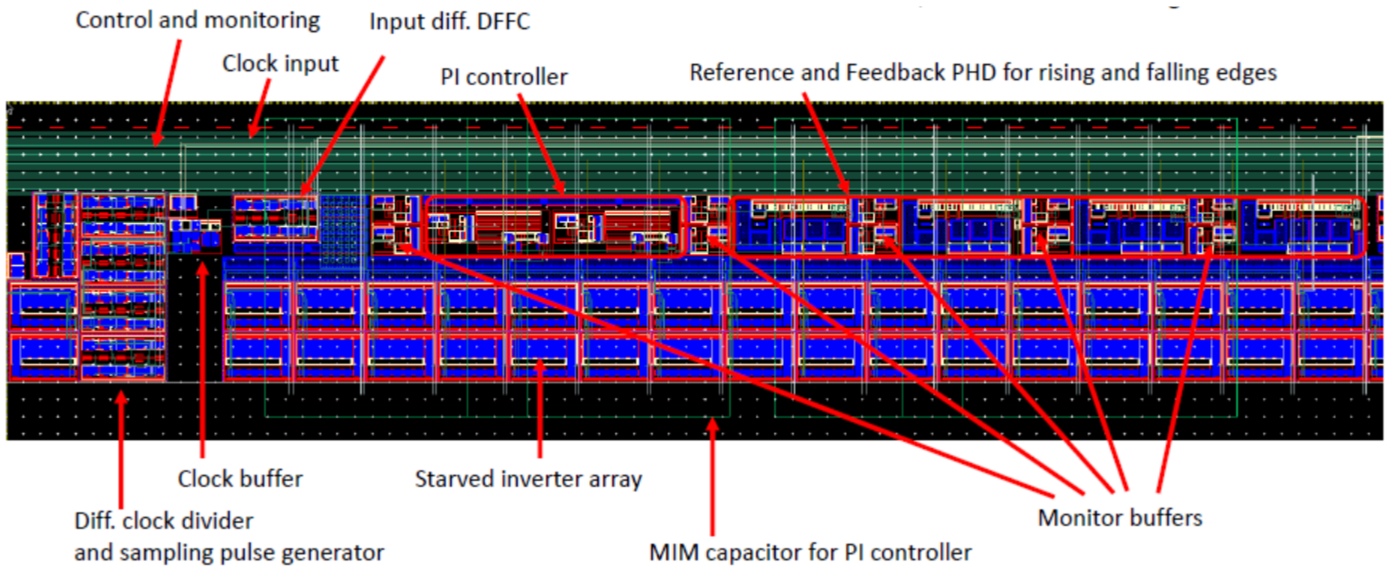
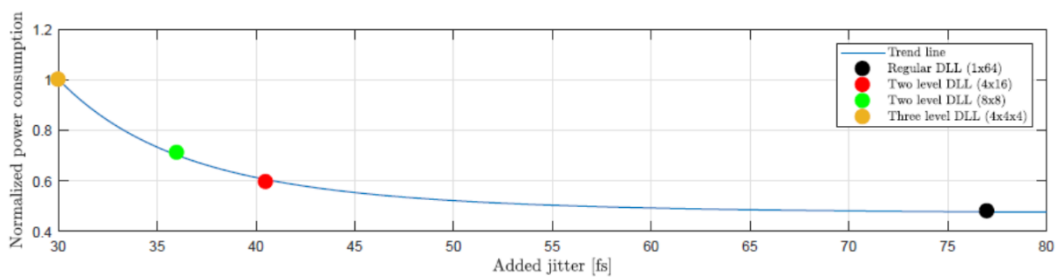
Waveform Sampling Readout – Lessons from the 10's of ps Belle II TOP and toward the fs regime

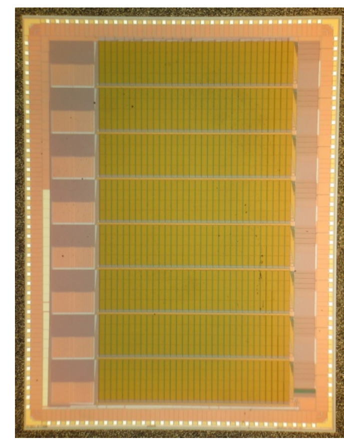




Peter Orel and Gary S. Varner

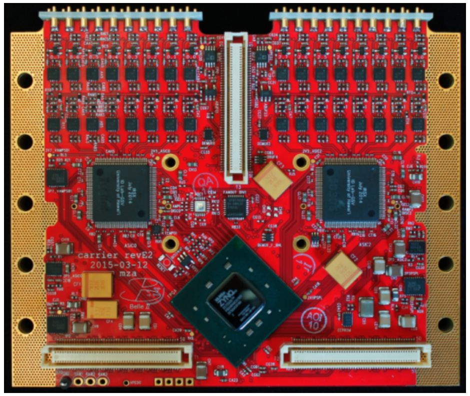
University of Hawai'i

psTiming WS, Torino June 2018

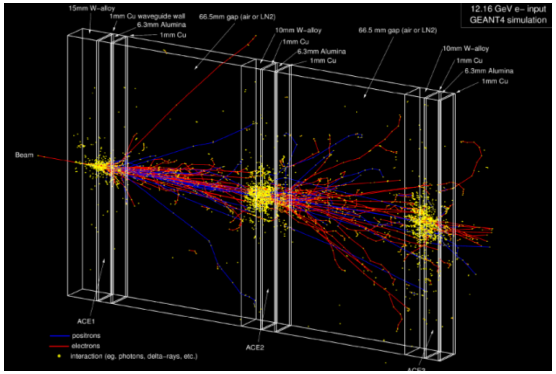


Outline

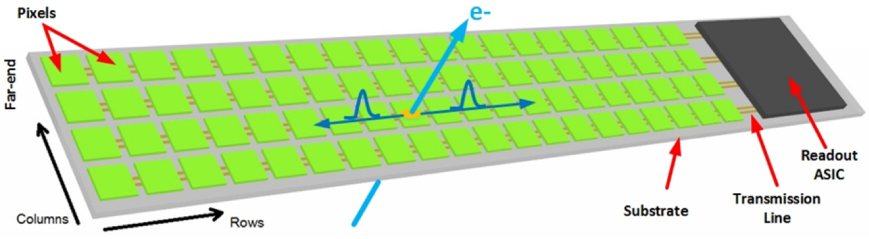
- Belle II Time Of Propagation [10’s of ps]
  - Highly integrated
  - First collisions



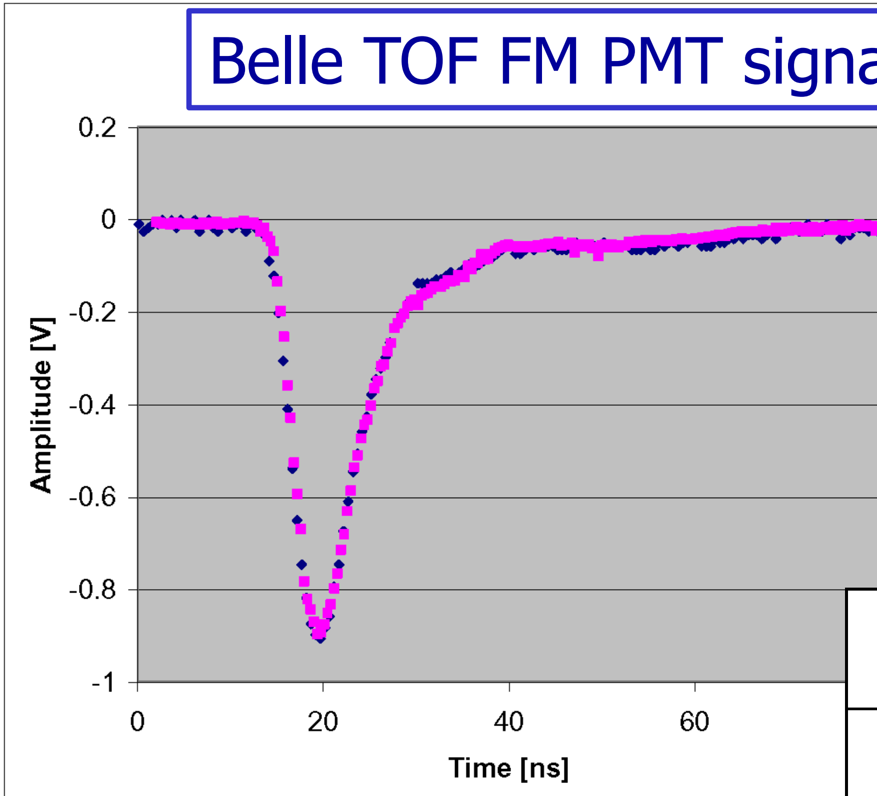
- ACE Calorimeter [few ps]
  - RF prompt component
  - Extension of techniques

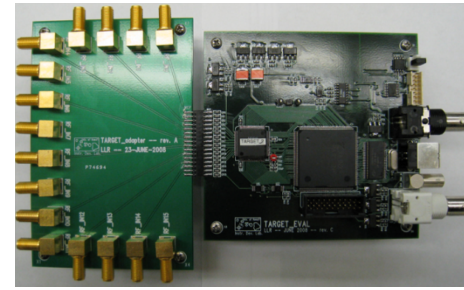


- Strawman Timing Vertexer [100’s fs]
  1. Explore space-time limit
  2. High precision timing **(latest)**
  3. Higher density



An Easily understood Starting Point

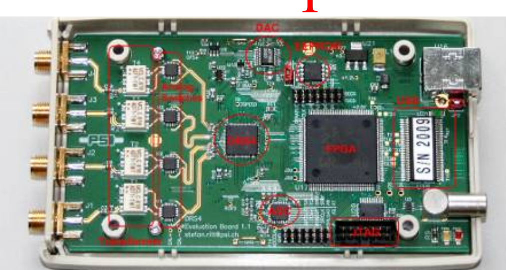


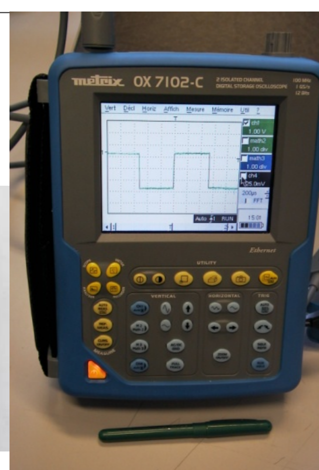


- 2 GSa/s, 1GHz ABW Tektronics Scope
- 2.56 GSa/s LAB

	WFS ASIC	Commercial
Sampling speed	0.1-6 GSa/s	2 GSa/s
Bits/ENOBs	16/9-13+	8/7.4
Power/Chan.	<= 0.05W	Few W
Cost/Ch.	< $10 (vol)	> 100$

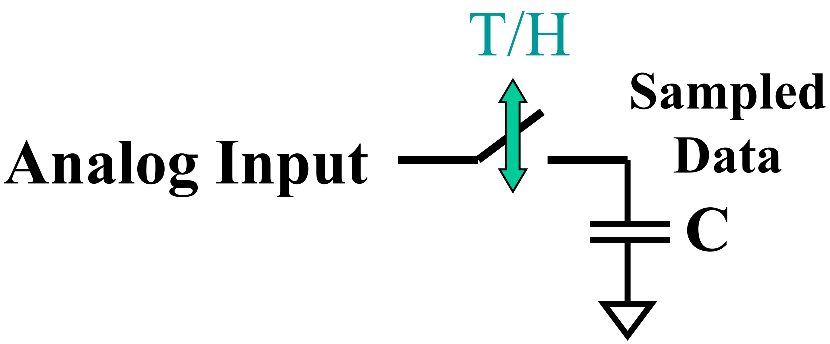
"oscilloscope on a chip"

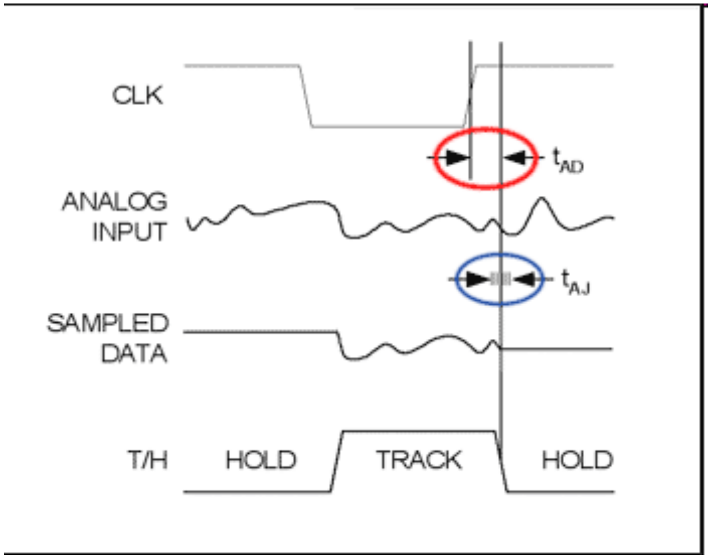




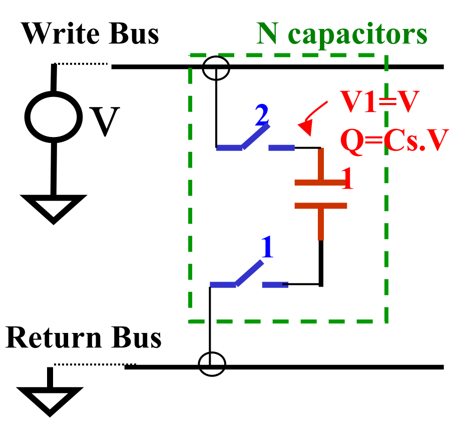
Underlying Technology

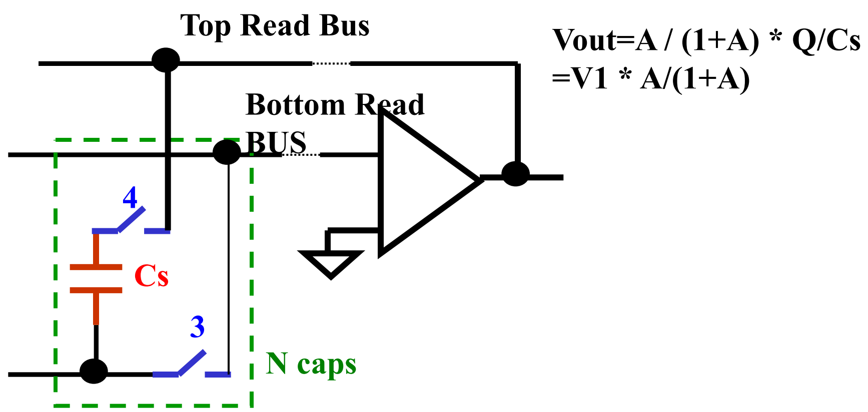
- Track and Hold (T/H)





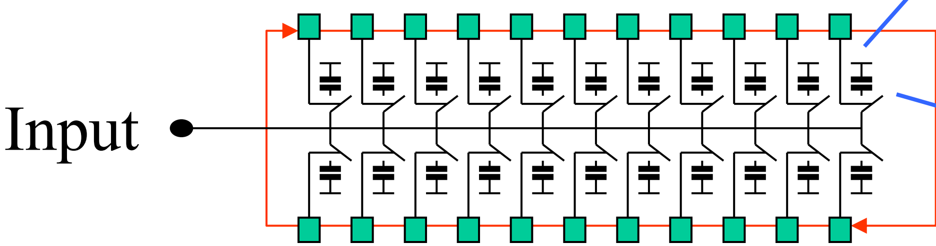
- Pipelined storage = array of T/H elements, with output buffering

