Experimental Challenges of the European Strategy for Particle Physics

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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.

Challenges:

•Primary challenge to the experiments is significant increase in intensity.

•There has been a long debate about the intensity level at which one can do physics in a general purpose detector like ATLAS or CMS.

•Significant historically is: R.Huson, L.M.Lederman and R. Schwitters, "A Primer on Detectors in High Luminosity Environments", in Snowmass 1982, Proceedings

(This paper was written the year before the US decided to scrap Isabelle, whose viability depended on pushing the intensity limit, in favor of the SSC.)

•Over past 20 years, US and European R&D has focused on issues of radiation damage to instrumentation caused by integrated dose. This activity also resulted tools to calculate effect on sensors.

•Very limited supported activity in mitigating pileup due to high Instantaneous rates (perhaps only work described in this talk-DOE ADRD grant to K. McDonald and SNW-co-PIs).

•At same time very significant investment by CERN in dealing with personnel protection (impact of activation).

CERN
EN-HE-HT
section =>

Our main task:

Design and development of remote handling equipment for interventions in radioactive areas at CERN.

INB

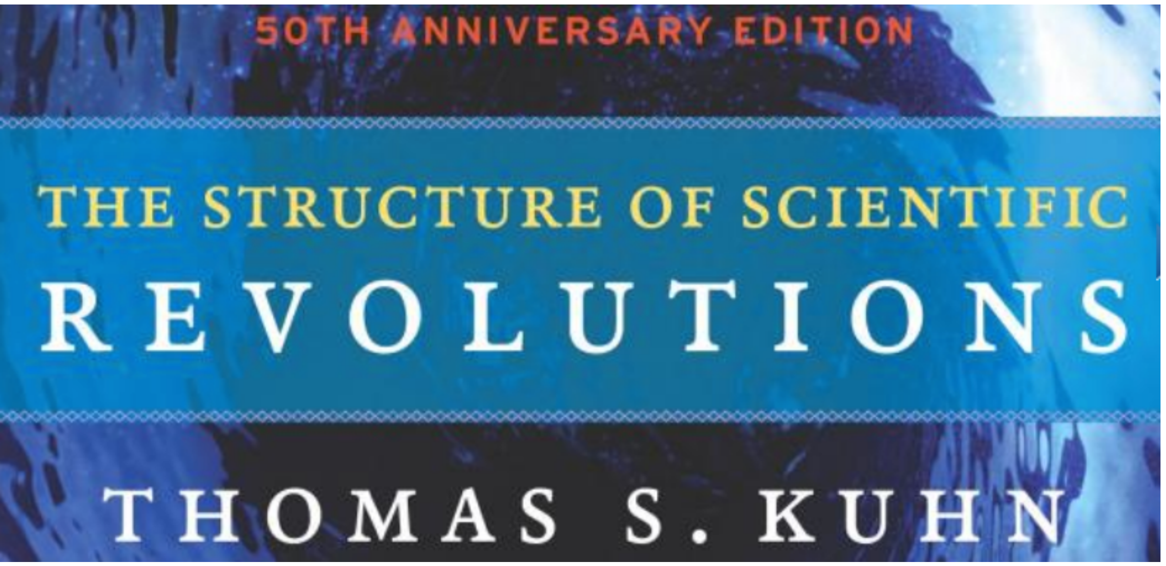
« Une installation nucléaire de base » est une dénomination réglementaire française pour une installation nucléaire fixée en un lieu

Dépend de l'ASN « Autorité de Sureté Nucléaire »

ALARA

« As Low As Reasonably Achievable »
« Aussi bas que raisonnablement possible »
Principe de précaution (ou d'optimisation) de la radioprotection

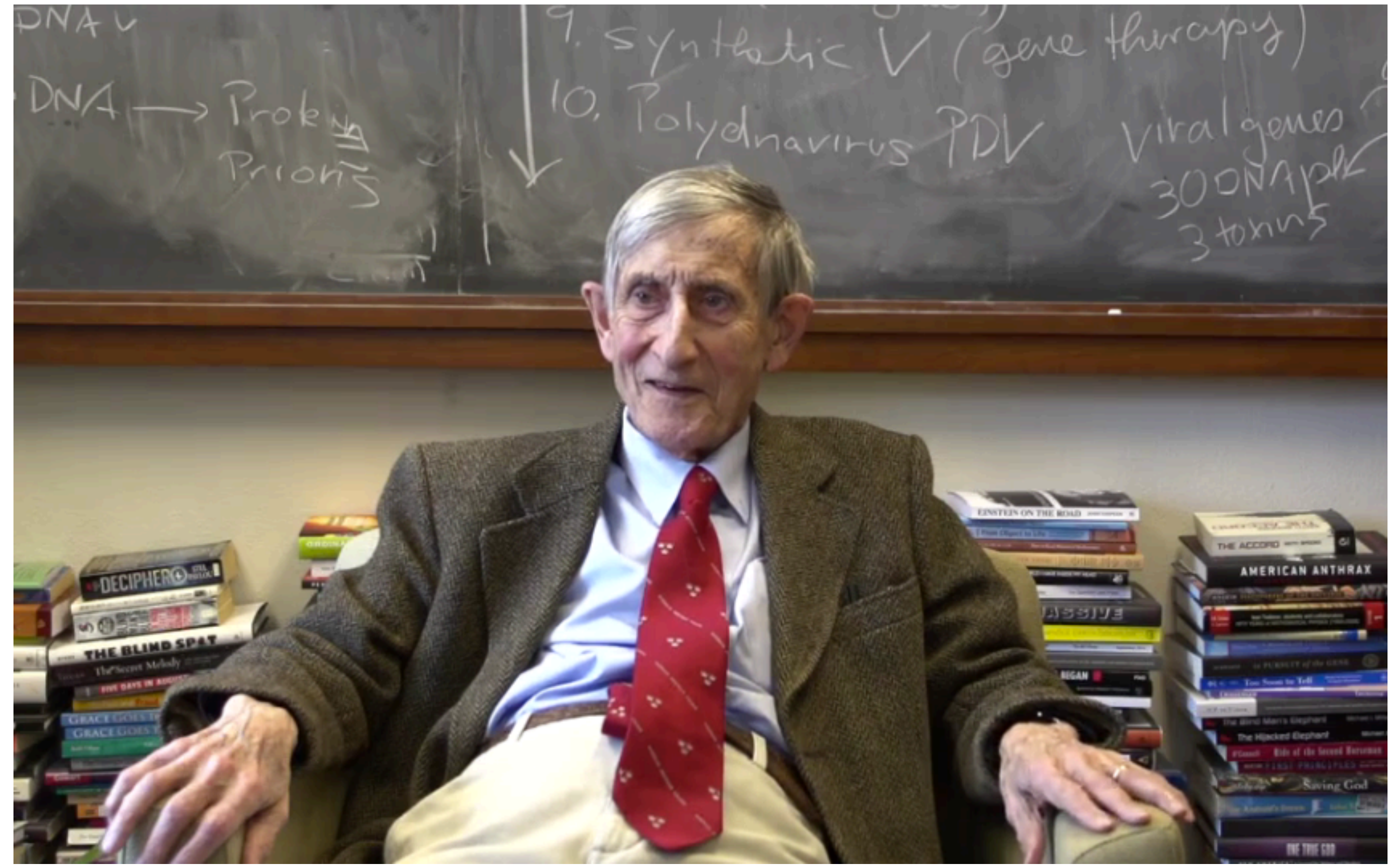
Ideas and Tools



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:

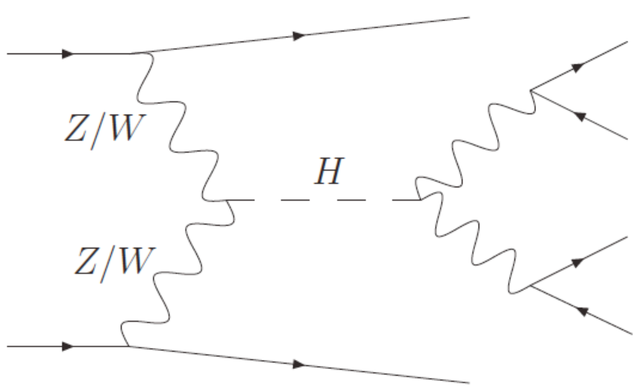
...2012 article in Science:``Is Science Mostly Driven by Ideas or by Tools?'' As you will see, the answer to the question is that both are important.   Sometimes ideas are dominant and sometimes tools.

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

the Challenge (2)

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 $t_{resolution} << t_{bunch\ crossing}$ (~200 picosec).
Developments in high rate picosec photosensors and trackers would be useful.



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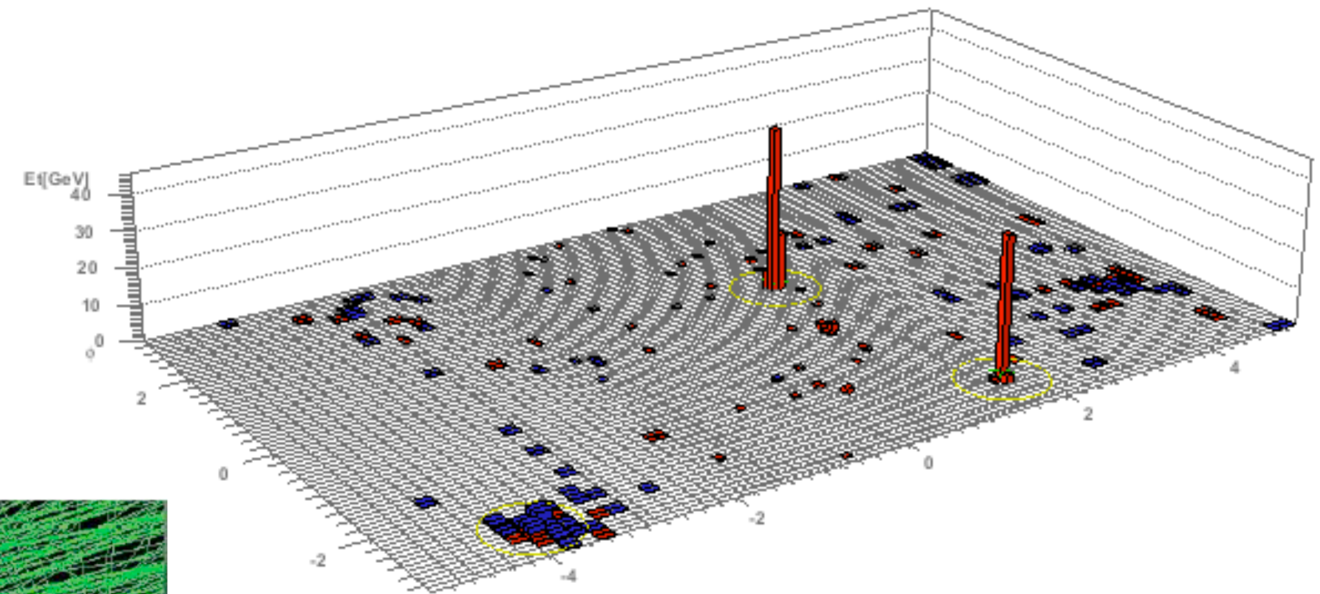
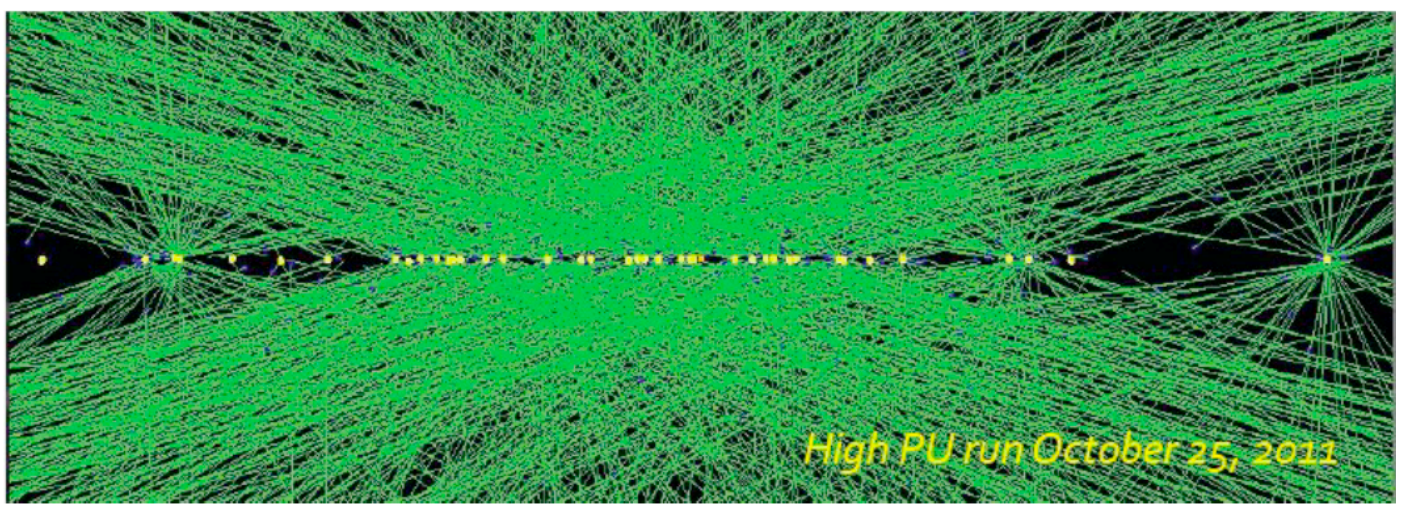




in above Higgs->2 gamma and proton jet fragments observed very forward region

How to associate them with proper vertex when pileup prese
Timing may provide a key tool.

many vertices in hi-PU event even today

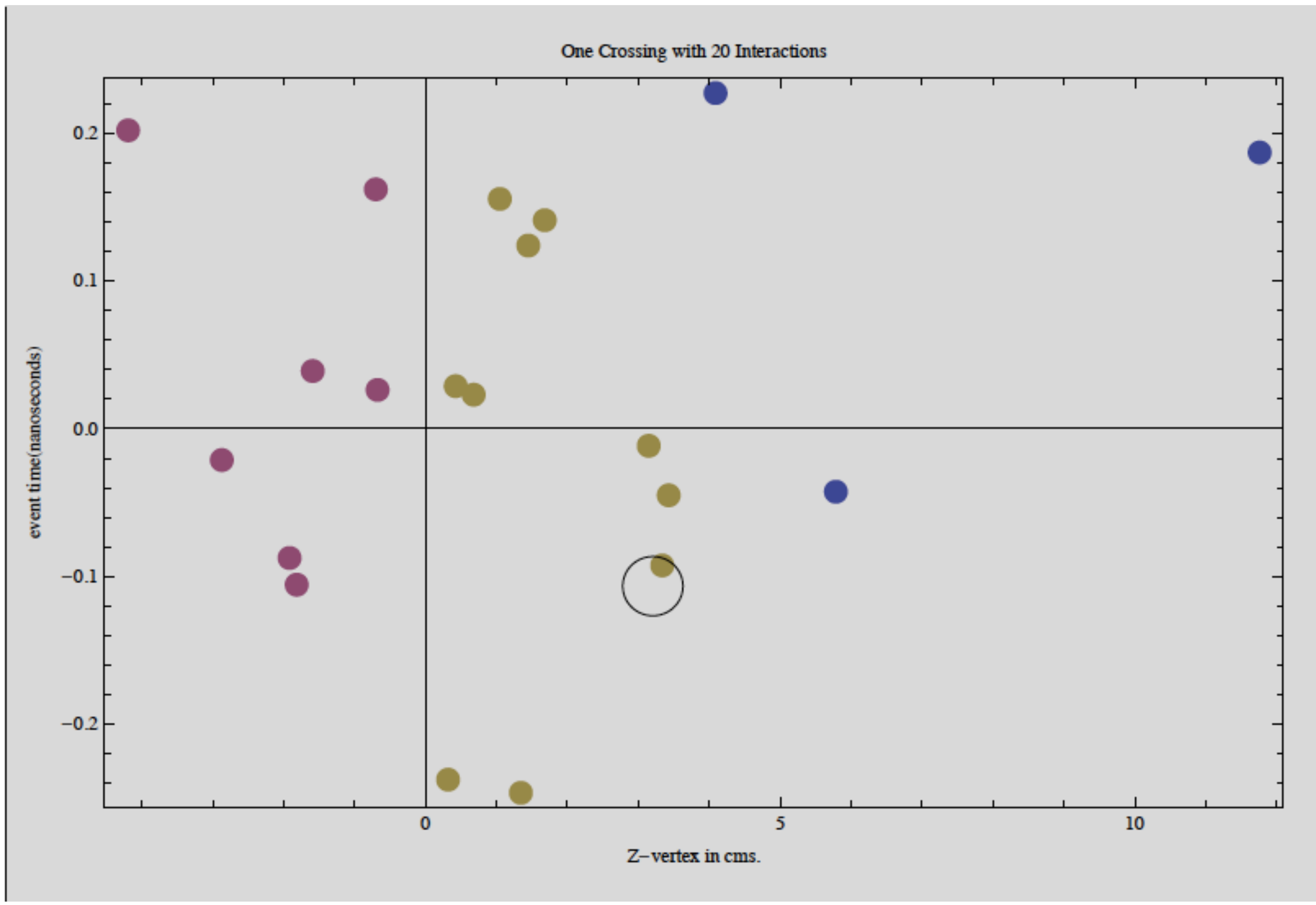
Work in CMS forward calorimeter task force and DOE AD R&D: K. McDonald & S. White- co-PI's

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.

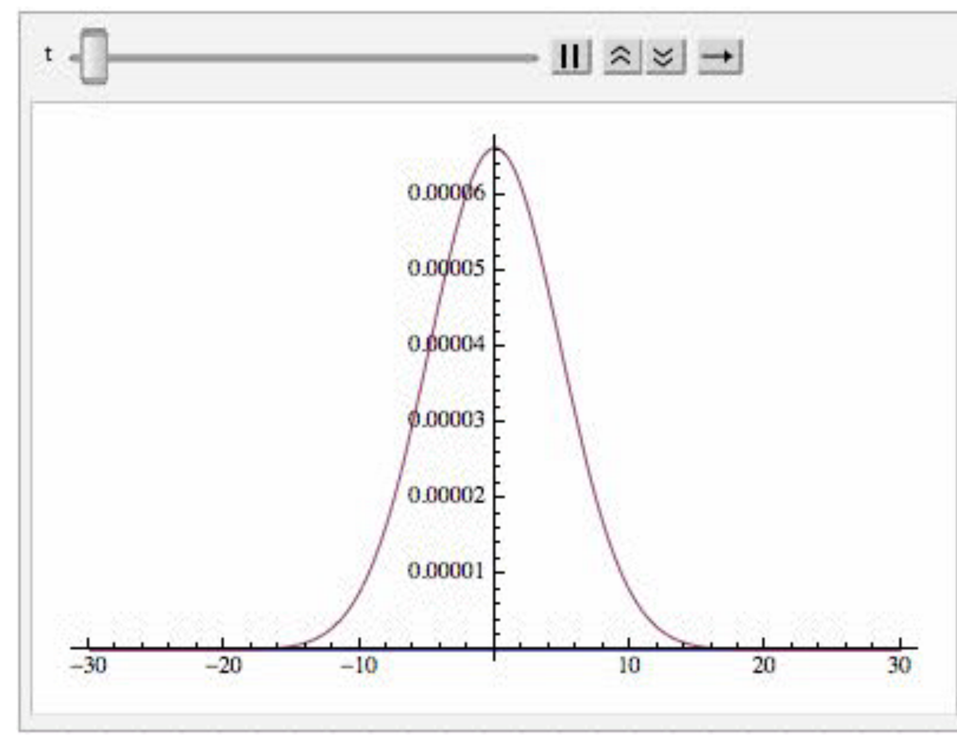
Nb: circled event needs both time and vertex to resolve.

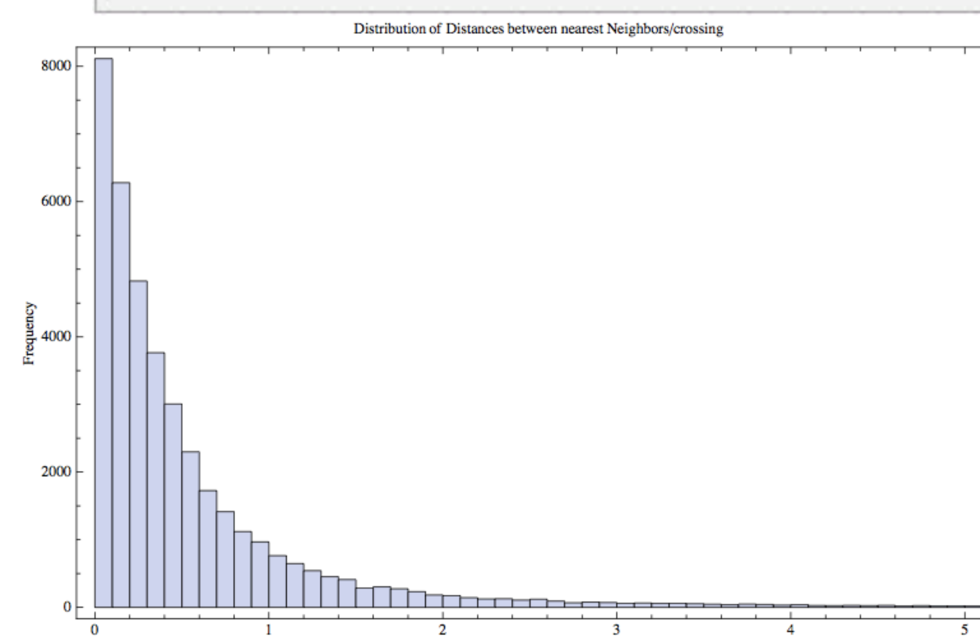


how effectively is PU resolved with n(or Jet) ideal time resolution of 10 picosec? Illustrated by error elipse

vertex distribution time invariant

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





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

Background

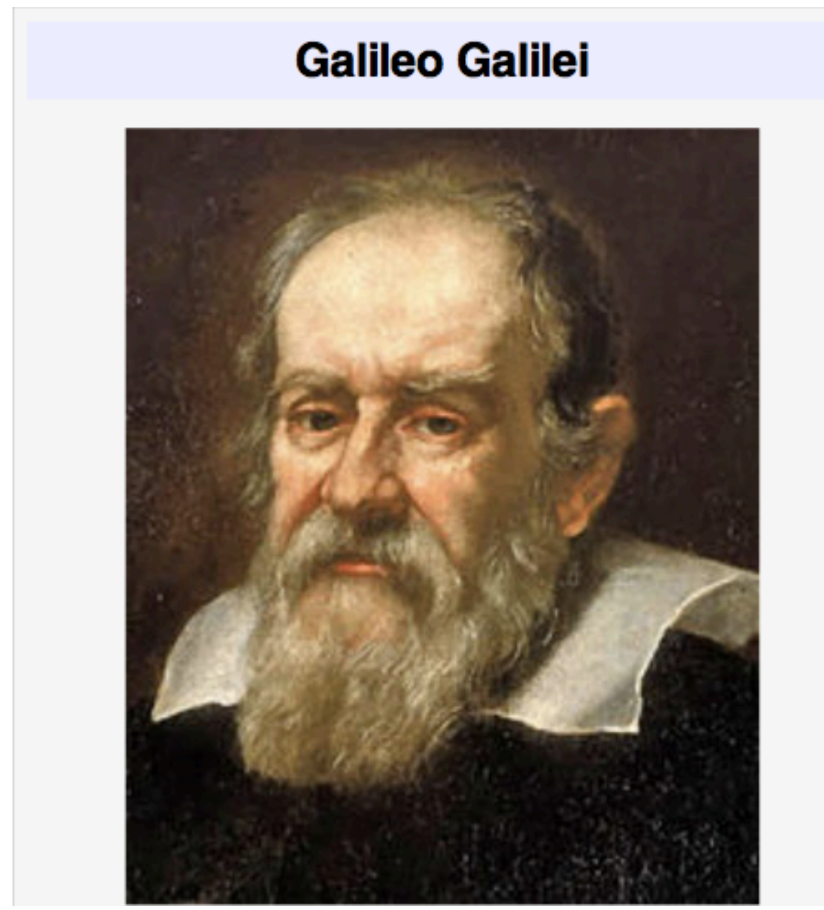
There has been very little emphasis on time measurement in ATLAS/CMS. But measurement of time has a long history in Physics.

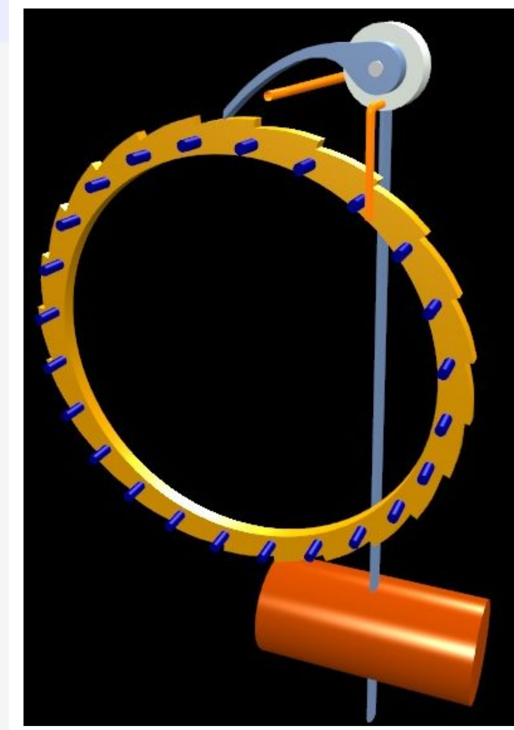
Last invention by Galileo (when he had gone blind in Arcetri) was escapement for the pendulum clock. He felt that it was critical to time stamp astronomical observations and was looking for improvement over measuring his pulse....

CTR Wilson discovered cloud chamber working as a meteorologist and utilized high speed photography techniques of Worthington.
A nuclear physicist-Bruno Rossi- introduced the critical step of making it triggerable.

Wilson insisted that photo should be time-stamped- ie put a clock in the image when doing CR studies.

