Probing anomalous quartic gauge couplings using proton tagging at the Large Hadron Collider

LHC Working Group on Forward Physics and Diffraction

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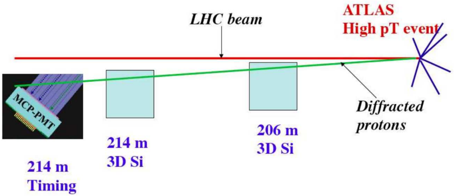
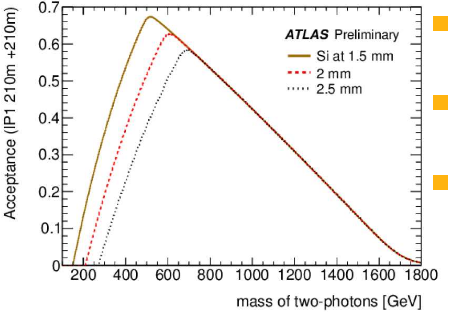
Forward proton detectors at the LHC

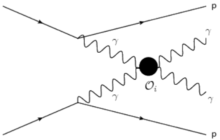
- The ATLAS Forward Physics Project (AFP) and the Precision Proton Spectrometer (PPS, CMS/TOTEM)





- $\xi_{1,2}$ 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**
- Final state can be $\gamma\gamma$, WW, ZZ → ideal to study **anomalous quartic gauge couplings (aQGC)**
- aQGC important for various topics: **electroweak symmetry breaking, extra-dimension models, ...**
- Drawback: reduced cross-sections (intact protons)

$WW\gamma\gamma$ 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

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

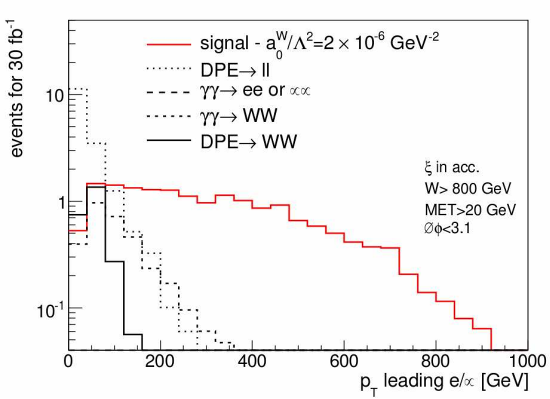
$$\mathcal{L}_6^C \sim \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W_\beta^- + W^{-\alpha}W_\beta^+) - \frac{e^2}{16\cos^2(\theta_W)}\frac{a_C^Z}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}Z^\alpha Z_\beta$$

- **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 and gave similar results

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

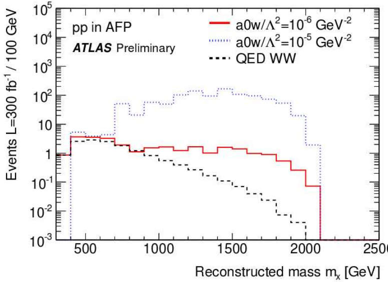
E. Chapon, C. Royon, O. Kepka, Phys. Rev. D ***81*** *(2010)*

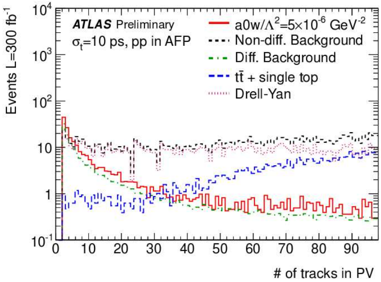
- $WW\gamma\gamma$ signal and background composition passing all the selection but the p_T cut on the leading lepton



ATLAS full simulation study

- The LHC is operated at **very high luminosity → high event multiplicites** in a single bunch-crossing (pile-up)
- 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
- Full simulation results





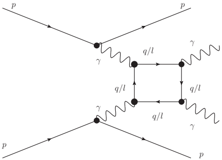
$WW\gamma\gamma$ and $ZZ\gamma\gamma$ sensitivities

