Timing detectors in particle physics and applications

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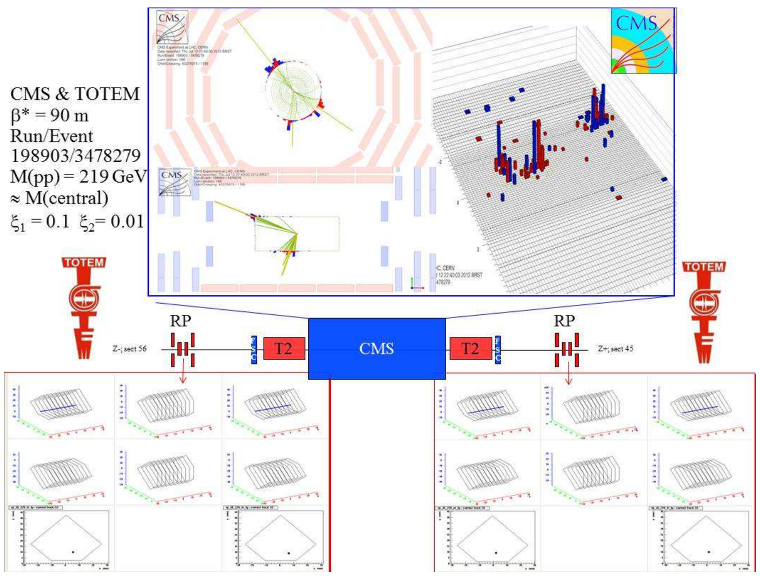
Contents:

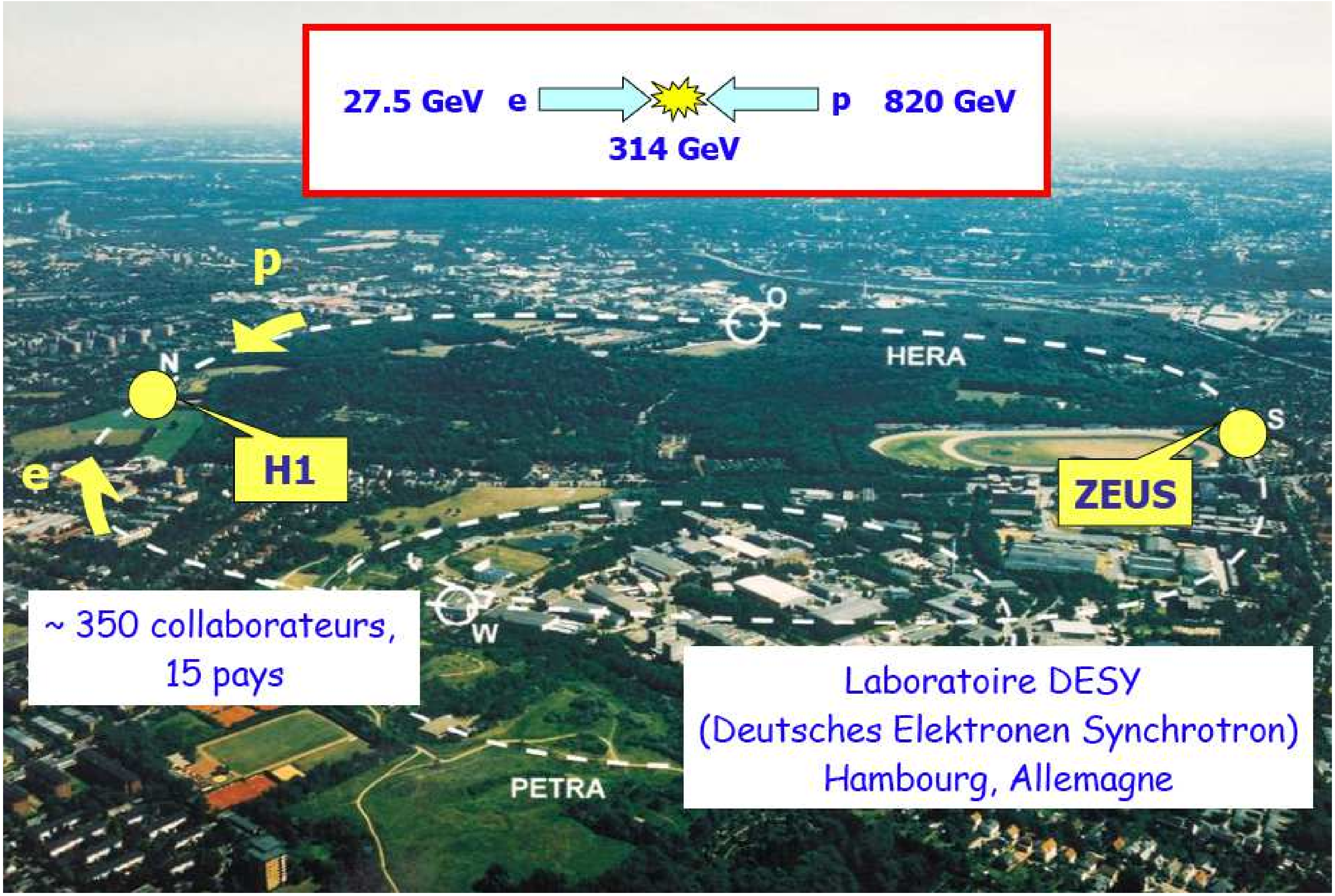
- Timing detectors in particle physics: pile up
- Physics motivation
- Applications (medicine...)

Work in collaboration with M. Saimpert, N. Minafra, V. de Cacqueray, N. Cartiglia, E. Delagnes, D. Breton, J. Maalmi

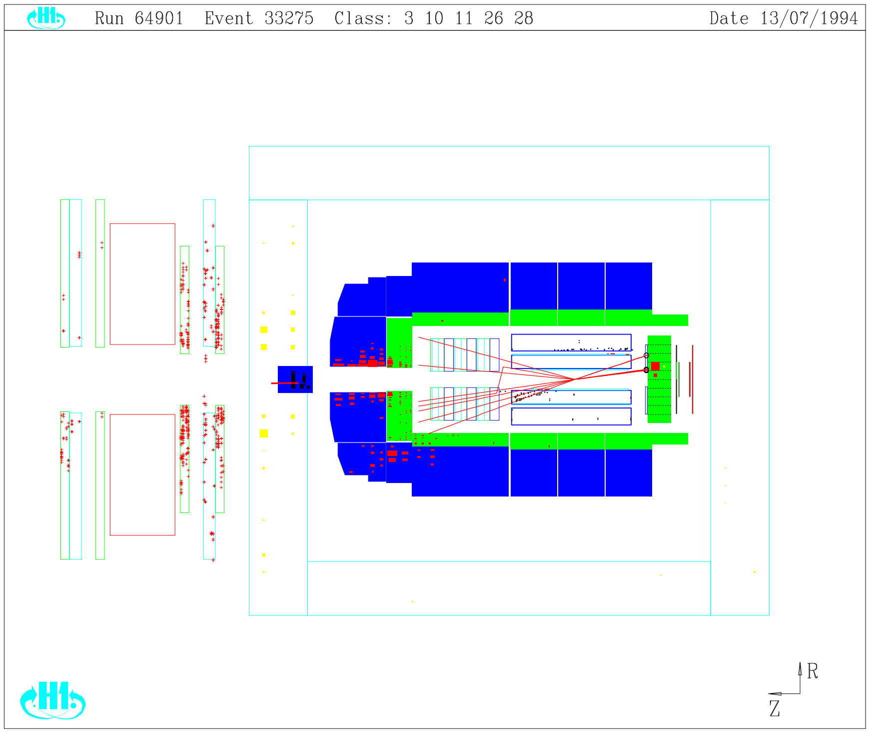


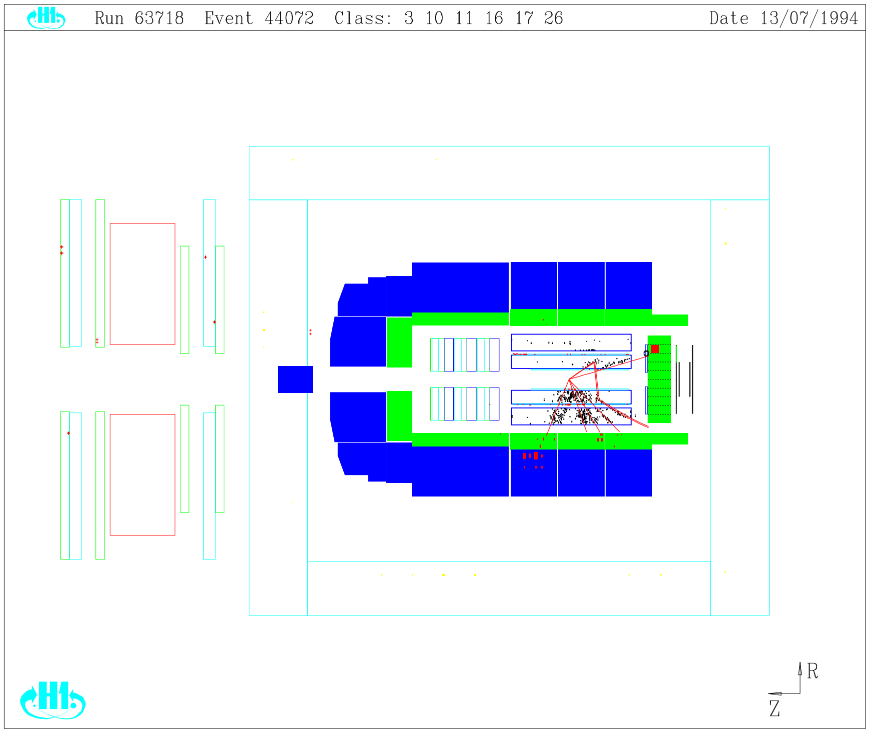
Why timing detectors in particle physics (I)?