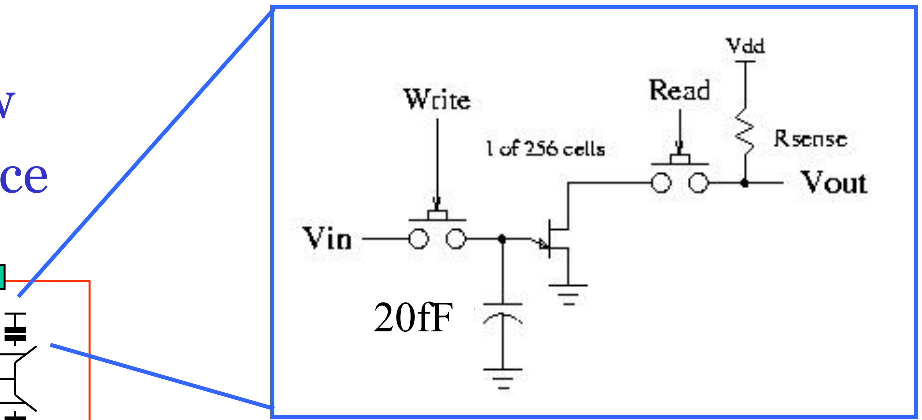




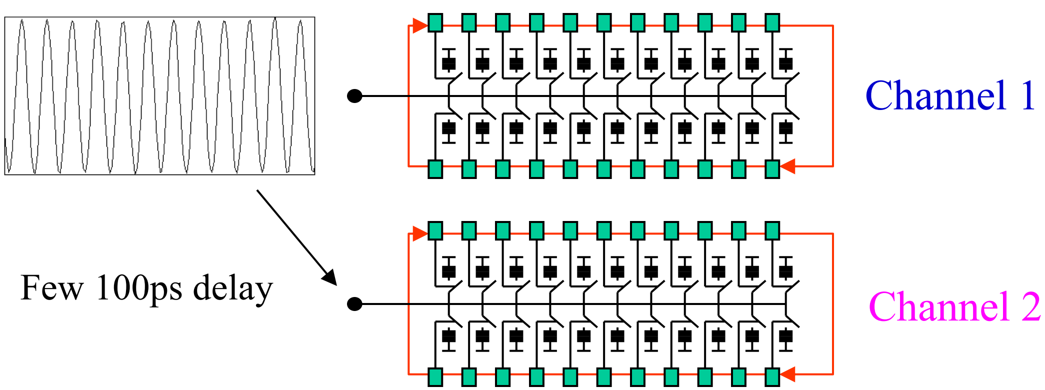
Switched Capacitor Array Sampling

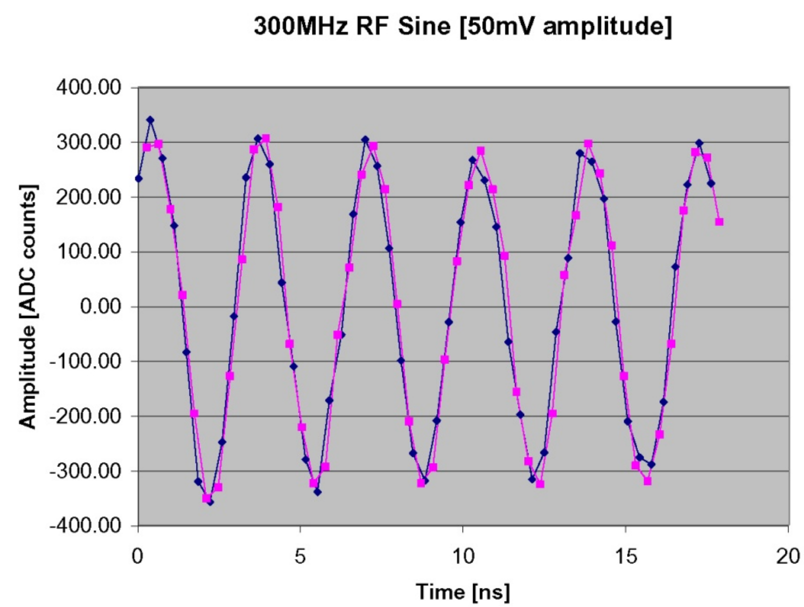
- Write pointer is ~few switches closed @ once



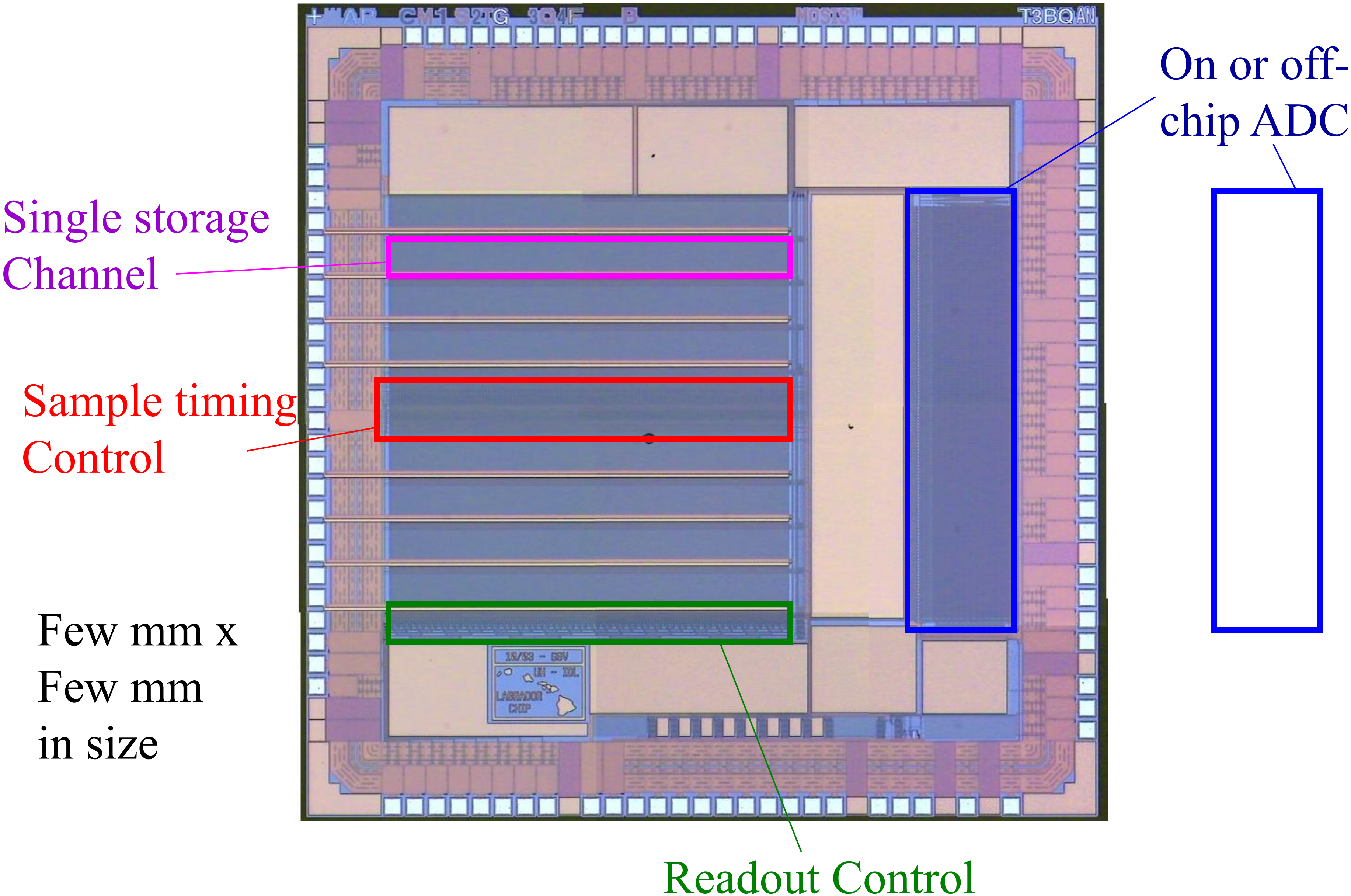


Tiny charge: 1mV ~ 100e^{-}





Basic Functional components

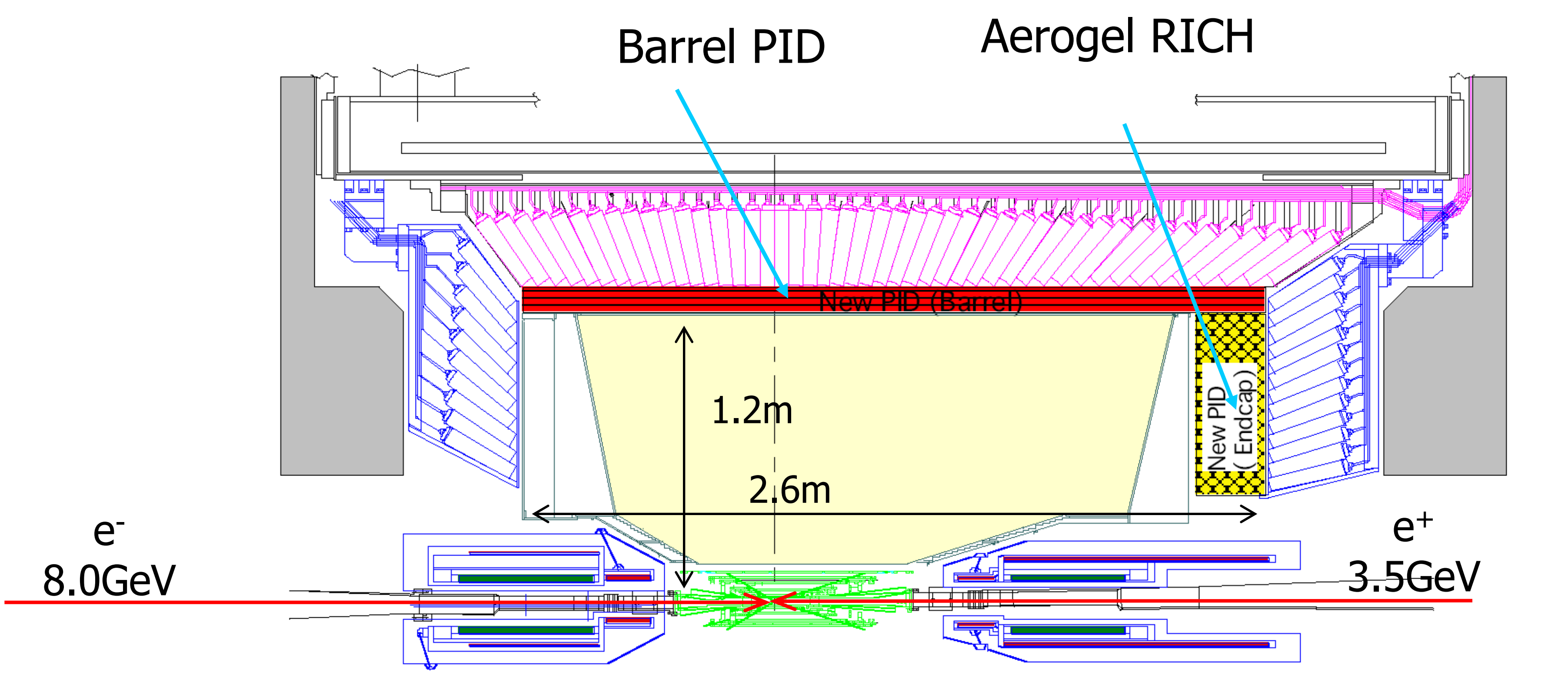


A specific example: Upgraded Belle detector

- PID (π/K) detectors
- Inside current calorimeter
- Use less material and allow more tracking volume

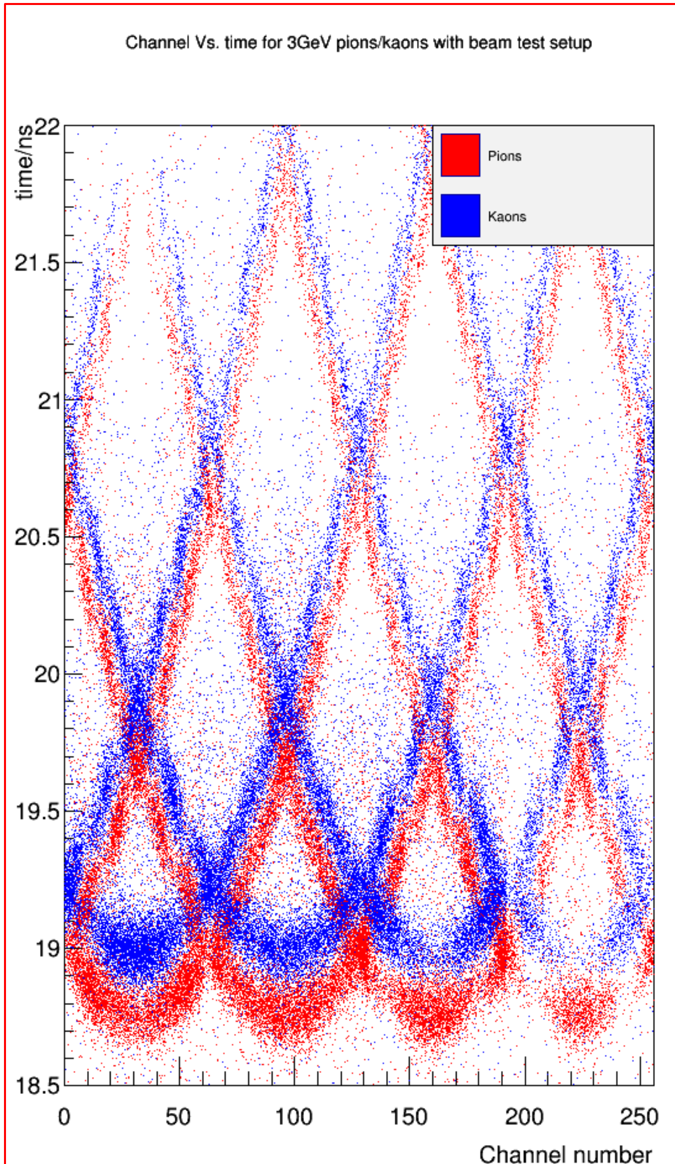
→ Available geometry defines form factor

