

# Timing capabilities of Ultra-Fast Silicon Detector

- A parameterization of time resolution
- A program to calculate Time resolution
- UFSD Timing capabilities

Nicolo Cartiglia

With

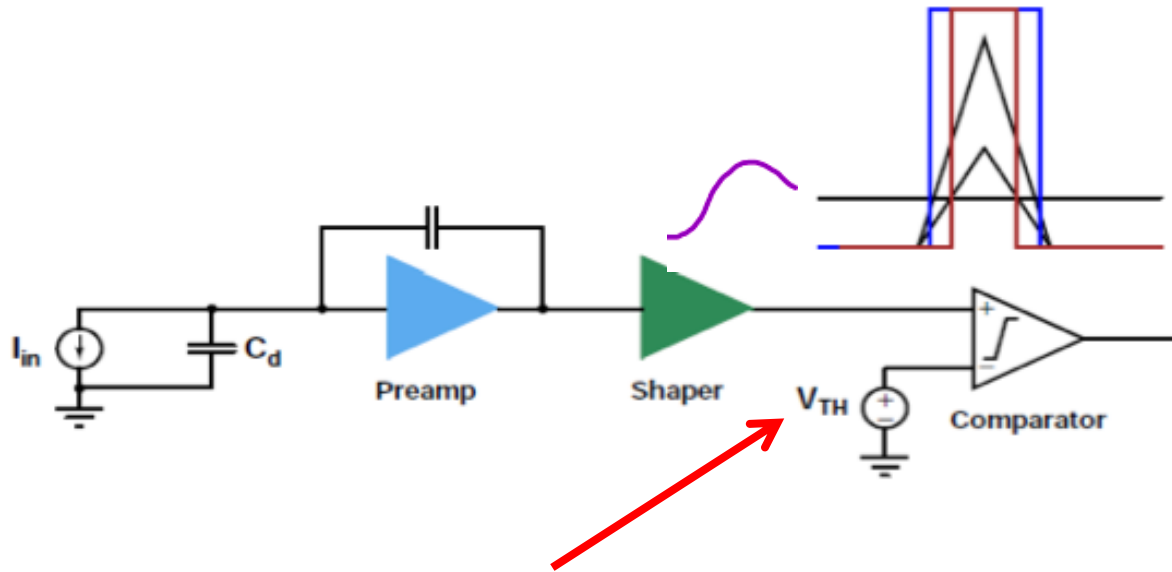
F. Cenna, F. Marchetto, A. Picerno F. Ravera, H. Sadrozinski, A. Seiden, A. Solano, A. Vinattieri, N. Spencer, A. Zatserklyaniy

# UFSD: a time-tagging detector

Sensor

Pre-Amplifier

Time measuring circuit



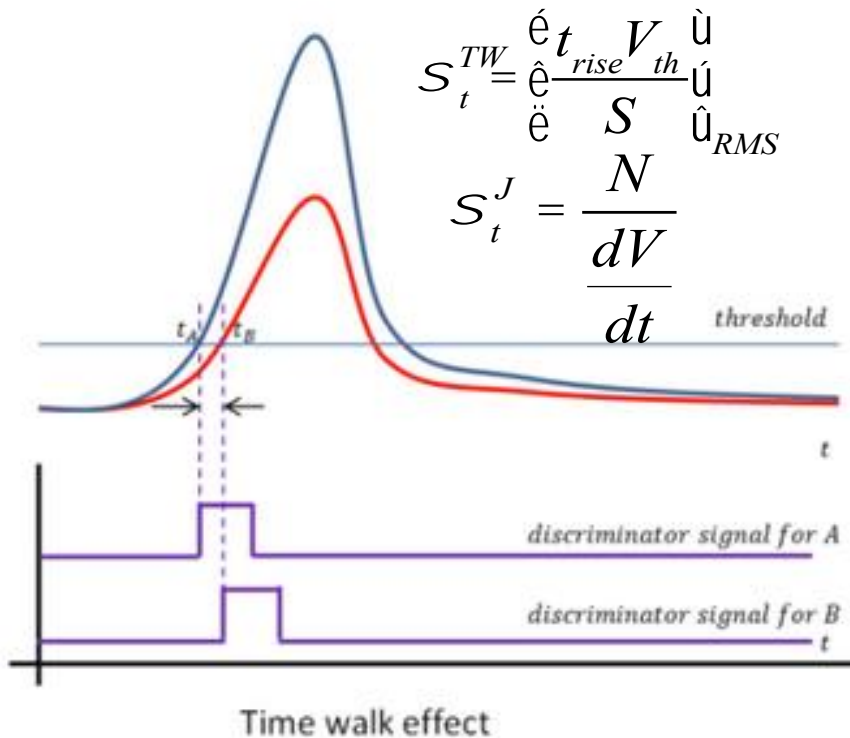
**Time is set when the signal crosses the comparator threshold**

The timing capabilities are determined by the characteristics of the signal at the output of the pre-Amplifier and by the TDC binning:

$$\sigma_{\text{Total}}^2 = \sigma_{\text{Jitter}}^2 + \sigma_{\text{Time Walk}}^2 + \sigma_{\text{TDC}}^2$$

# Time walk and Time jitter

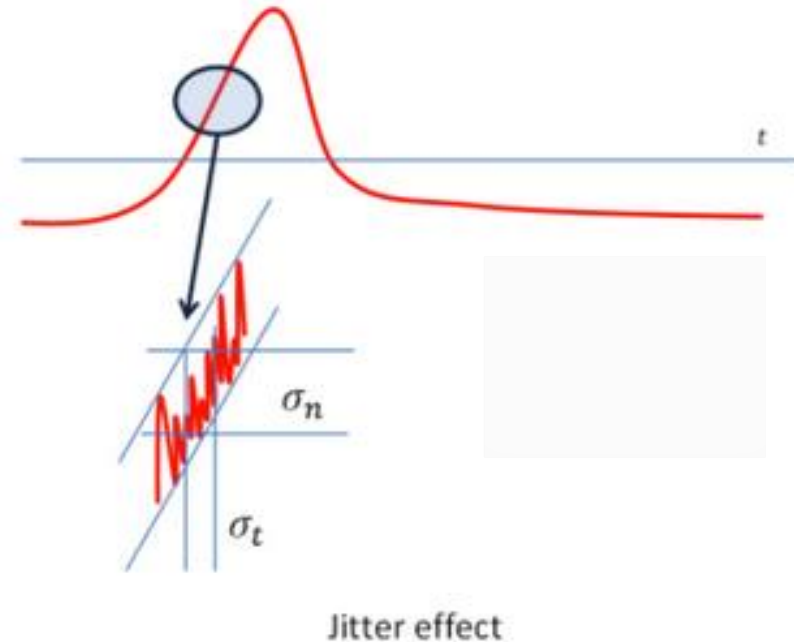
**Time walk:** the voltage value  $V_0$  is reached at different time for signal of different amplitudes



**Due to the physics of signal formation**

(see backup slides for full calculation and reduction techniques)

**Jitter:** the noise is summed to the signal, causing amplitude variations



**Mostly due to electronic noise**

(see backup slides for capacitance and noise values used)

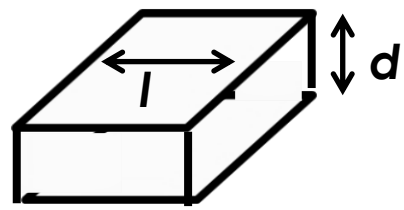
# A parameterization of $\sigma_t$

$$\sigma_t^2 = \zeta \frac{t_{rise}^2}{S/N} + \zeta \frac{t_{rise} V_{th}}{S u_{RMS}} + \zeta \frac{TDC_{bin}}{\sqrt{12}} \quad (1)$$

