Probing $\gamma\gamma XX$ anomalous gauge couplings with proton tagging at the LHC

New Trends in HEP and QCD workshop @ Natal, Brazil

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*C. Royon, O. Kepka, Phys. Rev. D **78** (2008)*

*E. Chapon, C. Royon, O. Kepka, Phys. Rev. D **81** (2010)*

S. Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert, Phys. Rev. D **89** (2014)

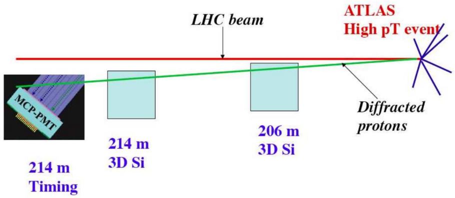
S. Fichet, G. von Gersdorff, B. Lenzi, C. Royon, M. Saimpert, to be submitted

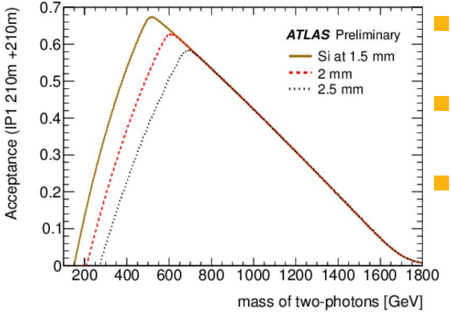
Summary of the presentation

1. **Motivations and description of the proposed measurements**
   What and why are we measuring?
2. The $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings cases in short
3. The $\gamma\gamma\gamma\gamma$ couplings case in details
4. Conclusion and plans

Forward proton detectors at the LHC

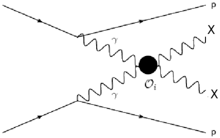
- The ATLAS Forward Physics (AFP) and the CMS-TOTEM Precision Proton Spectrometer (CT-PPS) upgrade projects





- $\xi_{1,2}$ proton momentum loss
- **missing proton mass** $m_{pp}^{miss} = \sqrt{\xi_1 \xi_2 s}$
- **mass acceptance** limited by the LHC beam and optics (low β^* case displayed)

Exclusive production via photon induced processes



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- Full reconstructed kinematics by comparing the forward to the central particles → **strong background reduction**

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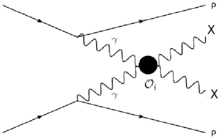

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- $\gamma\gamma$, WW, ZZ final states ideal to study **anomalous quartic gauge couplings (aQGC)**
- aQGC important for various physics topics: **electroweak symmetry breaking, extra-dimension models, ...**

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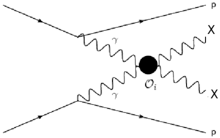

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- aQGC important for various physics topics: **electroweak symmetry breaking, extra-dimension models, ...**
- Drawback: smaller cross-sections

  (intact protons must be in the acceptance of the forward detectors)

Summary of the presentation

1. Motivations and description of the proposed measurements

2. **The $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings cases in short**

   Brief overview of the two studies published in 2008 and 2010.

   Comparison on the obtained sensitivies with the latest measurements.

3. The $\gamma\gamma\gamma\gamma$ couplings case in details

4. Conclusion and plans

$WW\gamma\gamma$ and $ZZ\gamma\gamma$ anomalous couplings

*C. Royon, O. Kepka, Phys. Rev. D **78** (2008)*

*E. Chapon, C. Royon, O. Kepka, Phys. Rev. D **81** (2010)*

- **Effective Field Theory (EFT): dimension 6 operators** parametrized with 4 different parameters

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

$$\mathcal{L}_6^C \sim \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W_\beta^- + W^{-\alpha}W_\beta^+) - \frac{e^2}{16\cos^2(\theta_W)}\frac{a_C^Z}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}Z^\alpha Z_\beta$$

- **Only the leptonic decays** of the heavy bosons are considered as final states (clean signal experimentally)
- **Background considered:** ND WW/ZZ production, dilepton photoproduction, DPE dilepton, DPE WW/ZZ
- Generation and simulation performed with the **Forward Physics MC generator (FPMC)** interfaced with the fast simulation of the ATLAS detector (ATLFast++ package)

ATLAS full simulation also performed to probe pile-up effects and gave similar results

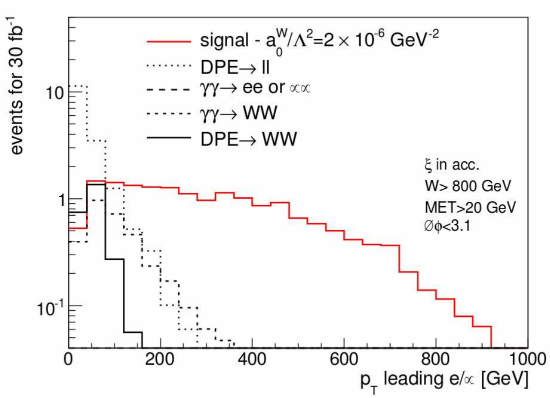
$WW\gamma\gamma$ and $ZZ\gamma\gamma$ anomalous signal

