

Higgs and new physics in Pomeron- and photon-induced processes at the LHC

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1 Introduction

The primary goal of the CERN Large Hadron Collider (LHC) is the production of new particles predicted within or beyond the Standard Model (SM): Higgs boson, supersymmetric (SUSY) partners of the SM particles ... By colliding “head-on” protons at multi-TeV energies, one expects to produce new heavy particles in the underlying high- p_T *parton-parton* scatterings. Such collisions are characterised by large QCD activity and backgrounds which often complicate the identification of novel physics signals. In this context, the clean topologies of *exclusive* particle production in “peripheral” pp processes mediated by colourless exchanges – such as di-gluon colour-singlet states (aka “Pomerons”) or two photons (Fig. 1, left) – is attracting increasing interest despite their much smaller cross sections, $\mathcal{O}(10^{-5})$ less, compared to the standard parton-parton interactions. Exclusive events are characterised by wide rapidity gaps (i.e. a large regions devoid of hadronic activity) on both sides of the centrally produced system and the survival of both protons scattered at very low angles with respect to the beam. The final-state is thus much cleaner, with a larger signal/background and the event kinematics can be constrained measuring the final protons.

A prime process of interest at the LHC is the Central Exclusive Production (CEP) of the Higgs boson, $pp \rightarrow p \oplus H \oplus p$, (\oplus represents a rapidity-gap). In order to detect both protons in the range of momentum loss appropriate for Higgs masses close to the LEP limit, $M_H \gtrsim 114 \text{ GeV}/c^2$, detectors must be installed a few mm’s away to the outgoing beams in the high-dispersion region 420 m away from the interaction points on each side of the ATLAS and CMS experiments. The FP420 R&D project [1] aims at assessing the feasibility of installing such near-beam detectors in the LHC tunnel in order to measure the leading protons issuing from central-exclusive or photon-exchange processes, in conjunction with the produced system measured in the central ATLAS and CMS detectors.

