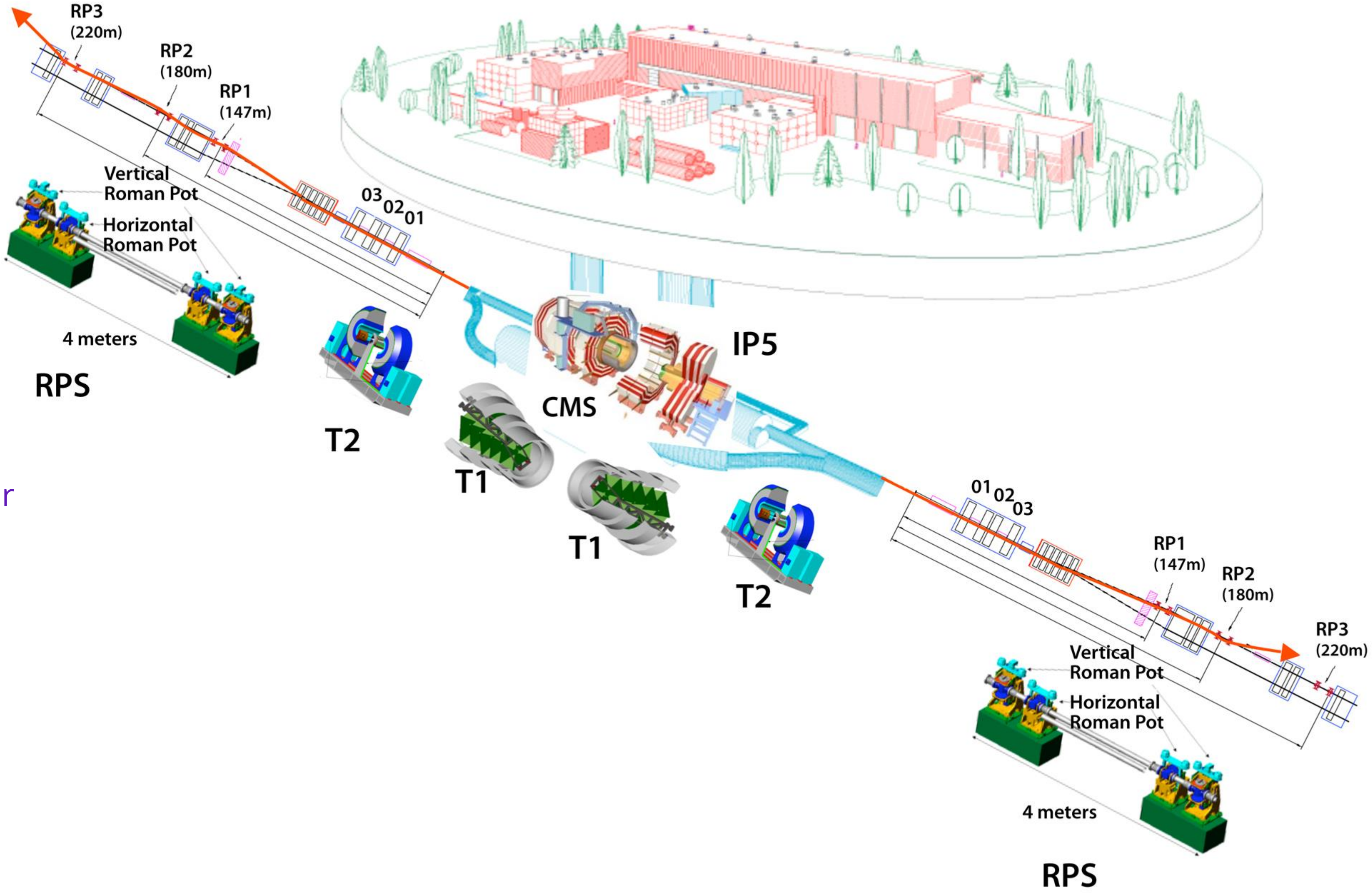
Timing with diamond detectors in TOTEM

Nicola Minafra
University of Kansas

On behalf of the TOTEM Collaboration

Workshop on picosecond timing detectors for physics and medical applications, Kansas City 15-18 September 2016

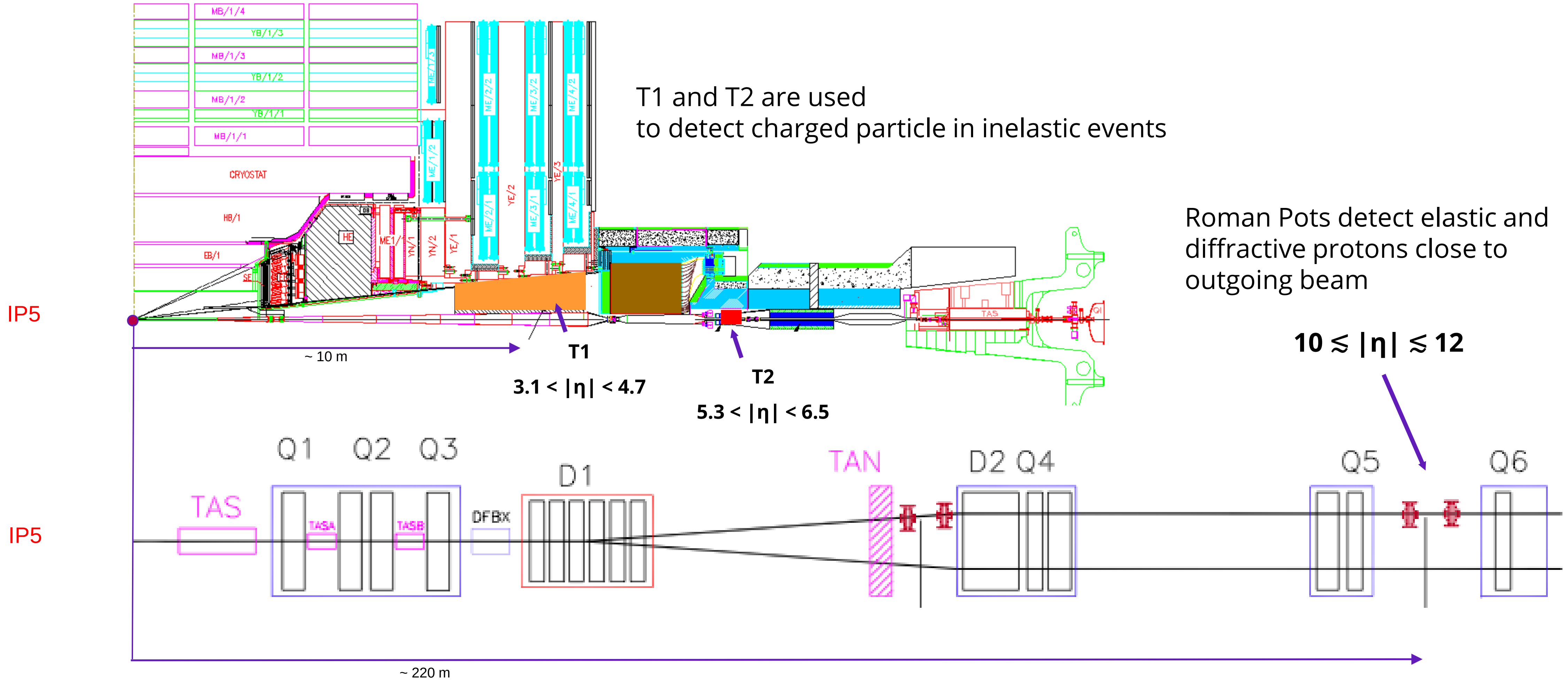
Outline



- TOTEM experiment at LHC
- Requirements of the timing detector
- Diamond detectors
- Front-end electronics
- The TOTEM timing detector

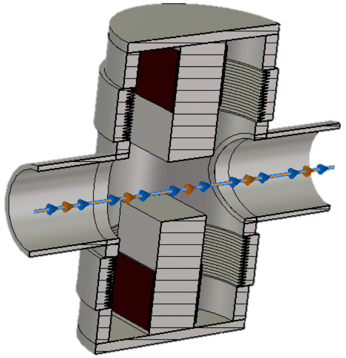
The TOTEM detector at the LHC

The TOTEM experimantal apparatus was designed to measure the Total Cross Section and to study Elastic Scattering and Diffraction Dissociation at the LHC

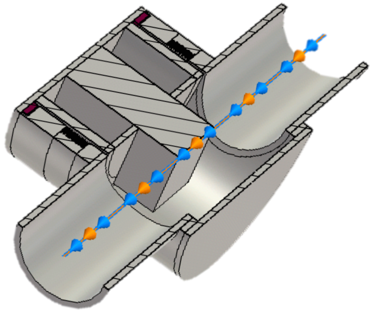


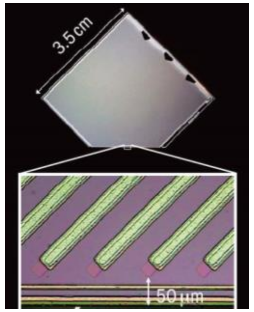
The TOTEM Roman Pot system

A Roman Pot is a movable section of the beam pipe that allows a detector to be placed at few millimeters from the beam.

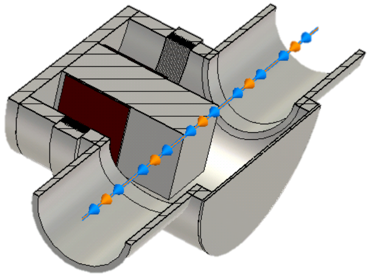


16 Vertical RPs

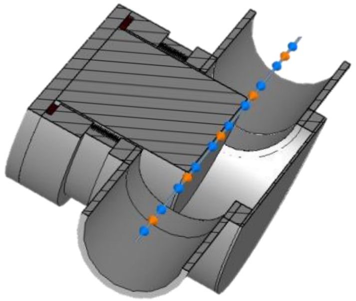


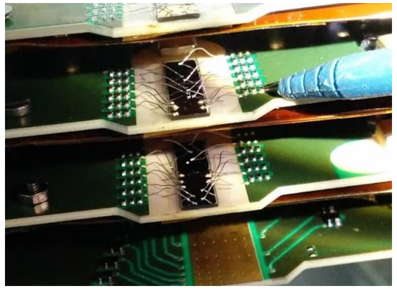


4 Shielded RPs
for high-luminosity operation



4 Horizontal RPs



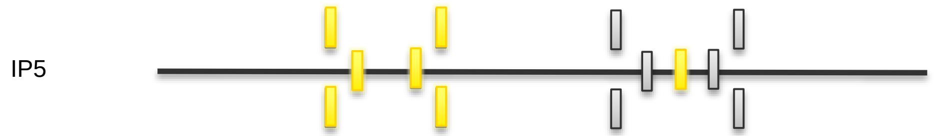


2 Cylindrical RPs
for time-of-flight detector

High intensity runs

- 4 Vertical RPs (per arm)

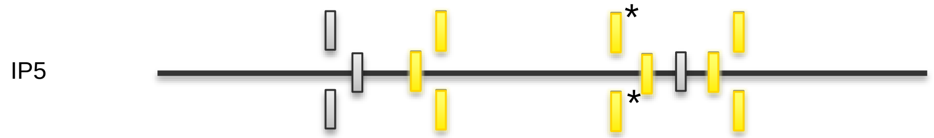
CT-PPS {
- 2 Shielded RPs
- Cylindrical RP



Dedicated runs

$\beta^* = 90\ m, 1\ km, 2.5\ km$

- 6 Vertical RPs
- 2 Horizontal RPs
- 1 Shielded RP



*: Si strip removed, waiting for timing detectors...

Total cross-section

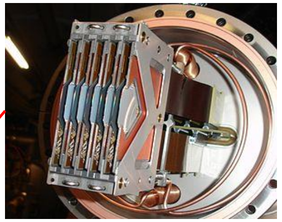
The Total cross-section can be measured with several techniques.

