Probing four photon couplings with proton tagging at the Large Hadron Collider

Workshop on photon-induced collisions at the LHC

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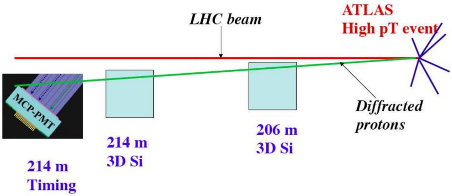
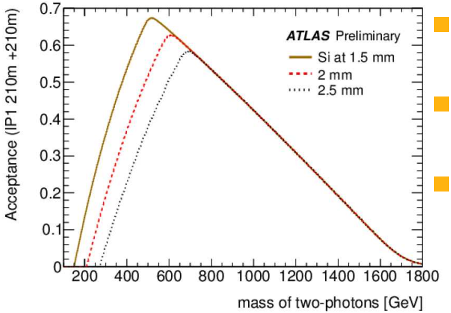
Forward proton detectors at the LHC

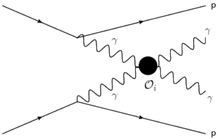
- The ATLAS Forward Physics Project (AFP) and the Precision Proton Spectrometer (PPS, CMS/TOTEM)





- $\xi_{1,2}$ 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



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- Requirement of two intact protons + kinematics constraints → **strong background reduction**

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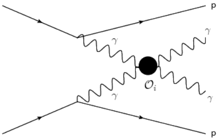

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- aQGC important for various physics topics: **electroweak symmetry breaking, extra-dimension models, ...**

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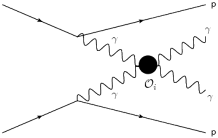

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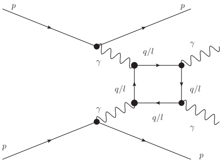
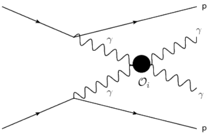
- aQGC important for various physics topics: **electroweak symmetry breaking, extra-dimension models, ...**
- Drawback: smaller cross-sections

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

$\gamma\gamma\gamma\gamma$ anomalous couplings





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  **loop induced production measurable at the LHC with heavy ions (see D. D'Enterria's talk)*

- **No constraints from collider experiments**

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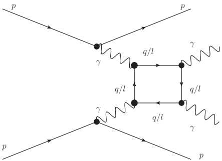

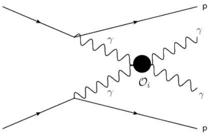

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  300 fb^{-1} of data expected at the LHC at $\sqrt{s} = 14$ TeV with $\boldsymbol{\mu} > \mathbf{50}$
- **Huge background** if only 2 high energy γ required
  (SM $\gamma\gamma$ production + fakes from electrons and jets)

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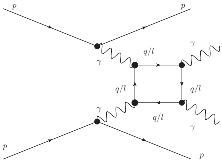

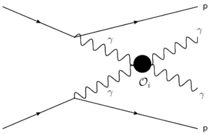

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Operators of the $\gamma\gamma\gamma\gamma$ couplings

*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

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

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  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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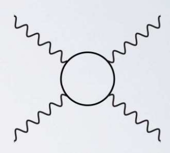
- Unitary requires $\zeta_i < 10^{-10}$ GeV^{-4}, $\simeq 10^4$ higher than our sensitivity limit
- The signal showed in the plots of this presentation are for a signal with $\boldsymbol{\zeta_1 \geq 0}$ **and** $\boldsymbol{\zeta_2 = 0}$ **and with f.f.**

  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

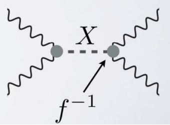
New physics contributions to 4γ couplings

1 New charged particles via loops

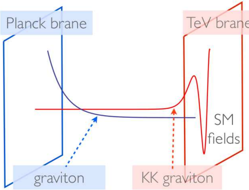


- Effective coupling only depends on the mass, charge and spin : $\zeta_i^\gamma \propto c_i^s Q^4 m^{-4}$
- Example: top partners

