Detecting leading protons in exclusive central diffractive processes at the LHC

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Abstract

The central exclusive diffractive process, $p\,p \rightarrow p + X + p$, provides a complementary way to scan for possible new particle states, X, such as the Higgs boson at the LHC. By detecting both leading protons produced in the process, one can reconstruct the mass of the central system with high precision as well as investigate its properties such as the spin-parity. This approach augments the standard methods for new particle searches at the LHC and also makes possible unique precision studies of gluons.

In this paper, the first systematic analysis of the precision of the measurement of the leading proton momentum and the accuracy of the reconstructed mass is presented. The analysis is done by tracking the scattered protons along the LHC beam line using the nominal $\beta^* = 0.5$ m LHC optics, accounting for uncertainties related to beam transport, and the detection of the scattered protons.

To search for and precisely measure new particles states 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 ~100 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 [1]:

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

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 range of predictions for the production cross section of the Standard Model Higgs boson through the exclusive process of Eq. 1 at LHC energies is constrained by the inclusive central diffractive di-jet measurements at the Tevatron [2], yielding 1-10 fb for the SM Higgs of mass around 120 GeV [3]. A recent analysis of the process based on perturbative QCD calculations including uncertainties in background and estimates of the rapidity gap survival probability gives a cross section prediction of 3 fb for the SM Higgs boson with the mass of 120 GeV [4].

In this analysis, the mass of the centrally produced system M, i.e. the Higgs mass in Eq. 1, is independently reconstructed from the four-momenta of the incoming ($p_{1,2}$) and scattered ($p'_{1,2}$) proton four-momenta as [5]:

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

The two scattered protons are expected to have small transverse momenta, therefore the mass of the central system can be approximated as:

$$M^2 \approx \xi_1 \xi_2 s, \tag{3}$$

where $\xi_{1,2} = 1 - |\vec{p}\,'_{1,2}|/|\vec{p}_{1,2}|$ denote the momentum loss fractions of the two scattered protons. In the following, the analysis and result of acceptances and accuracies in detecting the pair of leading protons and in reconstructing the mass of the central system in the process of Eq. 1 is presented.

2 Inputs to the analysis

The analysis employs a chain of simulation programs, which includes the event generation (ExHuME [6] or PHOJET [7]), simulation of the interaction point (IP) region, the tracking of protons through the LHC beam line, a detector simulation package and a proton momentum reconstruction algorithm using the detector information [8].

The following beam related uncertainties are inputs to the simulation programs[1]:

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

[1]The reference system (x, y, z) 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: $1.1 \cdot 10^{-4}$.

The IP position can be independently measured using the Higgs decay products to an accuracy of $\sigma_{x,y} = 10$ μm and $\sigma_z = 15$ μm [9]. Variations of the IP position in the longitudinal (beam) direction has a negligible effect on the reconstruction precision.

Concerning the detector response, only the horizontal scattering plane is considered and the following input parameters are assumed:

- The detector is assumed to be 100% active at a distance Δ from the beam center [10], where $\Delta = \mathrm{k}\sigma_x(z) + \delta$, and k = 10 describes the number of standard deviations of beam width, $\sigma_x(z)$, that is required as a safety margin for each detector location[2]. The physical edge of the detector is assumed to be at a distance of $\delta = 500$ μm from the area of the detector that is 100 % active.

- For the protons within the fiducial area of a detector, the reconstructed position uncertainty is introduced by smearing the predicted 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.

3 Leading proton transport calculation

The transverse displacement $(x(z), y(z))$ of a scattered proton is given by its coordinates $(x^*, y^*, 0)$ and scattering angles $\Theta^*_{x,y}$ at the IP:

$$
\begin{aligned}
y(z) &= v_y(z) \cdot y^* + L_y^{eff}(z) \cdot \Theta_y^* \\
x(z) &= v_x(z) \cdot x^* + L_x^{eff}(z) \cdot \Theta_x^* + \xi \cdot D(z)
\end{aligned}
\tag{4}
$$

where $L^{eff}_{x,y}(z)$ is the effective length, $v_{x,y}(z)$ the magnification and $D(z)$ the dispersion. The angles $\Theta^*_{x,y}$ are physical scattering angles with the respect to the beam direction and include the beam angular divergence. The protons are traced along the LHC beam line using the MAD (Methodical Accelerator Design) program [11] with the parameters corresponding to LHC optics layout version 6.2 ($\beta^* = 0.5$ m) [12]. Although the analysis was carried out for CMS/TOTEM (IP5), the results should be equally valid for ATLAS (IP1). At every accelerator element, each proton that remains within the beam pipe aperture is recorded.

