Searching for DM and ED at the LHC with intact protons

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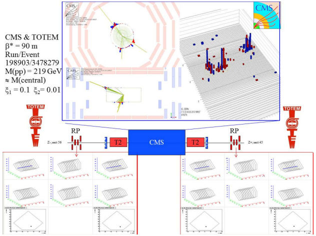
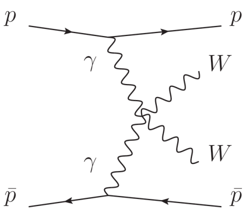
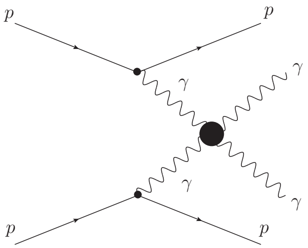


Content

- Proton tagging at the LHC
- Extra-Dimensions
- Polarizable Dark Particles
- Search for Axion-Like particles
- Fast timing detectors

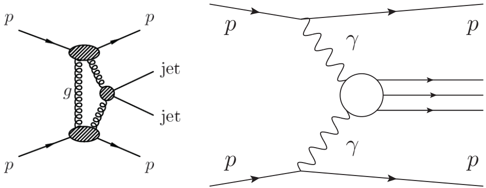
Search for $\gamma\gamma WW$, $\gamma\gamma\gamma\gamma$ quartic anomalous coupling

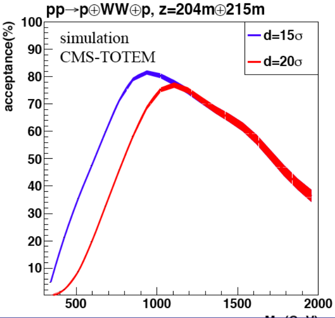




- Study of the process: $pp \to ppWW$, $pp \to ppZZ$, $pp \to pp\gamma\gamma$
- Standard Model: $\sigma_{WW} = 95.6$ fb, $\sigma_{WW}(W = M_X > 1 TeV) = 5.9$ fb
- Process sensitive to anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$; motivated by studying in detail the mechanism of electroweak symmetry breaking, predicted by extradim. models
- Rich $\gamma\gamma$ physics at LHC: see papers by C. Baldenegro, E. Chapon, S. Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert: Phys. Rev. D78 (2008) 073005; Phys. Rev. D81 (2010) 074003; Phys.Rev. D89 (2014) 114004 ; JHEP 1502 (2015) 165...

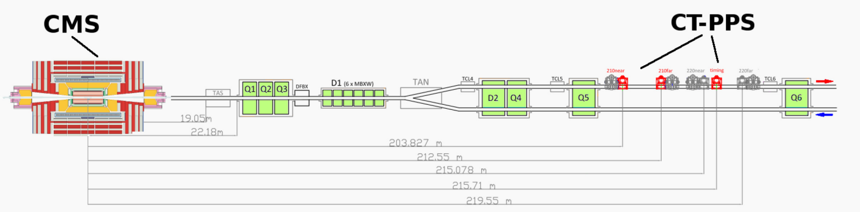
What is AFP/CT-PPS?

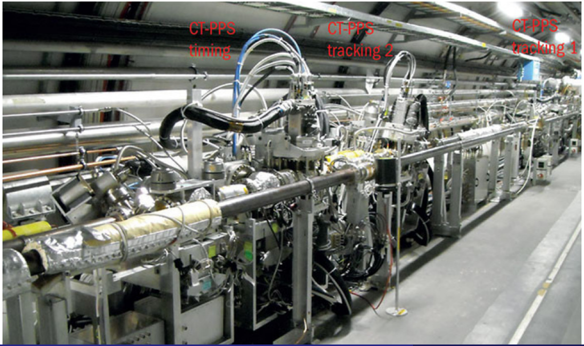




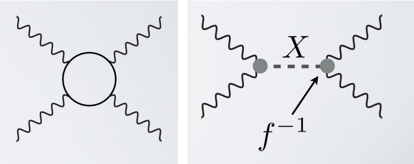
- Tag and measure protons at ± 210 m: AFP (ATLAS Forward Proton), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)
- All diffractive cross sections computed using FPMC (Forward Physics Monte Carlo)
- Complementarity between low and high mass diffraction (high and low cross sections): low lumi runs (high β^*) and high lumi (low β^*, standard LHC running)

What is AFP/CT-PPS?





