We discuss the special challenges posed by measuring diffractive and forward physics at the LHC at high luminosity and the solutions proposed by the FP420 R&D collaboration.

Keywords: Soft QCD; Forward Physics; Diffraction.

1. Introduction
The term “high luminosity” throughout this article is taken to mean “luminosities at which event pile-up is significant”. In that case, the rapidity gaps typical of diffractive events tend to be filled in by particles from the overlaid pile-up events. Hence the selection of diffractive events has to rely entirely on tagging the diffractively scattered protons which escape intact down the beam-pipe.

In recent years, theoretical advances have identified forward proton tagging at the LHC as a promising tool for the search for and the characterization of new particles at the LHC. At the highest LHC luminosities, central exclusive production (CEP) may become a tool for the discovery of any object that couples to gluons. A case in point is a Standard Model or MSSM Higgs boson with mass close to the gluons. A case in point is a Standard Model or MSSM Higgs boson with mass close to the current exclusion limit. CEP would provide a clean experimental signature for its discovery; would make possible an unambiguous determination of its quantum numbers; and would offer, as the sole channel at the LHC, a direct means of measuring the CP structure of the Higgs sector.

Forward proton tagging at high luminosities will also give access to a rich QCD program. Measuring diffraction in the presence of a hard scale will render possible the investigation of fundamental aspects of the proton structure as pioneered at HERA and the TEVATRON. Diffractive Parton Distribution Functions provide a view on the proton through a lens that filters out everything but the vacuum quantum numbers; Generalized Parton Distributions contain information on the correlations between partons in the proton. Along with these, the so-called rapidity gap survival probability can be experimentally determined. This quantity is closely linked to soft rescattering effects and to the features of the underlying event at the LHC.

2. The FP420 R&D project
For slightly off-momentum protons, the LHC beamline with its magnets is essentially a spectrometer. If diffractively scattered protons are bent sufficiently, but little enough to remain within the beam-pipe, they can be detected by means of detectors inserted into the beam-pipe and approaching the beam envelope as closely as possible.

At nominal LHC optics, an ideal position is at a distance of ±420 m from the interactions points of the ATLAS and CMS experiments, where coverage in the fractional momentum loss ξ of the proton of 0.002 < ξ < 0.02 can be achieved.

The FP420 R&D collaboration, with members from ATLAS, CMS and the LHC, aims at installing high precision tracking and fast timing detectors close to the beam at the 420 m location. The currently considered configuration foresees, over a length of...
10 m, 2 or 3 stations of Silicon detectors with about 8 layers each. Fast timing detectors complement this setup. They would be capable of determining, within a resolution of a few millimeters, whether the tagged proton candidates came from the same vertex as the hard scatter.

The region at ±420 m from the IP of ATLAS or CMS is located in the cold section of the LHC. The engineering challenge of integrating detectors operated at room temperature into a beamline operated at cryogenic temperatures can be resolved by effecting a cold-warm transition by means of modifying an already existing LHC beamline element, the LHC Arc Termination Module. The engineering design work is already well underway.

The currently preferred solution for a mechanism to insert the tracking detectors into the beam-pipe and to approach them to the beam to within about 3 mm is a movable beam-pipe section to which the detector stations would be attached. Beam pipe section and detectors would be kept in a position remote from the beam during injection, and would be moved as close as possible to the beam-line once the beam has stabilized and the narrow beam envelope of collision running has been reached.

The tracking detectors in the 420 m location have to be sufficiently radiation hard to be operable in the immediate vicinity of the LHC beam, and their insensitive area on the side closest to the beam envelope needs to be as small as possible to maximize acceptance. The technology currently foreseen is edgeless 3-D Silicon where the electrodes are processed inside of the Silicon bulk instead of being implanted on its surface and where the width of the insensitive volume at the edge is smaller than 5 µm. In addition, this novel type of Silicon detectors has been found to withstand the dose expected at 420 m for an integral of 5 years of LHC running at 10 times the LHC design luminosity. The current prototypes utilize the radiation-hard ATLAS pixel readout chip and were tested in a test beam at CERN this summer.

With a Silicon detector electrode pitch of 50 µm, a resolution in the two spatial dimensions of about 15 µm can be reached. Preliminary Monte-Carlo simulations indicate that for CEP of a Higgs boson with mass between 120 GeV and 200 GeV, this translates into a mass resolution of around 1.5 GeV, when the two protons are both detected at 420 m (420+420 tag).

3. Pile-up background

Single diffractive events contribute about 15% of the inclusive QCD cross section at the LHC, double Pomeron exchange events a few percent. In addition, a certain portion of non-diffractive events contain leading protons with a fractional momentum loss small enough that they can be observed in near-beam detectors. These generally soft events with leading protons are present in the event pile-up.

The unprecedented high luminosities at the LHC come at the cost of event pile-up, i.e. each hard scatter will be overlaid with a luminosity-dependent number of generally soft events. At an instantaneous luminosity of $2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$, the average number is 7 events per crossing, at $1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ it is 35. Of these pile-up events, of the order 1% contain a proton within the acceptance of near-beam detectors at 420 m from the IP.

For the selection of diffractive events at the LHC at high luminosities, these leading protons from pile-up are a major background source. To illustrate the point, we consider the case of a Higgs boson with 120 GeV mass that decays into a pair of $b$-jets. For the non-diffractive production of a Higgs boson of this mass and decay channel the background from inclusive dijet production is overwhelming.
case of CEP (i.e. double Pomeron exchange) suppress this background to a large extent. However, inclusive dijet events, when they occur in coincidence with pile-up events that have leading protons within the acceptance of the near-beam detectors at ±420 m, again appear to have the same signature as the signal. Simple combinatorics yields an estimate of 2 × 10\(^{33}\) cm\(^{-2}\) s\(^{-1}\) that of the order of a few per mill of inclusive dijet events are being mistaken as signal events. Given the much larger cross section of inclusive dijet events compared to the signal, this is the most important source of background.

