Laboratory and Beam Test Results of TOFFEE ASIC and Ultra Fast Silicon Detectors

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TWEPP 2017 - Topical Workshop on Electronics for Particle Physics

Outline

- **Motivation for TOFFEE**
- **UFSD sensors**
- **TOFFEE: description and characterization**
- **Beam Test measurements: preliminary results**
- **Plans**

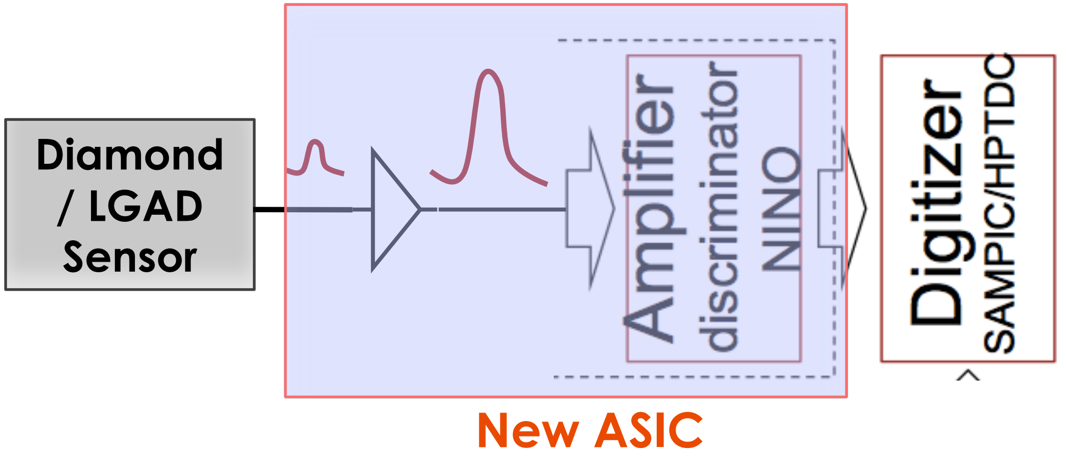
Motivation

Develop a **low-noise/high slew-rate read-out chip** for timing measurement of multi-channel LGAD devices:

- **Testing purposes**
- **Possible usage in CT-PPS timing stations:**
  - time-tagging of protons, scattered at low angle from the CMS interaction point – 20 ps time resolution per station

➡ Desired Time Resolution: 40-50 ps

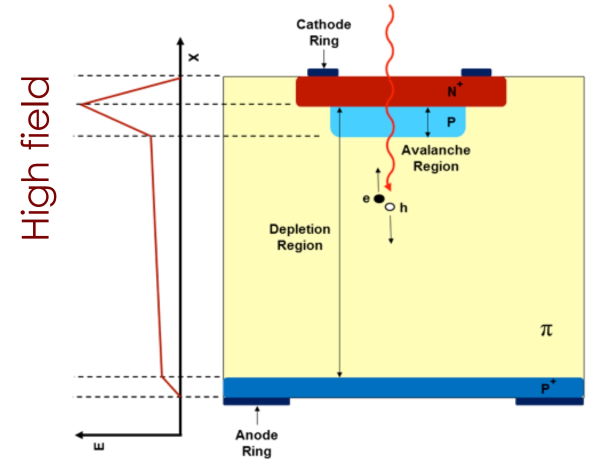
Existing CT-PPS timing read-out chain

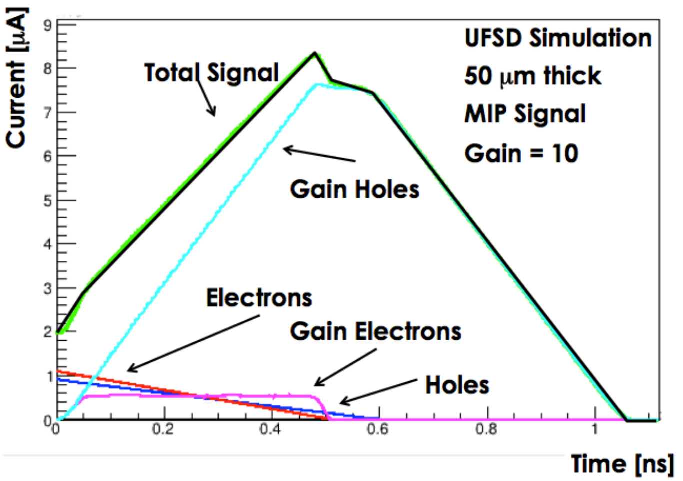


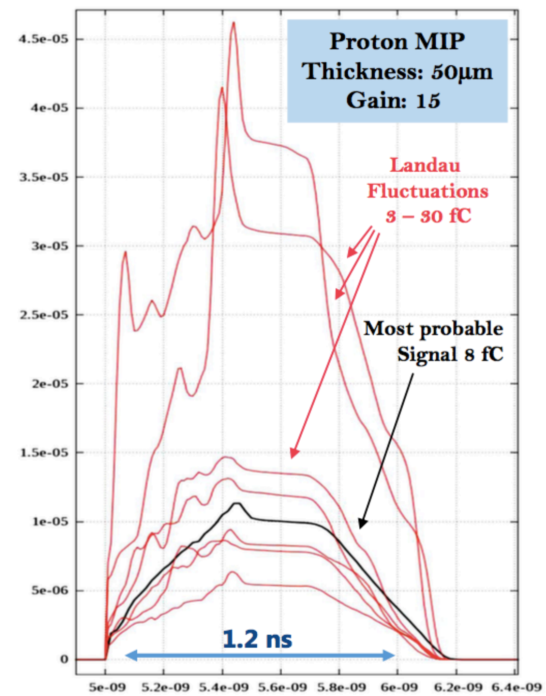
Ultra Fast Silicon Detectors

LGAD sensors optimized for timing measurement of MIPs

Low internal gain (~15-20) through thin multiplication layer
Low shot noise



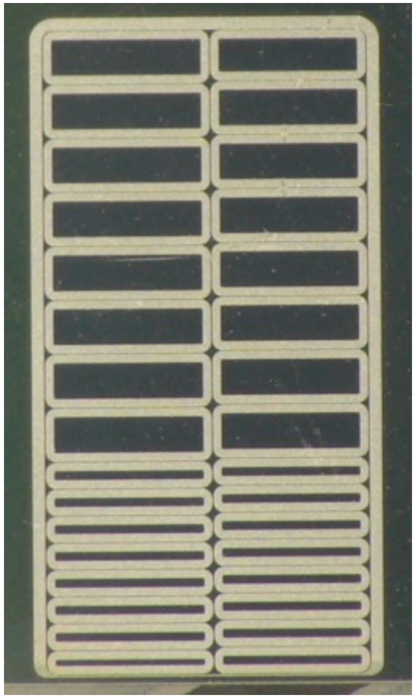




The main contribution to the signal comes from gain holes. The signal shape depends on the sensor thickness and gain

The CT-PPS UFSD sensor

PADS	16 narrow + 16 wide
Thickness	50 µm
Module size	12 mm × 6 mm
Strip size	3 mm × 0.5 mm 3 mm × 1 mm
Gain	15
Cdet	3 pF (narrow) 6 pF (wide)
Dead space	50 µm between pads



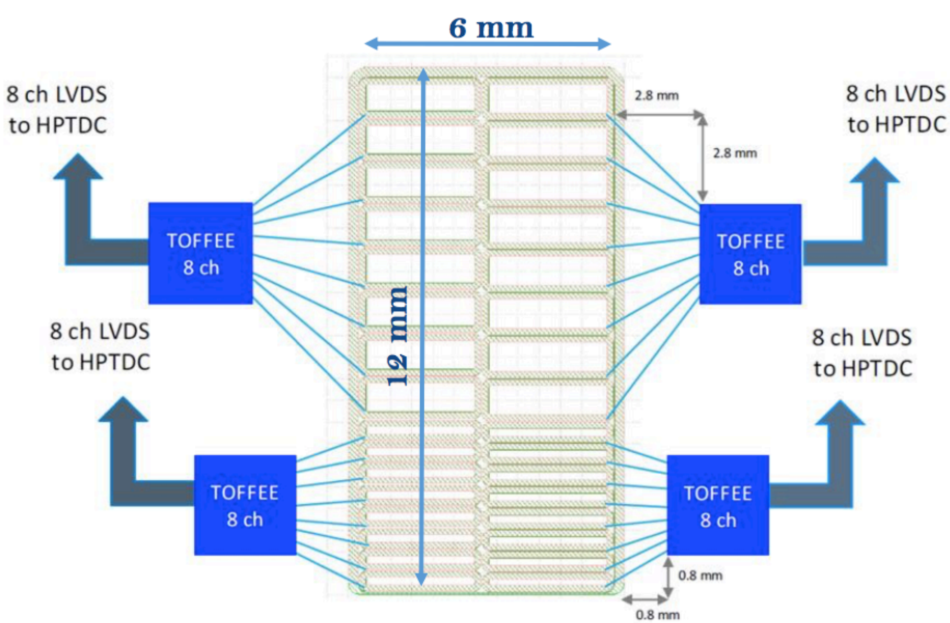
- Produced by **CNM, 50 microns thick**, segmented as in picture
- Slim edge of ~200 um on the side close to the beam
- Strips are **partially covered with aluminum metal**

