ATLAS HGTD upgrade and LGAD detectors

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HGTD: 7 countries - 22 Institutes

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Countries that expressed some interest to contribute to the HGTD construction

*(** institute with individual members up to now and no formal EoI)*

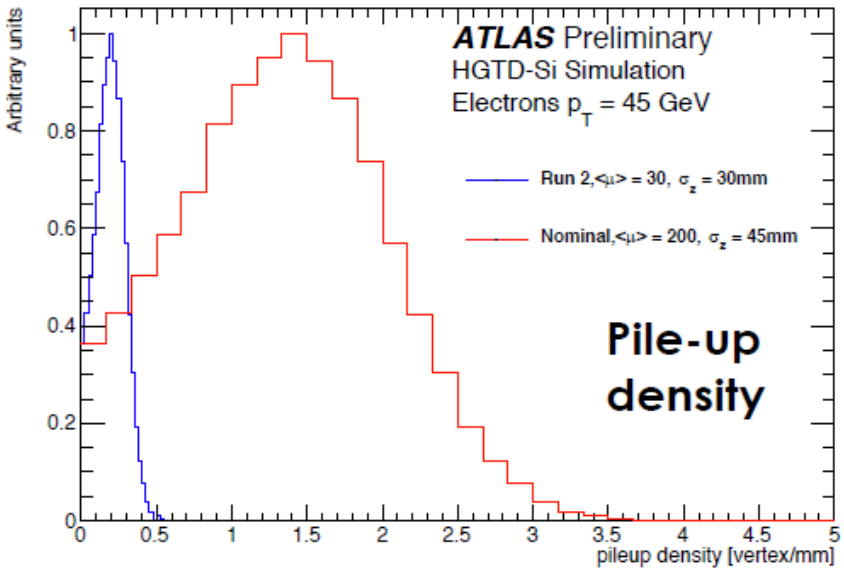
- **CERN**
- **France (3):**
  - LAL/Orsay
  - LPNHE/Paris
  - Omega/Paris
- **Germany (2):**
  - Justus-Liebig-Univ., Giessen (**)
  - Johannes-Gutenberg-Univ. of Mainz
- **Slovenia (1):**
  - IJS/Ljubljana
- **Spain (2):**
  - CNM-IMB-CSIC/Barcelona
  - IFAE/Barcelona
- **Sweden (1):**
  - KTH Royal Institute of Technology/Stockholm
- **Taiwan (1):**
  - Academia Sinica/Taipei
- **United States (10):**
  - ANL/Argonne
  - SMU/Dallas
  - BNL/Upton
  - Ohio State Univ. /Ohio
  - Univ. of California Santa Cruz/Santa Cruz
  - Univ. of Iowa/Iowa City
  - Univ. of Oregon/Eugene (**)
  - Univ. of Pennsylvania/Philadelphia
  - State Univ. of New York at Stony Brook/NY
  - SLAC/Stanford

Discussion ongoing with a new Institute (new country)

Discussion started about possible CORE contributions (information from 6/7 countries)

HGTD motivation

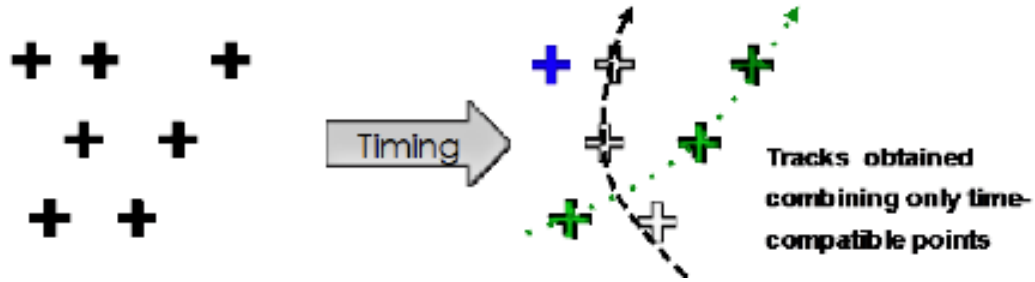
- HL-LHC pile-up will be higher (4-5 times) than run-II
  - Beam profile σ_z = 50 mm, σ_t = 180 ps
- The pileup density is comparable or larger than the longitudinal impact parameter resolution of the ITK above eta > 2.5

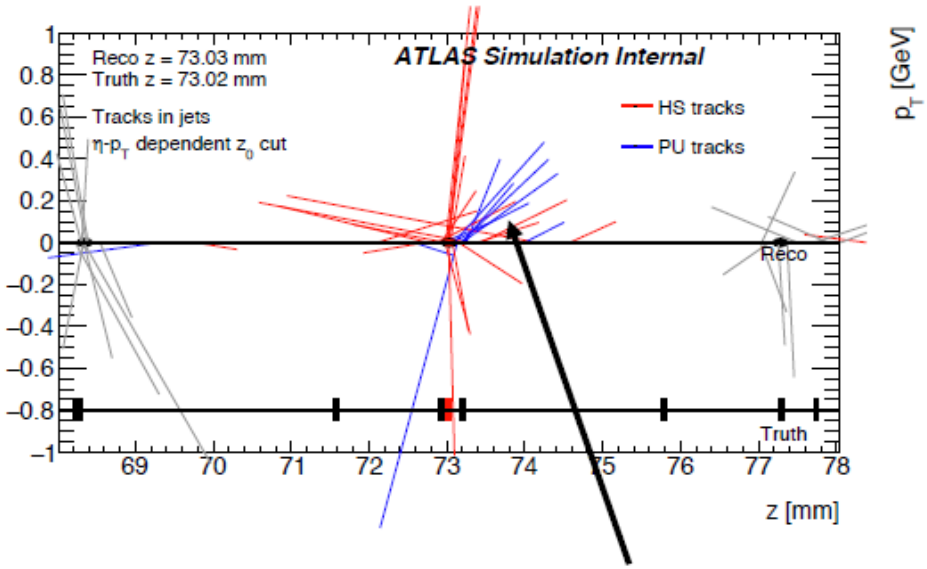


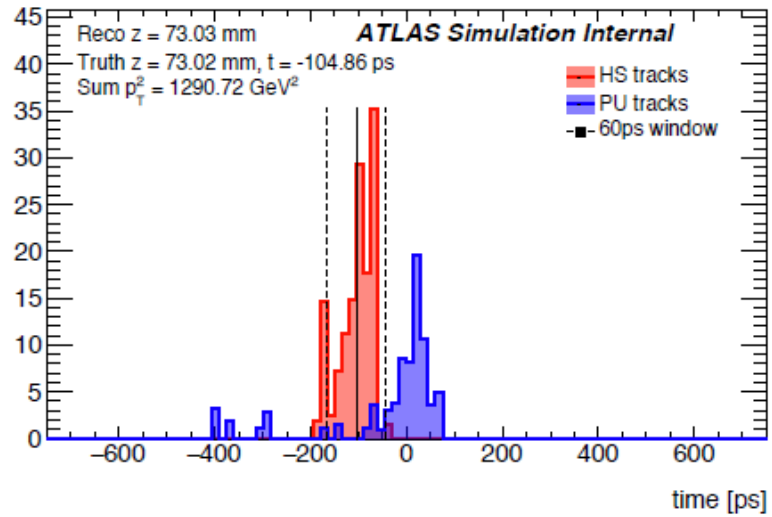
- A new layer (HGDT) of silicon detectors with precise timing measurement is necessary to maintain/improve performance at high pseudo-rapidity
  - Improves track-to vertex association, b tagging, lepton isolation, jet/Et_{miss}
  - Reduce the pileup contamination in tracks and vertexes
  - Improved luminosity measurement
  - Act as new minimum bias trigger

Timing resolution and tracking

- High timing resolution can improve both tracking algorithm and vertexing algorithm





