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Simulation of Landau fluctuations on timing performance of LGADs

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Authors:

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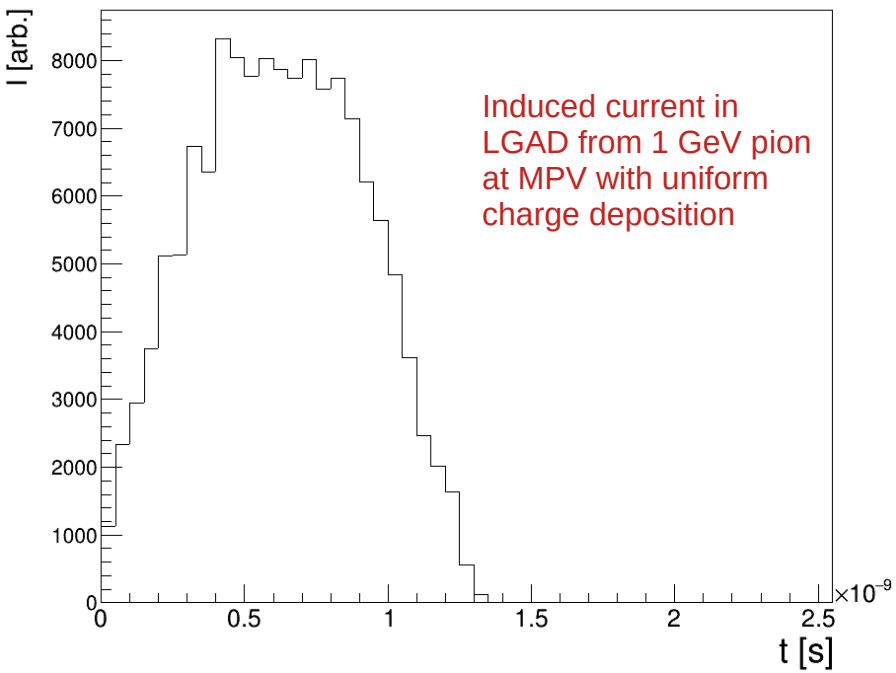
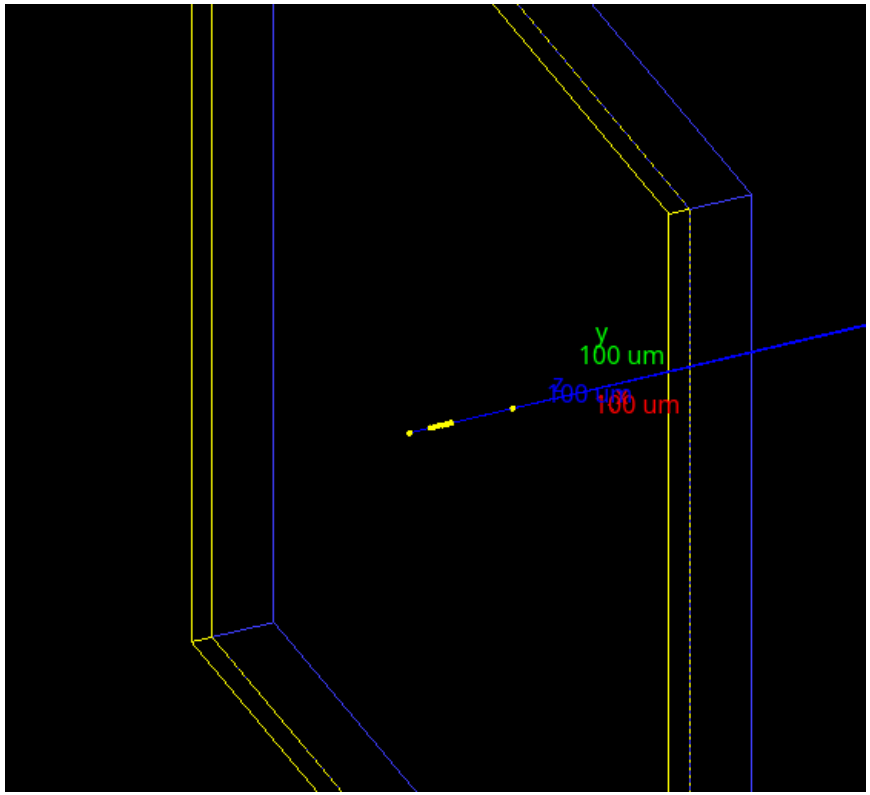
Motivation