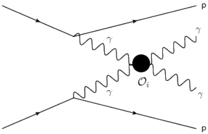
*E. Chapon, C. Royon, O. Kepka, Phys. Rev. D **81** (2010)*

- 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 D0 and CMS for $WW\gamma\gamma$ with reach of the order of 10^{-4} GeV^{-2} *(CMS-PAS-FSQ-12-010)*
- Sensitivites predicted at the LHC (P. J. Bell, ArXiV:0907.5299) 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	$\|a_0^W/\Lambda^2\|$	$\|a_C^W/\Lambda^2\|$	$\|a_0^Z/\Lambda^2\|$	$\|a_C^Z/\Lambda^2\|$	$\|a_0^W/\Lambda^2\|$	$\|a_C^W/\Lambda^2\|$	$\|a_0^Z/\Lambda^2\|$	$\|a_C^Z/\Lambda^2\|$
		limits [10^{-6} GeV^{-2}]				limits [10^{-6} GeV^{-2}]			
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

$\gamma\gamma\gamma\gamma$ anomalous couplings (2013-2014)





- **Direct coupling absent from the SM***
  loop induced production measurable at the LHC with heavy ions (D. D'Enterria, G. Da Silveira, PRL **111 (2013)*
- New couplings predicted by strongly-interacting composite states, extra-dimensions, ...
- **No constraints from collider experiments**

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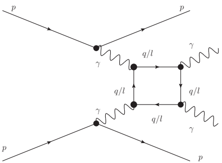

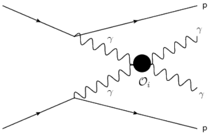

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- New couplings predicted by strongly-interacting composite states, extra-dimensions, ...
- **No constraints from collider experiments**
- Small couplings, high luminosity required, $\mu >$ **50**.
  (300 fb^{-1} of data expected at the LHC at $\sqrt{s} = 14$ TeV)
- **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 valid

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

- Unitary breaks down at large scale $\Lambda' \rightarrow$ **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 $\Lambda' = 1\ TeV$

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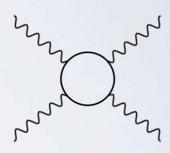
- **f.f. not necessary** when the new particles have a large enough mass
- The signal showed in the plots of this presentation are for a **signal with $\zeta_1 \geq 0$ and $\zeta_2 = 0$ and with f.f.**
  ζ_1 and ζ_2 have the same angular behaviour
- A table with sensitivities for both ζ_1 and ζ_2 are given at the end of the presentation

New physics contributions to 4γ couplings

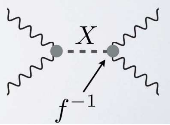
1 New charged particles via loops

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

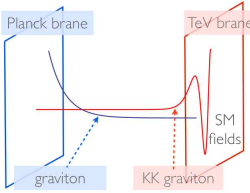


2 New neutral particles at tree level

- 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/radion (warped extra-dim)



if coupling $\simeq$ TeV and m$_{KK}$ $\simeq$ few TeV
$\rightarrow$predictions of $\zeta_i^\gamma \simeq 10^{-14}$-$10^{-13}$ GeV^{-4}, 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, ...
  - Should be less competitive on resonances searches
    ex: new neutral particles at tree level
  - Very difficult to quantify precisely the improvements compared to the central detector alone **(in progress)**

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- For the first time, we reach sensitivities allowing to **probe directly a large class of new models**
  - **Warped extra-dimensions:** KK gravitons, radion/dilaton, high κ untested domain (Randall-Sundrum model)
  - **Strongly-interacting composite states, monopoles:** generic searches of new heavy charged particles

$\gamma\gamma\gamma\gamma$ study

- Evaluate the LHC potential to probe 4γ couplings using proton tagging
  - 4γ aQGC operators implemented in the **FPMC generator** in summer 2013
  - Pile-up simulation with Pythia8 minimum bias events
  - Background estimation (very small)
  - **The backgrounds from pile-up should dominate**
  - 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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- **New:** implementation of generic **new heavy-charged fermions/vectors** contributions to the 4γ couplings in FPMC **(full amplitude)**

