Hyperfast time of arrival measurement for pileup Mitigation in CMS Phase II Upgrade

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Clermont-Fd, March 14, 2014

1. The Challenge of achieving 3000 /fb
2. Sensor development for hi-rate psec timing
   Si Hybrid APD/Micromegas w. RMD/Dynasil
   Gas PMT/microbulk detector w. Saclay
3. Beam and benchtest results on SiAPD
   preview of DESY data from 2 weeks ago
4. Fast Timing in Brain Imaging
5. Conclusion

CMS Phase II Upgrade R&D

Reporting on work started in 2007 on pileup mitigation through fast timing
In ATLAS/FP420 I was asked by Brian Cox to explore new detector options which could achieve 10-20 psec at sustained rates of 10**6-10**7 Hz/cm**2 (conclusion of FP420 report was that no such sensors existed at the time.
worked w. Hamamatsu Photonics (Suyama et al.) to evaluate pre-production HybridAPD ->11 picosec SPTR & 2-3 orders of magnitude lifetime increase over MCP-PMT -(T.Tsang&SNW 2008-2009)
though photosensor issue solved, actual application impeded by process leading to CMS decision on calorimeter technology (but I agree with Paul- DualReadoutCal very promising)
we were encouraged by the collaboration to propose a "baseline" standalone timing detector
this should accelerate process in simulation of potential benefits to CMS HL-LHC physics
Strong Collaboration for US-CMS funded R&D based on 2 technologies (SiAPD most advanced)

Development of Precision Timing Pileup Mitigation Tools within the Context of a Dual Readout Calorimeter for CMS: *Proposal Submitted to US-CMS*

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Experimental Challenges of the European Strategy for Particle Physics

ESPP summary:

"Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030."

context:

2012 was a very good year. LHC reached a peak luminosity of 80% of design goal and ATLAS/CMS experiments logged ~22 fb^{-1}. All involved saw the activity running flat out in terms of human effort, use of computing resources and complexity of events (due to pileup).
LHC is a very complex machine with enormous stored energy in the beams (nominal ~400 MJ/beam) and concerns about machine reliability and personnel protection will remain.
An extrapolation to 3000 fb^{-1} over the next 15-20 years implies new challenges for the experiments.

"The success of particle physics experiments, such as those required for the high-luminosity LHC, relies on innovative instrumentation, state-of-the-art infrastructures and large-scale data-intensive computing. Detector R&D programmes should be supported strongly at national institutes, laboratories and universities."

translation: We are running out of bullets. It's time to get a new gun.

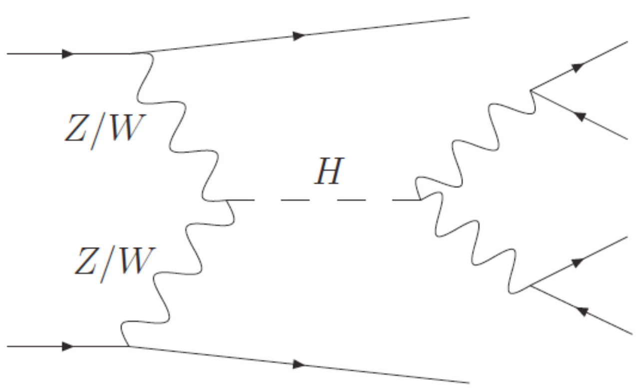
the Challenge

Emphasis on ie VBF Higgs production or WW scattering in future program of LHC is complicated by high event pileup.

In these examples (often forward) jets must be associated with observed Higgs or W candidates.

In the forward region associating jets with the right candidate is difficult using track vertexing. The complimentary time domain(event time) would be useful if $t_{resolution} \ll t_{bunch\ crossing}$ (~200 picosec).

Developments in high rate picosec photosensors and trackers would be useful.



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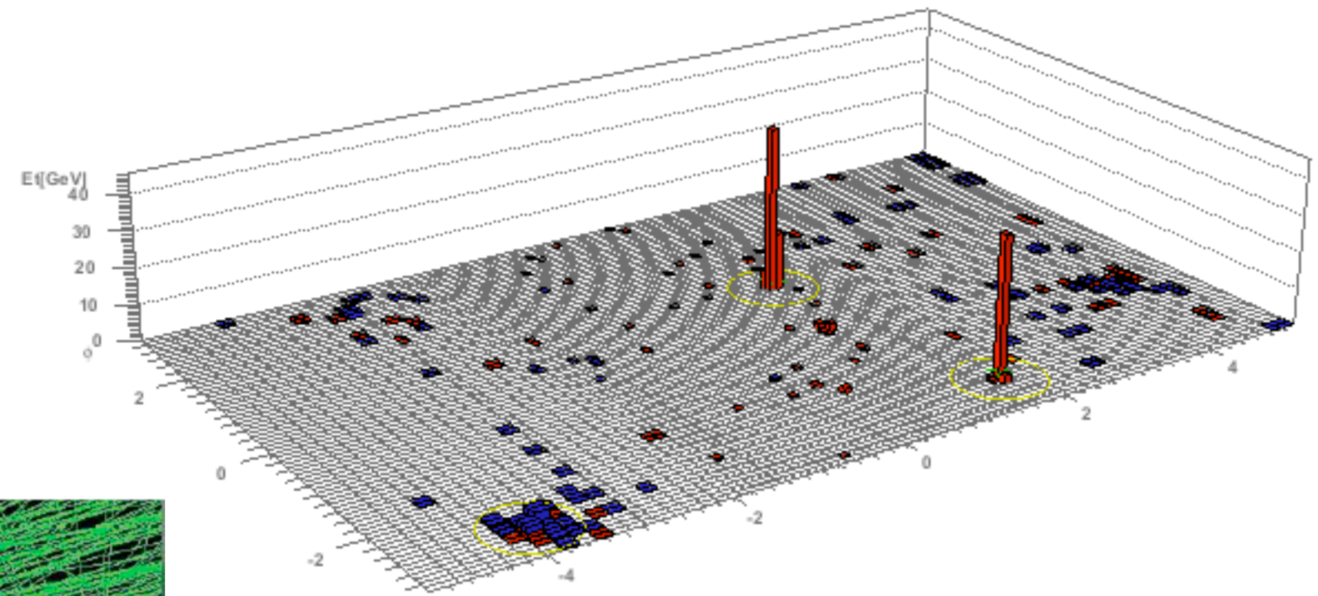
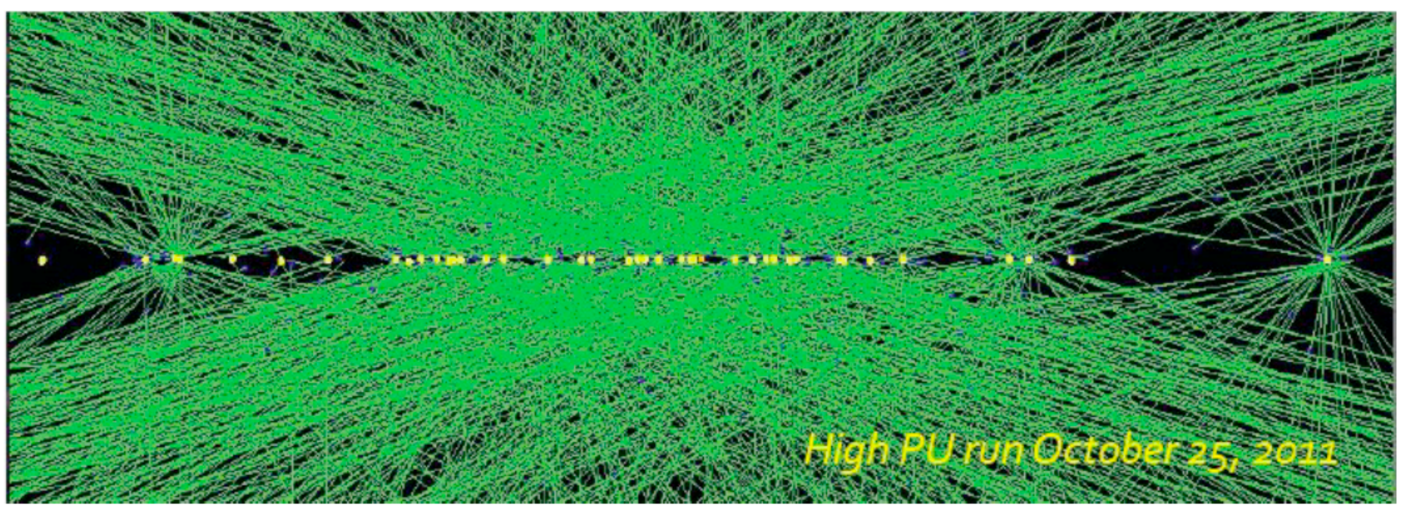




in above Higgs->2 gamma and proton jet fragments observed very forward region

How to associate them with proper vertex when pileup prese

Timing may provide a key tool.

many vertices in hi-PU event even today

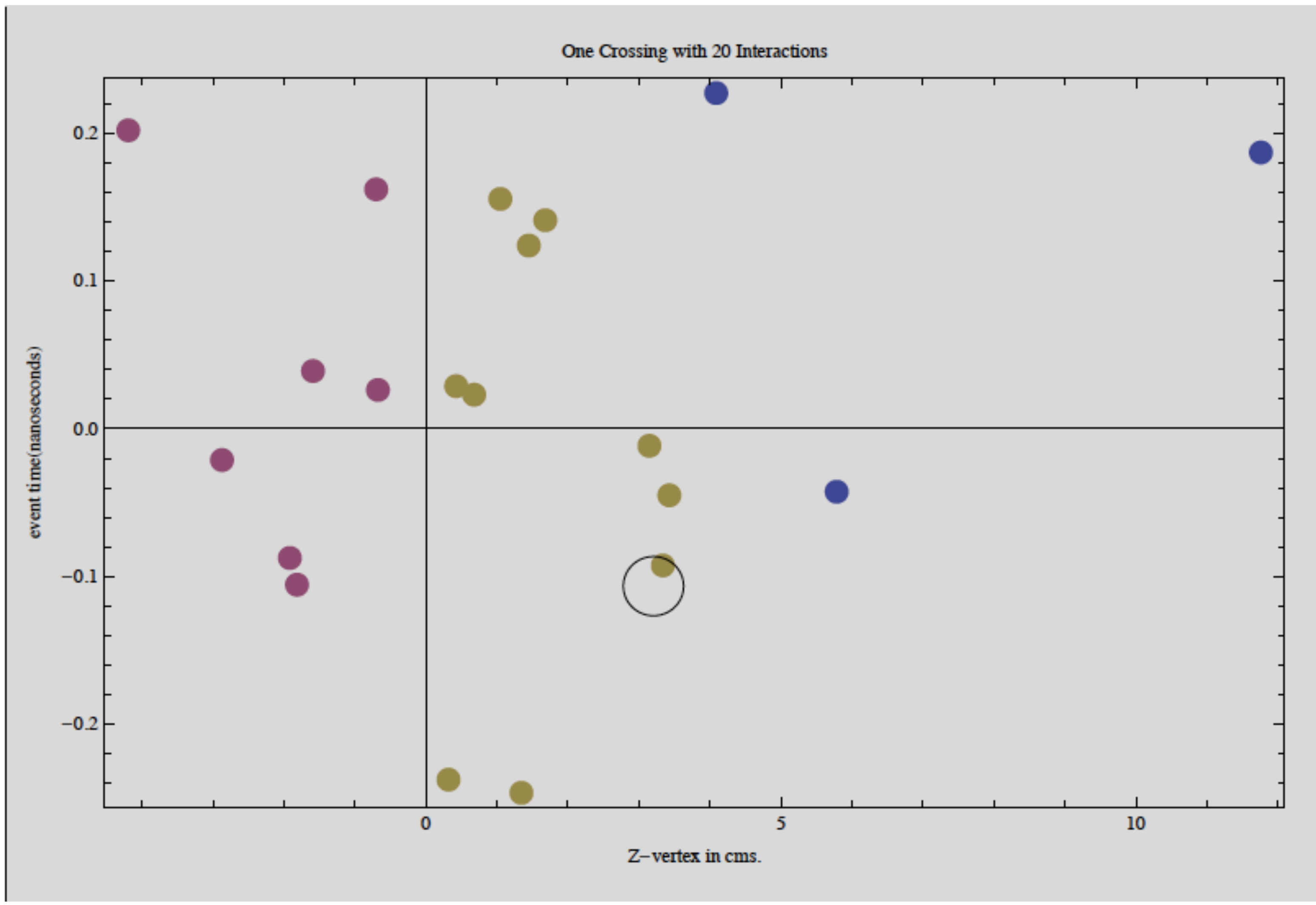
Work in CMS forward calorimeter task force and DOE AD R&D: K. McDonald & S. White- co-PI's

Start from LHC simulation of bunch crossing

2007 paper:**"On the Correlation of Subevents in the ATLAS and CMS/Totem Experiments", S.White, http://arxiv.org/abs/0707.1500**

in this example: 20 events/crossing, plotted as vertex(x-axis) vs. event time.

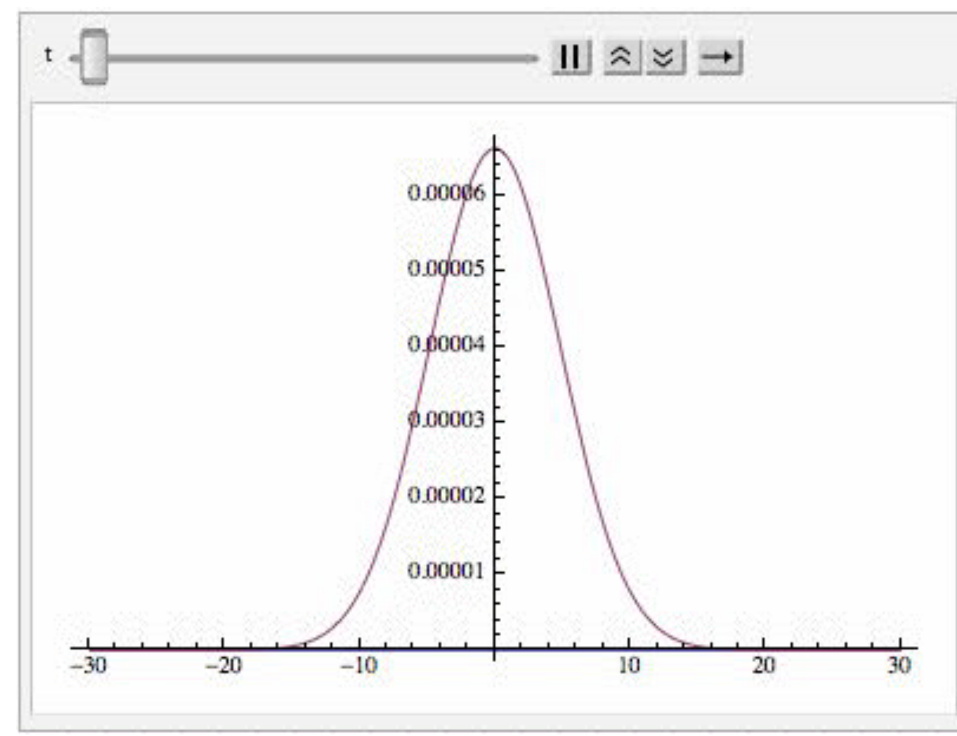
Nb: circled event needs both time and vertex to resolve.

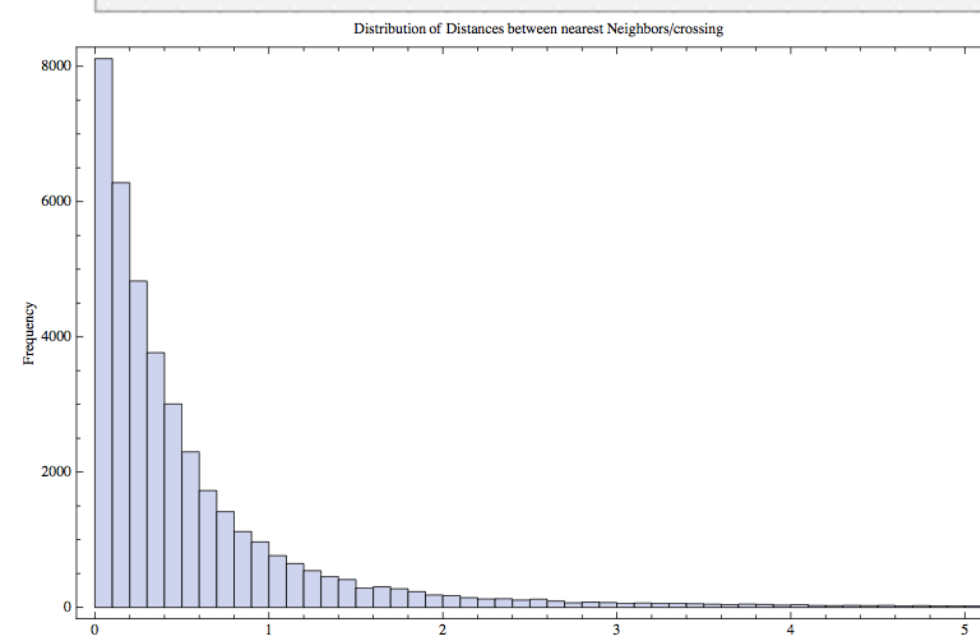


how effectively is PU resolved with n(or Jet) ideal time resolution of 10 picosec? Illustrated by error elipse

vertex distribution time invariant

$$L(z,t)=l(z,t)*l(z,-t)=\frac{e^{-\frac{(-c\,t+z)^2}{2\sigma_1^2}-\frac{(c\,t+z)^2}{2\sigma_1^2}}}{2\pi\sigma_1^2}=\frac{e^{-\frac{c^2t^2+z^2}{\sigma_1^2}}}{2\pi\sigma_1^2}=L(z)*L(t)$$

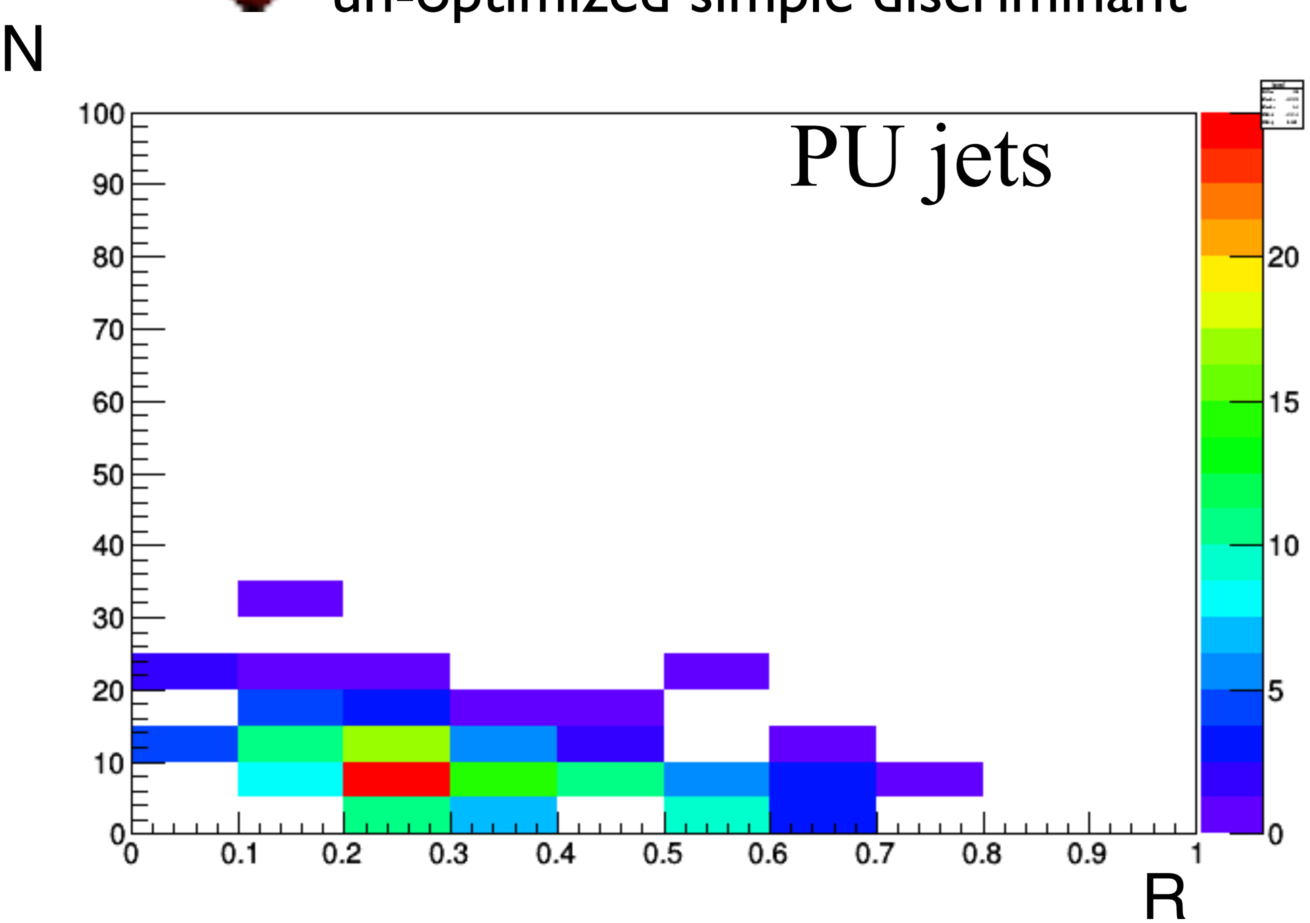


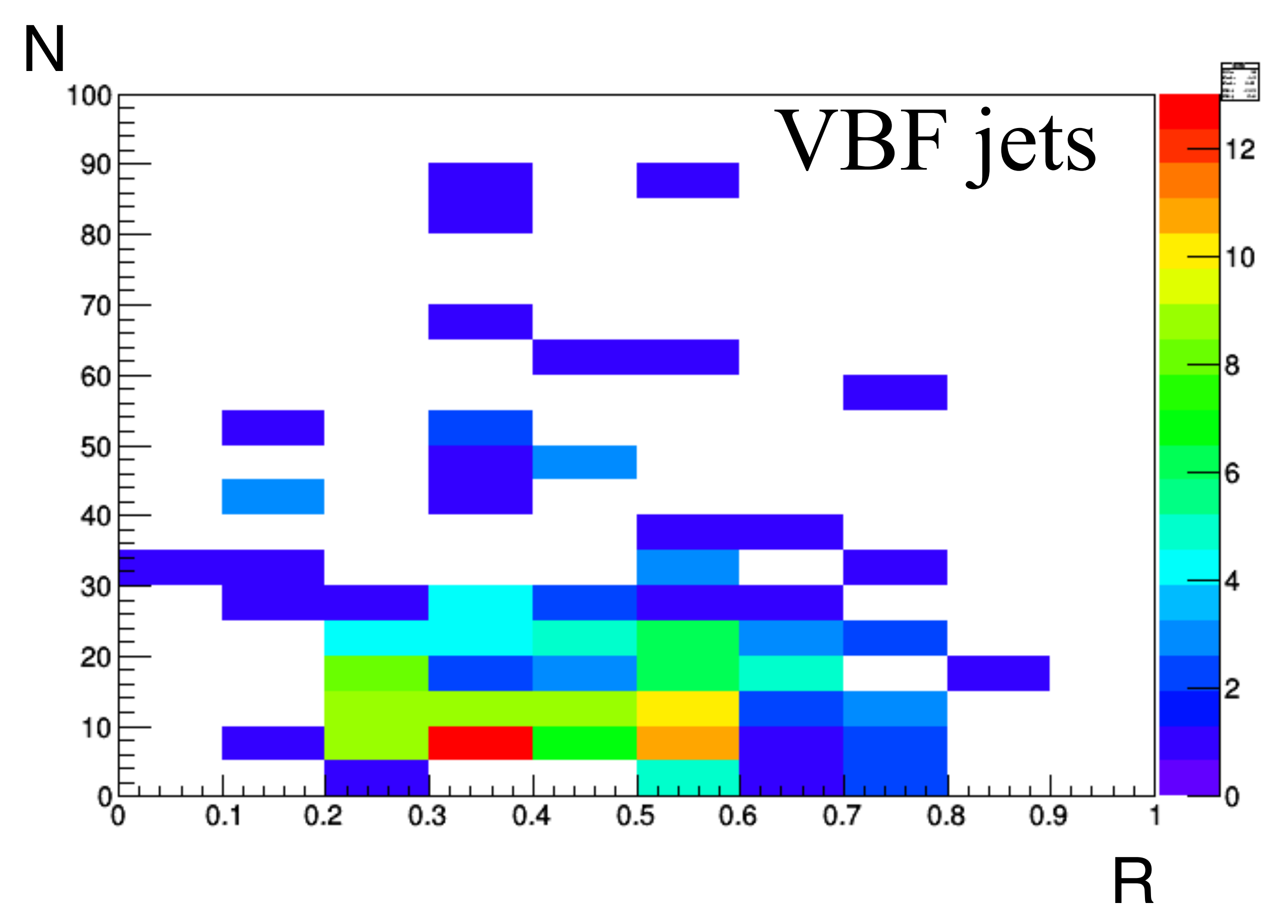


dist distribution exponential: see eg. p 362 Papoulis: Probability, random variables and stochastic processes (1991 ed)

