# Time Resolution of UFSD

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- Basics of Timing Resolution and Simulation
- Laser measurements of LGAD
- Beam Test with 300µm LGAD
  - Importance of Pulse Shapes
  - Importance of LGAD capacitance
- Extrapolation to thin LGAD with Weightfield2

# Time Resolution and Slew Rate

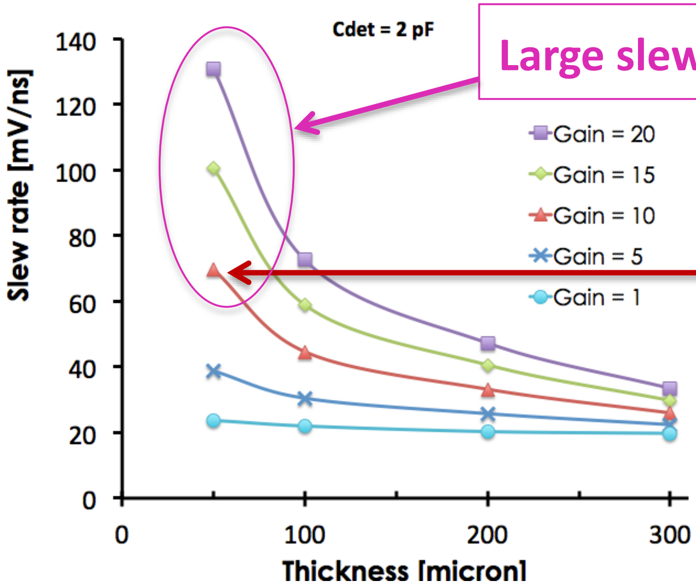
The time resolution $\sigma_t$ depends on the rise time $\tau_r$ i.e. the collection time (~ detector thickness) and signal amplitude S. It has 3 terms:
**time walk** due to amplitude variation, **time jitter** due to noise N, and **binning** resolution:

$$\sigma_t^2 = \left(\left[\tau_r \frac{V_{th}}{S}\right]_{RMS}\right)^2 + \left(\tau_r \frac{1}{S/N}\right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2 \Rightarrow \sigma_t^2 = \left(\left[\frac{V_{th}}{dV/dt}\right]_{RMS}\right)^2 + \left(\frac{N}{dV/dt}\right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2$$

introducing the **slew-rate signal/rise time $S/\tau_r$ = dV/dt.**

For constant noise N, to minimize the time resolution, we need to maximize the slew-rate dV/dt of the signal. **Need both large and fast signals.**

## Dependence of the slew-rate dV/dt on the LGAD thickness and gain




Large slew rate, good time resolution

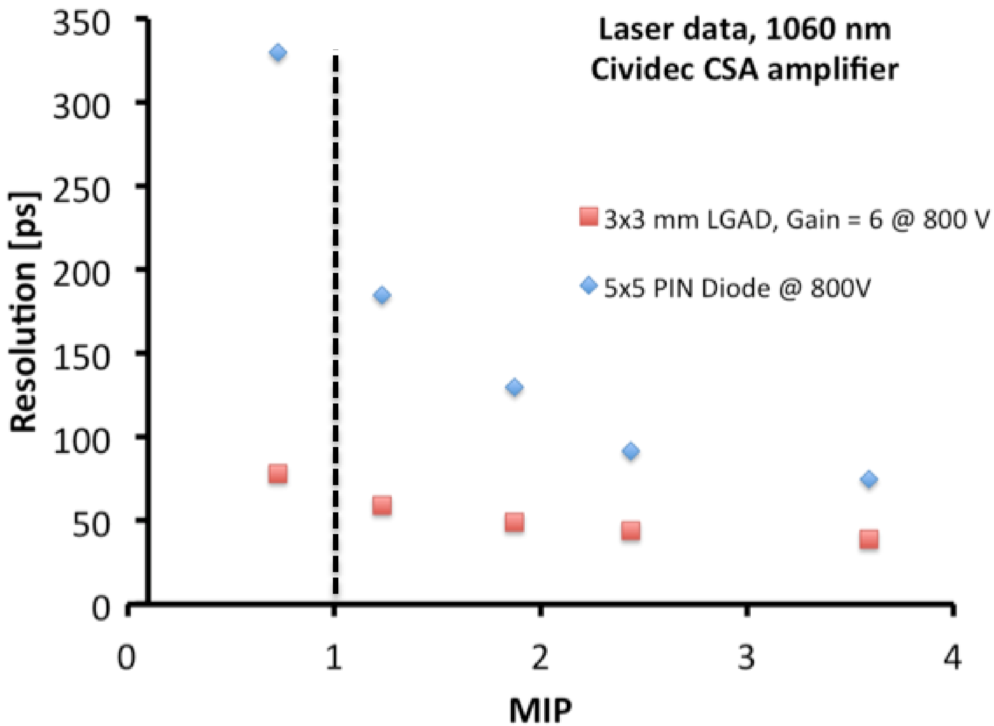
**50 micron:**
**~ 3x improvement**
**with gain = 10**

**WF2 Simulations**
F. Cenna, et al., Nucl. Instrum. Meth. A796 (2015) 149

**Significant improvements in time resolution require thin and small sensors**

# Measured Time Resolution of UFSD: IR Laser

IR Laser irradiating 300 µm sensors to measures the intrinsic time jitter, of both LGAD and no-gain diode ("PIN").