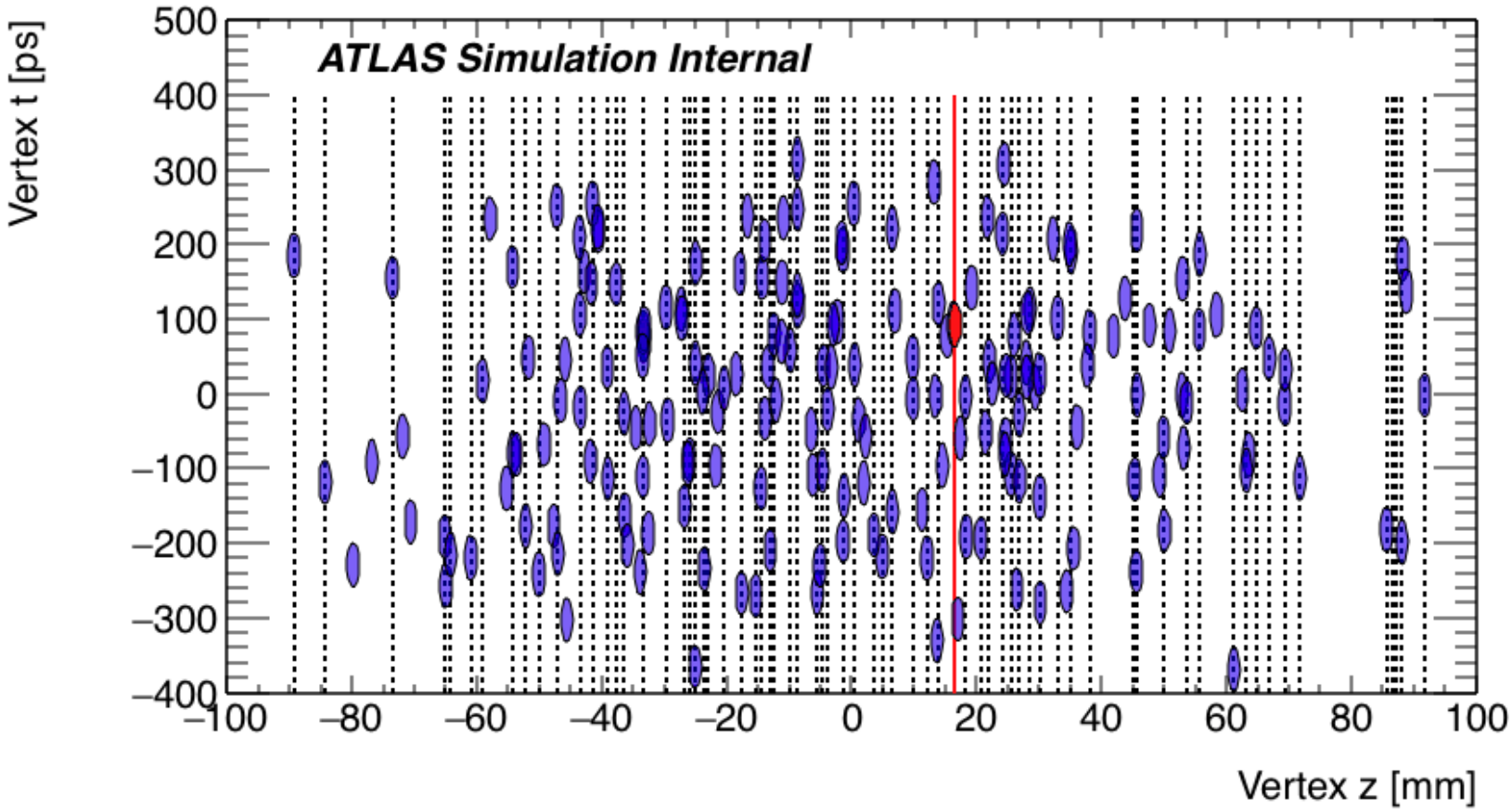


$$\frac{t_0 - t_{vtx}}{\sigma_{t0}} < 2$$

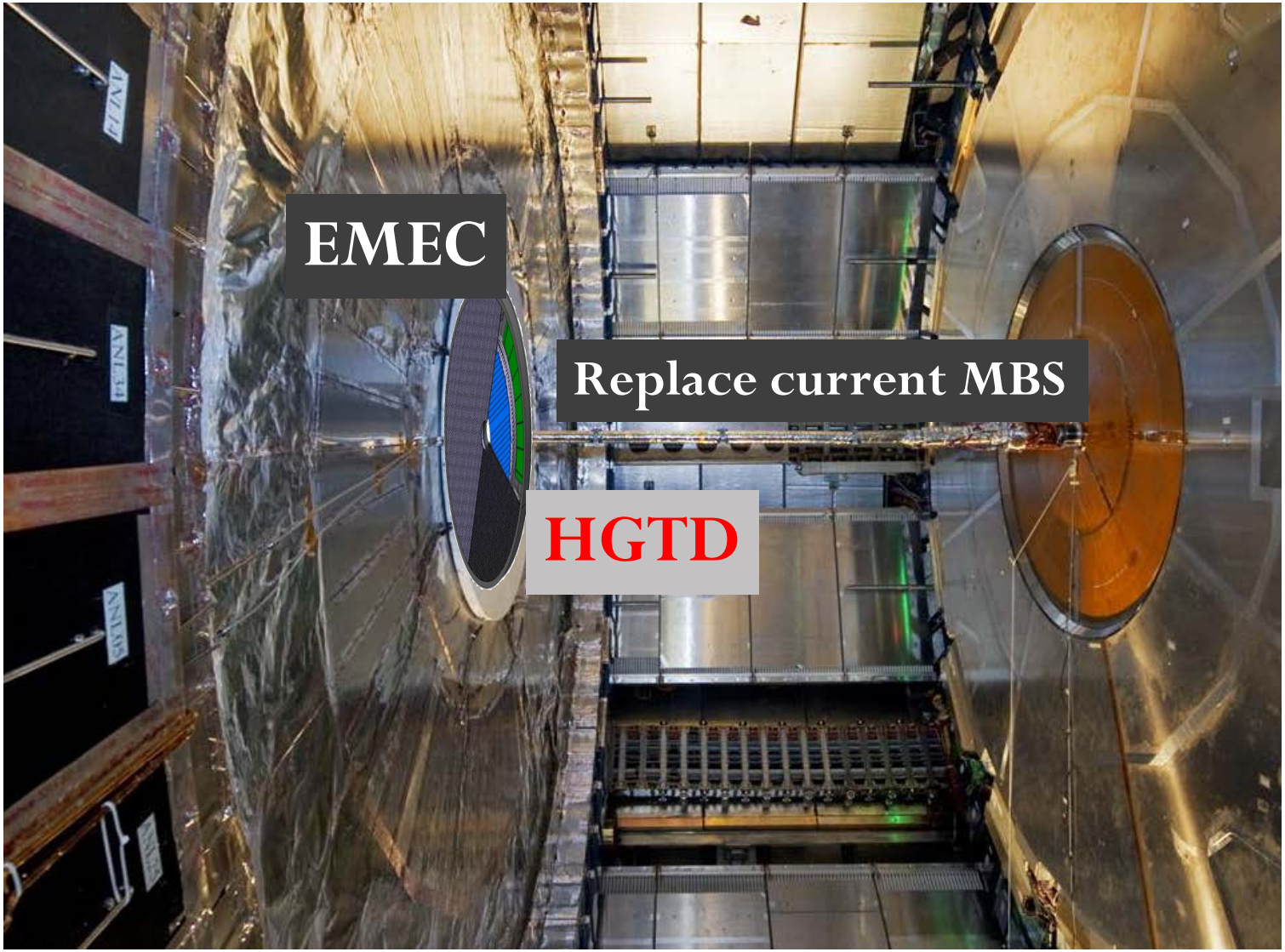
Pile-up jet misidentified as hard-scatter jet

Timing resolution and tracking

- HGDT timing resolution + ITk spatial resolution will reduce pile-up track and vertex contamination in HL-LHC conditions

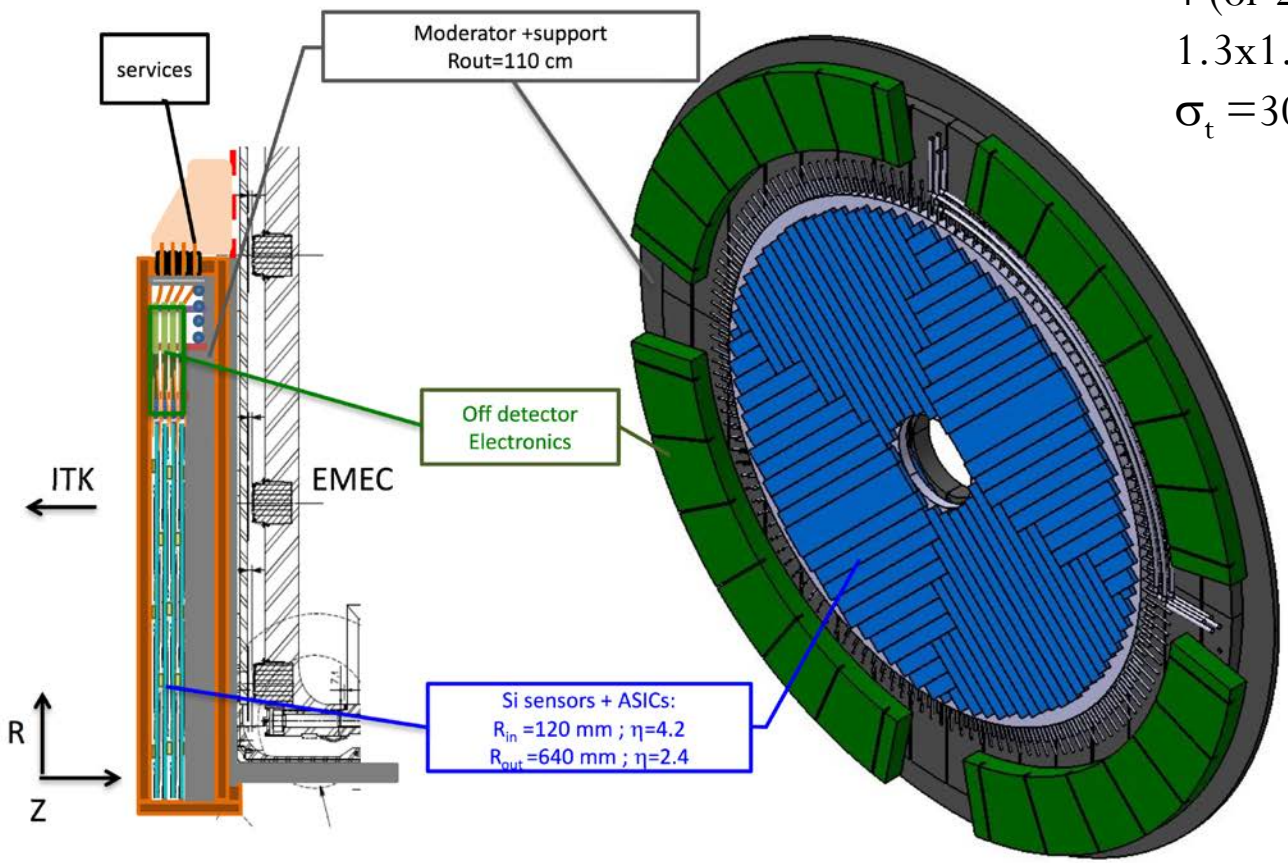


HGTD position and layout



HGTD position and layout

$2.4 < \eta < 4.2$
$\Delta Z = 75$ mm (+50 mm moderator)
4 (or 2+1) Si (LGAD) layers
1.3x1.3 mm^2 granularity
$\sigma_t = 30$ ps (< 60ps/mip/layer)

