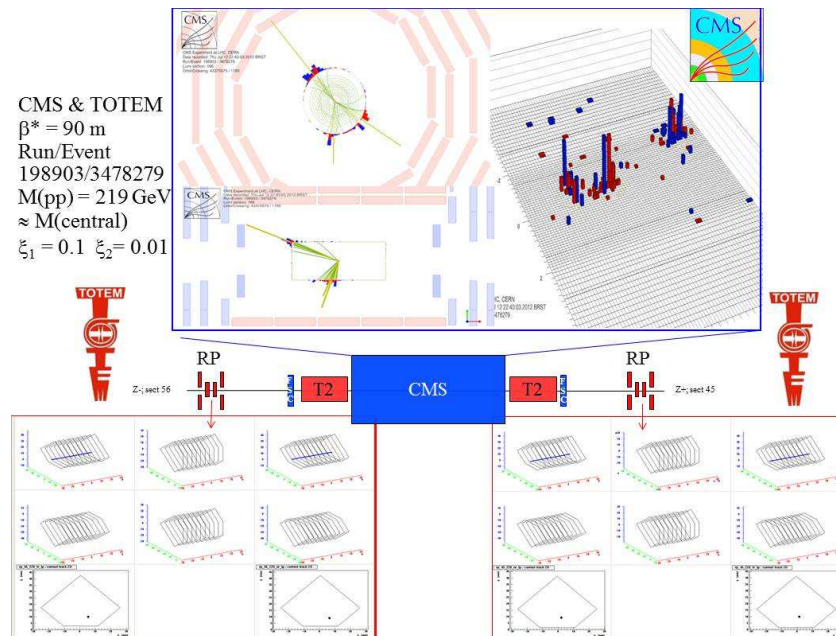


Anomalous coupling studies: a review

Christophe Royon

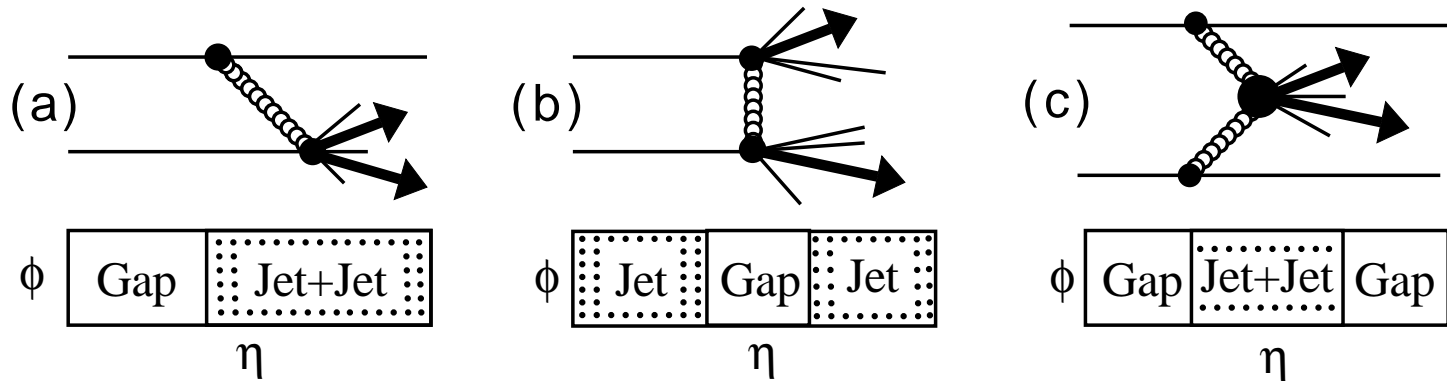
University of Kansas, Lawrence, USA

Workshop on Forward Physics and Heavy Ions, Trento, Italy,
September 26-30 2016



- Trilinear anomalous couplings
- Photon exchanges processes and beyond standard model physics
- Anomalous Quartic $\gamma\gamma WW$ and $\gamma\gamma ZZ$ couplings
- Anomalous quartic $\gamma\gamma\gamma\gamma$ couplings

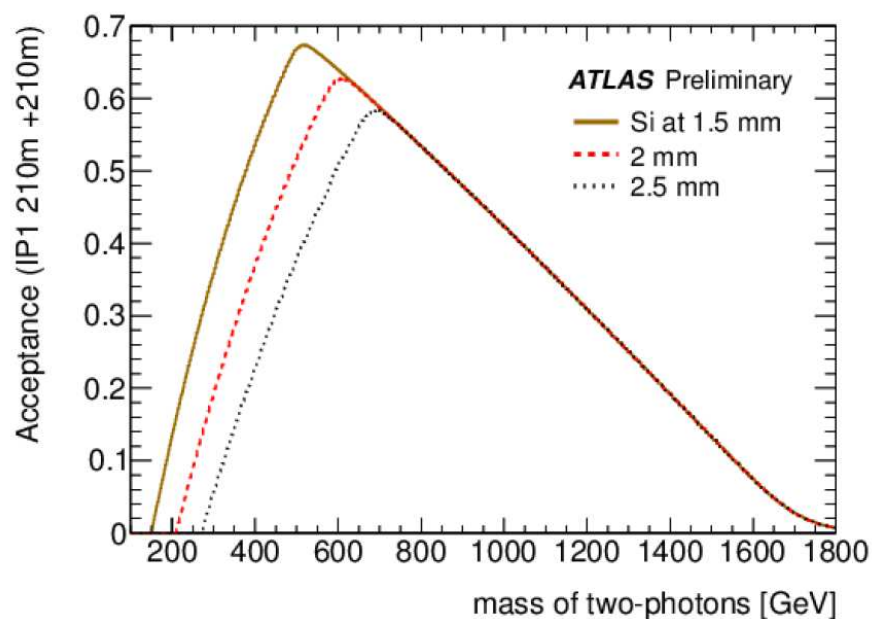
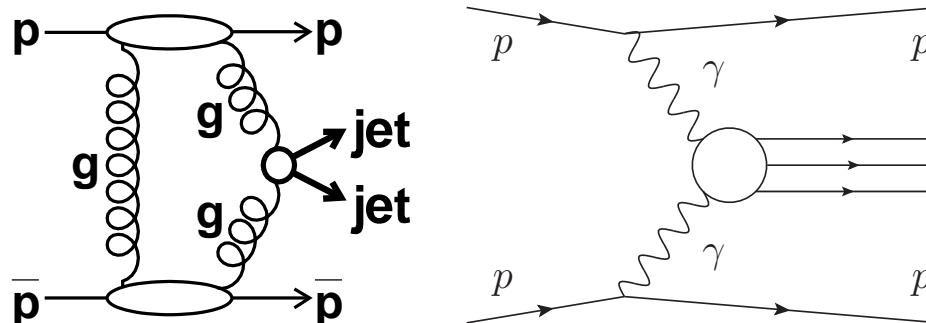
Diffraction at Tevatron/LHC