$$\sigma_{Laser} = \left(\frac{N}{dV/dt}\right)$$

**Increased Signal -> better Timing**

**For 1 MIP**, an UFSD with **gain ~ 6** shows a factor of 3 better time resolution than PIN diodes: 70 ps vs 200 ps

**For many MIPS** the difference is decreasing (important for timing calorimeter)

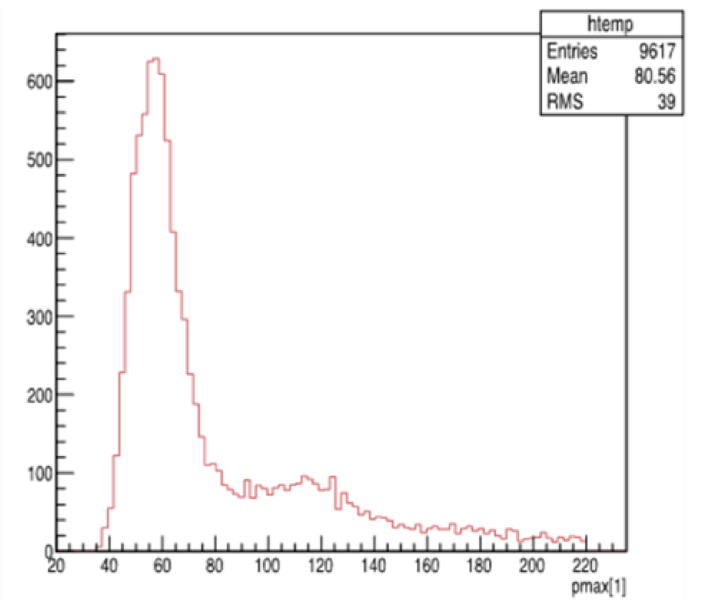
# Beam Tests with UFSD

2014 Frascati: 2 LGAD 7x7mm$^2$ 300µm (C = 12pF, Gain =10), CSA or BB
2014 CERN: 2 LGAD 7x7mm$^2$ 300 µm (C = 12pF, Gain =10-15), CSA and BB
2015 CERN: 2 LGAD 3x3mm$^2$ 300 µm (C = 4pF, Gain =15-20), CSA or BB

CSA: charge sensitive amplifier with gain of ~100, effective shaping ~200 Mhz
BB: Broad-band current amplifier with gain of ~100, BW 2.5 GHz
Pulse forms were recorded in a 2.5 GHz Digital scope with 50 ps bins

Goal: Study timing method, shaping time, noise, capacitance, gain, ..

**Optimize the timing extraction method:**
**fixed threshold,**
**extrapolation of slope,**
**constant-fraction discriminator CFD**



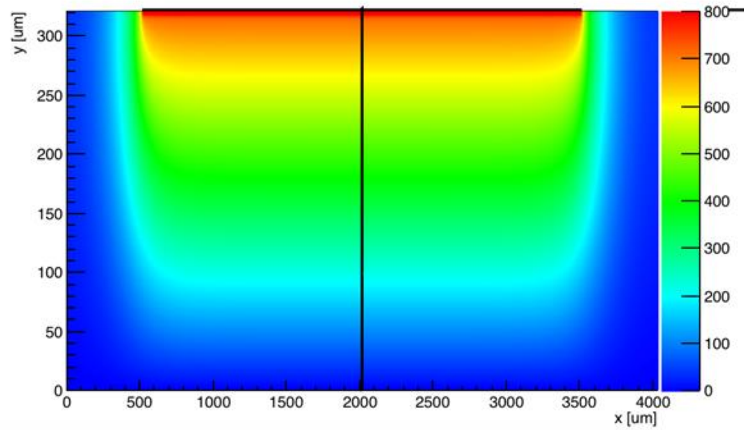

Pulse height spectrum allows to calibrate the energy scale
about 10% two-MIP events, ~1% three-MIP events

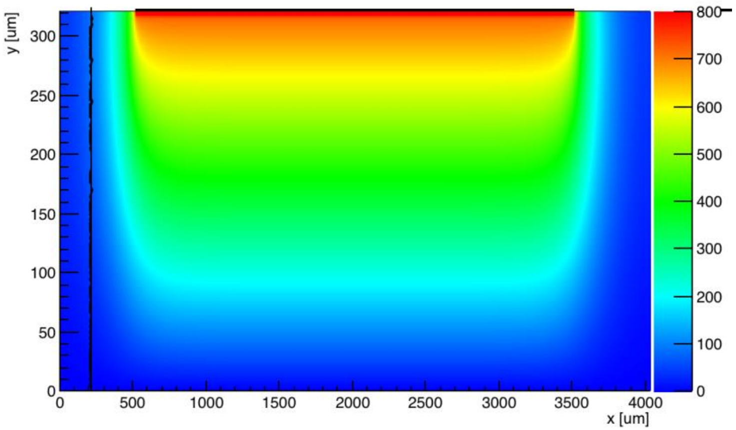
Acknowledge the support from Joern Lange and his team!

