Anomalous coupling studies with proton tagging and search for ALPs

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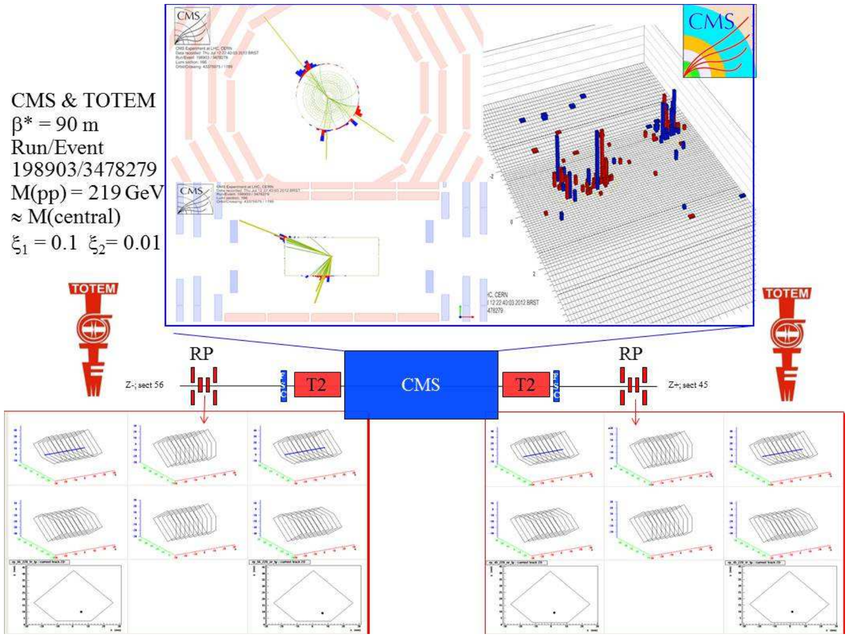
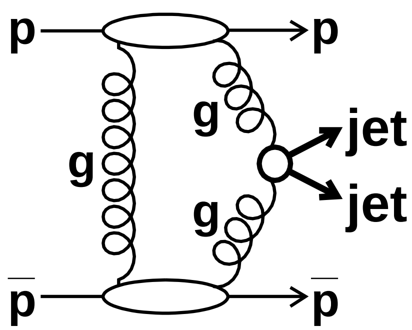
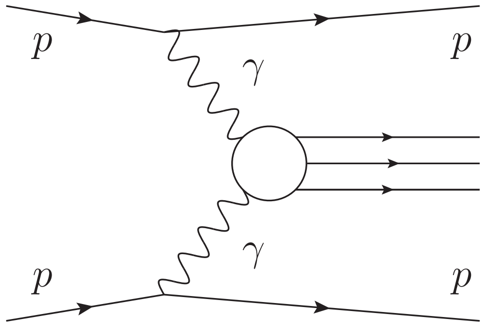
4th Elba Workshop on Forward Physics at LHC Energies
La Biodola, Elba Island, Italy, 24-26 May 2018

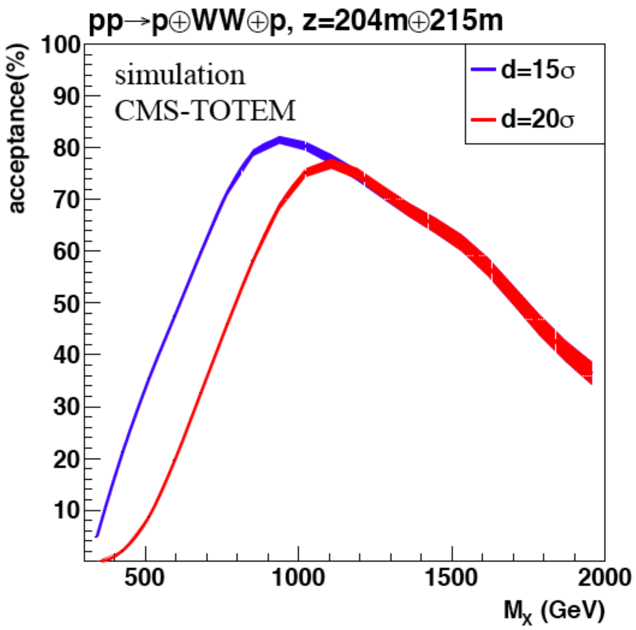


- Quartic anomalous coupling studies
- Search for axion like particles
- What about high lumi LHC?

What is CT-PPS/AFP?

