Timing detectors for proton tagging at the LHC

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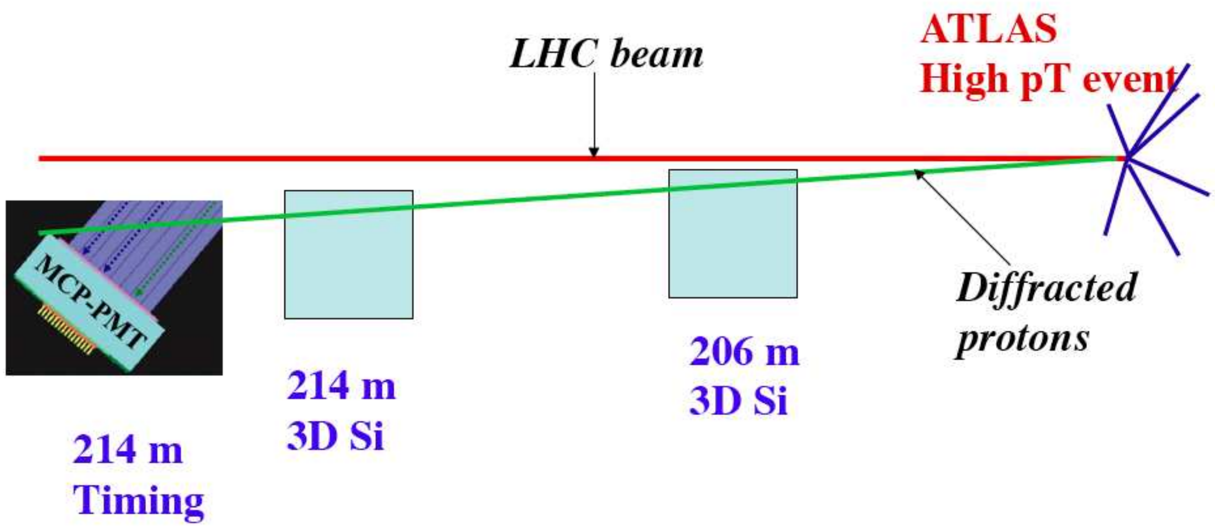
Contents:

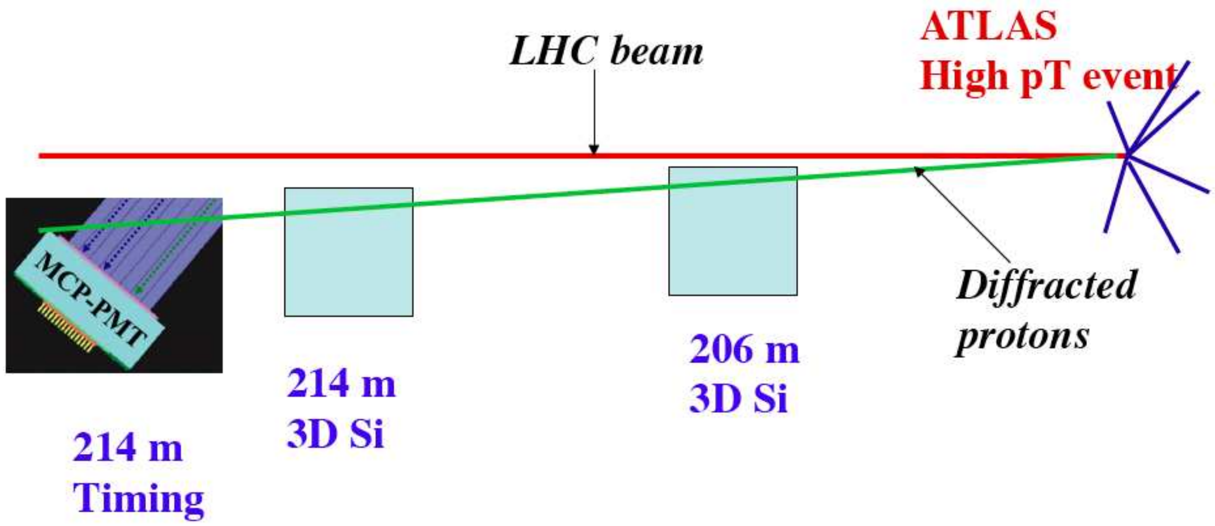
- Proton tagging (AFP/PPS)
- Physics motivation
- Pile up studies
- Timing detectors



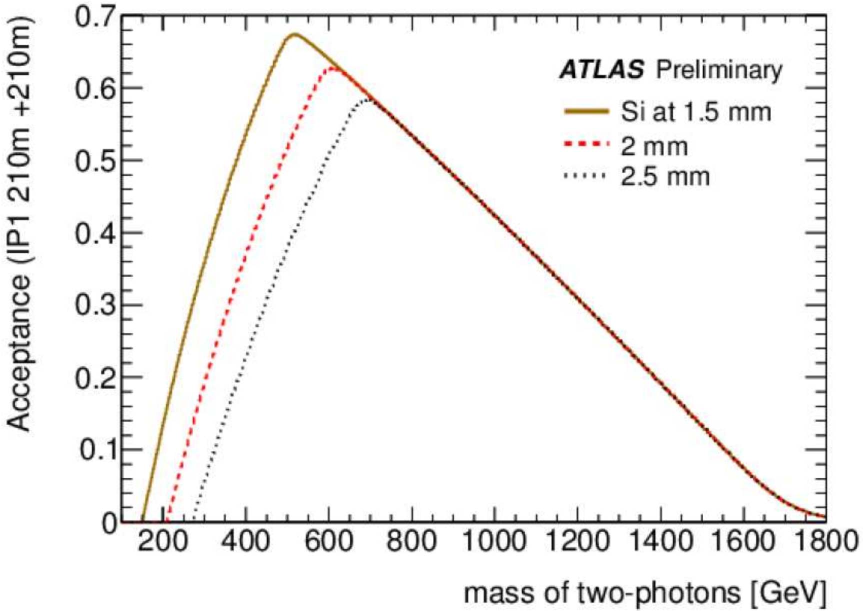
LHC: Tagging intact protons in CMS-Totem/ATLAS

