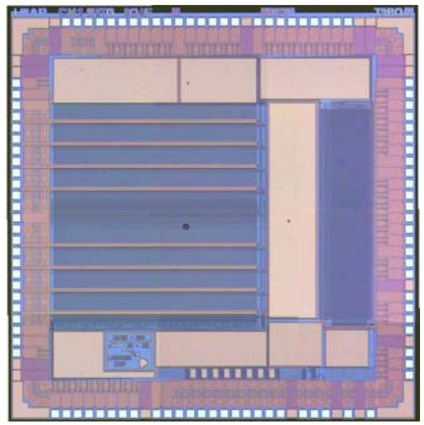
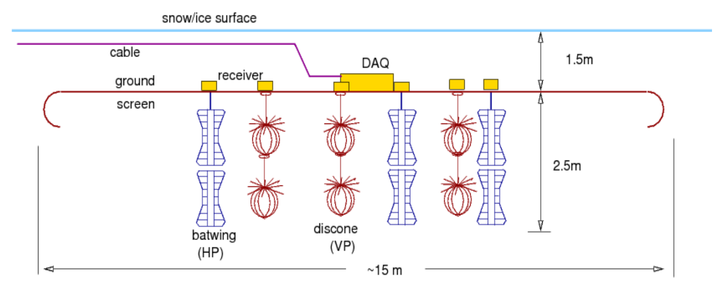
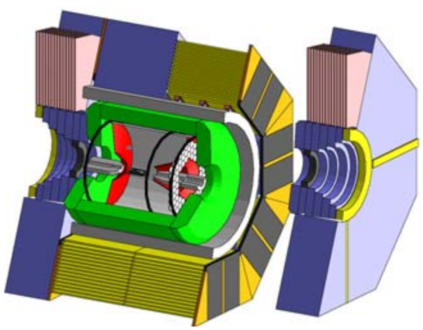
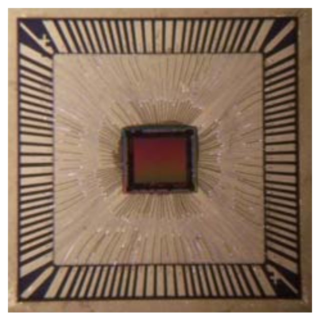
Large Analog Bandwidth Recorder and Digitizer with Ordered Readout (Perf, Results)







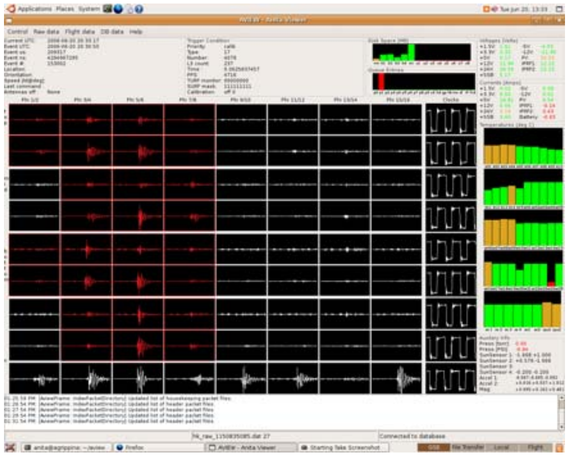


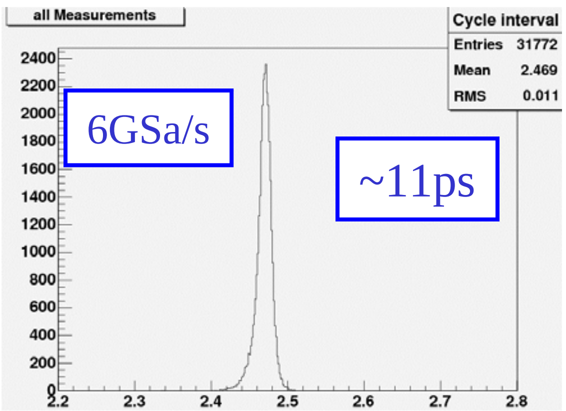
Gary S. Varner

University of Hawai'i

U Chicago Precision Timing Mtg Dec.07

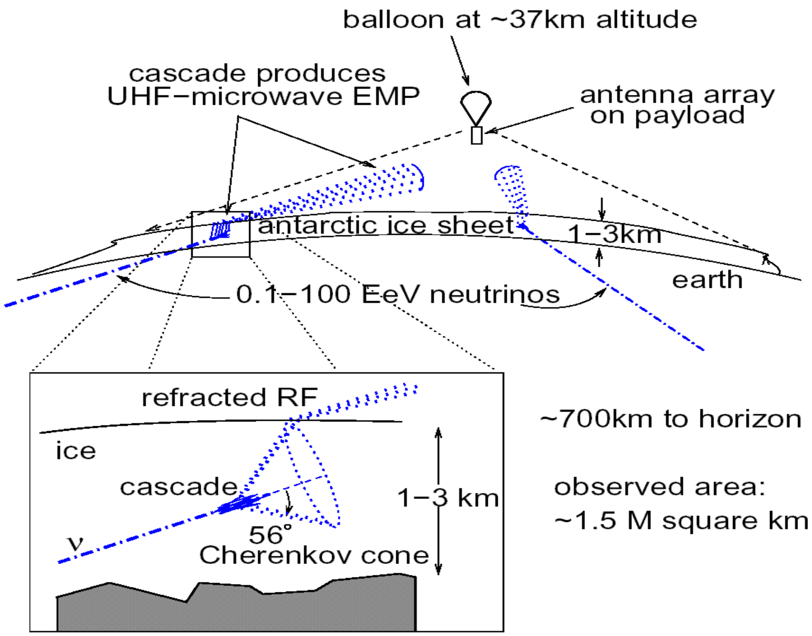
Topics

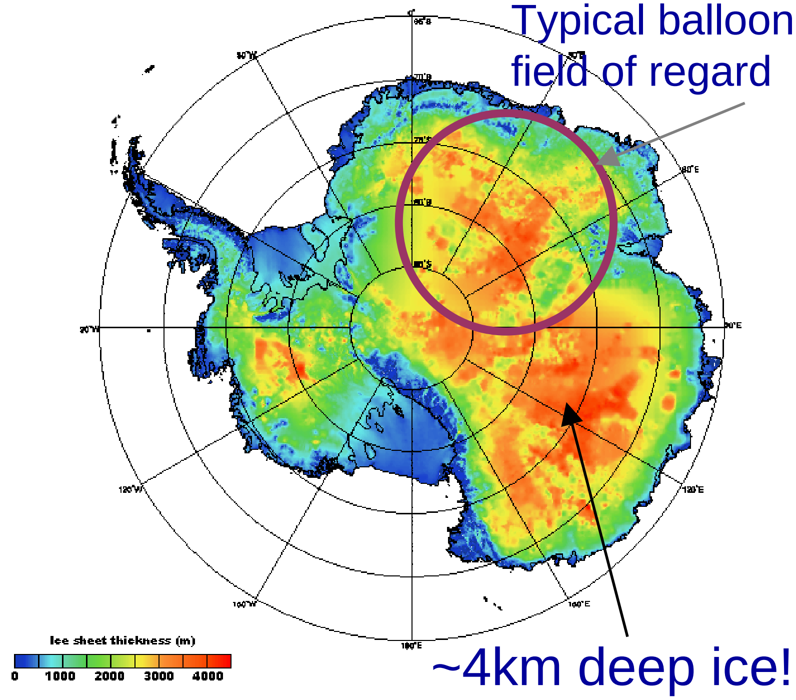




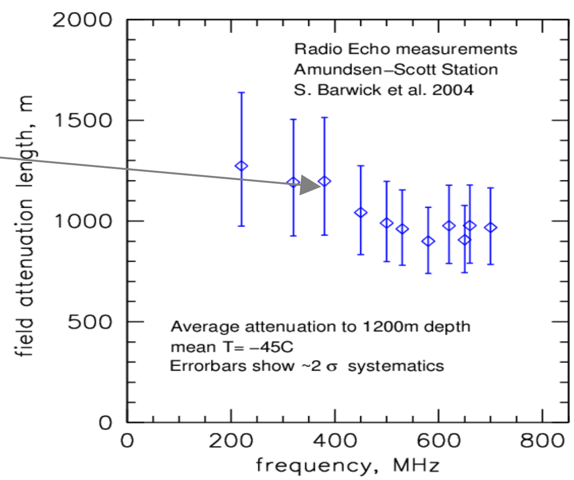
- Background to WFS Development
  - Antarctic Impulsive Transient Antenna (ANITA)
  - LABRADOR ASIC
- Improved Performance
  - Super Flavor Factory PID
  - Buffered LABRADOR (BLAB)
- Technique Limits
  - Streak Camera/Precision Timing
  - Next Gen ASIC

The ANITA Concept





Ice RF clarity: 1.2 km(!) attenuation length

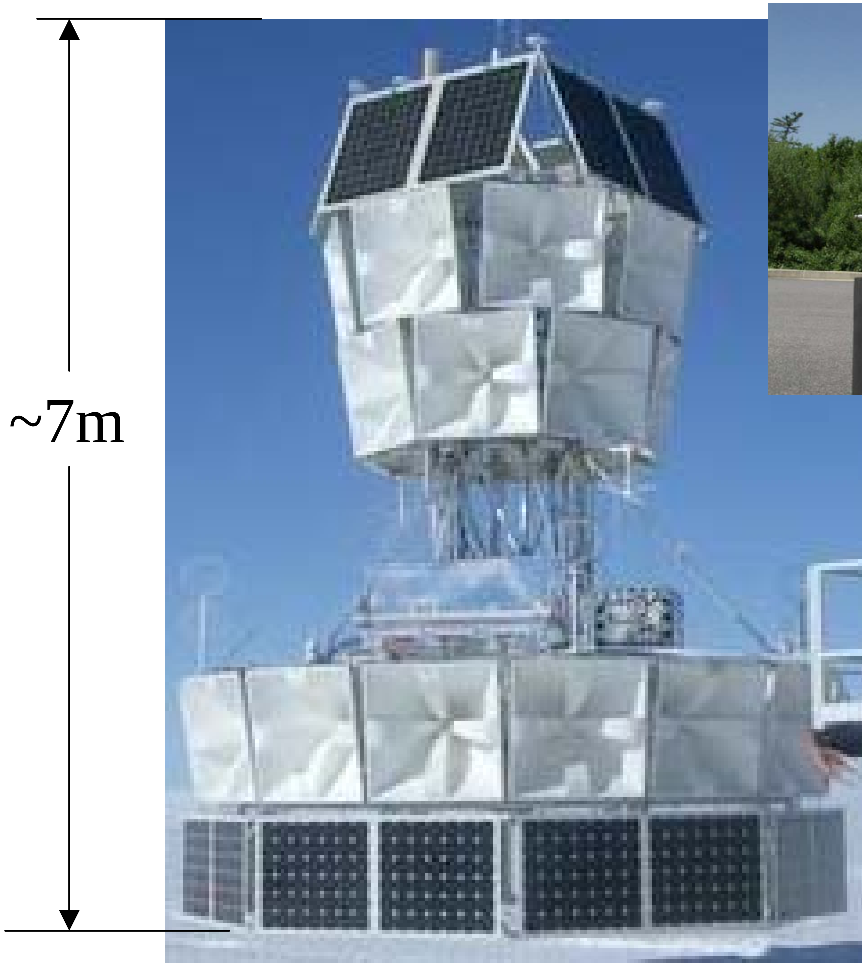


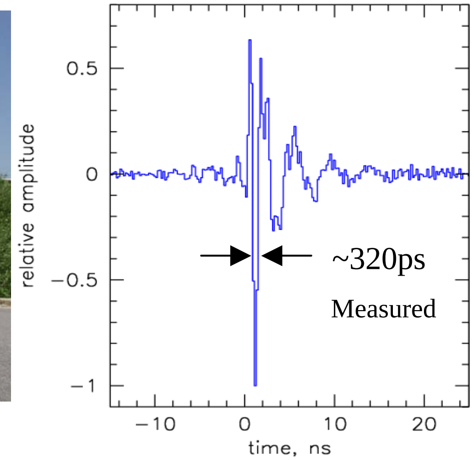
Effective "telescope" aperture:

- ~250 km^3 sr @ $10^{18.5}$ eV
- ~10^4 @ km^3 sr 10^{19} eV

(Area of Antarctica ~ area of Moon)

A demanding Application





Antarctic Impulsive Transient Antenna (ANITA)

- RF Transient (impulsive) Events (200-1200 MHz)
- 324 chan. @ 2.6GSa/s
- Completely solar powered (tight demands on power, few hundred W total)
- Sounds almost like a joke

Major Hurdles – these ν are elusive

- No commercial waveform recorder solution (power/resolution)

- 3σ thermal noise fluctuations occur at MHz rates (need ~2.3σ)

- Without being able to record or trigger efficiently, there is no experiment

STRAW2 Chip

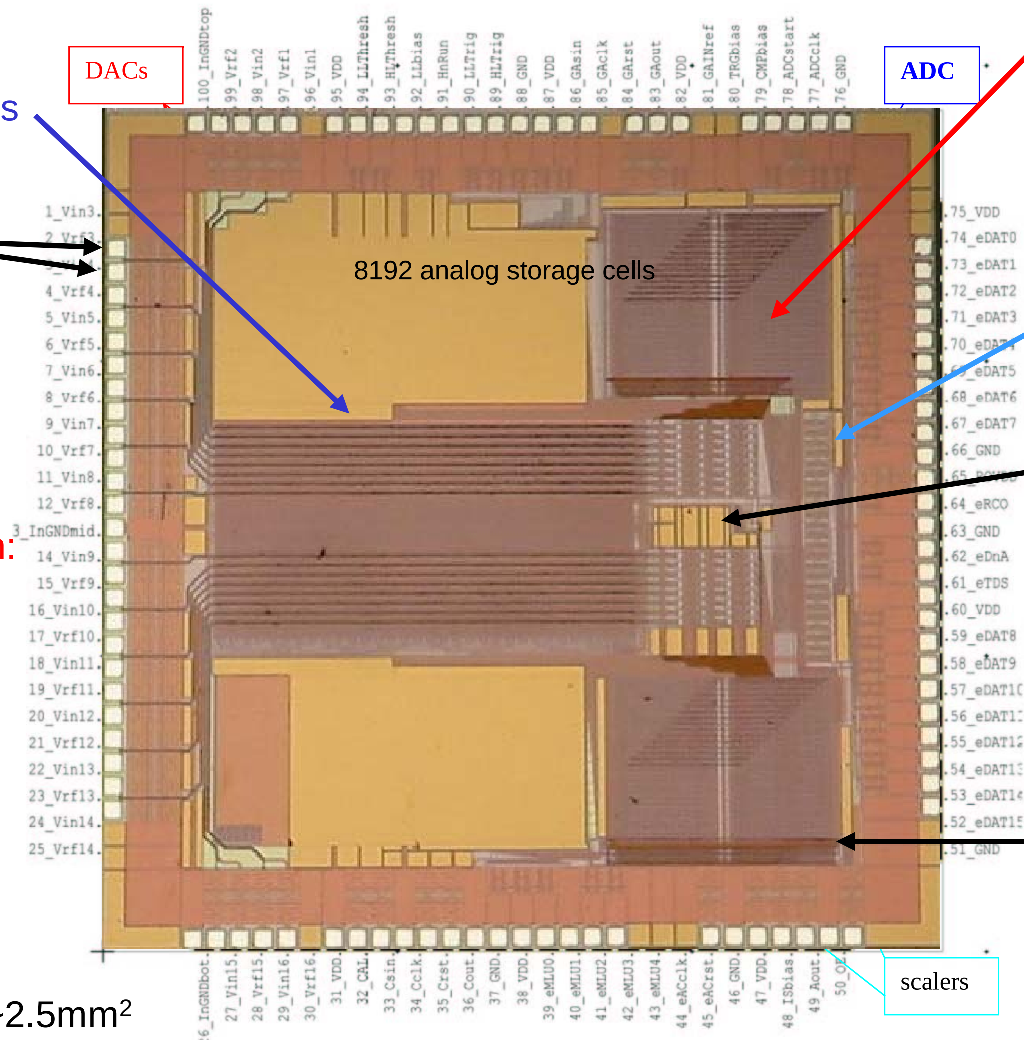
Self-Triggered Recorder Analog Waveform (STRAW)

16 Channels of
256 deep SCA buckets

Optimized for RF input
Microstrip 50Ω

Target input Bandwidth:
>700MHz

Record length:
128-256ns



Die:~2.5mm²

Self-Triggering:

-LL and HL (adj.)
for each channel

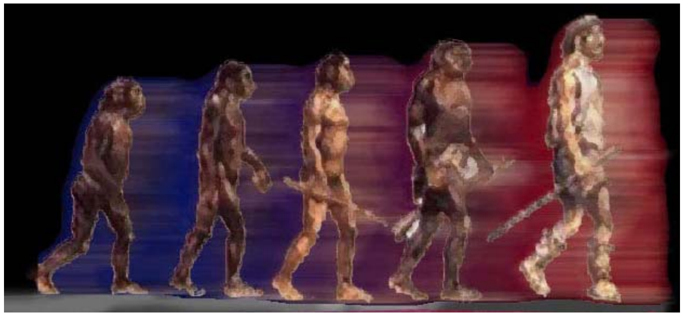
-Multiplicity trigger
for LL hits

On-chip ADC:
12-bit, >2MSPS

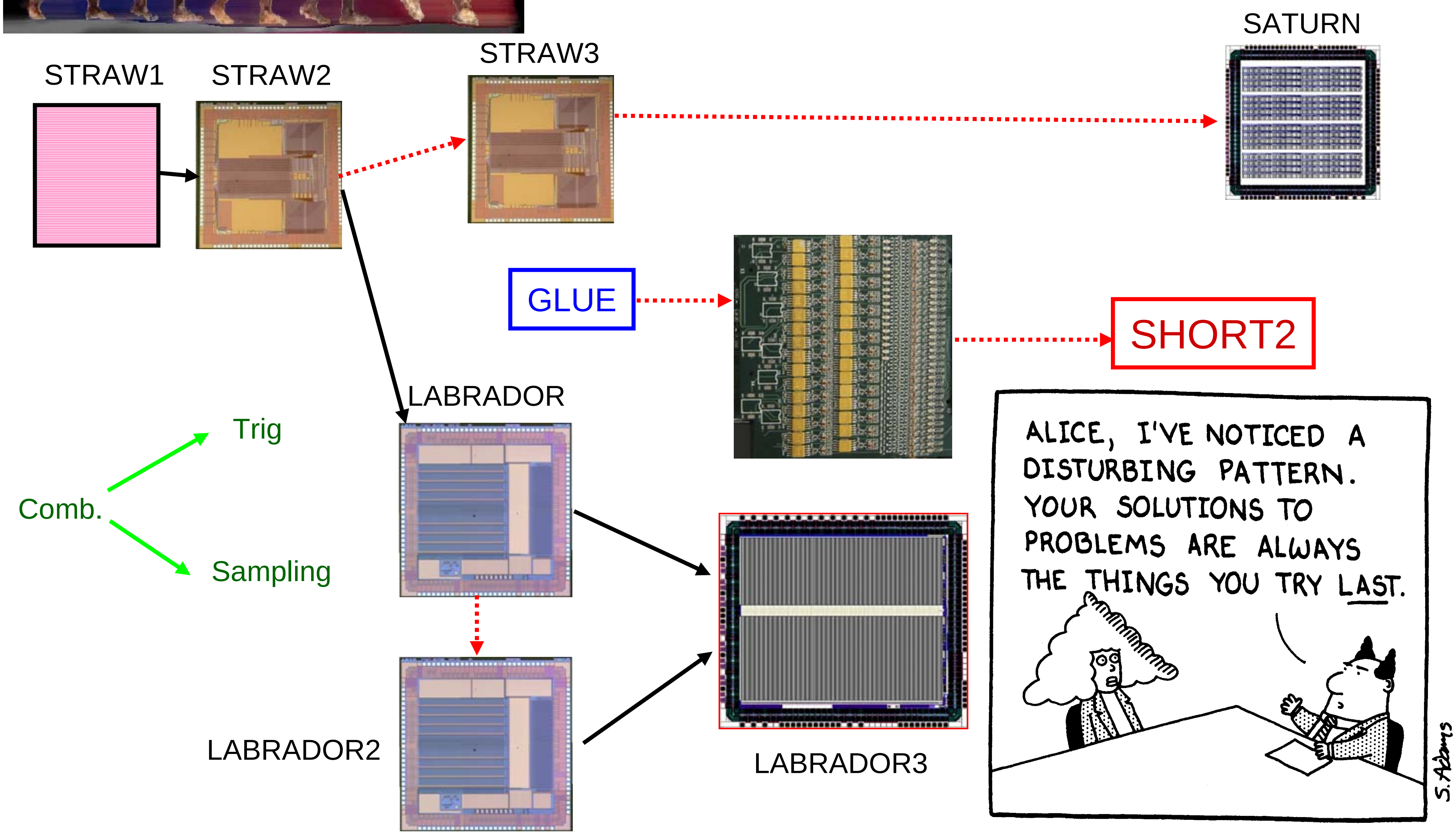
Sampling Rate:
1-3GSa/s (adj.)

Sampling Rates
>~4GSa/s possible
w/ 0.25µm process

External option:
MUXed Analog out

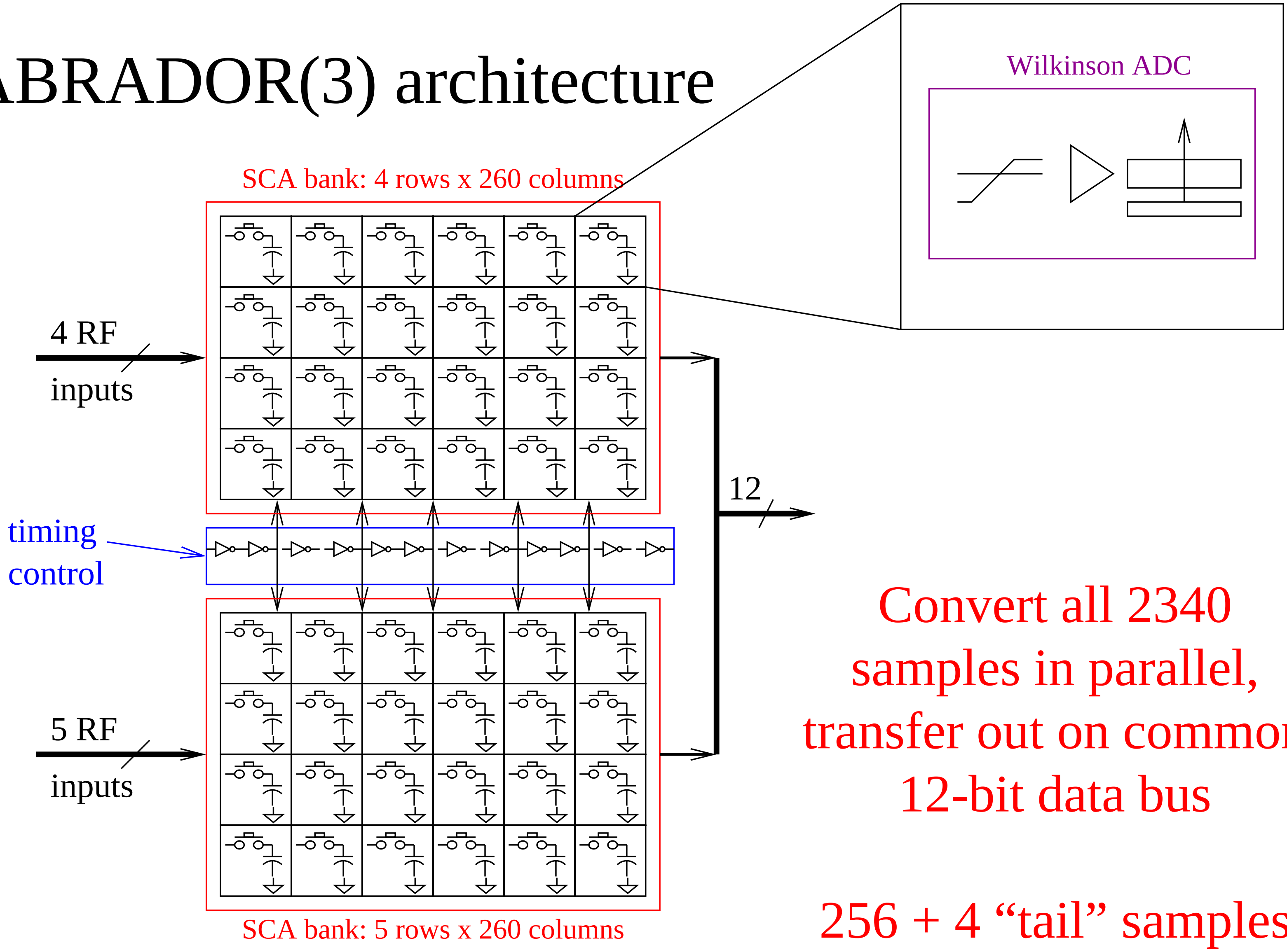


Intelligent Design?



9 x 260 samples = 2340 storage cells

LABRADOR(3) architecture



Convert all 2340 samples in parallel, transfer out on common 12-bit data bus

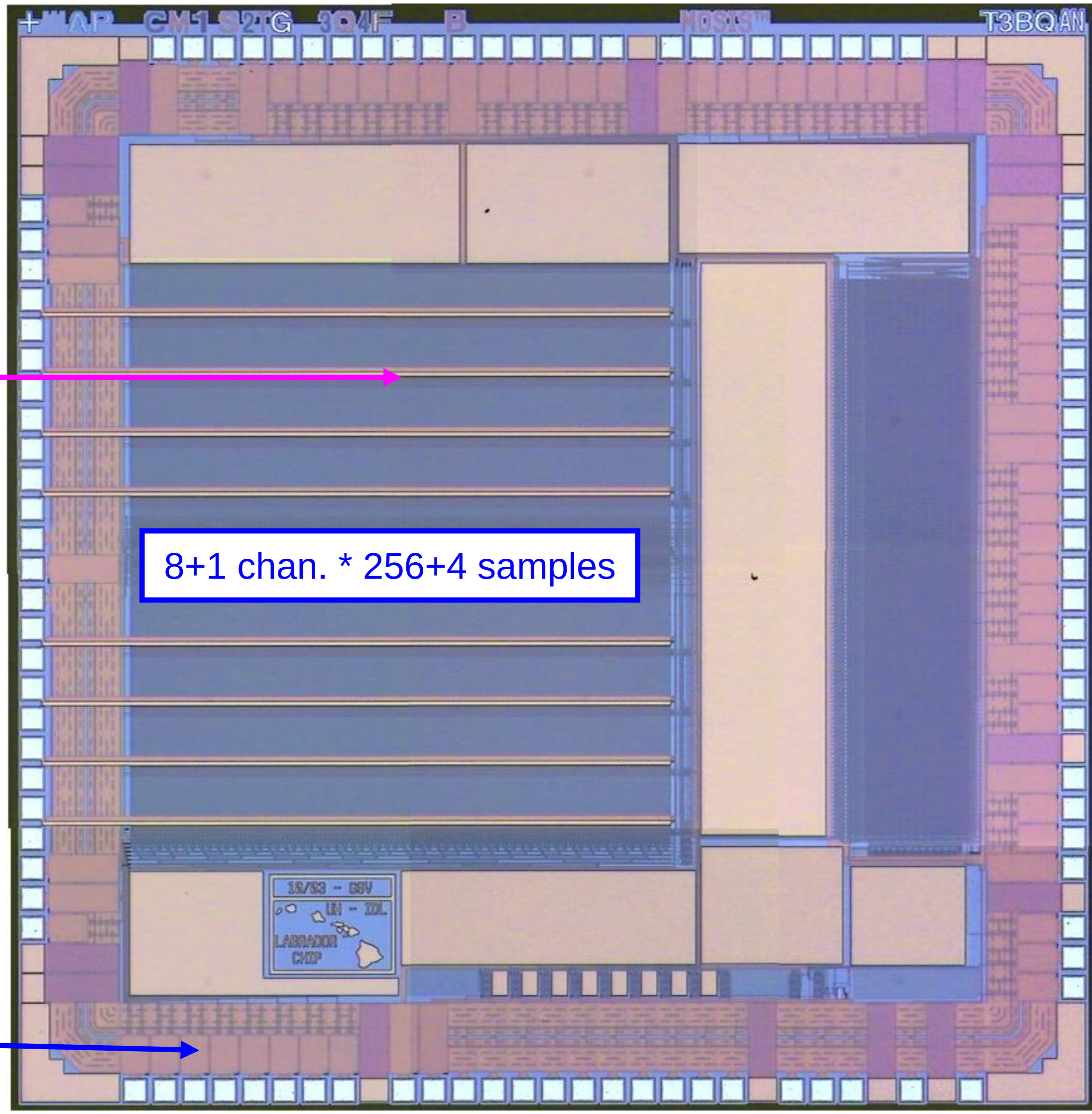
256 + 4 "tail" samples

Large Analog Bandwidth Recorder and Digitizer with Ordered Readout [LABRADOR]

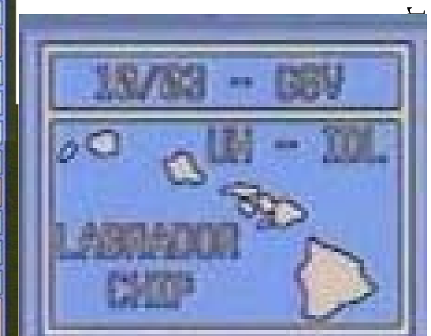
Straight Shot RF inputs

- Switched Capacitor Array (SCA)
- Massively parallel ADC array
- Similar to other WFS ASICs → <u>analog bandwidth</u>

Random access:

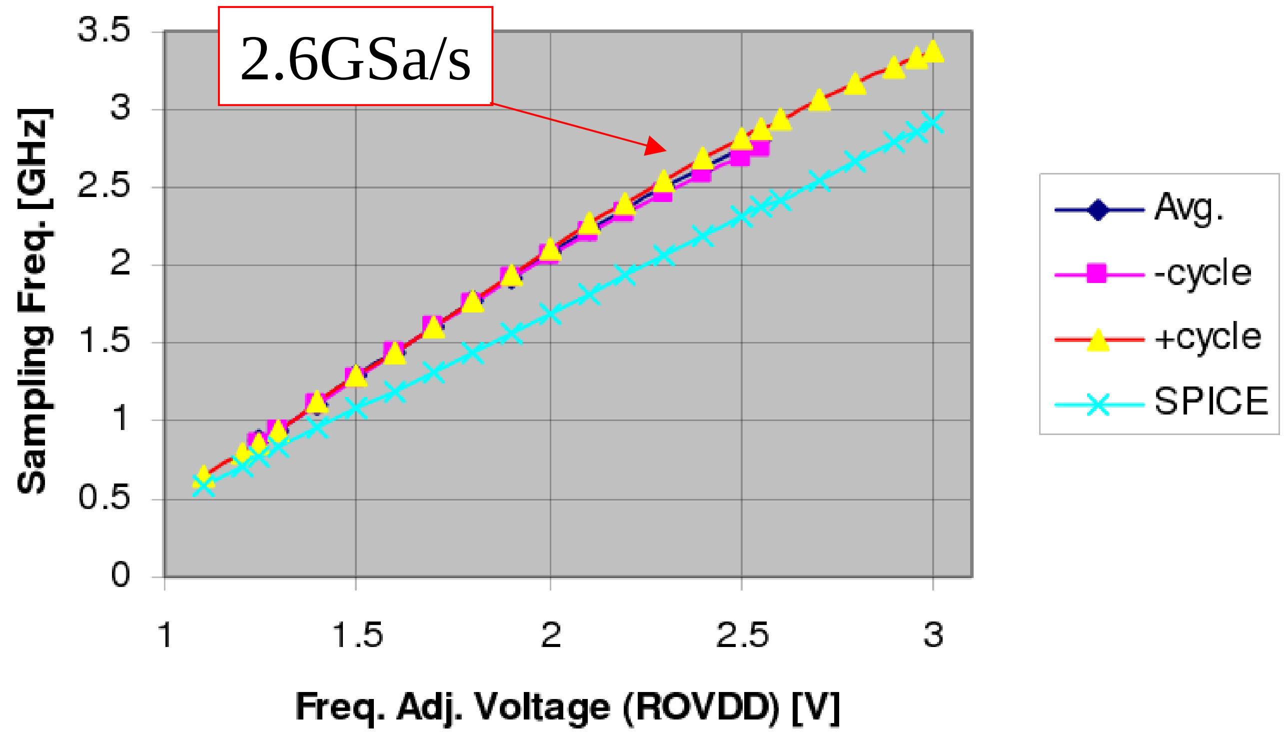


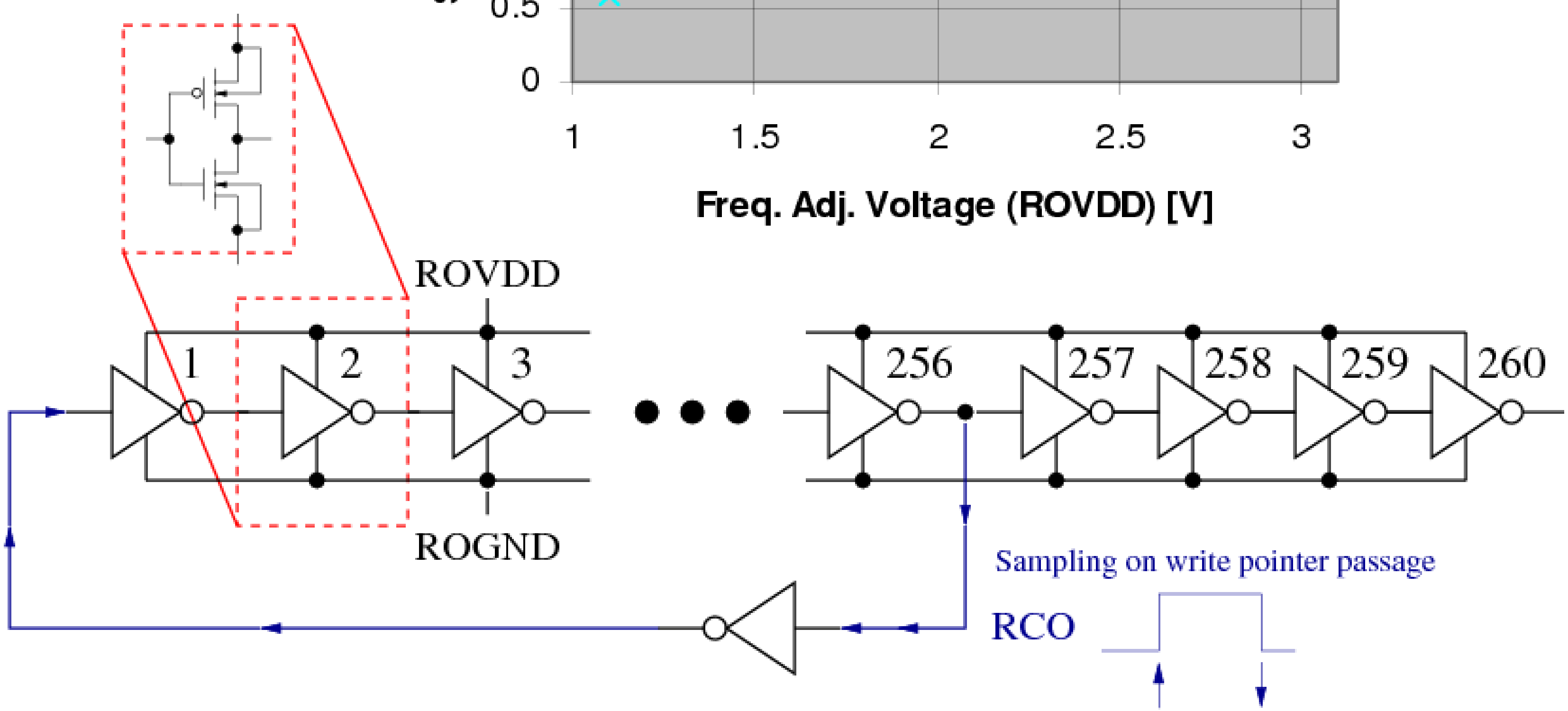
- Common STOP acquisition
- 3.2 x 2.9 mm
- Conversion in 31μs (all 2340 samples)
- Data transfer takes 80μs
- Ready for next event in <150μs



