# A correlation-based timing calibration and diagnostic technique for fast digitizing ASICs

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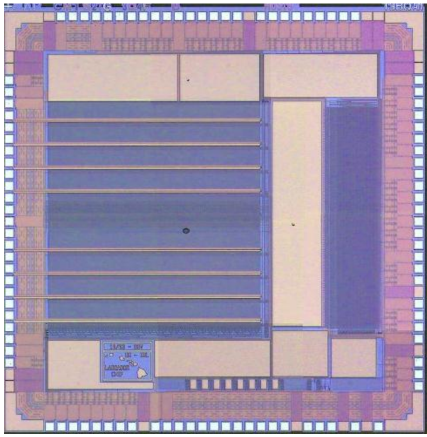
# Waveform Sampling ASICs

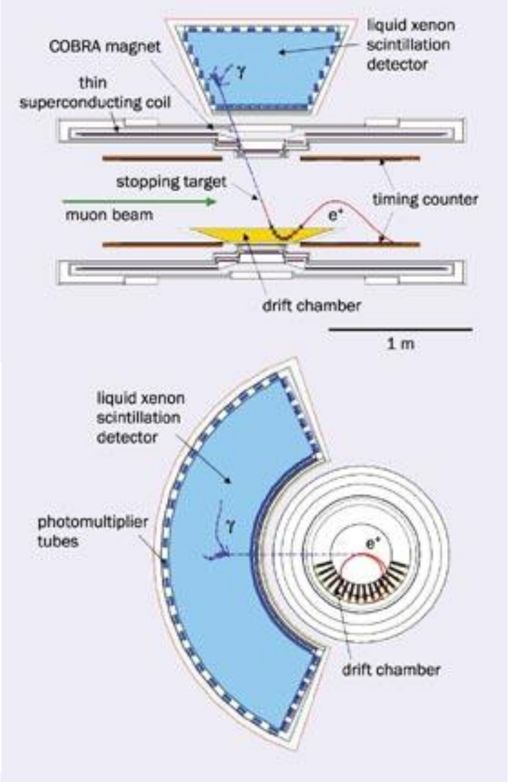
- Waveform sampling ASICs are increasingly desirable in detector systems:
  - High channel density
  - Low cost / channel for production quantities
  - Customized to application, e.g.,
    - Sampling rate
    - Front-end gain
    - Buffer depth

# Waveform Sampling ASICs

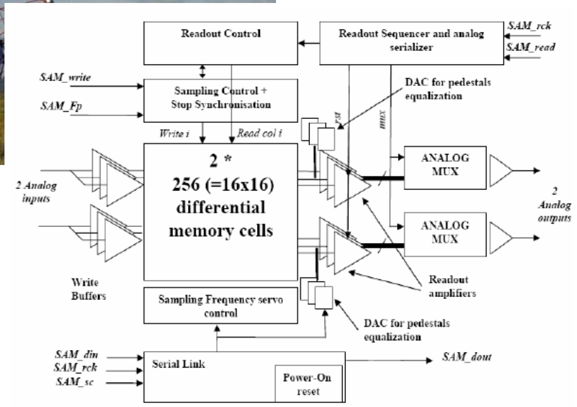
- Already in use in many experiments…




LABRADOR3,
ANITA Experiment

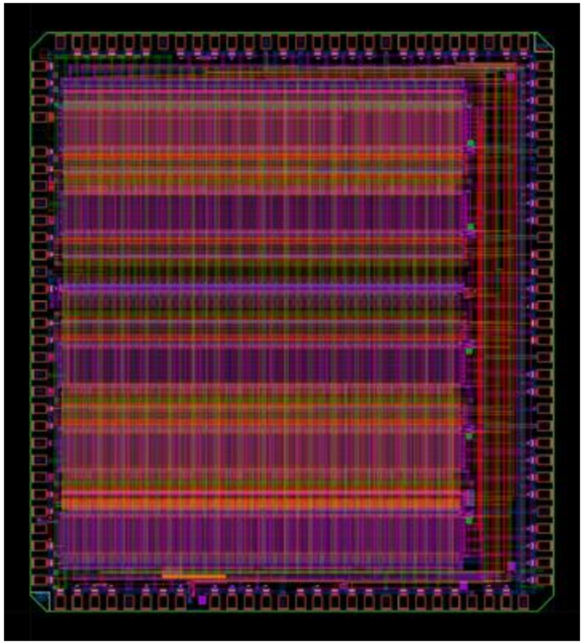

DRS4,
MEG Experiment


SAM,
H.E.S.S.-II

# Oscilloscope on a chip!

- Waveform sampling/digitizing ASICs are just like an oscilloscope!



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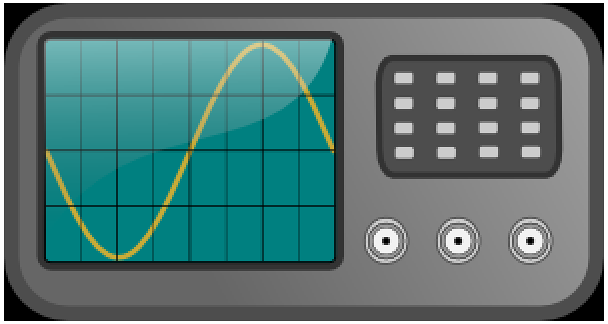
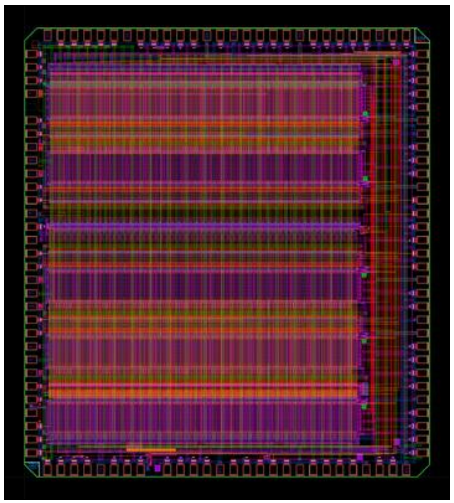


…right?

# Oscilloscope on a chip?

- Modified approximation:



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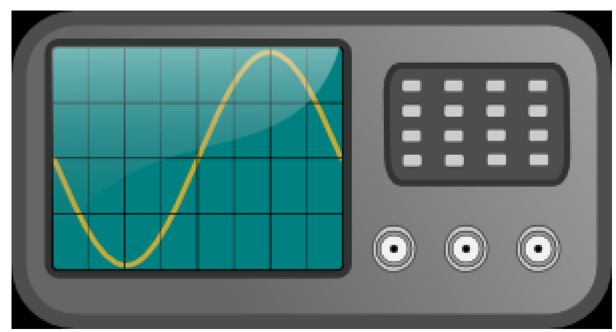
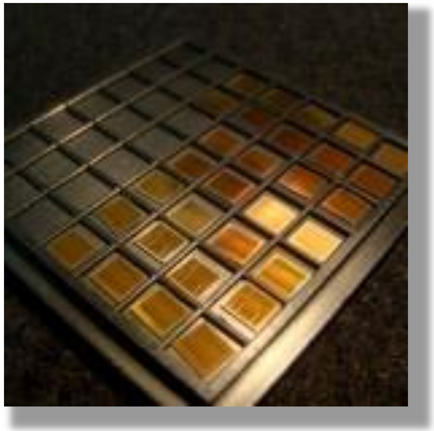


# Corrections required*:

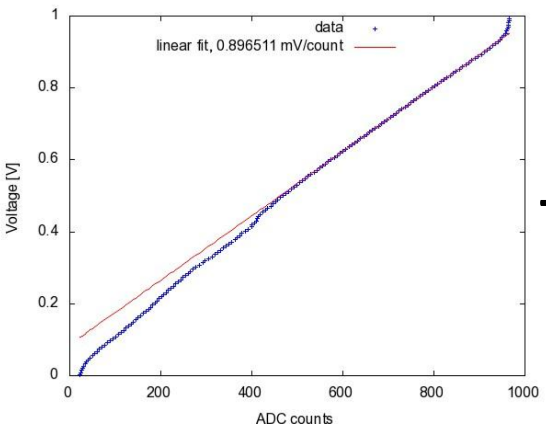
1. Voltage conversion:
   – Convert ADC counts to voltage.
2. Pedestal correction:
   – Remove cell-to-cell fixed DC patterns.
3. Time base correction:
   – Keep overall sampling rate constant (or correct for drift).
   – Correct for cell-to-cell variations in sampling rate.