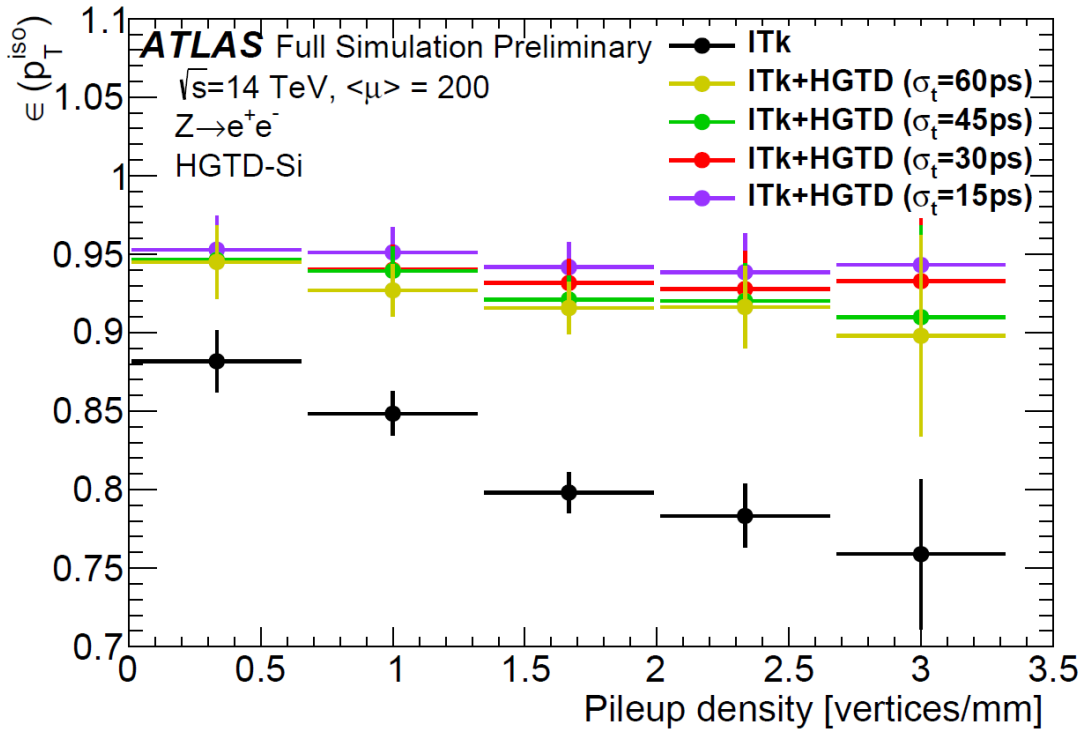


Physics performance

- Improved track to vertex association
  - Affects jets, lepton isolation, missing transverse energy…
- Provide an accurate estimate of the bunch-by-bunch luminosity
- New minimum bias trigger

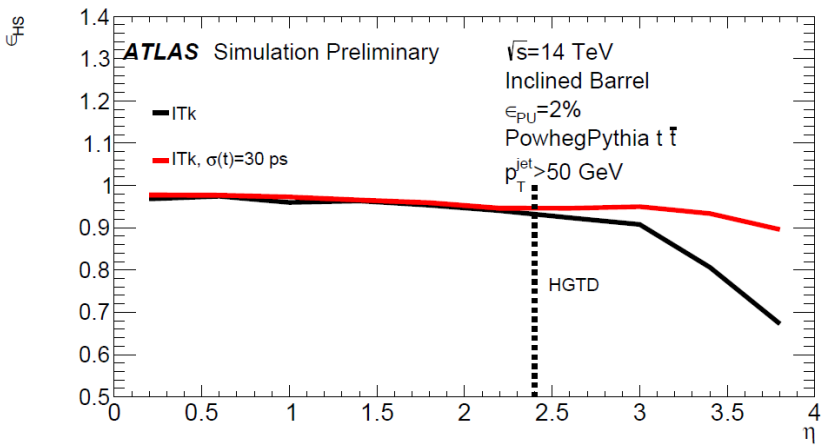
- Reduction of missing transverse energy tails

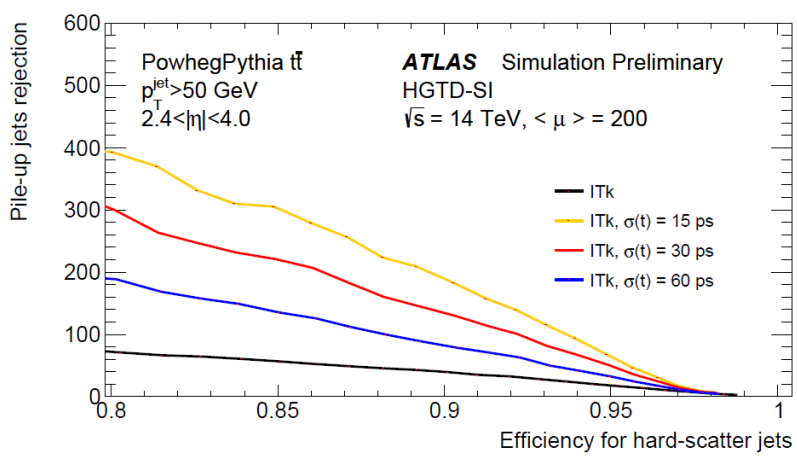
- 10-20% higher lepton isolation efficiency

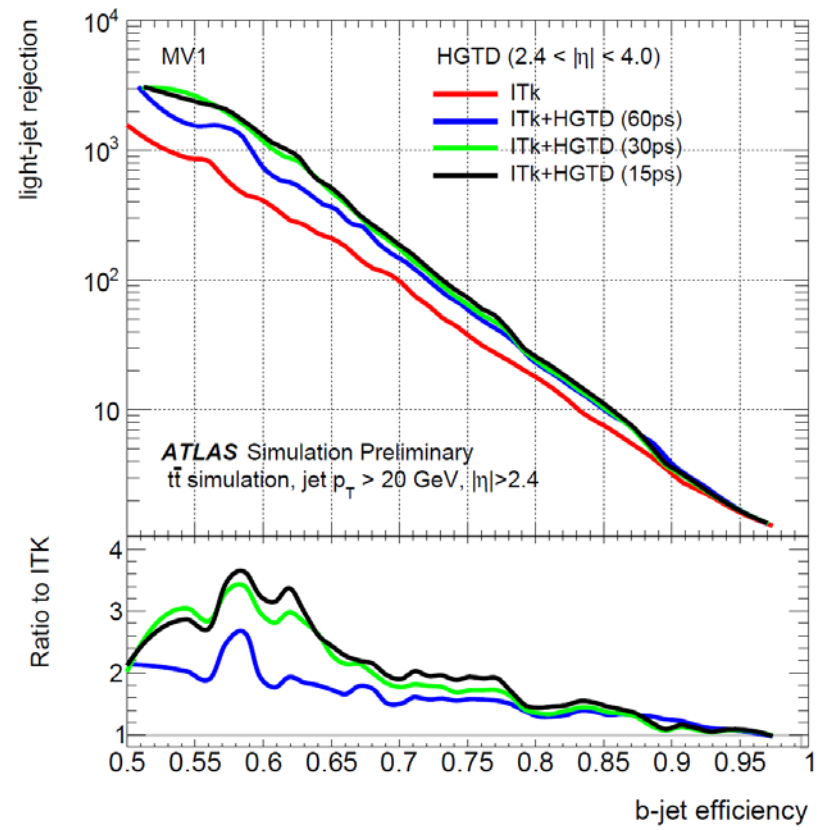


Physics performance - jets

- HGTD improves jet performance in forward region (eta>2.4)
  - Improved efficiency for hard-scatter jets
  - Improved Pile-up jet rejection in the Jet vertex fraction algorithm
  - Improved light jet rejection for b-jets







Physics potential

Enhance the physics potential of ATLAS

- Better PU jet rejection → VBF/VBS final states with activity in the forward region
- Improved b-tagging → Final states with forward b-jets
- Improved lepton isolation → Standard Model measurements that require forward leptons (weak mixing angle)
- Vertices with timing → Long lived particles at high pseudorapidity
- Improved luminosity → overall improvement in physics potential

Main cases

VBF final states, exploiting **improved forward pile-up suppression**

$VBF\ H \rightarrow \tau\tau$

$VBF\ H \rightarrow WW \rightarrow l\nu l\nu$

$\Delta\mu$ 5% improvement

Searches and measurements with forward b-quarks, **exploiting improved b-tagging**

