Minimum-Ionizing Fast Tracker
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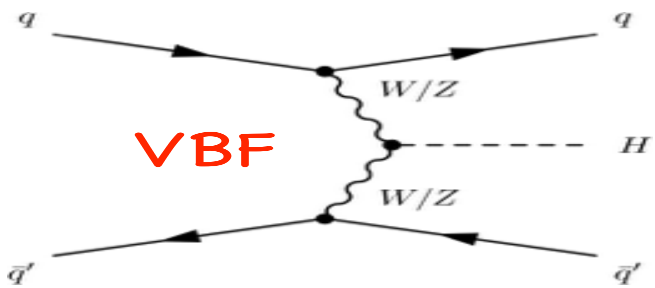
Outline

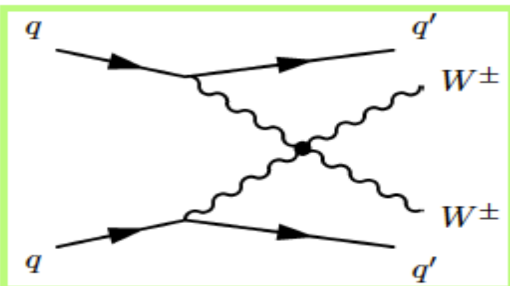
- Some important physics at the HL-LHC.
- Idea for Ultra-Fast Silicon Detectors to measure MIP signals and potential importance for the HL-LHC.
- Measurements made to establish detector performance.

Work is a collaboration of Hartmut Sadrozinski, Abe Seiden, and Nicolo Cartiglia (UCSC visiting scientist from University of Turin, member of CMS). Invaluable contributions from CNM (Barcelona), FBK (Trento) and HPK on the technology development and Ljubljana group on radiation damage issues.

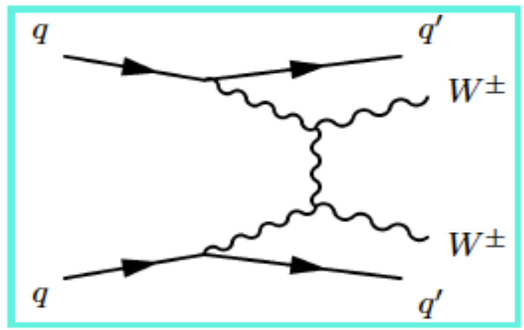
Important Electroweak Physics Studies at the HL-LHC



