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

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S. Fichet \textit{et al.}, Phys. Rev. D \textbf{89} (2014) 114004
S. Fichet \textit{et al.} JHEP \textbf{1502} (2015) 165
S. Fichet \textit{et al.}, in preparation

July, 23rd 2015

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Light-by-light scattering with intact protons at the LHC

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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
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
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)

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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 $\rightarrow$ 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 $\gamma$ required at the analysis level
  (Standard Model QCD $\gamma\gamma$ production + fakes from electrons and jets)
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)
- 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)

- 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)
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 foreseen 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
Integrated exclusive $\gamma \gamma$ cross-section for different subprocesses and cuts on the di-photon mass. (only photons with $p_T > 10$ GeV are considered.)
**SM exclusive $\gamma\gamma$ production at 14 TeV**

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

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

- **QCD contribution (KMR),** generated with ExHuME MC. gluon induced process ($gg \rightarrow \gamma\gamma$) dominant at low di-photon mass. V. Khoze, A. Martin, and M. Ryskin, Eur. Phys. J. C23 (2002) 311-327
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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) → very small irreducible background for New Physics searches!
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. 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 $4\gamma$ couplings

R.S. Gupta, Phys. Rev. D 85 (2012) 014006
S. Fichet and G. von Gersdorff, JHEP 1403 (2014) 102

\[ \sqrt{s_{\gamma\gamma}} << \Lambda, \text{ Effective Field Theory assumption (EFT)} \]

\[ L_{4\gamma} = \zeta_1 F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2 F_{\mu\nu} F^{\nu\rho} F_{\rho\sigma} F^{\sigma\mu} \text{ (dimension 8)} \]
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For low new physics masses, threshold effect must be taken into account → 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 $\Lambda' = 1 \text{ TeV} \simeq \sqrt{\hat{s}_{\gamma\gamma,\text{max}}}/2$

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

- $\sqrt{s_{\gamma\gamma}} \ll \Lambda$, Effective Field Theory assumption (EFT)
  \[ L_{4\gamma} = \zeta_1^\gamma F_{\mu\nu} F_{\mu\nu} F_{\rho\sigma} F_{\rho\sigma} + \zeta_2^\gamma F_{\mu\nu} F_{\nu\rho} F_{\rho\sigma} F_{\sigma\mu} \] (dimension 8)

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  We use
  \[ f.f. = \frac{1}{1 + (\frac{s_{\gamma\gamma}}{\Lambda'^2})^2} \] with $\Lambda' = 1$ TeV $\simeq \sqrt{s_{\gamma\gamma,\text{max}}}/2$

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

- The EFT signal shown in the plots of this presentation are always for a signal with $\zeta_1 \geq 0$ and $\zeta_2 = 0$ and with f.f.

- $\zeta_1$ and $\zeta_2$ have a very similar angular behaviour

- A table of final sensitivities for both $\zeta_1$ and $\zeta_2$, with and without f.f is given at the end of the presentation
New physics contributions to $4\gamma$ 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 $\sim$ TeV and $m_{KK} \sim$ few TeV, $\zeta_i^\gamma \sim 10^{-14}-10^{-13}$ 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).
  
  → Integrated luminosity normalized to 300 fb\(^{-1}\) and \(\mu > 50\)
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  $\rightarrow$ **Integrated luminosity normalized to** $300 \text{ fb}^{-1}$ and $\mu > 50$

- **Analysis performed at particle level** but taking into account dominant detector effects to get realistic predictions
  - Estimation of $\gamma$ conversion rates, fake photon rates, reconstruction efficiency from ECFA ATLAS studies
  - Smearing in $\gamma$ energies, in $\eta$ and $\phi$, and in $\xi$
  - Requirement of at least one converted photon $\rightarrow$ constraint on the $\gamma$ vertex, to combine with forward proton timing information
  - Very efficient signal event selection (see slide 16)
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- **Final outputs**
  - $5\sigma$ 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 misidentification (FPMC)
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 misidentification (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)
smearing, fake, reconstruction factors applied, ($\geq 1$ converted $\gamma$) required

$0.015 < \xi < 0.15$ (forward proton detector acceptance), $|\eta\gamma| < 2.37$ (central EM calorimeter acceptance), $p_{T1,(2)}^{\gamma} > 200$ (100) GeV

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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**)
Missing proton mass $\sqrt{\xi_1 \xi_2} s$ matches $m_{\gamma\gamma}$ for the signal

