



Silicon Detectors in Particle Physics Experiments

And beyond, what Jens thinks

Disclaimer

Given the setting, I wanted to talk about tracking detectors, but not just

Much of my history is ATLAS, hence many things I talk about hang on ATLAS examples

Pictures: I don't usually do [work content seminars](#) anymore or when I do, it's about [scroll reading](#) - content today may not always be well referenced, but I made some effort and hope to be forgiven for missing refs

Walter Snoeys gave a [very good seminar at CERN](#) summarising recent progress in many parts of the semiconductor detector world!

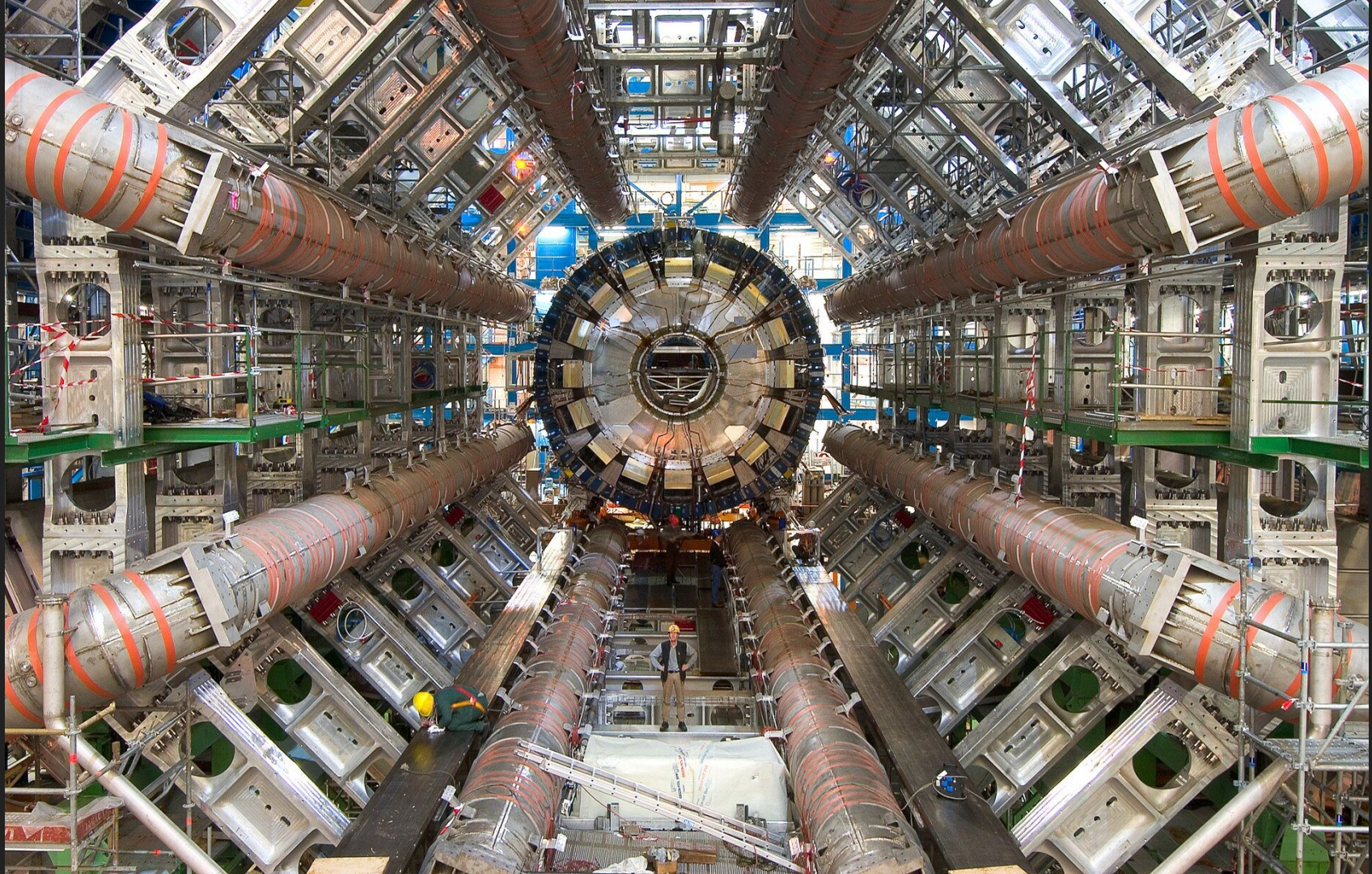
What I will talk about

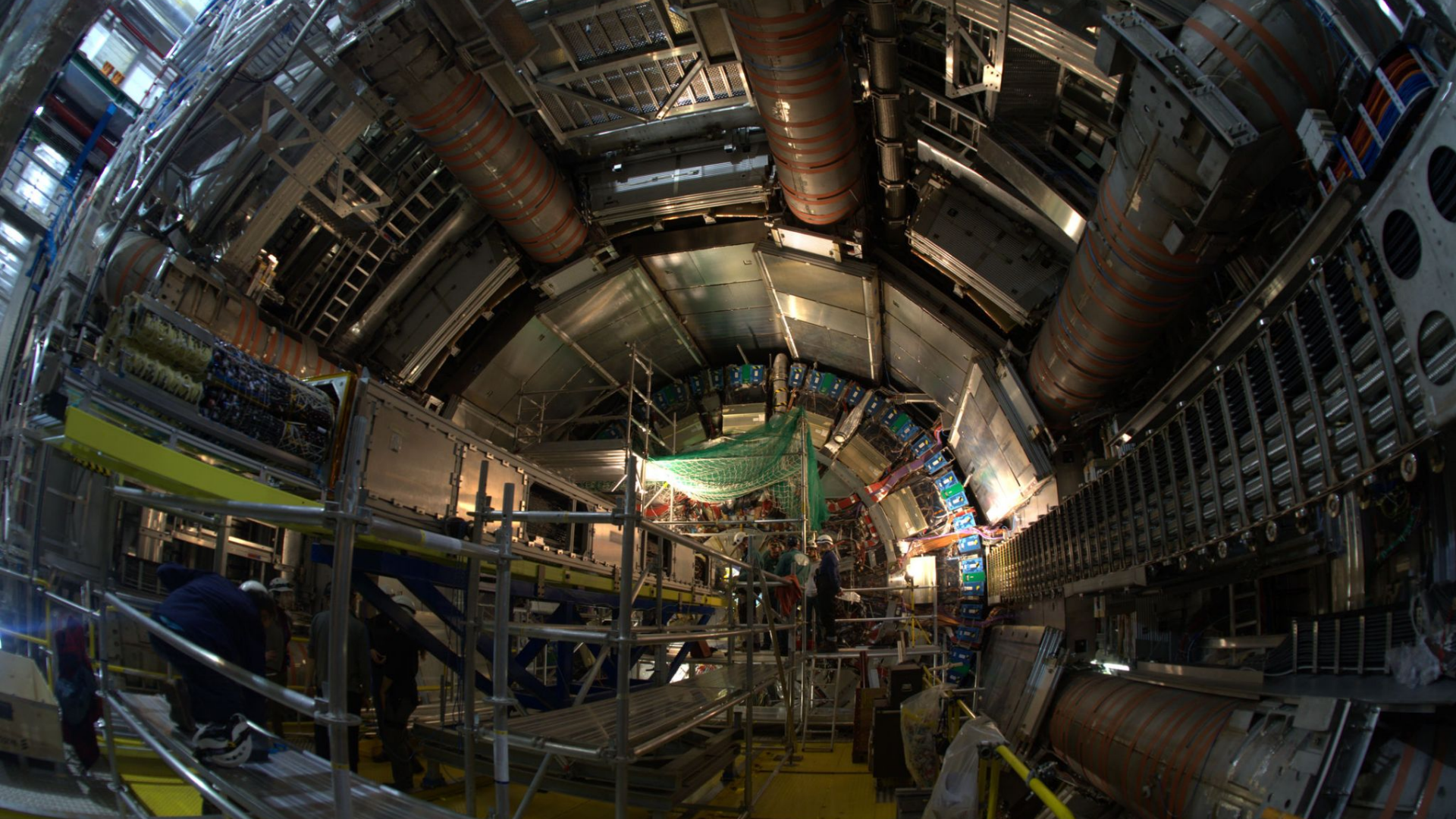
- Particle Tracking
- Using Semiconductors
- Recent examples of detectors and works in progress
- What we think we might do in the future and how to get there
- What we can (or should?) do along the way