# Event Selection

No tracking information was available:

Need to recognize no-gain events from the periphery

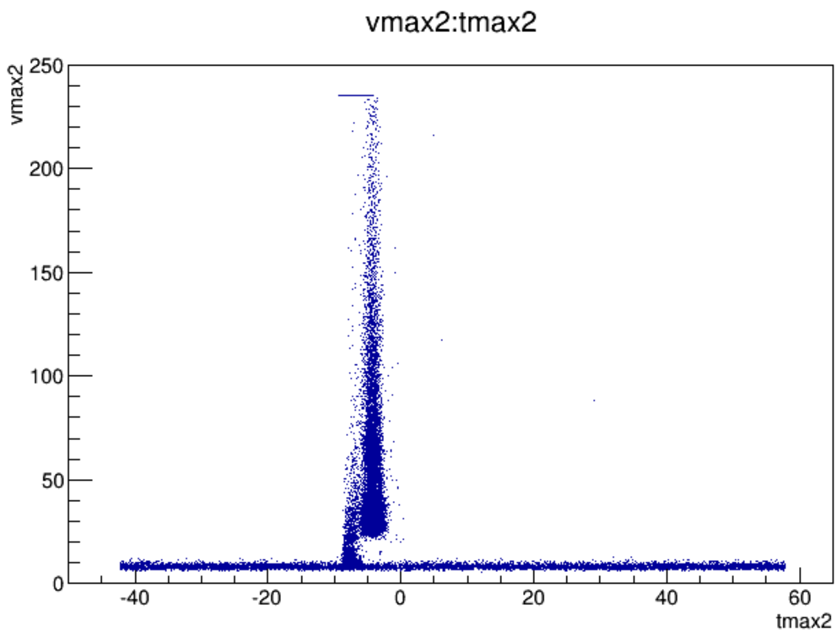


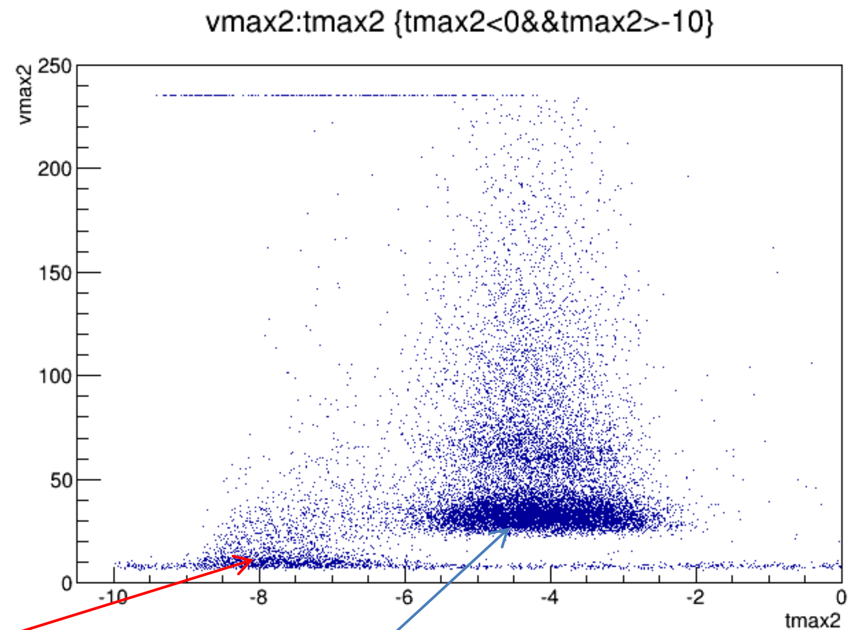



# Event Selection by Time of Pulse Maximum

Introduce time stamp tmax2 of the pulse maximum amplitude vmax2

Scatter pulse maximum amplitude (vmax2) vs. its time stamp (tmax2).
Events from the gain region and the periphery have similar start times, but very different peak times.




Channel 2: Scatter of vmax2 vs. tmax2 shows

1. clear separation of two contributions:

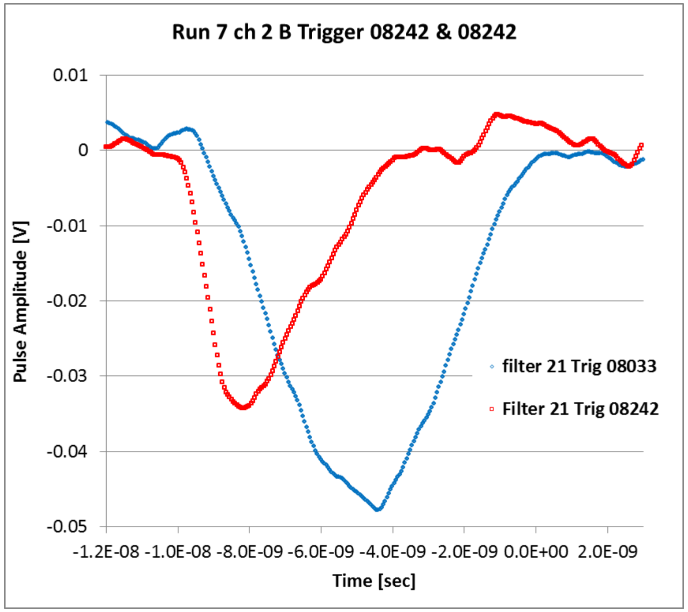
one at -8 ns = MIPs (?), one at -4.5 ns = events with gain

