University of Glasgow | Department of Physics & Astronomy

Recent developments in silicon sensors

Four-dimensional tracking with Low Gain Avalanche Detectors

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Outline

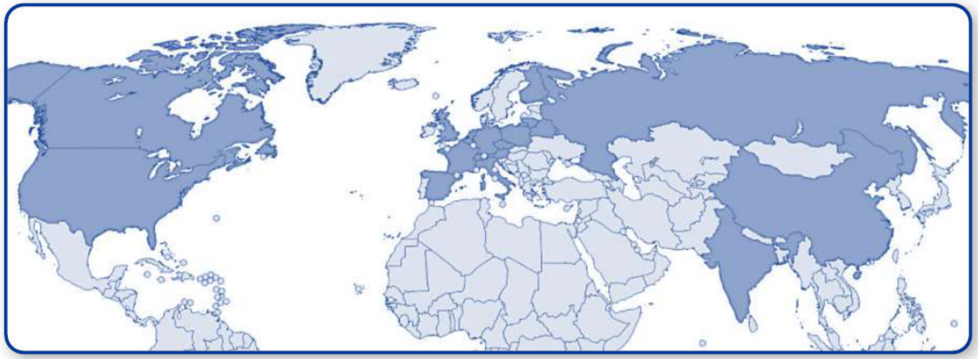
- Motivation for 4-D tracking in particle physics
- Silicon detectors and Low Gain Avalanche Detectors
- How gain allows 30 ps timing resolution
- Radiation damage
- Issues with Small pixels
- Conclusion

The RDS50 Collaboration

RD50: 63 institutes and more than 300 members (see http://cern.ch/rd50)

52 European institutes

Austria (Wien), Belarus (Minsk), Belgium (Louvain), Croatia (Zagreb), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), France (Paris, Marseille, Orsay), Germany (Bonn, Göttingen, Dortmund, Erfurt, Freiburg, Hamburg (2x), Karlsruhe, Munich (2x)), Greece (Athens), Italy (Bari, Perugia, Pisa, Trento, Torino), Lithuania (Vilnius), Netherlands (NIKHEF), Poland (Kraków, Warsaw (2x)), Romania (Bucharest (2x)), Russia (Moscow, St. Petersburg), Slovenia (Ljubljana), Spain (Barcelona (3x), Santander, **València**), Switzerland (CERN, PSI), United Kingdom (Birmingham, Glasgow, Lancaster, Liverpool, Manchester, Oxford, RAL)



8 North-America institutes

USA (Berkeley, BNL, Brown Uni, Fermilab, New Mexico, Santa Cruz, Syracuse), Canada (Montreal)

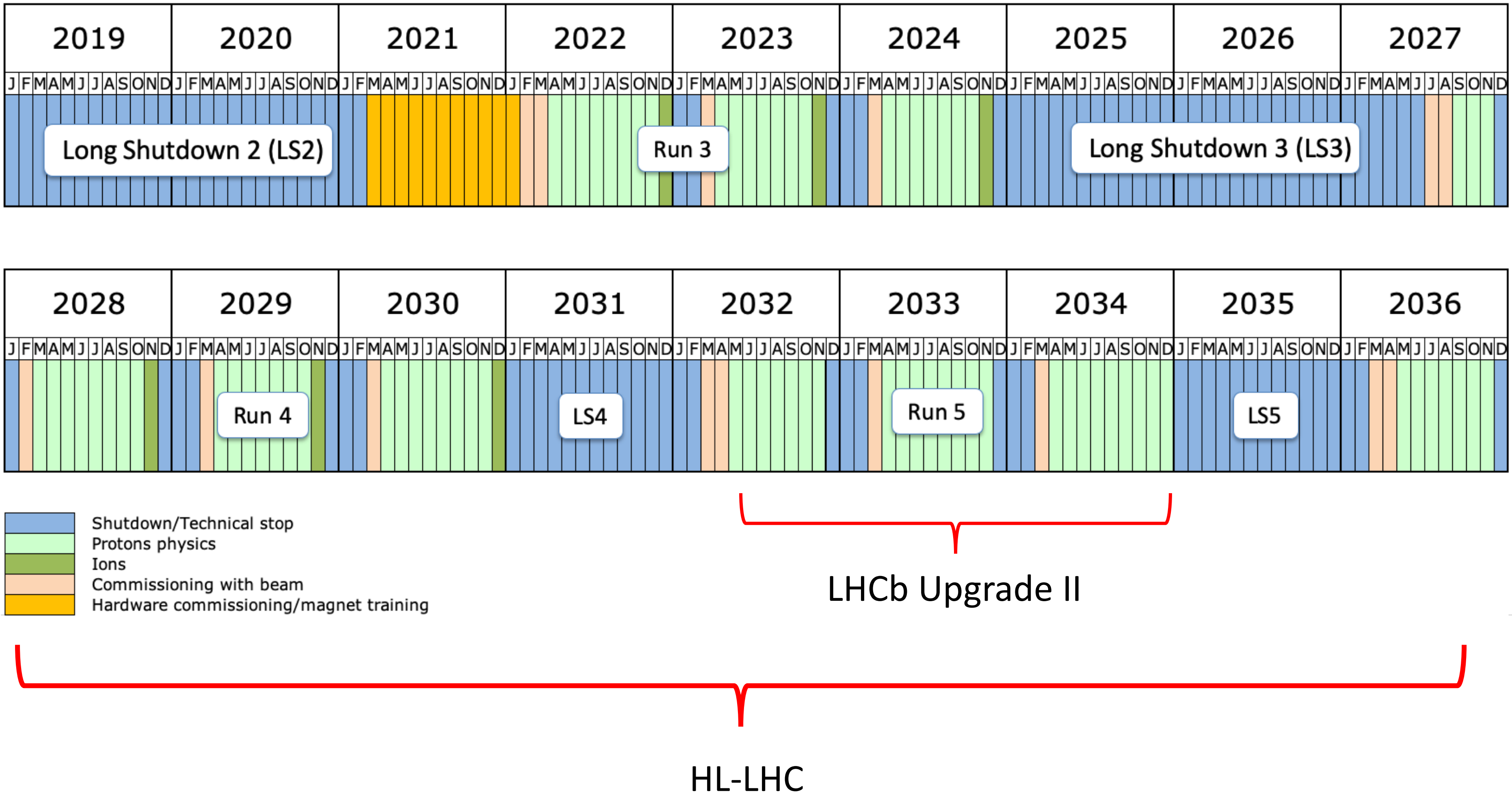
1 Middle-East institute

Israel (Tel Aviv)

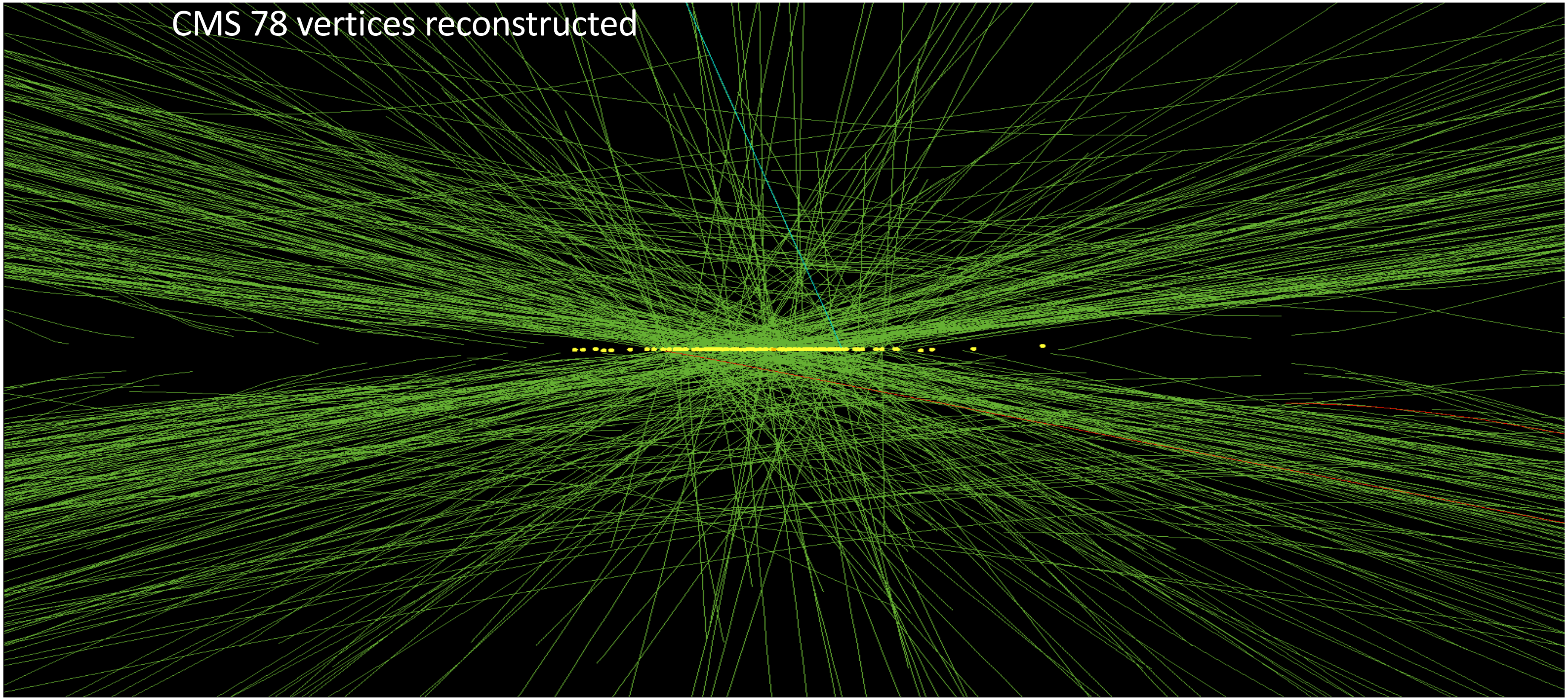
2 Asian institutes

India (Delhi), China (Beijing)

LHC upgrade timeline



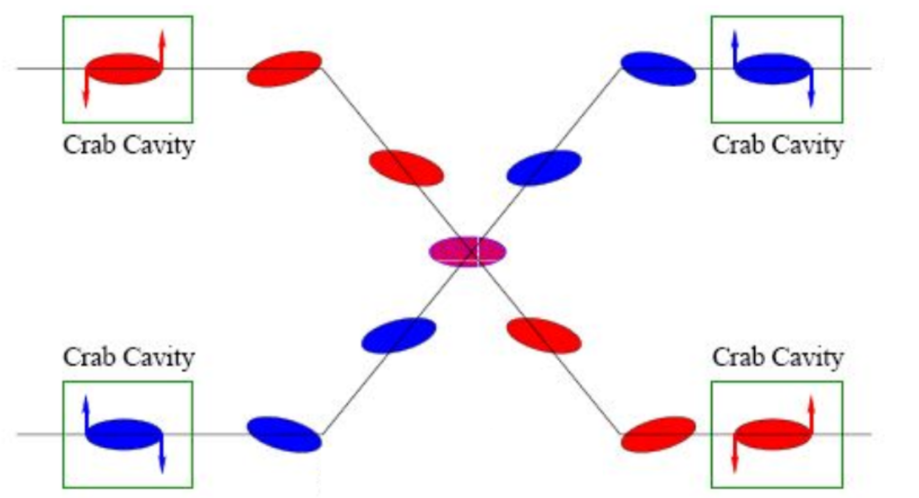
The HL-LHC challenge

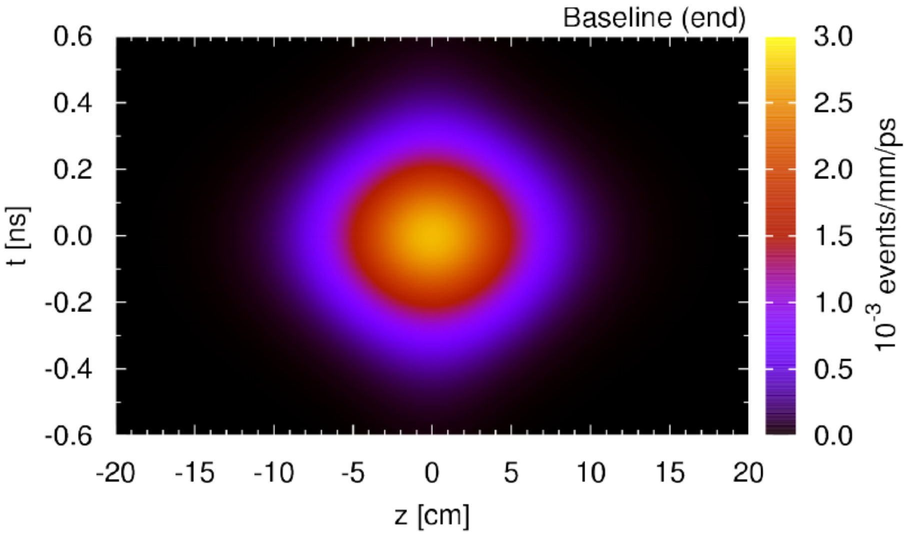


- The HL-LHC (and other future hadron colliders, like the FCC) represent a significant challenge for data processing
- Thousands of tracks, vertices, calorimeter clusters that must be analyzed for a physics analysis
- A mass of information, but not much of it is interesting physics!

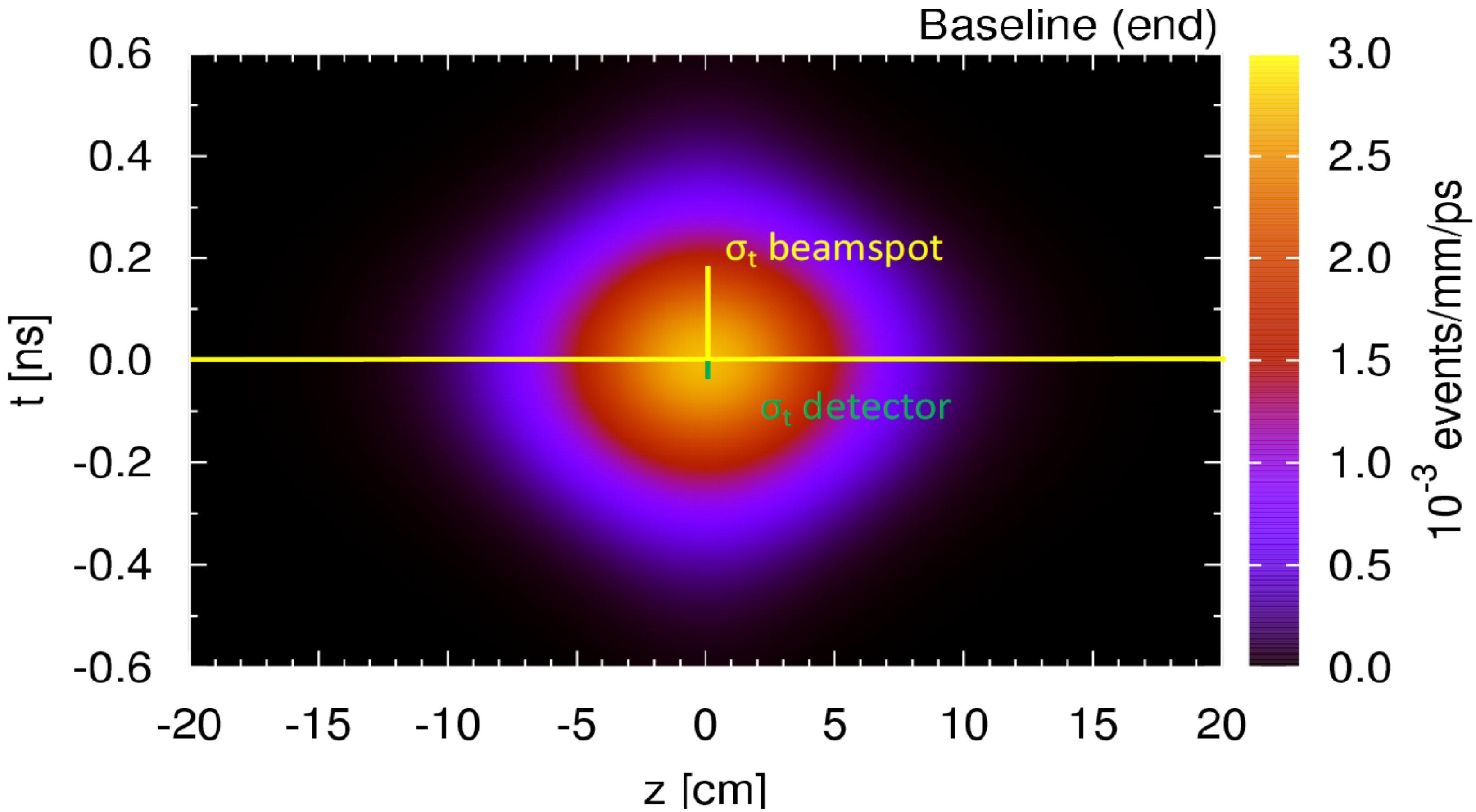
The structure of bunch crossings

- Bunch crossing extend in both z and time
- For nominal HL-LHC optics the core of the bunches passes through each other in ~300 ps
- When bunches overlap completely
  - ➔ maximum spread in z
  - ➔ maximum pile up
- An experiment sees the integral of this distribution over time





How to take advantage of beam-spot time spread



Need to discriminate vertices with time spread of ~180 ps, must have time track timing resolution significantly smaller than beam-spot spread so that tracks cluster in time, ~ 30 ps.