Optical Theorem, Elastic $\frac{d\sigma}{dt}$ extrapolated to t = 0

$$\sigma^2_{\mathrm{tot}} = \frac{16\pi(\hbar c)^2}{1+\rho^2} \left.\frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}t}\right|_{t=0}$$

Explicit dependency on $\mathcal{L}$:

$$\sigma^2_{\mathrm{tot}} = \frac{16\pi}{1+\varrho^2} \frac{1}{\mathcal{L}} \left.\frac{\mathrm{d}N_{\mathrm{el}}}{\mathrm{d}t}\right|_0$$



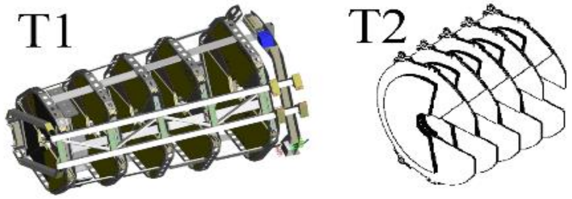
Measured using Roman Pots

$\sigma_{tot} = 98.3 \pm 2.8$ mb EPL 96(2011) 21002

$\sigma_{tot} = 98.6 \pm 2.2$ mb EPL 101(2013) 21002

Elastic + Inelastic measurement: no dependency on ρ

$$\sigma_{\mathrm{tot}} = \frac{1}{\mathcal{L}} (N_{\mathrm{el}} + N_{\mathrm{inel}})$$



Measured using T1 and T2

$\sigma_{tot} = 99.1 \pm 4.3$ mb EPL 101(2013) 21004

Elastic + Inelastic measurement: no dependency on $\mathcal{L}$

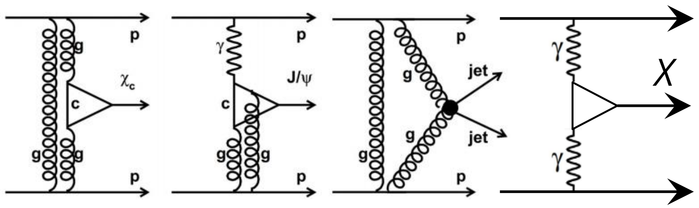
$$\sigma_{\mathrm{tot}} = \frac{16\pi}{1+\varrho^2} \frac{\mathrm{d}N_{\mathrm{el}}/\mathrm{d}t|_0}{N_{\mathrm{el}} + N_{\mathrm{inel}}}$$

$\sigma_{tot} = 98.0 \pm 2.5$ mb EPL 101(2013) 21004

The TOTEM timing detector

A precise measurement of the time of arrival of protons detected in the RPs can improve the experiment capabilities to explore and measure new physics in Central Diffractive (CD) processes.

$$p + p \rightarrow p \oplus X \oplus p$$



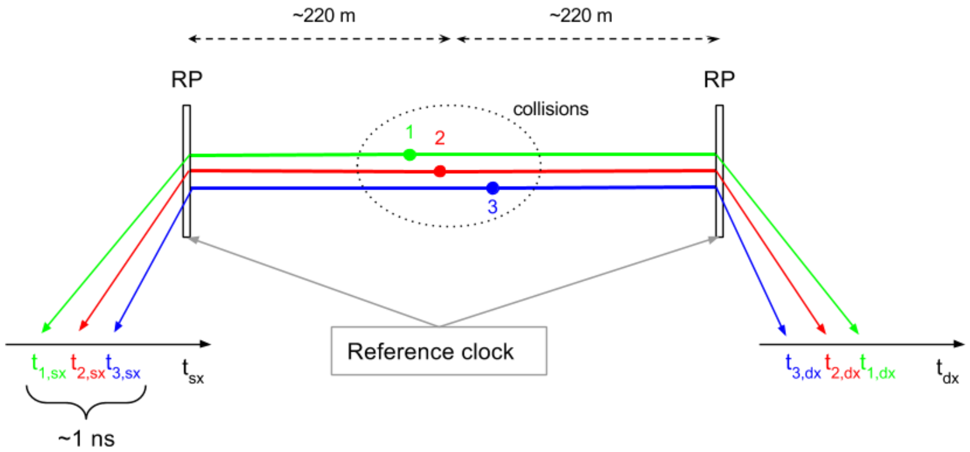
The most common CD processes are due to the exchange of gluons (i.e. Pomeron) or photons (i.e. photoproduction).

When X is a particle ($J_z^{CP} = 0^{++}$), its mass M_X can be computed using the momentum lost by the two leading protons:

$$M_X \sim \sqrt{s\xi_1\xi_2} \quad \text{with} \quad \xi = \frac{\Delta p}{p}$$

To associate the detected protons to the correct vertex, when there are multiple interaction per bunch crossing (pile-up) it is possible to measure the time difference between the arrival instants.

With a time resolution of 50 ps ($|Z_{CMS} - Z_{RP}| < 2$ cm) the impurity of the selected events equal to 5% (instead of 22% without the timing information).



Diamond detectors

Some of the properties of diamond make it ideal for timing applications

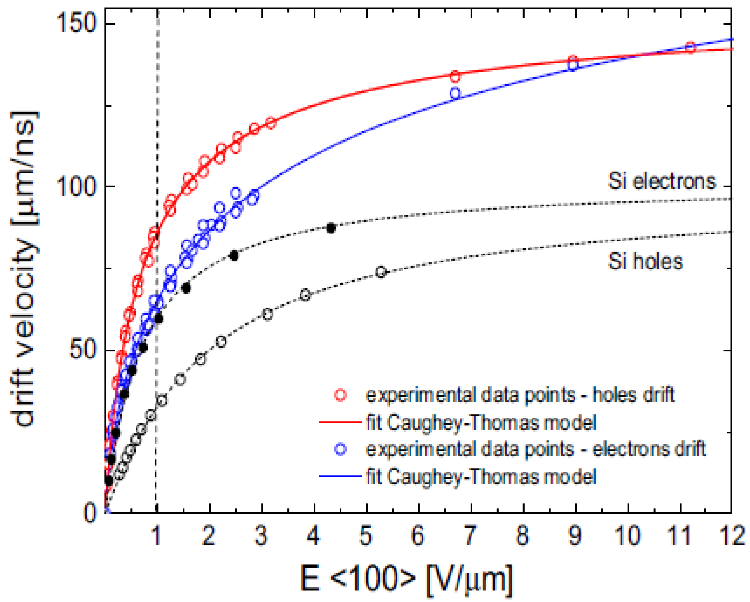
.... for particle detection

	Diamond	Silicon
band gap [eV]	5.48	1.12
intrinsic resistivity [Ω/cm]	> 10^{15}	2.3×10^5
electron mobility [cm^2/V s]	< 4600	1350
hole mobility [cm^2/V s]	< 3400	480
hole lifetime [s]	10^{-10} - 10^{-6}	10^{-3}
saturation velocity [cm/s]	1.6- 2.6 $\times 10^7$	10^7
density [g/cm^3]	3.52	2.33
dielectric constant	5.7	11.9
energy to create e-h [eV]	13.1	3.63
energy loss for MIPs [MeV/cm]	4.69	3.21
average pairs created / 1 μm	36	88.9
displacement energy [eV]	37.5 - 47.6	36

- ✓ High electrons and holes saturation velocity
- ✓ High resistivity
- ✓ Low dielectric constant

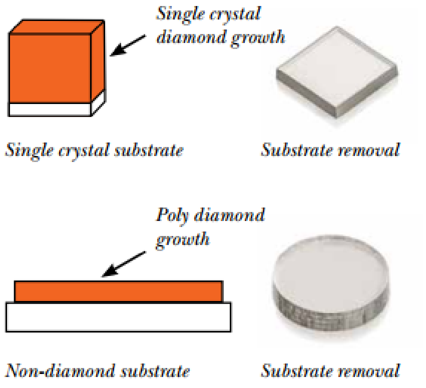
- ✗ Signal smaller than silicon
- ✗ High cost: high purity needed

scCVD



From the diamond to a particle detector

Two metal electrodes are deposited on a ultrapure single crystal diamond and are used for both polarization and read-out of the signal.

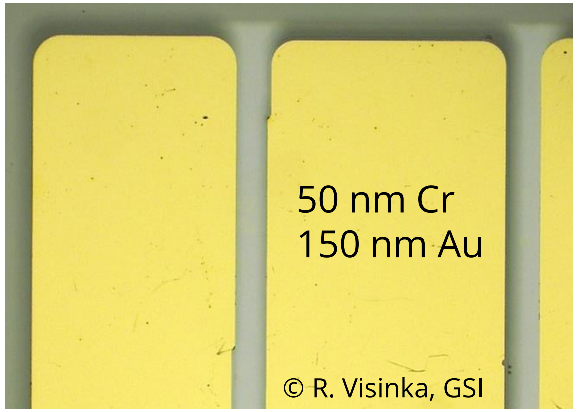


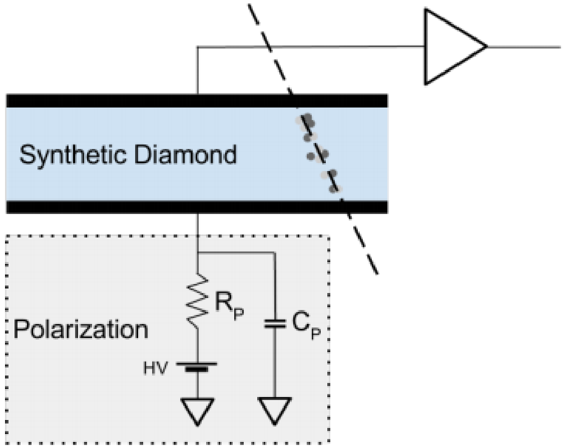
SINGLE CRYSTAL CVD DIAMOND GRADES	
SINGLE CRYSTAL MCC	Engineered replacement for natural type IIa diamond
OPTICAL GRADES	Controlled absorption and birefringence diamond
DETECTOR GRADE	Ultrahigh purity for quantum optics and electronics
POLYCRYSTALLINE CVD DIAMOND	
OPTICAL GRADE	Engineered for far infrared laser optical applications
ELECTRONIC GRADE	Ultrahigh purity material for large area passive electronics
THERMAL GRADES	High thermal conductivity diamond heat spreading
MECHANICAL GRADES	High strength diamond for precision machining
ELECTRO-CHEMISTRY GRADES	Boron doped diamond for electrochemical applications

A ultrapure single crystal diamond is needed to have a charge collection efficiency close to 100%

The metallization process has been optimized over the years to avoid poor collection efficiency and rate dependency of the collected charge.

The first samples were metallized at GSI,
then the high volume production was done at PRISM.





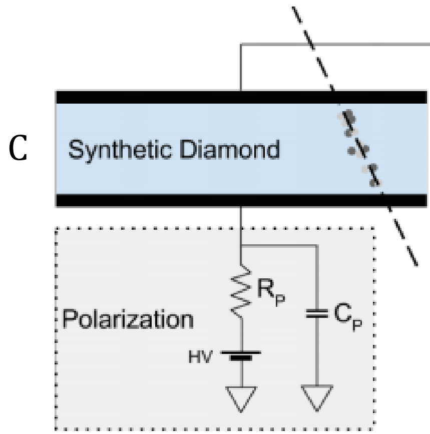
One of the electrodes is used for the polarization of the crystal, while the other is used to read-out the electric signal generated by the passage of the particle.

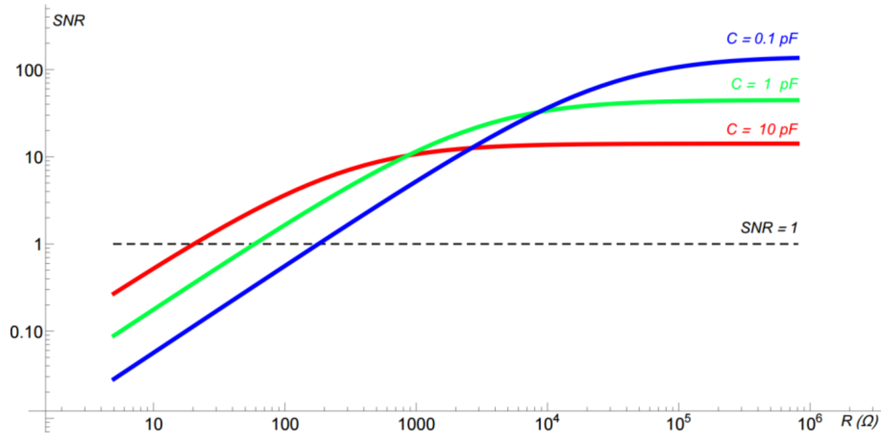
Front-end electronics: amplifier

It is useful to analyse the simplest possible case: a diamond detector read-out using a simple resistor.

For $R < \sim 100\ \Omega$ the signal is not separated from the noise ($SNR \sim 1$) also for $C \sim 0.1$ pF.

The only way to have a SNR > 1 is to increase the value of the read-out resistor.

