Photonis MCP-PMT and Fast Waveform Digitizer Studies at BNL

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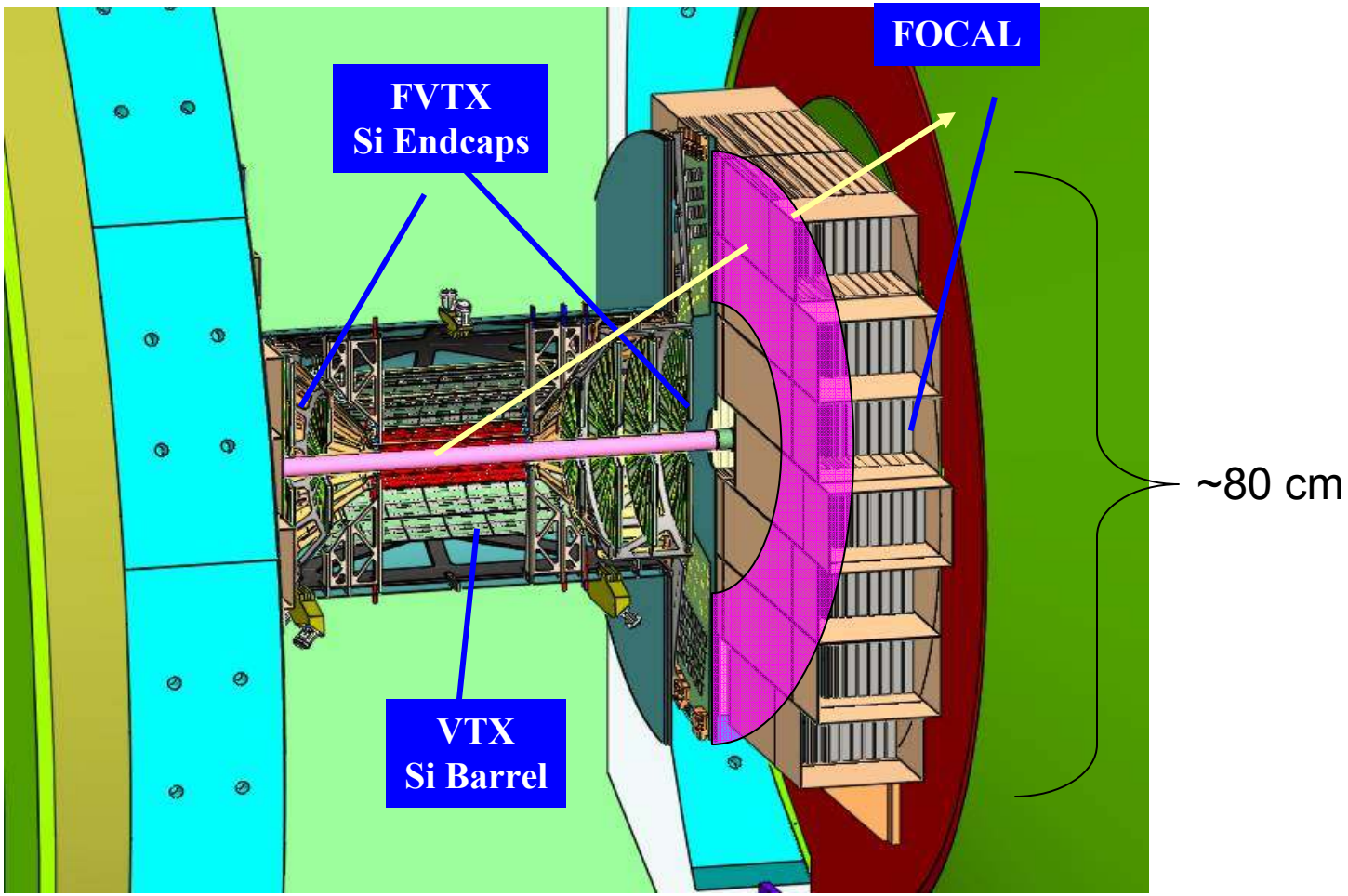
BROOKHAVEN NATIONAL LABORATORY

Near Term TOF Proposal for PHENIX

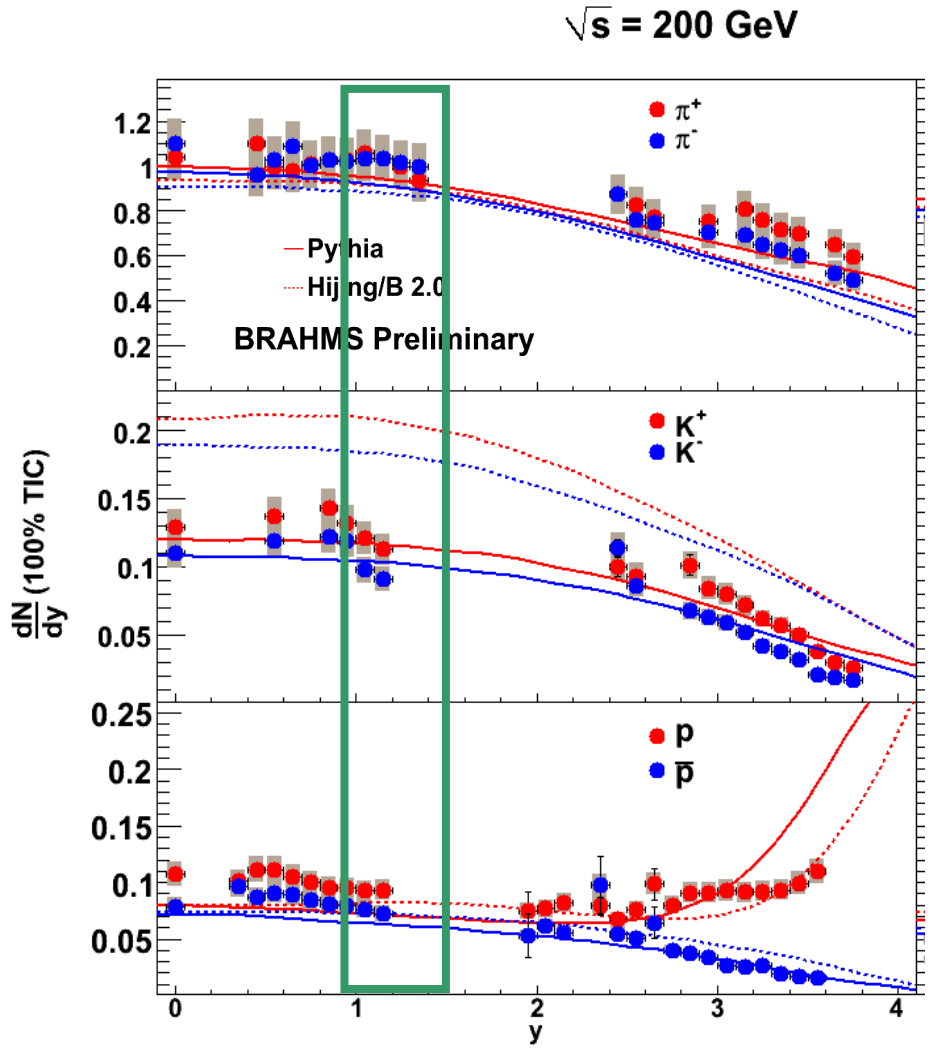


- 10 ps Large ACCEPTANCE TOF WALL, $0.8<\eta<1.5$ (FOTOF)
  - Will add dramatically to PHENIX physics program
  - Only ~50 cm flight path, and ~1 sq m total detector area
  - Need 5000 channels (detector element ~ cm^2) for <10% occupancy in 5% central Au+Au
  - Also need tracking layer to improve tracking
- Will possibly need to replace the BBC to give a start time, though one could also fill out inner ring

Possible Topics from Large Area TOF

Heavy Ion Physics

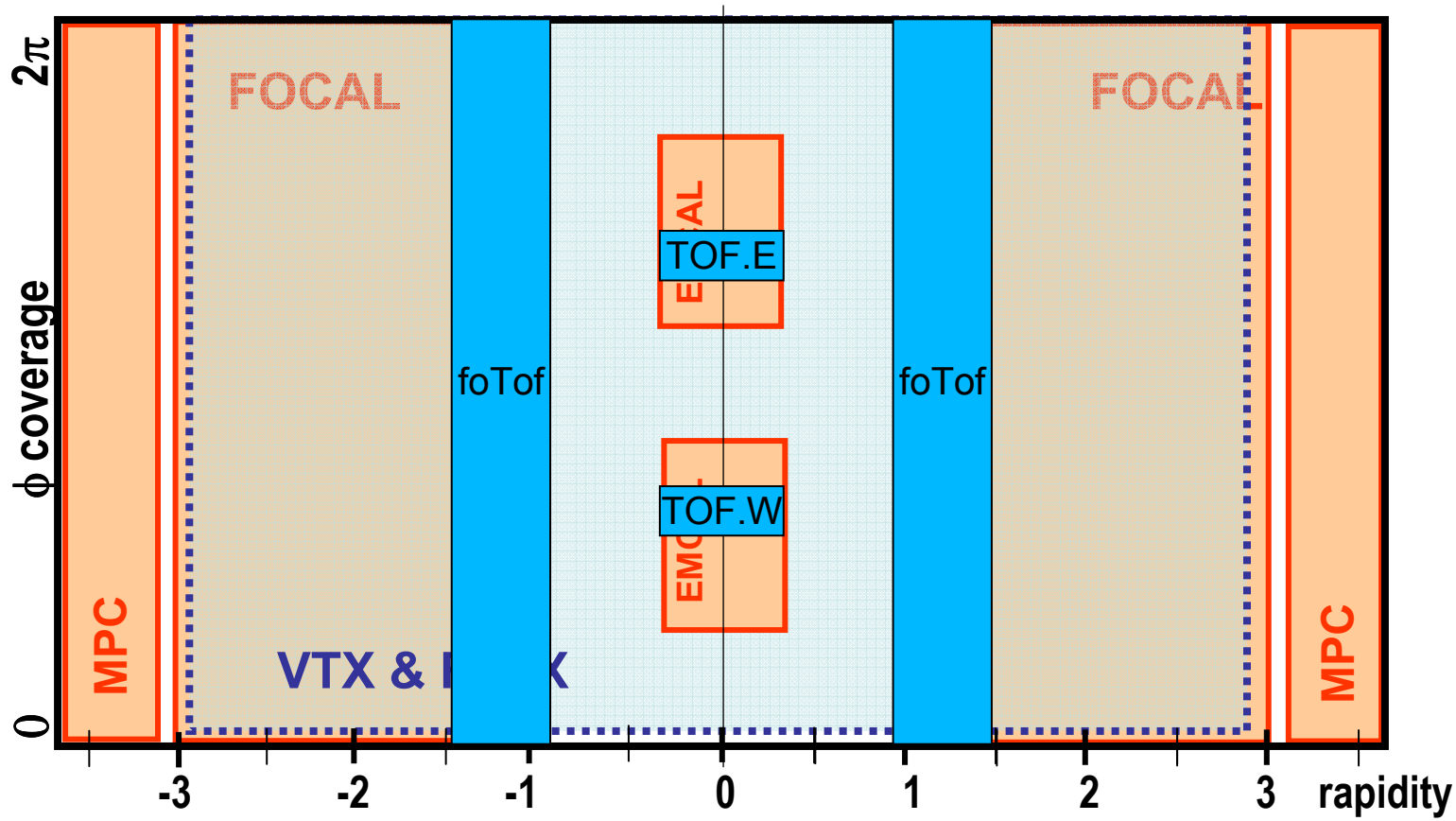
- PID'ed correlations studies
  - PID'ed studies of the ridge, shoulder, head, whatever
- Studies of the baryon/meson anomaly
- Direct Charm Reconstruction D meson -> pi+K
- PID v2
  - Quark Scaling Mechanisms
- Resonances at forward rapidities
  - Λ, ϕ
- PID in energy scan (horn, nose, ear)



Proton Spin Physics

- IFF*Transversity
  - Signal gets better when going forward
- Flavor A_N
  - K+,K- anomaly, flavor separation of A_N
  - Dependence of asymm on Quark Content
- Flavor ALL
- Longitudinal spin transfer to Lambda

Future PHENIX Acceptance for Hard Probes

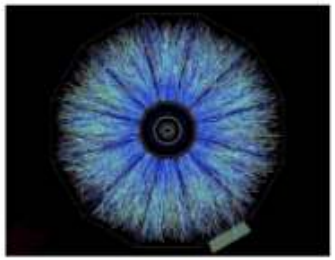


- Large Acceptance will be added with VTX and FVTX
- Particle ID in PHENIX is in a relative small region
- Adds enormous acceptance for PID (~8x), with hopefully comparable performance
  - Pi/K to p~2.5 GeV, K/p to p~4 GeV
  - Note that this translates to K/p p_T~ 2.5 GeV

Comparison of magnetic fields

The Earths magnetic field	0.6 Gauss
A common, hand-held magnet	100 Gauss
The strongest steady magnetic fields achieved so far in the laboratory	4.5×10^5 Gauss
The strongest man-made fields ever achieved, if only briefly	10^7 Gauss
Typical surface, polar magnetic fields of radio pulsars	10^{13} Gauss
Surface field of Magnetars	10^{15} Gauss

http://solomon.as.utexas.edu/~duncan/magnetar.html



Heavy ion collisions: the strongest magnetic field ever achieved in the laboratory

Off central Gold-Gold Collisions at 100 GeV per nucleon

$$e\,B(\tau = 0.2\,\mathrm{fm}) \;=\; 10^3 \sim 10^4\ \mathrm{MeV}^2 \sim 10^{17}\,\mathrm{Gauss}$$

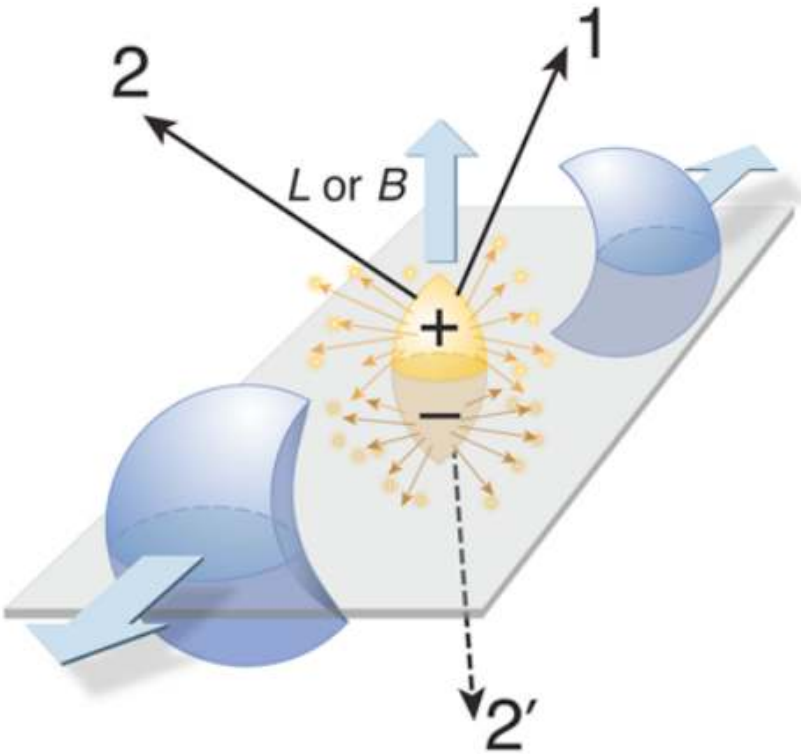
PRL 103, 251601 (2009)

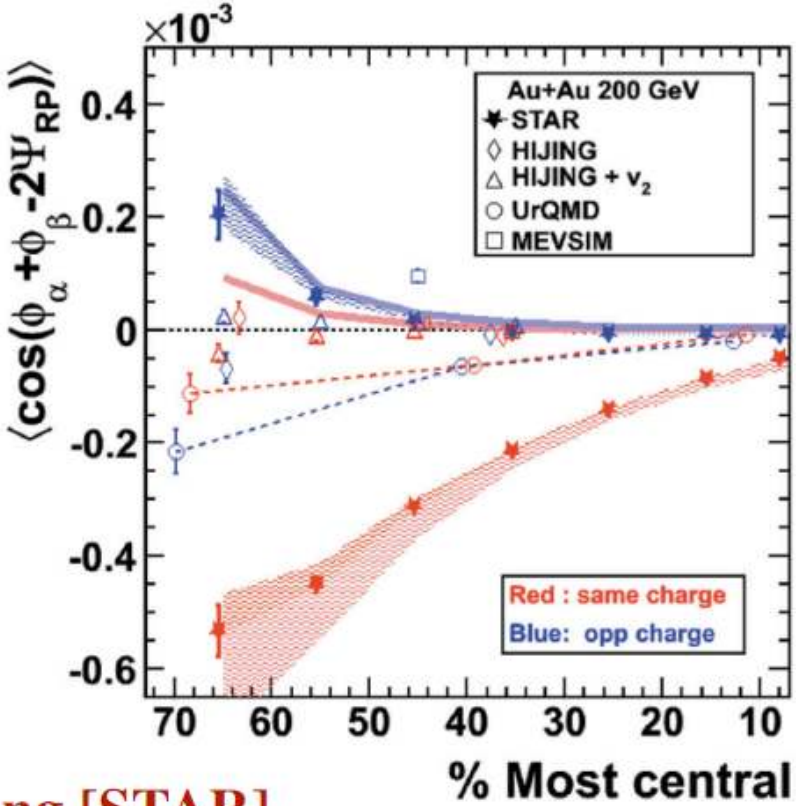
Selected for a Viewpoint
PHYSICAL REVIEW

week ending
18 DECEMBER 2009

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

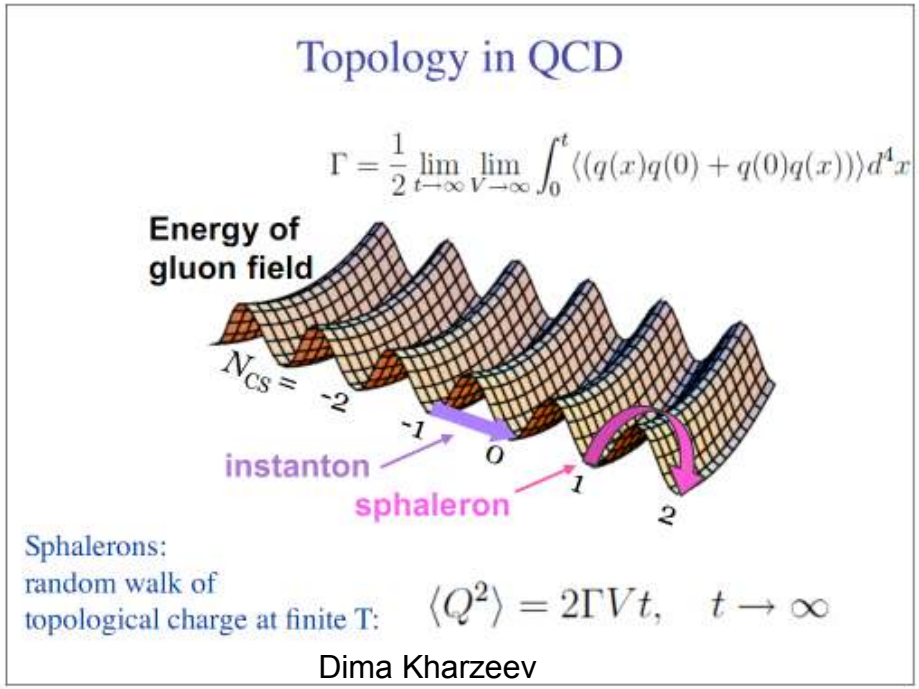
(STAR Collaboration)

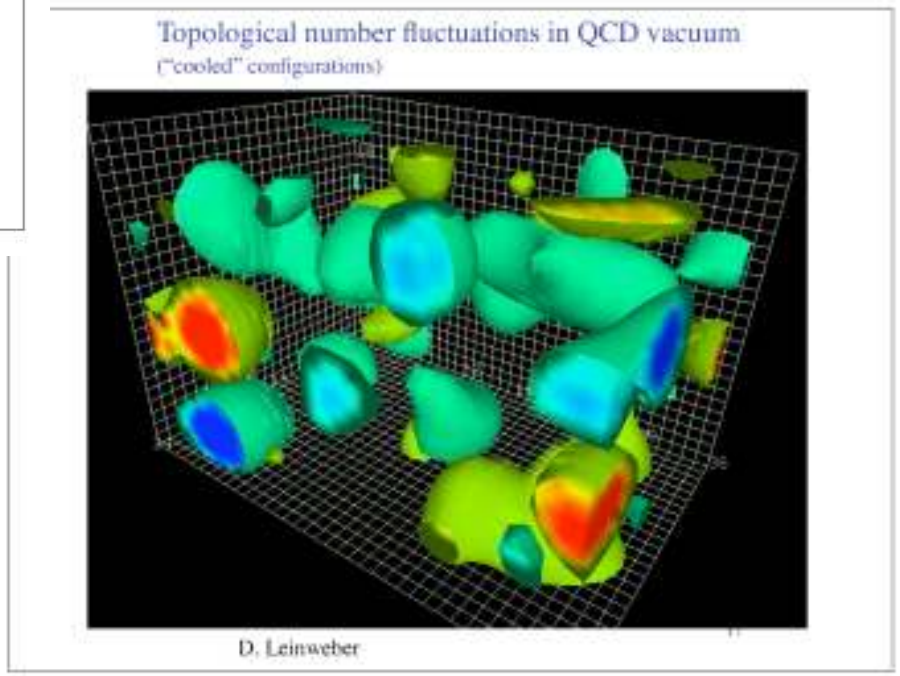




Talks by S. Voloshin and G. Wang [STAR]