## There are different populations!

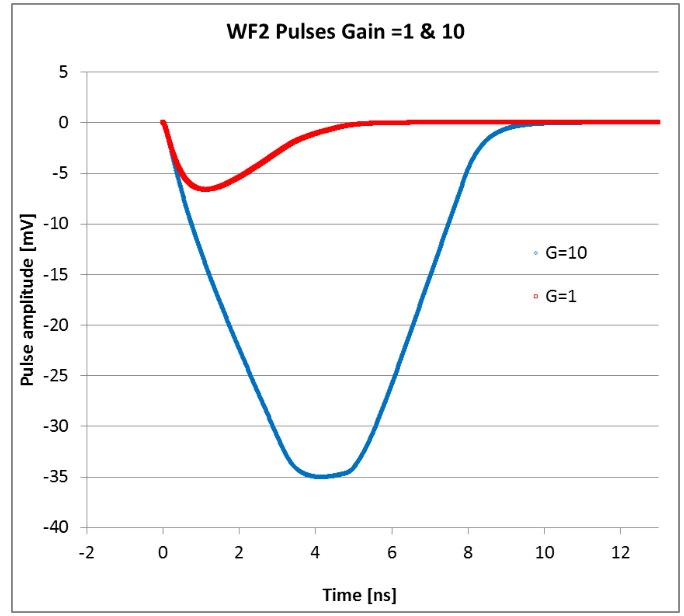
# Pulse Shapes indicate different Populations



BT Data



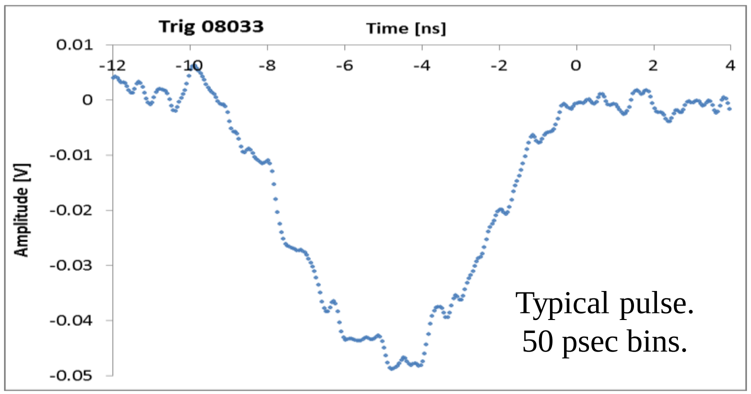

WF2 Simulations

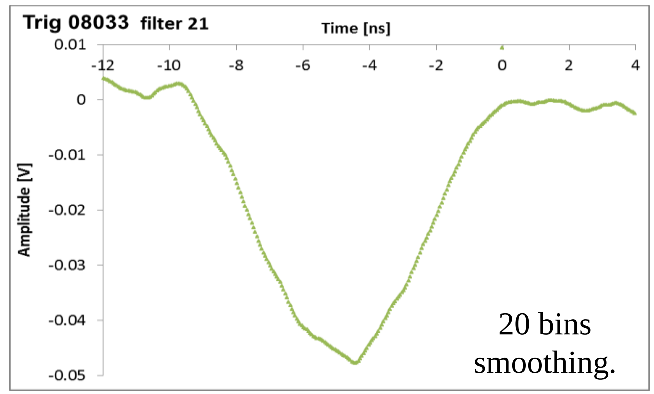


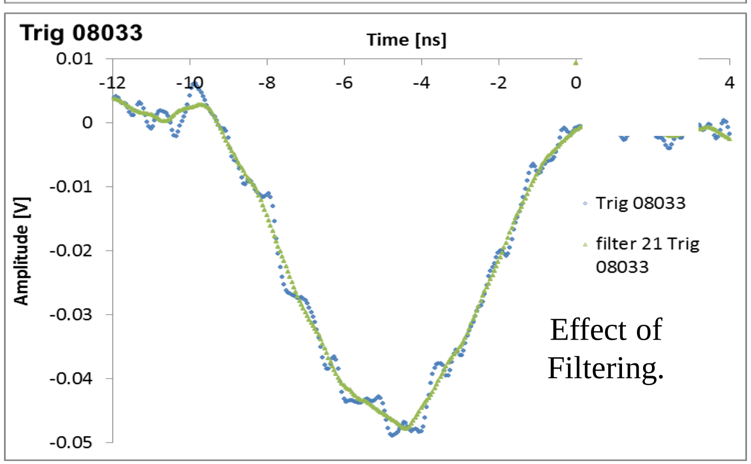

Pulse starts are within 1 ns, but pulse maxima within 4 ns!

