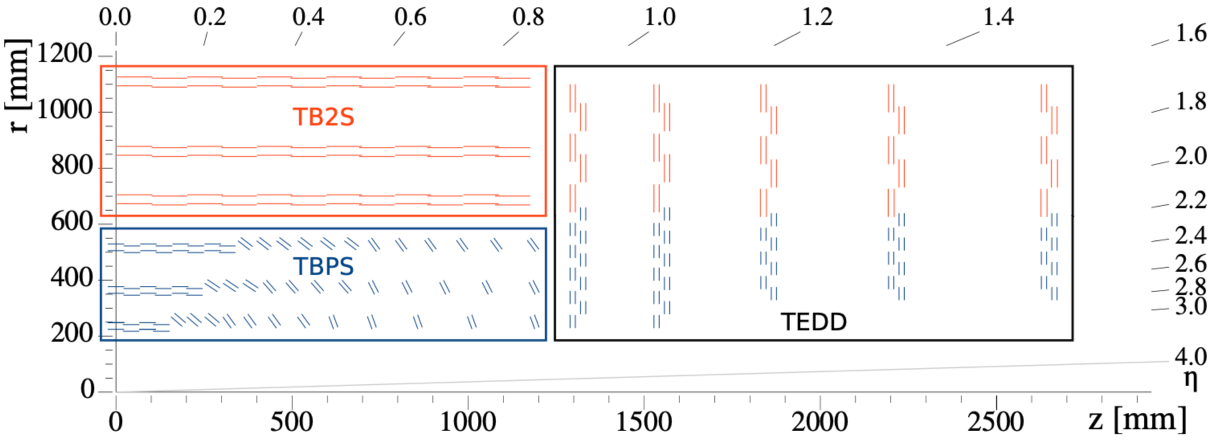
Phase 2 outer tracker

- Tracker Barrel (TB) region:

  TBPS: 3 double-sided layers of **PS modules** (flat and tilted)

  TB2S: 3 double-sided layers of **2S modules** (flat)

- Tracker Endcap Double Disks (TEDD): 5 double-sided disks



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Tracker material budget

- Dramatic reduction in total material budget compared to current tracker!

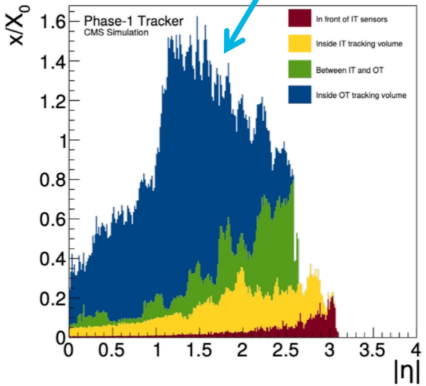
  Mechanical structures primarily made of **carbon fiber** and **carbon foam**

  Some **services** are moved outside of the detector volume

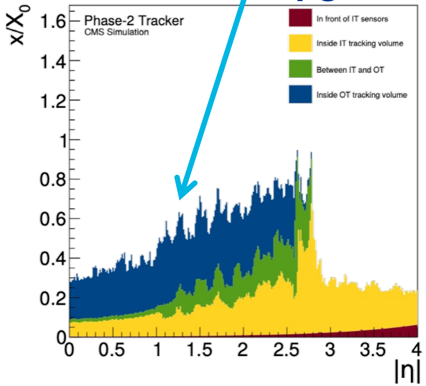
  Tilted section uses fewer modules than flat

  Dual-phase CO_2 cooling system uses far less material than current cooling system

Current



Upgrade



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Irradiation and test beam

- How do we make sure our devices will last?