Timing of VBF jets: PU suppression

- detecting time of tracks pointing to very forward jets allows for determination of both time (t_{vtx}) and position (Z_{vtx}) of the primary vertex
- examining consistency of t_{vtx} and Z_{vtx} for all tracks in the jets allows for separation of real jets (all tracks from the same vertex) from the PU jets (random overlaps of tracks from many vertices)
- Very-very preliminary DELPHES-based simulation results (assuming ~10ps resolution)
  - 140 pile-up events
  - un-optimized simple discriminant

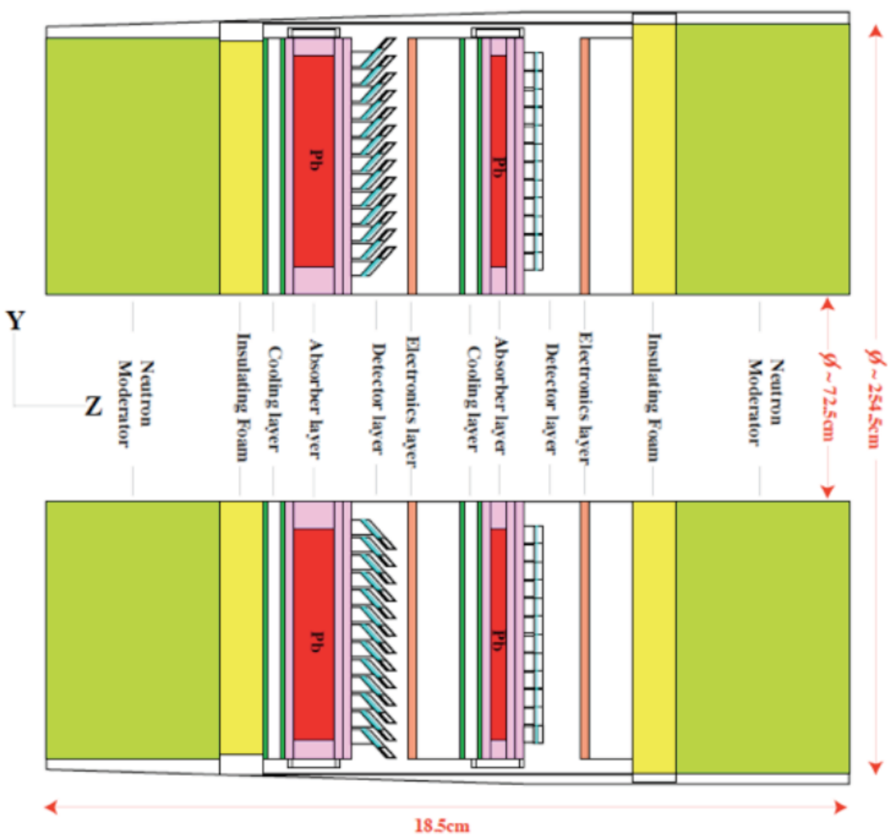




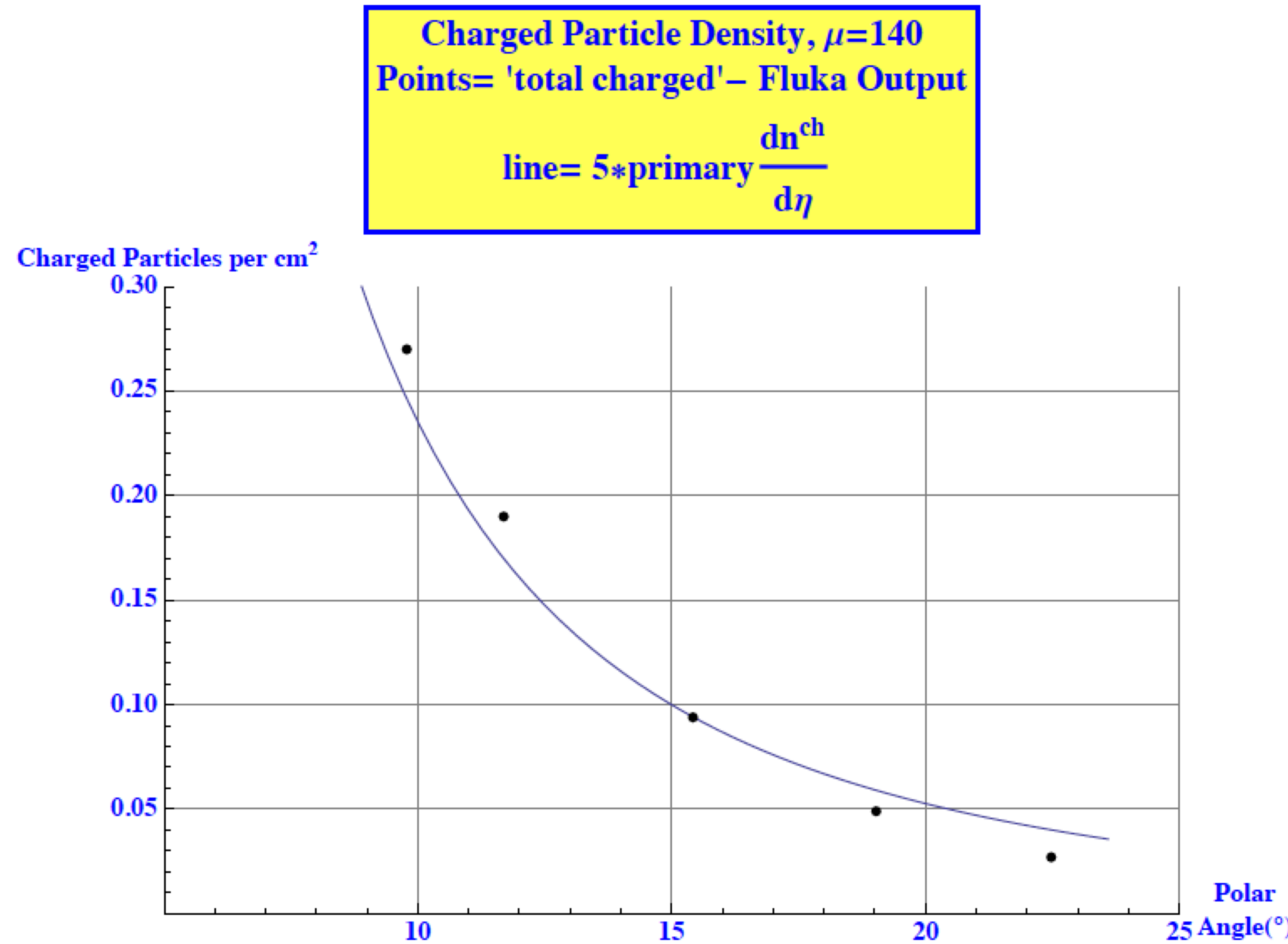
slide from Y.Gershtein

Opportunity for Fast timing layer in CMS Endcap

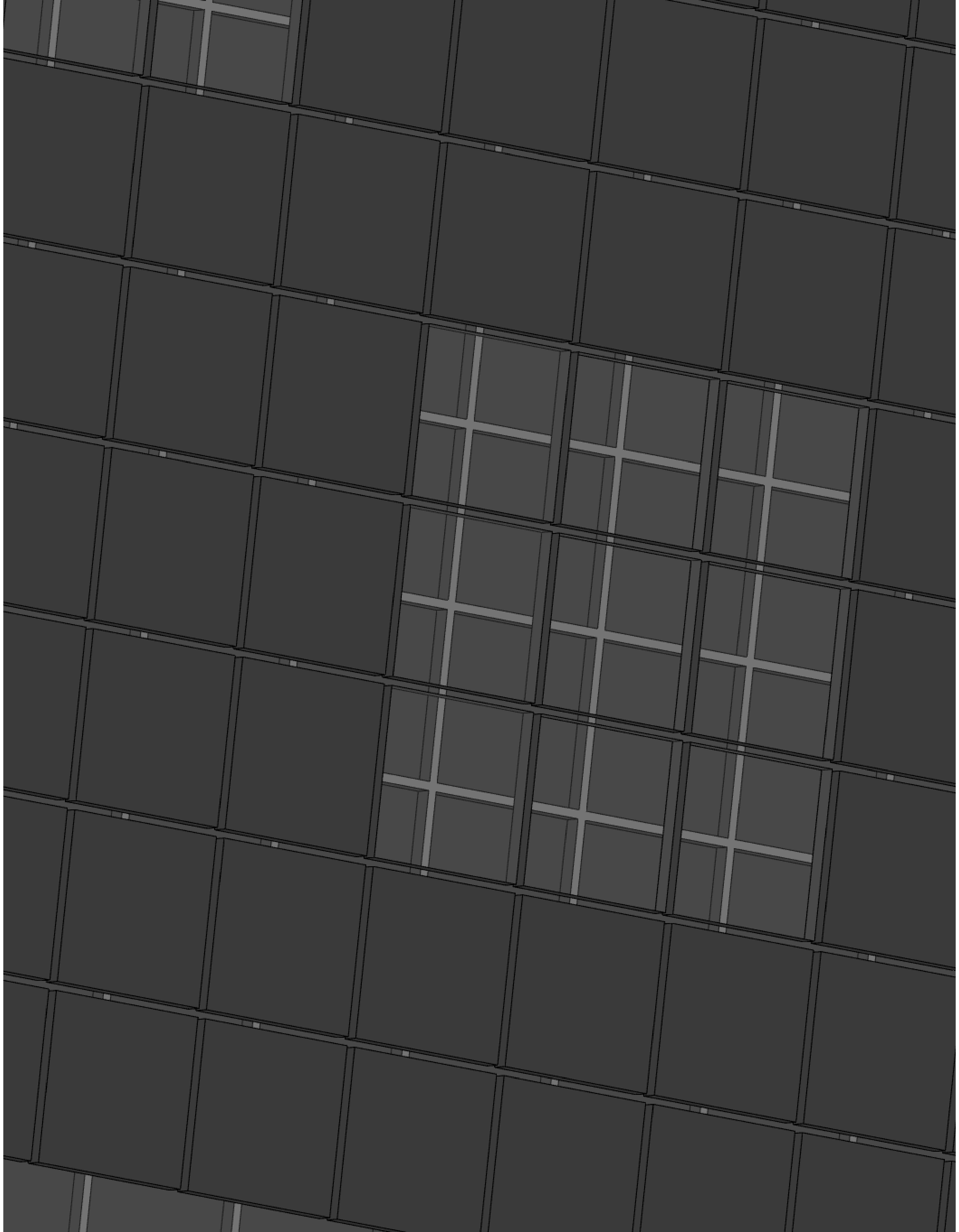
Current CMS pre-shower volume



for PhaseII simulation replace 1st sensor layer w. timing sensors



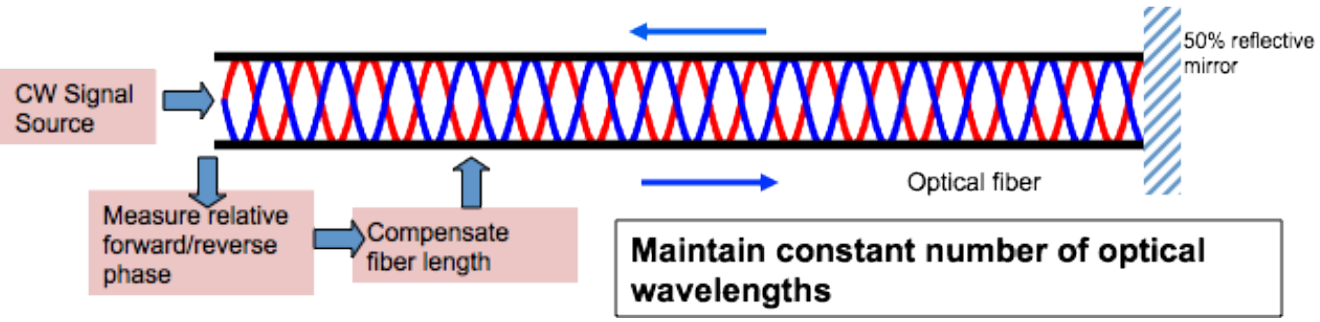
Fluka HL-LHC calculation shows 1 cm**2 is about right pixel size



Timing layers for simulation in CMS

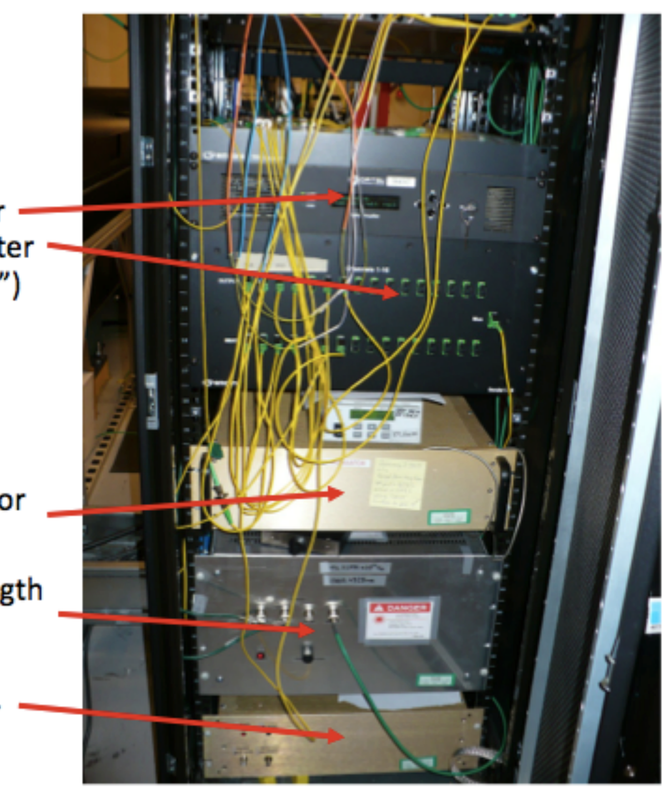
Tools: Clock Synchronization

FEL community has demonstrated 10 fsec over 100's of m.



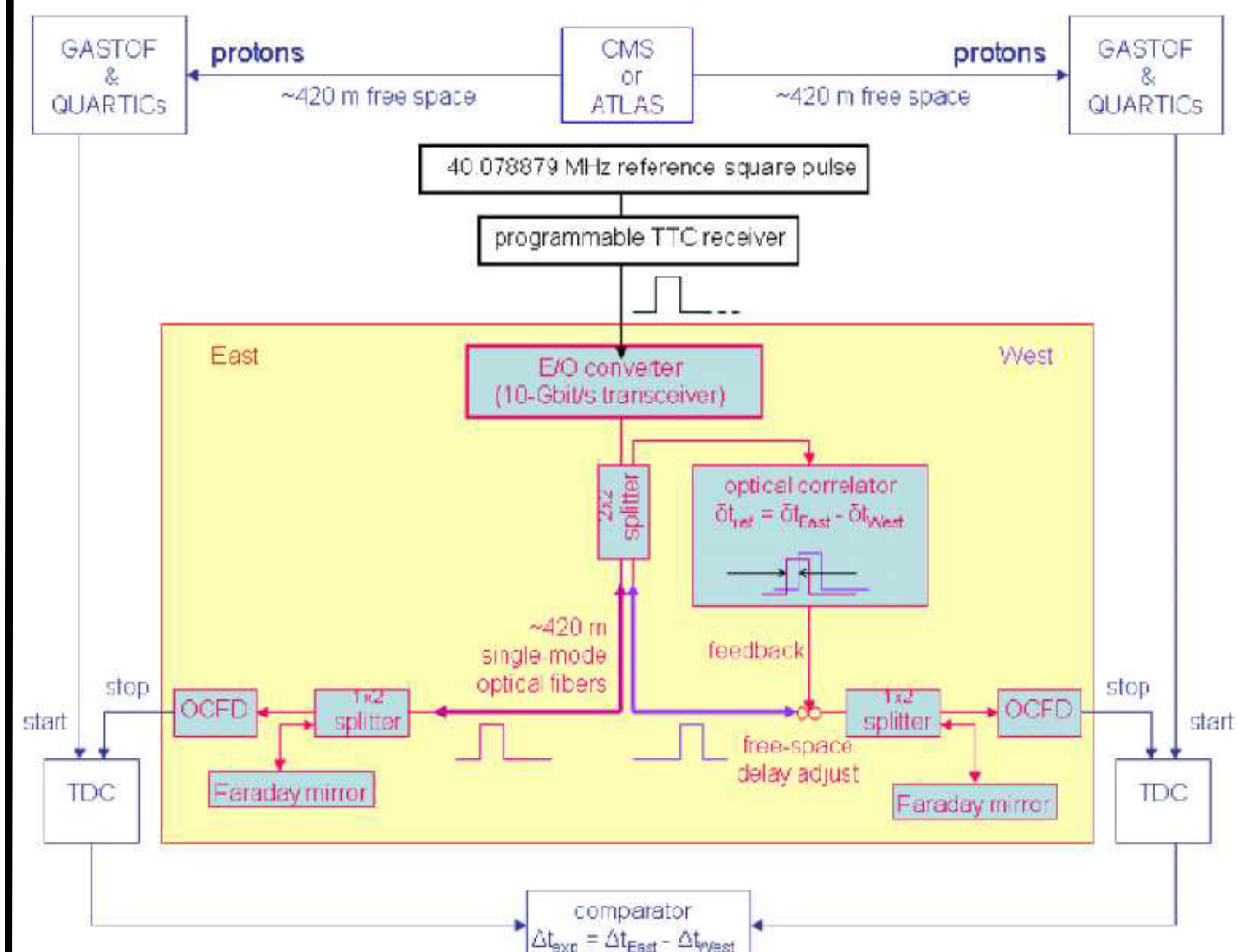
Interferometrical stabilization of eg. 20 picosec/deg.C/km thermal drift of optical fibres.

FEL community uses ethernet tech for synchronizing remote clocks to picosec level- eg. "white rabbit" project



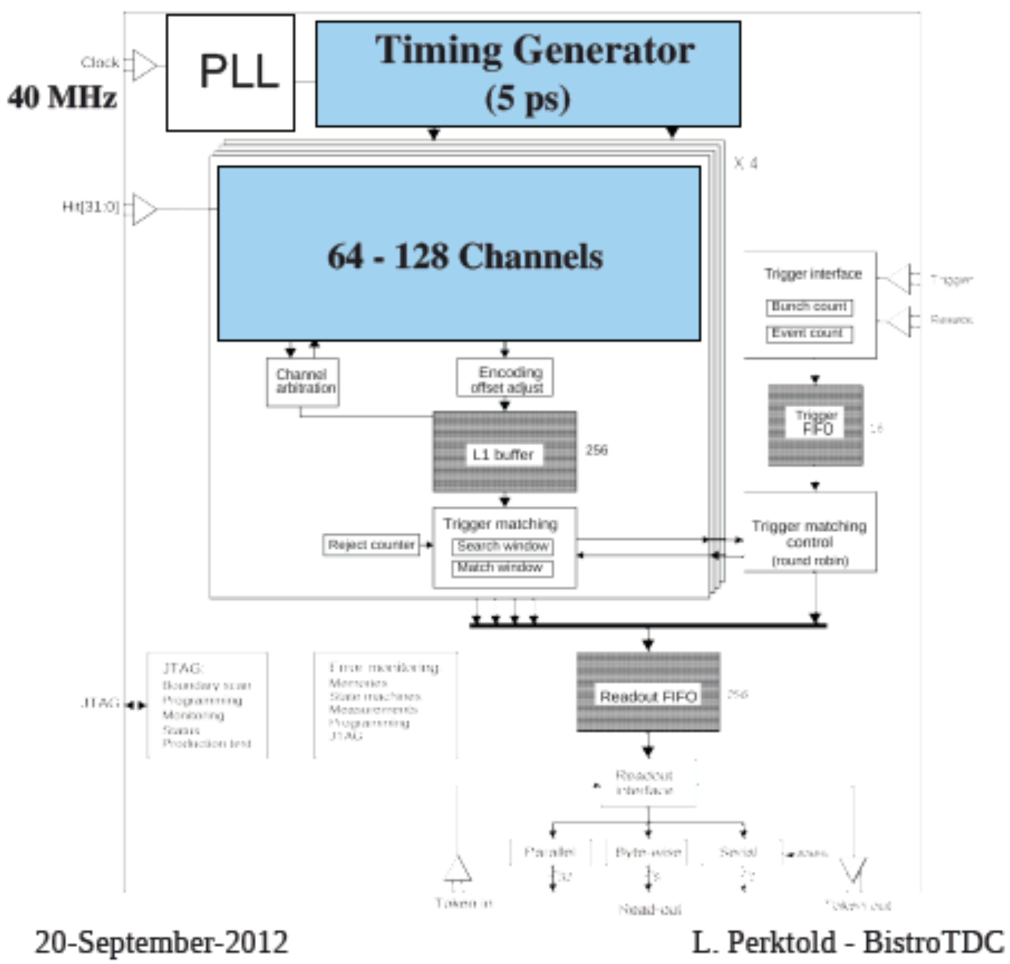
- Amplifier and splitter ("sender")
- Modulator
- Wavelength locker
- CW laser

We (T.Tsang & SNW) designed a $60k system based on optical correlator for 5 picosec stability. -see FP420 R&D report, 2008.



Tools: Digitization

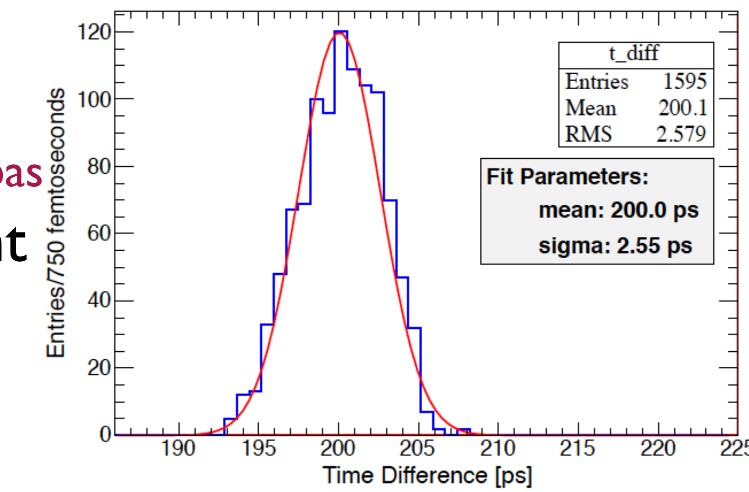
TDC Architecture:



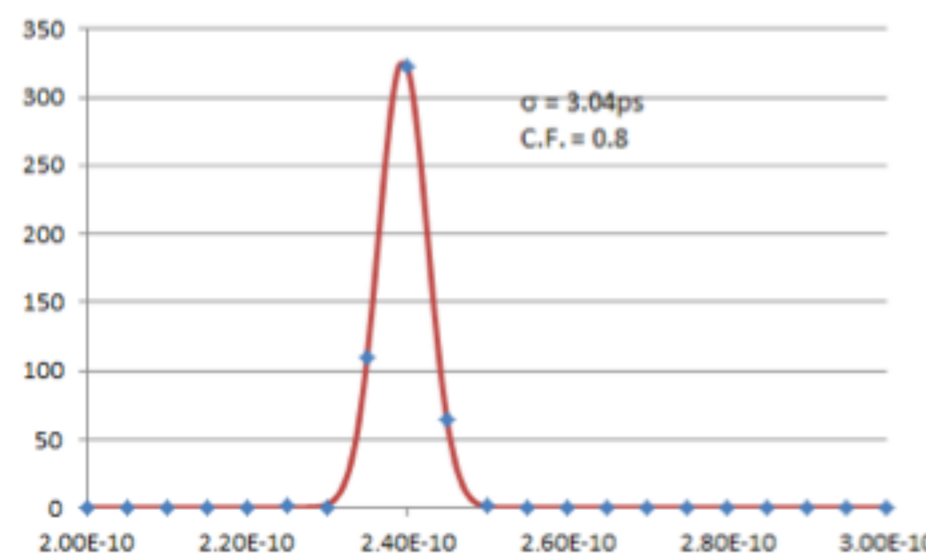
higher resolution version of TDC used by ALICE:
3 psec rms jitter in ASIC
<5psec goal in full system.

waveform digitizer approach:

psec4 chip,
contacts:Eric Oberla& Herve Grabas
similar result w. equivalent test on DRS4 (3.2 psec.)
S. Ritt- private comm.

