Light-by-light scattering with intact protons at the LHC: from Standard Model to New Physics

EPS Conference on HEP 2015 @ Vienna, Austria.

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S. Fichet *et al.*, Phys. Rev. D **89** (2014) 114004

S. Fichet *et al.* JHEP **1502** (2015) 165

S. Fichet *et al.*, in preparation

July, 23rd 2015

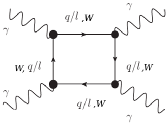
Summary of the presentation

1. Description and motivations of the proposed measurement
2. The $\gamma\gamma \rightarrow \gamma\gamma$ process in the Standard Model (SM)
3. Sensitivity of the $\gamma\gamma\gamma\gamma$ couplings to New Physics
4. Conclusion and plans

Summary of the presentation

1. **Description and motivations of the proposed measurement**
   What do we want to measure? Why?
2. The $\gamma\gamma \rightarrow \gamma\gamma$ process in the Standard Model (SM)
3. Sensitivity of the $\gamma\gamma\gamma\gamma$ couplings to New Physics
4. Conclusion and plans

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



- **Direct coupling absent from the Standard Model (SM)**
  Loop-induced production strongly suppressed in the SM (see slide 8)
- **Light-by-light scattering ($\gamma\gamma \rightarrow \gamma\gamma$) never measured**
  And no limits on anomalous $\gamma\gamma\gamma\gamma$ couplings claimed from collider experiments

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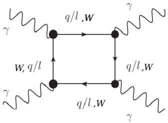

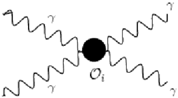

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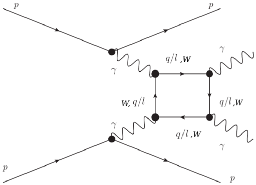
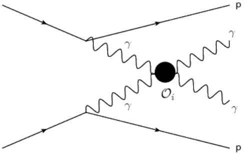
  And no limits on anomalous $\gamma\gamma\gamma\gamma$ couplings claimed from collider experiments
- **In the context of New Physics searches at the LHC,** high integrated luminosity required → high pile-up runs

  base case scenario:
  300 fb^{-1} of data at the LHC at $\sqrt{s} = 14$ TeV at $< \mu >$ = 50
- **Large background** if only 2 high energy γ required at the analysis level
  (Standard Model QCD $\gamma\gamma$ production + fakes from electrons and jets)

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





- At the LHC, possibility to take benefit from **the photon coherent fluxes emitted by the protons.** In this case, the protons have high chances to stay intact after interaction.
- **Possibility to detect in addition of the two photons in the central detector an intact proton in each dedicated forward detector.**

  (to be located left and right from the interaction point, see next slide)

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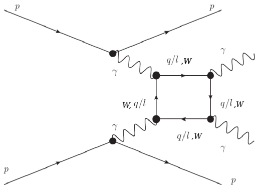

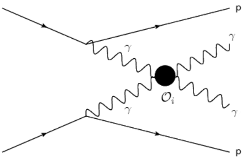

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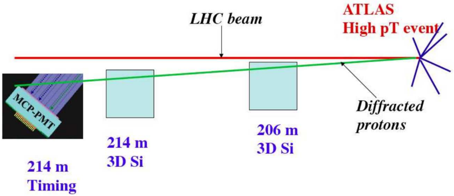
  (to be located left and right from the interaction point, see next slide)

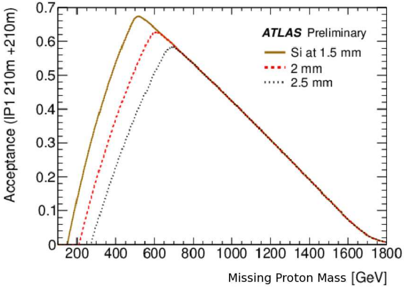
- **Cleaner signature, background much reduced and better controlled.**
  (no PDF uncertainties and all the particles at the final state are detected)

- **Smaller cross-sections.**
  (the protons must be intact and within the acceptance of the forward detectors, see next slide)

(Forward proton detectors at the LHC)

- The ATLAS Forward Physics (AFP) and the CMS-TOTEM Precision Proton Spectrometer (CT-PPS) upgrade projects aim to **detect intact protons emitted at low angle during the high luminosity LHC runs.**
  → *Installation forseen in 2016-2017*





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

  (acceptance shown for the nominal LHC optics configuration)

Summary of the presentation

1. Description and motivations of the proposed measurement

2. **The $\gamma\gamma \rightarrow \gamma\gamma$ process in the Standard Model (SM)**

   What are the exclusive di-photon production subprocesses in the SM?