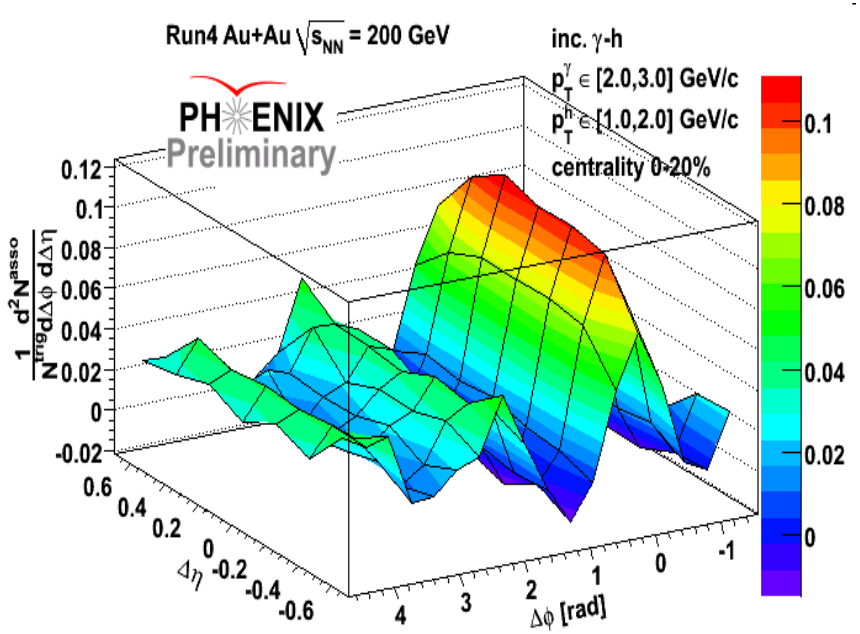
Possibly Can Probe QCD Vacuum

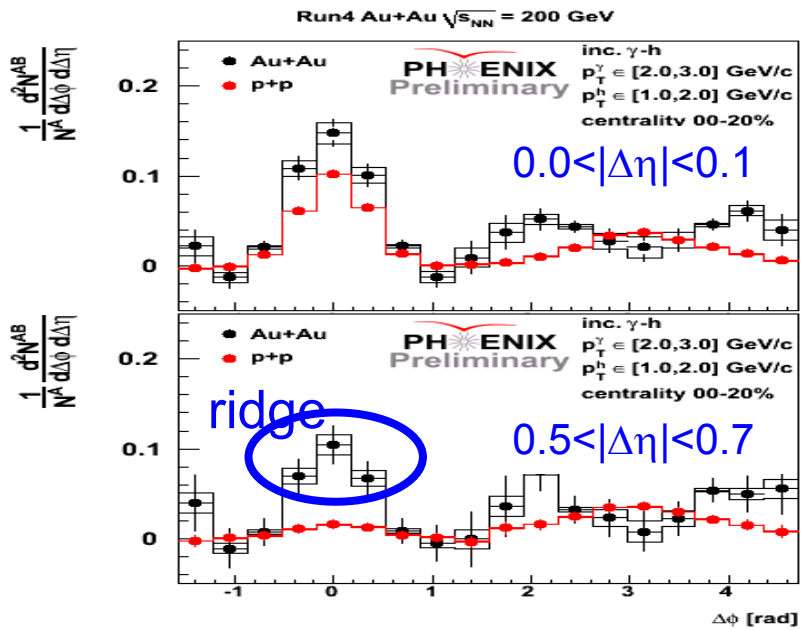




- According to Dima, forward PID is the most important
  - Vorticity
  - Chiral Magnetic Effect depends strongly on particle type
- Need both forward and backward (2 TOF walls)
- This really needs to be studied

Near and Long Range PID Correlations

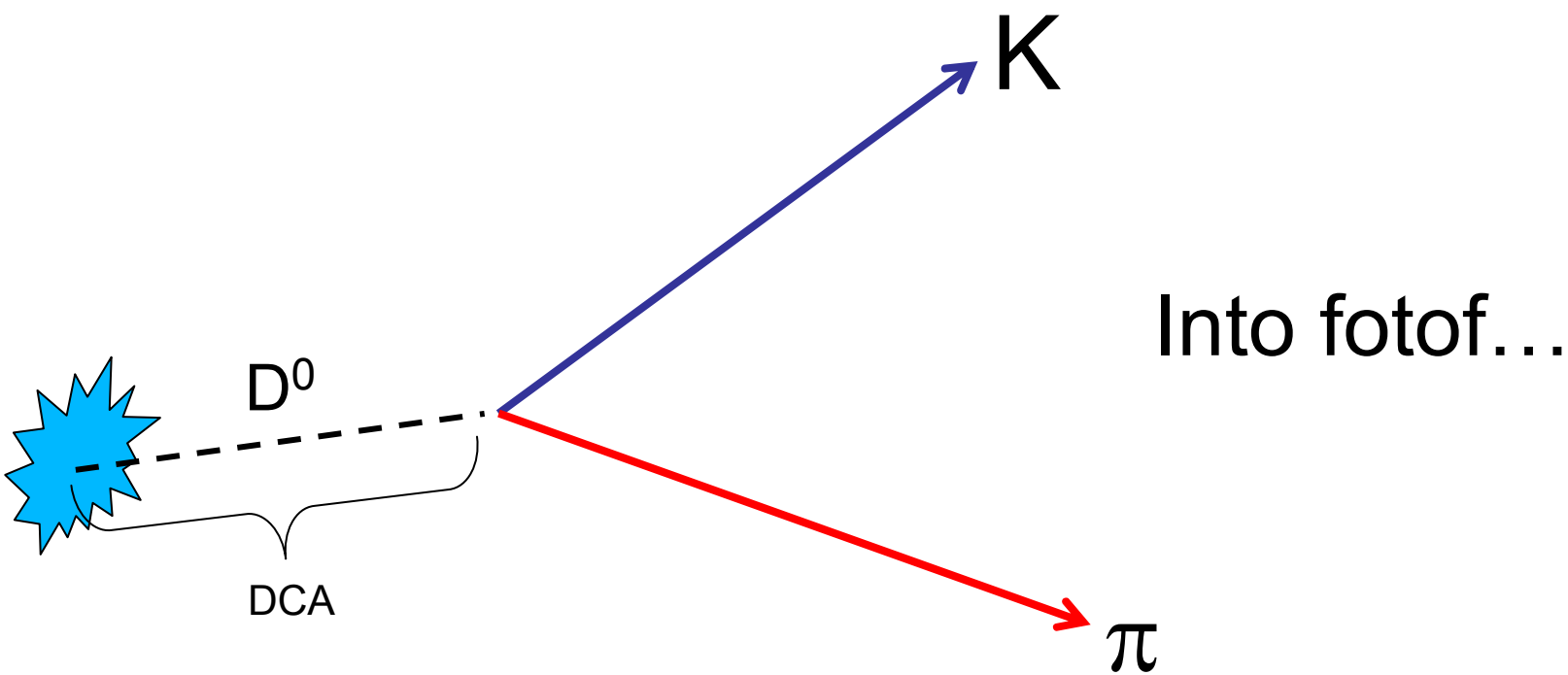




Ridge = Y_{near} @ $0.5<|\Delta\eta|<0.7$

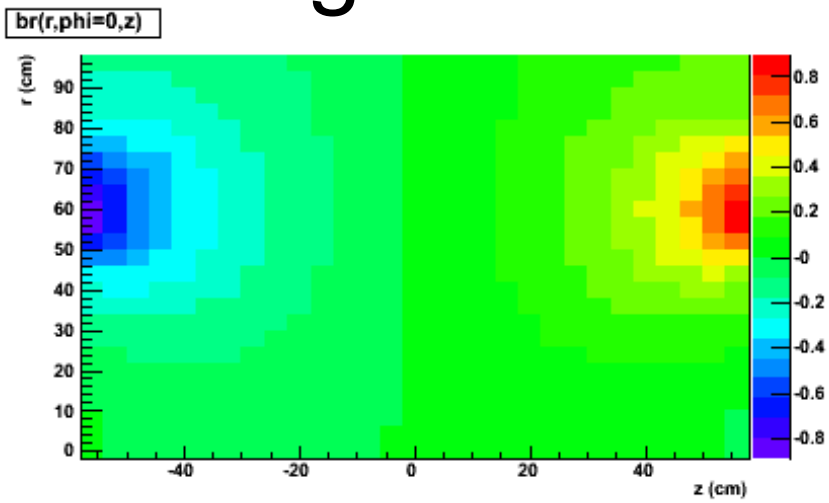
- Combining with FOCAL pi0's (in central Au+Au), one can extend the $\Delta\eta$ to -0.5 to +2.5 units of pseudorapidity
  - Can study head, shoulders, tails, necks, fingers…
- Large acceptance FOCAL X large acceptance TOF = LOTS of statistics
  - Sorry for not having quantified this yet, but will do so soon
- Physics – Medium modifications to jets, mach cones, recombination, etc.: ADS/CFT, glasma, q, gluon density at early times, etc.

Direct Reconstruction of $D \rightarrow K\pi$

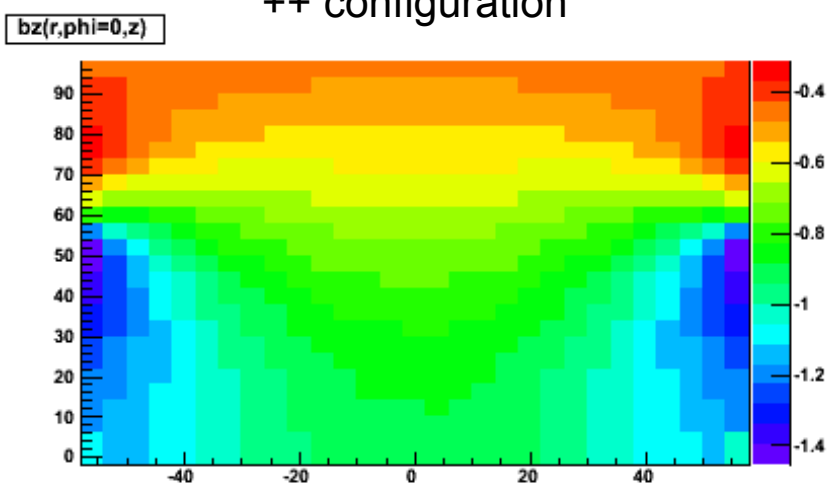


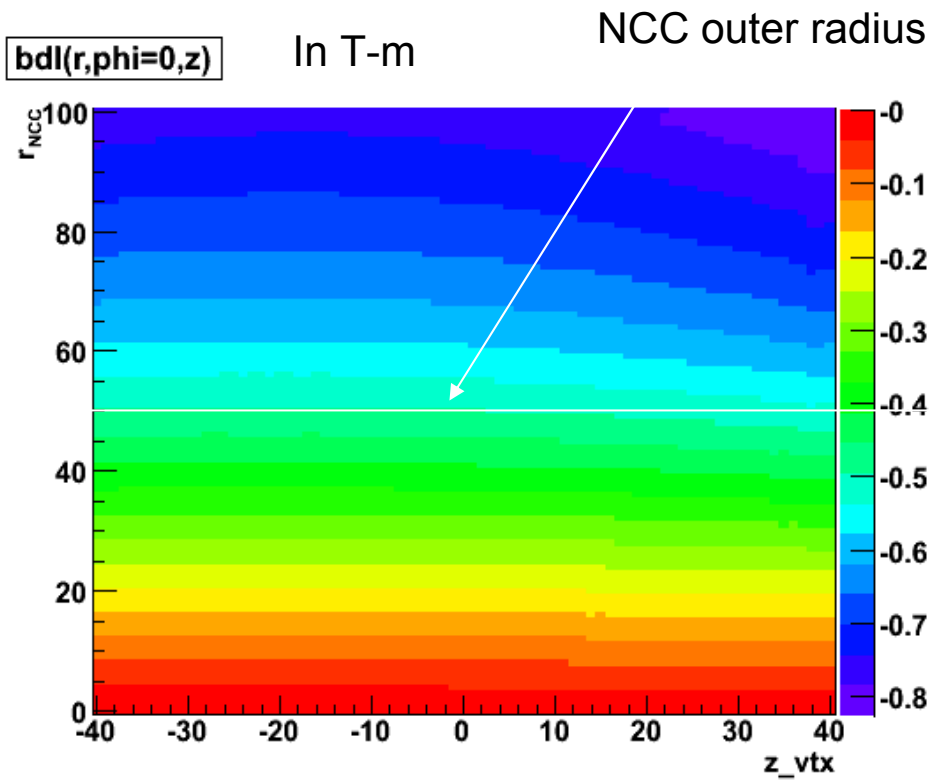
- This will allow for more easily interpretable information on charm
  - Systematic check on DCA only cuts on leptons
  - Region measured will be in between the central and muon arms, but not overlap…

Magnetic Field in the Inner Region



++ configuration

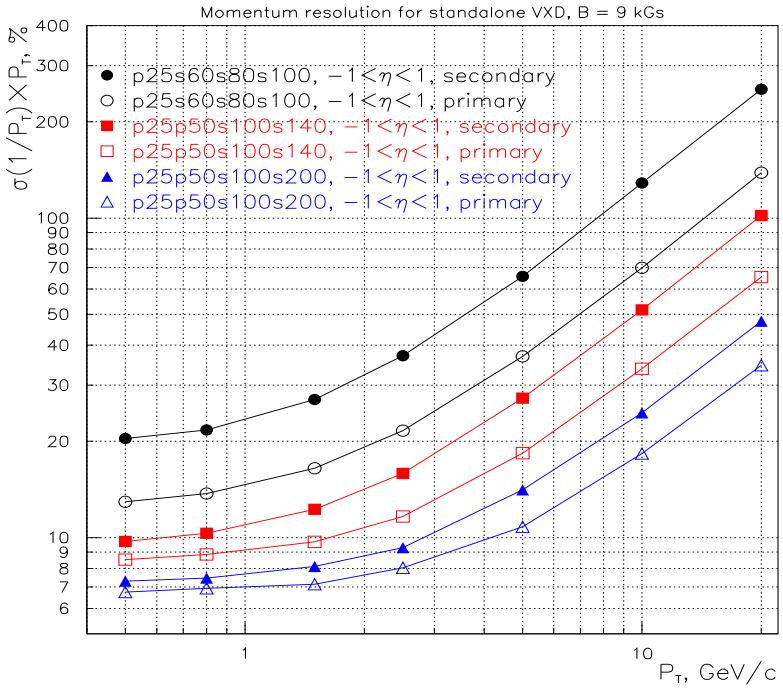


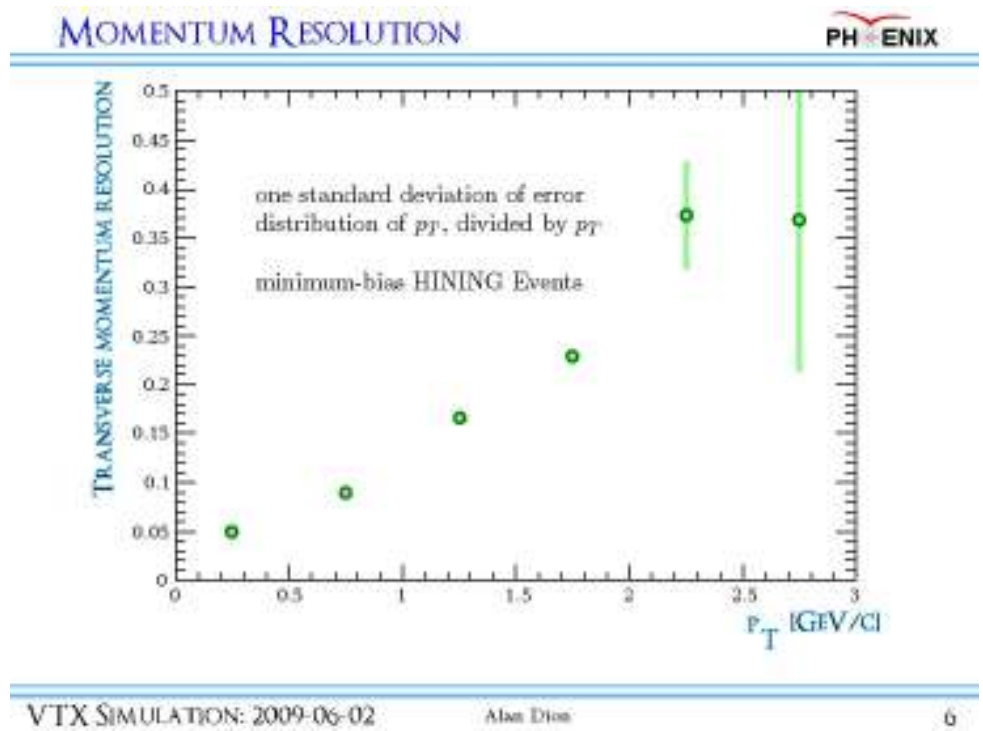


- One wants to determine the charge sign of high momentum electrons in order to do the W boson A_L measurement (and therefore measure the spin contribution of the sea quarks).

- At first since we are forward, one might think the integral(Bdl) is not good enough. But in the ++ configuration, it is not as bad as one might think, reaching up to 0.4 T-m at the outer edge of the NCC

Need to Really Improve FWD Tracking





Want to try to get dp/p ~0.2 @p~4

$$\frac{dm}{m} = \sqrt{\left(\frac{dp}{p}\right)^2 + \gamma^4\left(\frac{dt}{t} + \frac{dL}{L}\right)^2}$$

$$\sim ?\%p + 5\%?$$

$$\boxed{\sim 1\%p}$$

$$\gamma^2 = 1 + \frac{p^2}{m^2} \sim 17$$

For 4 GeV/c protons

$$\frac{10ps}{1600ps} \sim 0.006$$

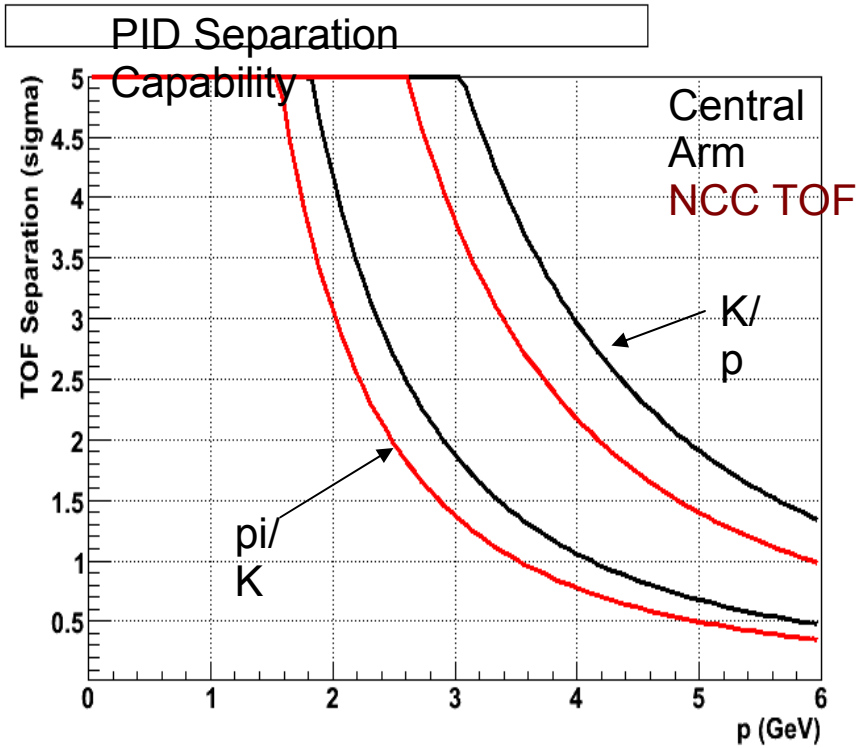
$$\boxed{\frac{0.1ns}{17ns} \sim 0.006}$$

$$\frac{0.5mm}{500mm} \sim 0.001$$

$$\boxed{\frac{1mm}{5000mm} \sim 0.0002}$$

Central arm

Momentum Error versus Time Error



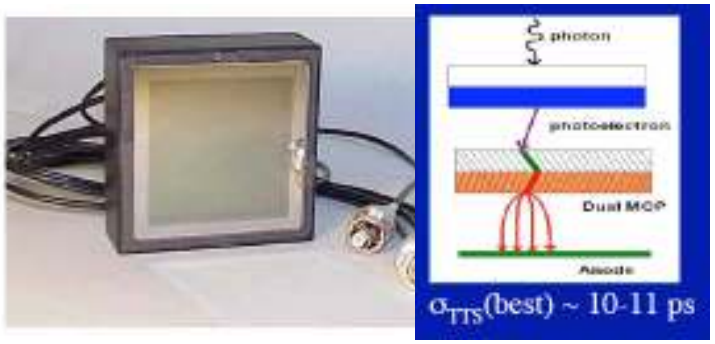
$$\frac{\Delta t_{AB}}{\sigma_t} = \frac{L}{c\sigma_t}\left\{\sqrt{1+\left(\frac{m_A c^2}{p}\right)^2} - \sqrt{1+\left(\frac{m_B c^2}{p}\right)^2}\right\}$$