Jitter

Time Walk

TDC



**d:** detector thickness [micron]

**l:** pitch [micron]

**C:** Detector capacitance [fF]

Depends on the pitch and thickness

**N:** Noise at preamp.

Dominated by the voltage term

**S:** Signal

**$t_{rise}$ :** Pre-Amp Shaping time

**$V_{th}$ :** Comparator threshold

Depends on the noise level

**TDC:** Width of the TDC LSB [ps]

$$C_{Det} = \epsilon \epsilon_o \frac{l * l}{d} + 0.2 * 4l + 50$$

$$N \mu \frac{C_{Det}}{\sqrt{t_{rise}}}$$

$$V_{th} = 10 * N$$

$$LSB = 20$$

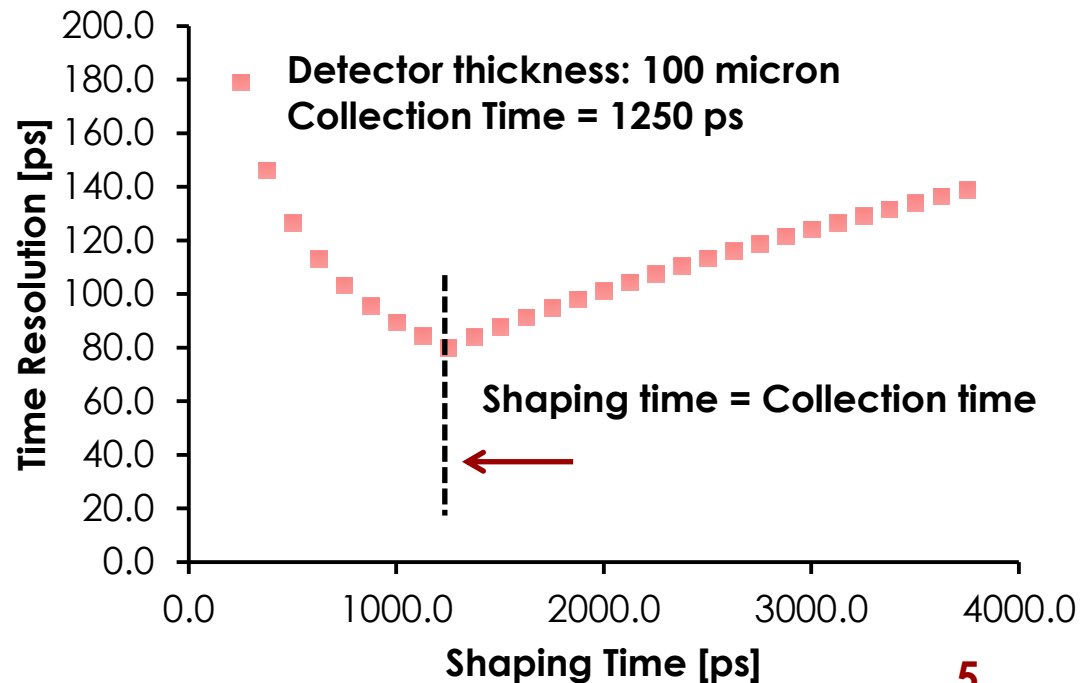
# What is the best shaping time ( $t_{rise}$ ) ?

$$S \propto \begin{cases} N \propto \frac{C_{Det}}{\sqrt{t_{rise}}} \\ t_{rise} \xrightarrow{\text{if}} t_{rise} \leq t_{col} \\ Const \xrightarrow{\text{if}} t_{rise} > t_{col} \\ V_{th} \propto N \end{cases} \Rightarrow S_t \propto \begin{cases} \frac{C_{det}}{\sqrt{t_{rise}}} \xrightarrow{\text{if}} t_{rise} \leq t_{col} \\ C_{det} * \sqrt{t_{rise}} \xrightarrow{\text{if}} t_{rise} > t_{col} \end{cases}$$

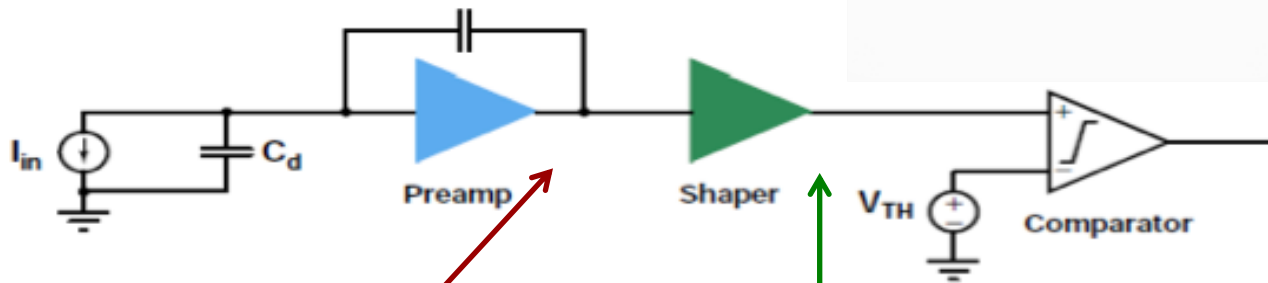
To minimize time resolution:

$$t_{rise} \sim t_{col}$$

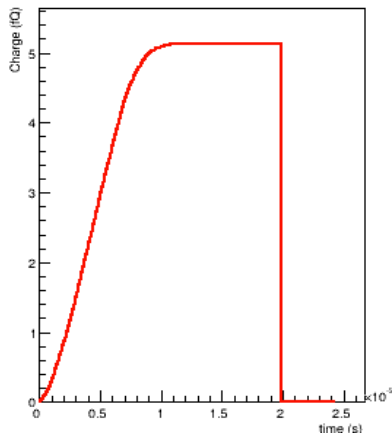
**Note:** This value also minimizes fake signals in neighboring pixels.



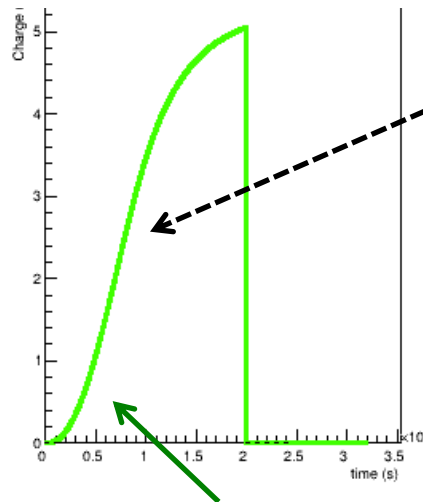
# Where to set the threshold



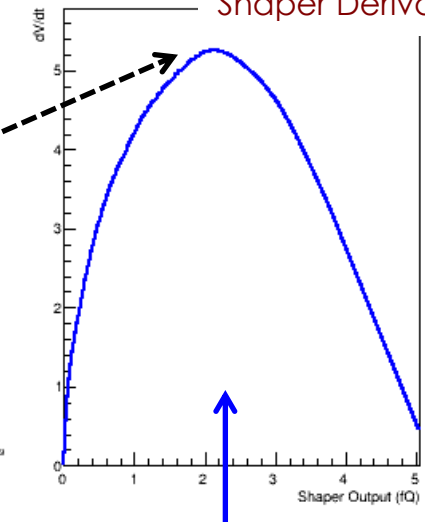
Charge Sensitive Amplifier output



Shaper Signal



Shaper Derivative



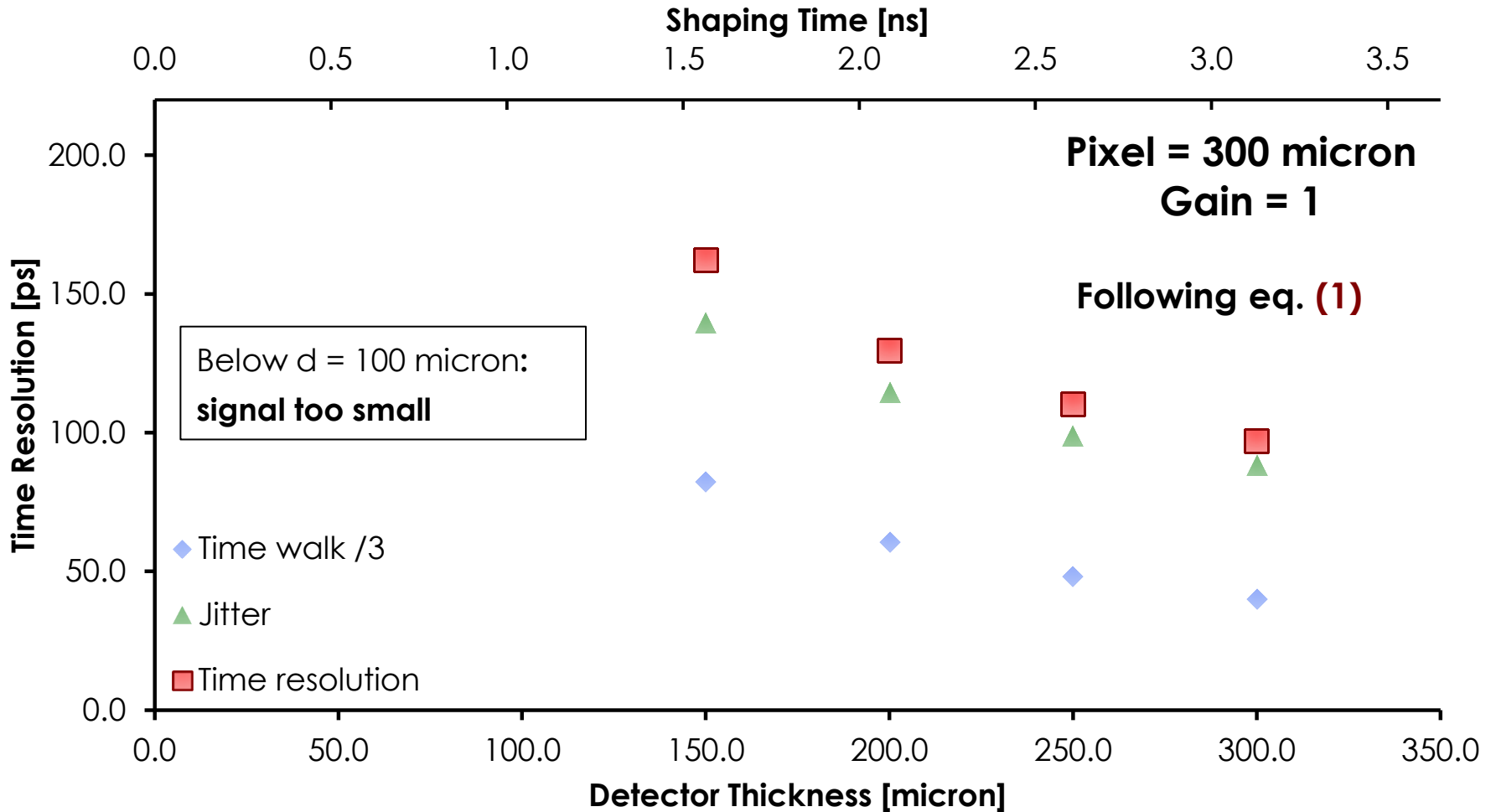
How to minimize  
Time Walk and Jitter:  
**Compromise!**

