The FP420 R&D Project: Forward Proton Tagging at the LHC as a Means to Discover New Physics

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Abstract. We review the theoretical and experimental motivations behind recent proposals to add forward proton tagging detectors to the LHC experiments as a means to search for new physics.

Keywords: Higgs, MSSM Higgs, Proton Tagging, LHC
PACS: 14.80.Bn,14.80.Cp,14.70.Fm,14.70.Hp,12.38.Aw

INTRODUCTION

There has been increasing interest in the past few years in the possibility of using diffractive interactions as a search tool for new physics (see for example [1, 2, 3, 4, 5] and references therein). In particular, it has been suggested that the so-called central exclusive production process might provide a particularly clean environment to search for, and identify the nature of, new particles at the LHC. By central exclusive, we refer to the process $PP \to P \oplus \phi \oplus P$, where $\oplus$ denotes the absence of hadronic activity ('gap') between the outgoing protons and the decay products of the central system ϕ. An example would be standard model Higgs Boson production, where the central system could consist of 2 b-quark jets, or the decay products of 2 W bosons, and no other activity.

There are three primary reasons why this process is attractive. Firstly, if the outgoing protons remain intact and scatter through small angles, then, to a very good approximation, the central system ϕ must be produced in a spin 0, CP even state, therefore allowing a clean determination of the quantum numbers of any observed particle. Secondly, the mass of the central system can be determined very accurately from a measurement of the transverse and longitudinal momentum components of the outgoing protons alone. The mass of any new particles produced in this way can therefore be precisely determined irrespective of their decay mode. Thirdly, because of the accurate mass measurement, the spin selection rules and the cleanness of the events in the central detectors, excellent signal to background rations are achievable for a wide range of Standard Model and MSSM Higgs production scenarios. We discuss these two possibilities in more detail in section 2. Another attractive feature is the ability to directly probe the CP structure of the Higgs sector by measuring azimuthal asymmetries in the tagged protons (a measurement previously proposed only at a future linear collider) [6].

In order to make use of the central exclusive production process at the LHC, proton tagging detectors must be installed on both sides of either the ATLAS and / or CMS detectors, with an acceptance that covers the appropriate mass range for Standard Model and MSSM Higgs bosons, and other possible new particles. For central systems in the 120 GeV mass range, the outgoing protons emerge in the region 420m away from the interaction points. The FP420 R&D project [7] aims to assess the feasibility of installing such detectors. We review the key technical issues to be addressed by this project in the following section .

There is also a wealth of QCD and 2-photon physics that becomes accessible if 420m proton detectors are installed. Of particular interest is the study of the quartic gauge couplings $\gamma\gamma WW$. It is estimated that approximately 1000 events could be collected in the semi and fully leptonic decay channels with 30 fb^{-1} of delivered luminosity, delivering a sensitivity to anomalous quartic couplings a factor of 10,000 better than the current LEP2 limits. There is similar sensitivity to the anomalous production of Z pairs in the process $\gamma\gamma \to ZZ$. The rich QCD program includes precision measurements of the diffractive structure functions of the proton in the HERA kinematic range, allowing detailed studies of rapidity gap survival probability (and hence the contribution of multi-parton interactions to the underlying event), and the off-diagonal unintegrated gluon distributions of the proton. For more details, see [7] and references therein.

THE FP420 R&D PROJECT

The 420m region at the LHC consists of a 15m drift space (i.e. no magnets), and is at present enclosed in a 'connection cryostat' which maintains a series of superconducting bus-bars, and the beam pipes themselves, at a temperature of 1.7K. The first goal of the FP420 project is to assess the feasibility of replacing the 420m interconnection cryostat to facilitate access to the beam pipes and therefore allow proton tagging detectors to be installed.The first opportunity to install such detectors would be the planned LHC shutdown in autumn 2008.

The resolution and acceptance of the proposed detectors is essentially fixed by the LHC high-luminosity beam optics. For the case of a 140 GeV central system, the acceptance for tagging both outgoing protons in the 420m detectors is 22%, and the mass resolution is expected to be ~ 1 %. The acceptance rises to 60 % if one of the protons is tagged using the proposed 220m detectors of CMS / TOTEM or the ATLAS luminosity system. The mass resolution for these asymmetric events is ~ 6 % [7].

A key challenge for the FP420 project is level 1 triggering. The 420m detectors are too far away from the interaction point to be included in the level 1 trigger systems of ATLAS or CMS without increasing the level 1 trigger latency. It is therefore necessary to save the interesting physics at level 1 using the central detectors, the forward detectors (T1, T2 and CASTOR in CMS / TOTEM and LUCID in Atlas), or the CMS / TOTEM or ATLAS Roman Pots at 220 m, if available. Central systems that contain high-pT leptons, such as $H \to WW$, are not a problem. The challenge arises in the case of low-mass states, such as the Standard Model Higgs boson, decaying into relatively low E_T jets.

