Anomalous coupling studies at the LHC with proton tagging

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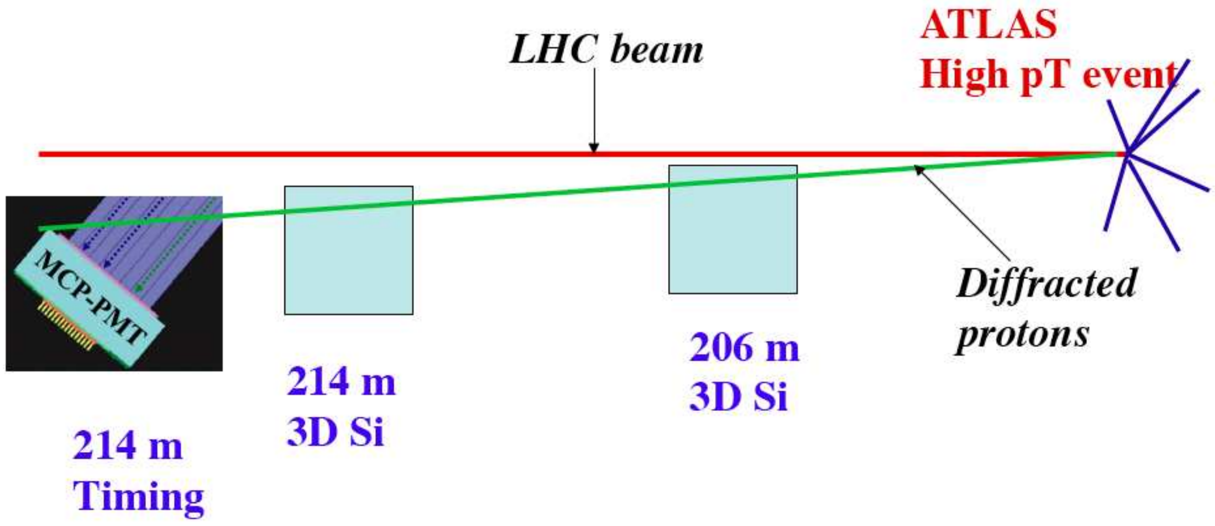
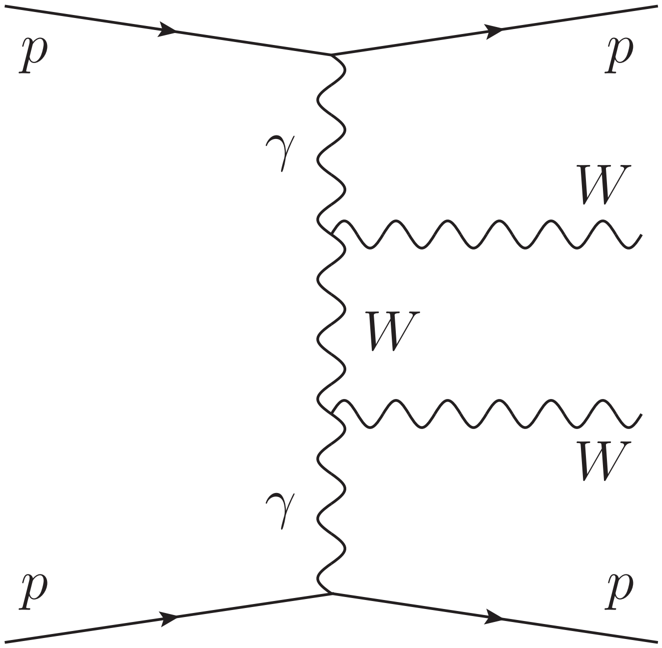
- $\gamma\gamma WW$ and $\gamma\gamma ZZ$ anomalous couplings
- $\gamma\gamma$ exclusive production in SM
- $\gamma\gamma\gamma\gamma$ anomslous coupling