HERA: ep collider in DESY, Hamburg, Germany

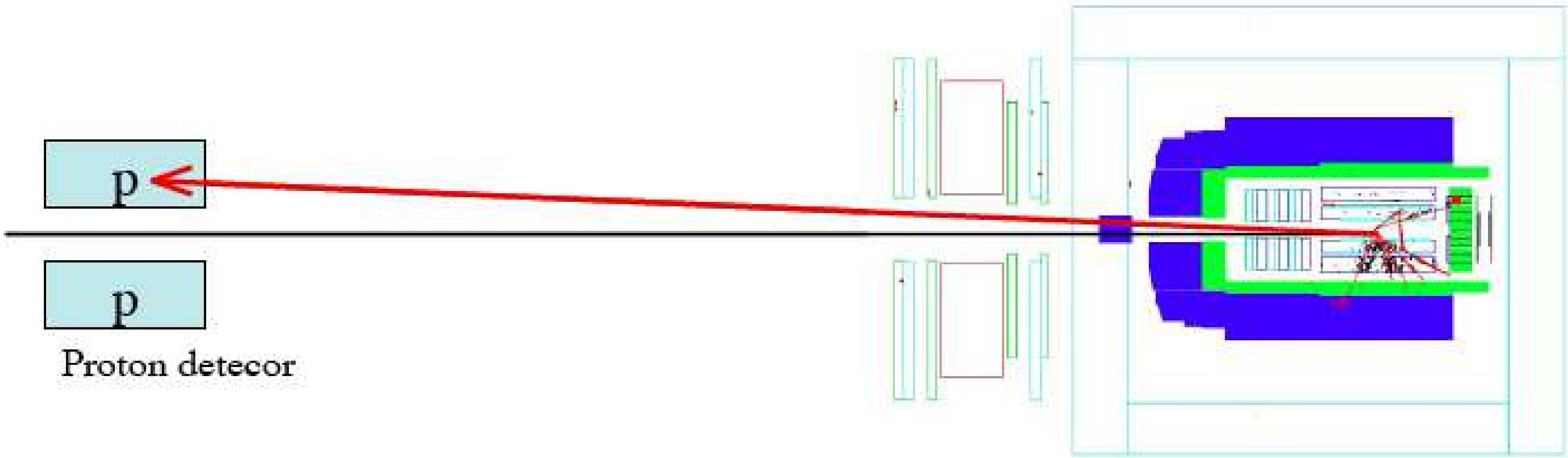


Why timing detectors in particle physics (II)?





Why timing detectors in particle physics (III)?
Detecting intact protons after interaction!

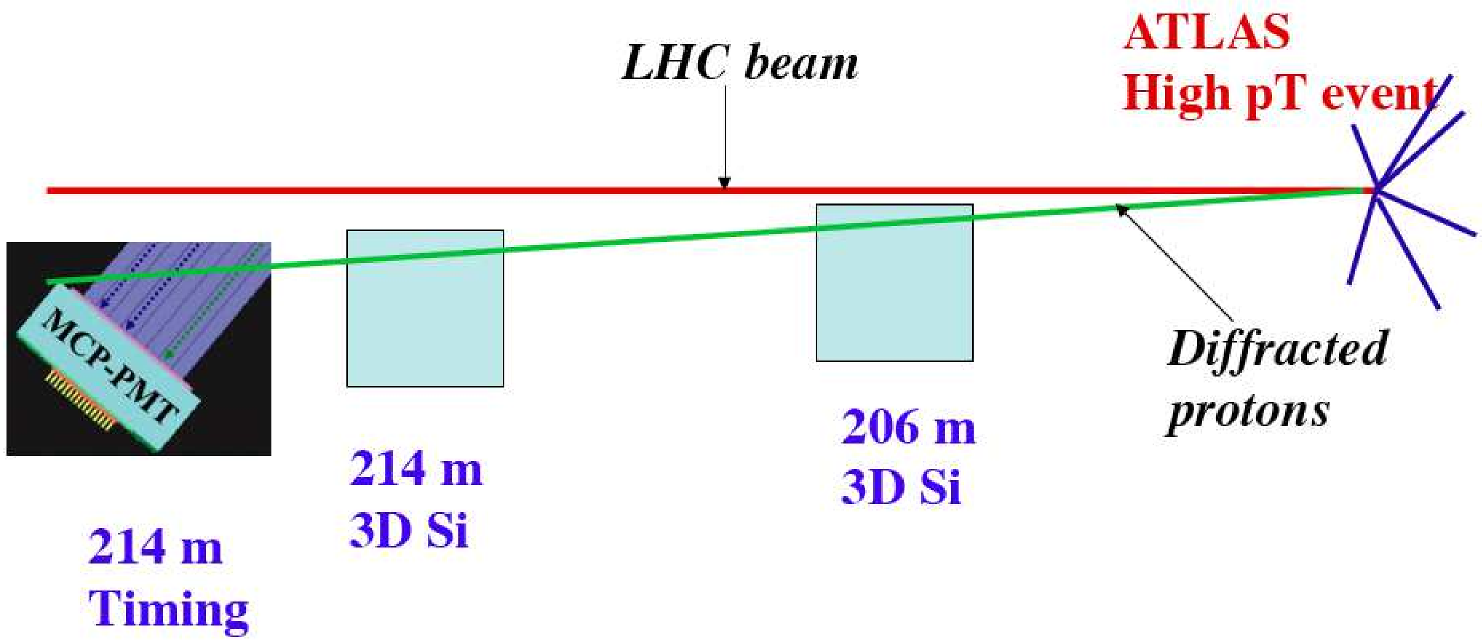


- Some strange events can be produced where the proton is not destroyed! The proton loses part of its energy
- These events are observed in electron-proton and proton-proton colliders
- Physics programme at the LHC including detection of intact protons: we will see why timing is important

LHC: Tagging intact protons in CMS-Totem/ATLAS

- Large Hadron Collider at CERN: proton proton collider with 13 TeV center-of-mass energy restarting in 2015
- Tagging intact protons at the LHC