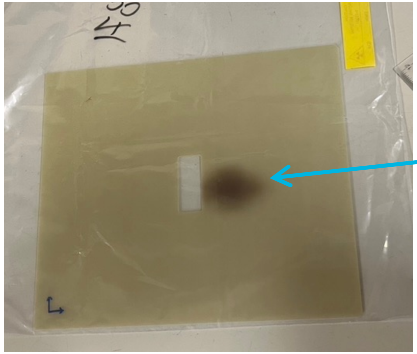
  They need to be radiation hard

- **Irradiation**: shoot silicon devices with an intense particle beam

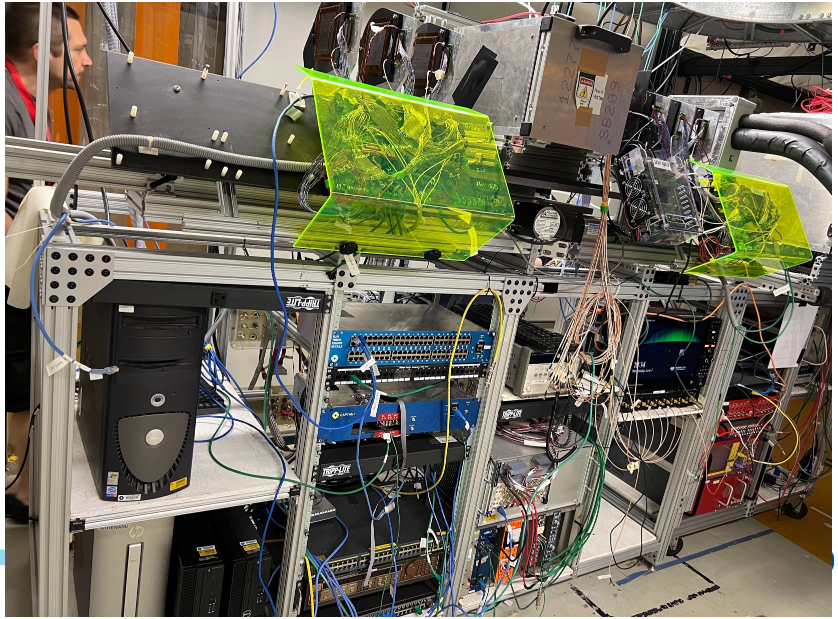
  Simulate the dose that the detector would receive by the end of its life

- **Test beam**: use the device to measure particles from a well-understood beam

  How does the performance change after irradiation?



10 minutes
400 MeV protons



A few words about the trigger

- The upgraded lowest level (L1) trigger can select more data to save

  Event rate of 100 kHz (now) ⟶ 750 kHz

Suppose we change nothing else in the trigger.

Use the same inputs, save data down to the same low p_T thresholds.

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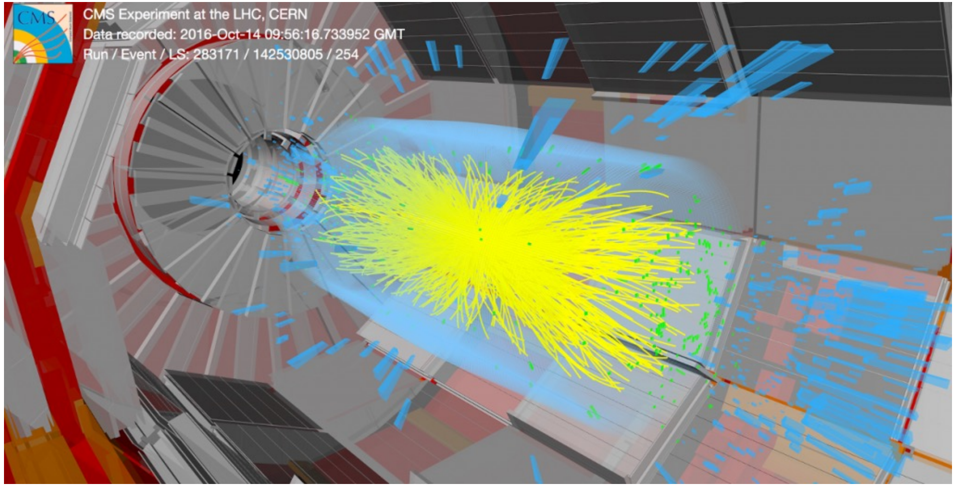
Suppose we change nothing else in the trigger.

Use the same inputs, save data down to the same low p_T thresholds.

It's not enough!

At pileup $<\mu> = 200$,
need **~4 MHz** !