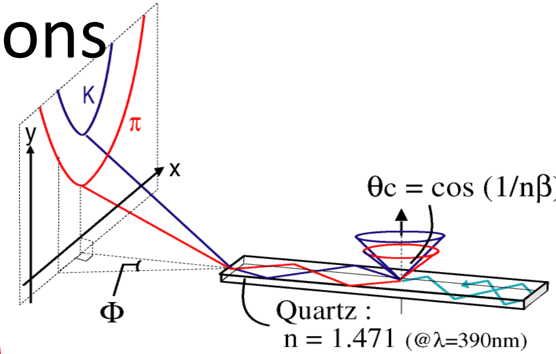
-

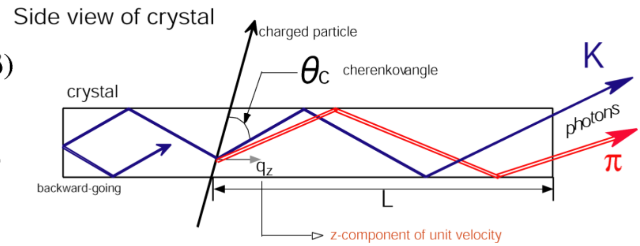


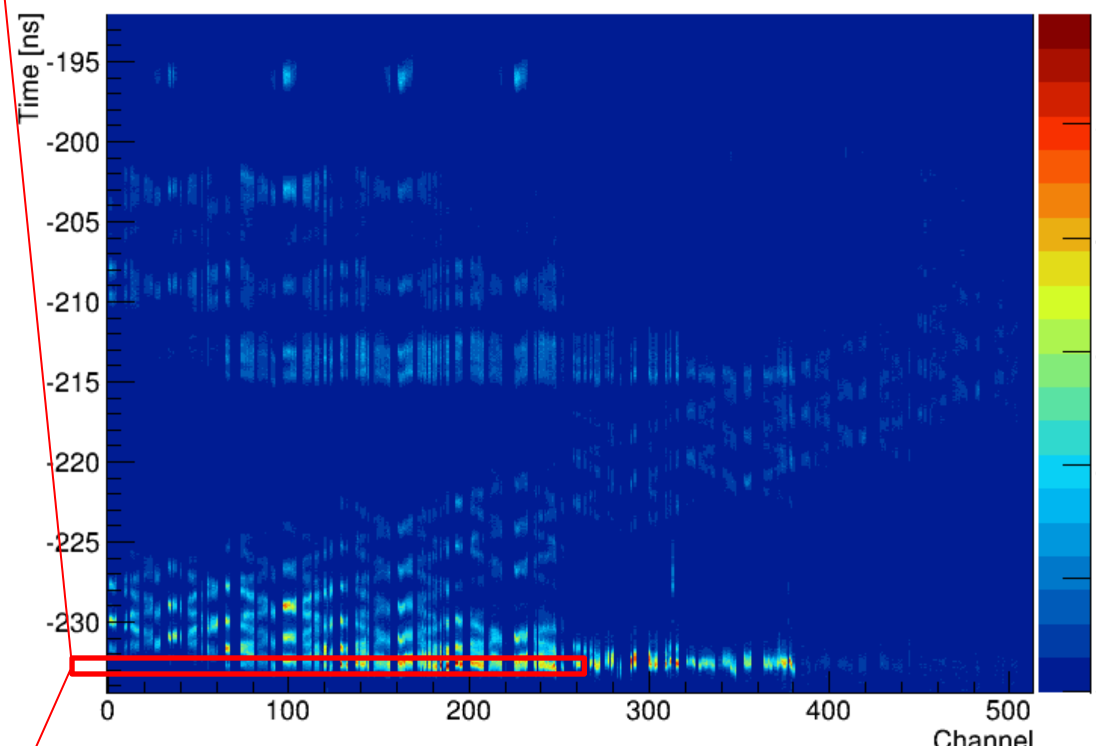
iTOP relativistic velocity

- Space-time correlations







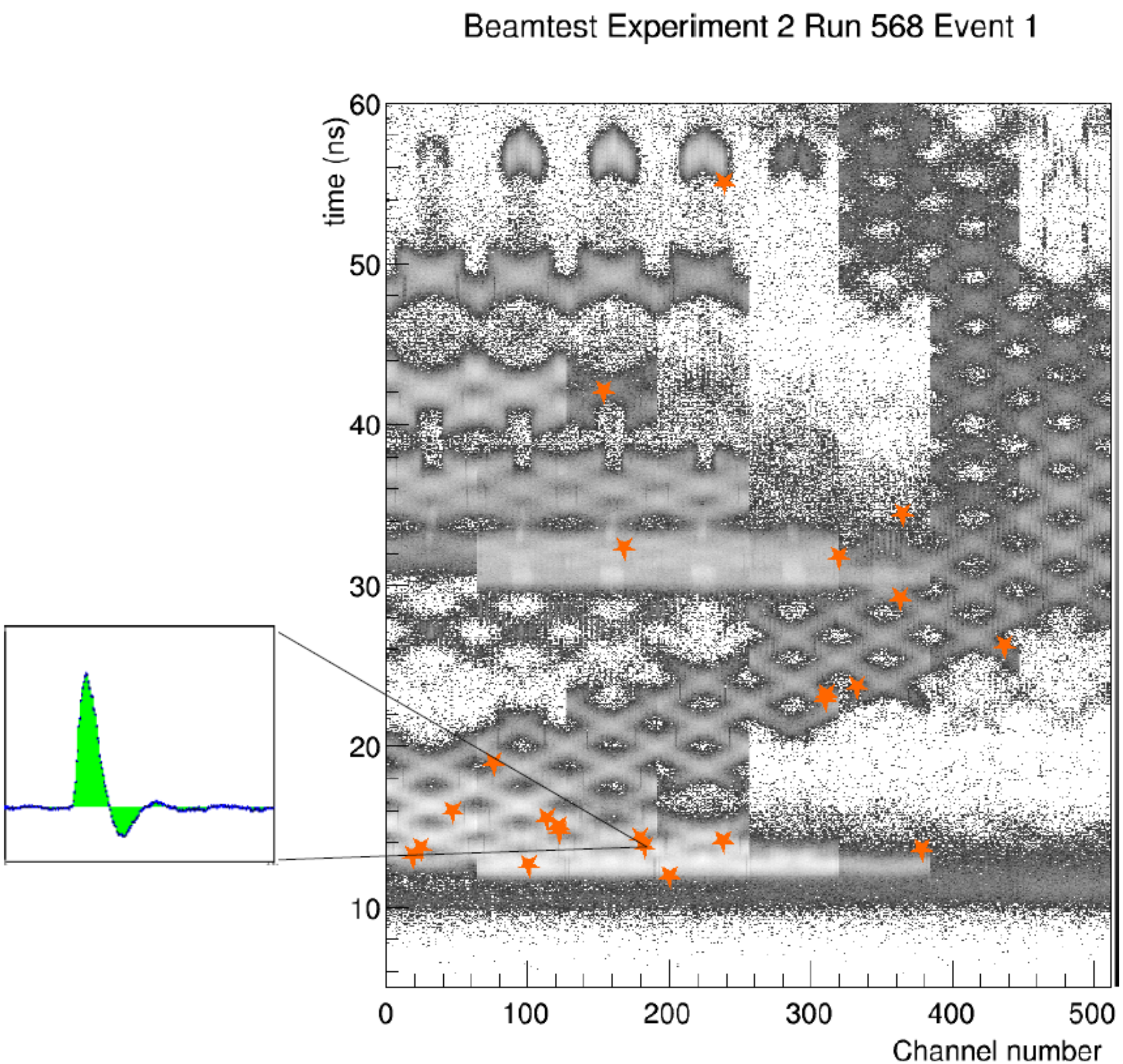


Beam Test Data

These are cumulative distributions

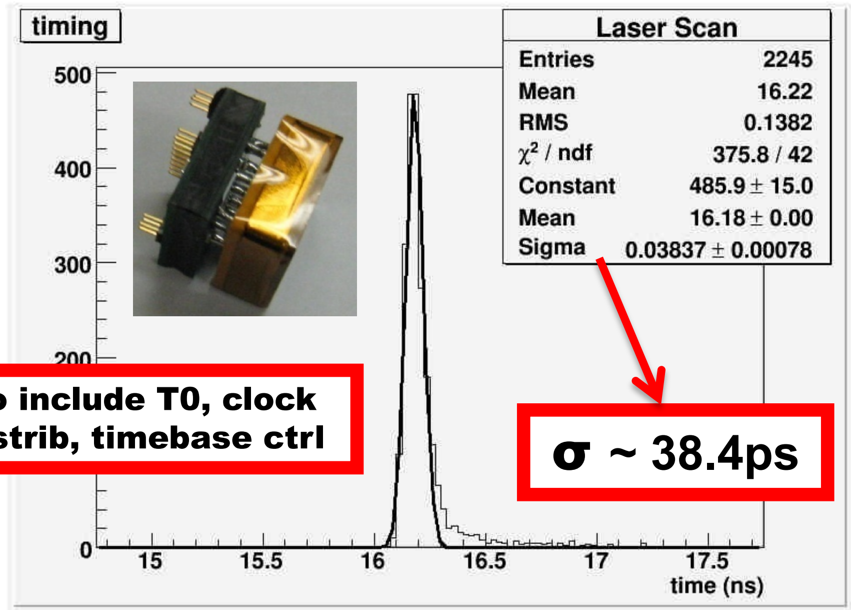
Actual PID is event-by-event

- Test most probable distribution



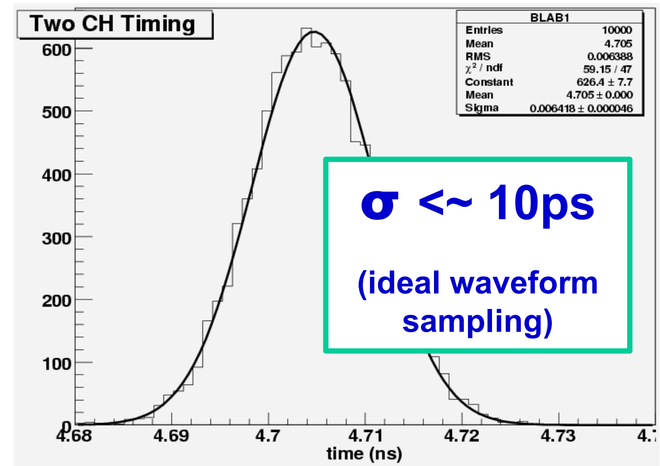
Single photon detection for TOP

- Single photon timing for MCP-PMTs



To include T0, clock distrib, timebase ctrl

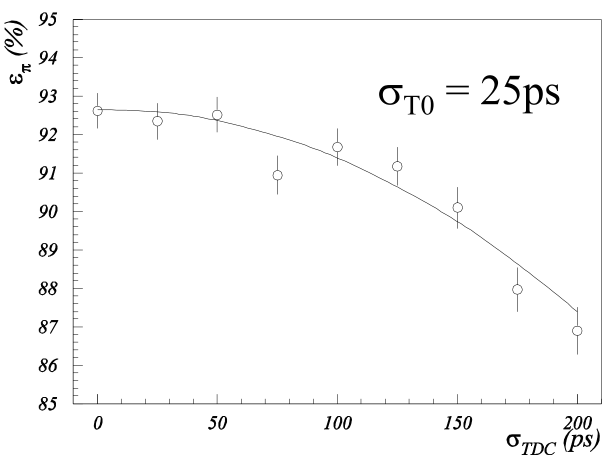
σ ~ 38.4ps

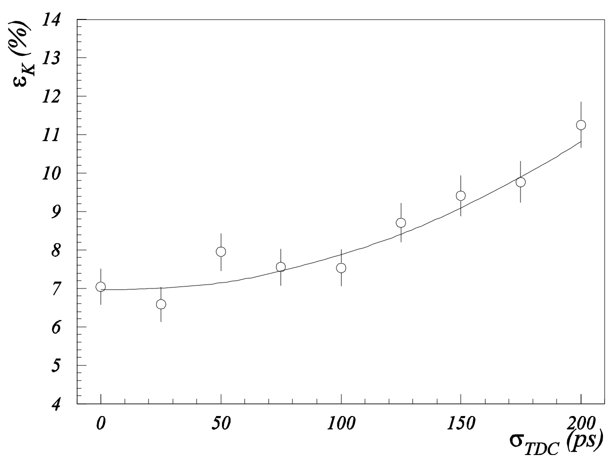


σ <~ 10ps

(ideal waveform sampling)

NIM **A602** (2009) 438



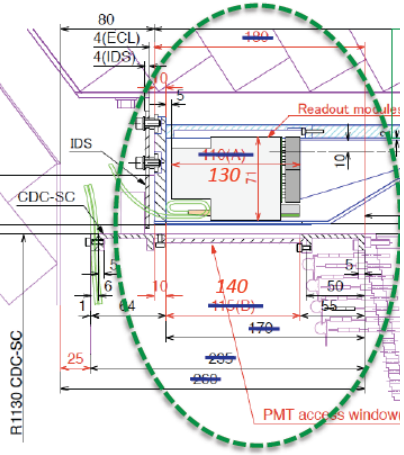


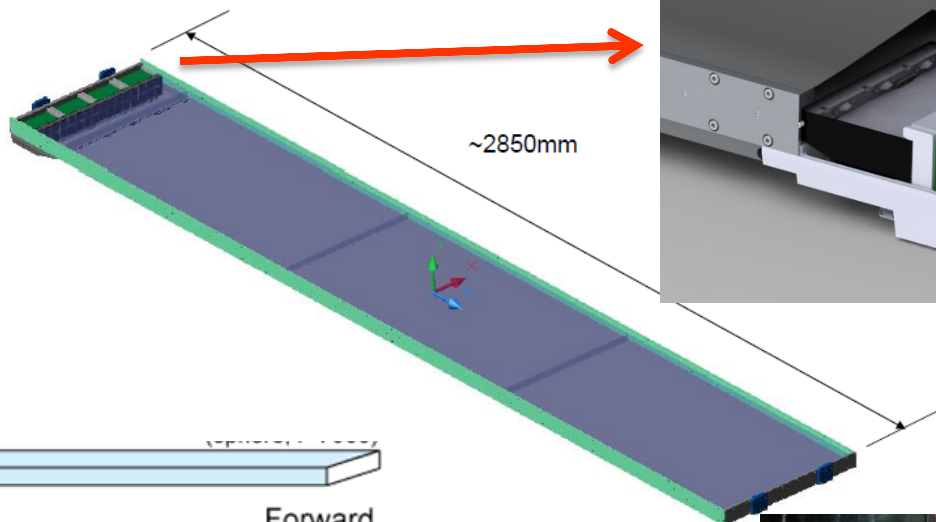
σ <~ 50ps target

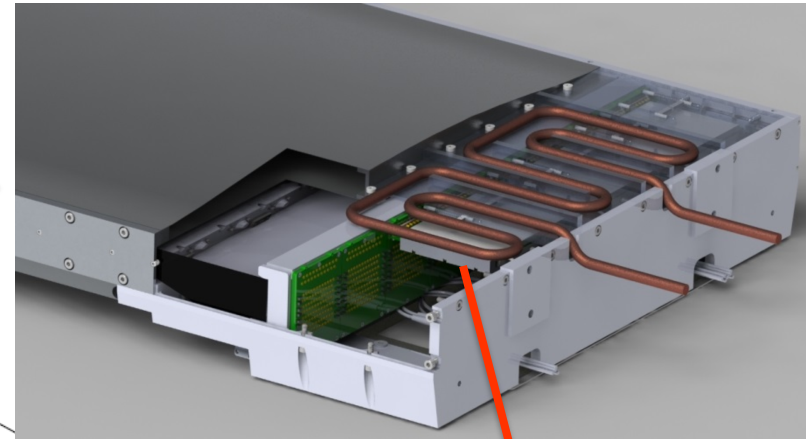
NOTE: this is single-photon timing, **not** event start-time "T_0"

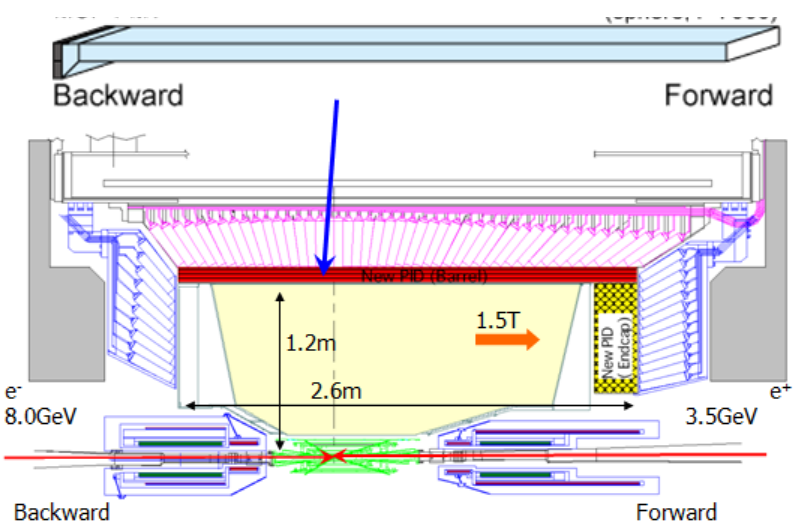
Highly integrated services

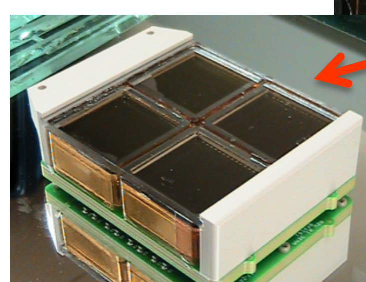
- A severely constrained space

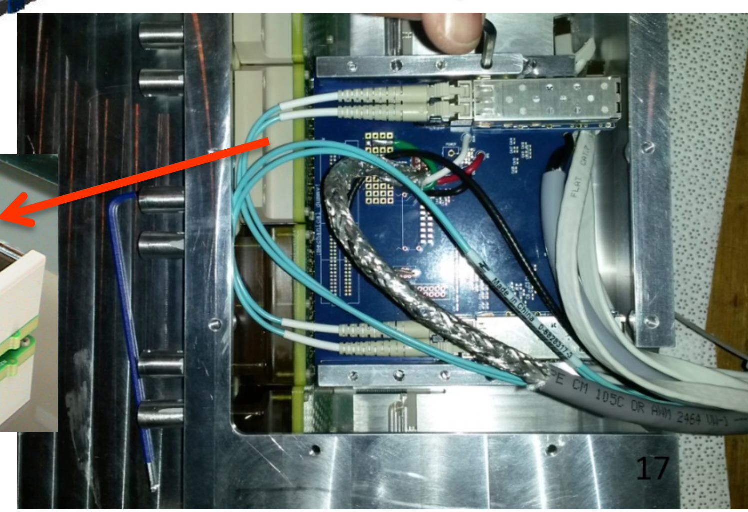










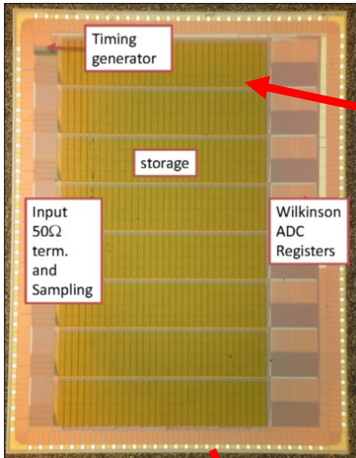


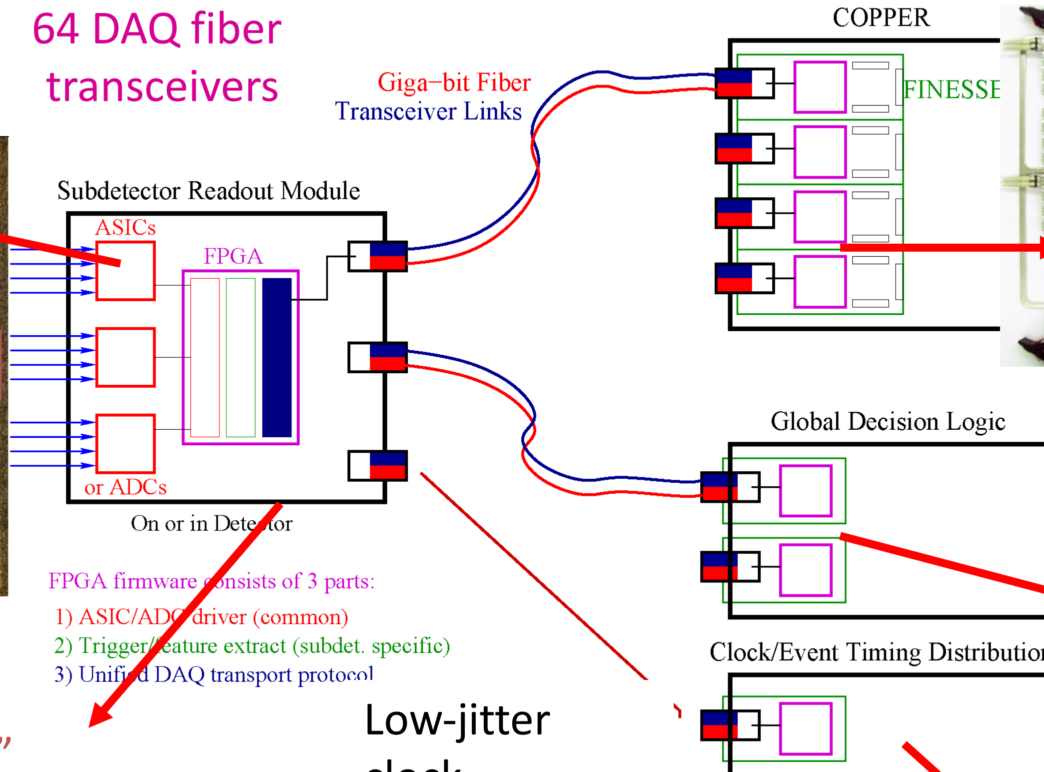
imaging TOP Readout (FDIRC proto)