Cloud Chamber 1950 NEVIS Cyclotron Lab

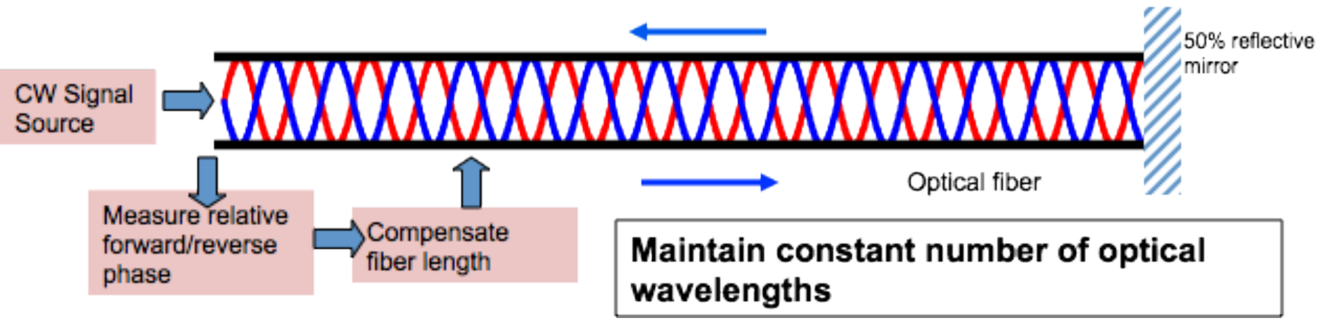




Time stamp was critical in SN1987a.

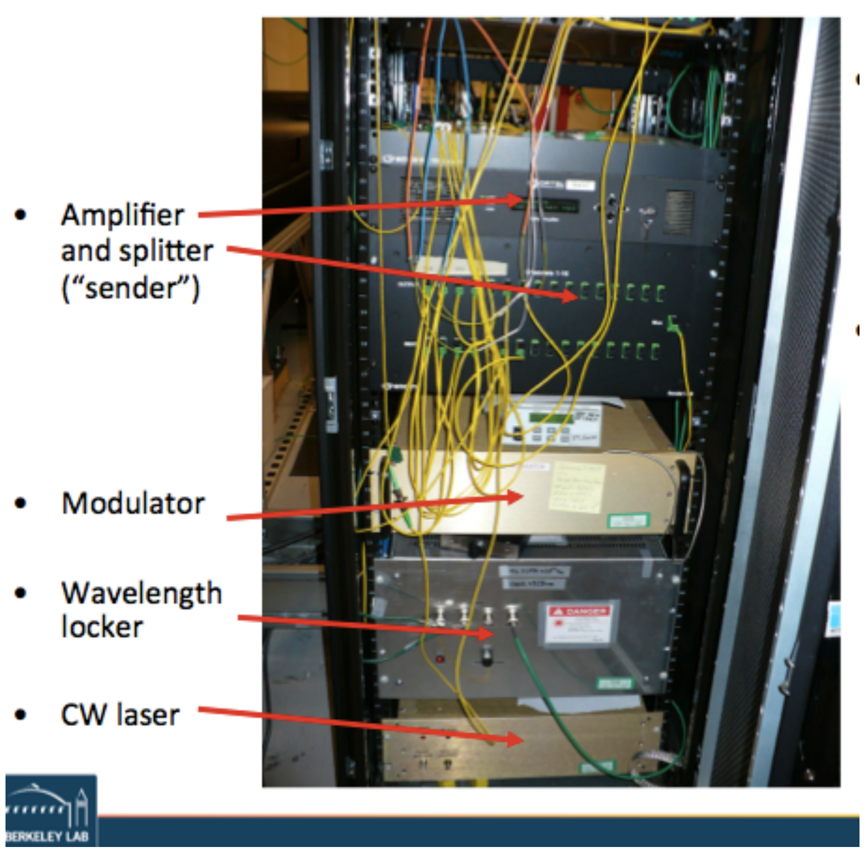
Tools: Clock Synchronization

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

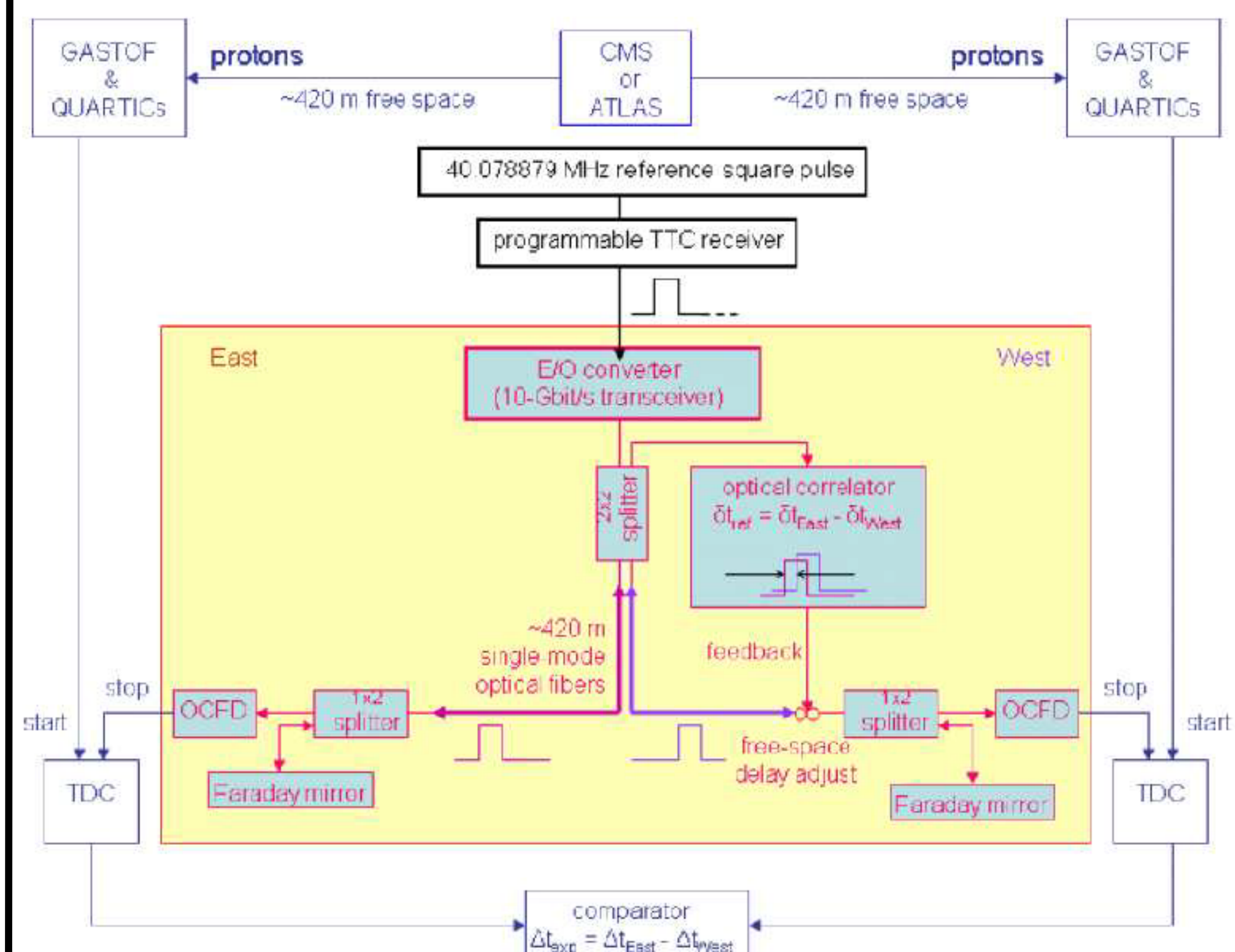


Interferometrical stabilization of eg. 20 picosec/deg.C/km thermal drift of optical fibres.

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

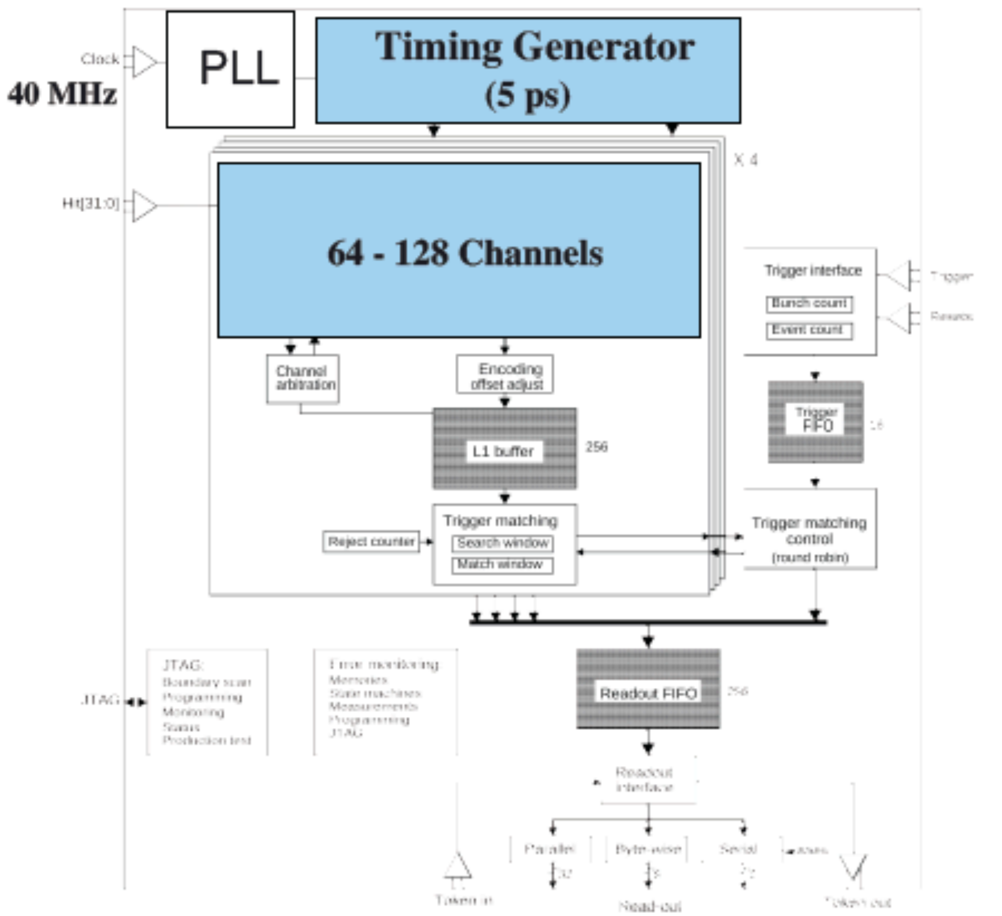


We (T.Tsang & SNW) designed a $60k system based on optical correlator for 5 picosec stability. -see FP420 R&D report, 2008.



Tools: Digitization

TDC Architecture:

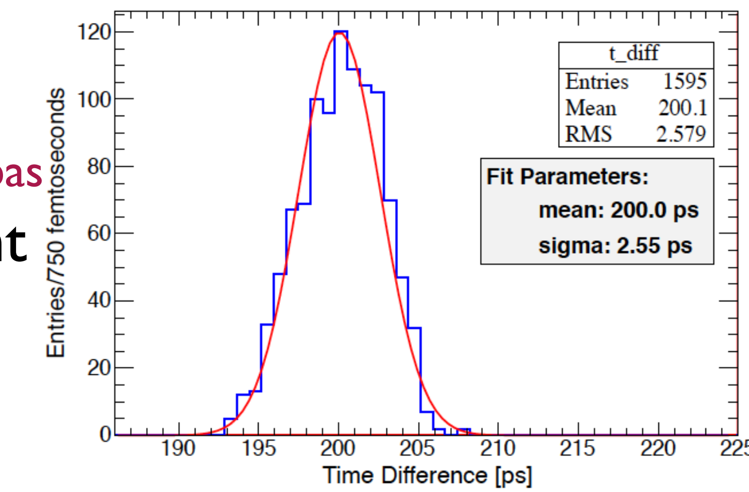


20-September-2012 L. Perktold - BistroTDC

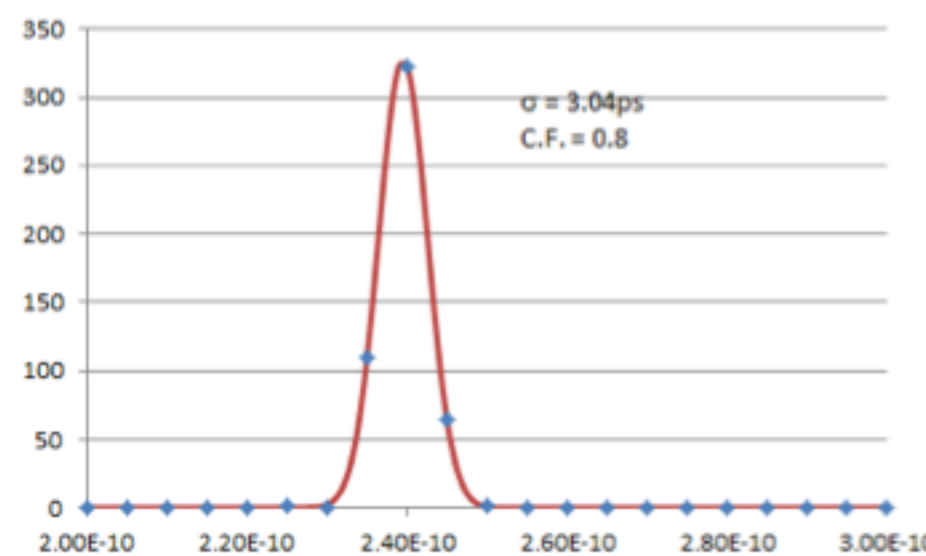
higher resolution version of TDC used by ALICE:
3 psec rms jitter in ASIC
<5psec goal in full system.

waveform digitizer approach:

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

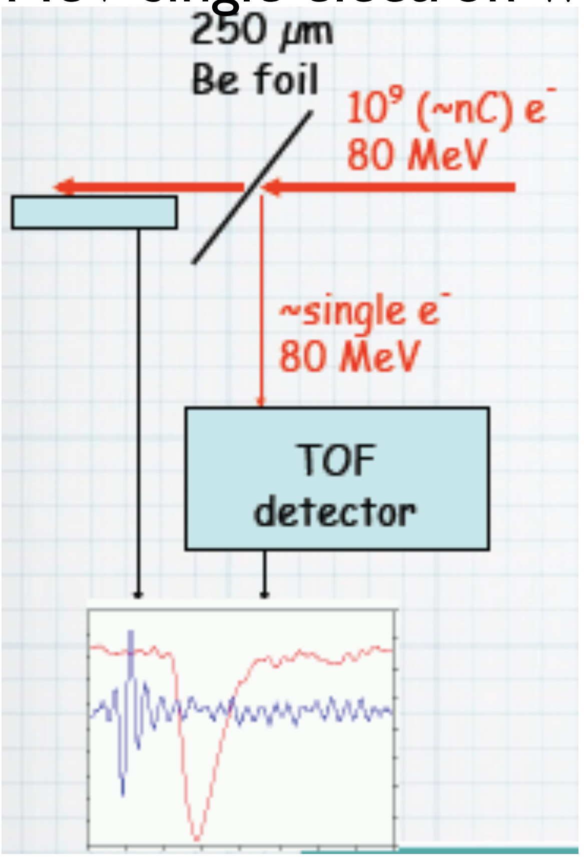


our result from time diff on 2 striplines at electron LINAC w. 3 picosec bunch length, SNR~100, trise~150 psec=>2.5 picosec rms. remeasured this year:



Tools for device testing

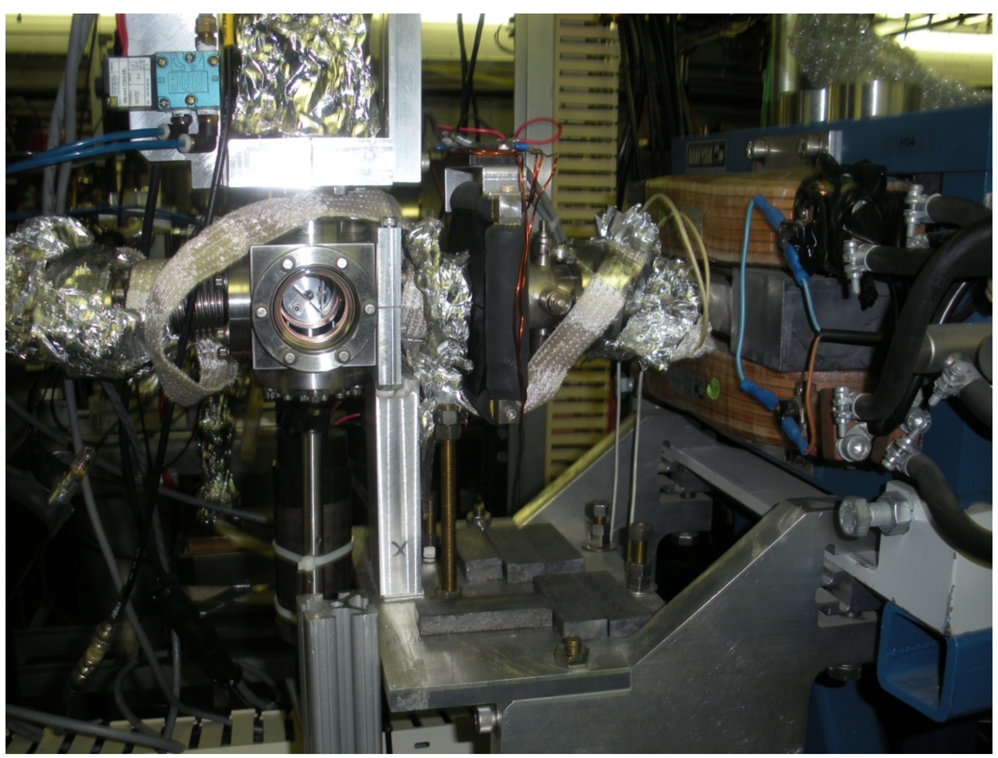
80 MeV single electron with 3 psec jitter

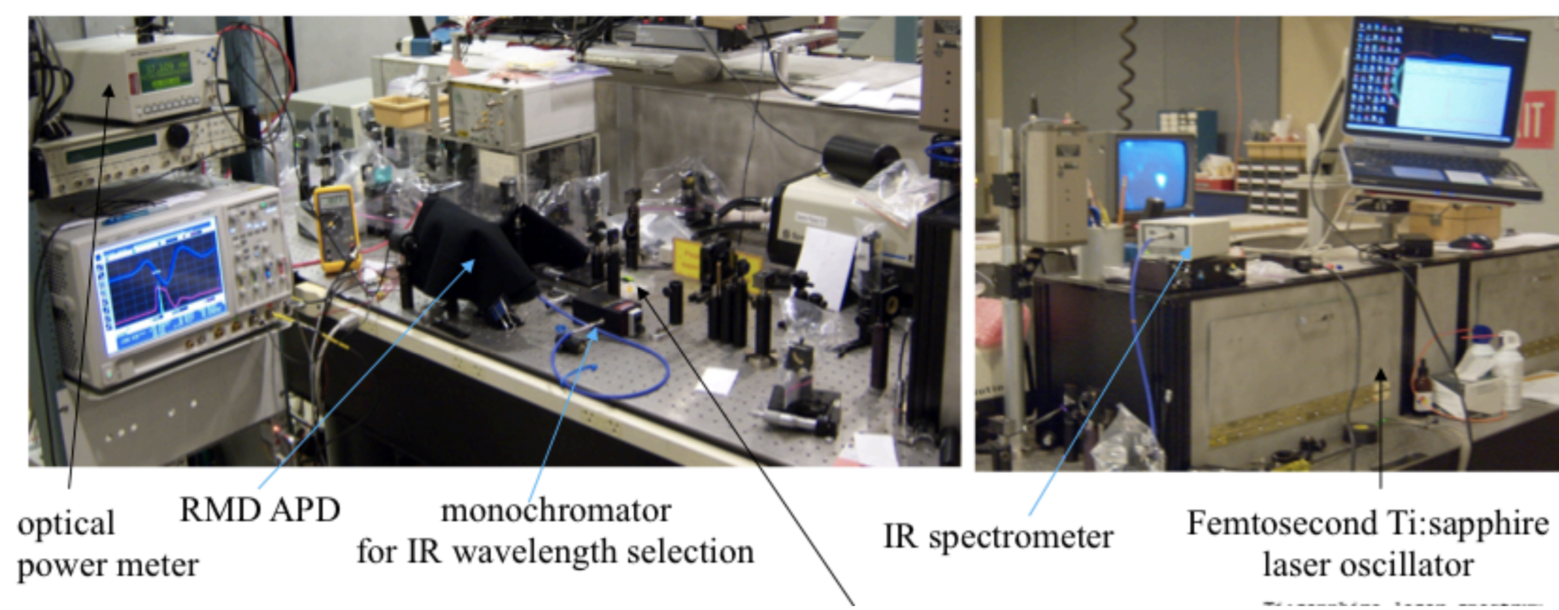


(also discussing similar possibility with LAL, Orsay)

1) ATF 2010->now.(and LAL?)
2) PSI (fall 2011 and May 2013)
3) Frascati (fall 2011)
4)CERN NA (Feb 2013)
5) femto sec laser for Si APD

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

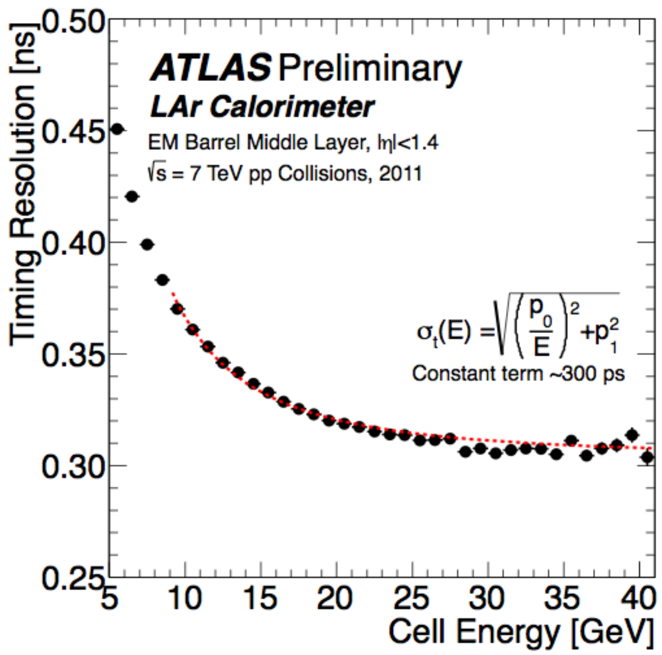
LHC itself could do things to make life easier:

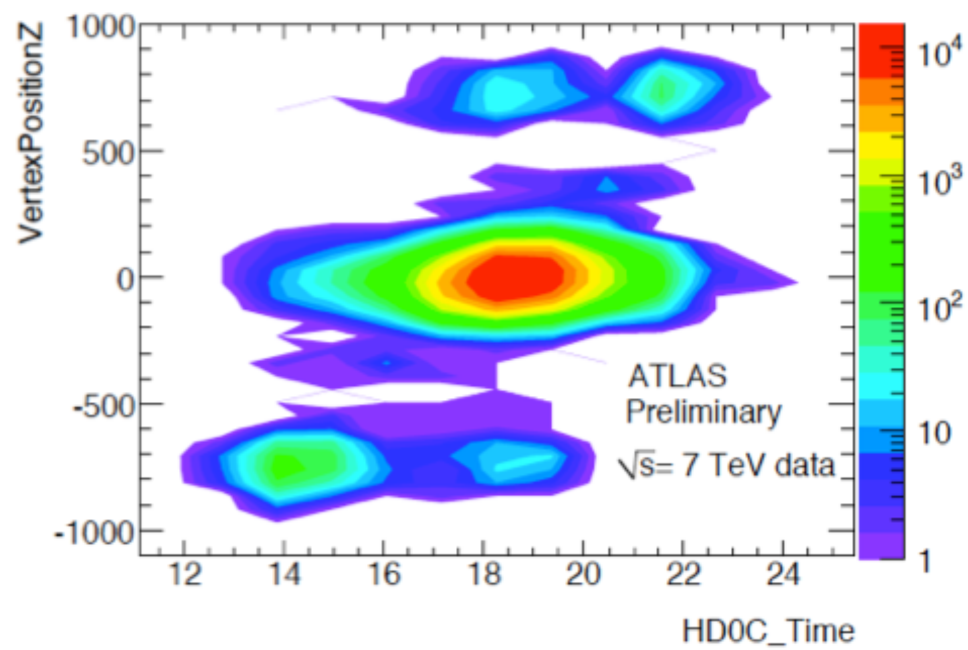
1)20->40 MHz crossing rate halves pileup

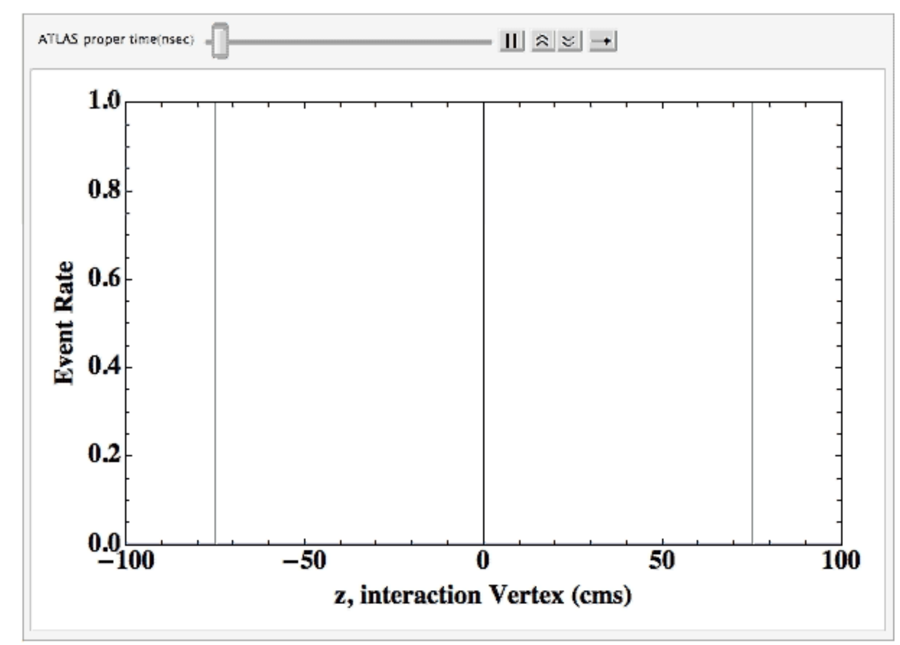
2) Exotic “crab crossing” “kissing” schemes will be discussed next month at ECFA

-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)

