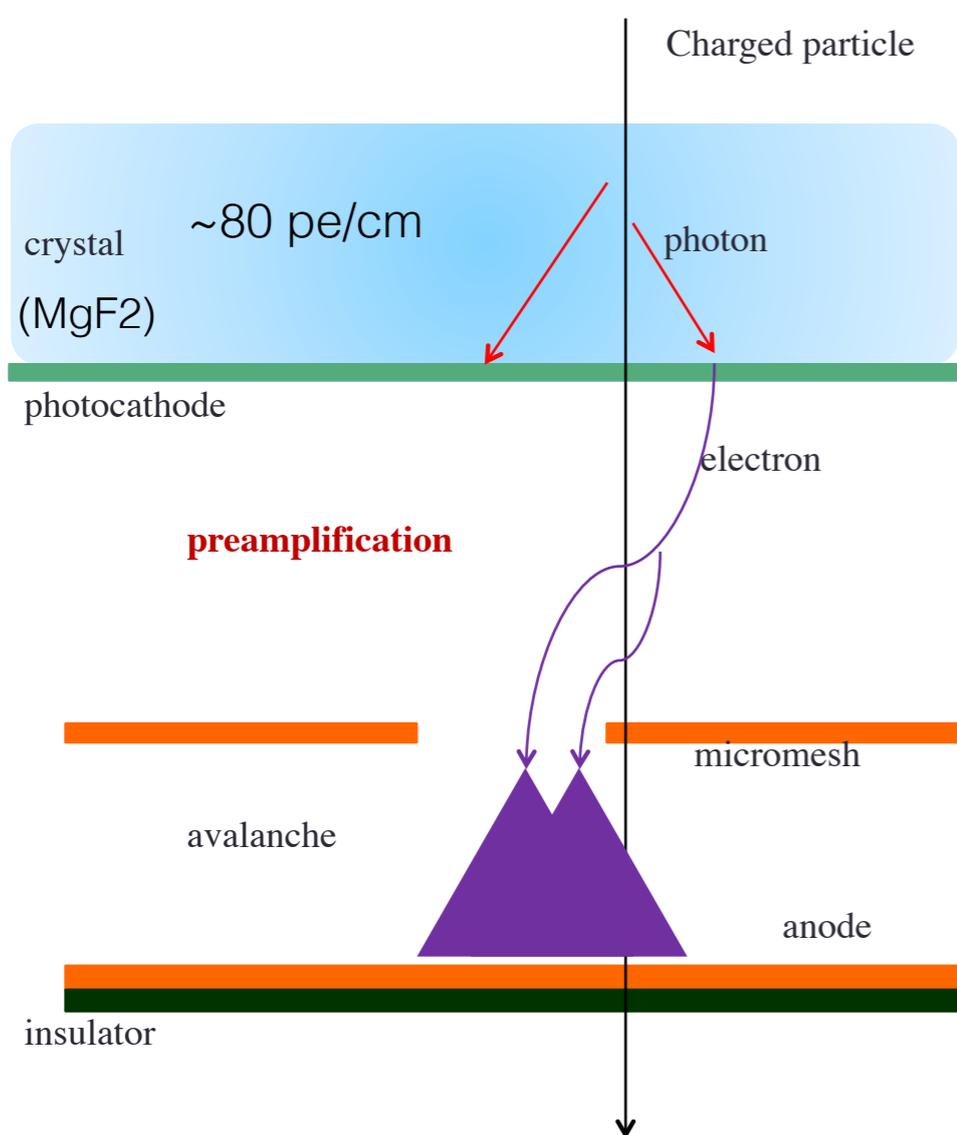


Large Area Photodetectors based on MicroPattern Sensors

Sebastian White CERN/Princeton

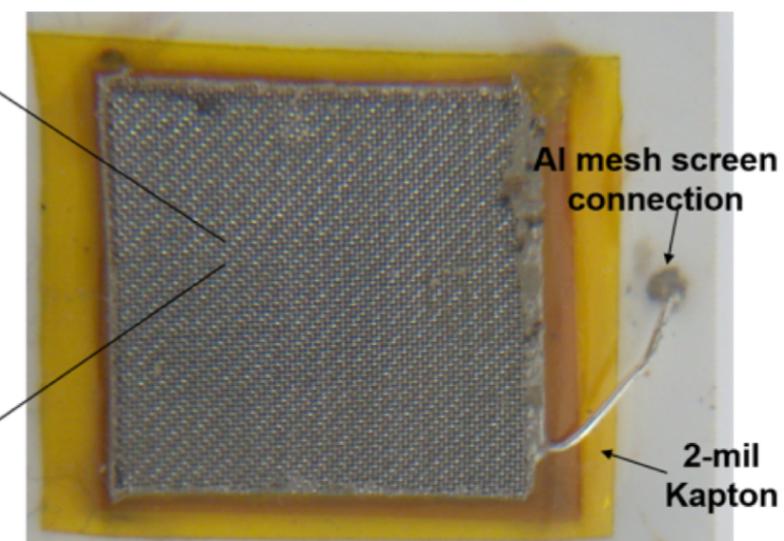
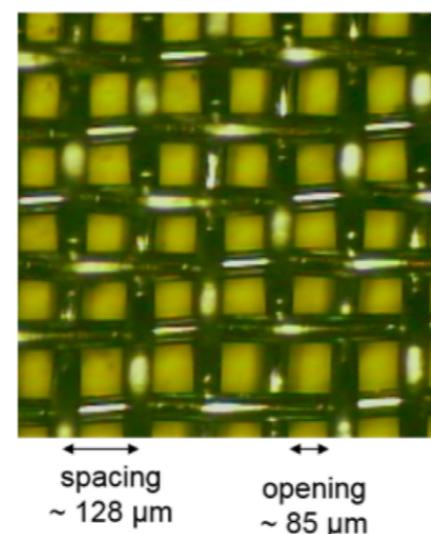
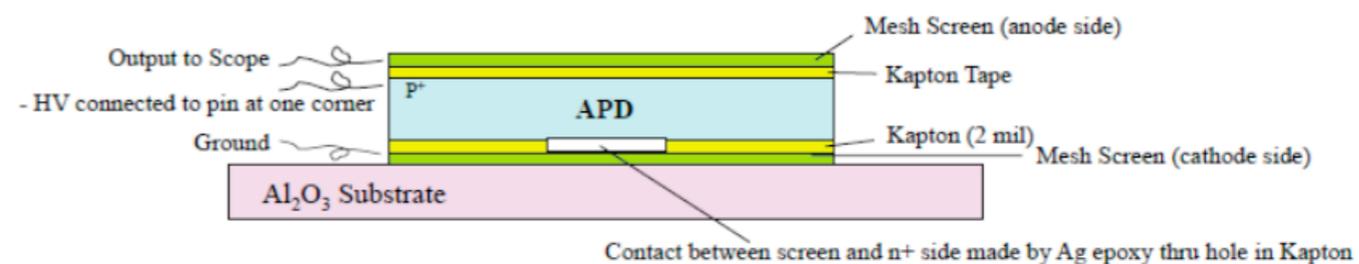
CPAD mtg. UT Arlington Oct 6, 2015

Gas MIP sensor retooled
->photosensor



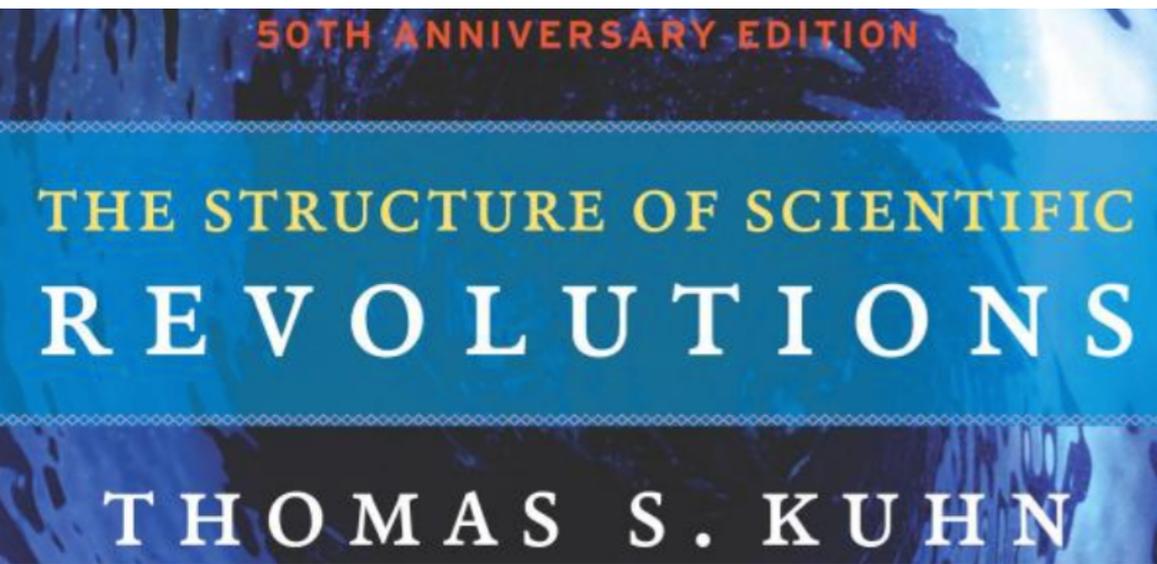
Si photosensor retooled
->MIP sensor

Top Screen Output Connection (capacitively coupled)



“How we stumbled on reversing the roles of 2 sensors”

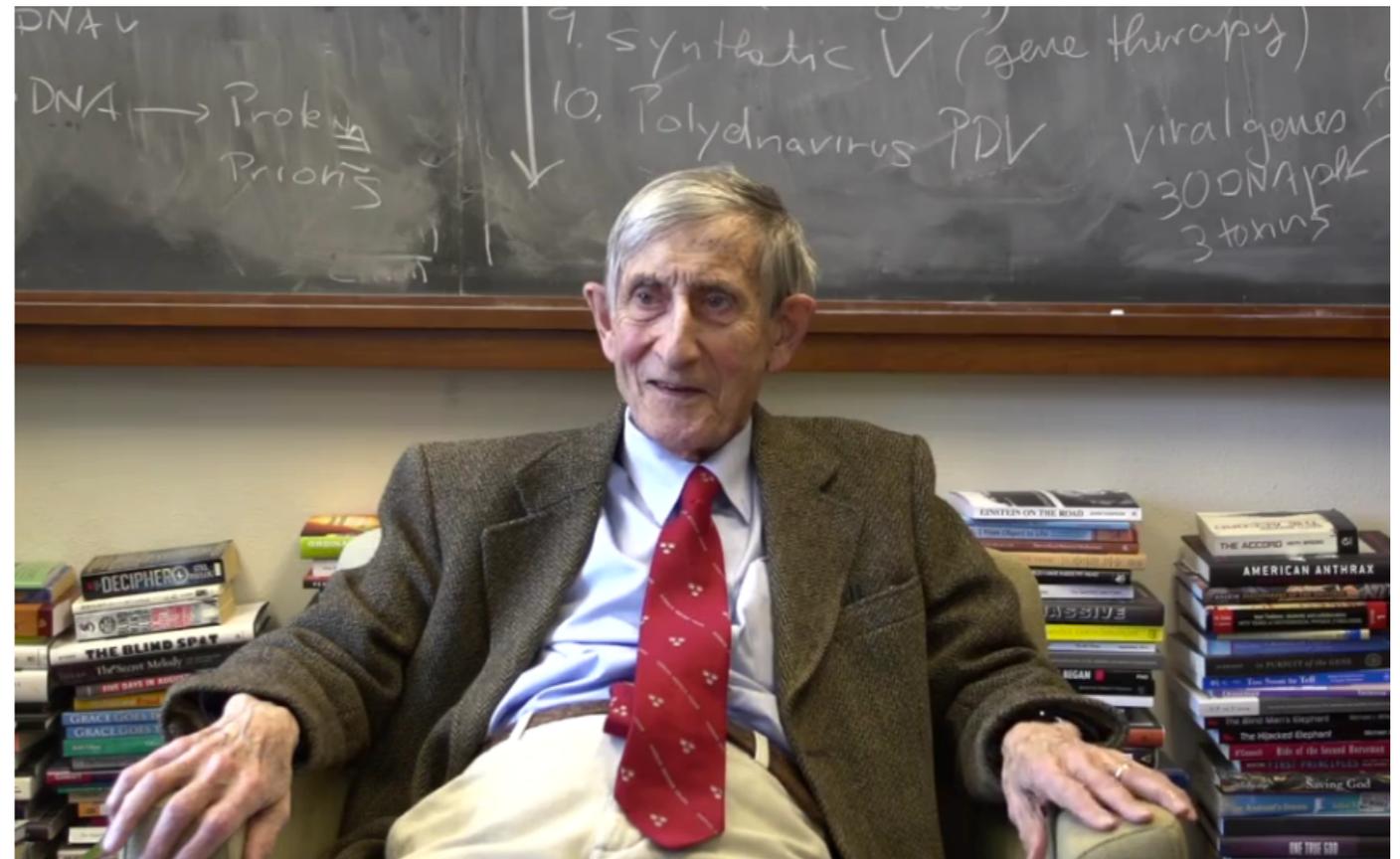
An Aside: Ideas and Tools (see Ian's opening talk)



HISTORY OF SCIENCE

Is Science Mostly Driven by Ideas or by Tools?

1. [Freeman J. Dyson](#)



"In almost every branch of science, and especially in biology and astronomy, there has been a preponderance of tool-driven revolutions..."

Freeman Dyson, "Imagined Worlds", 1997

Quoted by W. Riegler in 2008 CERN Academic Lectures. It became popular with managers arguing for Instrumentation funding (ie Snowmass). I recently corresponded with Dyson to get an update:

...2012 article in Science: "Is Science Mostly Driven by Ideas or by Tools?" As you will see, the answer to the question is that both are important. Sometimes ideas are dominant and sometimes tools.

You can quote me on both sides of many questions. I am glad to hear that Tolstoy is alive in Lausanne. Yours, Freeman.

Dyson, private communication, May 2013

Micropattern detectors enable Precision Tracking and Speed

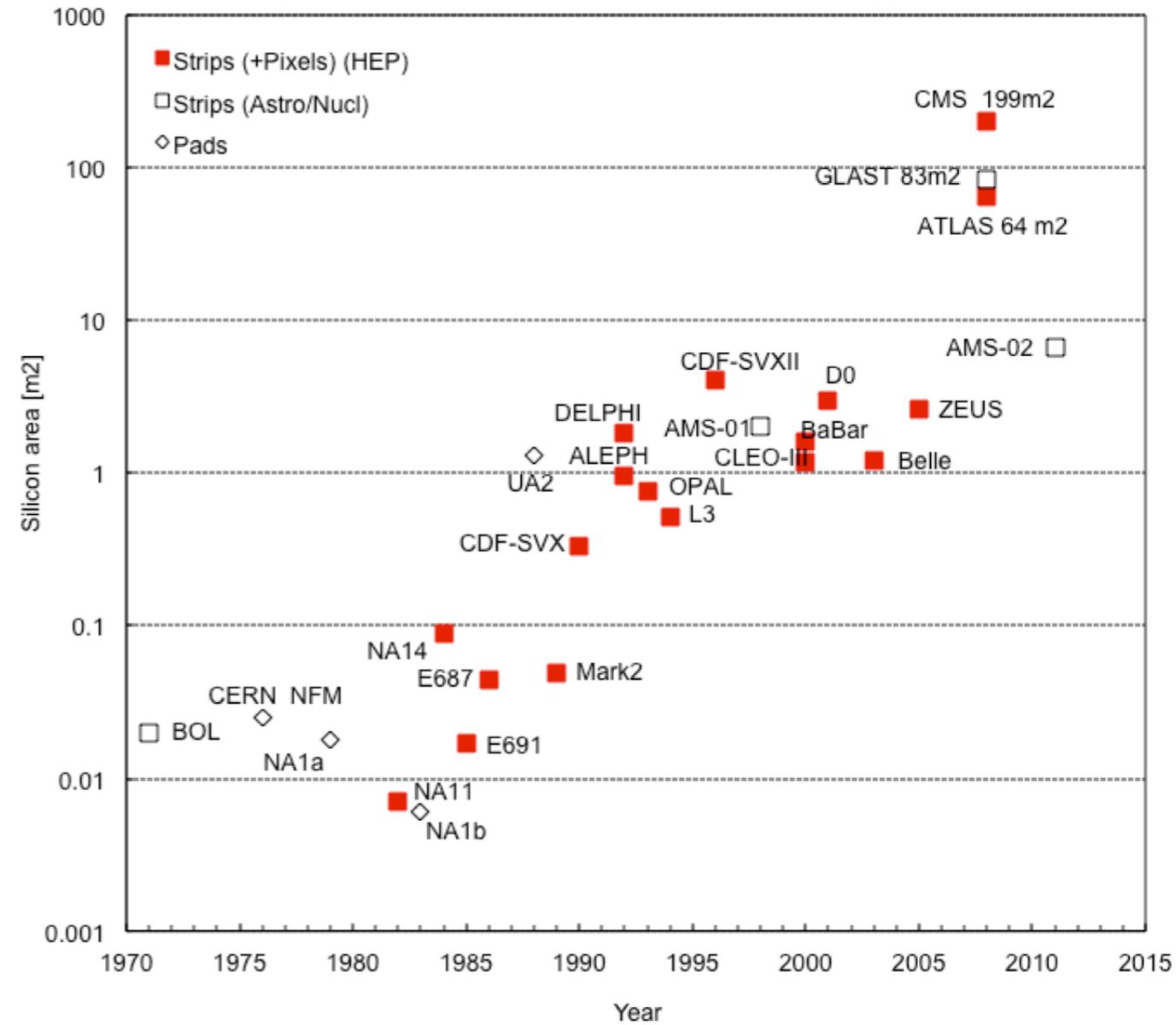
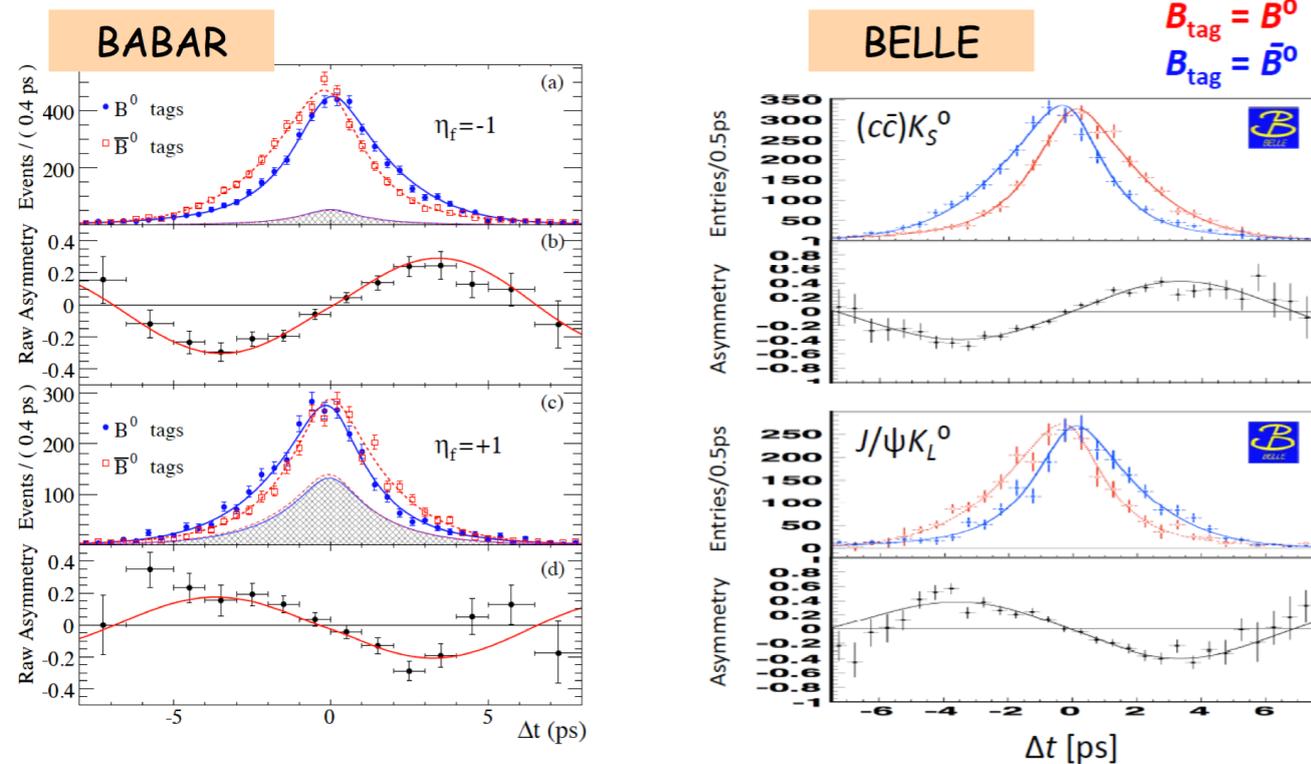
“Neutrino Flux Monitor”, Heijne, Jarron et al., 1976

November Revolution, c-quark, 1974

Upsilon, b-quark, 1979

A.B.Carter&A.I.Sanda, CP violation in b decay, 1981

file by Nobu Unno, KEK, updated June-August 2015 by Erik Heijne, CERN



but we accessed picoseconds with precision tracking

Does HL-LHC Provide an “unmet need” for Fast Timing?

we are in a transition Period

CDF/Tevatron

LHC

Burt Richter

<http://arxiv.org/pdf/1409.1196.pdf>

“up to pileup of 6”

www2.pv.infn.it/~ifae2006/talks/ModelloStandard/Vallecorsa.ppt



Table 1: Examples of 100 TeV colliders scaled from HL-LHC

Parameter	HL-LHC	LHC-100 8T	LHC-100 16T
Beam Energy (TeV)	7	100	100
Circumference (km)	27	190	95
L ($\text{cm}^2\text{sec}^{-1}$)	5×10^{34}	2.5×10^{36}	2.5×10^{36}
Bunch Spacing (ns)	25	25	25
Beam Current (Amp)	1.09	7.7	7.7
Synchrotron Rad Power (Mw)	0.0075	2.6	10.3
β^* (cm)	15	15	15
ϵ_n (micron)	2.5	2.5	2.5
Particles per Bunch	2.2×10^{11}	1.5×10^{12}	1.5×10^{12}
Events per bunch collision	140	7000	7000
Events per mm	1.3	0.0025	0.0025

(@LHC ALICE used $\sim 10^5$ channel 80 picosec TOF to enable precision matter/antimatter symmetry test. R&D of C. Williams et al- \rightarrow 16 picosec but @low rates.)