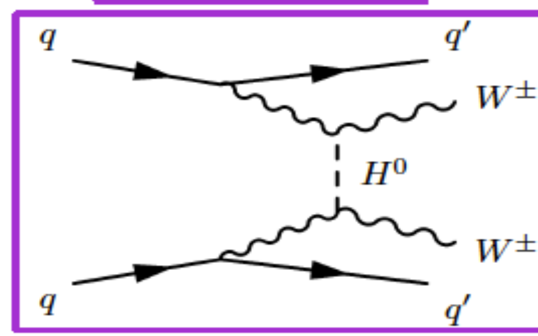
quartic scattering vertex

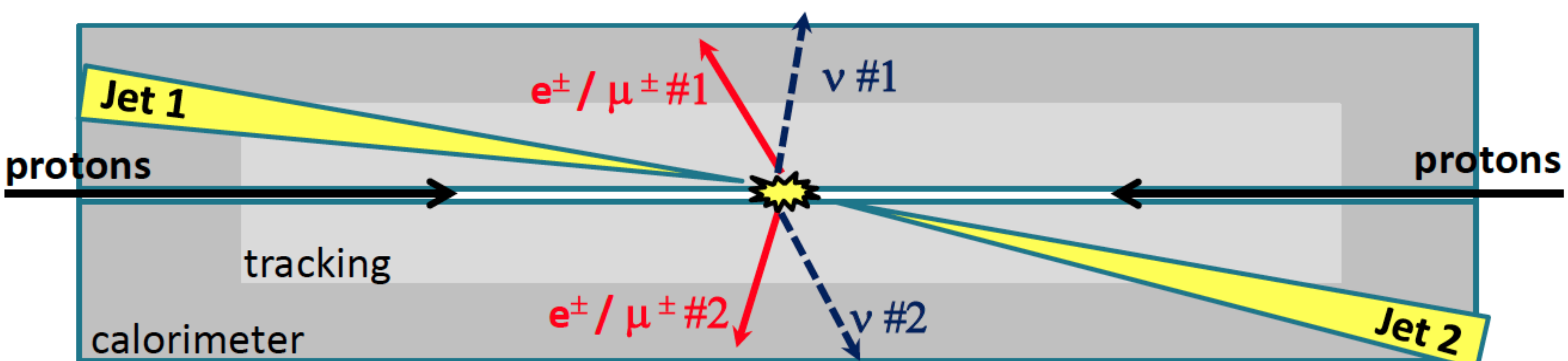


t-channel V exchange



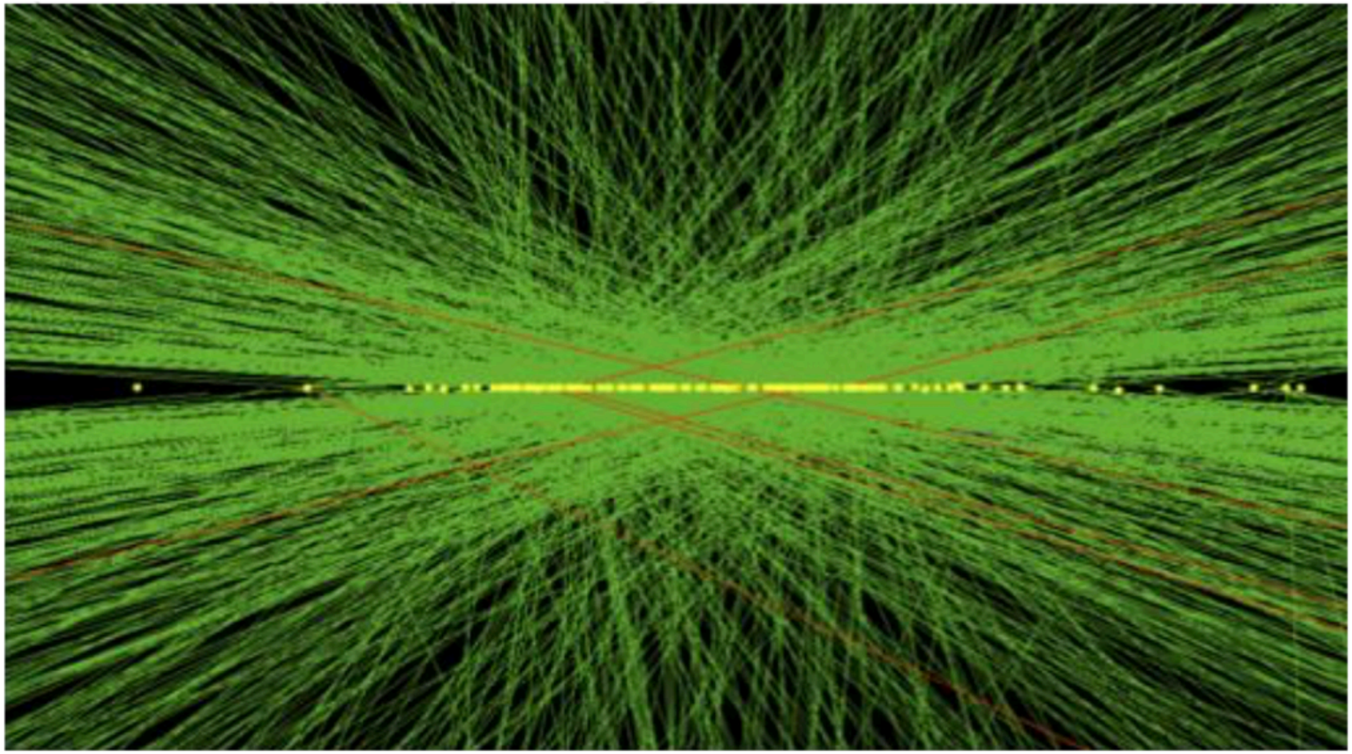
t-channel Higgs



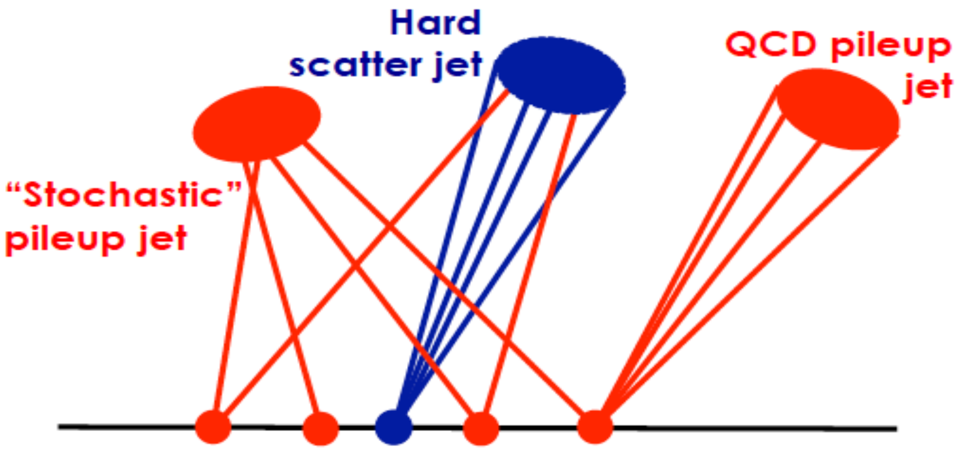


The HL-LHC Environment

The HL-LHC will have on average 200 overlapping events every beam crossing. Very difficult environment for finding tracks and associating to vertices. Probably even worse for future higher energy collider. Especially difficult in the forward region, where track density is very compressed spatially, but where we have to find the forward scattered jets for VBF studies.

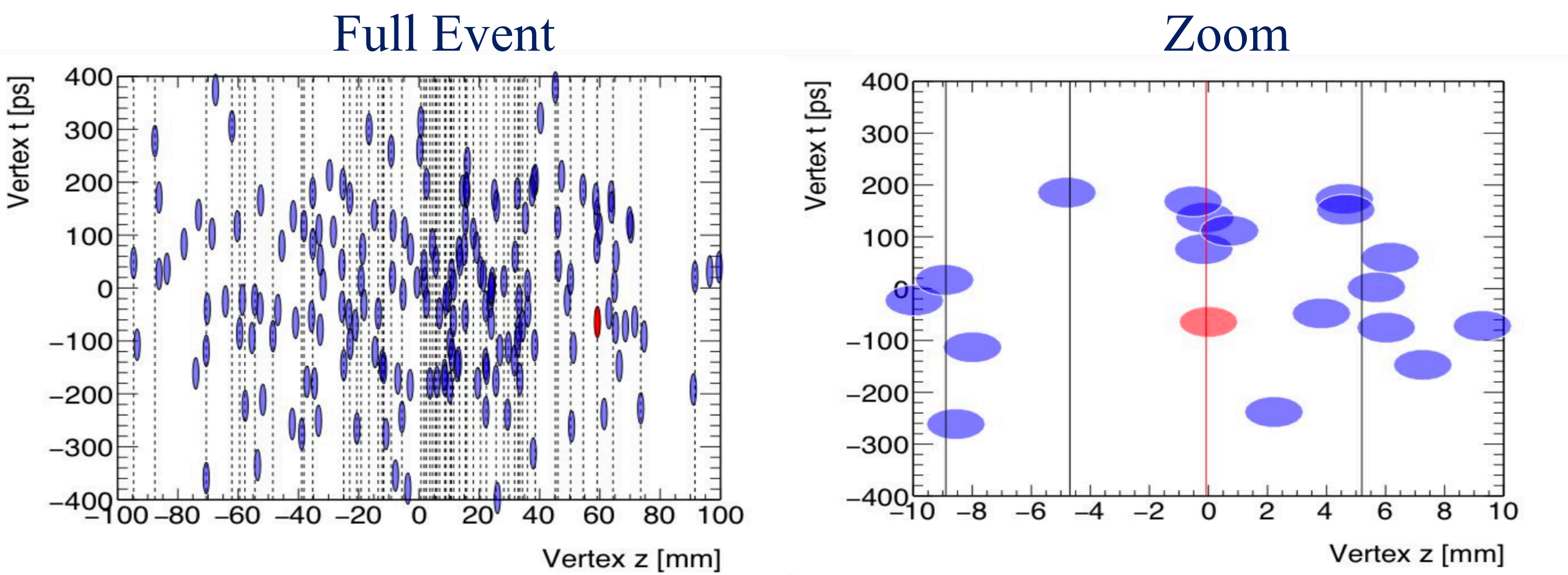


Leads to Various Backgrounds (in Red)



Very high rates give rise to extra tracks mixed into signal (hard scatter jet), completely fake jets made up of tracks from unrelated vertices, and high rate of real QCD jets.