*→ATLAS **fast** simulation study*

*E. Chapon, C. Royon, O. Kepka, Phys. Rev. D **81** (2010)*

- Anomalous signal appears at high energy

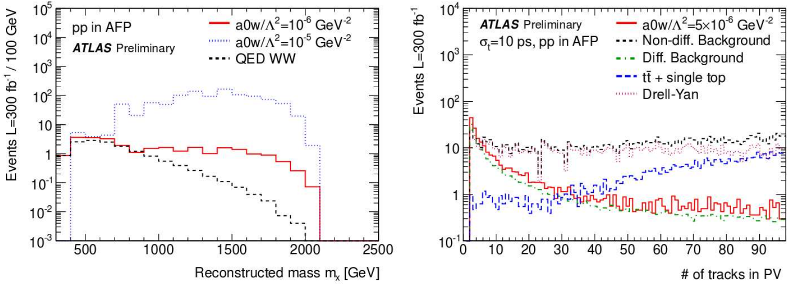
  $WW\gamma\gamma$ signal and background composition passing all the selection but the p_T cut on the leading lepton



Dealing with pile-up at the LHC

→*ATLAS* ***full*** *simulation study*

- The LHC is operated at **very high luminosity** → **high event multiplicites** in a single bunch-crossing (pile-up)
- Use of the **forward timing detectors** to constrain the vertex z-position of the interaction
  dependance on the timing detectors resolution
- 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



$WW\gamma\gamma$ and $ZZ\gamma\gamma$ sensitivities

*E. Chapon, C. Royon, O. Kepka, Phys. Rev. D **81** (2010)*

- **Limits from LEP (OPAL)**, $\simeq$ 0.1-0.2 GeV^{-2} (for each coupling)
  *Phys. Rev. D **70** (2004) 032005*
- **Recent papers from DØ** for $WW\gamma\gamma$ with reach of the order of 10^{-2}-10^{-3} GeV^{-2}
  *Phys. Rev. D **88** (2013) 012005*
- **Recent papers from CMS** for $WW\gamma\gamma$ with reach of the order of 10^{-4}-10^{-5} GeV^{-2}
  *Phys. Rev. D **90** (2014) 032008*
- **Sensitivities predictions with AFP** (30 and 200 fb^{-1})
  reach up to 10^{-6} GeV^{-2}, improvement up to a factor $\simeq$ 100

	form factor	limits $[10^{-6}\ \mathrm{GeV}^{-2}]$				limits $[10^{-6}\ \mathrm{GeV}^{-2}]$			
		$\lvert a_0^W/\Lambda^2\rvert$	$\lvert a_C^W/\Lambda^2\rvert$	$\lvert a_0^Z/\Lambda^2\rvert$	$\lvert a_C^Z/\Lambda^2\rvert$	$\lvert a_0^W/\Lambda^2\rvert$	$\lvert a_C^W/\Lambda^2\rvert$	$\lvert a_0^Z/\Lambda^2\rvert$	$\lvert a_C^Z/\Lambda^2\rvert$
95% c.l	$\Lambda_{cut}=\infty$	1.2	4.2	2.8	10	0.7	2.4	1.1	4.1
	$\Lambda_{cut}=2$ TeV	2.6	9.4	6.4	24	1.4	5.2	2.5	9.2
3σ evidence	$\Lambda_{cut}=\infty$	1.6	5.8	4.0	14	0.85	3.0	1.6	5.7
	$\Lambda_{cut}=2$ TeV	3.6	13	9.0	34	1.8	6.7	3.5	13
5σ discovery	$\Lambda_{cut}=\infty$	2.3	9.7	6.2	23	1.2	4.3	4.1	8.9
	$\Lambda_{cut}=2$ TeV	5.4	20	14	52	2.7	9.6	5.5	20

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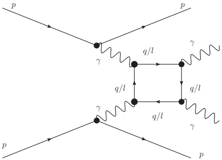
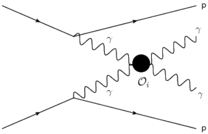
3. **The $\gamma\gamma\gamma\gamma$ couplings case in details**

   Review of the study published in 2014 and latest developments not published yet. Ideas for further developments.

