Tracking detectors at the LHC

corrinne mills

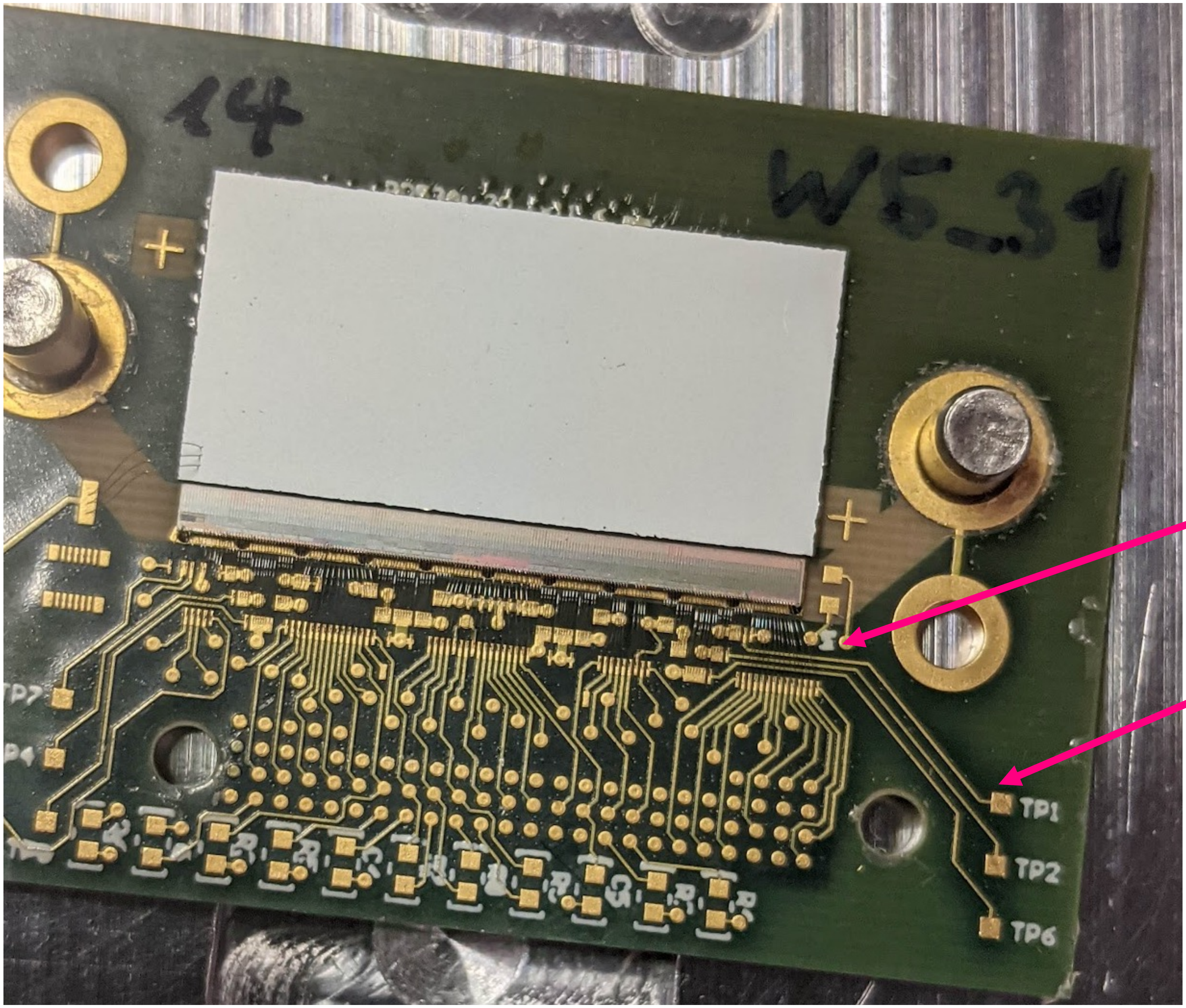
July 2024

Re-introduction

- Pick up where we left off
  - → *Real devices*
  - → *The effects of radiation damage*

- Explore breadth of current and future detectors
  - → *The present: CMS, ATLAS, LHCb*
  - → *The current future*
    - ▪ Pixel and strip detector upgrades
    - ▪ LGAD timing detectors
  - → *The future future*
    - ▪ MAPS and flexible detectors
    - ▪ smartpixels

Up-close view of a test device



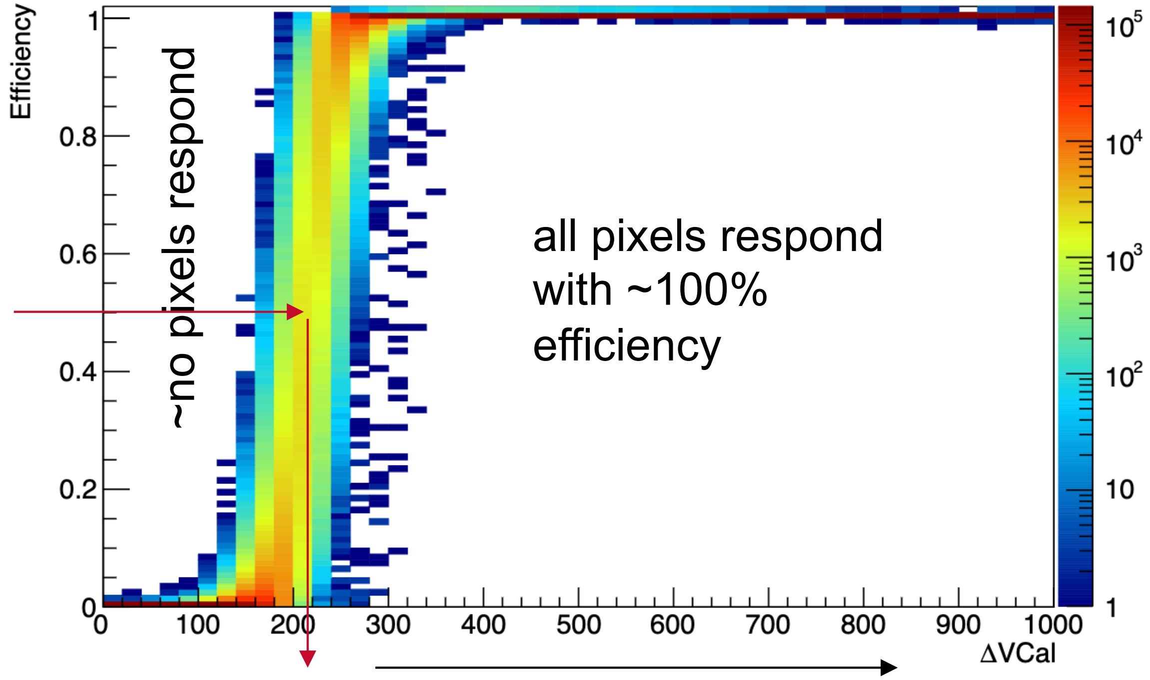
Close-up of a CMS Phase 2 pixel sensor prototype bump-bonded to an RD53A sensor

note the delicate wirebonds

and test points for checking voltages

Low voltage and ASIC tuning

- LV = low voltage, powers the *ASIC* (readout chip)
- ASIC has numerous *registers* that control threshold (global and per-pixel or per-strip), gain (DAC output → electrons map), etc
- Use internal charge injection circuits to calibrate the response
- Example: threshold tuning for a CMS Phase 2 pixel prototype



50% efficiency = threshold

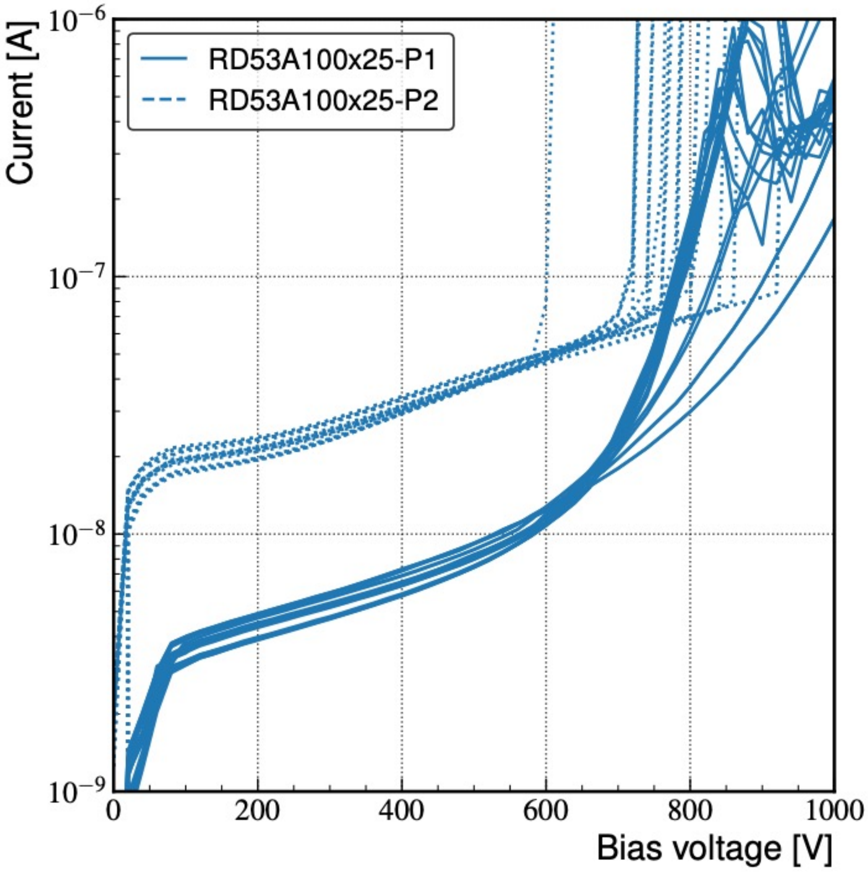
all pixels respond with ~100% efficiency

One entry per pixel per injected charge point

scan **injected charge** (ΔVCal maps to electrons)

High voltage and I-V curves

- HV = high voltage, depletes the *sensor*
  - → *Planar devices: up to 120V unirradiated, up to 800V irradiated*
  - → *3d devices: up to 30-40V unirradiated, up to ~120V irradiated*
- Current is called a "leakage current'
  - → *range nA (unirradiated planar sensor) to 10s of μA (irradiated sensors)*
- Leakage currents are strongly temperature dependent
  - → *A good way to test the HV connection is to see if the leakage current changes with the temperature.*



unirradiated CMS prototype planar pixel sensor (temp unknown) from NIM A1053 (2023) 168326

"NIEL hypothesis" of lattice damage

- Silicon detectors still susceptible to radiation damage
- Primary effect in sensors from *damage to the silicon crystal lattice*
- *Studied by hadron (usually p) bombardment of devices as a function of flux* Φ
- *Scale to units of* ***95 MeV neutron equivalent per cm²***

→ *Abbreviated to* n_{eq}/cm^2

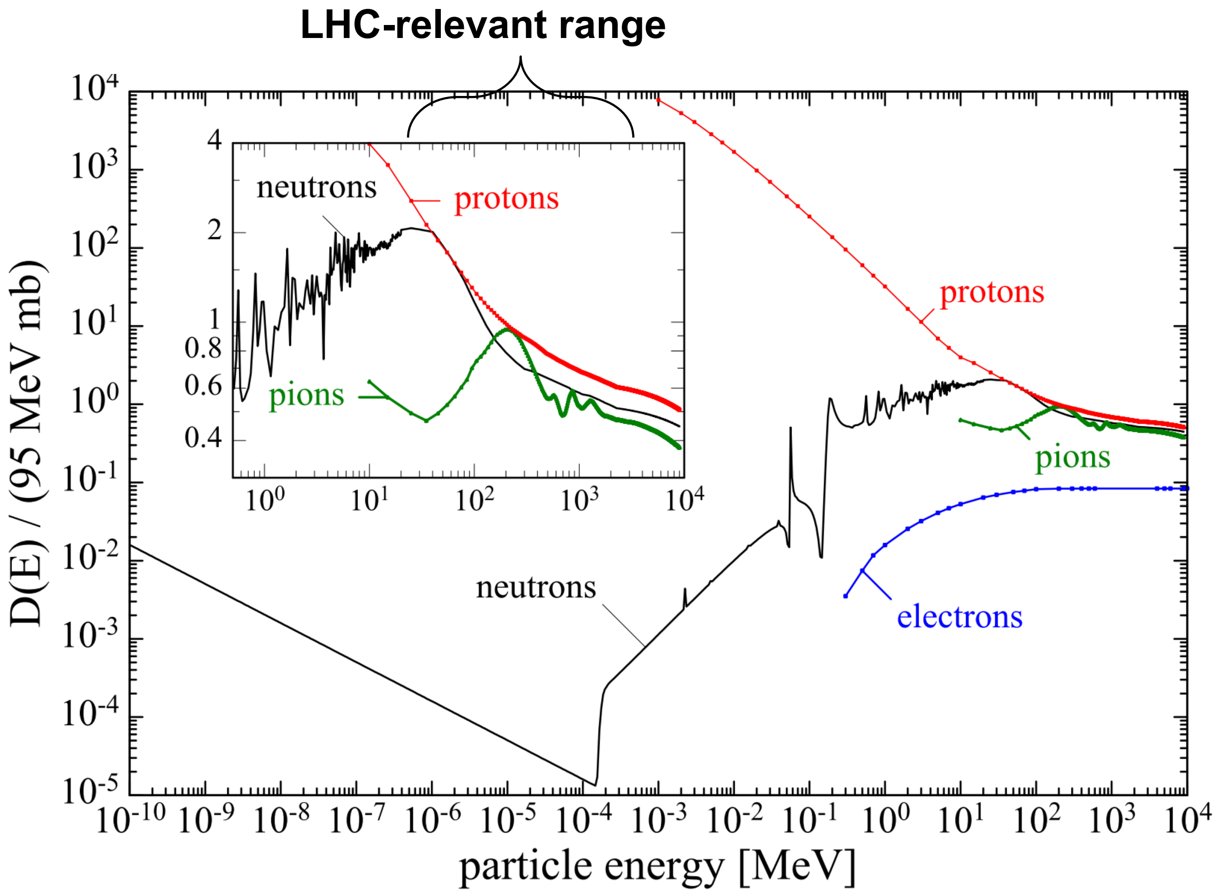
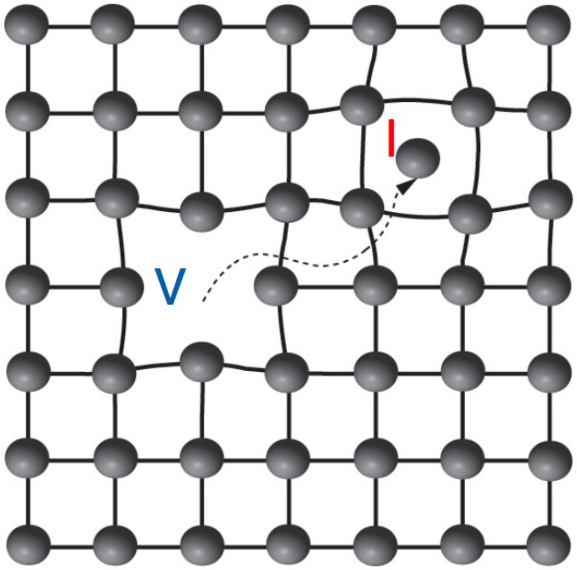


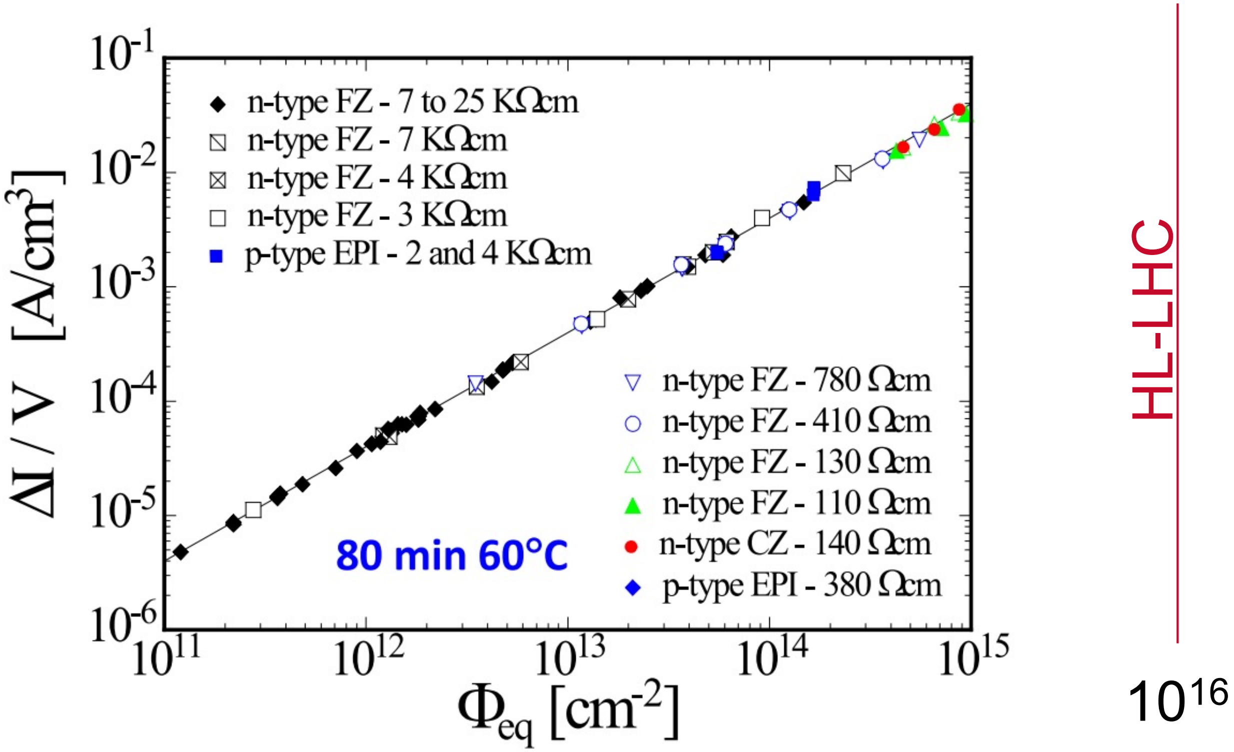
Fig. 3. NIEL cross sections normalized to 95 MeV mb. Data collected by A. Vasilescu and G. Lindstroem [22] based on [23]–[26] and private communications.