The effect of timing information

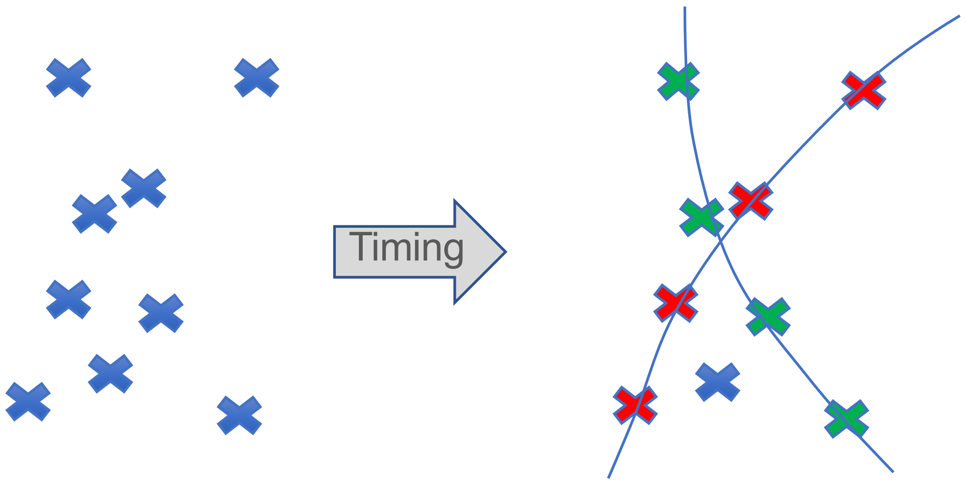
- The inclusion of track-timing in the event information is a paradigm shift which changes radically the design of experiments

- Timing can be available at different levels of the event reconstruction

1. Timing at each point along the track in the tracker
2. Timing in the event reconstruction
3. Timing at the trigger level

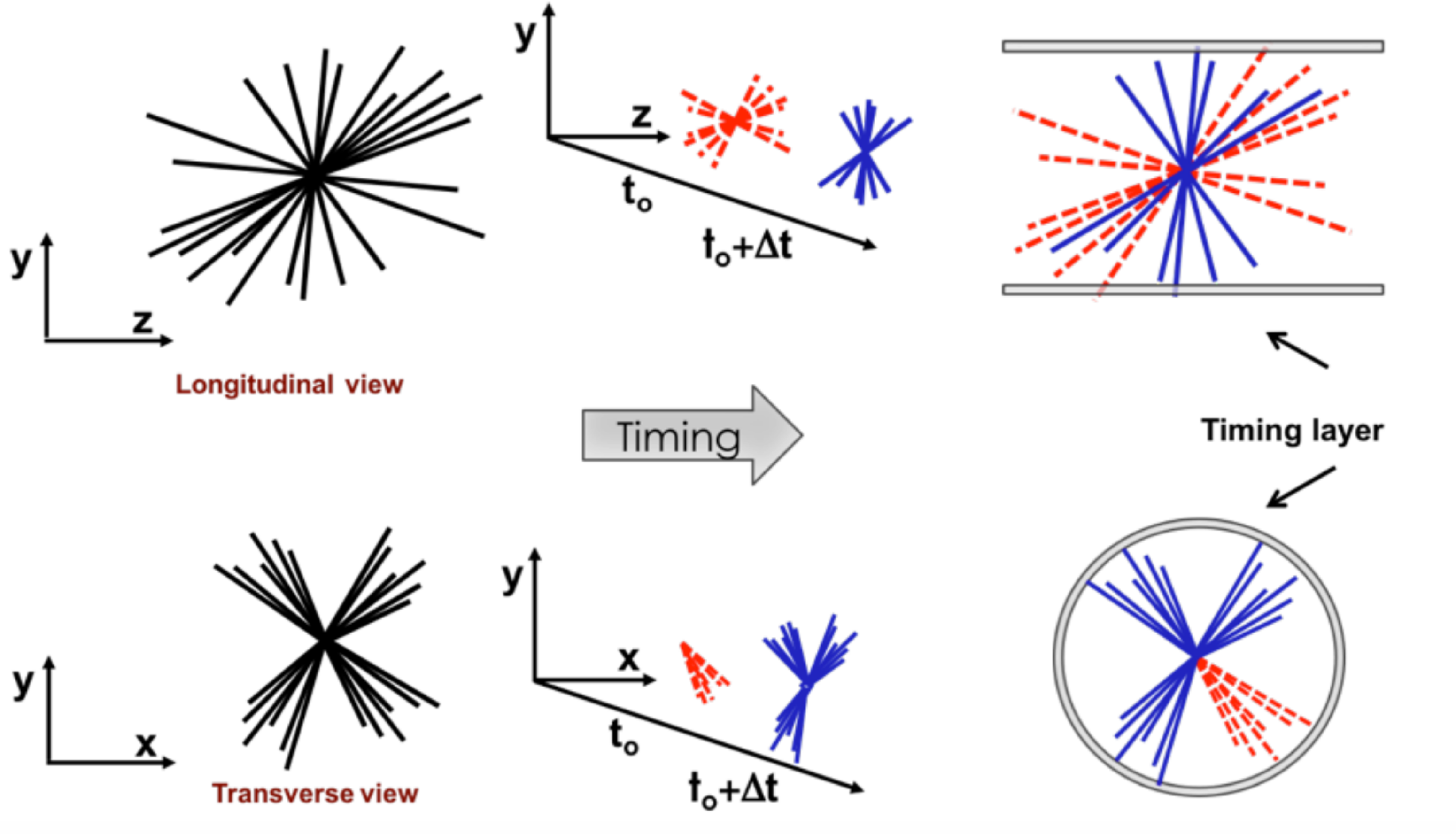
Timing at each point along the track

- Massive simplification of pattern recognition, new tracking algorithms will be faster even in very dense environments
- Use only points with compatible time stamps



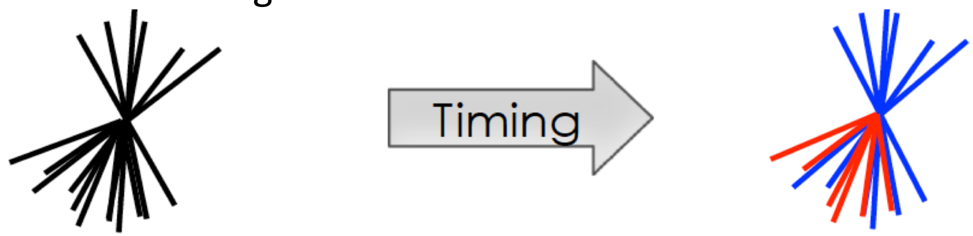
Timing in the event reconstruction

- Timing allows the disentanglement of overlapping events by means of an extra dimension

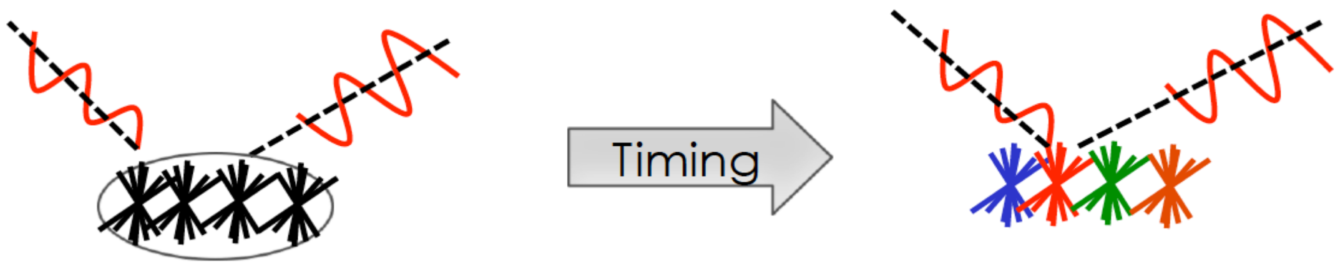


Timing in the event reconstruction

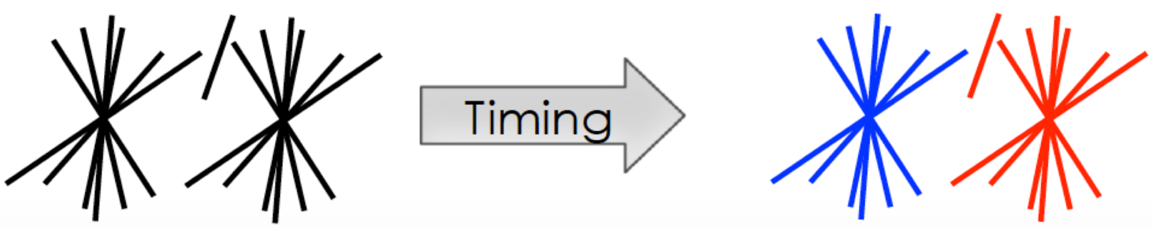
Missing Et: Consider overlapping vertexes, one with missing Et. Timing allows the HL-LHC to obtain the same resolution on missing Et that we have at the LHC



H-> γγ : The timing of the γγ allows one to select the area where the vertex is located. The vertex timing allows to select the correct vertex within this area.

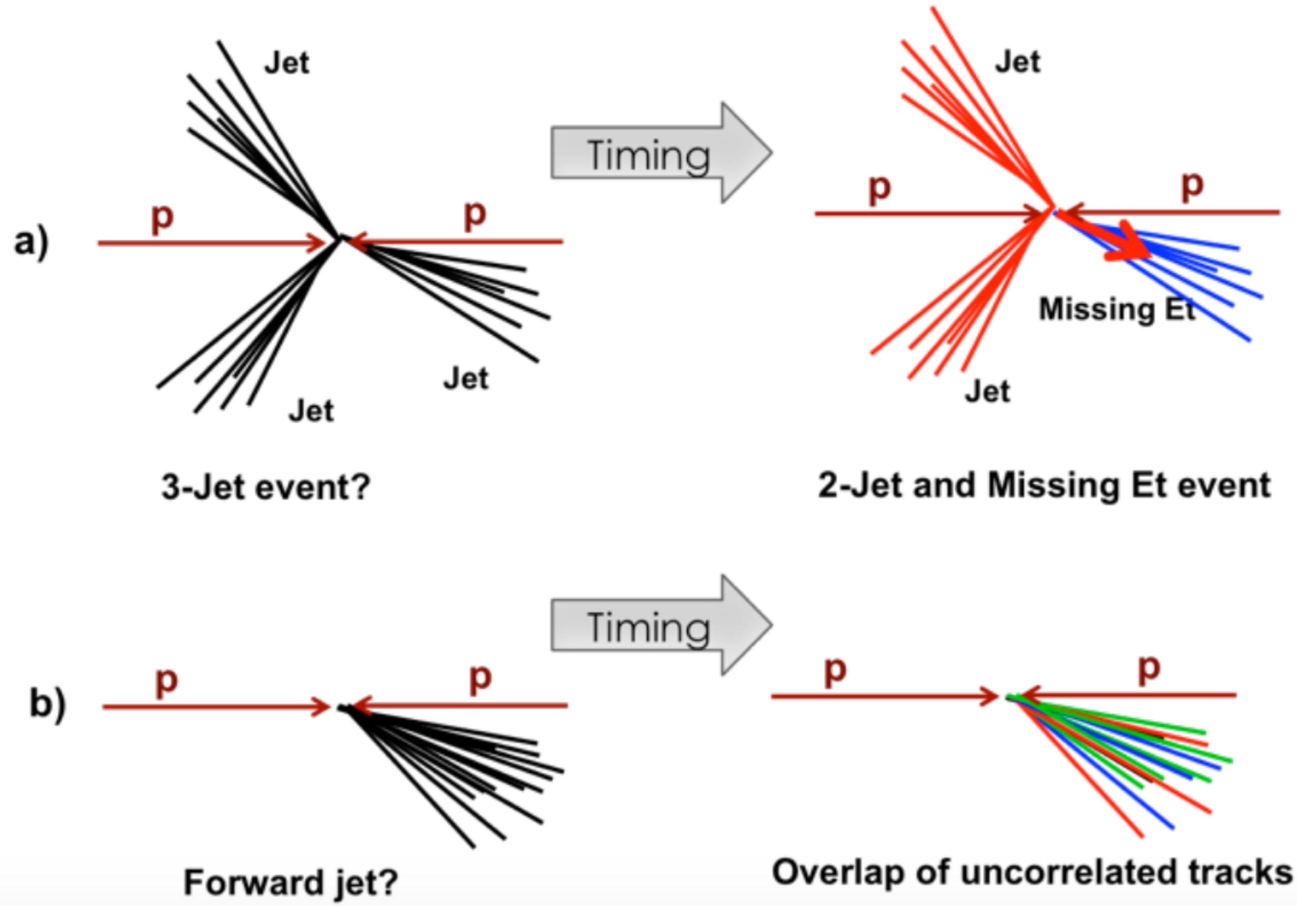


Displaced vertexes: The timing of the displaced track and that of each vertex allows the correct identification of the associated vertex



Timing at the trigger level

- Reduction of the trigger rate by rejecting topologies that look similar but are actually different!



Where to place the timing detector?

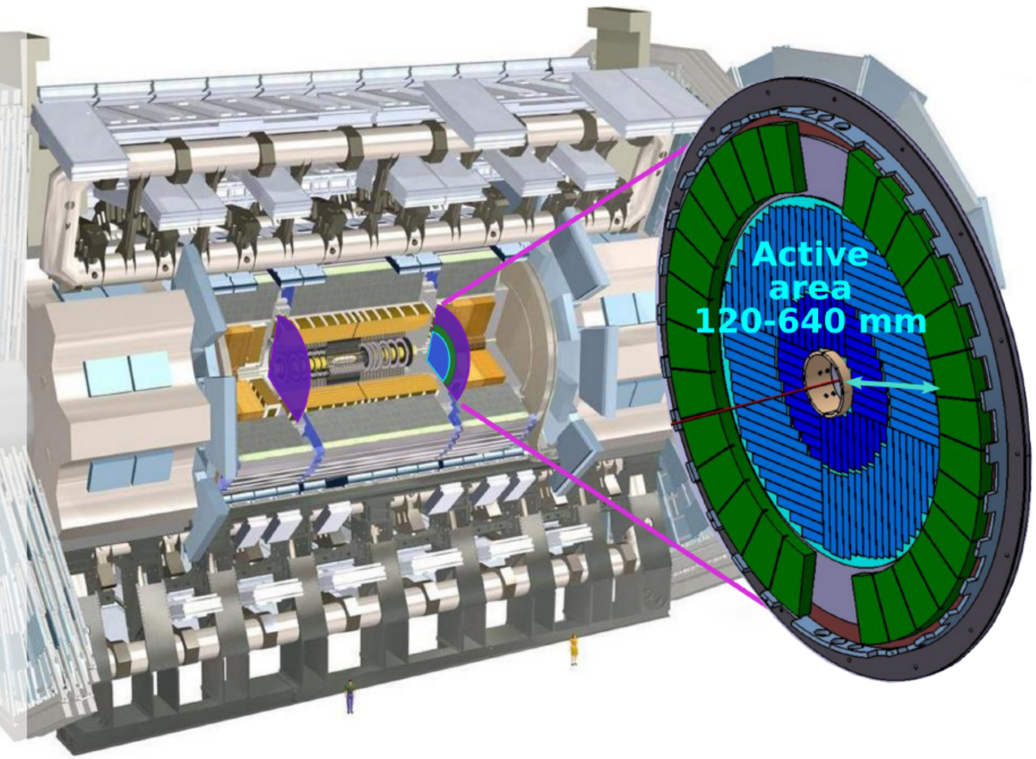
1. Re-design the tracker layer(s) to be timing layers
   - Require low mass silicon timing detectors
   - Require high position resolution with low power
2. An additional detector separated from the tracker

- ATLAS and CMS both pursuing timing layer concepts downstream of tracker. Course position resolution is acceptable.
  - ATLAS concept uses 2 Timing layer modules
  - CMS concept uses one layer in larger eta range