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

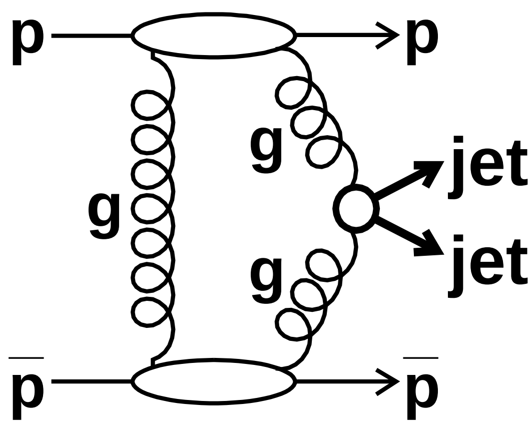


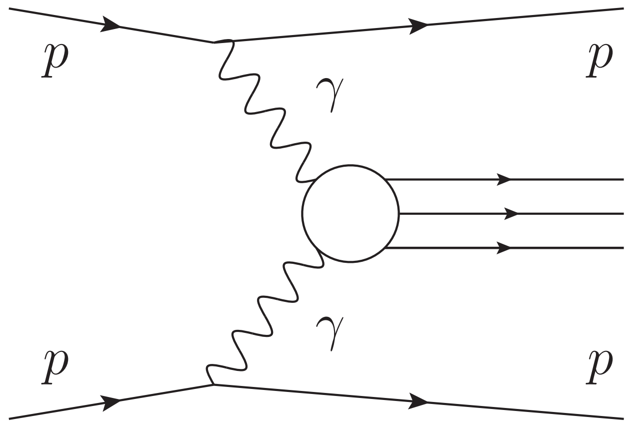
- Study of the process: $pp \to ppWW$
- Standard Model: $\sigma_{WW} = 95.6$ fb, $\sigma_{WW}(W = M_X > 1TeV) = 5.9$ fb
- Process sensitive to anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$; motivated by studying in detail the mechanism of electroweak symmetry breaking,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

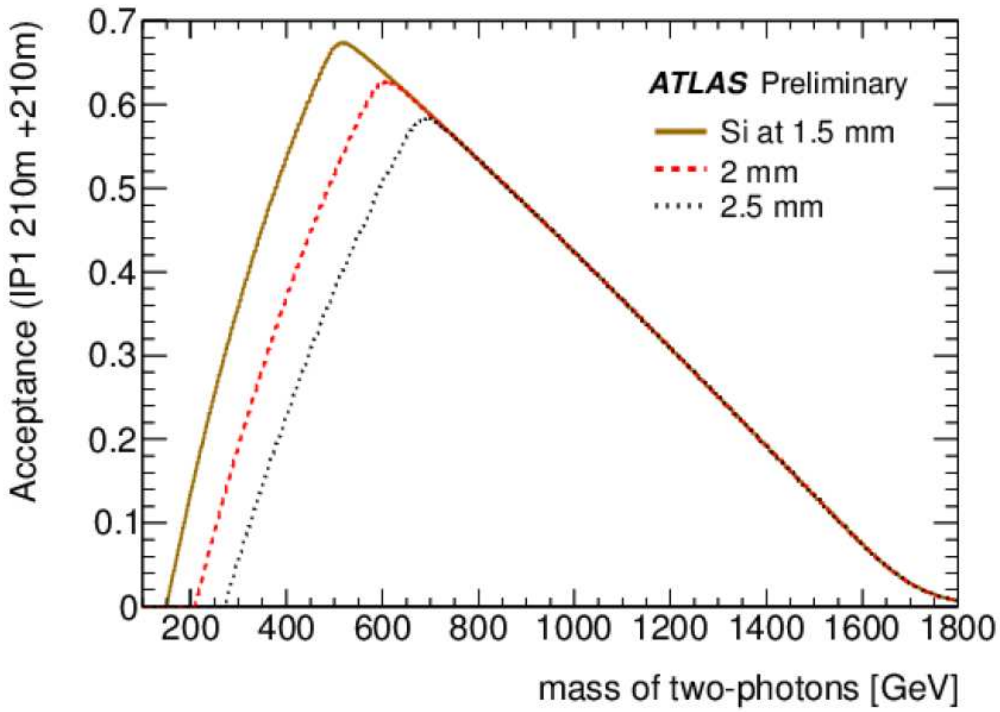
Forward Physics Monte Carlo (FPMC)

- 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 and also to the full simulation including pile up