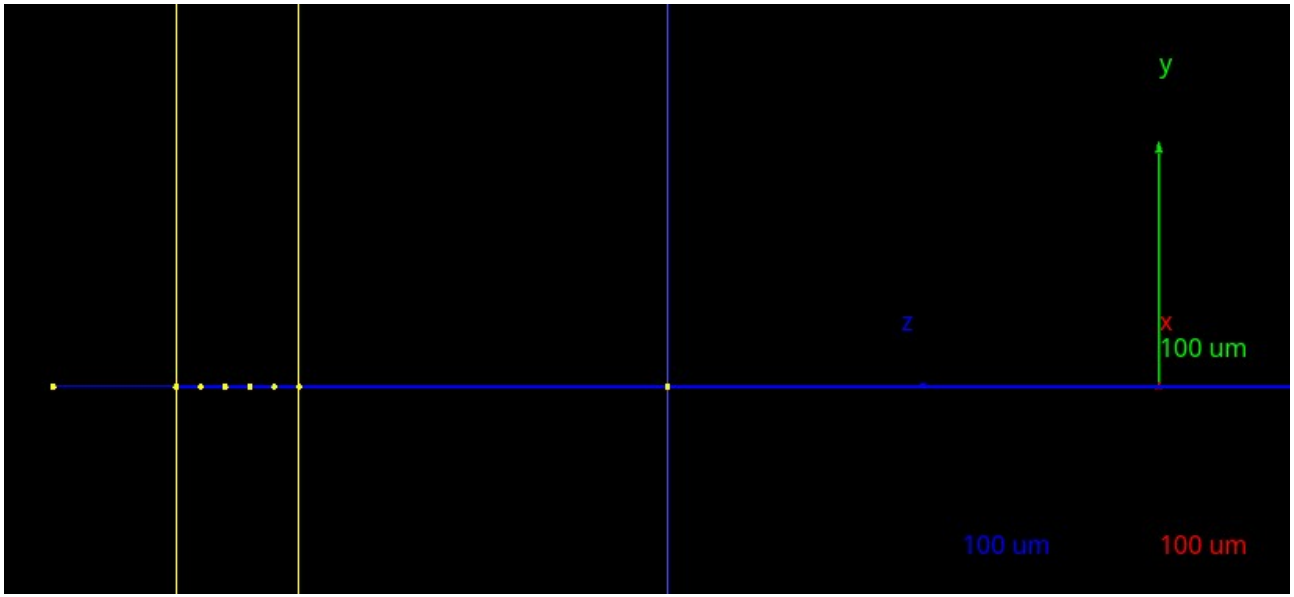
- Simulations of electronics responses have usually been performed with sensor signals from uniform charge deposition
- Here we focus on the study of responses with signals induced from **non-uniform** charge deposition due to Landau fluctuations
- Goals:
  - Isolate and evaluate the contribution of Landau fluctuations to timing resolution for different gains and thicknesses and explore performance limits
  - Determine the contribution of Landau fluctuations to the timing resolution of HPK-P2 and recent C-GL LGAD prototypes
- Energy deposition simulated and studied with Geant4
- LGAD signals simulated with KDetSim



Geant4 simulations

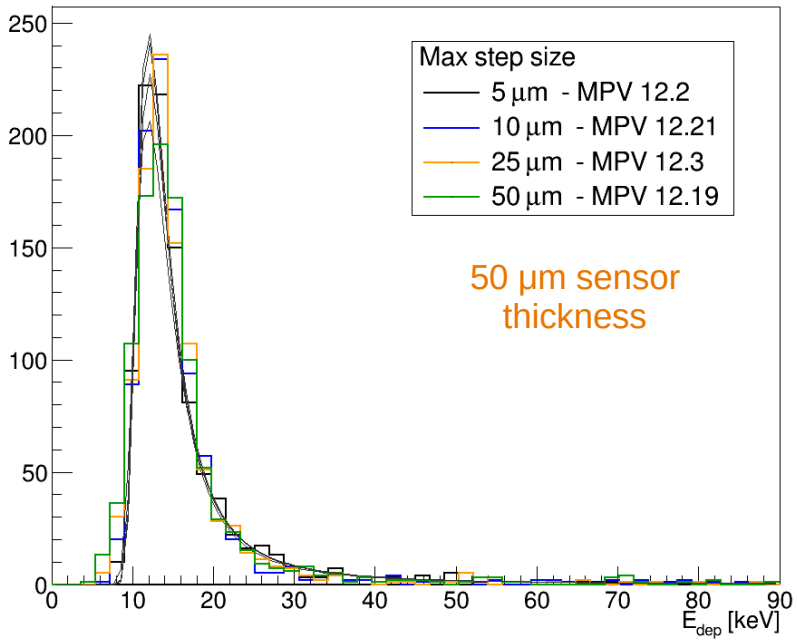
- Spatial distribution of energy depositions simulated with Geant4
  - 4 GeV electrons
  - 1 GeV pions
- Maximum step size was shortened to lengths less than the sensor thickness
- Variable simulation step sizes (5 μm – 50 μm) and sensor thicknesses (20 μm – 100 μm)
- Statistics over 1000 events