How did I get here?

- On my first day of Uni we had group introductions - I wanted to join the group that worked on the biggest complex Instrument I could imagine - ATLAS
- Many people in hardware spend time on very specific details becoming the expert, e.g. analogue front-end design, 3D integration, radiation hardness - I "was" a Data Acquisition (DAQ) person
- Went to CERN for installation and commissioning, which gave me an early insight into detector calibration and operation
 - Led me through various side-subjects like detector control systems, cooling, mechanics and mundane things like how to effectively strip a polyimide insulated wire (400C acid)





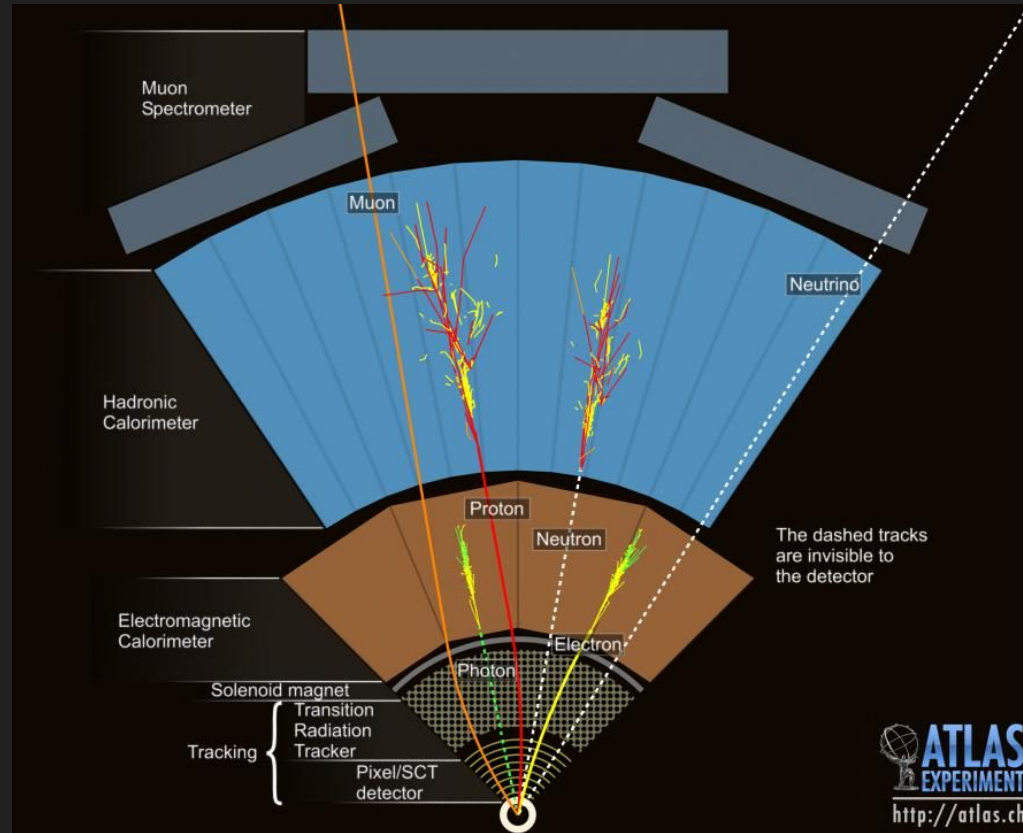


ATLAS

Typical "Onion-Shell" concept of a Detector:

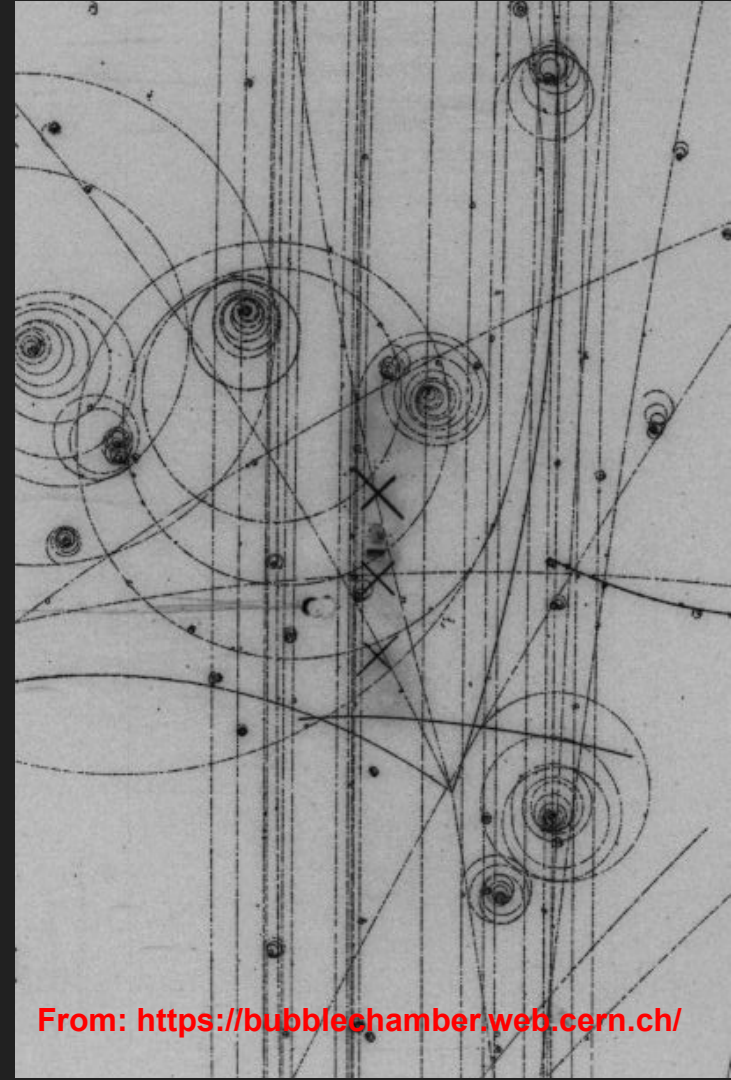
- Tracker
- EM Calorimeter
- Hadron Calorimeter
- Muon System