AFP/PPS acceptance in total mass



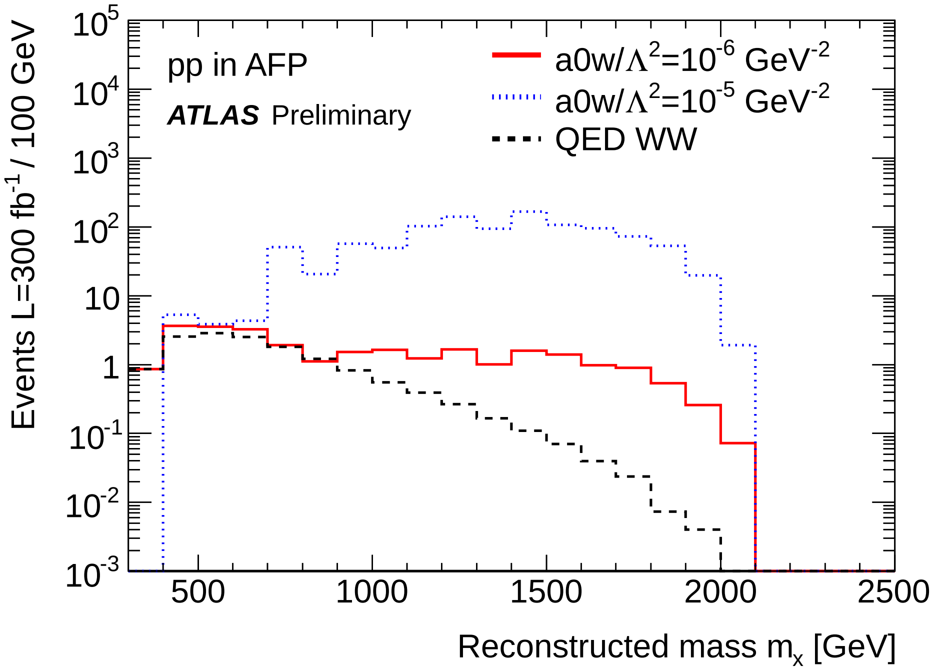


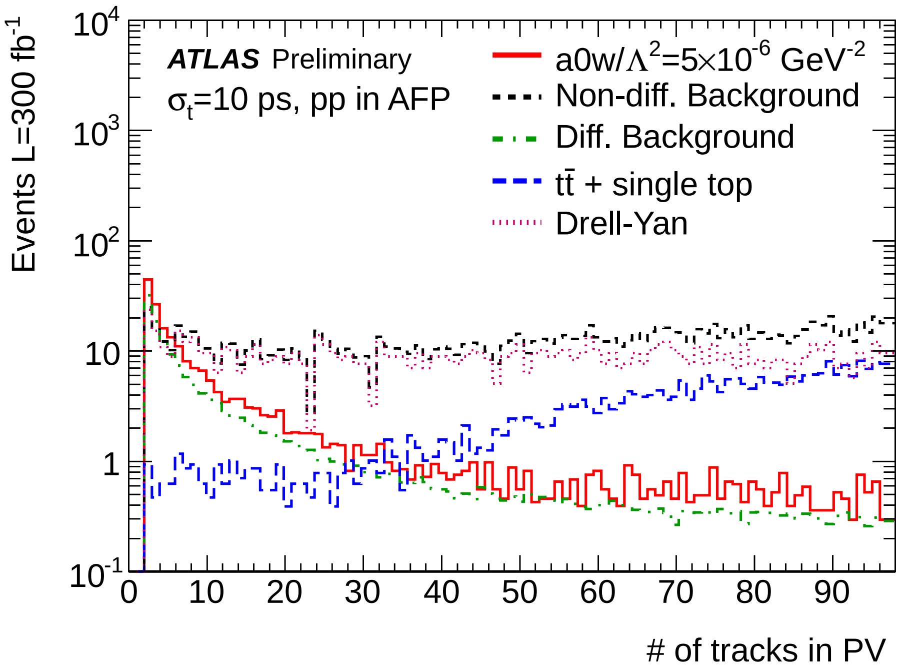


- Assume protons to be tagged at 210 m and/or 420 m
- Sensitivity to high mass central system, X, as determined using AFP
- Very powerful for exclusive states: kinematical constraints coming from AFP proton measurements

