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

Low x conference 2014 @ Kyoto, Japan

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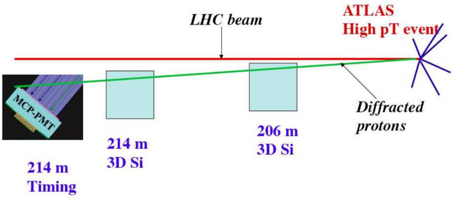
C. Royon, O. Kepka, Phys. Rev. D ***78*** *(2008)*

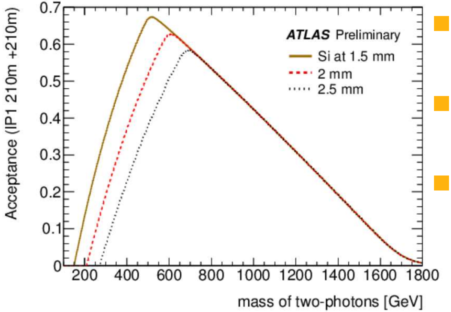
E. Chapon, C. Royon, O. Kepka, Phys. Rev. D ***81*** *(2010)*

S. Fichet et al, Phys. Rev. D ***89*** *(2014)*

Forward proton detectors at the LHC

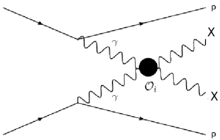
- The ATLAS Forward Physics (AFP) and the Precision Proton Spectrometer (PPS, CMS/TOTEM) upgrade projects





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

Exclusive production via photon induced processes



- **All particles at the final state are detected:** two protons in the forward detectors and two high energy particles in the central detector → **strong kinematics constraints**
- Requirement of two intact protons + kinematics constraints → **strong background reduction**

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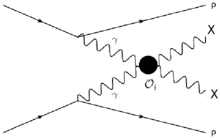

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- $\gamma\gamma$, WW, ZZ final states ideal to study **anomalous quartic gauge couplings (aQGC)**
- aQGC important for various physics topics: **electroweak symmetry breaking, extra-dimension models, ...**

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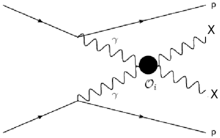

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- $\gamma\gamma$, WW, ZZ final states ideal to study **anomalous quartic gauge couplings (aQGC)**
- aQGC important for various physics topics: **electroweak symmetry breaking, extra-dimension models, ...**
- Drawback: smaller cross-sections
  (intact protons must be in the acceptance of the forward detectors)

$WW\gamma\gamma$ 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)*

- **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)
- **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

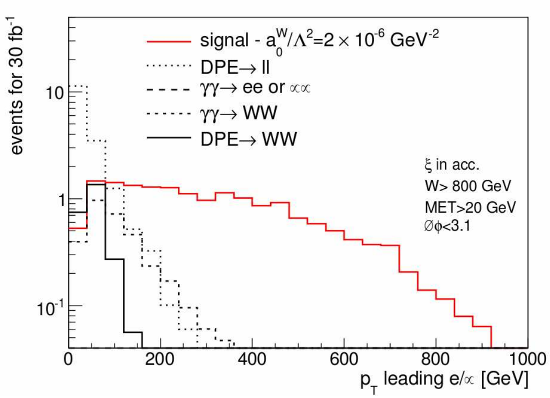
$WW\gamma\gamma$ and $ZZ\gamma\gamma$ anomalous couplings

*ATLAS **fast** simulation study*

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

- Anomalous signal appears at high energy

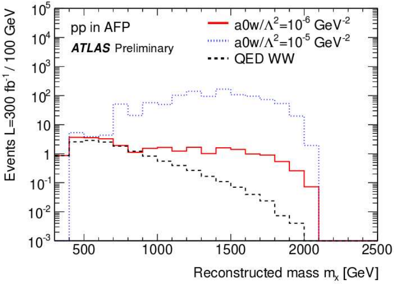
  $WW\gamma\gamma$ signal and background composition passing all the selection but the p_T cut on the leading lepton

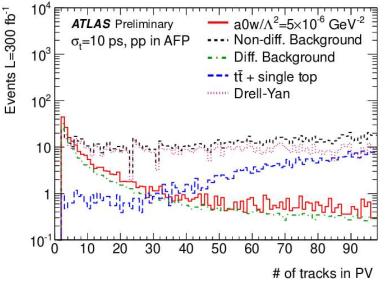


Dealing with pile-up at the LHC

*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 of the interaction
  dependant 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