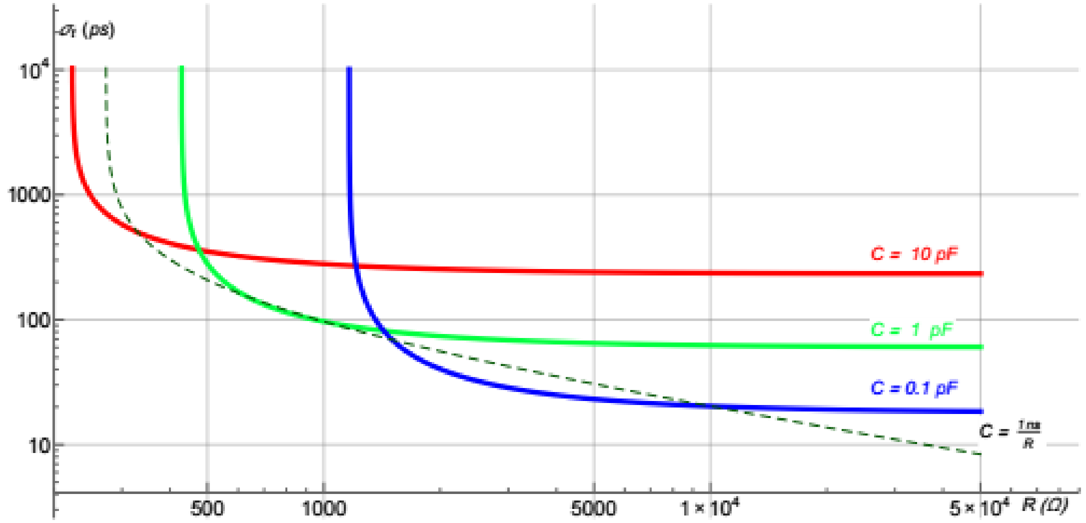




However, the time resolution is given by:

$$\sigma_t \sim \frac{\sigma_V}{MAX[\frac{dV}{dt}]}$$

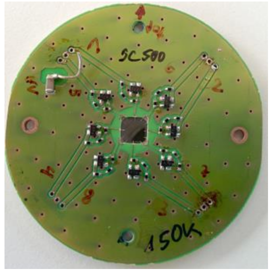
And higher R means slower signal:

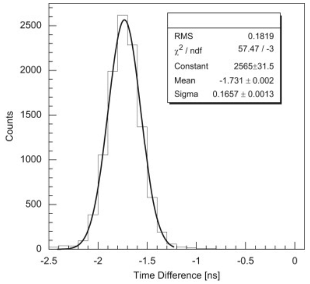


A useful rule of thumb: **minimize C and use R ~ 1 ns/C**

Amplifier as close as possible to the sensor (minimize C)
First stage with input resistor ~ kΩ

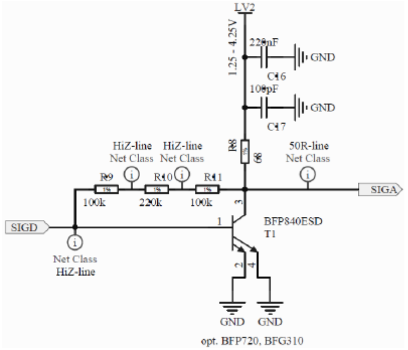
Strategy suggested by HADES @ GSI
10.1016/j.nima.2010.02.113





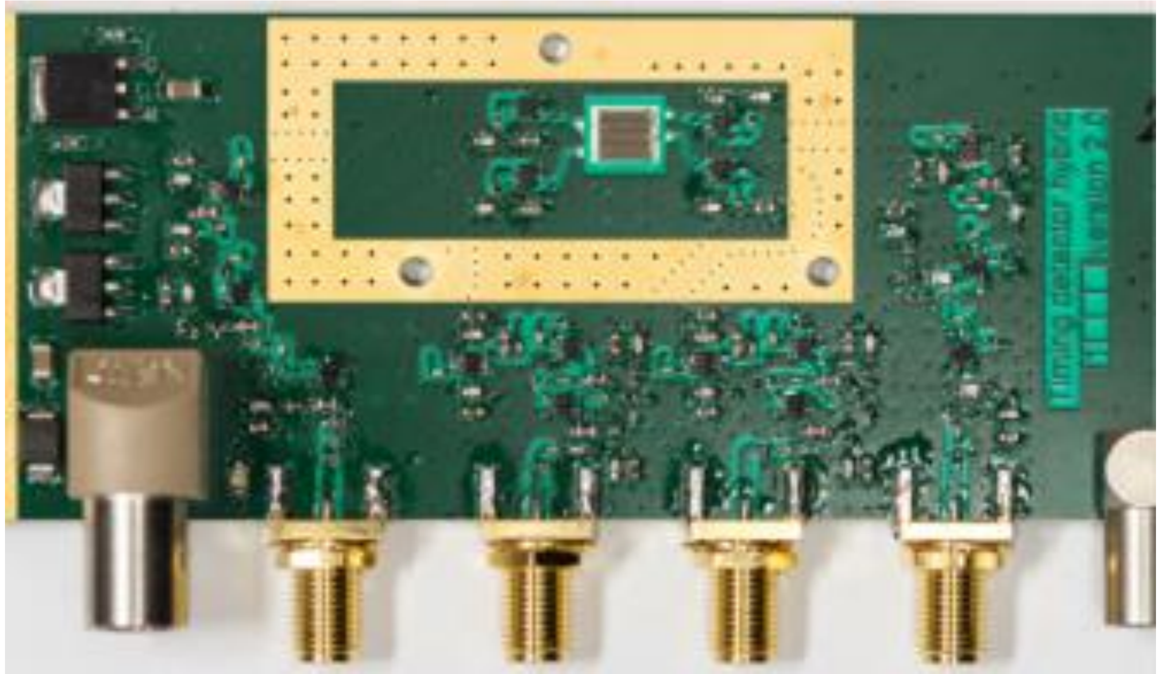
Front-end electronics: amplifier

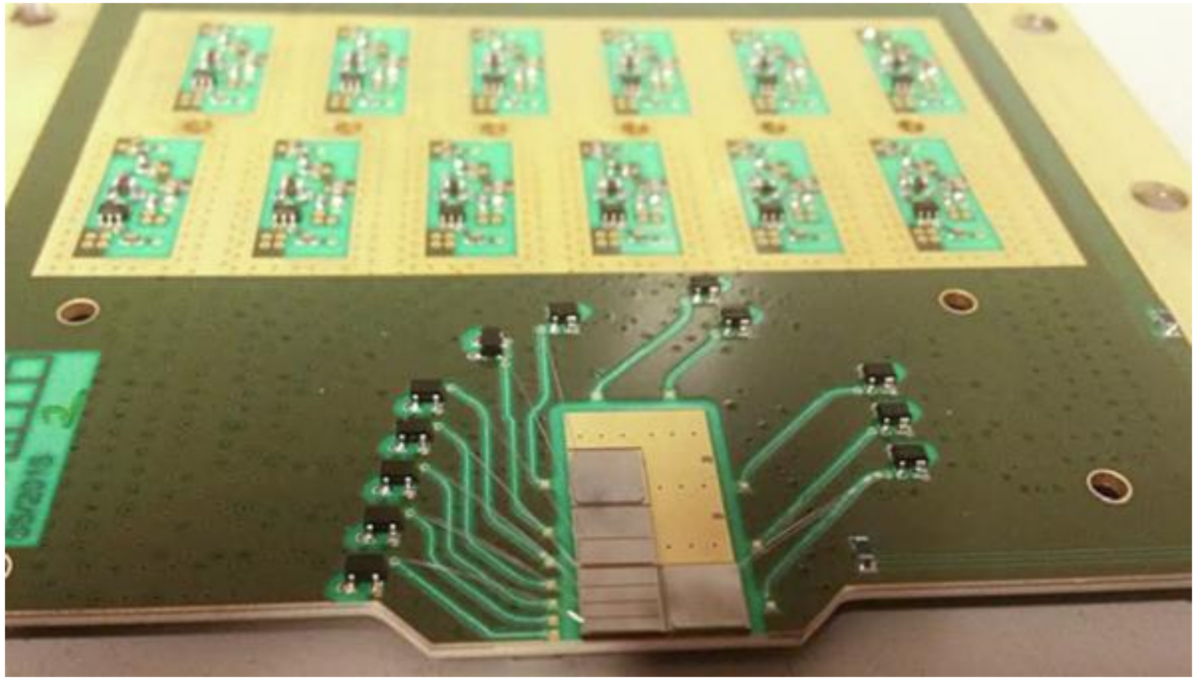
This approach was used to design an amplifier optimized on the geometry needed for the TOTEM timing detector



The first stage uses a SiGe BJT in a common emitter configuration at less than 1 cm from the sensor.
The input capacitance is given mainly by the sensors; hence C ~ 0.1 pF/mm^2 for a 500 µm thick diamond.

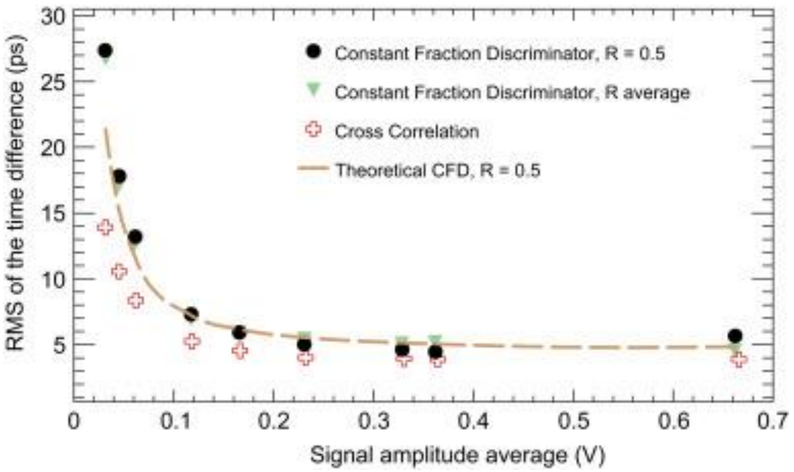
The first prototypes were designed to ease the tests on secondary beams; once the best design was selected, a board suited for the installation in a RP was designed, manufactured and tested.



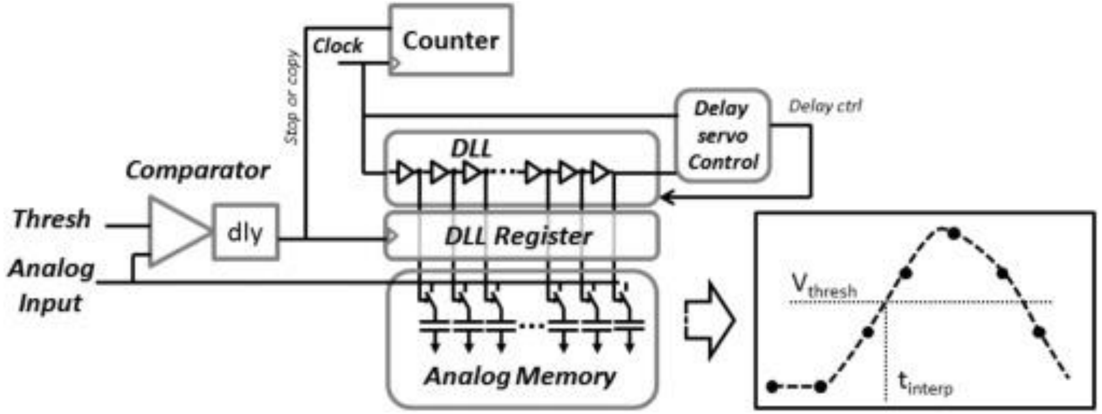


Front-end electronics: digitizer

A precise measurement of the arrival time requires a complex analysis of the signal produced by the detector.



The computation of the arrival time is done using numeric algorithms.
This is possible thanks to the use of a fast sampling device: SAMPIC



The signal is sampled in a series of capacitors and then digitized using a 11 bit Wilkinson ADC.

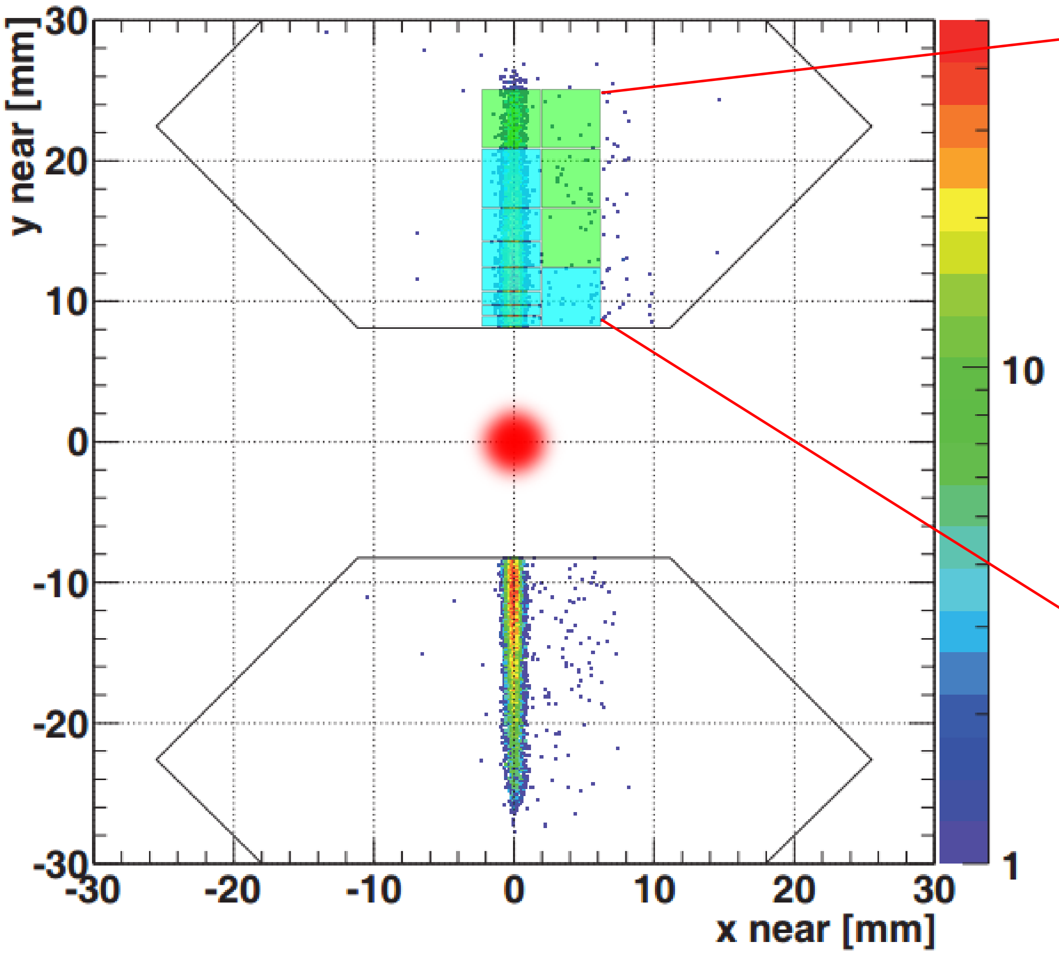
One chip can acquire 16 channels with a sampling rate up to 10 Gsa/s at rates up to 100 kHz.