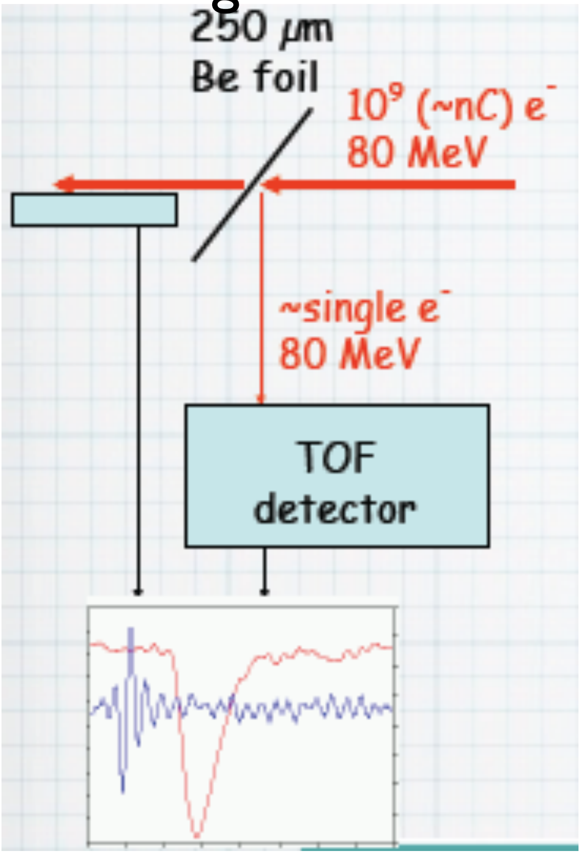


our result from time diff on 2 striplines at electron LINAC
w. 3 picosec bunch length, SNR~100,
trise~150 psec=>2.5 picosec rms. remeasured this year:



Tools for device testing

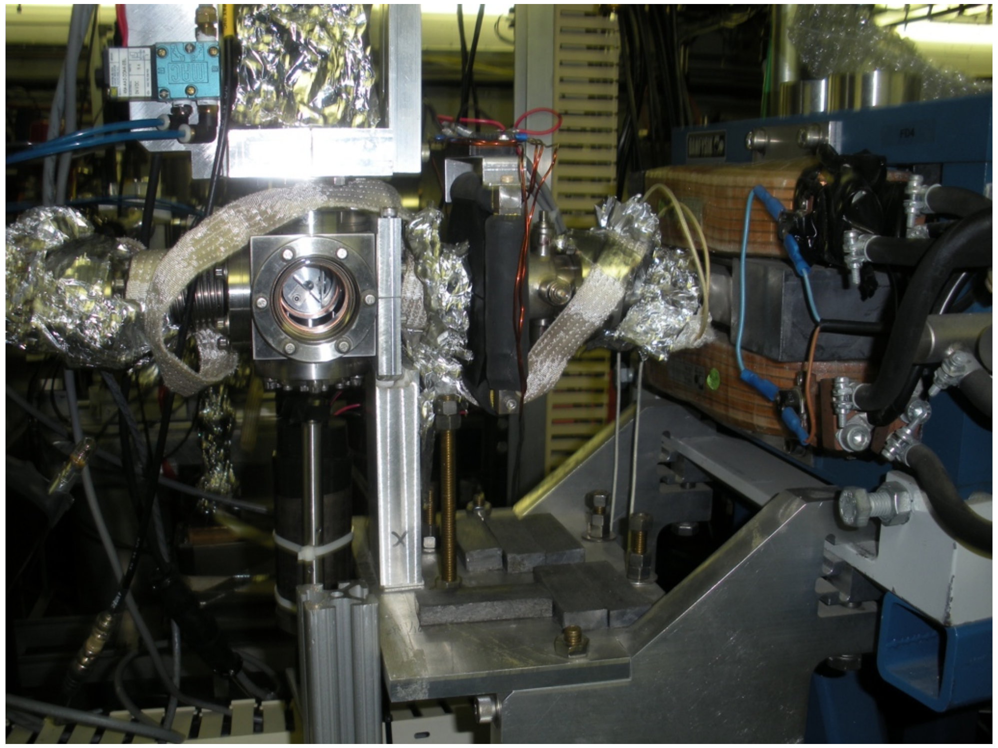
80 MeV single electron with 3 psec jitter

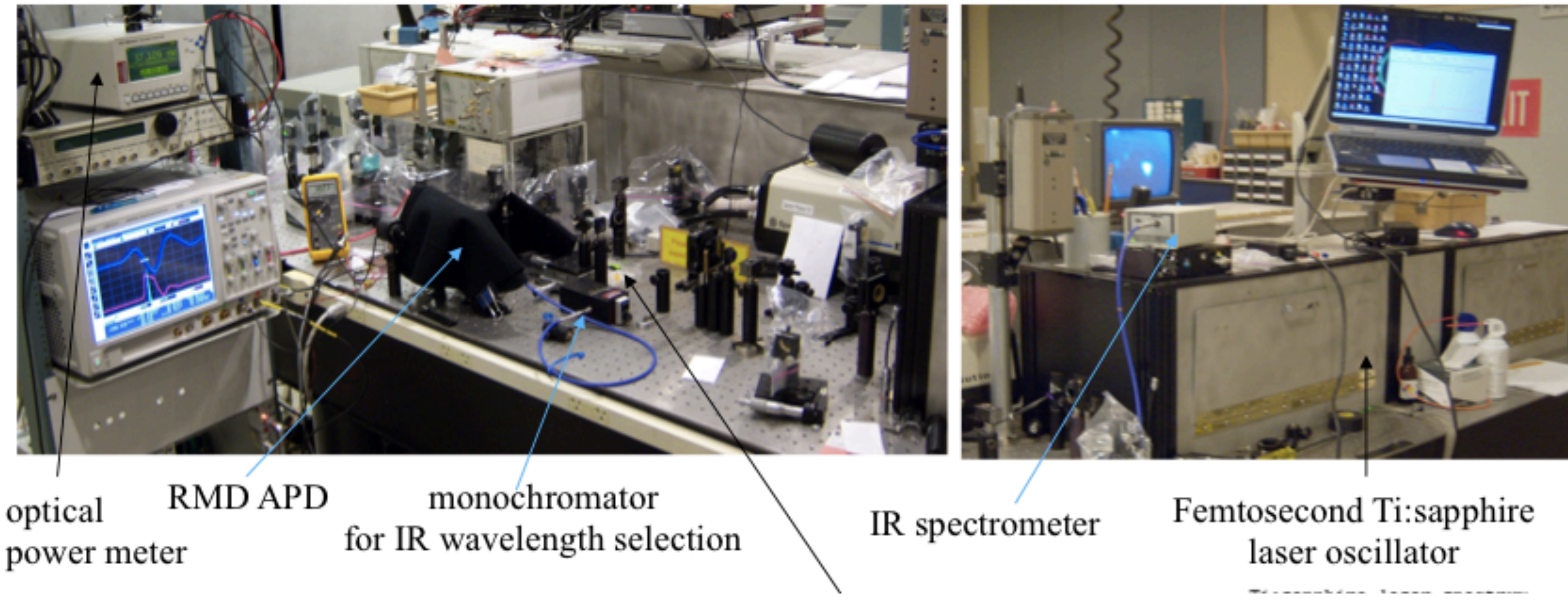


(also discussing similar possibility with LAL, Orsay)

1) ATF 2010->now.(and LAL?)
2) PSI (fall 2011 and May, Dec 2013)
3) Frascati (fall 2011)
4)CERN NA (Feb 2013)
5) femto sec laser for Si APD
7) DESY 5GeV e, March 1-2,2014

AE55 - Single Electron Experiment. Spokesperson: Sebastian White, Columbia and Kirk McDonald, Princeton (2010-)





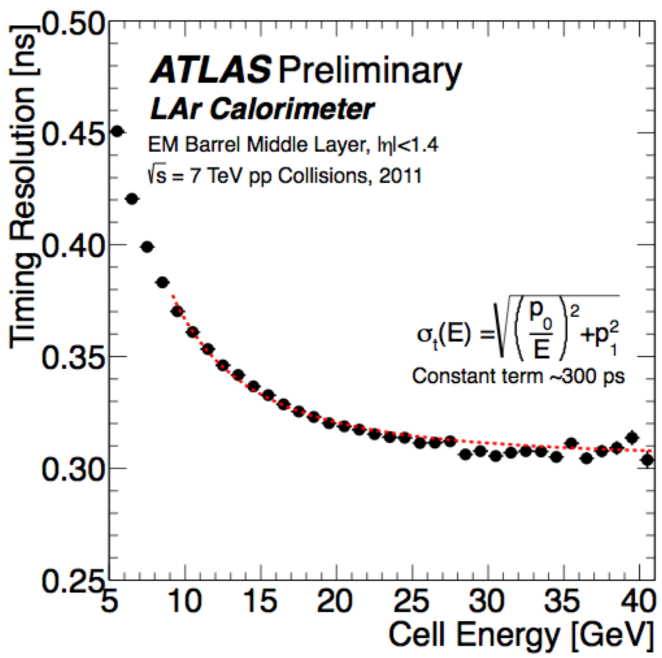
5. **Energy Calibration of Underground Neutrino Detectors using a 100 MeV electron accelerator** / White, Sebastian ; Yakimenko, Vitaly
An electron accelerator in the 100 MeV range, similar to the one used at BNL's Accelerator test Facility, for example, would have some advantages as a calibration tool for water cerenkov or Liquid Argon neutrino detectors. [...]
arXiv:1004.3068. - 2010.

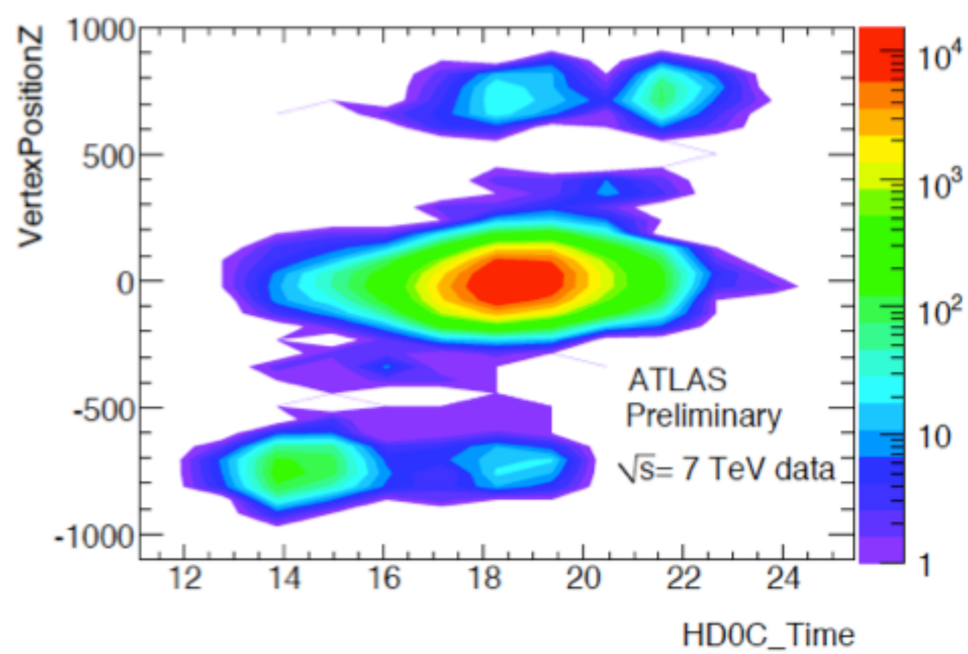
Pileup Mitigation

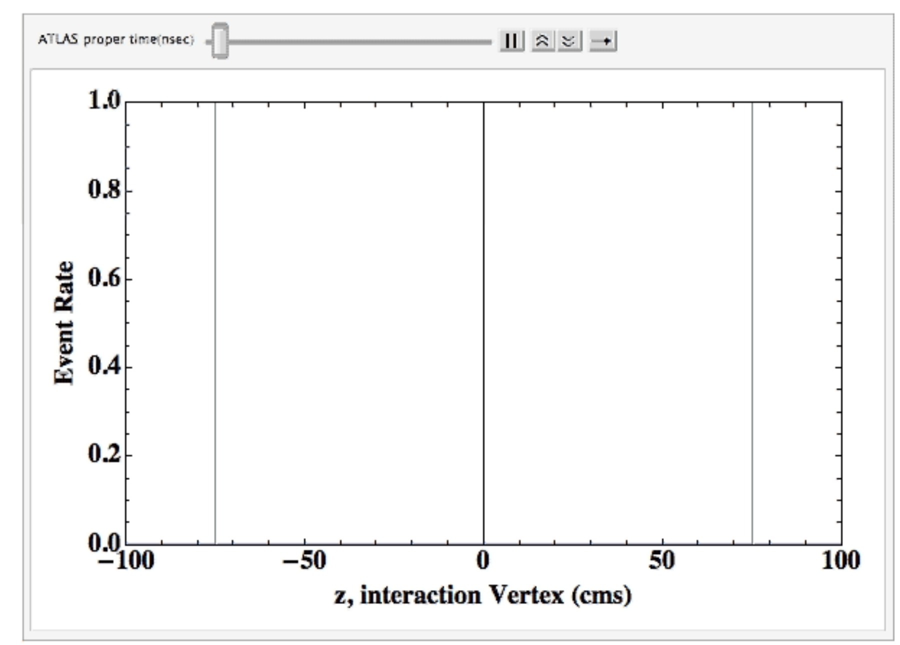
LHC itself could do things to make life easier:

1)20->40 MHz crossing rate halves pileup
2) Exotic "crab crossing" "kissing" schemes discussed at ECFA 2013
-however reliability of the machine will likely remain a priority

What can timing in ATLAS/CMS achieve today?







notes:
1) 300 psec includes 170 psec event time jitter
2) LAr testbeam showed ~60 psec/sqrt(E-GeV)
3)estimates of ultimate constant term ~60picosec (Simion and Cleland)
4) Similar studies in CMS

ATLAS Zero Degree Calorimeter achieved separation of micro-satelite bunches from timing (shower time resolution<100 picosec)

A dedicated tool for particle timing in CMS

=The jury is still out on level of timing achievable in calorimeters

=Or even detailed evaluation of benefit for physics objectives from pileup mitigation.

=But growing realization that we should anticipate the next question

- ie do we have anything in our toolkit that can achieve
- 10-20 picosecond timing at rates of 10^6-10^7 Hz/cm^2.

=The answer, up to now appears to be "No".

Nagoya R&D on dedicated timing detector

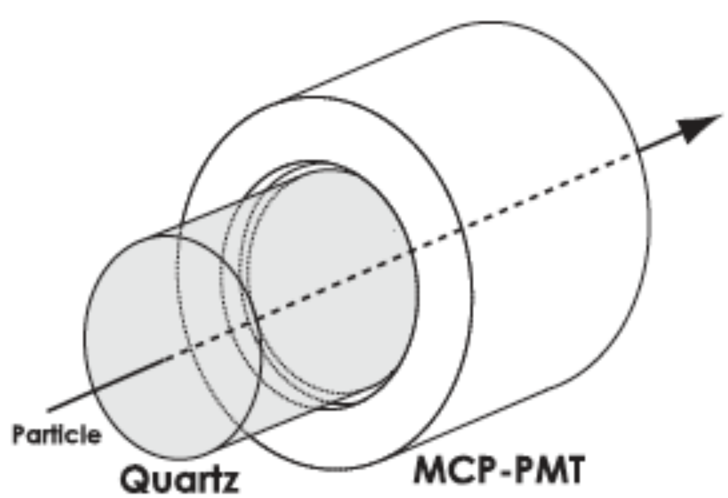
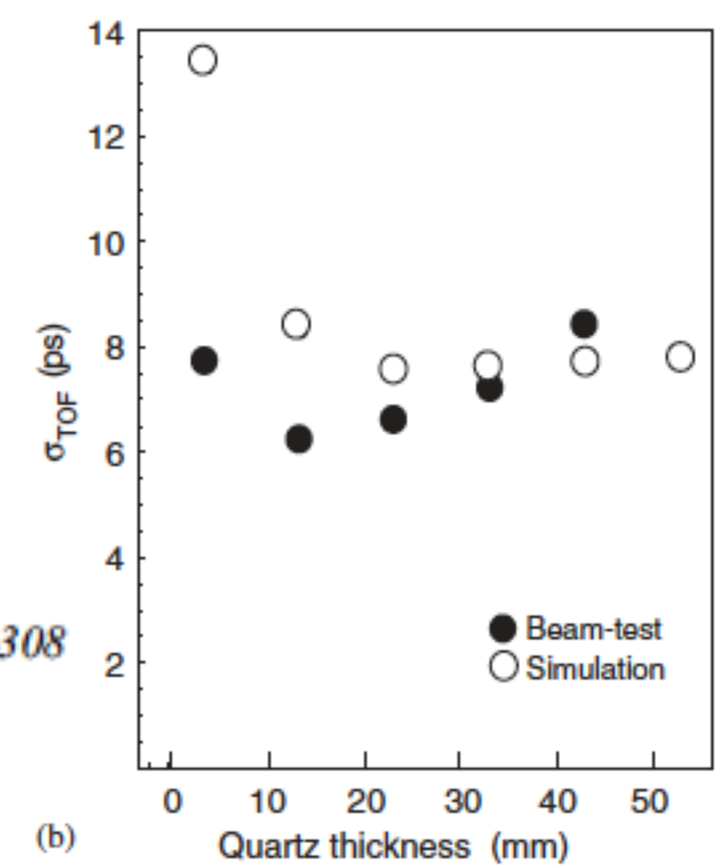


Fig. 1. Schematic drawing of the TOF counter.

K. Inami et al. / Nuclear Instruments and Methods in Physics Research A 560 (2006) 303–308



Very influential! Everyone went out and bought MicroChannelPlate PMTs. (thousands of $/cm^2.)

Photosensors

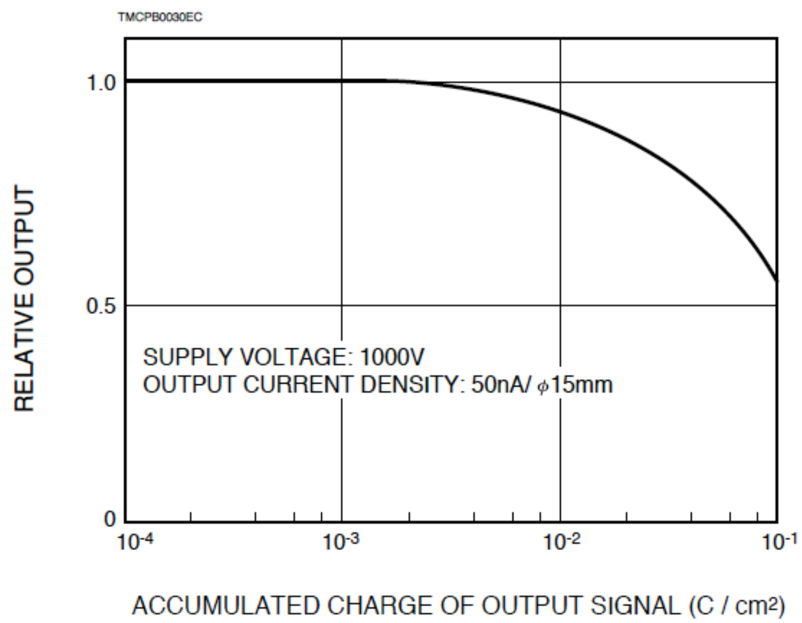
(we worked with Hamamatsu to evaluate options)

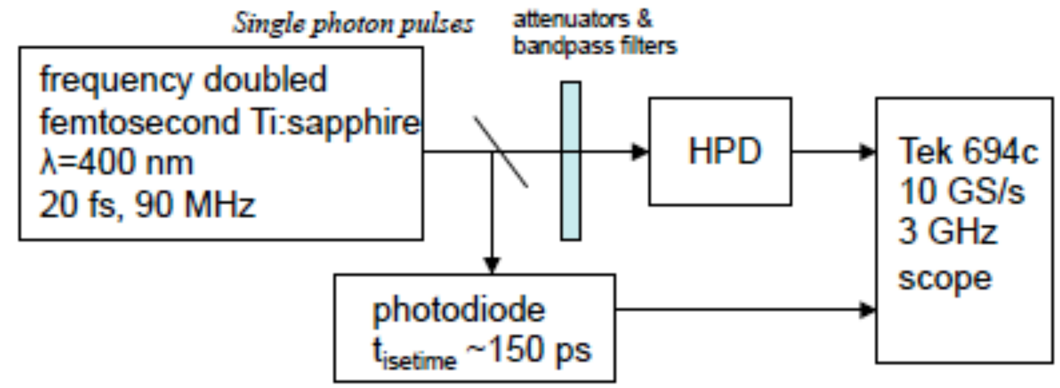
lifetime is an issue in MCP-PMT

compare Hamamatsu data on:

our measured single photon time response:

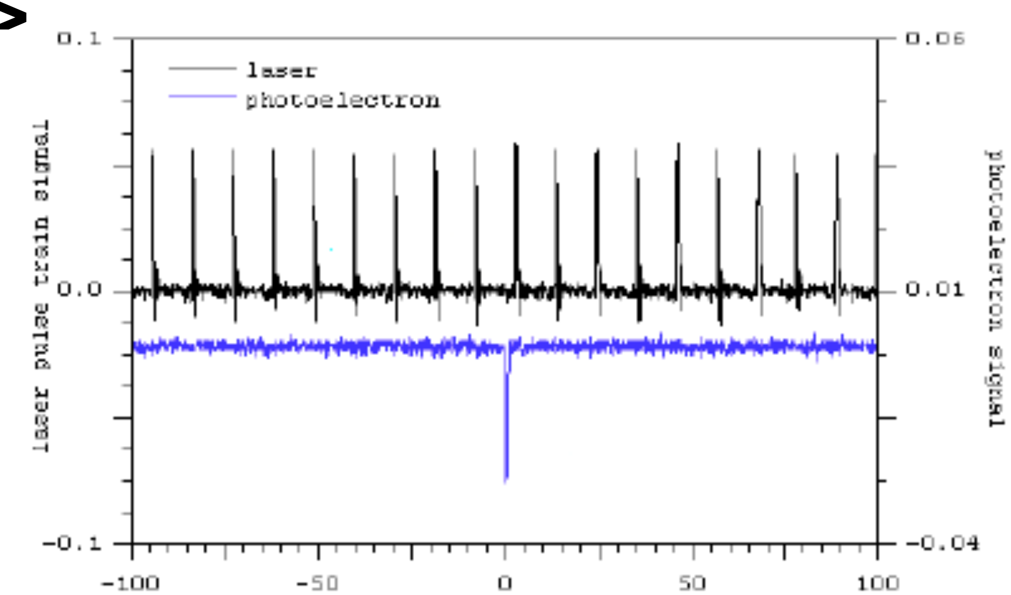
MCP · Life



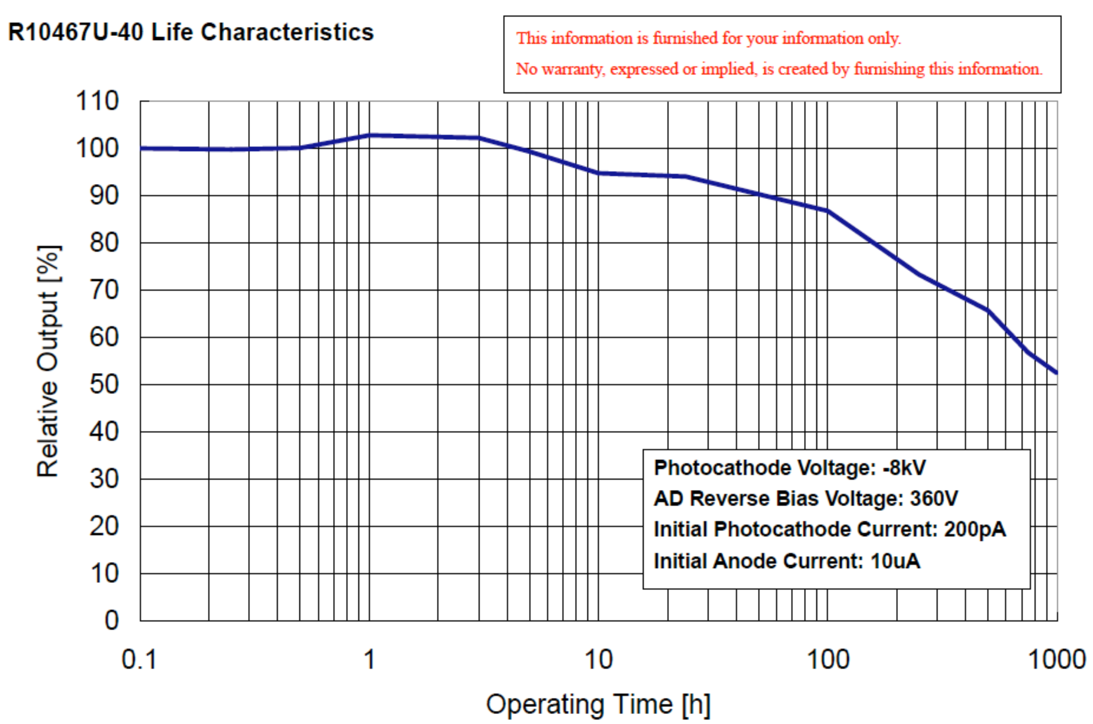


Ti:sapphire oscillator:
attenuate to
95 femtoWatt
~200 kHz count rate
~2x10⁵ photons/sec
(<0.002 photon/pulse)

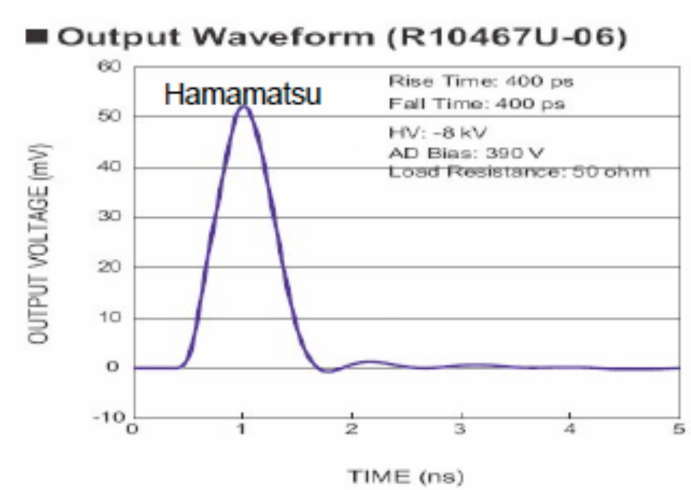
=>



compared to new technology evaluated by our collaboration:

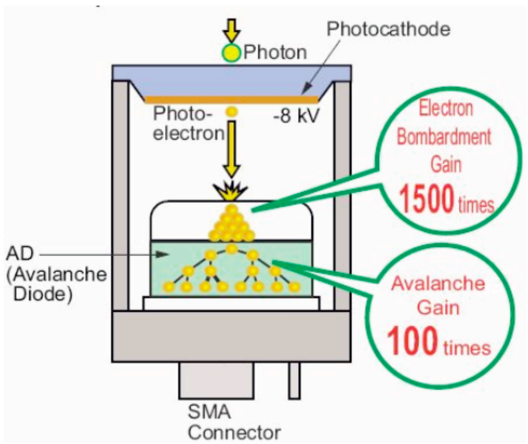


Measured jitter relative to photodiode=11 picosec!!



