Towards a 4th dimensional tracker system

XXIII DAE-BRNS High Energy Physics Symposium , Chennai, IITM, Dec 10th, 2018

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Outline

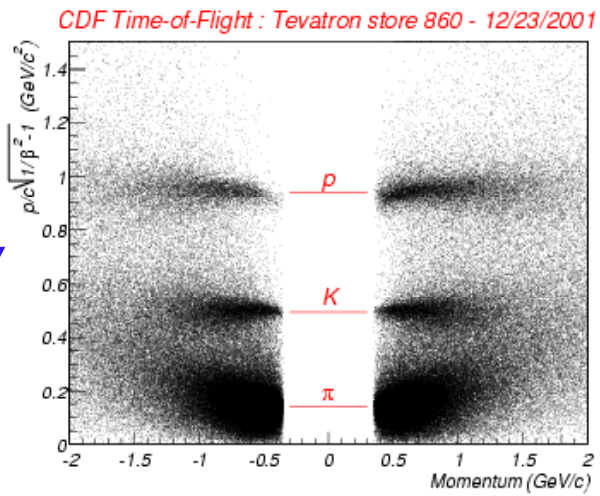
- **Introduction, Motivation & challenges for a 4th dimensional tracker system:**
  - Timing detectors in current and recent experiments.
  - The NA62 Gigatracker: a stepping stone towards a true 4th dimensional tracking.
  - Timing layers and particle-flow calorimeters at HL-LHC
  - Timing at the Future Circular Collider.
- **Sensors for timing 101**:
  - timing basics Silicon
  - Silicon diode detectors cases of use.
- **Inverse-Low Gain Avalanche Detectors (ILGAD) : A sensor for a large-scale high-precision 4th dimensional tracker system.**
  - Technology description.
  - Performance of proof-of-concept prototype

Timing detectors: the recent past (1)

- Precise time stamping of charged particles **($\Delta t \geq 100$ ps)** by dedicated Time-of-Flight (ToF) detectors.
- **Particle ID** of low momentum charged particles (mostly pion/kaon disentangling in flavor physics experiments)
- ToF detector determines speed of a charged particle by measuring flight time t across a known distance L. Knowing the particle momentum p, one determines the mass.

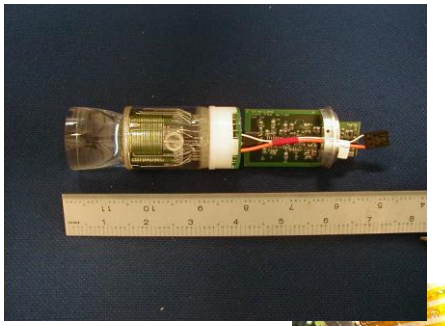
$$m = \frac{p}{c}\sqrt{\frac{c^2 t^2}{L^2} - 1}$$

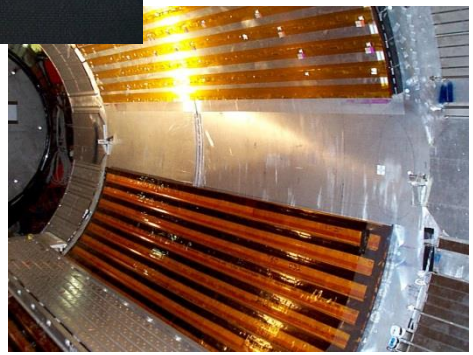
Mass vs momentum
CDF-II ToF detector at Tevatron



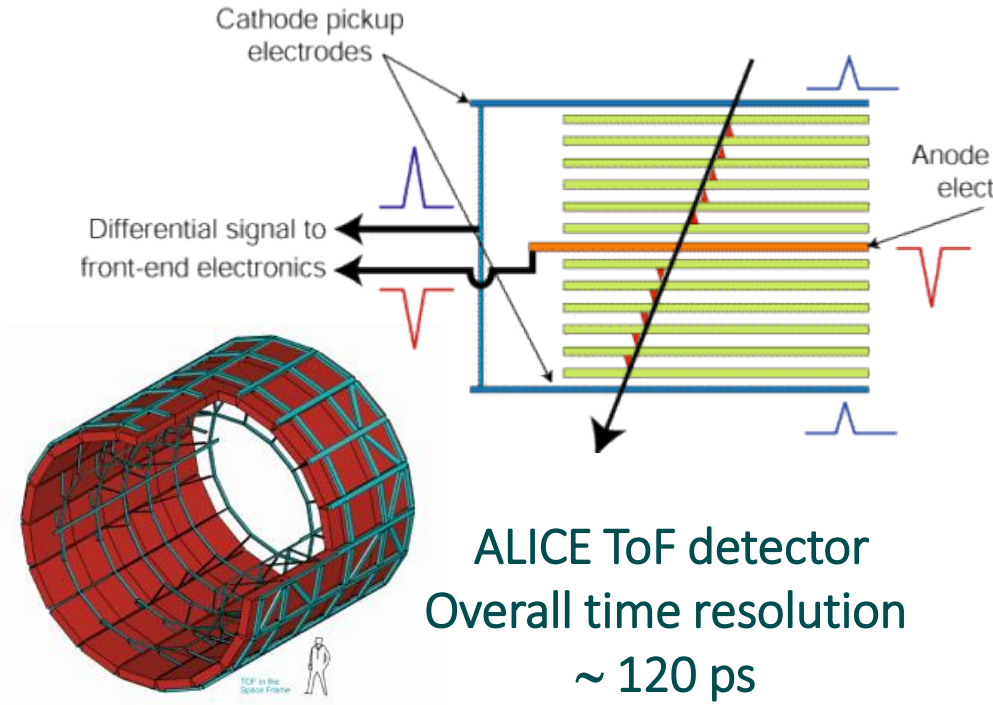
Timing detectors: the recent past (2)

- Fast detection sensing technologies:
  - Fast scintillators + conventional Photomultiplier Tubes
  - Resistive Plate Chambers (very large area detectors).
- Limitations:
  - Difficult to go below 100 ps timing resolution, severe gain reduction inside magnetic fields (PMT), bulky, scintillator and gaz radiation-induced aging, limited granularity (spatial resolution).





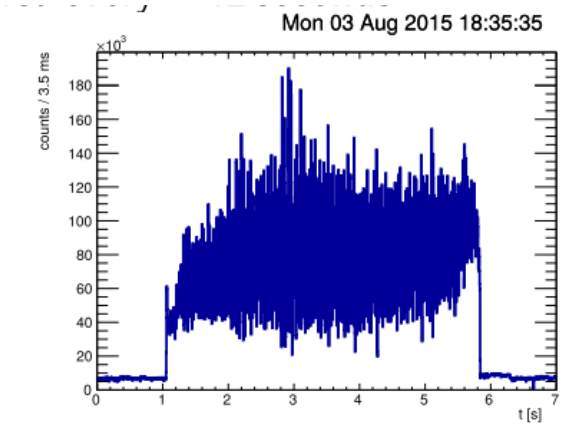
CDF & Belle ToF Detectors Overall Time resolution **~ 100 ps**

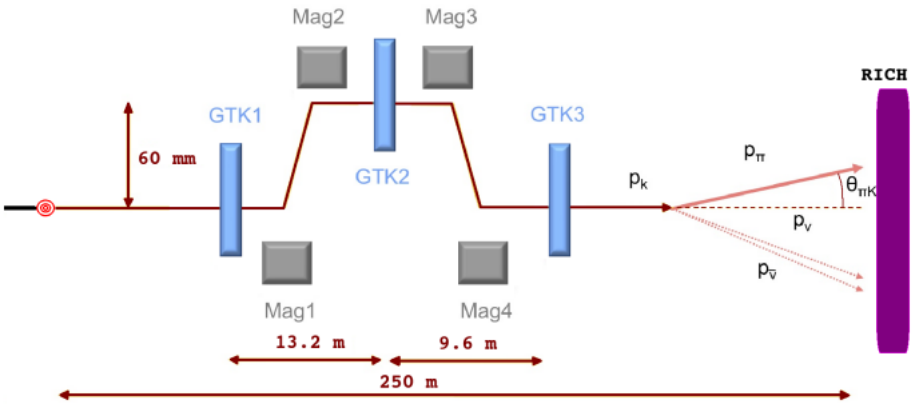


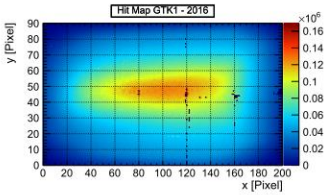
ALICE ToF detector Overall time resolution ~ 120 ps

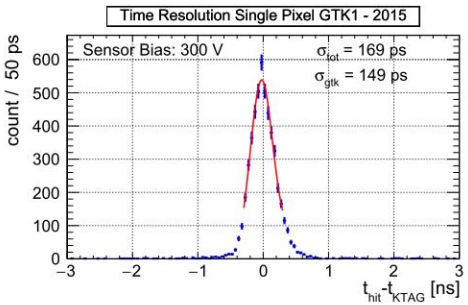
GigaTracker: A true 4th dimensional tracker

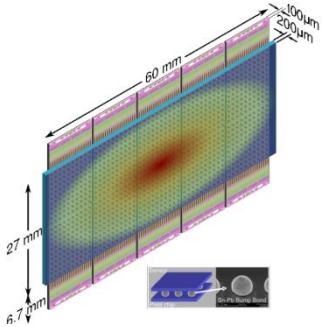
- Aim to measure Br(K+ π +νν) SM branching fraction very small ~ 10^{-10}
- Unstructured particle beam with ~5 second burst every ~42 seconds (instantaneous rate 750 MHz)

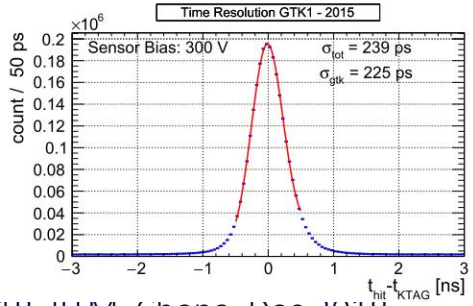












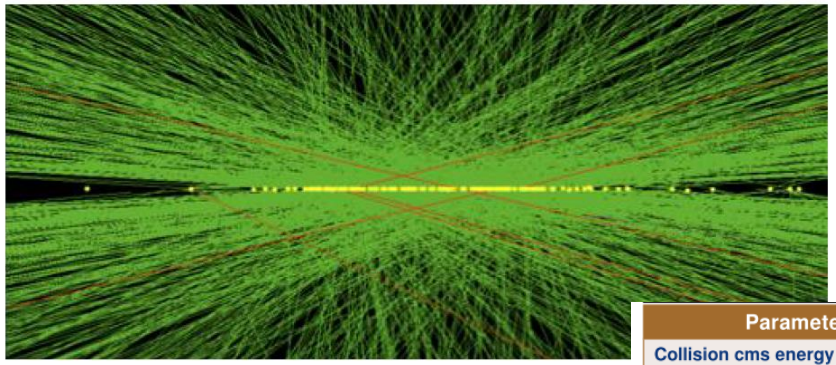
Hybrid pixel detector:

300 um × 300 um pixels

One sensor (~6×3 cm2) bump-bonded to 10 read-out chips

Motivation: Why do we need precise time stamping of particles? (1)

– Future hadronic colliders (HL-LHC, FCC) to increase many fold the current LHC luminosity: track multiplicity and bias events



Parameter	FCC-hh		HE-LHC	(HL) LHC
Collision cms energy [TeV]	100		27	14
Dipole field [T]	16		16	8.33
Circumference [km]	97.75		26.7	26.7
# IP	2 main & 2		2 & 2	2 & 2
Beam current [A]	0.5		1.12	(1.12) 0.58
Bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	(2.2) 1.15
Bunch spacing [ns]	25	25 (5)	25 (5)	25
beta* [m]	1.1	0.3	0.25	(0.20) 0.55
Luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	30	25	(5) 1
# Events/bunch crossing	170	<1020 (204)	~800 (160)	(135) 27
Stored energy/beam [GJ]	8.4		1.3	(0.7) 0.36
Synchrotron rad. [W/m/ap.]	28.4		4.6	(0.33) 0.17

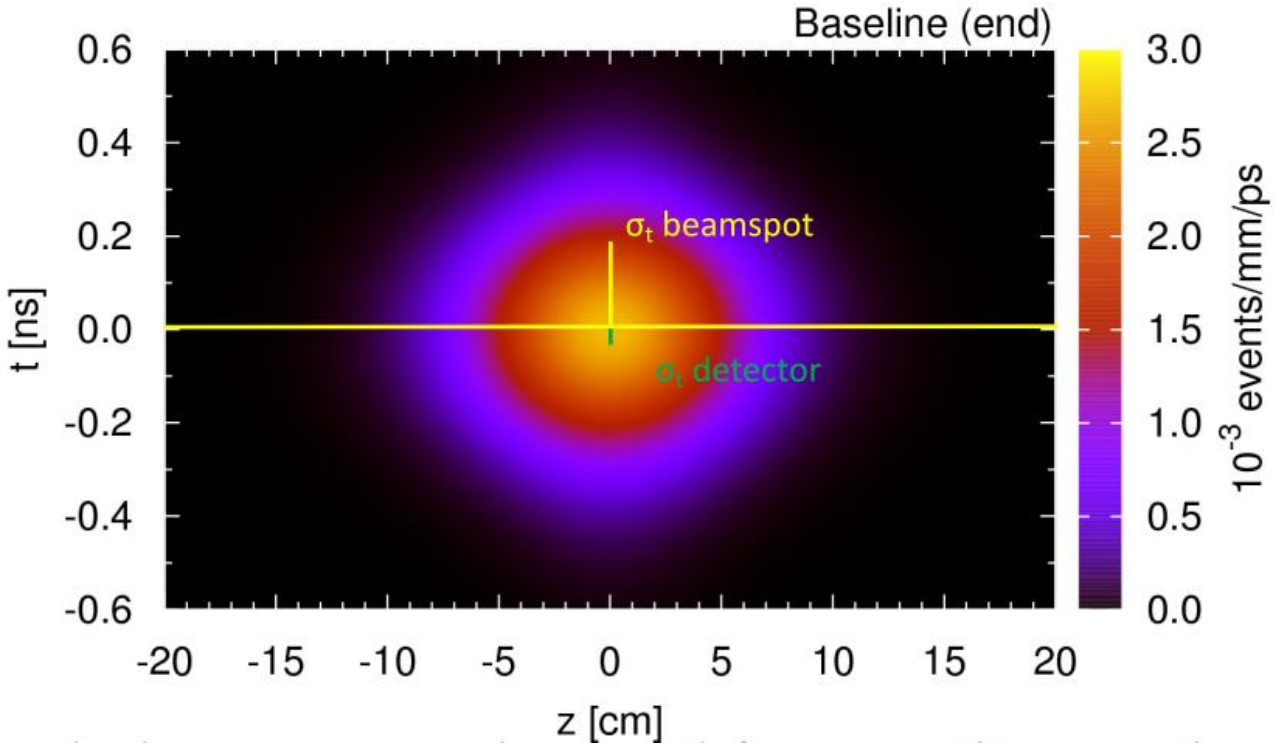
14TeV → 100 TeV
$\sigma_{inelastic}$: 80mb → 108mb
average p_T: 0.6 → 0.8 GeV/c
multiplicity$_{charged/unit\ \eta}$: 5.4 → 8

6x increase in luminosity wrt HL-LHC

Thousands of tracks, vertices, calorimeter clusters that must be disentangled and accurately determined

Motivation: Why do we need precise time stamping of particles? (2)

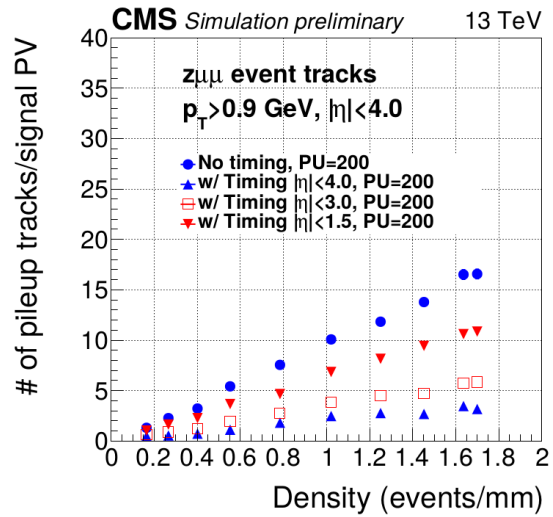
– Profit from primary vertices' time spread.

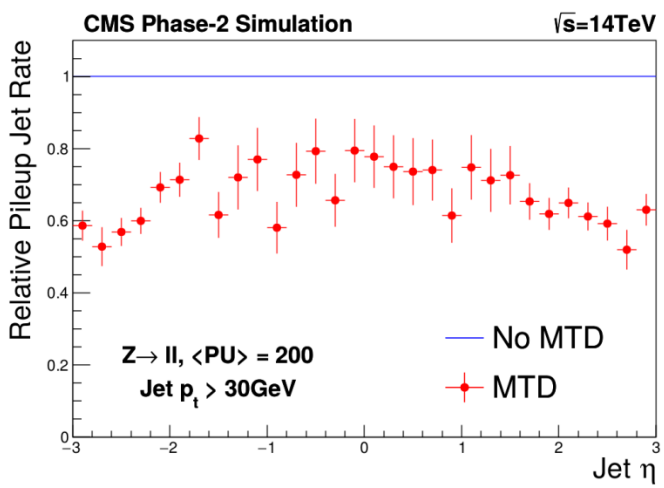


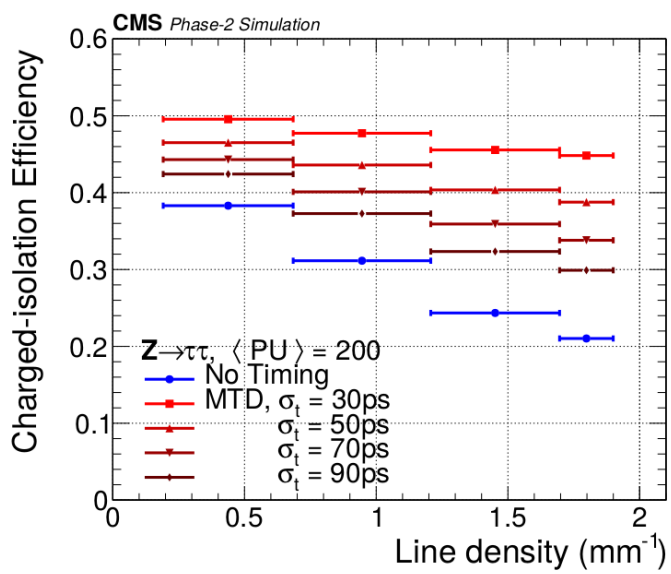
– With a time spread ~ 200ps then 20-30 ps of PV timing resolution is required to disentagle the different primary vertices.

Motivation: Why do we need precise time stamping of particles? (3)

– Suppression of mismatched PU tracks, Jet pileup and improved of track isolation.



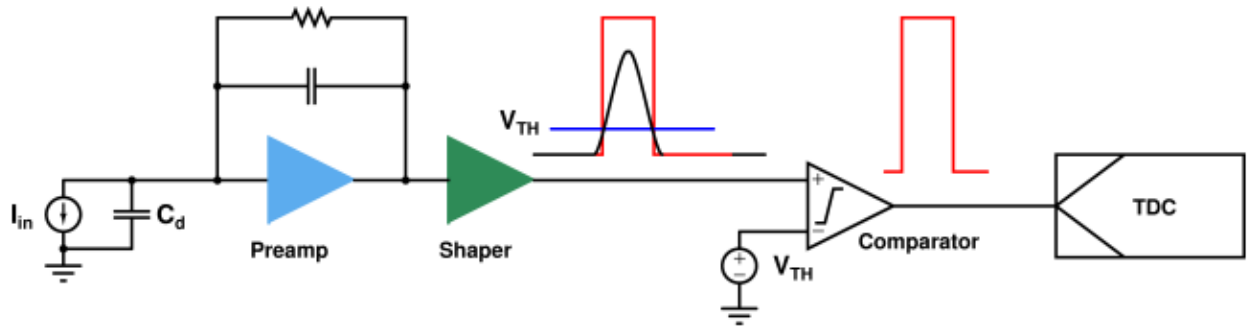




Sensors for timing: Basics

Sensors for Timing 101

Cannonical timing readout chain

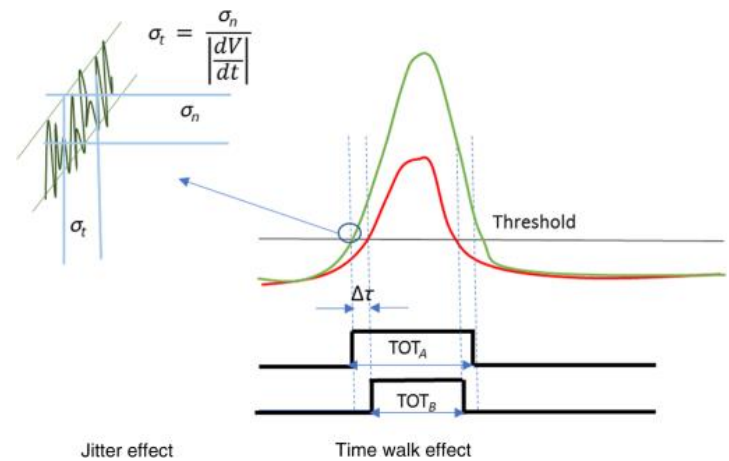


Here focus on **sensor's contribution**: dominated by **jitter** and **time walk** (pulse amplitude and leading edge distortion)

$$\sigma_t = \frac{\sigma_v}{\frac{dV}{dt}} \qquad \frac{dV}{dt} \approx \frac{V}{t_r} \rightarrow \sigma_t = \frac{t_r}{SNR}$$