4. Conclusion and plans

$\gamma\gamma\gamma\gamma$ SM and anomalous couplings





- **Direct coupling absent from the SM**
  Loop induced production strongly suppressed in the SM, measurable at the LHC in Pb-Pb (d'Enterria et al. Phys. Rev. Lett. **111** *(2013) 080405)*
- **Never measured in collider experiments**

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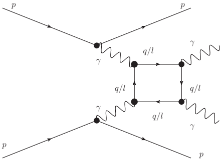

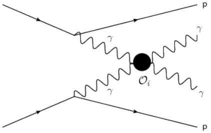

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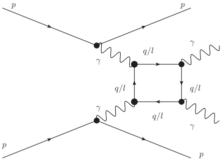
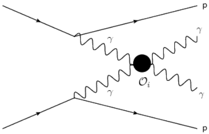
- New Physics search $\rightarrow$ high integrated luminosity required **(so high pile-up!)**
  300 fb^{-1} of data expected at the LHC at $\sqrt{s} = 14$ TeV with $\boldsymbol{\mu} >$ **50**
- **Huge background** if only 2 high energy γ required
  (SM $\gamma\gamma$ production + fakes from electrons and jets)

$\gamma\gamma\gamma\gamma$ SM and anomalous couplings





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- **Huge background** if only 2 high energy γ required
  (SM $\gamma\gamma$ production + fakes from electrons and jets)
- Additional requirement of **two intact protons** with forward detectors highly suppresses the background
  (All particles at the final state are detected)

Operators of the $\gamma\gamma\gamma\gamma$ couplings

*R.S. Gupta, Phys. Rev. D **85** (2012) 014006*

S. Fichet and G. von Gersdorff, arXiv:1311.6815

- $\sqrt{\hat{s}_{\gamma\gamma}} << \Lambda$, effective field theory assumption

$$L_{4\gamma} = \zeta_1^{\gamma} F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2^{\gamma} F_{\mu\nu}F^{\nu\rho}F_{\rho\sigma}F^{\sigma\mu} \text{ (dimension 8)}$$

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- For low new physics masses, threshold effect to be taken into account → **use of a form factor (f.f.) at the amplitude level**

  We use $f.f = \frac{1}{1+(\frac{\hat{s}_{\gamma\gamma}}{\Lambda'^2})^2}$ with $\Lambda' = 1\ TeV \simeq \sqrt{\hat{s}_{\gamma\gamma,max}}/2$

  (Unitarity requires $\zeta_i < 10^{-10}\ GeV^{-4}$, $\simeq 10^4$ higher than our sensitivity limit, so we are safe on this side)

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- The signal showed in the plots of this presentation are for a signal with **$\zeta_1 \geq 0$ and $\zeta_2 = 0$ and with f.f.**
  ζ_1 and ζ_2 have a very similar angular behaviour

- A table of final sensitivities for both ζ_1 and ζ_2, **with and without f.f** are given at the end of the presentation

$\gamma\gamma\gamma\gamma$ phenomenological study

- Evaluate the LHC potential to probe 4γ couplings using proton tagging and **effective field theory**
  - 4γ aQGC operators implemented in the **FPMC generator**
  - Simulation of the detector effects
  - Pile-up simulation with Pythia8 minimum bias events
  - Background estimation (expected to be very small thanks to the fully constrained kinematics)
  - Sensitivities calculation: significance (σ) = $S/\sqrt{B}$
  - 2 scenarios were considered
    - LHC full stat (ATLAS or CMS) : 300 fb^{-1}, $<\mu>= 50$
    - HL-LHC (ATLAS) : 3000 fb^{-1}, $<\mu>= 200$

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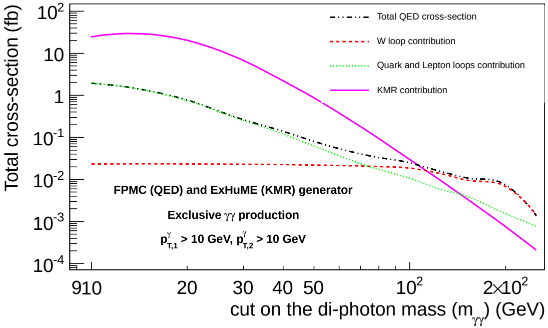
- Implementation of generic **new heavy-charged fermions/vectors** contributions to the 4γ couplings in FPMC **(full amplitude calculation)** **(see Sylvain's talk)**
- **Extra:** update of the exclusive $\gamma\gamma$ SM production in FPMC
  W loop contribution and the fermion masses included

SM exclusive $\gamma\gamma$ production **(preliminary)**



- Mass of the fermions, W loop contribution and related interference taken into account in the simulation
- W loop non negligible for $m_{\gamma\gamma} > 70$ GeV
- **Irreducible background for $\gamma\gamma\gamma\gamma$ new physics searches**
  Needs to be simulated accurately

