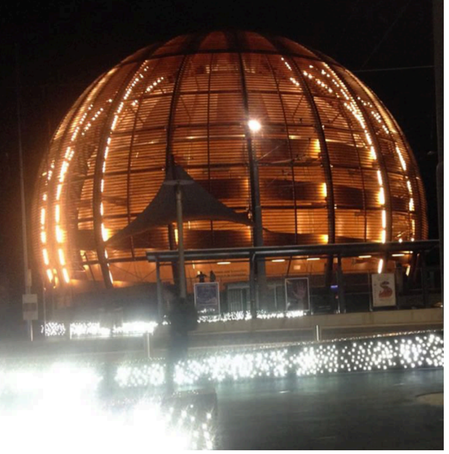


Virtual ASICs with Real Data

an Example from CMS (barrel) timing upgrade

Sebastian White, CERN/U.Virginia **March 19, 2021**

- Introduction
- Synergy between modeling and experimental data
- Integration of lab measurements with experimental data
- Test beam campaigns (gas and Si detectors)
- Signal modeling/ ASIC modeling (Timing detector Upgrade— BTL@CMS)

Introduction

HL-LHC upgrades renewed interest in Charged Particle timing* at << 100 picosecond resolution.
Mostly internal gain (ie SiPM,LGAD,DDAPD)…

High Quality Waveform acquisition key to PICOSEC collaboration's** sensor development
>>10^6 events from MPGD, AC coupled High Gain Silicon(DDAPD), MCP over ~5 years

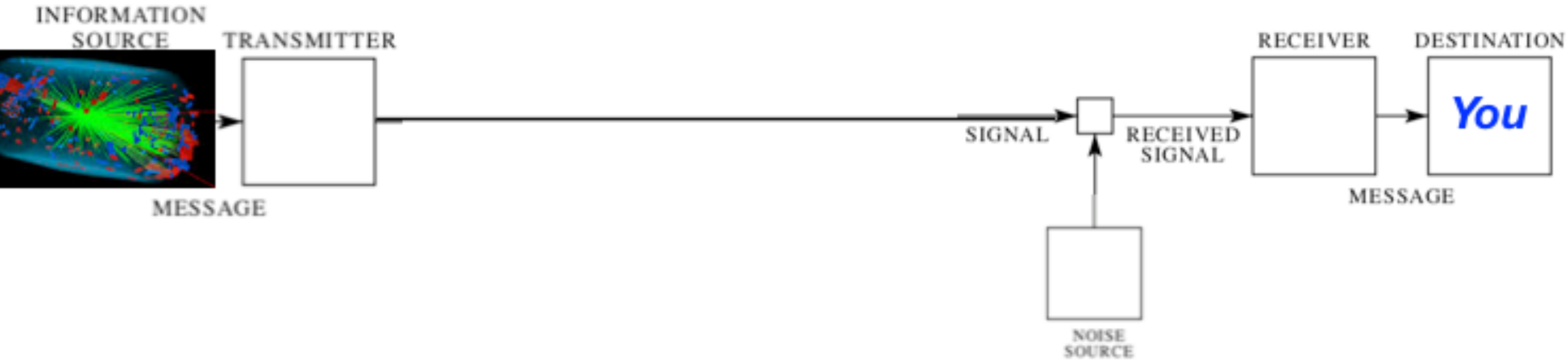
Here I report on work done w digitized waveforms to evaluate TOFHIR2 ASICs for CMS***

* "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

**"PICOSEC:Charged particle Timing w. 24 picosecond precision using MPGD", S. White @NDIP 2017, https://arxiv.org/pdf/1710.08258.pdf

***CMS Collaboration. A MIP Timing Detector for the CMS Phase-2 Upgrade. Technical Report CERN-LHCC-2019-003. CMS-TDR-020, CERN

“Misura il Misurabile”, G. Galilei



“Capability needs for 5 science drivers” addressed here:

- new sensors,
- Test beams,
- microelectronics,
- simulation (of ASIC response)

“Transformative discovery in science is driven by innovation in technology. Our boldest undertakings in particle physics have at their foundation precision instrumentation.”-I.Shipsey quoting BRN

How to encourage closer collaboration :
sensor development-> test beam campaigns-> Electronics design experts

Illustrate benefits resulting from large library of digitized waveforms.

Outline:

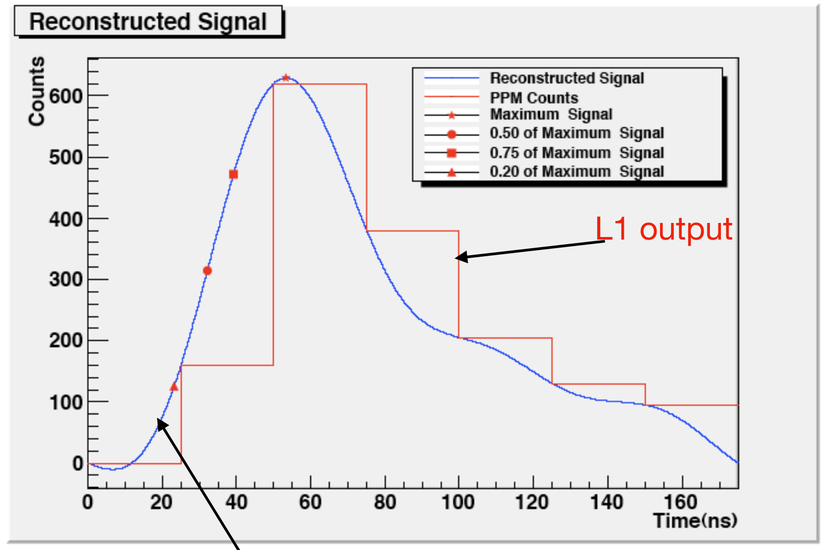
- Earlier work w Digitized Waveforms
- PICOSEC development with CIVIDEC, (+M. Newcomer) and Fast Oscilloscopes
- CMS Barrel Timing Layer(BTL) and Operation at High Dark Count Rates
- Benefits of digitized waveforms for collaboration
- Testing TOFHIR2 ASIC model with waveforms from 120 GeV protons

10 Years of digitized waveform analysis

from 40 MSa/s

to 40 GSa/s

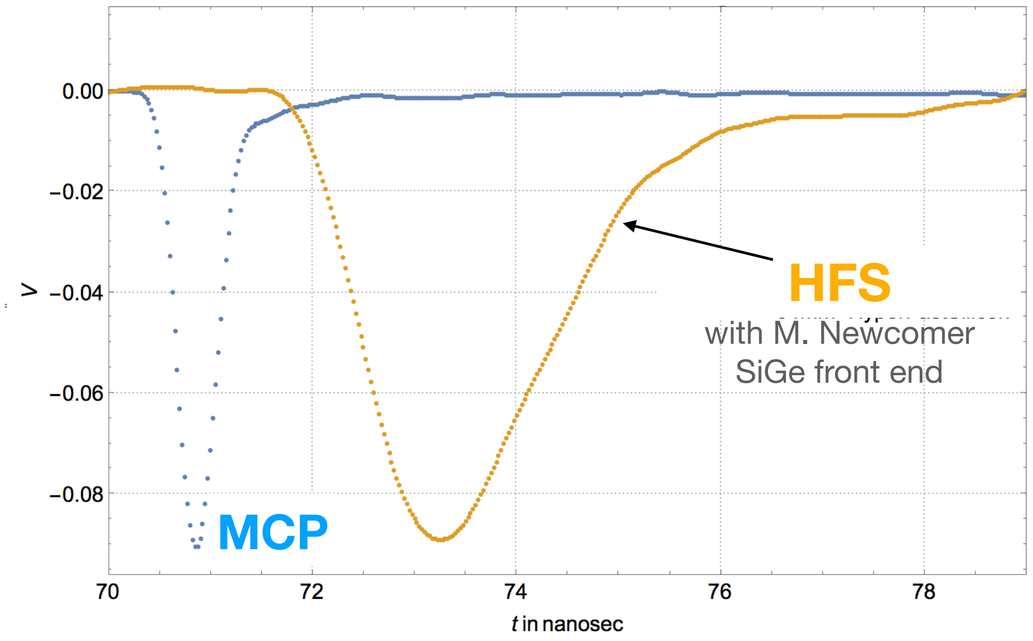
~2010 ATLAS ZDC waveforms
Output of L1 trigger processor
-> sub-100 picosecond resolution
"Diffraction 2010",SNW https://arxiv.org/abs/1101.2889



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

Aug. 2018 PICOSEC testbeam
Lecroy "Wavemaster"
MCP=Microchannel PMT, light from Cerenkov
HFS=AC coupled,Deep Depleted AvalancheDiode