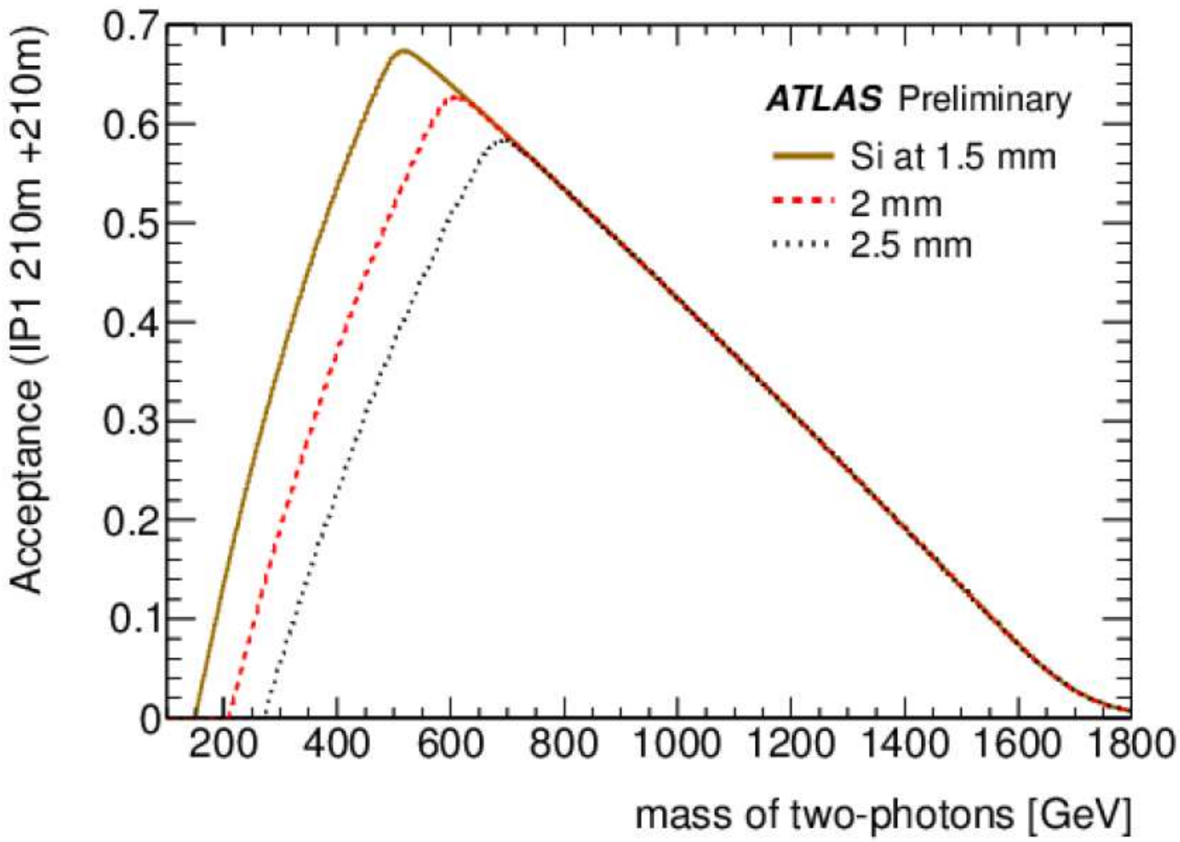
Proton detectors in CMS-TOTEM/ATLAS



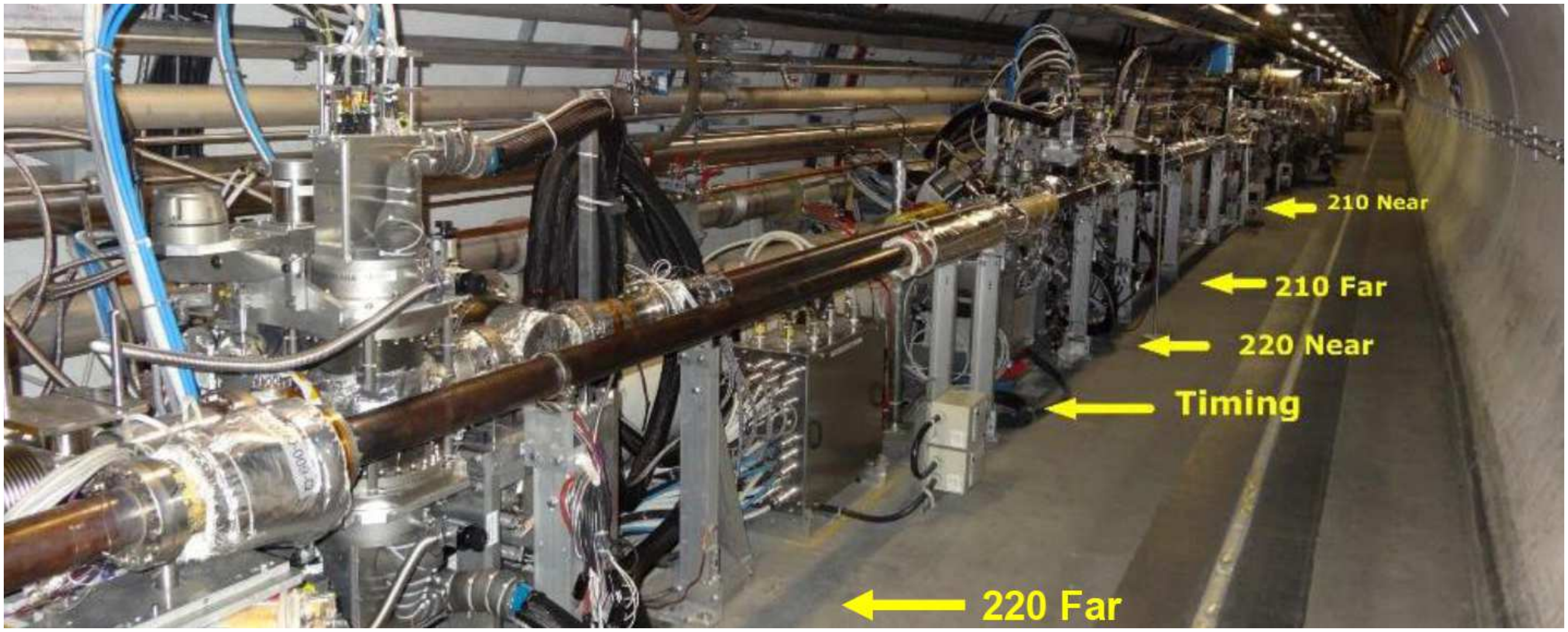
- Tag and measure protons at ± 210 m: AFP (ATLAS Forward Physics) in ATLAS, CT-PPS (CMS TOTEM - Precision Proton Spectrometer) in CMS/Totem
- AFP/CT-PPS detectors: measure proton position (Silicon detectors) and time-of-flight (timing detectors) (we will see later why this is important!)
- Many applications of timing detectors: medicine, drones....

The AFP/CT-PPS detector

- Tag and measure intact protons at ±210 m at the LHC
- Allows to access masses of produced object in ATLAS between 350 and 1.4 TeV: contrain the kinematics/mass of the produced object by measuring final state protons (system fully constrained)

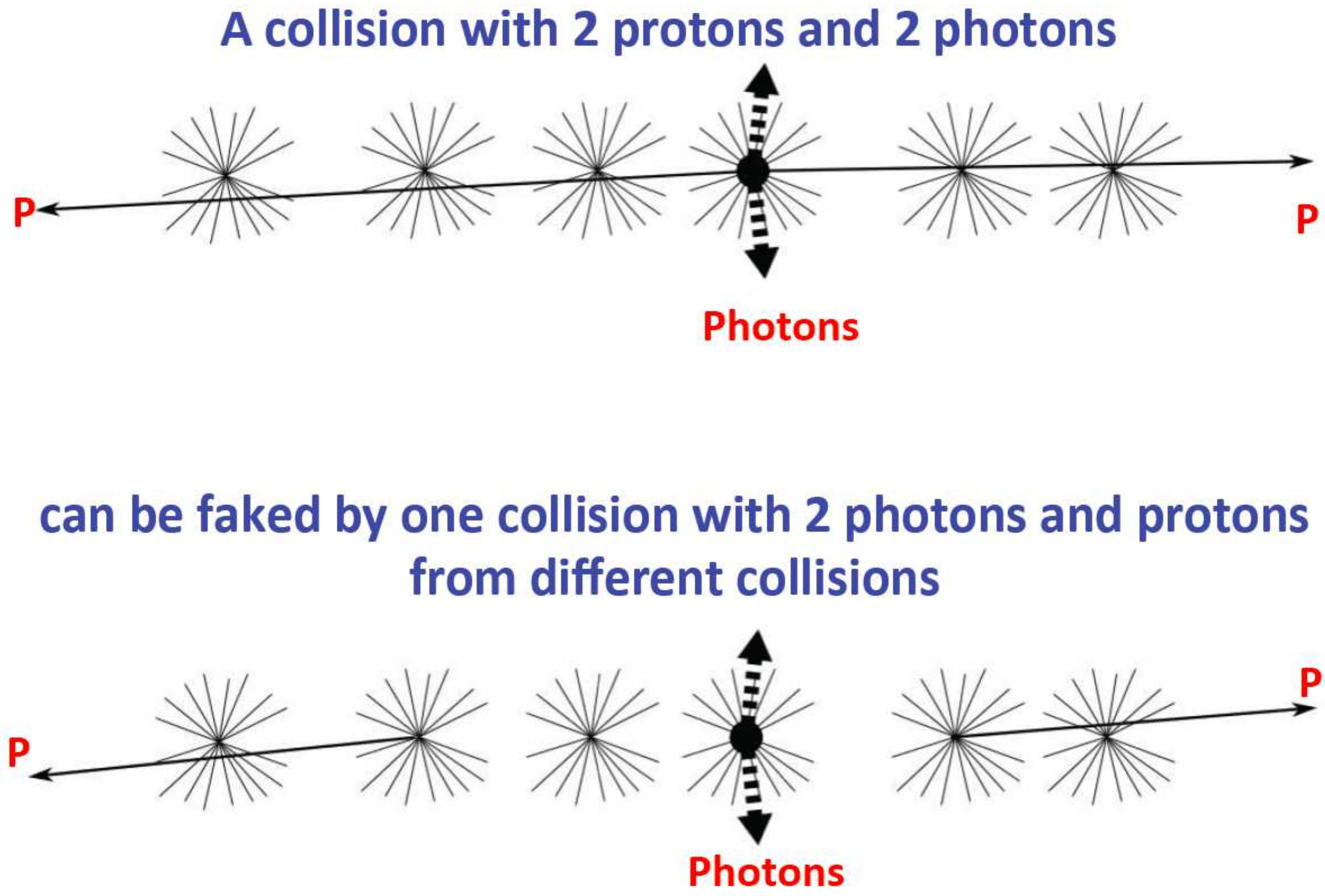


26 roman pots installed by TOTEM on both sides of CMS



- 26 roman pots installed on both sides of CMS by the TOTEM collaboration!
- Combination of vertical (CMS-TOTEM) and horizontal (CT-PPS) roman pots: see talk by Joao
- Different physics topics: low and high mass diffraction (QCD), sensitivity to new physics

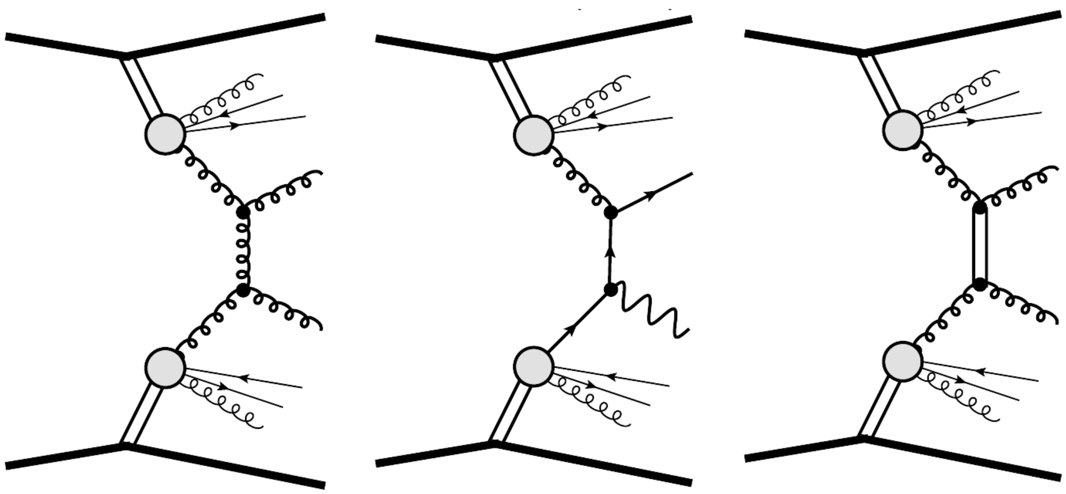
One aside: what is pile up at LHC?