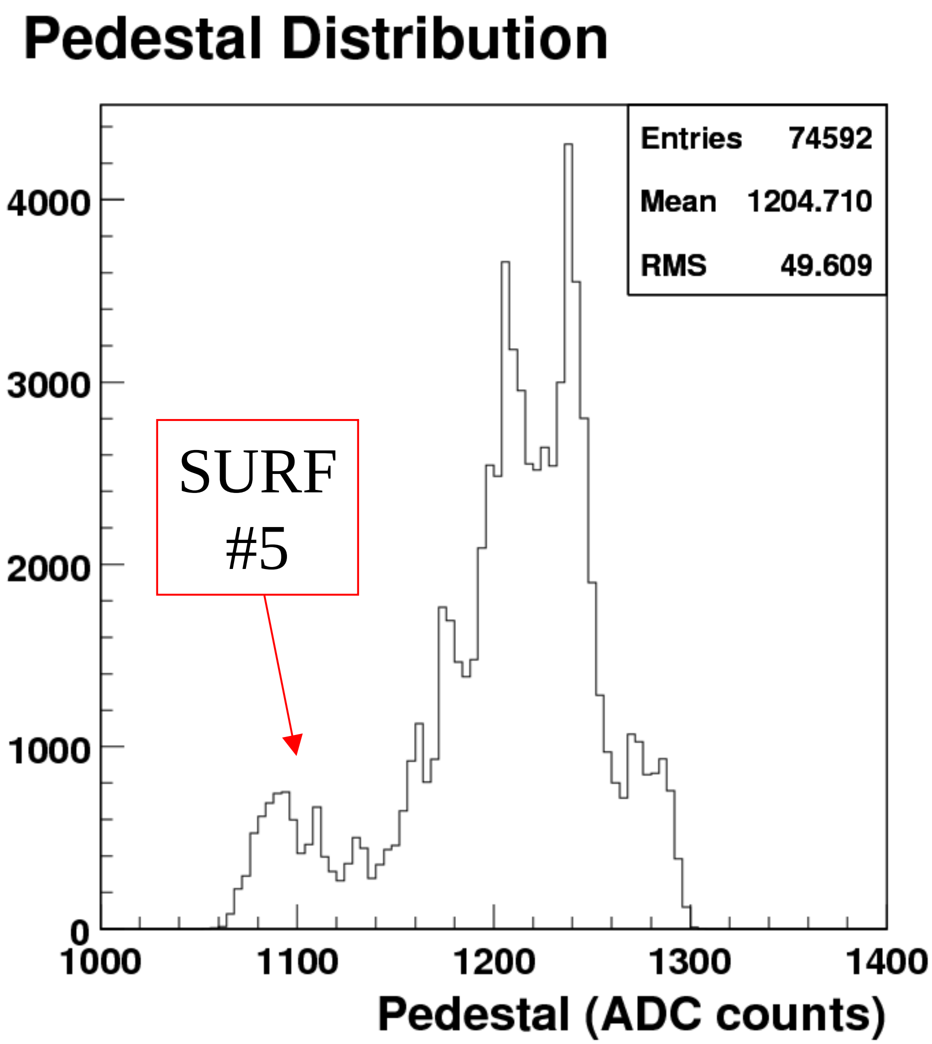
LABRADOR Sampling Speed

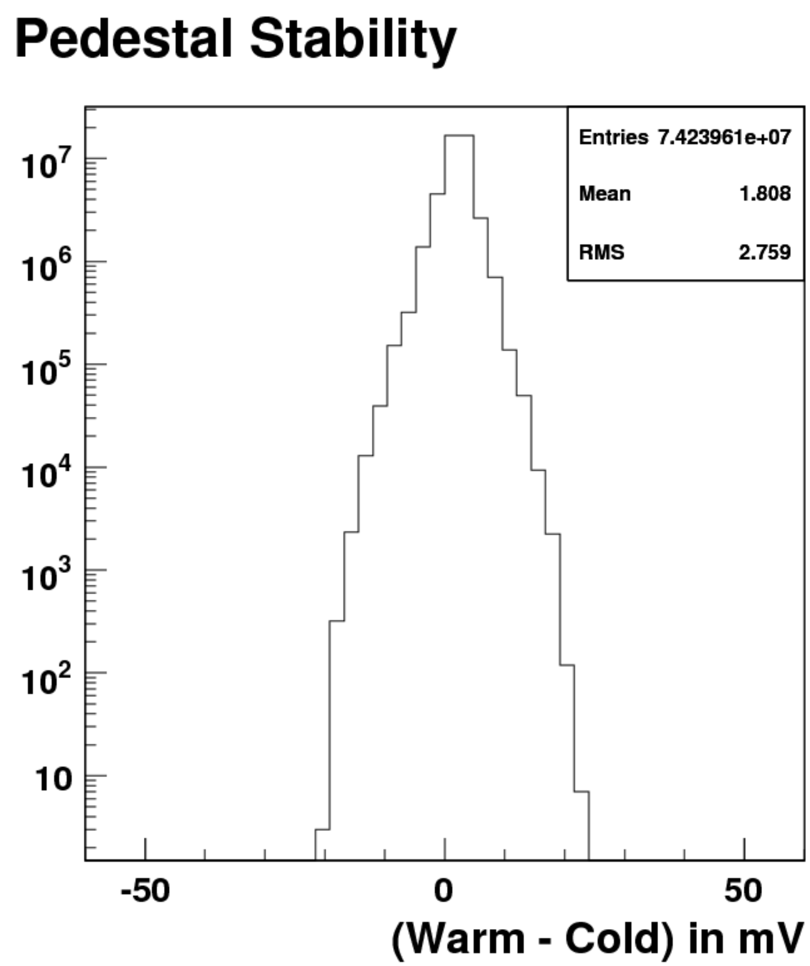
- XOR Look-ahead logic (sample on rising/falling edge)
- Sampling rates up to 4 GSa/s with voltage overdrive





Pedestal and Pedestal Stability





$\Delta T = 17C$ ($\delta t \sim 24$hours)
~ 0.052mV/C

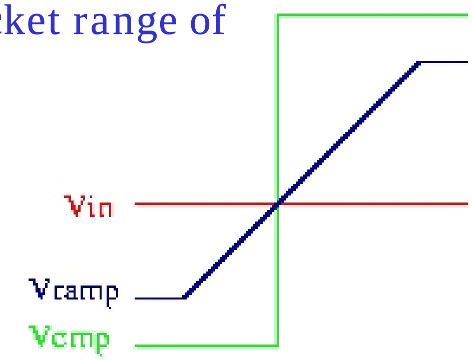
- AC coupled input

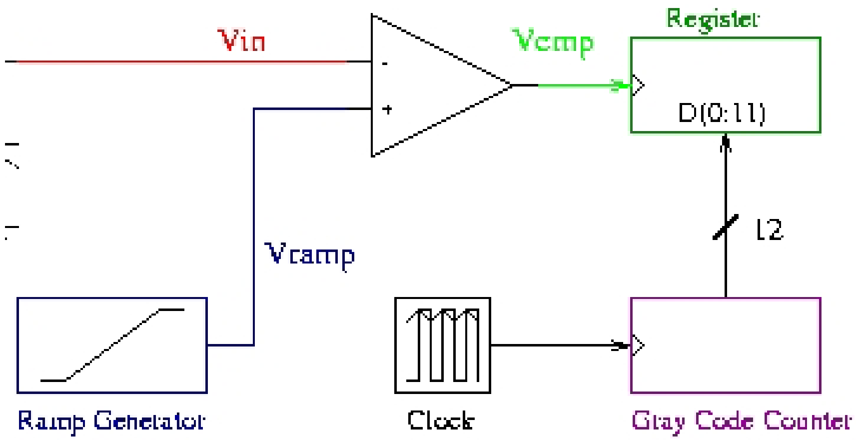
LABRADOR Digitization

Wilkinson ADC

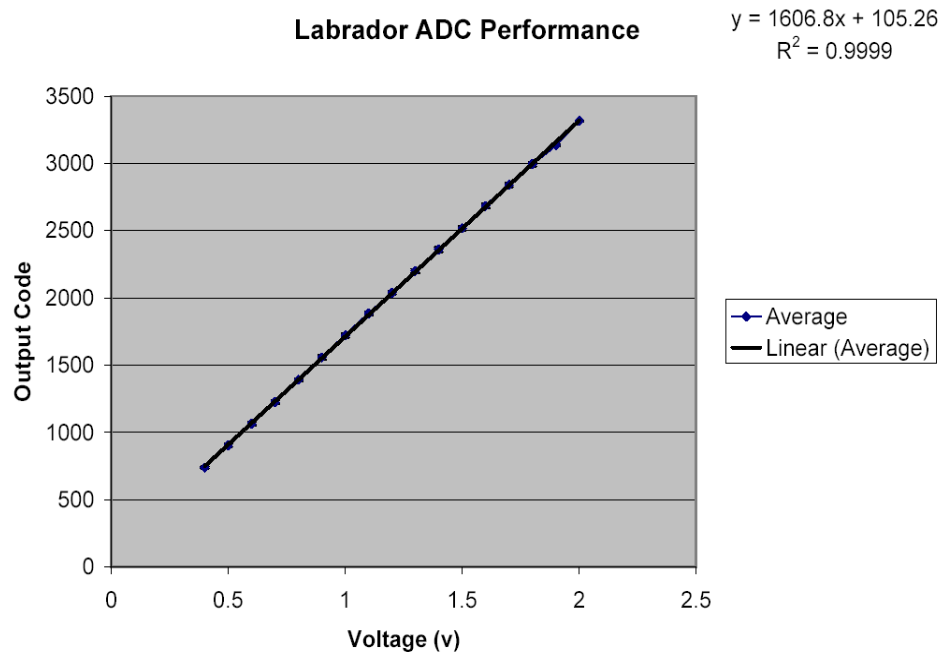
- No missing codes
- Linearity as good as can make ramp
- Can bracket range of interest

Run count during ramp



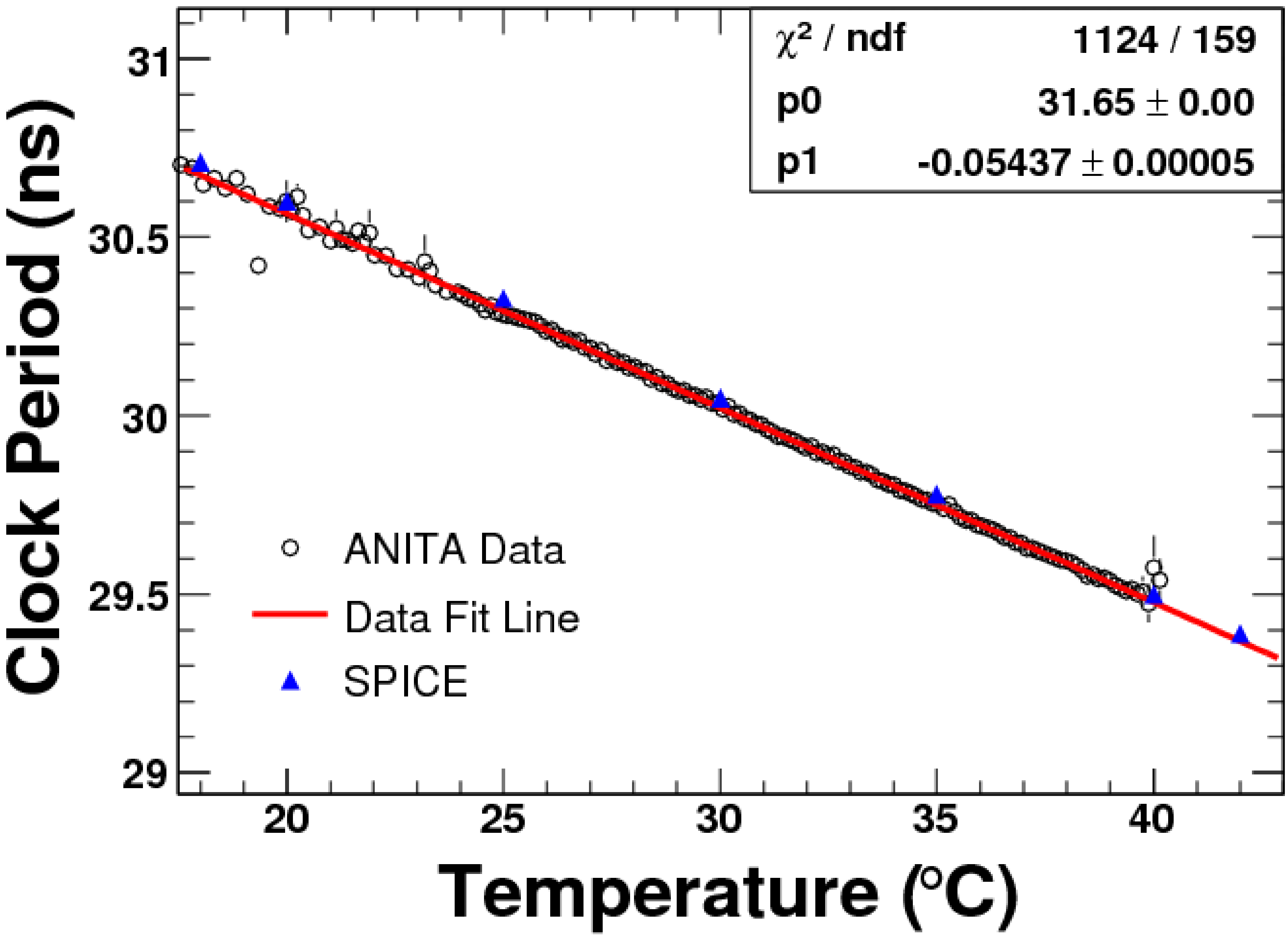


12-bit ADC

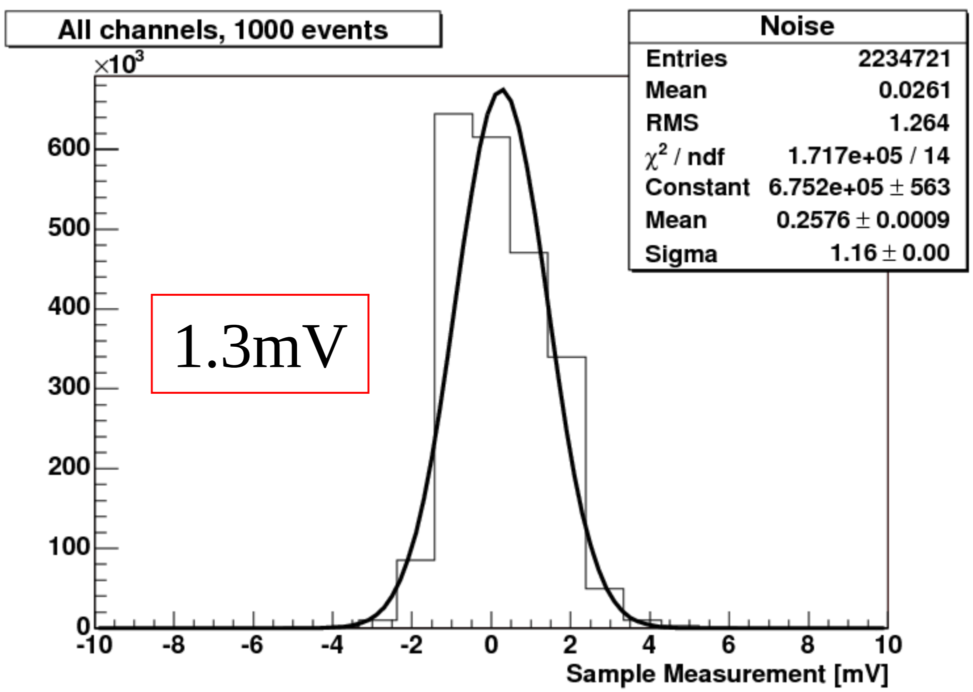


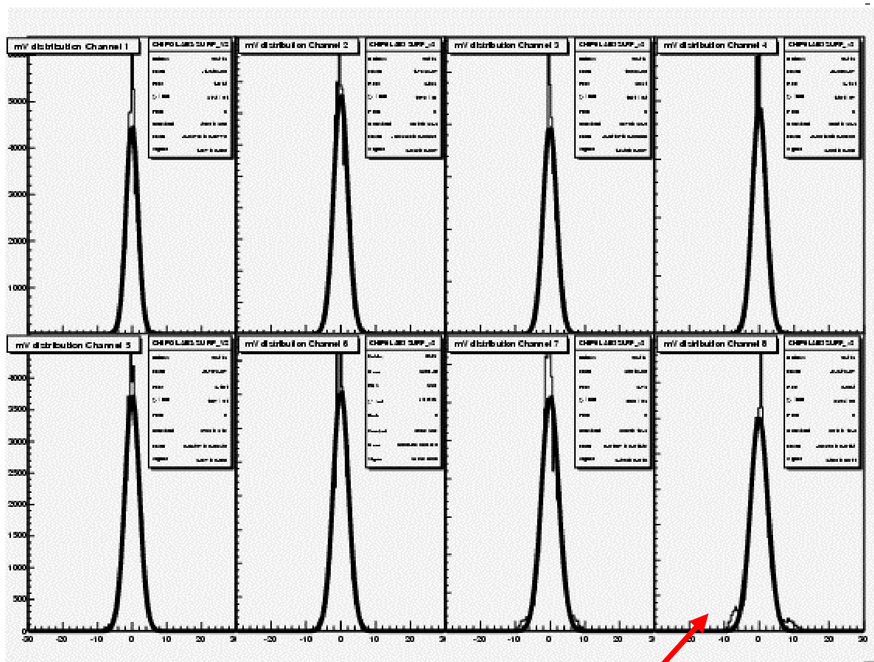
- Excellent linearity
- Basically as good as can make current source/comparator
- Comparator ~0.4 – 2.1V; 133MHz GCC max (~31us)

Sampling Rate Temperature Dependence



LABRADOR (SURF board) Noise



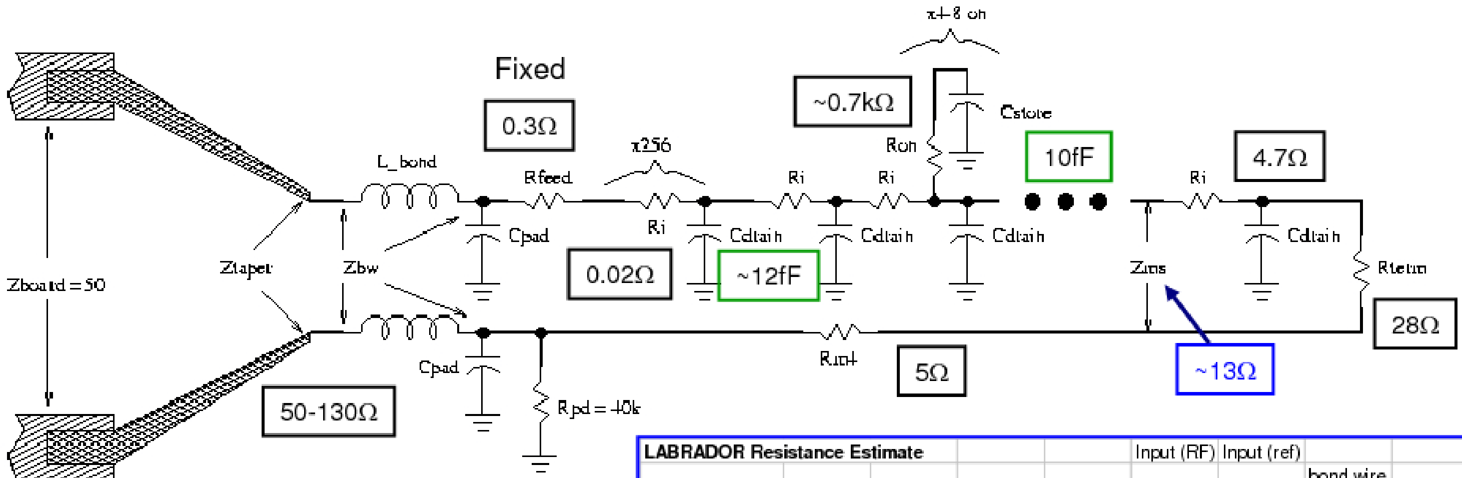


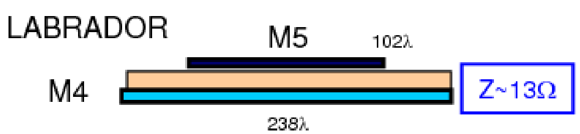
Ch.9
Vped noise

- 10 real bits (1.3V/1.3mV noise)

(2.5V VDD, rails smaller)

Bandwidth Limitations (LAB1 example)





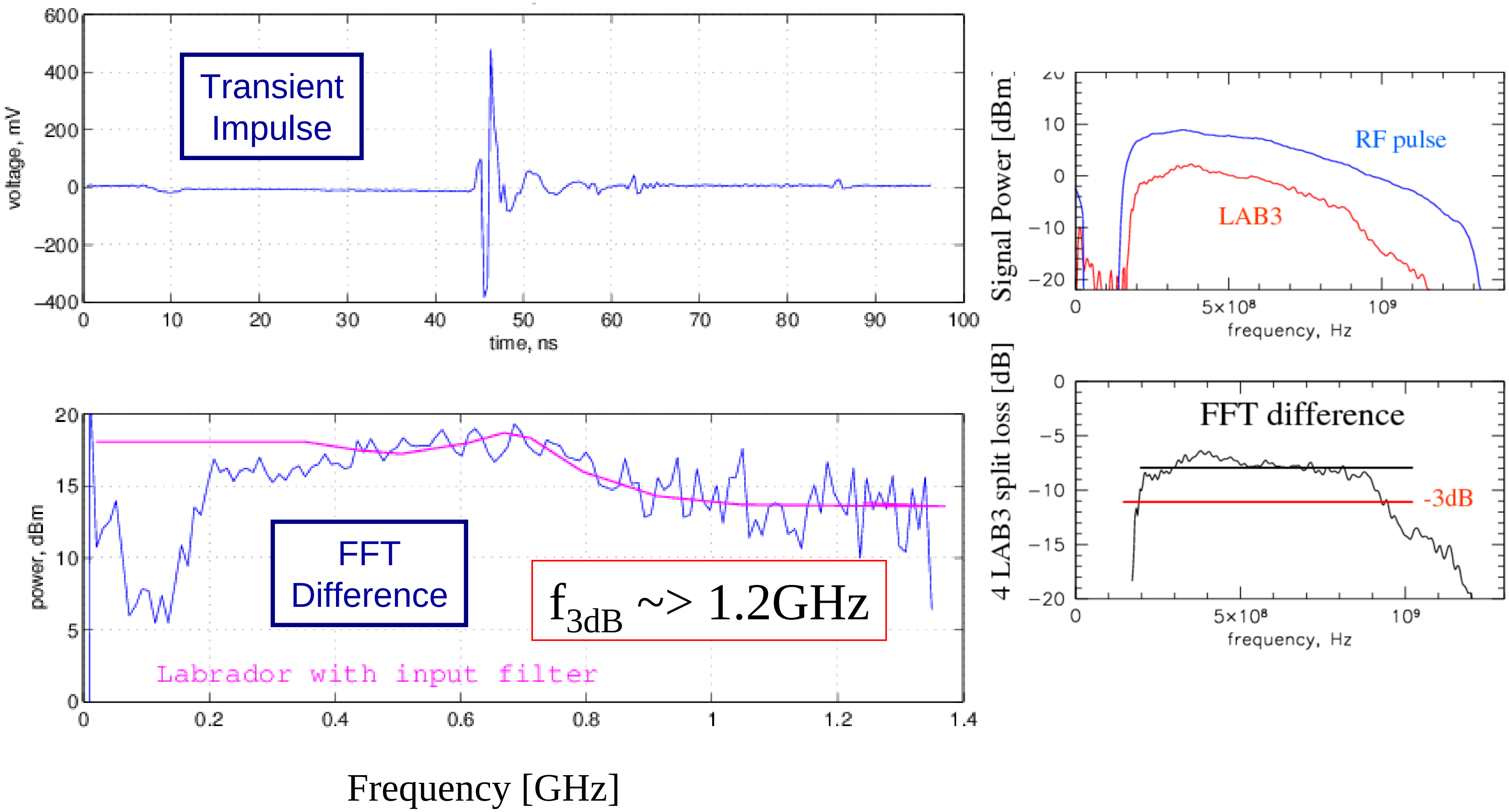
LABRADOR Resistance Estimate					Input (RF)	Input (ref)		
							bond wire	
Length	17000	λ			0.0	0.1	pad	
			70			0.2	M5-M4	
Metal 4(sheet) =	0.07	Ohm/sq		71.42857		5.0	typ length (sq.)	
Metal 5(sheet) =	0.03	Ohm/sq	166.6667		5.0		typ length (sq.)	
Poly contact =	5.1	Ohm	6	6	0.9	0.9		
via 1=	2.7	Ohm	6	3	0.5	0.9		
via 2=	5.35	Ohm	6	3	0.9	1.8		
via 3=	8.26	Ohm	6	3	1.4	2.8		
via 4=	11.34	Ohm	6		1.9			
					10.5	11.5	Total per feed	
						28	Rterminator	
		Measured:		Ohm		**50.0**	Grand Total	

$$f_{3dB} = 1/2\pi ZC$$

LAB3 → move R_{term} to front

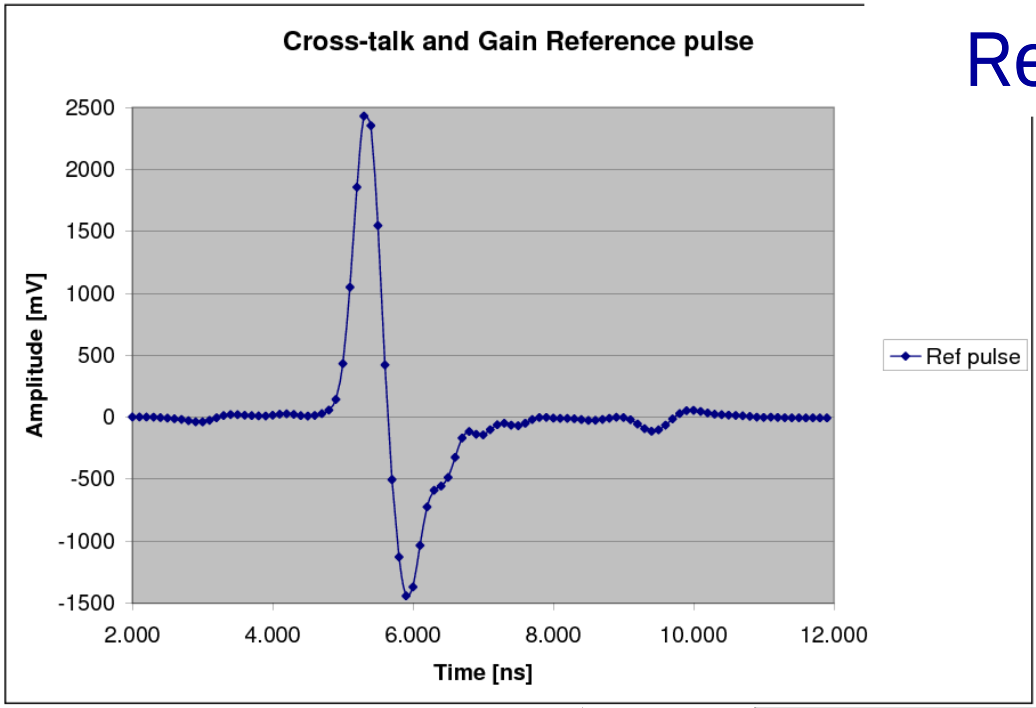
- For 1.2GHz, C <~ 2pF (NB input protection diode ~10pF)
- Minimize C, (C_{drain} not negligible x260)

