The Role of Timing at Hi-Lum LHC+Lessons from ATLAS ZDC
QCD@Cosmic Energies, Paris May14, 2013

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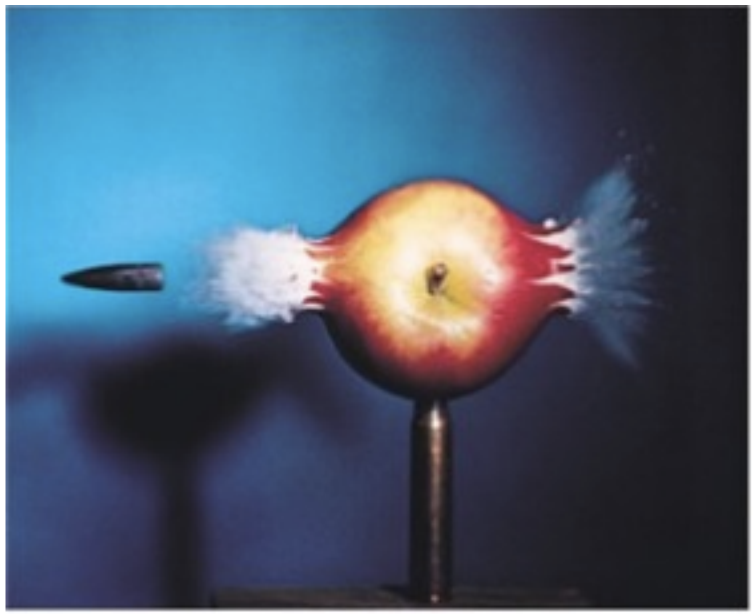


nb: not meant to be an official upgrade talk from a particular experiment although I work in the CMS Forward Calorimeter Task Force group. It does draw on results from:

>PHENIX EMCAL and ATLAS Zero Degree Calorimeter (I was Project Leader on both and both achieved calorimeter time resolution <100picosec).

>"Single Electron Project"- Active ATF Experiment, I'm co-spokesman with K. McDonald

>DOE Advanced Detector R&D-"Fast Timing Detectors for High-Rate Environments" with ""

>BNL ATF Experiment AE-55

>time too limited to talk in detail about our work (see several presentations on web-RD51,RD52,etc.)

The Challenge

January Update to European Strategy for Particle Physics:

"*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. "*

This Priority not surprising and probably consistent w. US Energy Frontier priority but:

-it limits the available phase space for discovery physics at an ILC

-it is not clear what detector configurations could deal with the new levels radiation load and event pileup (Integrated L ~3000fb^-1 and mu ~100-200 events/crossing).

There's a 20 year history of R&D addressing detector rad damage(Si displacement damage from NIEL, Scintillator and WLS attenuation, electronics rad hardness, etc).

-no similar program of R&D on pileup mitigation up to now (we're perhaps the only DOE funded activity).

-some (unofficial) sentiment that pileup has reduced flexibility/efficiency in Higgs analyses- especially when kinematic cuts on "rest of event" applied). Much worse in hi-lum.

-"We are running out of bullets. It's time to get a new gun"- J. Butler

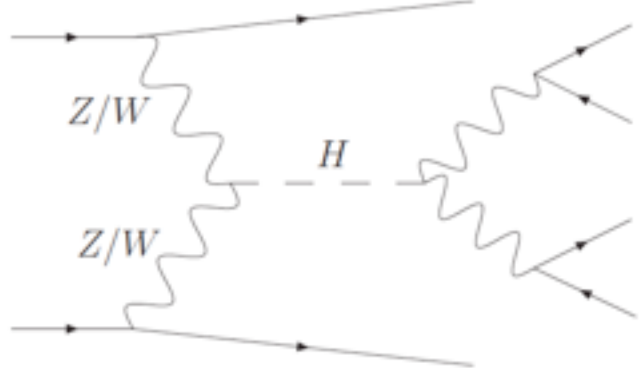
the Challenge (2)

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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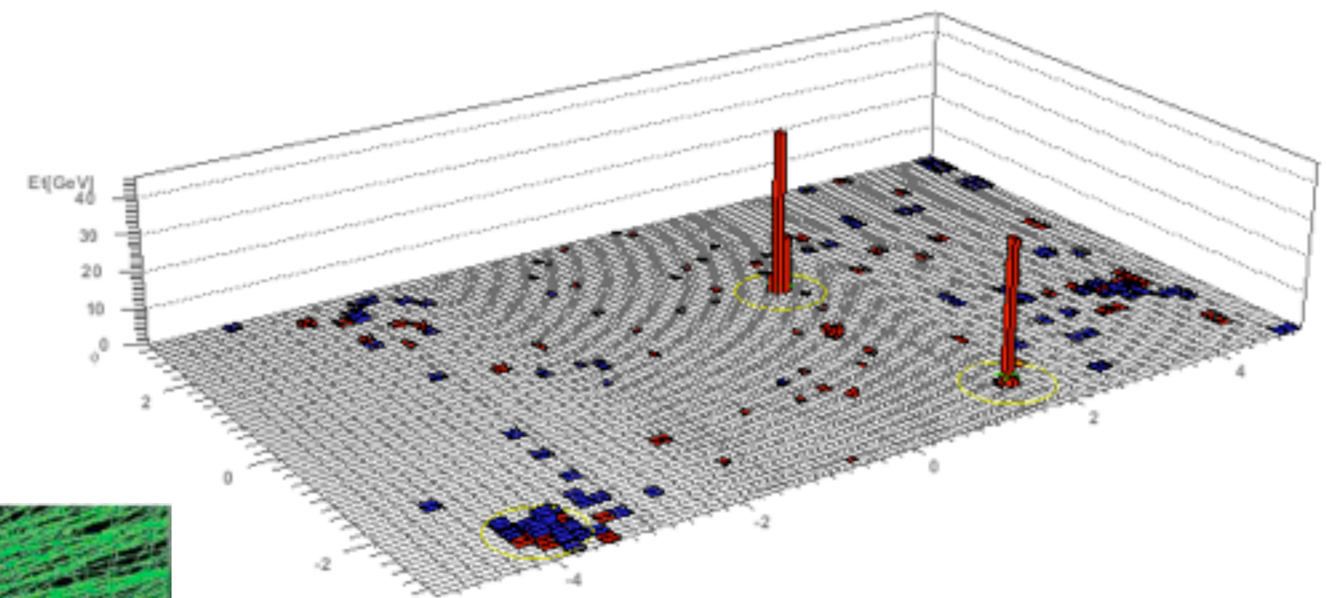
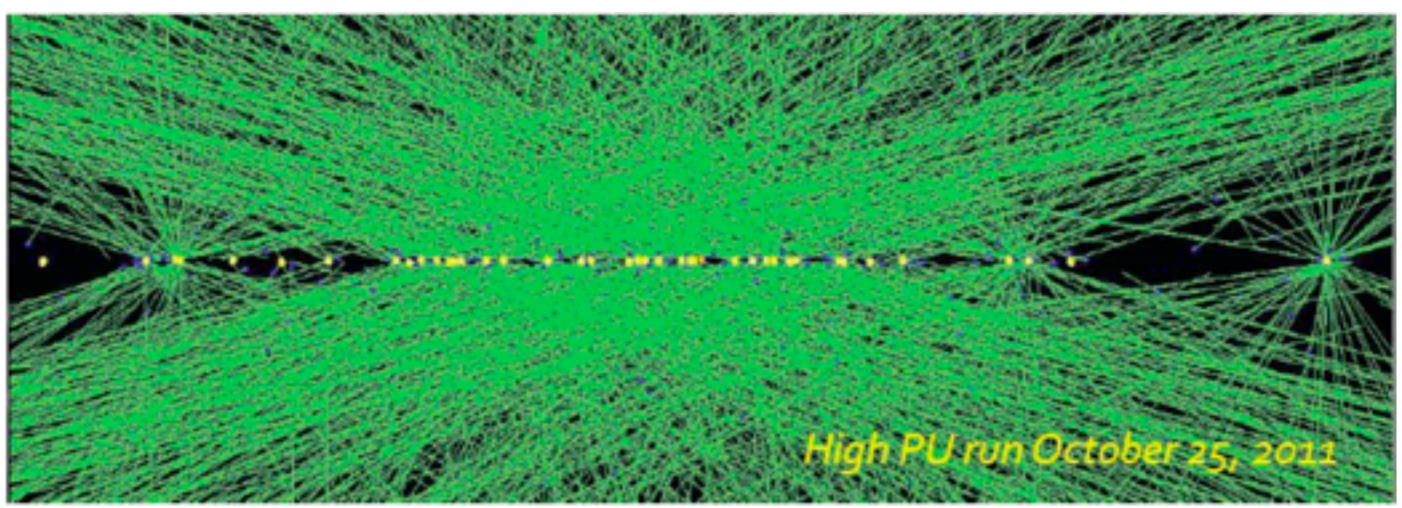




in above Higgs->2 gamma and proton jet fragments observed very forward region

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

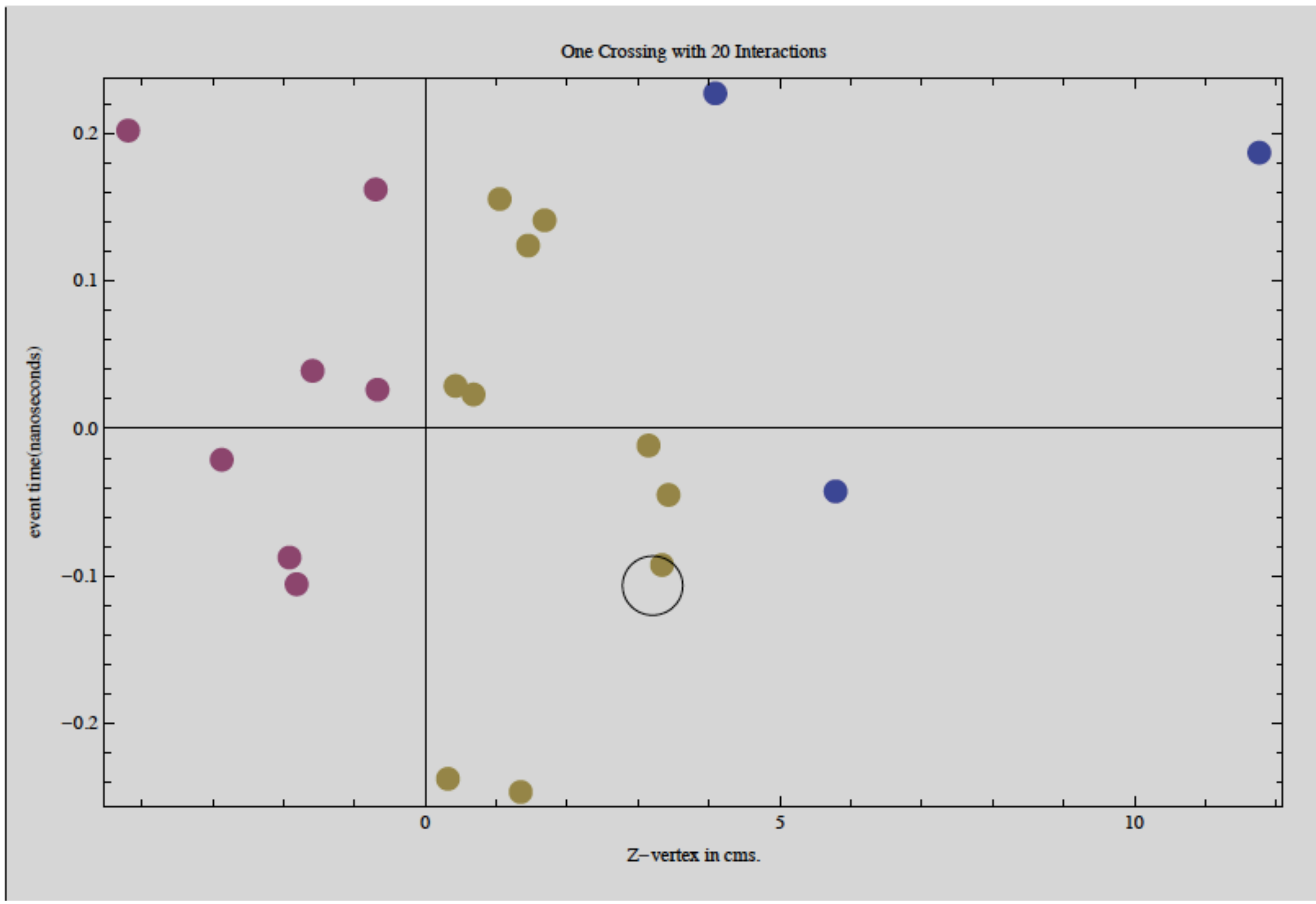
many vertices in hi-PU event even today

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

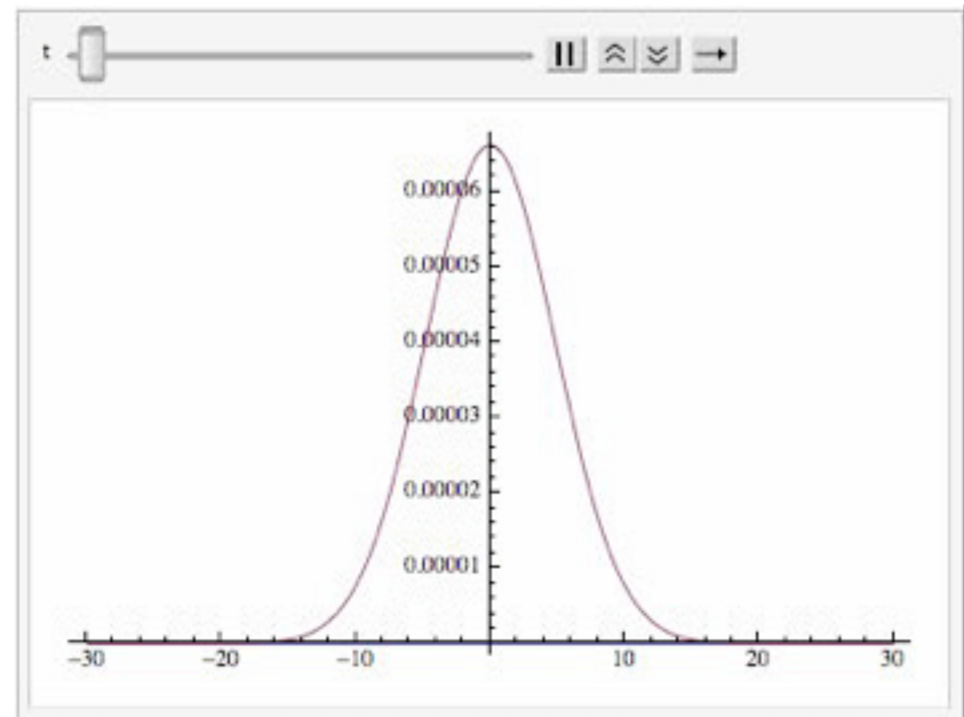
2007 paper:**"On the Correlation of Subevents in the ATLAS and CMS/Totem Experiments", S.White, http://arxiv.org/abs/0707.1500**

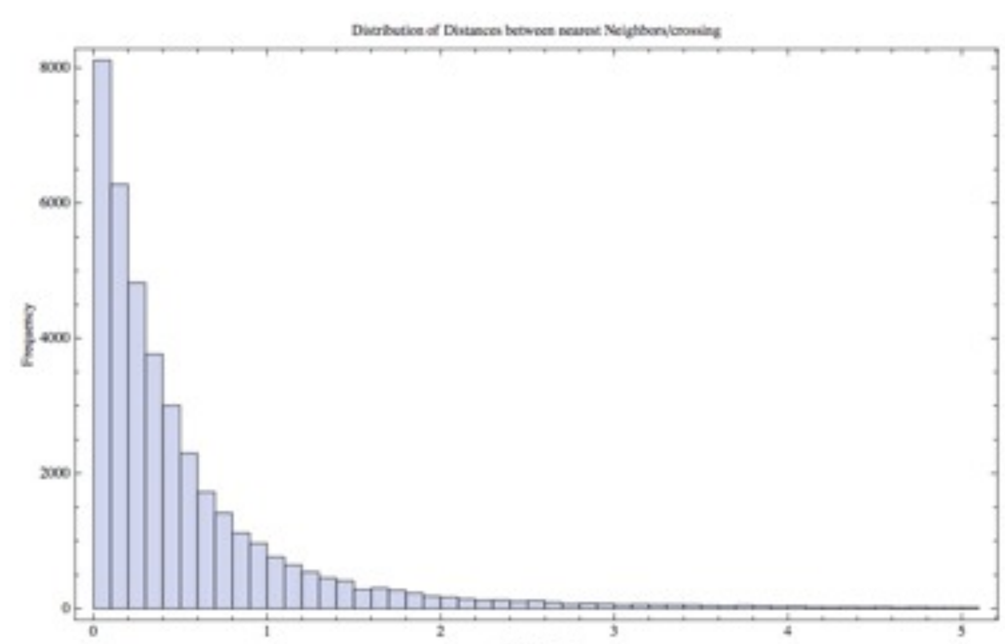
in this example: 20 events/crossing, plotted as vertex(x-axis) vs. event time.
Nb: circled event needs both time and vertex to resolve.



vertex distribution time invariant

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





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

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

Background

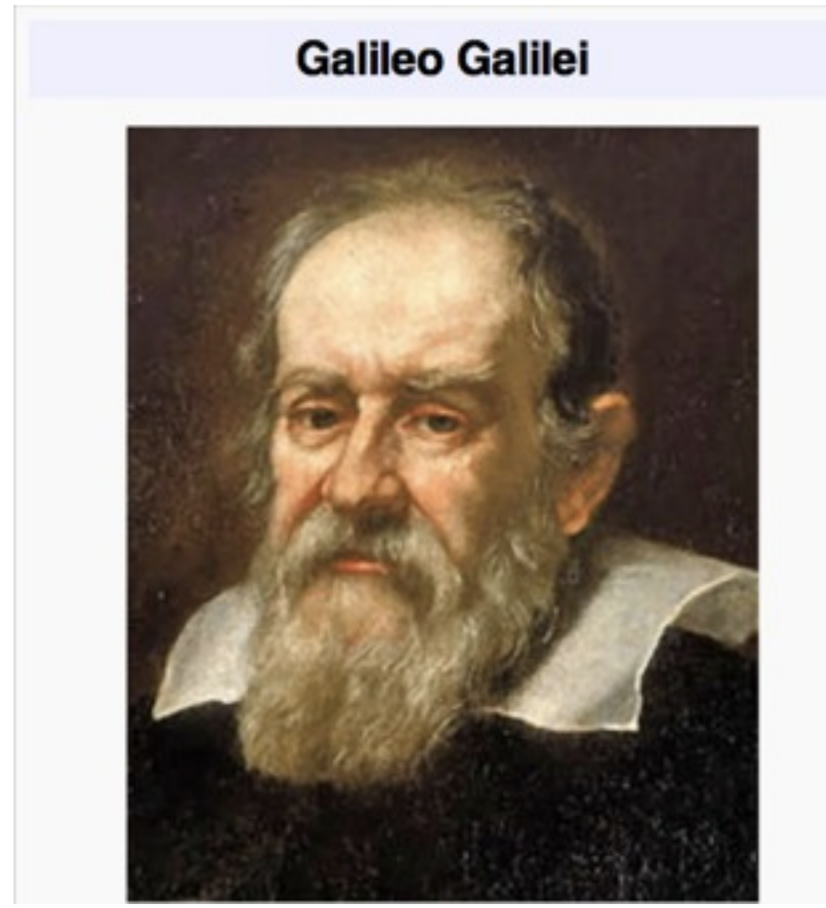
"New directions in science are launched by new tools much more often than by new concepts"-F.Dyson
Corollary: New tools are launched more often by serendipity than by committees.

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.

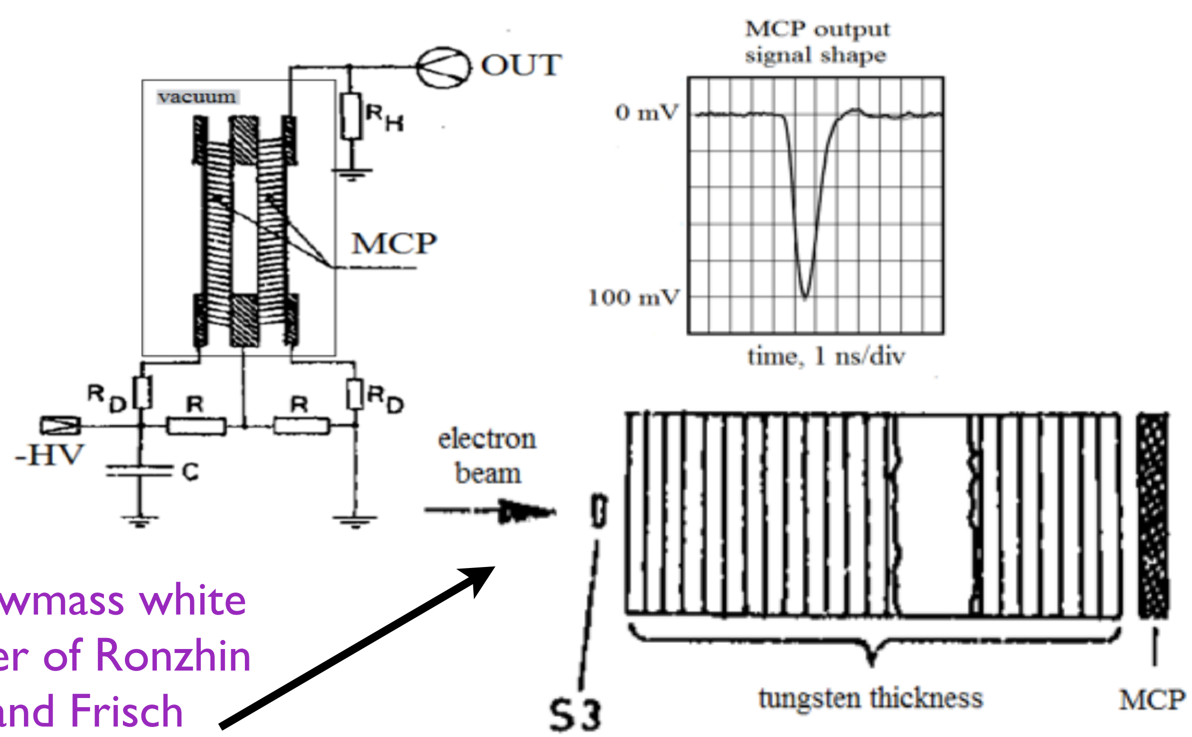
Cloud Chamber 1950 NEVIS Cyclotron Lab

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....

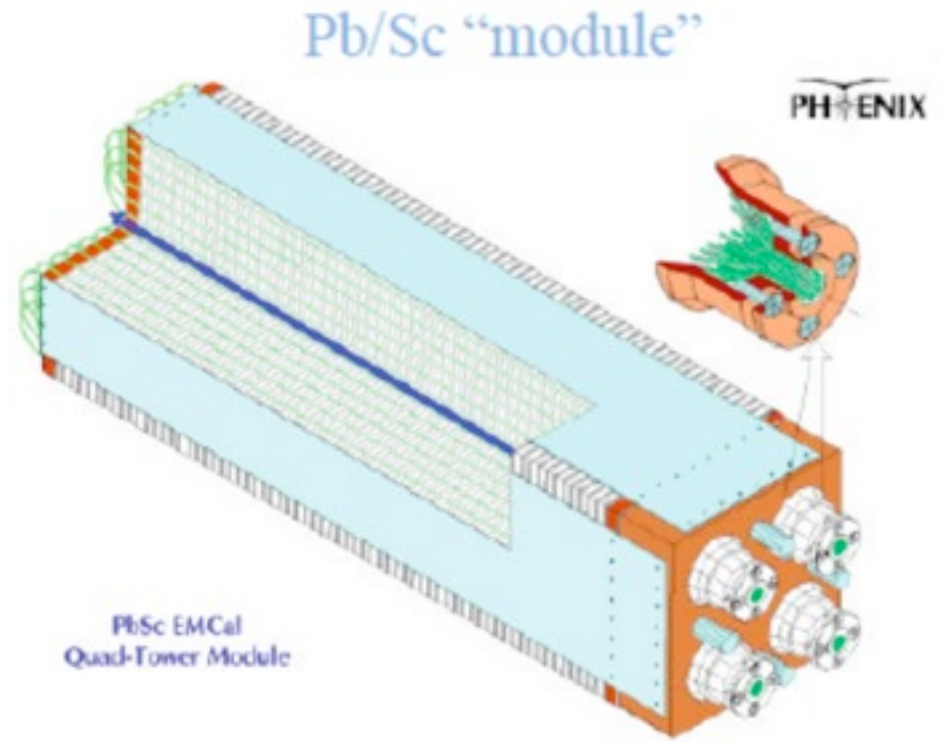


Time stamp was critical in SN1987a.