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

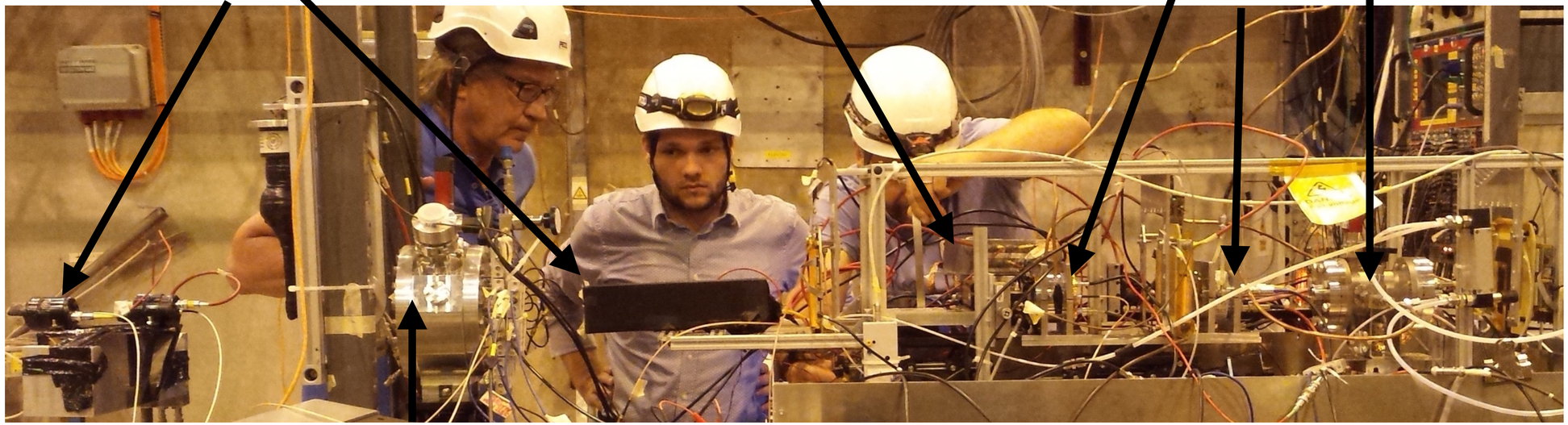


July/August 2017 PICOSEC testbeam

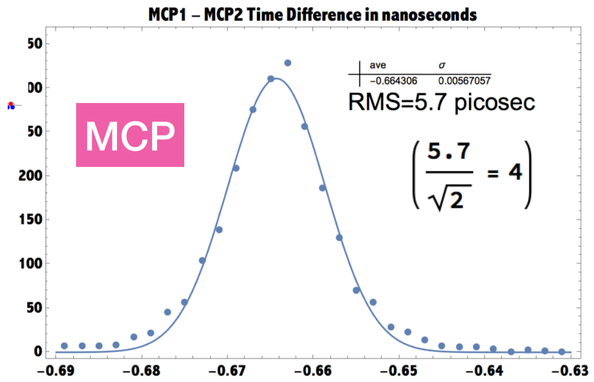
HPK MCP 's
+3mm Quartz
(measure ~4 picosec)

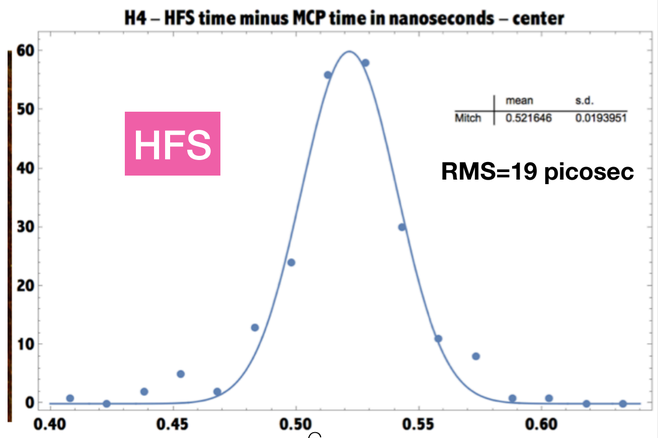
HyperFastSilicon(HFS)
64 mm² (AC coupled DD-AD)
(measure<20 picosec)

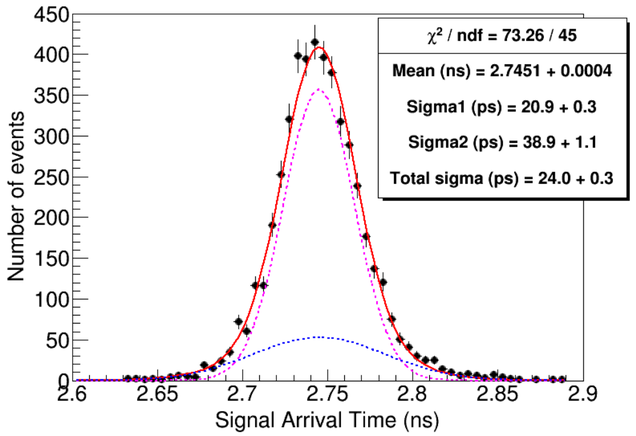
80 mm² MMegas-based
"PICOSEC"
(measure<25 picosec)



10 pad "PICOSEC"







Ne/C2H6/CF4

Fast Timing Projects based at CERN (sharing resources)

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

MicroPattern Gas

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]

eg NIM 2017 https://arxiv.org/pdf/1712.05256.pdf

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]

eg. NIM 2019 https://arxiv.org/pdf/1812.08433.pdf

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

Abundance of Oscilloscopes !

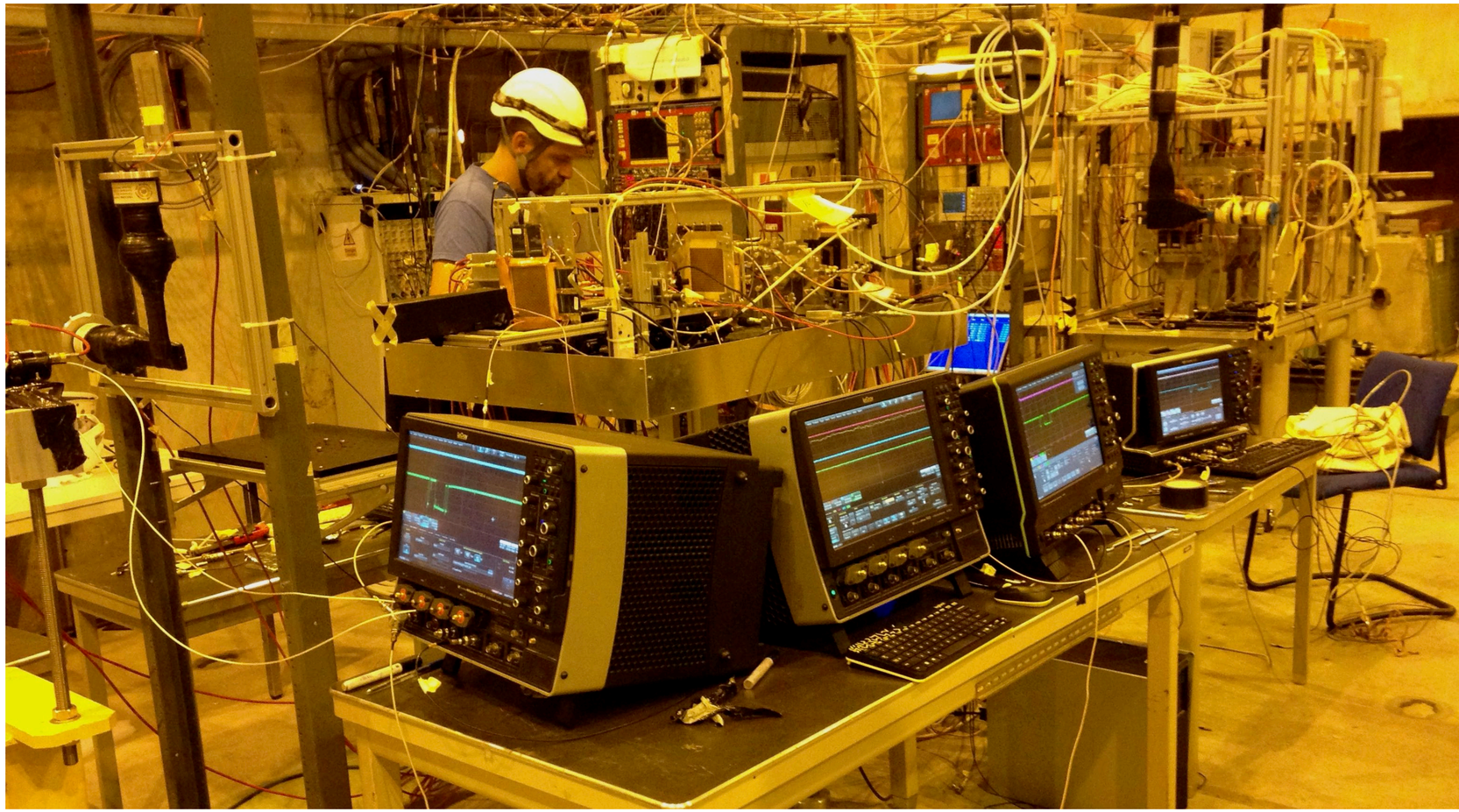
“How we’ve done 16-channel readout”