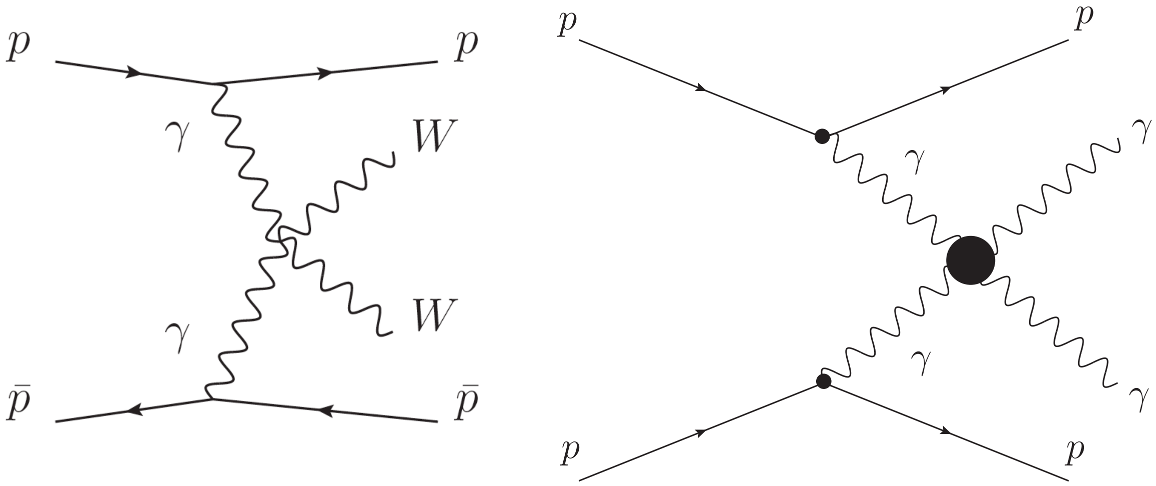






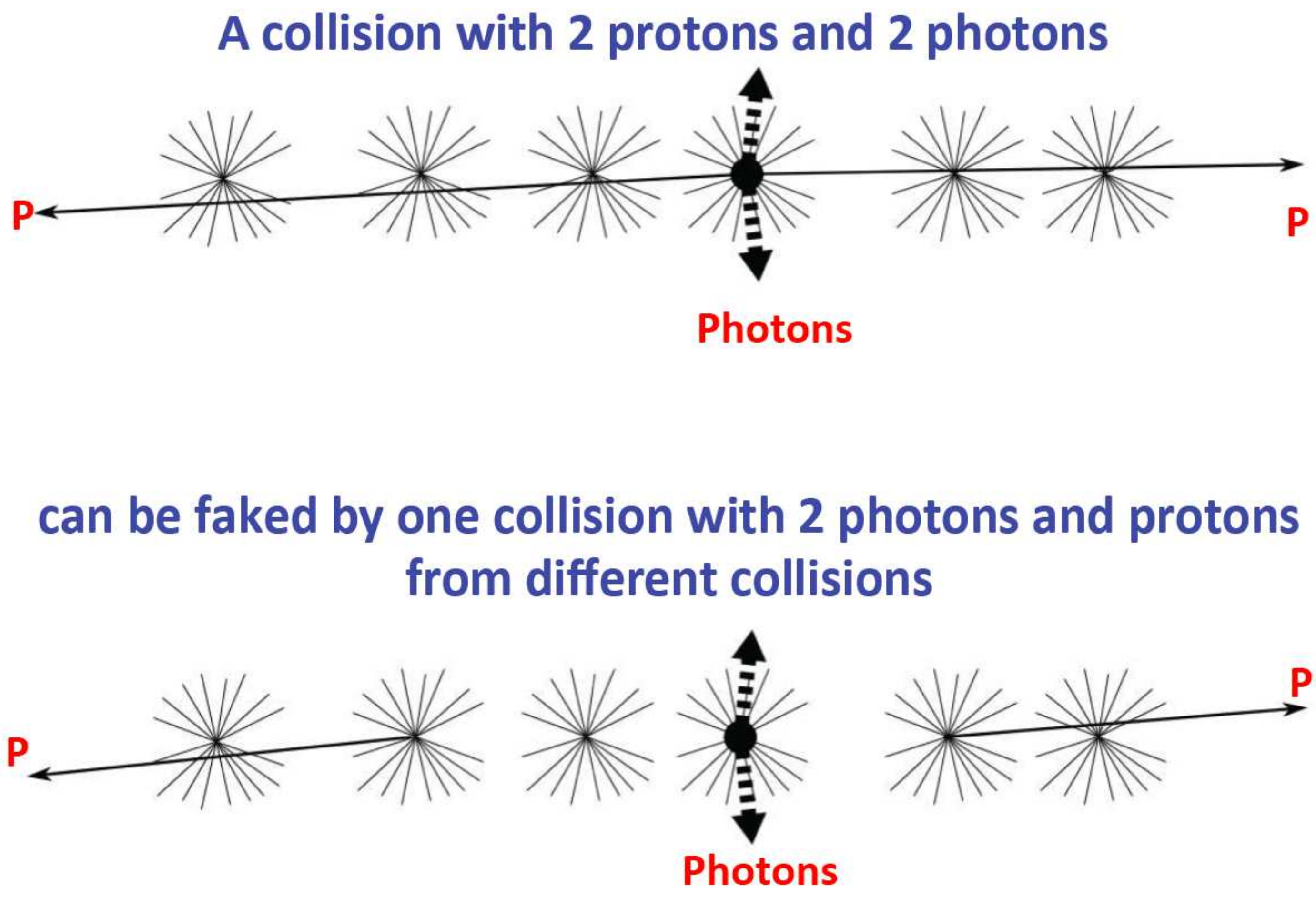
- Tag and measure protons at $\pm$210 m: CT-PPS (CMS TOTEM - Precision Proton Spectrometer) or AFP
- All photon-induced cross sections computed using FPMC
- for high lumi LHC, we assume that we can run the forward proton detectors with a pile up of 200 (enough pixelisation and not too much beam-induced background)

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, $\sigma_{WW}(W = M_X > 1TeV) = 5.9$ 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 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; Phys. Rev. Lett. 116 (2016) no 23, 231801; Phys. Rev. D93 (2016) no 7, 075031; JHEP 1706 (2017) 142

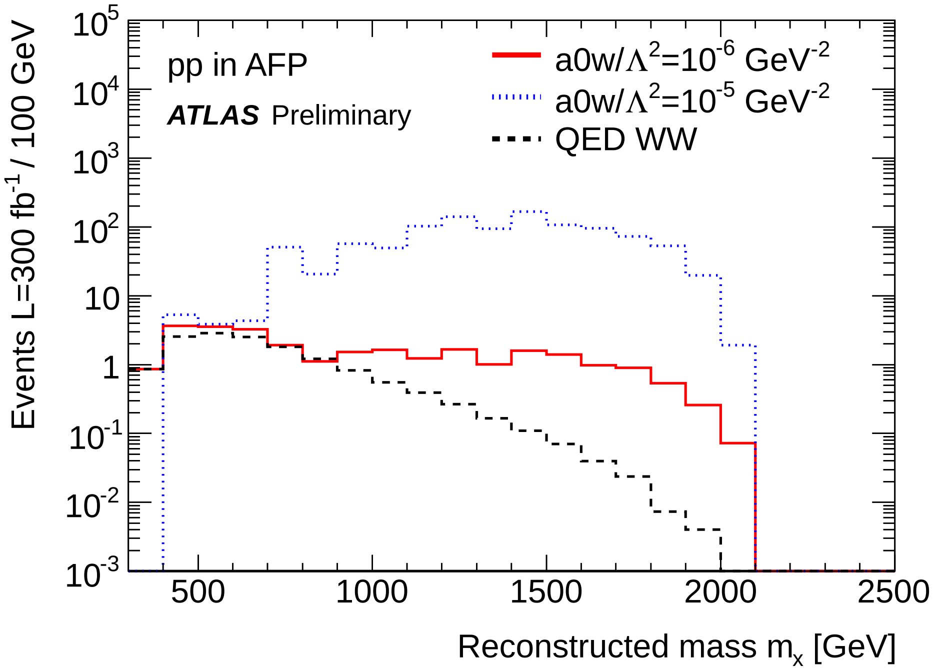
One aside: what is pile up at LHC?