Using a signal generator a time resolution below 5 ps was measured.

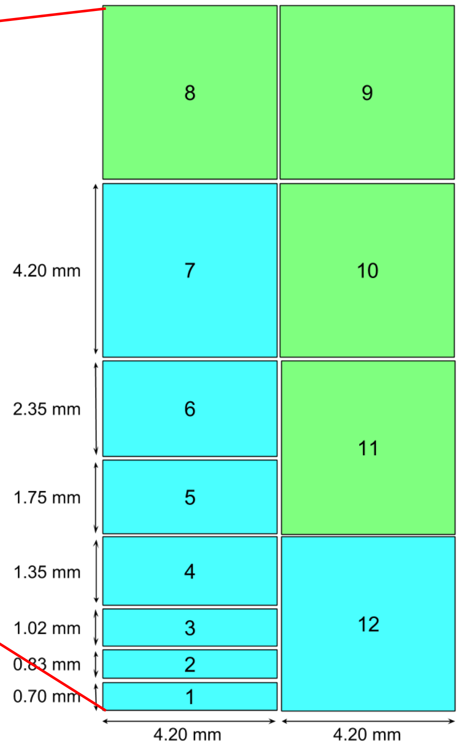
Measurements of timing resolution of ultra-fast silicon detectors with the SAMPIC waveform digitizer
http://dx.doi.org/10.1016/j.nima.2016.08.019

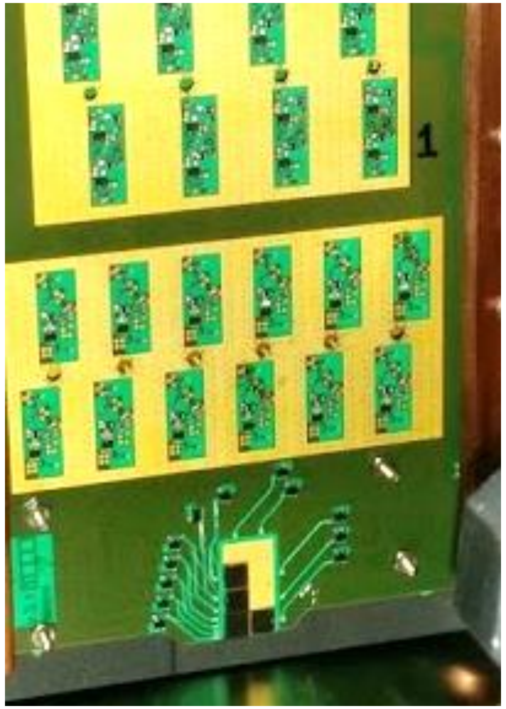
The TOTEM timing detector: geometry

The geometry of the timing detector has been optimized to minimize the probability of multiple hits in a single pad, using a relatively low number of channels.



$\sqrt{s} = 7\,TeV, \quad \beta^* = 90$ m



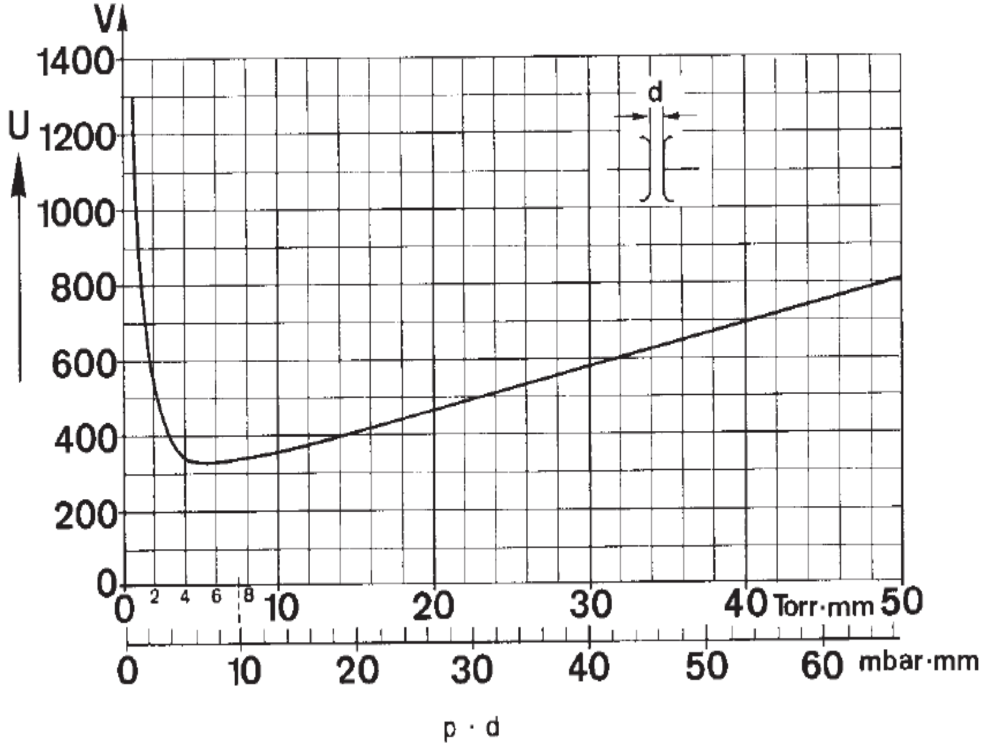


The region of interest during dedicated configurations of the LHC is concentrated in the central region of the acceptance of the RP tracking detectors.

An incremental installation process foresees a first stage with 4 diamonds (instead of 8) per plane.

The TOTEM timing detector: HV under vacuum

The time resolution depends on the bias voltage applied to the diamond.

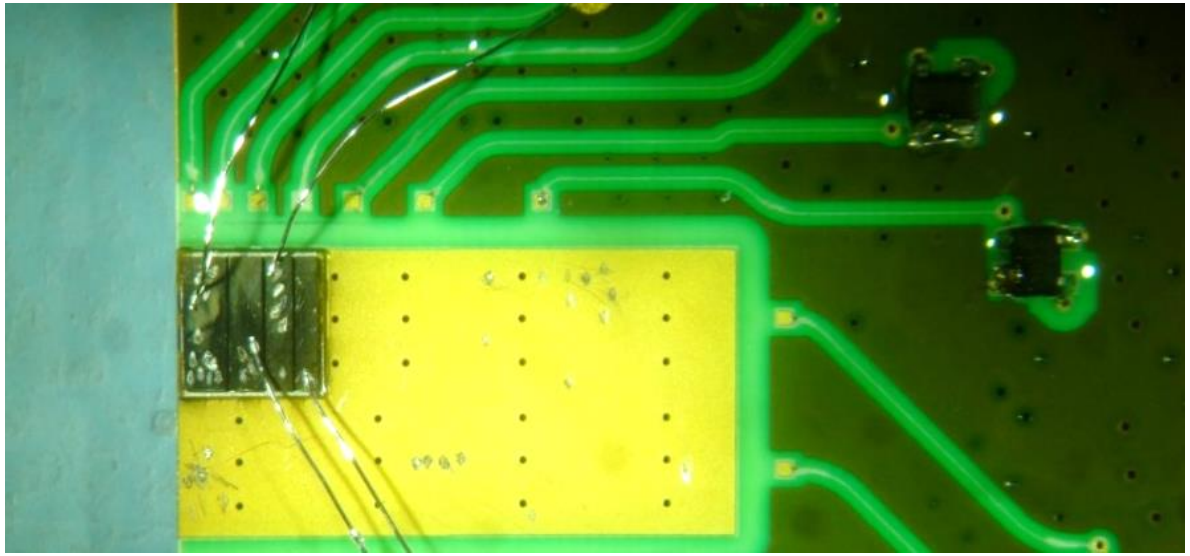


Breakdown voltage U between parallel electrodes in a homogeneous electrical field as a function of gas pressure p distance between electrodes d (in mm) (Paschen curve), for air

All the sensors were tested and all of them had a leakage current below 1 nA at 1000 V;
however, the detector has to be operated below 50 mbar.

The first boards were tested and were proven to be stable at 40 mbar up to 500V.

To further increase the maximum stable HV we used thicker bonding wires, space qualified components and a silicon based coating, in collaboration with Mipot (Cormons, Italy).



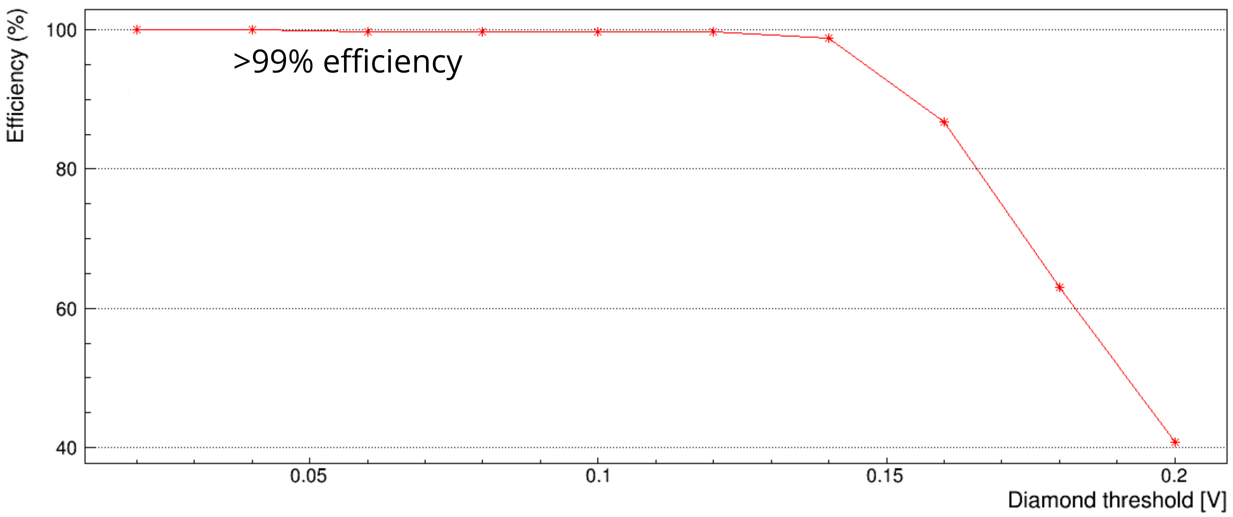
The TOTEM timing detector: efficiency

The efficiency of the detector was measured using different tracking detectors.

The efficiency of a prototype was measured at Desy (January 2015), using a silicon tracker (MIMOSA).

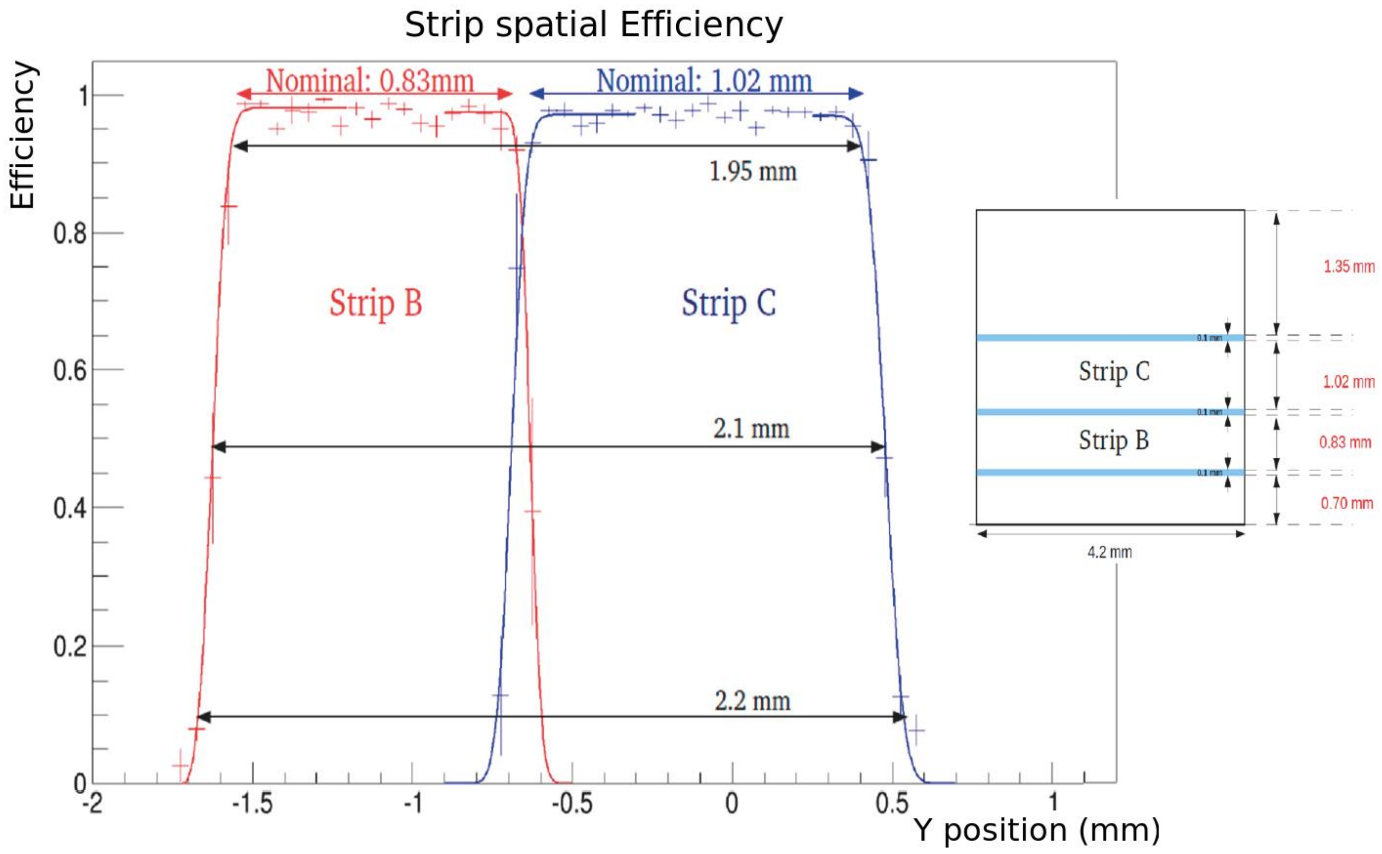
Then the final boards were tested using a GEM tracker installed in the North Area at CERN (rd51).