***Some much simpler than others, and not all are required for every chip or application… some extra may be required for some applications.**

# The PSEC3 ASIC



- Start with voltage and pedestal calibrations already applied.

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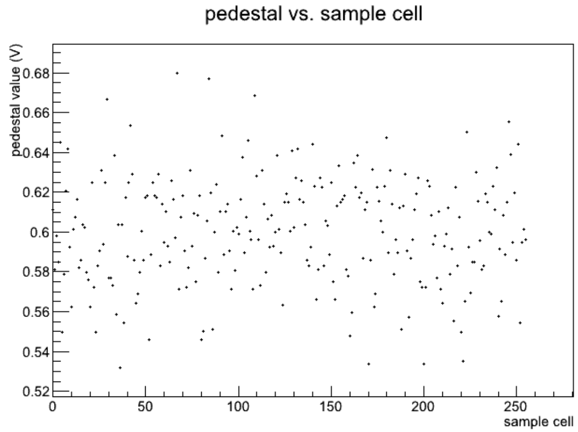
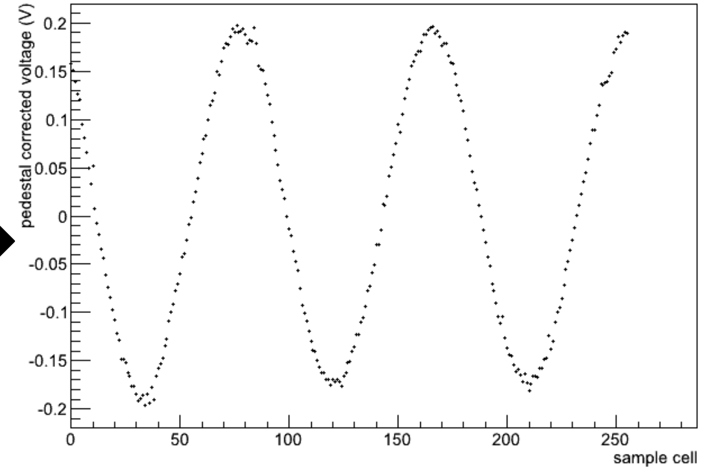


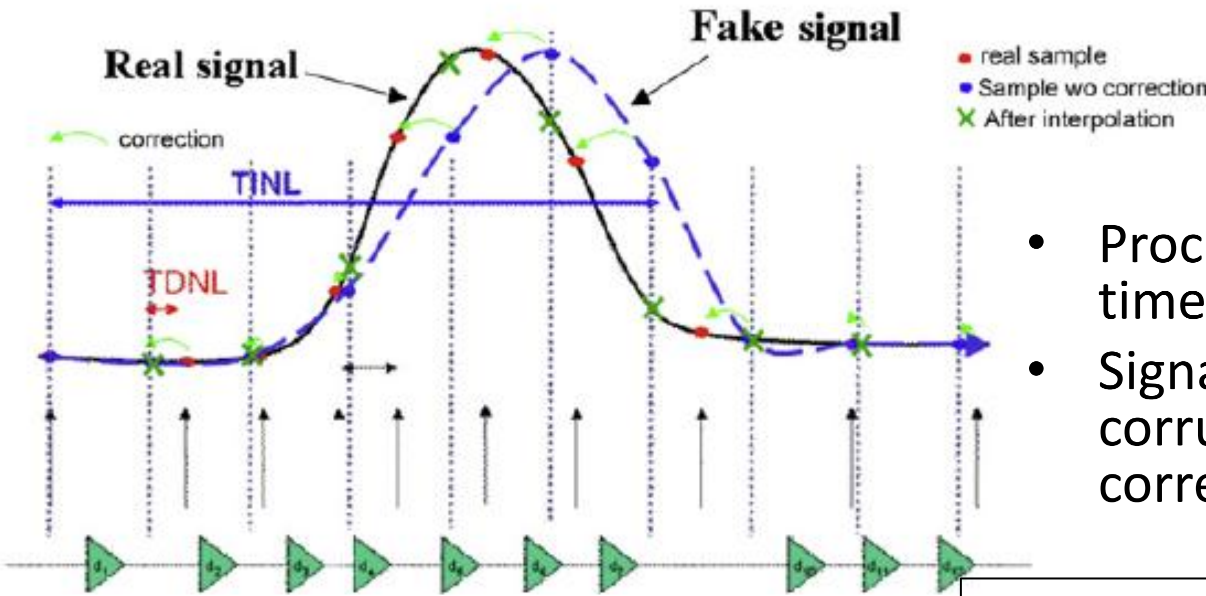

➔




- Focus: **timing calibration**.

***See E. Oberla's slides (Fri.), "A 4-Channel Waveform Sampling ASIC using 130nm CMOS technology" (Front-end Electronics)**

# Time Base Corrections




- Process variations cause sample times to be at uneven intervals.
- Signals are systematically corrupted unless this is corrected.

*Figure from D. Breton *et al.*, NIM A629, 123.

Required calibrations / corrections:

- Overall time base drift:
  - ☑ **On PSEC3, overall sampling rate is locked by DLL.**
- Still needed:
  - ❑ Measurement of the sampling rate.
  - ❑ Calibration of individual time delays between sample cells ($\Delta t_{i,i+1}$).
- Sine wave inputs of known frequency are a powerful tool!

# Calibration With Sine Waves

Possible strategies:

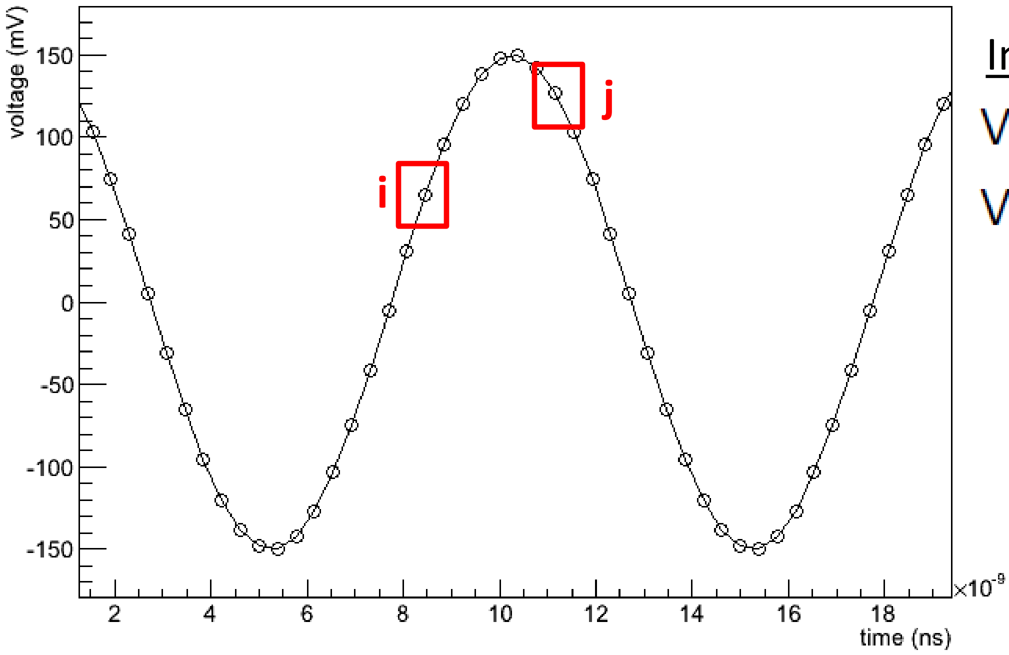
- Use zero crossings between sample cells.
  - Count zero crossing occupancies between samples.
  - Use sin(x) $\approx$ x near zero crossings.
- Fit to sine wave inputs:
  - Fit for amplitude, input phase, $\Delta$t between sample cells.

