The FP420 Project: The Physics Potential

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Abstract. The FP420 project proposes to complement the experiments CMS and ATLAS by installing additional near-beam detectors at 420m away from the interaction region. The presence of these detectors will allow to measure exclusive production of massive particles, such as the Higgs particle.

1. Introduction
The physics potential of forward proton tagging at the LHC has attracted much attention in the last years. The focus of interest is the central exclusive production (CEP) process $pp \rightarrow p + \phi + p$ in which the protons remain intact and the central system is separated from the outgoing protons by a large rapidity gap. A very interesting case is the CEP process of a Higgs particle. A picture of the basic process is shown in Fig. 1 (left).

There are several advantages of CEP:

- The selection rules for CEP are such that the central system is – to a good approximation – an $O^{++}$ state. Observing CEP thus gives access to the quantum numbers of the state $\phi$.
- The three particle final state is a very constrained system. As a consequence the azimuthal correlation between the outgoing protons is directly sensitive to CP quantum numbers and is a possible way to study CP violating Higgs scenarios in detail.

\[ \sigma \text{ Br}(h/H \rightarrow bb) \text{ (fb)} \]

\[ h, H \quad \tan\beta = 30 \]

\[ m_{h,H} \text{ (GeV)} \]

\[ 100 \quad 10 \quad 1 \quad \text{fb} \]

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Figure 1. (Left) Diagram for the CEP process; (Right) Cross section for SM and MSSM exclusive Higgs production.
The tagging of the protons allows for the measurement of the mass of the system $\phi$ with a precision of the order of 1-2 GeV, via the missing mass w.r.t. the incoming proton beams $M_{\text{miss}} = (p_1 + p_2 - p'_1 - p'_2)^2$ with $p_1, p_2$ the incoming and $p'_1, p'_2$ the outgoing protons. This measurement is independent of the way the central system $\phi$ decays.

- The QCD backgrounds such as $gg \rightarrow qq$ are strongly suppressed in LO.
- CEP can be a discovery channel in certain regions of the MSSM parameter space.
- CEP gives a unique access to a host of interesting QCD phenomena.

There has been a lot of controversy over the CEP Higgs cross sections at the start of the wave of papers on this topic. During the past few years the different approaches and results have been discussed in detail especially in the context of the HERA/LC workshops\cite{1}. Meanwhile the theoretical community has settled, and the results presented in \cite{2, 3} and shown in Fig. 1 (right) have now been established as 'base-line' cross sections for this channel. Several predictions using the same calculation techniques applied to processes that can be measured at the Tevatron have been broadly confirmed \cite{4}. There are still some issues and concerns on the CEP soft survival probability at the LHC and the uncertainties in the PDFs. This question will be settled with the first data at the LHC.

New detectors are needed to complement the CMS and ATLAS experiments to detect these protons \cite{5}. FP420 is an R&D collaboration that studies the feasibility to detect the protons of CEP with detectors at a distance of 420m away from the interaction point \cite{6}. Such detectors allow to accept protons with a fractional momentum loss (or $\xi$) of 0.1% to 1%. With these detectors the protons of CEP Higgs production in the mass range of $70 < M_{\phi} < 150$ GeV/c$^2$ can be detected. The acceptance of the forward detectors versus the mass of the central system $\phi$ is shown in Fig. 2 for detectors at 420m and for a combination of detectors at 420m and 220m. Detectors at 220m could be available for ATLAS and CMS in future. The acceptance is shown for different values of closest approach of the detectors to the beamline.

2. FP420: The physics potential
The main physics topics studied by FP420 are

- Central Exclusive Production, including Higgs production and searches for new physics.
- QCD and diffractive studies with tagged protons
- Photon induced processes with tagged protons
2.1. Higgs production

One of the key advantages of CEP is that the \( gg \rightarrow bb \) process is suppressed in LO, hence the decay \( H \rightarrow bb \) has less background and becomes potentially observable. The Higgs to \( b \)-quark Yukawa coupling is otherwise very difficult to access at the LHC. The inclusive \( H \rightarrow bb \) channel is not accessible due to the too large QCD backgrounds. Recently, the \( ttH \) channel was analysed with detailed simulation in [7] and found not to be accessible even with 60 fb\(^{-1}\). Also the \( WH \) associated channel was found to be marginally observable in the \( bb \) decay mode.

The cross section for the production of a Standard Model CEP Higgs and for a MSSM CEP Higgs (for \( \tan\beta = 30 \)) is shown in Fig. 1. These predictions are like a lower limit. Using eg. CTEQ instead of MRST structure functions in the calculation increases the cross section by more than a factor of two. Generator level calculations, including detector and trigger cuts, and estimates of selection efficiencies, show that the decay channels \( H \rightarrow bb \) and \( H \rightarrow WW \) are accessible. Eg. \( M_H = 120 \text{ GeV/}c^2 \) gives 11 events with O(10) events background for 30 fb\(^{-1}\) in the \( bb \) decay mode. For \( M_H \) values above 140 GeV/\( c^2 \) at least 5-6 events with no appreciable background for 30 fb\(^{-1}\) in the \( WW \) decay [8] will be observed, using channels with at least one lepton decay. There are however challenges: the signals from detectors at 420m cannot be used to trigger the events at the first trigger level in neither ATLAS nor CMS. Hence the event will have to be triggered at the first level with the information of the central detector. At the next trigger level the signals of FP420 can be used. While this is no problem for the \( WW \) decay channel, it is a challenge for the \( bb \) channel. Several additional selection cuts for a low mass Higgs-like object decaying into jets can be used, but generally, with di-jet thresholds of O(40) GeV and these additional cuts, the rate at first level for this trigger is very high: O(10) kHz. The usage of the FP420 information can however strongly reduce that rate at the next level, so this is not necessarily a show stopper.