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

Introduction: The AFP/PPS detector

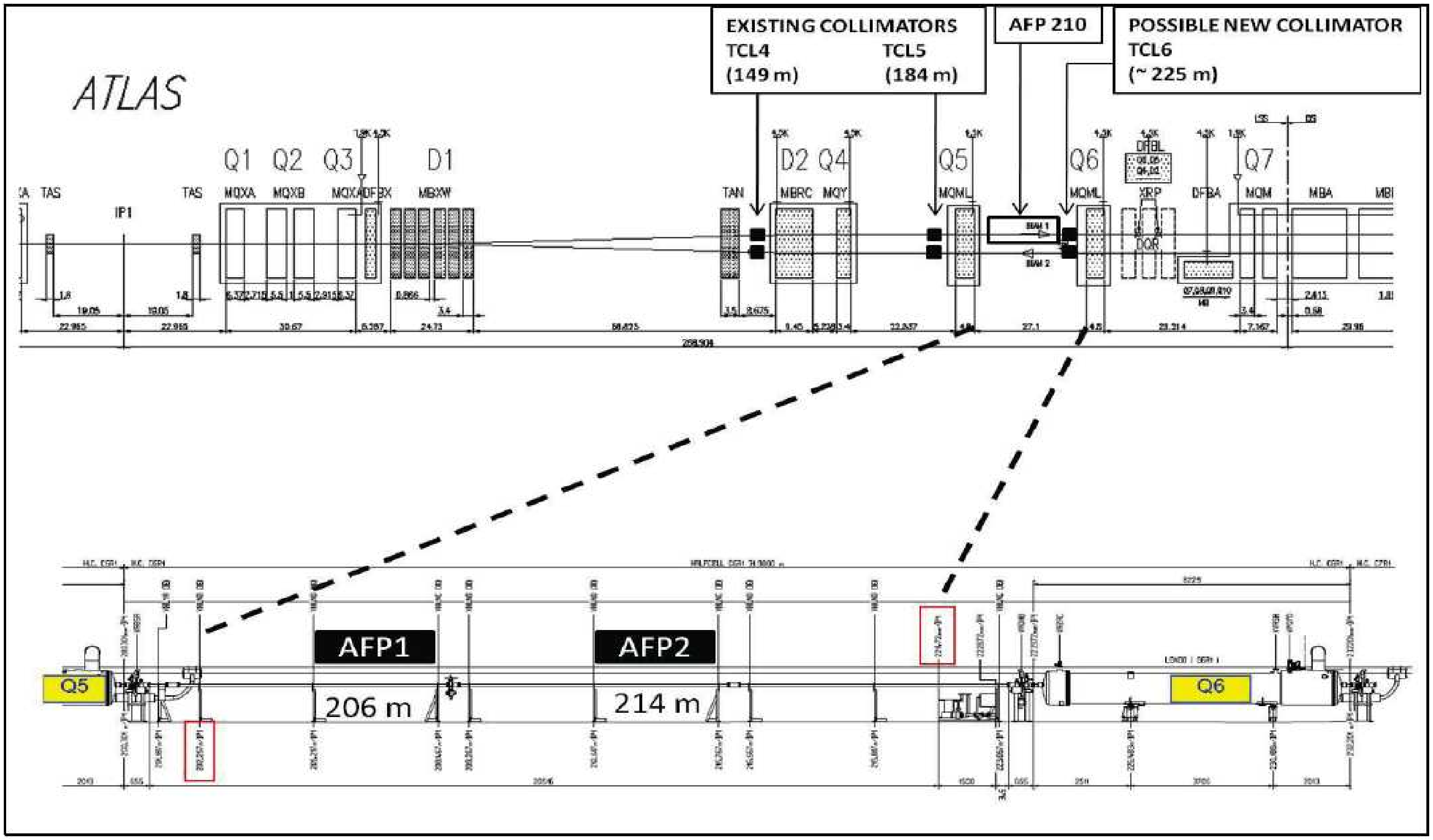


- Tag and measure intact protons at ±210 m at the LHC
- Allows to access masses of produced object in ATLAS between 350 and 1.4 TeV: contrain the kinematics/mass of the produced object by measuring final state protons (system fully constrained)



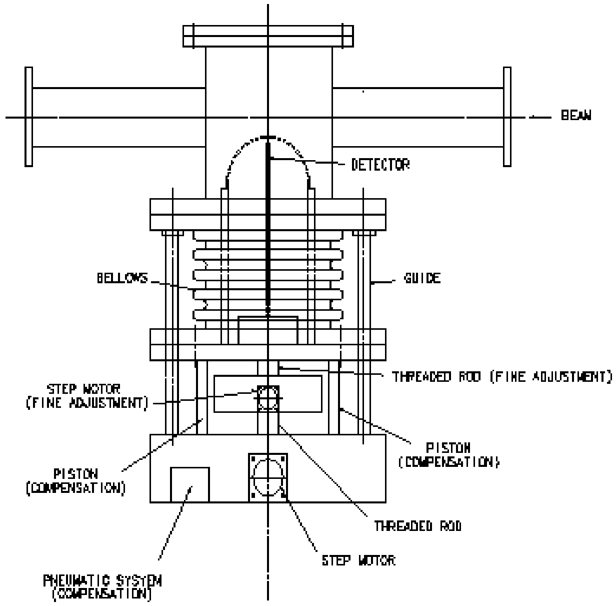
AFP detector location

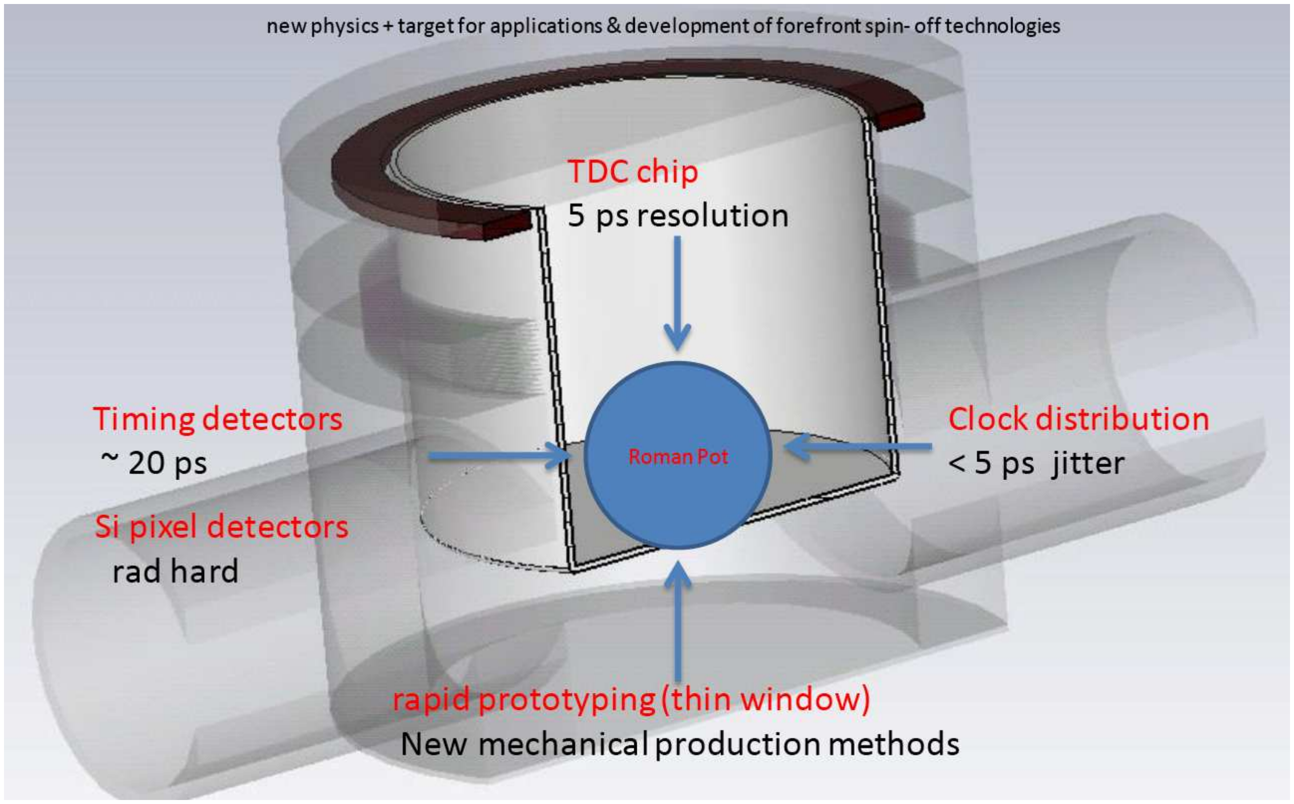
- Detect intact protons in the final states
- Detector stations located at 206 and 214 m on both sides of the ATLAS interaction point (similar for CMS/Totem)
- AFP detectors: Radiation hard "edgeless" 3D Silicon detectors, 10 ps timing detectors
- Allows running in high pile up conditions by association with correct primary vertex: Access to rare processes