Kinematic variables

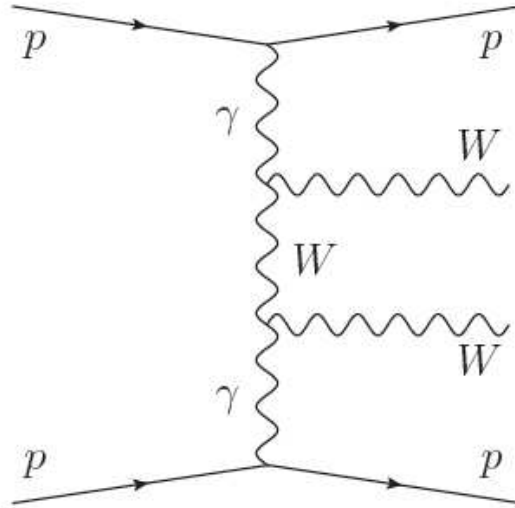
- t : 4-momentum transfer squared
- ξ_1, ξ_2 : proton fractional momentum loss (momentum fraction of the proton carried by the pomeron)
- $\beta_{1,2} = x_{Bj,1,2}/\xi_{1,2}$: Bjorken- x of parton inside the pomeron
- $M^2 = s\xi_1\xi_2$: diffractive mass produced
- $\Delta y_{1,2} \sim \Delta\eta \sim \log 1/\xi_{1,2}$: rapidity gap

What is AFP/CT-PPS?



- Tag and measure protons at ± 210 m: AFP (ATLAS Forward Physics), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)
- All diffractive cross sections computed using the Forward Physics Monte Carlo (FPMC)
- Sensitivity to high mass central system, X , as determined using AFP: Very powerful for exclusive states: kinematical constraints coming from AFP and CT-PPS proton measurements

Trilinear γWW anomalous gauge couplings



- Search for anomalous $WW\gamma$ couplings at the LHC using intact protons detected in AFP/CT-PPS
- **References:** O.Kepka, C. Royon, Phys. Rev. D 78 (2008) 073005; E. Chapon, O. Kepka, C. Royon, Phys. Rev. D 78 (2008) 073005

Trilinear anomalous gauge couplings

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

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

- 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/LHC: $-0.51 < \Delta\kappa^\gamma < 0.51$; $-0.12 < \lambda^\gamma < 0.13$
(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 $\Delta\kappa^\gamma$:

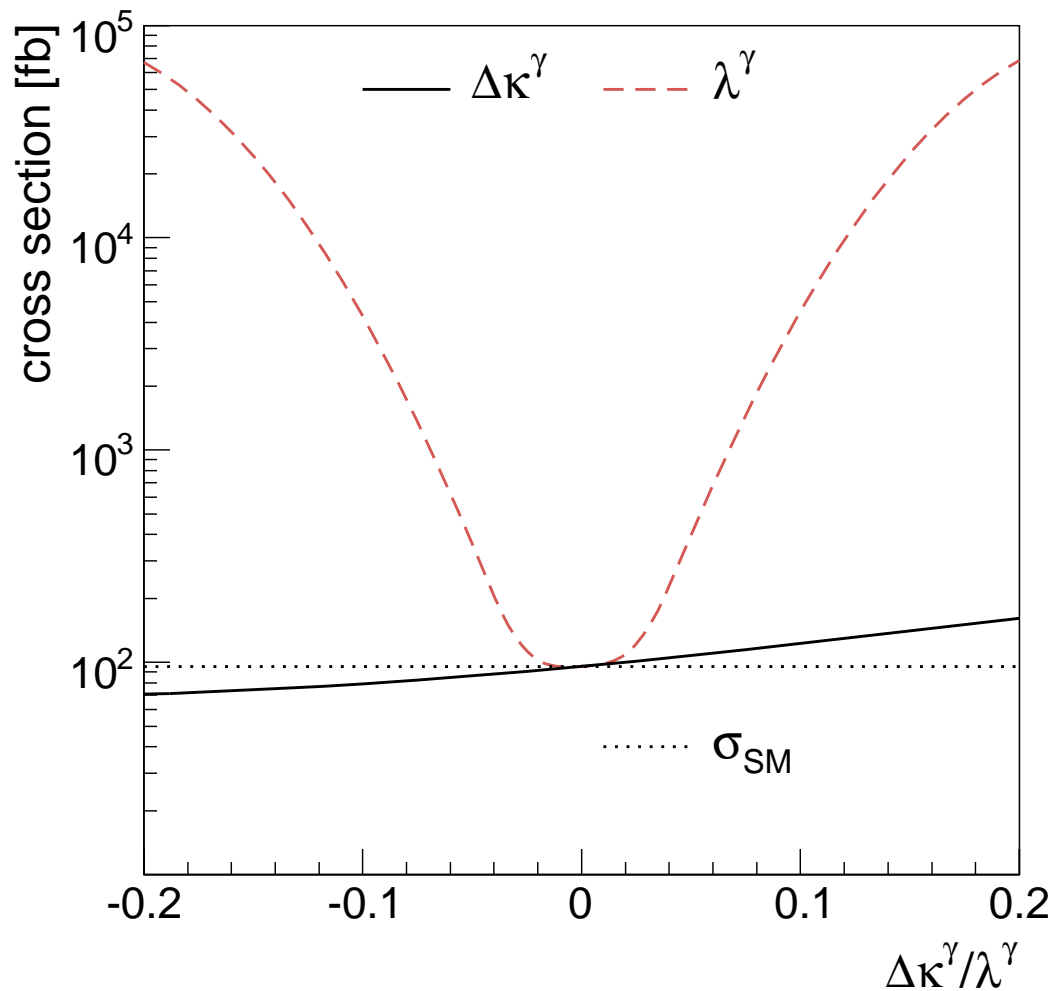
$$\begin{aligned}p_T^{lep1} &> 25 \text{ GeV} , p_T^{lep2} > 10 \text{ GeV} , \cancel{E}_T > 20 \text{ GeV} , \\ W &> 160 \text{ GeV} , \Delta\phi < 2.7, W < 500 \text{ GeV}\end{aligned}$$