Our collaboration focused on
sensor development:
-> Gas choice
->robust Photocathodes (CsI->DLC, etc)
-> high rate tolerance

but deferred electronics system design until
analysis of latest multi-pad data completed

Close collaboration
with E. Griesmayer, CIVIDEC (for MPGD)
and Mitch Newcomer (for Avalanche diodes)

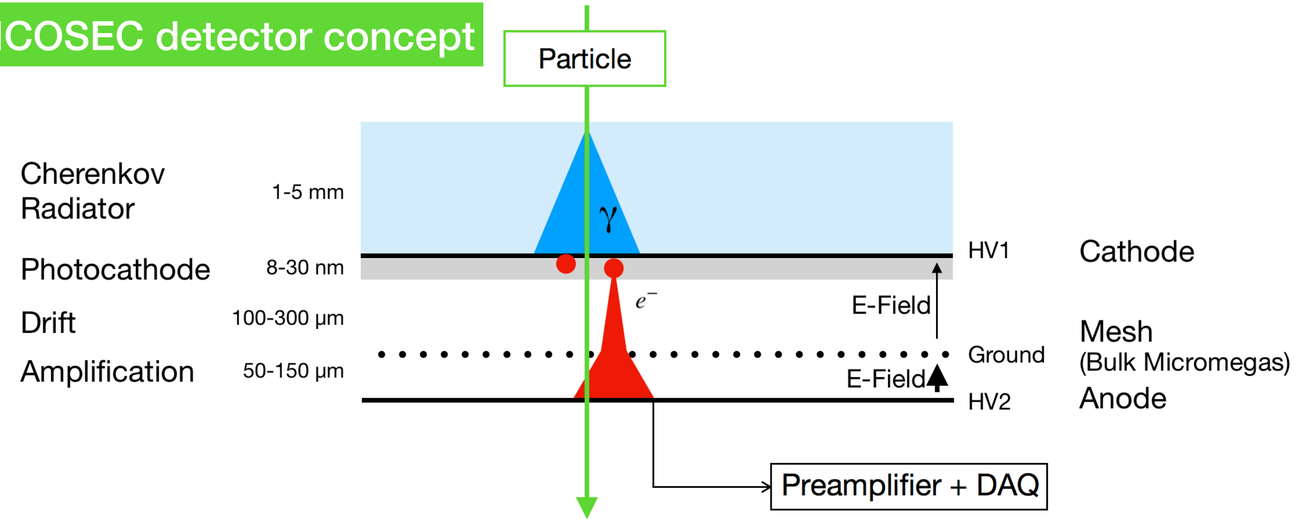
Essentially unlimited access
to Lecroy Scopes



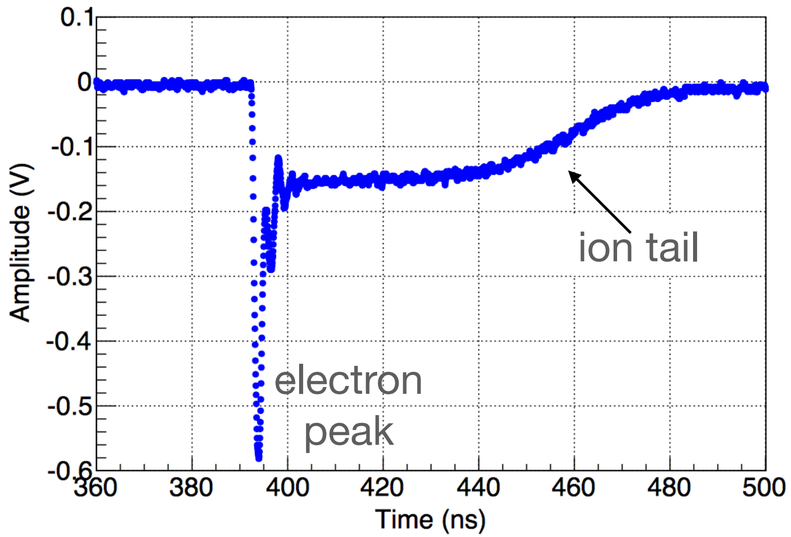
PICOSEC test beam in North Area of SPS
-> product placement for Lecroy/Teledyne

Towards multi-channel readout of PICOSEC multipad

PICOSEC detector concept



typical single photoelectron signal



Anode signal used to obtain ~24 picosecond MIP timing

- Can we obtain similar performance using a SAMPIC digitizer w maximum possible sampling rate of ~8.5 GSa/s ?-> Large Area PICOSEC

- We are currently analyzing library of waveforms in consultation with D. Breton(SAMPIC).

2017 PICOSEC Testbeam Picnic

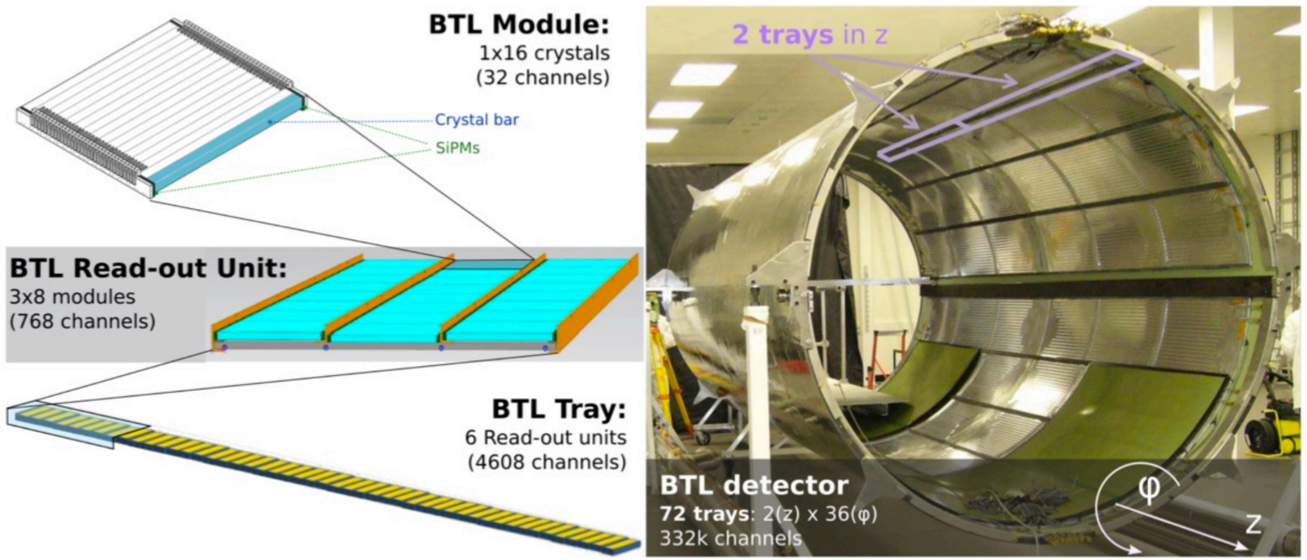
Development of CMS Timing Upgrade (BTL) Sensors and ASIC

• in contrast to PICOSEC, where development of digitizer has followed after long focus on sensors
CMS Barrel Timing Layer(BTL) Upgrade **Sensor** (LYSO crystals w SiPM readout) and **ASIC** testing more in sync

• in rest of talk I will focus on tests at Fermilab "FTBF" w 120 GeV proton beam
primarily data taken by U. Virginia team in Feb. 2020 (and upcoming Apr. 2021)

• also lab work at CERN w. A. Heering on Dark Count Noise electronic suppression techniques

- Single layer, 40 mm thick, segmented into 72 trays
- Each tray consists of 6 Readout Units with 24 modules each
- Sensor module : 16 LYSO bars, 2 SiPM arrays



- **MIP timing using layer of LYSO bars with SiPM coupled to each end**
- **MIP crossing bar deposits ~4 MeV**
- **fast signal but long decay of LYSO**
- **At HL-LHC rad damage to SiPM**
- **resulting in ~10's of GHz dark count rate(DCR)**
- **Challenge to ASIC design to mitigate DCR noise**
- **and pileup under HL-LHC conditions**

Signal Processing to deal w Pileup and Dark Count Noise

Lab Measurements of SiPM Time Resolution vs. Irradiation

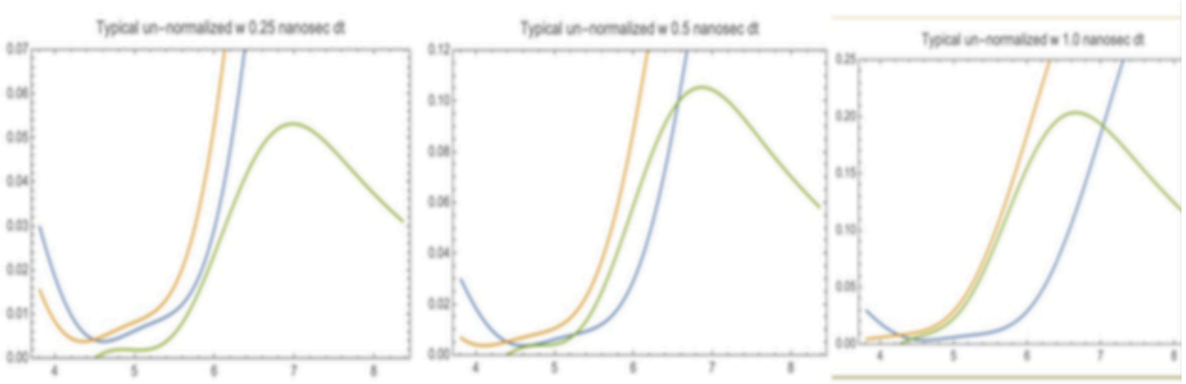
Sebastian White[a], Arjan Heering[b]