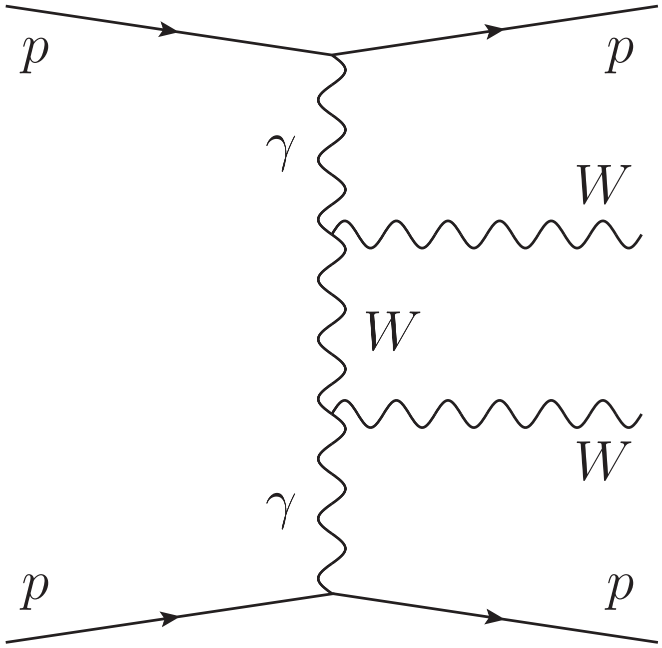
Detection of intact protons: roman pot technique

- How to detect intact protons? Tag the proton in the final state, scattered at small angles, using roman pot detectors





Physics: Search for $\gamma\gamma WW$ quartic anomalous coupling



- Study of the process: $pp \to ppWW$
- Standard Model: $\sigma_{WW} = 95.6$ fb, $\sigma_{WW}(W = M_X > 1TeV) = 5.9$ fb
- Process sensitive to anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$; motivated by studying in detail the mechanism of electroweak symmetry breaking, predicted by extradim. models
- Rich $\gamma\gamma$ physics at LHC: see E. Chapon, O. Kepka, C. Royon, Phys. Rev. D78 (2008) 073005; Phys. Rev. D81 (2010) 074003; S.Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert, ArXiv 1312.5153

Results from full simulation

- Effective anomalous couplings correspond to loops of charged particles, Reaches the values expected for extradim models (C. Grojean, J. Wells)

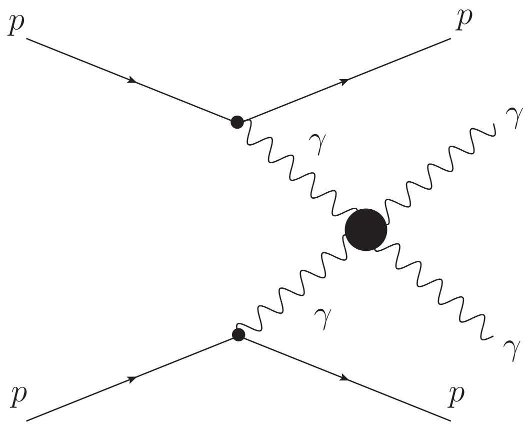
Cuts	Top	Dibosons	Drell-Yan	W/Z+jet	Diffr.	$a_0^W/\Lambda^2 = 5 \cdot 10^{-6}$ GeV^{-2}
timing < 10 ps $p_T^{lep1} > 150$ GeV $p_T^{lep2} > 20$ GeV	5198	601	20093	1820	190	282
M(ll)>300 GeV	1650	176	2512	7.7	176	248
nTracks ≤ 3	2.8	2.1	78	0	51	71
$\Delta\phi < 3.1$	2.5	1.7	29	0	2.5	56
$m_X > 800$ GeV	0.6	0.4	7.3	0	1.1	50
$p_T^{lep1} > 300$ GeV	0	0.2	0	0	0.2	35

Table 9.5. Number of expected signal and background events for 300 fb^{-1} at pile-up $\mu = 46$. A time resolution of 10 ps has been assumed for background rejection. The diffractive background comprises production of QED diboson, QED dilepton, diffractive WW, double pomeron exchange WW.

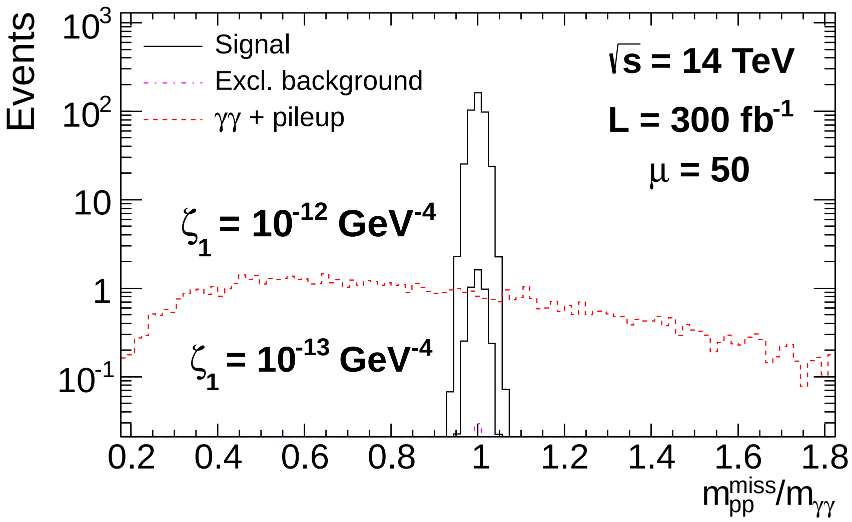
- **Improvement of "standard" LHC methods by studying $pp \to l^{\pm}\nu\gamma\gamma$ (see P. J. Bell, ArXiV:0907.5299) by more than 2 orders of magnitude with 40/300 fb^{-1} at LHC**