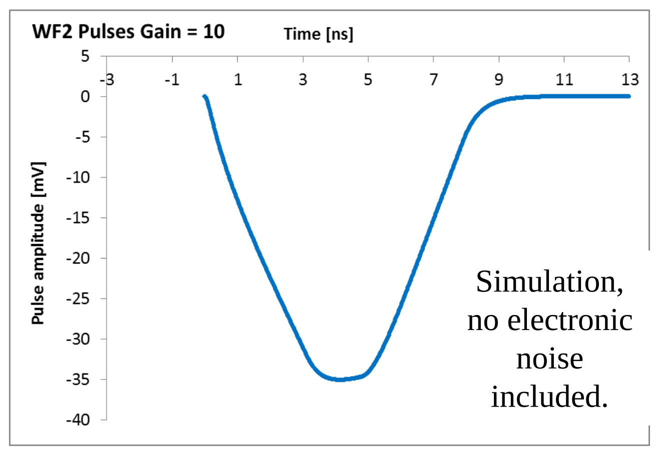
# Filtering the Pulses (Running average or FFT)

## FZ LGAD 300 µm, C = 12 pF, G=13, BB, 1000V, noise about 3 mV



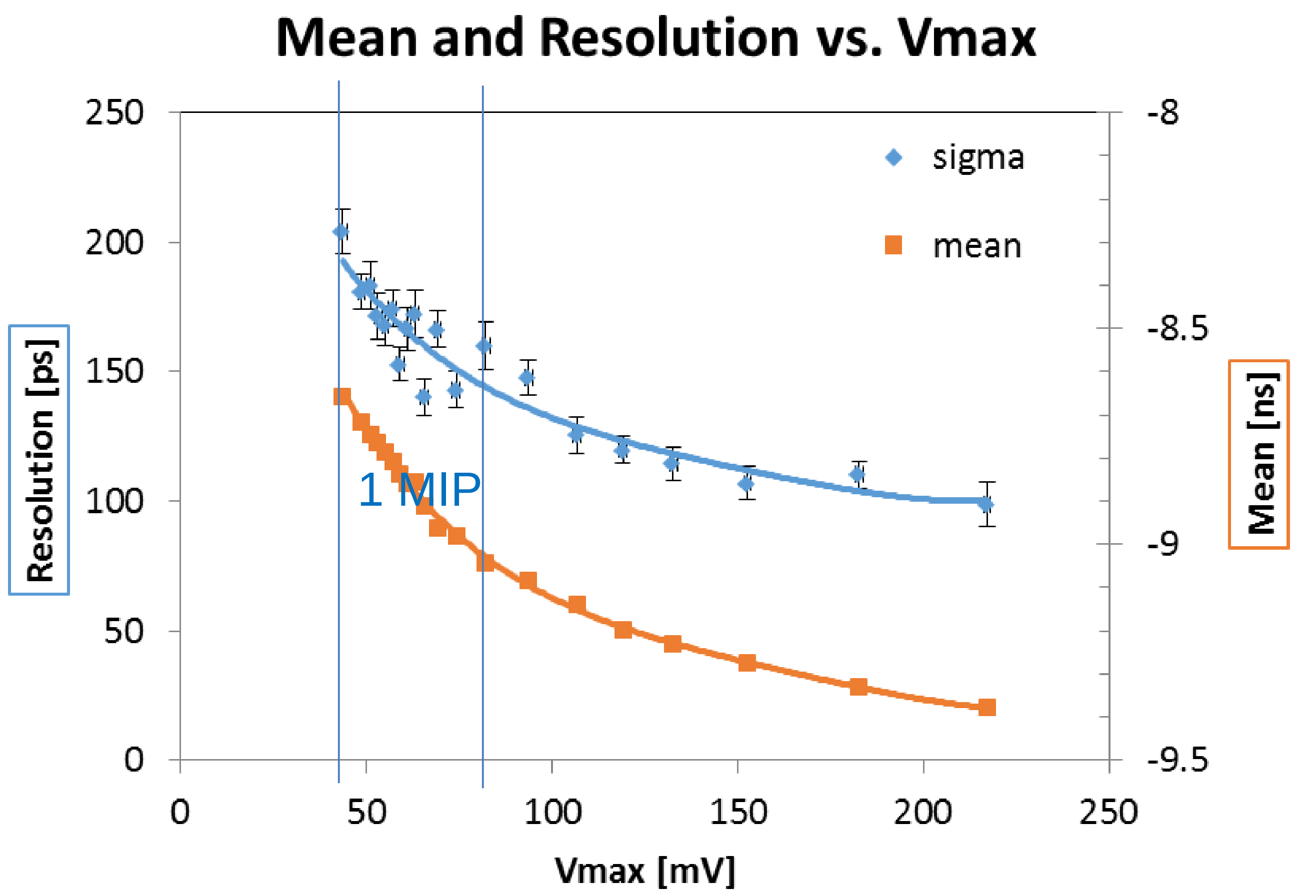



# BT Timing Resolution I (Fixed Threshold)

CERN 2014 Beam Test with independent trigger
FZ LGAD 300 µm,
**C = 12 pF**, G=10-13,
BB, Bias 1000V, fixed threshold = 10 mV, filtered with 20 bins

Time walk is large
~ 400ps for MIPs

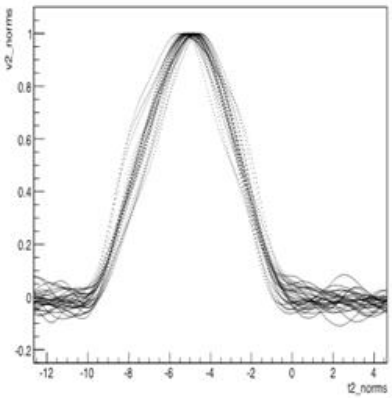
**Single MIP Resolution:**
**150 – 200 ps**