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

4 Proton momentum reconstruction

The observed proton x-coordinate, at any given location along the beam line, depends on three intial parameters of the scattered proton: its fractional momentum loss, ξ, its initial scattering angle, Θ_x^*, and its position of origin, x^*, at the IP (see Eq. 4). Consequently, more than one x-measurement of a particular proton is needed to constrain its parameters. A procedure was choosen where two x-measurements from a detector doublet are used to determine ξ and Θ_x^* neglecting the x^* dependence. The effect of the transverse vertex position on the reconstructed proton momentum will be treated as an independent source of uncertainty.

To extend the acceptance in proton fractional momentum loss, two detector locations are chosen. Based on the LHC beam optics layout and the already approved instrumentation [13], the following two detector locations, each consisting of a doublet of proton detectors, are:

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

The second location is in the cryogenic section of the machine and requires special design consideration.

Each detector doublet (i=1,2) yields two observables: the average horizontal proton coordinate with respect to the beam axis, $< x >_i = (x_{1,i} + x_{2,i})/2$, and the difference $\Delta x_i = x_{2,i} - x_{1,i} = \Theta_{ix} \Delta z_i$ for the two detectors in a doublet. The measured values of $< x >_i$ and Δx_i are related to the proton fractional momentum loss, ξ, and the scattering angle Θ_x^* at the IP. To obtain ξ and Θ_x^* from the measured values of $< x >_i$ and Δx_i in a given detector doublet, an unfolding procedure is required. First, a linear coordinate transformation is defined, that causes the $< x >_i$-Δx_i pairs to be more uniformly spread. Then to reconstruct the proton fractional momentum loss, the dependence of ξ on these transformed coordinates is parametrized by fitting a function to the observed average ξ values in the plane of the transformed coordinates [8].

The parameters for the unfolding were determined in a simulation, where no detector or beam related uncertainties were applied. The relative error of the resulting proton fractional momentum loss determination is found to be within 0.2% of nominal values over the whole ξ-range that is within the acceptance of each detector location.

Table 1: Leading proton acceptances in ξ of greater than 50% for the two detector locations.

detector location	clockwise moving protons	counter-clockwise moving protons
215 m	$0.024 \leq \xi \leq 0.20$	$0.026 \leq \xi \leq 0.20$
420 m	$0.0022 \leq \xi \leq 0.017$	$0.0018 \leq \xi \leq 0.013$

5 Acceptances and resolutions

5.1 Acceptances

The ξ acceptances of protons moving in the clockwise and counter-clockwise directions along the LHC beam line are shown in Fig. 1 for the two detector locations; corresponding ξ-ranges having efficiencies greater than 50% are given in Table 1.

5.2 Resolution

The relative resolution on ξ, $\Delta\xi/\xi = (\xi - \xi_{rec})/\xi$ as a function of ξ for protons circulating in the clockwise and counter-clockwise directions is shown in Figs. 2 and 3, for the 215 and 420 m locations, respectively. 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. Table 2 gives the range for the relative resolution on ξ obtained from all the studied sources of uncertainty for both detector locations.

5.3 Acceptance and resolution for the centrally produced system

The acceptance as function of the mass of the centrally produced system is shown in Fig. 4. Each leading proton is required to be within the acceptance of either the 215 or 420 m locations. Independently shown is the case (subset 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. Two event generators are considered, ExHuME and PHOJET.

Table 2: Summary of the relative resolution on ξ due to various uncertainties at the two detector locations.

uncertainty	215 m	420 m
transverse IP location	0.5 - 1.8 %	0.6 - 7.5 %
proton detector resolution	0.8 - 1.4 %	0.3 - 6.0 %
beam energy	$<$ 0.5 %	0.5 - 4.0 %
beam angular divergence	$<$ 0.5 %	$<$ 0.5 %
beam position at proton detector	$<$ 0.5 %	$<$ 0.5 %

The ξ_1-ξ_2 combinations result from the initial state gluon density functions in the proton and the mass of the centrally produced system (see Eq. 3). The ExHuME generator [6], which is based on the perturbative QCD calculation of Ref. [4] favours a harder gluon distribution than that in PHOJET and thus the produced Higgses are more central. This yields a higher acceptance for ExHuME than for PHOJET for the same mass.

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 [9]. 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. 5. 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.

The combined mass resolution for events with protons within the acceptance of either the 215 m or the 420 m location on either side would be a sum of two gaussians whose widths are shown in Fig. 5; since these widths are so different, no combined mass resolution for this class of events is quoted.