- for λ^γ :

$$\begin{aligned}p_T^{lep1} &> 160 \text{ GeV} , p_T^{lep2} > 10 \text{ GeV} , \cancel{E}_T > 20 \text{ GeV} , \\ W &> 800 \text{ GeV} , M_{ll} \notin \langle 80, 100 \rangle \text{ GeV}, \Delta\phi < 3.13 \text{ rad}\end{aligned}$$

Anomalous $WW\gamma$ triple gauge coupling

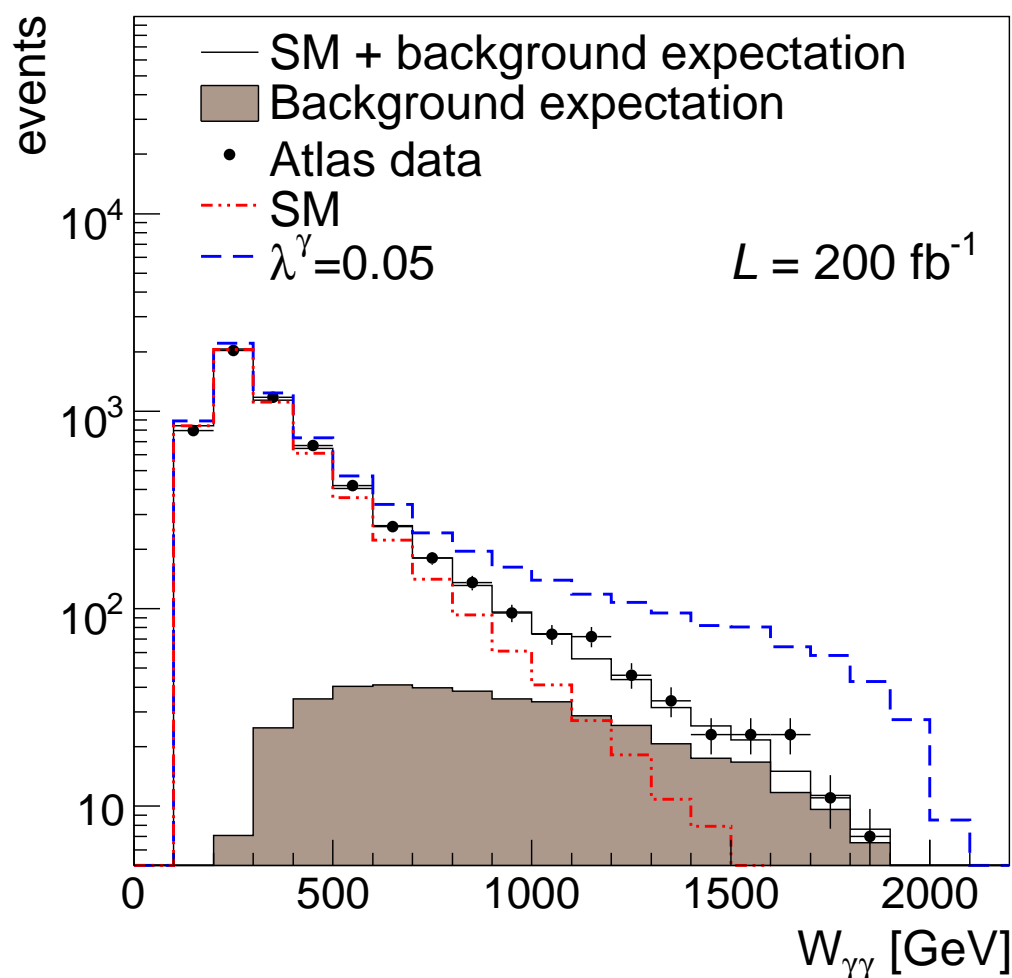
Different behaviour of the cross section as a function of anomalous couplings



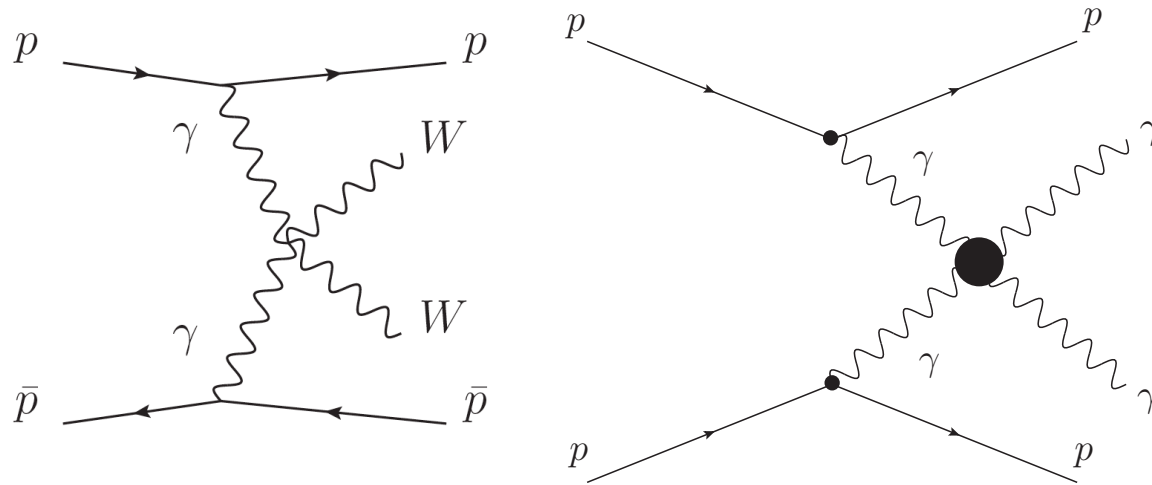
Measurement of WW events at high luminosities at LHC, $2W$ events and protons tagged in forward detectors