Time Of Flight Front-End Electronics: TOFFEE

- Fully custom-made analog ASIC for the amplification and discrimination of sensor signals
- INFN Torino/LIP Lisbon development
- Tailored on UFSD sensors

8 input channels - 8 LVDS output

Technology	CMOS 110 nm
Channels	8
Sensor capacitance	2-10 pF
Input dynamic range	3 fC – 60 fC
Analog gain	7 mV/fC
GBW	14 GHz
RMS noise (C=6pF)	800 μV
Discriminator output	2 – 14 ns
Power consumption	18 mW/ch
AVDD/DVDD	1.2 V/2.5 V

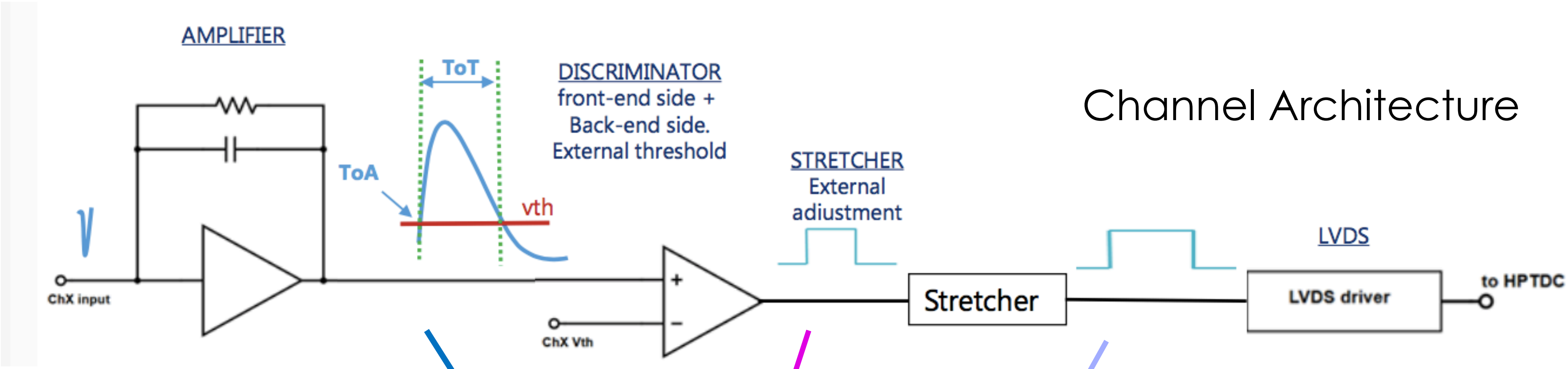


Output for time digitization with High Precision TDC[I] board (as a "NINO[II]-like" board)

[I] ***J. Christiansen, 2004, http://cds.cern.ch/record/1067476***

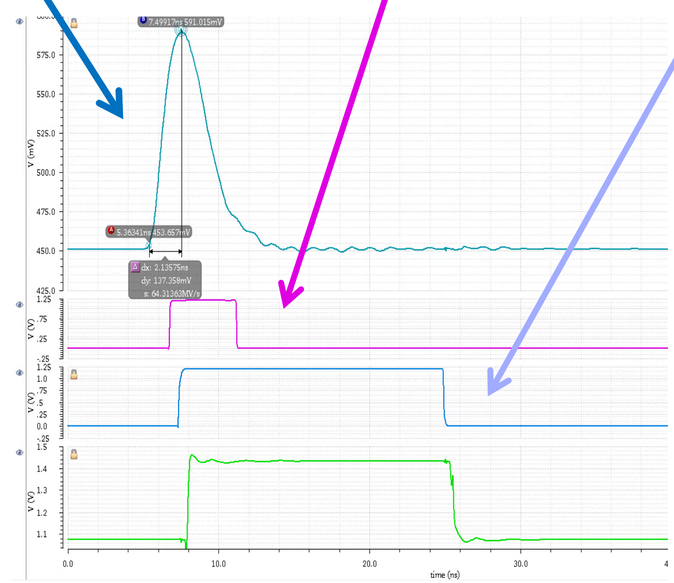
[II] ***F. Anghinolfi et al., 2004- Nucl. Instrum. Meth. A 533 183***

Time Of Flight Front-End Electronics: TOFFEE



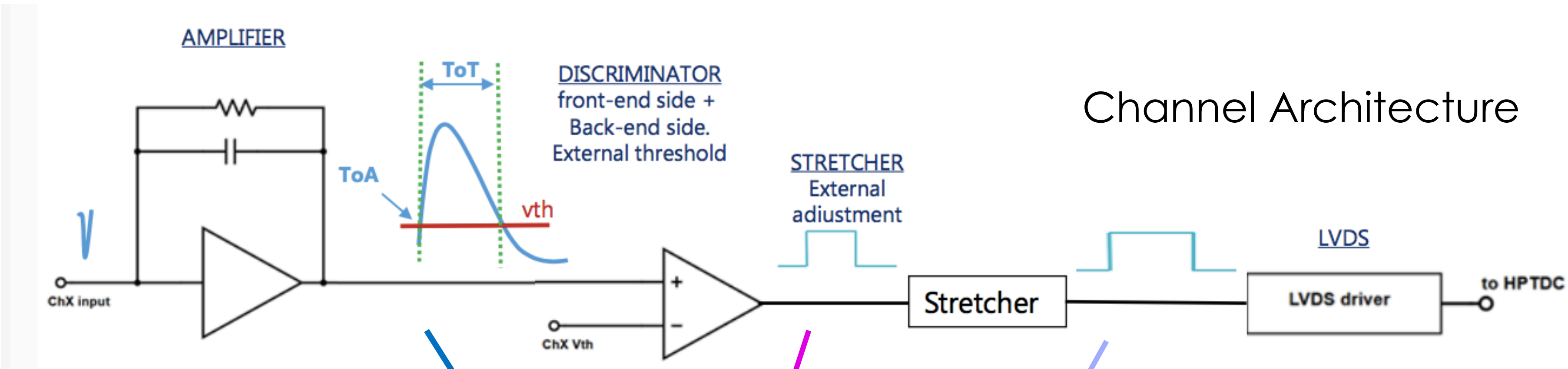
Channel Architecture

Simulation (SPICE)

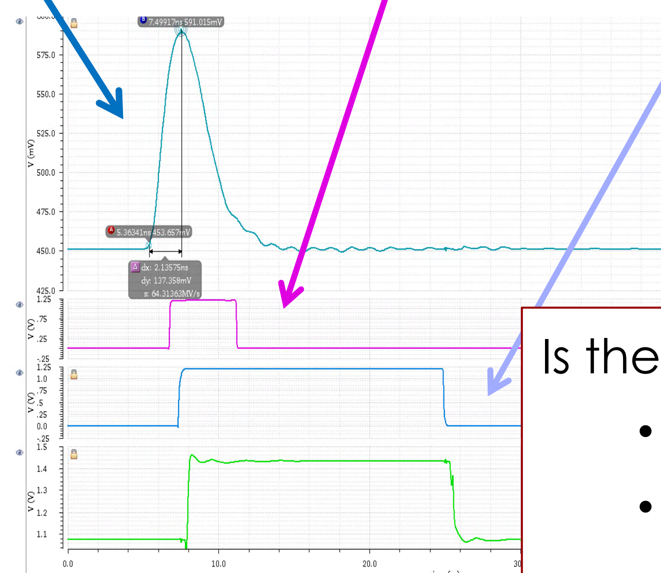


Time Of Flight Front-End Electronics: TOFFEE

Channel Architecture



Simulation (SPICE)



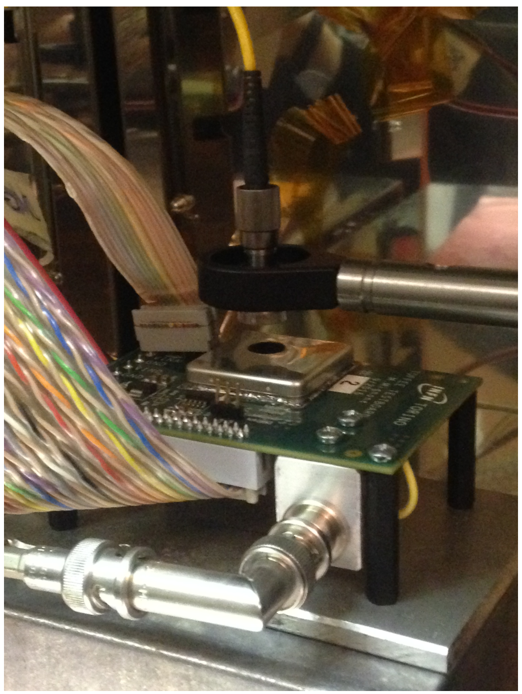
Is the TOFFEE working?