6 Conclusions

The first comprehensive analysis of the central exclusive diffractive (CED) process, $pp \rightarrow p + X + p$, at the LHC is reported. The study is based on detailed simulations of diffractively scattered protons along the LHC ring, while accounting for the known sources of uncertainties related to the interaction vertex, beam angular divergence, energy spread and detector techniques. The feasibility of recording CED processes during nominal LHC operation ($\beta^* = 0.5$m) for central masses below $\sim$200 GeV is addressed. Further studies on fast triggering of the CED events, and on detector alignement need to be made.

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 $\sim$140 GeV could be measured with a mass resolution of the order of 1 GeV. Such additional proton detectors would also enable a large statistics of pure gluon jets to be collected thereby using the LHC as a gluon factory.

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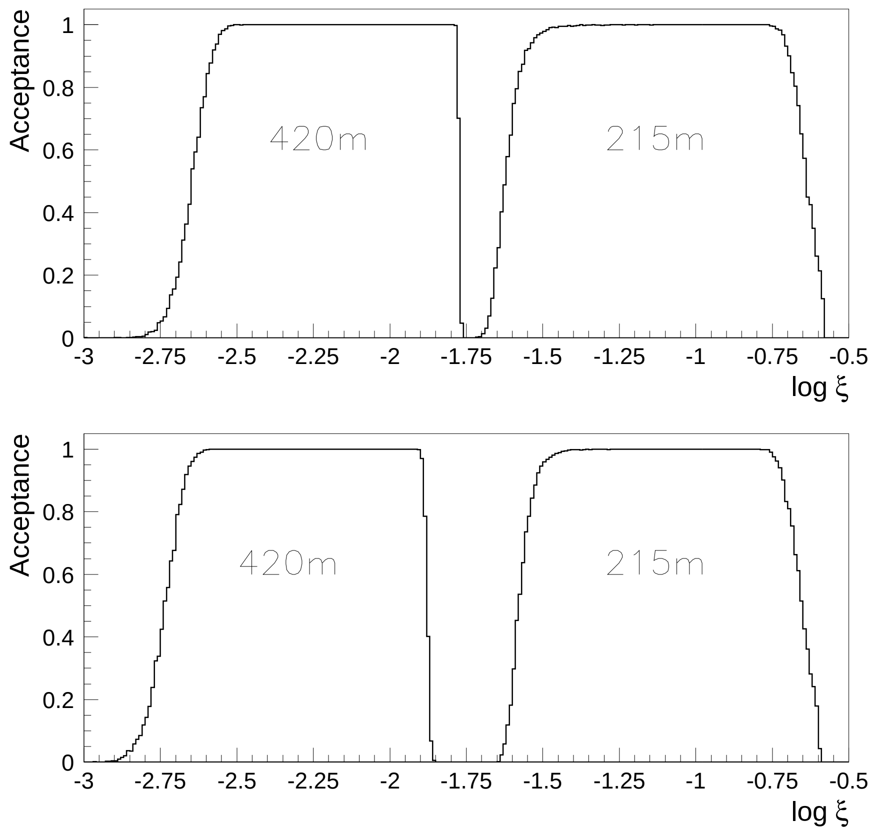

Figure 1: Proton momentum loss, ξ, acceptance for the set of detectors at 420 & 430 m ("420m") and at 215 & 225 m ("215m") from the interaction point. The upper plot is for protons circulating clockwise and the lower one for protons circulating counter-clockwise along the LHC beam line.