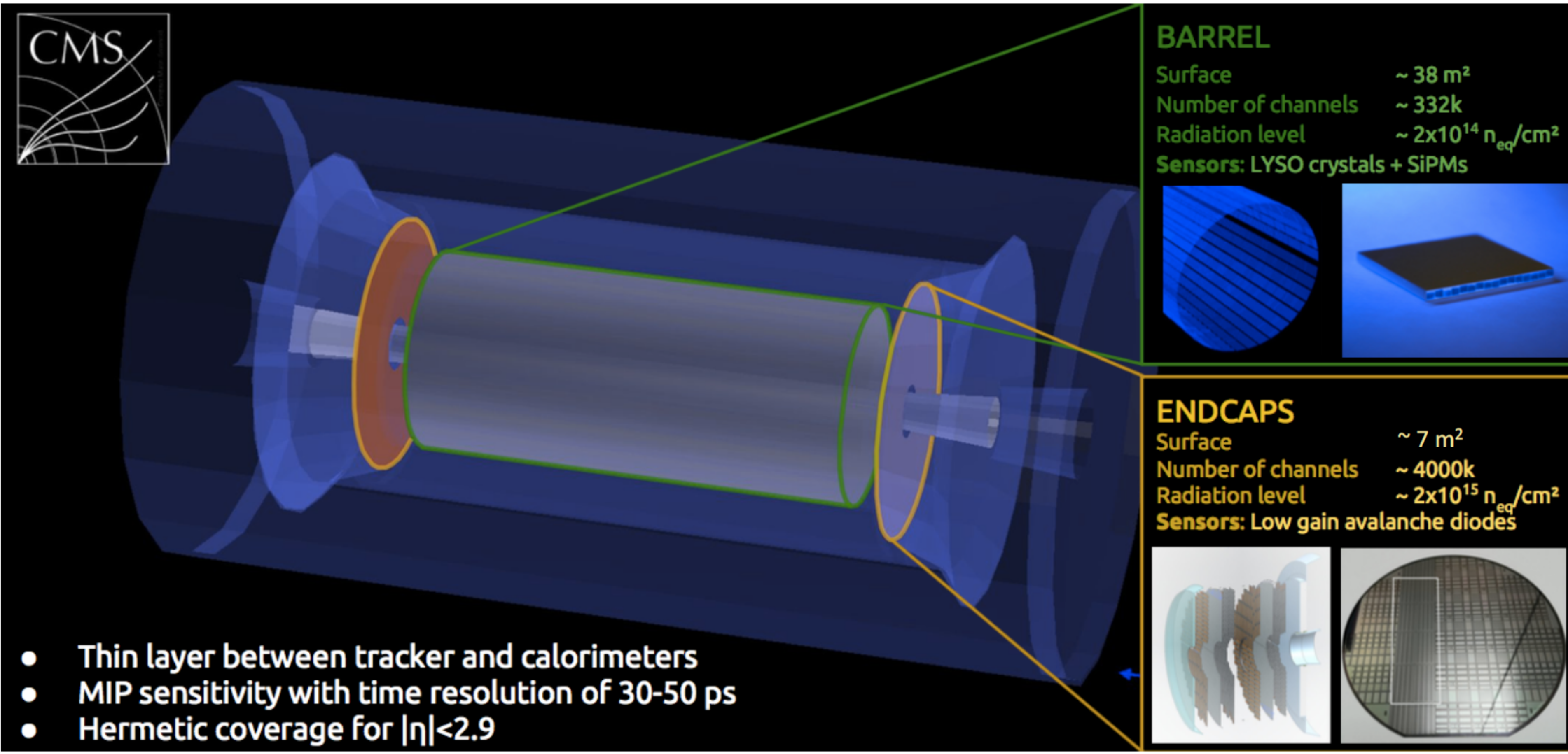
ATLAS Timing detector - HGTD

High Granularity Timing Detector

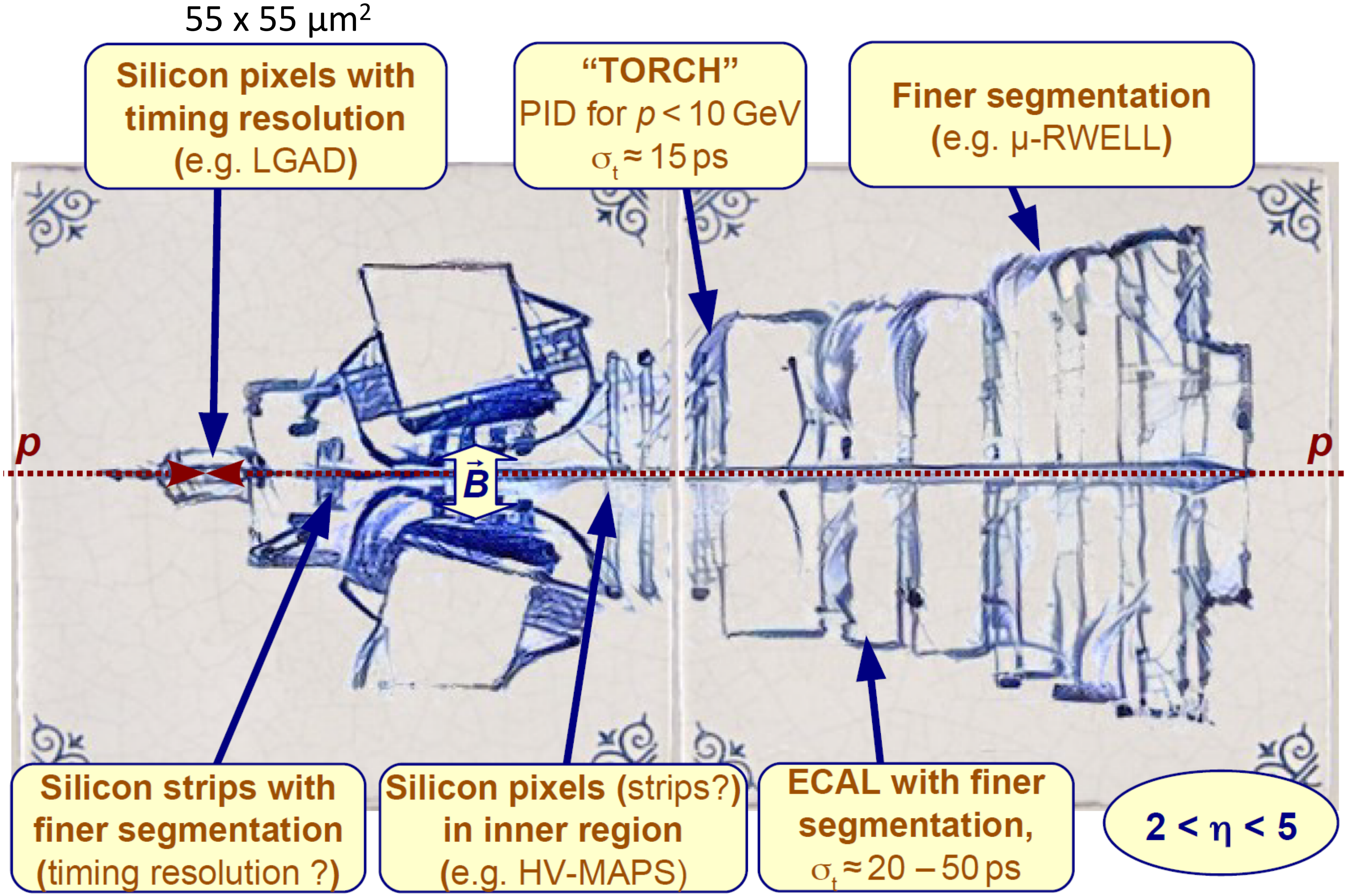
- $|z| = 3.5$ m
- 75 mm total thickness
- $2.4 < |\eta| < 4.0$
- 120 mm < R < 640 mm
- 2 layers
- 3 hits per track at $3.2 < |\eta| < 4$
- 2 hits per track at $2.4 < |\eta| < 3.2$
- $1.3\text{x}1.3\text{mm}^2$ granularity
- 30 ps time resolution per MIP
- max $5\text{x}10^{15}$ n_{eq}/cm^2, 4.7 MGy
- LGAD silicon sensors



CMS Timing detector

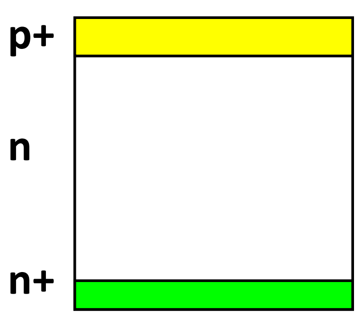


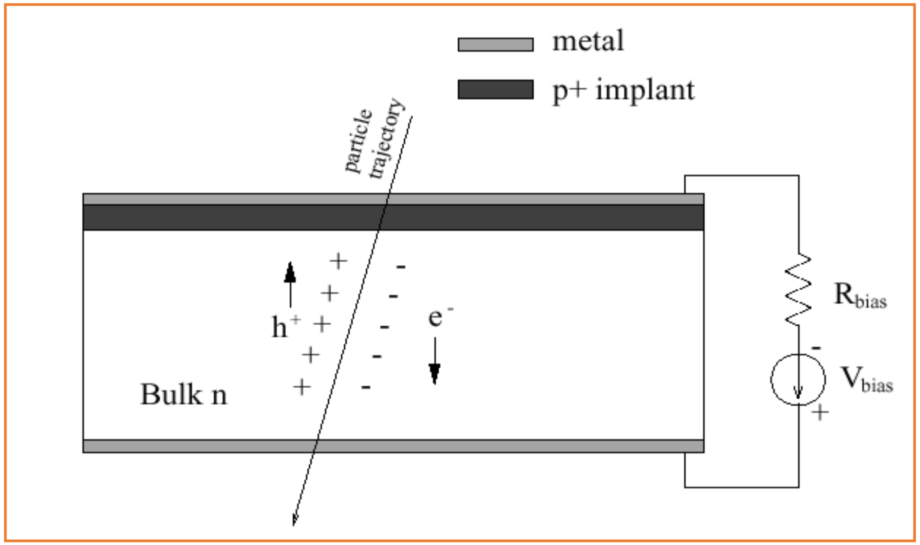
LHCb Upgrade II – Run 5



Recap on Silicon Detectors - Working Principles

- **Standard Si Detectors are p^+- n diodes made on high resistivity silicon:**
- **Float Zone silicon (FZ)**
- **n-type: 2…20 KΩcm**
- **[P] = 20…2×10^{11} cm^{-3} (very low concentration, below 1ppba)**
- **crystal orientation: <111> or <100>**

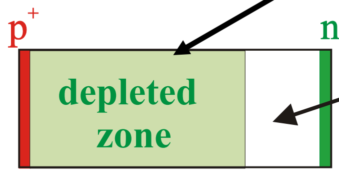




Reminder: Reverse biased abrupt p⁺-n junction

Poisson's equation

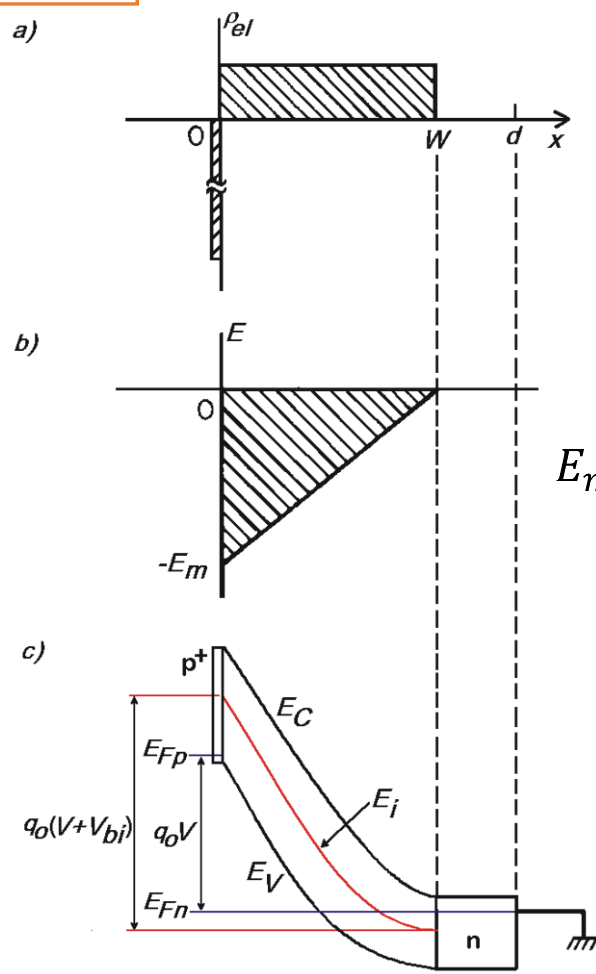
$$-\frac{d^2}{dx^2}\phi(x) = \frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}$$

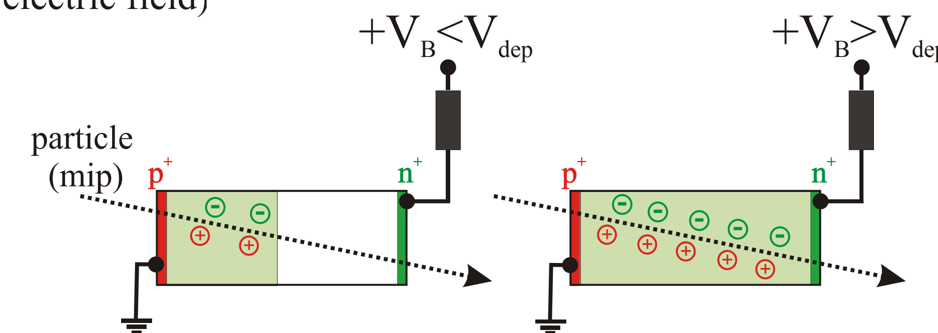


Electrical charge density

Electrical field strength

Electron potential energy





Full charge collection only for $V_B>V_{dep}$!

$$E_{max} = -\frac{Q_d}{\epsilon} = -\frac{qN_dW}{\epsilon}$$

depletion voltage

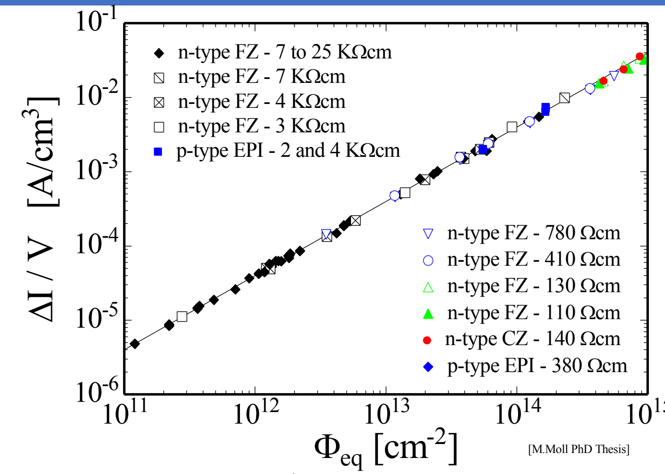
$$V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0}\cdot\left|N_{eff}\right|\cdot d^2$$

effective space charge density

Radiation damage

- Leakage current increase

$$\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}$$



- Charge trapping

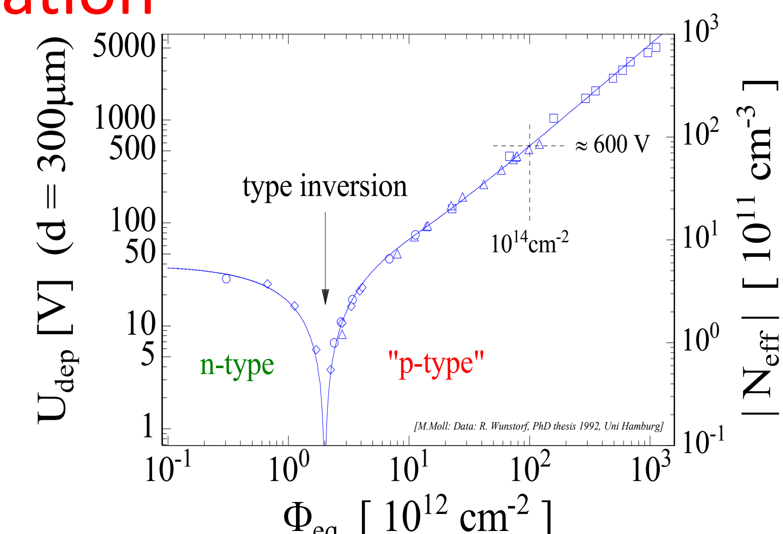
$$Q_{e,h}(t) = Q_{0_{e,h}} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t\right) \quad \textbf{where} \quad \frac{1}{\tau_{eff\ e,h}} \propto N_{defects}$$

- Dopant removal & Acceptor creation

Removal of shallow dopant level

Production of acceptor like defect

$$\Delta N_{eff}(\Phi) = \left| N_{C0}(1 - e^{-c\Phi}) - \beta \cdot \Phi \right|$$



Impact Ionization

- In high electric fields electrons and holes acquire enough energy to initiate sizeable charge multiplication