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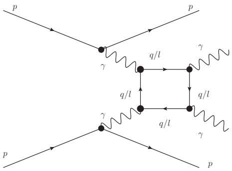
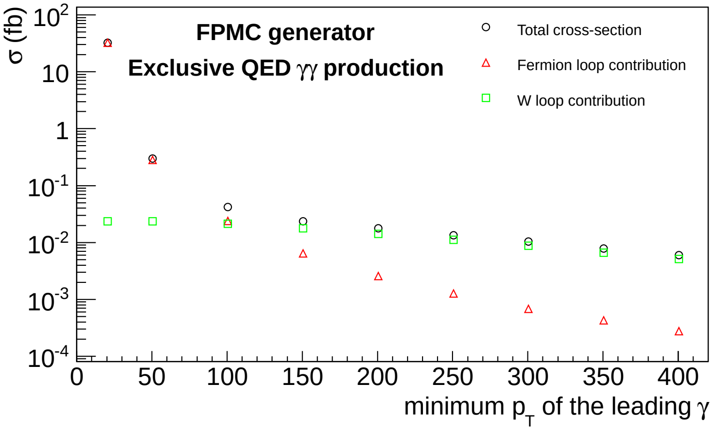
- **New:** implementation of generic **new heavy-charged fermions/vectors** contributions to the 4γ couplings in FPMC **(full amplitude)**
- **New:** update of the exclusive $\gamma\gamma$ SM production, adding the **W loop contribution and the fermion masses**

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)
- Interferences SM/Exotics added for the full amplitude calculation

SM QED exclusive $\gamma\gamma$ production



- W loop non negligeable for $p_{T,\gamma} > 50$ GeV
- QCD and DPE contributions to be added
- Same plot for the $\gamma\gamma$ mass is being made
- Mass of the fermions taken into account

$\gamma\gamma\gamma\gamma$ study

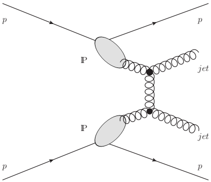
- Analysis at particle level
  - Estimation of γ **conversion rates** (η function), **fake photon rates**, photon and photon fake **reconstruction efficiency** (p_T functions) from ECFA ATLAS studies
  - **Smearing** of 1% in γ energies, 0.001 in η and ϕ (absolute), 2% for ξ to mimic detector resolution
  - 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 (see S12-S17)
- **Final outputs**
  - 5σ and 95% C.L sensitivities on the $\gamma\gamma\gamma\gamma$ vertex (effective field theory)
  - M-Q exclusion plane for generic exotic fermions/vectors (full amplitude)

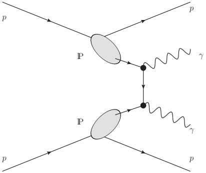
Conversion, fake and efficiency reconstruction rates

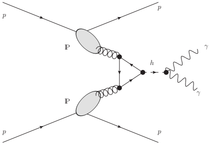
- Inputs from the **ECFA ATLAS studies**
- **Photon conversion factors:** 15% in the barrel, 30% in the end-caps
- **Photon and electron reconstruction efficiency**:
  $Eff(p_T) = 0.76 - 1.98\ exp^{\frac{-p_T}{16.1(GeV)}}$
- **Photon fake factors:** 1% for electron
  European Strategy studies
- **Fake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

Backgrounds (FPMC, ExHuME)

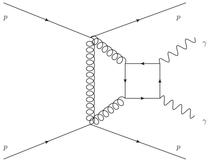
IP backgrounds (FPMC)



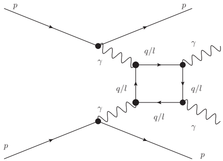


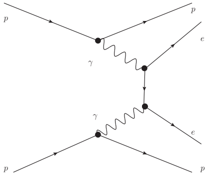


Exclusive QCD (ExHuME)



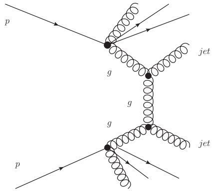
Exclusive QED (FPMC)



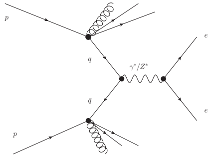


Pile-up backgrounds (HERWIG 6.5)