Conservatively factor of 360 improvement (MCP->HAPD) !!!

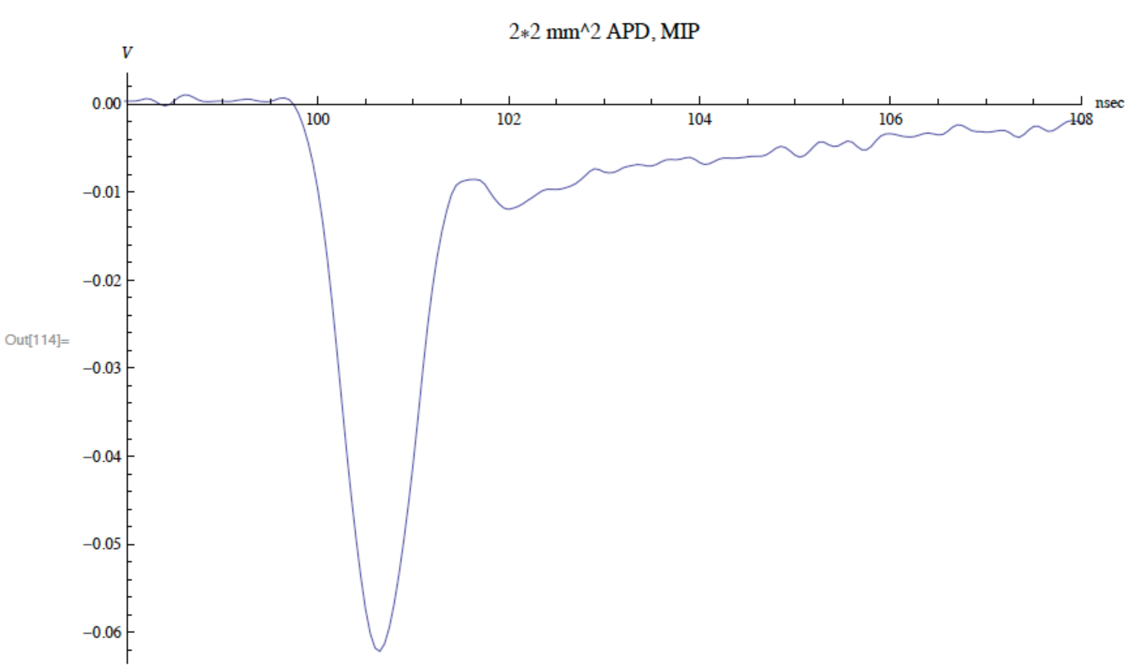
Picosecond Charged particle tracking:



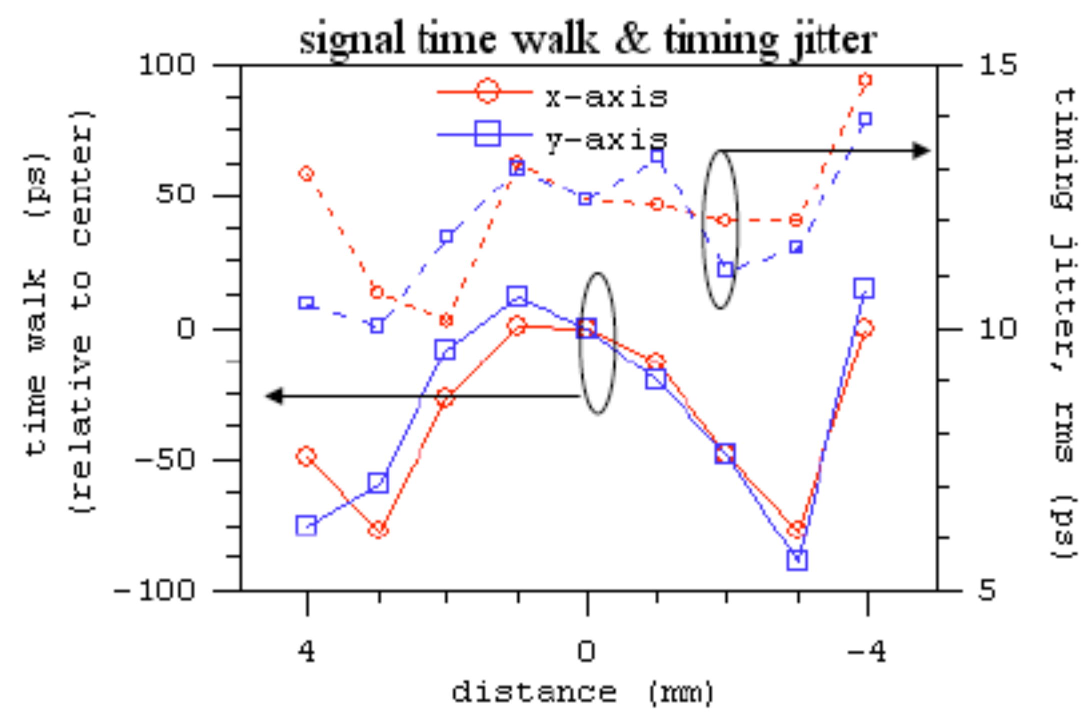
Hybrid APD (results on previous slide) is an accelerator followed by APD used as charged particle detector. Since it yields 11 picosec jitter why not use APDs as direct charged particle detector?

(Subject of rest of this talk)

Initial beamtests with deep-depleted APD's @ ATF, LNF, PSI yield high SNR & 600 picosec t_{rise} but poor uniformity. Improved with better metalization of APD.



in this figure noise level dominated by scope noise floor



intermediate results with early metalization improvement

Issues in charged particle timing

Nb: most of the relevant literature is to be found outside HEP-eg:

Information Theory:"Communication in the Presence of Noise",CLAUDE E. SHANNON, MEMBER, IRE-Classic Paper

Acoustics and Radar:"Time Delay Estimation",Iain Jameson,Electronic Warfare and Radar Division,Defence Science and Technology Organisation

at level of 10-20 picosec, digitization(see above) a new element

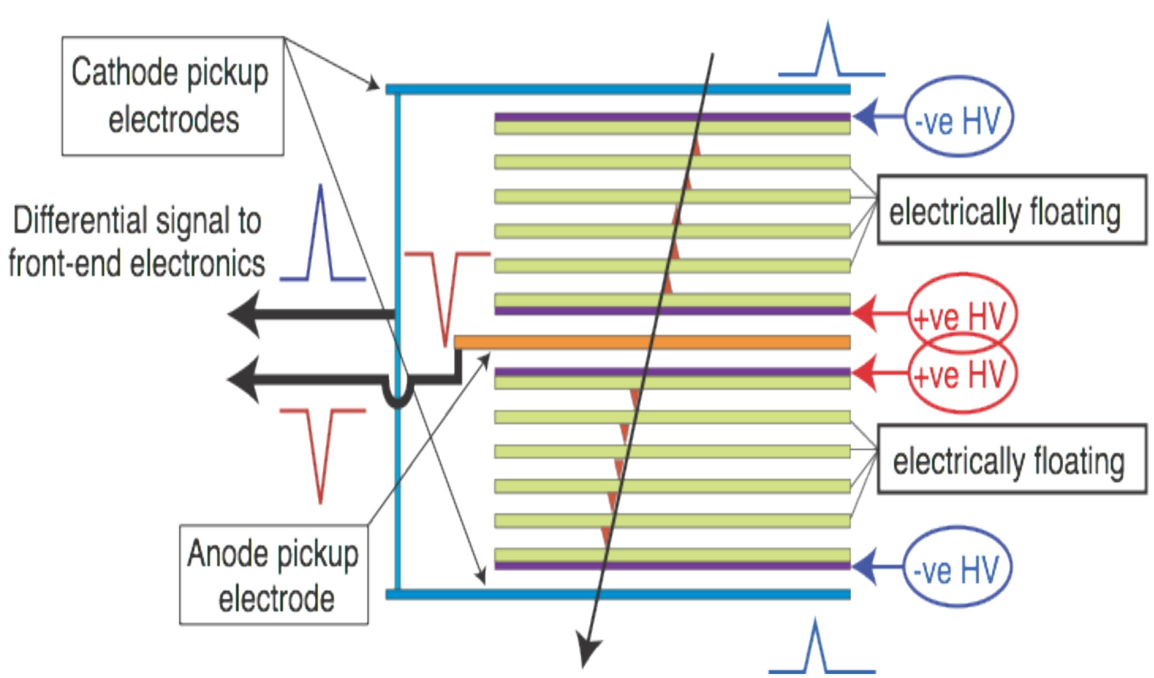
For our problem, principle issues are:

-familiar issue of SNR and risetime (jitter~T_rise/SNR)

-stochastic nature of signal formation (energy clustering in a gas or solid state detector)

-transit times in Signal collection

Current LHC record holder(ALICE)



~80 psec resolution in full system. C. Williams currently getting 16 picosec in R&D but <u>not focusing on rate issues</u> Limitation due to stochastic cluster formation addressed by multiple measurements

Charged Particle Timing (cont.)

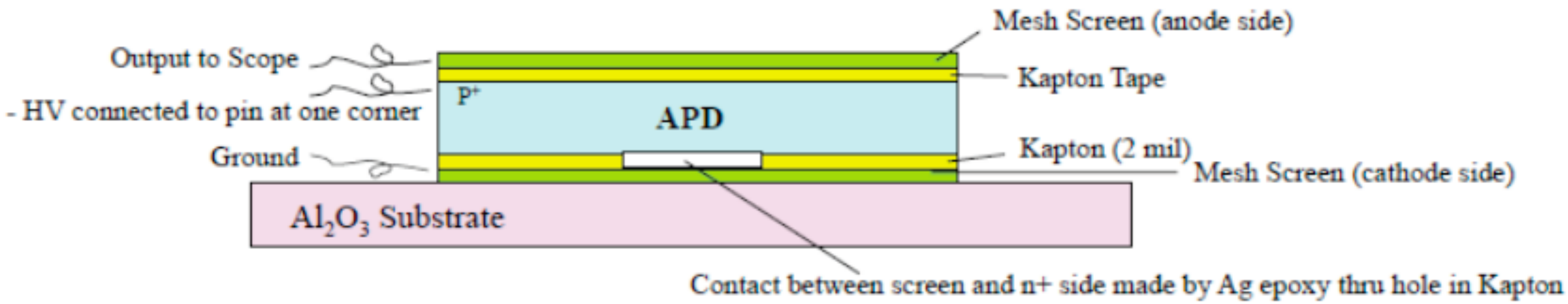
For dedicated timing layer, likely winner is Solid
-exploring an alternative (gas) approach using MicroMegas with Giomataris, Delagnes and Veenhof
-in rest of talk focus on Si detectors/APD
-Diamond tracker likely to yield 60-80 picosec
-NA62 Giga-Tracker (planar Si pixel det/ 200 micron) achieved ~180 picosec w. main limitation from weighting field(see below), but stochastic contribution from Landau also significant.
-one approach (Sadrozinski- see his DPF '13 talk) is very thin Si (5 micron and very low gain- yet to see how they deal w. SNR&field)
-Our approach, using Deep Depleted APD w. Micro Megas field shaping, addresses many of the NA62 issues.
-we have many APDs from Hamamatsu and they have asked us to evaluate more, similarly contact w. CNM. Vacchi looking into new structures
-but currently devices developed w. RMD most promising.

Signal detection on sense electrode

$$i(t) = \frac{E_w}{V_w} v e_0 N(t)$$

(Ramo's Theorem)
Where:
e0=electron charge
Ew="weighting field"
Vw=potential
V=charge velocity

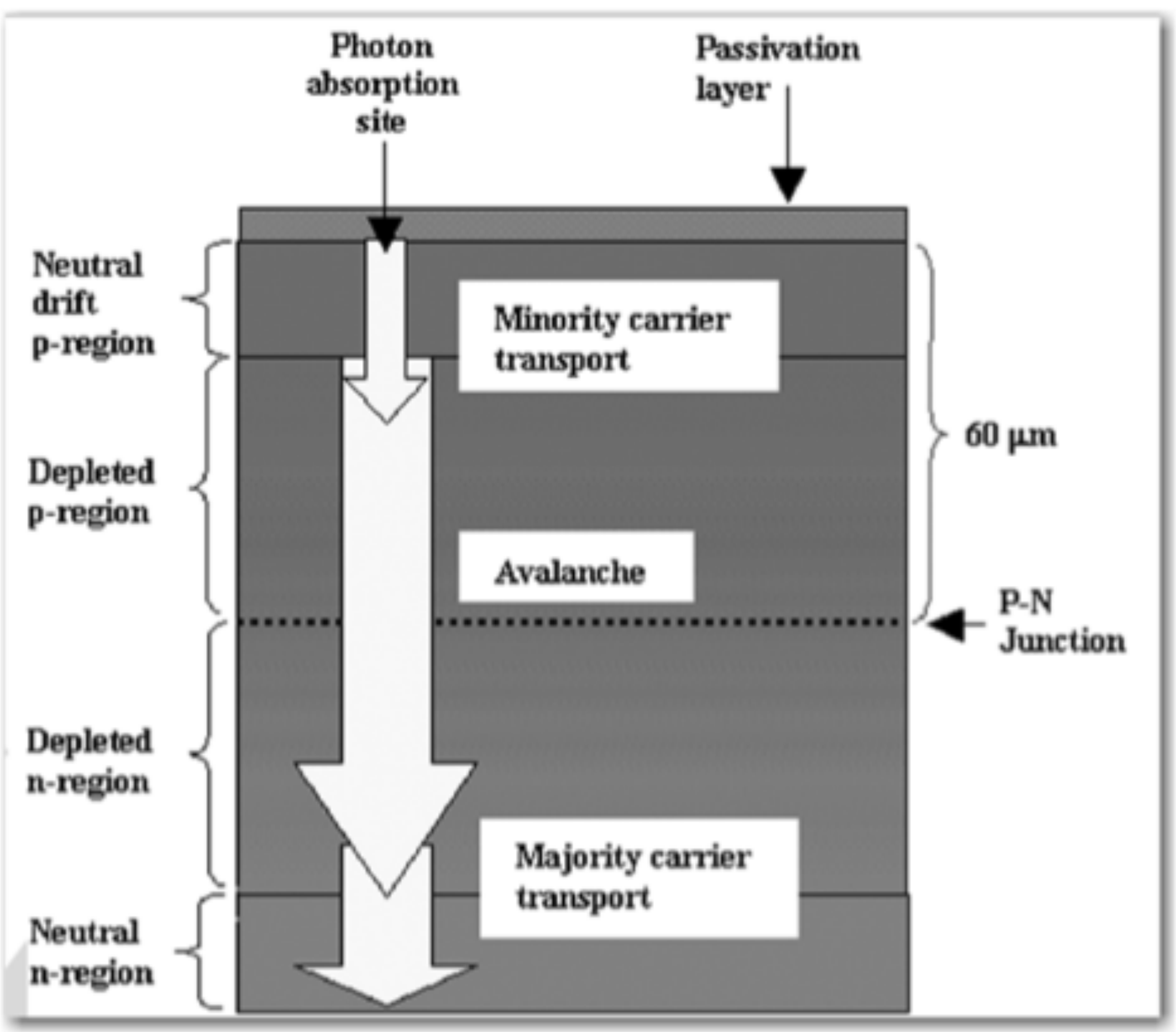
Top Screen Output Connection (capacitively coupled)

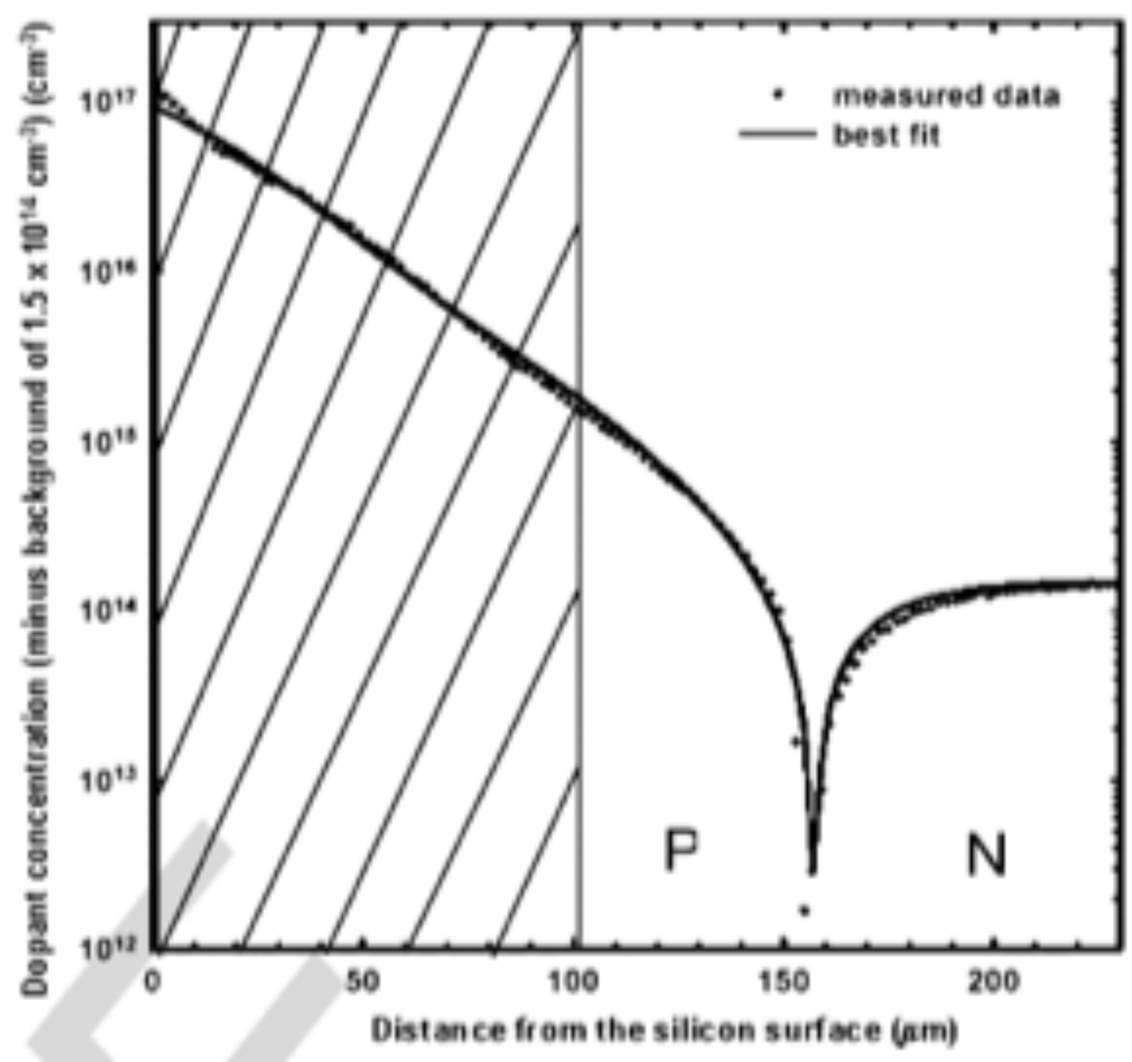


-MicoMegas Screen (top) eliminates large (~600 picosec) excursions due to intrinsic field variations-(which limited NA62)
-Expect time development due to varying electron arrival in amplifying(high field) region followed by tail (irrelevant for timing)