Motivations to look for quartic $\gamma\gamma$ anomalous couplings



- Two effective operators at low energies

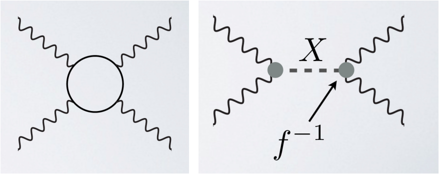
$$\mathcal{L}_{4\gamma} = \zeta_1^{\gamma} F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2^{\gamma} F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu}$$

- $\gamma\gamma\gamma\gamma$ couplings can be modified in a model independent way by loops of heavy charge particles

$$\zeta_1 = \alpha_{em}^2 Q^4 m^{-4} N c_{1,s}$$

where the coupling depends only on $Q^4 m^{-4}$ (charge and mass of the charged particle) and on spin, $c_{1,s}$ depends on the spin of the particle This leads to ζ_1 of the order of 10^{-14}-10^{-13}

Motivations to look for quartic $\gamma\gamma$ anomalous couplings



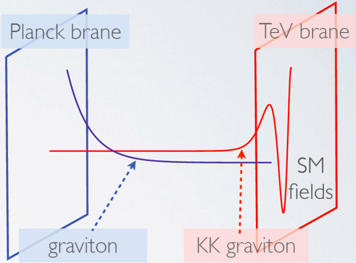
- Two effective operators at low energies

$$\mathcal{L}_{4\gamma} = \zeta_1^{\gamma} F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2^{\gamma} F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu}$$

- ζ_1 can also be modified by neutral particles at tree level (extensions of the SM including scalar, pseudo-scalar, and spin-2 resonances that couple to the photon) $\zeta_1 = (f_s m)^{-2} d_{1,s}$ where f_s is the $\gamma\gamma X$ coupling of the new particle to the photon, and $d_{1,s}$ depends on the spin of the particle; for instance, 2 TeV dilatons lead to $\zeta_1 \sim 10^{-13}$

Warped extra-dimensions

- ✘ Warped Extra Dimensions solve hierarchy problem of SM
- ✘ 5^{th} dimension bounded by two branes
- ✘ SM on the visible (or TeV) brane



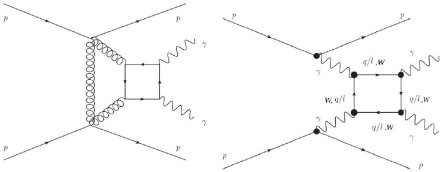
- ✘ The Kaluza Klein modes of the graviton couple with TeV strength

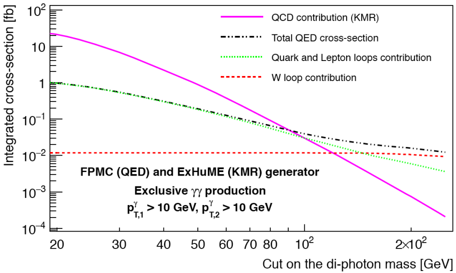
$$\mathcal{L}^{\gamma\gamma h} = f^{-2}\ h^{\text{KK}}_{\mu\nu}\ \left(\tfrac{1}{4}\eta_{\mu\nu}F^2_{\rho\lambda} - F_{\mu\rho}F_{\rho\nu}\right)$$

$$f \sim \text{TeV} \qquad m_{\text{KK}} \sim \text{few TeV}$$

- ✘ Effective 4-photon couplings $\zeta_i \sim 10^{-14} - 10^{-13}\ \text{GeV}^{-2}$ possible
- ✘ The radion can produce similar effective couplings

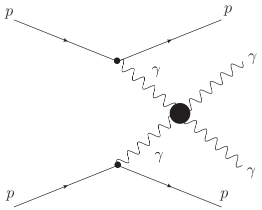
$\gamma\gamma$ exclusive production: SM contribution

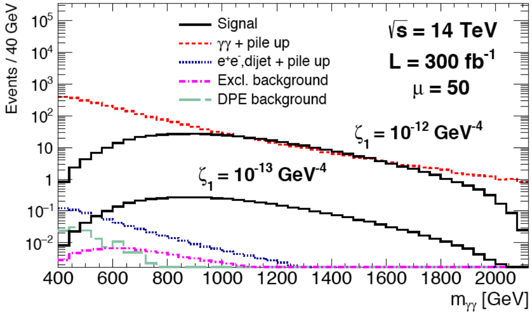




- QCD production dominates at low $m_{\gamma\gamma}$, QED at high $m_{\gamma\gamma}$
- Important to consider W loops at high $m_{\gamma\gamma}$
- At high masses ($>$ 200 GeV), the photon induced processes are dominant
- **Conclusion: Two photons and two tagged protons means photon-induced process**