[a] *CERN/University of Virginia*
[b] *Notre Dame*

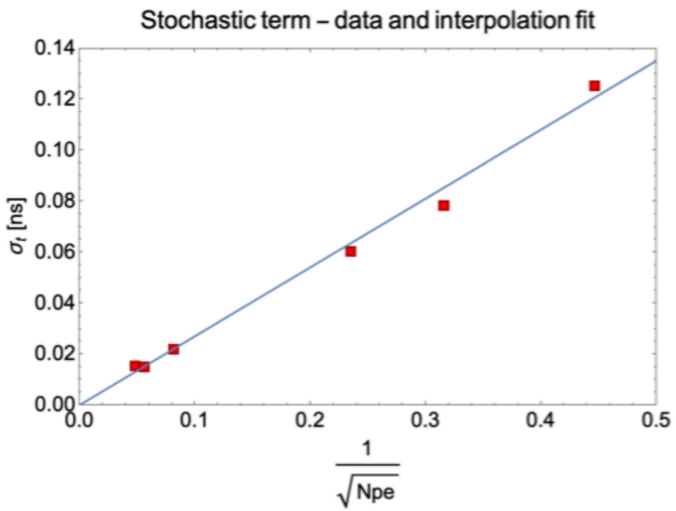
baseline restoration.
Signal processing algorithm, ie:

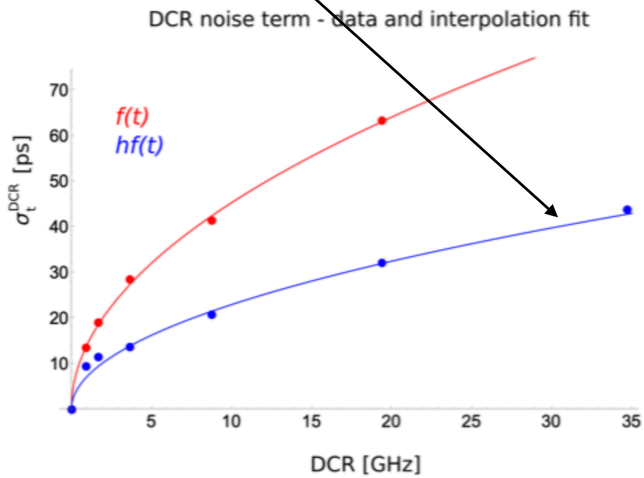
$$h\,f(t) = f(t) - f(t + \mathrm{d}t)$$

mitigates timing degradation due to dark count noise

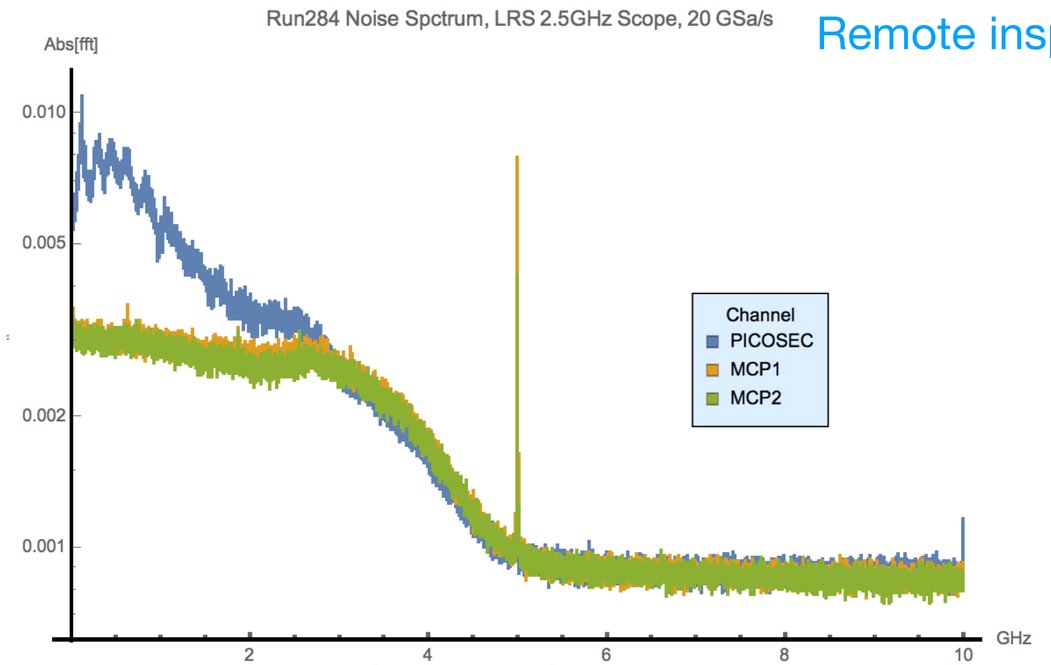


Examples of delay and subtract for dt= 0.25, 0.5 , 1.0 nanosec



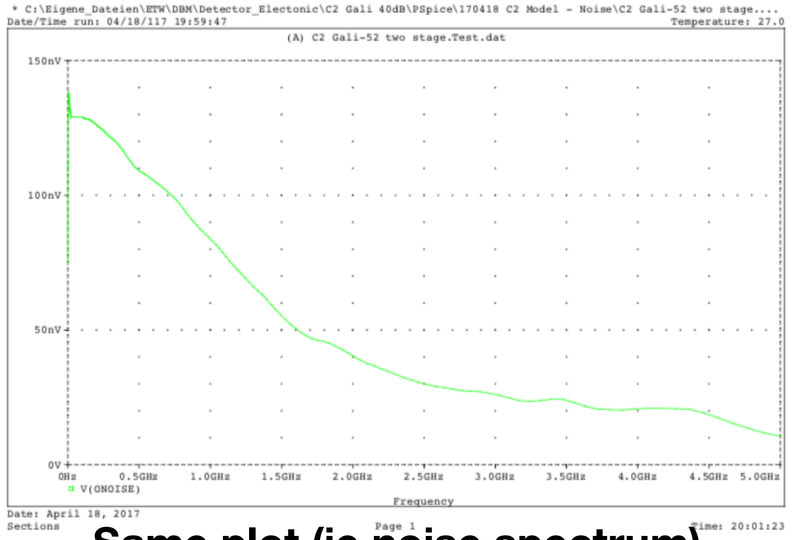


A Few applications: Discrete Fourier Transform-



our test beam noise spectrum

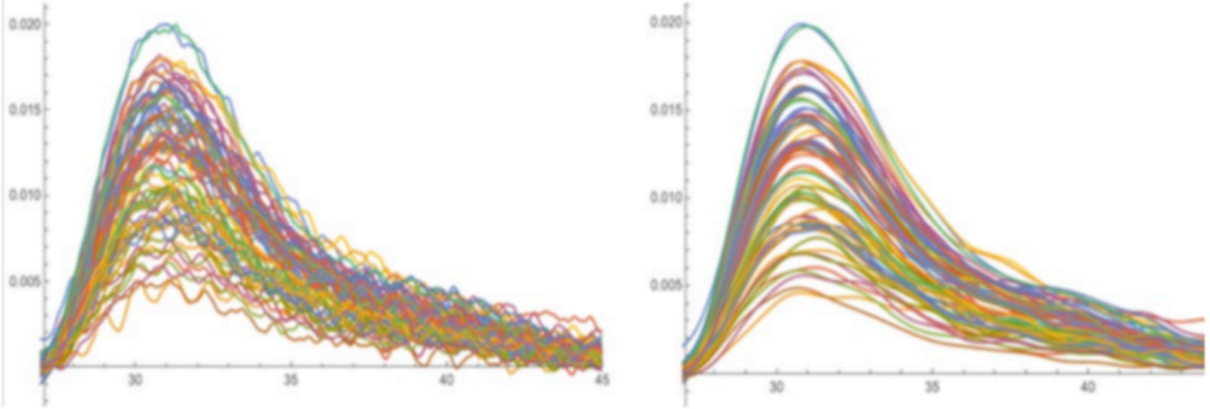
Remote inspection of Noise Characteristics (CERN<-> CIVIDEC)



Same plot (ie noise spectrum) verified by E. Griesmayer(Cividec)- SPICE

After the fact removal of pickup noise
from rf environment @ C. Joram lab at CERN
“brick wall filter”

SiPM waveforms before/after Digital “Brick Wall Filter”