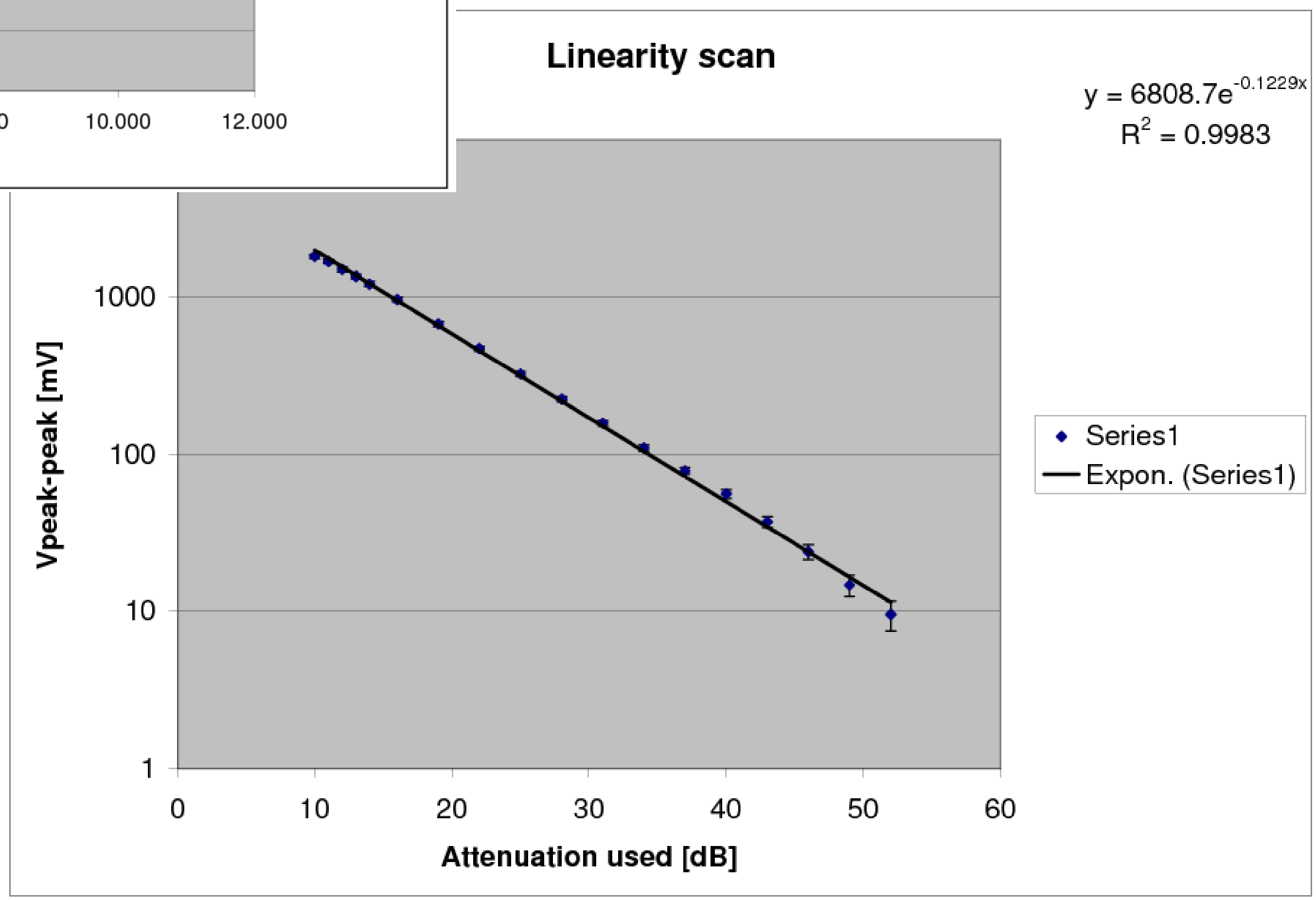
Bandwidth Evaluation



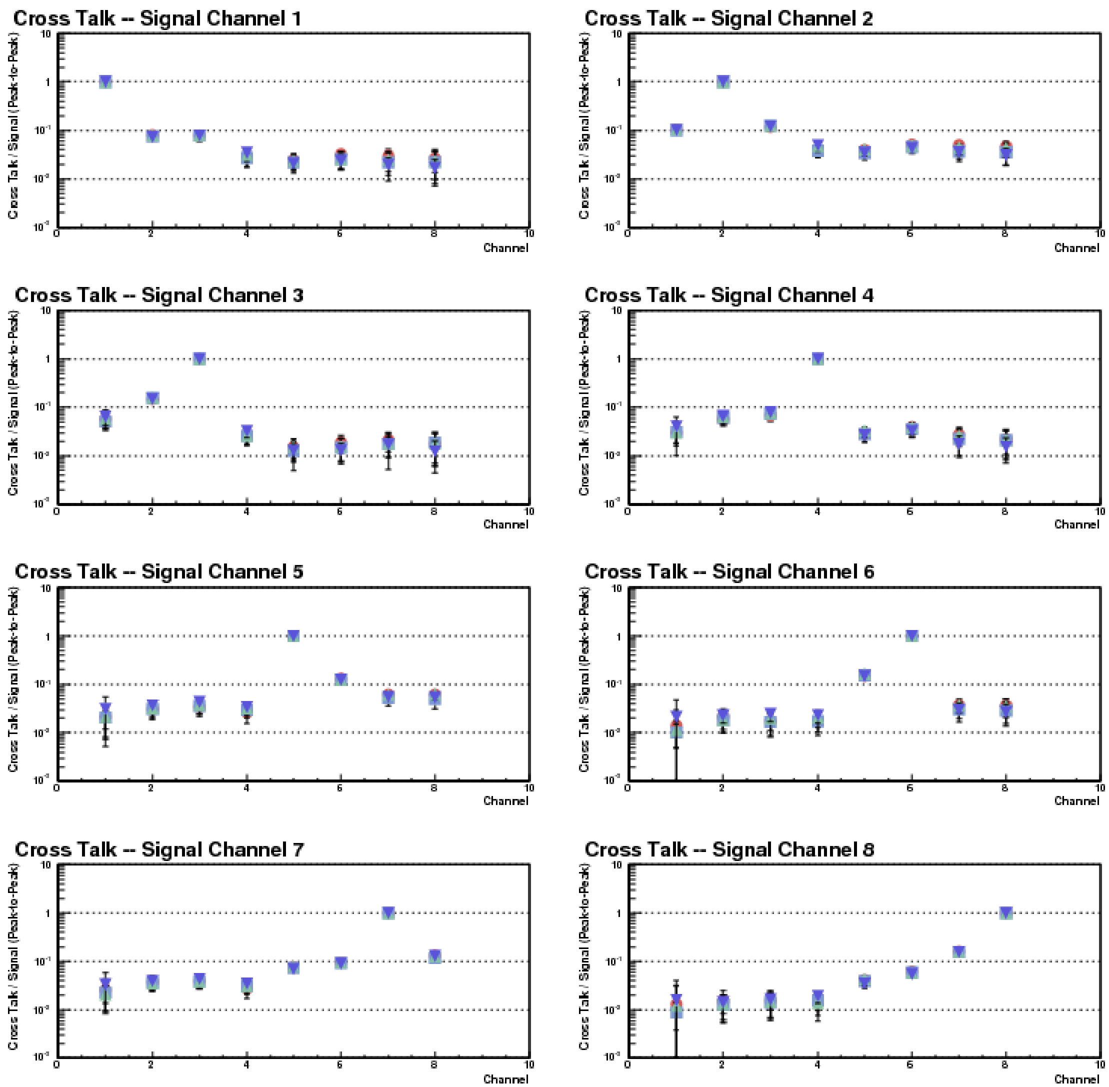
Response for RF Signals

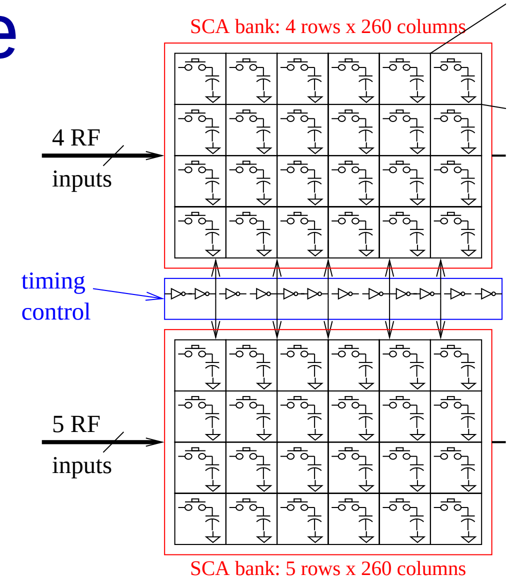
- 2.6 GSa/s, peak fit (@ board-level noise interference)

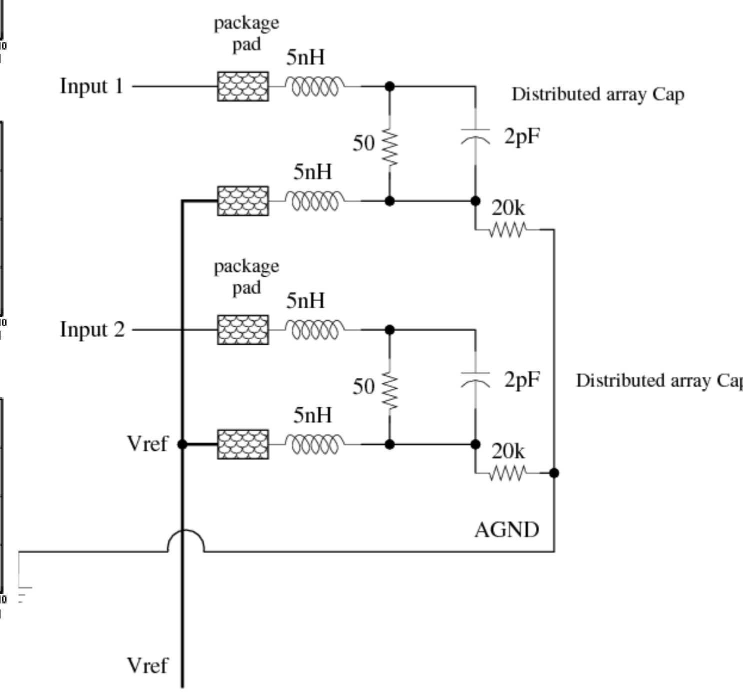




Cross-talk Amplitude

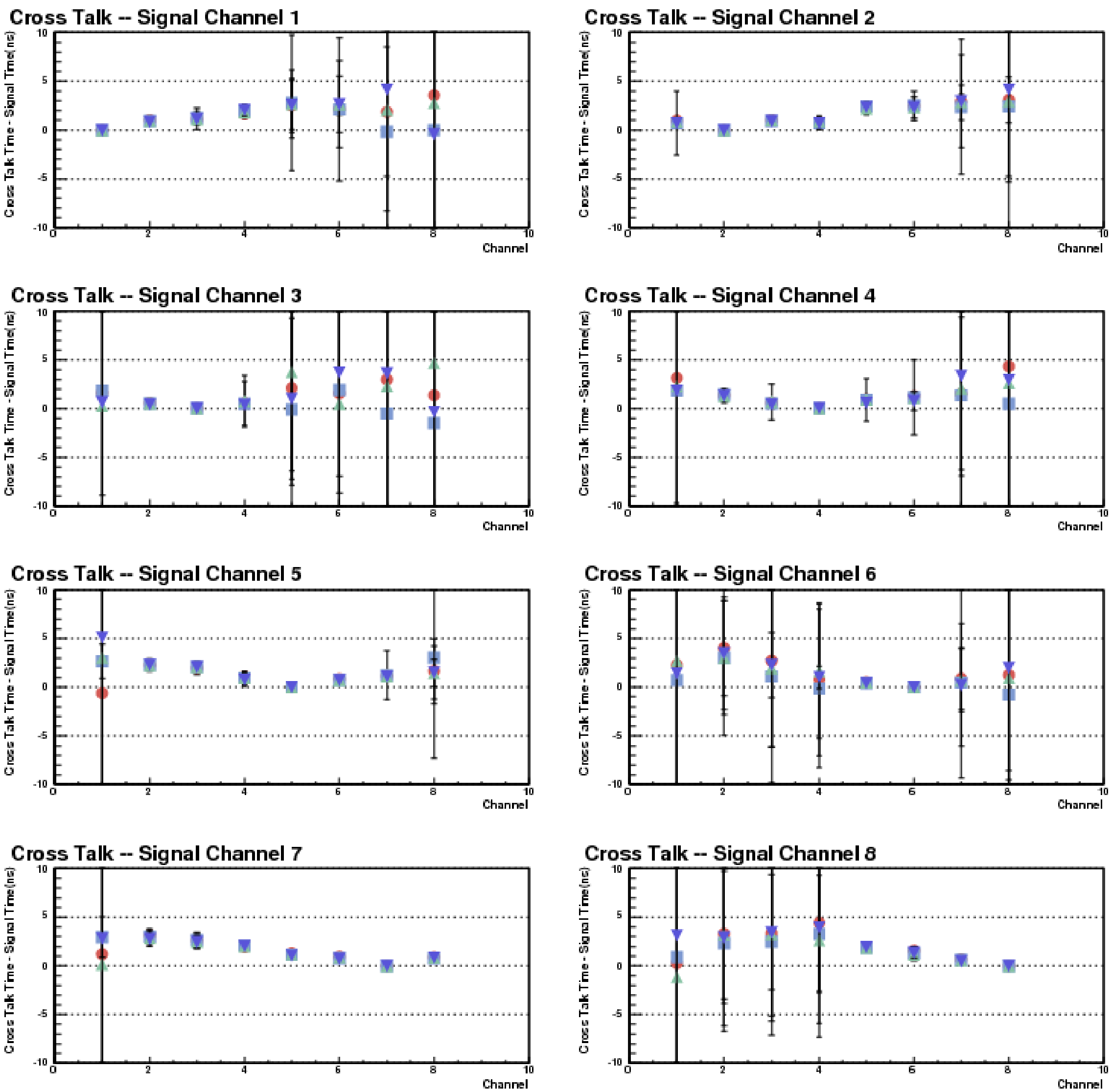


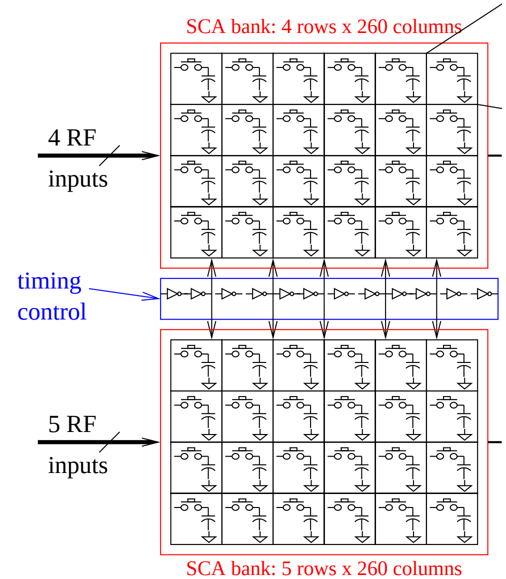


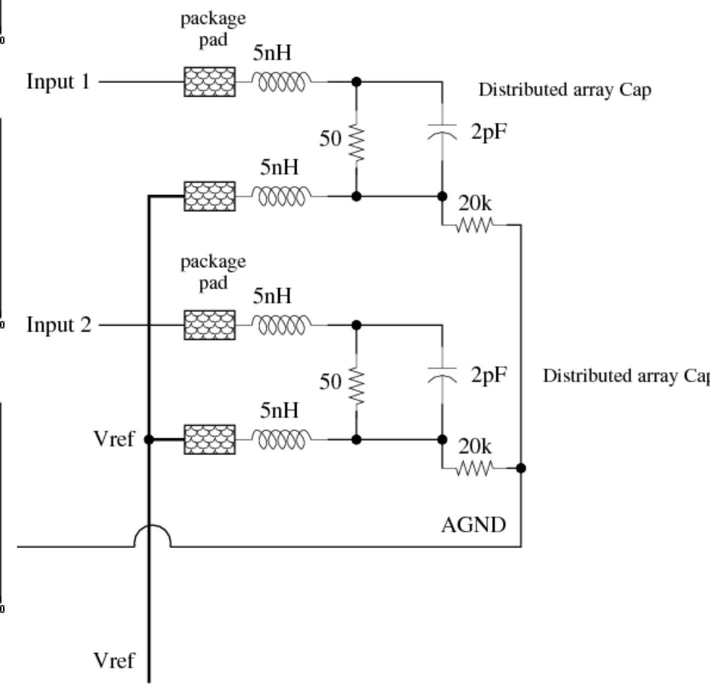


- Qualitative agreement obtained in SPICE

Cross-talk Phase

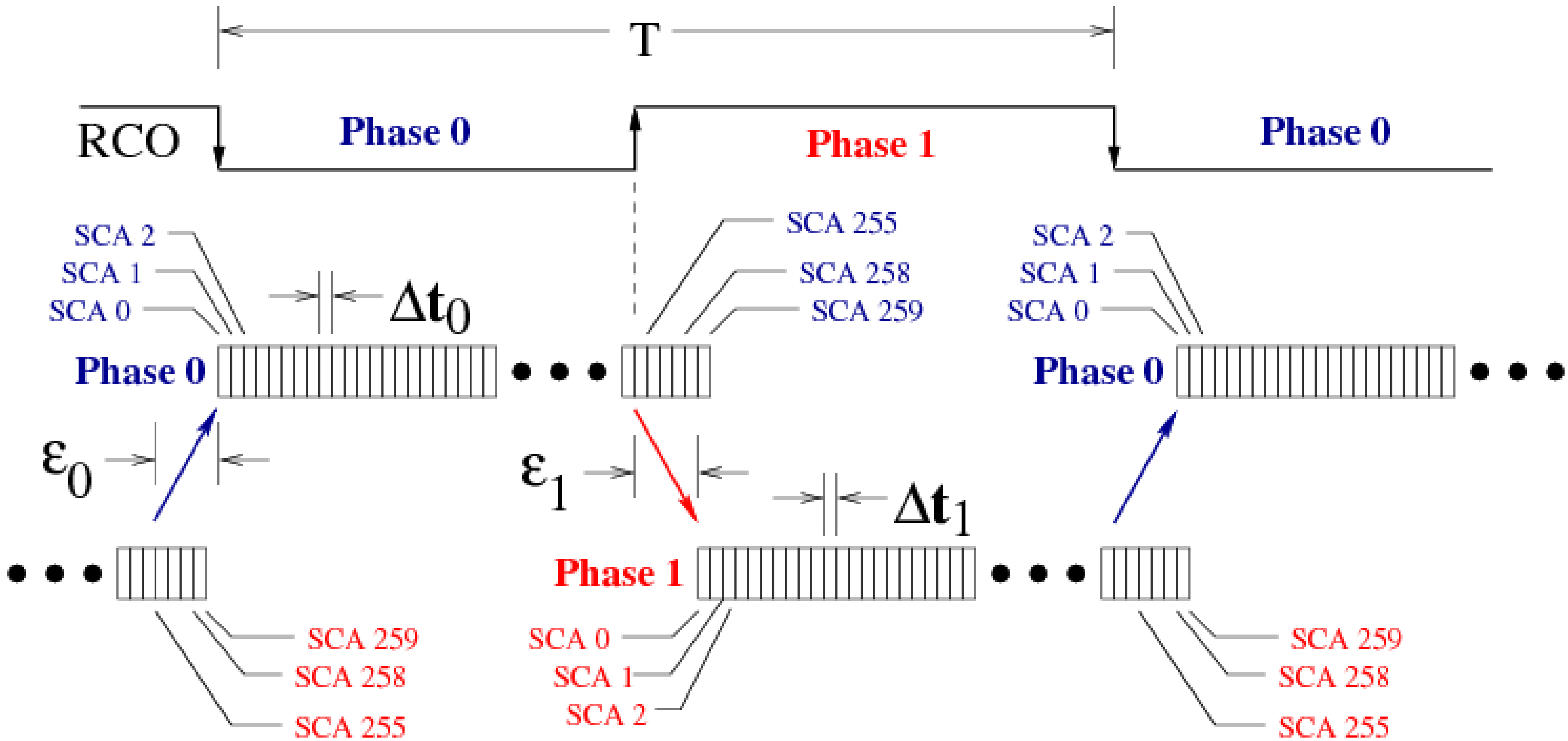






- Qualitative agreement obtained in SPICE

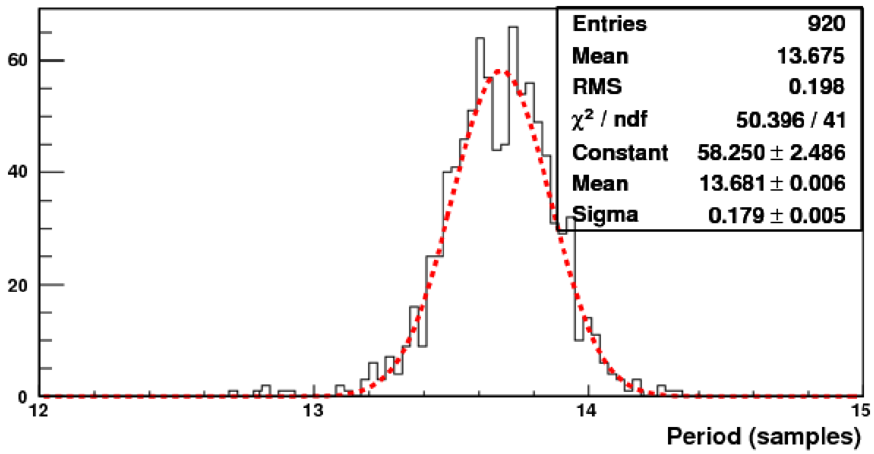
Timing Calibration Constants



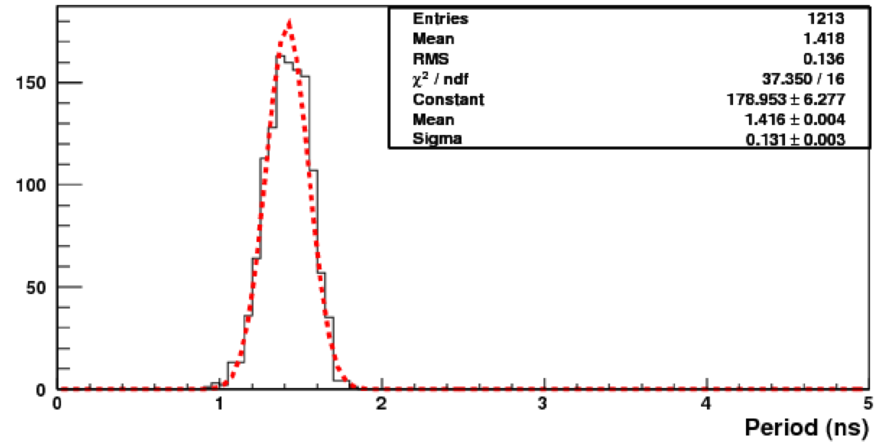
- T_0 != T_1 != ½ T
- Separate wrap time constants
- Need to determine Phase 0, 1 interleaving
- In general every Δt0, Δt1 different

Timing Calibrations (1)

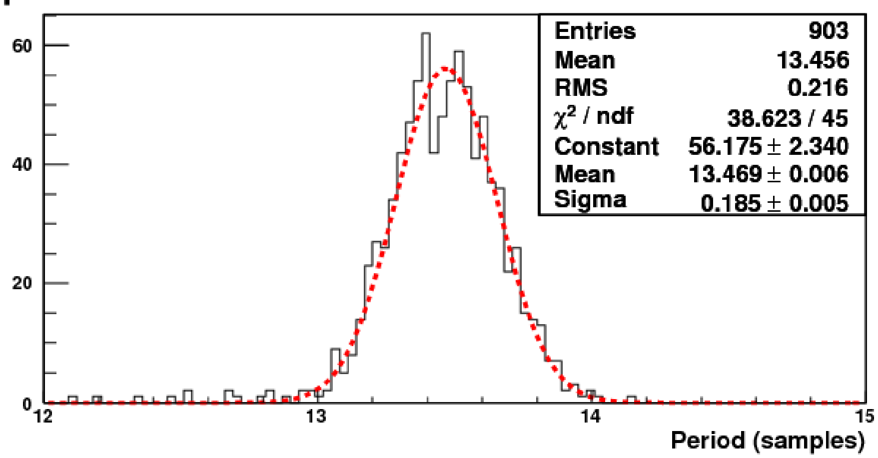
Square Wave Period -- Phase 0



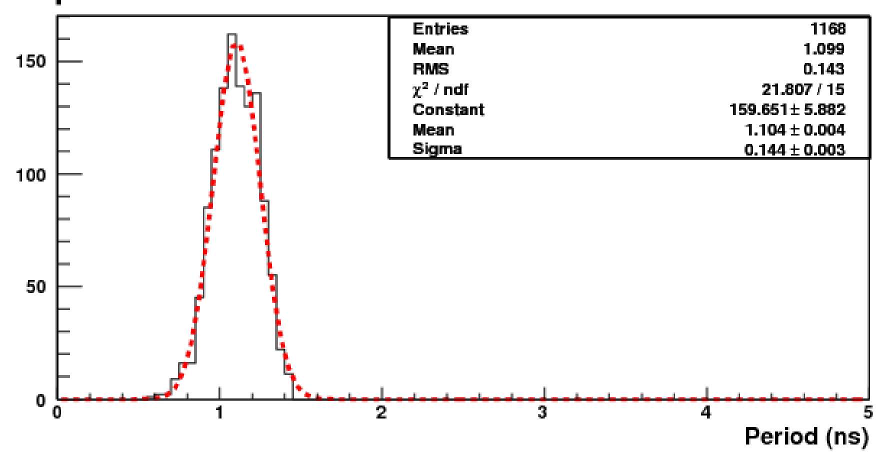
Wrap Offset -- Phase 0 to 1



Square Wave Period -- Phase 1



Wrap Offset -- Phase 1 to 0

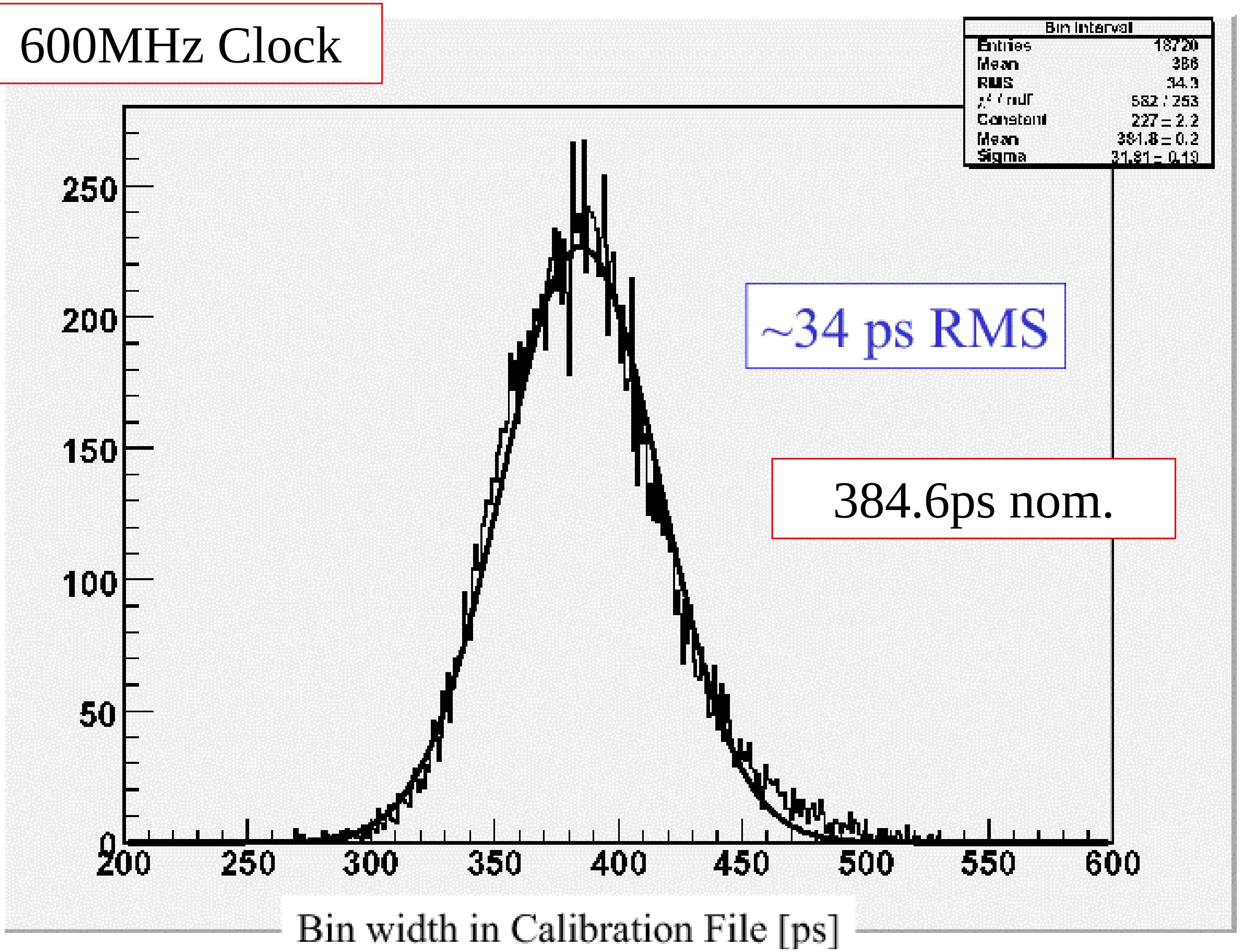


High-low != Low-high

Wrap-around time difference

Timing Calibrations (2)

600MHz Clock

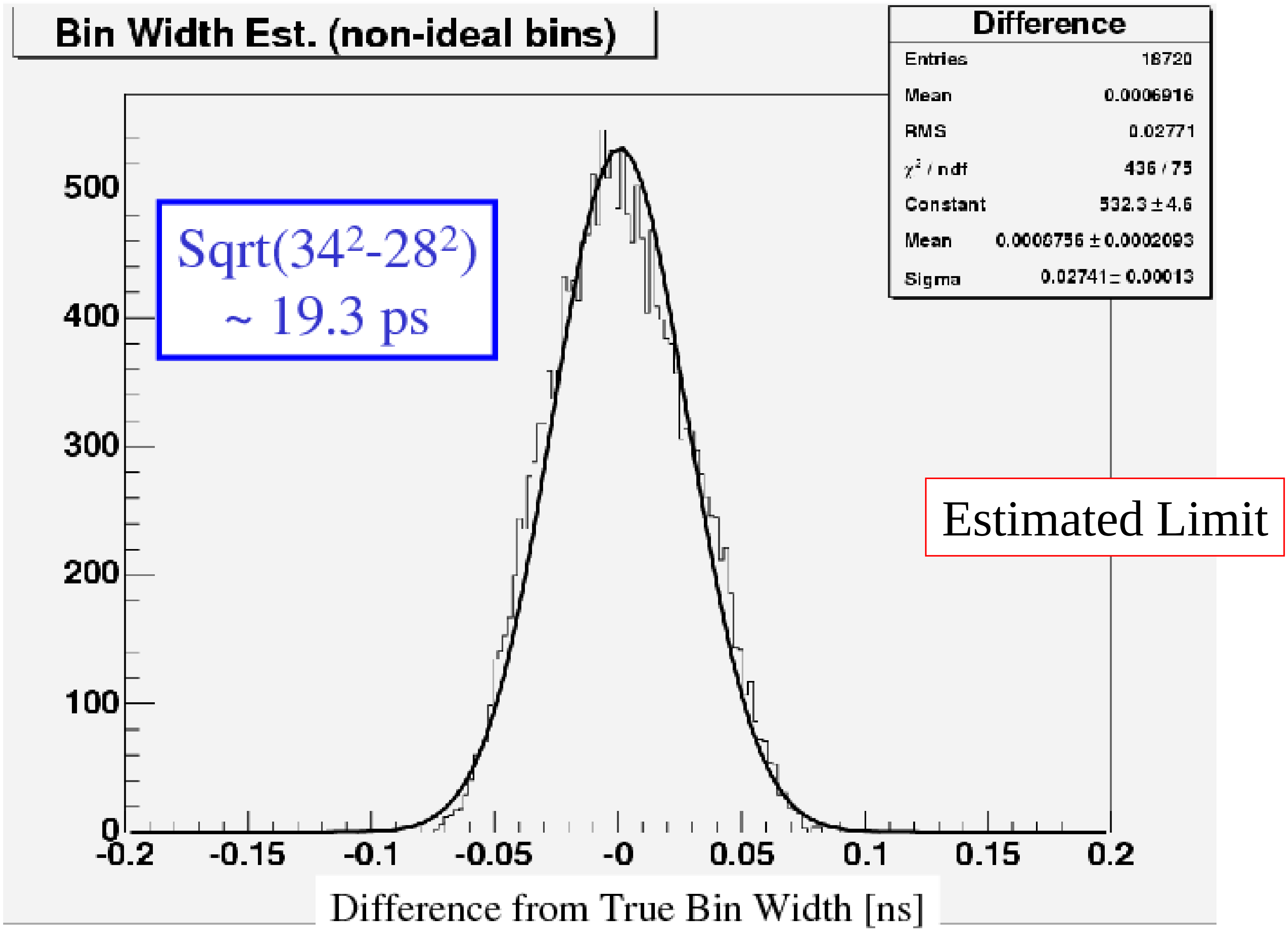


~34 ps RMS

384.6ps nom.