Magnets to provide momentum resolution in tracker and muon system



Particle Physics - Tracking

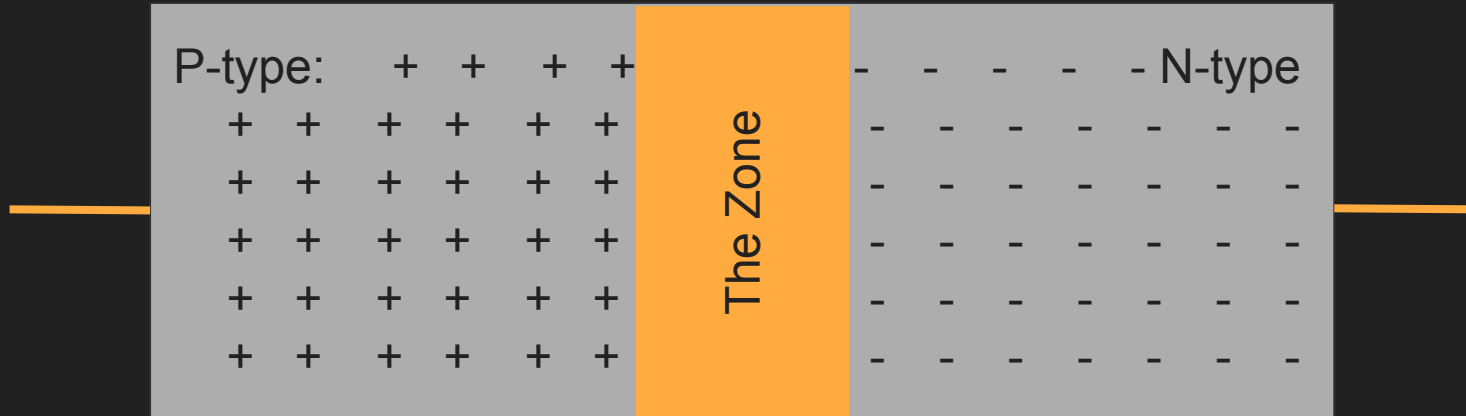
- Magnetic field to measure momentum, perpendicular to the axis you care about
 - Most experiments: Beams Axis
 - Forward experiments: perpendicular
- Need a measurement coordinate perpendicular to the magnetic field
 - Most experiments: Cylindrical layers with resolution across $R \cdot \phi$
 - Forward: Resolution perpendicular to beam and magnetic field
- Sagitta measurements provide for momentum measurements
 - Highest momentum you can usefully measure depends on B-field and resolution
 - Lowest momentum: Layer spacing, B-field and material budget



From: <https://bubblechamber.web.cern.ch/>

So, where to start on semiconductor detectors?

- Let's start by assuming we understand a diode:



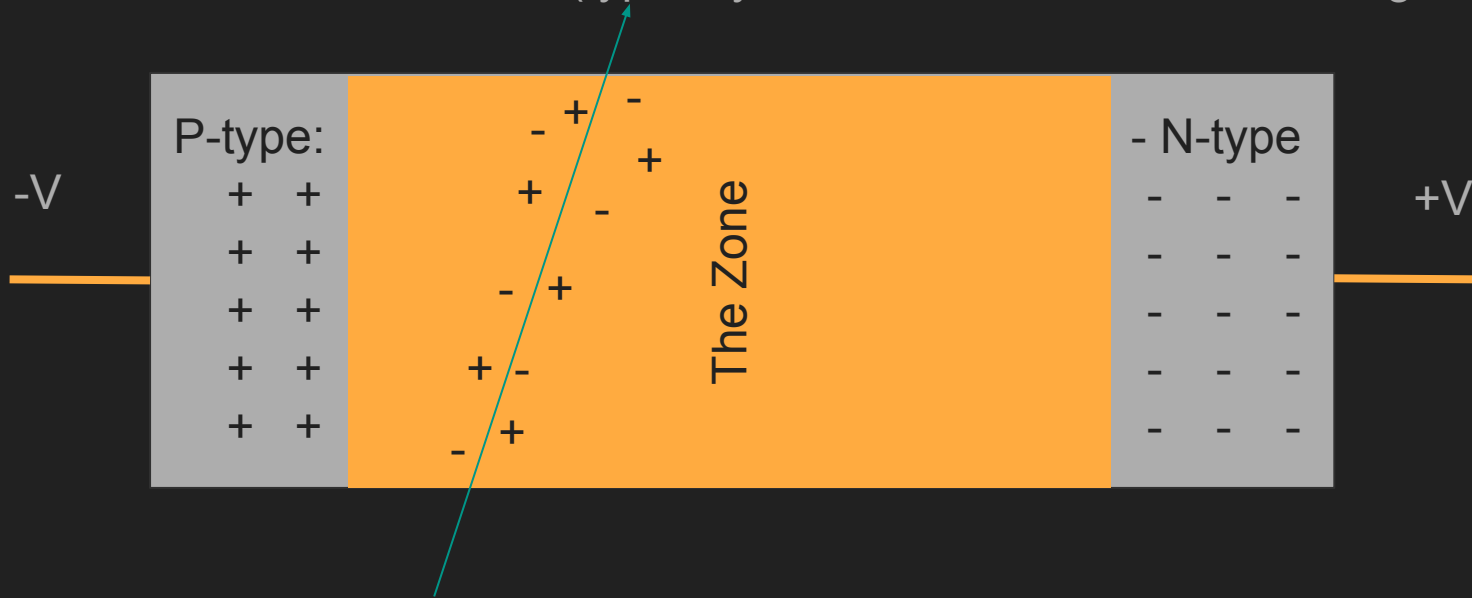
So, where to start on semiconductor detectors?