RMD/Dynasil Deep Depleted APD

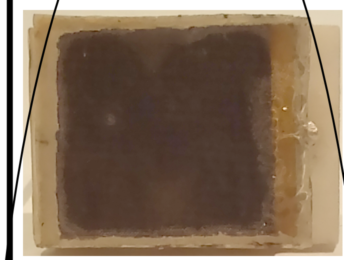
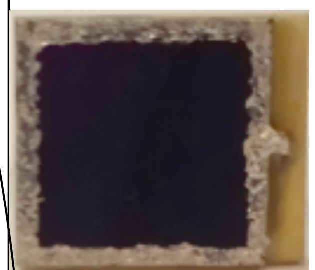
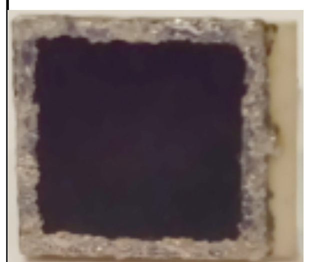
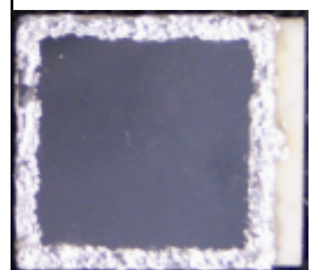
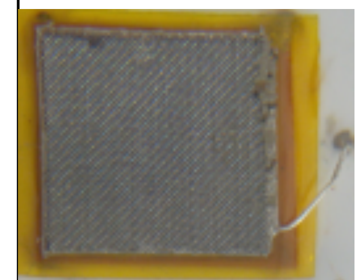
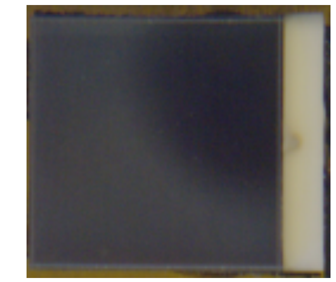
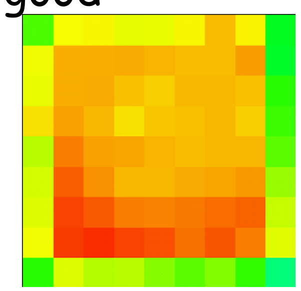
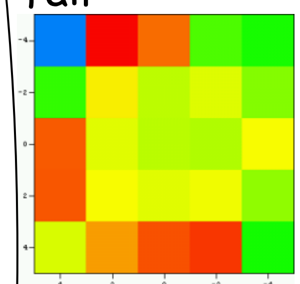
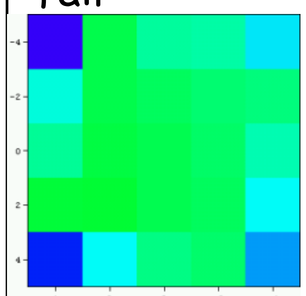
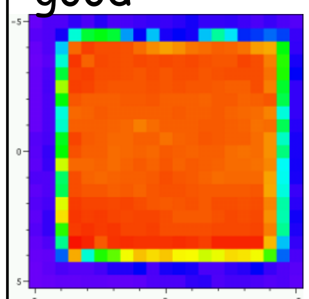
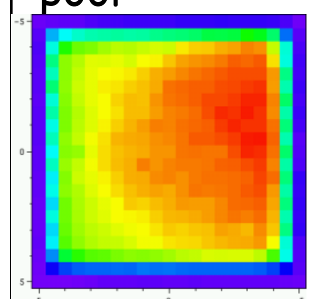
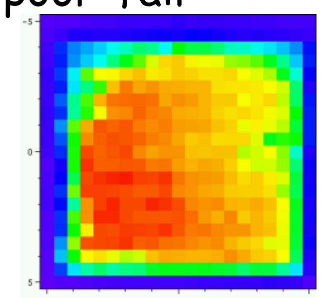
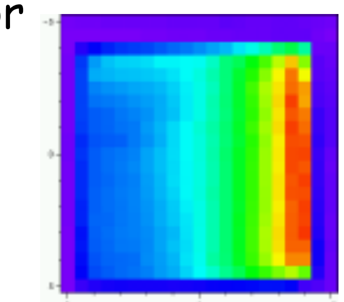
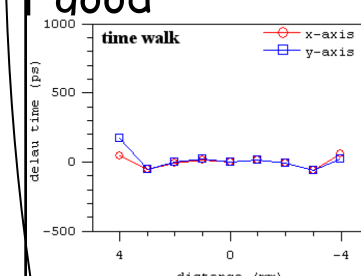
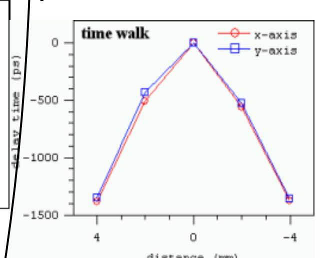
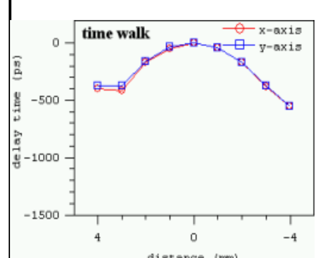
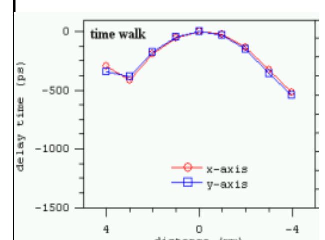
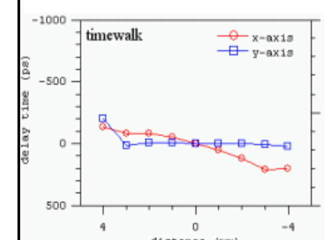
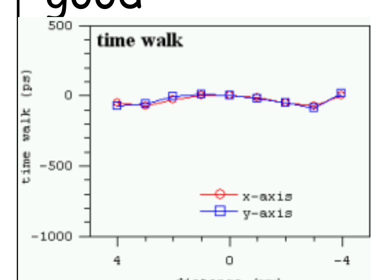
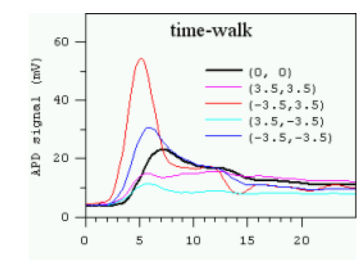
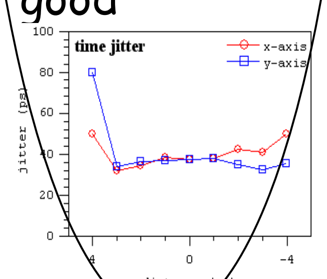
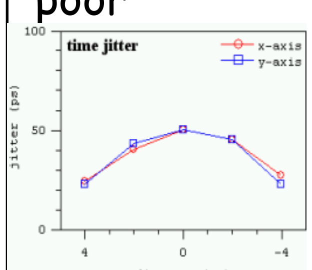
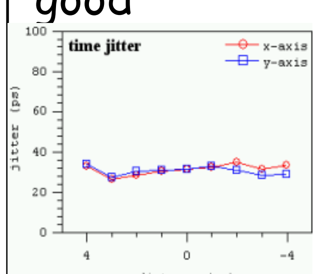
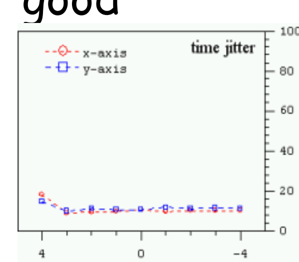
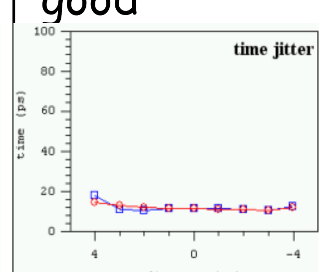
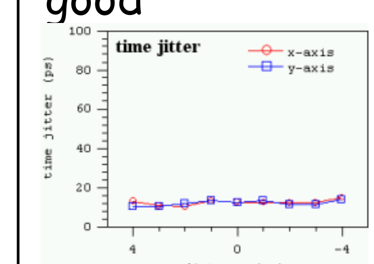
- very different from planar Si detector w/o gain
- signal modeling more similar to drift chamber
- effective thickness ~40 micron-> ~2.6 k e-h/MIP
- science of rad damage in APDs developed in CMS





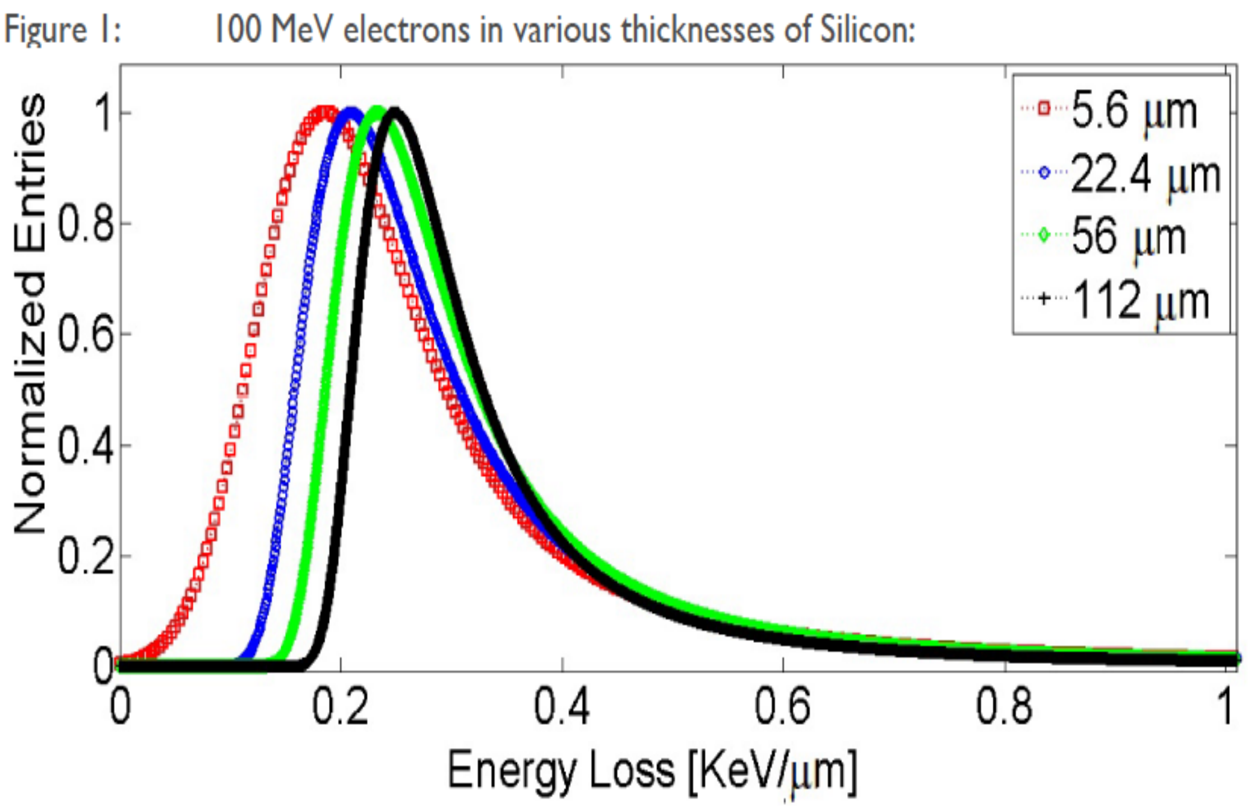
Summary of RMD 8x8 mm^2 APDs

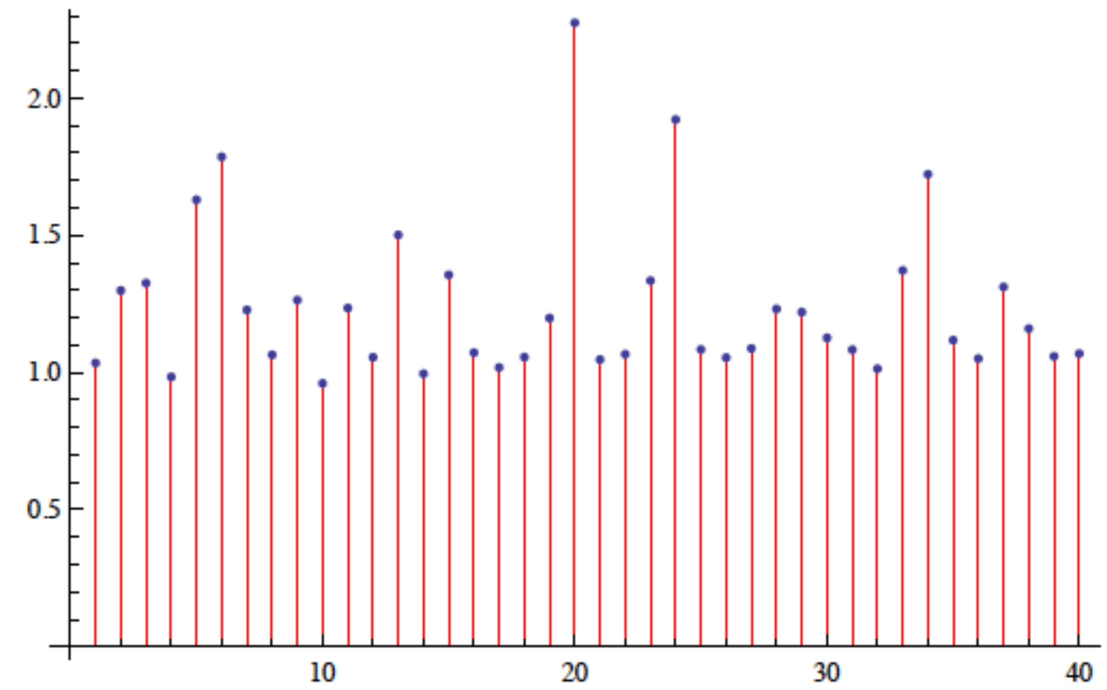
Dec. 13, 20

	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

Conclusion: metallic mesh with gold sintered device is the best of all

What about jitter due to stochastic cluster formation (Landau/Vavilov)?

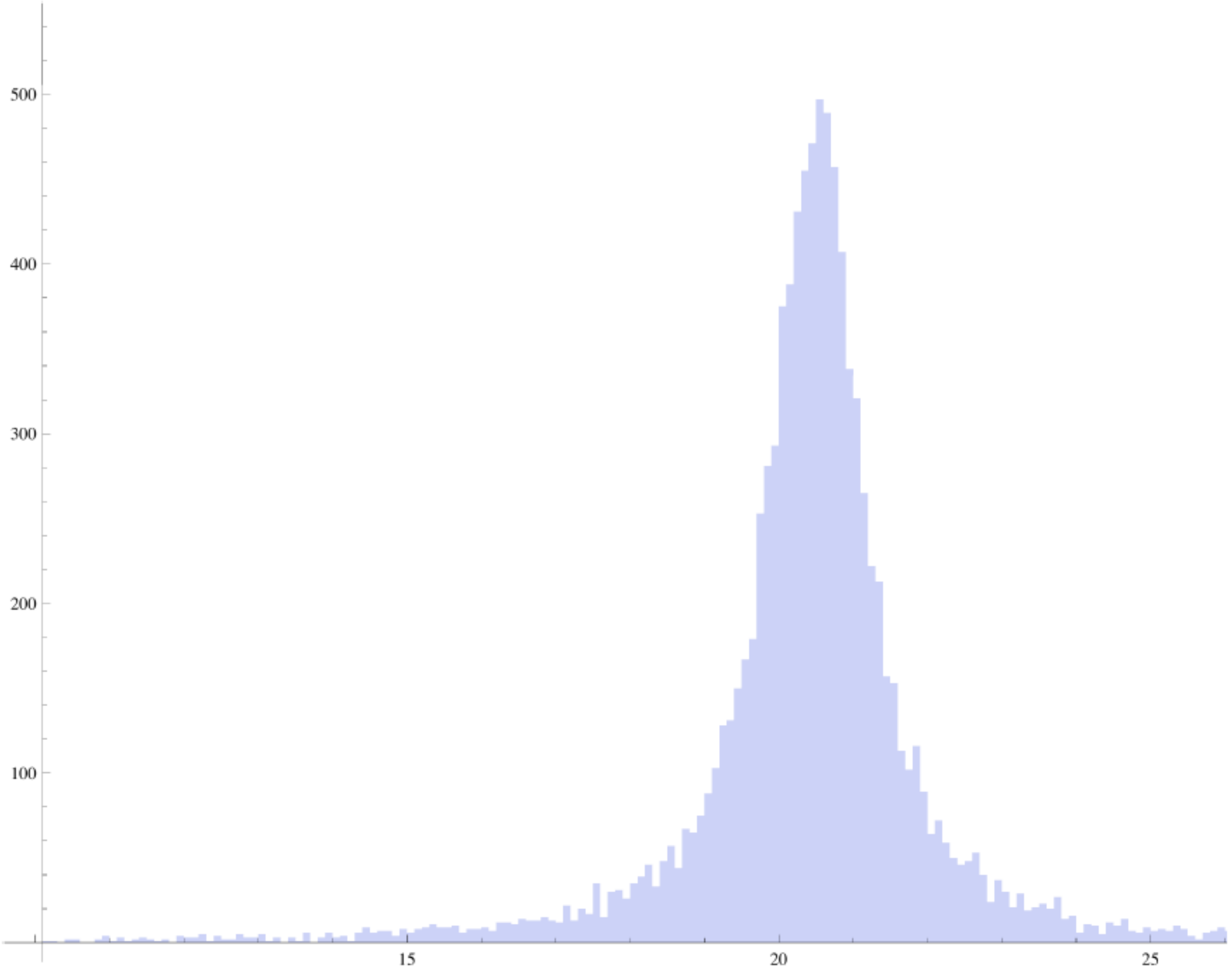




Calculated energy deposit distributions, compared to data in S. Meroli et al.

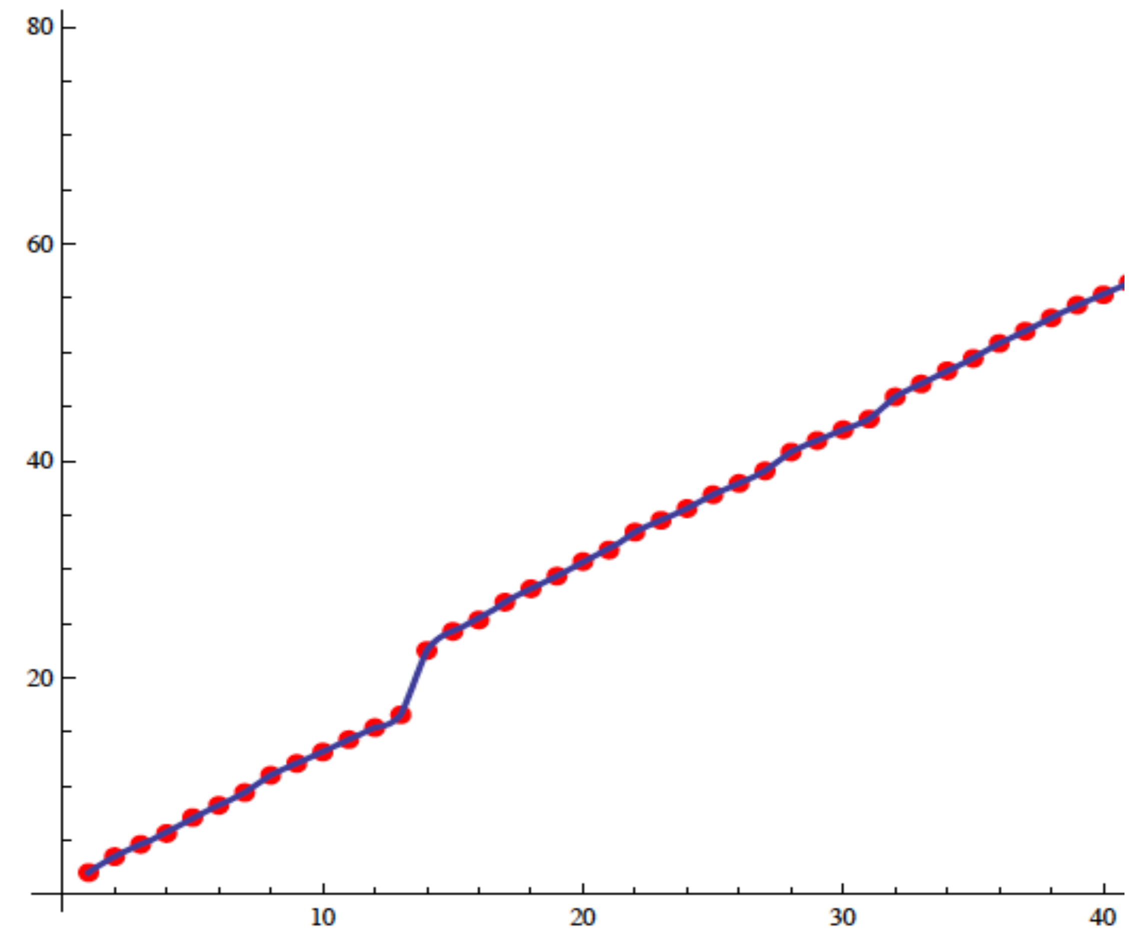
Simulated energy deposit/per each of 40 1 micron layers- typical event

Mean time of arrival: $< t >= \Sigma E(i)*t(i)/\Sigma E(i)$



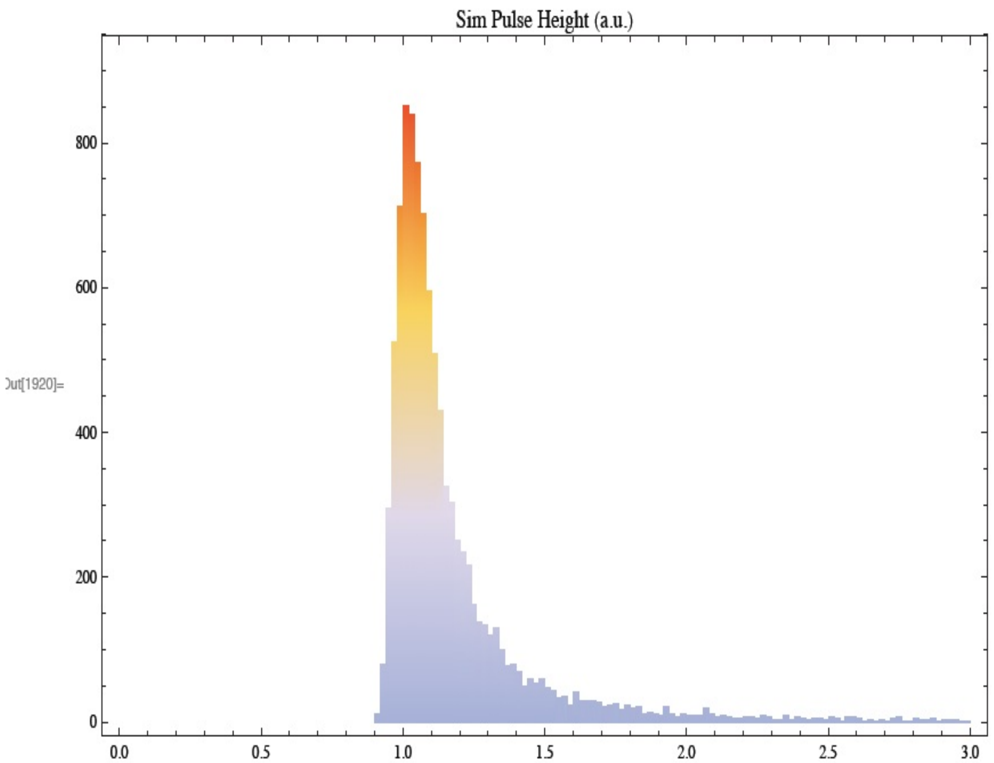
Mean time Distribution for 10k events(microns). Since saturated v=10 picosec/micron-> rms=20 psec dominated by tails

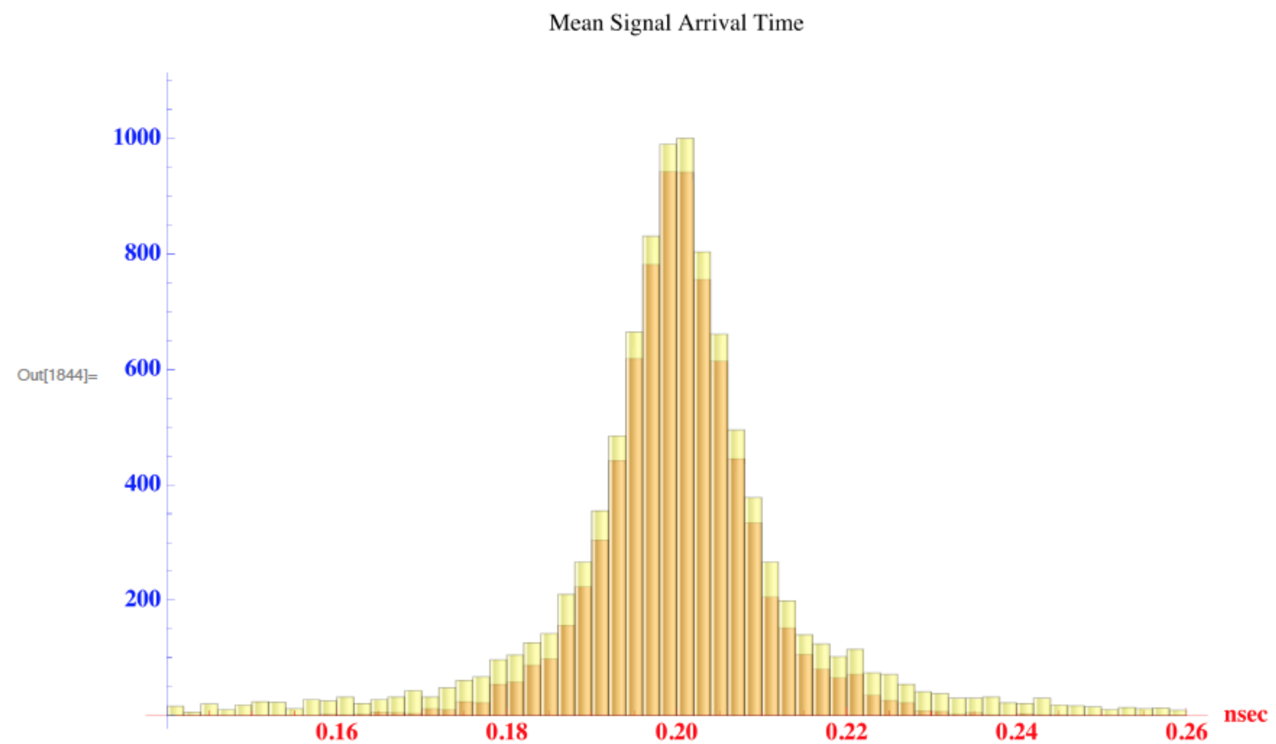
Constant Fraction method gives similar results