Electrons ≥ 300 kV/cm

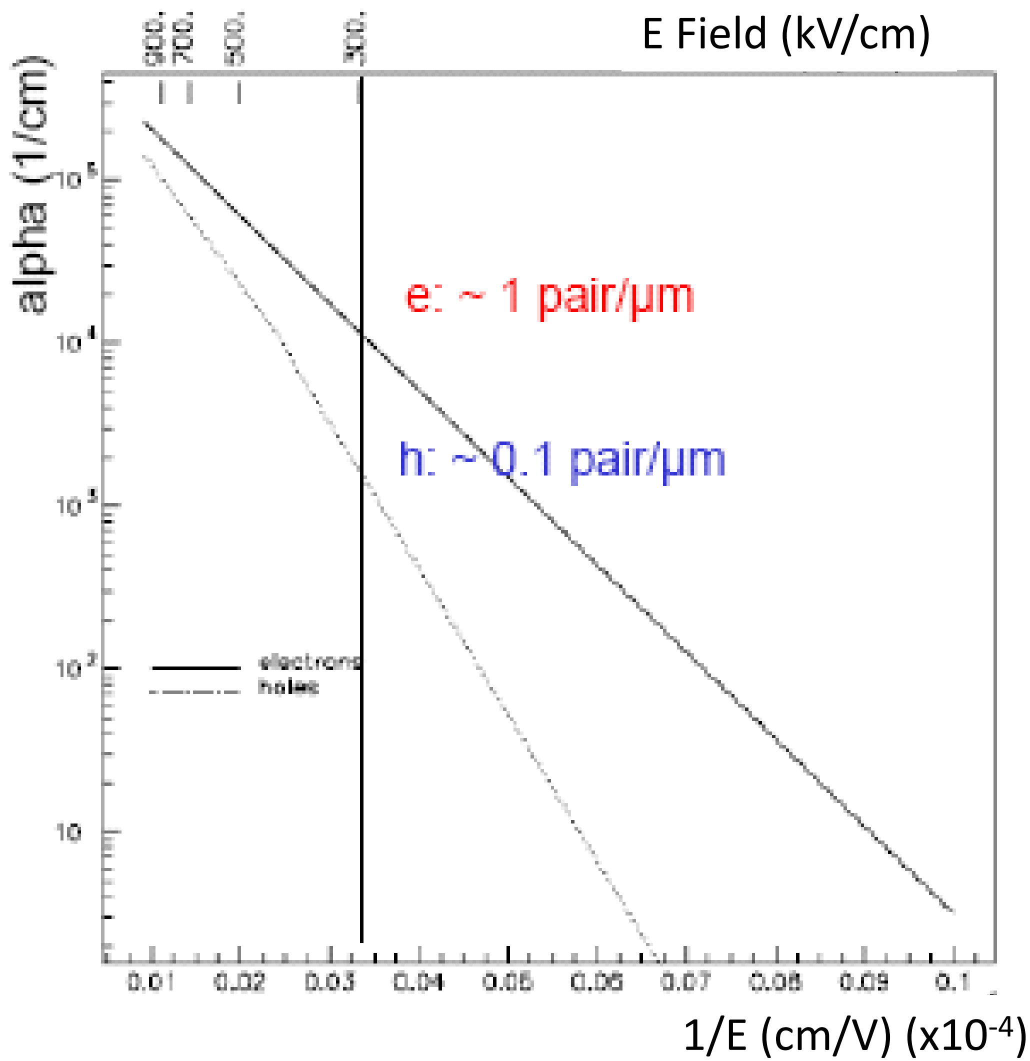
Holes ≥ 400 kV/cm

Charge multiplication in path length *ℓ:*

$$N(\ell) = N_0 \exp(\alpha\ell)$$

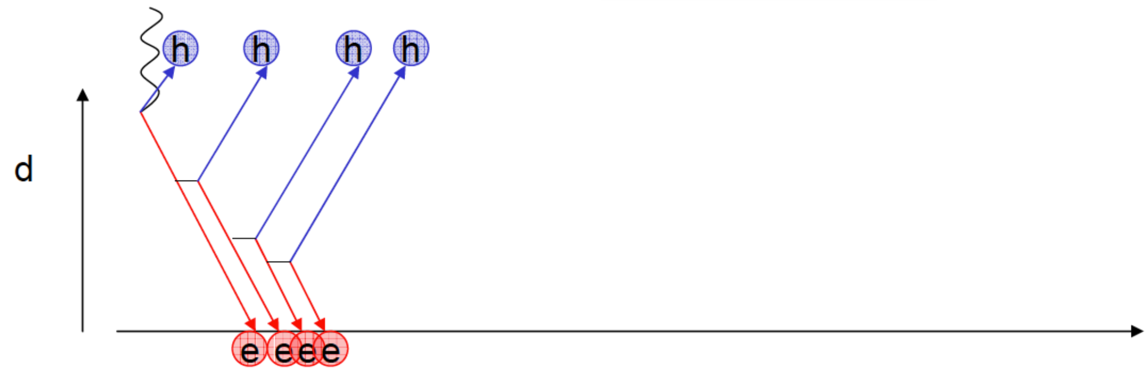
$$\alpha_{e,h}(E)$$

Overstraeten impact ionization model

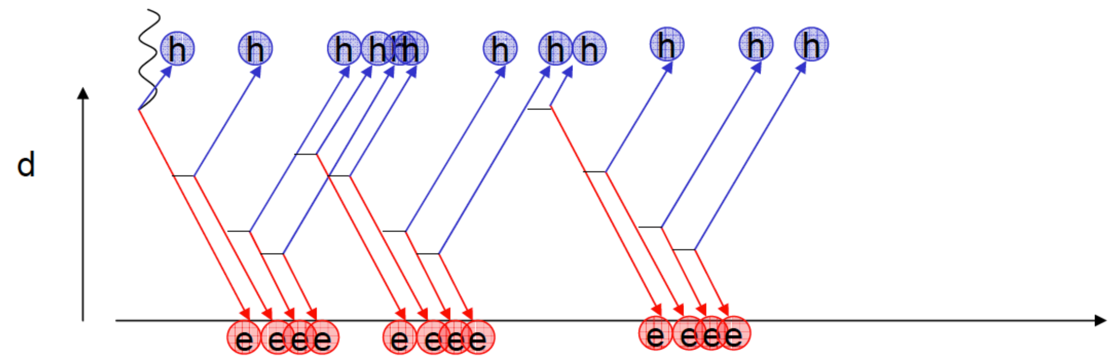


Three Gain Modes

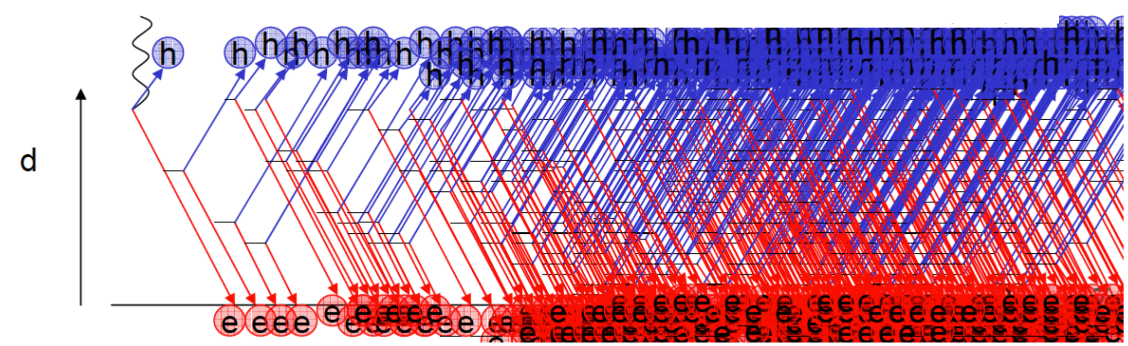
- 300 kV/cm < E < 400 kV/cm
  - Only electrons ionize
  - Linear mode
  - Gain < 10
  - N(l) = exp(αl) with l=path length in high electric field



- E ~ 400 kV/cm
  - Both electrons and (rarely) holes ionize
  - Still linear mode
  - Gain: 50 – 300
  - Excess noise: $\sigma(N) \sim k\,N$, $k=\alpha h/\alpha e$

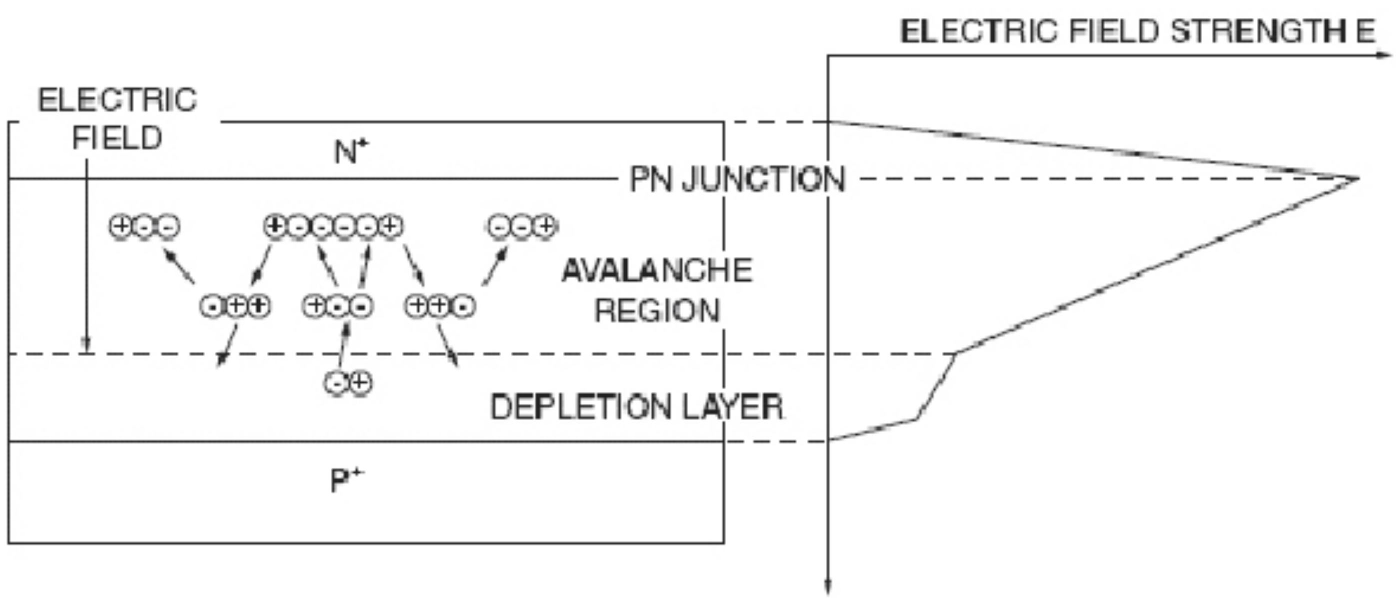


- E > 400 kV/cm
  - Both electrons and holes ionize
  - Geiger mode
  - Gain: infinite (breakdown)



Avalanche photodiode

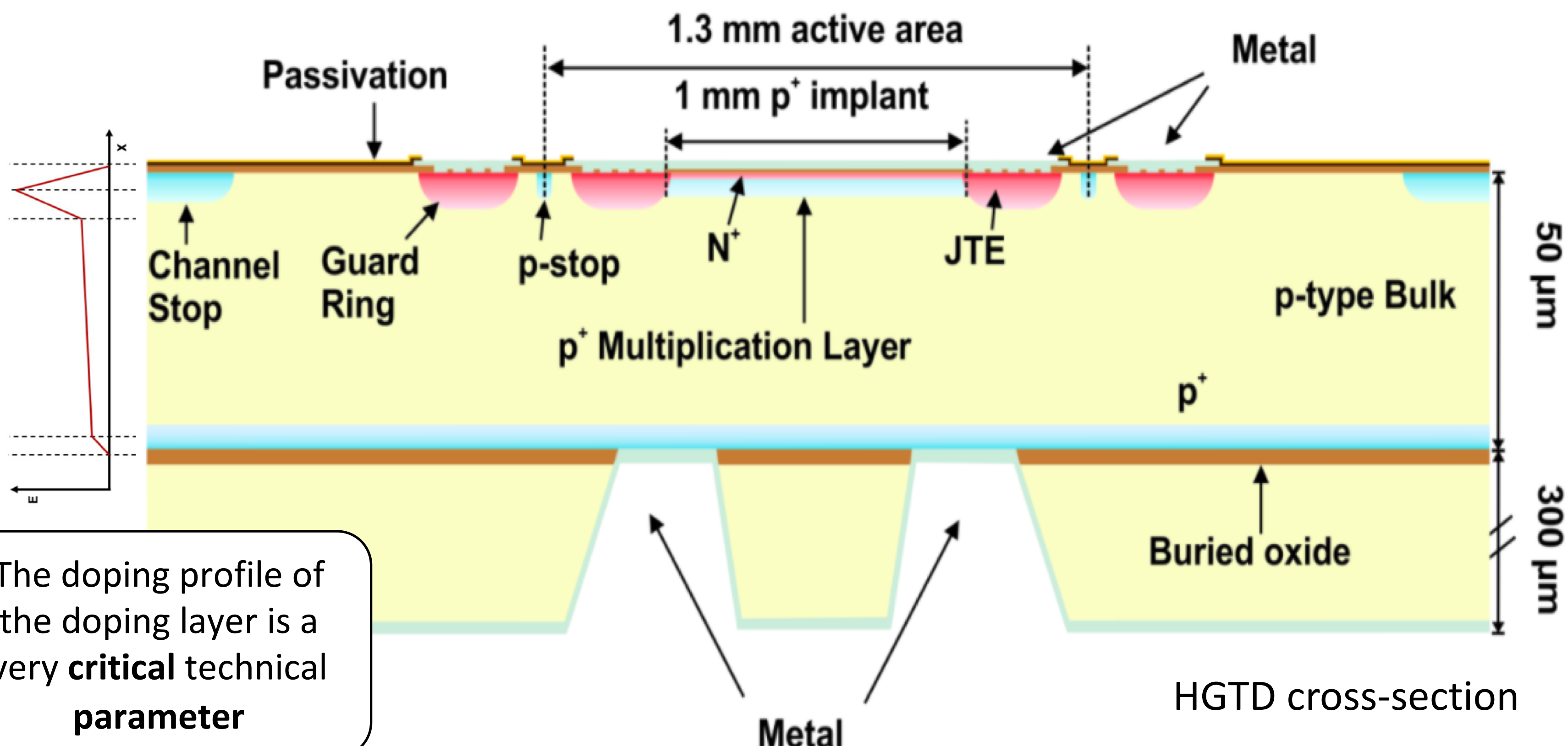
- High field region produced in APDs to create gains 10x to 100x
- Geiger mode for SP-APDs
  - APD operated just below breakdown voltage
  - Requires a quenching resistor to bring stability
  - Have excess noise & dark signals



Design of Low Gain Avalanche Detector

- LGAD has extra doping layer to rise E-Field near cathode
  - n^{++}-p^{+}-p^{-}-p^{+}
  - Q_d is very now large
  - Very large E-field in p^{+} region

$$E_{max} = -\frac{Q_d}{\epsilon} = -\frac{qN_dW}{\epsilon}$$



The doping profile of the doping layer is a very **critical** technical **parameter**

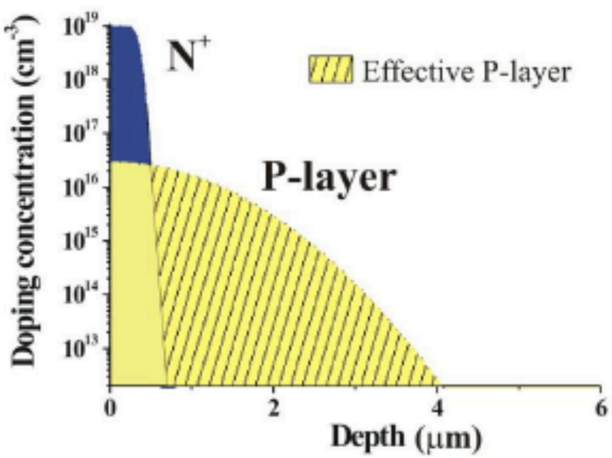
HGTD cross-section

Optimum design of multiplication doping layers

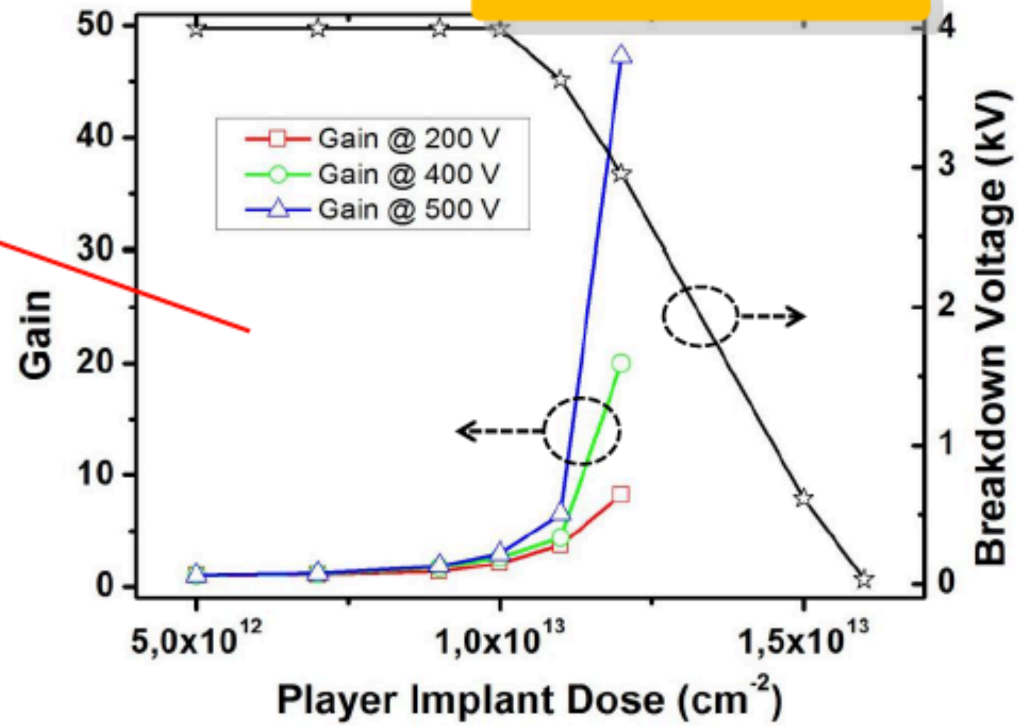
Gain/V_{BD} trade-off

✓ If implant dose increases:
- Gain increases
- V_{BD} decreases

❑ **Technological adjust of the multiplication region p-layer becomes critical.**



