Anomalous quartic and trilinear W, Z and γ couplings at the LHC

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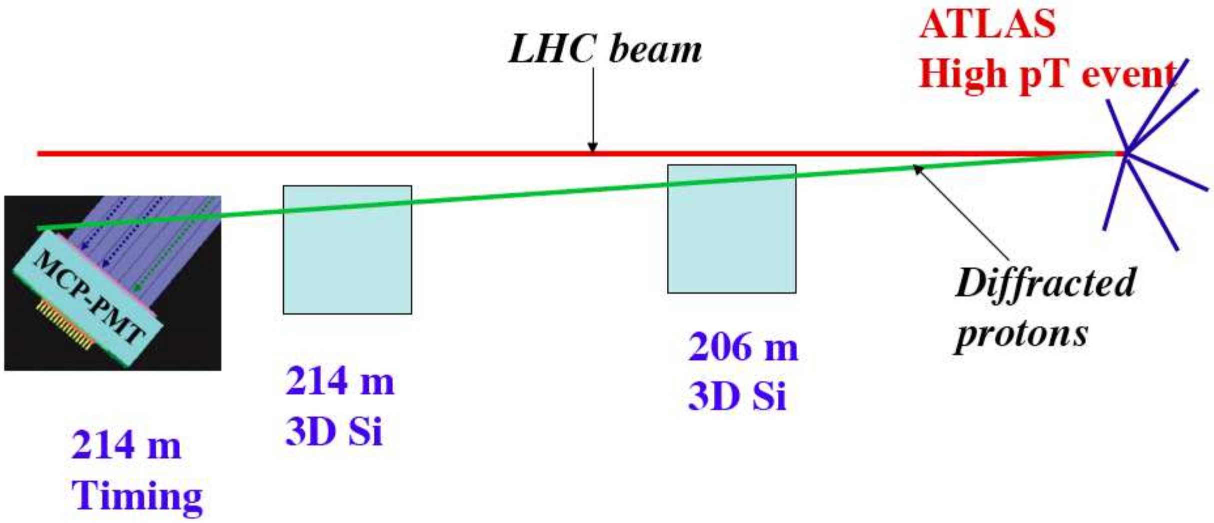
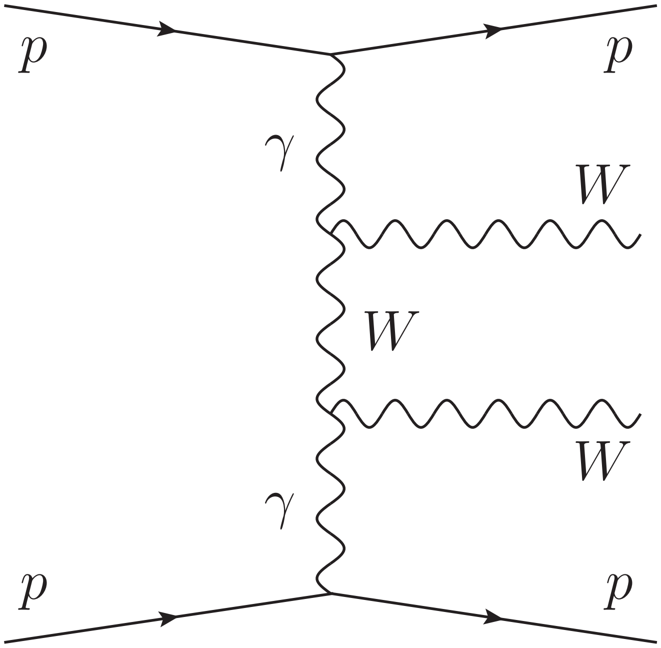
Contents:

- Proton tagging at the LHC
- Anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$
- Anomalous $\gamma\gamma W$ couplings



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

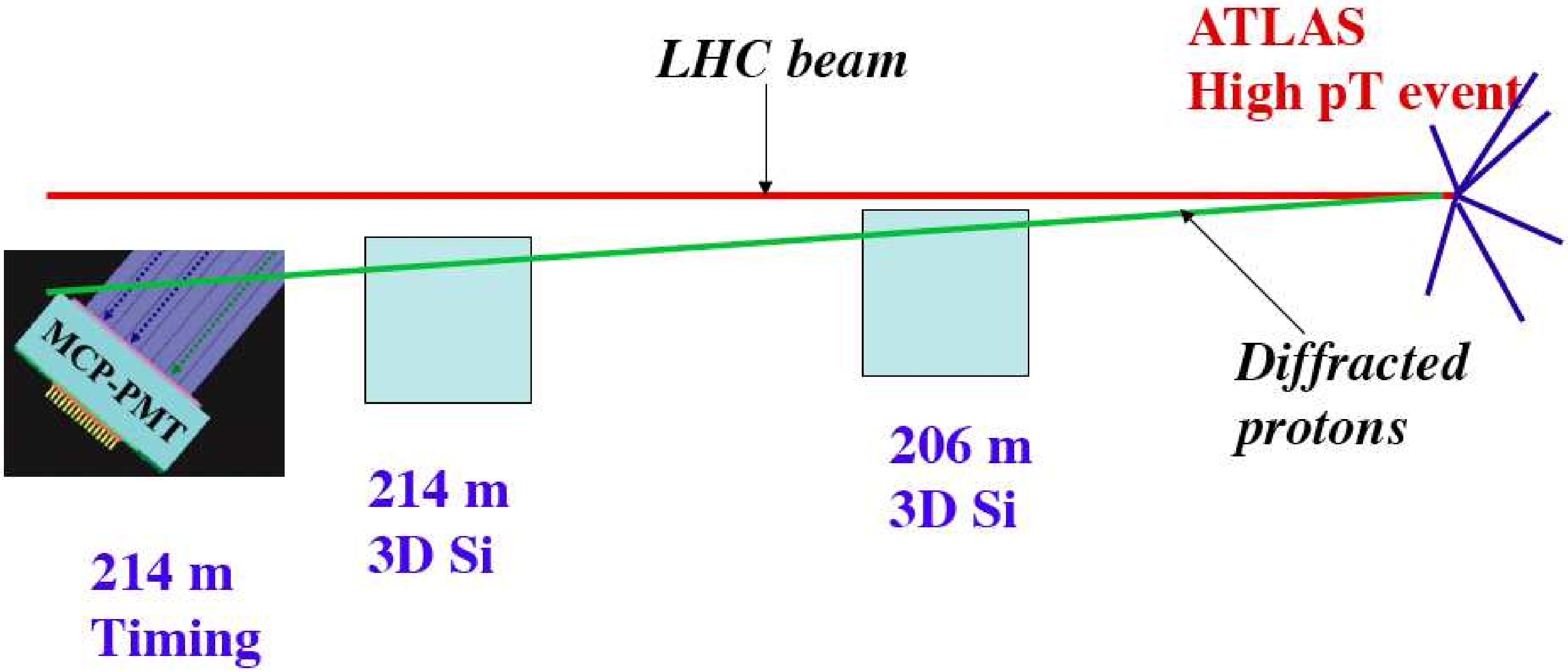


- Study of the process: $pp \to ppWW$
- Standard Model: $\sigma_{WW} = 95.6$ fb, $\sigma_{WW}(W = M_X > 1 TeV) = 5.9$ fb
- Process sensitive to anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$; motivated by studying in detail the mechanism of electroweak symmetry breaking, predicted by extradim. models
- Many additional anomalous couplings to be studied involving Higgs bosons (dimension 8 operators); $\gamma\gamma$ specially interesting (C. Grojean, S. Fichet, G. von Gersdorff)
- 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, in print in Phys. Rev. D

Forward Physics Monte Carlo (FPMC)