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}

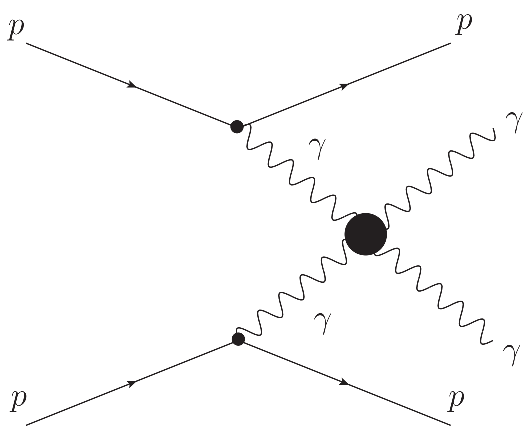
Reach at LHC

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

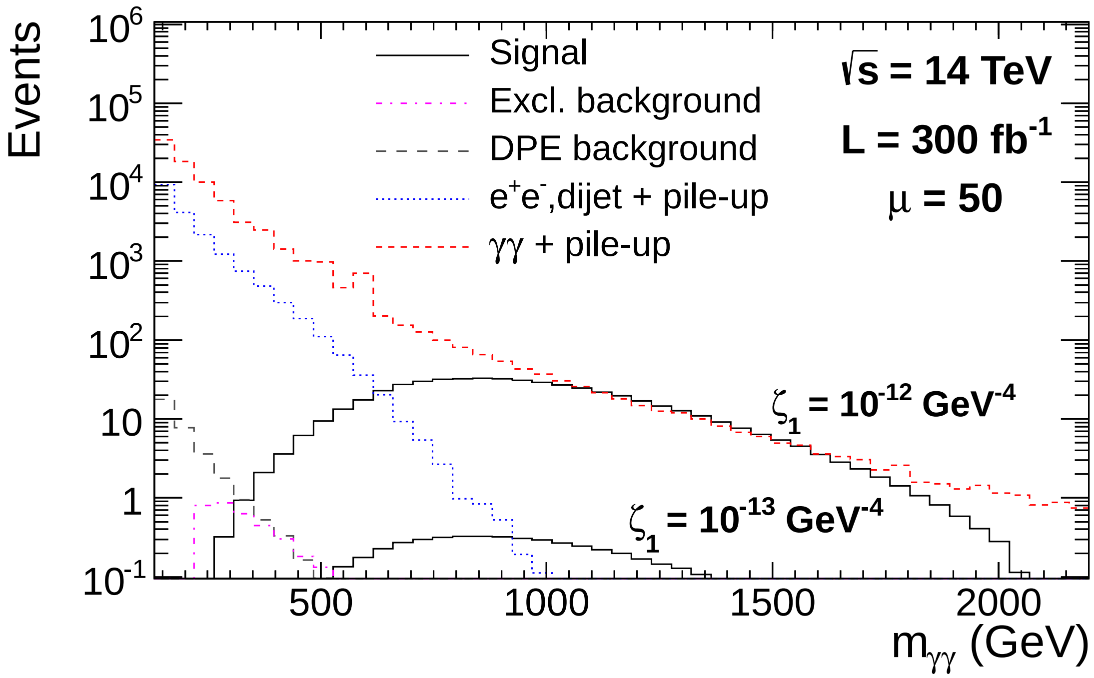
Couplings	OPAL limits [GeV^{-2}]	Sensitivity @ $\mathcal{L} = 30$ (200) fb^{-1} 5σ	95% CL
a_0^W/Λ^2	[-0.020, 0.020]	5.4 10^{-6} (2.7 10^{-6})	2.6 10^{-6} (1.4 10^{-6})
a_C^W/Λ^2	[-0.052, 0.037]	2.0 10^{-5} (9.6 10^{-6})	9.4 10^{-6} (5.2 10^{-6})
a_0^Z/Λ^2	[-0.007, 0.023]	1.4 10^{-5} (5.5 10^{-6})	6.4 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 LEP sensitivity by more than 4 orders of magnitude with 30/200 fb^{-1} at LHC, and of D0/CMS results by $\sim$two orders of magnitude (only $\gamma\gamma WW$ couplings)
- Reaches the values predicted by extra-dimension models

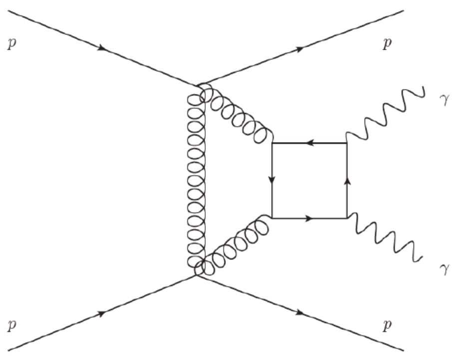
Search for quartic $\gamma\gamma$ anomalous couplings

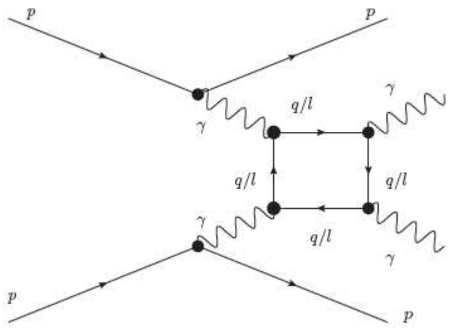


- Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- Analysis performed at hadron level including detector efficiencies, resolution effects, pile-up...