- Let's start by assuming we understand a depleted diode:



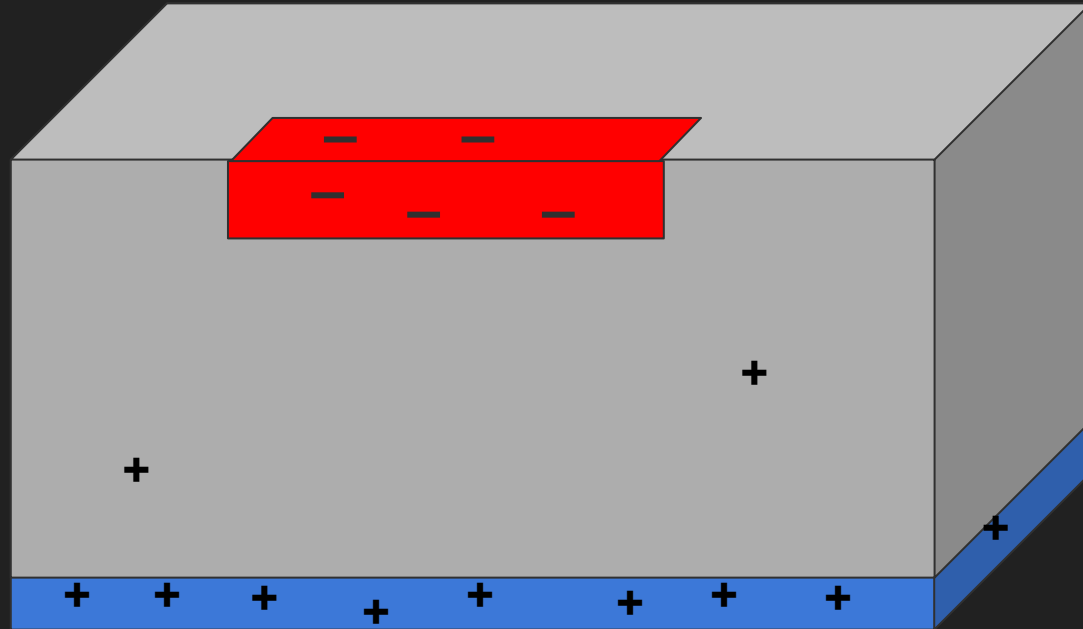
So, where to start on semiconductor detectors?

- Free charge carriers get released through a particle interacting and we should see a small current flow (typically a "countable" number of charge carriers)



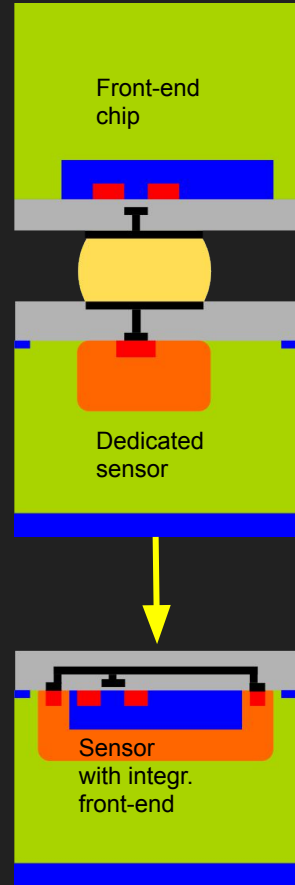
Patterning

Top-side pattern plus backside doping gives spatial resolution



Detector structure - How we make them

- Hybrid:
 - Leave the diodes be in their own place, connect them later to a front-end circuit that converts a signal into a (typically digital) output
 - Sensor and frontend are developed largely independently, radiation hardness not a question, signal size often to be large, to overcome issues of interconnect
 - Interconnect is costly (both money and time) and adds negative side-effects
- Monolithic:
 - Integrate the front-end circuit with the sensing element - various naming conventions depending on bias conditions and/or collecting node size
 - Can be radiation hard
 - Can be very low noise
 - Much more effort in design to reduce cross-talk between various close-up entities



That's it, the rest is engineering ... ish

- Remember where your native junction line is, or where you think it should be
- Remember where a depleted zone is, or where you think it should be

Some other details:

- Capacitance is your enemy
 - Interfaces are evil
- Surfaces are evil
- Funky stuff: <https://cds.cern.ch/record/2747752/>

Brief summary

Assume we now have a spatially resolved detector in a magnetic field, that can measure points on a track to deliver momentum measurements for individual charged particles

There's more to detectors, but as trackers go, we're quite good!

What do we care about in a (tracking) detector

- Signal / Noise (>10 , preferably more)
- Resolution:
 - Spatial (Typically $O(10\mu\text{m})$)
 - Time (Can reach 10s of ps, often just $O(25\text{ns})$)
- Radiation tolerance
- Material budget
- Power consumption
- And cost... (believe it or not)

The order of priority here depends on what you're aiming for, e.g. (personal choice):

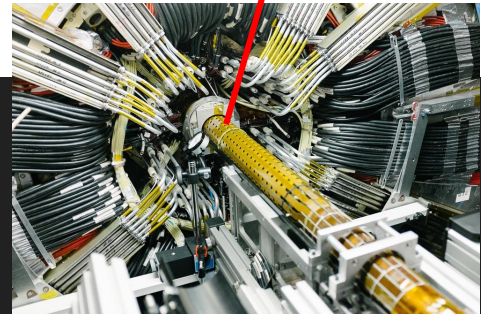
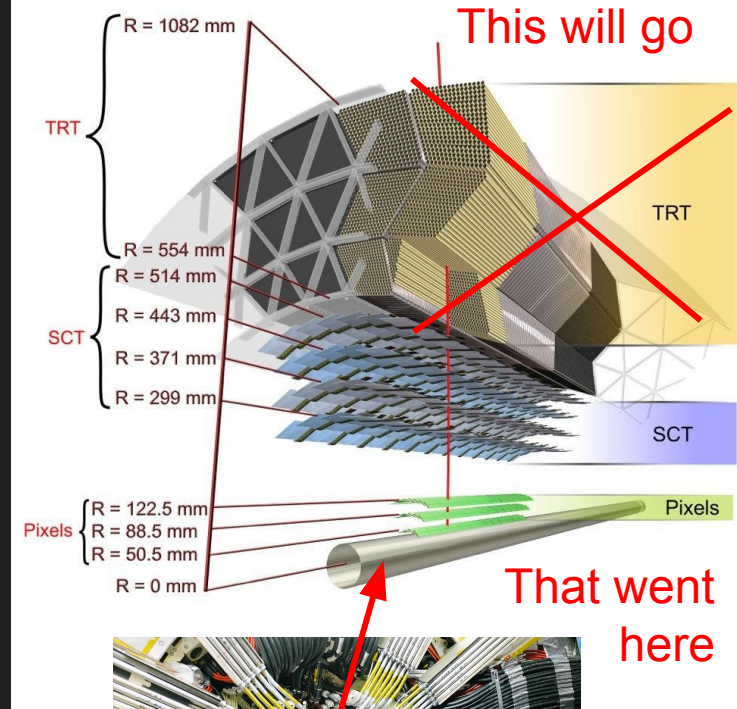
Tracking in hadron colliders: Radiation hardness