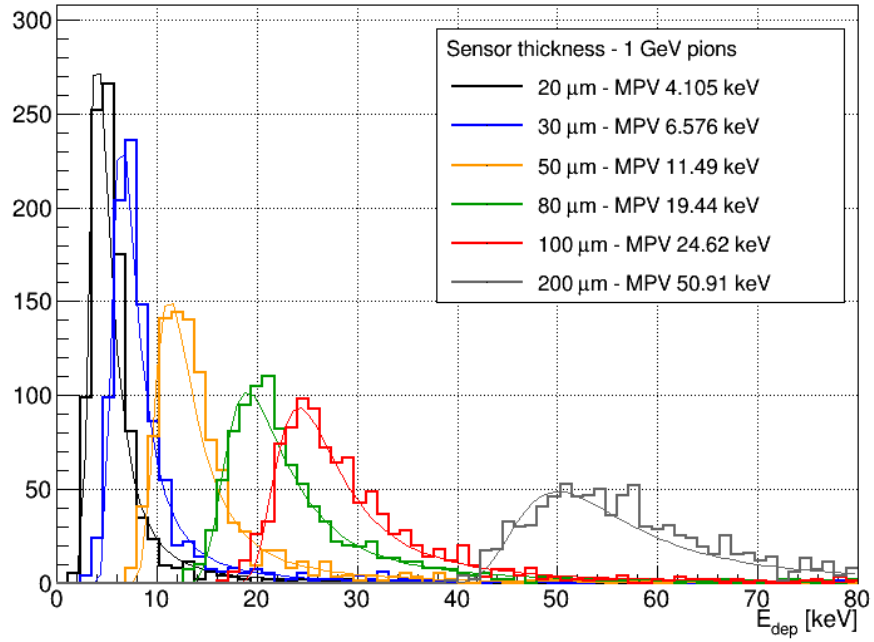


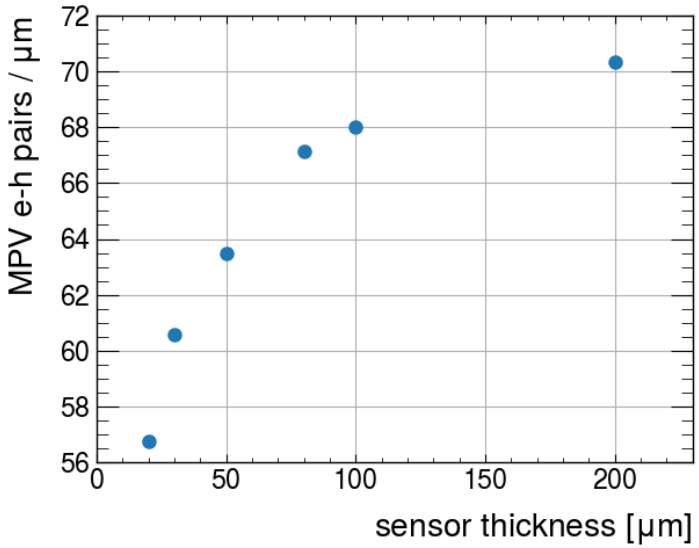


Geant4 step size consistency validation

Distributions of deposited energy within sensitive region – Landau fit



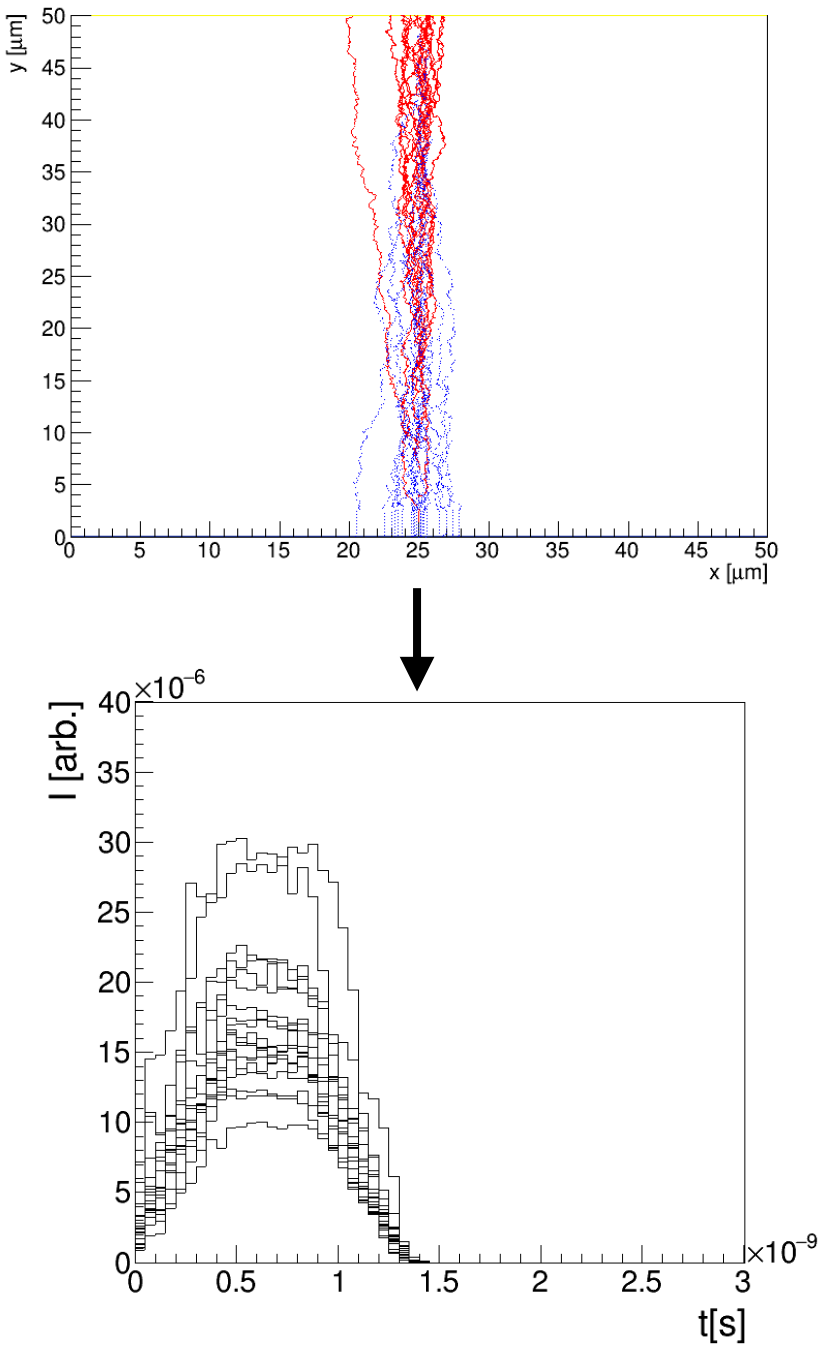




- Choosing different maximum step sizes for Geant4 simulation gives consistent energy deposition distributions for the entire range of simulated step sizes
- Changes in distribution for increasing sensor thicknesses as expected

