Gain and time resolution of 50 µm LGADs before and after irradiation

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Institut de Física d'Altes Energies

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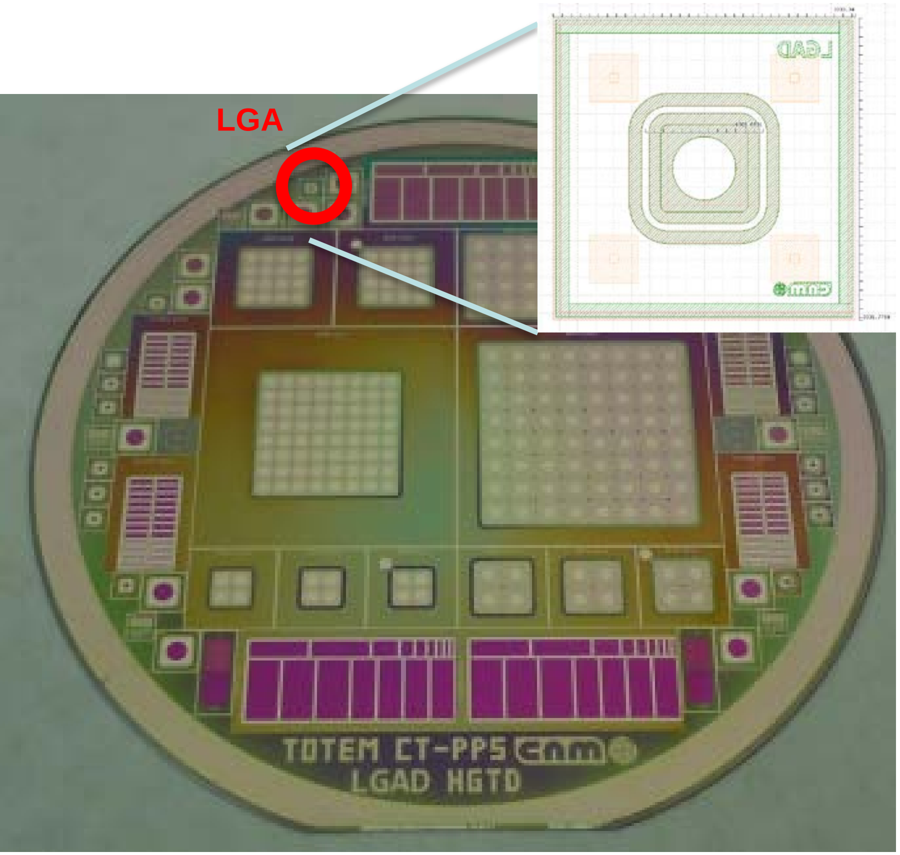
Samples from 50 µm LGAD Run

- Studied small LGAD pad diodes LGA from 50 µm SOI CNM run 9088
  - Active area 1.3x1.3 mm², multiplication area 1x1 mm²
  - 3 different CM-layer implantation doses: 1.8 (low), 1.9 (med) and 2.0 (high) x 10^{13} cm^{-2}
  - Before and after irradiation with neutrons at JSI Ljbuljana to 3e14 and 1e15 n_{eq}/cm^2
  - Performed gain measurements with TCT (Barcelona) and Sr90 (Ljbuljana) and test beam measurements (CERN SPS, 120 GeV pion) for time resolution

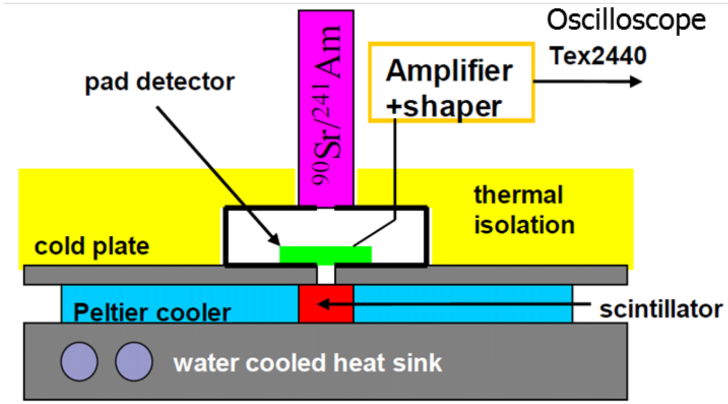


Sample	Dose [cm^{-2}]	Fluence [n_{eq}/cm^2]	Measurements
W3-LGA-61	1.8	0	TCT,TestBeam (TB)
W3-LGA-71	1.8	0	TCT,TB
W5-LGA-45	1.9	0	TCT,Sr90,TB
W5-LGA-81	1.9	0	TCT,Sr90,TB
W5-LGA-51	1.9	3e14	TCT,Sr90,TB
W7-LGA-45	1.9	3e14	TCT,Sr90,TB
W5-LGA-43	1.9	1e15	TCT,Sr90,TB
W7-LGA-35	1.9	1e15	TCT,Sr90,TB
W11-LGA-61	2.0	0	TCT
W11-LGA-71	2.0	0	TCT

Gain Measurement Setups

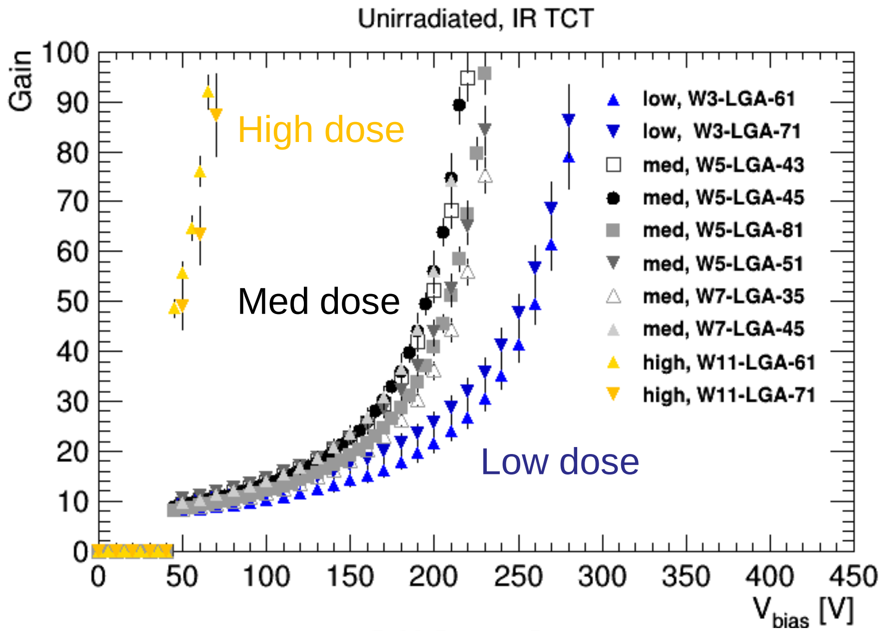
- TCT
  - TCT setup at IFAE Barcelona: scanning TCT from Particulars
  - IR laser from front-side
  - DRS4 readout
  - TCT PCB developed by DESY/Hamburg
  - Measurements performed on LGAD + reference without CM layer
    -> Gain as ratio
  - Measured LGADs before irradiation at room temperature

- Sr90 charge collection
  - Setup at Ljubljana
  - MIP-like β particles
  - Charge-sensitive preamplifier (Ortec 142B) + shaper (25 ns shaping time)
  - Oscilloscope readout
  - Calibrated with Am241
  - Mounted inside Al box with hole
  - Scintillator trigger
    -> but samples were quite small, still many noise events
    -> but Landau-Gauss fit possible
  - Room temperature before irradiation, -10°C after (Peltier)
  - Measurements performed on LGAD + reference without CM
    - Reference: 2880 e$^-$ (measured in big pad diode LGB)
      -> Gain as ratio

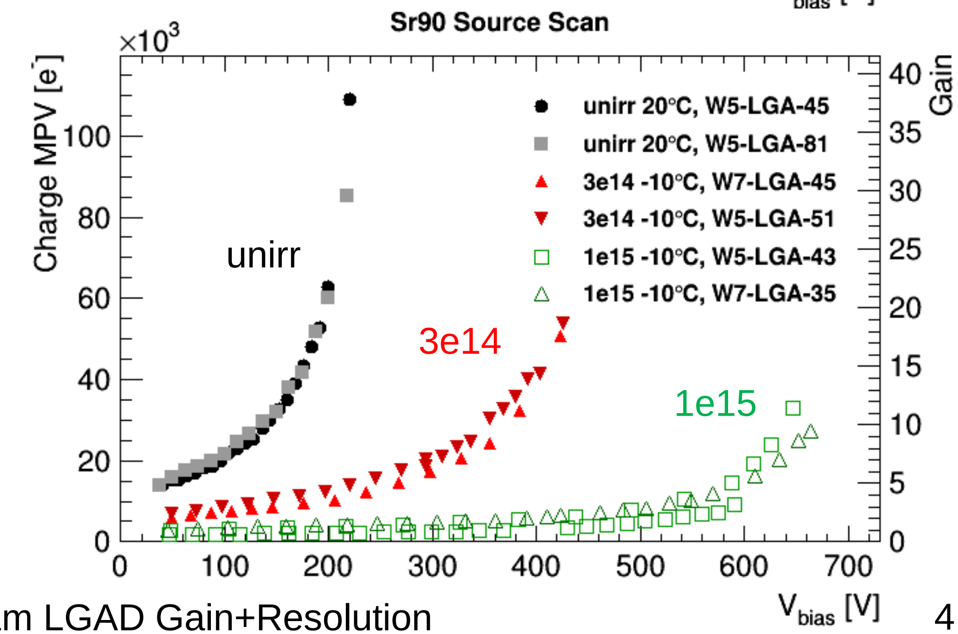


Gain and Charge Results

- TCT
  - Unirradiated for different doses
  - Relatively consistent results for same dose
    - Only small variation for med dose
  - Clear difference between doses
    - Much higher gain for higher dose
    - Breakdown at 70V (high), 230 V (med), 300 V (low)
      -> consistent with IV
  - Relatively high gain observed

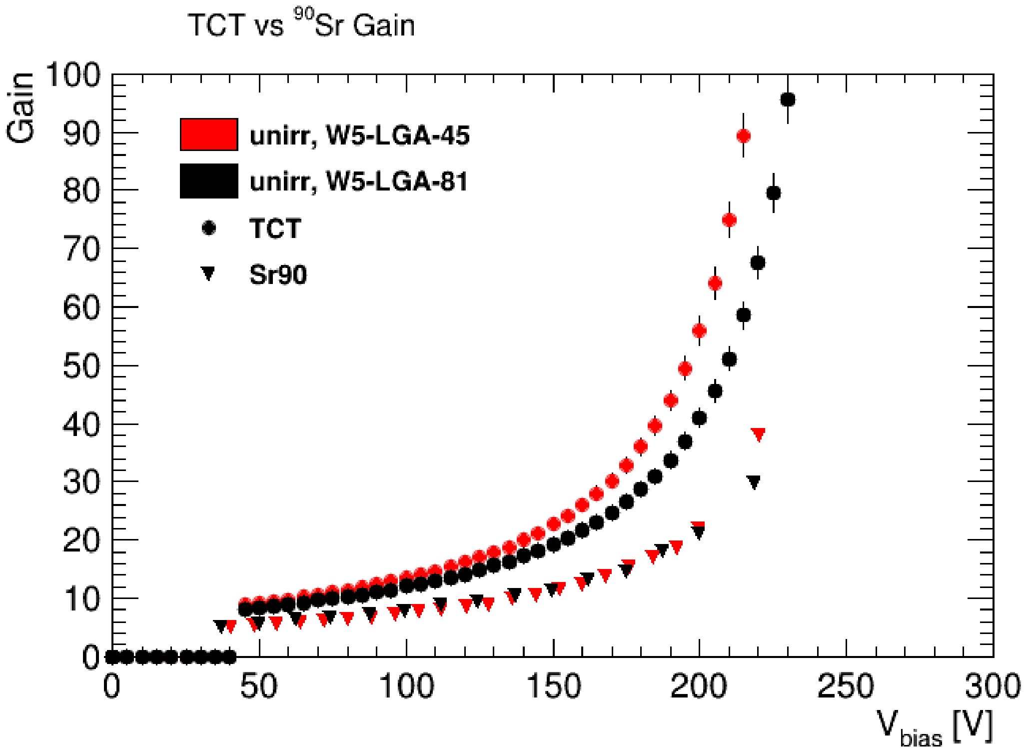


- Sr90
  - Unirradiated, 3e14, 1e15 for med dose
  - Clear difference between fluences
  - Breakdown higher for higher fluence
  - Measurements limited by noise and micro discharge increase at breakdown
  - Gain decreases strongly with fluence
    -> acceptor removal
  - Gains:
    - ~40 @ 220 V before irradiation
    - ~20 @ 420 V for 3e14
    - ~10 @ 650 V for 1e15