Tracking in ep colliders: Material budget

Digital Calorimetry: Power consumption/Cost

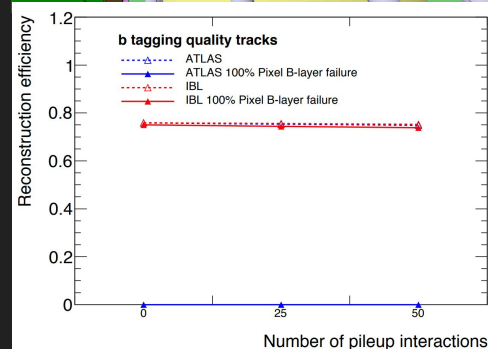
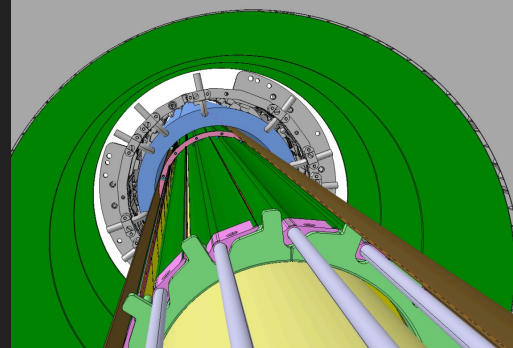
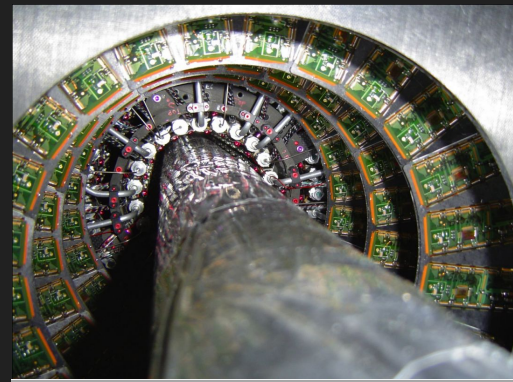
A ~~current~~ picture

- All LHC experiments currently use silicon in their tracking systems
- Typically hybrid detectors, FE-chip is separate from the sensor node
 - Latest example in general detectors: IBL
- Parameters in current GP detectors:
 - Track resolution around 10 μ m (r-phi)
 - Sensitive down to few 100 MeV
 - Near 2000 tracks per event can be handled at rate
- Things we tend to miss details on, while busy building:
 - Power
 - Material
 - Mechanics



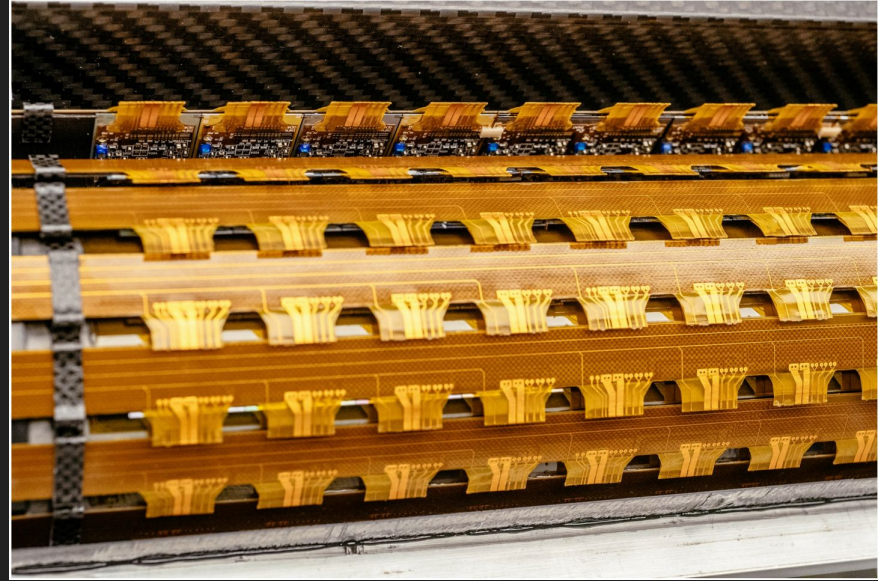
The IBL as an example

- ATLAS Pixel was meant to have a replaceable B-layer (to prevent tracking performance loss due to radiation dose)
 - Late in construction this was scrapped (for ease of assembly, if memory serves me right)
- New plans were made to replace the previous Beampipe in ATLAS with a smaller one, and installing a [new detector layer](#) in the intermediate space (3.3cm active radius)
- Original installation date: LS1 in roughly 2015
 - Problems with the LHC as well as many other things meant LS1 was pulled forward: 2013++
- IBL was suddenly pushed to deliver - mostly ok
 - New technology, 130nm IBM (many lessons on that)
- Success!



Success?

- Yes, definitely, but:
 - New 130nm ASICs were sensitive to [RINCE](#)
 - Power consumption changed during a run
 - Temperature changed during a run
 - Structure had not been fully re-verified in FEA
 - [IBL rotates \(dynamically within a run\)](#)
- This was overcome (very quickly) by per-Lumi-Block re-alignment!
- Beyond that
 - Working with an external supplier for connectors, we didn't resume wire-stripping as we learned in Pixel
 - Stripping caused issues, manufacturer recommended a late change to full copper wire
 - Massive increase in X0 in the forward region - FCAL still hates IBL



What's the lesson here?

- Making detectors isn't just about a very radiation hard sensing element, or designing a very high rate readout chip
- Everything matters and everything plays into final performance

Making a good final detector might involve making a slightly suboptimal choice early in the process of development, to then have enough time to follow through and implement it well!

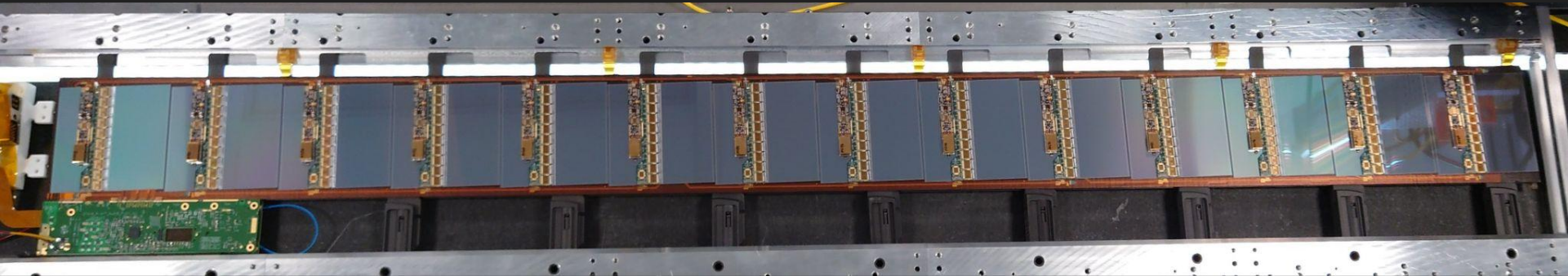
The near future

HL-LHC Parameter space

- With a higher luminosity era upon us, the current detectors will not just die from radiation:
 - Bandwidth limits
 - Latency restrictions
 - Occupancy limits (TRT is already mostly "on")
- HL-LHC increases inst. luminosity by another factor of 3-ish, heading for 200-pileup collisions
 - Looking at $O(10000)$ tracks to be distinguished, rather than the original 1000 we planned for with the LHC
 - To record more/better data, higher readout rate is a must