Both tests showed an excellent behaviour of the detectors:
Efficiency > 99% for all the channels at the centre of the pads.



The TOTEM timing detector: efficiency

The efficiency decreases at the edges of the pads but is never lower than 80%.



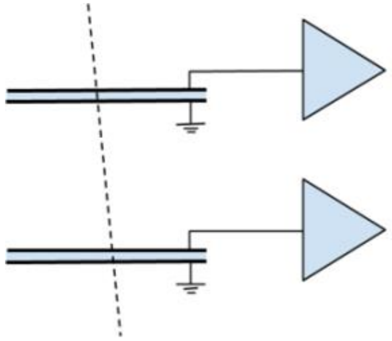
Efficiency as a function of the position for two neighbouring strips separated by 0.1 mm.

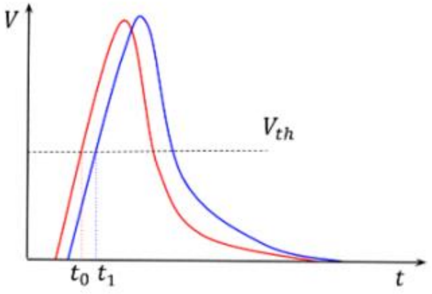
The efficiency decreases at the edges of the pads; however, the efficiency of a single pad always remains over 80%.

However, the time resolution for particles hitting the interstrip area will be lower due to a charge sharing between the neighbouring pads.

The TOTEM timing detector: timing performance

To measure the time resolution of two identical detectors it is possible to measure the arrival time of a particle crossing both sensors.



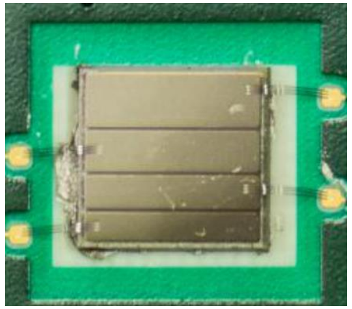


The measured time difference will be distributed around the true value because of the limited resolution of the detectors:

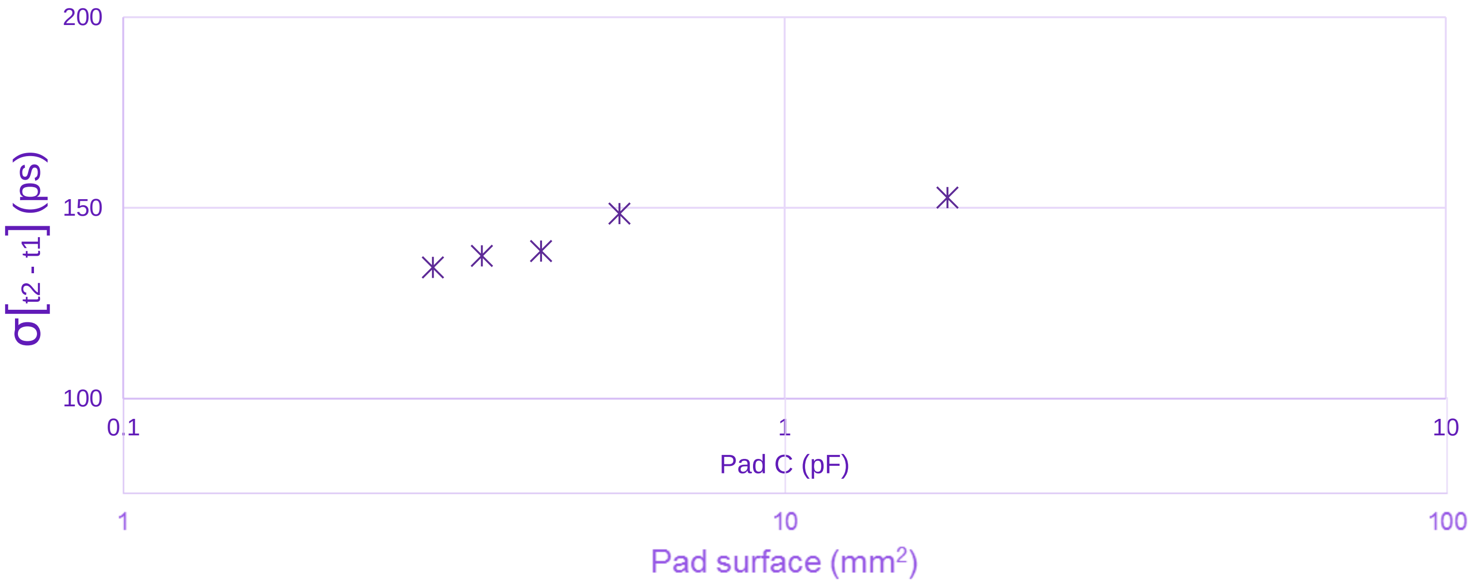
$$\sigma^2_{TOT} \sim \sigma^2_{det1} + \sigma^2_{det2} \sim 2\sigma^2_{det1} \longrightarrow \sigma_{meas} \sim \sqrt{2}\sigma_{det}$$

However, the time resolution depends on the capacitance of the detector!

A series of tests were done using a sensor with pads of different surface, i.e. capacitance.



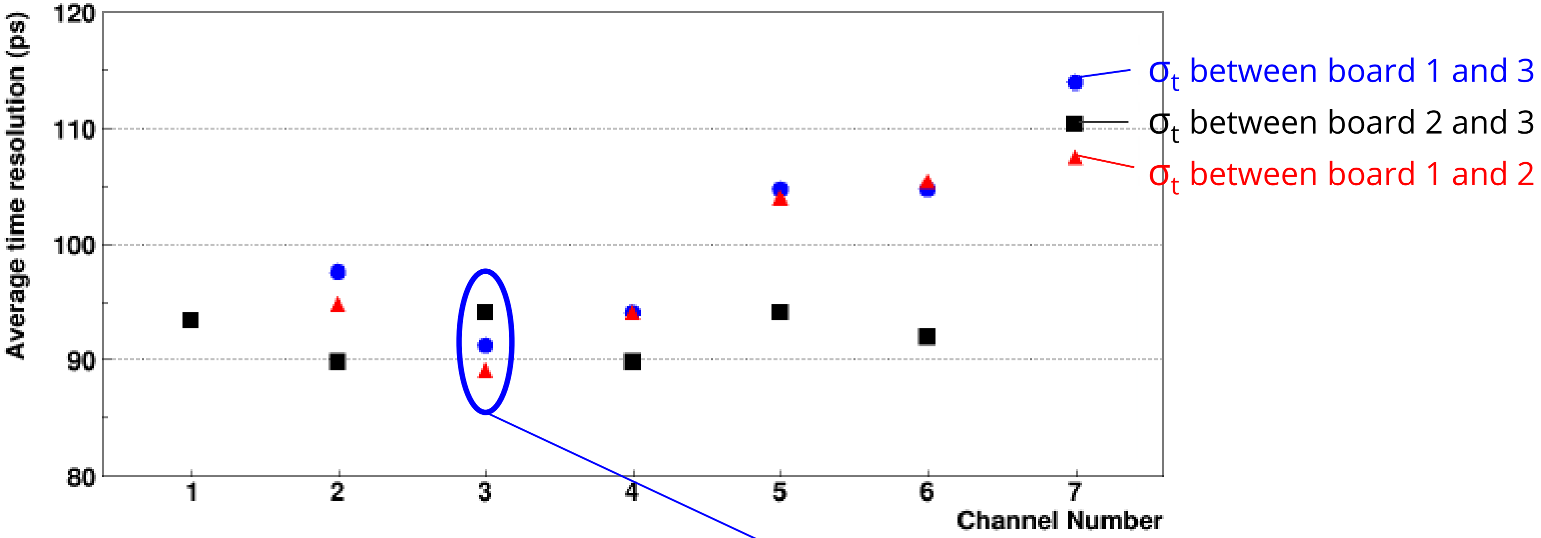
Time difference between a sensor of 17.6 mm² (~1.7 pF) and sensors of different size

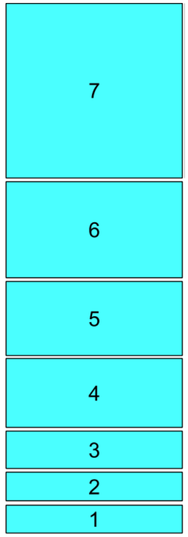


The TOTEM timing detector: timing performance

Using 3 identical boards it is possible to measure the time resolution of all the channels

The difference between the arrival time in aligned board is used to measure the timing resolution.



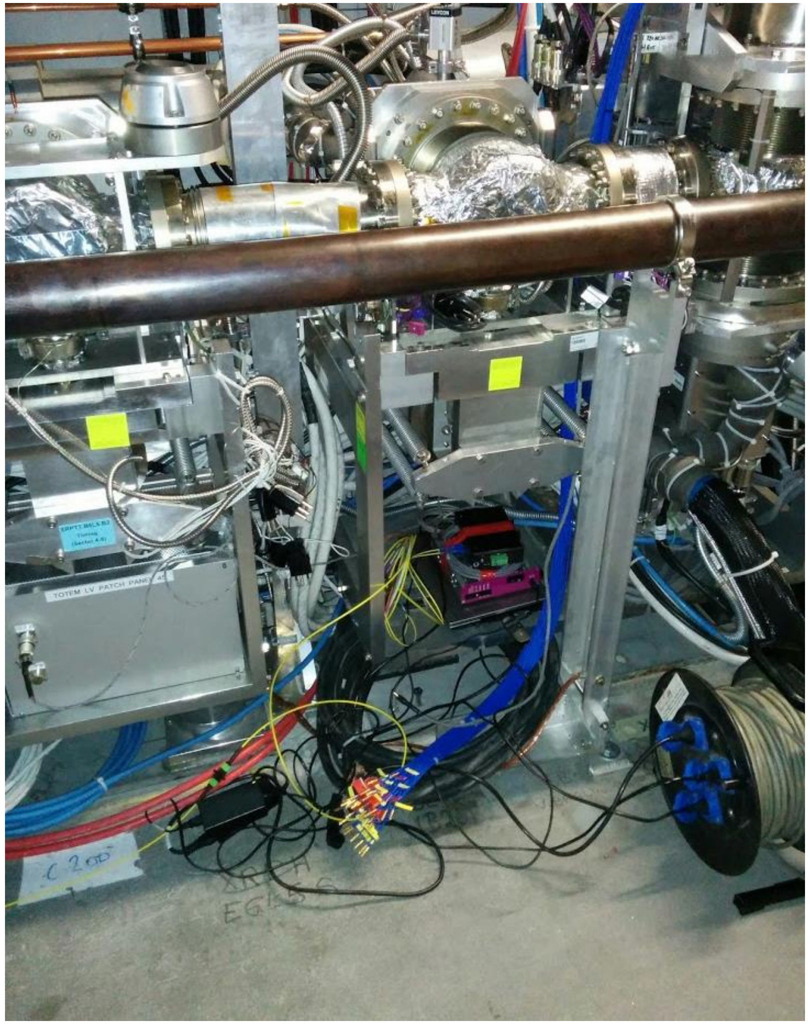


	OSCILLOSCOPE	SAMPIC	TRB3 + PaDiWa
σ_t	~ 95 ps	~ 95 ps	~ 126 ps

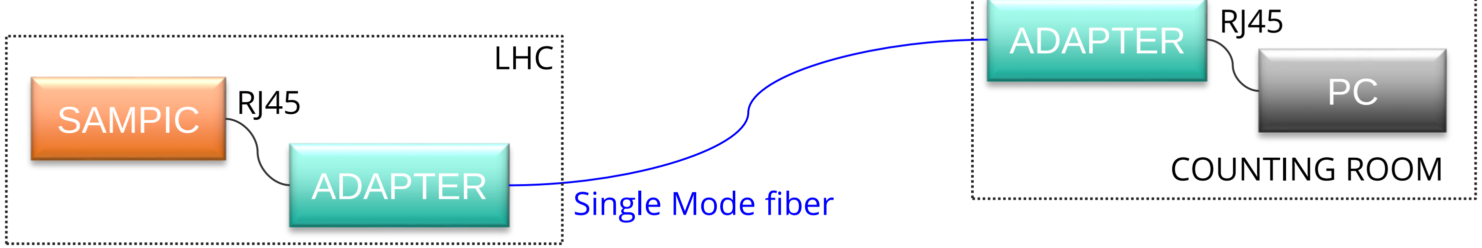
The time resolution was also measured with different digitization methods.