Modelisation of the detector effects

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- **Analysis performed at particle level** but taking into account main detector effects
  - Estimation of γ **conversion rates** (η function), **fake photon rates**, **reconstruction efficiency** (p_T functions) from ECFA ATLAS studies
  - **Smearing** of 1% in γ energies, 0.001 in η and ϕ (absolute), 2% for ξ to mimic detector resolution
  - Requirement of **at least one converted photon** → **constraint on the γ vertex**, possibility to combine with forward proton timing measurement
  - Selection on high p_T^γ, high diphoton mass, $\Delta\Phi^{\gamma\gamma}$, match proton missing/$\gamma\gamma$ mass (summary S17)

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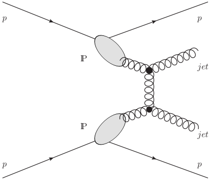
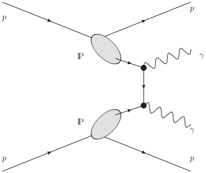
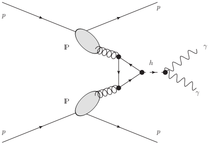
- **Final outputs**
  - 5σ and 95% C.L sensitivities on the $\gamma\gamma\gamma\gamma$ couplings at the LHC
    EFT, valid for m>2(1) TeV for tree-level (pair) production
  - M-Q exclusion plane for generic new fermions/vectors at the LHC
    full amplitude calculation, valid for all masses

Backgrounds (FPMC, ExHuME)

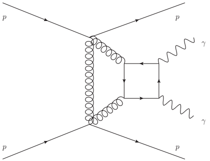
IP backgrounds (FPMC)



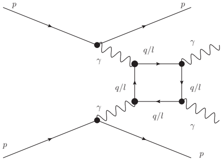


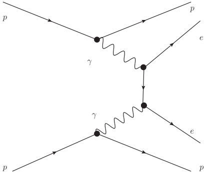


Exclusive QCD (ExHuME)



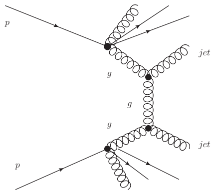
Exclusive QED (FPMC)



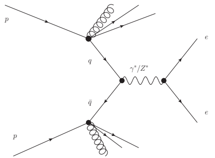


Pile-up backgrounds (HERWIG 6.5)

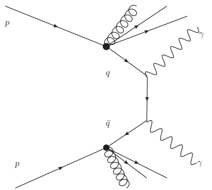
Dijet



Drell-Yan



Diphoton



+ intact protons generated from minimum bias events (Pythia 8)

transported to the forward detectors through the LHC magnets with FPTracker/MADX

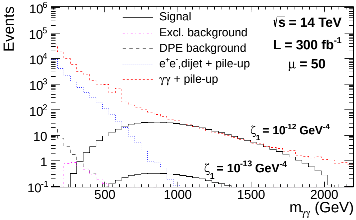
(used by the LHC machine people)

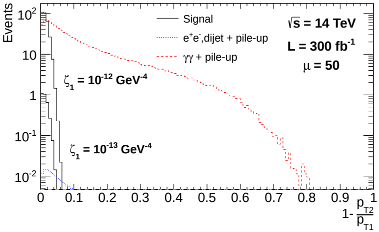
Mass and p_T balance distribution of signal and backgrounds

smearing, fakes and reconstruction factors, $\geq$ 1 converted γ required

$0.015 < \xi < 0.15$, $|\eta| < 2.37$,
$p^{\gamma}_{T1,2} > 50$ GeV ONLY

if we request also $m_{\gamma\gamma} > 600$ GeV
and $p_{T1,2} > 200, 100$ GeV



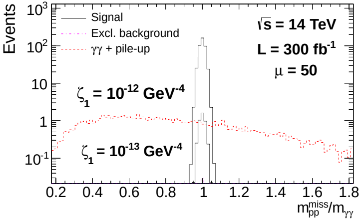


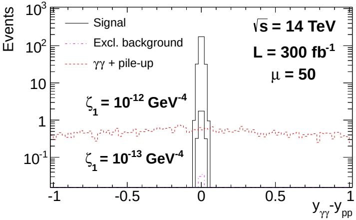
- By requesting $m_{\gamma\gamma} > 600$ GeV (left), **Only pile-up backgrounds remain**
- p_T ratio distribution after p_T and $m_{\gamma\gamma}$ cuts (right) provides another efficient cut **(exclusive process)**
- $\Delta\phi > \Pi$-0.01 also applied in the final selection

Use of the forward detector ξ measurement

smearing, fakes and reconstruction factors, $\geq$ 1 converted γ required

$0.015 < \xi < 0.15$, $|\eta| < 2.37$, $m_{\gamma\gamma} > 600$ GeV, $p_{T1,2} > 200, 100$ GeV, p_T ratio > 0.95, $\Delta\phi >$ Π-0.01