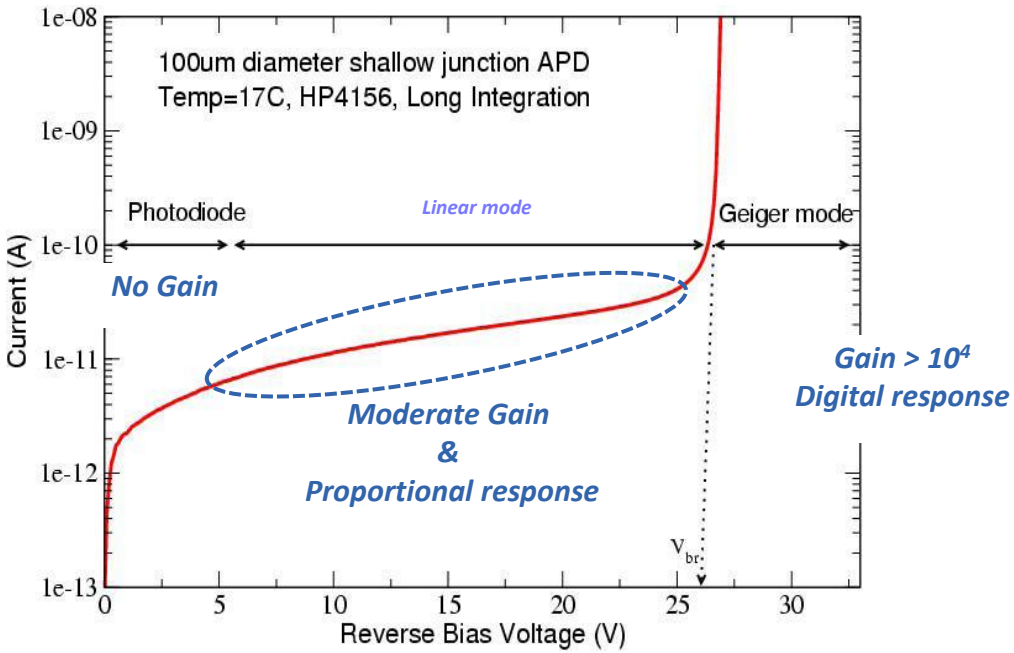
$$t_r \propto \frac{1}{BW}$$

Rise time limited by bandwith (partially due to sensor's capacitance)



Silicon-based sensors timing

- Silicon-based diodes provide both fast rise time and relative large signal/noise ratio.
- Three operating modes: no signal gain (**PIN**), proportional (**APD**) and Geiger mode (**SiPMT**).



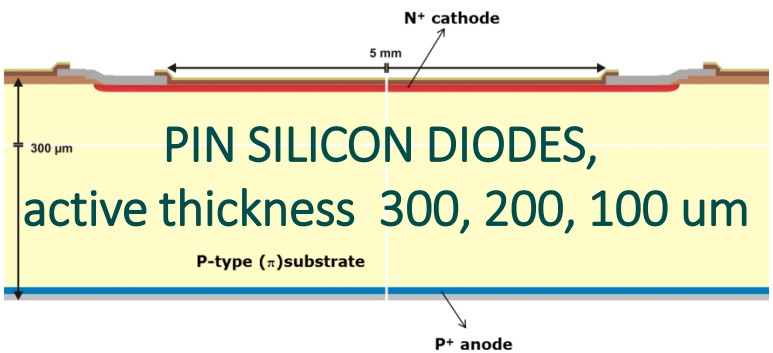
[1] A.G. Stewart et al. in Proc. of SPIE, Vol. 6119, 2006

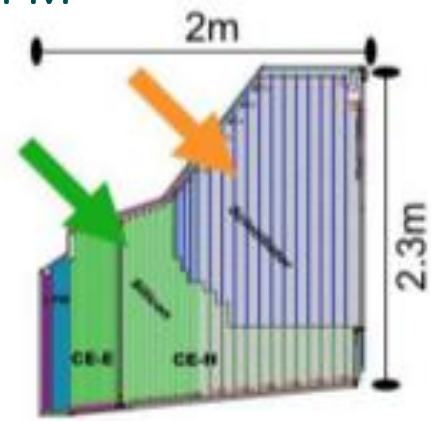
Timing with PIN diodes : CMS HGCAL as case of use

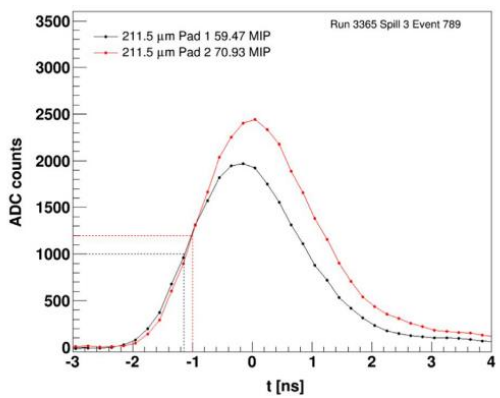
- Very reliable and mature mass producition technology
- Main limitation: low SNR

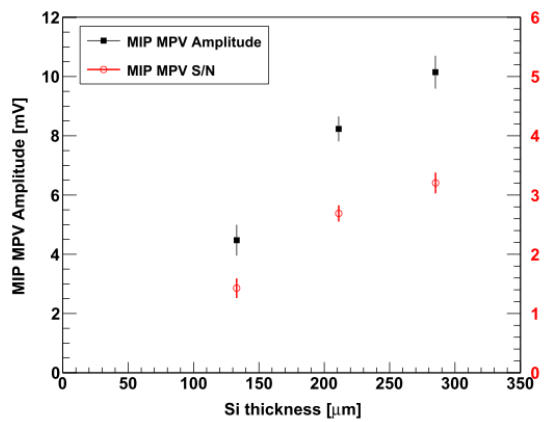
Scintillator + SiPM

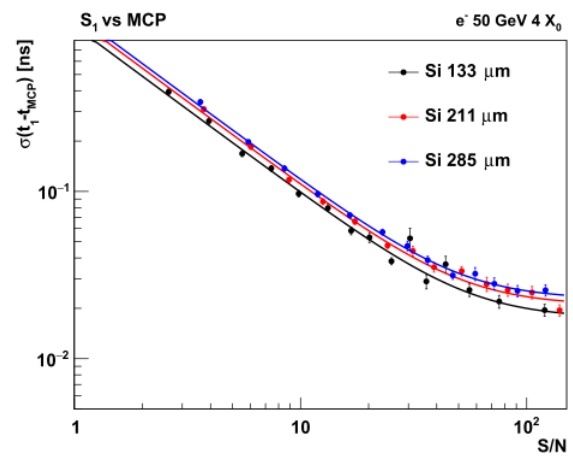
Pin diode





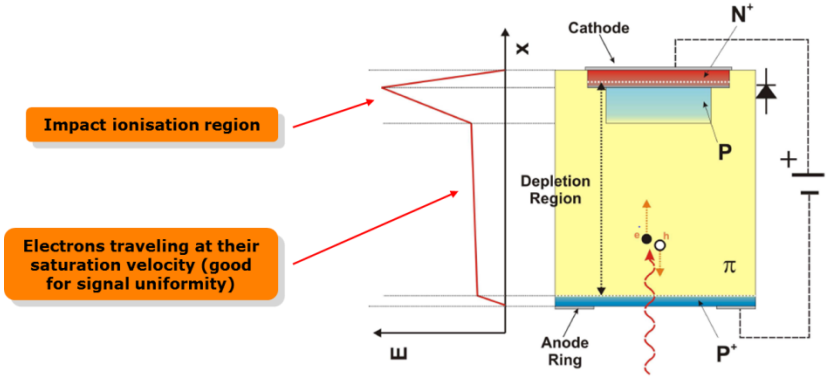


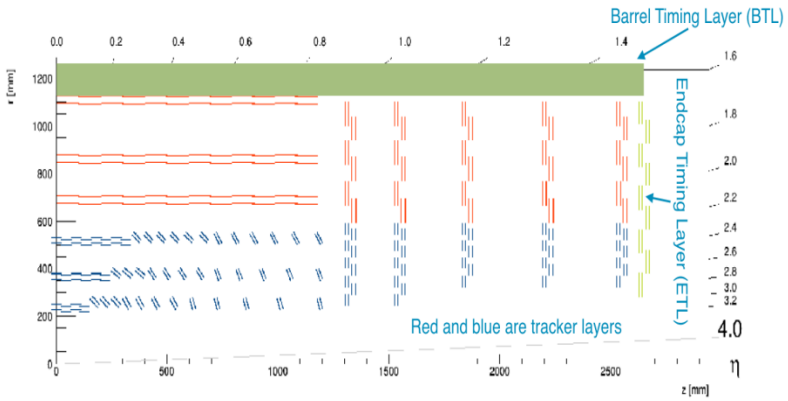


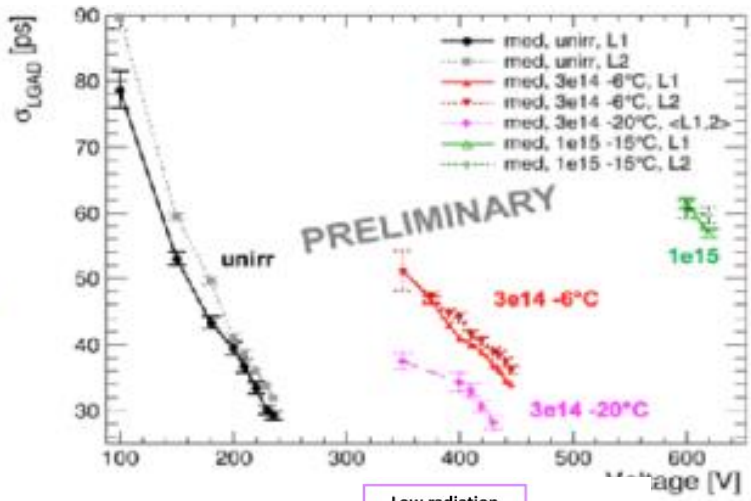


Avalanche mode diode(Low Gain Avalanche Detector .- LGAD) : Case of use ETL at CMS

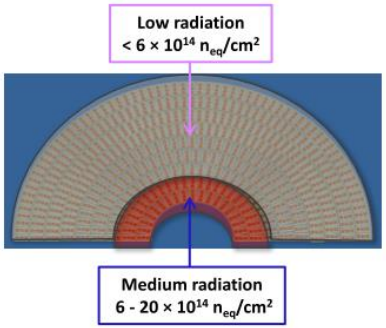
- Main advantage: custom SNR for optimal for timing and tracking
- Main limitation:. moderated radiation tolerance and yet to demonstrate as mass-scale production technology.