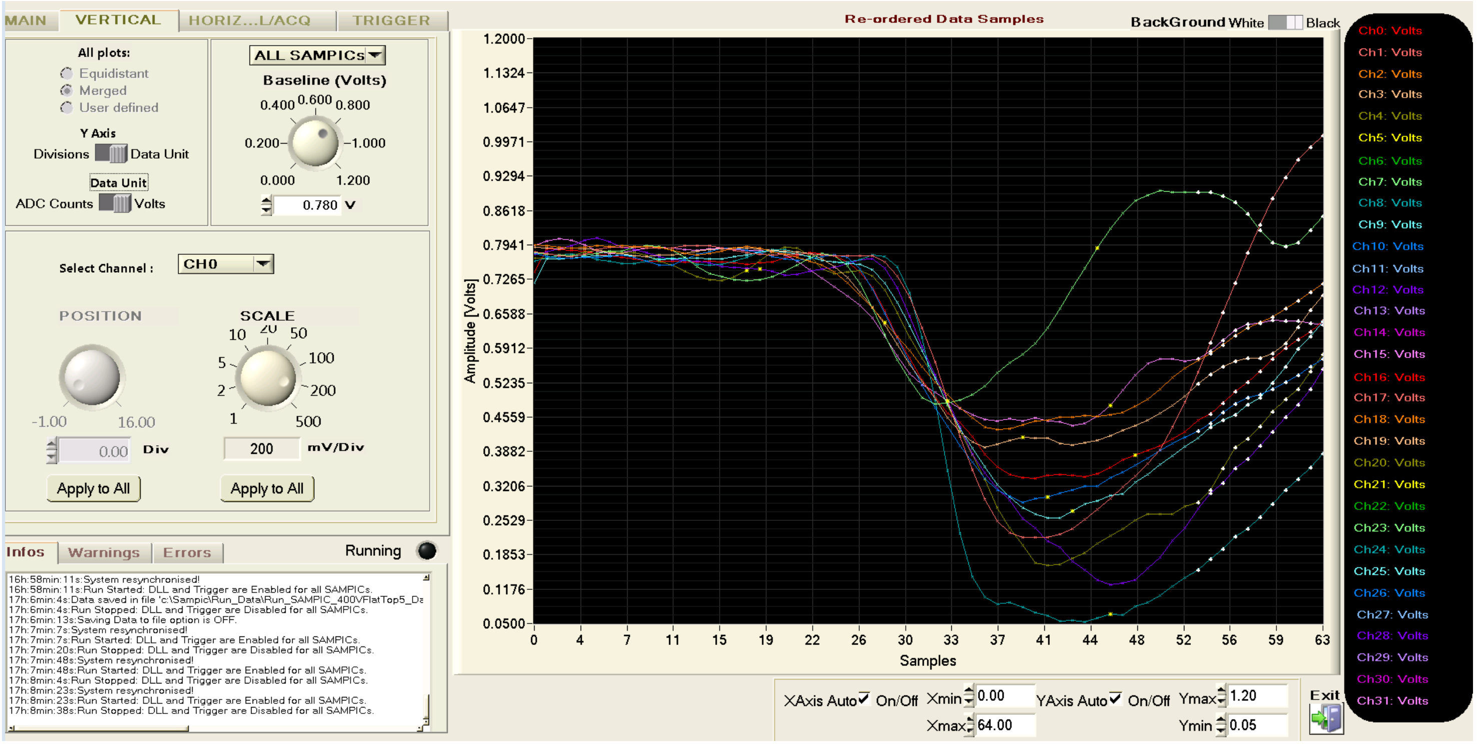
The TOTEM timing detector: LHC installation

A preliminary installation in the LHC proved the feasibility of a diamond timing detector with a resolution of ~50 ps installed in a Roman Pot.



The SAMPIC was read using an Ethernet connection.





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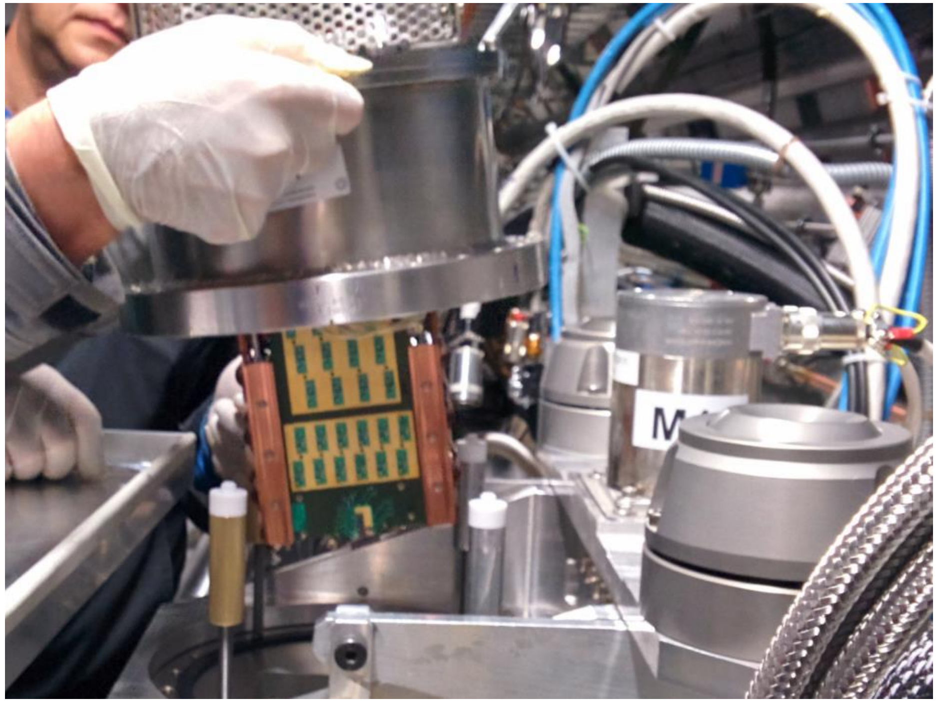
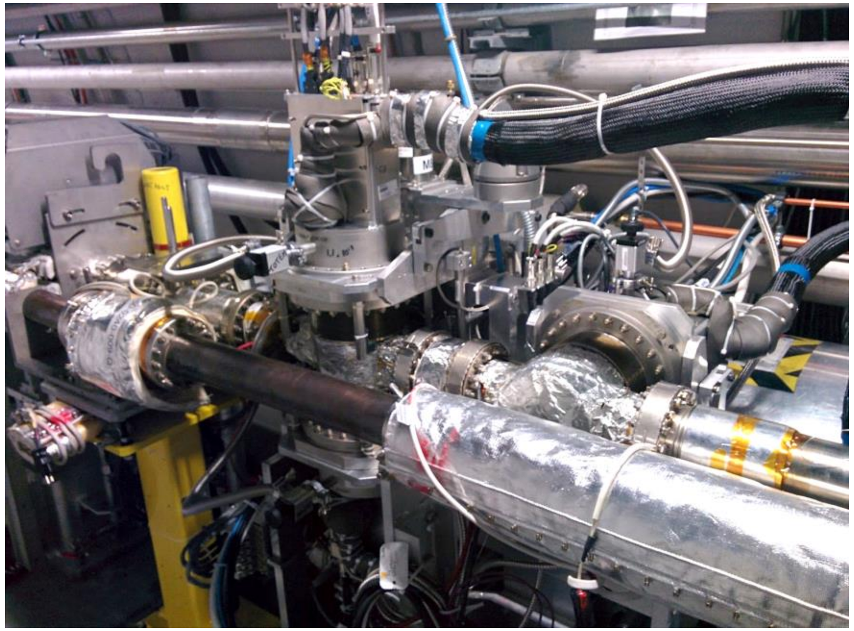
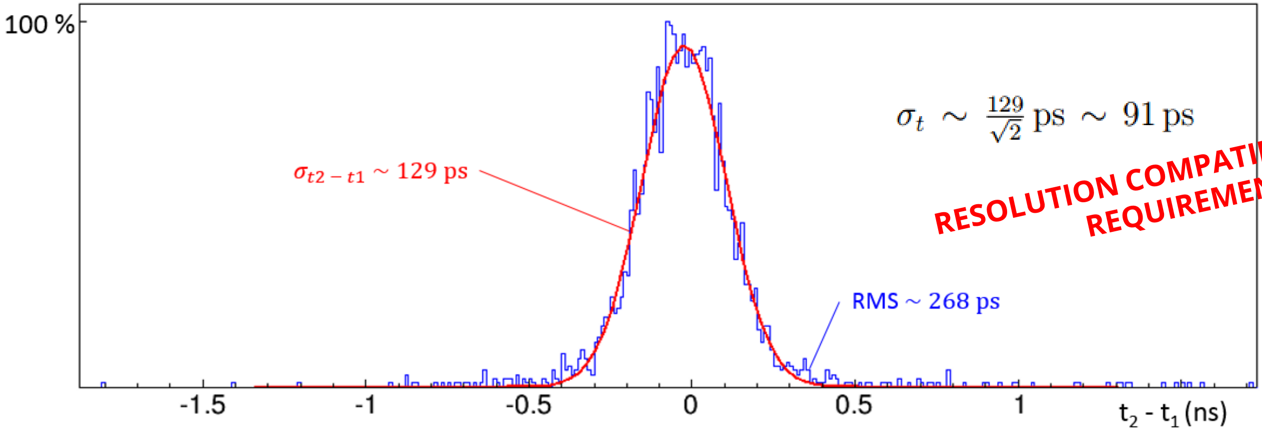


3 prototype planes were installed in a Roman Pot on the LHC, connected to the TOTEM DCS and DSS.

A standalone system was developed for the data acquisition.



The time difference between aligned pads of the different planes was measured using the LHC background (RP in garage).



RESOLUTION COMPATIBLE WITH THE REQUIREMENTS!

Timing with diamond detectors in TOTEM

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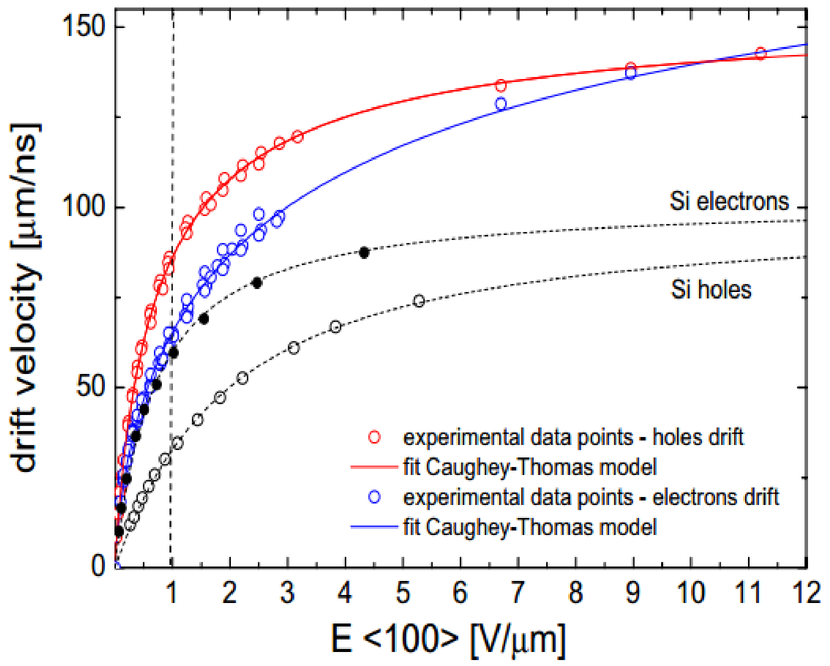
On behalf of the TOTEM Collaboration

Particular thanks to: R. Linhart, N. Minafra, M. Bozzo, E. Bossini, G. Antchev, V. Georgiev, T. Naaranoja, D. Lucsanyi, J. Baechler, N. Turini, D. Druzkin, I. Atanassov, A. Karev

Workshop on picosecond timing detectors for physics and medical applications, Kansas City 15-18 September 2016

Drift velocity in diamond and silicon



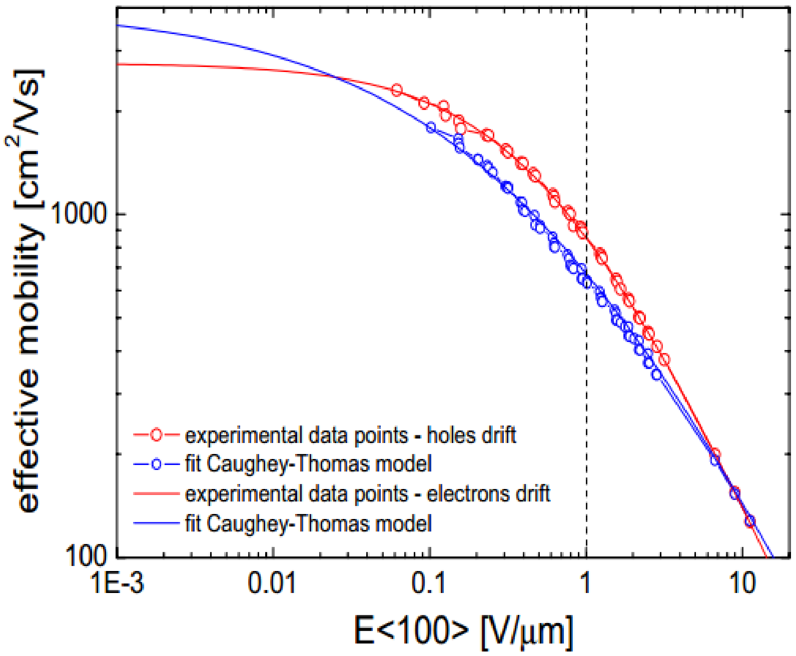


Table 6.1: Charge carrier transport parameters of scCVD-DDs obtained from fits to the experimental TCT data.