The near future: ATLAS ITk

- Rebuilding the tracker systems in all-silicon technology (Goodbye TRT):
 - Moving to electron collecting strips, upgraded to 130nm readout chips, modules loaded to a large carbon fibre support, strips go from 6M to 60M channels, near 200m² of silicon!
 - Pixels going thinner, but still hybrid, 65nm readout chips, 40k pixels/cm², innermost layers now completely in 3D sensors
 - CO2 cooling system all round
- Rate capability goes up, not just in hit rate, but also trigger rate:
100kHz -> 1MHz



Challenges the ITk was/is facing

- Changing parameter landscape
 - Used to have a two level trigger, now single level
 - 3 ASIC generations on the strip upgrade, we still have two layer triggering embedded into production ASICs using up real estate!
- Large and distributed production
 - Strip tracker UK cluster has 7 sites involved in strip-module production
- Dependence on chip-design and vendors
 - Pixel has started using the 3rd iteration of their front-end chip, these takes years to design and test, Production Readiness reviews are running with first sets of these...
- Base materials largely sourced from military suppliers and in competition with their other customers - often single source supplier!

Challenges we face(d)

- Strips saw induced noise only in cold operation - late finding during R&D
- Strips also saw cracking modules when going cold
 - We knew that building a CTE mis-matched stack of sensor and readout circuits wasn't ideal, but we hadn't tested it till we finally had the right numbers in hand!
- Aiming to build the lowest material support structure with the most exclusive materials we are now stuck with:
 - Surface flatness problems that require extra adhesive to solve it (more material !)
 - Highly variable material, but we're down to one (military) supplier
- Pixels is doing better
 - No cold noise, no cracking, no trouble with structures - but strips have loaded many tens of stave cores with 28 modules per core, Pixels is just starting

Could these have been prevented by better/earlier hollistic R&D?

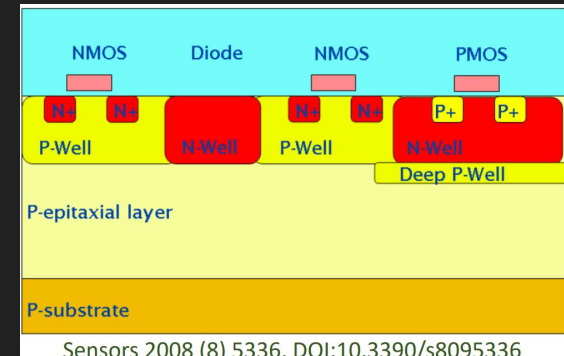
It's not all Doom

- Strips have overcome:
 - Loss of our preferred PCB manufacturer
 - Cold noise (mostly)
 - Cracking
 - Common power converter problems (first seen in strips)
 - Common readout chip issues
- Production has properly started!
 - Exciting times for Pixels
- Installation into Barrel and Endcaps should be starting soon, at which point we can start to look towards commissioning
 - Be sure to find time to be at CERN in about 2 years - I have spent the most exciting time of my life at CERN installing and commissioning detectors!

The actual (?) future

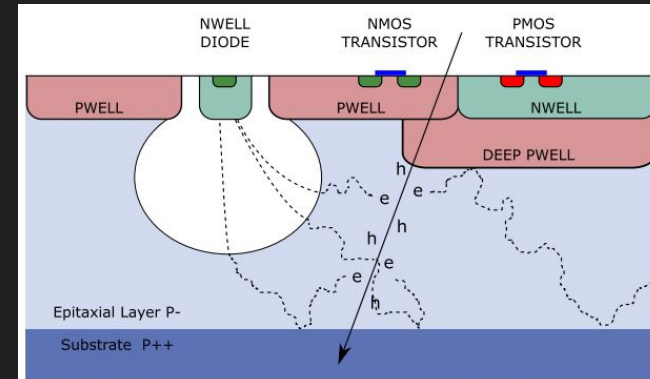
Monolithic Detectors

- Since the beginning of hybrid silicon detectors, physicists have dreamt of active sensors, where either the first stage of amplification or the whole front-end circuit are implemented with the sensitive silicon
- SLD had a [307Mpix CCD based vertex detector](#), that showed us what could be done with an integrated detector (slow however)
- Early candidates of CMOS devices appeared under the MIMOSA name
 - Believe it or not: Development lead by STFC, major process change introducing a deep P-well
 - Charge is collected by diffusion
 - Superbe resolution
 - Not radiation hard
 - Rolling shutter readout: Rate capability very limited
 - Used for the STAR tracker at RHIC (First time a CMOS sensor was used in "HEP")



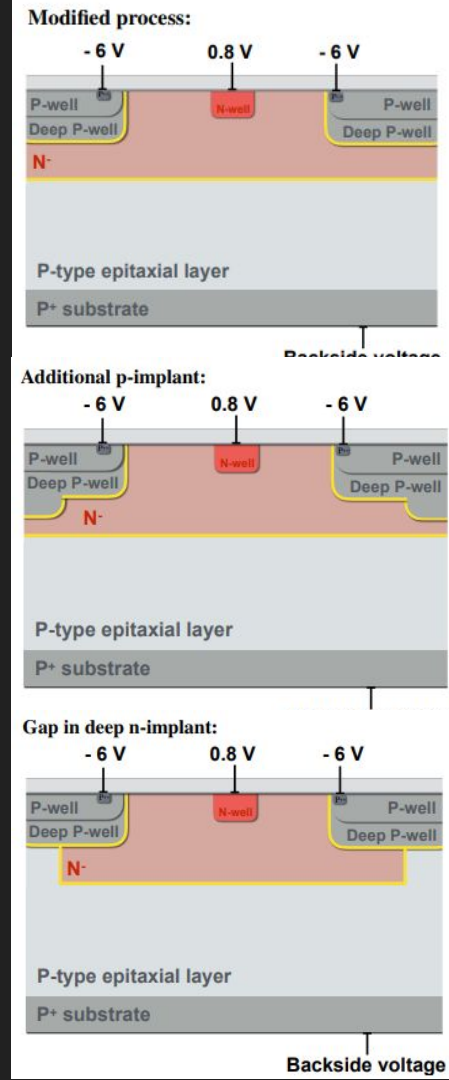
CMOS Sensors in HEP

- In the early teens the community became more active around CMOS sensors, e.g. [Ivan Peric \(now KIT\)](#)
- Community split into two camps:
 - Large collecting nodes with large bias: achieved sizeable depletion depth (increased later due to acceptor removal), large signal and speed, but also large noise due to collecting node size
 - Small collecting nodes: very low noise, but collection largely by diffusion
- ALICE used TJ180nm for a first version of their Alpide Chip, which now powers [the ITS 2](#)
 - Small collecting node design, but doesn't require collection by drift
 - Fully isolated CMOS structures based on TJ deep P-well



A success story to continue?