Cent Arm: L=500 cm, σ_t = 110 ps
FoToF: L=50 cm, σ_t = 15 ps

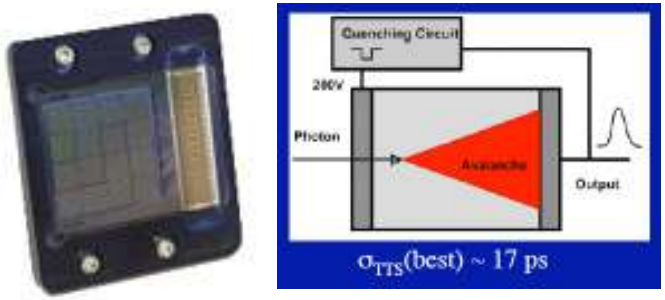
- The v. good time resolution of <10 ps is possible with MCP-PMTs (Hamamatsu, Burle, etc)..
  - Fairly expensive $$$, but small area to cover. Need O(10K) ch for central Au+Au, cost will be O($1-2 Million) for whole system, 1 arm.
  - Would be placed in front of NCC, could take up as little as 1" in z
- Would cover 1-3 in eta, only 1-2 for active tof measurement
- Would use particles in the inner part of TOF Wall as the start counter, BBC not good enough. This saves some cost.
- Momentum comes from VTX (and hopefully reconfigured FVTX)
- Mike T. said he would pay for this… (by selling his BMW?)
  - One physics topic is pid'ed correlations in ridge, but there are many more.

$$\frac{dm}{m} = \sqrt{\left(\frac{dp}{p}\right)^2 + \gamma^4\left(\frac{dt}{t} + \frac{dL}{L}\right)^2}$$

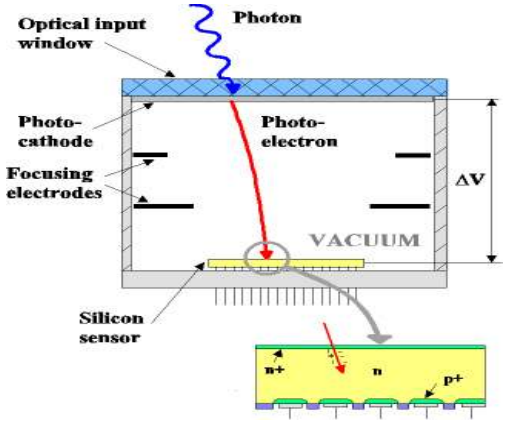
Detector Possibilities



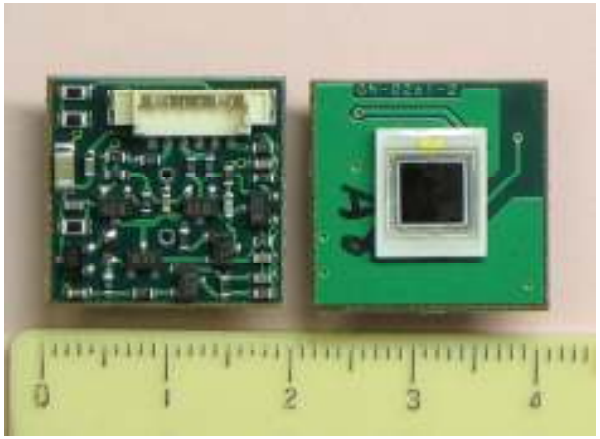
MCP-PMT



Si-PMT



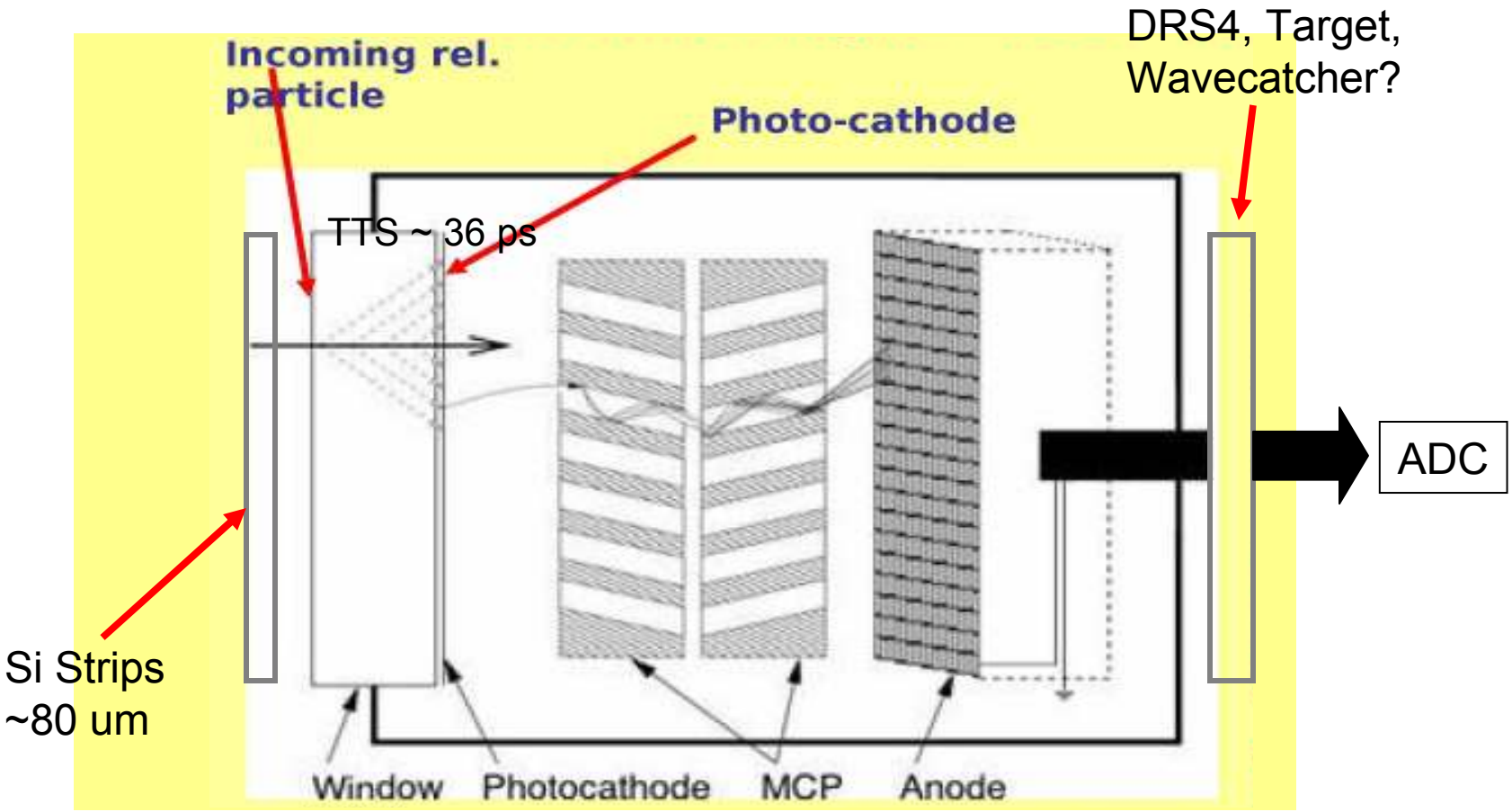
HPD



APD

•Many groups in the world working on 10 ps or better TOF: picosecond tof group/LAPPD (Chicago,Hawaii,et al), Nagoya U (SuperBelle), FP420 (LHC), mRPC (CERN)
•Many different possibilities with different tradeoffs in cost, rate capability, timing capability, tiling capability….

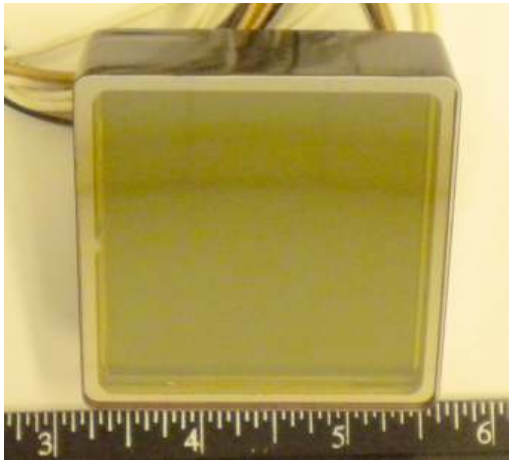
Detector Concept

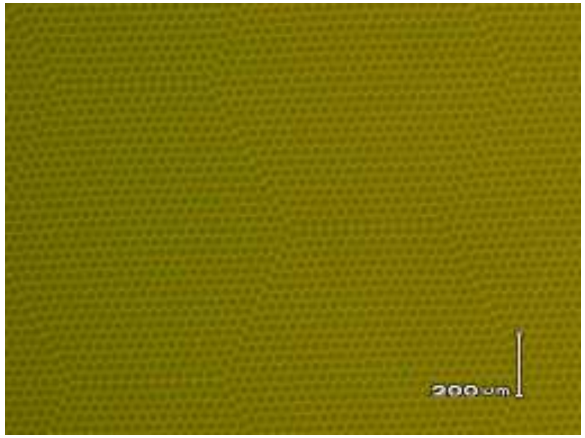


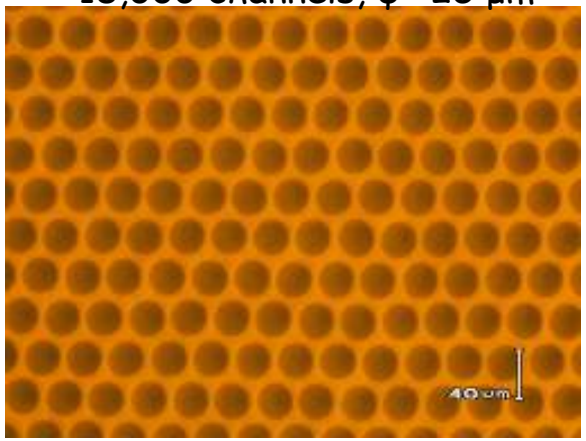
- 1 cm Fused Quartz can generate ~ 40-50 n.p.e.
- 2”x2” Burle/Photonis 85012 10 um, thickness ~3/4”
  - TTS ~ 36 ps → 6-7 ps timing resolution
- Requires Electronics of ~3-4 ps timing
- Photonis MPC-PMT costs about $2M / m^2
- Main technical impediment is electronics – not yet scaled to many channels
  - Possibility of fast waveform digitizers, $1M for electronics (assumes $200/ch)

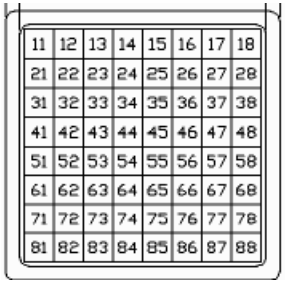
MCP-PMT, Planacon XP85012/A1, 8x8 anode, 53 mm square

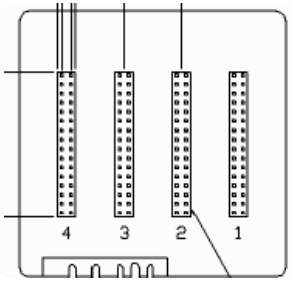
~18,000 channels, φ =25 μm

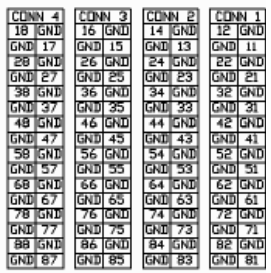


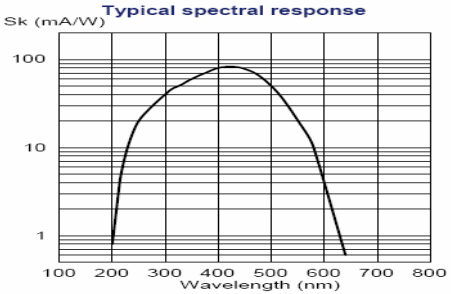


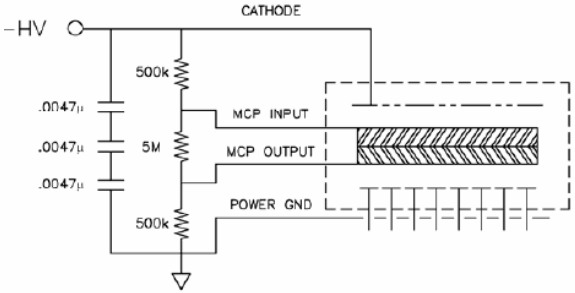








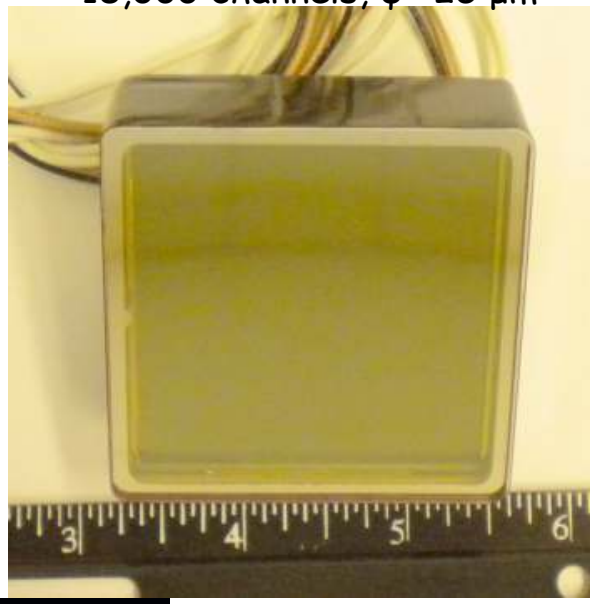


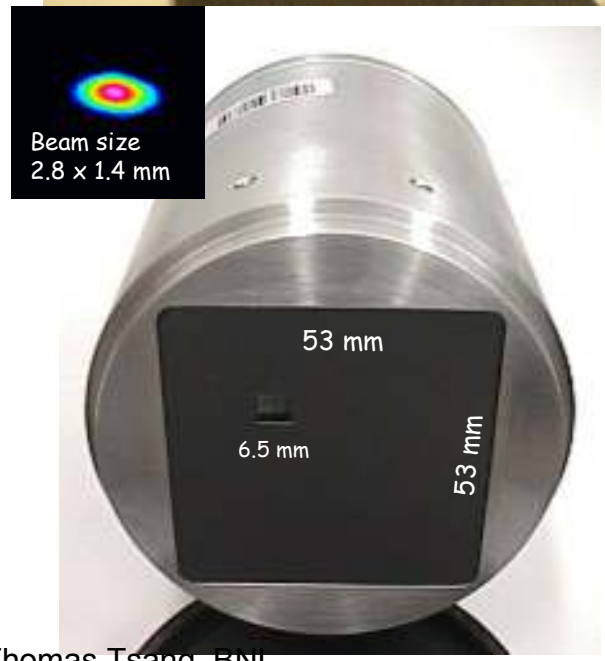


housing with BNC output connectors

MCP-PMT Planacon XP85021

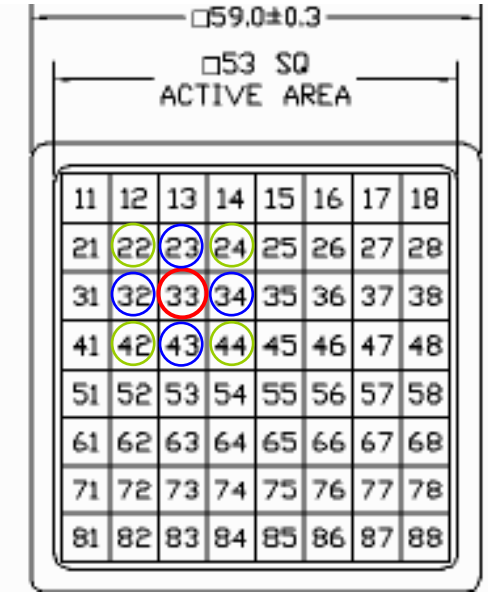
~18,000 channels, φ =25 μm





neighbor signal cross-talk

8 x 8 array array size: 6.5 x 6.5 mm



single photon signal (counts/sec)
dark count ~4/sec

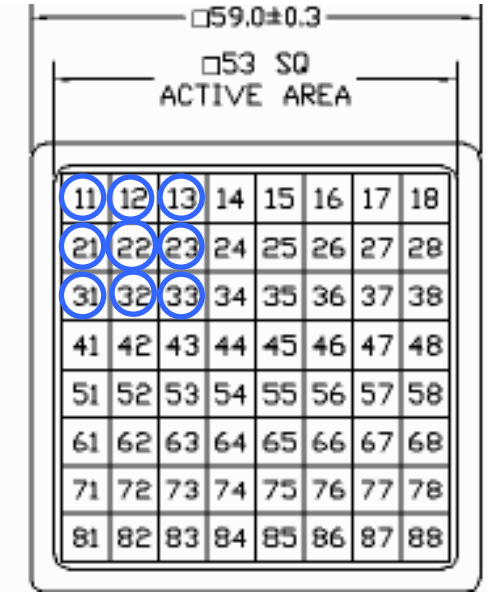
11	43	11
40	10000	27
16	47	7

cross-talk

- nearest neighbor -24 dB
- next nearest neighbor -29 dB

detector response uniformity

8 x 8 array array size: 6.5 x 6.5 mm



single photon signal (counts/sec)
dark count ~4-10/sec

600	1300	1600
590	2100	2600
610	2700	3000

photon response of MCP-PMT does not appear to have good uniformity

MCP-PMT Planacon XP85012: transit time spread & timing jitter (TTS)

$$\sigma_{TTS} = \sqrt{\sigma_{MCP}^2 - \sigma_{IRF}^2} = 47\ ps$$

attenuators

400 nm
fs pulse

MCP-PMT Planacon XP85021

Ortec 9306
1 GHz preamp

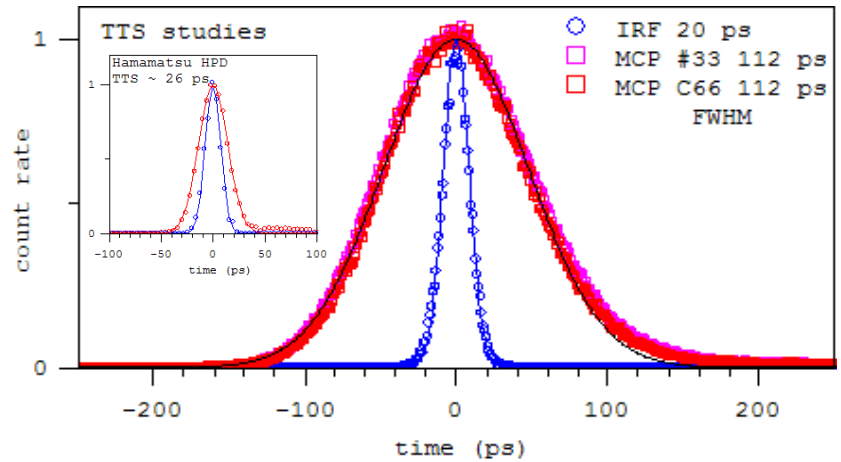
ET 2010 photodiode
$t_{isetime}$ ~150 ps

inverter

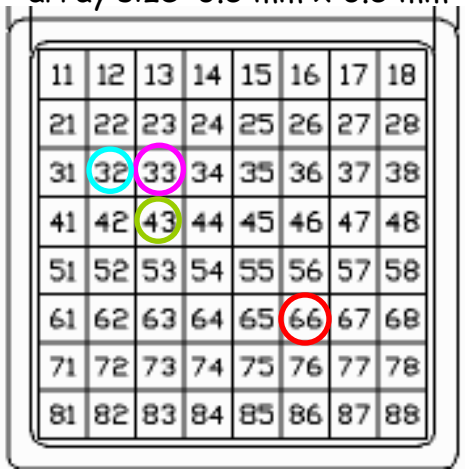
HydraHarp400
8-channels, 1ps/ bin
100 MHz syn rate
Time-to-Digital con.

