PROSPECTS FOR NEW PHYSICS SEARCHES AT THE LHC IN THE FORWARD PROTON MODE*

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(Received November 12, 2015)

The installation of forward proton detectors at the LHC will provide the possibility to observe central exclusive processes, opening a novel window on physics beyond the Standard Model. We review recent developments about the discovery potential from central exclusive light-by-light scattering. The search for this process is expected to provide bounds on a wide range of new particles, and turns out to be complementary from the new physics searches in central detectors.

DOI:10.5506/APhysPolBSupp.8.811
PACS numbers: 14.80.–j, 13.40.–f

1. Central exclusive processes and forward proton detectors

The installation of new forward detectors is scheduled at both ATLAS (ATLAS Forward Proton detector [1]) and CMS (CT-PPS detector [2]). The purpose of these detectors is to measure intact protons arising from diffractive processes at small angle. Among all the possible processes, the so-called central exclusive processes have the structure

$$pp \to p \oplus X \oplus p\,, \tag{1}$$

where the $\oplus$ denotes a gap with no hadronic activity between the central system X and the outgoing protons. These central exclusive processes can potentially provide a new window on physics beyond the Standard Model. The crucial feature is that, provided that the invariant mass of the proton system can be measured, the whole kinematics of the event is known, which, in turn, can be used to drastically reduce the backgrounds.

* Presented at EDS Blois 2015: The 16$^{\text{th}}$ Conference on Elastic and Diffractive Scattering, Borgo, Corsica, France, June 29–July 4, 2015.

The scheduled forward detectors are designed to perform such measurement of the outgoing protons. They will be built at ~ 200 m on both sides of CMS and ATLAS. The detectors should host tracking stations, as well as timing detectors (see Fig. 1). The proton taggers are expected to determine the fractional proton momentum loss ξ in the range of $0.015 < \xi < 0.15$ with a relative resolution of 2%. In addition, the time-of-flight of the protons can be measured within 10 ps, which translates into ~ 2 mm resolution on the determination of the interaction point along the beam axis z.

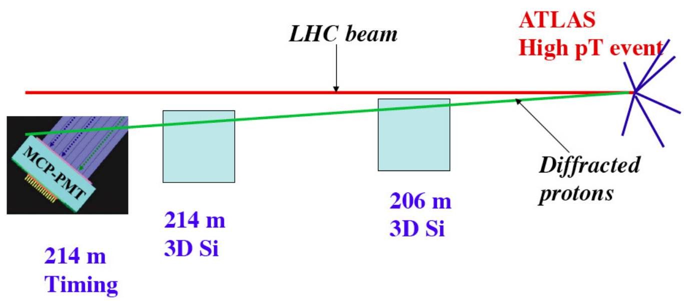

Fig. 1. Scheme of the AFP detector. Roman pot hosting Si and timing detectors will be installed on both sides of ATLAS at 206 and 214 m from the ATLAS nominal interaction point. The CMS–TOTEM Collaboration will have similar detectors.

This experimental set-up provides a clean environment to look for physics beyond the SM. Central exclusive processes with intermediate photons are the mostly studied ones, because the equivalent photon approximation is well understood. In principle, at the LHC energies, intermediate W, Z bosons could also happen, however a precise estimation of the fluxes is needed. In terms of an effective theory description of the new physics effects, operators like $|H|^2 V_{\mu\nu} V^{\mu\nu}/\Lambda^2$ induce anomalous single or double Higgs production (for the MSSM case, see [3, 4]). The flavour-changing dipole operators like $\bar{q}\sigma_{\mu\nu} t V^{\mu\nu}/\Lambda^2$ induce single-top plus one-jet production (see [5]). Finally, the four-photon operators of Eq. (3) induce light-by-light scattering. This last process is pictured in Fig. 2. Such self-interactions of neutral gauge

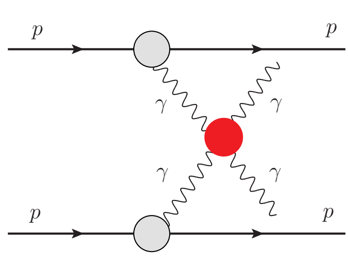

Fig. 2. Light-by-light scattering with intact protons.

bosons are particularly appealing to search for new physics, because the SM irreducible background is small. These interactions constitute smoking gun observables for new physics. Studies using proton tagging at the LHC for new physics searches can be found in [6–21].