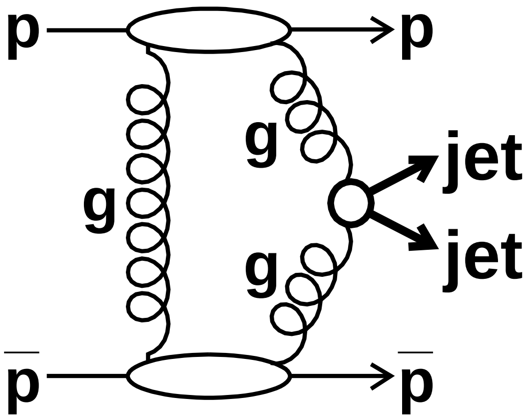
- FPMC (Forward Physics Monte Carlo): implementation of all diffractive/photon induced processes
- List of processes
  - two-photon exchange
  - single diffraction
  - double pomeron exchange
  - central exclusive production
- Inclusive diffraction: Use of diffractive PDFs measured at HERA, with a survival probability of 0.03 applied for LHC
- Central exclusive production: Higgs, jets...
- FPMC manual (see M. Boonekamp, A. Dechambre, O. Kepka, V. Juranek, C. Royon, R. Staszewski, M. Rangel, ArXiv:1102.2531)
- Survival probability: 0.1 for Tevatron (jet production), 0.03 for LHC, 0.9 for γ-induced processes
- Output of FPMC generator interfaced with the fast simulation of the ATLAS detector in the standalone ATLFast++ package

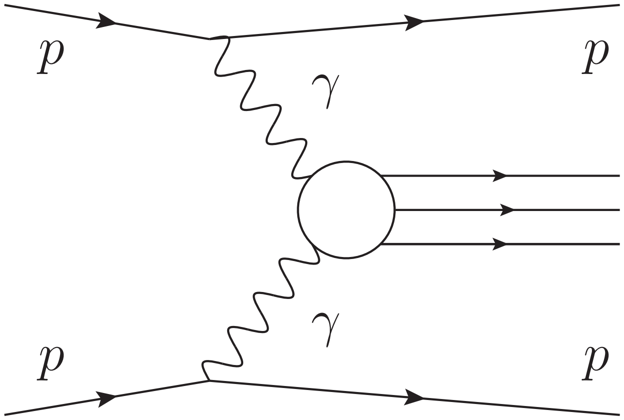
What is AFP/PPS?

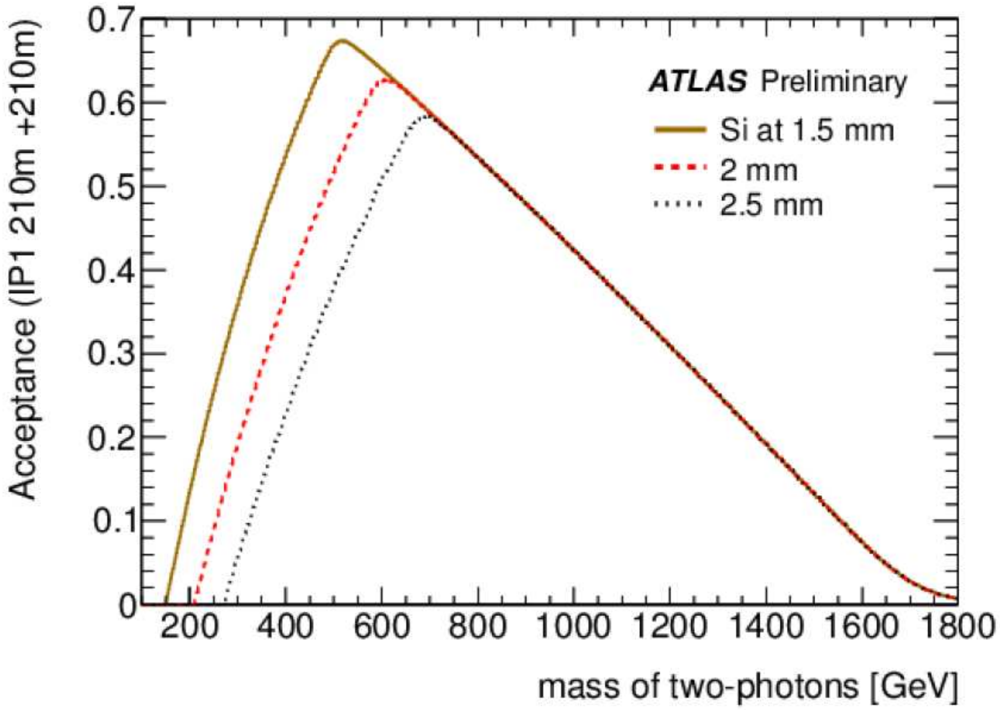


- Tag and measure protons at ±210 m: AFP in ATLAS, PPS in CMS/Totem
- AFP detectors: measure proton position (Silicon detectors) and time-of-flight (timing detectors)

AFP/PPS acceptance in total mass







- Assume protons to be tagged at 210-220 m
- Sensitivity to high mass central system, X, as determined using AFP
- Very powerful for exclusive states: kinematical constraints coming from AFP proton measurements

Quartic anomalous gauge couplings

- Quartic gauge anomalous $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings parametrised by a_0^W, a_0^Z, a_C^W, a_C^Z

$$\mathcal{L}_6^0 \sim \frac{-e^2}{8}\frac{a_0^W}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W_\alpha^- - \frac{e^2}{16\cos^2(\theta_W)}\frac{a_0^Z}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}Z^\alpha Z_\alpha$$

$$\mathcal{L}_6^C \sim \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W_\beta^- + W^{-\alpha}W_\beta^+) - \frac{e^2}{16\cos^2(\theta_W)}\frac{a_C^Z}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}Z^\alpha Z_\beta$$

- Anomalous parameters equal to 0 for SM
- Best limits before LHC from LEP, OPAL (Phys. Rev. D 70 (2004) 032005) of the order of 0.02-0.04, for instance $-0.02 < a_0^W < 0.02$ GeV^{-2}
- New limits from D0/CMS: 1.5 10^{-4} (2.5 10^{-3}), and 5 10^{-4} (9.3 10^{-3} for CMS (D0) for a_0^W and a_c^W with a form factor at 500 GeV
- Dimension 6 operators → violation of unitarity at high energies

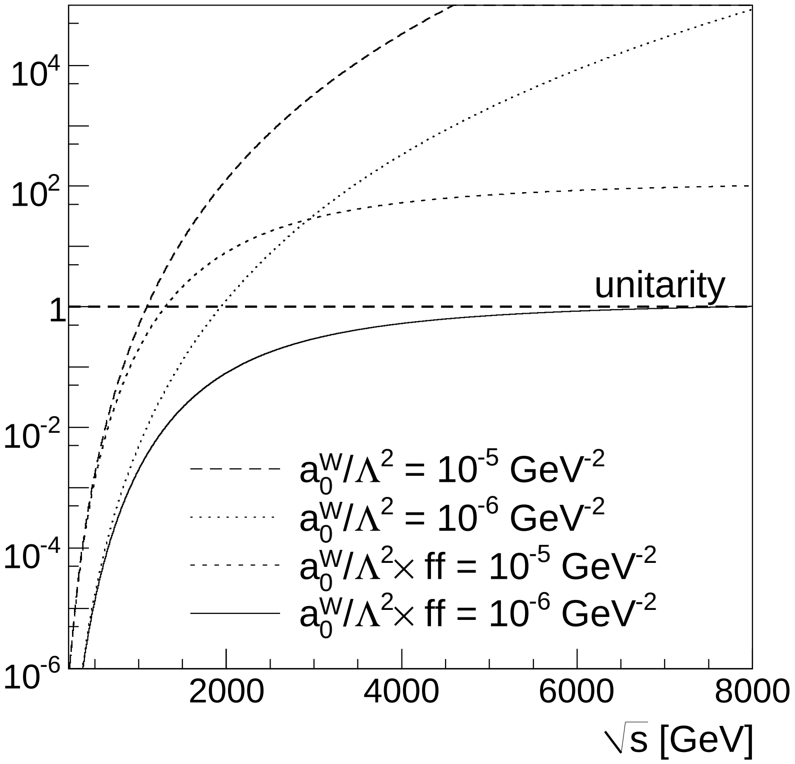
Quartic anomalous gauge couplings: form factors