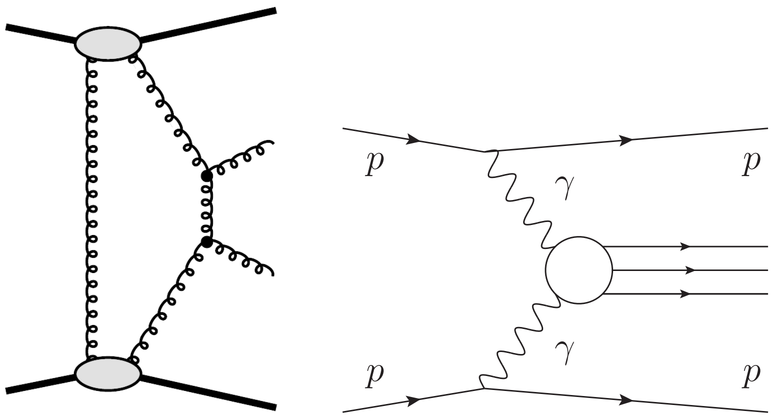
- The LHC machine collides packets of protons
- Due to high number of protons in one packet, there can be more than one interaction between two protons when the two packets collide
- Typically up to 50 pile up events in Run II

Physics motivation (I)

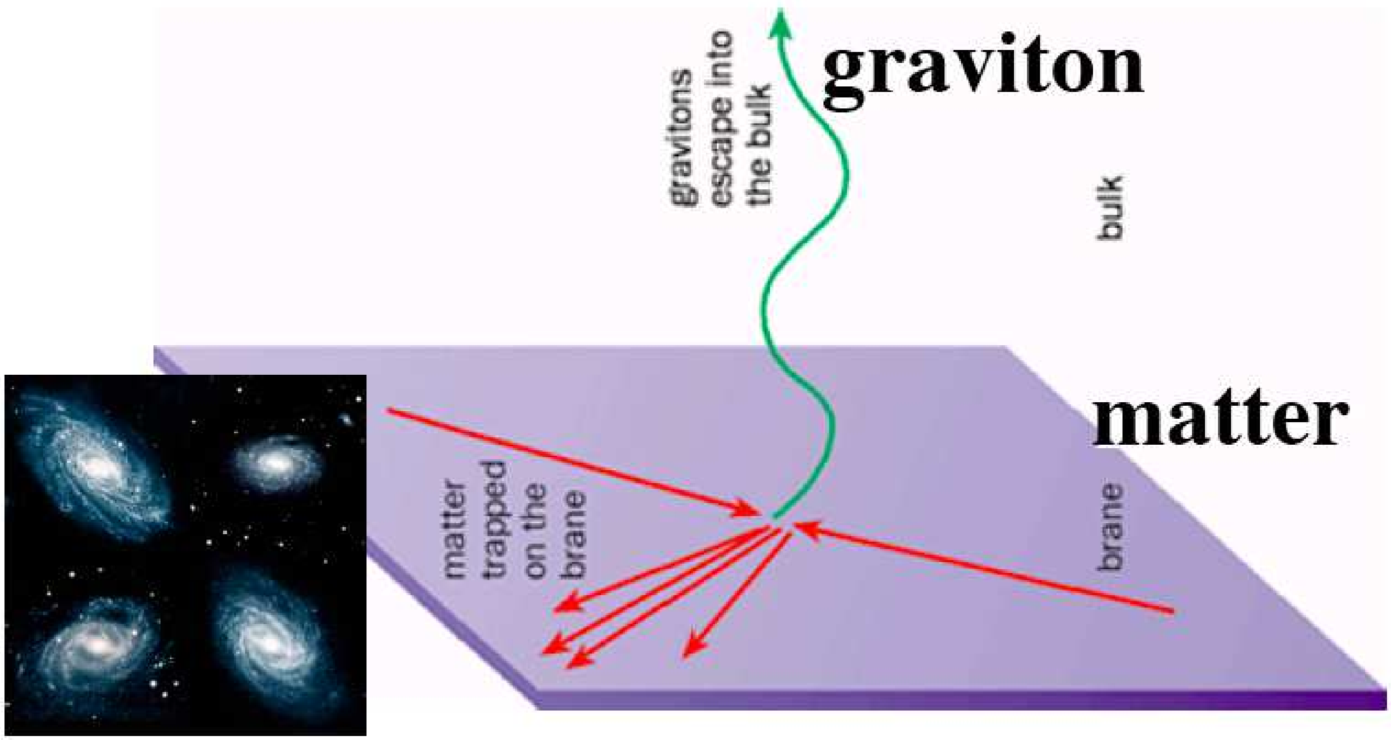
- "Inclusive" diffraction: Structure of the colorless object that is exchanged (gluon, quark) (C. Marquet, C. Royon, M. Saimpert, D. Werder, arXiv:1306.4901); C. Marquet, C. Royon, M. Trzebinski, R. Zlebcik, Phys. Rev. D 87 (2013) 034010; O. Kepka, C. Marquet, C. Royon, Phys.Rev. D79 (2009) 094019; Phys.Rev. D83 (2011) 034036)



- "Exclusive" diffraction: Understand mechanism in QCD, possibility of new discoveries (global, SUSY, extra-dimensions, composite Higgs...)

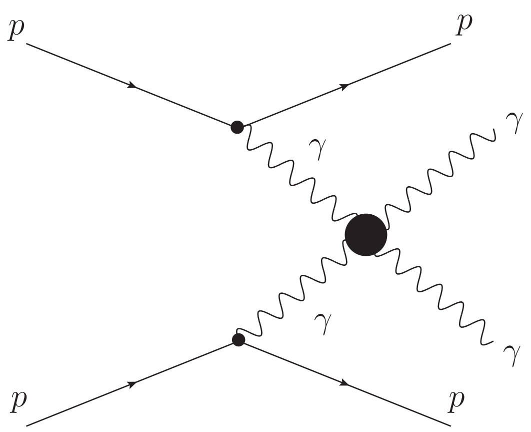


Physics motivation (II): Looking for extra-dimensions in the universe

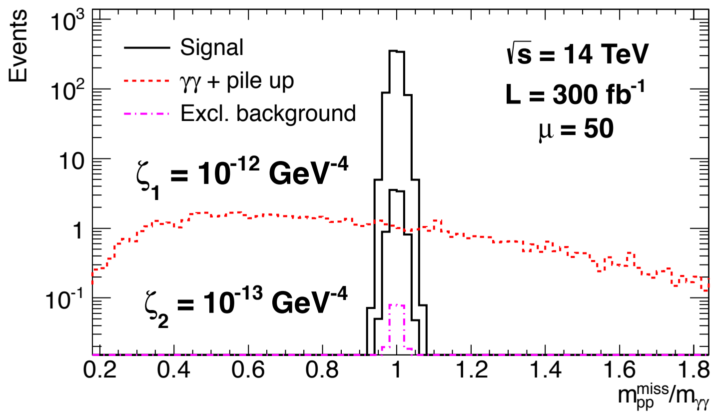


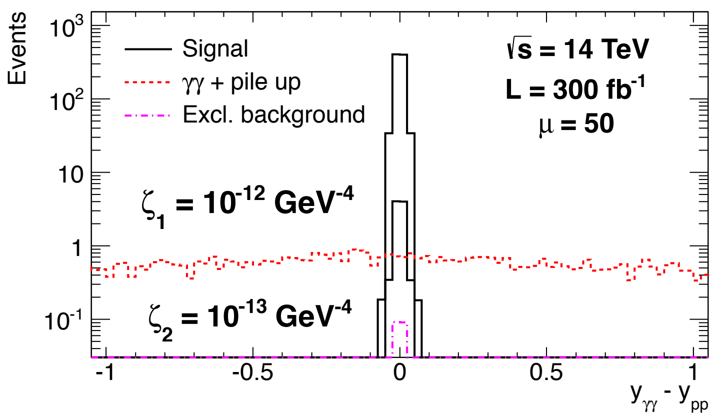
- We live in a 4 dimension space: time and space
- Gravity might live in extra-dimensions: exploration at the LHC for instance by looking for new couplings between particles and production of new particles
- If discovered at the LHC, this might lead to major changes in the way we see the world

Physics motivation (III): Search for extra dimensions in the universe using $\gamma\gamma$ and two intact protons