2. Measuring light-by-light scattering

Given the promising possibilities of forward detectors, a realistic simulation of the search for anomalous $\gamma\gamma \to \gamma\gamma$ at the 14 TeV LHC has been carried out in [20]. The search for light-by-light scattering at the LHC without proton tagging has been first thoroughly analysed in [22]. Let us review the set-up, the backgrounds, the event selection, and the sensitivity to the $\zeta_{1,2}$ anomalous couplings expected at the 14 TeV LHC.

The Forward Physics Monte Carlo generator (FPMC, [23]) is designed to produce within the same framework the double Pomeron exchange (DPE), single diffractive, exclusive diffractive and photon-induced processes. The emission of photons by protons is correctly described by the Budnev flux [24, 25], which takes into account the proton electromagnetic structure. The SM $\gamma\gamma \to \gamma\gamma$ process induced by loops of SM fermions and W, the exact contributions from new particles with arbitrary charge and mass, and the anomalous vertices described by the effective operators Eq. (3) have been implemented into FPMC.

The backgrounds are divided into three classes. Exclusive processes with two intact photons and a pair of photon candidates include the SM light-by-light scattering, $\gamma\gamma \to e^+e^-$ and the central-exclusive production of two photons via two-gluon exchange, simulated using ExHuME [26]. Processes involving DPE can result in protons accompanied by two jets, two photons and a Higgs boson that decay into two photons. Finally, one can have gluon or quark-initiated production of two photons, two jets or two electrons (Drell–Yan) with intact protons arising from pile-up interactions.

The knowledge of the full event kinematics is a powerful constraint to reject the background from pile-up. The crucial cuts consist in matching the missing momentum (rapidity difference) of the di-proton system with the invariant mass (rapidity difference) of the di-photon system, which is measured in the central detector. Extra cuts rely on the event topology, using the fact that the photons are emitted back-to-back with similar $p_{\rm T}$. Further background reduction could even be possible by measuring the protons time-of-flight, which provides a complete reconstruction of the primary vertex with a typical precision of 1 mm.

3. Discovery potential for heavy new physics

In a scenario where new particles are too heavy to be produced on-shell at the LHC, one expects that the first manifestations show up in precision measurements of the SM properties. Assuming that the new physics scale Λ is higher than the typical LHC energy reach $E_{\rm LHC}$, the correlation functions of the SM fields can be expanded with respect to $E_{\rm LHC}/\Lambda$. At the Lagrangian level, this generates a series of local operators of higher dimension, which describe all the manifestations of new physics observable at low-energy. This low-energy effective Lagrangian reads

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{i,n} \frac{\alpha_i^{(n)}}{\Lambda^n}\,. \tag{2}$$

The effective Lagrangian is somehow the natural companion of precision physics. In all generality, the goal of SM precision physics is to get information on the coefficients $\alpha_i^{(n)}$ and the new physics scale Λ[1]. For $\Lambda > E_{\rm LHC}$, four-photon interactions are described by two pure-gauge operators

$$\mathcal{L}_{4\gamma} = \zeta_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2 F_{\mu\nu}F^{\nu\rho}F_{\rho\lambda}F^{\lambda\mu}\,. \tag{3}$$

The effect of any object beyond the SM can be parametrized in terms of the ζ_1, ζ_2 parameters, as well as any experimental search results.