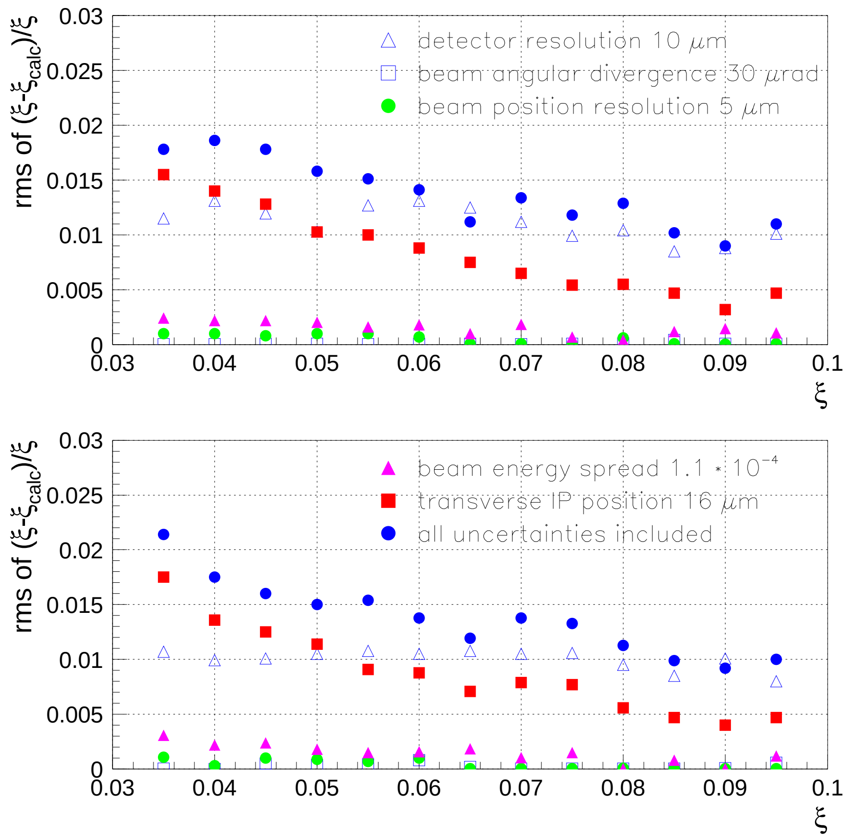

Figure 2: Summary of all effects studied contributing to the over-all ξ resolution for the set of detectors at 215 & 225 m from the interaction point. The upper plot is for protons circulating clockwise and the lower one for protons circulating counter-clockwise along the LHC beam line.

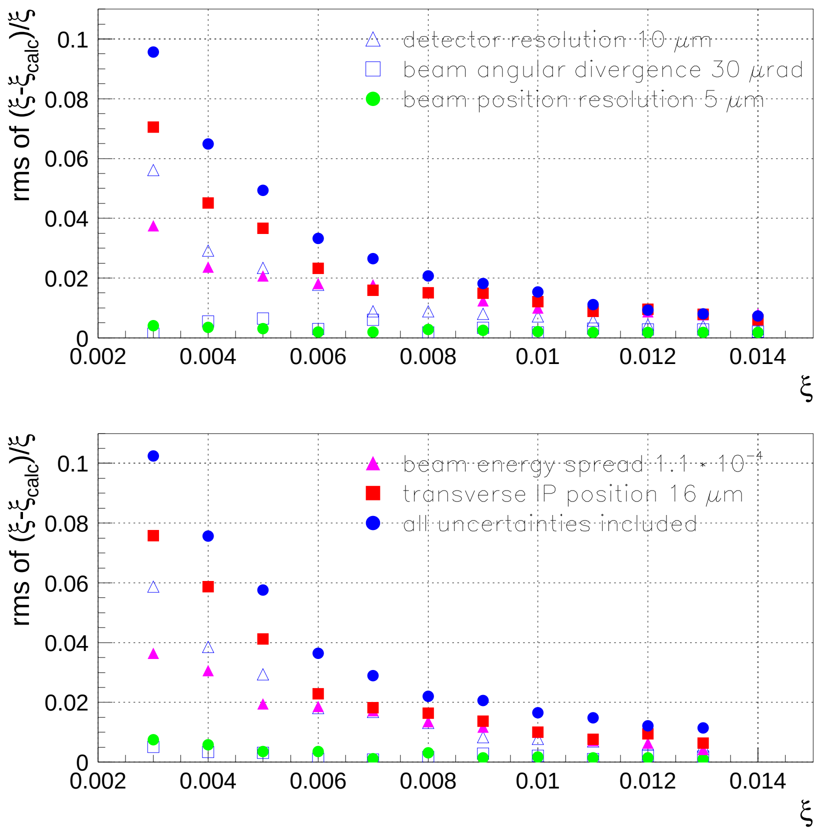

Figure 3: Summary of all effects studied contributing to the over-all ξ resolution for the set of detectors at 420 & 430 m from the interaction point. The upper plot is for protons circulating clockwise and the lower one for protons circulating counter-clockwise along the LHC beam line.