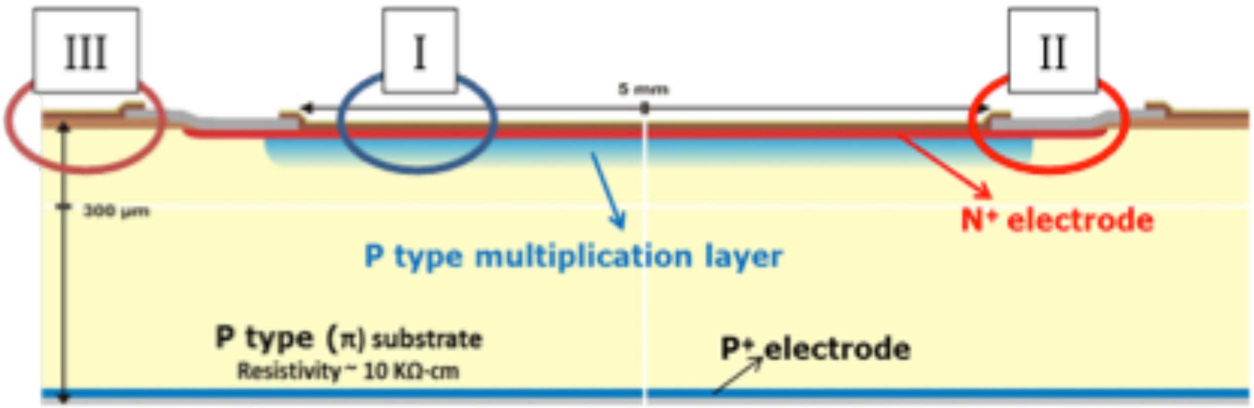
Pile-up Rejection in Two Dimensions

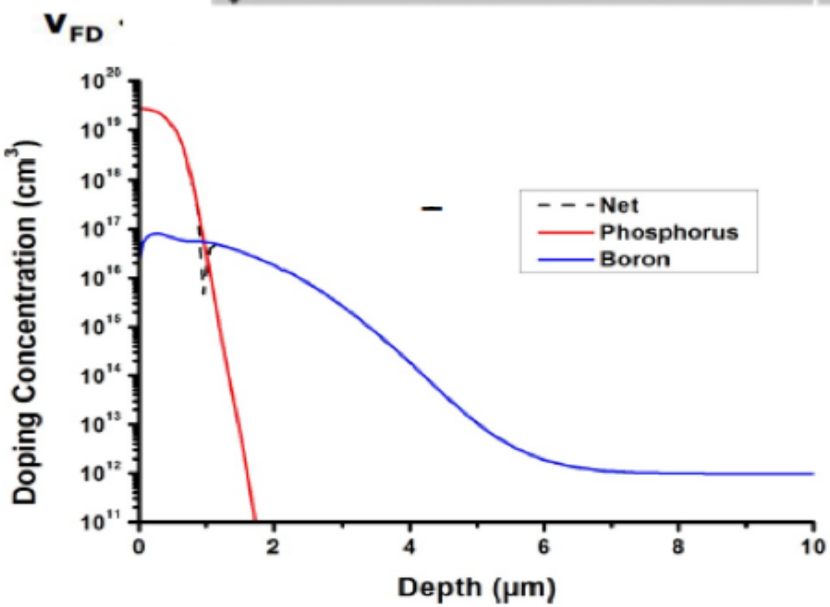


Event display showing the time and z position of all vertices in an event with 200 additional interactions. Blue ellipses correspond to truth vertices. The size of the ellipses are 30ps and 1mm. The red ellipse indicates the truth hard-scatter vertex. The dotted lines indicate the position of the reconstructed primary vertices in the event. The right plot is a zoom around the hard-scatter vertex.

Timing information would add powerful pile-up rejection capabilities, but how do we make a timing detector with very good resolution for MIPs?

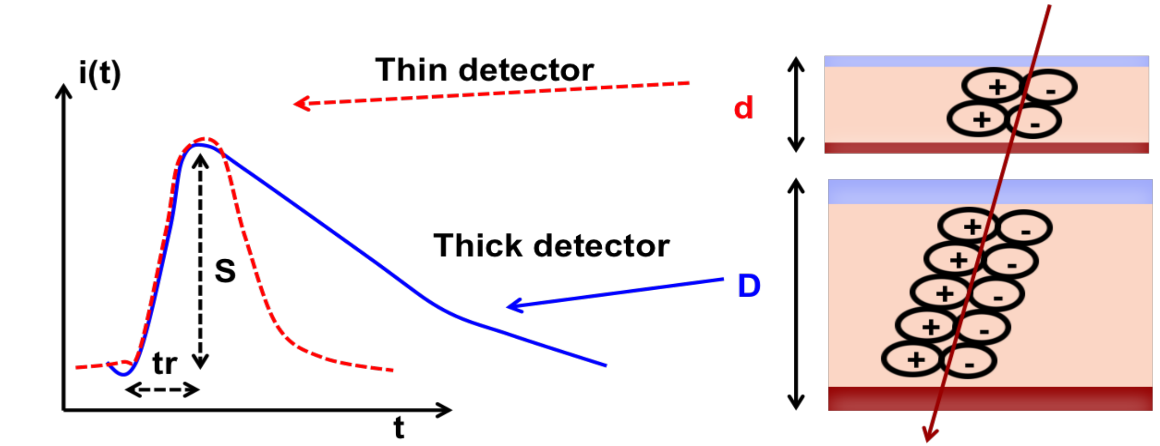
Ultra-Fast Silicon Detectors: LGAD (Low Gain Avalanche Detectors) Detectors with Gain and Large Electron Drift Velocity



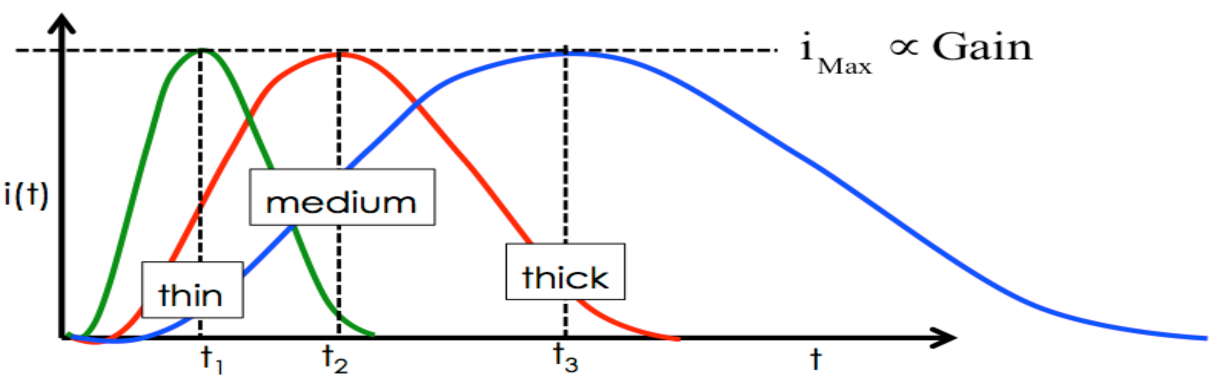


Goal: Gain field ~ 300 kV/cm over a few μm near junction.
Bulk field ~ 20 kV/cm, gives a saturated electron drift velocity ~ 10^7cm/sec. Want to have gain for electrons but not holes, leads to gain ~ 20.

Detector Thickness and Signal Shapes for a Pad Detector with Saturated Drift Velocities.



Conventional detector: Rise time similar for thick and thin, same slew rate.



Detector with a gain of 20: Rise time (and slew-rate) are different. Rise time ~ electron collection time, is proportional to detector thickness. Can get large and fast signals.

Note: LGADs can be made into an array with high rate capability just like ordinary silicon detectors.