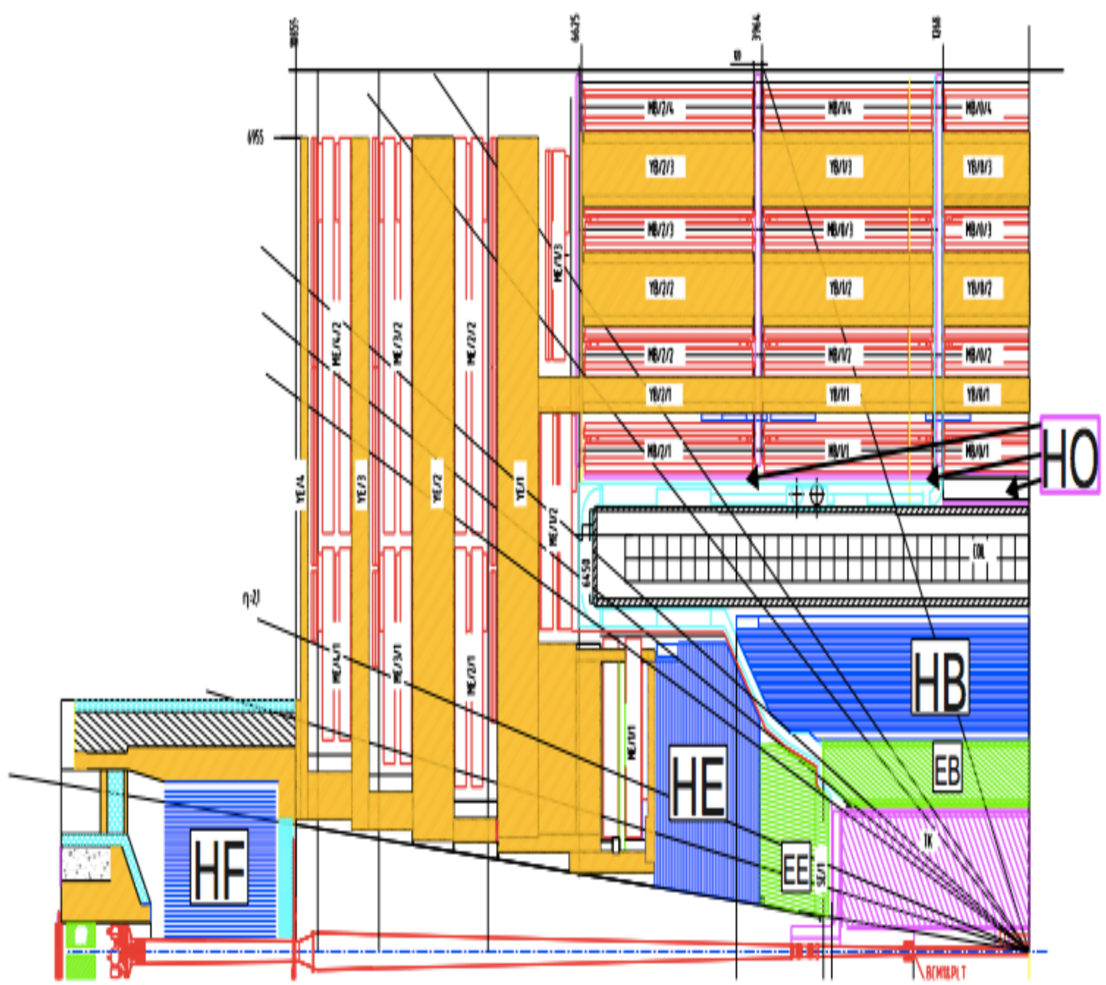
4) Similar studies in CMS

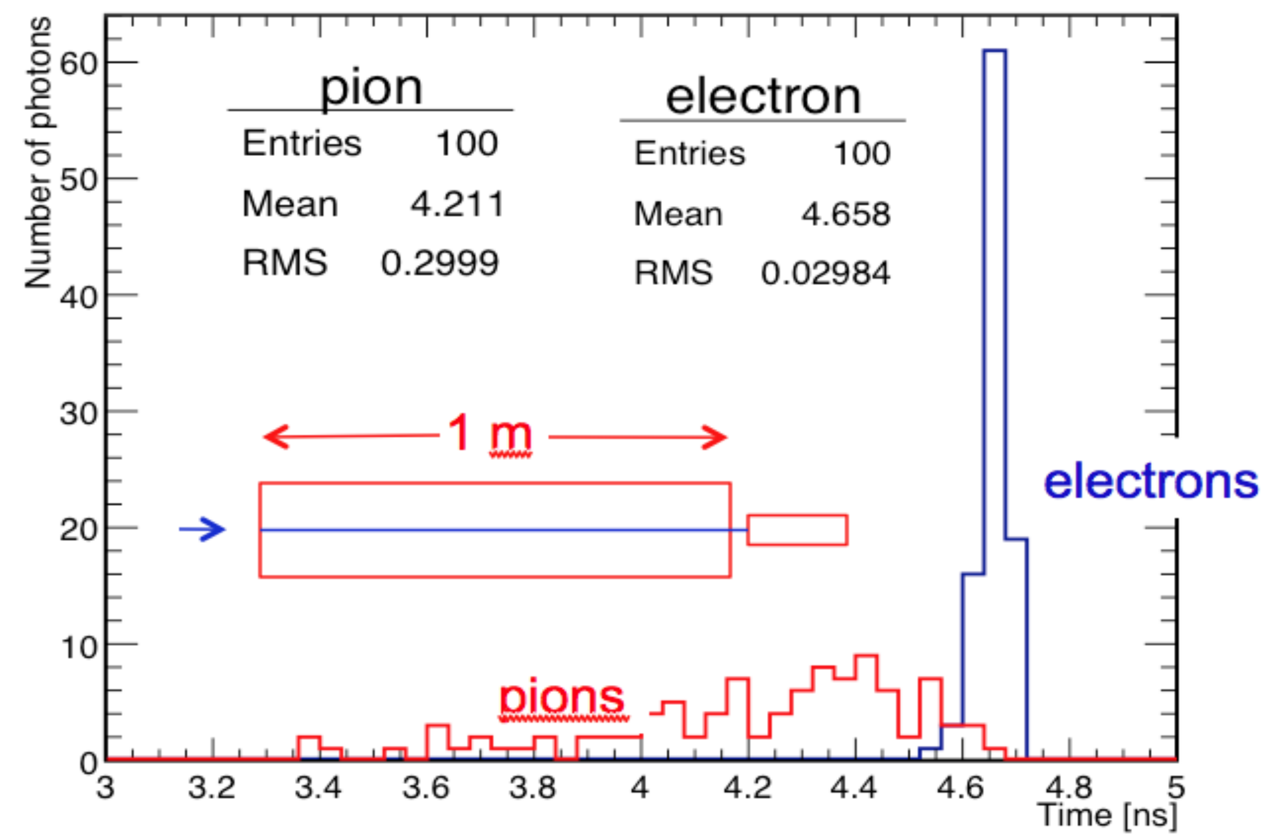
ATLAS Zero Degree Calorimeter achieved separation of micro-satelite bunches from timing (shower time resolution<100 picosec)

Opportunities in New Calorimeter Projects for CMS Phase-II

CMS is considering upgrades of Forward Calorimetry. In addition, space will become available for a possible dedicated timing detector in front. Due to removal of T1.

One promising option, the Combined Forward Calorimeter, shows very low time jitter on time-of-arrival for EM component in simulations.





Nb: time structure of light signal can also be used to distinguish EM and hadronic.

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

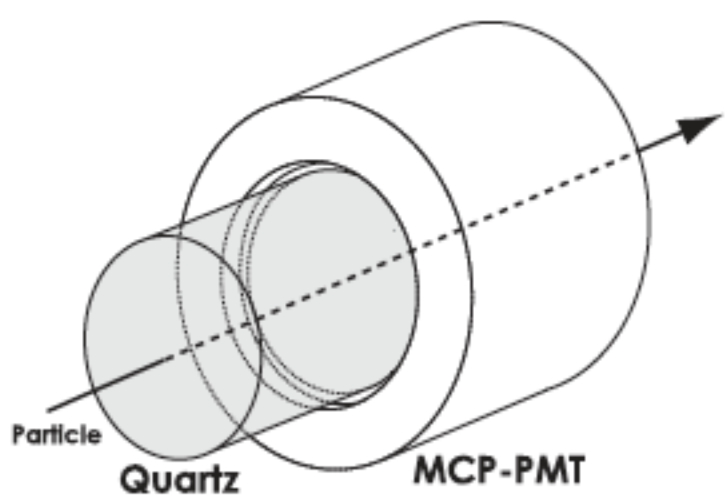
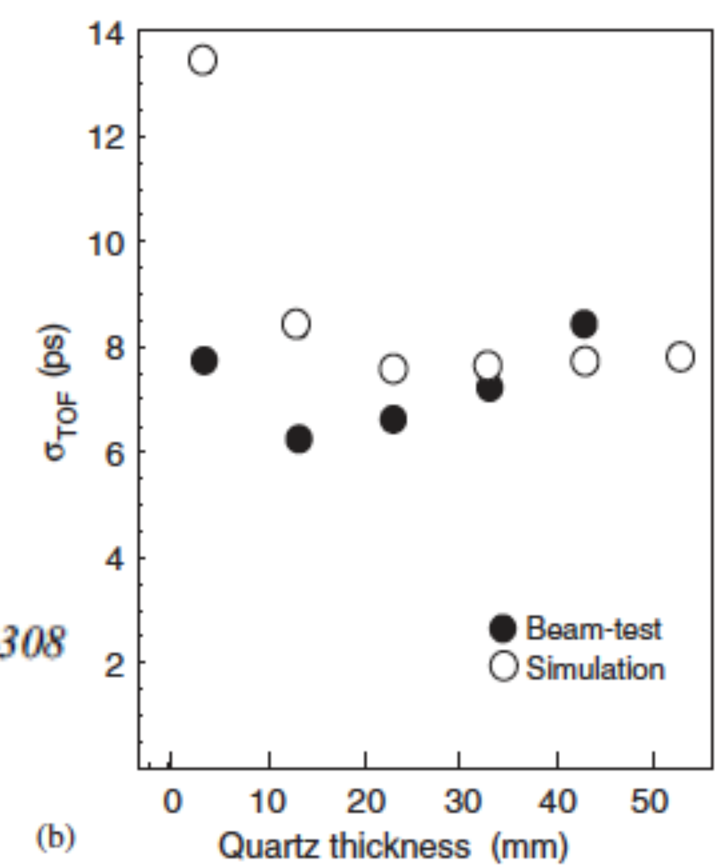


Fig. 1. Schematic drawing of the TOF counter.

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



(b)

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

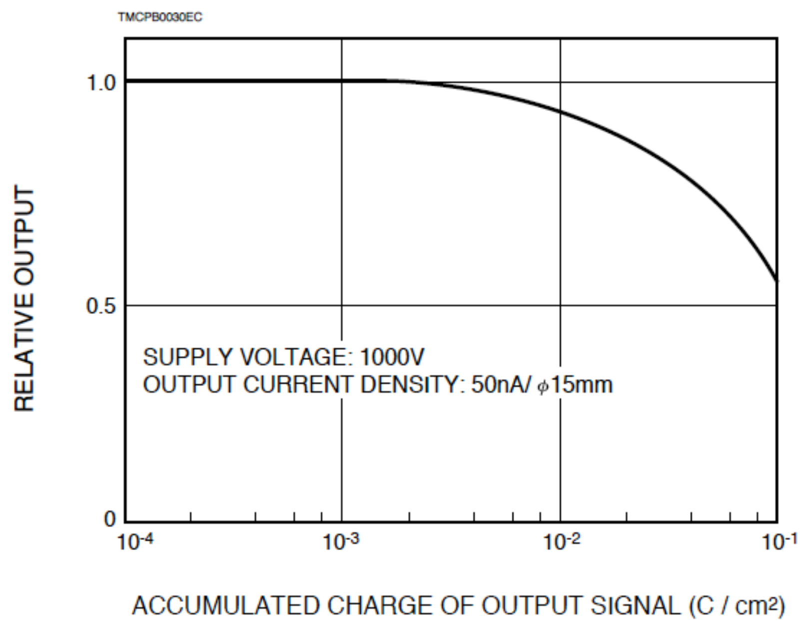
Photosensors

(we worked with Hamamatsu to evaluate options)

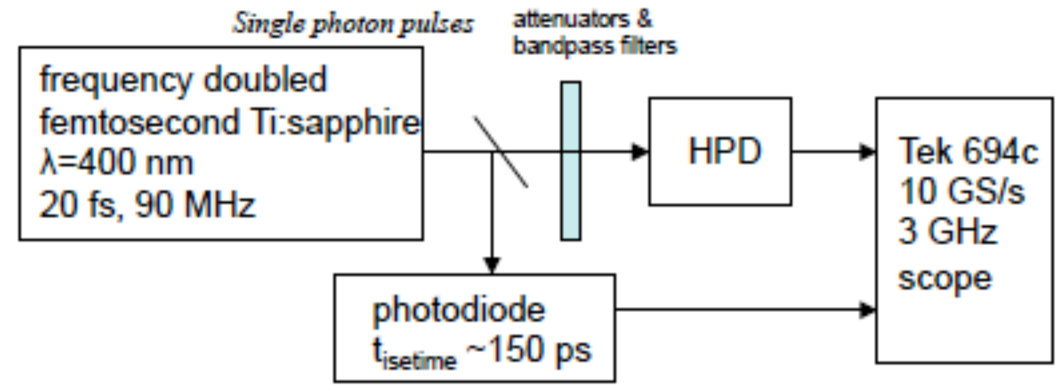
lifetime is an issue in MCP-PMT

compare Hamamatsu data on:

MCP · Life

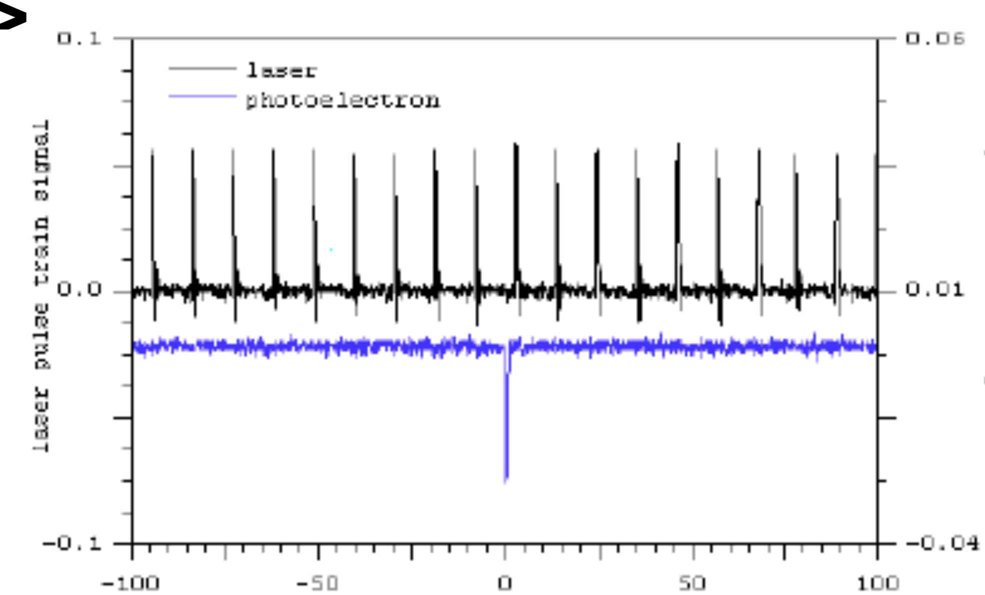


our measured single photon time response:

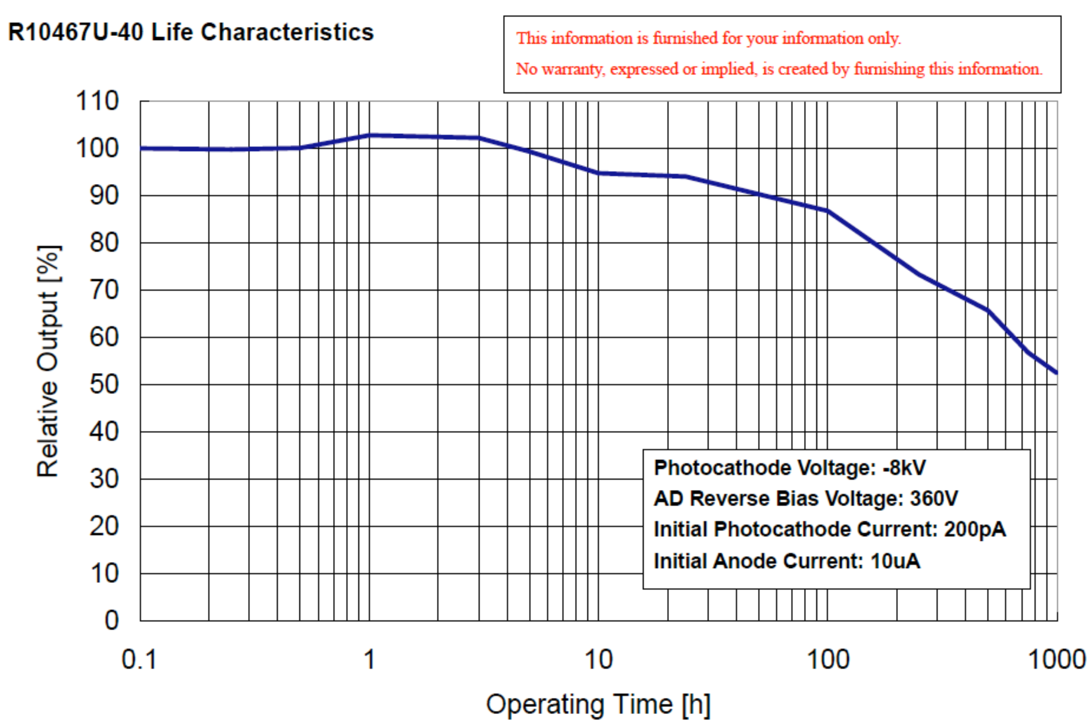


Ti:sapphire oscillator:
attenuate to
95 femtoWatt
~200 kHz count rate
~2x10^5 photons/sec
(<0.002 photon/pulse)

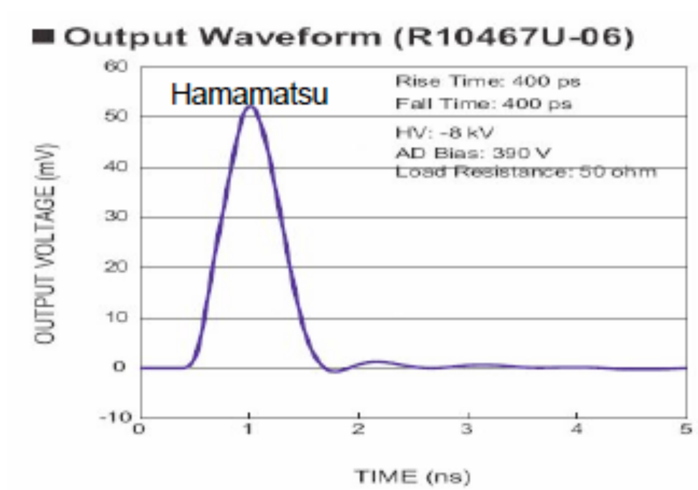
=>



compared to new technology evaluated by our collaboration:

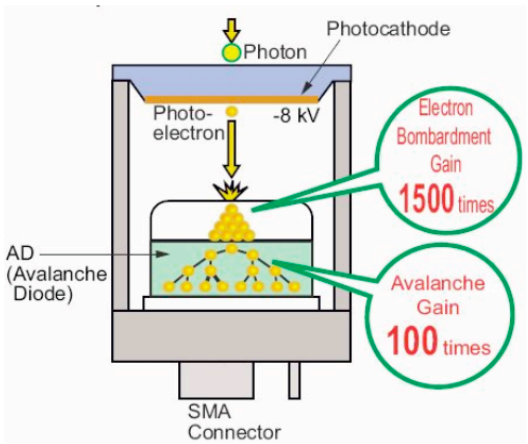


Measured jitter relative to photodiode=11 picosec!!



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

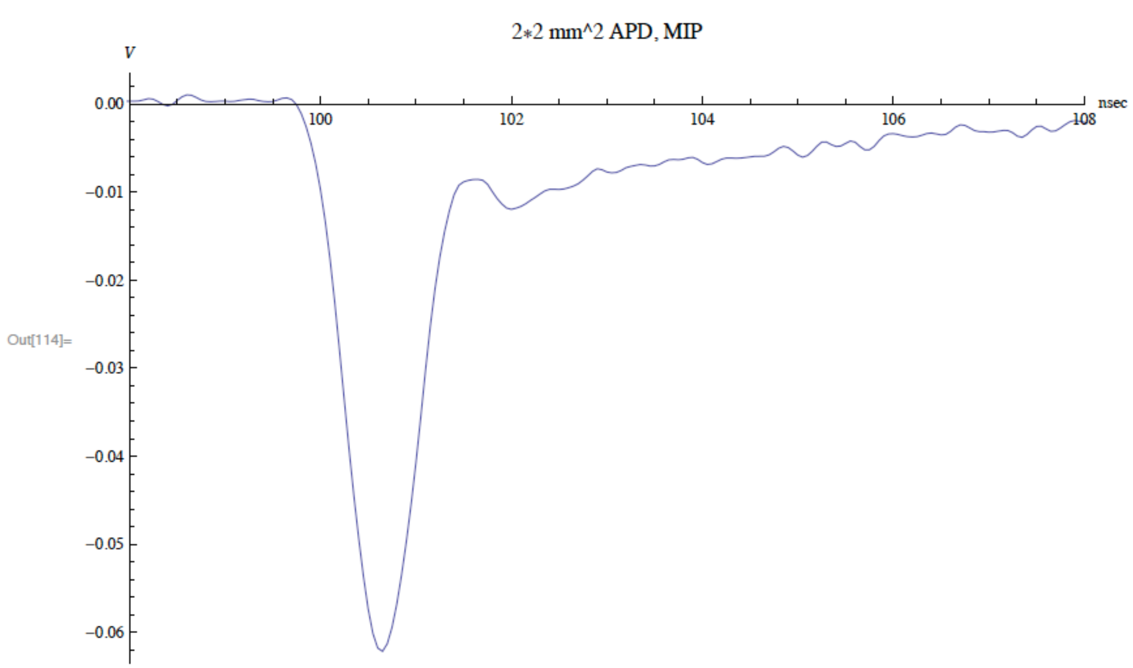
Picosecond Charged particle tracking:



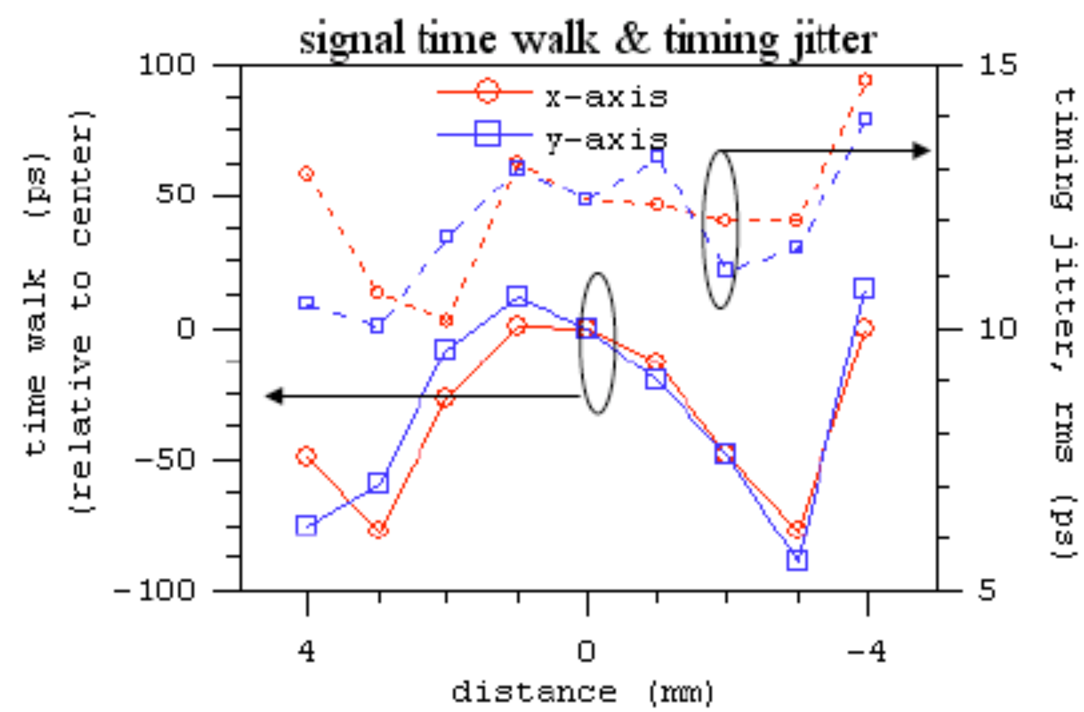
Hybrid APD (results on previous slide) is an accelerator followed by APD used as charged particle detector. Since it yields 11 picosec jitter why not use APDs as direct charged particle detector?