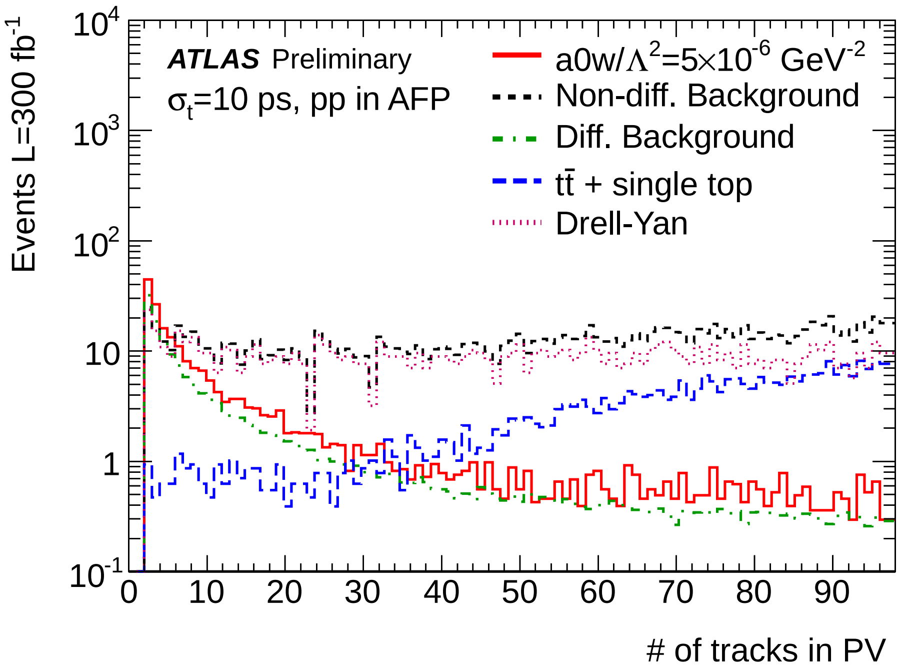


- The LHC machine collides packets of protons
- Due to high number of protons in one packet, there can be more than one interaction between two protons when the two packets collide
- Typically up to 50 pile up events, 200 for high lumi LHC

Anomalous couplings studies in WW events

- Reach on anomalous couplings 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 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}

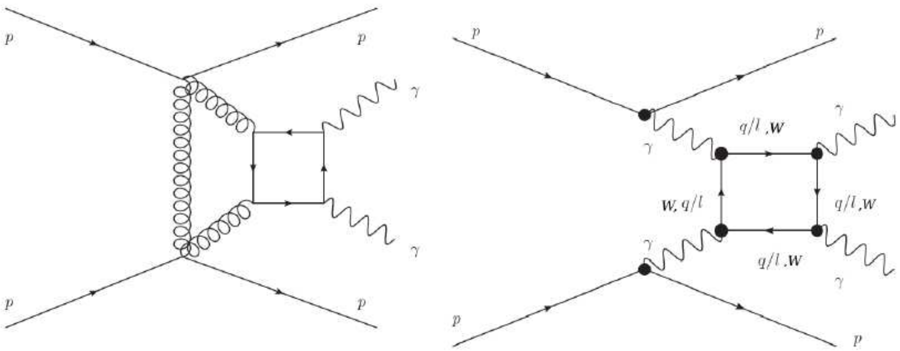
Reach at LHC for $\gamma\gamma WW$ and $\gamma\gamma ZZ$

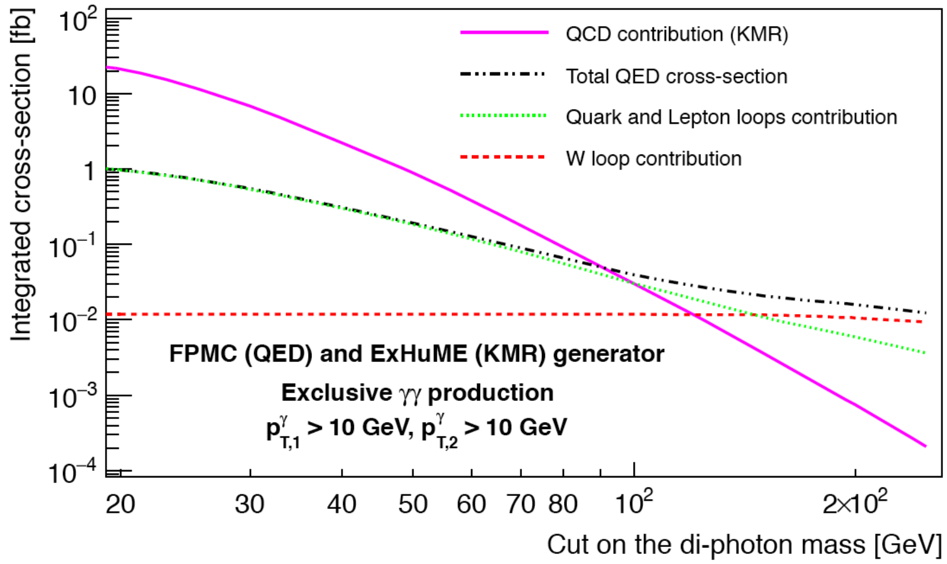
Reach at high luminosity on quartic anomalous coupling using fast simulation (study other anomalous couplings such as $\gamma\gamma ZZ$...)

Couplings	OPAL limits [GeV^{-2}]	Sensitivity @ $\mathcal{L} = 30$ (200) fb^{-1} 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 LHC usual sensitivity by more than 2 orders of magnitude with 200 fb^{-1}
- Possible improvements: we only considered leptonic decays of W and Z bosons, need to consider also hadronic decays into fat jets (in progress); 4 lepton decays of ZZ promising at high lumi

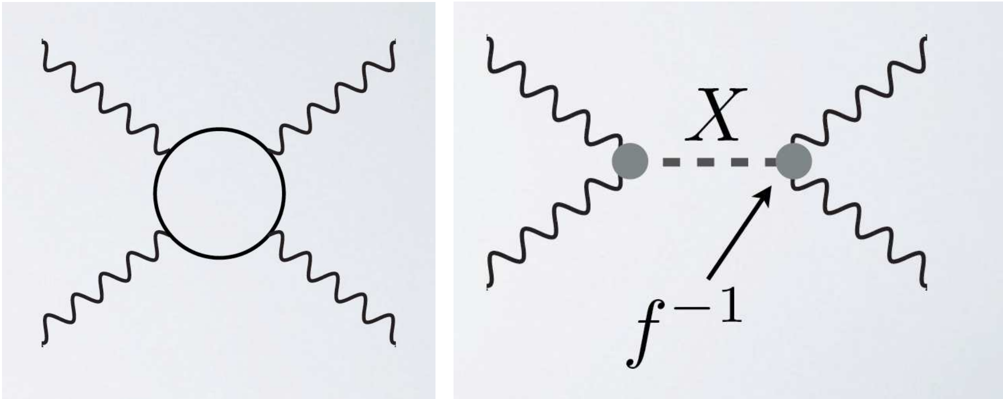
$\gamma\gamma$ exclusive production: SM contribution