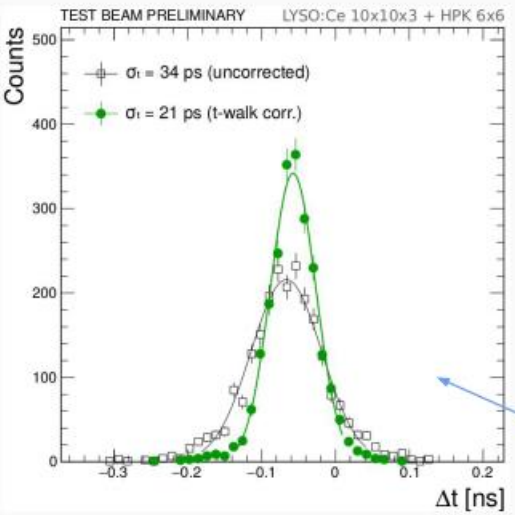


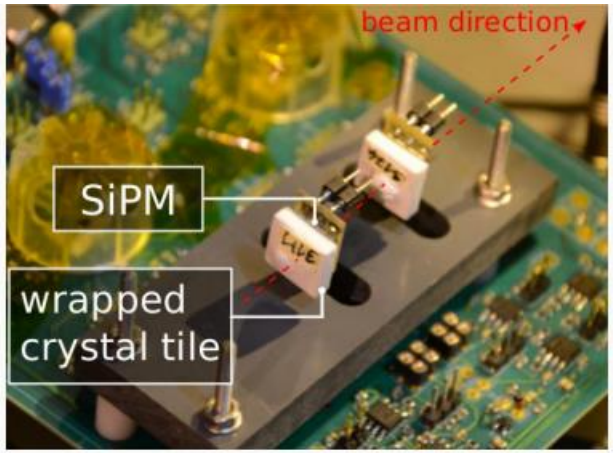
Endcap LGAD
$1.5 < \lvert\eta\rvert < 3.0$
~ 12 m^2
$\sim$1.8 kW/m^2
$\leq$ 2e15 neq/cm^2
2024

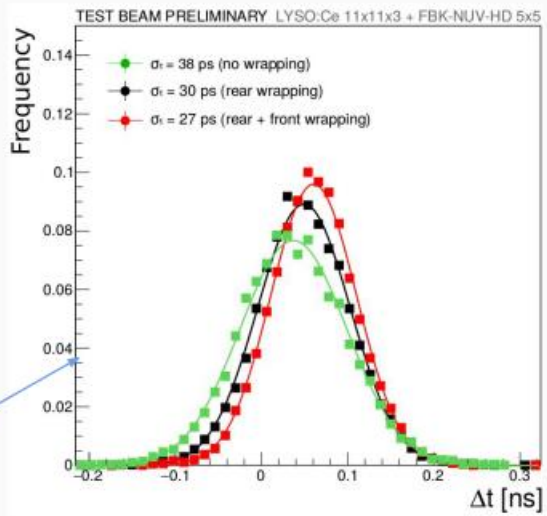


Silicon Photomultipliers: (Geiger-mode APD)
Case of use BTL detector at CMS

- Mature technology, mass produced and cheap sensing element.
- Main limitation: moderate radiation tolerance < $2x10^{14}$ n_{eq}/cm2 and concept with intricsic poor spatial resolution.





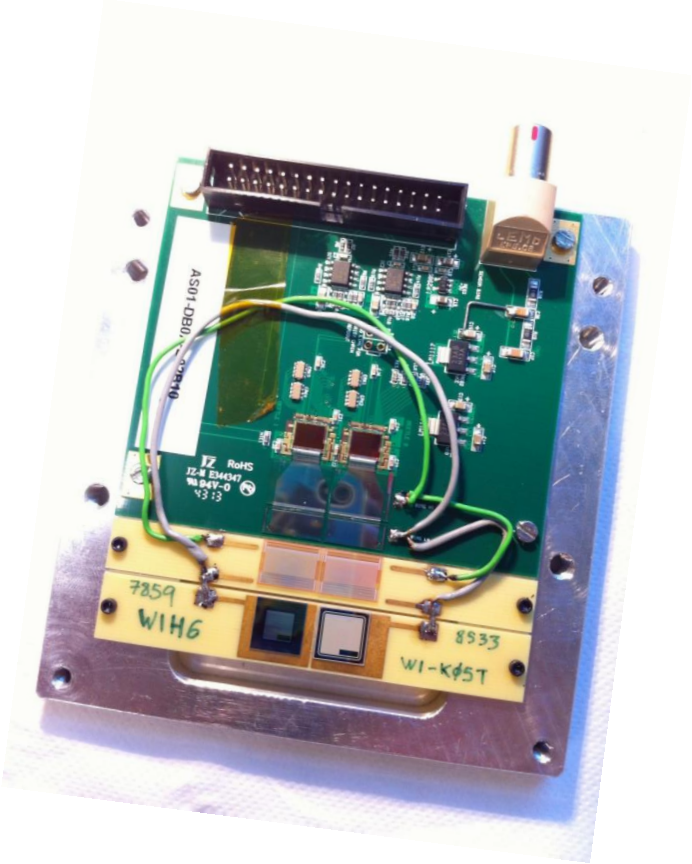


30 ps resolution demonstrated

Silicon –based timing: Performance Comparison

TECHNOLOGY	RISE – TIME (DRIVEN BY CAPACITANCE)	SNR	RADIATION TOLERANCE	MASS PRODUCTION (AFFORADABLE)	DRIVING LIMITATION
PIN (NO GAIN)	FAST < 1ns	LOW	HIGH	POSSIBLE	LOW SIGNAL
LGAD (PROPORTIONAL GAIN)	FAST <1ns	MEDIUM-HIGH	MEDIUM	POSSIBLE TO BE DEMONSTRATED	RADIATION TOLERANCE
SIPM (GEIGER MODE)	FAST <1ns	VERY HIGH	MEDIUM	POSSIBLE	RADIATION TOLERANCE & POOR SPATIAL RESOLUTION

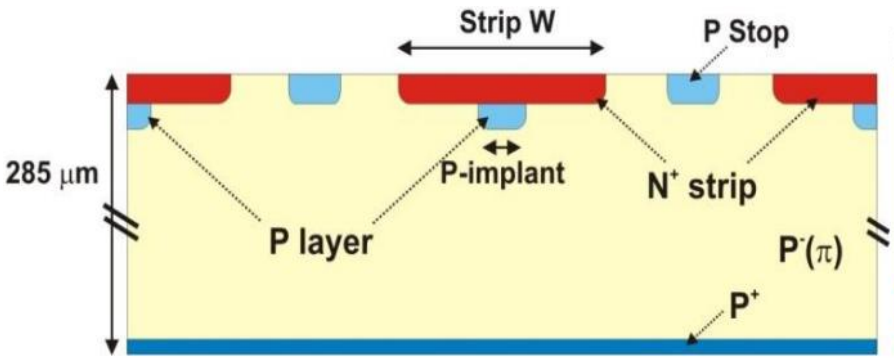
Inverse-Low Gain Avalanche Detector a full fledged 4th dimensional sensor

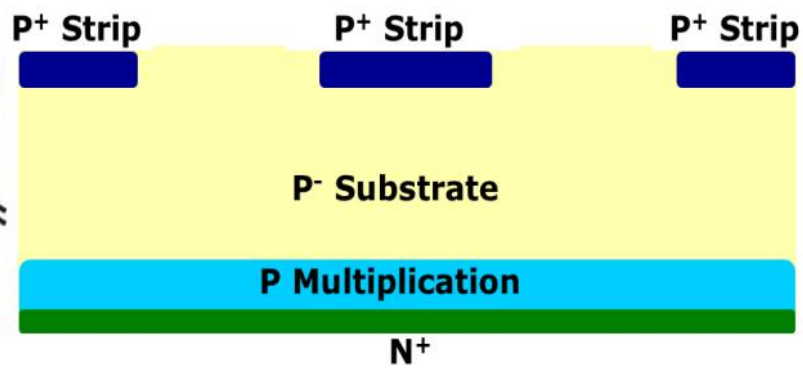


I-LGAD basics: a 4th dimensional tracking sensor

Multiplication layer divided into strip
Collects negative carriers (e)
Simple single side process

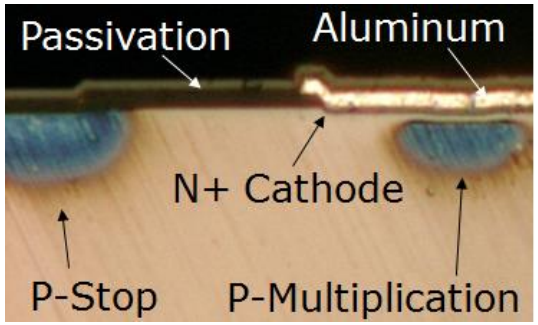
Multiplication layer extended over the electrode
Collects positive carriers (h)
Complex double side process