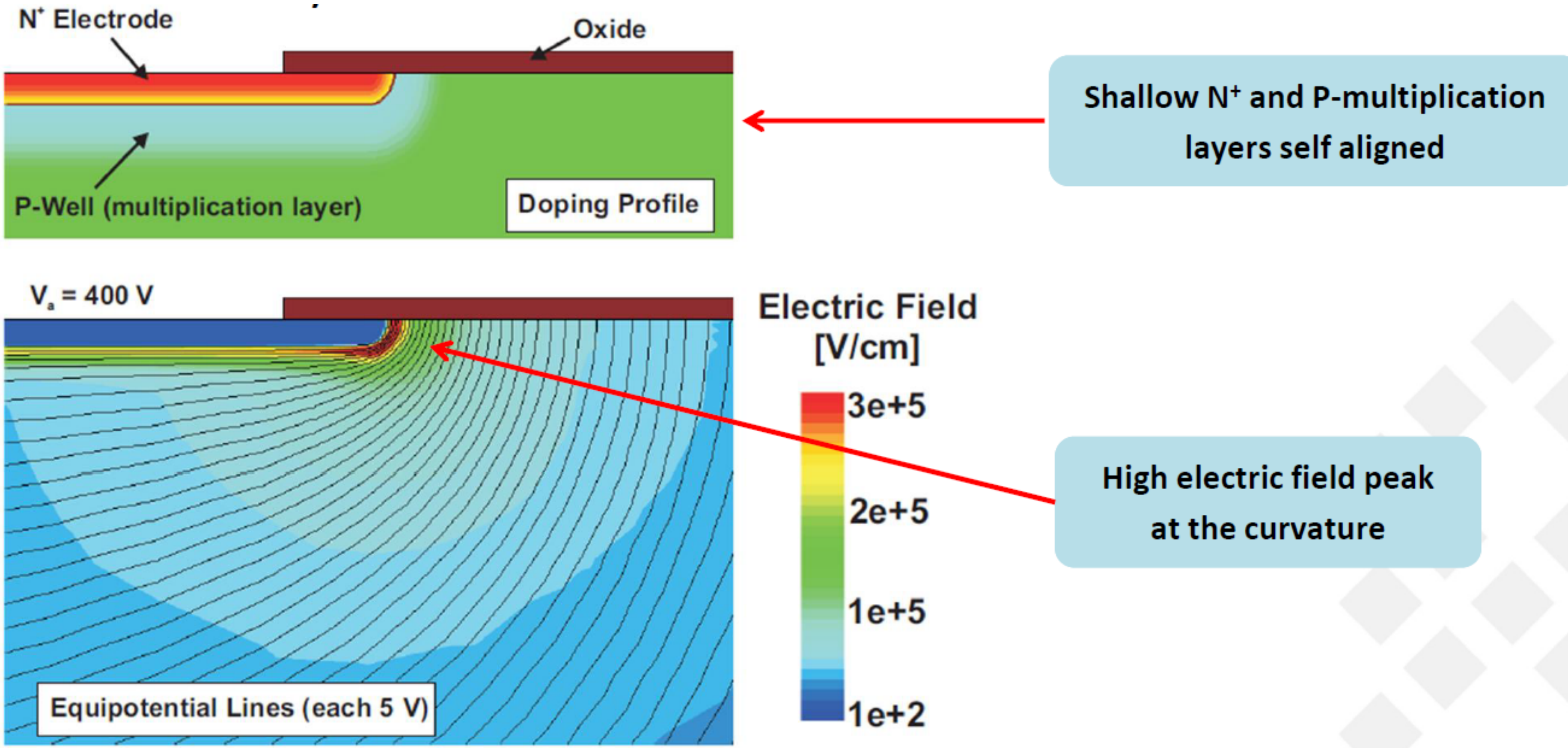
1D Simulation @ Pad Centre



Small modifications in the Boron implant dose (~ 2×10^{12} cm^{-2}) induce great changes in Gain and V_{BD}

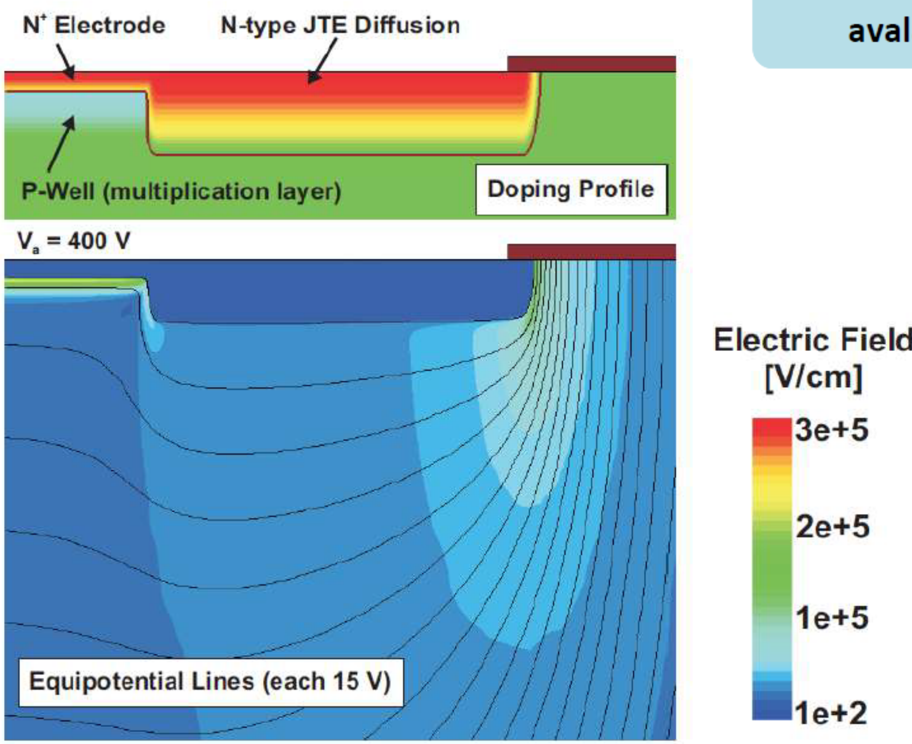
Edge Termination: Why is it needed?

- The electric field at the corner curved section of the N^{++}/P^{+} junction is much higher than that of the flat junction region
  - where Gain is required
- Avalanche at the N^{+}/P^{+} curvature at a very low reverse voltage
  - -> premature breakdown

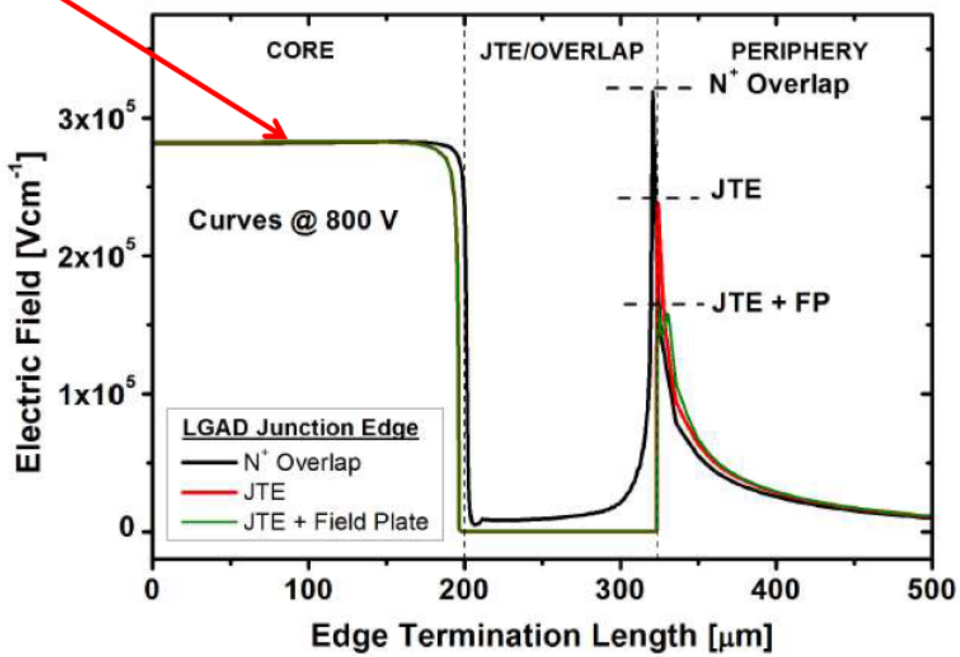


Edge termination with Junction Termination Extension

- Deep N++ diffusion with high curvature radius
  - Long anneal process
- Reduced electric field peak at the JTE diffusion
- Highest electric field at the plane junction
  - Gain control
  - $V_{BD\text{-}Plane} < V_{BD\text{-}JTE}$

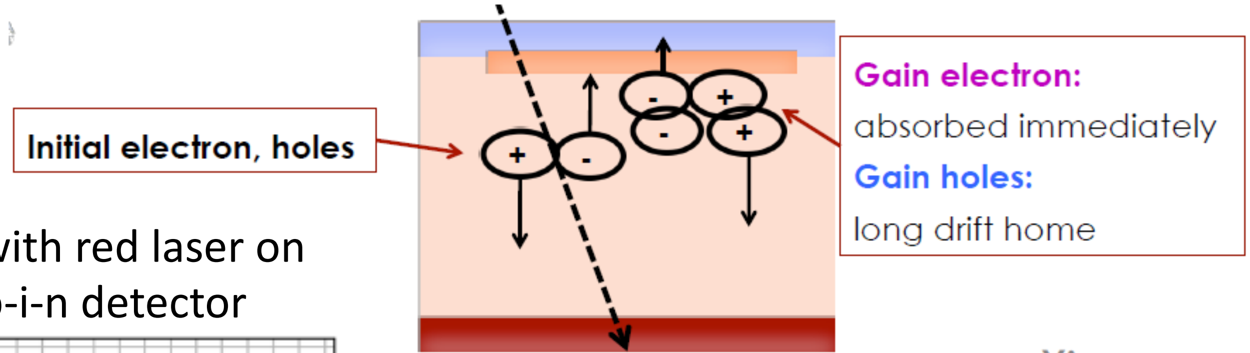


Multiplication and avalanche control

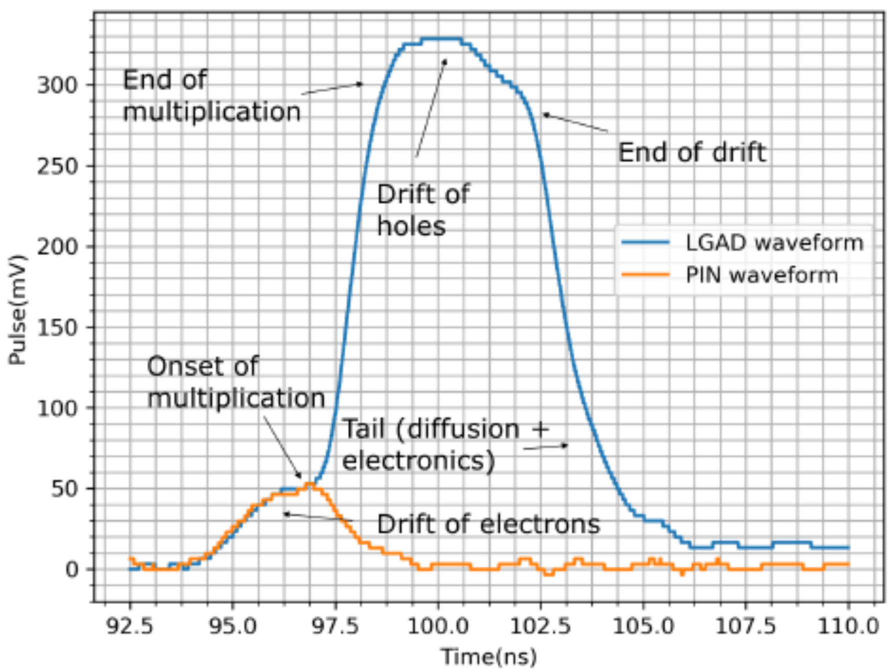


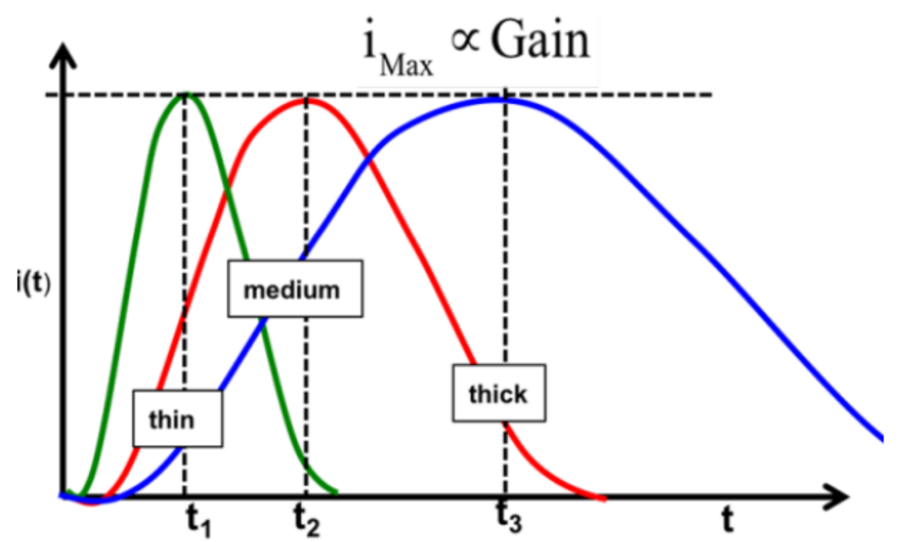
Do we get gain from our signal?

- Electrons collected at front contact
- Holes at rear



Backside illumination with red laser on 200 µm thick LGAD & p-i-n detector

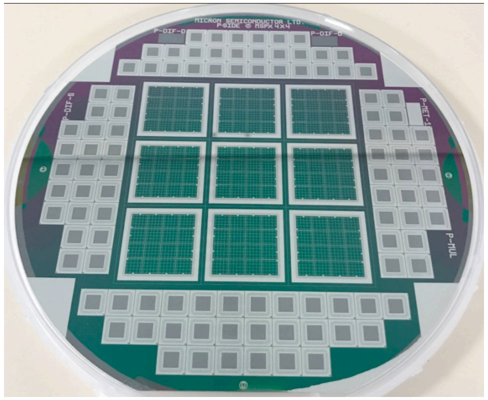




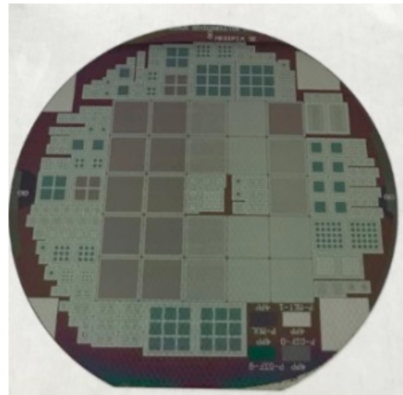
Maximum current does not depend on device thickness