The Russians



Snowmass white paper of Ronzhin and Frisch

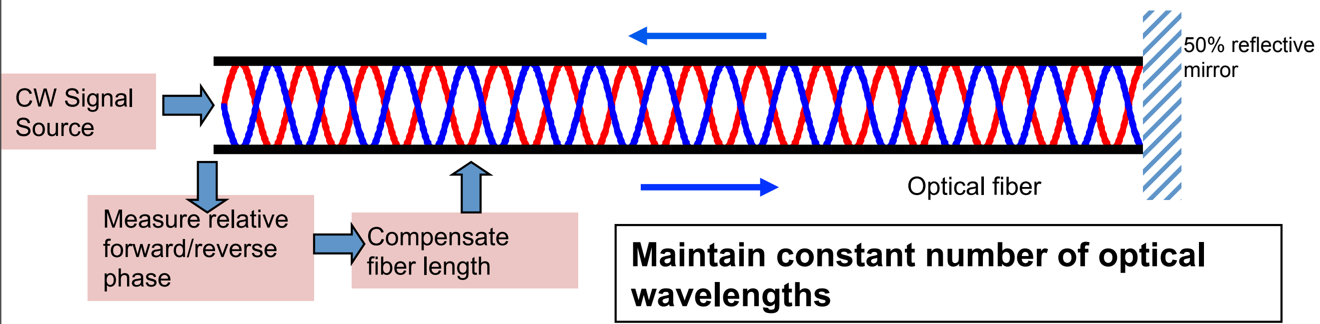


Volodja Issakov

a large number of calorimetry ideas bubbling out of IHEP and INR in 1990's

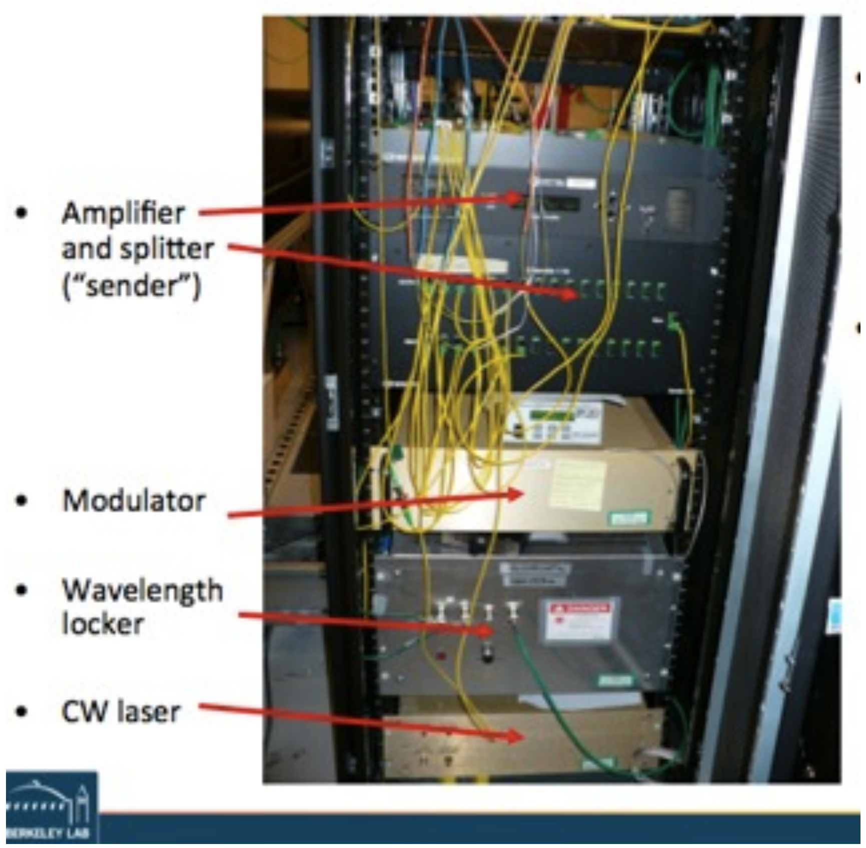
Tools: Clock Synchronization

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

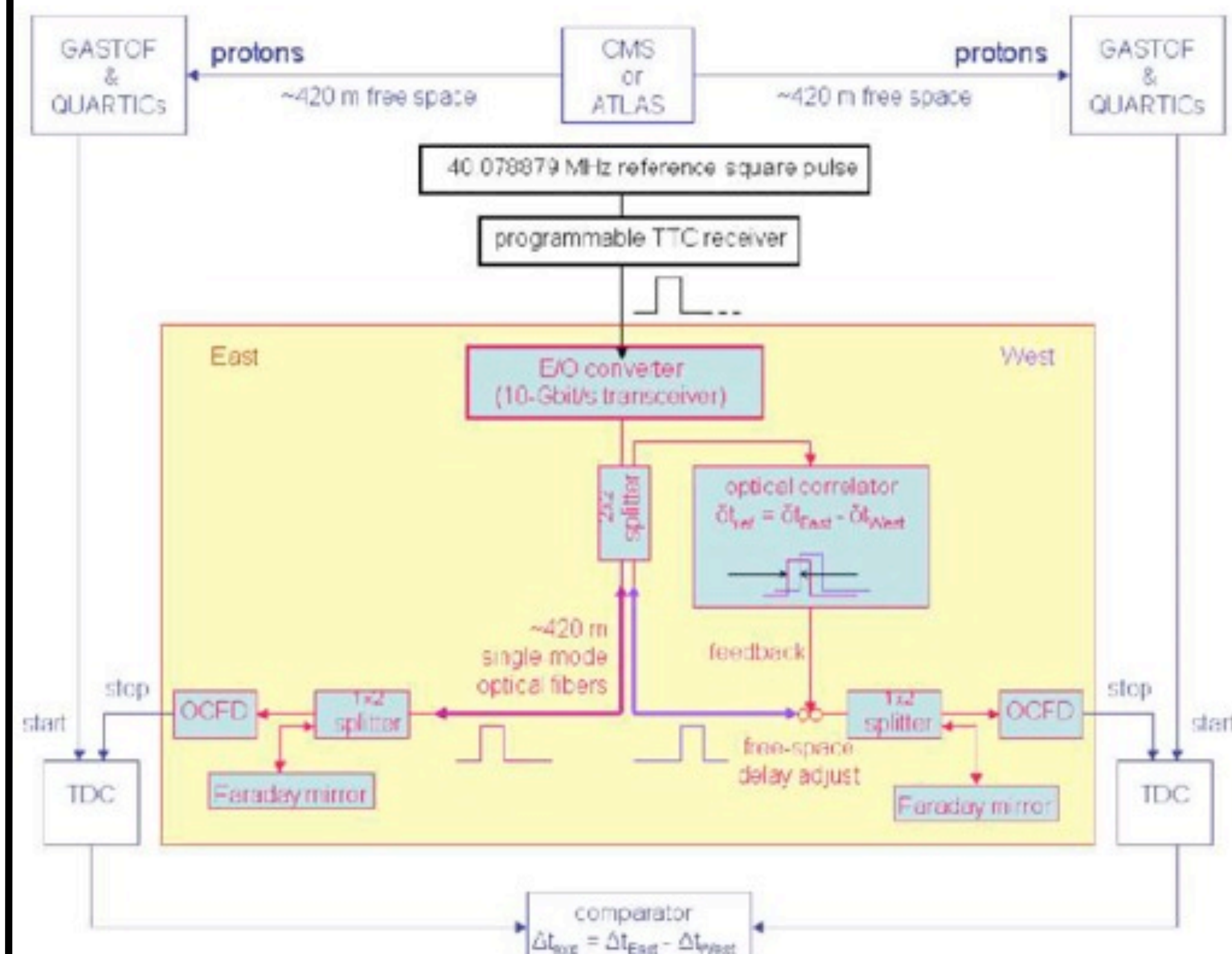


Interferometrical stabilization of eg. 20 picosec/deg.C/km thermal drift of optical fibres.

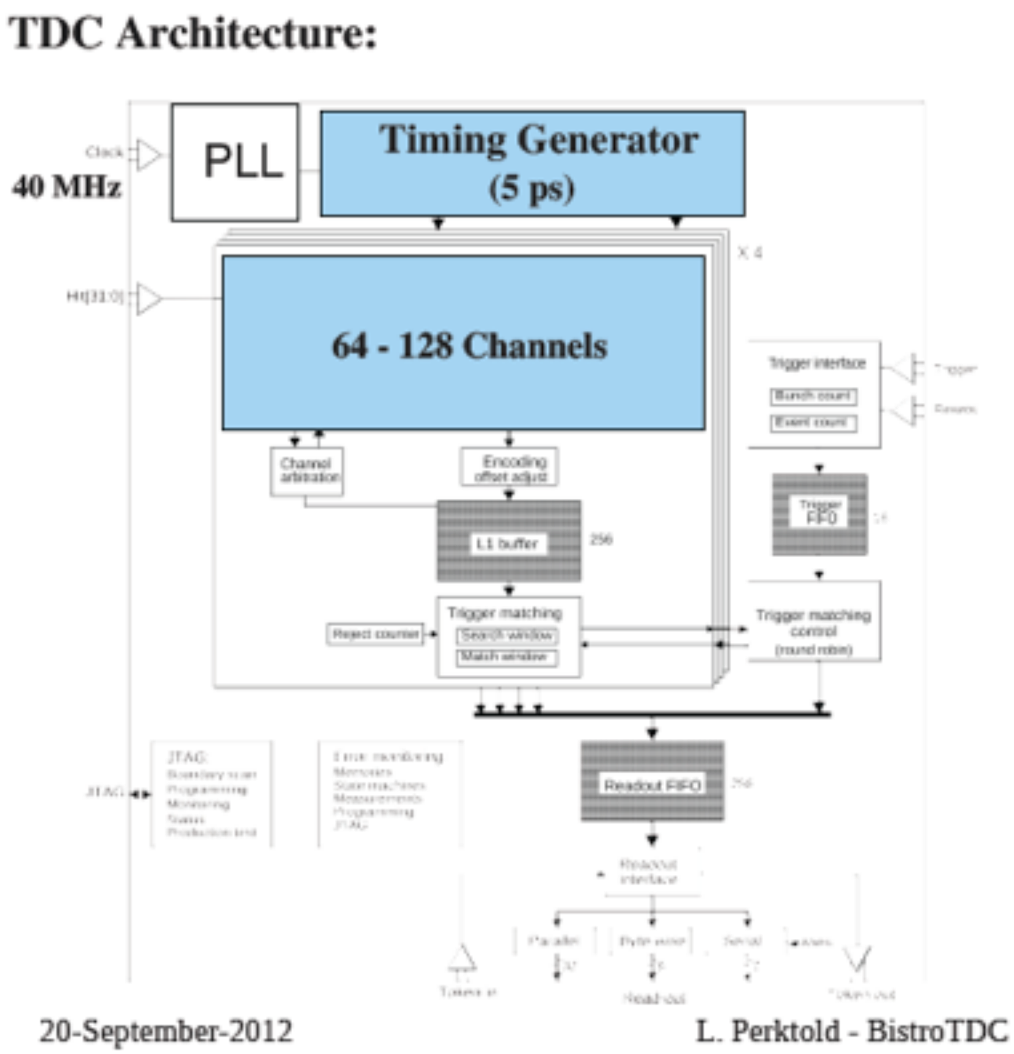
FEL community uses ethernet tech for synchronizing remote clocks to picosec level- eg. "white rabbit" project



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



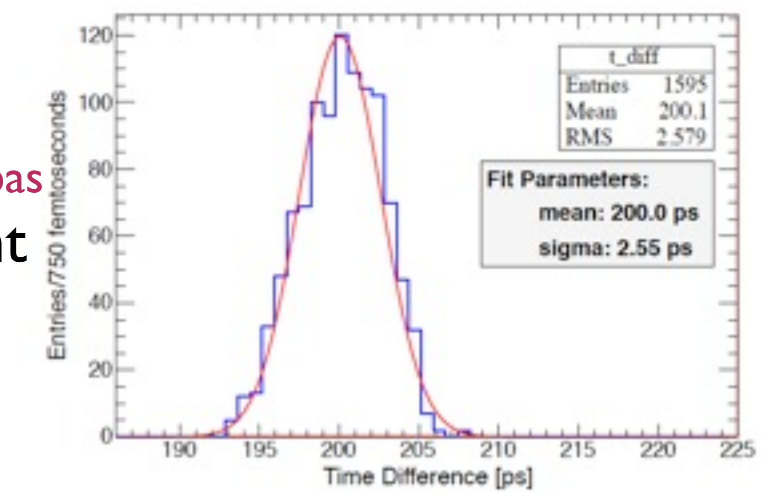
Tools: Digitization



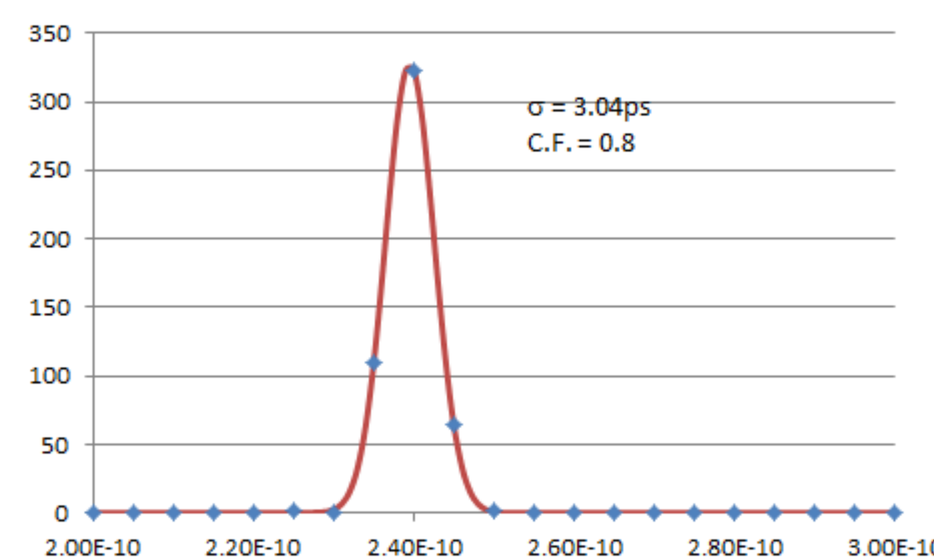
higher resolution version of TDC used by ALICE:
3 psec rms jitter in ASIC
<5psec goal in full system.

waveform digitizer approach:

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

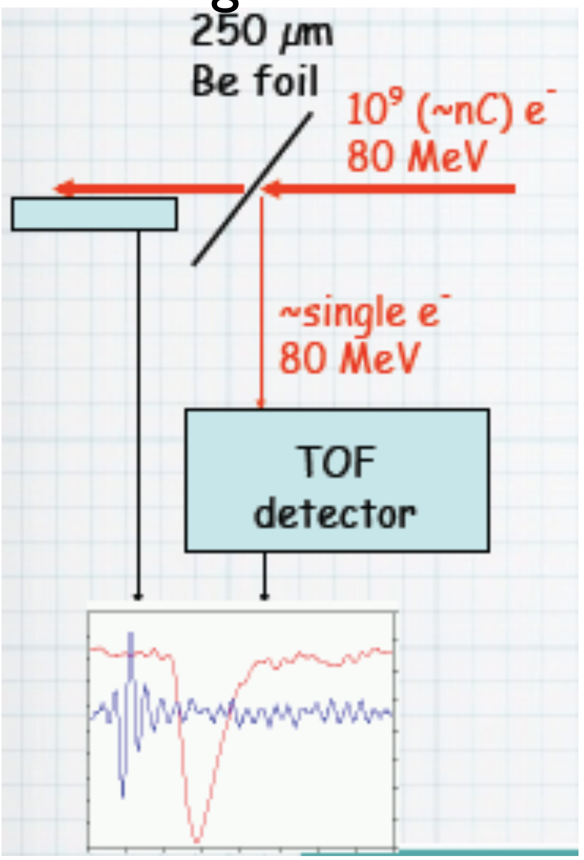


our result from time diff on 2 striplines at electron LINAC
w. 3 picosec bunch length, SNR~100,
trise~150 psec=>2.5 picosec rms. remeasured this year:



Tools for device testing

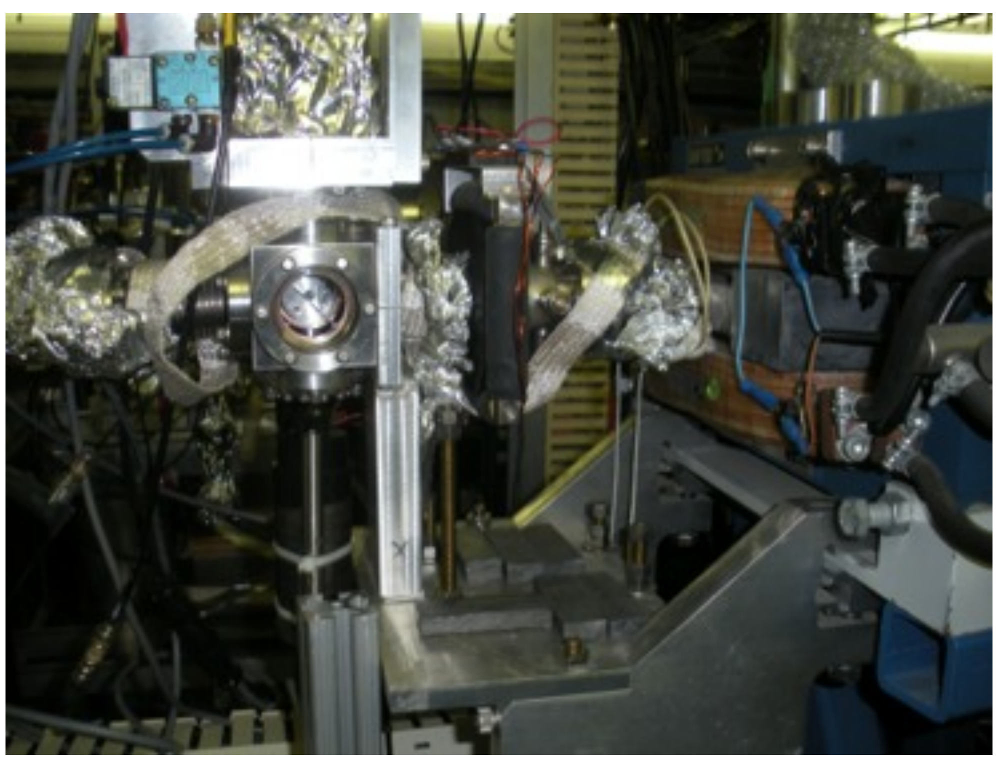
80 MeV single electron with 3 psec jitter

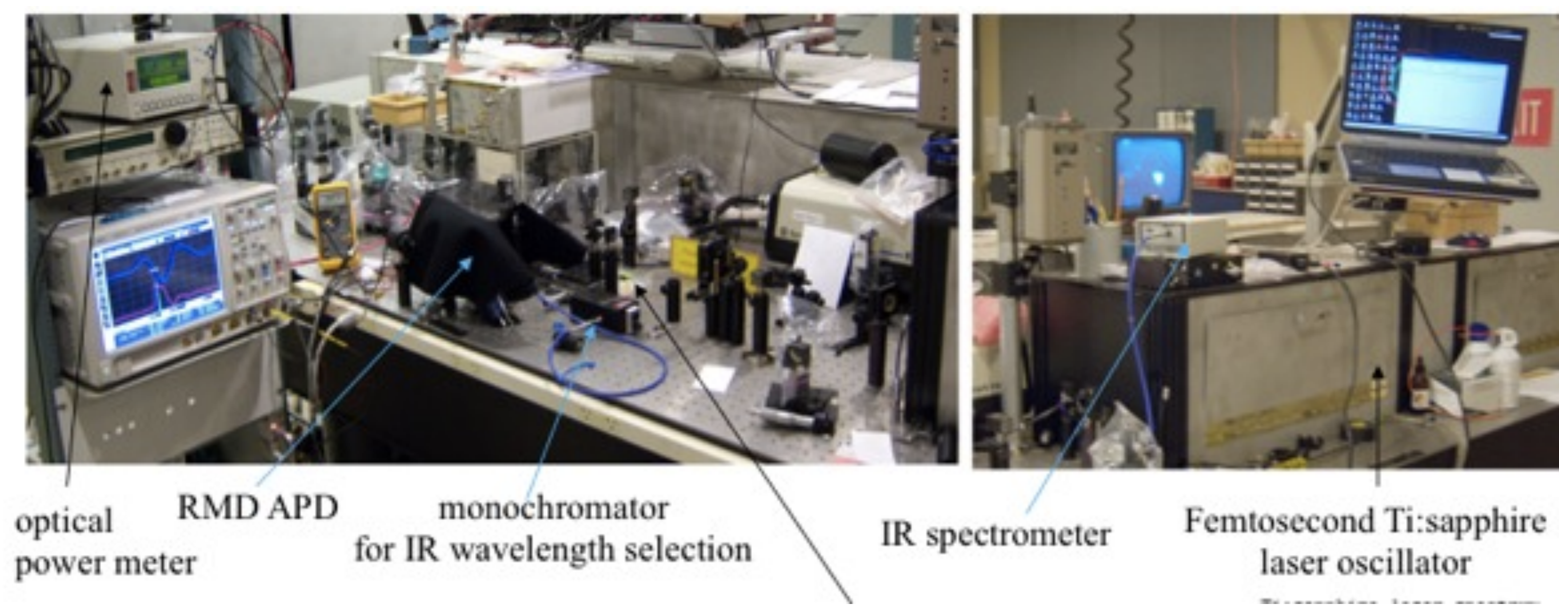


(also discussing similar possibility with LAL, Orsay)

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-)

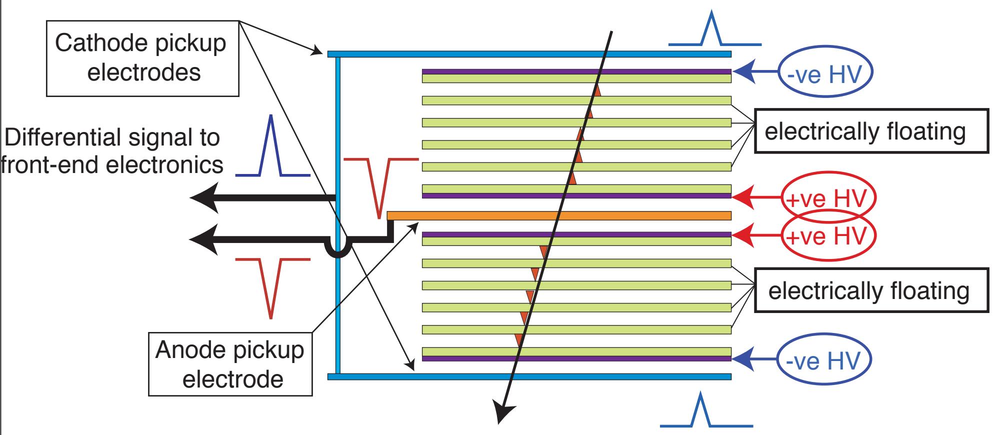




5. **Energy Calibration of Underground Neutrino Detectors using a 100 MeV electron accelerator** / White, Sebastian ; Yakimenko, Vitaly
An electron accelerator in the 100 MeV range, similar to the one used at BNL's Accelerator test Facility, for example, would have some advantages as a calibration tool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