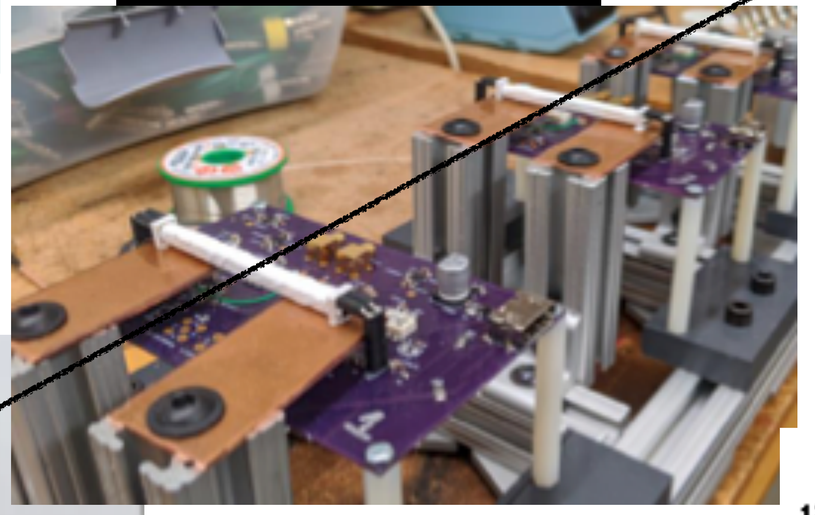


CMS LYSO/SiPM Testbeam data analyzed using transfer functions extracted from CADENCE

Our Main Topic: Test beam Sensor data Analyzed using ASIC Model

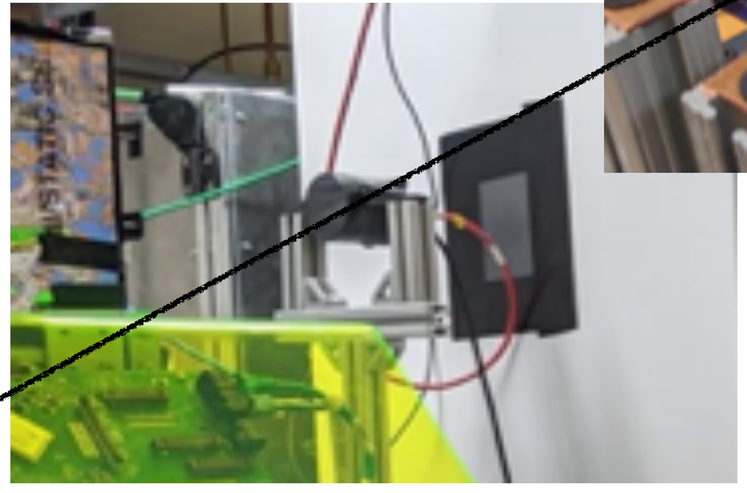
I will discuss data from this setup (used LRS scope)

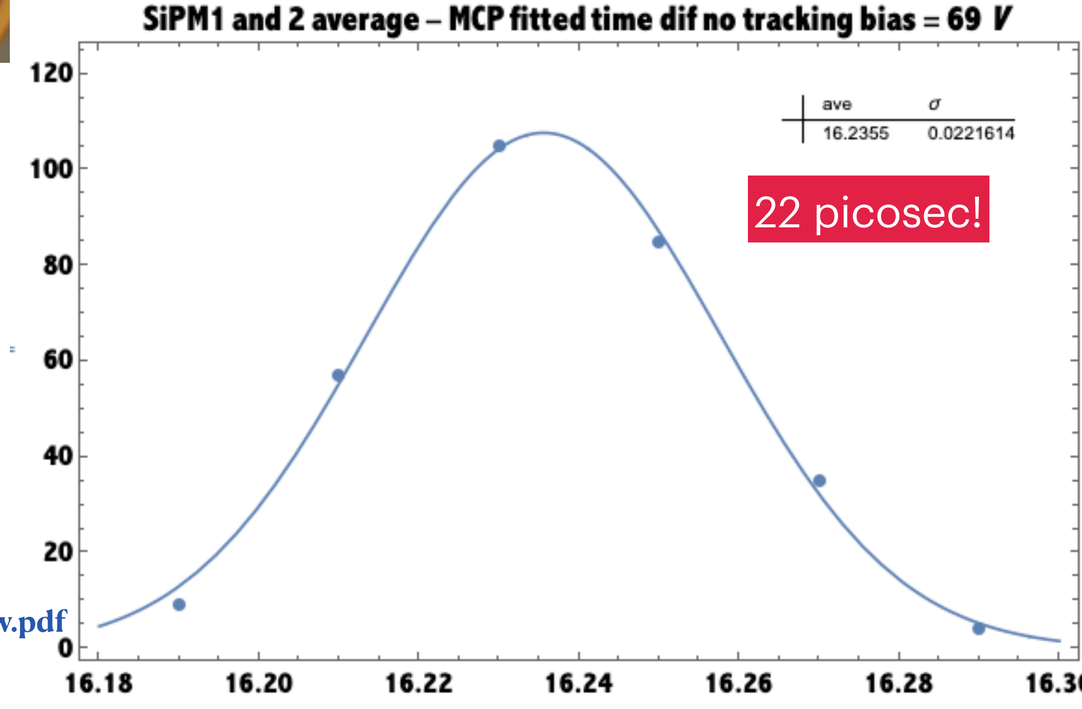
UVa Test Setup



3 LYSO SiPM bars covering full anticipated range of DCR (Dark Count Rate) for HL-LHC

MCP for t_0





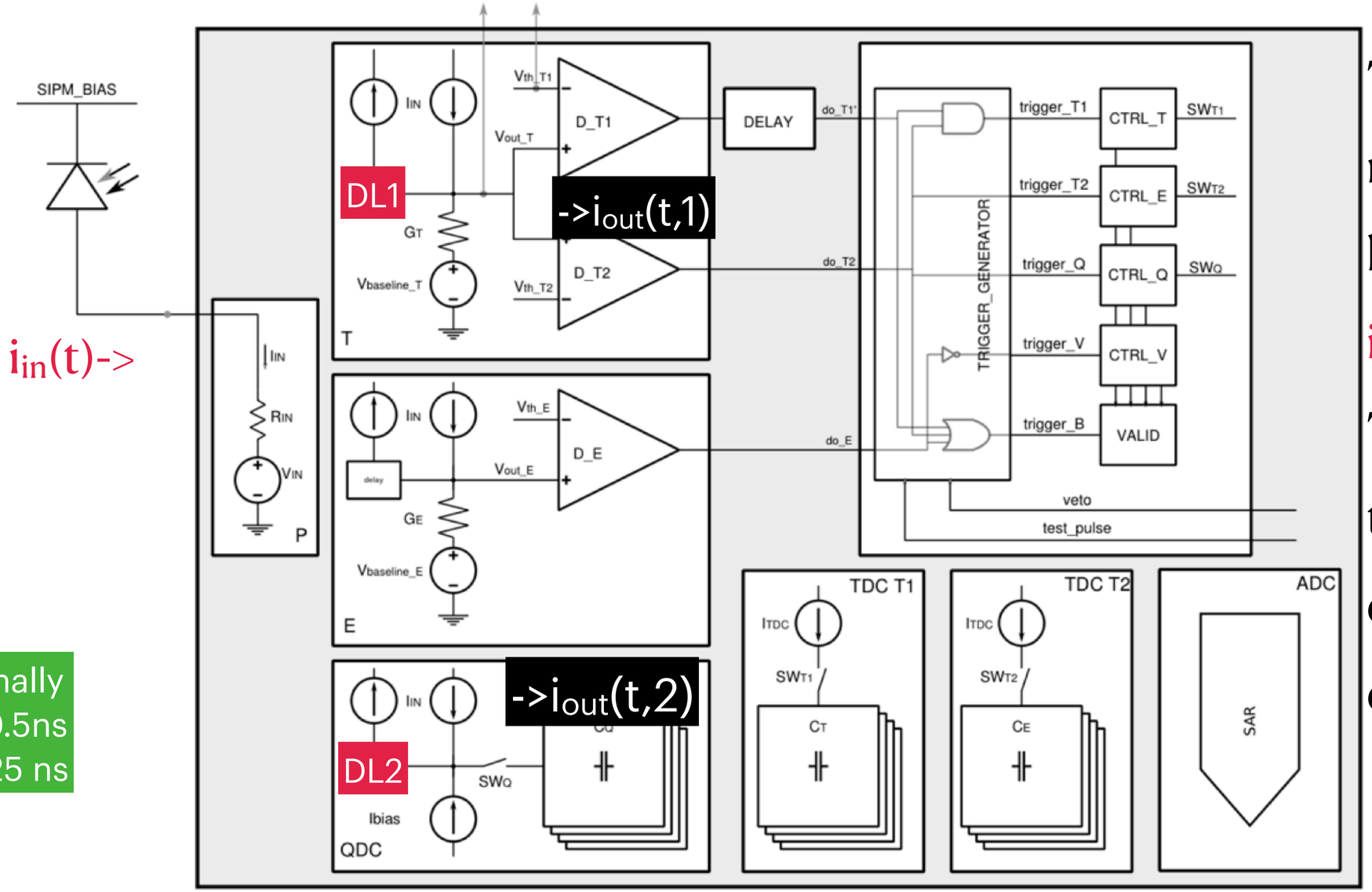
Reality check: Achieve Nice result Under Day-0 HL-LHC conditions using full waveform analysis —22 picoseconds!