Sensor Simulation

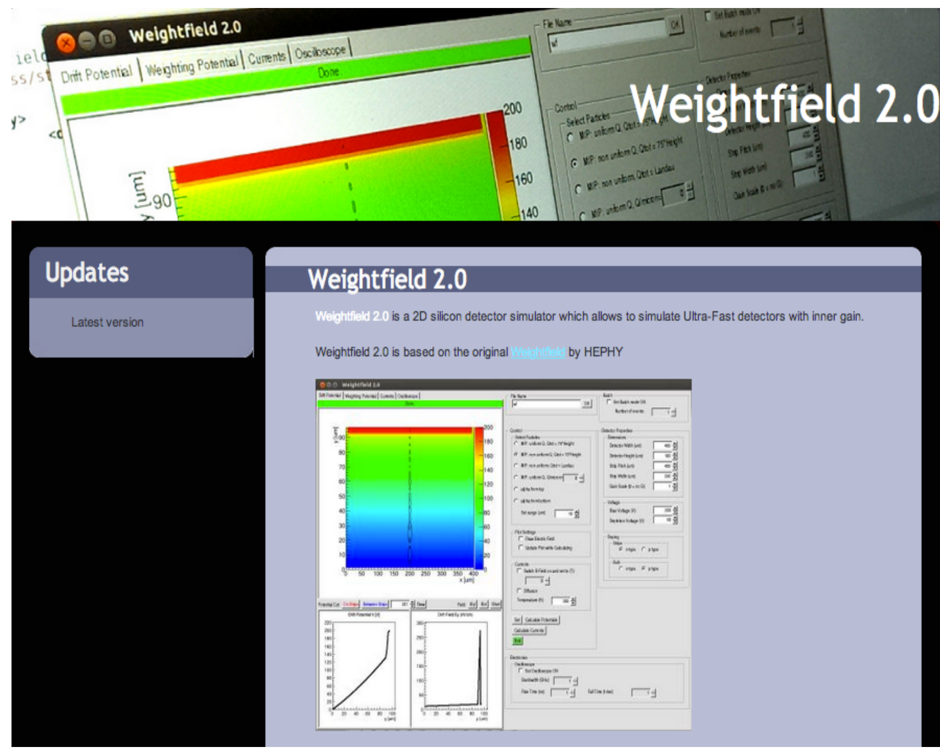
Nicolo Cartiglia developed a full sensor simulation to optimize the sensor design

WeightField2, F. Cenna, N. Cartiglia 9^{th} Trento workshop, Genova 2014

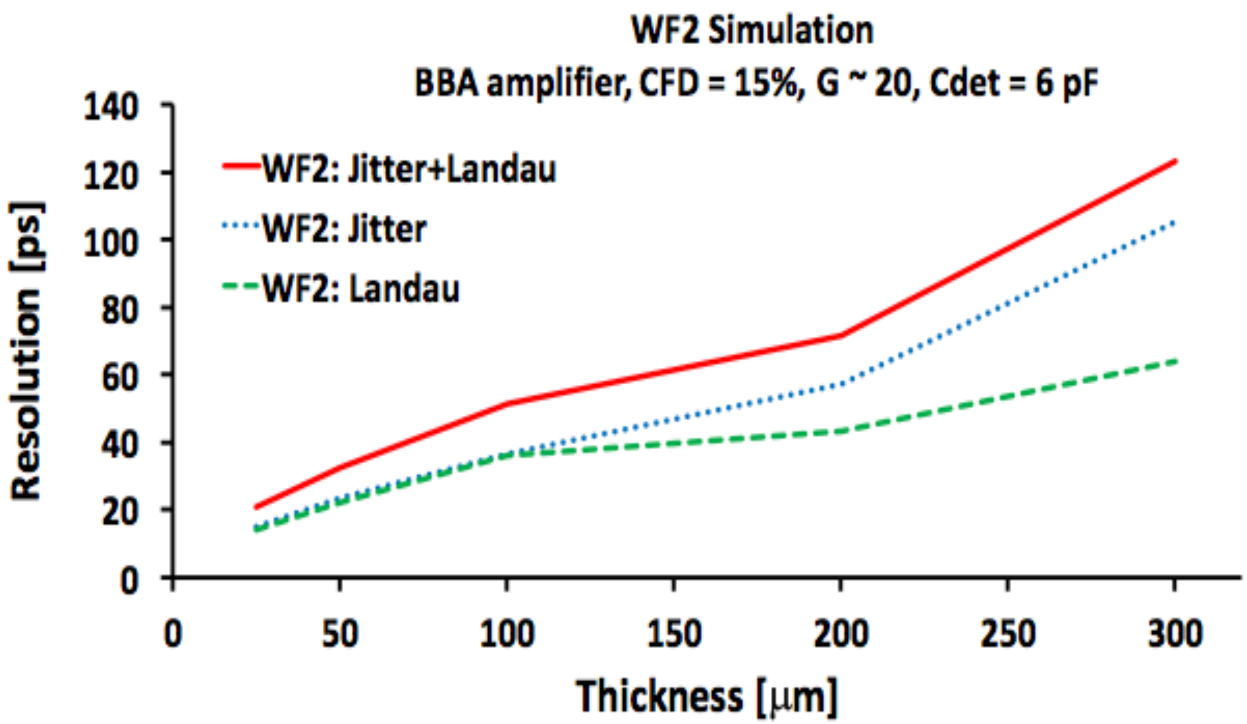
Available at http://personalpages.to.infn.it/~cartigli/weightfield2

It includes many "bells & whistles" required for the detailed description of the signals, i.e. charge generation, drift and collection.