Is there a limit to all this?

see eg. :R.**Huson**, L.M.**Lederman** and R. **Schwitters**, "A Primer on Detectors in High Luminosity Environments", in Snowmass 1982, Proceedings

Impact of pileup on reco

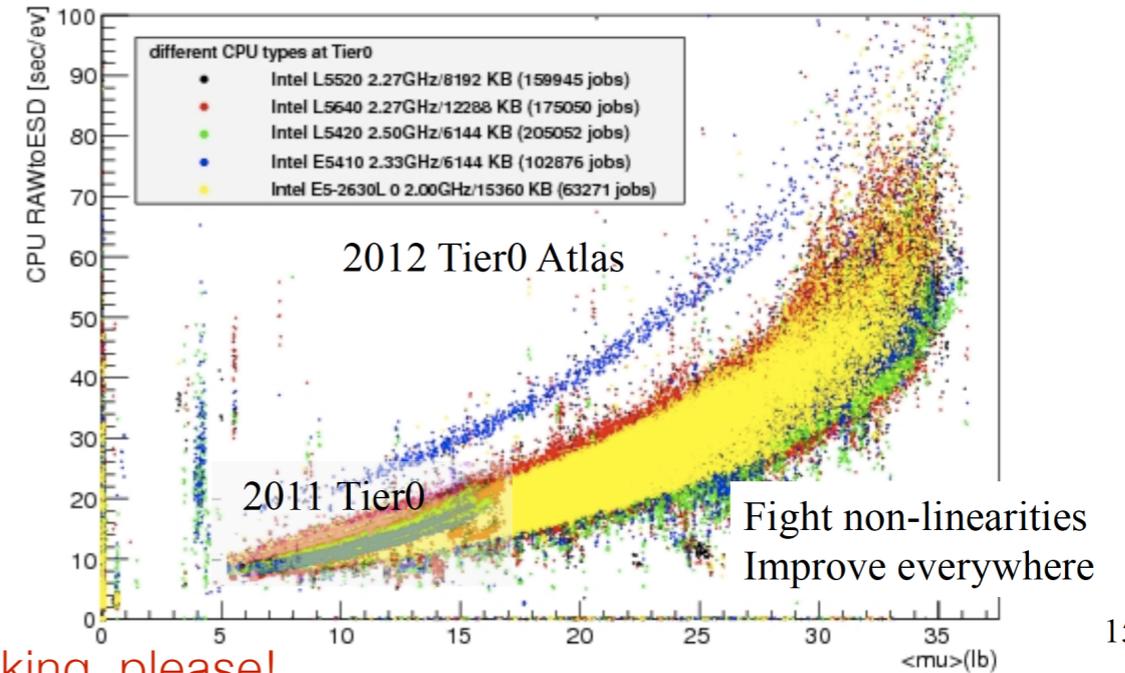


Reconstruction CPU time at Tier0 vs pileup (Jet stream)

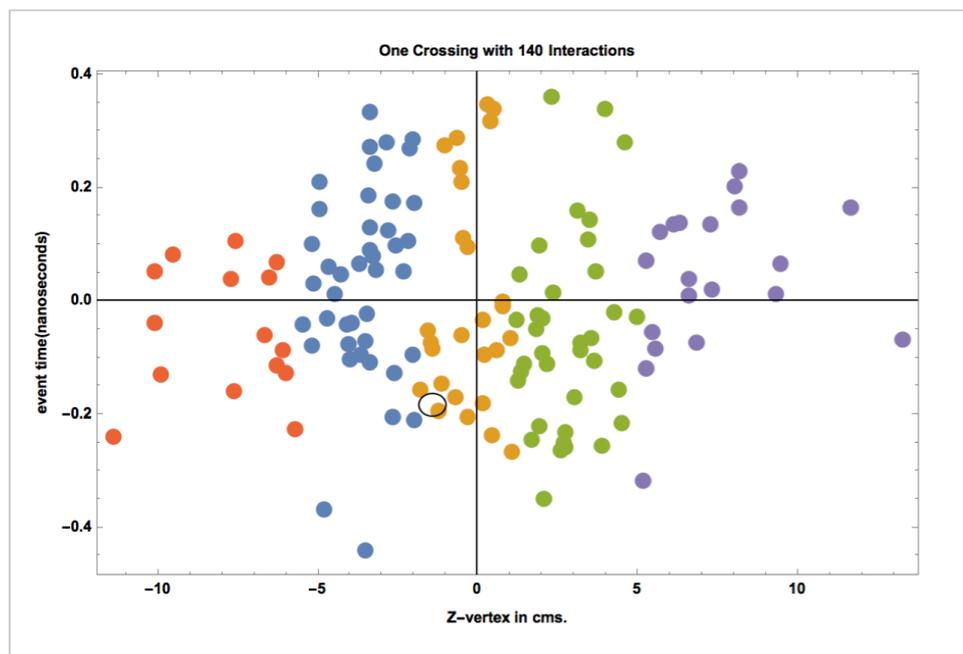
D. Rousseau, ATLAS
ECFA 2013



- when will this plot go North?
- general feeling that better algorithms will be found. Are there tradeoffs?
- could "hit time" aid reconstruction?



SNW, <http://arxiv.org/pdf/0707.1500.pdf>, 2007 No crab-smacking, please!
dt is useful.



dt~20psec



Distribution of z-vertex Distances between nearest Neighbors/crossing (time cut and uncut)

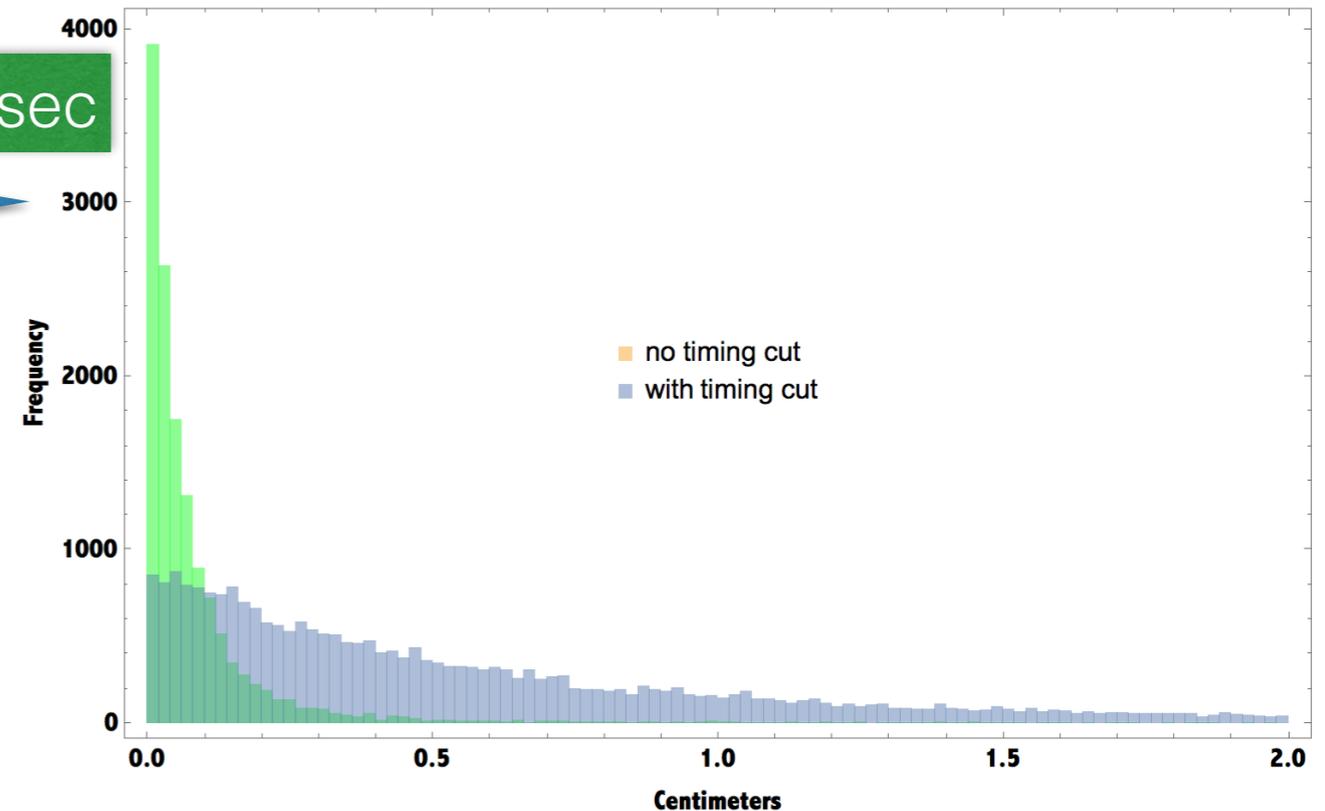
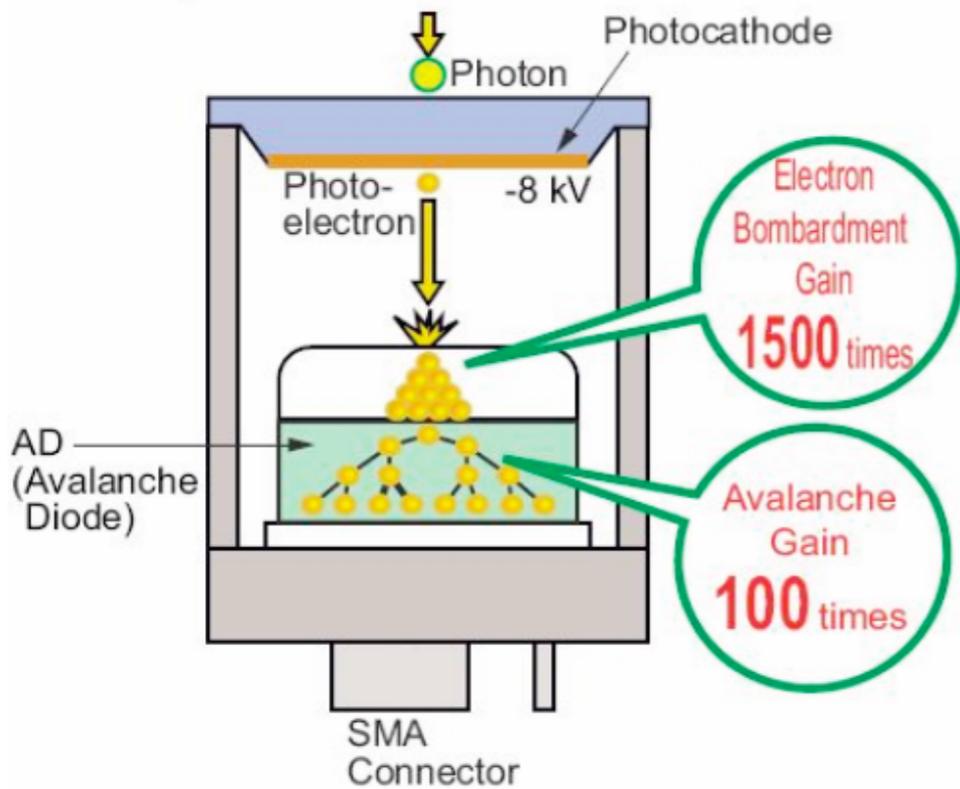
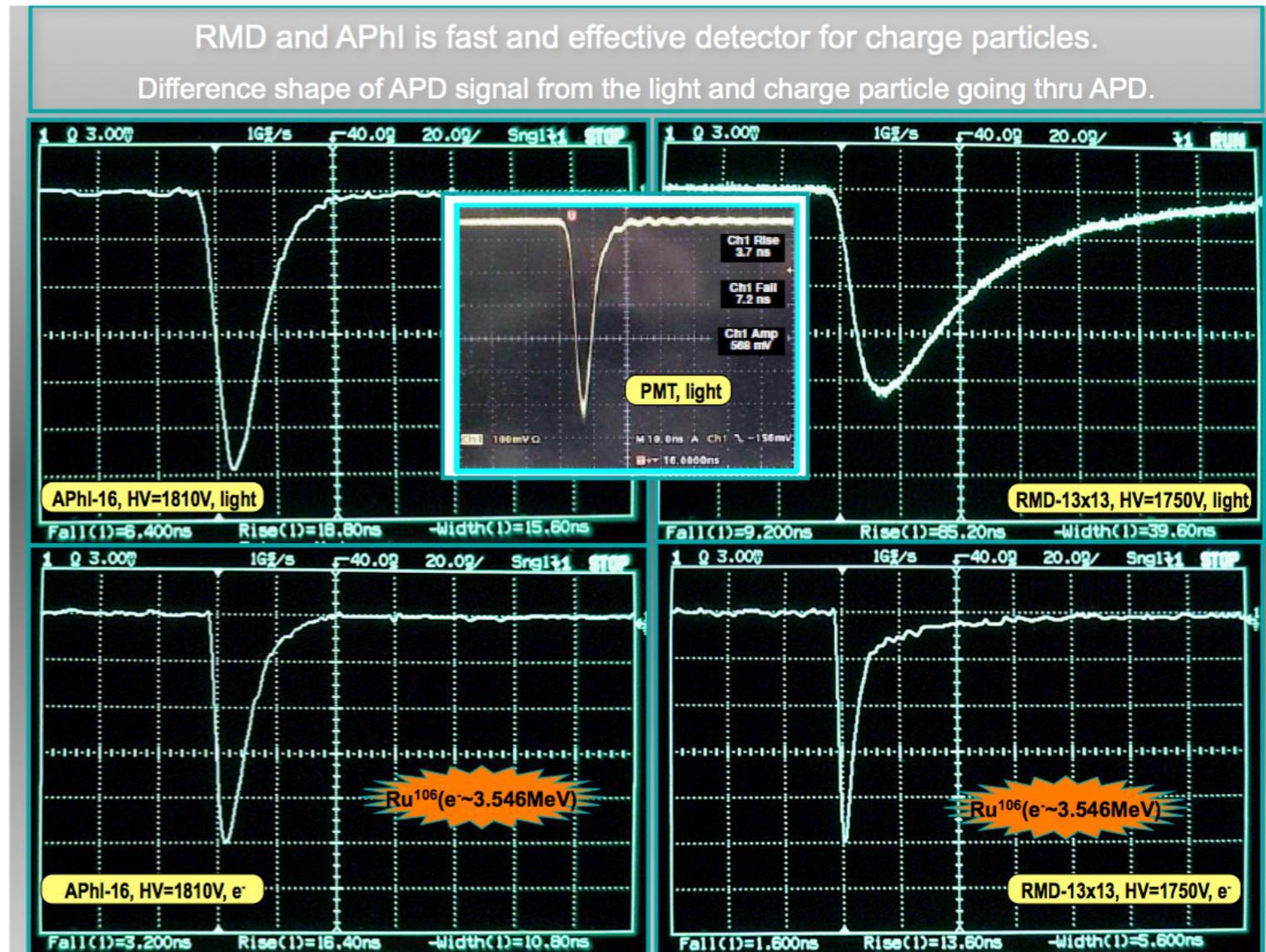


Fig. 1. Simulation of the space(z-vertex) and time distribution of interactions within a single bunch crossing in CMS at a pileup of 140 events- using LHC design book for crossing angle, emittance, etc. Typically events are distributed with an rms-in time- of 170 picoseconds, independent of vertex position.

How we got into Avalanche Diodes

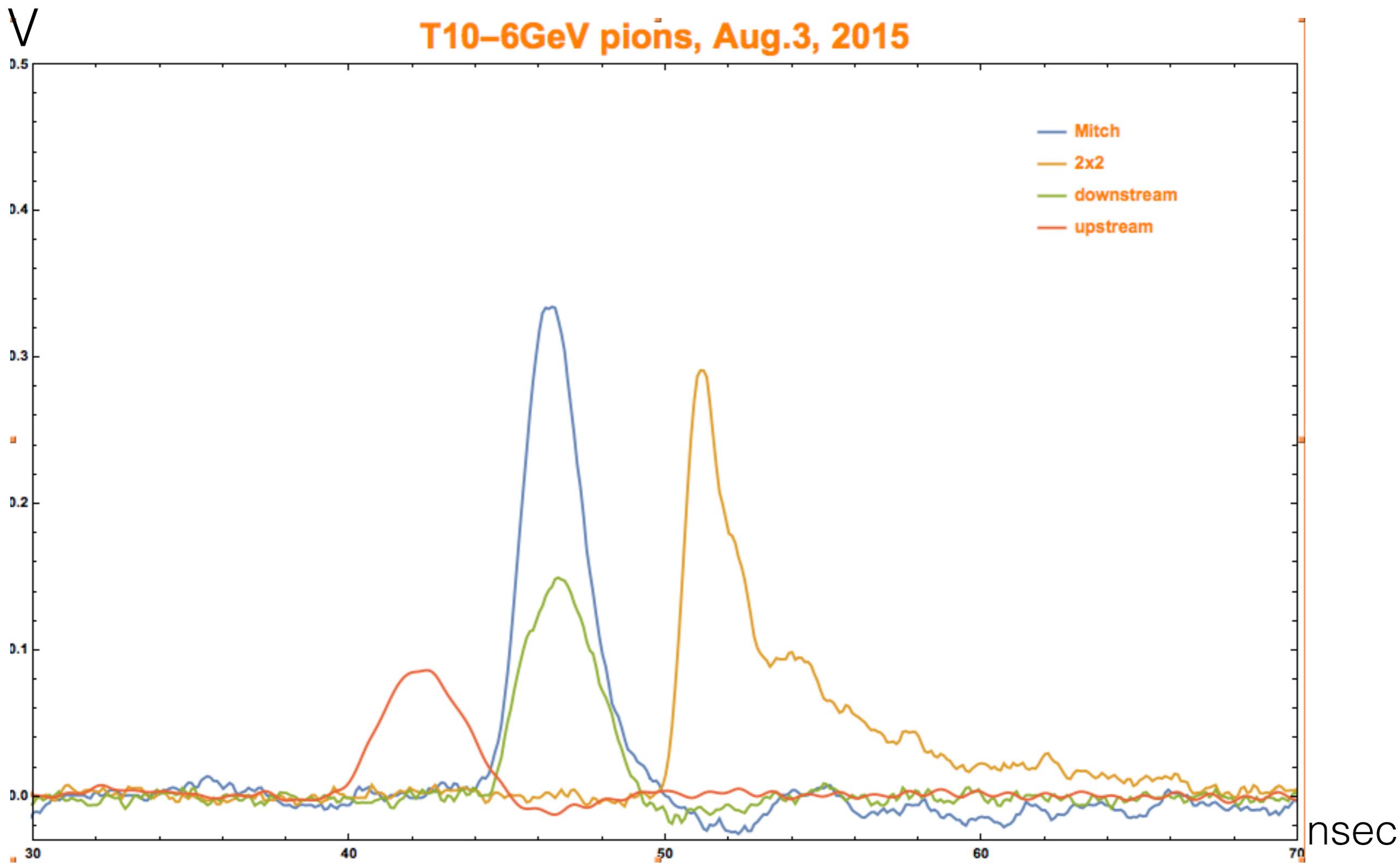


Koei Yamamoto, Motohiro Suyama, HPK
 In 2009 we evaluated their pre-production alternative to MCP
 we found 11 pico sec SPTR
 Clear indication that Avalanche diode intrinsically a fast charged particle detector!



Could such an intrinsically fast device with very large MIP signal be exploited for timing?

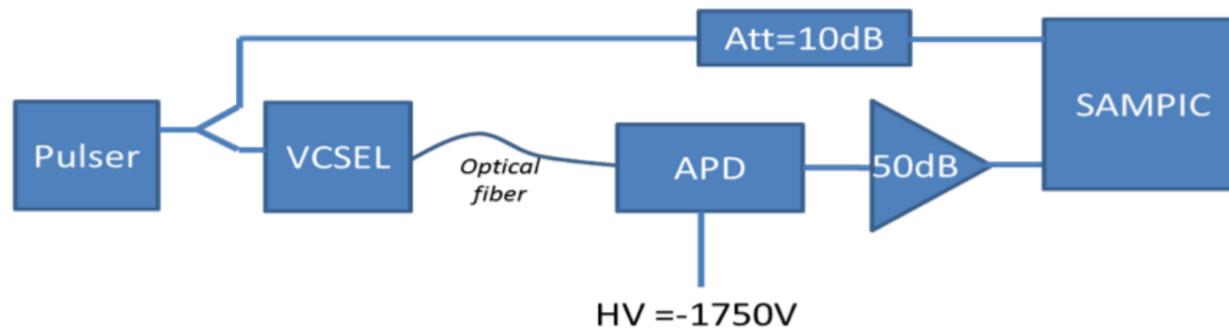
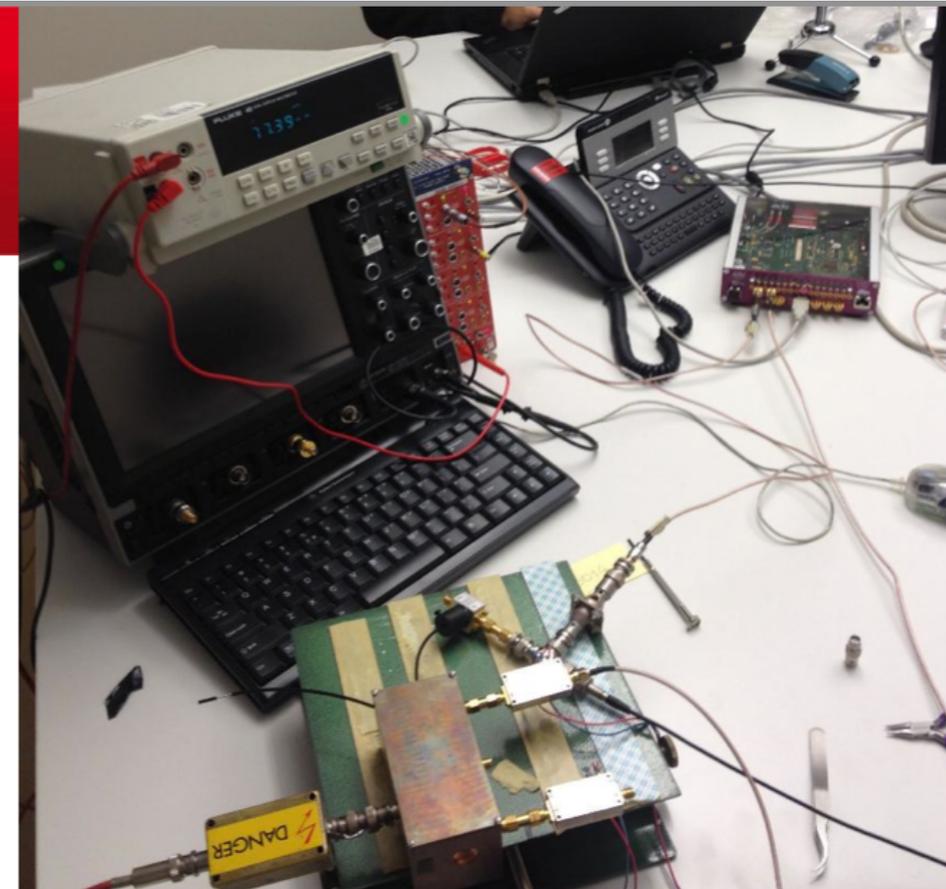
the answer is yes. But it has taken a long development cycle- still in progress
see: CERN Detector seminar “Fast Timing R&D for the HL-LHC Era”
SNW, Sept 25, 2015 <https://indico.cern.ch/event/439571/>



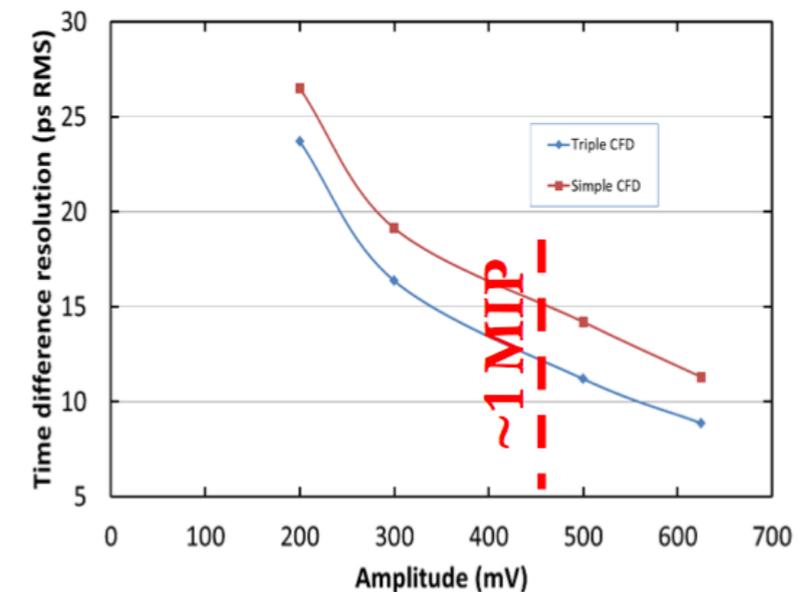
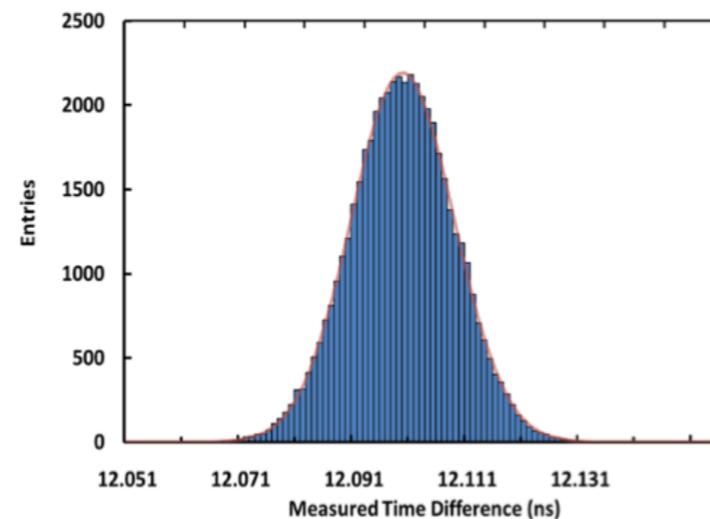
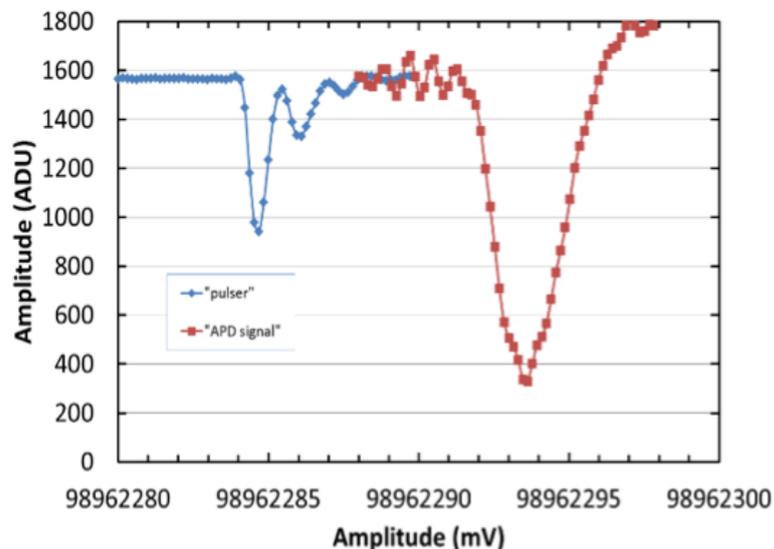
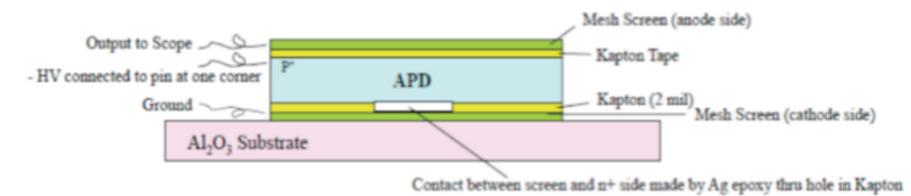
pre-existing collaboration with Orsay/Saclay on timing- see D. Breton's Elba talk:

MEASURING PICOSECONDS ...