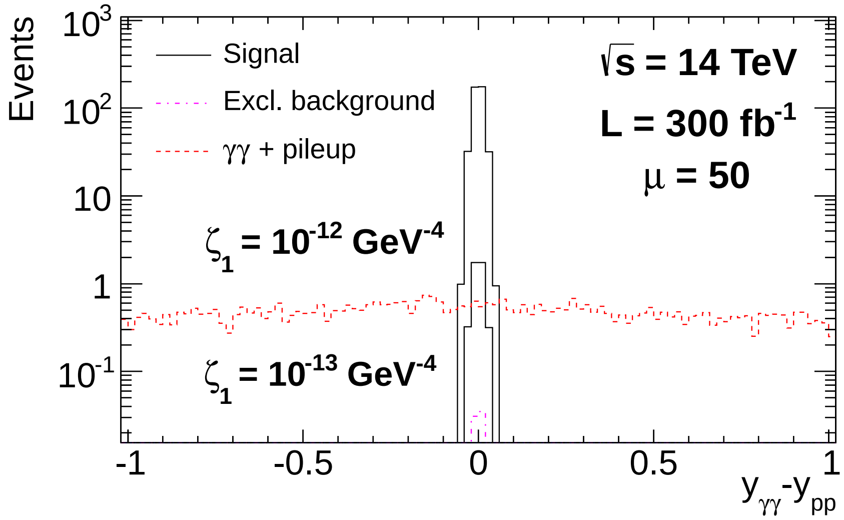
	5σ	95% CL
$\mathcal{L} = 40\ fb^{-1}, \mu = 23$	5.5 10^{-6}	2.4 10^{-6}
$\mathcal{L} = 300\ fb^{-1}, \mu = 46$	3.2 10^{-6}	1.3 10^{-6}

Physics: Search for quartic $\gamma\gamma$ anomalous couplings



- Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- Use forward detectors to suppress background





Search for quartic $\gamma\gamma$ anomalous couplings: Results

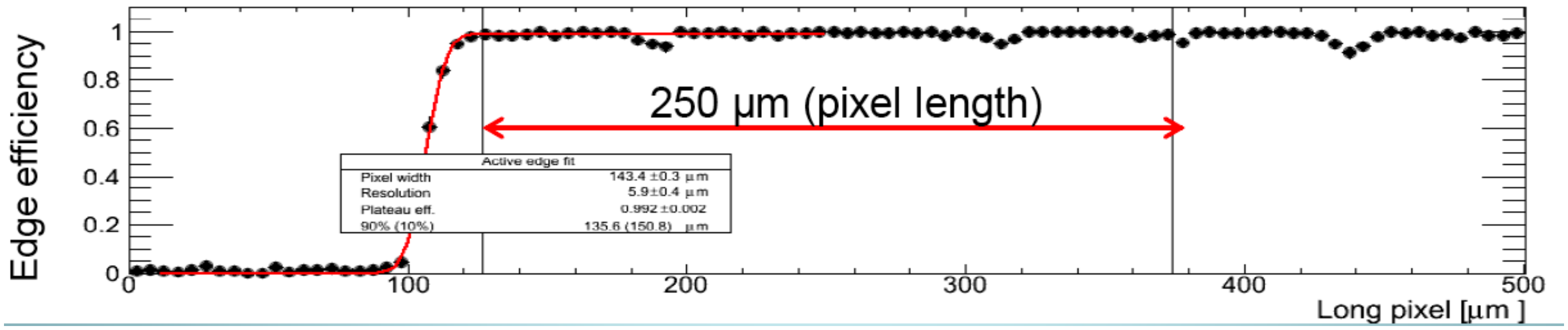
Cut / Process	Signal	Excl.	DPE	e^+e^-, dijet + pile-up	$\gamma\gamma$ + pile-up
$0.015 < \xi < 0.15$, $p_{T1,2} > 50$ GeV	20.8	3.7	48.2	$2.8\ 10^4$	$1.0\ 10^5$
$p_{T1} > 200$GeV, $p_{T2} > 100$ GeV	17.6	0.2	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	16.6	0.1	0.	0.2	1023
$p_{T2}/p_{T1} > 0.95$, $\|\Delta\phi\| > \pi - 0.01$	16.2	0.1	0.	0.	80.2
$\sqrt{\xi_1\xi_2 s} = m_{\gamma\gamma} \pm 3\%$	15.7	0.1	0.	0.	2.8
$\|y_{\gamma\gamma} - y_{pp}\| < 0.03$	15.1	0.1	0.	0.	0.

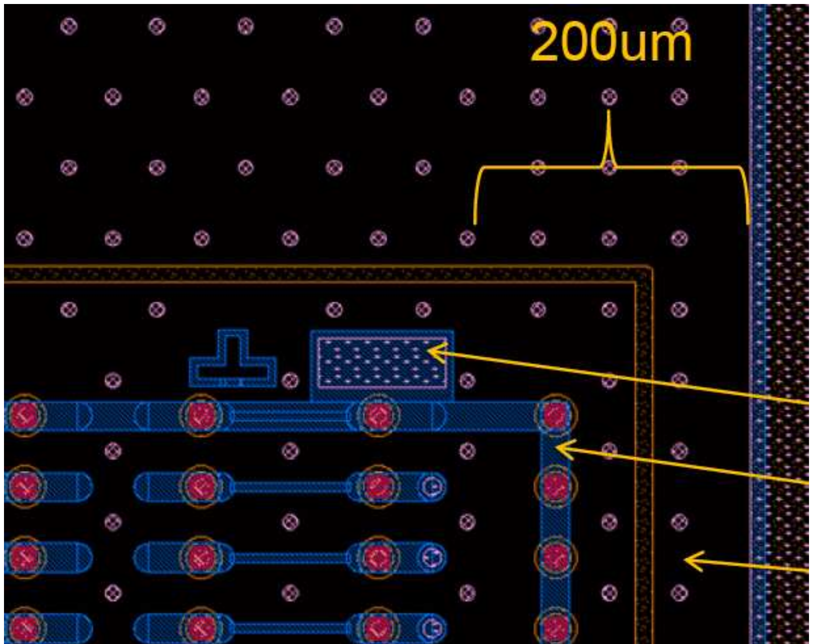
- No background after cuts for 300 fb^{-1} **without needing time detector information**
- Exclusivity cuts needed to suppress backgrounds:
- String theory/grand unification models predict couplings via radions/heavy charged particles/dilatons for instance up to 10^{-14}-10^{-13}
- See S.Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert, ArXiv 1312.5153