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
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- We reach sensitivities allowing to **probe directly a large class of new models**
  - **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 and the effective field theory
  - 4γ aQGC operators implemented in the **FPMC generator** in summer 2013
  - Pile-up simulation with Pythia8 minimum bias events
  - Rough simulation of the detector effects (see S11)
  - 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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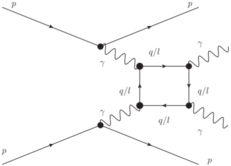
- Implementation of generic **new heavy-charged fermions/vectors** contributions to the 4γ couplings in FPMC **(full amplitude)**
- Update of the exclusive $\gamma\gamma$ SM production, adding the **W loop contribution and the fermion masses**

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, usually not included in the MCs)
- Interferences SM/Exotics added for the full amplitude calculation of new heavy charged particles

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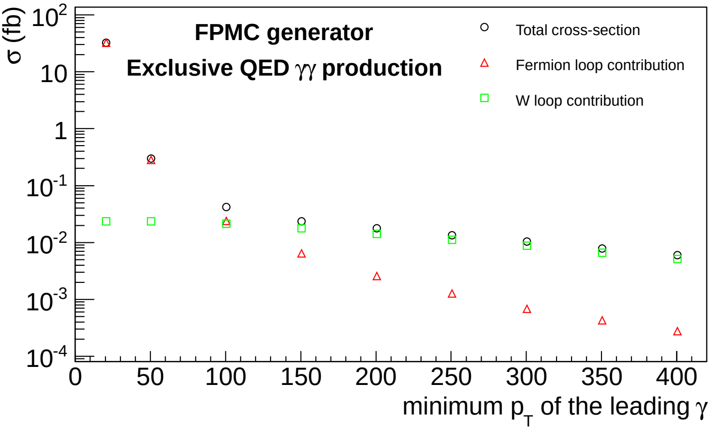

- W loop non negligeable for $p_{T,\gamma} > 50$ GeV
- QCD and DPE contributions to be added
- Same plot against the diphoton mass (in progress)
- Mass of the fermions taken into account

$\gamma\gamma\gamma\gamma$ 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** → **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 S21)

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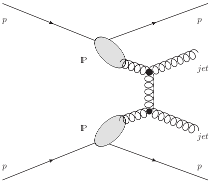
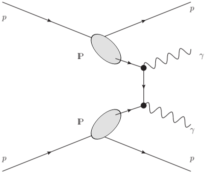
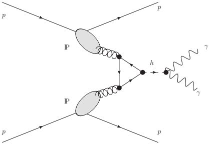
- **Final outputs**
  - 5σ and 95% C.L sensitivities on the $\gamma\gamma\gamma\gamma$ vertex (effective field theory)
  - M-Q exclusion plane for generic exotic fermions/vectors (full amplitude)

Backgrounds (FPMC, ExHuME)

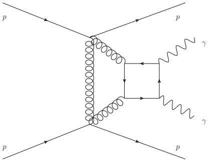
$\mathbb{P}$ backgrounds (FPMC)



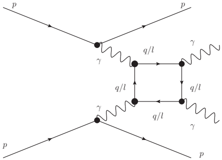


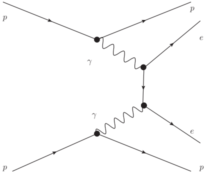


Exclusive QCD (ExHuME)



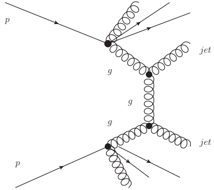
Exclusive QED (FPMC)



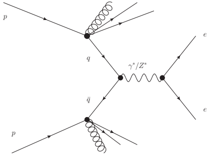


Pile-up backgrounds (HERWIG 6.5)

