Quartic anomalous coupling studies at the LHC

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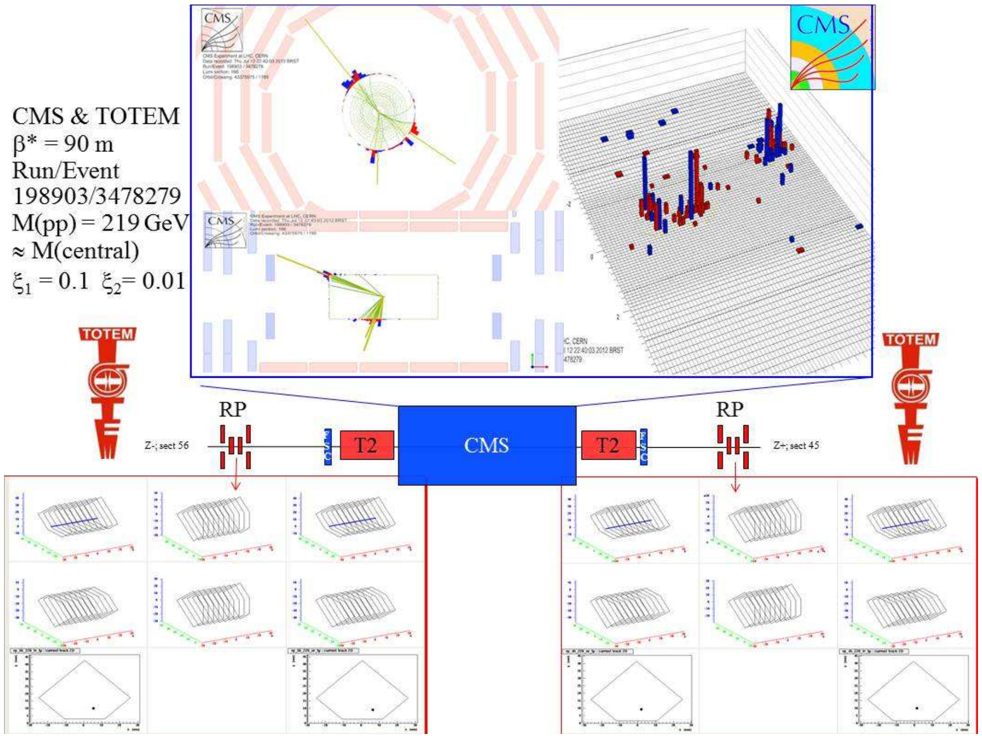
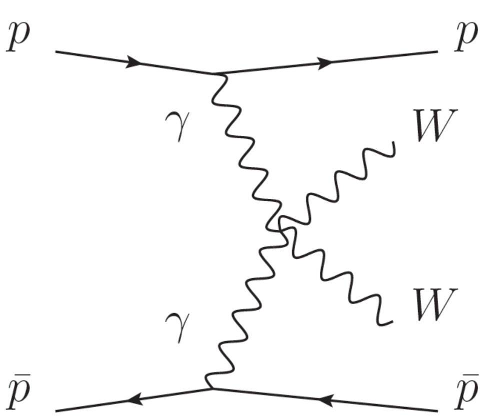
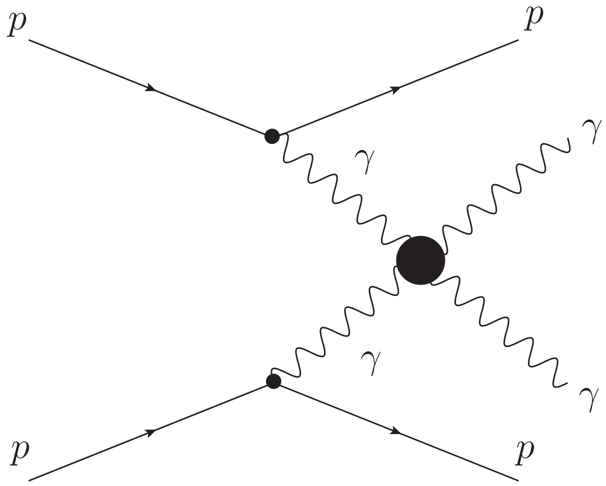


Contents:

- Anomalous $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings
- Anomalous $\gamma\gamma\gamma\gamma$ couplings: effective model
- Anomalous $\gamma\gamma\gamma\gamma$ couplings: full model