Accumulated signal, 1 event

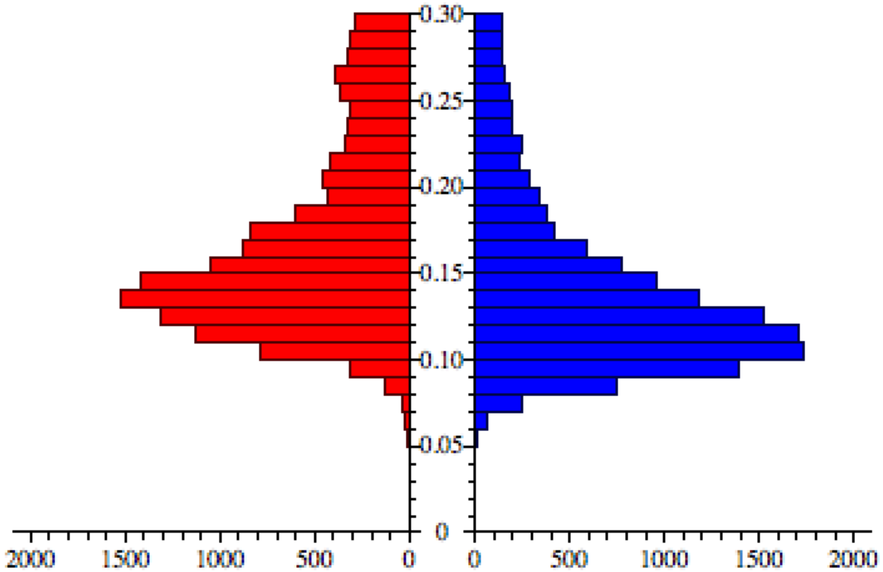
From DESY data 2 weeks ago it became obvious that WD method gives us a tool to kill tails



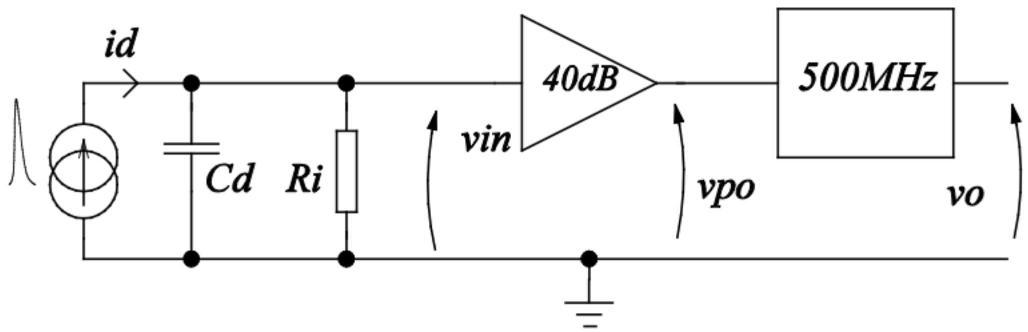



```
Cut in Signal amplitude at 77.35
 % efficiency reduces time jitter from 0.022641 to 0.00870866nsec
```

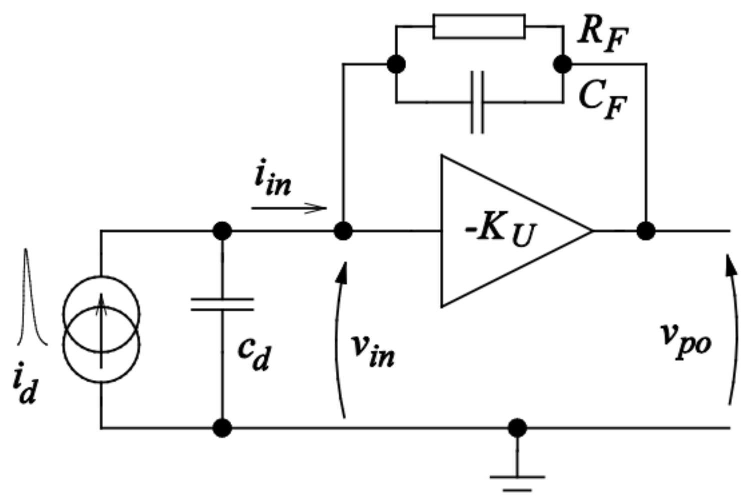
Sim and DESY data



fe electronics issues for 60 pF fast timing detector



50 ohm input voltage amplifier(cp. Cividec&Wenteq 2GHz 40 dB amplifiers in data presented below). compared to fast (tr=700 picosec) response w. 4 pF APDs longer tr and smaller signal w. 60 pF

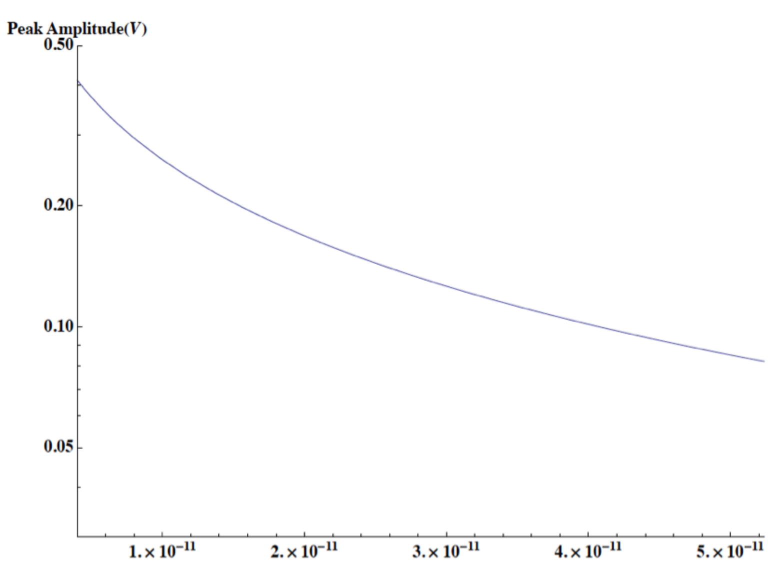


we are addressing this with new high bandwidth transimpedance amplifier employing Si-Ge technology, in collaboration with Mitch Newcomer, U. Penn. (10 times lower effective input) impedance

(see our presentation at next week’s ACES 2014)

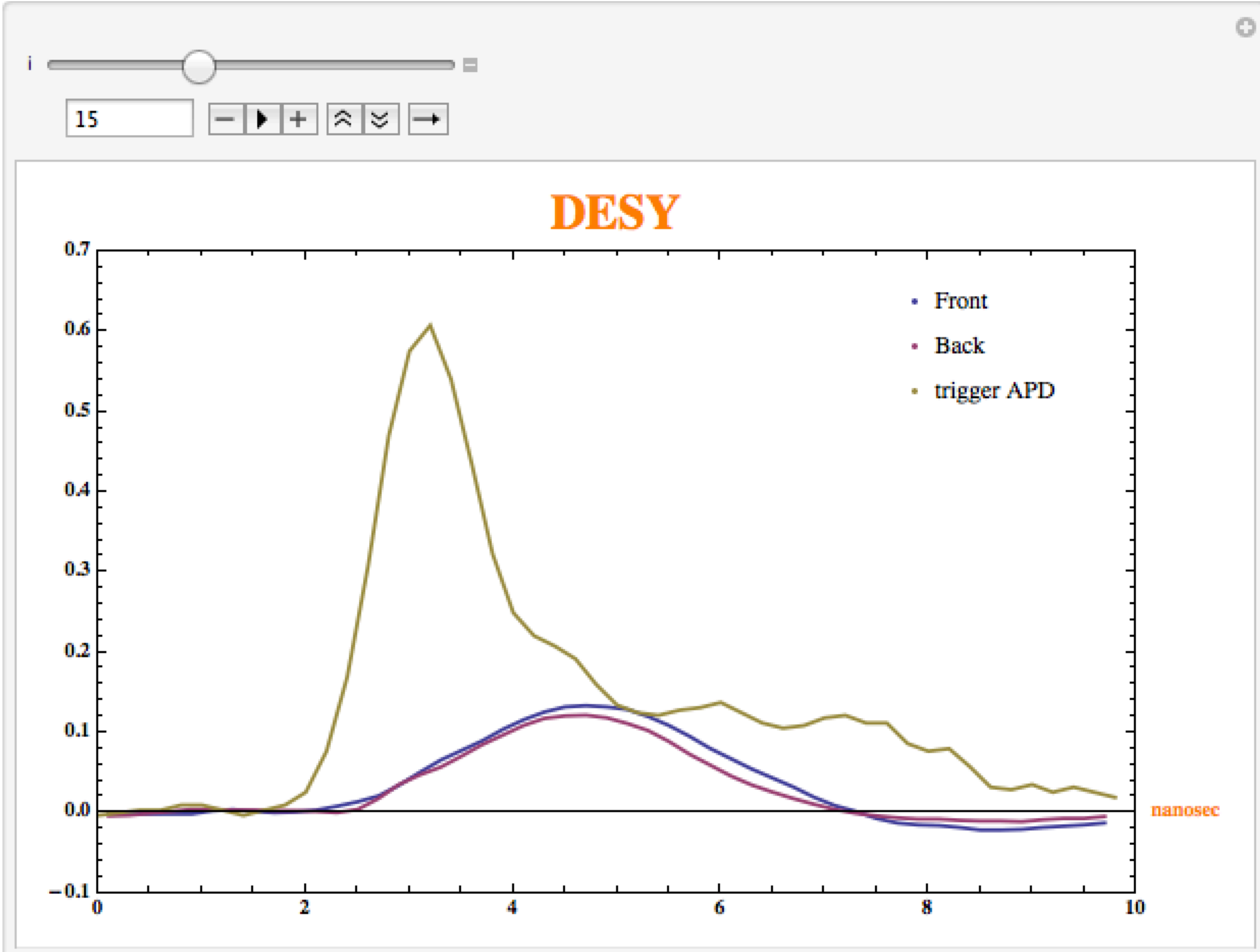
Electronics Challenges for HL-LHC pileup Mitigation with Fast Timing

Changuo Lu(1), Kirk McDonald(1), Mitch Newcomer(2), Thomas Tsang(3), Sebastian White(4), H.H.Williams(2)
1)Princeton,2)U. Pennsyvania,3)BNL Instrumentation,4)The Rockefeller U.



<-simulation of signal loss in voltage amp

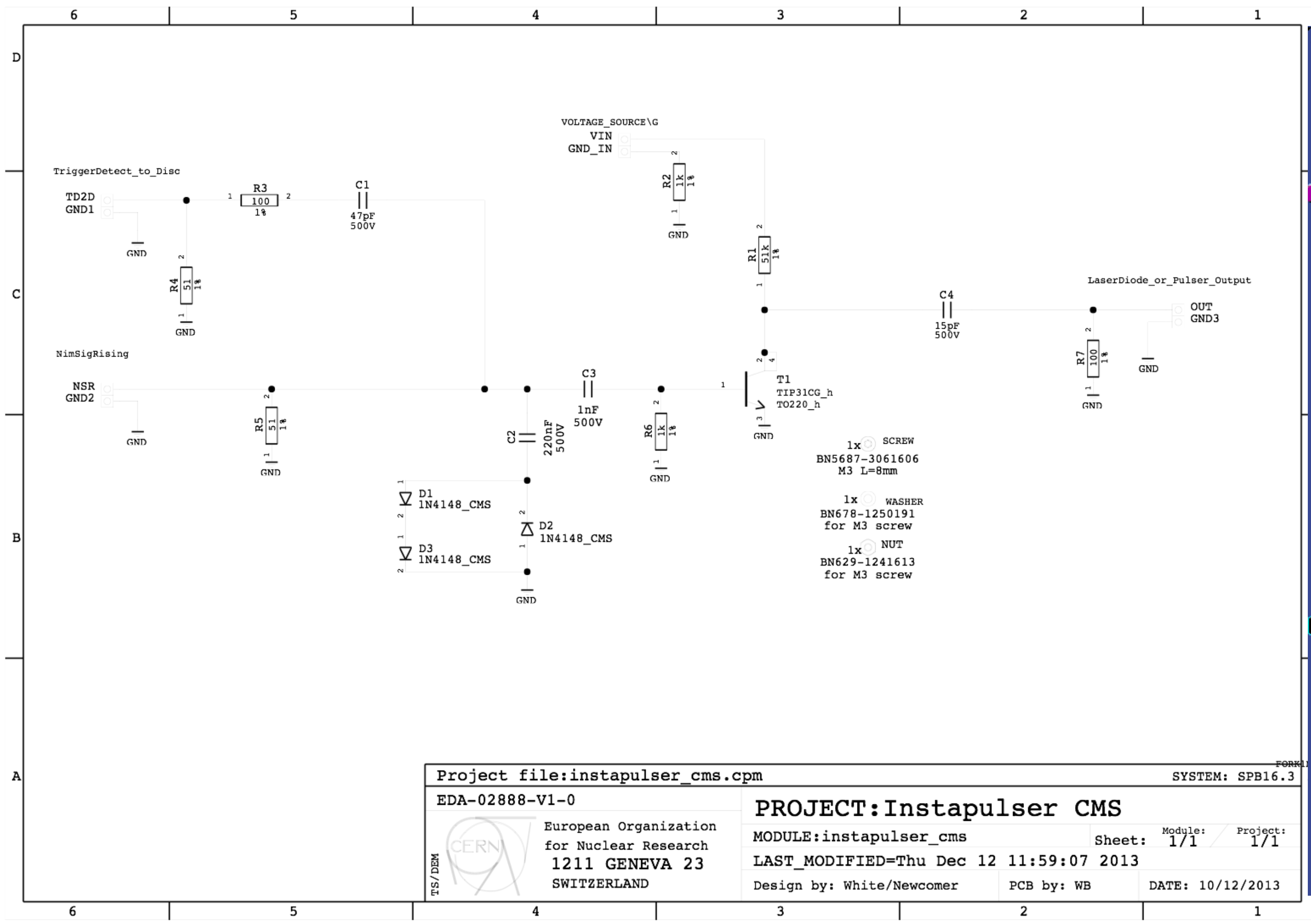
Expected features reproduced in DESY data

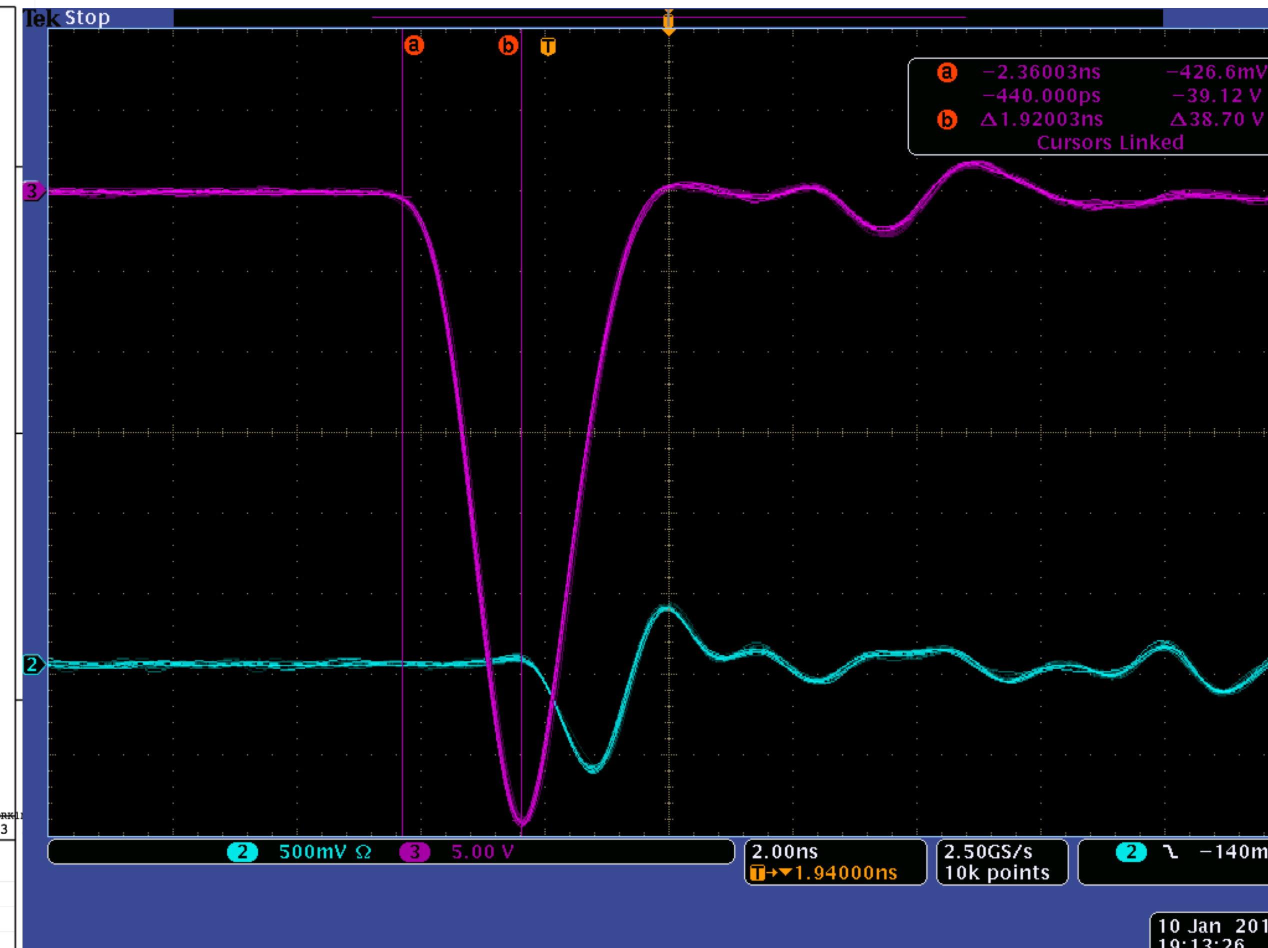


Peak amplitude 1/5 that of 4 pF detector
in large area 60 pF detector
and
Risetime degraded from 0.7 to 2 nsec when using 50 ohm voltage amp
We expect significant improvement in Spring PSI run w. new amp.

Cheap sub-nanosecond pulser for device testing

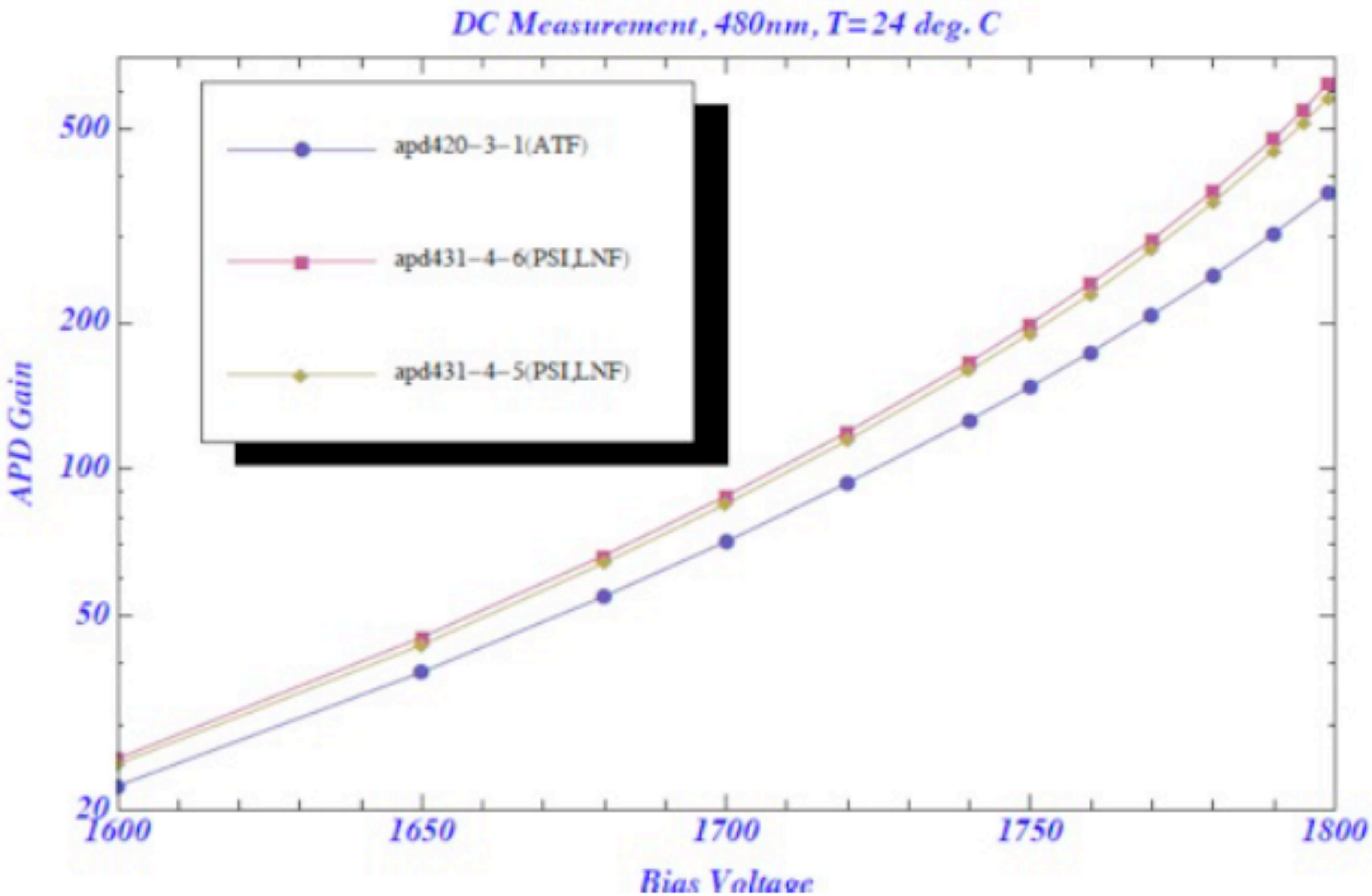
(developed for fast Vcsel driver for our APD tests but now several at CERN)





width and amplitude controlled
w. output capacitor

RMD/Dynasil APD Gain vs. HV



Most beam data taken at 1776-1814 V

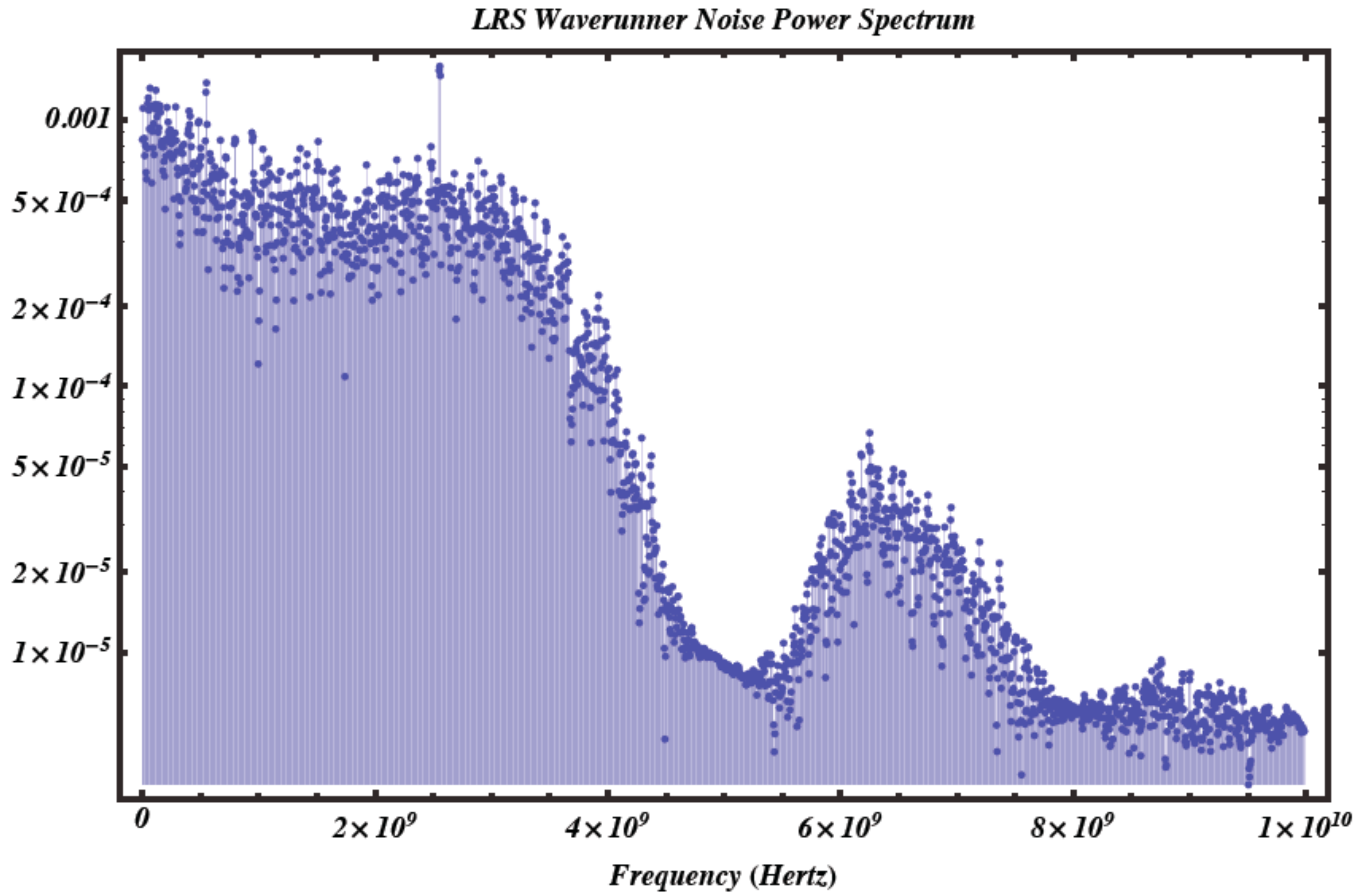
-> Signal into Amp ~10^6 electrons

Signal and noise

- Signal: calculate 90 e-h pairs/micron*APD gain(520)*Ampgain(100)=600mV, exactly as seen in DESY data
- In large area detector w. old amp signal reduced by 1/5.
- Noise: significant level expected from 8-bit scope
- Took data at 200 mV, 50 mV and dual range (200mV/10mV) volts/division and observed (8mV, 3mV and ? Noise level)

