Physics with forward FP420/FP220 tagging systems.

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Abstract
We discuss selected physics topics in relation to proposals to upgrade the ATLAS and CMS detectors by the installation of forward silicon detector systems close to the beam line at distances of approximately 220 m and 420 m from the respective interaction points. The physics motivation and some of the aspects of the apparatus and its performance are briefly described.

1 Introduction

An important part of the physics programme at HERA has been the measurement of diffractive processes, in which the proton exchanges a colourless object, commonly referred to as the pomeron, with the incoming virtual photon. Two types of process here are of particular interest: the production of exclusive final states such as vector mesons, and hard processes in which the photon interacts with partonic components of the structure of the pomeron, which can be modelled in various ways. The hard processes can be induced by photons of varying virtuality, ranging from quasi-real photons to highly virtual photons that give deep inelastic scattering off the partons associated with the pomeron.

In a similar way, high energy photon-photon physics has been exploited at LEP, with processes that can be categorised in a similar manner. There is also an active program of diffractive physics at the Tevatron.

At the LHC, much higher energies are available than at HERA and LEP, enabling these physics programmes to be extended into areas where new physics can be discovered or studied. This is the subject of the present section. We outline first the physical setup that is envisaged, in which new detector systems will be installed close to the beam line at suitable locations downstream of the interaction points. We then present a summary of some of the new processes that should become open to investigation, and finally return to discuss the physical apparatus in further detail with an outline of its capabilities.

2 The basic proposal for forward detectors

Figure 1 illustrates the configuration of the LHC beamline on one side of an interaction point, showing the separate incoming and outgoing beams and the form of the particle trajectories on entering and leaving the interaction region. At distances greater than 260 m, the beam is dominated by the main bending magnets and is in the form of an irregular arc, which has been straightened

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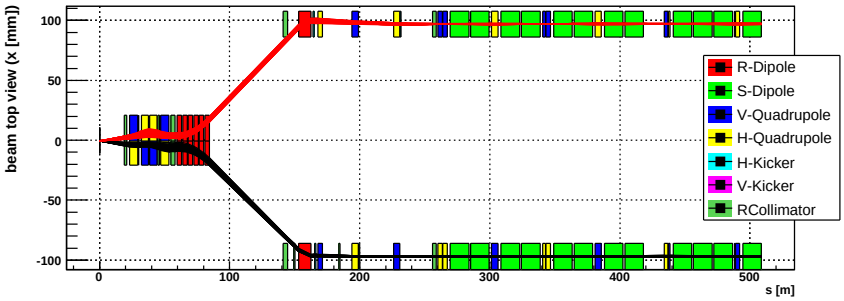

Fig. 1: Schematic representation of the LHC beamline on one side of an intersection point. The ATLAS or CMS detector is located at the origin of coordinates, and the incoming and outgoing beamlines are indicated, with the main bends straightened out for illustrative convenience.

out in the Figure. At two regions, namely around 220 m and 420 m from the interaction point, there are intervals in the beamline that are not occupied by magnets. Each of these regions provides approximately ten metres of clear space within which physics detectors can be stationed. It is proposed to install sets of silicon detectors in these regions, allowing them to be positioned as closely as possible to the outgoing beam. These detectors will detect diffractively scattered outgoing protons.

One or both protons in a pp collision may be scattered diffractively. In such a case, the fractional energy loss ξ suffered by the proton is typically small, as is the angle of scatter. These protons will continue to travel along the beam line, but in due course they will no longer be contained by the beam optics and will be bent either into a collimator or out of the beam line altogether. It is found that protons that have lost a few tens of GeV in the initial collision emerge out of the beam typically in the 420 m regions, and those that have lost a few hundreds of GeV emerge in the 220 m regions. By installing detector systems in these regions, we can identify the double diffractive production of exclusive centrally produced states whose mass is above a minimum value of the order of 100 GeV/c^2, provided that the state itself records a suitable signature in the central detector allowing its identification. Figure 2 illustrates the kind of process that we are interested in for the case of a Higgs particle denoted as H. A measurement of the energies of the outgoing protons makes possible a good determination of the mass of the centrally produced object, and in most cases this has better resolution than the measurement made in the central detector.

