Signal formation in LGAD detectors

- Initial Ionization process and Landau distribution in PiN diodes
  (bare with me in this step, it is interesting)
- Space charge effects during e/h drift
- Gain quenching in LGAD
- Temporal resolution in LGADs
- Landau distribution in LGADs
- A novel method to measure LGAD gains

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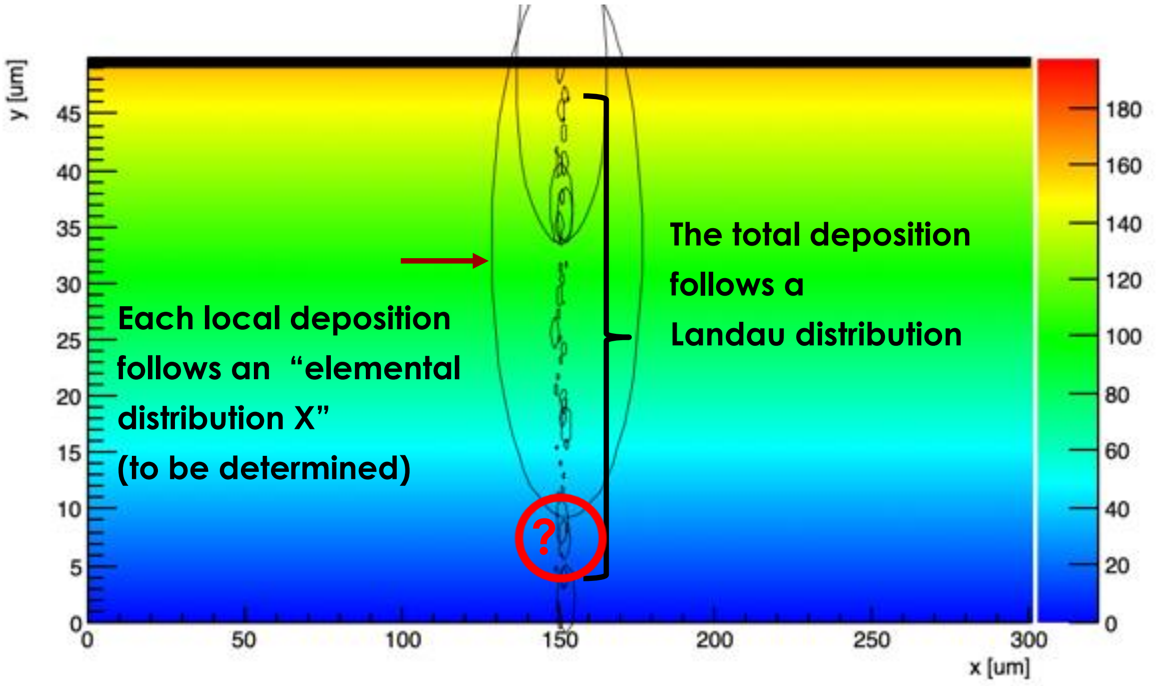
Torino

Landau distribution in PIN diodes

1. In each event, the impinging particle creates clusters of charges along its path.
2. These localized energy deposits follow some unknown "elemental distribution X".
3. The sum of the energy deposits is the total energy deposition.
4. The total energy deposition follows a Landau distribution



Each local deposition follows an "elemental distribution X" (to be determined)

The total deposition follows a Landau distribution

Question: which distribution X is such that the sum of random numbers from this distribution is a Landau?

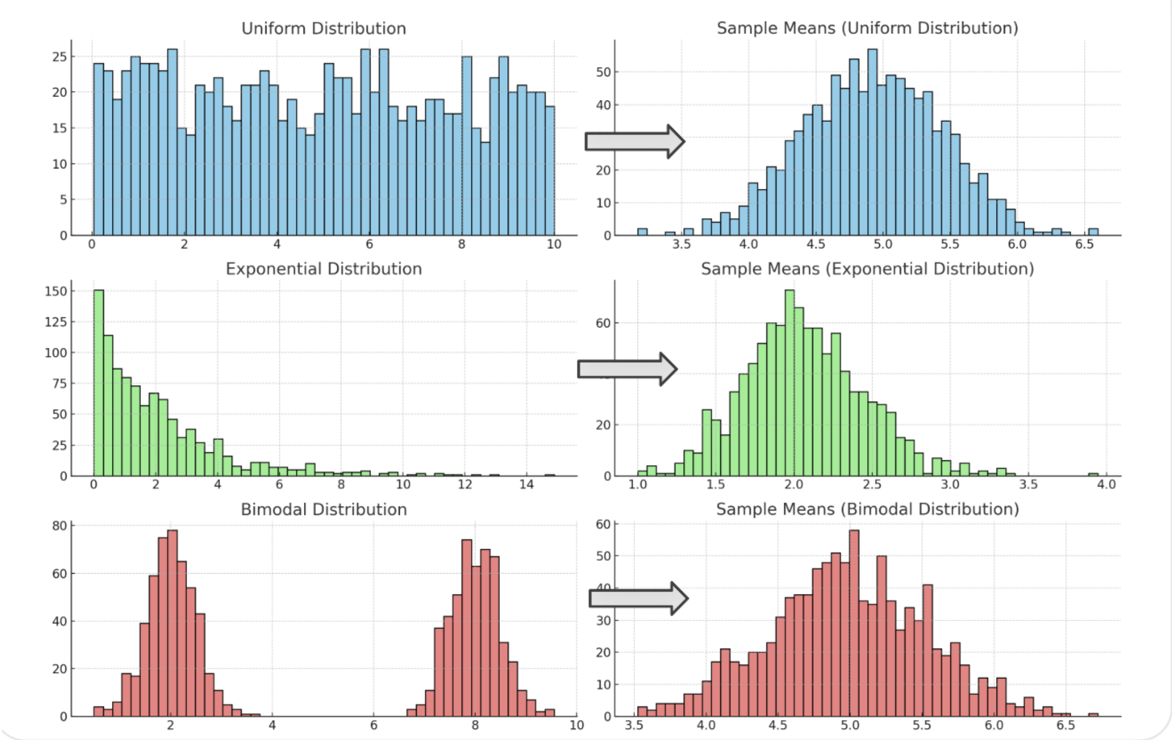
$$\boldsymbol{Landau\ (MPV, FWHM) = Dist\left(\sum_{i=1}^{n} random(X)_i\right)}$$

n = number of draws

Suppose: n = thickness in micron

The central limit theorem does not apply

The sum (or average) of a large number of independent and identically distributed random variables, regardless of the original distribution of the data, as the sample size becomes large, **will approach a normal (Gaussian) distribution**,


Uniform Distribution

Sample Means (Uniform Distribution)

Exponential Distribution

Sample Means (Exponential Distribution)

Bimodal Distribution

Sample Means (Bimodal Distribution)

provided that the variables have a finite mean and variance.

Since the resulting distribution is a Landau and not a Gaussian,

the elemental distribution X does not have finite mean and variance.

Stable distributions

For a special class of functions, stable distributions, the sums of random variables result in a distribution of the same type.

The Landau distribution is a stable distributions, therefore:

the sum of random numbers from a Landau distribution is also distributed as a Landau distribution.

Properties of the $Landau(MPV, FWHM)$ distribution obtained by drawing *n* random numbers from a $Landau_o\ (MPV_o, FWHM_o)$

$$\boldsymbol{MPV = MPV_o * ln(n)}$$

$$\boldsymbol{FWHM = FWHM_o}$$

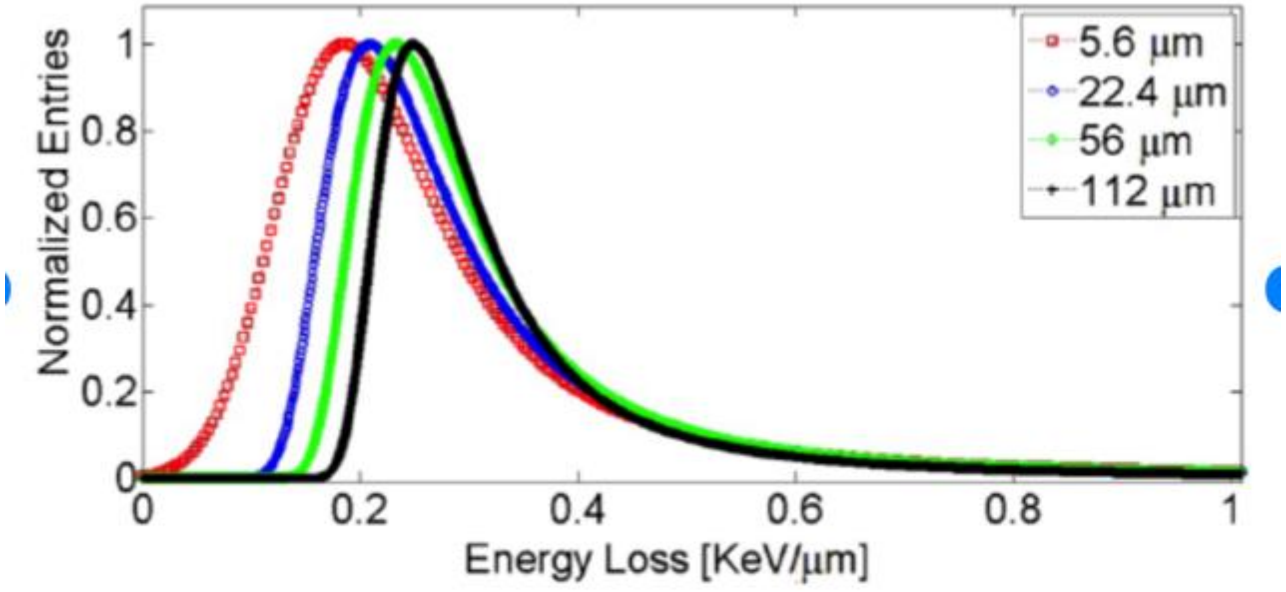
The MPV increases proportionally to ln(n)

The FWHM remains constant

How does this compare with the measured results?

The measured Landau distribution in PiN diodes

Meroli S., Passeri D., Servoli. L. (2011). Energy loss measurement for charged particles in very thin silicon layers. JOURNAL OF INSTRUMENTATION, vol. 6 / 2011



Average energy loss per micron of a ionizing particle in silicon layers of different thicknesses.

The MPV scales logarithmically:

$$\boldsymbol{MPV = 0.027 * \ln(thickness) + 0.126}$$

This is consistent with the elemental distribution X to be a Landau

The FWHM decreases with thickness:

$$\boldsymbol{FWHM = \frac{0.31}{thickness^{0.19}}}$$

This is not consistent with the elemental distribution X to be a Landau.

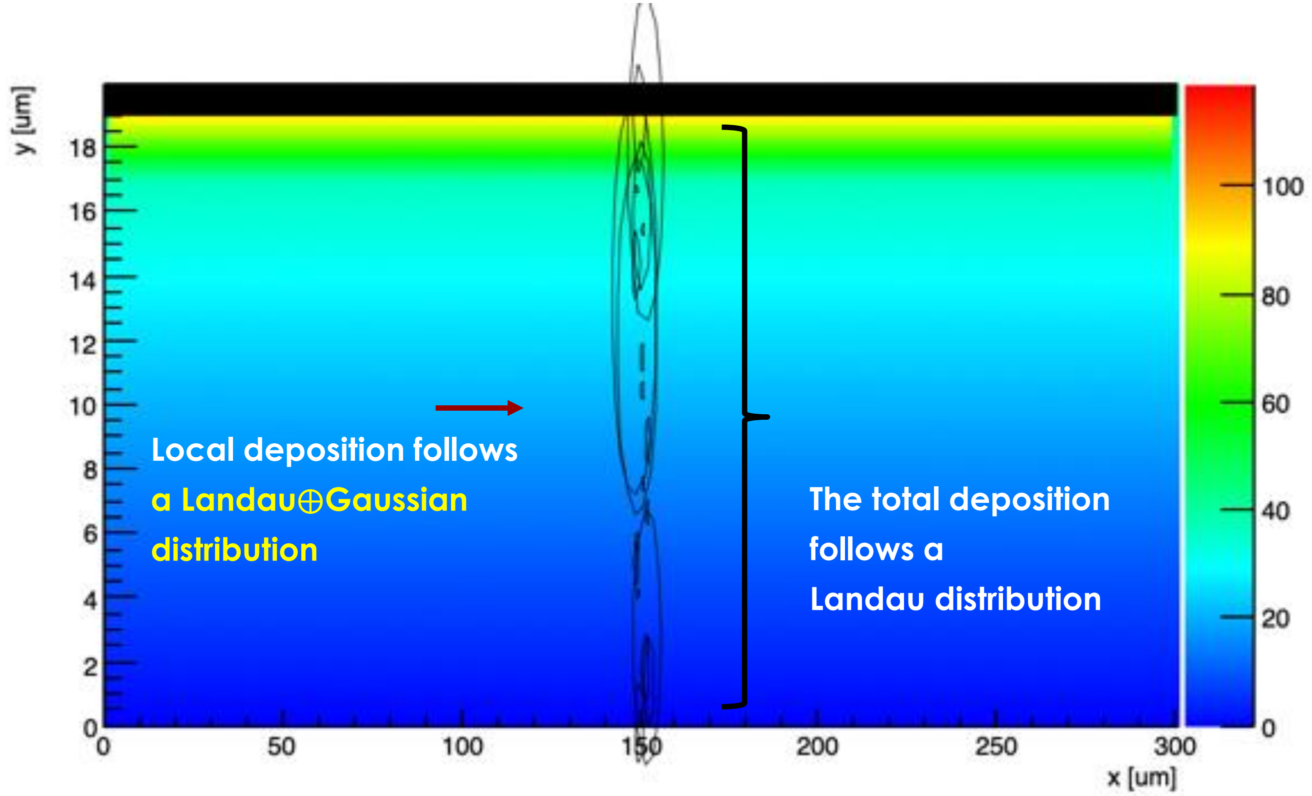
==> Convolution of a Landau with a Gaussian of mean = 0.

The correct choice of the elemental distribution X is the convolution of a Landau with a Gaussian
(approx. of the Vavilov distribution)

Starting point

In the WF2, **the energy deposition in a sensor of arbitrary thickness is therefore obtained as a sum of deposits chosen randomly from an elemental distribution, the convolution of a Landau ⊕ Gaussian.**

The program correctly reproduces the measured MPV and the FWHM dependence on the sensor thickness.