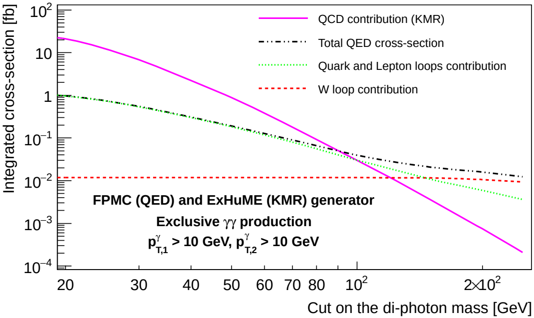
   What are their contributions to the total cross section?

3. The sensitivity of the $\gamma\gamma\gamma\gamma$ couplings to New Physics

4. Conclusion and plans

SM exclusive $\gamma\gamma$ production at 14 TeV

*S. Fichet, G. von Gersdorff, B. Lenzi, C. Royon, M. Saimpert, JHEP **1502** (2015) 165*



- **Integrated exclusive $\gamma\gamma$ cross-section** for different subprocesses and cuts on the di-photon mass. *(only photons with $p_{\mathrm{T}} > 10$ GeV are considered.)*

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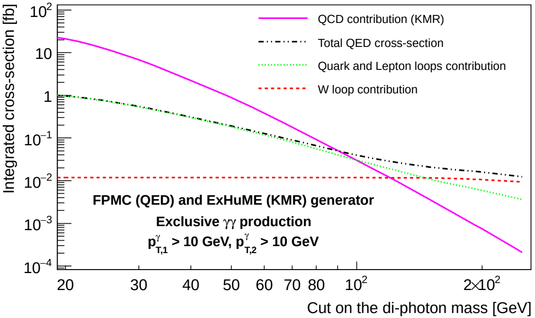

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  gluon induced process ($gg \to \gamma\gamma$) dominant at low di-photon mass.
  *V. Khoze, A. Martin, and M. Ryskin, Eur. Phys. J. **C23** (2002) 311-327*

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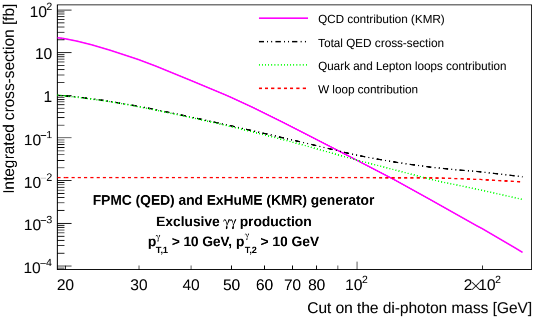

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- **QED contribution**, implemented in our own MC generator (FPMC).
  Include all fermion and W loop contributions with interference at LO
  (NLO corrections available but negligible)

  $\to$ **very small irreducible background for New Physics searches!**

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2. The $\gamma\gamma \to \gamma\gamma$ process in the Standard Model (SM)
3. **The sensitivity of the $\gamma\gamma\gamma\gamma$ couplings to New Physics**
   - ***To which new physics process the $\gamma\gamma\gamma\gamma$ are the most sensitive?***
   - ***How to estimate accurately the cross sections of the exotic signals?***
4. Conclusion and plans

Operators of the anomalous 4γ couplings

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

S. Fichet and G. von Gersdorff, JHEP ***1403*** *(2014) 102*

- $\sqrt{\hat{s}_{\gamma\gamma}} << \Lambda$, Effective Field Theory assumption (EFT)

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

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- For low new physics masses, threshold effect must be taken into account $\rightarrow$ **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 $\Lambda' = 1\ TeV \simeq \sqrt{\hat{s}_{\gamma\gamma,max}}/2$

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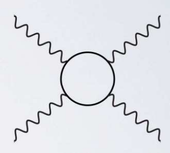
  (unitarity requires $\zeta_i < 10^{-10}\ GeV^{-4}$, $\simeq 10^4$ higher than our sensitivity limit, so we are safe on this side)