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The upgraded level 1 trigger

- The upgraded lowest level (L1) trigger can select more data to save

  Event rate of 100 kHz (now) $\longrightarrow$ 750 kHz

- Has more time to decide what to save: latency of 4 μs (now) $\longrightarrow$ 12.5 μs

- **Receives info from the tracker**

  Not possible in current detector, but critical for the HL-LHC!

Example: single muon trigger

Efficiency

Do we save most of the target process above $p_T > 20$ GeV?

Rate

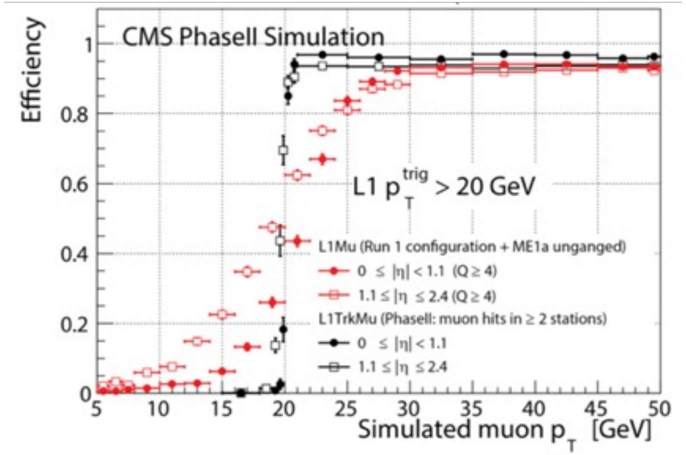
Does the amount of data that we save fit within the limitations?

Example: single muon trigger

Efficiency

Do we save most of the target process above $p_T > 20$ GeV?

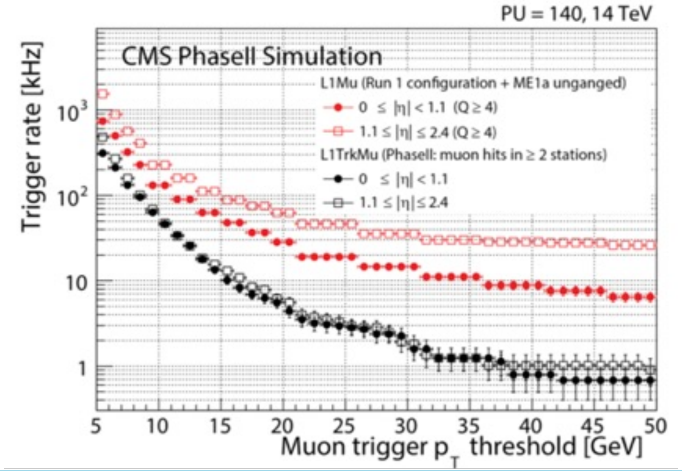
- ⚫ With tracks: yes
- 🔴 No tracks: not near the threshold



Rate

Does the amount of data that we save fit within the limitations?

- ⚫ With tracks: yes
- 🔴 No tracks: not for low thresholds



Trigger: design of p_T modules

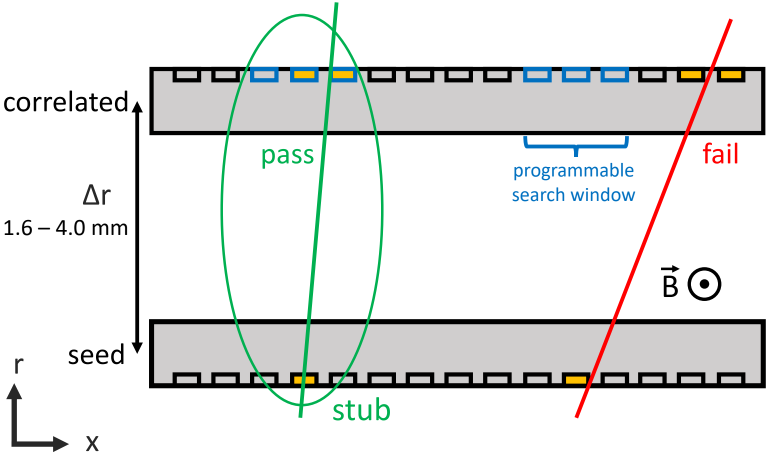
- Each module consists of two **closely spaced sensors**
- Given a hit in the inner sensor, the position of the hit in the second sensor depends on

