Anomalous Gauge Coupling Detection by using the LHC as a Virtual Photon Collider

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Despite the discovery of the Higgs boson and an immensely comprehensive physics program at the LHC, a consistent description of the Standard Model and what might be beyond it remains elusive. The gauge sector lies at the core of many of the major issues: such as the stability of the Higgs mass to radiative corrections, which involve vector boson loops, and why the electroweak mass scale is so many orders of magnitude below the Planck scale. Typical solutions to these problems invoke new particles, interactions, or extra-dimensions that result in modifications to electroweak gauge couplings. One of the main messages from the Electroweak Interactions working group at Snowmass 2013 was to search for these new processes in vector boson couplings [1].

While traditional techniques searching for new physics are running up against the limits of energy reach and overwhelming background contamination at the LHC, there is an emerging technique that provides a fresh approach with high sensitivity to directly probe the electroweak gauge sector of the Standard Model. By exploiting the central exclusive production mechanism and taking advantage of new detector capabilities of the CMS/ATLAS experiments, we are able to turn the existing LHC accelerator into a virtual photon collider while operating normally with proton collisions. This allows us to identify a theoretically clean subset of proton collisions particularly sensitive to electroweak processes with extra kinematic constraints that provide powerful background rejection capability not available to standard LHC data analysis techniques.

Central exclusive production (CEP) refers to the process $pp \to p{+}X{+}p$, where the initial protons remain intact and produce an intermediate state via virtual photons from the electromagnetic field of the colliding protons, see Fig. 1. The centrally produced intermediate state can be quite massive as there can be very large momentum transfer from the proton beams at the LHC. Since there is no "underlying event" background from the breakup of the protons these events are experimentally clean compared to the typical hard collisions at the LHC. For completeness we should mention that there is an additional colorless gluon exchange mechanism that can result in intact protons, or protons with highly forward disintegration products. These QCD processes are part of a broader forward physics program, while in this LOI we focus on photon interactions to study electroweak gauge processes.

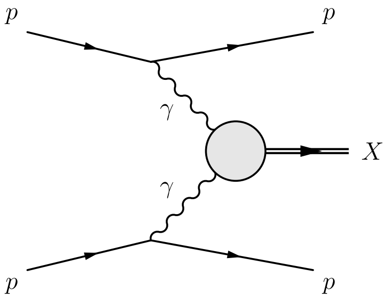

Figure 1: Central exclusive production mechanism.

Central exclusive production in proton(antiproton) collisions was first explored at the Tevatron, where CDF observed electron and muon pair final states and D0 conducted a search for W-boson pairs [2–5]. Along with a small group of LHC physicists at CERN, we formed the FP420 R&D Collaboration to pursue this technique in conjunction with the large collider experiments CMS and ATLAS [6, 7]. This led to the first measurements at the LHC of CEP production of lepton pairs [8–10] and subsequently the observation of CEP WW [11–14].

Intermediate exclusive states that couple directly to vector bosons, such as W^+W^- as shown in Fig. 2, provide a sensitive probe to modifications of electroweak interactions. The effect from new physics can be treated in a model-independent way

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as an extra (anomalous) coupling constant from an effective Lagrangian contribution originating from the new physics. These anomalous couplings for the gauge particles appear in many different types of LHC analyses, including central exclusive production modes as well typical proton interactions. The CMS result, which was led be the authors, was the first ever observation of CEP WW process and also the most sensitive limit on anomalous quartic gauge couplings from the LHC Run 1.