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 W s



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



- Study of the process: $pp \rightarrow ppWW$, $pp \rightarrow ppZZ$, $pp \rightarrow pp\gamma\gamma$
- Standard Model: $\sigma_{WW} = 95.6 \text{ fb}$, $\sigma_{WW}(W = M_X > 1\text{TeV}) = 5.9 \text{ fb}$
- 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; S. Fichet, G. von Gersdorff, C. Royon Phys. Rev. Lett. 116 (2016) no 23, 231801 and Phys. Rev. D93 (2016) no 7, 075031; J. de Favereau et al., arXiv:0908.2020.

Quartic anomalous gauge couplings

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

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

- 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 $-0.02 < a_0^W < 0.02 \text{ GeV}^{-2}$
- New limits from D0/CMS: $1.1 \cdot 10^{-4}$ ($2.5 \cdot 10^{-3}$), and $4.2 \cdot 10^{-4}$ ($9.3 \cdot 10^{-3}$) 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):

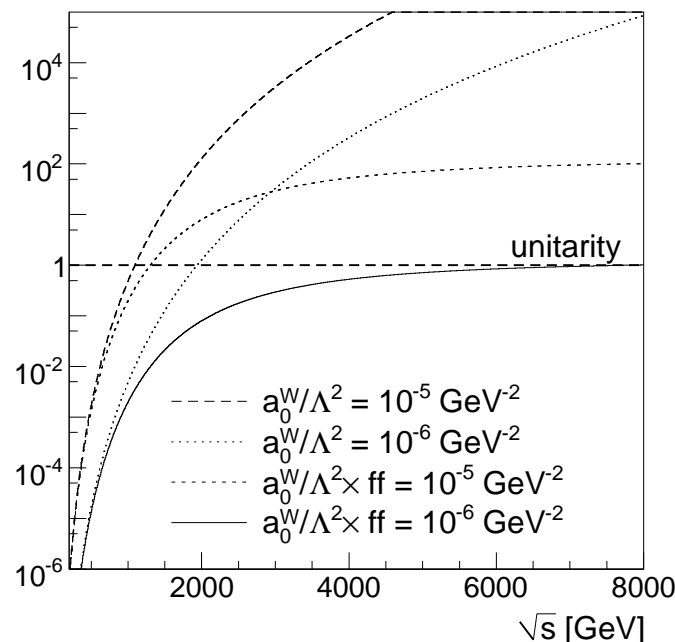
$$4 \left(\frac{\alpha a s}{16} \right)^2 \left(1 - \frac{4M_W^2}{s} \right)^{1/2} \left(3 - \frac{s}{M_W^2} + \frac{s^2}{4M_W^4} \right) \leq 1$$

where $a = a_0/\Lambda^2$

- Introducing form factors to avoid quadratical divergences of scattering amplitudes due to anomalous couplings in conventional way:

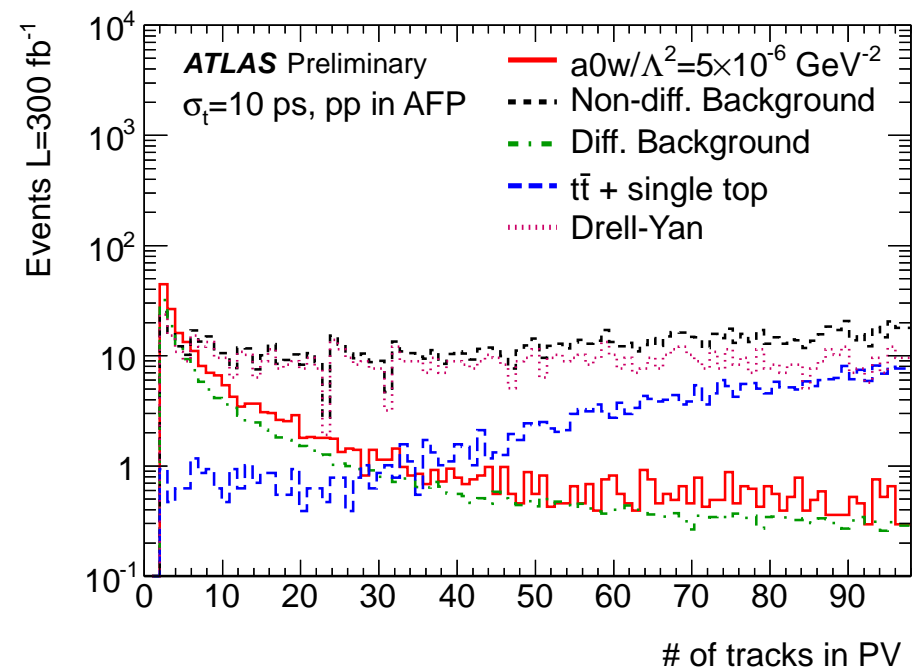
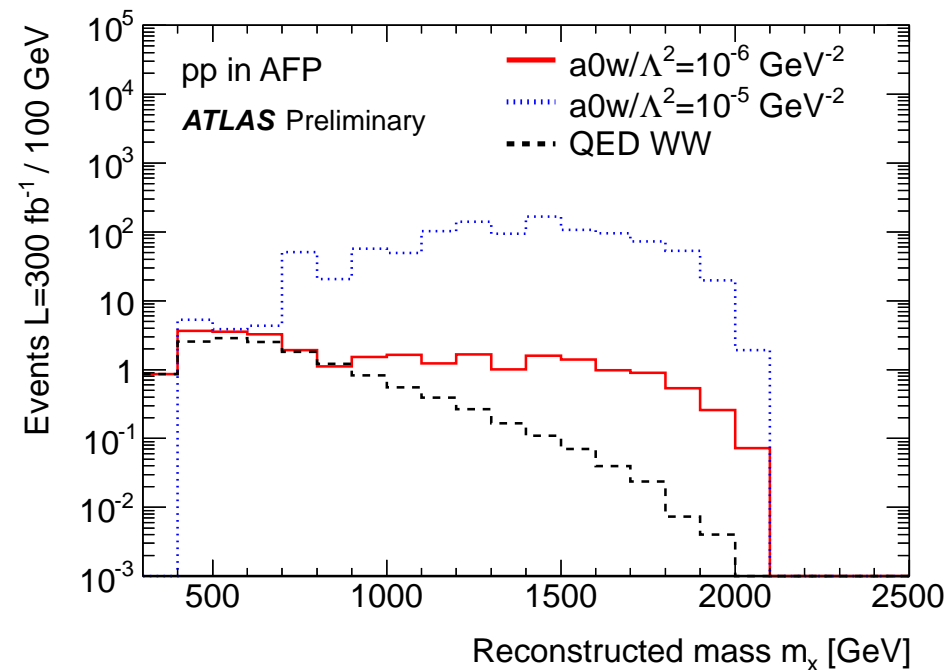
$$a_0^W/\Lambda^2 \rightarrow \frac{a_0^W/\Lambda^2}{(1+W\gamma\gamma/\Lambda_{cutoff})^2} \text{ with } \Lambda_{cutoff} \sim 2 \text{ TeV, scale of new physics}$$