Other Current LHC Systems

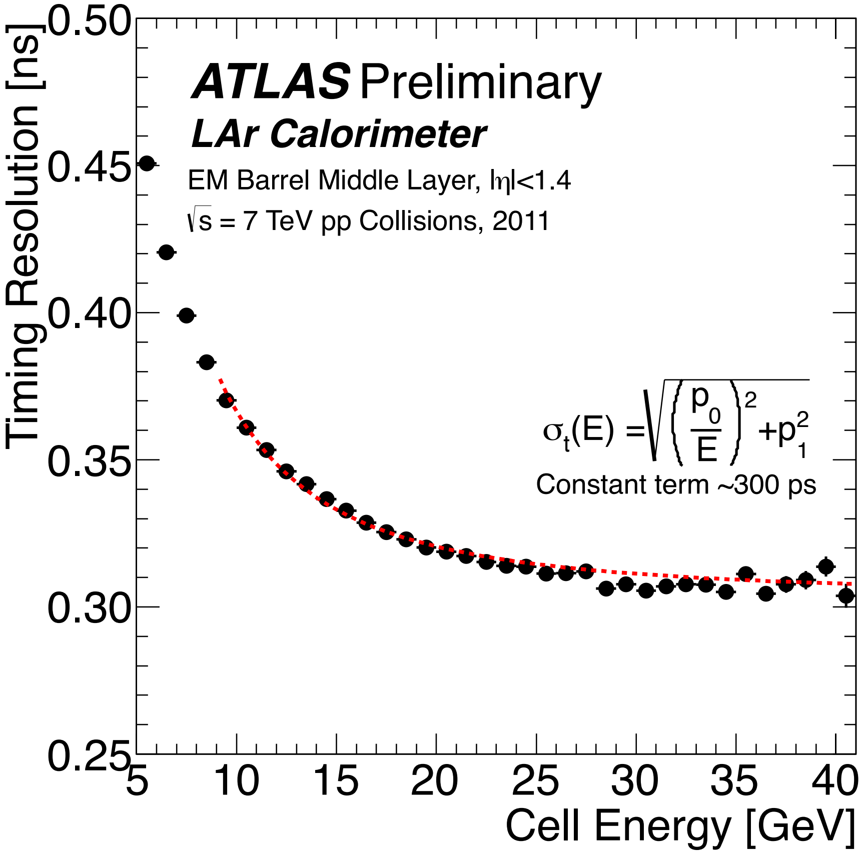
ALICE Tof:



~80 psec resolution in full system. C.Williams currently getting 16 picosec in R&D but not focussing on rate issues

ATLAS LAr:

(see de La Torre's talk)



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)

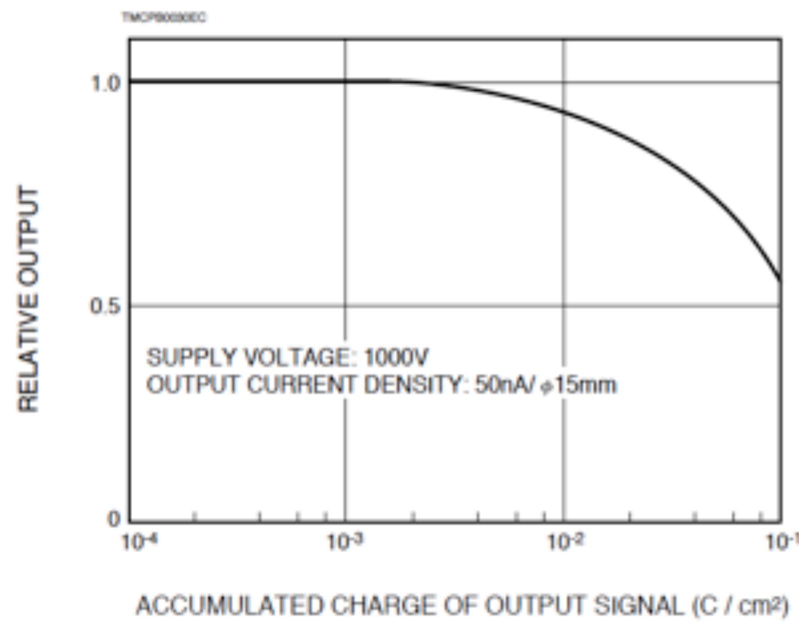
4) Similar studies in CMS (Bornheim)

Photosensors

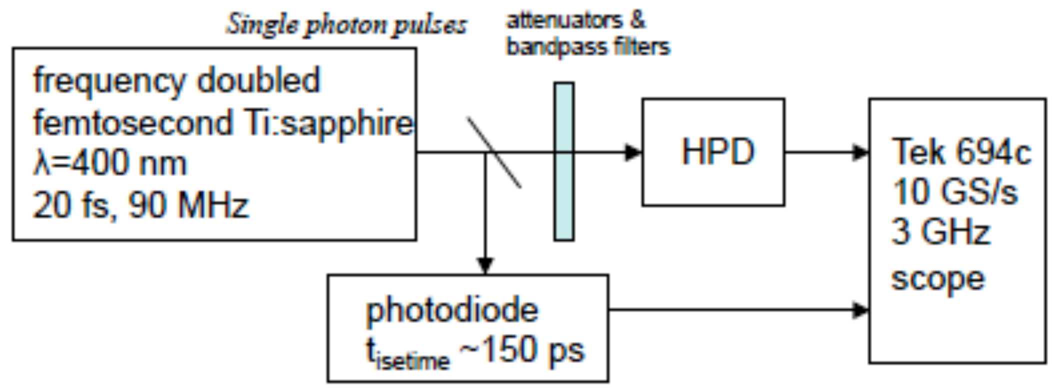
lifetime is an issue in MCP-PMT

compare Hamamatsu data on:

MCP · Life

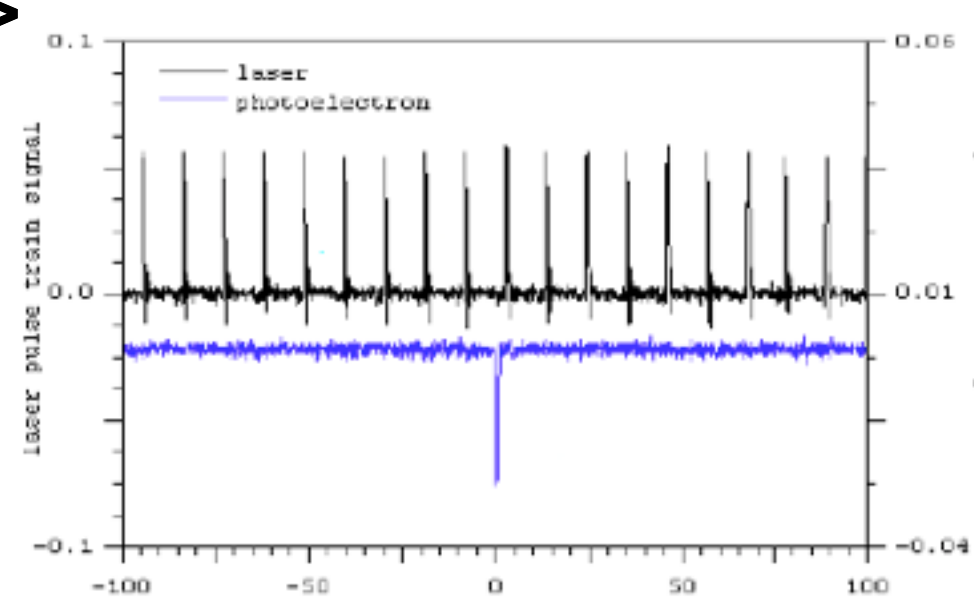


our measured single photon time response:

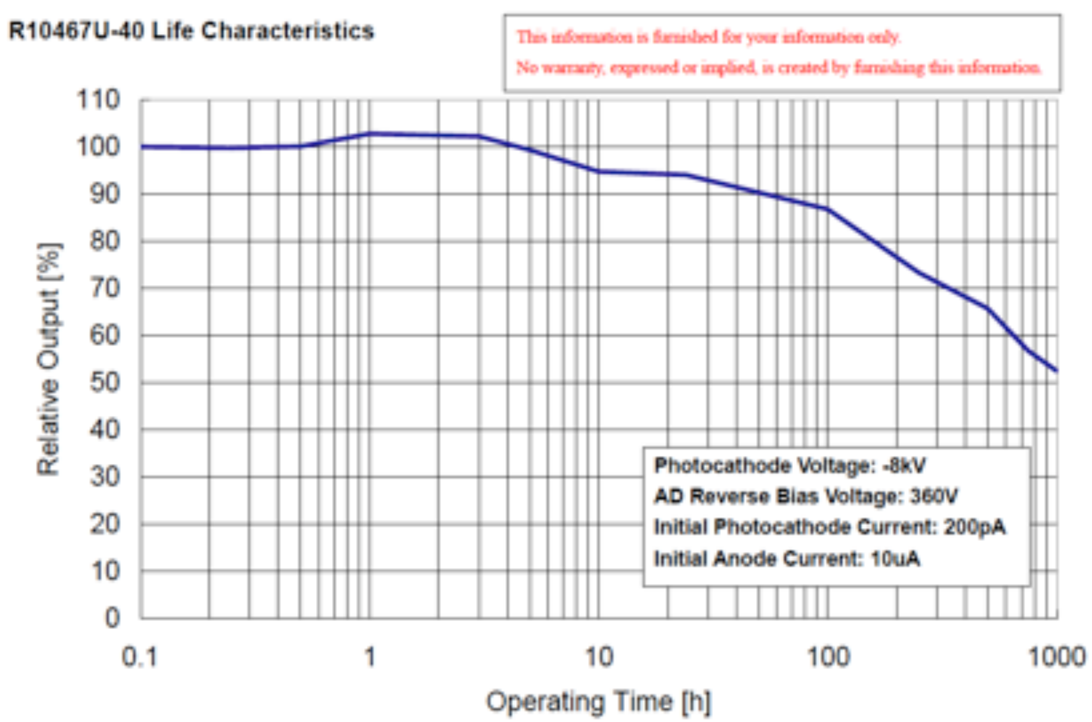


Ti:sapphire oscillator:
attenuate to
95 femtoWatt
~200 kHz count rate
~2x10⁵ photons/sec
(<0.002 photon/pulse)

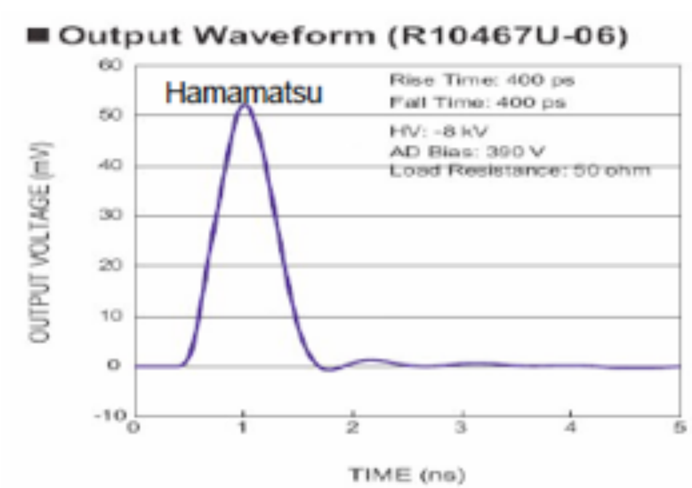
=>



compared to new technology evaluated by our collaboration:

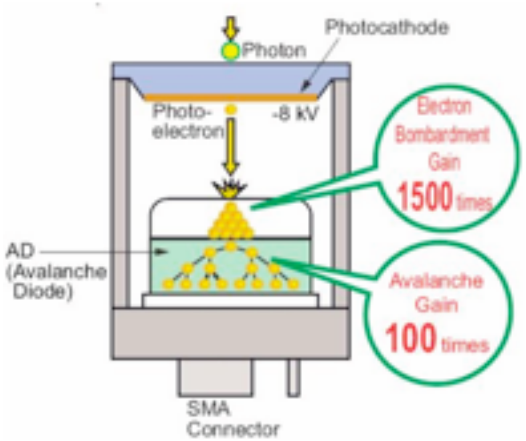


Measured jitter relative to photodiode=11 picosec!!



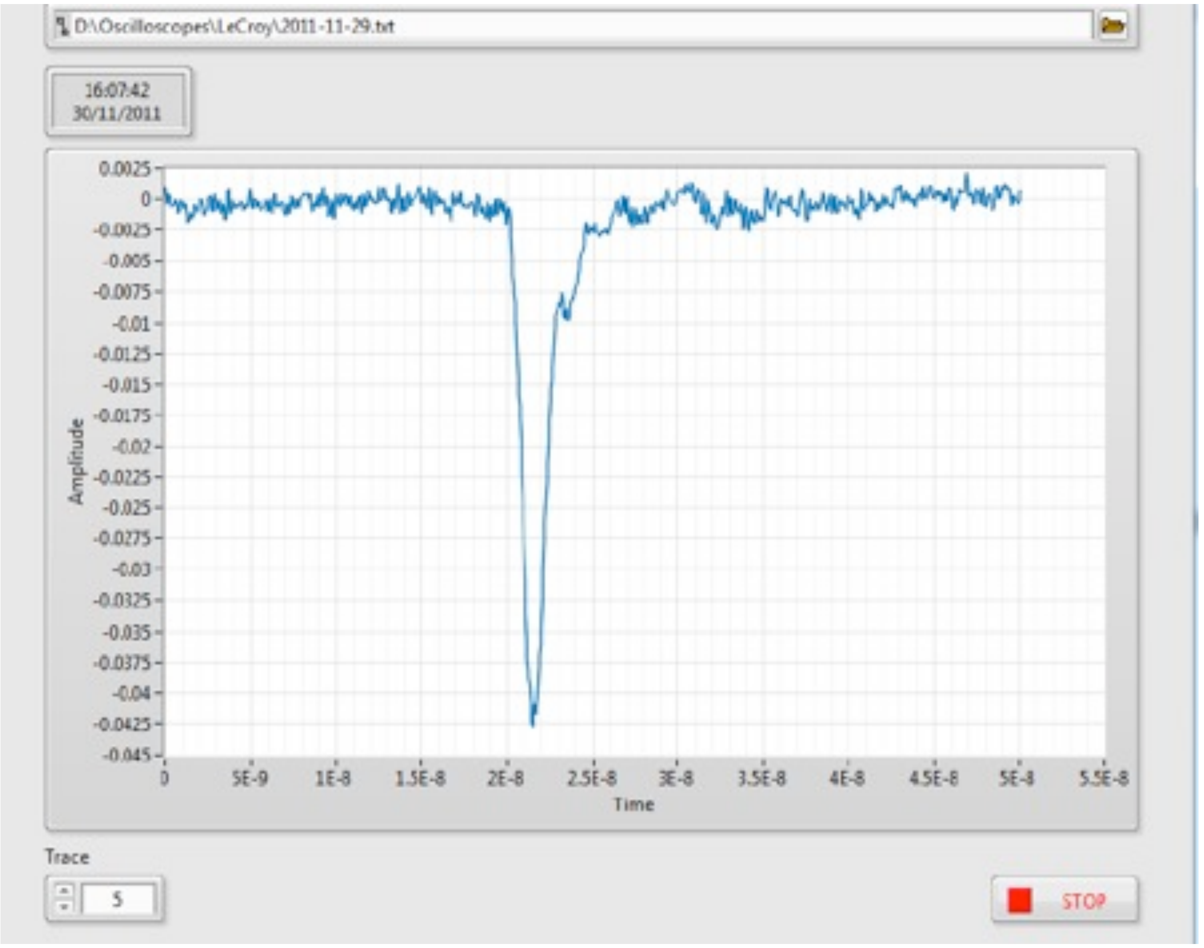
Conservatively factor of 360 improvement (MCP->HAPD) !!!

Picosecond Charged particle tracking:

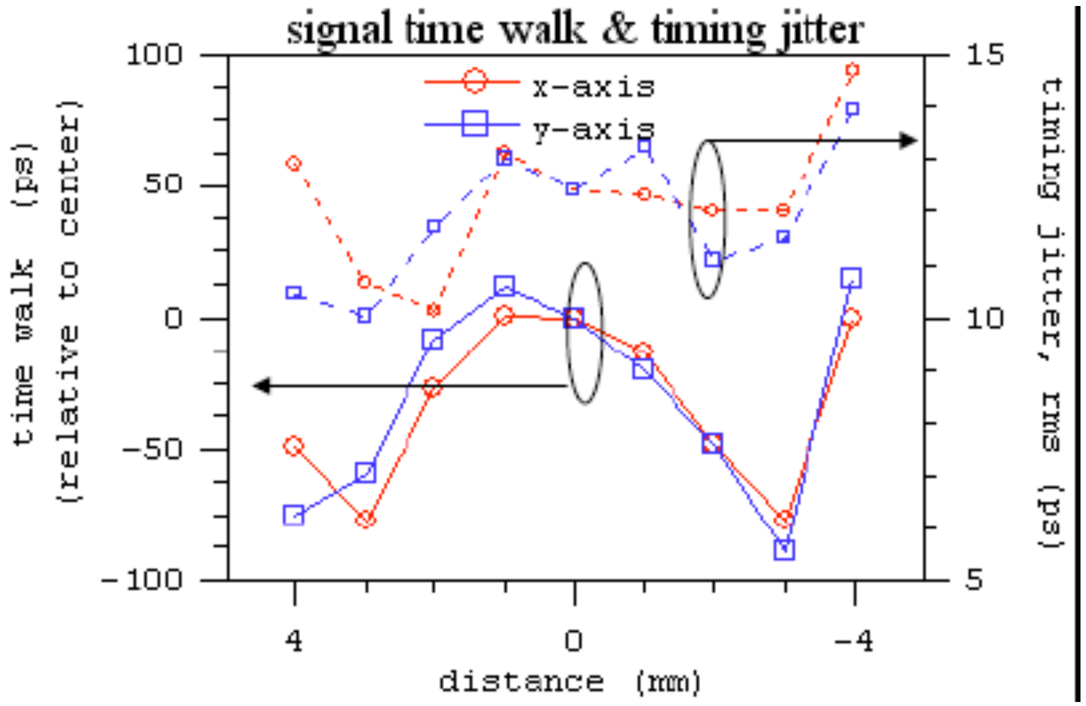


Hybrid APD (results on previous slide) is an accelerator followed by APD used as charged particle detector. Since it yields 11 picosec jitter why not <u>use APDs as direct charged particle detector</u>?

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.

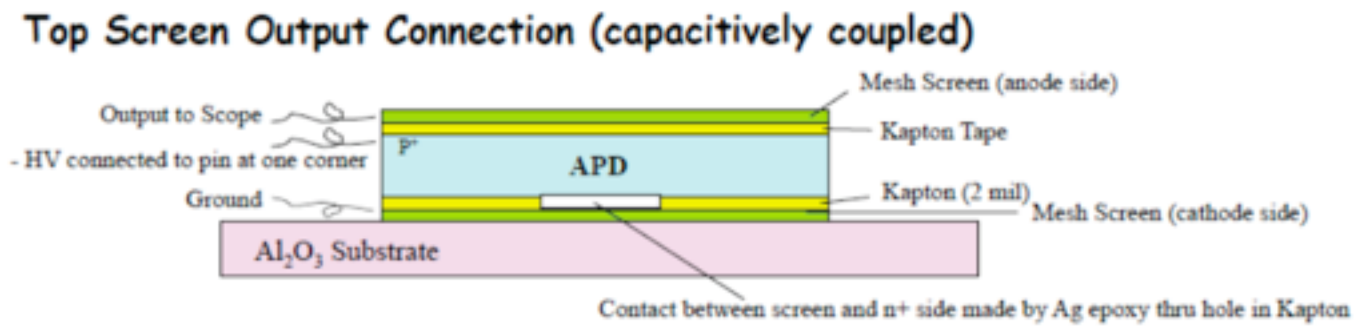


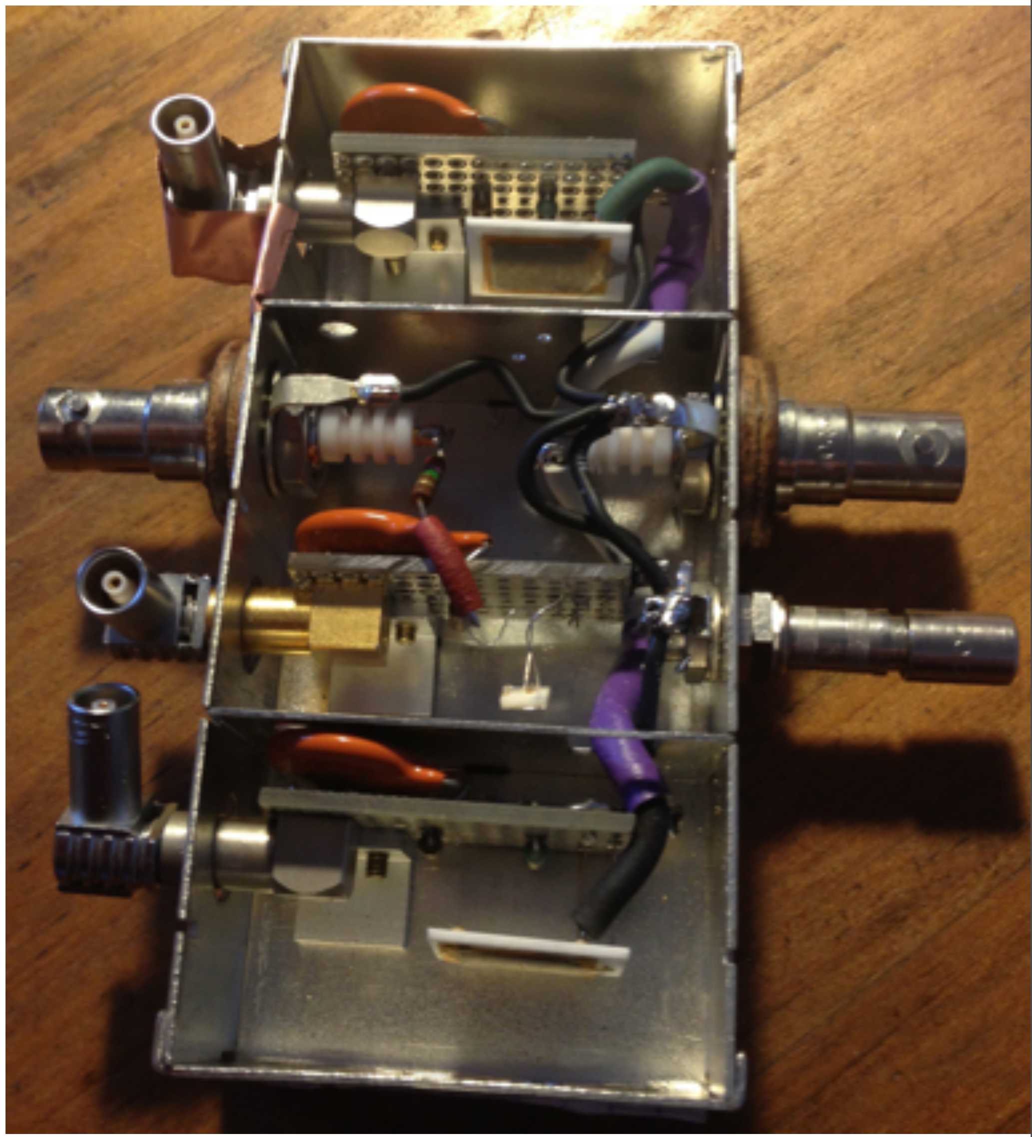
in this figure noise level dominated by scope noise floor



intermediate results with early metalization improvement

Deep Depleted APD with MicroMegas mesh for field shaping





"telescope" for Jan-Feb 2013 beam test at SPS.=>
Since characterization with laser (intensity and wavelength to match MIP charge deposition) now shows good uniformity, initial run planned without need of external tracking device.

Rad hardness and lifetime:

Initial studies based on CMS APD scaling laws showed several years at 10^7 Hz/cm^2. (http://arxiv.org/abs/0901.2530)
In December 2012 completed initial rad damage tests at PS. Results soon.