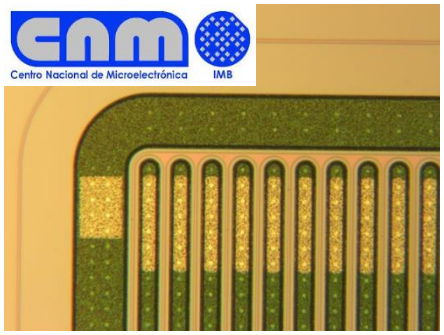




LGAD | N on P microStrip

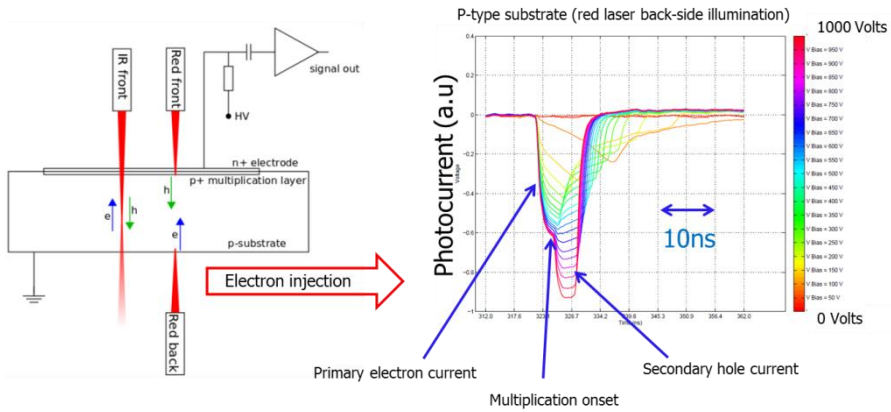
P on P microStrip | iLGAD



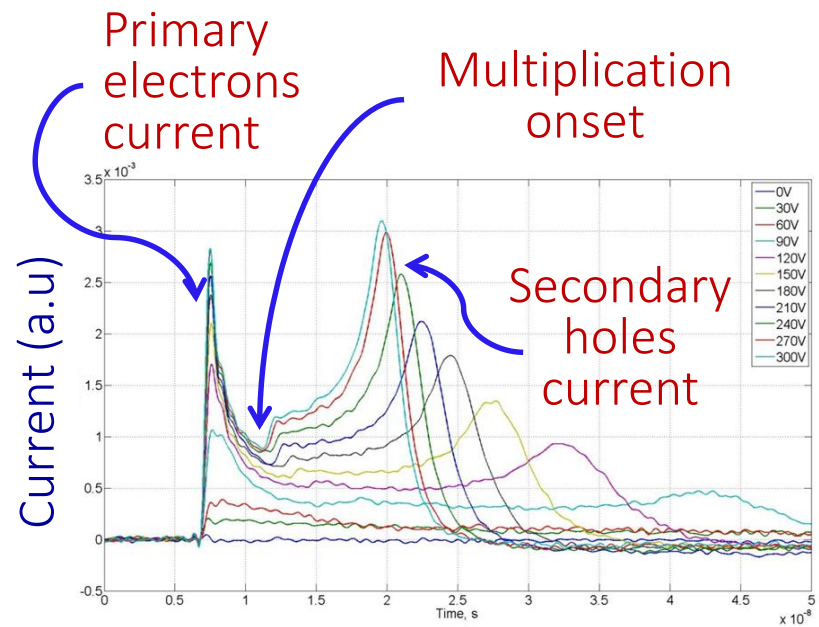


I-LGAD basics: multiplication footprint

- Distinct signature of signal amplification: cathode illumination with red laser
- Injections of electron into the cathode, resulting transient current is a sequential contribution of primary electrons reaching the amplification layer and secondary holes drifting towards the anode.



PAD-like LGAD



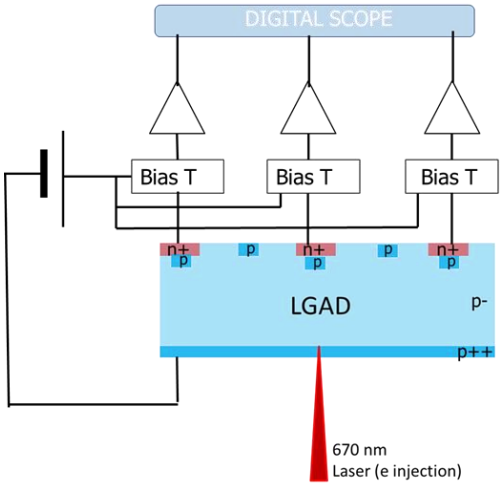
Strip-like I-LGAD

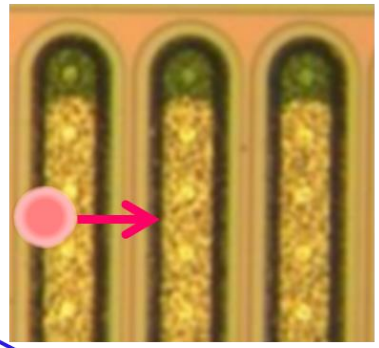
Gain Spatial Uniformity: the fill factor issue

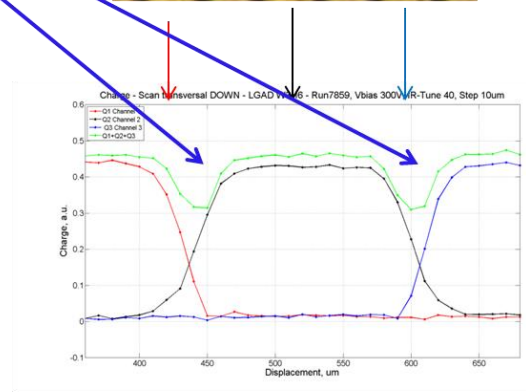
– Conventional LGAD: multiplication layer interspace presents reduced/suppressed gain.

Back-side red laser scanning transversal to the strip direction

Signal deeps between the Strips (no multiplication layer)





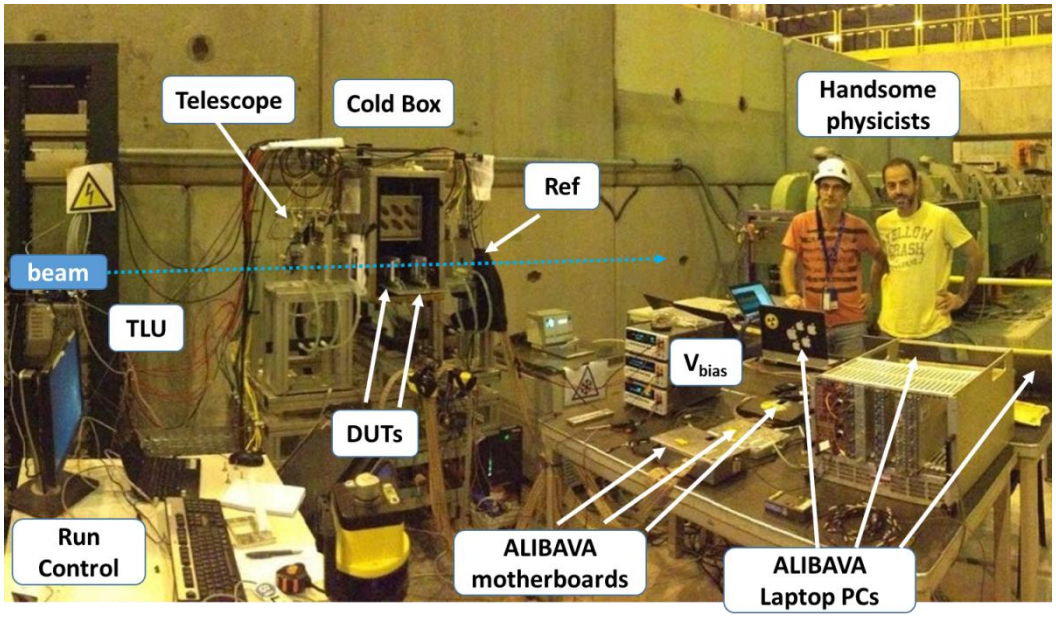


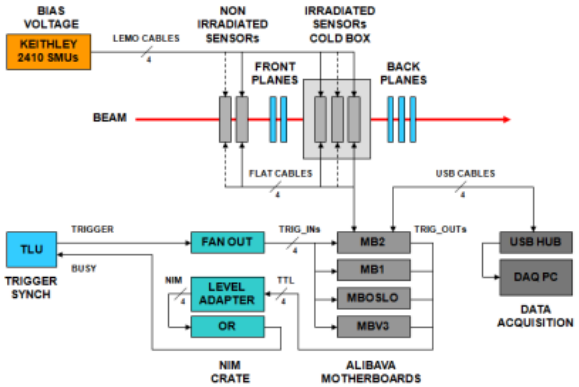
– I-LGAD: non-segmented multiplication layer should present uniform gain.

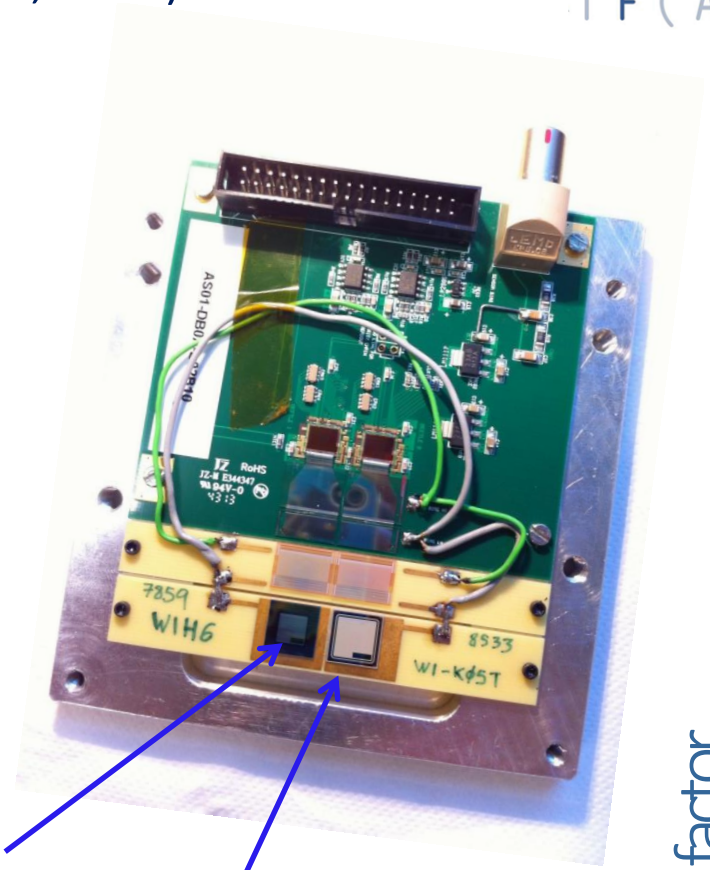
I-LGAD fill factor

Gain Spatial Uniformity: Validation with MIPs

AIDA-2020 WP7 Setup AKA as Atlas ITK setup (2016, 2017)





