Working With Waveforms

Sebastian White, CERN/U.Virginia   Sept. 12, 2018

"ULTIMA 2018"   Argonne National Lab

HL-LHC upgrade program has renewed interest in Charged Particle timing*
at << 100 picosecond resolution. Usually with internal gain.

Acquiring high quality waveforms has been key in PICOSEC
sensor development-> >>10^6 events from MPGD,Silicon,MCP over 4 years

In this talk I will describe methodology and illustrate benefits of this approach

* see "Experimental Challenges of the European Strategy for Particle Physics",SNW
* CHEF 2013- Paris April 2013, http://inspirehep.net/record/1256027/files/CHEF2013_Sebastian_White.pdf

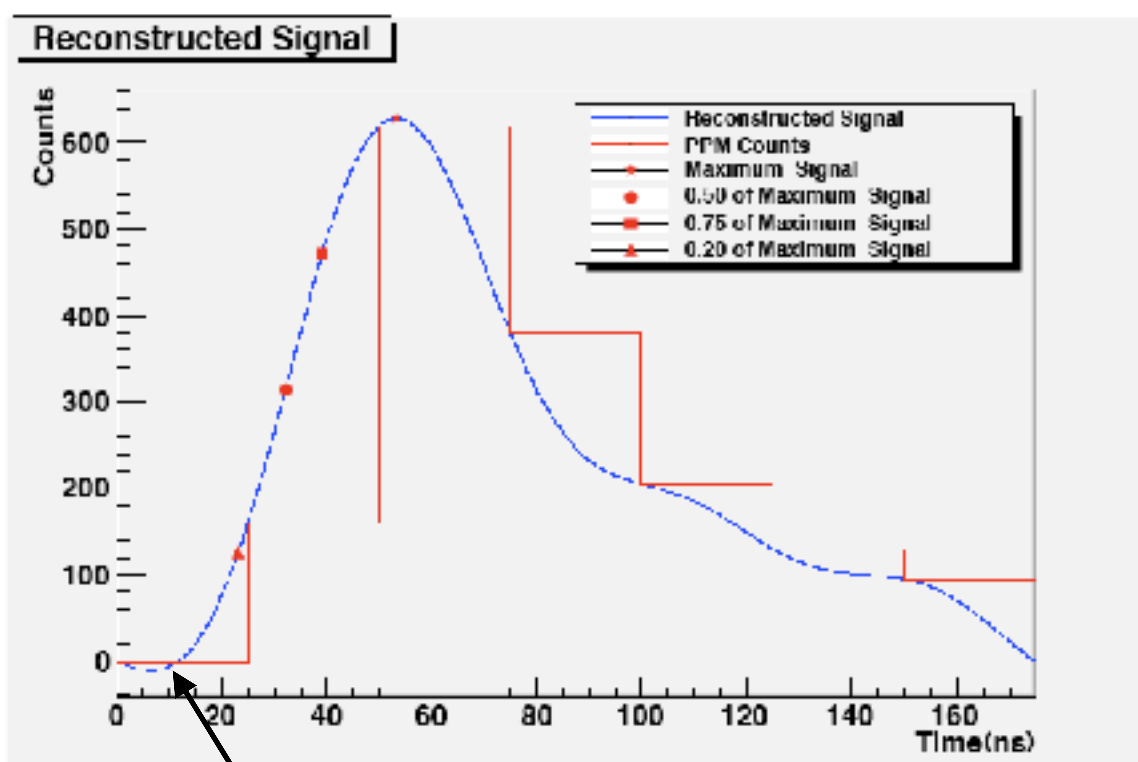
10 Years of waveform analysis from 40 MSa/s to 40 GSa/s

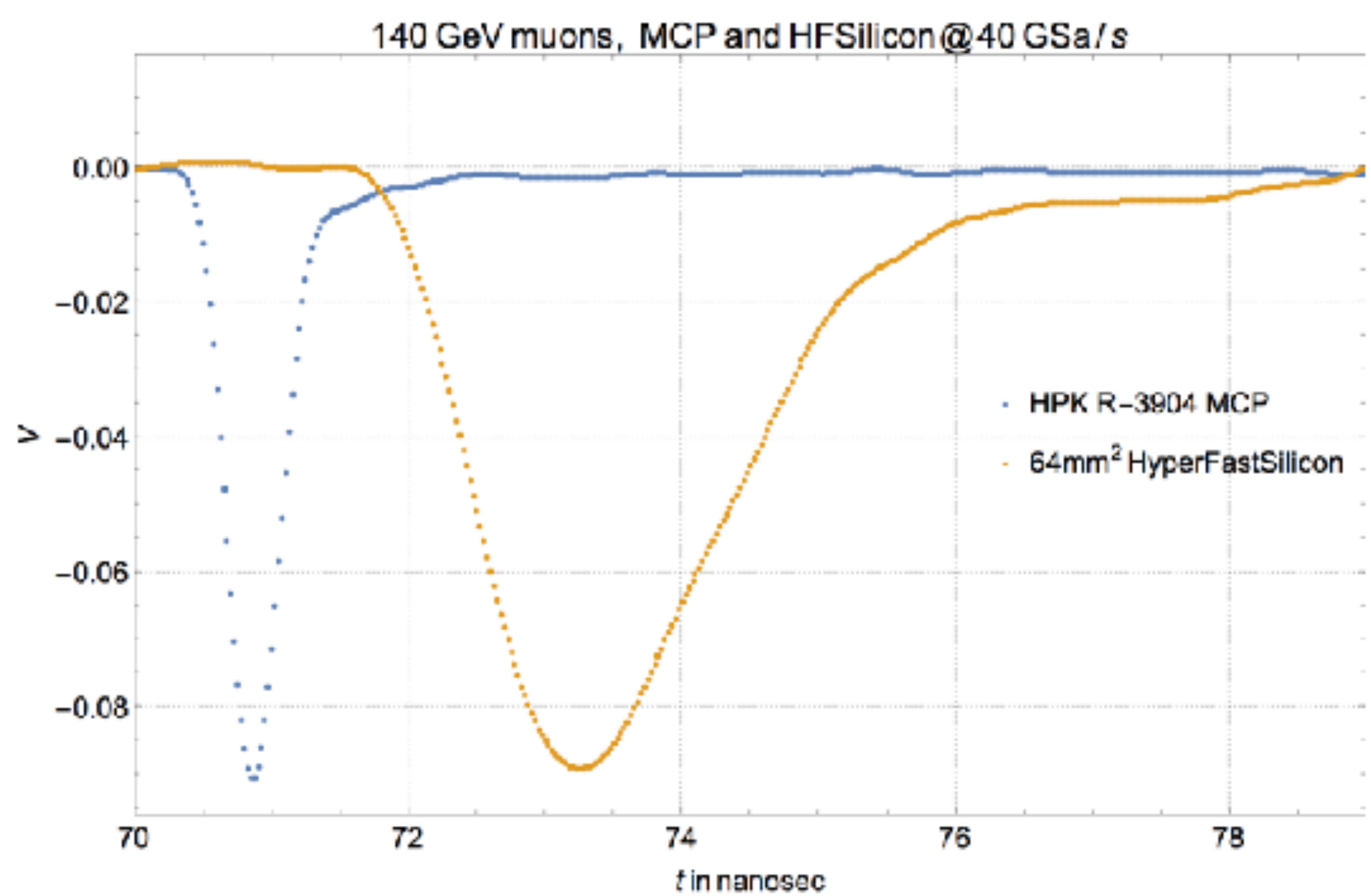
~2010 ATLAS ZDC waveforms
reconstructed from PPM samples
-> sub- 100 picosec resolution
SNW, Diffraction 2010 https://arxiv.org/abs/1101.2889
http://library.wolfram.com/infocenter/Articles/7716/

Aug. 2018 PICOSEC Test Beam
MCP* ref. time, HyperFastSilicon

$\sigma_t^{MCP} \sim 4$ picosec, $\sigma_t^{HFS} \sim 20$ picosec

LRS "Wavemaster"





$\frac{\sin[x]}{x}$ interpolation of digitized waveform

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

* MCP= MicroChannel PMT
detecting Cerenkov from window

July/Aug 2017 PICOSEC data

4x 6micron HPK MCP 's
+3mm Quartz
(measure ~4 picosec)

HyperFastSilicon(HFS)
(mesh readout DD-AD)
64 mm²/pixel
(measure<20 picosec)

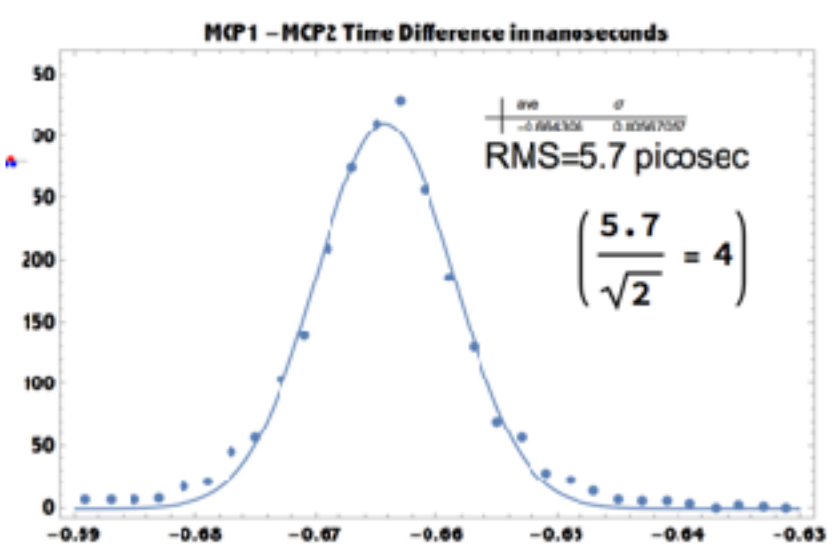
MMegas-based
"PICOSEC"
80 mm² pixel
(measure<25 picosec)

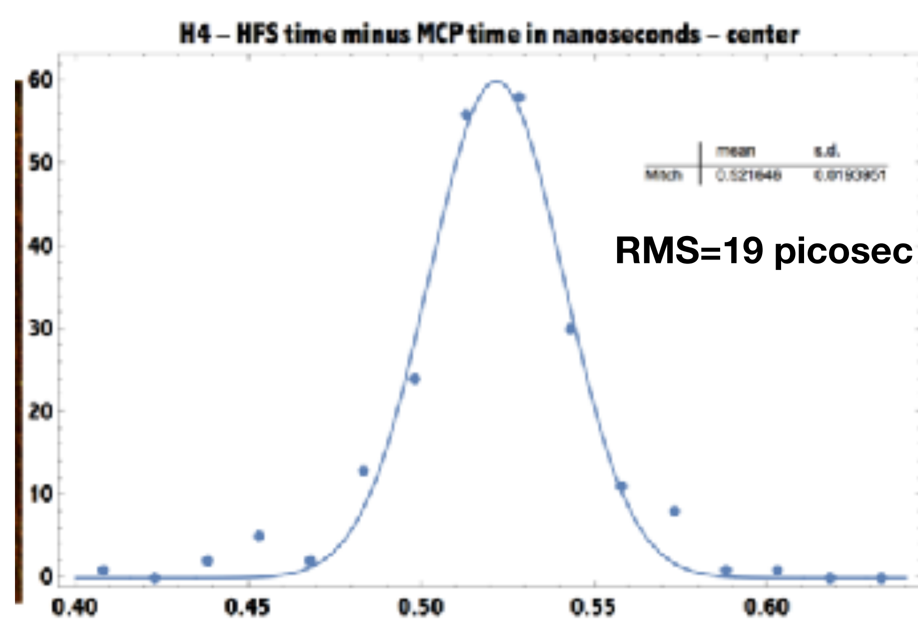
10 pad "PICOSEC"

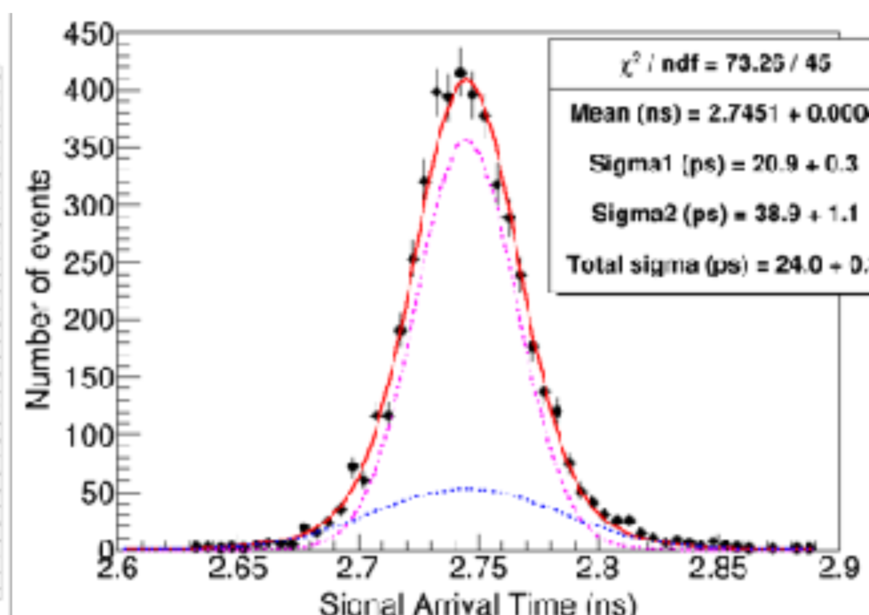
vacuum

Si- Gallium doped

Ne/C2H6/CF4







2 Fast Timing Projects based at CERN (we share resources, beam, ++)

PICOSEC: RD51 common Fund proposal in 2014 by SNW and I. Giomataris

MPGD

J. Bortfeldt [b], F. Brunbauer [b], C. David [b], D. Desforge [a], G. Fanourakis [e], J. Franchi [b], M. Gallinaro [g], I. Giomataris [a], D. González-Díaz [i], T. Gustavsson [j], C. Guyot [a], F.J. Iguaz [a,*], M. Kebbiri [a], P. Legou [a], J. Liu [c], M. Lupberger [b], O. Maillard [a], I. Manthos [d], H. Müller [b], V. Niaouris [d], E. Oliveri [b], T. Papaevangelou [a], K. Paraschou [d], M. Pomorski [k], B. Qi [c], F. Resnati [b], L. Ropelewski [b], D. Sampsonidis [d], T. Schneider [b], P. Schwemling [a], L. Sohl [b,1], M. van Stenis [b], P. Thuiner [b], Y. Tsipolitis [f], S.E. Tzamarias [d], R. Veenhof [h,2], X. Wang [c], S. White [b,3], Z. Zhang [c], Y. Zhou [c]

new paper this week:

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 903, 21 September 2018, Pages 317-325

HFSilicon: "Sensors with Internal Gain"-started in 2015

Silicon

M. Centis Vignali[1], M. Gallinaro[1,2], B. Harrop[3], C. Lu[3], M. McClish[4], K. T. McDonald[3], M. Moll[1], F. M. Newcomer[5], S. Otero Ugobono[1,6], and S. White[1,7]

subset originated in 2011 DOE AD R&D award to:

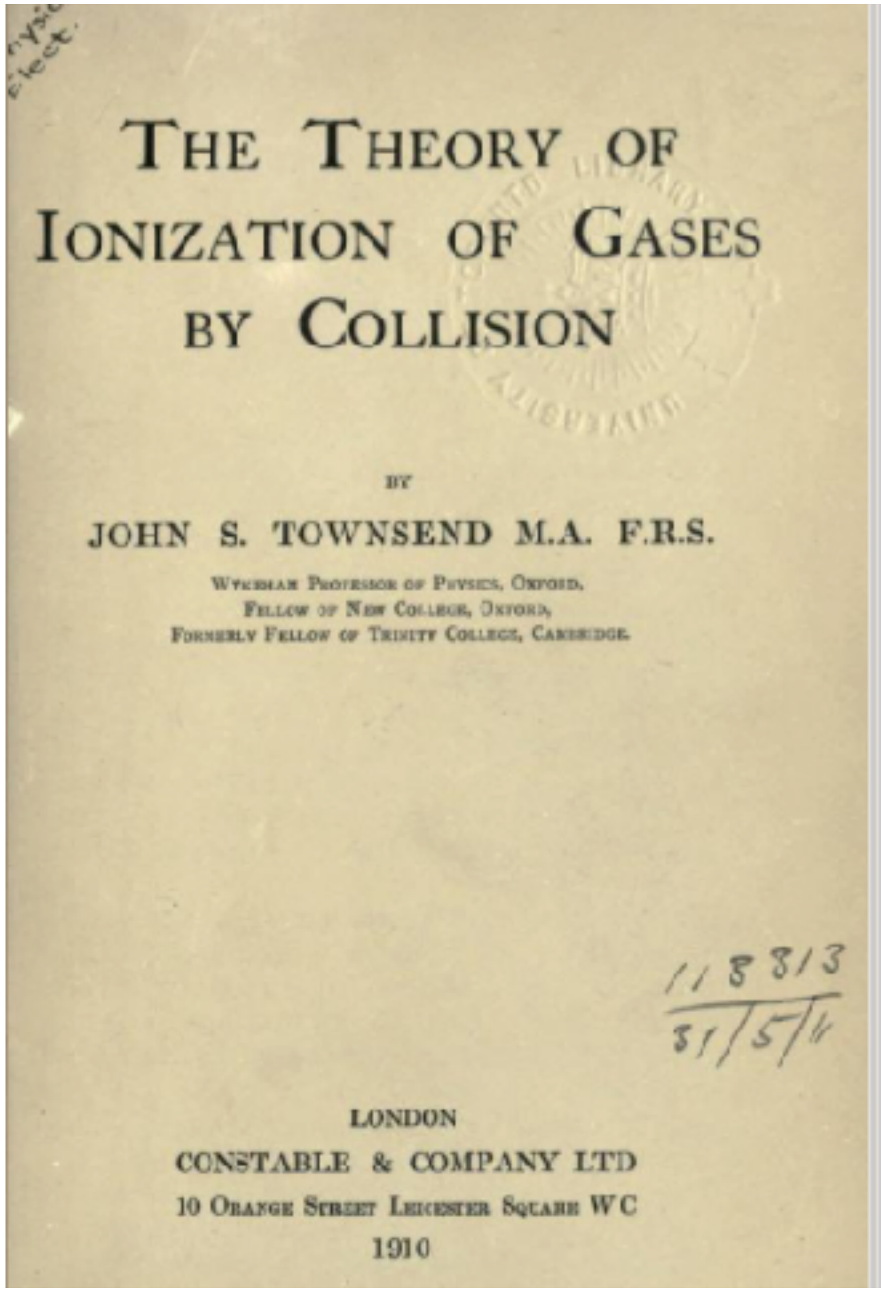
Growing, highly motivated group w. serious commitment to Instrumentation

Outline

1) **Development of PICOSEC MPGD based detector (24 picosec)**
   -Cerenkov Radiator, similarities to MCP
   -Drift Region-dominant role of diffusion and Gain
2) **Application of similar modeling tools (SILVACO) for Silicon (20 picosec)**
   -SILVACO tct-edge scan tool- with Ranjeet Dalal, Delhi
   -realistic Landau/Vavilov- thin samples- with Su Dong, Stanford
3) **tools for FEE development**
   -CIVIDEC development -w E.Griesmayer, Vienna
   -Transimpedance amp -w. M. Newcomer(+E.Morales), U. Penn
   -quad fast ASIC (SiGe)- “ “-(w. US/CMS support)
4) **Strategies for digitization**
   -CMS Barrel Timing Layer prototype data (LYSO/SiPM)
   -other applications

It Takes Time

detection/multiplication in Gas detectors (1910)


THE THEORY OF IONIZATION OF GASES BY COLLISION

BY

JOHN S. TOWNSEND M.A. F.R.S.

WYKEHAM PROFESSOR OF PHYSICS, OXFORD,
FELLOW OF NEW COLLEGE, OXFORD,
FORMERLY FELLOW OF TRINITY COLLEGE, CAMBRIDGE

LONDON
CONSTABLE & COMPANY LTD
10 ORANGE STREET LEICESTER SQUARE WC
1910

in Silicon detectors(1972)

The distribution of gains in uniformly multiplying avalanche photodiodes: Theory
R.J. McIntyre
IEEE Transactions on Electron Devices
Year: 1972, Volume: 19, Issue: 6
Pages: 703 - 713
Cited by: Papers (271) | Patents (9)
IEEE Journals & Magazines

Factors affecting the ultimate capabilities of high speed avalanche photodiodes and a review of the state-of-the-art
R.J. McIntyre
1973 International Electron Devices Meeting
Year: 1973
Pages: 213 - 216
Cited by: Papers (12)
IEEE Conferences

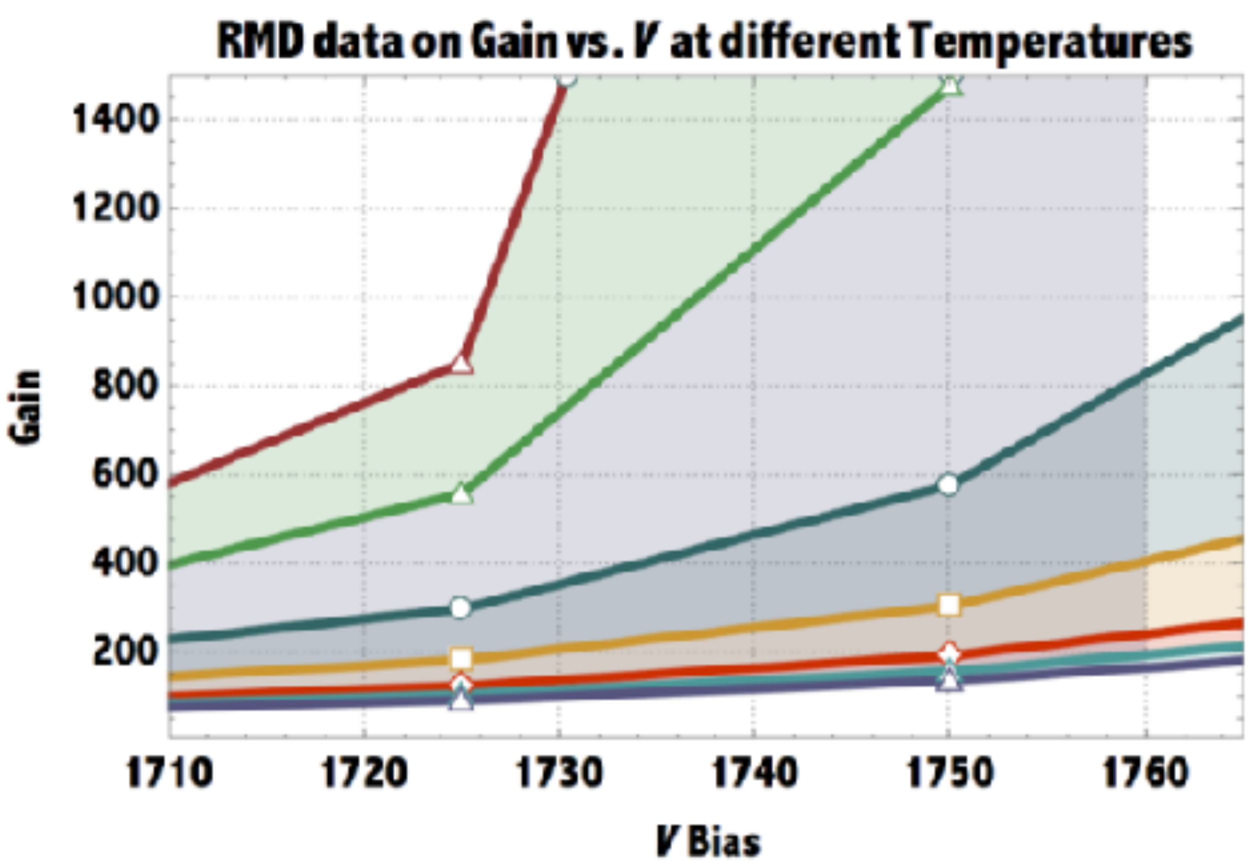
Theory and practice of Si w. internal gain relatively new.