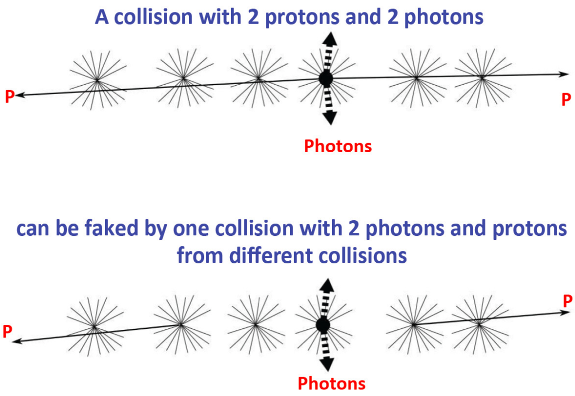
Search for quartic $\gamma\gamma$ anomalous couplings





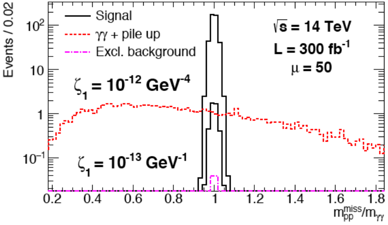
- Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- Analysis performed at hadron level including detector efficiencies, resolution effects, pile-up...

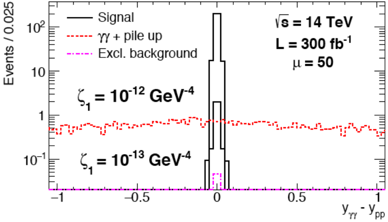
One aside: what is pile up at LHC?



- 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 (200 for high lumi LHC)

Search for quartic $\gamma\gamma$ anomalous couplings





Cut / Process	Signal (full)	Signal with (without) f.f (EFT)	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15,$ $p_{\mathrm{T}1,(2)} > 200, (100)$ GeV]	65	18 (187)	0.13	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	64	17 (186)	0.10	0	0.2	1023
$[p_{\mathrm{T}2}/p_{\mathrm{T}1} > 0.95,$ $\lvert\Delta\phi\rvert > \pi - 0.01]$	64	17 (186)	0.10	0	0	80.2
$\sqrt{\xi_1\xi_2 s} = m_{\gamma\gamma} \pm 3\%$	61	16 (175)	0.09	0	0	2.8
$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	60	12 (169)	0.09	0	0	0

High lumi: Search for quartic $\gamma\gamma$ anomalous couplings: Results from effective theoryScales and tools

Luminosity	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	3000 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.	$1.5 \cdot 10^{-13}$	$7.5 \cdot 10^{-14}$	$4 \cdot 10^{-14}$	$3.5 \cdot 10^{-14}$
ζ_1 no f.f.	$3.5 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$	$1 \cdot 10^{-14}$	$1 \cdot 10^{-14}$
ζ_2 f.f.	$2.5 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$8.5 \cdot 10^{-14}$	$7 \cdot 10^{-14}$
ζ_2 no f.f.	$7.55 \cdot 10^{-14}$	$4.5 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$

- Unprecedented sensitivities at hadronic colliders: no limit exists presently on $\gamma\gamma\gamma\gamma$ anomalous couplings
- Reaches the values predicted by extra-dim or composite Higgs models
- Introducing form factors to avoid quadratical divergences of scattering amplitudes due to anomalous couplings in conventional way: $a \rightarrow \frac{a}{(1+W\gamma\gamma/\Lambda_{cutoff})^2}$ with $\Lambda_{cutoff} \sim 2$ TeV
- **Conclusion: background free experiment**