- SAMPIC module has been connected to **S.White's fast mesh-APD** at CERN (see S.White's poster).
- Goal : measure the **time difference between the pulser and the APD signal** => detector time resolution
- All measurements below performed in **~1 hour**.
- Best measurement **< 10 ps rms**



Top Screen Output Connection (capacitively coupled)



Above work within framework of Hyperfast Si Development

1) HFS=Mesh Readout Si

representing:

C. Williams*, P.Lecoq*, SNW -in collaboration w. M. Moll, C. Gallrapp,
M. Fernandez-Garcia(CERN)

E. Delagnes (CEA/Saclay)

K. McDonald, C. Lu, K. Mei, C. Tully & SNW (Princeton)

M. Newcomer (U. Penn)

for USCMS Phase II Upgrade R&D

industrial partner RMD/DYNASIL: M. McClish, R. Farrell

outside collaborators T. Tsang (BNL Instrumentation)

Remainder of talk focus on Micro-pattern Gas Detectors (MPGD) (see also latest CERN courier)

RD51 common fund project Awarded 3/2015

Title of project: **Fast Timing for High-Rate Environments: A Micromegas Solution**

Contact persons: Sebastian White (co-PI), CERN/Princeton sebastian.white@cern.ch
Ioannis Giomataris (co-PI), Saclay [ioa@hep.saclay.cea.fr](mailto:ioa@hep.saclay cea.fr)

RD51 Institutes:

1. IRFU-Saclay, contact person Ioannis Giomataris ioa@hep.saclay.cea.fr
E. Delagnes, T. Papaevangelou, M. Kebbiri, E. Ferrer Ribas, A. Peyaud, C. Godinot
2. NCSR Demokritos, contact person George Fanourakis gfan@inp.demokritos.gr
3. CERN, contact person, Leszek Ropelewsky Leszek.Ropelewski@cern.ch
E. Olivieri, H. Muller, F. Resnati, SNW
+ RD51&Uludag University, Rob Veenhof veenhof@mail.cern.ch
4. Universidad de Zaragoza, Diego González Díaz diegogon@unizar.es

Ext. Collaborators:

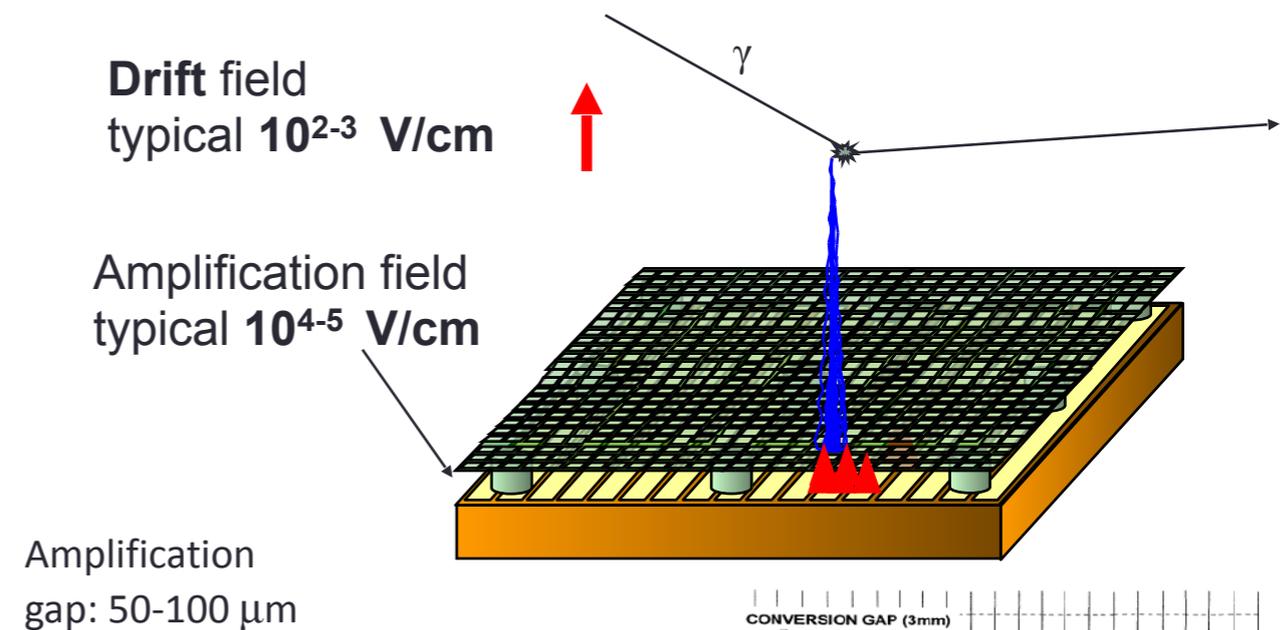
1. Princeton University, contact person K.T. McDonald, kirkmcd@princeton.edu
Changguo Lu, SNW

Micromegas concept

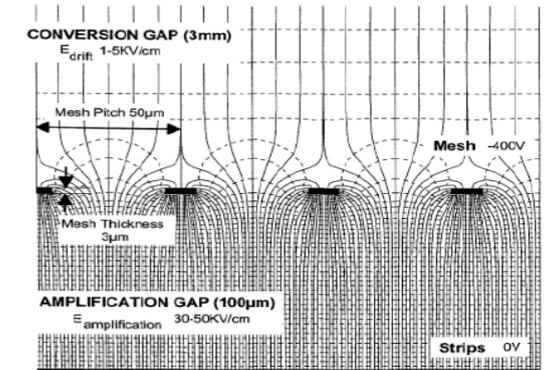
Two-region gaseous detector **separated by a Micromesh** :

- Conversion region
 - Primary ionization
 - Charge drift towards A.R.
- Amplification region
 - Charge multiplication
 - Readout layout
 - Strips (1/2 D)
 - Pixels

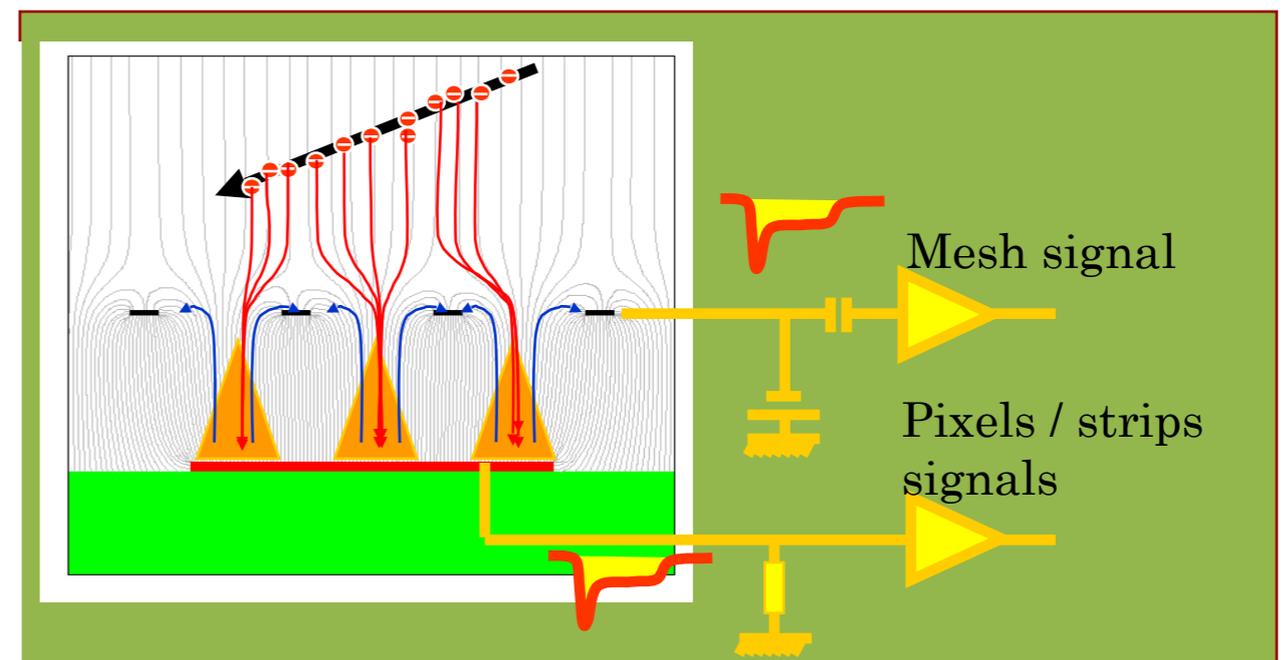
- Very strong and uniform electric field
- metallic micromesh (typical pitch 50 μ m)
- sustained by 50-150 μ m pillars
- single stage of amplification
 - fast and natural ion collection
 - limited ion backflow
 - discharges non destructive
 - low cost ($\sim 10\text{kE}/\text{m}^2$)



MICROMESH Gaseous Structure
Giomataris, Charpak (1996)
 Y. Giomataris et al., NIM A 376 (1996) 29



In 1st Micromegas
Fishing line spacers have been used

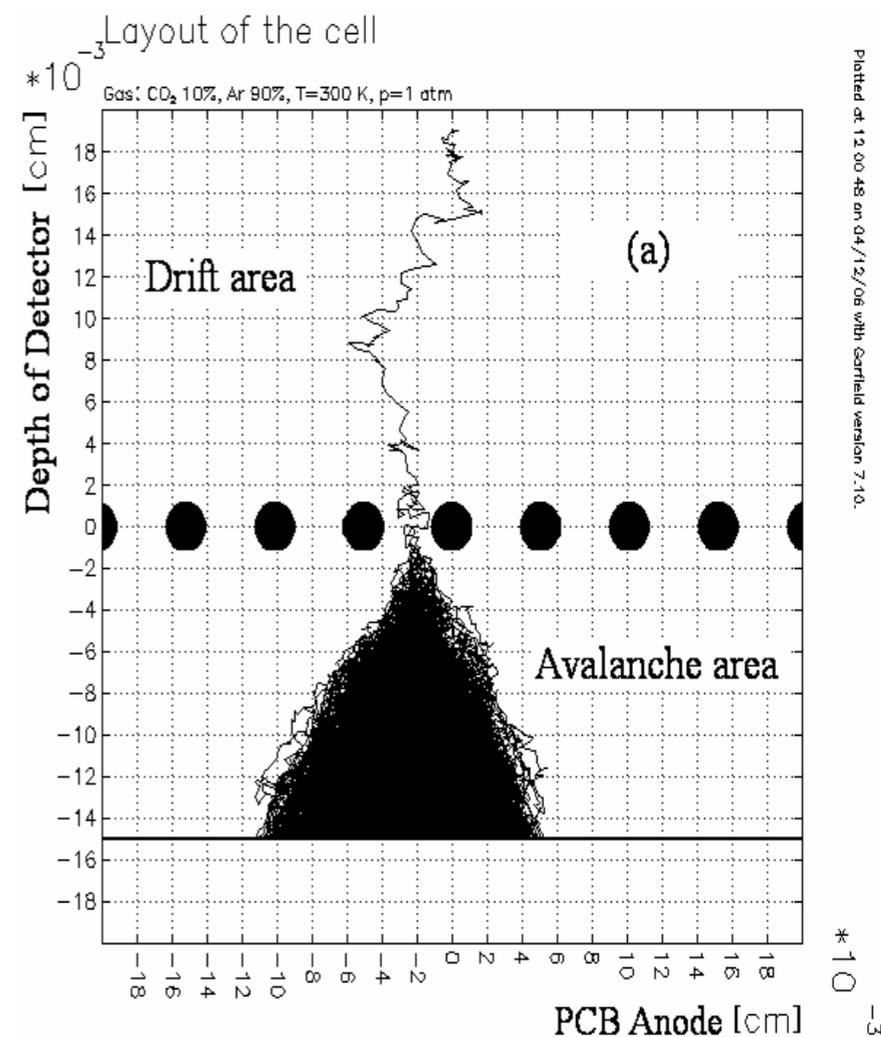
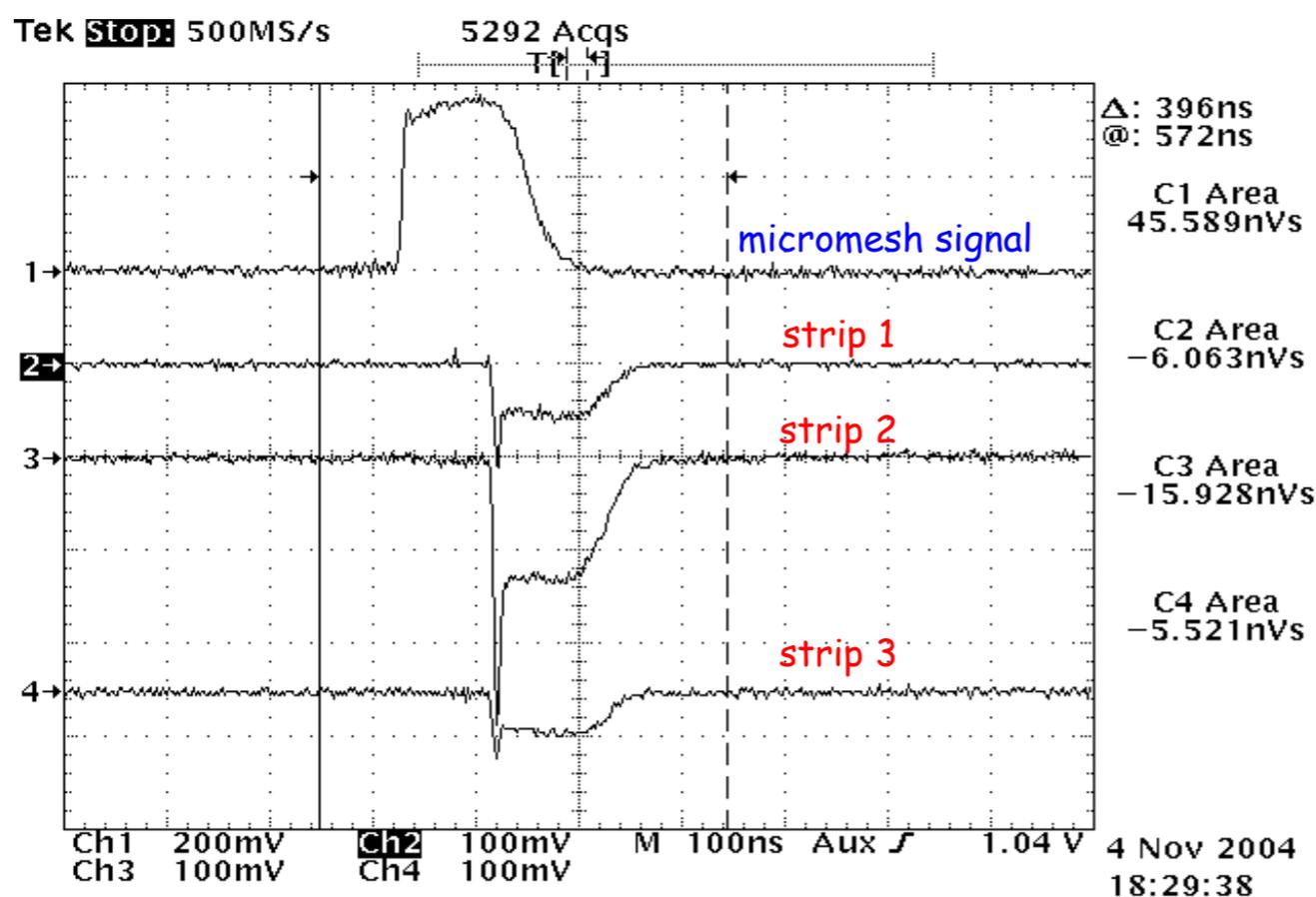


Micromegas time scales

The multiplication takes place in high E field (> 20 kV/cm) between the anode (strips, pads) and the mesh in one stage

small amplification gap (50-150 μm)

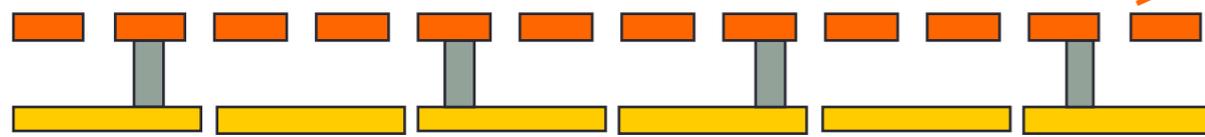
- fast signals (~ 1 ns)
- short recovery time (~ 50 ns)
- high rate capabilities (> MHz/cm²)
- high gain (up to 10^5 or more)



Time response is limited from the continuous ionization on the drift gap

Bulk technology

Readout plane + mesh all in one



Well established technique (lamination)

Bulking: Process to encapsulate the mesh on a PCB
(mesh = stretched wires)

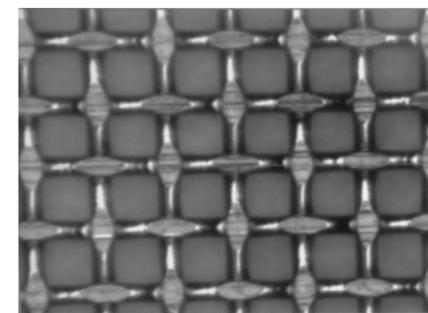
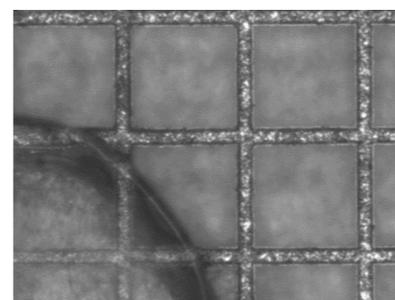
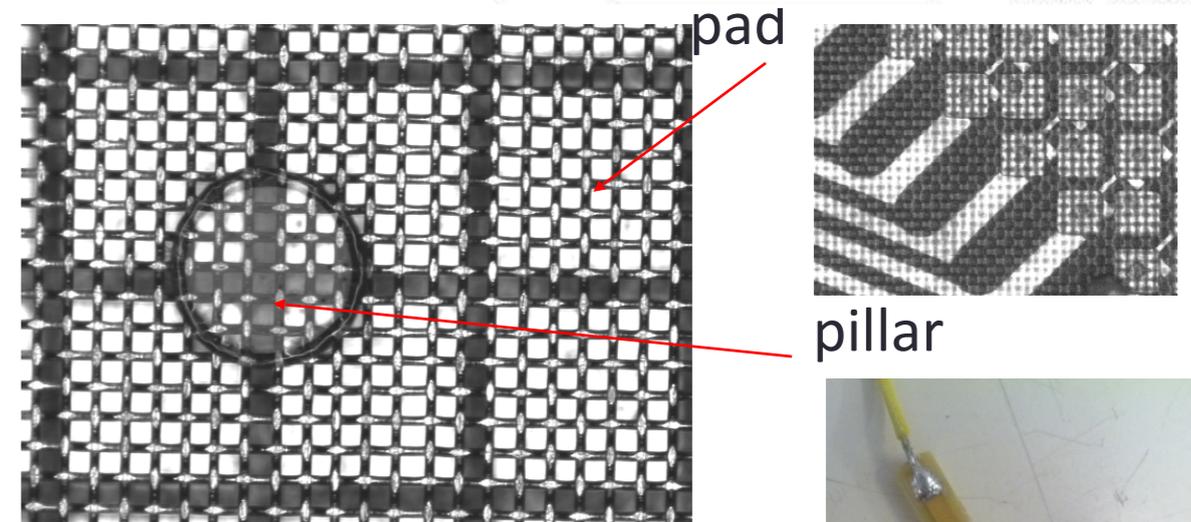
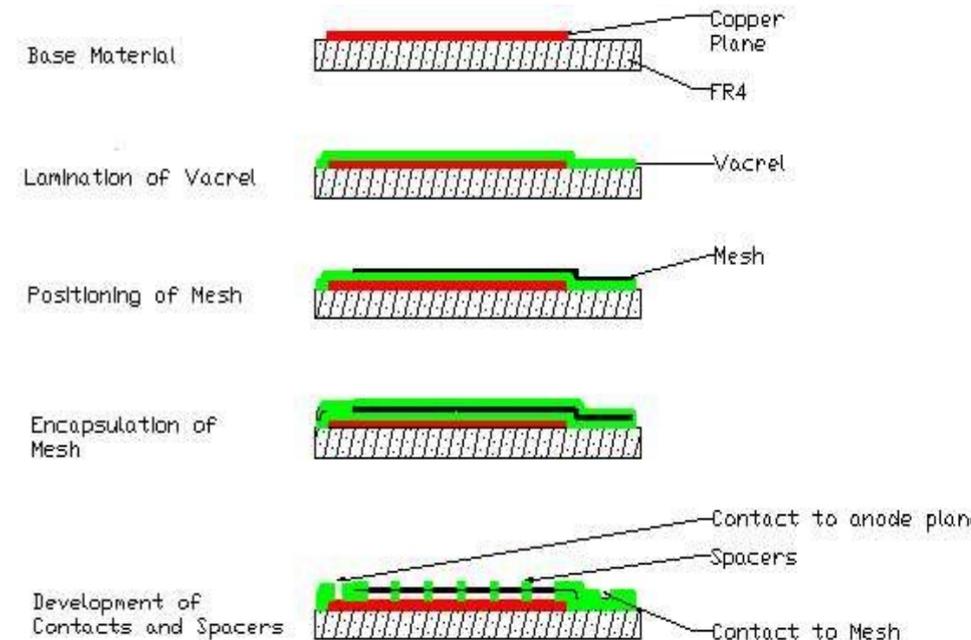
The pillars are attached to a woven mesh and to the readout plane (PCB)

Typical mesh thickness 30 μm , gap 128 μm

Uniformity, robustness, low cost, no supporting frame,

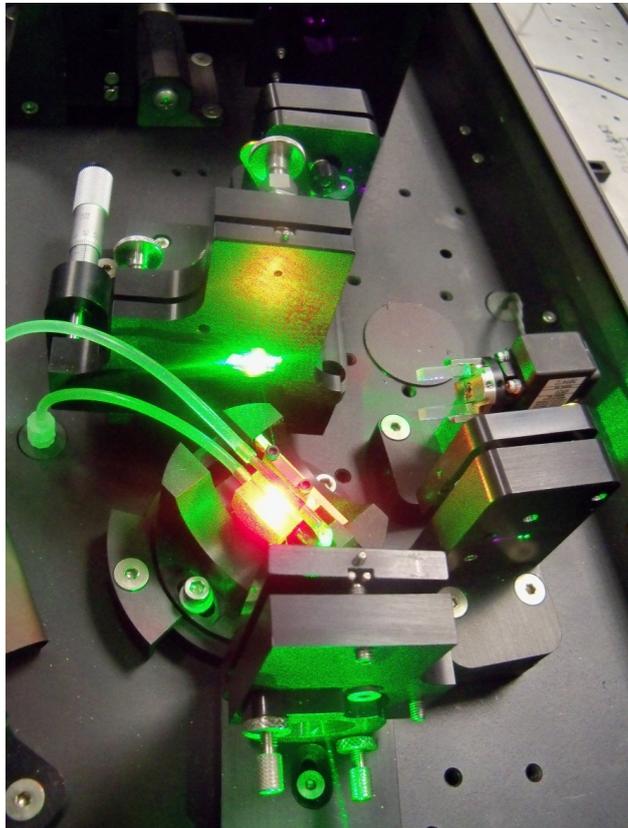
- ✓ Easy fabrication
- ✓ Large area detectors
- ✓ Mass production!
- ✓ **Ideal gap for Ne/He - based mixtures**

✗ One main disadvantage: Woven mesh
→ **Not possible to deposit the photosensitive material**



MPGD & Si Characterization with picosecond Lasers Key Throughout

- 1) The Ti:Sa wavelength is tunable from 700 to 1000 nm
 - 2) The fundamental laser pulse length at 800 nm is 120 femtoseconds. The Ti:Sa oscillator runs at 76 MHz repetition rate
 - 3) We used an OPO to obtain ~ 550 nm radiation, which were passed through a pulse-picker in order to decrease the repetition rate from 76 MHz to 11 kHz
 - 4) We then frequency doubled the ~ 550 nm radiation in a 5 mm BBO crystal, obtaining ~ 275 nm radiation.
 - 5) There are important losses in the pulse-picker so we had only about 0.15 pJ / pulse at 11 kHz ($275 \text{ nm} = 4.5 \text{ eV} \Rightarrow 1.75 \times 10^7$ photons / pulse)
 - 6) We use the residual 550 nm radiation leaking through a dichroic UV mirror in order to trig the electronics.
- (Generation of ultrashort pulses by “magic“ mode-locking was discovered in 1990.)