- Unitarity bounds can be computed (Eboli, Gonzales-Garcia, Lietti, Novaes):

$$4\left(\frac{\alpha a s}{16}\right)^2\left(1-\frac{4M_W^2}{s}\right)^{1/2}\left(3-\frac{s}{M_W^2}+\frac{s^2}{4M_W^4}\right)\leq 1$$

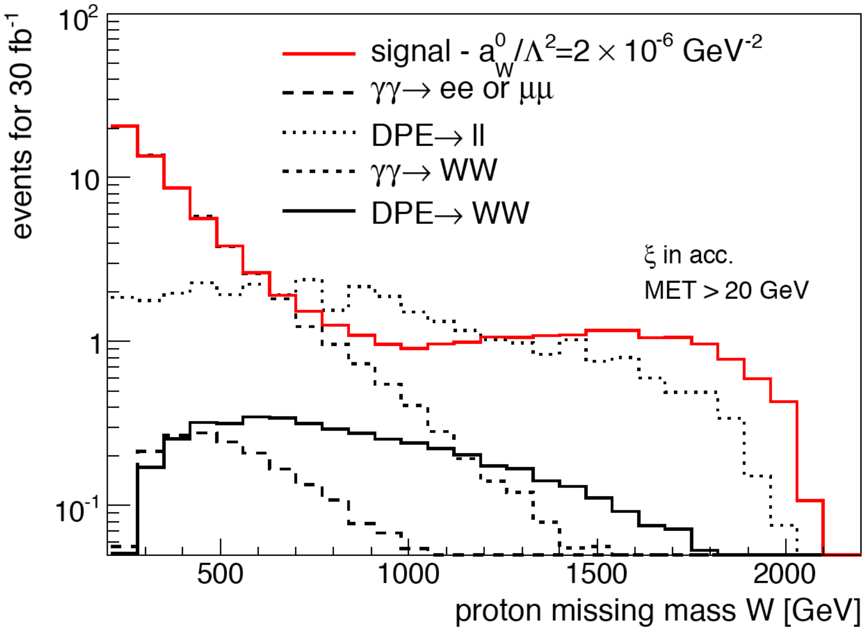
  where $a = a_0/\Lambda^2$

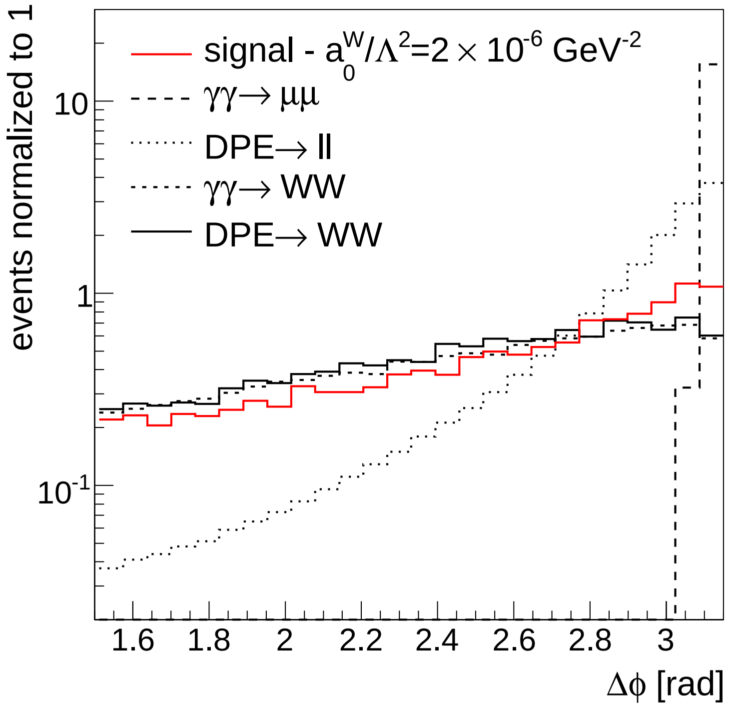
- Introducing form factors to avoid quadratical divergences of scattering amplitudes due to anomalous couplings in conventional way: $a_0^W/\Lambda^2 \rightarrow \frac{a_0^W/\Lambda^2}{(1+W\gamma\gamma/\Lambda_{cutoff})^2}$ with $\Lambda_{cutoff} \sim 2$ TeV, scale of new physics
- For $a_0^W \sim 10^{-6}$ GeV^{-2}, no violation of unitarity



Strategy to select quartic anomalous gauge couplings events

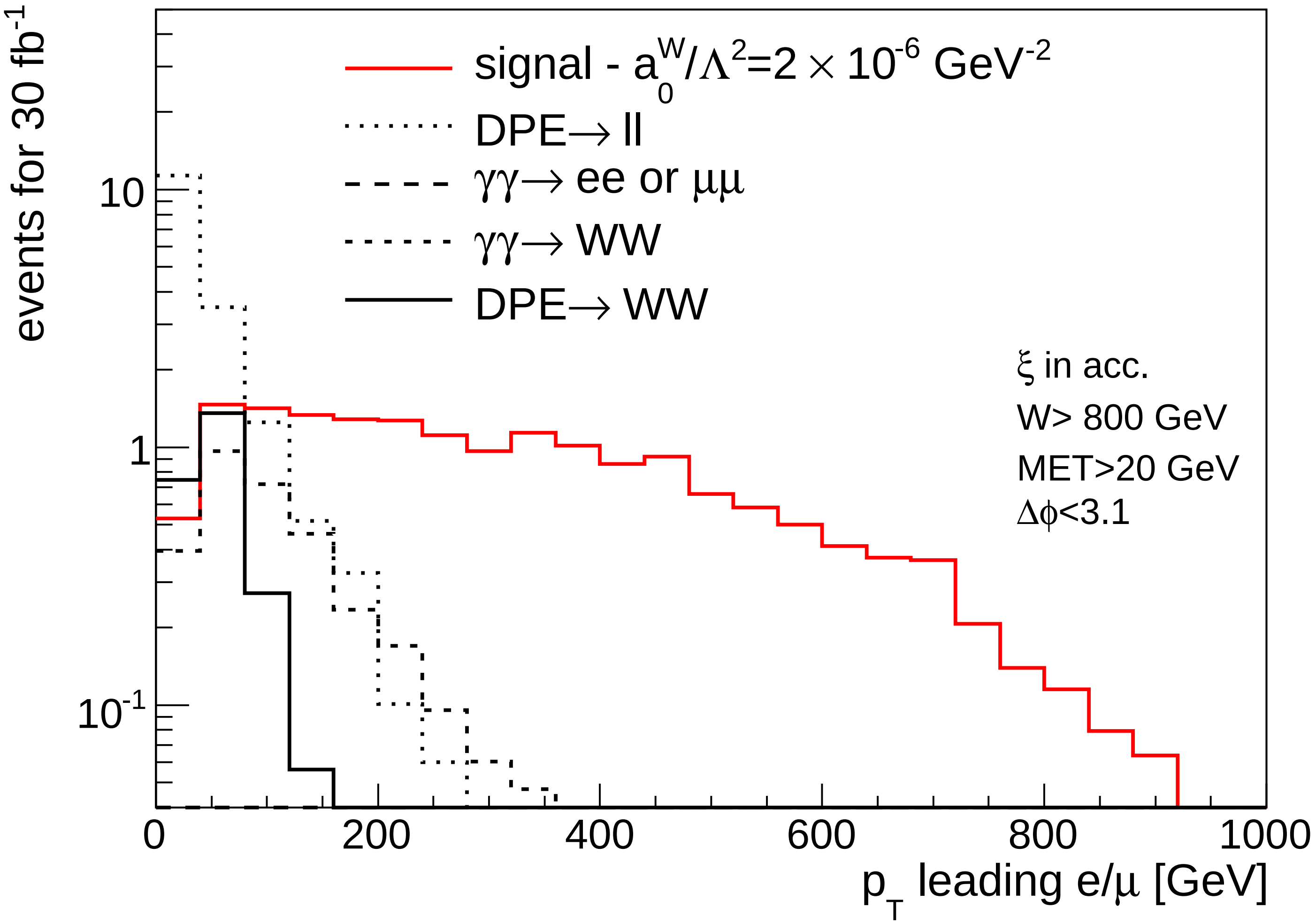
- p_T of the leading lepton: request high p_T lepton to remove background
- Missing E_T distribution: natural to be requested for W pair production
- Diffractive mass computed using the forward proton detectors $\sqrt{\xi_1 \xi_2 S}$: request high mass objects to be produced
- $\Delta\Phi$ between both leptons: avoid back-to-back leptons