Many productions

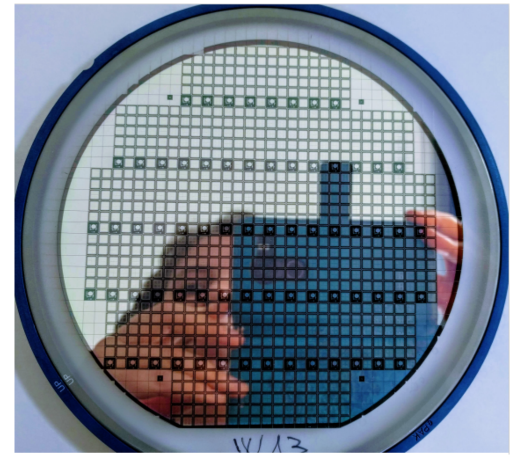
Micron pad devices



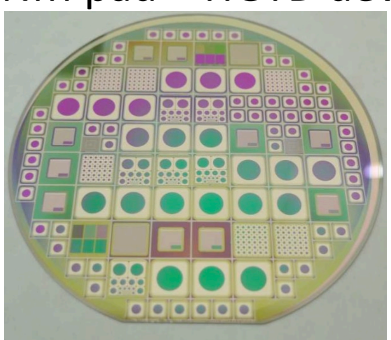
Micron TimepPix + HGTD



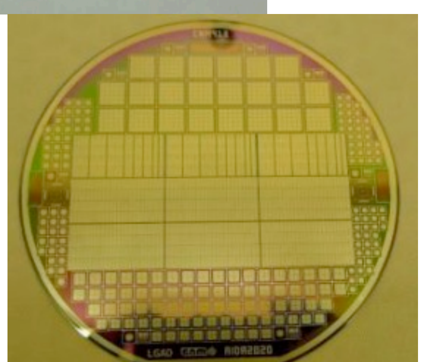
FBK guard ring investigations



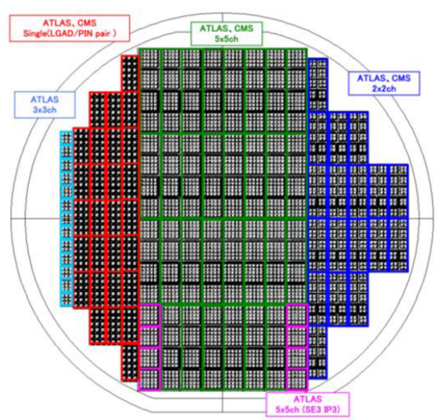
CNM pad + HGTD devices



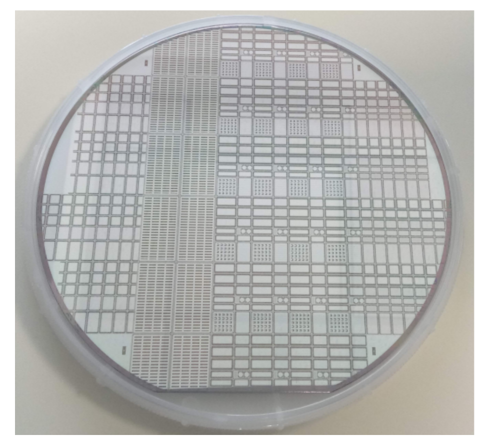
CNM AIDA



HPK – ATLAS & CMS



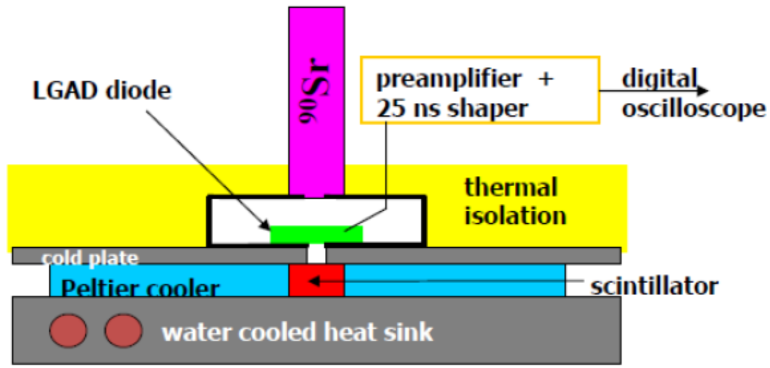
FBK Doping investigations



Measurement techniques

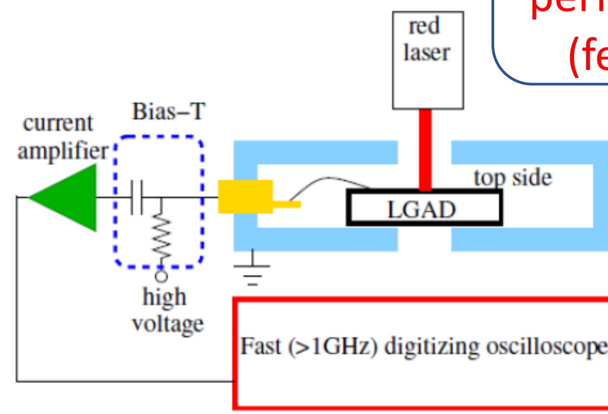
“MIP” charge collection

CCM setup

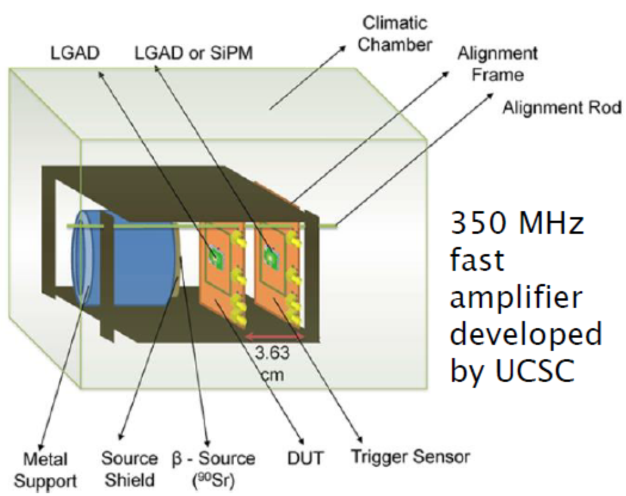


TCT setup

Spatial and temporal performance (few μm)



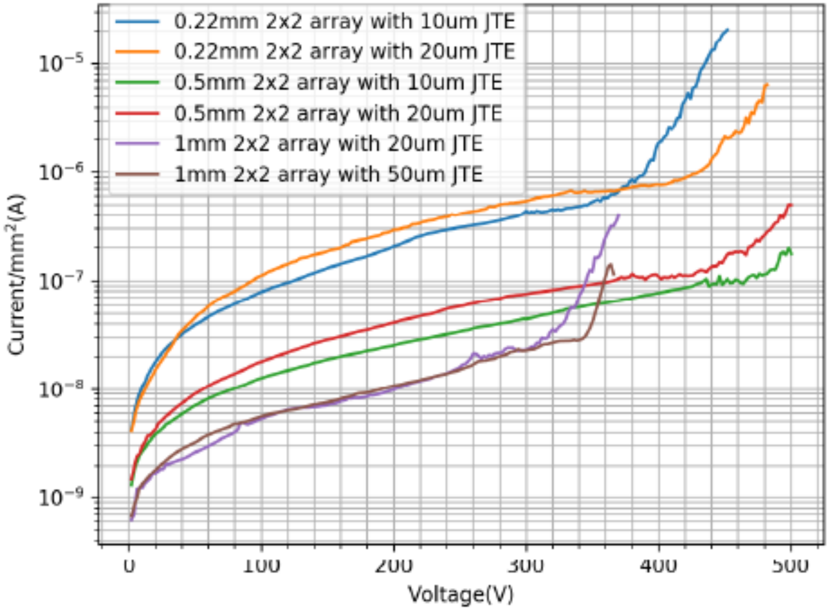
Timing setup



350 MHz fast amplifier developed by UCSC

Timing resolution (few ps)

Electrical characterisation

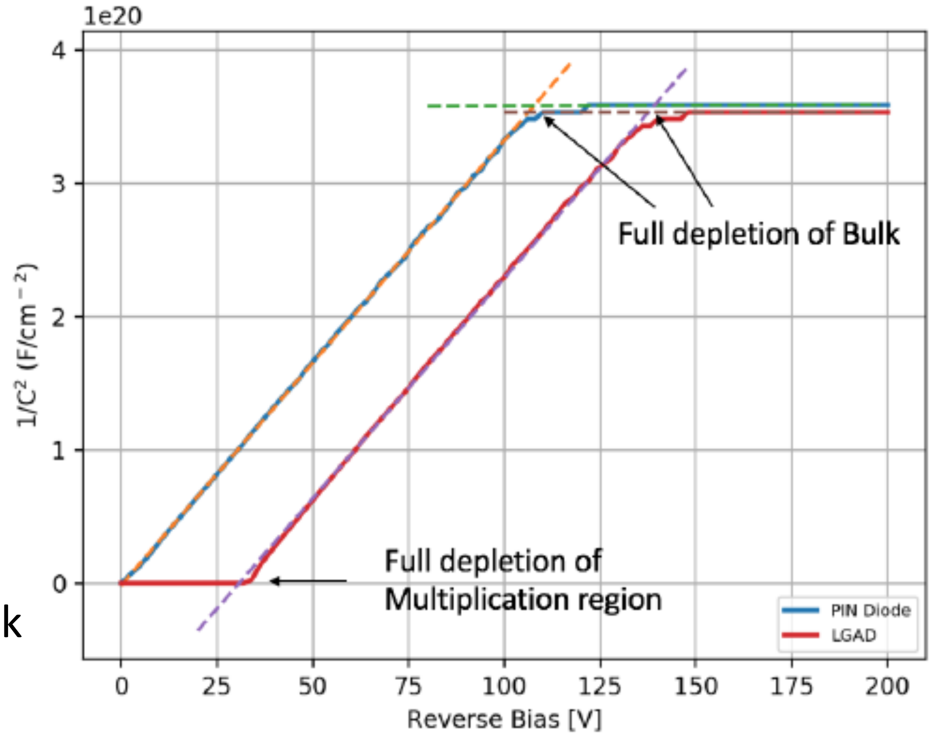


Current comparable to PIN

Current density higher for small pads

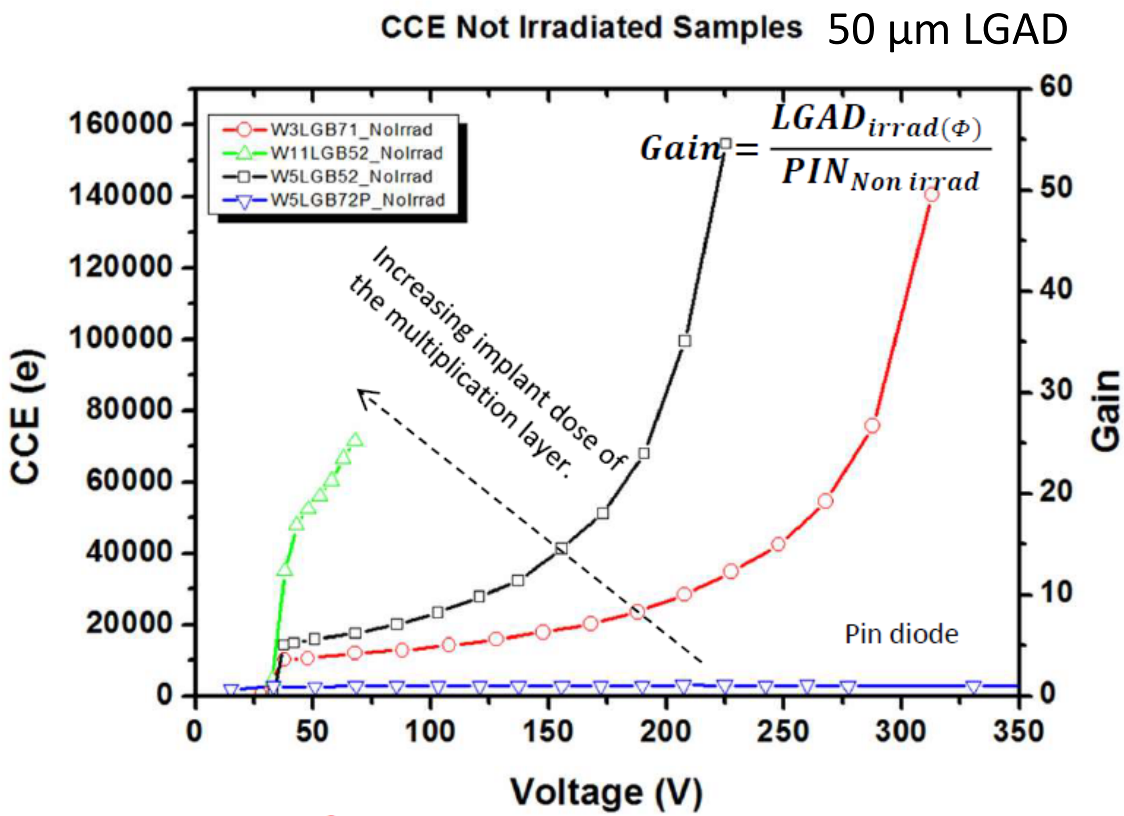
-> higher E-fields

VBD increased with wider JTE



Depletion of Gain implant followed by bulk

LGAD results – Charge collection



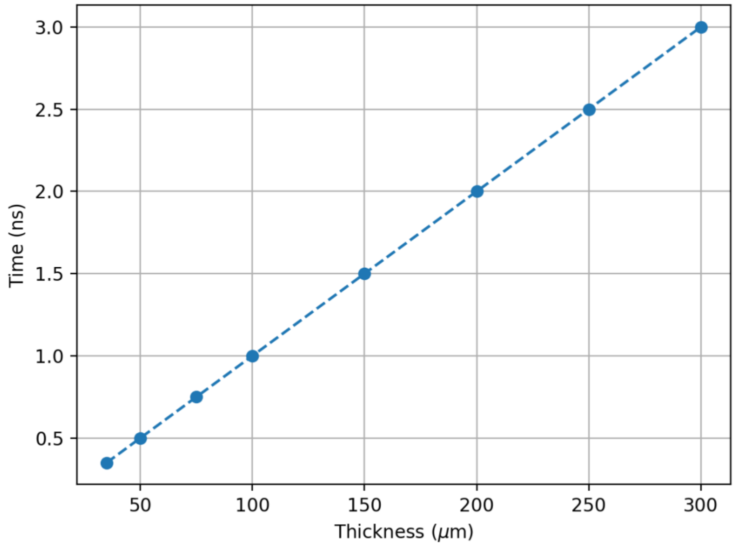
Dose1=1.8e13 cm^{-2}
Dose2=1.9e13 cm^{-2}
Dose3=2.0e13 cm^{-2}

- Increasing implant dose-> higher gain

  -> lower breakdown voltage

Ultra fast silicon detectors

- You get fast detectors from Thin detectors operating with saturated carrier drift velocities
- For MIPs the deposited charge depends on sensor thickness
  - Thin devices have small deposited charge
  - Charge multiplication will give sufficient charge



Electron drift time as a function of sensor thickness

Collected charge & collection time

Signal = thickness*EPM (electrons deposited per micron)

Collection time = thickness/saturation velocity (80μm/ns)

Thickness [um]	BackPlane Capacitance [fF]	Signal [# of e-]	Coll. Time [ps]	Gain req. for 2000 e
0.1	2500	8.3	1.3	241.0
1	250	83	12.5	24.1
2	125	166	25.0	12.0
5	50	415	62.5	4.8
10	25	830	125.0	2.4
20	13	1660	250.0	1.2
100	2.5	8300	1250.0	0.2
300	0.8	24900	3750.0	0.1

Realistic gain & cap

Good time resolution

For thickness > 5 um, Capacitance to the backplane Cb << Cint

For thickness = 2 um, Cb ~ ½ of Cint, charge spreading issues?

Timing resolution factors

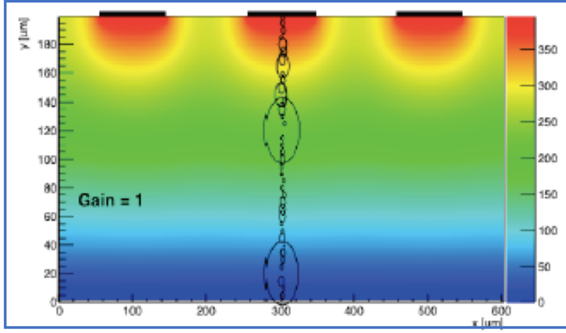
- Timing resolution depends on

$$\sigma^2_{Total} = \sigma^2_{Jitter} + \sigma^2_{Time\ Walk} + \sigma^2_{TDC} + \sigma^2_{Landau\ Noise} + \sigma^2_{Distortion}$$

Signal digitisation - electronics

Non-Uniform Weighting field

$$i(t) = -q v_{drift} \cdot E_w$$



Decreases with detector thickness

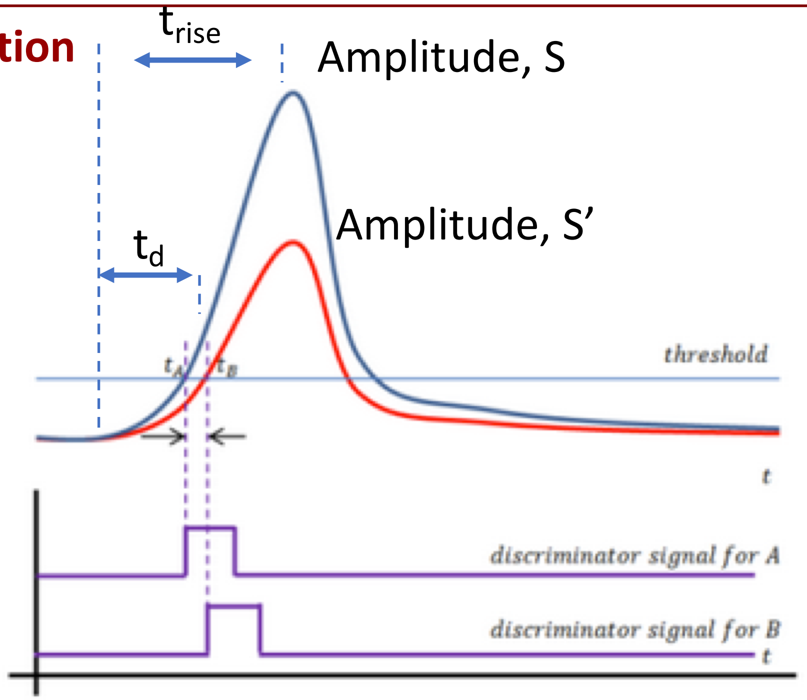
Limit $\sigma_{Landau\ Noise} \approx 20ps$

Time Walk

$$\sigma^2_{Total} = \sigma^2_{Jitter} + \sigma^2_{Time\ Walk} + \sigma^2_{Landau}$$

Time walk: the threshold voltage, V_{th}, is crossed at different time for signal of different amplitudes.