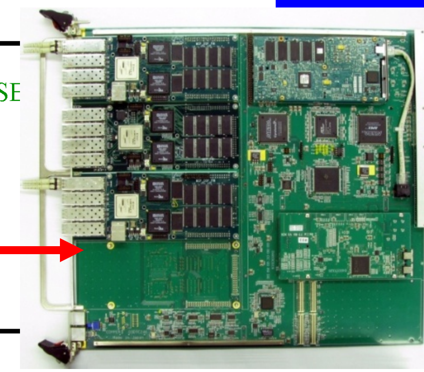
Belle II

Waveform sampling ASIC

64 DAQ fiber transceivers





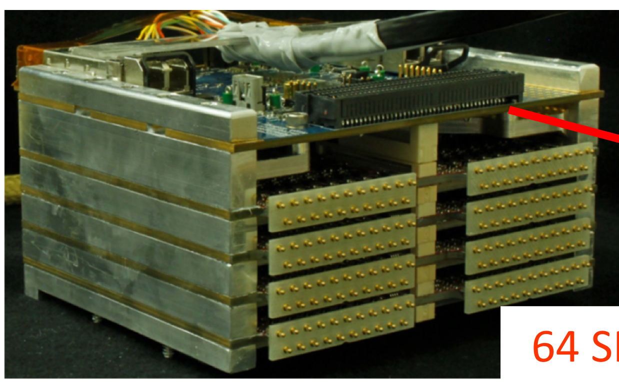


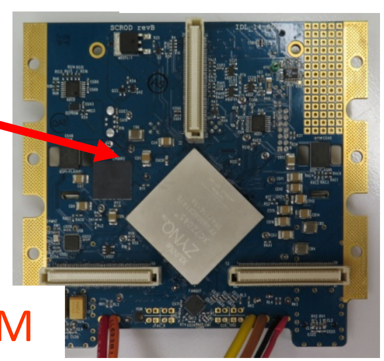
64 FINESSE
16 COPPER

8k channels
1k 8-ch. ASICs
64 "board stacks"

2x UT3 Trigger modules

Low-jitter clock





64 SRM

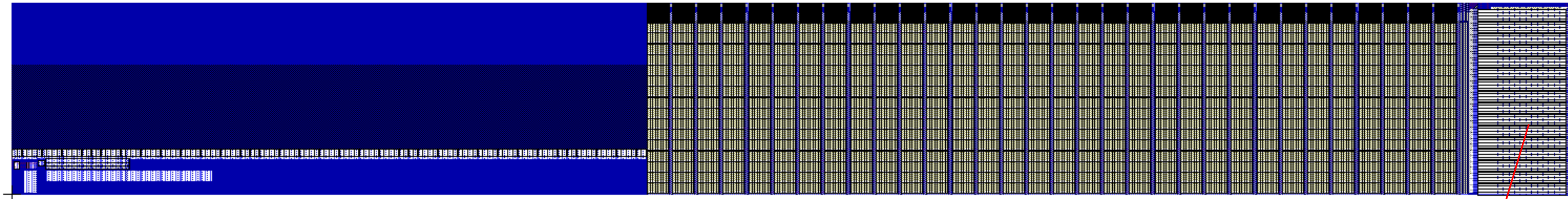
Clock, trigger, programming module (FTSW)

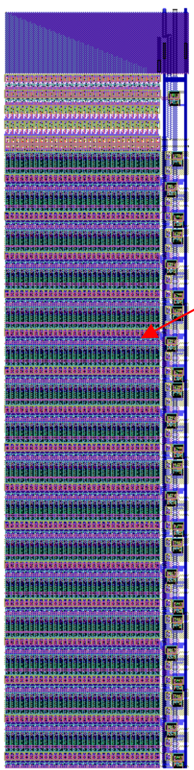
8 FTSW

IRSX Single Channel

- Sampling: 128 (2x 64) separate transfer lanes

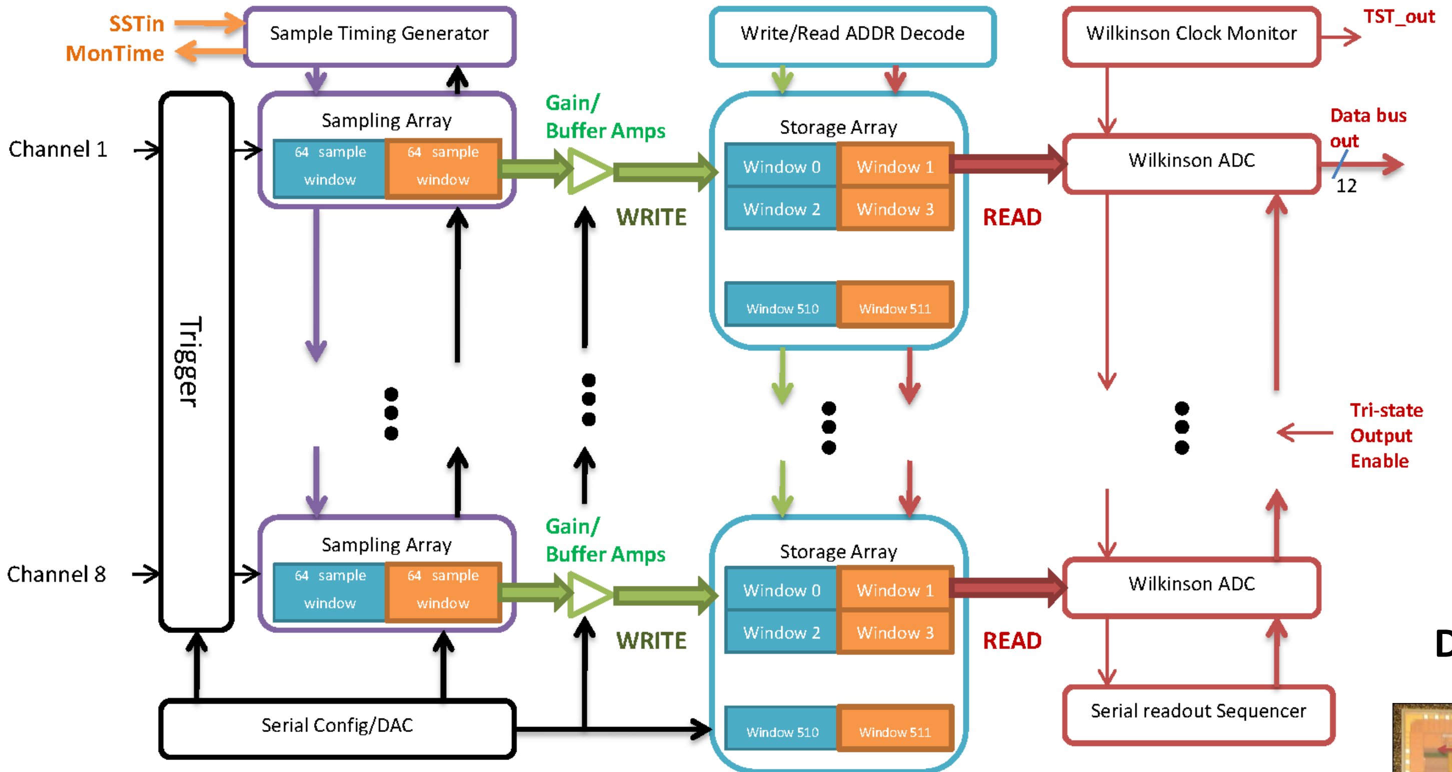
Recording in one set 64, transferring other (“ping-pong”)



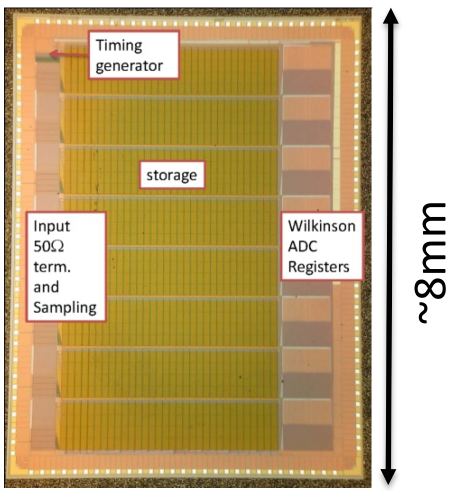


- Concurrent Writing/Reading
- Only 128 timing constants
- Storage: 64 x 512 (512 = 8 * 64)
- Wilkinson (64x1): was (32x2)
  - 64 conv/channel

IRSX ASIC Overview



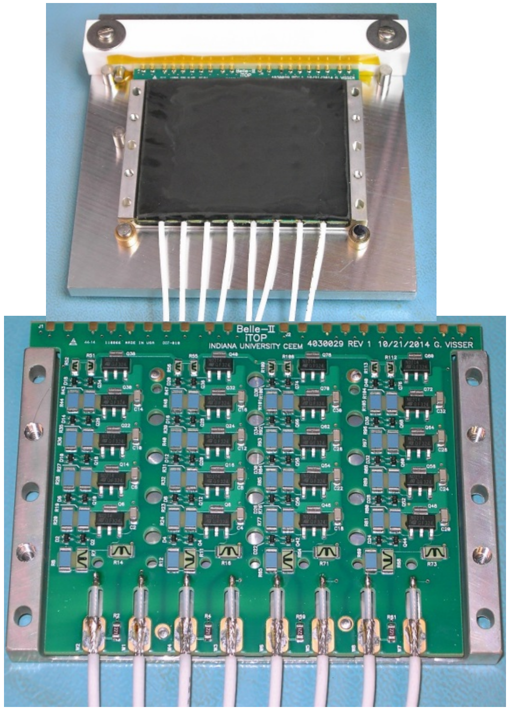
Die Photograph

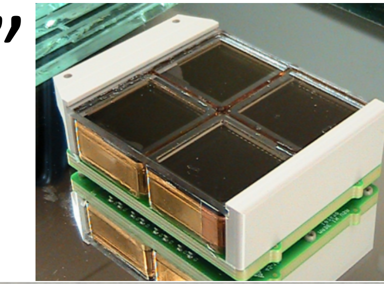


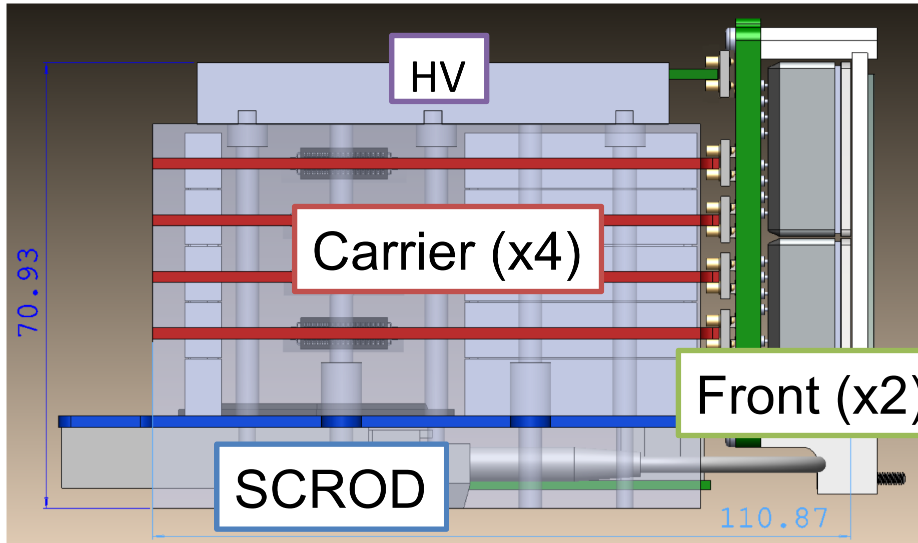
- **8 channels per chip @ 2.8 GSa/s**
- **Samples stored, 12-bit digitized in groups of 64**
- **32k samples per channel (11.6us at 2.8GSa/s)**
- **Compact ASICs implementation:**
  - **Trigger comparator and thresholding on chip**
  - **On chip ADC**
  - **Multi-hit buffering**

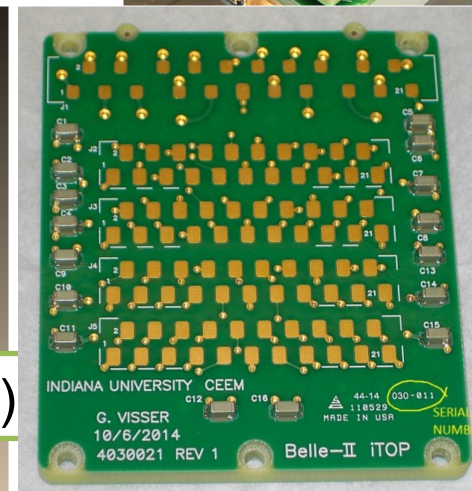
iTOP Readout "boardstack"

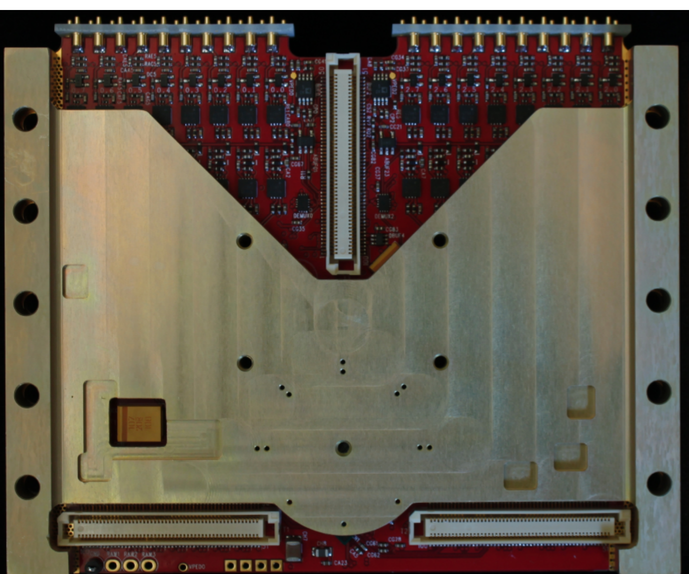
(1 of 4 per TOP Module)