**Time Walk:**  
set the threshold  
at the minimum  
possible value

**Jitter:** set the  
threshold at the  
maximum derivative

$$S_t^J = \frac{N}{\frac{dV}{dt}}$$

# State of the Art



**Best resolution achievable: ~ 100 ps**  
(assuming Time Walk reduction of ~ 3)

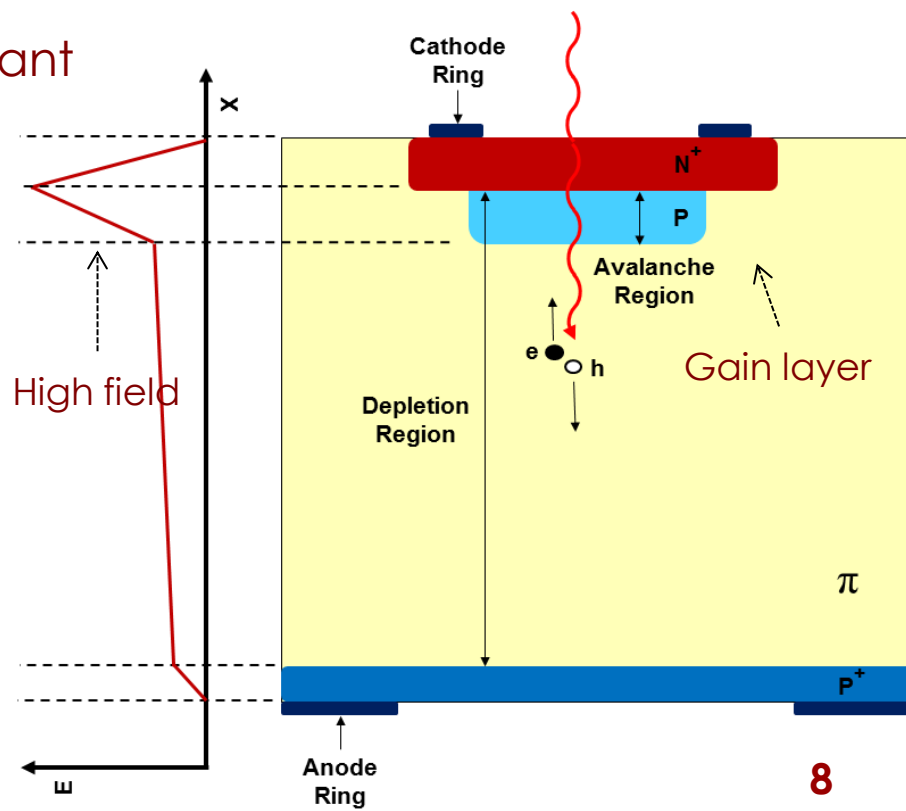
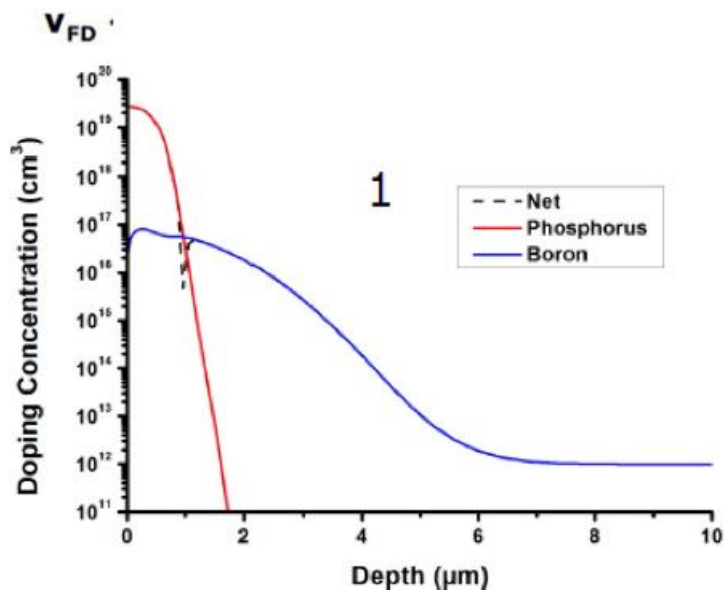
# Sensor: Ultra-Fast Silicon Detector

UFSD: pixelated silicon detector with internal gain

**Main point:** boost the signal

- Minimize jitter and TW
- Allows for very thin detector

**UFSD gain:** Add an extra deep p+ implant



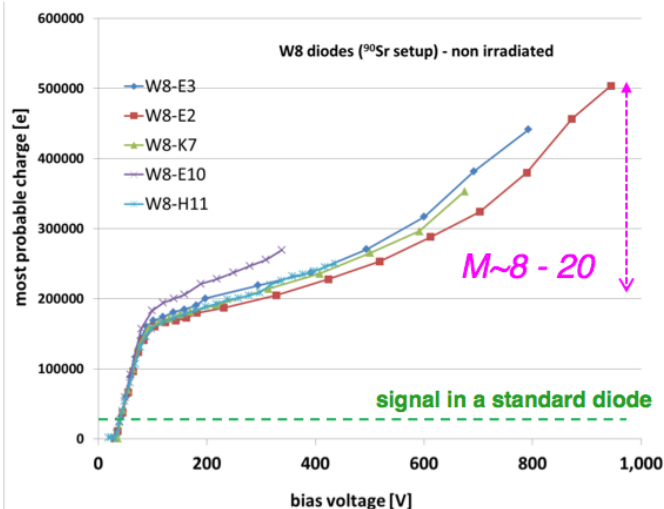
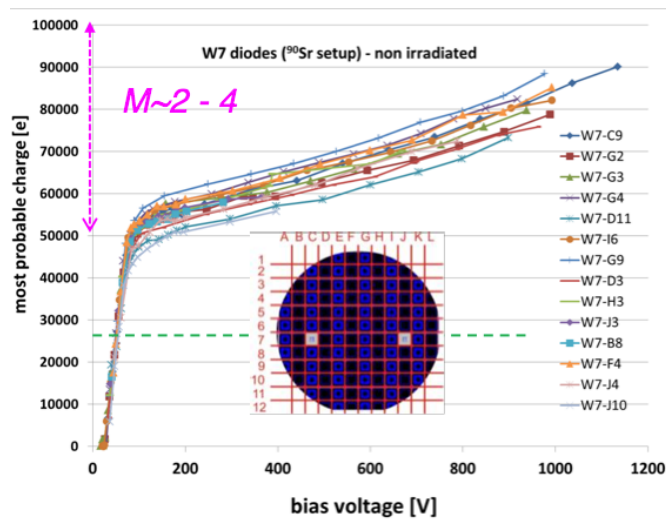


# Sensor: Status

Presented at the 9<sup>th</sup>  
Trento Workshop, 2014 Genova

**Measured Gain: 2-10**

The LGAD diodes processed by CNM exhibit good gain  $M_Q \sim 3-10$  and uniform multiplication over the diode surface.



Wafers have different gains:

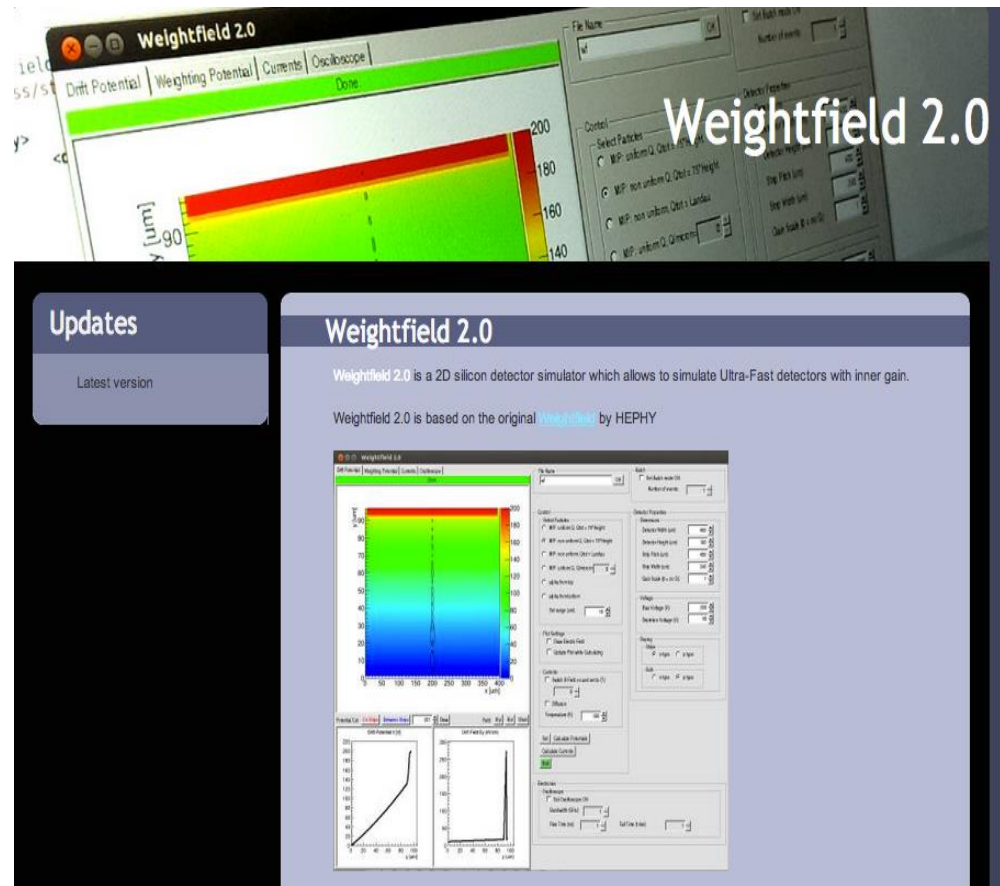
- Good uniformity of gain over the wafer
- Very good stability of some diodes up to >1000 V.
- For W8 samples the gain at >900 V is difficult to measure – amplifier saturates due to too large signals – note steeper increase of gain for  $U > 500V$ .