Potential drawbacks:

- Use zero crossings between sample cells.
  - Zero crossings are sparse, most data is not used.
  - Gives relative timing intervals. Need another procedure to get an absolute calibration.
  - Pedestals offsets cause issues.
- Fit to sine wave inputs:
  - Global fits have many free parameters. Convergence is challenging.
  - Unknown phases are nuisance parameters in fit.

# Timing Calibration w/ Correlations

- Plot correlations between pairs of samples:
  - To determine $\Delta t_{ij}$, plot $V_i - V_j$ versus $V_i + V_j$




Input signals given by:

$V_i = A \sin(\omega t_i + \phi)$

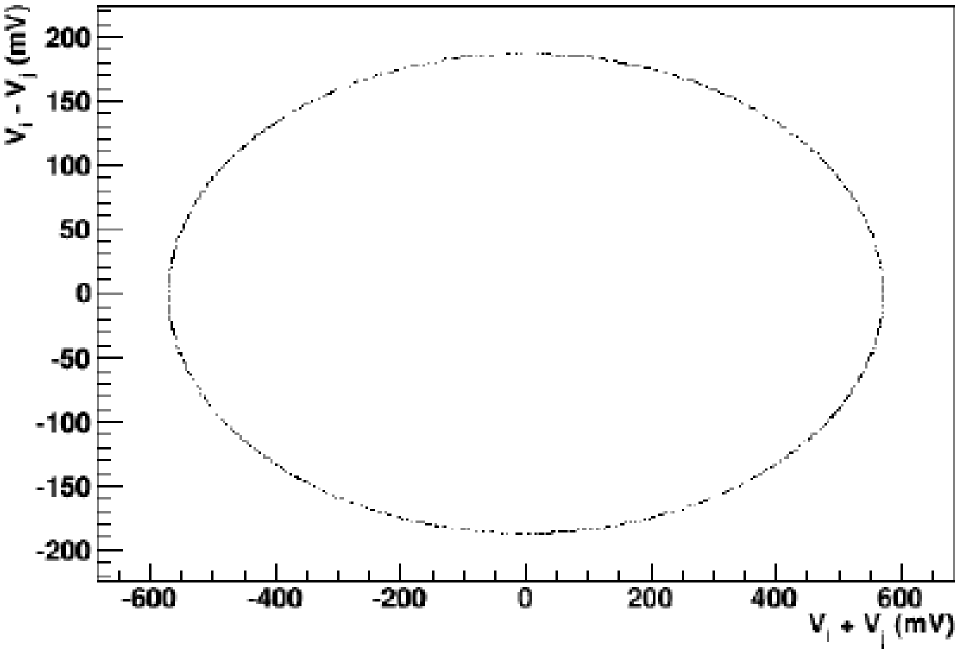
$V_j = A \sin(\omega t_j + \phi)$

**For any given event, phase is unknown (but common). This is a nuisance for techniques that rely on fitting sine waves.**

- **i and j can be adjacent (or not), but with no extra information on timing intervals, cycle ambiguities exist if > 1 period apart.**

# Timing Calibration w/ Correlations

- Plot correlations between pairs of samples:
  - To determine $\Delta t_{ij}$, plot $V_i - V_j$ versus $V_i + V_j$




Input signals given by:

$V_i = A \sin(\omega t_i + \phi)$

$V_j = A \sin(\omega t_j + \phi)$

Effectively rotate by 45°:

$x := V_i + V_j$

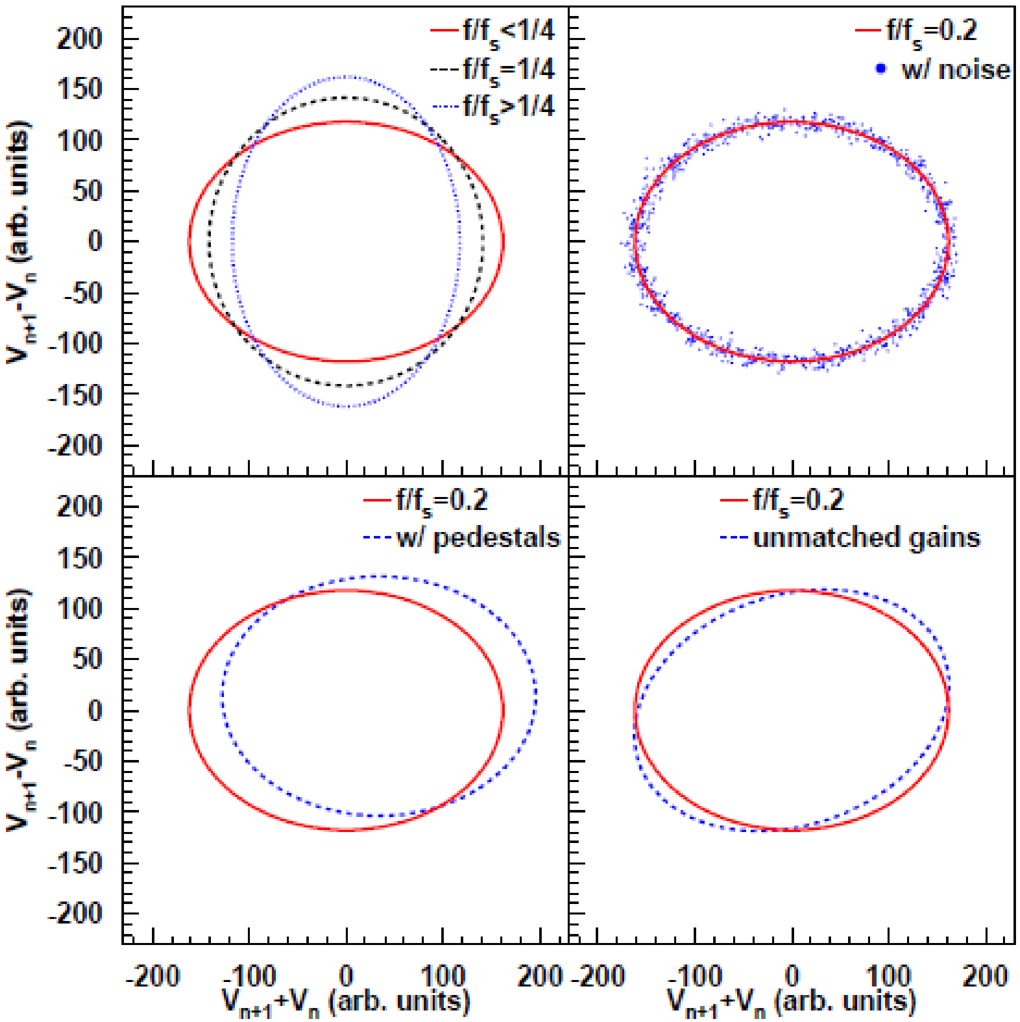
$y := V_i - V_j$

**The unknown phase populates the ellipse, but does not appear in x,y relation. No need to fit for it.**

$$\rightarrow \frac{x^2}{4A^2\cos^2(\omega\delta t/2)} + \frac{y^2}{4A^2\sin^2(\omega\delta t/2)} = 1$$

- **i and j can be adjacent (or not), but with no extra information on timing intervals, cycle ambiguities exist if > 1 period apart.**

# Timing Calibration w/ Correlations




<u>Ellipse features</u>:

1) Different $\Delta$t (for known sampling frequency) give different major/minor radii.