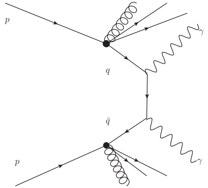
Dijet



Drell-Yan



Diphoton

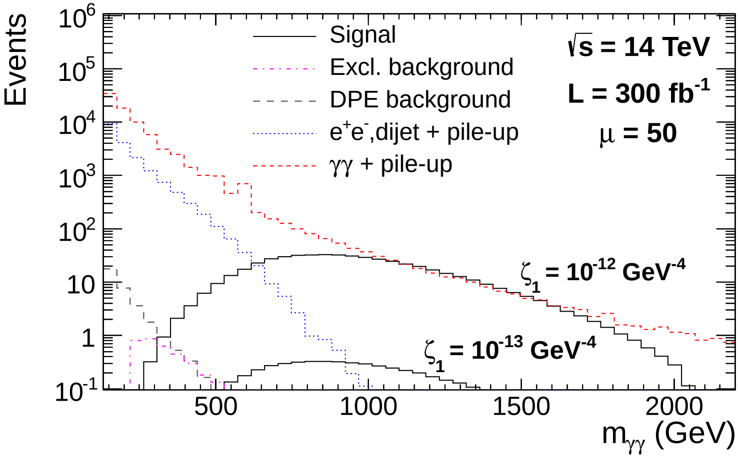


+ protons generated from **minimum bias events** (Pythia 8)

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

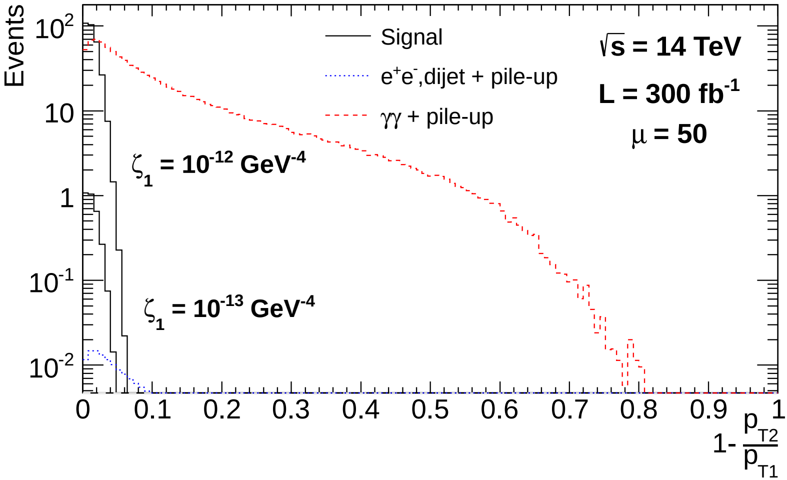
Mass distribution of signal and backgrounds

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



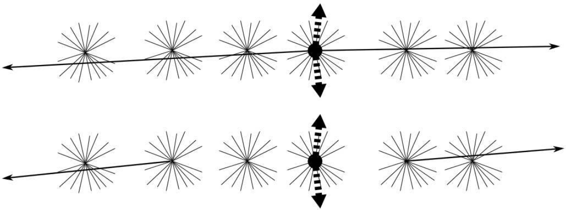
- By requesting $m_{\gamma\gamma} > 600$ GeV, Only pile-up backgrounds remain

Exclusive signal: p_T ratio



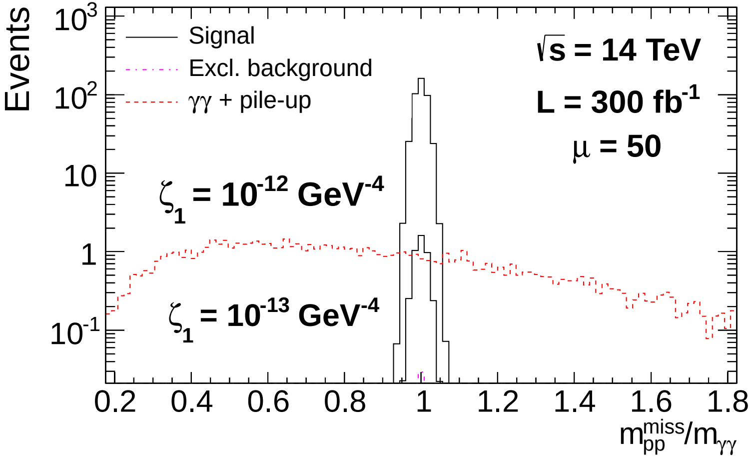
- p_T ratio distribution after p_T and $m_{\gamma\gamma}$ cuts