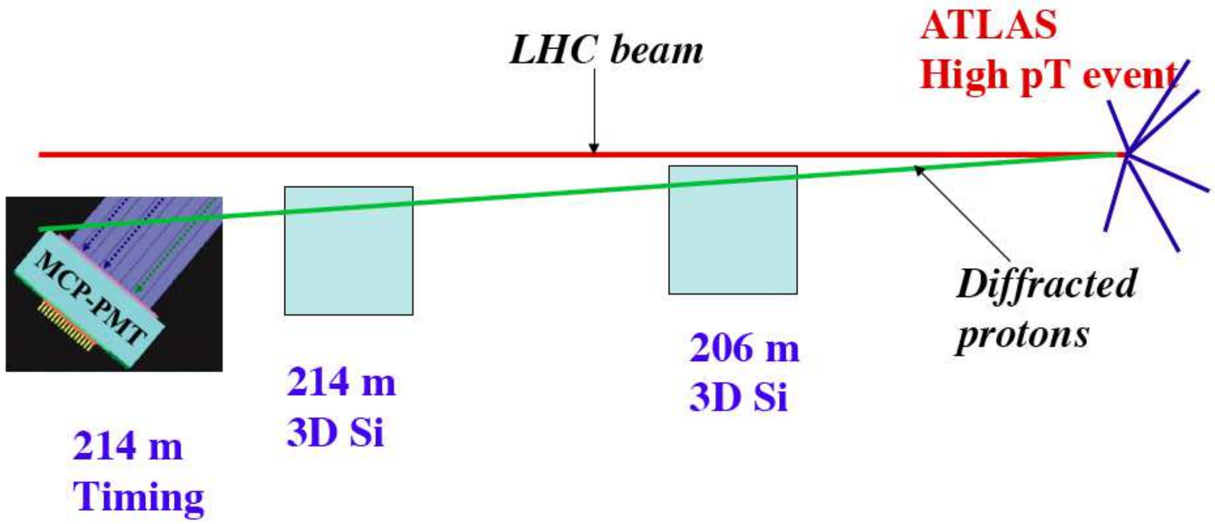


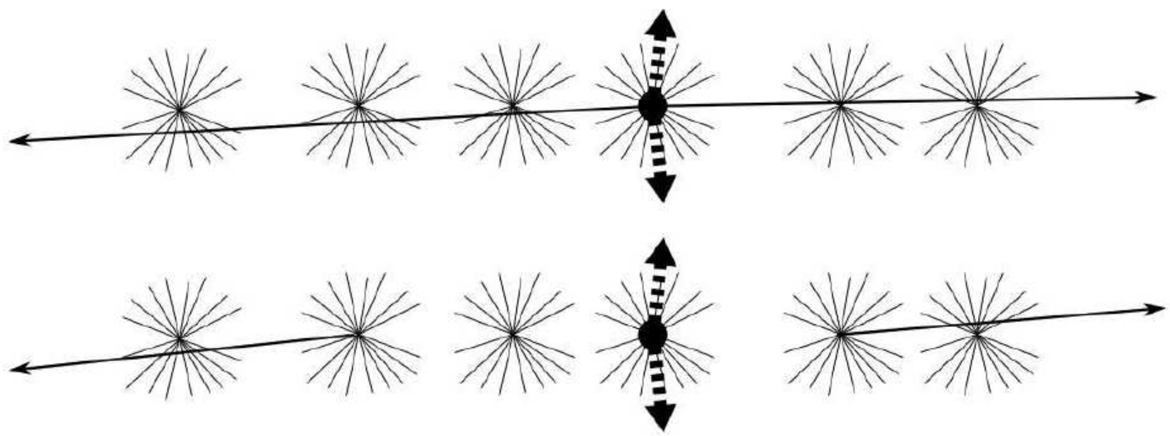
- Search for production of two photons and two intact protons in the final state: $pp \rightarrow p\gamma\gamma p$ (also WW, ZZ productions)
- Number of events predicted to be increased by extra-dimensions, composite Higgs models
- Discovering those extra-dimensions would be a very fundamental discovery in physics E. Chapon, C. Royon, O. Kepka, Phys. Rev. D 81 (2010) 074003; S. Fichet, G. von Gersdorff, B. Lenzi, C. Royon. M. Saimpert, HEP 1502 (2015) 165, Phys. Rev. D 89 (2014) 114004





Removing pile up: measuring proton time-of-flight

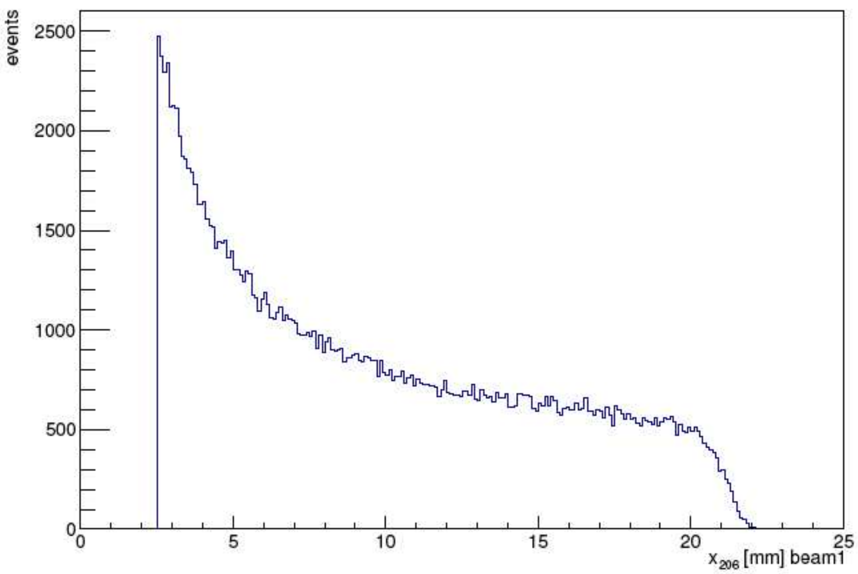


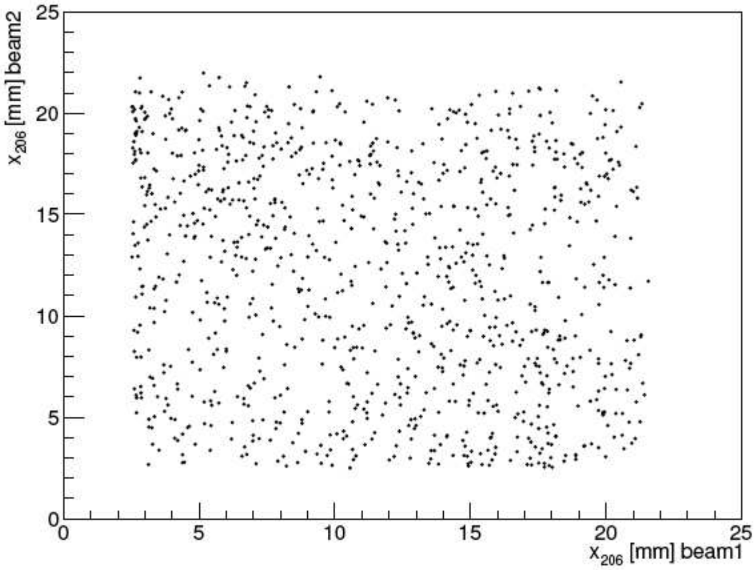


- Measure the proton time-of-flight in order to determine if they originate from the same interaction as our photon
- Typical precision: 10 ps means 2.1 mm

Pile up treatment and Proton distribution in AFP

- Generation of 7 TeV protons (Single diffractive and Double Pomeron Exchange events) with PYTHIA 8
- Transport at AFP/CT-PPS position from the Interaction Point (IP) with FPTRACKER/MADX (program from the LHC beam division allowing transport through the magnets)

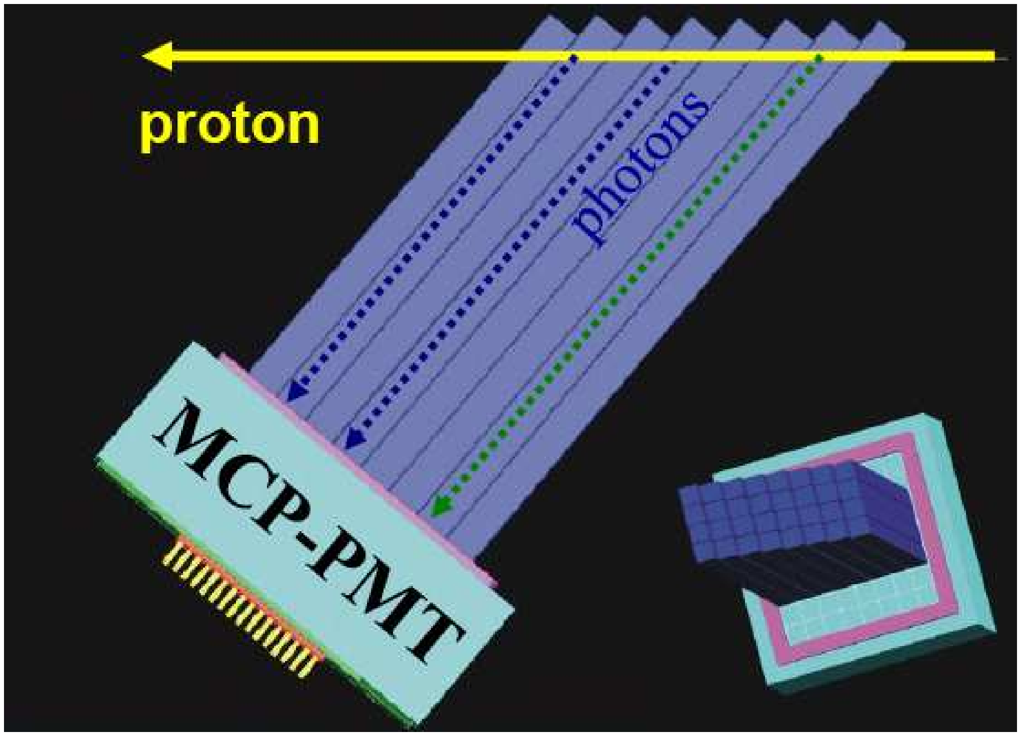




- Proton distribution (X distance from the horizontal axis on one side for SD, and correlations between both x on each side of ATLAS for DPE events)
- Probability for a proton to be tagged (taking into account SD/DPE cross sections) for one bunch crossing: 0.01% (double tag on each side), 1.6% (single tag on one side), 97% (no tag)

Timing detectors: from quartz bars to Si/diamonds

- Measure the vertex position using proton time-of-flight: Requirements for timing detectors
  - 10 ps final precision (factor 40 rejection on pile up)
  - Efficiency close to 100% over the full detector coverage
  - High rate capability (bunch crossing every 25 ns)
  - Segmentation for multi-proton timing
  - level 1 trigger capability
- Utilisation of quartz bars or more pixelised detectors: diamond or Silicon