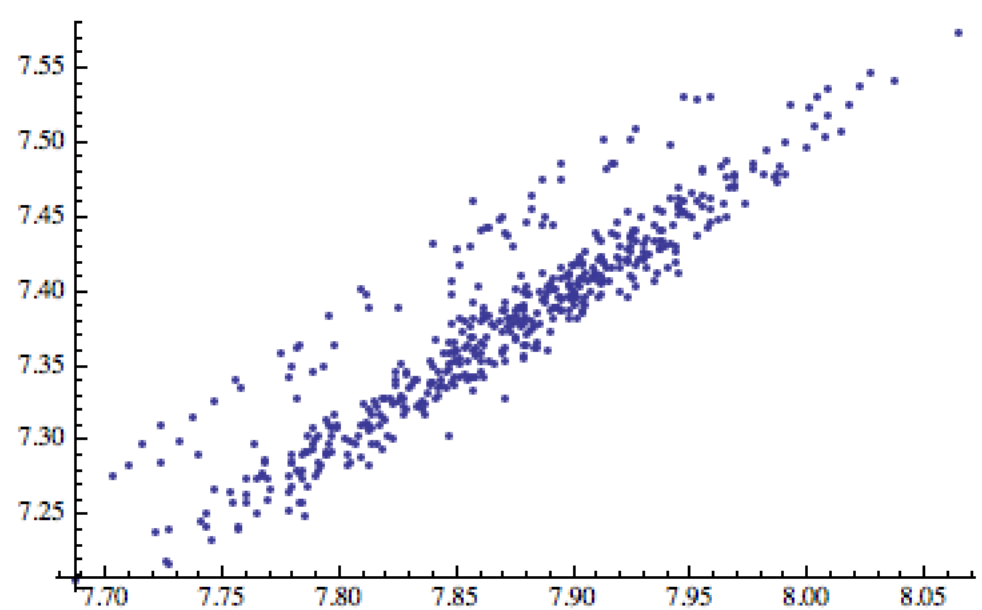
Scope contribution to jitter

Out[1077]=



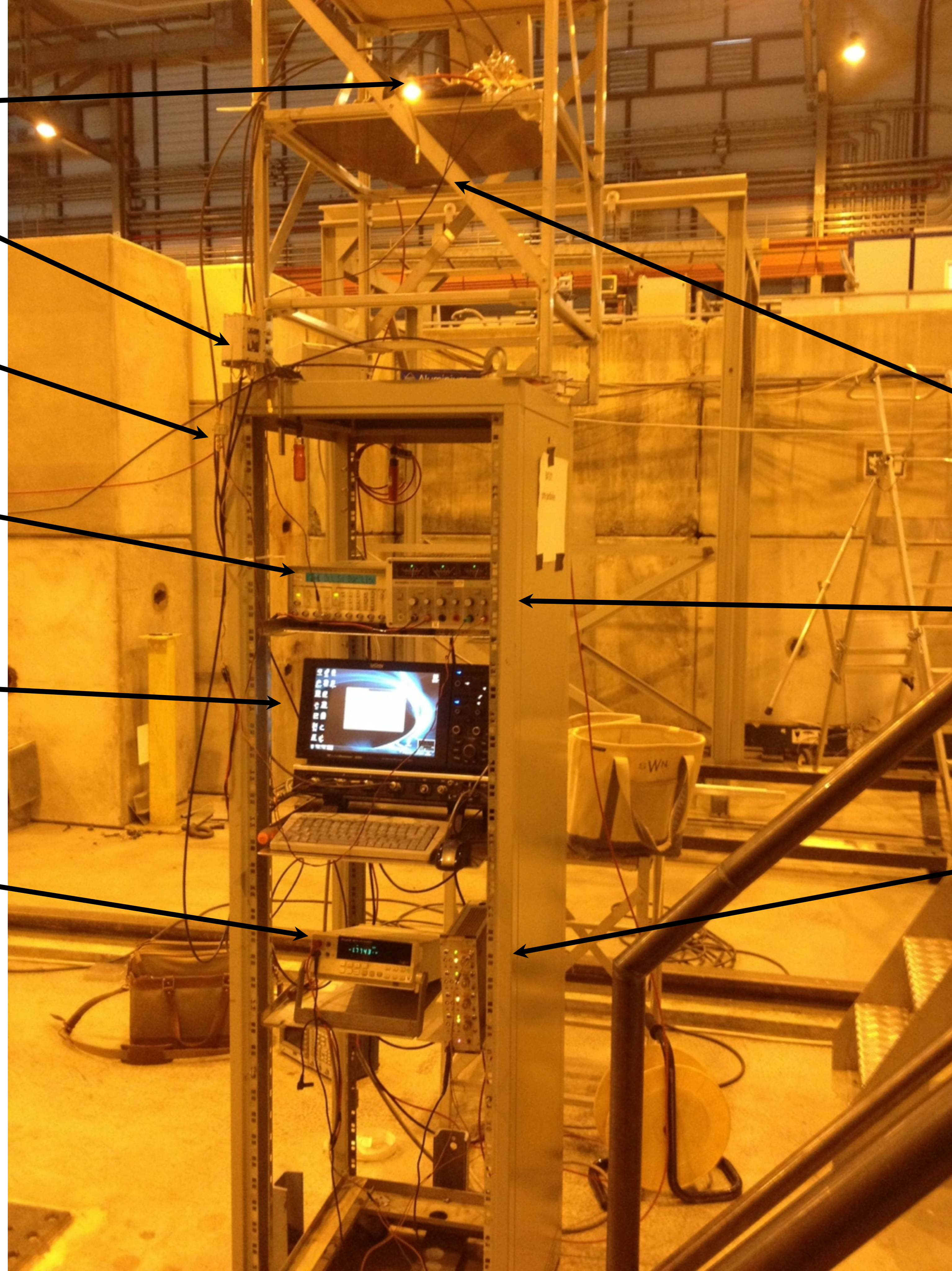
Frequency spectrum of noise
w. 2.5 GHz
20 GHz

```
ListPlot[Transpose[{v1centroid, v2centroid}]]
```



lrf test: word of caution about interleaving in scopes

H2 Setup
Feb. ’13



APD telescope

500 MHz, 20 dB amplifiers

3 GHz, 13dB amplifier

vcsel pulser

2.5 GHz “waverunner” DAQ

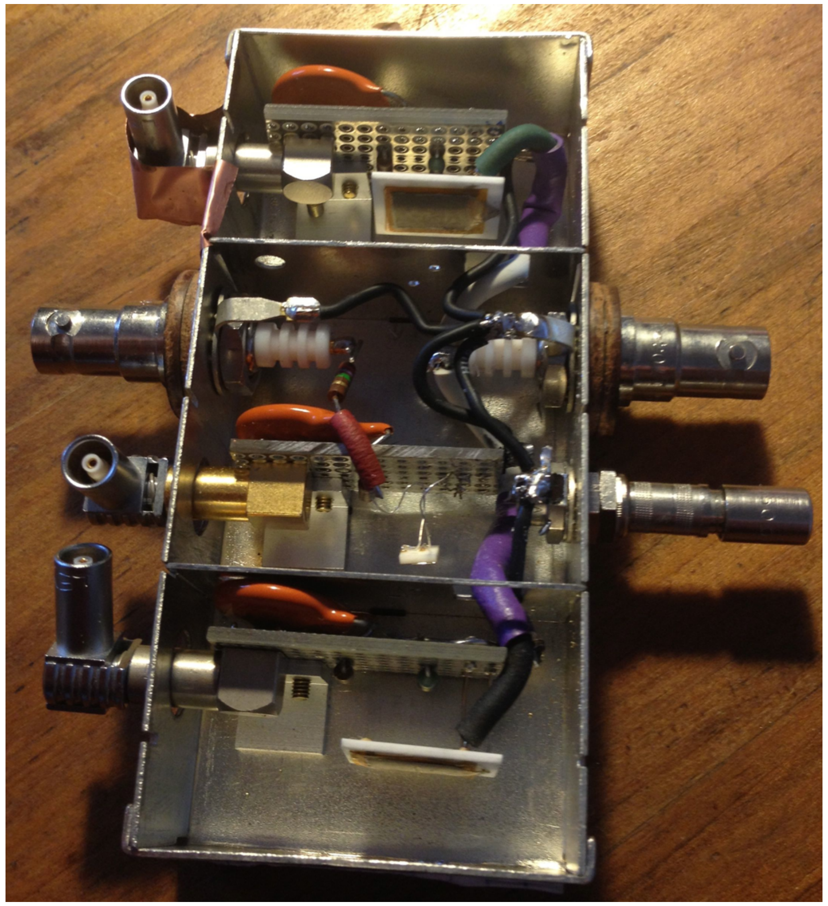
APD bias monitor

fiber splitter from vcsel

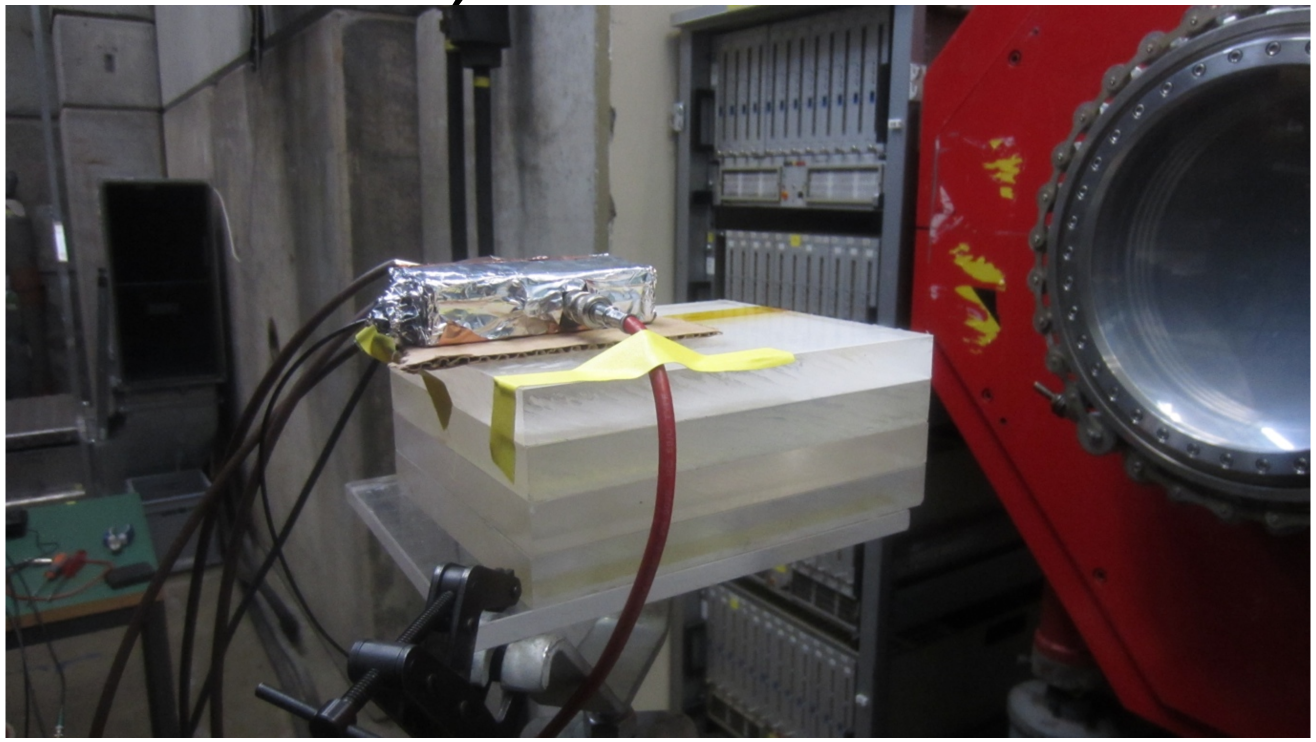
Amp power

APD bias

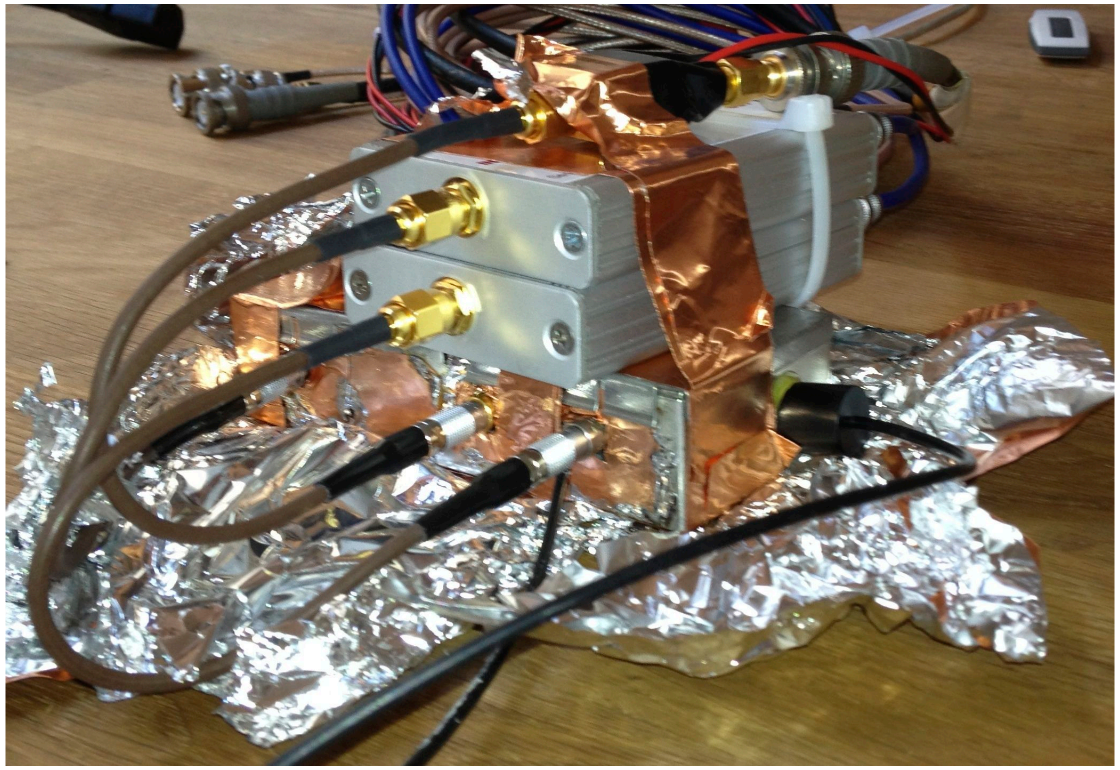
Testbeams (SPS and PSI)



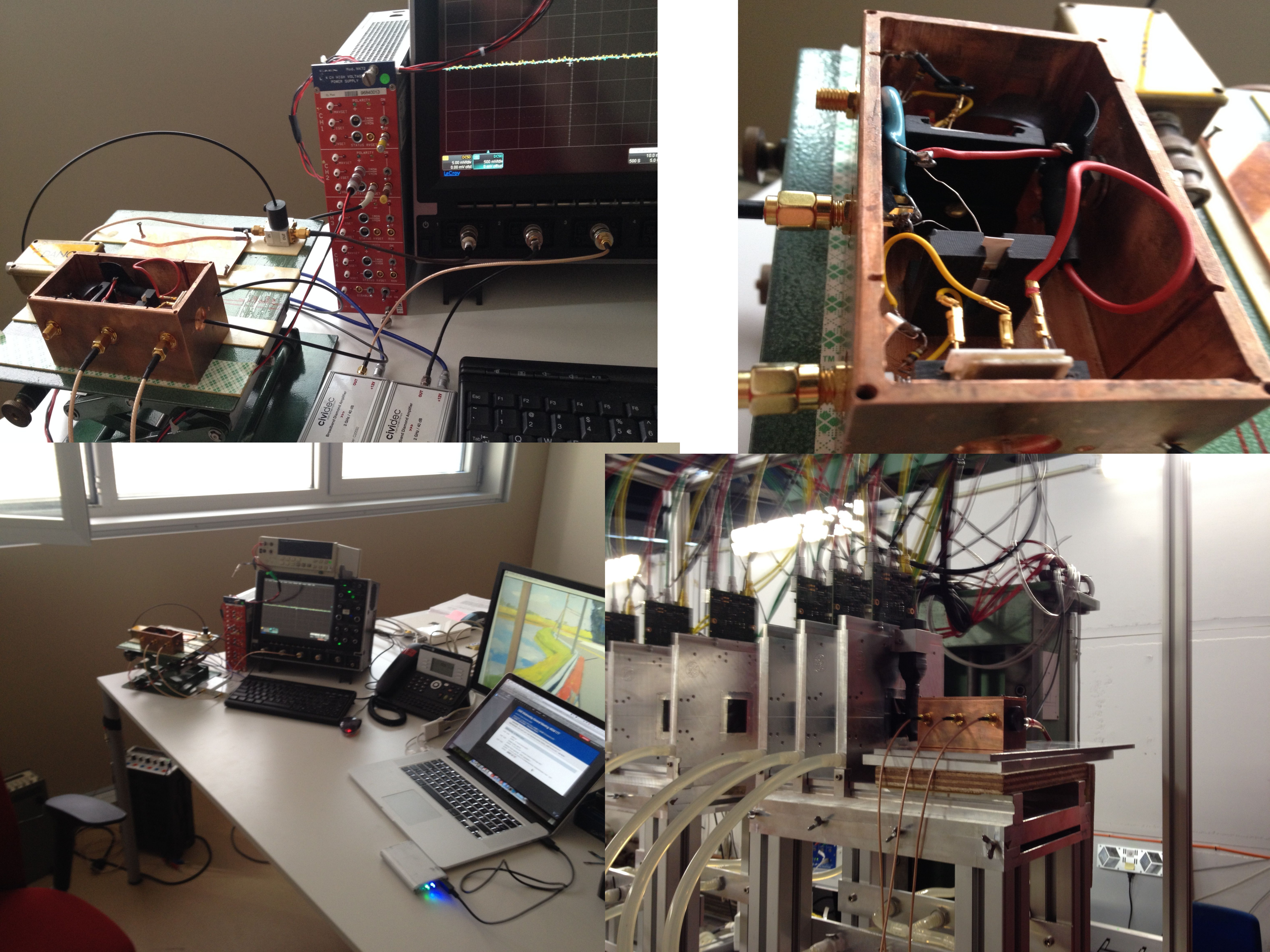
telescope



PSI

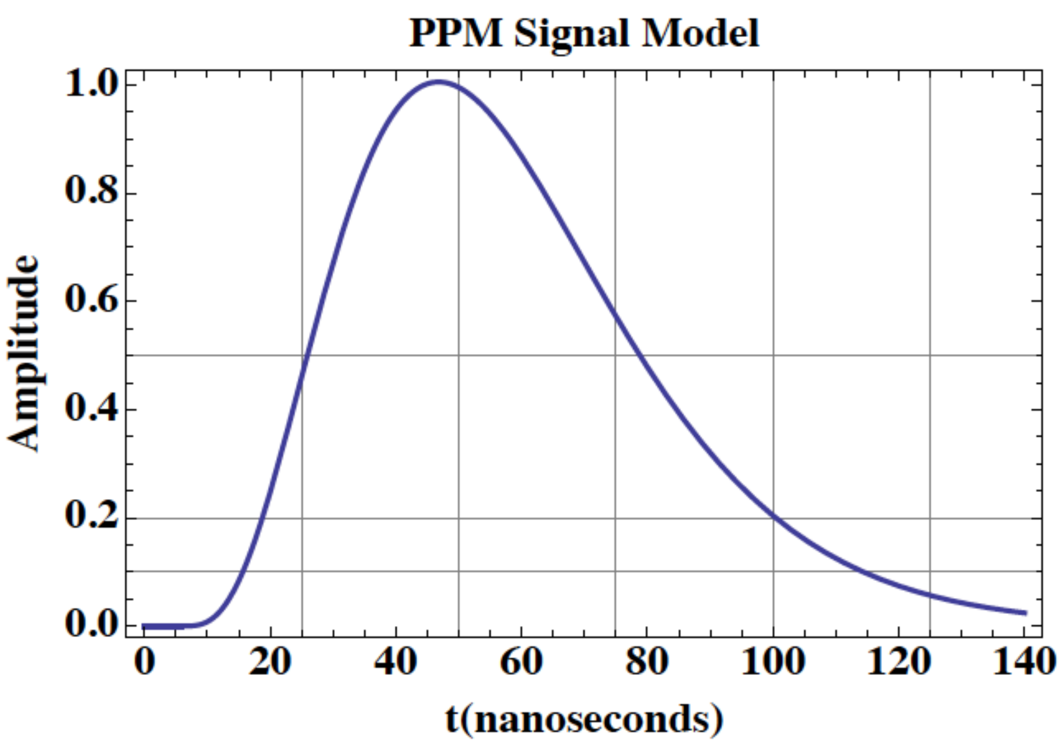


Rf shielding



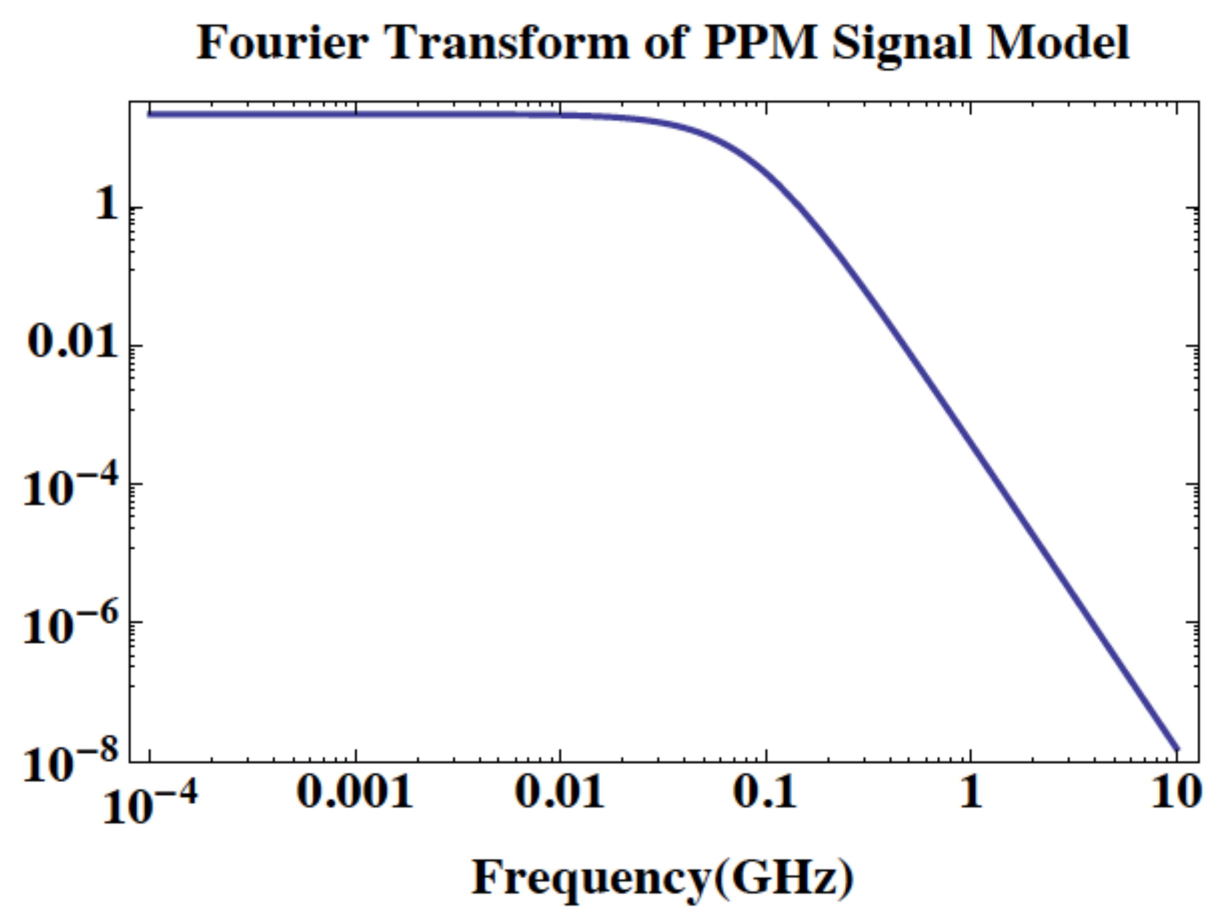
4 CH HIGH VOLTAGE POWER SUPPLY
LeCroy
cividec
Broadband Diamond Amplifier
2 GHz / 40 dB