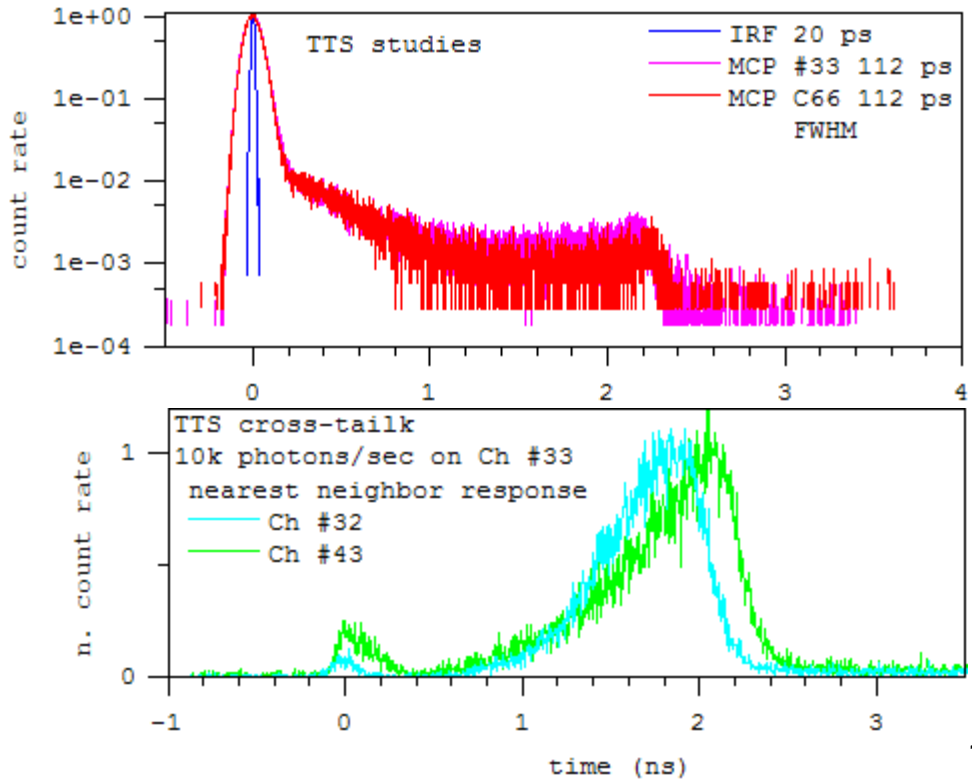
STOP: Ch1
Detector input

START: Syn input



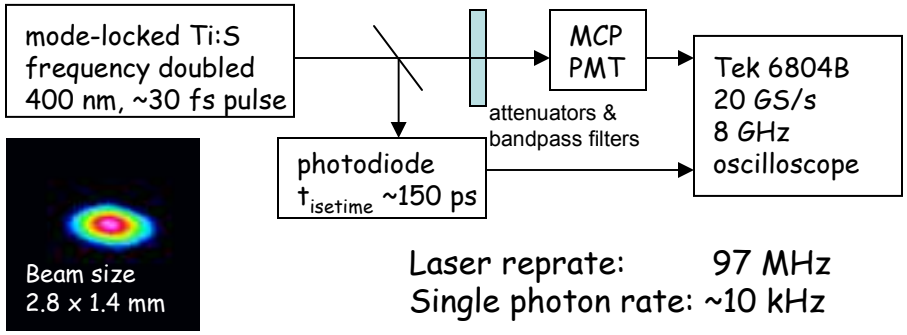
8 x 8 array
array size: 6.5 mm x 6.5 mm



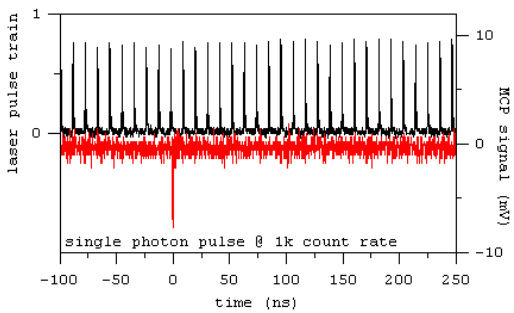


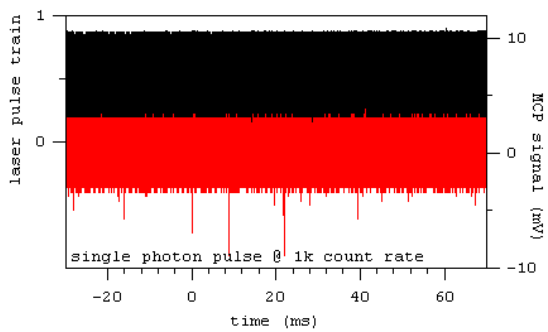
MCP-PMT Planacon XP85012: single photon temporal response

single photon pulses

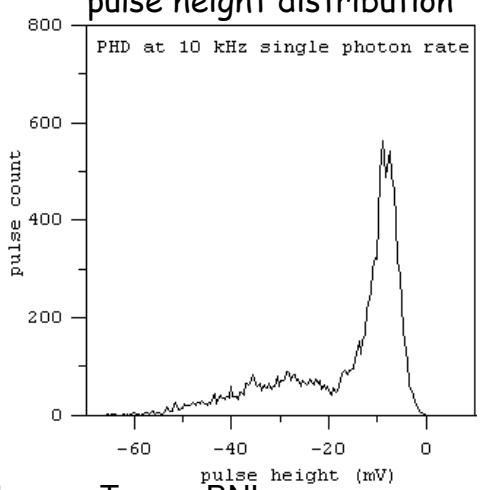


Laser reprate: 97 MHz
Single photon rate: ~10 kHz

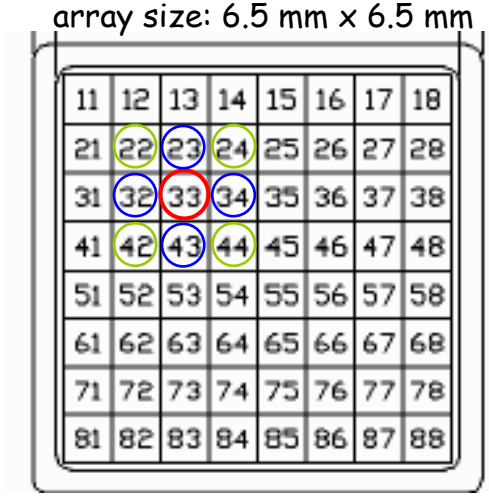




single photon
pulse height distribution



8 x 8 array
array size: 6.5 mm x 6.5 mm



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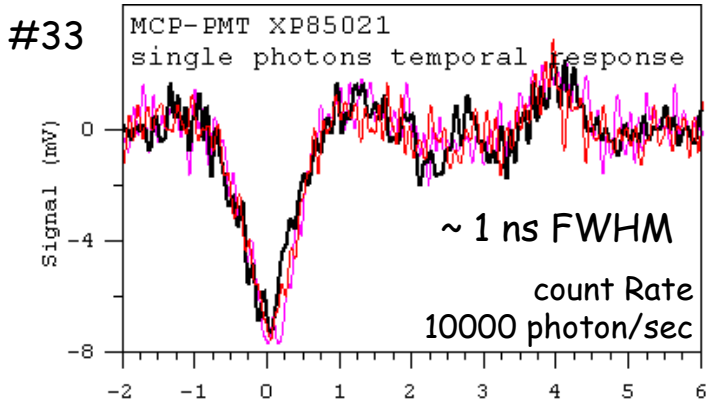

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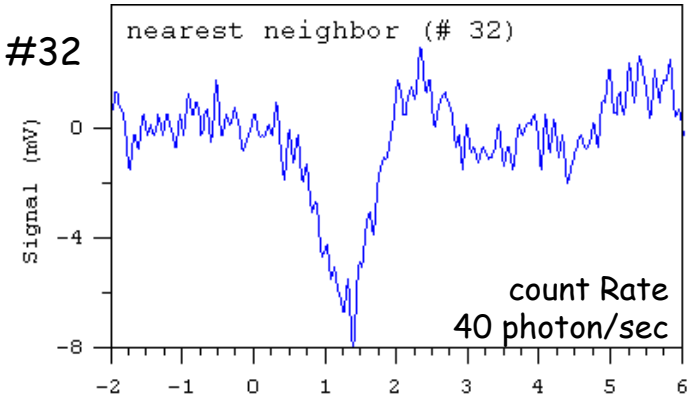

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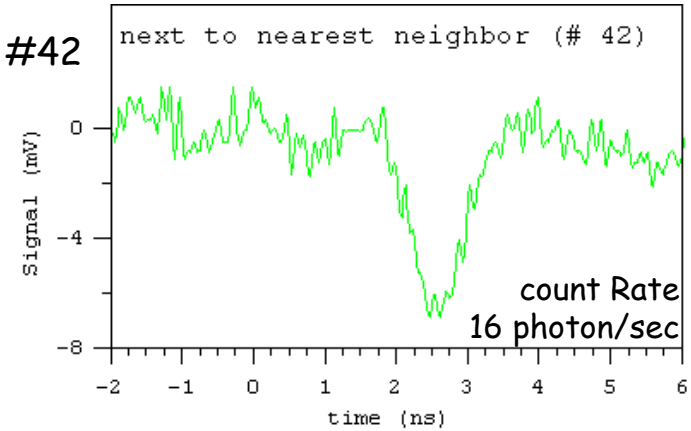
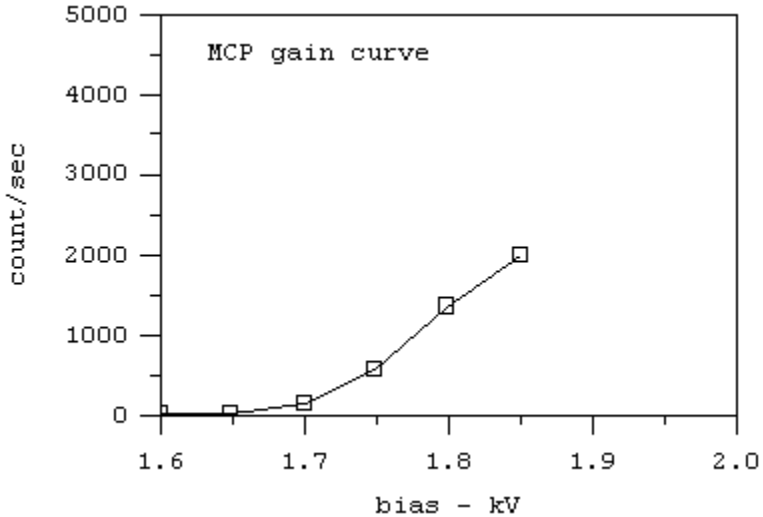
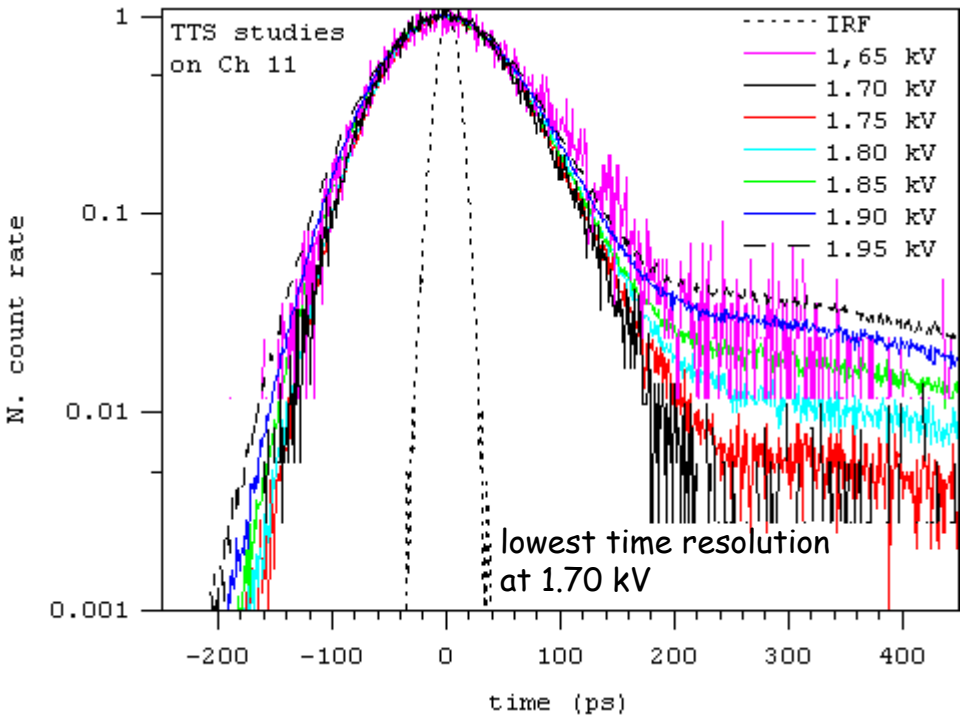


MCP-PMT Planacon XP85012: rate dependence

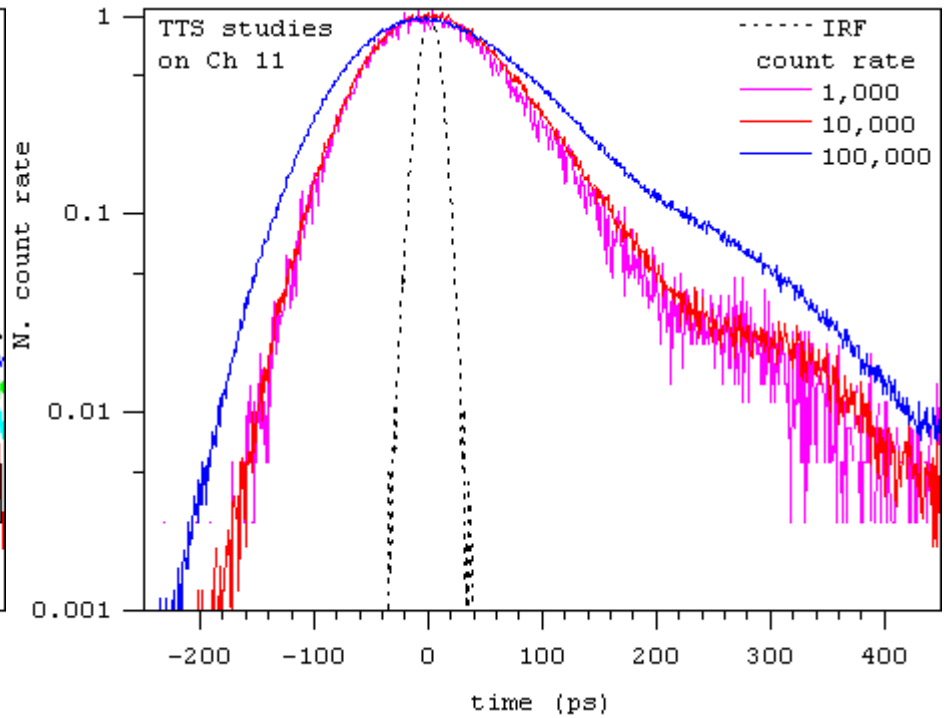


•Good rate dependence (no change at 10kHz for single p.e.)

Time resolution: bias voltage dependence

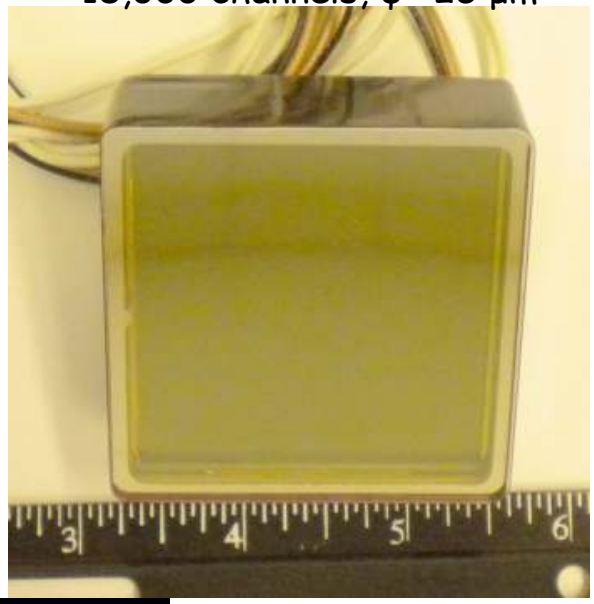


Time resolution: photon count rate dependence



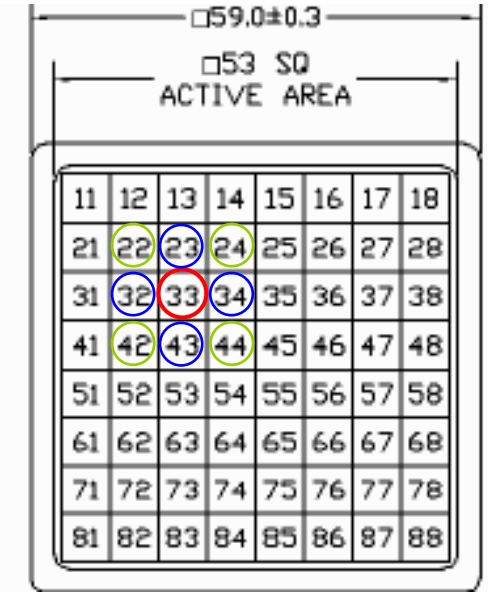
MCP-PMT Planacon XP85021

~18,000 channels, φ =25 μm



neighbor signal cross-talk

8 x 8 array array size: 6.5 x 6.5 mm



single photon signal (counts/sec)
dark count ~4/sec

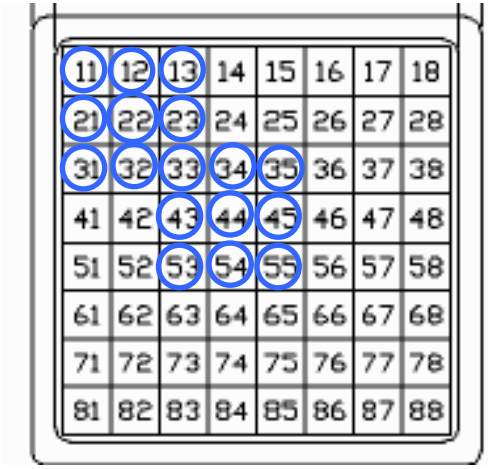
11	43	11
40	10000	27
16	47	7

cross-talk

- nearest neighbor -24 dB
- next nearest neighbor -29 dB

detector response map

8 x 8 array array size: 6.5 x 6.5 mm

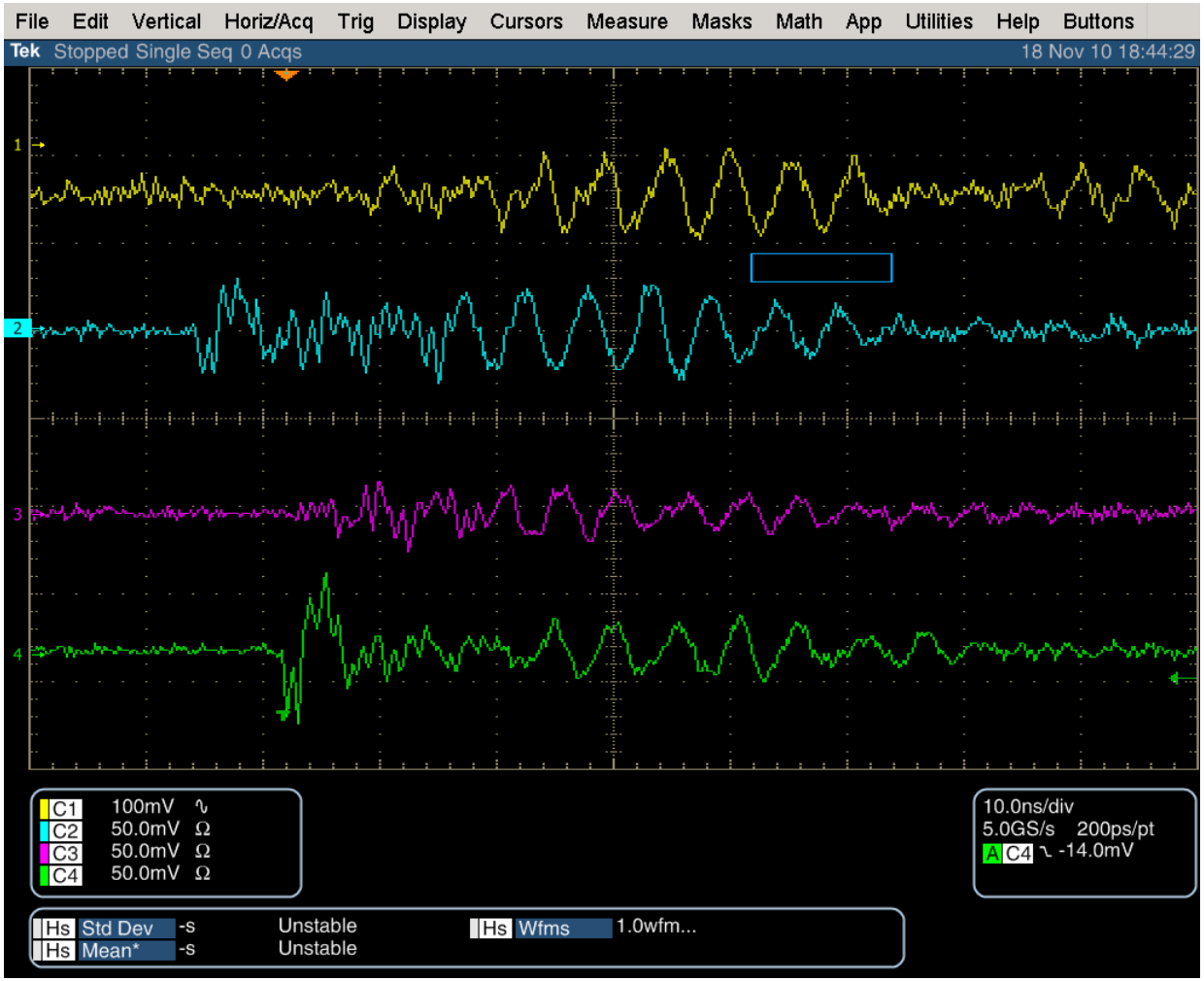


single photon signal (counts/sec)
dark count ~4-10/sec

0.15	0.32	0.39		
0.14	0.51	0.63		
0.15	0.66	0.73	0.84	0.85
		0.85	0.94	0.75
		1	0.94	0.81

photon response of MCP-PMT does not appear to have good uniformity

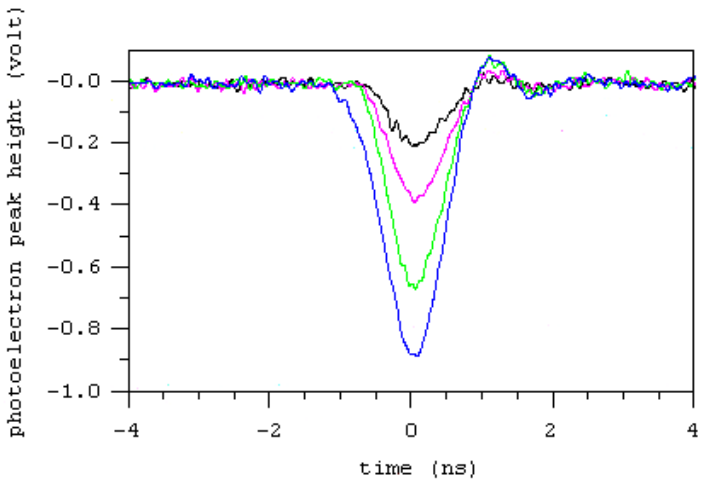
XP85012 Dark Counts



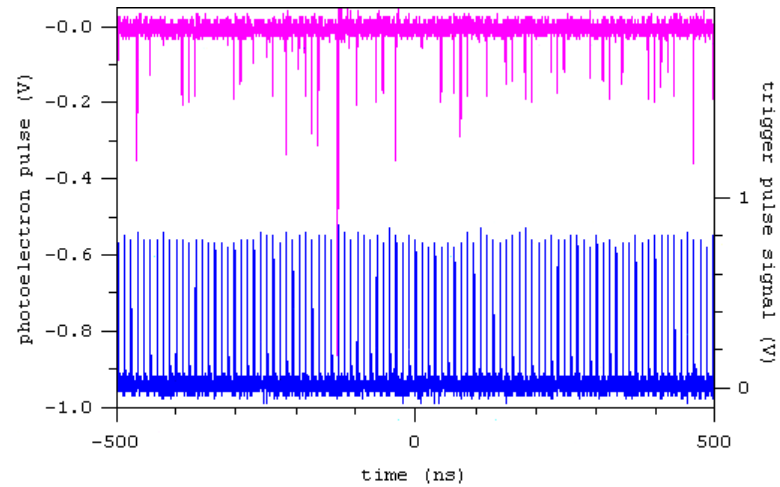
MCP-PMT dark count @ - 1.75 kV bias after 9306 1-GHz preamp	
Ch #	Ave Counts/sec
33	1.3
34	1.5
35	2.2
43	2.5
44	2.0
45	2.7
53	2.0
54	2.3
55	2.2
MCP	7-19

- Low Dark Count Rate but massive signals (on all channels, ~100 mV amplitudes, ~80 ns long
- Cause unknown. Discharge across HV gap?