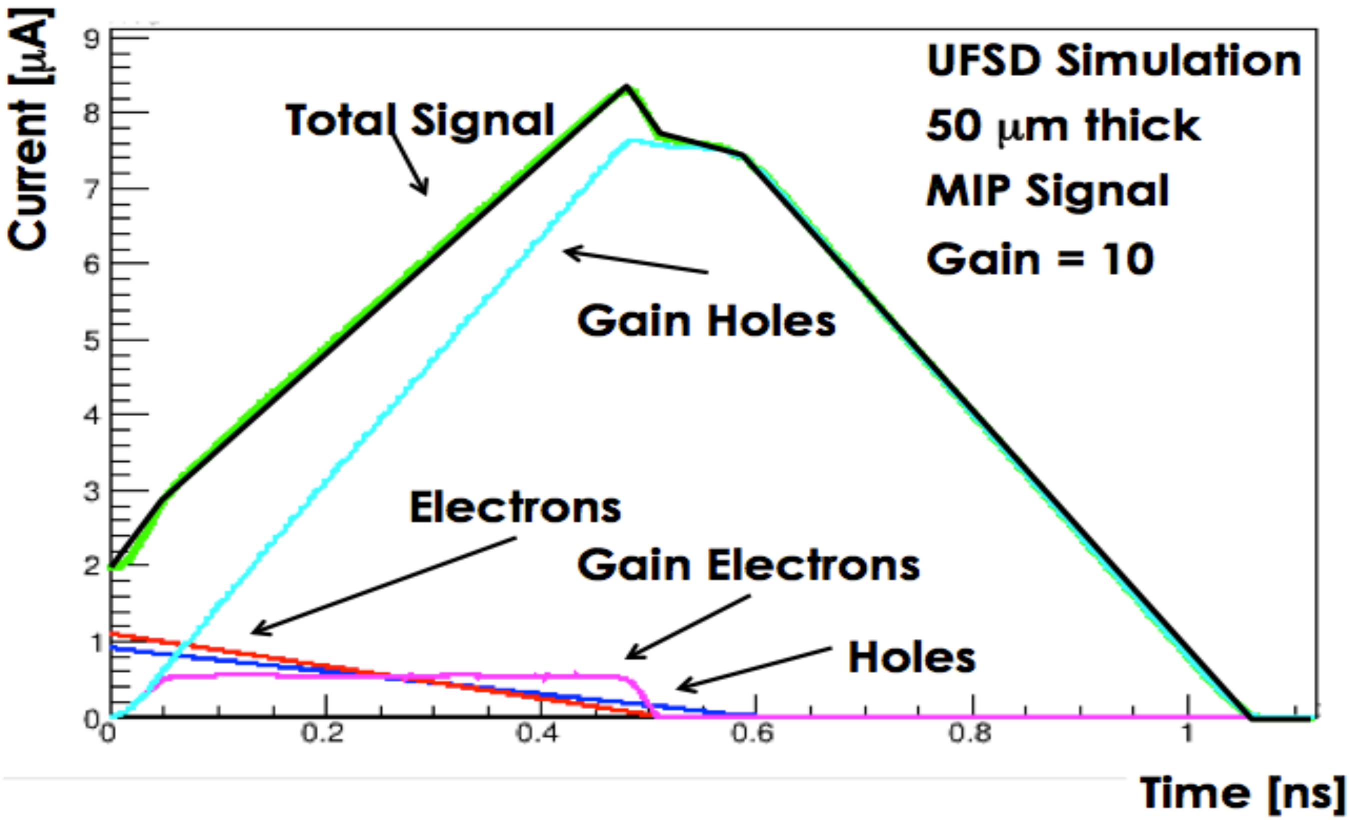
It allows to separate the properties of the current source from the amplifier shaping.



Simulations tell us to go thin!



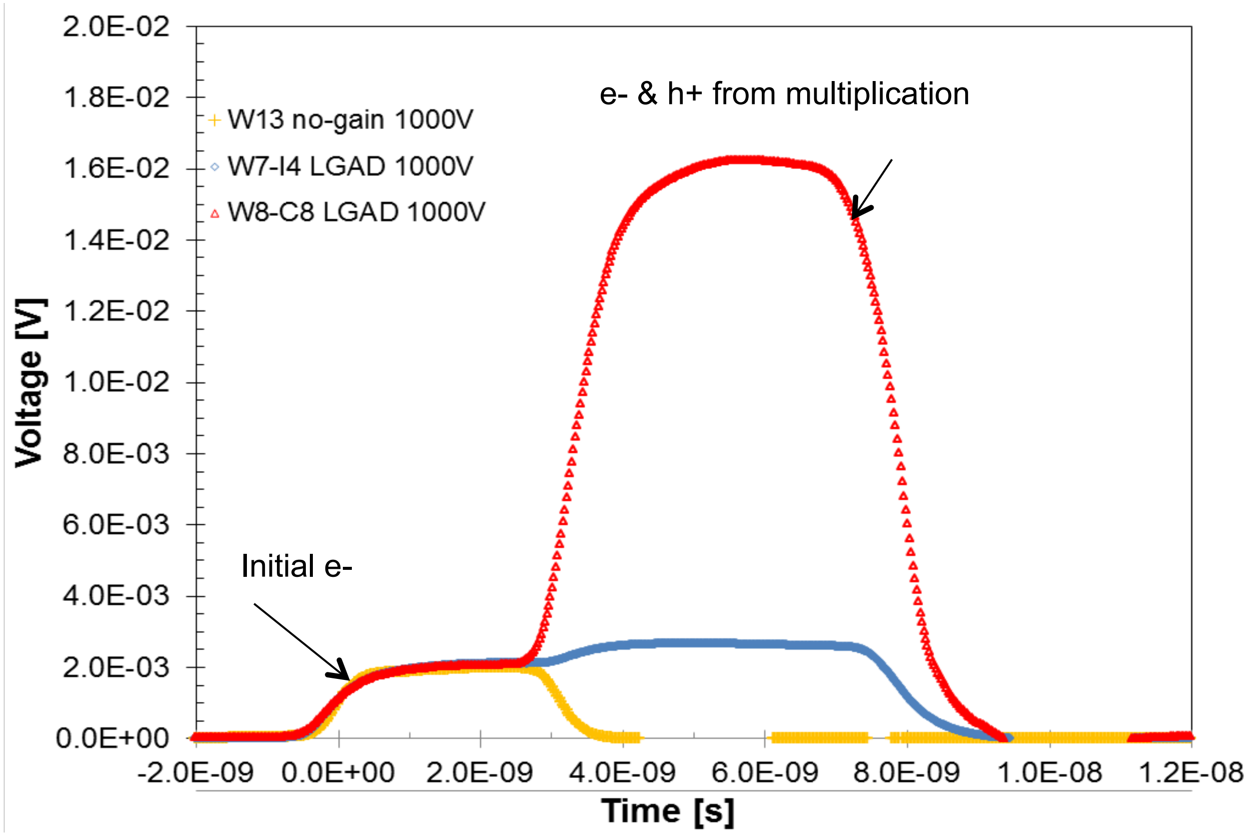
Simulations: 50 Micron Thick n-on-p LGAD, Response to a MIP.



Components making up signal (50 μm thick detector): primary e^- signal collected in about 0.5 nsec, gain signal peaks at about 0.5 nsec.

Gain Calibration with α' s from Am(241)

Pulse shapes for high-gain (red), low-gain (blue) LGAD and no-gain sensor (yellow)
300 micron thick detectors.