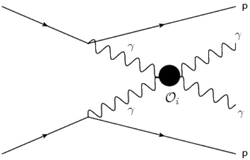


- **Missing proton mass** $\sqrt{\xi_1 \xi_2 s}$ matches $m_{\gamma\gamma}$ for the signal
  A mass window of 3% (= resolution) is required in the event selection
- Same effect with **rapidity variables**
  $|y_{\gamma\gamma} - y_{pp}| < 0.03$ *with* $y_{pp} = (0.5 * \ln(\frac{\xi_1}{\xi_2}))$ *is applied*
- The small width of the signal distributions is due to the smearing applied to simulate detector effects

Very efficient cuts due to very good ξ resolution, **absolutely needed in order to suppress the pile-up background**

Event selection: summary

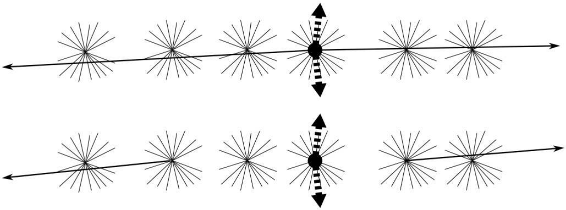
- **Kinematic cuts**
  1. $p_{T1}^{\gamma} > 200\ GeV, p_{T2}^{\gamma} > 100\ GeV$
  2. $m_{\gamma\gamma} > 600\ GeV$



- Selection of **exclusive events**
  1. $\frac{p_{T2}}{p_{T1}} > 0.95$
  2. $|\Delta\Phi| > \pi - 0.01$

- **Forward detectors** cuts
  1. $m_{pp}^{miss} = m_{\gamma\gamma} \pm 3\%$
  2. $|y_{\gamma\gamma} - y_{pp}| < 0.03$
     with $y_{pp} = (0.5 * ln(\frac{\xi_1}{\xi_2}))$
  3. Possible proton timing measurement with forward detectors **(Not used)**

Possible extra-cut: proton timing requirement



- Proton timing will be measured by forward detectors
  - 10 ps resolution assumed $\rightarrow$ proton vertex constrained within 2.1 milimeters
  - Requirement of 1 converted $\gamma \rightarrow < 1$ mm resolution on the γ vertex
  - **Resolution on the vertex position driven by forward timing detectors**
- Matching the two proton and photon vertices provide an additional background rejection factor of $\simeq 40$ at $\mu = 50$
- No need to use for this study, **robustness of the $\gamma\gamma\gamma\gamma$ analysis** $\rightarrow$ *needed for $\gamma\gamma WW$ and $\gamma\gamma ZZ$!*
- can be used for unknown backgrounds (beam-induced)

Expected events for ζ_1^γ = 2 10^{-13}.GeV^{-4}

- $\sqrt{s} = 14$ TeV, L = 300 fb^{-1}, at least one converted γ

Cut / Process	Signal	Excl.	DPE	e^+e^-, dijet + pu	$\gamma\gamma$ + pu
$0.015 < \xi < 0.15$, $p_{T1,2} > 200$, 100GeV	37.0	0.25	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	34.9	0.20	0	0.2	1023
$p_{T2}/p_{T1} > 0.95$, $\lvert\Delta\phi\rvert > \pi - 0.01$	34.0	0.19	0	0	80.2
$\sqrt{\xi_1\xi_2 s} = m_{\gamma\gamma} \pm 3\%$	33.0	0.18	0	0	2.8
$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	31.7	0.18	0	0	0

- **Signal selection efficiency** $>$ **70%** (after detector effects)
  - Signal increased by a factor 3-4 when relaxing the $>$1 conv. photon requirement
    (the di-photon vertex cannot be identified accurately anymore from the central detector)

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- **Signal selection efficiency $>$ 70%** (after detector effects)
  - Signal increased by a factor 3-4 when relaxing the $>$1 conv. photon requirement
    (the di-photon vertex cannot be identified accurately anymore from the central detector)
- **Background completely suppressed thanks to forward detectors ξ measurement**
  - Very high significance per observed event
  - $<$ 5 background events expected at μ = 200
    Robust analysis, good background control
  - proton time-of-flight **not used**
    Possible additional rejection factor of 40 at μ = 50

Final discovery (5σ) and exclusion (95% CL) sensitivities on ζ_1 and ζ_2

EFT approach: *S. Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert, Phys. Rev. D* ***89*** *(2014)*

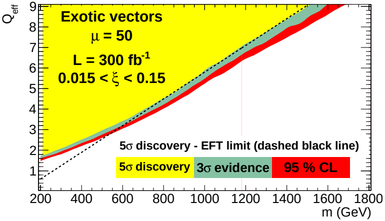
Update of the EFT + full amplitude calculation: *S. Fichet, G. von Gersdorff, B. Lenzi, C. Royon, M. Saimpert, to be submitted*