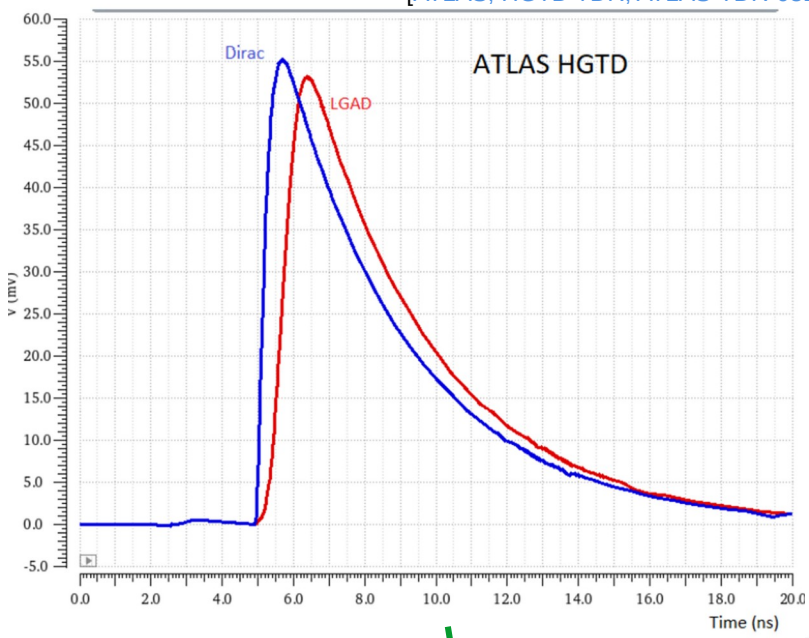
KDetSim simulation

- Signal formation was simulated with KDetSim
  - IJS impact ionization model used
- Different configurations used (**all unirradiated**):
  - HPK-P2-W43 (V_{gl} = 50.5 V, V_{fd} = 60 V, V_{bd} = 240 V, 50 µm, deep gain layer – Gaussian profile at 2.25 µm)
  - Carbon gain layer (C-GL) sample (V_{gl} = 24 V, V_{fd} = 35 V, V_{bd} = 170 V, 50 µm, shallow gain layer – Gaussian profile at 0.75 µm)
  - Ideal case with saturated drift velocity
  - No gain