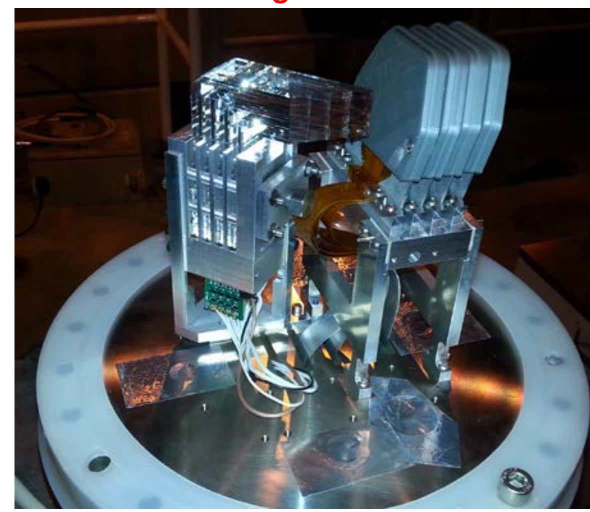
Comparison of Gains TCT-Sr90

- Difference between TCT and Sr90 measurements
  - Gain higher at same voltage for TCT measurement
  - Difference seems to increase with V
  - Also spread between samples higher in TCT
  - Similar differences seen by other groups
  - Reason still under investigation
    - Reflections of laser at back side metal? But why different for reference and LGAD?
    - Different charge carrier concentrations?

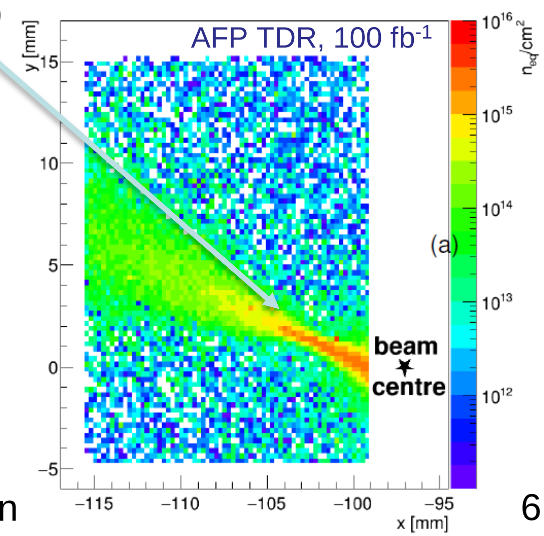


LGADs in AFP Beam Tests

- First timing measurements of 50 µm LGADs before and after irradiation in AFP beam tests
  - June/July -> med dose, unirradiated
  - September -> med + low dose, unirradiated
    -> med dose, 3e14 + 1e15 n_{eq}/cm^2

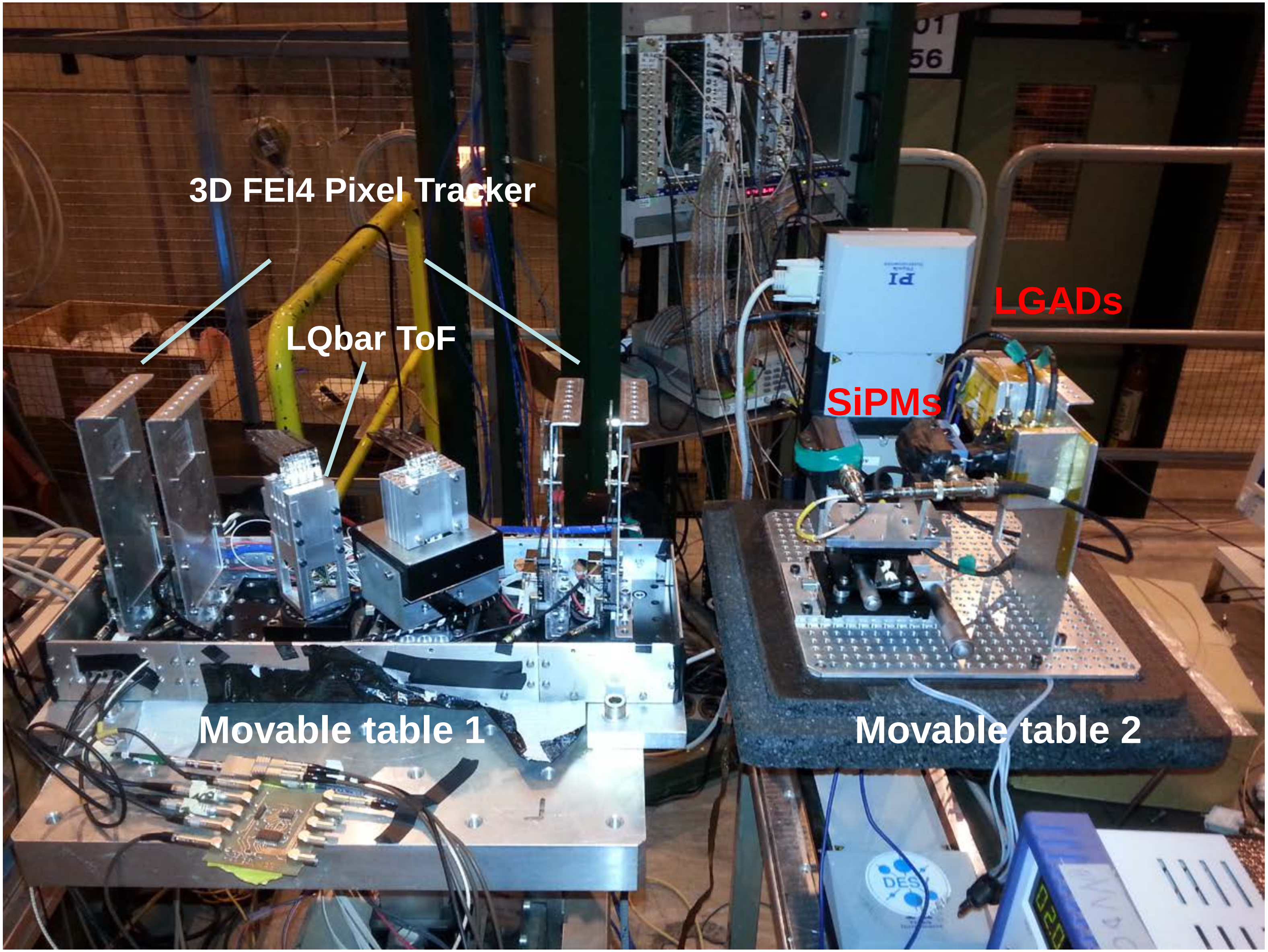


- AFP: ATLAS Forward Proton detector
  - Precision 3D tracking (3 µm) and timing (design goal: 10 ps)
  - Similar to CT-PPS
  - Trackers already (half) installed
  - Need 10-20 ps timing detectors for installation end of the year!
  - Baseline: L-shaped Cherenkov radiating Quartz LQbars + MCP-PMT
    - 12 ps resolution achieved (w/o TDC)
  - LGADs very interesting competing technology
    - Higher segmentation: advantage for very high pile-up conditions
    - But need radiation hardness:
      non-uniform irradiation with peak of 1e15 n_{eq}/cm^2 for 35 fb^{-1} (1 year)
  - Long experience with ps timing, infrastructure available at beam tests
    - Amplifiers, CFDs, HPTDC, tracker, scopes, read out system
    - 3x Quartz+SiPM reference detectors with 10 ps resolution

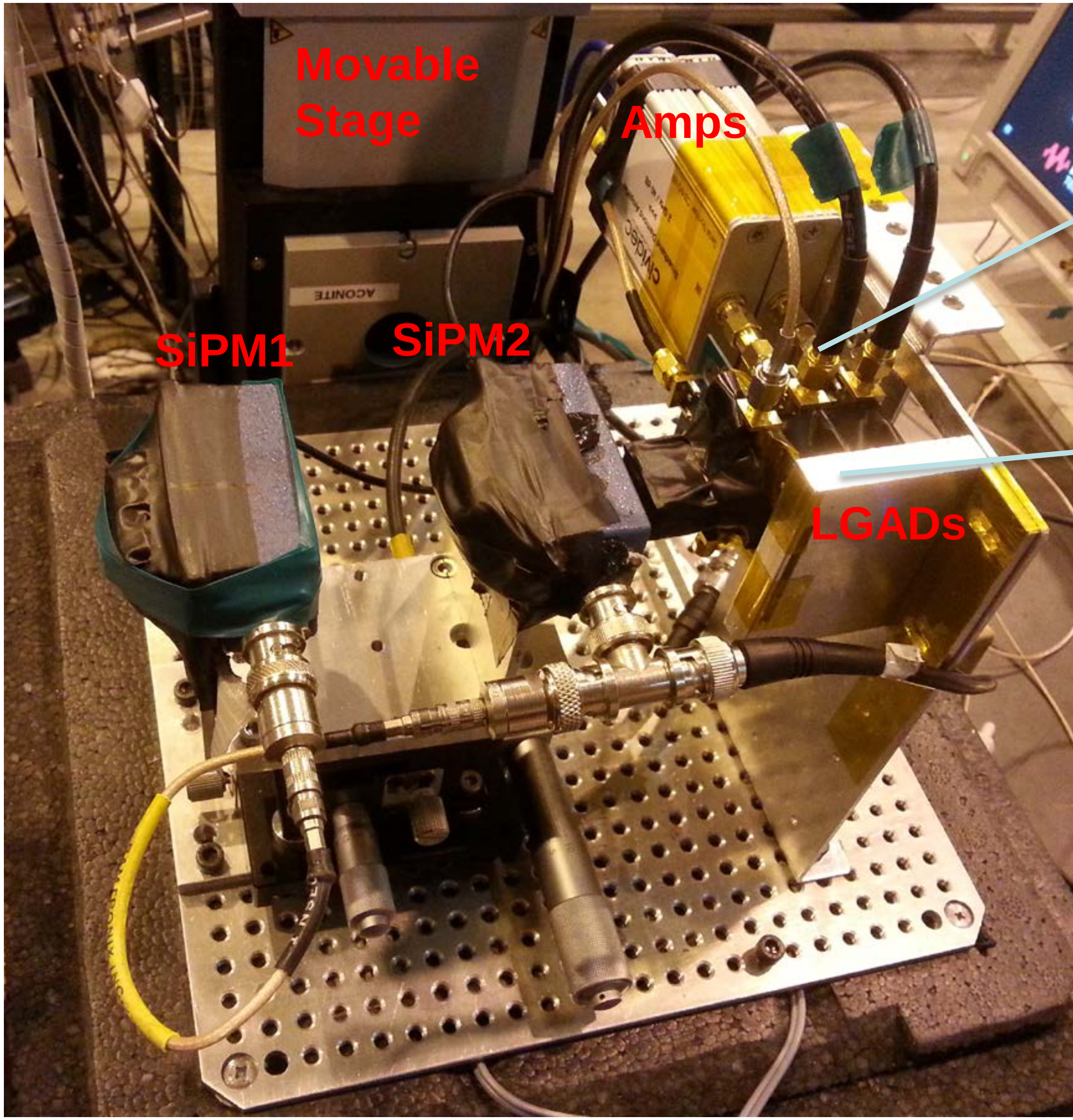


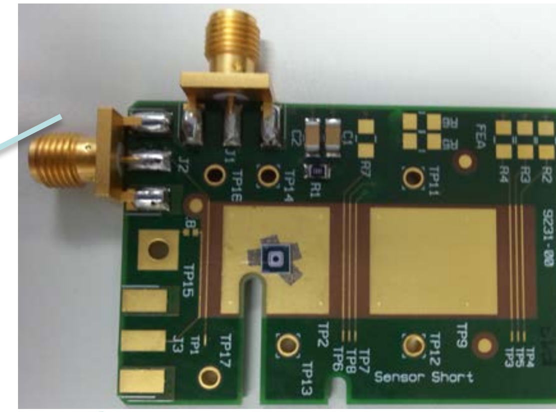
J. Lange et al., JINST 11 (2016) P09005

AFP Beam Test Setup



TB Setup – SiPMs and LGADs





- TCT PCB developed by DESY/Hamburg
- Advantage: one mount for both measurements
- Disadvantage: long wirebond + SMA connector before amplifier
  -> sensitive to pick-up noise, reflection