Detector I: Different scenarii for a quartz bar detector

- 3 different kinds of pile up conditions to be considered: 50, 100 and 300

μ	P_N	$P_{S,left}$	$P_{S,right}$	P_D
0	0.97	0.016	0.016	9.9e-05
50	0.189	–	0.248	0.316
100	0.036	–	0.155	0.655
300	0.	–	0.007	0.986

- 3 different scenarii of QUARTIC considered (bar 1 is the closest to the beam):
  - Scn1: 7 bar detector: 2 mm width for bar 1, 3.25 for the others
  - Scn2: 10 bar detector, 2 mm width for all bars
  - Scn3: 20 bar detector, 1 mm width for all bars
- Inefficiency calculation: Probability to get a proton from pile up and a proton from signal in the same bunch crossing

Detector I: Bar inefficiencies

Inefficiencies - Scenario 1							
Bar	1	2	3	4	5	6	7
$\mu = 50$	**0.129**	**0.130**	**0.095**	0.078	0.070	0.057	0.005
$\mu = 100$	**0.185**	**0.187**	**0.136**	0.111	0.101	0.082	0.007
$\mu = 300$	**0.226**	**0.229**	**0.166**	0.137	0.125	0.102	0.008

Inefficiencies - Scenario 2										
Bar	1	2	3	4	5	6	7	8	9	10
$\mu = 50$	**0.129**	**0.085**	**0.067**	0.057	0.049	0.046	0.043	0.040	0.036	0.011
$\mu = 100$	**0.185**	**0.122**	**0.097**	0.082	0.071	0.066	0.062	0.057	0.051	0.016
$\mu = 300$	**0.226**	**0.149**	**0.118**	0.100	0.087	0.081	0.077	0.071	0.063	0.020

Inefficiencies - Scenario 3										
Bar	1	2	3	4	5	6	7	8	9	10
$\mu = 50$	**0.074**	**0.056**	**0.046**	0.039	0.035	0.032	0.030	0.027	0.026	0.024
$\mu = 100$	**0.101**	**0.080**	**0.066**	0.056	0.051	0.046	0.043	0.040	0.037	0.034
$\mu = 300$	**0.129**	**0.097**	**0.081**	0.068	0.062	0.056	0.052	0.048	0.045	0.042
Bar	11	12	13	14	15	16	17	18	19	20
$\mu = 50$	0.023	0.022	0.022	0.021	0.020	0.020	0.019	0.017	0.010	0.001
$\mu = 100$	0.034	0.032	0.032	0.030	0.029	0.028	0.027	0.024	0.015	0.001
$\mu = 300$	0.041	0.040	0.039	0.037	0.036	0.035	0.033	0.030	0.018	0.001

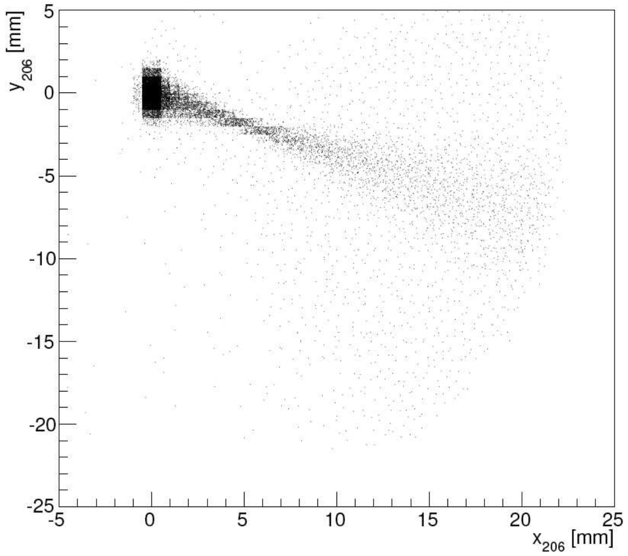
- Inefficiencies below typically 12% for bars closest to the beam
- Additional issue: Potential background created to the beam and in other detectors since in many cases, protons are destroyed in quartz bars (lots of material)
- Explore other solutions for upgrade: Si, diamonds pixels and may be nanotechnology materials (see talk by Nicolo)

Detector II: Inefficiencies for pixel solution

Inefficiencies - 20x8 pixel design - $\mu = 50$ - Scenario 3										
Row/Column	1	2	3	4	5	6	7	8	9	10
8	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
7	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
6	**0.026**	0.002	0.	0.	0.	0.	0.	0.	0.	0.
5	**0.047**	**0.054**	**0.036**	0.004	0.001	0.	0.	0.	0.	0.
4	0.	0.001	**0.010**	0.034	0.030	0.017	0.008	0.004	0.002	0.002
3	0.	0.	0.	0.001	0.005	0.013	0.016	0.013	0.009	0.006
2	0.	0.	0.	0.	0.	0.001	0.004	0.007	0.009	0.008
1	0.	0.	0.	0.	0.	0.	0.001	0.002	0.004	0.005

Row/Column	11	12	13	14	15	16	17	18	19	20
8	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
7	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
6	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
5	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
4	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.	0.
3	0.004	0.003	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.
2	0.007	0.005	0.004	0.003	0.003	0.002	0.002	0.002	0.001	0.
1	0.005	0.005	0.005	0.004	0.004	0.003	0.003	0.002	0.002	0.

Leads to slightly smaller inefficiencies

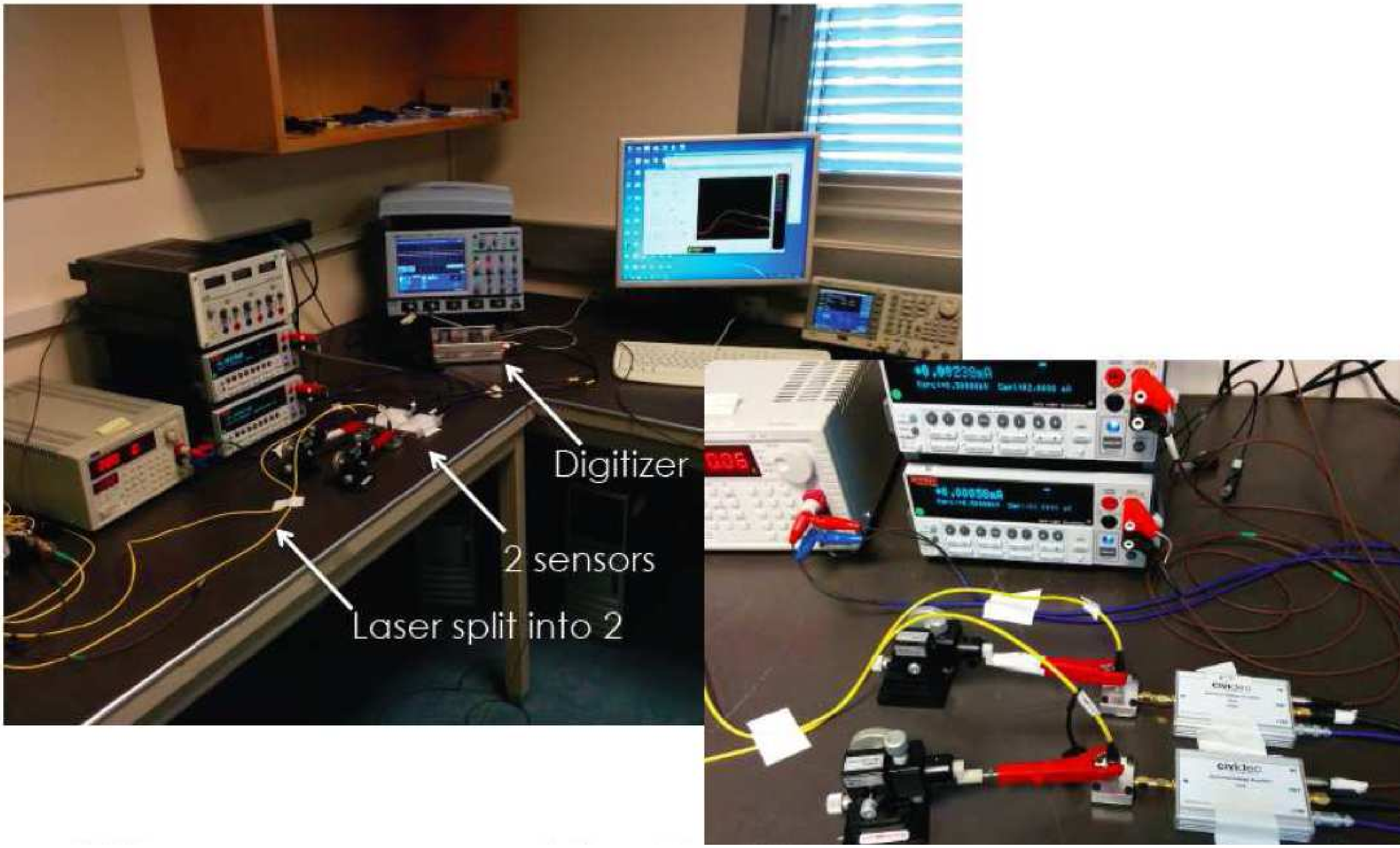


Measuring the proton time-of-flight: the SAMPIC concept

- The general idea is to measure the signal created by the protons inside a quartz, diamond or Silicon detector
- New electronics developed in Saclay/Orsay called SAMPIC that acquires the full waveform shape of the detector signal: about 3 ps precision!
- SAMPIC is cheap ($\sim$ 10 Euros per channel) (compared to a few 1000 Euros for previous technologies)
- See talk by Dominique, Victor