- The EFT signal shown in the plots of this presentation are always for a signal with $\boldsymbol{\zeta_1 \geq 0}$ **and** $\boldsymbol{\zeta_2 = 0}$ **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** is given at the end of the presentation

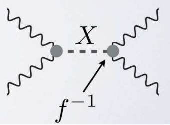
New physics contributions to 4γ couplings

1 New charged particles via loops



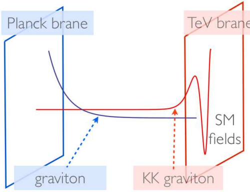
- Effective coupling only depends on the spin, charge and mass : $\zeta_i^\gamma \propto c_i^s Q^4 m^{-4}$
- Example: top partners
- **EFT (for high masses) + full amplitude calculations implemented in FPMC**

2 New neutral particles at tree level



- Effective coupling depends on spin, non-renormalizable $\gamma\gamma X$ coupling and mass : $\zeta_i^\gamma \propto b_i^s f^{-2} m^{-2}$
- Example: KK gravitons
- **full amplitude calculation for spin-0 and 2 resonances in progress, EFT valid for high masses if not too strongly coupled**

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



Generation and modeling of the detector effects

- **Signal generation:** EFT and full amplitudes for generic new charged particles implemented in FPMC. *(amplitudes for spin-0 and 2 resonances in progress)*
- **Background generation:** irreducible, from fakes, due to pile up, ... *(see next slide)*.

  $\rightarrow$ **Integrated luminosity normalized to 300 fb^{-1} and $\mu > 50$**

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  → **Integrated luminosity normalized to 300 fb^{-1} and $\mu > 50$**

- **Analysis performed at particle level** but taking into account dominant detector effects to get realistic predictions
  - Estimation of γ conversion rates, fake photon rates, reconstruction efficiency from ECFA ATLAS studies
  - Smearing in γ energies, in η and ϕ, and in ξ
  - Requirement of at least one converted photon → constraint on the γ vertex, to combine with forward proton timing information
  - Very efficient signal event selection (see slide 16)

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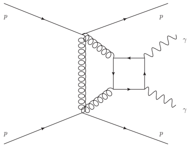
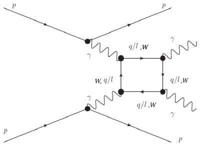
- **Final outputs**
  - 5σ and 95% C.L sensitivities on the $\gamma\gamma\gamma\gamma$ couplings using $\gamma\gamma \rightarrow \gamma\gamma$ *EFT, valid for m>2(1) TeV for tree-level (loop-induced) production*
  - M-Q sensitivity plane for generic new fermions/vectors ($\gamma\gamma \rightarrow \gamma\gamma$) *full amplitude calculation, valid for all masses*
  - New tree-level production sensitivities - full amplitude calculation *in progress*

Backgrounds (FPMC, ExHuME, HERWIG 6.4 + Pythia8)

Irreducible: exclusive $\gamma\gamma$



(ExHuME, 0 at high mass)

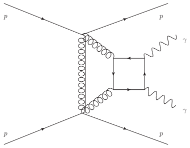


(FPMC, very small at high mass)

Other (reducible): exclusive *ee* with misidentfication *(FPMC)*

Backgrounds (FPMC, ExHuME, HERWIG 6.4 + Pythia8)

Irreducible: exclusive $\gamma\gamma$



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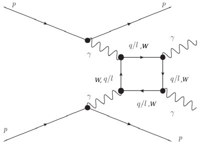
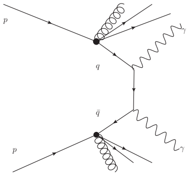


(FPMC, very small at high mass)

Other (reducible): exclusive *ee* with misidentfication *(FPMC)*

Reducible (with fwd detectors!)