Luminosity	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	6000 fb^{-1}
pile-up (μ)	50	50	50	200
coupling (GeV^{-4})	$\geq$ 1 conv. γ 5 σ	$\geq$ 1 conv. γ 95% CL	all γ 95% CL	all γ 95% CL
ζ_1 f.f.	$1 \cdot 10^{-13}$	$7 \cdot 10^{-14}$	$4 \cdot 10^{-14}$	$2 \cdot 10^{-14}$
ζ_1 no f.f.	$3 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$1 \cdot 10^{-14}$	$6 \cdot 10^{-15}$
ζ_2 f.f.	$3 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$8 \cdot 10^{-14}$	$4 \cdot 10^{-14}$
ζ_2 no f.f.	$7 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$1 \cdot 10^{-14}$

Detector I: 3D Si detector

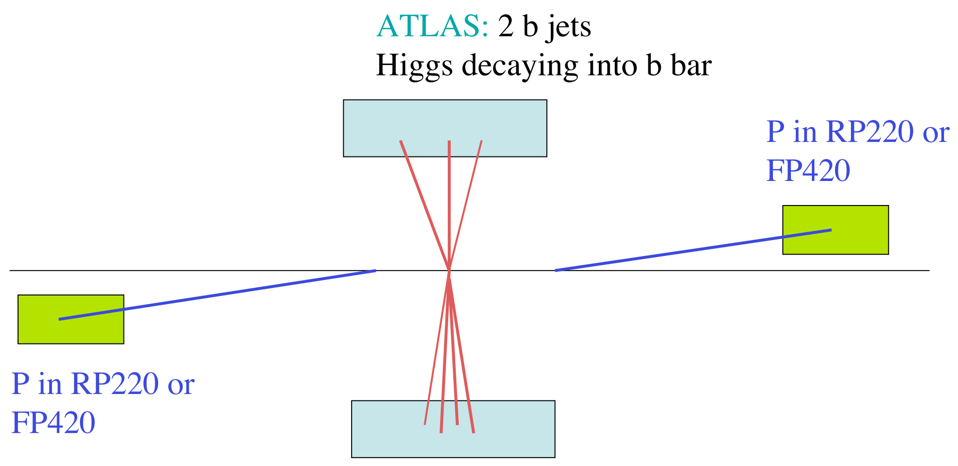
- Key requirements for the Si detector
  - Spatial resolution of 10 (30) μm in x (y) direction over the full detector coverage (2 cm $\times$ 2 cm); Angular resolution of 1 μrad
  - Minimal dead space at the edge and radiation hardness
- Sensors: double-sided 3D 50$\times$250 micron pixel detectors (FBK) with slim-edge dicing (Trento) and CNM 3D pixel detectors with slim-edge dicing (dead zone of 80 microns instead of 250)
- Upgrade with 3D edgeless detectors by 2020: SLAC, Manchester, Oslo, Bergen...

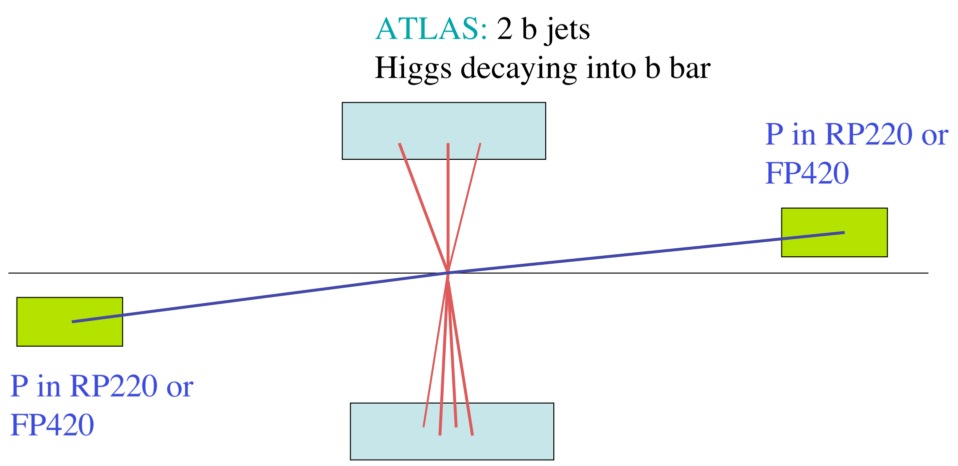




Why do we need timing detectors?

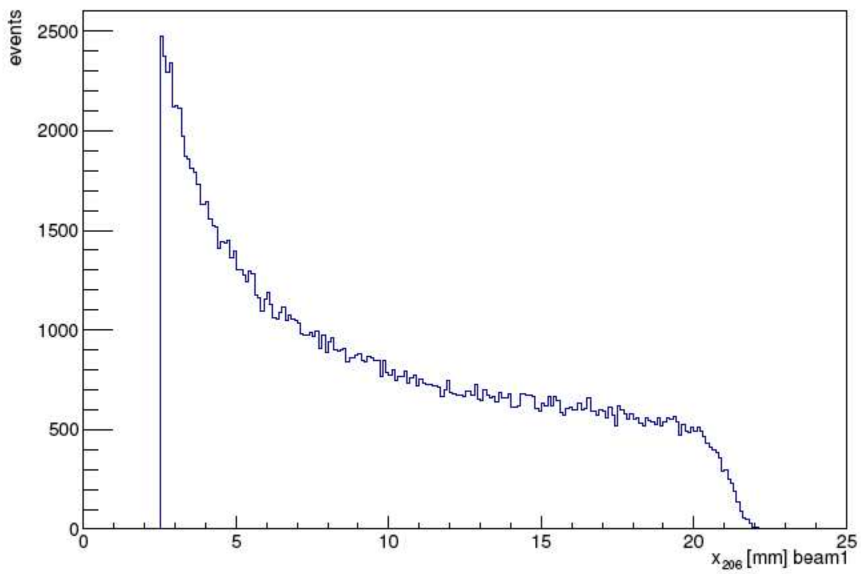
We want to find the events where the protons are related to anomalous event production and not to another soft event (up to 35 events occuring at the same time at the LHC!!!!)

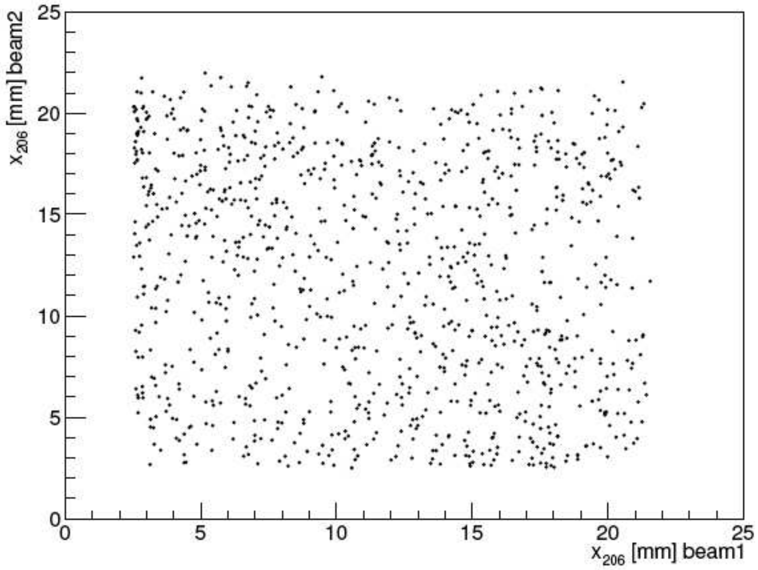




Pile up treatment and Proton distribution in AFP

- Generation of 7 TeV protons (Single diffractive and Double Pomeron Exchange events) with PYTHIA 8
- Transport at 206 metres from the Interaction Point (IP) with FPTRACKER/MADX (program from the LHC beam division allowing transport through the magnets)