	E_c [kV/cm]	μ_0 [cm^2/Vs]	v_{sat} [cm/s]	β
electrons	5.779 ± 0.772	4551 ± 500	$(2.63 \pm 0.2) \times 10^7$	0.42 ± 0.01
holes	5.697 ± 0.529	2750 ± 70	$(1.57 \pm 0.14) \times 10^7$	0.81 ± 0.01

holes $R^2 = 0.999$, electrons $R^2 = 0.998$

M. Pomorski, Electronic Properties of Single Crystal CVD Diamond and its Suitability for Particle Detection in Hadron Physics Experiments

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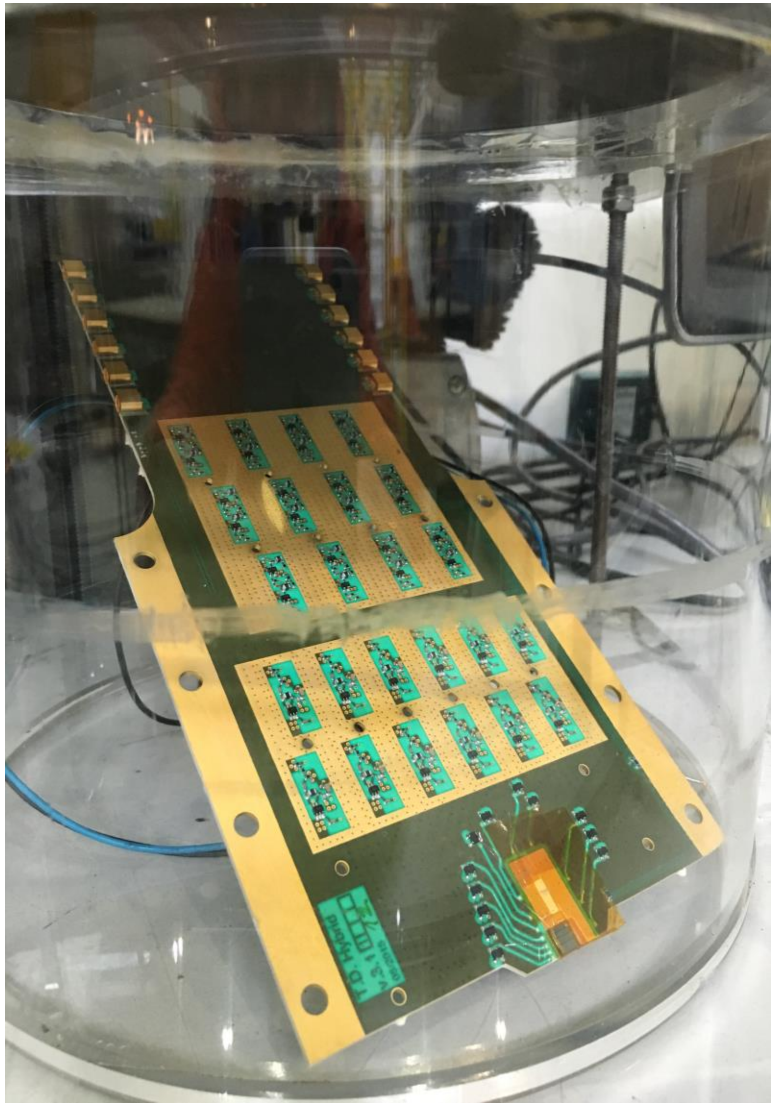
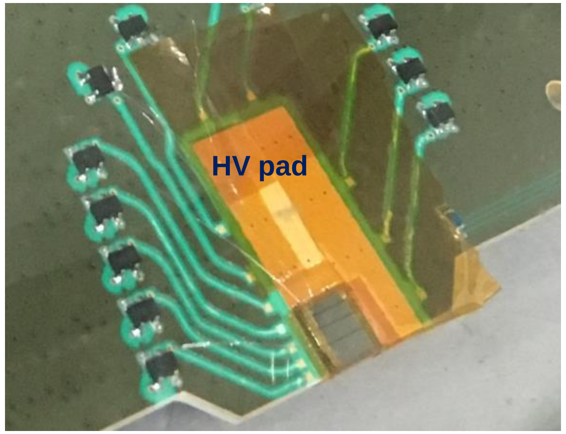
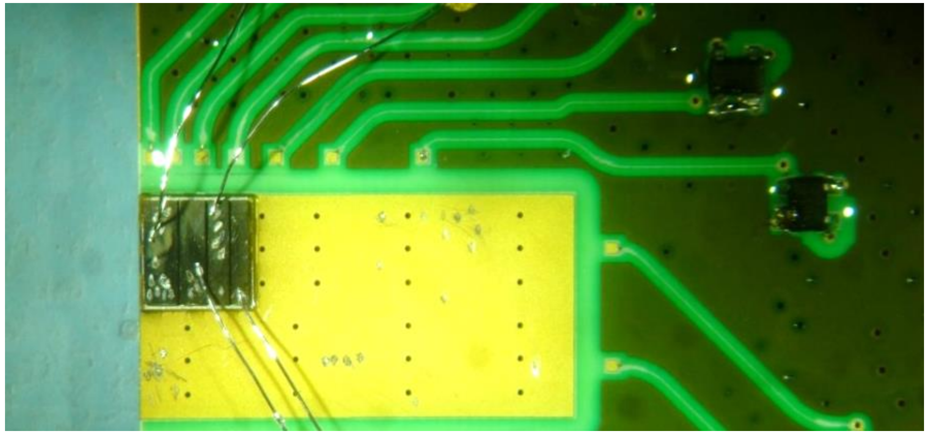
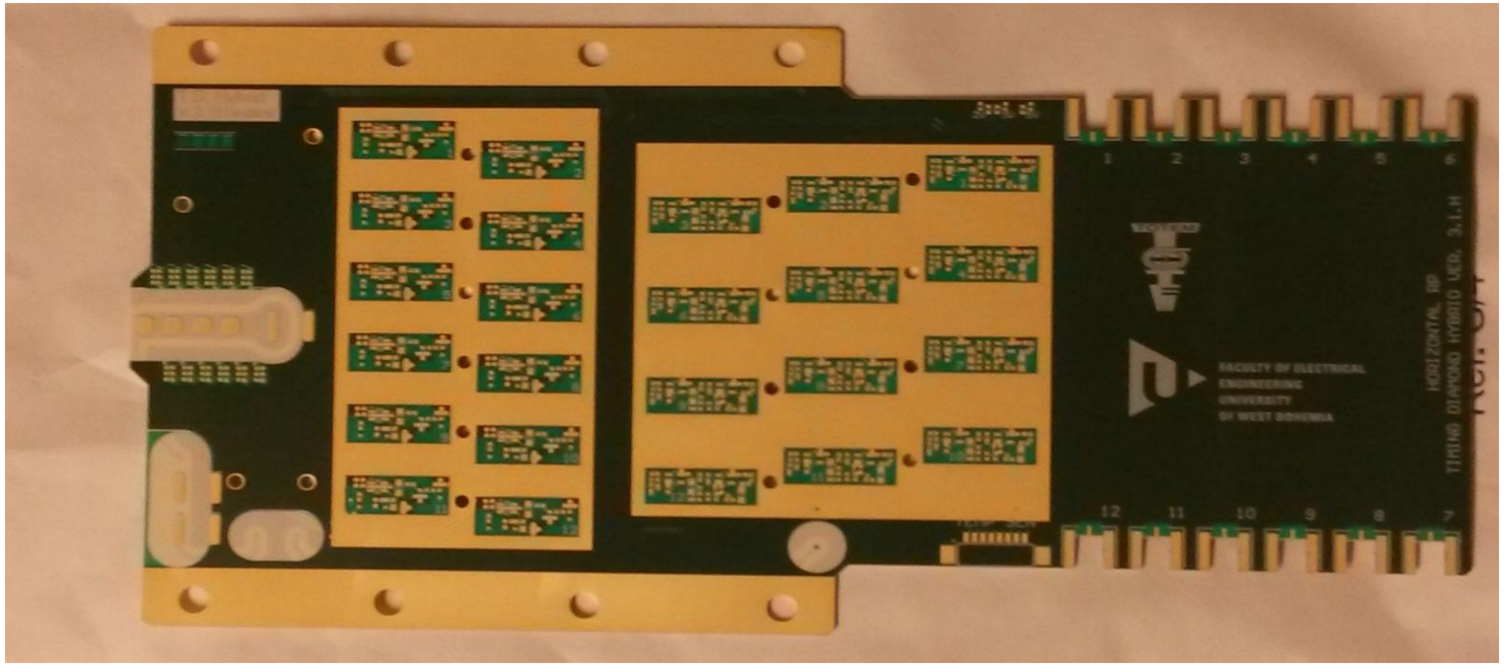
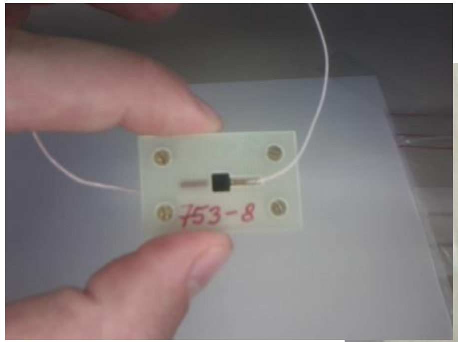