Base plate in styro-foam box (dry ice cooling possible)

Readout

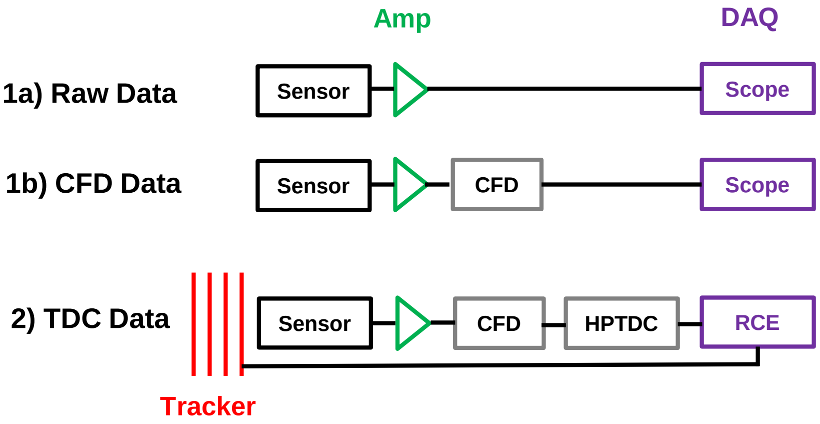
1) Oscilloscope readout: ToF stand-alone

- Scopes:
  - Agilent infiniium DSA91204A, 12 GHz, 40GS/s -> default shown here
    - Typically down-tuned to 1 GHz (optimum)
  - LeCroy 2GHz 20GS/s (2ch) -> only in June/July, not shown here
- 10 ps timing reference: Quartz + SiPM + CFD, 3x3x30 mm
- Pre-amps:
  - CIVIDEC C2 TCT broadband 10kHz-2GHz, 40dB -> default shown here
  - CIVIDEC C2 broadband 1MHz-2GHz, 40dB
  - CIVIDEC CSA C6 4 ns shaping
  - Particulars TCT
  - AFP PAa+Pab
  - Uni Geneva CSA 1 ns shaping
- 1a) Direct raw/analog waveform recorded
  -> main topic of this talk
- 1b) Optional Constant Fraction Discriminator (CFD)
  - SiPMs always measured with CFDs
  - LGADs only tested in June/July with CFDs
  - Fixed threshold 50 mV for noise rejection
  - Fractional threshold 50% for time evaluation

Thanks to M.Moll, M.Fernandez, E.Curras, E.Griesmayer, L.Paolozzi

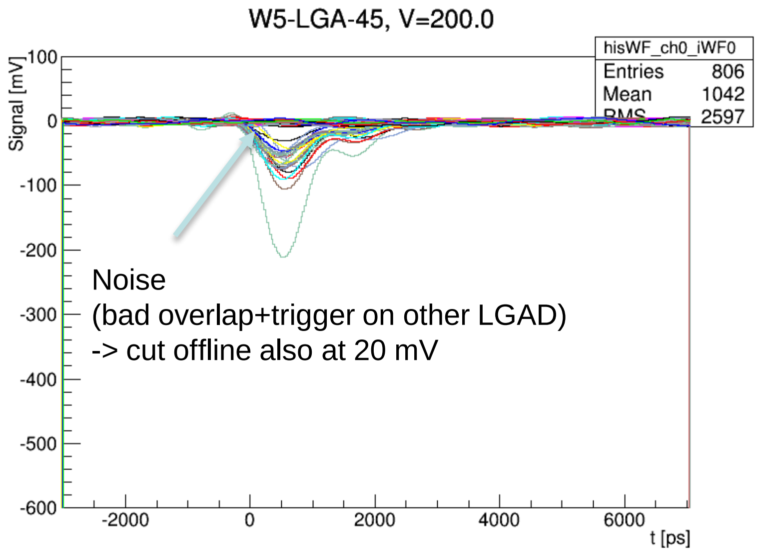
2) Integrated: FEI4 Tracker+ToF+HPTDC+RCE readout

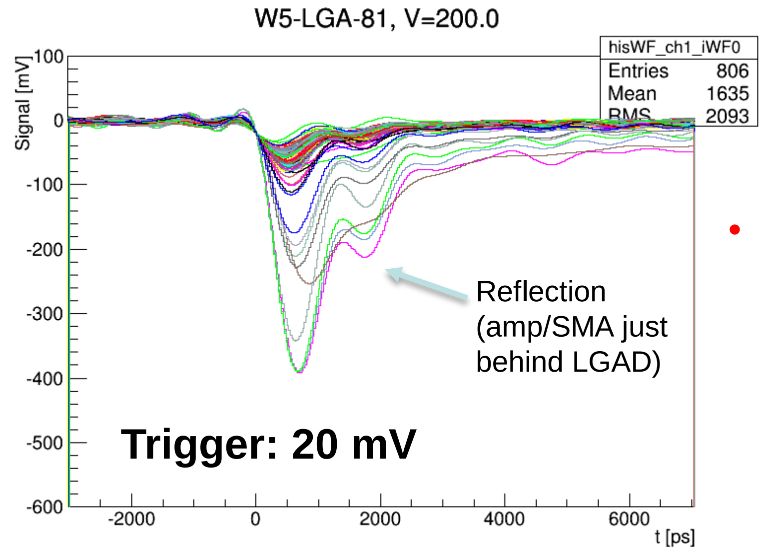
- Also useful for alignment
- Data not yet analysed



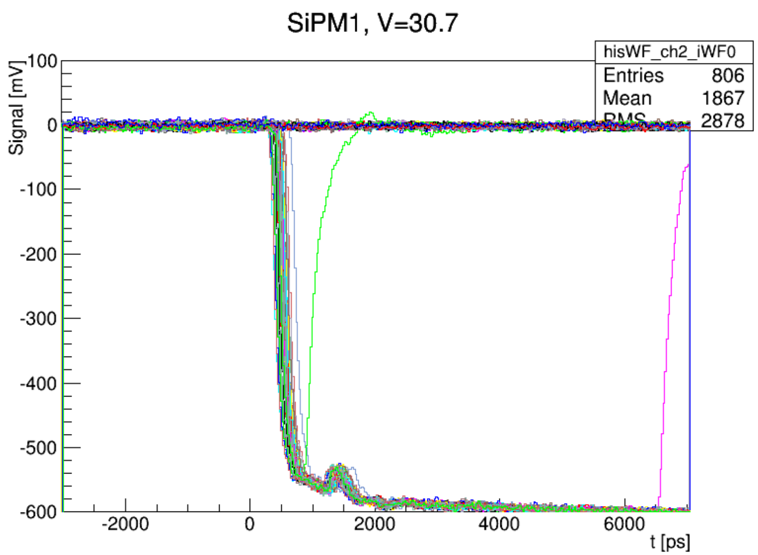
Waveforms (unirr)