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



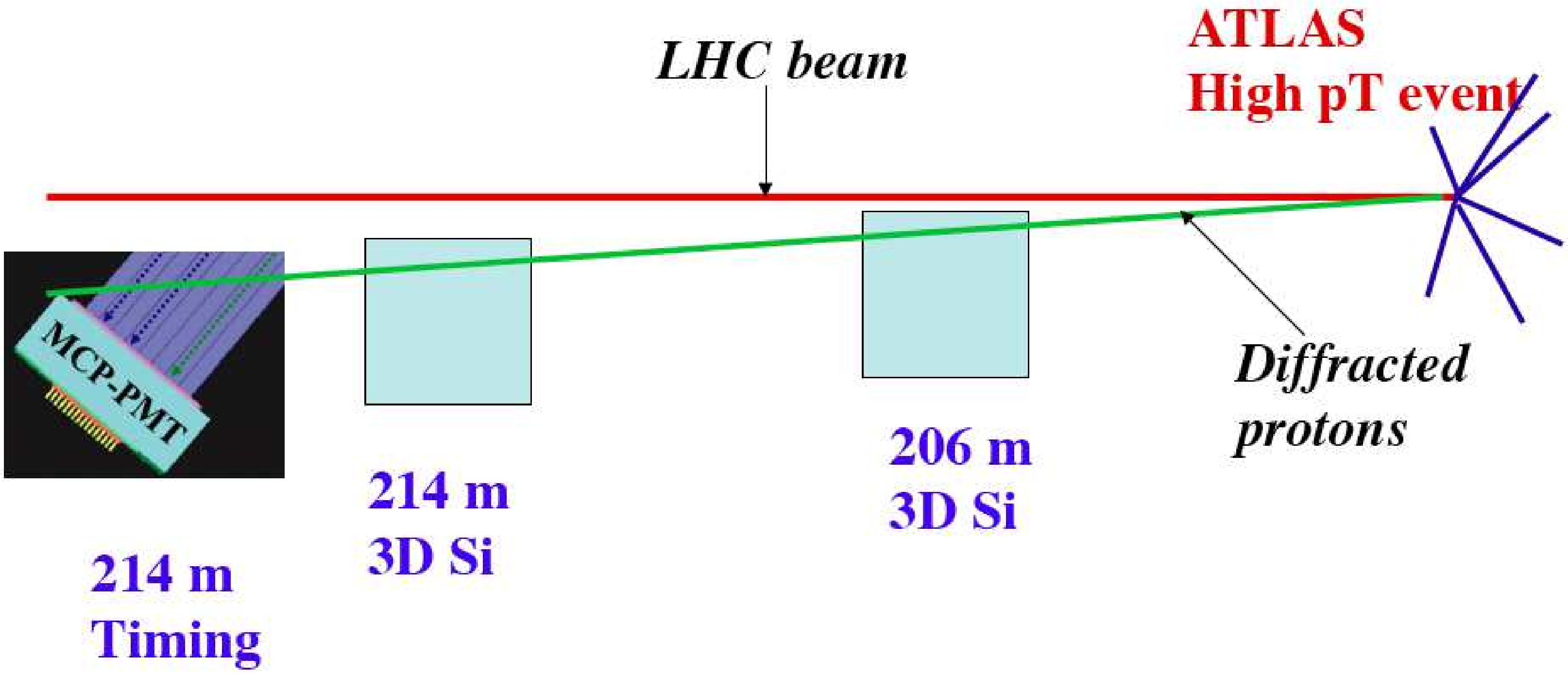


- Study of the process: $pp \to ppWW$, $pp \to ppZZ$, $pp \to pp\gamma\gamma$
- Standard Model: $\sigma_{WW} = 95.6$ fb, $\sigma_{WW}(W = M_X > 1TeV) = 5.9$ fb
- Process sensitive to anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$; motivated by studying in detail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

Forward Physics Monte Carlo (FPMC)

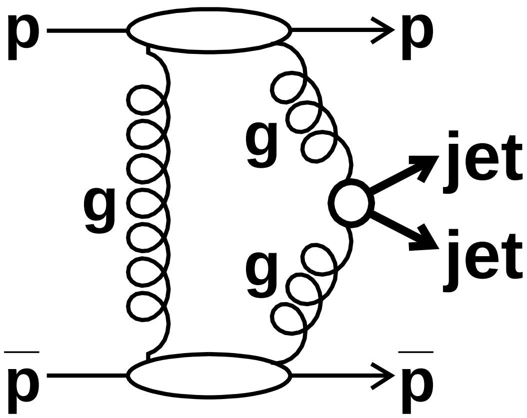
- FPMC (Forward Physics Monte Carlo): implementation of all diffractive/photon induced processes
- List of processes
  - two-photon exchange
  - single diffraction
  - double pomeron exchange
  - central exclusive production
- Inclusive diffraction: Use of diffractive PDFs measured at HERA, with a survival 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

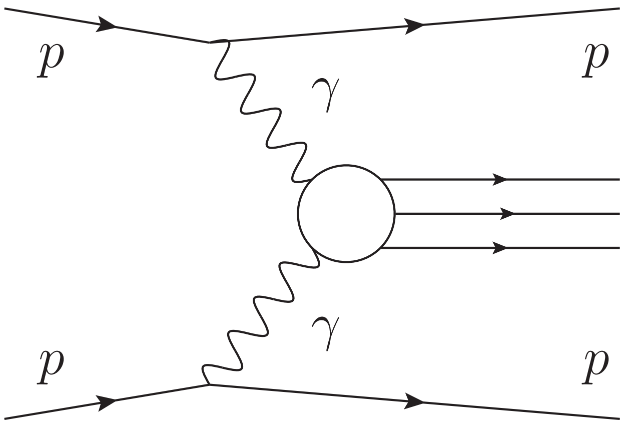
AFP and CT-PPS?