- 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**

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

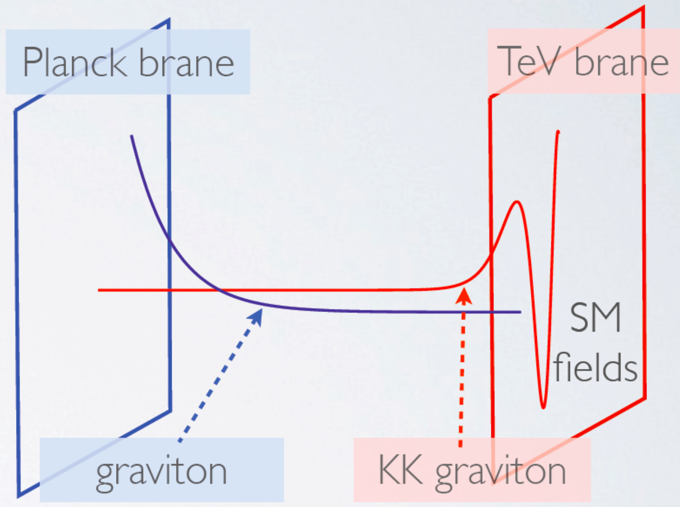
$$\zeta_1 = \alpha_{em}^2 Q^4 m^{-4} N c_{1,s}$$

  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}

- 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

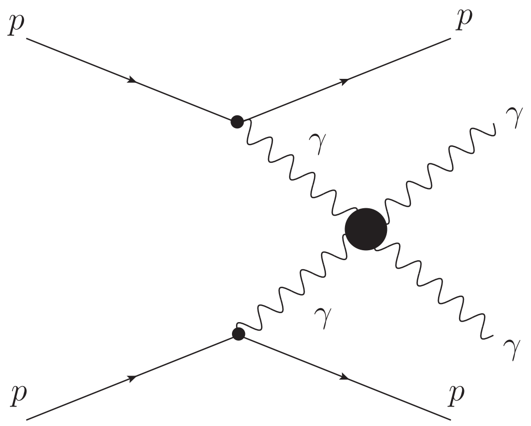
$$\mathcal{L}^{\gamma\gamma h} = f^{-2}\, h^{\rm KK}_{\mu\nu}\, (\tfrac{1}{4}\eta_{\mu\nu}F^2_{\rho\lambda} - F_{\mu\rho}F_{\rho\nu})$$

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

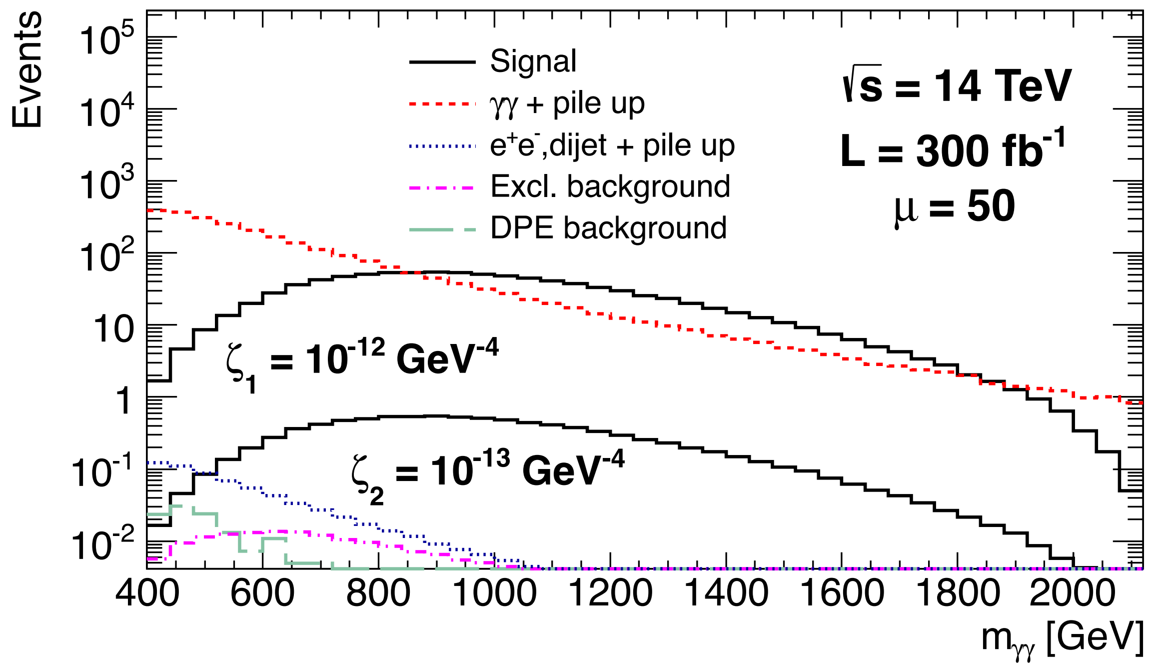
- ✘ Effective 4-photon couplings $\zeta_i \sim 10^{-14} - 10^{-13}\ {\rm GeV}^{-2}$ possible
- ✘ The radion can produce similar effective couplings

- Which models/theories are we sensitive to using AFP/CT-PPS
- Beyond standard models predict anomalous couplings of $\sim 10^{-14}$-10^{-13}
- Work in collaboration with Sylvain Fichet, Gero von Gersdorff

