TOTEM forward measurements: exclusive central diffraction

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Abstract
In this contribution, we present a first systematic study of the precision of the momentum measurement of protons produced in the central exclusive diffractive processes, $pp \rightarrow p + X + p$, as well as the accuracy of the reconstructed mass for particle state X based on these proton measurements. The scattered protons are traced along the LHC beam line using the nominal LHC optics, accounting for uncertainties related to beam transport and proton detection.

To search for and precisely measure new particle states X with masses below 200 GeV, additional leading proton detectors are required at about 420 m from the interaction point in addition to the already approved detectors. Using these additional detectors, a mass resolution of the order of 1 GeV can be achieved for masses beyond ~120 GeV.

1 Introduction

It has been recently suggested that the Higgs boson mass could be measured to an accuracy of $\mathcal{O}$(1 GeV) in the central exclusive diffractive process (CED) [1,2]:

$$pp \rightarrow p + H + p \tag{1}$$

In contrast to this, the direct measurement of the Higgs boson mass, based on the two final state b-jets in $H \rightarrow b\bar{b}$, is estimated to yield a precision of $\mathcal{O}$(10 GeV). The precise reconstruction of the centrally produced system X, i.e. the Higgs mass in Eq. 1, is based on the four-momenta of the incoming ($p_{1,2}$) and scattered ($p'_{1,2}$) protons and since the two scattered protons are expected to have small transverse momenta, the following approximation for the mass of the centrally produced system can be made:

$$M^2 = (p_1 + p_2 - p'_1 - p'_2)^2 \approx \xi_1 \xi_2 s\,, \tag{2}$$

where $\xi_{1,2} = 1 - |\vec{p}\,'_{1,2}|/|\vec{p}_{1,2}|$ denote the momentum loss fractions of the two scattered protons.

The acceptance for forward leading protons for nominal LHC runs ($\beta^* \sim$ 0.5 m) is described in detail elsewhere (see [3]). This contribution focuses on the CED process and the precision with which the proton momenta and the mass of the centrally produced system can be reconstructed.

2 Leading proton uncertainties and transport

The study is done in multiple steps, which include the event generation (ExHuME [4] or PHOJET [5]), simulation of the interaction point (IP) region, tracking of the protons through the LHC beam line, a detector simulation and a proton momentum reconstruction algorithm using the detector information [6]. The following beam related uncertainties are inputs to the study[1]:

- pp interaction region width: $\sigma_{x,y}$ = 16 μm, σ_z = 5 cm,
- beam angular divergence: $\Theta_{x,y}$ = 30 μrad

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[1]The reference system (x, y, z) used in the study corresponds to the reference orbit in the accelerator; the z-axis is tangent to the orbit and positive in the beam direction; the x-axis (horizontal) is negative toward the center of the ring.

– beam energy spread: $1.1 \cdot 10^{-4}$.

Concerning the detector response, only the horizontal plane is considered with the following inputs:

– The detector is assumed to be fully efficient at a distance $10\sigma_x(z)$ + 0.5 mm from the beam center[2], where $\sigma_x(z)$ is the horizontal beam width at distance z. The second term takes into account the distance from the bottom of the vacuum window to the edge of the fully sensitive detector area.
– For the protons within the fully sensitive detector area, a position reconstruction uncertainty is introduced by smearing the hit coordinates according to a Gaussian distribution with a σ of 10 μm.
– The uncertainty due to the beam position knowledge at each detector location is accounted for by smearing the hit coordinates by a correlated Gaussian distribution with a σ of 5 μm.

The transverse displacement $(x(z), y(z))$ of a scattered proton at a distance z from the IP is determined by tracing the proton along the LHC beam line using the MAD program [7]. The optics layout version 6.2 for nominal LHC runs (β^* = 0.5 m) with a 150 μrad horizontal crossing angle is used [8]. Although the study was carried out for CMS/TOTEM (IP5), the results should be equally valid for ATLAS (IP1).

3 Proton momentum reconstruction

The x-coordinate of the proton observed at any given location along the beam line, depends on three initial parameters of the scattered proton: its fractional momentum loss, ξ, its initial horizontal scattering angle, Θ_x^*, and its horizontal position of origin, x^*, at the IP. Consequently, more than one x-measurement of a particular proton is needed to constrain its parameters. In the procedure chosen, two x-measurements from a detector doublet are used to determine ξ and Θ_x^*, neglecting the x^* dependence. The effect of the x^* on the reconstructed proton momentum will be treated as an independent source of uncertainty.

To obtain a large acceptance in ξ, the following two detector locations, each consisting of a doublet of proton detectors, are chosen based on the LHC optics layout:

– 215 and 225 meters from IP5 ("215 m location"), and
– 420 and 430 meters from IP5 ("420 m location").

The 215 m location corresponds to a TOTEM approved Roman Pot location [9], while the 420 m location in the cryogenic section of the accelerator will require special design and further investigation.

Each detector doublet yields two observables, which are related to the horizontal offset and angle with respect to the beam axis. The ξ dependence of these observables has been derived by fitting a functional form to the simulated average values of ξ, as a function of the values of the two observables [6].