A detailed study of the backgrounds to this process was presented in [9, 10]. At high luminosity, ie. \( 10^{33} \text{ cm}^{-2}\text{s}^{-1} \) and higher, the pile-up is considerable, coming mainly from single diffractive interactions. Several techniques such as correlations between the detectors at 420m, vertices, event multiplicities and especially fast timing are essential to reduce the pile-up background. Rapidity gaps can obviously not be used due to the many interactions per bunch crossing. But in any case, studies both using detailed[9] and fast[10] simulations show that the measurement of the SM Higgs decay into \( bb \) will be very challenging, even with the highest luminosities.

The rate is much larger for MSSM Higgs production as shown in Fig. 1, thus leading to a much more favourable signal to background ratio than for the SM Higgs. The cross section can be a factor 10 or more larger than the SM model one. This has recently been explored in a systematic way in [11]. A typical result is shown in Fig. 3 (left), for a Higgs decaying in \( bb \). The lines in the plot show the relative cross section increase w.r.t. the SM cross section. In some regions of the phase space the CEP process could be a discovery channel. Fig. 3 (right) shows an example of a signal for 60 fb\(^{-1}\) after acceptance cuts, trigger efficiencies etc., for a MSSM Higgs with a cross section that is a factor 8 enhanced w.r.t the the SM Higgs, based on the so-called \( m_t^{\text{max}} \) scenario[12], with \( m_A = 120 \text{ GeV} \) and \( \tan\beta = 40 \). A clear signal over background is observable.

Furthermore, to a very good approximation the central system in CEP is constrained to be a colour singlet, \( J_Z = 0 \) state, and, due to the strongly constrained three particle final state, the measurement of azimuthal correlations between the two scattered protons will allow to determine the CP quantum numbers of the produced central system[3]. Hence this is a way to get information on the spin of the Higgs, giving added value to the LHC Higgs measurements.

It was pointed out recently [13] that in case of CPV models the \( h, A, H \) may mix into states \( h_1, h_2, h_3 \) which may be quasi-degenerate in mass, with mass differences of the order of a few GeV or less. Due to the interference these will show up as one broad mass distribution, with
Figure 3. (Left) Contours for the ratio of signal events in the MSSM to those in the SM in the $H \rightarrow bb$ channel in CEP production in the $M_A - \tan \beta$ plane. The ratio is shown in the no-mixing scenario with $\mu = +200$ GeV. The values of the mass of the heavier CP-even Higgs boson, $m_H$, are indicated by dashed contour lines. (Right) A typical mass fit for 3 years of data taking at $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ (60 fb$^{-1}$), using only events with both protons tagged at 420m.

A structure that is sensitive to the underlying parameters. Analyzing the three-way mixing scenario [13] it was found that the different peaks can be detected with a 1 GeV mass resolution, but would need a few hundred fb$^{-1}$ of accumulated luminosity. Other CP violating benchmark scenarios may lead to larger differences between the Higgs peaks and may be easier to detect.

2.2. Other topics

Other searches for new physics in this channel are possible as well. It has been pointed out that the mass of long lived gluinos, as predicted in split SUSY models, can be determined with CEP events to better than 1%, with 300 fb$^{-1}$ for masses up to 350 GeV [14]. More spectacular are the predictions presented in [15], where a very high cross section of CEP $WW$ and $ZZ$ events is expected, in a color sextet quark model.

Other, more conventional, physics topics include QCD and diffraction. FP420 can tag and measure protons which have lost 1% to 0.1% of there initial momentum, and study in detail diffractive reactions in that range. An extensive program of two photon physics and photon-proton physics becomes accessible as well. In particular the study of the processes $\gamma\gamma \rightarrow WW$ and $ZZ$ is of interest and can give precise measurements of the anomalous couplings. The QED processes $\gamma\gamma \rightarrow \mu\mu, ee$ can be precise monitors of the luminosity. Two photon processes can also be used to search for chargino pair production.

3. The FP420 project

The FP420 project is schematically presented in Fig. 4. The aims of the R&D study are

- Redesign the area of the machine around 420m. Right now this area contains a connecting cryostat, but no magnet elements.
- Study the mechanics, stability, services for detectors at 420m
- Design and test tracking detectors to operate close to the beam
- Design fast timing detectors (with $O(10)$ psec resolution)
- Study RF pickup, integration, precision alignment, radiation and resolution issues
- Study trigger, event selection, and pile-up issues.
- Study the operation of FP420 detectors at the highest LHC luminosity.
The FP420 collaboration has members from ATLAS, CMS, and 'independent' physicists, and has excellent contacts with the LHC machine group. In the emerging design the principle of FP420 is based on moving "pockets" which contain tracking and timing detectors. The tracking detectors that are developed are 3D silicon pixel detectors, which are radiation hard and can detect particles close to the edge. Timing detectors include both gas and crystal radiators. The first test beam results of all these detector types are very encouraging and a full pocket beam-test is foreseen for October 2007. Discussions on the implementation of FP420 in the ATLAS and CMS experiments have started. More technical details on FP420 will become available in [16].

4. Conclusion
The R&D for FP420 is nearing its completion. It offers a unique opportunity to measure CEP processes at the LHC, in particular exclusive Higgs production. The earliest date for data taking with these detectors is 2010.

5. References
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