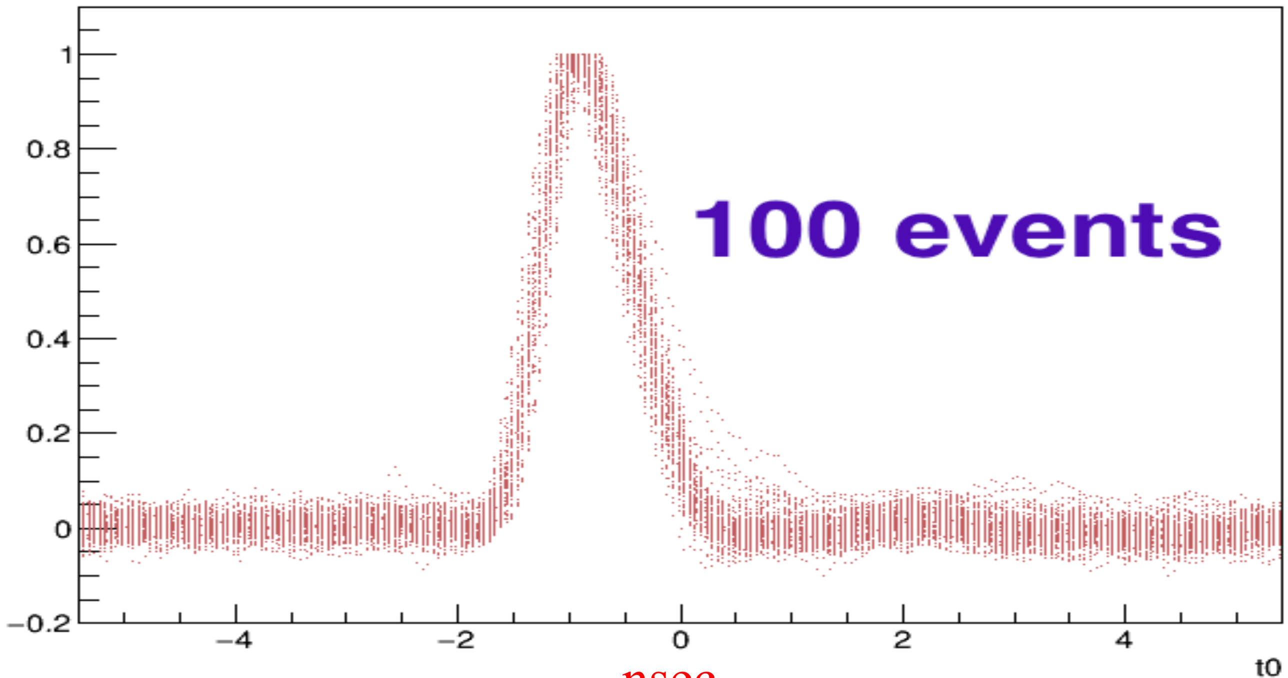


$$Gain = \frac{electrons + holes}{initial \cdot electrons}$$

Some Advantages of LGAD (Beyond Just Large Signal Due to Gain).

In general the time of the pulse peak is determined by collection of the last electron. At this point all gain holes are still drifting. So for constant weighting field and constant velocity the time of the peak, to good approximation, is independent of the ionization and gain (determine the total number of holes drifting) and Landau fluctuations (determines the clumping of the ionization). This uniformity in time of the peak is very useful for measuring time.

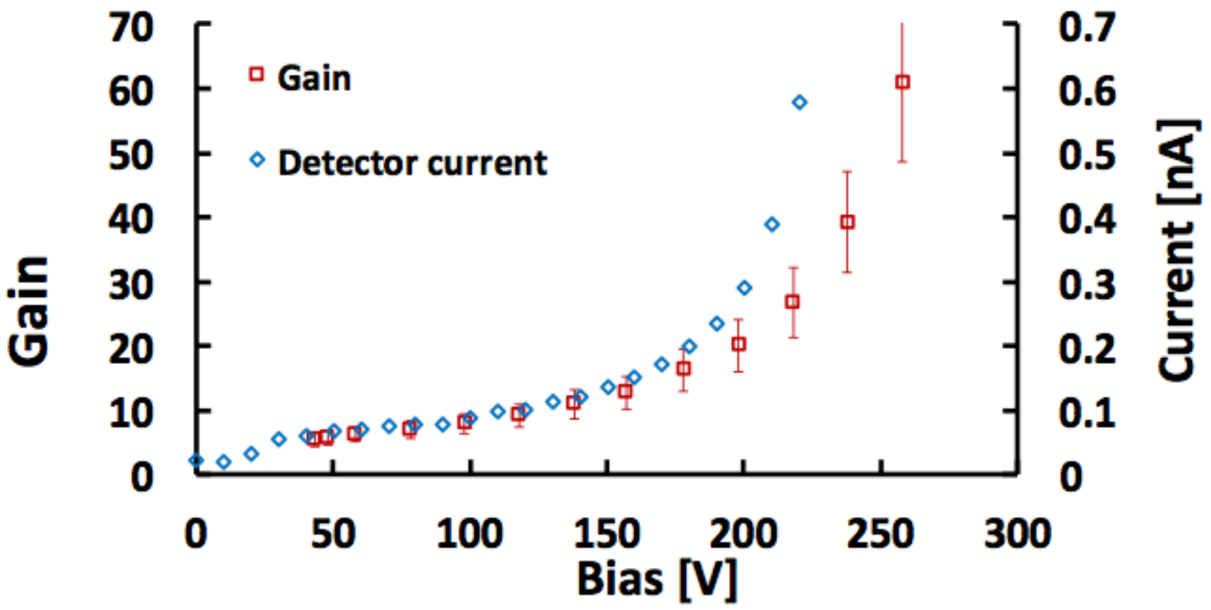
Scaled Pulses: Beam Test Last August. 50 micron thick sensor



nsec

Pulse height divided by maximum value. Gives a standard pulse shape, which is very stable. This is why constant fraction discriminator works so well.

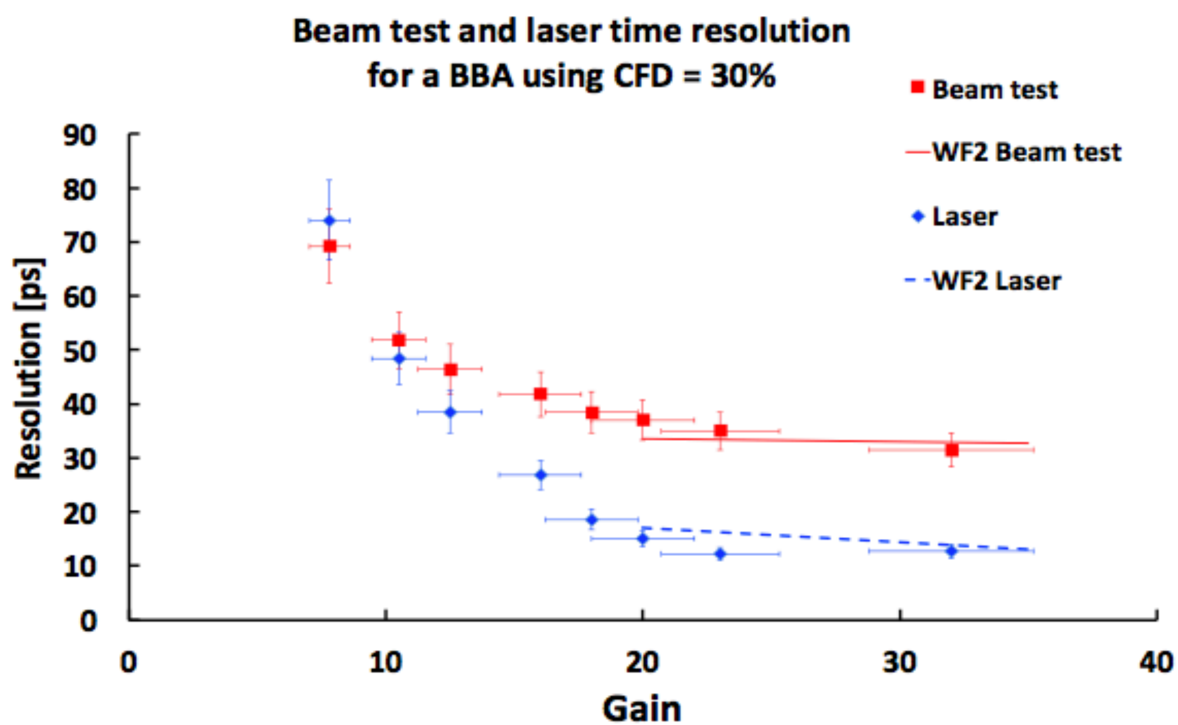
Let's Look at Data for LGAD: 50 μm thick from CNM