4 Acceptance and resolution on ξ and mass

The ξ and t acceptance of protons moving in the clockwise and counter-clockwise directions are slightly different due to differences in the optical functions, for details see [3]. As a summary: a proton from the CED process is seen when its ξ is between 0.025 (0.002) and 0.20 (0.015) for the 215 (420) location.

The relative resolution on ξ, $\Delta\xi/\xi = (\xi - \xi_{rec})/\xi$ as a function of ξ for protons produced in the CED process and seen in either the 215 m or the 420 m location is shown in Fig. 1 for protons circulating in the LHC both in the clockwise and counter-clockwise direction. Included are the separate effects from the uncertainty of the transverse IP position, the resolution of the proton detector, the beam energy uncertainty, the beam angular divergence at the IP, and the beam position resolution at the proton detector.

At both detector locations, major contributors to the over-all ξ resolution are the uncertainty of the transverse IP position and the resolution of the proton detector. In addition to these two uncertainties, the beam energy uncertainty contributes significantly to the resolution at the 420 m location.

[2]The LHC collimators extend to $6\sigma_x(z)$. The closest safe position can be assumed to lay anywhere between 10 and 15.

The acceptance as function of the mass of the centrally produced system is shown in Fig. 2a. Each leading proton is required to be within the acceptance of either the 215 or 420 m locations. Independently shown is the case (sub-set of above) where both protons are within the acceptance of the 420 m locations. In the mass range shown, there is no acceptance for detecting both protons at the 215 m location. The ξ_1-ξ_2 combinations result from the gluon density function in the proton and the mass of the centrally produced system (see Eq. 2). The ExHuME generator favours a harder gluon distribution than that of PHOJET. Thus, the Higgses are produced more centrally. This yields a higher acceptance for ExHuME.

The resolution effects of the two scattered protons are, in general, uncorrelated from each other. The only correlation comes from the production point, whose transverse component is determined by the rms spread of the beam at the IP and by an independent measurement using the Higgs decay products [10]. It can be determined to 10 μm or better, and therefore for the mass resolution of the centrally produced system, a 10 μm uncertainty on the transverse IP position is used. For the mass resolution, all other uncertainties are assumed to be uncorrelated between the two protons.

The mass resolutions for events with protons within the acceptance of the 420 m location on both sides, and for events with one proton within the acceptance of the 215 m location on one side and the other proton within the acceptance of the 420 m location on the other side (labelled "asym." in the figure) are shown as a function of the mass of the centrally produced system in Fig. 2b. The values quoted in the figure are based on Gaussian fits to the reconstructed mass distributions. The two-proton acceptance requirement imposes a restriction on the allowed ξ_1-ξ_2 combinations; as a result the mass resolutions obtained with ExHuME and PHOJET are very similar.

5 Conclusions

The first comprehensive study of the CED process at the LHC is reported. The study is based on detailed simulations along the LHC beam line of the diffractively scattered protons, accounting for the known sources of uncertainties related to beam transport and proton detection. The feasibility of measuring such events during nominal LHC runs for masses of the central system, X, below $\sim$200 GeV is addressed.

On the basis of this study, it is concluded that with an additional pair of leading proton detectors at $\pm$420 m from the interaction point, a Higgs boson with a mass of 120–180 GeV could be measured with a mass resolution of the order of 1 GeV. Such additional proton detectors would also enable large statistics of pure gluon jets to be collected, thereby turning the LHC into a gluon factory.

References

[1] A. De Roeck, V.A. Khoze, A.D. Martin, R. Orava and M.G. Ryskin, Eur. Phys. J. **C35**, 391 (2002).

[2] J. Kalliopuska, T. Mäki, N. Marola, R. Orava, K. Österberg, M. Ottela and S. Tapprogge, **HIP-2003-11/EXP** (2003).

[3] V. Avati and K. Österberg, "TOTEM forward measurements: leading proton acceptance", these proceedings.

[4] J. Monk and A. Pilkington, **hep-ph/0502077** (2005).

[5] R. Engel, Phys. Rev. **D51**, 3220 (1995).

[6] T. Mäki, Master thesis: "Exclusive production of Higgs boson at LHC collider: Higgs mass measurement via leading proton detection", Helsinki University of Technology (2003).

[7] The MAD program, Methodical Accelerator Design, `http://www.cern.ch/mad`.

[8] Lattice & Optics, `http://lhc-new-homepage.web.cern.ch/lhc-new-homepage/`.

[9] The TOTEM collaboration, TOTEM Technical Design Report, **CERN-LHCC-2004-002** (2004).

[10] P. Vanlaer, Hadron Collider Physics Conference, Les Diablerets, Switzerland (2005).