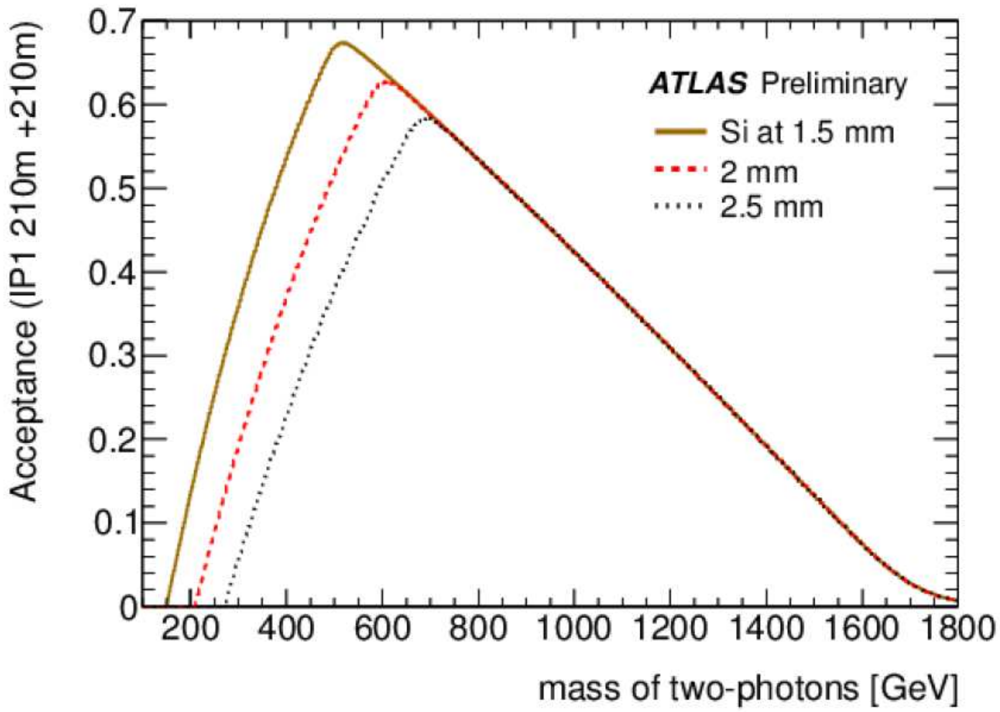


- Tag and measure protons at $\pm$210 m: AFP in ATLAS, CT-PPS in CMS/Totem
- AFP and CT-PPS detectors: measure proton position (Silicon detectors) and time-of-flight (timing detectors)

AFP/CT-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/CT-PPS 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 $\rightarrow$ violation of unitarity at high energies

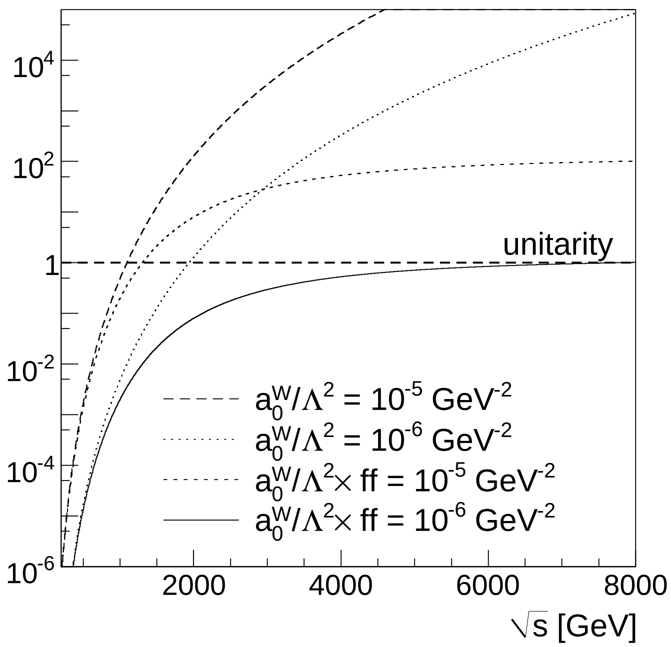
Quartic anomalous gauge couplings: form factors