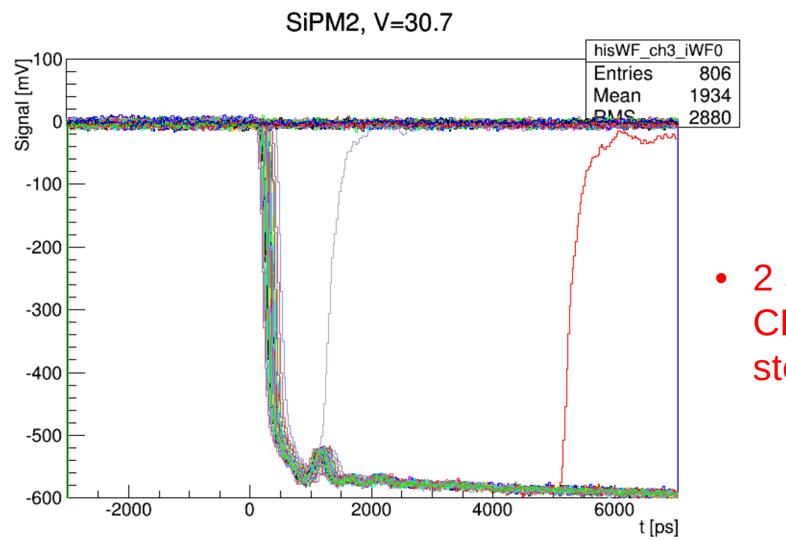
Run 274
Medium dose, unirradiated
200 V





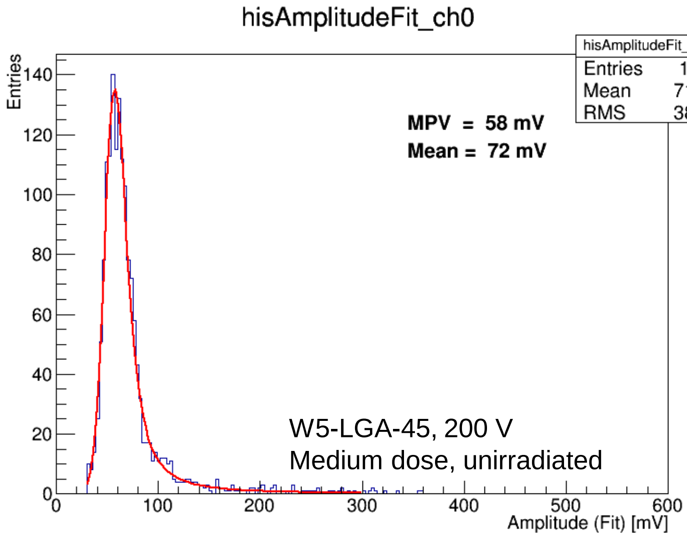
- 2 LGADs: Raw analog waveform

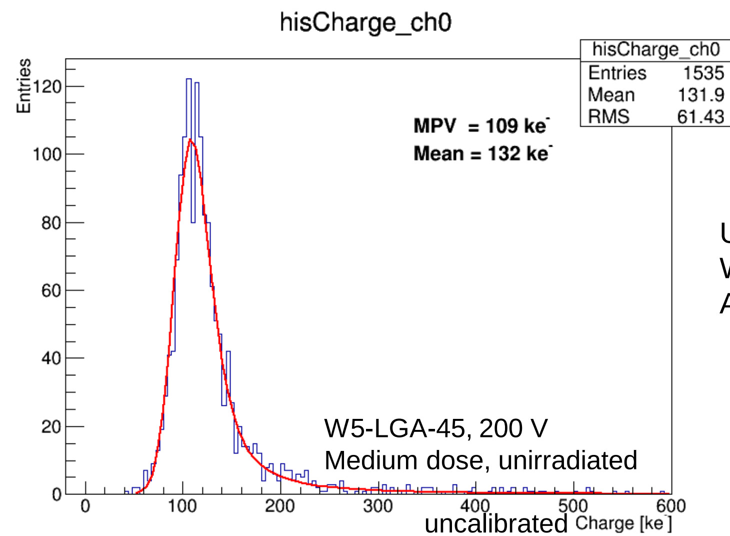




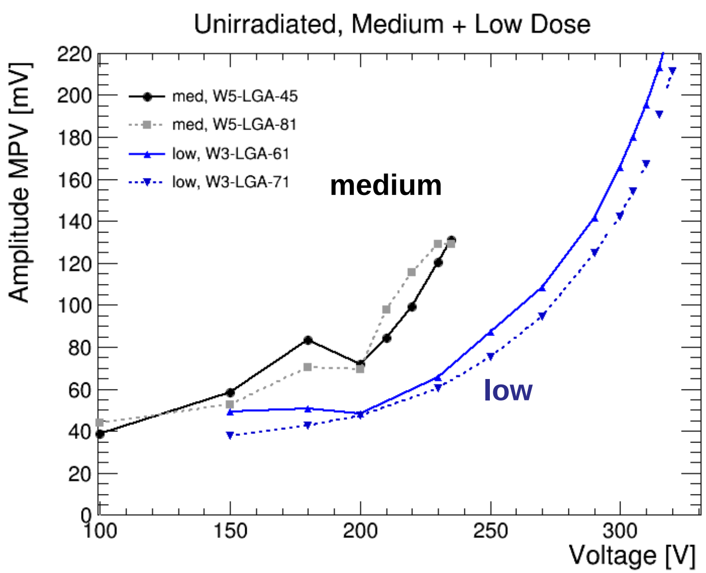
- 2 SiPMs: CFD digital steep signal

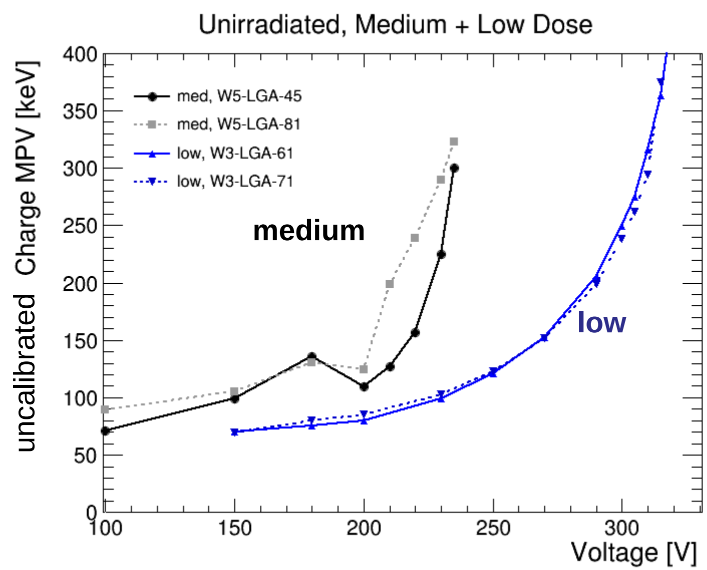
Amplitude and Charge (unirr)





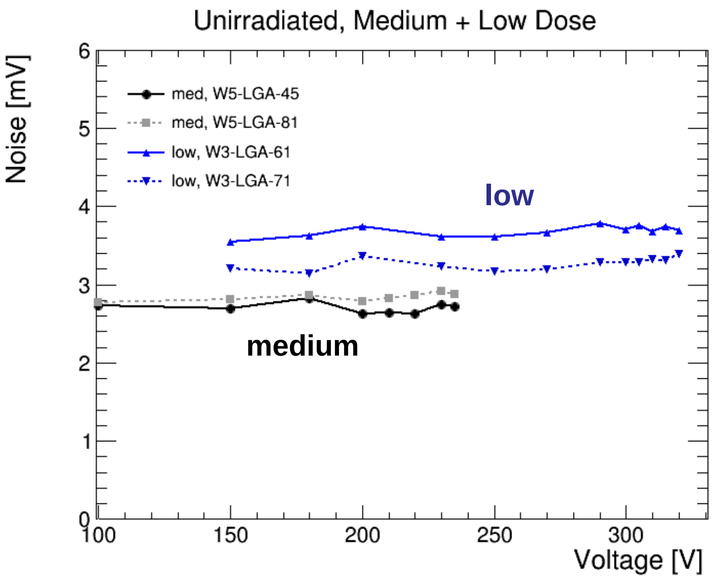
Uncalibrated charge:
Waveform integral -1 to 6 ns
Assuming amp gain 100x, 50Ω

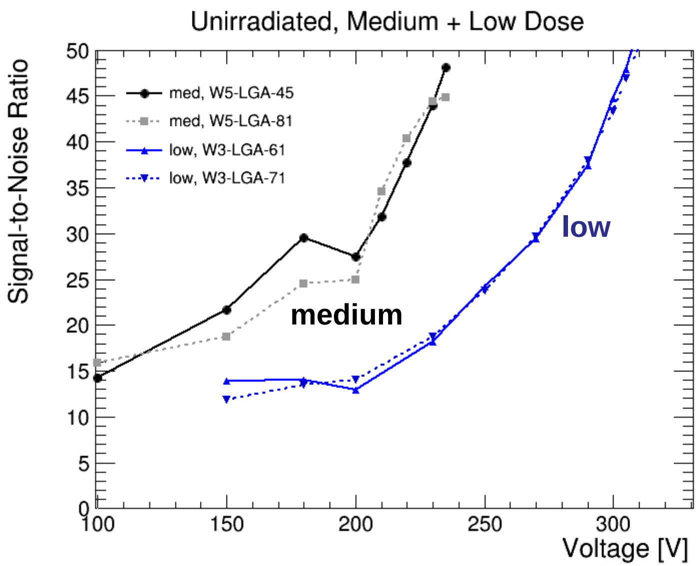




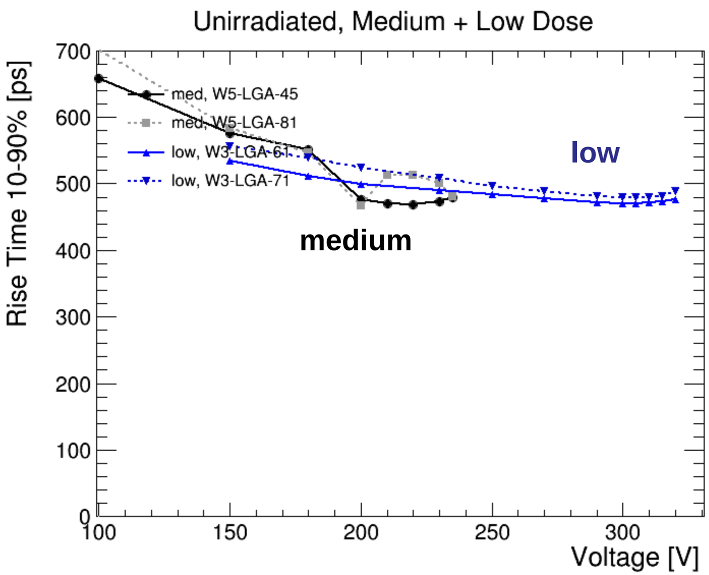
- 2 LGADs of same dose similar
- Lower values for lower dose at same V (as expected)
- But lower dose can be measured up to higher values

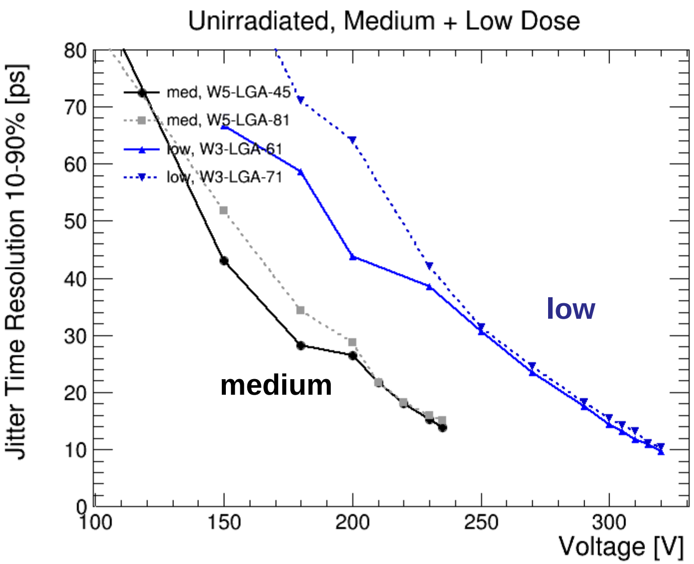
Noise, SNR, Rise Time, Jitter (unirr)





- Noise 2.8-3.8 mV, higher for low dose (but run-dependent!), constant!
- Similar SNRs achievable (at different V)