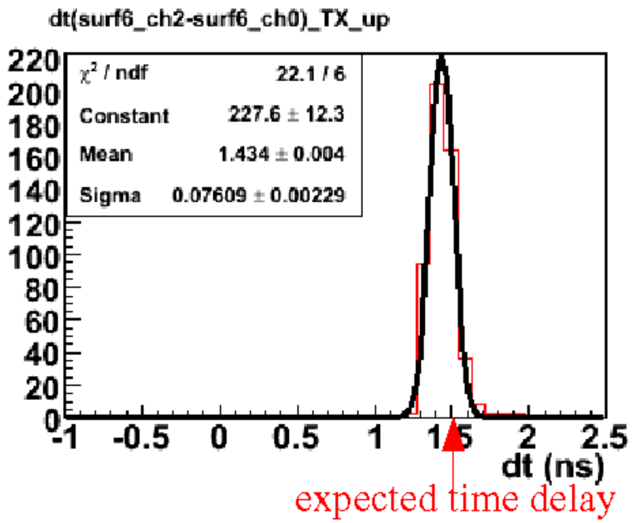
Bin-by-bin

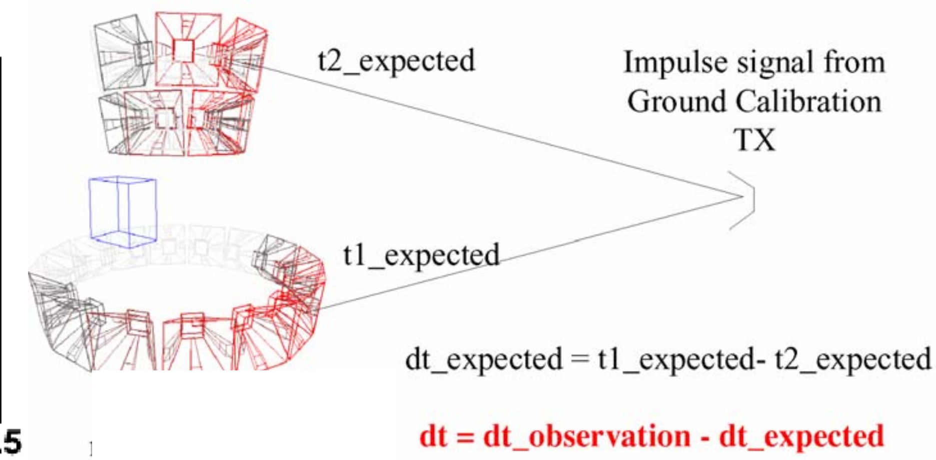
MC study of Calibration Technique



Timing vs Angle (with Impulse Calibration Radio Signal)

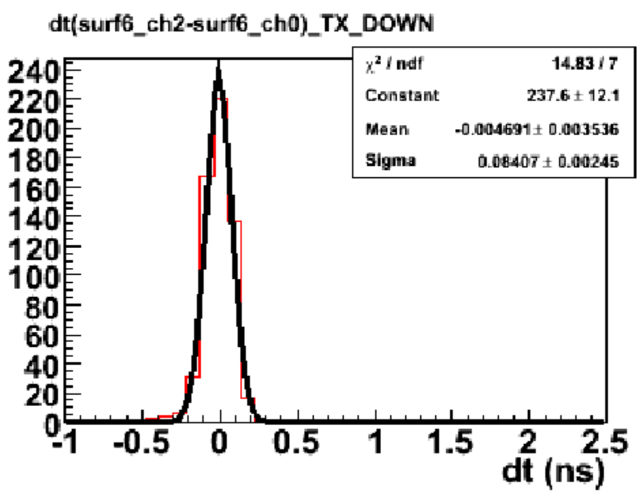
TX Up
by 1.56 m

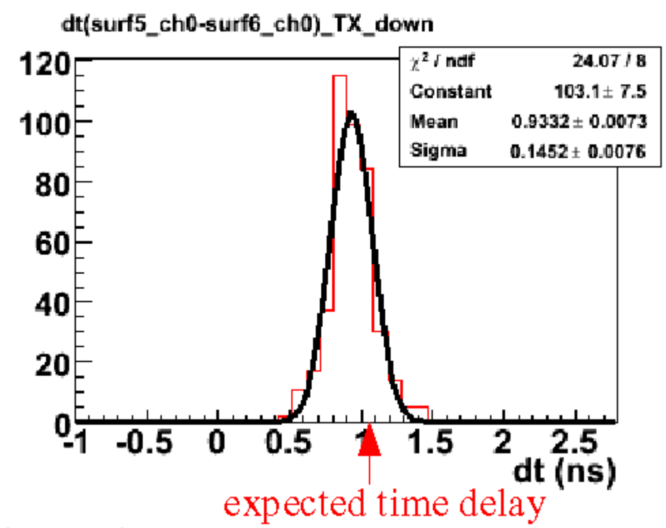




Vertical Angle
Dependency

TX Down



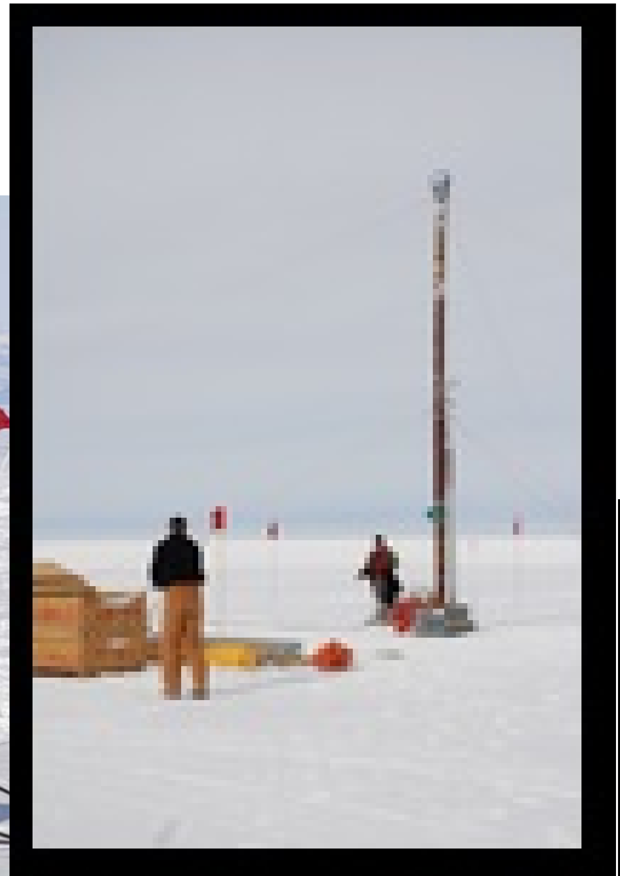


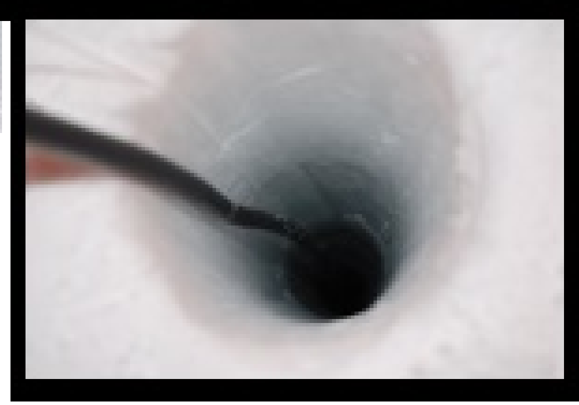
Jiwoo Nam
UC Irvine

Face to TX ← Horizontal Angle Dependency → Off by 1 Antenna

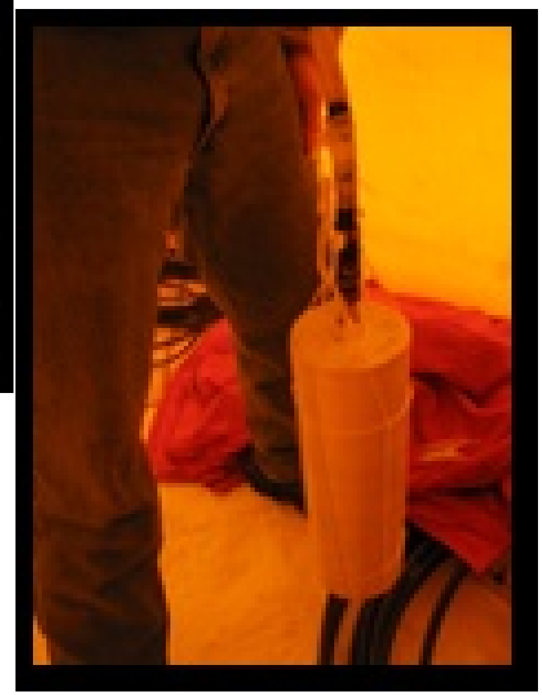
Calibration with Realistic Signals

Ground pulser





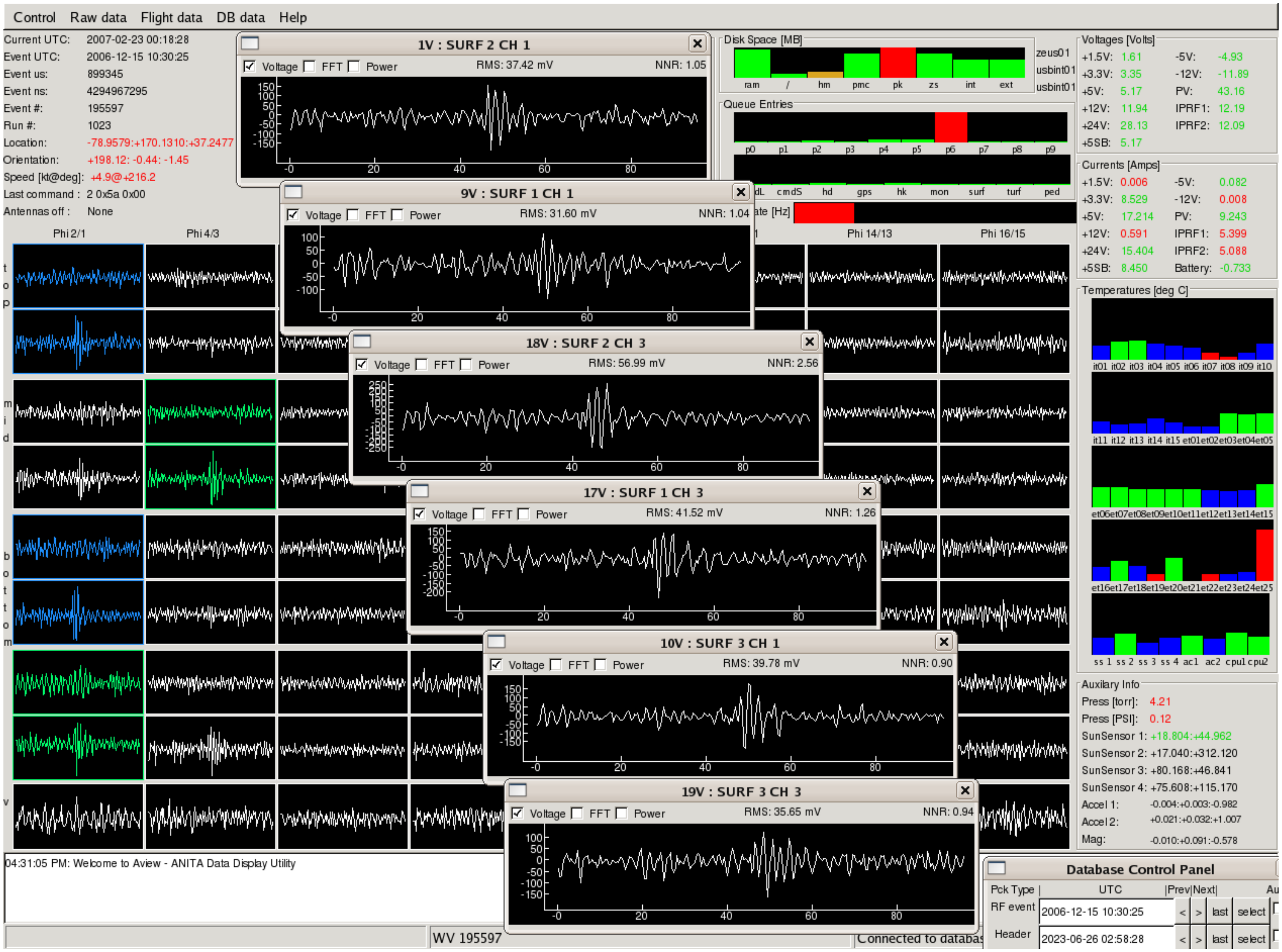
Bore hole pulser



- Ice 80m thick and messy

Dipole

Validation data: borehole pulser



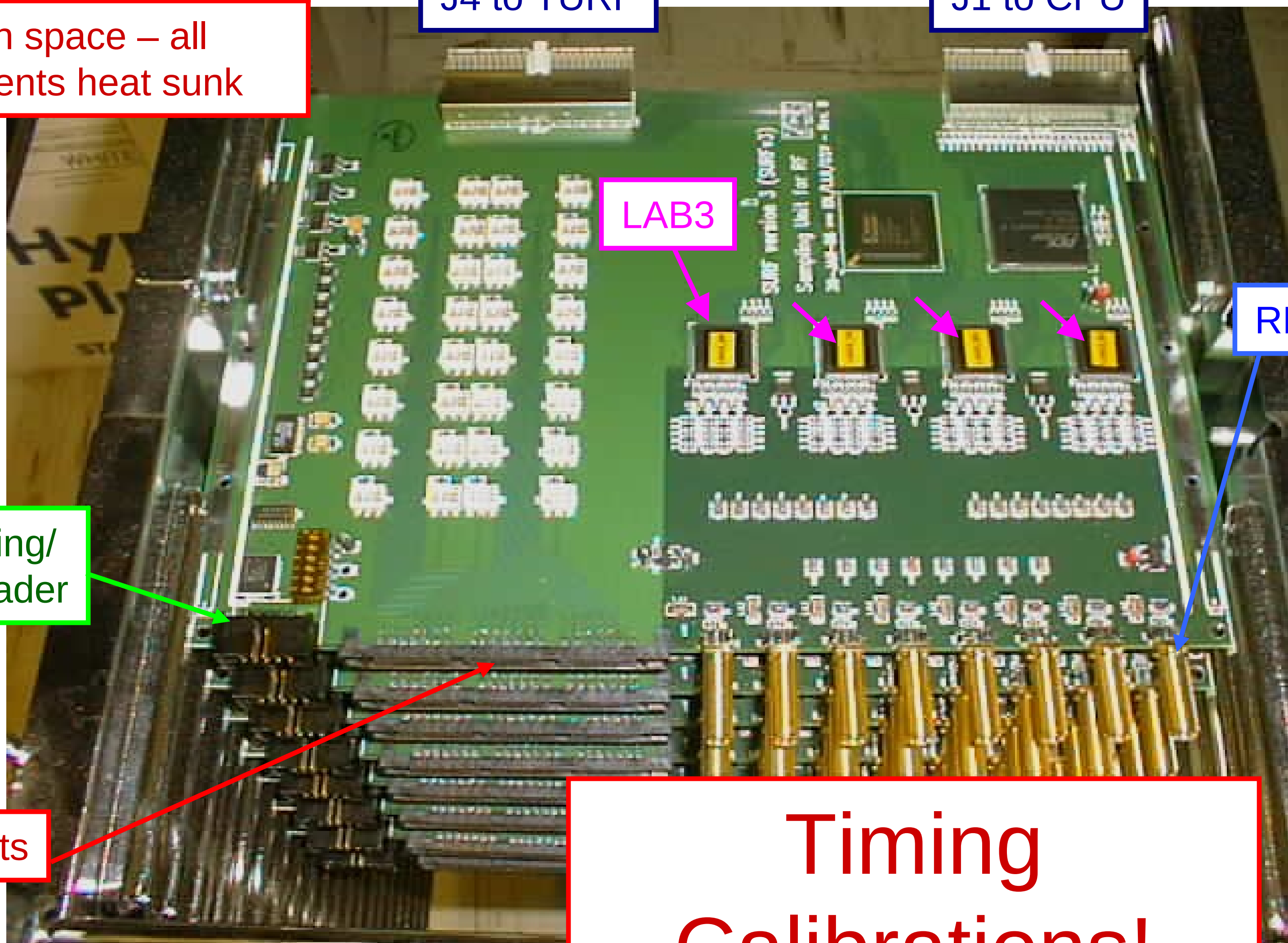
- RF Impulses from borehole antenna at Williams field

- Detected at payload out to 300-400 km, consistent with expected sensitivity

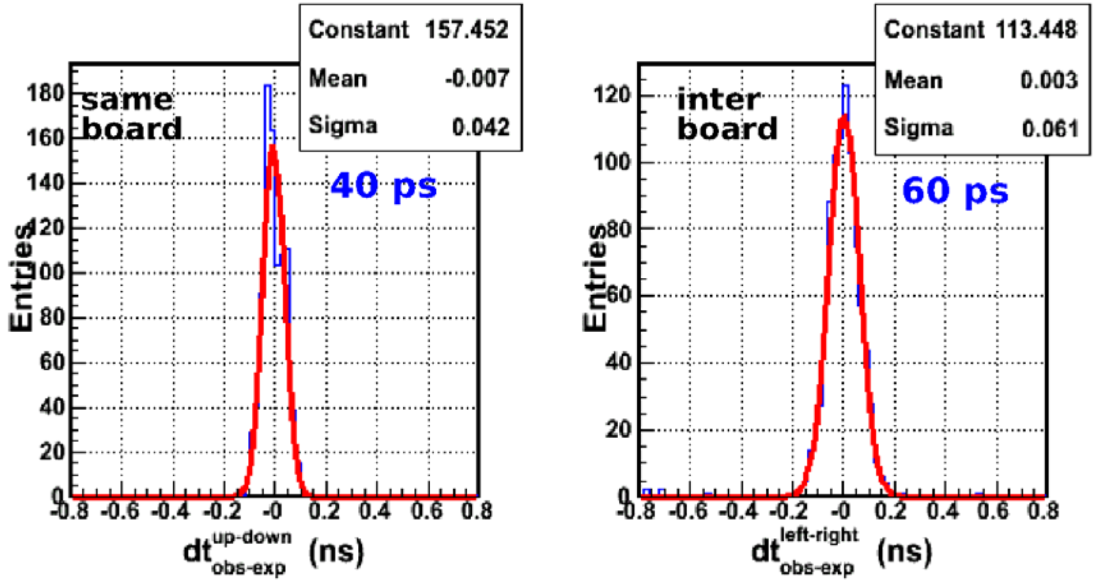
- Allows trigger & pointing calibration

SURFv3 Board

(SURF = Sampling Unit for RF)
(TURF = Trigger Unit for RF)



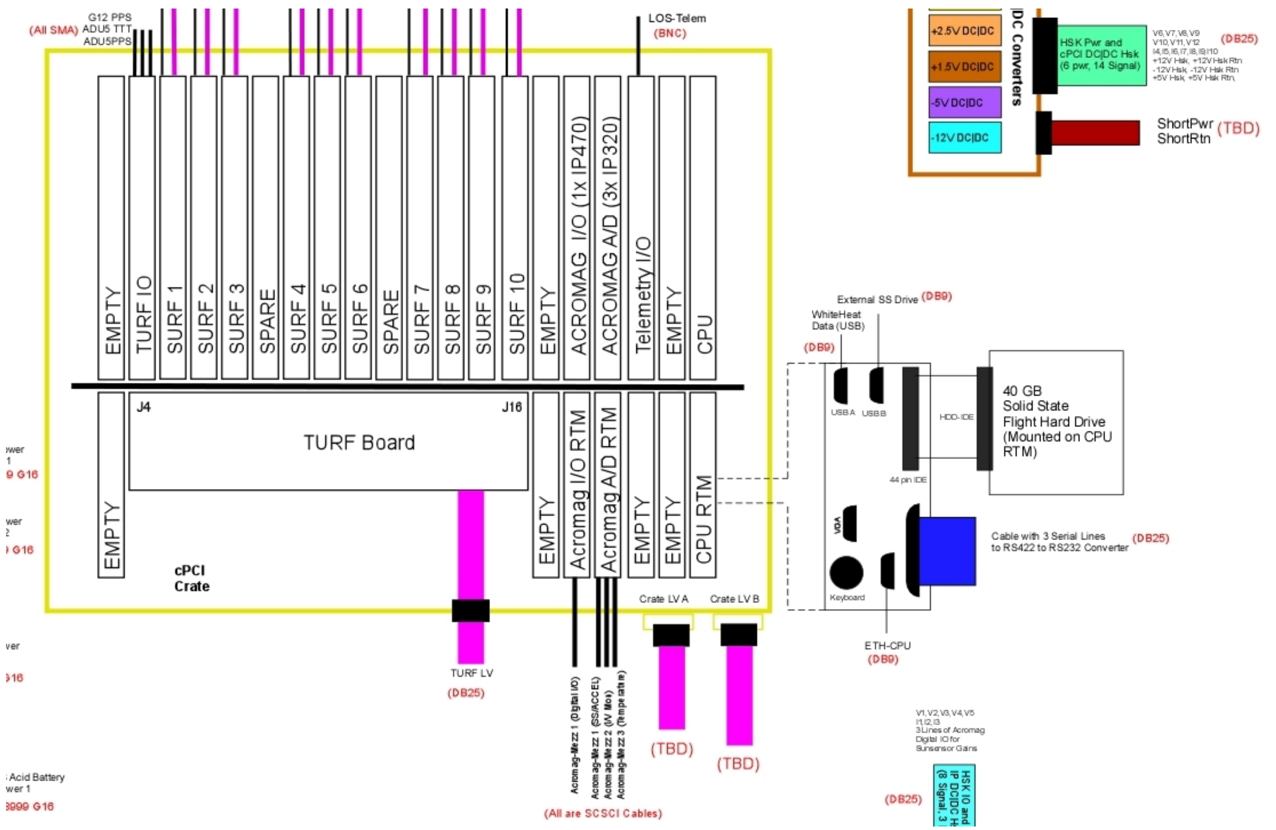
Timing Calibrations!



Jiwoo Nam
Natl Taiwan U.

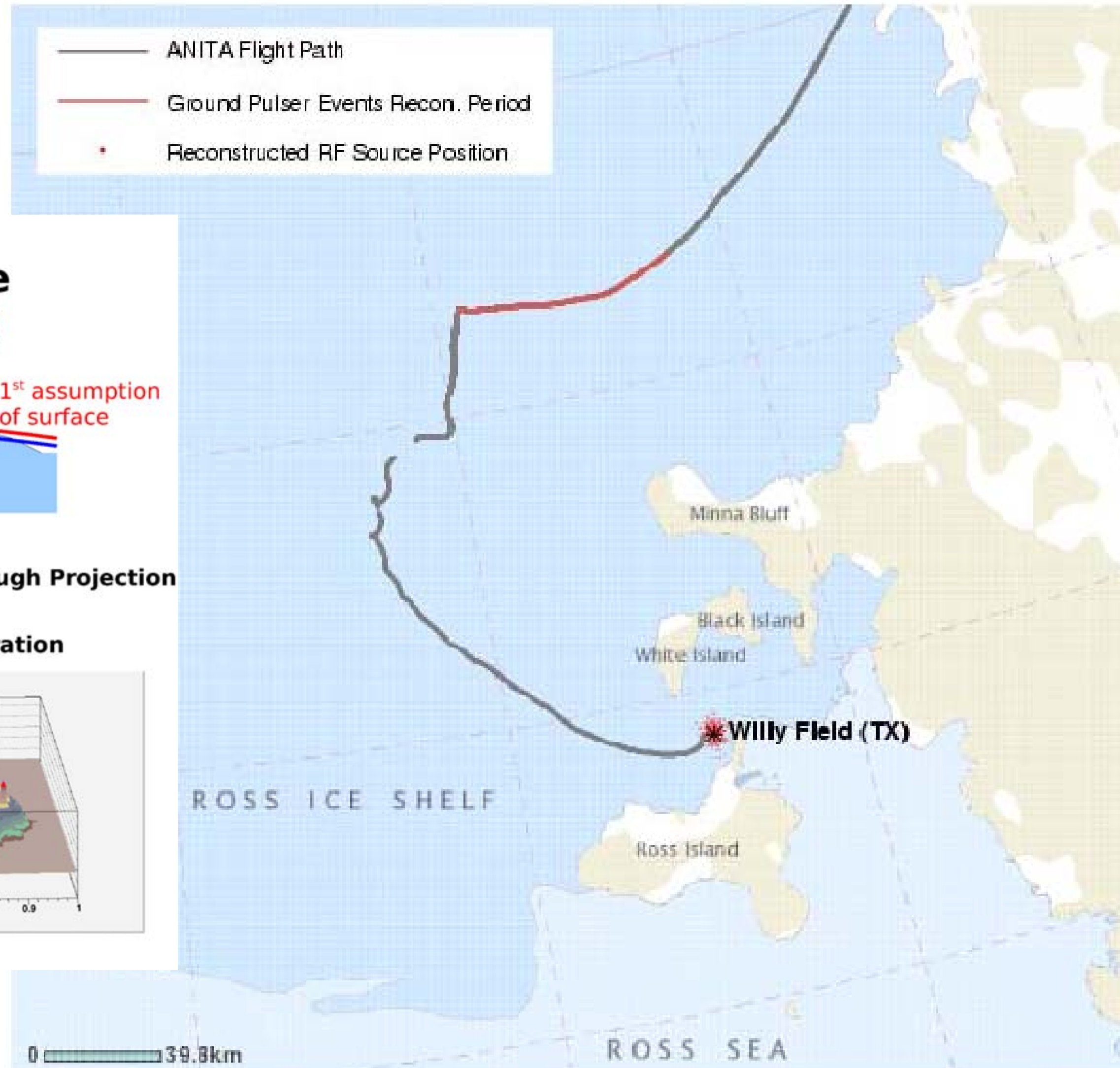
~47ps due to
Time Ref.
Passing

(33MHz clock)

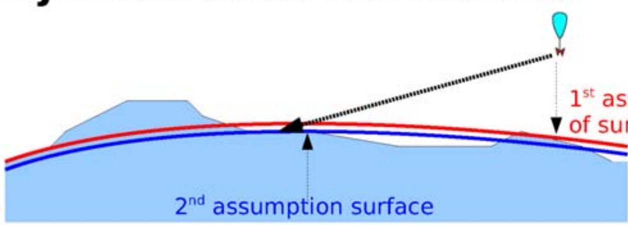


G. Varner -- LABRADOR ASIC Family -- U-Chicago Timing Meeting

After full calibration – 100's km downrange



RF Projection onto the surface

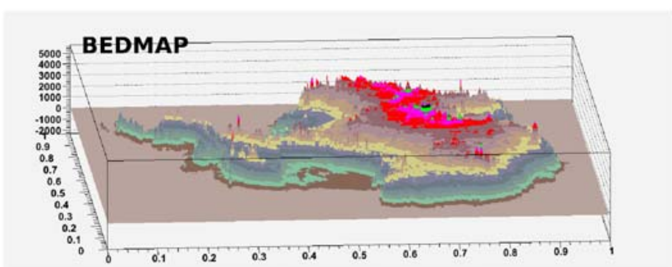


Fast Algorithm: Line Sphere intersection

1st R_{earth} =Geoid + Surface @ Ballon position -> Rough Projection

2nd R_{earth} = Geoid + Surface @ (position from 1st)

3rd: one more iteration -> converged after 2nd iteration



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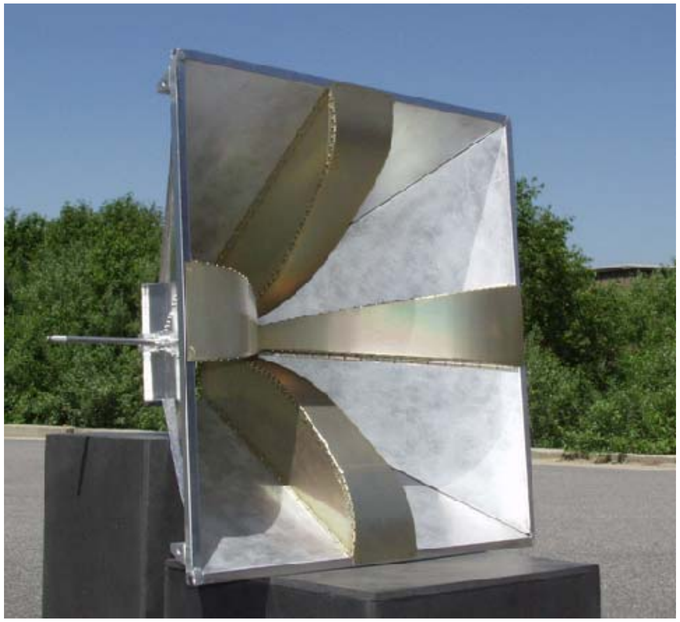
If simply scale:

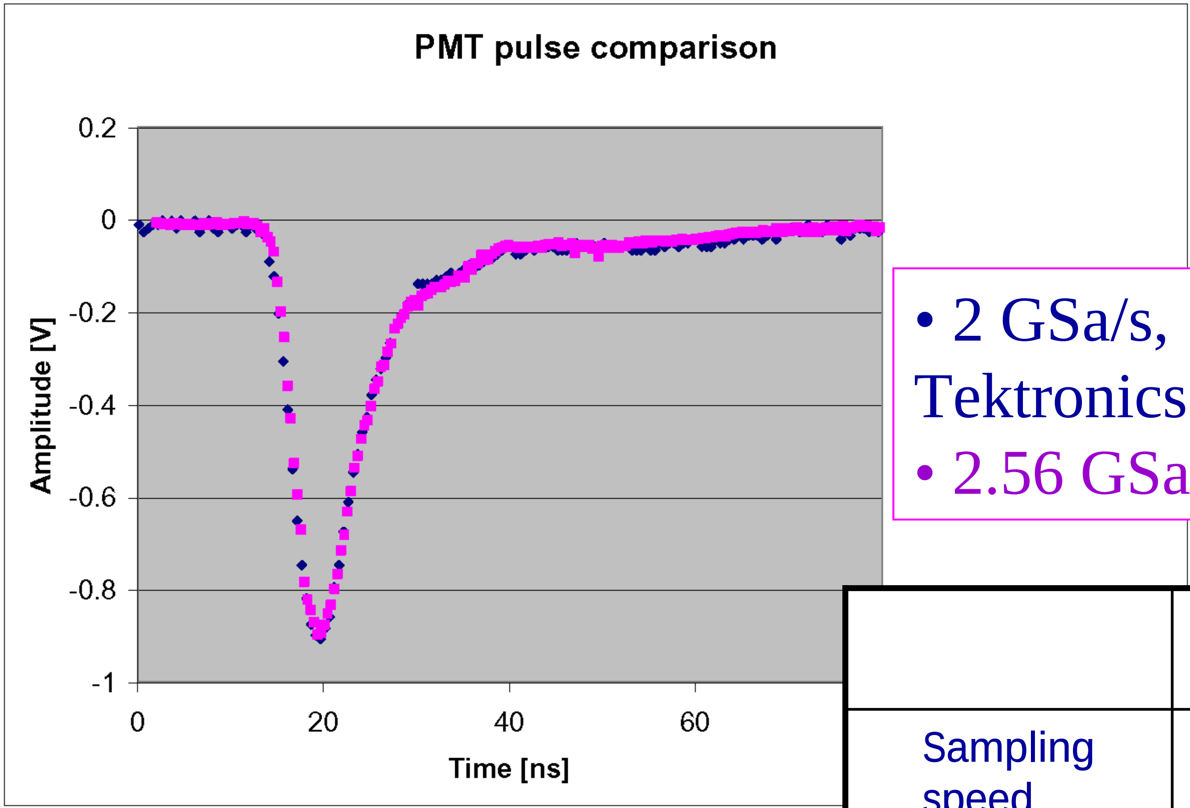


35cm → 350nm (10^6)
40ps → 40as !

Why doesn't this work?