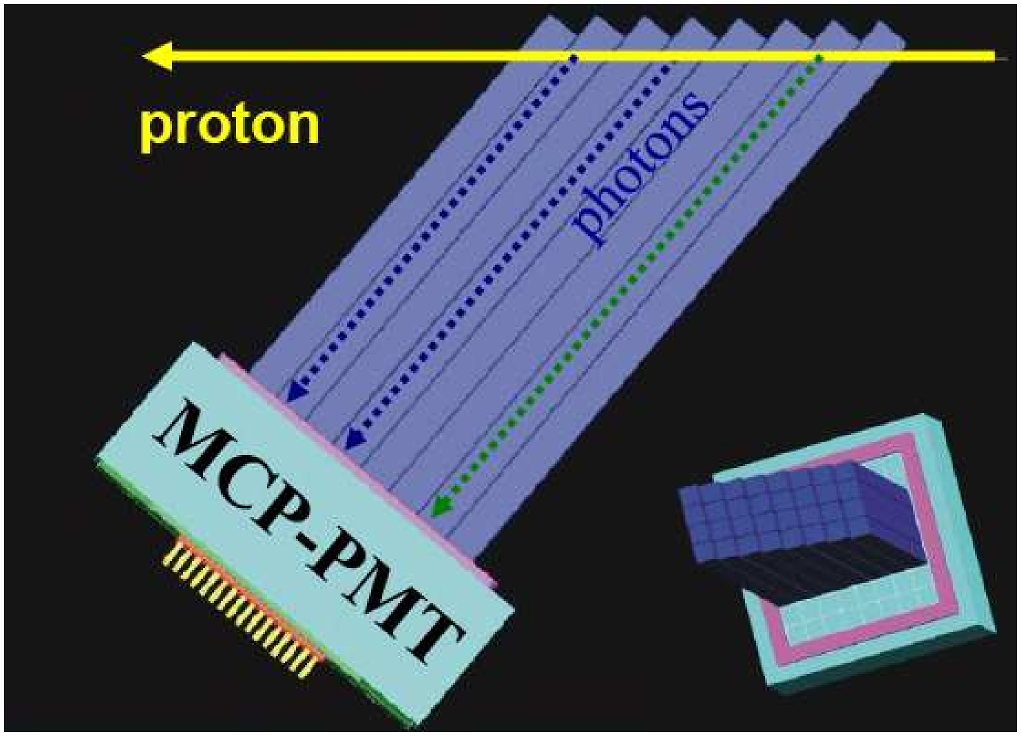




- Proton distribution (X distance from the horizontal axis on one side for SD, and correlations between both x on each side of ATLAS for DPE events)
- Probability for a proton to be tagged (taking into account SD/DPE cross sections) for one bunch crossing: 0.01% (double tag on each side), 1.6% (single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

Detector II: first kind of timing detectors

- Measure the vertex position using proton time-of-flight: suppresses high pile up events at the LHC (50 events in the same bunch crossing), allows to determine if protons originate from main interaction vertex
- 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
- QUARTIC has 4×8 array of quartz bars; Each proton passes through eight bars in one of the four rows and one only needs a 30-40 ps measurement/bar since one can do it 8 times



Timing detectors

- Irradiance and Texas Collaboration: improve lifetime of MCP-PMTs: generation 2 25 μm pore Planacon, resolution of the order of 20 ps; similar results with Hamamatsu with orthogonal ion barrier approach
- Resolution of 14-15 ps achieved in beam tests
- Difficulty to get full pixelisation with this detector close to the beam (important for high pile up beyond 2020)
- See talks by Andrew/Michael/Jim

Component	δt(ps) Current	δt(ps) Projected (8 ch +cable)	Improvement	δt(ps) Phase 0 (8 channels)
Radiator (fused silica bar) ~10 pe's	22	22	Optimize radiator	17
MCP-PMT (64 channel 25 um Planacon)	20	20	10 um tube	15
CFD	5	5	-	5
HPTDC	16	16	-	15
Reference Clock	-	3	-	3
Total/bar	34	34		28
Cable		15%	retune CFD	5%
Total/ detector	14	14	-	10

Different QUARTIC detector scenarii

- 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

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

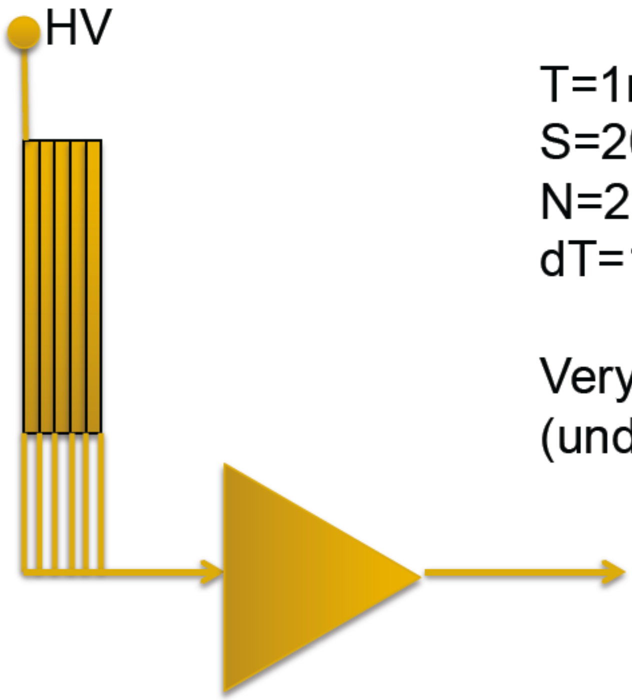
Bar	11	12	13	14	15	16	17	18	19	20
$\mu = 50$	0.023	0.022	0.022	0.021	0.020	0.020	0.019	0.017	0.010	0.001
$\mu = 100$	0.034	0.032	0.032	0.030	0.029	0.028	0.027	0.024	0.015	0.001
$\mu = 300$	0.041	0.040	0.039	0.037	0.036	0.035	0.033	0.030	0.018	0.001

Pixel solution I: Thin diamond sensors

See talk by Gabriele

INFN Roma Tor-Vergata group (R. Cardarelli et al.):

- Sensor thinning means faster signal and less polarization effects
- Using 100 um planar sensors
- Packaging 5 layers in series (under test, results soon, test beam co