https://indico.cern.ch/event/904342/contributions/3817313/attachments/2017654/3372597/TBanalysis_2020_snw.pdf

How does ASIC perform on these data? 3 relevant nodes

diagram of the TOFHIR2 channel

TOFHIR2 ASIC developed at Lisbon/PETSYS

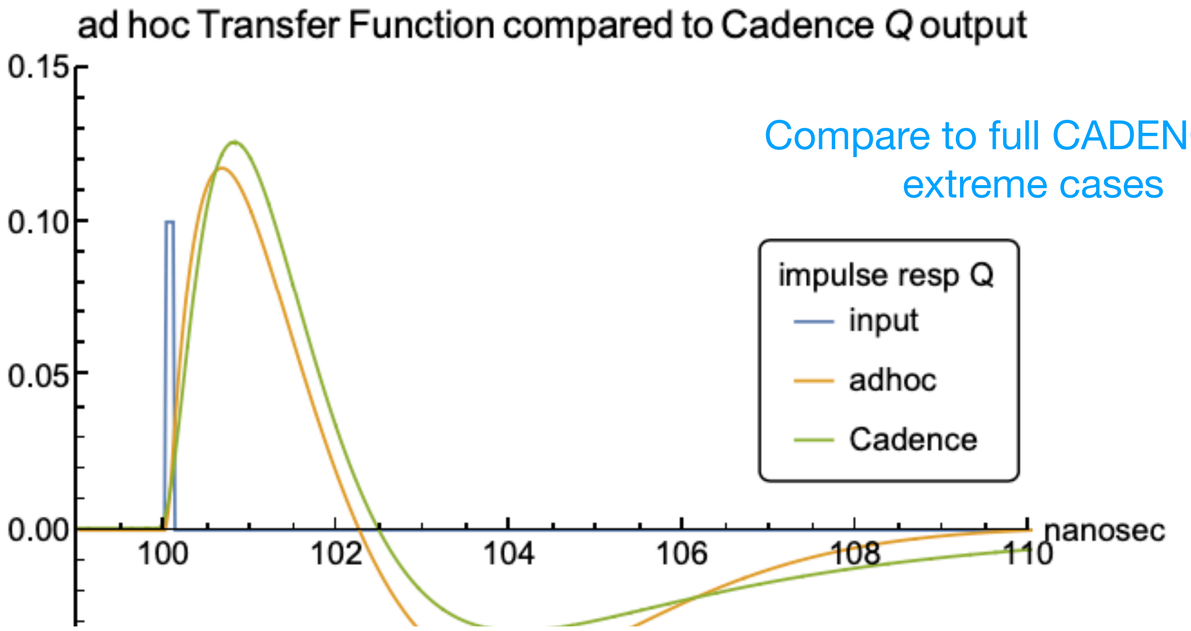


nominally
Dl1->0.5ns
Dl2->25 ns

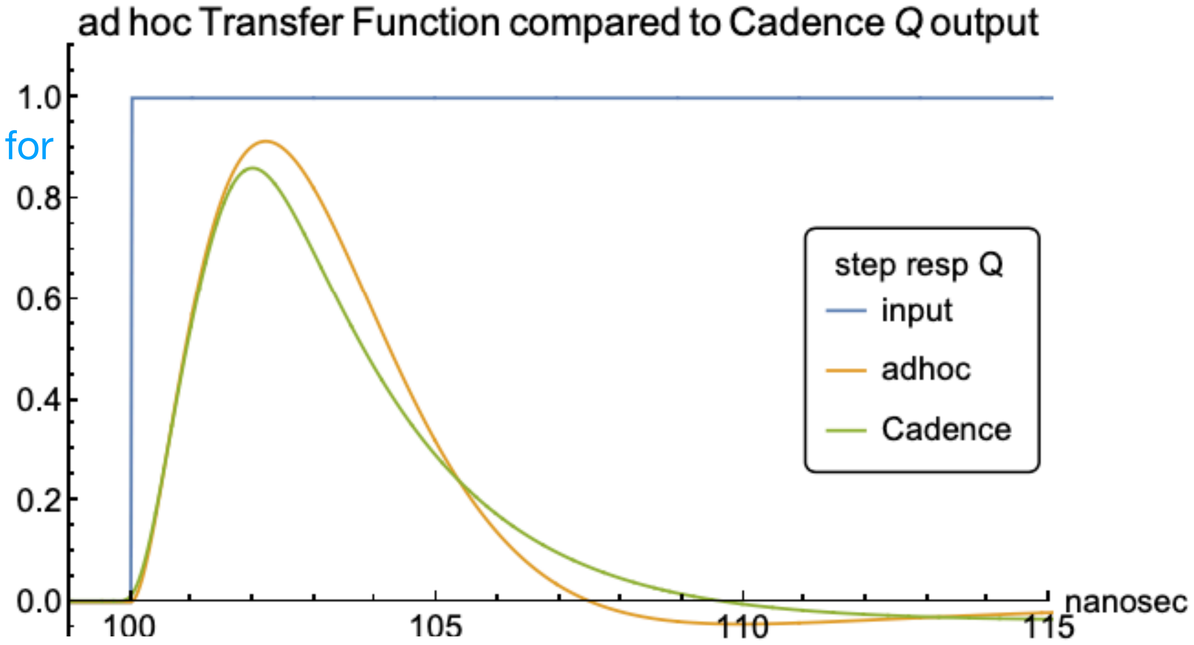
To answer this meaningfully need to know how $i_{in}(t)$->$i_{out}(t,1)$ or $i_{out}(t,2)$

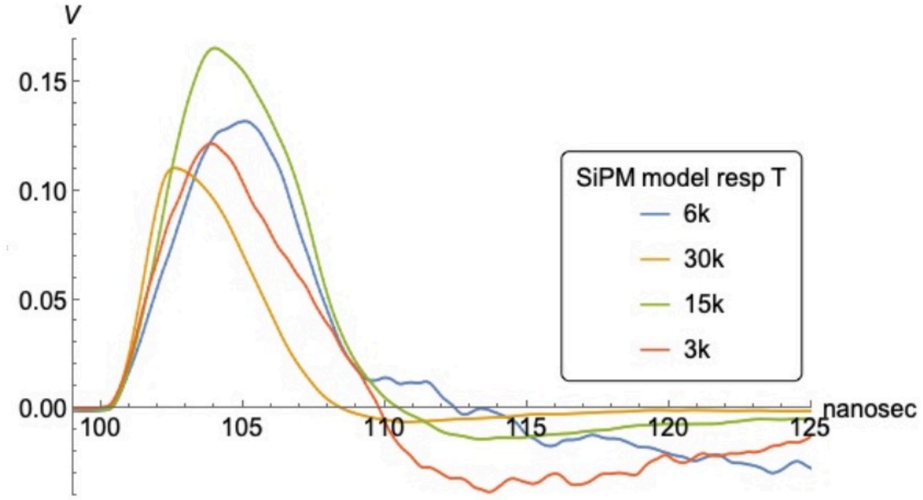
This is called the transfer function, H[t] depending on correct description of DL1,2.

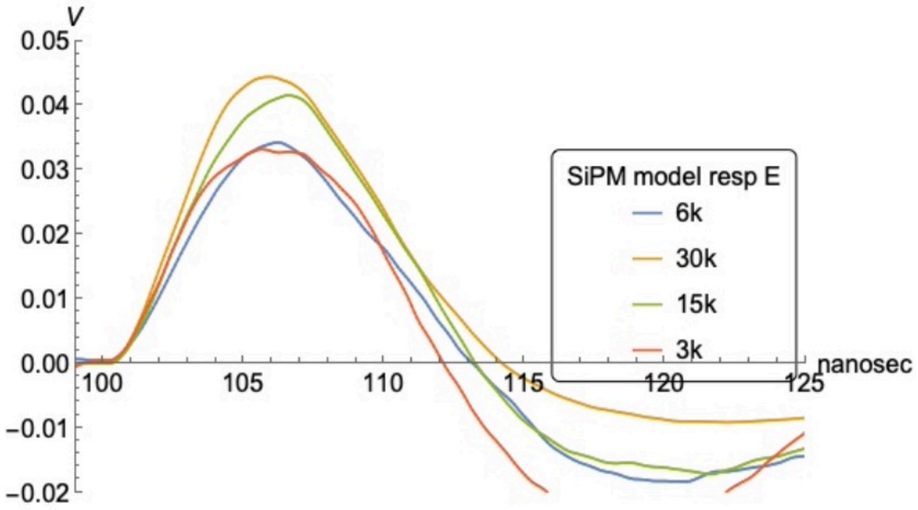
Probe CADENCE model to get “lightweight” code for xfer Functions