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

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

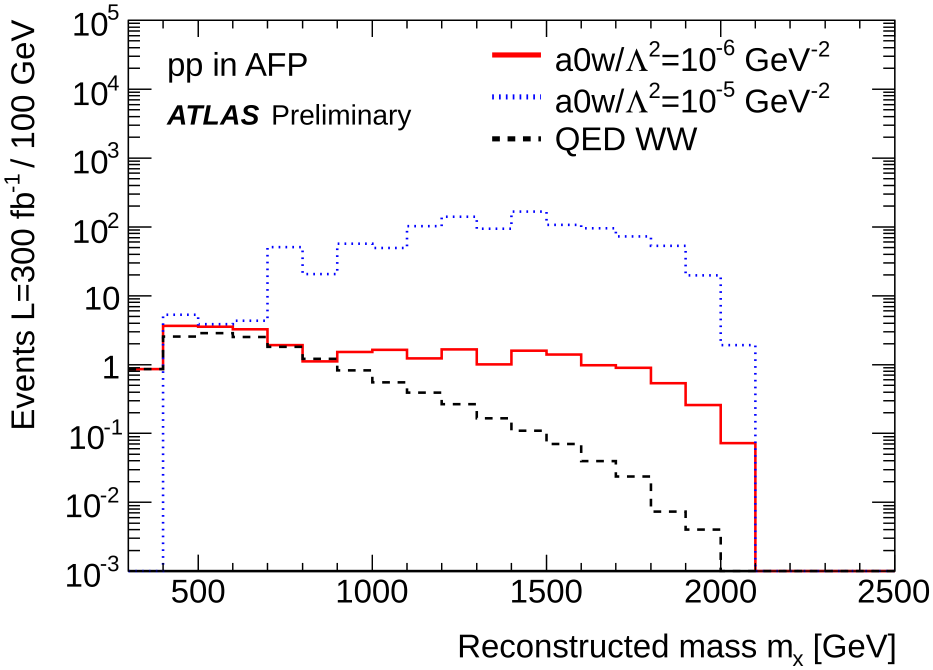
where $a = a_0/\Lambda^2$

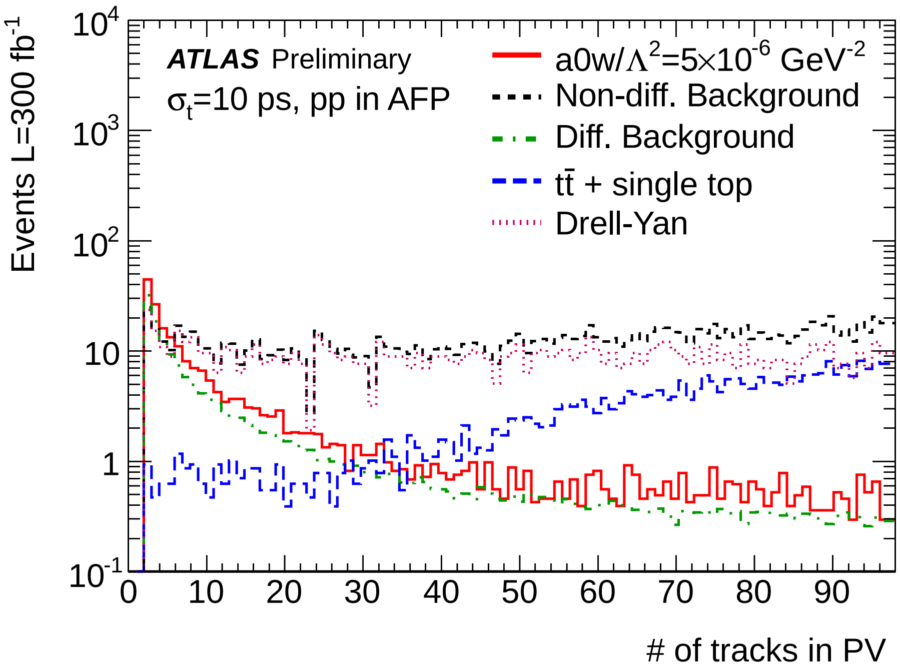
- Introducing form factors to avoid quadratical divergences of scattering amplitudes due to anomalous couplings in conventional way: $a_0^W/\Lambda^2 \to \frac{a_0^W/\Lambda^2}{(1+W\gamma\gamma/\Lambda_{cutoff})^2}$ with $\Lambda_{cutoff} \sim 2$ TeV, scale of new physics
- For $a_0^W \sim 10^{-6}$ GeV^{-2}, no violation of unitarity, but results depend on value of Λ_{cutoff} if new particle masses are of the same order as the LHC center-of-mass energy



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 $pp \to l^{\pm}\nu\gamma\gamma$ (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}

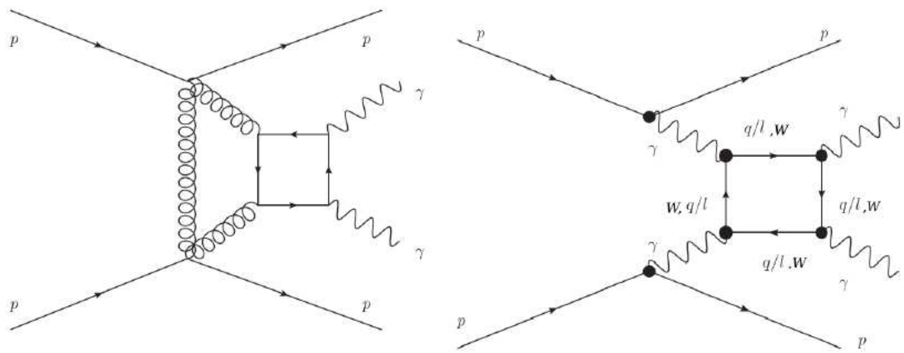
Reach at LHC

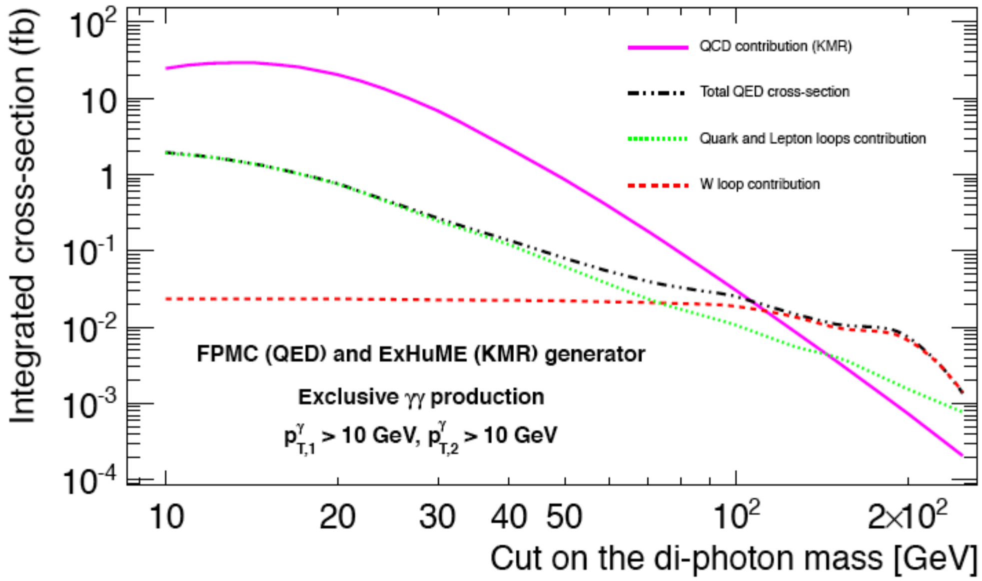
Reach at high luminosity on quartic anomalous coupling using fast simulation (study other anomalous couplings such as $\gamma\gamma ZZ$...)

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

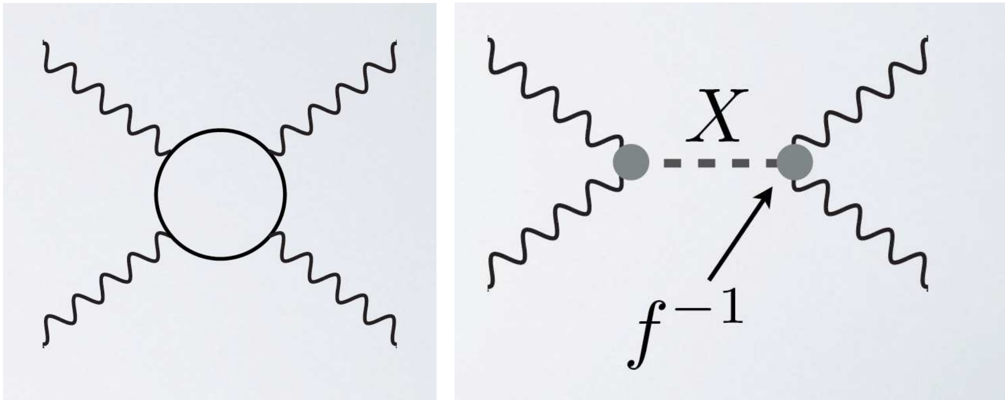
SM $\gamma\gamma$ exclusive production





- QCD production dominates at low $m_{\gamma\gamma}$, QED at high $m_{\gamma\gamma}$
- Important to consider W loops at high $m_{\gamma\gamma}$
- Possibility to measure KMR contribution at low $m_{\gamma\gamma}$ in high β^* runs: with two protons tagged in TOTEM/ALFA, $\sigma \sim$ 372 fb for $m_{\gamma\gamma} > 10$ GeV, $p_T^{\gamma} > 5$ GeV