Sensor technologies:

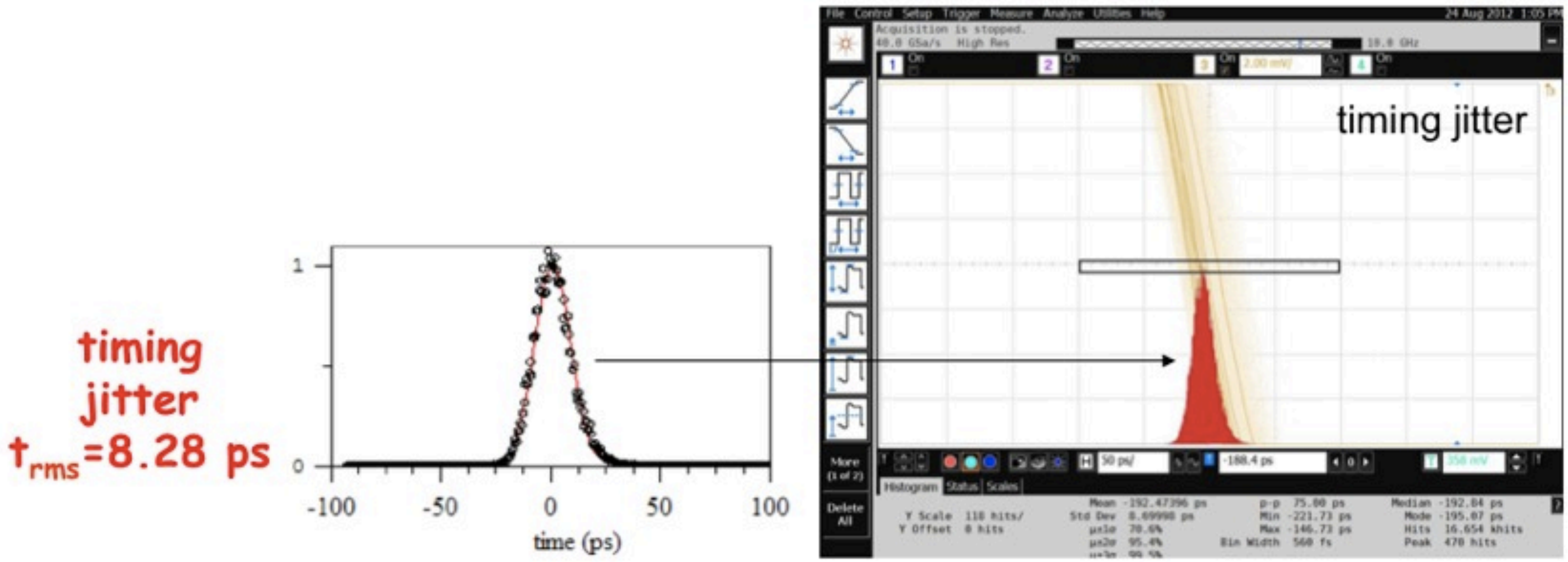
Our recent work has focused on HAPD photosensor and hybrid Deep-depleted APD/Micromegas direct charged particle timing.

A number of other technologies studied but fail time resolution (ie CVD diamond) or rate/lifetime (ie MPC and RPC) goal.
Also re-visiting Micro Megas timing limitation with Giomataris and Veenhof.

Other approaches out there:

- Aggressive program to address lifetime issues of MCP's with goal of orders of magnitude improvement-> LAPPD project at Argonne/Chicago.
- gAPDs with C radiator
- RPCs w. low conductivity glass
- etc.

several reasons to bet on direct charged particle timing: more flexibility w. dedicated det. and it's nice to make plots like this:



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

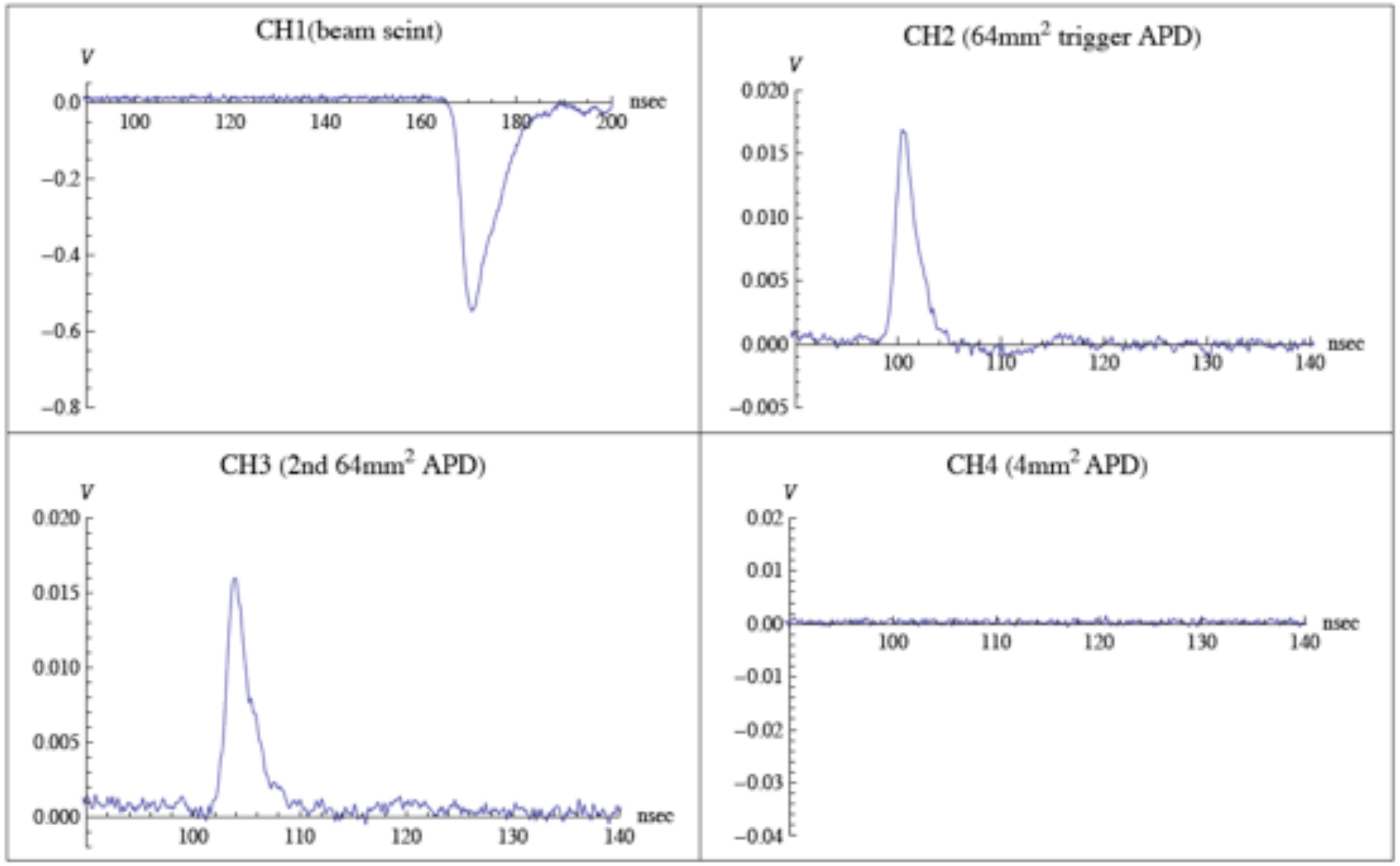
Amp power

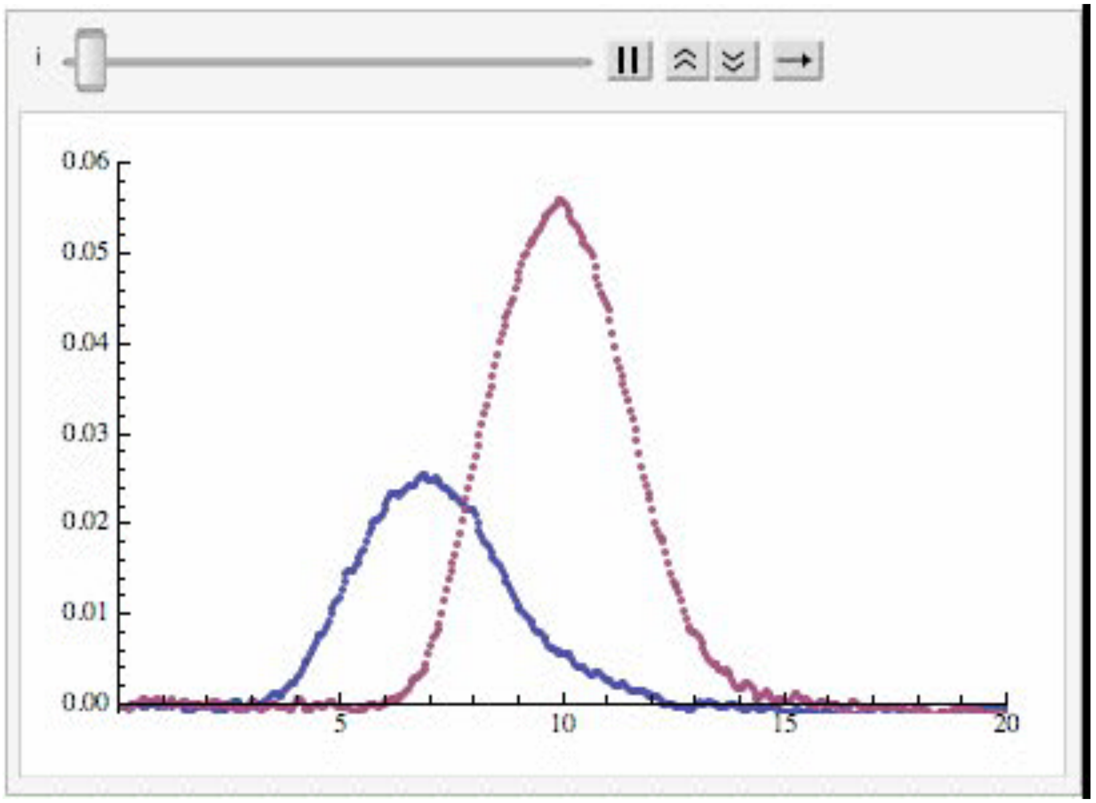
APD bias

Analysis of H2 data

beam events: fast <1nsec trise, low statistics

vcsel data: slower (used 6 nsec pulser)



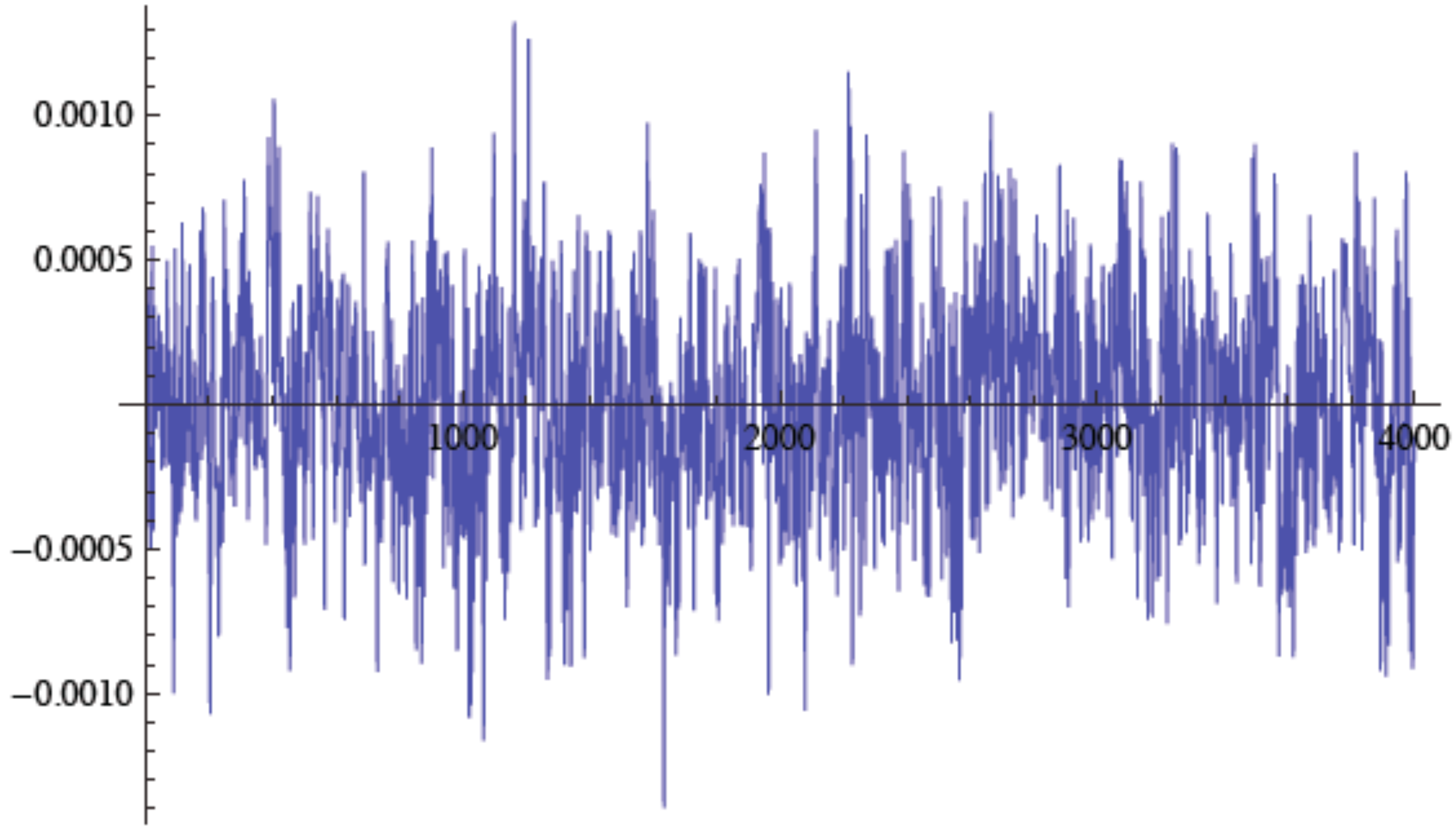


nb:Ch4 is smaller area APD to select sub-class of events in center. Not in trigger.

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]=

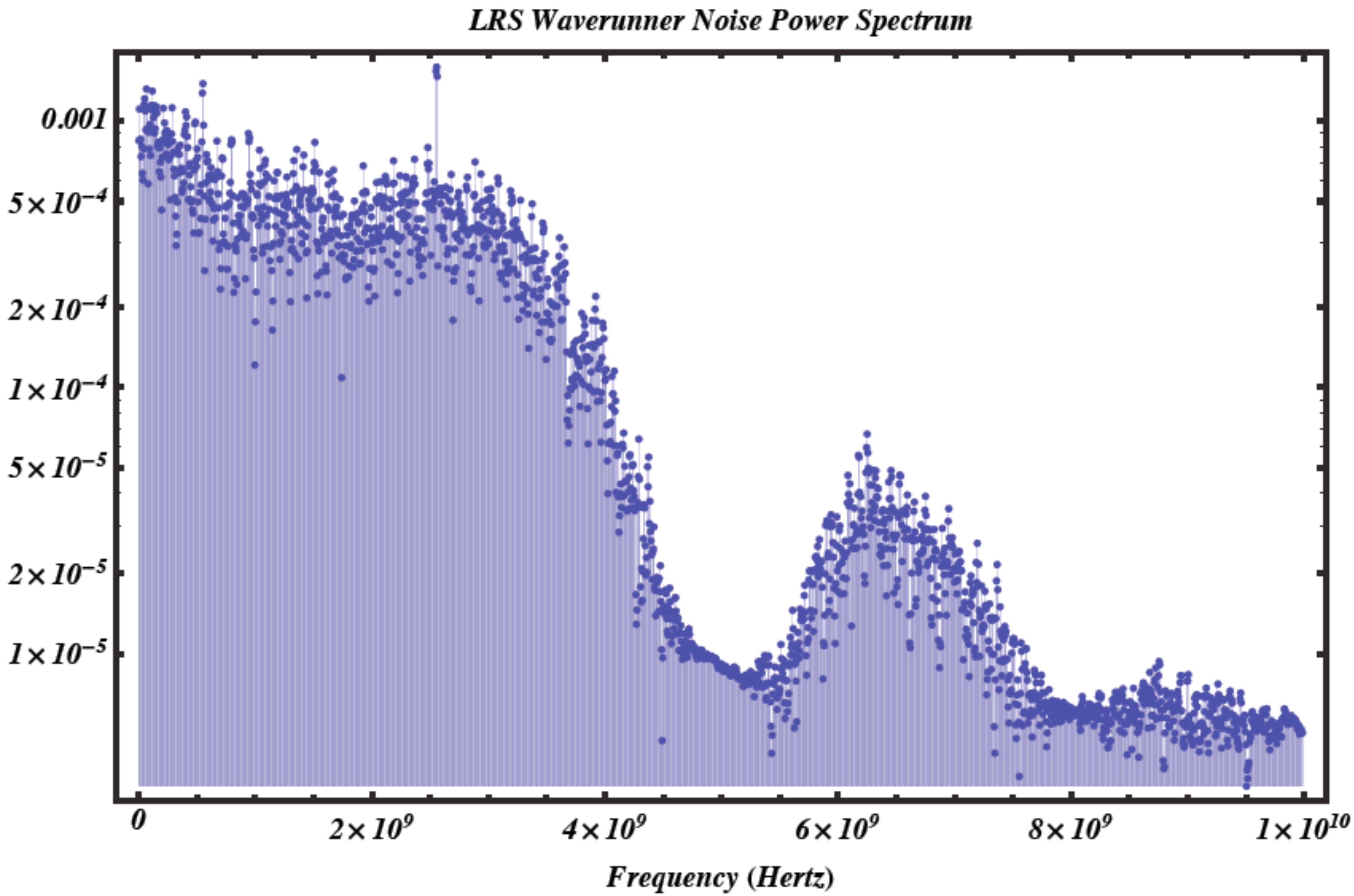


In[1056]:=

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

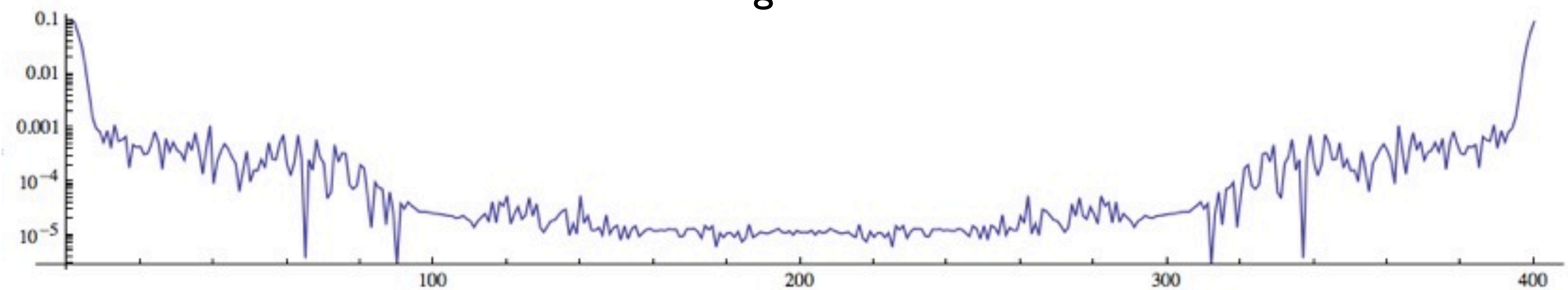
```
Noise Level=   0.351737 mV RMS
```

I did a Fourier Transform of the noise spectrum

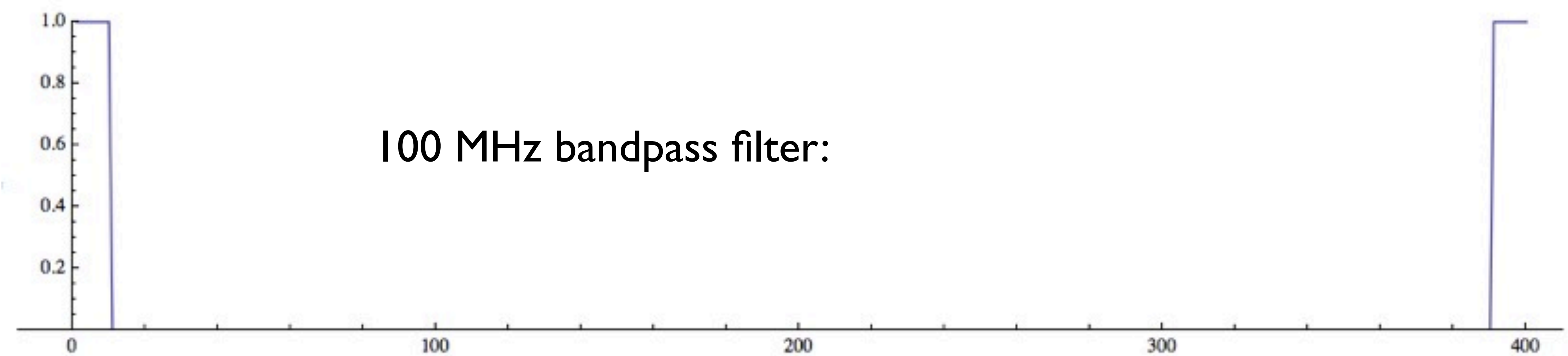


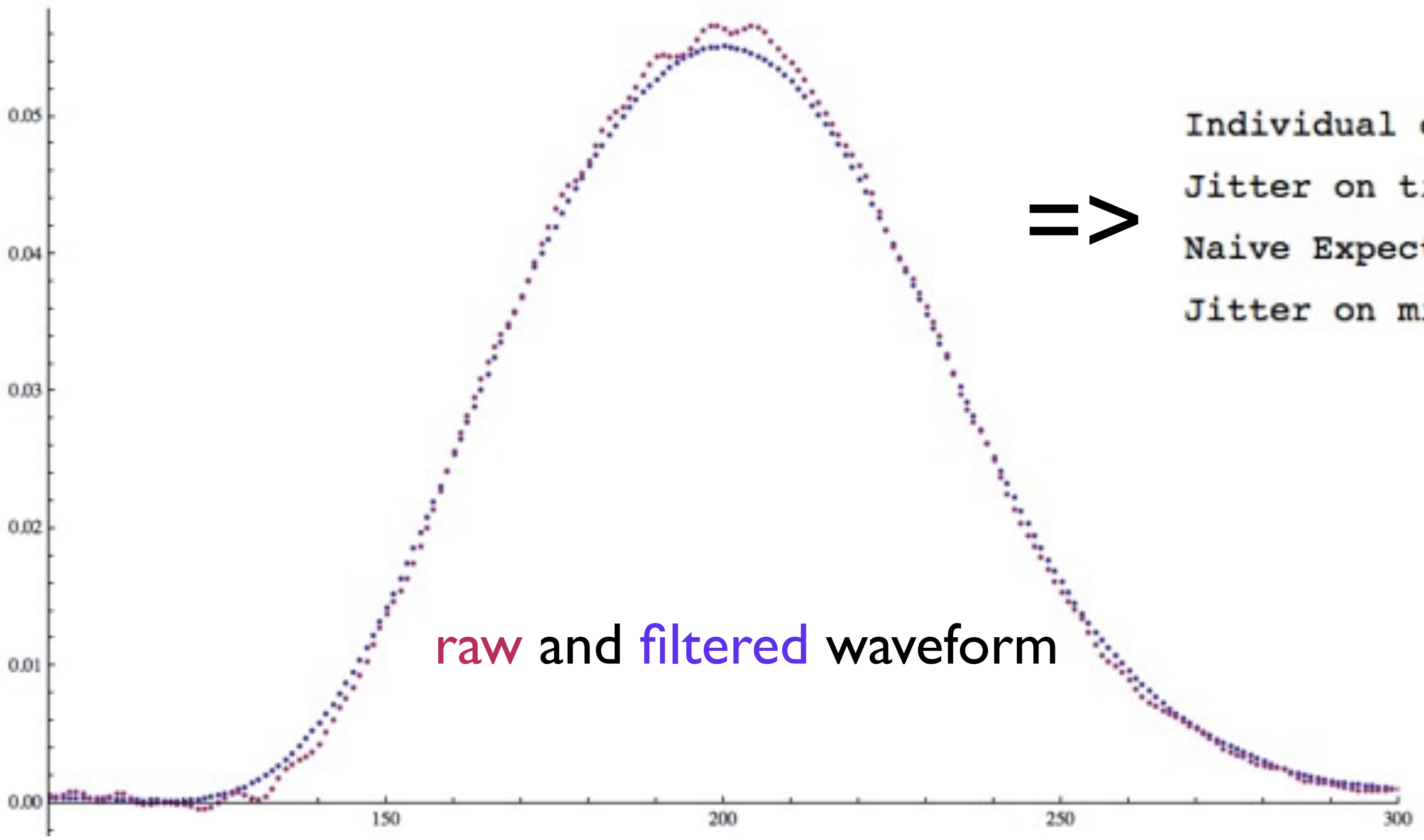
studying a variety of algorithms on vcsel data sets before turning to the MIP data. Optimize on vcsel and apply, without bias to small MIP data set. High statistics data expected in May at PSI. One example below:

FFT of vcsel signal:



100 MHz bandpass filter:



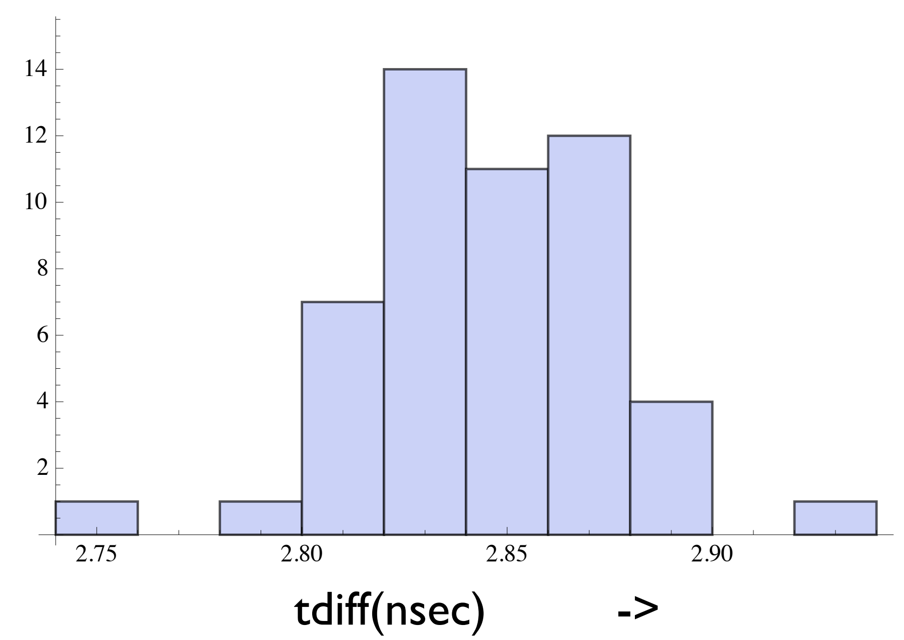


=>

```
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

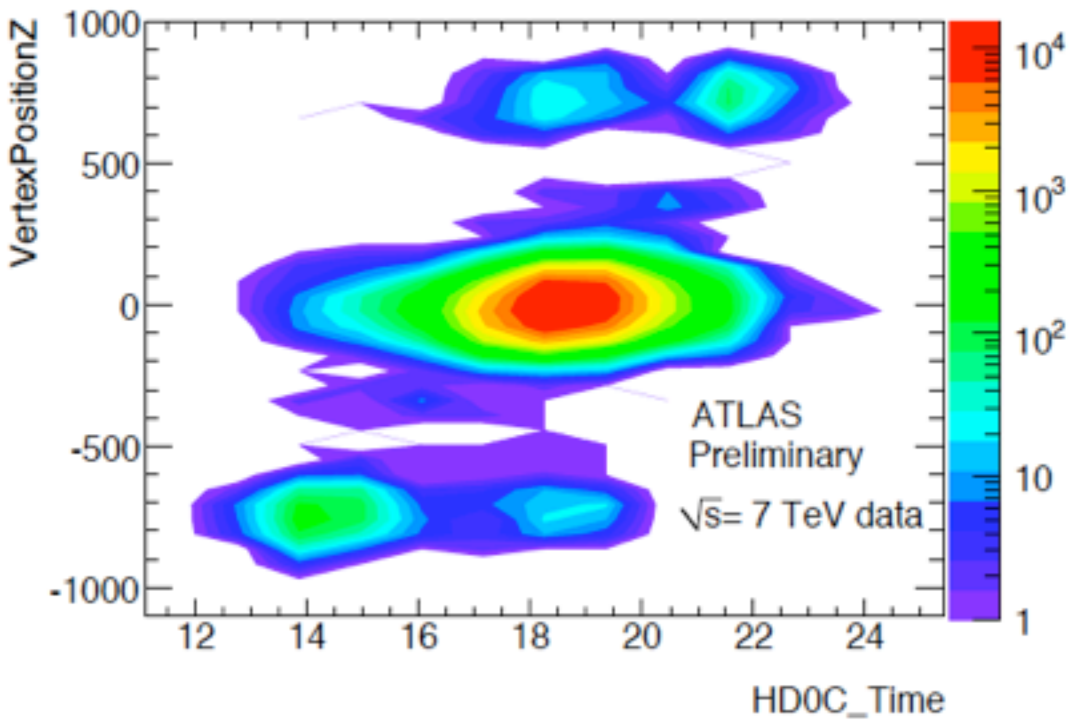
=>



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

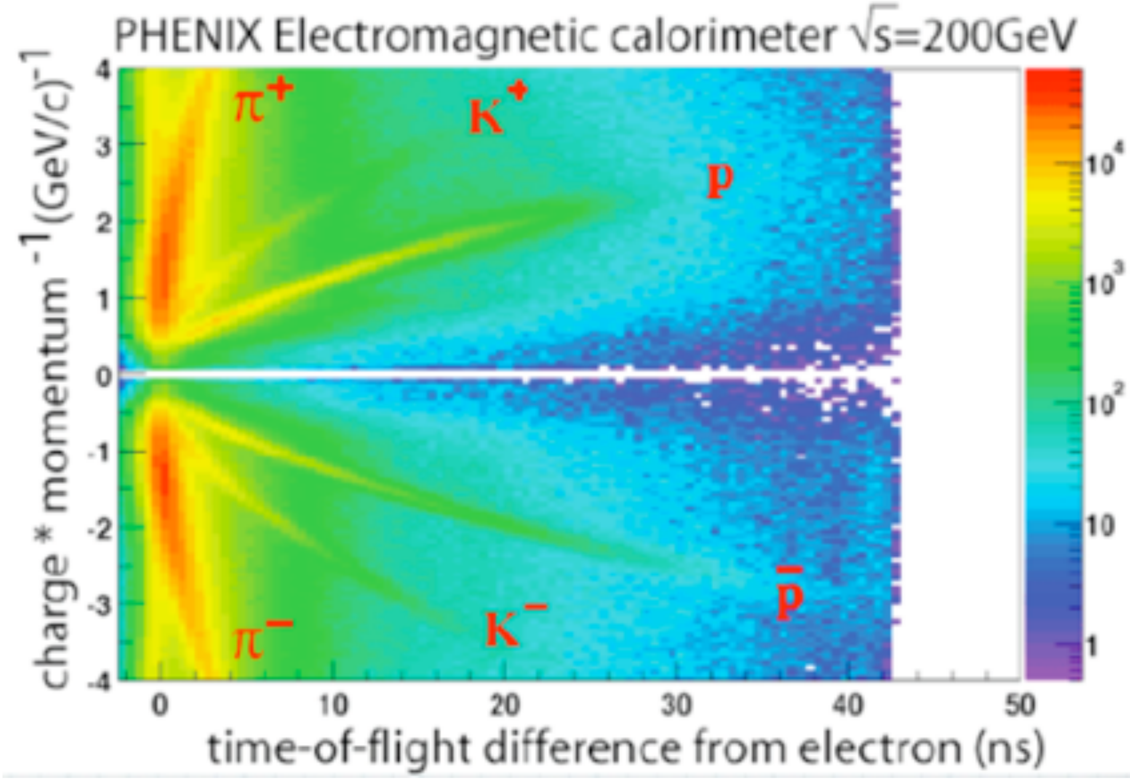
Interest in Timing w. ATLAS ZDC from LHC diagnostics

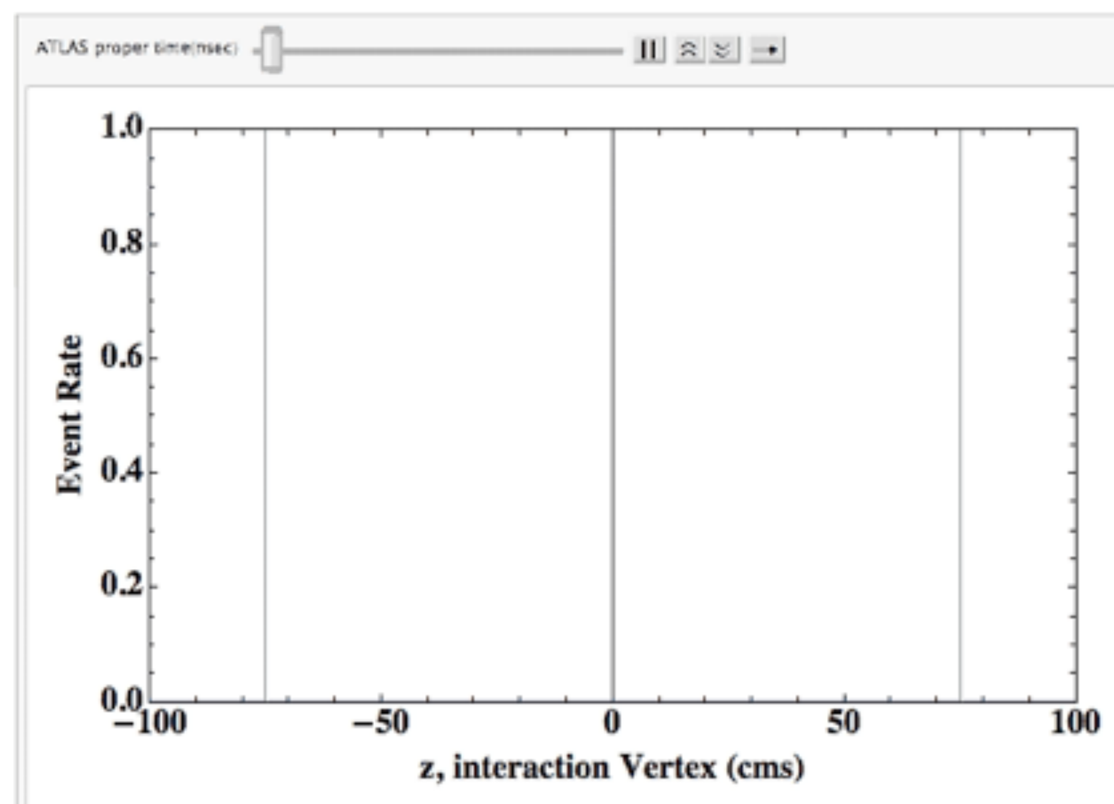
BNL-Yale built ATLAS ZDC timing(Quartz-Tungsten Shashlik) resolves 400 MHz micro-bunch structure in LHC (only LHC detector to achieve this?)
despite reduced bandwidth from low quality cable runs & 40 MSa/s sampling

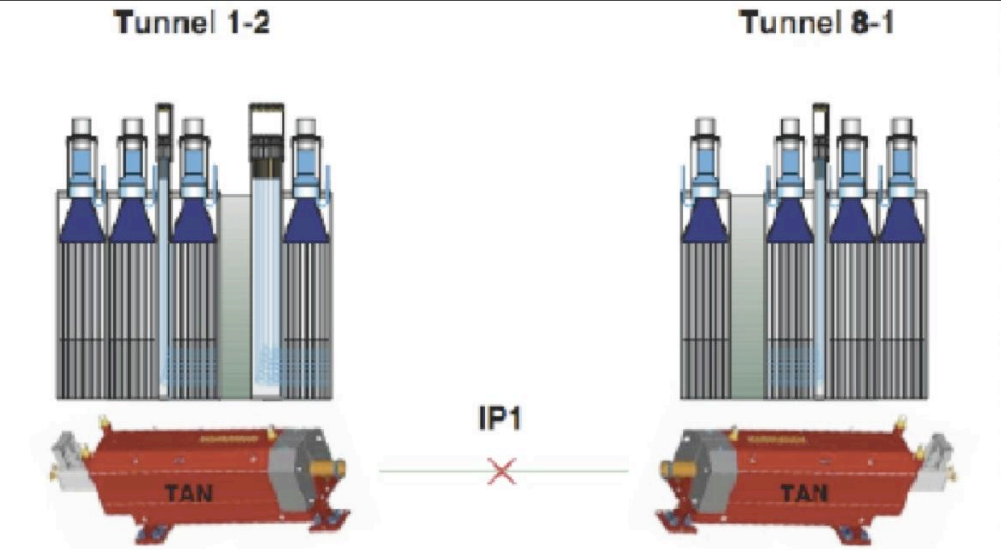


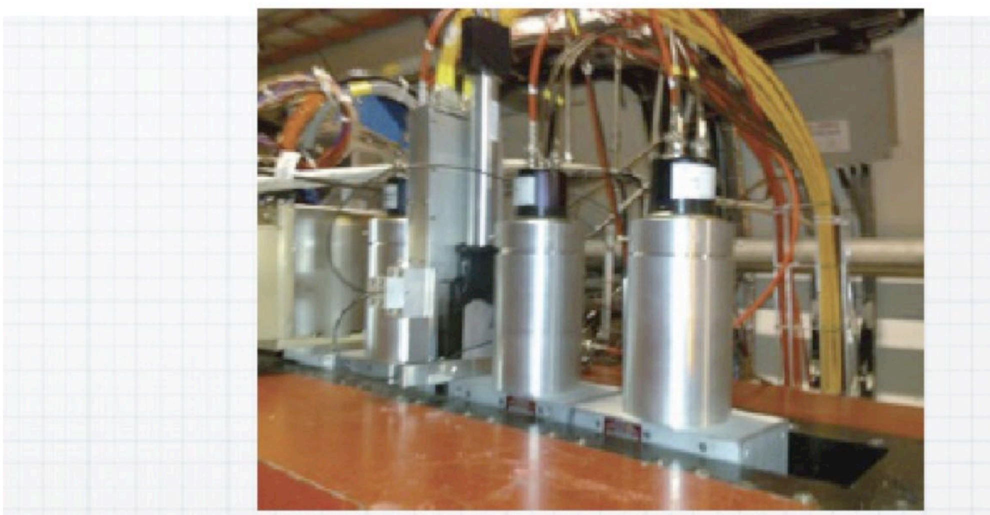
The Z vertex distribution from inner tracker vs. the time of arrival of showers in ZDC-C relative to the ATLAS clock calculated from waveform reconstruction using Shannon interpolation of 40 MegaSample/sec ATLAS data (readout via the ATLAS L1calo Pre-processor modules). Typical time resolution is ~200 psec per photomultiplier (see ATL-COM-LUM-2010-022). The two areas outside the main high intensity area are due to satellite bunches. Note that this plot also provides a more precise calibration of the ZDC timing (here shown using the ZDC timing algorithm not corrected for the digitizer non-linearity discussed in ATL-COM-LUM-2010-027). With the non-linearity correction the upper and lower satellite separations are equalized.

15,552 tower PHENIX shashlik also used for hadron id via TOF
despite low energy deposit of ~0.5 GeV hadrons and TTS in un(longitudinally)-segmented calorimeter









More on ATLAS ZDC

ATLAS ZDC had severe constraints compared to PHENIX
-5 Giga Rad/yr rad dose @ design lum
=200 Watt continuous beam deposition
LHC politics vis. LHCf, LUMI...

despite constraints
-> ATLAS is the only imaging ZDC (x,y,z) on the planet
"shashlik"/layer sampling hybrid

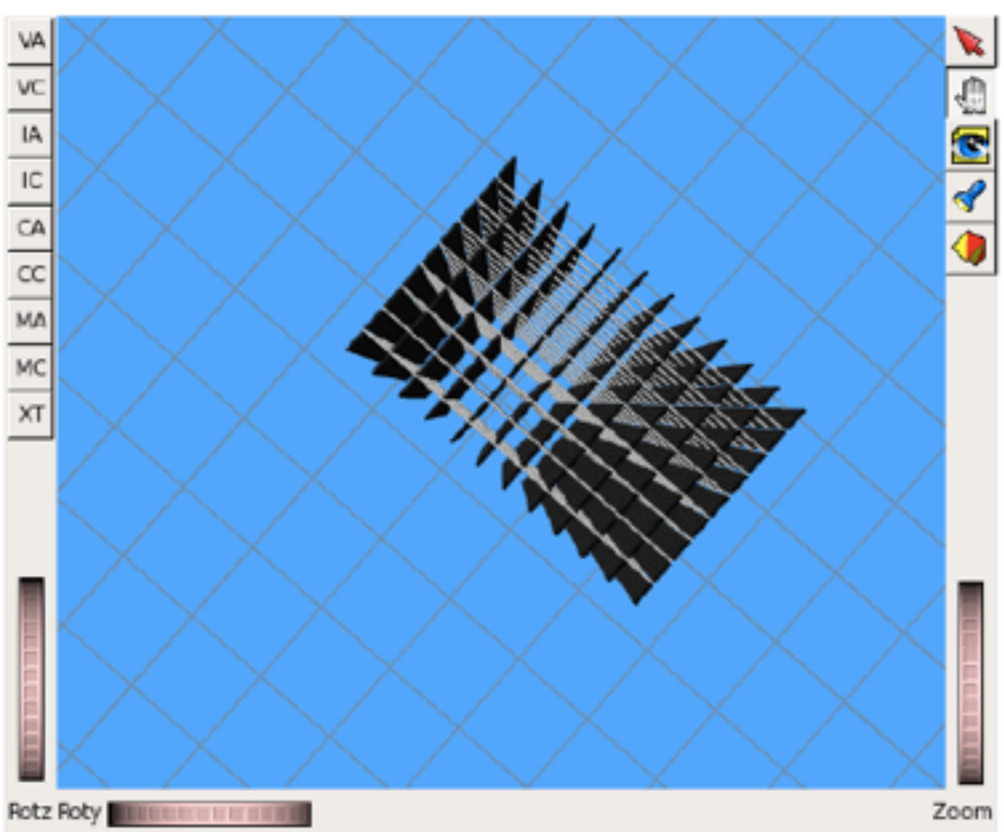
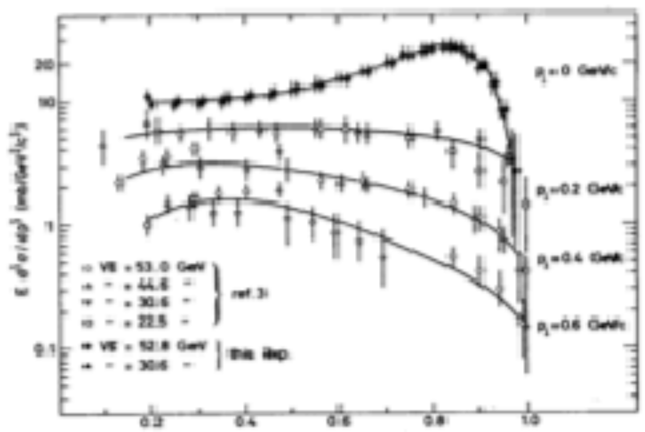
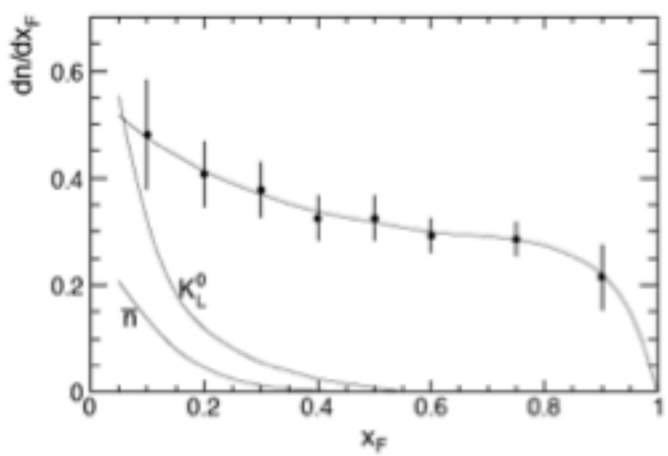


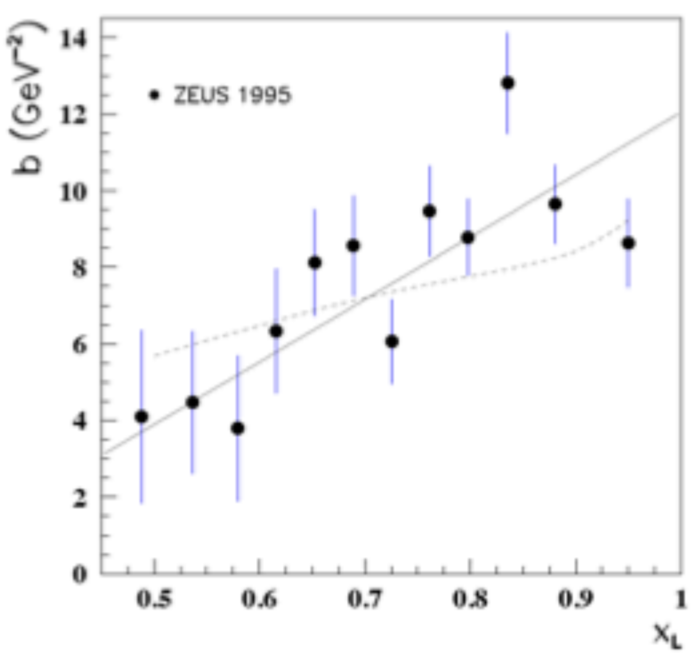
Figure 4: ZDC Drawn with VP1. Plot shows the grid of Strips and Pixels within the EMXY Module

ATLAS ZDC designed to give physics-based luminosity for early pp LHC running. Data from HERA, Tevatron and RHIC incorporated in Acceptance/cross section calculations

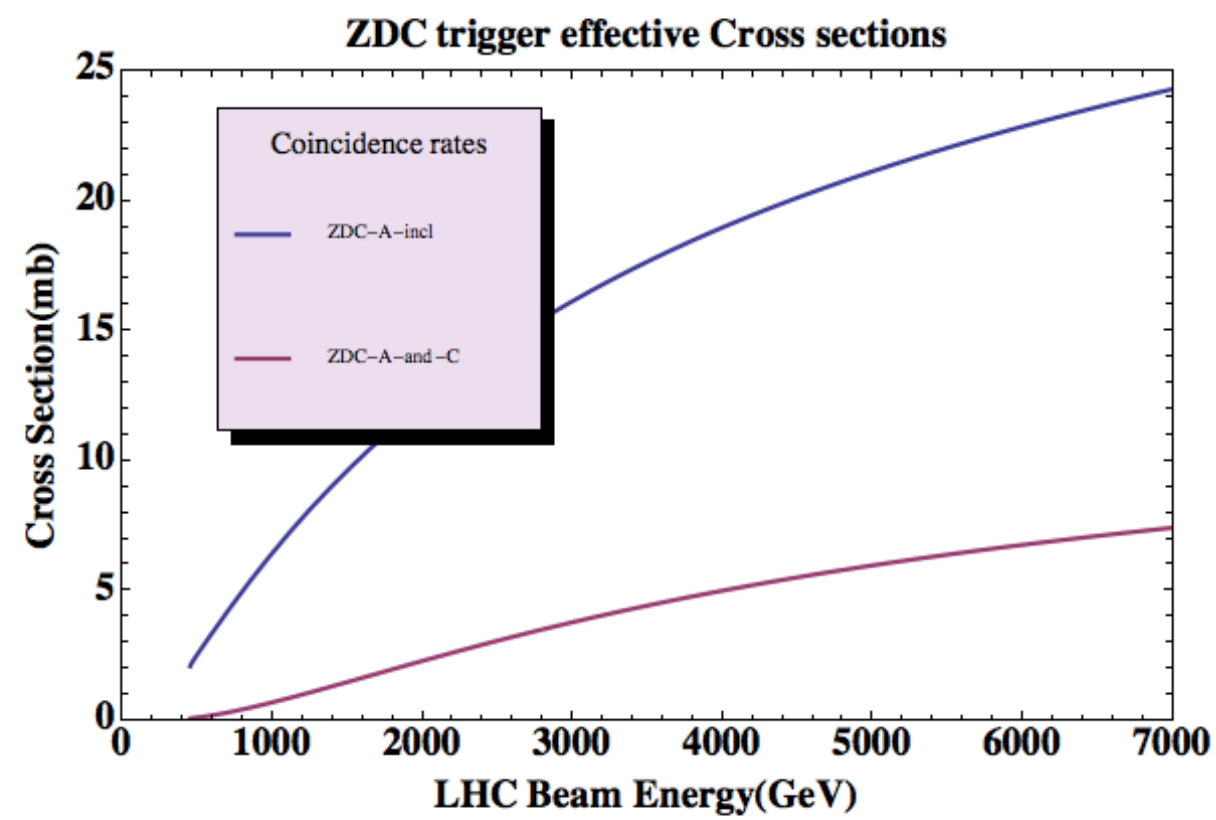




$\langle x_L \rangle$	b GeV^{-2}	$\pm(stat.)$ GeV^{-2}
0.49	4.10	1.10
0.54	4.47	1.00
0.58	3.80	1.10
0.62	6.33	1.00
0.65	8.12	0.90
0.69	8.56	0.90
0.73	6.06	0.80
0.76	9.46	0.90
0.80	8.78	0.80
0.84	12.81	1.10
0.88	9.65	0.90
0.95	8.63	1.10

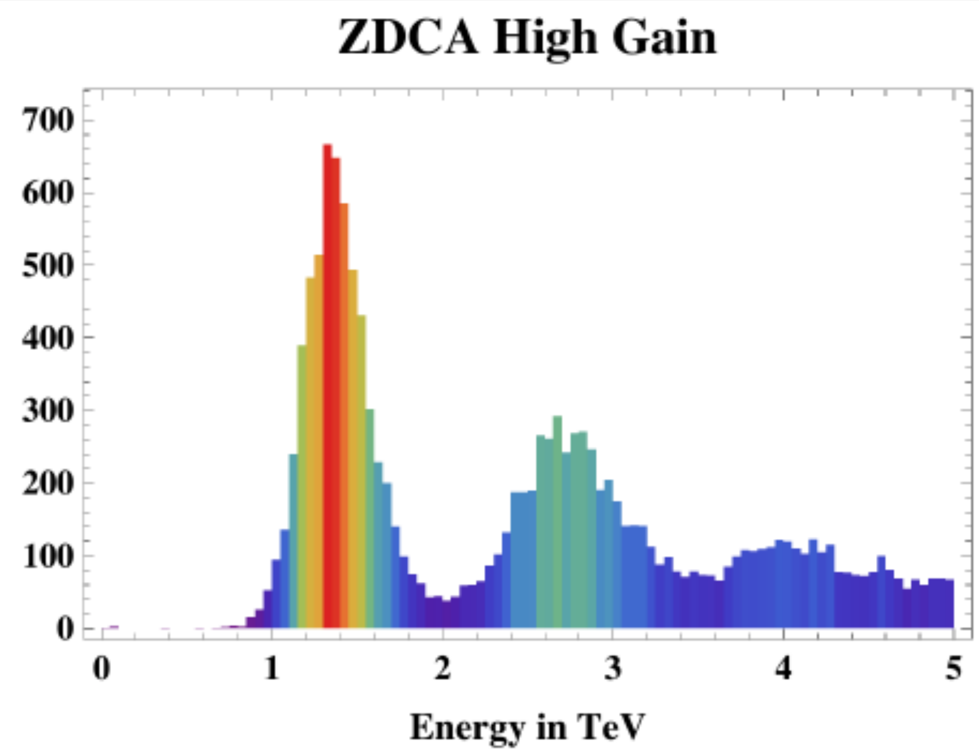


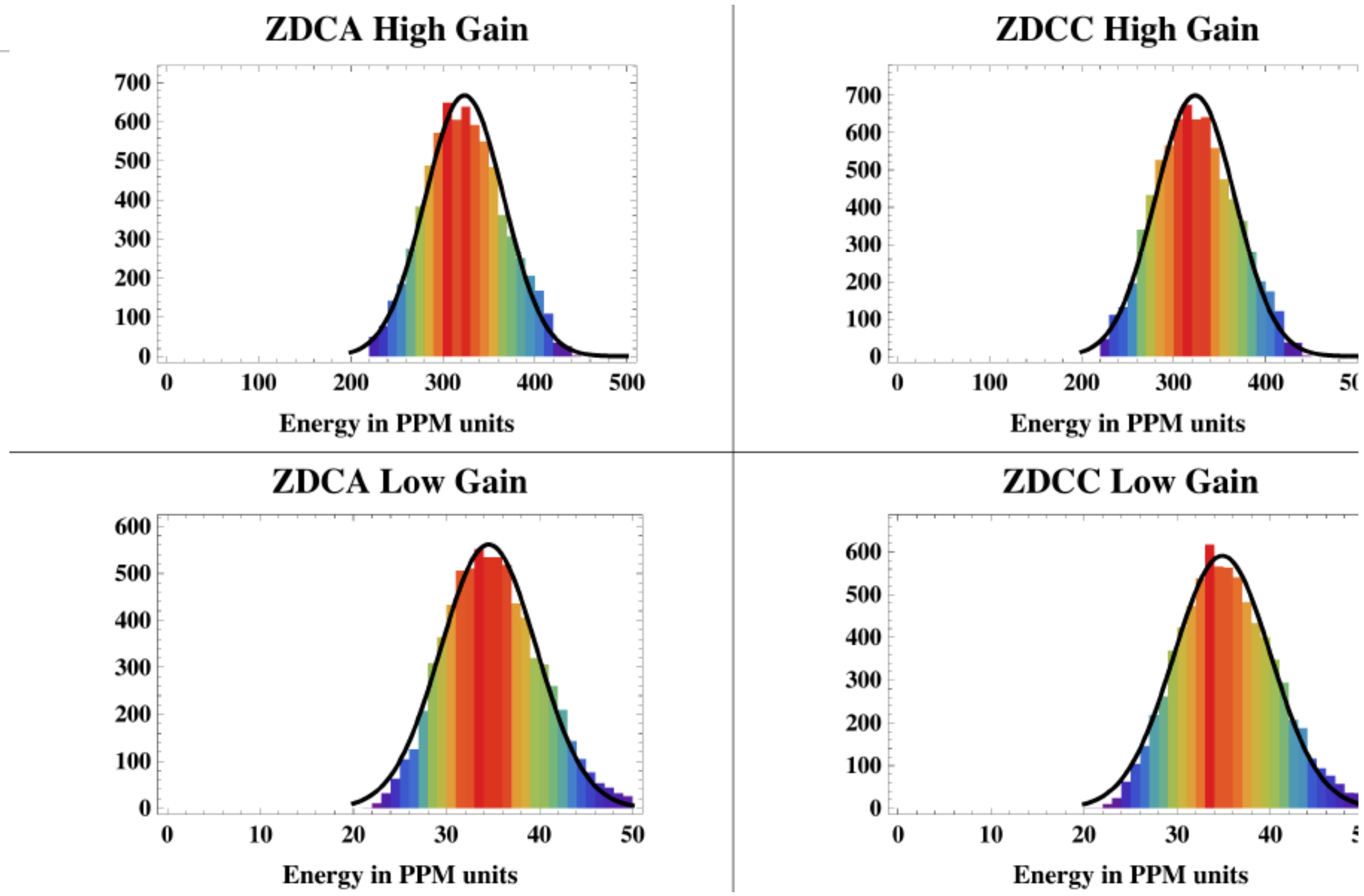