- Multiple steps on from Alpede, ALICE 3 aims to produce wafer sized stitched sensors with a [deep junction](#) that allows full depletion of the epitaxial silicon
 - Very low noise (e) and good amount of charge collection
 - Charge collection speed under deep wells has been optimised through patterning of deep implants
 - Displacement damage tolerant up to $1e15$ n/cm²
- If thinned and handled correctly, these wafers can be bent into radial shapes that allow them to be largely self-supporting
 - Stitched sensors make these sizeable enough to wrap around a beampipe!



Other Directions?

- [Silicon-Germanium developments for fast detectors](#) show working models with around 20ps time resolution achievable
 - ~50ps at 10^{16} 1MeV neq/cm²
- 3D stacking promises to allow one to decouple the digital parts of a sensor from the analog parts, integrating smaller feature nodes for high density digital systems with larger feature nodes for analog quality
 - Longevity? Price? Access?

Sensor-wise:

- LGADs have taken off everywhere as the thing to do
- 3D sensors and Wide-band-gap semiconductors towards radiation hardness

Cost driven Detector Developments

- Vertexers are often $\sim 1\text{m}^2$ -> knock your funding agency out!
- Tracking detectors are currently trying to cover $O(100\text{m}^2)$
- Calorimetry wants $10\text{k}+$ m^2 for digital calorimeters
 - Power density needs to be low - Alpile is a good model here
 - Needs digital processing, otherwise data rates remove that benefit
 - Cost needs to be minimal -> CMOS looked like a way to get a cost reduction by x10 from classic detectors, but not the way we currently produce them
- Current working models all rely on very specific processes with large cost attached, including early developments for calorimetry e.g. DECAL
 - TJ180nm process, deep implants, epitaxial silicon, stitching possible
 - Options offered are amazing, cost is prohibitive
- What to do if we need cheap?

Back to the roots?

- Early high-voltage based developments used standard processes, often only triple-well
 - Coarse feature size (350nm/180nm), 4-6 metals, no copper
 - No special substrates, particularly no epitaxy
 - Very low costs for early engineering runs
 - Charge Coupled Pixel Devices (CCPD) allowed to be integrated with a frontend chip of different feature size by inexpensive adhesive connection, but made integration hard - can we fix that?
- HV based sensors have been successfully tested up to $1e16$ n/cm²
- Resolution may pose a limit for calorimetric applications
- Why have we not seen [ATLASpix3](#) more?

The future future

Where we are heading

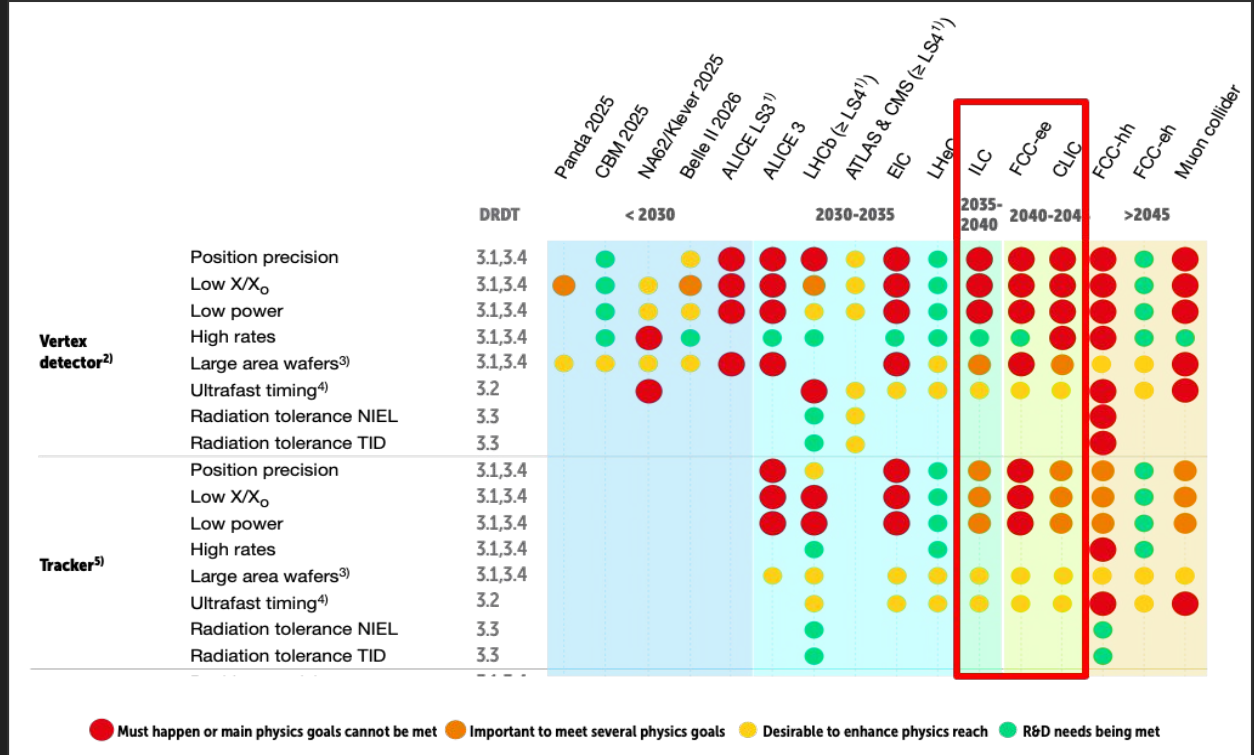
- A follow-up from the ECFA Strategy Update 2020 is the European Detector R&D Roadmap: <https://cds.cern.ch/record/2784893>
- We have much of the detector technology required for the next detector(s) already in hand
 - e+e- is similar in requirements to ALICE
- I think this is good - we can spend time on making the "other bits" work:
 - Mechanics, Cooling & Powering
 - Readout
 - Calibration
- It pushes other colliders further into the future and allows us to perform basic R&D for these:
 - Radiation hardness beyond the current levels
 - New Materials
 - Timing

Status according to the 2021 Roadmap

Roadmap highlights developments needs

Notice e+e- collider similarities with Heavy Ion colliders!