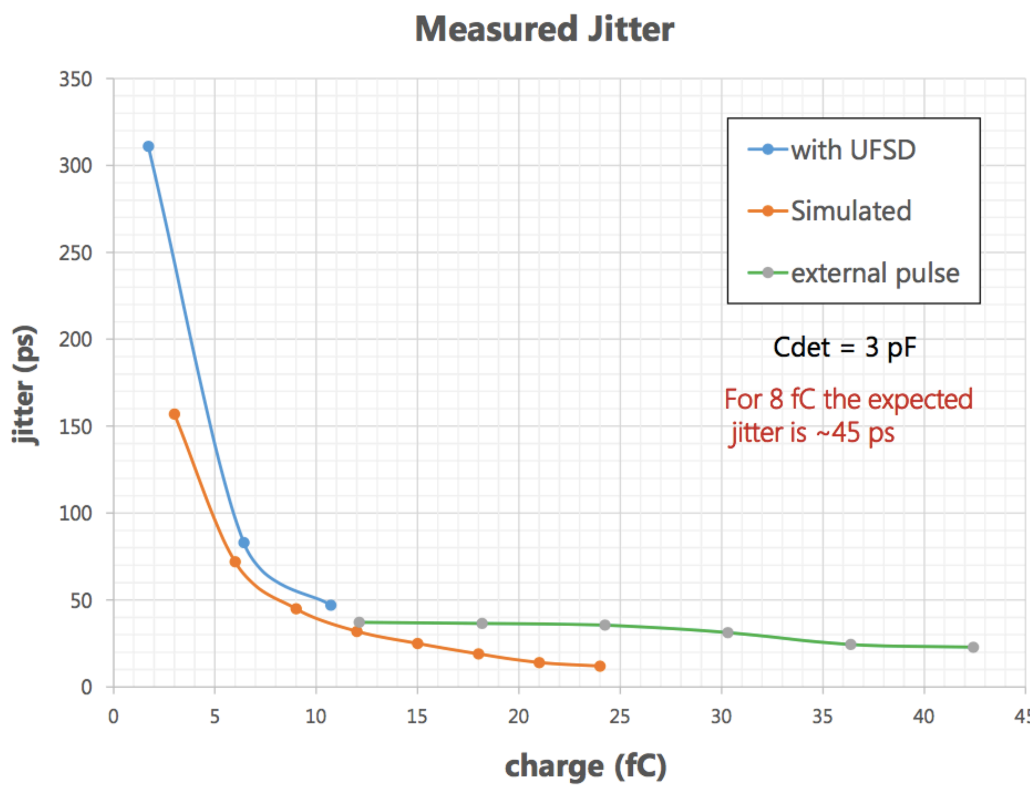
- preAmplifier (gain)
- TOT / stretcher
- Which jitter?

Initial characterization of the chip

Jitter versus input charge: post layout sim/ Laser measurements / external pulse (capacitor)

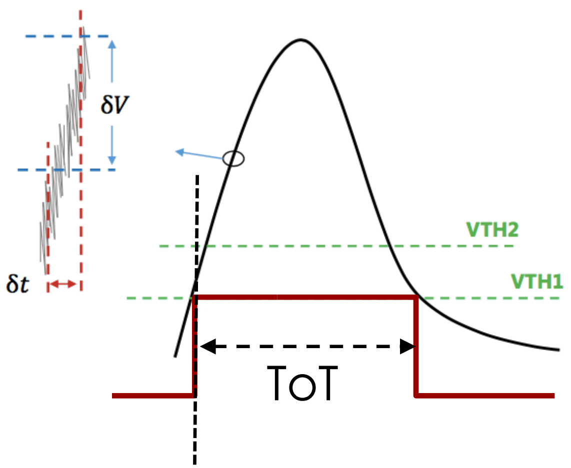
- **UFSD CT-PPS sensor 8 3-pF strips, wire bonded to one TOFFEE chip**

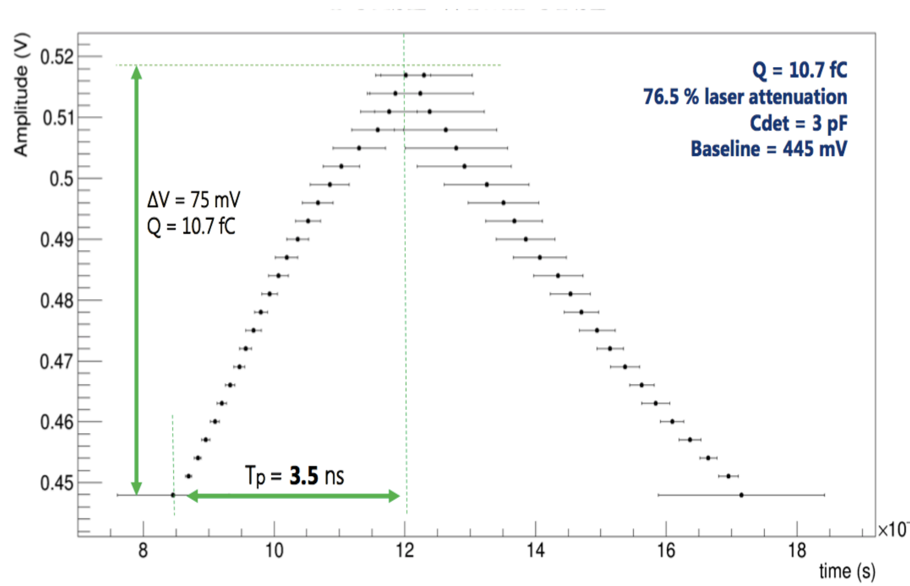




Initial characterization of the chip

PreAmp output signal reconstruction: done using the ToA and the ToT measured during a threshold scan



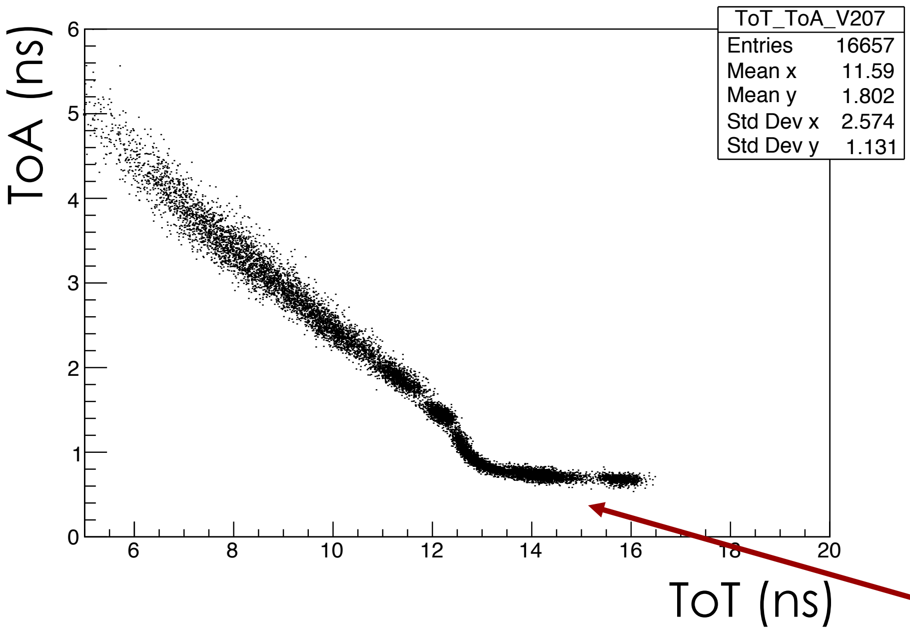


Rise Time: 3.5 ns. (compatible with post layout value ~3 ns)
Slew Rate: 25 mV/ns
Noise: ~ 0.8 mV

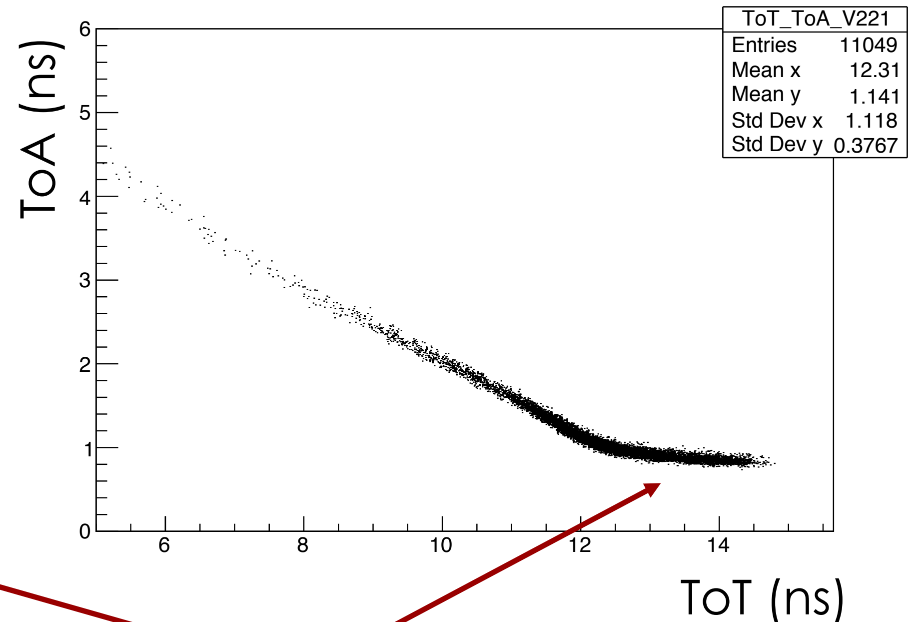
More Tests in Lab: ToA vs ToT

Time measurement of TOFFEE output with variable laser intensity, to explore the response in a large range of ToT. Repeated for different Vth (UFSD sensor at 200 V)