Compare to full CADENCE for extreme cases



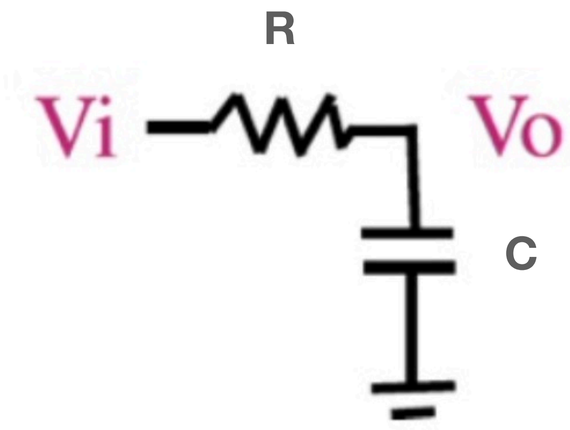


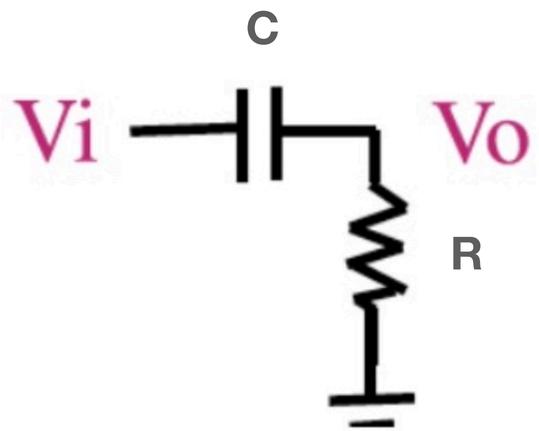


Probe nodes at Disc inputs to show circuit response linearity

The “ad hoc” model to process $I_{in}[t]$ from SiPM

- first there is a 2-step RC network (ie Figure -left) each with RC time constant “t_{RC}" then a CR network (ie Figure -right) with CR time constant “t_{CR}".
- depending on the branch (T,E orQ) the delayed signal passes through a 5-stage RC network (ie Figure -left) with the component values provided by LIP as above.
- then the delayed signal is subtracted from the un-delayed copy.
- we then tune the “t_{RC}" and “t_{CR}" RC/CR components to give the best match to the CADENCE response.

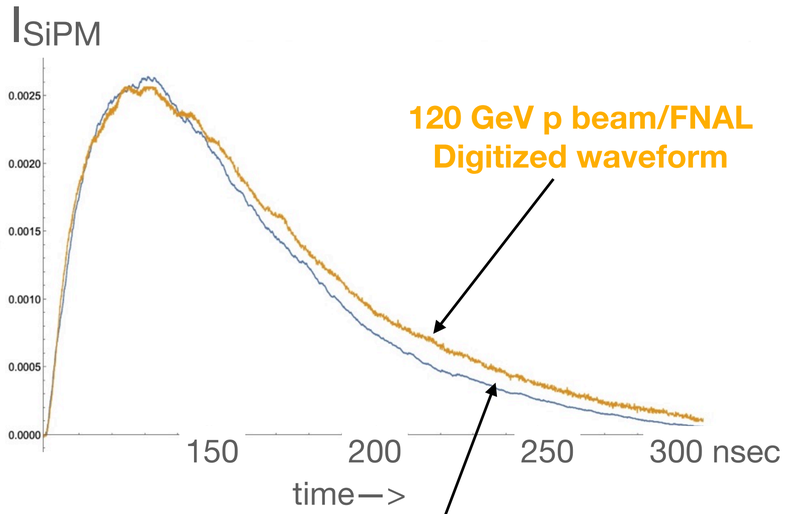




An example from CMS Timing Upgrade Detector(BTL)

capturing transfer functions
to model ASIC signal processing

Input waveform
(SiPM output current from LYSO sensor)



Model used by LIP/PETSYS for CADENCE sim
F.Corsi et al., IEEE NSSMIC.2006.356076

ASIC response to input current signal
at various nodes

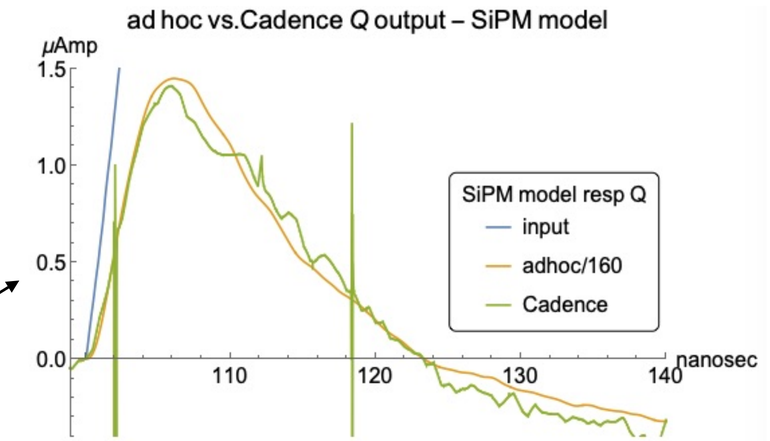
1)Charge integrator

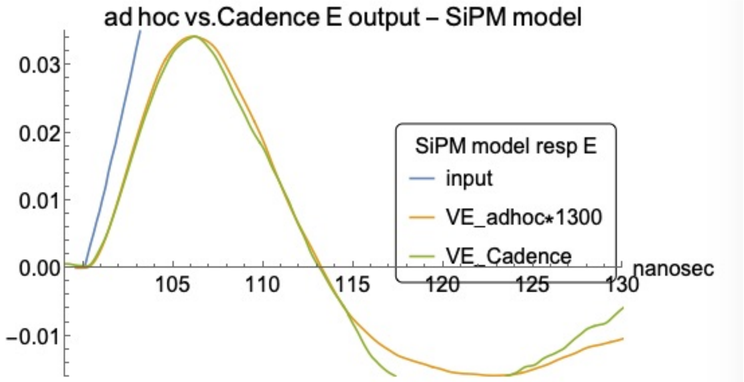
2) trigger discriminator

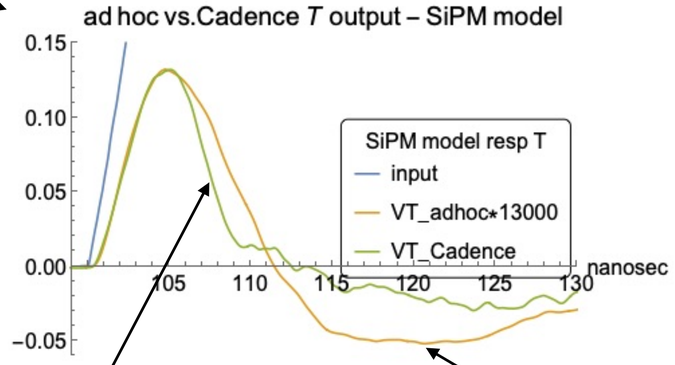
3) low threshold Discriminator

Transfer Functions from CADENCE
or simple RC networks (this work)

(collaboration with T. Niknejad/LIP)