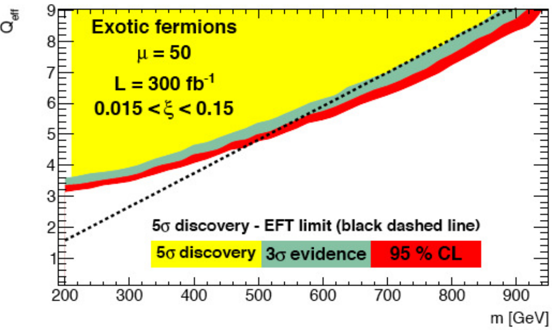
Full amplitude calculation

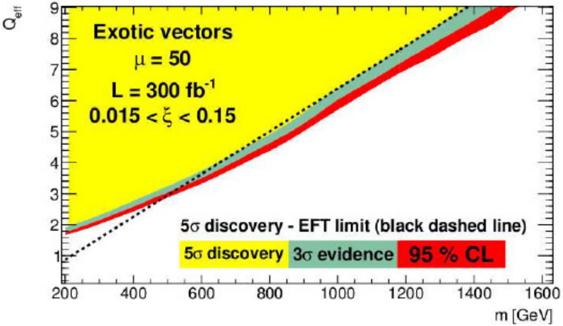
- 5 σ discovery sensitivity on the effective charge of new charged fermions and vector boson for various mass scenarii for 300 fb^{-1} and $\mu = 50$

Mass (GeV)	300	600	900	1200
Q_{eff} (vector)	2.3	3.7	5.6	7.8
Q_{eff} (fermion)	3.9	6.2	9.1	-

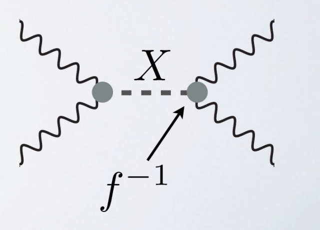
- Unprecedented sensitivites at hadronic colliders reaching the values predicted by extra-dim models - For reference, we also display the result of effective field theory (without form factor) which deviates at low masses from the full calculation
- For $Q_{Jeff} = QN^{1/4} = 4$, we are sensitive to new vectors (fermions) up to 700 (370) GeV for a luminosity of 300 fb^{-1}

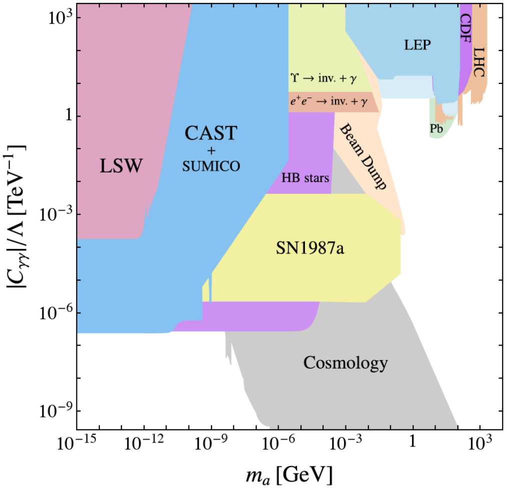
Full amplitude calculation

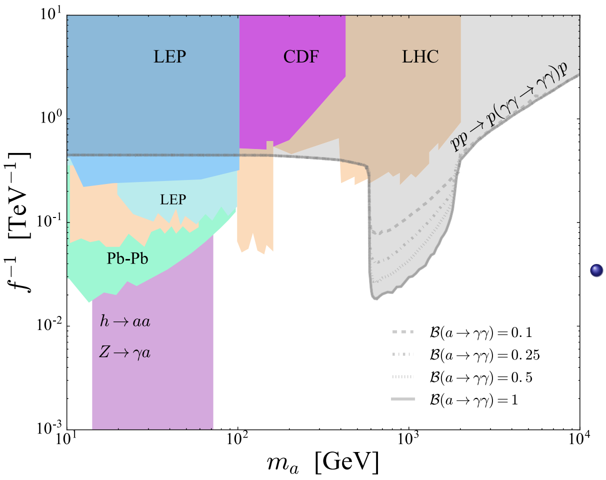




Generalization - Looking for axion like particles

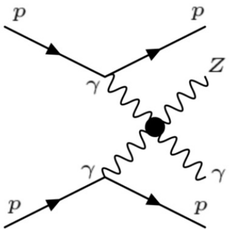


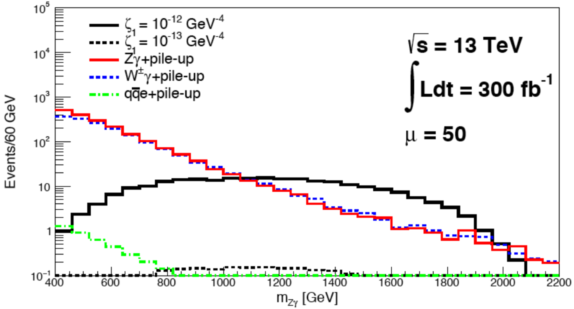




- Production of axions via photon exchanges and tagging the intact protons in the final state complementary to the usual search at the LHC (Z decays into 3 photons): sensitivity at high axion mass (spin 0 even resonance, width 45 GeV)- C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, ArXiv 1803.10835
- Complementarity with Pb Pb running: sensitivity to low mass diphoton, low luminosity but cross section increased by Z^4