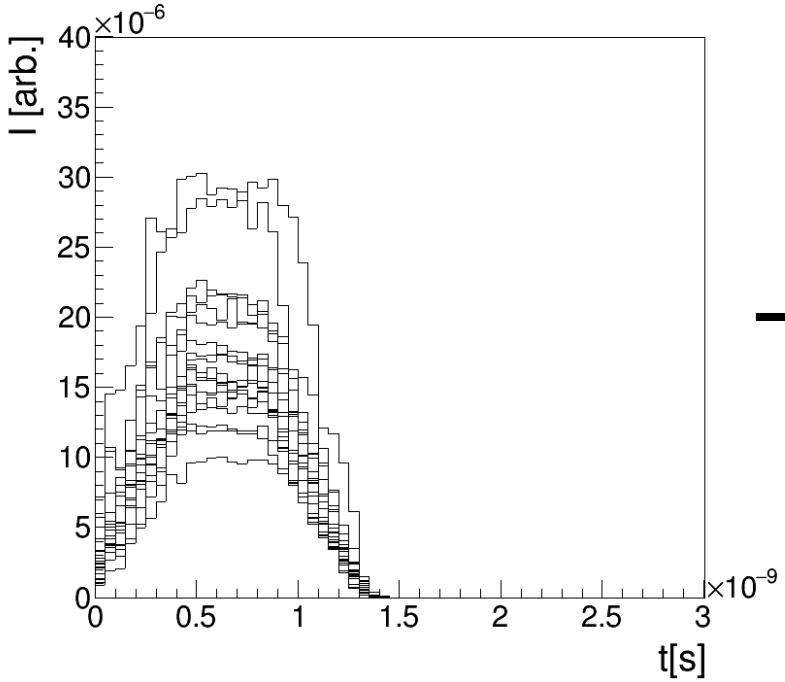


Convolution with electronics

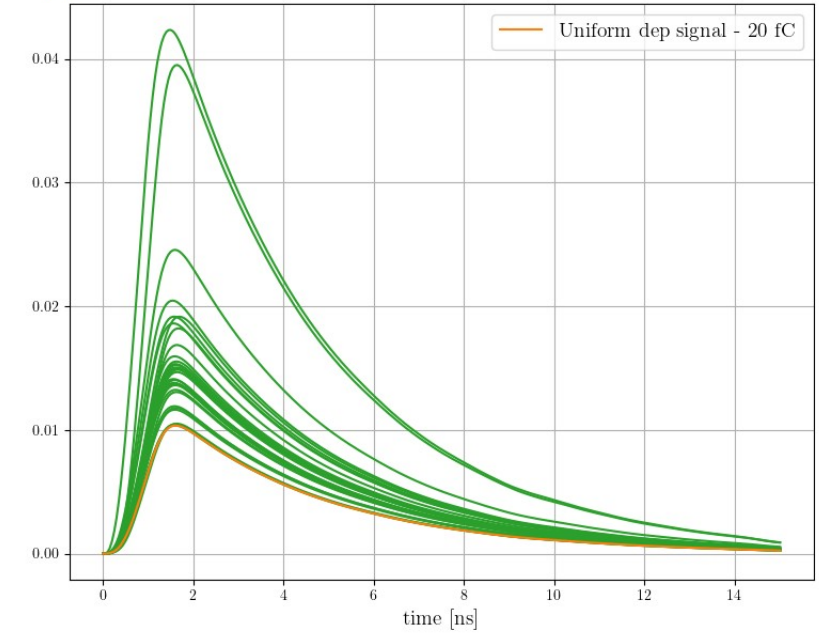
[ATLAS, HGTD TDR, ATLAS-TDR-031, 2020]



- Signals are convoluted with the delta response of electronics
- ALTIROC ASIC (front-end for HGTD) used as a typical electronics example
- No electronics noise added!
- ToA obtained with CFD at 20 % max
- Timing resolution obtained as spread of ToA after CFD



Convolution

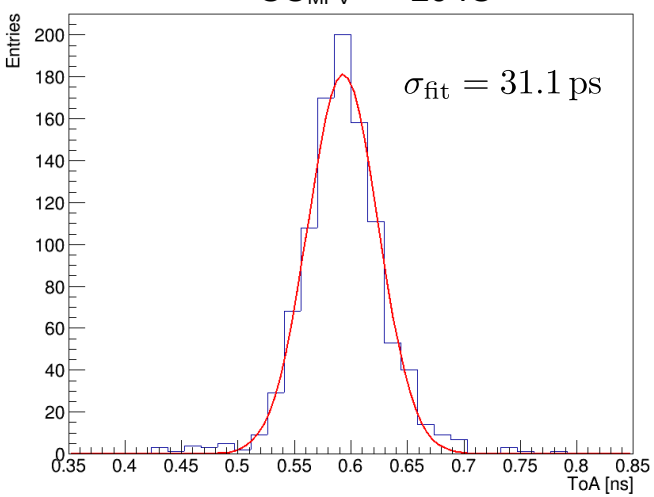


Results

- 4 GeV electrons
- 50 µm sensor thickness
- 10 µm step size

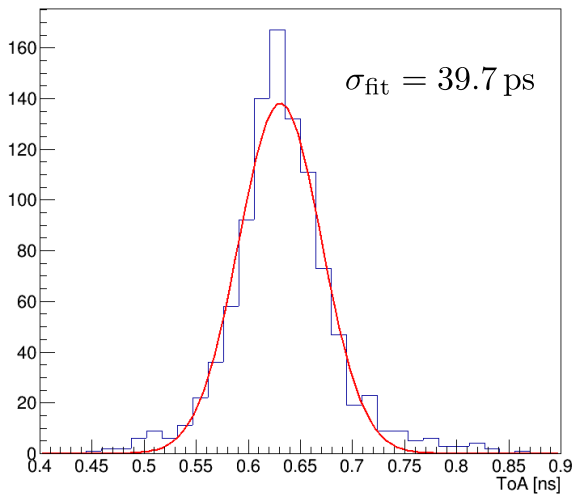
HPK-P2-W43 at -30 °C
Peak doping concentration in gain layer = 3.2e16 cm^{-3}