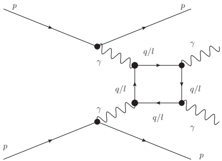
E. Chapon, C. Royon, O. Kepka, Phys. Rev. D ***81*** *(2010)*

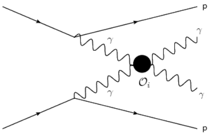
- **Best limits from LEP**, OPAL (Phys. Rev. D **70** (2004) 032005) of the order of 0.02-0.04 GeV^{-2} for each coupling

- **Recent papers from DØ and CMS** for $WW\gamma\gamma$ with reach of the order of 10^{-4} GeV^{-2} (CMS-PAS-FSQ-12-010)
  Former reference (P. J. Bell, arXiv:0907.5299): sensitivites predicted at the LHC of the order of a few 10^{-4} GeV^{-2}

- **Sensitivities predictions with AFP** (30 and 200 fb^{-1})
  improvement by 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
	$\Lambda_{cut} = 2\,\mathrm{TeV}$	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
	$\Lambda_{cut} = 2\,\mathrm{TeV}$	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
	$\Lambda_{cut} = 2\,\mathrm{TeV}$	5.4	20	14	52	2.7	9.6	5.5	20





- **Direct coupling absent from the SM***

  loop induced production measurable at the LHC with heavy ions (d'Enterria et al. Phys. Rev. Lett.* **111 *(2013) 080405)*

- **No constraints from collider experiments**

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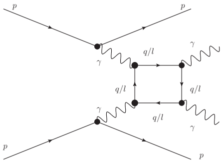

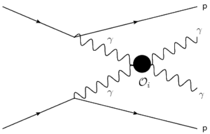

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- Small couplings → high luminosity required

  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)

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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

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, production threshold can be reached → **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 $\Lambda' = 1\ TeV \simeq \sqrt{\hat{s}_{\gamma\gamma,max}}/2$

  Unitary requires $\zeta_i < 10^{-10}\ GeV^{-4}$, $\simeq 10^4$ higher than our sensitivity limit

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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 the same 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

$\gamma\gamma\gamma\gamma$ study

- Evaluate the LHC potential to probe 4γ couplings using proton tagging and the effective field theory
  - 4γ aQGC operators implemented in the **FPMC generator**
  - Rough simulation of the detector effects (see S12)
  - Pile-up simulation with Pythia8 minimum bias events
  - Background estimation (expected to be very small)
  - Sensitivities calculation: 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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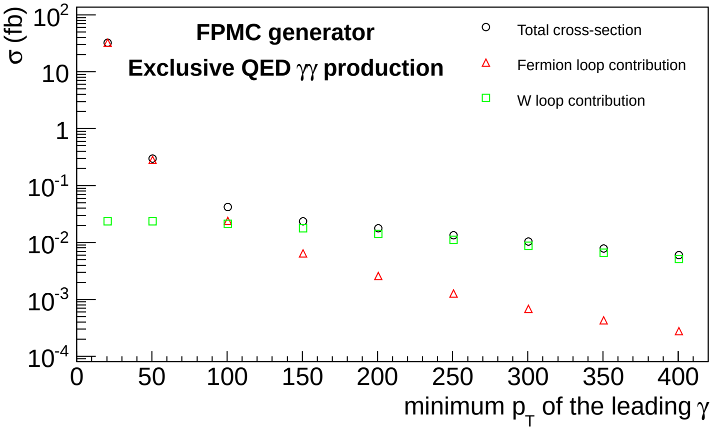
- Implementation of generic **new heavy-charged fermions/vectors** contributions to the 4γ couplings in FPMC **(full amplitude)**
- **Extra:** update of the exclusive $\gamma\gamma$ SM production in FPMC
  includes the ***W loop contribution and the fermion masses***

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



- Mass of the fermions taken into account
- W loop non negligeable for $p_{T,\gamma} > 50$ GeV
- QCD and DPE contributions to be added
- Same plot against the diphoton mass (in progress)

$\gamma\gamma\gamma\gamma$ study

- Analysis at **particle level** 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** $\rightarrow$ **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 S18)

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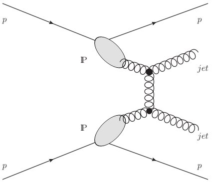
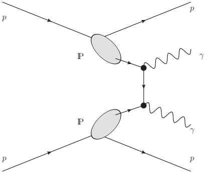
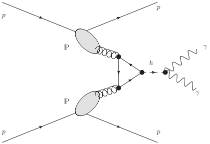
- **Final outputs**
  - 5σ and 95% C.L sensitivities on the $\gamma\gamma\gamma\gamma$ couplings *effective field theory*
  - M-Q exclusion plane for generic exotic fermions/vectors *full amplitude*