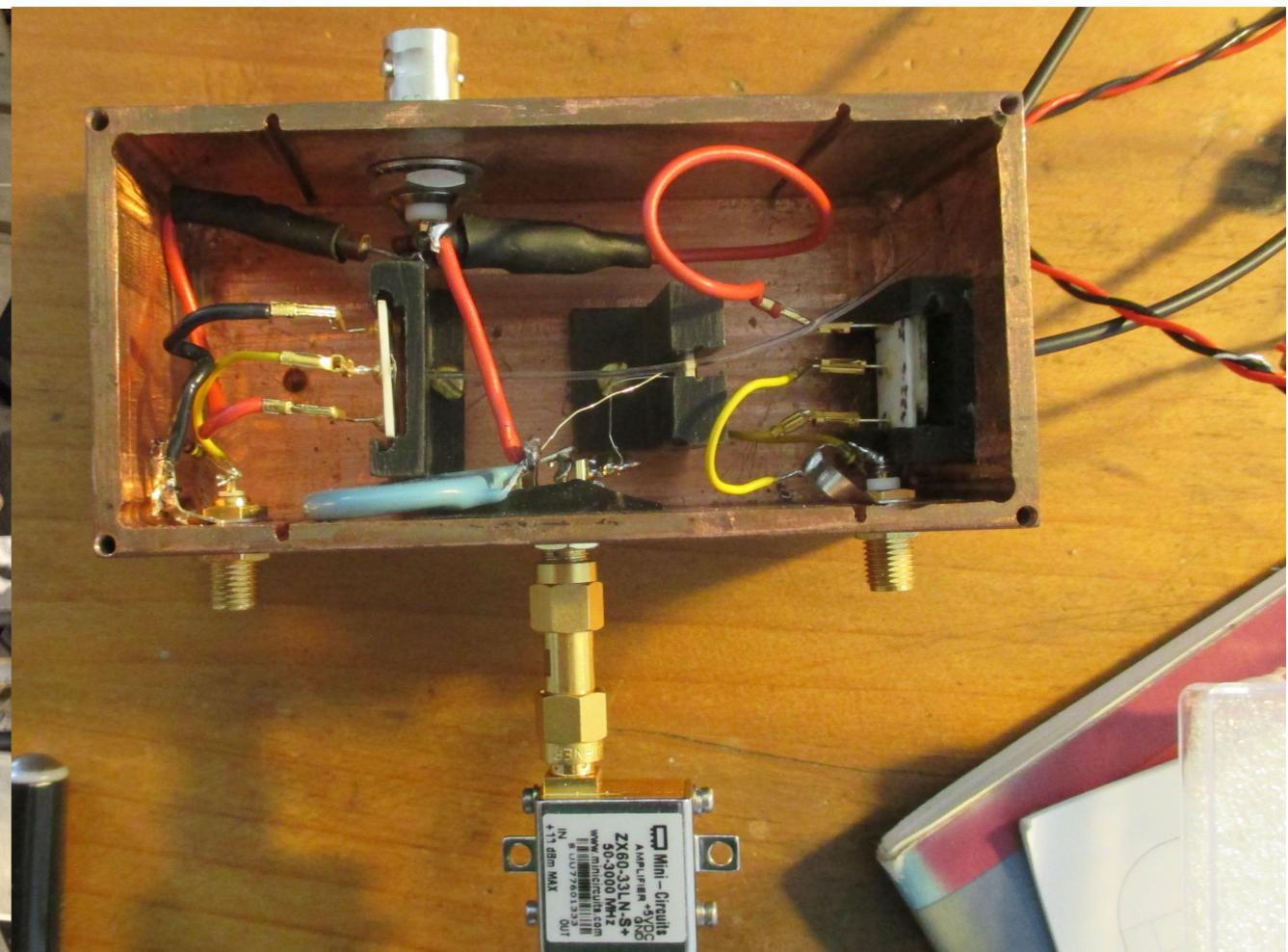
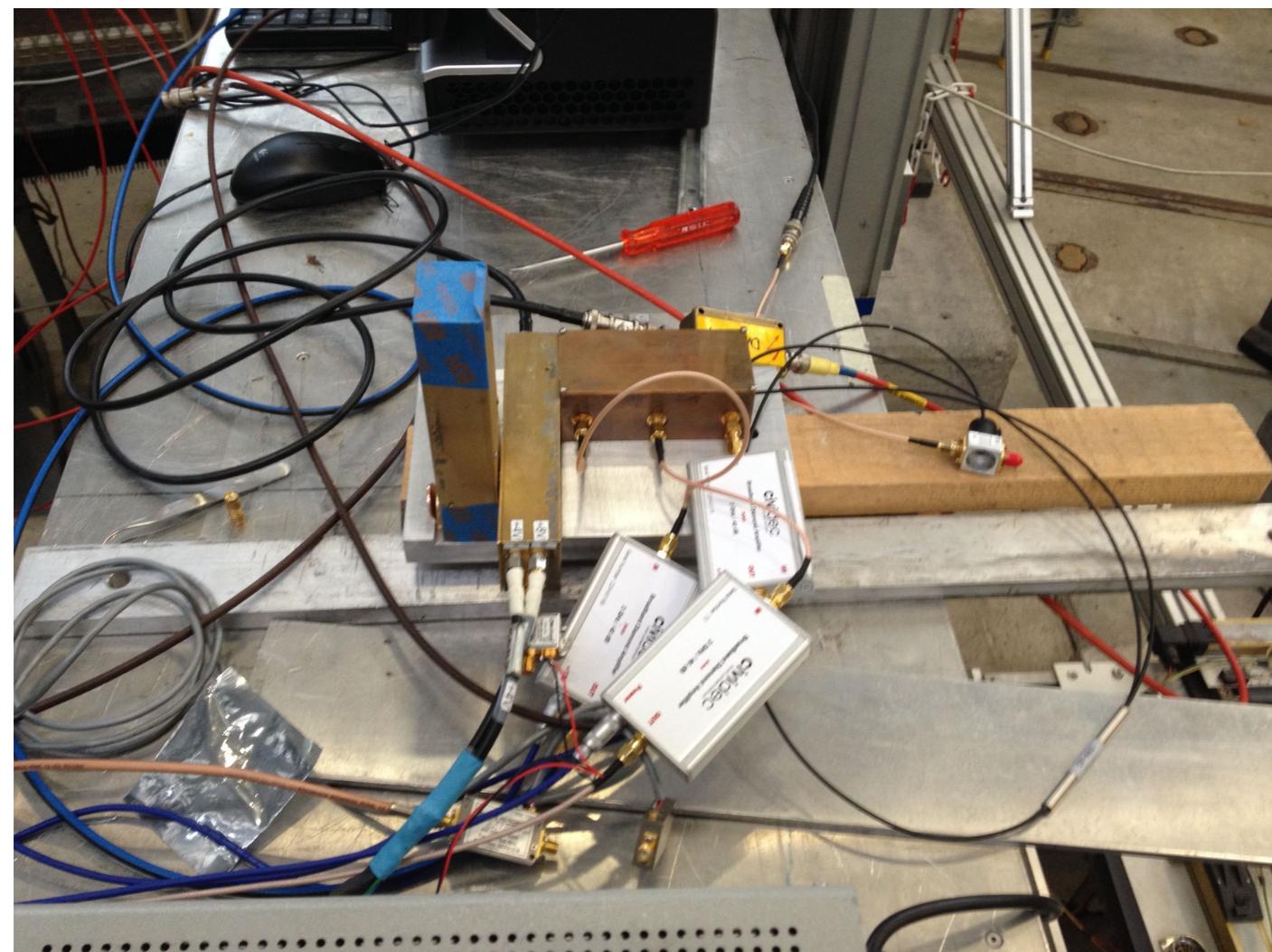


(Details from Thomas Gustavsson, IRAMIS)

We used ~ 1000 nm for Si (Thomas Tsang, Instrumentation Division)
-model for MIP deposition through Si detector
and 275 nm for MPGD (low q_e Al photocathode)

MIP Testing in Particle Beams

- High Brightness Electron Linacs \rightarrow $\text{RMS}_{\text{bunch}} \sim 3$ picosec
- \rightarrow ATF Expt Be44 (K.McDonald&SNW+V. Yakimenko, 2010)
- ~ 1 scattered 80MeV electron from 10^8 e bunch
- great for single device testing (in back yard)- also LAL?
- But abundant available beams @few GeV \rightarrow \sim dozen Si telescope tests at DESY, PSI, LNF, FNAL, PS&SPS in last 3 years



Model for Timing Layer Cell

1/2-1 cm² cell size
 down to ~8°
 ie well into “endcap”

we identified a chamber from “for fire”
 (an earlier Saclay MMegas project)
 special chamber also completing @CERN

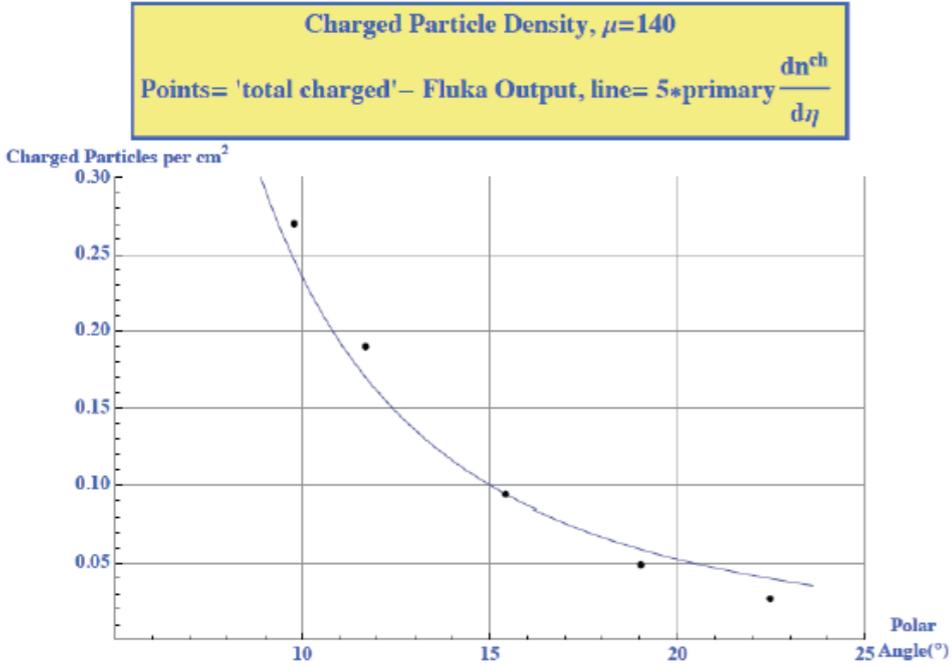
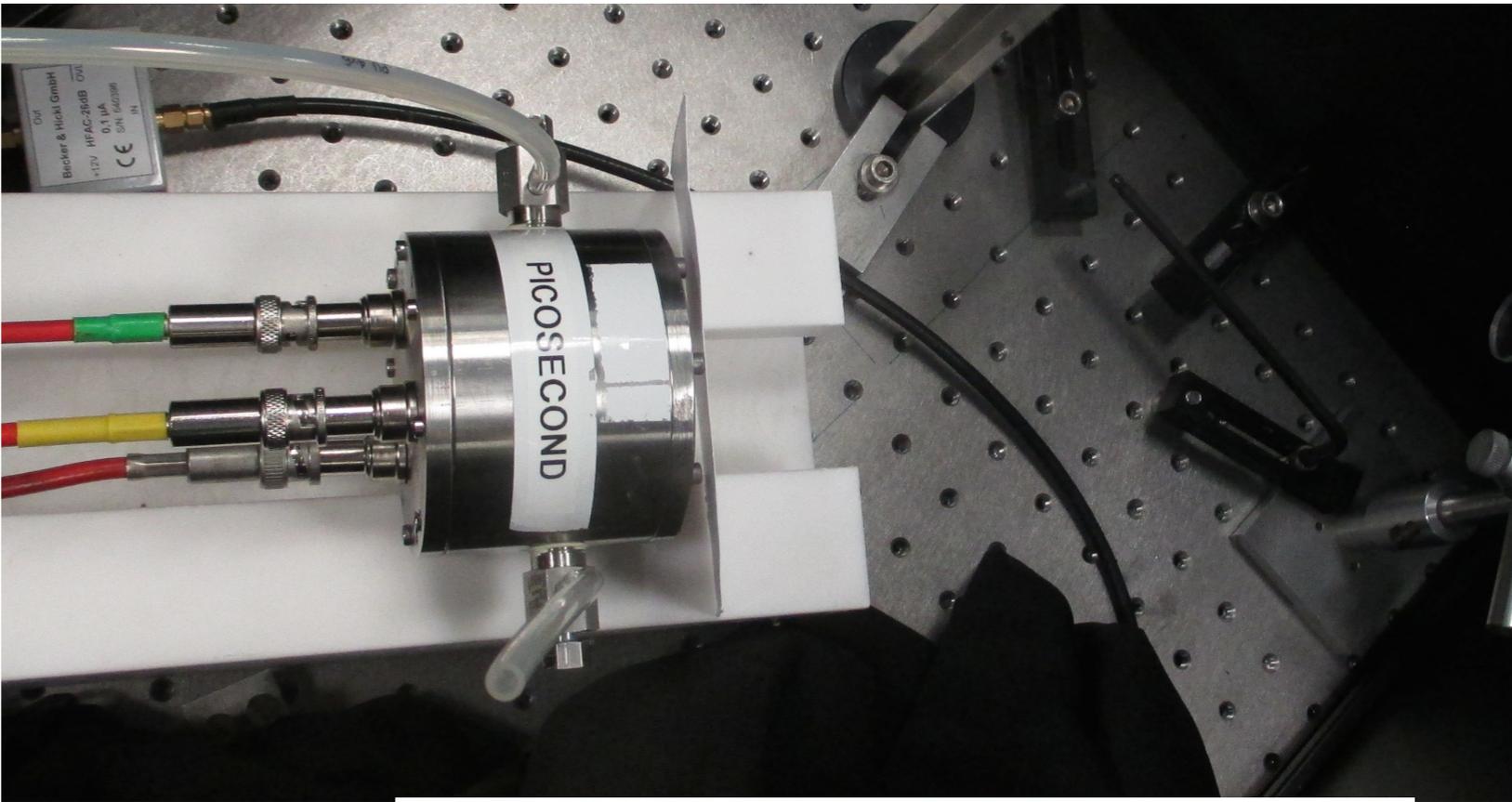
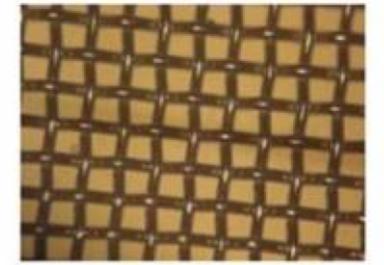


Figure 2: The charged particle density in the region of the dedicated timing detector. The points are FLUKA output for “total charged”. The line is calculated from estimates of primary charged particle density- $dn/d\eta$ - scaled up by a factor of 5. FLUKA output is roughly consistent with a constant factor over this angular range.



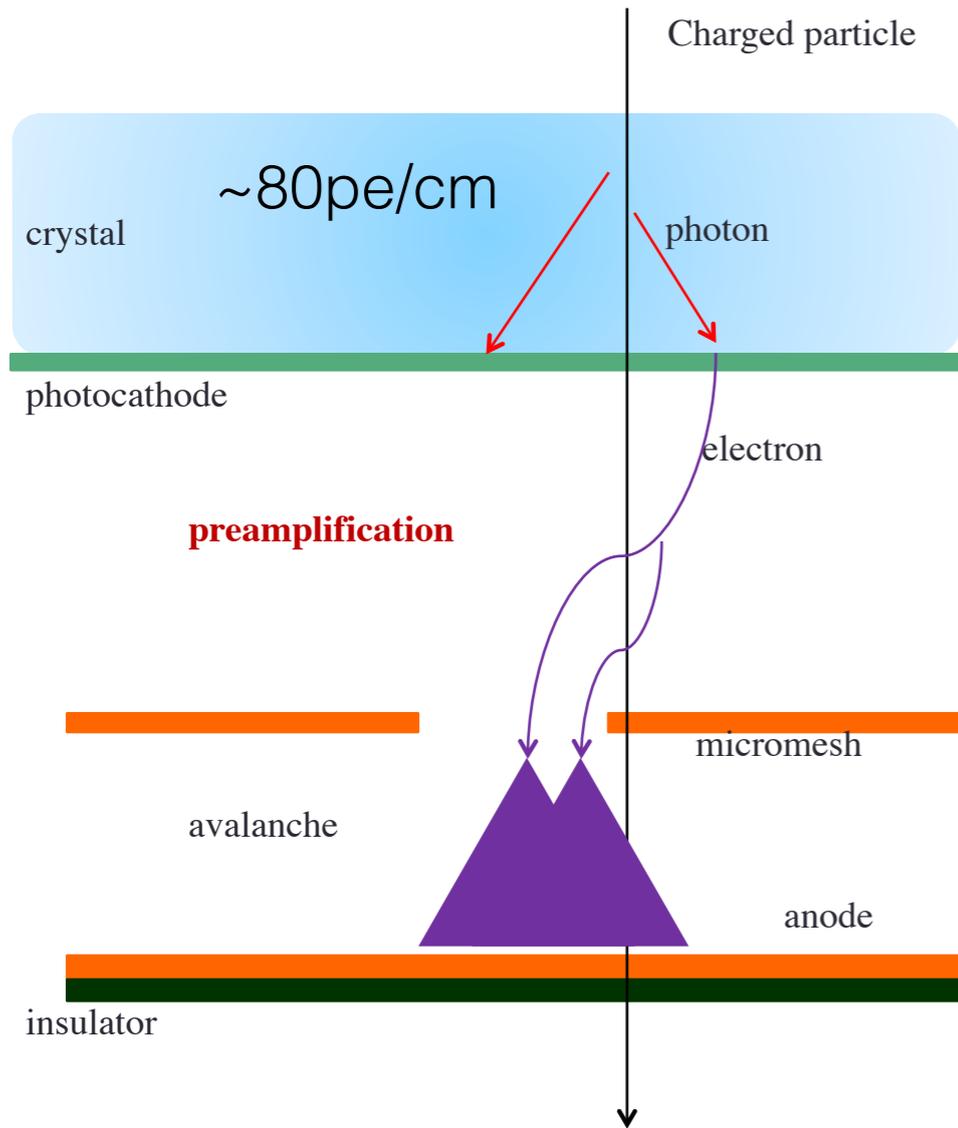
chamber consists of
 1) quartz window w. Al pc
 2) 0.2mm drift
 3) “Bulk 128” MMegas

The bulk-micromegas technique uses PCB production tools and methods
 The mesh is placed at a well controlled distance on top of a PCB, what opens the door to industrial fabrication

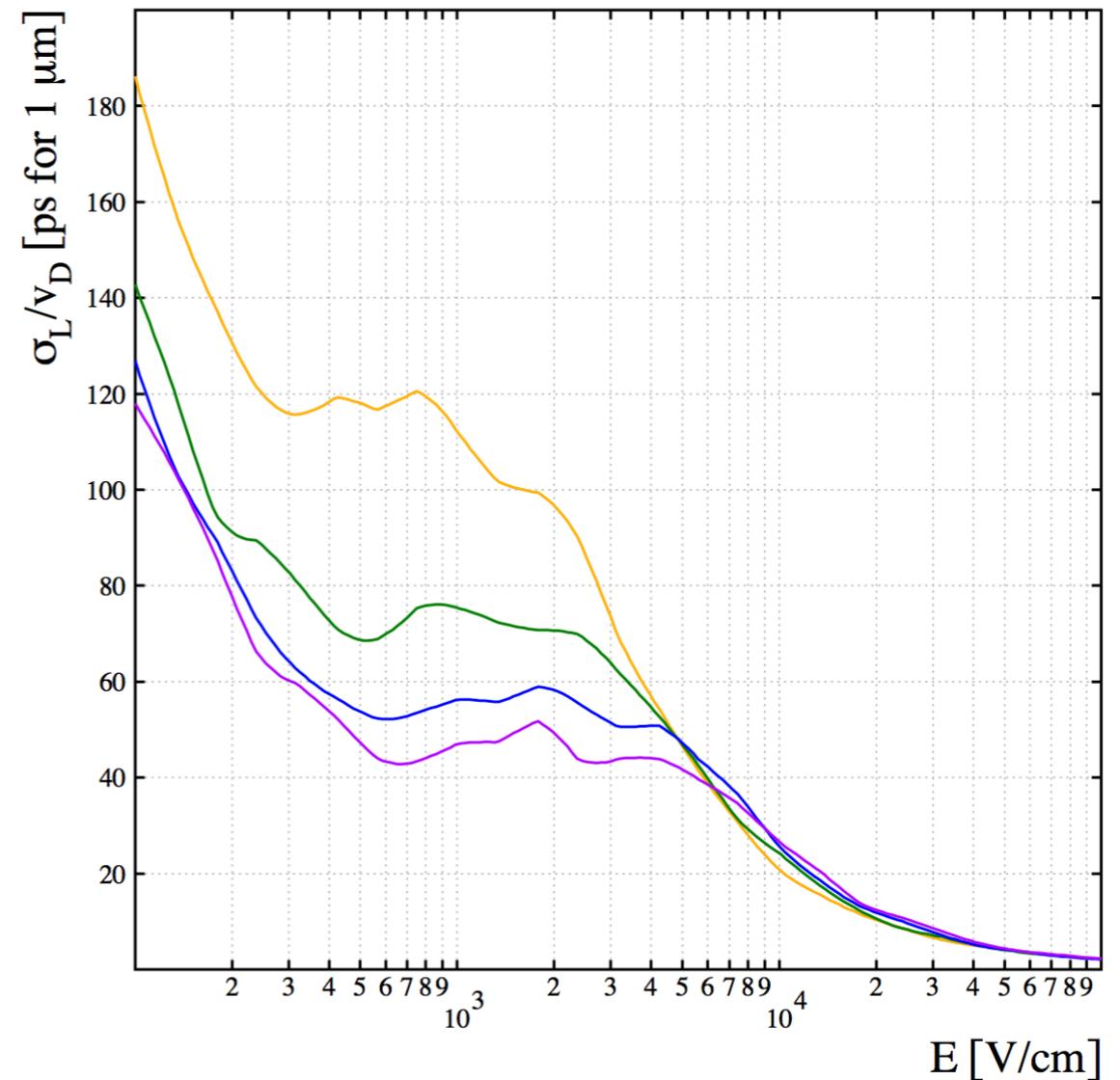


- Standard configuration
- Pillars every 5 (or 10) mm
 - Pillar diameter ≈350 μm
 - Dead area ≈1.5 (0.4)%
 - Amplification gap 128 μm
 - Mesh: 325 lines/inch