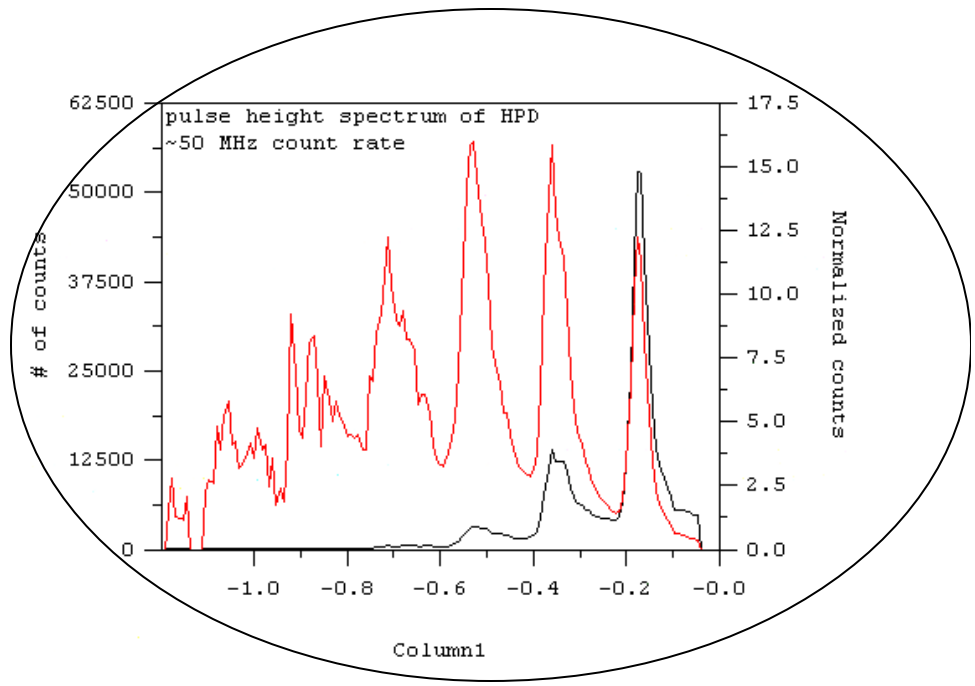
HPD single and multiphoton response



~50 MHz count rate (<0.5 photon/pulse)

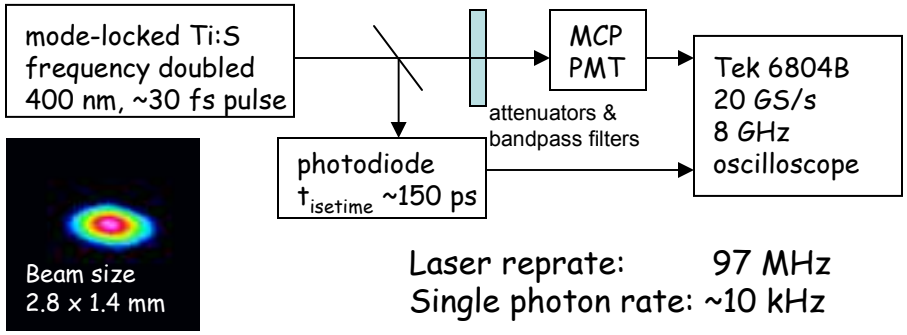


n (# of photoelectrons)	pulse height after preamp (Volt)	pulse height before preamp (mV)	normalized count rate
1	0.176	2.2	1
2	0.36	4.5	0.26
3	0.528	6.6	0.061
4	0.71	8.9	0.009
5			~0.0014
6			~0.0002

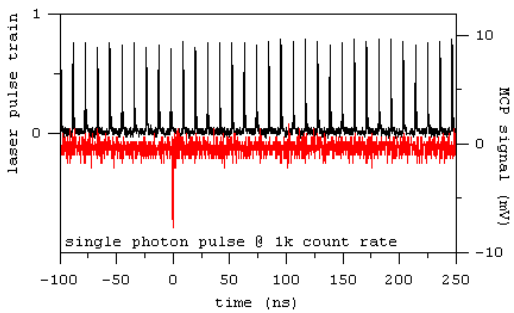


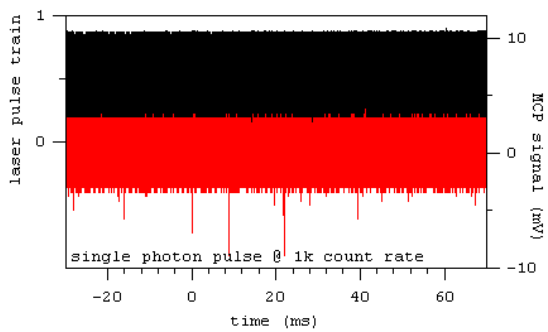
MCP-PMT Planacon XP85021: single photon temporal response

single photon pulses

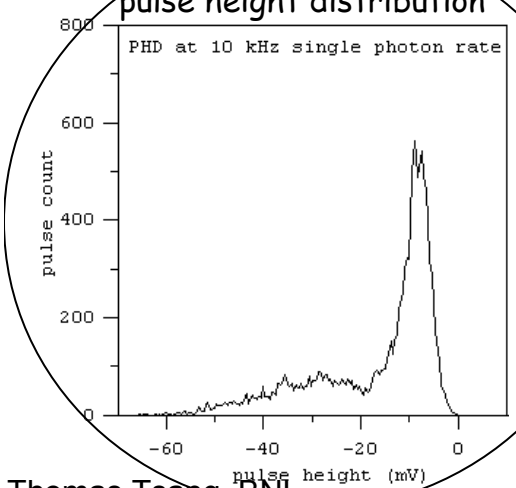


Laser reprate: 97 MHz
Single photon rate: ~10 kHz

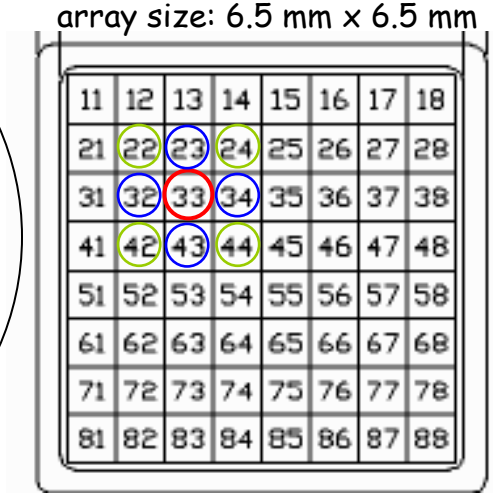




single photon
pulse height distribution



8 x 8 array
array size: 6.5 mm x 6.5 mm



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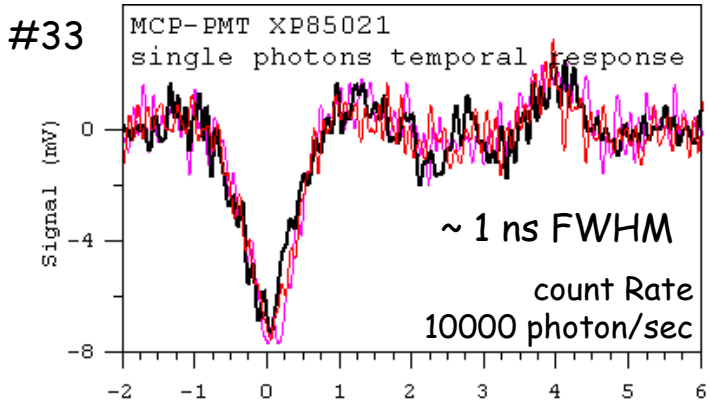

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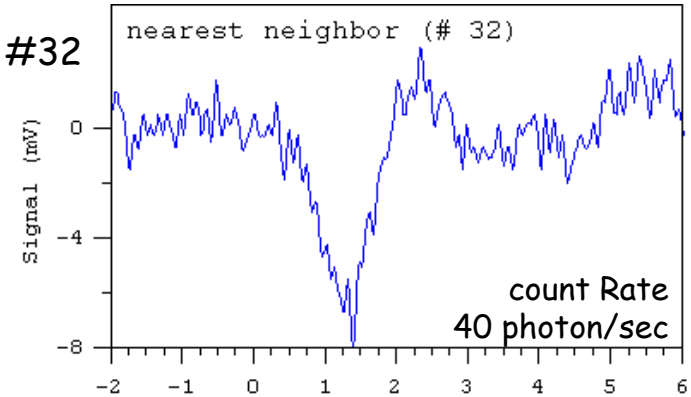

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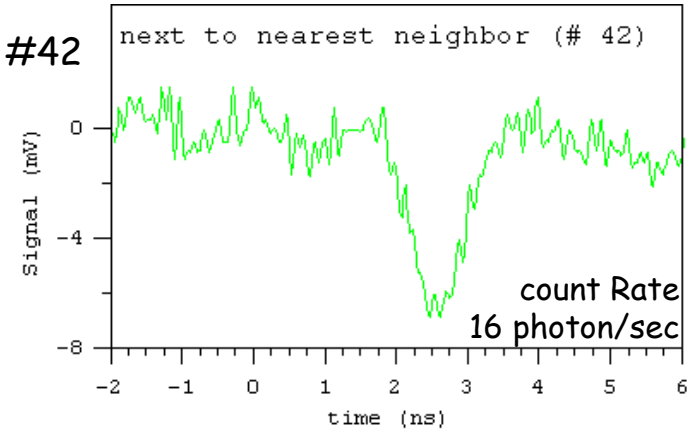
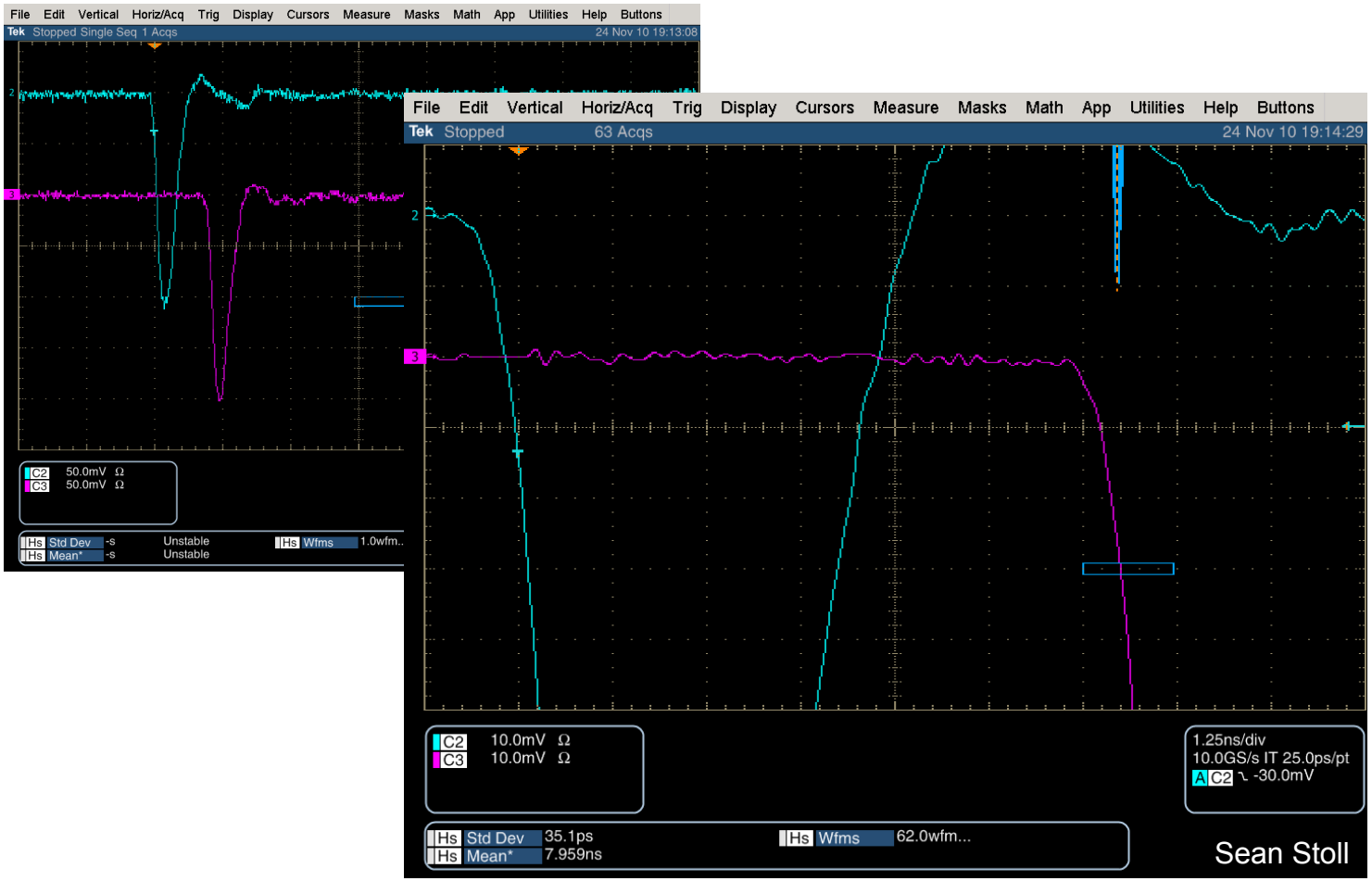


Thomas Tsang, BNL

Brighter Laser Test of Time

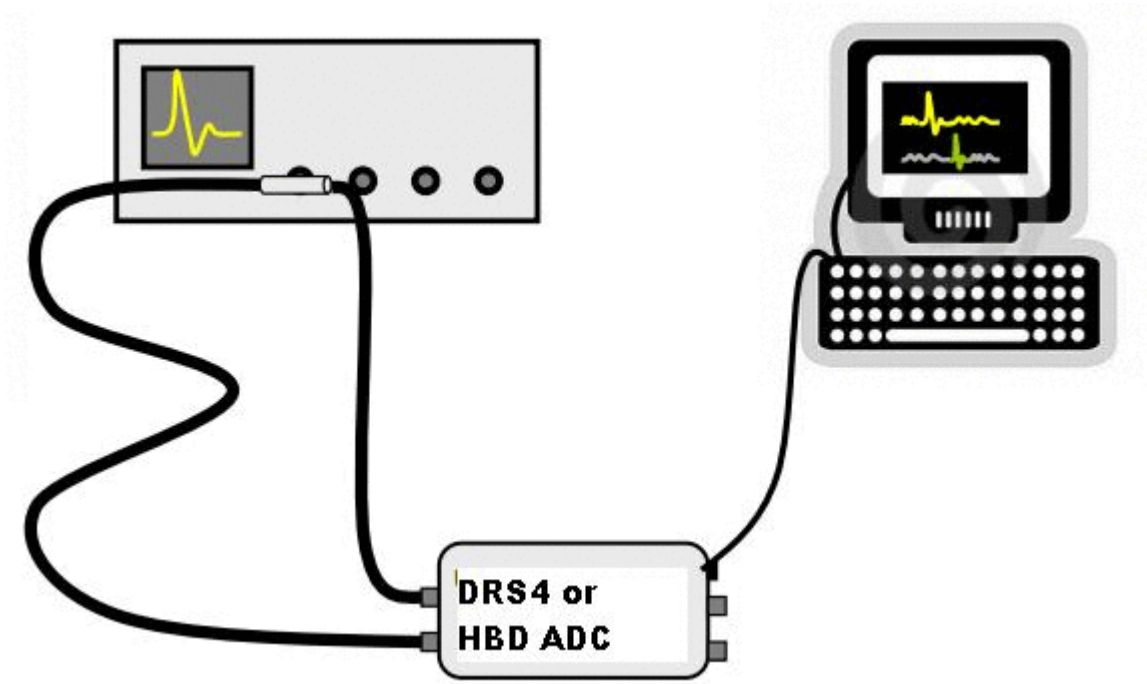


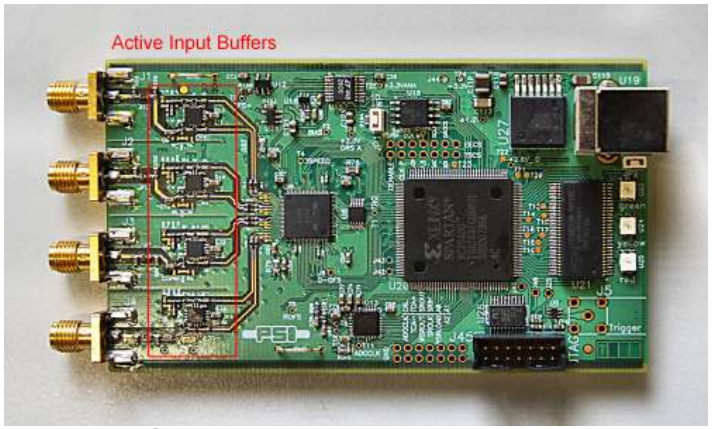
- Just with a scope (10 GSa/s), and tuning laser amplitude to give approximately the right number of n.p.e., we get ~20 ps resolution.
- Working on fine tuning this, should be able to get many improvements.
- Studying realistic system (quartz radiator coupled to MCP-PMT) using cosmic ray test stand (somewhat slow)