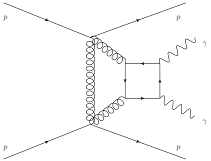
$\mathbb{P}$ backgrounds (FPMC)



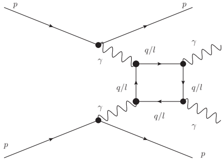


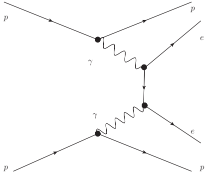


Exclusive QCD (ExHuME)

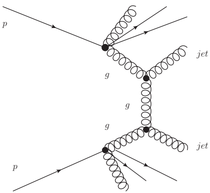


Exclusive QED (FPMC)

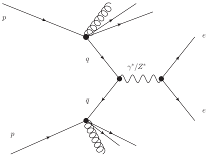




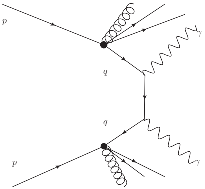
Dijet



Drell-Yan



Diphoton



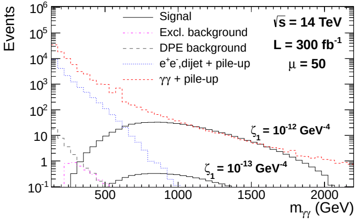
+ protons generated from **minimum bias events** (Pythia 8)

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

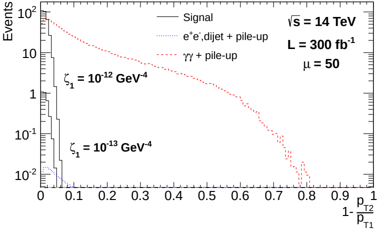
Mass and p_T balance distribution of signal and backgrounds

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

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



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

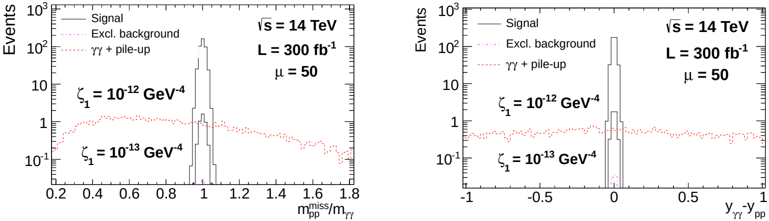


- By requesting $m_{\gamma\gamma} > 600$ GeV (left), **Only pile-up backgrounds remain**
- p_T ratio distribution after p_T and $m_{\gamma\gamma}$ cuts (right) provides another efficient cut **(exclusive process)**
- $\Delta\phi > \Pi$-0.01 also applied later in the selection

Use of the forward detector ξ measurement

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

$0.015 < \xi < 0.15$, $|\eta| < 2.37$, $m_{\gamma\gamma} > 600$ GeV, $p_{T1,2} > 200$, 100 GeV



- **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**

Expected events for $\zeta_1^\gamma = 2\ 10^{-13} \cdot \mathrm{GeV}^{-4}$

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

Cut / Process	Signal	Excl.	DPE	e^+e^-,dijet + pu	$\gamma\gamma$ + pu
$0.015 < \xi < 0.15$, $p_{T1,2} > 50$ GeV	20.8	3.7	48.2	$2.8 \cdot 10^4$	$1.0 \cdot 10^5$
$p_{T1} > 200$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

- **Signal selection efficiency** $>$ **70%** (after preselection)
  - Acceptance increased by a factor 3-4 when adding all unconverted photons (with EM "pointing")

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$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	15.1	0.1	0	0	0

- **Signal selection efficiency** $>$ **70%** (after preselection)
  - Acceptance increased by a factor 3-4 when adding all unconverted photons (with EM "pointing")
- **Background completely suppressed thanks to forward detectors ξ measurement**
  - Very high significance per observed event
  - 1.5 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

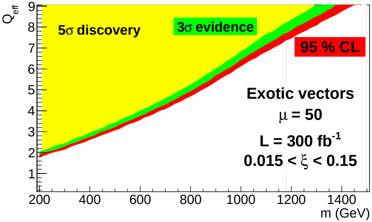
S. Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert, Phys. Rev. D ***89*** *(2014)*