V_{bias} = 160 V
CC_{MPV} = ~20 fC



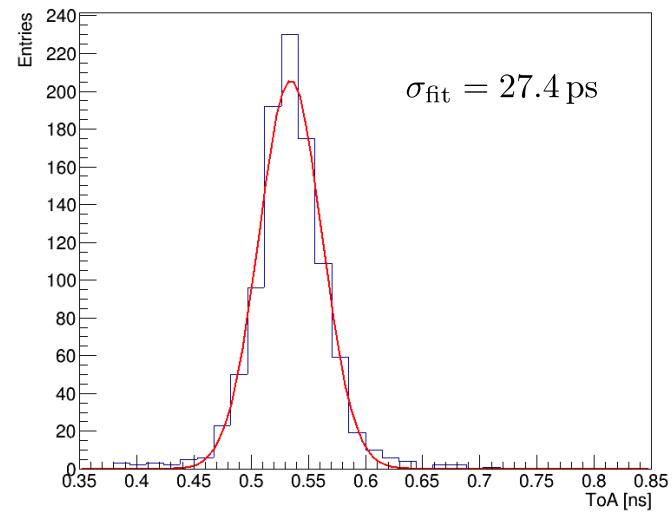
Carbon gain layer at -30 °C
Peak doping concentration in gain layer = 4.4e16 cm^{-3}

V_{bias} = 100 V
CC_{MPV} = ~20 fC



"Ideal" case – saturated drift velocity
Peak doping concentration in gain layer = 1.72e16 cm^{-3}

V_{bias} = 700 V
CC_{MPV} = ~20 fC

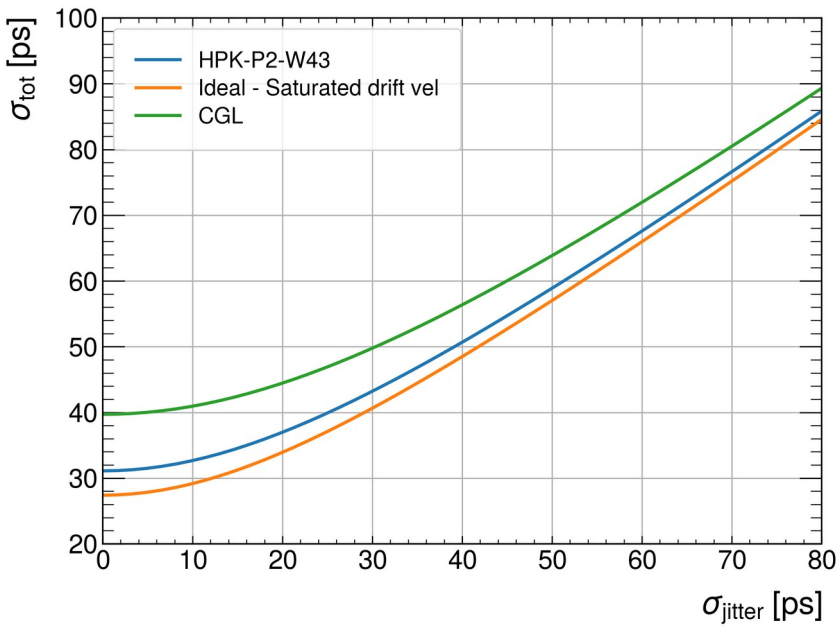


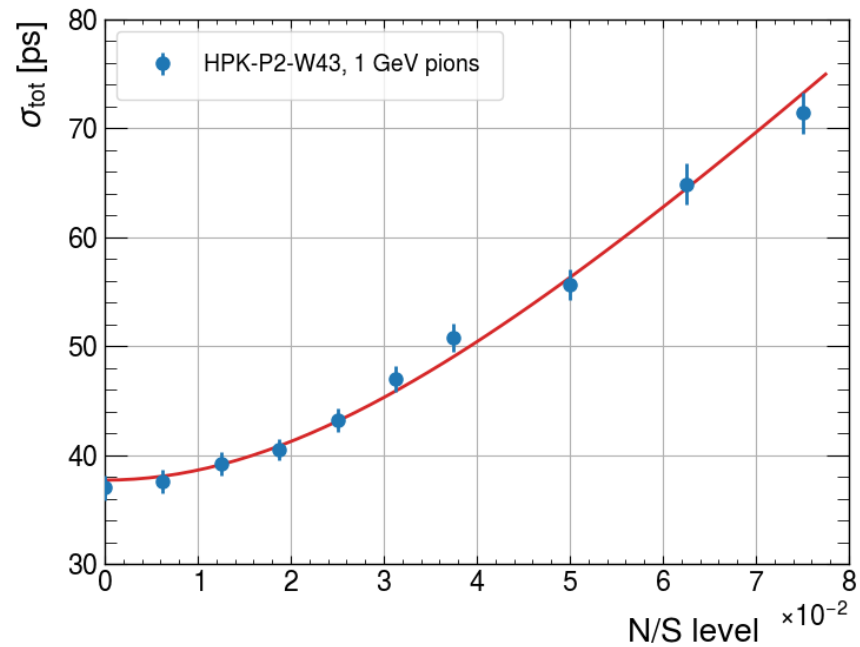
- Typical ATLAS HGTD sensor before irradiation