WF2 program:
https://www.to.infn.it/~cartigli/Weightfield2/index.html

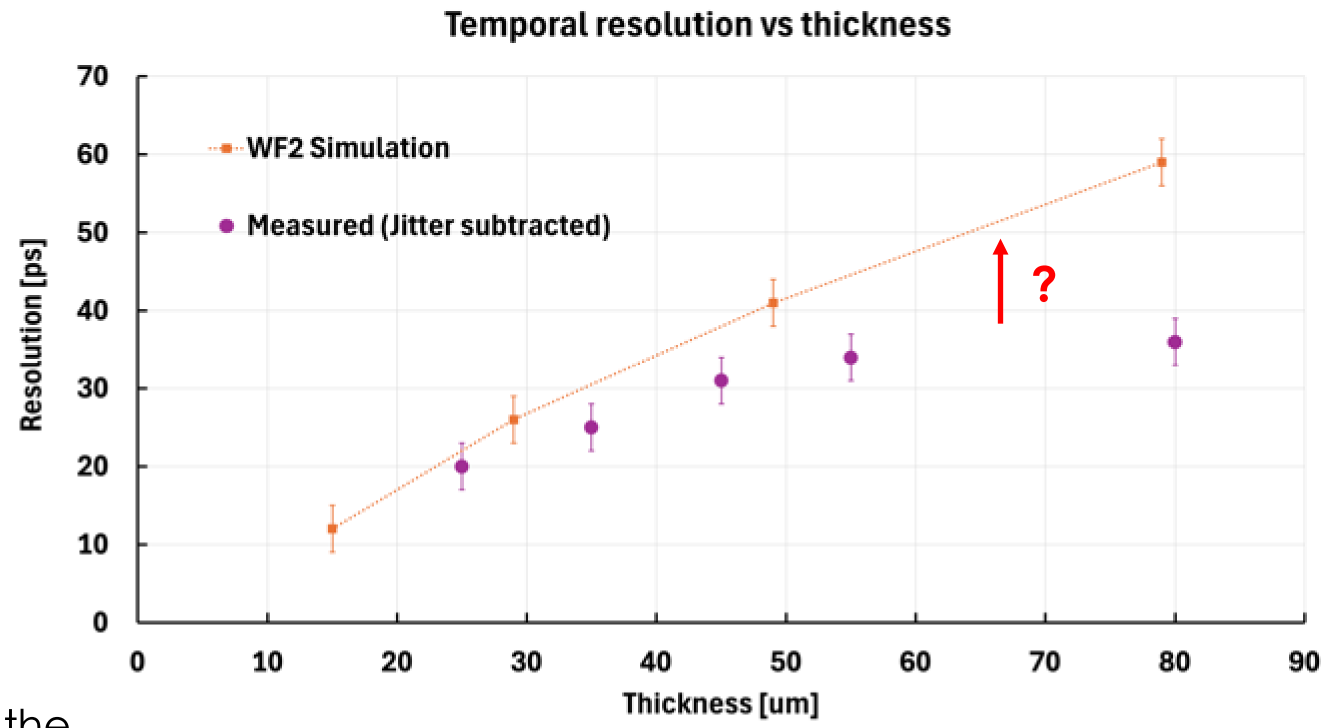
LGAD Temporal resolution vs sensor thickness

Let's compare the measured temporal resolution of sensors of various thicknesses with the WF2 predictions

Problem: the predicted temporal resolution is much worse than the measured resolution.

This discrepancy increases with thickness.

The root of the problem: events in the high tail of the Landau distribution degrades the resolution.



This plot reports the resolution due to non-uniform charge deposition; jitter is subtracted.

The correct simulation of the initial Landau distribution leads to the wrong prediction of the temporal resolution

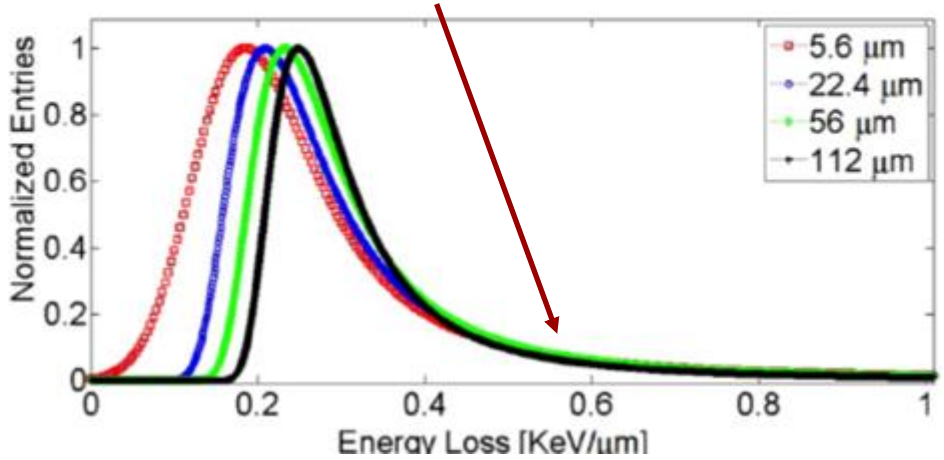
Data from: **"Beam test results of 25 um and 35 um thick UFSD",** F. Carnesecchi, S. Strazzi et al, Eur. Phys. J. Plus (2023) 138:99
"**Optimization of the gain layer design of Ultra-Fast Silicon Detectors**", F. Siviero et al, NIMA 1033 (2022) 166739

Landau distribution and temporal resolution

The temporal resolution is degraded if one energy deposit is much larger than the average.

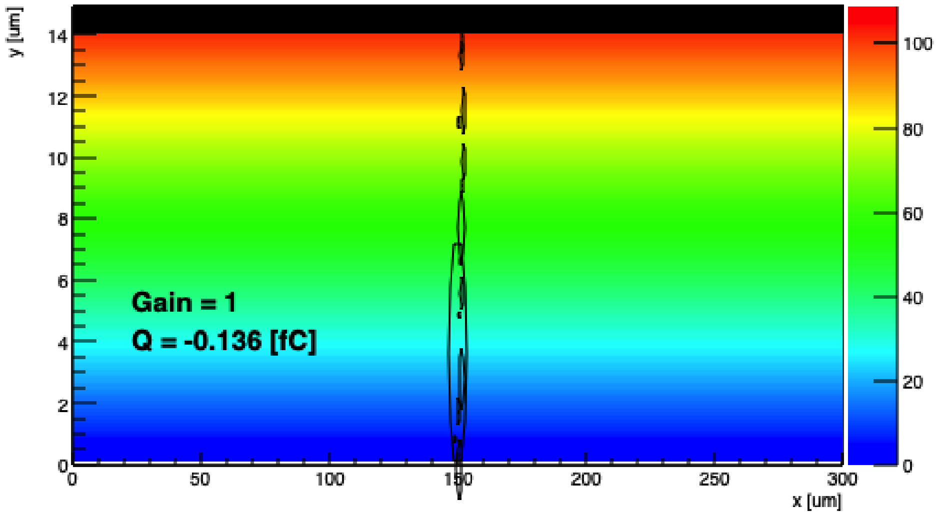
Thick sensors have worse temporal resolution because it is more likely that **at least one energy deposit is much larger.**

The events in the Landau tail spoil the temporal resolution.

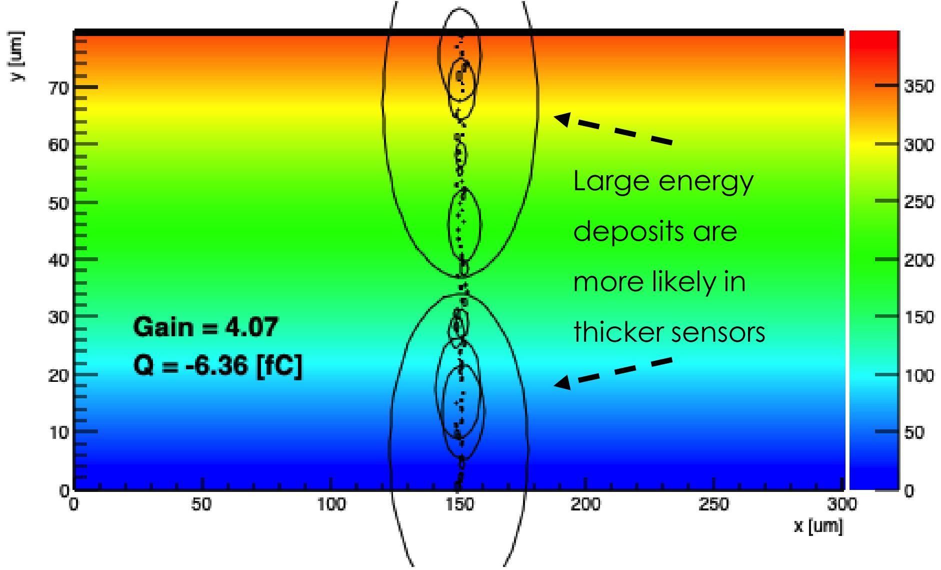


WF2 Simulated energy deposits

15-micron thick sensor



80-micron thick sensor



Large energy deposits are more likely in thicker sensors

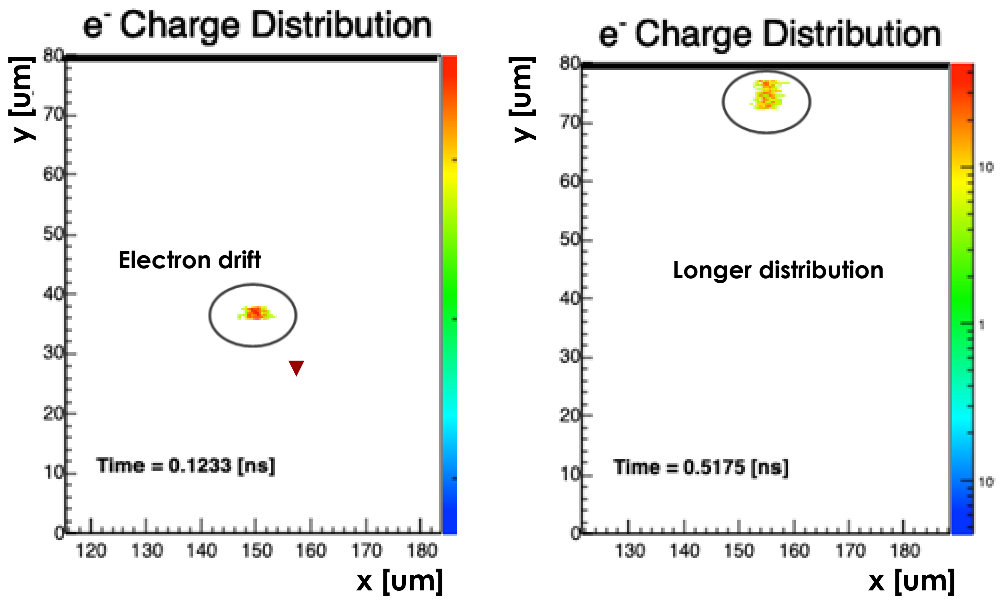
What are we missing in the simulation?

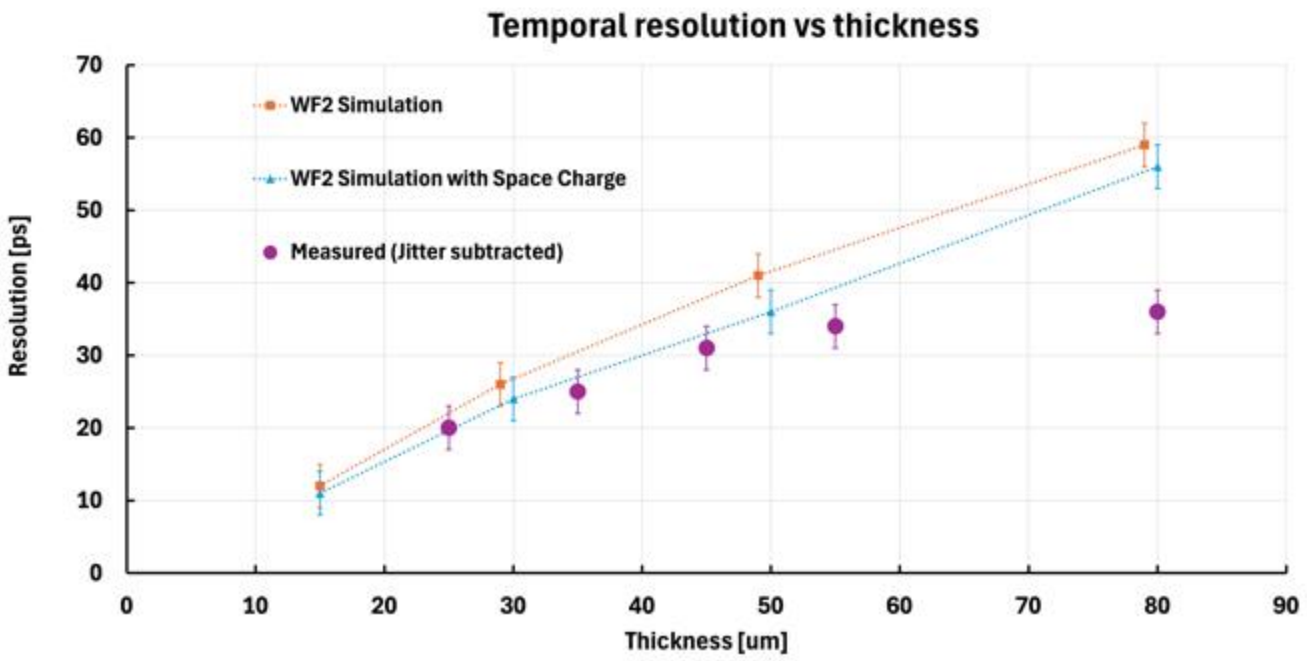
- Space charge effects
- Gain saturation

Space charge effects

During the e/h drift, the charge density decreases due to space charge effects

WF2 simulation of a charge cloud drifting toward the electrode





Charge density decreases during drift, equalizing the current

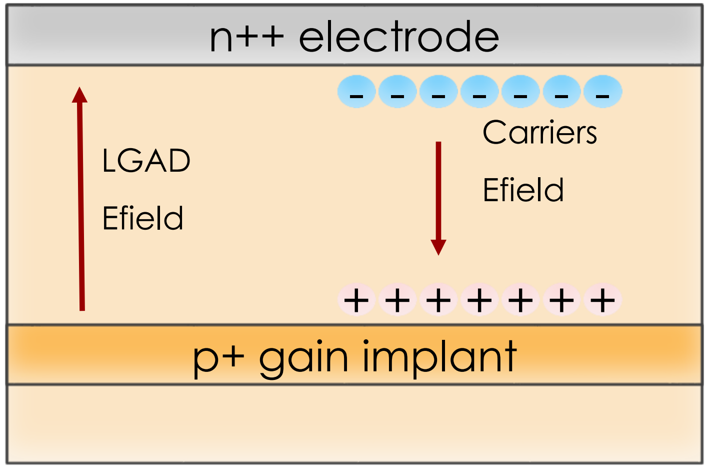
(connected with the talk “Finding sharks..” M. Moll)

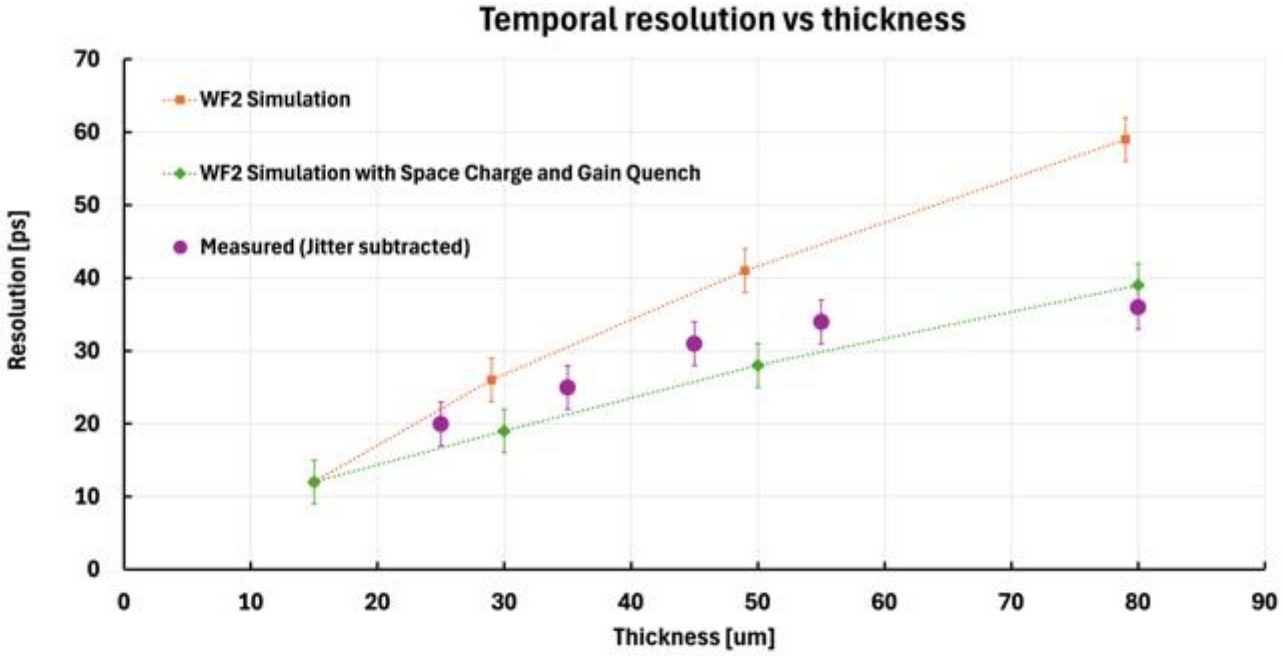
With Space charge repulsion, the temporal resolution in WF2 is slightly closer to the measured resolution

Gain quenching

The LGAD gain is not constant, it is smaller for large charge clusters

The charge carriers in the gain layer produce a field that is opposite to the LGAD field, lowering the gain.