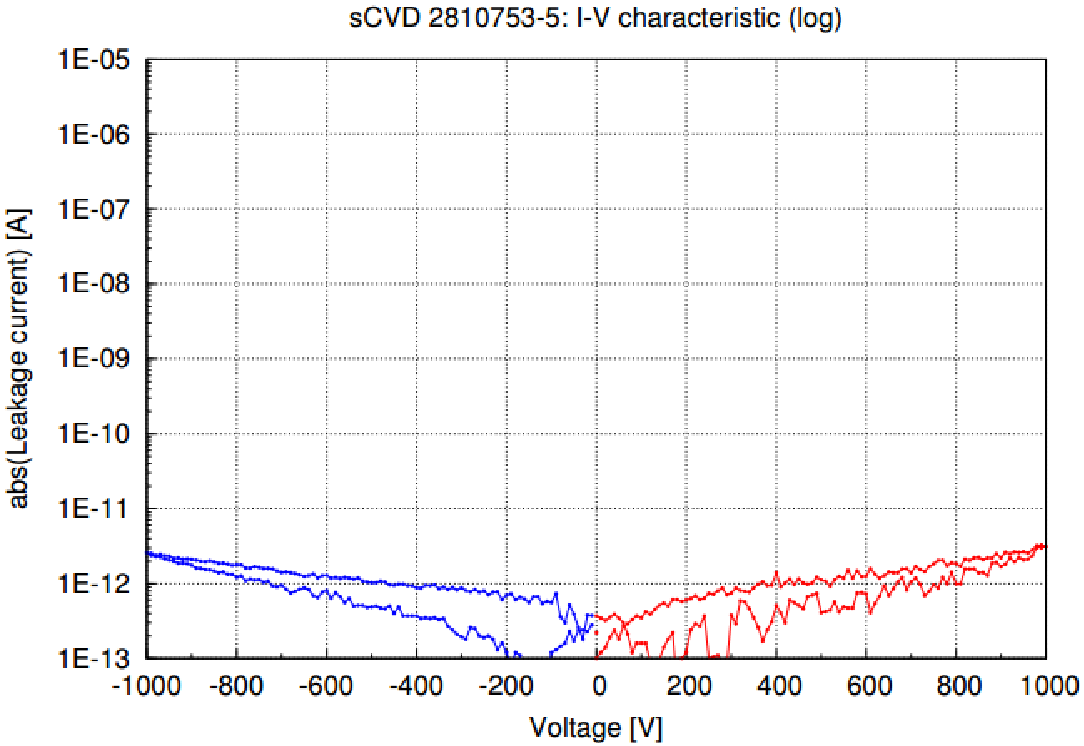


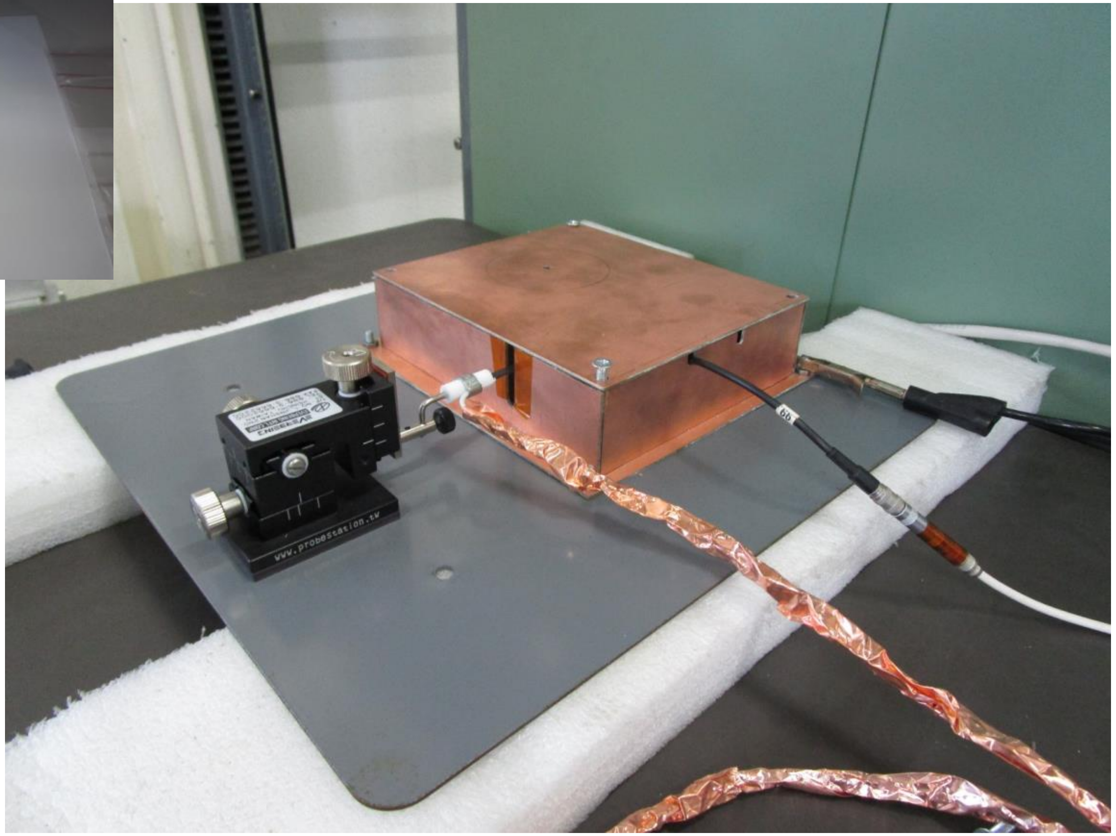




IV curves of diamonds



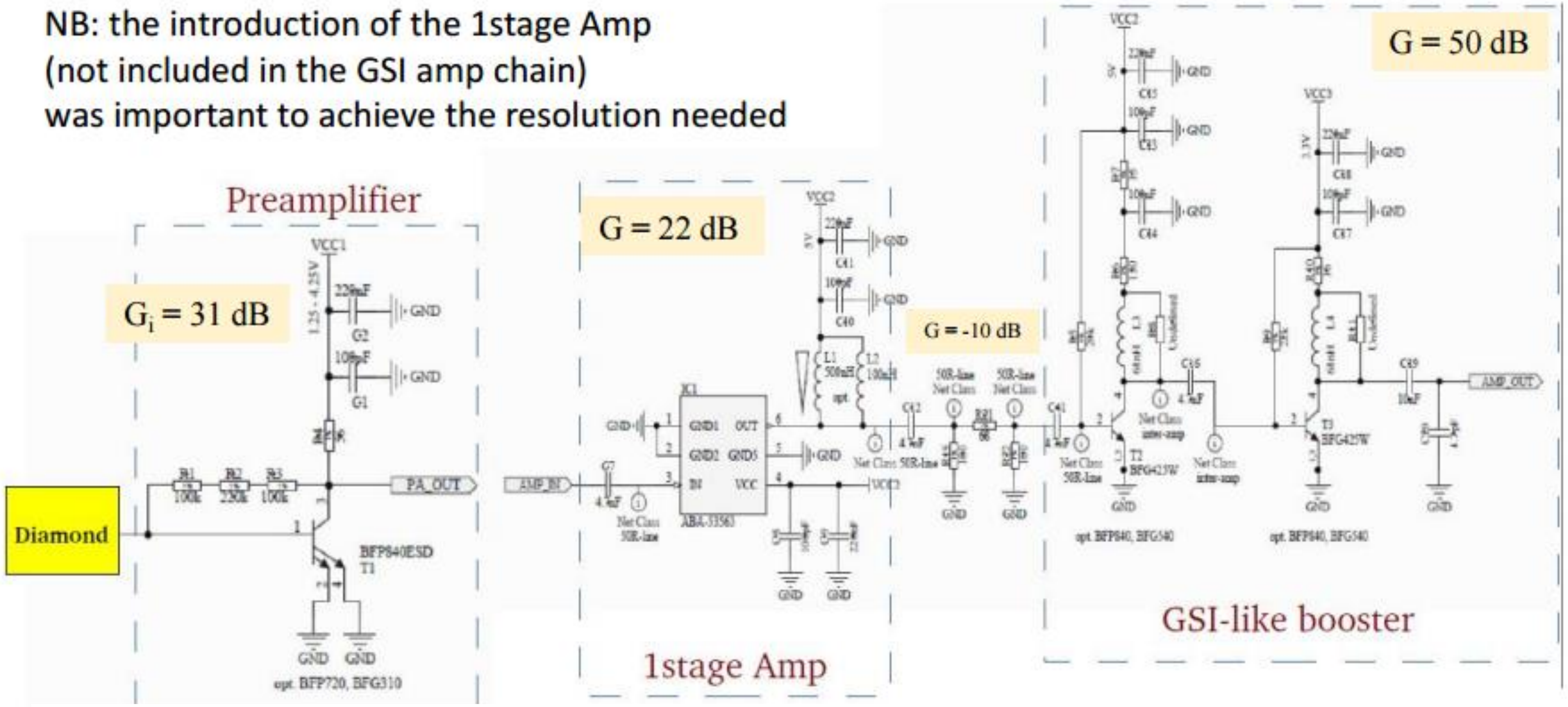


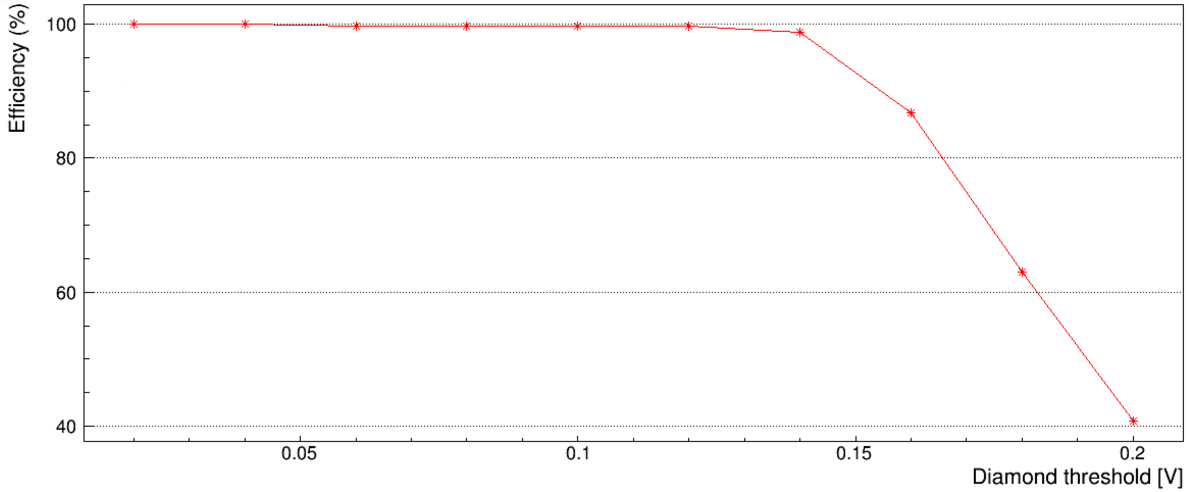


First tests performed in Desy (Thanks to W. Lohman and M. Hempel)

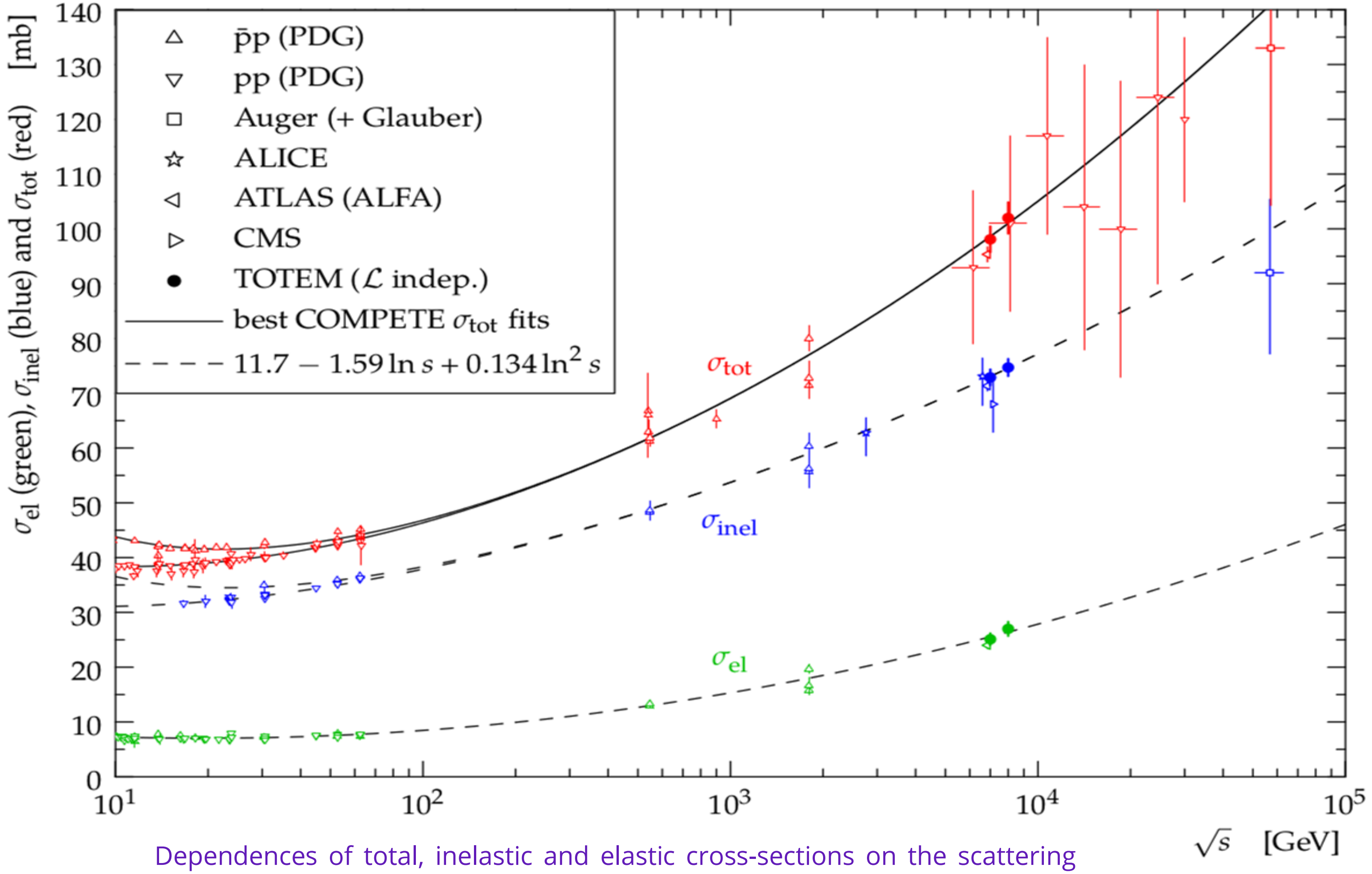
The TOTEM timing detector

NB: the introduction of the 1stage Amp
(not included in the GSI amp chain)
was important to achieve the resolution needed





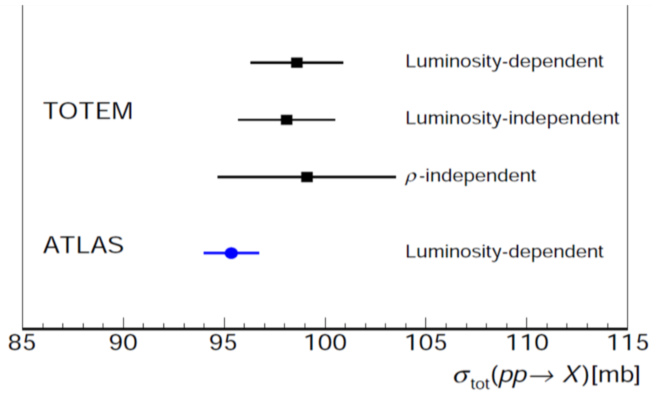
Total cross-section



Dependences of total, inelastic and elastic cross-sections on the scattering energy √s

EPL 101 (2013) 21004
Phys. Rev. Lett. 111, 012001 (2013)

EPL 101 (2013) 21004 - 7 TeV
σ_{el} = 25.1 ± 1.1 mb
σ_{inel} = 72.9 ± 1.5 mb
σ_{tot} = 98.0 ± 2.5 mb
(luminosity independent)



PRL 111 (2013) 012001 - 8 TeV
σ_{el} = 27.1 ± 1.4 mb
σ_{inel} = 74.7 ± 1.7 mb
σ_{tot} = 101.7 ± 2.9 mb
(luminosity independent)