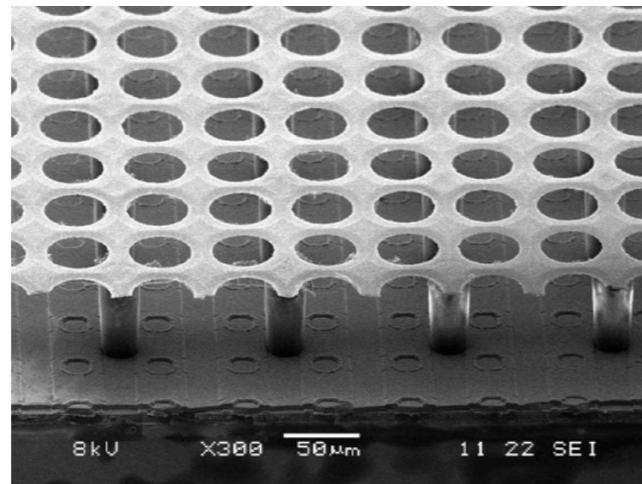
Detector Concept: Diffusion limited time jitter



Ne-C₂H₆ (10%)-green, +other fractions



reflective pc
also attractive:

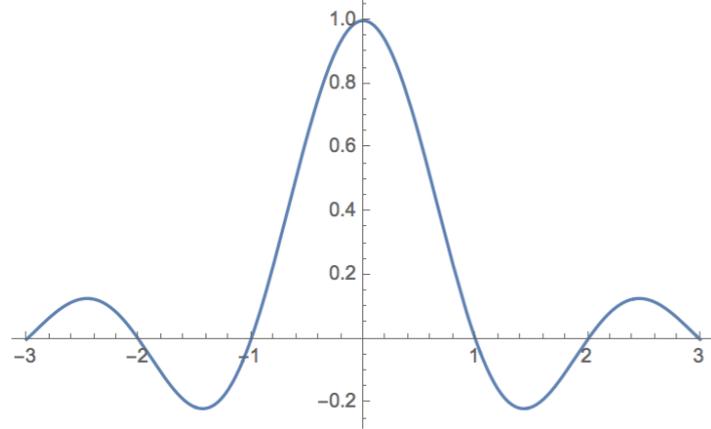


so far, tests in high drift field $\rightarrow 10\text{kV/cm}$, 200 micron gap
 $\rightarrow 200\text{-}300$ pico sec per photoelectron

Now try for a fit function that will better scale with amplitude using the Sinc (wavelet) treatment. This yields stable fits for the amplitude (ie Npe) but the earlier method using normalized waveforms gives more stable fits for the phase, so I combine these methods.

```
In[145]:= Plot[Sinc[Pi * x], {x, -3, 3}]
```

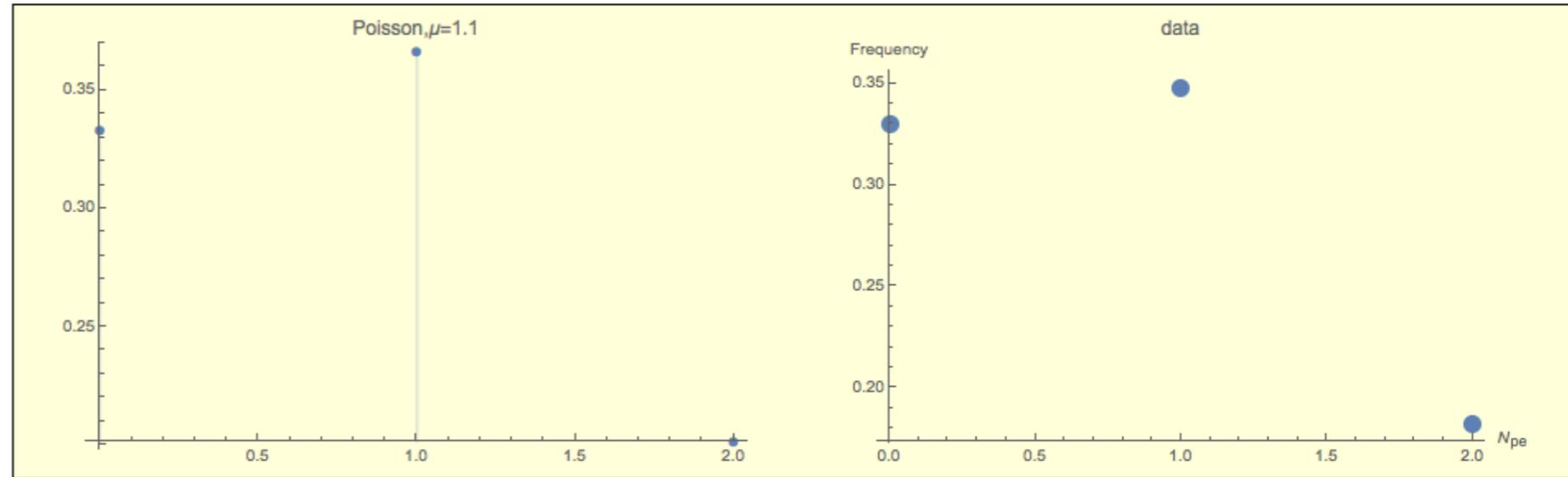
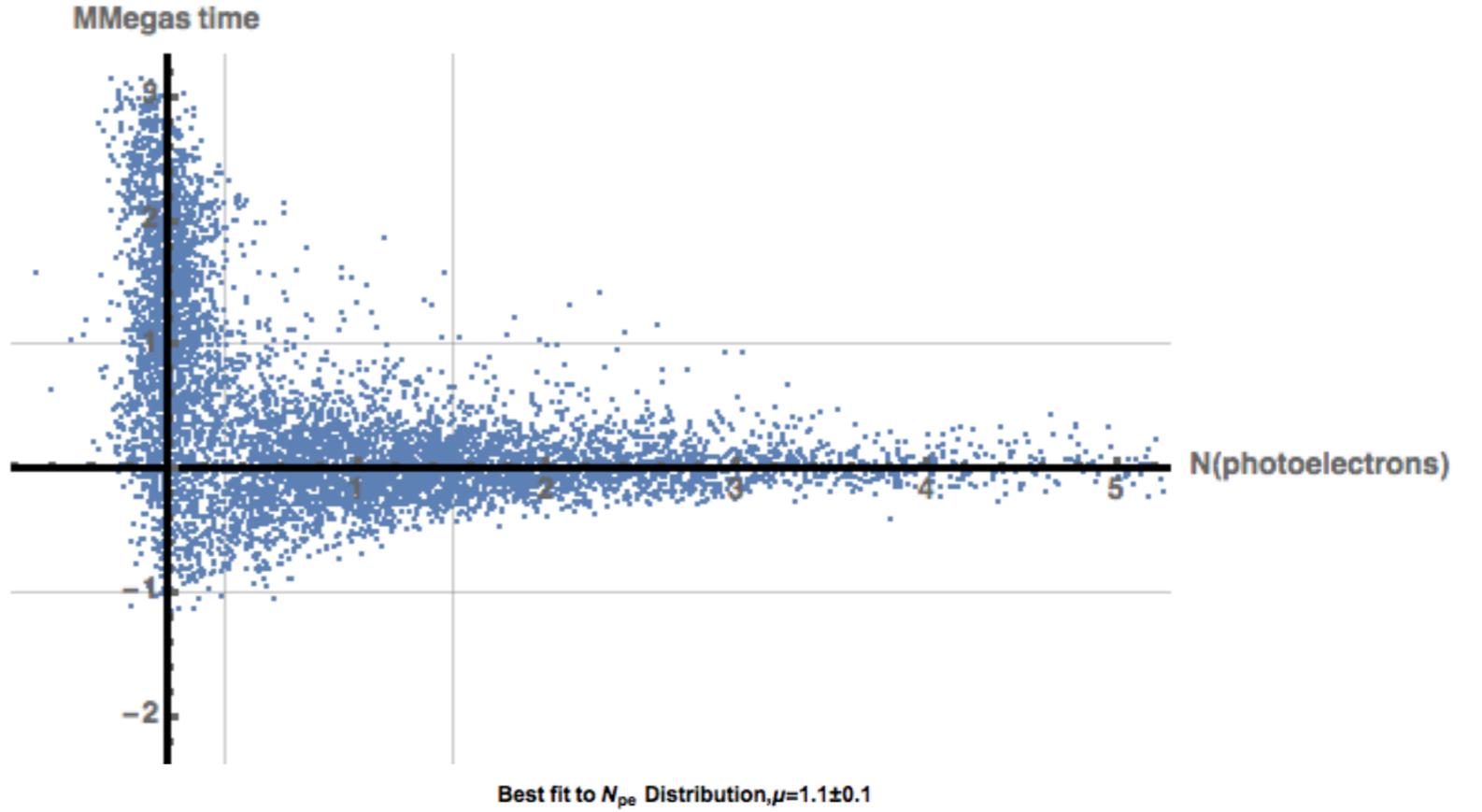
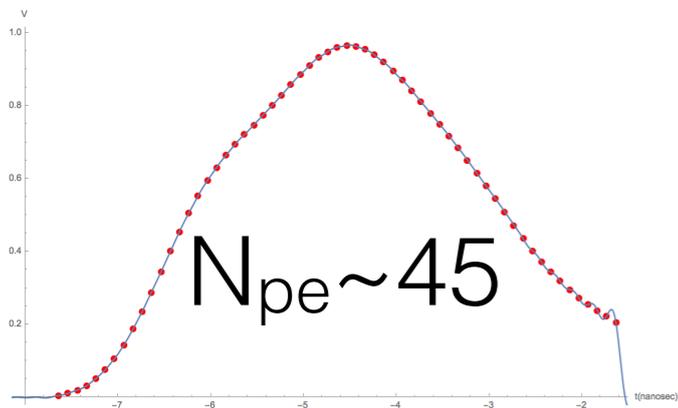
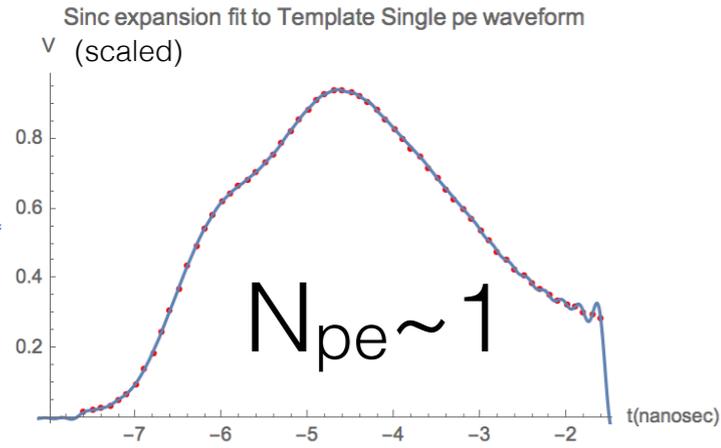
Out[145]=



```
avewave = 1/2 (v01[[5]] + v01[[7]]);
```

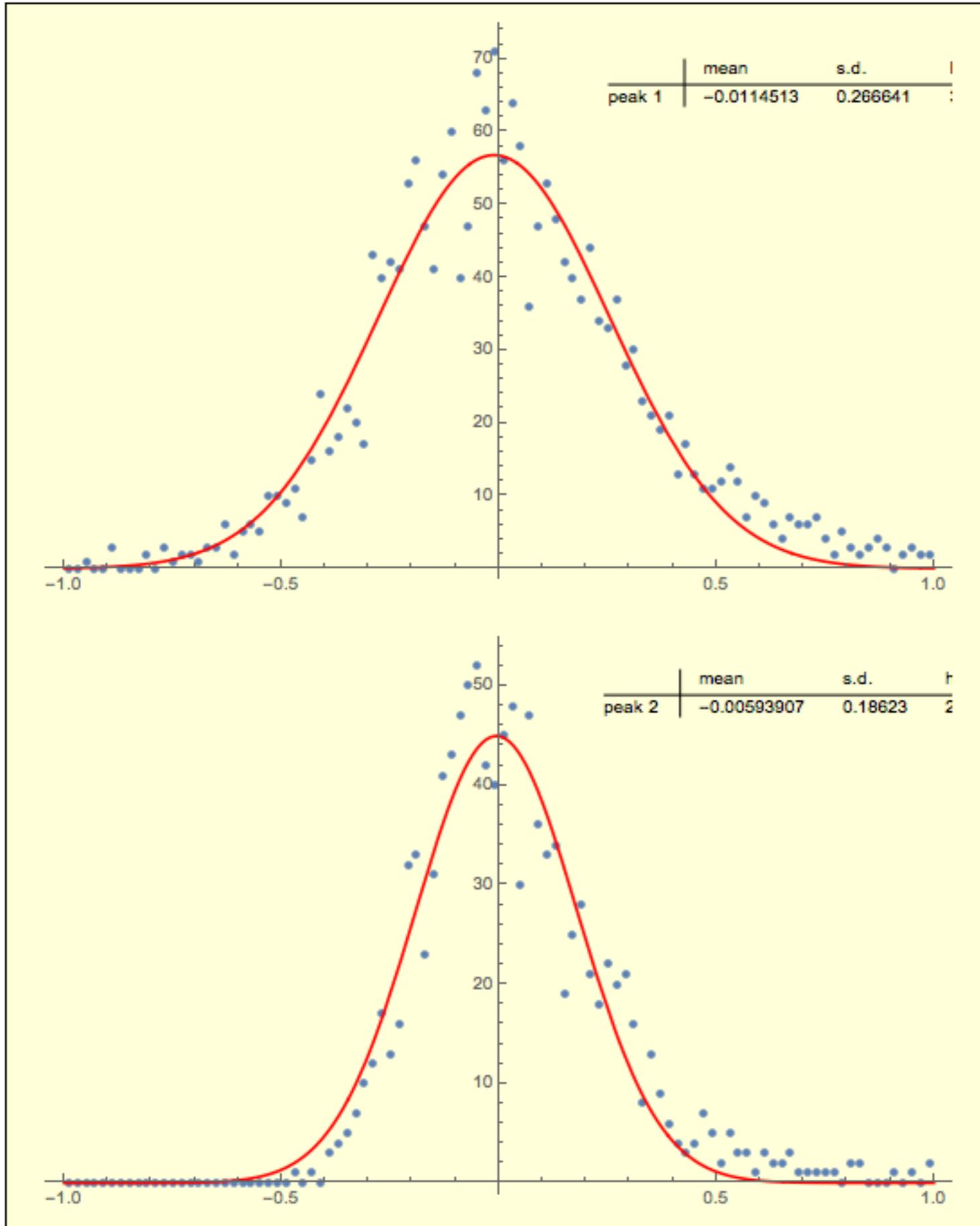
```
templatefit(x_) := Sum[avewave[[i]] Sinc[Pi (x - ttt[[i]]) / 0.1], {i, 1, 61}]
```

Out[148]=



Time jitter for 1,2 pe

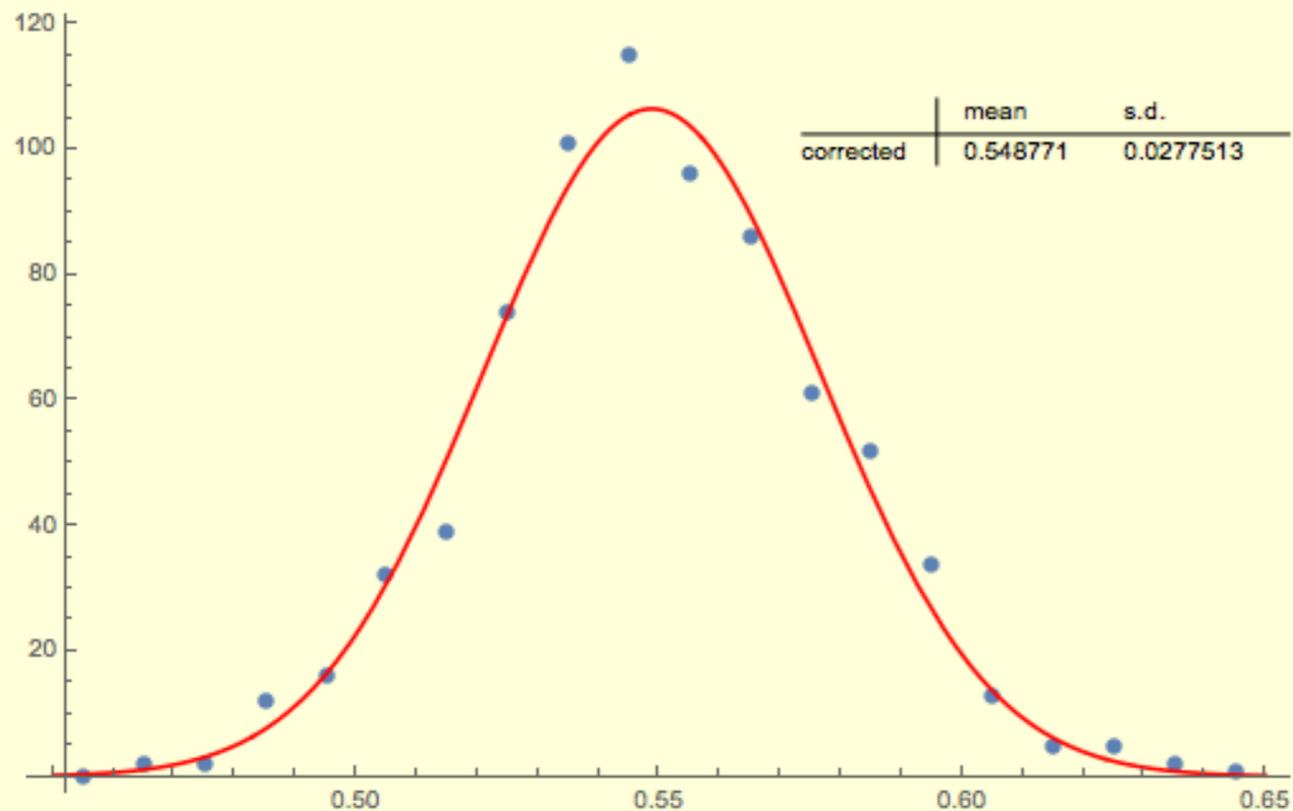
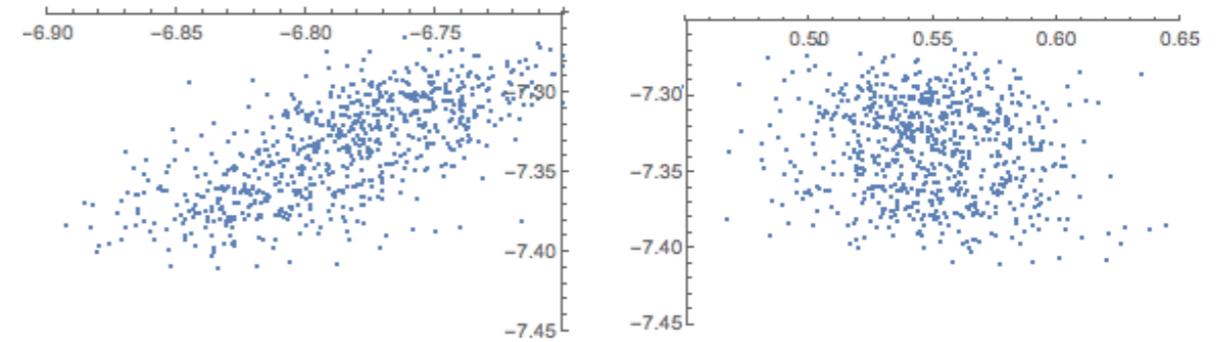
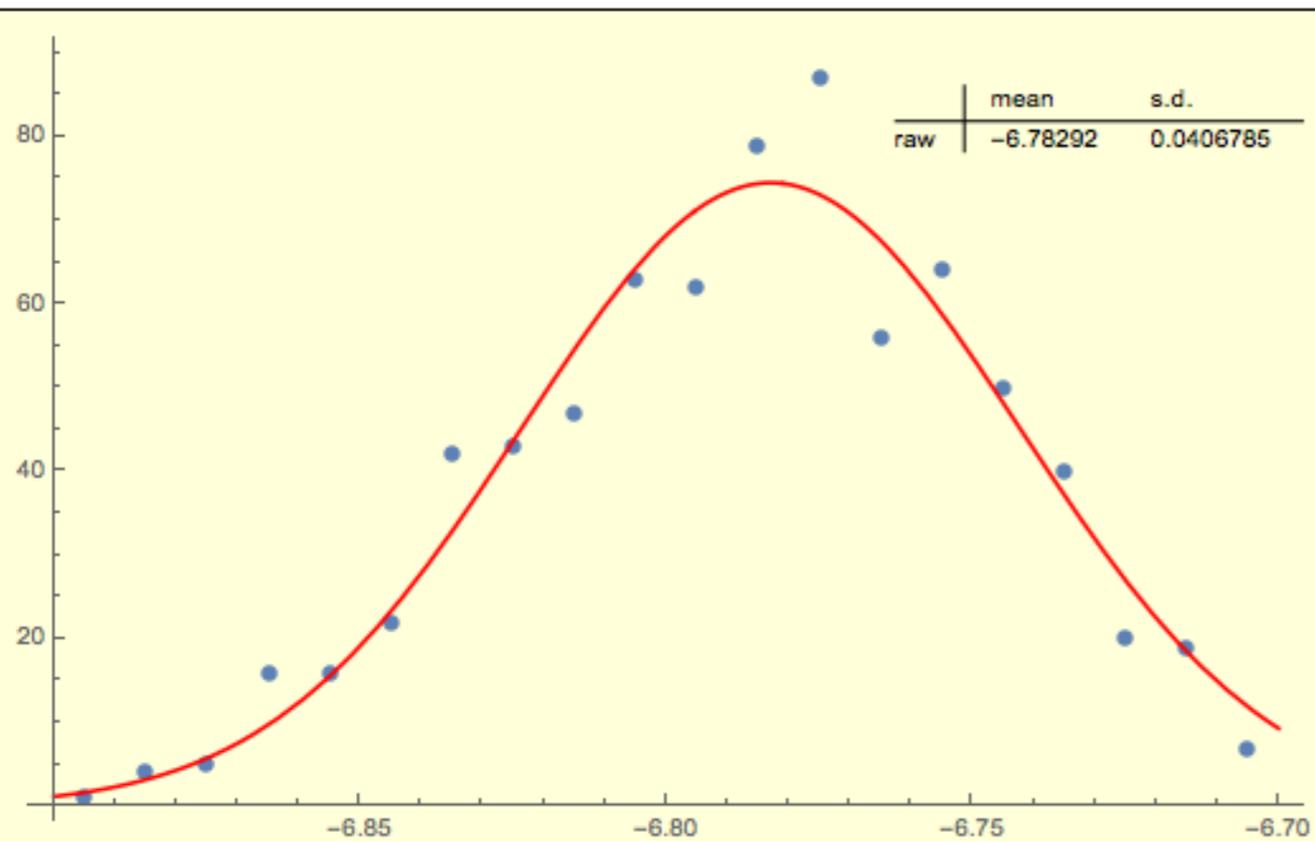
Best fit time jitter with 1,2 photoelectrons