Including electronics noise (jitter)

- Adding jitter gives the total timing resolution

$$\sigma_{\mathrm{tot}} = \sqrt{\sigma^2_{\mathrm{Landau}} + \sigma^2_{\mathrm{jitter}}}$$

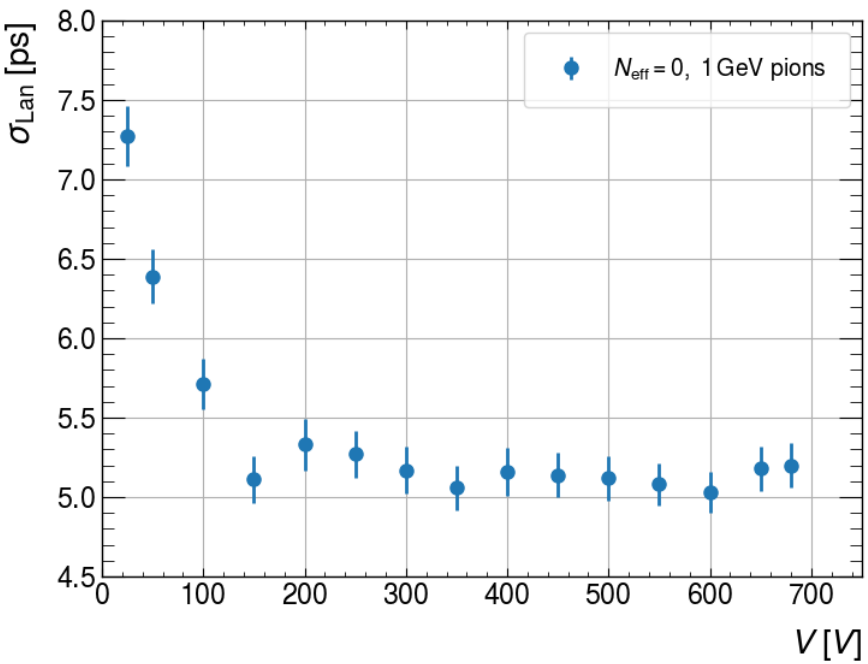




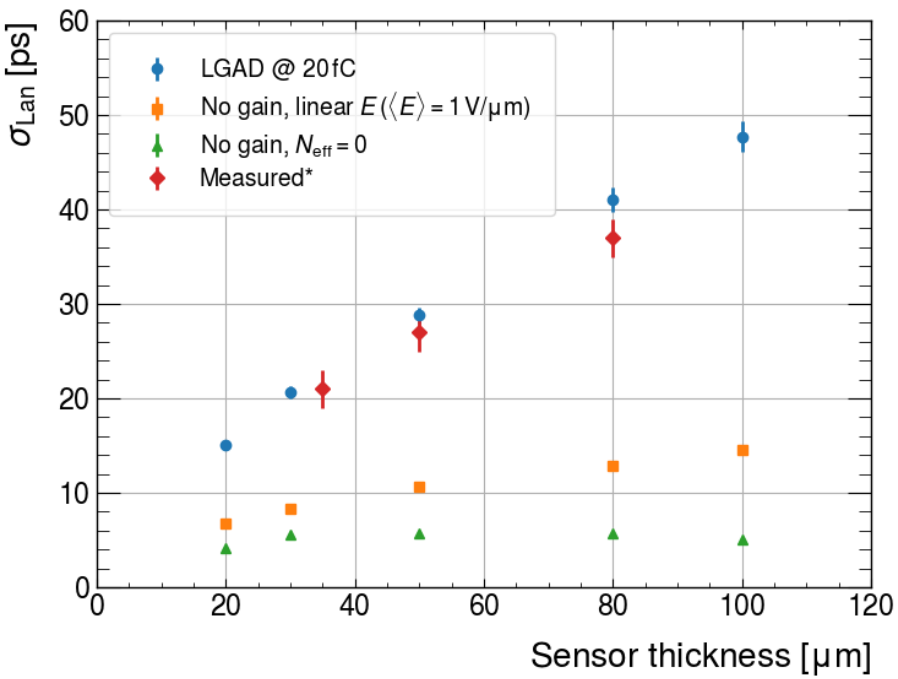
- Noise added to electronics responses for each simulated signal
- Total timing resolution behaves as expected

Results

- Study of time resolution voltage dependence for the case $N_{eff} = 0 \rightarrow$ No gain
- Theoretical limit that can be achieved from charge collection
- At lower voltages (i.e. smaller drift speeds) timing resolution degrades
- Residual non-zero resolution due to different saturation velocities of electrons and holes
- 1 GeV pions
- 50 µm sensor thickness
- 10 µm step size