This and graphs on the following slides from Moll review on radiation damage, IEEE TNS (2018)

Leakage current increases

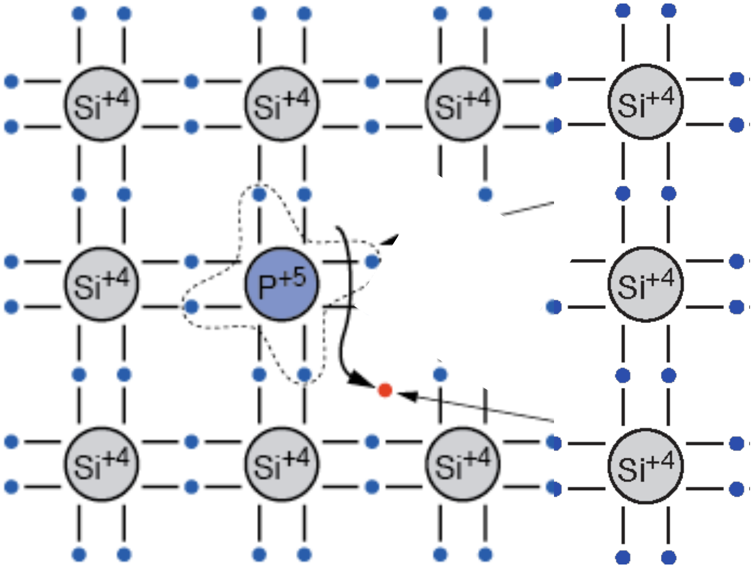
- Damage to crystal lattice complicates the band structure with intermediate states
  - → *Trapping centers reduce charge collection efficiency*
  - → *Generation centers increase leakage current (proportional to fluence)*

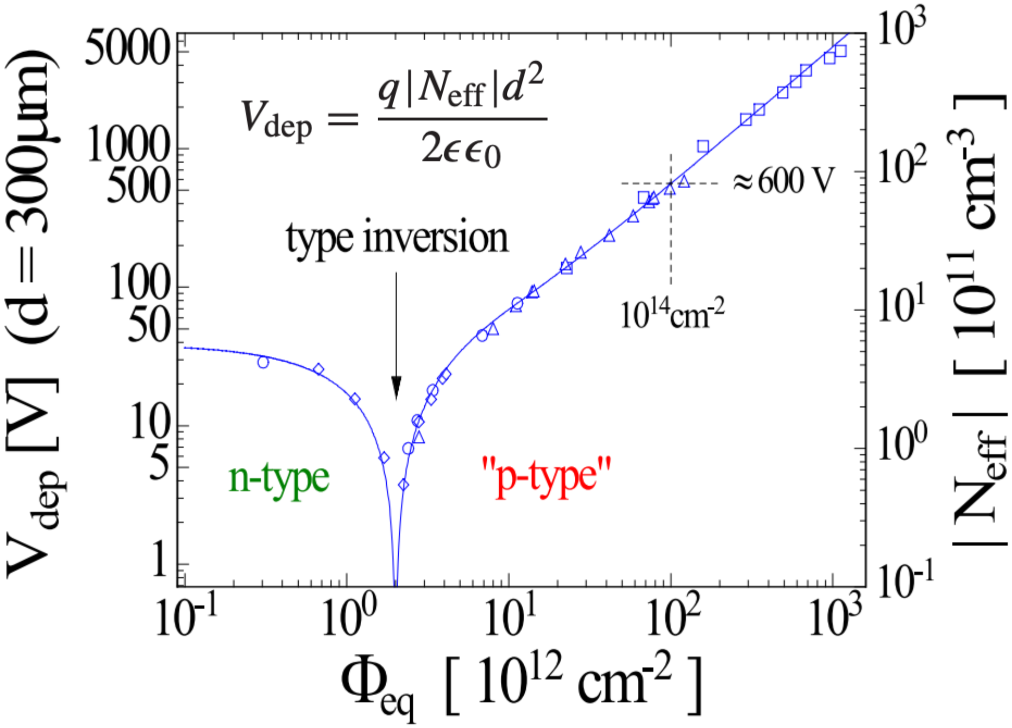




Depletion requires more voltage

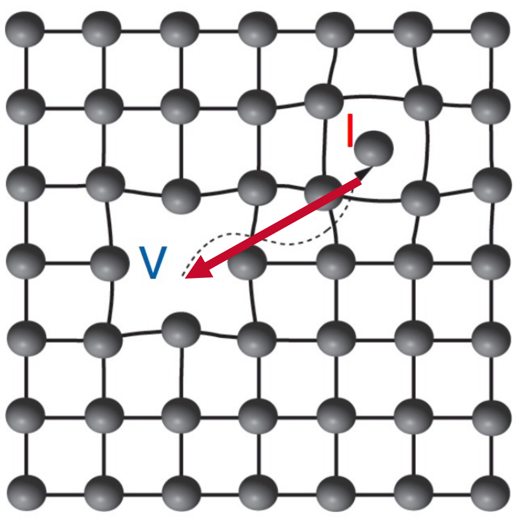
- Lattice structure damage also changes effective doping concentration
  - → *Example: Vacancy + phosphorous removes the donor property of P*
  - → *Many competing effects*
  - → *Space charge sign inversion, sometimes referred to as "type inversion"*
- Primary effect is on depletion voltage → much more required to operate sensor at full efficiency

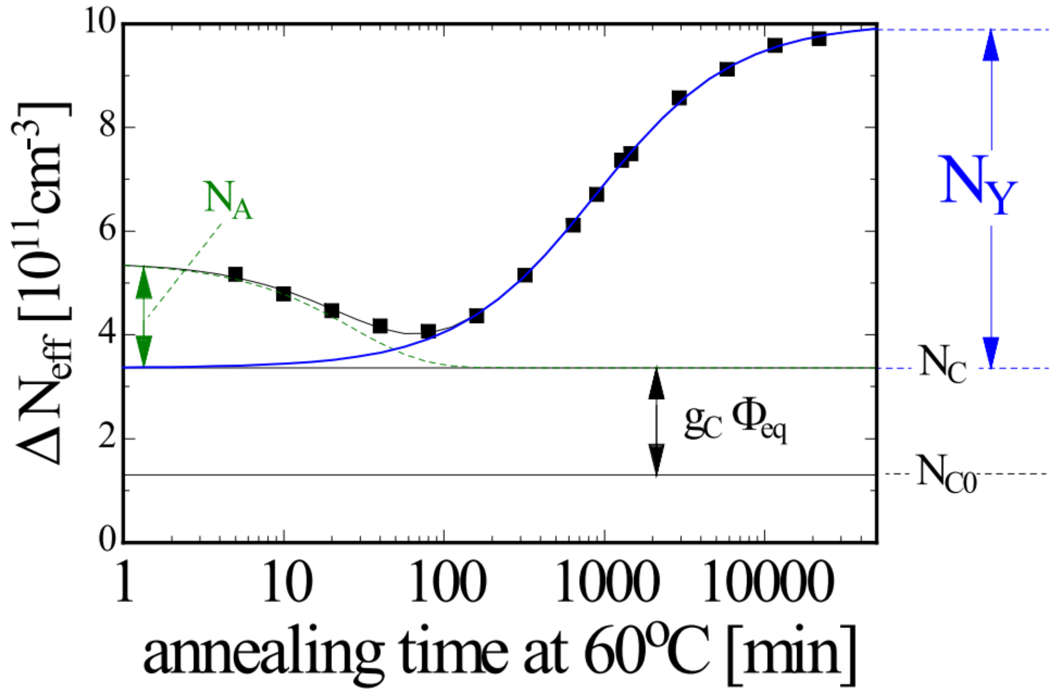




Annealing helps (and then hurts)

- Annealing also changes the effective doping concentration (N_{eff})
- Competing effects with different time constants
  - → *"Beneficial" annealing: recombination of vacancy and interstitial (τ ~ hours)*
  - → *"Reverse" annealing: more complex defects can combine (τ ~ days)*
    - V+V → double vacancy (charge trapping), vacancy + impurity
- Thermal process: vacancies and interstitials are *mobile*
  - → *Reason to keep silicon detectors **cold** (-20C -> -35C)*



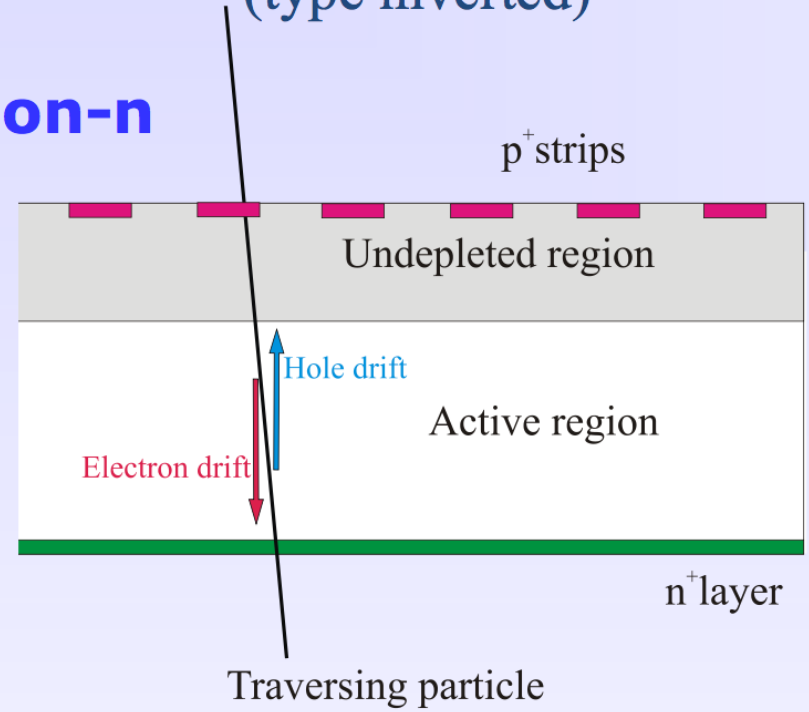


Sensor doping and radiation

n-type silicon after high fluences:

(type inverted)

p^+on-n



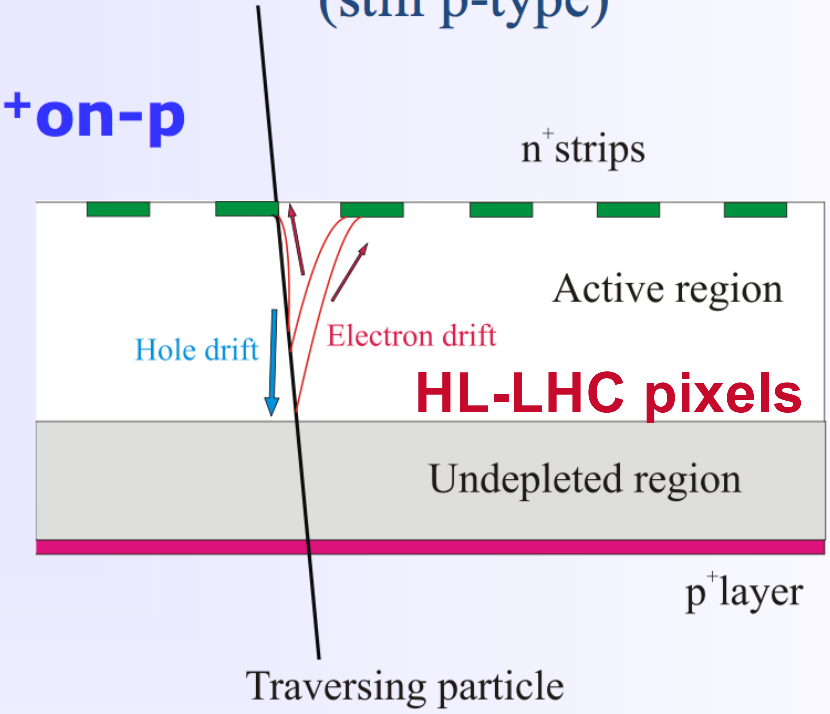
p-on-n silicon, under-depleted:

- **Charge spread – degraded resolution**
- **Charge loss – reduced CCE**

p-type silicon after high fluences:

(still p-type)

n^+on-p



HL-LHC pixels

n-on-p silicon, under-depleted:

- **Limited loss in CCE**
- **Less degradation with under-depletion**
- **Collect electrons (3 x faster than holes)**

Comments:

- Instead of n-on-p also n-on-n devices could be used

Michael Moll

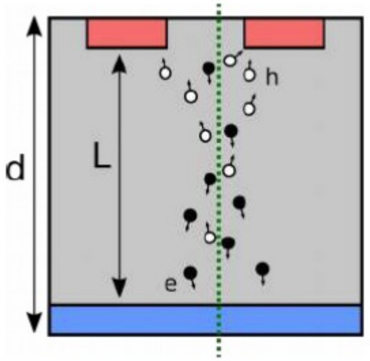
***as they are in current CMS pixels**

Rad-hard design: planar and 3D

- Change to n-in-p (previous slide)
- Reduce the drift length through the sensor geometry to mitigate radiation damage
  - → *Thinner planar sensors (CMS Phase 2 is 150 μm)*
  - → *Change the drift path from **transverse** to **parallel** to sensor surface*
    - Maintain signal amplitude, which is proportional to sensor depth

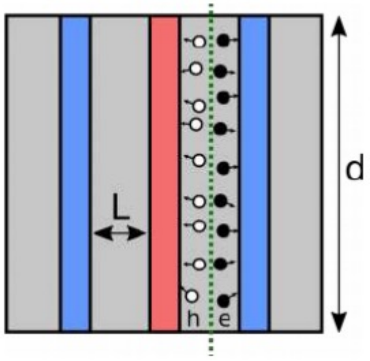
thin-planar sensor

- drift length L<200µm (now: 300µm)
- n-in-p (e signal)
- **outer** and **possibly also innermost layers/rings**



3D sensor

- shorter drift length L
- lower depletion voltage
- technically more challenging
- **inner layer (at most one)**



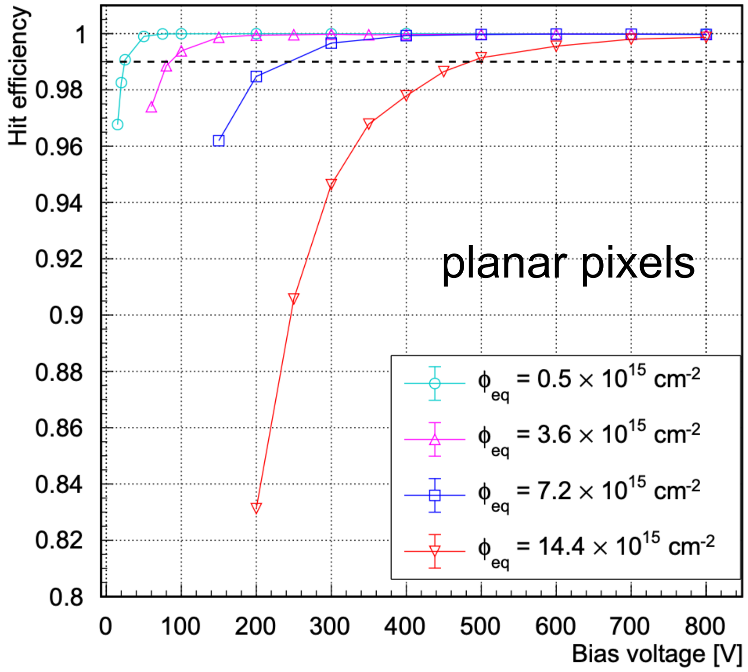
Key metric: Efficiency

$$\text{Efficiency} = \frac{N(\text{tracks with matched clusters})}{N(\text{tracks})}$$

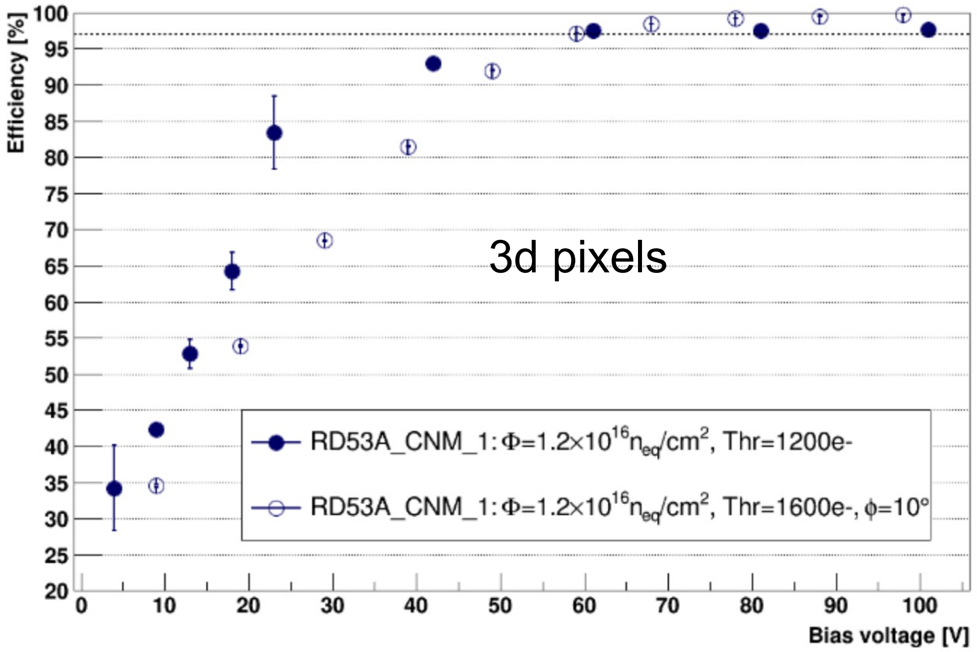
- Answers the question: if there should be a hit there, is there one?
- Should be > 99% for unirradiated devices
- Increases with bias voltage

→ *unirradiated planar devices can be nearly fully efficient at 0V*

examples from Phase 2 pixels



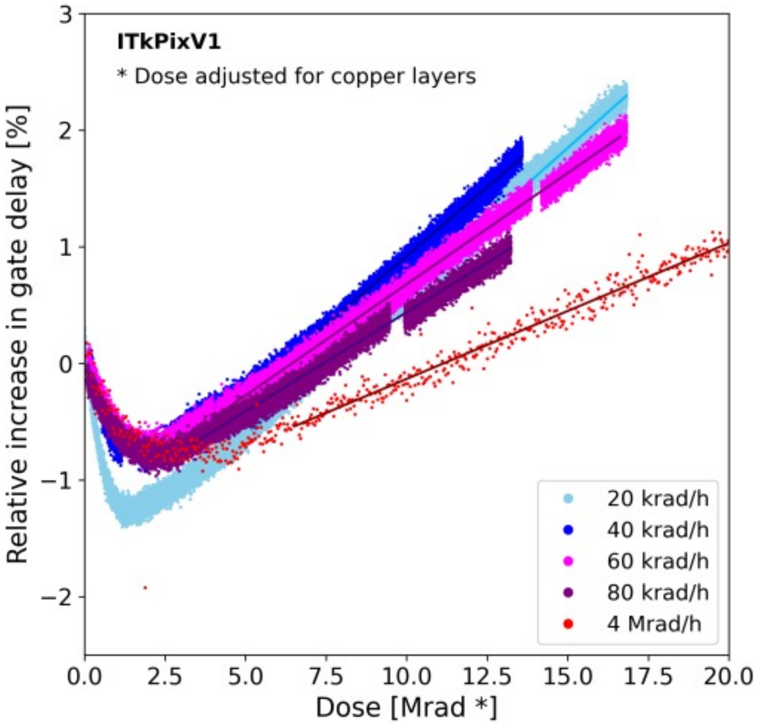
NIM A1053 (2023) 168326



publication forthcoming

Radiation and electronics

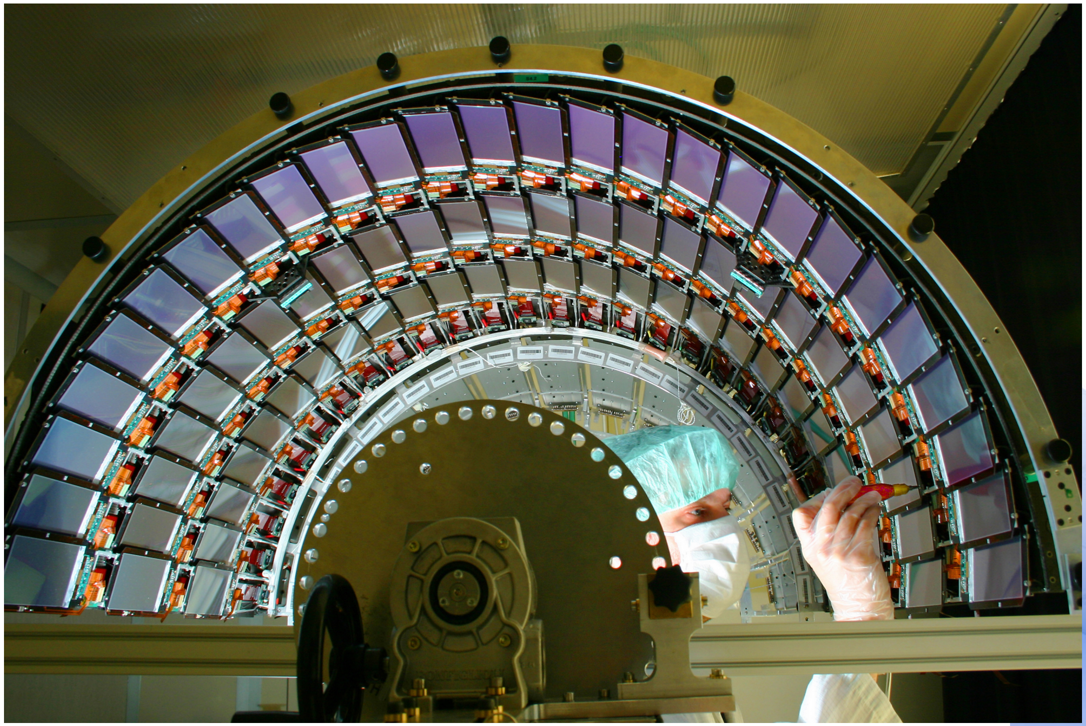
- Electronics are also sensitive to radiation, but differently so
  - → *EM damage = the “dose”, vs. fluence for the sensors*
  - → *Typically tested through exposure to x-ray and gamma photons*
- Single-event upset (SEU) – flipped bit
  - → *Guard against through “triple modular redundancy” for important registers: majority vote of three replicas*