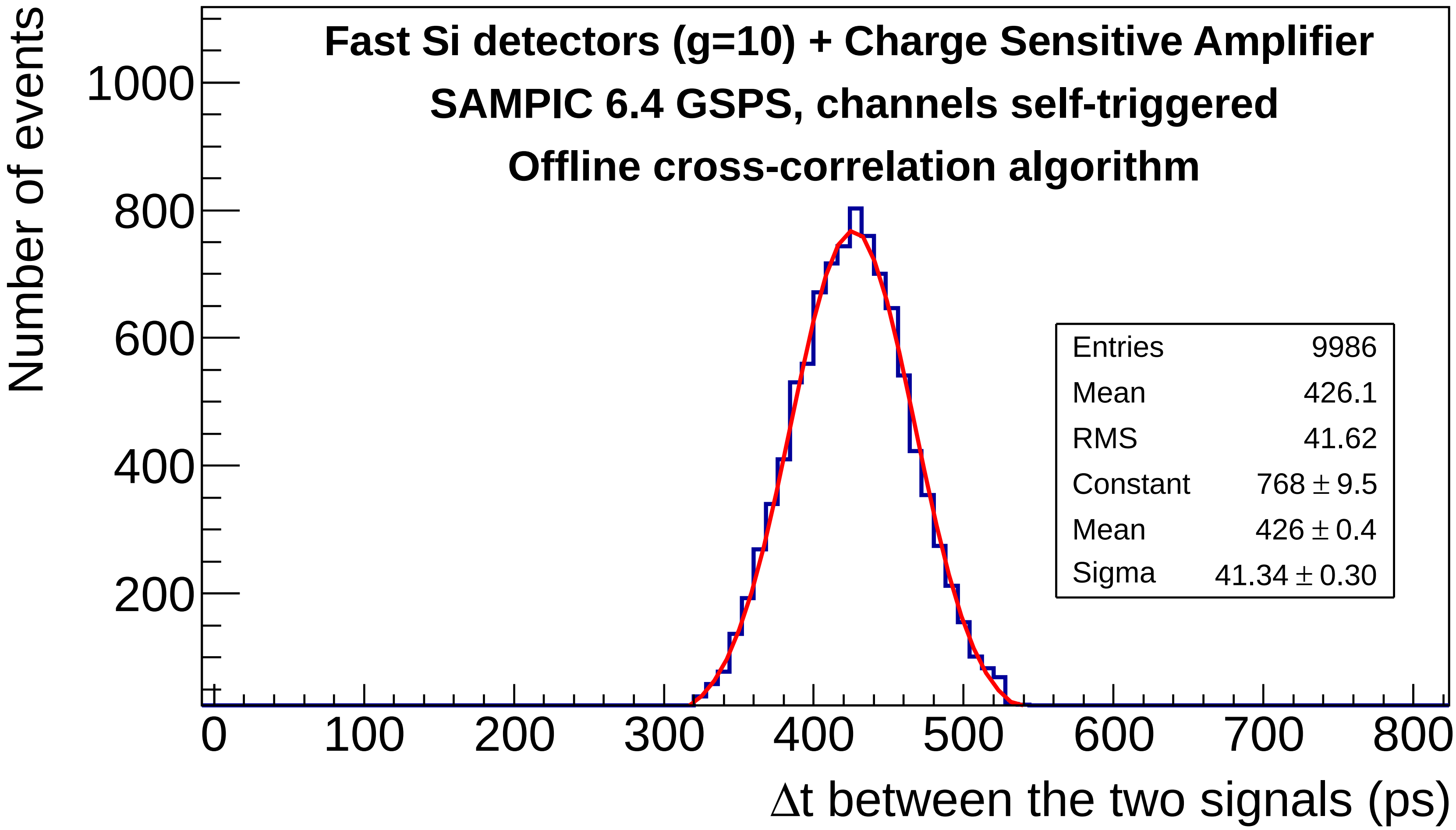
Time resolution using Si detectors

- Test setup using a laser signal split in 2 read out by fast Si detector
- Time difference and resolution measured by SAMPIC



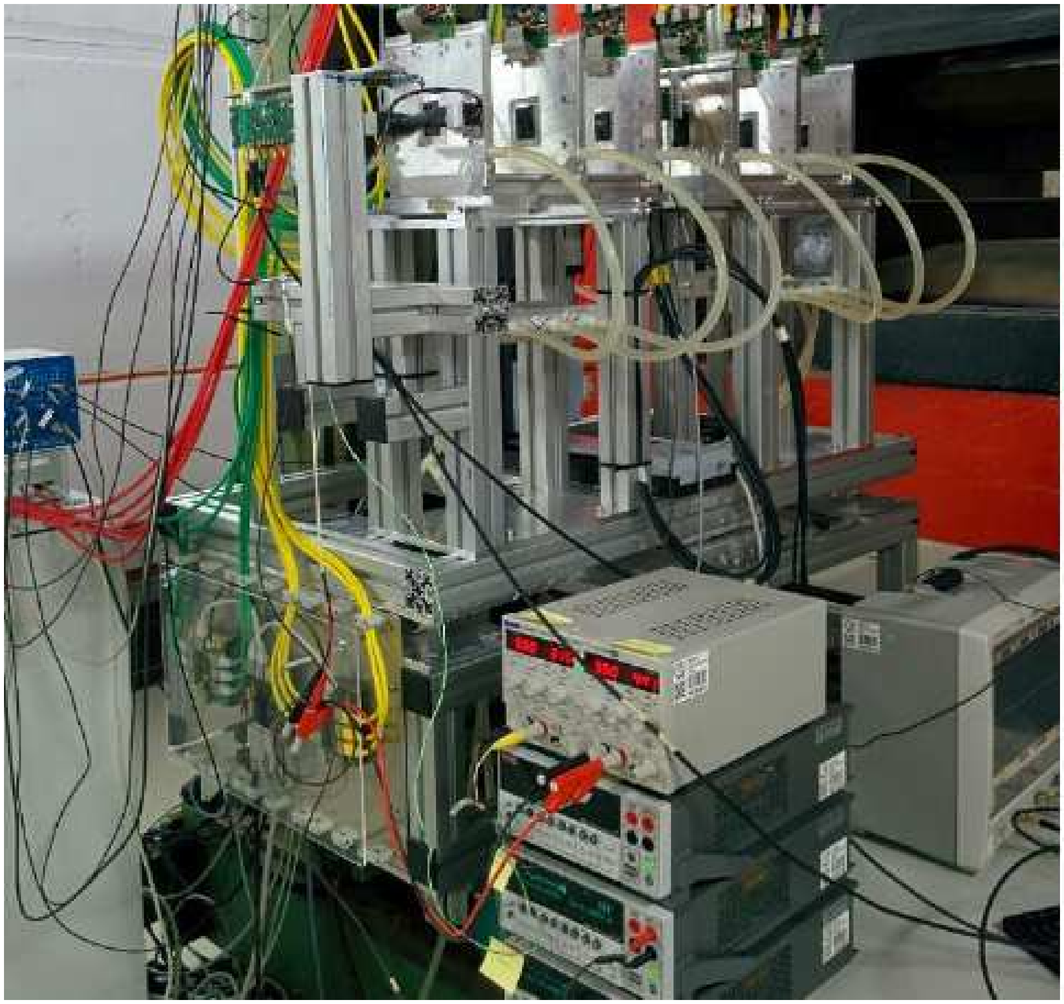
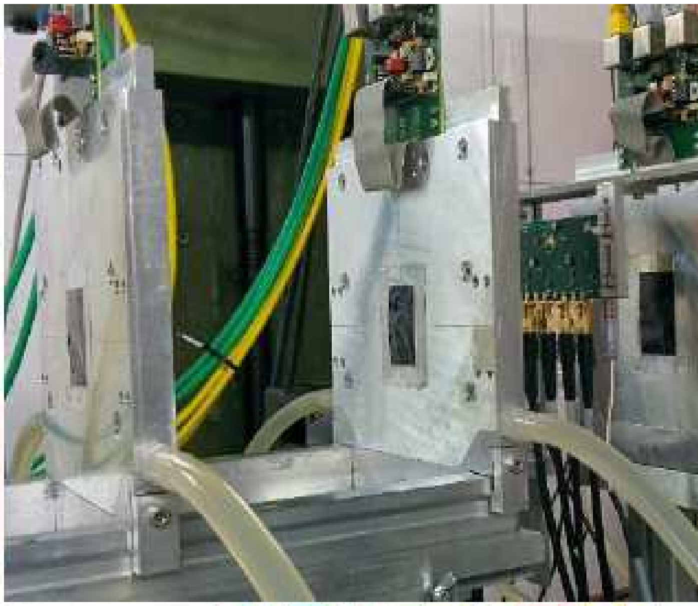
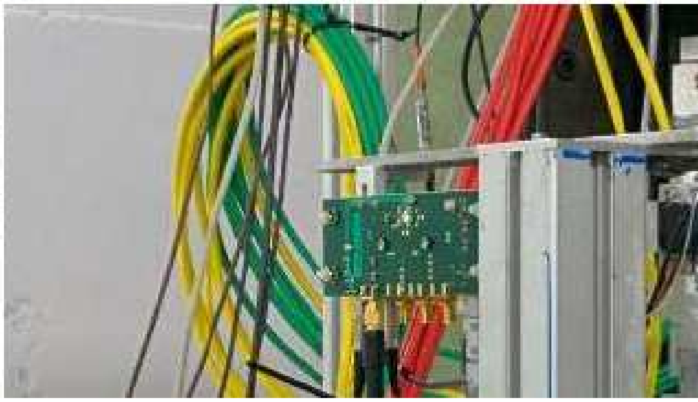
Time resolution using Si detectors

- Time resolution using sampic and fast Si detectors: measure the time difference between two channels
- Time resolution: (dominated by detector): $\sim$ 30 ps (SAMPIC gives $\sim$3 ps, better than 1mm), very promising for the LHC!