- Caveats:
- 1) robust method for 1,2 photoelectrons is template fit
 - 2) for higher N_{pe} find that CF method better
 - 3) also some overlap of 1,2

for large Npe correlated jitter from scope trigger easily corrected e-by-e

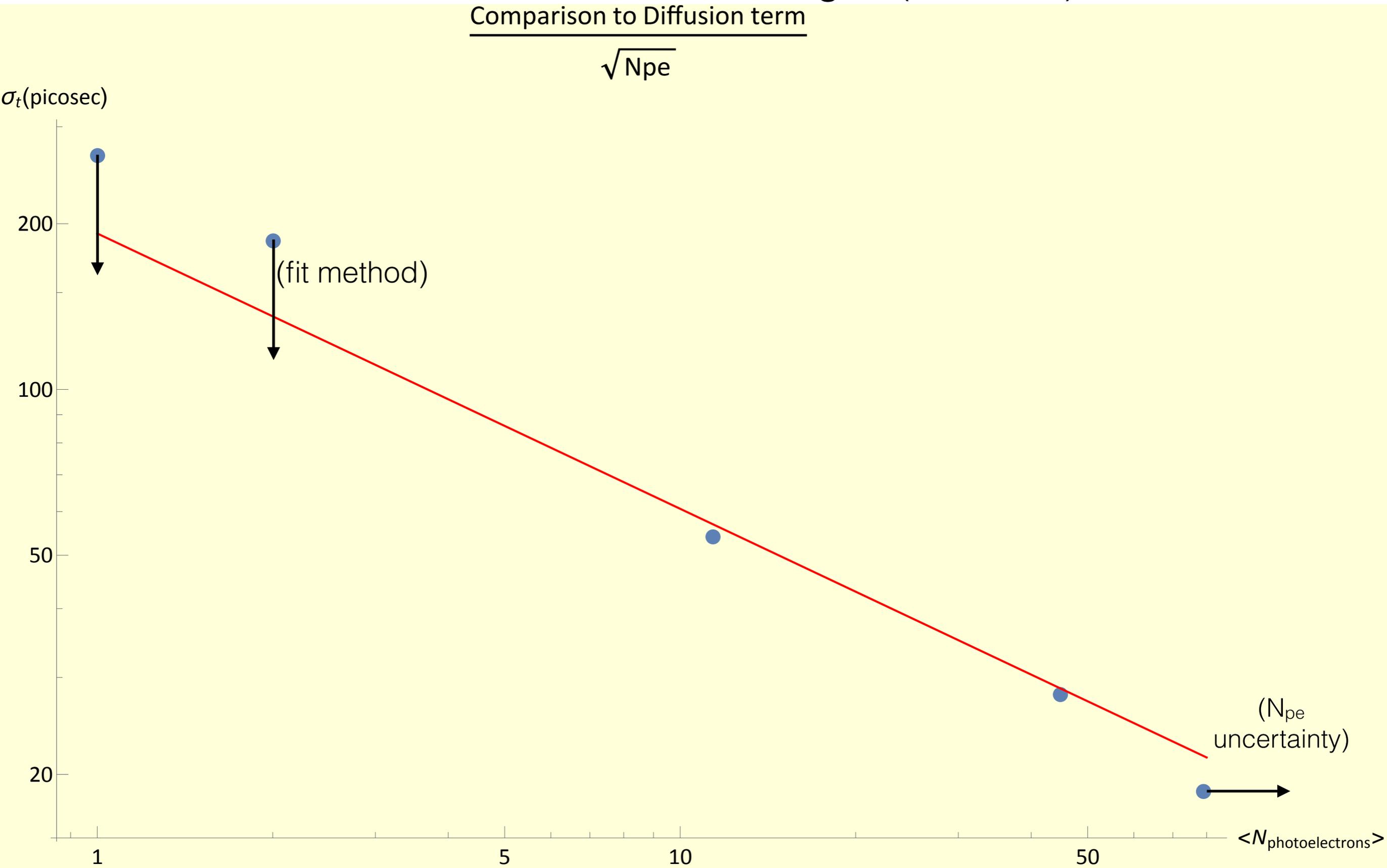
Fit to MMegas time jitter and including laser PD correction, $\langle N_{\text{photoelectron}} \rangle = 45$



many internal checks on Npe vs. run

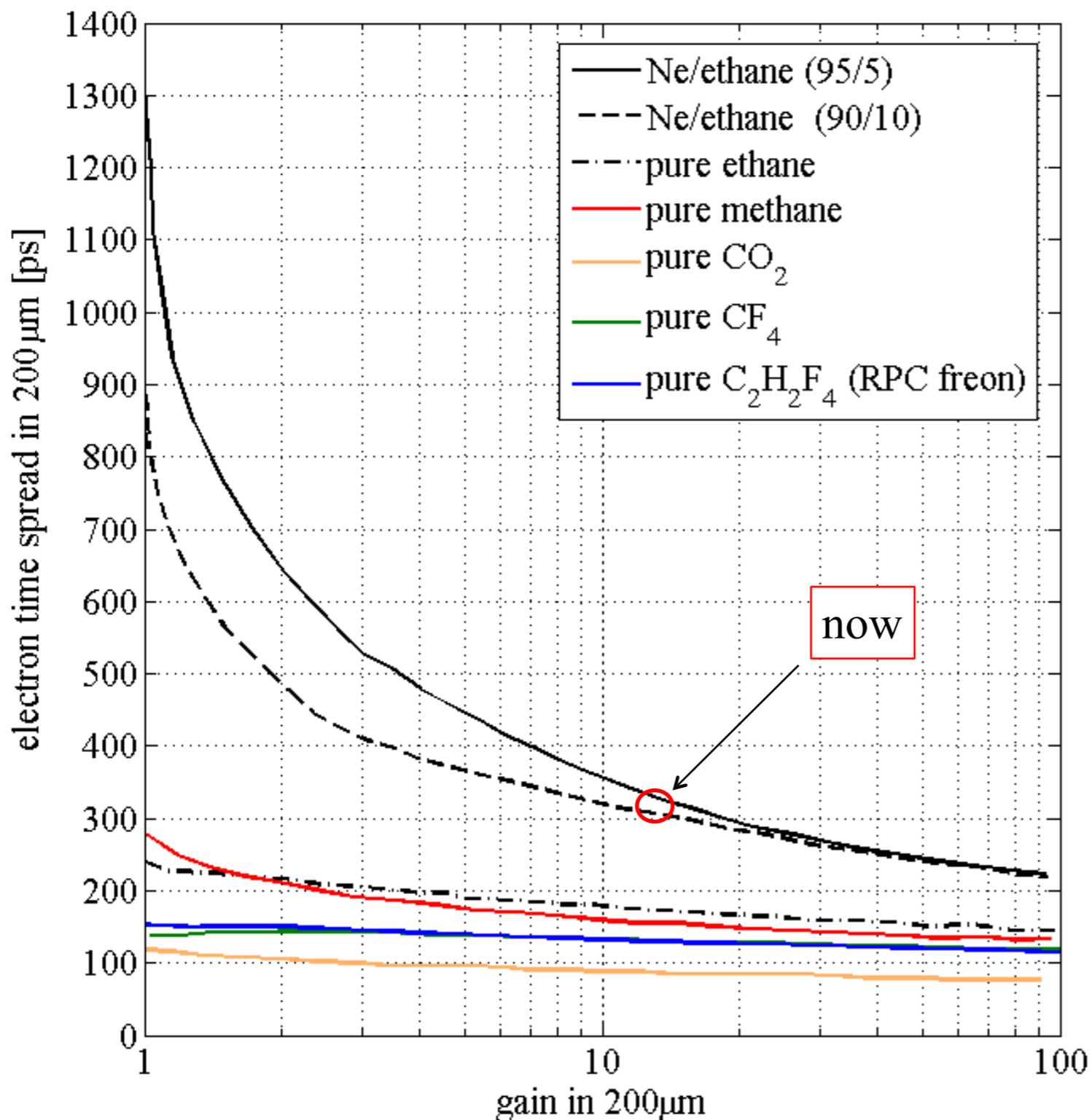
- 1) recalibrated optical filters
- 2) line width $\sim 1/\text{Sqrt}[N_{\text{pe}}]$
- 3) amplitude

Summary of Ne-Ethane(10%): Efield=10kV/cm; Drift Gap =0.2 mm
1,2 pe data points consistent with 40% worse template method
fitted curve->~2xbetter than Sigma(diffusion)



Optimum gas mixtures in timing Micromegas? (D. Gonzalez&R. Veenhof)

Look for the minimum time spread ('fastest mixture') at any given gain



Simulations from Rob Veenhof (C₂H₂F₄ from data)

There's still room at the bottom!

Notes:

- Working fields in the MM for pure quenchers need to be about x2 higher. May limit the gain in case of defects.
- Drift fields for pure quenchers need to be about x3 higher.
- Dissociative attachment for CO₂ and freons expected to be compensated by gain. Needs to be verified.

Could we eliminate need for radiator?
->Secondary emission
->Proposals by Princeton, Saclay

Plans(MPGD)

- continue tests w. Saclay chamber- laser and bench-> write up proof of concept
- parallel development here at CERN of other test structures
- expect to have full, charged particle detector assemblies for beam tests in fall
- many interesting issues to follow proof of concept: gas & field configuration optimization, rate effects, photocathode development , possible benefits of reflective photocathode, etc.
- our activity in device modeling benefitting parallel effort for our Hyperfast Si development-(Signal formation, Ramo weighting, amplifier chain)
- our development of hi-BW Si-Ge based transimpedance amplifier with Penn likely useful also for the MPGD project

Potential for low cost, large area Photosensors

- our interest similar to that of LAPPD project
- much experience at CERN w. CsI and used in ALICE, Compass. see “Photocathode manufacturing at CERN” C. Joram: https://indico.cern.ch/event/392833/session/4/contribution/13/attachments/785877/1077255/RD51_event.pdf
- We would like to continue pc development also in visible

=>non-overlapping proposals by Saclay and Princeton

➤ Secondary Emitter (**Collaboration with CEA/DRT**)

✓ Replace the crystal + photocathode with secondary electron emitter

☞ Robustness / spark reduction

☞ Free choice of substrate material

✓ Investigate materials with high secondary electron yield.

(Doped-) diamond deposition, DLC, graphene...

☞ Conductive

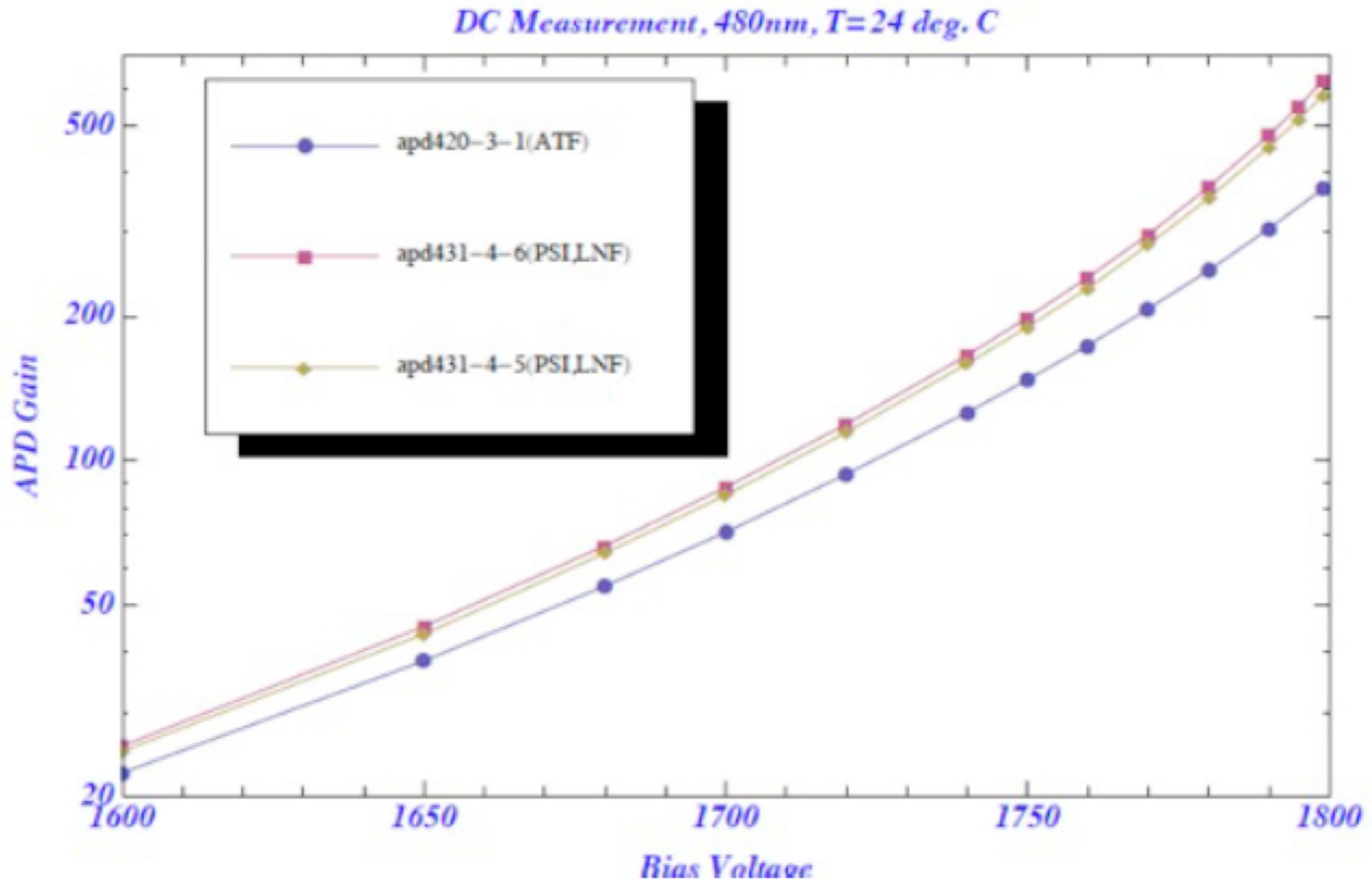
☞ Robust

☞ **Multi layer detector**

✓ **Diamond / graphene layer for photocathode protection ?**

Backup

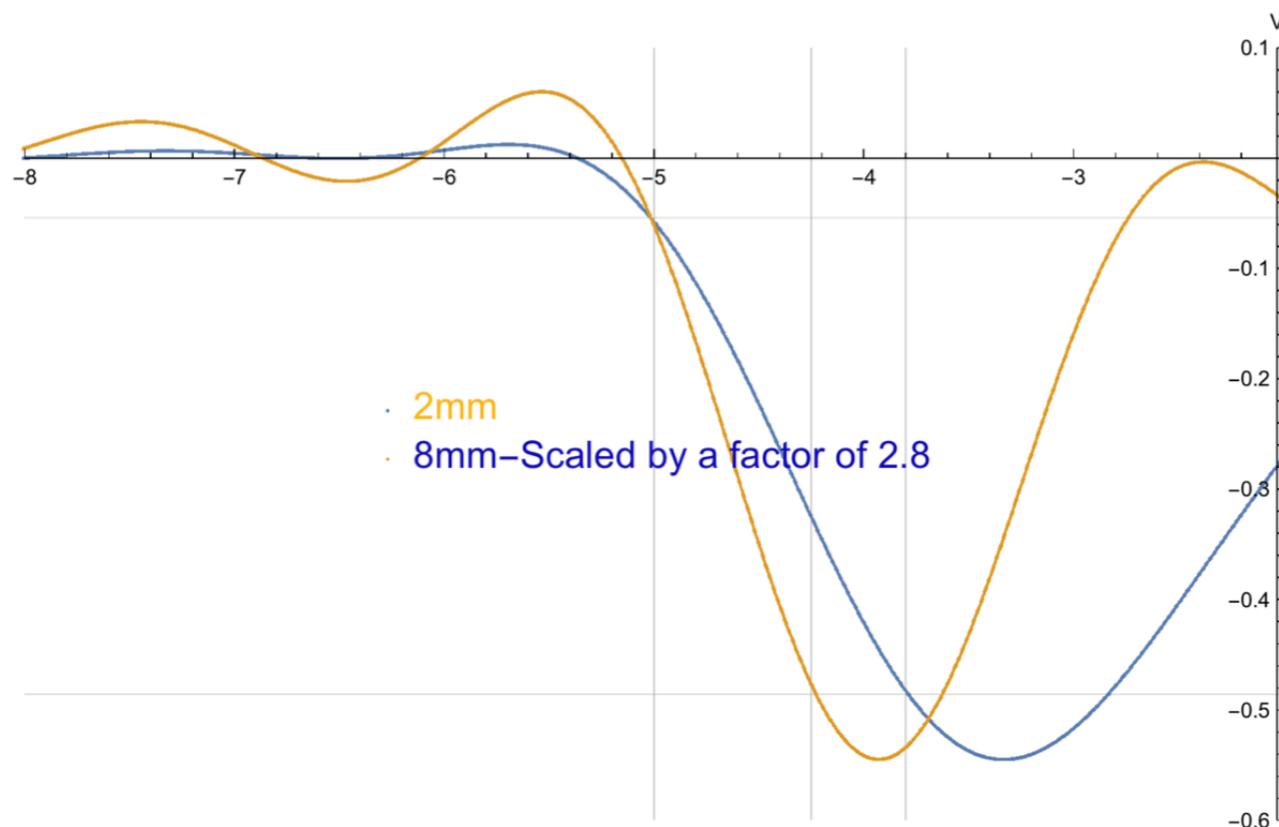
testbeam data taken at SPS, DESY, PSI, FNAL
typically at detector bias $\sim 1770-1800V$



back to electronics:

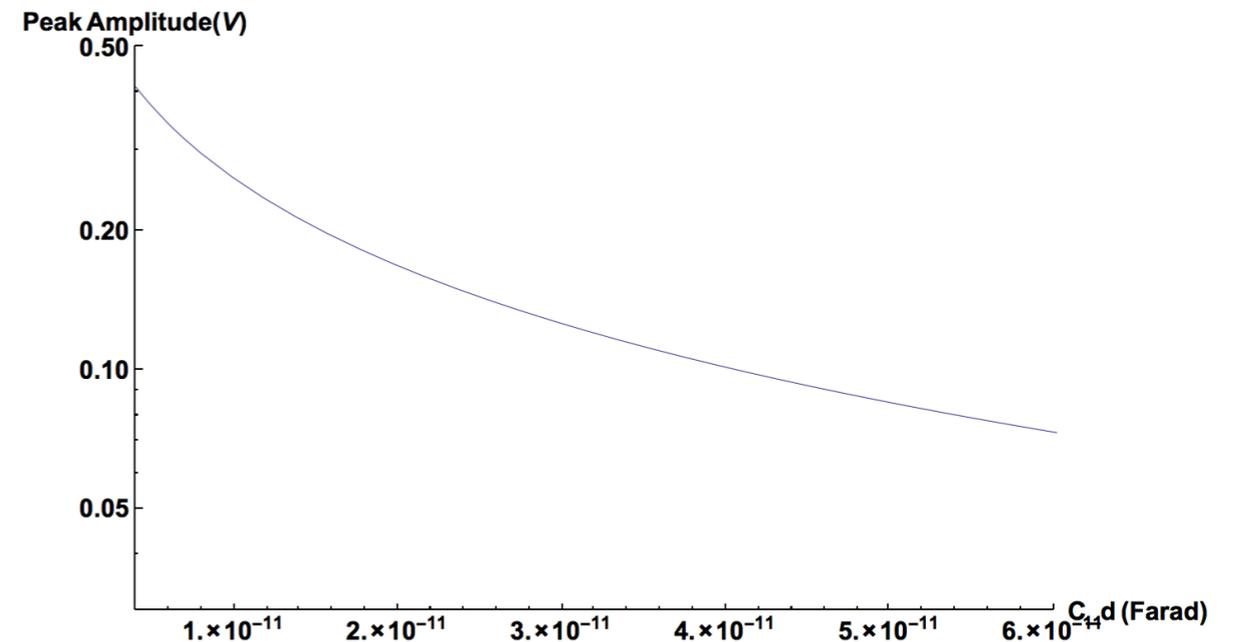
- following these developments, electronics is now our limit to timing. Why do we get 10 rather than 4 picoseconds?
- primarily due to our choice of pixel size.
- C_{det} for diamond typically < 2 pF.
- currently ours is ~ 25 pF

measurement



```
LogPlot[maxresp, {cd, 4 * 10^-12, 100 * 10^-12}, AxesLabel -> { C_d[Farad], Peak Amplitude[V]},
PlotRange -> {{4 * 10^-12, 60 * 10^-12}, {.03, .5}}, LabelStyle -> Directive[Bold, Larger]]
```

$$k_u Q_i r_i \left(- \frac{\left(\frac{cd ri}{\tau_{aup0}} \right)^{- \frac{cd ri}{cd ri - \tau_{aup0}}}}{cd ri - \tau_{aup0}} + \frac{\left(\frac{cd ri}{\tau_{aup0}} \right)^{- \frac{\tau_{aup0}}{cd ri - \tau_{aup0}}}}{cd ri - \tau_{aup0}} \right)$$



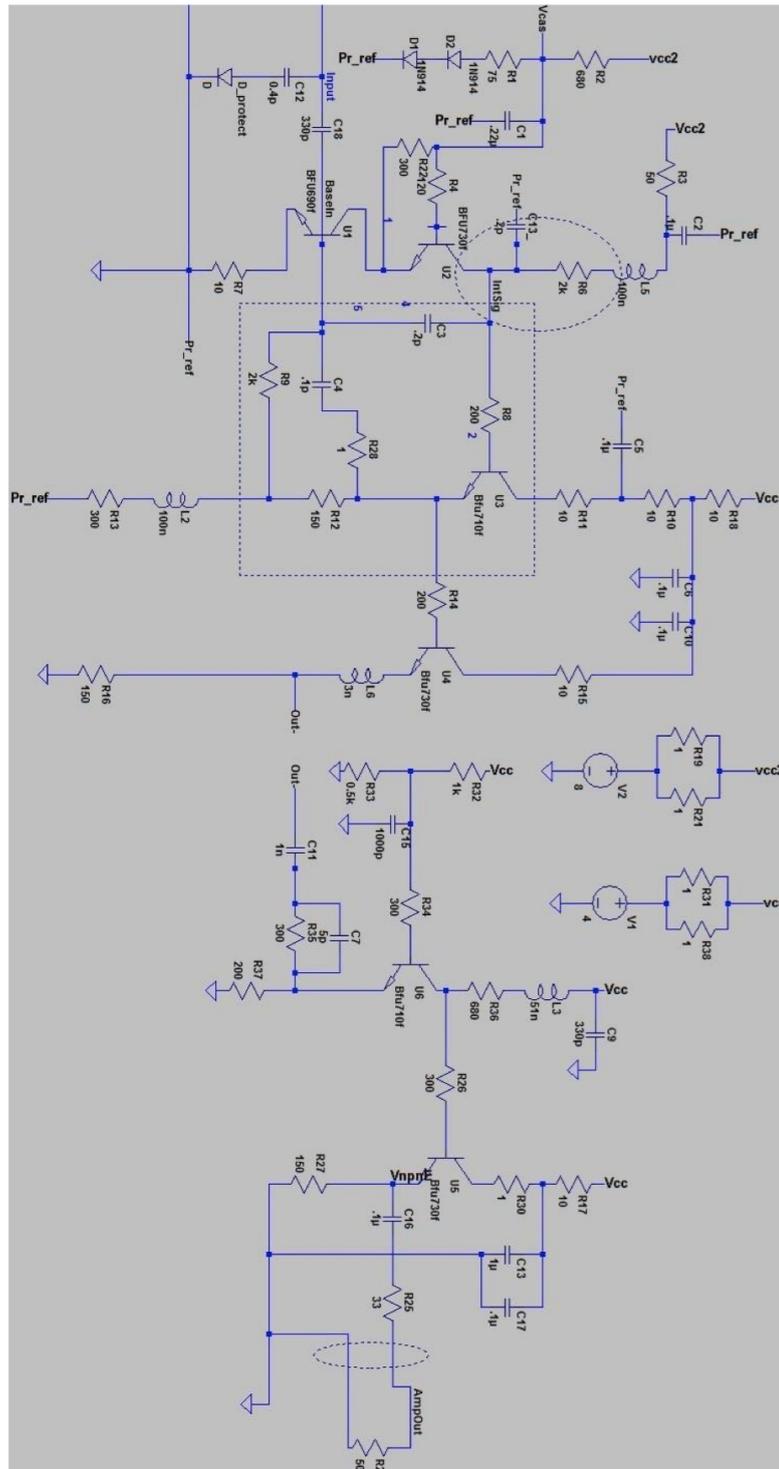
circuit model

can we optimize amp
for timing w. 25 pF detector?
ASIC development at Penn is
part of this project

Amp Development at Penn

(Mitch Newcomer, Emmanuel Morales, Susan Fowler)

The following LTspice schematic shows all the connections and values on the board.



extensive testing w. Fe⁵⁵
ready for the Aug. '15 T10 test

Si-Ge IBM process

Tools: Clock Distribution

clock distribution with few pico sec jitter not common in HEP but wide use in FEL.. accel. world

Point-to-Point

we (SNW&T.Tsang) designed an inexpensive demonstrator for FP420

Within a crate:

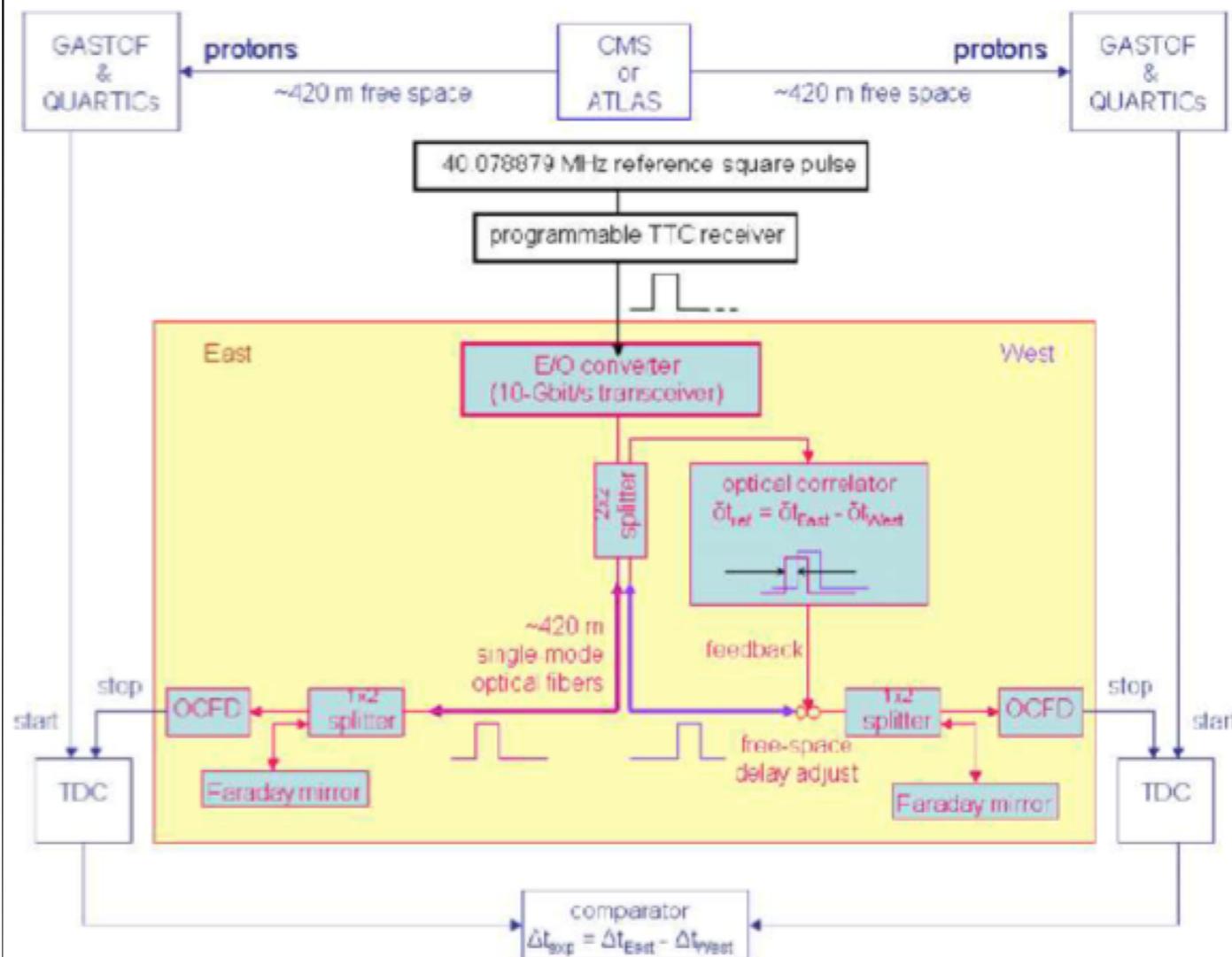
Hello Sebastian,

Trigger and clock distribution inside a crate can indeed be done with accuracies and precisions in the order of a few picoseconds. Typically, modern standard platforms such as PXIe and MTCA.4 provide a timing distribution infrastructure in the form of a star in the backplane, i.e. there is a slot from where copper lines (in the backplane) go to every other slot in the crate.