ALICE 3 development seems well in hand



How will these developments be pushed

- CERN based setup of Detector R&D Collaborations (DRD)
 - Intention is to make sure required strategic R&D happens
 - Thematic along the Roadmap, e.g.: DRD3 for solid state detectors
 - Boundaries sometimes up to definition - e.g. monolithic CMOS sensors fit into DRD3 (solid state), DRD7 (electronics) and DRD6 (when used for digital calorimetry)
- Collaborations are established, but still variable - many to be reconfirmed late this year/early next
- Currently lacking coherent funding support in many countries, incl. UK
 - Typical funding model used to evolve around experiment collaborations and their internal R&D
 - Currently still active on ATLAS/CMS upgrades as well as the LHCb Upgrade II and e.g. the Electron Ion Collider
 - ~~Worse, the latter two get IF money, which has other problems attached!~~ (I wrote that a year ago)
 - Extracting funding from there into a harmonised effort is a societal challenge, not technical

Personal thoughts

- Detector R&D has to change, we can't afford many design iterations in multiple experiments
 - We don't need them either - capture requirements correctly and work from there
 - Where requirements differ, one needs to come to the common denominator that helps de-risk projects, e.g. separate digital nodes developed for a common front-end design?
 - This is not to say you shouldn't do basic R&D, but when it comes to designing a large scale experiment, focus on what can be made to work in a given timeframe (+ -)
- The UK as a whole cannot cover everything - what are we good at?
 - Apart from general test facilities, the UK also has major irradiation facilities, hence we can cover all testing requirements for particle physics detectors
 - Past involvement with data acquisition and testing has given us a figurehead role in current detectors - can we rebuild that for the future
 - We are still looked to as people who understand how to get large complex, systems working!

What can you do towards the future?

- Focus on validation and testing
 - Validation based on simulation and testbeam need to go further than they used to
 - On the plus side, this is a skill that industry wants, so we should argue for it
- Very good electronics capability as well as a good workshop
 - Physically near a national lab, where large design effort exists (atm) for ASIC and sensor design, already some collaboration to build on!
 - Tapping into such effort is a challenge we must (as a community) overcome if we want to take part in current leading developments
- Bring in young people!

Summary

- Future semiconductor detectors are facing challenging developments - that means they are fun to work on!
 - Power density requires more work
 - Readout should (always) be better than it is
 - Smartness could well increase - but don't go overboard with setting requirements
 - All requires extensive validation (or else we repeat our past mistakes)
- Making them "easier to use" should help us improve the case for future particle physics development
 - Should also provide better spin-off opportunities - value that supports our scientific case
- With the GPD upgrade at the LHC coming to life in the next 5 years, there is a lot to be validated and learned from our current developments!
- I have spent the most exciting time of my life getting a detector to work at CERN, can only recommend it!

Title said "and beyond", didn't it?

Detectors in application

- I genuinely believe we need to pursue fundamental science for the sake of doing it - developments for that should not require further justification!
- That being so - I do believe that we produce things that have greater benefit than "just" making Higgs Bosons or "just" measuring a mixing angles
 - The biggest problem in transfer is the two ends of the spectrum don't often meet - the people in the development don't push in the direction of end-users and the people on the other end do not want to pursue the steps necessary to pull a product out and make it ready
- Detectors we are looking to produce for future hadron collider applications have good usability in proton therapy systems
 - Electron collider detectors will turn out very sensitive and thin, so there will be good places for them, too - currently sitting on a few electrons of noise!

Arts & Humanities

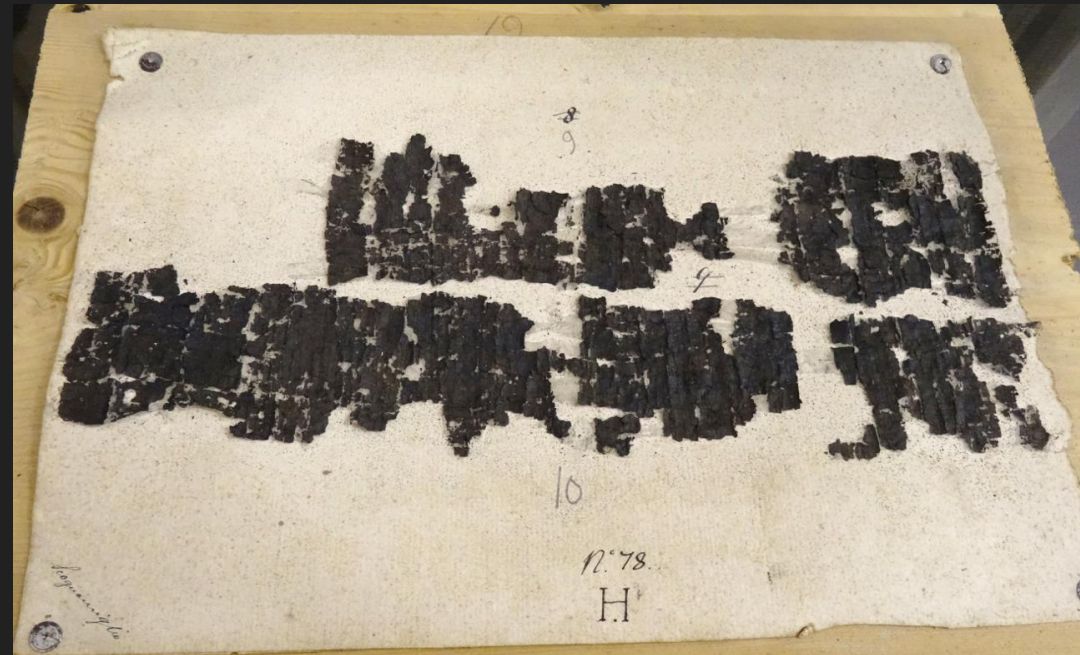
- My favourite subject, apologies!
- Question: What do particle physics driven detector developments have to do with reading ancient scrolls?
- When unrolling this:



Arts & Humanities

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- When unrolling this:
- It turns into this:

Using X-rays instead, allows to scan the interna of the scrolls without mechanical damage



Sensors and their applications

- Medical is a thing that springs to mind right away, but there are so many other things that can benefit from PP sensor developments
- Arts & Humanities were not high on my list, but turns out they care about
 - X-rays
 - Neutrons
 - Muon (-tomography)
- We have the solutions for many a thing (though scrolls aren't quite solved yet), all we need is the problems
- To find them - step out there, do "other" stuff!
 - Or in my case - speak to the person next to you during a 12h flight!

Closer to home?

SPADs for Direct Dark Matter detection

- Like collider physics, other fields tend to avoid major change (human notion)
- Highest sensitivity experiments are pursuing detector builds based on photomultiplier tubes
 - The devil you know
- These can be made from low radioactivity glass and we know their efficiency
- What if we instead used Single Photon Avalanche Diodes?
 - Based on high purity silicon, inherent low radioactivity
 - Can be produced to be directly sensitive in UV
 - Digital construction would leave m^2 of these being operated through a very low wire count, not 1 per device!
 - Reduced material in insulation, as well as reduced weight leading to lower weight support structure!
- Darkside is following this route with SiPMs
- Silicon detectors (and ASICs) have a lot to give and we must make sure we have the future expertise to develop them

Summary (again)

- Semiconductors have changed the way the world works in the last 50 years
- Particle physics, working on limited resource and requiring extensive validation, is behind the curve in terms of semiconductor use (~20 years)
- That means there's a lot yet to come for us
- Focus on where we need stable deployment vs where major changes can be made?
 - Given the current funding situation in the UK, we need both to support our case

Backup, other stuff

Further reading

<https://arxiv.org/pdf/1509.09052>

<https://indico.cern.ch/event/951972/#1-digital-sipms-for-the-darwin>

A round of [everything semiconductor production](#)