(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

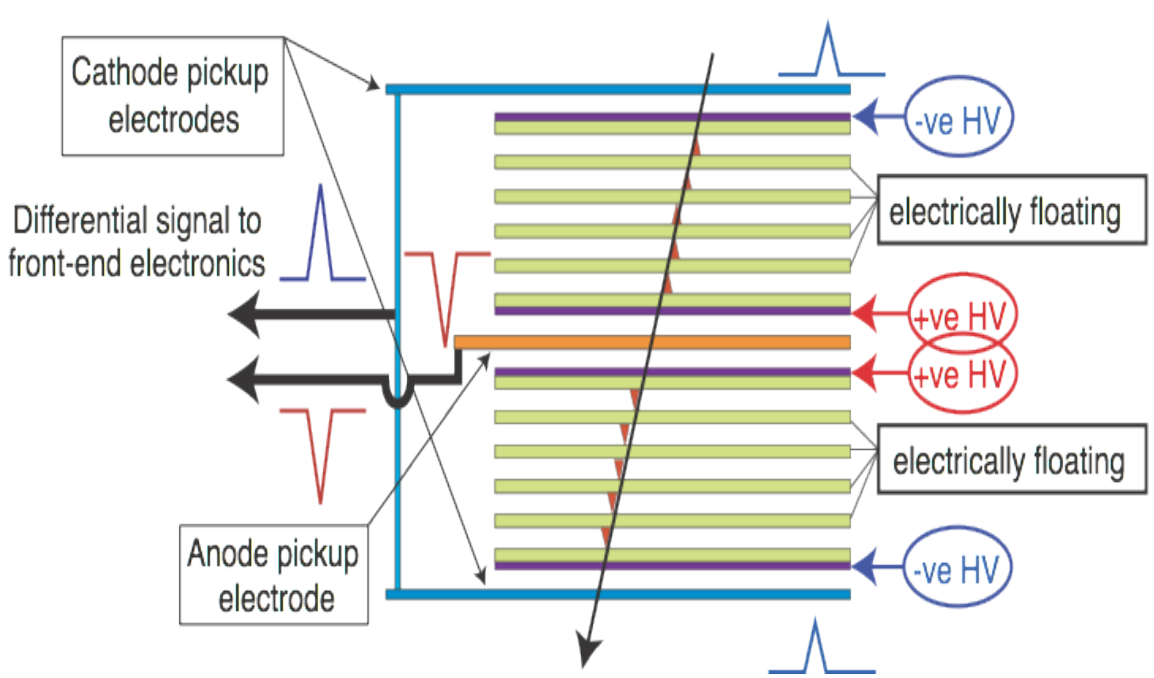
For our problem, principle issues are:

-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)



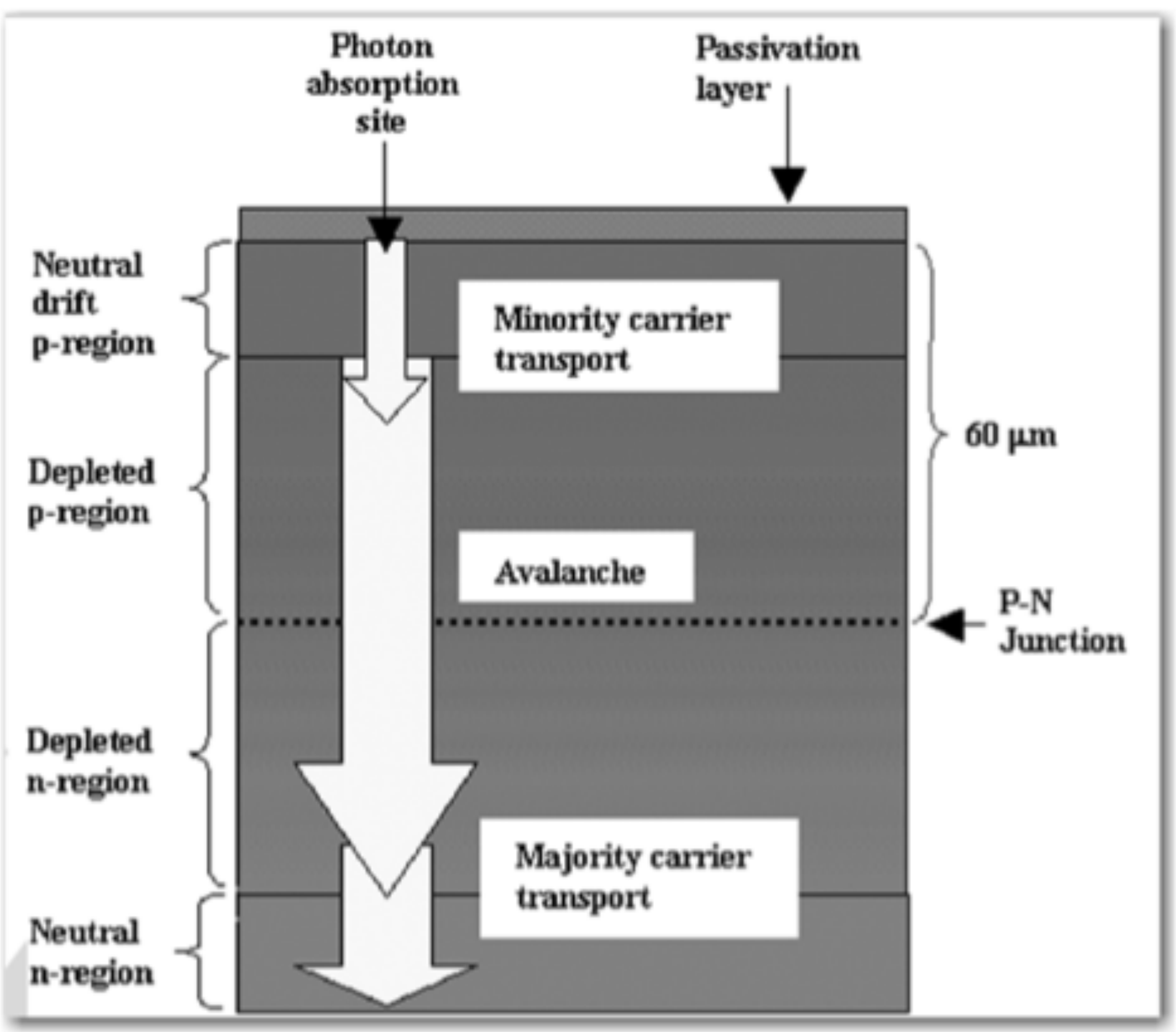
~80 psec resolution in full system. C. Williams currently getting 16 picosec in R&D but <u>not focusing on rate issues</u> Limitation due to stochastic cluster formation addressed by multiple measurements

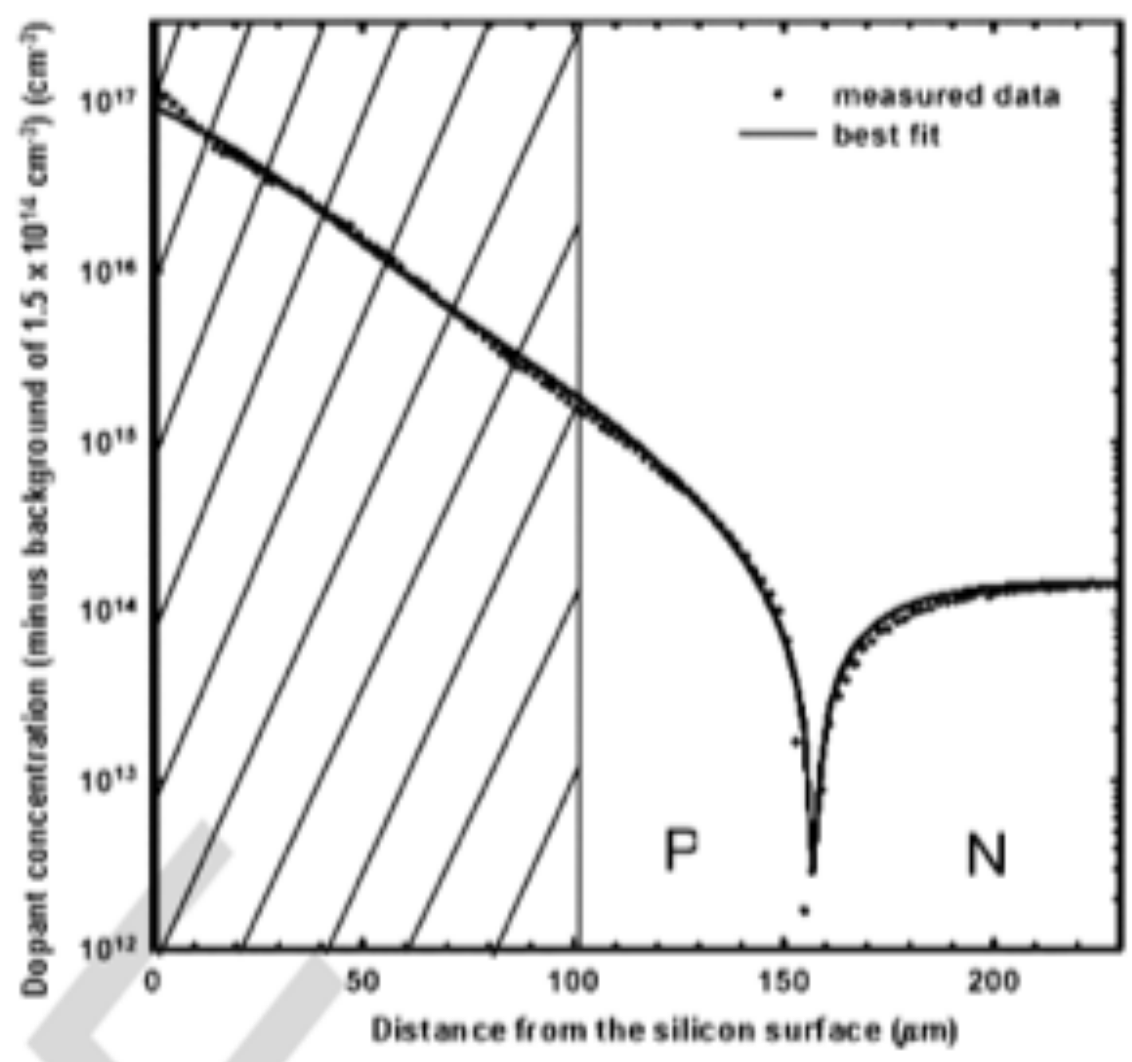
Charged Particle Timing (cont.)

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
-Our approach, using Deep Depleted APD w. Micro Megas field shaping addresses many of the NA62 issues. Alternative of thin APD discussed with Hamamatsu but present approach seems better.

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

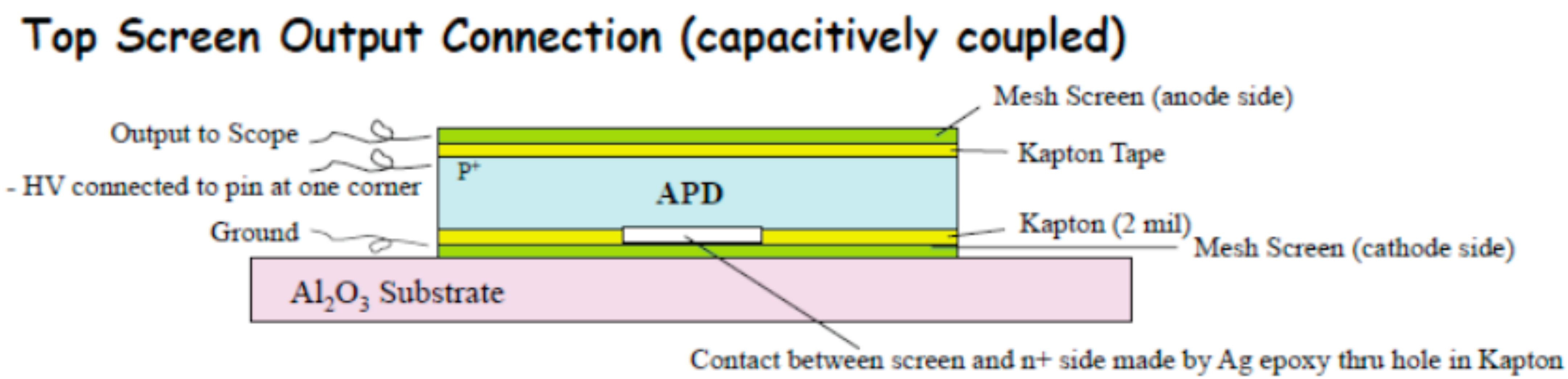




Signal detection on sense electrode

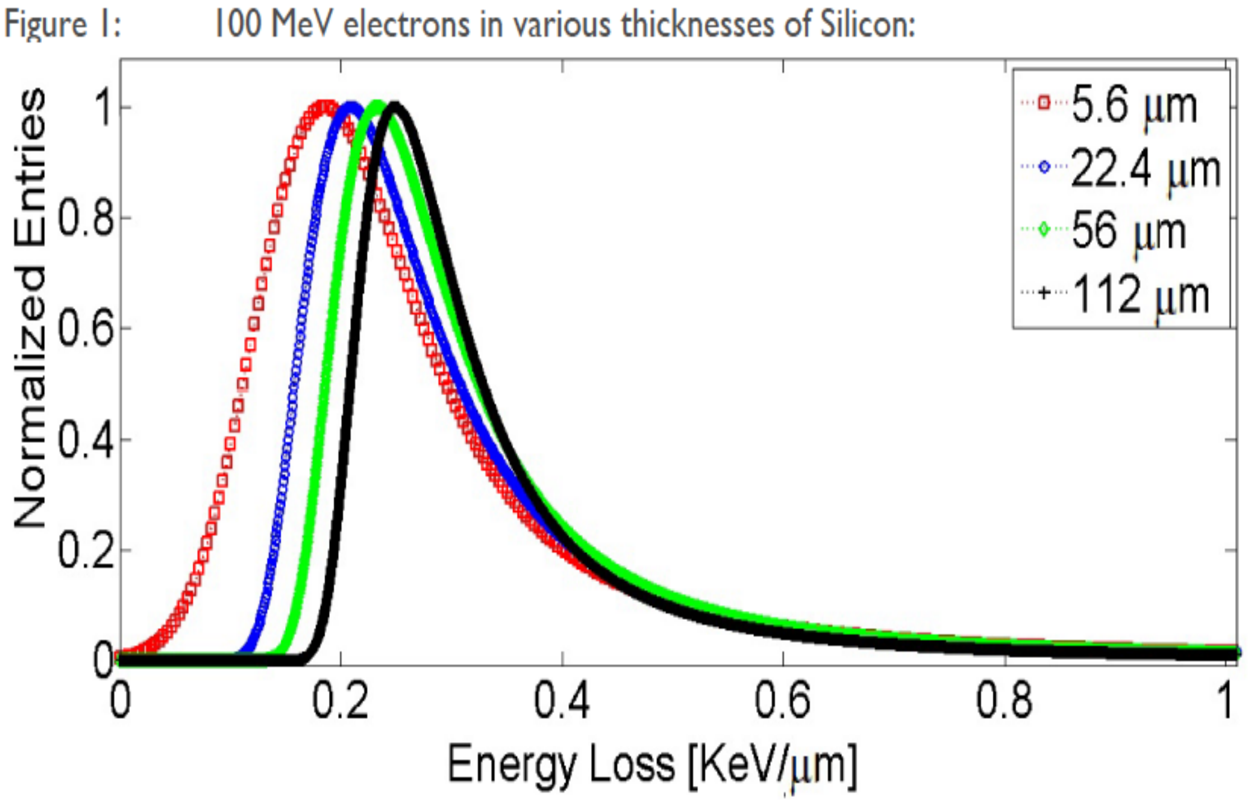
$$i(t) = \frac{E_w}{V_w} v e_0 N(t)$$

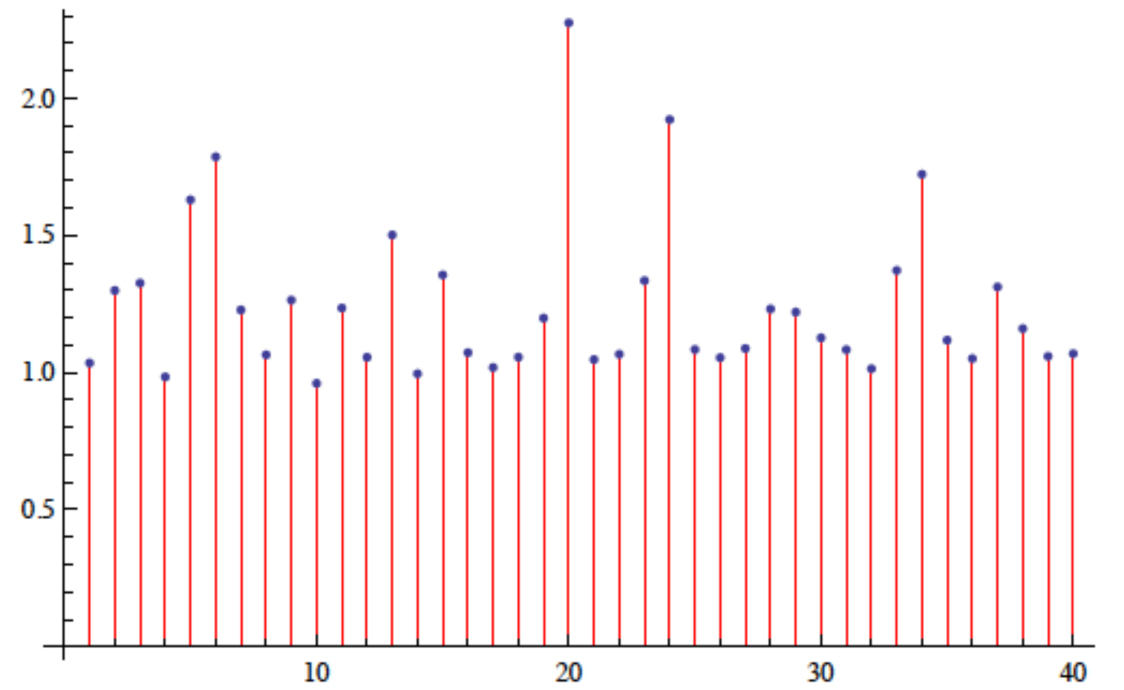
(Ramo's Theorem)
Where:
e0=electron charge
Ew="weighting field"
Vw=potential
V=charge velocity



-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)

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

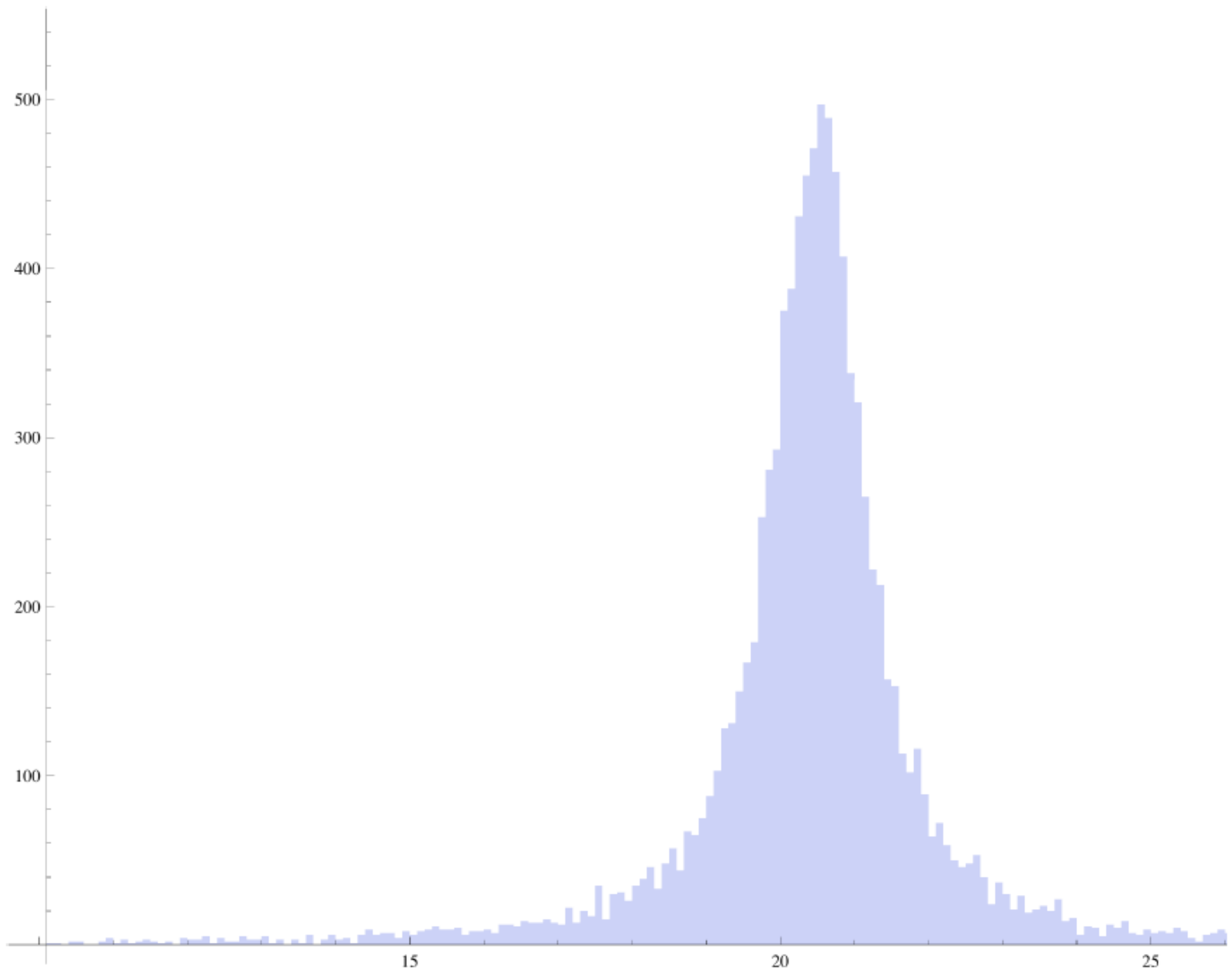




Calculated energy deposit distributions, compared to data in S. Meroli et al.

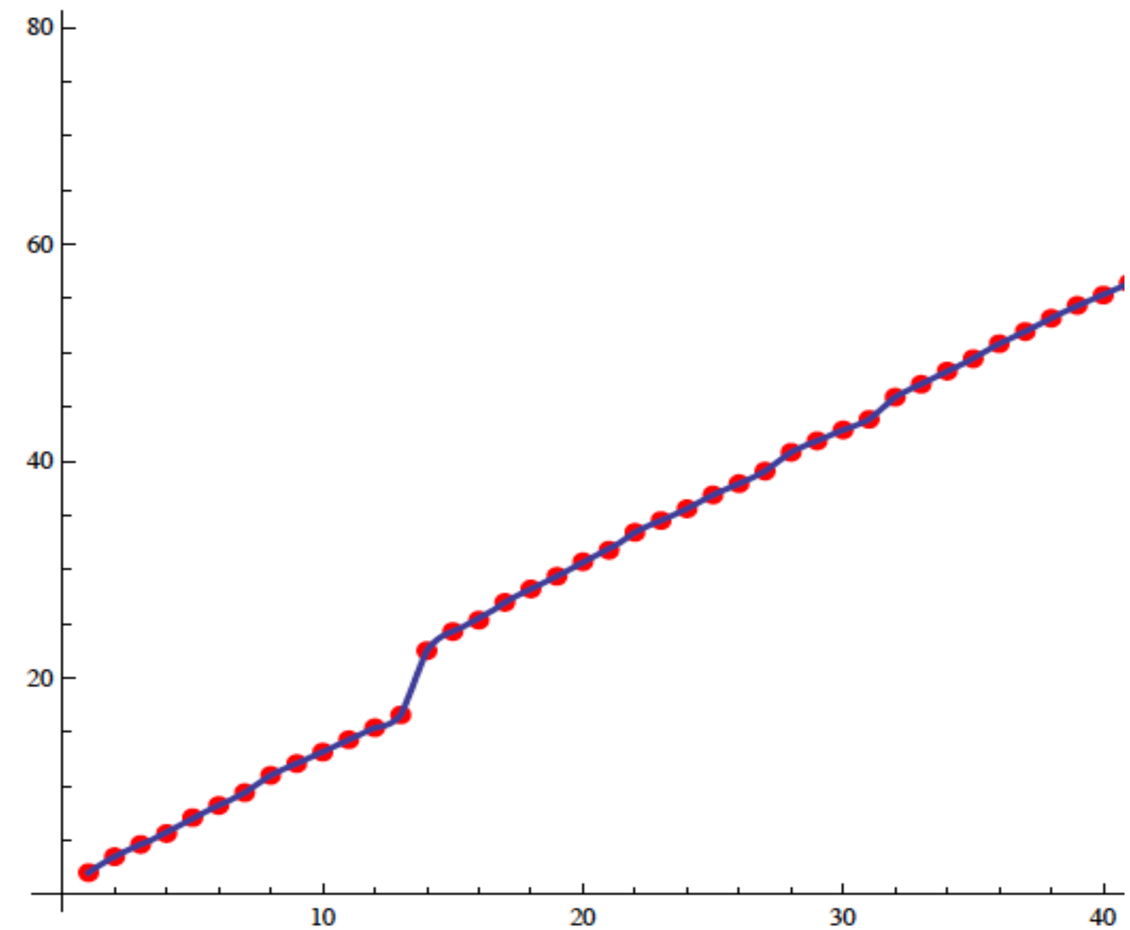
Simulated energy deposit/per each of 40 1 micron layers- typical event

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



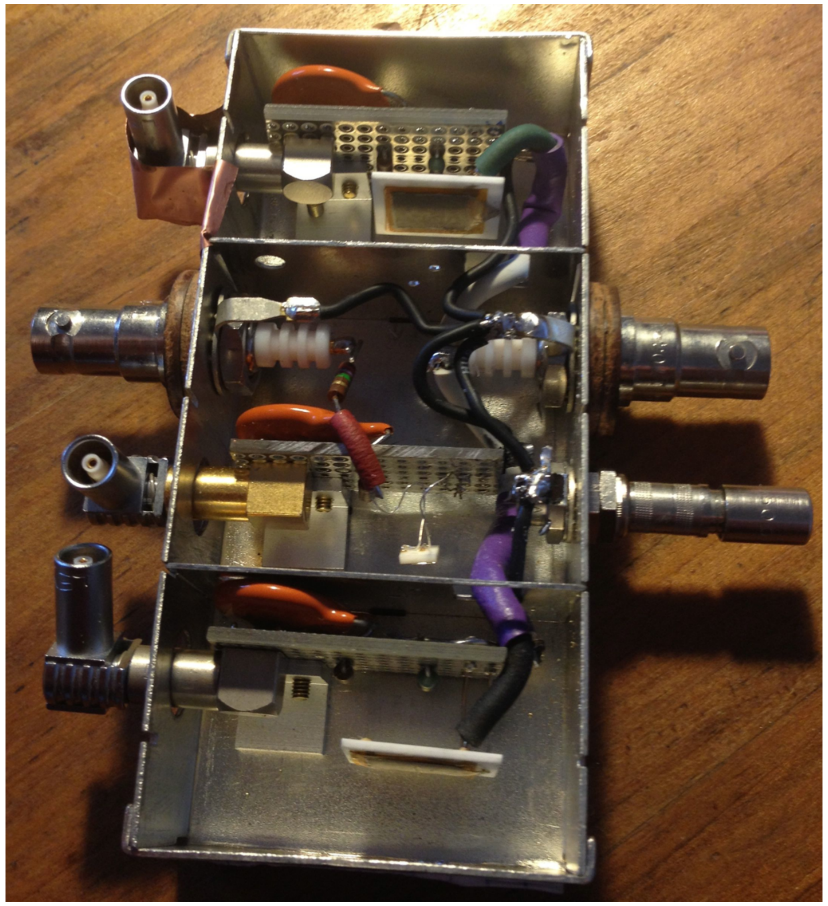
Mean time Distribution for 10k events(microns). Since saturated v=10 picosec/micron-> rms=20 psec dominated by tails