$t(H \rightarrow \gamma\gamma)$

$t(H \rightarrow bb)$

σ 10% improvement

To be studied, work in progress

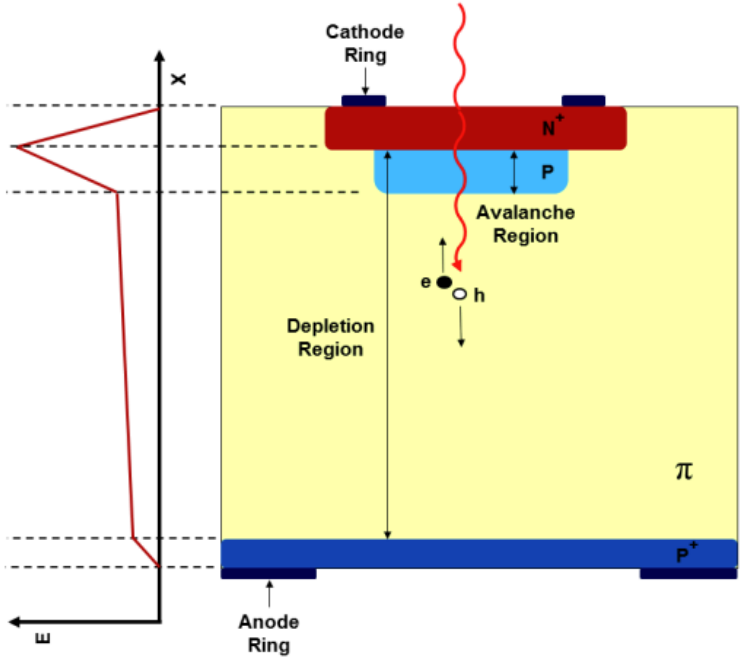
Searches and measurements with forward leptons, exploiting **improved lepton efficiency**

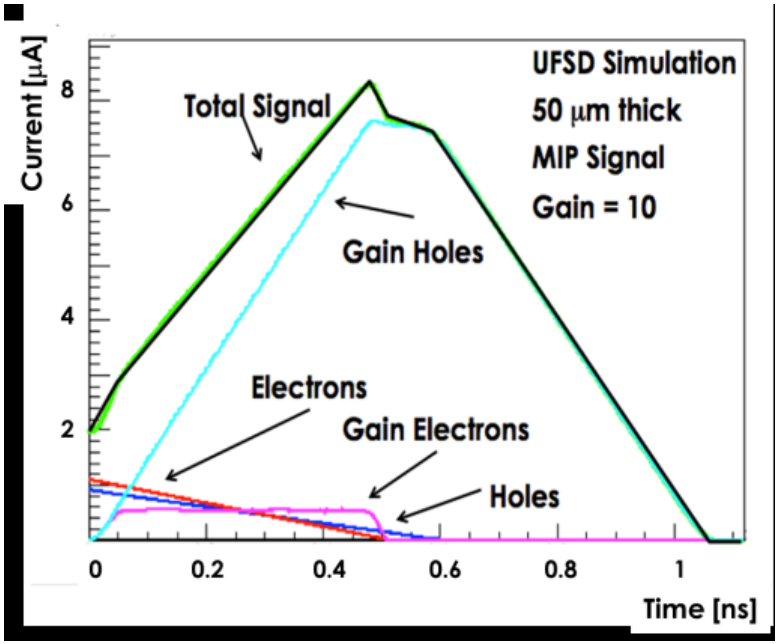
$sin^2\theta_W$

Long lived slow particles, exploiting **time measurements**

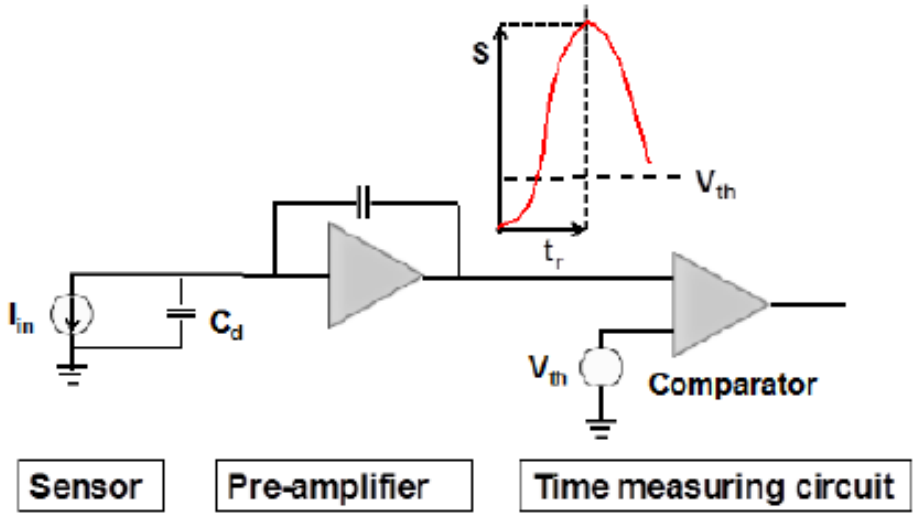
HGTD sensor - LGADs

- HGTD Sensor requirements
  - time resolution <60 ps/layer
  - Radiation hardness to 4.5e15 neq/cm²
  - Segmentation of 1.3x1.3 mm² (<10% occupancy)
- HGTD Sensor Baseline: Low Gain Avalanche Detectors (LGADS)
  - Gain around 10 from multiplication layer
    - Better signal to noise ratio → improved timing
  - Thinner detectors have shorter rise time and less Landau fluctuations
    - At least 50 μm and testing down to 30 μm
- 3 vendors of thin LGADs
  - CNM (Spain), HPK (Japan), FBK (Italy)





LGADs timing measurement



$$\sigma_{\tilde{t}} = \sigma_{\tilde{TimeWalk}} + \sigma_{\tilde{LandauNoise}} + \sigma_{\tilde{Distortion}} + \sigma_{\tilde{Jitter}} + \sigma_{\tilde{TDC}}$$

$$\sigma_{TimeWalk} = \left[\frac{V_{th}}{S/t_{rise}}\right]_{RMS} \propto \left[\frac{N}{\frac{dV}{dt}}\right]_{RMS}, \quad \sigma_{Jitter} = \frac{N}{dV/dt} \approx \frac{t_{rise}}{S/N}$$

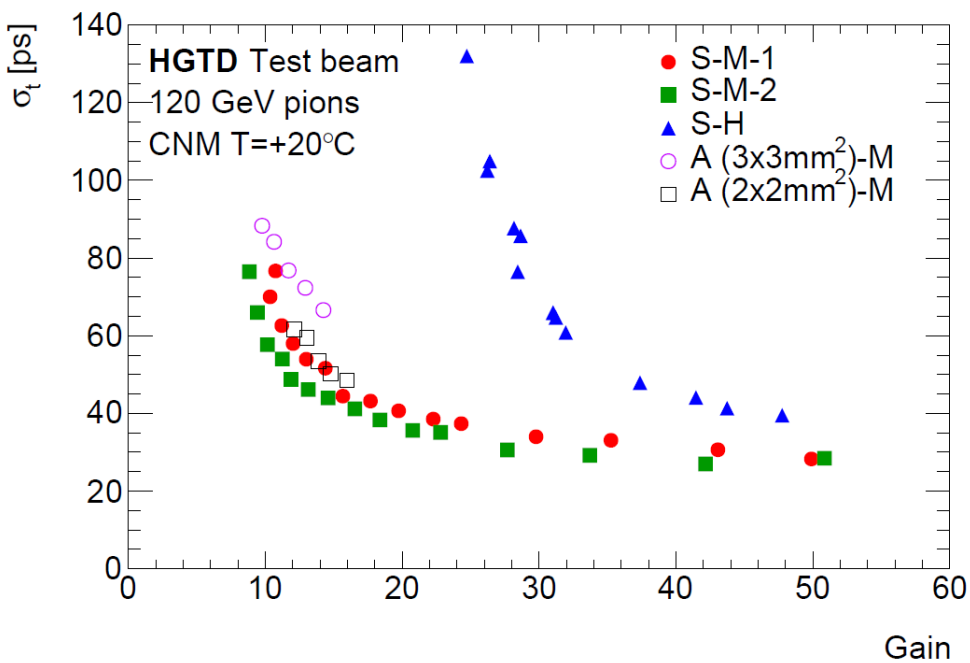
- Maximize slope dV/dt (i.e. large and fast signals)
- Signal ~ gain, expect jitter ~ 1/G
- Minimize noise N
- Time walk is corrected by using constant-fraction discriminator CFD