Vth = 7 mV

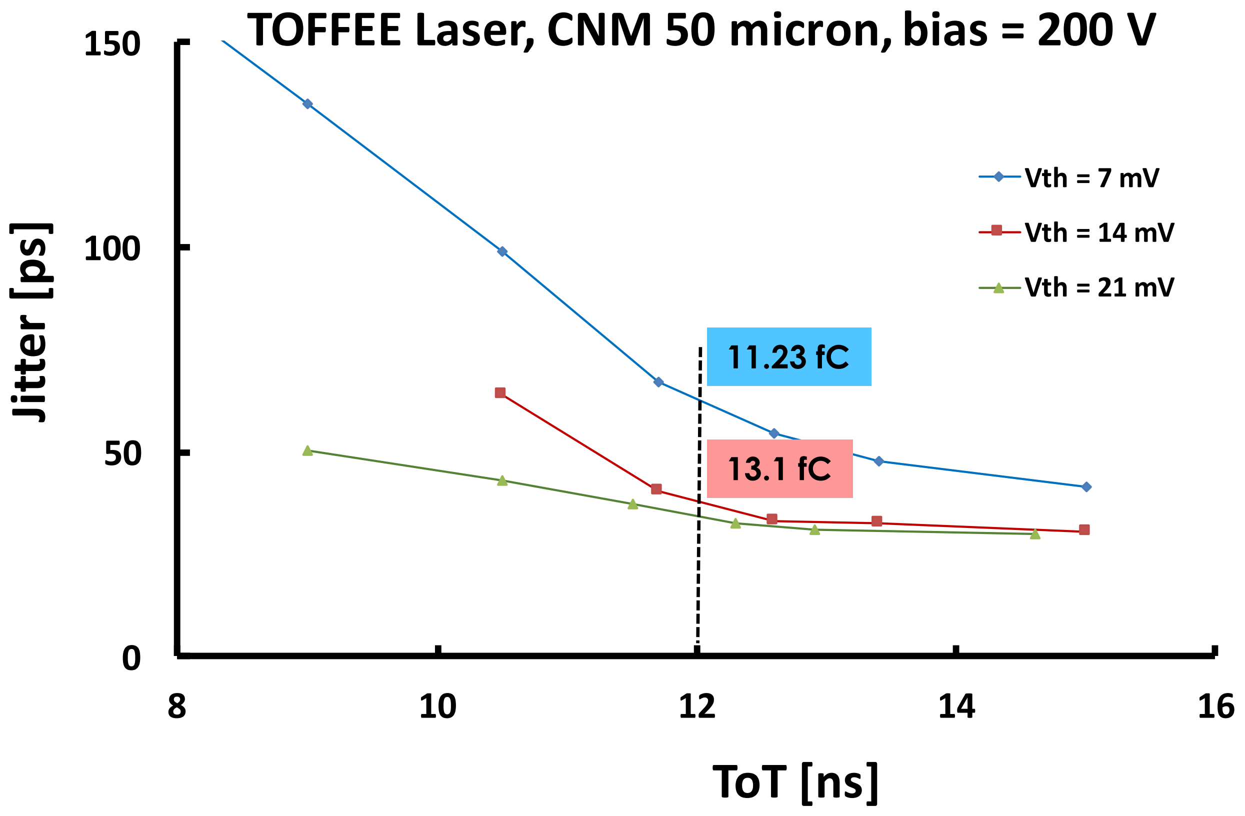


Vth = 21 mV



Slew rate saturation for high signals

More Tests in Lab: Jitter measurement



Jitter measured in bins of ToT (from previous sets of data) for three different thresholds. In pleasing agreement with initial characterization.

TOFFEE @ Beam Test

Three Beam Tests, at CERN SPS - H8

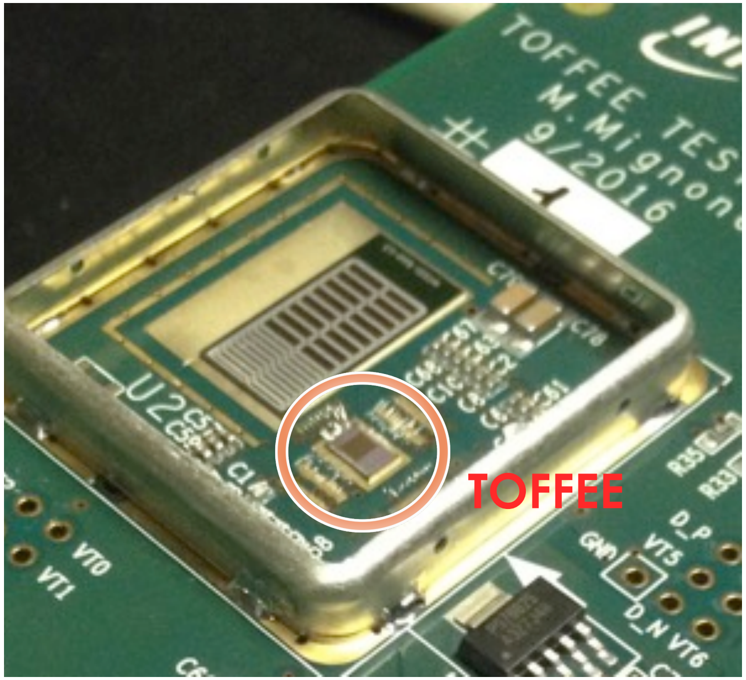
In H8: 120 GeV/c pion beam

May:

- Telescope 3 TOFFEE boards + HPTDC
- Scan in sensor Vbias – fixed Vth

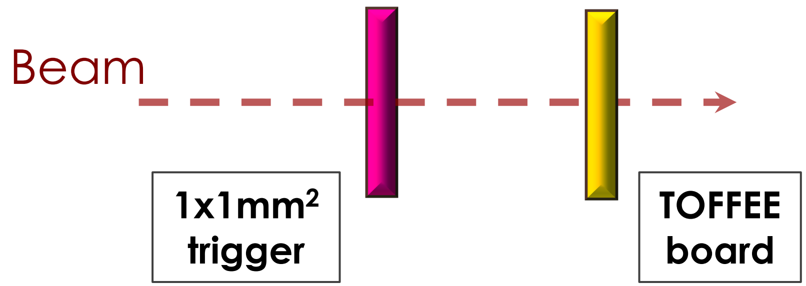
July and End of August:

- TOFFEE board, read-out with differential probe
- UFSD CNM 1x1 mm^2 + USCS preAmp board (time resolution ~ 35 ps)
- Both recorded by a 4 GHz scope (LeCroy HDO9404)
- Several studies done



TOFFEE @ Beam Test

Beam test at CERN @H8 (End of August)