$\gamma\gamma$ + intact protons from pile up



(HERWIG 6.4 + Pythia8 minimum bias)

Others : di-jet, Drell-Yan + intact protons from pile up

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

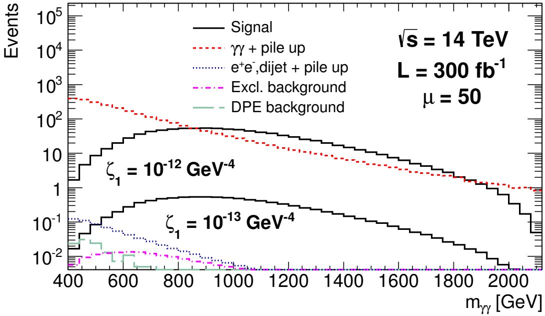
Others : Double Pomeron Exchange backgrounds (intact protons, but not exclusive due to Pomeron remnants) *(FPMC)*

Distribution of signal and backgrounds

smearing, fake, reconstruction factors applied, ($\geq$ 1 converted γ) required

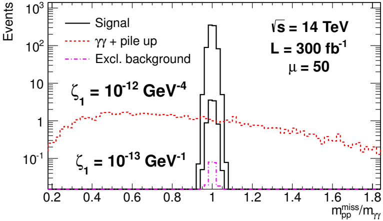
$0.015 < \xi < 0.15$ (forward proton detector acceptance),

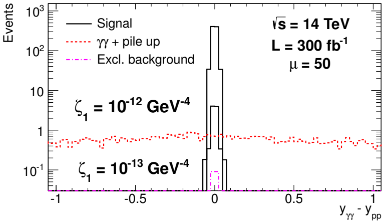
$|\eta^{\gamma}| < 2.37$ (central EM calorimeter acceptance), $p^{\gamma}_{T1,(2)} > 200$ (100) GeV



- By requesting $p_{T1,(2)} > 200$ (100) GeV and $m_{\gamma\gamma} > 600$ GeV, **practically only the signal and the $\gamma\gamma$ + pile up background remain.**
- p_T ratio distribution provides another efficient cut **(exclusive process)**
- $\Delta\phi_{\gamma\gamma} > \pi$ - 0.01 also applied in the final selection **(exclusive process)**

Use of the forward detector ξ measurement





- **Missing proton mass $\sqrt{\xi_1 \xi_2 s}$ matches $m_{\gamma\gamma}$ for the signal**
  A mass window of 3% ($\simeq$ resolution) is required in the event selection
- **Same feature of the signal with rapidity variables**
  $|y_{\gamma\gamma} - y_{pp}| < 0.03$ *is applied with* $y_{pp} = (0.5 * ln(\frac{\xi_1}{\xi_2}))$
- The small widths of the signal distributions are due to the smearing applied to $\xi_{1,2}$ to simulate detector effects

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

Expected events for a charged boson with Q_{eff}=4, m=340 GeV (ζ_1^γ = 2.10^{-13} GeV^{-4})

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

Cut / Process	Signal (full)	Signal with (without) f.f (EFT)	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15$, $p_{T1,(2)} > 200$, (100) GeV]	130.8	36.9 (373.9)	0.25	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	128.3	34.9 (371.6)	0.20	0	0.2	1023
$(p_{T2}/p_{T1} > 0.95$, $\lvert\Delta\phi\rvert > \pi - 0.01)$	128.3	34.9 (371.4)	0.19	0	0	80.2
$\sqrt{\xi_1\xi_2 s} = m_{\gamma\gamma} \pm 3\%$	122.0	32.9 (350.2)	0.18	0	0	2.8
$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	119.1	31.8 (338.5)	0.18	0	0	0

- **Full amplitude numbers in between EFT with/without f.f. numbers**
- **Very high signal selection efficiency**
  - Signal increased by a factor 3-4 if no conversion requirement
    (the di-photon vertex not identified accurately anymore from the central detector)
- **Background completely suppressed thanks to the forward detectors (ξ)**
  - Very high significance per observed event
  - $<$ 5 background events expected at $< \mu >$ = 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) 114004.*

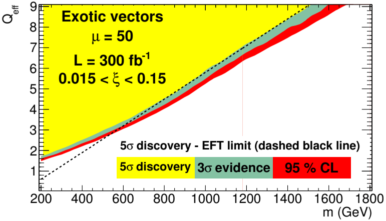
Update of the EFT + full amplitude calculation: *S. Fichet, G. von Gersdorff, B. Lenzi, C. Royon, M. Saimpert, JHEP* ***1502*** *(2015) 165.*