A mass window of 3% ($\sim$ 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 $y_{pp} = (0.5 \times \ln(\xi_1/\xi_2))$

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 $\xi$ resolution, absolutely needed in order to suppress the background from pile up.
Expected events for a charged boson with $Q_{\text{eff}} = 4$, $m = 340$ GeV ($\zeta_1^\gamma = 2.10^{-13}$ GeV$^{-4}$)

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

| Cut / Process | Signal (full) | Signal with (without) f.f (EFT) | Excl. | DPE | DY, di-jet + pile up | $\gamma\gamma$ + pile up |
|---------------|---------------|---------------------------------|-------|-----|---------------------|-------------------------|
| $[0.015 < \xi_{1,2} < 0.15, \nonumber \nonumber\nonumber\nonumber$ $p_{T1,2} > 200, (100) \text{ GeV}]$ $m_{\gamma\gamma} > 600 \text{ GeV}$ $(p_{T2}/p_{T1} > 0.95, \nonumber \nonumber\nonumber\nonumber$ $|\Delta\phi| > \pi - 0.01)$ $\sqrt{\xi_1 \xi_2 s} = m_{\gamma\gamma} \pm 3\%$ $|y_{\gamma\gamma} - y_{pp}| < 0.03$ | 130.8 | 36.9 (373.9) | 0.25 | 0.2 | 1.6 | 2968 |
|               | 128.3         | 34.9 (371.6)     | 0.20 | 0   | 0.2              | 1023     |
|               | 128.3         | 34.9 (371.4)     | 0.19 | 0   | 0                | 80.2     |
|               | 122.0         | 32.9 (350.2)     | 0.18 | 0   | 0                | 2.8      |
|               | 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 ($\xi$)**
  - 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 $\mu = 50$
Final discovery ($5\sigma$) and exclusion (95% CL) sensitivities on $\zeta_1$ and $\zeta_2$

**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$^{-4}$) | $\geq 1$ conv. $\gamma$ | $\geq 1$ conv. $\gamma$ | all $\gamma$ | all $\gamma$ |
| $\geq 5 \sigma$ | $5 \cdot 10^{-14}$ | $1.5 \cdot 10^{-14}$ | $3 \cdot 10^{-14}$ | $2.5 \cdot 10^{-14}$ |
| $\zeta_1$ f.f. | $2.5 \cdot 10^{-14}$ | $1.5 \cdot 10^{-14}$ | $9 \cdot 10^{-15}$ | $7 \cdot 10^{-15}$ |
| $\zeta_1$ no f.f. | $8 \cdot 10^{-14}$ | $1 \cdot 10^{-13}$ | $2 \cdot 10^{-14}$ | $4.5 \cdot 10^{-14}$ |
| $\zeta_2$ f.f. | $2 \cdot 10^{-13}$ | $1 \cdot 10^{-13}$ | $6 \cdot 10^{-14}$ | $1.5 \cdot 10^{-14}$ |
| $\zeta_2$ no f.f. | $5 \cdot 10^{-14}$ | $4 \cdot 10^{-14}$ | $2 \cdot 10^{-14}$ | $1 \cdot 10^{-14}$ |

- 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 $\sim 2 \ (1)$ 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 $Q_{\text{eff}} = Q.N^{1/4}$,
  
  \[(N = \text{multiplicity of the new particles with respect to electromagnetism)}\]

- 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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4. Conclusion and plans
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
  - $\gamma\gamma$ couplings: reach of $10^{-14}$ - $10^{-15}$ GeV (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)  
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.
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SM exclusive $γγ$ production at 14 TeV: a possible measurement at the LHC?

| Cut / Process                        | QCD Exclusive (KMR) | QED Fermion loop | W loop |
|--------------------------------------|---------------------|------------------|--------|
| $m_{γγ} > 10 \text{ GeV}, p_{T1,2} > 5 \text{ GeV}$ | 372 fb              | 5.5 fb           | 0.01 fb|
| $m_{γγ} > 20 \text{ GeV}, p_{T1,2} > 10 \text{ GeV}$ | 21 fb               | 1.0 fb           | 0.012 fb|
| $m_{γγ} > 50 \text{ GeV}, p_{T1,2} > 10 \text{ GeV}$ | 0.9 fb              | 0.18 fb          | 0.012 fb|
| $m_{γγ} > 100 \text{ GeV}, p_{T1,2} > 10 \text{ GeV}$ | 0.03 fb             | 0.03 fb          | 0.012 fb|
| $m_{γγ} > 200 \text{ GeV}, p_{T1,2} > 10 \text{ GeV}$ | 0.0007 fb           | 0.005 fb         | 0.010 fb|
| $m_{γγ} > 500 \text{ GeV}, p_{T1,2} > 10 \text{ GeV}$ | 3·10^{-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 $\sqrt{s} = 14 \text{ TeV}$ for various requirements on the di-photon mass ($m_{γγ}$) 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 $\simeq 0.1 \text{ fb}^{-1}$.