Constant Fraction method gives similar results

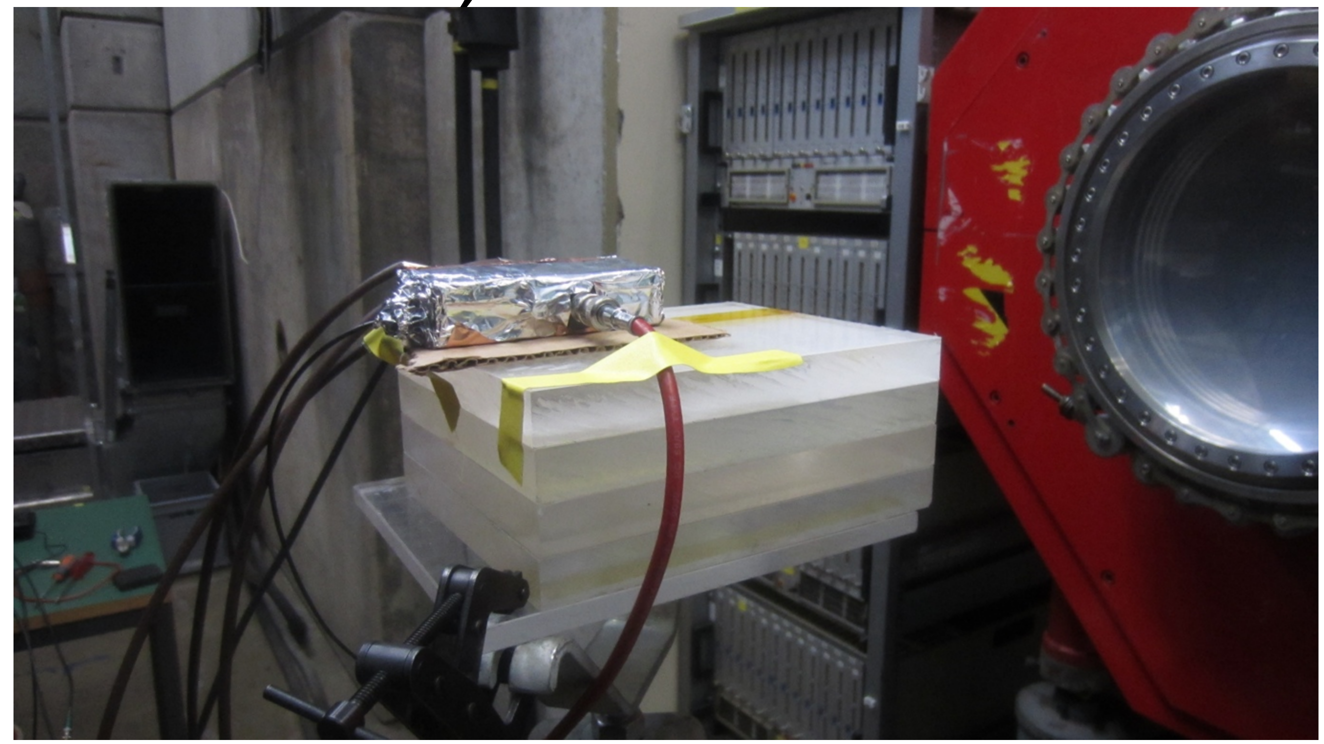


Accumulated signal, 1 event

Testbeams (SPS and PSI)

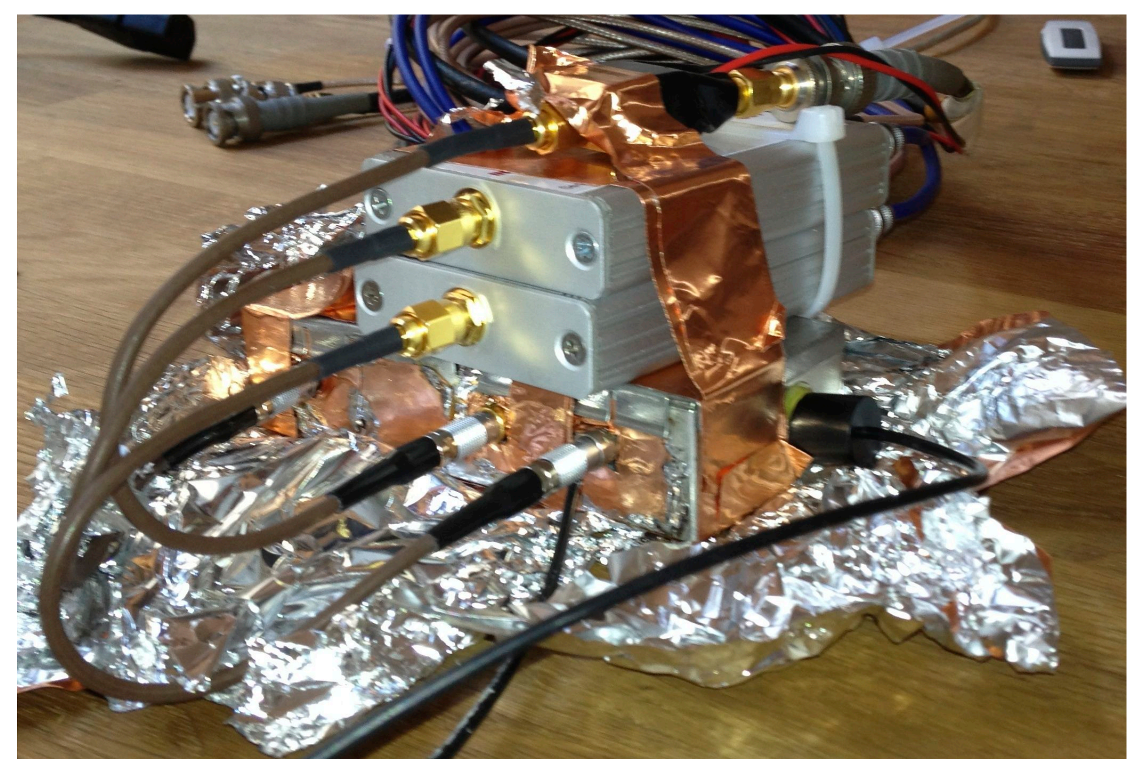


telescope

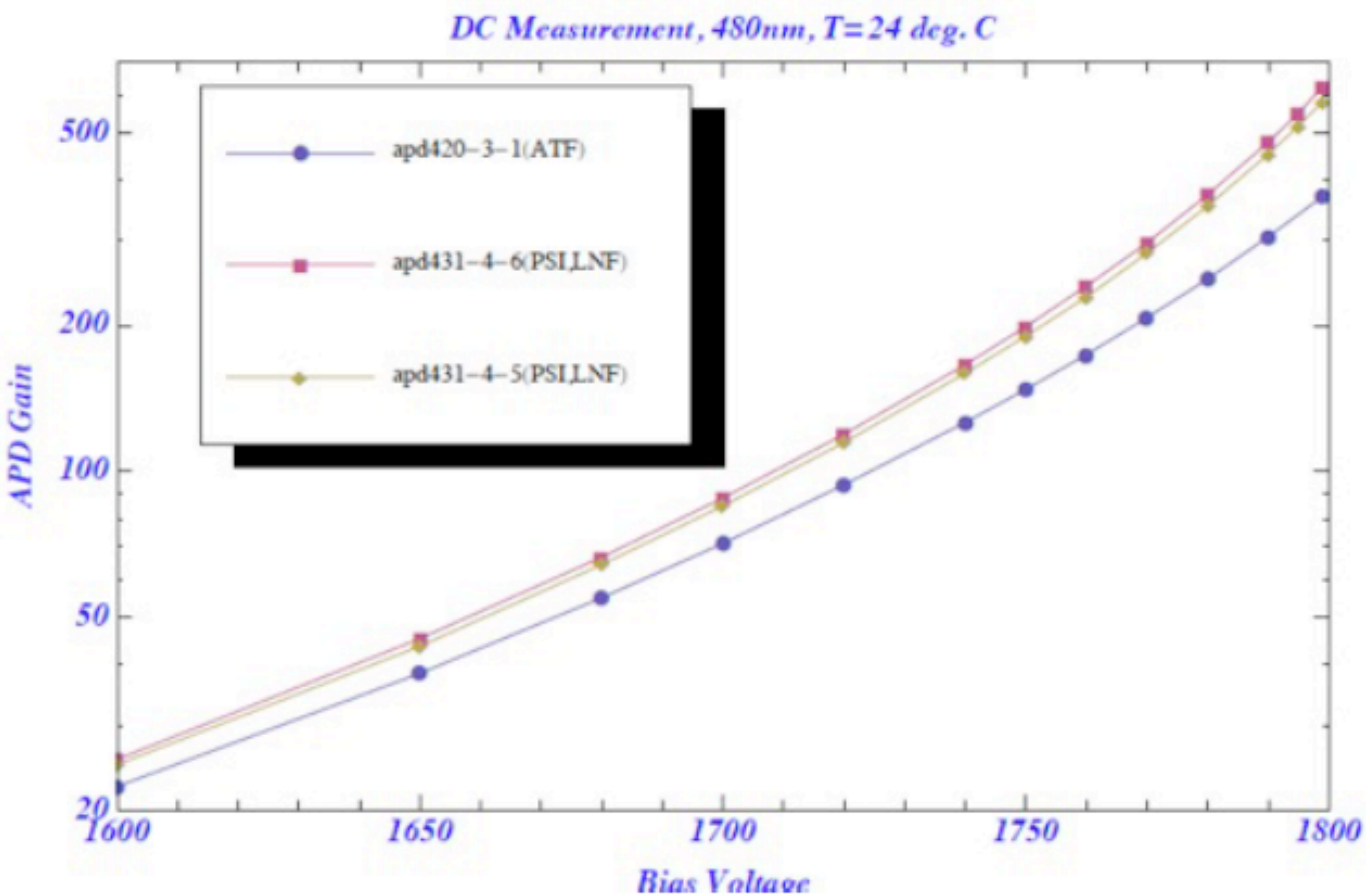


PSI

Rf shielding



RMD/Dynasil APD Gain vs. HV



Most beam data taken at 1776-1814 V

-> Signal into Amp ~10^6 electrons

Optimizing Electronics

Preamp in voltage mode

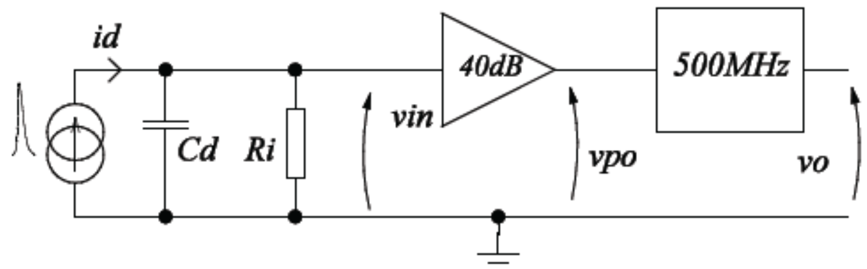


Fig1. Preamplifier working in voltage mode.

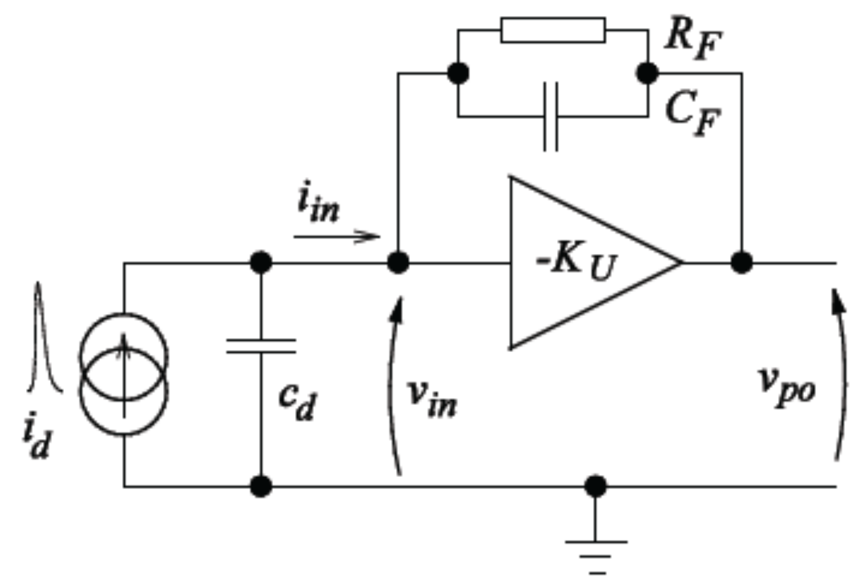
Response (vo(t)) can be found solving following equations.

Voltages:

$$vin = id\,\frac{1}{s\,Cd + \frac{1}{Ri}} = id\,\frac{Ri}{1 + s\,Cd\,Ri} \qquad vo = vin\,Ku(s) = vin\,\frac{Ku}{1 + s\,\tau_{P0}}$$

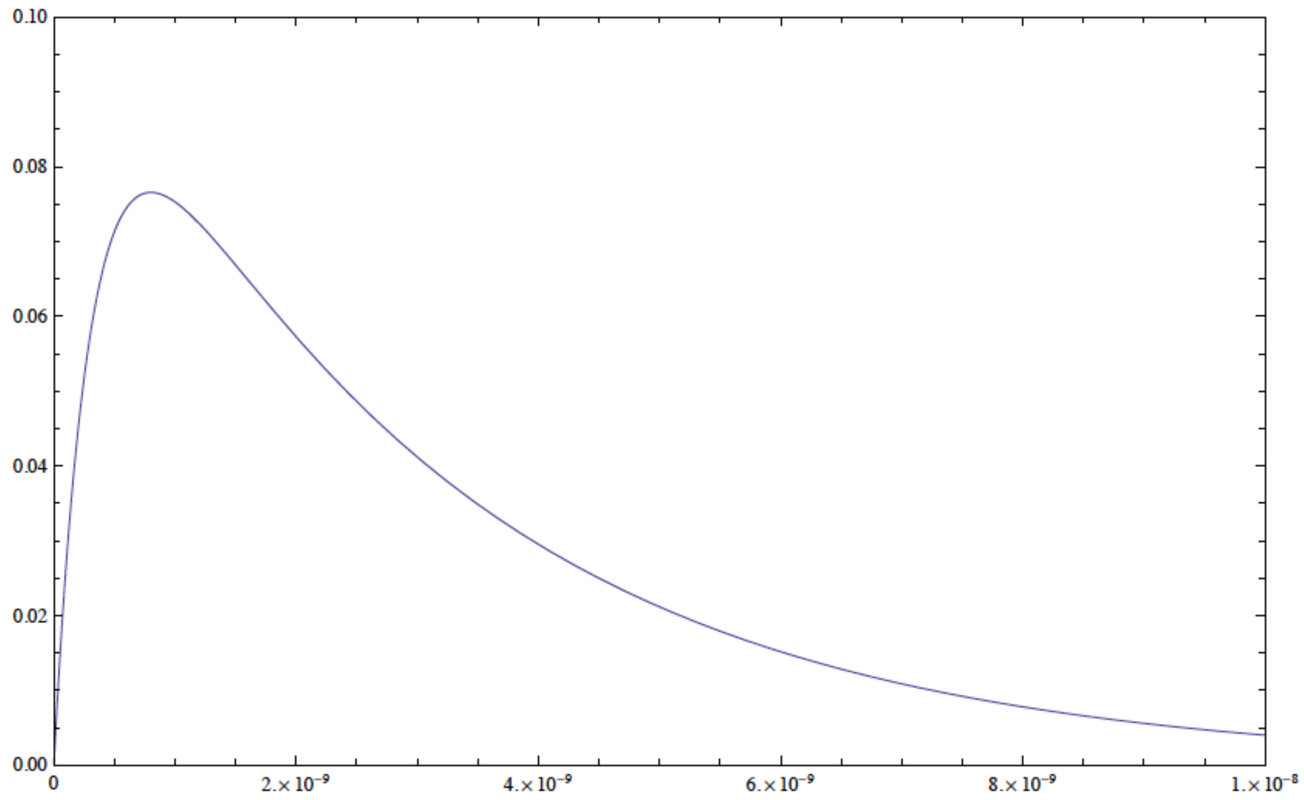
Where τ_{P0} defines bandwidth of the amplifier (for 500MHz 3dB bandwidth τ_{P0} =0.32ns)

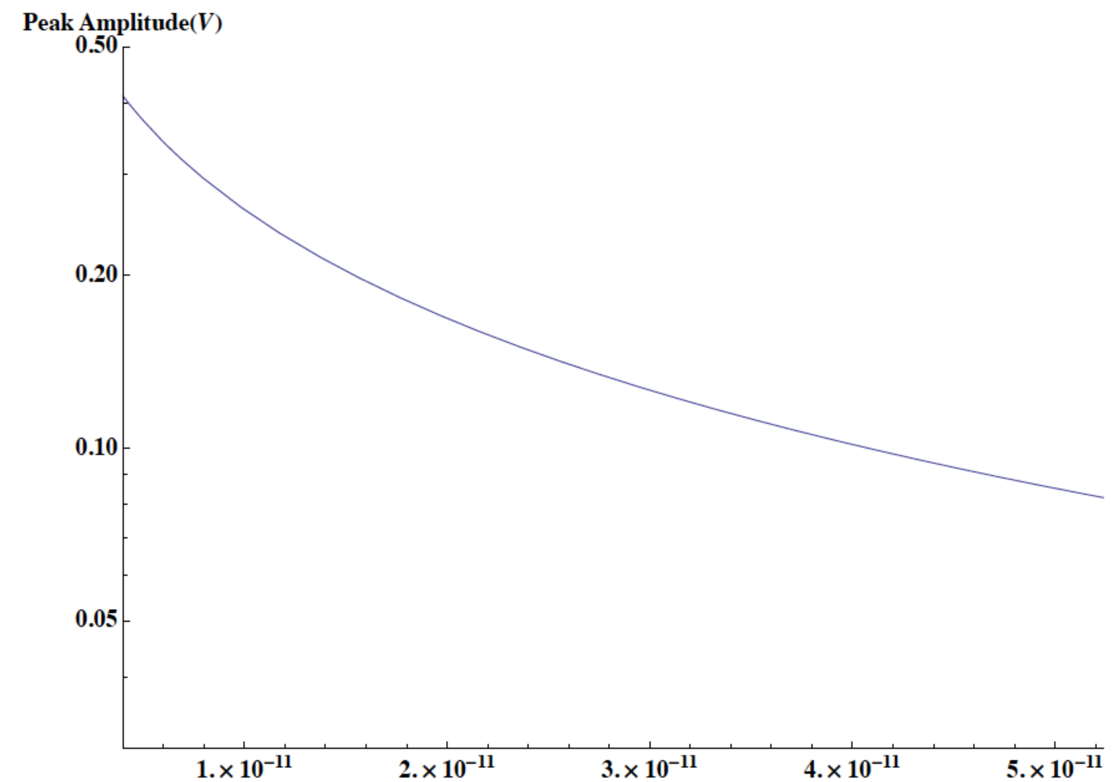
Preamp in charge/transimpedance mode



Assuming high Ku the amplitude response does not depends in first order on c_d.

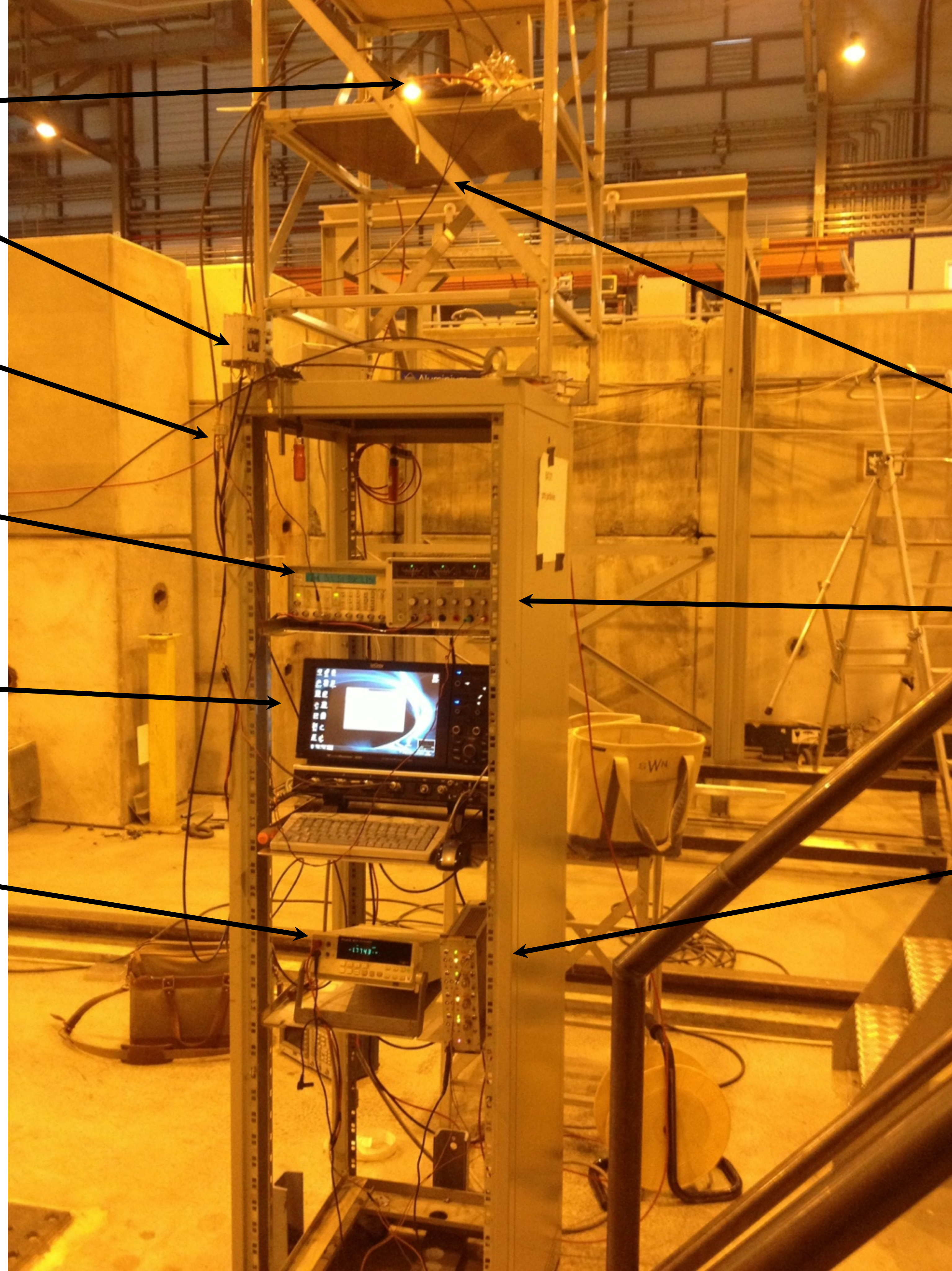
Following slide is simulation of voltage mode case





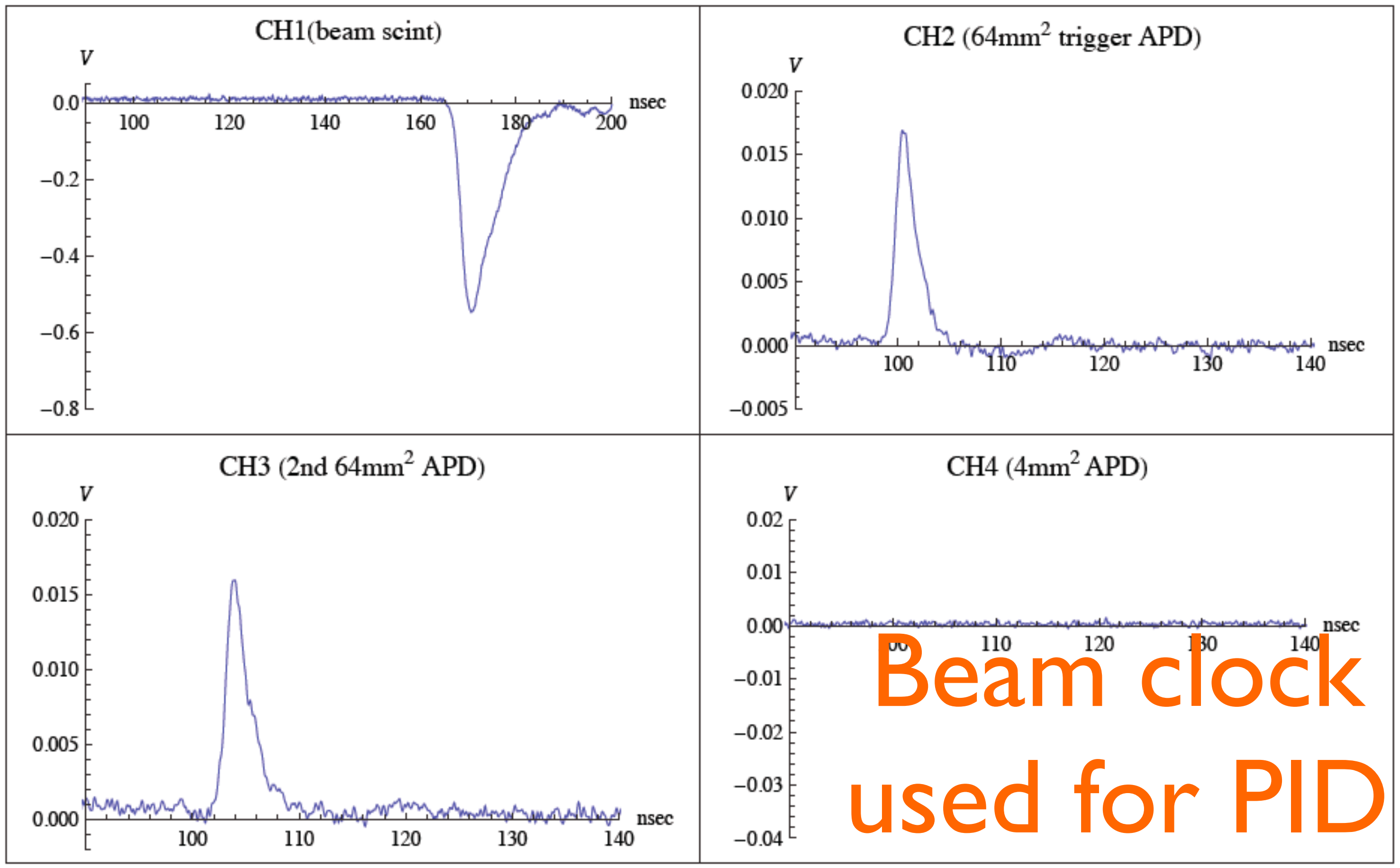
Simulated impulse response

H2 Setup
Feb. ’13



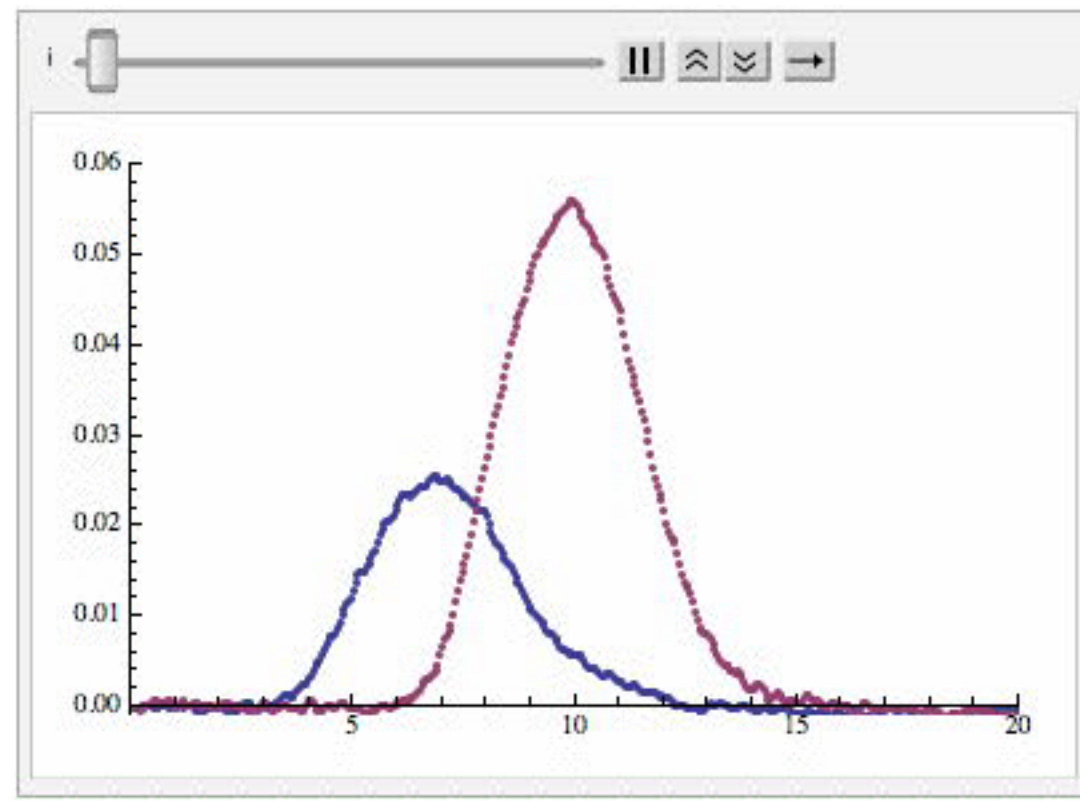
Signal and Noise

beam events: fast <1nsec trise, low statistics



nb:Ch4 is smaller area APD to select sub-class of events in center. Not in trigger.