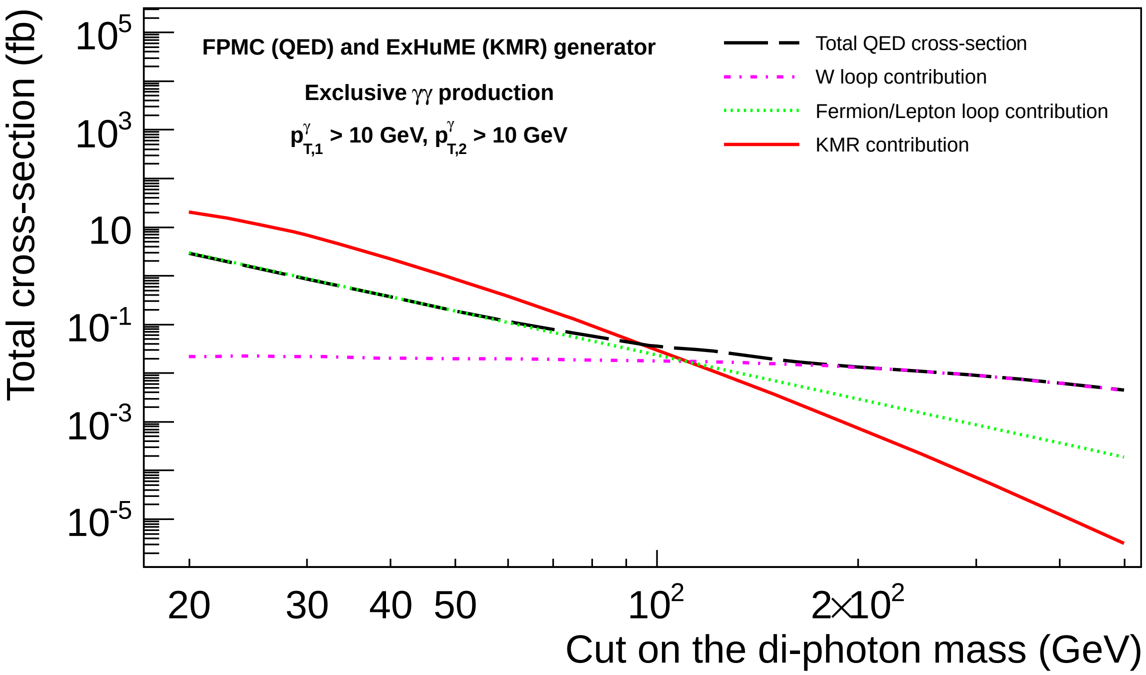


SM QED exclusive $\gamma\gamma$ production

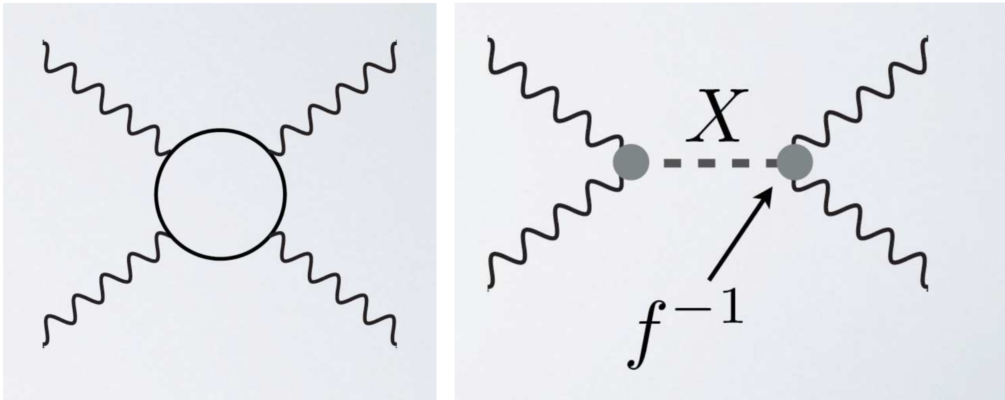




- QCD exclusive contribution dominant at low masses (KMR)
- Different loop contributions: fermions (quarks, leptons), vectors (W bosons)
- W loop contributions and massive fermions added in the calculation: W loop dmminates at high mass