3 Central exclusive production

The central exclusive production of a Standard Model Higgs at the LHC has been the subject of a number of calculations. The cross section is strongly dependent on the gluon distributions that are assumed in the proton, and the detected cross section depends on the ability to trigger the process in the apparatus. Here we are faced with the difficulty that the present trigger electronics in ATLAS and CMS do not allow a first-level trigger to be based on the detection of a proton at 420 m, since the signal arrives too late. This forces the detection of a 120 GeV/c^2 central state to

be based on central detector triggers, which are not highly efficient in the case of a SM Higgs at this mass. In our favour is that the background of quark-antiquark jets is suppressed dynamically relative to the signal by the $J_z = 0$ selection rule [1]. An exclusive double-diffractively produced state is constrained to have $J^{PC} = 0^{++}$, so that if a Higgs or other particle is seen at all in this process, we have a good determination of its quantum numbers which may be hard to determine unambiguously by central detector measurements alone.

Recently the CDF Collaboration has observed for the first time the existence of central exclusive dijet production in hadronic collisions [2]. Exclusive production of the charmonium state χ_c has also been reported [3], with a cross section of the predicted magnitude. These are major milestones, since the central exclusive production of known final states can be used as "standard candles" to confirm mechanisms and extract cross sections with small model uncertainties. Establishing the potential experimental dijet background is an important item in the search for new particles such as the Higgs.

From Fig. 3 (left) it is clear that measurements of the proton structure at HERA and the Tevatron have a strong relevance to predicting the strength of a possible SM Higgs signal in double diffraction at LHC. With the set-up that is currently envisaged, the prospects seem rather marginal. However there are additional opportunities if the Higgs occurs within a supersymmetric framework. There are two particularly important parameters of the SUSY scenario, denoted as m_A and $\tan\beta$, within whose parameter space a number of the features of the theory can be illustrated. Figure 3 (right) illustrates the enhancements to the SM Higgs cross section that might be obtained for the lighter of the two neutral SUSY Higgs particles, denoted as h, and showing also some contours of different h masses, taken from Heinemeyer et al. [4].

On this basis, the quantity of LHC luminosity needed for 3-σ evidence and 5-σ discovery of neutral SUSY Higgs in the exclusive double-diffractive mode can be estimated, as illustrated for the heavier SUSY Higgs H in Fig. 4 [5]. Contour plots of this kind have been presented by these authors for the h and H in a variety of related situations. This gives improved hope of being able to make Higgs studies with forward detectors at the LHC, although there is no advance guarantee that the values of the SUSY parameters will be favourable and the integrated luminosity needed might be substantial.

More cleverly thought-out triggers and cuts may improve the situation. Figure 5 illustrates some studies carried out by Pilkington et al [6]. The mass of the central object has been reconstructed using modelled measurements of the forward proton trajectories at 420 m, with

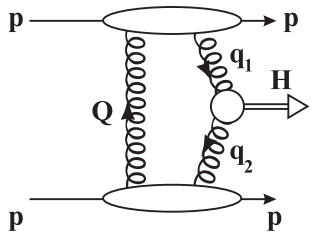

Fig. 2: Double diffractive production of a centrally produced object, denoted as H, by a colourless exchange modelled in terms of gluons.

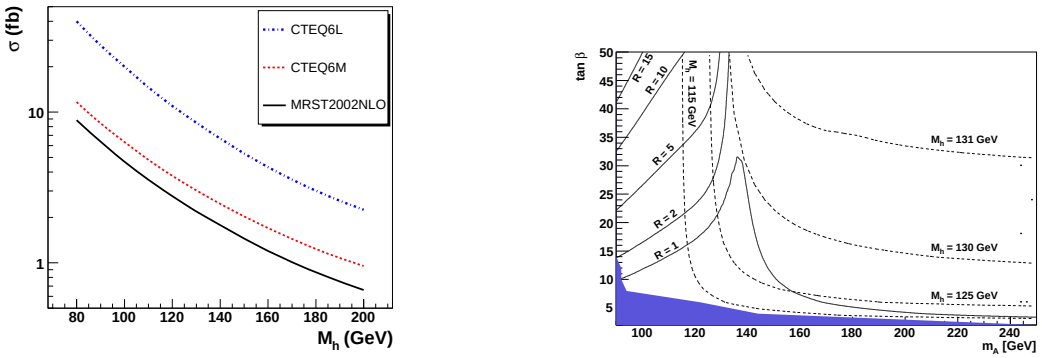

Fig. 3: Left: Variation of Higgs cross section with some parton models of the proton. Right: Contours for the ratio of signal events in the MSSM to those in the SM in the $h \to b\bar{b}$ channel in the m_A–$\tan\beta$ plane. The ratio is shown in the $M_h^{\max}$ benchmark scenario (with $\mu = +200$ GeV). The values of the mass of the light Higgs boson, M_h, are indicated by dashed contour lines. The CMS acceptance was approximately modelled.