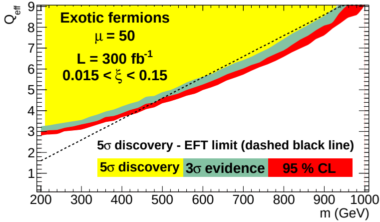
Luminosity	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
pile-up (μ)	50	50	50	200
coupling (GeV^{-4})	$\geq$ 1 conv. γ 5 σ	$\geq$ 1 conv. γ 95% CL	all γ 95% CL	all γ 95% CL
ζ_1 f.f.	$8 \cdot 10^{-14}$	$5 \cdot 10^{-14}$	$3 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$
ζ_1 no f.f.	$2.5 \cdot 10^{-14}$	$1.5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

- A large panel of extra-dimension models can be probed in **the multi-TeV range** (see Sylvain's talk)
- The form factor is not needed for any new physics scale **beyond $\simeq$ 2 TeV**
  because of the forward detector acceptance (see slide 9)

Full amplitude computation for generic heavy charged fermions/vectors contributions **(preliminary)**

- **The existence of new heavy charged particles** will enhance the $\gamma\gamma\gamma\gamma$ coupling at high mass via loops
- This enhancement can be parametrized by **only the mass and the effective charge** $Q_{eff} = Q.N^{1/4}$, N multiplicity (= values taken by the new degree of freedom)
- Generic full amplitude implementation for fermions and vectors implemented in FPMC
- Paper in preparation, preliminary M-Q_{eff} exclusion plane





Summary of the presentation

1. Motivations and description of the proposed measurements
2. The $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings cases in short
3. The $\gamma\gamma\gamma\gamma$ couplings case in details
4. **Conclusion and plans**

Where does proton tagging do better?

- Proton tagging allows a **very high background rejection** at the cost of a **smaller cross-section**
  - A single observation has **a high significance**
  - Ideal to probe small deviations from the Standard Model like aQGC
    ex: new charged particles via loops, ADD gravity effects, ...
  - Interesting "subleading" constraints on resonances searches at tree level
    ex: new neutral particles at tree level
  - Hard to be more quantitative: no $\gamma\gamma\gamma\gamma$ limits from collider experiments yet (with intact protons or not)
- We reach sensitivities allowing to **probe directly a large class of new models**
  - **Extra-dimensions:** KK gravitons, dilaton, high κ untested domain (Randall-Sundrum model)
  - **Strongly-interacting composite states, monopoles:** generic searches of new heavy charged particles

Conclusion

- **Forward proton tagging at the LHC seems promising to probe anomalous $\gamma\gamma XX$ Gauge Couplings**
  - proton tagging associated with high energy object in the central detector allow to highly suppress the background
  - $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings sensitivity improvement by a factor up to 100 compared to latest the CMS measurement
  - $\gamma\gamma\gamma\gamma$ couplings: sensitivities around $10^{-13} - 10^{-14}$ GeV^{-4}, down to $7{\cdot}10^{-15}$ GeV^{-4} $\rightarrow$ allows to probe directly a large panel of new physics models in the multi-TeV range (KK gravitons, strongly-interacting heavy dilaton, ...)
    (no previous constraints from collider experiments)

- **$\gamma\gamma\gamma\gamma$ couplings: a way to probe exotic heavy charged vectors/fermions in a completely model-independant way**
  $\rightarrow$ *very interesting subleading constraints in addition to direct searches at the LHC*

Conclusion

- **Forward proton tagging at the LHC seems promising to probe anomalous $\gamma\gamma XX$ Gauge Couplings**
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- **$\gamma\gamma\gamma\gamma$ couplings: a way to probe exotic heavy charged vectors/fermions in a completely model-independant way**
  → *very interesting subleading constraints in addition to direct searches at the LHC*

- The cross-section of those potential new contributions seems to be very dependant on the spin value of the new particles
  → **sensitivies to higher sping resonances under study**
  (requires further theoretical development)

Probing $\gamma\gamma XX$ anomalous gauge couplings with proton tagging at the LHC