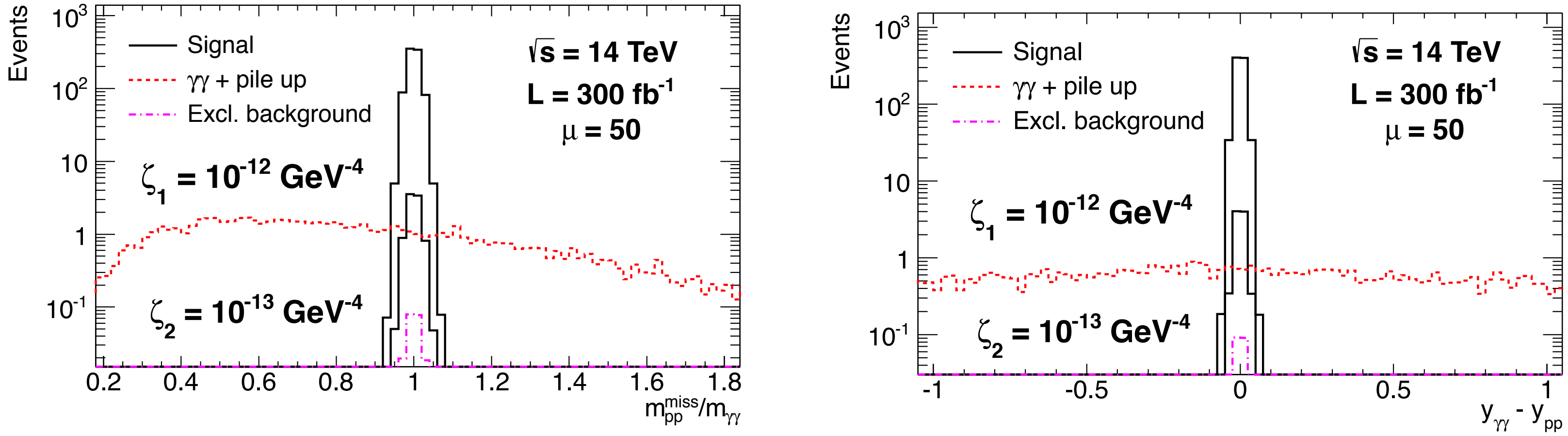
Search for quartic $\gamma\gamma$ anomalous couplings



- 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...



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
$[0.015 < \xi_{1,2} < 0.15,$ $p_{T1,(2)} > 200, (100)$ GeV]	130.8	36.9 (373.9)	0.25	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	128.3	34.9 (371.6)	0.20	0	0.2	1023
$[p_{T2}/p_{T1} > 0.95,$ $\|\Delta\phi\| > \pi - 0.01]$	128.3	34.9 (371.4)	0.19	0	0	80.2
$\sqrt{\xi_1\xi_2 s} = m_{\gamma\gamma} \pm 3\%$	122.0	32.9 (350.2)	0.18	0	0	2.8
$\|y_{\gamma\gamma} - y_{pp}\| < 0.03$	119.1	31.8 (338.5)	0.18	0	0	0

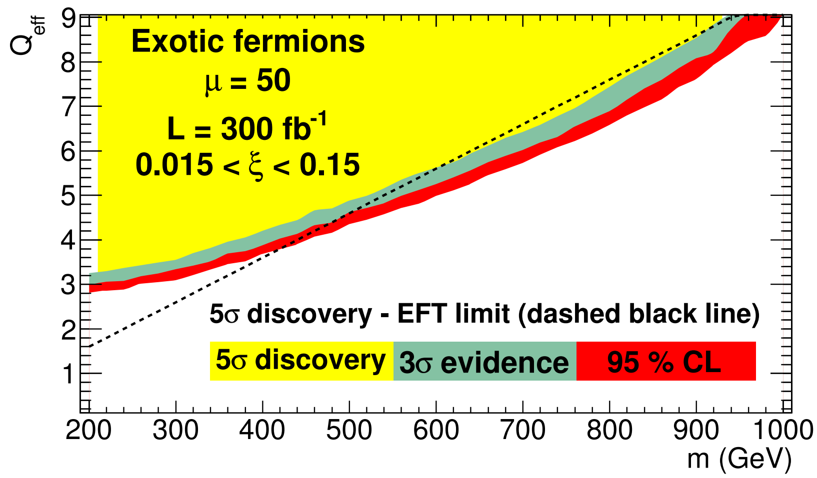
- No background after cuts for 300 fb^{-1}: sensitivity up to a few 10^{-15}, better by 2 orders of magnitude with respect to “standard” methods
- Exclusivity cuts using proton tagging needed to suppress backgrounds (no exclusivity cuts using CT-PPS: background of 80.2 for 300 fb^{-1})
- With 3000 fb^{-1}, gain on sensitivity of at least a factor 2-3 possible (can be improved using precise timing detectors, to be studied)

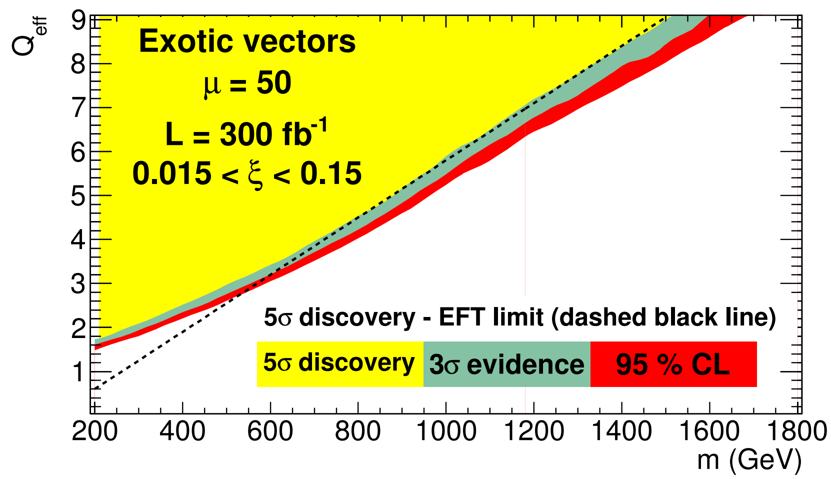
Full amplitude calculation

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

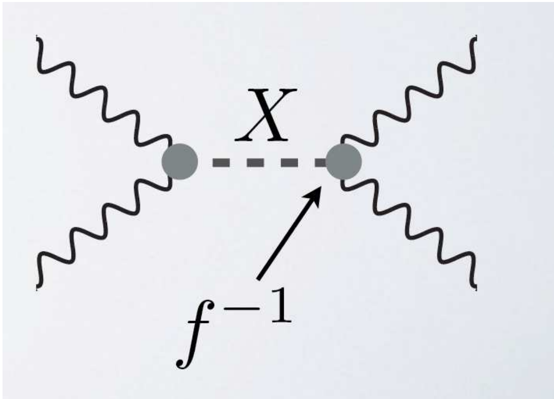
Mass (GeV)	300	600	900	1200	1500
$Q_{\rm eff}$ (vector)	2.2	3.4	4.9	7.2	8.9
$Q_{\rm eff}$ (fermion)	3.6	5.7	8.6	-	-