=>

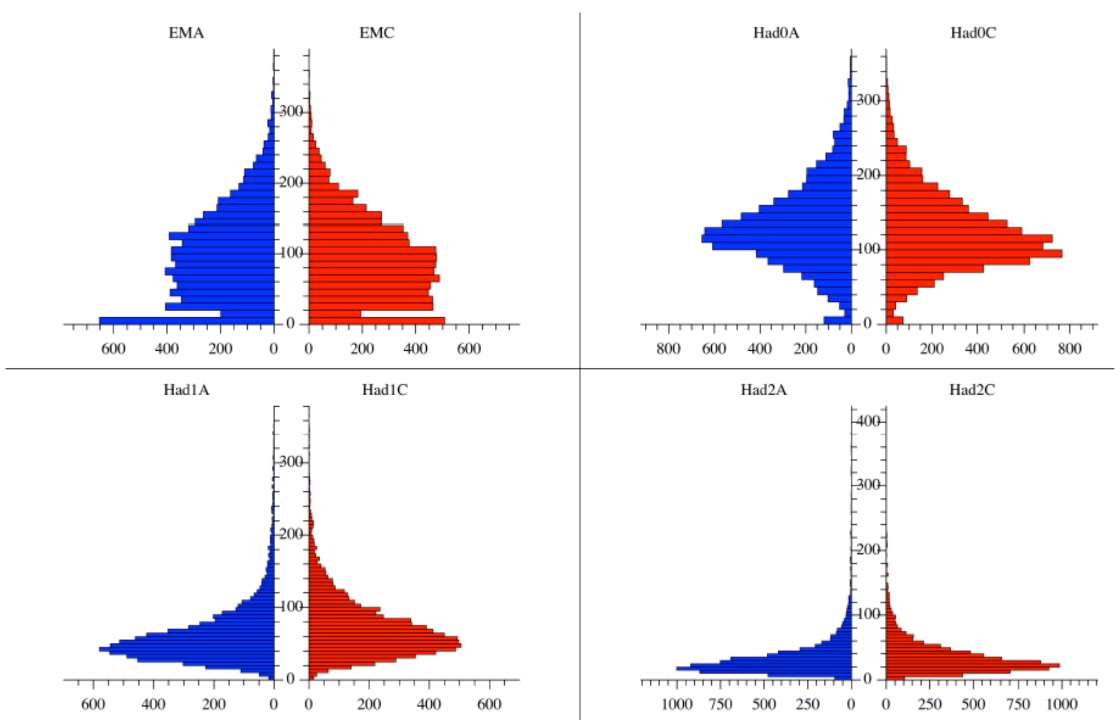


this gave excellent agreement with LHC machine extimates of Lumi.
Not the case for PHOJET, PYTHIA, etc

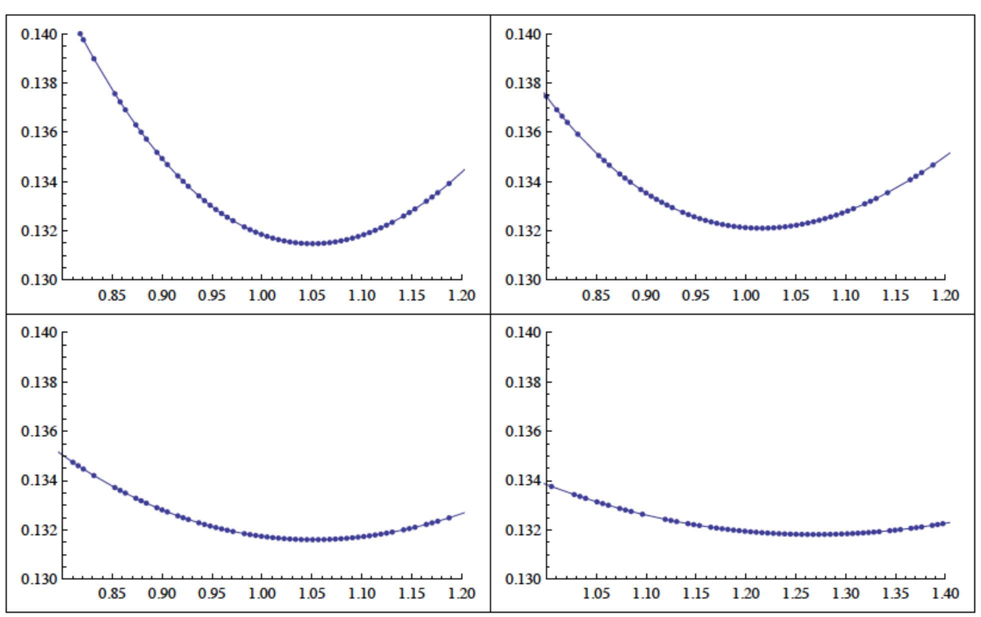
Many aspects of ZDC are self-calibrating: ie Energy scale, cross-sections

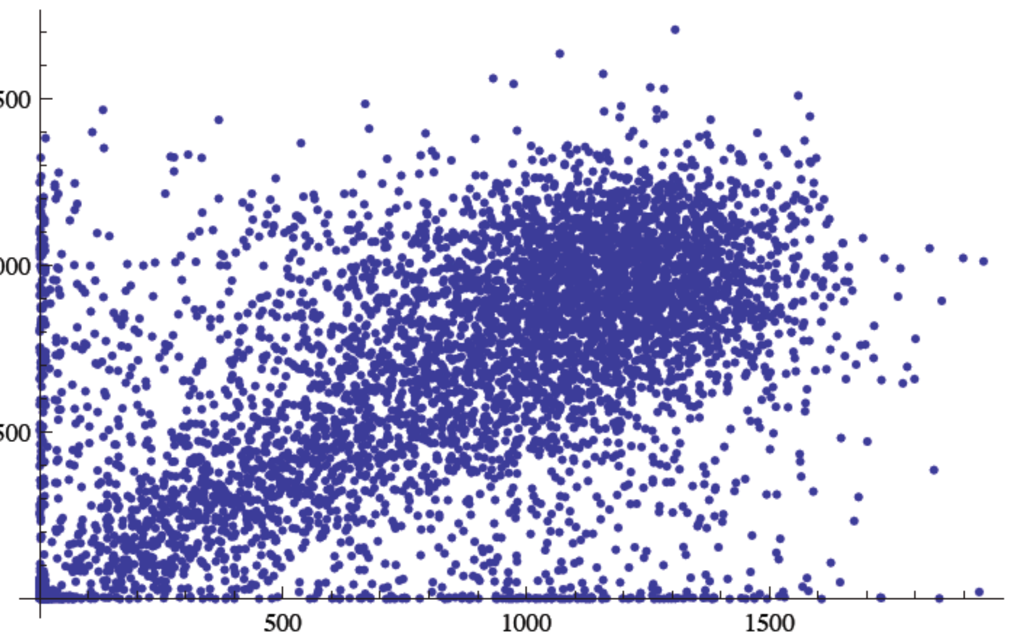






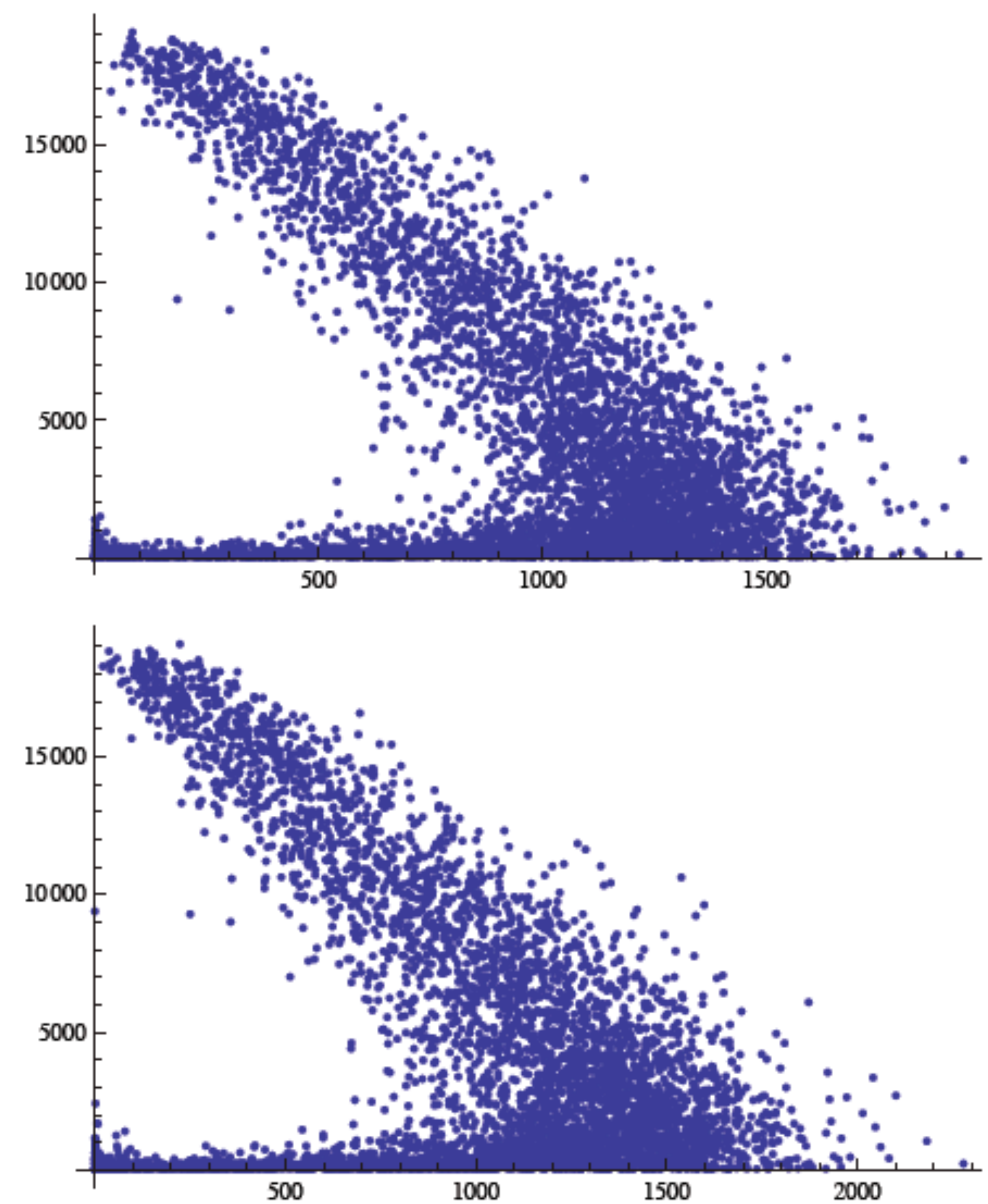
Perform offline gain balancing by minimizing rms/mean of the 1 neutron peak wrt a correction factor in EM, Had0, Ha1 and Had2 modules. A side :



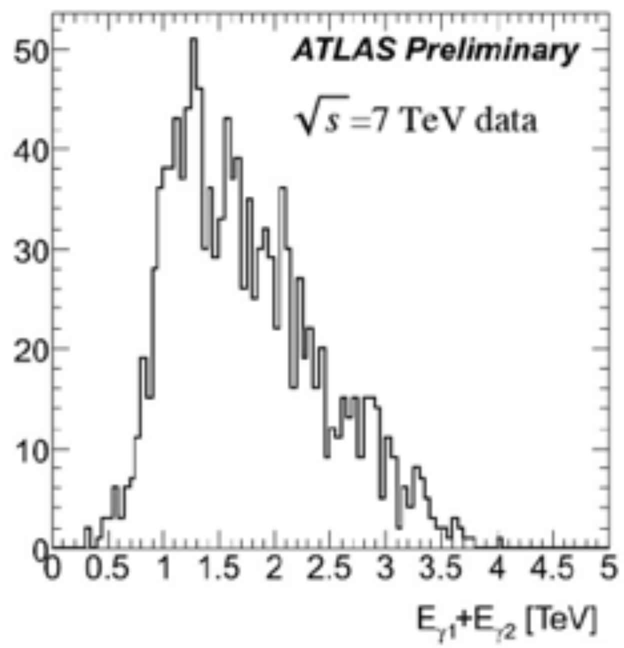


ZDC-A vs ZDC-C in Pb-Pb

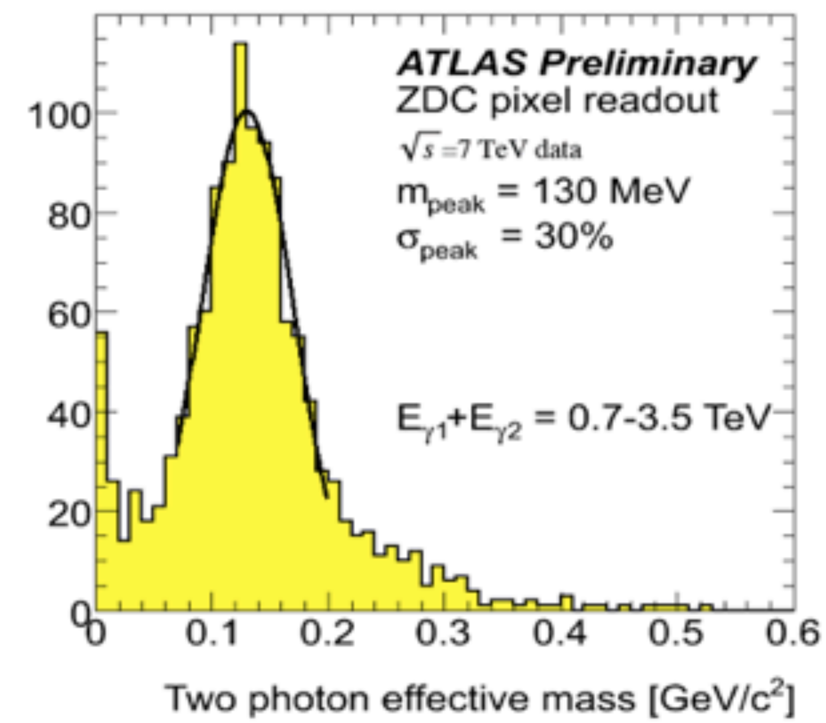
ZDCA orC vs. Central Multiplicity



2- photon reconstruction

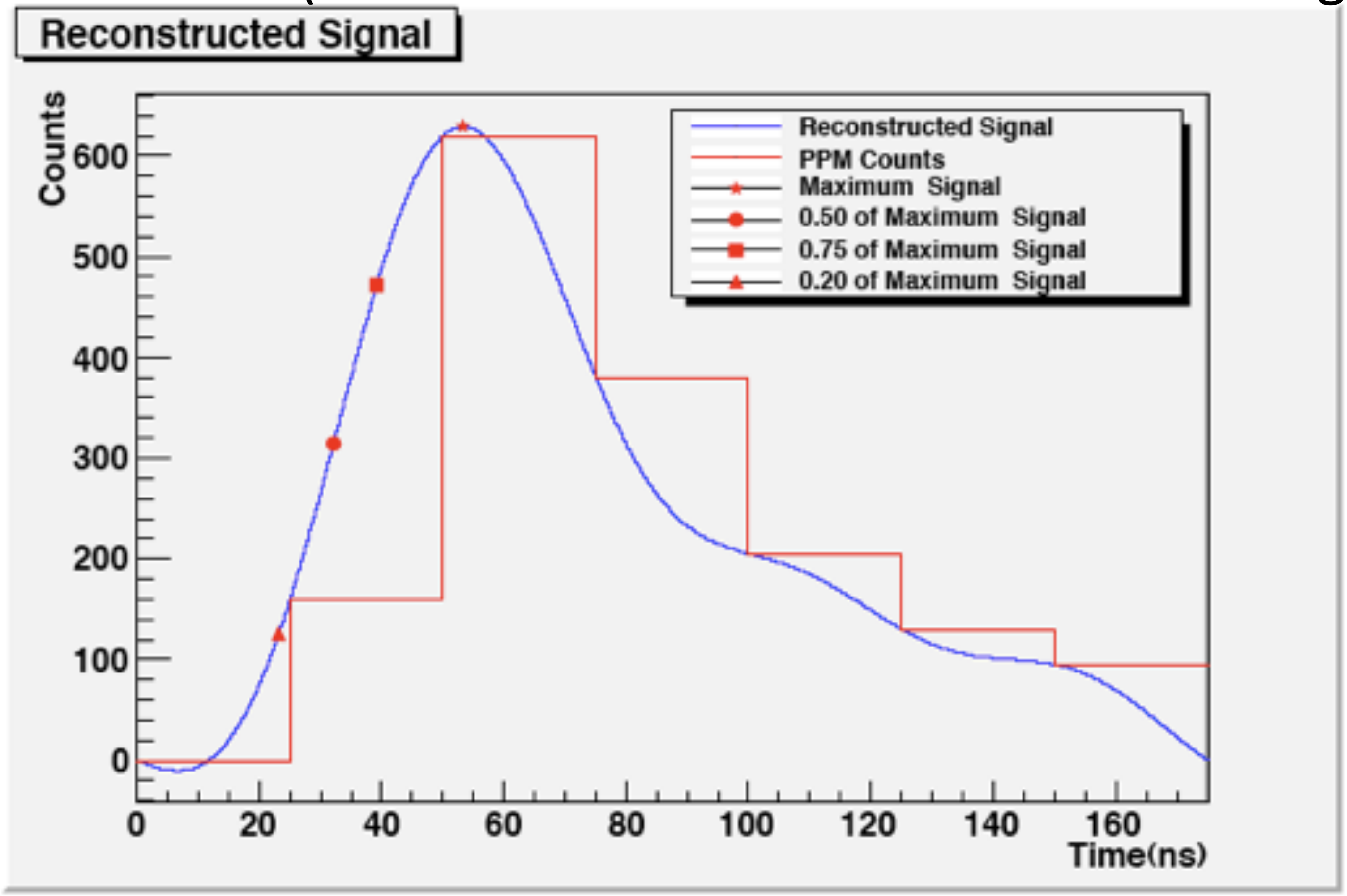


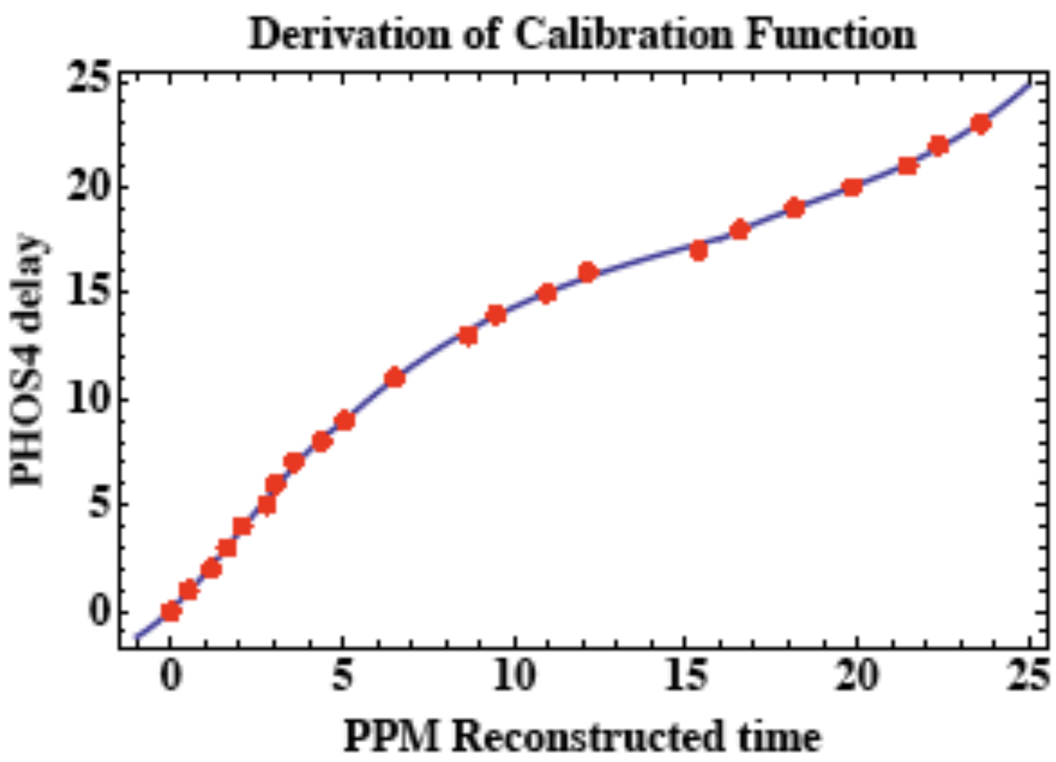
Energy distribution of 2 photon candidates in the ZDC, selected using the longitudin shower profile. The ZDC energy scale was established using the endpoint measured in 7 TeV collision data. Since the shower energy is concurrently measured in the "pixel" coordinate readout channels this allows energy calibration to be established for these channels also.



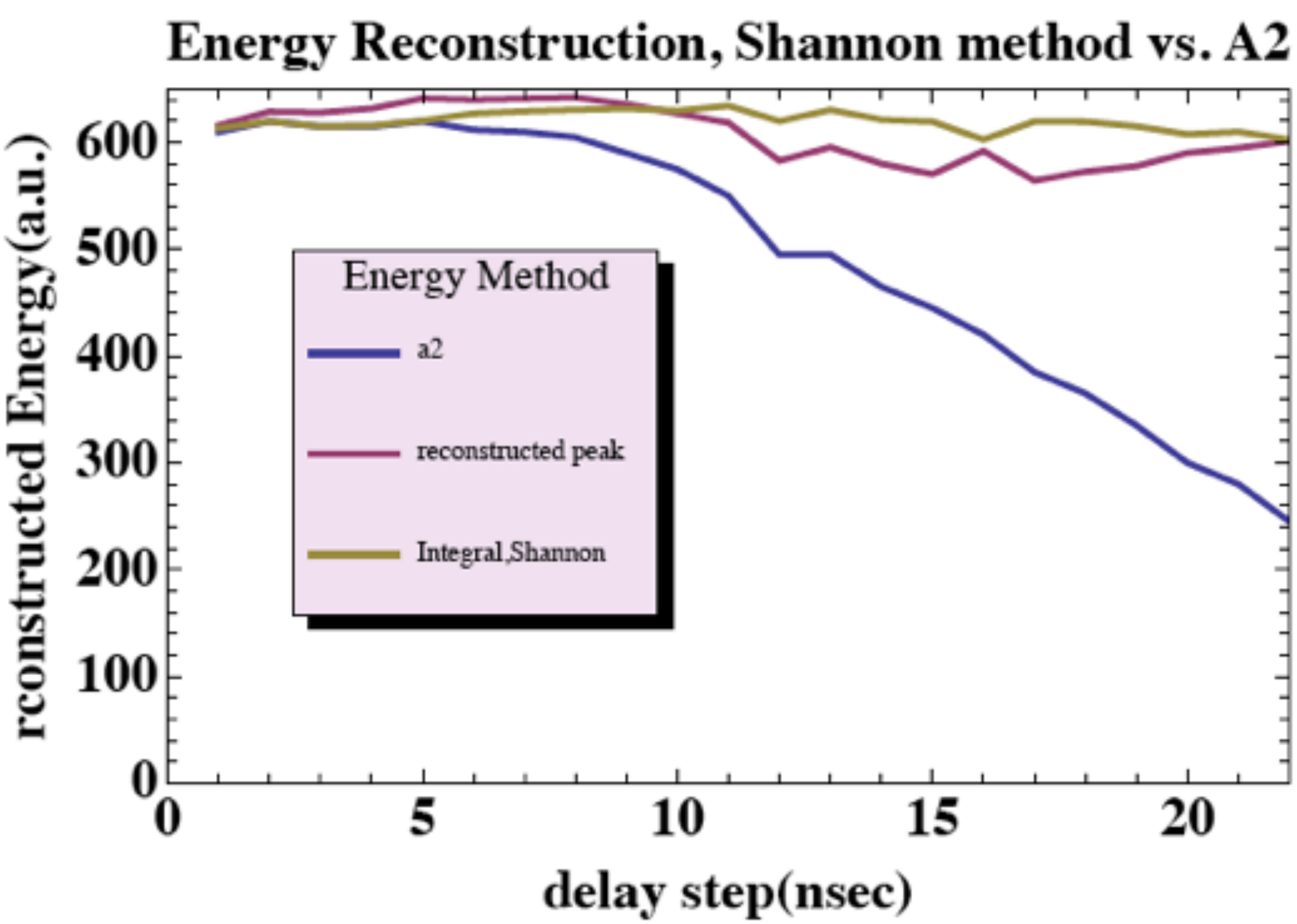
For 7 TeV collision data taken prior to LHCf removal the first ZDC module is the so-called "Hadronic x,y" which has identical energy resolution to all of the other ZDC modules. The coordinate resolution, however, is inferior to that of the high resolution EM, installed 7/20/10. Nevertheless, the reconstructed mass resolution is found to be 30% at m=130 MeV. As is found in ongoing simulation of pi0 reconstruction within the full ATLAS framework (see ZDC simulatic TWIKI), the pi0 width is completely dominated by the energy resolution. Therefore, the current state of ATLAS ZDC photon energy resolution can be inferred from this plot.

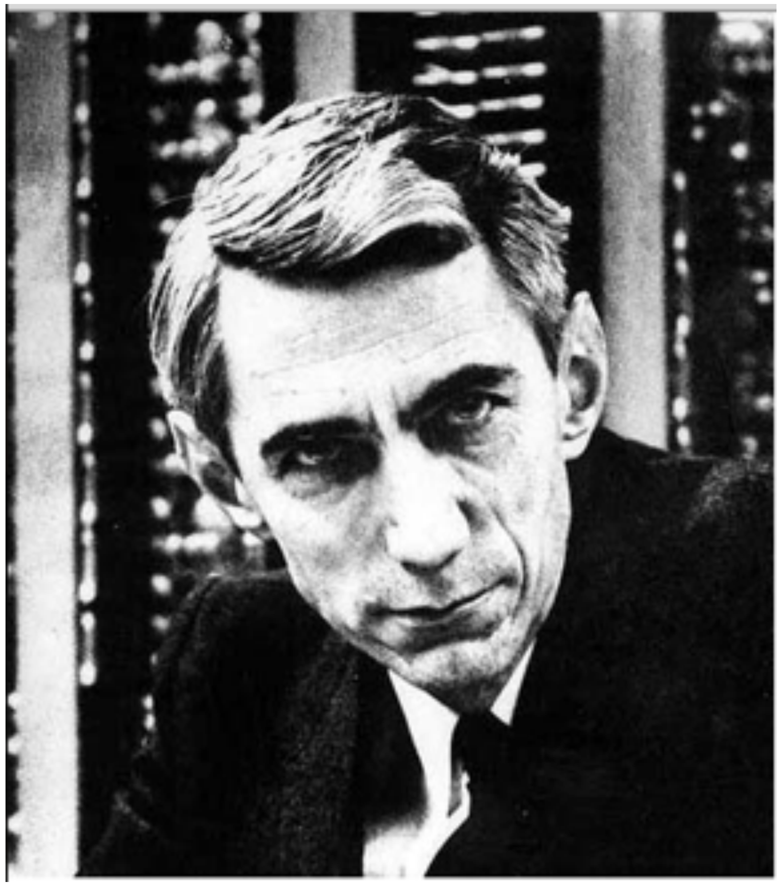
(More detailed discussion of methodology for ZDC timing on arxiv.)





(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.

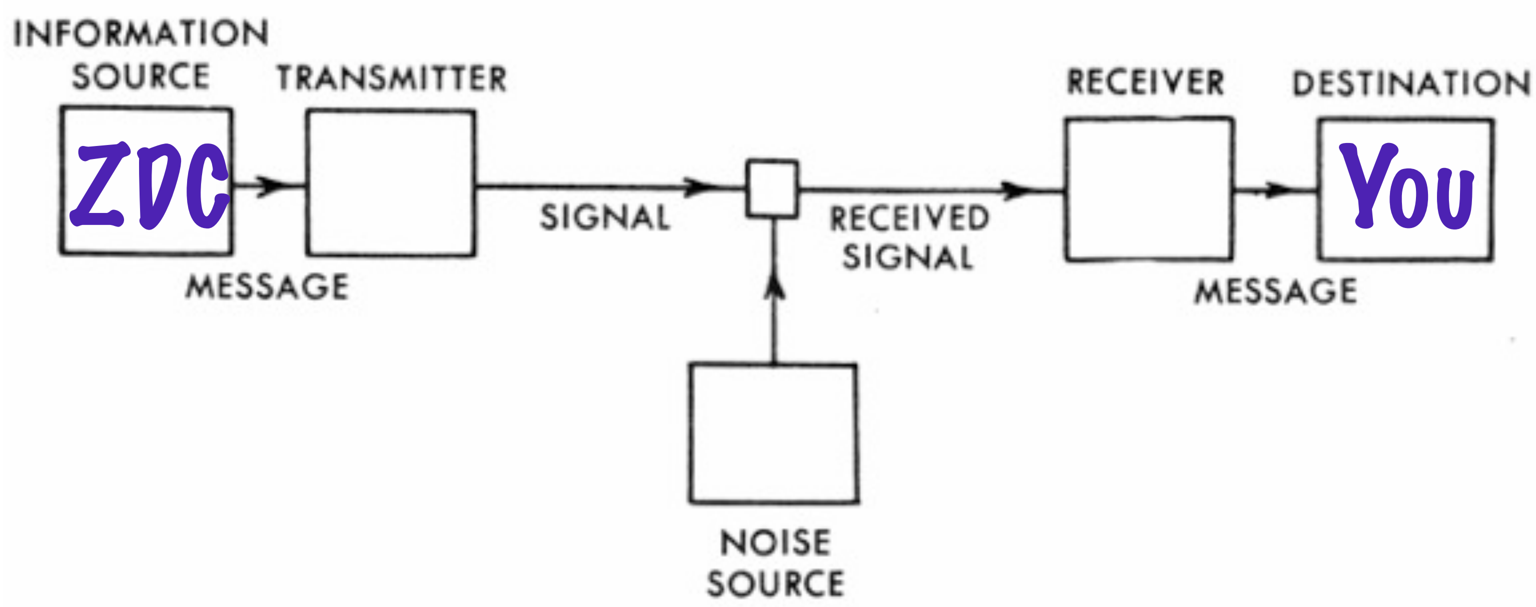
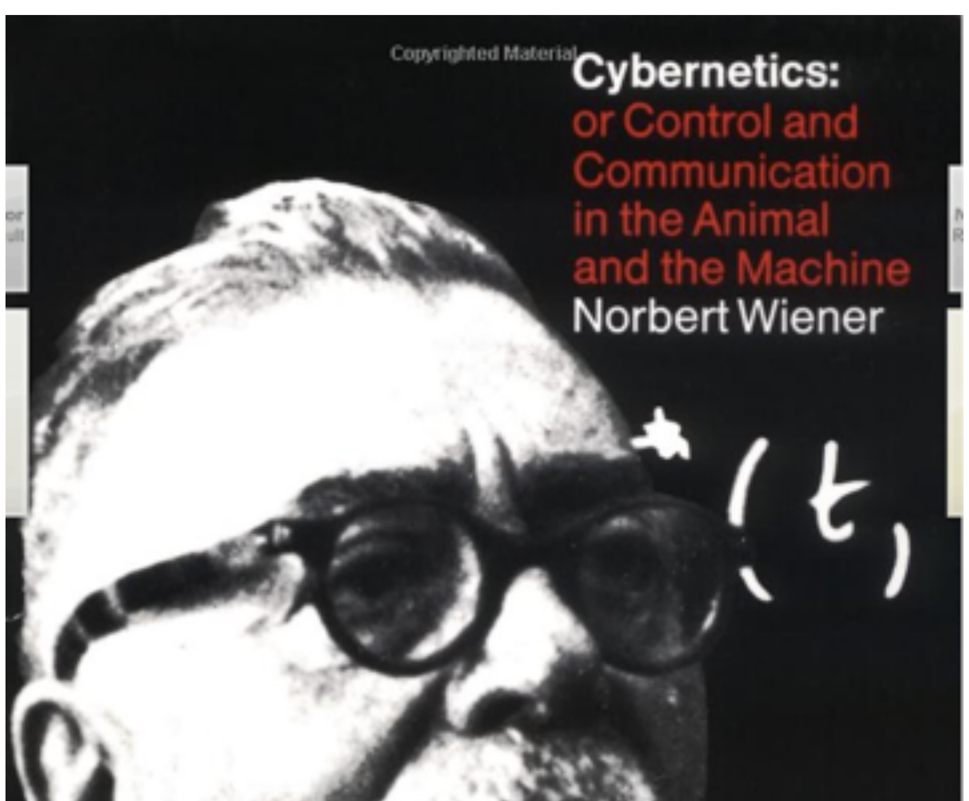
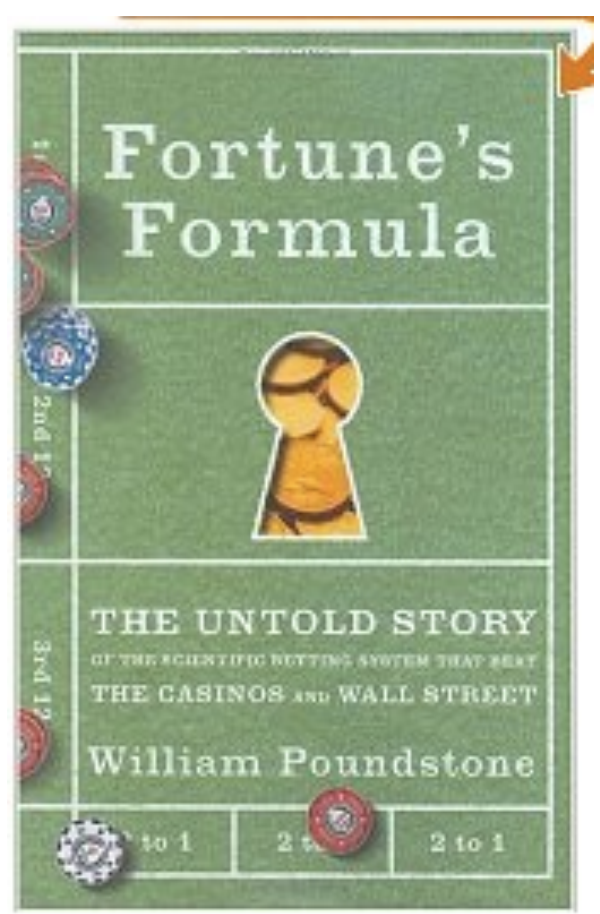


Fig. 1. — Schematic diagram of a general communication system.

books about Shannon:



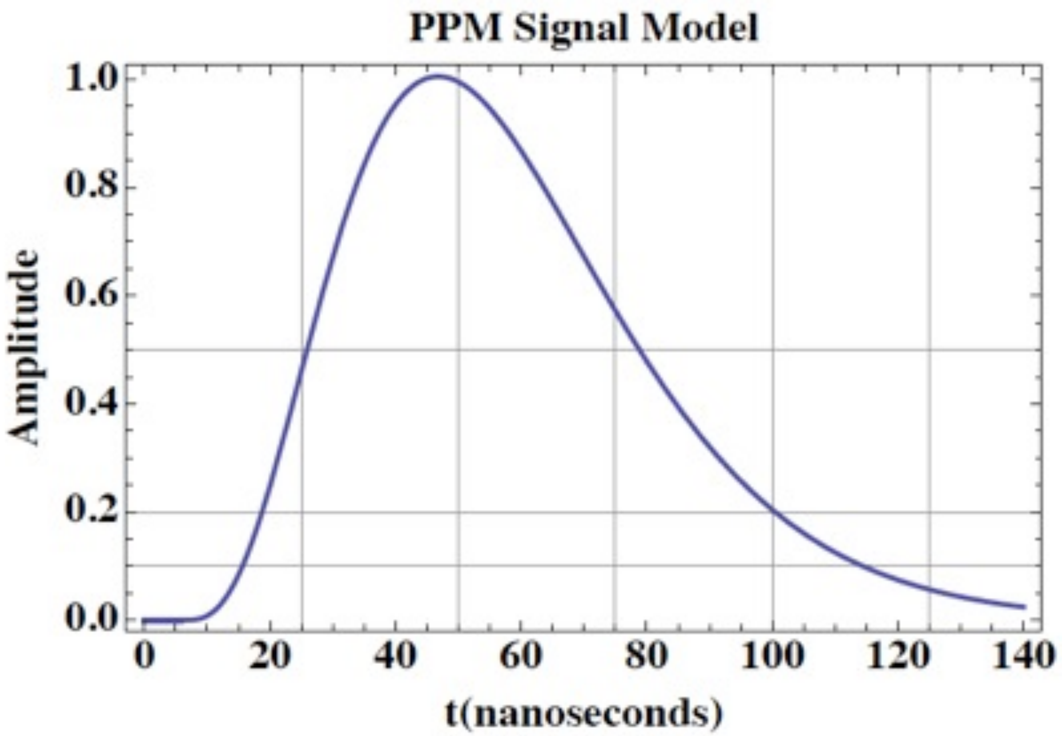


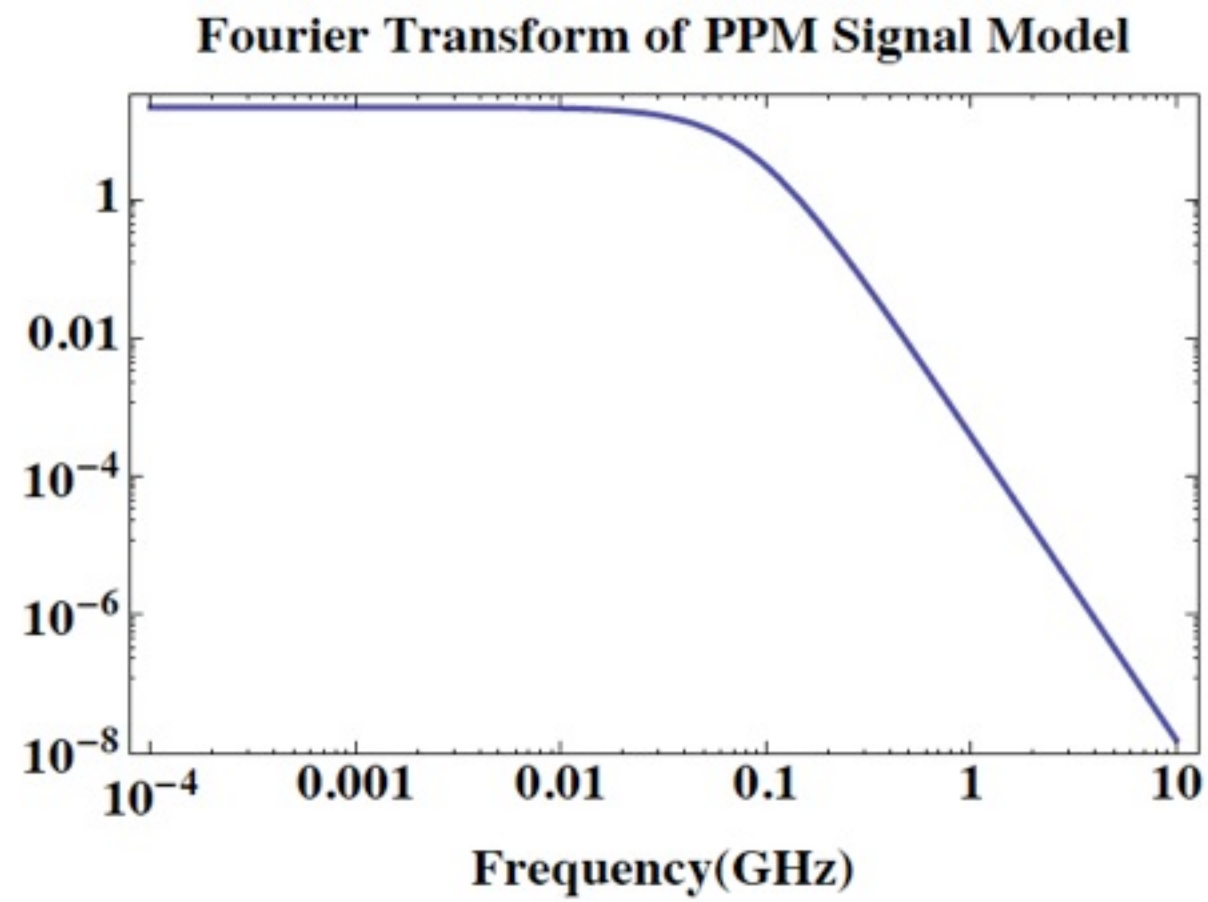
In 1956 two Bell Labs scientists discovered the scientific formula for getting rich. One was the mathematician Claude Shannon, neurotic father of our digital age, whose genius is ranked with Einstein's. The other was John L. Kelly, Jr., a gun-toting Texas-born physicist. Together they applied the science 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]
```