- BW 1GHz → 1PHz
- N γ ~ Infty.
- Anyway, only talking about factor 40
- Photonics in its infancy – direct O-O

High Speed sampling



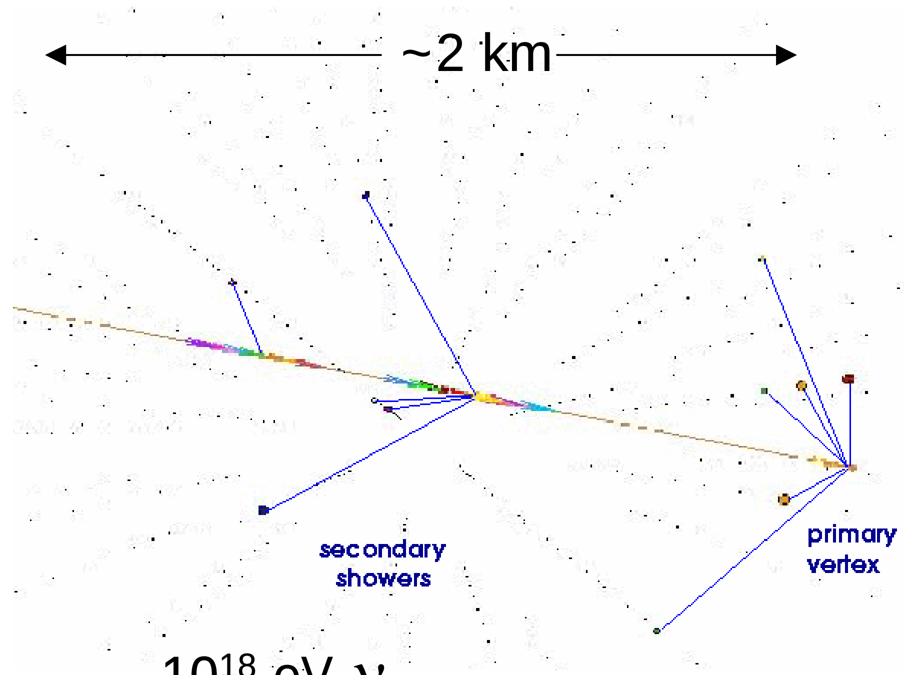
- 2 GSa/s, 1GHz ABW Tektronics Scope
- 2.56 GSa/s LAB

	LABRADOR	Commercial
Sampling speed	1-3.7 GSa/s	2 GSa/s
Bits/ENOBs	12/9-10	8/7.4
Power/Chan.	<= 0.05W	5-10W
Cost/Ch.	$10 (vol)	> 1k$

"oscilloscope on a chip"

Deeper sampling Desired for

Extensive radio array for UHE neutrino

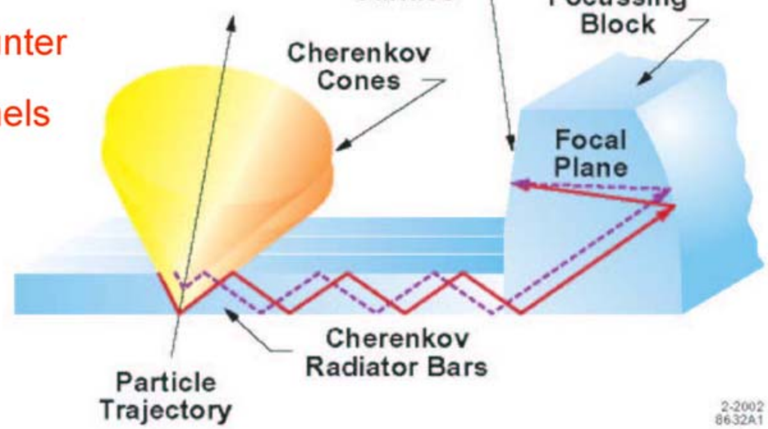


10^{18} eV ν_μ

Focusing DIRC

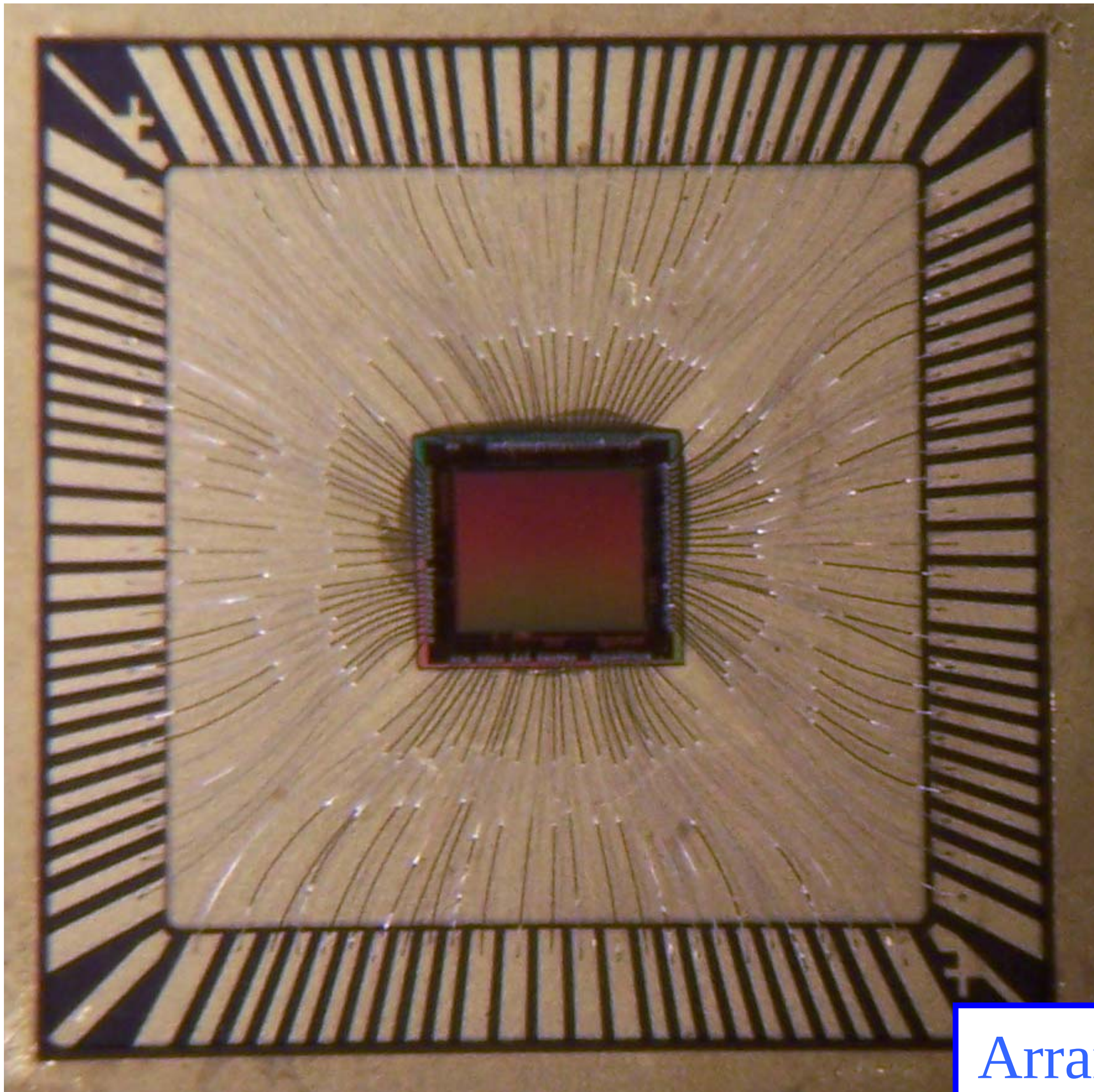
~few mm x few mm: few kCh/counter

*~100 counters: few 100k channels



PID Upgrade – precision timing

Buffered LABRADOR (BLAB1) ASIC



3mm x 2.8mm, TSMC 0.25um

- Single channel
- 64k samples deep, same SCA technique as LAB, no ripple pointer
- Multi-MSa/s to Multi-GSa/s
- 12-64us to form Global trigger

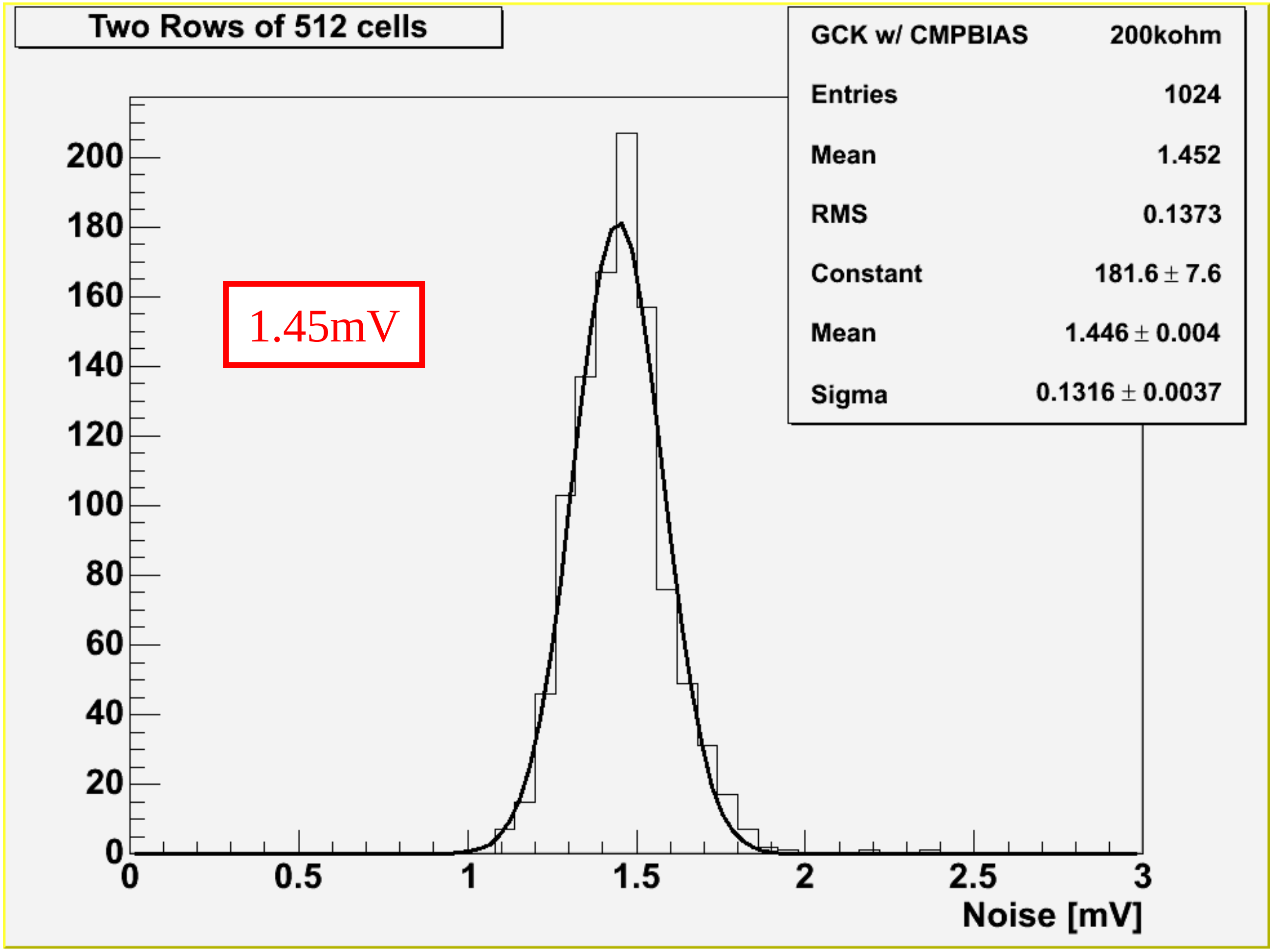
Arranged as 128 x 512 samples
Simultaneous Write/Read

Buffered LABRADOR (BLAB1) ASIC

- 10 real bits of dynamic range, single-shot

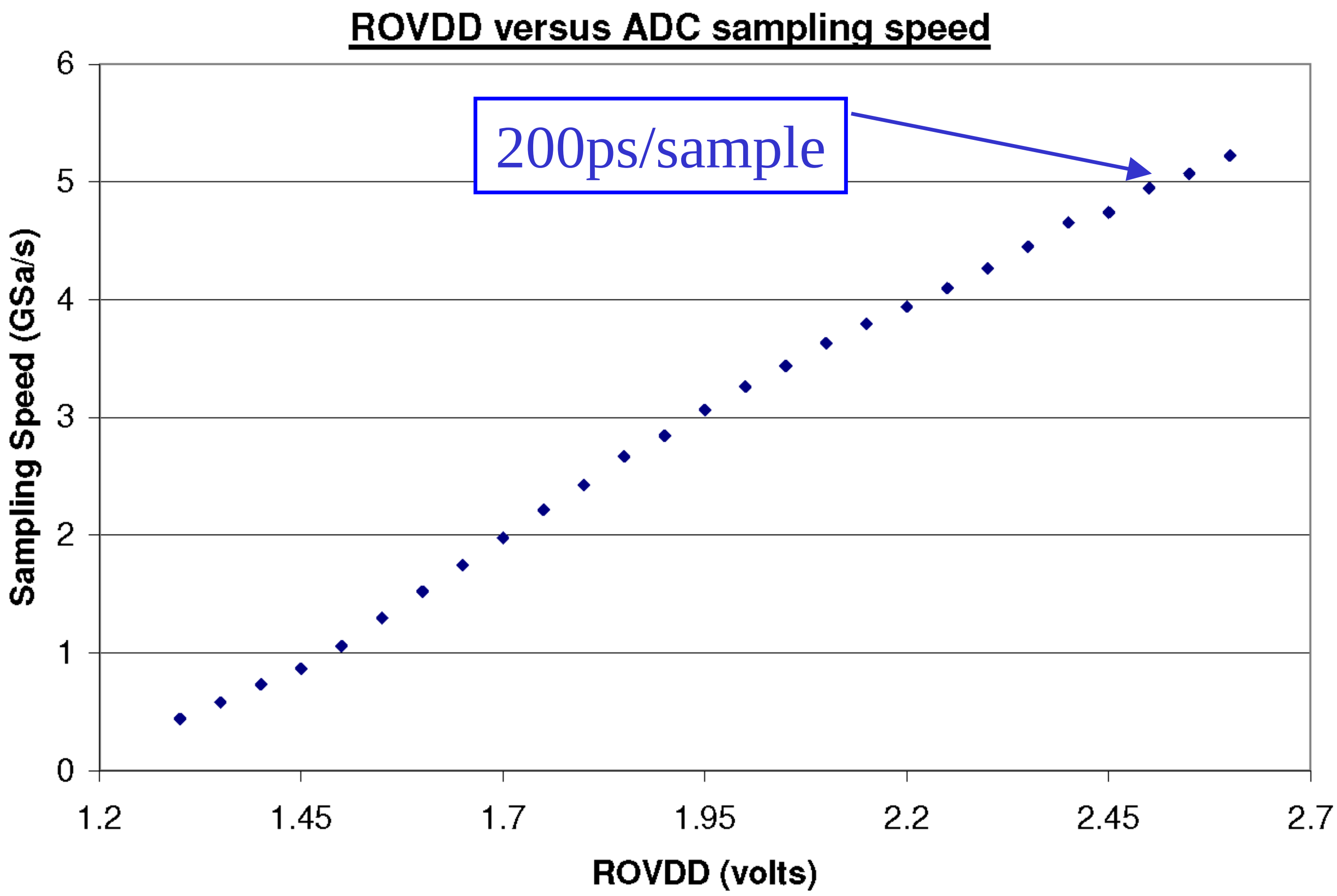
Measured Noise

1.6V dynamic range



BLAB1 Sampling Speed

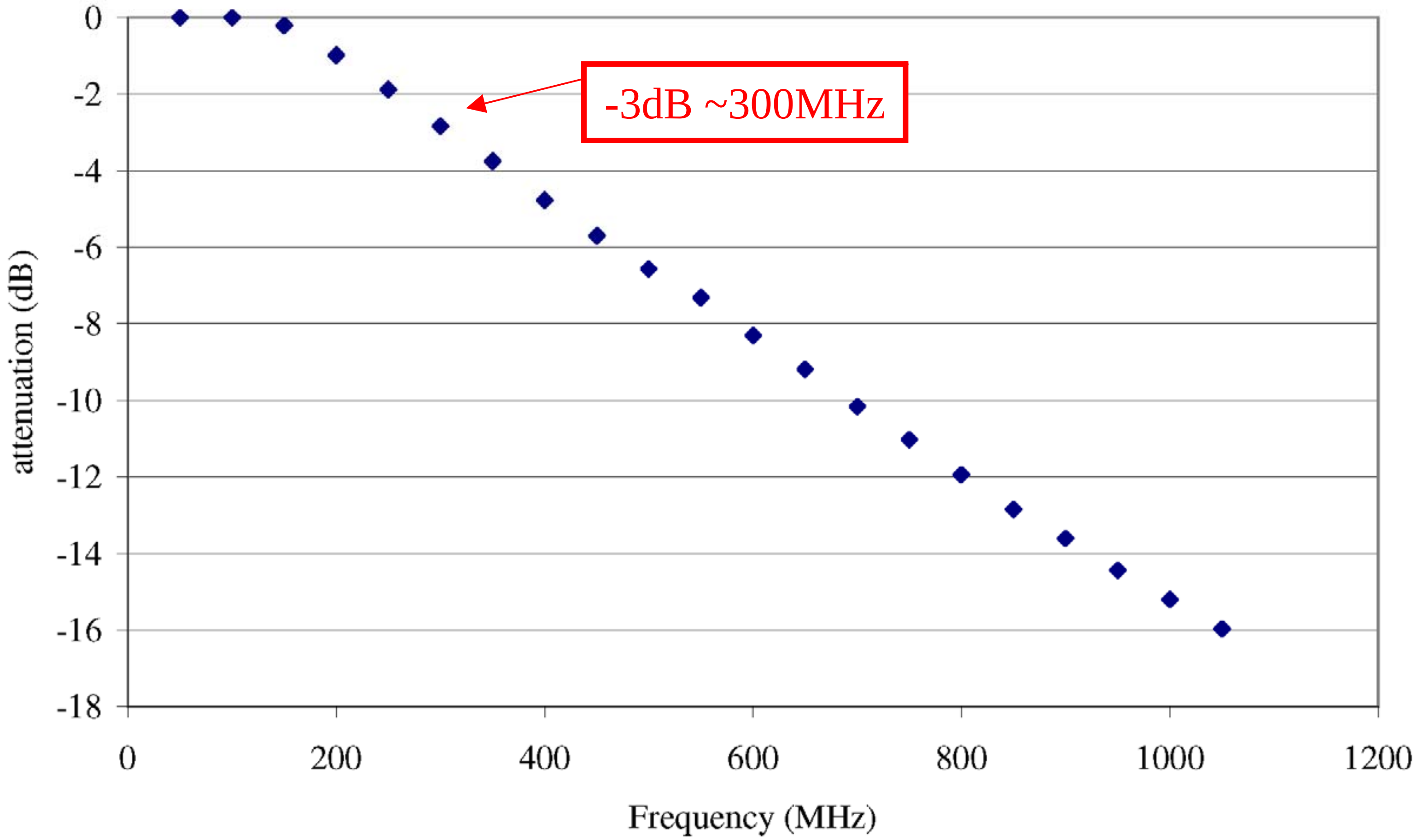
Can store 13us at 5GSa/s (before wrapping around)



Single sample:
200/SQRT(12)
~ 58ps

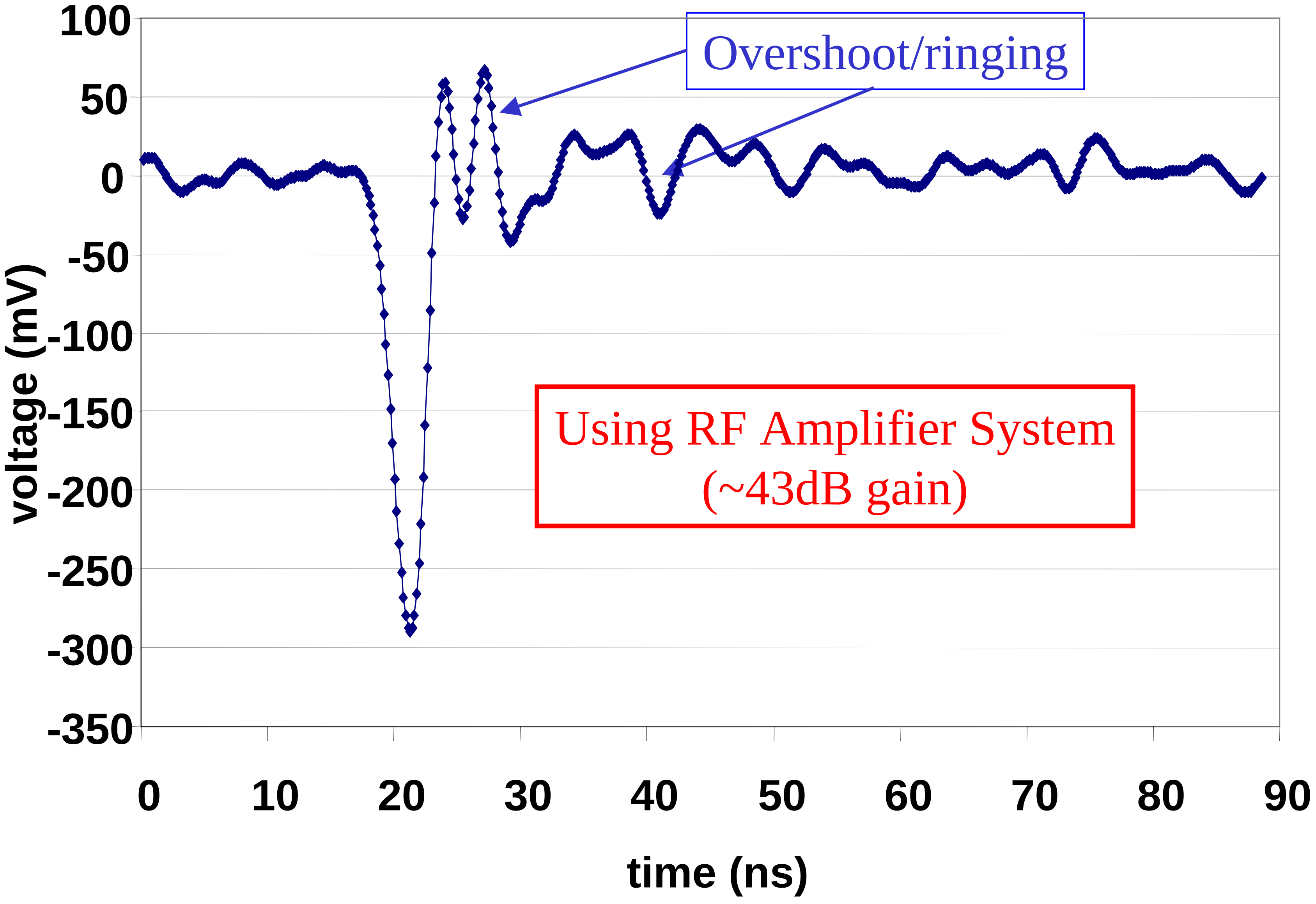
But, have
Complete
Waveform
Information

BLAB1 Analog Bandwidth

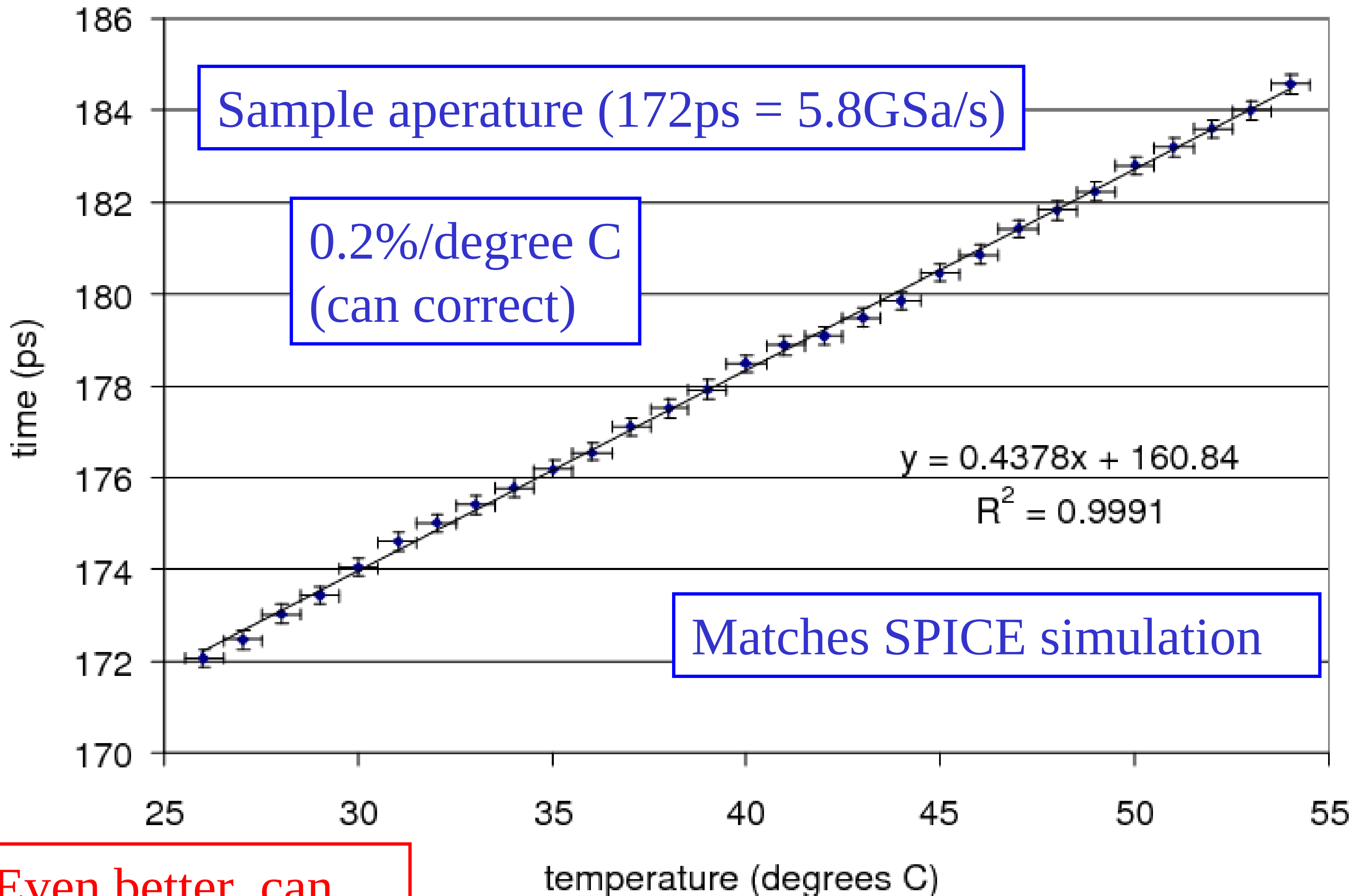


- A few fixes (lower power, higher BW)
- Multi-channel: BLAB2 (16), TARGET (16 w/ gain), LARC (32) and PrX

Typical single p.e. signal [Burle]

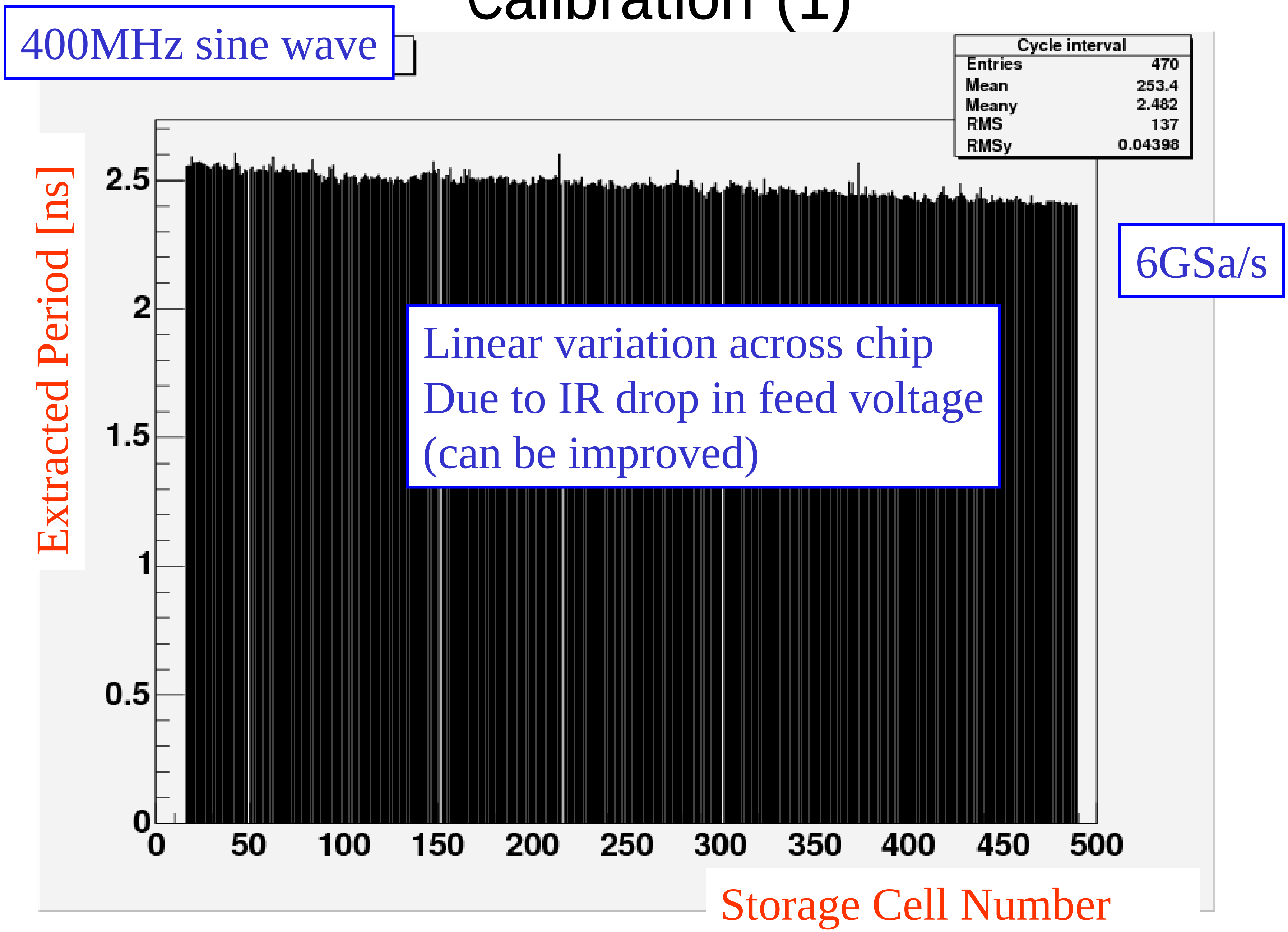


Temperature Dependence



Even better, can delay lock

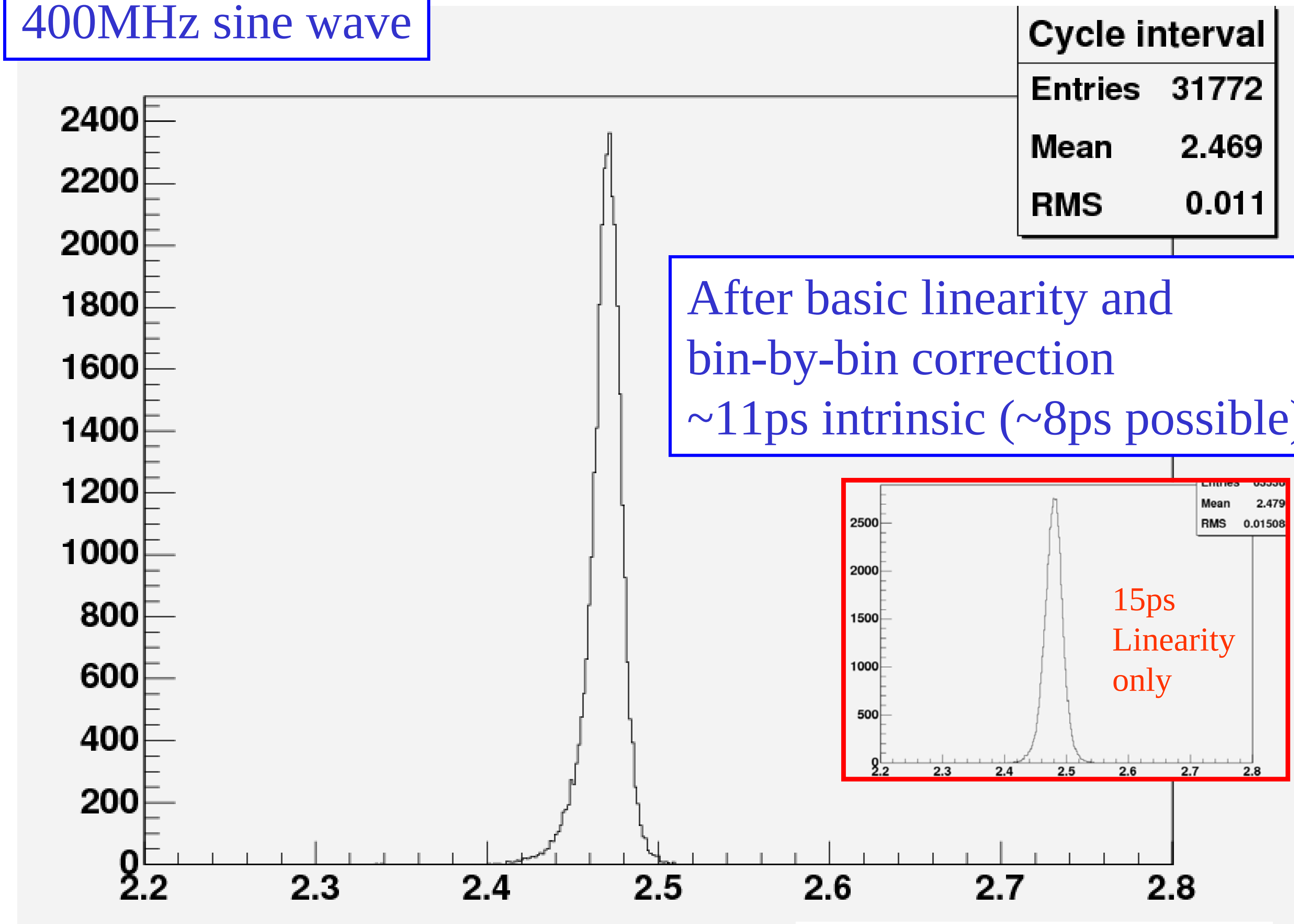
Calibration (1)



Calibration (2)