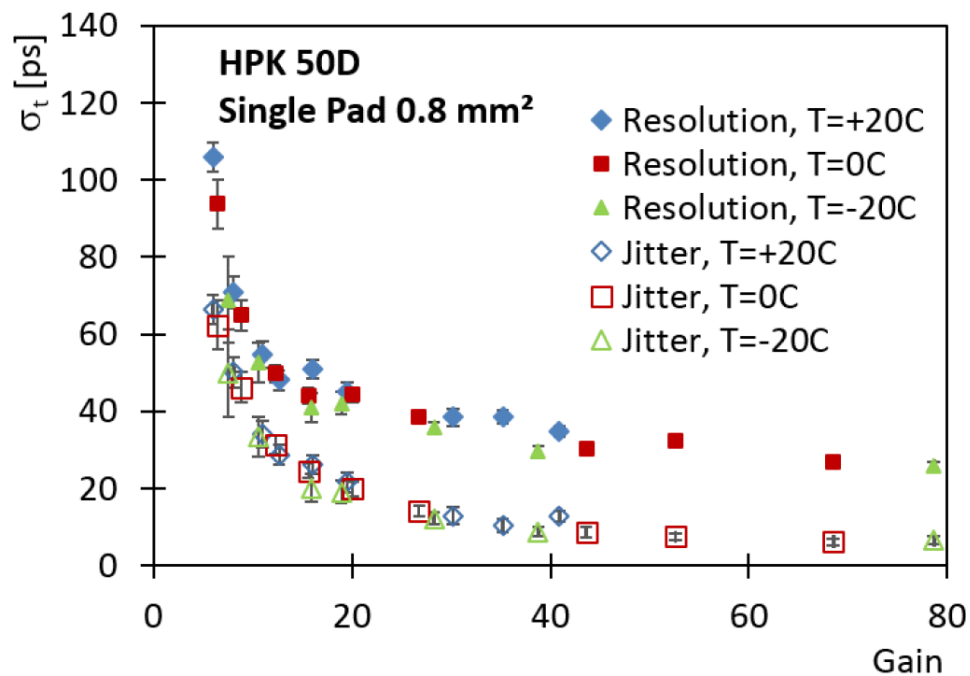
Detector testing at SCIPP

- Laboratory electrical testing (IV, CV): Verify LGAD performance, breakdown voltage, doping level, test yield
- Laboratory dynamic testing (β-telescope, laser): Signal shape, noise, charge, gain, time resolution, uniformity
- Understand the **radiation damage**: run the same tests non-irradiated and irradiated sensor
- **Test beam** at CERN, Fermilab and SLAC (in the future)

Time resolution vs gain:

- Left: CNM detectors tested with test beam (single-pad sensors ("S") and arrays ("A") of medium ("M") and high ("H") doping)
- Right: HPK detectors tested with β-source (different temperatures)

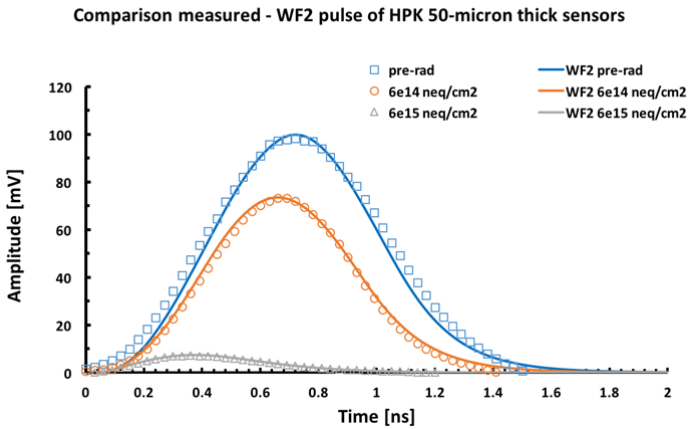


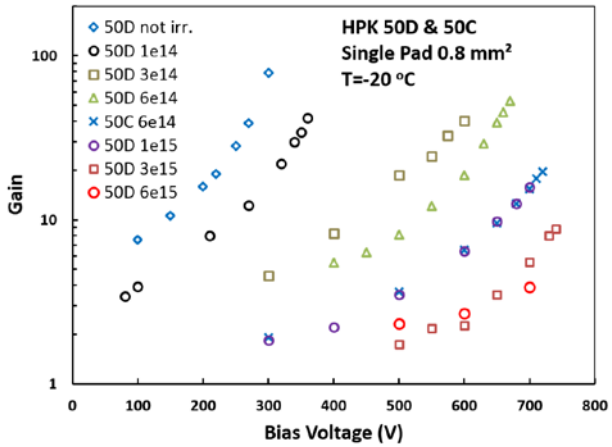


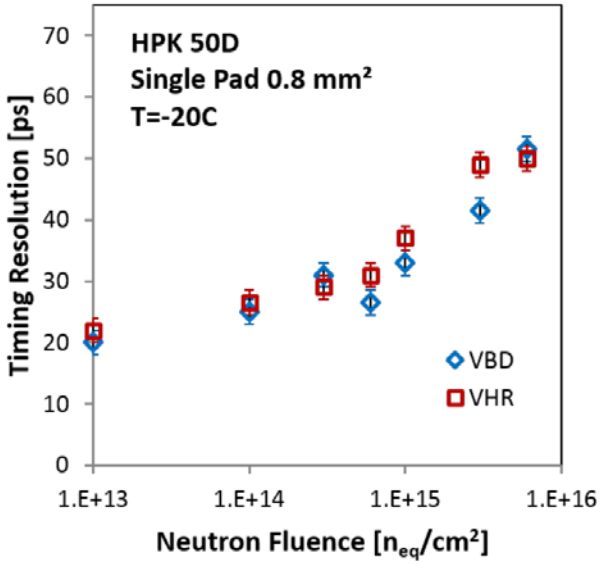
Irradiated sensors

- Irradiation of sensor from CNM, HPK and FBK
  - Increased bias voltage after irradiation
  - Decrease of gain (at same voltage)
  - But decrease of rise time
- Loss of gain (acceptor removal process) recovered by increasing Vbias

- Several radiation fluence:
  - 1e14 → 6e15 n/cm^2
- Studies ongoing on the effect on time resolution: for now 20 → 50 ps





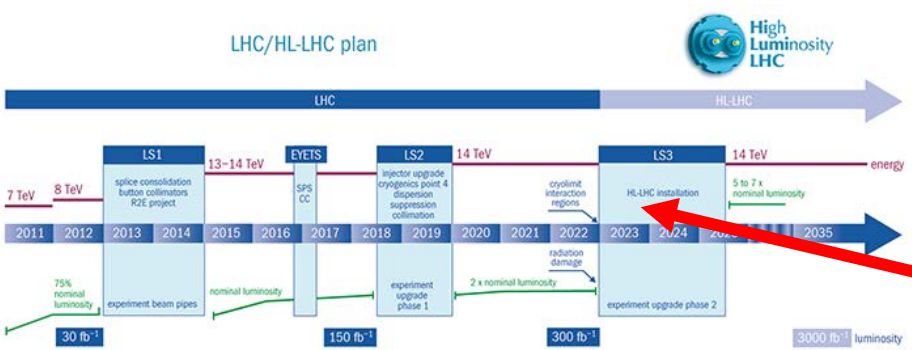


Conclusions

- HGTD is going forward as scheduled
  - Official start for sensor R&D 2018
- UCSC SCIPP group is giving a significant contribute with LGAD detectors R&D

Expression of Interest ready:

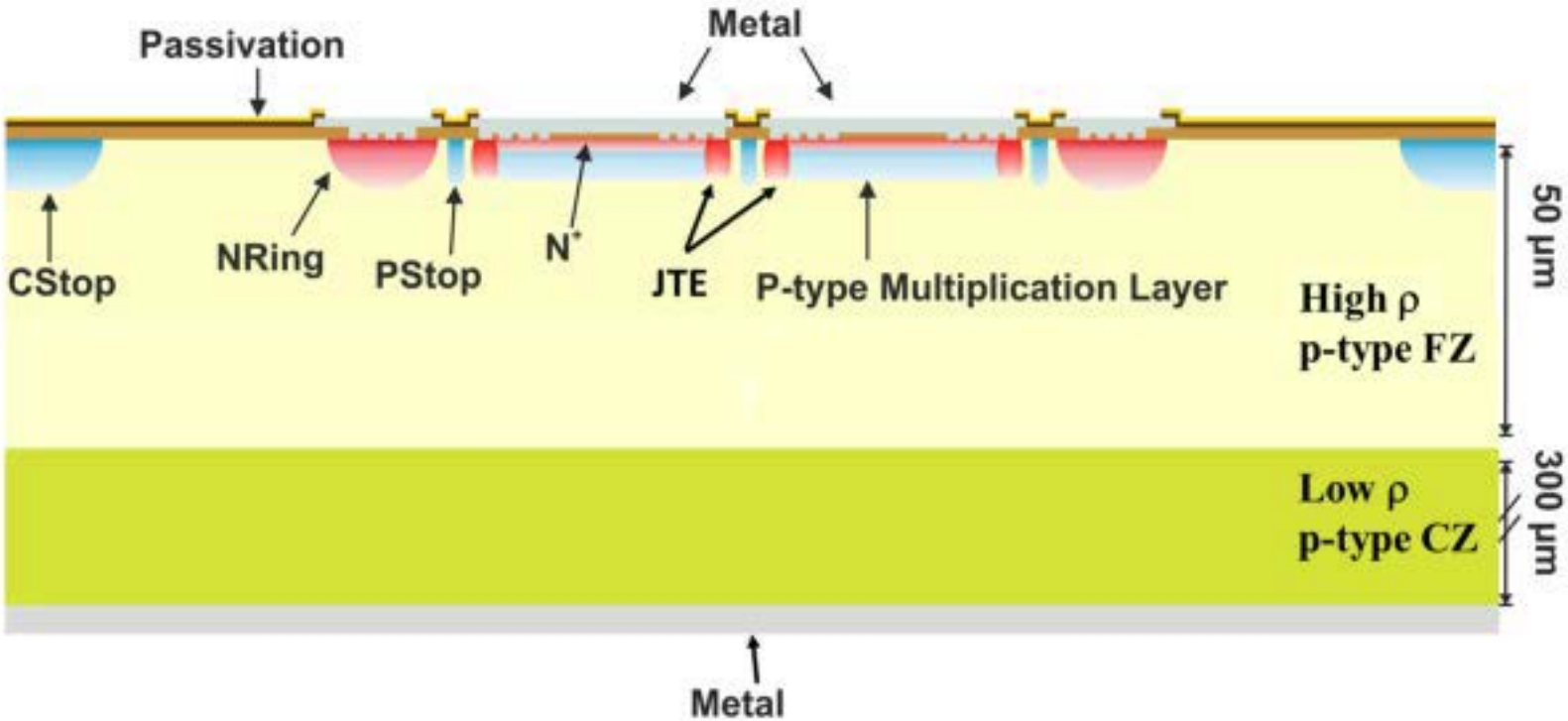
- A High-Granularity Timing Detector for ATLAS Phase-2 Upgrade
- Internal only: https://cds.cern.ch/record/2290829/