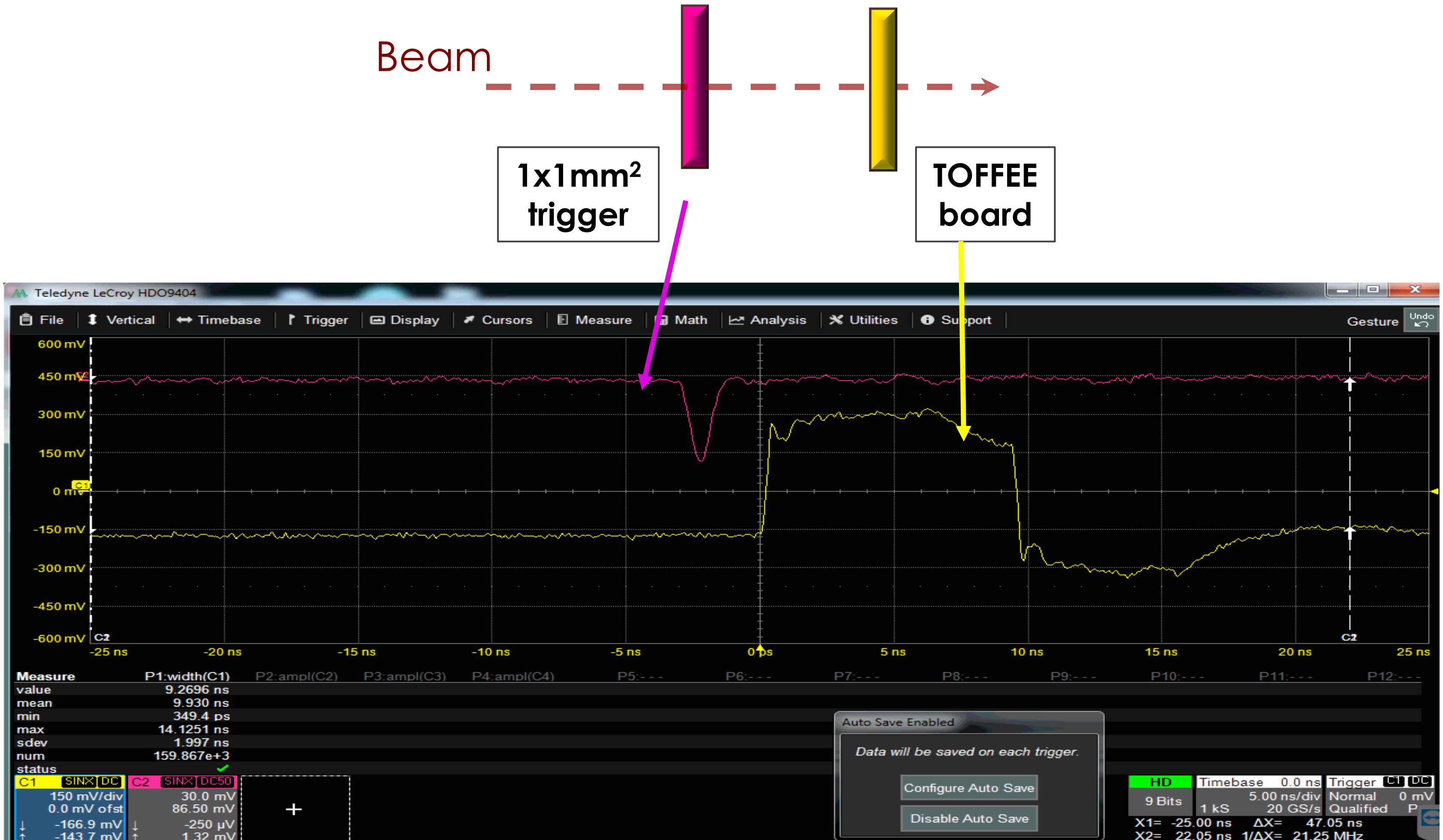
"Trigger" board operated at 220 V – reliable and well known reference signal, used in previous beam tests (time resolution ~ 35 ps)

- **Scans of Vbias (different UFSD gain)** = 100V, 120V, 140V, 160V, 180V, 200V, 210V, 220V, 230V
- **Different discriminator thresholds Vth**: low (7 mV), medium (14 mV), high (21 mV)
- 3 TOFFEE channels (partially overlapping with trigger sensor)

UFSD: a "Vbias controlled" calibrated charge source

TOFFEE @ Beam Test

Beam test at CERN @H8 (End of August)



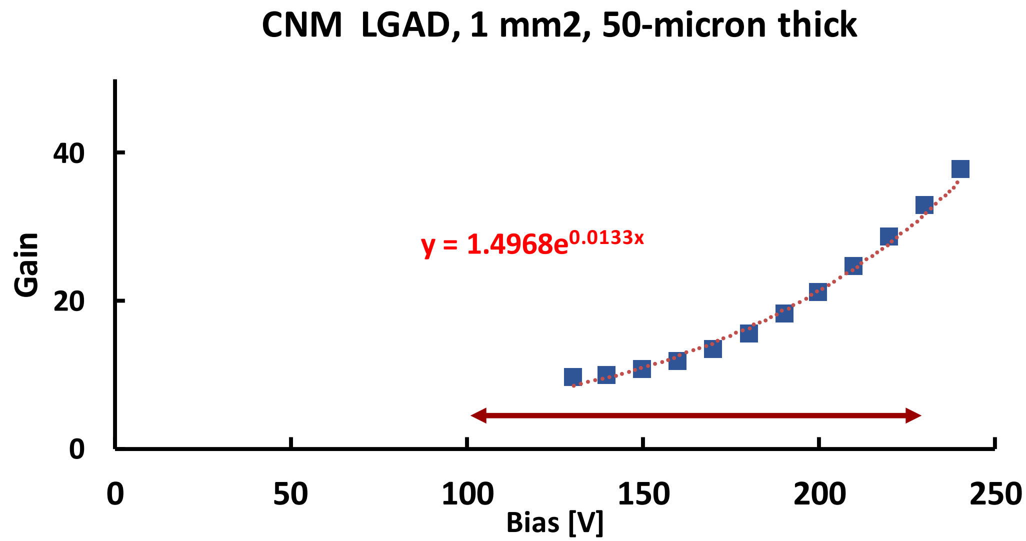
Determination of preAmp gain

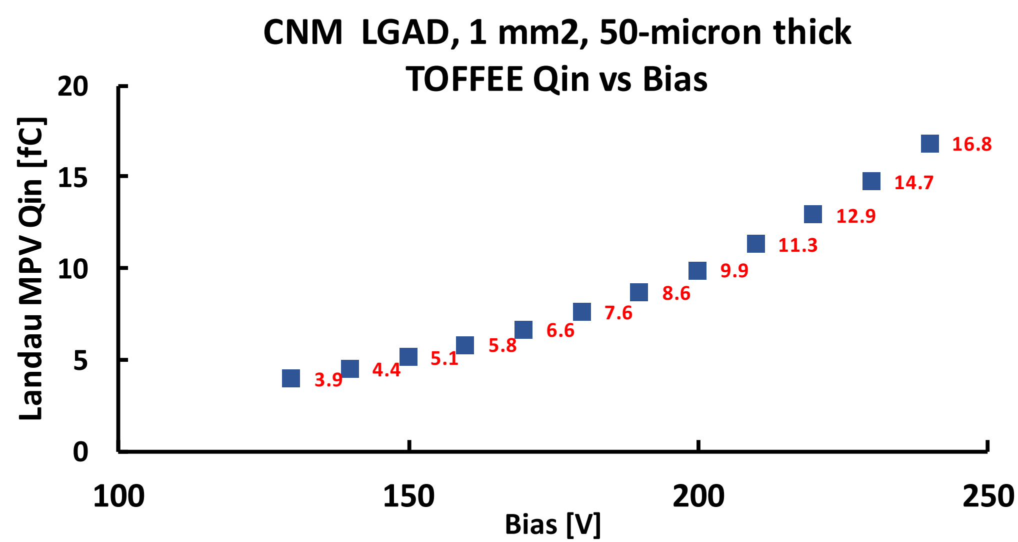
The **gain of UFSD varies with Vbias**. The curve is very well known for the CNM wafer in use (from previous lab and beam tests)

The MPV charge deposited by a MIP has been evaluated to be 0.46 fC.

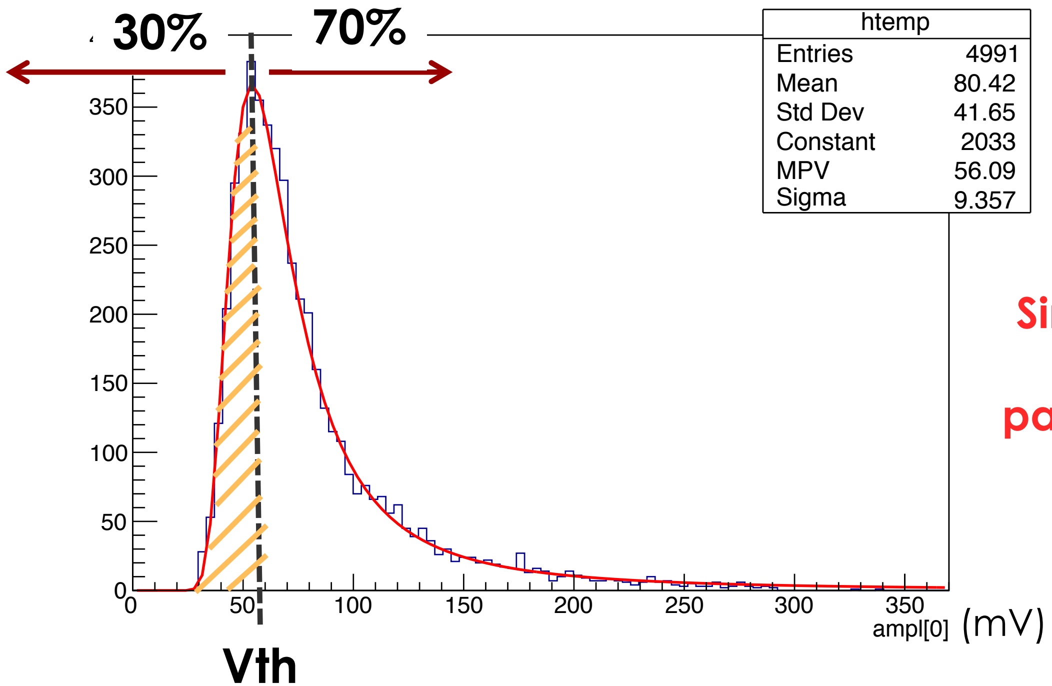
So 0.46*Gain gives the TOFFEE input charge.