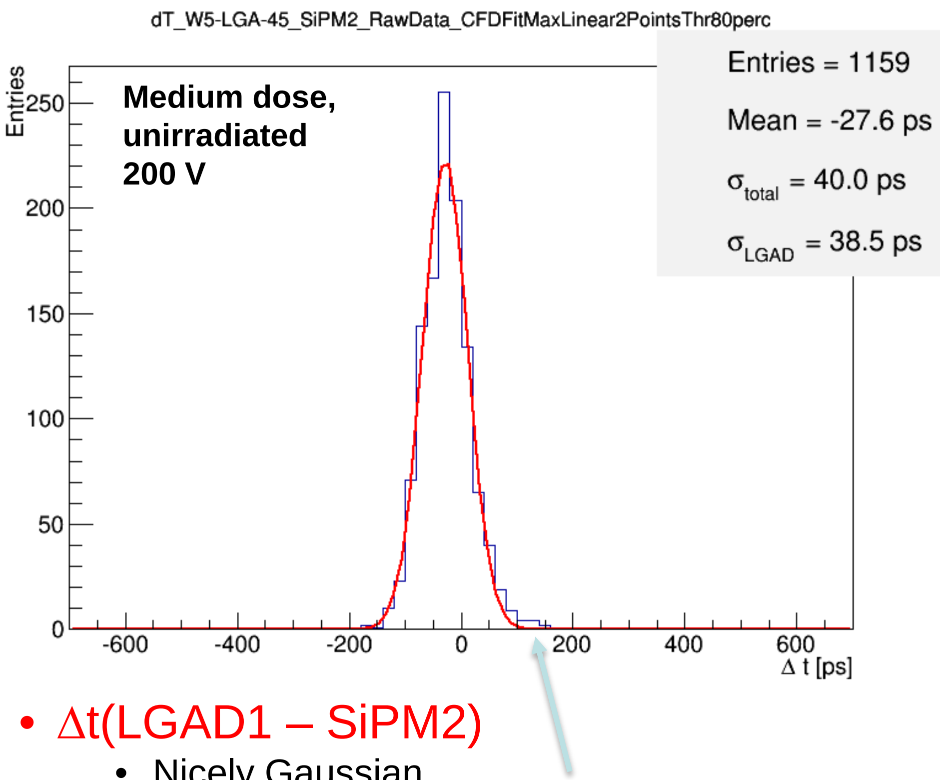


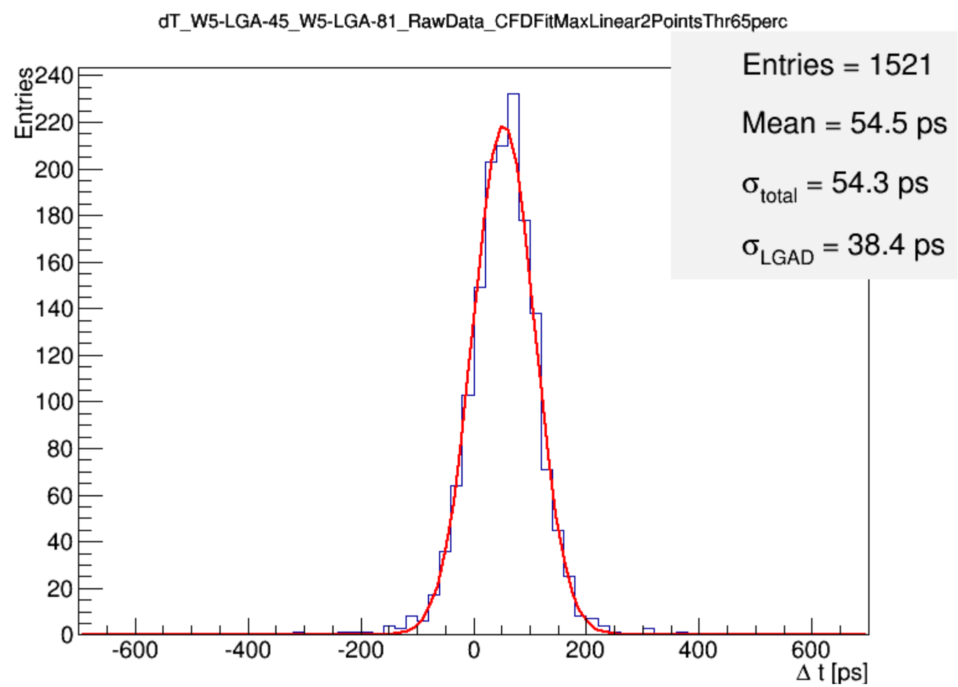


- Rise time ~500 ps, slowly decreasing with V
- Strong decrease of jitter=noise/slew rate, 10-15 ps achievable at high V

Time Resolution Distributions

- Time resolution from difference of arrival time between two channels, Δt
- CFD algorithm:
  - Linear interpolation of 2 bins surrounding threshold
  - CFD fraction (% of maximum) optimised individually at each voltage

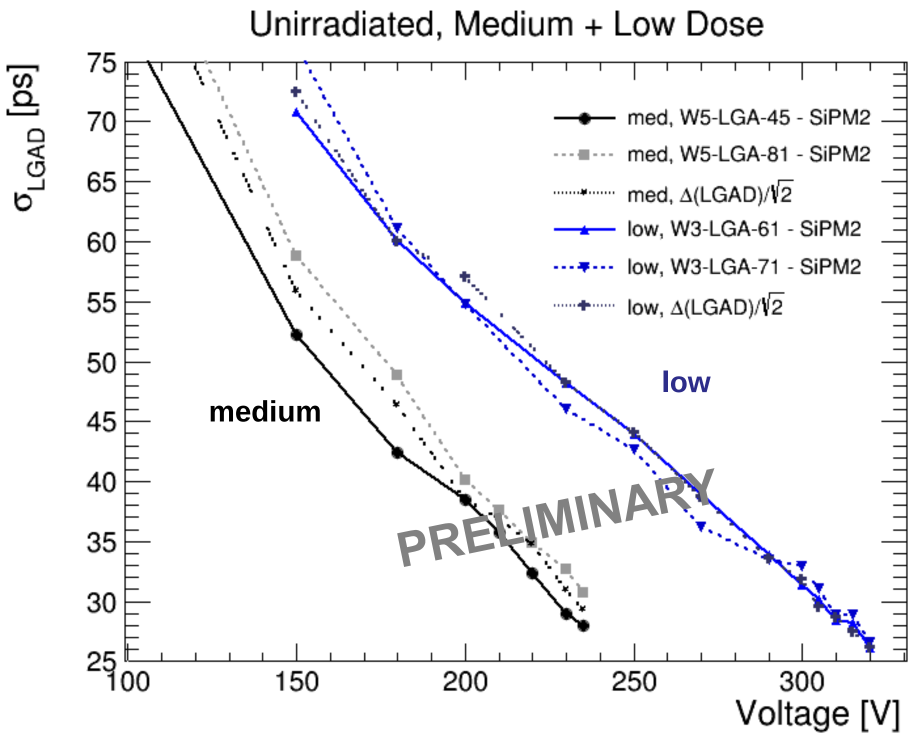


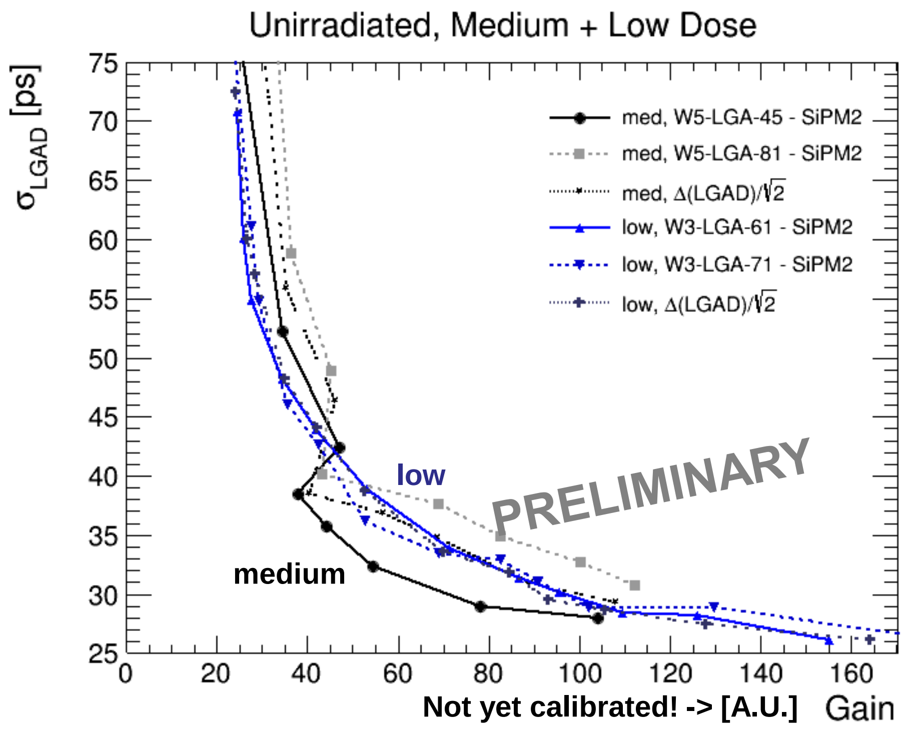


- Δt(LGAD1 – SiPM2)
  - Nicely Gaussian
  - Sometimes small non-Gaussian shoulder (must be from SiPM)
  - σ_{LGAD} from subtracting 11 ps (SiPM)

- Δt(LGAD1 – LGAD2)
  - Nicely Gaussian
  - No non-Gaussian shoulder
  - σ_{LGAD} (average) from $\sqrt{2}$ division

Time Resolution (unirr)



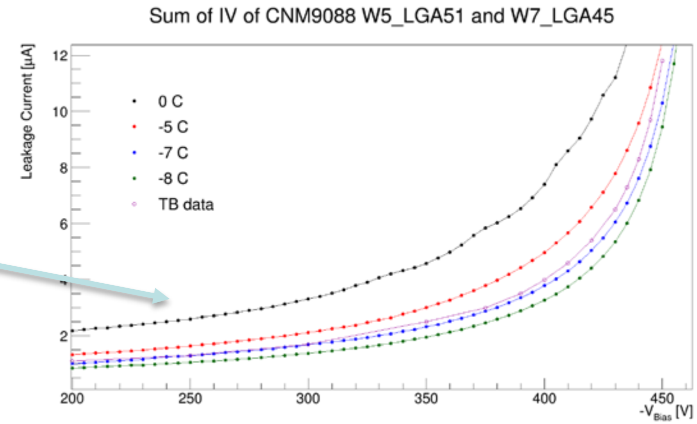


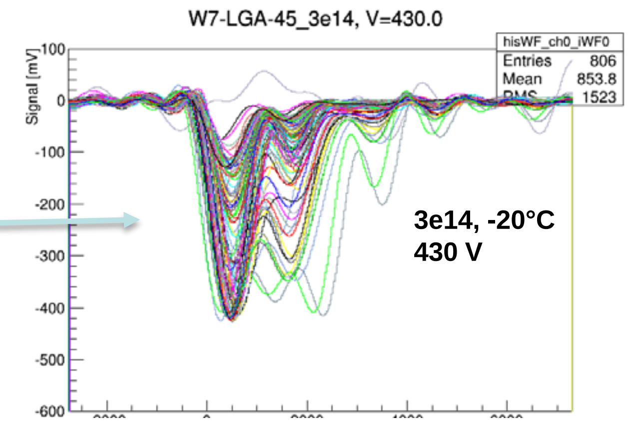
- Similar results for different devices and methods (wrt. SiPM or other LGAD) at same dose
- As a function of V
  - Almost linear decrease
  - Medium dose ~15 ps better at same V
  - Both reach similar end point at 235 V (medium) or 320 V (low)
  - **26 ps achieved!**
- As a function of Gain
  - Decreasing slope, need increasingly higher gain for resolution improvement
  - Similar **universal behaviour** for both doses

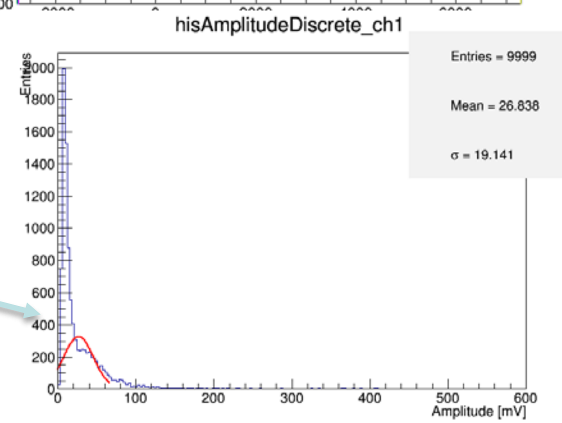
Similar to HGTD and UCSC/Torino results

Beam Test of Irradiated LGADs

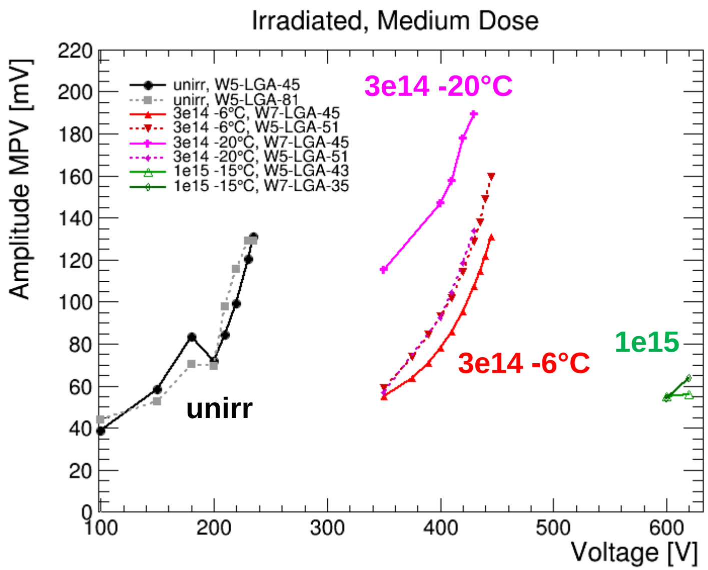
- Almost all measurements done in same setup as for unirradiated devices (“DO box”)
  - Cooled with dry ice
  - Temperature on-sensor extracted from IV (comparing to lab climate chamber measurements)
    - 3e14: ~ -6°C
    - 1e15: ~ -15°C
- One measurement for 3e14 in climate chamber (“MPI cooling box”)
  - T ~ -20°C
  - Only the 2 LGADs measured (SiPM needed in other setup)
  - Waveform fluctuated already at low V
    - Not clear if due to lower T or different noise/environmental conditions in other setup
    - Trigger: coincidence of both LGADs
    - Time resolution still well measurable
- Issues at 1e15
  - Sensors became instable at ~620 V
  - Both broke at that V after 1h of no beam (heating? Thermal runaway?) -> now breakdown V < 1V
  - At 620 V only beginning S/N separation
    -> offline cut at 30 mV cuts into lower Landau part
    -> results are a bit biased to higher amplitudes