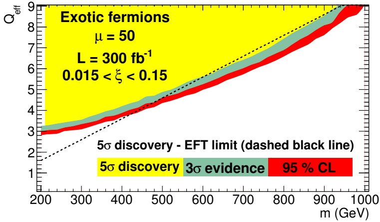
Luminosity	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
pile-up $<\mu>$	50	50	50	200
coupling (GeV^{-4})	≥ 1 conv. γ 5 σ	≥ 1 conv. γ 95% CL	all γ **95% CL**	all γ 95% CL
ζ_1 f.f.	$8 \cdot 10^{-14}$	$5 \cdot 10^{-14}$	$3 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$
ζ_1 no f.f.	$2.5 \cdot 10^{-14}$	$1.5 \cdot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

- A large panel of extra-dimension models can be probed in **the multi-TeV range**
- The form factor is not needed for any new physics scale **beyond $\simeq$ 2 (1) TeV for new tree-level (pair) production** *(due the forward detector acceptance, see slide 6 and 10)*

Full amplitude computation for generic heavy charged fermions/vectors contributions

- **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 spin, mass and effective charge** $Q_{eff} = Q.N^{1/4}$,
  (N = multiplicity of the new particles with respect to electromagnetism)
- **Interesting model-independent constraints, complementary to direct searches** (usually much more model-dependent)
- Good agreement between the EFT and the full amplitude calculations
- **Full amplitude calculation for new tree-level productions in progress**





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Conclusion and plans

- **The measurement of the exclusive $\gamma\gamma$ (*WW*,*ZZ*) production with proton tagging at the LHC allows a very high background rejection at the cost of a reduced cross-section**
  - A single observation has a high significance
  - **Ideal to probe small deviations from the Standard Model**
    ex: broad resonances, some gravity effects, virtual loops, ...
  - Interesting model-independent constraints on many models

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- **Sensitivities allowing to probe directly a large class of new models are reached with the LHC run 2 statistics**
  - $\gamma\gamma\gamma\gamma$ **couplings :** reach of 10^{-14}-10^{-15} GeV^{-4} (EFT).
    A large panel of extra-dimension models can be tested.
    aQGC never searched before in a collider experiment.
  - ***WW*$\gamma\gamma$ and *ZZ*$\gamma\gamma$ couplings** sensitivity improvement by a factor up to 100 compared to the latest the CMS measurement.
    *C. Royon, O. Kepka, Phys. Rev. D **78** (2008)*
    *E. Chapon, C. Royon, O. Kepka, Phys. Rev. D **81** (2010)*

Conclusion and plans

- **The measurement of the exclusive $\gamma\gamma$ (*WW*,*ZZ*) production with proton tagging at the LHC allows a very high background rejection at the cost of a reduced cross-section**
  - A single observation has a high significance
  - **Ideal to probe small deviations from the Standard Model**
    ex: broad resonances, some gravity effects, virtual loops, ...
  - Interesting model-independent constraints on many models

- **Sensitivities allowing to probe directly a large class of new models are reached with the LHC run 2 statistics**
  - $\gamma\gamma\gamma\gamma$ **couplings :** reach of 10^{-14}-10^{-15} GeV^{-4} (EFT).
    A large panel of extra-dimension models can be tested.
    aQGC never searched before in a collider experiment.
  - ***WW*$\gamma\gamma$ and *ZZ*$\gamma\gamma$ couplings** sensitivity improvement by a factor up to 100 compared to the latest the CMS measurement.
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- Full amplitude calculation done for any new charged particle contribution (spin 1/2 and 1). Higher spins in progress.

- Full amplitude calculation for new tree-level contributions in progress.

Light-by-light scattering with intact protons at the LHC: from Standard Model to New Physics

Back-up

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O. Kepka, B. Lenzi, C. Royon

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July, 23rd 2015

SM exclusive $\gamma\gamma$ production at 14 TeV : a possible measurement at the LHC?