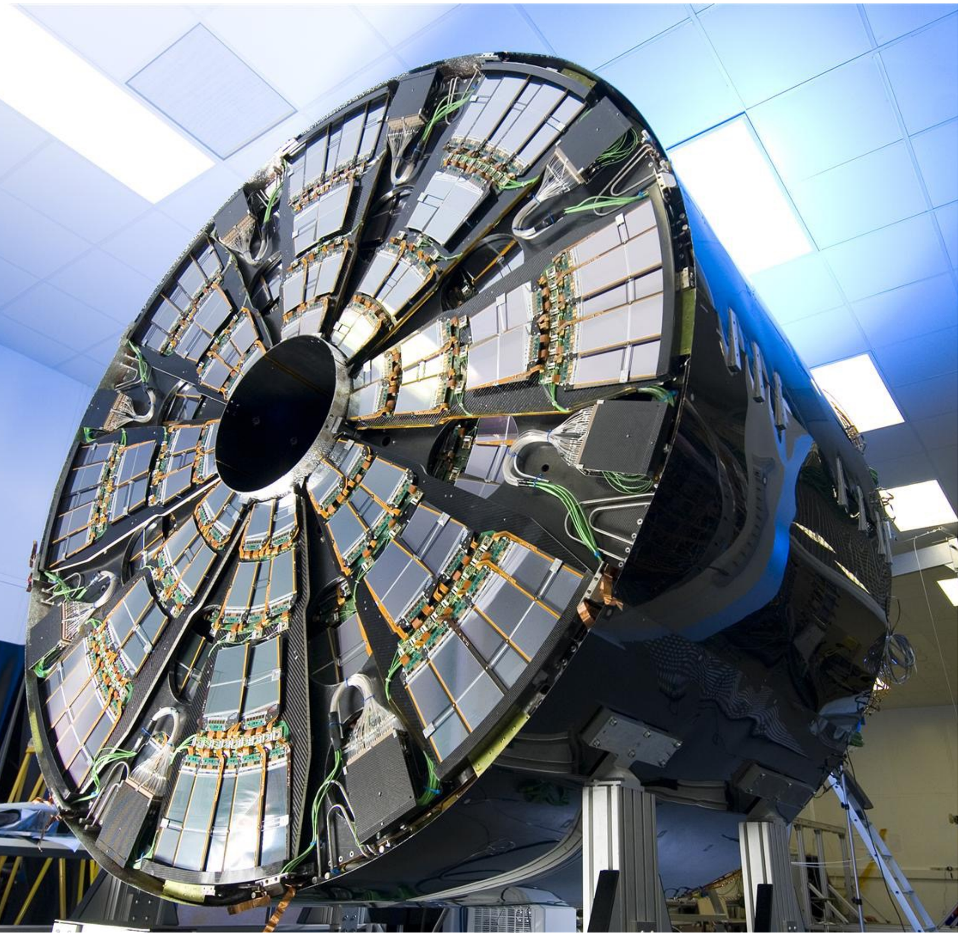
- Damage to transistors – affects switching time
  - → *shrink transistor size (130 nm → 65 nm)*
- Dose rate dependence is a standing concern

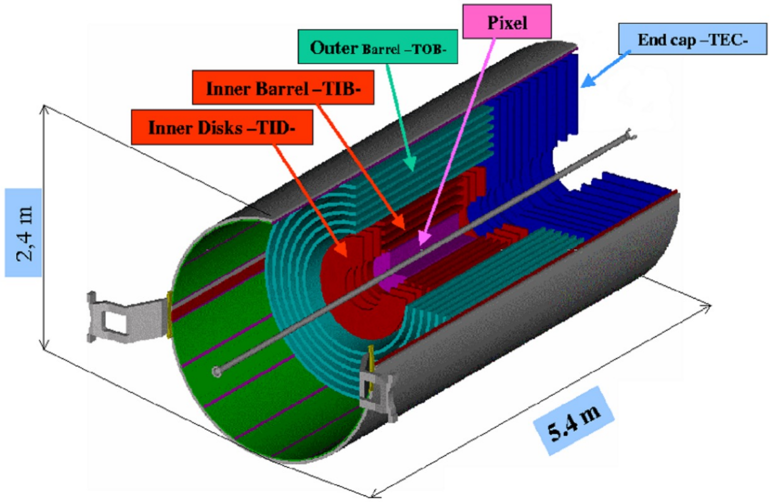
ATLAS pixel chip in X-ray irradiations
[arXiv:2404.10963 [physics.ins-det]](https://arxiv.org/abs/2404.10963)

CMS Outer tracker: Si strips



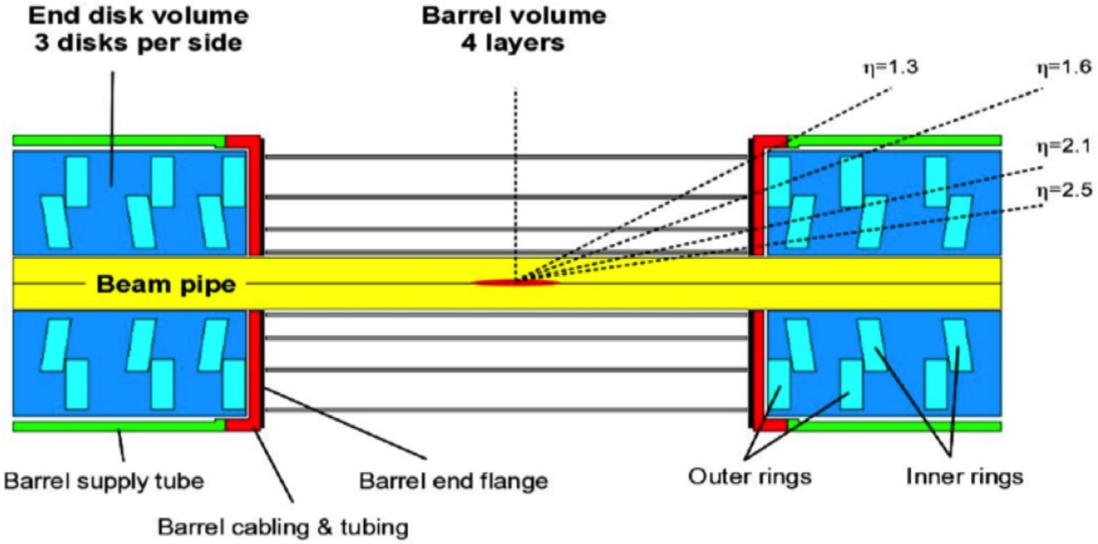
- First hadron collider detector to use all-silicon tracking – unprecedented scale



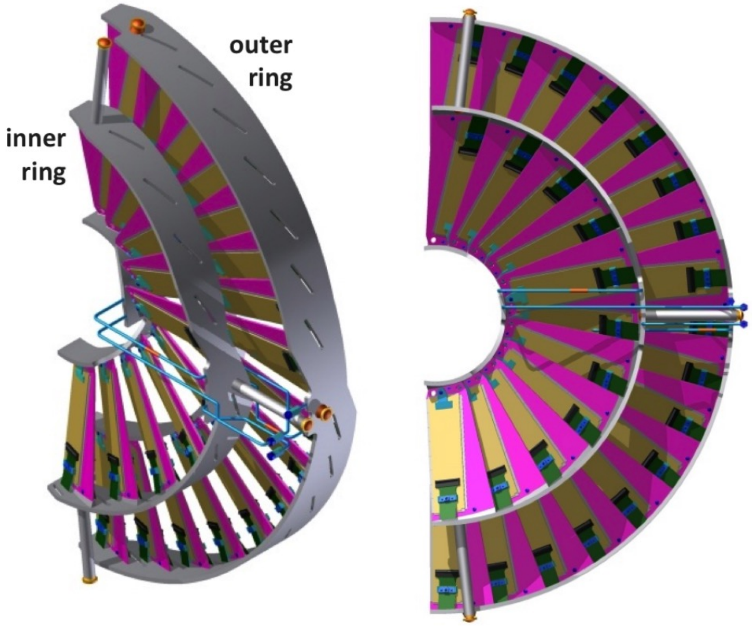


CMS inner tracker: Si pixels

- “Phase 1” pixel detector installed early 2017
  - → *Challenges, but handles the current data rates, + improved performance*

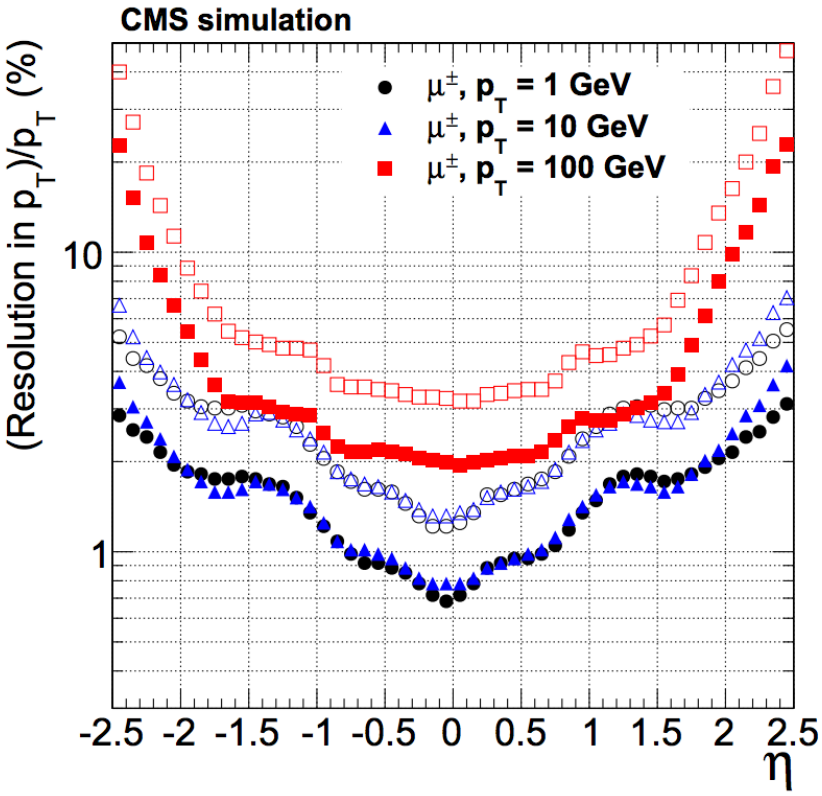


forward pixel “fans”, built at Fermilab

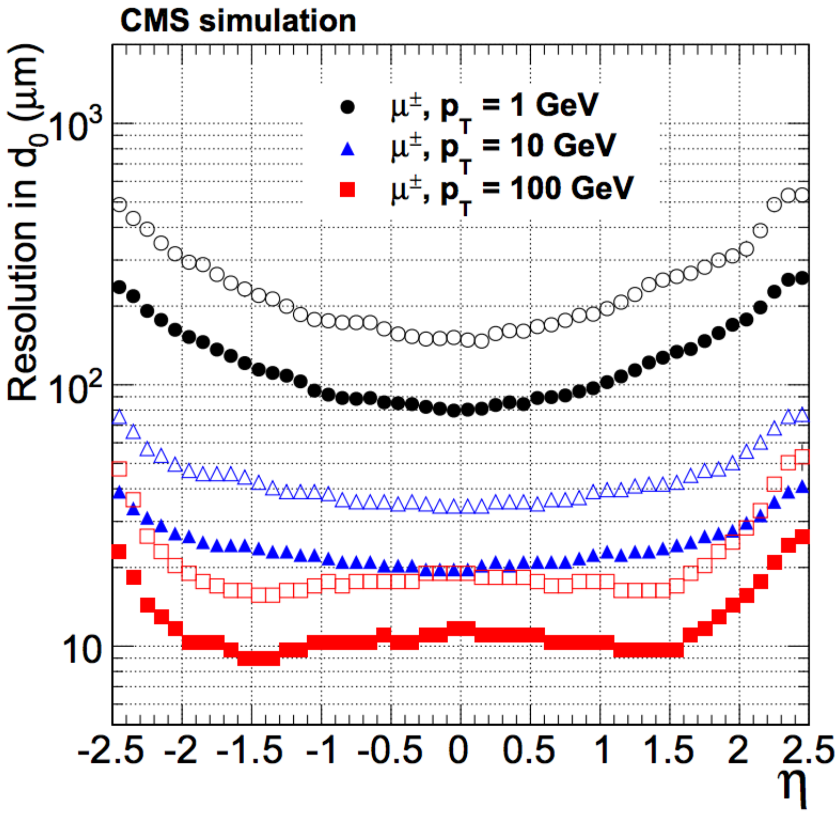


Angle detector modules to optimize charge sharing for improved position measurements (nonzero incidence; Lorentz angle)

Tracking performance at CMS



Harder to measure curvature of straighter (higher-momentum) tracks

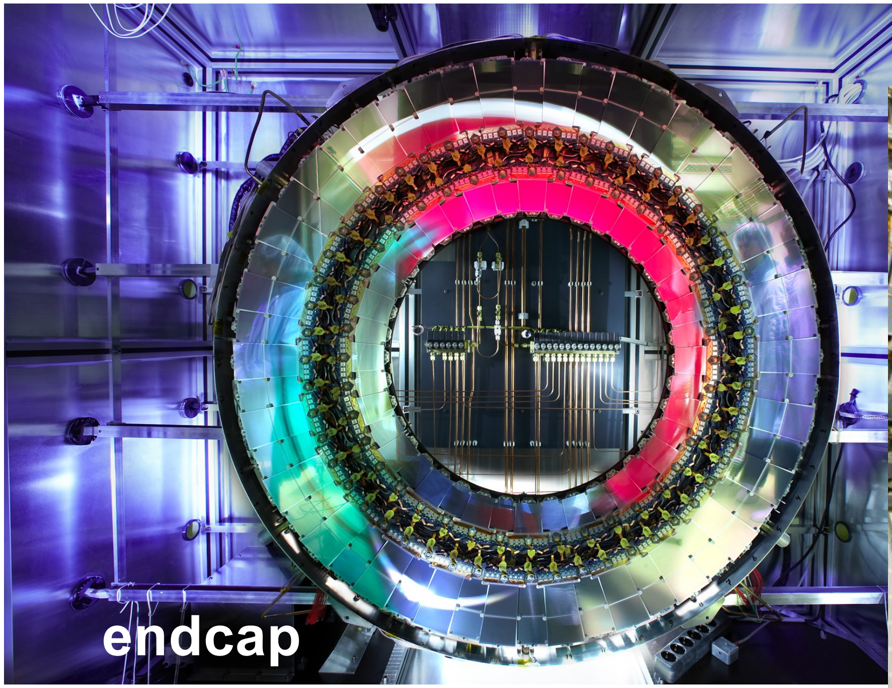


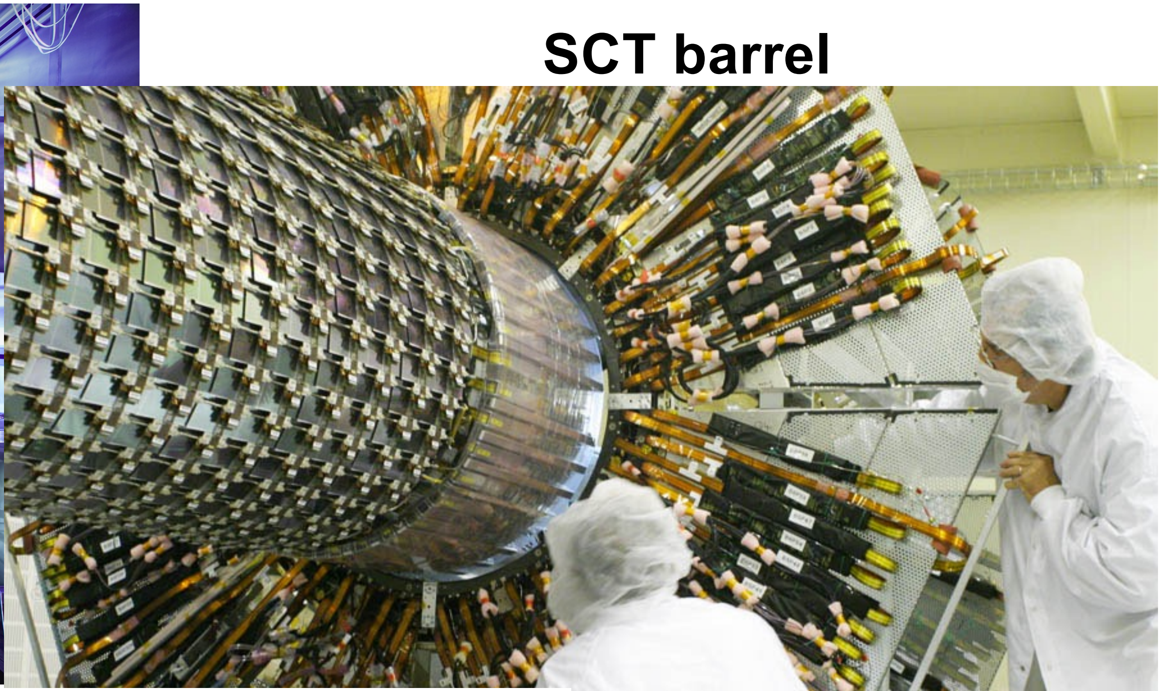
Harder to extrapolate lower-momentum tracks: scattering in material matters

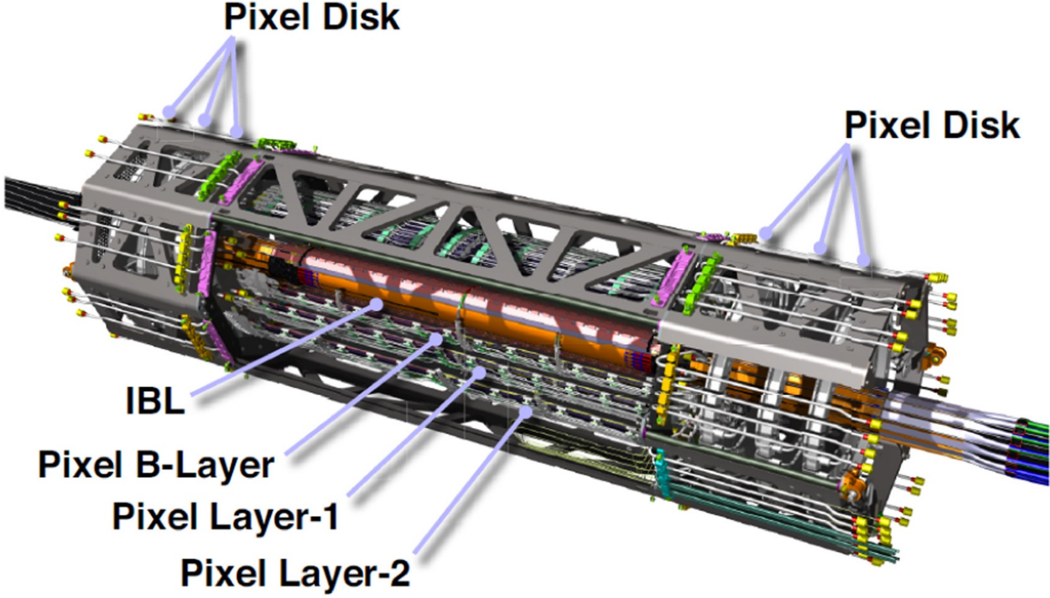
$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 \propto \underbrace{\boxed{c_1 \cdot \left(\frac{p_T}{BL^2}\sqrt{\frac{720}{N+4}}\right)^2}}_{\text{curvature}} + \underbrace{\boxed{c_2 \cdot \left(\frac{1}{B\sqrt{LX_0}}\right)^2}}_{\text{multiple scattering}}$$