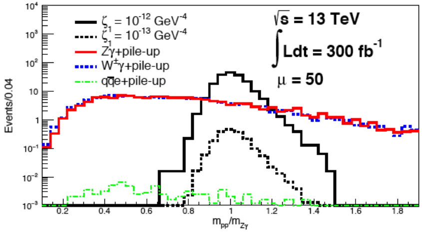
$\gamma\gamma\gamma Z$ quartic anomalous coupling

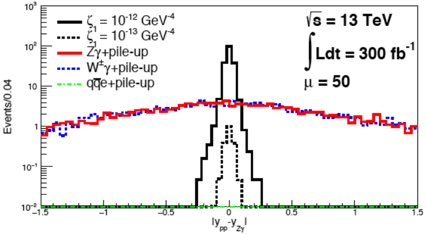




- Look for $Z\gamma$ anomalous production
- Z can decay leptonically or hadronically: the fact that we can control the background using the mass/rapidiy matching technique allows us to look in both channels (very small background)

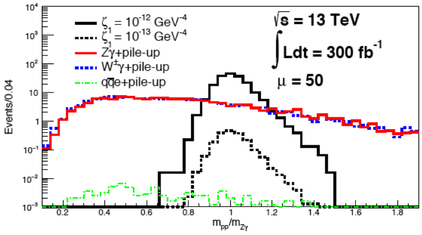
$\gamma\gamma\gamma Z$ quartic anomalous coupling

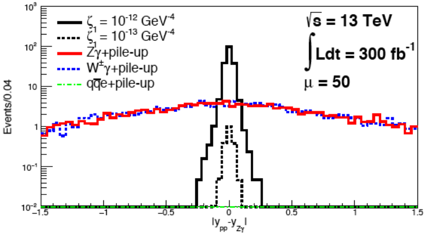




Coupling (GeV^{-4})	ζ ($\tilde{\zeta}=0$)		$\zeta = \tilde{\zeta}$	
Luminosity	300 fb^{-1}		300 fb^{-1}	
Pile-up (μ)	50		50	
Channels	5 σ	95% CL	5 σ	95% CL
$\ell\bar{\ell}\gamma$	$2.8 \cdot 10^{-13}$	$1.8 \cdot 10^{-13}$	$2.5 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$
$jj\gamma$	$2.3 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$2 \cdot 10^{-13}$	$1.3 \cdot 10^{-13}$
$jj\gamma \bigoplus \ell\bar{\ell}\gamma$	$1.93 \cdot 10^{-13}$	$1.2 \cdot 10^{-13}$	$1.7 \cdot 10^{-13}$	$1 \cdot 10^{-13}$

$\gamma\gamma\gamma Z$ quartic anomalous coupling

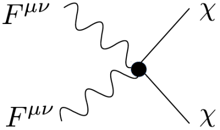




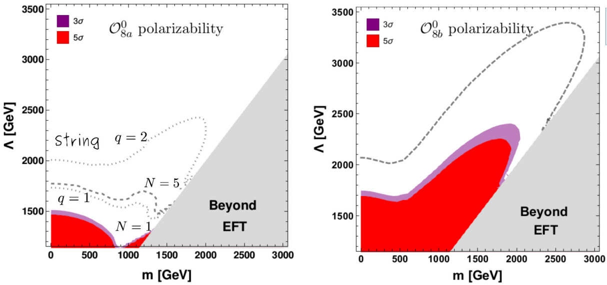
- C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1706 (2017) 142
- Best expected reach at the LHC by about three orders of magnitude
- Advantage of this method: sensitivity to anomalous couplings in a model independent way: can be due to wide/narrow resonances, loops of new particles as a threshold effect

Search for polarizable dark particles

Polarizable dark particles:

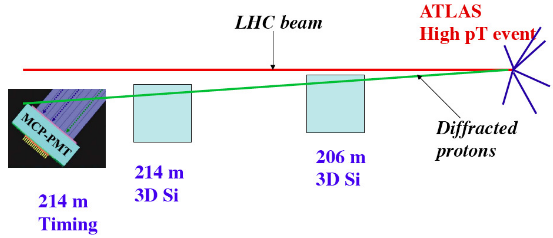


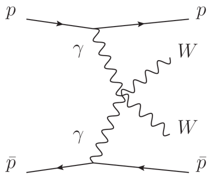
$$\frac{1}{\Lambda^2}\phi^2(F^{\mu\nu})^2, \ \frac{1}{\Lambda^4}\partial_\mu\phi\partial_\nu\phi F^{\mu\rho}F_\rho^{\ \nu}, \ \ldots$$

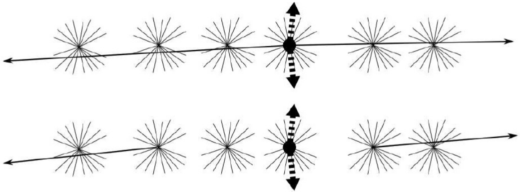


- Production of loops of polarizable dark particles
- Assume that they decay in $\gamma\gamma$ or γZ

Removing pile up: measuring proton time-of-flight



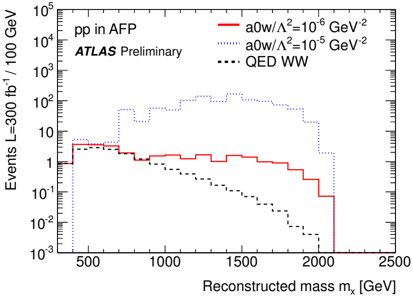


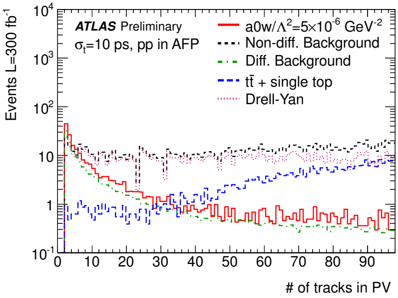


- Measure the proton time-of-flight in order to determine if they originate from the same interaction as our Ws
- Typical precision: 10 ps means 2.1 mm
- Development of fast timing precision for CT-PPS, CMS upgrade and applications (medicine, chemistry, cosmic ray

Anomalous couplings studies in *WW* events

- Reach on anomalous couplings studied using a full simulation (pile-up effects); only leptonic decays of *W*s are considered
- Signal at high lepton p_T and dilepton mass and high diffractive mass
- 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.

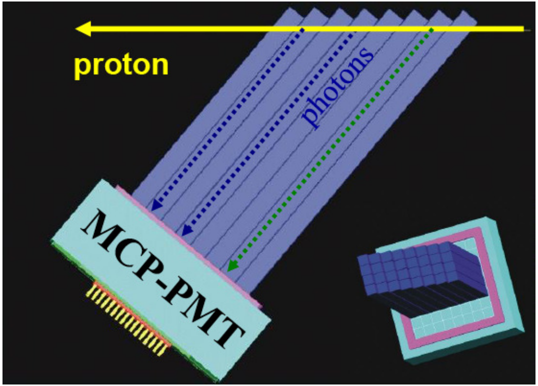
Results from full simulation

- **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 (CMS mentions that their exclusive analysis will not improve very much at high lumi because of pile-up)**

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

Timing detectors

- Measure the vertex position using proton time-of-flight: 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
- Utilisation of quartz, diamond, gas or Silicon detectors

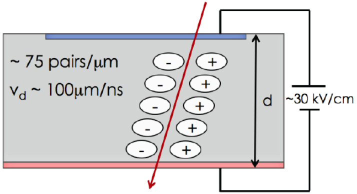


Silicon Low Gain Avalanche Detectors

Signal shape is determined by Ramo's Theorem:

$$i \propto q v E_w$$

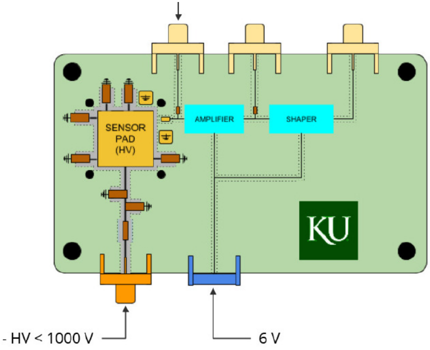
Drift velocity — Weighting field



- Large velocity needed, which means fast detector
- Large fields and large pad to have uniform field
- Lots of charge