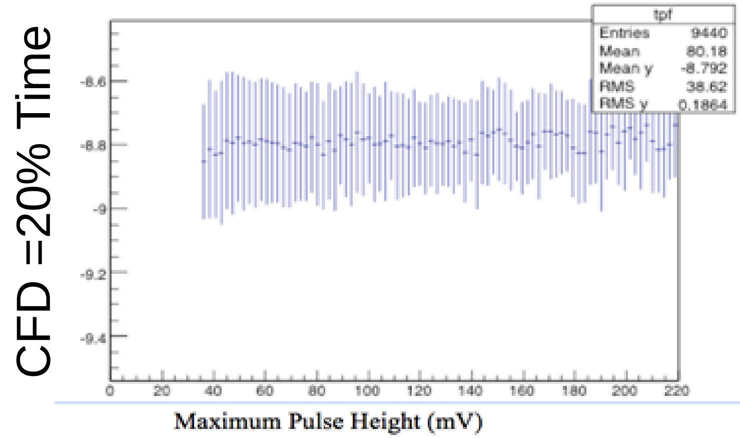

Analysis: Chi Wing Ng (Tom) & Sze Ning Mak (Hazel)

# BT Timing Resolution II (Constant Fraction Disc.)

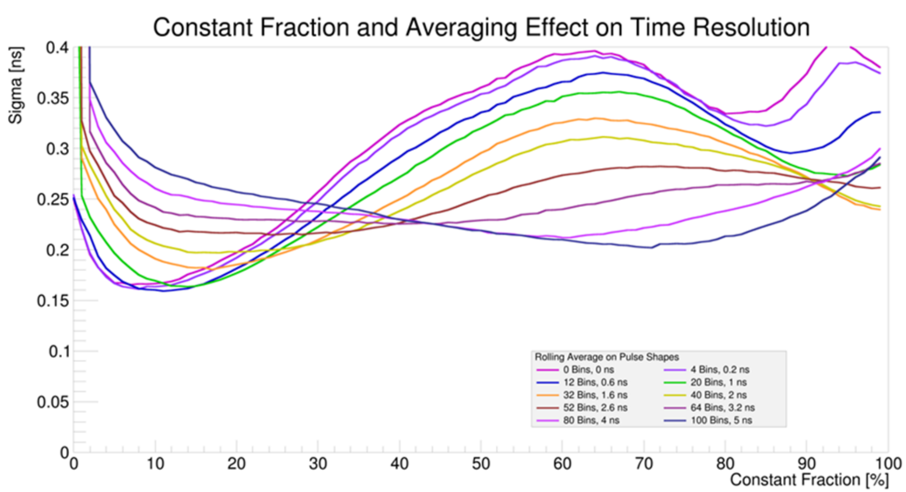
Abe’s unified pulse shape indicates uniformity of pulse shapes.
A low CDF has best resolution.




CDF = 20% has no time walk




**Timing resolution vs. CFD threshold for varying BW cut-off.**
**Optimize the filter (i.e. shaping time) for each CFD threshold**