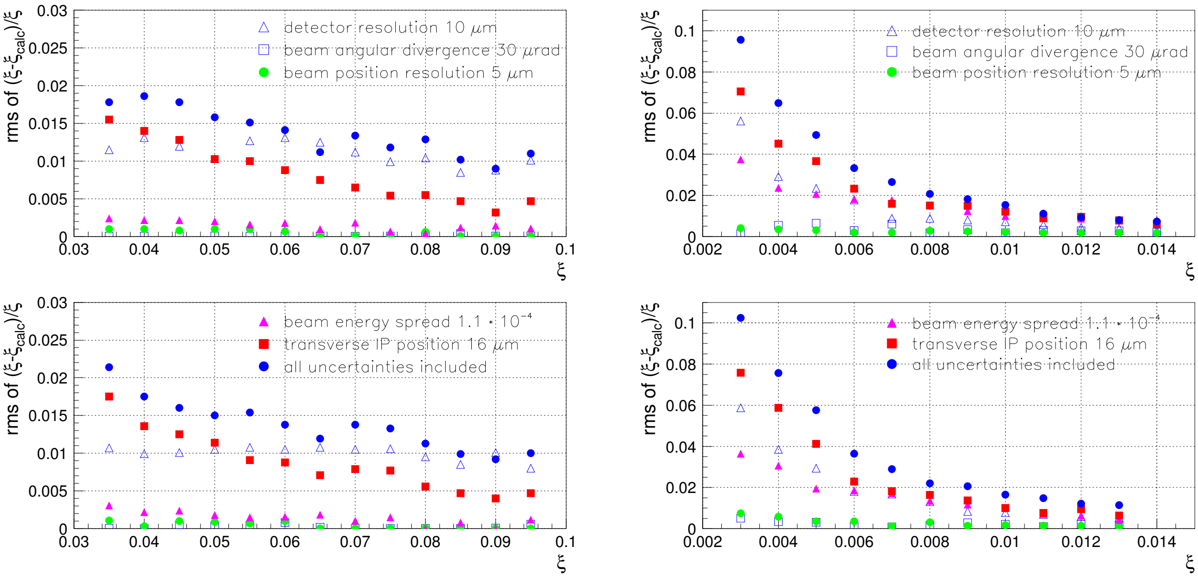

Fig. 1: Summary of all effects studied contributing to the over-all ξ resolution for the 215 m (left) and 420 m location (right). The upper and lower plots are for protons circulating clockwise and counter-clockwise along the LHC beam line, respectively. The t values of the protons used for each ξ bin is similar to the t distribution originating from central exclusive diffraction.

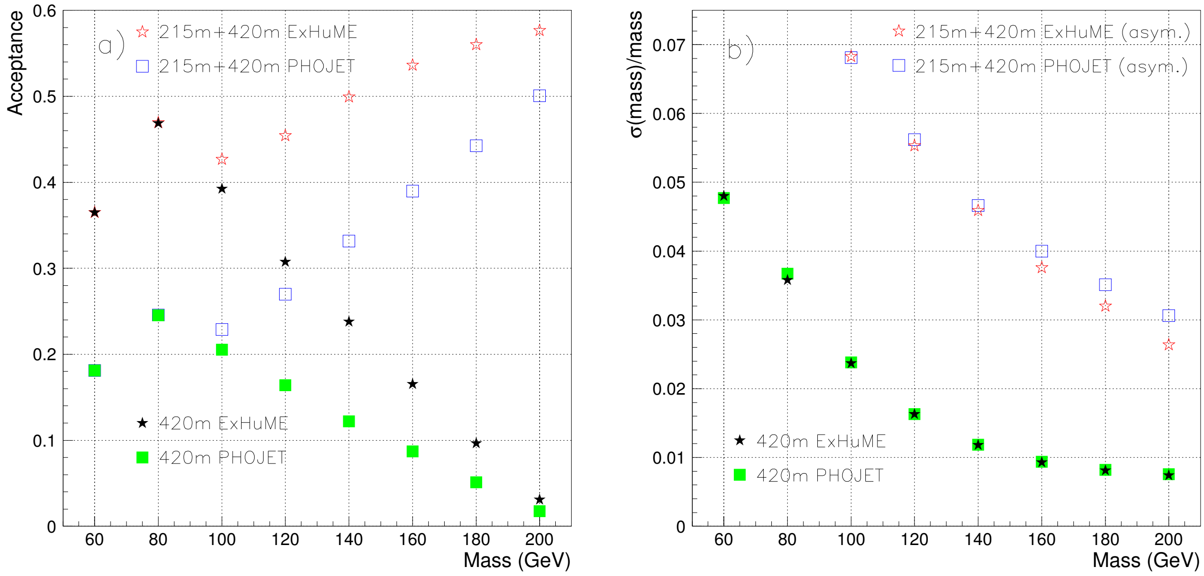

Fig. 2: a) Mass acceptance for events with protons within the acceptance of the 420 m location on each side of the interaction point ("420m"); and for events with protons within the combined acceptance of the 215 m and 420 m location on each side of the interaction point ("215m+420m"). b) Mass resolution for events with protons within the acceptance of the 420 m location on each side of the interaction point ("420m"); and for events with one proton within the acceptance of the 215 m location on one side of the interaction point and the other proton within the acceptance of the 420 m location on the other side ("215m+420m (asym.)"). ExHuME or PHOJET denotes the generator used for producing the central exclusive diffractive events.