Gain of 20 is a very nice place to run.

Beam Test Results

UFSD Timing resolution		
	Vbias = 200 V	Vbias = 230 V
N = 1	34 ps	27 ps
N = 2	24 ps	20 ps
N = 3	20 ps	16 ps



Thin Sensor, From Other Considerations, Best for Timing Applications at the LHC

1) For cooling, much reduced voltage and leakage current for a 50 μm sensor compared to thicker sensors results in much less heat generated.
2) For radiation damage the much shorter drift distance reduces trapping problems. Many more studies of radiation effects in progress now.
3) A negative for thinner sensors, larger capacitance. However have established excellent performance for sensor pads with areas up to about $4mm^2$.

Use of one to a few layers over a large area allows sorting of hits with a common time. Adding the tracking information allows association of tracks into individual vertices greatly mitigating pileup effects. Can expect improvements in measurement of MET and also b-tagging.

Radiation Hardening the LGAD

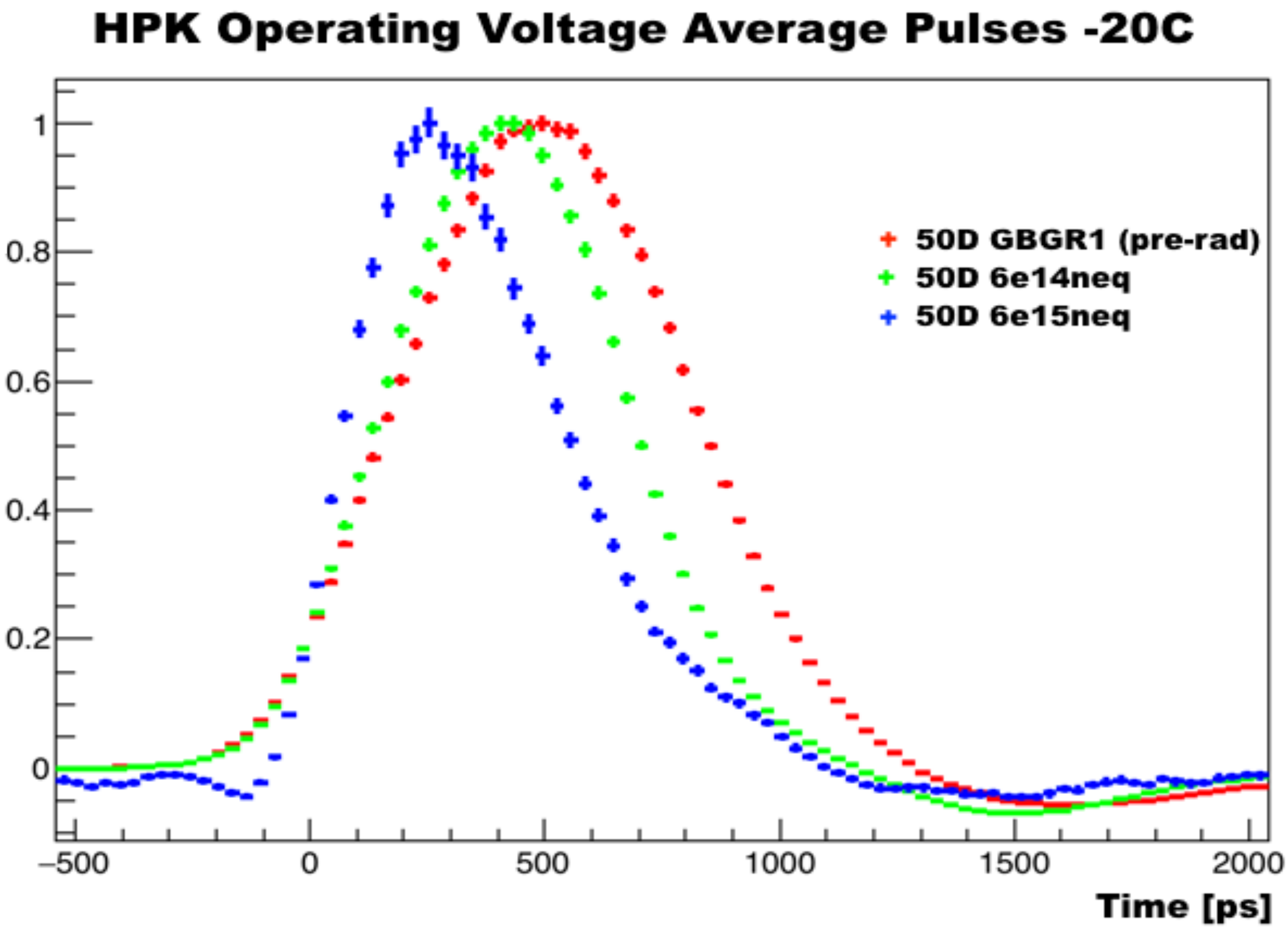
Defects created by radiation tend to remove the effect of boron in the gain layer (acceptor removal). Mainly a problem for fluences beyond 10^{15} neq/cm^2 (10 years of running at radii smaller than about 25 cm at the HL-LHC). Some approaches to mitigating this problem, all being investigated:

1) Raise the voltage. This works best for a thin sensor where the depletion voltage by itself isn't too large, so room to raise the voltage. Choice of 50 μm thickness (or less) critical for this approach.