Due to the physics of signal formation



Time walk effect

$$\sigma_{TW} = [t_d]_{RMS} = \left[\frac{V_{th}}{S/t_{rise}}\right]_{RMS} = \left[\frac{N}{dV/dt}\right]_{RMS}$$

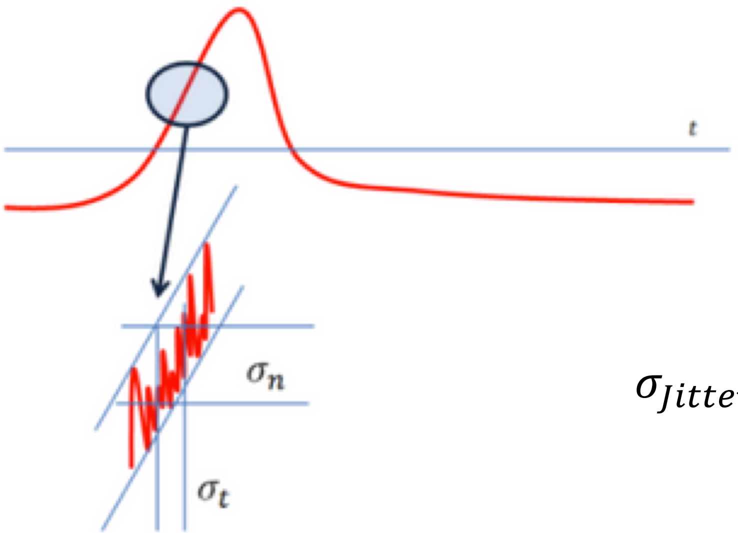
To minimize the time resolution error
-> maximize the signal slew rate dV/dt

Time jitter

$$\sigma^2_{Total} = \sigma^2_{Jitter} + \sigma^2_{Time\ Walk} + \sigma^2_{Landau}$$

Jitter: the electronics noise is summed to the signal, causing amplitude variations

Mostly due to electronic noise



$$\sigma_{Jitter} = \left[\frac{N}{dV/dt}\right]_{RMS} = t_{rise}/\left(\frac{S}{N}\right)$$

To minimize the time resolution error we need to maximize the S/t_{rise} term i.e. the slew rate dV/dt of the signal & electronics

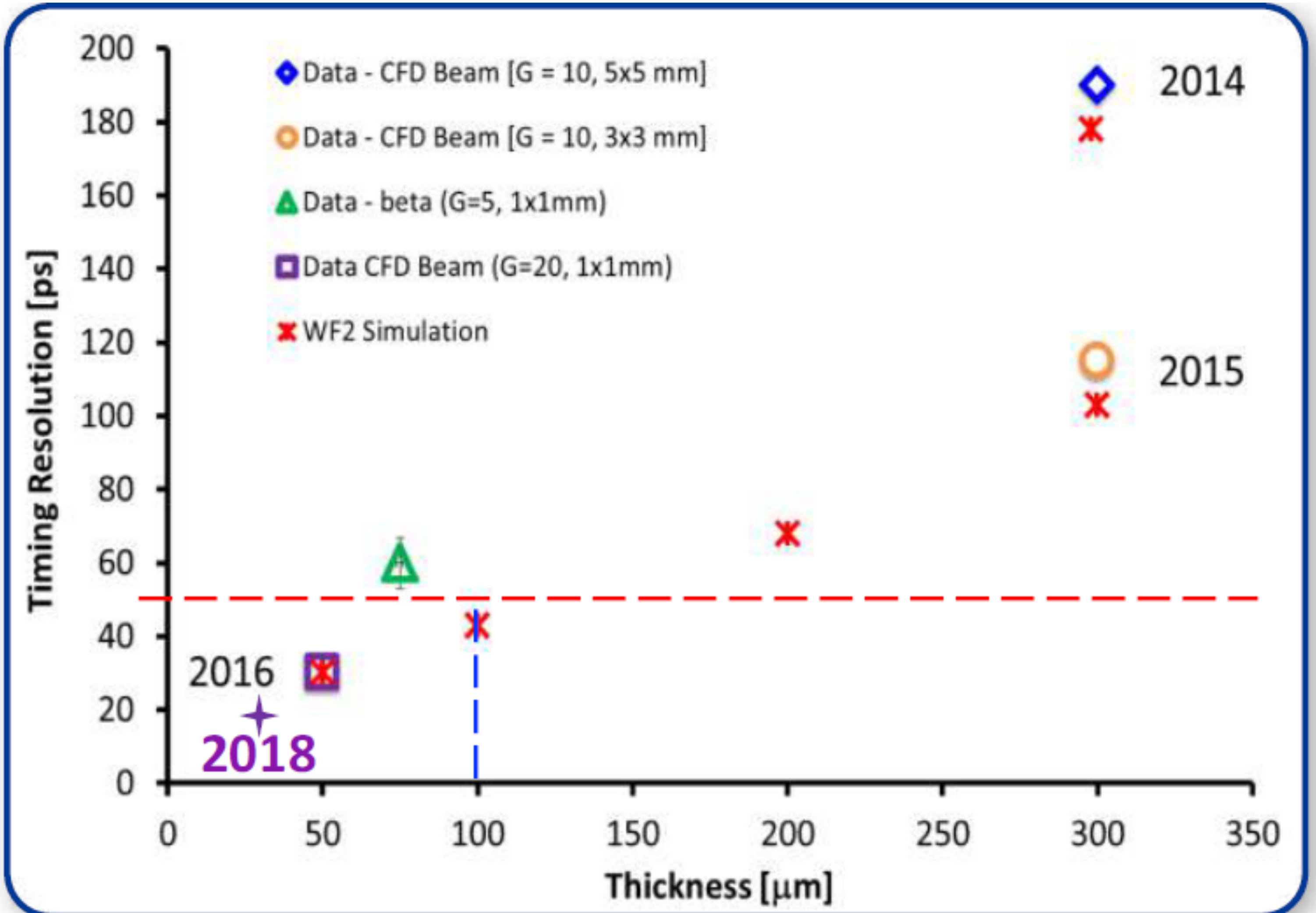
Timing Summary

- Small Landau fluctuations -> thin detectors
- Fast collection times -> thin detectors
- Uniform weighting field
- Max Signal -> High Gain
- Small Noise-> No excess noise from gain mechanism

  -> moderate gain

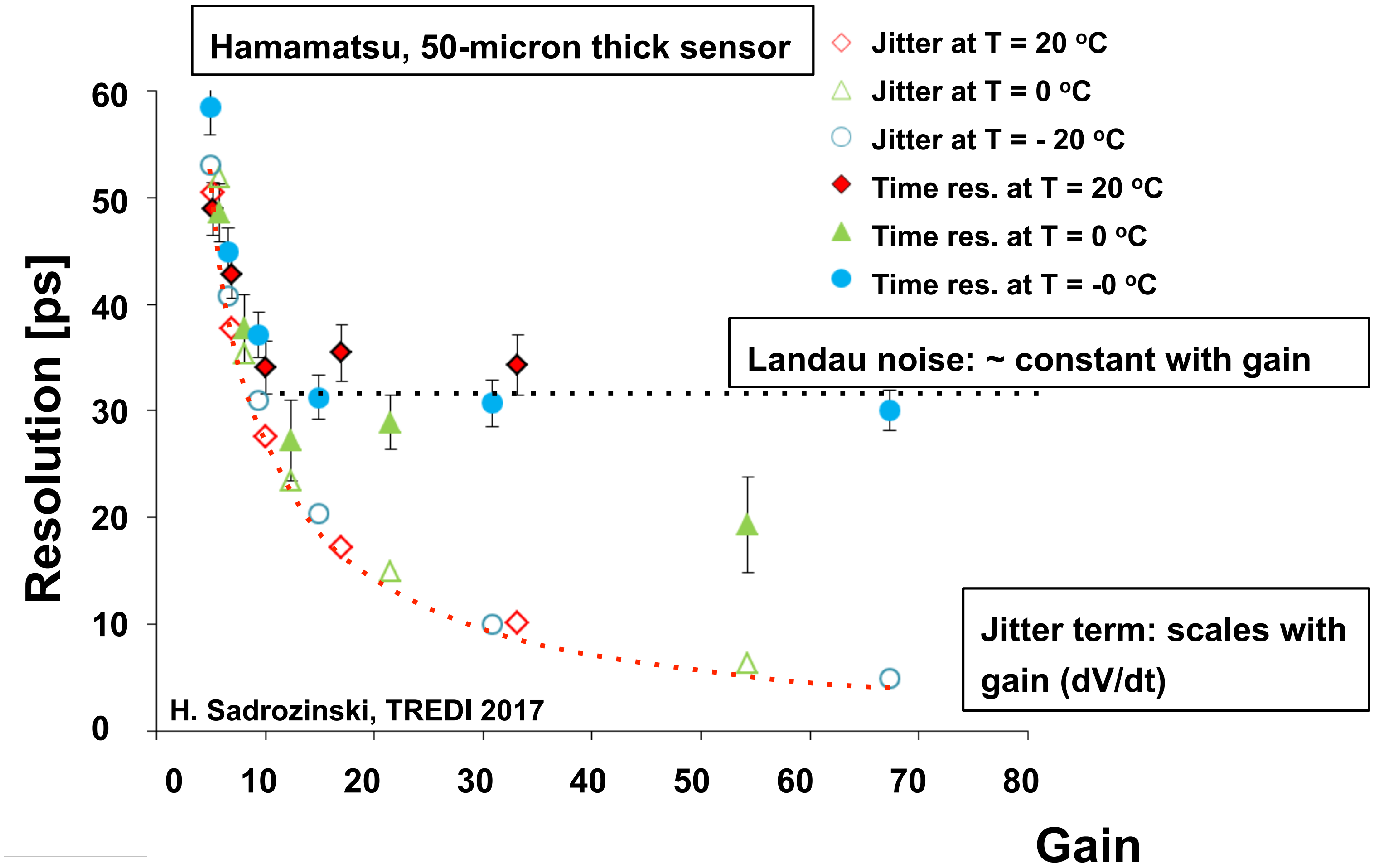
- Thinner detectors improve radiation hardness
  - But increase capacitance

Timing resolution versus thickness



H. F.-W. Sadrozinski, RD50 workshop, Jun 2018

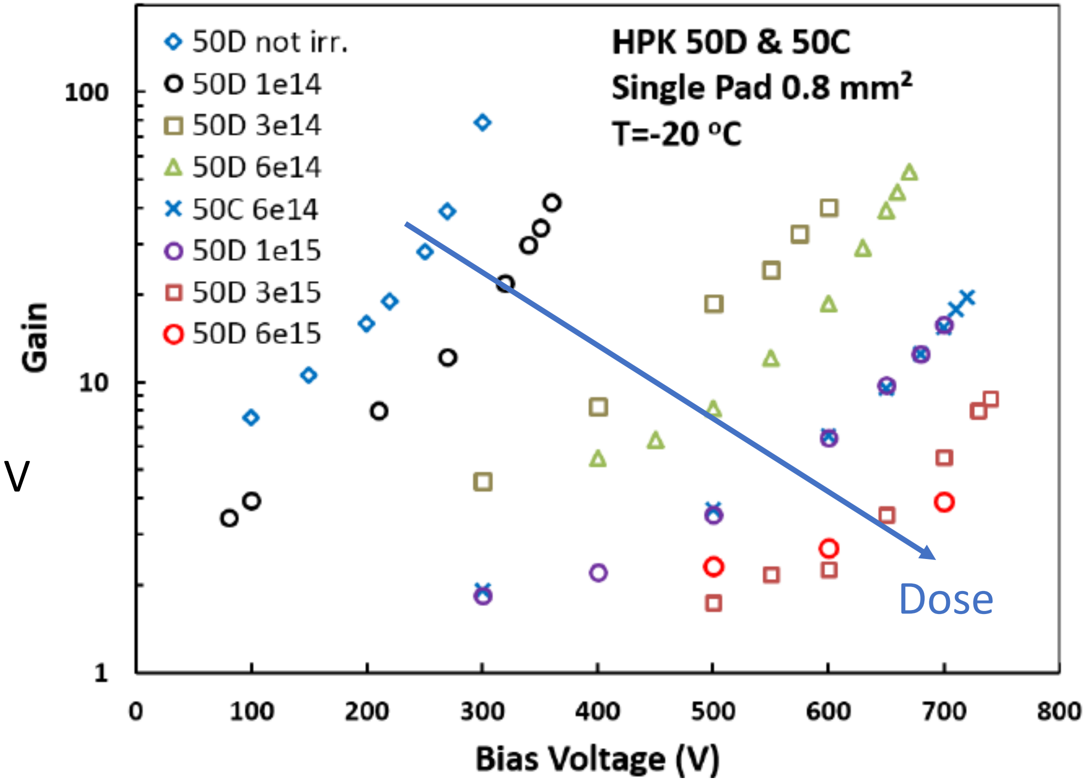
Timing resolution versus Gain



Radiation effects – reduced Gain

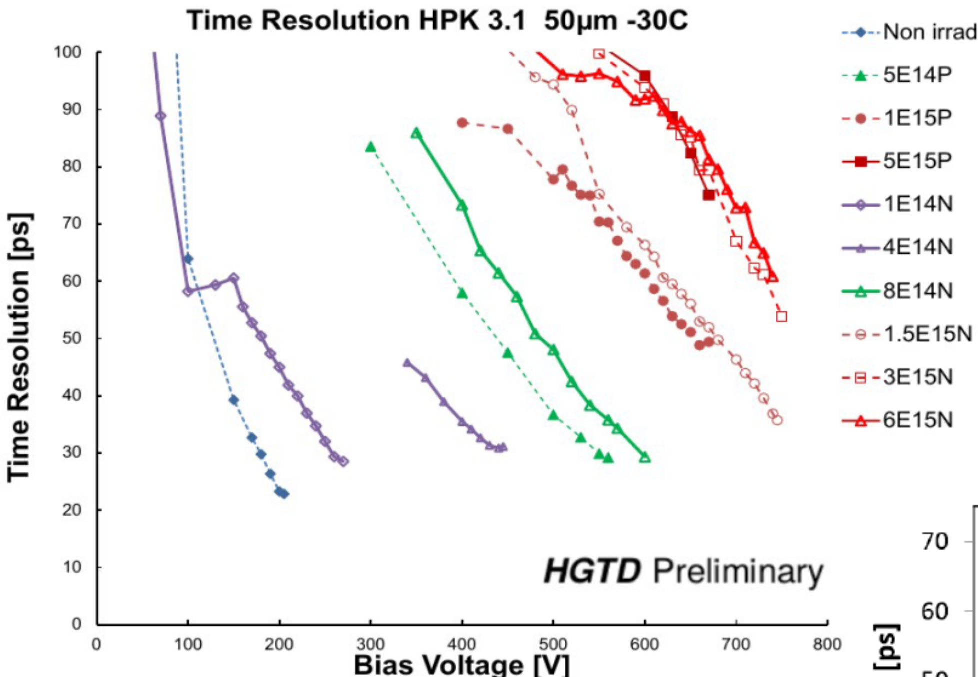
- Acceptor removal
  - Boron in multiplication implant adversely affected
  - Gain reduced
- Deep traps in bulk

HPK LGAD, 50 μm thick

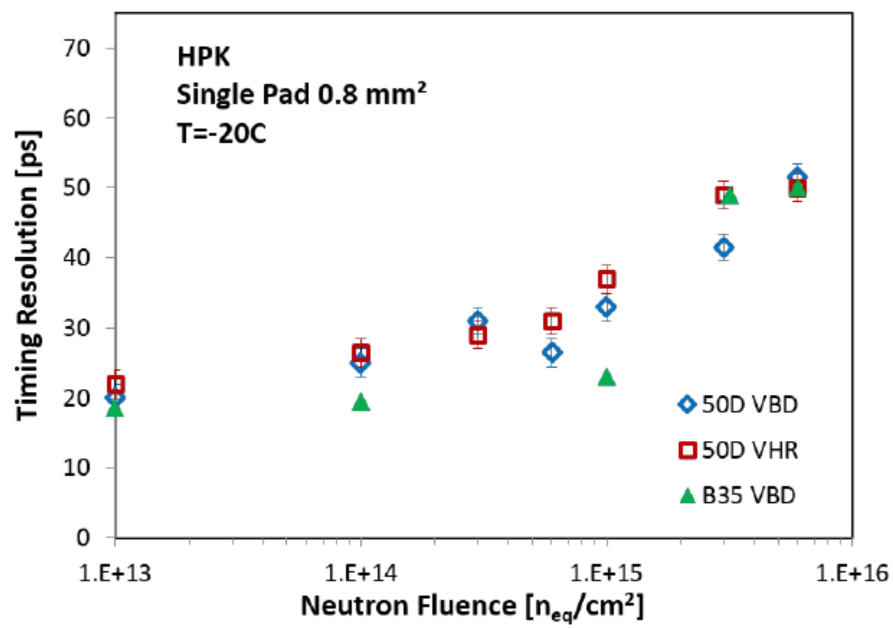


3 x 10^{15} cm^{-2} Gain of 10 at 700 V

Radiation effects – Reduced timing resolution



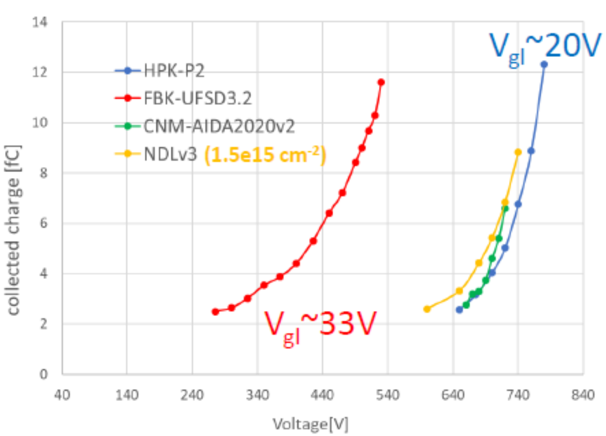
Compensate reduced gain with increased bias voltage

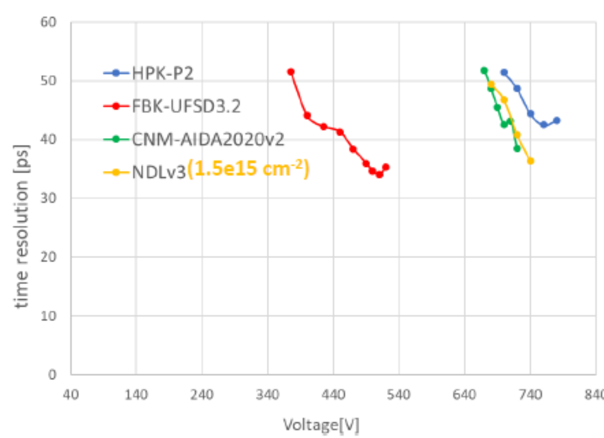


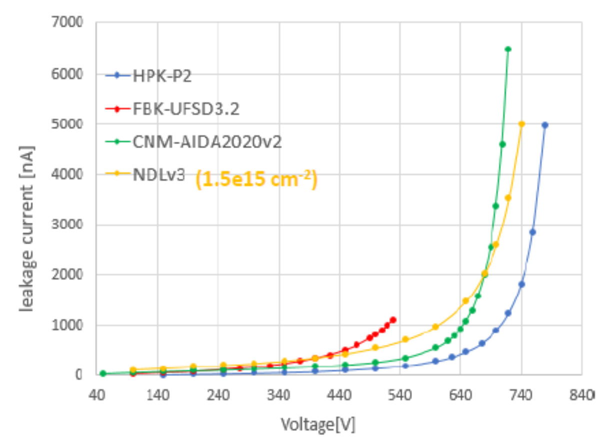
Co-implant Carbon doping

- Ga & Carbon has slower radiation induced removal rate
- FBK performed a process run with Boron and Carbon
- Devices perform very well
  - Except lower breakdown voltages