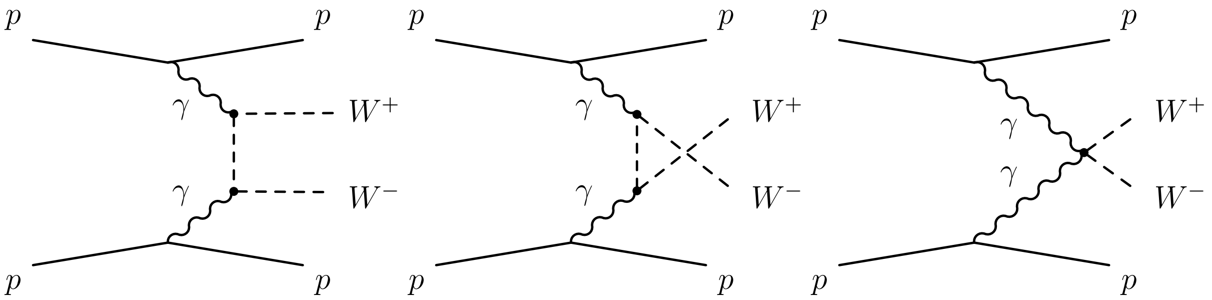

Figure 2: Standard Model diagrams for central exclusive production of W^+W^-.

All of the measurements described above rely on the ability to locate the origin of the production of the outgoing particles and require that it be sufficiently separate from all other particles within the same event. As the luminosity of the LHC continues to increase, the increase in "pile-up" of multiple interactions within the same proton-bunch crossing drastically reduces the efficiency of the isolation requirement. To combat this problem both CMS and ATLAS have implemented detector upgrades to tag and measure the momentum of the outgoing protons from the CEP process. In addition to being an unambiguous trigger, tagging both outgoing protons provides the complete kinematic information of the interaction, which can then be used in the reconstruction of the central intermediate state and rejection of background from pileup events.

The authors are part of the original team that designed, built, and commissioned the Precision Proton Spectrometer (PPS) subdetector for CMS [15]. PPS is the implementation of the FP420 R&D effort to develop a detector system capable of measuring the momentum and arrival time of off-energy protons in the LHC. In 2014, the CMS collaboration approved the construction of PPS to place tracking and timings detectors on both sides of the CMS interaction point at a distance of 215 m. The detectors are placed inside the beam pipe and can move in and out towards the beam. During data taking the detectors are positioned within a few mm of the beam. In 2016 the construction and commissioning of the detectors was completed and PPS has been part of the high luminosity running of the LHC since. The proton tracking configuration implemented for Run 2 corresponds to a mass acceptance of the centrally produced state of around 350 GeV to 2 TeV. Approximately 100 fb^{-1} of integrated luminosity from 2016-2018 were collected with the PPS detectors in Run 2.

From this Run 2 data set CMS was the first to observe proton-tagged CEP events by detecting dilepton and $\gamma\gamma$ final states [16, 17]. The authors currently lead the first analysis of the proton-tagged CEP WW boson events. This will not only extend the limits on anomalous coupling (assuming new physics signals do not appear), but also provide the first analysis free from interpretation issues related to unitarity violation inherent in the effective Lagrangian formalism of the new physics model. We have also begun to explore the natural extensions of our WW analysis to the ZZ final states, for which there is no tree-level Standard Model contribution. These analyses represents just the beginning of a rich physics program to explore multiboson final states, $WW, ZZ, \gamma\gamma, \gamma Z$, produced by the CEP process [18–25]. In terms of the effective field theory formalism described in the previous Snowmass study, out of the eighteen possible operators involving quartic gauge couplings, sixteen can be probed by photon-induced CEP processes. [1].

The prognosis is also good for improved detection capability in the future. PPS has been approved for Run 3 and a further upgrade for the HL-LHC is being discussed with CMS and LHC management. PPS recently delivered a letter of interest for the HL-LHC that details the installation of detectors at 196 m, 220 m, 234 m, and 420 m, increasing the mass acceptance at both the lower and higher bounds. The mass acceptance increase to 50-2700 GeV and improvements in the LHC enable significant gains in anomalous gauge coupling detection as well as additional physics reach for low-mass QCD physics, exclusive Higgs production for CP studies, and novel SUSY model searches.

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