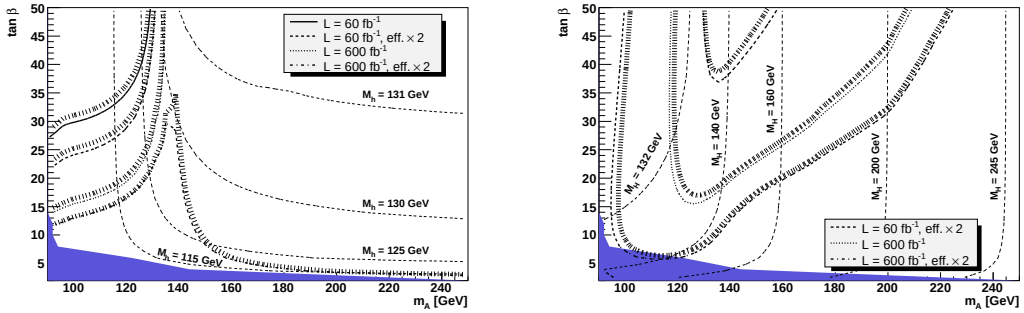

Fig. 4: Contours for 3-σ evidence (left) and 5-σ discovery (right) for the h and H SUSY Higgs in the scenario discussed in the text (S. Heinemeyer et al.)

estimated backgrounds from other processes included. During the first years of running, a measurement using 60 fb^{-1} seems a reasonable target and could produce evidence indicated by the first illustrated histogram. Higher luminosities will clearly assist, but will generate combinatorial backgrounds from overlapping events ("pile-up"). If these can be removed, as is envisaged, using precise timing measurements to isolate the event of interest, a signal might be seen giving a 5-σ discovery with 100 fb^{-1} of running.

Particular attention was given during the workshop to the study of event pile-up at the LHC (Taševský, Pilkington). By exploiting the difference between particle multiplicities in central exclusive and non-diffractive processes, a further reduction of the pile-up background may be possible. Here, only tracks from the primary vertex associated with the hard-scale event are relevant. Additional reduction factors of 10 to 100 may be possible; at present there are uncertainties here due to model dependence, soft underlying event tune dependence and track selection criteria.

4 Photoproduction processes.

TeV-energy protons are surprisingly efficient at radiating high energy photons. Single photoproduction off the second proton, and photon-photon processes are both of interest at LHC. Kinematically, photoproduction resembles diffractive scattering but with the tendency to a smaller transverse momentum transfer to the proton. The $\gamma\gamma$ cross sections are harder than the pomeron-pomeron processes, overtaking the latter in cross section at $W_{\gamma\gamma} \approx 1$ TeV. Since diffraction produces mainly gluon jets and photoproduction produces quark jets, there is little interference between the processes.

Single photoproduction will be of interest at the LHC in the production of electroweak particles. There are possibilities for the associated production of Higgs bosons and for the production of anomalous single top via FCNC. These processes are tagged by a single forward proton, but must be triggered and identified in the central detectors, and there will be potential difficulties at high luminosities since the use of timing to associate the forward protons with a central vertex requires two such forward protons. A number of generic cross sections are indicated in Fig. 6 (left), together with the forward detection system that will tag in different $W_{\gamma p}$ ranges.

The $\gamma\gamma$ process is capable of inducing the production of any type of charged particle-antiparticle pair. Of particular interest here is the possible production of charged SUSY particles, such as charginos and sleptons, whose signatures in the central detector will be high transverse energy leptons and missing energy carried by neutrinos or the lightest SUSY particle (LSP) if it is neutral. Figure 6 (right) shows cross sections for producing fermion and scalar charged particle pairs, compared to that for W^+W^- production, which is likely to be a very prolific background. ZZ production is possible only by anomalous couplings. The dimuon process is seen as good for the calibration of the forward detectors and even for LHC luminosity monitoring.