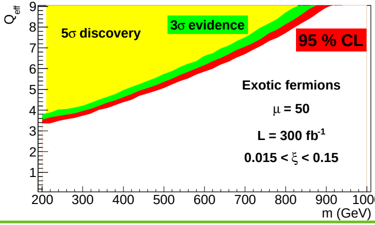
Luminosity	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
pile-up (μ)	50	50	50	200
coupling (GeV^{-4})	$\geq$ 1 conv. γ 5 σ	$\geq$ 1 conv. γ 95% CL	all γ 95% CL	all γ 95% CL
ζ_1 f.f.	$1 \cdot 10^{-13}$	$9 \cdot 10^{-14}$	$5 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$
ζ_1 no f.f.	$3.5 \cdot 10^{-14}$	$2.5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

- A large panel of extra-dimension models can be probed in **the multi-TeV range**
- The form factor is not needed anymore for a 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)**

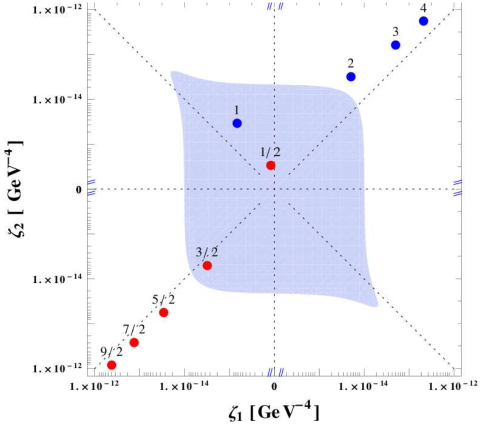
- **The existence of new heavy charged particles** will enhance the $\gamma\gamma\gamma\gamma$ coupling at high mass via loops
- This enhancement can be parametrized by **only the mass and the effective charge** $Q_{eff} = Q.N^{1/4}$, N multiplicity
- Generic implementation for fermions and vectors implemented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





Higher spin resonances and link with EFT **(preliminary)**

- Dots mark generic exotic charged particles of **high spin** with M = 1 TeV, Q_{eff} = 3 (300 fb^{-1}, all γ, μ = 50)
- 5 σ sensitivity is represented by the white region



Conclusion

- Forward proton tagging at the LHC seems promising to probe **anomalous $\gamma\gamma XX$ Gauge Couplings**
  - proton tagging associated by high energy object detections in the central EM calorimeter allow to highly suppress the background
  - $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings sensitivity improvement by a factor $>$ **100**
  - $\gamma\gamma\gamma\gamma$ 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

    (no previous constraints from collider experiments)

- $\gamma\gamma\gamma\gamma$ coupling: **a channel probing exotic heavy charged vectors/fermions** in a completely **model-independant** way
  - sensitive for vectors (fermions) **up to 1400 (920) GeV**

    (Preliminary result)

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

Back-up

Matthias Saimpert[1]
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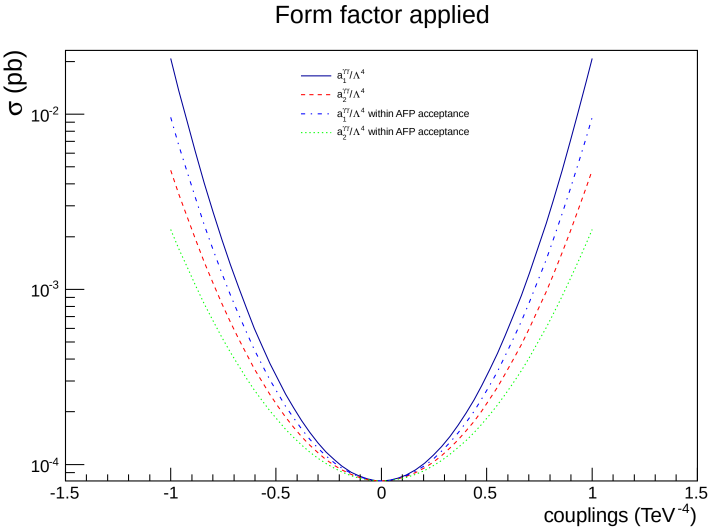
June 20th 2014

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

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

- Cross section has a simple form

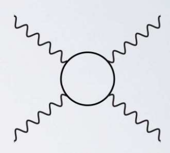
$$\frac{d\sigma}{d\Omega} = \frac{1}{16\pi^2 \, s} (s^2 + t^2 + st)^2 \left[48\zeta_1^2 + 40\zeta_1\zeta_2 + 11\zeta_2^2 \right]$$