The estimation of the LHC sensitivities to effective four-photon couplings ζ_i provided by measuring light-by-light scattering with proton tagging is performed in [14, 20]. These sensitivities are given in Table I for different scenarios corresponding to the medium luminosity at the LHC (300 fb^{-1})

TABLE I

5σ discovery and 95% C.L. exclusion limits on ζ_1 and ζ_2 couplings in GeV^{-4} (see Eq. (3)). All sensitivities are given for 300 fb^{-1} and $\mu = 50$ pile-up events (medium luminosity LHC) except for the numbers of the last column which are given for 3000 fb^{-1} and $\mu = 200$ pile-up events (high luminosity LHC).

Luminosity	300 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
Pile-up [μ]	50	50	200
Coupling [GeV^{-4}]	5 σ	95% C.L.	95% C.L.
ζ_1	1.5×10^{-14}	9×10^{-15}	7×10^{-15}
ζ_2	3×10^{-14}	2×10^{-14}	1.5×10^{-14}

[1] In order to get meaningful bounds on Λ, a statistical subtlety has to be taken into account (see [27]), that conceptually boils down to require new physics to be testable.

and the high luminosity (3000 fb^{-1} in ATLAS). It turns out that the selection efficiency is sufficiently good so that the background amplitudes are negligible with respect to the anomalous $\gamma\gamma \to \gamma\gamma$ signal. A handful of events is, therefore, enough to reach a high significance. The 5σ discovery potential as well as the 95% C.L. limits with a pile-up of 50 are given in Table I. The discovery reach as a function of ζ_1, ζ_2 is shown in Fig. 3, where contributions from various models are also included.

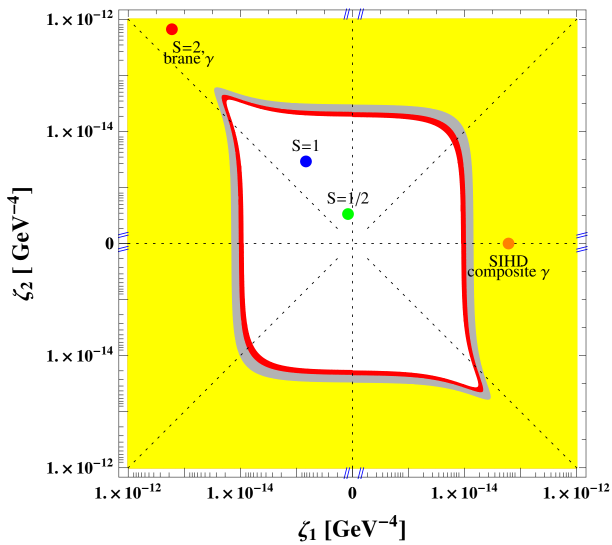

Fig. 3. (Colour on-line) Experimental sensitivity and models in the EFT parameter space. Axes follow a logarithmic scale spanning $|\zeta_i| \in [10^{-12}, 10^{-16}]$. The light grey/yellow, dark grey, and black/red regions can be probed at 5σ, 3σ and 95% C.L. using proton tagging at the LHC, while the white region remains inaccessible. The limits are given for the medium luminosity LHC with all photons (no conversion required) and no form-factor (see Table I). Also shown are contributions from electric particles with spin 1/2 and 1, charge $Q_{\rm eff} = 3$, mass $m = 1$ TeV, the contribution from warped KK gravitons with mass $m_{\rm KK} = 3$ TeV, $\kappa = 2$ and brane-localized photon, and the contribution from a strongly-interacting heavy dilaton (SIHD) with mass $m_\varphi = 3$ TeV coupled to a composite photon.

4. Discovery potential for charged particles

New electrically charged particles contribute to anomalous gauge couplings at one-loop. Because of gauge invariance, these contributions can be parametrized in terms of the mass and quantum numbers of the new particle [13]. In the case of four-photon interactions, only electric charge matters.