  The particle's momentum (p_T)

  The separation Δr between the sensors

  Where the module is in the detector (r)

$$\Delta x = r \Delta r \frac{qB}{2 p_T}.$$



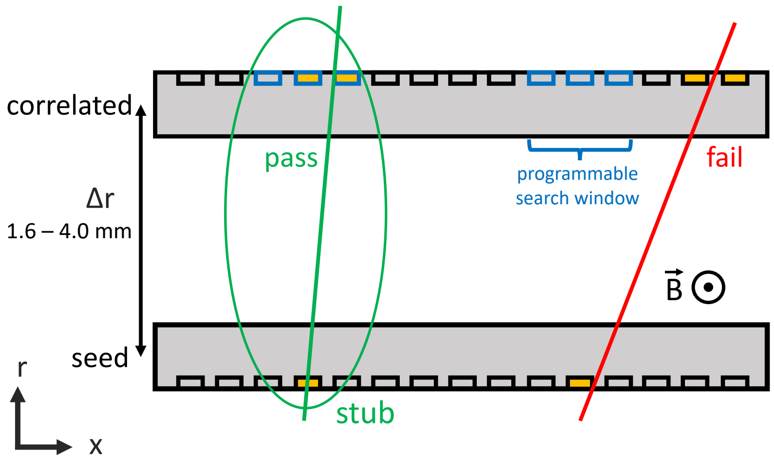
Trigger: design of p_T modules

- For a given Δr, can define a search window where the second hit will be for all tracks with **$p_T > 2$ GeV**

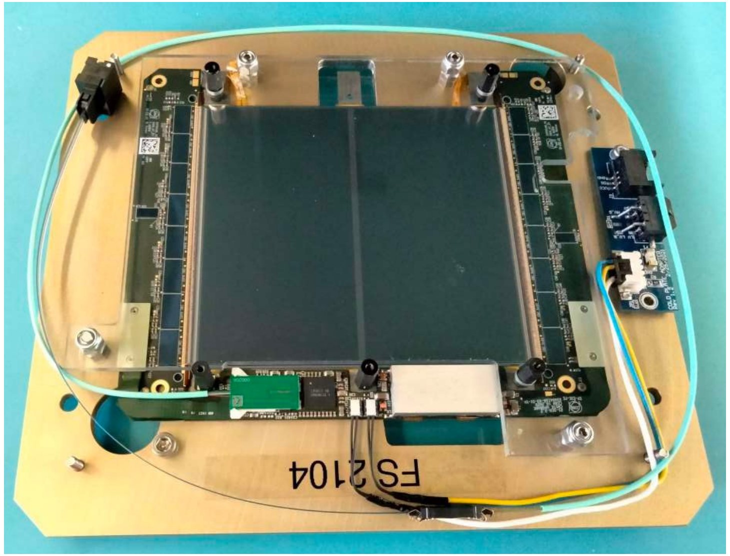
  Position and width of stub window depend on where the module is in the detector (programmable)