Forward detectors measurements



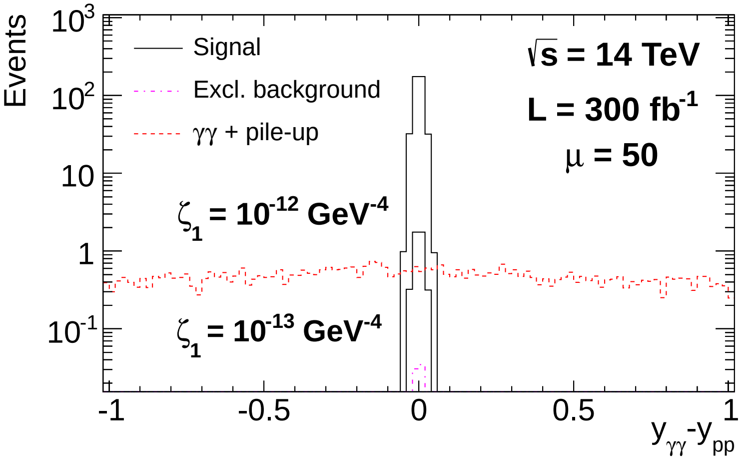
- **Proton missing mass** measurement with 3% resolution in case of double tag
- **It matches the central $\gamma\gamma$ mass for signal**. Can match as well for pile-up backgrounds as a statisical fluctuation
- **Double tag probability** from pile-up protons on the forward detectors (no missing mass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

Mass matching and pile-up



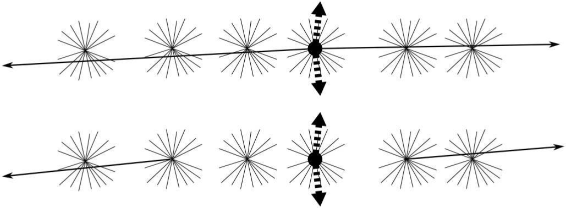
- A mass window of 3% (= resolution) is required in the event selection

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 $\xi_{1,2}$

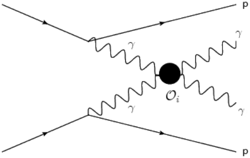
Possible extra-cut: proton timing requirement



- Proton timing will be measured by forward detectors
  - 10 ps resolution assumed → 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)

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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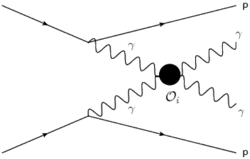

- Selection of **exclusive events**
  1. $\frac{p_{T2}}{p_{T1}} > 0.95$
  2. $|\Delta\Phi| > \pi - 0.01$

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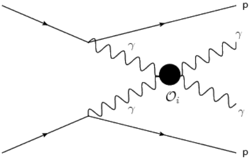

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  1. $\frac{p_{T2}}{p_{T1}}$>0.95
  2. $|\Delta\Phi| > \pi$ - 0.01
- **Forward detectors** cuts
  1. $m_{pp}^{miss} = m_{\gamma\gamma} \pm 3\%$
  2. $|y_{\gamma\gamma} - y_{pp}| < 0.03$ with y_{pp} = $(0.5 * ln(\frac{\xi_1}{\xi_2}))$
  3. Possible proton timing measurement with forward detectors