# Sensor: Simulation

We developed a full sensor simulation (WeightField2, F. Cenna, 9<sup>th</sup> Trento workshop) available at <http://personalpages.to.infn.it/~cartigli/weightfield2>

## It includes:

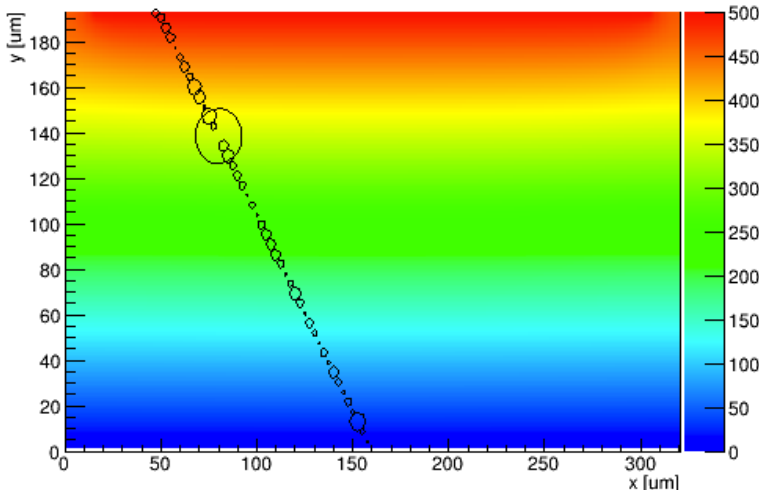
- Custom Geometry
- Calculation of drift field and weighting field
- Currents signal via Ramo's Theorem
- Gain
- Diffusion
- Temperature effect
- Non-uniform charge deposition
- Electronics



# WeightField2: a program to simulate silicon detectors

Drift Potential | Weighting Potential | Currents and Oscilloscope | Electronics

Done.



Control

Select Particles

- MIP: uniform Q, Qtot = 75\*Height
- MIP: non uniform Q, Qtot = 75\*Height
- MIP: non uniform, Qtot = Landau
- MIP: uniform Q, Q/micron=
- alpha from top
- alpha from bottom

Set range (um):

Plot Settings

- Draw Electric Field
- Update Plot while Calculating

Currents

- Switch B-Field on and set to (T):
- Diffusion
- Temperature (K):

Set Calculate Potentials

Calculate Currents Stop

Exit

Batch

- Set Batch mode ON
- Number of events:

Detector Properties

Dimensions

- Detector Width (um):
- Detector Height (um):
- Strip Pitch (um):
- Strip Width (um):
- Gain Scale (1 = no G):

Voltage

- Bias Voltage (V):
- Depletion Voltage (V):

Doping

Strips

- n-type  p-type

Bulk

- n-type  p-type

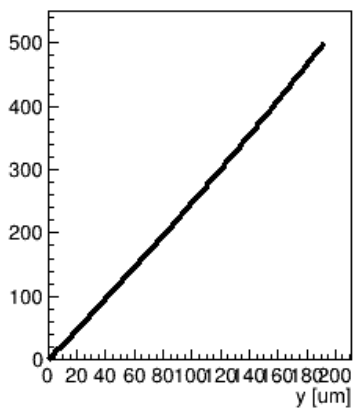
Electronics

- ON
- Oscilloscope BW (GHz):
- Shaper Int. Time (ns):
- Shaper Decay Time (ns):
- Vth (in noise unit):

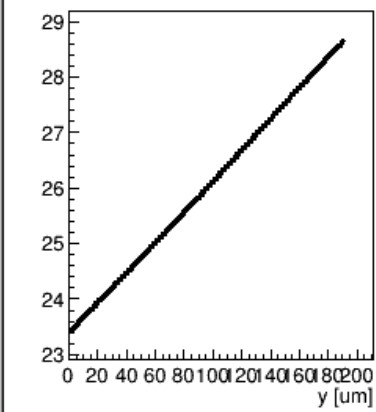
Potential Cut:  On Strips  Between Strips  Draw

Field:  |Ey|  |Ex|  |Etot|

Drift Potential V [V]



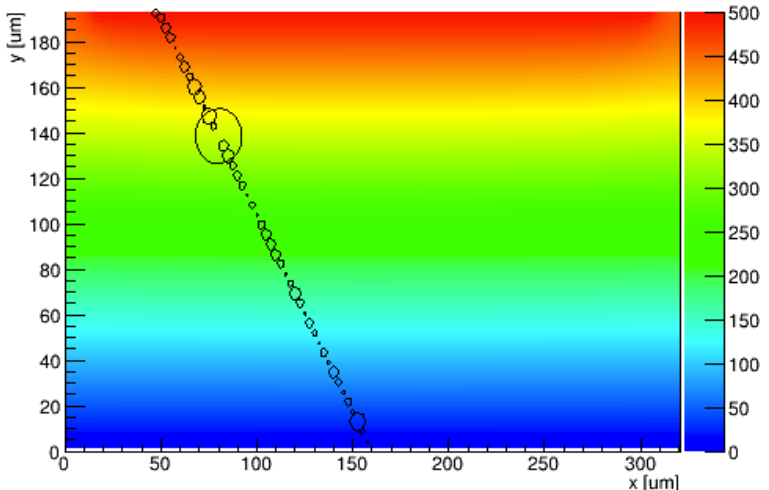
Drift Field E (kV/cm)



# WeightField2: a program to simulate silicon detectors

Drift Potential | Weighting Potential | Currents and Oscilloscope | Electronics

Done.



Control

Select Particles

- MIP: uniform Q, Qtot = 75\*Height
- MIP: non uniform Q, Qtot = 75\*Height
- MIP: non uniform, Qtot = Landau
- MIP: uniform Q, Q/micron=
- alpha from top
- alpha from bottom

Set range (um):

Plot Settings

- Draw Electric Field
- Update Plot while Calculating

Currents

- Switch B-Field on and set to (T):
- Diffusion
- Temperature (K):

Set Calculate Potentials

Calculate Currents Stop

Exit

Batch

- Set Batch mode ON
- Number of events:

Detector Properties

Dimensions

- Detector Width (um):
- Detector Height (um):
- Strip Pitch (um):
- Strip Width (um):
- Gain Scale (1 = no G):

Voltage

- Bias Voltage (V):
- Depletion Voltage (V):

Doping

Strips

- n-type  p-type

Bulk

- n-type  p-type

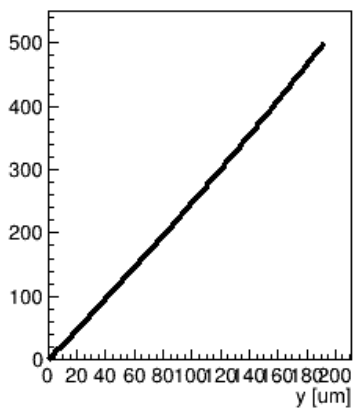
Electronics

- ON
- Oscilloscope BW (GHz):
- Shaper Int. Time (ns):
- Shaper Decay Time (ns):
- Vth (in noise unit):

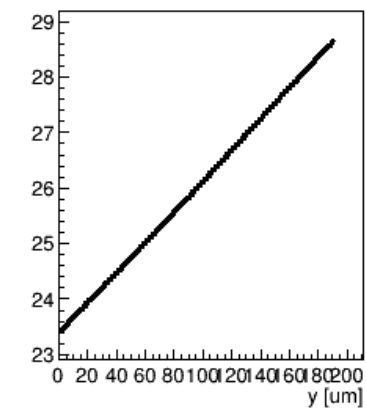
Potential Cut:  On Strips  Between Strips  Draw

Field:  |Ey|  |Ex|  |Etot|

Drift Potential V [V]



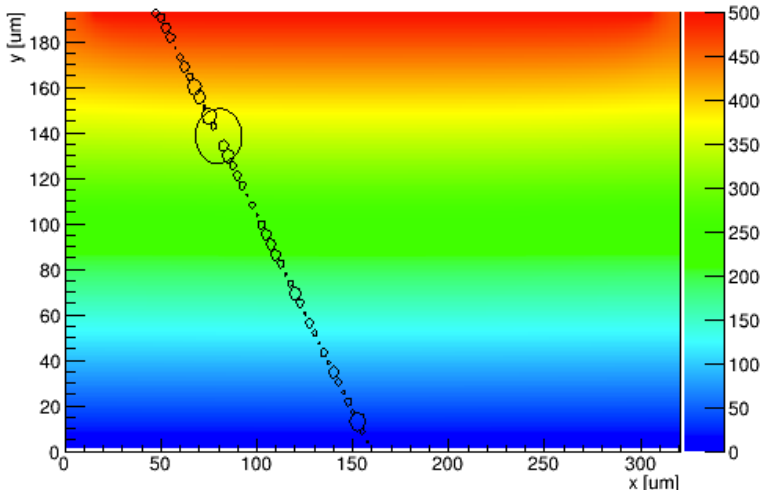
Drift Field E (kV/cm)



# WeightField2: a program to simulate silicon detectors

Drift Potential | Weighting Potential | Currents and Oscilloscope | Electronics

Done.