There are many possible SUSY mass scenarios. The possibilities that have been studied here are in terms of the so-called LM1 scenario, which involves a light LSP and light sleptons and charginos. This type of scenario will give the most favourable set of cross sections. The most natural variable to plot in order to separate SUSY signals from WW background would be the $W_{\gamma\gamma}$ value reconstructed from the forward protons (Fig. 7a)) However the background is

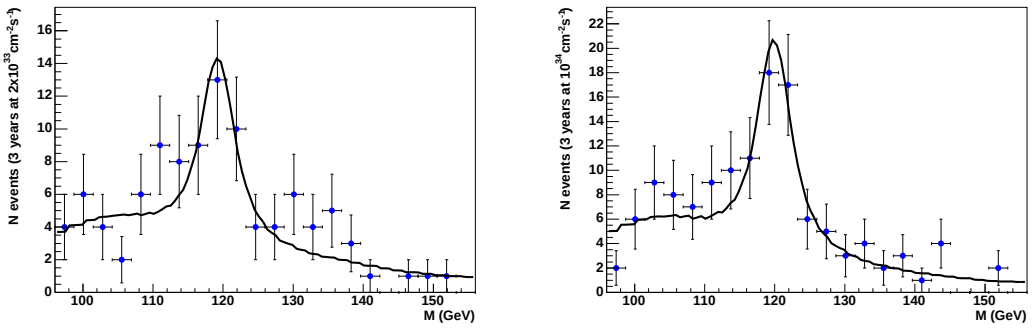

Fig. 5: Example analyses of an MSSM SUSY signal calculated with $\tan\beta = 40$ and $m_A = 120$ GeV (A. Pilkington).

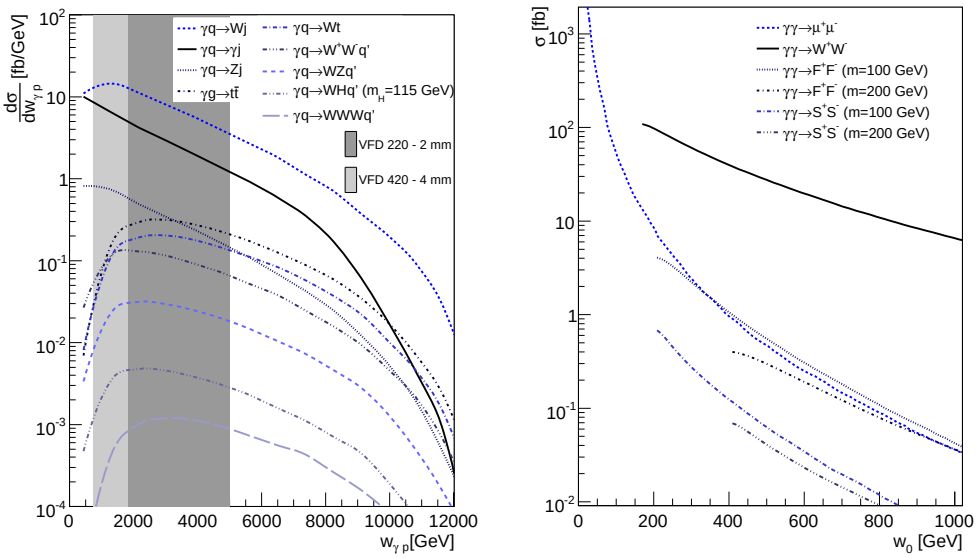

Fig. 6: Cross sections for various single photoproduction processes at LHC (left), as a function of photon-proton mass, and for various generic double photoproduction processes (right).

much more tractable when the variable $W_{miss} = \sqrt{E^2_{miss} - P^2_{miss}}$ is plotted (Fig. 7b), where the missing energy and momentum are calculated from the forward protons and the kinematics of the observed final state particles. Combinations of $W_{\gamma\gamma}$ and W_{miss} give even more power (Fig. 7c) and can generate a distribution (Fig. 7d) that might give a 5-σ discovery with only 25 fb^{-1} of integrated luminosity.