Top
35 34 33
45 44 43
55 54 53

Top

Electronics Timing Resolution



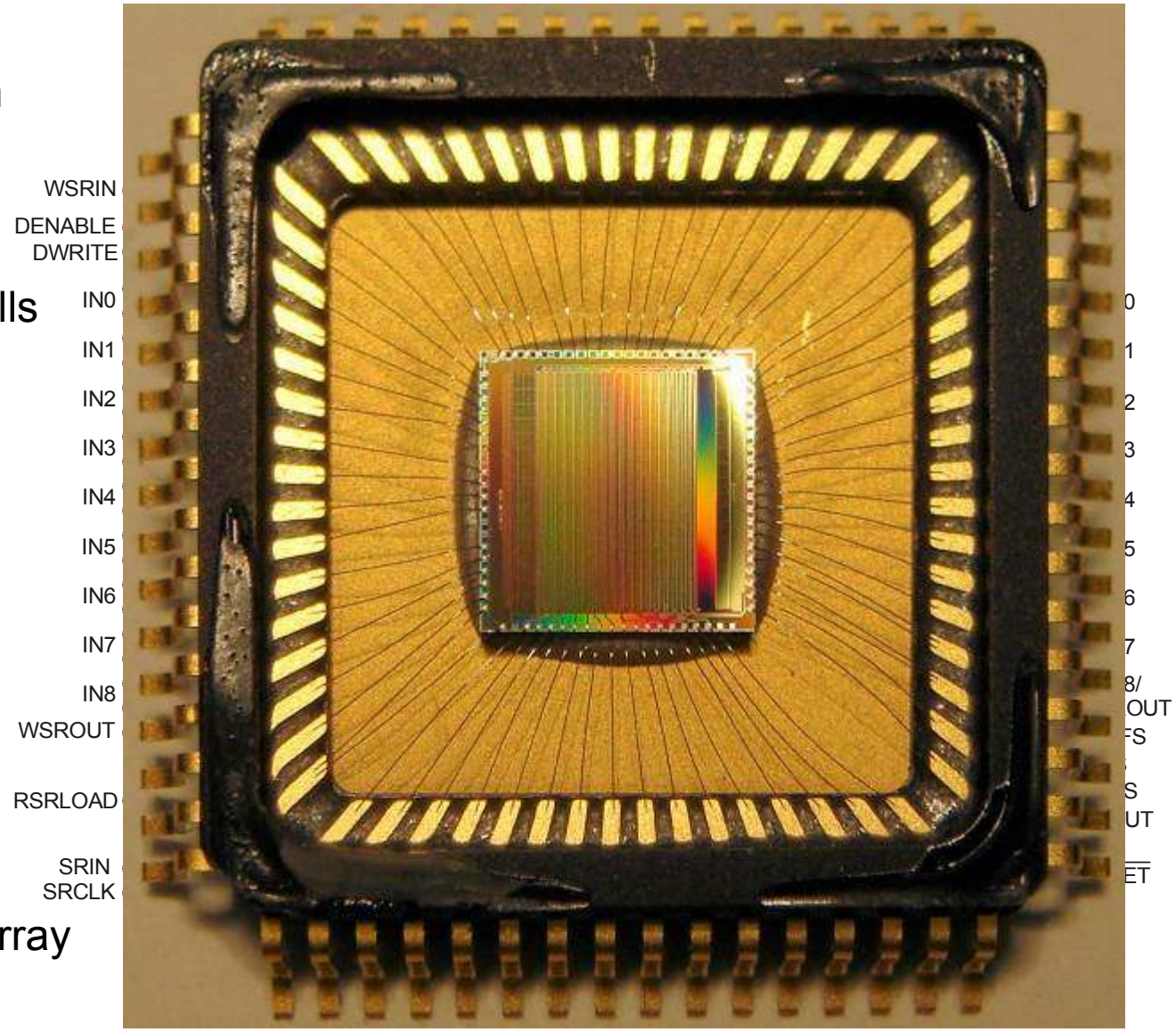


DRS4 Evaluation Board V3

PHENIX HBD FEE

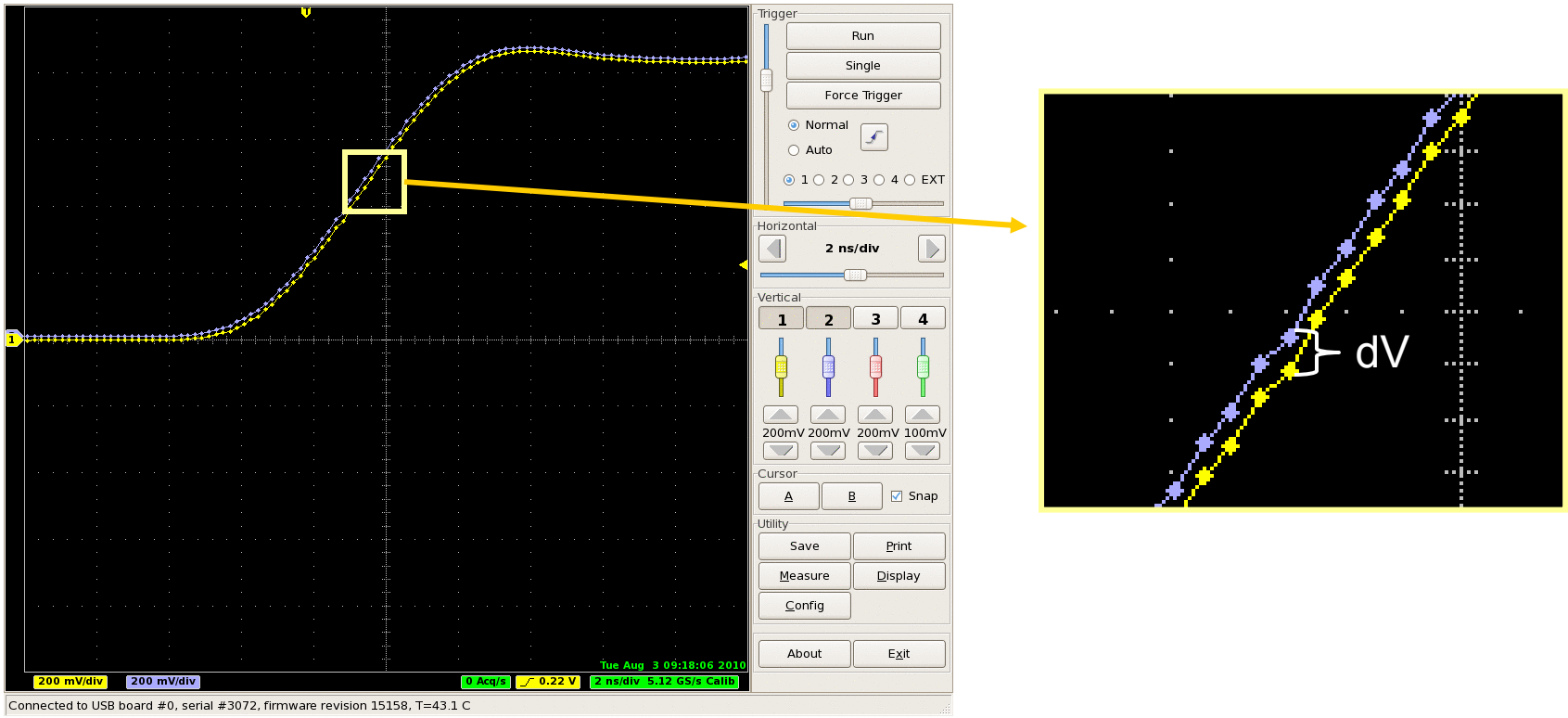
DRS4 ASIC

- Fabricated in 0.25 μm 1P5M MMC process (UMC), 5 x 5 mm^2, radiation hard
- 8+1 ch. each 1024 cells
- Differential inputs, differential outputs
- Sampling speed 500 MHz … 6 GHz, PLL stabilized
- Readout speed 30 MHz, multiplexed or in parallel
- ~40 mW/channel
- ~$10/channel
- Switched Capactior Array
  - Buffer is a Big Limit



Stefan Ritt, http://drs.web.psi.ch/

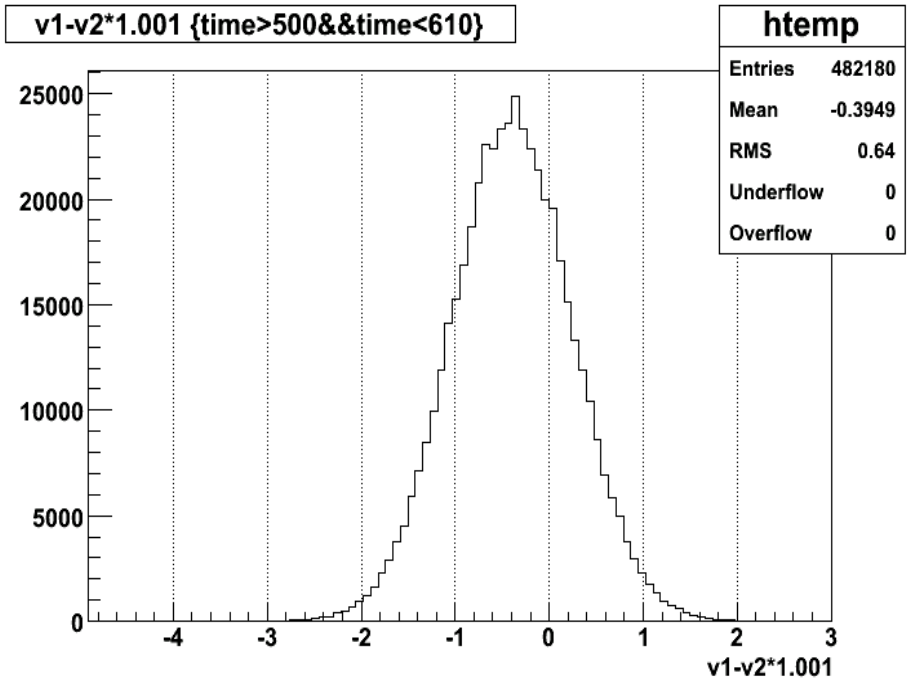
Scheme

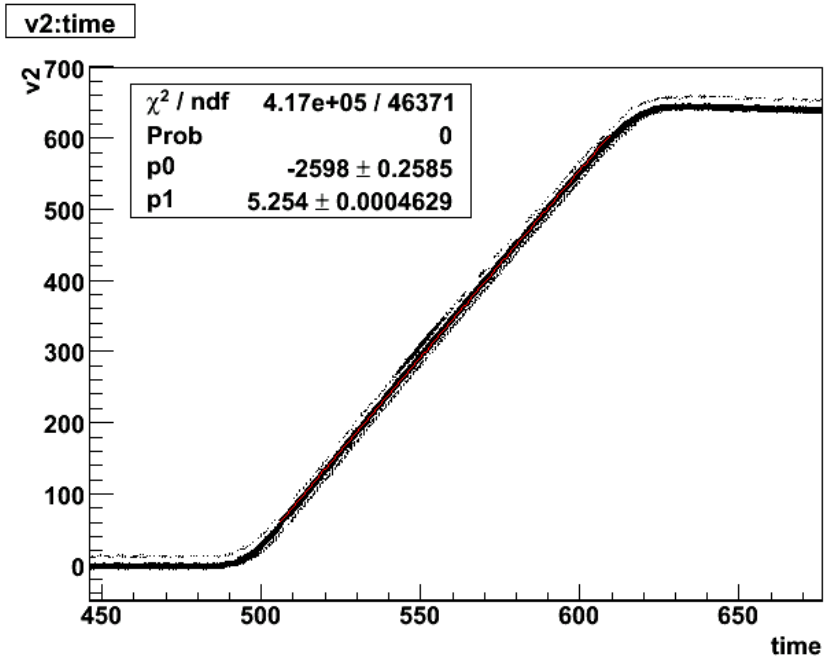


- Split signal, measure difference between signals
- Electronics reads out at fixed sampling intervals, so we can't measure directly dt using one sample, only get dV
- Can use voltage resolution to get time resolution for a single sample using linear approximation

$$\frac{dV}{dt} = m \rightarrow dt = \frac{dV}{m}$$

Slow Test Pulse, 1 GSa/s





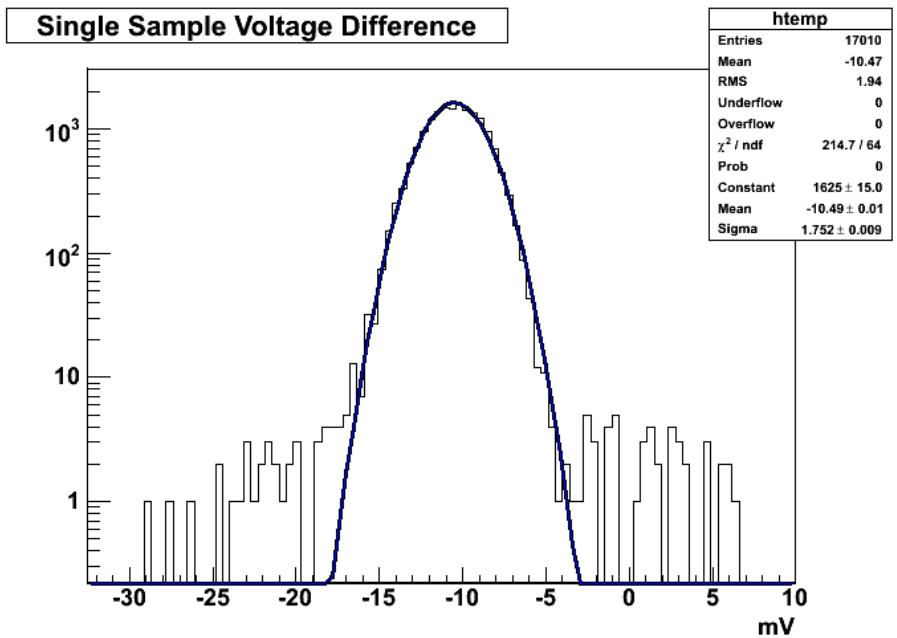
dV = 0.64 mV

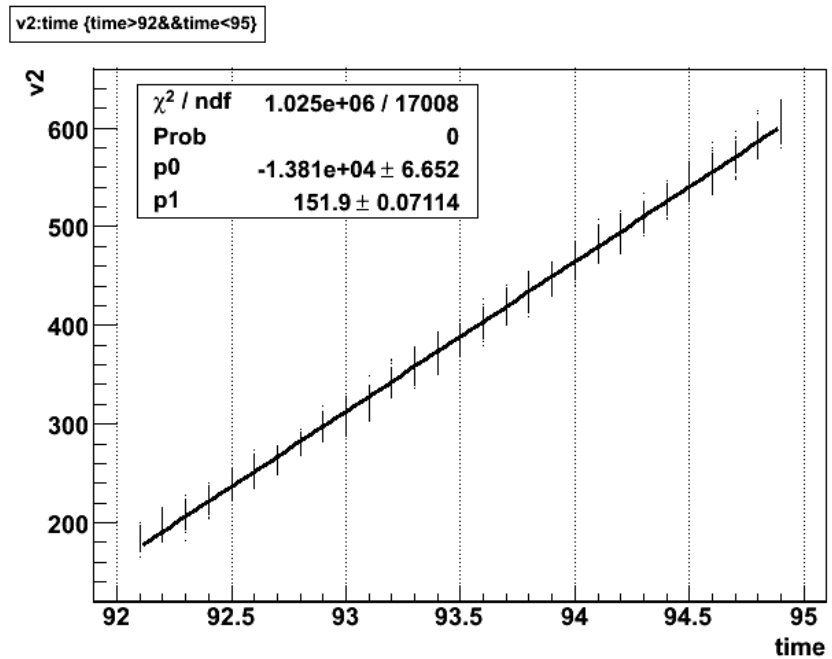
m=5.254 mV/ns

dt = 122 ps. For a single pulse it is $122/\sqrt{2}$ = 86 ps

Limited by speed of pulse

Single Sample Time Resolution, Faster Pulse, 5 GSa/s





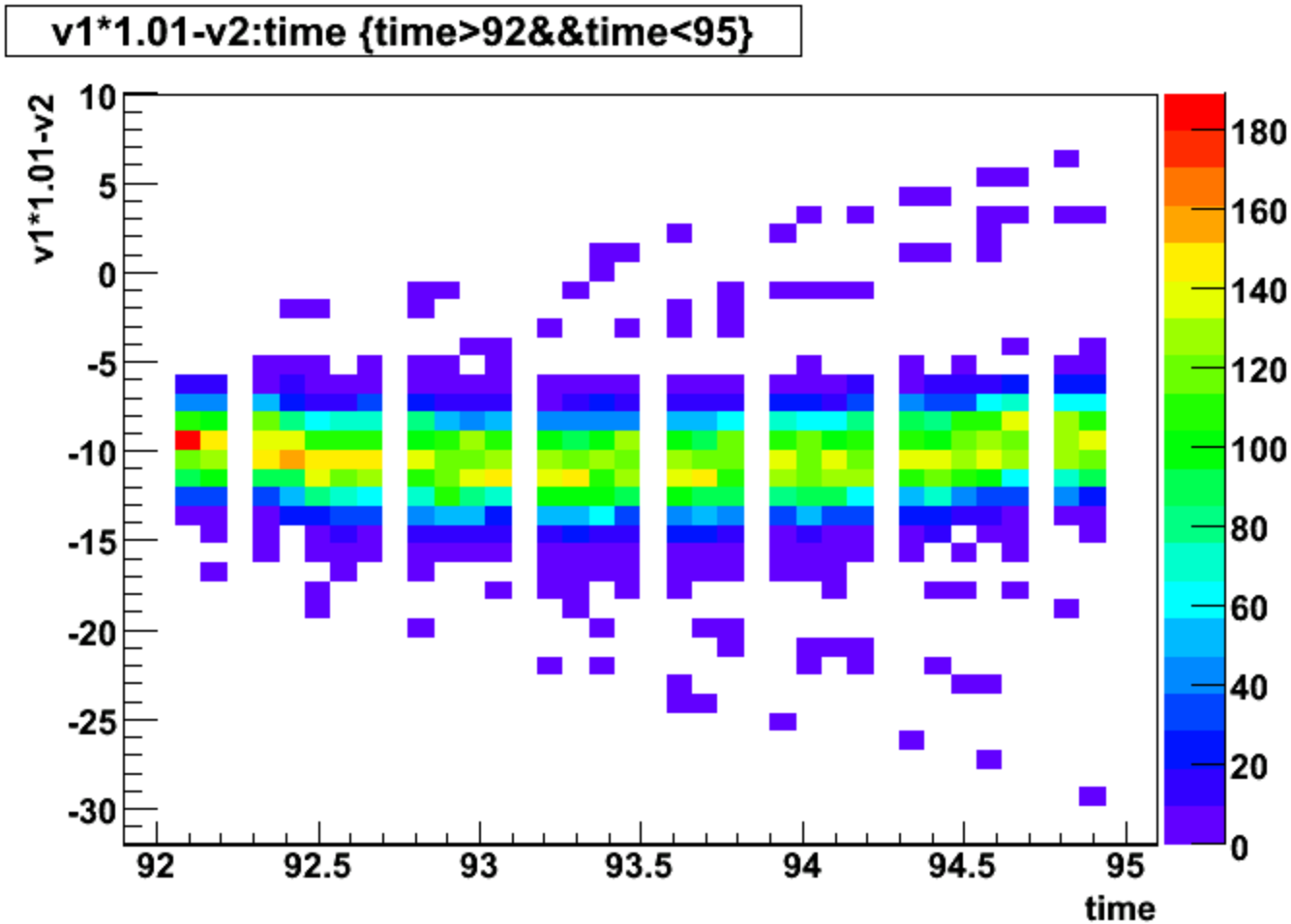
dV = 1.94 mV (or 1.75 ignoring outliers)

m=151.9 mV/ns

dt = dV/m = 12.7 ps (or 11.5)

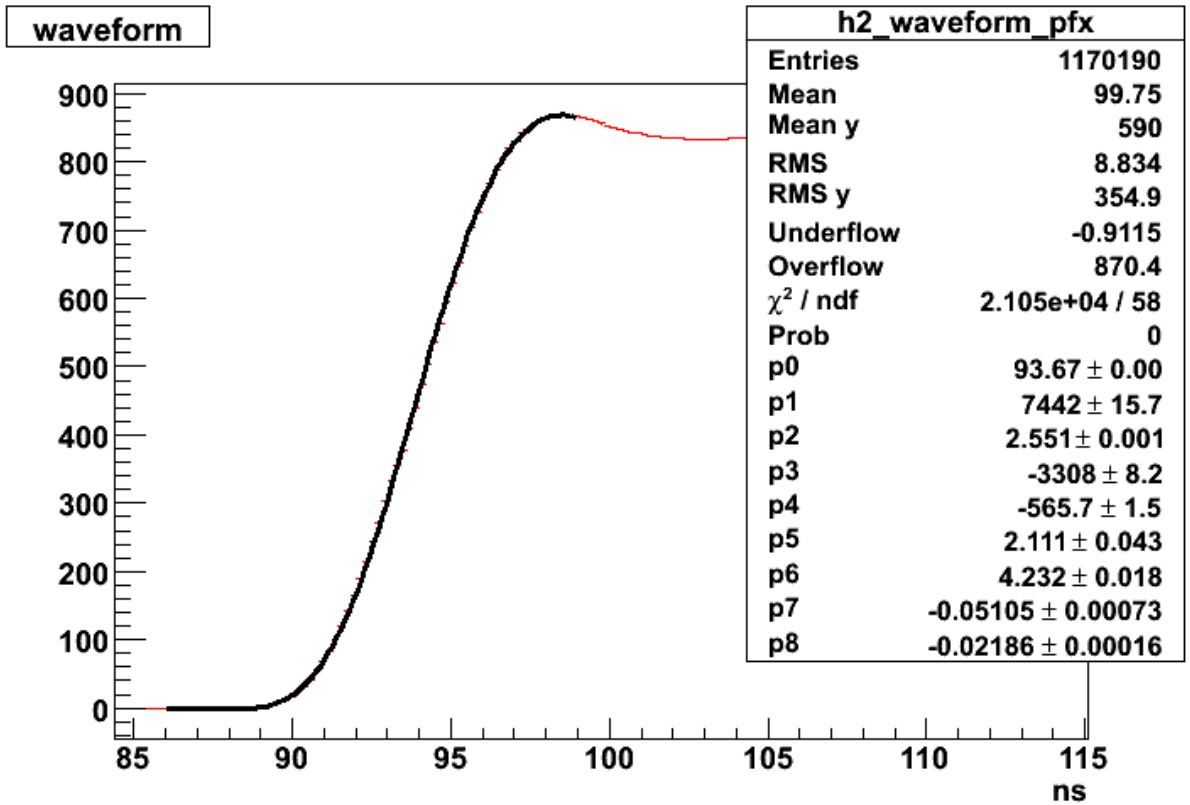
For a single pulse it is 122/√2 = 9 (8) ps