For CMS:
magnetic field **B** = 3.8 T
tracker radius **L** = 1.2 m
number of measurements **N** >10

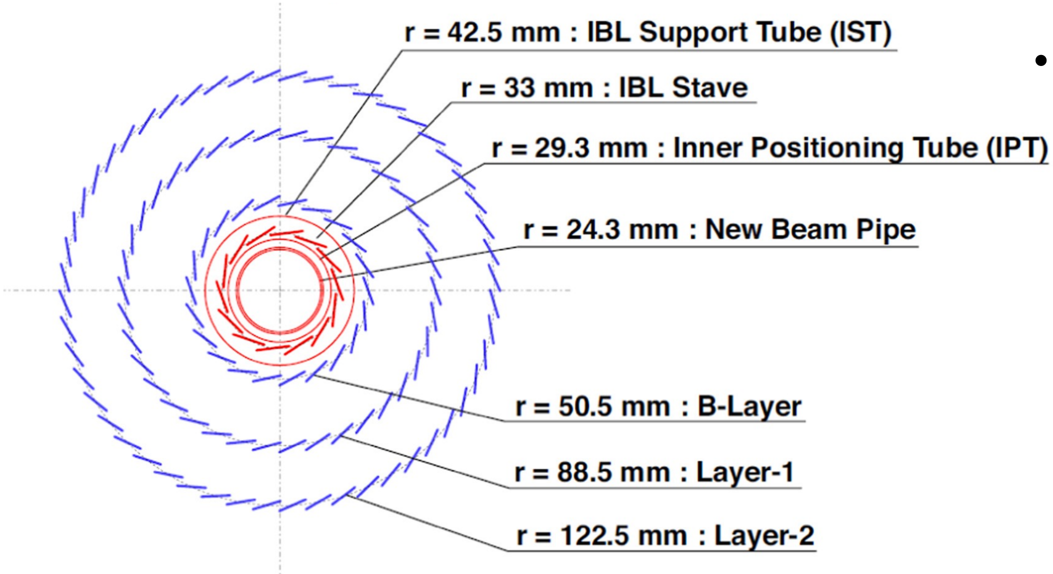
Silicon detectors: ATLAS







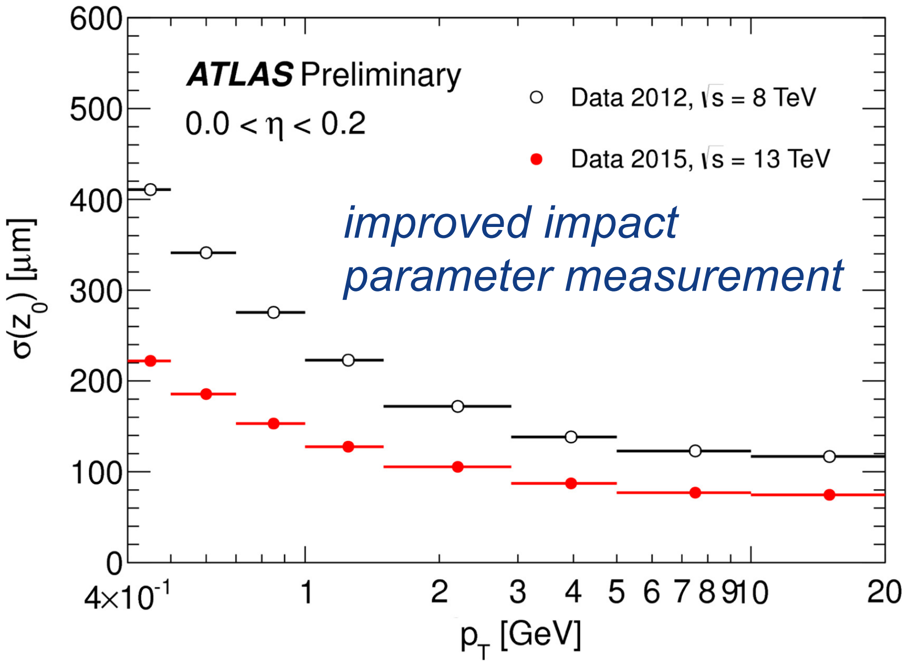
ATLAS: the IBL



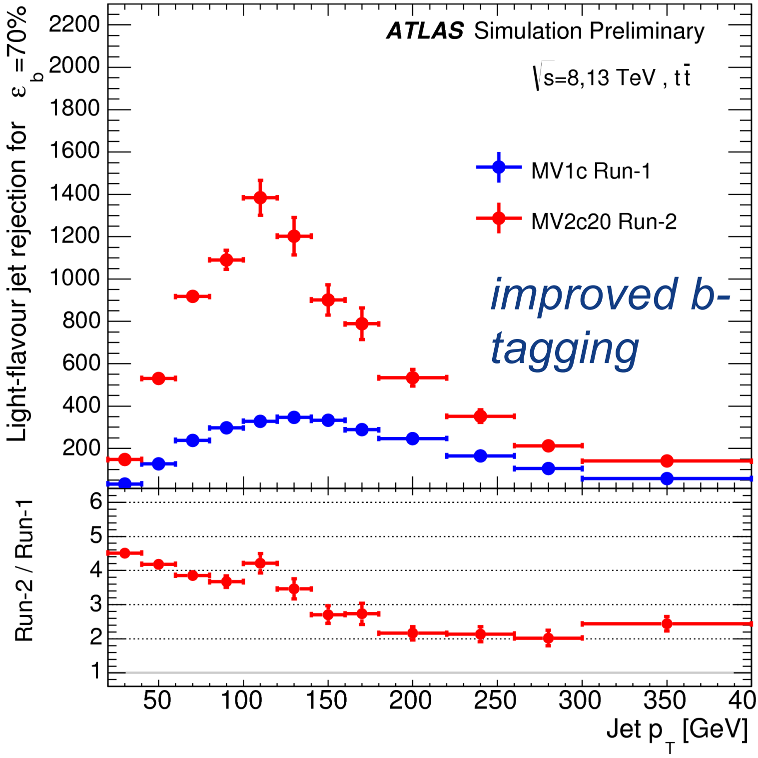
- “Insertable Barrel Layer” placed between previous innermost layer and beampipe in summer 2014

→ *Reduced pixel size in Z 400 → 250 μm*

→ *First use of 3d pixels in a collider experiment*



improved impact parameter measurement

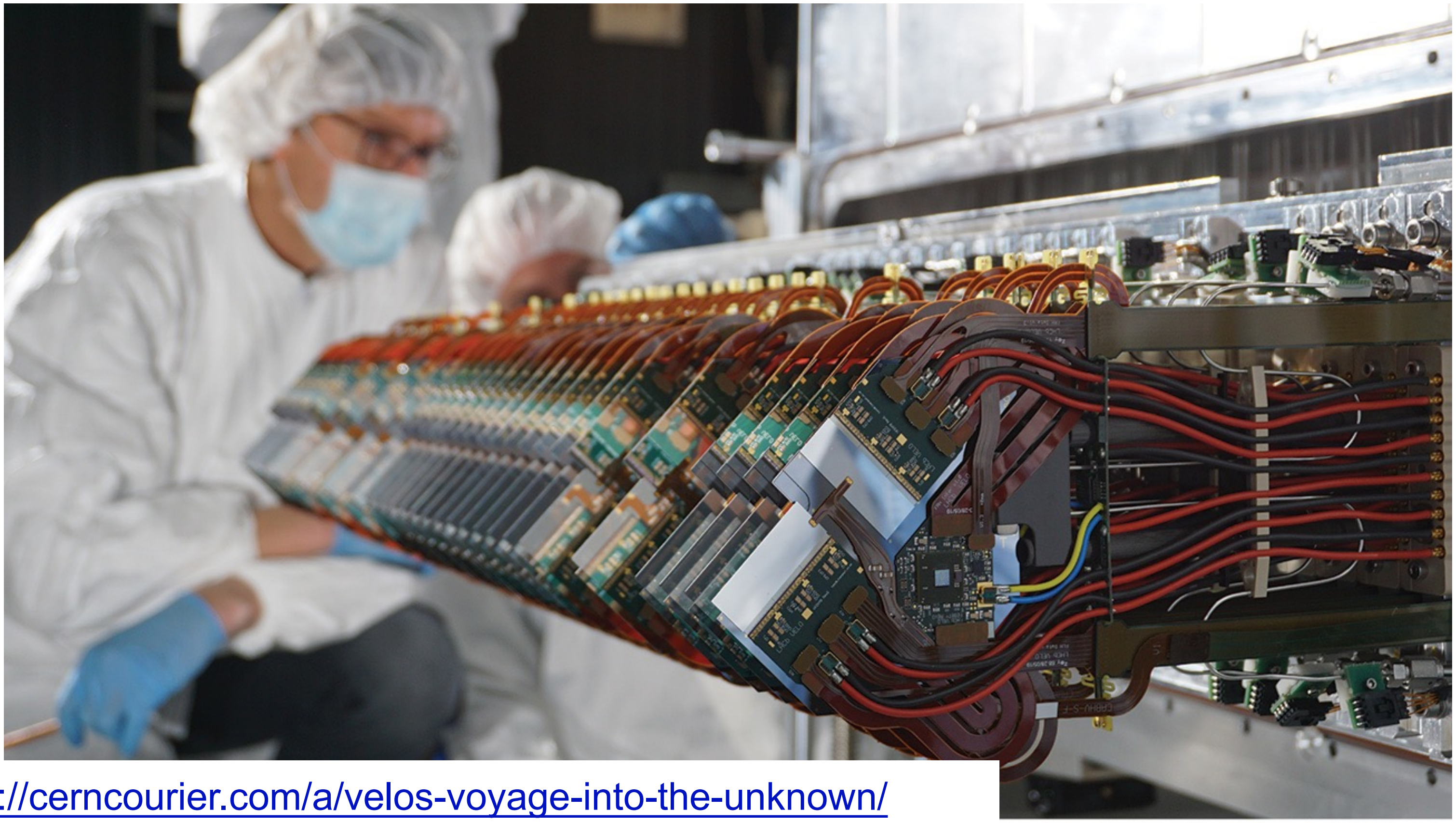


improved b-tagging

ATL-PHYS-PUB-2015-022

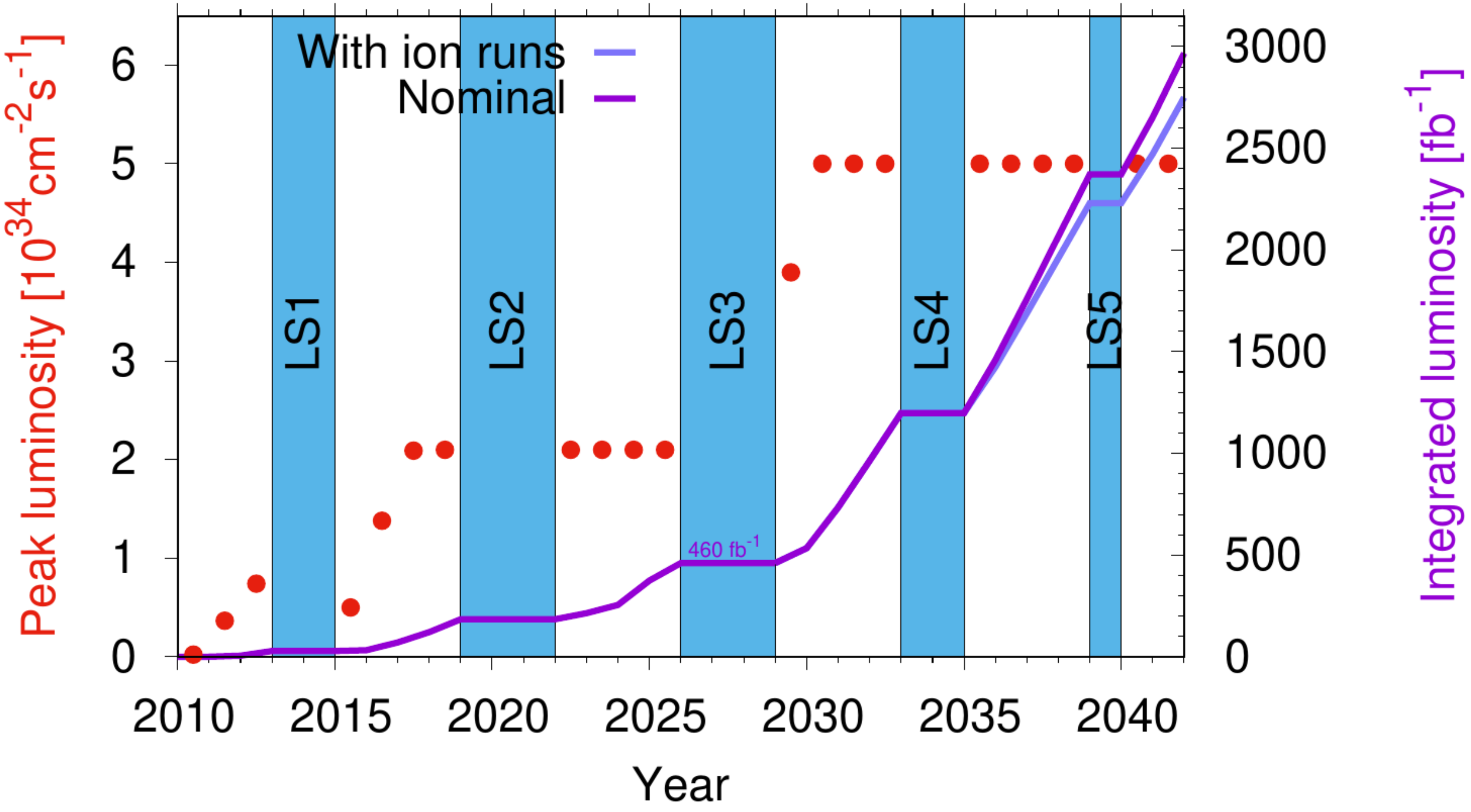
Silicon detectors: LHCb "VELO"

- Upgraded microstrip → pixel detector for vertexing in LS2
  - → *p-in-n sensors, 55 x 55 μm^2 pitch*
- Retractable, moved into place for stable beams, encircling the interaction point 5 mm from beam
- micro-channel CO_2 cooling etched into wafers



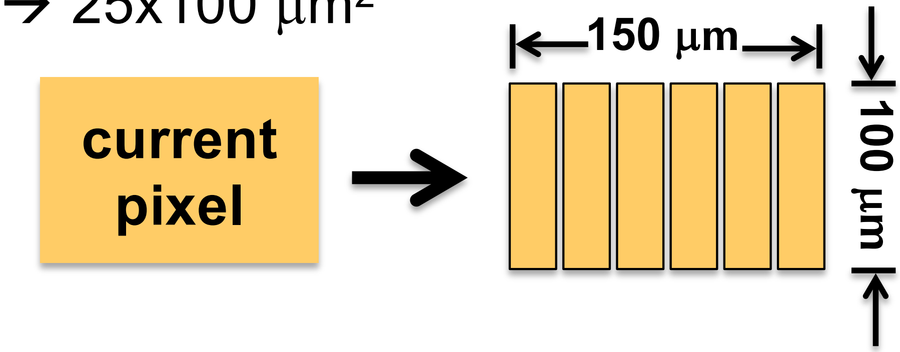
https://cerncourier.com/a/velos-voyage-into-the-unknown/

HL-LHC and beyond

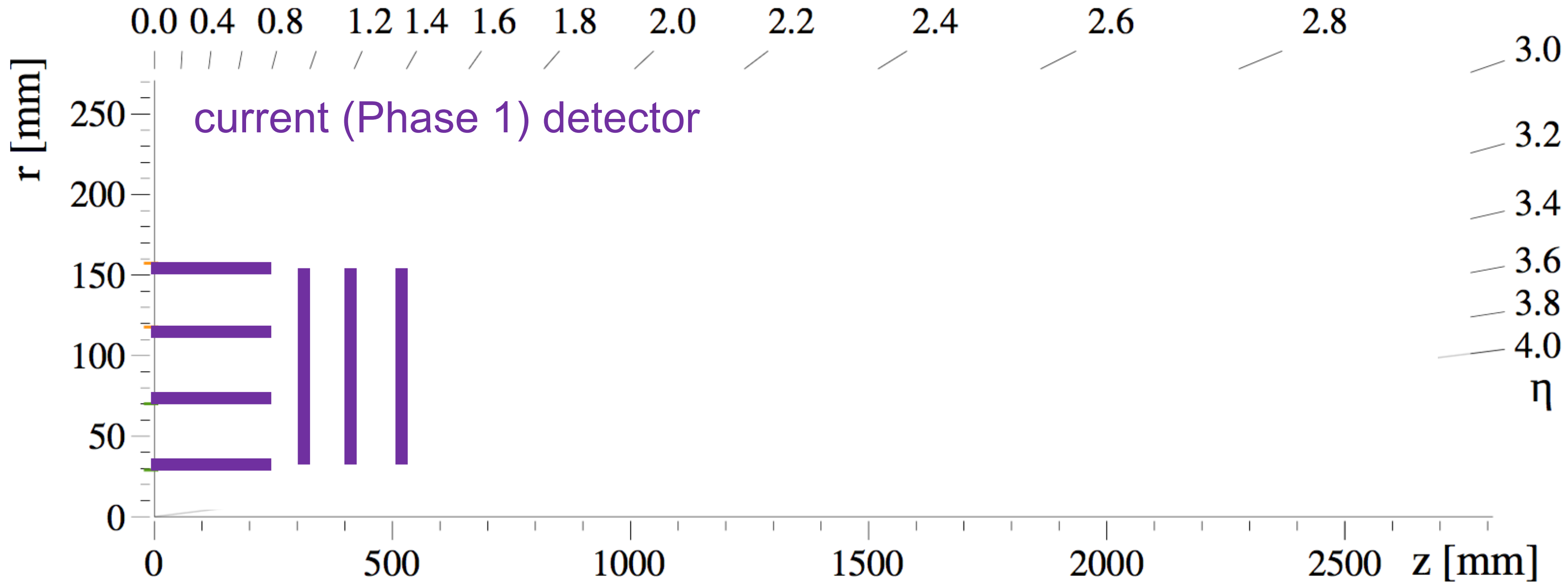


CMS Pixels for the HL-LHC

- Thinner sensors: 300 → 150 μm
- Shrink the pixels 100 x 150 μm^2 → 25x100 μm^2
- and build a bigger detector
  - → *3 → 12 pixel disks on each side*
  - → *Coverage $|\eta| < 2.4$ → $|\eta| < 4.0$*