5 Other physics processes

An intriguing example of completely new physics has been proposed by A. White in which a new SU(5) gauge theory obviates the need for a Higgs particle and gives remarkable experimental signatures for which pomeron physics may be an essential diagnostic tool [8]. An extended range of SUSY processes may also be accessible. One study made during this workshop has been the detection of pairs of long-lived gluinos in central exclusive processes [9]. Such particles can occur in split-SUSY models, where the sfermions have masses far above the TeV scale. The gluinos are lighter and therefore long lived, and may form bound states with gluons or quarks called R-hadrons. These will mimic the behaviour of muons and may be detected in muon chambers. For $300 fb^{-1}$ approximately 10 events are expected for gluino masses up to 350 GeV. The advantage of using proton detectors lies again in the excellent accuracy for the reconstruction of the mass of the centrally produced object. The forward detectors at 220m and 420 m give access to the wide range of masses that such particle pairs may have.

Present space permits no more than a brief mention of other items in the range of physics processes that will be made observable by the use of forward tagging systems at LHC. The work initiated at HERA on hard pomeron scattering and structure can be continued by means of

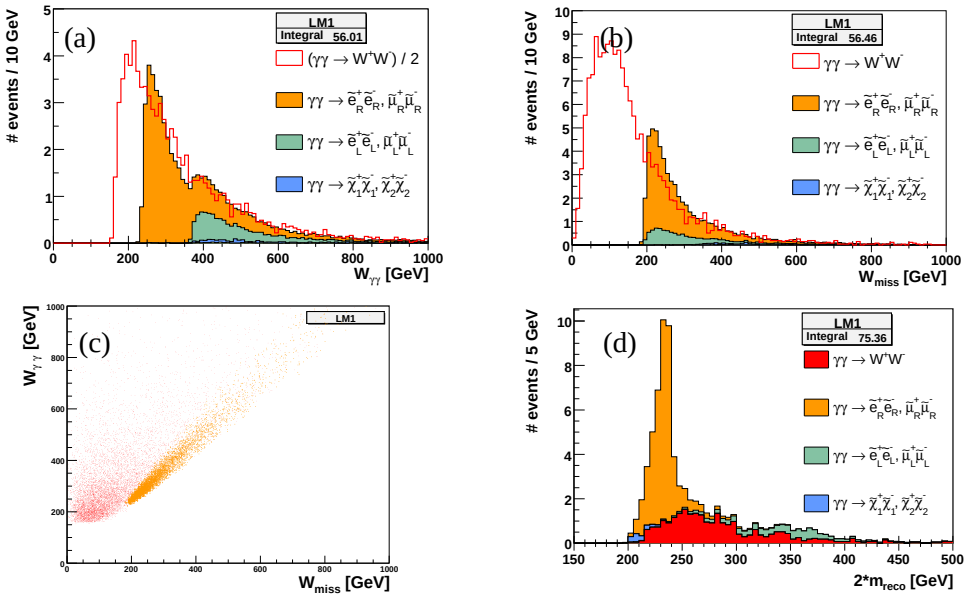

Fig. 7: Examples of the analysis of the double photoproduction of SUSY particles, as a function of the parameters $W_{\gamma\gamma}$ and W_{miss}, to illustrate a possible way to isolate a clean SUSY signal [7].

photon-pomeron and pomeron-pomeron processes. It should be noted that the $q\bar{q}$ final state is suppressed in the pomeron-pomeron process at low quark masses, assisting in the identification of potential new physics processes. There will be extended opportunities for further studies of the nature of the pomeron. In the early stages, at low LHC luminosities, the study of rapidity-gap survival will be interesting and important, generalised gluon distributions can be studied, and a variety of QCD effects can be investigated; a recent review by Khoze, Martin and Ryskin gives more details here [10].

6 The proposed apparatus

Traditionally, forward detection systems have consisted of relatively small installations mounted at suitable locations such that the detector systems can be moved towards the beam within localised structures known as Roman Pots. This idea has been expanded in the proposals for LHC so that there is planned to be an entire section of beam pipe that is movable, the so-called "Hamburg Pipe" scheme. It will be necessary to replace the cryostat connection between the portions of the beamline either side of the 420 m installations. Sets of silicon detectors will be mounted in the Hamburg Pipe. The best performance is envisaged if two sets of detectors are installed in each pipe, separated by approximately 10 m to make full use of the available space, so that the position and angle of the trajectory of an emerging proton can be measured. In the horizontal plane, precisions of approximately 10 μm in position and 1 μrad in angle should be obtainable. The vertical plane is less critical, and less good precisions in the vertical measurements will be accepted. The silicon detectors are of a recent "edgeless" technology to allow the sensitive area