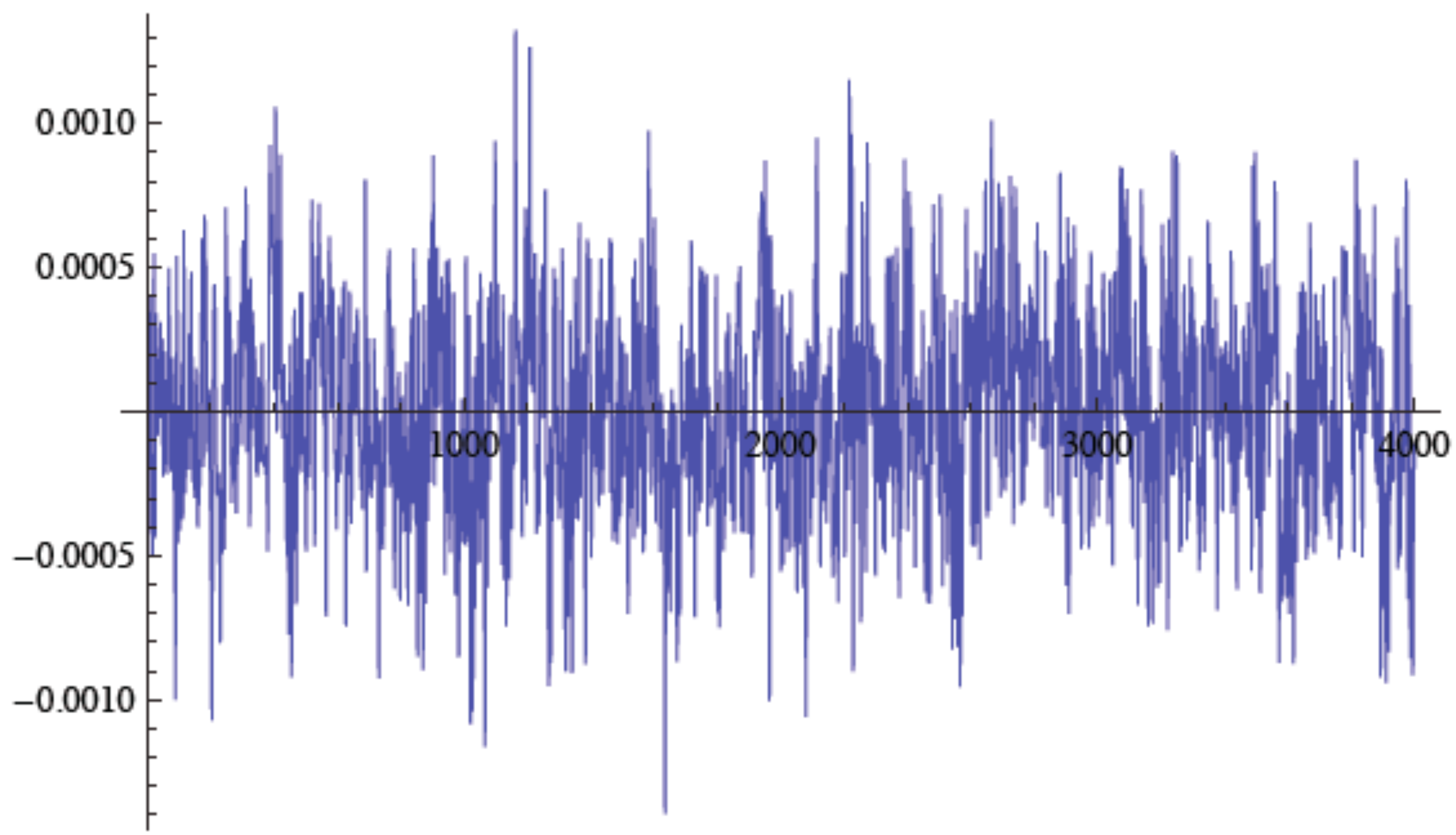
vcsel data: slower (used 6 nsec pulser)



trise~2*MIP events
same noise (digitization)
same amplitude
->predict MIP 2* better
jitter due to baseline subtraction

Observed waverunner Pro noise @2.5GHz, 20 Gsa/s, 10 mV/div-> consistent with specs

Out[1055]=

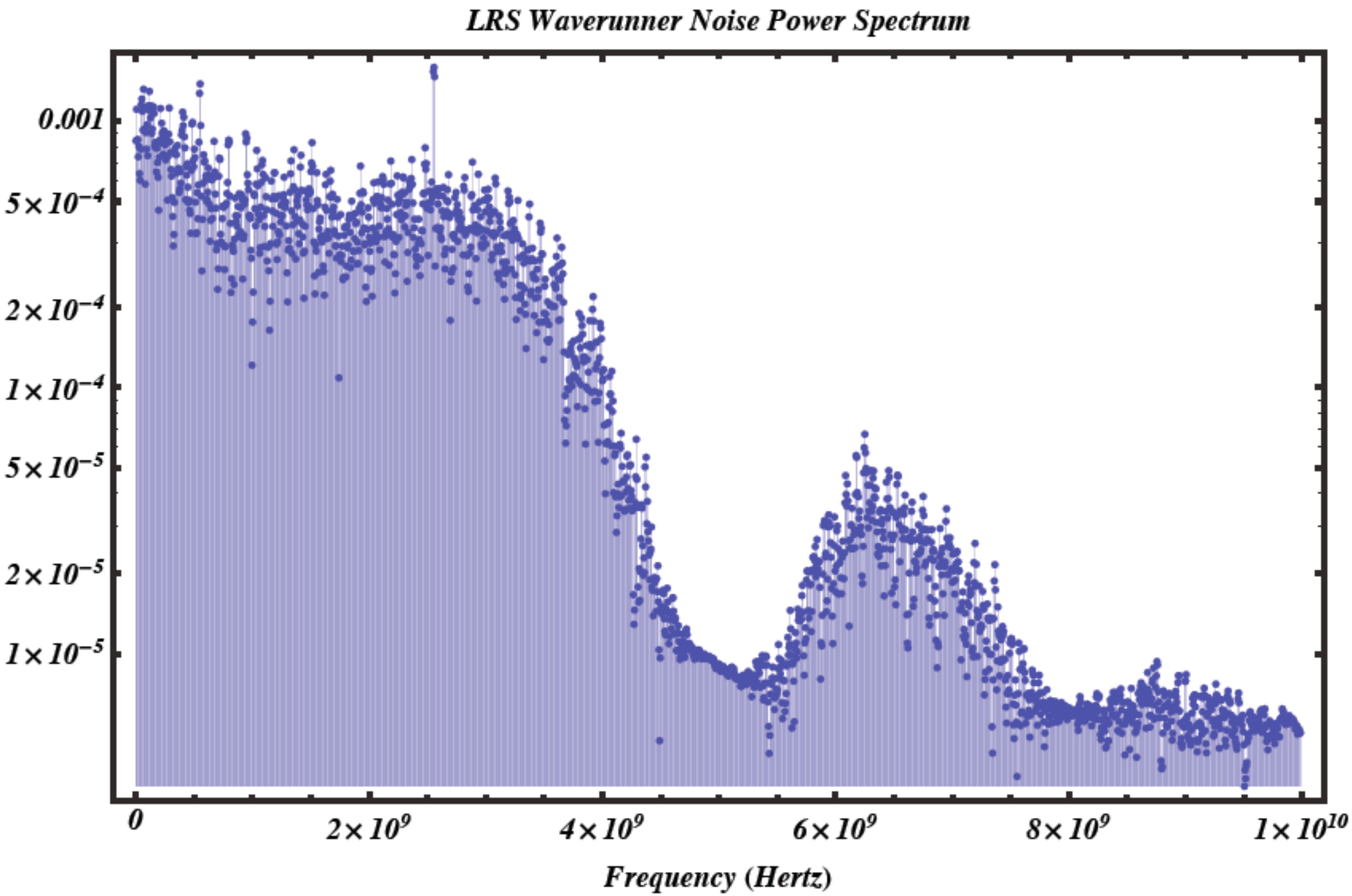


In[1056]:=

```
noiserms = RootMeanSquare[gain];
Print["Noise Level=    ", 1000 * noiserms, " mV RMS"]
```

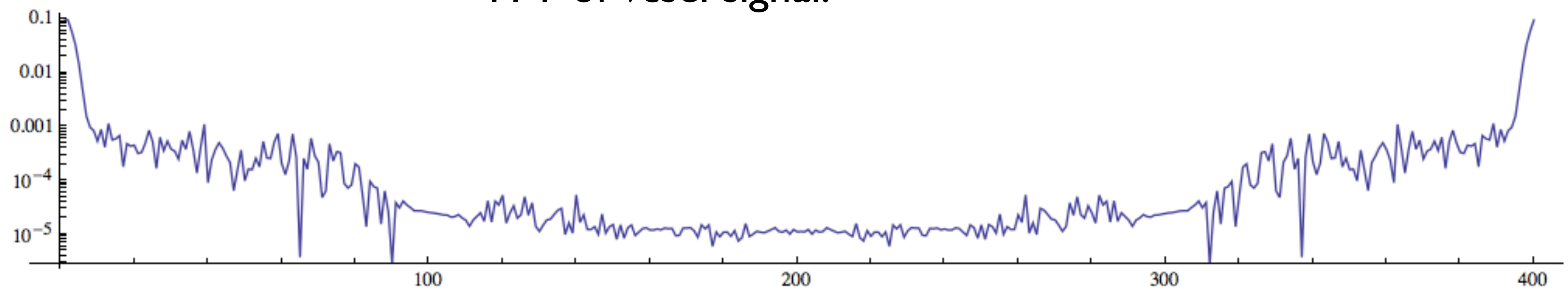
```
Noise Level=    0.351737 mV RMS
```

I did a Fourier Transform of the noise spectrum

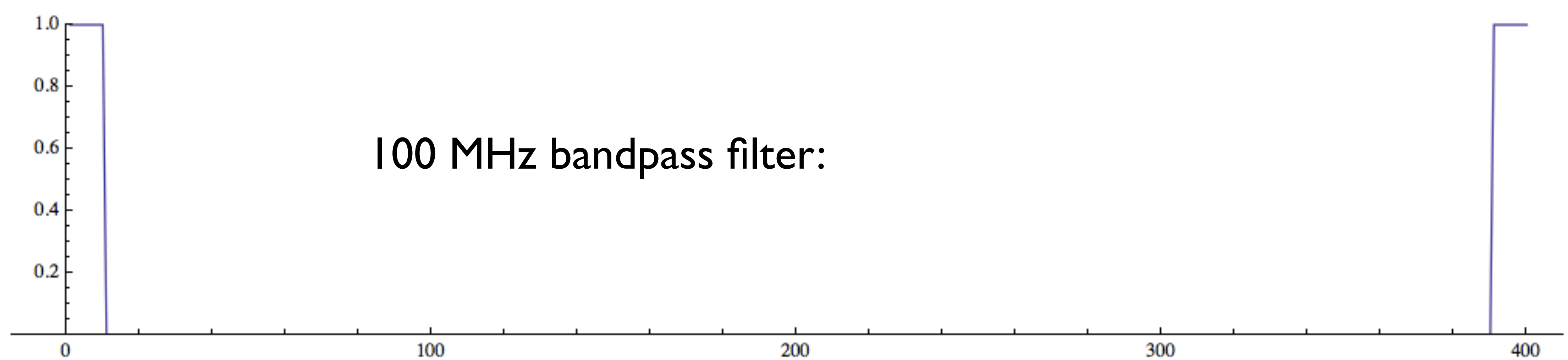


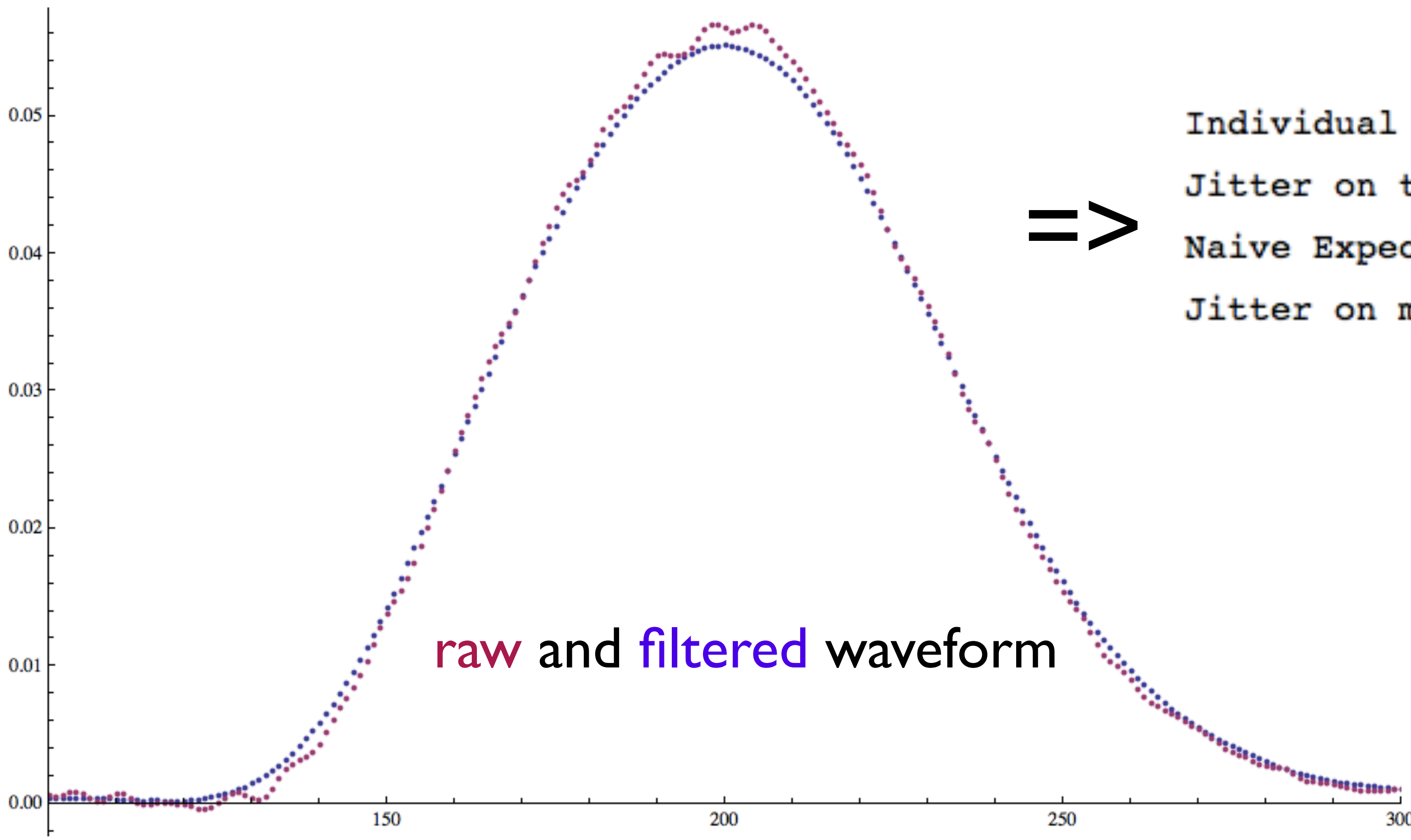
studying a variety of algorithms on vcsel data sets before turning to the MIP data. Optimize on vcsel and apply, without bias to small MIP data set. High statistics data expected in May at PSI. One example below:

FFT of vcsel signal:



100 MHz bandpass filter:



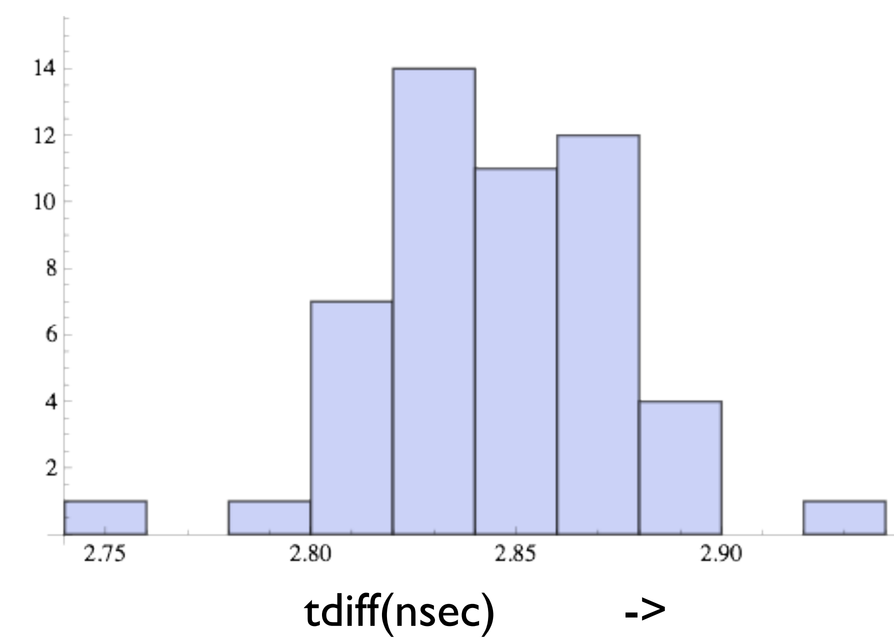


=>

```
Individual channel jitter= 0.0383898 and 0.0382536 nanosec
Jitter on time difference= 0.0345567 nanosec
Naive Expectation from Noise= 0.038779nanosec
Jitter on mixed events= 0.060214 nanosec
```

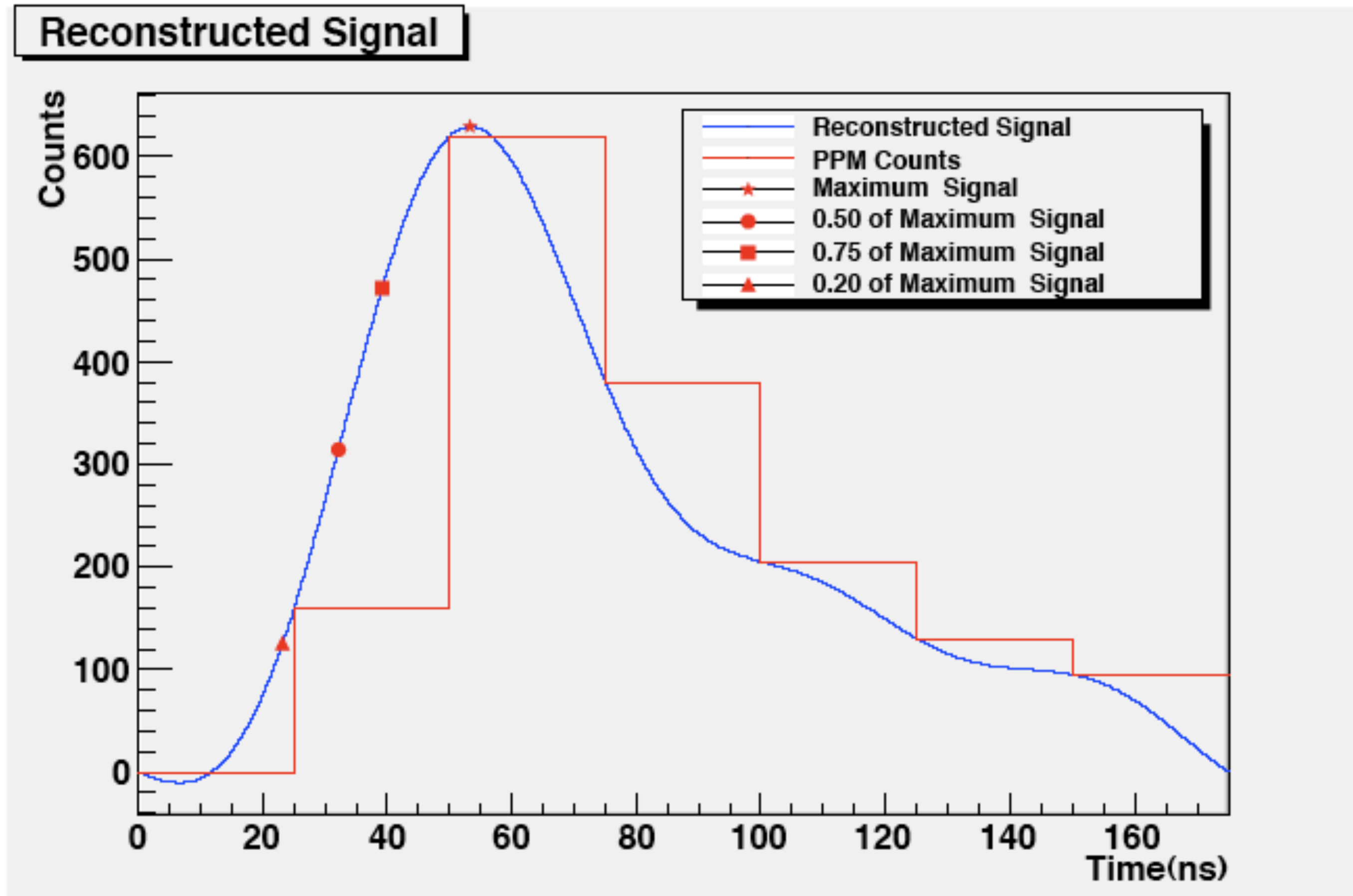
some improvement timing on centroid rather than CF