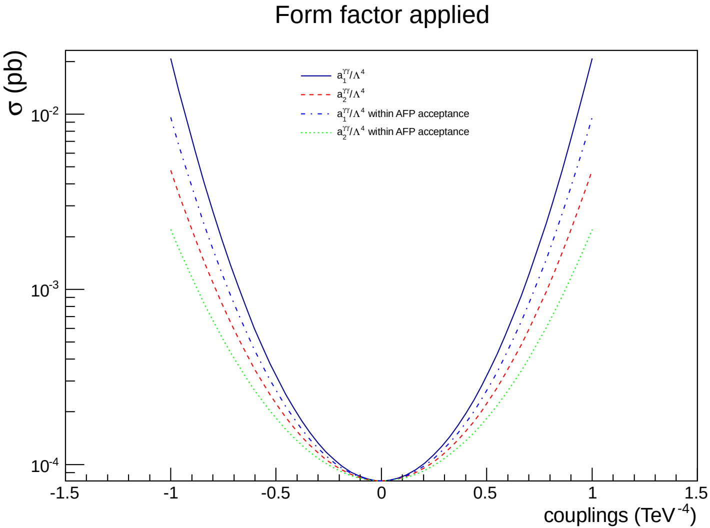
Back-up

Matthias Saimpert[1]
E. Chapon, S. Fichet, G .von Gersdorff,
O. Kepka, B. Lenzi, C. Royon[1]

[1]CEA Saclay - Irfu/SPP

November, 5th 2014

Integrated total cross-section against couplings for anomalous $\gamma\gamma\gamma$ couplings



Effective Field Theory cross-section of the 4γ couplings (G. Von Gersdorff)

EFT of 4 Photon Interactions

- Focus on AAAA (AAZZ and AAWW see [Chapon et al '12])
- EFT for 4-photon interaction contains two dim-8 structures

$$\mathcal{L}_{4\gamma} = \zeta_1 \left(F_{\mu\nu}F^{\mu\nu}\right)^2 + \zeta_2 F_{\mu\nu}F^{\nu\rho}F_{\rho\sigma}F^{\sigma\mu}$$

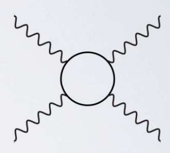
- Cross section has a simple form

$$\frac{d\sigma}{d\Omega} = \frac{1}{16\pi^2 s}(s^2+t^2+st)^2\left[48\zeta_1^2 + 40\zeta_1\zeta_2 + 11\zeta_2^2\right]$$

- Unitarity breaks down for $\zeta_i s^2 \gtrsim 2\pi$
- Demanding unitarity for LHC energies $\Rightarrow$ $\zeta_i \lesssim 10^{-10}\mathrm{GeV}^{-4}$
- In explicit models EFT breaks down before that!
- LHC sensitivities to ζ_i are ~$10^{4\text{-}5}$ better than unitarity bound

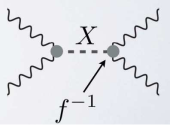
New physics contributions to 4γ couplings

1 New charged particles via loops

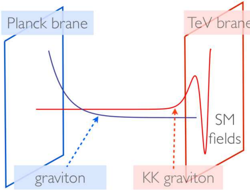


- Effective coupling only depends on the mass, charge and spin : $\zeta_i^\gamma \propto c_i^s Q^4 m^{-4}$
- Example: top partners

2 New neutral particles at tree level



- Effective coupling depends on mass, spin and the non-renormalizable $\gamma\gamma X$ coupling $\zeta_i^\gamma \propto b_i^s f^{-2} m^{-2}$
- Example: KK gravitons, dilaton (warped extra-dimension)

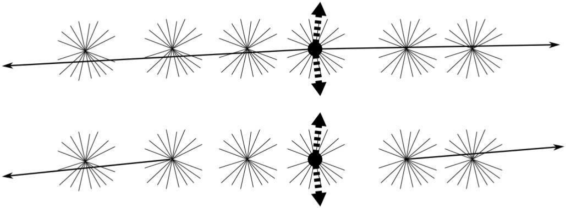


if coupling $\simeq$ TeV and $m_{KK} \simeq$ few TeV, $\zeta_i^\gamma \simeq 10^{-14}$-$10^{-13}$ GeV^{-4} achievable, which we are sensitive

Conversion, fake and efficiency reconstruction rates

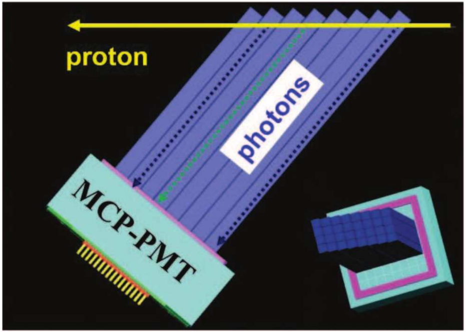
- Inputs from the **ECFA ATLAS studies**
- **Photon conversion factors:** 15% in the barrel, 30% in the end-caps
- **Photon and electron reconstruction efficiency**:
  $Eff(p_T) = 0.76 - 1.98\ exp^{\frac{-p_T}{16.1(GeV)}}$
- **Photon fake factors:** 1% for electron
  European Strategy studies
- **Fake photon $\mathbf{p}_T$ for jets:** gaussian draw (Mean=75%,σ=13%) on the jet p_T and use of
  $Eff_{fake}(p_T) = 0.0093\ exp^{\frac{-min(p_T,200GeV)}{17.5(GeV)}}$
  almost no fake γ from jets at very high $\mathbf{p}_T$