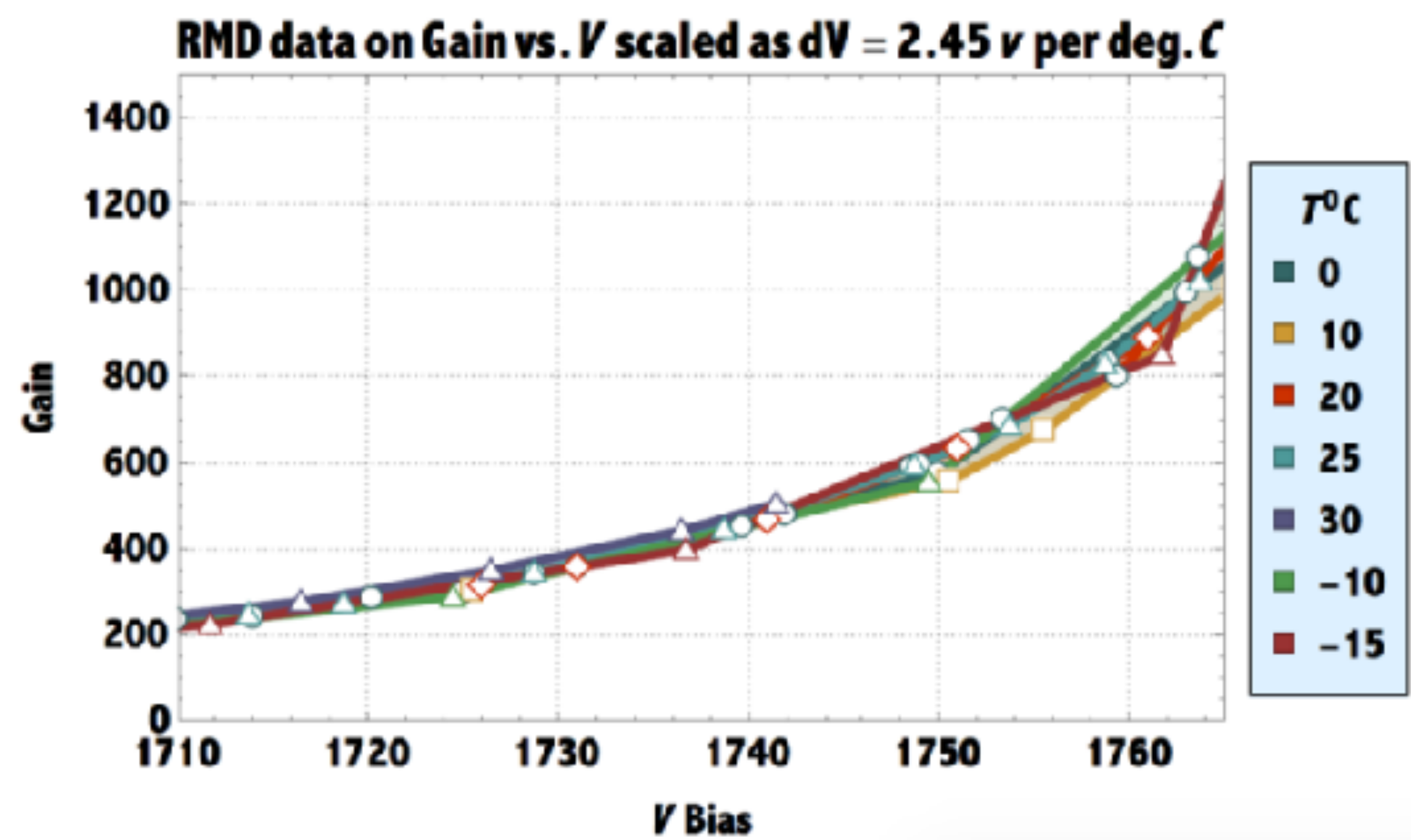
1) *most common,"reachthrough" diodes (aka "lgad") ~1970's, MIP timing in '90's*
2) *higher gain, "deep depleted" (our focus) started in '90's*

cooperative R&D w Gas(RD51) benefitted less mature Si modeling

ATLAS/CMS timing upgrades all based on Si w gain
->justifies continued development of underpinnings

interesting, possibly deep, phenomena not yet traceable to particular gain model





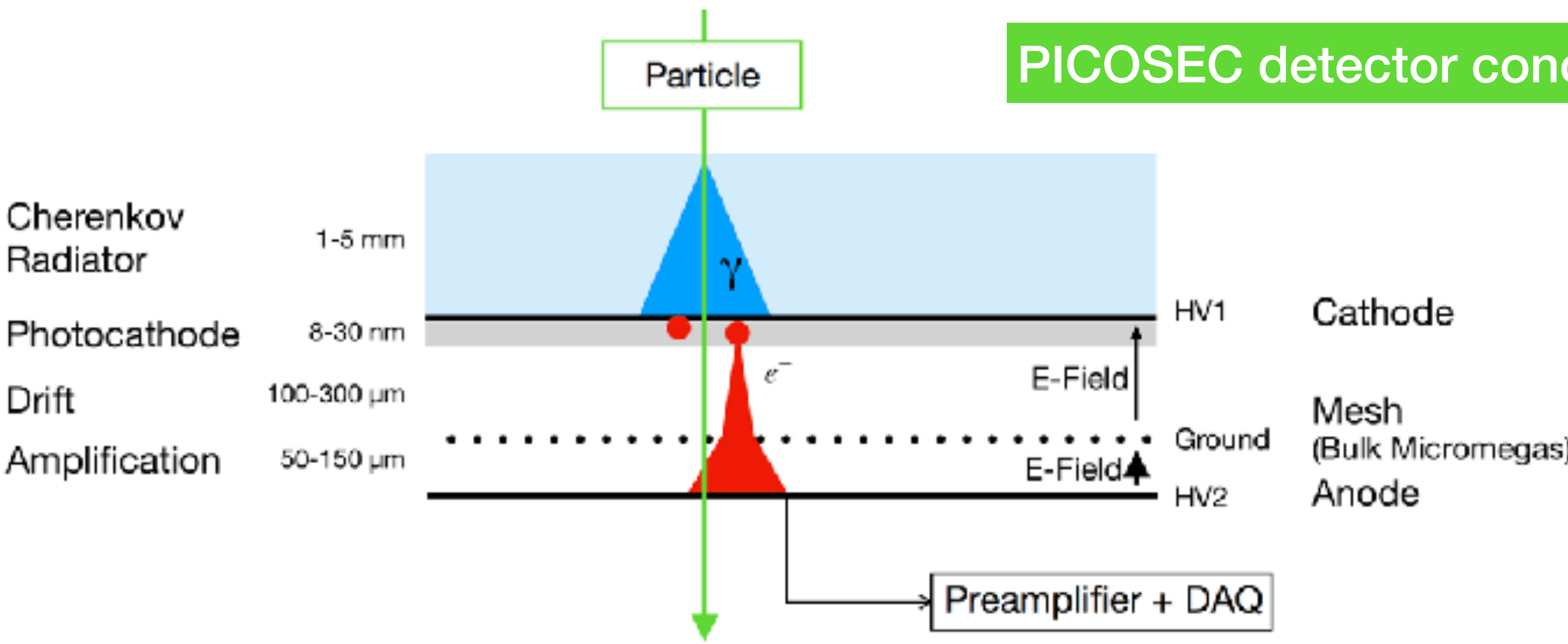
waveform data may reveal features not anticipated in models
->Si structure modification to mitigate degradation (~x2) due to Landau?
-> “”” “ “ degradation due to radiation damage? ……

this worked w. PICOSEC (see below)-> then traced to simulation tools

In any case waveform data key in guiding FEE and digitizer strategy.

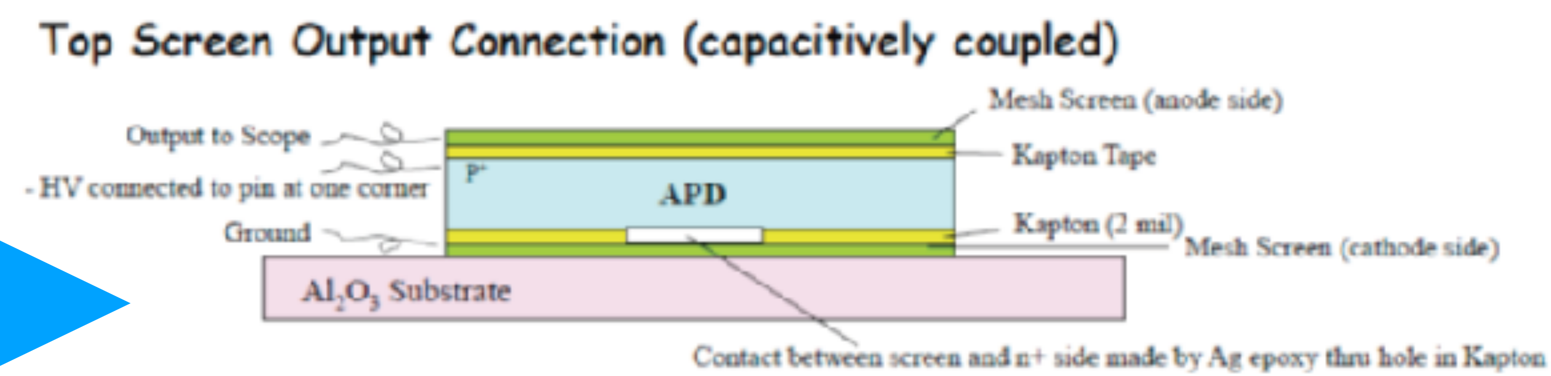
Ionization or Photodetection?

PICOSEC detector concept

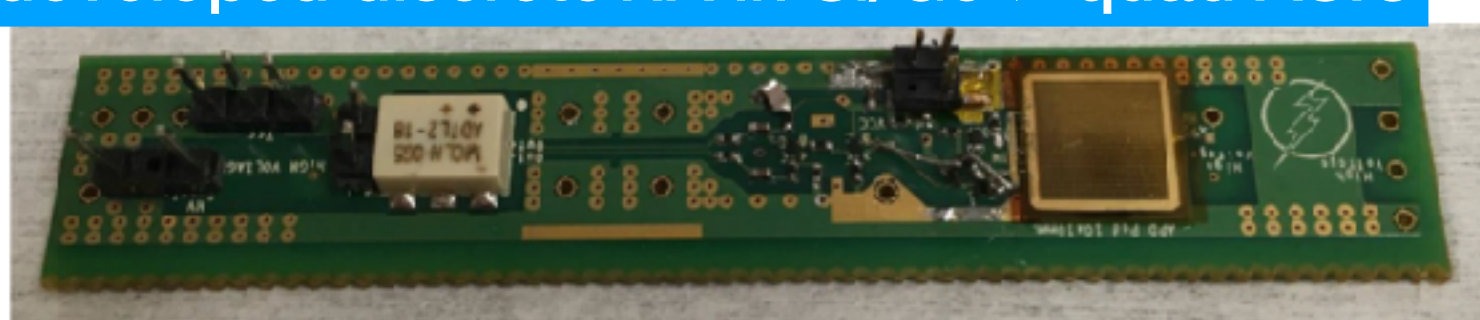


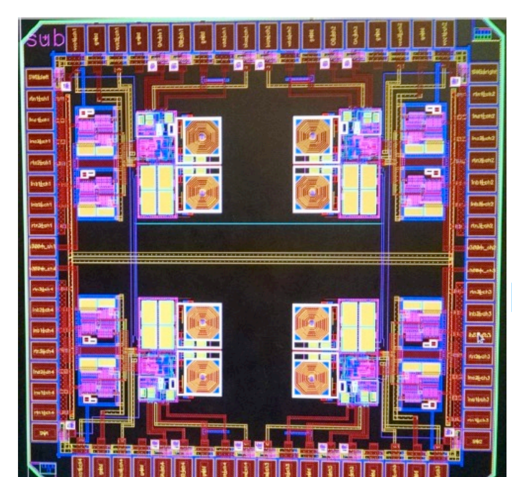
note similarity to MCP (next)

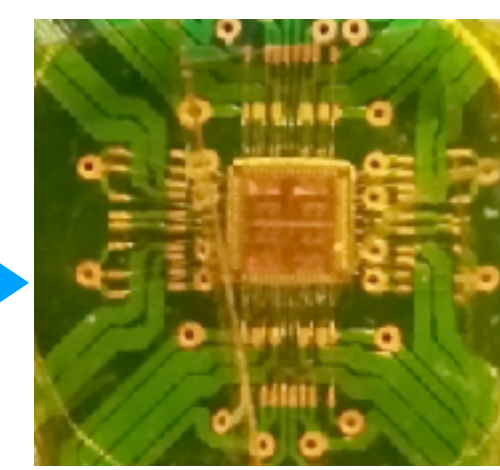
mesh readout deep-depleted AD aka “HyperFast Silicon”



developed discreteTIA in Si/Ge-> quad ASIC

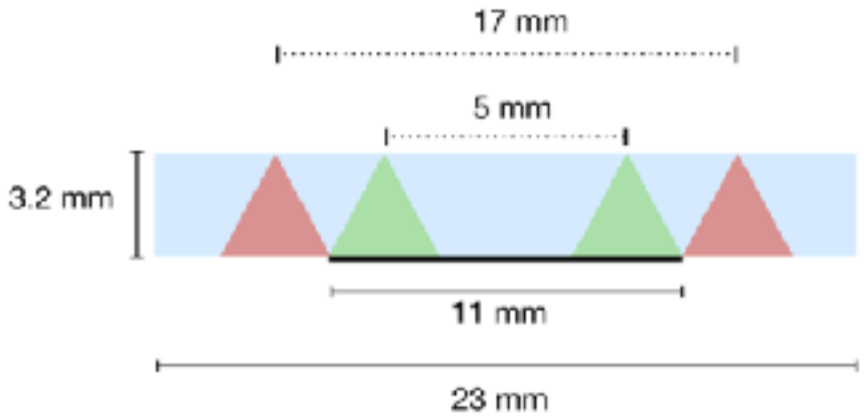




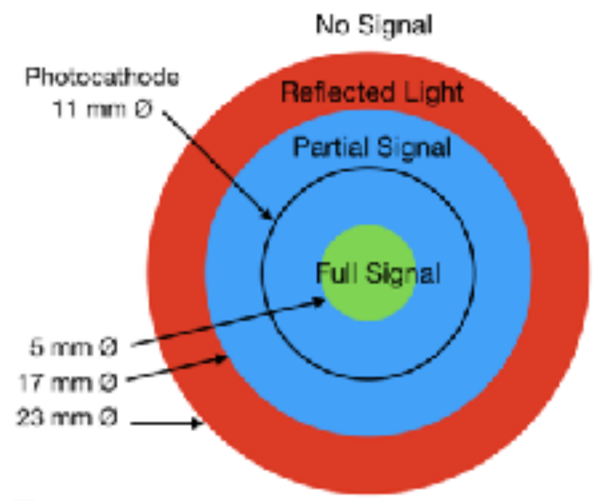


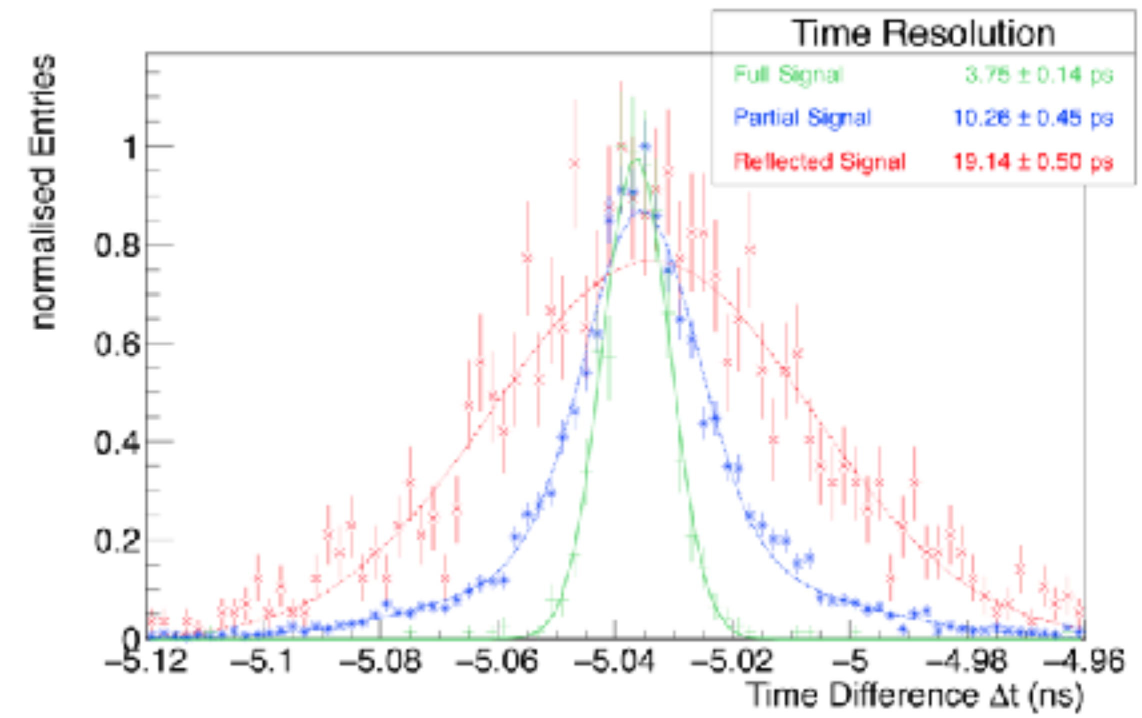
detailed understanding of MCP applies to-> PICOSEC

see L. Sohl 2018 Elba

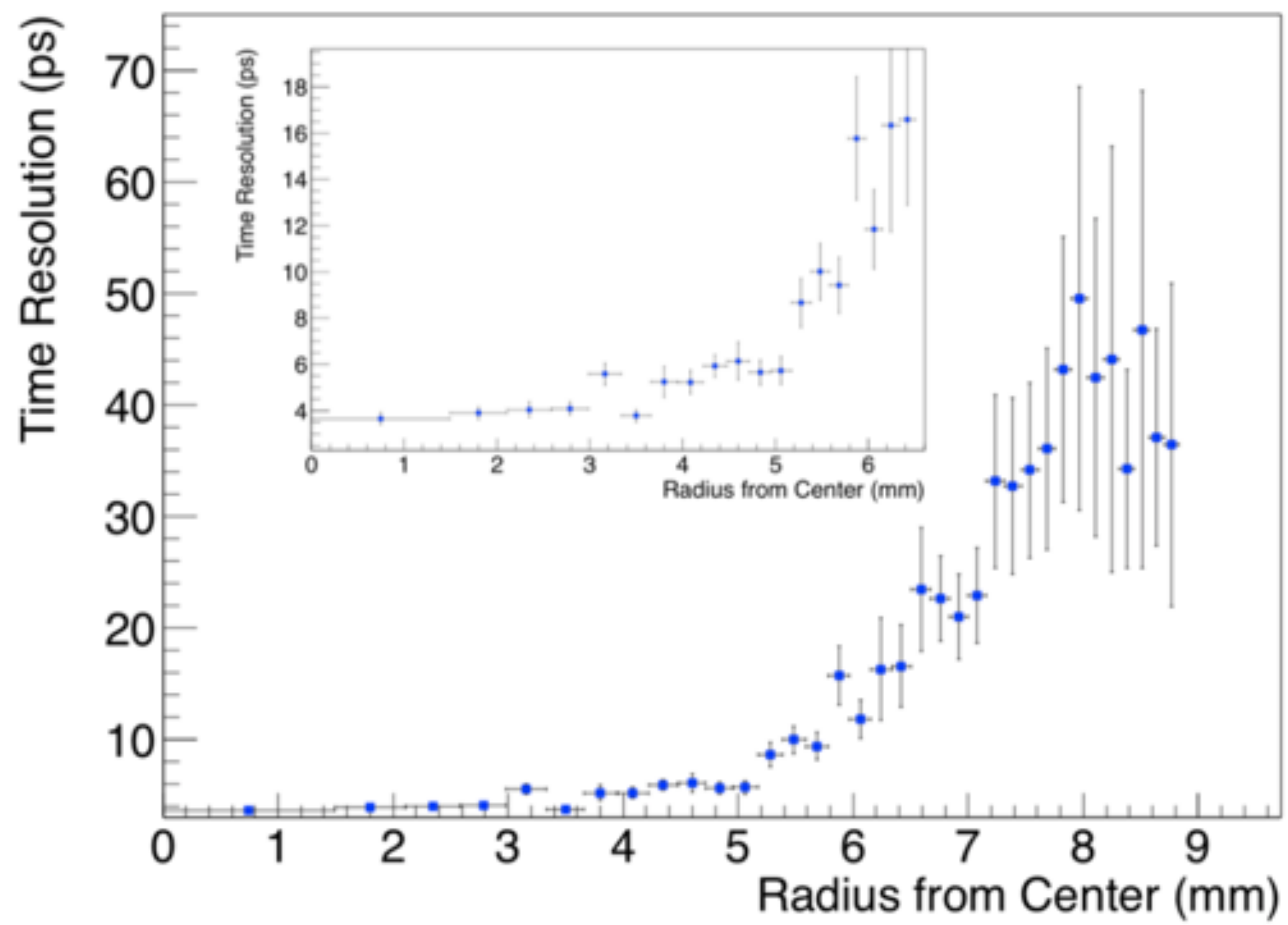


Cerenkov in HPK MCP window (note similar to MMegas 3mm)



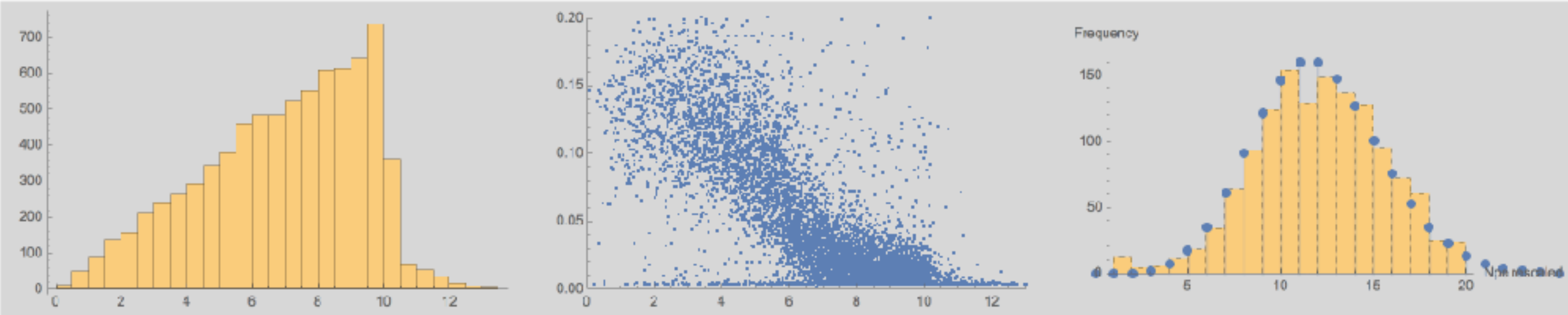


in multi-pad PICOSEC combine pads to restore “full signal”