Cut / Process	QCD Exclusive (KMR)	QED Fermion loop	W loop
$m_{\gamma\gamma} > 10$ GeV, $p_{T1,2} > 5$ GeV	372 fb	5.5 fb	0.01 fb
$m_{\gamma\gamma} > 20$ GeV, $p_{T1,2} > 10$ GeV	21 fb	1.0 fb	0.012 fb
$m_{\gamma\gamma} > 50$ GeV, $p_{T1,2} > 10$ GeV	0.9 fb	0.18 fb	0.012 fb
$m_{\gamma\gamma} > 100$ GeV, $p_{T1,2} > 10$ GeV	0.03 fb	0.03 fb	0.012 fb
$m_{\gamma\gamma} > 200$ GeV, $p_{T1,2} > 10$ GeV	0.0007 fb	0.005 fb	0.010 fb
$m_{\gamma\gamma} > 500$ GeV, $p_{T1,2} > 10$ GeV	$3 \cdot 10^{-6}$ fb	0.0003 fb	0.004 fb

Table: Integrated cross sections of the different SM exclusive di-photon production processes at the LHC at $\sqrt{s} = 14$ TeV for various requirements on the di-photon mass ($m_{\gamma\gamma}$) and photon transverse momenta ($p_{T1,2}$).

- Cross section too small at high mass/p_T to perform a measurement with nominal high luminosity LHC runs (trigger prescales, pile up effects, ...)
- **Dedicated LHC *pp* collisions at low luminosity** with different optics configurations are planned. Estimated integrated luminosity $\simeq 0.1$ fb^{-1}.
- **Measurement of KMR production might be possible** if the di-photon trigger can go down to $p_T^\gamma > 5$ GeV for those dedicated runs
- **Measurement of QED production seems out of reach in *pp* collisions.** Might be possible in lead-lead *(d'Enterria et al. Phys. Rev. Lett.* **111** *(2013) 080405)*

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

cea

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

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

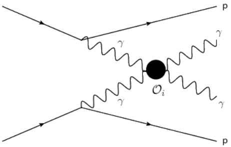
- Unitarity breaks down for $\zeta_i s^2 \gtrsim 2\pi$
- Demanding unitarity for LHC energies $\Rightarrow$ $\zeta_i \lesssim 10^{-10}\mathrm{GeV}^{-4}$
- In explicit models EFT breaks down before that!
- LHC sensitivities to ζ_i are ~$10^{4\text{-}5}$ better than unitarity bound

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 $\mathbf{p_T}$

Event selection: summary

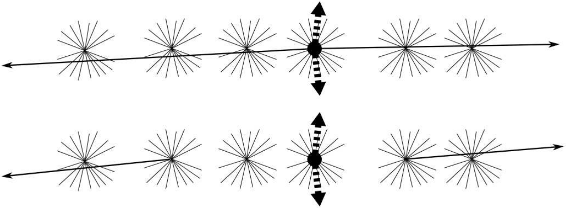
- **Kinematic cuts**
  1. $p_{T1}^{\gamma} > 200$ GeV, $p_{T2}^{\gamma} > 100$ GeV
  2. $m_{\gamma\gamma} > 600$ GeV



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

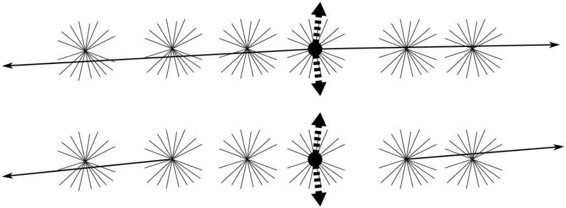
- **Forward detectors cuts**
  1. $m_{pp}^{miss} = m_{\gamma\gamma} \pm 3\%$
  2. $|y_{\gamma\gamma} - y_{pp}| < 0.03$
     with y_{pp} = $(0.5 * ln(\frac{\xi_1}{\xi_2}))$
  3. Possible proton timing measurement with forward detectors **(Not used)**

Possible extra-cut: proton timing requirement



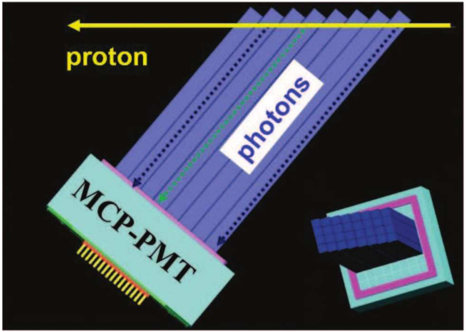
- **Proton timing will be measured by forward detectors**
  - 10 ps resolution assumed → proton vertex constrained within 2.1 milimeters
  - Requirement of 1 converted $\gamma \rightarrow < 1$ mm resolution on the γ vertex
  - **Resolution on the vertex position driven by forward timing detectors**
- 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**
  → *proton timing required for $WW\gamma\gamma$ (and $ZZ\gamma\gamma$)!*
- can also be used for unknown forward backgrounds (beam-induced)