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}

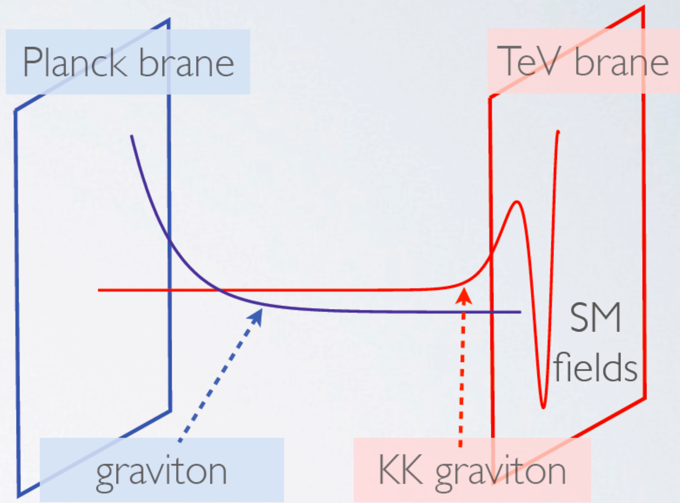
- ζ_1 can also be modified by neutral particles at tree level (extensions of the SM including scalar, pseudo-scalar, and spin-2 resonances that couple to the photon) $\zeta_1 = (f_s m)^{-2} d_{1,s}$ where f_s is the $\gamma\gamma X$ coupling of the new particle to the photon, and $d_{1,s}$ depends on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

Warped extra-dimensions (Gero von Gersdorff)

✘ 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

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

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

✘ Effective 4-photon couplings $\zeta_i \sim 10^{-14} - 10^{-13}\ \text{GeV}^{-2}$ possible

✘ The radion can produce similar effective couplings

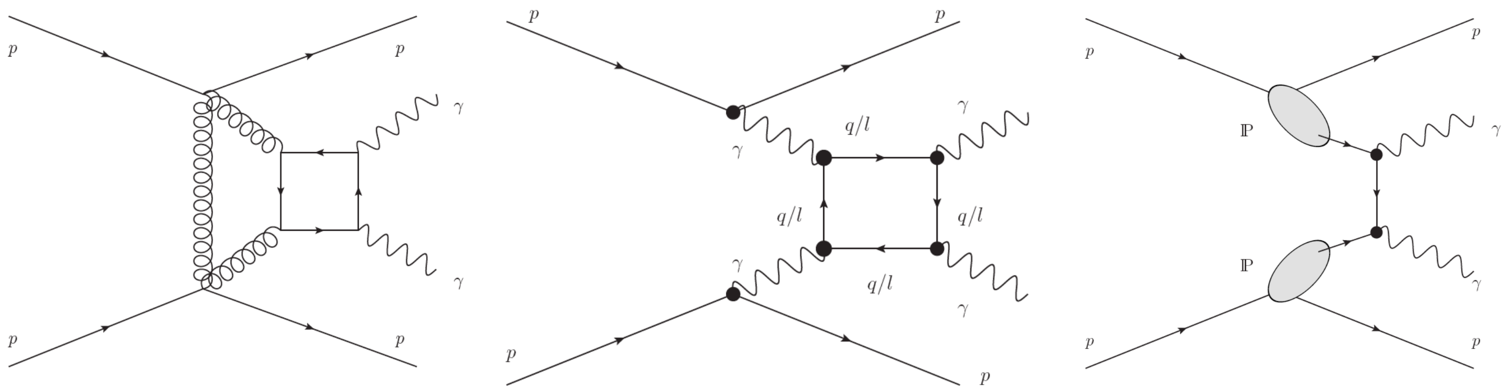
- Which models/theories are we sensitive to using AFP/PPS
- Beyond standard models predict anomalous couplings of $\sim 10^{-14}$-10^{-13}
- Work in collaboration with Sylvain Fichet, Gero von Gersdorff

Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings: Analysis flow

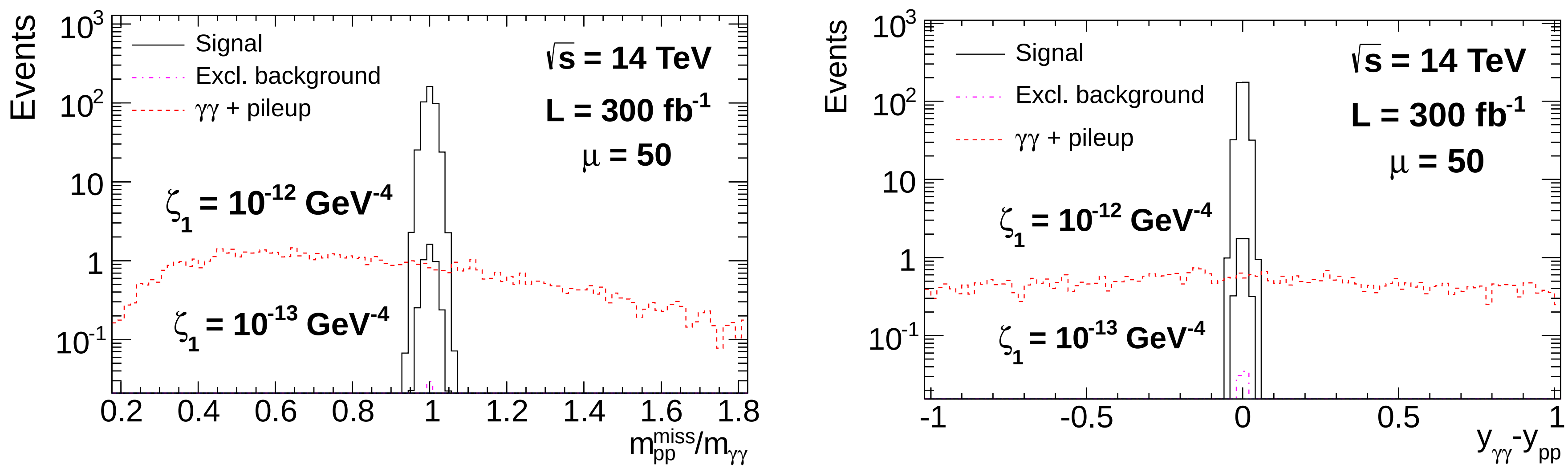
- Studies performed at hadron level but taking into account the main detector/pile-up effects
- By default, $> 1\gamma$ converted is requested (1 mm resolution), but all γ are also considered, and can handle pile-up thanks to the "pointing" ATLAS calorimeter (contrary to CMS...)
- pile-up simulated in AFP: 50, 100, 200 pile-up events per bunch crossing are considered
- Exclusive diffractive /DPE/ND backgrounds are considered and the largest one is pile-up
- Main detector effects are included (from ATLAS ECFA studies ATL-PHYS-PUB-2013-009), for instance:
  - Photon conversion probability: 15% in barrel, 30% in the end-caps; γ rapidity, Φ, and p_T resolutions taken into account as well as the reconstruction efficiency
  - Misidentification of electron as a γ: 1%
  - Misidentification of jet as a γ: 1/4000,
  - See: S.Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert, Phys. Rev. D89 (2014) 114004
  - Interesting to look also in the heavy ion mode: study in progress

Considered background

- Background leading to two photons in the final state: DPE diphoton production, exclusive diphotons (quark box, exclusive KMR), DPE Higgs decaying into $\gamma\gamma$
- Background related to misidentification: Exclusive dilepton production, dijet production, same for DPE (using misidentification probanilities in ATLAS)
- Pile up background: Non diffractive production and pile up (50, 100, 200), Drell-Yan, dijet, diphoton
- Assume at least 1 photon to be converted, high p_T photons (above 200 GeV)
- Further reduction using timing detectors: Reject background by a factor 40 for a pile up of 50 (10 ps resolution assumed)



Search for quartic $\gamma\gamma$ anomalous couplings



- Trigger: 2 high p_T central photons, $p_{T_1} > 200$ GeV, $p_{T_2} > 150$ GeV, no special AFP trigger needed
- Protons are detected in AFP at high $\xi >\sim 0.04$: massive objects are produced, we do not need to be very close to the beam
- Exclusivity cuts: diphoton mass compared from missing mass computed using protons, rapidity difference between diphoton and proton systems: suppresses all pile-up backgrounds
- For 300 fb^{-1} and a pile-up of 50: 0 background event for 15.1 (3.8) signal events for an anomalous coupling of 2 10^{-13} (10^{-13})
- Exclusivity cuts are fundamental to suppress all background and increase the sensitivity
- NB: theoretical uncertainties are larger in the case of non-exclusive production (usual study in ATLAS) since it is sensitive to the poorly known photon structure function at high energy

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

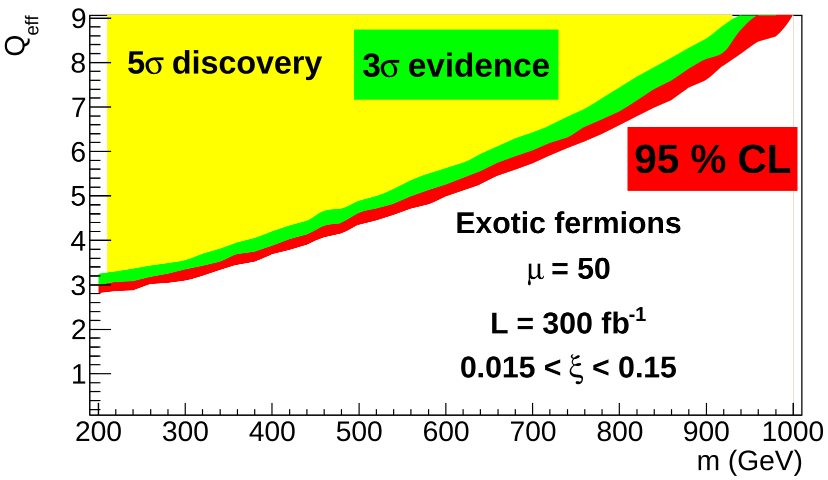
Cut / Process	Signal	Excl.	DPE	e^+e^-, dijet + pile-up	$\gamma\gamma$ + pile-up
$0.015 < \xi < 0.15$, $p_{T1,2} > 50$ GeV	20.8	3.7	48.2	$2.8\ 10^4$	$1.0\ 10^5$
$p_{T1} > 200$GeV, $p_{T2} > 100$ GeV	17.6	0.2	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	16.6	0.1	0.	0.2	1023
$p_{T2}/p_{T1} > 0.95$, $\lvert\Delta\phi\rvert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