Due to gain quench, the gain is lower for large charge depositions

Gain quenching acts as a dumper, equalizing the current

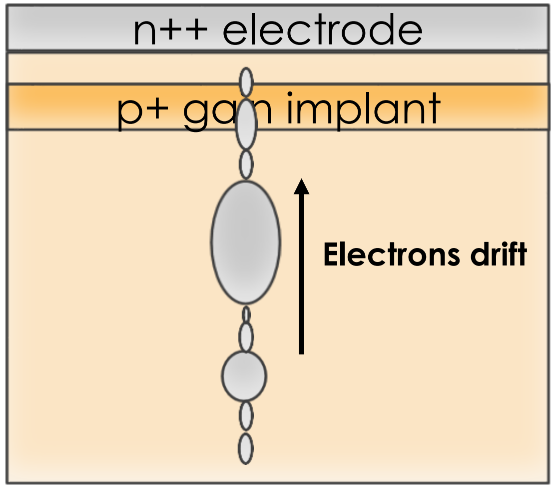
With Space charge repulsion and gain quench, the temporal resolution in WF2 is very similar to the measured resolution

N. Cartiglia, INFN Torino

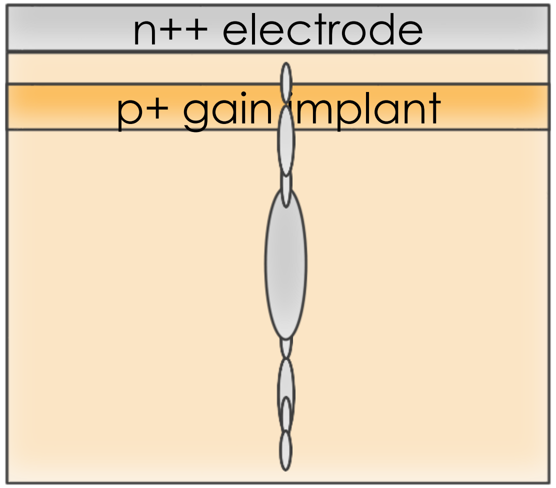
LGAD signal formation: pictorial rappresentation

LGAD signal formation needs to include these three mechanisms:

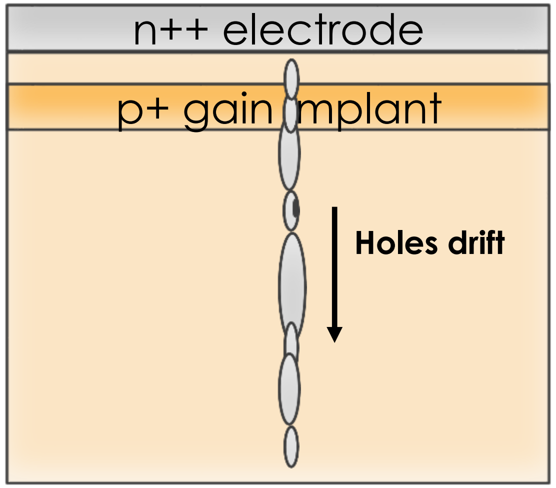
- An initial non-uniform energy deposition obtained as sum of elemental deposits
- Space Charge effects during the particle drift.
- Gain Quench during multiplication.



Initial energy deposition



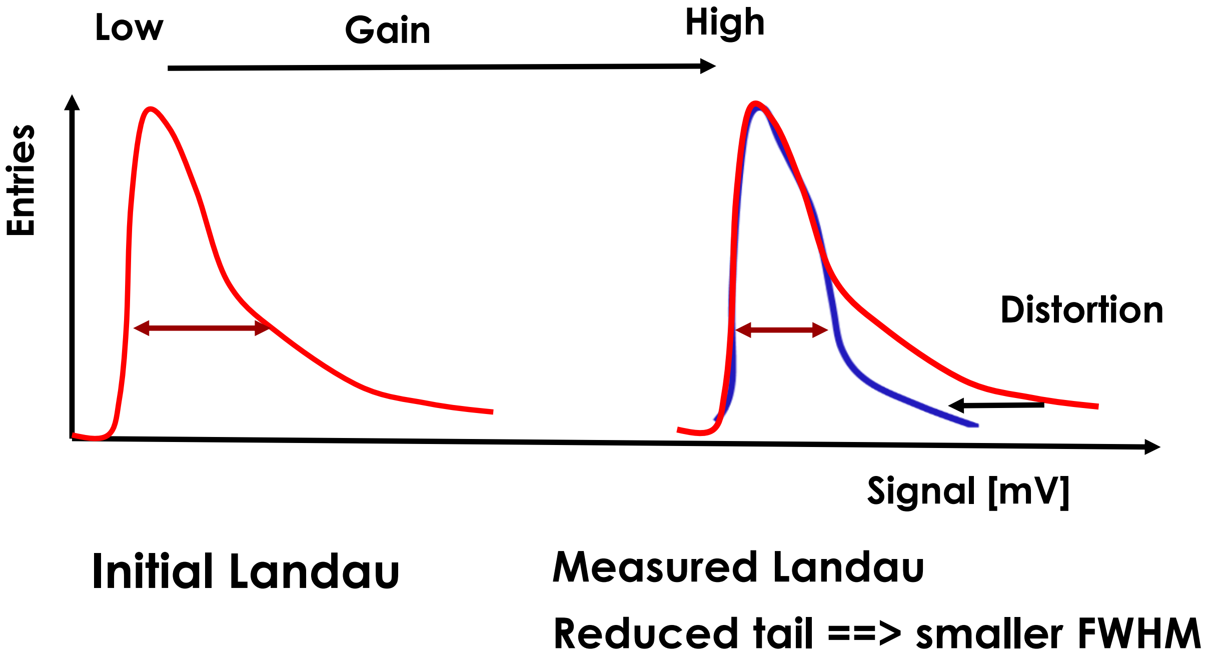
Space Charge effects



Gain Quenching

Effect of gain quench on the LGAD Landau distribution

Since the gain is lower for large charge deposits, **the gain mechanism distorts the initial Landau distribution**, decreasing the Landau high tail.

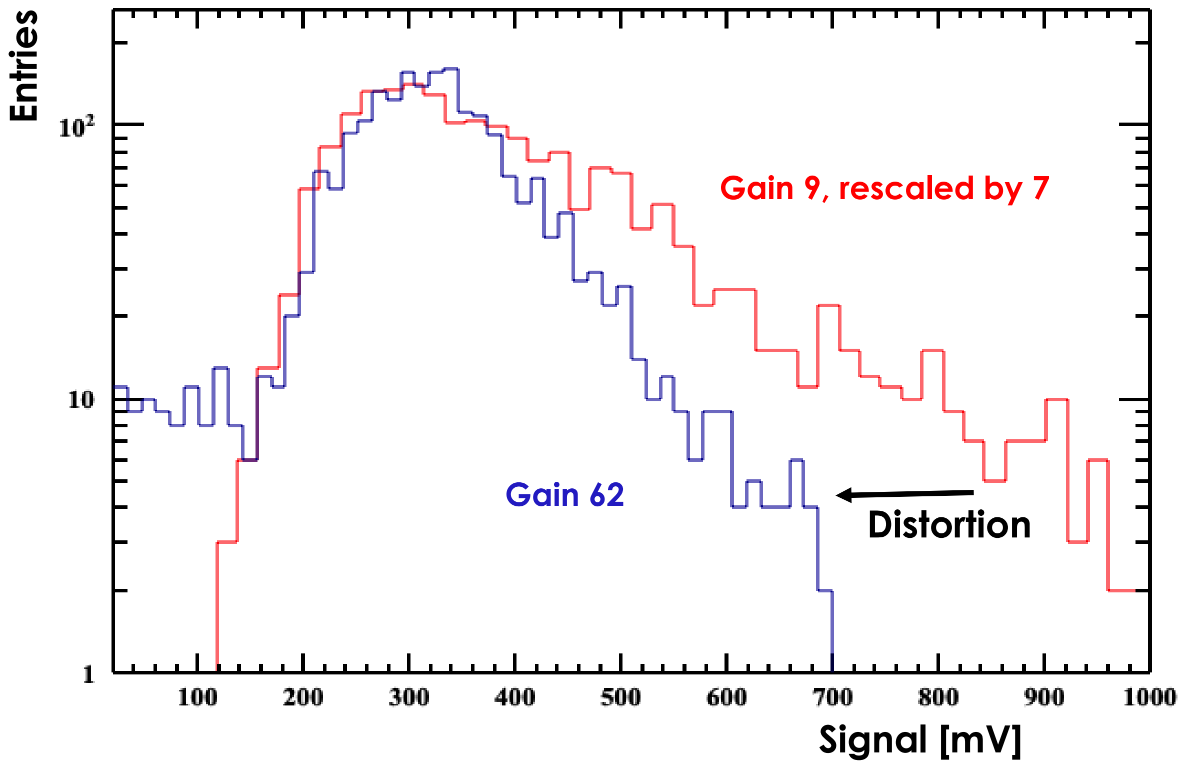


Initial Landau

Measured Landau

Reduced tail ==> smaller FWHM

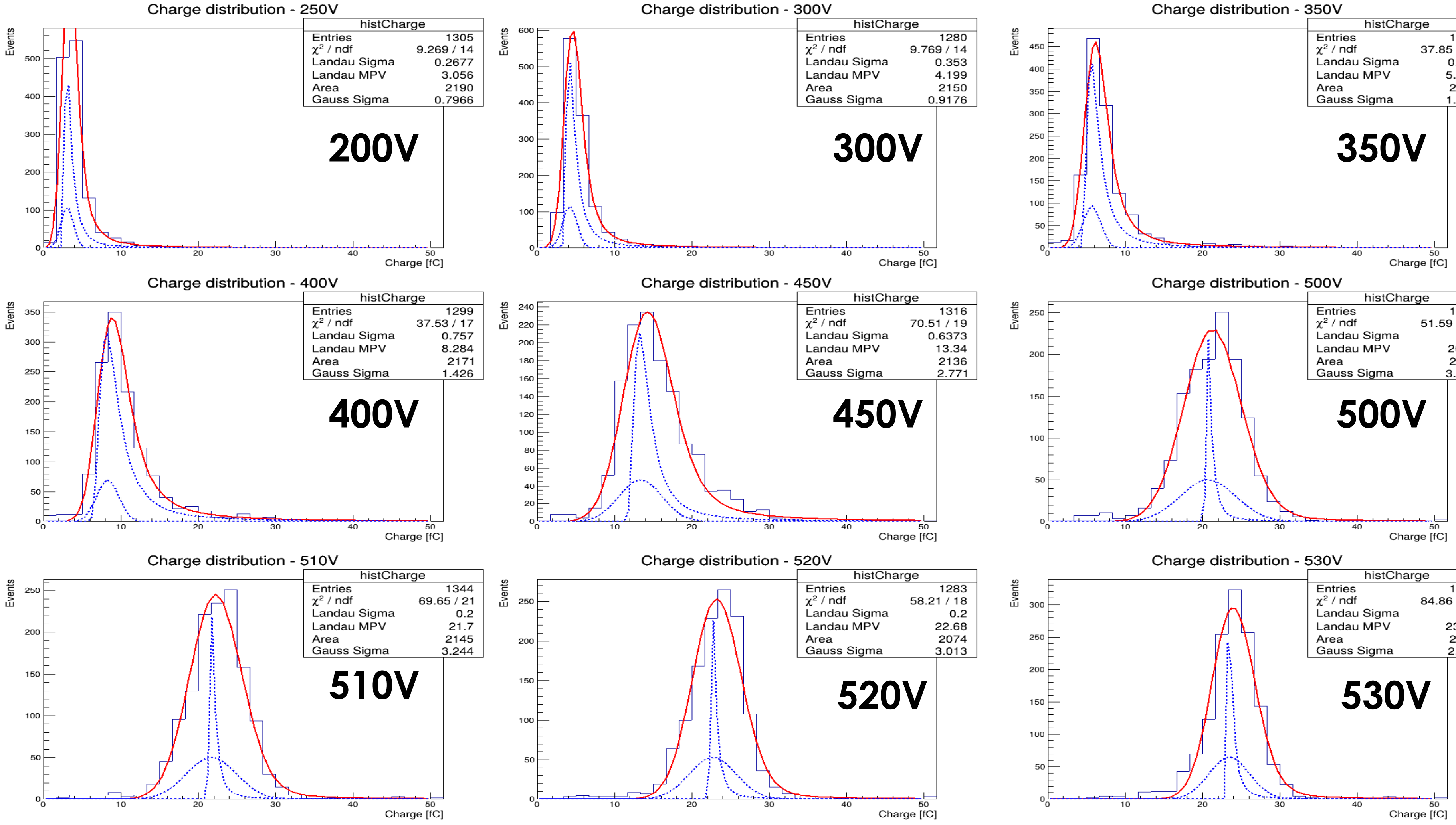
HPK2 beta measurement



Measured LGAD Landau distribution as a function of gain

Gain quenching transforms the initial Landau distribution into a Gaussian distribution