Quartic anomalous gauge couplings

Distribution of the leading lepton p_T after all cuts (proton tagged, $\not\!\!E_T$, diffractive mass, $\Delta\Phi$) except the cut on leading lepton p_T



Quartic anomalous gauge couplings

Background events for 30 fb^{-1}

cut / process	$\gamma\gamma \to ll$	$\gamma\gamma \to WW$	DPE$\to ll$	DPE$\to WW$
$p_T^{lep1,2} > 10$ GeV	50619	99	18464	8.8
$0.0015 < \xi < 0.15$	21058	89	11712	6.0
$\not{E}_T > 20$ GeV	14.9	77	36	4.7
$W > 800$ GeV	0.42	3.2	16	2.5
$M_{ll} \notin < 80, 100 >$	0.42	3.2	13	2.5
$\Delta\phi < 3.13$	0.10	3.2	12	2.5
$p_T^{lep1} > 160$ GeV	0	0.69	0.20	0.024

Signal events for 30 fb^{-1}

cut / couplings (with f.f.)	$a_0^W/\Lambda^2 = 5.4 \cdot 10^{-6}$	$a_C^W/\Lambda^2 = 20 \cdot 10^{-6}$
$p_T^{lep1,2} > 10$ GeV	202	200
$0.0015 < \xi < 0.15$	116	119
$\not{E}_T > 20$ GeV	104	107
$W > 800$ GeV	24	23
$M_{ll} \notin < 80, 100 >$	24	23
$\Delta\phi < 3.13$	24	22
$p_T^{lep1} > 160$ GeV	17	16

Reach at LHC

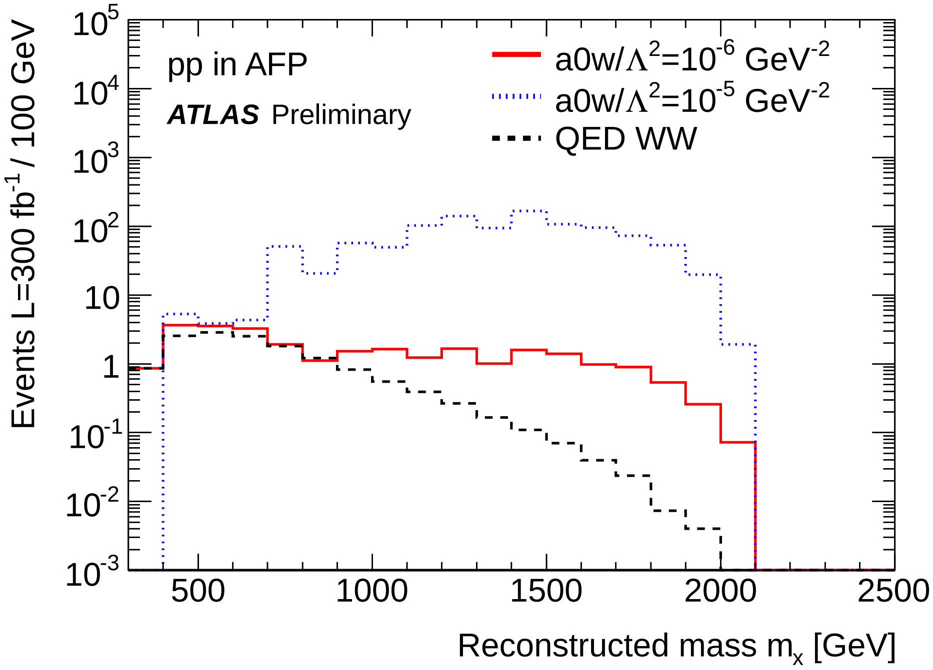
Reach at high luminosity on quartic anomalous coupling

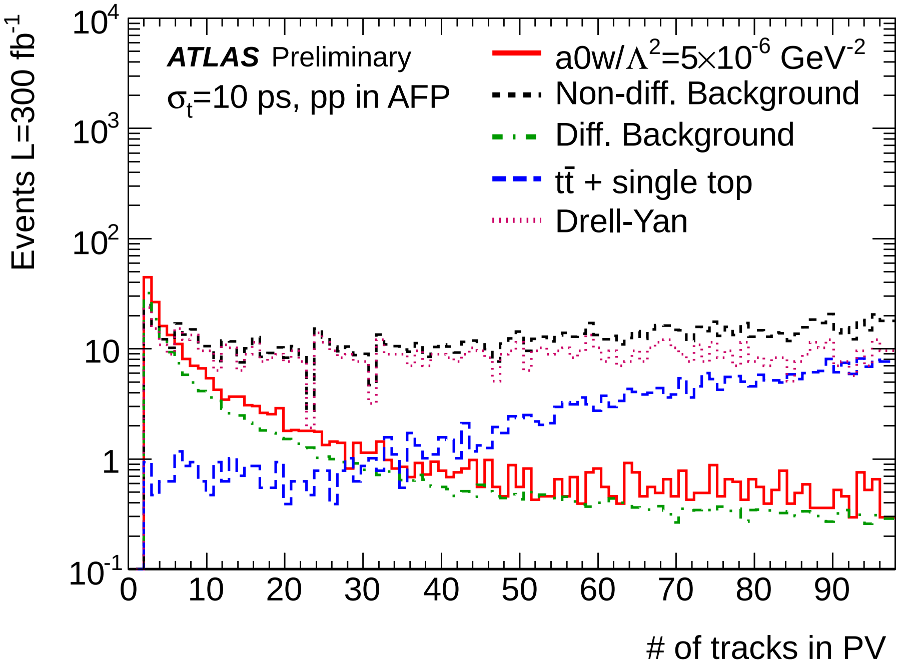
Couplings	OPAL limits	Sensitivity @ $\mathcal{L} = 30$ (200) fb^{-1}	
	[GeV^{-2}]	5σ	95% CL
a_0^W/Λ^2	[-0.020, 0.020]	5.4 10^{-6} (2.7 10^{-6})	2.6 10^{-6} (1.4 10^{-6})
a_C^W/Λ^2	[-0.052, 0.037]	2.0 10^{-5} (9.6 10^{-6})	9.4 10^{-6} (5.2 10^{-6})
a_0^Z/Λ^2	[-0.007, 0.023]	1.4 10^{-5} (5.5 10^{-6})	6.4 10^{-6} (2.5 10^{-6})
a_C^Z/Λ^2	[-0.029, 0.029]	5.2 10^{-5} (2.0 10^{-5})	2.4 10^{-5} (9.2 10^{-6})