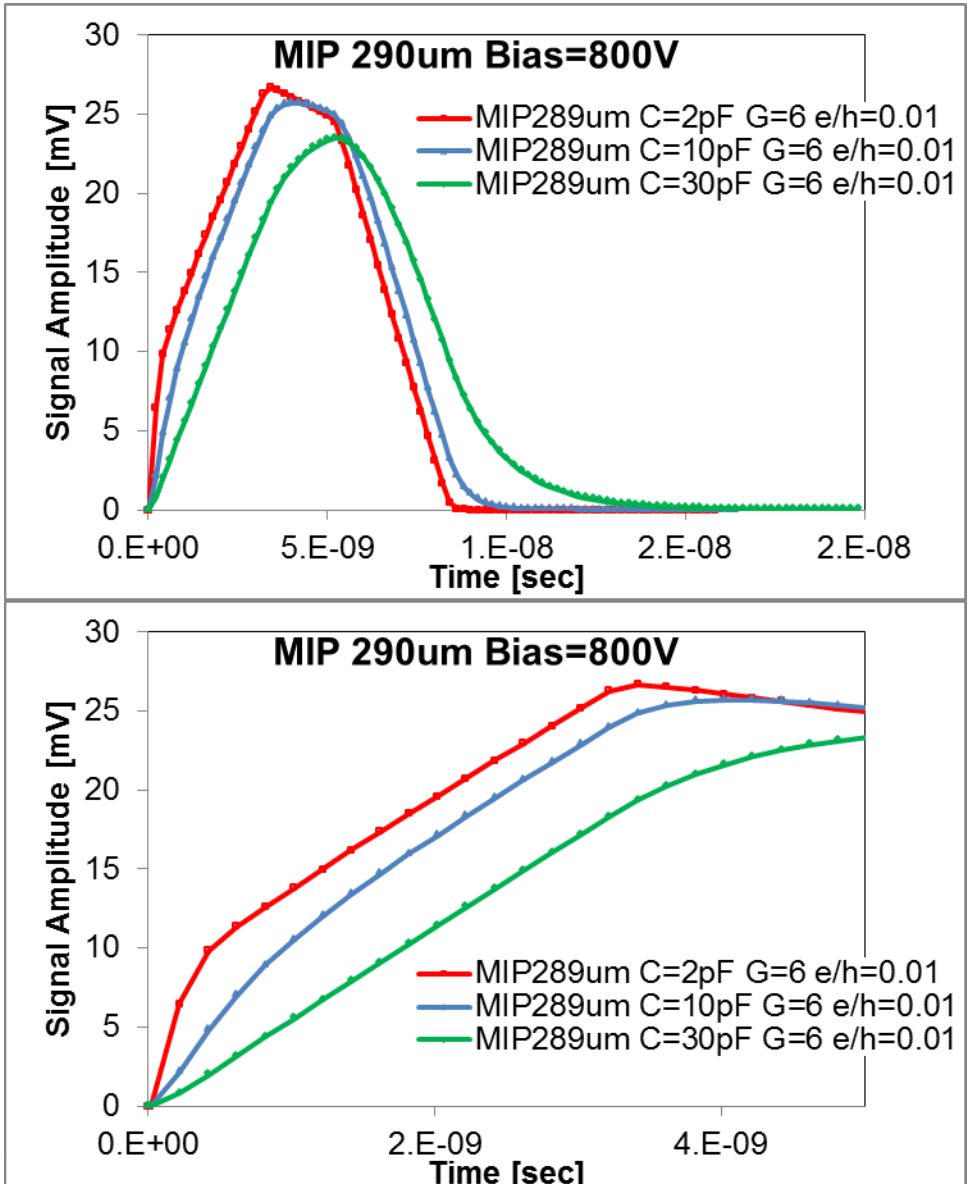

Analysis: Abe Seiden, Natasha Woods, Ben Gruey

**Nov. 2014 CERN BT:**
**Best time resolution (160 ps)**
at low CFD threshold

**CFD is easily incorporated into an ASIC.**

# Effect of LGAD Capacitance

## FZ LGAD 300 µm WF2 simulation of pulse shape

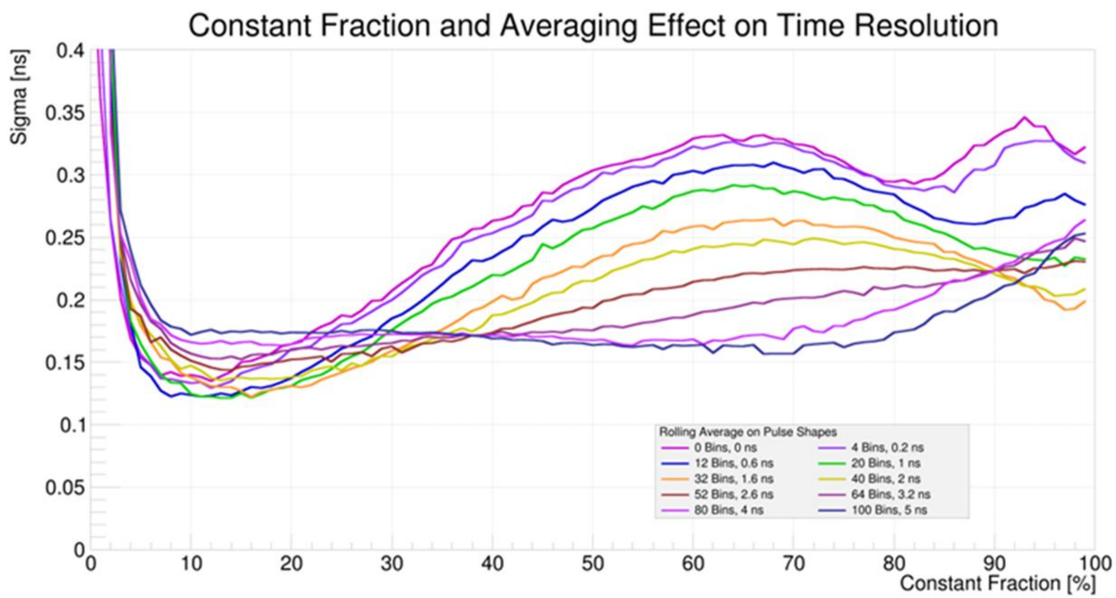



CERN Nov Beam Test: Cap = 12 pF

Going from C = 12 to C = 4 pF improves the slew-rate by factor ≈1.5

# BT Timing Resolution III (Lower Capacitance)

July 2015 beam test, **2 FZ LGAD 300 µm**, **C = 4 pF** (instead of 12 pF before), G=15 & 8, BB
Bias: 900V, CFD: 0->100%, filtered with variable BW.
Resolution: Time difference between two channels divided by sqrt(2).