2) Noise makes ellipse “fuzzy”

3) Nonzero pedestals shift origin

4) Difference in gain between two cells causes a rotation.

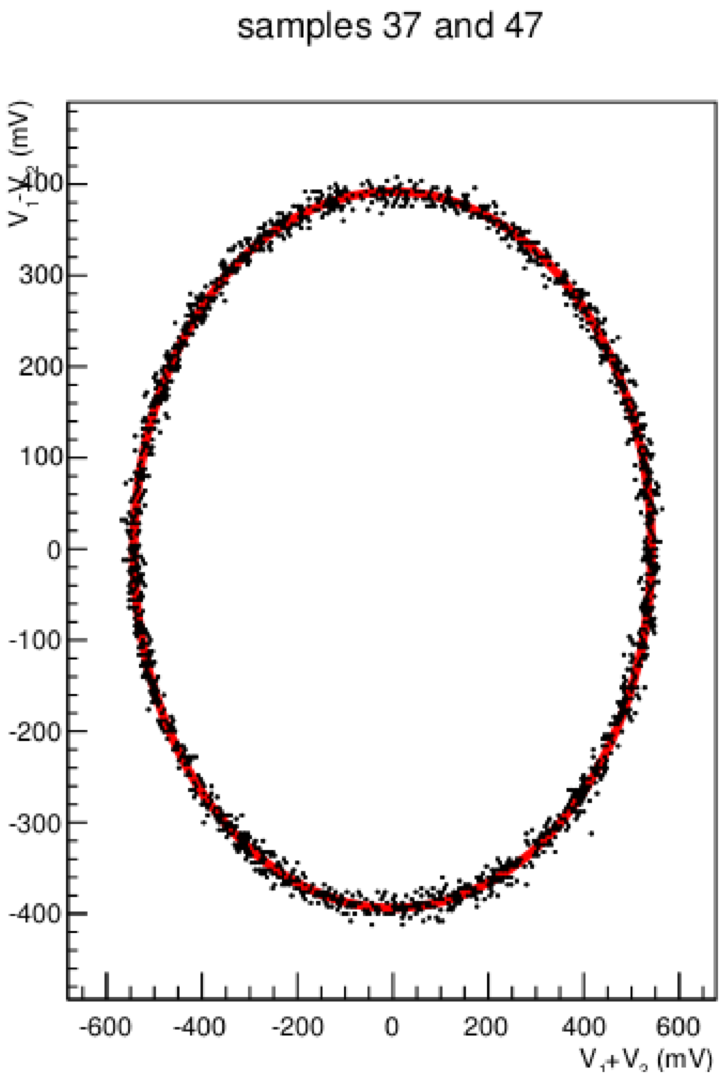
➔ We have written an ellipse fitter to perform this method.

➔ Even without fitting, it provides nice qualitative check on results.

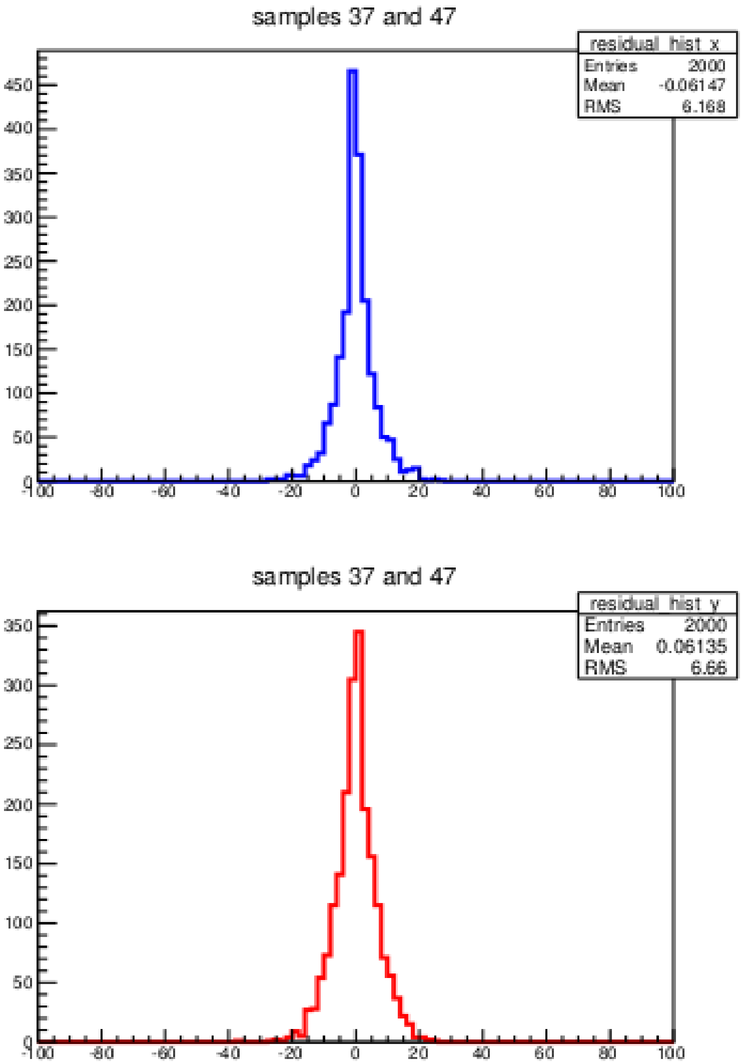
- **<u>Procedure first tested on fast scope data…</u>**

# Validation w/ Scope Data (TDS6804B)

**Data and fit**



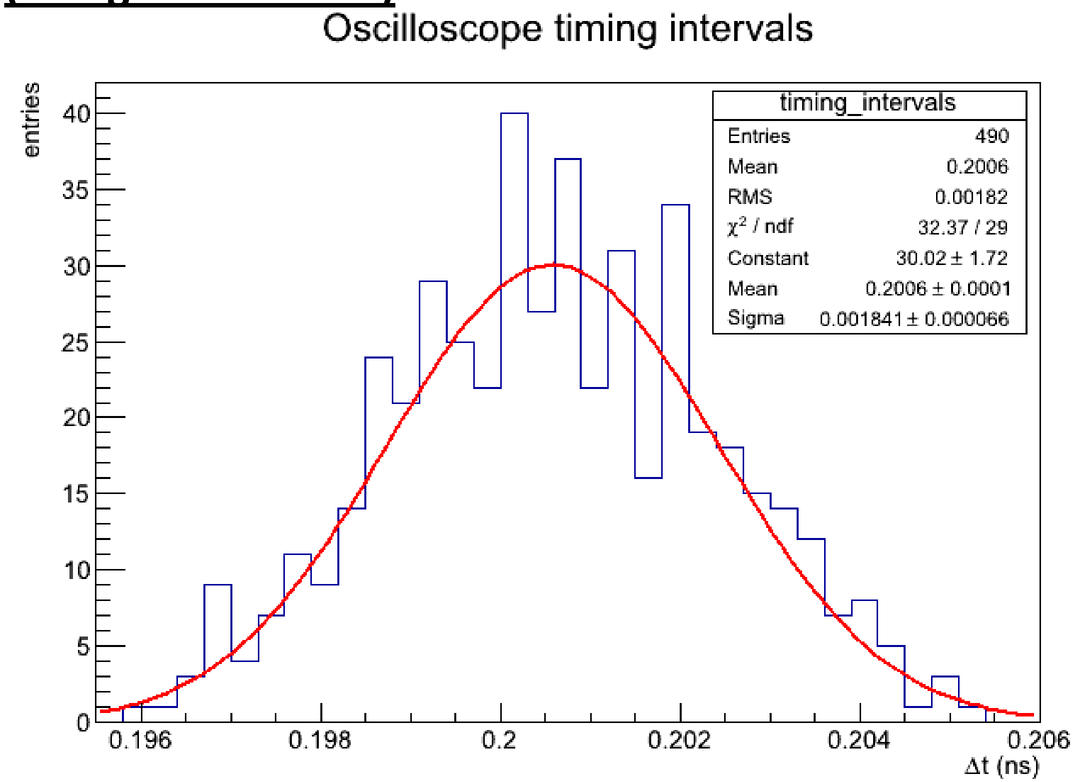

**Residuals in x, y**




➔ All fits very well behaved.