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

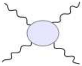


Inefficiencies - 2mm bar detector										
Bar	1	2	3	4	5	6	7	8	9	10
$\mu = 50$	0.129	0.085	0.067	0.057	0.049	0.046	0.043	0.040	0.036	0.011
$\mu = 100$	0.185	0.122	0.097	0.082	0.071	0.066	0.062	0.057	0.051	0.016

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

$\gamma\gamma\gamma\gamma$ 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

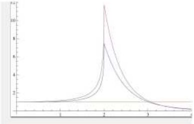
- For example in the effective theory limit : $\zeta_i^\gamma = \alpha_{\rm em}^2 Q^4\, m^{-4}\, N\, c_{i,s}$

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

Scalar loops are smaller !

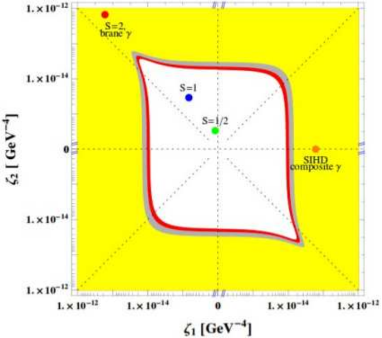
- Full amplitudes for fermions and vectors are now implemented in FPMC.

- Amplitudes get enhanced near the threshold



EFT sensitivies applied to actual models (S. Fichet)

Discovery potential for heavy new physics



- KK graviton (IR brane photon): $m_{\rm KK} < 5670\,{\rm GeV}\,(5\,\sigma)$
  Strongly-interacting heavy dilaton: $m_\varphi < 4260\,{\rm GeV}\,(5\,\sigma)$ [SF/Gersdorff '13]

⇨ Actual models can be discovered

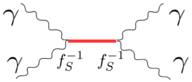
Discovery potential for new neutral particles

- The effects of generic neutral particles can also be classified using simplified models. Only S=0 (CP even or odd) and S=2 are possible at tree-level. The generic Lagrangian is therefore

$$\mathcal{L}_{\gamma\gamma} = f_{0^+}^{-1}\,\varphi\,(F_{\mu\nu})^2 + f_{0^-}^{-1}\,\tilde{\varphi}\,F_{\mu\nu}F_{\rho\lambda}\,\epsilon^{\mu\nu\rho\lambda} + f_2^{-1}\,h^{\mu\nu}\,(-F_{\mu\rho}F_{\nu}{}^{\rho} + \eta_{\mu\nu}(F_{\rho\lambda})^2/4)\,,$$

  Unlike charged particles, neutral particles can be strongly-coupled.

- There are only 2 parameters (coupling and mass). However this is a tree-level parametrisation. Not sufficient because neutral particles can resonate, and because these tree-level diagrams violate unitarity.



- Both issues are solved at one-loop. The exact generic propagator (with no NWA) reads

$$\frac{i}{s - m^2 + i(a_2 s^2/(4\pi f_0^2) + m\Gamma_{\text{const}})}$$

  with $a_2 \geq 1$ because the scalar always decays into photons by assumption.
- Only consistency constraint is $E/4\pi f_0 \ll 1$

Higher spin objects (S. Fichet)

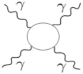
Low-energy effect of higher-spin objects

- Any strongly-interacting extension of the SM potentially features higher-spin composites in its spectrum. In low-energy strings scenarios, strings feature higher-spin excited modes. Assuming the size of the high-spin object is small, it appears to be pointlike at low-energy.

  ⇒ EFT Lagrangian for higher-spin particles

- HS couplings to the SM have to be bilinear, ie $\mathcal{L} \supset \mathcal{O}\phi_{(s)}\phi^*_{(s)}$

  ⇒ HS particles could be spotted in loops.

- A naive generalization of the background field computation gives 

 $\propto S^5$

  ⇒ Light-by-light scattering might be a good place to look for HS particles

- HS QFT computations: never done and challenging... STAY TUNED !