Beam tests in TOTEM using diamond detectors (I)

- Beam tests performed at DESY and CERN by TOTEM using diamonds detectors and SAMPIC

Beam tests in TOTEM using diamond detectors (II)

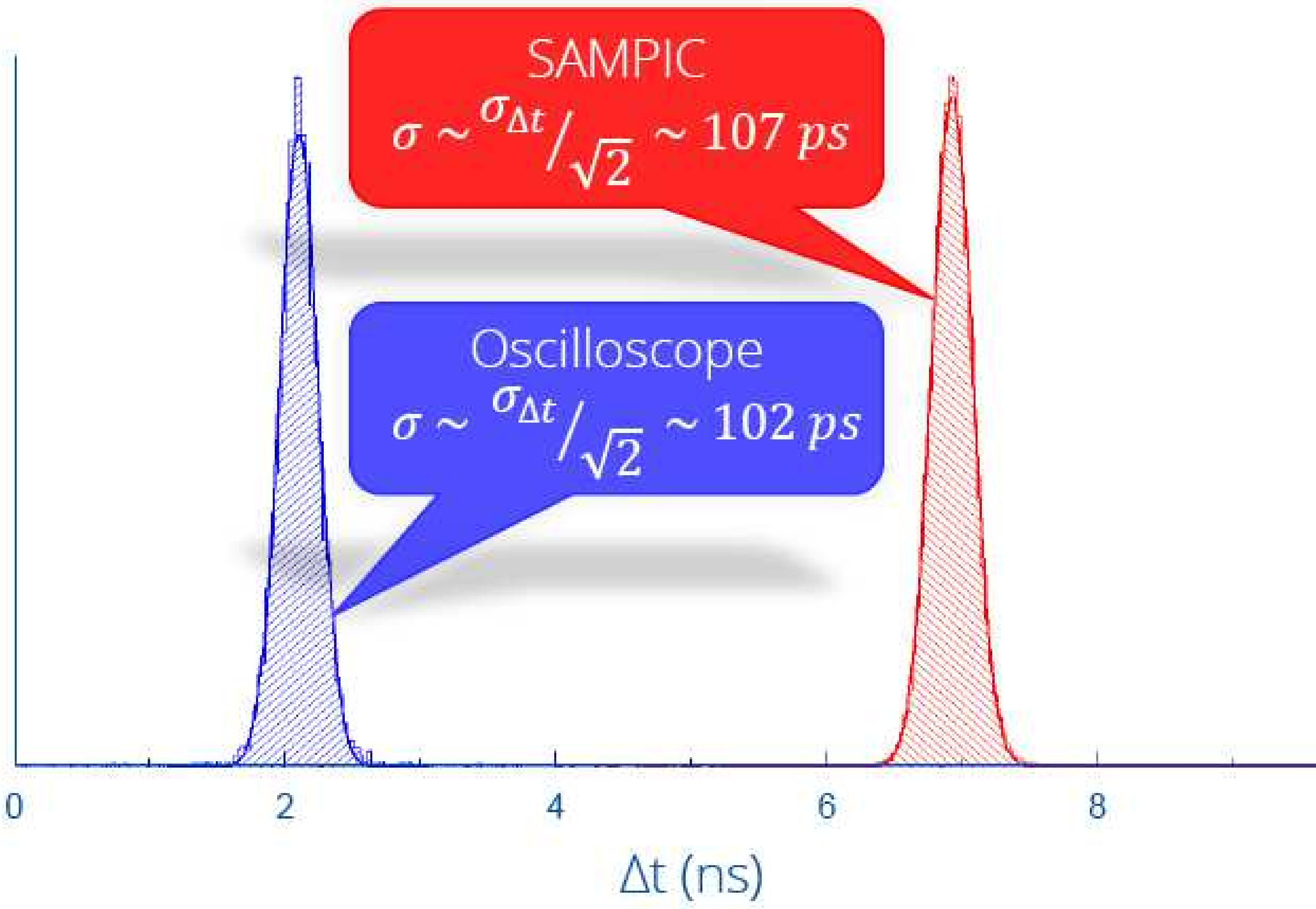
- Beam tests performed at DESY and CERN by TOTEM using diamonds detectors and SAMPIC

Agilent DSO 9254A
2.5 GHz bandwidth
10 Gs/s
8 bit
> 1000 samples
4 channels
Maximum rate ~100 Hz

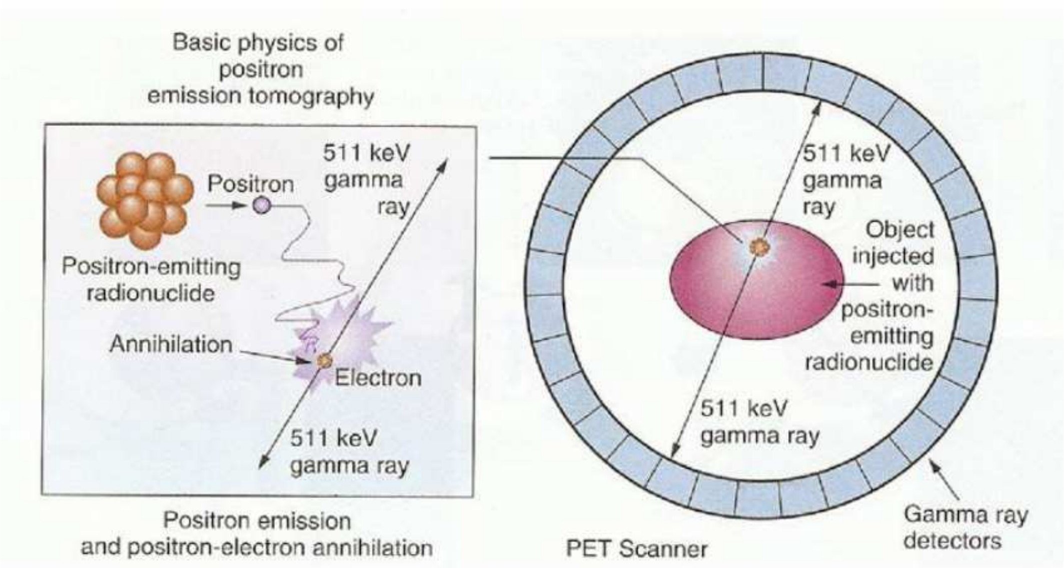
SAMPIC
2.5 GHz bandwidth
10 Gs/s (used at 6.4 Gs/s)
11 bit
64 samples
16 channels
Maximum rate ~500 kHz

Beam tests in TOTEM using diamond detectors (III)

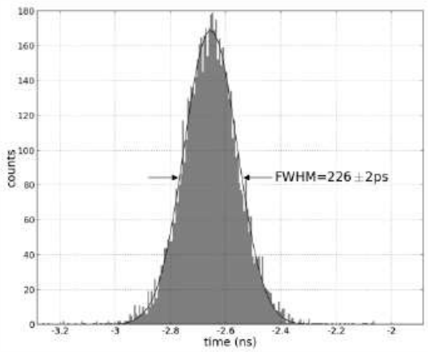
- Measure the resolution on the time difference between two channels

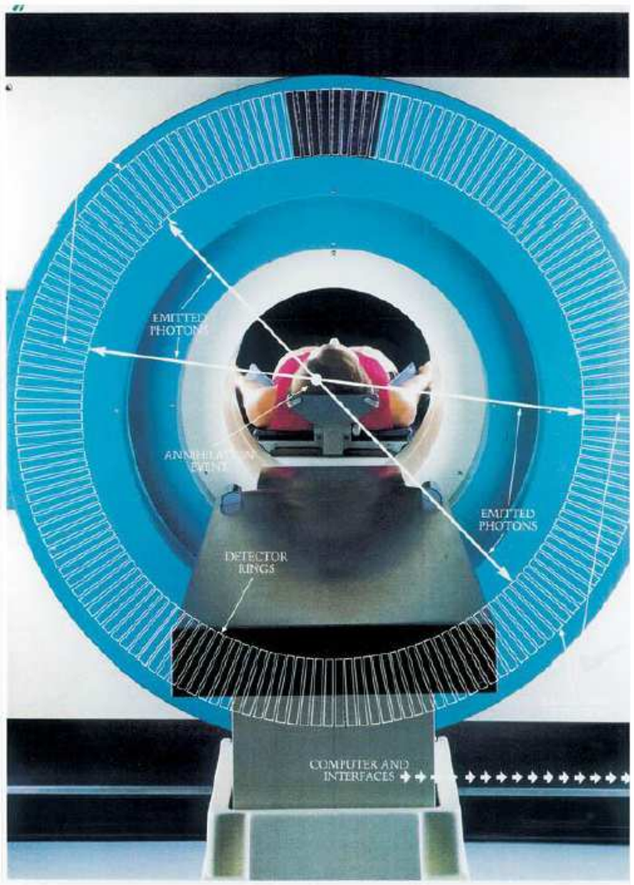


The future: Application: Timing measurements in Positron Emission Tomography



Coincidence Resolving Time:





- The Holy grail: 10 picosecond PET (3 mm resolution)
- What seemed to be a dream a few years ago seems now to be closer to reality
- Other possible application in drone technology: fast decision taking and distance measurement using laser

Conclusion

- AFP/CT-PPS and CMS-TOTEM aim at detecting intact protons: QCD (structure of Pomeron...), search for extra-dimensions in the universe via anomalous couplings between γ, W, Z...)
- Timing detectors: needed to reject pile up background
- Bar solution (quartic) leads to small inefficiencies if enough number of bars
- Pixelised solution leads to better efficiencies, also less material inducing background: diamonds, Si
- Many applications especially in PET imaging, drones...