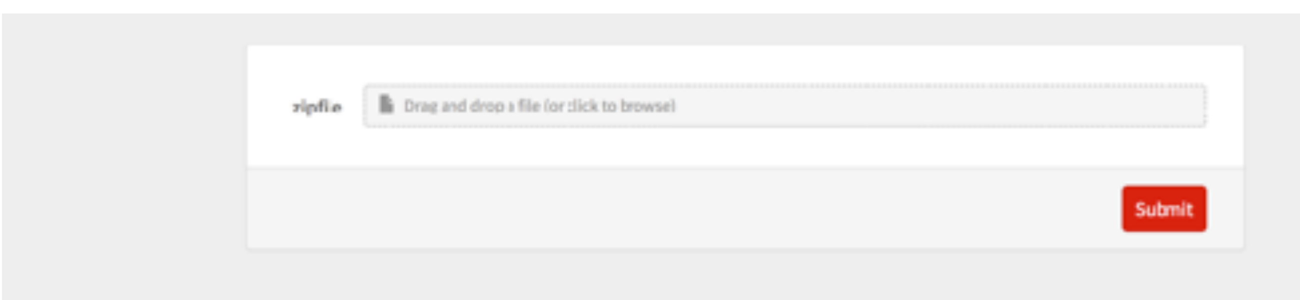
as with MCP, PICOSEC(next) timing with full Cerenkov cone

Track Impact for hits above noise in MCP, Peak Amplitude vs. Impact and Peak Distribution for RMCP < 4.5 mm



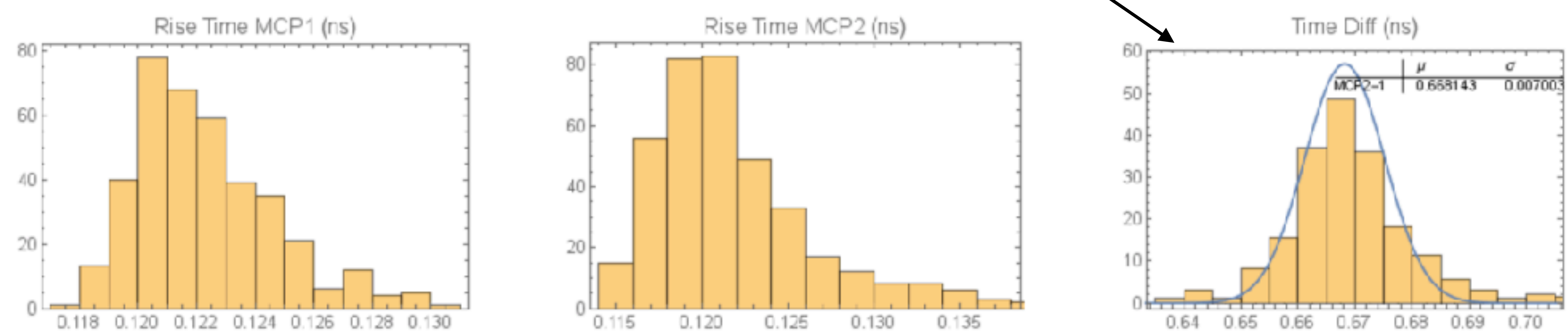
unlike PICOSEC, MCP response to photoelectrons simple!
-> tools (in collaboration w Wolfram Research) to do complete analysis in cloud

see. M. Guth talk at DIANA-HEP Oct. 30, 2017



<-drop binary scope file in cloud app

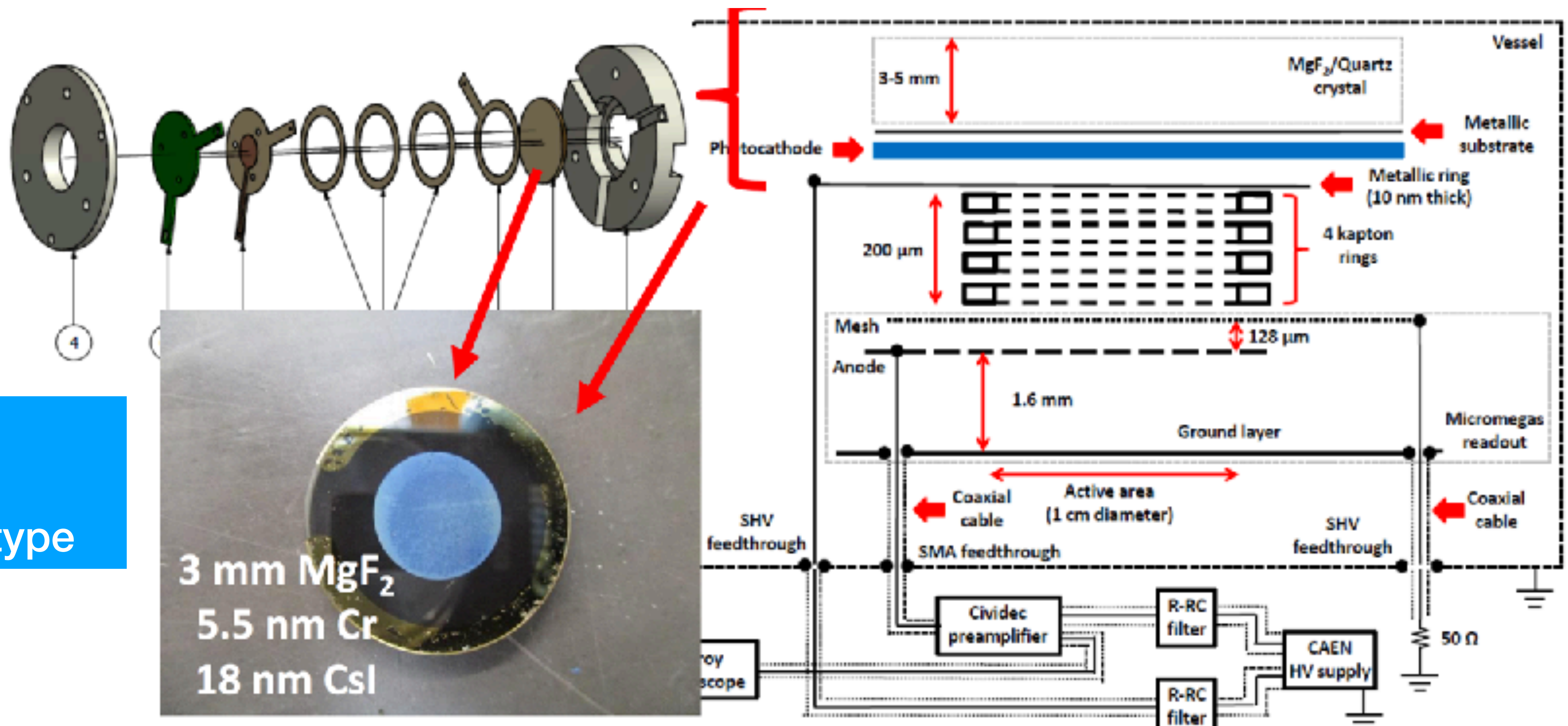
it sends you back report



very good data quality from HFS in 2017!
why initiate something in MPGD?

- **big enthusiasm in GDD/RD51 because speed ensures continued relevance**
- **potential benefit of continuous MIP signature (ie no Landau)**
- **a hedge against rad hardness of Silicon w Internal Gain**
- **“this seems like the right way to get inexpensive, large area timing”-R. Horisberger**

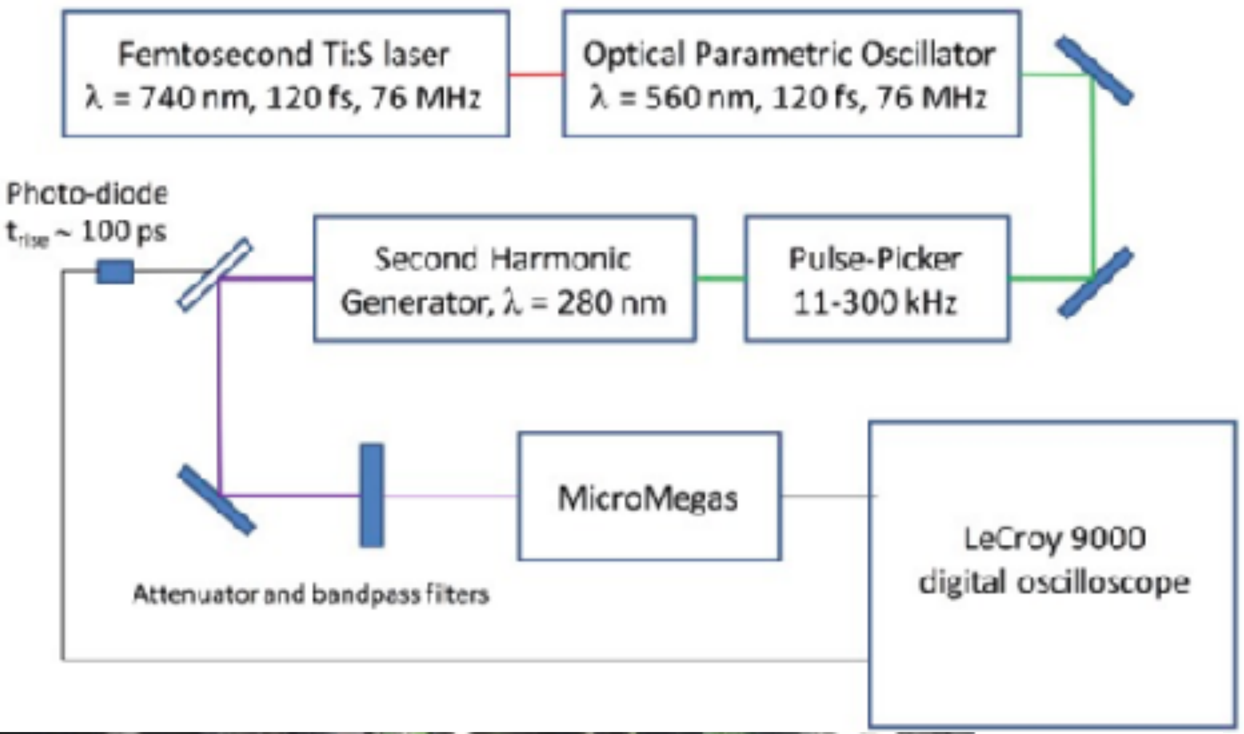
Original single-pixel PICOSEC prototype

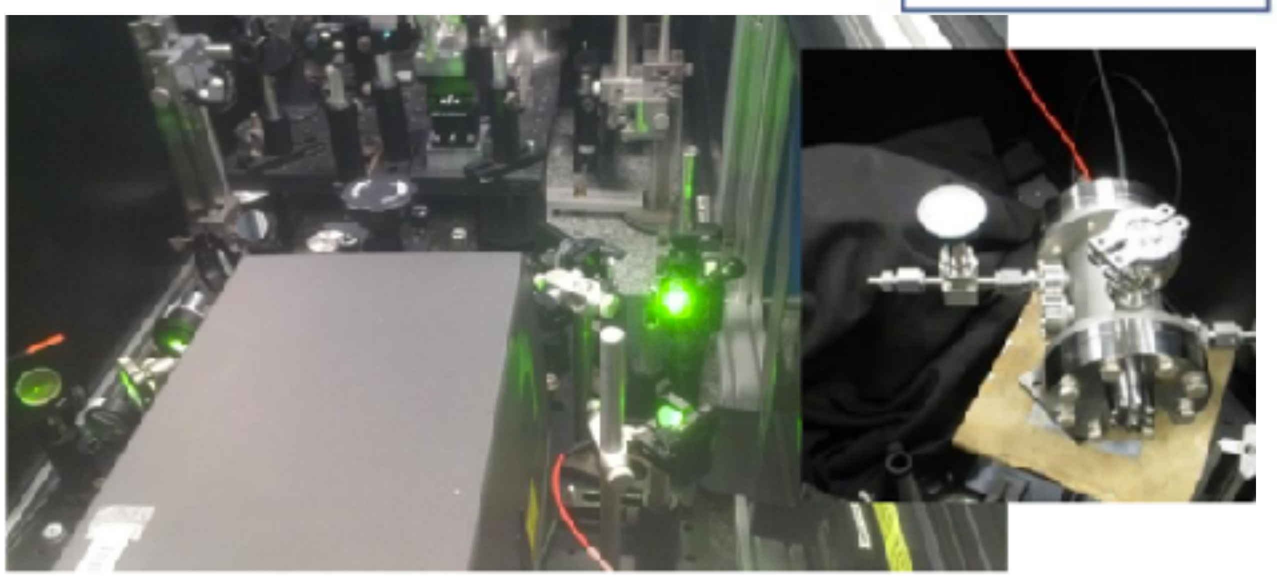


Main elements:
- Bulk MM readout.
- 3 kapton rings spacers to define the drift.
- A crystal + photocathode.

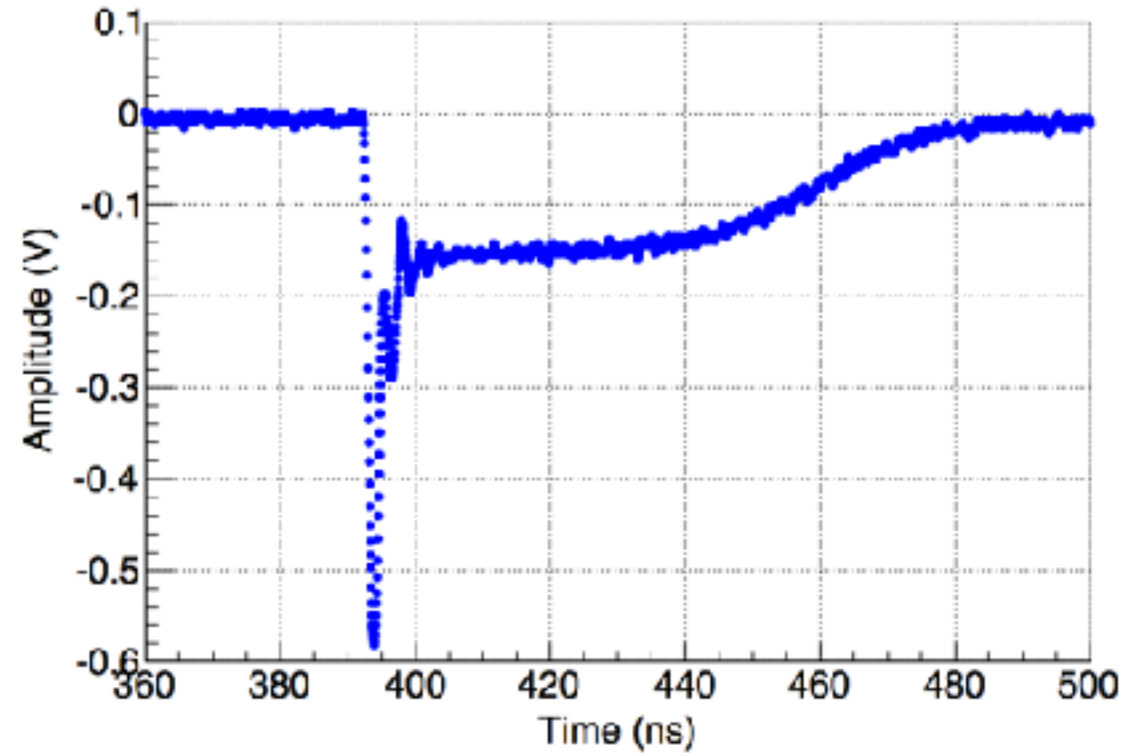
Ongoing Program of laser (for single photoelectron response) and H4 (150 GeV Muon beam)

Laser





typical single pe signal w. 40 dB CIVIDEC



we measure signal time-of-arrival
from leading edge of fast electron part
using “local CF”, Leading edge fit,
and full pulse modeling
ie corrected for electronic slewing

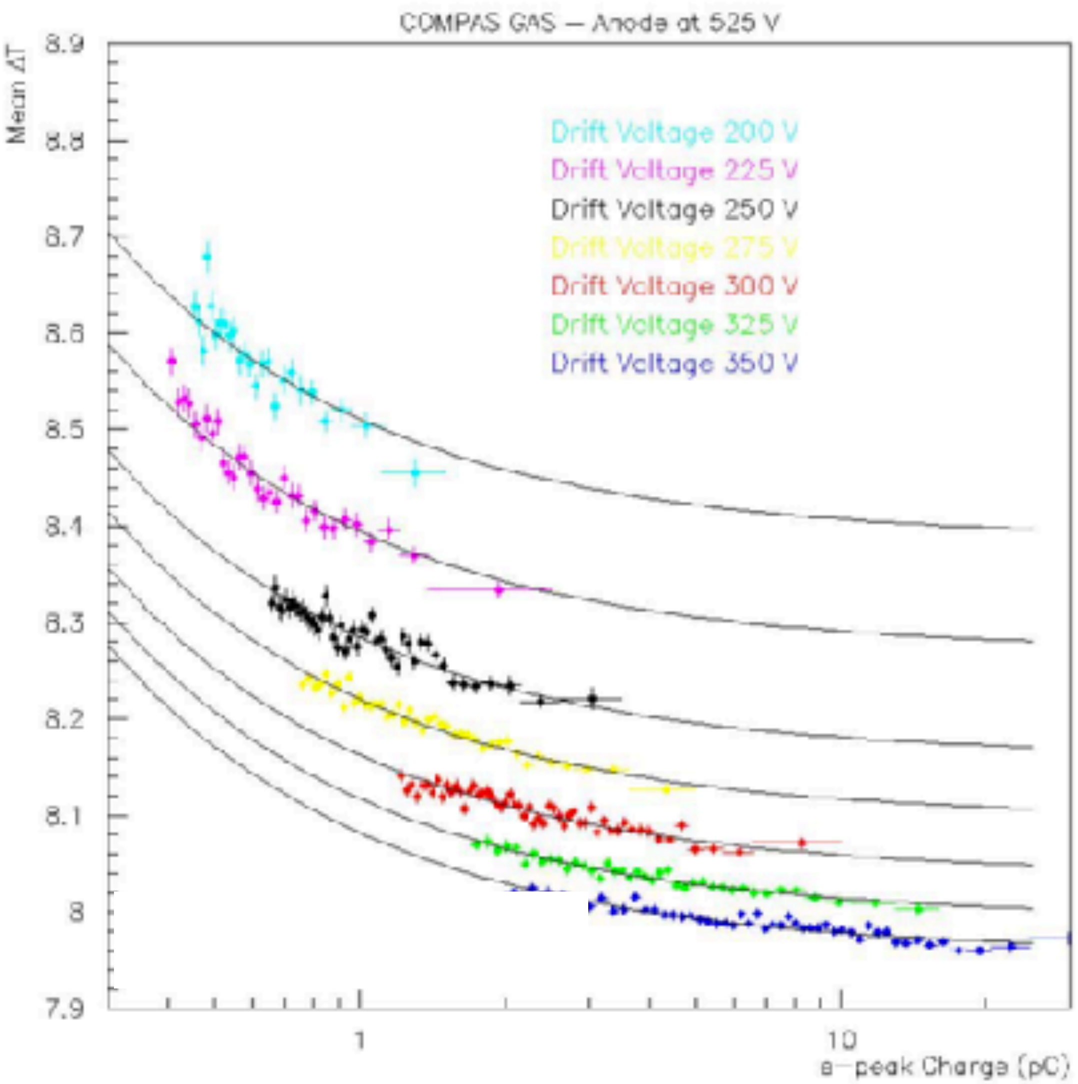
Gas choice:
optimize σ_L and v_{Drift}
but favor stability

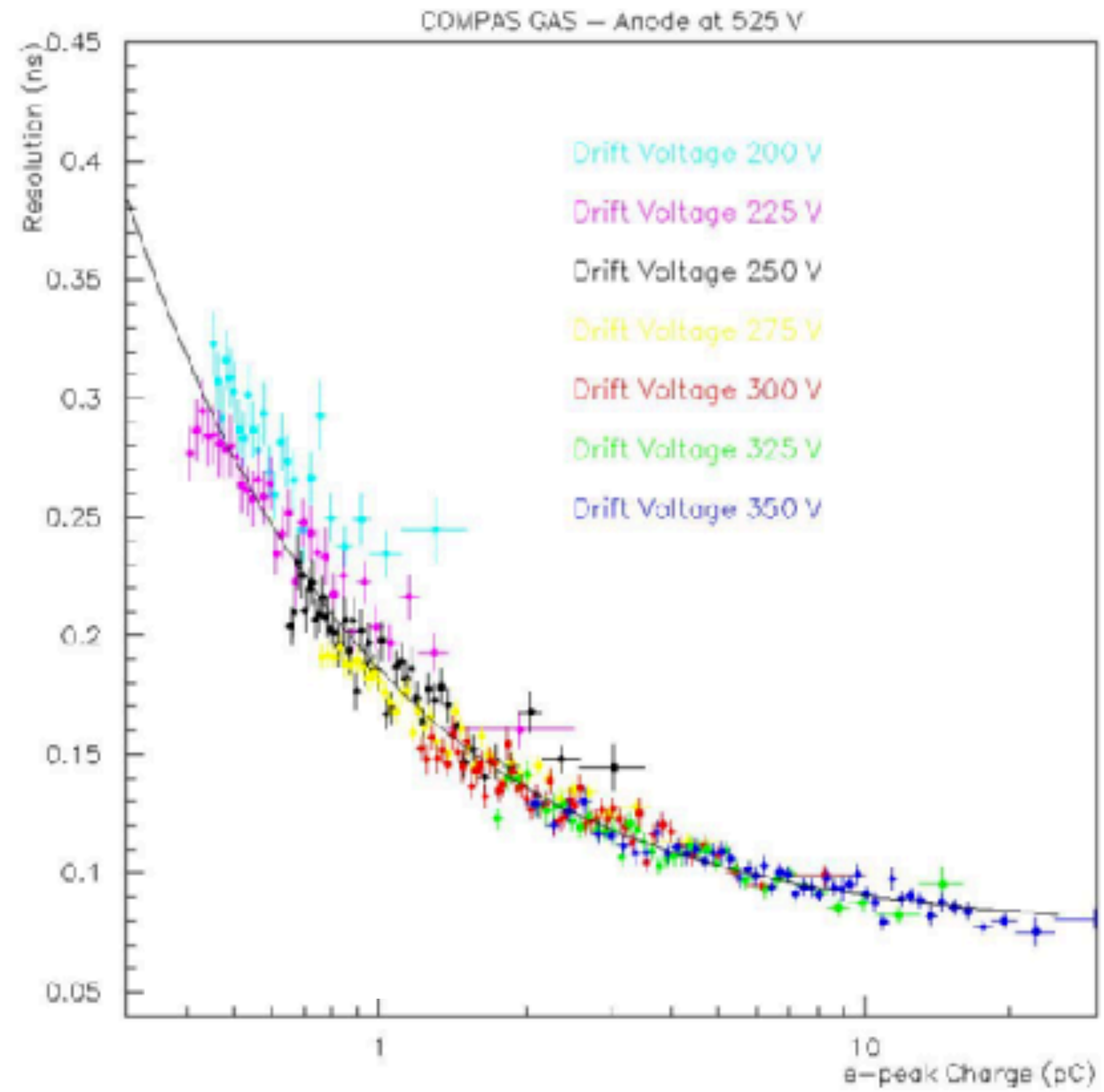
several CF4+ quencher
<u>Ne/Ethane/CF4</u>
<u>mostly showing 90:10:10</u>