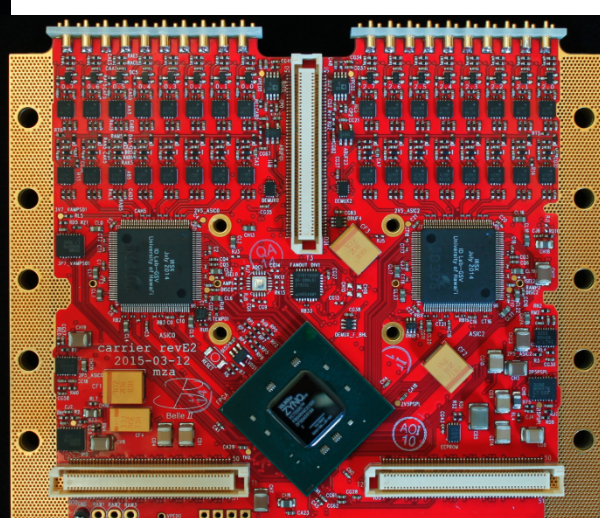


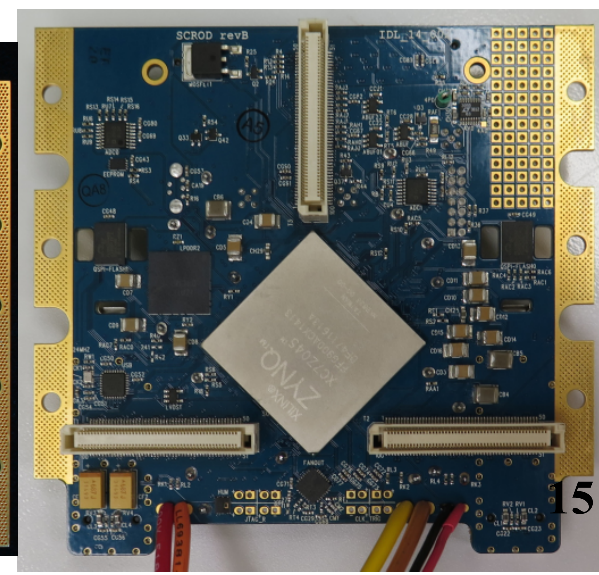




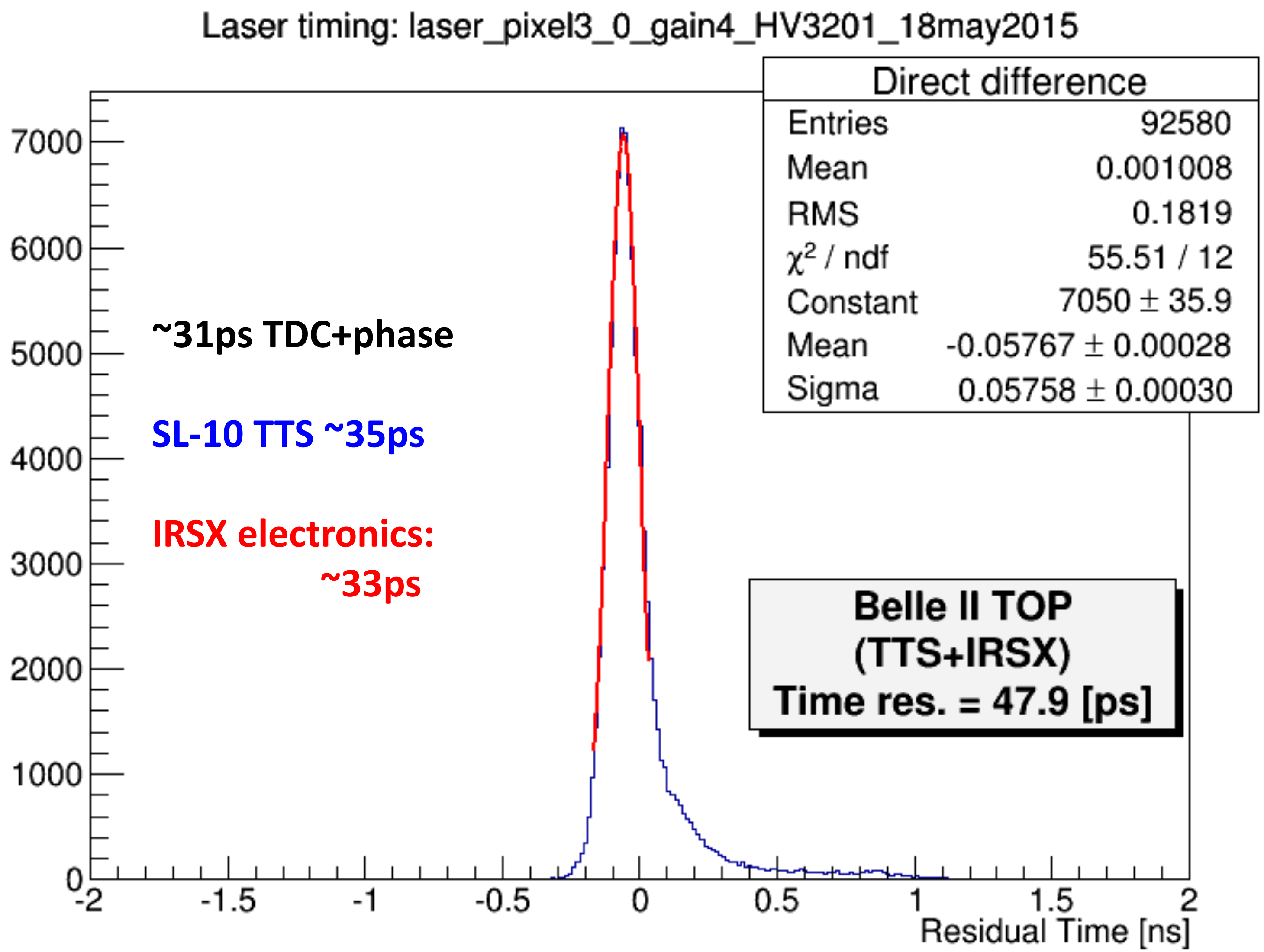








Production single photon testing

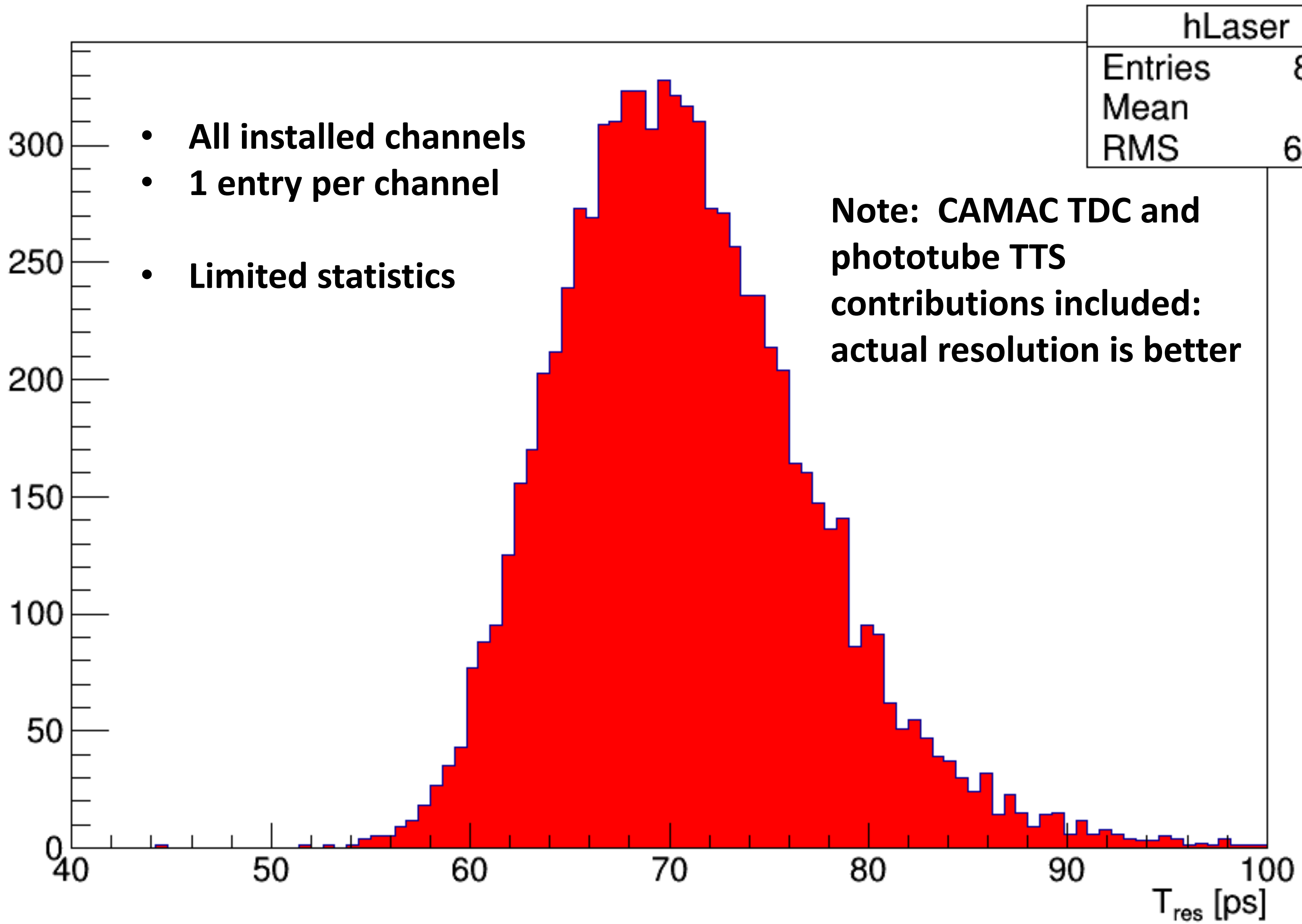


Production – initial single photon timing

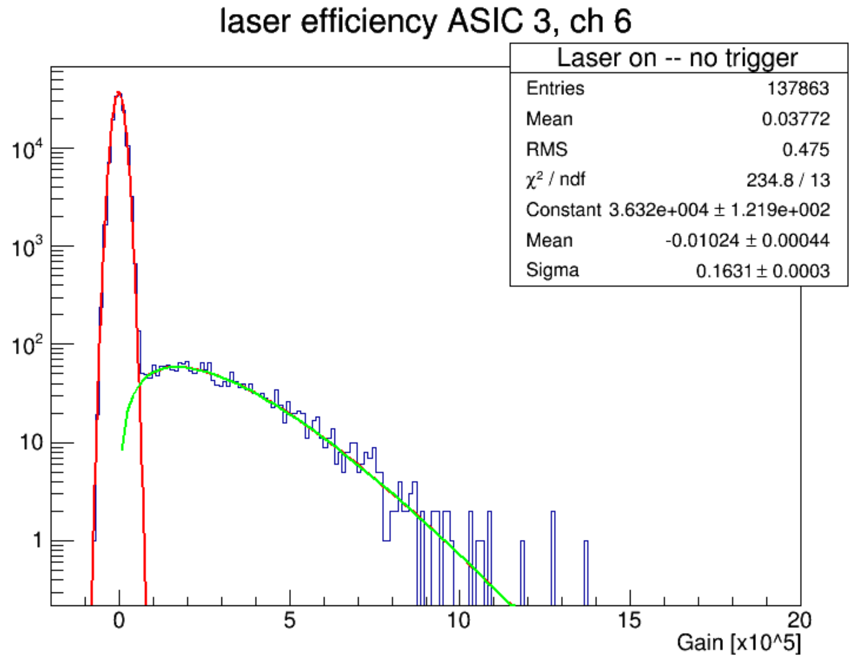
- **All installed channels**
- **1 entry per channel**

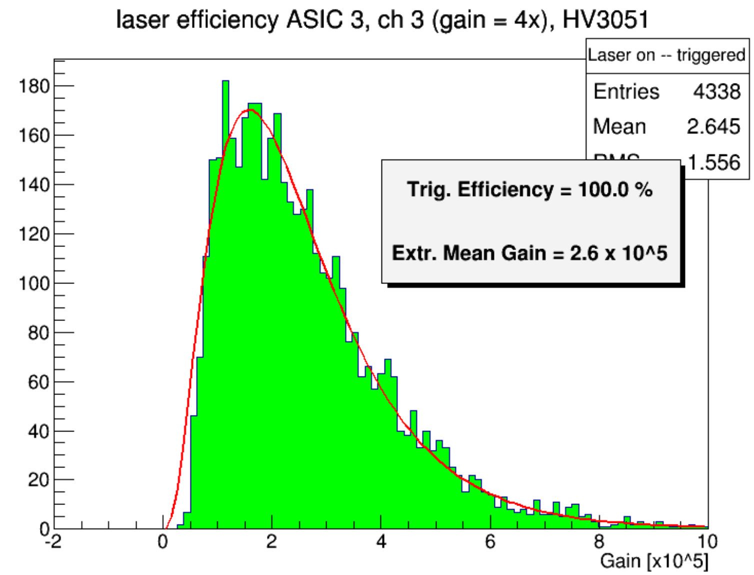
- **Limited statistics**

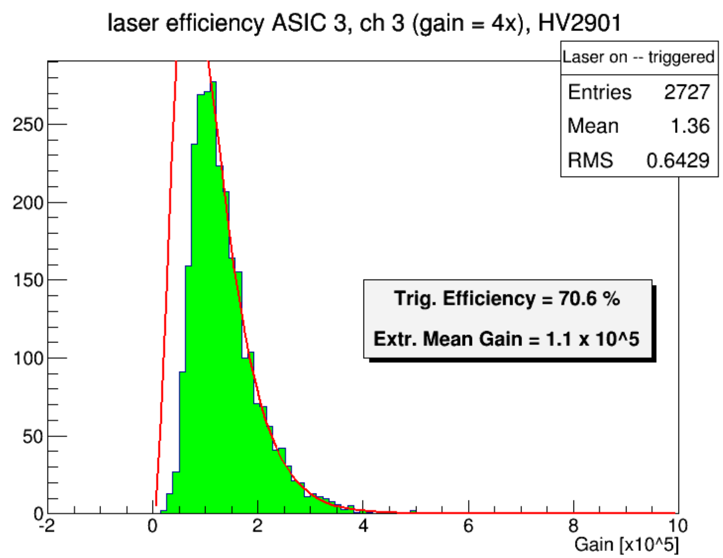
Note: CAMAC TDC and phototube TTS contributions included: actual resolution is better

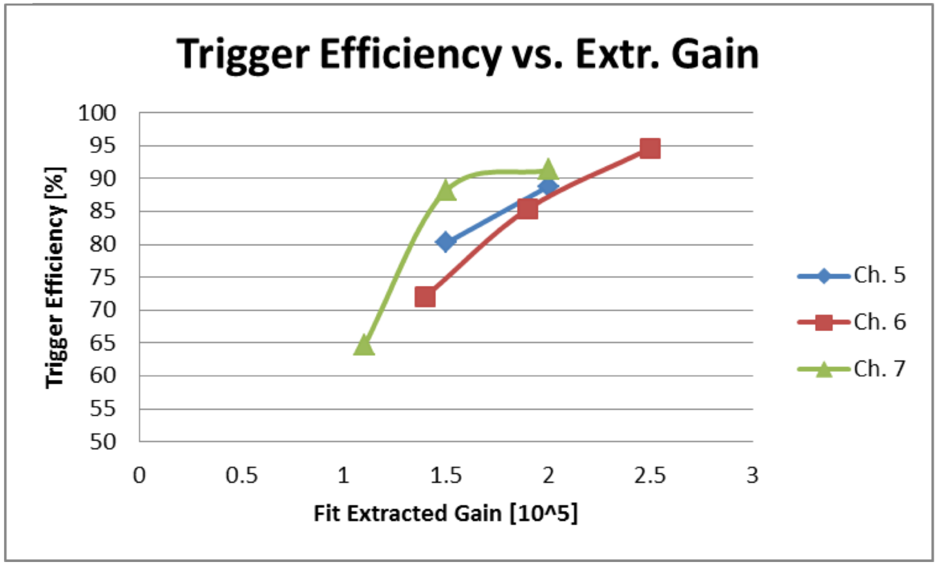


If single photon, why bother?