Forward detectors measurements



- **Proton missing mass** measurement with 3% resolution in case of double tag
- **It matches the central $\gamma\gamma$ mass for signal**. Can match as well for pile-up backgrounds as a statisical fluctuation
- **Double tag probability** from pile-up protons on the forward detectors (no missing mass requirement) :
  32% ($\mu = 50$) 66% ($\mu = 100$) 93% ($\mu = 200$)

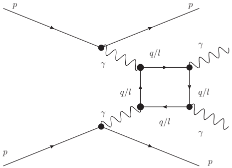
Forward timing detectors : inefficiencies due to pile-up protons



Inefficiencies - 2mm bar detector										
Bar	1	2	3	4	5	6	7	8	9	10
$\mu = 50$	0.129	0.085	0.067	0.057	0.049	0.046	0.043	0.040	0.036	0.011
$\mu = 100$	0.185	0.122	0.097	0.082	0.071	0.066	0.062	0.057	0.051	0.016

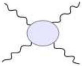
M. Saimpert. Search for new states of matter wih the ATLAS experiment at the LHC, Master Thesis MINES ParisTech (2013)

SM QED exclusive $\gamma\gamma$ production



- Different loop contributions: fermions (quarks, leptons), vectors (W)
- **W loop contribution** and **massive fermions** added to the process in FPMC rev.913 (negligible at low mass but not at high mass, usually not included in the MCs)
- Interferences SM/Exotics added for the full amplitude calculation of new heavy charged particles

The BSM amplitudes



- Loops of spin 0,1/2, 1 new electric particles contribute to 4γ . Because all vertices are fixed by gauge invariance, the NP contributions depend only on spin, mass and electric charge ! ⇨ Very model-independent

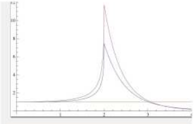
- For example in the effective theory limit : $\zeta_i^\gamma = \alpha_{\rm em}^2 Q^4 \, m^{-4} \, N \, c_{i,s}$

$$c_{1,s} = \begin{cases} \frac{1}{288} & s=0 \\ -\frac{1}{36} & s=\frac{1}{2} \\ -\frac{5}{32} & s=1 \end{cases}, \quad c_{2,s} = \begin{cases} \frac{1}{360} & s=0 \\ \frac{7}{90} & s=\frac{1}{2} \\ \frac{27}{40} & s=1 \end{cases}$$

Scalar loops are smaller !

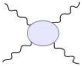
- Full amplitudes for fermions and vectors are now implemented in FPMC.

- Amplitudes get enhanced near the threshold



$\gamma\gamma\gamma\gamma$ full amplitude calculation (S. Fichet)

The SM background



- All electric particles of the SM contribute : leptons, quarks and W bosons
- The imaginary part of certain W helicity amplitudes grows with the energy, while the fermion ampliudes are finite. Background is dominated by the W loop
- When the new particle is real, it interfers with the W loop.
  ⇨ On-shell NP signal enhanced by SM interference
- All SM background amplitudes are implemented in FPMC (+ swiches to separately turn off them)
- One can check that SM fermions contributions are negligible.
  ⇨ Keeping only the W loop provides a huge gain of CPU time !

Full amplitude computation for generic heavy charged fermions/vectors contributions **(preliminary)**

- **Link full amplitude - effective field theory**

  $\zeta_i^\gamma = c_i^s Q_{eff}^4 m^{-4} \alpha_{em}^2$, $c_i \simeq 0.01$ (0.1) for fermions (vectors)

- Typical sensitivity with the **full amplitude calculation**

  M = 800 GeV, $Q_{eff} > 7$ (4) for fermions (vectors)

- Gives a coupling of $\simeq \mathbf{3.10}^{-15}$ in terms of ζ_i

- Same order of magnitude than the sensitivity we had using the effective field theory → **successful cross-check of the method**

Conclusion: additional information

- Effective field theory: 5σ discovery with less luminosity ($1\ \mathrm{fb}^{-1}$, $10\ \mathrm{fb}^{-1}$, $50\ \mathrm{fb}^{-1}$) : $7{\cdot}10^{-13}$, $2{\cdot}10^{-13}$, $9{\cdot}10^{-14}$ GeV^{-4}
- $\gamma\gamma\gamma\gamma$ paper: S. Fichet et al Phys. Rev. D **89** (2014)
- More detailed paper including the full amplitude calculations for loop contributions and SM exclusive production update in preparation