Expectation that
Preamp Gain in drift
-> mitigate σ_L
see following

Key to MIP performance is:
time-of-arrival and jitter vs. single pe signal

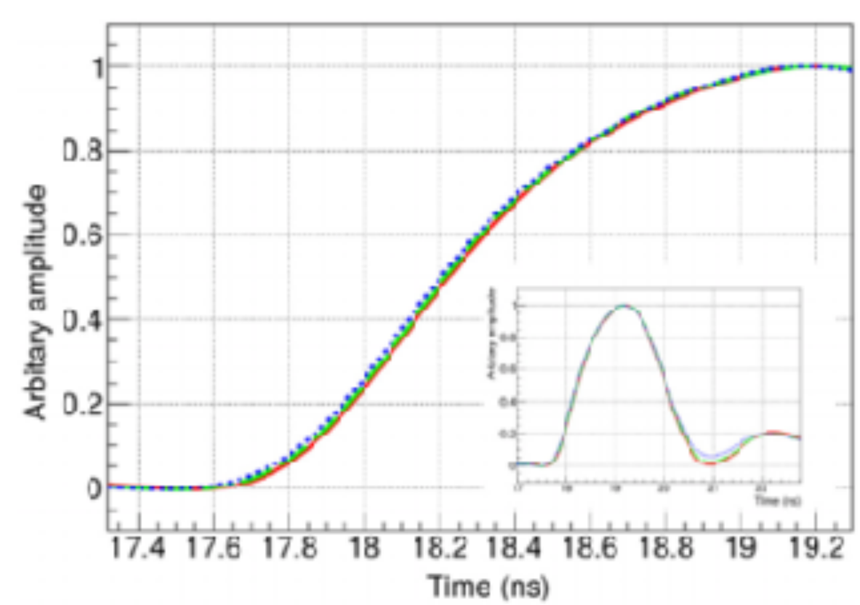
"Compass Gas"=Ne/Ethane/CF4 90:10:10



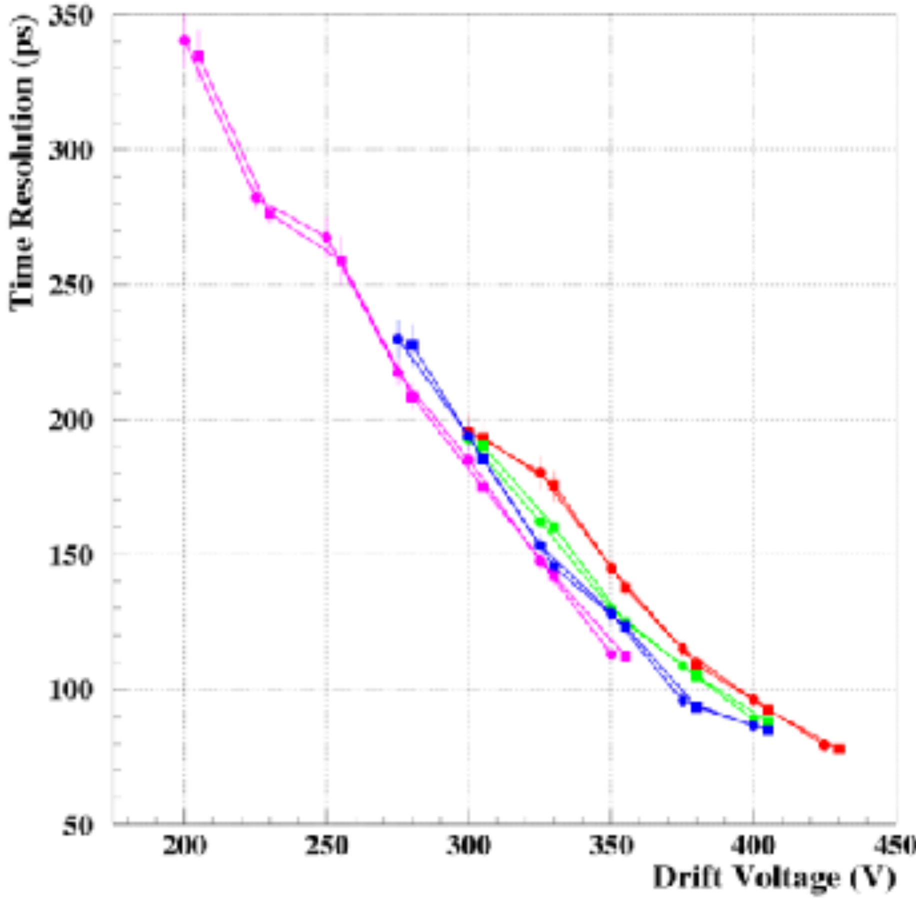


above dT "time-walk" corrected
->residual shift from physics of Gain

whole waveform shifts
slices of Gain (by factor 4)— — ->

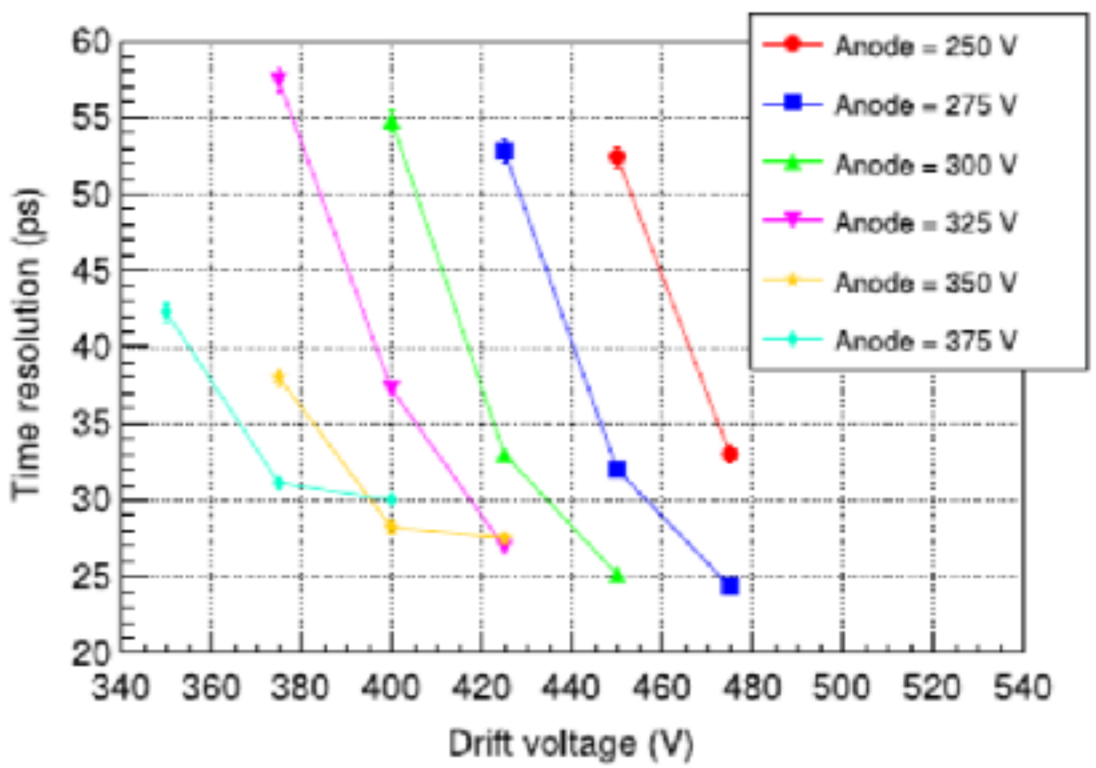


Summary of selected Single pe and MIP timing PICOSEC
(July, Aug, Oct 2017)

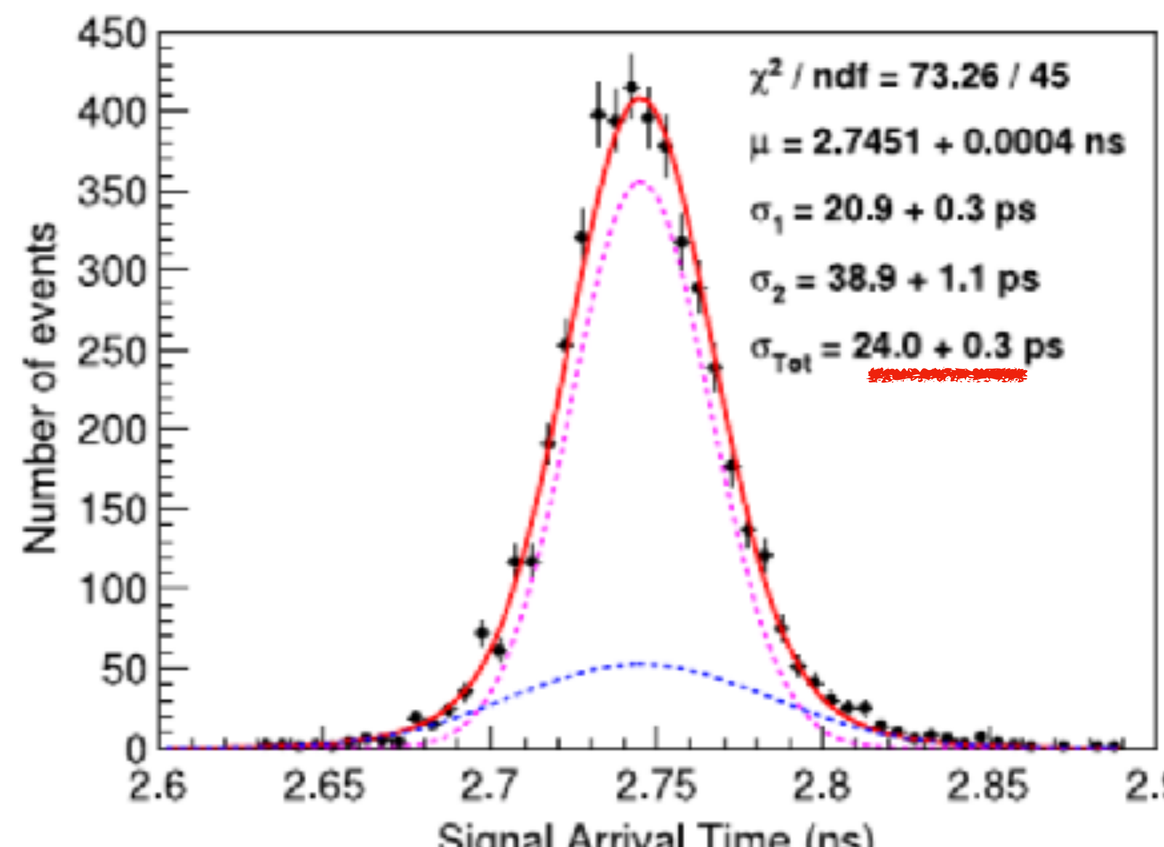


consistency between
<— — —single pe
and
150 GeV Muon results
$<N_{pe}>\sim 10$

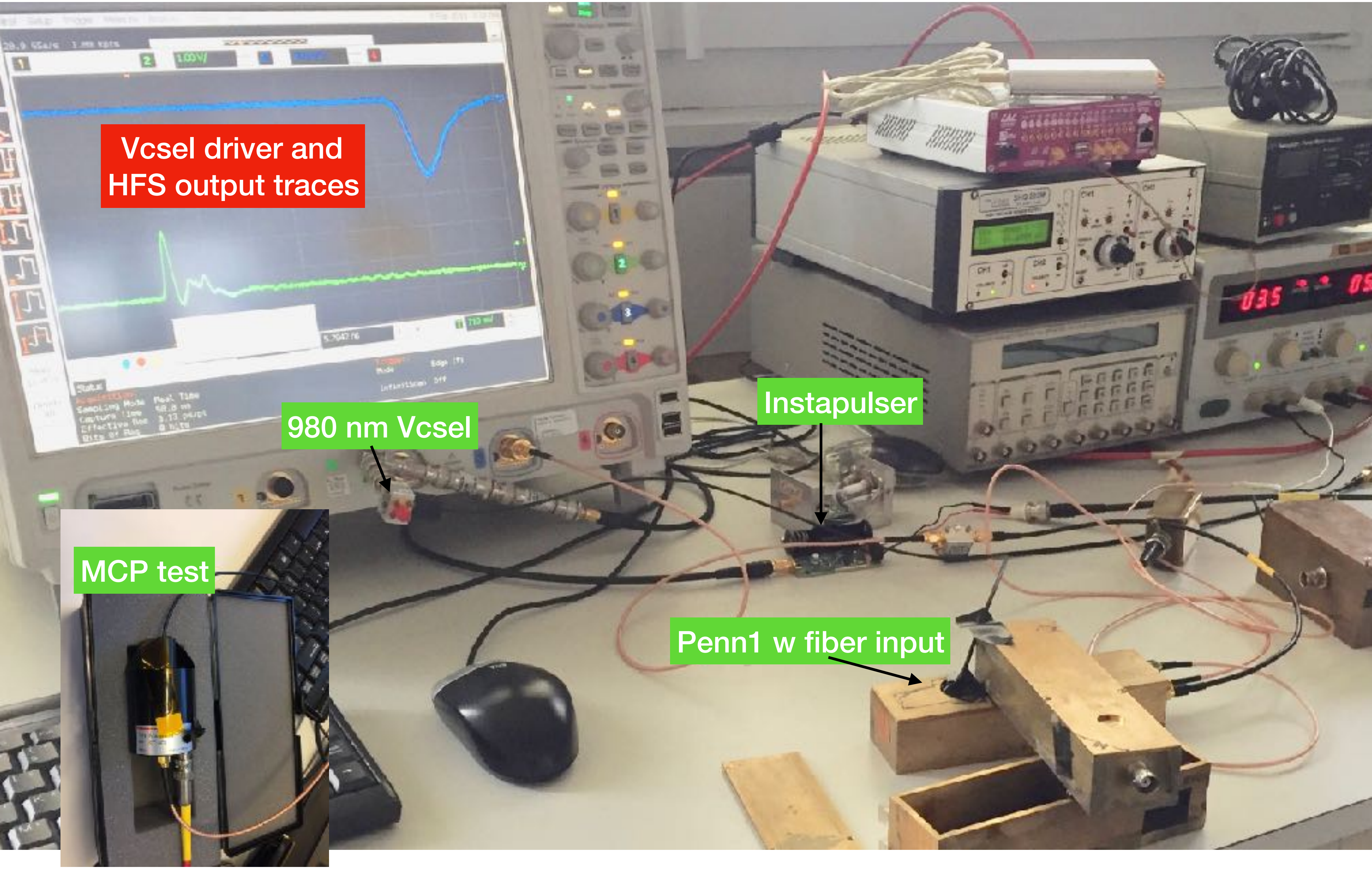
many similarities between PICOSEC and HFS mutually beneficial



H4 Testbeam resolution(PICOSEC)



HyperFast Silicon: low cost laser , 1 MeV e-source, 140 MeV muon beam



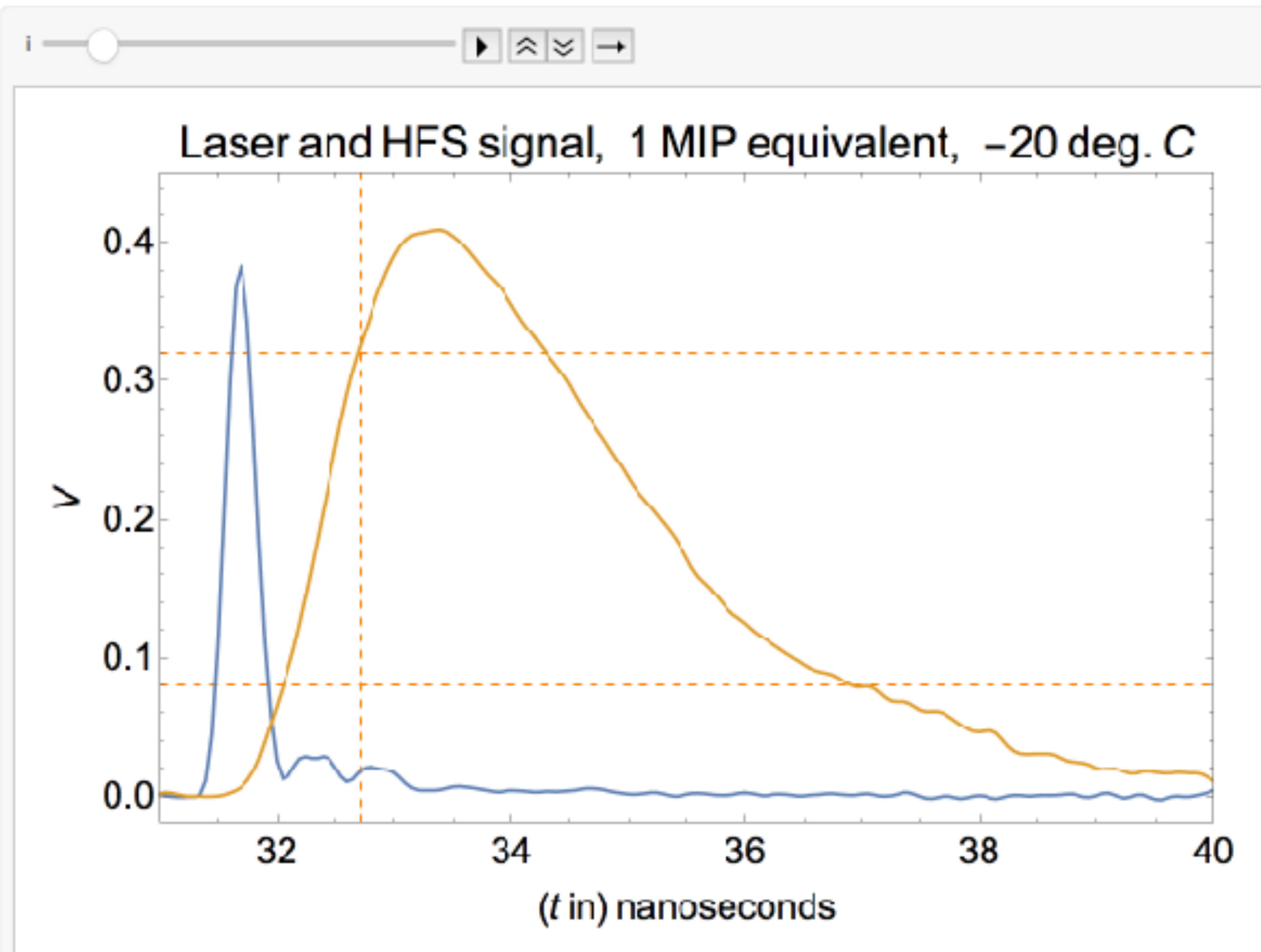
What is best time jitter for 1MIP equiv?

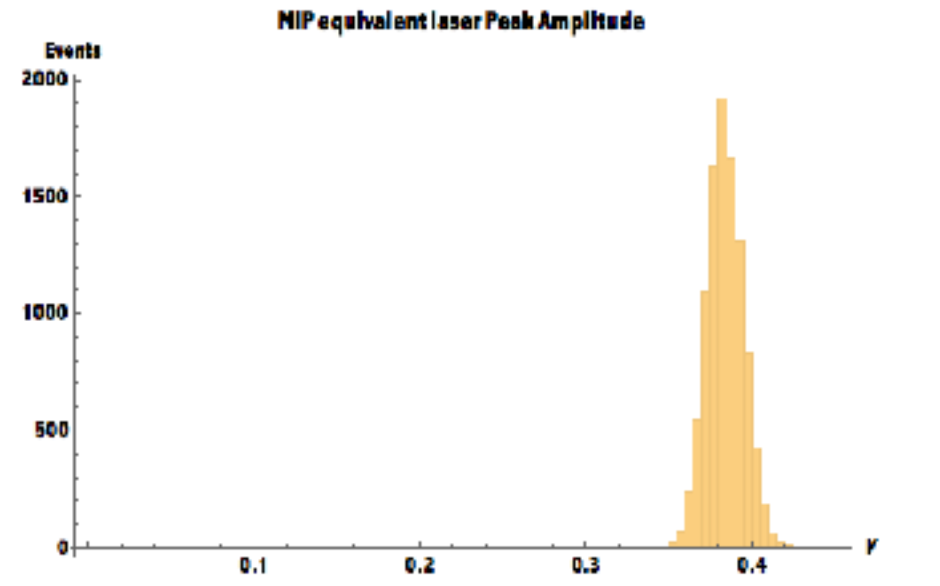
- Eric Delagnes and I tried this w. earlier FEE and SAMPIC see:

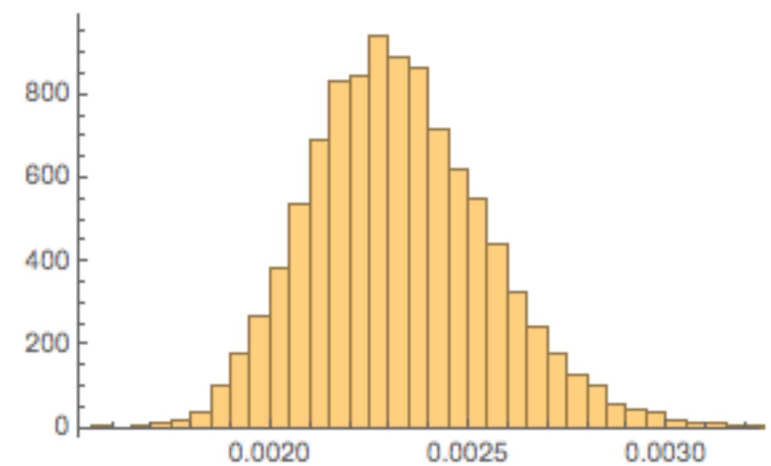
D. Breton: Elba 2015

https://agenda.infn.it/getFile.py/access?contribId=138&sessionId=11&resId=0&materialId=slides&confId=8397

here we look at data from lab using Mitch's amp







V_{RMS}

unfiltered baseline noise ~2.2mV rms ->SNR~400/2.2=180. Risetime=0.65ns

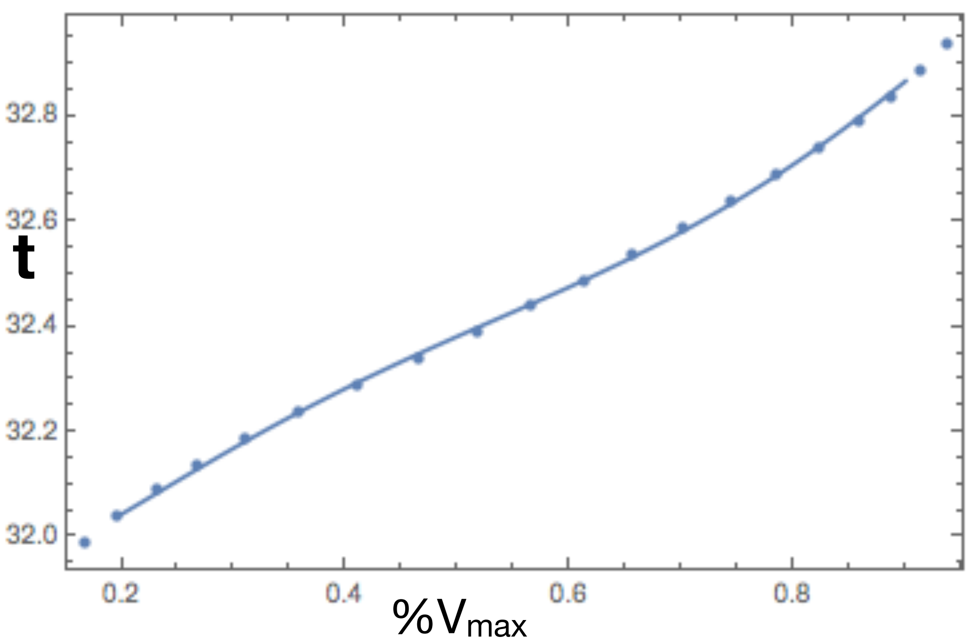
naively jitter from noise-> dt~tR/SNR=3.6 picosec

timing algorithm

- since there is some spread in laser amplitude we typically do simple Constant Fraction timing on the leading edge at ~20%. Other techniques such as filtering (usually Wiener) and fit, signal modeling, etc. all give equiv results for this example.

- here we do a simple power law fit to the full waveform.