Control

Select Particles

- MIP: uniform Q, Qtot = 75\*Height
- MIP: non uniform Q, Qtot = 75\*Height
- MIP: non uniform, Qtot = Landau
- MIP: uniform Q, Q/micron =
- alpha from top
- alpha from bottom

Set range (um):

Plot Settings

- Draw Electric Field
- Update Plot while Calculating

Currents

- Switch B-Field on and set to (T):
- Diffusion
- Temperature (K):

Set Calculate Potentials

Calculate Currents Stop

Exit

Batch

- Set Batch mode ON
- Number of events:

Detector Properties

Dimensions

- Detector Width (um):
- Detector Height (um):
- Strip Pitch (um):
- Strip Width (um):
- Gain Scale (1 = no G):

Voltage

- Bias Voltage (V):
- Depletion Voltage (V):

Doping

Strips

- n-type  p-type

Bulk

- n-type  p-type

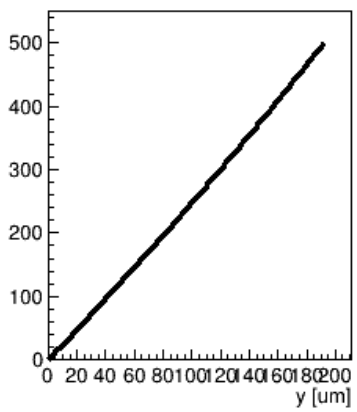
Electronics

- ON
- Oscilloscope BW (GHz):
- Shaper Int. Time (ns):
- Shaper Decay Time (ns):
- Vth (in noise unit):

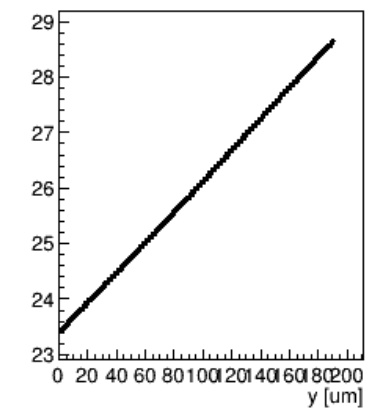
Potential Cut:  On Strips  Between Strips  Draw

Field:  |Ey|  |Ex|  |Etot|

Drift Potential V [V]



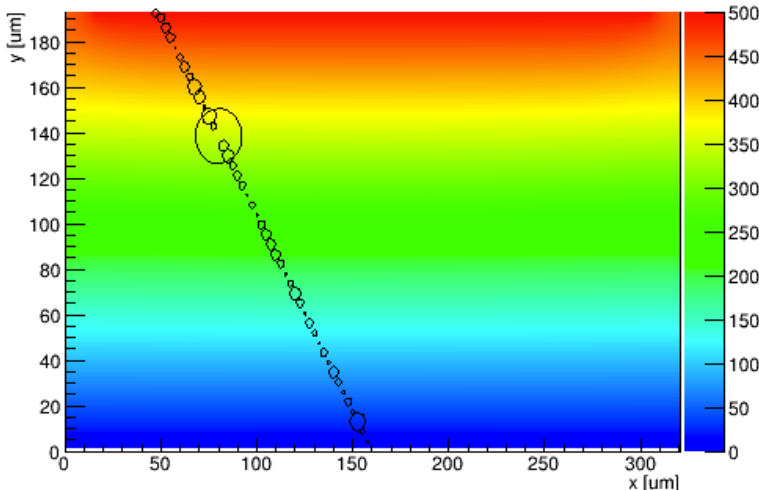
Drift Field E (kV/cm)



# WeightField2: a program to simulate silicon detectors

Drift Potential | Weighting Potential | Currents and Oscilloscope | Electronics

Done.



Control

Select Particles

- MIP: uniform Q, Qtot = 75\*Height
- MIP: non uniform Q, Qtot = 75\*Height
- MIP: non uniform, Qtot = Landau
- MIP: uniform Q, Q/micron=
- alpha from top
- alpha from bottom

Set range (um):

Plot Settings

- Draw Electric Field
- Update Plot while Calculating

Currents

- Switch B-Field on and set to (T):
- Diffusion
- Temperature (K):

Set Calculate Potentials

Calculate Currents Stop

Exit

Batch

- Set Batch mode ON
- Number of events:

Detector Properties

Dimensions

- Detector Width (um):
- Detector Height (um):
- Strip Pitch (um):
- Strip Width (um):
- Gain Scale (1 = no G):

Voltage

- Bias Voltage (V):
- Depletion Voltage (V):

Doping

Strips

- n-type  p-type

Bulk

- n-type  p-type

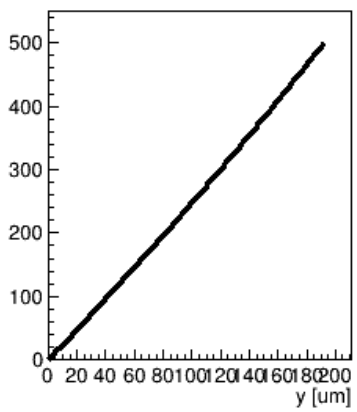
Electronics

- ON
- Oscilloscope BW (GHz):
- Shaper Int. Time (ns):
- Shaper Decay Time (ns):
- Vth (in noise unit):

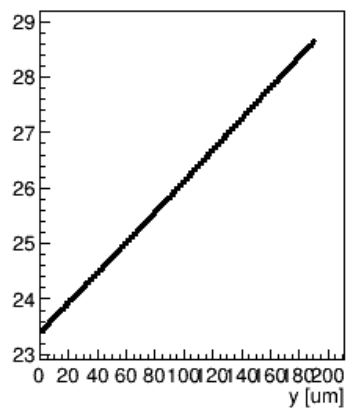
Potential Cut:  On Strips  Between Strips  Draw

Field:  |Ey|  |Ex|  |Etot|

Drift Potential V [V]



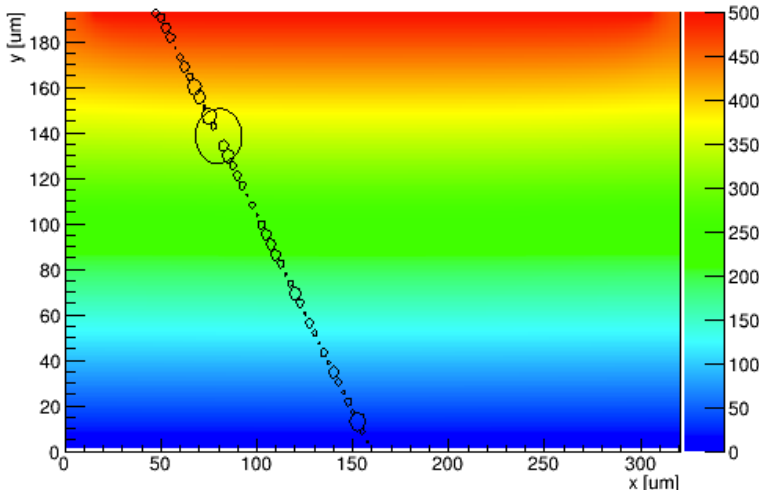
Drift Field E (kV/cm)



# WeightField2: a program to simulate silicon detectors

Drift Potential | Weighting Potential | Currents and Oscilloscope | Electronics

Done.