- **Measurement of KMR production might be possible** if the di-photon trigger can go down to $p_γ^T > 5 \text{ GeV}$ 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)
EFT OF 4 PHOTON INTERACTIONS

- Focus on \textbf{AAAA} (\textbf{AAZZ} and \textbf{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 \textbf{LHC energies} \( \Rightarrow \zeta_i \lesssim 10^{-10} \text{GeV}^{-4} \)
- In explicit models EFT breaks down before that!
- LHC sensitivities to \( \zeta_i \) are \( \sim 10^{4-5} \) \textbf{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:**
  \[ \text{Eff}(p_T) = 0.76 - 1.98 \exp^{-\frac{p_T}{16.1(\text{GeV})}} \]

- **Photon fake factors:** 1% for electron
  
  *European Strategy studies*

- **Fake photon \( p_T \) for jets:** gaussian draw (Mean=75%, \( \sigma = 13\% \)) on the jet \( p_T \) and use of
  \[ \text{Eff}_{\text{fake}}(p_T) = 0.0093 \exp^{-\frac{\min(p_T,200\text{GeV})}{17.5(\text{GeV})}} \]

  almost no fake \( \gamma \) from jets at very high \( p_T \)
Event selection: summary

- **Kinematic cuts**
  1. $p_T^{\gamma_1} > 200$ GeV, $p_T^{\gamma_2} > 100$ GeV
  2. $m_{\gamma\gamma} > 600$ GeV

- **Selection of exclusive events**
  1. $\frac{p_T^{\gamma_2}}{p_T^{\gamma_1}} > 0.95$
  2. $\Delta \phi_{\gamma\gamma} > \pi - 0.01$

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

- **Proton timing will be measured by forward detectors**
  - 10 ps resolution assumed $\rightarrow$ proton vertex constrained within 2.1 millimeters
  - Requirement of 1 converted $\gamma \rightarrow < 1$ mm resolution on the $\gamma$ 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 $\approx 40$ at $\mu = 50$

- No need to use for this study, robustness of the $\gamma\gamma\gamma\gamma$ analysis $\rightarrow$ 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 statistical 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

| 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 with the ATLAS experiment at the LHC, Master Thesis MINES ParisTech (2013).
The BSM amplitudes

- Loops of spin 0, 1/2, 1 new electric particles contribute to $4\gamma$. 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:

\[
\zeta_i^\gamma = \alpha_{em}^2 Q^4 m^{-4} N c_{i,s}
\]

\[
c_{1,s} = \begin{cases} 
\frac{1}{288} & s = 0 \\
-\frac{1}{36} & s = \frac{1}{2} \\
-\frac{5}{32} & s = 1 
\end{cases}, \\
\]

\[
c_{2,s} = \begin{cases} 
\frac{1}{360} & s = 0 \\
\frac{7}{90} & s = \frac{1}{2} \\
\frac{27}{40} & s = 1 
\end{cases}
\]

Scalar loops are smaller!

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

- Amplitudes get enhanced near the threshold
Discovery potential for heavy new physics

- KK graviton (IR brane photon): $m_{KK} < 5670 \text{ GeV} (5 \sigma)$
- Strongly-interacting heavy dilaton: $m_\varphi < 4260 \text{ GeV} (5 \sigma)$

[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

$$\mathcal{L}_{\gamma\gamma} = f_0^{-1} \varphi (F_{\mu\nu})^2 + f_0^{-1} \bar{F}_{\mu\nu} F_{\rho\lambda \rho\lambda} e^{\mu\nu\rho\lambda} + f_2^{-1} h^{\mu\nu} (-F_{\mu\rho} F_{\nu\rho} + \eta_{\mu\nu} (F_{\rho\lambda})^2 / 4),$$

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

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

with $a_2 \geq 1$ because the scalar always decays into photons by assumption.

- Only consistency constraint is $E/4\pi f_0 \ll 1$
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 \( \mathcal{L} \supset O \phi(s) \phi^*(s) \)

  - 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!