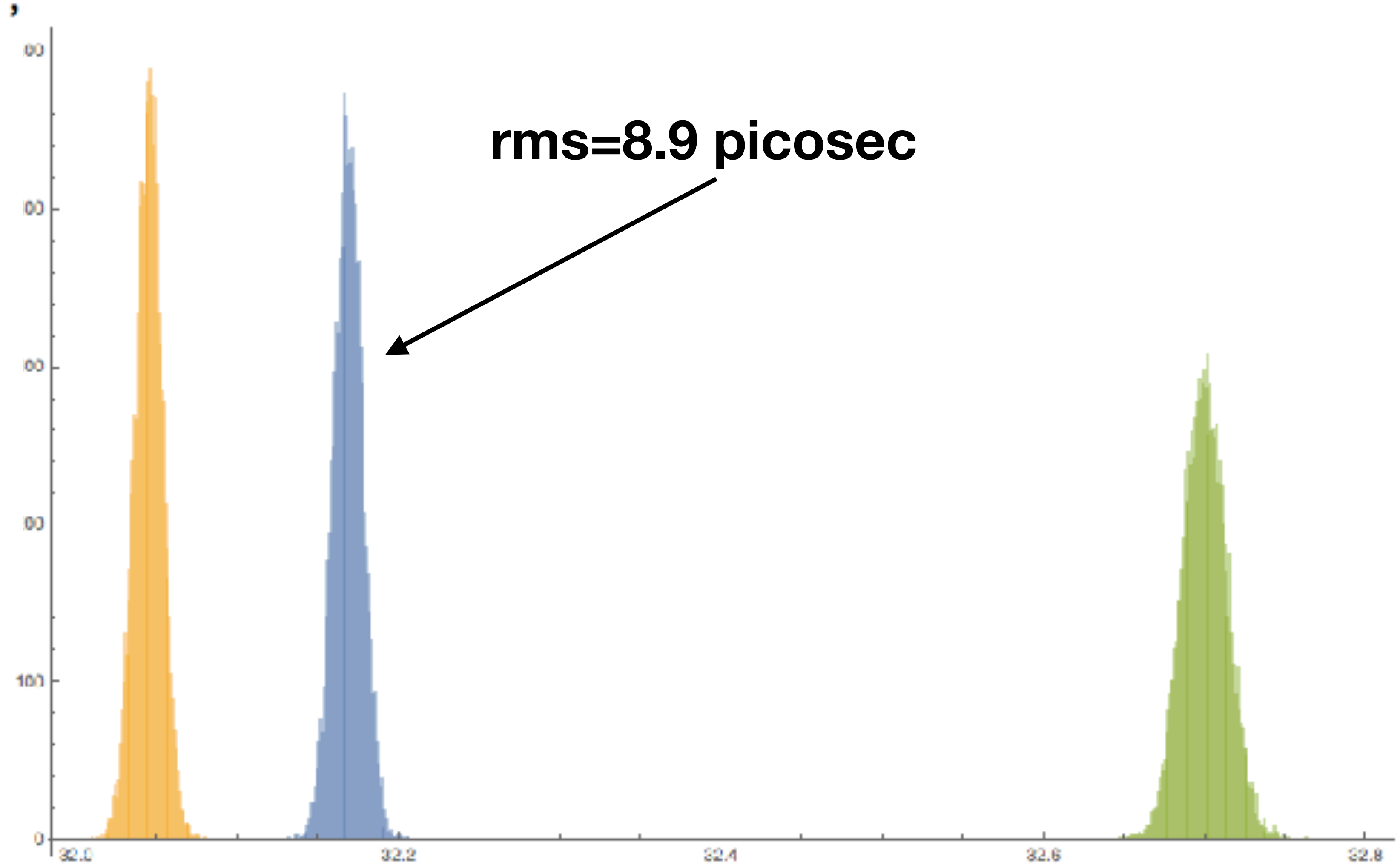
```
Show[ListPlot[data], Plot[nlm[x], {x, 0.2, 0.9}],
```



transposed leading edge

nice result but
contribution from trigger jitter?

no



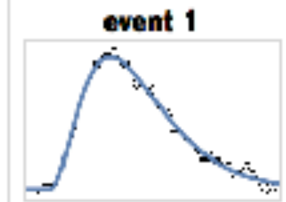
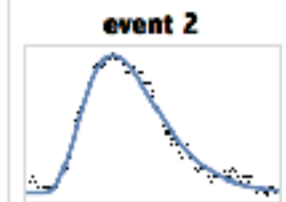
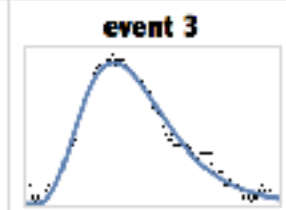
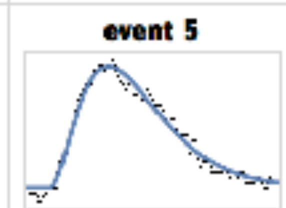
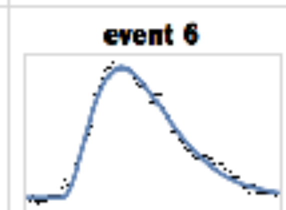
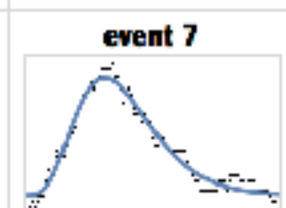
20% 30% 80% time(nsec)

alternative to local Constant fraction fit is signal modeling for which Mathematica has some nice tools

Map function across waves

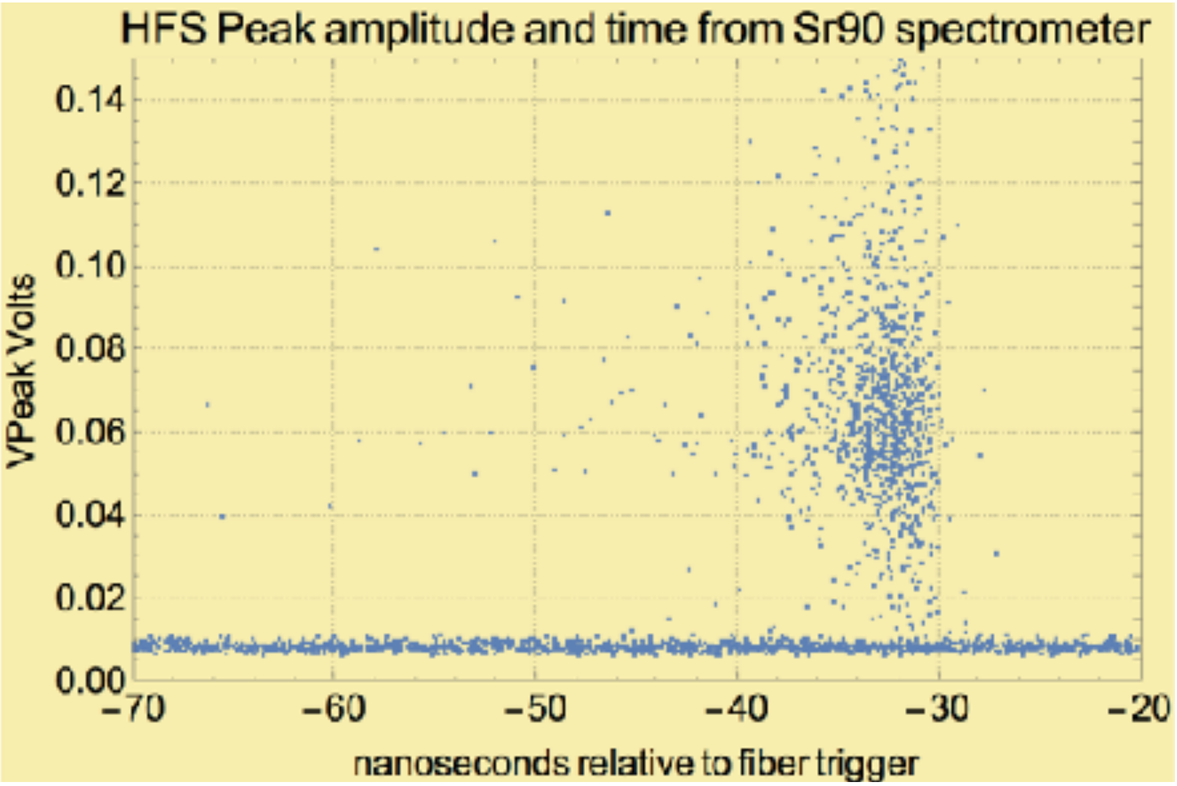
Here I use MapIndexed (this allows me to use the position as an argument). Dataset groups the results together.

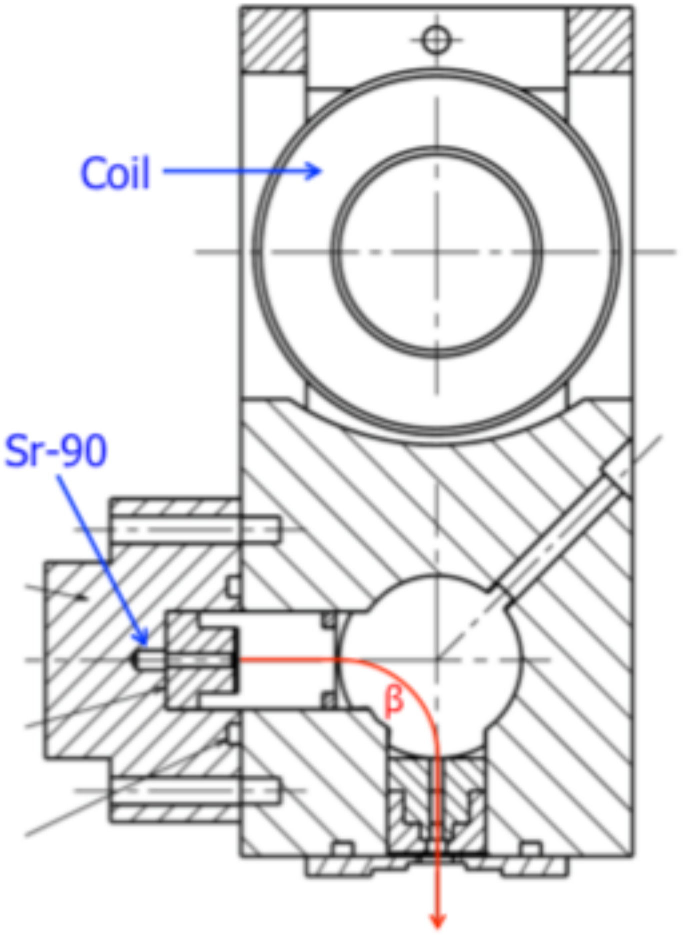
```
ds = Dataset[MapIndexed[fit[#1, #2[[1]]] &, wave4[[1 ;; 100]]]]
```

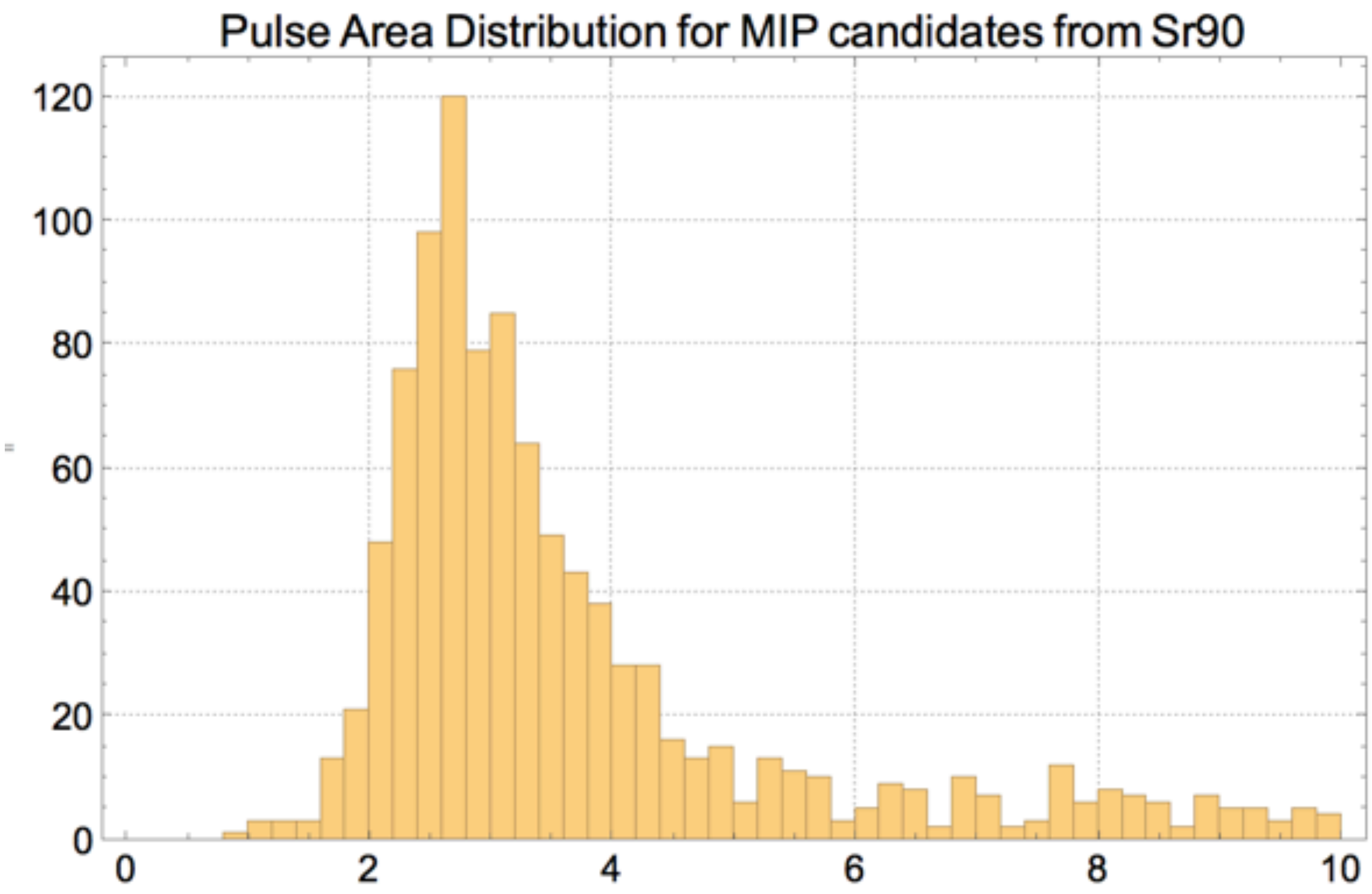
event	bestFitParameters	adjustedRSquared	plot
1	{A → 0.119864, n → 2.11306, to → 0.592996, toff → 6.41963}	0.994857	
2	{A → 0.0962981, n → 3.7208, to → 0.401652, toff → 11.3142}	0.992228	
3	{A → 0.11766, n → 3.70992, to → 0.454327, toff → 4.29665}	0.994448	
4	NonlinearModelFit::sszero	—	
5	{A → 0.0926168, n → 2.05265, to → 0.595536, toff → 7.40185}	0.991077	
6	{A → 0.11257, n → 2.50197, to → 0.506459, toff → 17.7226}	0.9939	
7	{A → 0.0667517, n → 4.39367, to → 0.377799, toff → 27.448}	0.986334	

an alternative to HE beam

small device (~6”)
~1 Amp drive current
selects to +/-10% 1 MeV electrons
Argonne made similar in
SSC era, fell into disuse

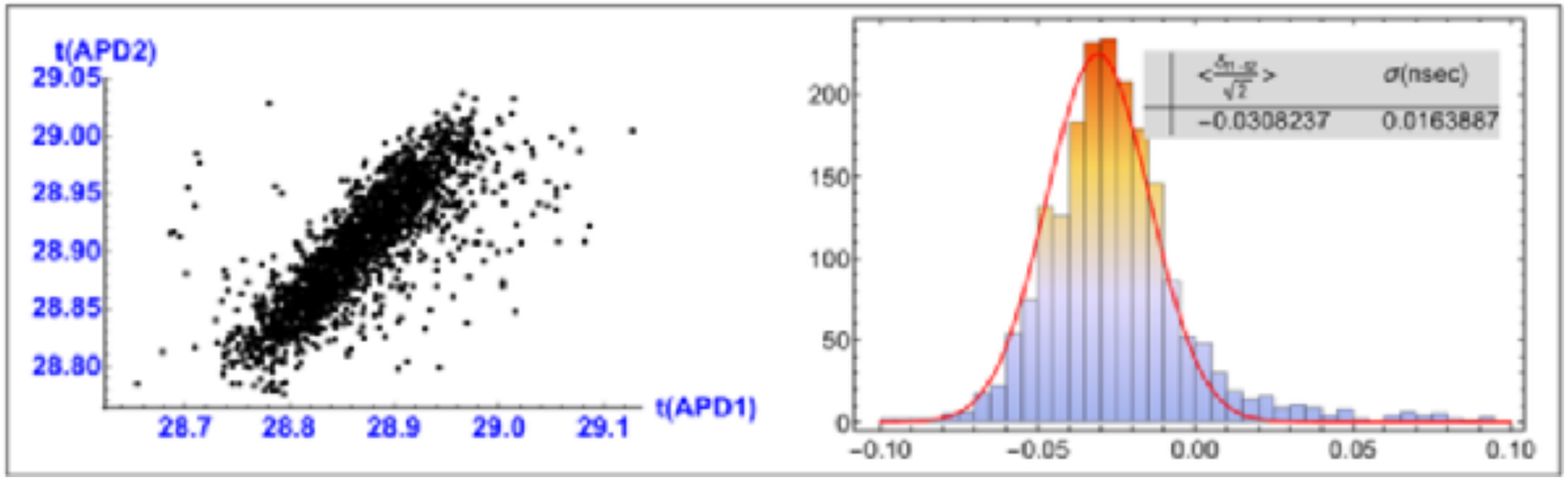


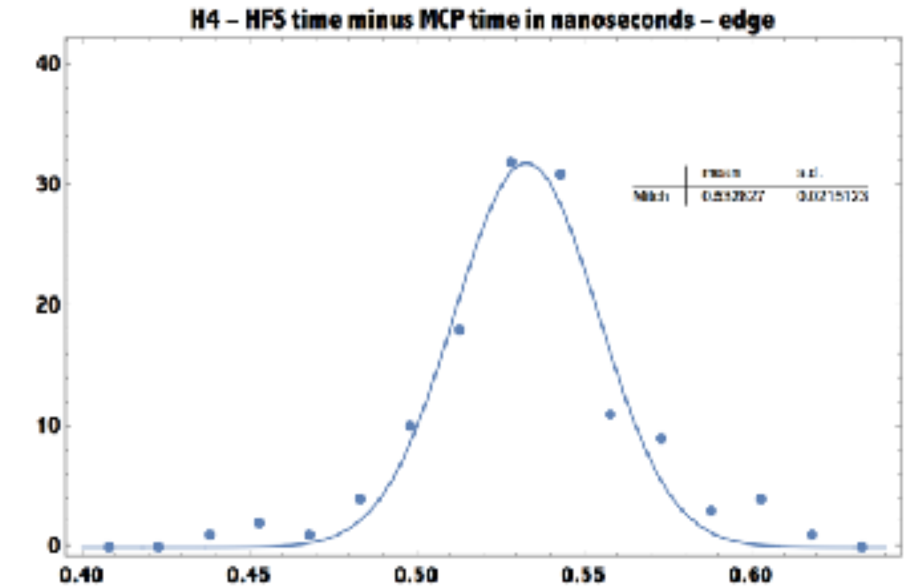


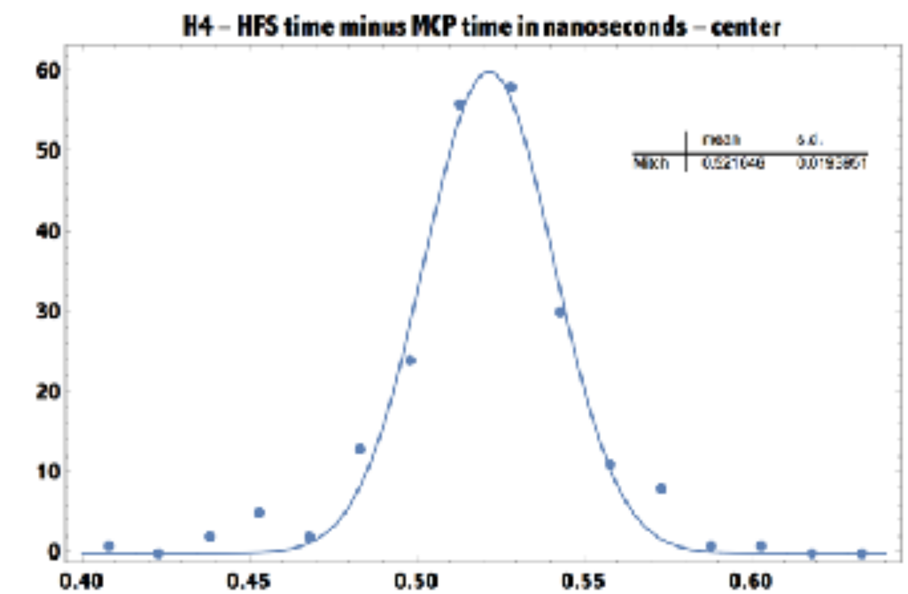


Some test beam results from 2016-17

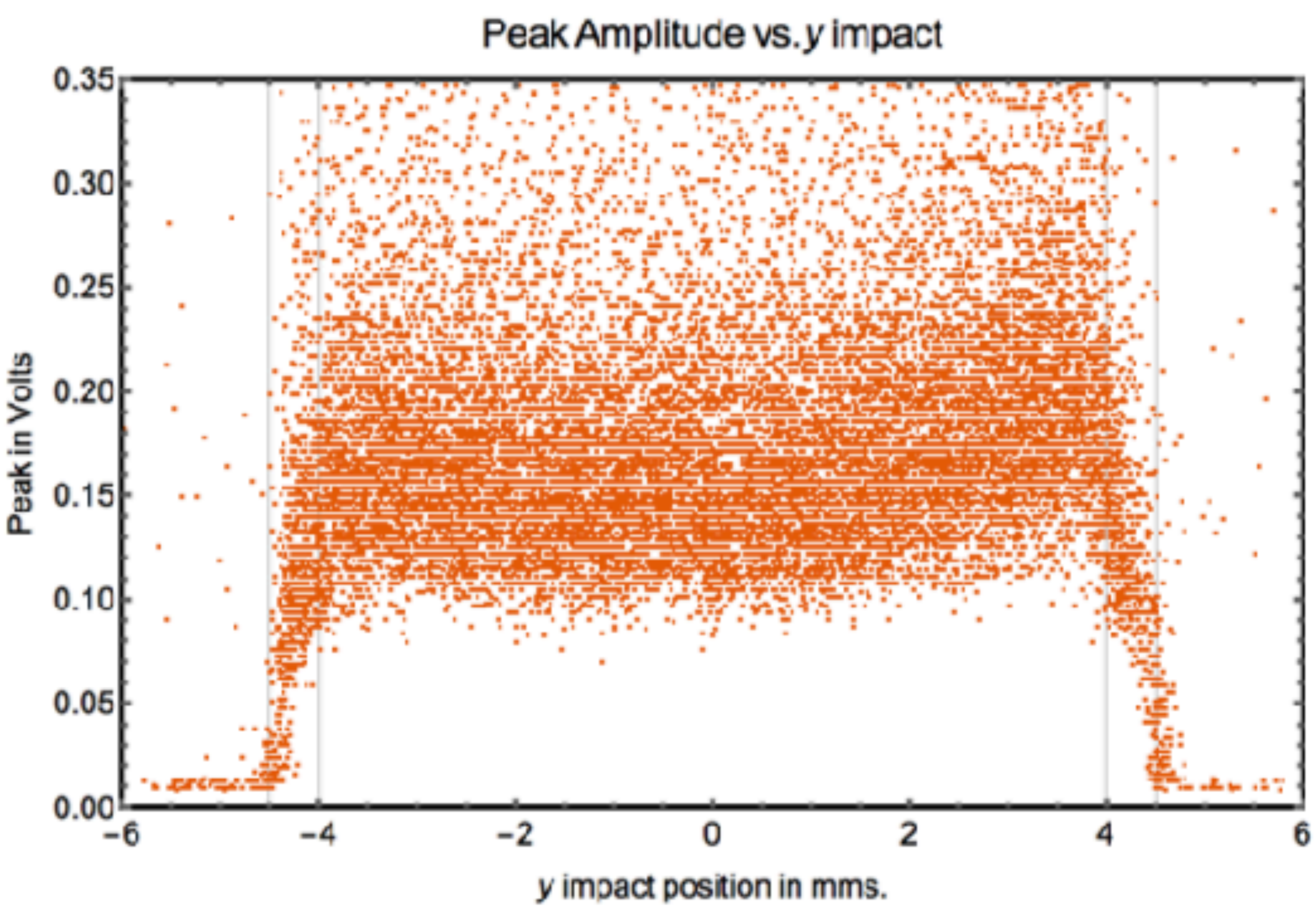
early result showing promise of HFS







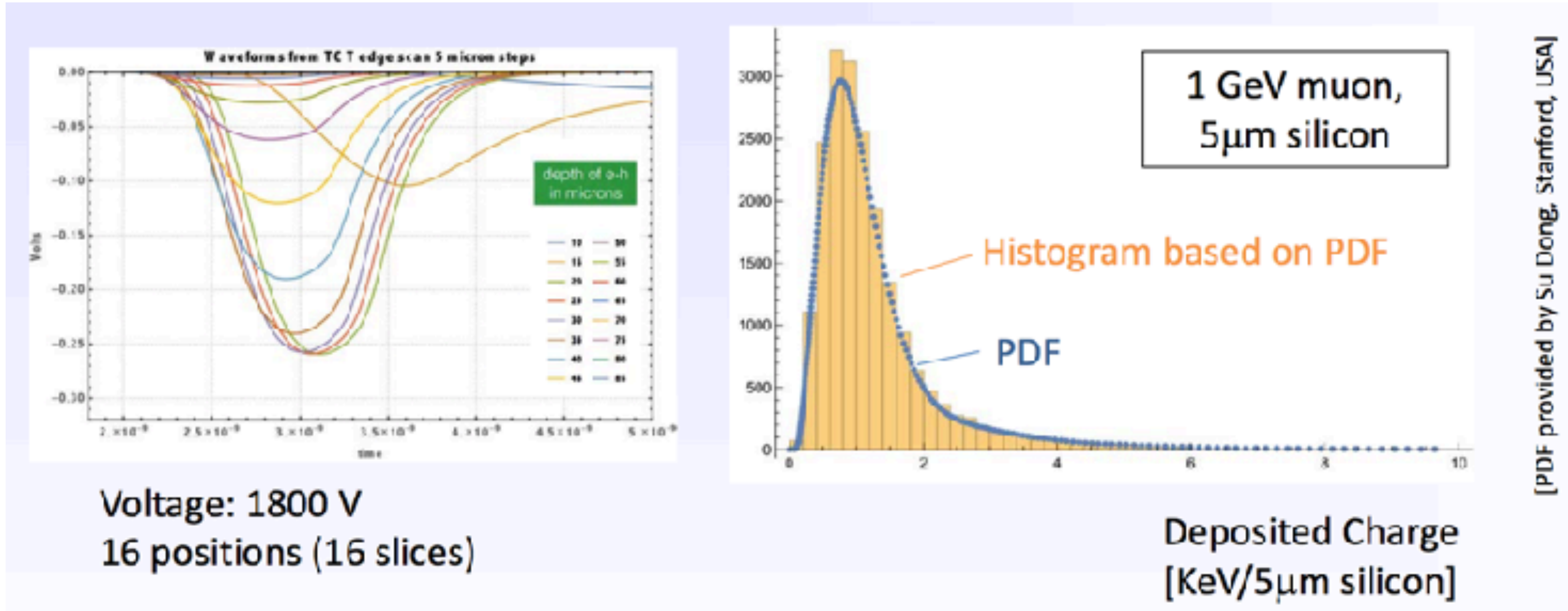
2016: Nice Amplitude Uniformity over 64 mm² pixel



similar time res. at edge & center
however 10-20 picos time walk
-> attributed to packaging/interconnect
goal of 2017 to eliminate walk