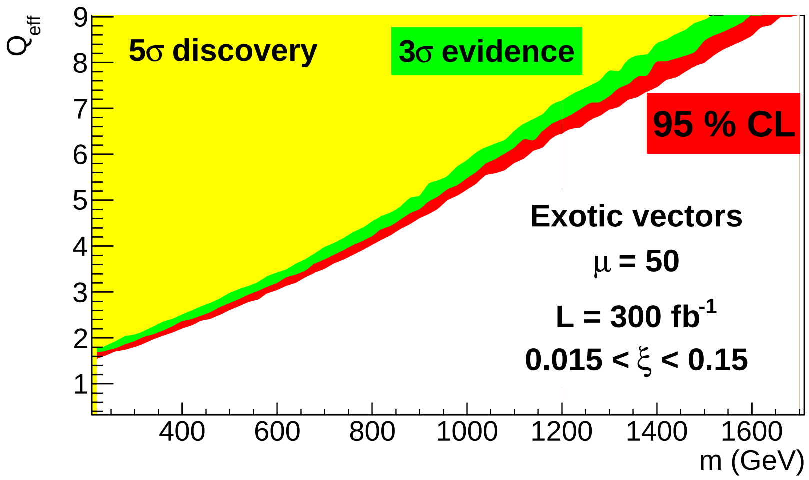
- No background after cuts for 300 fb^{-1} **without using timing detector information**
- Exclusivity cuts needed to suppress backgrounds:
  - Without exclusivity cuts using AFP: background of 80.2 for 300 fb^{-1} for a signal of 16.2 events ($\zeta_1 = 2\ 10^{-13}$)
  - With exclusivity cuts: 0 background for 15,1 signal
- String theory/grand unification models predict couplings via radions/heavy charged particles/dilatons for instance up to 10^{-14}-10^{-13}

Luminosity	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
pile-up (μ)	50	50	50	200
coupling (GeV^{-4})	≥ 1 conv. γ 5 σ	≥ 1 conv. γ 95% CL	all γ 95% CL	all γ 95% CL
ζ_1 f.f. ζ_1 no f.f.	$1 \cdot 10^{-13}$ $3.5 \cdot 10^{-14}$	$9 \cdot 10^{-14}$ $2.5 \cdot 10^{-14}$	$5 \cdot 10^{-14}$ $1.5 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$ $7 \cdot 10^{-15}$
ζ_2 f.f. ζ_2 no f.f.	$2.5 \cdot 10^{-13}$ $7.5 \cdot 10^{-14}$	$1.5 \cdot 10^{-13}$ $5.5 \cdot 10^{-14}$	$1 \cdot 10^{-13}$ $3 \cdot 10^{-14}$	$4.5 \cdot 10^{-14}$ $1.5 \cdot 10^{-14}$

Full amplitude calculation

- Full amplitude calculation for generic heavy charged fermion/vector contribution
- Existence of new heavy charged particles enhances the $\gamma\gamma\gamma\gamma$ couplings in a model independant way
- Enhancement parametrised with particle mass and effective charge $Q_{eff} = QN^{1/4}$ where N is the multiplicity
- Publication in preparation with G. von Gersdorff, S. Fichet, M. Saimpert, O. Kepka, B. Lenzi, C. Royon
- Unprecedented sensitivites at hadronic colliders reaching the values predicted by extra-dim models





Conclusion

- Explaratory physics I: look for $\gamma\gamma WW$ and $\gamma\gamma ZZ$ anomalous couplings
- Exploratory physics II: Anomalous $\gamma\gamma\gamma\gamma$ couplings, test extra-dimension models with unprecedented precision, reaching the values predicted by some generic models