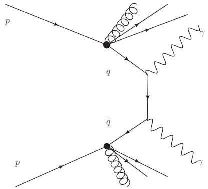
Dijet



Drell-Yan



Diphoton

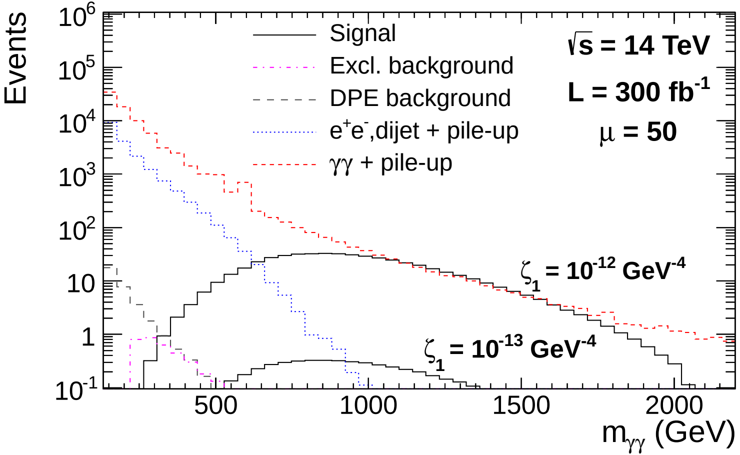


+ protons generated from **minimum bias events** (Pythia 8)

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

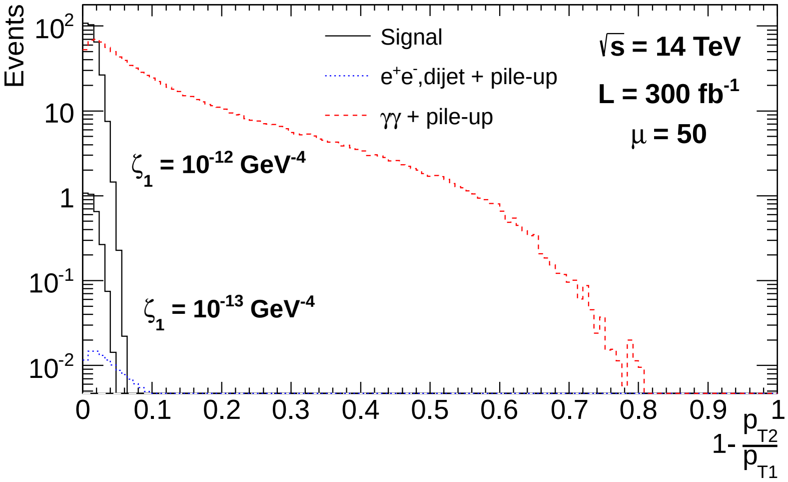
Mass distribution of signal and backgrounds

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



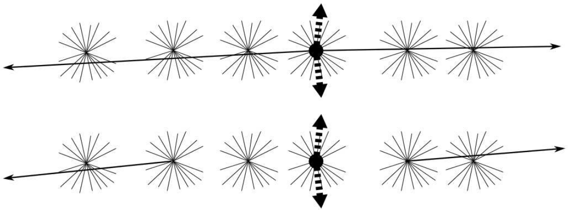
- By requesting $m_{\gamma\gamma} > 600$ GeV, Only pile-up backgrounds remain

Exclusive signal: p_T ratio



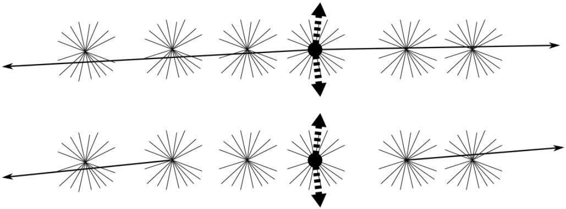
- p_T ratio distribution after p_T and $m_{\gamma\gamma}$ cuts

Forward detectors measurements



- **Proton missing mass** measurement with 3% resolution in case of double tag

Forward detectors measurements



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- **It matches the central $\gamma\gamma$ mass for signal**. Can match as well for pile-up backgrounds as a statisical fluctuation