Activity name	Start	Finish
Sensor R&D	Q1/18	Q3/19
Final Sensor and pre-production	Q4/19	Q3/20
Sensor production and tests	Q4/20	Q4/21
ASIC R&D	Q1/18	Q3/19
ASIC final chip and pre-production	Q4/19	Q3/20
ASIC production and tests	Q4/20	Q4/21
Module assembly R&D	Q1/18	Q2/20
Module 0	Q3/20	Q2/21
Module production	Q3/21	Q4/23
Module loading	Q3/22	Q1/24
Layer integration HGTD-A	Q3/23	Q4/23
Layer integration HGTD-C	Q1/24	Q3/24
Off-detector electronics R&D	Q1/18	Q4/19
Off-detector electronics prototype production	Q1/20	Q4/20
Off-detector electronics production	Q1/21	Q2/22
Mechanics R&D	Q1/18	Q1/20
Mechanics components prototypes	Q2/20	Q4/20
Mechanics components production	Q2/21	Q4/21
Services R&D	Q1/18	Q2/19
Services prototypes	Q3/19	Q4/19
Services production	Q3/22	Q2/23
Services installation	Q1/24	Q4/24
Back End, LV/HV in USA15 installation	Q3/23	Q2/25
Installation HGTD-A	Aug/24	Sept/24
Commissioning HGTD-A	Q1/25	Q4/25
Installation HGTD-C	Dec/24	Jan/25
Commissioning HGTD-C	Q1/25	Q4/25

Backup

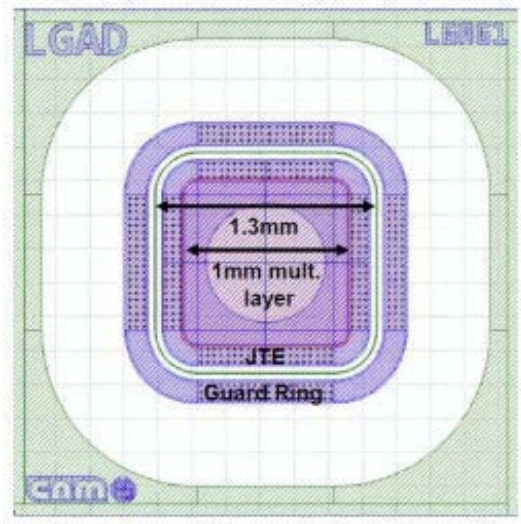
LGADs structure

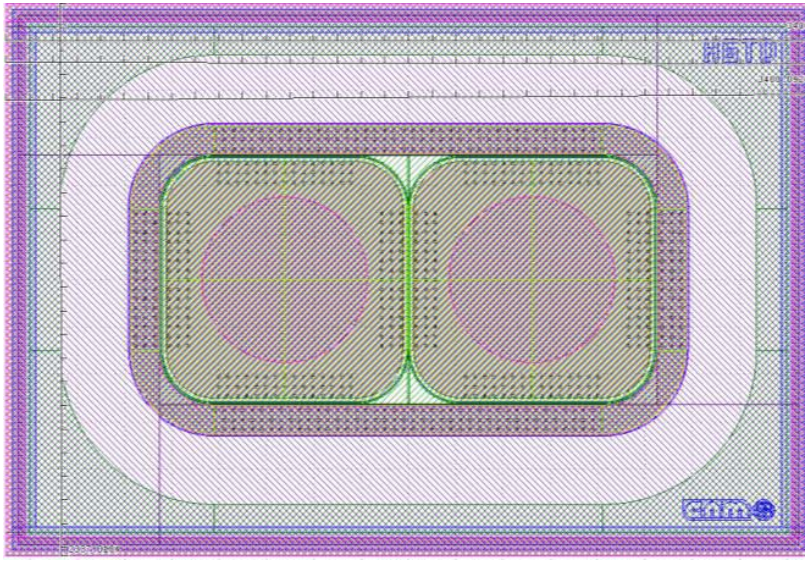


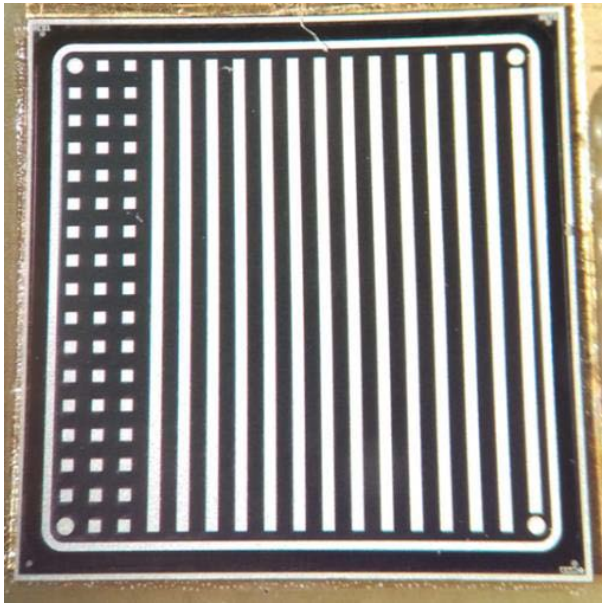
Manufacturer	Wafer size [inch]	Substrate	Thickness [μm]	Sensor types	Size [mm]	Technology enhancement
CNM	4" (2017 6")	Epi, SoI, Si-Si-bond	300, 75, 45	Single pads, 2x2 up to 8x8 array	1, 2, 3	B->Ga substitution C implantation
FBK	6"	Si-Si-bond	300, 50	Single pads, many arrays	1, 2, 3	B->Ga substitution C implantation
HPK	6"	Si-Si-bond	80, 50, 30	Single pads, 2x2 arrays	1, 3	<50 μm thick

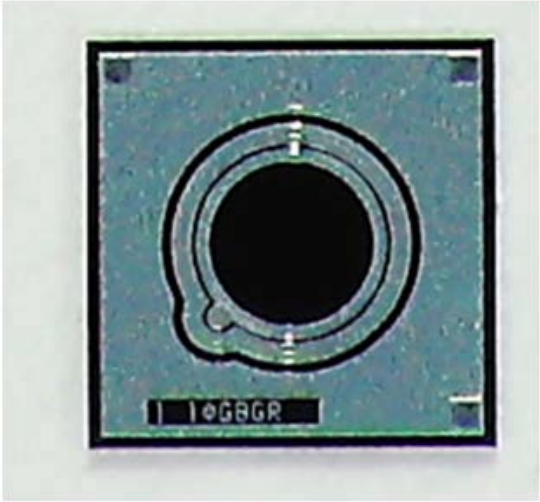
LGADs structure

- Several layouts/vendors under test:
  - Single pads
  - 2x2 arrays
  - 8x8 arrays
  - AC coupled LGADS
  - AC coupled array of strips and pixels