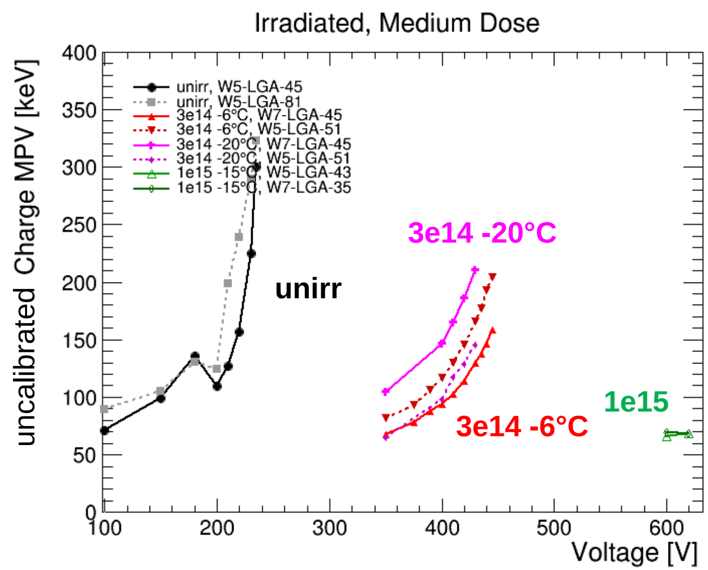




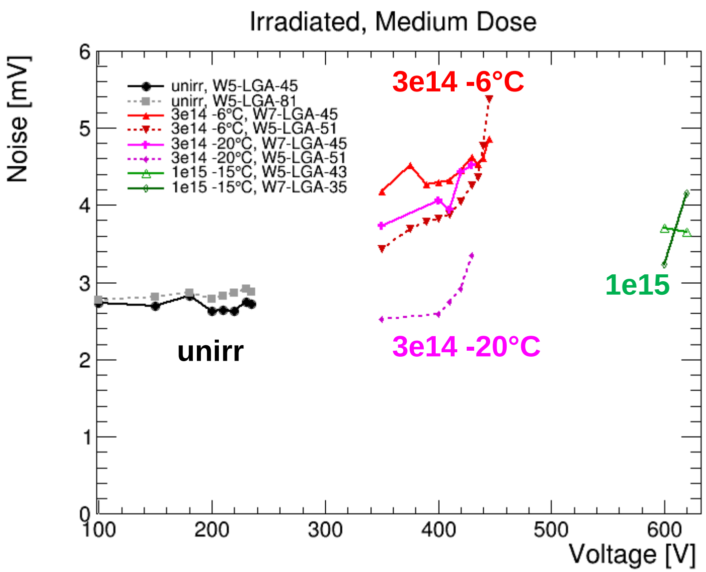


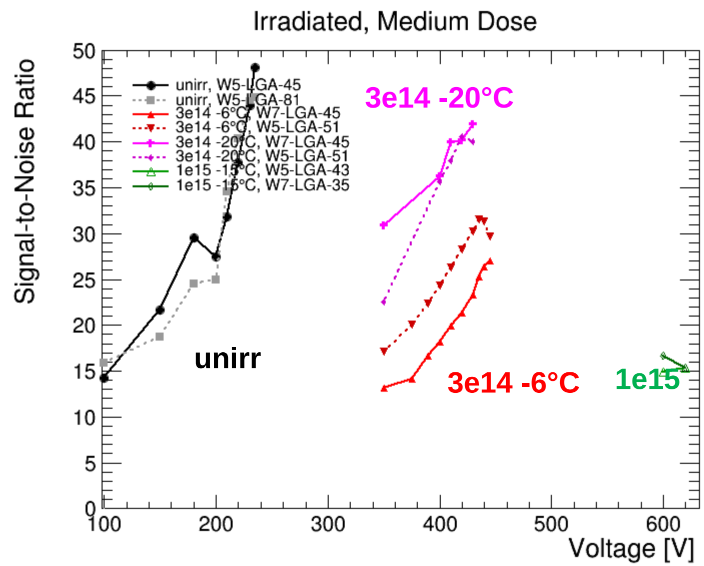
Ampl., Charge, Noise, SNR (irr)





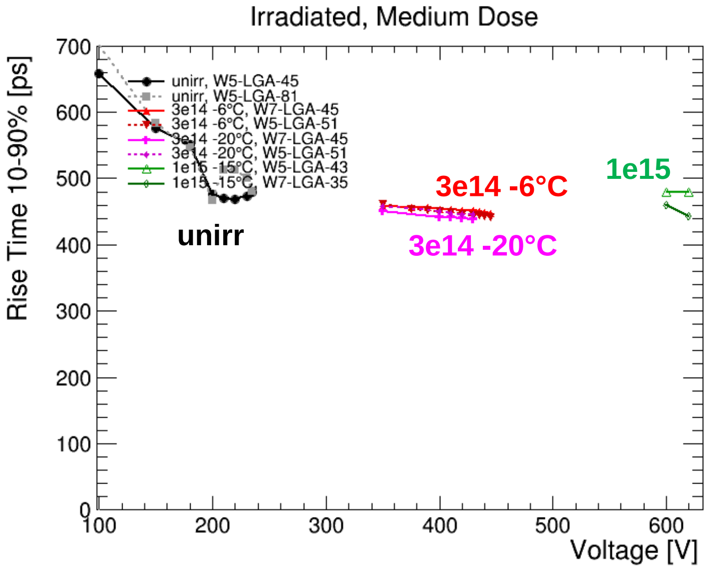
- At higher fluences need higher V for similar amplitude/charge

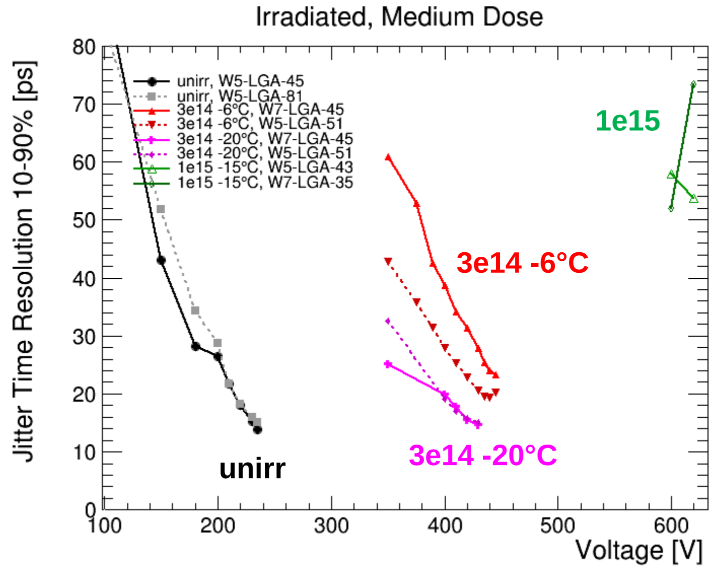




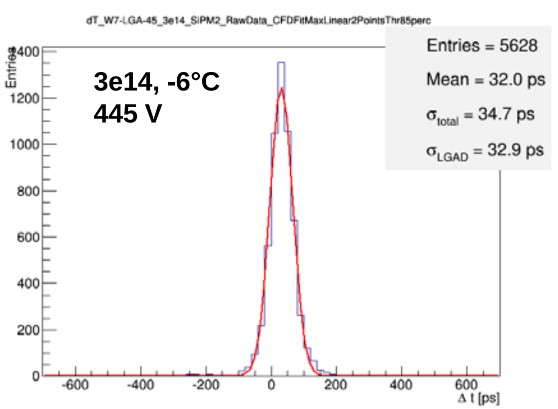
- Higher noise after irrad. (but unclear if due to conditions or sensor)
- SNR higher at -20°C than -6°C for 3e14, similar values as before irr. achievable; but very low at 1e15

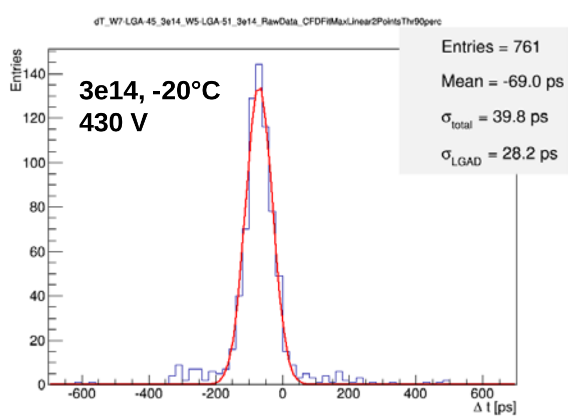
Rise Time, Jitter, Δt (irr)

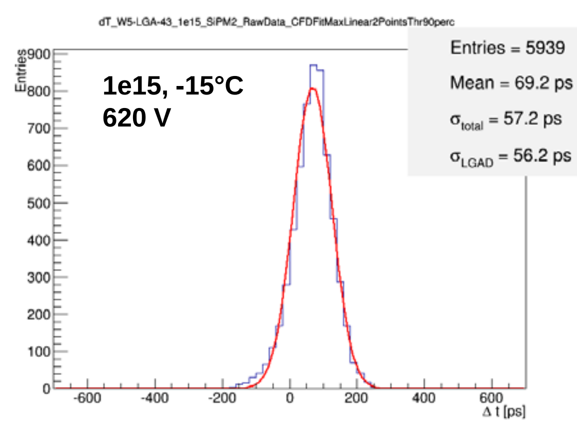




- Rise time ~500 ps, slowly decreasing with V
- Similar jitter values as before irradiation achievable at 3e14 (15-20 ps), but much worse at 1e15