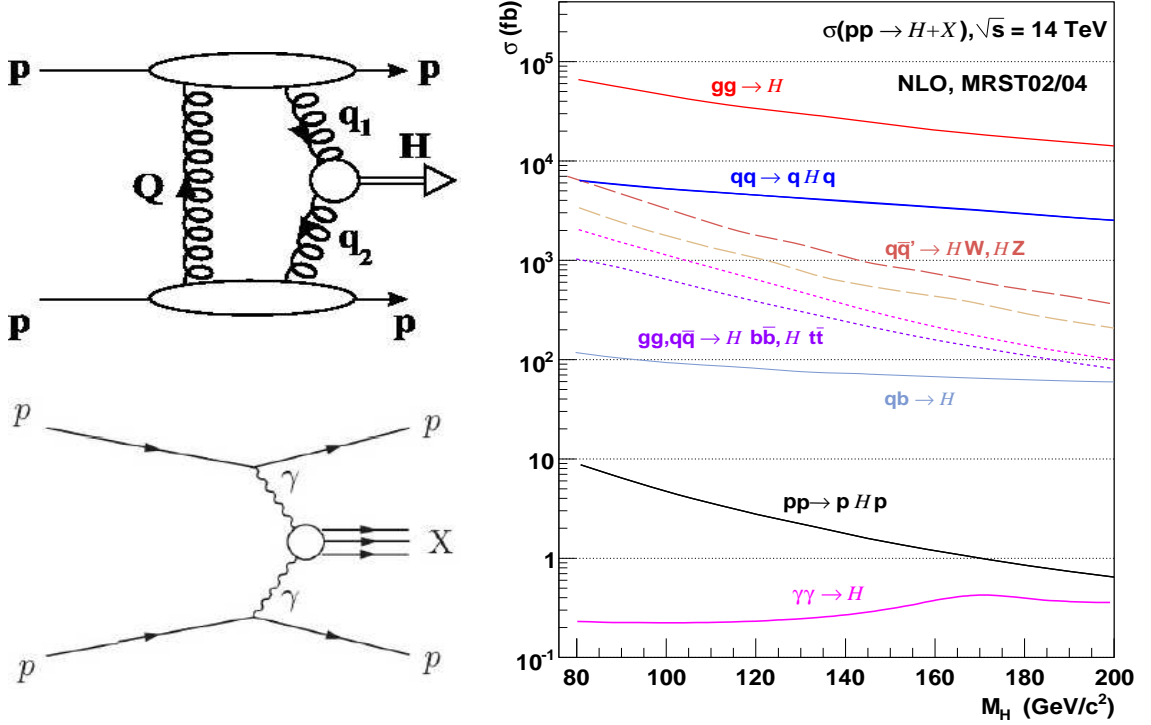


Figure 1: Left: Diagrams for central exclusive Higgs production (top) and photon-photon interactions (bottom). Right: Cross sections for the SM Higgs versus M_H in production channels accessible at the LHC [2] (σ_{pHp} is from [1] and $\sigma_{\gamma\gamma\rightarrow H}$ from [3]).

2 Higgs physics

The ATLAS [4] and CMS [5] experiments have been designed to discover the SM Higgs, if it exists, in pp collisions at $\sqrt{s} = 14$ TeV with a few tens of fb^{-1} in at least one or two decay modes, in the dominant gluon-gluon or vector-boson-fusion (VBF) production channels (Fig. 1, right). As important as discovering a Higgs-like resonance, it is to characterise its properties and confirm that it is the particle responsible of the SM electroweak symmetry breaking. The following Higgs properties are very challenging to determine in the traditional LHC searches:

- Coupling to b -quark: Testing the mass-dependent Yukawa couplings of Higgs to the various SM fields is crucial. Yet, the $H \rightarrow b\bar{b}$ decay channel is now considered inaccessible at the LHC [4,5] due to the overwhelming QCD background: $\sigma(H \rightarrow b\bar{b}) \approx 20 \text{ pb} \ll \sigma(b\bar{b}) \approx 500 \mu\text{b}$.
- Quantum numbers: The expected SM Higgs spin-parity $J^{PC} = 0^{++}$ is very

difficult to determine at the LHC in the currently favoured range of masses¹ $M_H \lesssim 180 \text{ GeV}/c^2$.

- Nearly-degenerate Higgs bosons: Possible additional Higgs states with similar masses (but different parities) predicted in various extensions of the SM, are not easy to separate.
- Mass & width in invisible decays: Details on possible invisible branching ratios remain very difficult as their presence can only be determined in counting-type measurements in VBF channels.
- (N)MSSM Higgs'es: Additional Higgs bosons in (next-to) minimal SUSY extensions of the SM, with largely enhanced third-family (b, τ) decays, with CP -violating mixings, or with complicated decay channels (e.g. $h \rightarrow aa \rightarrow 4\tau$) remain very problematic (if possible at all).

The main motivation of a CEP Higgs measurement is that it can help to address all these issues well before a possible future e^+e^- linear collider becomes operational. Indeed, observation of a Higgs-like resonance in the CEP channel benefits from (i) enhanced signal over backgrounds (giving access to the difficult $b\bar{b}$ decay channel) [6, 7, 8, 9, 10]; (ii) quantum numbers measurement via azimuthal asymmetry of the leading protons [11]; (iii) mass determination with $\mathcal{O}(2 \text{ GeV}/c^2)$ resolution from the leading protons via the ‘‘missing mass’’ method, $M_h^2 = (p_1 + p_2 - p'_1 - p'_2)$ [12], irrespective of the (e.g. possibly invisible [13]) decay modes; (iv) separation of scalar from pseudoscalar degenerate states, as the CEP system is scalar with an approximate $J^{PC} = 0^{++}$ selection rule [14]; and (v) discovery possibilities ($b\bar{b}, \tau\tau$ decays) in complicated regions of the MSSM [7, 15, 16] or NMSMM [17].