The input charge explored @ Beam Test:
2.5 fC (G = 5) – 12 fC (G = 25)





Determination of preAmp gain



Simulated preAmp signal for a MIP passing a 50 micron sensor

To determine the gain we exploit the properties of the Landau distribution:

the cumulative distribution till the MPV value is 30% of the total distribution

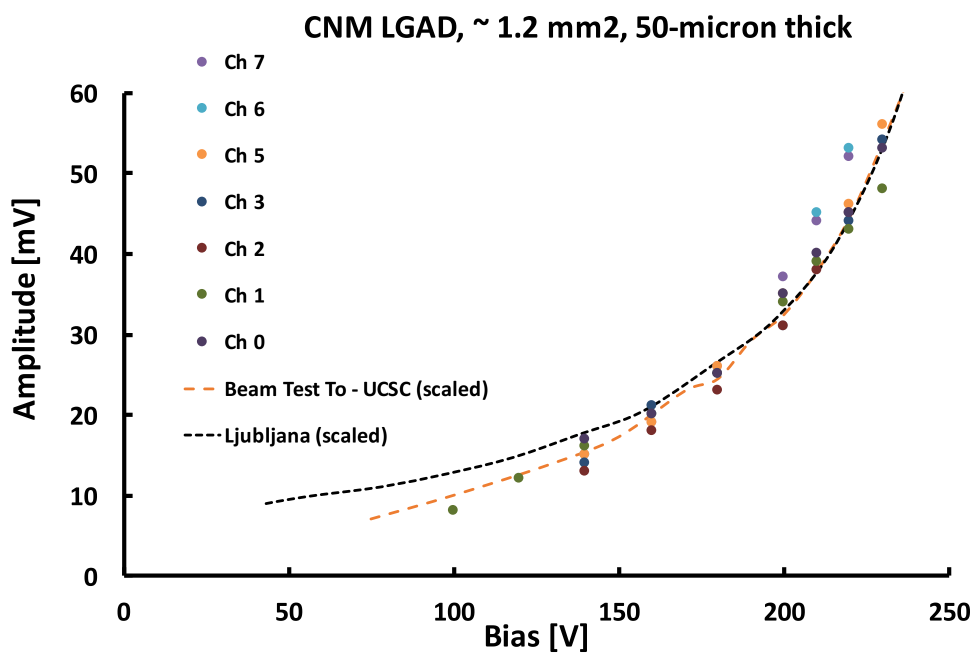
In a SPS spill: ~ fixed number of particles (some hundreds)

At very low Vth, we collect the full Landau distribution.

The **Vth value which keeps 70% of the events/spill corresponds to the Landau MPV**

Comparison of MPV measurements

At the beam test, we found these 70% Vths for each TOFFEE channels and for various Vbias …

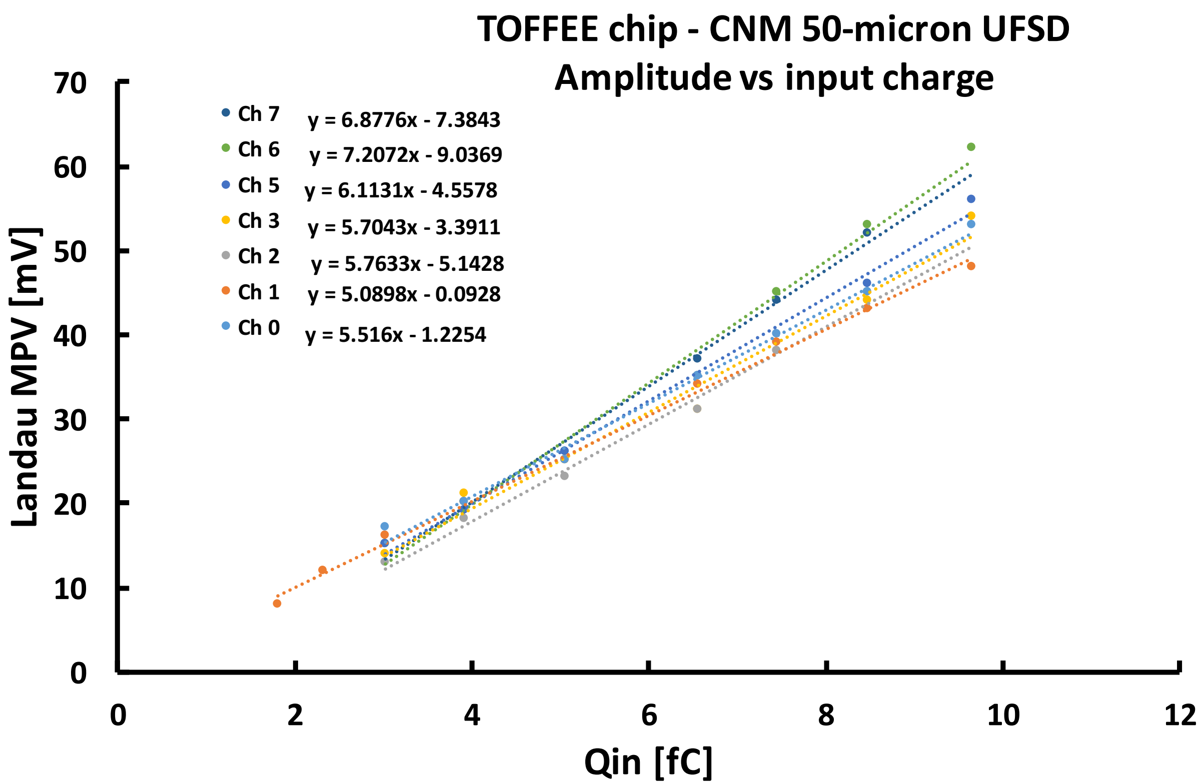


Closure test: **comparison of 3 different methods**. MPV as measured:

- during August 2016 beam test (To-UCSC)
- by the Ljubljana group (lab tests)
- TOFFEE 70% Vth points

TOFFEE Amplitude vs Qin

We can correlate **Qin and Amplitude** via their dependence on Vbias



This plot suggests that the preAmplifier gain is 6 mV/fC (in post layout simulation G = 7 mV/fC @ 23 °C, with a slight temperature dependence)

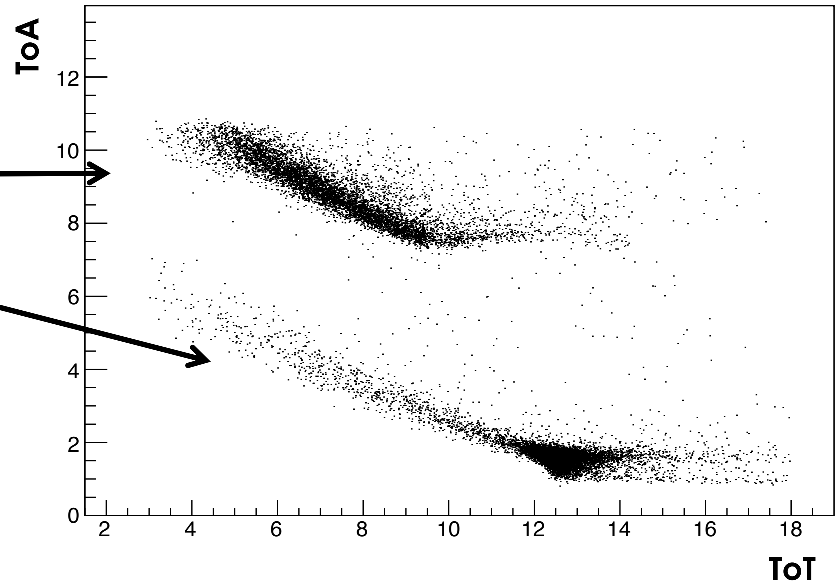
Good agreement!