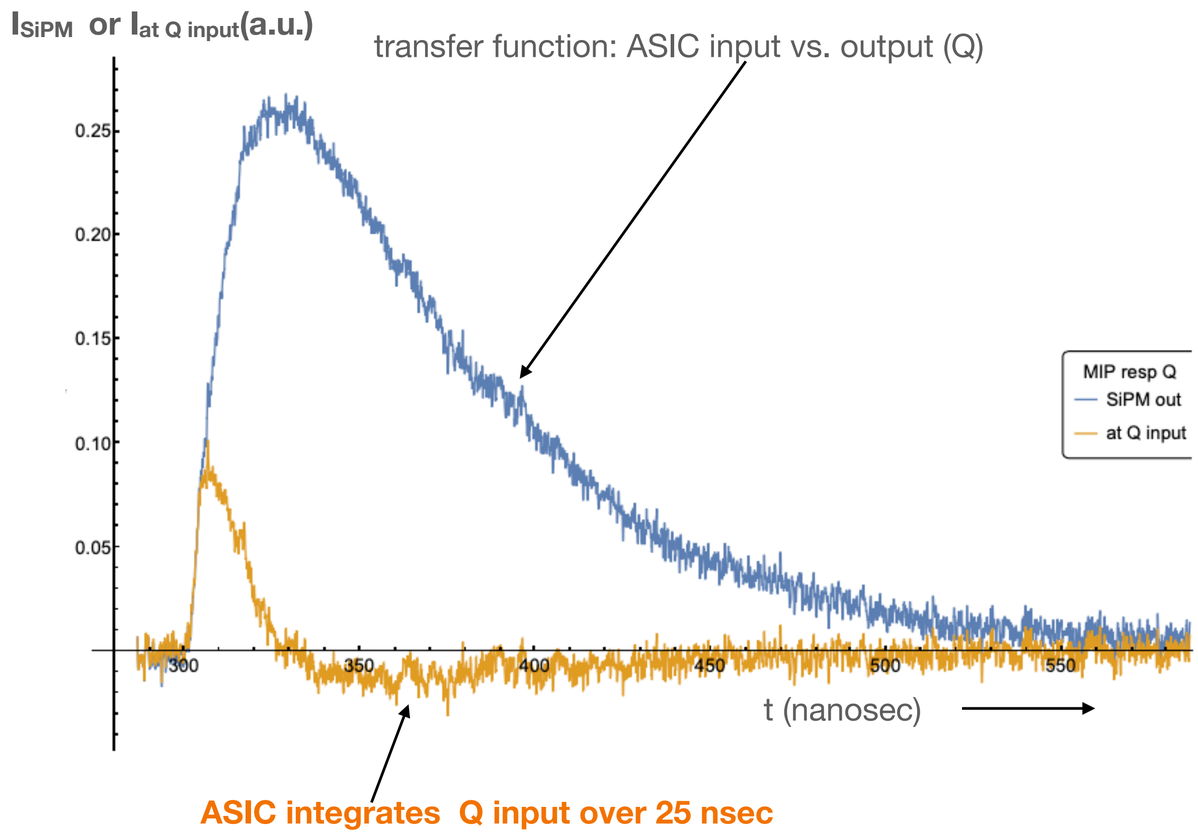


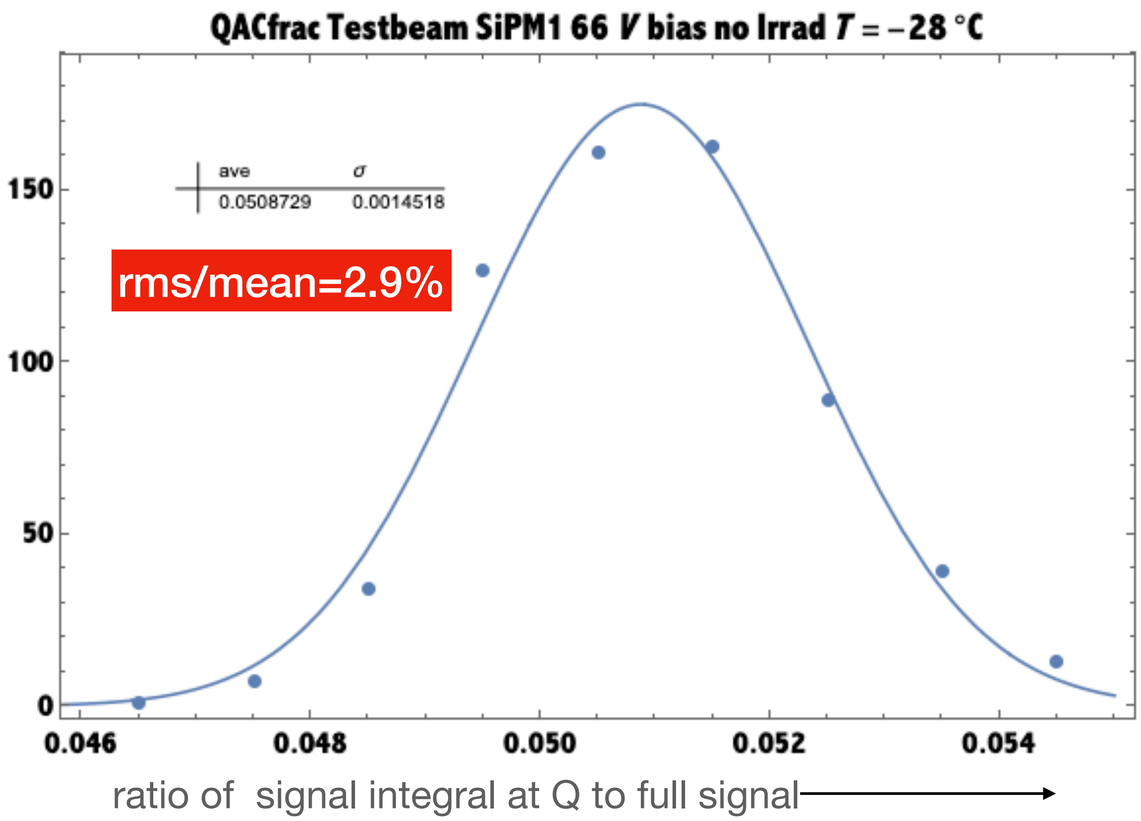




Full CADENCE compared to this work("ad hoc")

Illustrative Application: How accurately does ASIC capture full Q?





Demonstrates that Q accuracy (for "Amplitude Walk Correction") of ~5% achieved for a real data set.

Summary

- Illustrated usefulness of building “waveform library” through life of project
- has been also useful for maintaining close collaboration w. FEE experts
- This has allowed revisiting readout options for Multipad/large area PICOSEC
- In the CMS Barrel timing upgrade, we combined these with a tool using extracted ASIC transfer functions from TOFHIR2A(which is now under test) and TOFHIR2B (expected final version, submission likely in April)
- This approach makes best use of limited testbeam resources

Backup

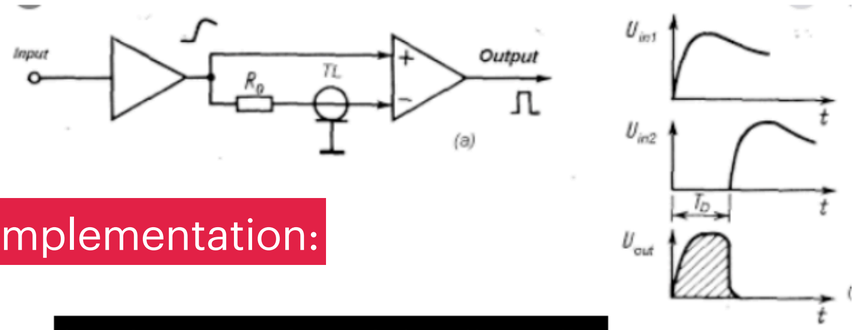
A word on signal processing on Digitized Waveforms:

Implementation of delay and invert:

hi DCR:(10^{13} neq/cm^2, +10 ^{0}C)

In ASIC the delay line is approximated by

an RC network->successive Low pass filters



hardware Implementation:

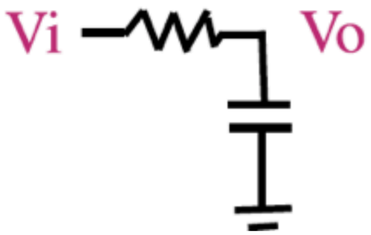
implemented w. delay line clip since Amp AC coupled

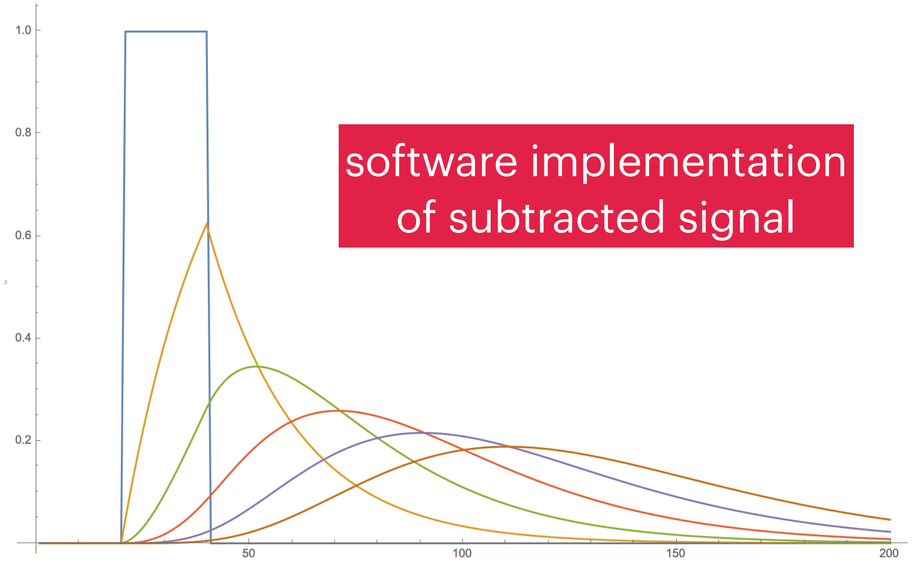
Below is standard formula for n-stage RC "low pass filter".

$Vo(j) = \alpha Vo(j-1) + (1-\alpha)Vi(j)$

$\alpha = (RC/\Delta t)/(1+RC/\Delta t)$

```
In[•]:= Do[
        Do[
          If[i == 1, vout[[i]] = 0, vout[[i]] = alpha * vout[[i - 1]] + (1. - alpha) * vin[[i]]];
          , {i, 200}];
        vin = vout;
         vfin[[n]] = vout;
         , {n, 5}];
```





software implementation of subtracted signal

InverseLaplaceTransform[1/(s + a)^n*(Exp[-20 s] - Exp[-40 s])/s, s, t] // FullSimplify