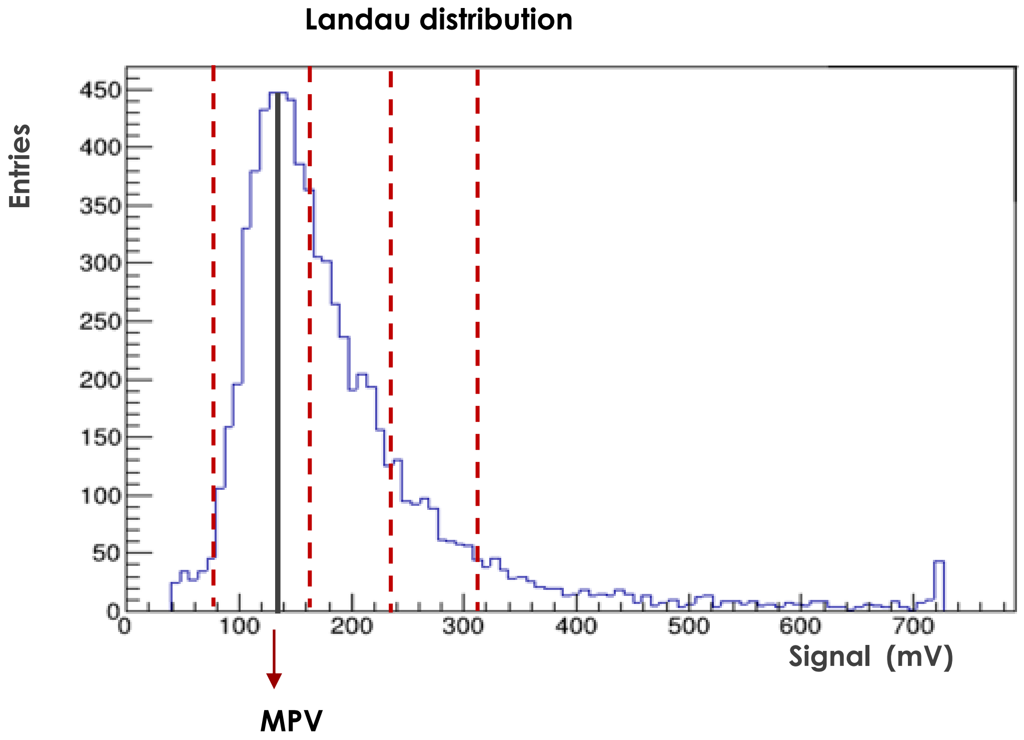
Landau

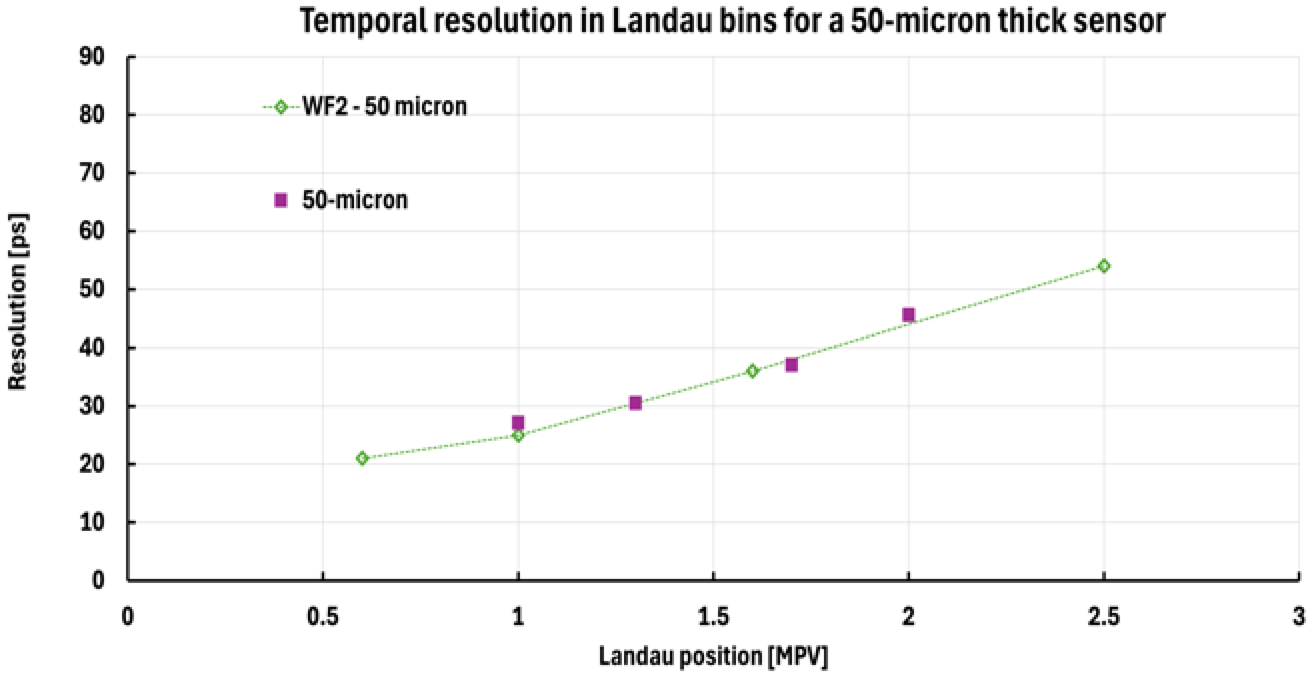


Gaussian

LGAD Temporal resolution vs Landau position

What is the temporal resolution as a function of the event position in the Landau?


Landau distribution


Temporal resolution in Landau bins for a 50-micron thick sensor

Events in the tail have a worse temporal resolution (as expected)

Data from: Ongoing study, C. Marinuzzi et al

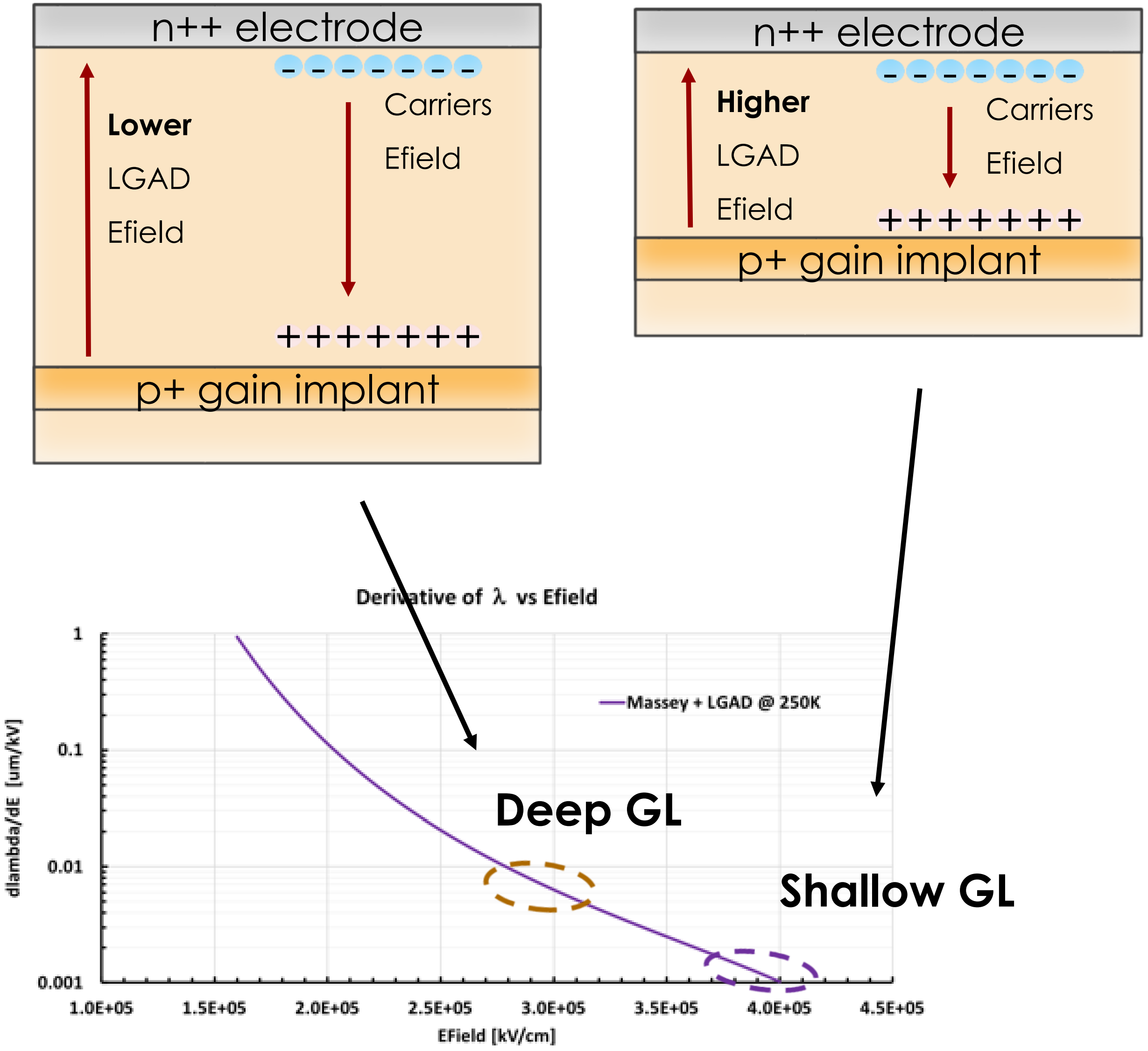
"**Optimization of the gain layer design of Ultra-Fast Silicon Detectors**", F. Siviero et al, NIMA 1033 (2022) 166739

Can we use gain quenching to our advantage?

Gain layers with deeper implant work at lower values of the electric field and **the change of the mean free path with Efield is higher.**

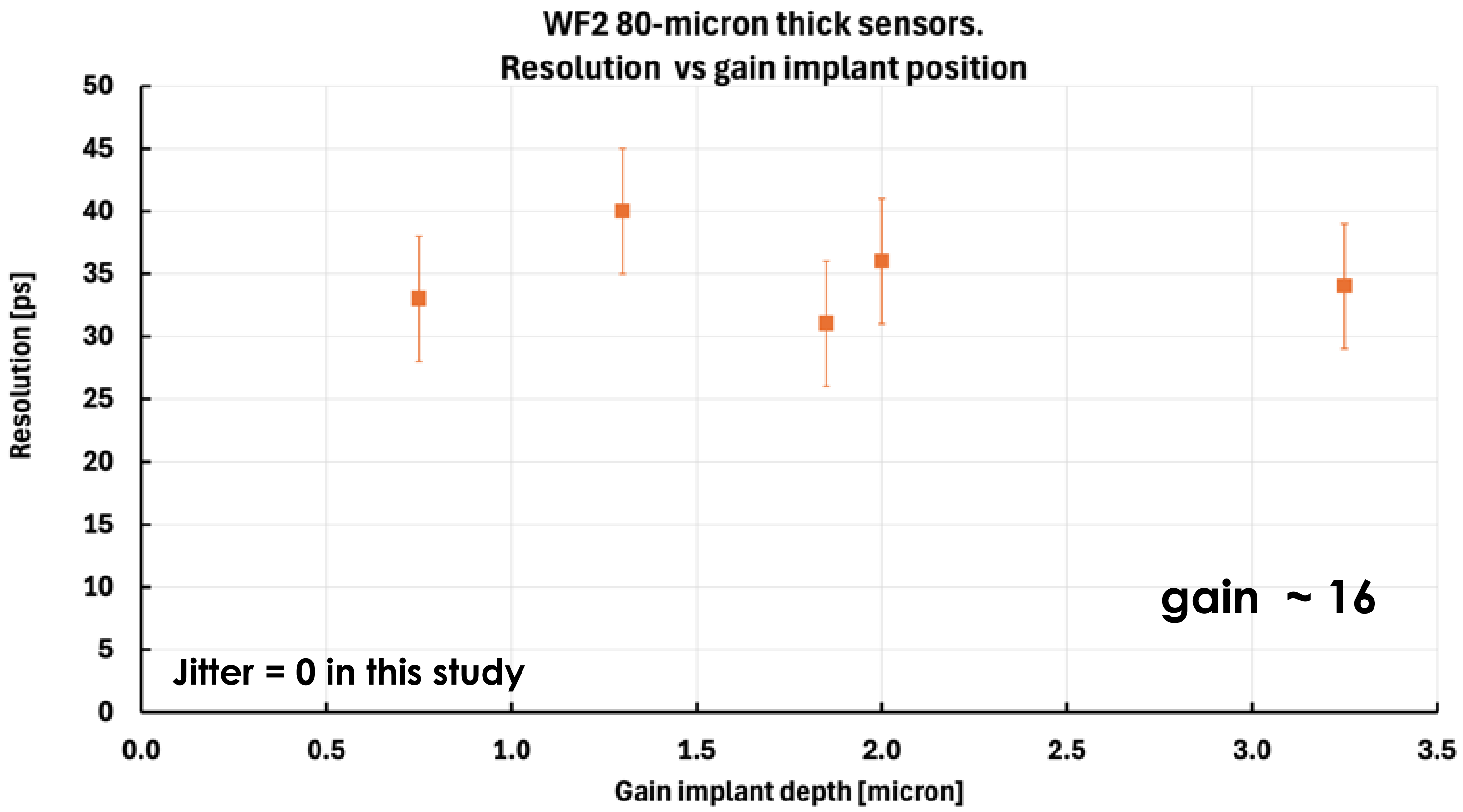
Therefore, the field generated by the e/h has a more significant impact on Lambda.

Can we exploit this aspect to design LGADs that perform better?



Temporal resolution vs gain implant position

(signals with amplitude > 2*MPV in 80-micron thick sensors)



gain ~ 16

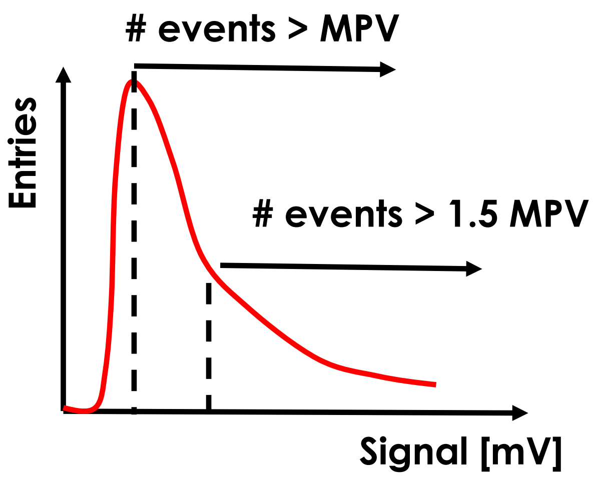
Jitter = 0 in this study

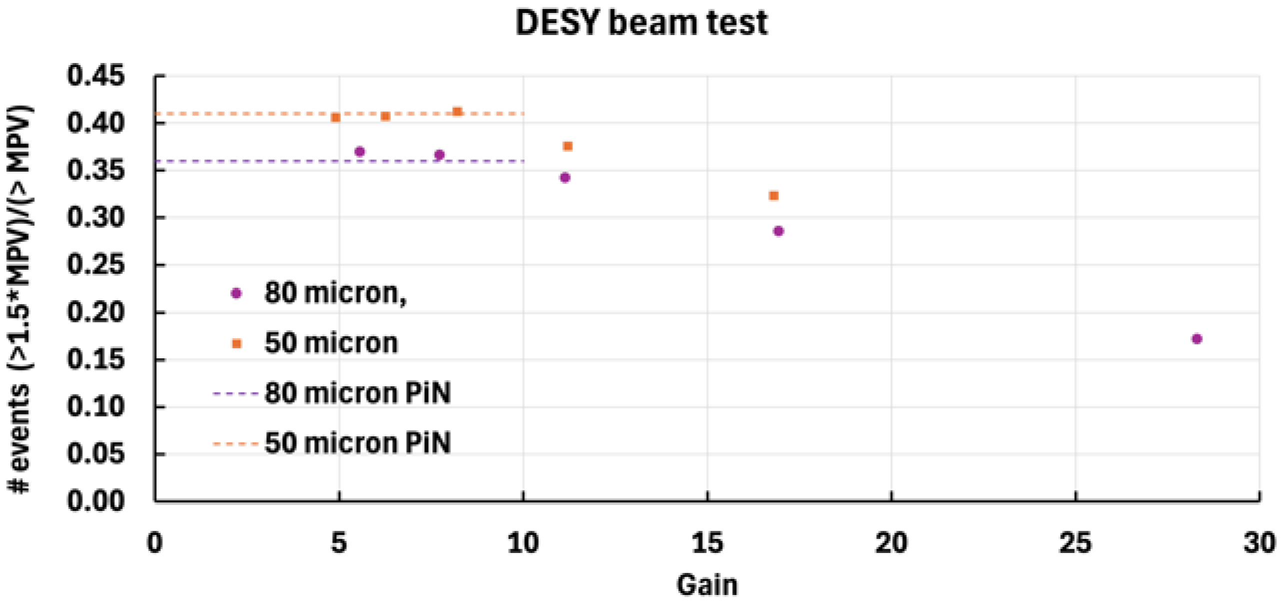
Unfortunately

WF2 predicts that, in our regime of operation, the gain implant depth does not affect the LGAD temporal resolution

Landau method to measure gain

Can we use the distortion of the LGAD Landau to measure the LGAD gain?