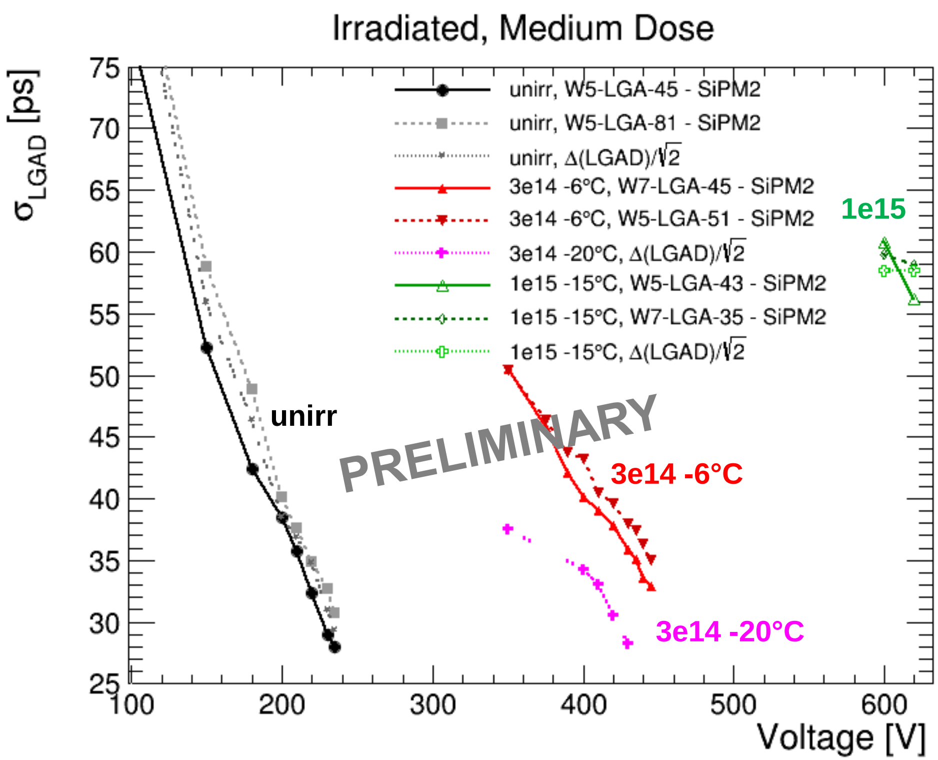


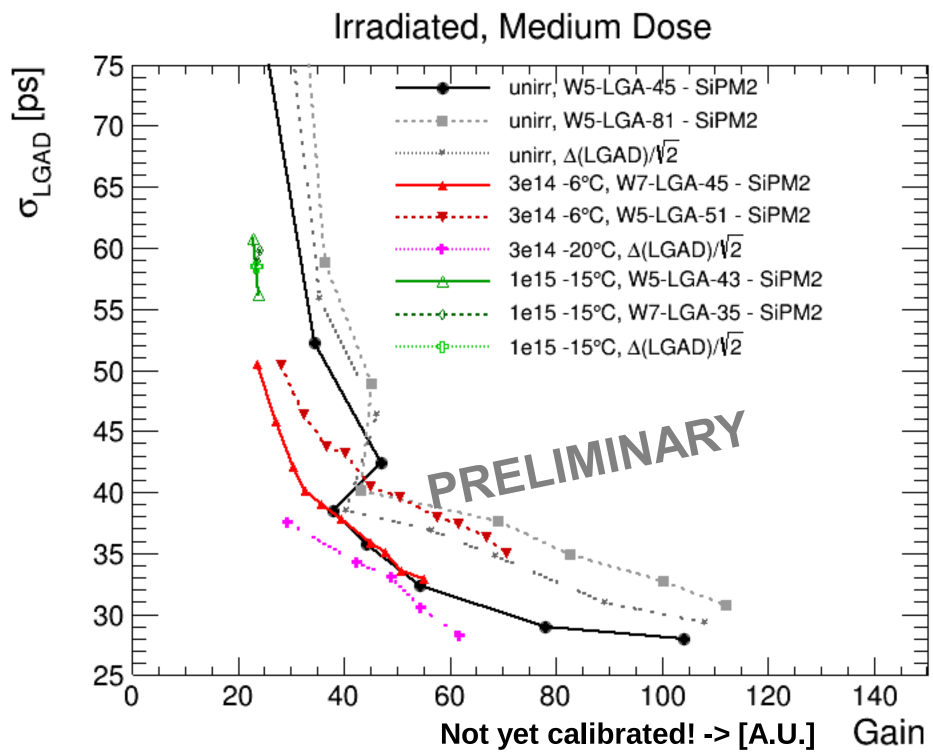




- Δt: Good Gaussian behaviour also after irradiation
  - Some tails at -20°C due to waveform fluctuations

Time Resolution (irr)

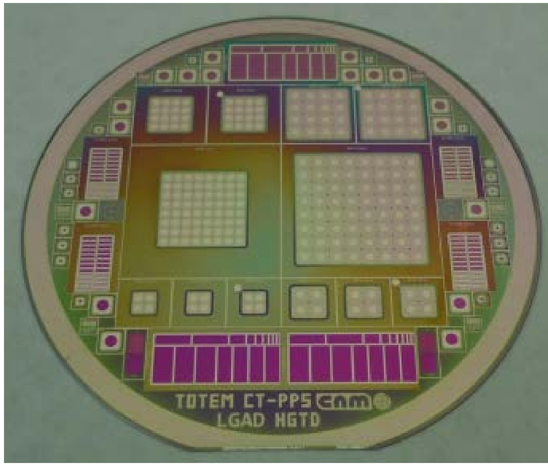




- At 3e14 similar time resolution achieved as before irradiation (at higher V)
  - -6°C: 33 ps at 445 V
  - -20°C: 28 ps at 430 V
- At 1e15 gain is highly reduced and voltage stability not high enough to compensate for it
  - 55-60 ps at 620 V
- Gain dependence in all cases similar to before irradiation
  -> “universal”

Summary

- Studied gain and time resolution of 50 µm thick LGAD from new CNM run 9088
  - For different implantation doses
  - Before and after irradiation up to 1e15 n_{eq}/cm^2



- Gain (TCT and Sr90)
  - Higher for higher implantation doses
  - Clear degradation after irradiation
  - Gains for medium dose (Sr90):
    - ~40 @ 220 V before irradiation
    - ~20 @ 420 V for 3e14 n_{eq}/cm^2
    - ~10 @ 650 V for 1e15 n_{eq}/cm^2
  - Difference between TCT (IR laser) and Sr90 not yet understood

- Measured time resolutions in AFP beam tests
  - 10 ps SiPM references available and other infrastructure (CFDs, TDCs, telescope, etc.)
  - C2 Cividec and 1 GHz scope bandwidth found to give best performance
  - Voltage dependence: Resolution decreases ~linearly, large offsets for different doses and fuences
  - Almost universal behaviour as a function of gain for all doses and fluences
  - **<30 ps resolution achieved** at 235 V (med) or 320 V (low dose) before irradiation
  - **Similar resolution at 3e14 n_{eq}/cm^2 at ~440 V**
    -> LGADs can survive in AFP/PPS >10 fb^{-1} (>1/3 year at full LHC luminosity or special runs)
  - **At 1e15 n_{eq}/cm^2 achieved 55-60 ps at 620 V**
    - Gain reduction and high voltage stability currently not good enough to achieve more
      -> Further investigations needed if LGADs would survive full year in AFP/PPS at full LHC luminosity (and HGTD)

- **Promising first results**, but need to investigate further options to increase radiation hardness


5th Beam Telescopes & Test Beams Workshop
24th - 27th January 2017, Barcelona
https://indico.desy.de//event/bttb5
In 2010 RD50 Workshop venue!!
(Raval, downtown)
Tour and dinner in Gaudi house!
Topics:
Beam lines & infrastructures
Beam telescopes & device integration
Data analysis, tracking, alignment
Simulations & software packages
Abstract submission deadline: 23-12-2016
Registration deadline: 23-12-2016
Organising Committee:
Jan Dreyling-Eschweiler (DESY)
Hendrik Jansen (DESY)
Joern Lange (IFAE)
Iván López (IFAE)
Simon Spannagel (CERN)
Stefano Terzo (IFAE)

IFAE DESY

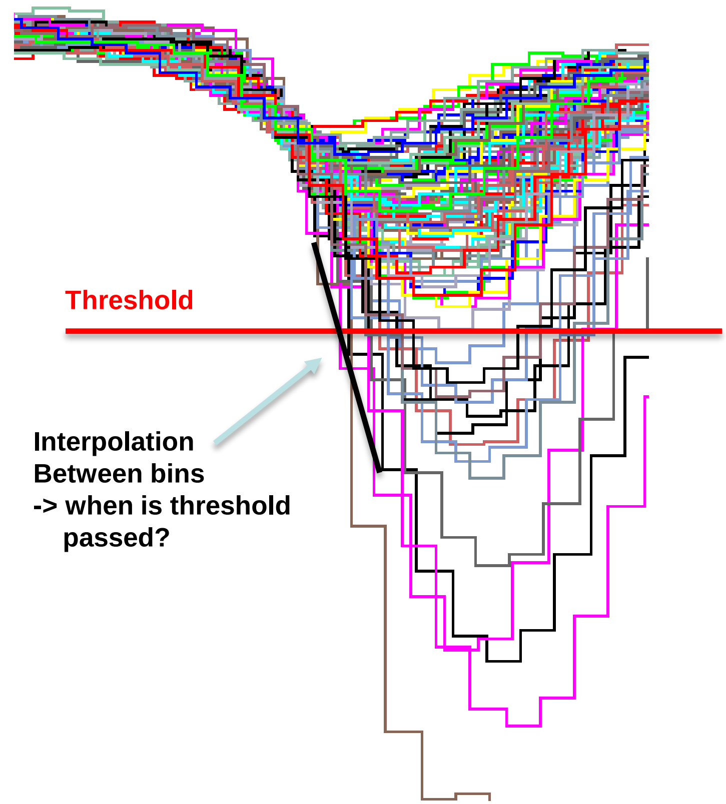
Summary Plots

Pre-Studies and Remarks

- The system was carefully studied with unirradiated LGAD, med dose, typically at 200 V
- Reproducibility
  - Many measurements taken, typical reproducibility few ps
  - But noise and other environmental influences (T) fluctuating, test beam area known to be “noisy”
    - Cause and influence not yet well understood
    - Some results worse by 10 ps than best one -> default: best ones presented
- Studied impact of different triggers (different LGADs, SiPMs)
  - No systematic differences found -> default: LGAD trigger to increase purity/statistics
- Oscilloscope bandwidth variations studied (0.5 – 12 GHz)
  - Optimum found at 1-2 GHz -> default: 1 GHz
- Different oscilloscopes/sampling rates
  - No big difference (for 10-40 GS/s) at same band width -> default 40 GS/s
- Oscilloscope voltage scale
  - Influences precision and noise! Best to keep as low as possible without saturating signals -> default 50 mV/div
- Amplifiers
  - Best: CIVIDEC C2 (TCT) -> default
  - Particulars + AFP PAa+PAb ~5-10 ps worse
  - CIVIDEC CSA, 4 ns shaping, much worse (~100 ps)!
  - Uni Geneva CSA not optimized in Sep; much better after optimisations in Oct (similar to CIVIDEC C2)
- Raw/analog waveform vs. CFD data
  - No systematic difference found (within few ps) -> default raw data (full information + simpler)
  - But re-assuring for later use in real experiment with CFDs