Control

Select Particles

- MIP: uniform Q, Qtot = 75\*Height
- MIP: non uniform Q, Qtot = 75\*Height
- MIP: non uniform, Qtot = Landau
- MIP: uniform Q, Q/micron=
- alpha from top
- alpha from bottom

Set range (um):

Plot Settings

- Draw Electric Field
- Update Plot while Calculating

Detector Properties

Dimensions

- Detector Width (um):
- Detector Height (um):
- Strip Pitch (um):
- Strip Width (um):
- Gain Scale (1 = no G):

Voltage

- Bias Voltage (V):
- Depletion Voltage (V):

Doping

Strips

- n-type  p-type

Bulk

- n-type  p-type

Electronics

- ON
- Oscilloscope BW (GHz):
- Shaper Int. Time (ns):
- Shaper Decay Time (ns):
- Vth (in noise unit):

File Name:   ON

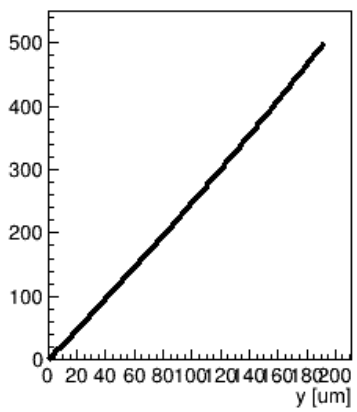
Batch

- Set Batch mode ON
- Number of events:

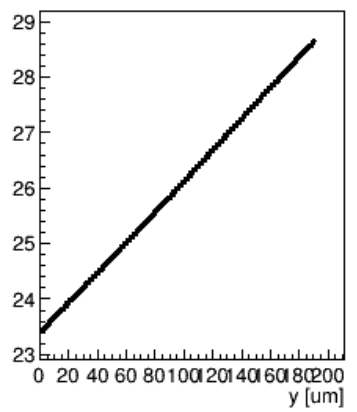
Potential Cut:  On Strips  Between Strips  Draw

Field:  |Ey|  |Ex|  |Etot|

Drift Potential V [V]



Drift Field E (kV/cm)



Currents

- Switch B-Field on and set to (T):
- Diffusion
- Temperature (K):

Set Calculate Potentials

Calculate Currents Stop

Exit

# WeightField2: a program to simulate silicon detectors

Weightfield 2.0

Drift Potential | Weighting Potential | **Currents and Oscilloscope** | Electronics

File Name: wf  ON

Batch:  Set Batch mode ON  
Number of events: 1

Control

Select Particles

- MIP: uniform Q, Qtot = 75\*Height
- MIP: non uniform Q, Qtot = 75\*Height
- MIP: non uniform, Qtot = Landau
- MIP: uniform Q, Q/micron = 75
- alpha from top
- alpha from bottom

Set range (um): 10

Plot Settings

- Draw Electric Field
- Update Plot while Calculating

Currents

- Switch B-Field on and set to (T): 0
- Diffusion
- Temperature (K): 300

Detector Properties

Dimensions

- Detector Width (um): 300
- Detector Height (um): 200
- Strip Pitch (um): 300
- Strip Width (um): 290
- Gain Scale (1 = no G): 1

Voltage

- Bias Voltage (V): 500
- Depletion Voltage (V): 50

Doping

Strips:  n-type  p-type

Bulk:  n-type  p-type

Electronics

- ON
- Oscilloscope BW (GHz): 1
- Shaper Int. Time (ns): 5.5
- Shaper Decay Time (ns): 9
- Vth (in noise unit): 10

Particle hits Detector at: 160 Angle (deg): 30

Charge Collection

e- charges (e): 6645	h+ charges (e): 8064	e- + h+ charges (e): 14709
Gain e- charges (e): 0	Gain h+ charges (e): 0	Gain e- + h+ charges (e): 0
Total e- charges (e): 6645	Total h+ charges (e): 8064	Total Charges (e): 14709

Lorentz Drift

e- Lorentz Angle (degree): 0.00	h+ Lorentz Angle (degree): 0.00
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Electrons Gain El. Holes Gain Holes Total

3.33

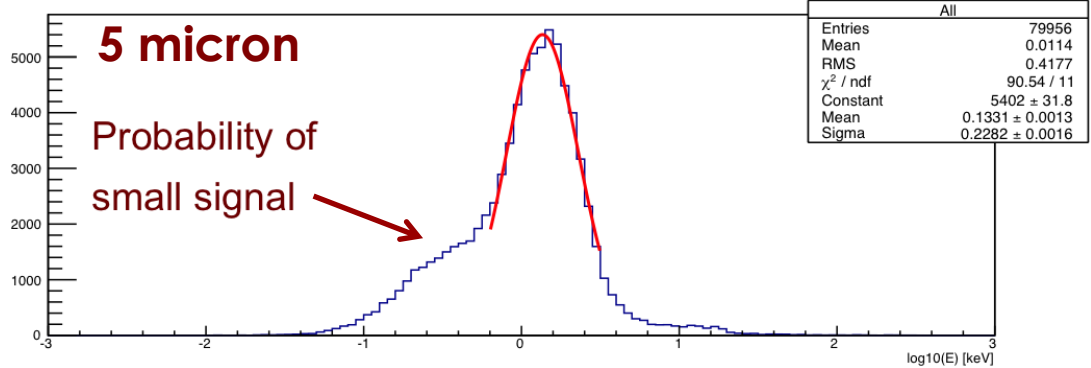
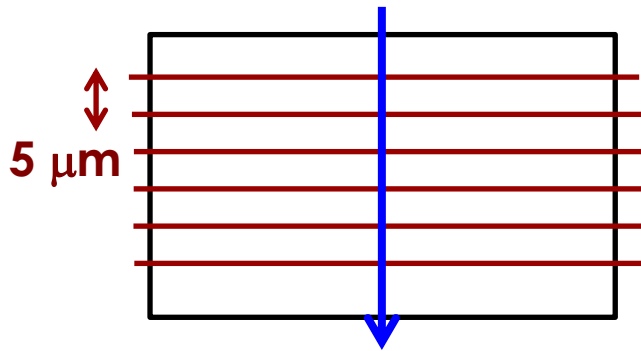
Set Calculate Potentials

Calculate Currents Stop

Exit

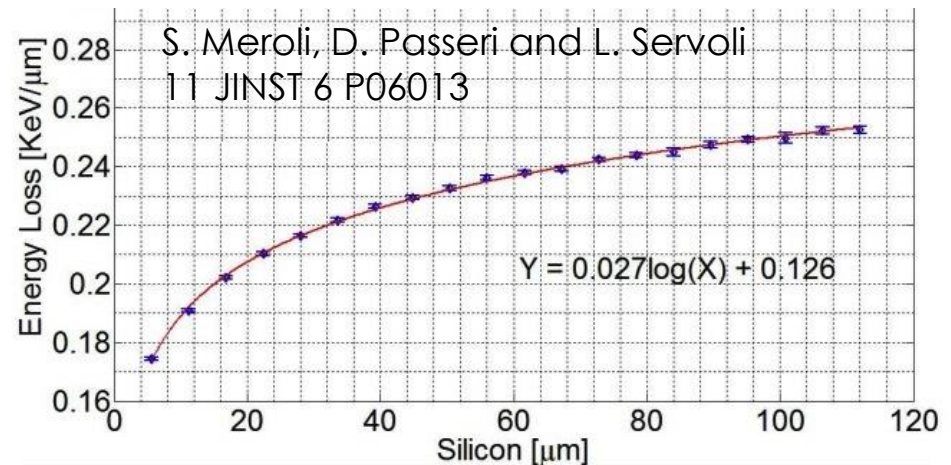
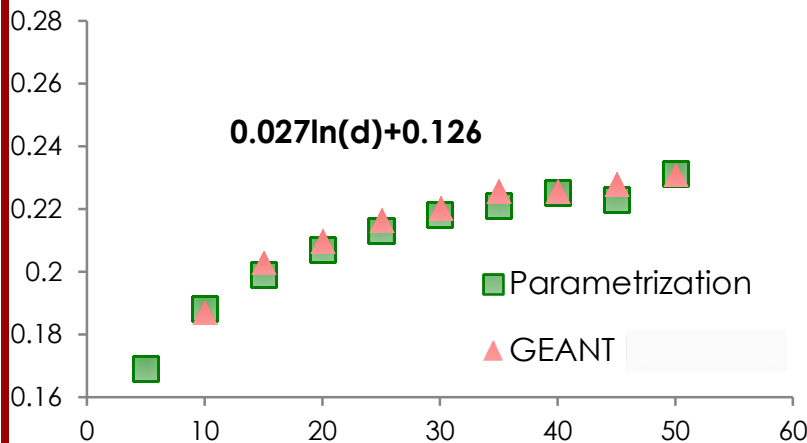


# Aside: Non-Uniform Energy deposition



We have created, using GEANT4, a library of the energy depositions of a MIP in silicon, every 5 micron. Using this library, we can predict the value in any thickness

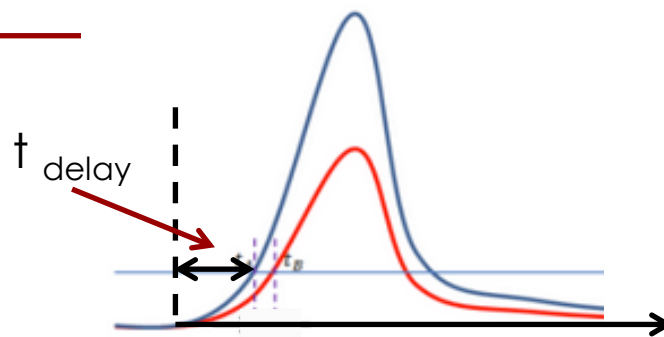
Comparison with the measurement presented in 2011 JINST 6 P06013