SILVACO used to model radiation damage & Landau Contribution to Timing

M. Moll, RD50 mtg.
June 2016



Meanwhile, Packaging evolution

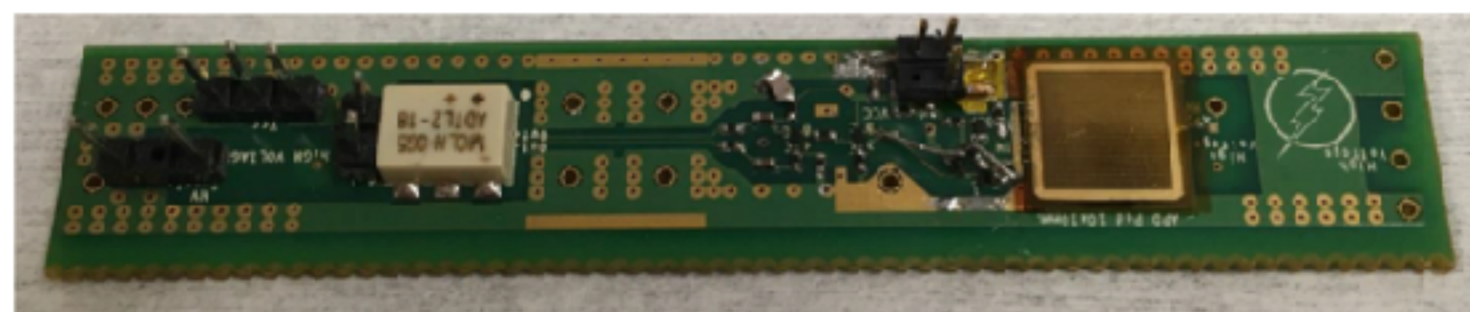


Figure 10. A photograph of a 1st generation PCB with a mounted mesh APD seen on the right-hand side of the PCB.

Packaging by Bert Harrop, Princeton
discrete TIA from U. Penn.(M.Newcomer)

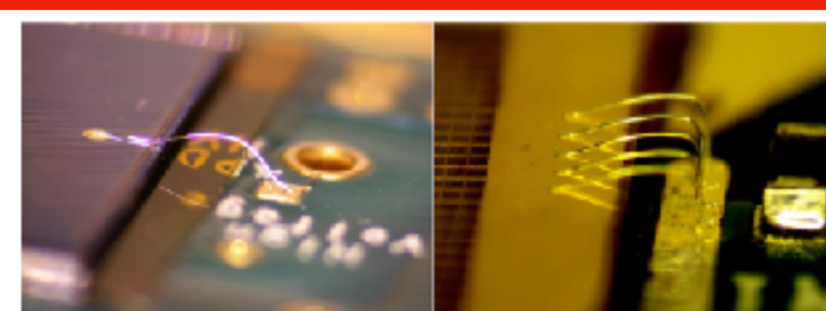
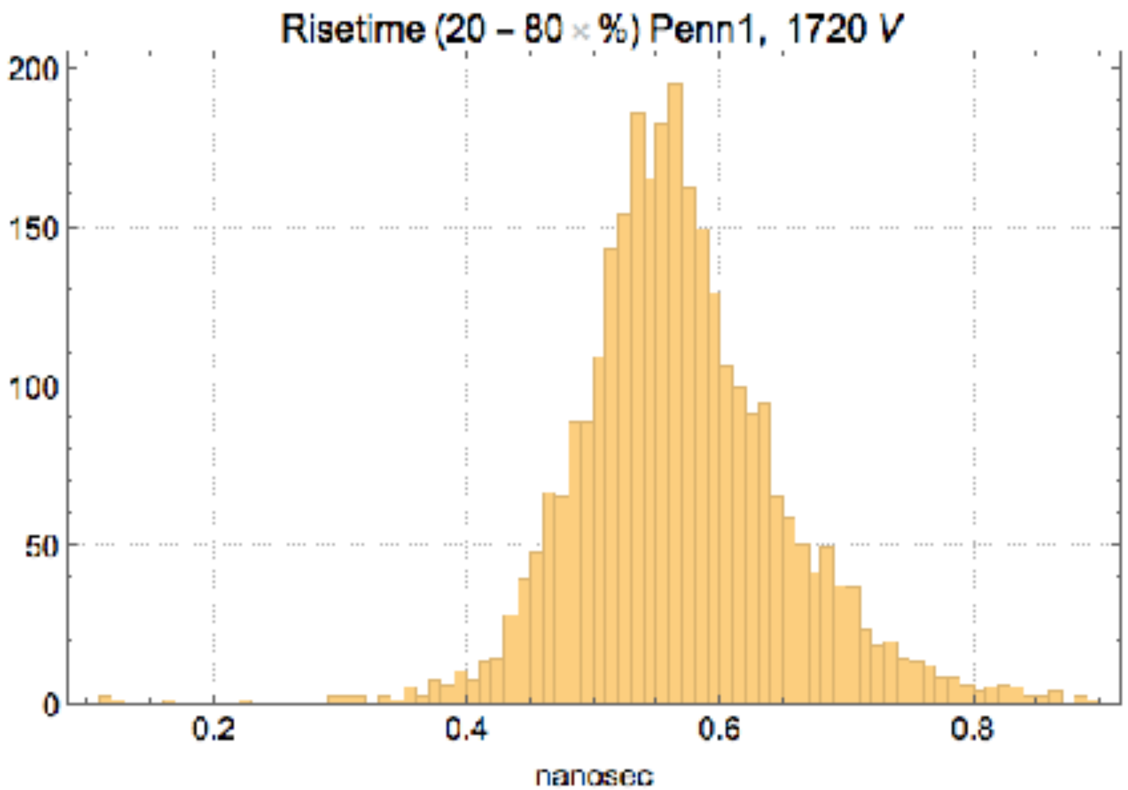
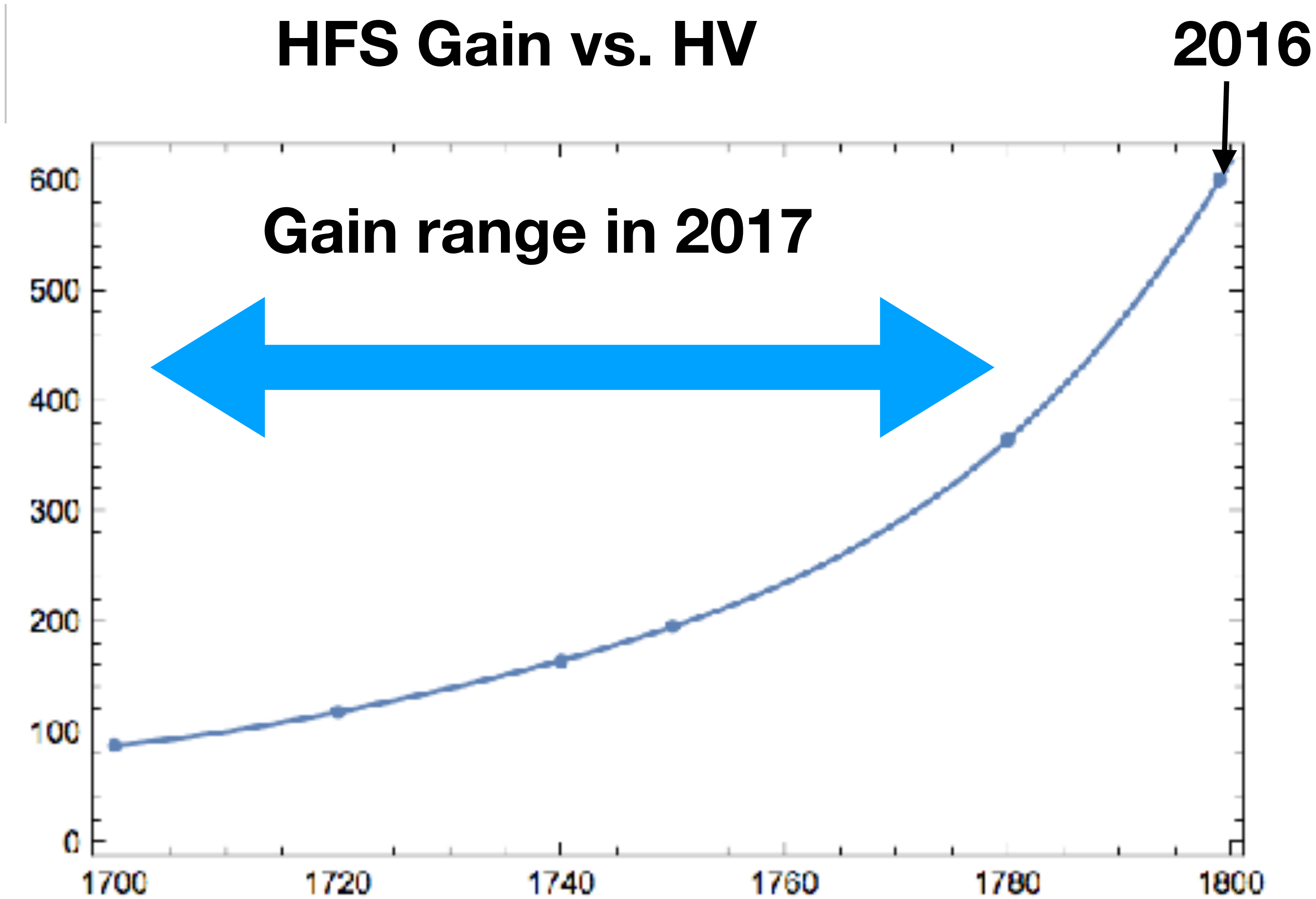
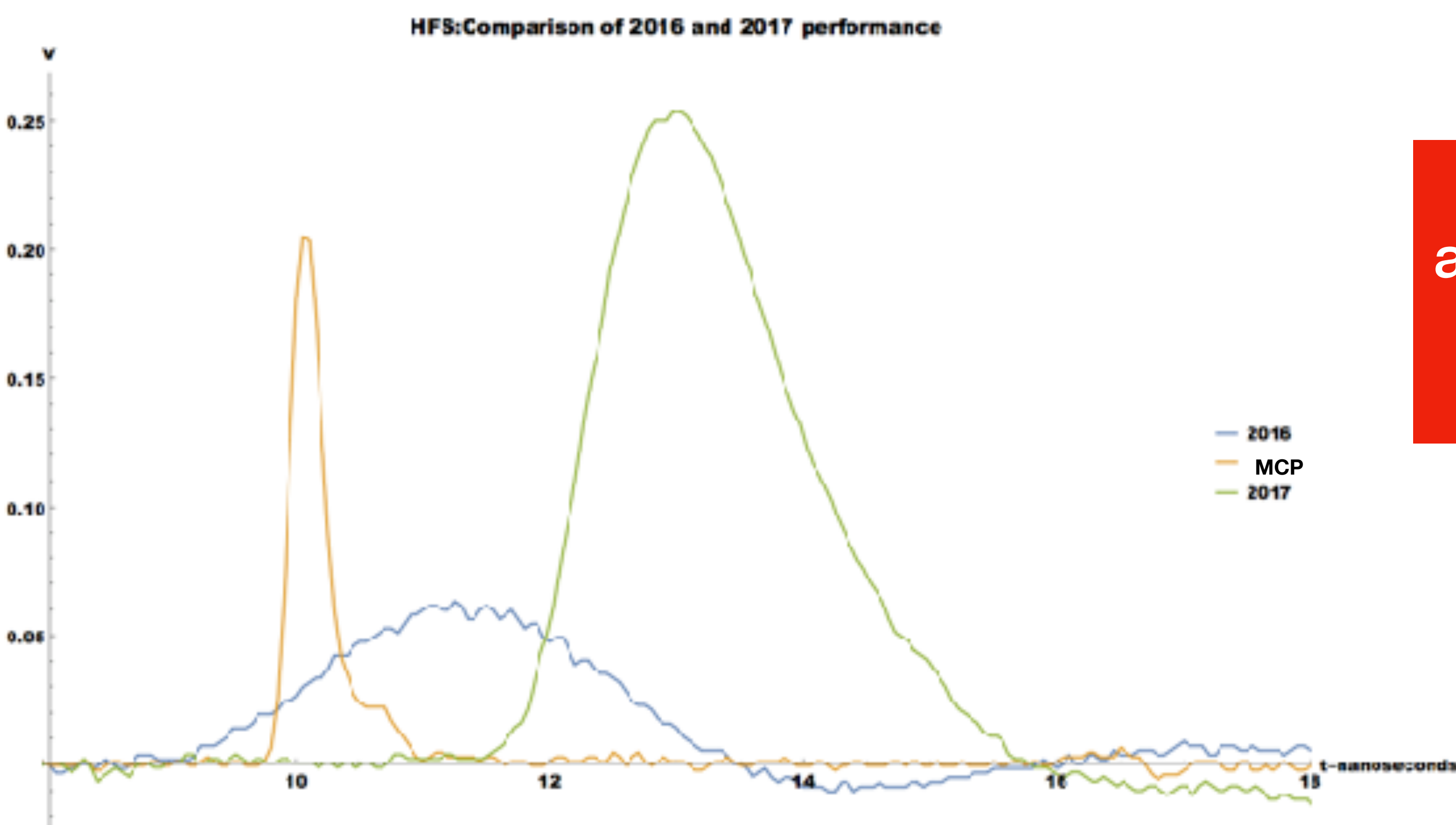


Figure 11. (Left) A close up photograph showing the wire bonded APD anode. (Right) A close up photograph showing the wire bonded Ni mesh screen.

2017,2018 (150 GeV muons)=> improved speed from FEE Integration



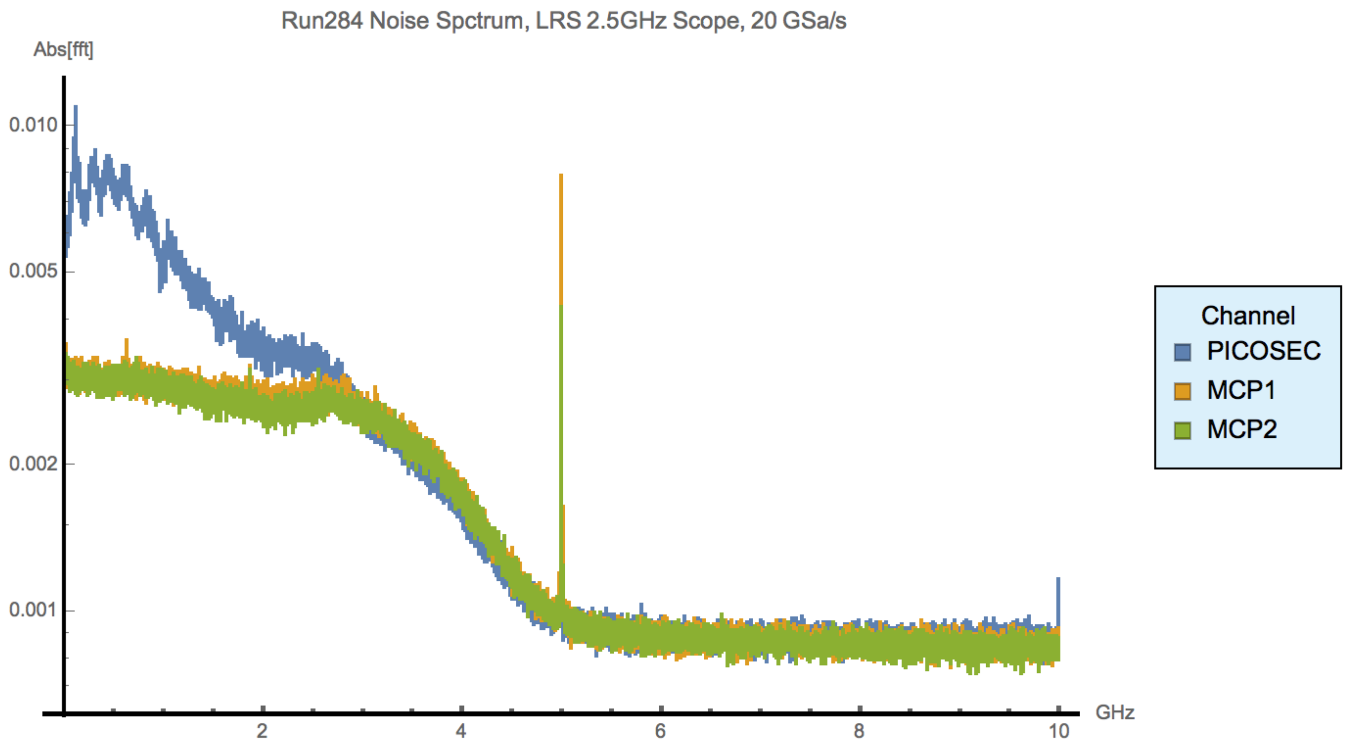




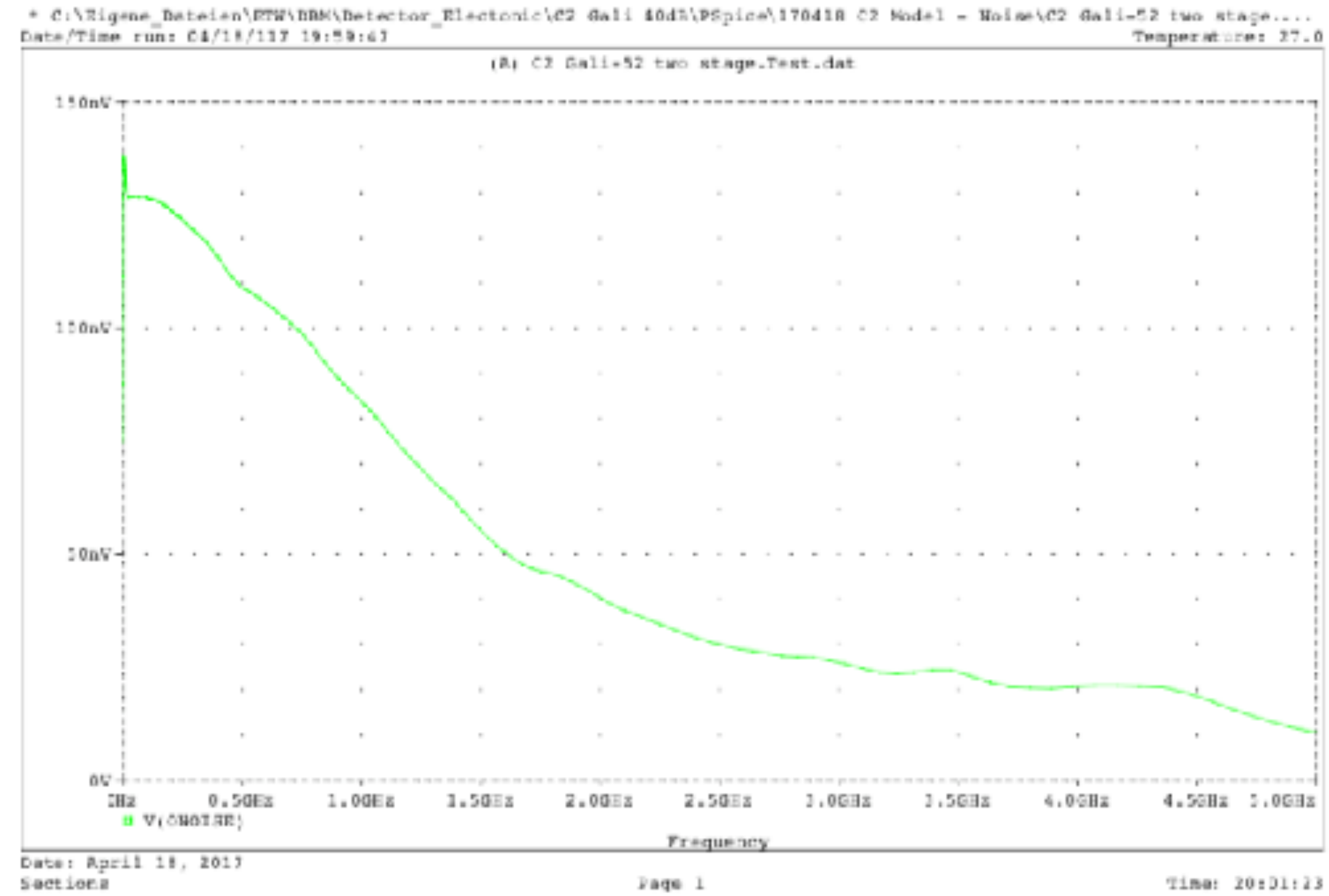
with improved integration
and constant iterations in Penn design
see real impact on signal quality
thank you Mitch & Bert!