Here is one example of a timing distribution module in PXIe format:

—Javier Serrano

see also “White Rabbit”



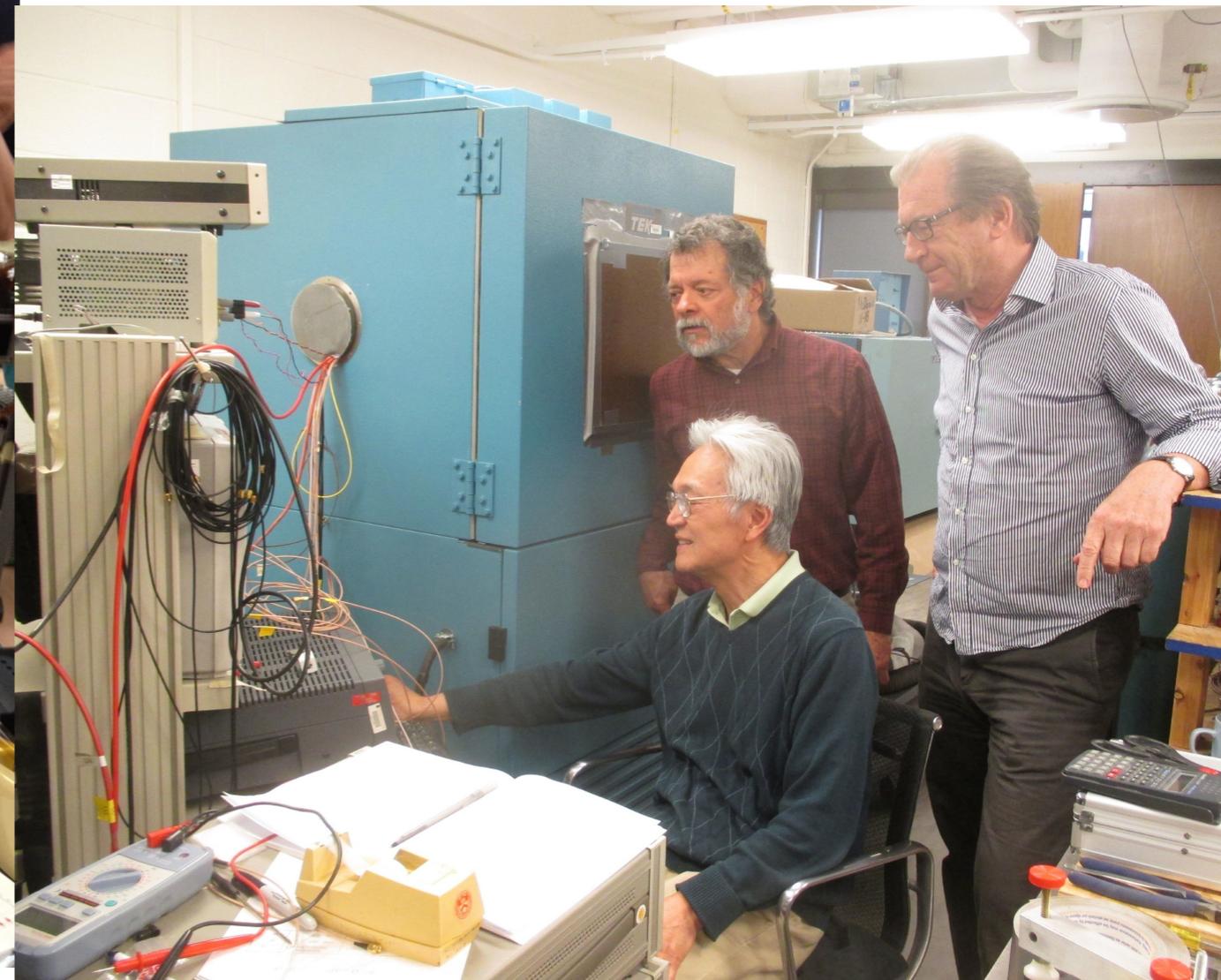
Tools:FEE

- many low noise >1 GHz voltage amplifiers (50 Ohm) on market:Minicircuits,Wenteq, Miteq.....mostly for aerospace/communications
- high end Amp from Cividec developed for Diamonds, great input protection!
- within our project we developed a hi-BW low noise Si-Ge transimpedance amp (Mitch Newcomer) which does better for higher C_{det}
- help in modelling from Jan Kaplon, Erich, Fritz Caspers and others.

Erich



Mitch



Tools: Digitization

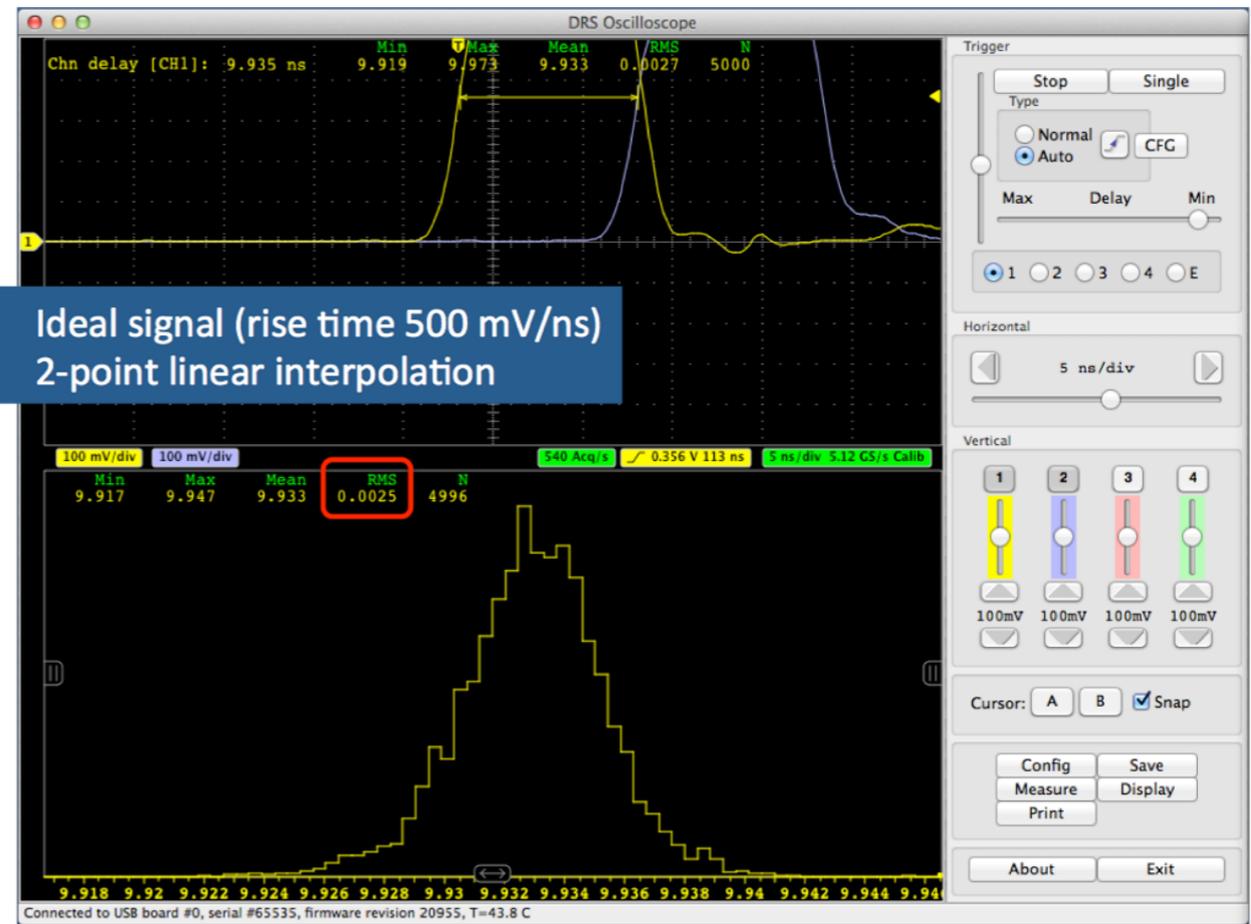
Xavier

Stefan Ritt- Dec 2013

First inter-channel 2.5 ps measurement



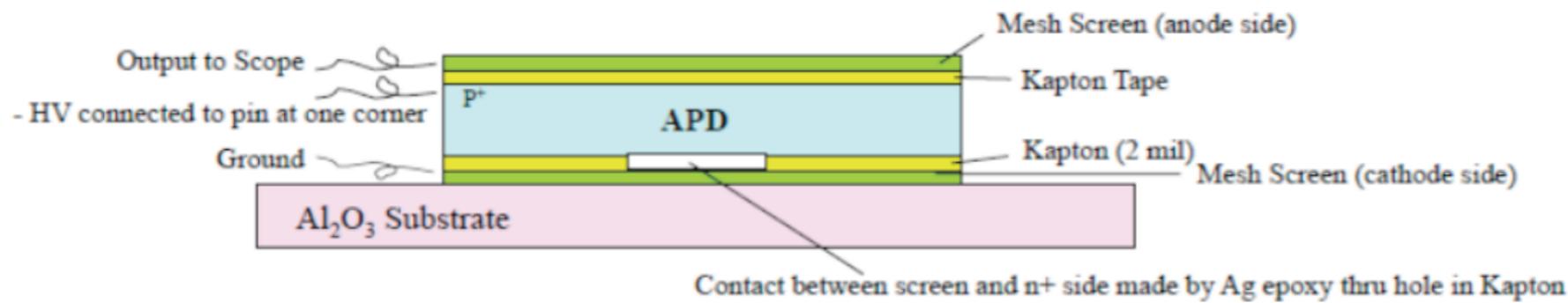
preferred daq tool-lot's of
Lecroy scopes
w. R. Zuyeuski's Labview software



also alternate to WFD: High Performance TDC-J. Christiansen et al.

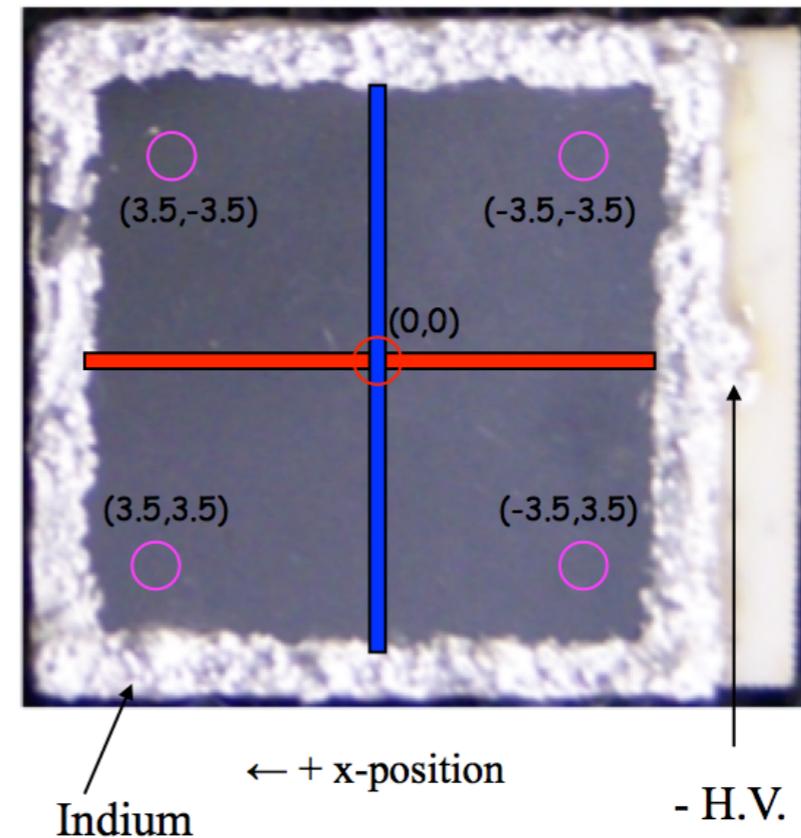
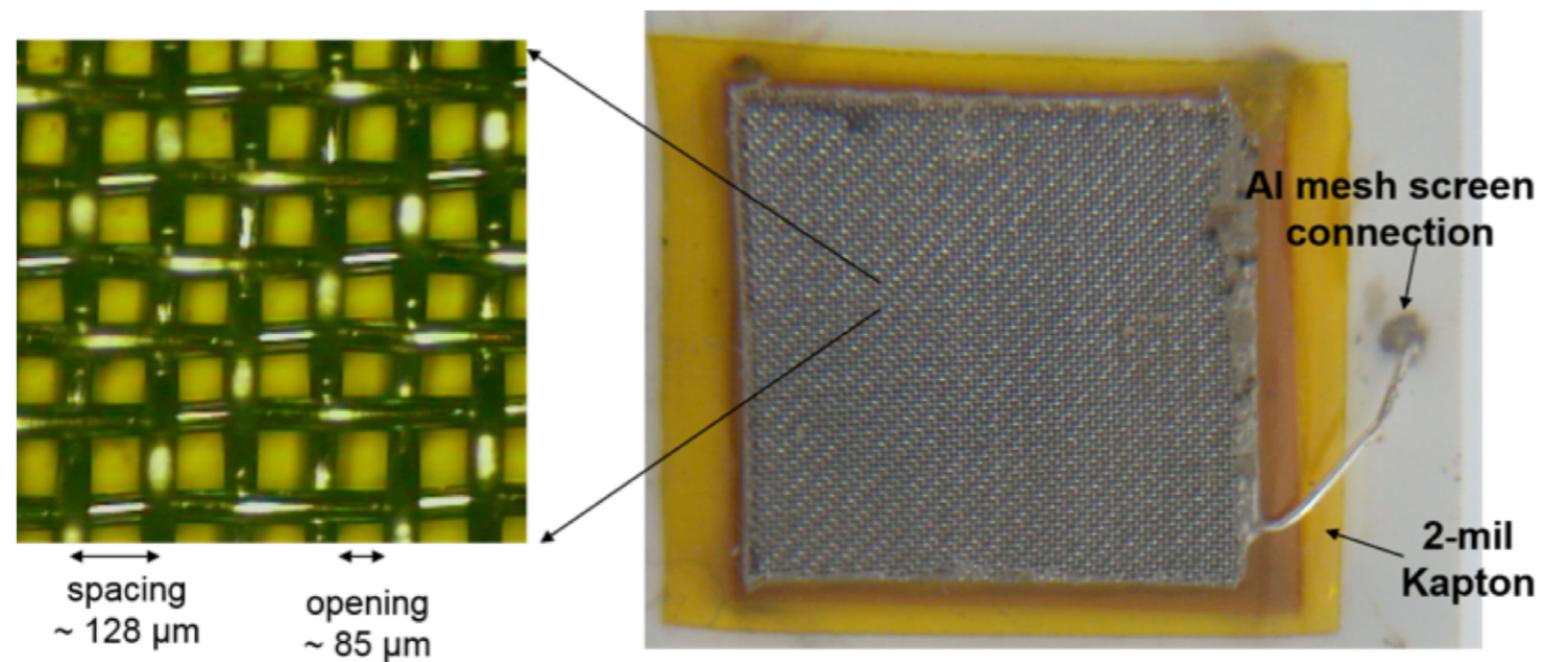
Detector Concept

Top Screen Output Connection (capacitively coupled)



top view

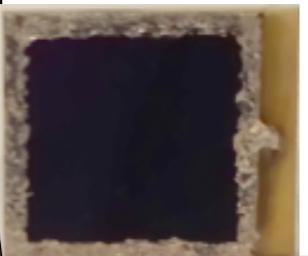
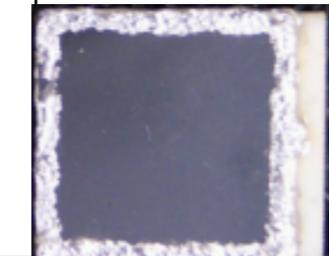
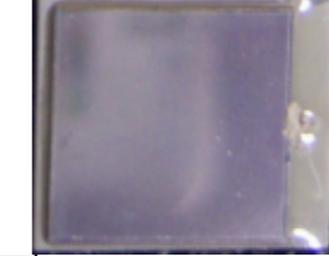
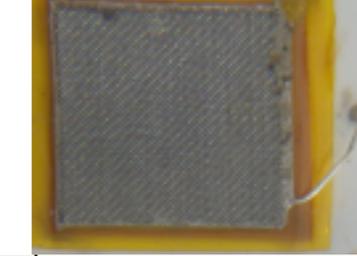
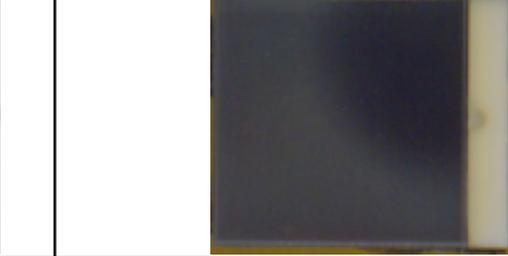
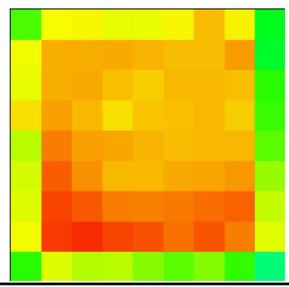
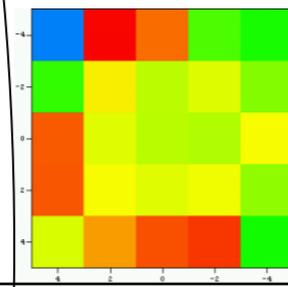
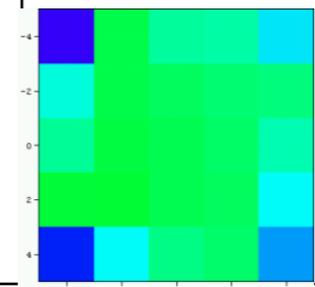
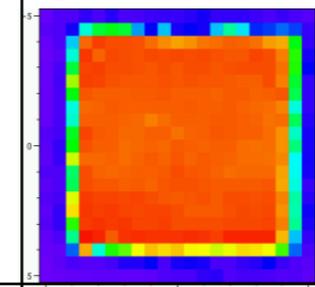
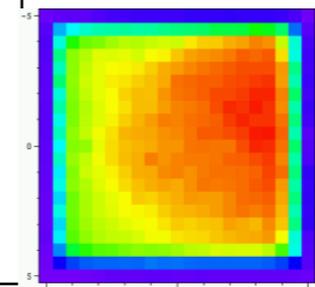
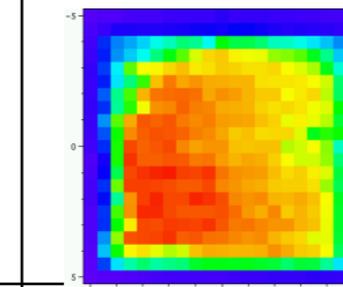
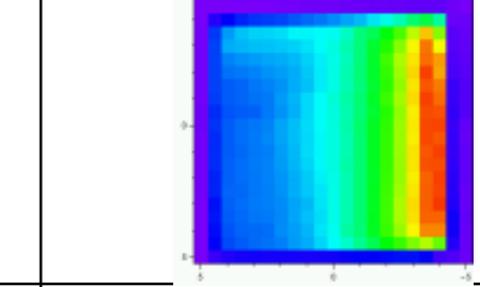
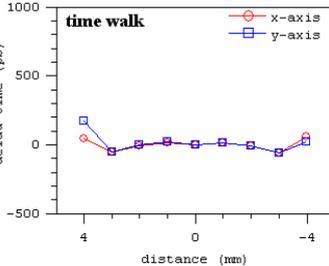
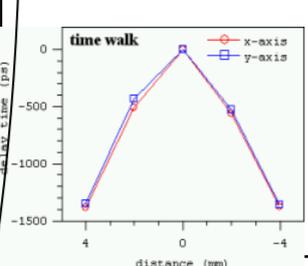
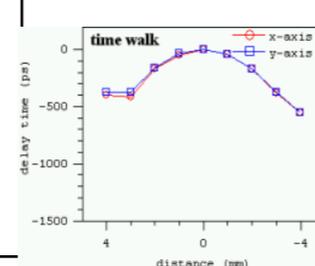
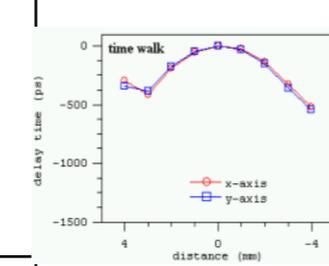
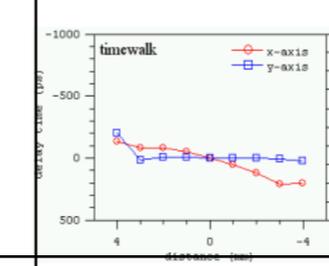
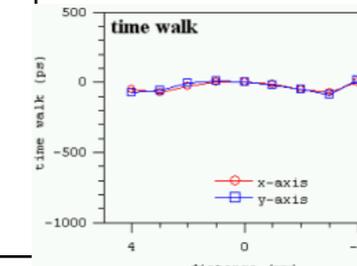
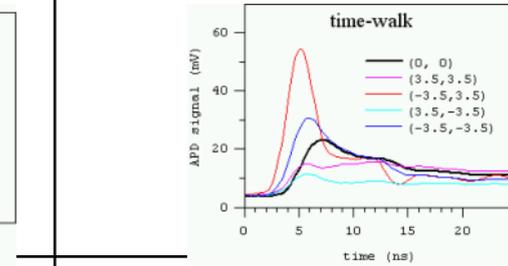
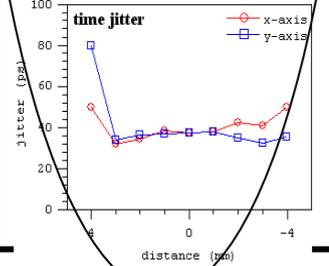
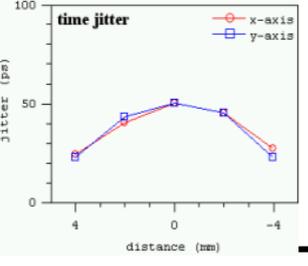
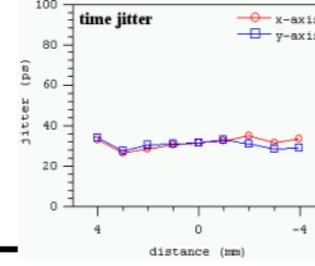
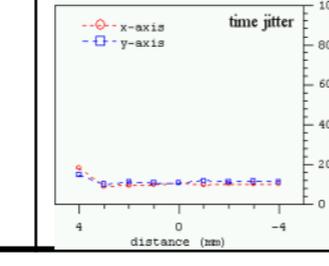
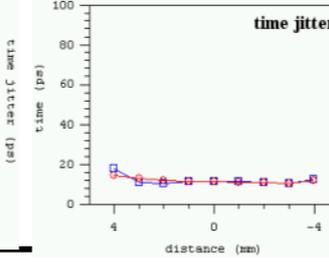
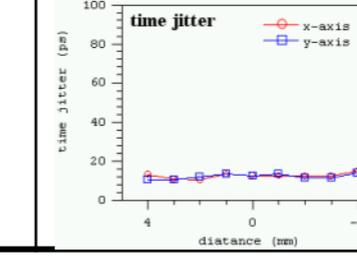
early variant