# Calculated $\Delta$t values for TDS6804B

**(Using 2000 events)**




**w/ scope set to 5 GSa/s:**

**$\Delta t$ = 200.6 ps**

**$\sigma_{\Delta t}$ = 1.8 ps**

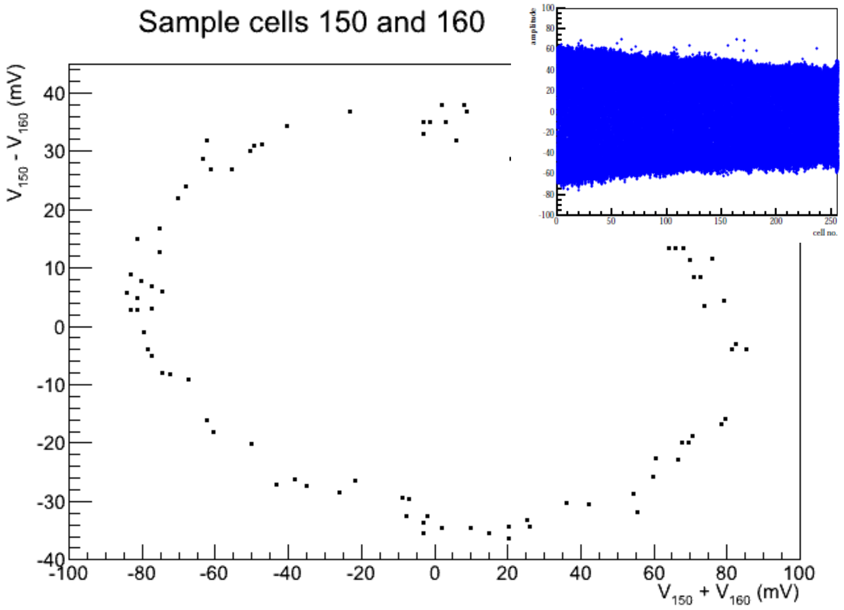
**Excellent resolution even with a modest dataset.**

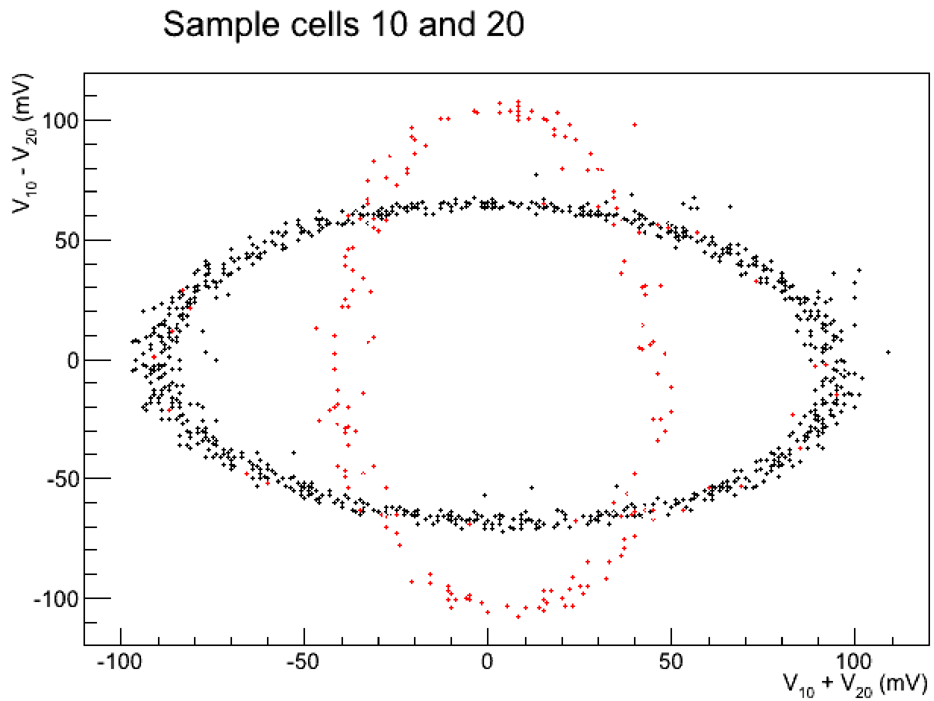
**Next try w/ PSEC3…**

**TDS6804B Datasheet**

| | |
|---|---|
| Aperture uncertainty, typical | Short term:<br>≤1.5 ps rms, records having duration ≤100 ms ≤800 fs rms, records having duration ≤10 µs<br>Long term:<br>≤15 parts per trillion rms, records having duration ≤1 minute |

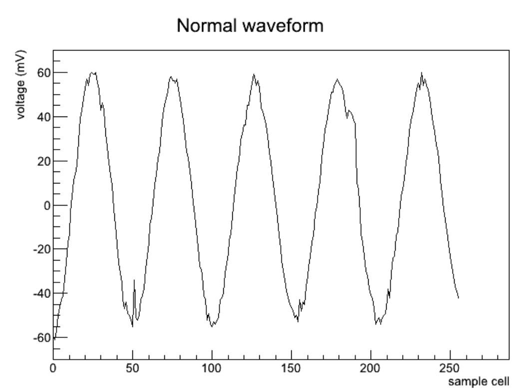
# Qualitative Results with PSEC3

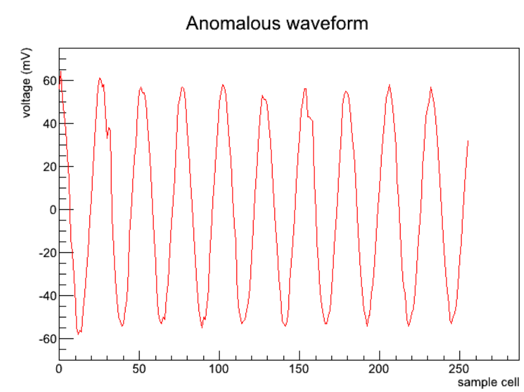



**Immediate visual feedback**:

**(Above)** Data with 120 MHz input signal, obvious gain difference (rotation) along array (see Eric Oberla's PSEC3 talk).