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

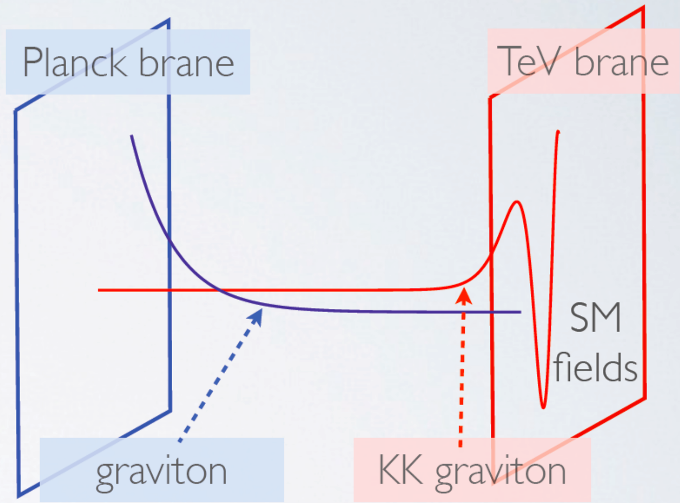
$$\zeta_1 = \alpha_{em}^2 Q^4 m^{-4} N c_{1,s}$$

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

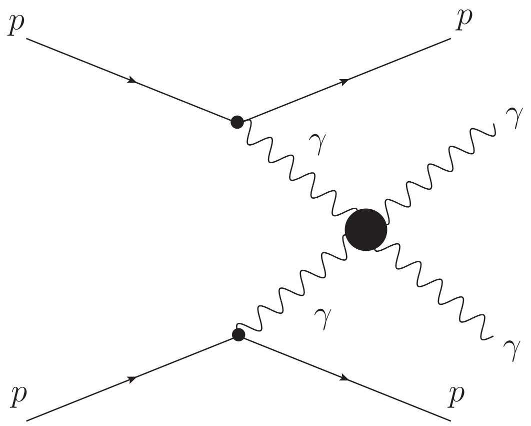
$$\mathcal{L}^{\gamma\gamma h} = f^{-2}\, h^{\rm KK}_{\mu\nu} \left(\tfrac{1}{4}\eta_{\mu\nu}F^2_{\rho\lambda} - F_{\mu\rho}F_{\rho\nu}\right)$$

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

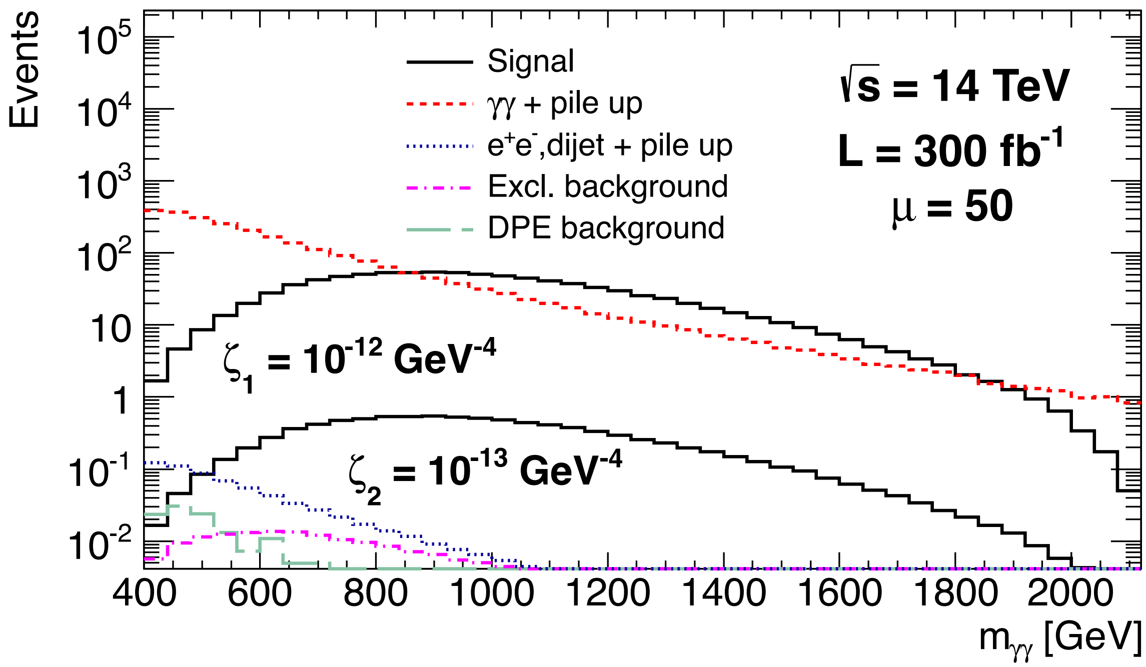
- ✘ Effective 4-photon couplings $\zeta_i \sim 10^{-14} - 10^{-13}\ \mathrm{GeV}^{-2}$ possible
- ✘ The radion can produce similar effective couplings

- 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...