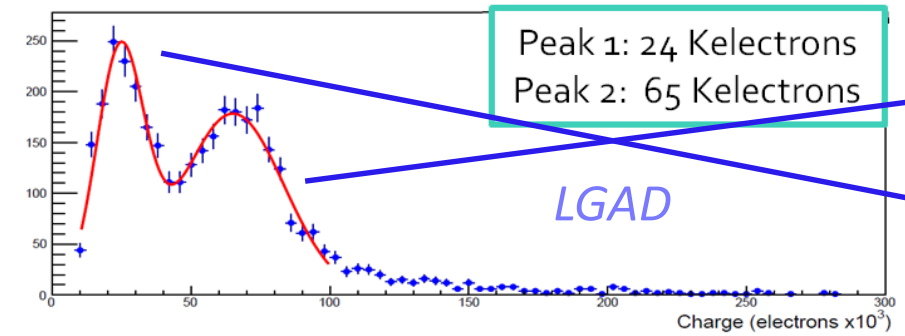


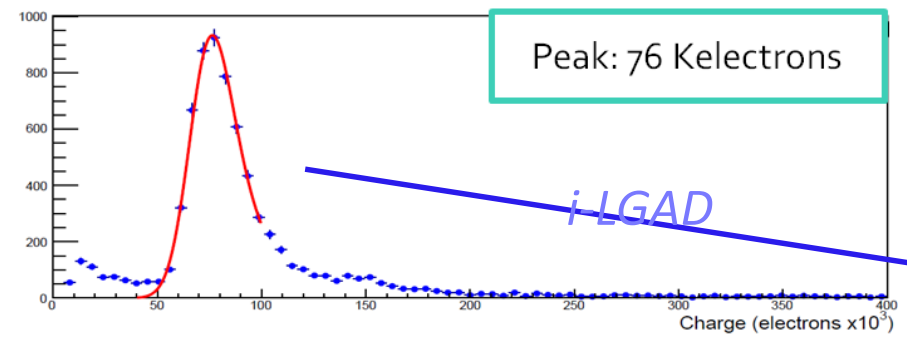
Strip LGAD

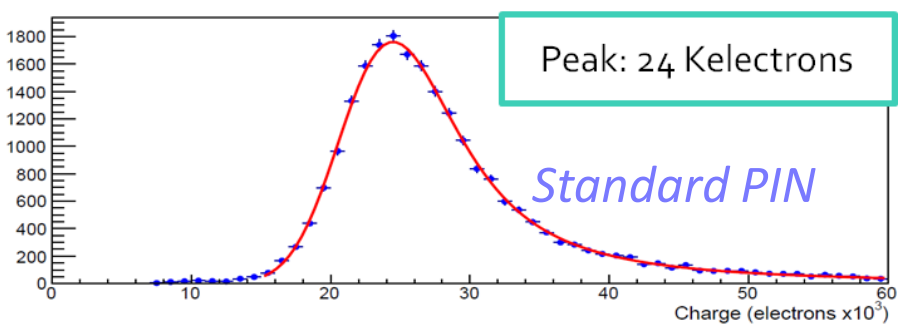
I-LGAD
(8533W1K05T, 45 strips 160 um, non-irradiated)

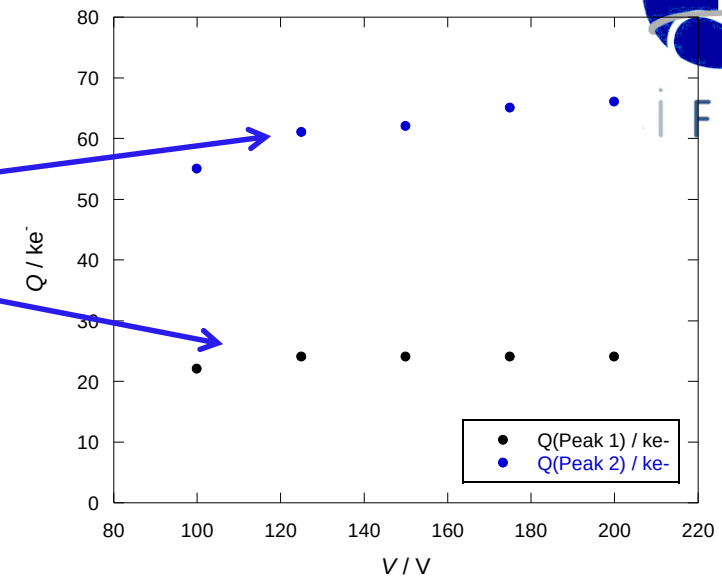
I-LGAD fill factor

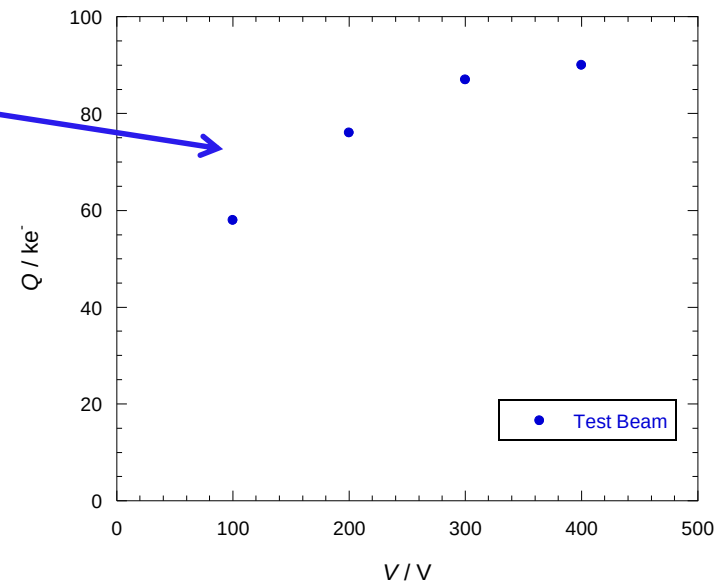
Gain Spatial Uniformity: Collected Charge











I-LGAD fill factor

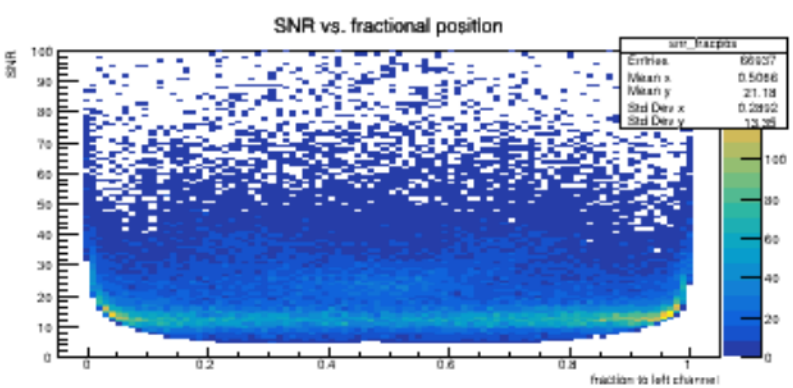
Gain Spatial Uniformity: Gain vs. Hit position (1)

– Dependence of the Signal-to-Noise Ratio with the "fractional position" χ_η for cluster of size two.

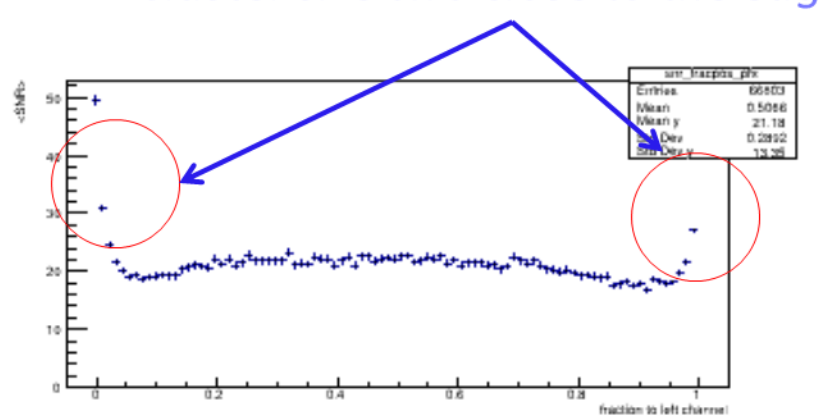
$$\frac{dN}{d\eta}, \qquad \eta \equiv \frac{Q_{Right}}{Q_{Left} + Q_{Right}}$$

$$x(\eta) = \frac{1}{N_0} \int_0^\eta \frac{dN}{d\eta} d\eta$$

Standard Strip sensor
Uniform SNR ratio over the strip width



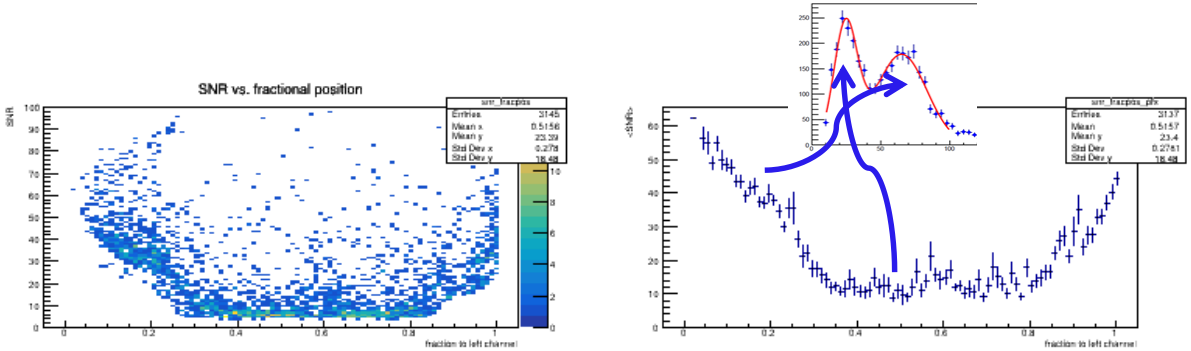
Artifact (selection algorithm,
Cluster size two close to the edges)



LGAD fill factor

Gain Spatial Uniformity: Gain vs. Hit position (2)