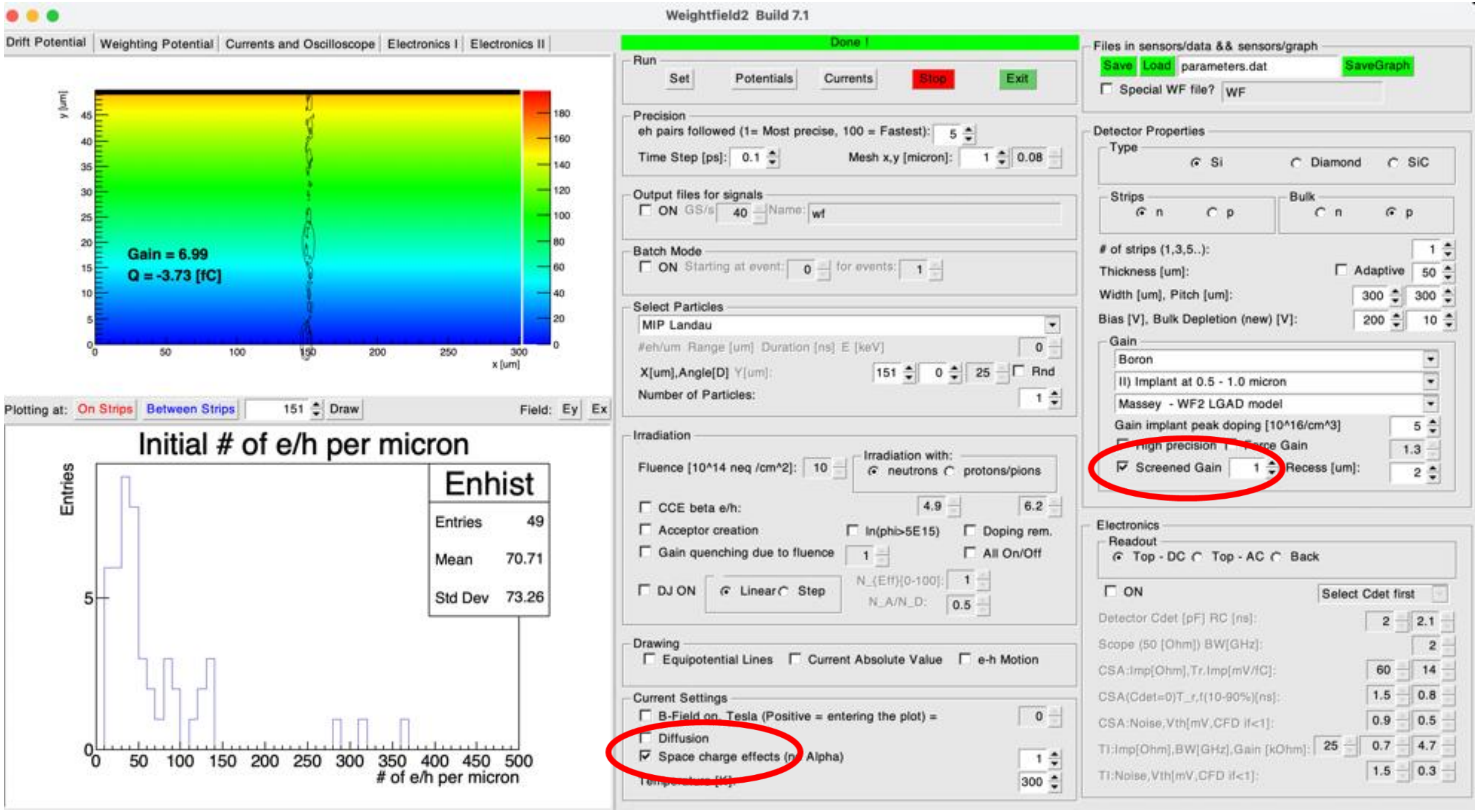




- Consider a quantity that is sensitive to the magnitude of the Landau tail, for example

  (# of events >1.5*MPV)/(# of events >MPV)
- Up to gain ~ 7-10, the ratio remains similar to that of the PiN Landau
- At higher gain, there is a linear dependence from the gain
- **Self calibrating,** no need to know anything about the electronics (it just needs to be linear)

WF2 control panel



Files in sensors/data && sensors/graph

parameters.dat

☐ Special WF file? WF

Run

Precision

eh pairs followed (1= Most precise, 100 = Fastest): 5

Time Step [ps]: 0.1

Mesh x,y [micron]: 1 0.08

Output files for signals

☐ ON GS/s 40 Name: wf

Batch Mode

☐ ON Starting at event: 0 for events: 1

Select Particles

MIP Landau

#eh/um Range [um] Duration [ns] E [keV] 0

X[um],Angle[D] Y[um]: 151 0 25 ☐ Rnd

Number of Particles: 1

Irradiation

Fluence [10^14 neq /cm^2]: 10

Irradiation with: ● neutrons ○ protons/pions

☐ CCE beta e/h: 4.9 6.2

☐ Acceptor creation ☐ In(phi>5E15) ☐ Doping rem.

☐ Gain quenching due to fluence 1 ☐ All On/Off

☐ DJ ON ● Linear ○ Step N_{Eff}[0-100]: 1 N_A/N_D: 0.5

Drawing

☐ Equipotential Lines ☐ Current Absolute Value ☐ e-h Motion

Current Settings

☐ B-Field on, Tesla (Positive = entering the plot) = 0

☐ Diffusion

☑ Space charge effects (n Alpha) 1

Temperature [K]: 300

Detector Properties

Type: ● Si ○ Diamond ○ SiC

Strips: ● n ○ p

Bulk: ○ n ● p

# of strips (1,3,5..): 1

Thickness [um]: ☐ Adaptive 50

Width [um], Pitch [um]: 300 300

Bias [V], Bulk Depletion (new) [V]: 200 10

Gain

Boron

II) Implant at 0.5 - 1.0 micron

Massey - WF2 LGAD model

Gain implant peak doping [10^16/cm^3] 5

☐ High precision ☐ Force Gain 1.3

☑ Screened Gain 1 Recess [um]: 2

Electronics

Readout: ● Top - DC ○ Top - AC ○ Back

☐ ON Select Cdet first

Detector Cdet [pF] RC [ns]: 2 2.1

Scope (50 [Ohm]) BW[GHz]: 2

CSA:Imp[Ohm],Tr.Imp[mV/fC]: 60 14

CSA(Cdet=0)T_r,f(10-90%)[ns]: 1.5 0.8

CSA:Noise,Vth[mV,CFD if<1]: 0.9 0.5

TI:Imp[Ohm],BW[GHz],Gain [kOhm]: 25 0.7 4.7

TI:Noise,Vth[mV,CFD if<1]: 1.5 0.3

If you use WF2, be aware of these two options

Summary

Seemingly uncorrelated effects find an explanation in the shared underlying process of gain quench and space charge repulsion.

The following experimental quantities have been considered and correctly simulated in this study:

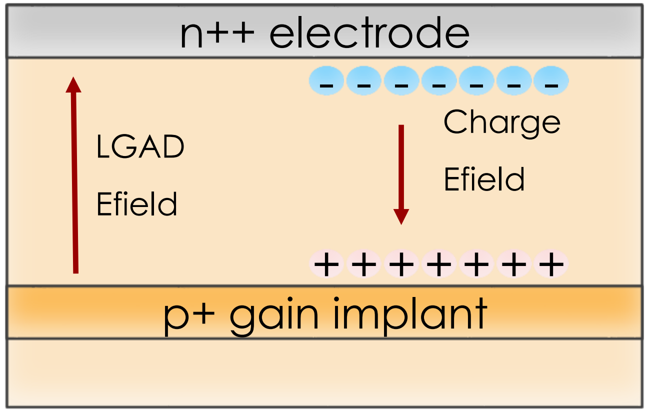
- The initial energy deposition by a MIP
    - The MPV and FWHM dependence upon sensor thickness
- The reduction of the Landau tail as a function of the LGAD gain
- The LGAD temporal resolution as a function of sensor thickness
- The temporal resolution in bins of the Landau distribution

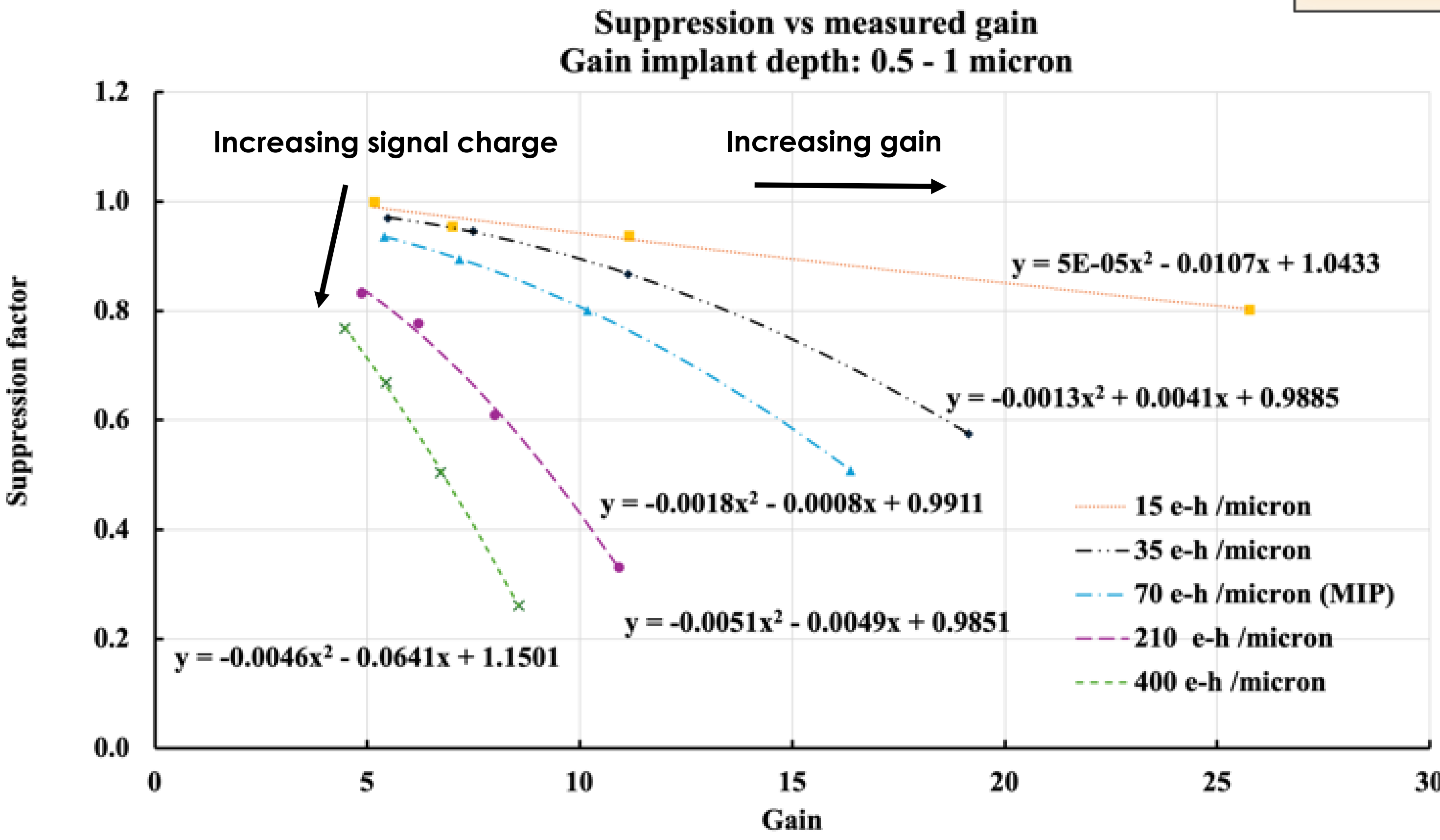
Extra

WF2 Gain quench simulation

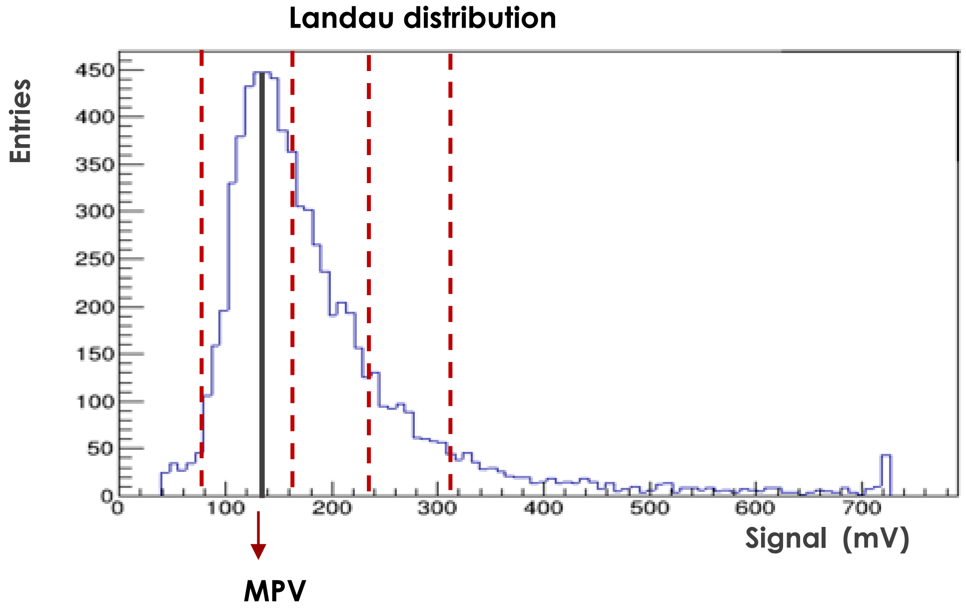
Gain quench increases:

- When the gain increases
- When the number of incoming electrons increases

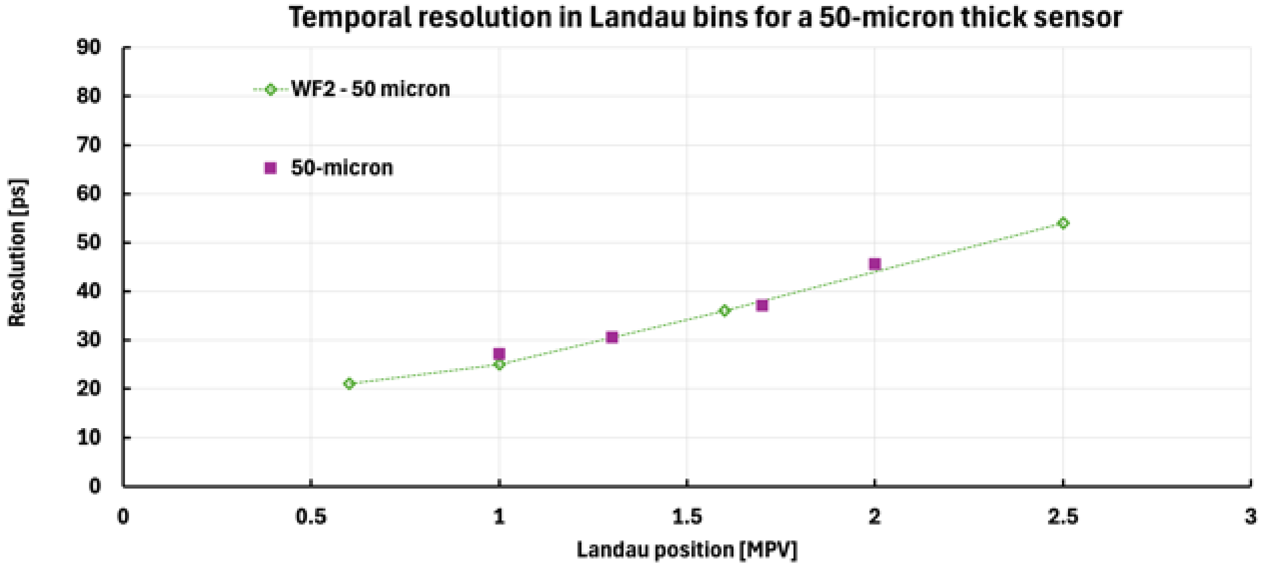


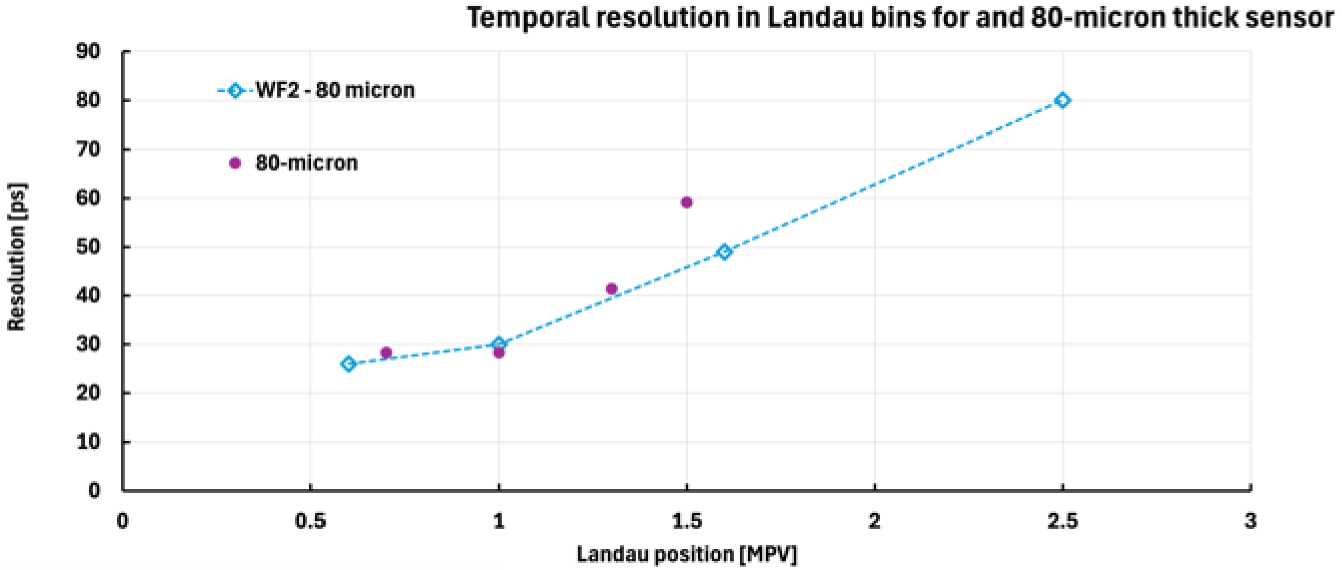


LGAD Temporal resolution vs Landau position



Events in the tail have a worse time resolution (as expected)





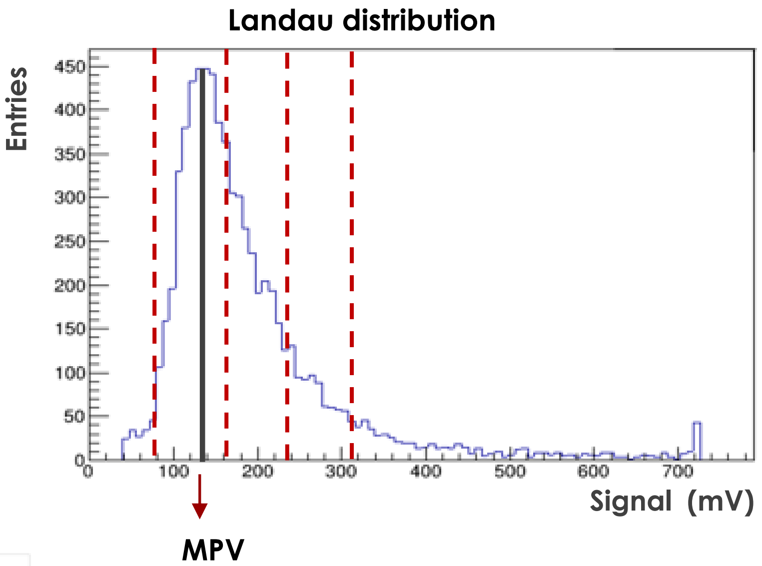
Data from: Ongoing study, C. Marinuzzi et al

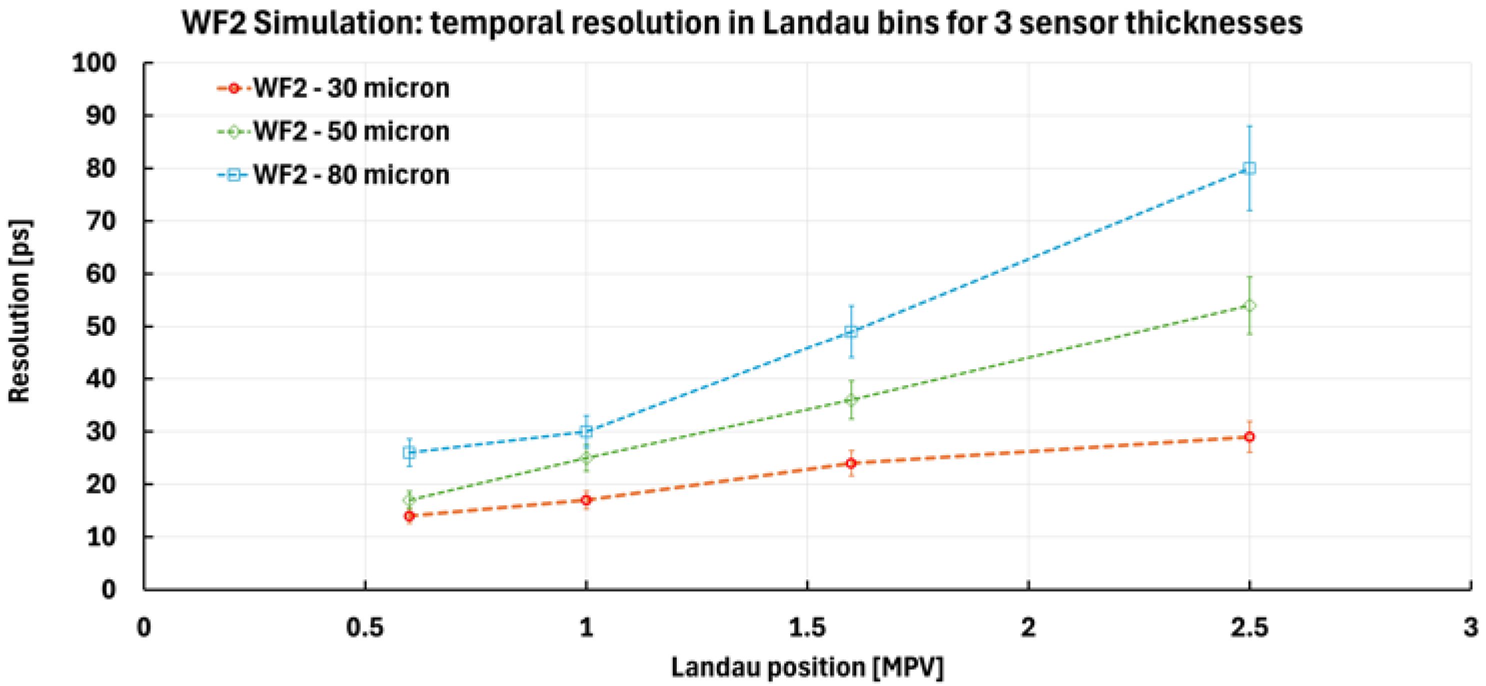
"**Optimization of the gain layer design of Ultra-Fast Silicon Detectors**", F. Siviero et al, NIMA 1033 (2022) 166739

WF2 prediction: LGAD Temporal resolution vs Landau position

The events in the tail of the distribution contains very large localized energy depositions.

The signal shape is irregular, so the temporal resolution is degraded.

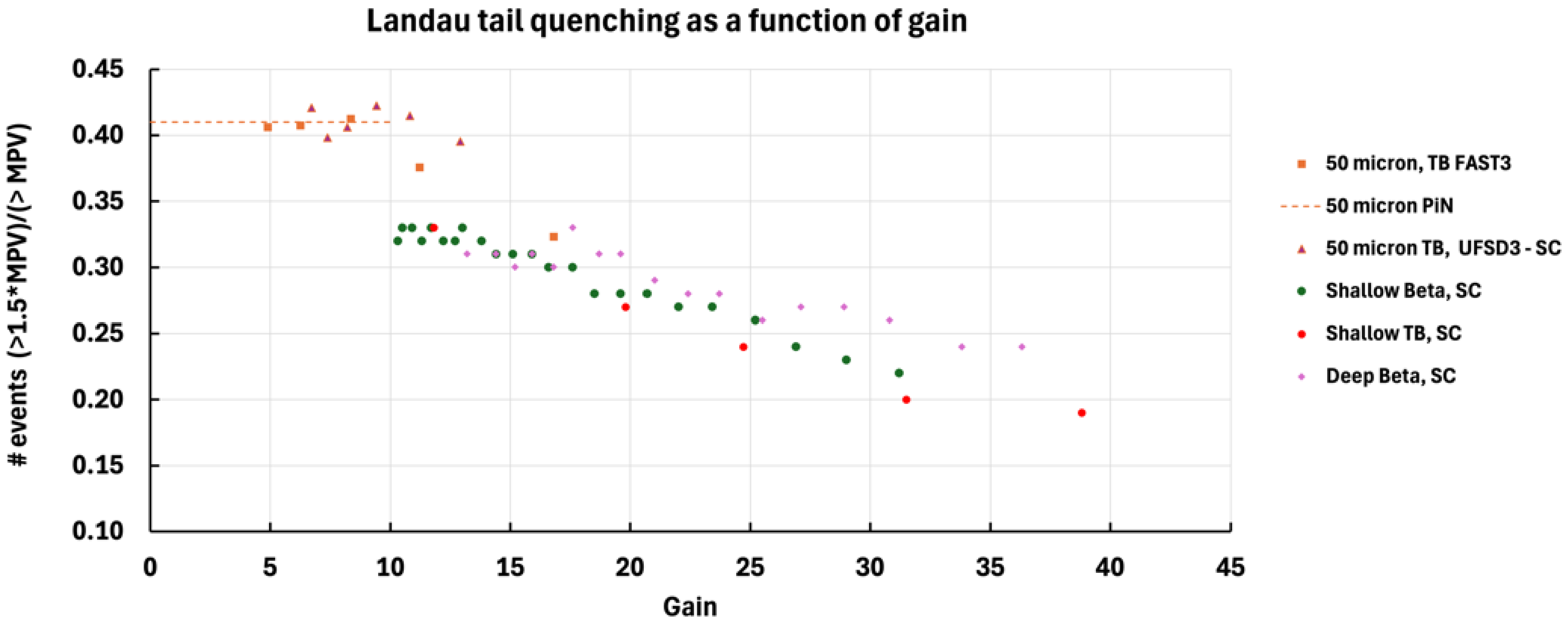




In thicker sensors, the temporal resolution degradation for events in the tail of the Landau distribution is more severe.

This is "simply" because is more likely to have large energy deposits

Additional data on quenching



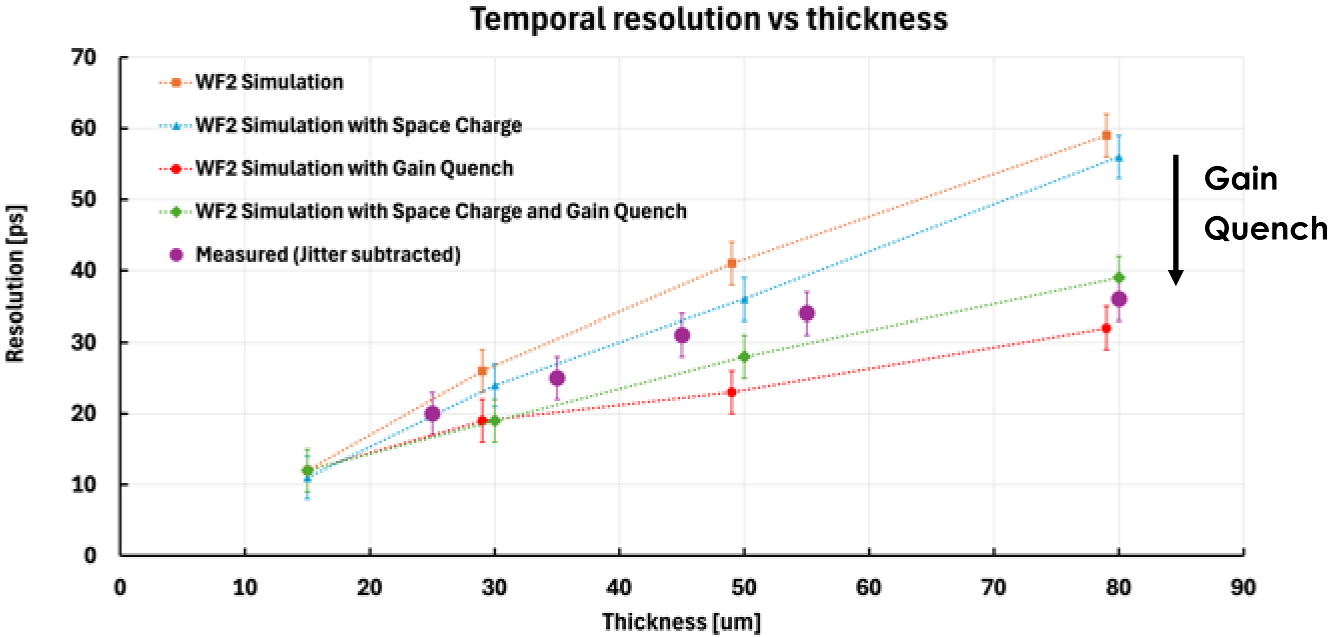
LGAD Temporal resolution vs sensor thickness

Let’s compare the measured temporal resolution with the WF2 predictions, including:

- Space charge
- Gain quench

In the simulation,

- Gain quench, making the signal smoother, has a very strong effect on the temporal resolution.
- Space charge effects improve slightly the temporal resolution with respect of the initial deposition
- Space charge effects, when added to gain quench, degrade slightly the resolution.