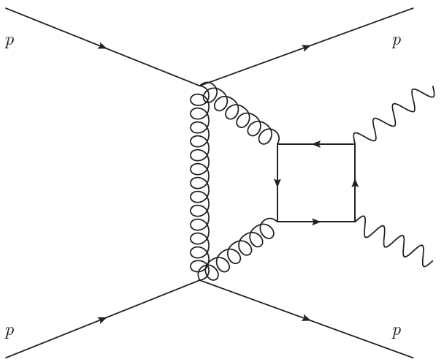


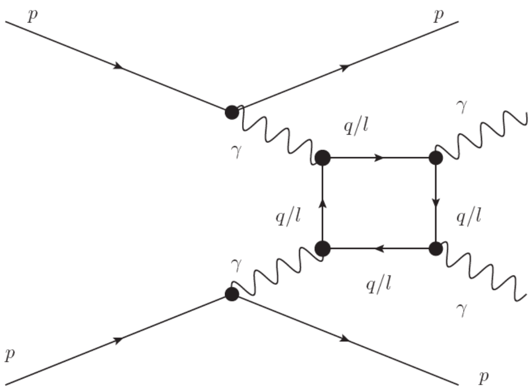
Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings: Analysis flow

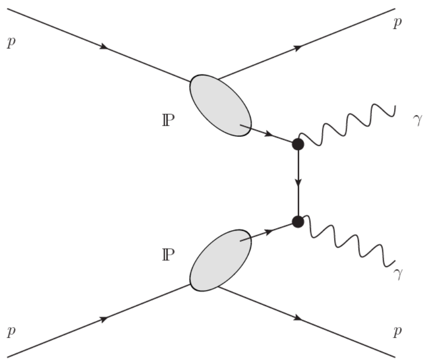
- Studies performed at hadron level but taking into account the main detector/pile-up effects
- By default, $> 1\gamma$ converted is requested (1 mm resolution), but all γ are also considered, and can handle pile-up thanks to the "pointing" ATLAS calorimeter (CMS leads to slightly worse results)
- pile-up 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,

Considered background

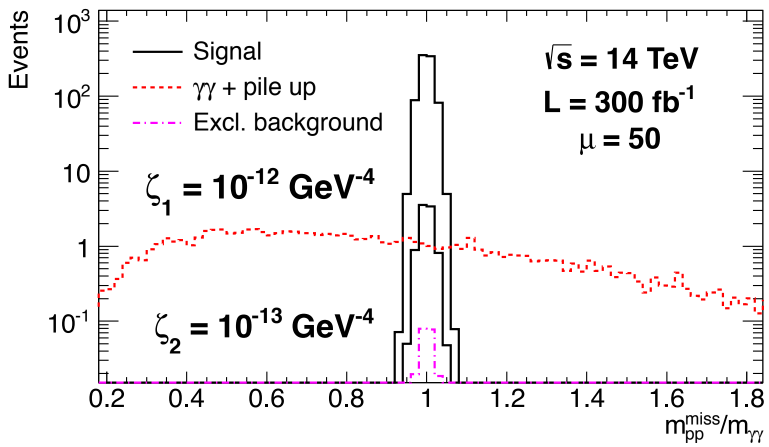
- Background leading to two photons in the final state: DPE diphoton production, exclusive diphotons (quark box, exclusive KMR), DPE Higgs decaying into $\gamma\gamma$
- Background related to misidentification: Exclusive dilepton production, dijet production, same for DPE (using misidentification probanilities 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)

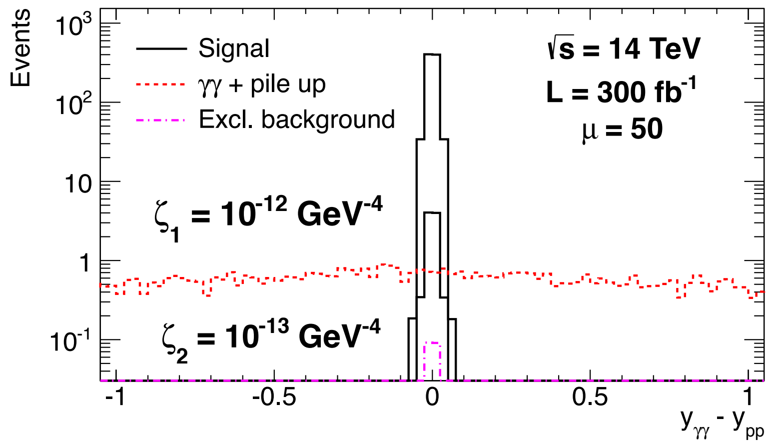






Search for quartic $\gamma\gamma$ anomalous couplings





- Trigger: 2 high p_T central photons, $P_{T_1} > 200$ GeV, 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: 0.2 background event for 32 signal events for an anomalous coupling of 2 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 from effective theory

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
$[p_{T2}/p_{T1} > 0.95,$ $\lvert\Delta\phi\rvert > \pi - 0.01]$	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
$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	119.1	31.8 (338.5)	0.18	0	0	0