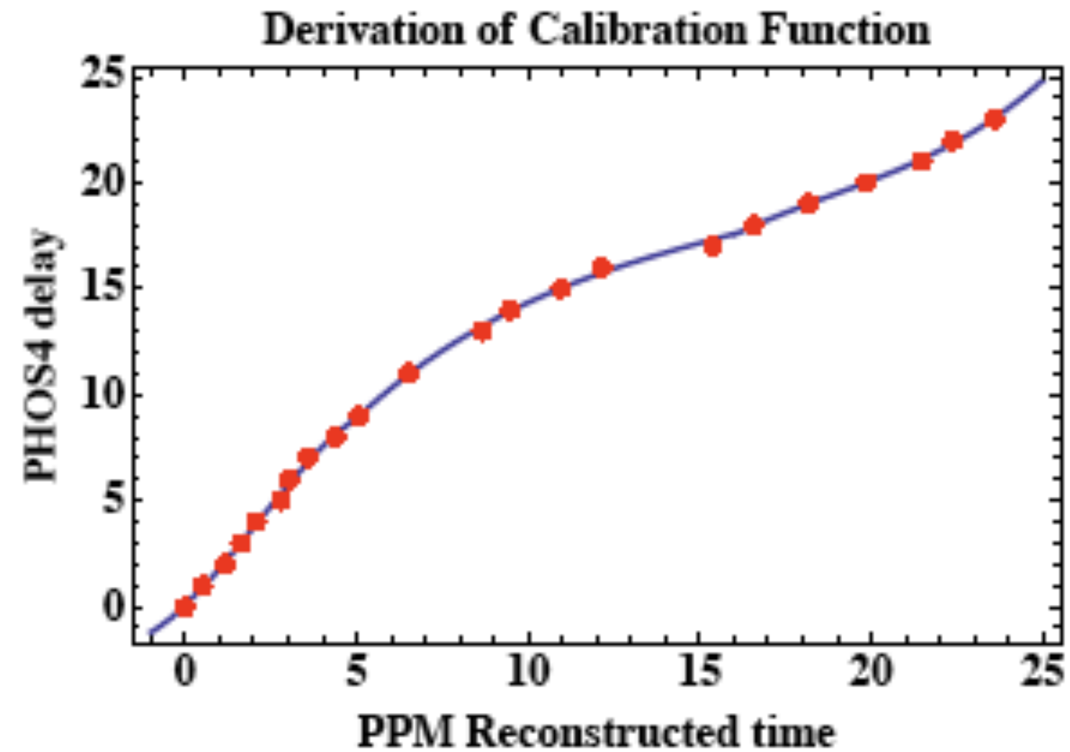
=>



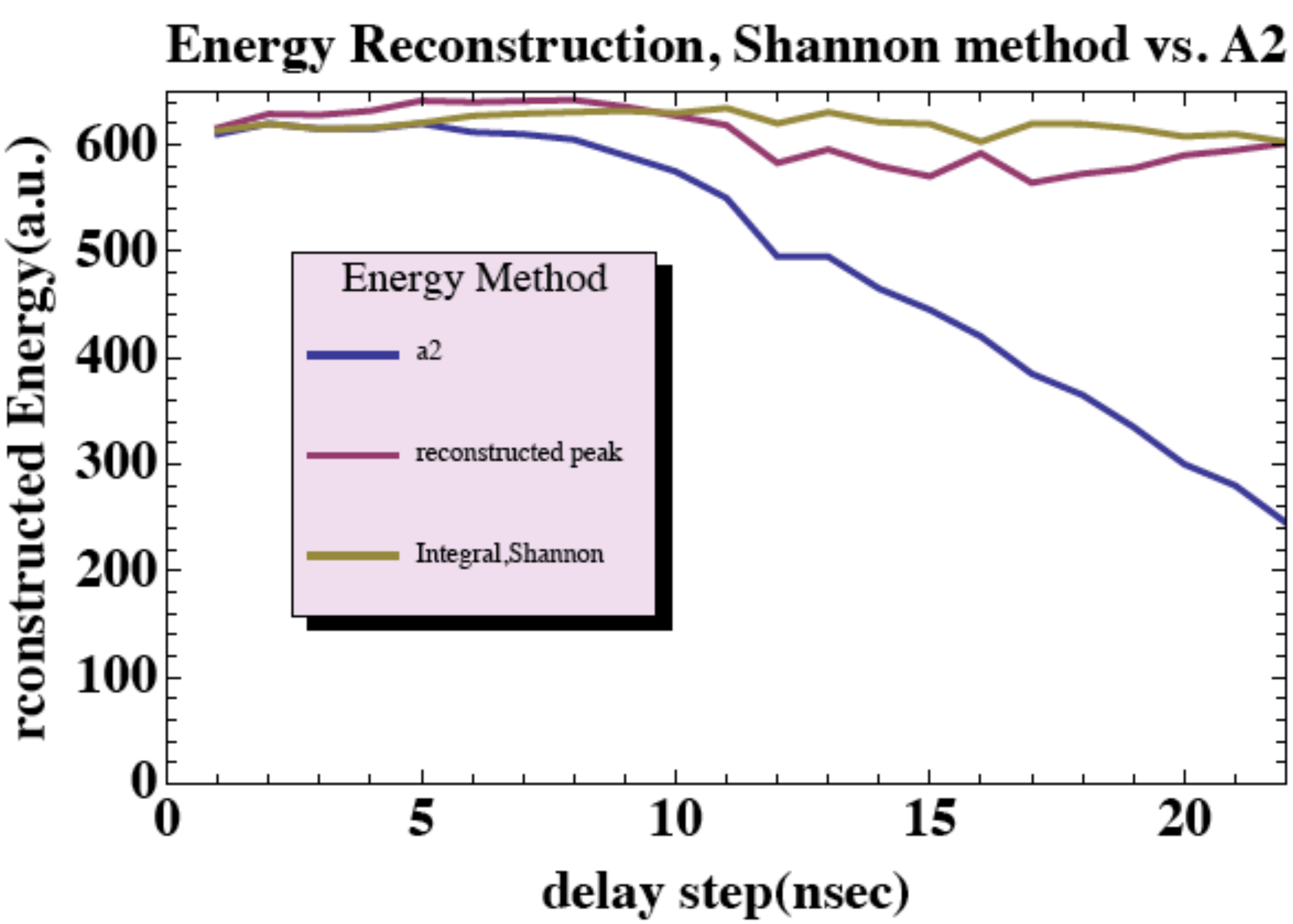
ie 30 picosec on tdiff with vcsel, implying 10 picosec res on single APD for MIP

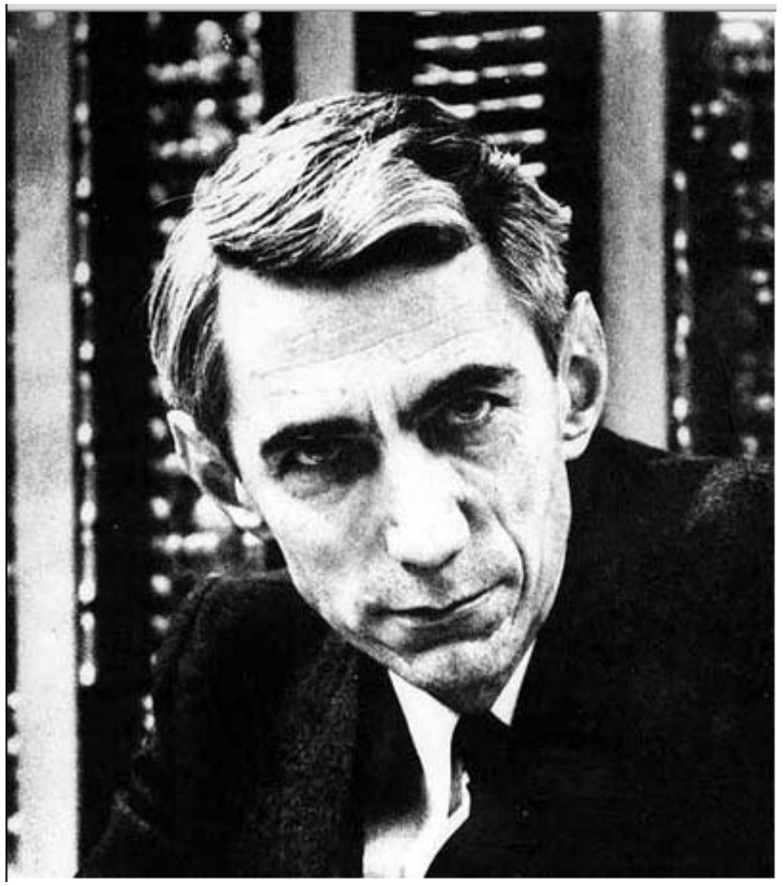
(More detailed discussion of methodology for ZDC timing on arxiv.)





(d) Piecewise fit to the full range.





Optimal reconstruction of sparsely sampled ZDC waveforms

* resulted in Shannon's 1940 PhD thesis at MIT, *An Algebra for Theoretical Genetics*[6]

* Victor Shestakov, at Moscow State University, had proposed a theory of electric switches based on Boolean logic a little bit earlier than Shannon, in 1935, but the first publication of Shestakov's result took place in 1941, after the publication of Shannon's thesis.

* The theorem is commonly called the **Nyquist sampling theorem**, and is also known as **Nyquist–Shannon–Kotelnikov**, **Whittaker–Shannon–Kotelnikov**, **Whittaker–Nyquist–Kotelnikov–Shannon**, **WKS**, etc., sampling theorem, as well as the **Cardinal Theorem of Interpolation Theory**. It is often referred to as simply ***the sampling theorem***.

* The theoretical rigor of Shannon's work completely replaced the *ad hoc* methods that had previously prevailed.

* Shannon and Turing met every day at teatime in the cafeteria.[8] Turing showed Shannon his seminal 1936 paper that defined what is now known as the "Universal Turing machine"[9][10] which impressed him, as many of its ideas were complementary to his own.

* He is also considered the co-inventor of the first wearable computer along with Edward O. Thorp.[16] The device was used to improve the odds when playing roulette.

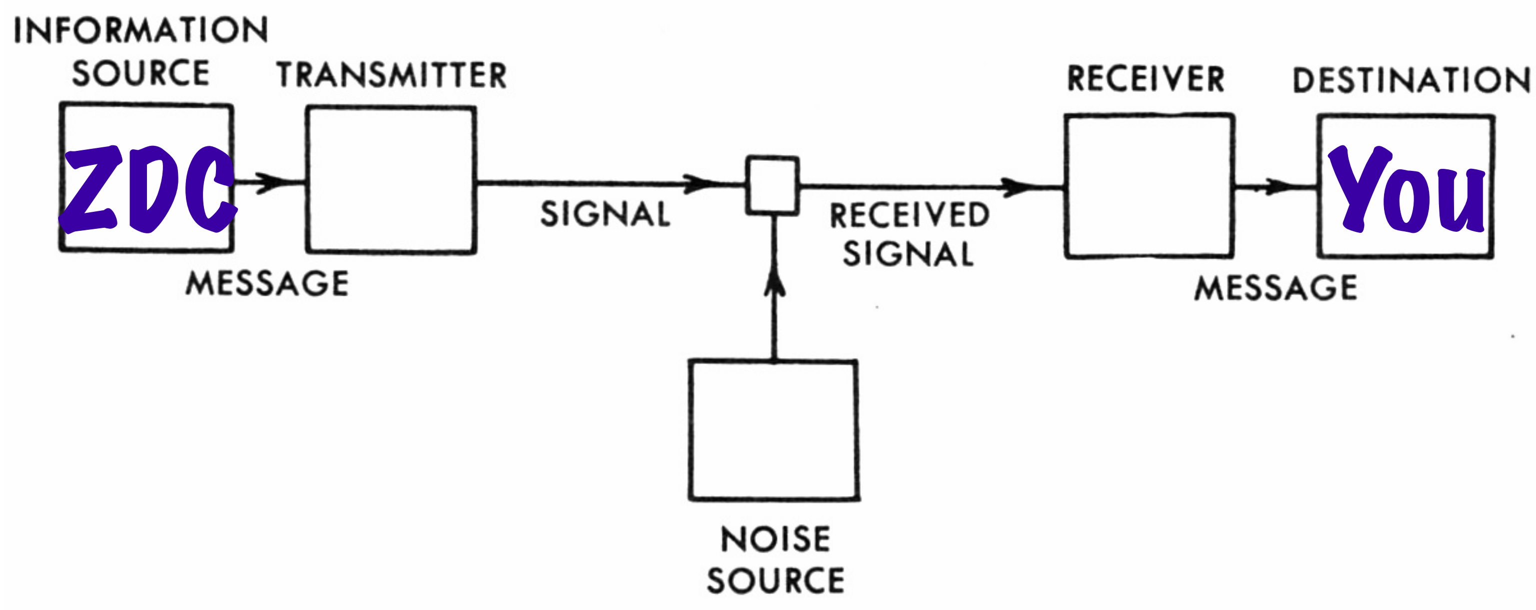
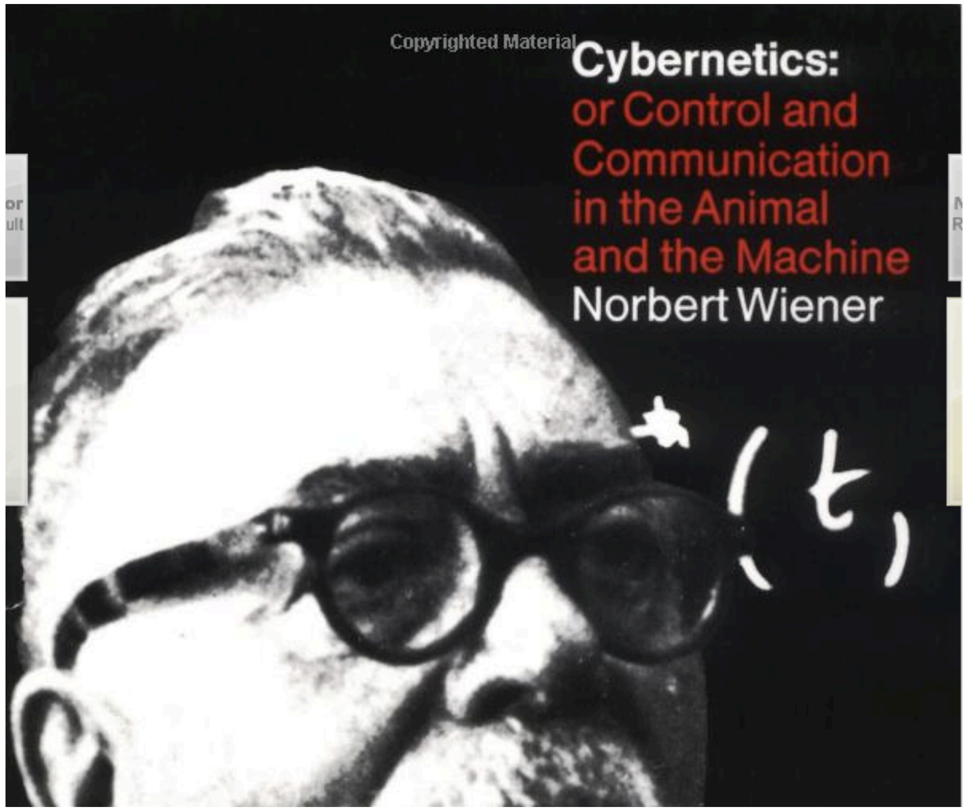
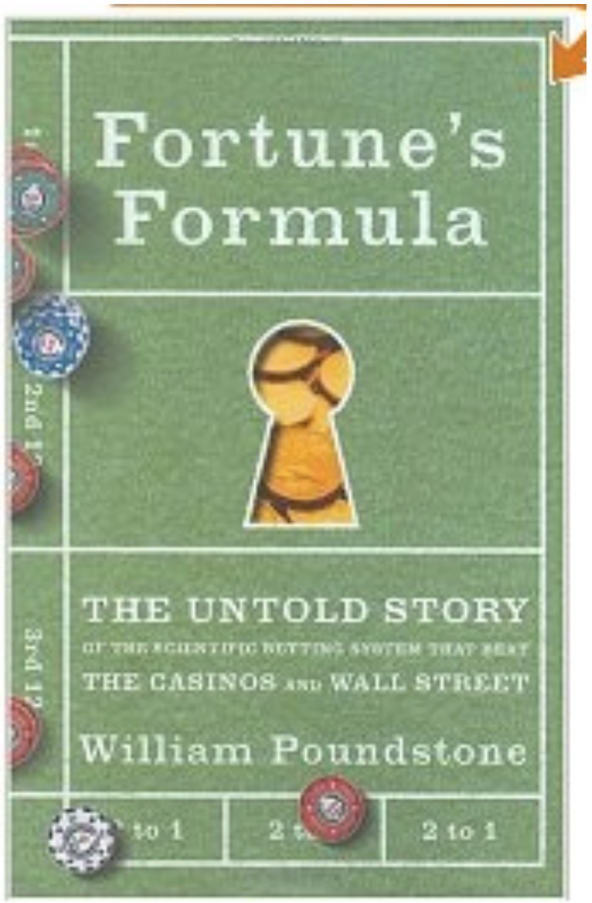


Fig. 1.—Schematic diagram of a general communication system.

books about Shannon:



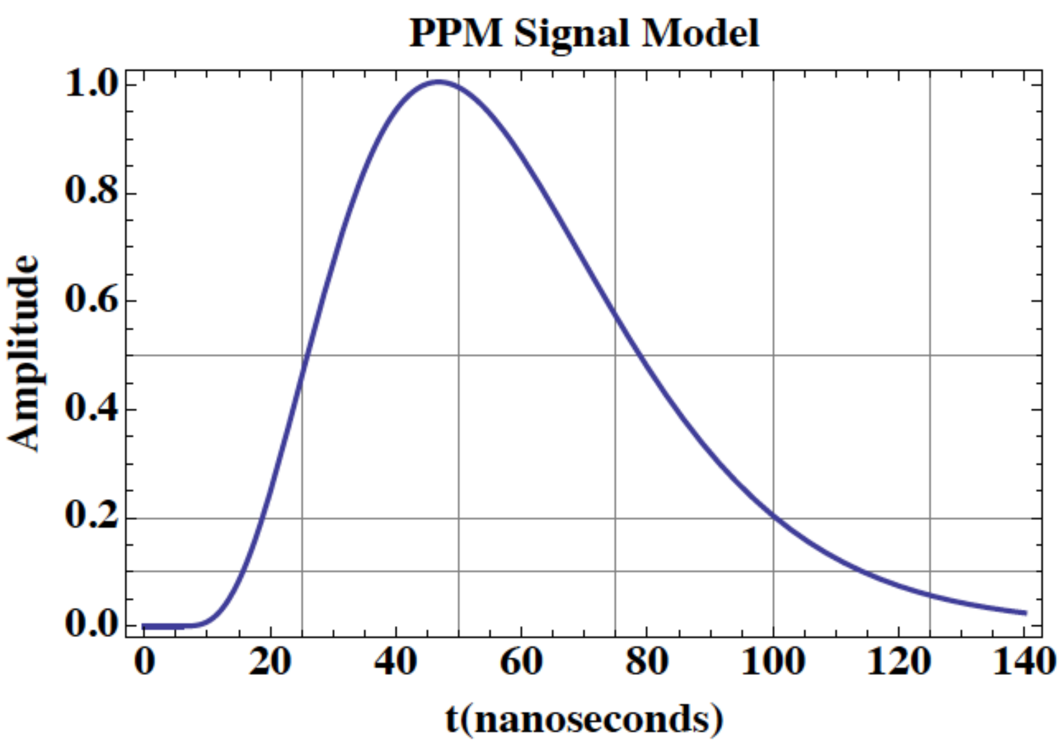


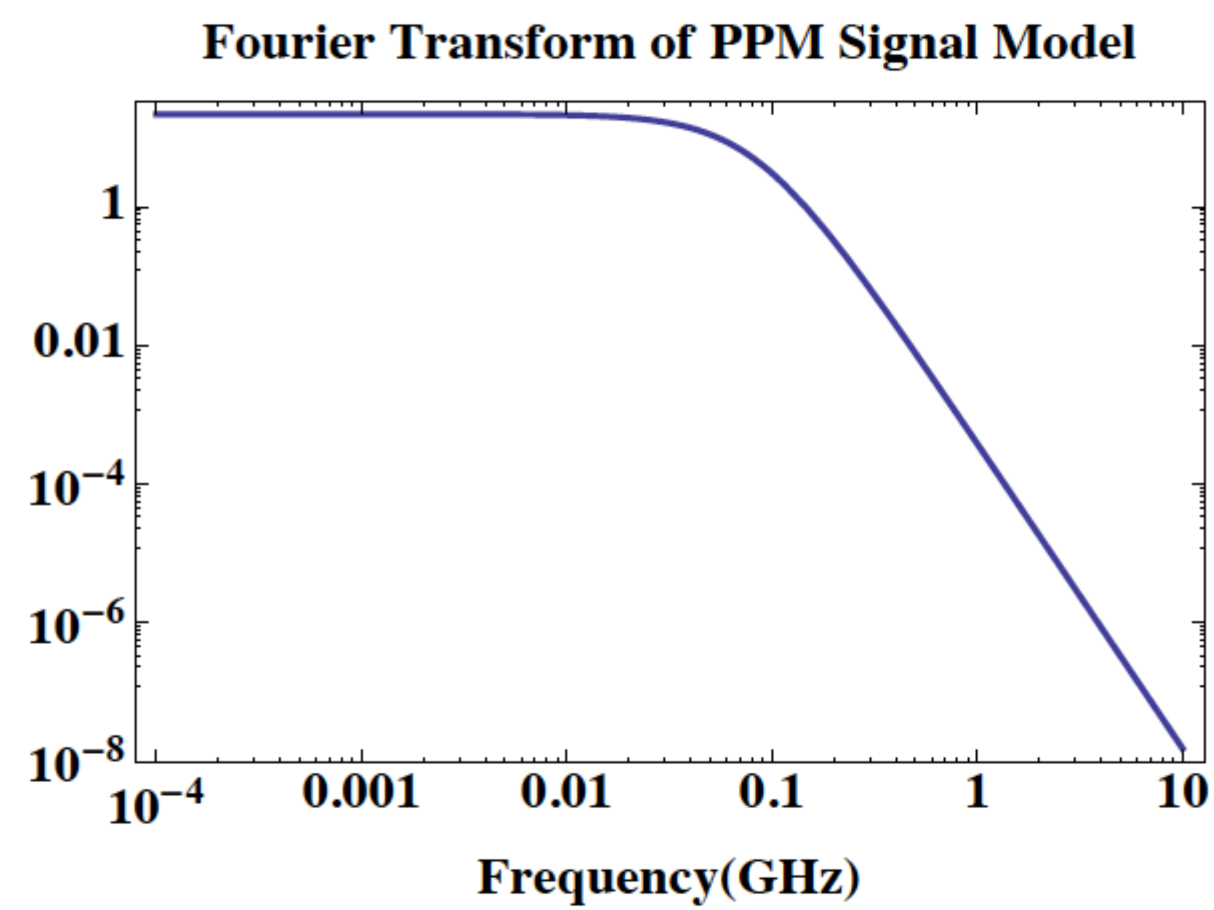
In 1956 two Bell Labs scientists discovered the scientific formula for getting rich. One was the mathematician Claude Shannon, neurotic father of our digital age, whose genius is ranked with Einstein's. The other was John L. Kelly, Jr., a gun-toting Texas-born physicist. Together they applied the science of information theory—the basis of computers and the Internet—to the problem of making as much money as possible, as fast as possible. Shannon and MIT mathematician Edward O. Thorp took the "Kelly formula" to the roulette and blackjack tables of Las Vegas. It worked. They realized that there was even more money to be made in the stock market, specifically in the risky trading known as arbitrage. Thorp used the Kelly system with his phenomenally successful hedge fund Princeton-Newport Partners. Shannon became a successful investor, too, topping even Warren Buffett's rate of return and

no time to discuss Shannon's method for getting rich

will discuss Shannon's method for reconstructing digitized waveforms

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>

$$shannon[t] = \sum_{i=1}^{nslice} slice[i] \times Sinc[\pi \times (t - time(i))/25] \qquad (6)$$

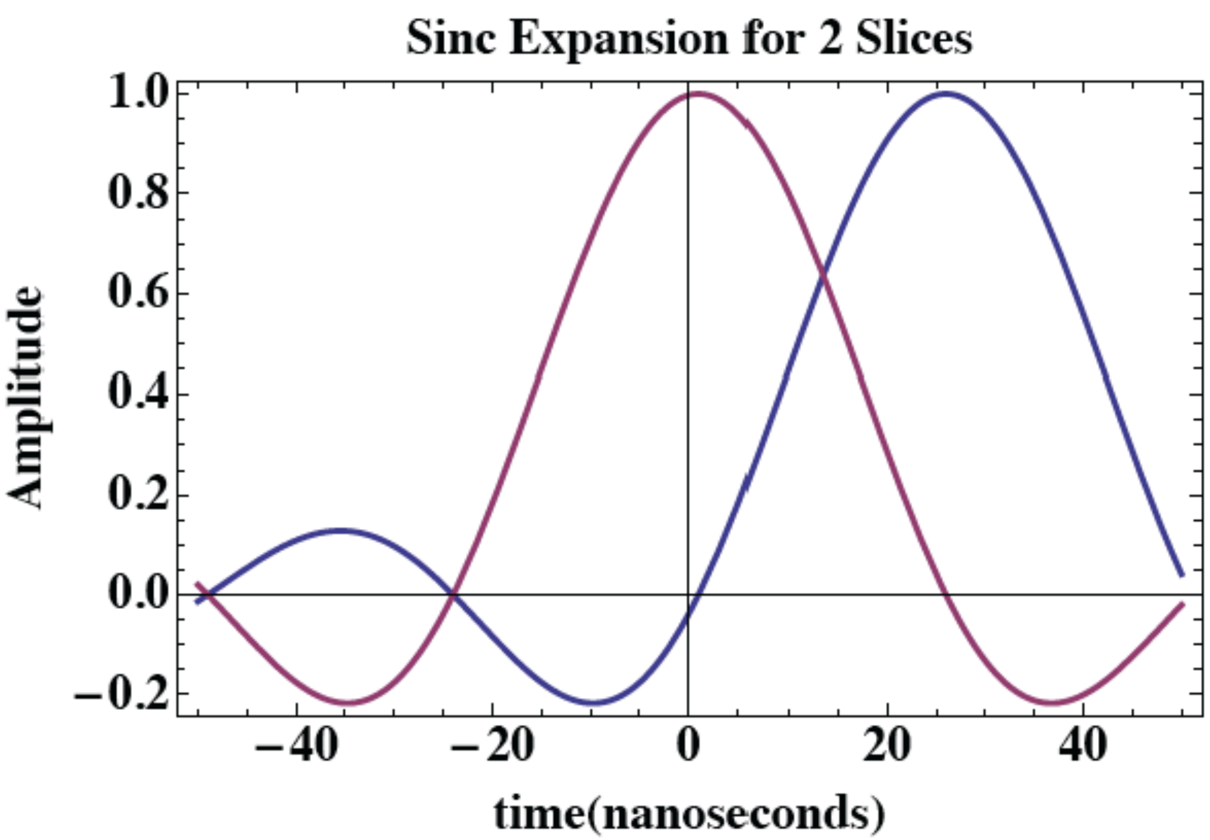
An animated gif can be found at:
http://www.phenix.bnl.gov/phenix/WWW/publish/swhite/ShannonFilm.gif