- For $a_0^W \sim 10^{-6} \text{ GeV}^{-2}$, 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 W s 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	Diff.	$a_0^W/\Lambda^2 = 5 \cdot 10^{-6} \text{ GeV}^{-2}$
timing < 10 ps $p_T^{lep1} > 150 \text{ GeV}$ $p_T^{lep2} > 20 \text{ GeV}$	5198	601	20093	1820	190	282
M(l \bar{l})>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
$m_X > 800 \text{ GeV}$	0.6	0.4	7.3	0	1.1	50
$p_T^{lep1} > 300 \text{ GeV}$	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 $40/300 \text{ fb}^{-1}$ at LHC (CMS mentions that their exclusive analysis will not improve very much at high lumi because of pile-up)

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

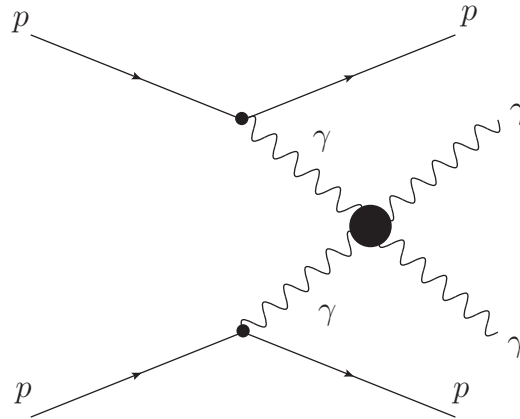
Reach at LHC

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

Couplings	OPAL limits [GeV ⁻²]	Sensitivity @ $\mathcal{L} = 30$ (200) fb ⁻¹	
		5 σ	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)

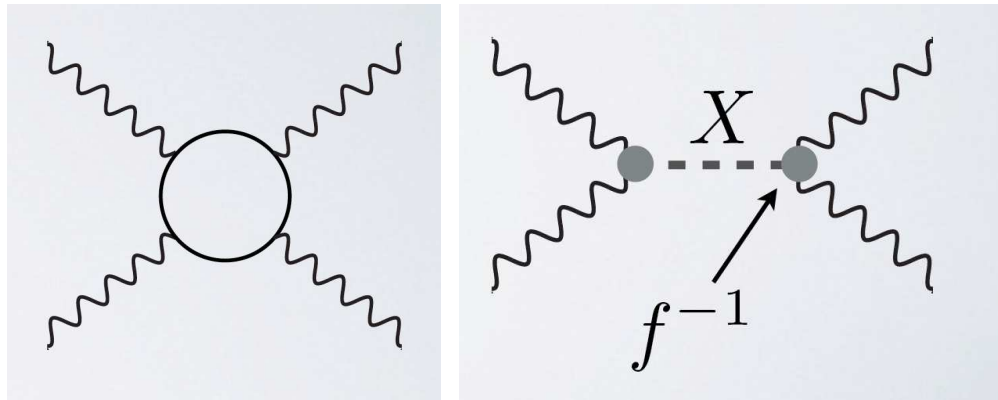
- Improvement of LEP sensitivity by more than 4 orders of magnitude with 30/200 fb⁻¹ at LHC, and of D0/CMS results by \sim two orders of magnitude (only $\gamma\gamma WW$ couplings)
- Reaches the values predicted by extra-dimension models

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...
- **See talk by Justin:** Diphoton signal appears at high mass where the gluon-induced processes (KMR) show a very small cross section, high masses are only photon-induced processes