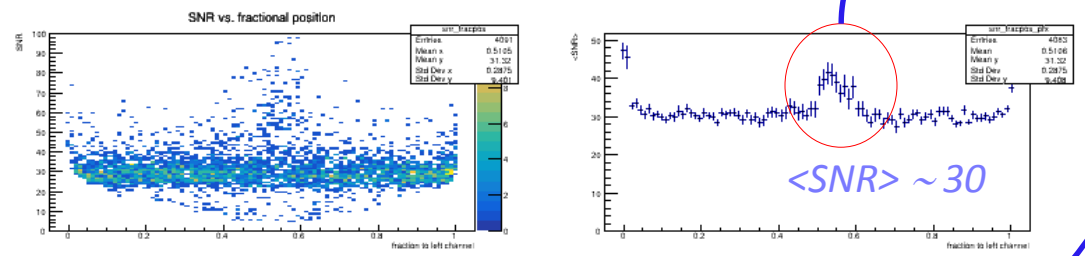
LGAD Strip



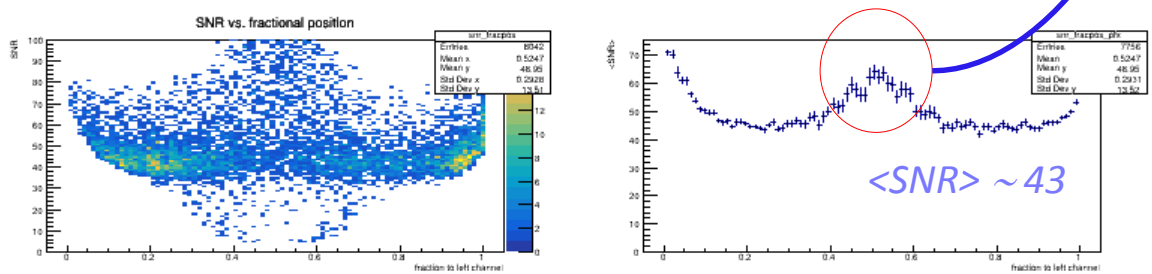
i-LGAD Strip

Artifact due to front-end saturation

100 Volt bias



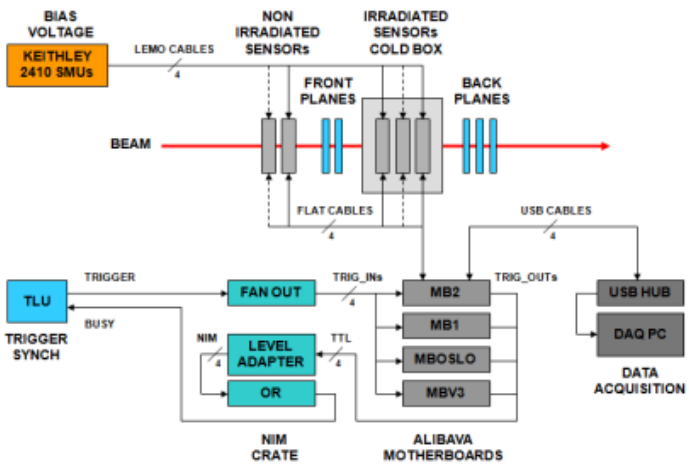
400 Volt bias

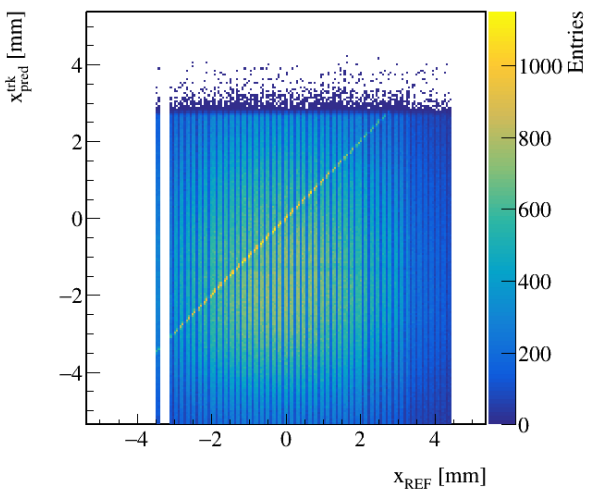


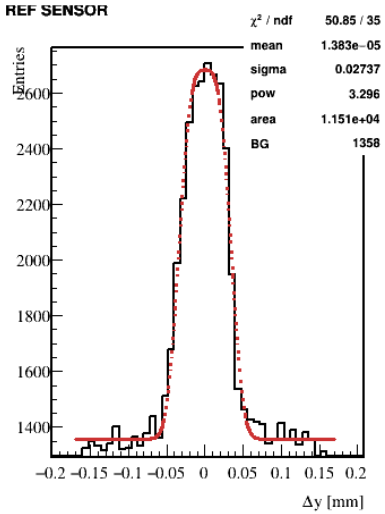
I-LGAD fill factor

Tracking performance: Reference strip sensor

- Challenges:
  - Difficult synchronization between Alibava daq (x3) and Eudaq.
  - Saturation of the Alibava ADC.



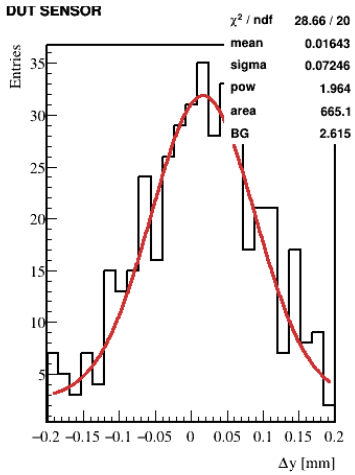


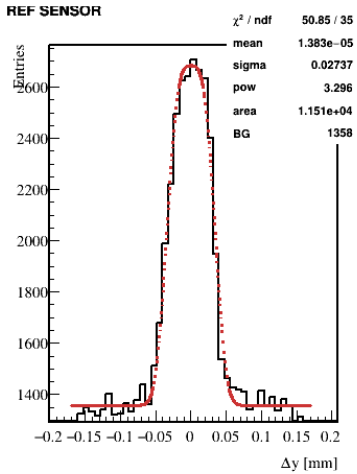


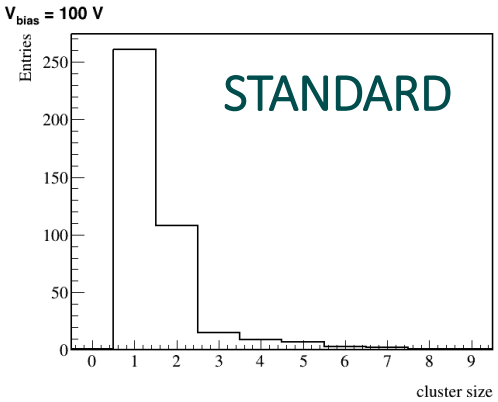
HLGAD tracking

Tracking performance: I-LGAD strip sensor

– Hit resolution biased by saturation of the Alibava ADC ?

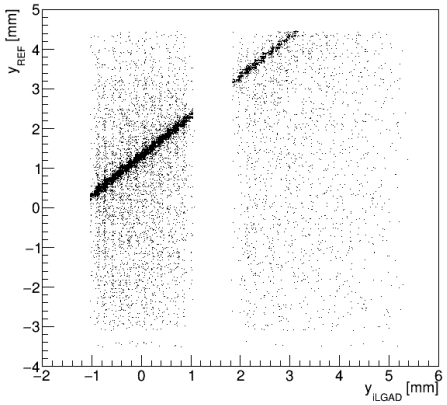


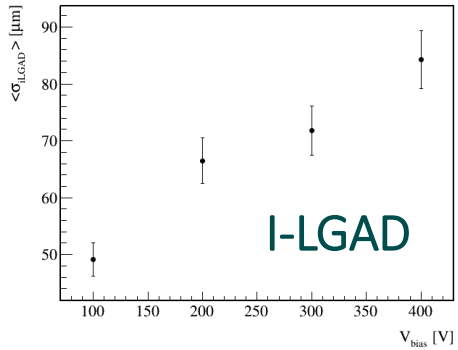


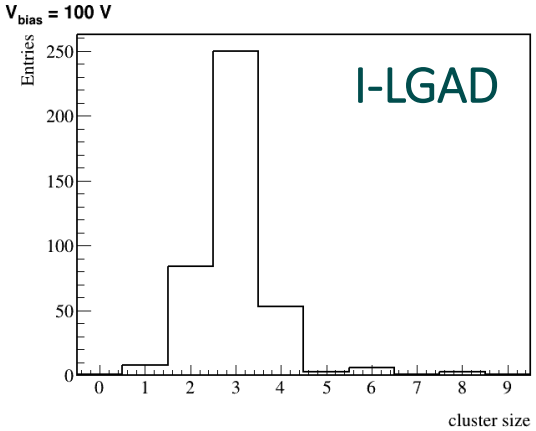


I-LGAD

STANDARD

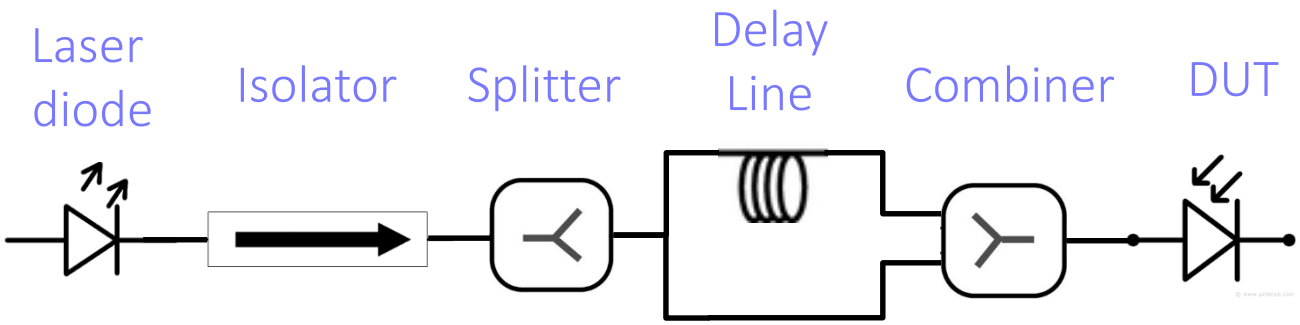


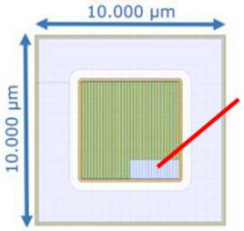




I-LGAD tracking

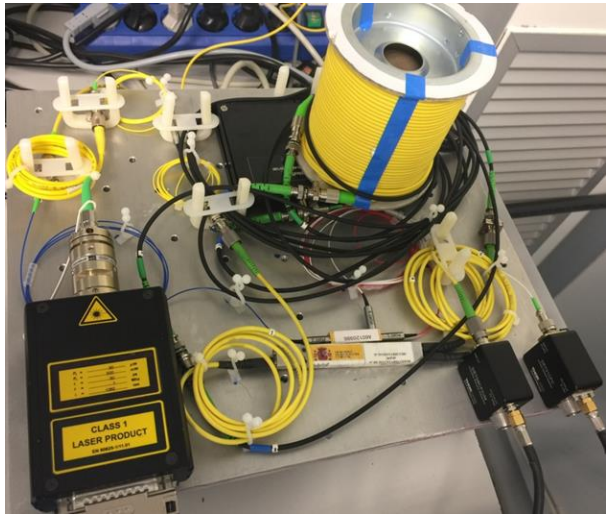
Set-up for timing characterization and DUT