Including Gain Quench (and Space Charge effects to a lesser extent) **in the simulation brings the predictions much closer to the measured values.**

Signal formation in LGAD detectors

This contribution examines several PIN Diodes & LGAD properties and searches for the shared underlying physical processes at their root.

Observables:

- The shape of the Landau distribution in PiN diodes
  - The MPV and FWHM dependence upon the sensor thickness
- The shape of the Landau distribution in LGAD as a function of gain
- The temporal resolution of LGADs as a function of the sensor thickness
- The temporal resolution in bins of the Landau distribution

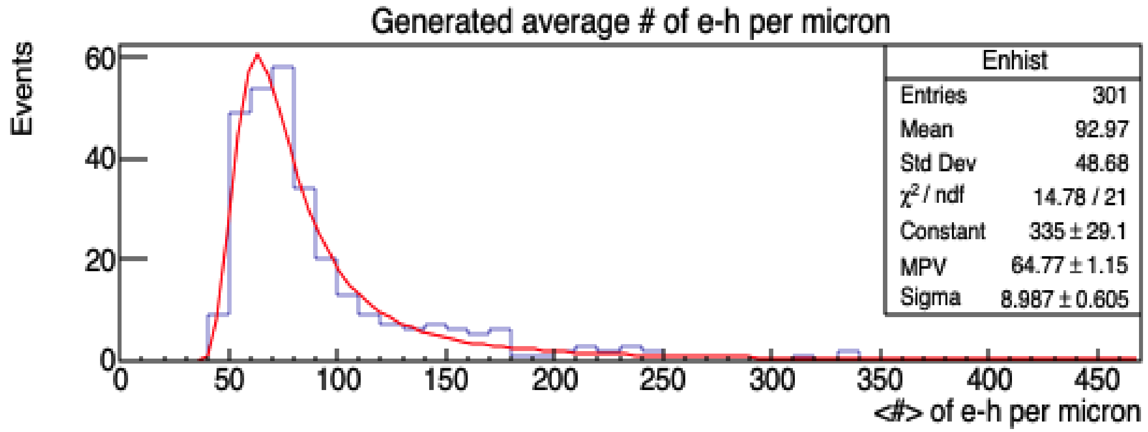
The Weightfield2 program has been used to validate/confute various hypotheses.

WF2 program:
https://www.to.infn.it/~cartigli/Weightfield2/index.html

WF2: LGAD Landau distribution as a function of gain

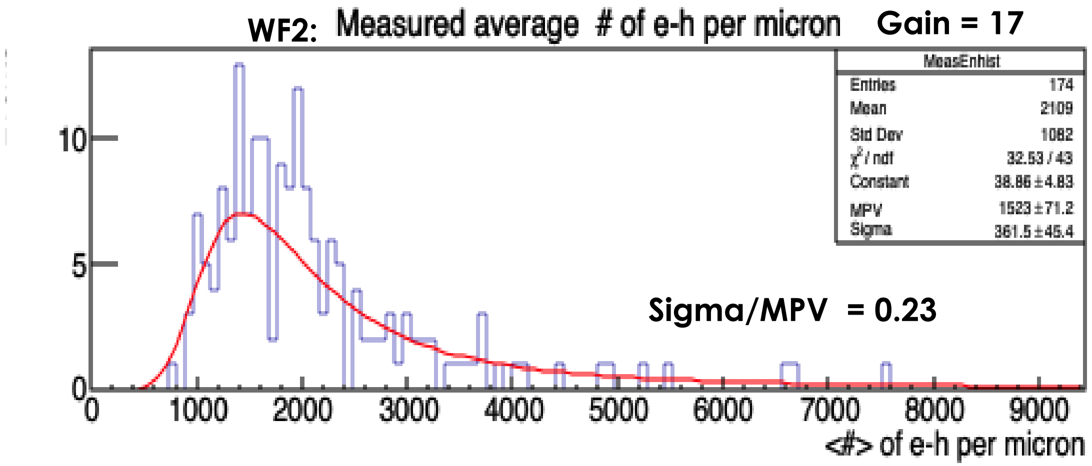
WF2 simulation for an 80-micron thick sensors

Sigma/MPV can be used to describe the importance of the Landau tail.

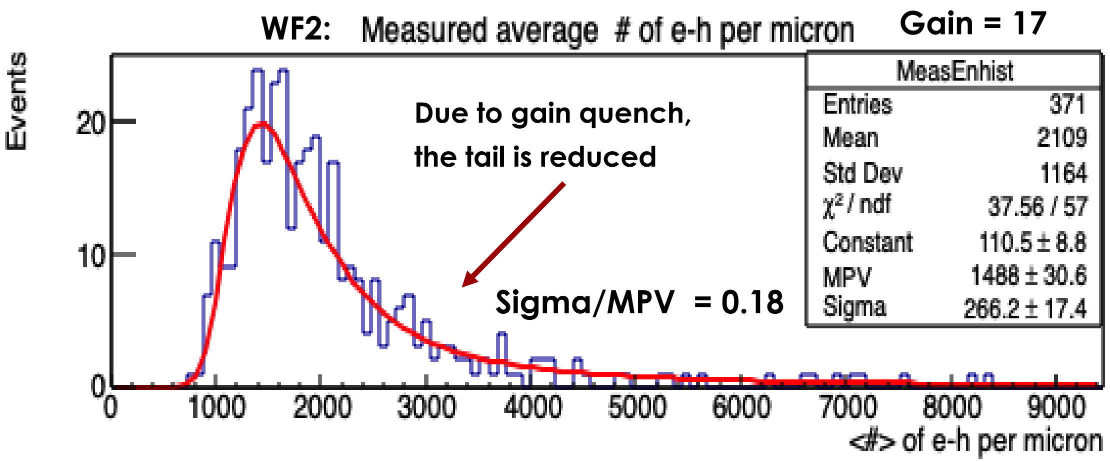

Generated average # of e-h per micron

LGAD Landau distribution without gain quench

LGAD Landau distribution with gain quench


WF2: Measured average # of e-h per micron **Gain = 17**

Sigma/MPV = 0.23

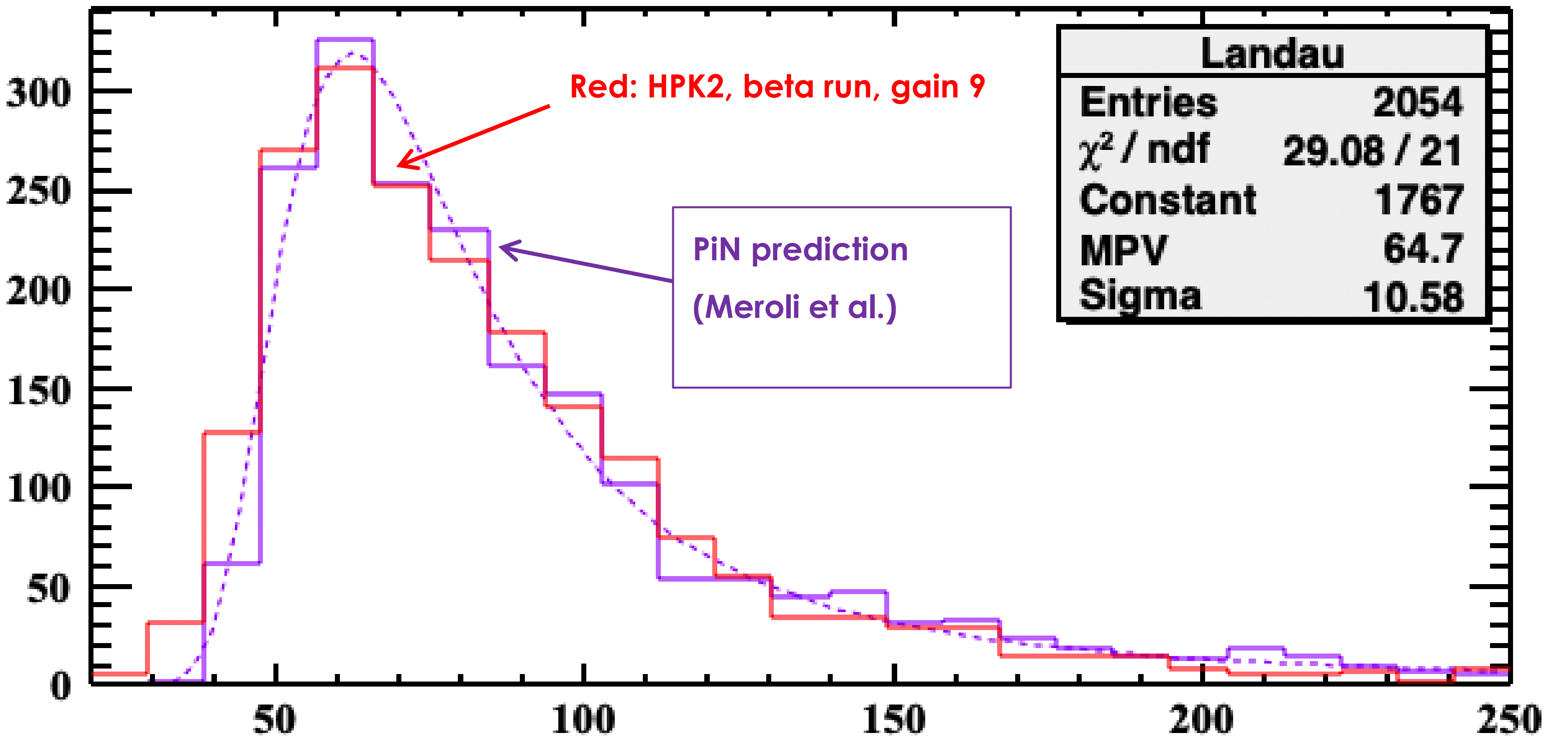

WF2: Measured average # of e-h per micron **Gain = 17**

Due to gain quench, the tail is reduced

Sigma/MPV = 0.18

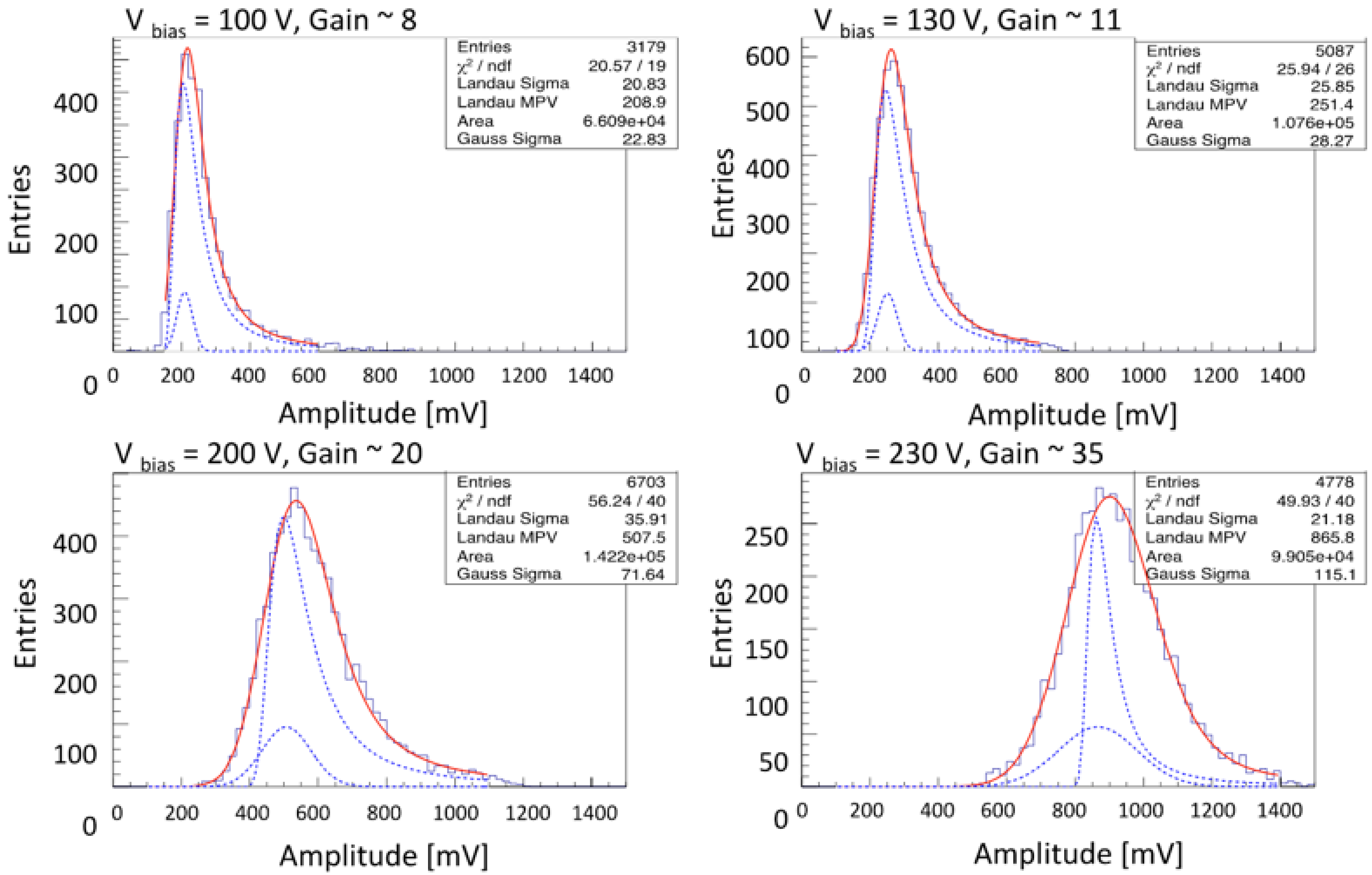
Effect of gain quench on the LGAD Landau distribution

At low gain, the LGAD Landau distribution is compatible with the parametrization of the Landau for PIN diodes