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
$0.015 < \xi < 0.15$, $p_{T1,2} > 50$ GeV	20.8	3.7	48.2	$2.8 \cdot 10^4$	$1.0 \cdot 10^5$
$p_{T1} >$ 200GeV, $p_{T2} >$ 100 GeV	17.6	0.2	0.2	1.6	2968
$m_{\gamma\gamma} >$ 600 GeV	16.6	0.1	0	0.2	1023
$p_{T2}/p_{T1} > 0.95$, $\|\Delta\phi\| > \pi - 0.01$	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
$\|y_{\gamma\gamma} - y_{pp}\| < 0.03$	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")

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 unconverted photons (with EM “pointing”)
- **Background completely suppressed thanks to forward detectors ξ measurement**
  - 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

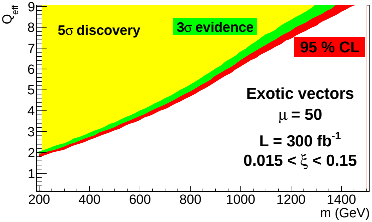
S. Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert, arXiv:1312.5153 (2013)

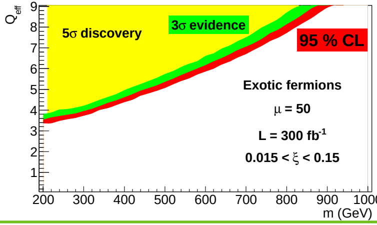
Luminosity	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
pile-up (μ)	50	50	50	200
coupling (GeV^{-4})	$\geq$ 1 conv. γ 5 σ	$\geq$ 1 conv. γ 95% CL	all γ 95% CL	all γ 95% CL
ζ_1 f.f.	$1 \cdot 10^{-13}$	$9 \cdot 10^{-14}$	$5 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$
ζ_1 no f.f.	$3.5 \cdot 10^{-14}$	$2.5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

- Gravity effects (extra-dimension models) can be probed in **the multi-TeV range in a model-independant way**

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

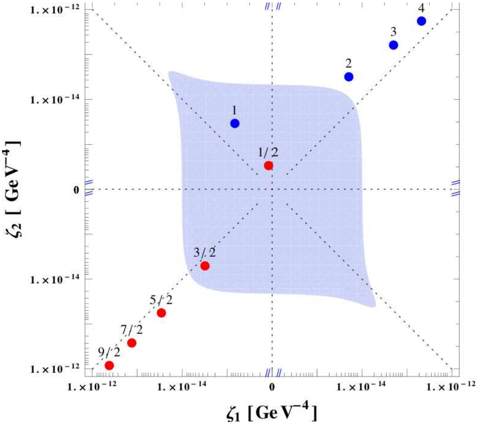
- **The existence of new heavy charged particles** will enhance the $\gamma\gamma\gamma\gamma$ coupling at high mass via loops
- This enhancement can be parametrized by **only the mass and the effective charge** $Q_{eff} = Q.N^{1/4}$, N multiplicity
- Generic implementation for fermions and vectors implemented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





Higher spin resonances and link with EFT
(S. Fichet, 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 Quartic 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 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}→ 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** (scalars, smaller sensitivity) 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 accepted by PRD : arXiv:1312.5153
- More detailed paper including the full amplitude calculations for loop contributions and SM exclusive production update in preparation