- Improvement of CMS sensitivity by almost 2 orders of magnitude with 30/200 fb^{-1} at LHC
- Reaches the values predicted by extradimension models, see E. Chapon, O. Kepka, C. Royon, Phys. Rev. D81 (2010) 074003 for more details

Anomalous couplings studies in WW events: full simulation

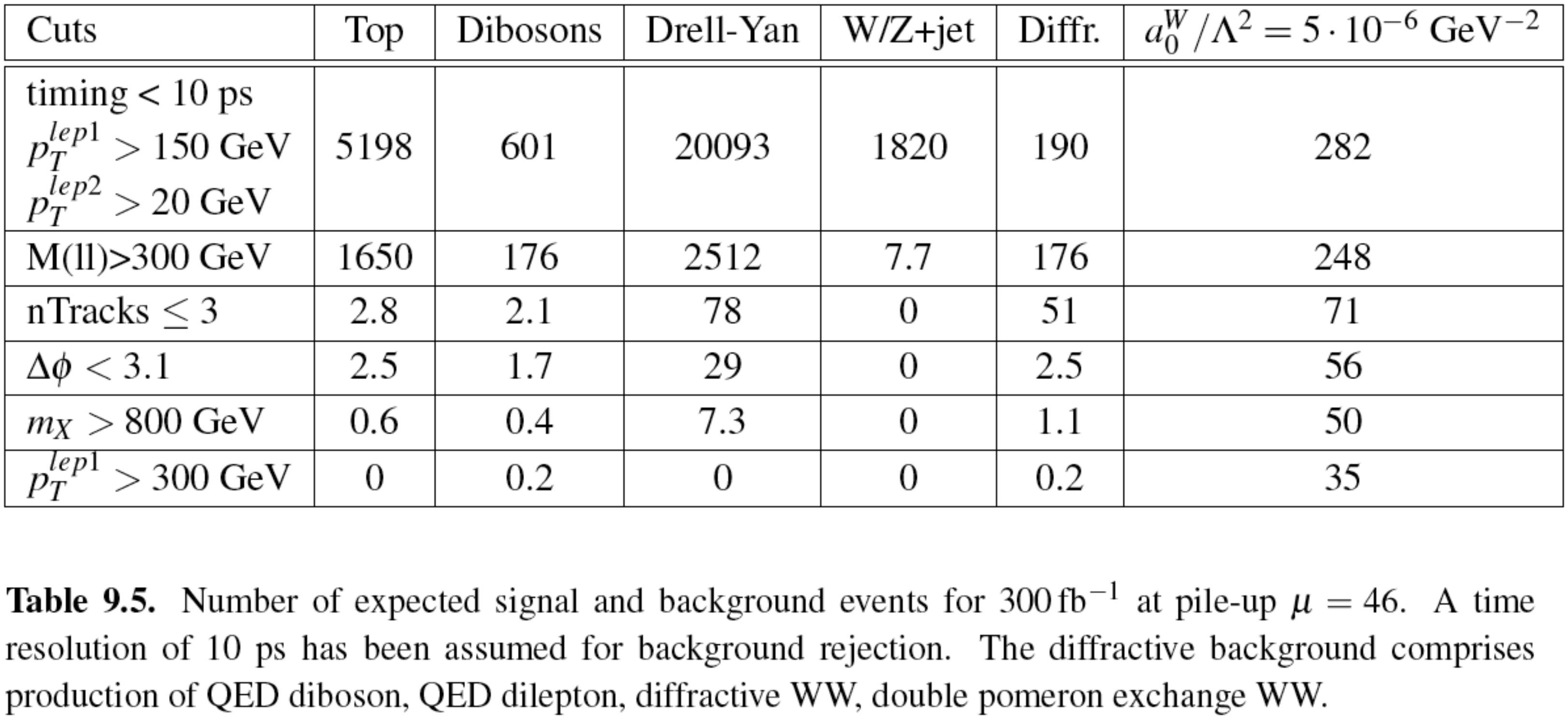
- Reach on anomalous couplings alos studied using a full simulation of the ATLAS detector, including all pile-up effects; only leptonic decays of Ws are considered
- Signal appears at high lepton p_T and dilepton mass (central ATLAS) and high diffractive mass (reconstructed using forward detectors)
- Cut on the number of tracks fitted to the primary vertex: very efficient to remove remaining pile-up after requesting a high mass object to be produced (for signal, we have two leptons coming from the W decays and nothing else)





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 $pp \rightarrow l^{\pm}\nu\gamma\gamma$ (see P. J. Bell, ArXiV:0907.5299) by about 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}

Trilinear anomalous gauge couplings

- Lagrangian with trilinear gauge $WW\gamma$ anomalous couplings λ^γ and $\Delta\kappa^\gamma$

$$\begin{aligned}\mathcal{L} \sim\; & (W^\dagger_{\mu\nu} W^\mu A^\nu - W_{\mu\nu} W^{\dagger\mu} A^\nu) \\ & + (1 + \Delta\kappa^\gamma) W^\dagger_\mu W_\nu A^{\mu\nu} + \frac{\lambda^\gamma}{M_W^2} W^\dagger_{\rho\mu} W^\mu{}_\nu A^{\nu\rho}\end{aligned}$$

- Present limits on trilinear gauge anomalous couplings:
  - From LEP: $-0.098 < \Delta\kappa^\gamma < 0.101$; $-0.044 < \lambda^\gamma < 0.047$ (Inconvenient: mixture of γ and Z exchanges in $e^+e^- \rightarrow WW$)
  - From Tevatron: $-0.51 < \Delta\kappa^\gamma < 0.51$; $-0.12 < \lambda^\gamma < 0.13$ (direct limits)
- Same strategy as for quartic anomalous couplings with the caveat that the signal appears at high mass for λ^γ, and $\Delta\kappa^\gamma$ only modifies the normalisation and the low mass events have to be retained:
  - for $\Delta\kappa^\gamma$:

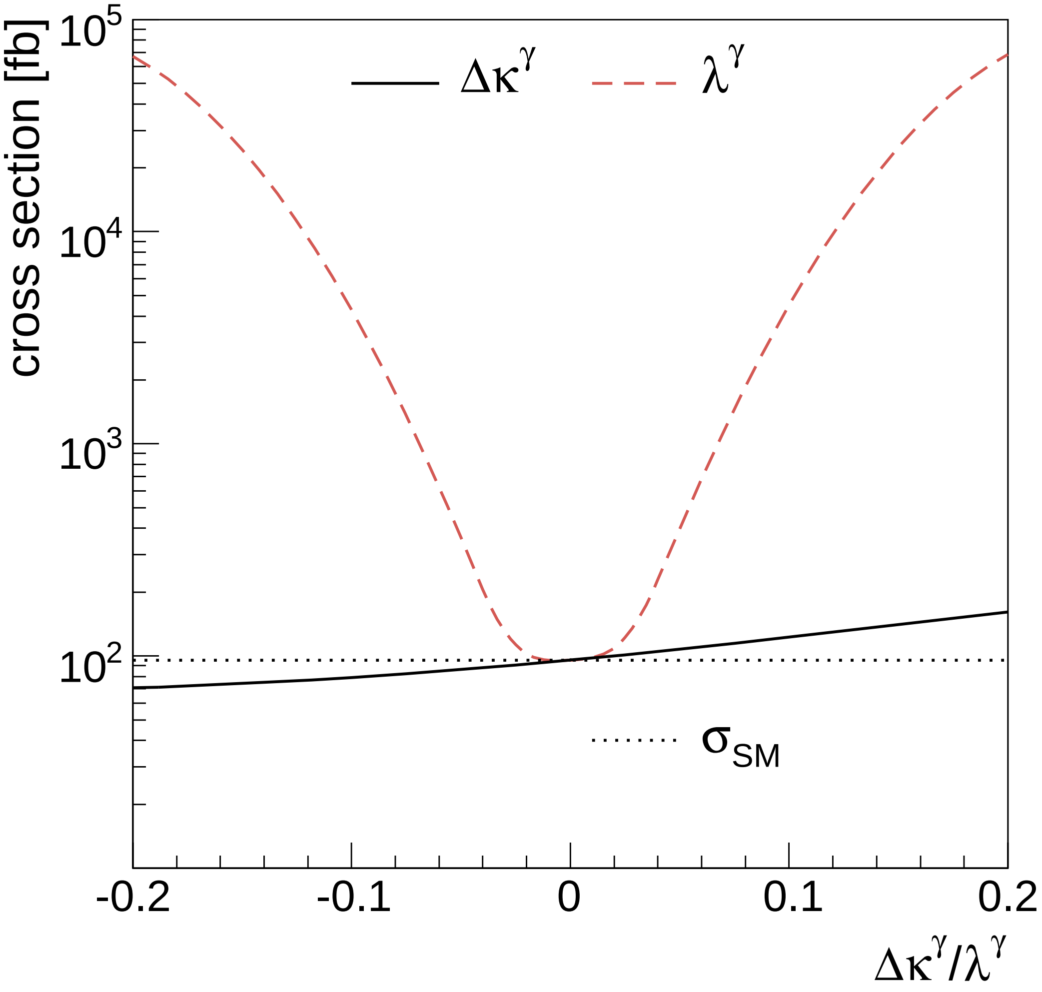
$$\begin{aligned}& p_T^{lep1} > 25 \text{ GeV} \;,\; p_T^{lep2} > 10 \text{ GeV} \;,\; 0.0015 < \xi < 0.15,\; \not{E}_T > 20 \text{ Ge} \\ & W > 160 \text{ GeV} \;,\; \Delta\phi < 2.7,\; W < 500 \text{ GeV}\end{aligned}$$

  - for λ^γ:

$$\begin{aligned}& p_T^{lep1} > 160 \text{ GeV} \;,\; p_T^{lep2} > 10 \text{ GeV} \;,\; 0.0015 < \xi < 0.15,\; \not{E}_T > 20 \text{ G} \\ & W > 800 \text{ GeV} \;,\; M_{ll} \notin \langle 80, 100\rangle \, GeV,\; \Delta\phi < 3.13 rad\end{aligned}$$

Anomalous $WW\gamma$ triple gauge coupling

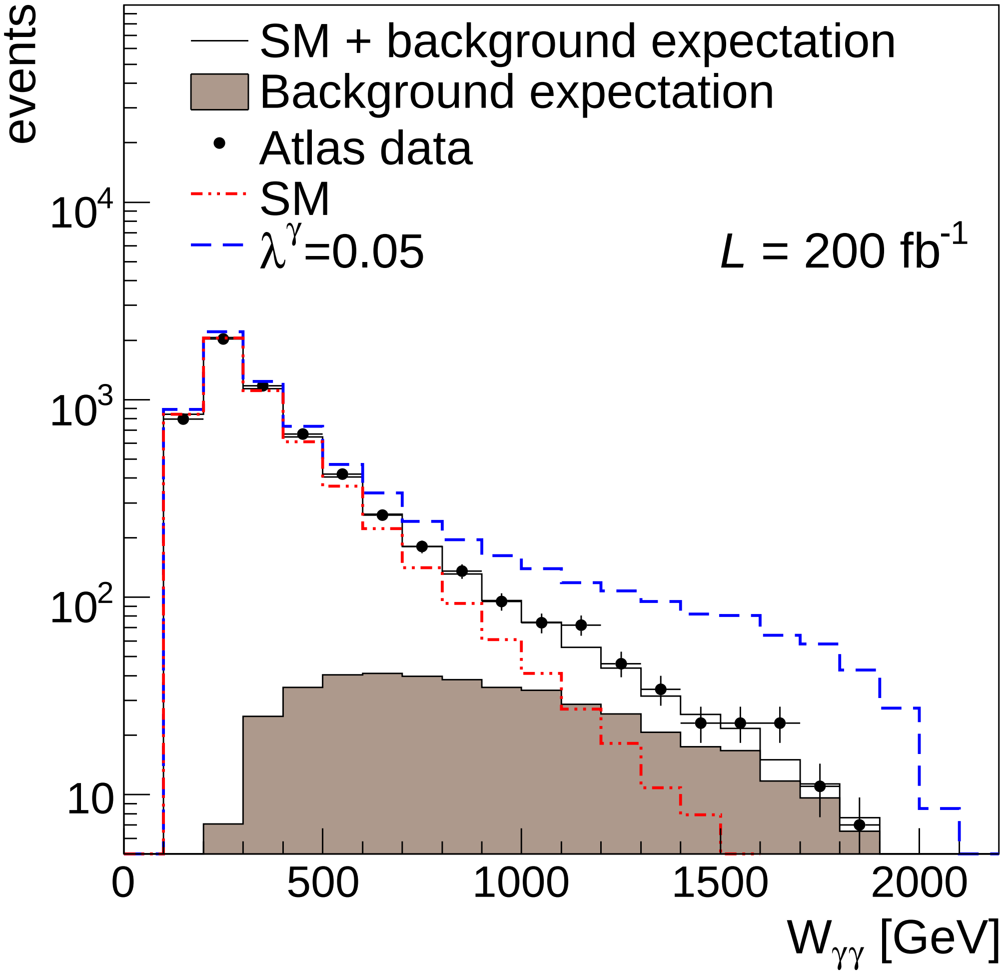
Different behaviour of the cross section as a function of anomalous couplings



Measurement of WW events at high luminosities at LHC, $2W$ events and protons tagged in forward detectors