Comparison after 2.5 x 10^{15} cm^{-2}







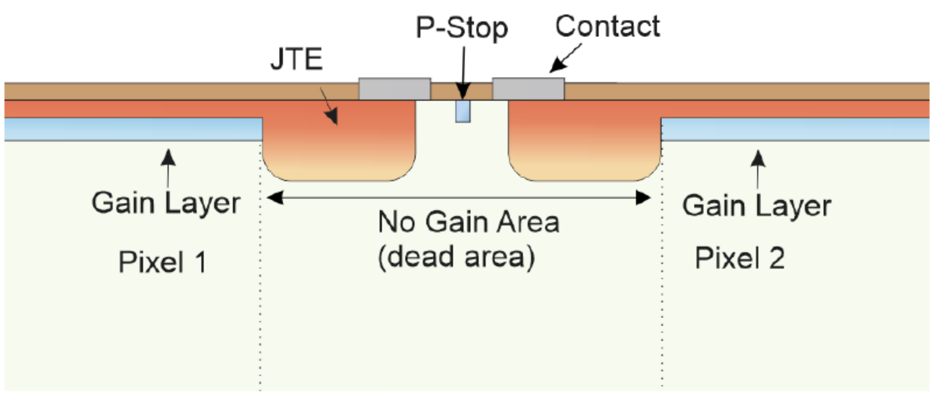
V_{gl} = gain layer depletion voltage

Devices 45 – 55 µm thick

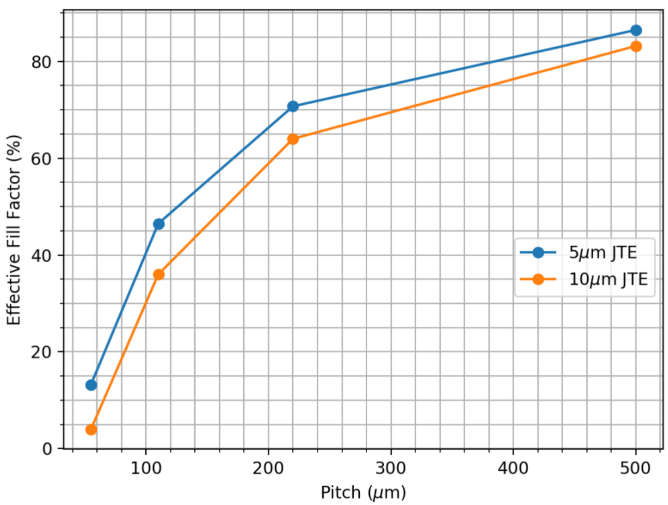
Small pixels – fill factor

- Geometric fill factor
  - Caused by JTE around each pixel
  - Need to take into account diffusion on JTP

$$Fill\ Factor = \frac{Gain\ Area}{Total\ Area}$$

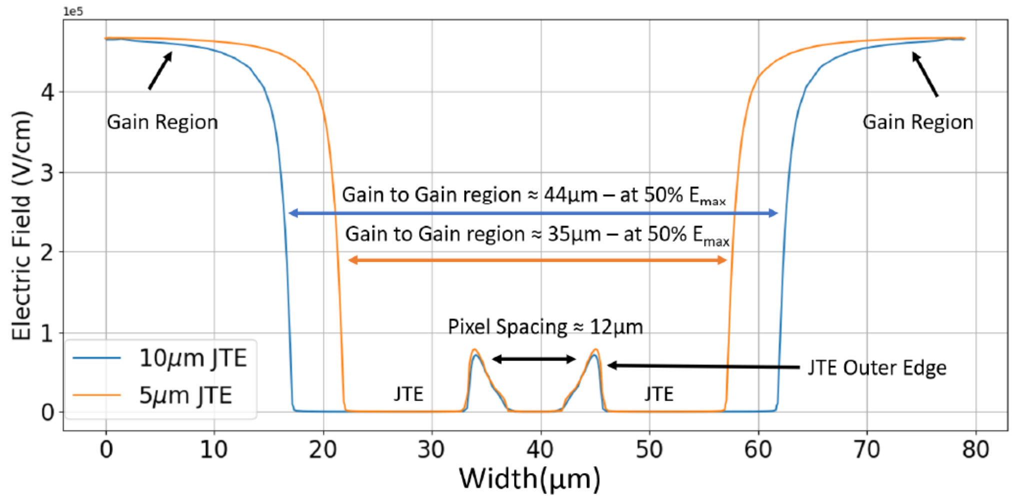


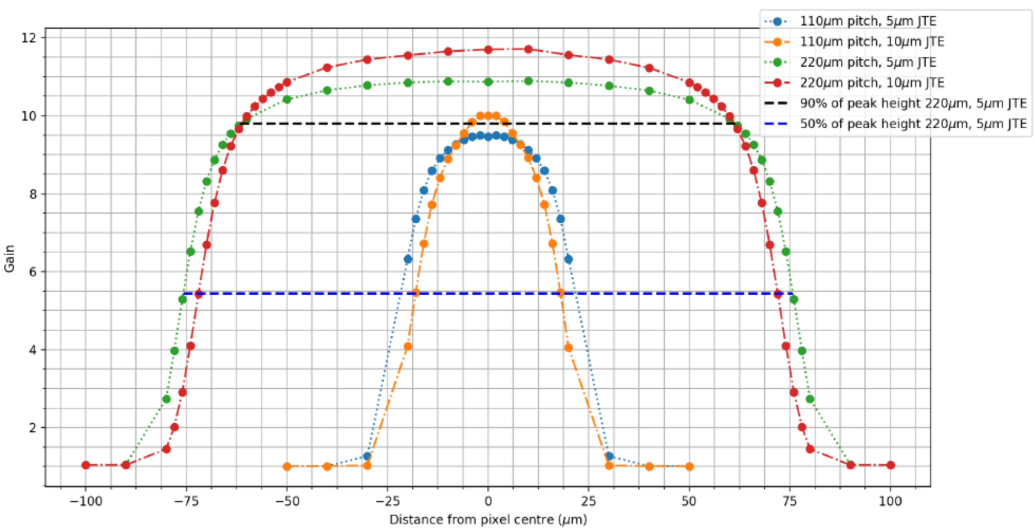
50 x 50 μm² pixel – JTE 10 μm -> fill factor < 10%



Gain fill factor

- JTE reduces E-field at edge of pixel
  - Increases "no gain" area of pixel
  - Reduces fill factor further



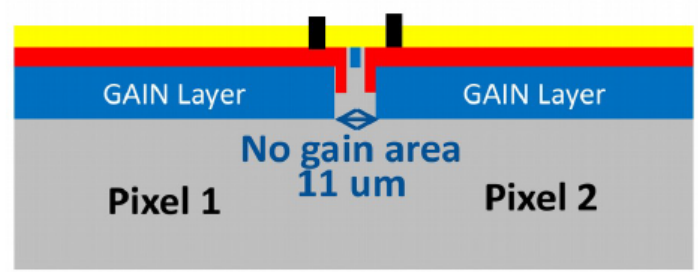


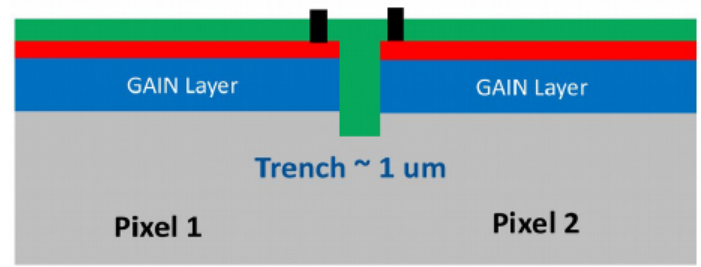
- JTE shields multiplication junction
  - Charge is collected on JTE NOT multiplied
  - 50 μm^2 pixel – 0% Fill factor
  - 110 μm^2 pixel – 18% Fill factor
  - 220 μm^2 pixel – 47% Fill factor

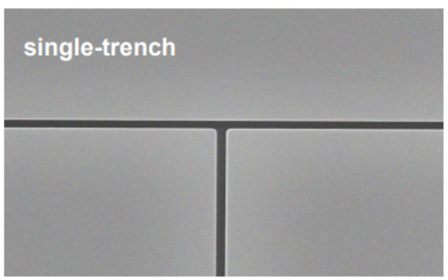
Options for small pixels - Trench isolation

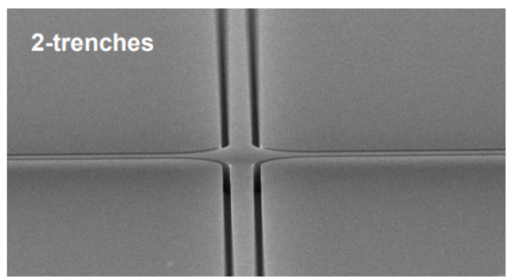
- No JTE
- Uniform Gain layer
- Pixel isolation via physical trench
- Reduce space between pixels to 7 um

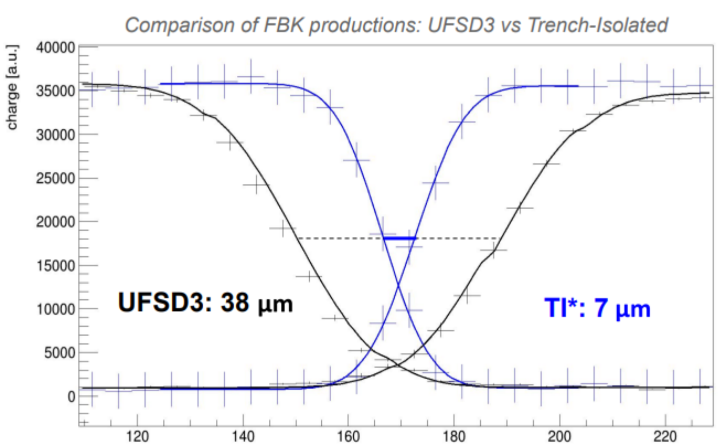
TI-LGADs feature either single-trench and 2-trenches isolation

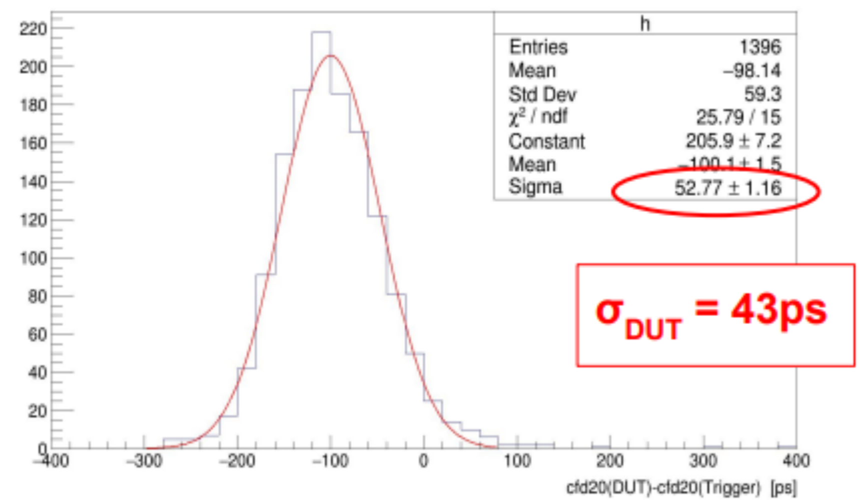








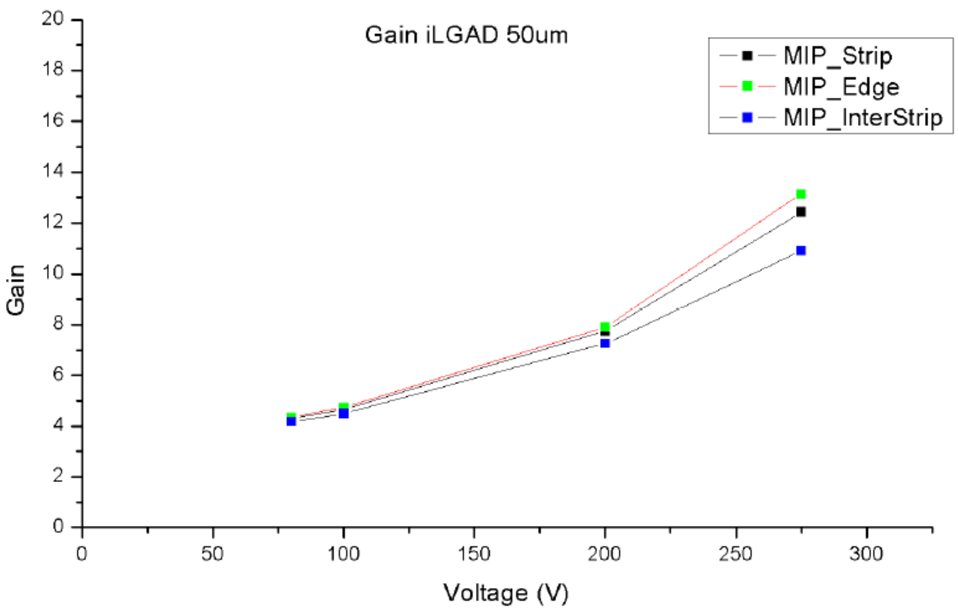




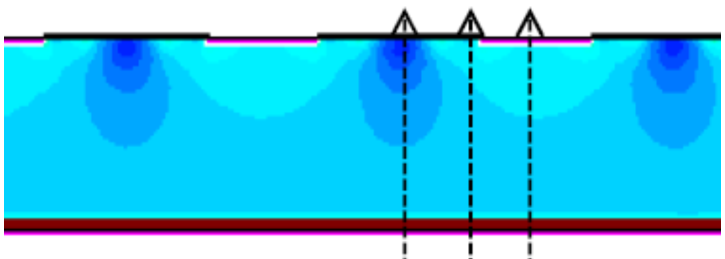
Good timing resolution with Sr90 source

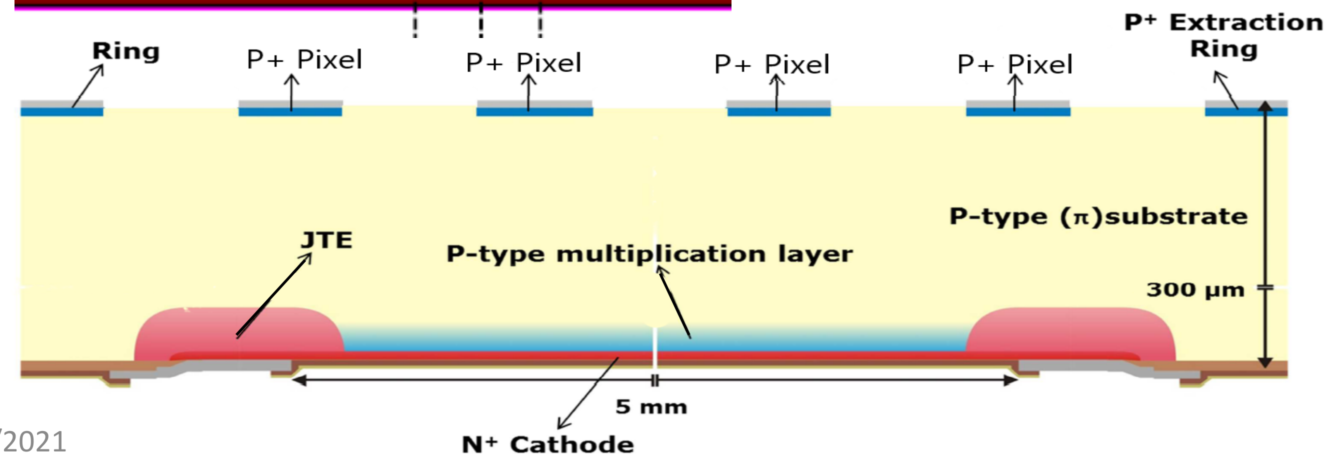
Options for small pixels - inverse LGAD

- Move Gain layer to backside
- JTE around whole pixel matrix
  - On back side
- Double side processing
  - Backside Sensitive to Scratches
- Needs to be fully depleted
- Uniform Drift field
- Full fill factor



80 µm pitch, 30 µm implant, 50 µm thick





Conclusions

- Timing is desired for HL-LHC operation
- Timing of 30 ps a reality today
- Radiation hardness demonstrated to 5×10^{15} cm^{-2}
  - Gain & time resolution falls at a given bias
  - Operate at higher bias
  - Include Carbon (or Ga) doping for Multiplication junction
- Large pixels (1×1 mm^2) have good performance
  - Proposed for ATLAS & CMS upgrades
- Reducing pixel size is a new challenge
  - iLGAD and trench isolation under investigation

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Thank you for your time