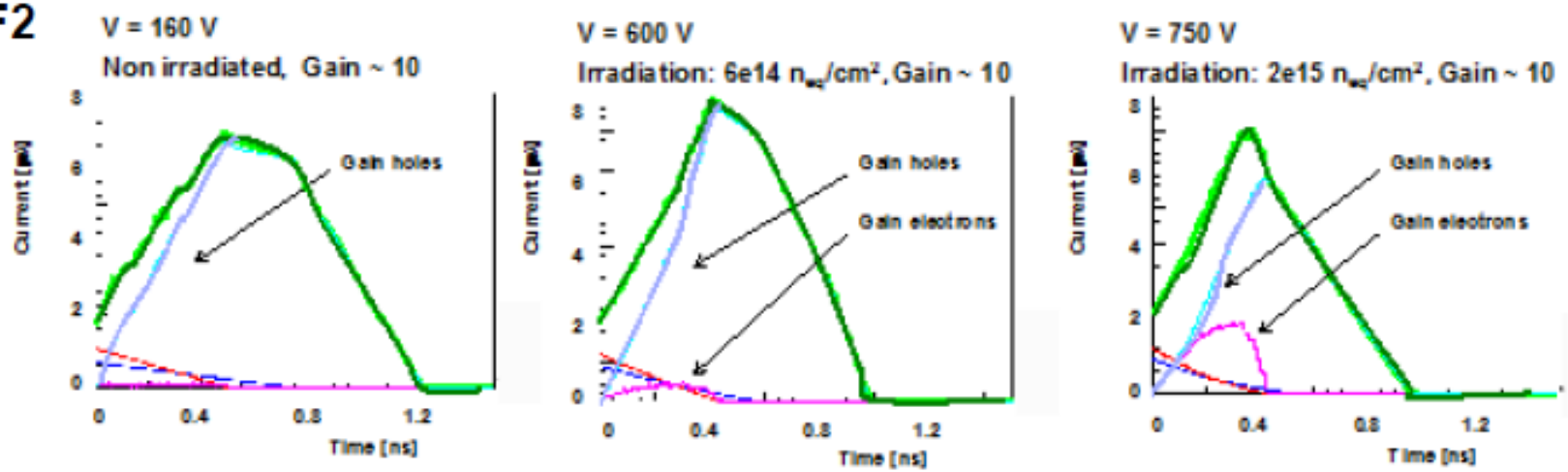




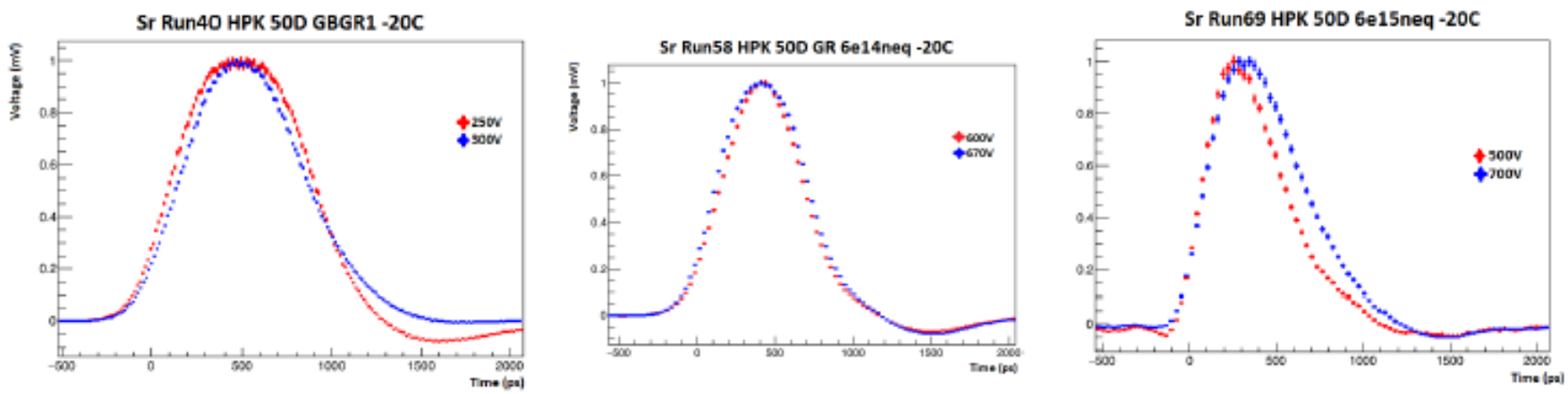


Simulation with WF2

WF2

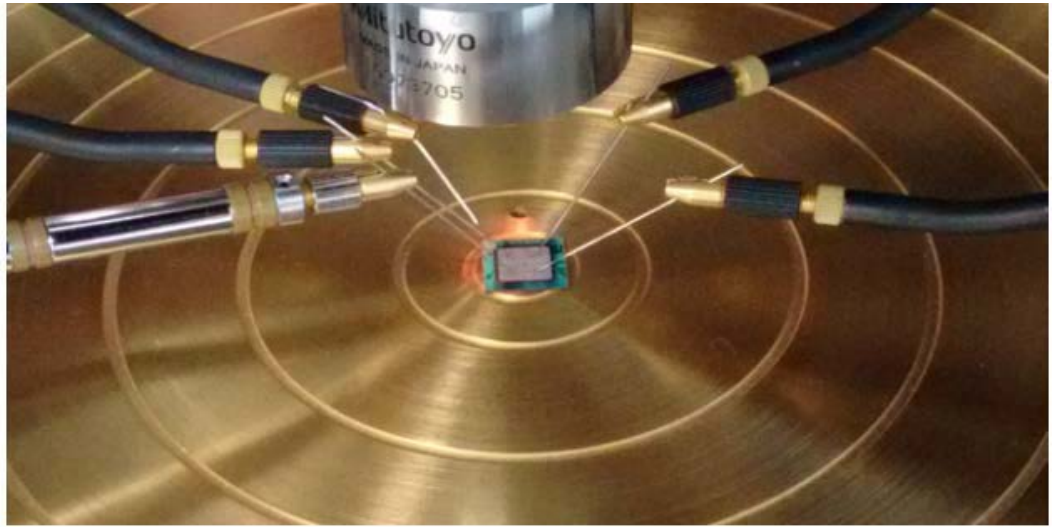


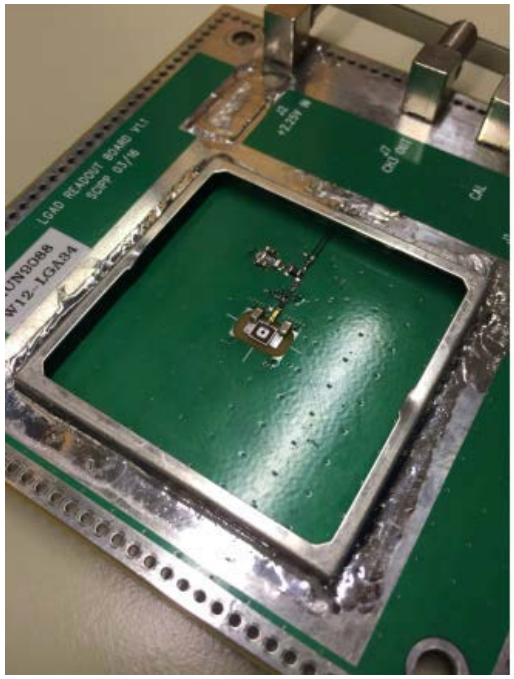
Data



SCIPP LGAD RnD

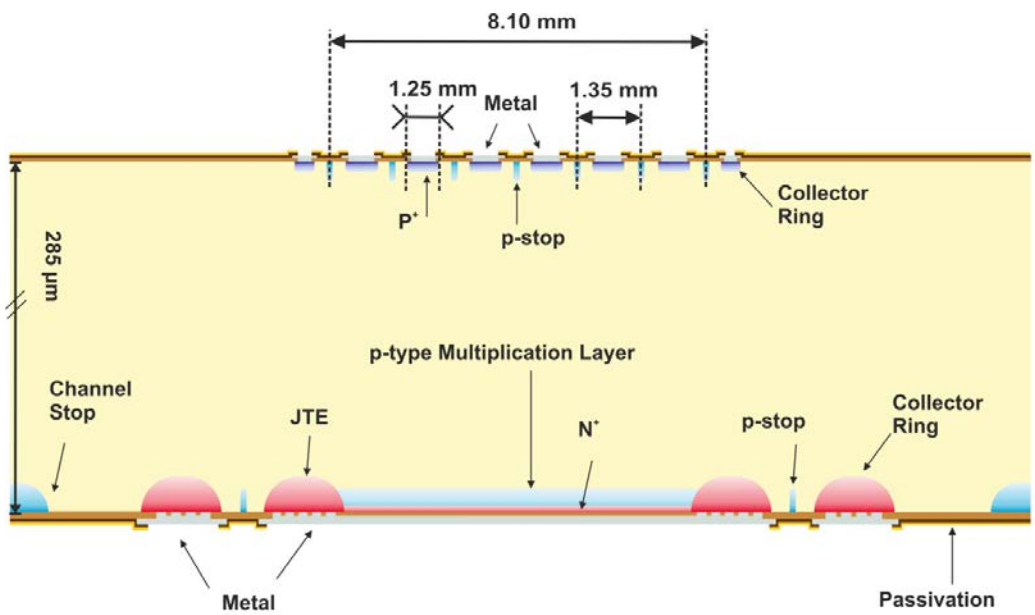
- Laboratory electrical testing (IV, CV)
  - Verify LGAD performance, breakdown voltage, doping level, test yield
- Laboratory dynamic testing (β-telescope, laser)
  - Signal shape, noise, charge, gain, time resolution, uniformity
- Test non-irradiated and irradiated sensor