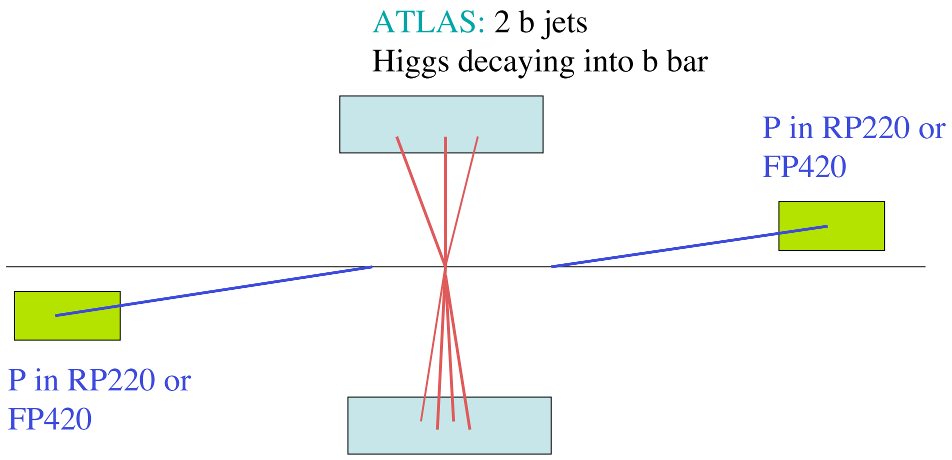
Reach on anomalous coupling

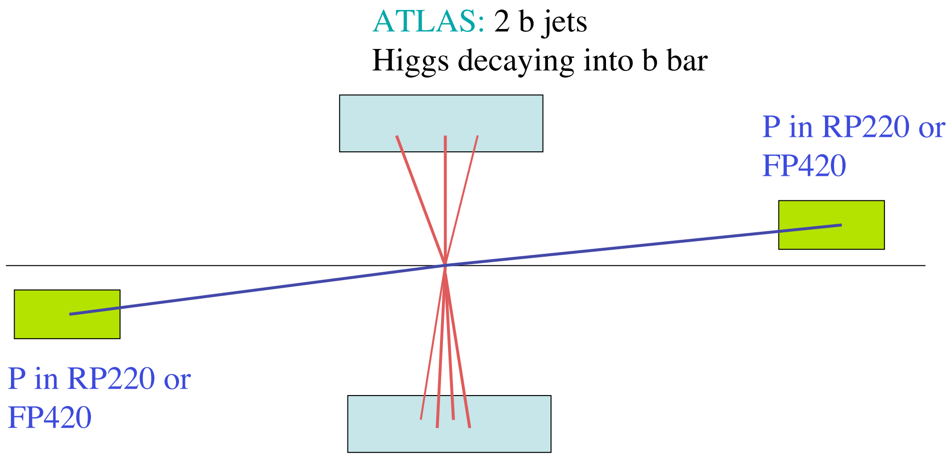
- Reach on anomalous coupling at the LHC using a luminosity of 200 fb^{-1}
  - 5σ discovery: $-0.26 < \Delta\kappa^\gamma < 0.16$; $-0.053 < \lambda^\gamma < 0.049$
  - 95% CL limit: $-0.096 < \Delta\kappa^\gamma < 0.057$; $-0.023 < \lambda^\gamma < 0.027$,
- One of the best reaches before ILC, which can be improved using semi-leptonic decays of Ws



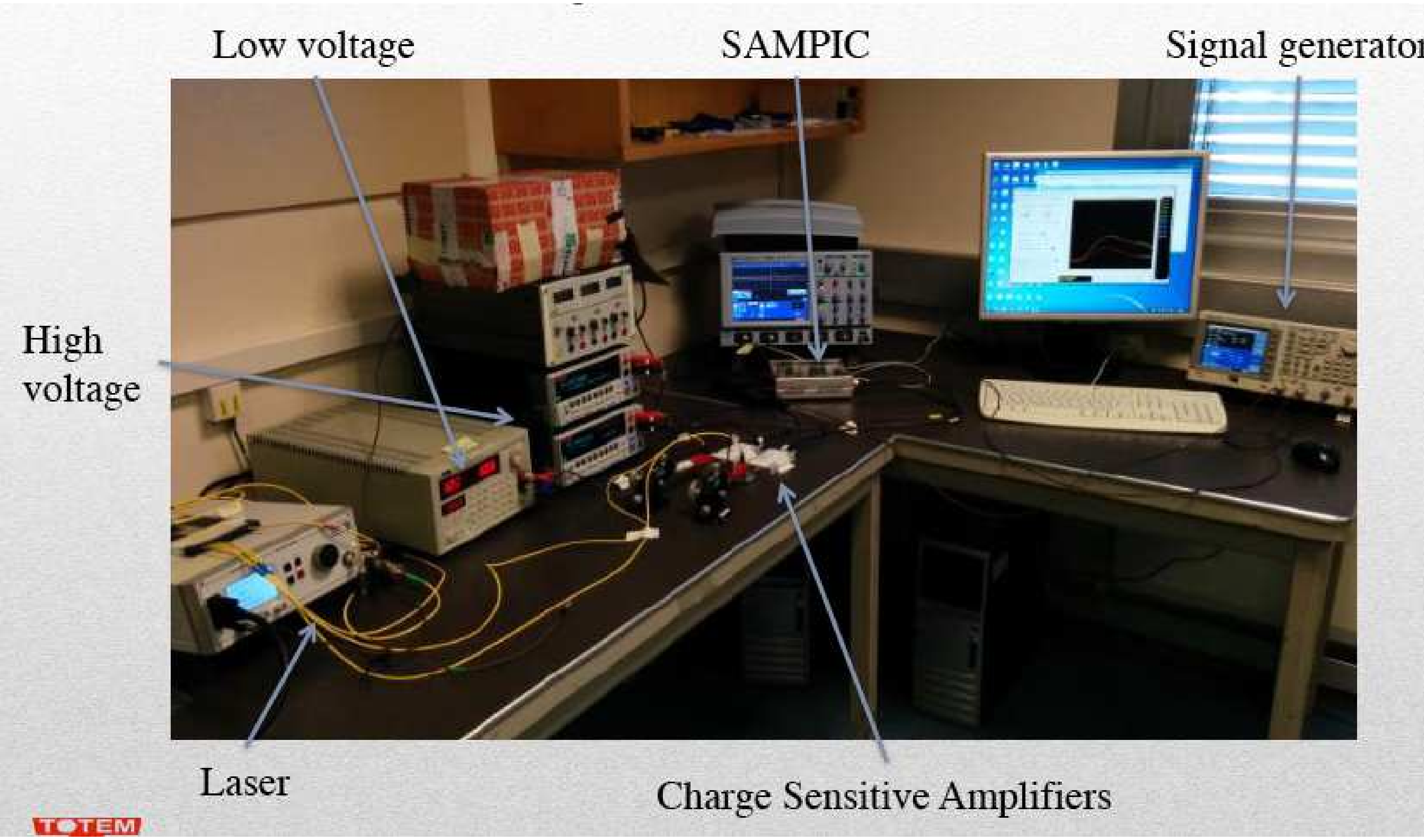
Experimental aspect: need of timing detectors