- Unitarity breaks down for $\zeta_i s^2 \gtrsim 2\pi$
- Demanding unitarity for LHC energies ⇒ $\zeta_i \lesssim 10^{-10} \mathrm{GeV}^{-4}$
- 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

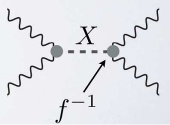
1 New charged particles via loops

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

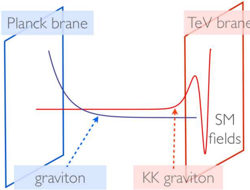


2 New neutral particles at tree level

- 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



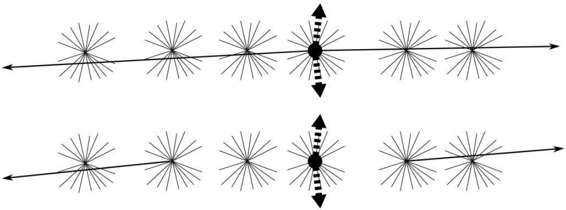
Where does proton tagging do better?

- 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
  - Very difficult to quantify precisely the improvements compared to the central detector alone **(in progress)**
- 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

Conversion, fake and efficiency reconstruction rates

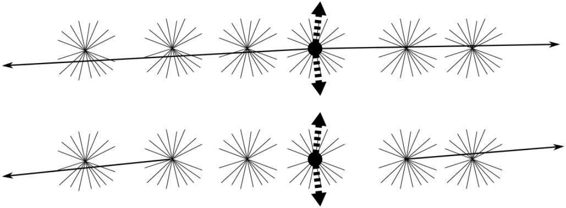
- Inputs from the **ECFA ATLAS studies**
- **Photon conversion factors:** 15% in the barrel, 30% in the end-caps
- **Photon and electron reconstruction efficiency**:
  $Eff(p_T) = 0.76 - 1.98\ exp^{\frac{-p_T}{16.1(GeV)}}$
- **Photon fake factors:** 1% for electron
  European Strategy studies
- **Fake 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



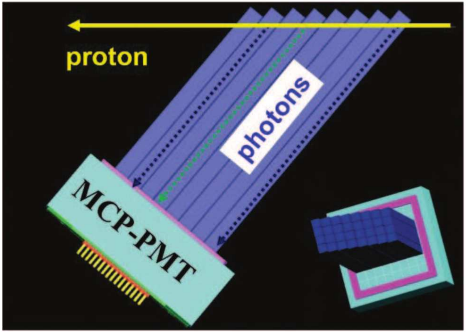
- **Proton missing mass** measurement with 3% resolution in case of double tag
- **It matches the central $\gamma\gamma$ mass for signal**. Can match as well for pile-up backgrounds as a statisical fluctuation
- **Double tag probability** from pile-up protons on the forward detectors (no missing mass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

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**
- additional background rejection factor of 40 at $\mu = 50$
- No need to use for this study, **robustness of the analysis**
- can be used for unknown backgrounds (beam-induced)

Forward timing detectors : inefficiencies due to pile-up protons

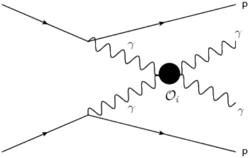


Inefficiencies - 2mm bar detector										
Bar	1	2	3	4	5	6	7	8	9	10
$\mu = 50$	0.129	0.085	0.067	0.057	0.049	0.046	0.043	0.040	0.036	0.011
$\mu = 100$	0.185	0.122	0.097	0.082	0.071	0.066	0.062	0.057	0.051	0.016

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

Event selection: summary

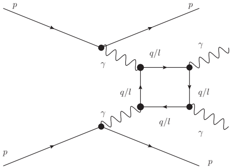
- **Kinematic cuts**
  1. $p_{T1}^{\gamma} > 200\ GeV, p_{T2}^{\gamma} > 100\ GeV$
  2. $m_{\gamma\gamma} > 600\ GeV$



- 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)**

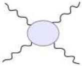
SM QED exclusive $\gamma\gamma$ production



- 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

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

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

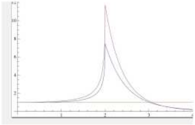
- For example in the effective theory limit : $\zeta_i^\gamma = \alpha_{\rm em}^2 Q^4\, m^{-4}\, N\, c_{i,s}$

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

Scalar loops are smaller !

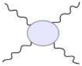
- Full amplitudes for fermions and vectors are now implemented in FPMC.

- 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 $\rightarrow$ **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