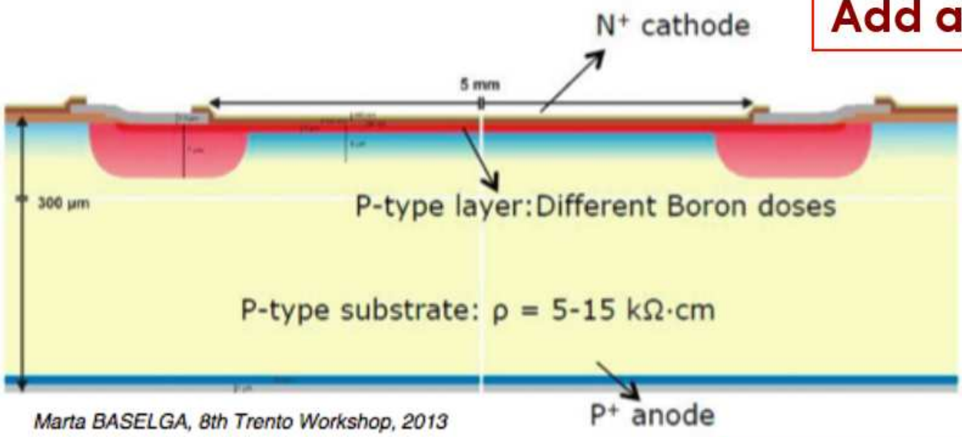
T=1ns
S=20000 e-
N=200e-
dT=10 ps !!!

Very good electronics neede
(under development)

Pixel solution II: Timing with silicon detectors

See talk by Nicolo

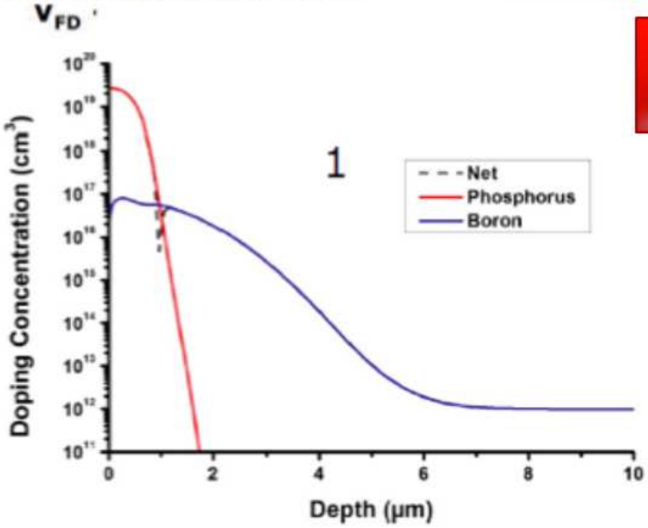
Add a layer of doping to obtain gain



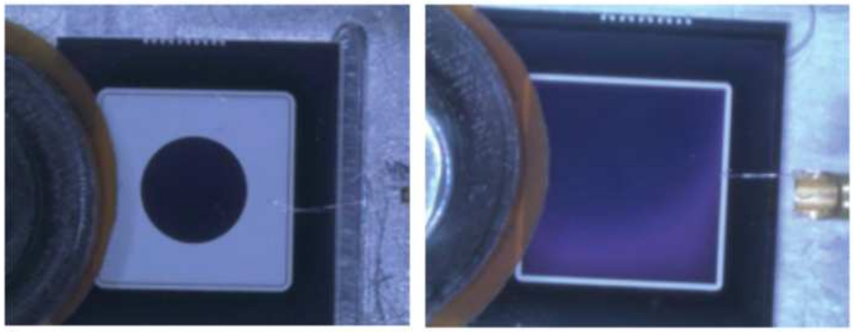
Marta BASELGA, 8th Trento Workshop, 2013

n^{++} - p^{+} - p – p^{+} stucture

$10^{16\text{-}17}$ cm^{-3} – much larger than in the bulk. Large N_{eff} provokes avalanche multiplication by impact ionization.

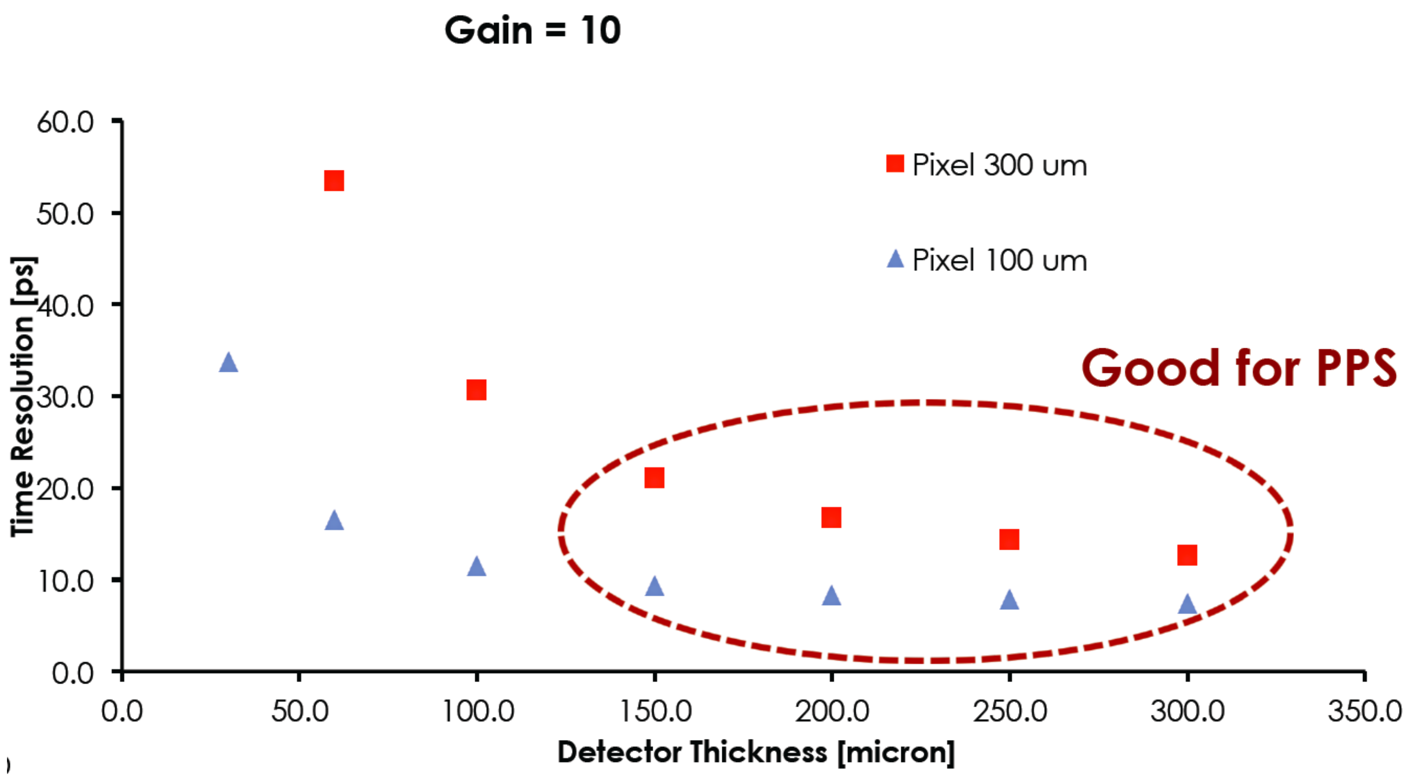


Prototype Detectors exist!