- Laser measurements confirm a jitter value compatible with expectations
- PreAmplifier gain determined at beam test is in good agreement with the design specs
- ToT maps correctly Qin: Qin = A e $^{B\ ToT}$ (not shown here)

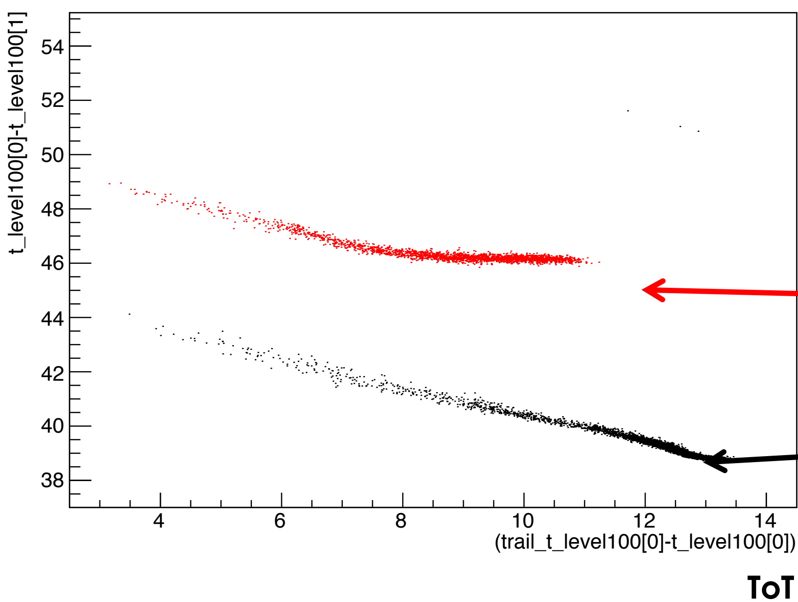
Beam test: ToA versus ToT

The collected data show two families of events:

- Short ToT at 5-6 ns from the trigger
- Long ToT with a timing close to the trigger timing



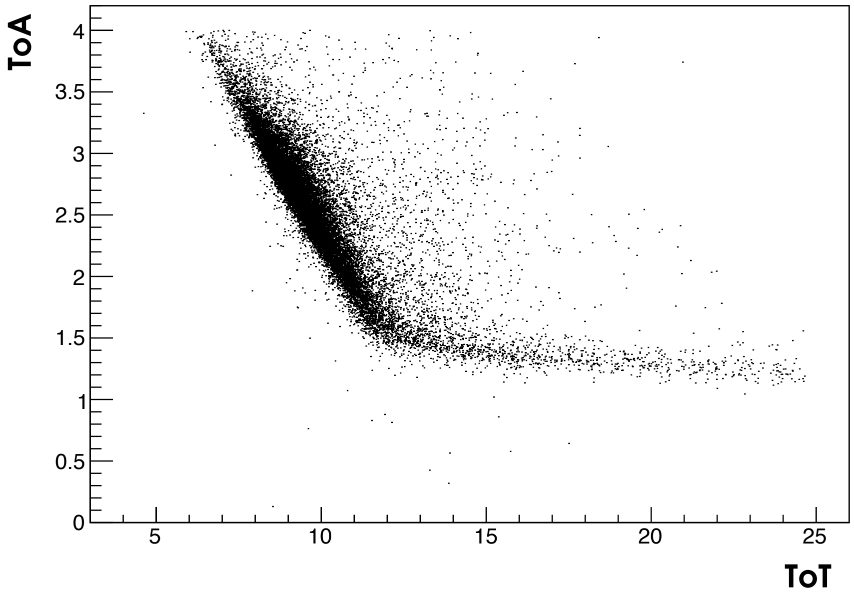
STUDY WITH LASER SYSTEM in the LAB



Laser on neighboring strip

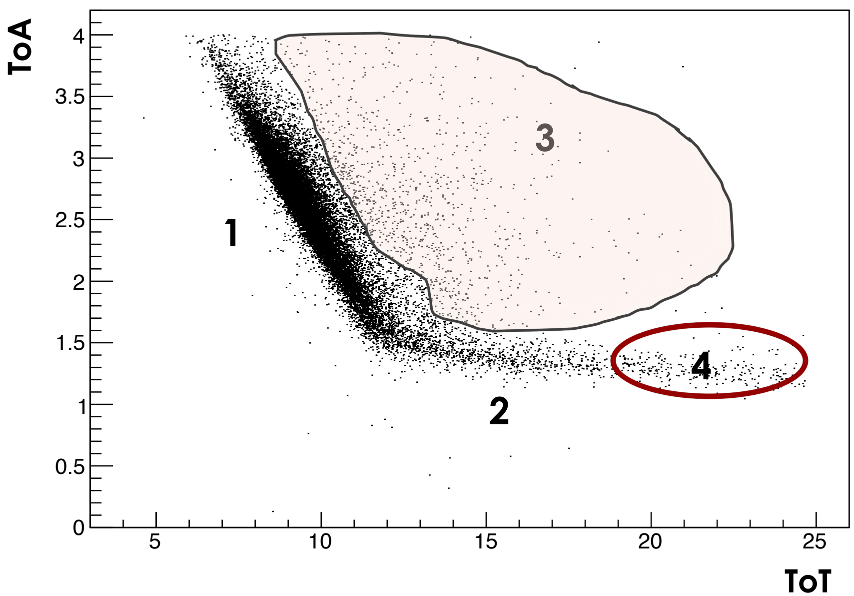
Laser on read-out strip

Beam test: ToA versus ToT



Example of data taken at high Vth (21 mV – 3 fC), V bias = 200 V:

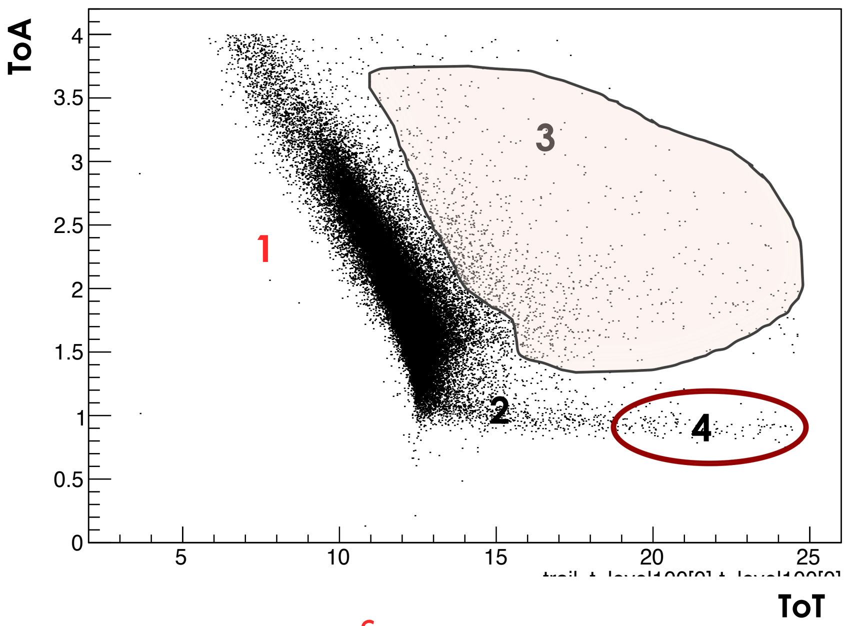
Beam test: ToA versus ToT



Example of data taken at high Vth (21 mV – 3 fC), V bias = 200 V:

1) **expected ToA/ToT correlation**
2) **expected slew rate saturation for high signals**
3) **??** events with **incompatible ToA/ToT** (not present in Laser data)
4) **Very long tail**, possible re-triggering