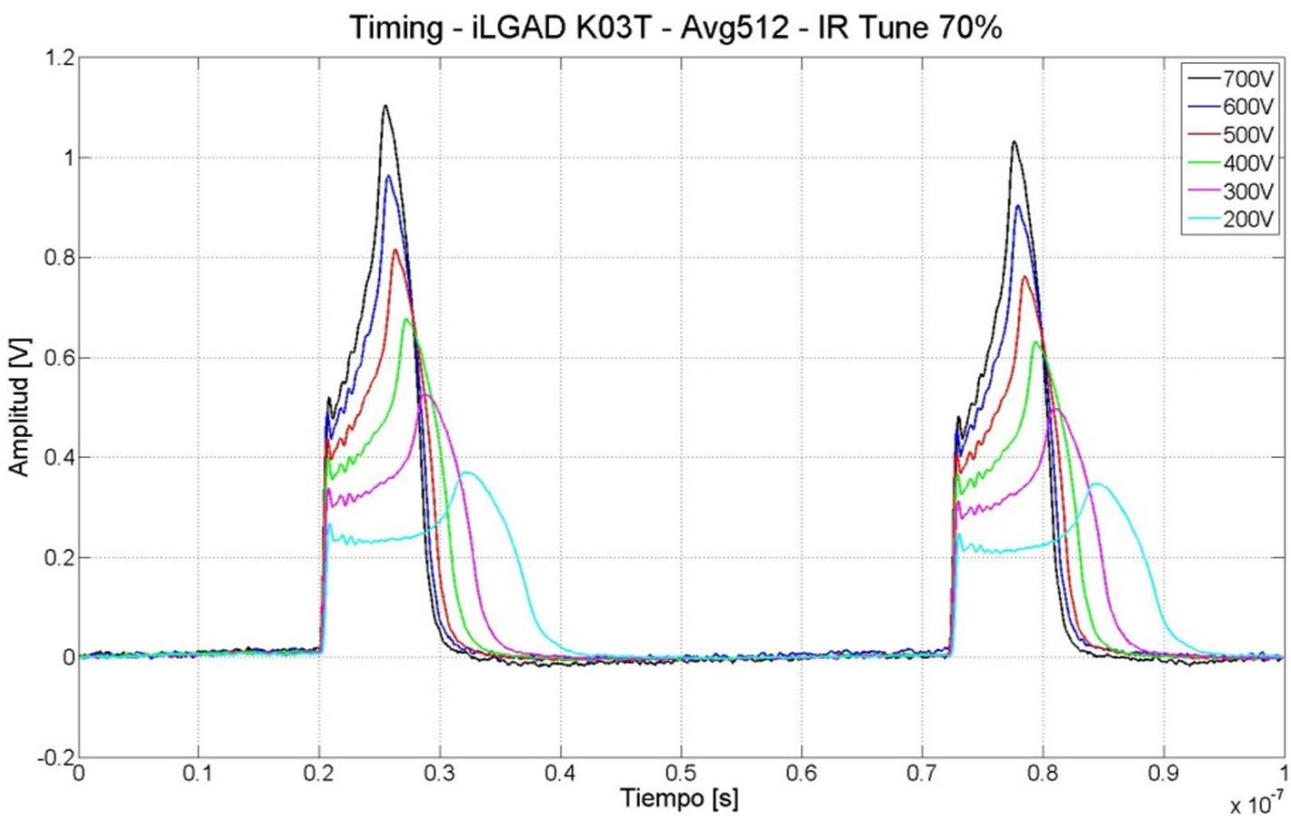
45 strips
Pitch 160 µm

- **Time standard:** constant time interval between two picosecond IR laser pulses (1060 nm)
- Fixed time interval between laser pulses generated by optical splitting and delayed recombination of a single laser pulse.



Set-up for timing characterization and DUT (2)

- Signal amplified (60db, miteq 1660) & digitized (20Gs)
- Acquired averaged waveform from I-LGAD with a time interval of 52.23 ns between pulses.

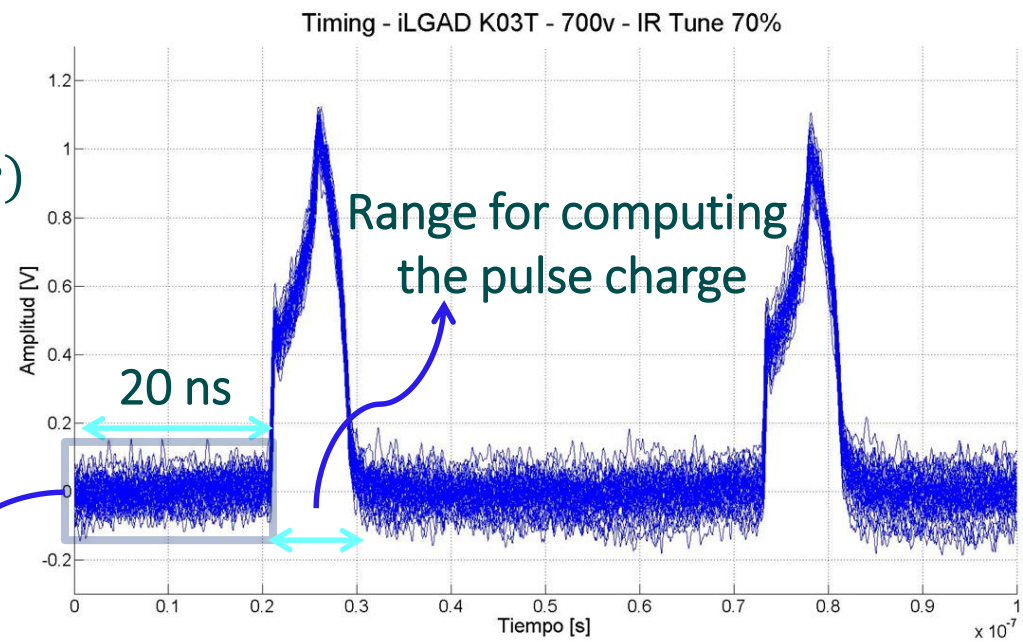


Parameter extraction of the waveform.

- Single-shot (non-averaged) superposition of signals
- For each shot measured: Rise time, Signal amplitude and noise.
- **Signal estimation** as the charge under the transient waveform
- **Noise estimation** as the RMS of charge (from the first 20ns of the waveform)

$$\sigma \equiv RMS\ (Charge\ baseline)$$

$$SNR \equiv \frac{Signal\ Charge}{\sigma}$$



Waveform section from where the baseline noise is estimated

I-LGAD Timing error estimation

- For each Bias voltage five thousand waveform acquired.
- The timing error $\sigma_{\Delta t}$ estimated from the width (sigma) of the distribution of the measured time intervals (Δt)
- Assuming timing errors similar for both pulses then σ_t for I-LGAD is given by $\sigma_{\Delta t} / \sqrt{2}$ (quadratic sum of errors)

Vbias [V]	Rise Time 1 [ps]	Rise Time 2 [ps]	Vp1 [V]	Vp2 [V]	$\sigma_{baseline}$ [au]	SNR1	SNR2	Charge 1 [u. a.]	Charge 2 [u. a.]	Δt [ns]	$\sigma_{\Delta t}/\sqrt{2}$ [ps]
700	334	357	1.105	1.034	13.5	20.6	19.41	279.0	262.0	52.23	25.45
600	326	327	0.965	0.905	14.8	17.02	15.99	252.0	236.6	52.23	26.87
500	330	327	0.815	0.762	14.8	16.0	14.97	237.0	221.6	52.23	27.58
400	357	353	0.677	0.631	14.4	14.3	13.34	206.0	192.1	52.23	31.82
300	357	355	0.526	0.496	15.1	11.5	10.77	174.8	162.6	52.23	37.48
200	354	358	0.370	0.347	14.6	9.5	8.63	139.0	126.0	52.23	46.67

Time error dependence with the SNR

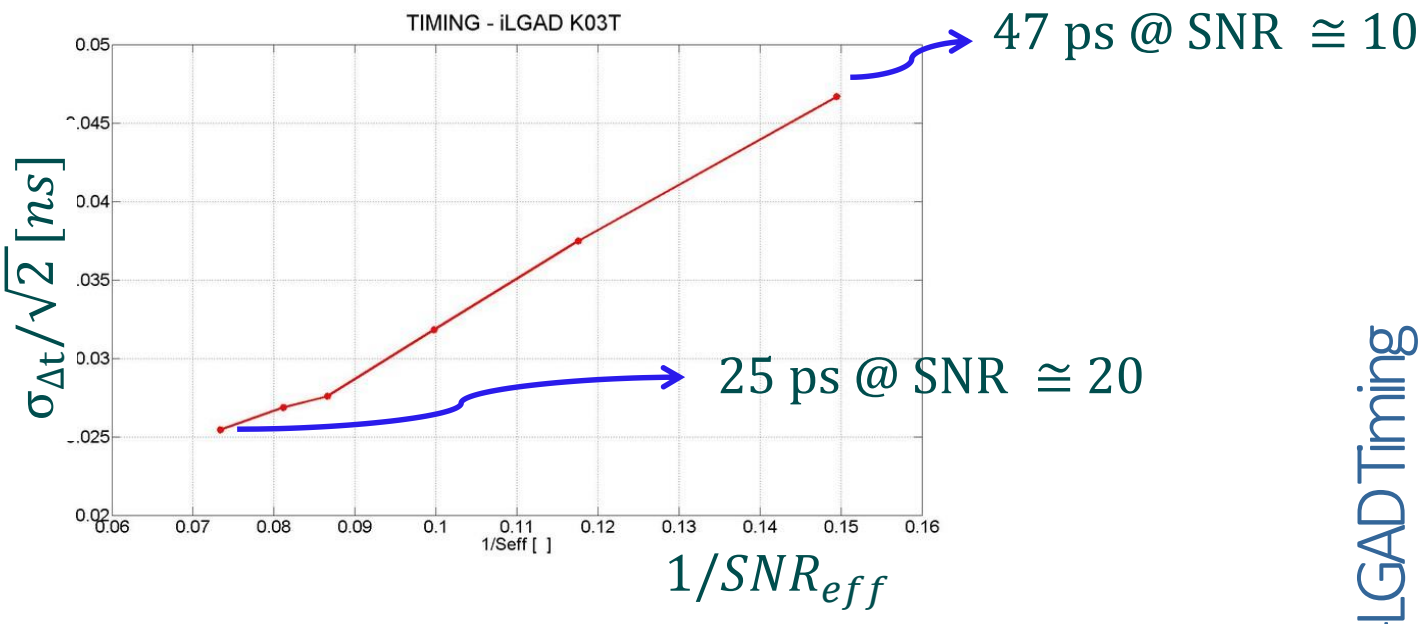
Expected time error dependence with SNR

$$\sigma_t \propto \frac{\text{rise time}}{\text{SNR}}$$

Defining the effective SNR as

$$SNR_{eff} \equiv SNR_1 SNR_2 / \sqrt{SNR_1{}^2 + SNR_2{}^2}$$

$$\boxed{\sigma_{\Delta t}{}^2 = \sigma_{t1}{}^2 + \sigma_{t2}{}^2 \Rightarrow \sigma_{\Delta t} \propto \frac{1}{SNR_{eff}}}$$



Summary and Outlook

- Precise time stamping a must for future detectors to cope with very high pileup and track occupancy conditions .
- Several technological implementations under development.
- A p-in-p Low Gain Avalanche Detector (I-LGAD) to provide both high precision tracking and timing.
- As today, radiation tolerance remains the limiting issue.

THANK YOU FOR YOUR ATTENTION

… a particular case concerning radiation tolerance.

- The layout of the proposed LHC timing detectors: a mosaic of mini-pads (elements with area of few mm^2)
- **A pad-like LGAD is also a pad-like I-LGAD therefore they exhibit the same radiation tolerance**