# Time walk

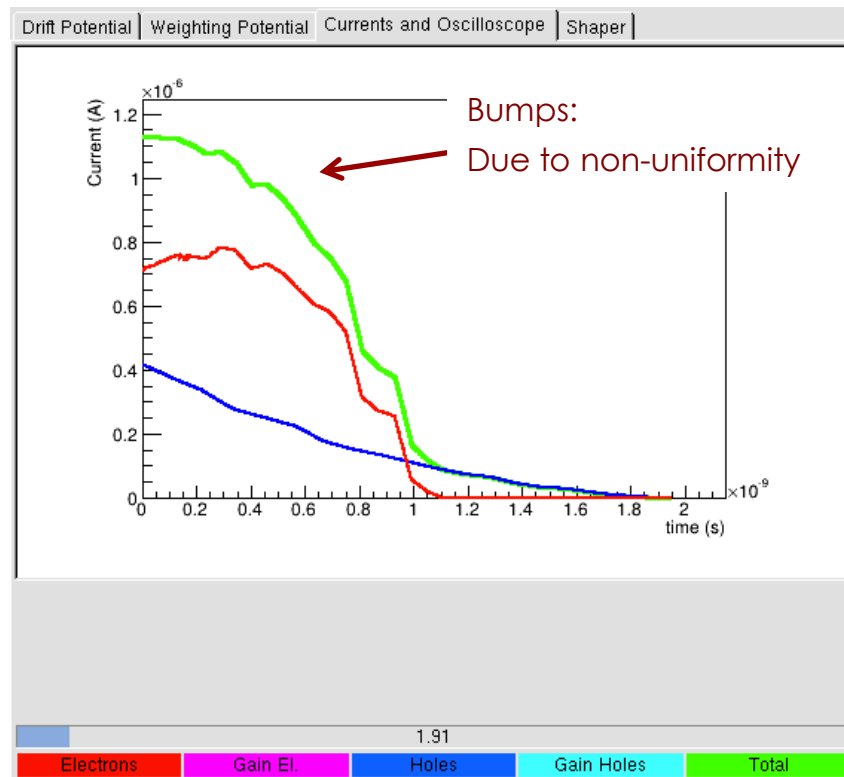
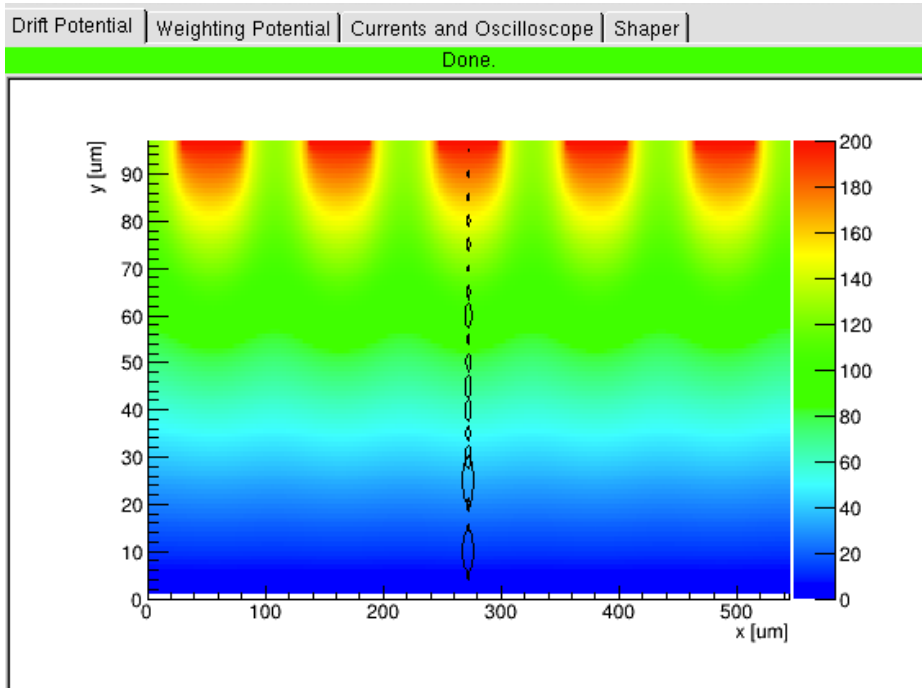
Signals cross a given threshold with a delay that depends on their amplitude, on the rise time and on the value of the threshold:

$$t_{\text{delay}} = t_{\text{rise}} \frac{V_{\text{th}}}{V}$$



Time walk has 2 different source:

1. Amplitude variation (Landau distributed)
2. Non-uniformity charge deposition

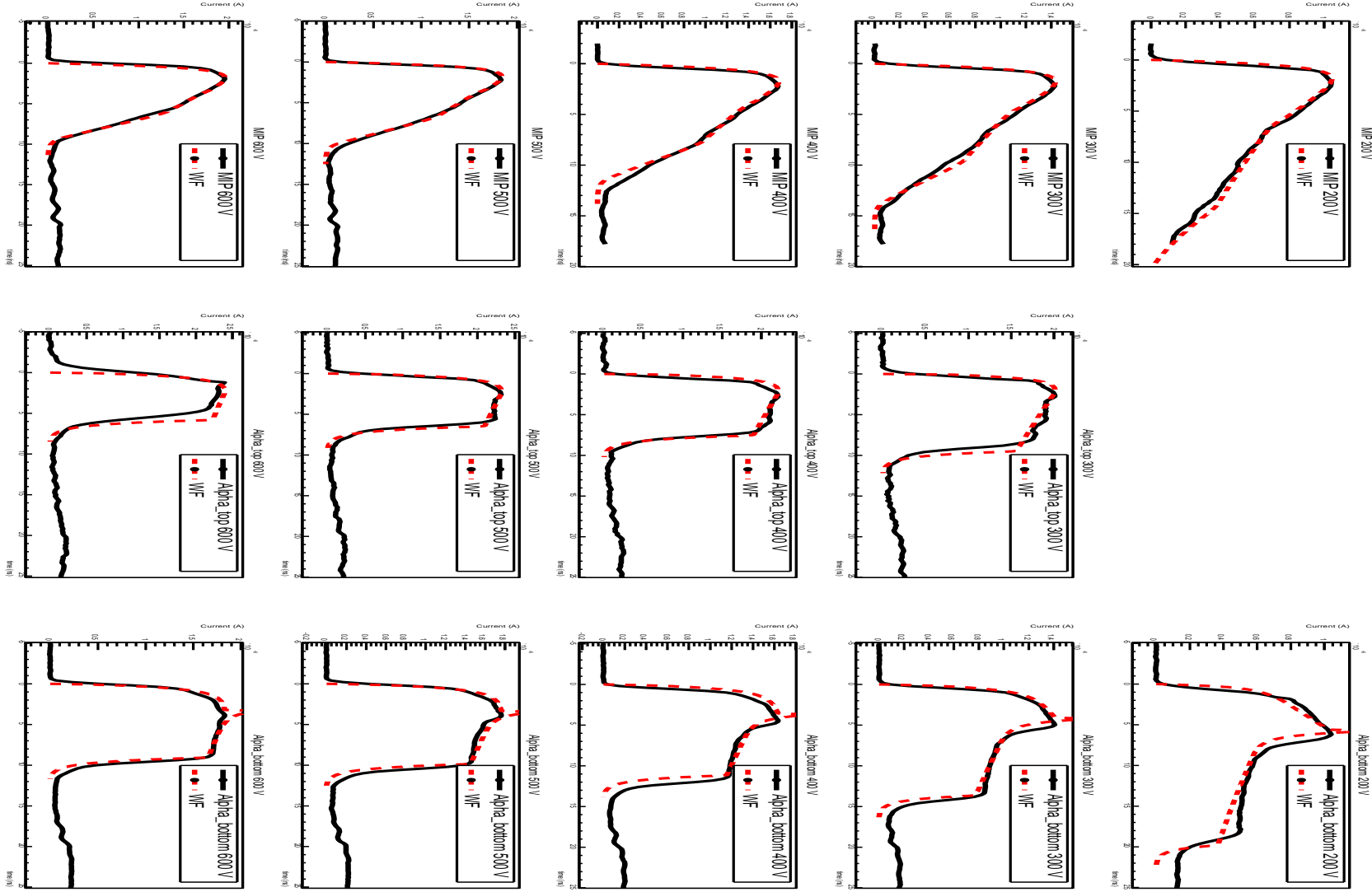


# Comparison Data-Simulation

MIP

Alpha from Top

Alpha from bottom

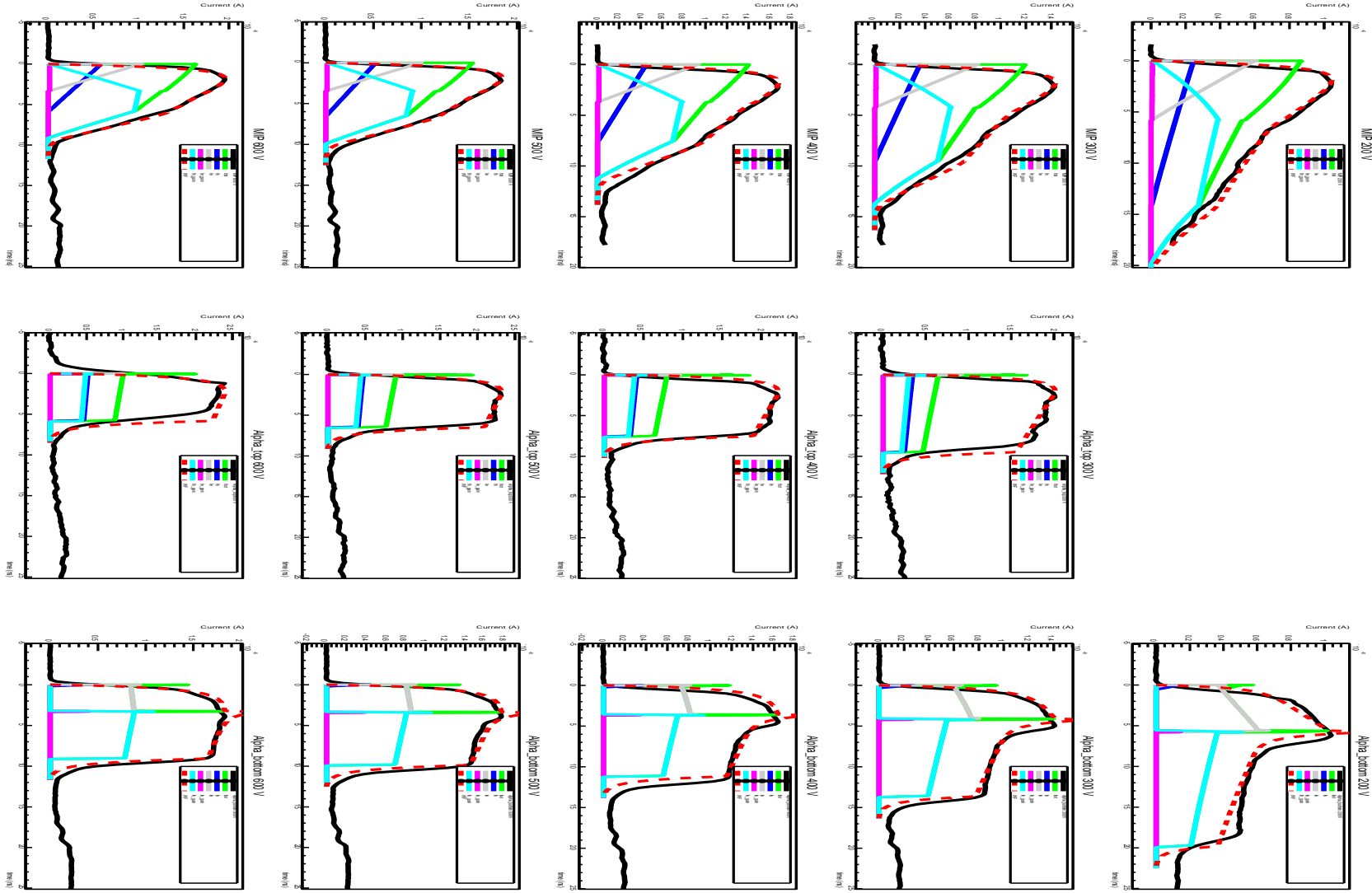


# Comparison Data Simulation

MIP

Alpha from Top

Alpha from bottom



# Simulation prediction

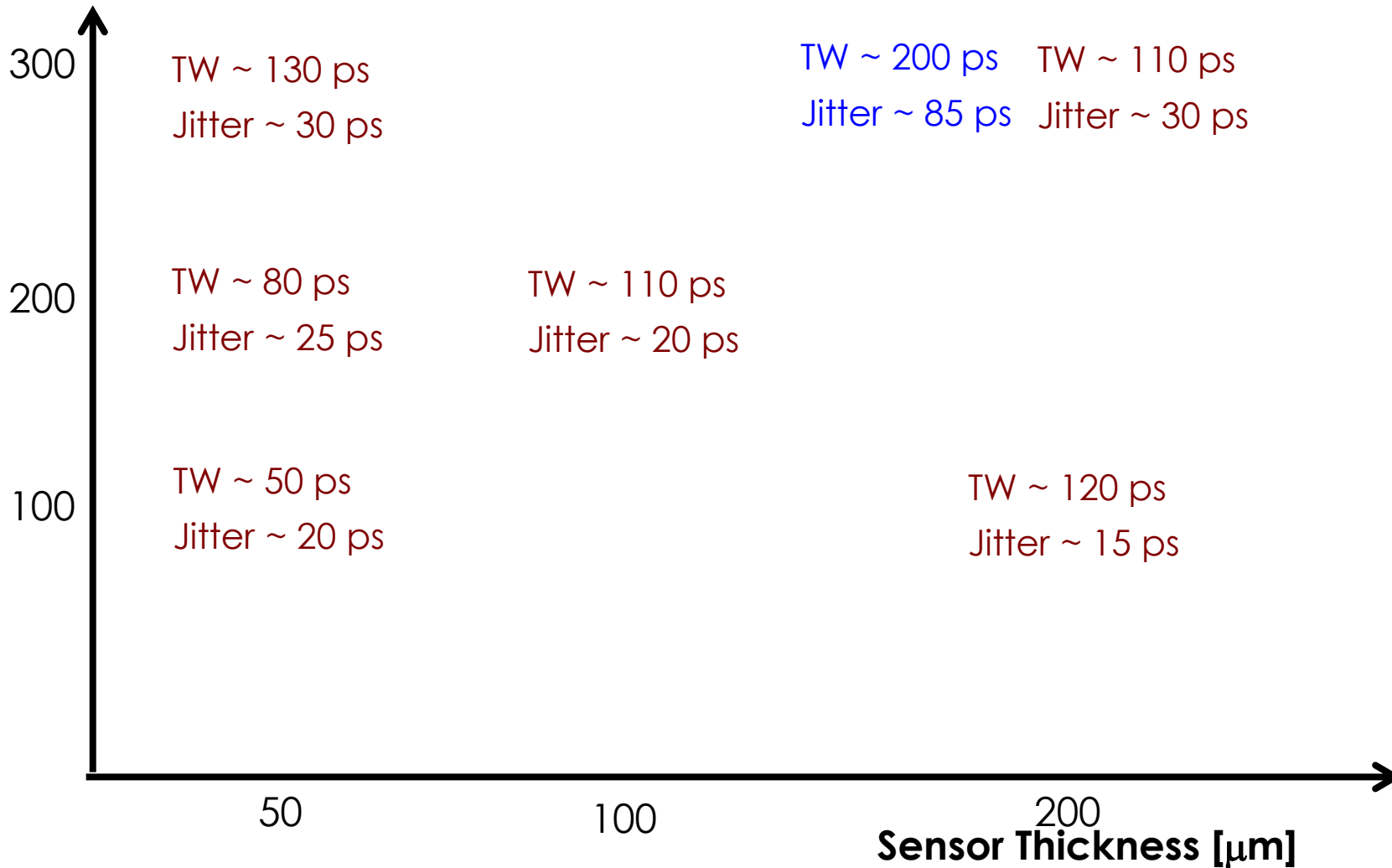
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Using **Weightfield** we are able to simulate many geometries, and to predict the timing capabilities of UFSD.

**NOTE:** We simulate the value of TimeWalk without any correction. Constant Fraction Discriminator and Time-Over-Threshold circuits are able to reduce this component by a large fraction (3-10)

# UFSD – Timing Capability

Pixel size [ $\mu\text{m}$ ]



UFSD with Gain = 10

Blue = NA62

# UFSD – Summary

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We are just starting to understand the timing capability of UFSD

The internal gain of UFSD makes them ideal for accurate timing studies

We developed a program, **Weightfield2.0**, that is able to reproduce accurately the output response of UFSD

(available at <http://personalpages.to.infn.it/~cartigli/Weightfield2.0/>)

Many geometries allow for small jitter (~20 ps) and TimeWalk (~ 100 ps)

**10 ps looks really difficult, 20 ps looks 1/4 as difficult, 30 ps 1/9 ...**

# References

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Several talks at the 22<sup>nd</sup> and 23<sup>rd</sup> RD50 Workshops:

23<sup>rd</sup> RD50: <https://indico.cern.ch/event/265941/other-view?view=standard>

22<sup>nd</sup> RD50: [http://panda.unm.edu/RD50\\_Workshop/](http://panda.unm.edu/RD50_Workshop/)

9<sup>th</sup> Trento Workshop, Genova, Feb 2014.

F. Cenna “**Simulation of Ultra-Fast Silicon Detectors**”

N. Cartiglia “**Timing capabilities of Ultra-Fast Silicon Detector**”

Papers:

[1] N. Cartiglia, **Ultra-Fast Silicon Detector**, 13th Topical Seminar on Innovative Particle and Radiation Detectors (IPRD13), 2014 JINST 9 C02001, <http://arxiv.org/abs/1312.1080>

[2] H. Sadrozinski, N. Cartiglia et al., **Ultra-fast Silicon Detectors**, NIM-A, RESMDD12 proceeding (2012), Firenze, <http://dx.doi.org/10.1016/j.nima.2013.06.033>