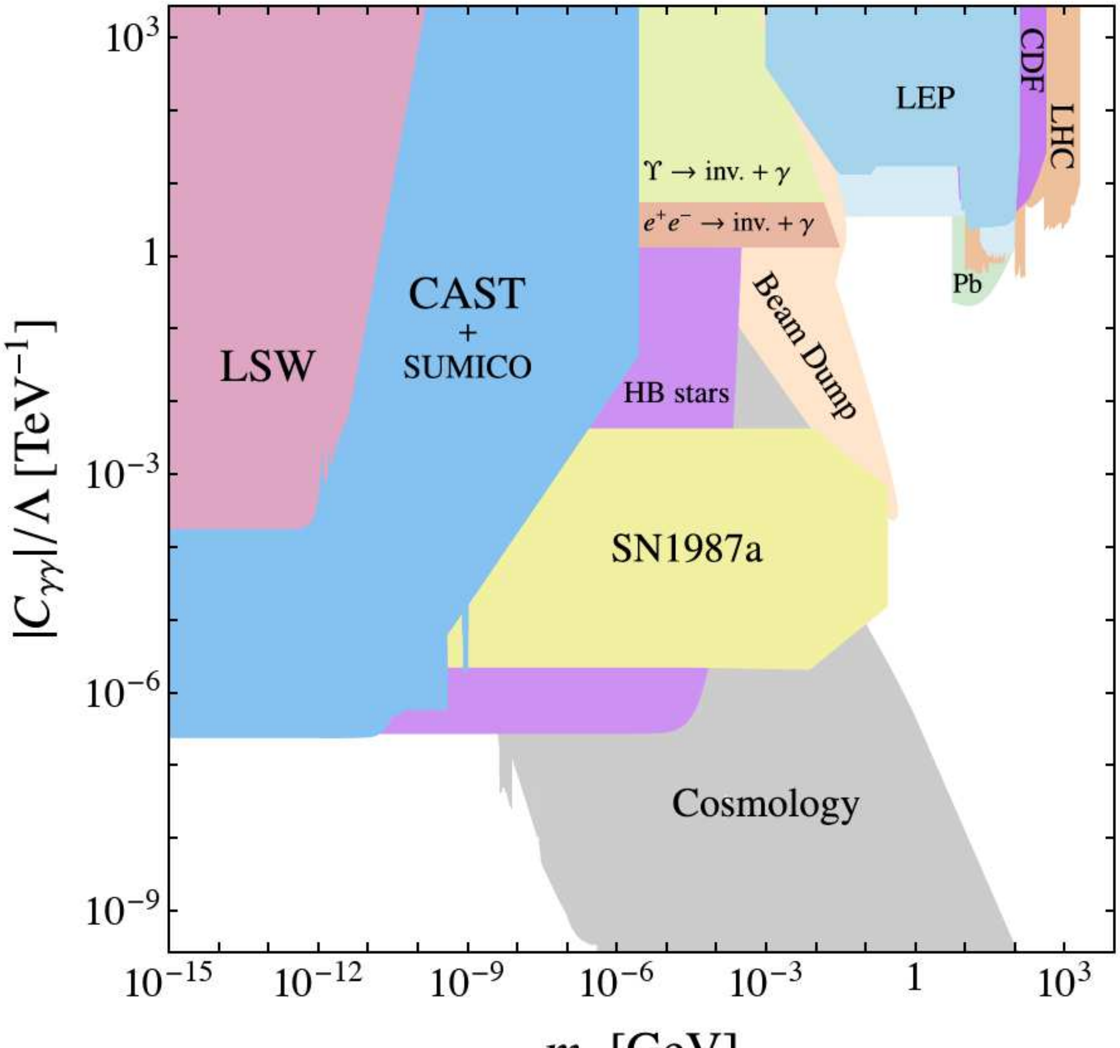
- Unprecedented sensitivites at hadronic colliders reaching the values predicted by extra-dim models - For reference, we also display the result of effective field theory (without form factor) which deviates at low masses from the full calculation
- For $Q_{Jeff} = QN^{1/4} = 4$, we are sensitive to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