$$0.0000662123 \left(\frac{6.14786\, e^{6 i \omega}}{\left(\frac{1}{12} - i\omega\right)^{4.4}} + \frac{0.\, e^{-6 i \omega}}{\left(\frac{1}{12} + i\omega\right)^{4.4}} + (0. + 0.\, i)\, \text{Hypergeometric1F1}\left[1, 5.4, -\frac{1}{2} - 6 i \omega\right] - \right.$$

$$\left(4.26326 \times 10^{-13} + 1.25056 \times 10^{-12}\, i\right) \text{Hypergeometric1F1}\left[1, 5.4, -\frac{1}{2} + 6 i \omega\right] +$$

$$\frac{(0. + 0.\, i)\, \text{HypergeometricPFQ}\left[\{-3.4, -3.9\}, \{-3.4, -3.9\}, -\frac{1}{2} - 6 i \omega\right]}{\left(\frac{1}{12} + i\omega\right)^{4.4}} -$$

$$\left. \frac{(0.967912 + 2.97893\, i)\, \text{HypergeometricPFQ}\left[\{-3.4, -3.9\}, \{-3.4, -3.9\}, -\frac{1}{2} + 6 i \omega\right]}{\left(\frac{1}{12} - i\omega\right)^{4.4}} \right)$$