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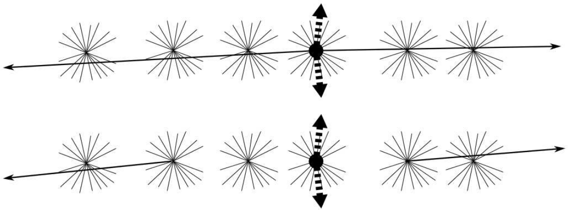
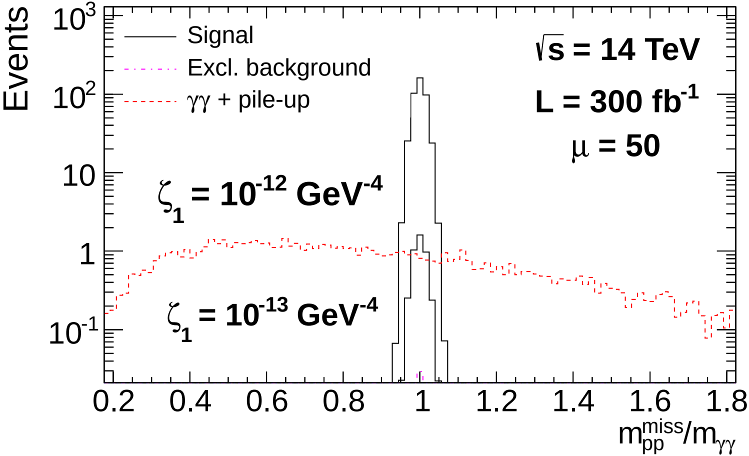


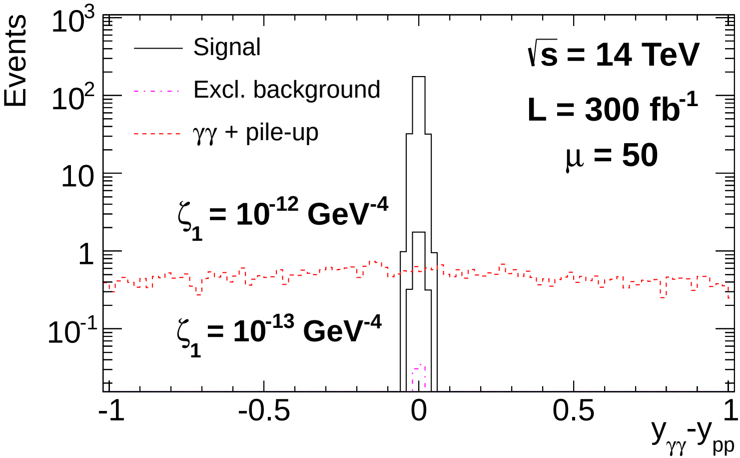
- **Proton missing mass** measurement with 3% resolution in case of double tag
- **It matches the central $\gamma\gamma$ mass for signal**. Can match as well for pile-up backgrounds as a statisical fluctuation
- **Double tag probability** from pile-up protons on forward detectors (no mass requirement)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

Mass matching and pile-up



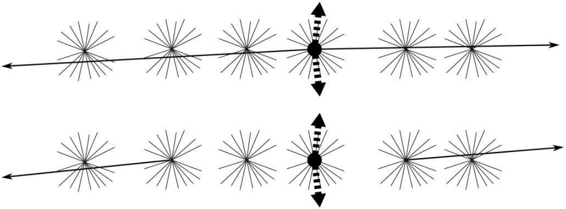
- A mass window of 3% (= resolution) is required in the event selection

Rapidity cut



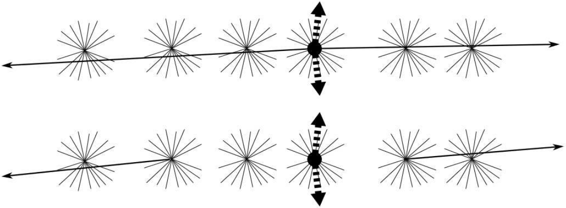
- $|y_{\gamma\gamma} - y_{pp}| < 0.03$ with $y_{pp} = (0.5 * ln(\frac{\xi_1}{\xi_2}))$
- Small width for signal due to the resolution on $y_{\gamma\gamma}$ and $\xi_{1,2}$