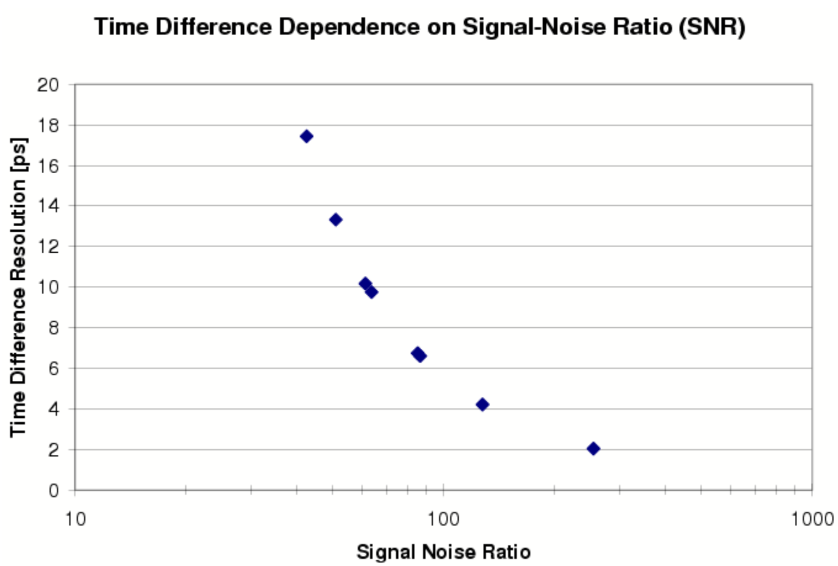






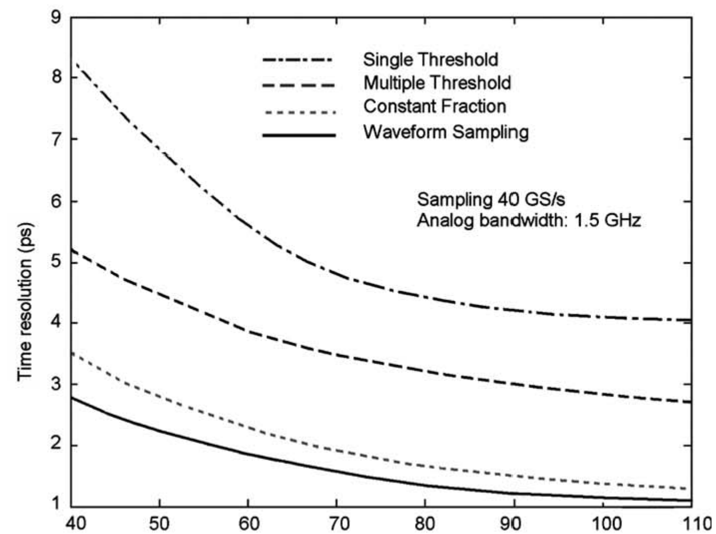
Technology has room to improve

1GHz analog bandwidth, 5GSa/s



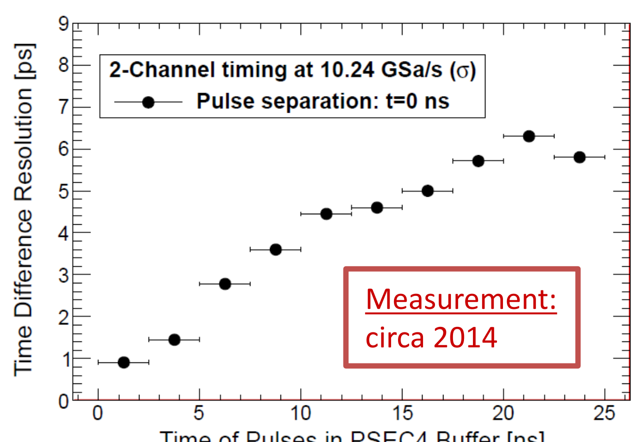
G. Varner and L. Ruckman
NIM A**602 (2009) 438-445**.

Simulation includes detector response



J-F Genat, G. Varner, F. Tang, H. Frisch
NIM A**607 (2009) 387-393**.

E. Oberla, J-F Genat,
H. Grabas, H. Frisch,
K. Nishimura, G. Varner
NIM A**735 (2014) 452-461**.



Extending to 1ps and lower, with advanced calibration techniques

A very different kind of Calorimeter

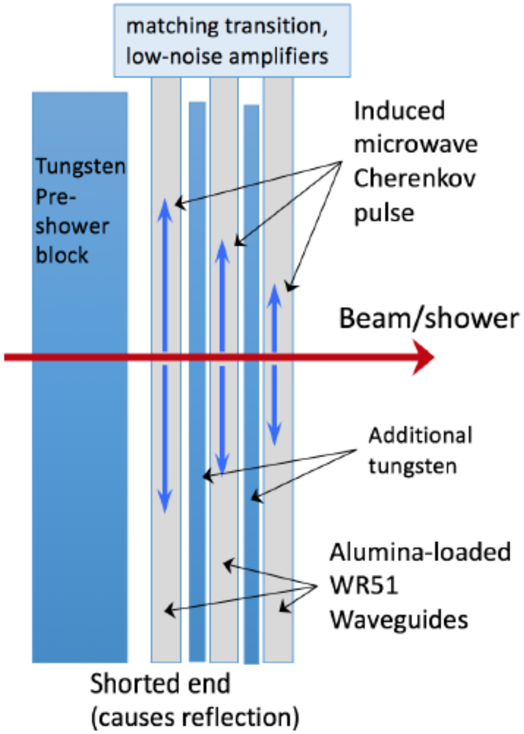
Askaryan Calorimeter Exp (ACE)

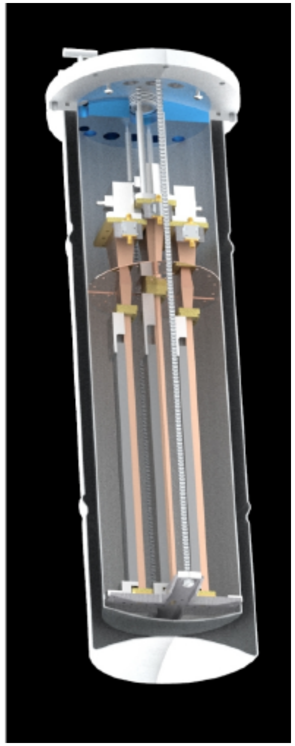
Radio (mm wave)

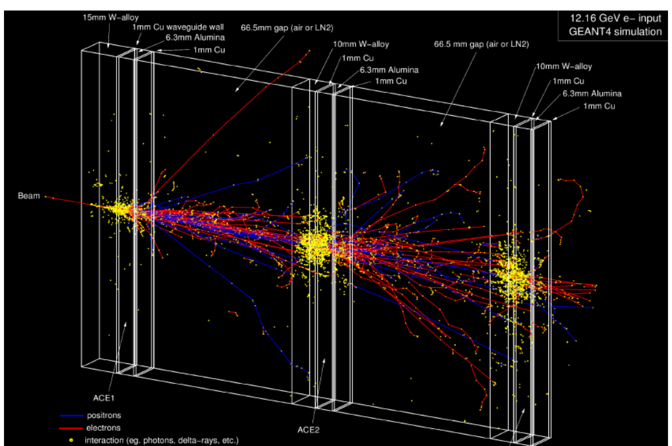
arXiv:1708:01798

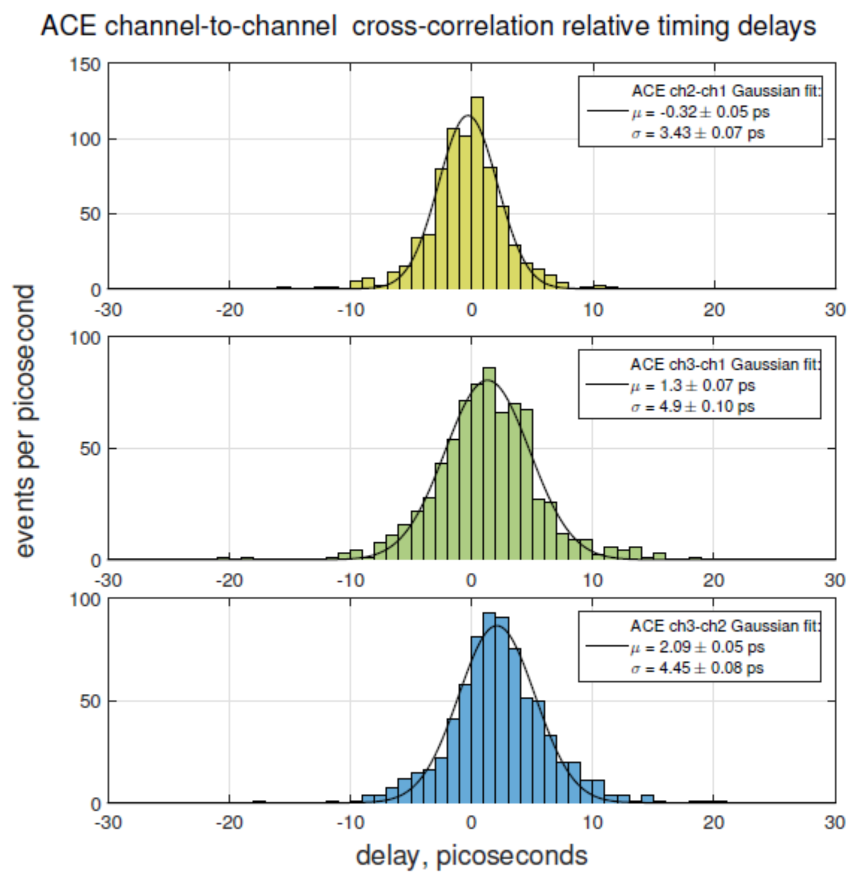
2.3ps intrinsic timing resolution

(SLAC ESTB measurement)

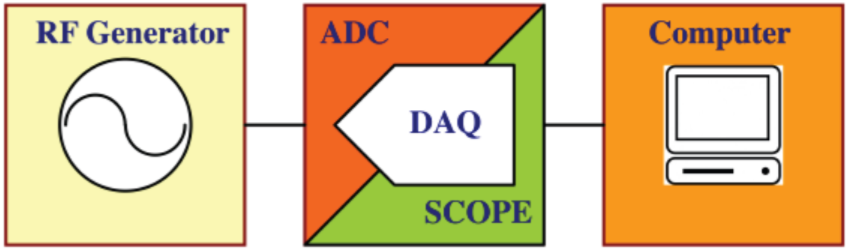






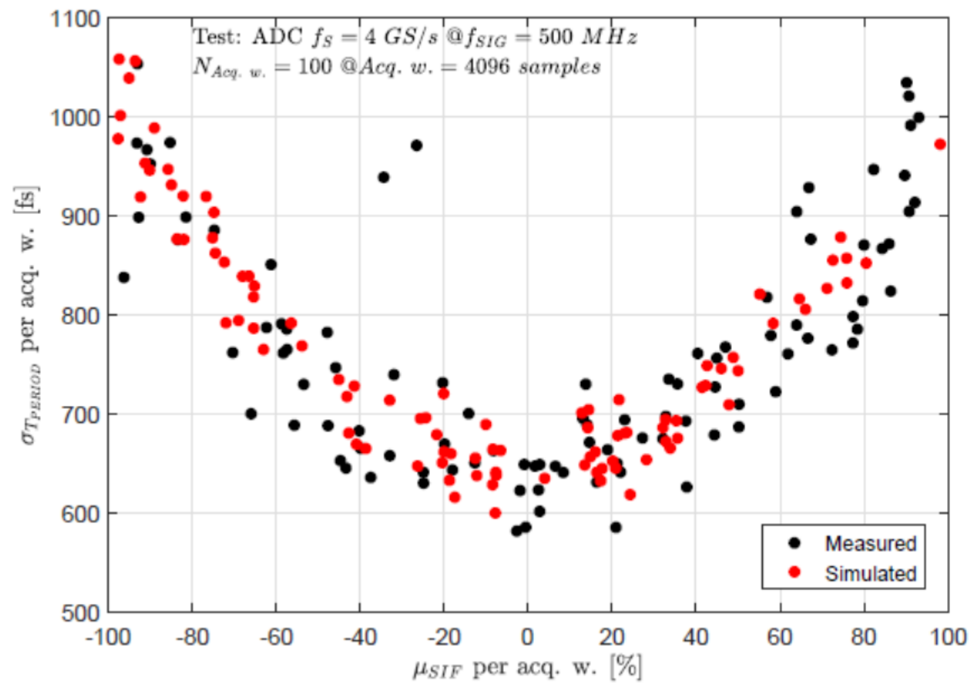


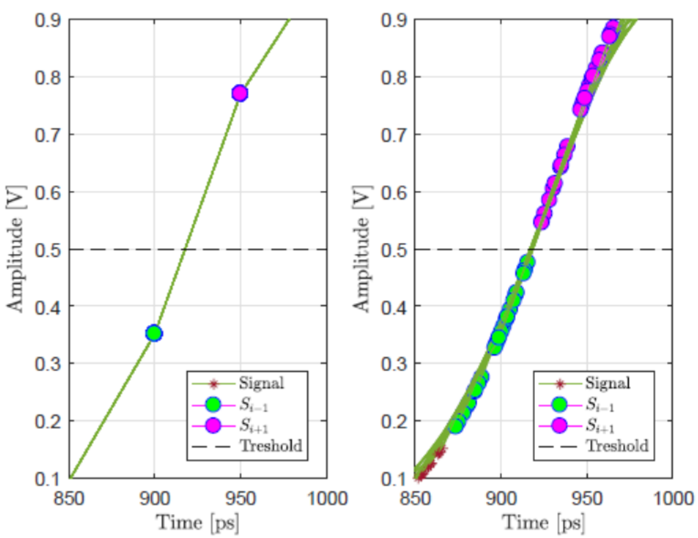
Understanding waveform sampling limits



DAQ	f_{SIG}	Measured $\sigma_{T_{PER}}$	Simulated $\sigma_{T_{PER}}$
SCO1	$3\ GHz$	$1.78\ ps$	$2.96\ ps$
SCO1	$6\ GHz$	$2.28\ ps$	$3.03\ ps$
SCO2	$3\ GHz$	$1.38\ ps$	$1.42\ ps$
SCO2	$4\ GHz$	$1.68\ ps$	$1.58\ ps$
SCO3*	$400\ MHz$	$5.68\ ps$	$5.86\ ps$
SCO3*	$500\ MHz$	$4.27\ ps$	$5.75\ ps$

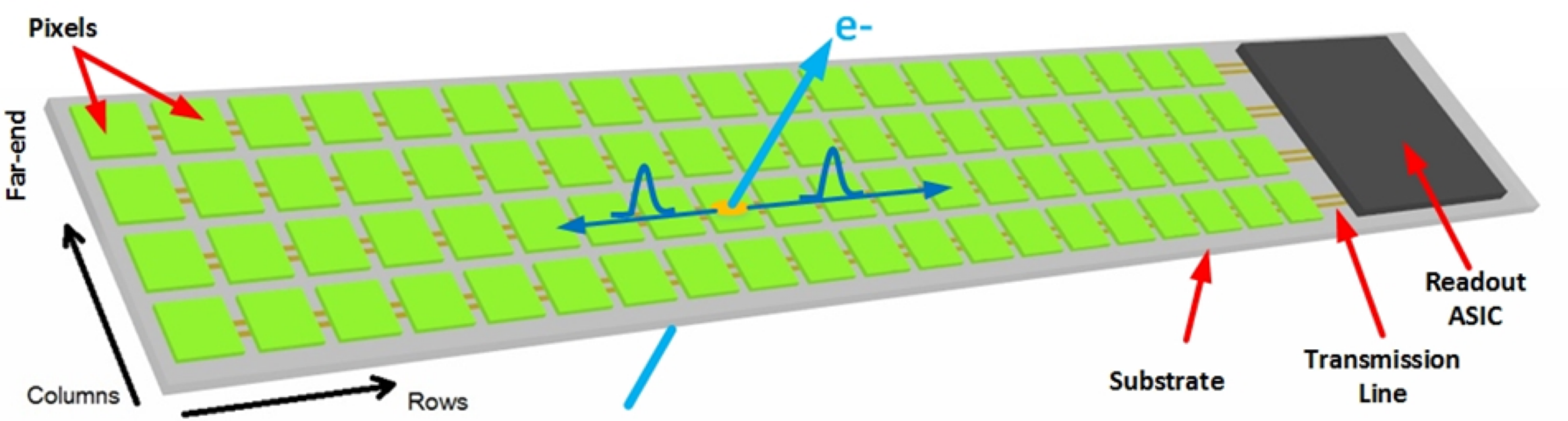
* Signal amplitude equal to $0.475\ Vpp$.





Detailed simulation model developed to allow exploration of phase space – first need to verify results

What would it take?