ZDC waveform: bandwidth limited by low quality cable

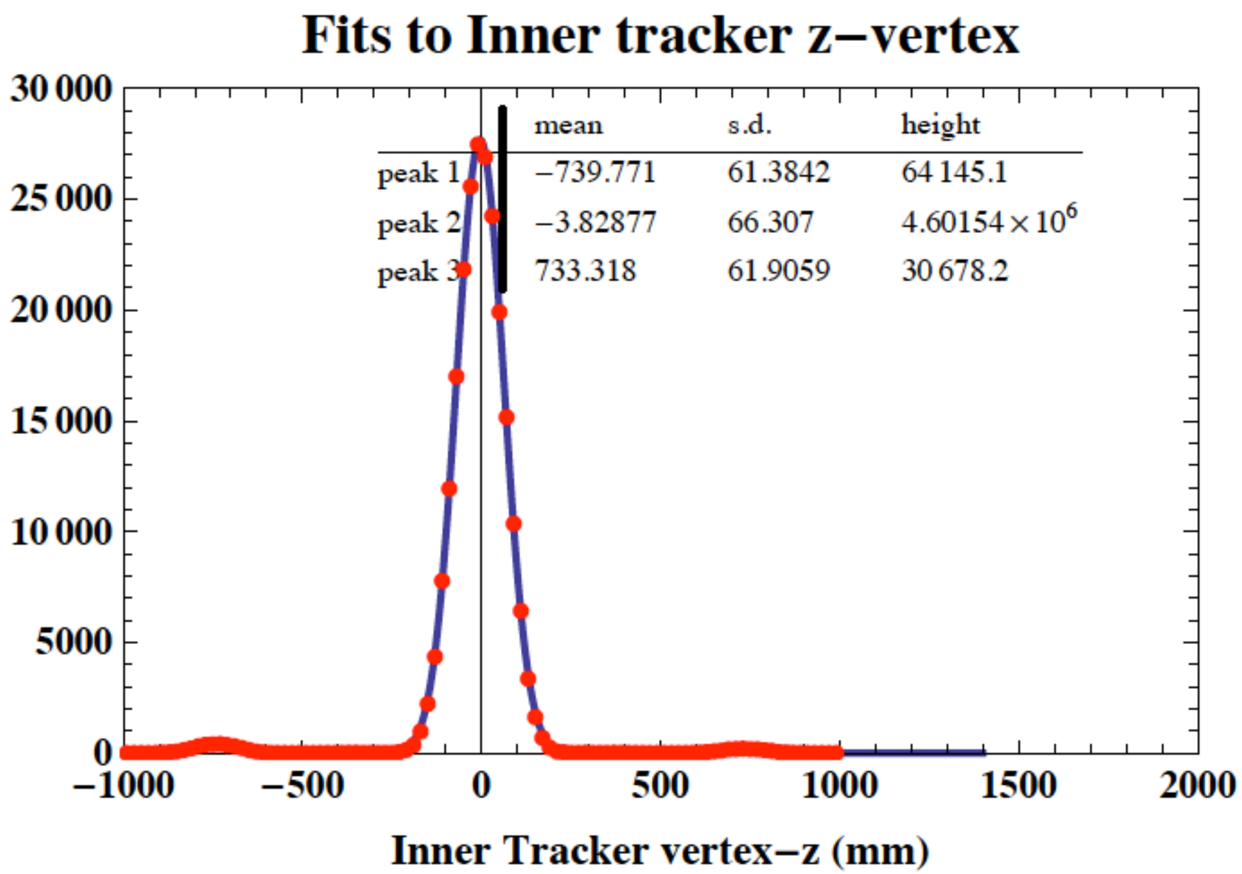


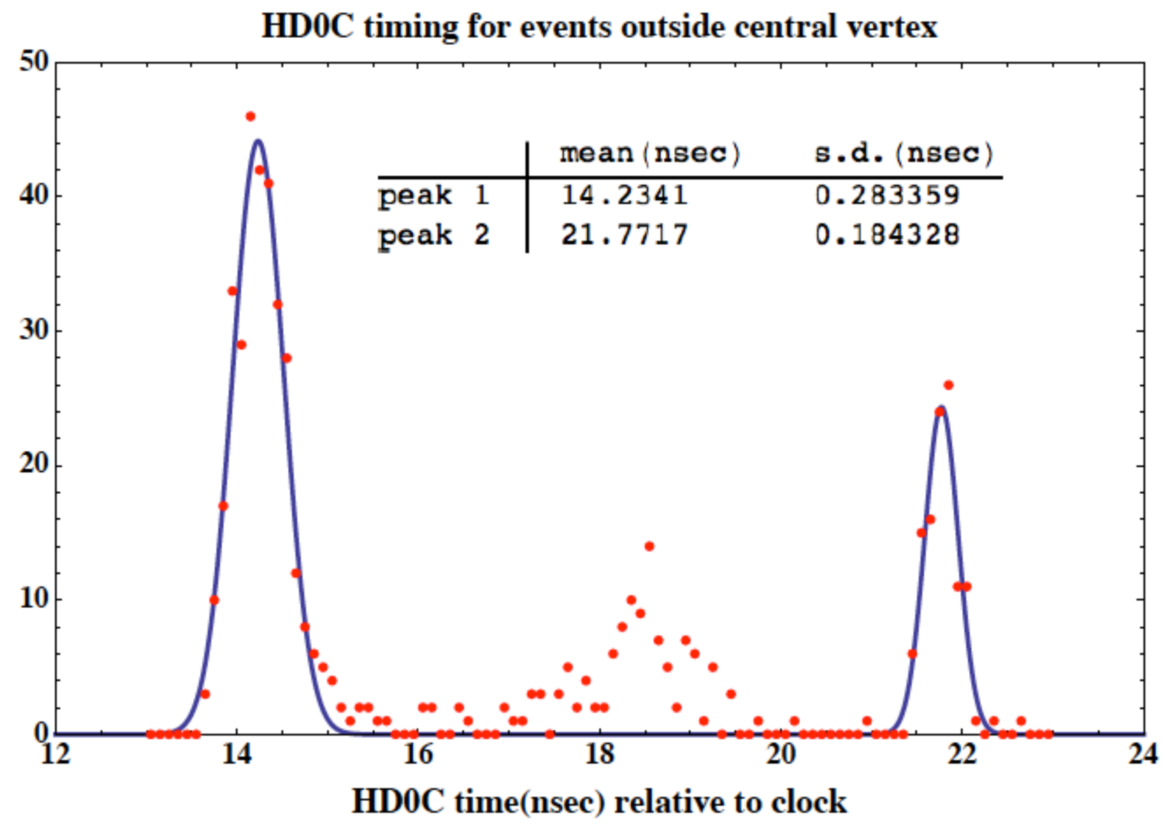

```
FourierTransform[(((t - toff) / tdecay) ^trise) * .47 * Exp[- (t - toff) / tdecay], t, ω]
```

$$0.0000662123 \left(\frac{6.14786\, e^{6 i \omega}}{\left(\frac{1}{12} - i \omega\right)^{4.4}} + \frac{0.\, e^{-6 i \omega}}{\left(\frac{1}{12} + i \omega\right)^{4.4}} + (0. + 0.\, i)\, \text{Hypergeometric1F1}\left[1, 5.4, -\frac{1}{2} - 6 i \omega\right] - \left(4.26326 \times 10^{-13} + 1.25056 \times 10^{-12}\, i\right) \text{Hypergeometric1F1}\left[1, 5.4, -\frac{1}{2} + 6 i \omega\right] + \frac{(0. + 0.\, i)\, \text{HypergeometricPFQ}\left[\{-3.4, -3.9\}, \{-3.4, -3.9\}, -\frac{1}{2} - 6 i \omega\right]}{\left(\frac{1}{12} + i \omega\right)^{4.4}} - \frac{(0.967912 + 2.97893\, i)\, \text{HypergeometricPFQ}\left[\{-3.4, -3.9\}, \{-3.4, -3.9\}, -\frac{1}{2} + 6 i \omega\right]}{\left(\frac{1}{12} - i \omega\right)^{4.4}} \right)$$

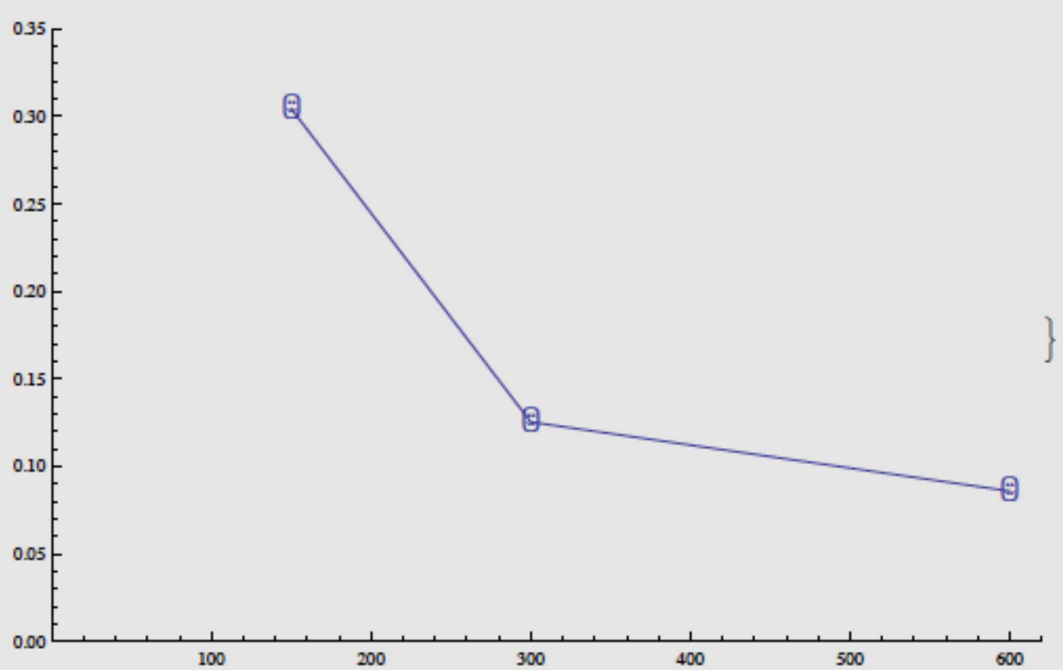


<u>=>a sampling frequency of 40 or 80 Mz is below Shannon-Nyquist frequency (=2*B)</u>



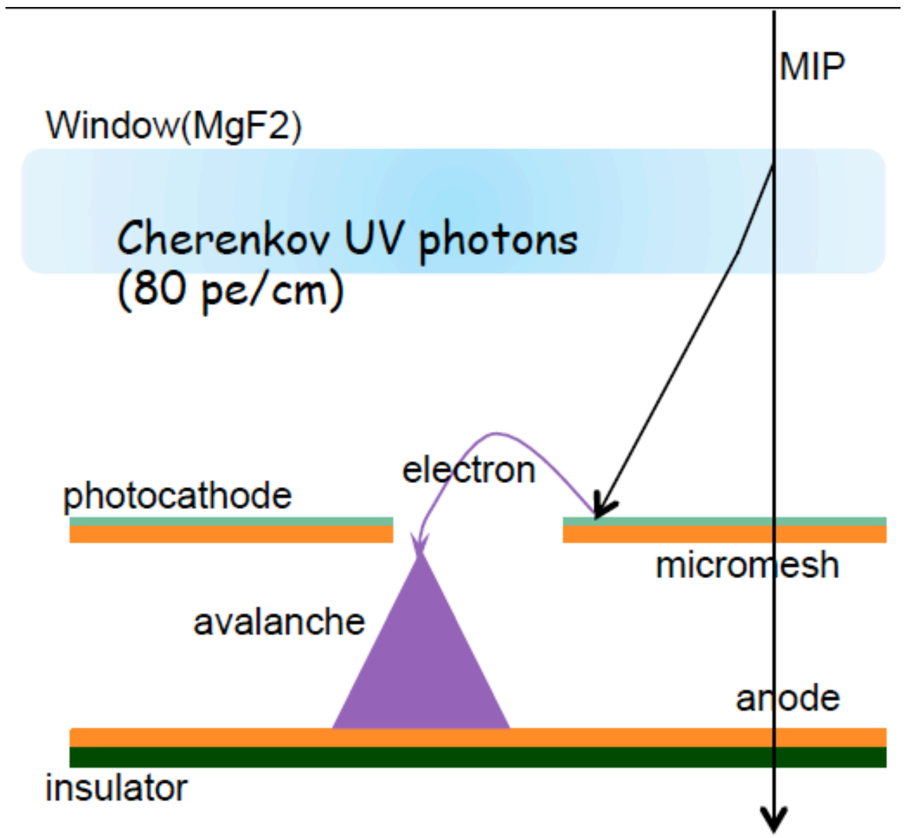


	mean (nsec)	rms
ZDC_EMA	23.4269	0.161383
ZDC_EMA_100-200	23.4313	0.304363
ZDC_EMA_200-400	23.4084	0.125345
ZDC_EMA_400-800	23.4356	0.0859118

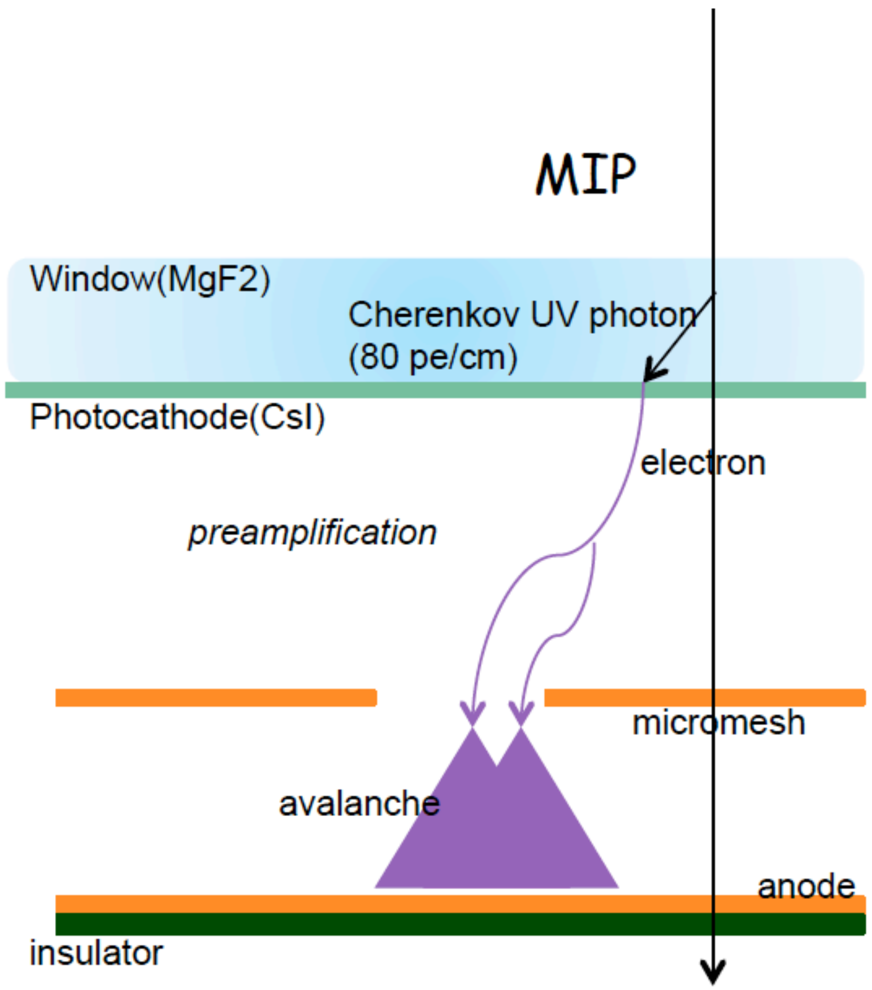


simple test of energy dependence

Gas-PMT for 10 psec charged particle timing: encouraging results from simulations over past year. Preparing test at Saclay.



reflective PC



transparent PC

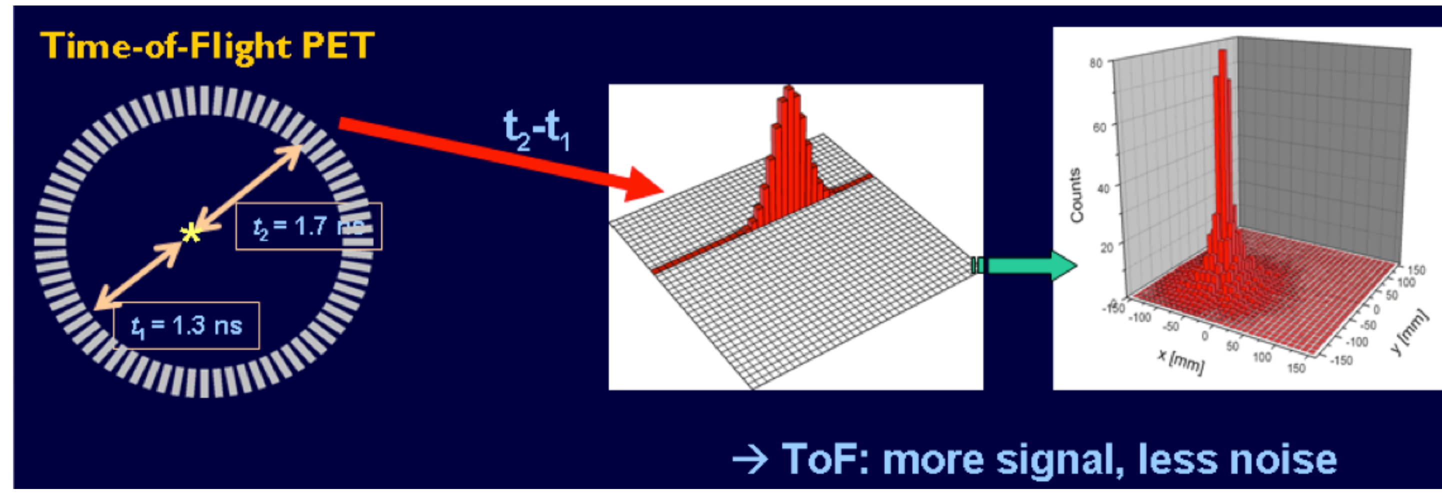
Fast Timing in Brain Imaging

“detector-centric” objective

->EU “Picosec” initiative but

- PET images the level of Sugar-uptake in the brain.
- Sugar is not the main energy source.
- The level of activity not necessary indicator of Cognitive Function

=>

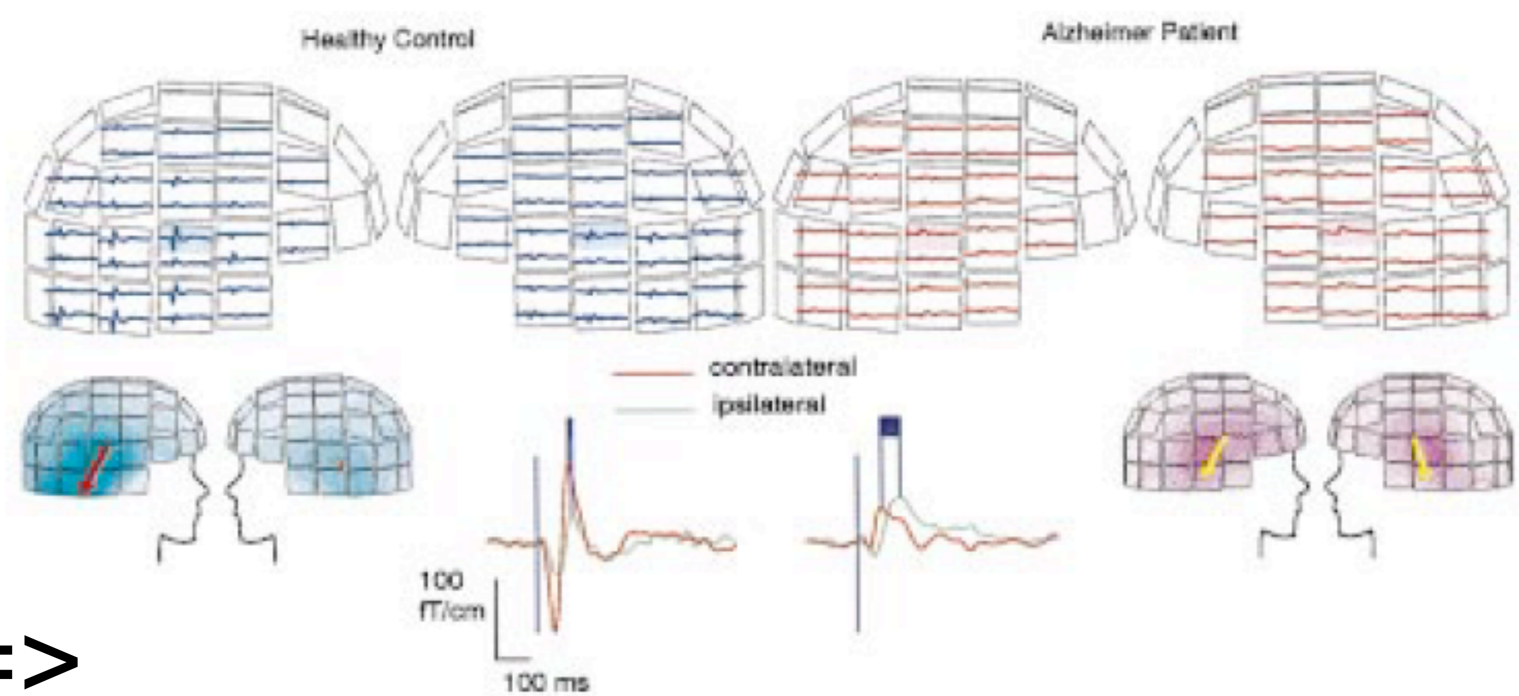


Neuroscientist Objective

- MagnetoEncephalography is the only non-invasive technique to image the brain on the time scale of neuronal activity.
- Delayed response to external stimulus and its dependence on complexity of the pathway is potentially a powerful bio-marker for Alzheimer’s and other diseases.
- It could be used to provide early detection and guide therapies, etc.

=>

E. Pekkonen et al. / Clinical Neurophysiology 110 (1999) 1942–1947



some conclusions:

- Simulations are at an early stage for settling questions concerning to what degree pileup mitigation can be accomplished in calorimeter itself and whether a dedicated timing layer is needed.

-This collaboration consisted of me, McDonald and Lu (Princeton), Tsang(laser scientist at Instr. Div.), Farrel (Vice President for APD Research at Dynasil).

-Many have contributed expertise in electronics, beams, etc. from beyond the CMS application.

-developing a model for such a collaboration that extends beyond CMS but some initial support from USCMS. Waiting for ESPP strategy to kick in.

-new results coming from our DESY run 2 weeks ago- already at <40 picosec