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



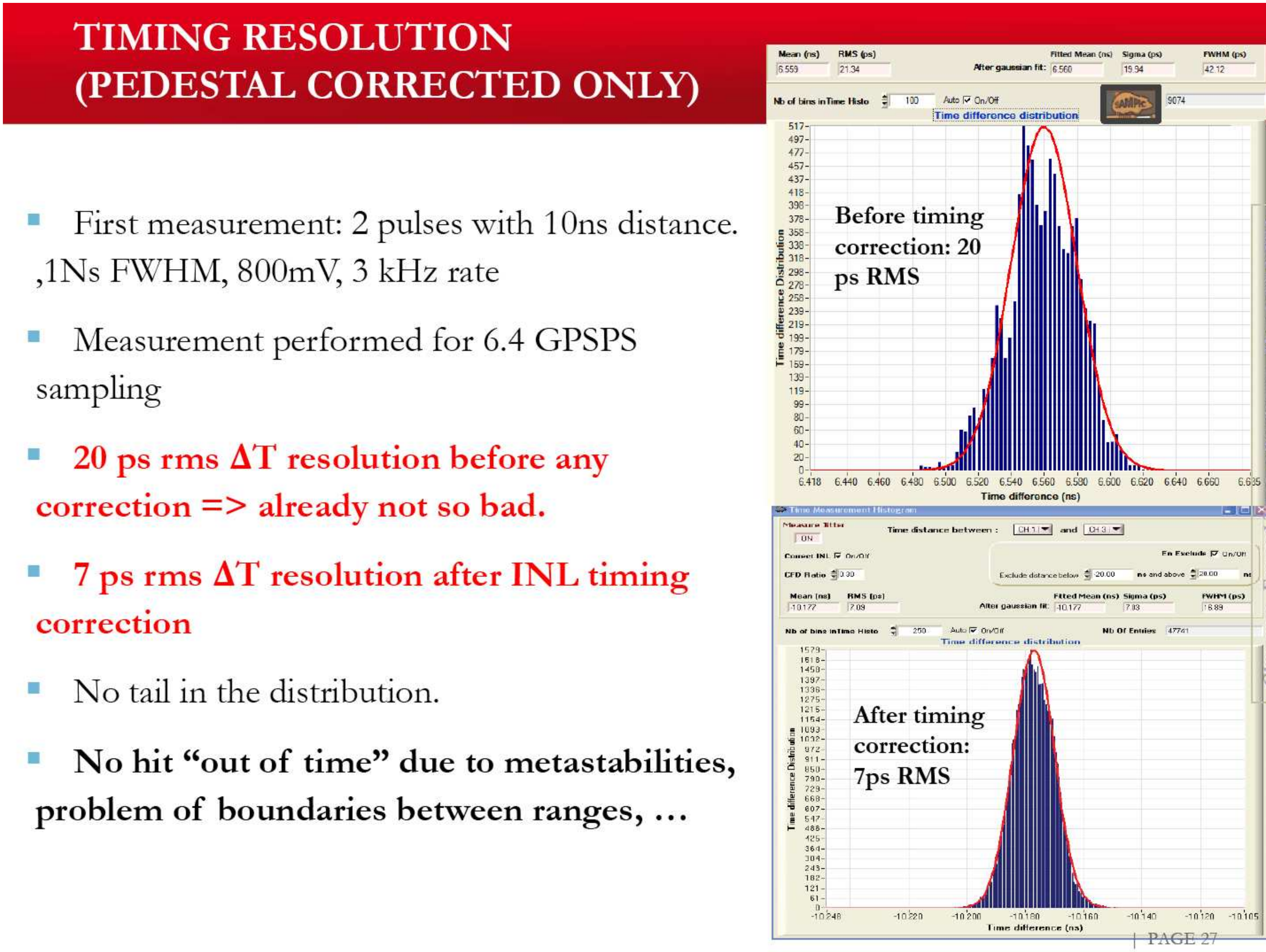


Tests between ATLAS and CMS/TOTEM



- Use different techniques to measure time-of-flight: Diamonds, Si... need pixelisation to fight background
- Time resolution due to readout electronics (SAMPIC): $\sim$ 4 ps
- Time resolution due to detector: $\sim$ 30 ps
- Tests in progress: standalone tests, beam tests...

Timing resolution: SAMPIC alone



TIMING RESOLUTION (PEDESTAL CORRECTED ONLY)

- First measurement: 2 pulses with 10ns distance. ,1Ns FWHM, 800mV, 3 kHz rate
- Measurement performed for 6.4 GPSPS sampling
- **20 ps rms ΔT resolution before any correction => already not so bad.**
- **7 ps rms ΔT resolution after INL timing correction**
- No tail in the distribution.
- **No hit "out of time" due to metastabilities, problem of boundaries between ranges, …**

Mean (ns) 6.559 RMS (ps) 21.34 After gaussian fit: Fitted Mean (ns) 6.560 Sigma (ps) 19.94 FWHM (ps) 42.12

Nb of bins in Time Histo 100 Auto ☑ On/Off 9074

Before timing correction: 20 ps RMS

Measure Jitter ON

Time distance between : CH 1 and CH 3

Correct INL ☑ On/Off

Fn Exclude ☑ On/Off

CFD Ratio 0.30

Exclude distance below -20.00 ns and above 20.00 ns

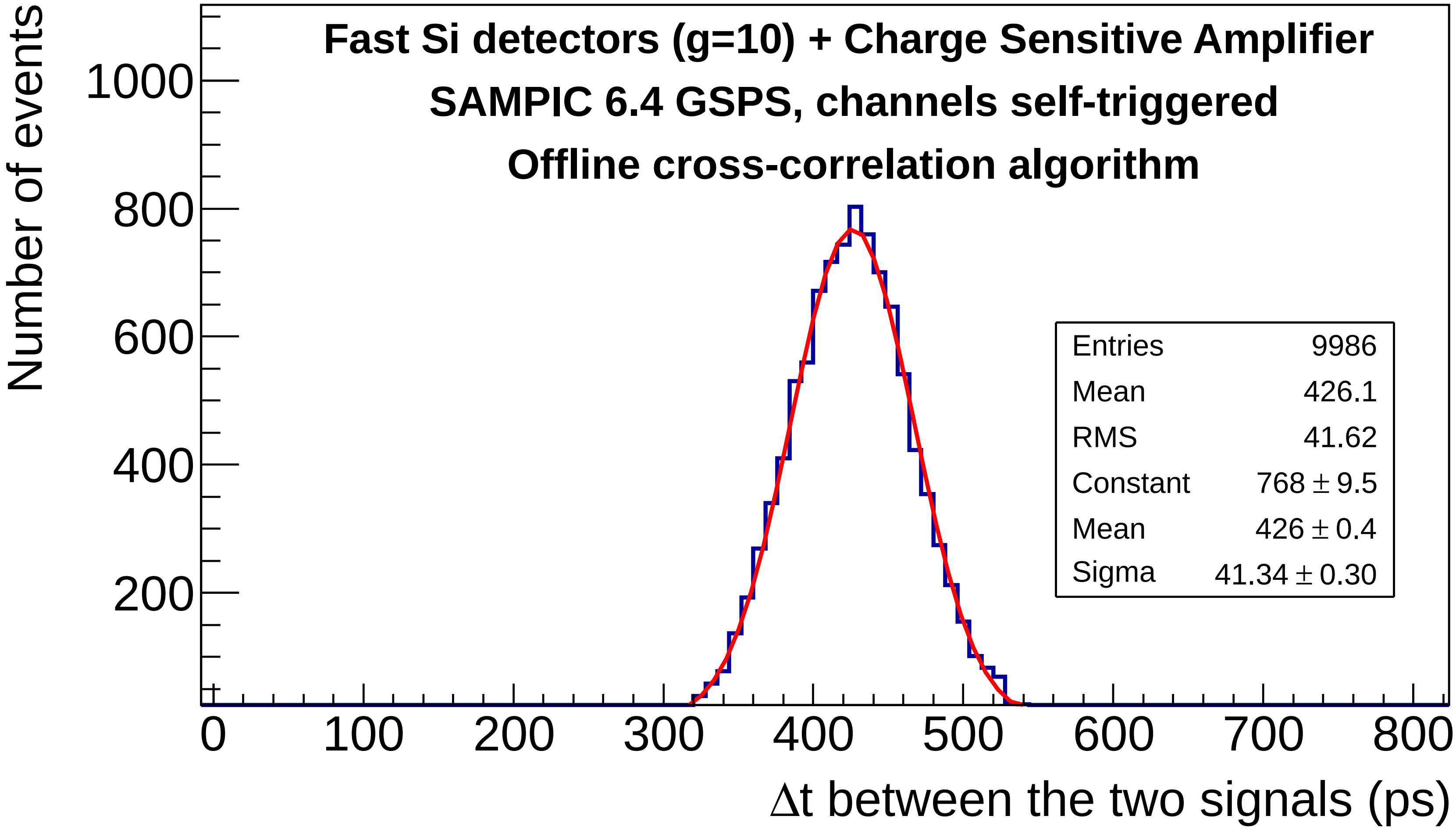
Mean (ns) -10.177 RMS (ps) 7.09 After gaussian fit: Fitted Mean (ns) -10.177 Sigma (ps) 7.03 FWHM (ps) 16.89

Nb of bins in Time Histo 250 Auto ☑ On/Off Nb Of Entries 47741

After timing correction: 7ps RMS

Time resolution using Si detectors

- Time resolution using sampic and Si detectors: measure the time difference between two channels
- Time reolution: (dominated by detector): ∼ 30 ps



Conclusion

- Proton tagging will allow us to control background in searches for $WW\gamma\gamma$, $ZZ\gamma\gamma$ quartic anomalous couplings
- Gain on sensitivity of about two orders of magnitude with respect to CMS results using proton tagging for $\gamma\gamma WW$ and $\gamma\gamma ZZ$ anomalous couplings
- Improvement not as large for triple gauge anomalous couplings but still interesting
- Timing detectors are crucial in order to get rid of background
- See talk by David about light by light scattering at the LHC
- See talk by Matthias about $\gamma\gamma\gamma\gamma$ anomalous couplings