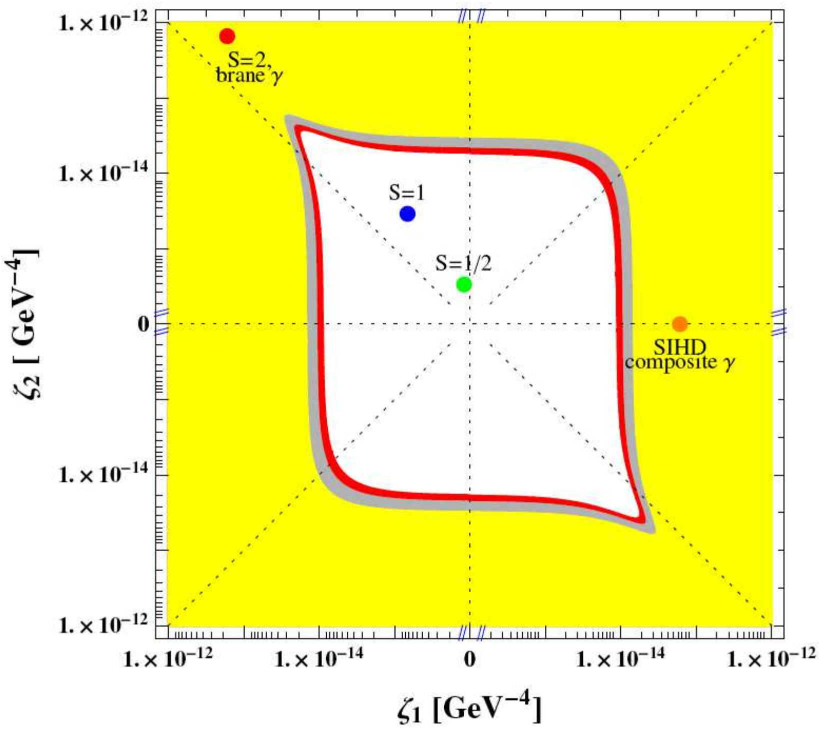
- No background after cuts for 300 fb^{-1} **without needing timing detector information**
- Exclusivity cuts needed to suppress backgrounds:
  - Without exclusivity cuts using AFP: background of 80.2 for 300 fb^{-1} for a signal of 34.9 events ($\zeta_1 = 2\ 10^{-13}$)
  - With exclusivity cuts: 0.18 background for 31.8 signal
- String theory/grand unification models predict couplings via radions/heavy charged particles/dilatons for instance up to 10^{-14}-10^{-13}

Search for quartic $\gamma\gamma$ anomalous couplings: Results from effective theory

Sensitivities reaching values of extradim models

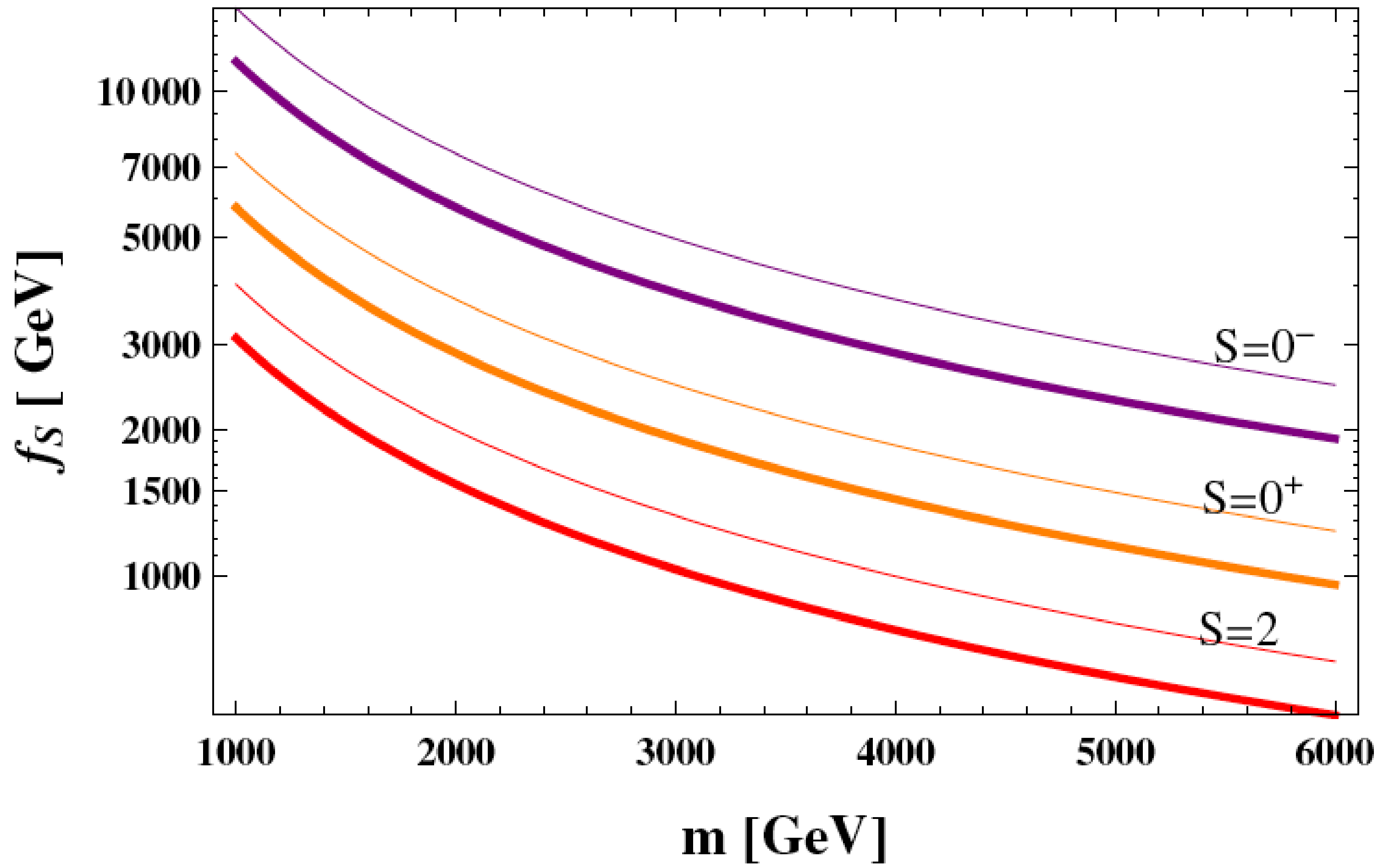
Luminosity	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
pile-up (μ)	50	50	50	200
coupling (GeV^{-4})	$\geq$ 1 conv. γ 5 σ	$\geq$ 1 conv. γ 95% CL	all γ 95% CL	all γ 95% CL
ζ_1 f.f. ζ_1 no f.f.	$8 \cdot 10^{-14}$ $2.5 \cdot 10^{-14}$	$5 \cdot 10^{-14}$ $1.5 \cdot 10^{-14}$	$3 \cdot 10^{-14}$ $9 \cdot 10^{-15}$	$2.5 \cdot 10^{-14}$ $7 \cdot 10^{-15}$
ζ_2 f.f. ζ_2 no f.f.	$2. \cdot 10^{-13}$ $5 \cdot 10^{-14}$	$1. \cdot 10^{-13}$ $4 \cdot 10^{-14}$	$6 \cdot 10^{-14}$ $2 \cdot 10^{-14}$	$4.5 \cdot 10^{-14}$ $1.5 \cdot 10^{-14}$