- emphasis of our development has been to deal with weighting field uniformity for fast signals
- essential outcome is that detectors look like a good capacitor at high frequencies
- relevance in the NA62 Gigatracker development where it was found that dominant jitter from:
 - weighting field
 - Landau fluctuations
- developments in signal processing/filtering, timing algorithms for LHC application to address
 - Landau/Vavilov
 - radiation induced bulk leakage-> shot noise induced time jitter

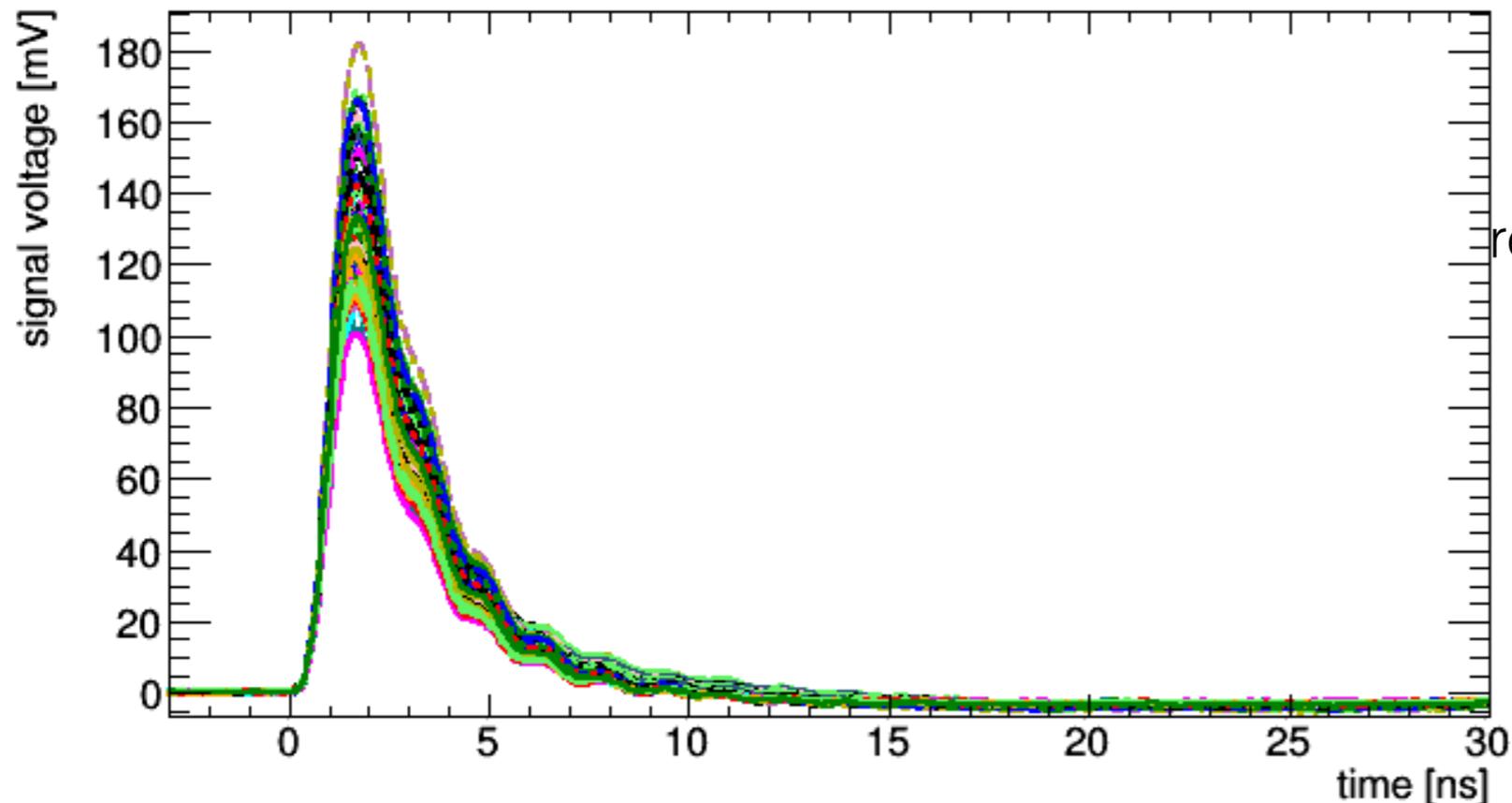
Summary of RMD 8x8 mm² APDs

Dec. 13, 2013

	Dec.13, 2013 432-6 Mesh	Nov.14, 2013 4 (previously graphene)	Nov.14, 2013 432-6-In	Oct.22, 2012 193A-6-In	Oct.22, 2012 420-3-4	Nov. 20, 2012 432-5	Sept. 26, 2012 unknown
	Al-mesh Au sintered	In-edged No Au	In-edged Au sintered	In-edged Au sintered	Al-coated No Au	Al-mesh No Au	standard n+ diffusion No Au
							
spatial uniformity	good 	fair 	fair 	good 	poor 	poor-fair 	poor 
time walk	good 	poor 	fair 	fair 	good 	good 	poor 
time jitter	good 	poor 	good 	good 	good 	good 	poor data not available

2) weighting field uniformity (and internal series resistance elimination)-recent scan data->~3 pico sec time walk in 8mm

2015- M. Moll Lab



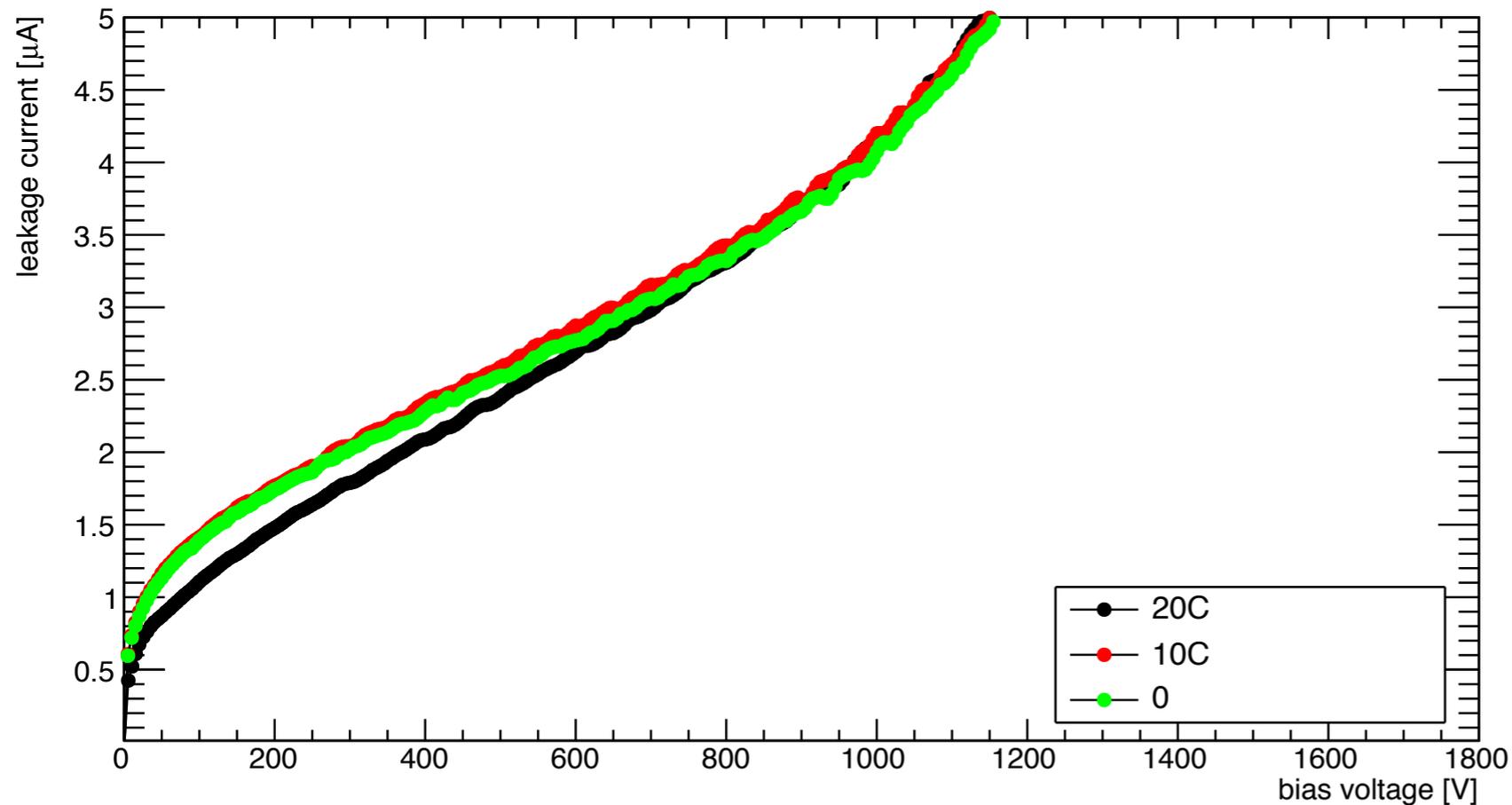
IR-surface scan of $2 \times 2 \text{ mm}^2$
detector wo. screen
reasonable time walk but worse amplitude
uniformity- C. Gallrapp

RD50 infrastructure enabling us to address open questions which can aid modeling

- 1) relative importance of top-side screen and bottom sintered Au
- 2) have we also created a faster photodetector?
- 3) how critical is metallization at smaller pixel size?
- 4) Is there an optimum gain for intrinsic time jitter?
- 5) what is optimum dielectric thickness (lowering C_{det})?
- 6) rad dam issues- leakage current and Gain stability- So far to 10^{14} p/cm^2

Radiation Exposures

I -- V : APD Set-1950 $9.28E13$ p/cm² scaled to 20C



Initial Exposure this year to 9.3×10^{13}

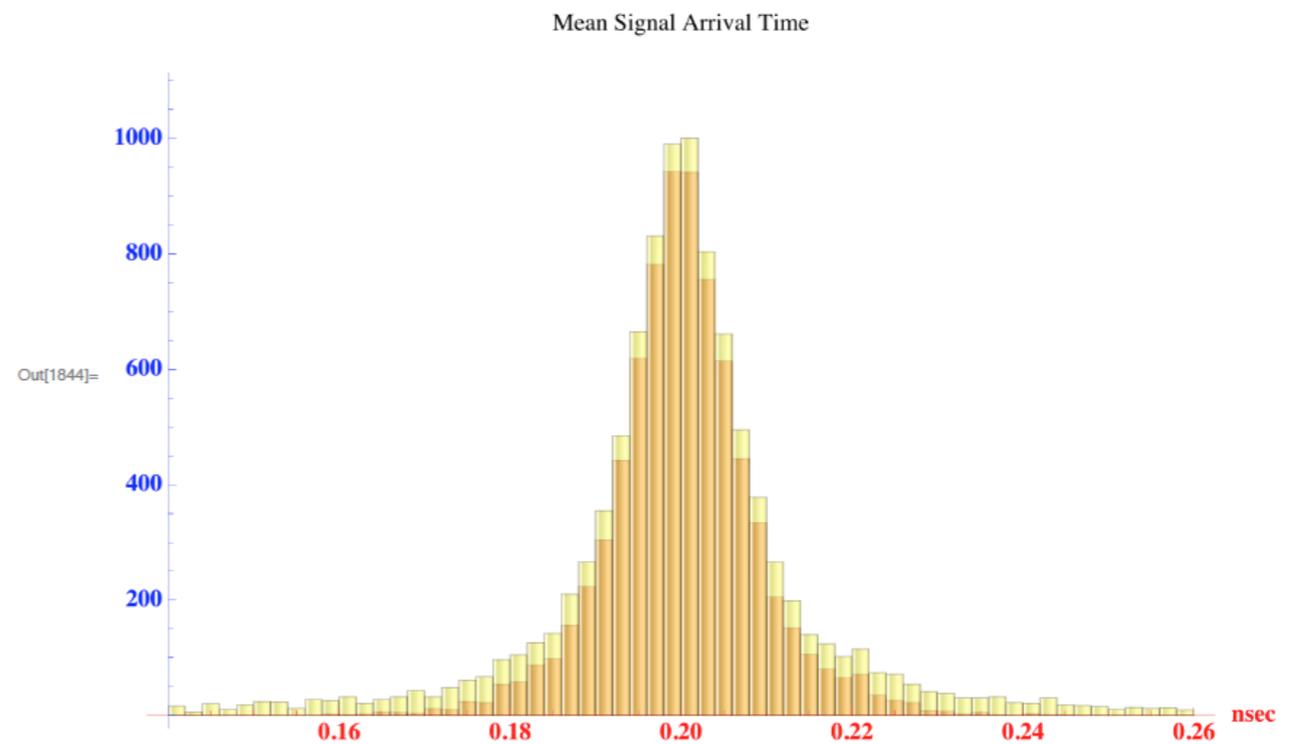
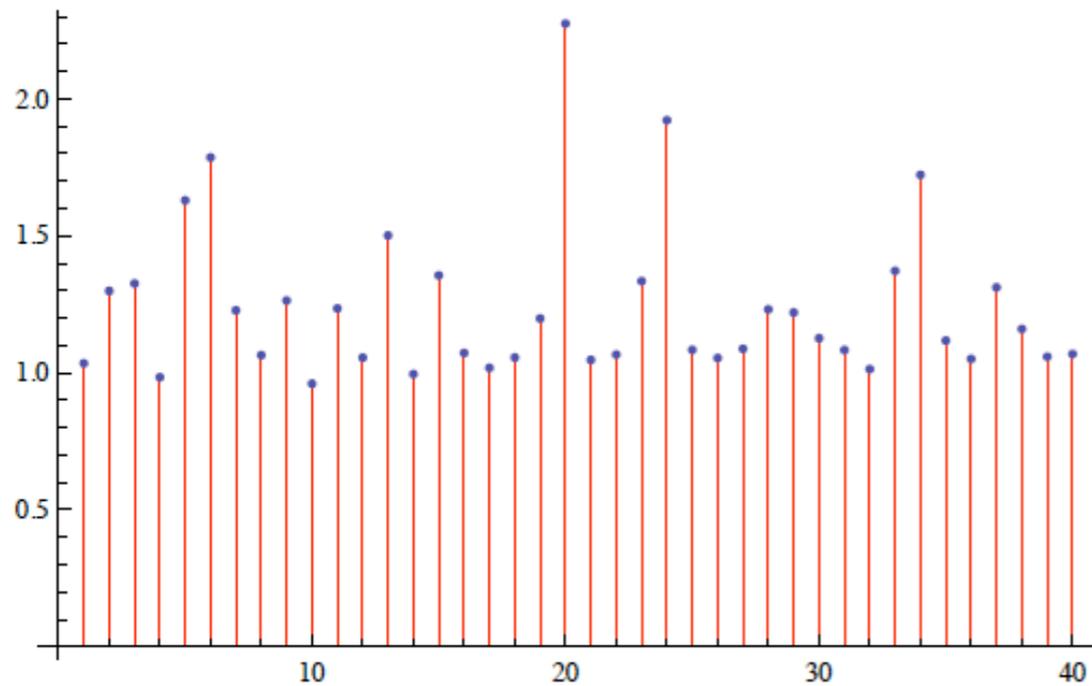
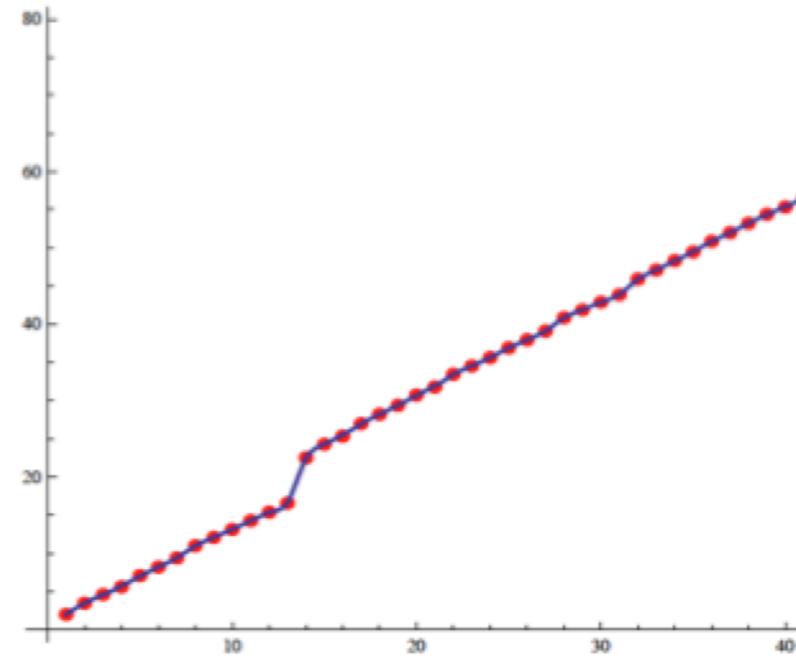
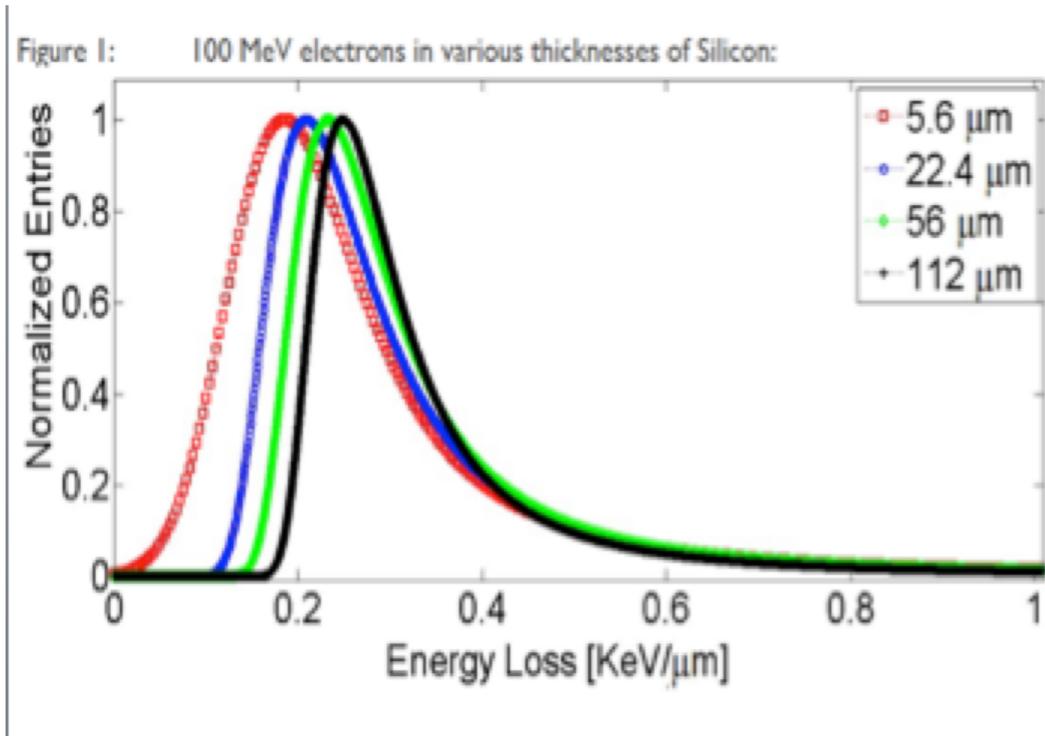
growth in bulk leakage from displacement damage as predicted. (SNW et al. <http://arxiv.org/abs/0901.2530>)

Further tests on Gain stability after more complete baseline measurements.

Relevant for another RD50 project (LGAD) since we use heavier element doping-ie not Boron.

Landau/Vavilov contribution

(original model)



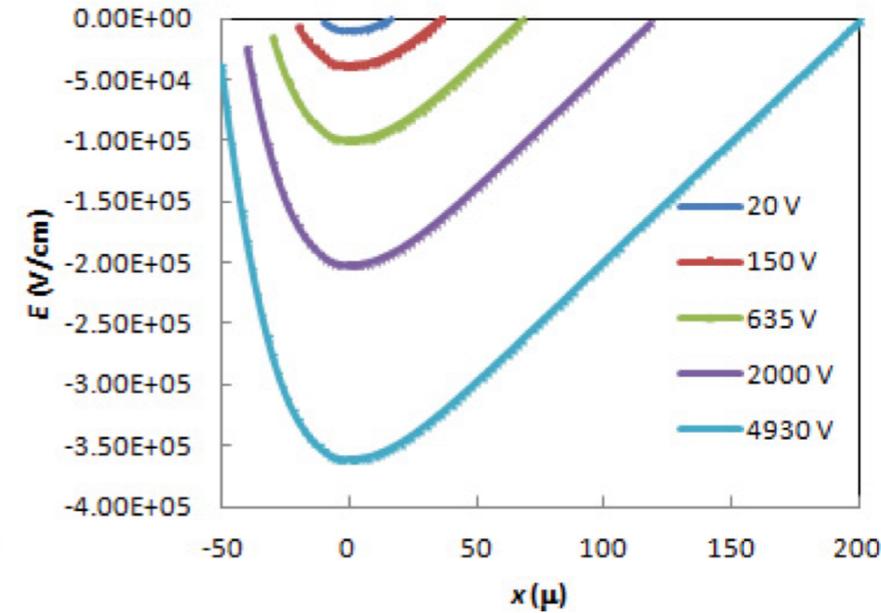
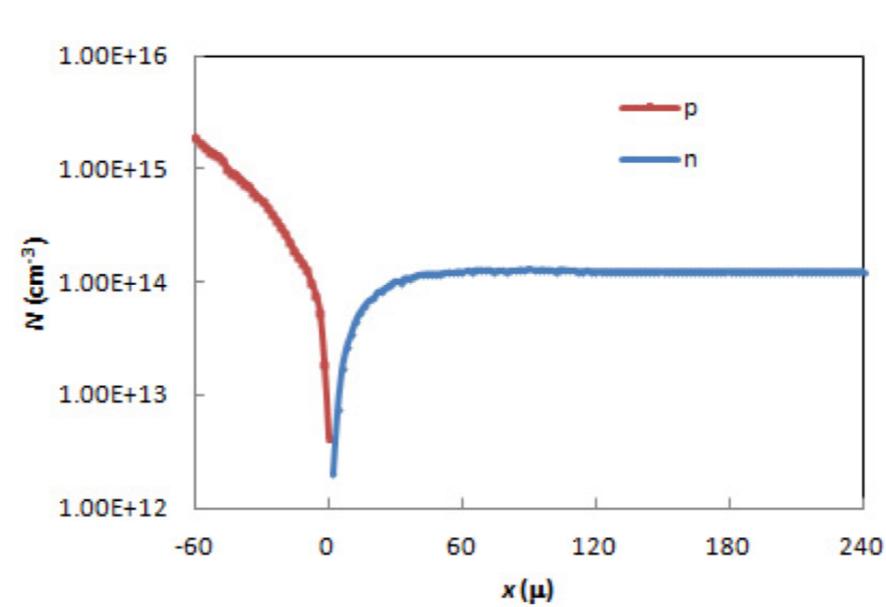
Cut in Signal amplitude at 77.35
% efficiency reduces time jitter from 0.022641 to 0.00870866nsec

Develop Model for signal source

see eg. K.T. McDonald, Electric Field Distribution in a

Reverse-Biased p-n Junction (Sept. 13, 2015),

<http://physics.princeton.edu/~mcdonald/examples/diode.pdf>



data

Aug. 3, 2015 PS, 3 HFS detectors, Peak value(V)– compare Meroli et al.