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

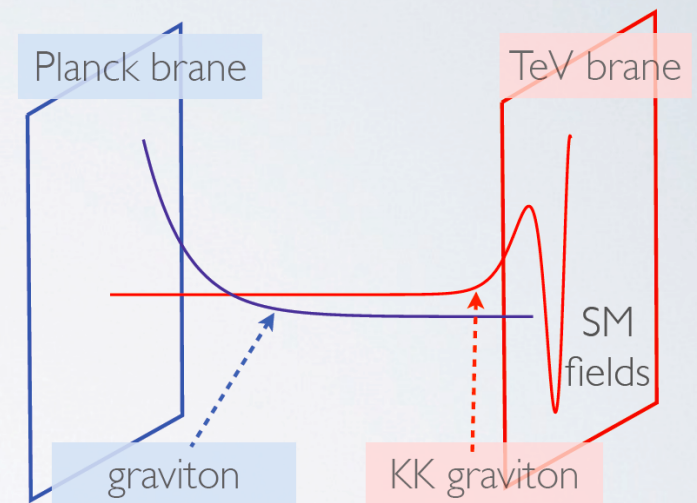
- ✗ Warped Extra Dimensions **solve hierarchy problem** of SM
- ✗ 5th dimension bounded by two branes
- ✗ SM on the visible (or TeV) brane

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

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

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

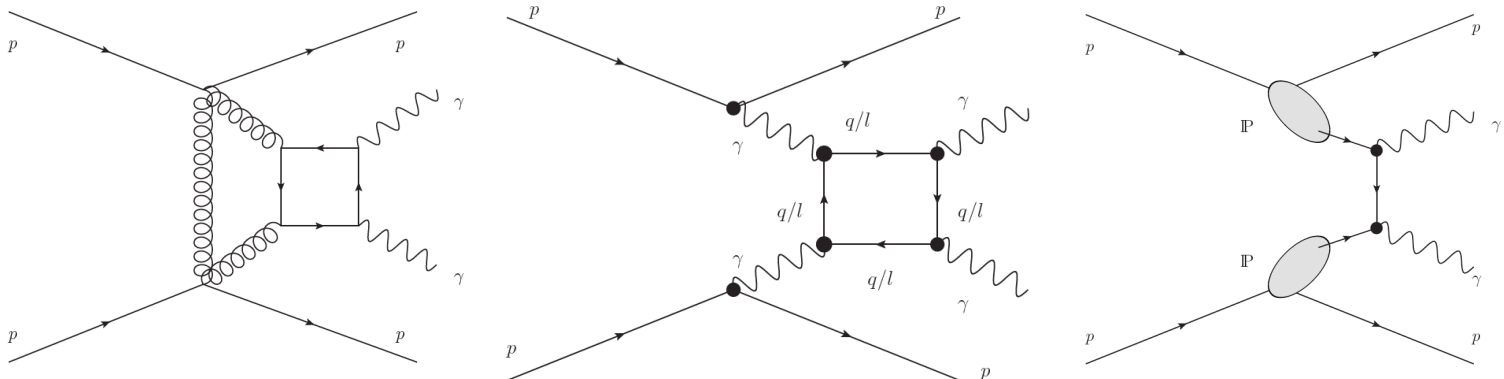
- ✗ Effective 4-photon couplings $\zeta_i \sim 10^{-14} - 10^{-13} \text{ GeV}^{-2}$ possible
- ✗ The **radion** can produce similar effective couplings



- 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

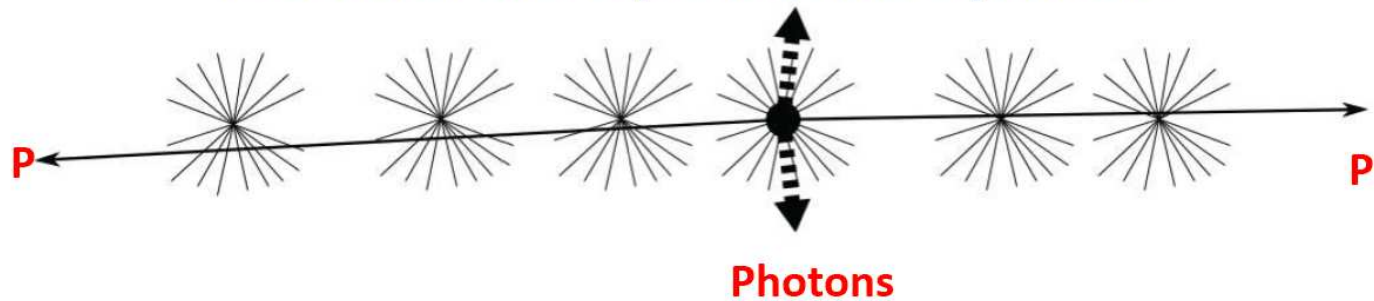
Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings: Analysis flow

- 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
- pile-up simulated in AFP/CT-PPS: 50, 100, 200...
- 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,
- All backgrounds were considered: DPE diphoton production, Higgs decaying into photons, exclusive production of diphoton, dilepton, dijet with lepton/jet misidentified, pile up (ND production of Drell-Yan, dijet, diphoton...)

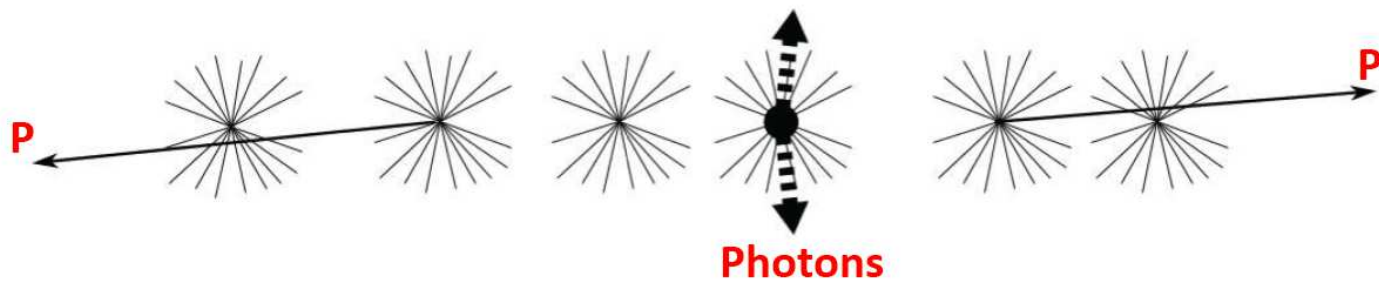


One aside: what is pile up at LHC?