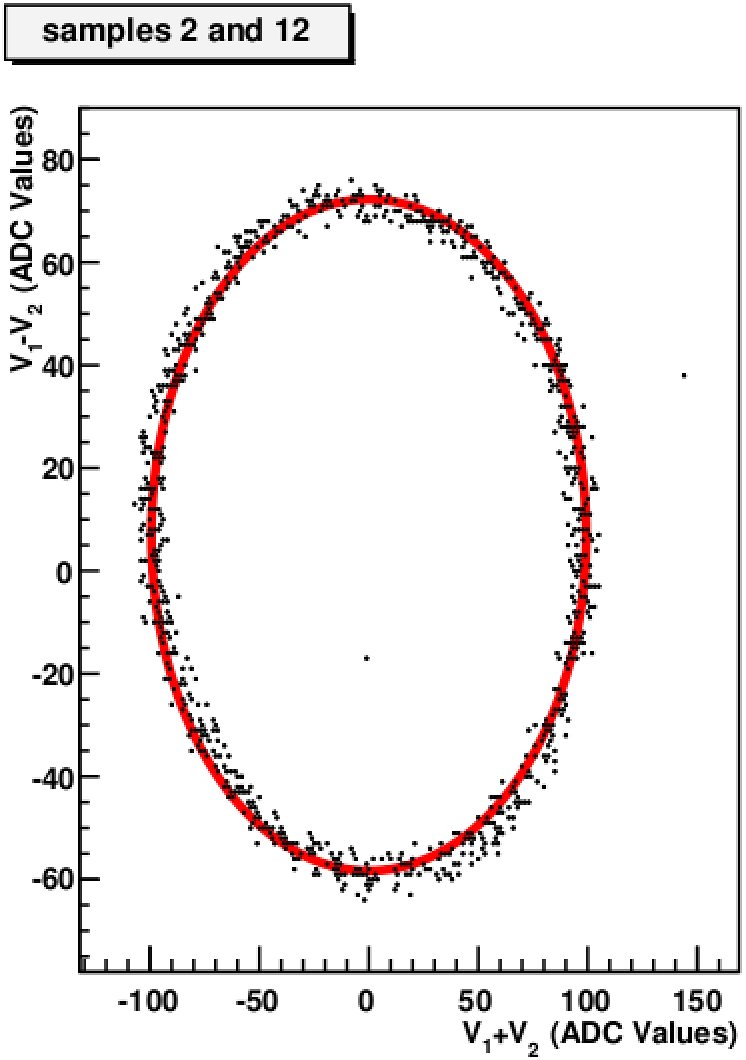


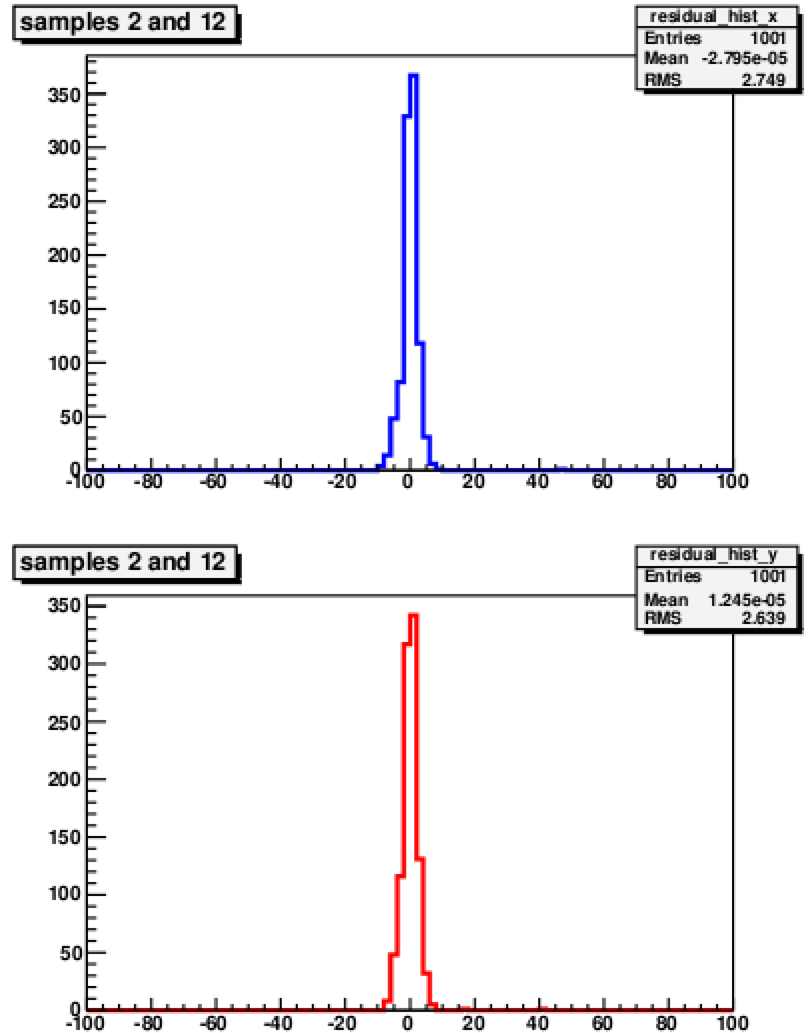

**(Right)** Data with 100 MHz input signal, two sampling rates seen. Quickly identified a subset of events where sampling rate slipped.

# Example Fit w/ PSEC3 Data

**Data and fit**



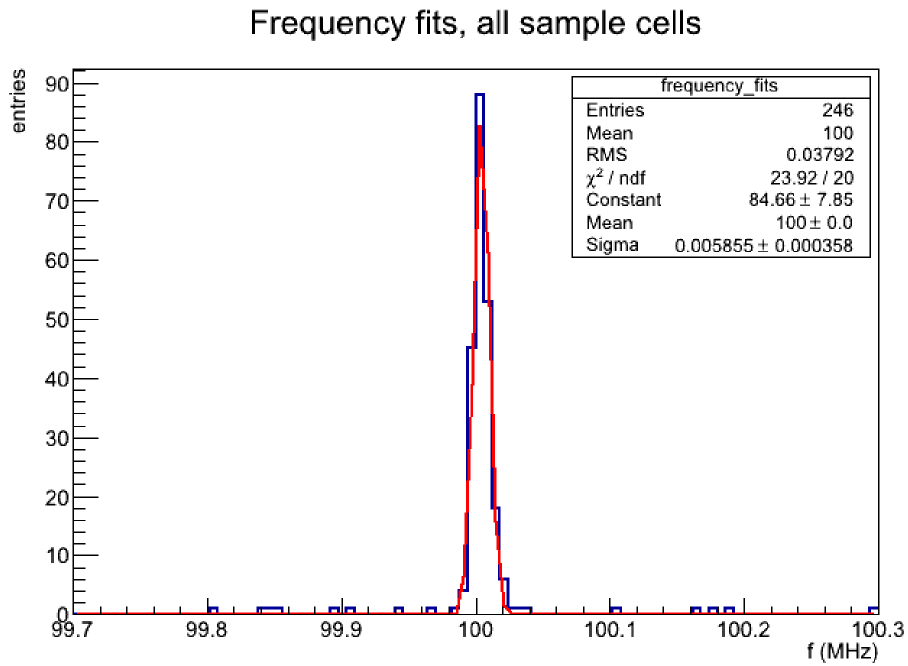

**Residuals in x, y**




- **Fits are well behaved, converge nicely.**
- **An obvious place to improve: outlier removal.**

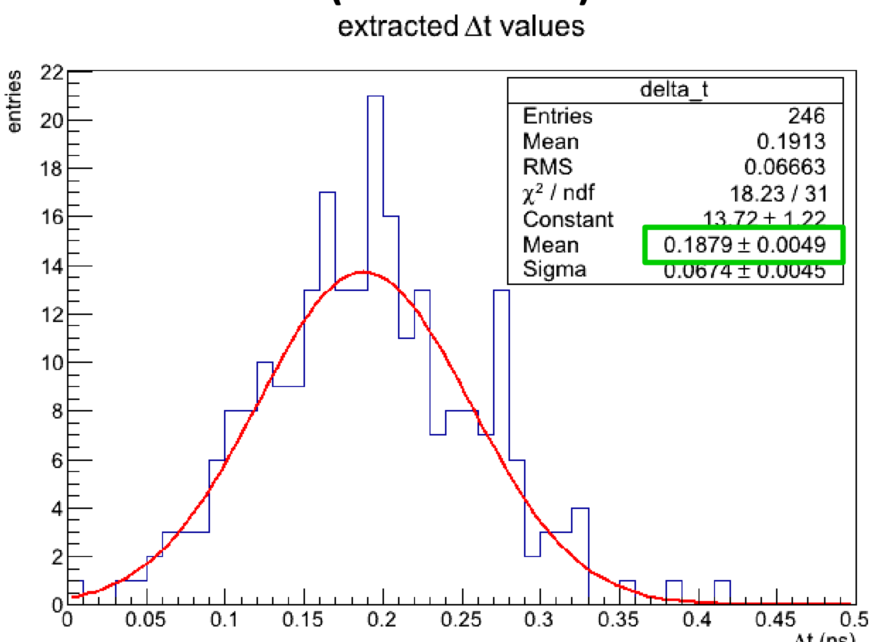
# Fit Validation & Results

- Use a small independent dataset, fit again w/ $\Delta$t values fixed and the input frequency floating.