- Effect of sensor thickness
- LGAD gain adjusted (varying the gain layer doping) to achieve constant collected charge of 20 fC
- Best resolution for uniform field (no doping)
- Introducing a field gradient already worsens performance
- Good agreement with measurements for LGAD sim
- 10 µm step size



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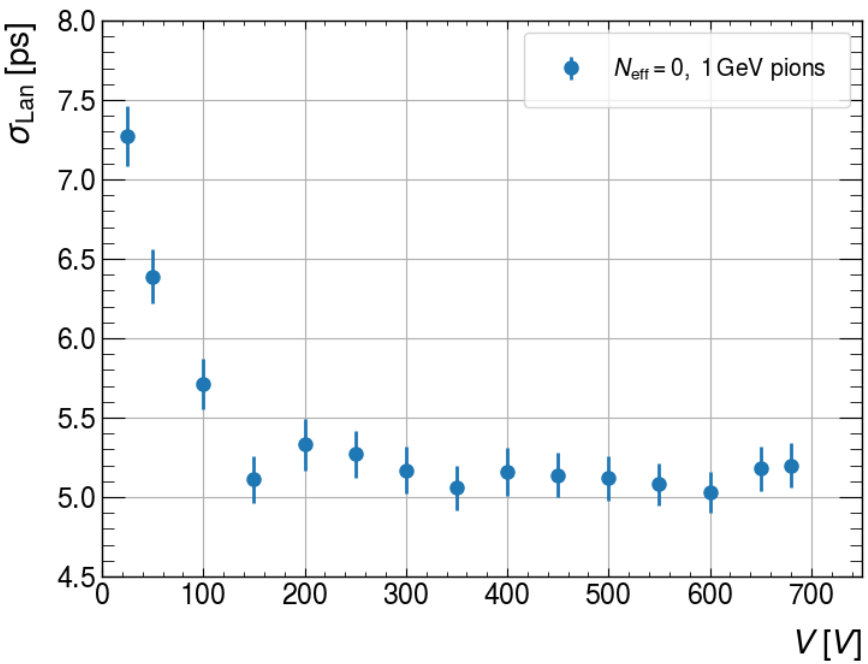

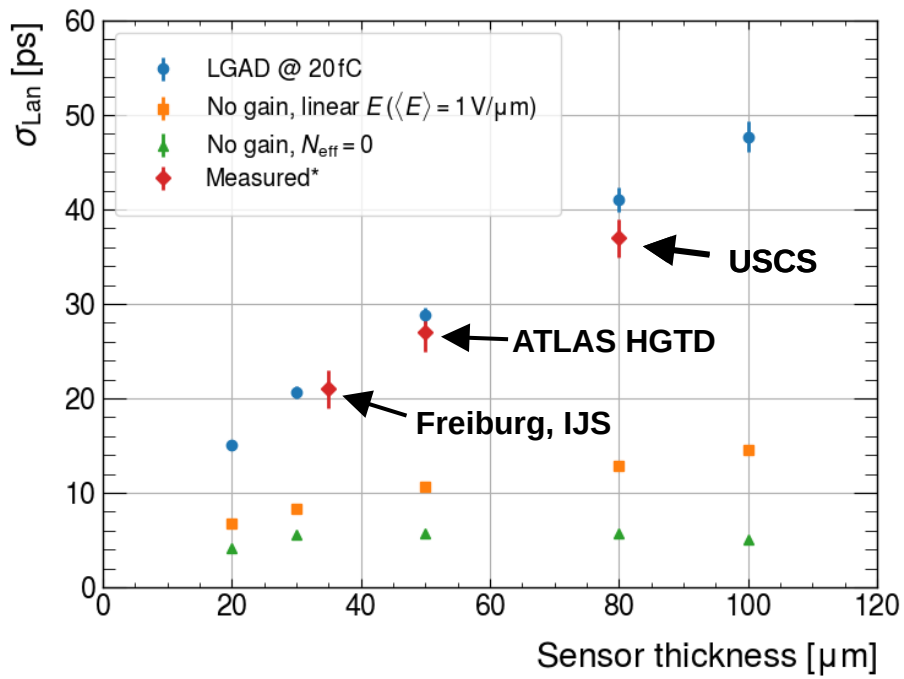

Conclusion

- Simulations of LGAD sensor signals for non-uniform charge deposition coming from Landau fluctuations
- Timing resolution obtained from spread of ToA from electronics responses (convolution with delta response of ALTIROC chip)
- For HPK-P2 sensor with 4 GeV electrons, a Landau fluctuation contribution of ~ 31 ps was observed; ~ 40 ps for C-GL sensors
- Without gain, the timing resolution limit is ~ 5 ps for 50 μm sensor thickness and increases at low bias voltages
- Increasing the sensor thickness shows a corresponding increase of Landau fluctuation contribution and degrades LGAD timing performance