Time Resolution Along Pulse



- No significant difference along pulse, since this is created by pulse generator
  - In real signal expect best resolution at earliest times

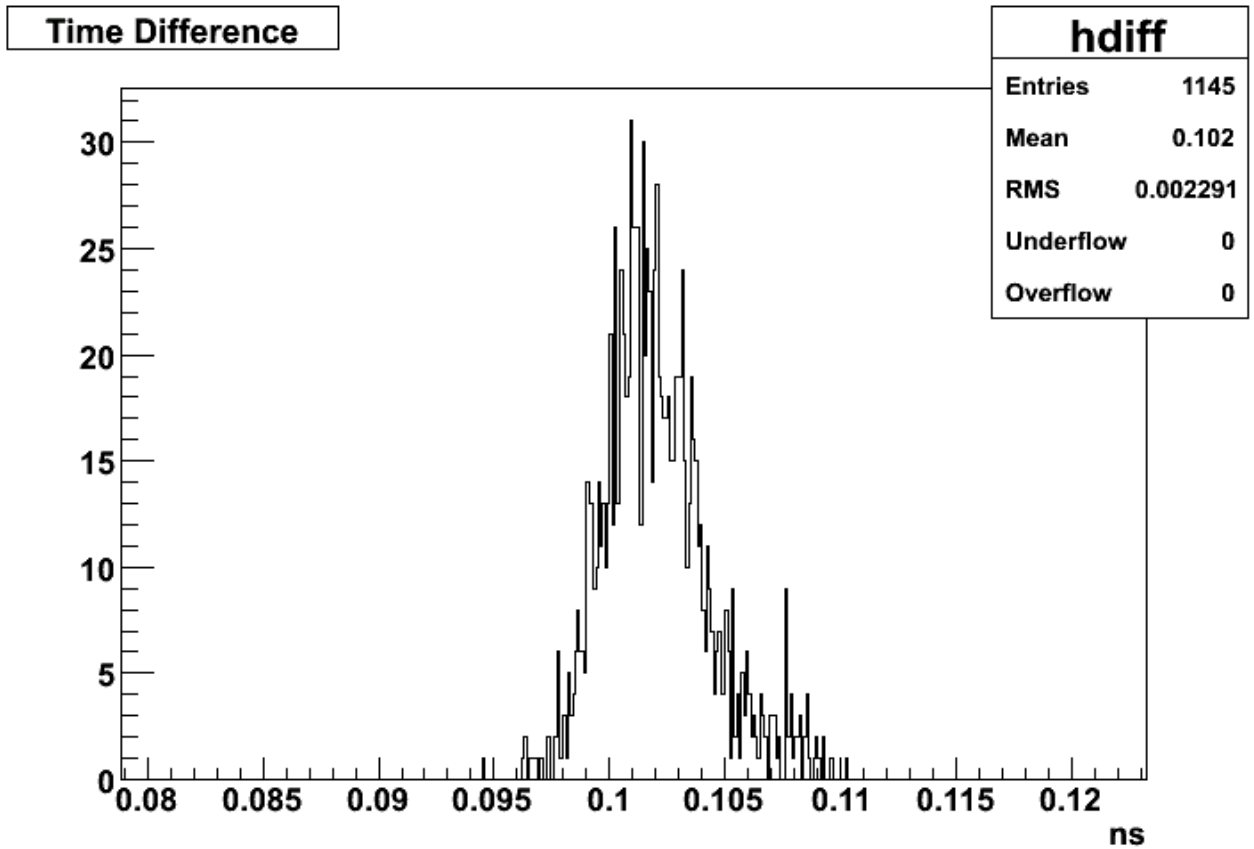
Fit to Test Pulse



$$f = \frac{A}{1+\exp\left(\frac{-(x-t_0)}{r}\right)} + B + C(x-t_0) + D(x-t_0)^2 + E(x-t_0)^3 + F(x-t_0)^4 + G(x-t_0)^5$$

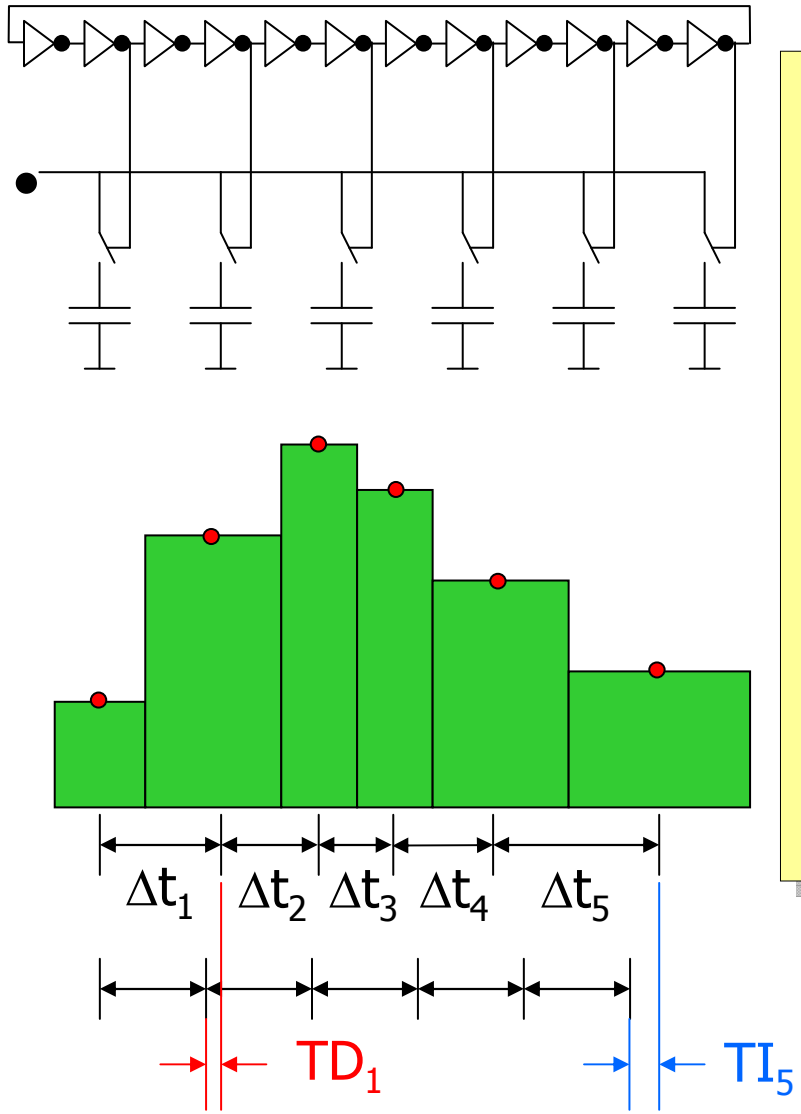
- Can parametrize the test pulse using a Woods-Saxon + 5th order polynomial
- We can then let the t0 be a free parameter, fixing the other parameters (A,B,C,…) to get the start time

Using Fit To Get Start Time



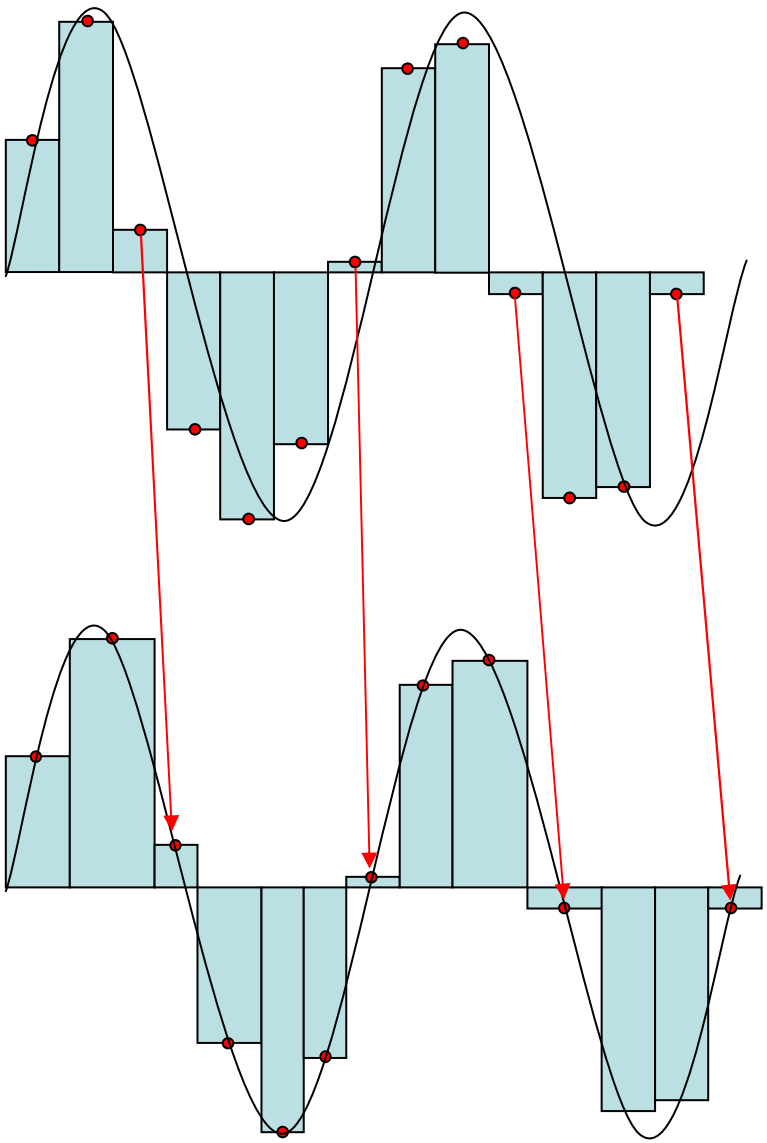
- We fit each of the split test pulse using the parametrization, and extract t0 from each
- Difference in start time is RMS=2.29 ps!
  - Each pulse gives resolution of 2.29/√2 = 1.62 ps
  - Roughly consistent with Sgl Sample Resolution:
    - Number of points sampled on rise, ~30, eg, 9 ps / √30 = 1.64

Timing jitter



- Inverter chain has transistor variations
  → Δt_i between samples differ
  → "Fixed pattern aperture jitter"
- "Differential temporal nonlinearity"
  $TD_i = \Delta t_i - \Delta t_{nominal}$
- "Integral temporal nonlinearity"
  $TI_i = \Sigma \Delta t_i - i \cdot \Delta t_{nominal}$
- "Random aperture jitter" = variation of Δt_i between measurements

Fixed jitter calibration

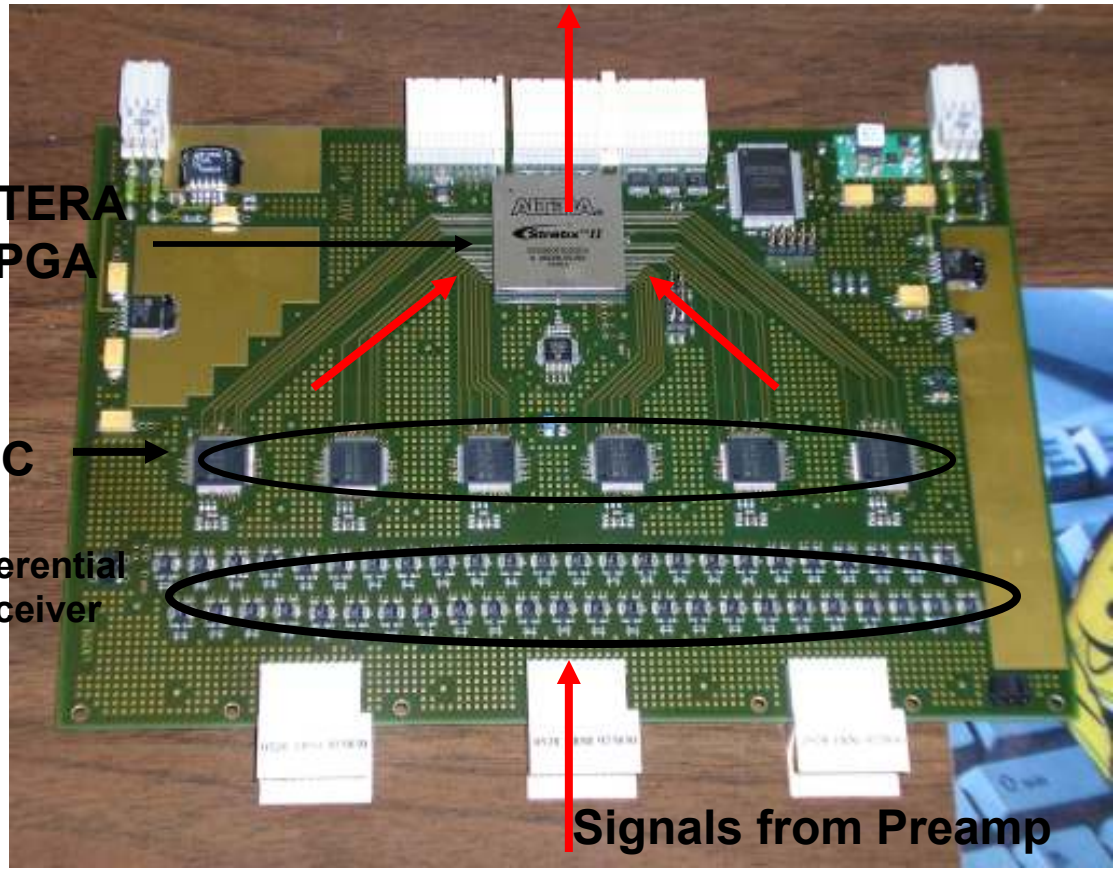


- Fixed jitter is constant over time, can be measured and corrected for
- Several methods are commonly used
- Most use sine wave with random phase and correct for TD_i on a statistical basis

HBD ADC board

We use ALTERA STRATIX II 60 FPGA to receive the 6 ADC's data

It has 8 SERDES blocks. ALTERA provides de-serializer Mega function block.
6XADC clock → SERDES clock
→ data de-serialized as 6 bit 120 MHZ
→ Regroup to 12 bits at 60 MHz , 45 degree phase adjustment step. Timing Margin → 270 degree.

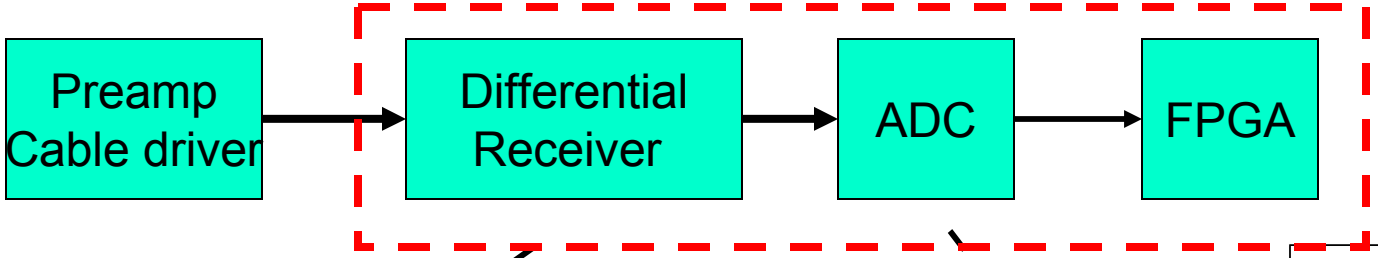


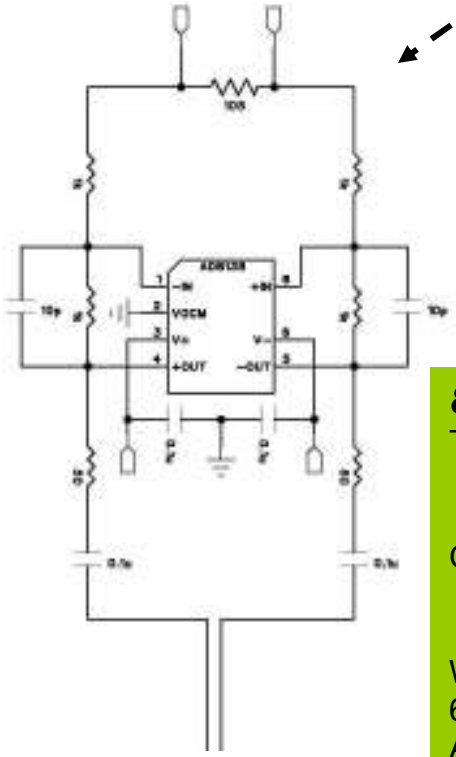
The FPGA also provides

- L1 delay (up to 240 samples)
- 8 events buffer
- ADC setting download
- Offline slow readback
- *7 threshold levels for L1 trigger primitives per channel*.

48 channels per board
6U X160 mm size

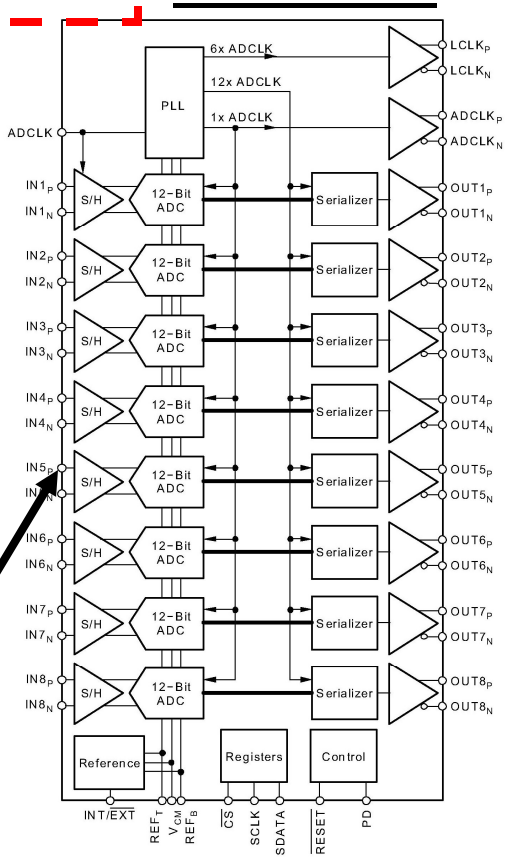
FEM receiver + ADC





Based on AD8138 receiver
Unity gain

TI ADS5272



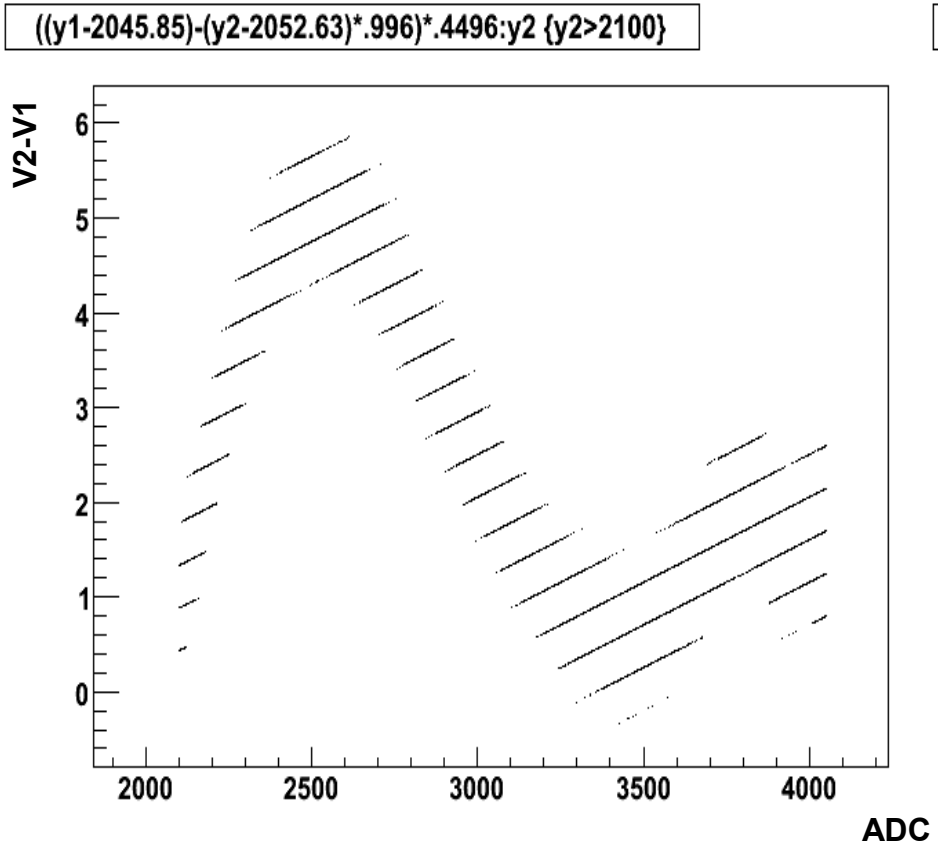
8 CHANNEL 65 MHz 12 bits ADC (80 TQFP)