A collision with 2 protons and 2 photons

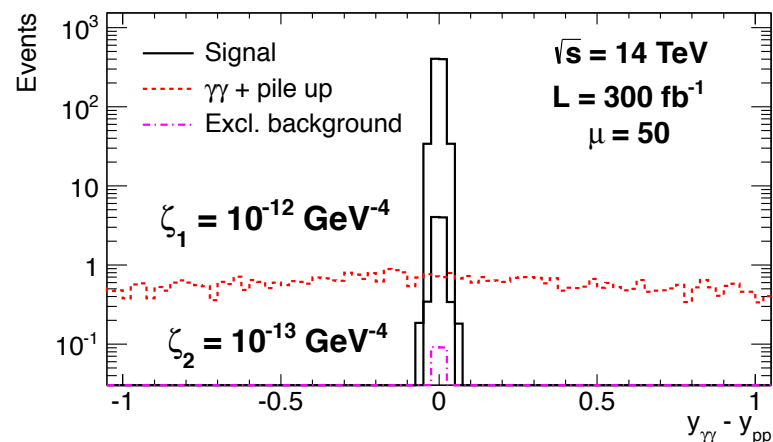
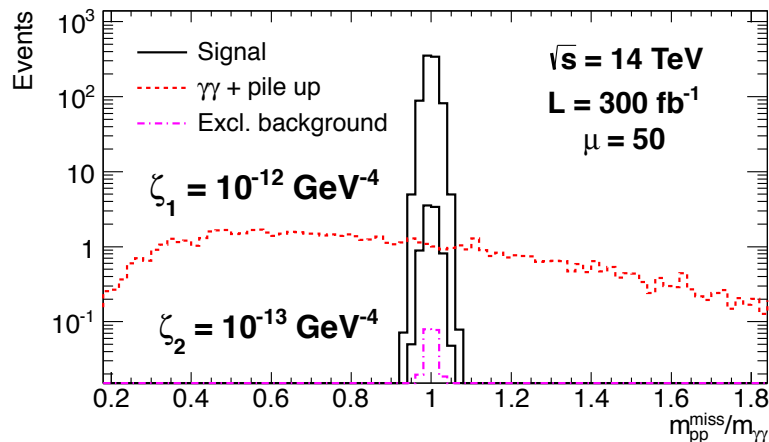


can be faked by one collision with 2 photons and protons from different collisions



- 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

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
$[0.015 < \xi_{1,2} < 0.15,$ $p_{T1,(2)} > 200, (100) \text{ GeV}]$	130.8	36.9 (373.9)	0.25	0.2	1.6	2968
$m_{\gamma\gamma} > 600 \text{ GeV}$	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} **without needing timing detector information**
- Exclusivity cuts using proton tagging needed to suppress backgrounds (Without exclusivity cuts using CT-PPS: background of 80.2 for 300 fb^{-1})

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

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.	$8 \cdot 10^{-14}$	$5 \cdot 10^{-14}$	$3 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$
ζ_1 no f.f.	$2.5 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$	$9 \cdot 10^{-15}$	$7 \cdot 10^{-15}$
ζ_2 f.f.	$2 \cdot 10^{-13}$	$1 \cdot 10^{-13}$	$6 \cdot 10^{-14}$	$4.5 \cdot 10^{-14}$
ζ_2 no f.f.	$5 \cdot 10^{-14}$	$4 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$

- **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, scale of new physics
- **Full amplitude calculation leads to similar results:** avoids using a form factor and parameters dependence of the results
- **Conclusion: background free experiment**

Full amplitude calculation

- Effective field theory valid if $S \ll 4m^2$, S smaller than the threshold production of real particles
- Since the maximum proton missing mass is ~ 2 TeV at the 14 TeV LHC, the effective theory needs to be corrected for masses of particles below ~ 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 independent 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
$[0.015 < \xi_{1,2} < 0.15,$ $p_{T1,(2)} > 200, (100) \text{ GeV}]$	130.8	36.9 (373.9)	0.25	0.2	1.6	2968
$m_{\gamma\gamma} > 600 \text{ GeV}$	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

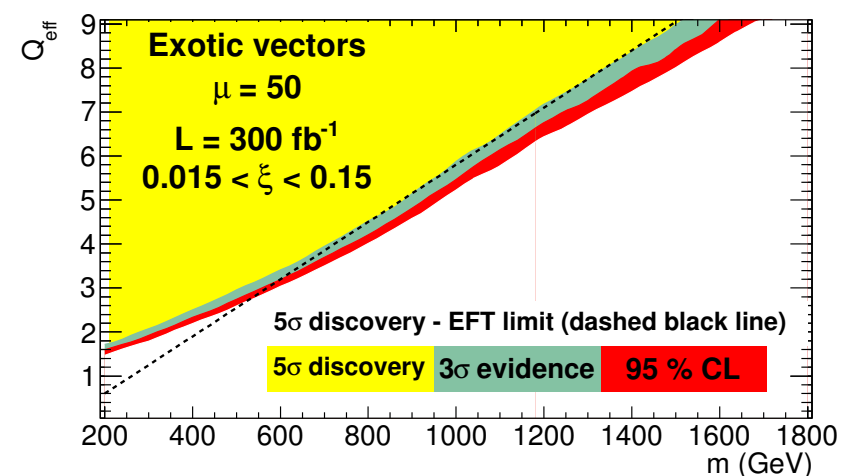
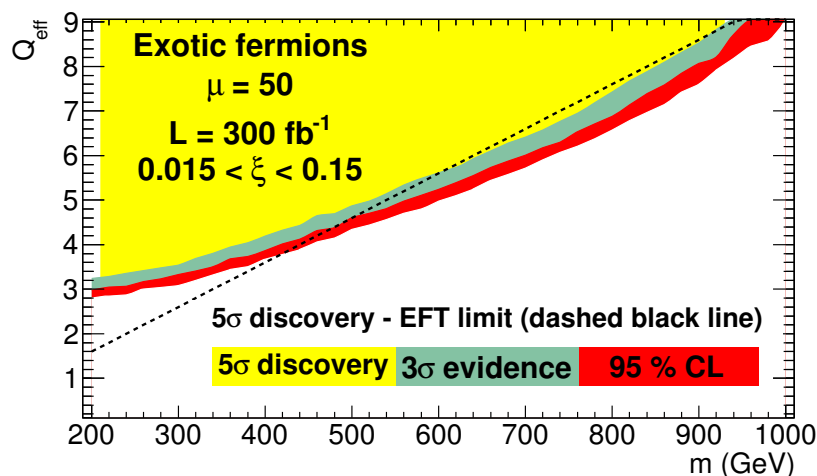
- No background after cuts for 300 fb^{-1} **without needing timing detector information**
- For signal: 119.1 events for $Q_{eff} = 4$, $m = 340 \text{ GeV}$
- Results for full calculation lay between the effective field result with/without form factor as expected since effective calculation not valid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