The CEP Higgs process (top diagram in Fig. 1) is dominated by a hard scale, $\Lambda_{\text{QCD}}^2 \ll Q^2 \ll M_H^2$, and thus calculable with perturbative QCD techniques. The QCD factorization theorem is applicable with the addition of an extra factor accounting for non-perturbative effects (see below). Schematically,

$$\sigma_{pp \rightarrow pHp} = uPDF(x_{1,2}, Q^2) \oplus \sigma_{gg \rightarrow H} \oplus S_{\text{gap survival}}^2.$$

Here $uPDF(x_{1,2}, Q^2)$ are proton ‘unintegrated parton distribution functions’ which can be approximated in terms of standard gluon distribution functions, $g(x, Q^2)$ evaluated at $x = M_H/\sqrt{s}$ and $Q = M_H/2$, times a ‘Sudakov suppression factor’ encoding the probability that the fusing gluons do not radiate in their evolution from Q up to the hard scale. The possibility of soft rescatterings where particles from

¹At higher masses, the azimuthal asymmetry of the SM Higgs VBF-jets or ZZ -decay can be used to confirm its CP numbers.

the underlying pp event (i.e. from other parton interactions) populate the gaps, is basically independent of the short-distance subprocess and can be taken into account with a multiplicative gap survival probability factor S^2 , computable within eikonal approaches [18,19]. For $S^2 = 0.03$, the expected SM CEP Higgs cross section ($M_H = 120 \text{ GeV}/c^2$) is around 3 fb (Fig. 1, right). The reliability of such theoretical calculations has been cross-checked at the Tevatron in the exclusive production of high-mass dijets, $p\bar{p} \rightarrow p+jj+\bar{p}$ [20] and scalar quarkonium states $p\bar{p} \rightarrow p+\chi_{c0}+\bar{p}$ [21], which are well described by the theory. In certain regions of the MSSM, at high $\tan\beta$ and small M_A , with enhanced Higgs coupling to fermions, $\sigma_{pp \rightarrow p H p}$ can be a factor of 10–100 larger [7, 15].

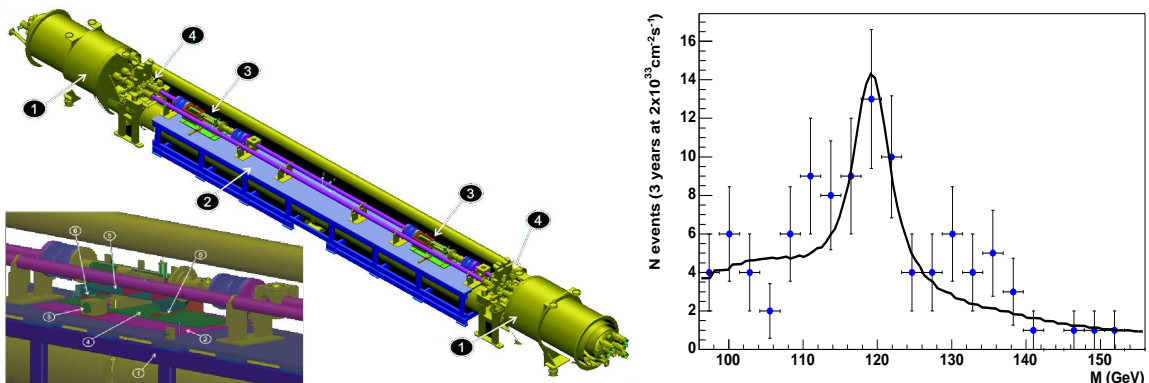


Figure 2: Left: Top view of the proposed FP420 system on top of the moving ‘Hamburg’ pipe in the cold area of the LHC tunnel (zoom shows the support table with one detector section). Right: Expected mass fit for the MSSM $h \rightarrow b\bar{b}$ decay ($M_H = 120 \text{ GeV}/c^2$), measured with FP420 in 60 fb^{-1} integrated luminosity [16]. (The significance of the fit is 3.5σ).