A preliminary study of Level 1 triggering in this case was carried out in [7]. The conclusions were that L1 triggering is not a problem as long as there is no pile-up, since the forward detectors can be used to veto events in which there are no forward rapidity gaps. For a 25 ns bunch structure, it is possible to collect ~ 6 fb^{-1} of clean (no pile-up) events within 3 years of LHC running. This is enough to detect signals with central exclusive cross sections in the 50 fb range. An example would be the high $\tan\beta$ MSSM scenario, to be discussed in the following section. At higher luminosities, up to $\sim 2\times10^{33}$ cm^{-2}s^{-1}, events in which one proton is detected at 220m can be saved. If the Roman Pot detectors at 420 m could be used, requiring that a proton be seen on both sides would yield a signal efficiency of $\sim$ 15 % and an L1 trigger rate at a luminosity of 10^{34}cm^{-2}s^{-1} of $\sim$ 7 kHz [7]. No trigger problems are foreseen for final states containing high-p_T leptons, such as the WW decay modes of the Standard Model Higgs boson.

THE CENTRAL EXCLUSIVE PRODUCTION OF SM AND MSSM HIGGS BOSONS

The benchmark central exclusive production process for new physics searches is Standard Model (SM) Higgs production. The cross section for $pp \to p\oplus H\oplus p$ was calculated in [8, 9] to be 3 fb for $M_H = 120$ GeV, falling to $\sim$ 1 fb at $M_H = 200$ GeV. The simplest channel to observe the SM Higgs from an experimental perspective is the WW decay channel. For $M_H = 140$ GeV, 19 exclusive $H\to$ WW events are expected to have double proton tags using both 220m and 420m detectors (none using 220m detectors alone), for an LHC luminosity of 30 fb^{-1}. This rises to 25 at 160 GeV. Of these, approximately 25 % will be taken by the standard ATLAS and CMS level 1 leptonic triggers, although it is expected that with further optimisation of the trigger thresholds this efficiency should rise to close to 50 % [9]. In the gold plated semi-leptonic channels, the signal to background ratio will be in excess of unity, and observation of SM Higgs in this channel will cleanly establish its quantum numbers with 30 fb^{-1} of delivered luminosity.

More challenging from a trigger perspective is the b-jet decay channel. That this channel is possible to observe at all is a consequence of the spin-0 selection rules for central exclusive production [10], which heavily suppresses exclusive b-jet production; in conventional channels this signal is swamped by the copious QCD background. For $M_H = 120$ GeV, we expect 60 exclusive $H\to bb$ events to have double proton tags using both 220m and 420m detectors. A recent study [1] found that, after taking into account losses due to b-tagging efficiencies and kinematic cuts to reduce backgrounds, and the likely achievable mass resolution of the proton tagging detectors, 11 signal events remain with a signal to background ratio of order unity for a luminosity of 30 fb^{-1}.

The b-jet channel becomes extremely important in the so-called intense coupling regime of the MSSM. This is a region of MSSM parameter space in which the couplings of the Higgs to the electroweak gauge bosons are strongly suppressed, making discovery challenging at the LHC by conventional means [11]. The rates for central exclusive production of the two scalar MSSM Higgs bosons are enhanced by an order of magnitude in these models, however. We expect close to 1000 exclusively produced double-tagged h and H bosons with 220m and 420m detectors in 30 fb^{-1} of delivered luminosity, for $M_{h,H}\sim 125$ GeV and $\tan\beta = 50$ [12]. Under the same assumptions as for the SM Higgs, approximately 100 would survive the experimental cuts, with a signal to background ratio of order 10. It is also worth noting that the pseudo-scalar Higgs (A) is practically not produced in the central exclusive channel, allowing for a clean separation of the scalar Higgs bosons which is impossible in conventional channels. For such regions of the MSSM, central exclusive production is likely to be the discovery channel.

SUMMARY

Installing proton tagging detectors in the 420m region at the LHC will open up a rich QCD, electroweak, Higgs and BSM program, with the potential to make measurements which are unique at LHC, and difficult even at a future linear collider. The FP420 R&D project aims to assess the feasibility of installing such detectors, as an upgrade to either ATLAS and / or CMS. Full details of the R&D proposal can be found in [7].

ACKNOWLEDGMENTS

We would like to thank all the authors of the FP420 LOI, whose contributions have been summarised in this article. This work was supported in the UK by PPARC.

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