6GSa/s

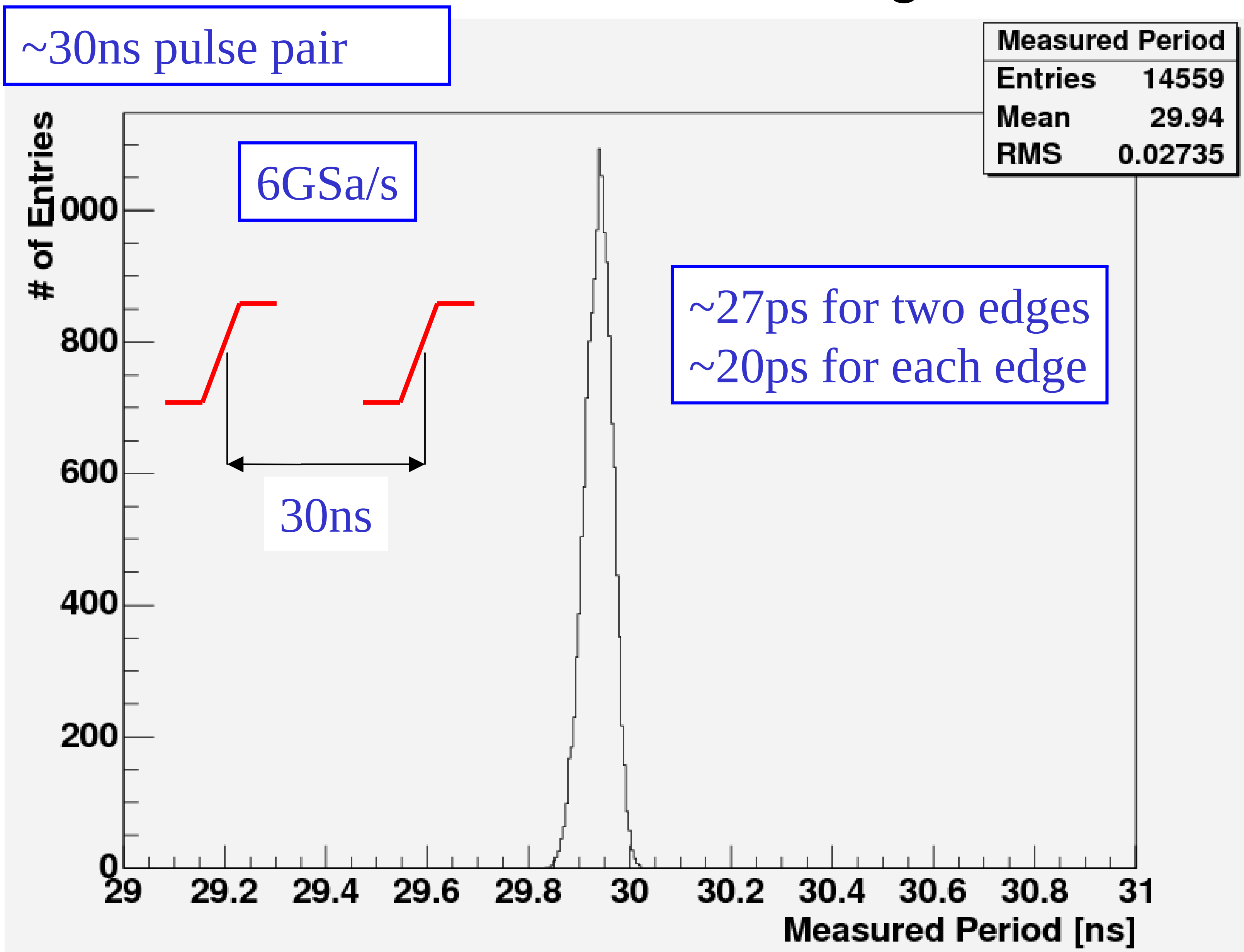
400MHz sine wave



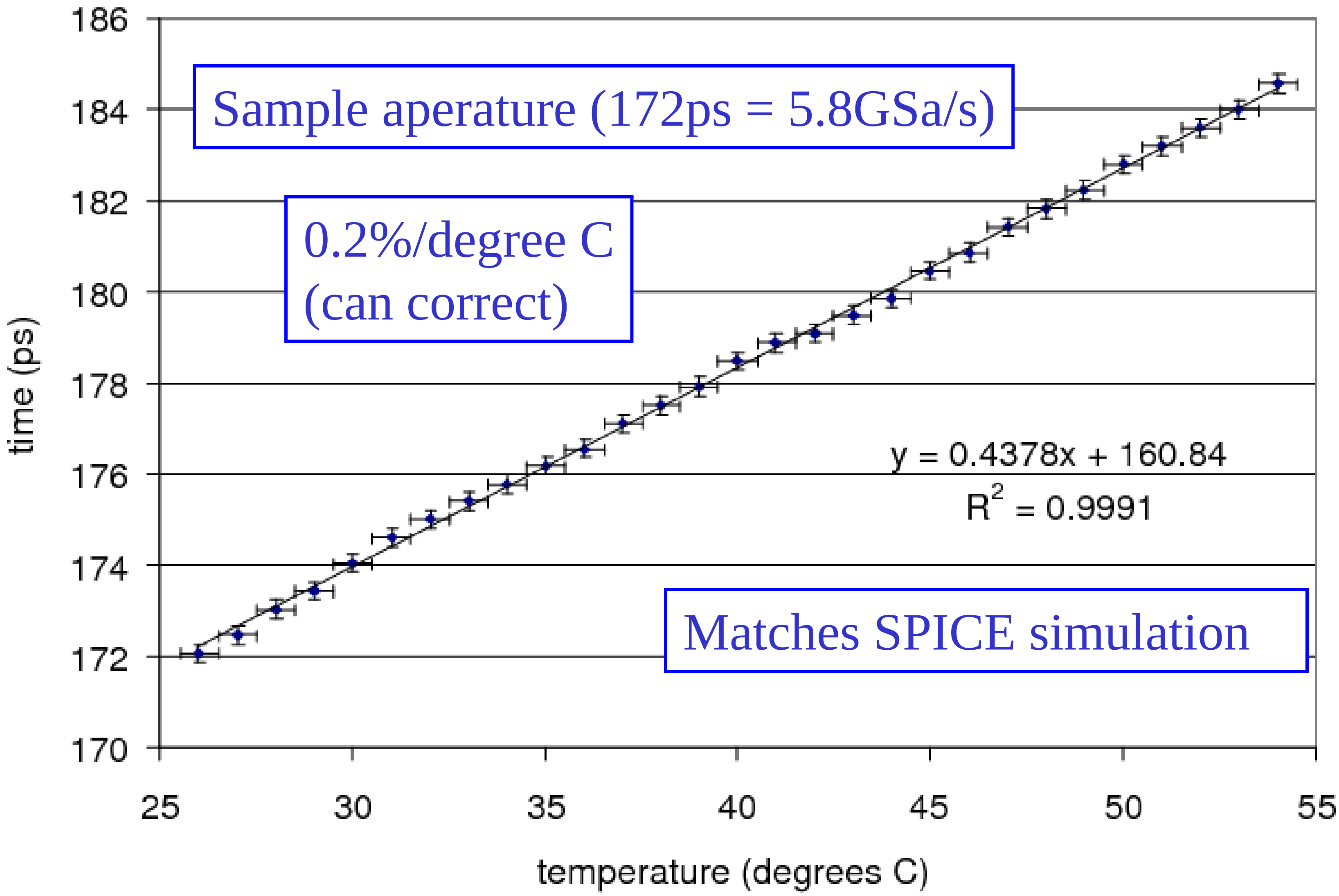
After basic linearity and bin-by-bin correction
~11ps intrinsic (~8ps possible)

Extracted Period [ns]

Bench Test timing



Temperature Dependence

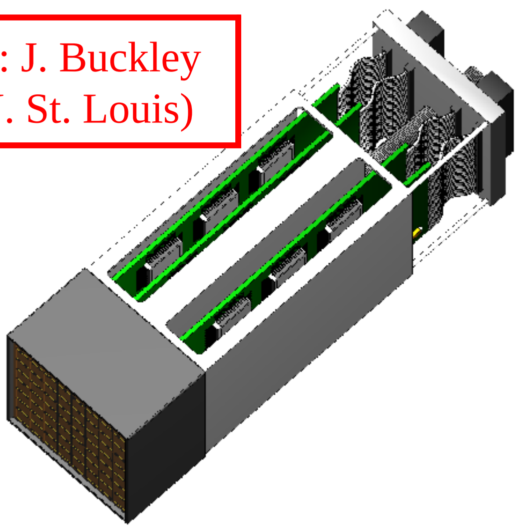


BLAB2

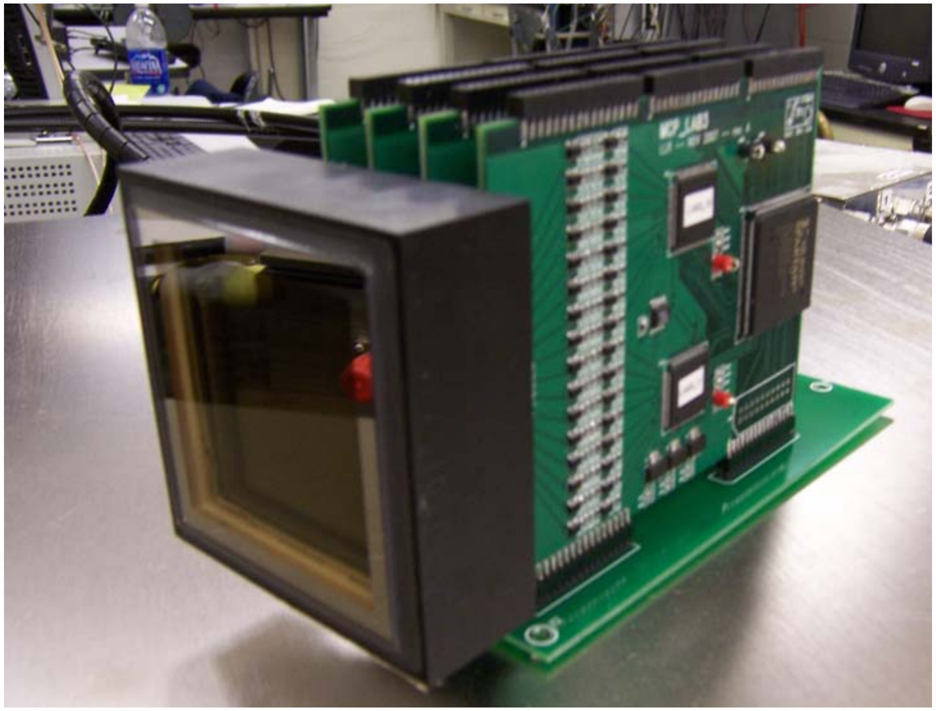
- **Initial Target: New f-DIRC Readout System**

TABLE II: *BLAB2 ASIC Specifications.*

Item	*Value*
Photodetector Input Channels	16
Linear sampling arrays/channel	2
Storage cells/linear array	512
Sampling speed (Giga-samples/s)	2.0 - 10.0
Outputs (Wilkinson)	32



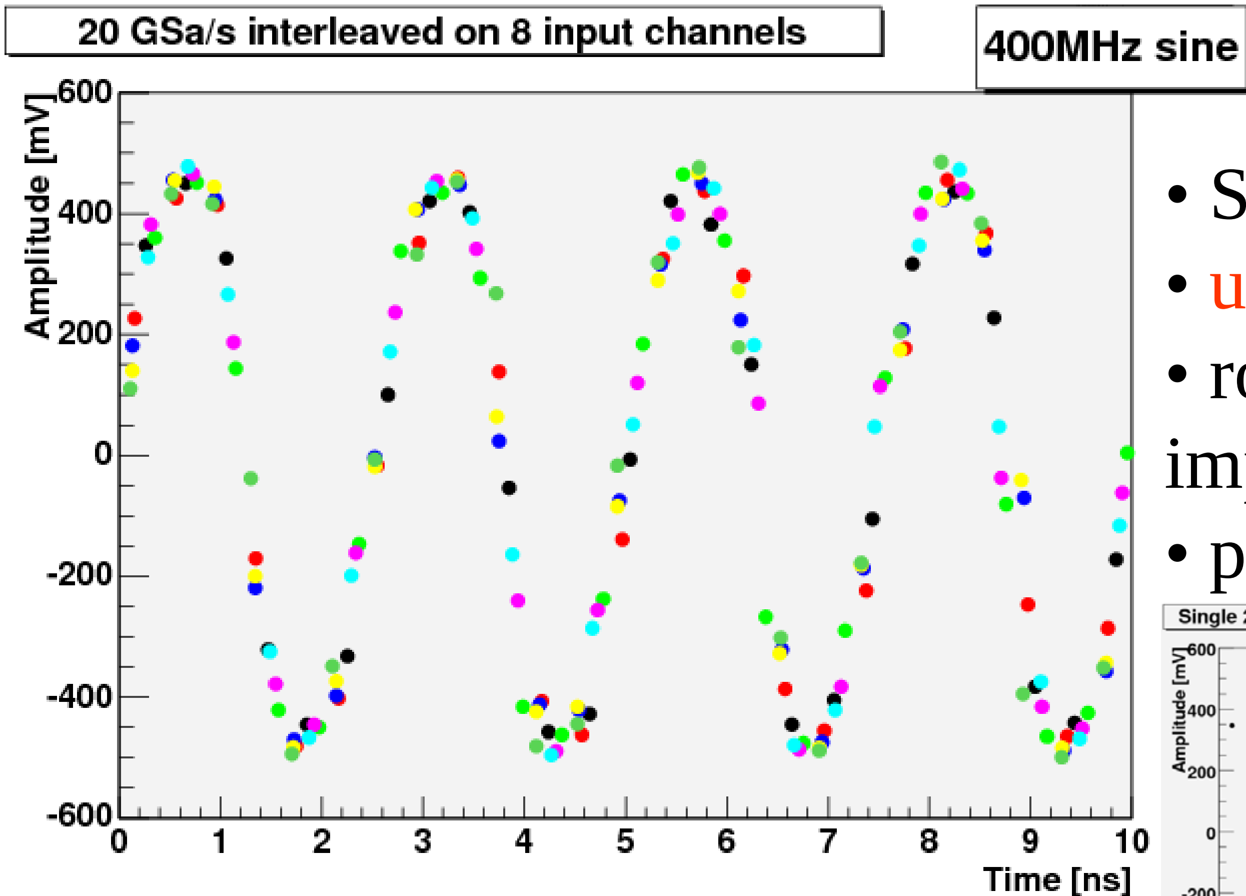
Courtesy: J. Buckley (Wash U. St. Louis)



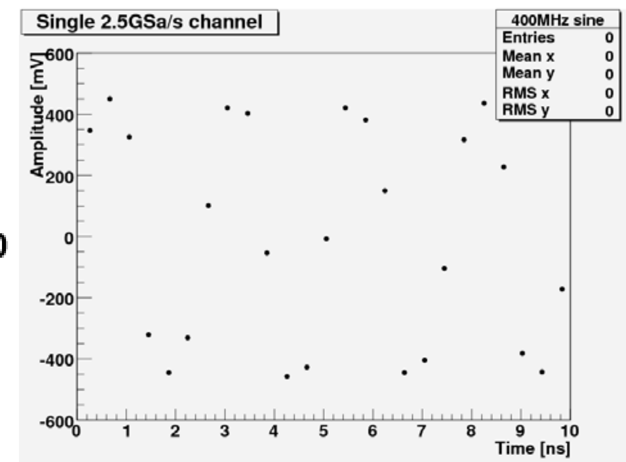
Gen. 0 Prototype (LAB3)

Target Submission: Feb. 11, 2008

Interleaved Operation



- Single shot
- uncalibrated
- room for improvement
- push BW higher



LARC ASIC:

64 chan @ 5 GSa/s = 384GSa/s

→Streak camera type applications – ps timing

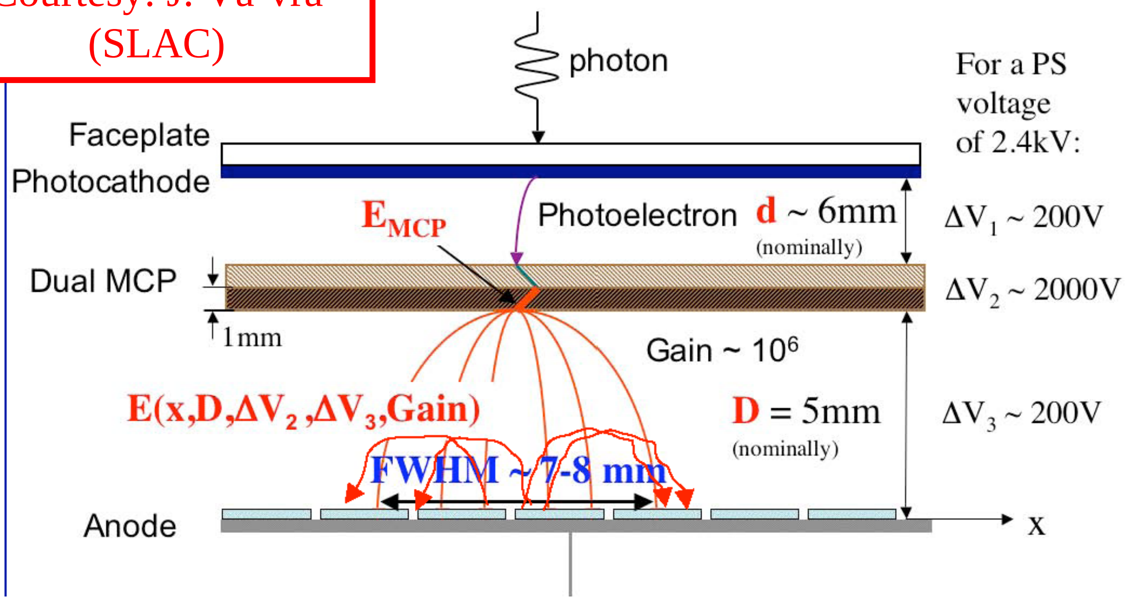
If jitter due to random noise, more samples better

Limitations 1: Analog Bandwidth

Difficult to couple in Large BW (C is deadly)

At what point stop getting useful information?

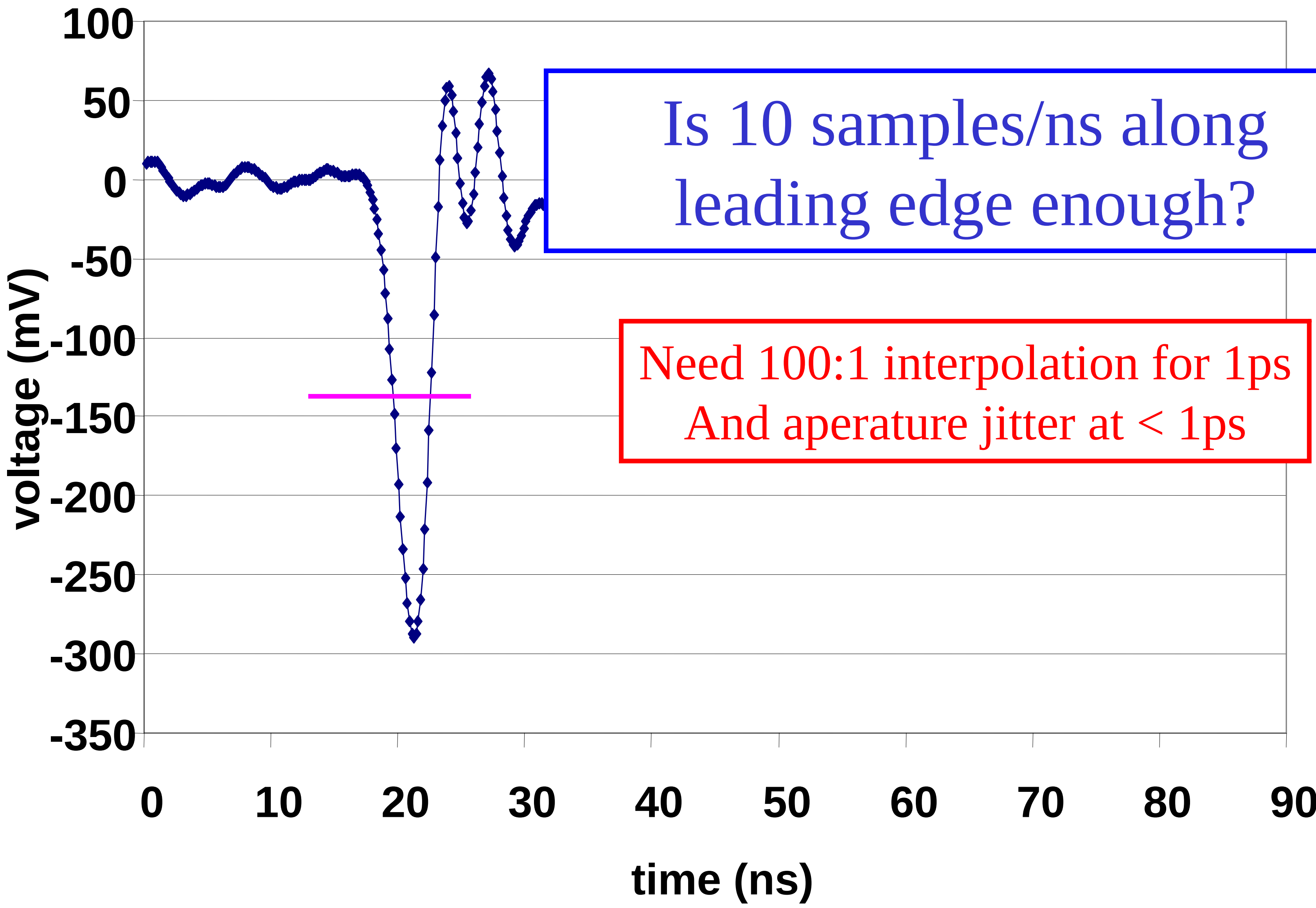
Courtesy: J. Va'vra (SLAC)



$$f_{3dB} = 1/2\pi ZC$$

Limitations 2: Interpolation Error

Tied to Bandwidth Issue



Is 10 samples/ns along leading edge enough?

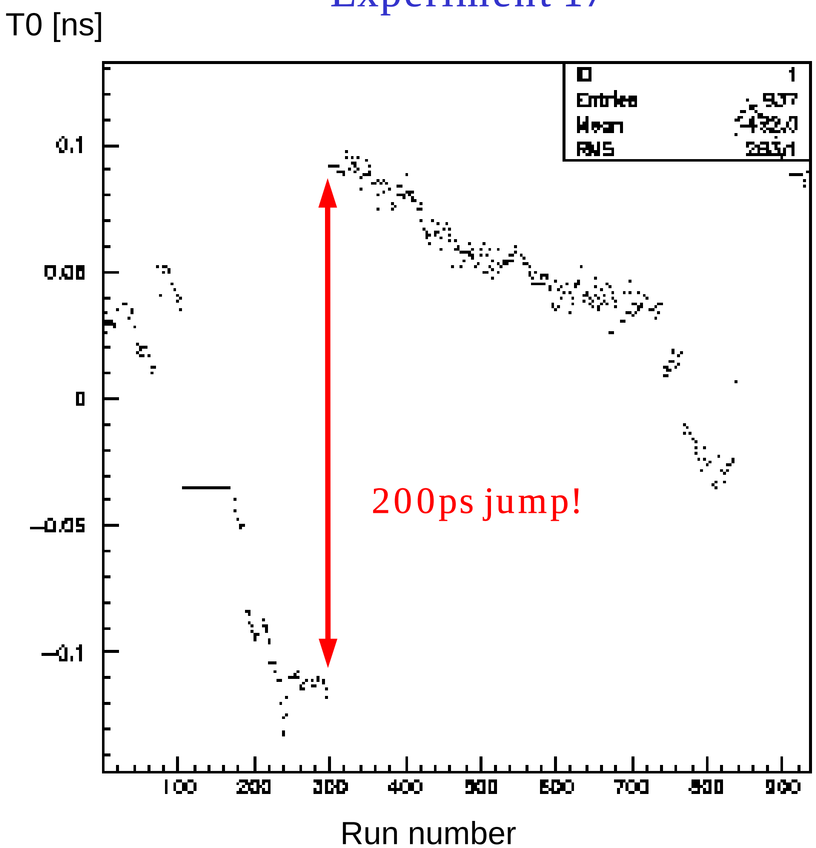
Need 100:1 interpolation for 1ps
And aperature jitter at < 1ps

Limitations 3: Systematic Errors

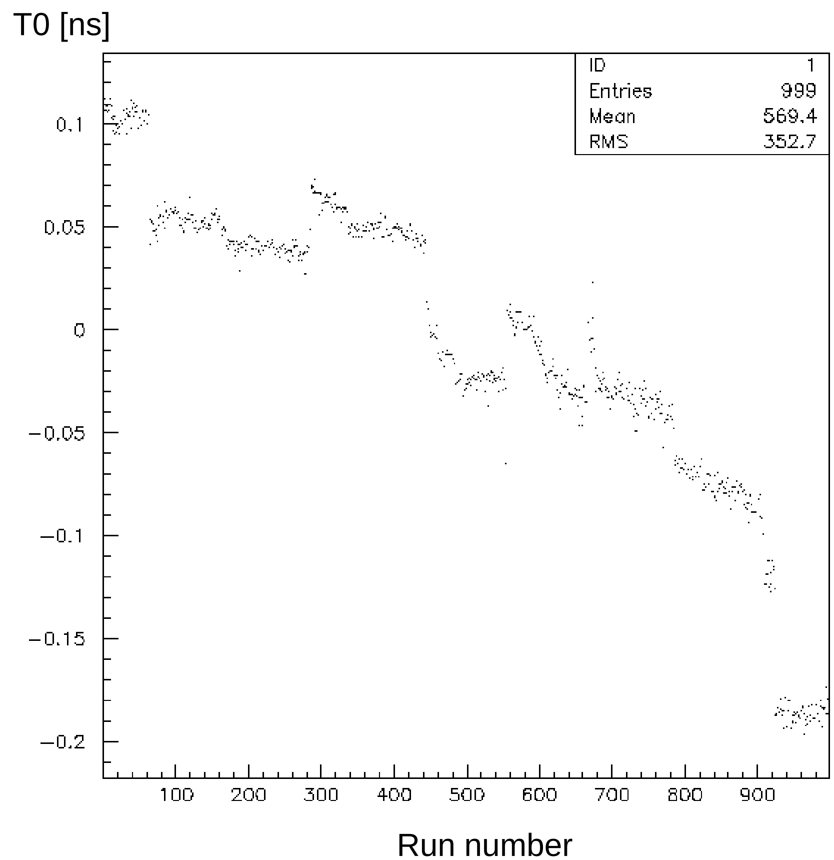
Experience with running Belle TOF System for ~ a decade

Any jitter/shift/jump in reference time is fatal? (differential measurements)

Experiment 17



Experiment 19



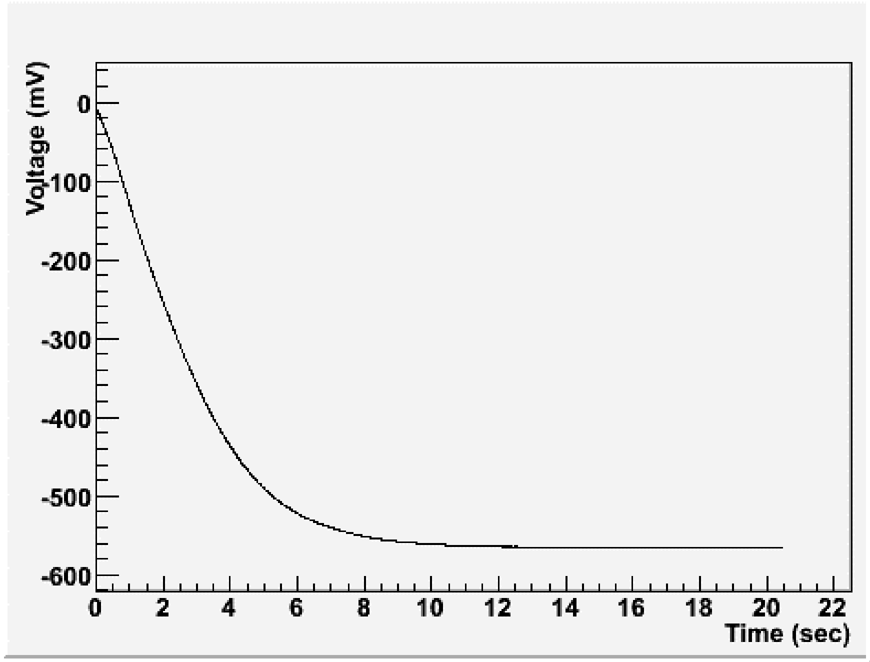
- Run-by-run T_0

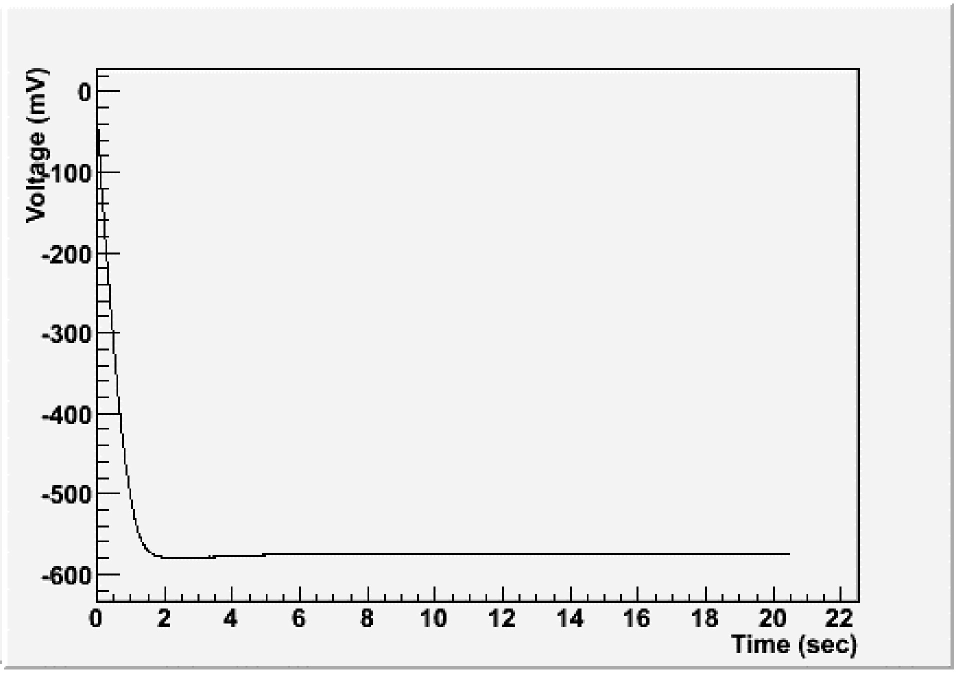
G. Varner -- LABRADOR ASIC Family -- U-Chicago Timing Meeting

Limitations 4: Leakage Current

Need small C for Input Coupling

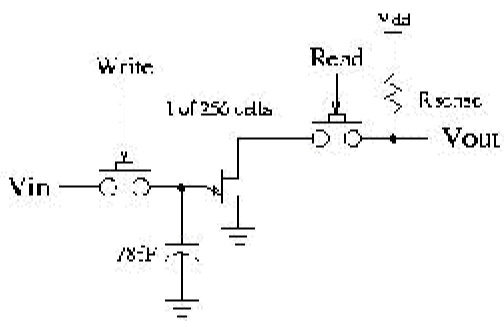
Can Improve? (readout faster)