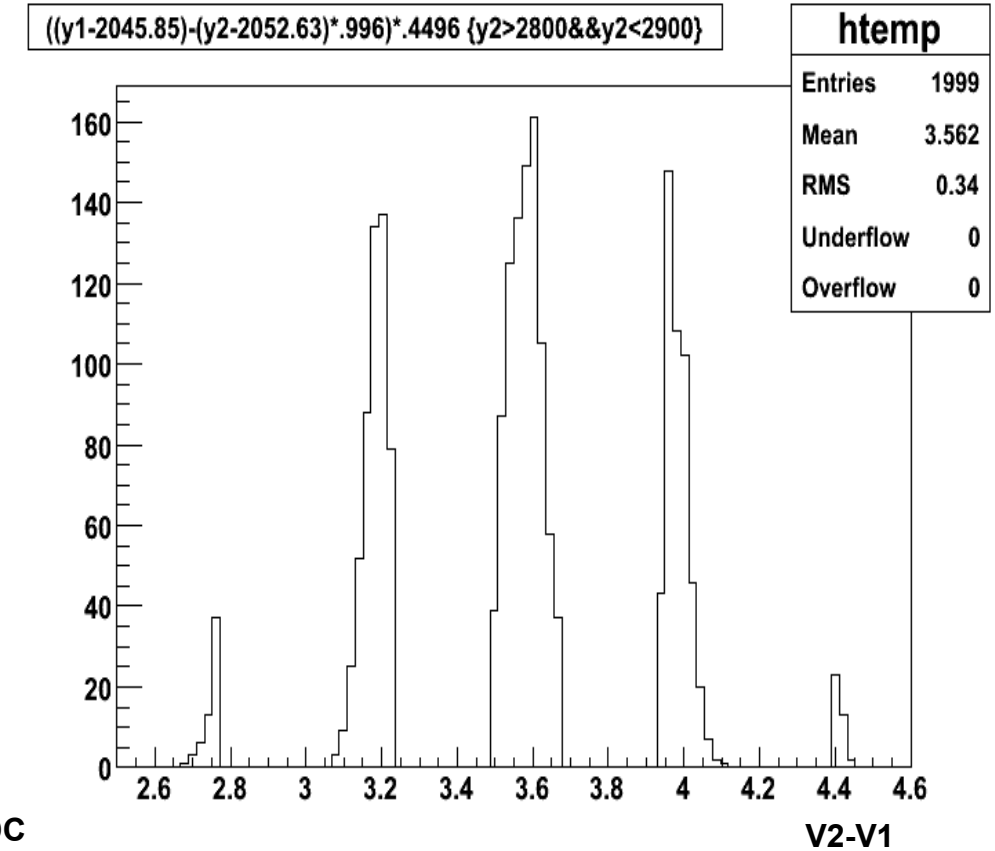
The +/- input can swing from 1V to 2V, V_{cm}=1.5V
+ side 2V, - side 1V -> highest count
- side 2V, + side 1V -> lowest count

Our +/- input will swing from 1.5 to 2V/ 1.5 to 1V
we will only get 11 bits out of 12 bits
16fc will be roughly sitting at 200 count

We will run the ADC at 6X beam crossing clock
6X9.4 MHz = 56.4 MHz or ~17.7ns per samples
ADC data are serialized LVDS at **12*56.4 MHz= 678 MHz**

HBD Electronics Timing

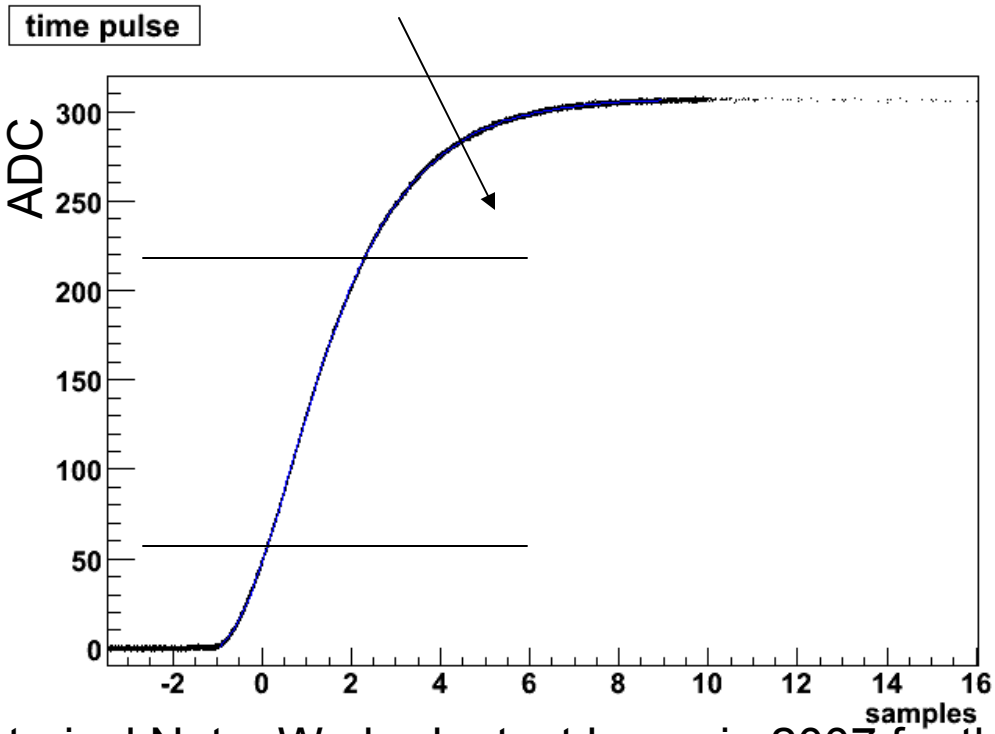




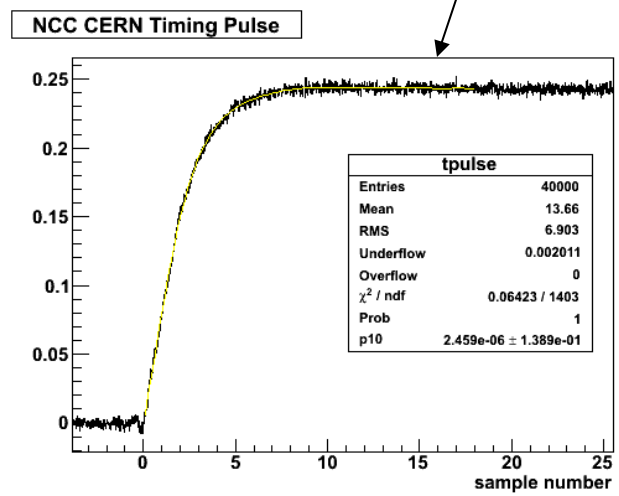
- HBD performance also could be fairly good, once one calibrates the strong dependence of the risetime differences between channels.
  - Resolution similar to DRS4, ~9 ps per sample
- Input is the same 5 ns rise time signal as for the DRS4 study, but due to the shaping at the input and limited bandwidth of the HBD ADC, the risetime becomes 30 ns, which is good considering it is a 60 MHz ADC (16.6 ns sampling).
- Shows that SNR is very important. Want to have fast risetime input signal, then optimize shaping to get good SNR to get best timing resolution which works with the ~3-4 samples we can read out.

NCC Test Beam Start Time Calibration

Digitized timing pulses, corrected for time, over an entire runs



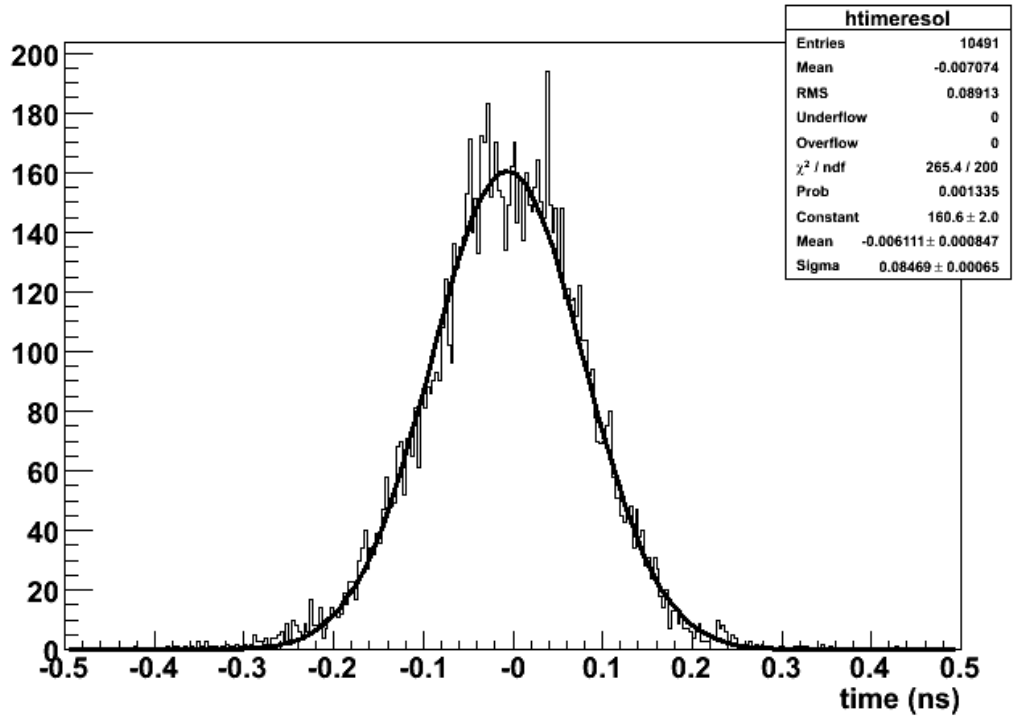
scope trace of start time signal



•Historical Note: We had a test beam in 2007 for the W-Si prototype, and we needed a start counter, so we stretched the Beam Scintillator pulse and read it into the HBD ADC. We only needed a few ns resolution.

•Amazingly, we discovered that using the HBD FEE, which samples every 16 ns, we could get better than 100 ps resolution! This led us to start looking into waveform digitizers for timing electronics.

Start Time Resolution



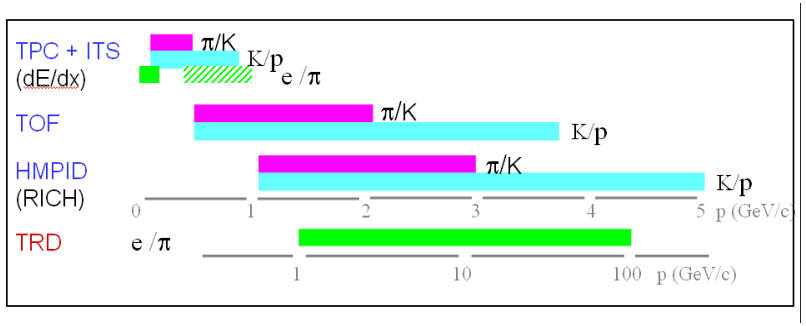
Taking these best data points (along the rising edge of the timing pulse), we see a resolution of about 85 ps. This represents the resolution of one sample (σ_1) plus the resolution of the fit to the timing pulse (σ_{TIME}). Since we get about 4 samples per timing pulse, the resolution of one sample = 4*σ_{TIME}. Thus, the resolution of one sample is ~ 76 ps, since

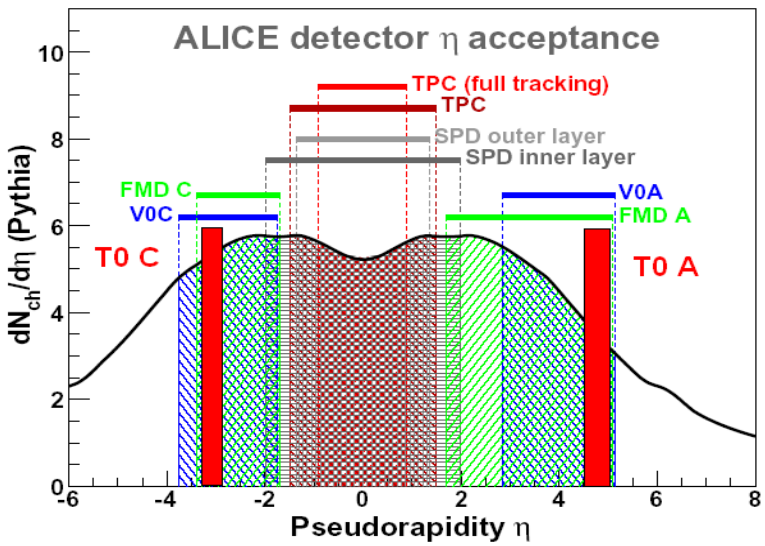
$$\sigma_1 \oplus \sigma_{TIME} = 85\,ps$$

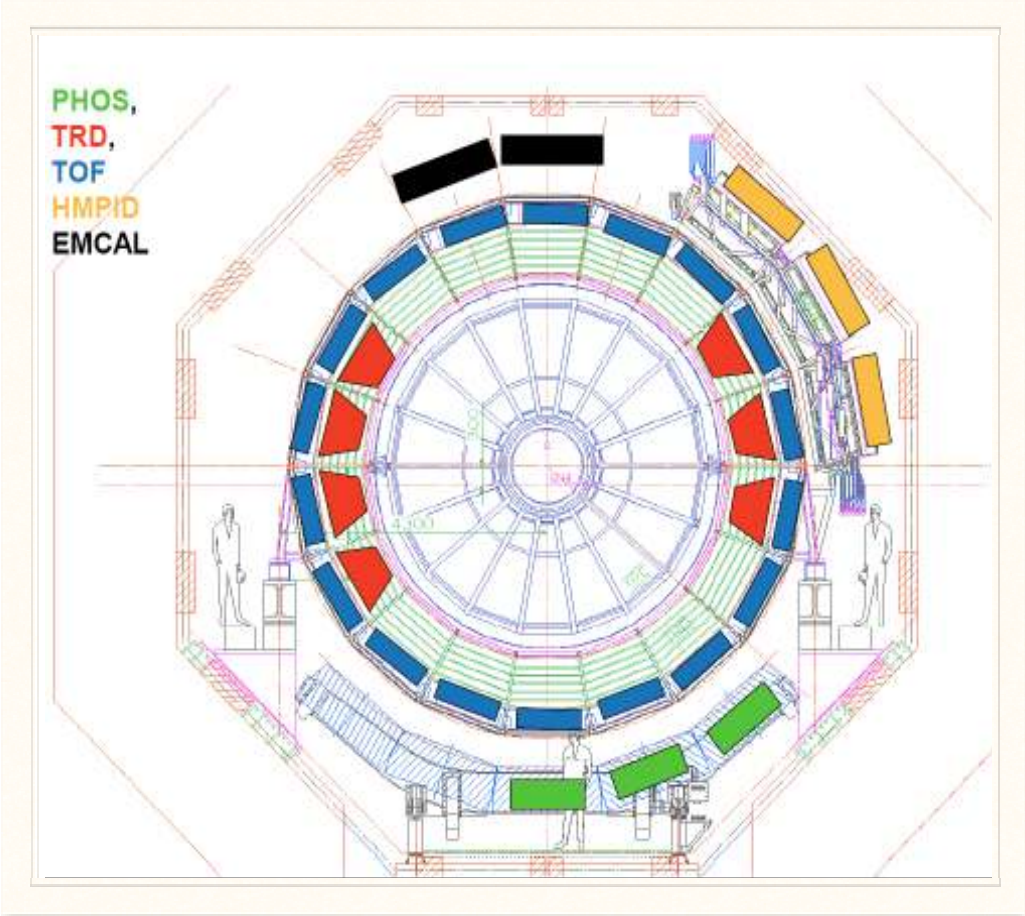
$$\sigma_1 \approx 2\sigma_{TIME}$$

Conclusion: The HBD ADC contributes at most ~76 ps to the timing resolution

ALICE PID



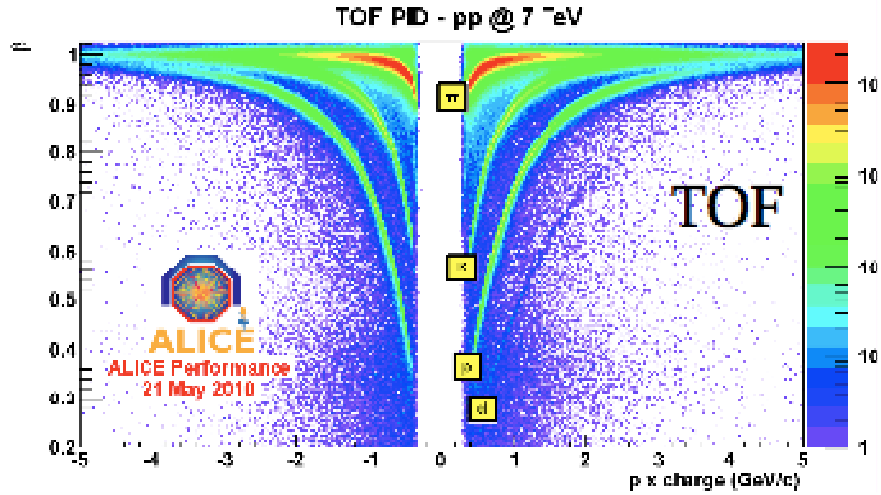


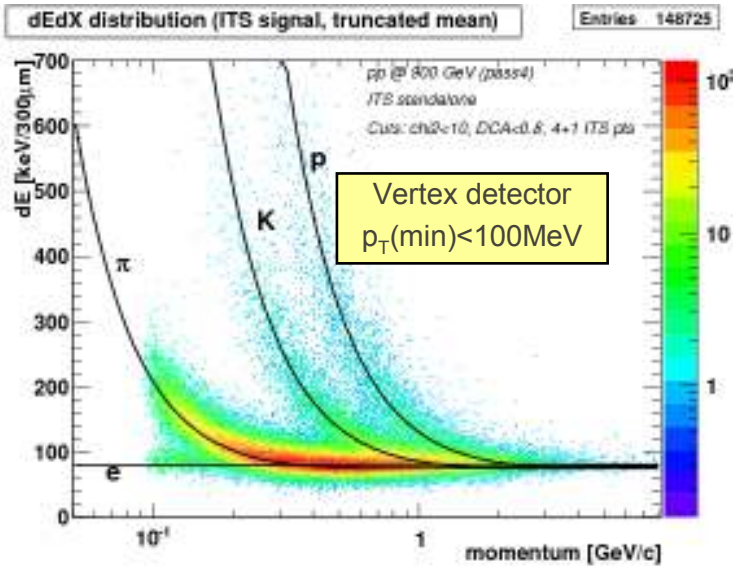


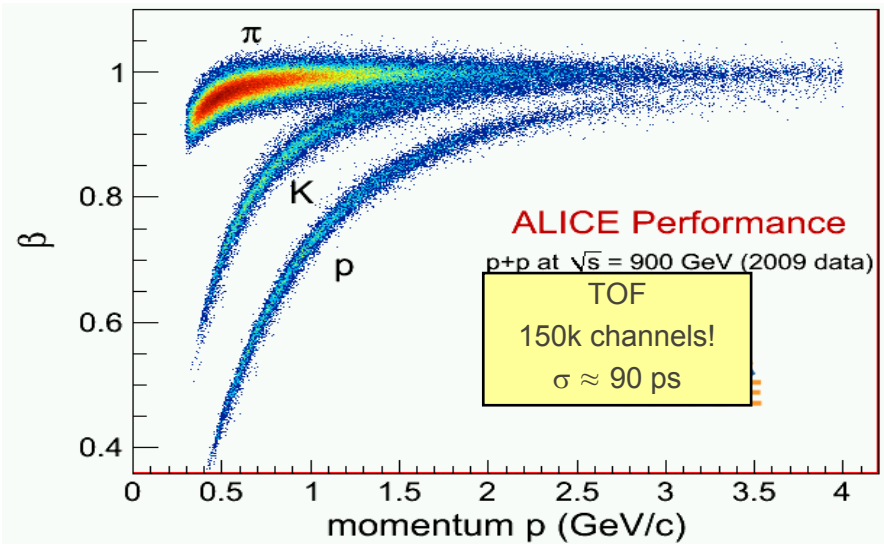
- ALICE and STAR have full barrel coverage TOF for |eta|<1.0
- FIRST TIME that LARGE ACCEPTANCE PID has been done at ultra-relativistic HI collisions
    - We don't know what we might have missed, but we will find out at QM2011

Particle Identification

TPC dE/dx
7 TeV pp
$\sigma \approx$5-6%







Summary

- We have identified a promising path to a large acceptance TOF system for PHENIX in the near term
  - Photonis MCP-PMTs with 1 cm Fused Quartz Radiators
  - HBD ADC or possibly DRS4-like ASIC
- Reasonable cost – roughly $3M for one arm, materials cost (includes electronics)
- Want to make it in by 2013, same as STAR HFT upgrade
- Proposal in next year
  - In a new rapidity range – possible new physics?
    - 3D Description of HI Collision, ie, we can go to 3D hydro
    - Best region to study possible P or CP violation?
    - Large rapidity correlations possible, etc…
- This might have a path to an eventual upgraded or new detectors for RHIC/EIC
  - Perhaps new BBC for sPHENIX? V. Forward TOF around Beampipe?
- The R&D work here, especially for the electronics, is very important for realizing the next generation PID detectors for the Collider upgrade (most likely EIC)
- Many thanks to Thomas Tsang, Sean Stoll, Sebastian White, and Henry Frisch (for loaning us the DRS4 evaluation board)