Beam test: ToA versus ToT



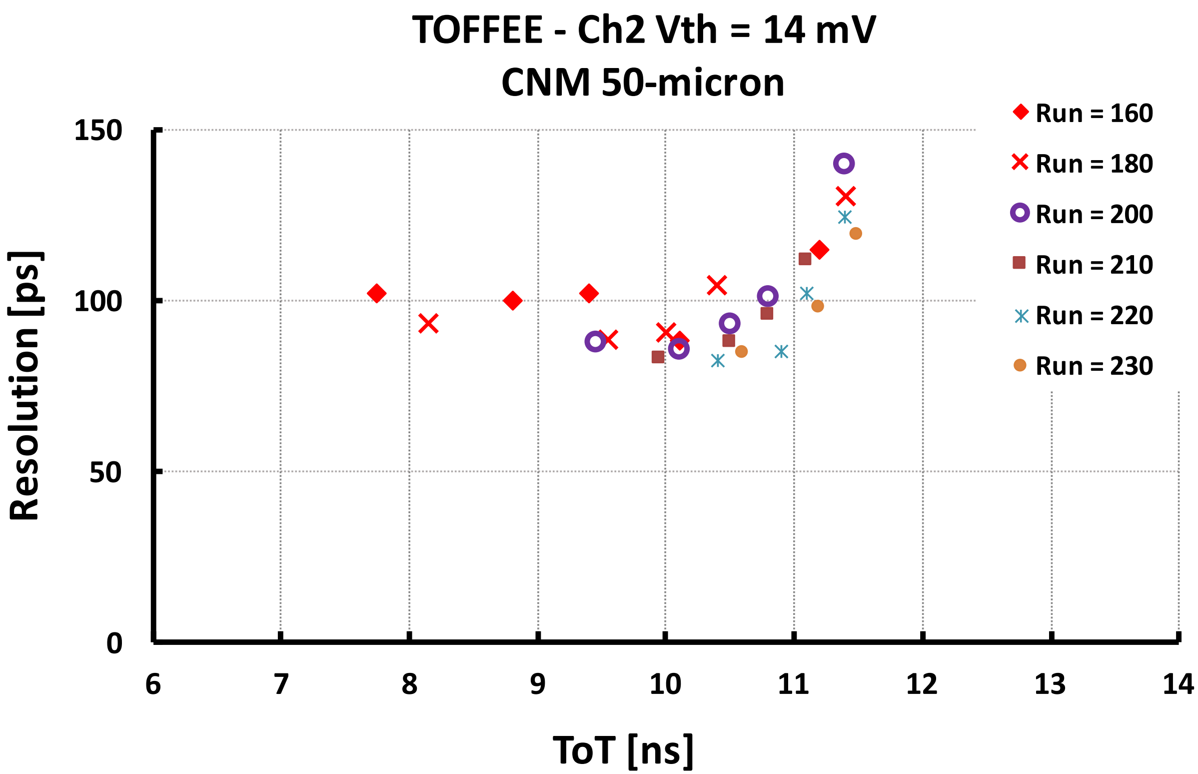
Work in progress

Example of data taken at low Vth (7 mV – 1 fC), summing up over different Vbias

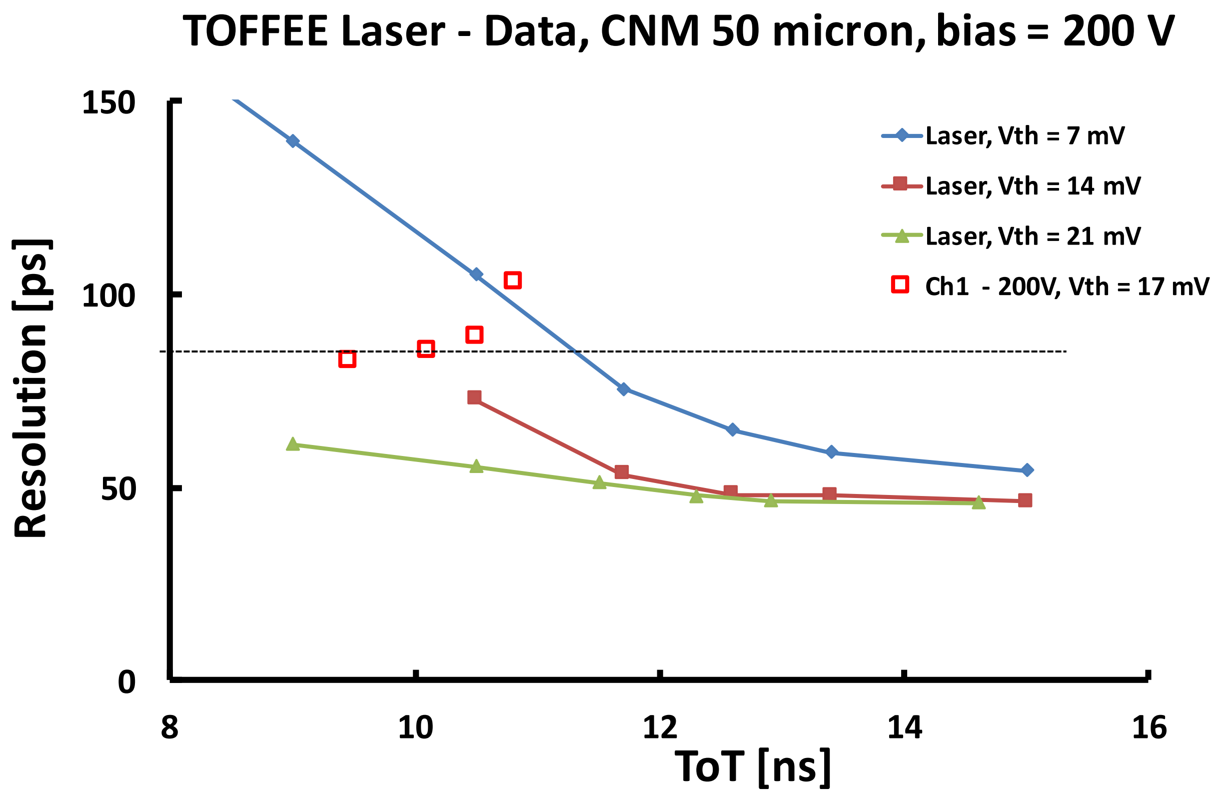
1) **ToA/ToT correlation is wider and appears to have unexpected contribution(s) → the threshold might be too low**
2) **expected slew rate saturation for high signals**
3) **??** events with **incompatible ToA/ToT** (not present in Laser data)
4) **Very long tail**, possible re-triggering

Time Resolution versus TOT

Time resolution in bins of ToT, time walk corrected, for different Vbias.
Medium discriminator threshold Vth = 14mV



Laser/Beam Test comparison



Comparison of time resolution as measured with the laser setup, with the data acquired at the beam test.
A 35 ps contribution, accounting for the non-uniform charge deposition effect, has been added to the jitter contribution (laser measurements)

Conclusions and Plans

Laser measurements demonstrate that TOFFEE works quite well:

- PreAmp Gain and ToT behavior as expected
- For a 2 fC discriminator threshold, **the electronic jitter is better than 40 ps above 12 fC.**

Preliminary beam test results:

- For a 2.5 fC discriminator threshold, **the time resolution is <= 90 ps in the 4.4 - 6.5 fC range**
- At larger charges, the time resolution degrades, due to not yet understood issues

  ⟹ might be connected to the detector

Next steps:

- Extensive lab measurements ongoing
- Preparing for a new Beam test (mid-October):
  - telescope with 2 TOFFEE connected to 1x1 mm^2 pad (HPK UFSD)

Acknowledgments

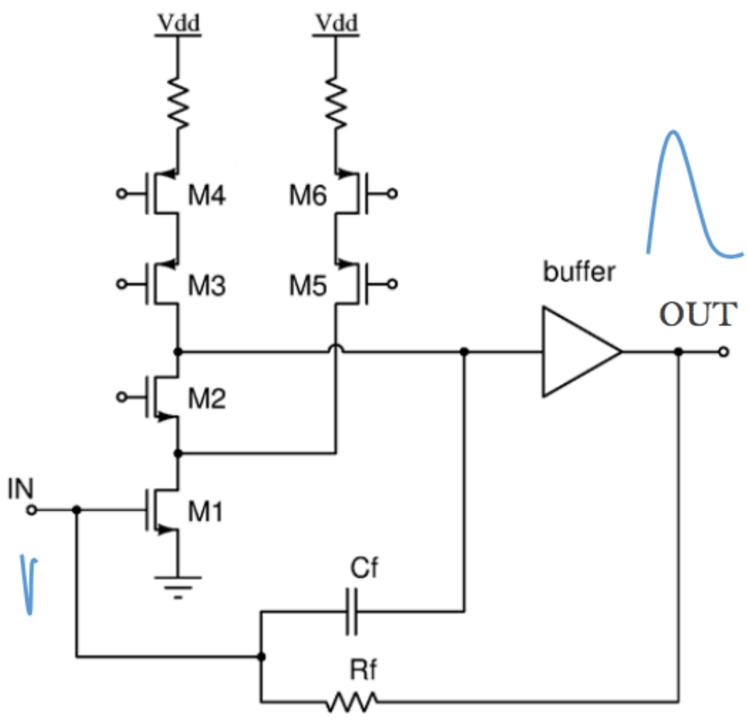
We wish to thank all the Torino UFSD group for the precious support.

We kindly acknowledge the following funding agencies:

- INFN – GruppoV
- Horizon 2020 Grant URC 669529
- Ministero degli Affari Esteri, Italy, MAE

Backup

TOFFEE pre-amplifier



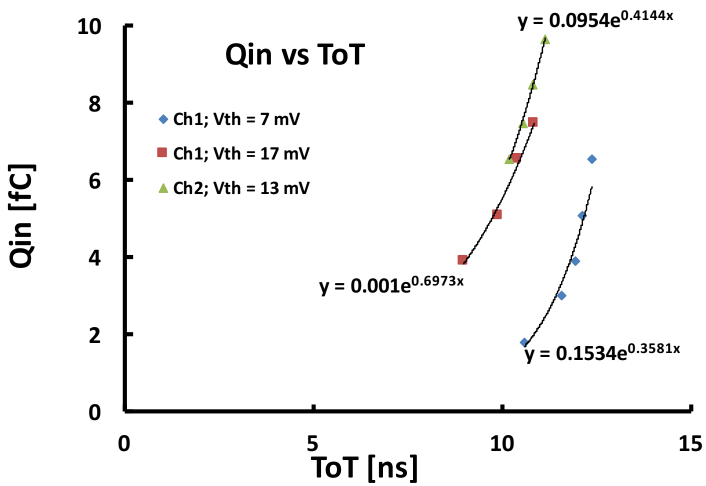
High GBW | High Slew Rate | High Dynamic Range | Low noise

- **Telescopic Cascode** common source with split bias current
- Most of the current is injected by the right branch
- Output driver buffer for feedback resistance isolation and capacitive load driving (Cdet = 6pF)
- **Resistors for source degeneration** of current source

Courtesy JONHATAN OLAVE TREDI 2017

Qin versus ToT

Using the Vth "70%" point, for each given Vbias we can obtain the ToT MPV value.



$$Qin = 0.001e^{0.6973*ToT}$$