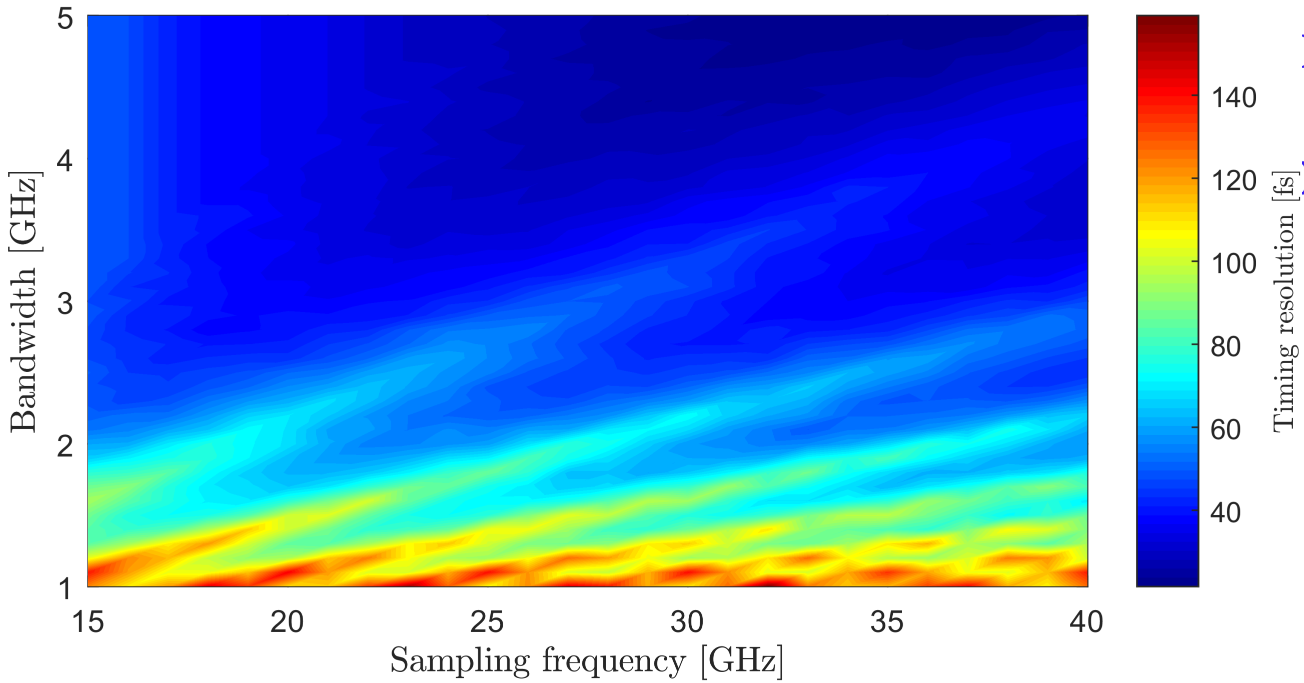
- Micron spatial pixel resolution (using timing)

→ Fast timing brings many benefits:

- *Minimal pile-up (fast clearing)*
- *Improved event timing (direct T0 for TOF/TOP measurements)*

Pushing to the femtosecond regime

Pushing sampling speed and analog bandwidth

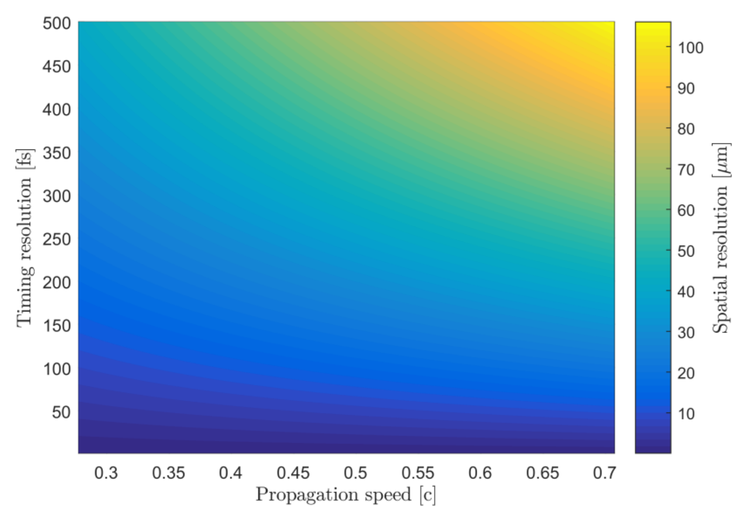


P. Orel, G. Varner
and P. Niknejadi
NIM A**857 (2017) 31-41**.

And pushing the **space-time limit**
(new type of PID or DIRC devices?)

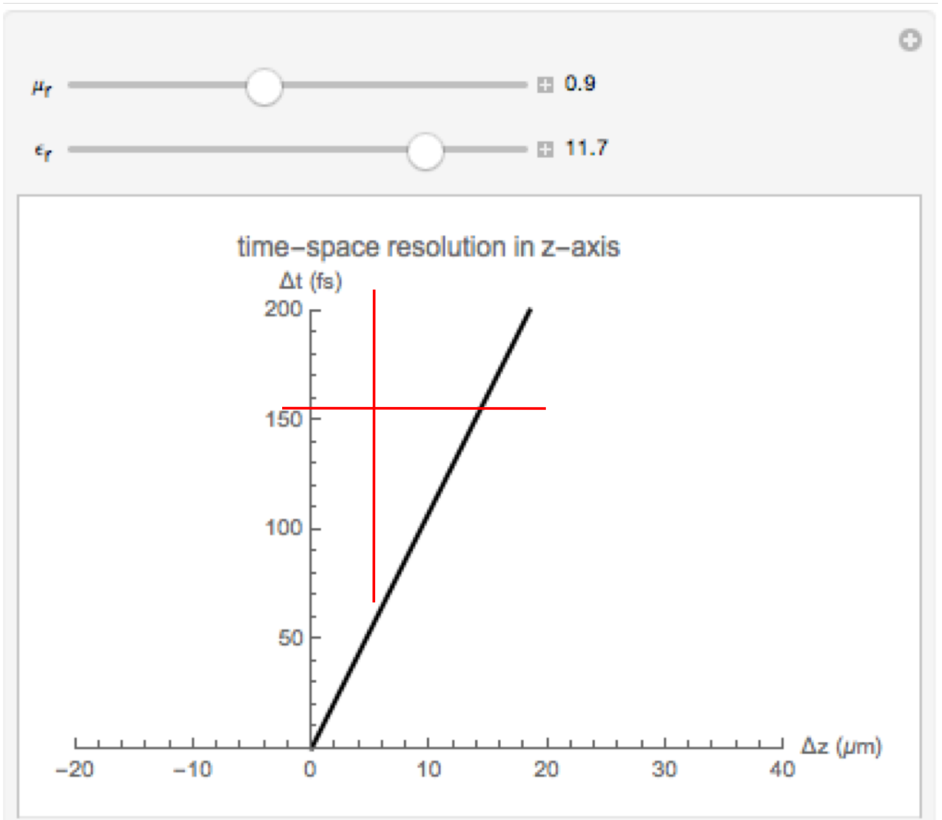
P. Orel and G. Varner

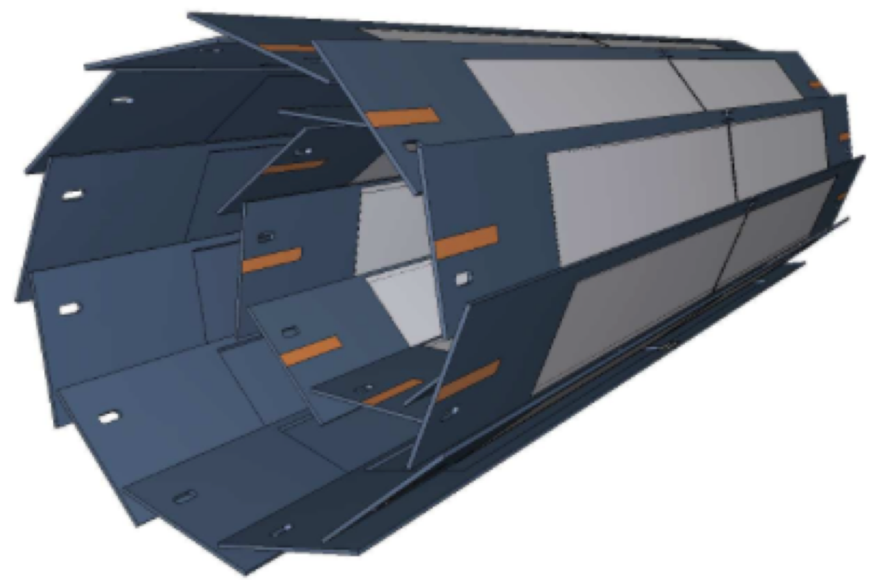
IEEE Trans. Nucl. Sci. **64 (2017) 1950-1962**.



Exploration of the space-time limit

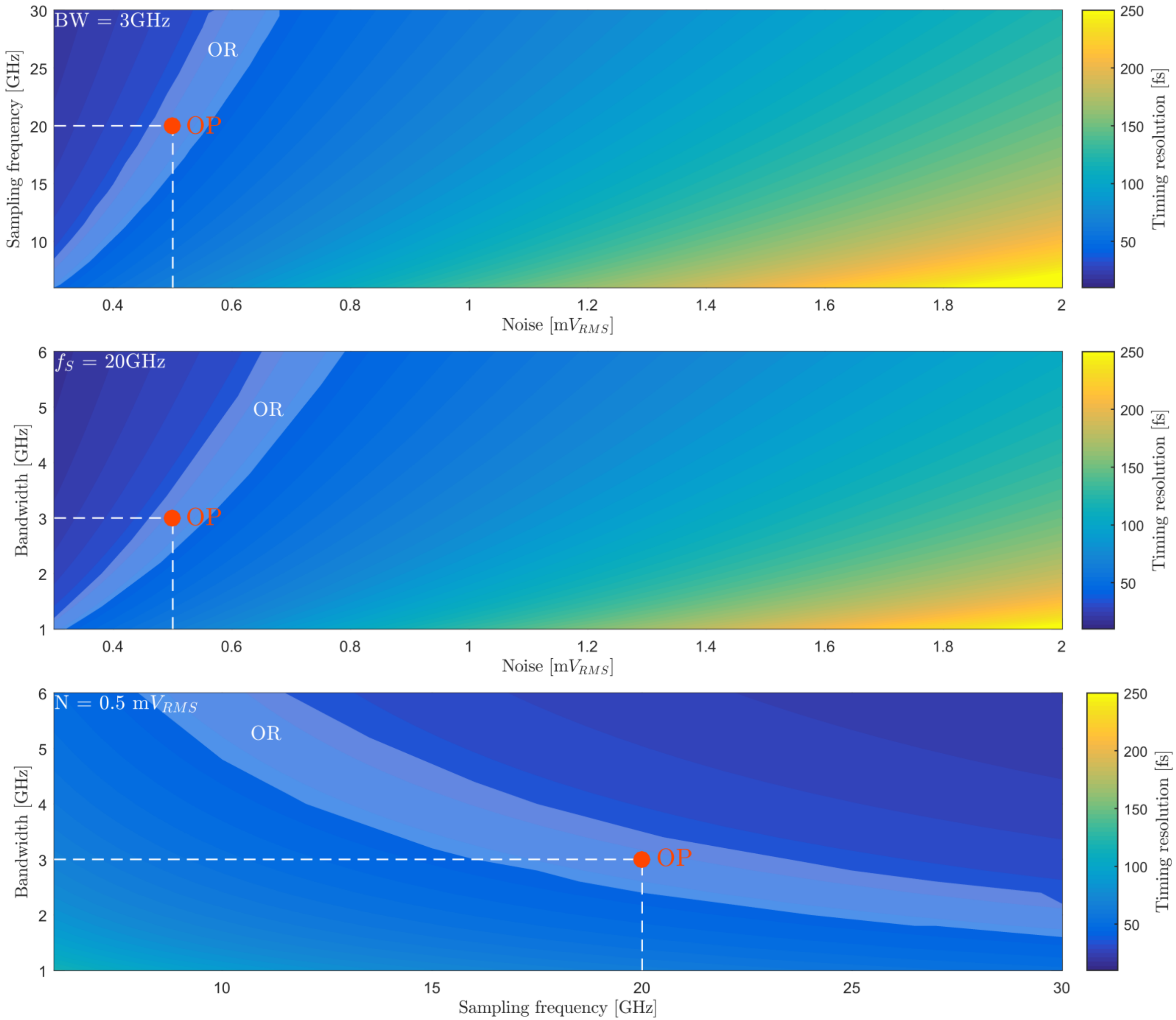
-Sampling at high sampling rate and high bandwidth
-Resolve small distances
Current Goals: Spatial resolution of 10μm in z and 20μm in rφ
In Silicon 10μm in z corresponds to timing resolution of about 100fs
20μm in rφ will depend on the SNR





Pixel detector (PDX) at SuperKEKB

Performance Parameter Space



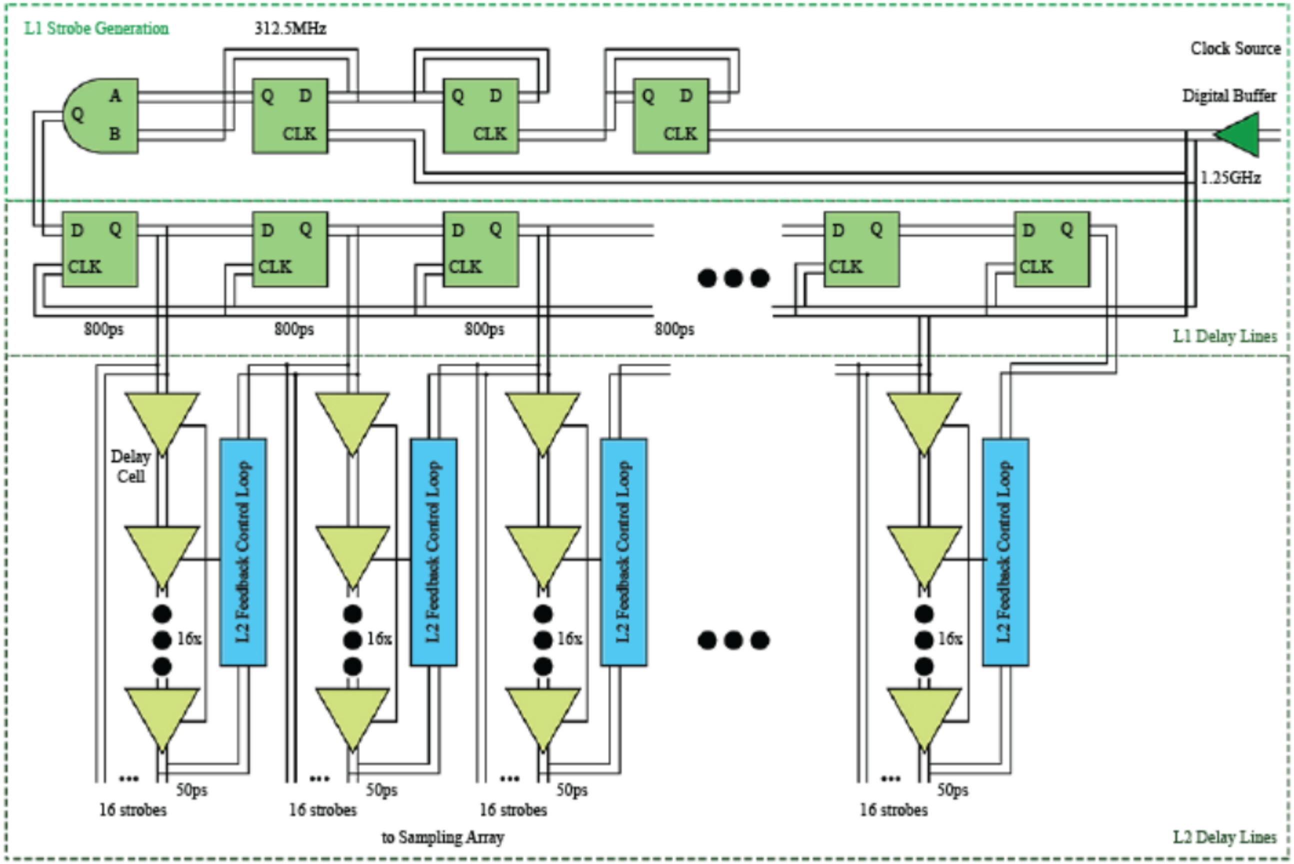
Target Specifications

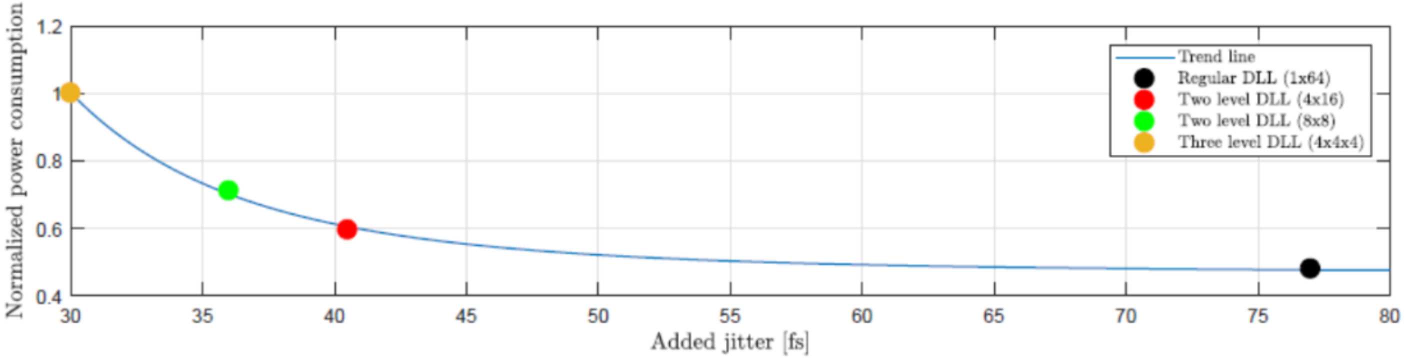
Parameter	Minimum desired value
Sampling frequency (ASIC)	20 GHz
Bandwidth (Detector and ASIC)	3 GHz
Signal to Noise Ratio (Detector and ASIC)	58dB (V_{signal}=1 Volt)
Velocity of Propagation (Transmission Line/ strip line)	0.35c
Number of Bits of Resolution	9.4 bit