**(Left)**
**Input frequency: 100 MHz**

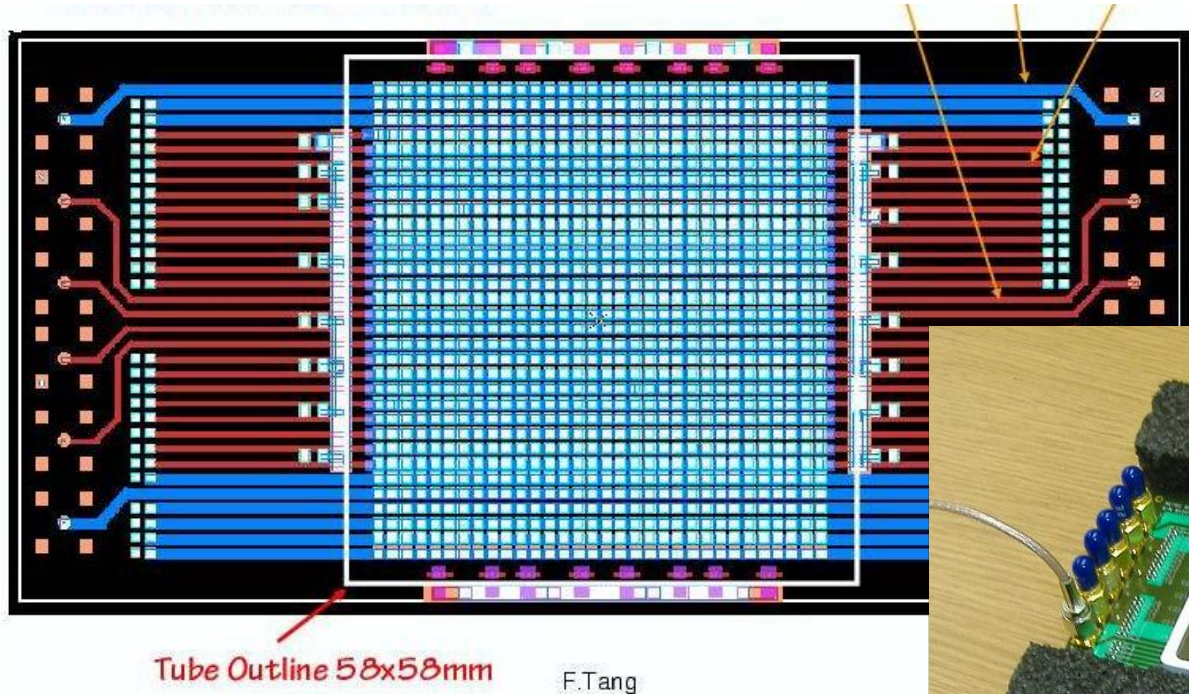
**Fitted output: 100 MHz $\pm$ 0.5 kHz**
**Fitted resolution: 6 kHz**
**(38 kHz RMS)**



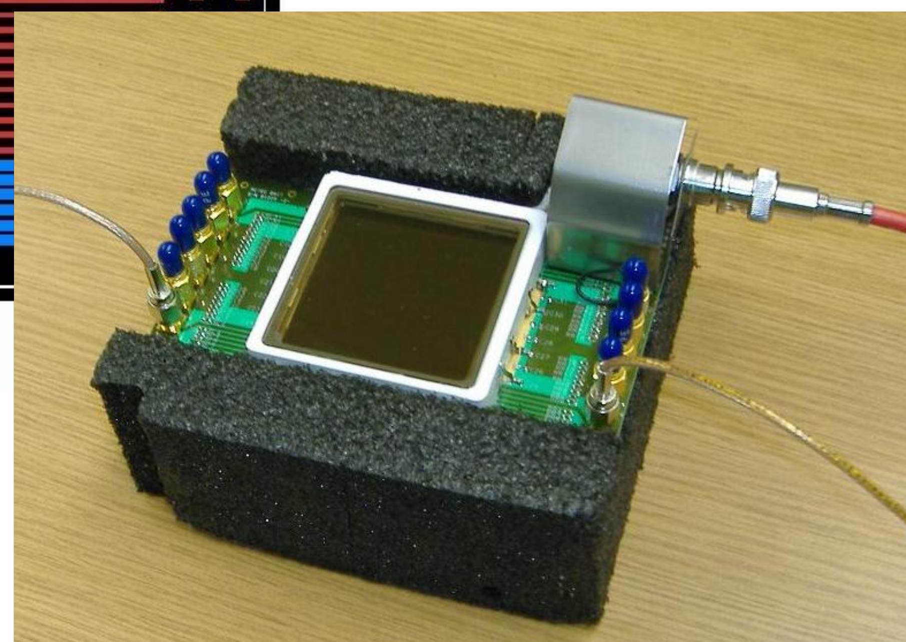

**(Right)**
**Mean is consistent with expected sampling rate, ~5 GSa/s.**

# PSEC3 with Stripline PMT

- PSEC3 is designed for Large Area Picosecond Photo-Detector (LAPPD) project (http://psec.uchicago.edu)