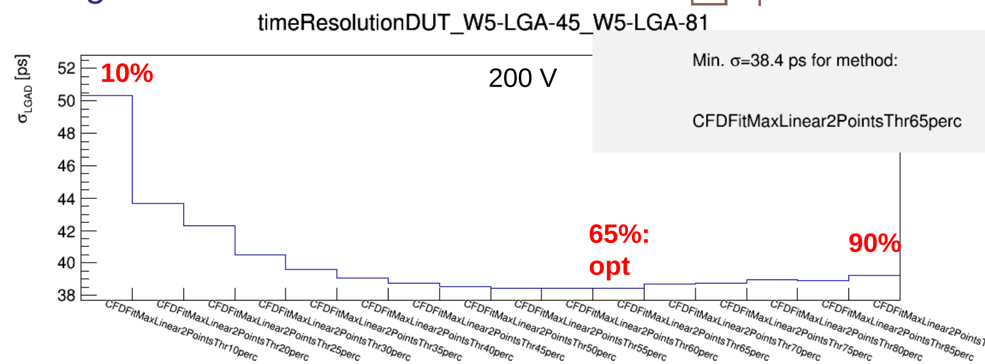
Time Resolution Algorithm

- Time resolution from difference of arrival time between two channels, Δt

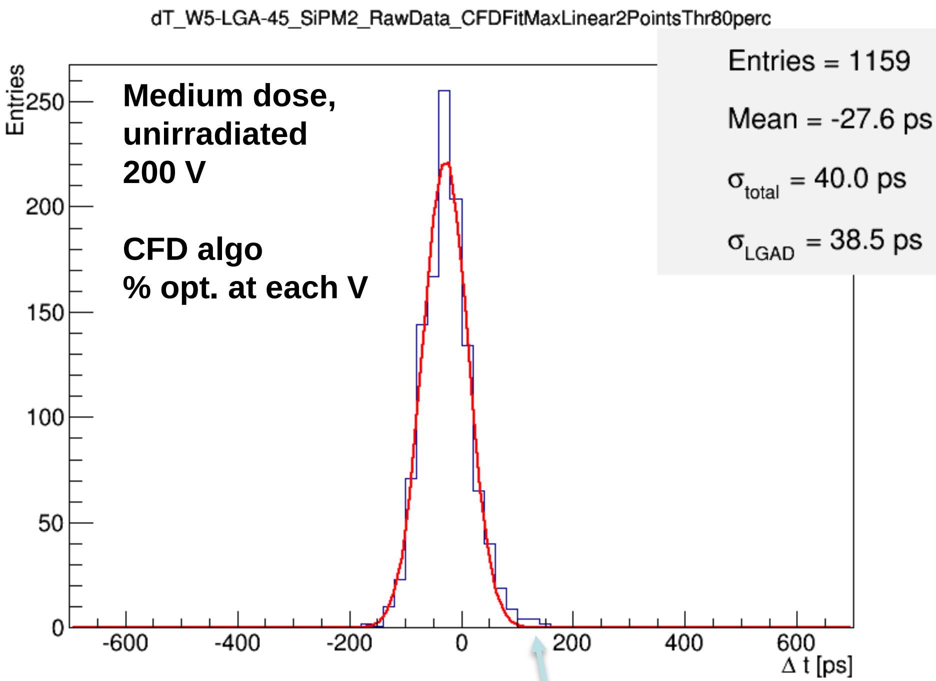


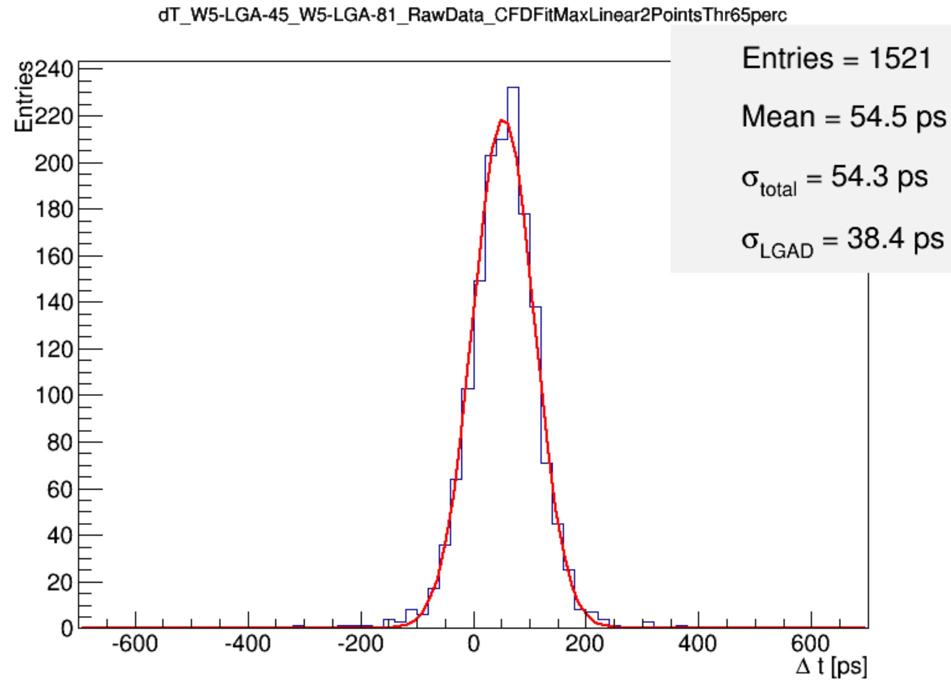
- Different analysis methods for time-of-arrival studied
  - A) Different threshold methods
    - Fixed threshold at different levels
    - Constant Fraction Discrimination (offline algo) at different fractional levels (10-90%)
  - B) For each threshold method one can interpolate bins in different ways to decide when threshold is passed
    - Linear interpolation of 2 surrounding bins
    - Linear fit of +/- N surrounding bins
    - Polynomial fits (3^{rd} and 5^{th} degree) of N surrounding bins
    - Fit from 20-80% or 10-90% of maximum
    - Spline Interpolation
  - C) Completely different methods
    - Time of max. amplitude

- Default: CFD algo with linear interpolation of 2 surrounding bins
  - Much better than fixed threshold (w/o time walk corr.)
  - Simple interpolation not much worse than others but simpler and more robust
  - Optimal CFD fraction depends on V (shape of waveform!) -> scan for each point and take optimum



Time Resolution Distributions

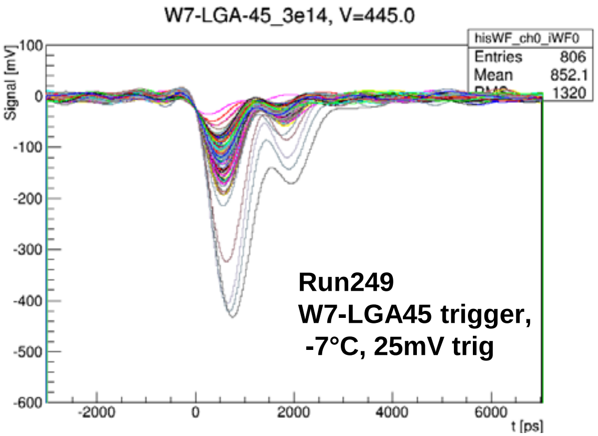


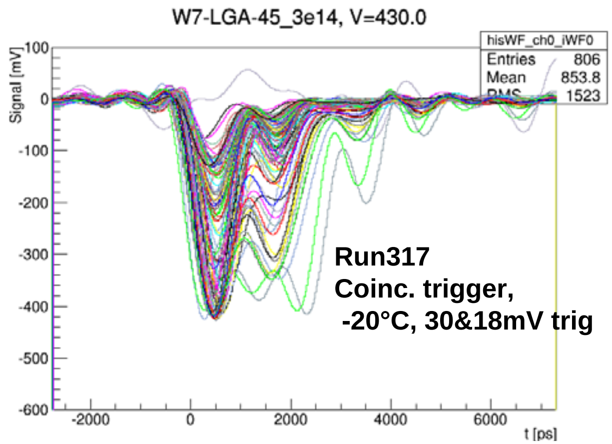


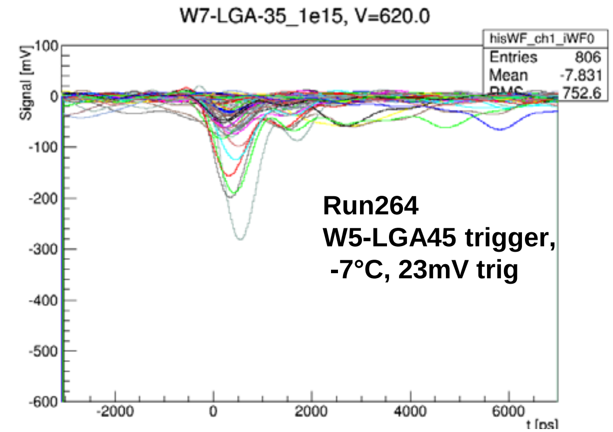
- Δt(LGAD1 – SiPM2)
  - Nicely Gaussian
  - Sometimes small non-Gaussian shoulder (must be from SiPM)
  - σ_{LGAD} from subtracting 11 ps (SiPM)
  - SiPM2 seems to have slightly better resolution, results ~1-2 ps better than from SiPM1 -> not yet corrected for (ps effect)
  - In following results wrt. SiPM2 shown

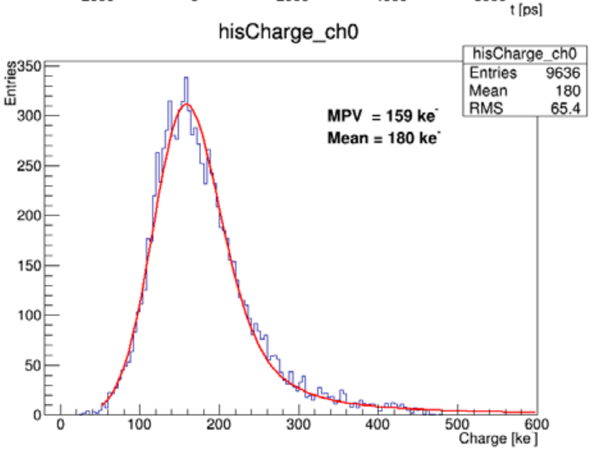
- Δt(LGAD1 – LGAD2)
  - Nicely Gaussian
  - No non-Gaussian shoulder
  - σ_{LGAD} (average) from $\sqrt{2}$ division

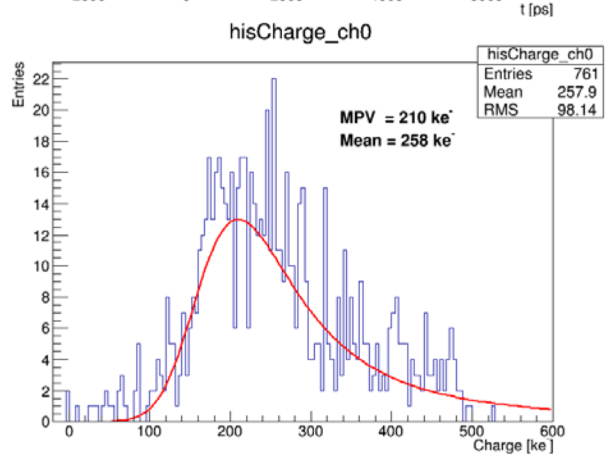
Irradiated LGADs

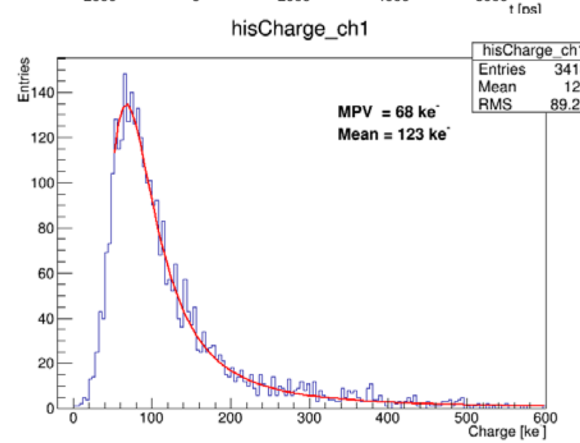


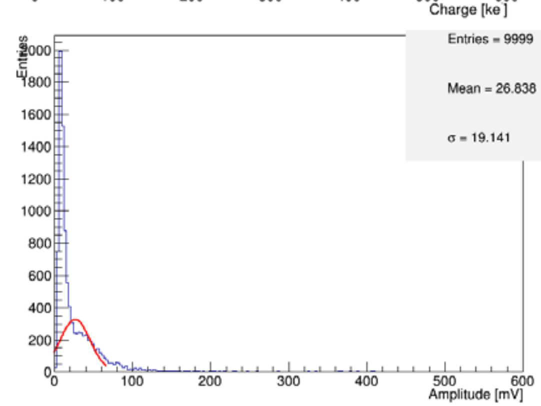












IV

- Great performance before irrad.
  - Break at ~230 V

- After irrad.
  - -10C, ~μA
  - Break at ~350 V (3e14), 550 V (1e15)