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

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

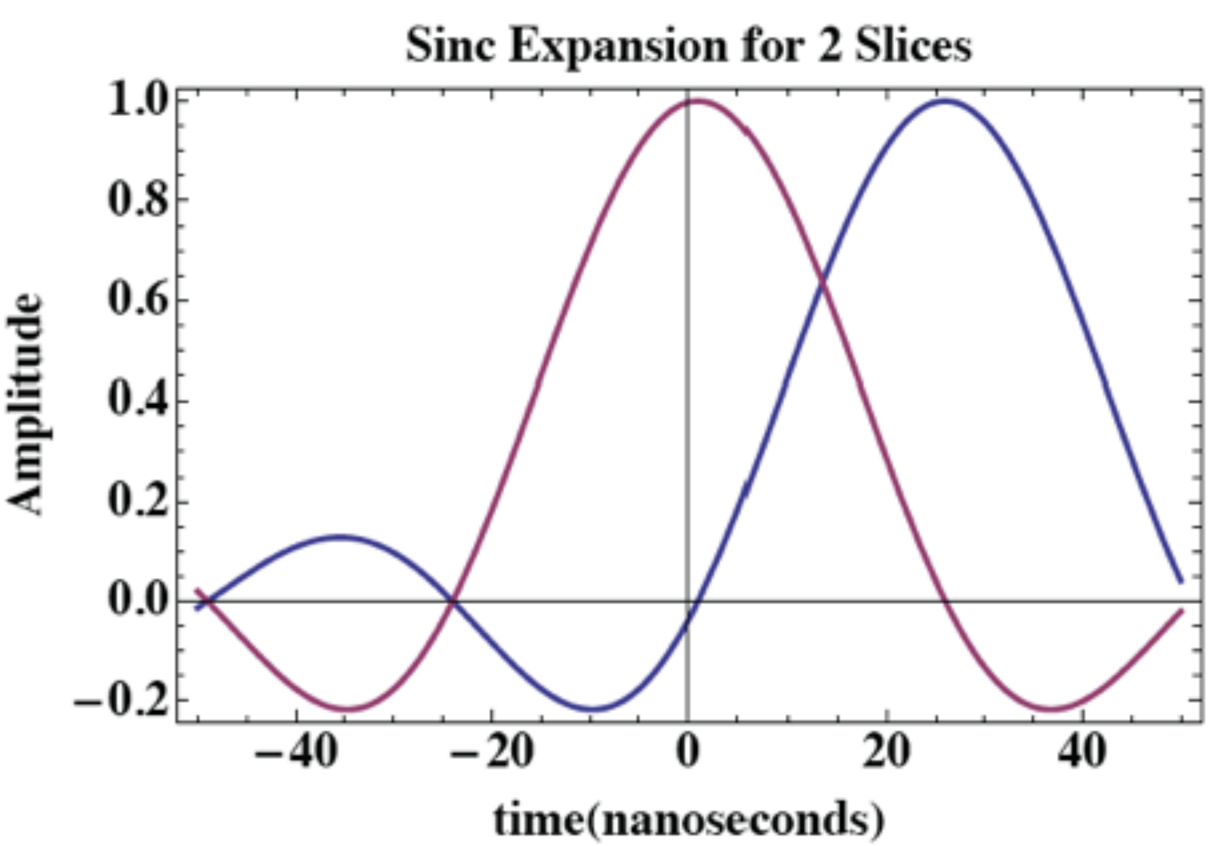
An animated gif can be found at:
http://www.phenix.bnl.gov/phenix/WWW/publish/swhite/ShannonFilm.gif

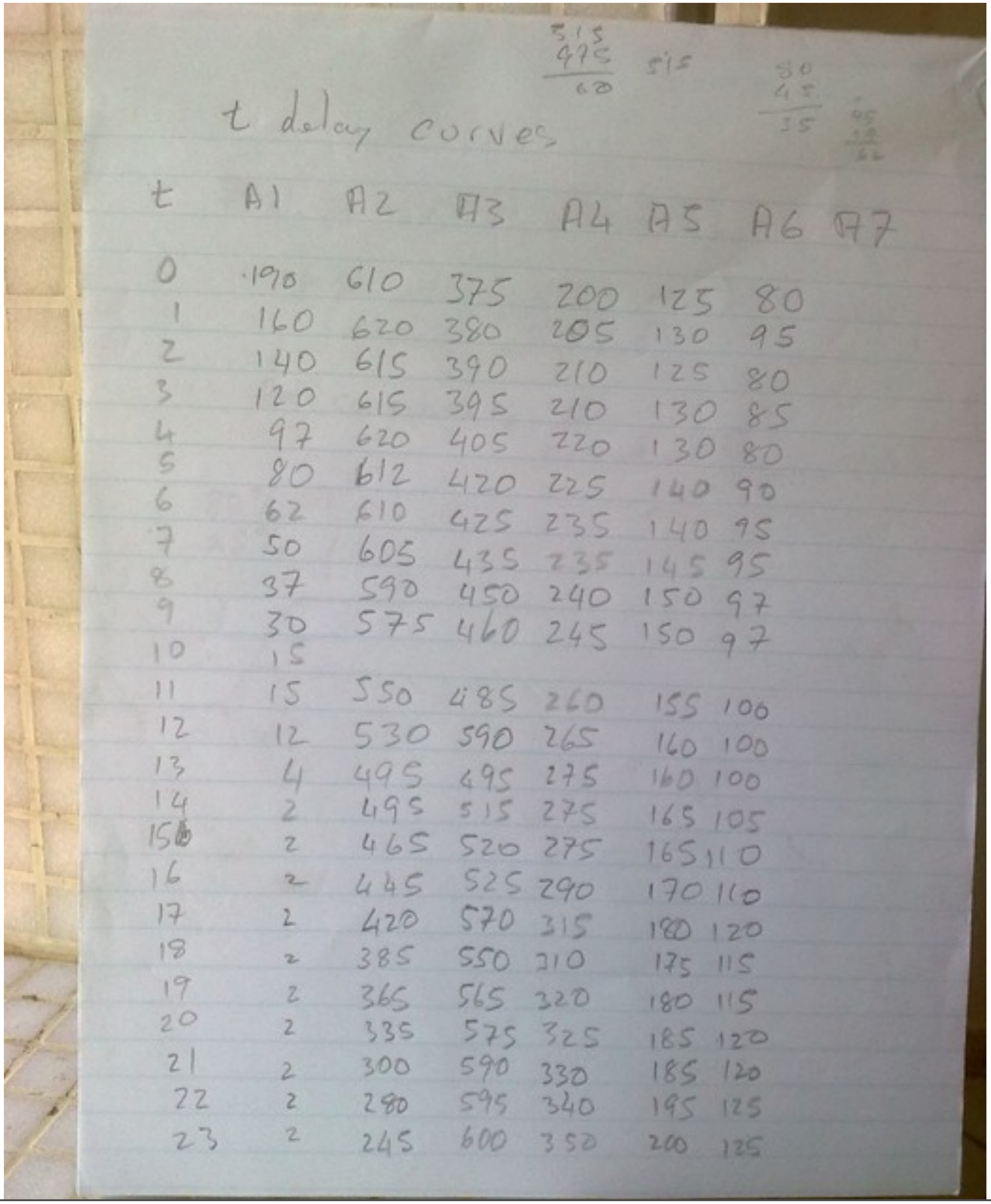
ATLAS data set used to develop ZDC reconstruction and do L1calo calibration (in Mathematica 7.0)

Reconstruction of ZDC Pre-Processor Data and its timing Calibration

Soumya Mohapatra, Andrei Poblaguev and Sebastian White

Aug.8,2010





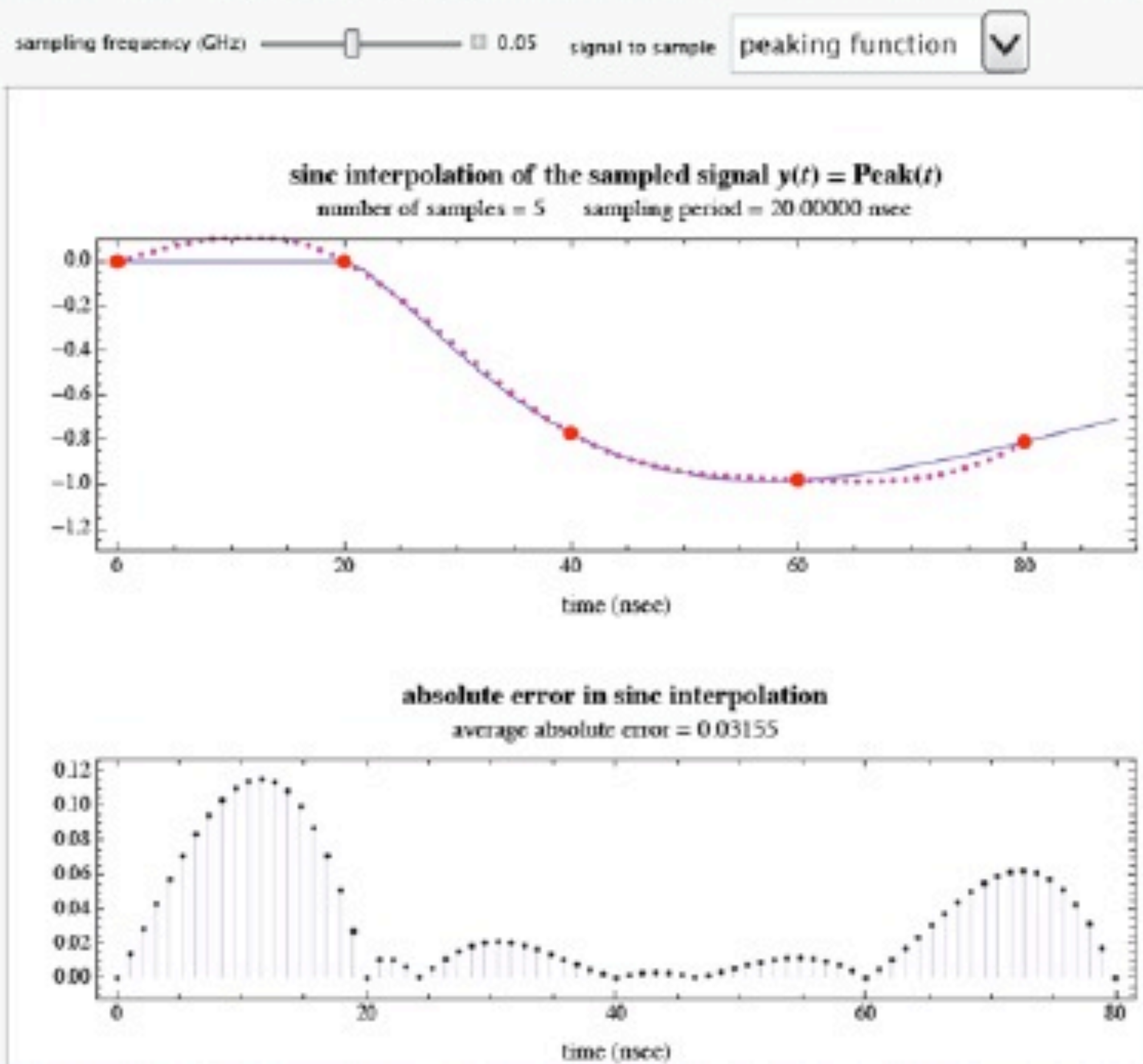
515
475
60
515
50
45
35

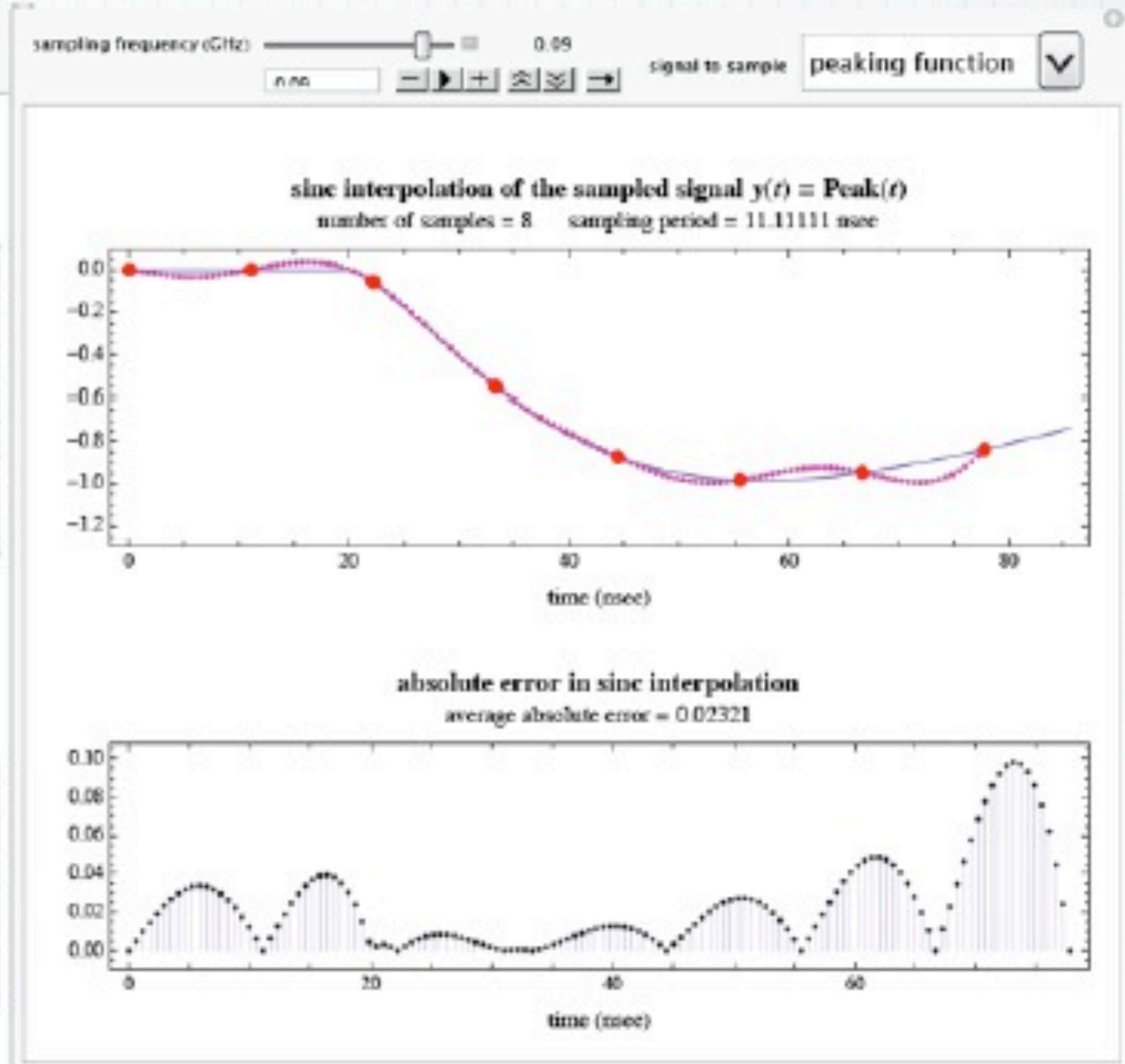
t delay curves

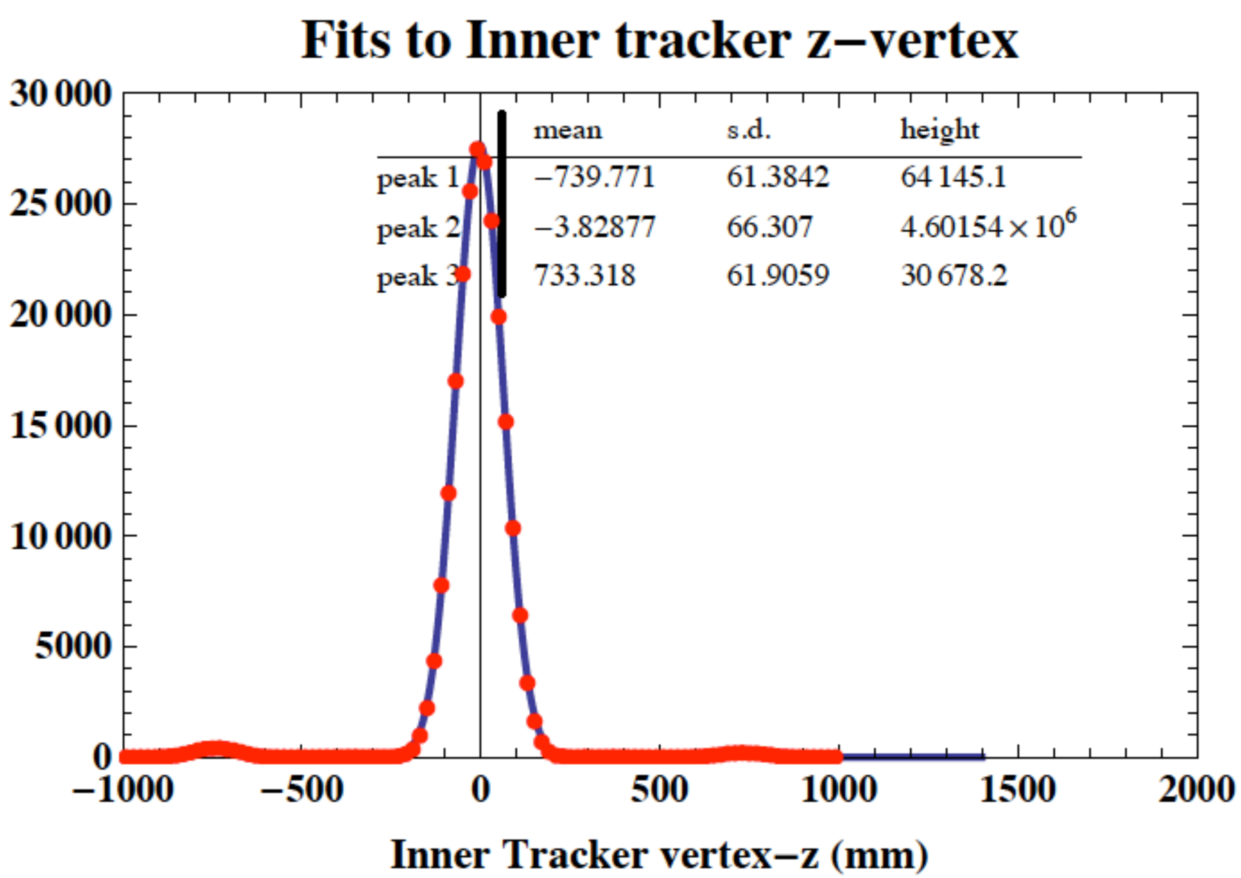
t	A1	A2	A3	A4	A5	A6	A7
0	·190	610	375	200	125	80	
1	160	620	380	205	130	95	
2	140	615	390	210	125	80	
3	120	615	395	210	130	85	
4	97	620	405	220	130	80	
5	80	612	420	225	140	90	
6	62	610	425	235	140	95	
7	50	605	435	235	145	95	
8	37	590	450	240	150	97	
9	30	575	460	245	150	97	
10	15						
11	15	550	485	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	

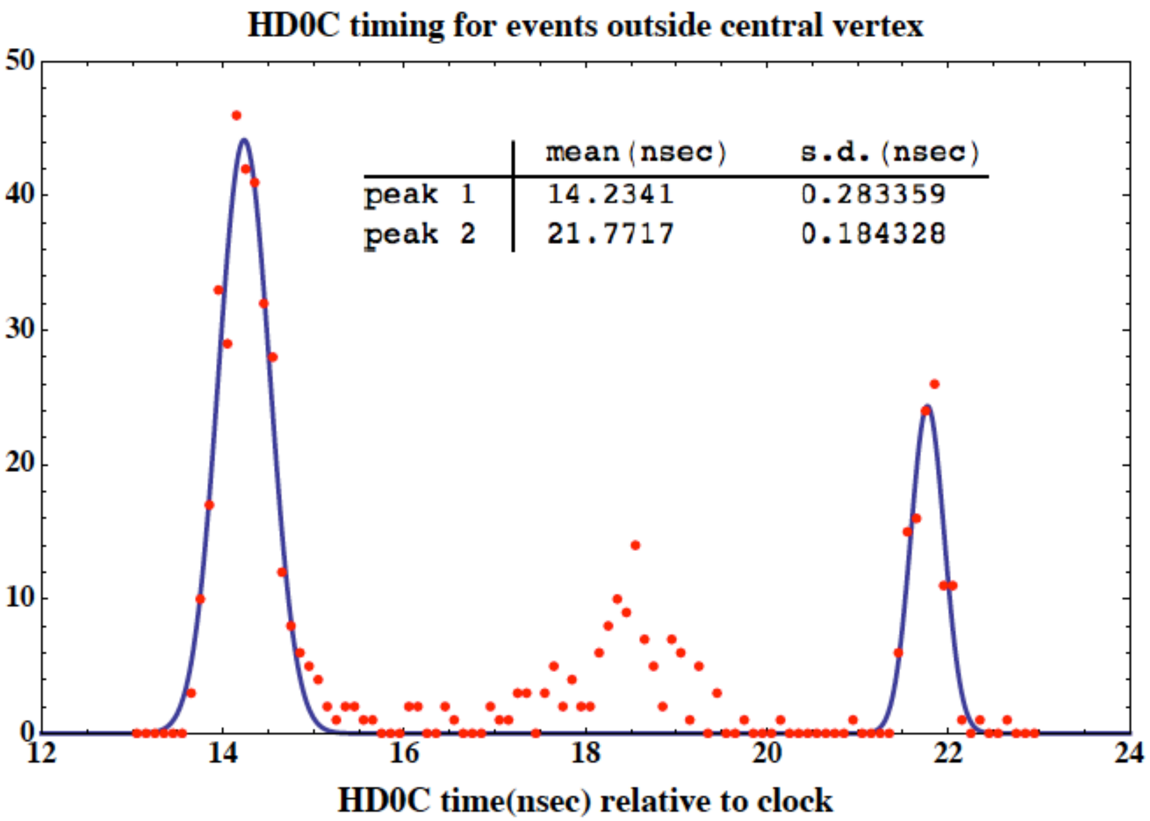
Signal Reconstruction

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

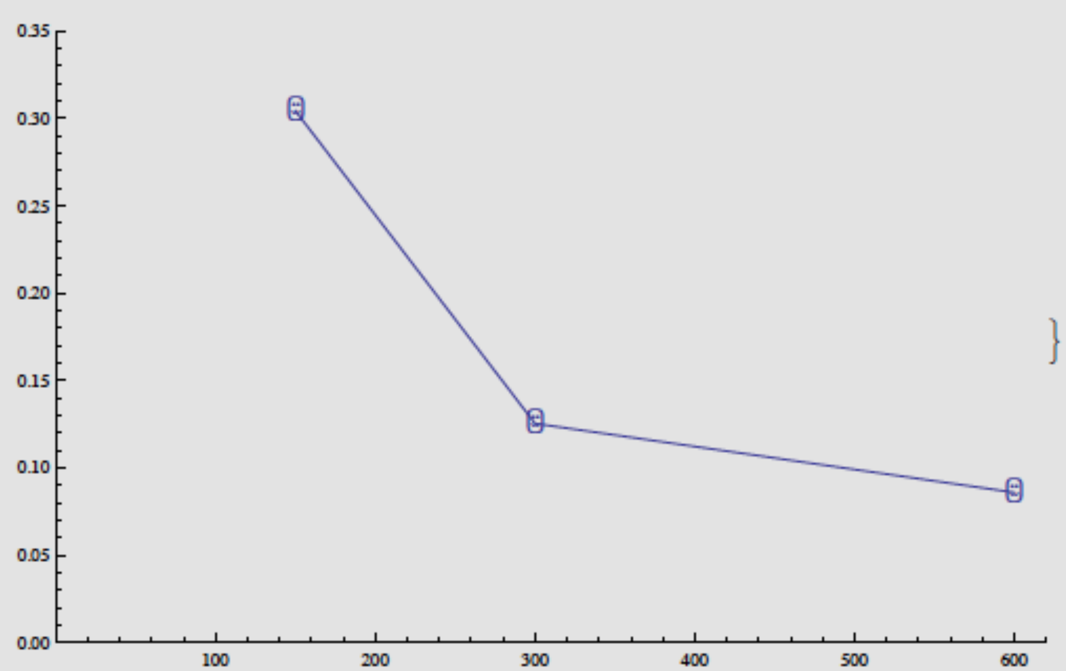








	mean (nsec)	rms
ZDC_EMA	23.4269	0.161383
ZDC_EMA_100-200	23.4313	0.304363
ZDC_EMA_200-400	23.4084	0.125345
ZDC_EMA_400-800	23.4356	0.0859118



simple test of energy dependence

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.
- We are beginning to identify technologies which could satisfy both pileup and rate/rad-dose requirements.
- Our community is in discussions concerning merging fast timing and calorimetry generic R&D.
- Growing appreciation that we are behind schedule with focusing realistic effort on phase II upgrades.
- Near term busy testing schedule to which others are welcome.