Possible extra-cut: proton timing requirement



- Proton timing will be measured by forward detectors

Possible extra-cut: proton timing requirement



- Proton timing will be measured by forward detectors
    - 10 ps resolution assumed → proton vertex constrained within 2.1 milimeters

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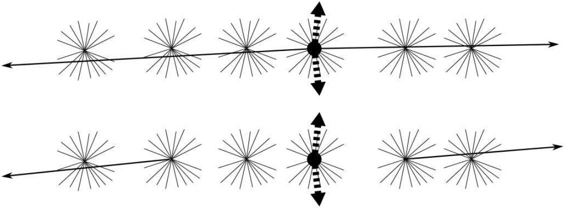

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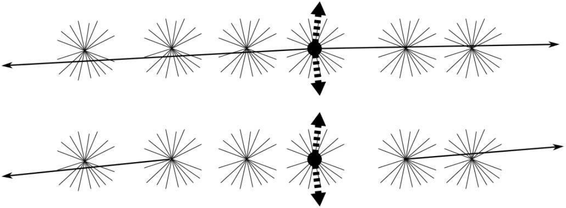

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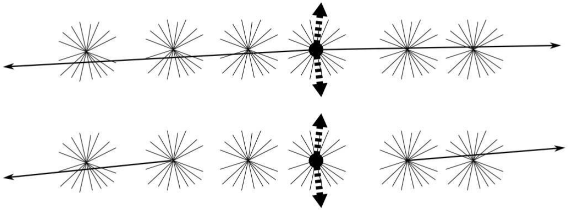
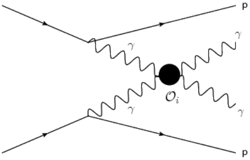


- Proton timing will be measured by forward detectors
  - 10 ps resolution assumed $\rightarrow$ proton vertex constrained within 2.1 milimeters
  - Requirement of 1 converted $\gamma \rightarrow < 1$ mm resolution on the γ vertex
  - **Resolution driven by forward timing detectors**
- additional background rejection factor of 40 at $\mu = 50$
- No need to use it for us, **robustness of the analysis**
- can be used for unknown backgrounds (beam-induced)

Event selection summary

- **Kinematic cuts**

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



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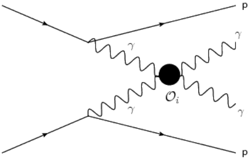

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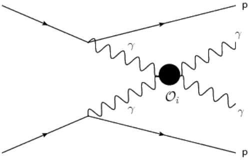

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- **Forward detectors** cuts
  1. $m_{pp}^{miss} = m_{\gamma\gamma} \pm 3\%$
  2. $|y_{\gamma\gamma} - y_{pp}| < 0.03$
     with y_{pp} = $(0.5 * ln(\frac{\xi_1}{\xi_2}))$
  3. Possible proton timing measurement with forward detectors

Expected events for $\zeta_1^\gamma = 2\ 10^{-13}$.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
$0.015 < \xi < 0.15$, $p_{T1,2} > 50$ 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 unconverted photons (with EM "pointing")
- **Background completely suppressed thanks to forward detectors ξ measurement**
  - 1.5 background events expected at μ = 200
    Robust analysis, very 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

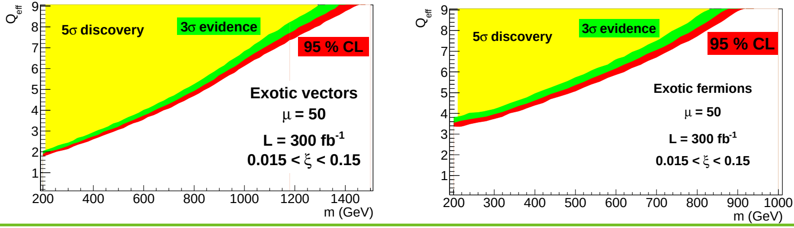
S. Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert, arXiv:1312.5153 (2013)