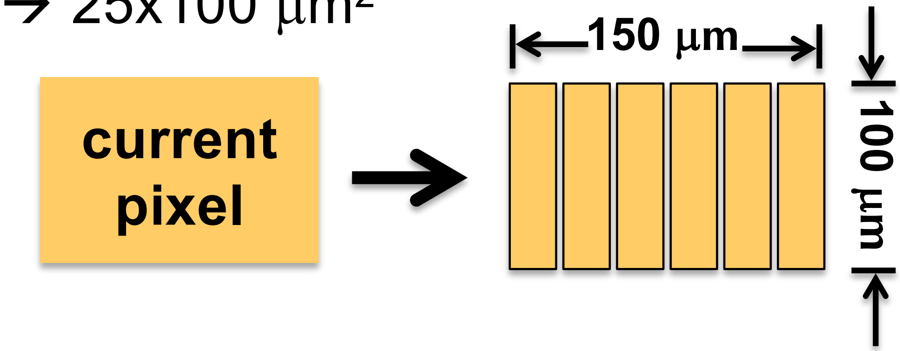


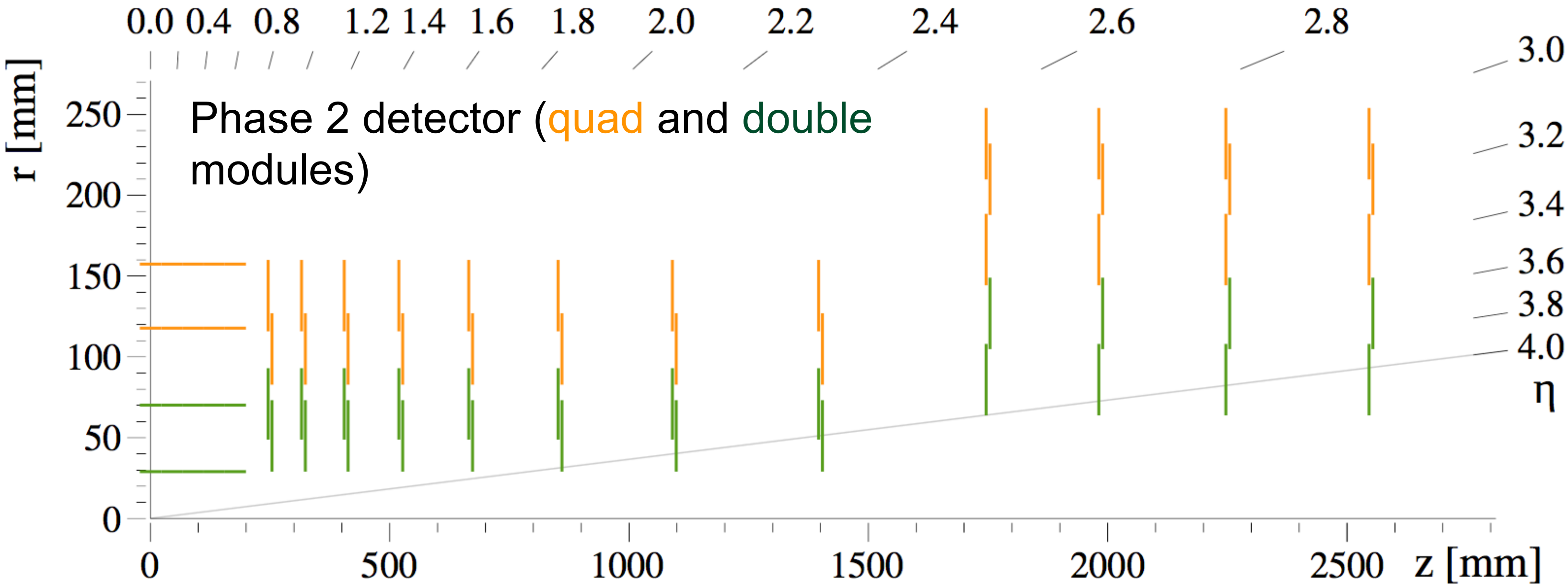
current pixel



CMS Pixels for the HL-LHC

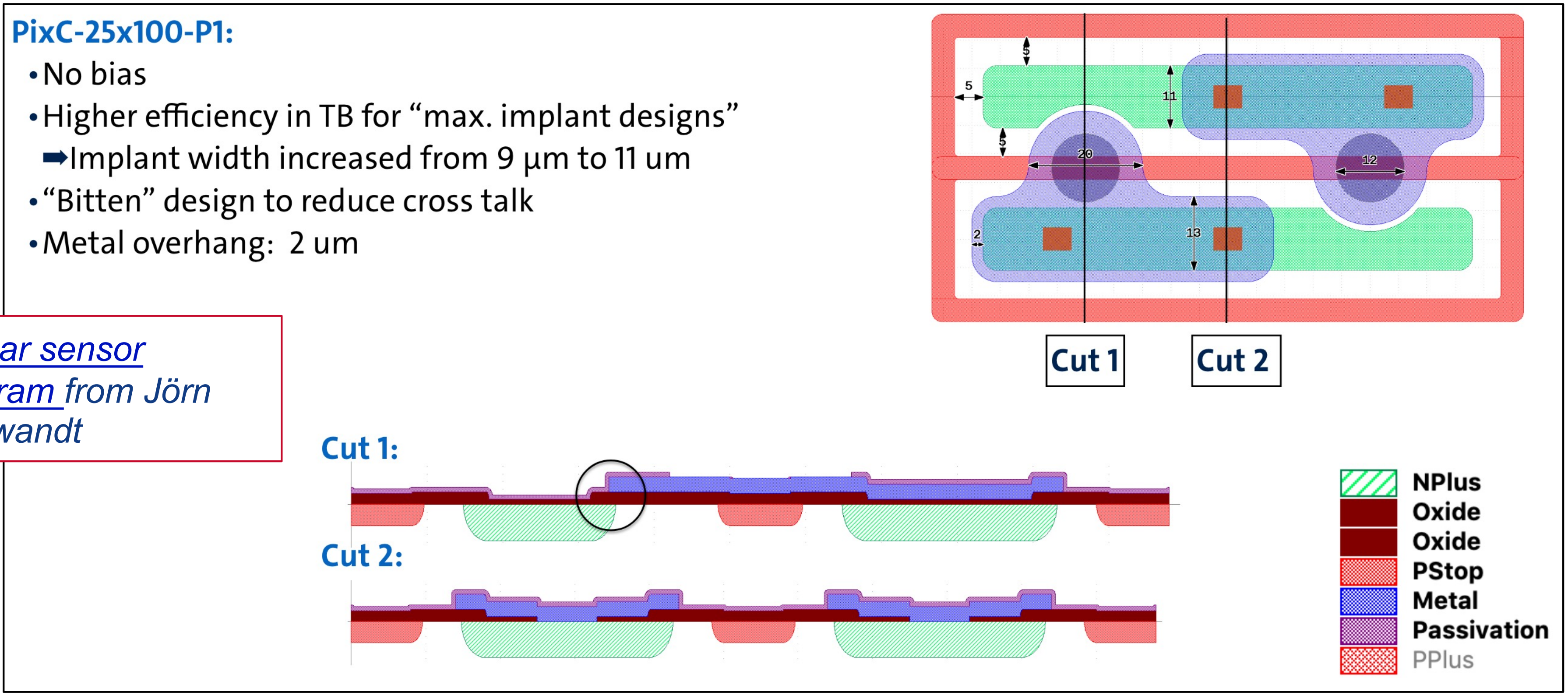
- Thinner sensors: 300 → 150 μm
- Shrink the pixels 100 x 150 μm^2 → 25x100 μm^2
- and build a bigger detector
  - → *3 → 12 pixel disks on each side*
  - → *Coverage $|\eta| < 2.4$ → $|\eta| < 4.0$*




Phase 2 detector (quad and double modules)

The CMS Phase 2 sensors

- The short direction measures the global phi coordinate, and the long direction measures z (R) in the barrel (endcap).
- Reasons: marginally better impact parameter measurement (compared to 50x50 μm^2) and smaller cluster size at the edges of the barrel (data rate considerations)



PixC-25x100-P1:

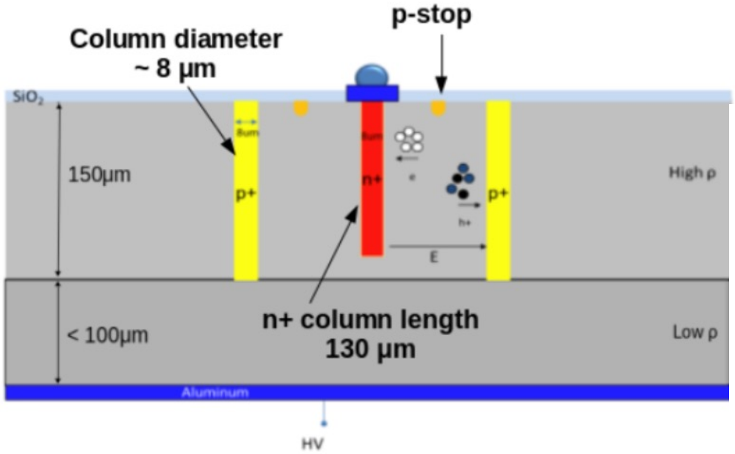
- No bias
- Higher efficiency in TB for "max. implant designs"
  - ➡Implant width increased from 9 µm to 11 um
- "Bitten" design to reduce cross talk
- Metal overhang: 2 um

Planar sensor diagram from Jörn Schwandt

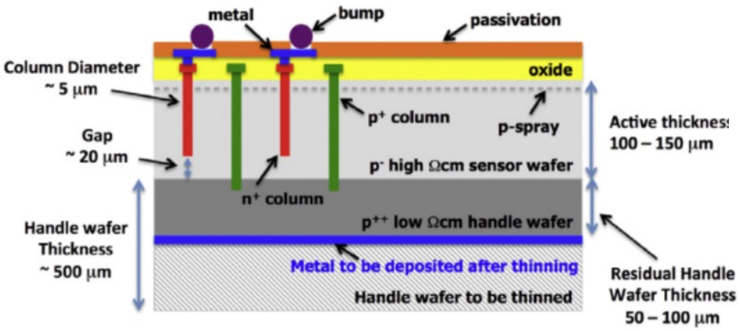
3d pixel sensors for CMS

- 3D is chosen for the innermost barrel layer for radiation hardness and critically *smaller power dissipation*

→ *Leakage currents grow with irradiation, and cooling capacity is finite*



(a)



(b)

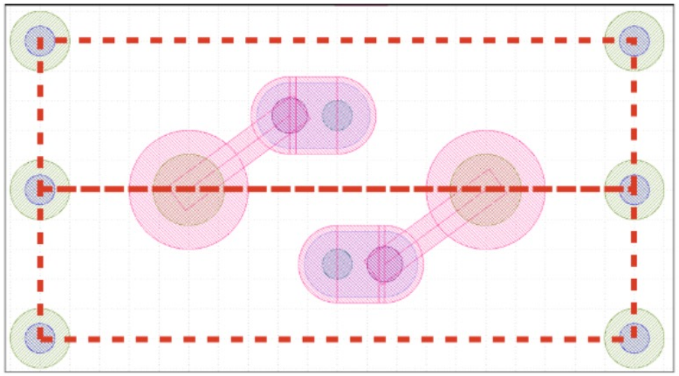


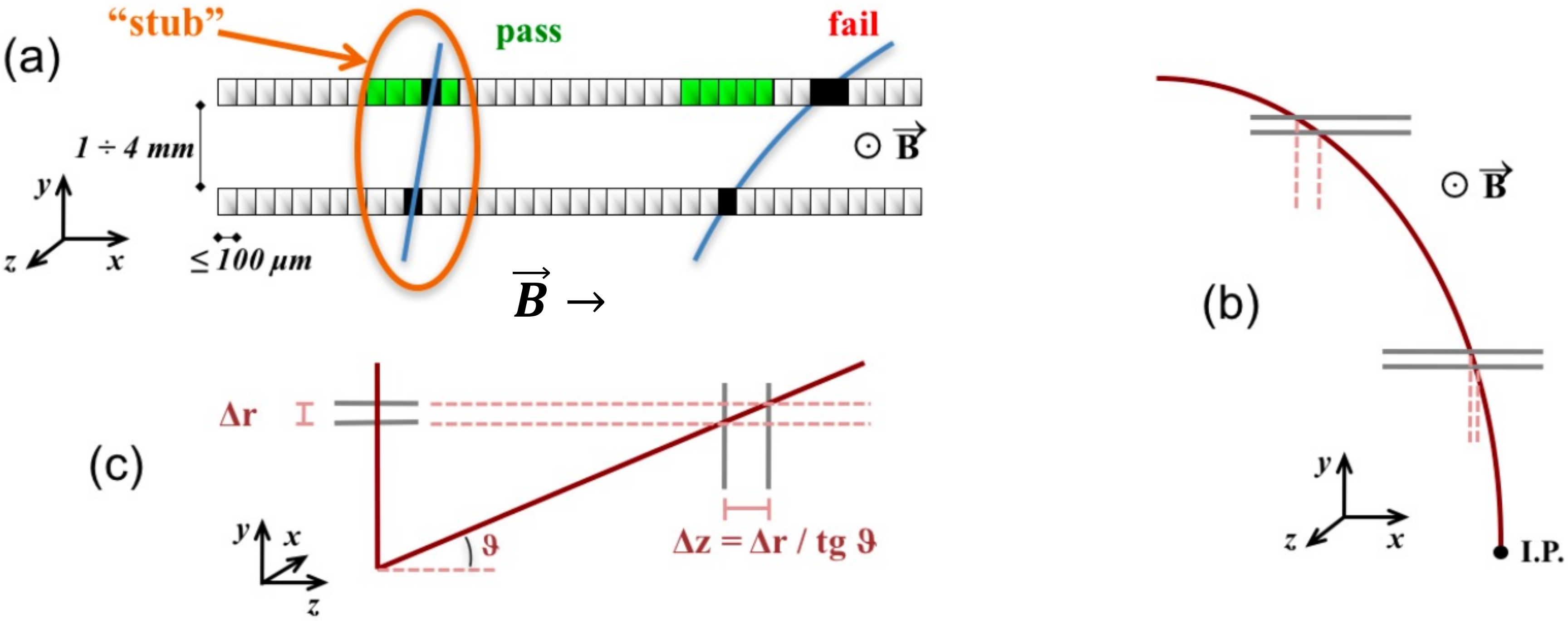
Figure 5: Schematic view of two adjacent pixel cells, together with the routing from the bump pads, between cells, to the junction columns, near the center of the pixel cells.

publication forthcoming

Outer tracker → L1 track trigger

- Use the bending of tracks in the magnetic field to distinguish between low- and high-p_T tracks
- Closely-spaced sensors allow correlation of hits between layers

→ *Design overall tracker geometry to account for track intersection with layers*



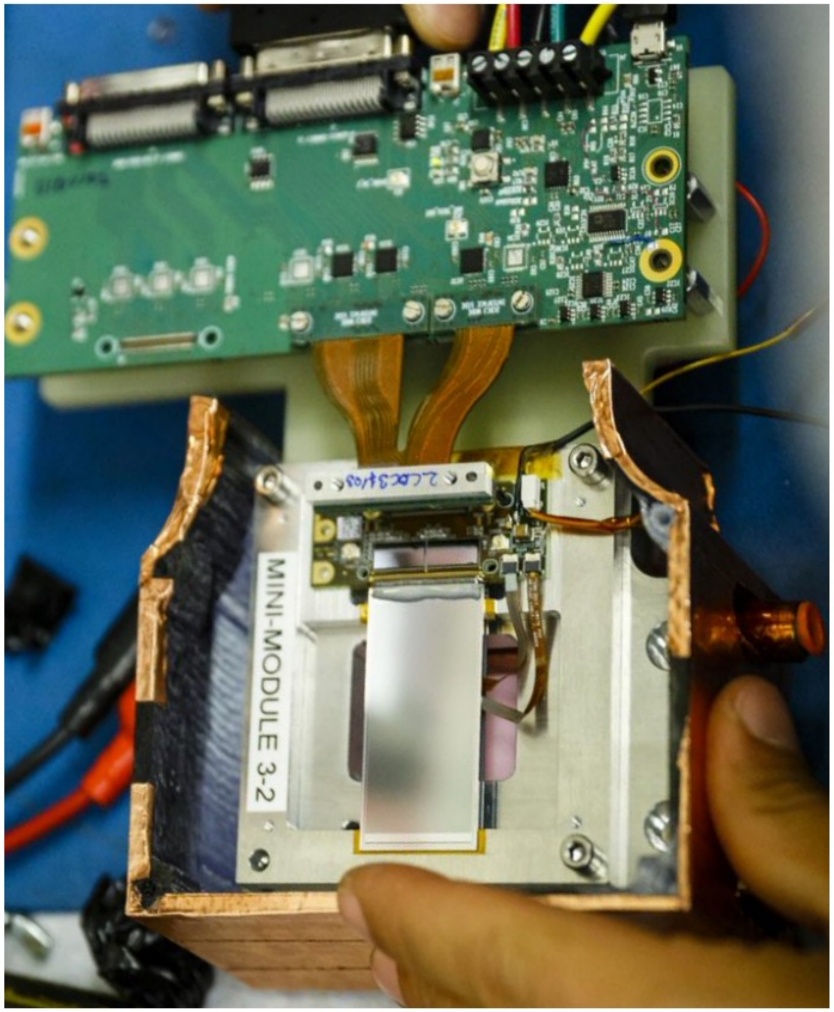
barrel vs endcap, view from the side: larger spacing needed

barrel, view down beamline

track trigger review paper

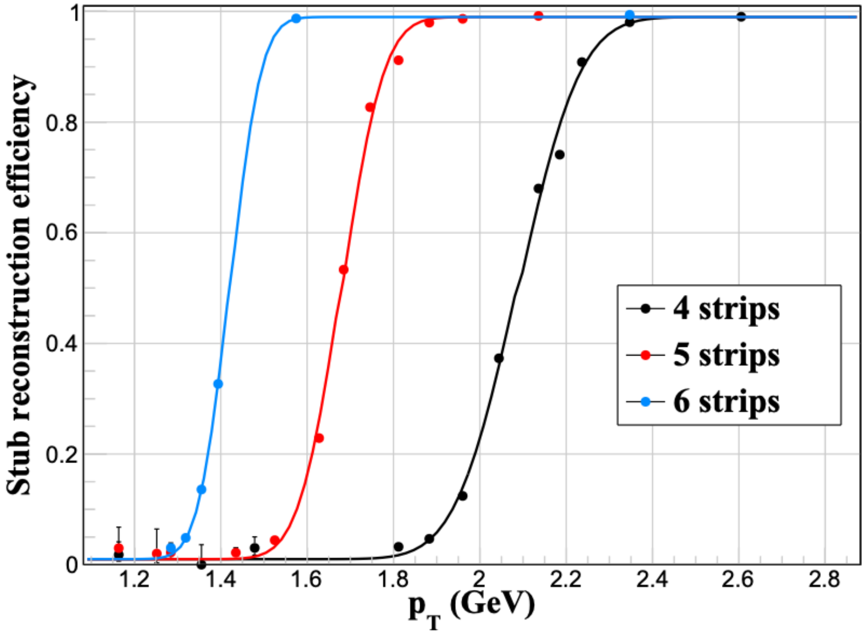
Si Strip detector of “p_T modules”

- Prototypes demonstrate ability to resolve momentum*



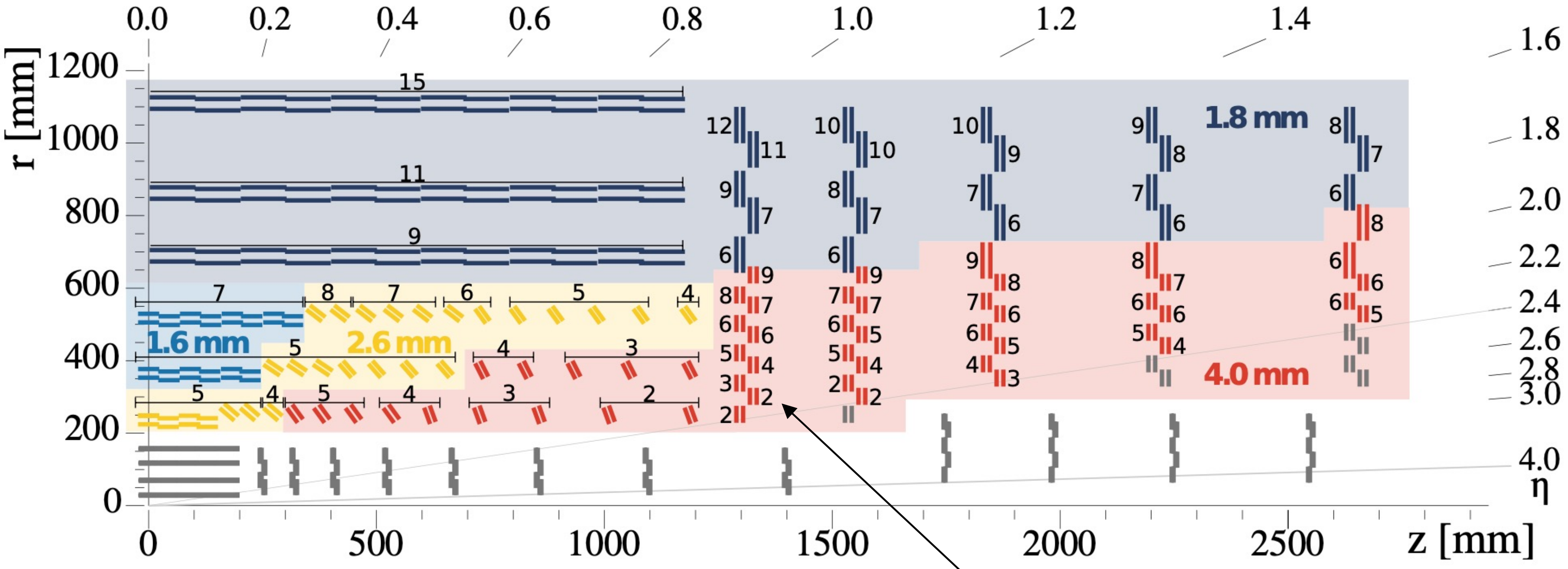
** No magnetic field at the testbeam so turn the module to simulate the bending*

$$p_T[\mathrm{GeV}] \approx \frac{0.57 \cdot R[\mathrm{m}]}{\sin\beta}$$



CMS Tracker group *JINST* 18 P04001 (2023)