Probing four photon couplings with proton tagging at the Large Hadron Collider

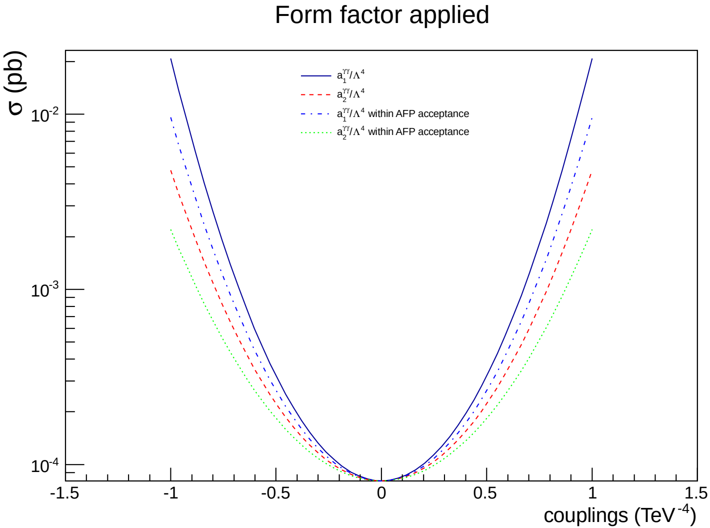
Back-up

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

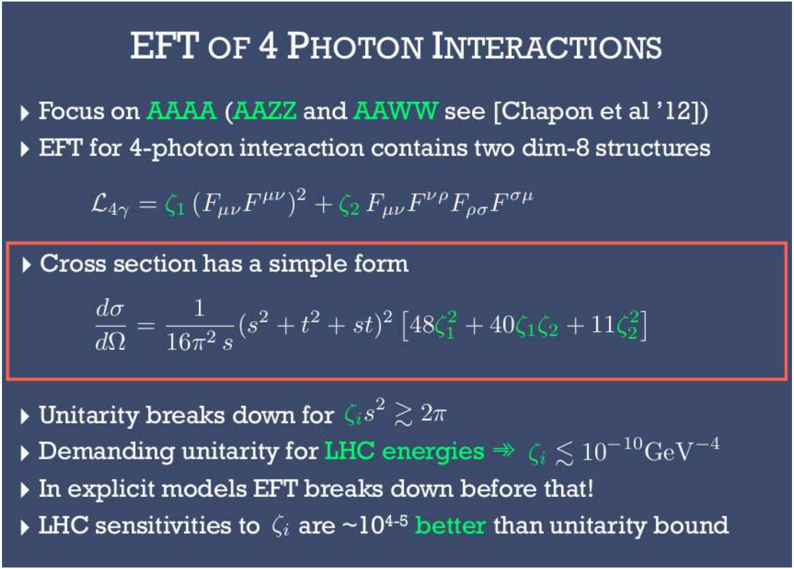
[1]CEA Saclay - Irfu/SPP

June 3rd 2014

Integrated total cross-section against couplings



Effective Field Theory cross-section of the 4γ couplings



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

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

- 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

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**:

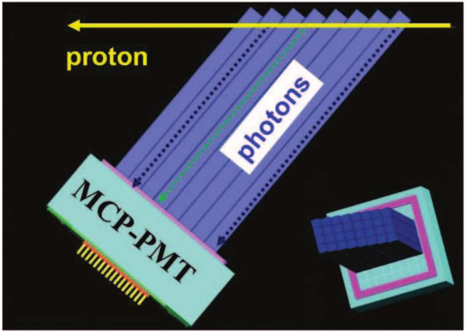
  $Eff(p_T) = 0.76 - 1.98\ exp^{\frac{-p_T}{16.1(GeV)}}$
- **Photon fake factors:** 1% for electron

  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 timing detectors : inefficiencies due to pile-up protons

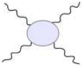


Inefficiencies - 2mm bar detector										
Bar	1	2	3	4	5	6	7	8	9	10
$\mu = 50$	0.129	0.085	0.067	0.057	0.049	0.046	0.043	0.040	0.036	0.011
$\mu = 100$	0.185	0.122	0.097	0.082	0.071	0.066	0.062	0.057	0.051	0.016

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

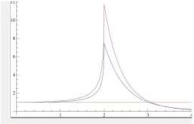
- For example in the effective theory limit : $\zeta_i^\gamma = \alpha_{\rm em}^2 Q^4 \, m^{-4} \, N \, c_{i,s}$

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

Scalar loops are smaller !

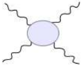
- Full amplitudes for fermions and vectors are now implemented in FPMC.

- 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 !

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**