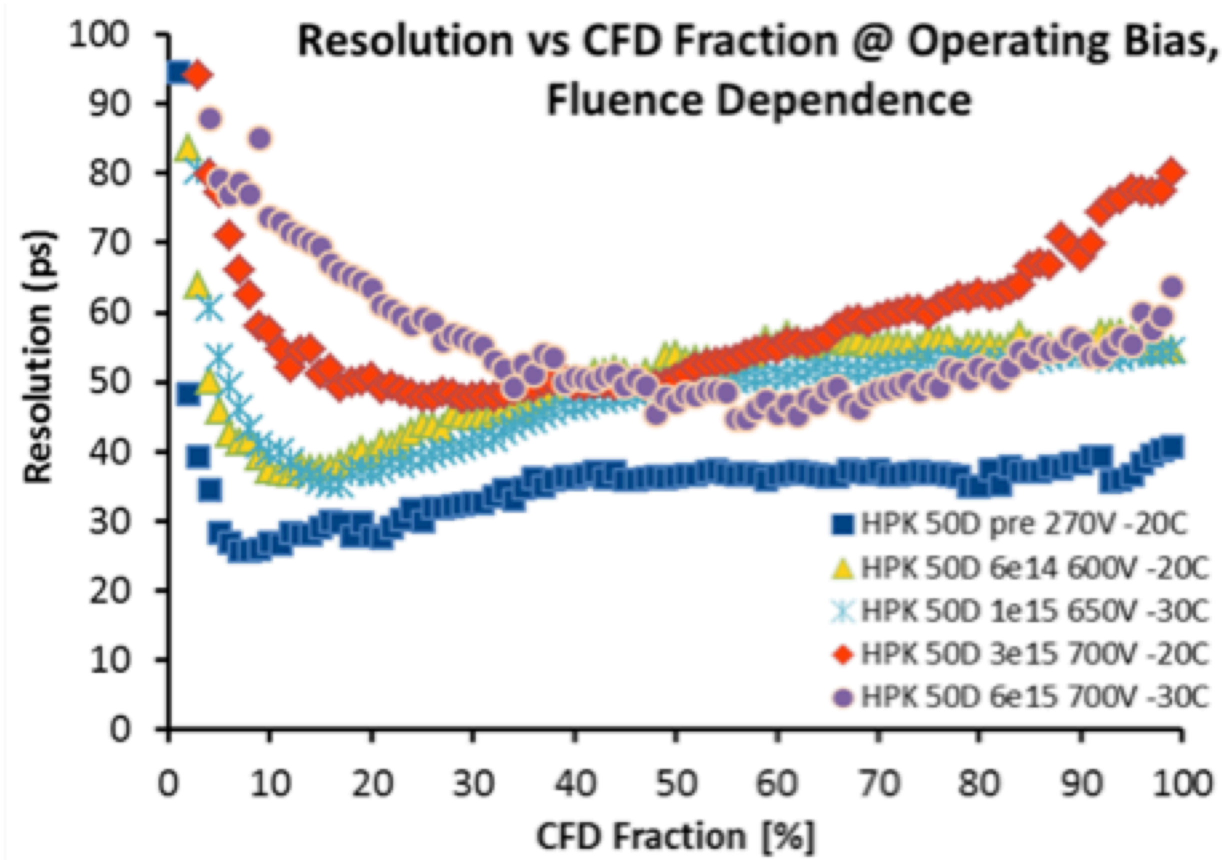
2) Replace boron with gallium – has been shown in space applications of solar cells to be more radiation hard.

3) Add carbon, which tends to tie up defects more readily than boron, so gain layer is less affected.

4) Optimize gain layer – thickness versus doping density. Thinner, more highly doped, layer may be better?



Shape changes with irradiation. Achievable gain also goes down significantly (gain about 7 at 6e15 neq/cm^2).

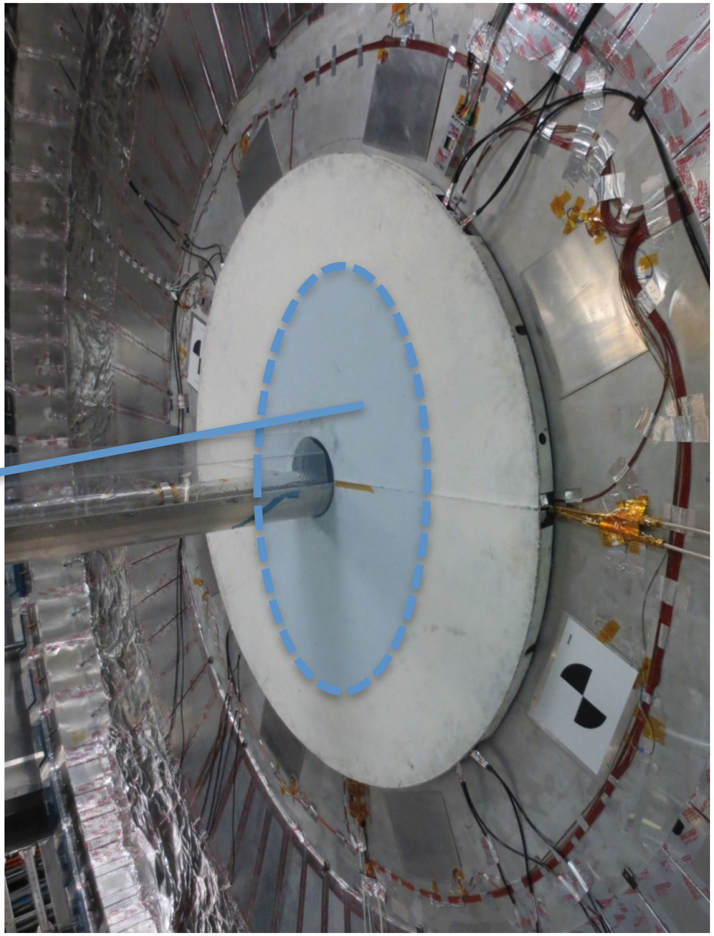


Time resolution as a function of CFD threshold for the different fluences and temperatures.

ATLAS HGTD High Granularity Timing Detector (HGTD)for HL-LHC

HGTD
$2.4<\eta<4.2$
$R_{min} = 11$ cm
$R_{max} = 65$ cm
$Z \sim 3.5$ meters
4 layers spaced over $\Delta Z \sim 6$ cm
$\Delta t < 50$ ps/mip

Each layer has array made of LGAD cells~ 2 mm^2 in area, 50 μm thick.



HGTD: 4 Si layers on each side of the detector.

Conclusions

Detectors fabricated with gain layer show that stably operating detectors with gain ~ 20 can be made with good gain uniformity. These are capable of high rate operation. Simulation program (Weightfield2) allows prediction of performance based on detector and electronics parameters.

Best method to deal with changes from radiation beyond 10^{15} neq/cm^2 to be established this year. Have now a rather good understanding of the detector behavior and effort shifting into developing an electronics readout system. Has much potential for use at the HL-LHC. In other applications could use to form an excellent time of flight system using layers spaced in distance or if a very accurate start time is known.

References on Technology Development

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[2] N. Cartiglia et al., "Beam test results of a 16 ps timing system based on ultra-fast silicon detectors", Nucl. Instrum. Meth. A850, (2017), 83–88.

[3] RD50 Krakow Workshop talks:
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[7] N. Cartiglia et al, "Performance of Ultra-Fast Silicon Detectors", JINST 9 (2014) C02001.

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[9] RD50 collaboration, http://rd50.web.cern.ch/rd50/