OT Built for the track trigger



One quarter of the OT layout with modules colored by sensor separation distance (grey is not used in the trigger)

→ smallest separation in the barrel

Numbers give the size of the acceptance window in N(strips)

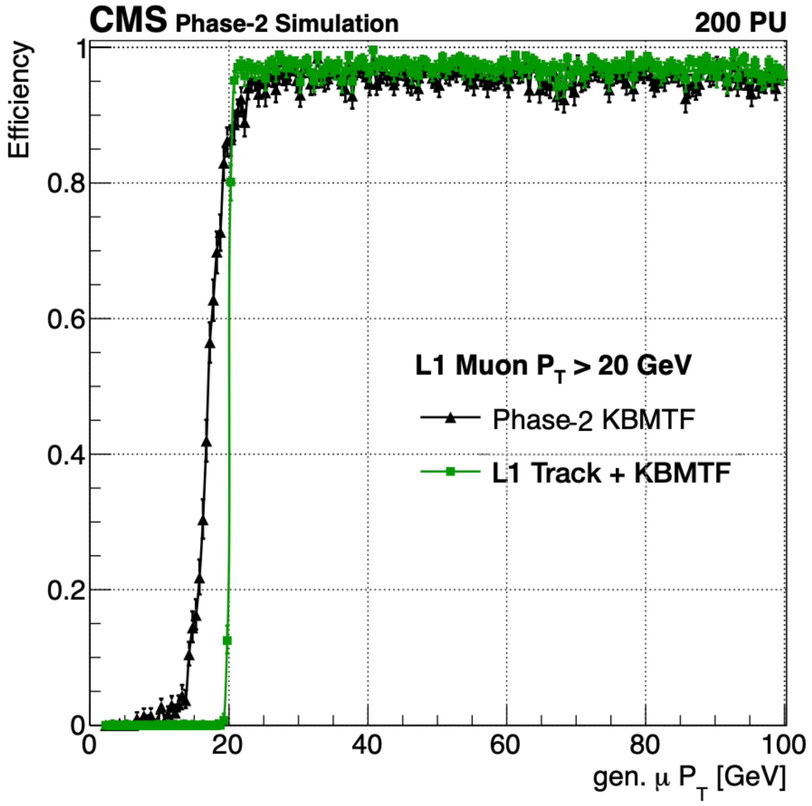
→ smaller values at lower R

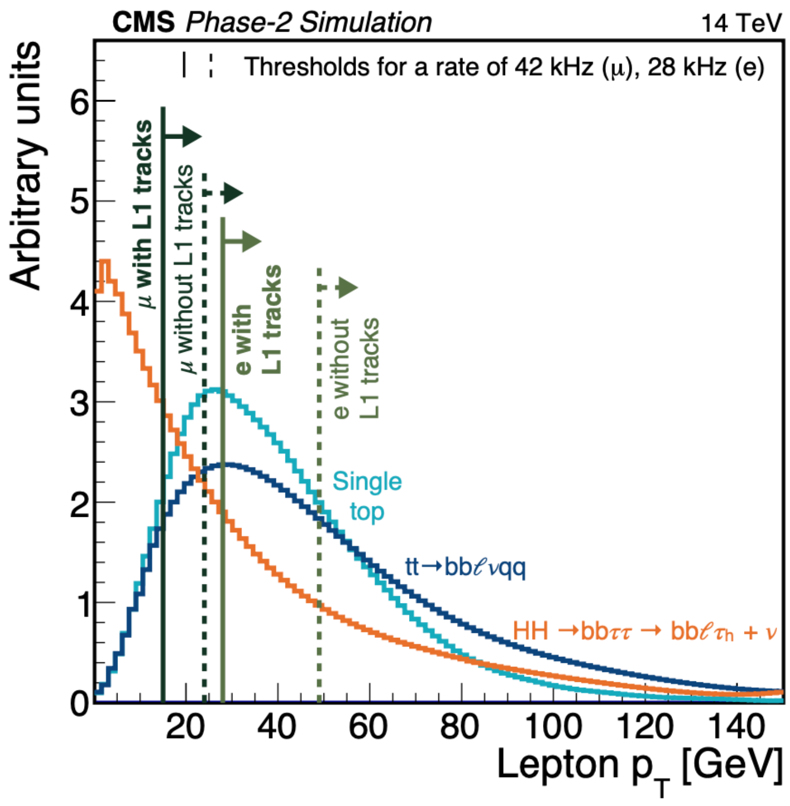
CMS [Phase 2 tracker TDR]

Sharper turn-on curves → lower thresholds

- Improved trigger performance directly affects physics capabilities

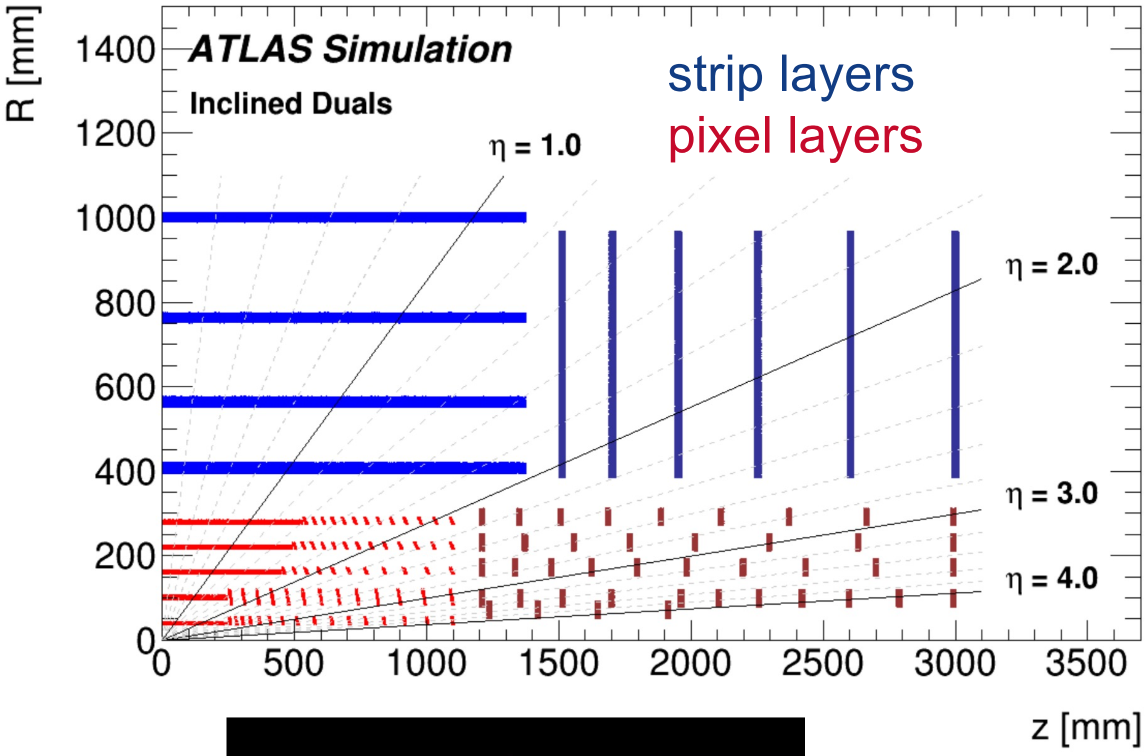
→ *Starting from the hardware design*



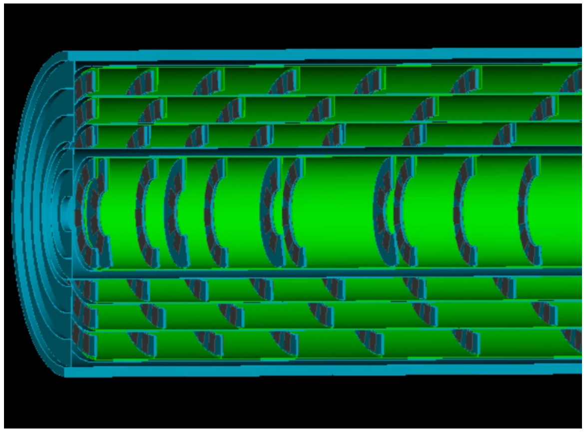


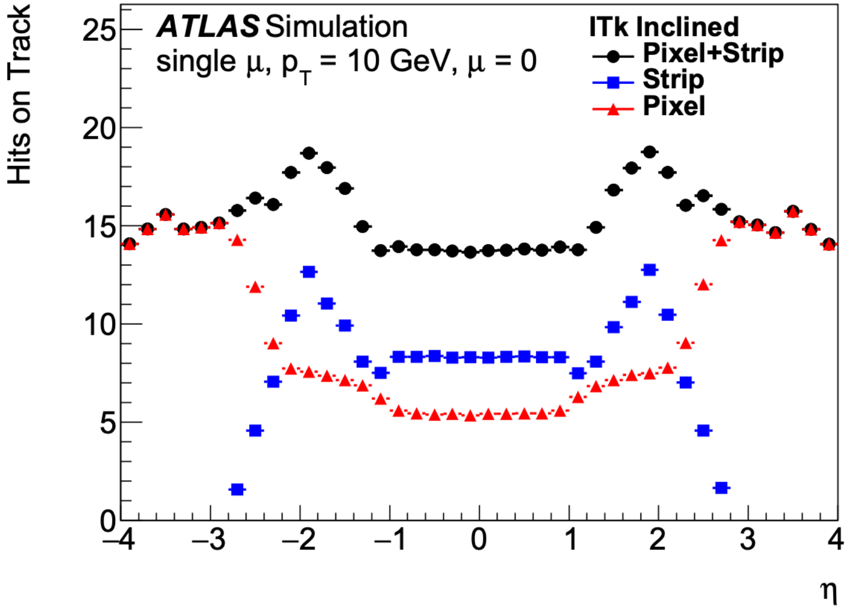
CMS Phase 2 tracker TDR

ATLAS goes all-in on silicon



- Pixels: similar to CMS
  - → *n-in-p, 3d on innermost layer, planar elsewhere*
  - → *Similar ROC (from RD53)*
- Strip detector at large R
  - → *75.5 μm pitch, small-angle stereo for z/R information*
- Extension of η acceptance

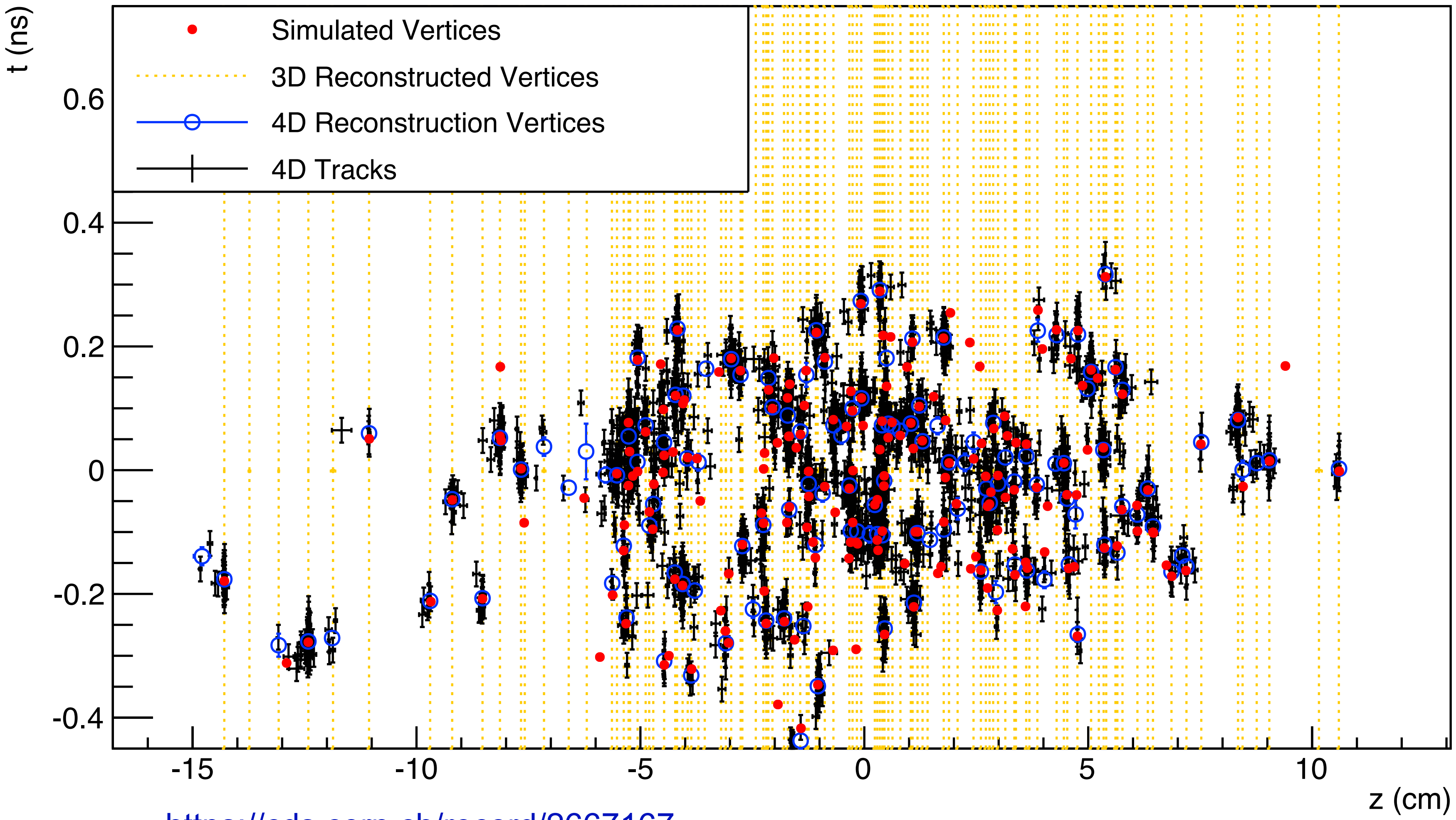




ITk pixel TDR; ITk strips TDR

Four-dimensional vertexing?

- Focused thus far on three-dimensional reconstruction, but these 200 events per bunch crossing are also distributed in time in an uncorrelated way – but need time resolution in 10s of picoseconds

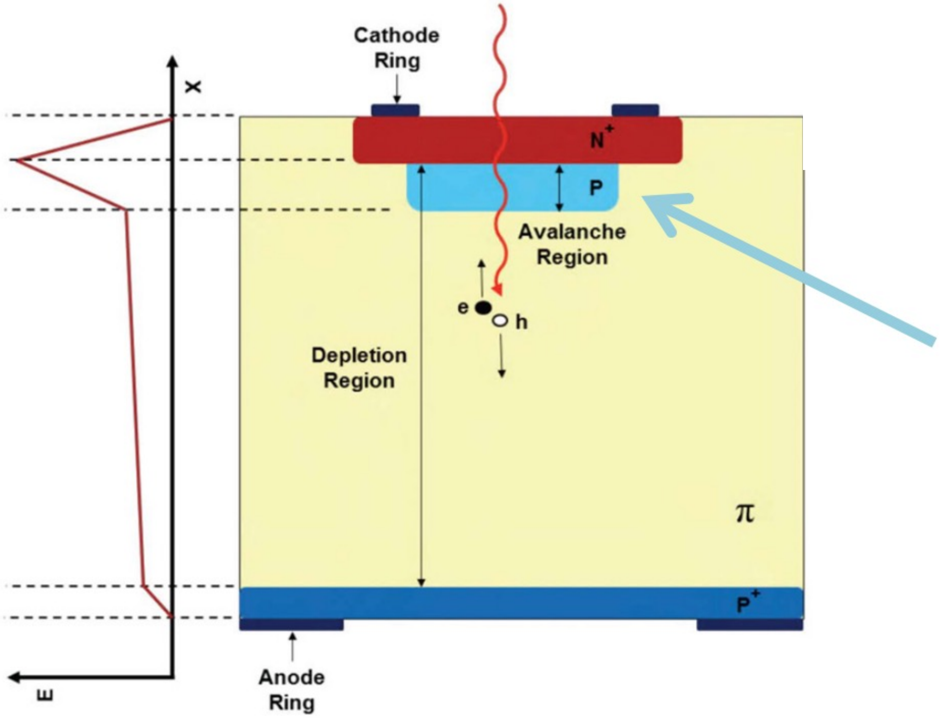


https://cds.cern.ch/record/2667167

Sensors for precision timing

- LGAD = Low Gain Avalanche Diode

→ *Charge **multiplication** --> fast rise time of induced signal --> precision timing*



Principle:

Add to n-on-p Silicon sensor an extra thin p-layer below the junction which increases the E-field so that charge multiplication with **moderate gain** of 10-50 occurs without breakdown.