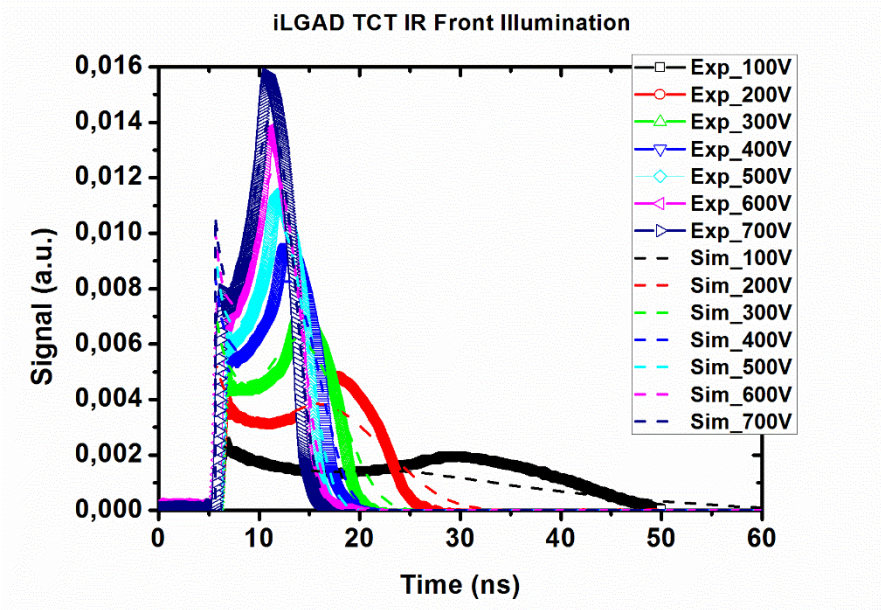




iLGAD detectors

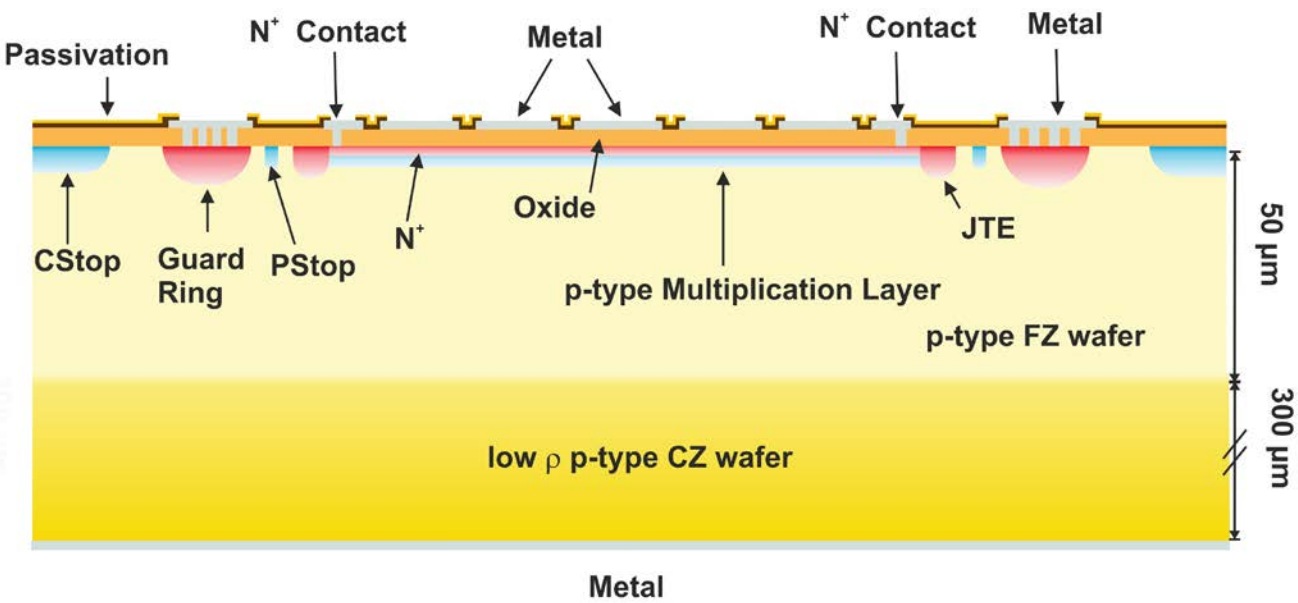
- Segmentation of gain layer needs a junction termination extension because of the high field in the edge
  - Limits the fill factor of pixels/strips
- iLGAD: 2-sided, gain layer on the other side from the pixels
  - TCT tests on iLGAD at SCIPP
  - Unfortunately the detector/board connection breaks easily

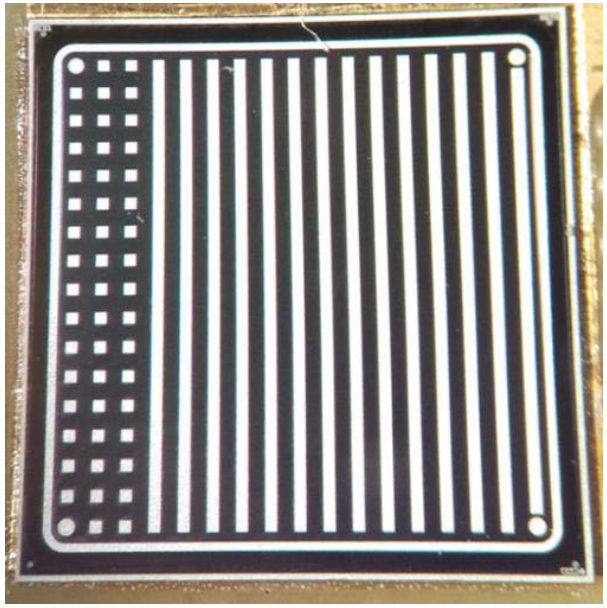




AC-LGAD detectors

- AC-LGAD: 1 sided, N+ implant and oxide layer. No segmentation of gain layer. Contacts AC coupled to signal
  - Several studies on-going at SCIPP on AC detectors
  - Problems with detector break down at low voltage (25 V) but TCT measures shows an AC signal in strips/pixels





HGTD position and layout

Pseudorapidity coverage	$2.4 < \|\eta\| < 4.2$
Position in z	$3420 < z < 3545$ mm including 50 mm of moderator
Position of active layers	$3435 < z < 3485$ mm
Radial extension (active area)	110–1100 mm (120 mm–640 mm)
Number of layers	4 per side
Time resolution	30 ps / mip (< 60 ps / mip / layer)
Sensor size	1.3×1.3 mm^2
Number of channels	6.3M
Number of Si modules (2×4 cm^2 each)	13952
Number of ASICs (2×2 cm^2 each)	27904
Total active area (Si sensors)	11.16 m^2

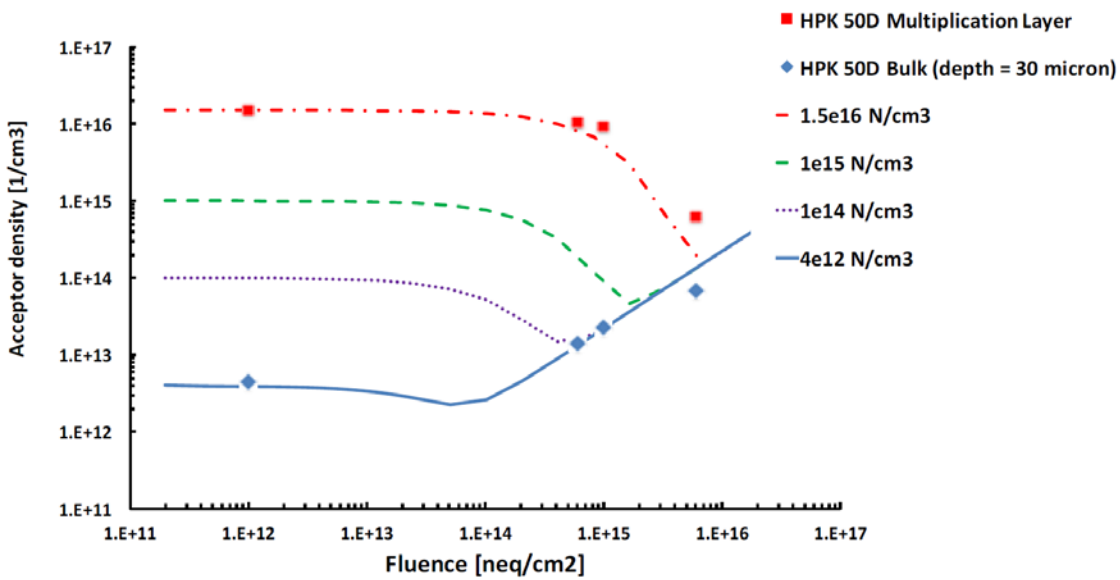


Figure 17: Evolution of the acceptor density in the bulk (blue) and in the multiplication layer (red) as a function of fluence, measured on HPK 50D sensors and predicted from Ref [1].

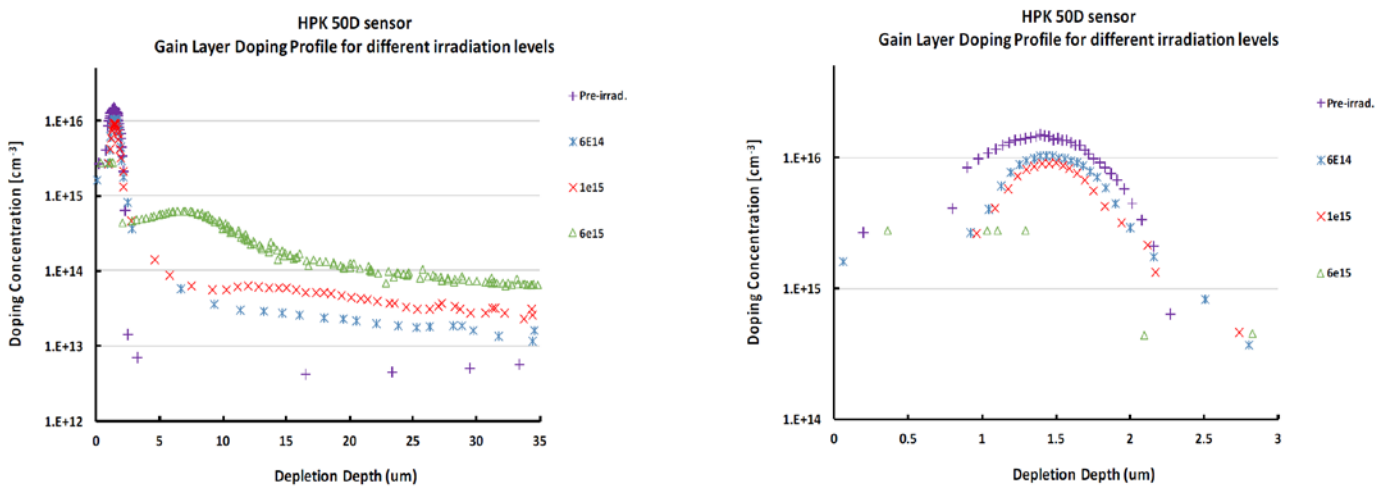


Figure 16: Doping profile for four fluences. The curves are based on fits to the $1/C^2$ vs. bias plots.