- Patterns of hits consistent with high p_T tracks are passed to L1 trigger

  These are called **stubs**



2S module design



- Two silicon strip sensors

  Area 10x10 cm^2

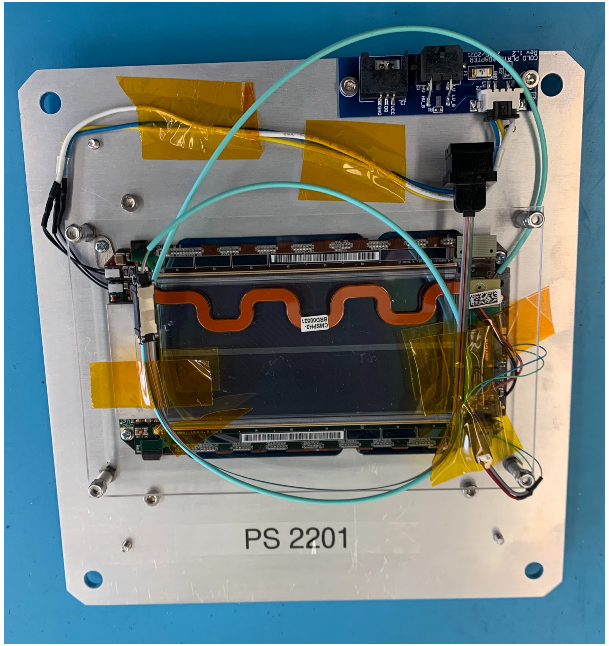
  👵 Thickness of **300 μm**

  🐾 2 rows of **90 μm x 5 cm** strips

- Two front end hybrids, each with
  - 8x ASICs for sensor readout, stub logic (CBC)
  - 1x Concentrator ASIC (CIC) for data aggregation, clustering, etc.
- Prototype assembly and testing underway
  - Assembly planned in Germany, Belgium, US, India, & Pakistan

PS module design

- Two silicon sensors with area 5x10 cm^2
  - 👵 Thickness of **300 μm**
- Top: strip sensor
  - 🐾 Two rows of strips, **100 μm x 2.4 cm**
- Bottom: Macro-Pixel Sub-Assembly (**MaPSA**)
  - Macro pixel sensor bump bonded to 16 MPA ASICs
  - MPA ASIC does the stub logic
- Two front-end hybrids, each with
  - 8x ASICs (SSA) for readout of strip sensor
  - 1x Concentrator ASIC (CIC) for data aggregation, clustering, etc.



In summary,

- Silicon detectors are very effective for HEP applications!
- Changing accelerator conditions ⟶ need for upgraded detectors

  Plus, we can integrate newer technologies at the same time
- The Phase 2 upgrade of the CMS tracker will
  - 🐾 Provide robust tracking capabilities in high-pileup events
  - 👵 Perform well through the end of HL-LHC data-taking
  - 💿 Contribute to the level trigger (critical at high pile-up!)

Any questions?

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Thanks for materials:

- Manfred Krammer & Frank Hartmann
- Farrah Simpson
- Doug Berry, Hannsjörg Weber, Corrinne Mills

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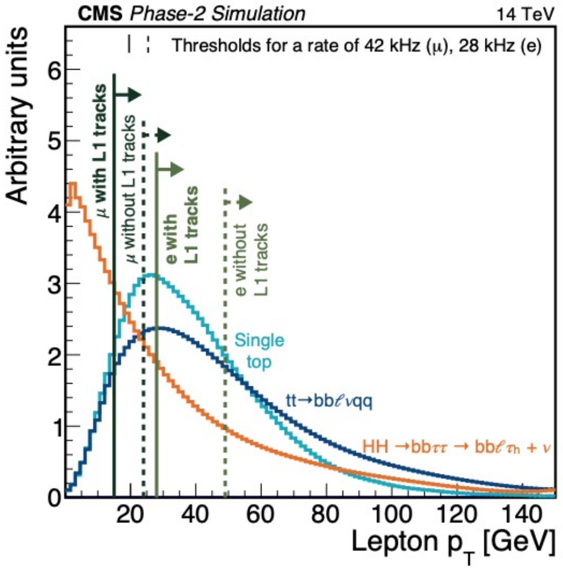
Additional material

Track info in the trigger gives us:

- **Charged particle candidates** in the trigger

  Not only electrons and muons, but hadronic jets. Can even tell us about jet flavor and substructure

- Information about **isolation**
  - Are there a lot of tracks near a particle candidate?



Track info in the trigger gives us:

- **Charged particle candidates** in the trigger

  Not only electrons and muons, but hadronic jets. Can even tell us about jet flavor and substructure

- Information about **isolation**
  - Are there a lot of tracks near a particle candidate?
- **A collision vertex!**
  - Gives photons, missing energy something to point to
  - Rejection of pileup, which corresponds to the wrong vertex