Full amplitude calculation

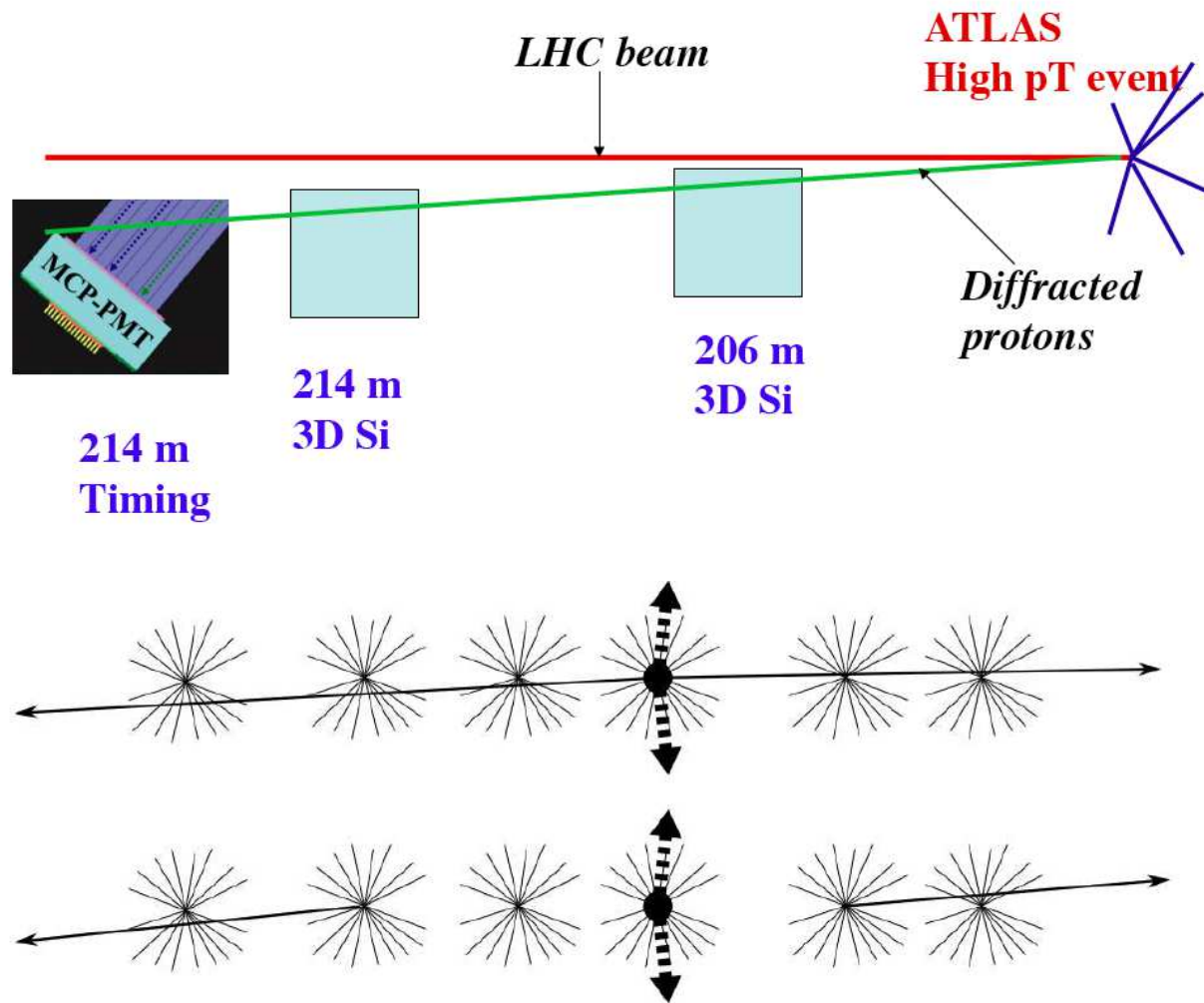
- 5 σ discovery sensitivity on the effective charge of new charged fermions and vector boson for various mass scenarii for 300 fb^{-1} and $\mu = 50$

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 sensitivities 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 $Q_{\text{eff}} = 4$, we are sensitive to new vectors (fermions) up to 700 (370) GeV for a luminosity of 300 fb^{-1}



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 photon
- Typical precision: 10 ps means 2.1 mm
- Fundamental when one does not detect all final state particles (neutrinos in W decays) or detect them with worse resolution (jets)

Conclusion

- High sensitivity looking for $\gamma\gamma WW$ and $\gamma\gamma ZZ$ quartic anomalous couplings and trilinear anomalous couplings
- $\gamma\gamma\gamma\gamma$ anomalous coupling studies
 - Exclusive process: **photon-induced processes** $pp \rightarrow p\gamma\gamma p$ (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 probability in better control than in the QCD (gluon) case
- CT-PPS/AFP allows to probe BSM diphoton production in a model independent way: sensitivities to values predicted by extradim or composite Higgs models
- **Look into other channels: WW , ZZ , $Z\gamma$ (specially interesting), jet jet**