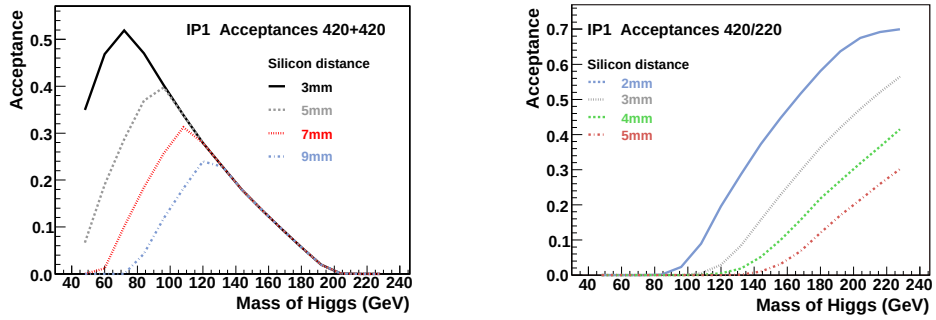

Fig. 8: Acceptance of the forward tagging systems as a function of the mass of the centrally produced system, taken here as a Higgs.

to be moved as close as possible to the main outgoing proton beam.

To perform the tracking of the protons into the relevant detector regions, two programs (FPtrack and Hector) have been written for ATLAS and CMS respectively [11]. They enable us to evaluate the acceptance of the apparatus under various conditions; this is illustrated in Fig. 8. The 420 m systems used on their own provide substantial acceptance for exclusively produced masses up to approximately 150 GeV/c^2, and even if the silicon can be moved only to 7 mm from the beam, the acceptance at the critical region of 120 GeV/c^2 is not affected. By using the 420 m systems in conjunction with those at 220 m, a greatly extended mass range is achieved with excellent acceptances.

Figure 9(a) illustrates the distribution of the outgoing protons at 420 m in position, horizontally and vertically. The vertical beam spread is small and The mass M_X of an exclusively produced final state can be evaluated if the momenta of the forward protons can be reconstructed; this is achievable by means of polynomial-based formulae in terms of the horizontal position and angle in the detector regions. The value of M_X is then $2\sqrt{p_0 - p_1)(p_0 - p_2)}$ for an incoming beam momentum p_0 and outgoing proton momenta p_1, p_2. Various uncertainties smear out this calculation, notably the intrinsic spread on p_0. Figure 9(b) shows the mass uncertainty that can be achieved under reasonable assumptions. In nearly all cases this is more precise than the direct measurement in the central detector. An exception to this is when the central state consists of two photoproduced muons. This promises to be a key process which can be used to calibrate the proton momentum measurements.

7 Summary

Forward tagging opens up a wide range of diffraction and photoproduction processes at LHC. Following from the HERA experiences, we hope to study these mechanisms at high energy, in which a number of new processes should be observable. There is discovery potential in some cases, while in others, known processes can be studied in more depth. This is a major new area of physics for the LHC.

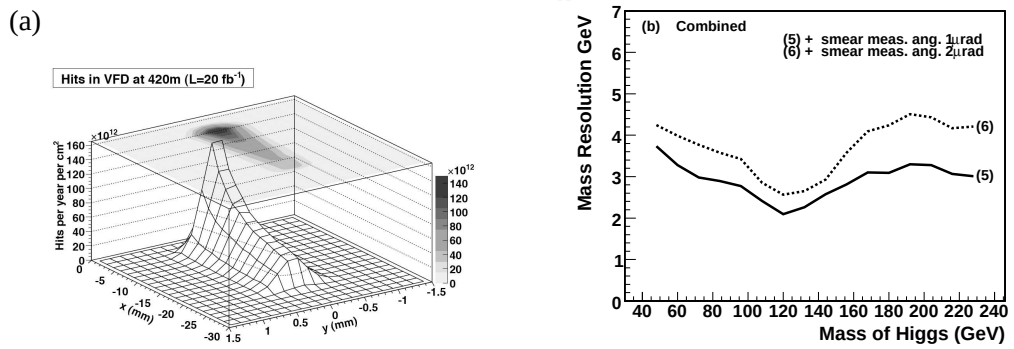

Fig. 9: (a) Typical distribution of a forward proton in a detector system at 420 m (X. Rouby). (b) Mass resolution using 420 m and/or 220 m detector systems if the resolution on the angular measurement is 1 μrad or 2 μrad. (PJB)

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