Pixel solution II: Timing with silicon detectors

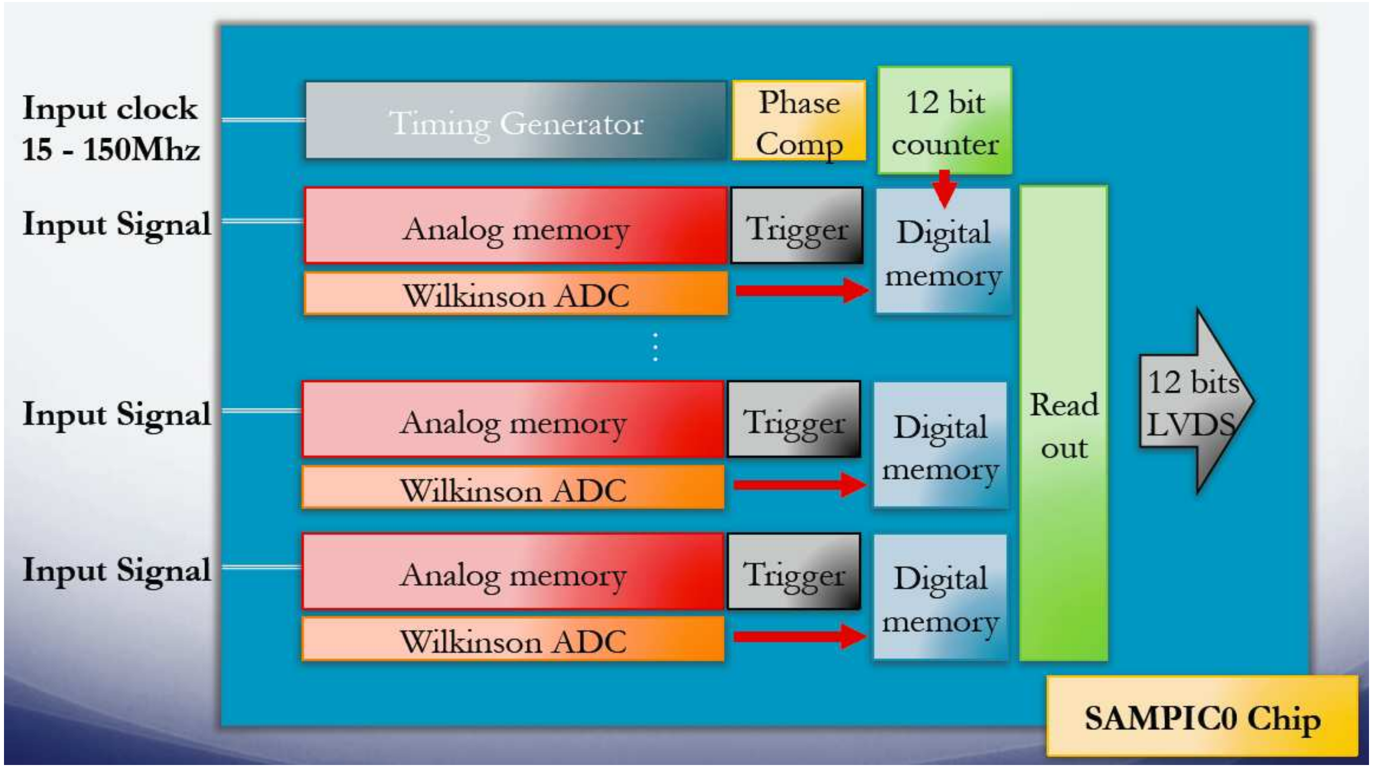
Resolution for 100 and 300 μm pixel



Excellent time resolution requires **thicker detectors**

Readout Electronics: SAMPIC chip

- Development of a fast timing chip in Saclay SAMPIC:
  - Uses waveform sampling method
  - Sub 10 ps timing, 1GHz input bandwidth, no dead time for targeted data taking at 2 Gbit/s
  - 10 bit Wilkinson on chip for analog to digital conversion; Wilkinson digitisation at 2Gsamples/s
  - Low cost: 10 $ per channel
- See talk by Eric, Dominique



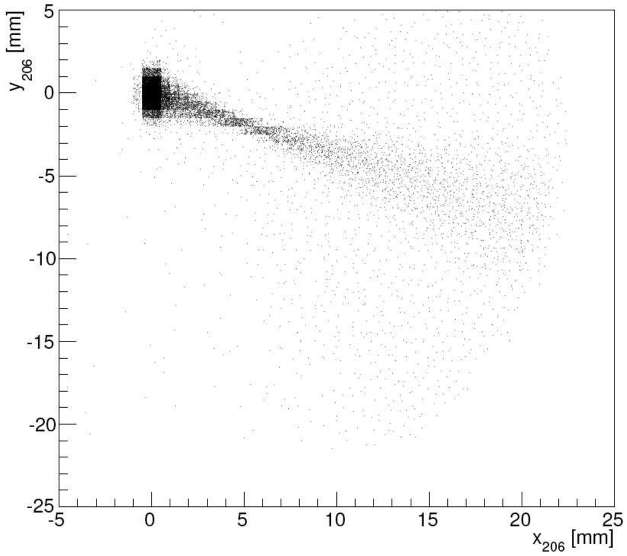
Inefficiencies for pixel solution

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



Conclusion on pile up studies

- Scenario with 7 bars leads to small but non negligible inefficiencies, up to about 20% for the cloesest bar for a pile up of 100, and of $\sim 10\%$ further away
- Scenarii with 10 or 20 bars lead to smaller inefficiencies especially far away from the beam of $\sim 3\%$
- Pixel solution does not lead to smaller inefficiencies close to the beam since events do not spread much in (x, y) plane
- However, pixel solution is better from beam-induced background (beam wall...) that could lead to a localised background in the detector
- Development of SAMPIC readout chip useful for pixel detectors

Conclusion

- AFP/PPS detectors to be installed in 2015 Winter shutdown
- AFP/PPS aims at detecting intact protons in ATLAS: increases the physics potential of ATLAS (QCD, search for extra-dimensions in the universe via anomalous couplings between γ, W, Z...)
- Detector: Movable beam pipe; 3D Silicon position detectors (10-15 μm precision); Timing detectors (Quartz or diamond detector, SAMPIC electronics)
- Many applications especially in PET imaging (Manjit Dosanjh)