For Higgs masses close to the LEP limit, $M_H \approx 120 \text{ GeV}/c^2$, both protons lose a longitudinal momentum fraction $\xi_{1,2} \approx 1\%$ (using $M_X^2 \approx \xi_1 \xi_2 s$) and, after accounting for the LHC beam optics [22], the optimal proton tagging acceptance is beyond the current ALFA [23] and TOTEM [24] Roman Pots (RPs) detectors around 220 m, with p acceptances for larger masses ($0.02 < \xi < 0.2$). The proposed FP420 detector system [1] – a magnetic spectrometer consisting of a moveable 3-D silicon tracking system and fast Čerenkov detectors located in a 12-m-long region at about 420 m from the ATLAS and CMS IPs (Fig. 2, left) – allows for the detection of both outgoing protons scattered by a few hundreds μrads (i.e. 3 – 9 mm at 420 m) relative to the LHC beamline. A measurement of the protons relative-time of arrival in the 10 ps range is required for matching them with a central vertex within ~ 2 mm. Such a vertex matching is required to reject a large fraction of the simultaneous pp pile-up collisions at high-luminosities. Under such circumstances, MSSM Higgs line-shapes

can be reconstructed e.g. in the $b\bar{b}$ channel with a 3σ or better significance with an integrated luminosity of 60 fb^{-1} (Fig. 2, right) [16].

3 Photon-proton and photon-photon physics

A significant fraction of pp collisions at the LHC will also involve quasi-real (low- Q^2) photon interactions: one photon is emitted by one (or both) incoming proton(s) which then subsequently collides with the other proton (photon) producing a system X (Fig. 1, bottom left). The LHC thus offers the unique possibility to study $\gamma\gamma$ and γp processes at centre-of-mass (c.m.) energies well beyond the electroweak scale. Such photon-induced interactions are less central (i.e. take place at larger impact parameters) than Pomeron-induced processes and, thus, the exchanged squared-momentum $t \approx p_T^2$ is smaller². Differential cross sections for $pp(\gamma q/g \rightarrow X)pY$ reactions, as a function of the γ -proton c.m. energy, are presented in Fig. 3 (left) together with the acceptance of forward proton taggers. A large variety of processes have sizeable cross section well in the TeV energy range. Fig. 3 (right) shows various pair production cross sections (for charged and colourless fermions and scalars of two different masses) as a function of the minimal photon-photon c.m. energy $W_{\gamma\gamma}$.

Various exclusive photon-induced processes sensitive to new physics are accessible to measurement at the LHC with forward proton taggers [25]:

1. two-photon production of W and Z pairs sensitive to anomalous quartic gauge couplings [26],
2. two-photon production of SUSY pairs [27], and
3. anomalous single top photoproduction [28].

Many physics scenarios beyond the SM, with novel interactions and/or particles, lead to modifications of the gauge boson (γ , W and Z) self-interaction vertices. Two-photon production of W, Z pairs provides an excellent opportunity to investigate anomalous *quartic* gauge couplings. The WW process has a total cross section of more than 100 fb, and a very clear experimental signature. The processes $\gamma\gamma \rightarrow W^+W^- \rightarrow l^+l^-\nu\bar{\nu}$ and $\gamma\gamma \rightarrow ZZ \rightarrow l^+l^-jj$ have been investigated via the signature of two leptons (e or μ) within the CMS [26] acceptance. The calculated cross section upper limits can then be converted to limits on the anomalous quartic couplings which are about 4000 times stronger than the best limits established at LEP2.

²The t -distribution is of the type $\exp(-b t)$ with slope $b \approx 4$ (40) GeV^{-2} for double-Pomeron (double-photon) collisions.