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.	$7.5 \cdot 10^{-14}$	$5.5 \cdot 10^{-14}$	$3 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$

- KK gravitons and strongly-coupled dilaton/radion (warped extra-dimensions) can be discovered in **the multi-TeV range**

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



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 $\simeq \mathbf{10}^{-15}$ in terms of ζ_i

- Corresponds to the sensitivity we had using the effective field theory → **successful cross-check of the method**

Conclusion

- Forward proton tagging at the LHC seems promising to probe **anomalous Quartic Gauge Couplings**
  - proton tagging associated by high energy object detections in the central EM calorimeter allow to **completely suppress the background**
  - $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings already studied with positive outputs (improvement by a factor $>$ **100**)
  - $\gamma\gamma\gamma\gamma$ coupling: 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** (even scalars, sensitivity is smaller) in a completely **model-independant** way
  - sensitive for vectors (fermions) **up to 1400 (920) GeV**

Conclusion

- 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 submitted : arXiv:1312.5153

- More detailed paper including the full amplitude calculations for loop contributions in preparation

Probing anomalous quartic gauge couplings using proton tagging at the Large Hadron Collider

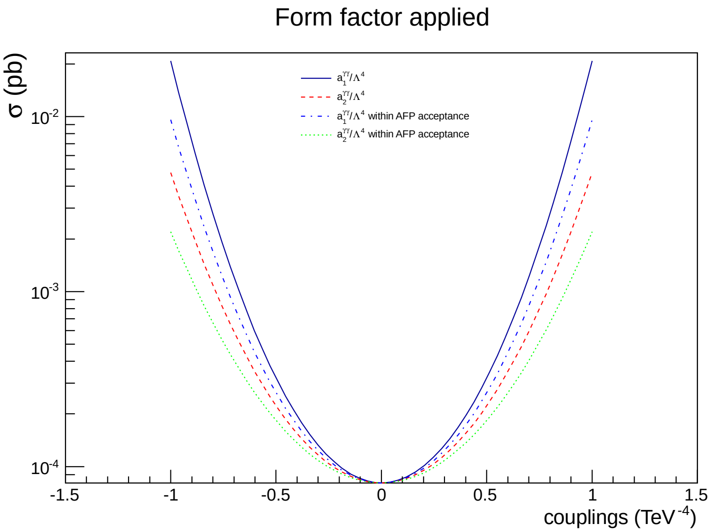
Back-up

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

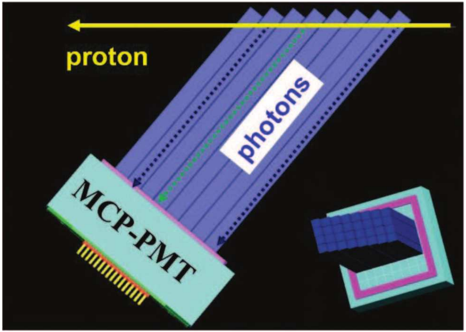
[1]CEA Saclay - Irfu/SPP

16/04/2014

Integrated total cross-section against couplings



Forward timing detectors : inefficiencies due to pile-up protons

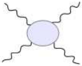


Inefficiencies - 2mm bar detector										
Bar	1	2	3	4	5	6	7	8	9	10
$\mu = 50$	0.129	0.085	0.067	0.057	0.049	0.046	0.043	0.040	0.036	0.011
$\mu = 100$	0.185	0.122	0.097	0.082	0.071	0.066	0.062	0.057	0.051	0.016

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

$\gamma\gamma\gamma\gamma$ 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

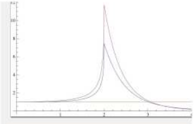
- For example in the effective theory limit : $\zeta_i^\gamma = \alpha_{\rm em}^2 Q^4\, m^{-4}\, N\, c_{i,s}$

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

Scalar loops are smaller !

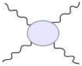
- Full amplitudes for fermions and vectors are now implemented in FPMC.

- 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 !