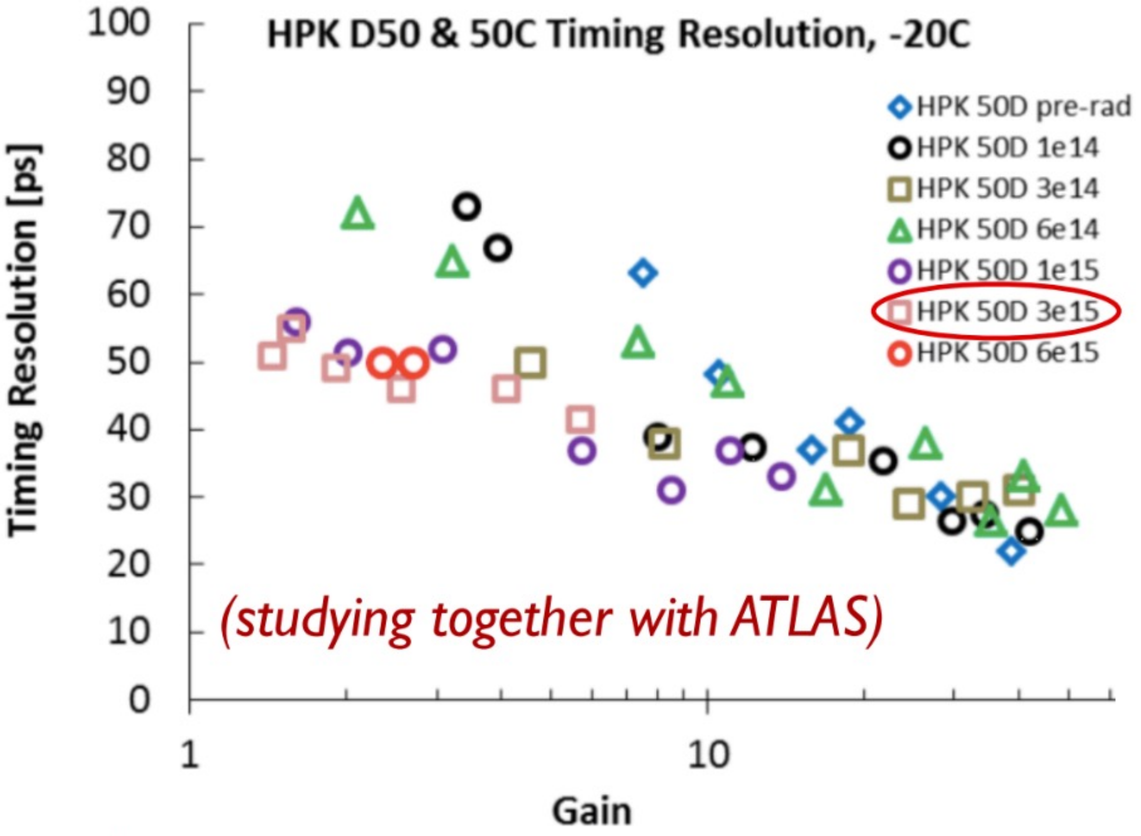
Timing characteristics depend on both the bulk (i.e. thickness) and the multiplcation layer.

https://indico.cern.ch/event/577879/contributions/2740418/

MIP Timing Detector

- Single layer surrounding entire CMS detector

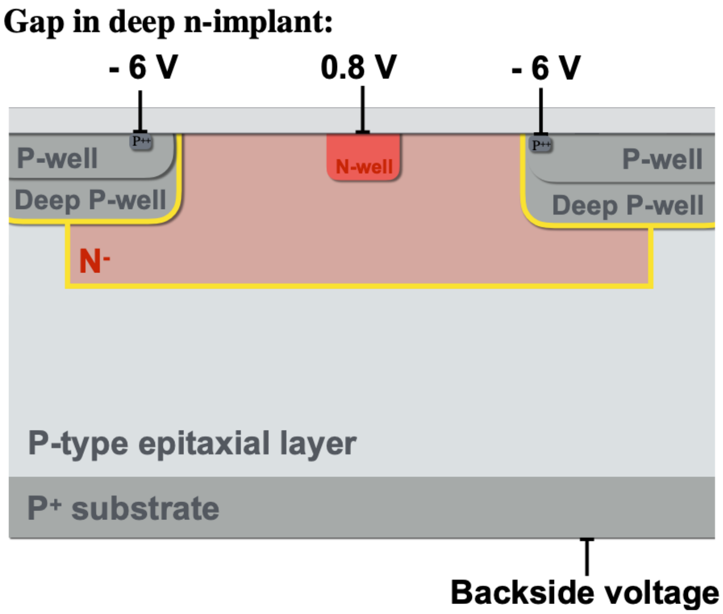
  → *LGADs for forward detector,*
- Technological proof-of-concept: performance as needed even after irradiation

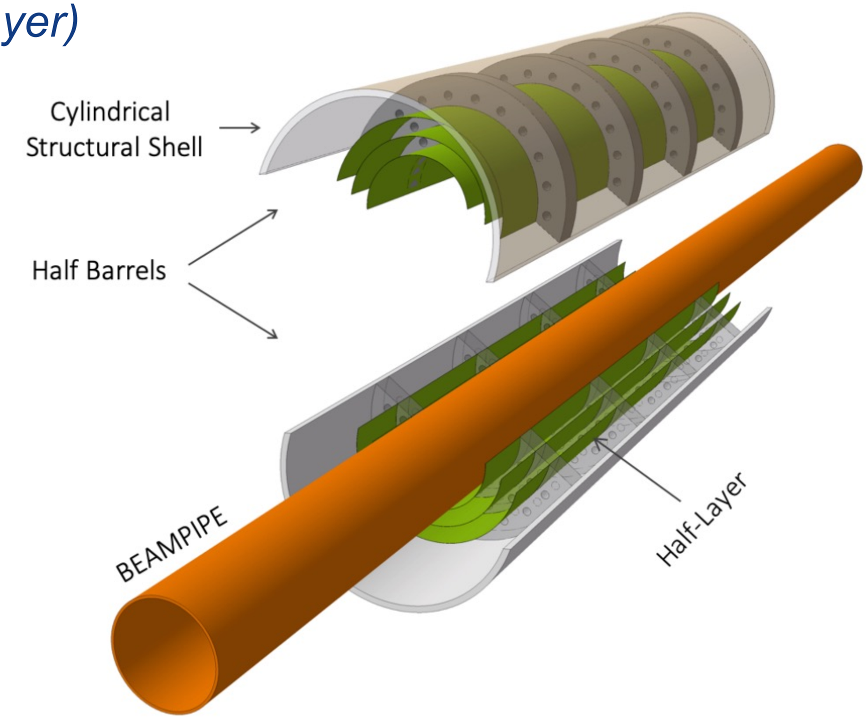


ALICE ITS3: CMOS

- Another future path is material reduction: no bump bonding, low-power electronics, no active cooling (no metal tubes)
- ALICE experiment focuses on nuclear physics, so lower-momentum (< 1 GeV) tracks are important

→ *Multiple scattering dominates momentum resolution at these momenta, motivating aggressive material reduction   0.05% X_0 per layer (compare to CMS pixel barrel at ~2.5% X_0 per layer)*



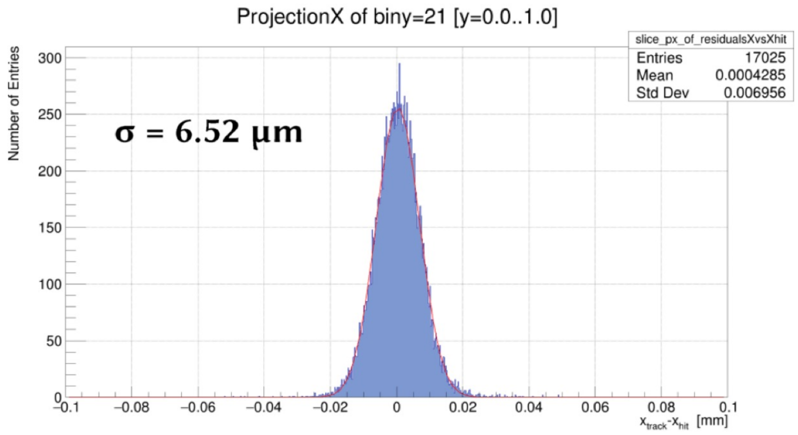


https://iopscience.iop.org/article/10.1088/1748-0221/14/05/C05013

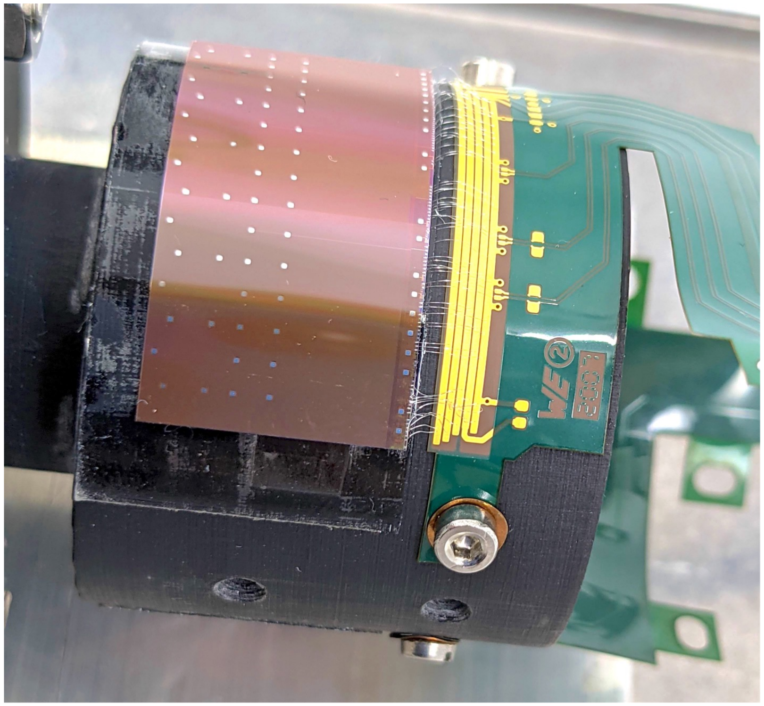
ITS3 Letter of Intent https://cds.cern.ch/record/2703140/files/LHCC-I-034.pdf

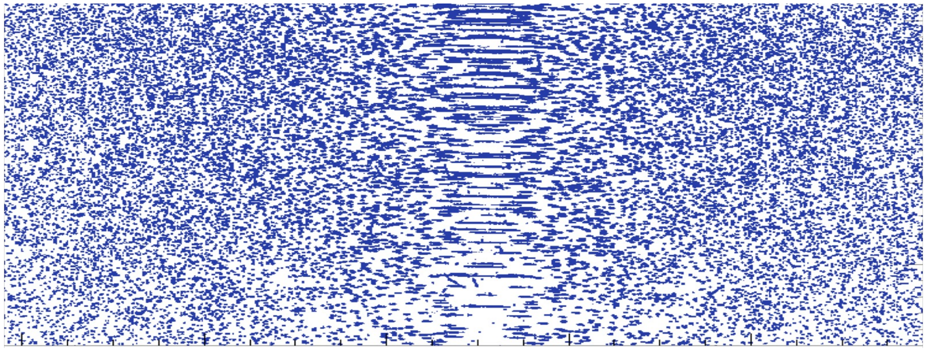
Silicon works after bending

- Beam tests of partial detectors have been successful



Spatial resolution reasonable for 10 μm pitch





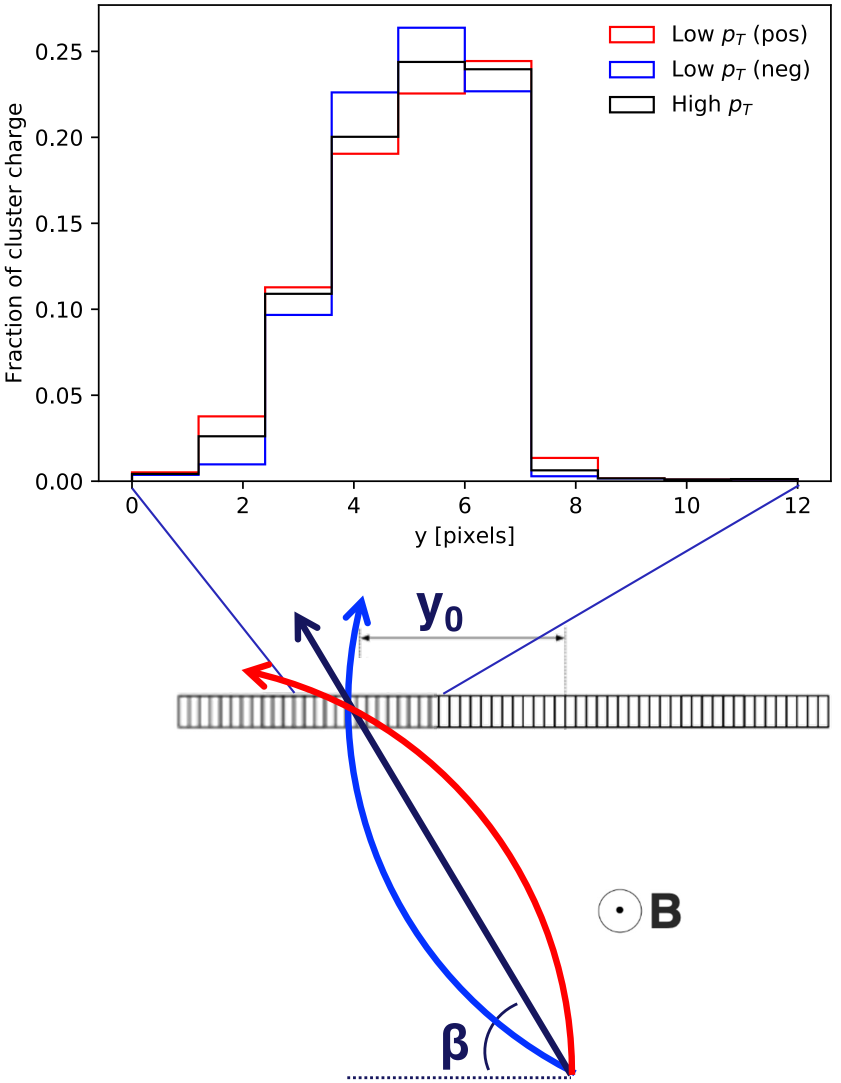
tracks through the detector

Installation planned for HL-LHC

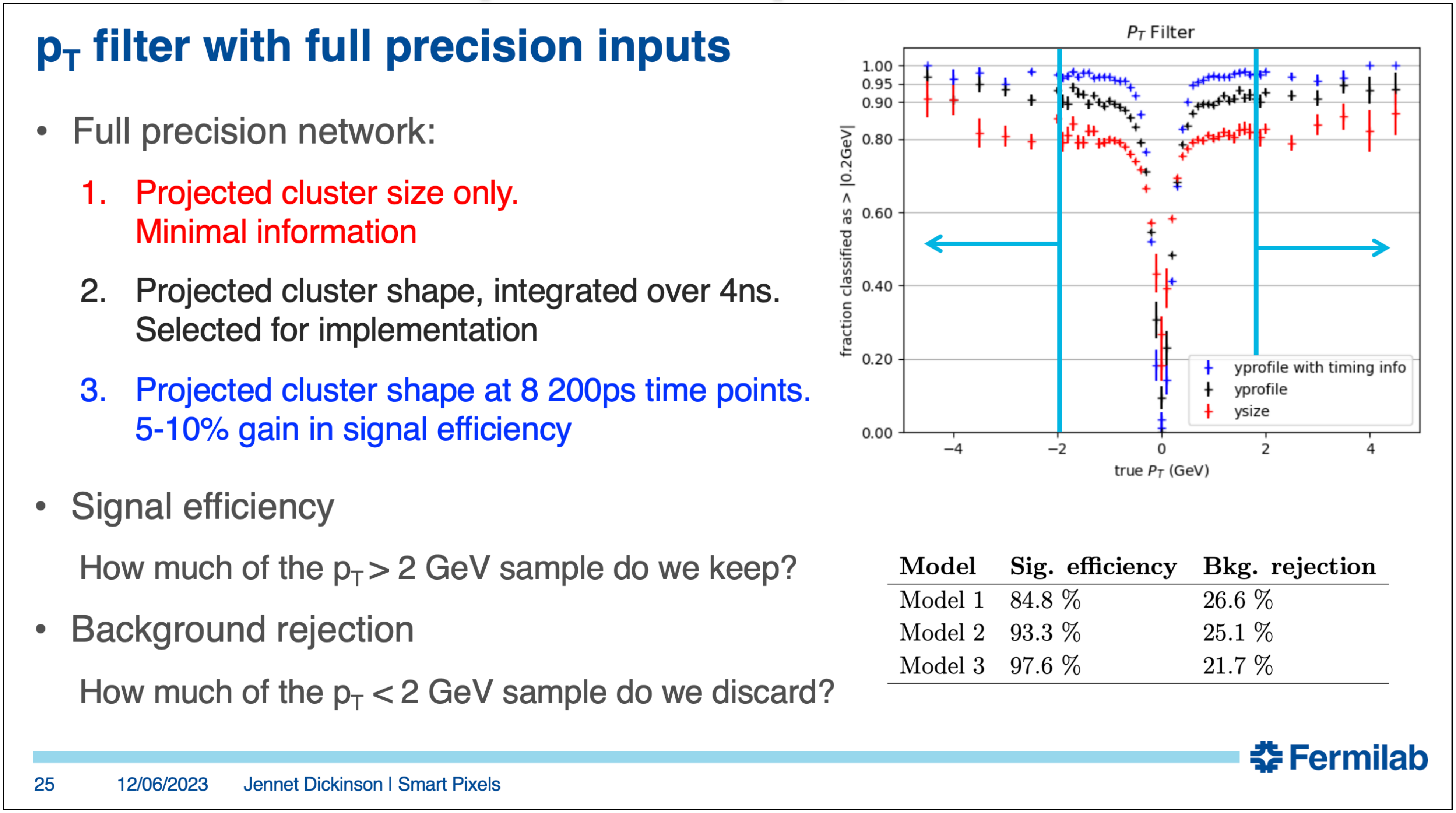
https://indico.cern.ch/event/1044975/contributions/4663684/

What are smartpixels?

- Can be used to infer transverse momentum or regress track angles, given sufficiently granular pixels
- Read out cluster information → data reduction at the source (detector) using ML
- Two strategies
  - → *Filter: reject tracks with low (< 200 MeV) pT*
  - → *Regression: infer track position and angles*



Snapshot: p_T filter



p_T filter with full precision inputs

- Full precision network:
  1. Projected cluster size only.
     Minimal information
  2. Projected cluster shape, integrated over 4ns.
     Selected for implementation
  3. Projected cluster shape at 8 200ps time points.
     5-10% gain in signal efficiency
- Signal efficiency

  How much of the $p_T > 2$ GeV sample do we keep?
- Background rejection

  How much of the $p_T < 2$ GeV sample do we discard?

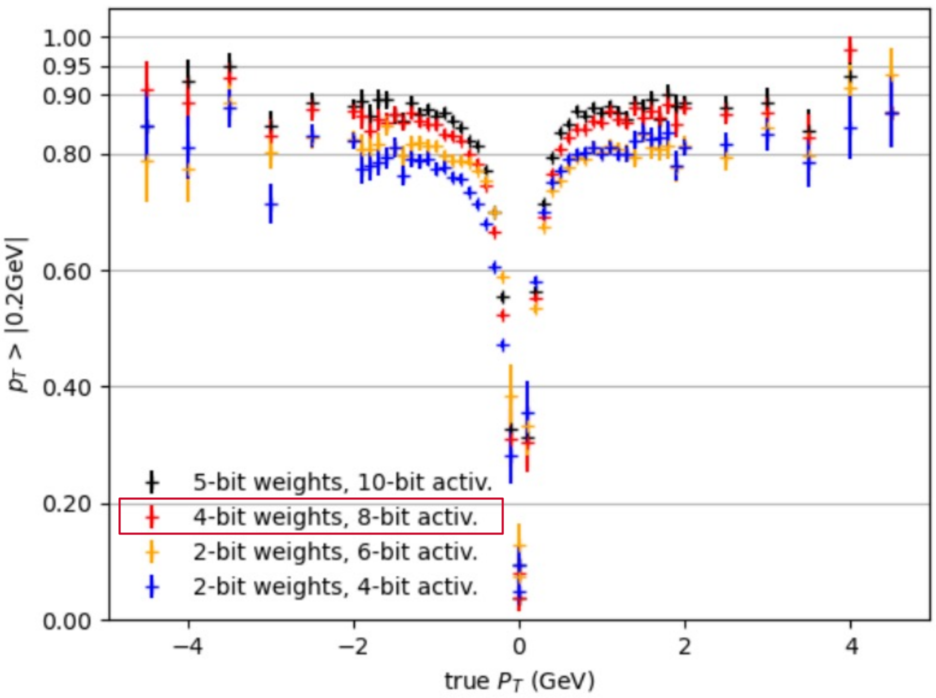
Model	Sig. efficiency	Bkg. rejection
Model 1	84.8 %	26.6 %
Model 2	93.3 %	25.1 %
Model 3	97.6 %	21.7 %

25 12/06/2023 Jennet Dickinson | Smart Pixels

Fermilab

https://arxiv.org/abs/2310.02474

p_T filter on an ASIC, performance



ADC output	Charge interval $[e^-]$
00	< 400
01	$400 - 1600$
10	$1600 - 2400$
11	> 2400

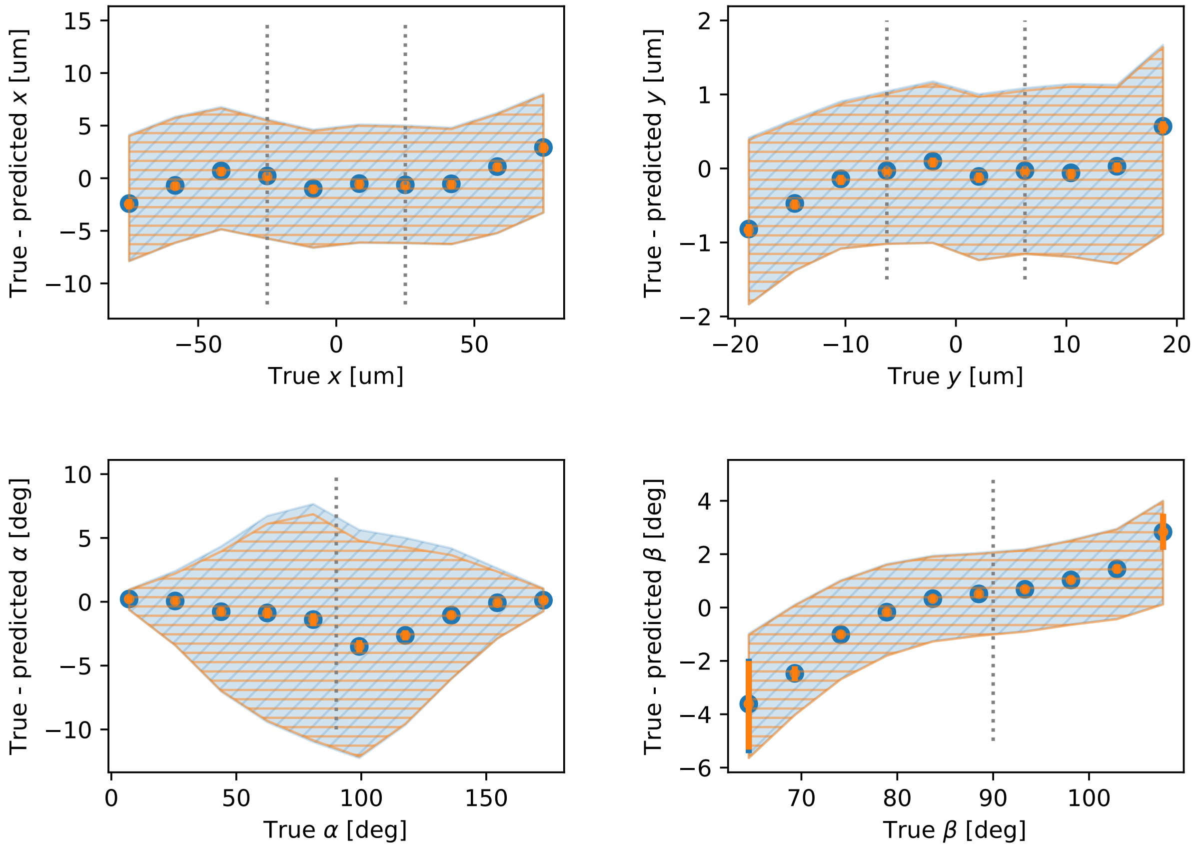
3: Mapping between 2-bit ADC output and collected charge.