This is an ongoing study – update
Completed as P. Orel PhD Thesis

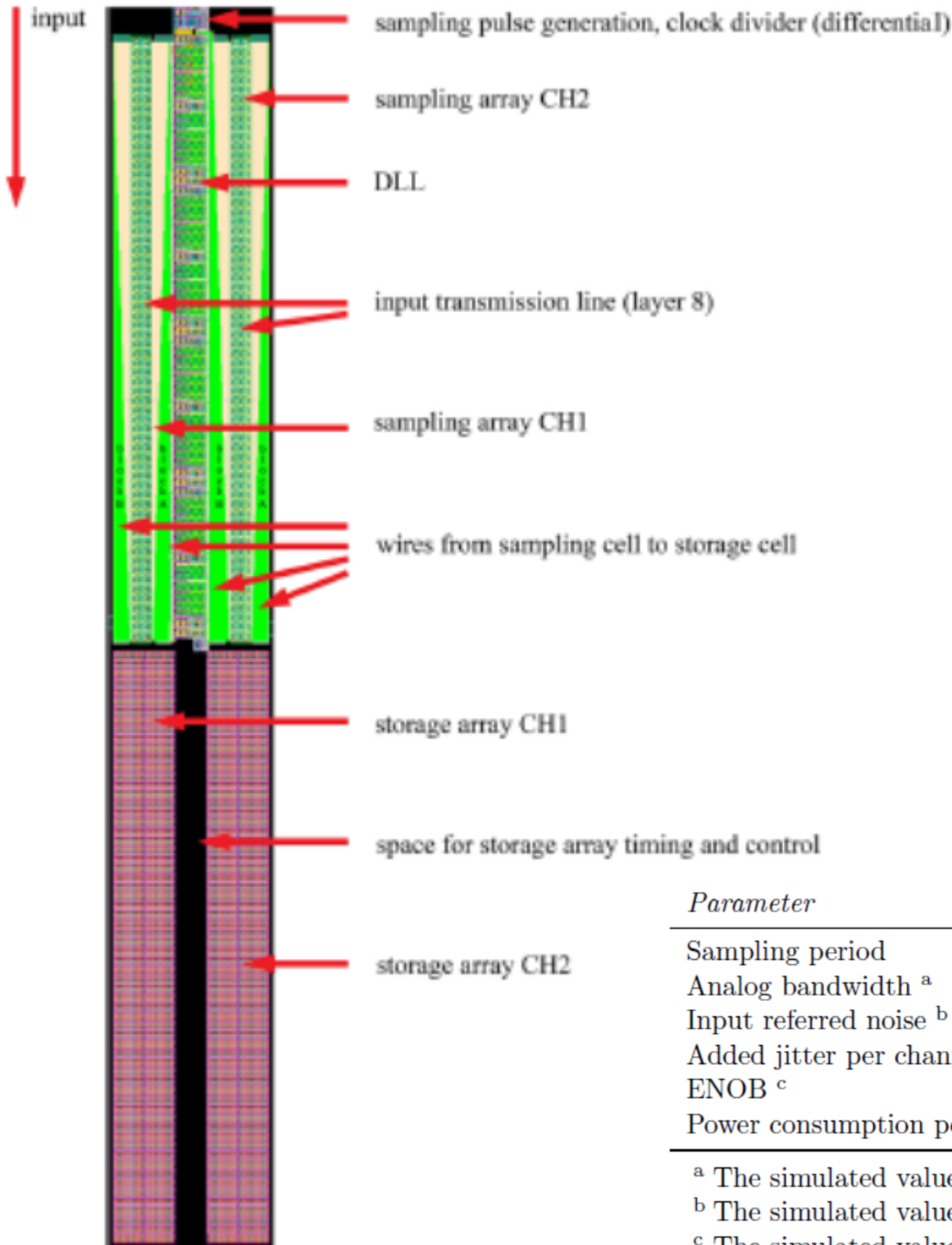
Getting to < 200fs very challenging, but
device with <=1ps (independent of aperture) interesting

Example of a critical component





RFpix1 ASIC Design Status



Key Design components verified

Work still needed on the digital control/address decoding

Parameter	*Desired value*	*Simulated value*
Sampling period	$50\ ps$ @20 GS/s	$50\ ps$ @20 GS/s
Analog bandwidth [a]	$\approx 3\ GHz$	$\approx 3.56\ GHz$
Input referred noise [b]	$\leq 0.5\ mV_{RMS}$	$\approx 1.05\ mV_{RMS}$
Added jitter per channel	$\approx 40\ fs$	$\approx 29\ fs$
ENOB [c]	≥ 10	≈ 9.6
Power consumption per channel [b]	$40\ mA$	$41.71\ mA$

[a] The simulated value is the tracking bandwidth of the SCA.
[b] The simulated value does not take into account the input buffer.
[c] The simulated value does not take into account distortion.

Summary

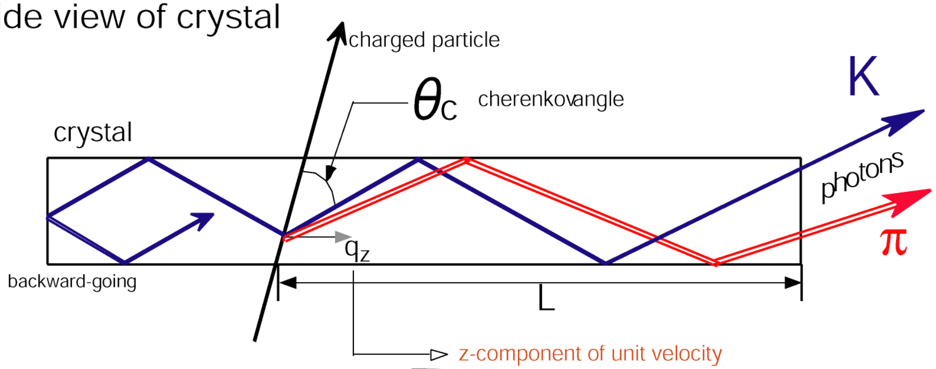
Numerous ASICs have been developed and evolving toward exquisite timing performance

- **Optical Cherenkov:**
  - **10's of ps resolution**
  - **Low power, high density**
- **RF impulse:**
  - **Single ps**
  - **At reach of existing devices**
- **Toward the space-time limit:**
  - **Spatial extent of electronics at 100's fs level**
  - **Detailed engineering, but nothing fundamental**

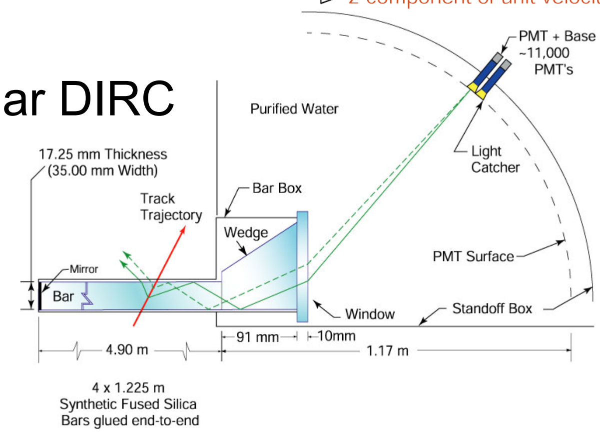
imaging TOP (iTOP)

Concept: Use best of both TOP (timing) and DIRC while fit in Belle PID envelope

Side view of crystal

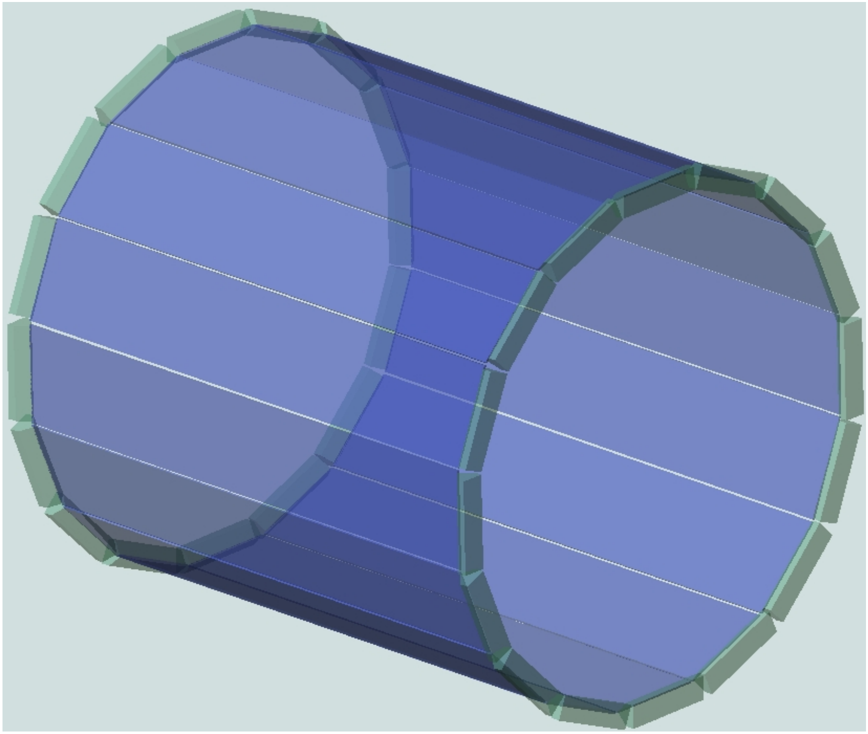


BaBar DIRC



Use wide bars like proposed TOP counter

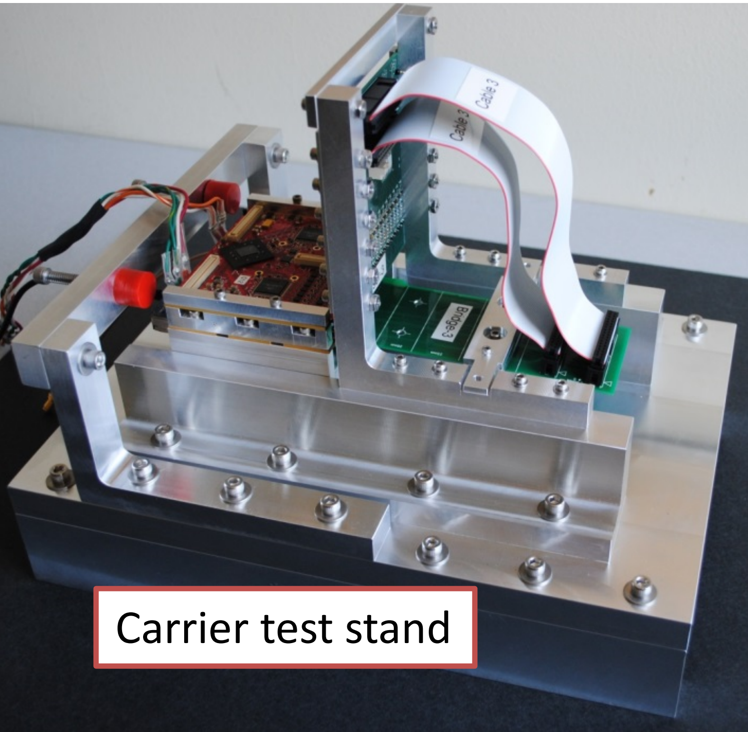
NIM A623 (2010) 297-299.

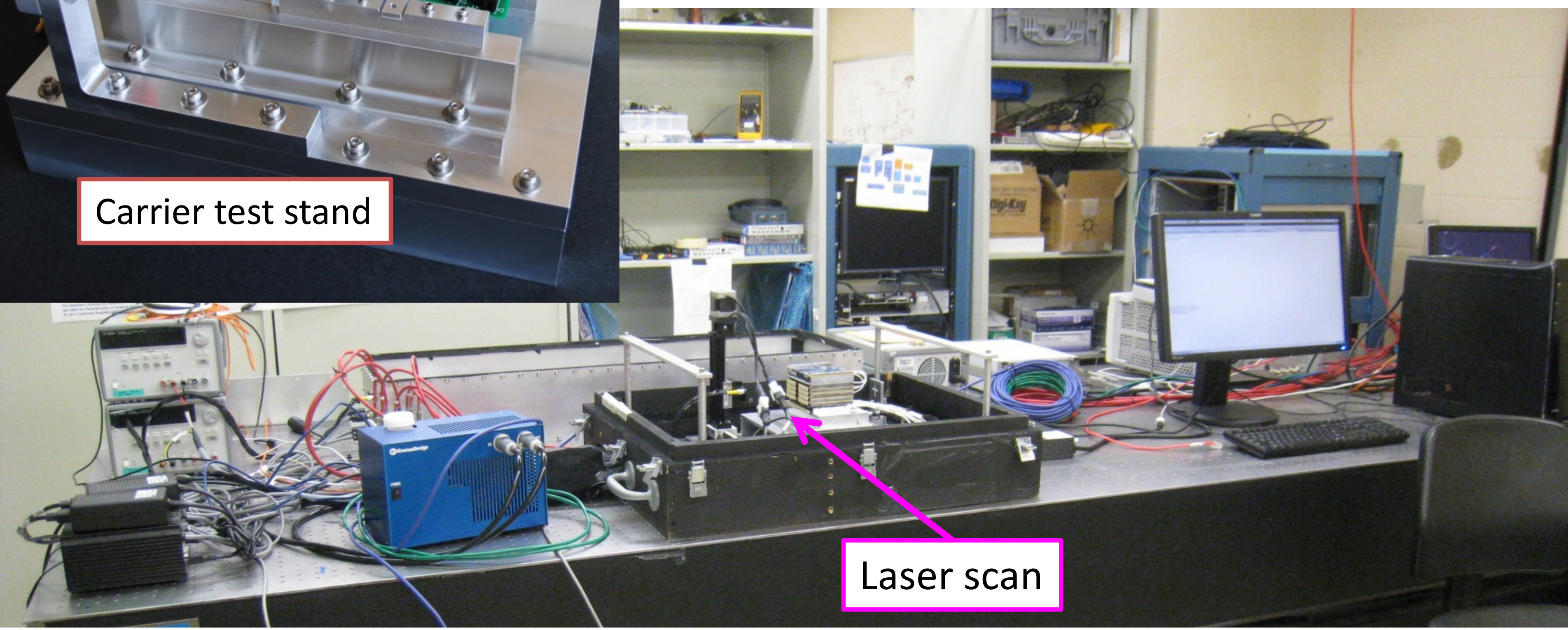


- Use new, high-performance MCP-PMTs for sub-50ps single p.e. TTS
- Use simultaneous T, θ_c [measured-predicted] for maximum K/π separation
- Optimize pixel size

iTOP Readout Production Testing

- **2x Carrier test stations at South Carolina, 1x backup in Hawaii**
- **Laser test stand Hawaii**
- **SCROD test stand in Pittsburgh**
- **Firmware test at PNNL**





Laser timing calibration/alignment

- To synchronize the channels within a single module, we flash them with a pico-second laser pulse through optical fibers.
- The system has been developed by Italian group (Padova/Torino)