New particles with exotic electric charges can, for example, appear in composite Higgs model [28] or in warped extra-dimension models with custodial symmetry [29]. The new particles have, in general, a multiplicity $N_{\rm em}$ with respect to electromagnetism. For instance, the multiplicity is three if the particles are coloured. It is convenient to take into account this multiplicity by defining

$$Q^4_{\rm eff} = N_{\rm em} Q^4 \,. \tag{4}$$

The SM loops have been computed in Refs. [30–33] and are collected in Ref. [20]. At LHC energies, the W loop dominates over all fermion loops including the top because it grows logarithmically.

The results of the simulation with full amplitudes are given in Table II and Fig. 4 where are displayed the 5σ discovery, 3σ evidence and 95% C.L. limit for fermions and vectors for a luminosity of 300 fb^{-1} and a pile-up of 50. It is found that a vector (fermion) with $Q_{\rm eff} = 4$ can be discovered up to mass $m = 700$ GeV (370 GeV). At high mass, the exclusion bounds follow isolines $Q \propto m$, as dictated by the EFT couplings [14]. Extrapolating the same analysis to a higher luminosity of 3000 fb^{-1} for a pile-up of 200 leads to a slightly improved sensitivity of $m = 740$ GeV (410 GeV) for vectors (fermions).

TABLE II

5σ discovery limits on the effective charge of new generic charged fermions and vectors for various masses scenarios and full integrated luminosity at the medium-luminosity LHC (300 fb^{-1}, $\mu = 50$).

Mass [GeV]	300	600	900	1200	1500
$Q_{\rm eff}$ (vector)	2.2	3.4	4.9	7.2	8.9
$Q_{\rm eff}$ (fermion)	3.6	5.7	8.6	—	—

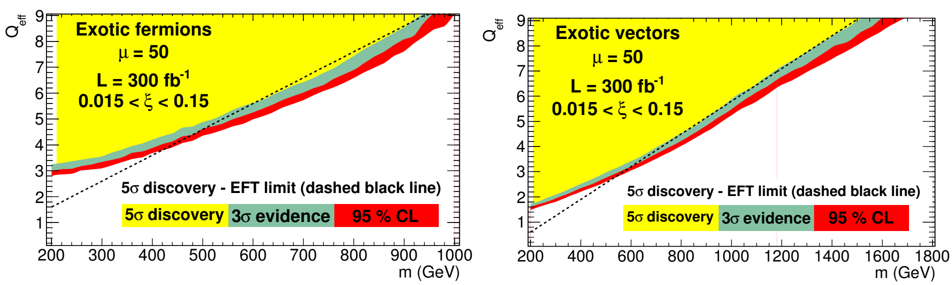

Fig. 4. Exclusion plane in terms of mass and effective charge of generic fermions and vectors with full integrated luminosity at the medium-luminosity LHC (300 fb^{-1}, $\mu = 50$).

One may notice that some searches for vector-like quarks, as motivated from *e.g.* Composite Higgs models, already lead to stronger bounds than the ones projected here. For instance, vector-like top partners arising from the $(2,2)$ (corresponding to $Q_{\rm eff} \approx 2.2$) of mass $m = 500$ GeV would be excluded from present LHC data, while they would be out of reach using light-by-light scattering. On the other hand, the light-by-light scattering results are completely model-independent. They apply just as well to different effective charges, are independent of the amount of mixing with the SM quarks, and even apply to vector-like leptons!