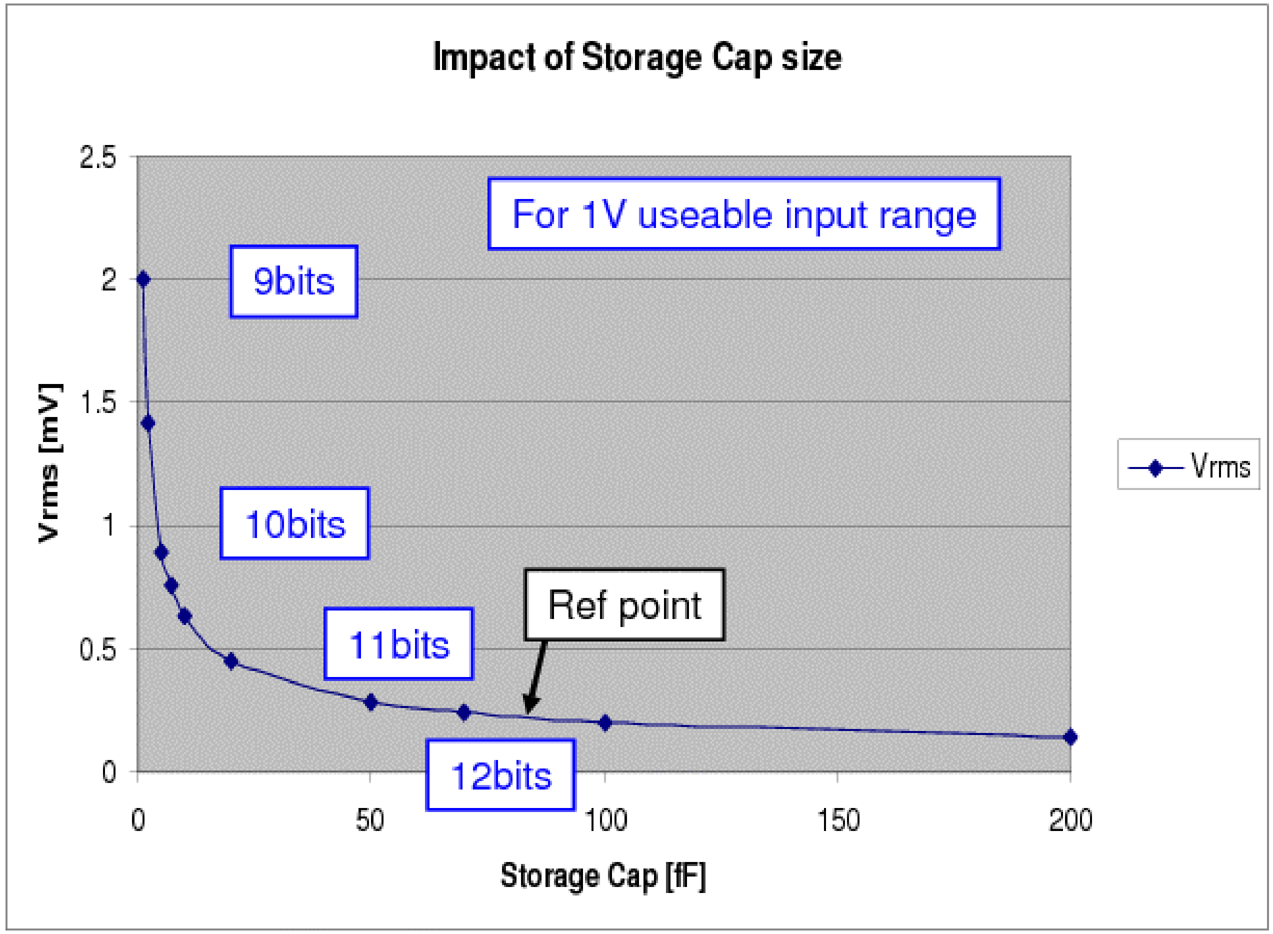
Limitations 5: kTC Noise

Need small C for Input Coupling



$$v_{rms} = \sqrt{\frac{kT}{C_{store}}} = 0.23mV$$

C_{store} = 78fF

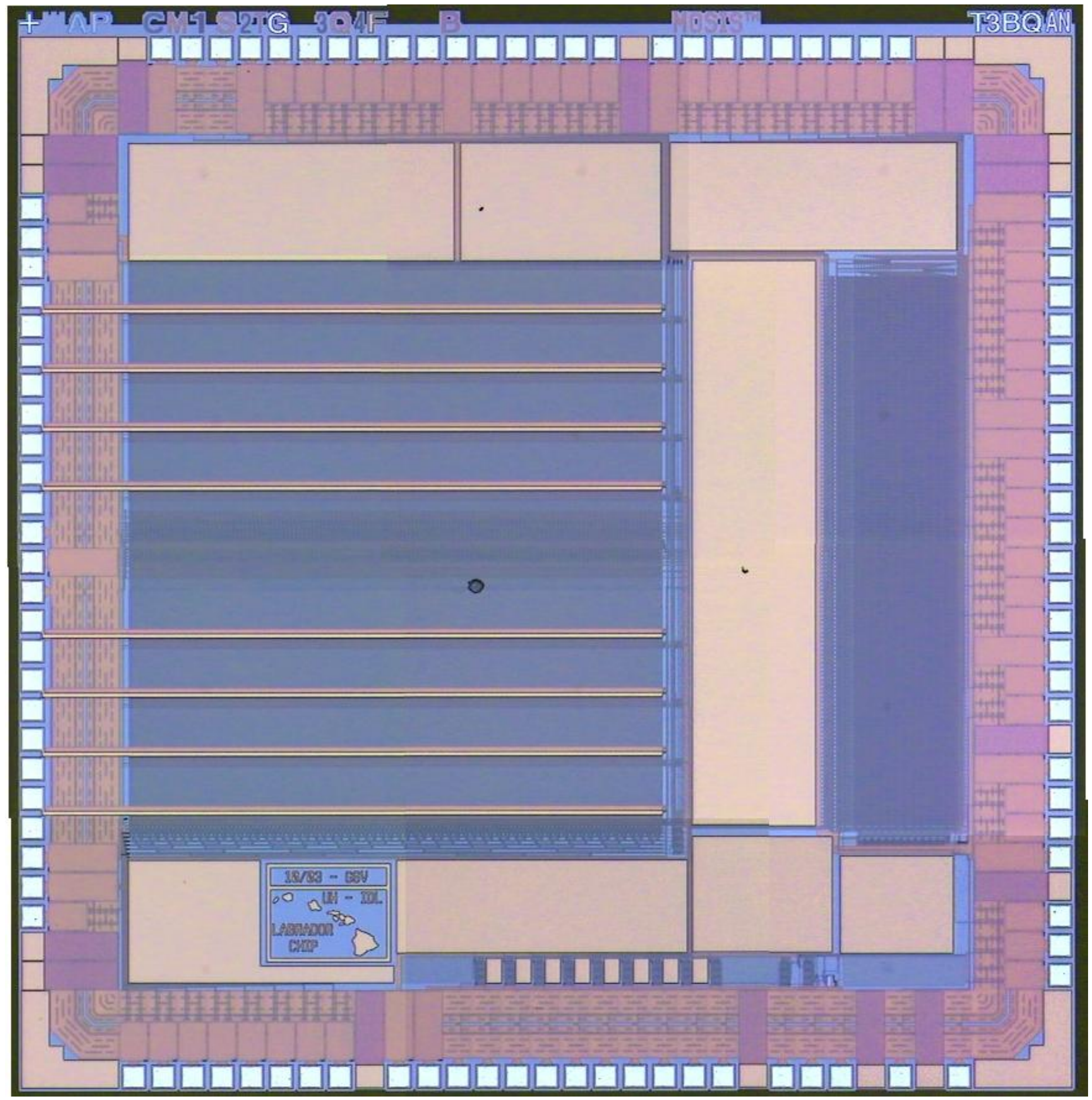


Summary

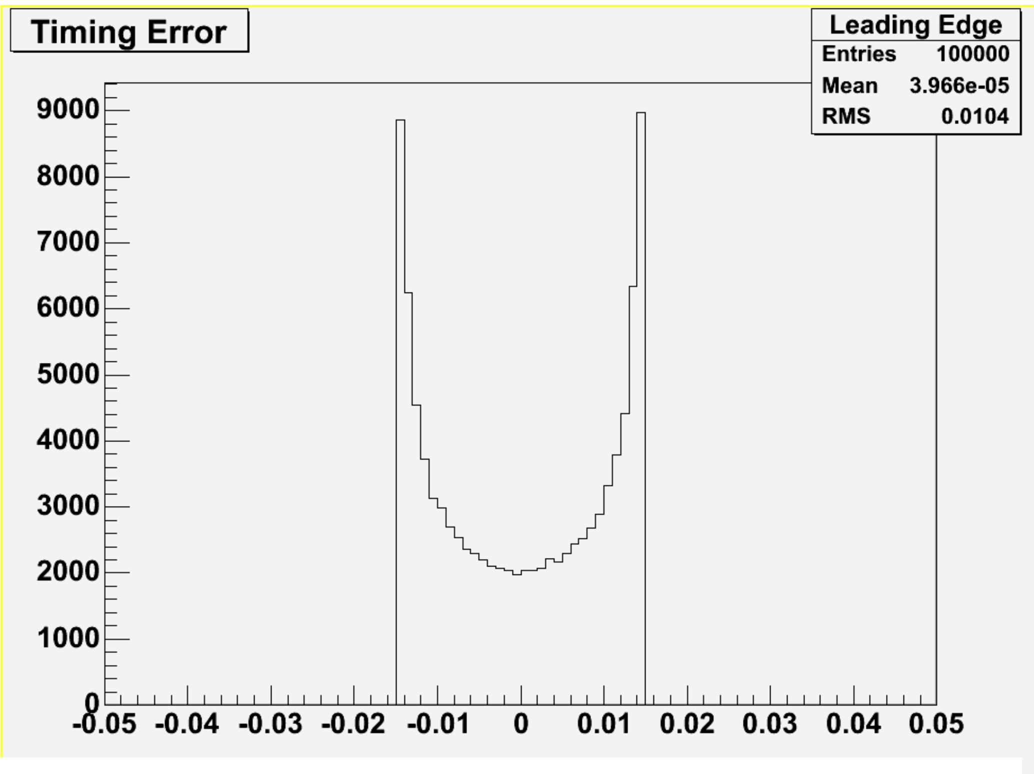
Exciting Stuff!

- 30ps (PET) seems quite feasible without TDC (fast discriminator)
- Timing Systematics!
- 1ps resolution, need to pull out all of the stops

Back-up slides

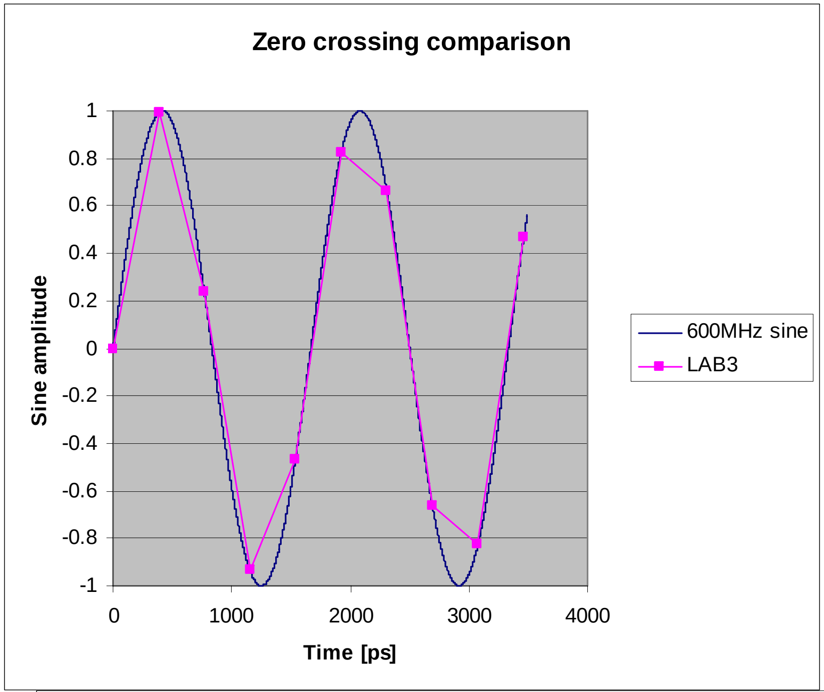


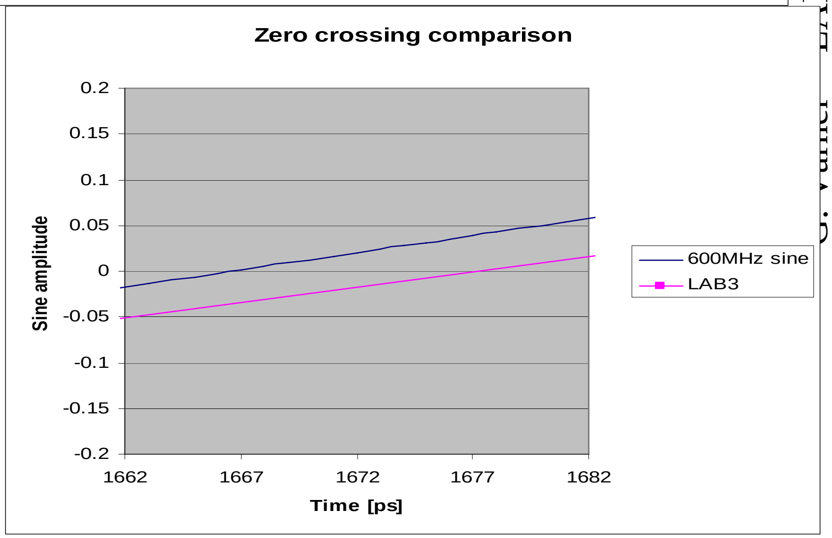
600MHz sine and 2.6GSa/s well matched



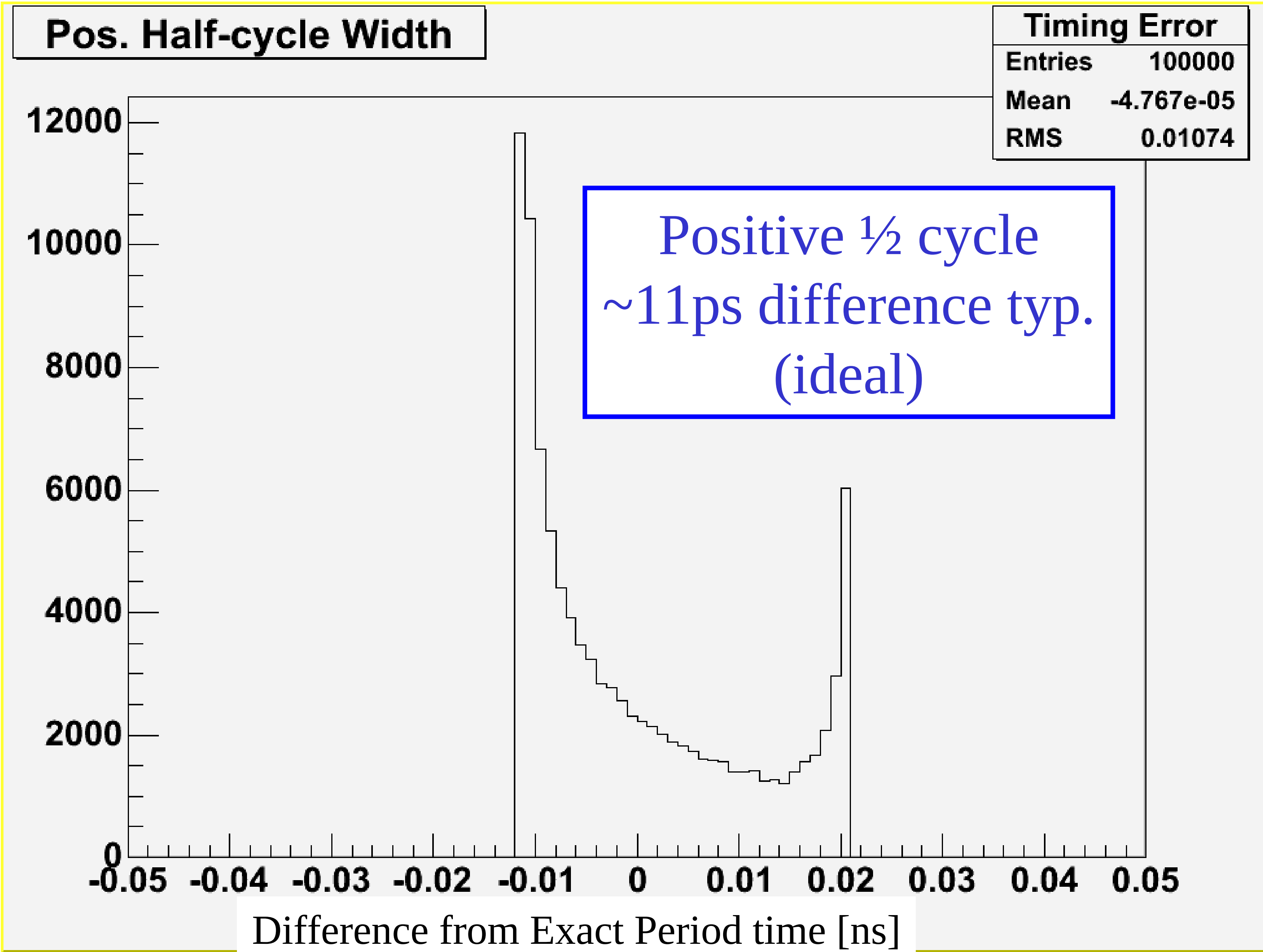
Difference from Exact zero-crossing time [ns]

10ps difference typ.
(ideal)

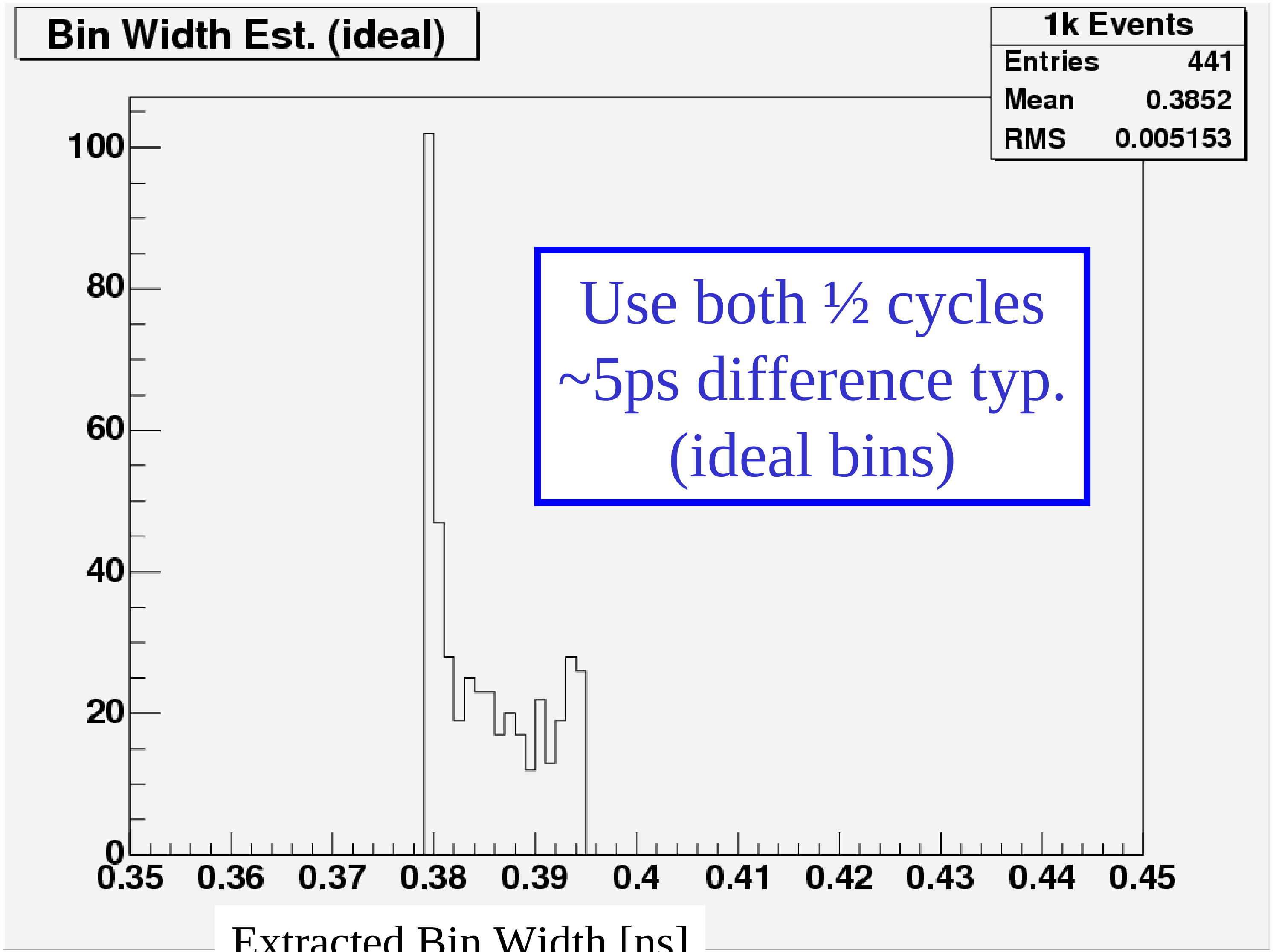




600MHz sine and 2.6GSa/s well matched

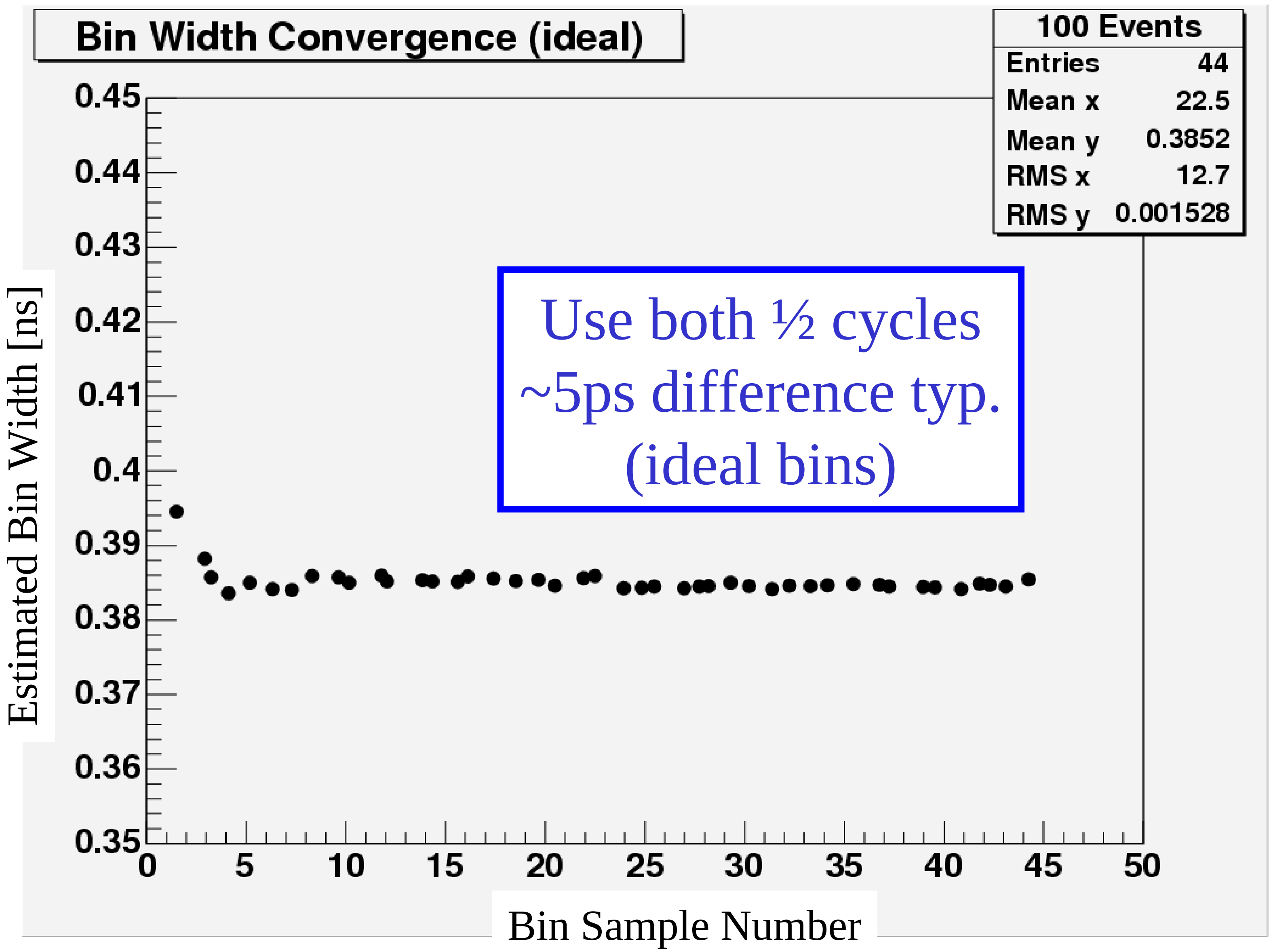


Using Ideal Extraction

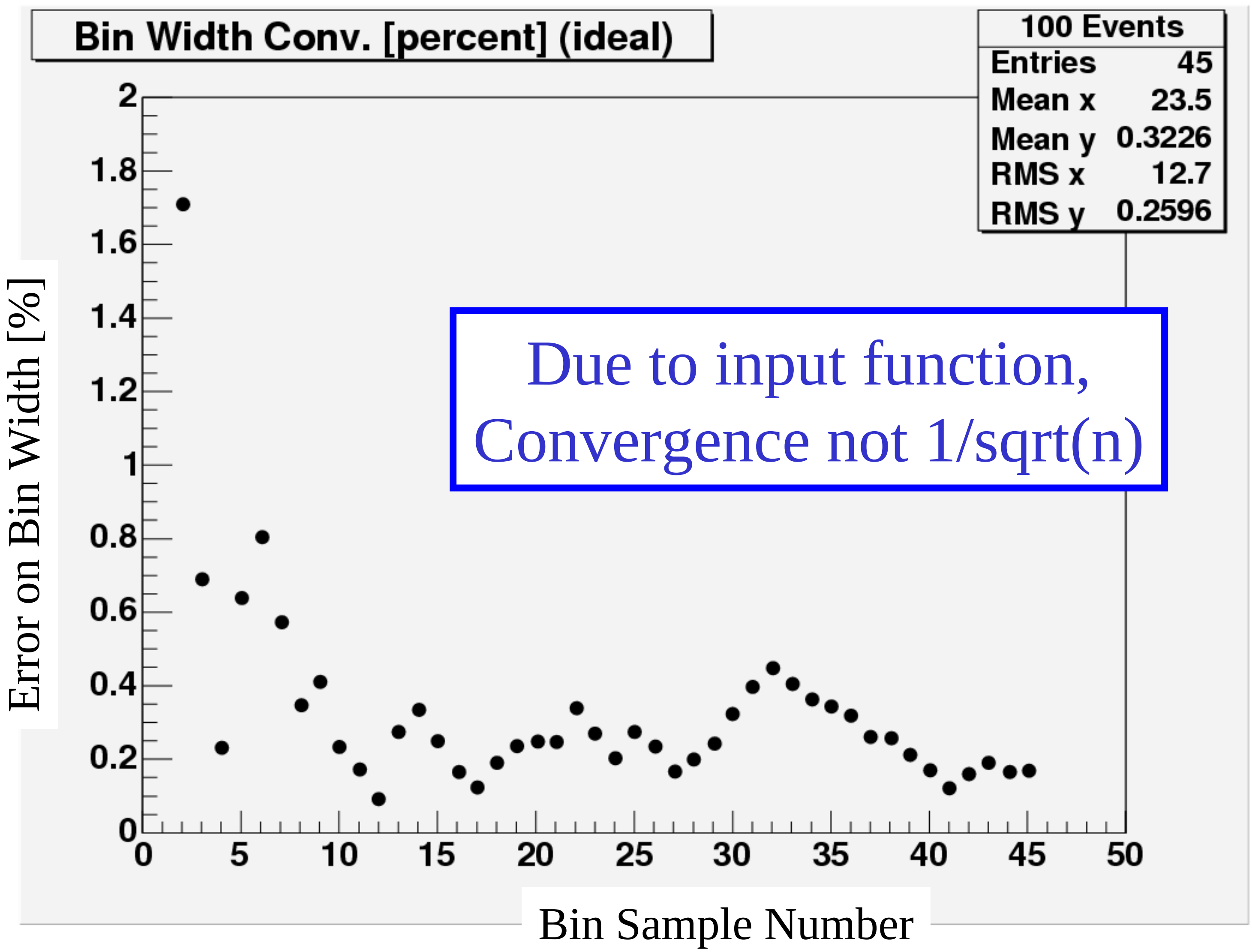


Extracted Bin Width [ns]

Running Average converges very quickly

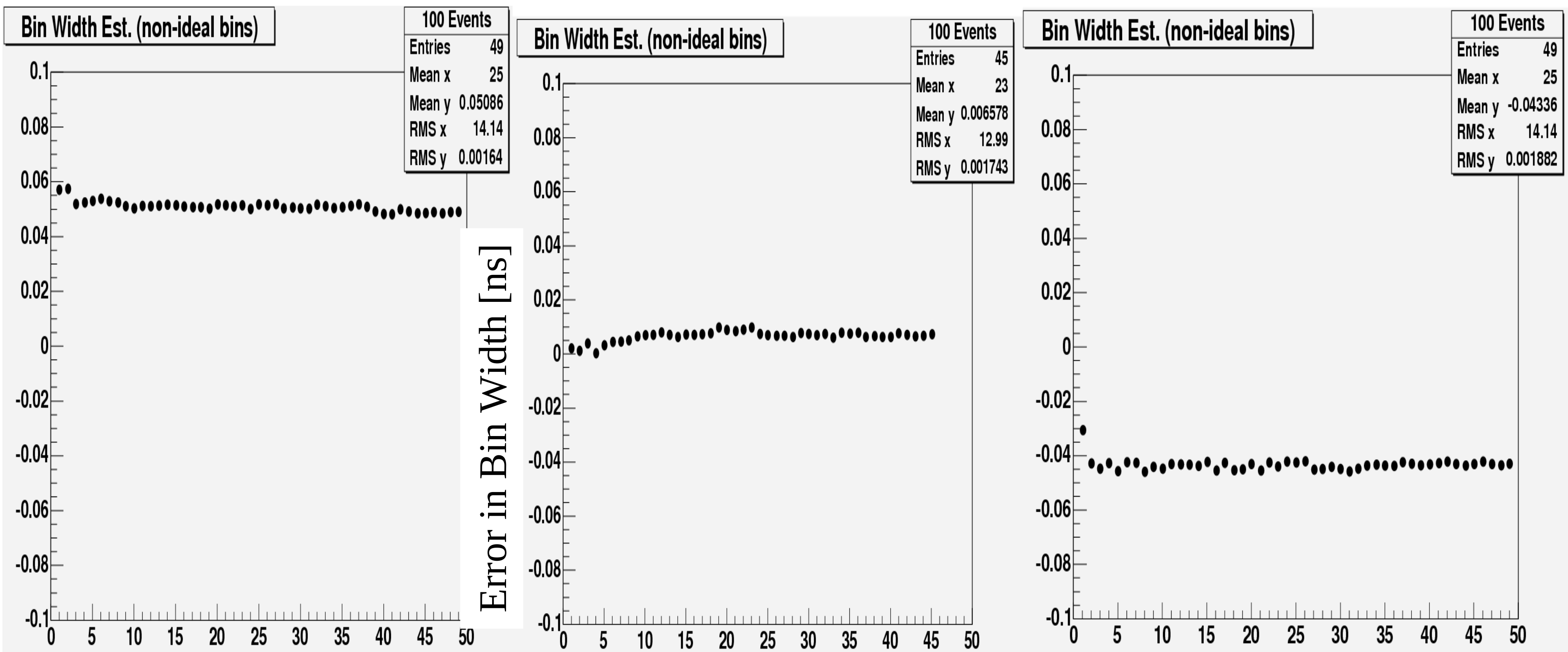


Running Average converges very quickly



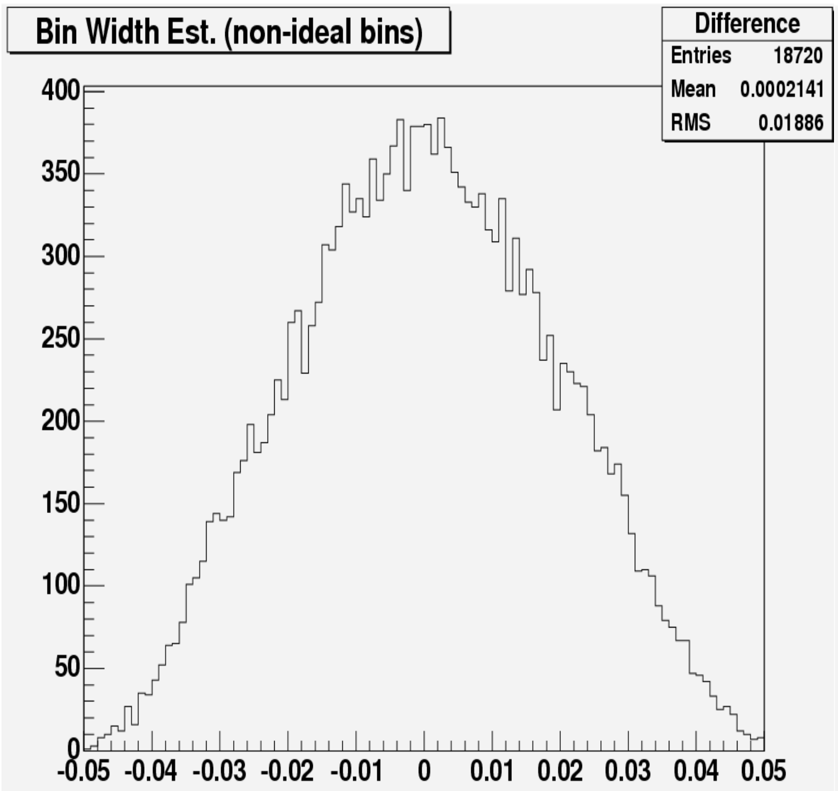
However, when input +/- 10% bin scatter

Fast convergence, but with offsets

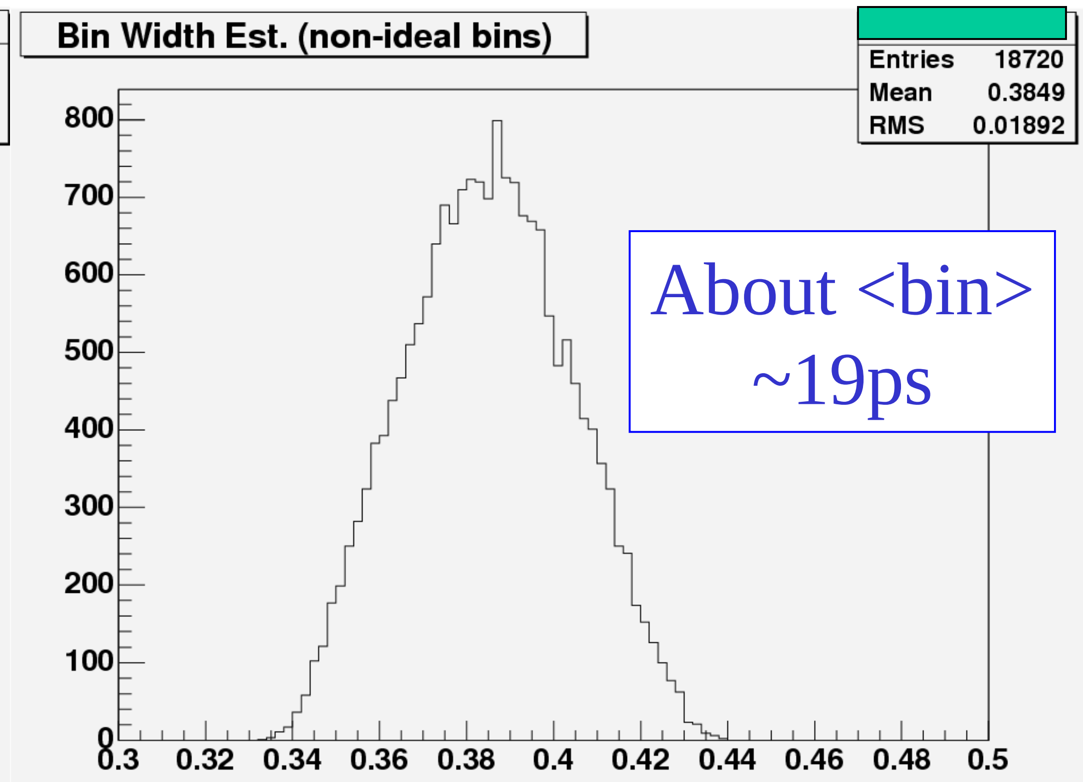


Number of Samples in Bin

Impact on estimation (+/- 10% true difference)