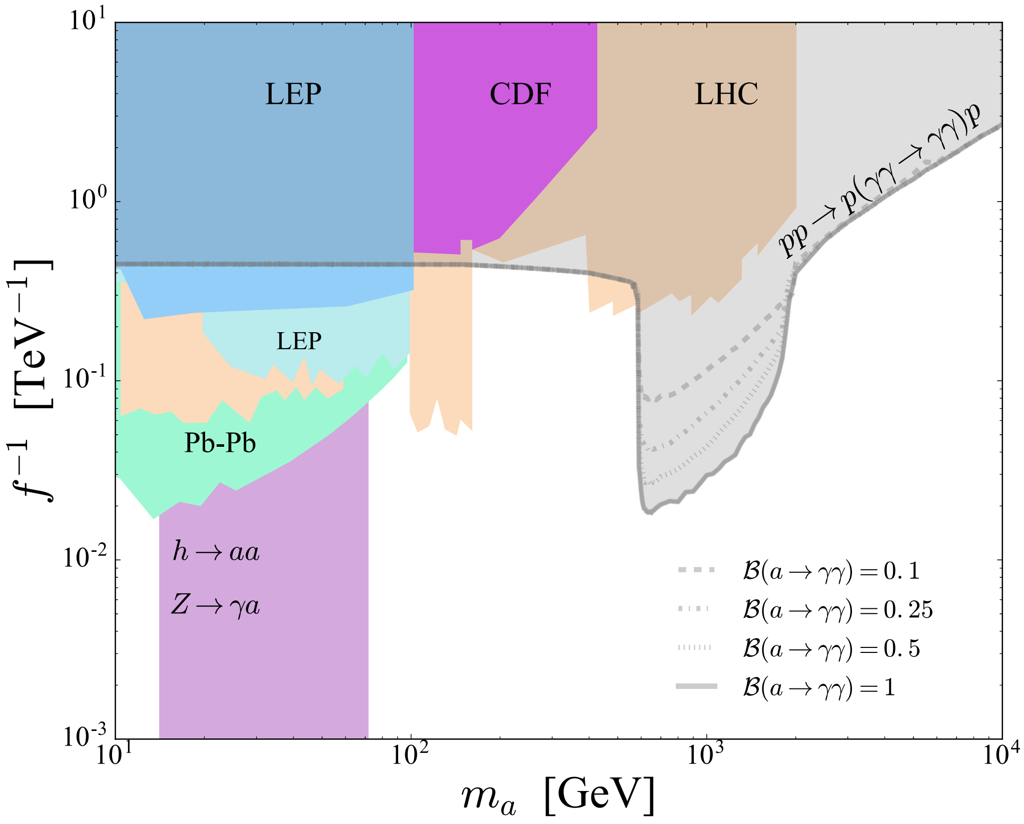


Generalization - Looking for axion like particles



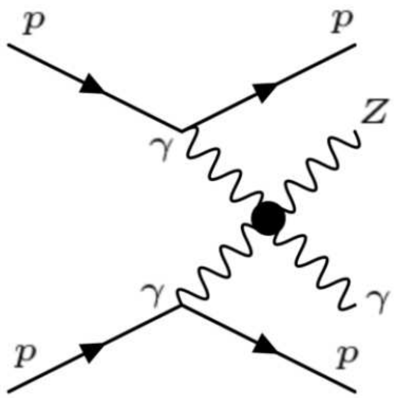


Search for axion like particles

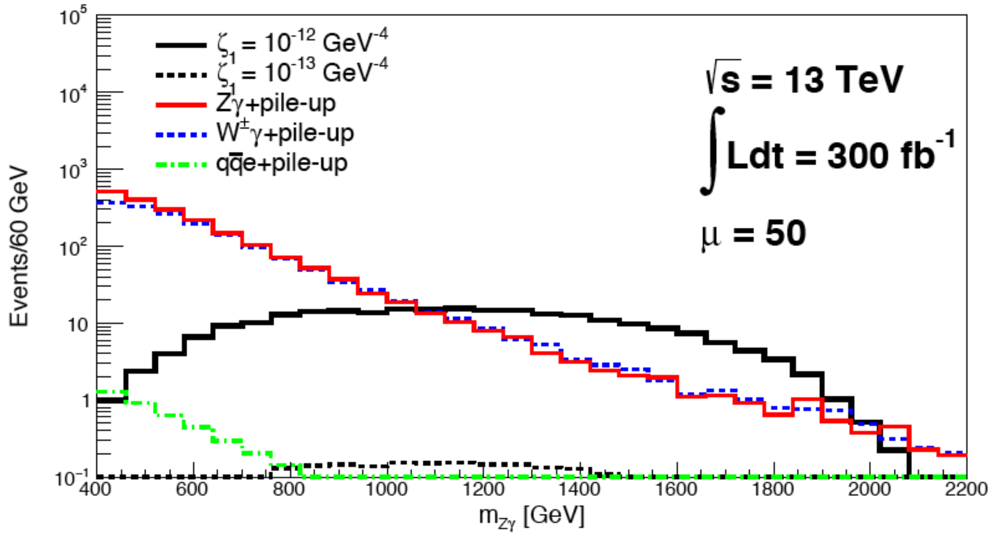


- Production of axions via photon exchanges and tagging the intact protons in the final state complementary to the usual search at the LHC (Z decays into 3 photons): sensitivity at high axion mass - C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, ArXiv 1803.10835
- Gain on sensitivity by about one order of magnitude on the coupling with 3000 fb^{-1} (dependence on the square value of the coupling)
- Complementarity to Pb Pb running: sensitivity to low mass diphoton, low luminosity but cross section increased by Z^4

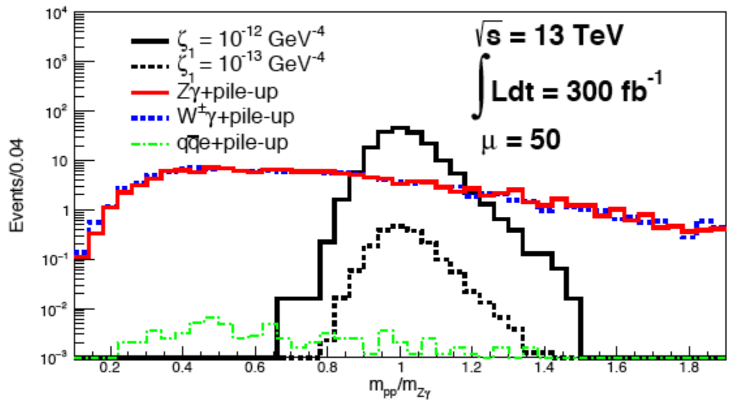
$\gamma\gamma\gamma Z$ quartic anomalous coupling

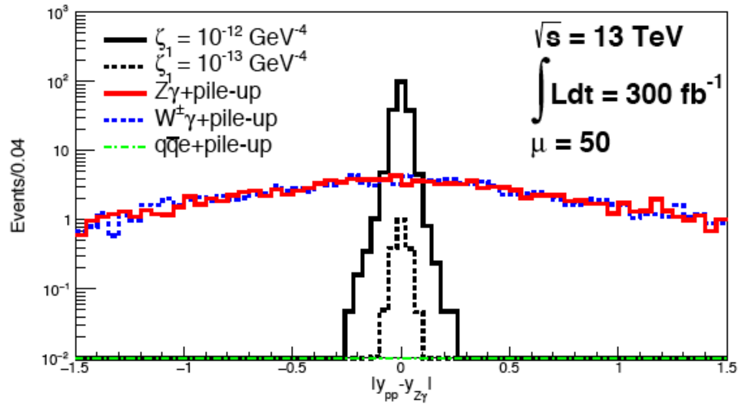


- Look for $Z\gamma$ anomalous production
- Z can decay leptonically or hadronically: the fact that we can control the background using the mass/rapidiy matching technique allows us to look in both channels (very small background)