Mitch N’s ASIC (funded by US/CMS)
also back from MOSIS
first look in Aug ’18 beam

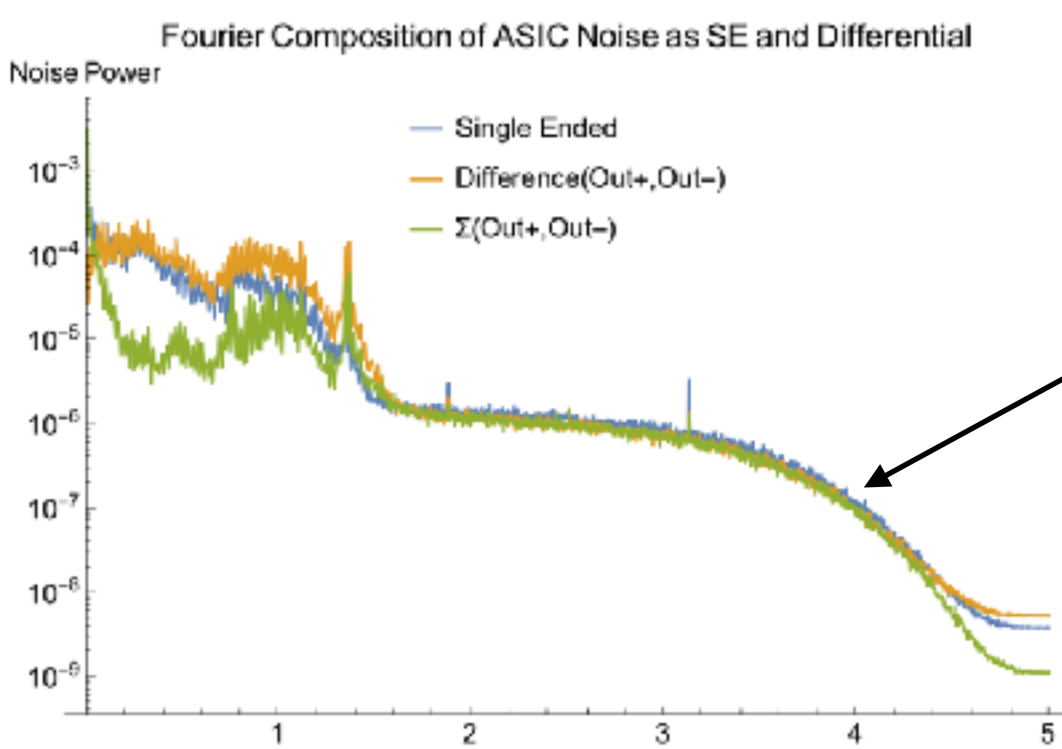
Discrete Fourier Transform
-useful language to correspond w FEE designers



our test beam noise spectrum



confirmed by E. Griesmayer(Cividec)- SPICE

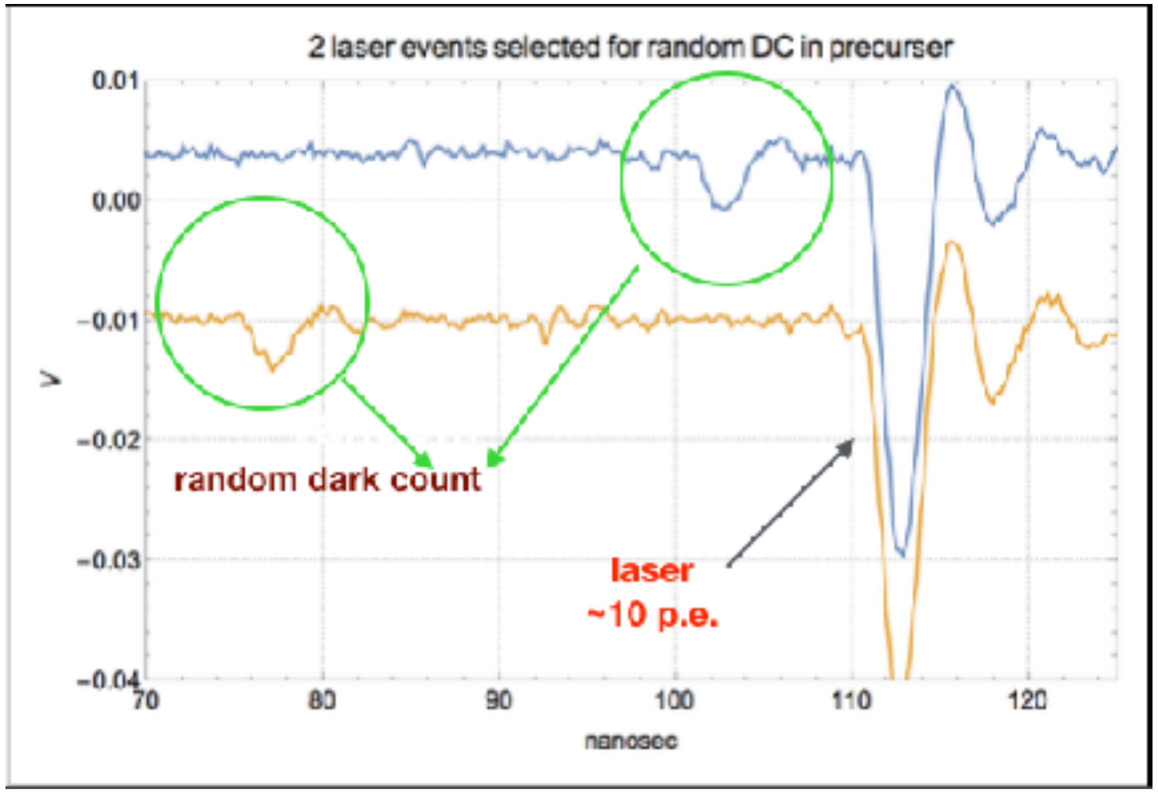


first testbeam exposure of HFSilicon w Mitch Newcomer's new ASIC Aug.2018

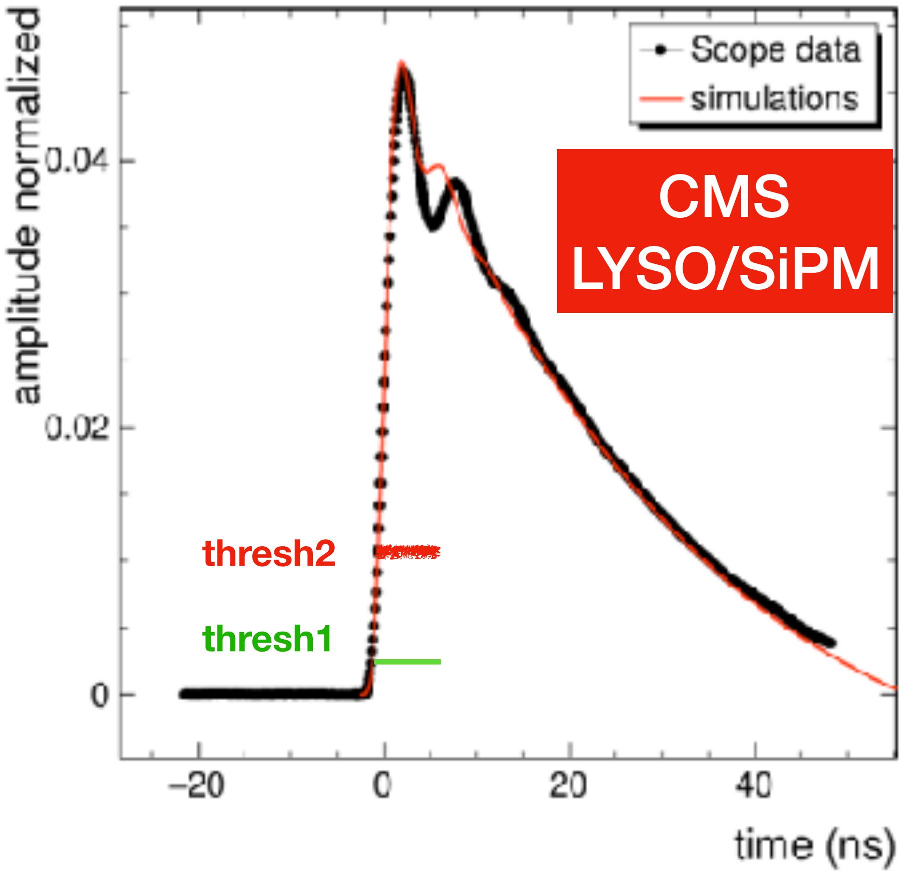
Useful interaction on architecture for CMS Readout
(LIP,CERN, U. Virginia)

“end of life” x10^5 increase in Dark counts
a challenge for CMS baseline subtraction

-> collaborate w LIP design team using laser and dc waveforms to validate simulations



could 2 threshold tdc replace
1 threshold + pulse area in CMS Barrel?
“yes, maybe better”-A.Ledovskoy, U.Va.



similar questions in other fields:

ACCEPTED MANUSCRIPT

A 100-ps Multi-Time over Threshold data acquisition system for cosmic ray detection

some conclusions:

- we are in an interesting domain where detector physics rather than electronics (SNR, rise time) govern resolution

- the principle technology choices of the LHC upgrades are based on Silicon with internal gain

- unlike the case with gas detectors, the fundamental timing limitations not fully modeled.-> well worth pursuing

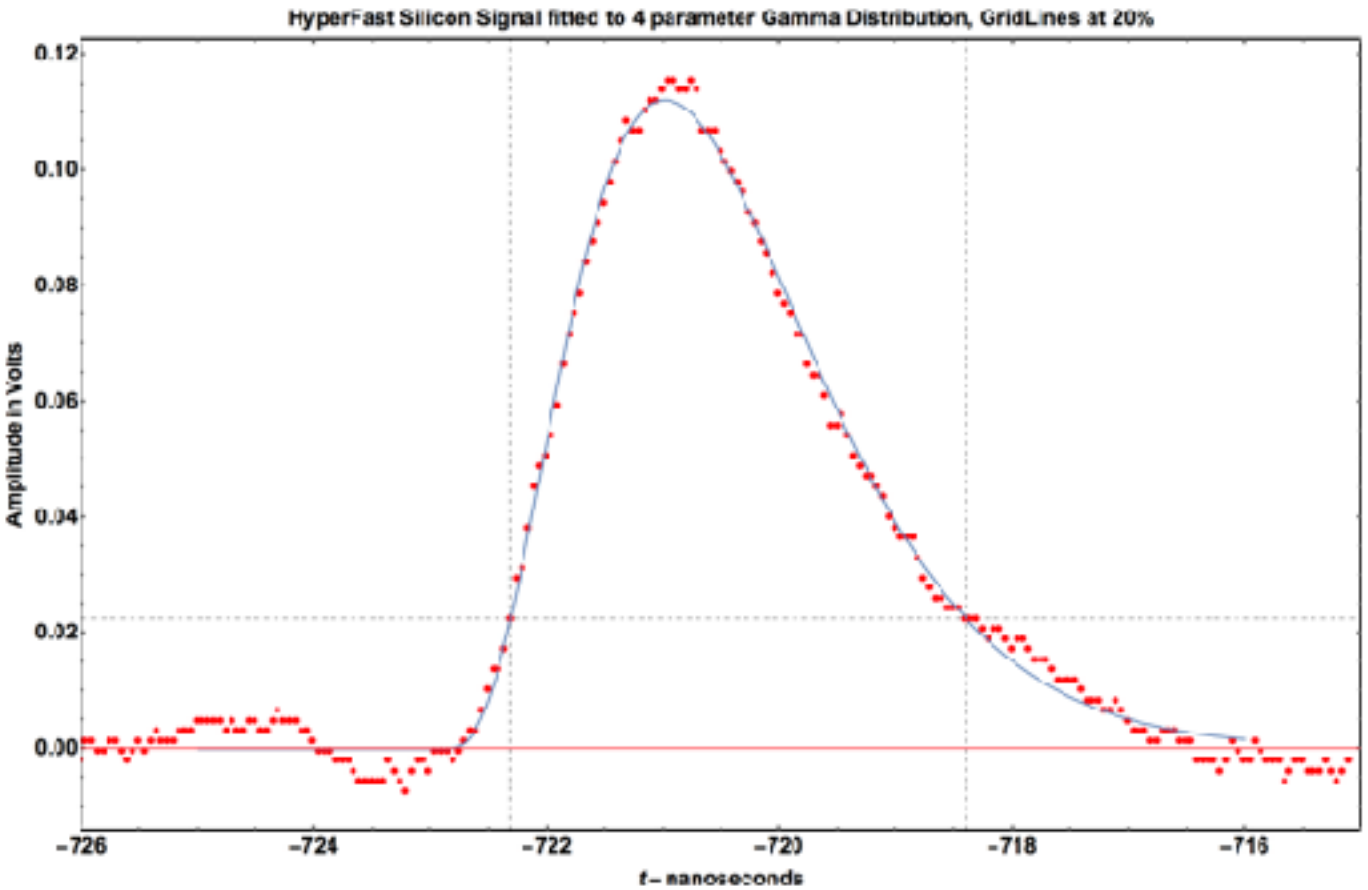
- at the same time there is a real opportunity to use a combination of modeling and machine learning on a large data set to further develop signal processing algorithms. Subject of a current proposal with Wolfram Research.

thanks for your attention!

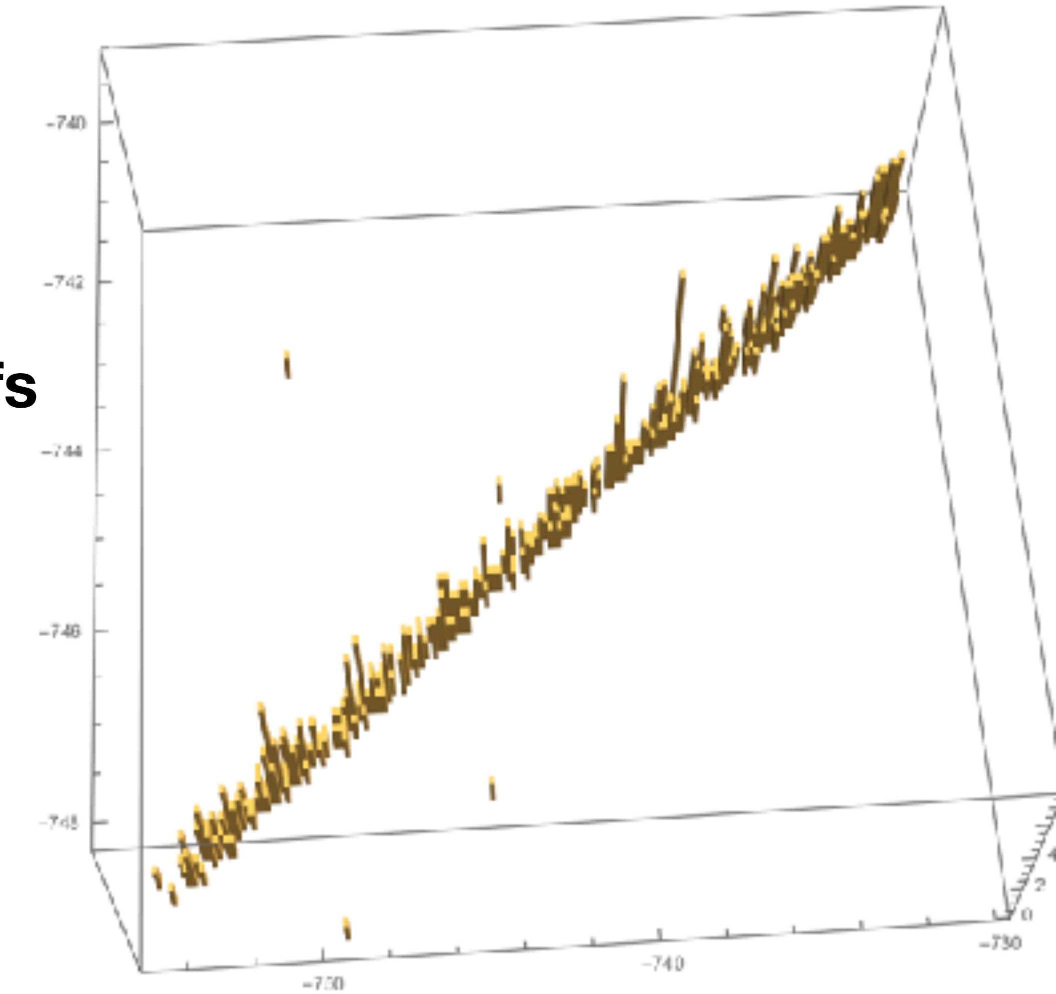
BACKUP

2017 beam Campaigns within PICOSEC infractructure (cont)

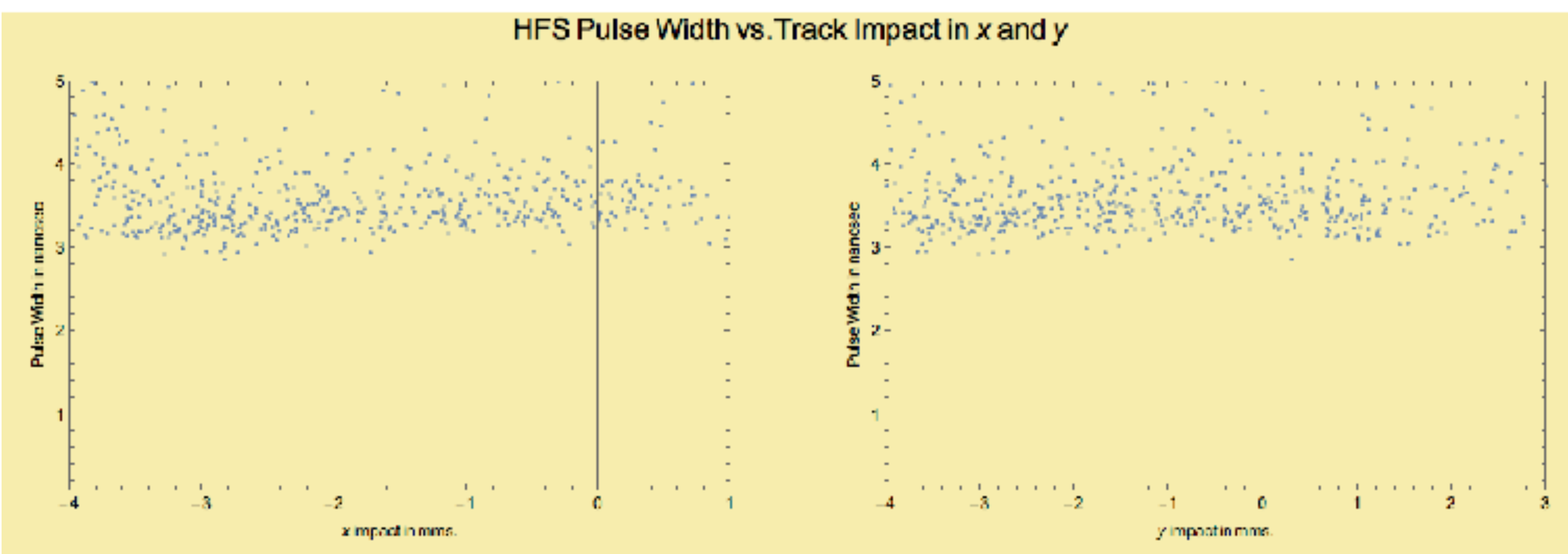
Signal modeling useful to probe position dependence

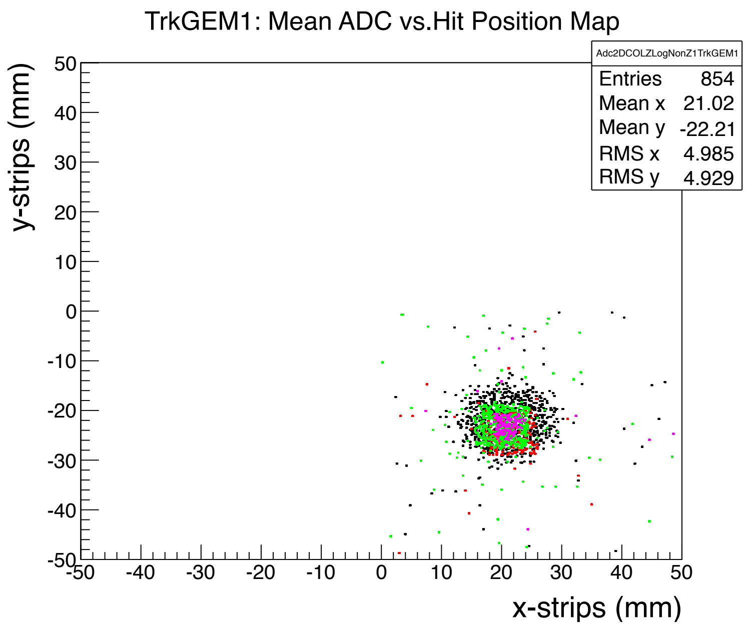


hfs



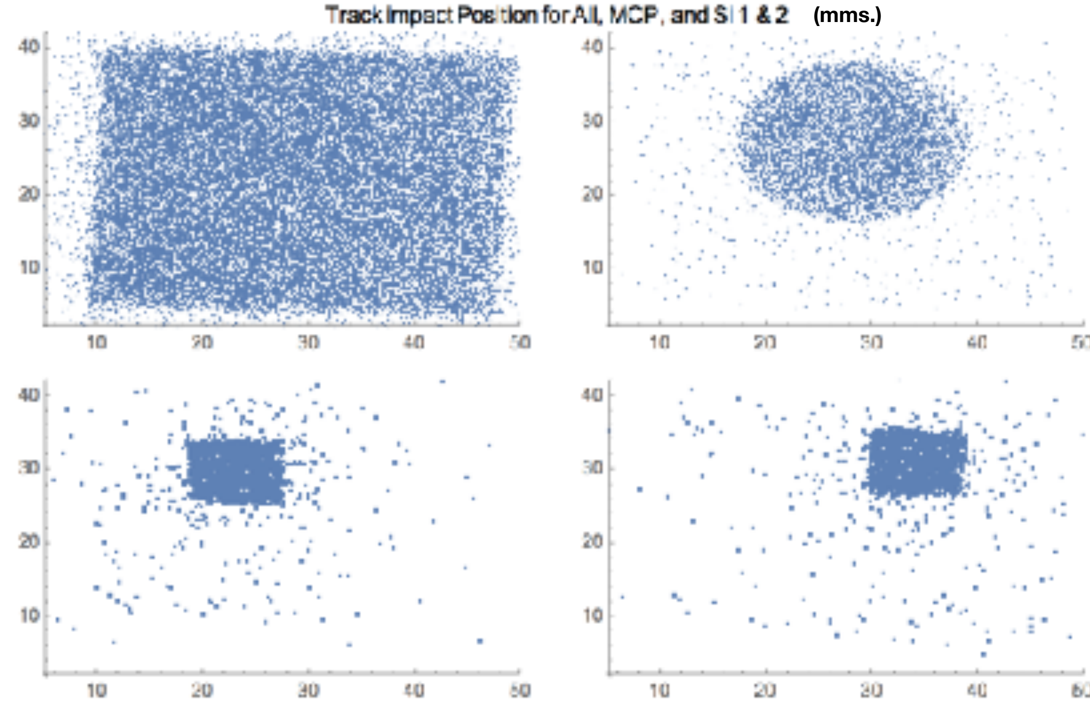
mcp



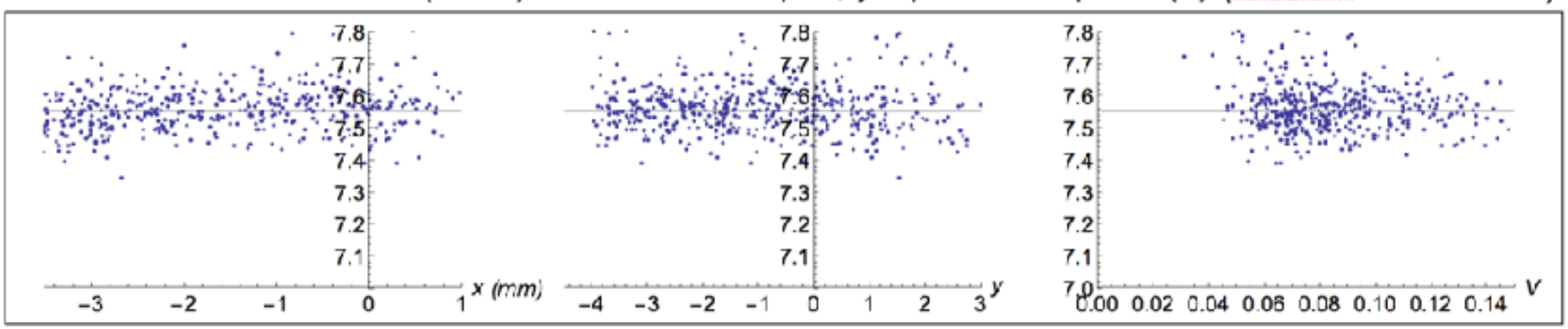


<—small area, aligned

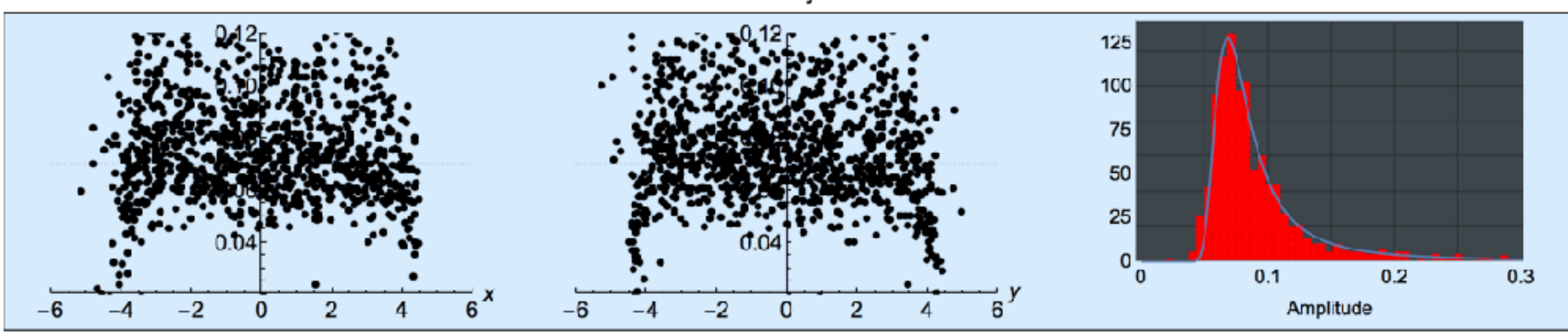
large area trigger->



HFS (Penn2) – MCP time vs. *x* impact, *y* impact and Amplitude (*V*) -*(nanosec vertical scale)*