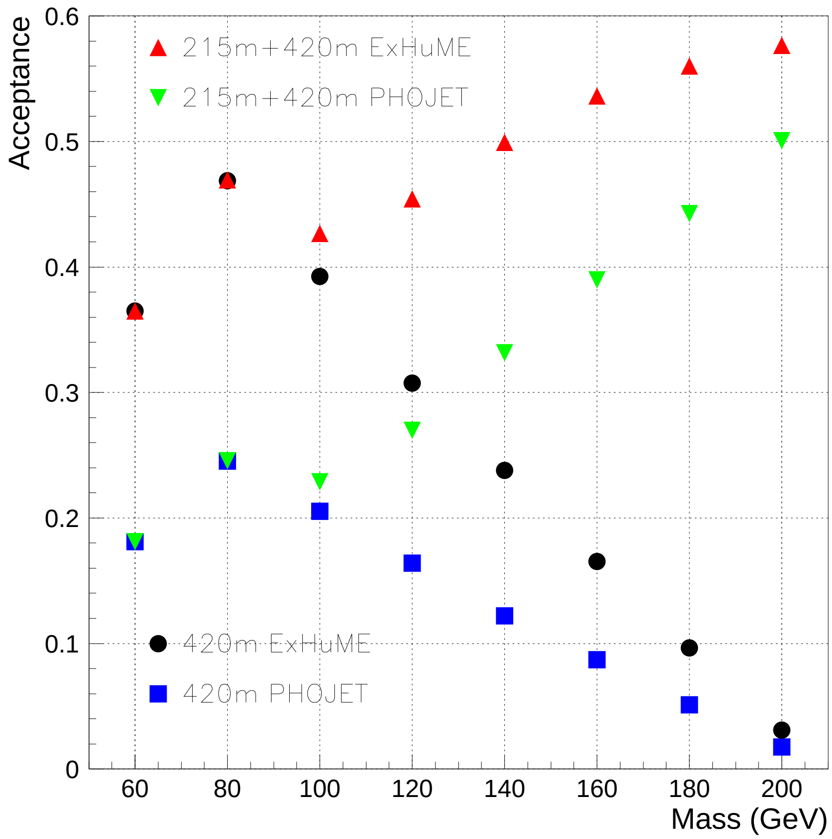

Figure 4: Mass acceptance for events with protons within the acceptance of a set of detectors at 420 & 430 m on both sides of the interaction point (”420m”); and for events with protons within the combined acceptance of the two sets of detectors at 215 & 225 m and 420 & 430 m on both sides of the interaction point (”215m+420 m”). ExHuME or PHOJET denotes the event generator used.

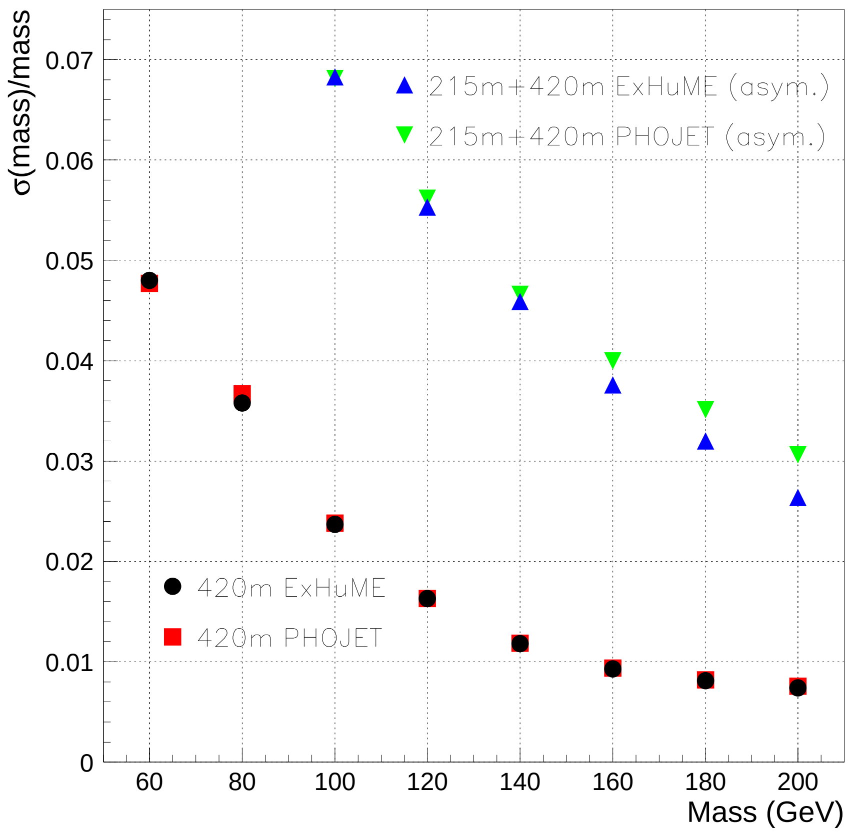

Figure 5: Mass resolution for events with protons within the acceptance of the set of detectors at 420 & 430 m on both sides of the interaction point ("420m"); and for events with one proton within the acceptance of the set of detectors at 215 & 225 m on one side of the interaction point and the other proton within the acceptance of the set of detectors at 420 & 430 m on the other side ("215m+420 m (asym.)"). ExHuME or PHOJET denotes the event generator used.