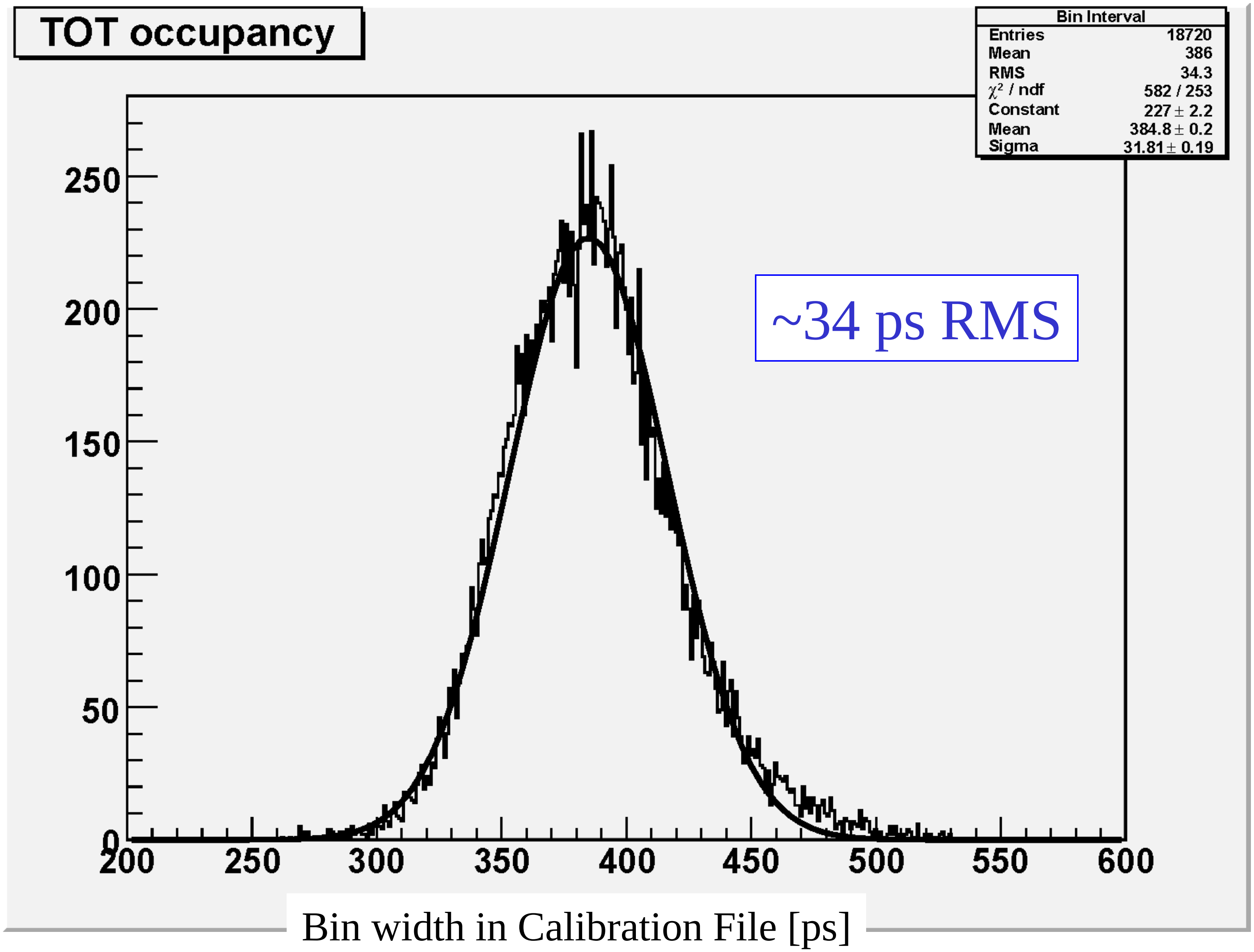


Difference from Actual Bin Width [ns]

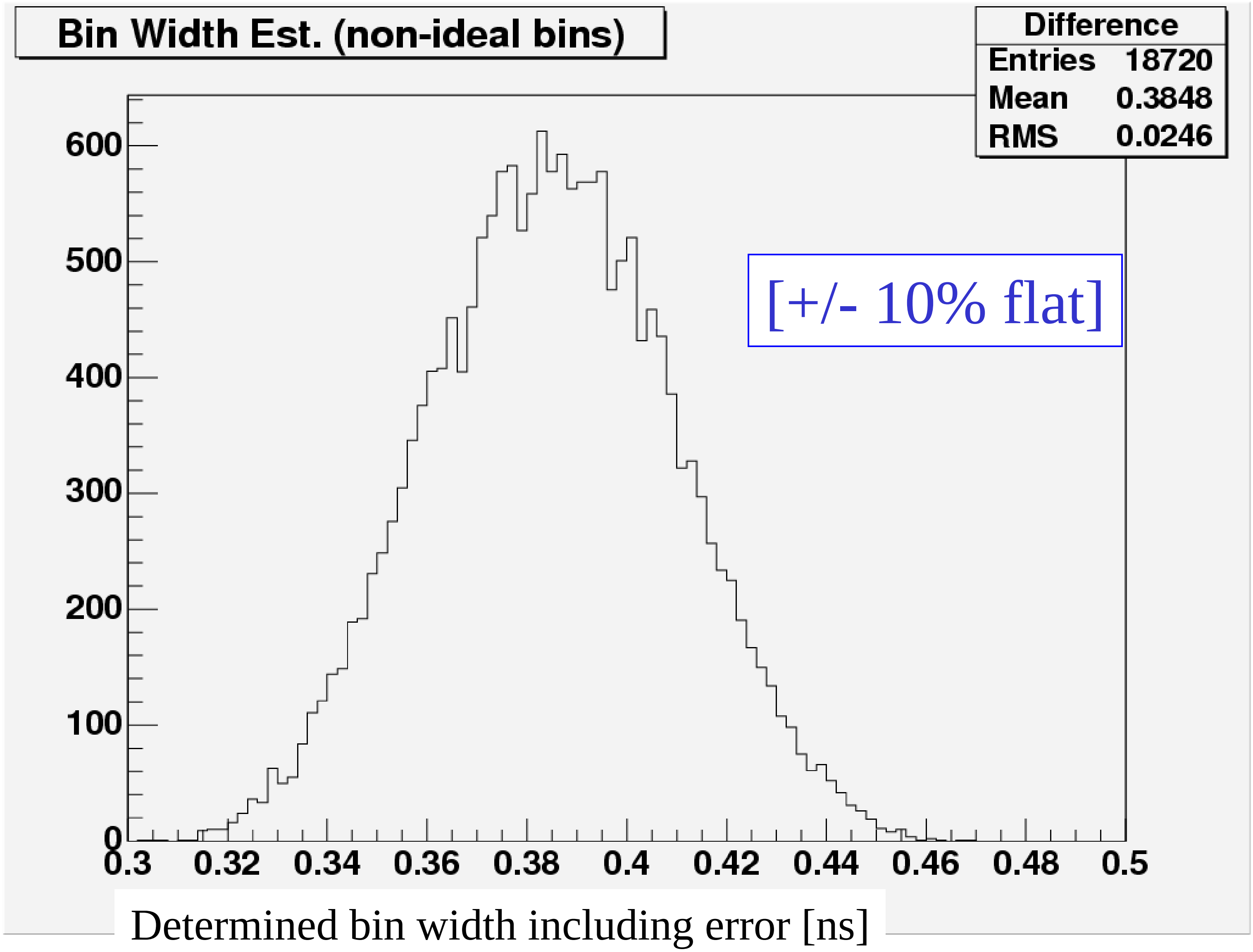


Difference from true Width, referenced to mean [ns]

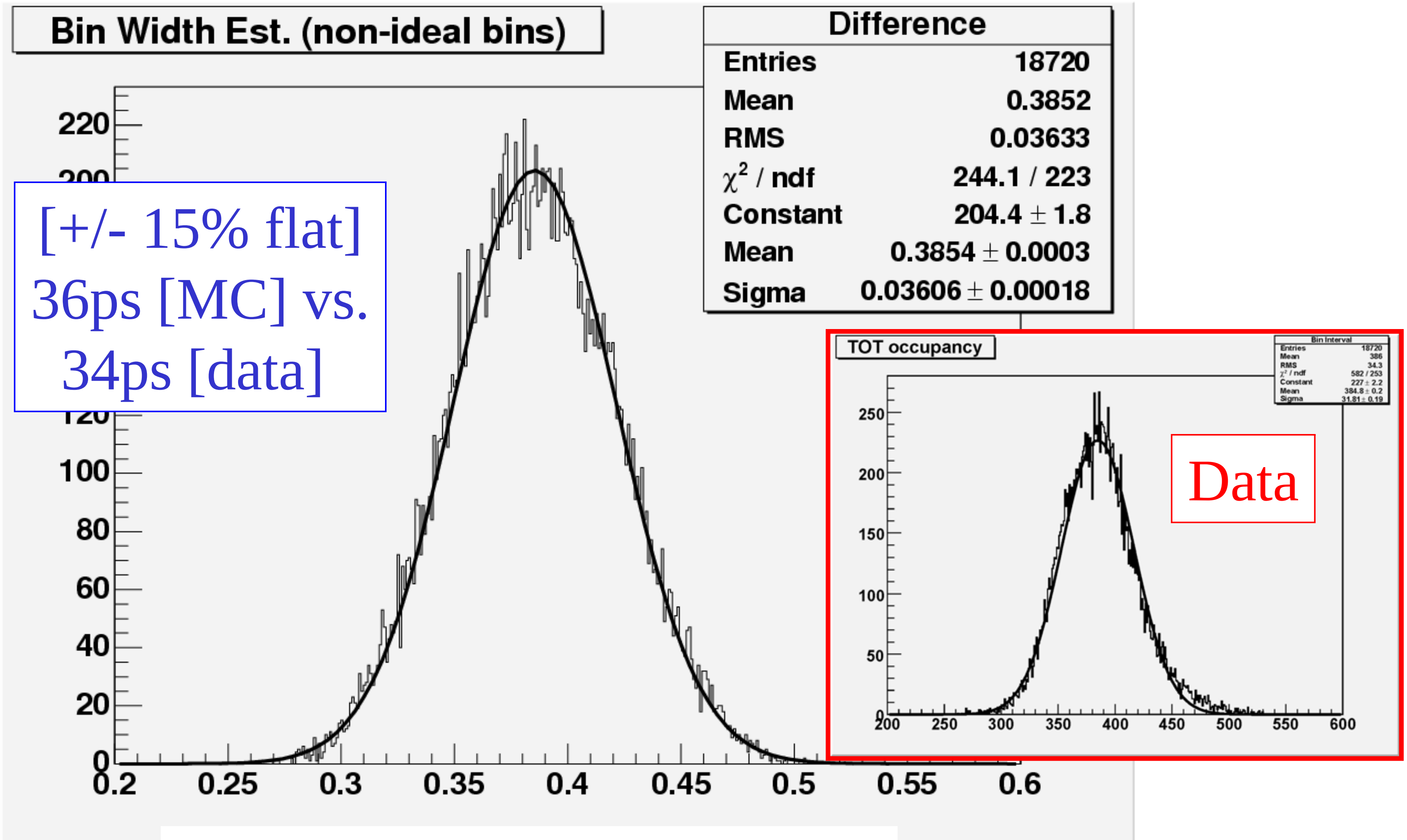
Data: Bin-by-bin Calibration Constants



General trend – larger intrinsic spread

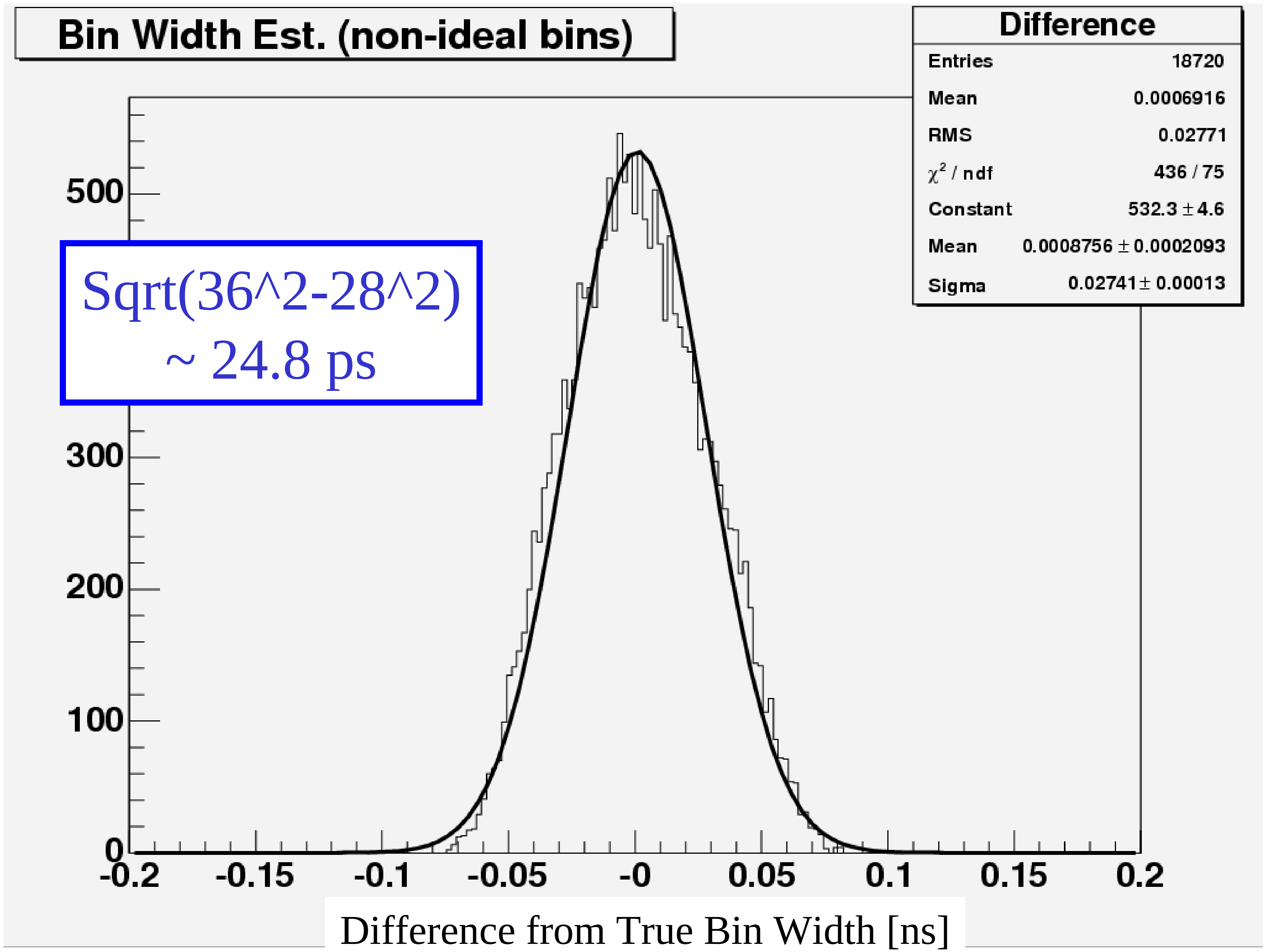


Consider Slightly larger input spread

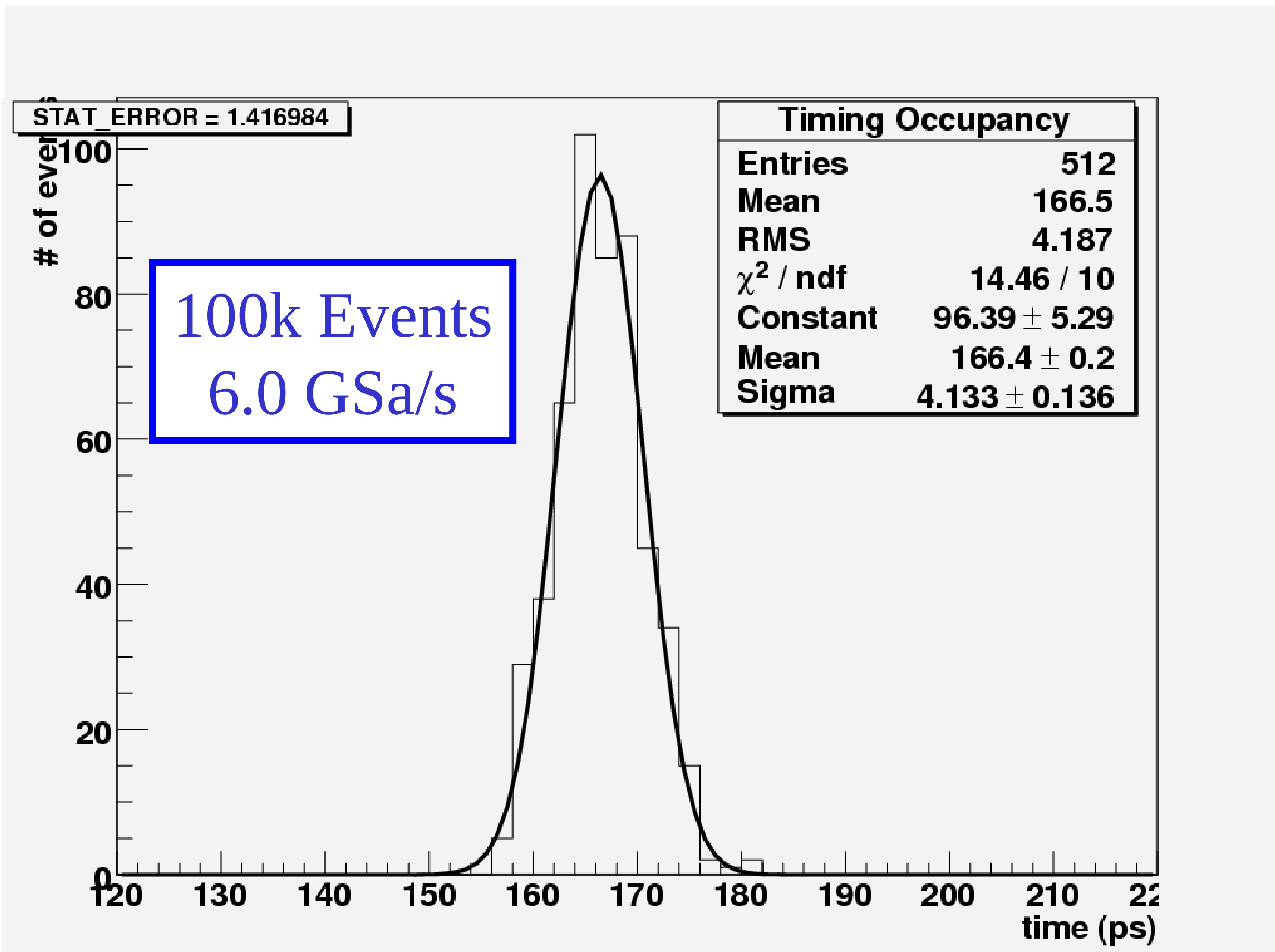


Determined bin width including error [ns]

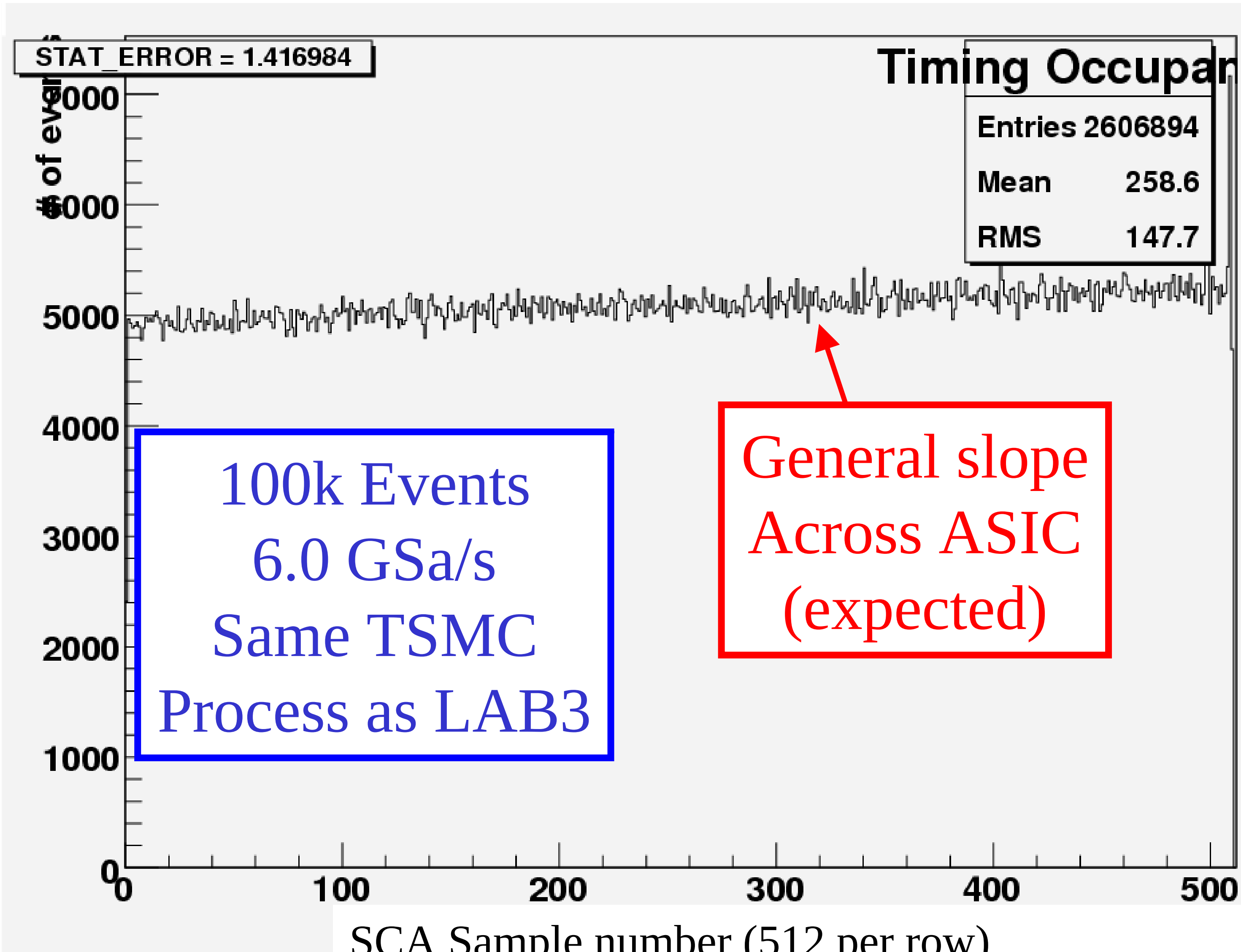
However, the errors are non-negligible



Cross-check: BLAB1 ASIC
"Brute Force" occupancy method

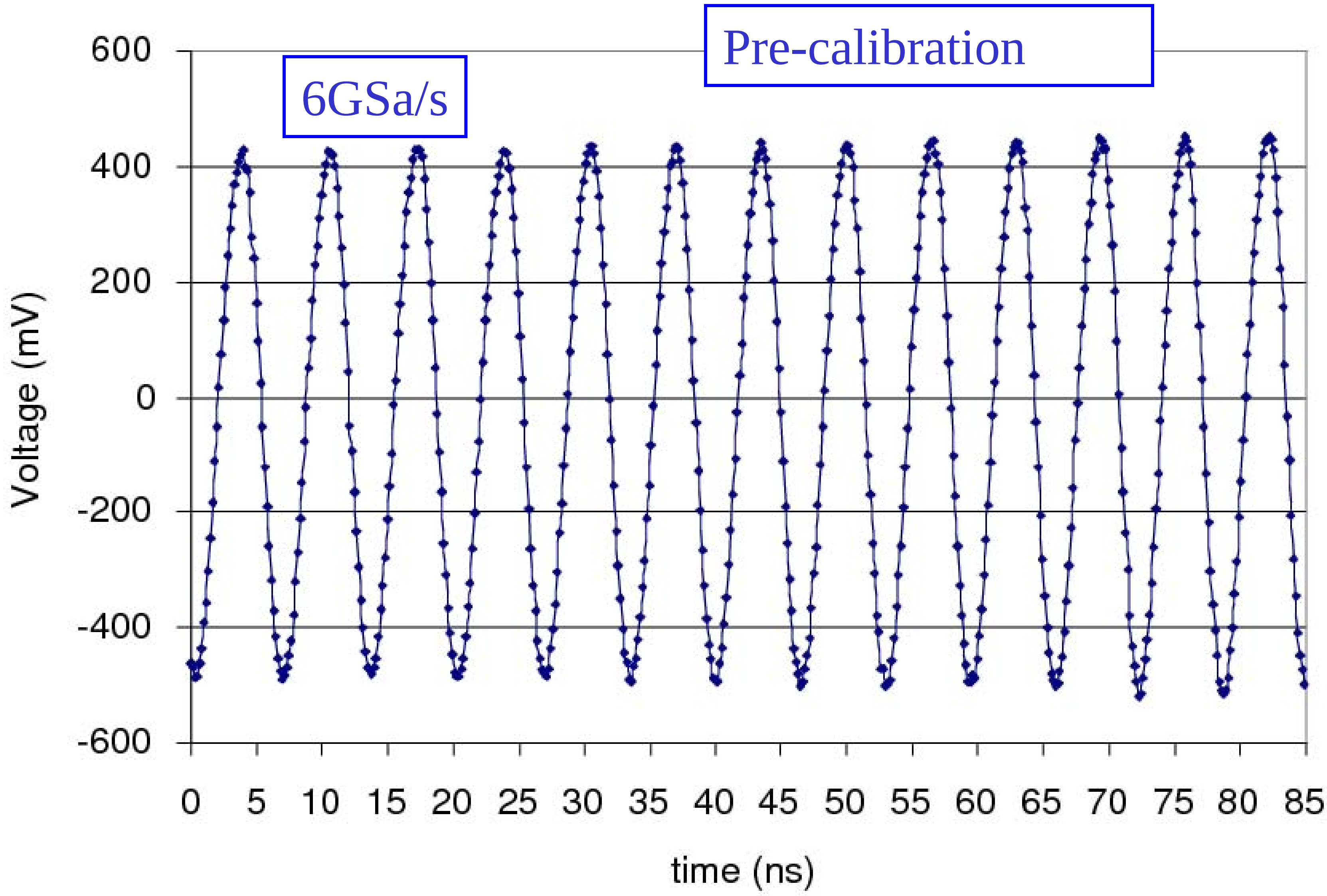


Cross-check: BLAB1 ASIC
"Brute Force" occupancy method

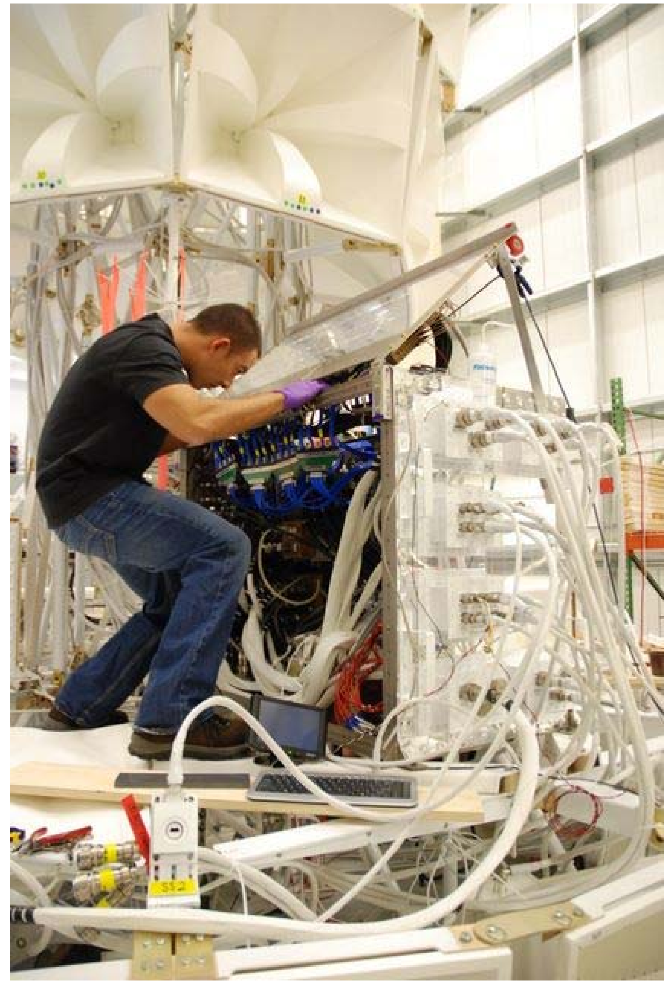


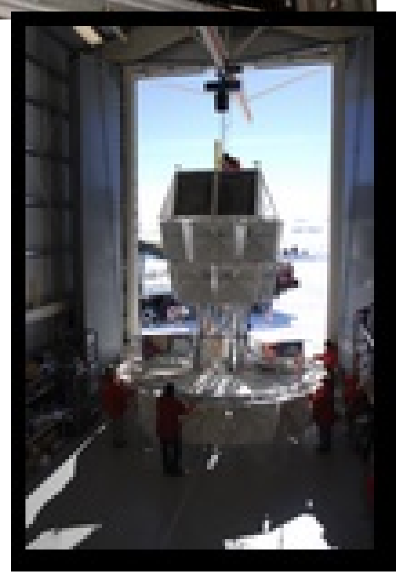
SCA Sample number (512 per row)

125MHz sine wave

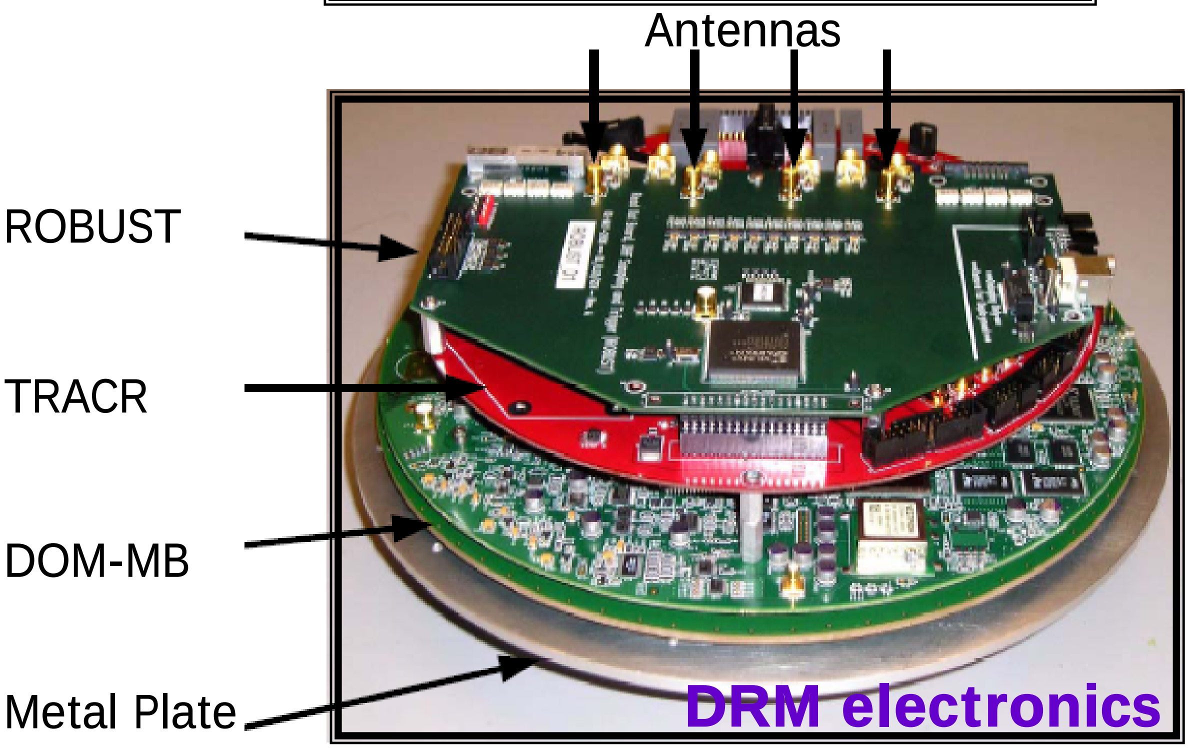


ANITA Payload



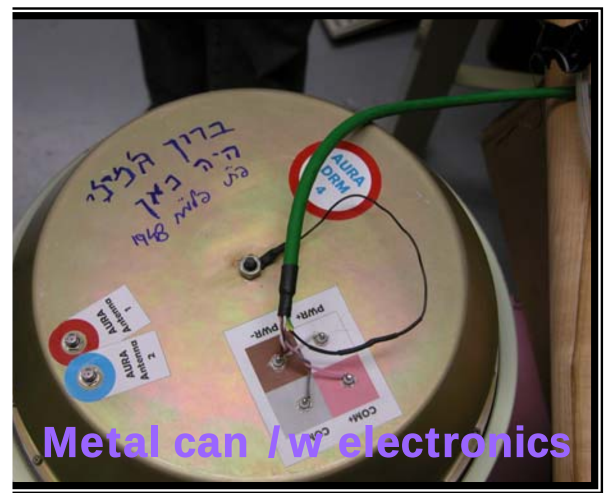


Sealing the DRM



DRM electronics

Surface Test



Metal can /w electronics