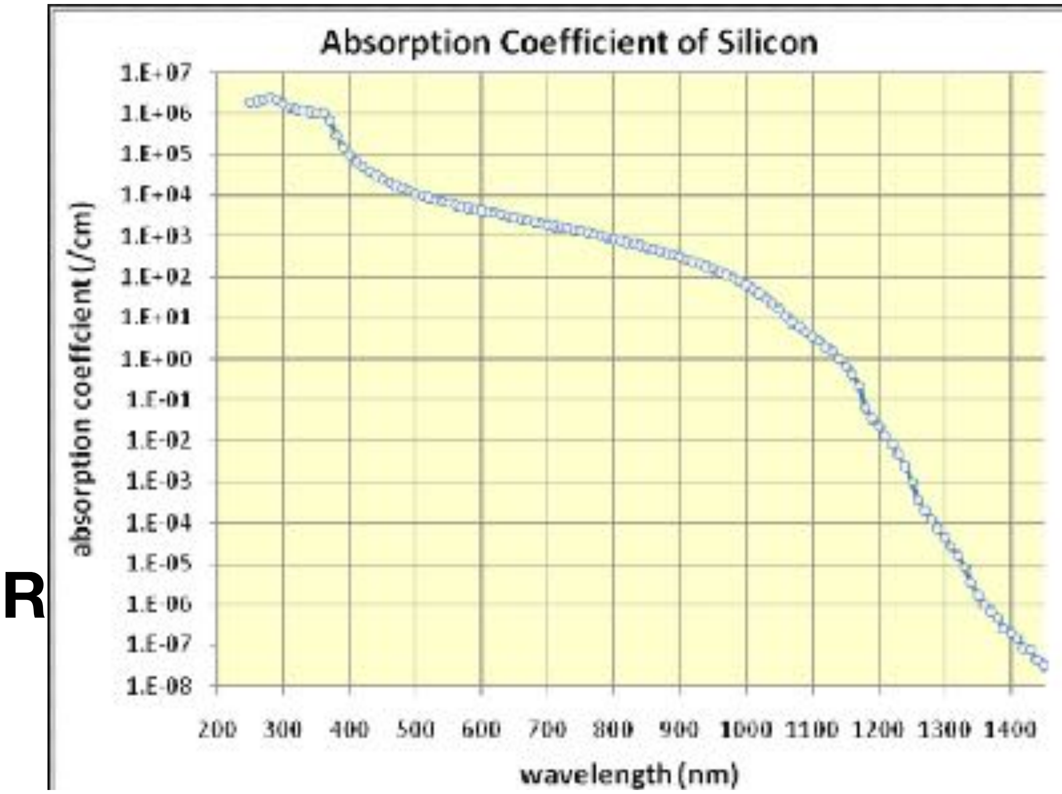


HFS Penn2 Peak vs. *x* – – – – – – – – – – – – – – and Peak vs. *y* and – – – – – – – – – – – – – – – Full Landau Distribution

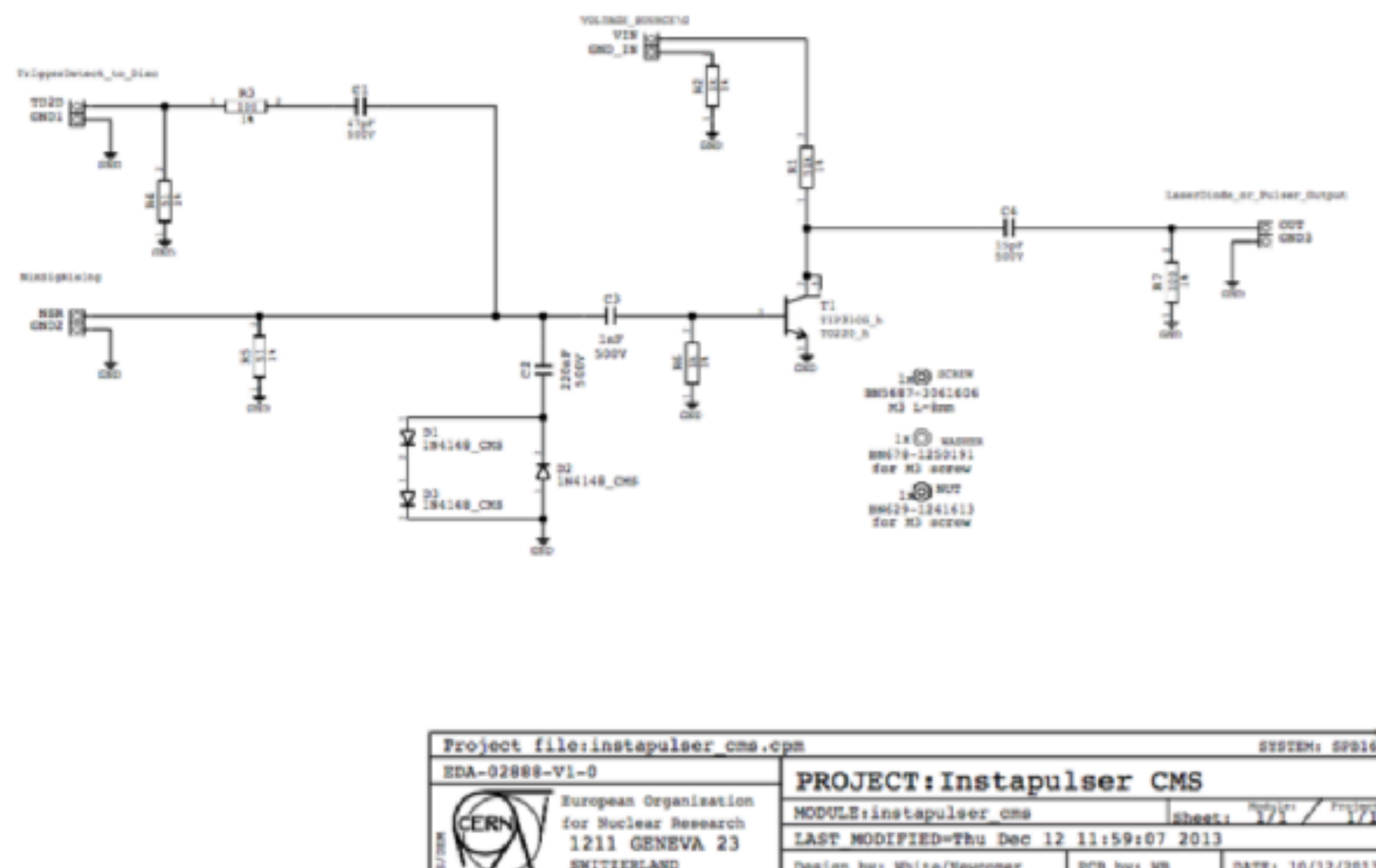


a tour of HFS laser

- Laser characterization was useful for developing capacitive(mesh) readout, etc.
- it provides a baseline performance, free of time jitter due to Landau/Vavilov
- Goal is to make a laser pulse that deposits same average charge profile as a MIP
- few 10's of micron Si pretty transparent~ 1000nm IR
- we use typically 980nm or 1060nm



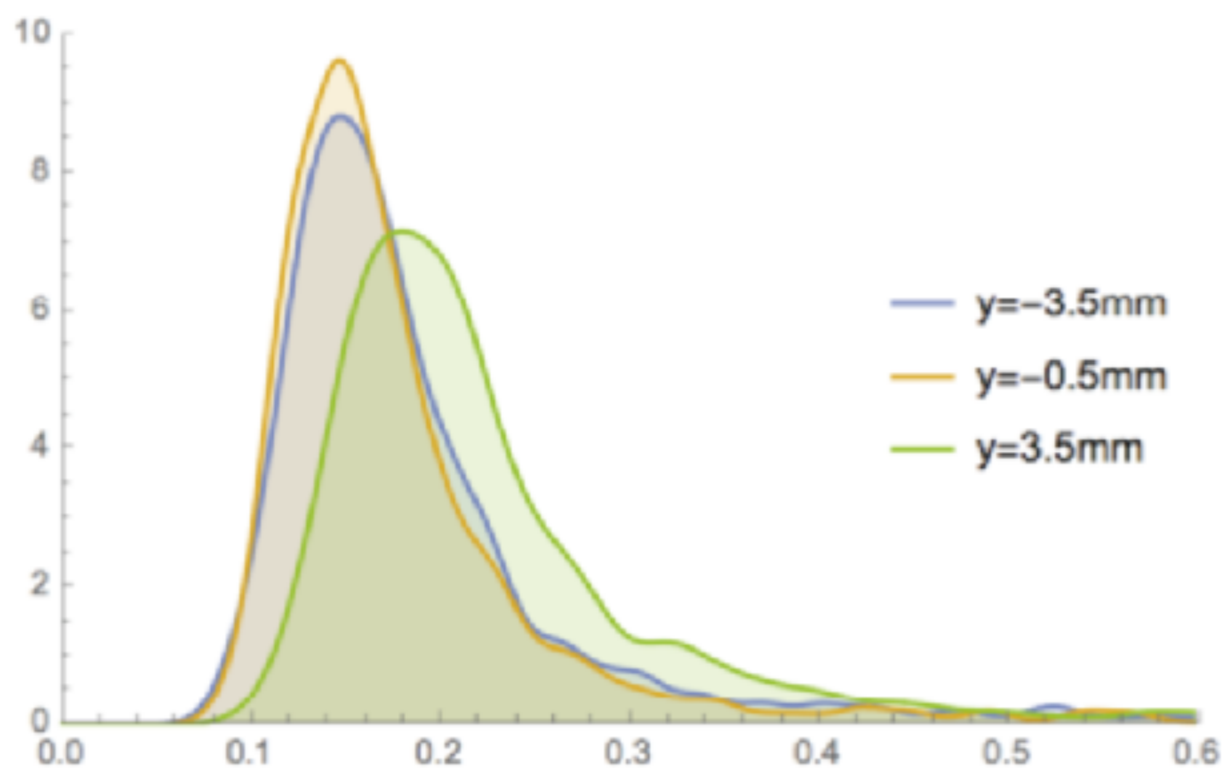
few 100 picosec laser drivers typically pricey so Mitch Newcomer and I developed a cheap one "Instapulser CMS"



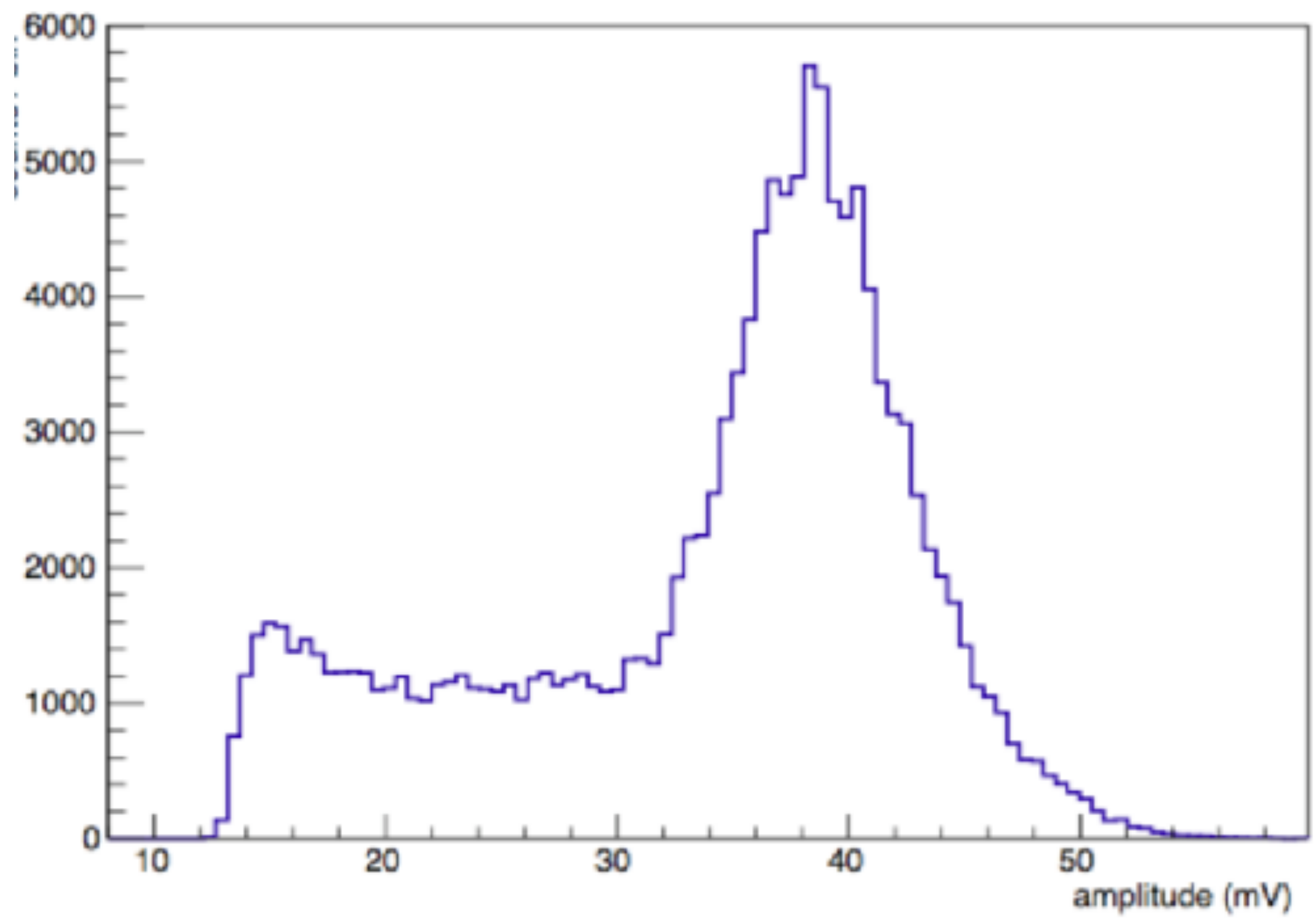
Laser Pulse Intensity

- rather than dead-reckoning (ie calculating e-h pairs/micron and gain elements) we compare, in situ, HE beam response to a stable reference (ie Fe55 X-ray source). Also nice momentum selected 1MeV electron source.

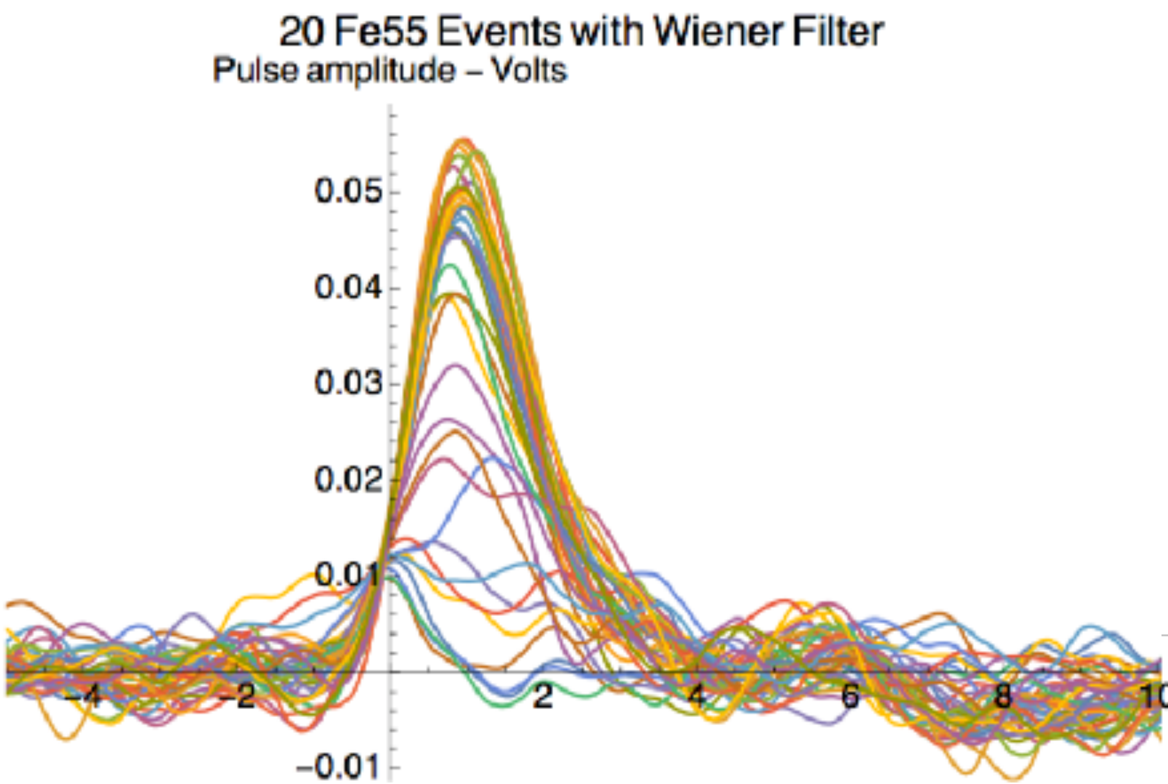
MIP signal ~ 140 mV

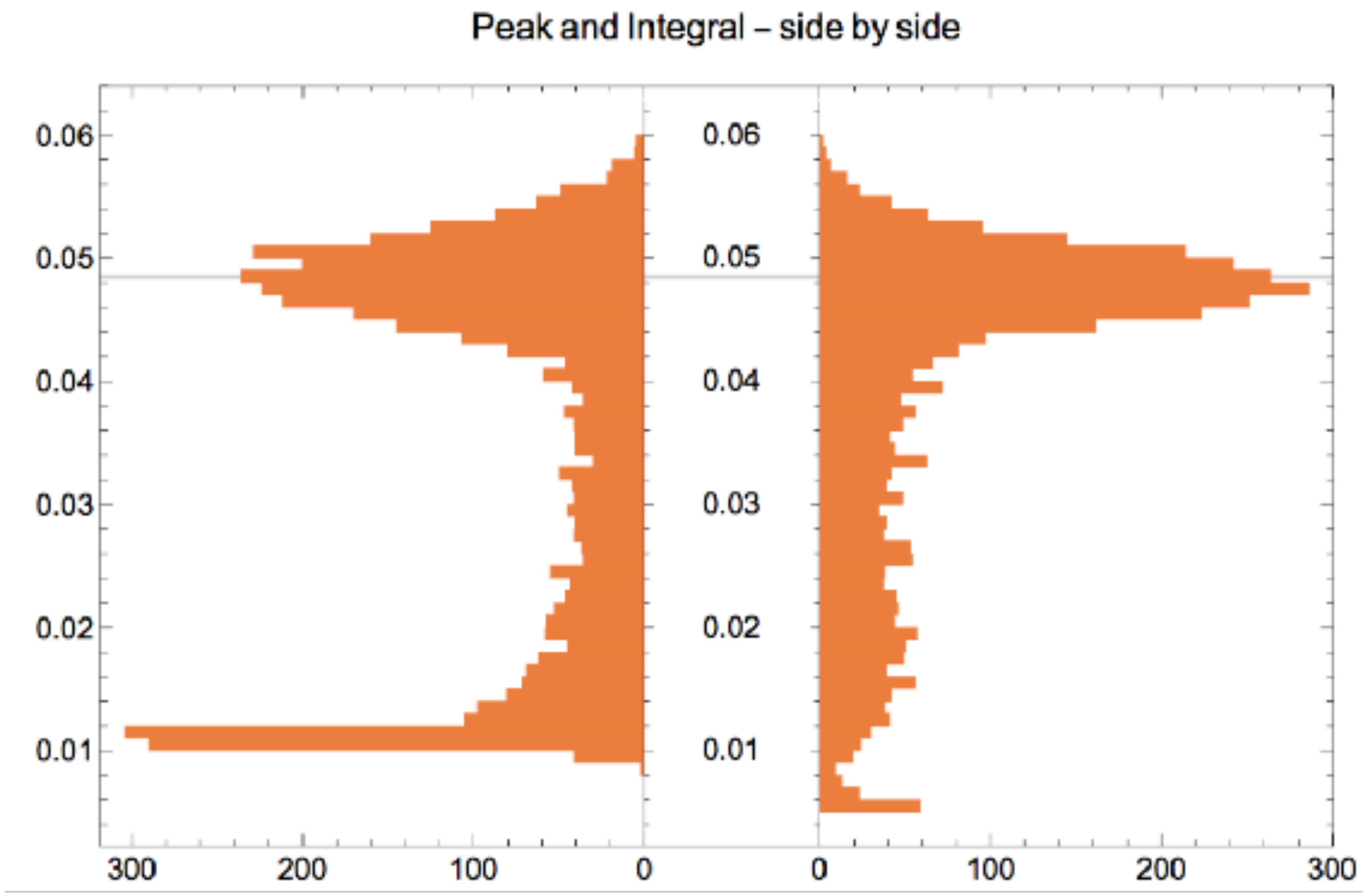


peak pulse height distribution
from 5.4 keV Cr X-rays
~1/3 of most probable MIP(150 GeV muons)



routinely adjust laser intensity vs. Fe55 once this equivalence established





Most probable signal for 5.9 keV X-ray (~1600 e-h pairs) easily seen for a given detector bias.
-> set laser intensity for roughly 3* larger signal.
Then vary bias to set different internal gain in HFS.