- Digitization
  - → *Of charge: 2-bit “flash” ADC*
  - → *Of weights and activation: choose 4-bit weight + 8-bit activation*

- Preliminary estimate: 54-75% data reduction
  - → *Includes single-pixel hits (noise), loopers, and low-pT tracks rejected by the algorithm*
  - → *Most rejection comes from “untracked” clusters*
    - 55-60% of data, work ongoing to understand these better
  - → *Based on simulation, hope to look at min-bias and testbeam data in the future*

https://arxiv.org/abs/2310.02474

Snapshot: parameter regression



Use *time-sliced* information with convolutional layers to predict **not just local position and angles but their uncertainties as well.**

β = angle in the bending plane
Colors represent hls4ml synthesized (orange cross-hatched) vs. QKeras (blue) – both quantized

Hit position x, y

Pattern of bias repeats across each pixel

Mean predicted uncertainties:

$<\sigma_x> = 5.7\ \mu m$

$<\sigma_y> = 1.1\ \mu m$

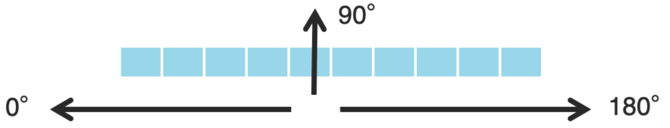
Angles α, β

Largest uncertainty near α=90° due to single pixel hits

Dataset covers limited range in β

$<\sigma_\alpha> = 3.8^\circ$

$<\sigma_\beta> = 1.7^\circ$



https://arxiv.org/abs/2312.11676

Summary and outlook

- Is particle tracking a "solved" problem? *No!*
- Numerous advances in capabilities in the last 10 years
  - → *Improved sensor engineering and fabrication*
    - Fast precision timing
    - 3d pixels
    - MAPs and ultra-lightweight detectors
  - → *Pushing computation towards the detector*
    - Track trigger
    - Smart pixels

- Don't lose sight of older ideas and technologies, either
  - → *eg. PID from transition radiation*
  - → *Old ideas have a way of coming back around, and different collider configurations have different demands (and opportunities)*

- Your generation of physicists will launch the next generation of collider detectors
  - → *Keep alive the tradition of innovation combined with attention to detail*

Backup

Sunset at Wilson Hall, December 2020 (c mills)

Silicon References

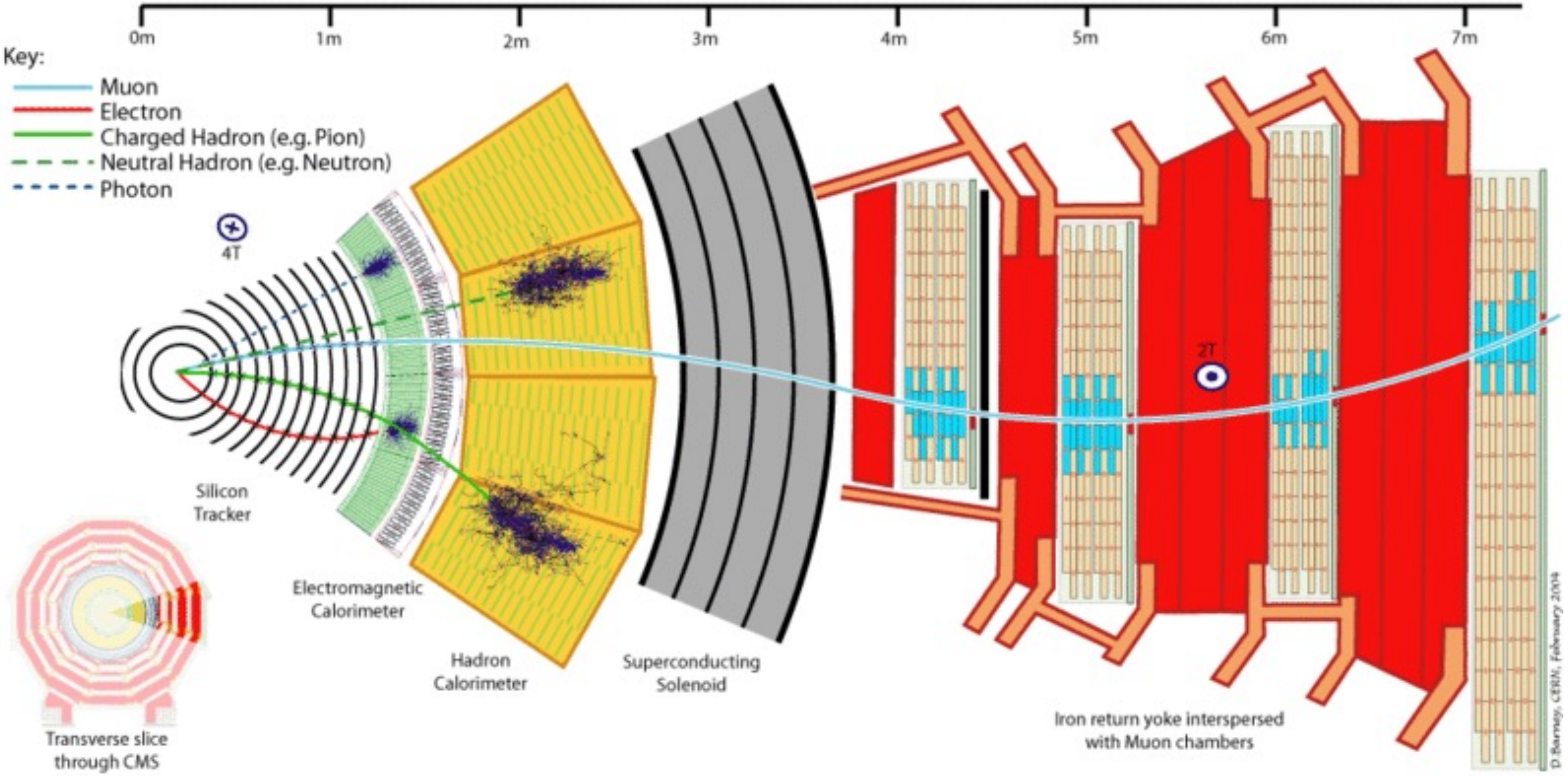
- Thanks to Julia Thom for her notes, slides, and resources that got me started with giving this sort of lecture
- Frank Hartmann's summer school lectures (LPC 2014 etc)
- *Evolution of Silicon Sensor Technology in Particle Physics*, Second Edition (2017), Frank Hartmann, Springer Tracts in Modern Physics
- *Detectors in Particle Physics: A Modern Introduction* (2024), Georg Viehhauser, Tony Weidberg, CRC Press
  - → *pdf available at https://www.taylorfrancis.com/books/oa-mono/10.1201/9781003287674/detectors-particle-physics-tony-weidberg-georg-viehhauser*
- CMS Run1 tracking: https://arxiv.org/pdf/1405.6569.pdf *JINST* **9** P10009
- CMS Phase 2 tracker TDR: https://cds.cern.ch/record/2272264
- ATLAS ITk pixel TDR; ITk strips TDR
- 3D sensors for IBL: https://doi.org/10.1016/j.nima.2012.07.058
- Moll review on radiation damage, https://doi.org/10.1109/TNS.2018.2819506
- Track trigger review paper: https://doi.org/10.1146/annurev-nucl-020420-093547

Additional References

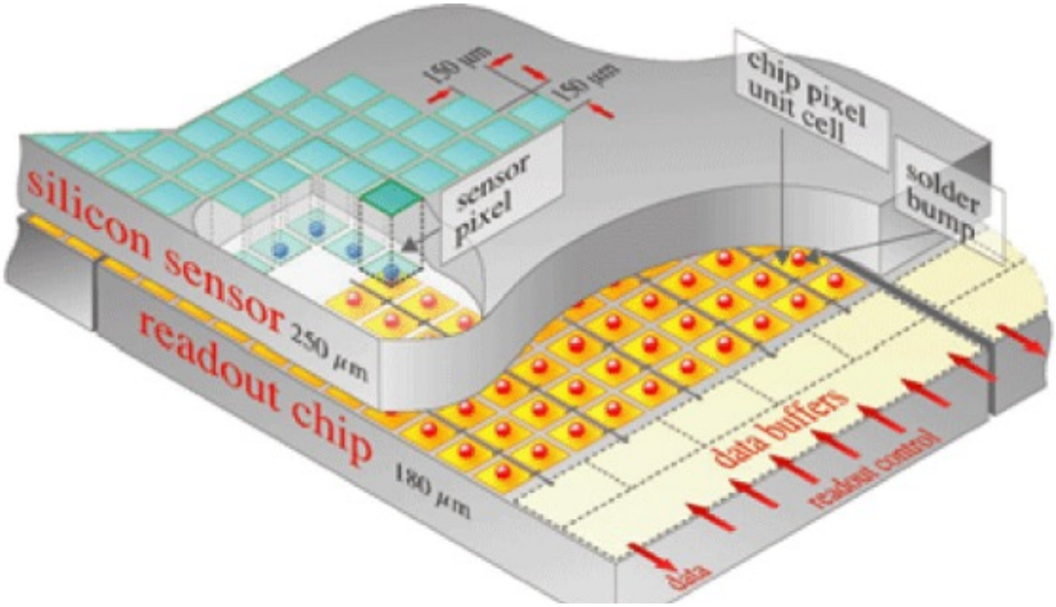
- PDG reviews
  - → *Passage of Particles through Matter https://pdg.lbl.gov/2023/reviews/rpp2023-rev-passage-particles-matter.pdf*
  - → *Particle Detectors at Accelerators https://pdg.lbl.gov/2023/reviews/rpp2023-rev-particle-detectors-accel.pdf*
- Charge deposition (energy loss) in thin materials (Bischsel) https://journals.aps.org/rmp/pdf/10.1103/RevModPhys.60.663
- Shockley-Ramo Theorem: NIM A Volume 463, Issues 1–2, 1 May 2001, Pages 250-267

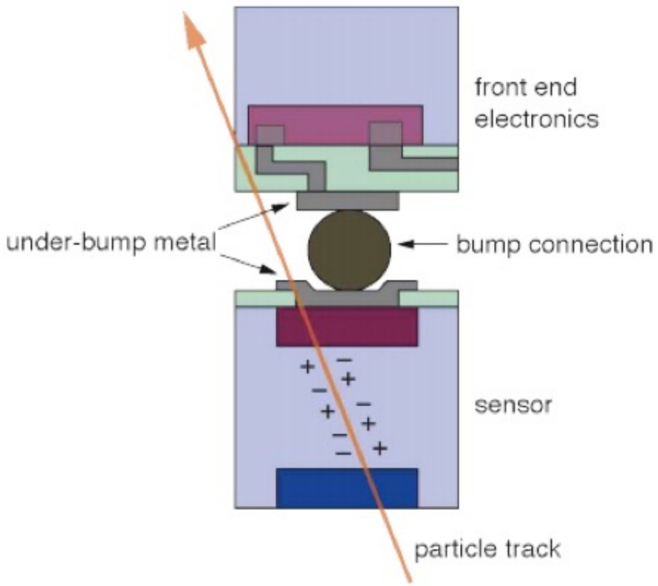
- TRT performance in Run 1: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/IDET-2015-01/

How we reconstruct particles

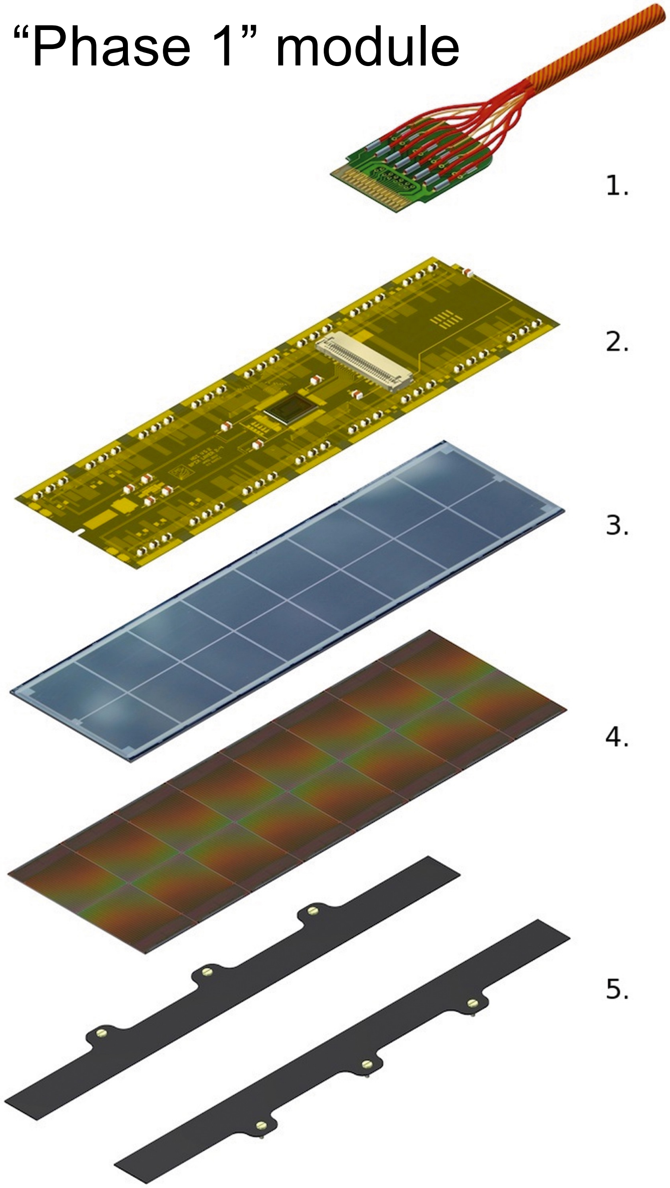


Pixel detector modules





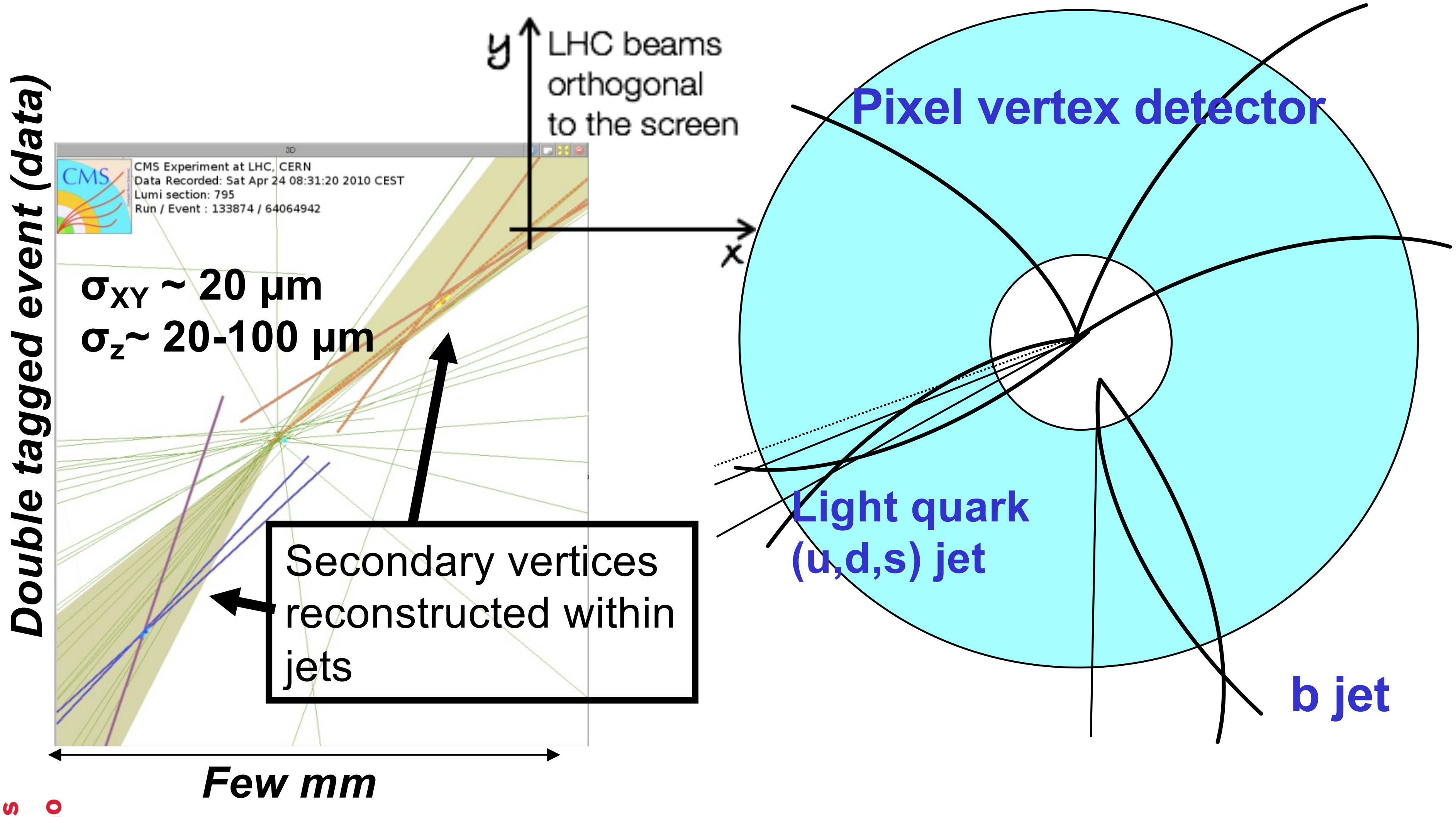
CMS “Phase 1” module



https://doi.org/10.1016/j.nima.2016.03.030

Identifying b-quark jets

- Identify jets originating from b- quark by long lifetime of B hadrons



$\sigma_{XY} \sim 20\ \mu m$

$\sigma_z \sim 20\text{-}100\ \mu m$

Secondary vertices reconstructed within jets

- For H to bb, typically 70% b-tagging efficiency