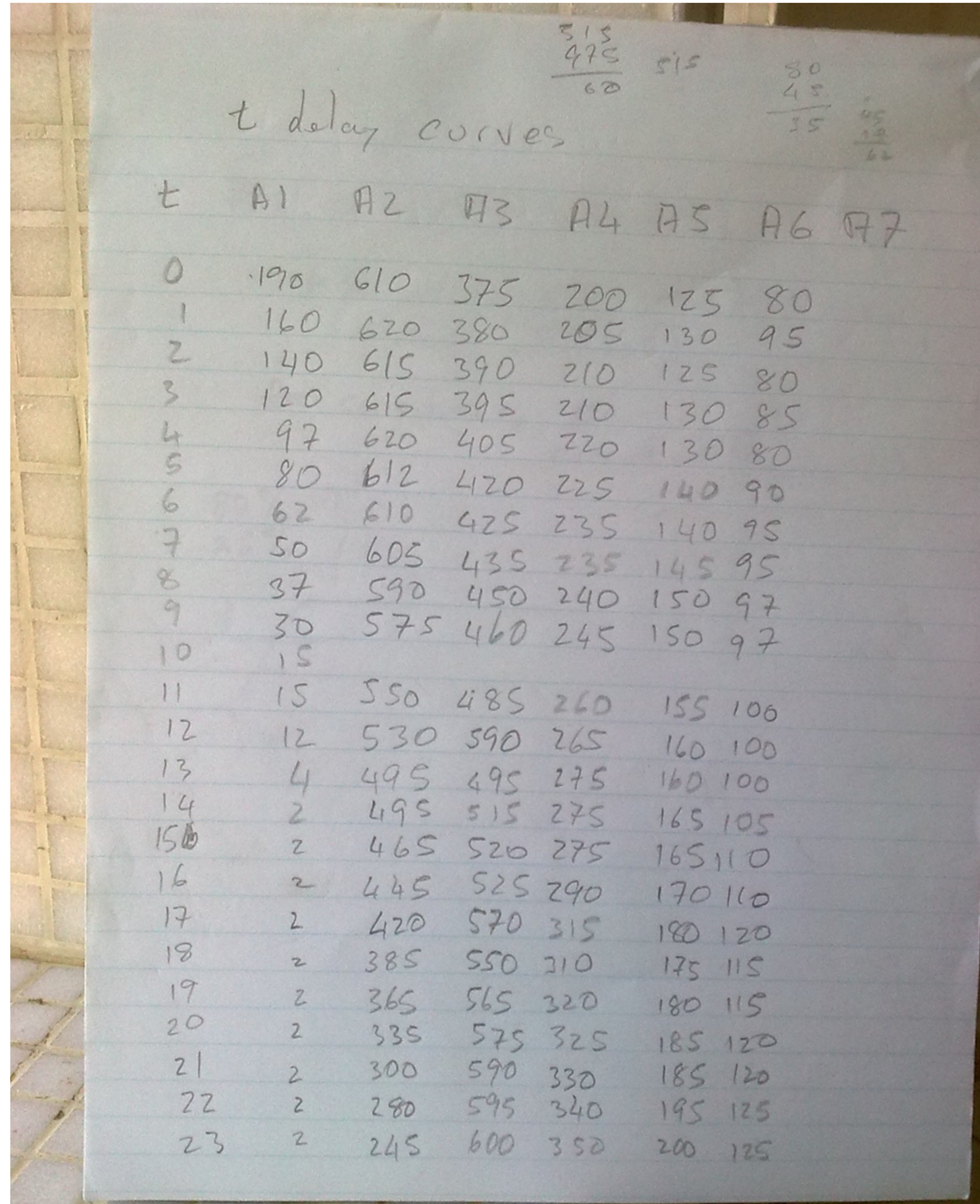
ATLAS data set used to develop ZDC reconstruction and do L1calo calibration (in Mathematica 7.0)

Reconstruction of ZDC Pre-Processor Data and its timing Calibration

Soumya Mohapatra, Andrei Poblaguev and Sebastian White

Aug.8,2010





515
475
60

515

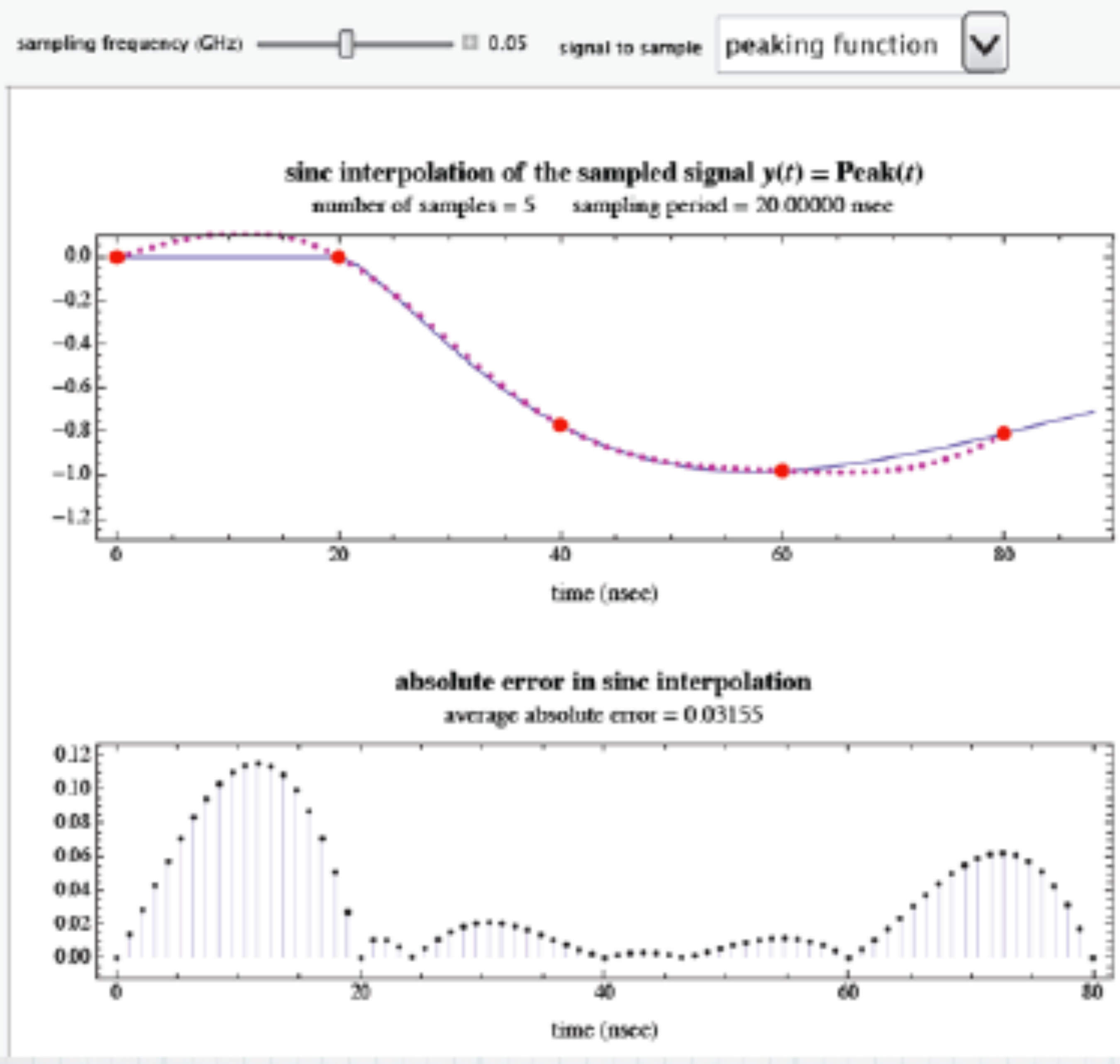
80
45
35

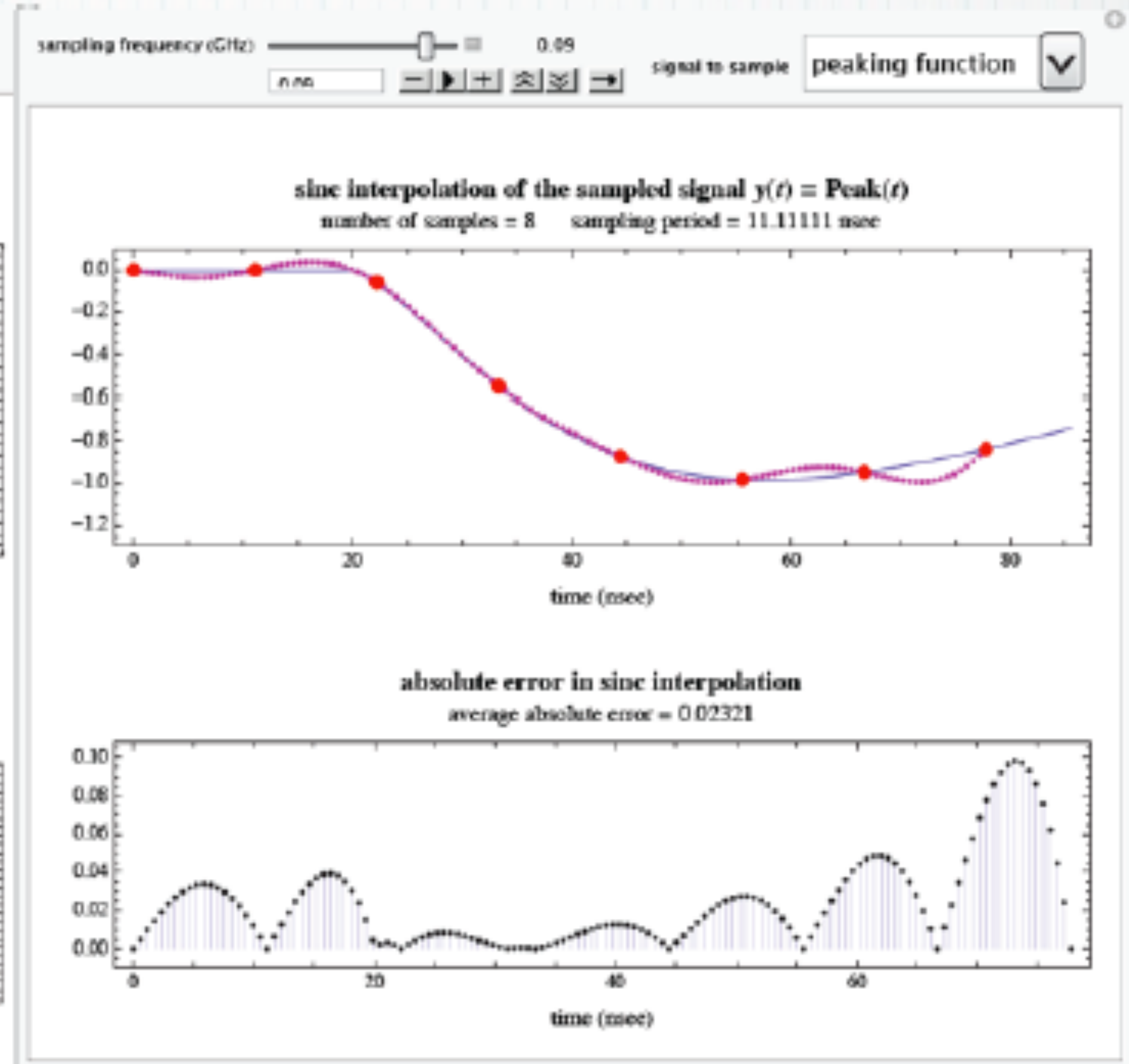
t delay curves

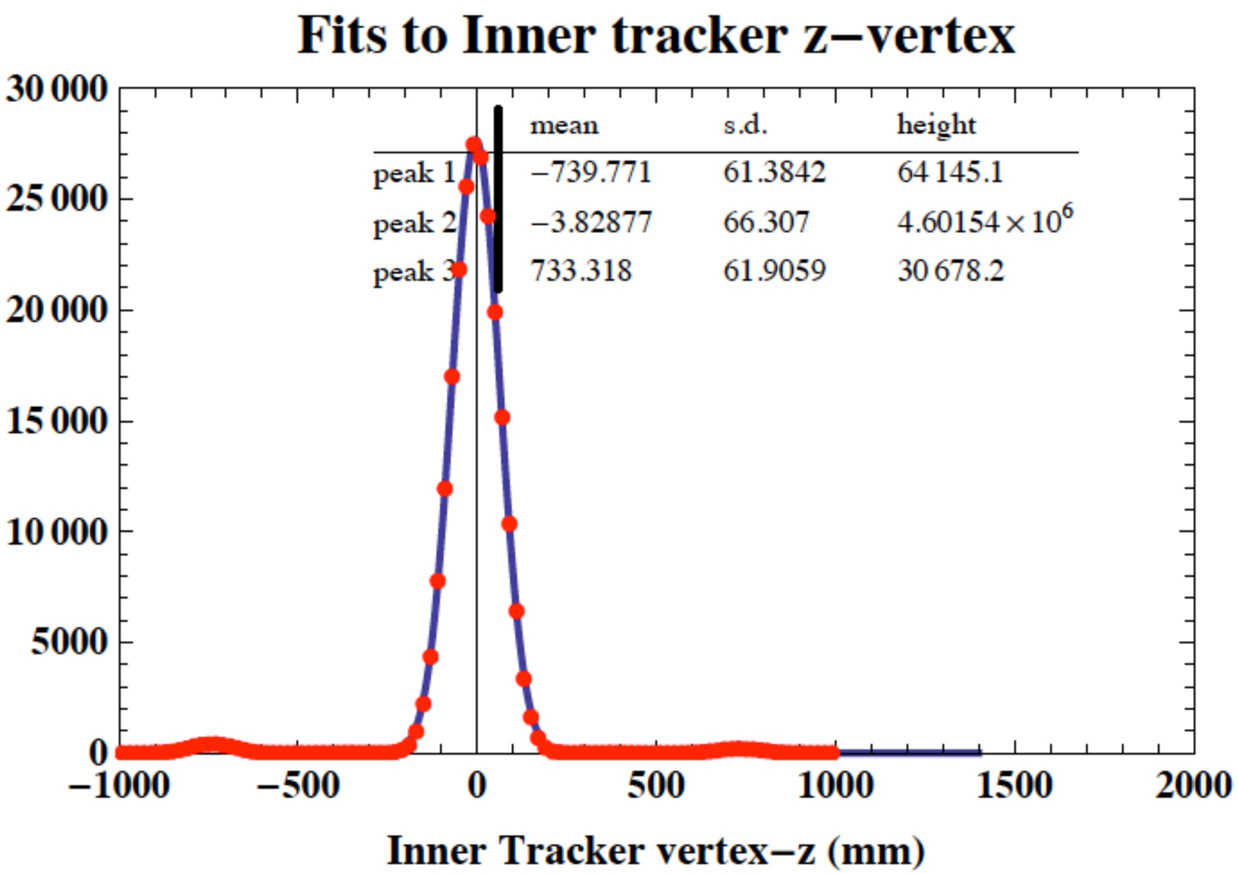
t	A1	A2	A3	A4	A5	A6	A7
0	·190	610	375	200	125	80	
1	160	620	380	205	130	95	
2	140	615	390	210	125	80	
3	120	615	395	210	130	85	
4	97	620	405	220	130	80	
5	80	612	420	225	140	90	
6	62	610	425	235	140	95	
7	50	605	435	235	145	95	
8	37	590	450	240	150	97	
9	30	575	460	245	150	97	
10	15						
11	15	550	485	260	155	100	
12	12	530	590	265	160	100	
13	4	495	495	275	160	100	
14	2	495	515	275	165	105	
15	2	465	520	275	165	110	
16	2	445	525	290	170	110	
17	2	420	570	315	180	120	
18	2	385	550	310	175	115	
19	2	365	565	320	180	115	
20	2	335	575	325	185	120	
21	2	300	590	330	185	120	
22	2	280	595	340	195	125	
23	2	245	600	350	200	125	

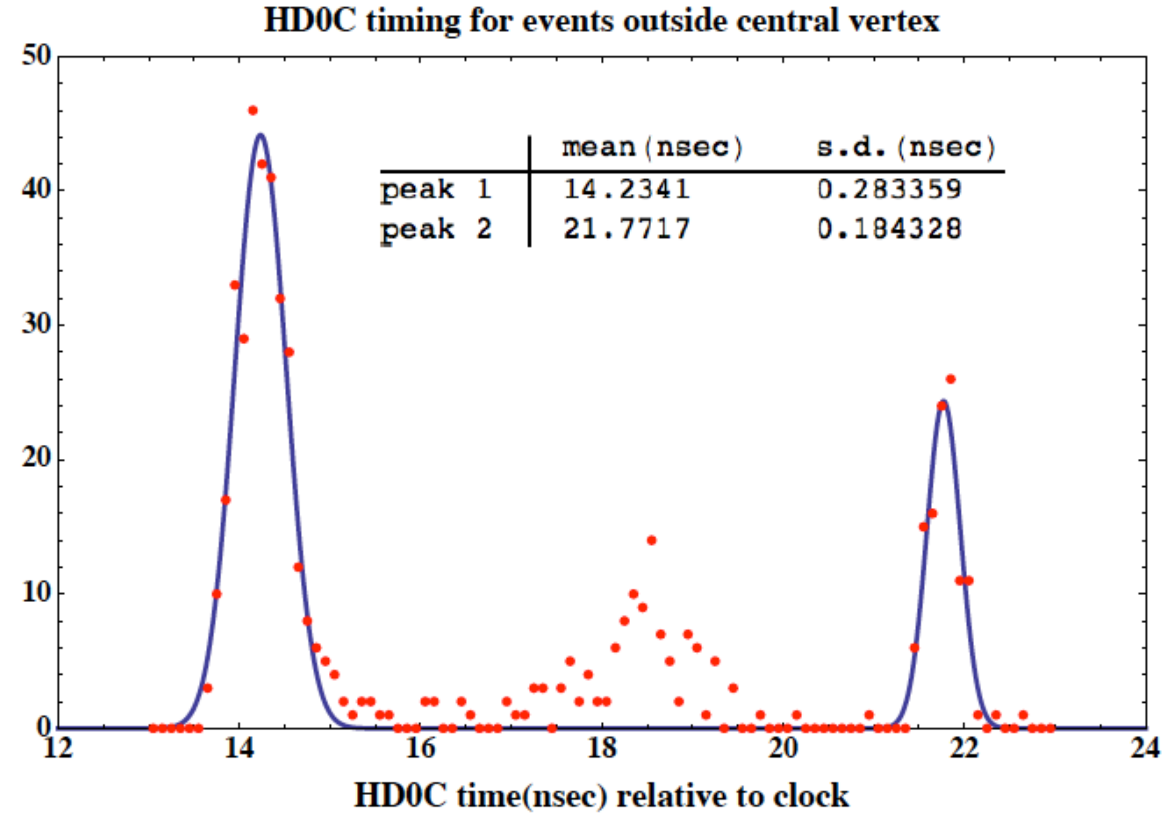
Signal Reconstruction

The document ATL-COM-LUM-2010-027
Title: Reconstruction of ZDC Pre-Processor Data and its timing Calibration
Author(s): Mohapatra, S :SUNYSB
Poblaguev, A :Yale:BNL
White, S :BNL

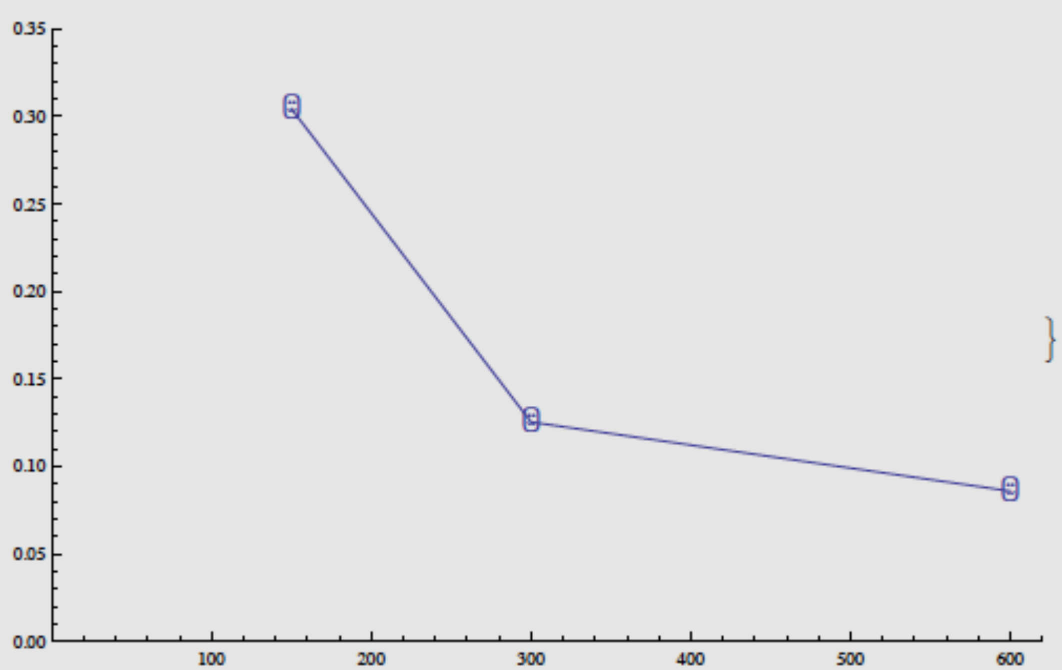








	mean (nsec)	rms
ZDC_EMA	23.4269	0.161383
ZDC_EMA_100-200	23.4313	0.304363
ZDC_EMA_200-400	23.4084	0.125345
ZDC_EMA_400-800	23.4356	0.0859118



simple test of energy dependence

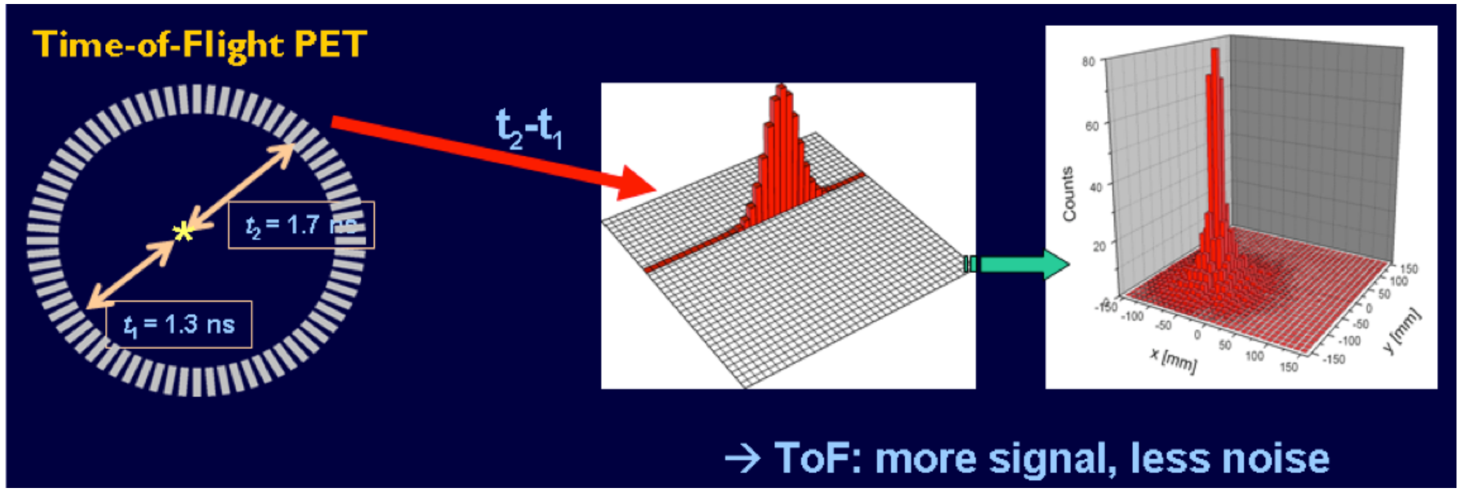
Fast Timing in Brain Imaging

"detector-centric" objective

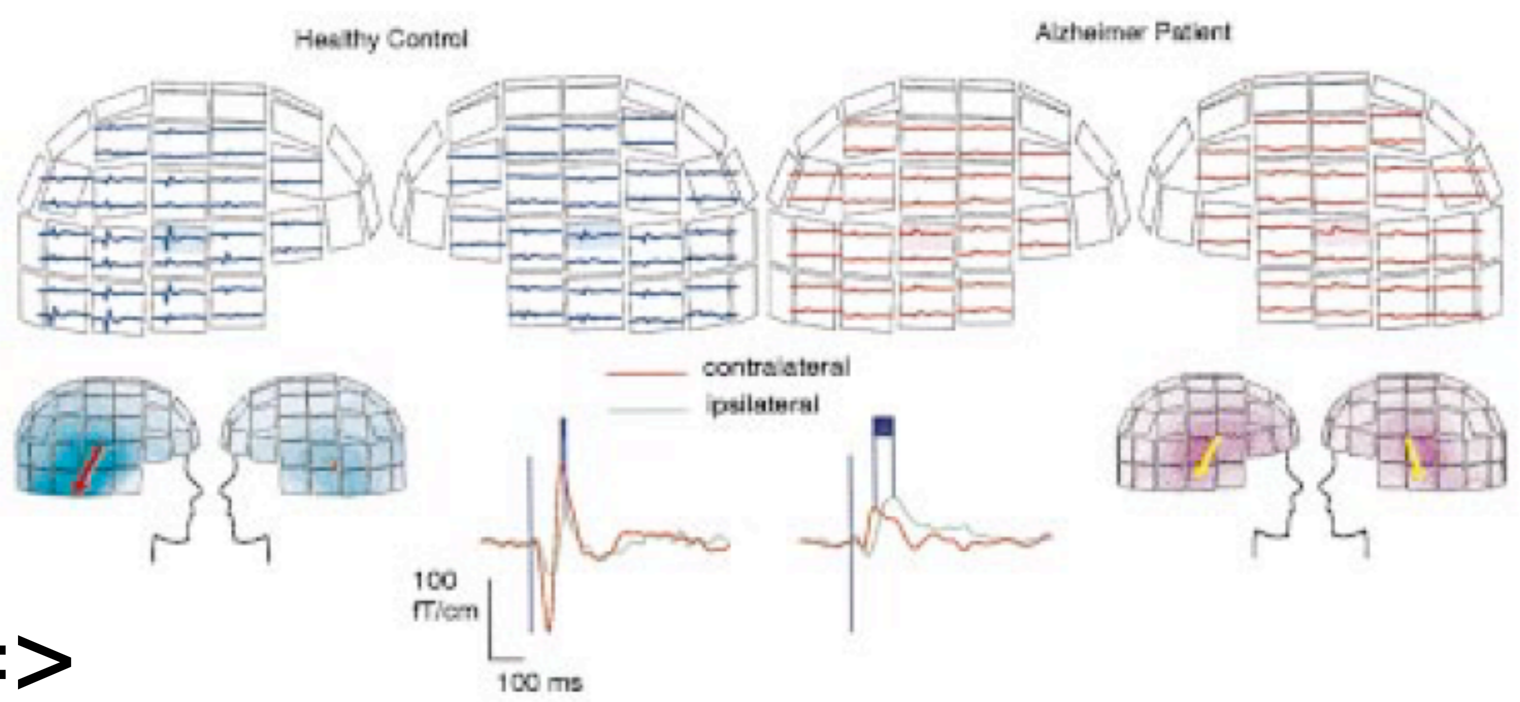
->EU "Picosec" initiative but

- 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

=>



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



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.

=>

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.