Sensitivity in the (ζ_1, ζ_2) plane



- Sensitivities for charged particle production (loops) in the (ζ_1, ζ_2) plane
- Yellow, grey and red: 5σ, 3σ, 95% CL limits with 300 fb^{-1} and μ =50
- Contributions from electric particles with spin 1/2 and 1, charge $Q_{Jeff} = 3$, mass =1 TeV; warped KK graviiton with mass 3 TeV (κ =2), brane localized photon; strongly interacting heavy dilaton (SIHD) with mass 3 TeV coupled to a composite photon
- Sensitivities to KK gravitons up to masses of 6.5 TeV (for κ =2, coupling strength of the order 1), and to dilatons up to 4.8 TeV, which is the best sensitivity at the LHC

Sensitivity on resonance production



- Sensitivities for neutral particle resonant production in the (m, f_S) plane
- Thick lines correspond to 5 σ discoveries and thin lines to 95% CL limits

Full amplitude calculation

- Effective field theory valid if $S << 4m^2$, S smaller than the threshold production of real particles
- Since the maximum proton missing mass is $\sim$ 2 TeV at the 14 TeV LHC, the effective theory needs to be corrected for masses of particles below $\sim$ 1 TeV $\rightarrow$ use of form factor which creates an uncertainty on the results (depends on the exact value of form factors)
- Solution: compute the full momentum dependence of the 4 photon amplitudes: computed for fermions and bosons
- 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

Search for quartic $\gamma\gamma$ anomalous couplings: Results from full theory

Cut / Process	Signal (full)	Signal with (without) f.f (EFT)	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
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$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	119.1	31.8 (338.5)	0.18	0	0	0

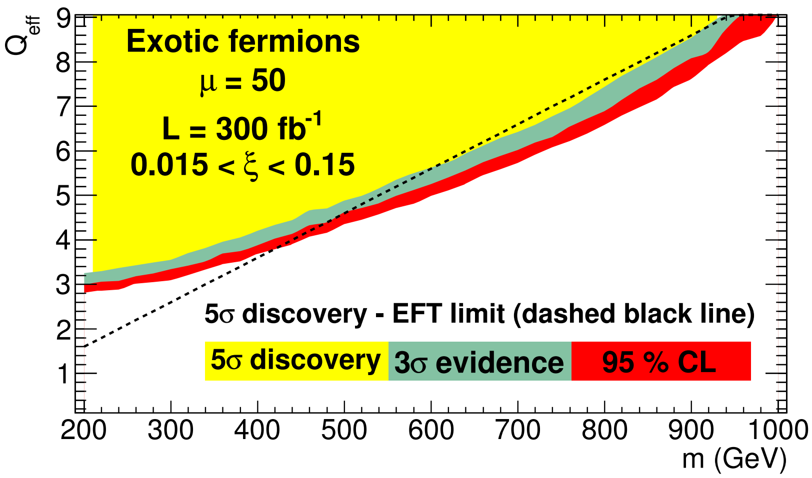
- No background after cuts for 300 fb^{-1} **without needing timing detector information**
- For signal: 119.1 events for $Q_{eff} = 4$, $m =$340 GeV
- Results for full calculation lay between the effective field result with/without form factor as expected since effective calculation not valid in the region of $S \sim m^2$

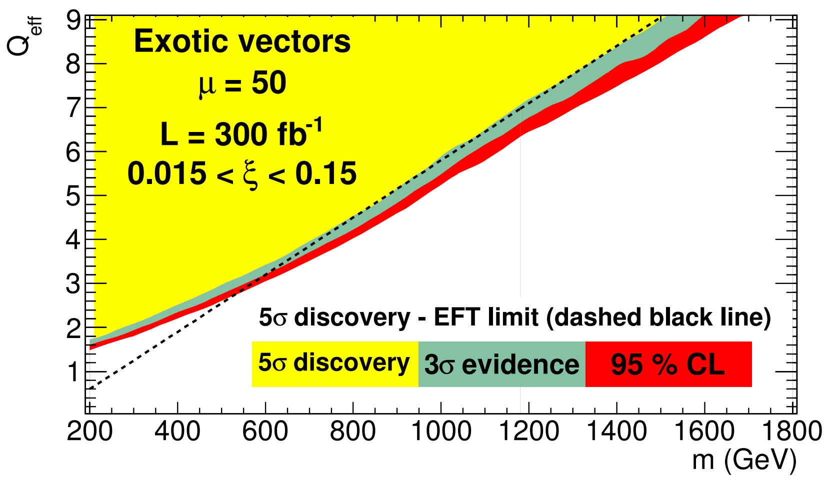
Full amplitude calculation

- 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_{eff} (vector)	2.2	3.4	4.9	7.2	8.9
Q_{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 $Q_{Jeff} = 4$, we are sensitive to new vectors (fermions) up to 700 (370) GeV for a luminosity of 300 fb^{-1}





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
- Unprecedented sensitivities to $\gamma\gamma\gamma\gamma$ anomalous couplings reaching the values predicted by extra-dim models: effective theories and full models are used
- Proton tagging is crucial to suppress the background (mainly pile up) for exclusive events; matching between proton and diphoton information (mass, rapidity)
- Timing detectors are crucial for WW production, less important (not used in the analysis) for $\gamma\gamma$ production