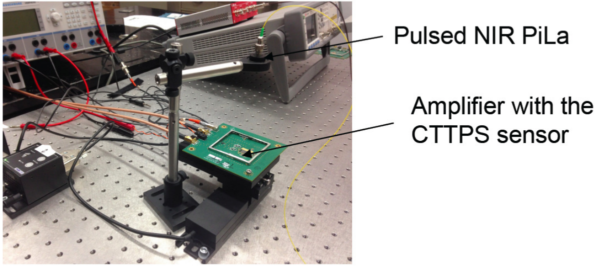
Performance with a real Ultra Fast Silicon detector

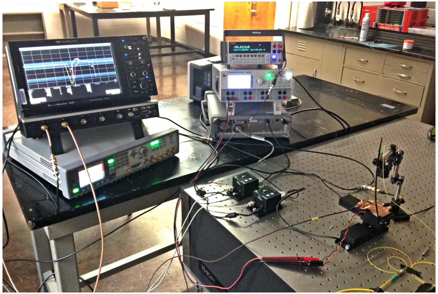
- The output signal of the Ultra Fast Si Detector is amplified before going into the readout electronics
- Design of a new multi-purpose electronics board for testing, many different applications, and lower cost compared to commercially available solutions (patent in progress)



Test stand at the University of Kansas

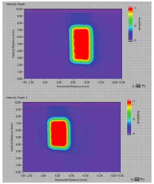
Preliminary time measurements currently being performed at KU

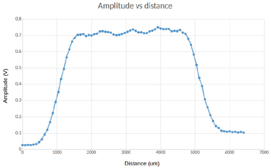


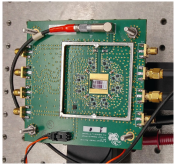


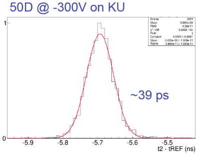
- Full test stand installed at the University of Kansas: readout of a Si detector
- Using laser or radioactive source in front of the detector

Preliminary time measurements currently being performed at KU





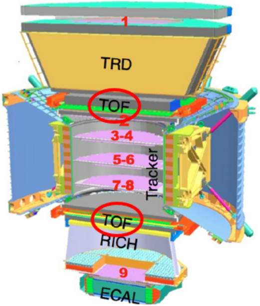




- Visualize pixels from Si detectors: Pixel size: $\sim$3 mm
- Test timing detectors at Fermilab: Timing resolution per layer of Si detector: $\sim$ 39 ps

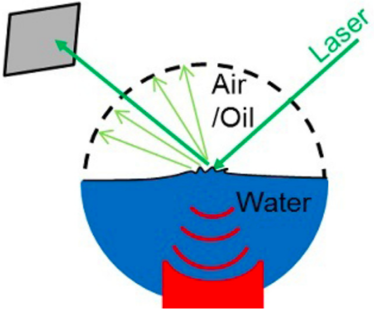
Timing in space: few examples

- Analysis of cosmic ray particles
- Use different sizes of Si detector that can be sensitive to the kinds of particles that are produced
- Analyze the signal using the same method of digitization described before



Spada, F. "**AMS-02 on the International Space Station.**"

Another application: understanding catalysis in chemistry



- Better understanding of the liquid-gas or liquid-liquid interfaces and their evolution as a function of time: Measure a snapshot every 50 ps or so
- Understanding catalysis in chemistry
- Many applications: Desalinization of sea water, improve medicine performance by understanding better the interface between the medicine and human cells

Conclusion

- $\gamma\gamma\gamma\gamma$, $\gamma\gamma ZZ$, $\gamma\gamma WW$, $\gamma\gamma\gamma Z$ anomalous coupling studies
  - Exclusive process: **photon-induced processes** $pp \to p\gamma\gamma p$ (gluon exchanges suppressed at high masses):
  - Theoretical calculation in better control (QED processes with intact protons), not sensitive to the photon structure function
  - **“Background-free” experiment** and any observed event is signal
- CT-PPS/AFP allows to probe BSM diphoton production in a model independent way: sensitivities to values predicted by extradim or composite Higgs models e
- Timing detectors: development for LHC, many applications