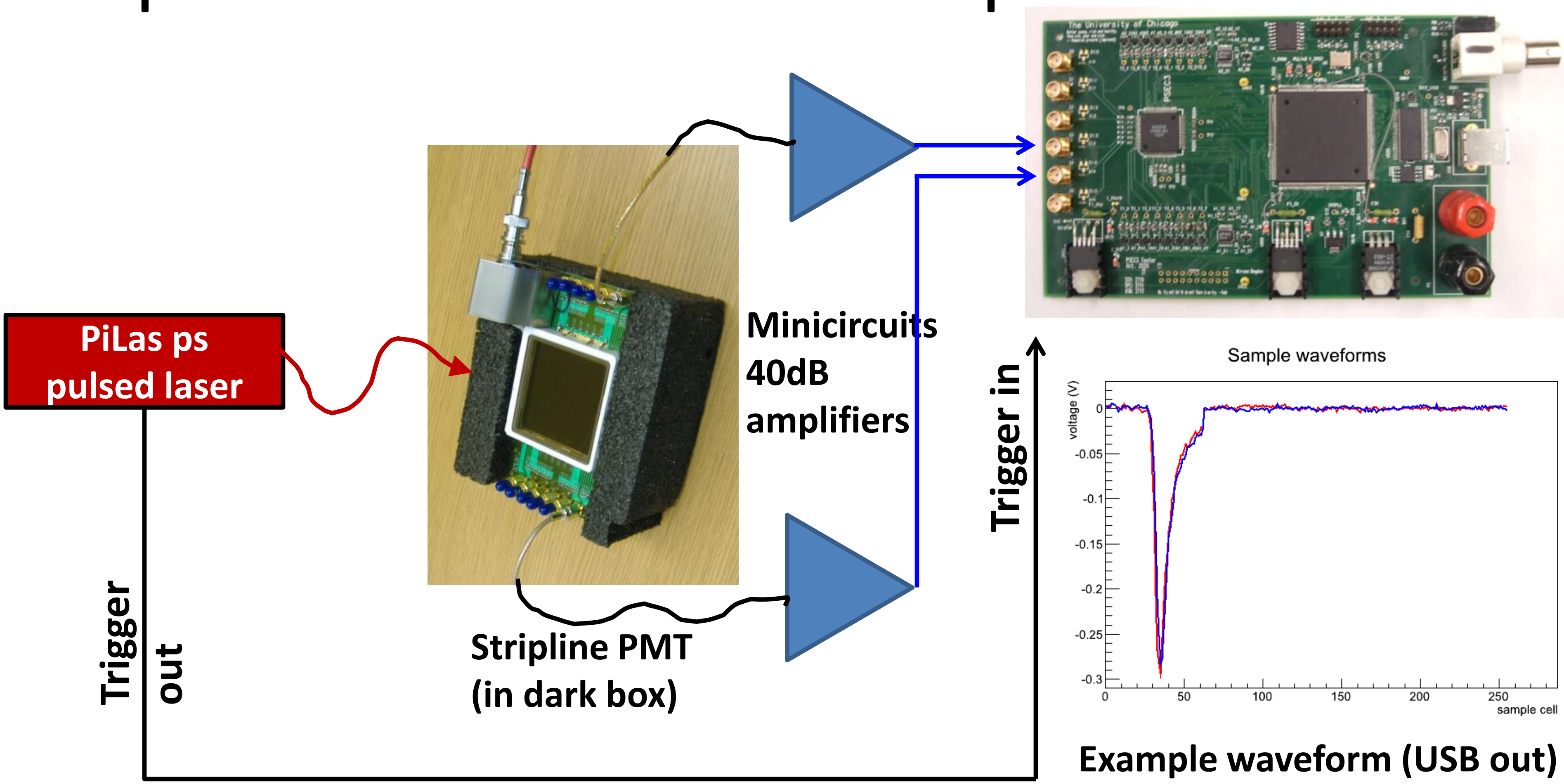

- Planacon MCP-PMT w/ 25 $\mu$m pore and prototype transmission line PCB readout.



- Time resolution along a strip directly impacts position resolution.

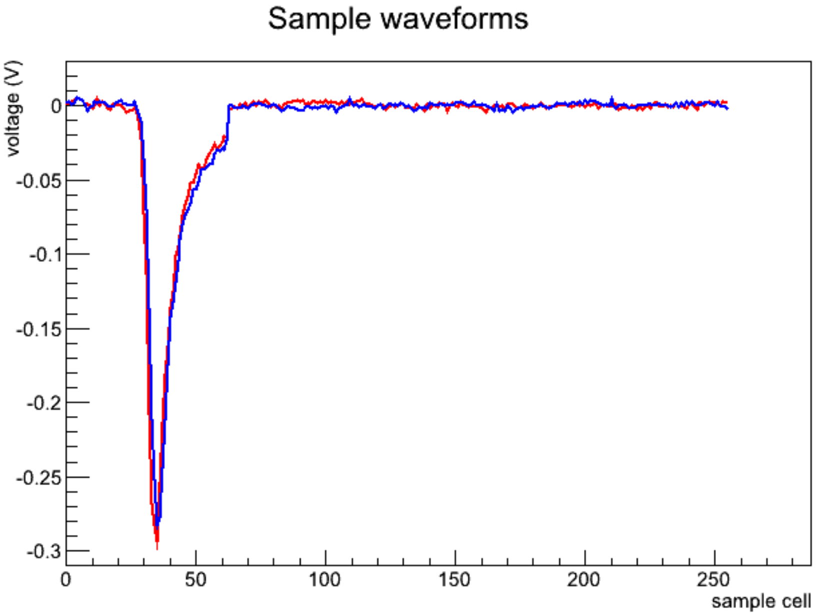
➔ How well can we do with PSEC3?

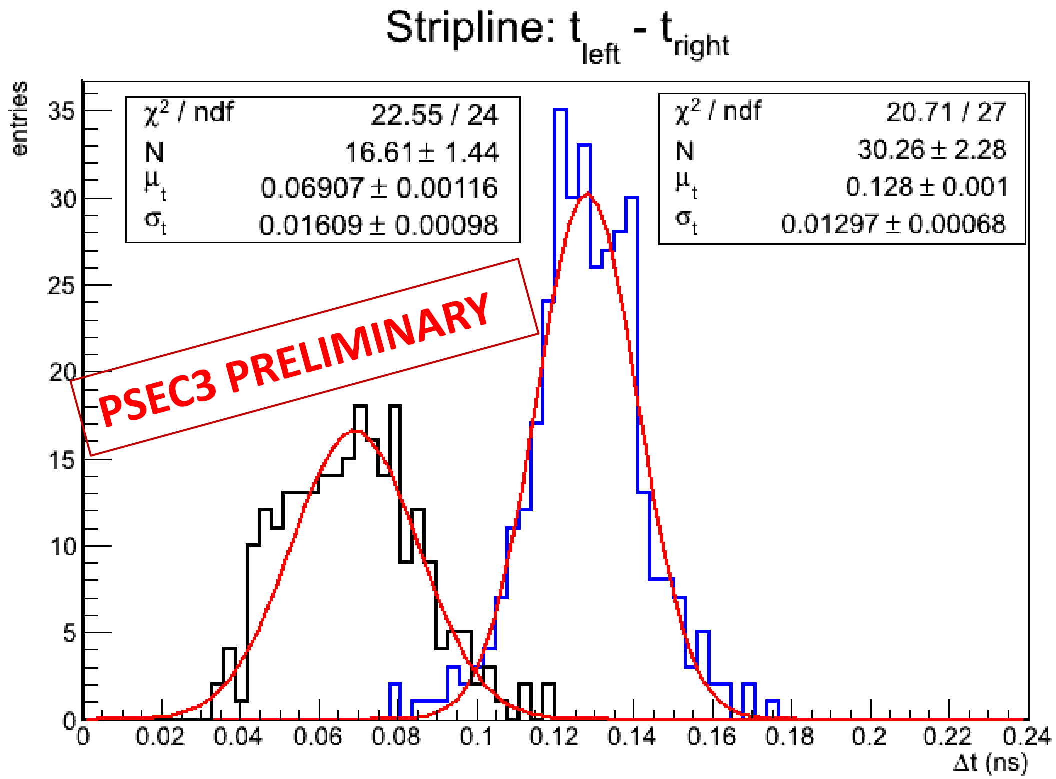
# Stripline MCP + PSEC3 Setup




- Use constant fraction technique to determine pulse time.
- Measure $t_{left} - t_{right}$ with nominal and calibrated $\Delta t$ values.

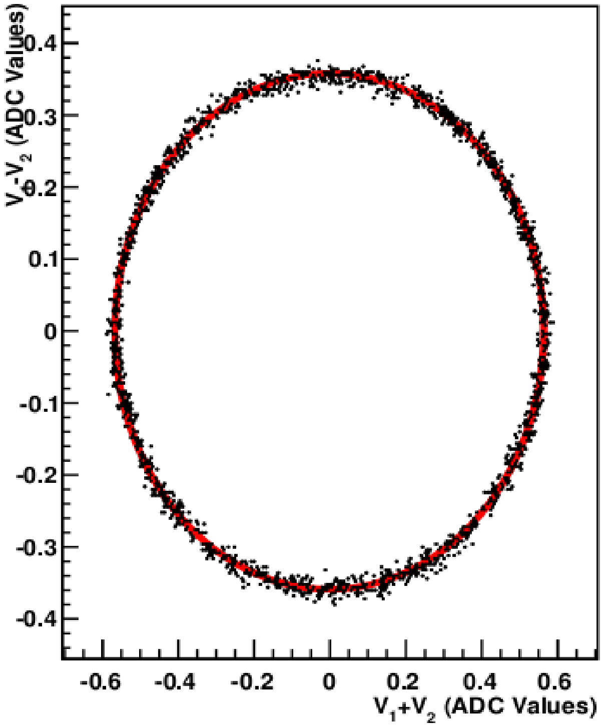
# Stripline PMT Resolutions




- Resolution improves from $\sigma_t$ ~ 16 ps to $\sigma_t$ ~ 13 ps.
  - Resolution w/ 20 GSa/s scope: ~10 ps.
  - The procedure is still being refined and cross-checked.

# Summary & Conclusions




- We propose a new technique for timing calibration of waveform sampling ASICs based on correlated sample values.
- Avoids some problems, adds some features:
  - Converges with relatively small data sets.
  - Includes terms to allow for nonzero pedestals.
  - Automatically provides absolute time calibration.
  - Immediate visual feedback on data quality.
- Validated w/ PSEC3 ASIC and oscilloscope data, and we are continuing to refine and add functionality.