Measured LGAD Landau distribution as a function of gain

50-micron thick sensors, CERN beam test

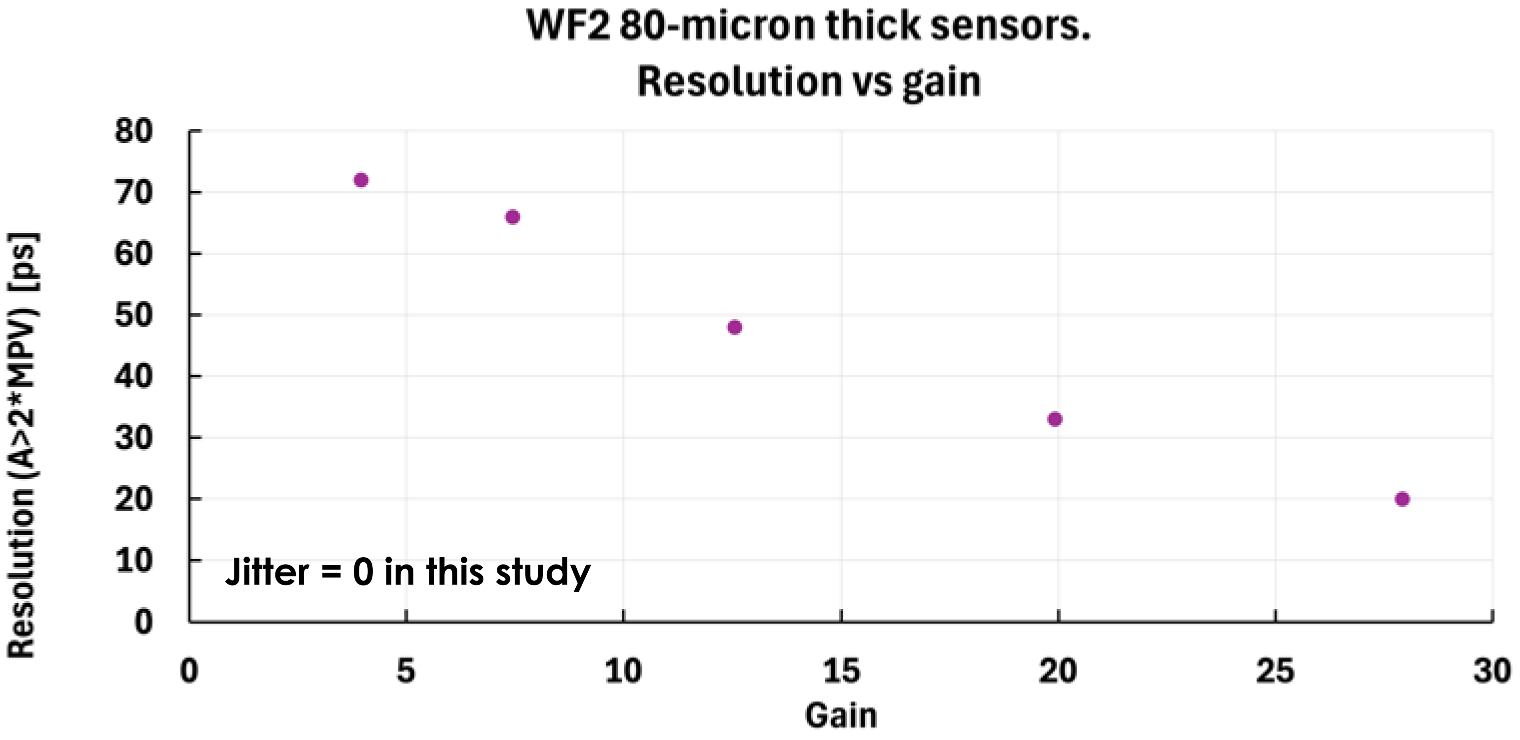


"**Beam test results of a 16 ps timing system based on ultra-fast silicon detectors**",
N. Cartiglia et al, NIMA 850 (2017) 83 - 88

Temporal resolution vs gain

Consider the temporal resolution for signals with amplitude > 2*MPV in 80-micron thick sensors.
(these events are very irregular, so they are a good testing ground)

As the gain increases, quenching smooths the signal shape more and more, and the resolution improves.


WF2 80-micron thick sensors.
Resolution vs gain

Jitter = 0 in this study

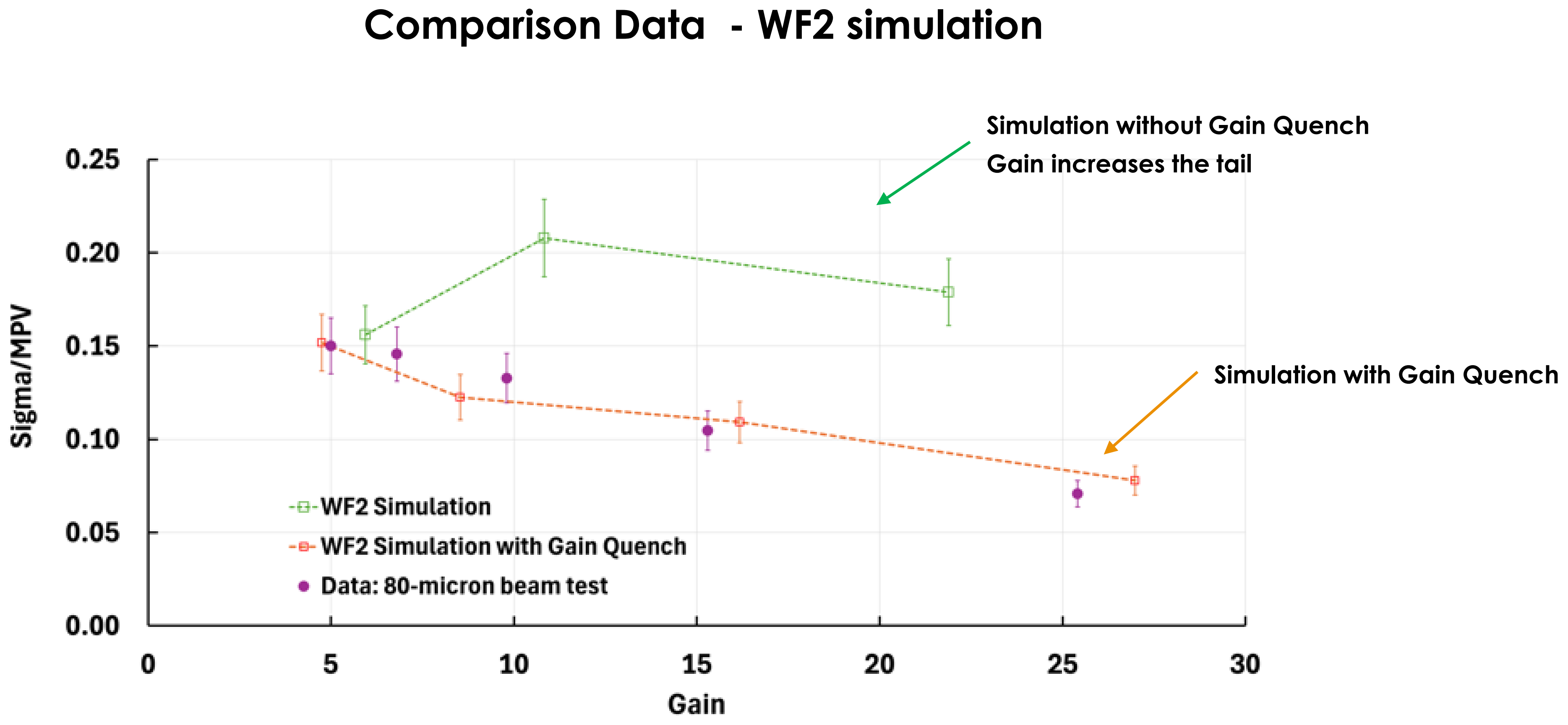
Properties of the Landau - II

The next step is to connect Landau's mathematical properties and the measured results.

In the following, the number of random numbers n and the sensor thickness play the same role, n = sensor thickness in micron

This will allow us to determine the elemental distribution to build any measured Landau.

LGAD Landau distribution as a function of gain

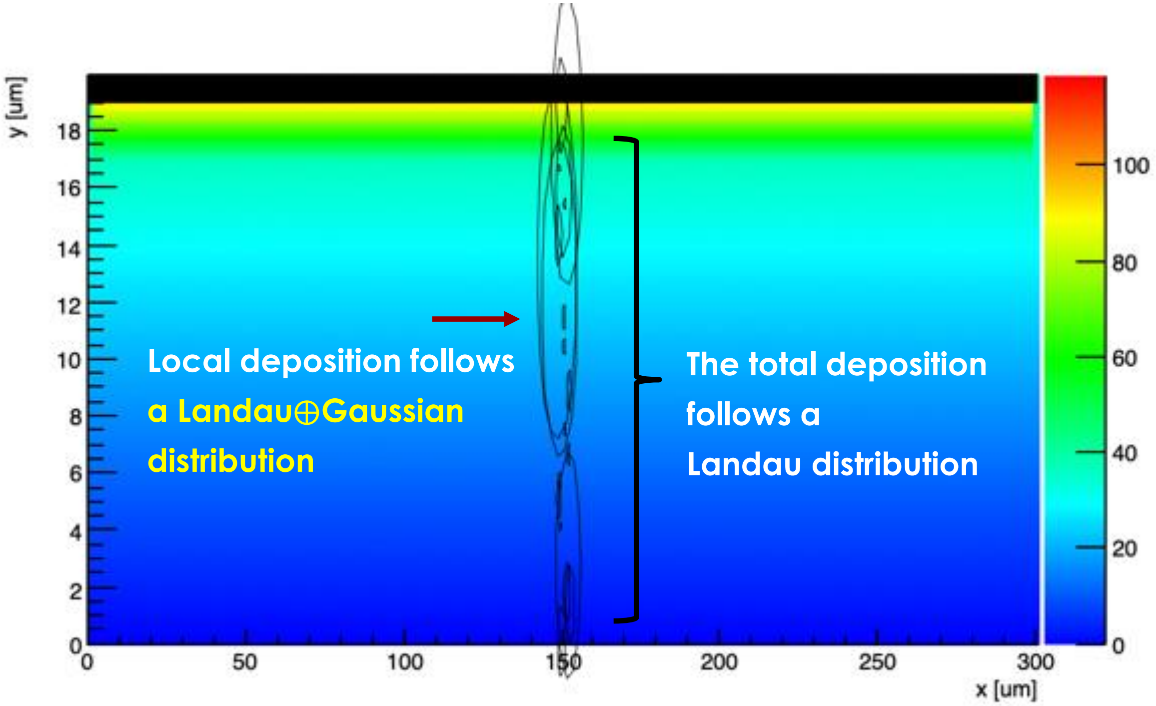


- With Gain Quench, WF2 reproduces well the evolution of the ratio Sigma/MPV.
- Without gain quench, Sigma/MPV is roughly constant, not matching the data.

Starting point of the WF2 simulation

The correct choice of the elemental distribution X is the convolution of a Landau with a Gaussian

==> This distribution is a good approximation of the Vavilov distribution, which is known to reproduce the energy deposits in thin sensors.



Local deposition follows a Landau⊕Gaussian distribution

The total deposition follows a Landau distribution

In the WF2, the energy deposition in a sensor of arbitrary thickness is therefore obtained as a sum of deposits chosen randomly from an elemental distribution, the convolution of a Landau ⊕ Gaussian.

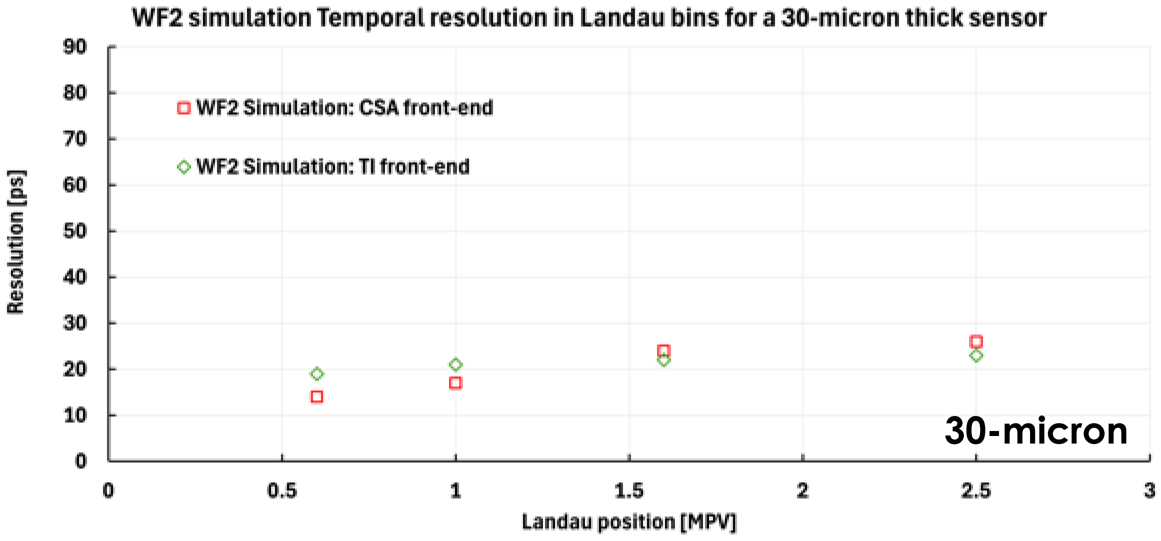
The program correctly reproduces the measured MPV and the FWHM dependence on the sensor thickness.

In the following slides, the consequences of this step will be examined

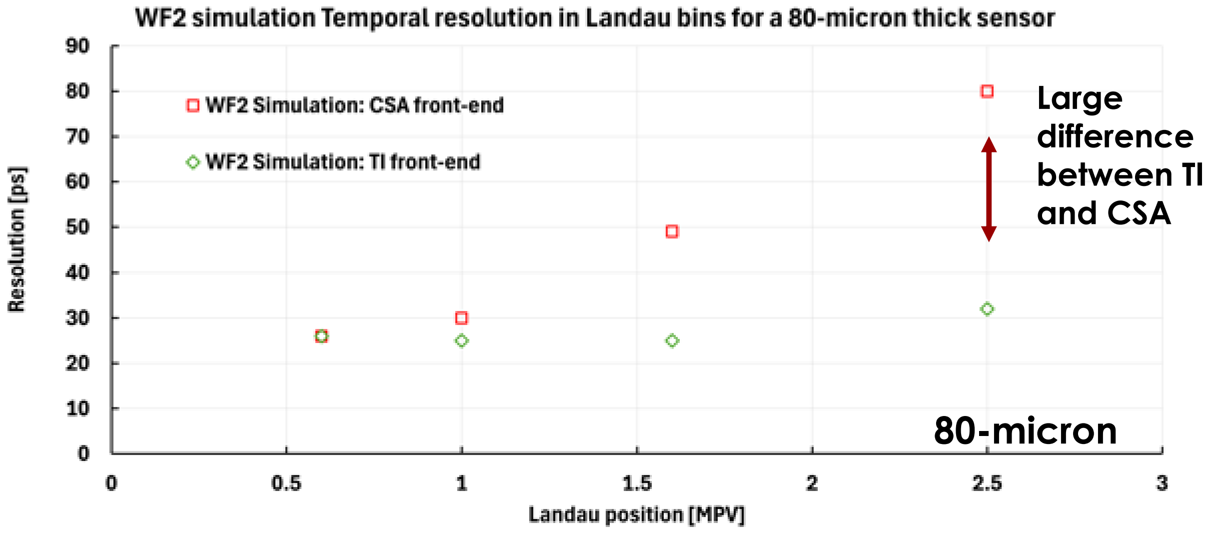
What read-out architecture is a better for LGADs?

These two plots compare the temporal resolution due to non-uniform ionization for a Trans-Impedance (TI) or Charge Sensitive Amplifier (CSA) for two different sensor thicknesses (30-micron and 80-micron).

- For signals around the MPV (regular shape), the resolution is the same
- In thin sensors (that have relatively uniform signals), the resolution is the same
- In the tail of thick sensors (irregular signals), the TI architecture is much better



WF2 simulation Temporal resolution in Landau bins for a 30-micron thick sensor



WF2 simulation Temporal resolution in Landau bins for a 80-micron thick sensor

Large difference between TI and CSA

LGAD Read-out architecture