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





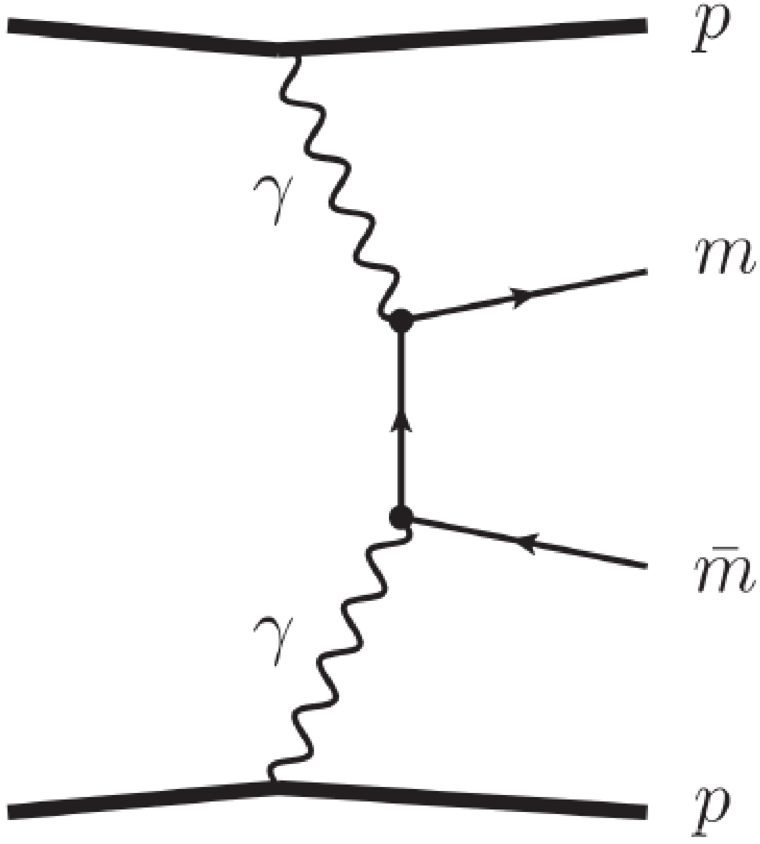
Coupling (GeV^{-4})	ζ ($\tilde{\zeta}=0$)		$\zeta=\tilde{\zeta}$	
Luminosity	300 fb^{-1}		300 fb^{-1}	
Pile-up (μ)	50		50	
Channels	5 σ	95% CL	5 σ	95% CL
$\ell\bar{\ell}\gamma$	$2.8\cdot10^{-13}$	$1.8\cdot10^{-13}$	$2.5\cdot10^{-13}$	$1.5\cdot10^{-13}$
$jj\gamma$	$2.3\cdot10^{-13}$	$1.5\cdot10^{-13}$	$2\cdot10^{-13}$	$1.3\cdot10^{-13}$
$jj\gamma\bigoplus\ell\bar{\ell}\gamma$	$1.93\cdot10^{-13}$	$1.2\cdot10^{-13}$	$1.7\cdot10^{-13}$	$1\cdot10^{-13}$

Coupling	ζ ($\tilde{\zeta}=0$)		$\zeta=\tilde{\zeta}$	
Luminosity	3000 fb^{-1}		3000 fb^{-1}	
Pile-up	200		200	
Channel	5σ	95 % C.L.	5σ	95% C.L.
$\ell\bar{\ell}\gamma$	$1.8\cdot10^{-13}$	$1.1\cdot10^{-13}$	$1.25\cdot10^{-13}$	$7.8\cdot10^{-14}$

- C. Baldenegro, S. Fichet, G. von Gersdorff, C.R., JHEP 1706 (2017) 142; high lumi: need timing detectors, gain of a factor 10
- Need to study the case when Z boson decays into fat jets

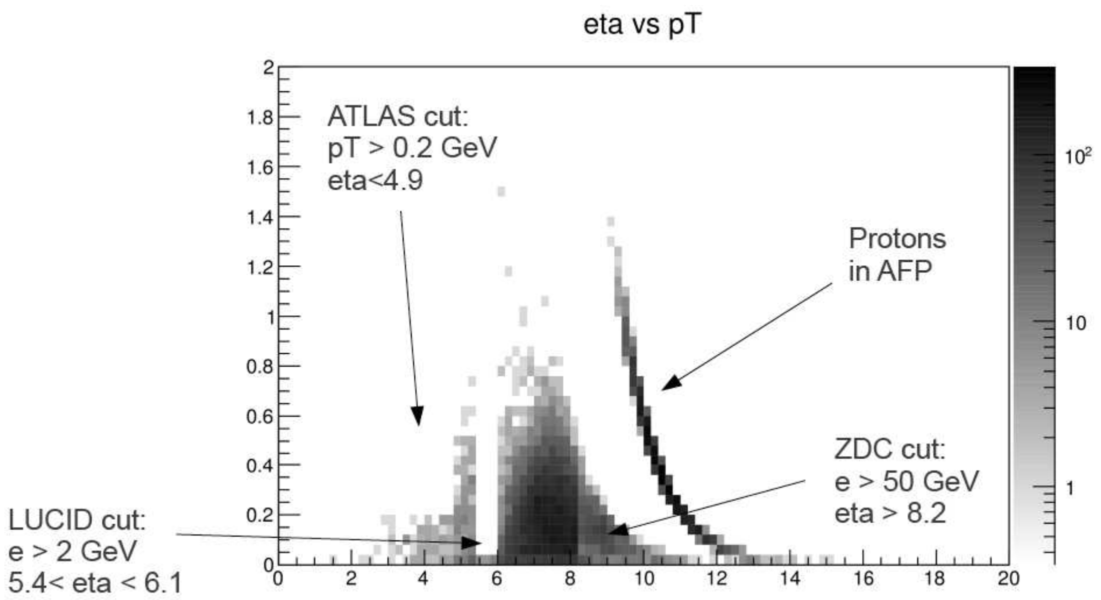
Invisible objects in CMS

- Production of pairs of magnetic monopoles
- Production of pairs of dark matter particles
- Signature: nothing in ATLAS/CMS, 2 protons of high mass in CT-PPS, AFP....
- A few issues: Trigger rate, background? (we do not see anything in CMS/ATLAS and any quasi-elastic event is a background)



How to see invisible events? Some ideas...

- The vertex where dark matter particles, monopoles are produced is not known; neither the double diffractive background
- We assume that the two protons originate form that vertex and we measure the time of flight of produced particles
- We now assume that we measure the time-of-flight of all particles produced in the very forward region (ZDC...) and we can get that information at trigger level; this means that we know from which vertex these particles are originating
- We need to request that there is incompatibility between the two proton vertex (found using time detectors) and the vertex found using particles in very forward region
- This requires few upgrades: timing measurements in forward detectors, possibility of triggering on high mass proton pairs



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
  - NB: Survival probablity in better control than in the QCD (gluon) case
- CT-PPS/AFP allows to probe BSM diphoton production in a model independent way
- Different channels: $\gamma\gamma$, ZZ, $Z\gamma$ in leptonic modes do not need timing detectors, additional channels require timing measurements (ZZ, $Z\gamma$, WW in hadronic/semi-leptonic channels, jet jet
- Search for axion like particles at high mass