5. Discovery potential for neutral particles

Non-renormalizable interactions of neutral particles are also present in common extensions of the SM. Such theories can contain scalar, pseudo-scalar and spin-2 resonances, respectively denoted by φ, $\tilde{\varphi}$ and $h^{\mu\nu}$ [14], that can be potentially strongly-coupled the SM. The full effective theory for such neutral resonances has been recently given in [34]. For the coupling to the photon, the most general interactions read

$$\begin{aligned}\mathcal{L}_{\gamma\gamma} \; = \; & f_{0^+}^{-1}\,\varphi\,(F_{\mu\nu})^2 + f_{0^-}^{-1}\,\tilde{\varphi}\,F_{\mu\nu}F_{\rho\lambda}\,\epsilon^{\mu\nu\rho\lambda}/2 \\ & + f_2^{-1}\,h^{\mu\nu}\,\left(-F_{\mu\rho}F_{\nu}{}^{\rho} + \eta_{\mu\nu}(F_{\rho\lambda})^2/4\right)\,, \end{aligned} \tag{5}$$

where the f_S have mass dimension one.

A subtlety, however, is that the width of such resonances can be very broad. This implies that the momentum dependence of the width has to be kept. From the experimental point of view, this also implies that the standard bump searches become inefficient, and have to be replaced by searches for broad deviations, which are typically more challenging.

Here, we focus on the case of the CP-even scalar resonance. The complete propagator of such resonance can be written as

$$\langle\phi(p)\phi(-p)\rangle = \frac{i}{p^2 - m^2 + i\left(a\,p^4/\left(4\pi f_\gamma^2\right) + bp^2 + c\right)}\,, \tag{6}$$

where $a \geq 1$. Unitarity remains respected at any energy in this effective theory. The case of $a = 1$, $b = c = 0$ corresponds to the minimal case where ϕ can decay only through photons, so that the total width goes as s^2/f_γ^2.

In Fig. 5, we show the discovery potential of the scalar neutral resonance through central exclusive light-by-light scattering. As a most optimistic case, we let $b = c = 0$ and we vary a. The region below the thick white/red line is accessible at 5σ for $300\,{\rm fb}^{-1}$, $\mu = 50$. As an indication, we also show the limit at which the narrow-width approximation is not valid anymore, such that standard bump searches cannot be applied.

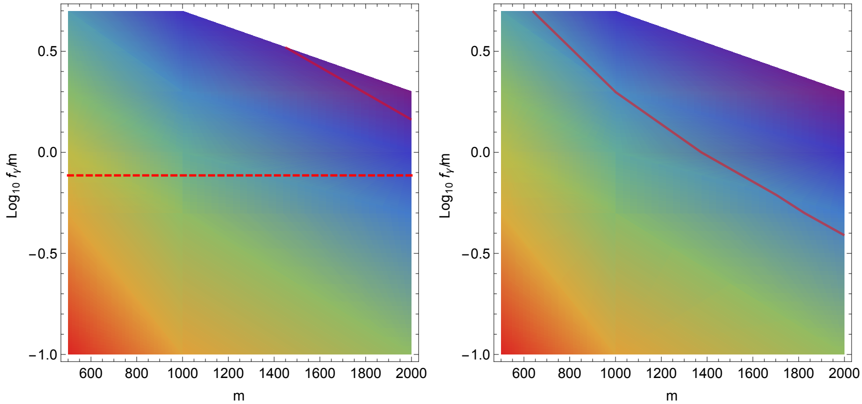

Fig. 5. (Colour on-line) Exclusion plane in terms of mass and effective coupling f_γ for full integrated luminosity at the medium-luminosity LHC ($300\,\mathrm{fb}^{-1}$, $\mu = 50$). Left pannel: $a = 1$. Right pannel: $a = 10$. The region below the white/red line can be probed using central exclusive light-by-light scattering. The region above the dashed line can be probed by bump searches in central detectors.

It turns out that central exclusive searches can probe the strong coupling region, while bump searches can probe the weak coupling region. For $a = 10$, for example, bump searches cannot be applied at all in the region displayed. We conclude that central exclusive and bump searches are complementary. However, to obtain a complete picture of the sensitivity from different kind of searches, one should also evaluate the reach from broad resonance searches in central detectors. A more detailed study of the discovery potential for neutral broad resonances is in progress [35].

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