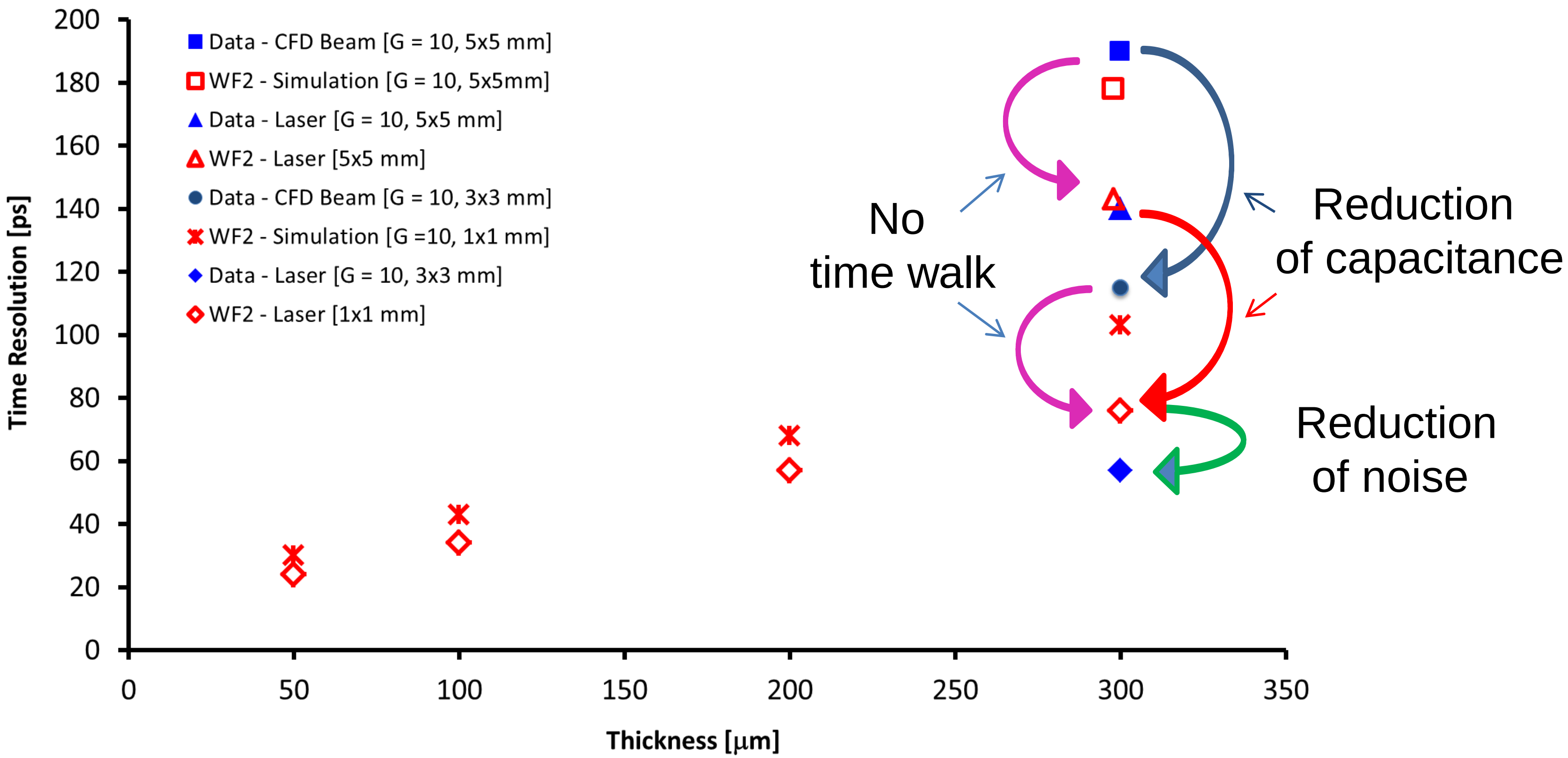

**Best resolution 120 ps with CFD @ 8 -15% with BW cutoff ≈ 0.8 GHz**
(c.f. 100 MHz for 3.5 ns rise time)

The two LGADs used have different gain. It's difficult to assign correctly the two time resolutions, but using simply the inverse of the gain G, we get:
**σ**(G = 8) **≈ 140 ps**, **σ(**G = 15) **≈ 100 ps.**

Analysis: Abe Seiden, Natasha Woods, Ben Gruey

# Timing Resolution of UFSD (Laser, BT, WF2)

**Up to now the only MIP data available are for 300 µm LGAD.**
**Good agreement between data (beam test & laser) and simulations (WF2).**
(Laser data have no time walk.)
**Improvements are due to reduction of capacitance which increases the slew-rate (dV/dt) and due to reduction of the noise.**
**Prediction: resolution of 30 ps for 50 µm LGAD with gain of 10, needs ASIC**



# Conclusions

- Beam tests and laboratory laser tests measure the timing performance of the UFSD. We observe an improvement of the resolution with LGAD of smaller capacitance.
- At present, data are available for 300 µm thick LGAD only, and we reach the resolution of 100 ps which is the ultimate limit for MIPs at that thickness.
- Simulations with Weightfield 2 (WF2) confirm the timing resolutions extracted from beam and laser tests for 300 µm thick LGAD.
- WF2 is ready to be used to extrapolate to thin sensors. For a 50µm thick LGAD of small area, we expect a timing resolution of ~ 30 ps.
- We expect to receive sensors of 50 – 200 µm thickness early next year and will be able to check our prediction. Will need a beam test with a fast trigger.
- One of the first application of the RD50 developed LGAD is the ATLAS High Granularity Timing Detector (HGTD). Timing requirement is 50 – 100 ps.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