This background can be reduced by exploiting the correlations between quantities measured in the main detector and those measured with the near-beam detectors. One possibility is to estimate the fractional momentum loss, \(\xi\), of the protons with the help of the dijet system as:

\[
\xi_{1,2} = \frac{1}{\sqrt{s}} \left( \sum E_{T}^{jet} e^{\pm \eta} \right),
\]

where the sum is over the two jets and \(\eta\) denotes their pseudorapidity.

Another possibility is the use of fast timing detectors that determine whether the protons seen in the near-beam detectors come from the same vertex as the hard scatter. Fast timing detectors with an expected vertex resolution of better than 3 mm are part of the FP420 project. Preliminary Monte-Carlo studies indicate that with nominal LHC running conditions a rejection of about 97\% is possible of events that appear to be double Pomeron exchange events, but where the protons in reality originated from coincidences with pile-up events.

Two prototypes are currently under discussion, one using Quartz as Cherenkov medium, the other gas. Both utilize micro channel plate photo-multipliers which are known to have yielded a time resolution of about 10 ps in Cherenkov-light based Time-of-Flight detectors. Results from test-beam measurements at Fermilab with the two prototypes this summer will be available soon.

4. Detectors at 220 m distance

Additional near-beam detectors closer to the IP than 420 m would increase the physics reach for forward and diffractive physics, notably with respect to triggering and with respect to the acceptance for centrally produced mass states of higher values. A suitable location is at ±220 m from the ATLAS or CMS IP. At nominal LHC optics, detectors there provide an acceptance of 0.02 < \(\xi < 0.2\), i.e. quite complementary to the acceptance at ±420 m.

In CEP, the mass of the centrally produced system, \(M\), and the fractional momentum loss, \(\xi_1, \xi_2\), of the two protons are correlated via:

\[
M^2 = \xi_1 \xi_2 s,
\]

where \(\sqrt{s} = 14\) TeV at the LHC. This translates into a minimum observable mass of about 30 GeV, when the protons are seen in the 420 m detectors on each side. For masses above about 80 GeV, a marked increase in the efficiency results from events with asymmetric \(\xi\) values, where one proton is observed at 420 m and the other at 220 m. At \(M = 200\) GeV, for example, 420+420 tags limit the selection efficiency to about 10\%, while it is almost 90\% for 420+220 tags.\(^5\)

Preliminary Monte-Carlo studies indicate for CEP of a Higgs boson that the achievable mass resolution with 420+220 tag varies between less than 3 GeV (3.5 GeV) for ATLAS (CMS) at a Higgs mass of 120 GeV, and less than 2.5 GeV (3 GeV) for ATLAS (CMS) at a Higgs mass of 200 GeV.

The 420 m location is too far away for signals to be processed within the first level trigger (L1) latency at both ATLAS and CMS. Hence, events with protons tagged at 420 m need to be triggered either with the central detector alone or with near-beam detectors closer to the IP.

In the case of CEP of a Higgs boson of 120 GeV mass decaying into two b-jets, triggering with central detector conditions alone is only possible with high \(p_T\) muons. About
10% of signal events are accepted by the L1 muon trigger stream. The L1 thresholds foreseen for dijets are generally too high. Adding a L1 trigger stream that combines a dijet condition with requiring a tag on one side at 220 m makes it possible to lower the dijet L1 thresholds sufficiently to retain about 10% of the signal events, while the output rate stays within the L1 bandwidth limits for luminosities up to $2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$.\(^6\)

The option of placing near-beam detectors at $\pm 220$ m from the ATLAS IP, which would extend the ATLAS luminosity detector program at 240 m, is currently under investigation by several ATLAS groups. Near-beam detectors at $\pm 220$ m from the CMS IP are foreseen as part of the TOTEM experiment. The trigger and DAQ systems of TOTEM will be integrated with those of CMS such that joint data taking will be possible. The two collaborations are in the process of defining a joint diffractive and forward physics program.\(^7\) The TOTEM Silicon detectors are expected to withstand the order of only 1 fb\(^{-1}\) of integrated luminosity. In order to use detectors at $\pm 220$ m in routine CMS data taking and at high luminosities, the TOTEM Silicon detectors will require replacement with more radiation hard detectors, an option that is currently under investigation.

5. Status of the FP420 R&D project

Design and prototyping of the FP420 detectors and their mechanical and electrical support systems are well underway. Engineering studies are well advanced to establish the necessary modifications to the existing cryogenic LHC elements at 420 m in order to accommodate detectors operated at room temperature. The remaining R&D work is fully funded till the middle of 2007.

The FP420 collaboration plans to provide a detailed Technical Design Proposal to the ATLAS and CMS collaborations in the first half of 2007. If ATLAS and/or CMS decide to build the detectors FP420 suggests, Technical Design Reports could be provided to the LHCC in 2007.

Installation of the proposed detectors could take place well after the LHC startup phase, during the first long break in the LHC running schedule, possibly in 2009/2010.

6. Conclusions

Measuring diffractive events at the LHC at luminosities where pile-up is present requires forward proton tagging capabilities. A rapidity gap based selection is no longer possible. The FP420 R&D project at CERN aims at providing the appropriate means: radiation-hard Silicon detectors located in the cold region of the LHC at $\pm 420$ m from the ATLAS or CMS IP, complemented with fast timing detectors to reject fake diffractive events with protons from coincidences with pile-up events. Ways of adding detectors at $\pm 220$ m from the IP for high-luminosity data taking are under study and discussion in ATLAS, CMS and TOTEM.

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