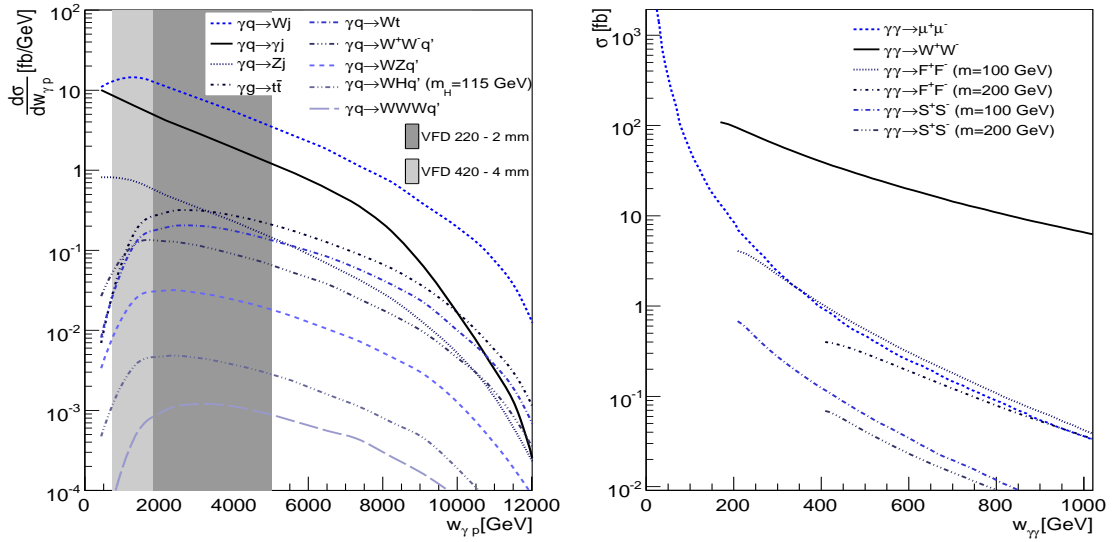


Figure 3: Left: Differential cross-sections for various $pp(\gamma q/g \rightarrow X)pY$ processes as a function of the c.m. energy in γ -proton collisions, $W_{\gamma p}$. The acceptance of RPs (220 m at 2 mm from the beam-axis, and 420 m at 4 mm from the beam-axis) is also sketched [25]. Right: Cross sections for various $\gamma\gamma$ processes at the LHC as a function of the minimal $W_{\gamma\gamma}$ c.m. energy [25].

The SUSY pair cross-section at the LHC, e.g. $\gamma\gamma \rightarrow \tilde{l}^+\tilde{l}^-$, has cross-sections $\mathcal{O}(20 \text{ fb})$ still consistent with the LEP search limits. Two-photon exclusive production of pairs of new charged particles benefits from (i) the possibility to significantly constrain their masses, using double leading-proton information, and (ii) in the case of SUSY pairs, the presence of simple final states without cascade decays, characterised by two (acoplanar) charged leptons with large missing energy with low backgrounds, and large trigger efficiencies. With this technique and sufficient statistics, masses could be measured with precision of a few GeV/c^2 by looking at the minimal c.m. energy required to produce the heavy pair [27].

Single top photo-production in the SM is only possible for higher-order electroweak interactions, since neutral currents preserve quarks flavour at tree level. The observation of a large number of single top events would hence be a sign of Flavour Changing Neutral Currents (FCNC) induced by processes beyond the SM. A general effective Lagrangian for such processes can be written with anomalous couplings $k_{tu\gamma}$ and $k_{tc\gamma}$. Strong limits on the anomalous coupling $k_{tu\gamma}$ (of which the current best value, from ZEUS, is around 0.14) and the unprobed $k_{tc\gamma}$ can be obtained with forward proton taggers in photon-proton collisions after 1 fb^{-1} of integrated luminosity [28].

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