Prospects for Diffraction at the LHC

Albert De Roeck
CERN, 1211 Geneva 23 Switzerland and University of Antwerp

Abstract
A short review is given on the opportunities for diffractive and forward physics measurements at the LHC.

1 Introduction

The Large Hadron Collider (LHC) [1], is a proton-proton collider being installed in the Large Electron Positron (LEP) tunnel at the CERN Laboratory (the European Laboratory for Particle Physics near Geneva, Switzerland). It will be a unique tool for fundamental physics research and the highest energy accelerator in the world for many years following its completion. The LHC will provide two proton beams, circulating in opposite directions, at an energy of 7 TeV each (center-of-mass $\sqrt{s} = 14$ TeV). These beams upon collision will produce an event rate about 100 times higher than that presently achieved at the Tevatron $p\bar{p}$ collider. The first collisions at 14 TeV are expected for early summer 2008.

The physics potential of the LHC is unprecedented: it will allow to study directly and in detail the TeV energy scale region. The LHC is expected to elucidate the electroweak symmetry breaking mechanism (EWSB) and provide evidence of physics beyond the Standard Model (SM) [2]. The LHC will be also a pivotal instrument to study QCD at the highest energies. Diffraction is an important component in hadronic collisions, and the LHC will shed new light on these still relatively poorly understood interactions. The type of diffractive collisions, or collisions with rapidity gaps expected at the LHC, is shown in Fig. 1 (left).

Diffractive collisions are usually pictured as the result of a diffractive exchange (aka pomeron). In this language the high energy of the LHC beams effectively leads to "pomeron beams" with an energy close to a TeV, allowing to study partonic collisions with fractional momenta of the partons in the "pomeron" of 10^{-3}, and p_T^2 transfers of more than 1 (TeV$/c)^2$. The gap dynamics is presently not fully understood and events with multi-gaps (Fig. 1) will allow new insights.

Historically diffractive measurements have been made at the $Sp\bar{p}S$, Tevatron and HERA Colliders. An example is given in Fig.1 (right) which shows one of the pioneering measurements for diffractive hard scattering from the UA8 experiment [3], with evidence for a very hard component in the diffractive structure. Beautiful measurements of the diffractive structure became available from HERA, and impressive diffractive di-jets, W, J/ψ and more measurements came from the Tevatron.

2 Diffraction and forward physics at the LHC

Diffractive measurements at present colliders have been made through the detection of rapidity gaps, as is obvious from Fig. 1 (left). This technique has been used extensively at HERA and the

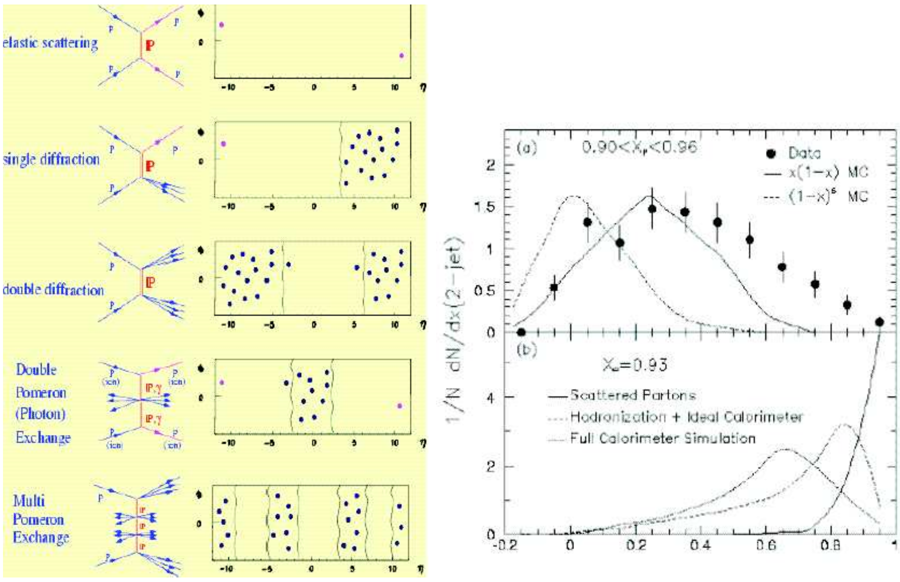

Fig. 1: (Left) Rapidity gap configurations for diffractive events at the LHC; (Right) x(2jet) distribution compared to simulations assuming a soft(dashed) and hard (solid) diffractive structure.

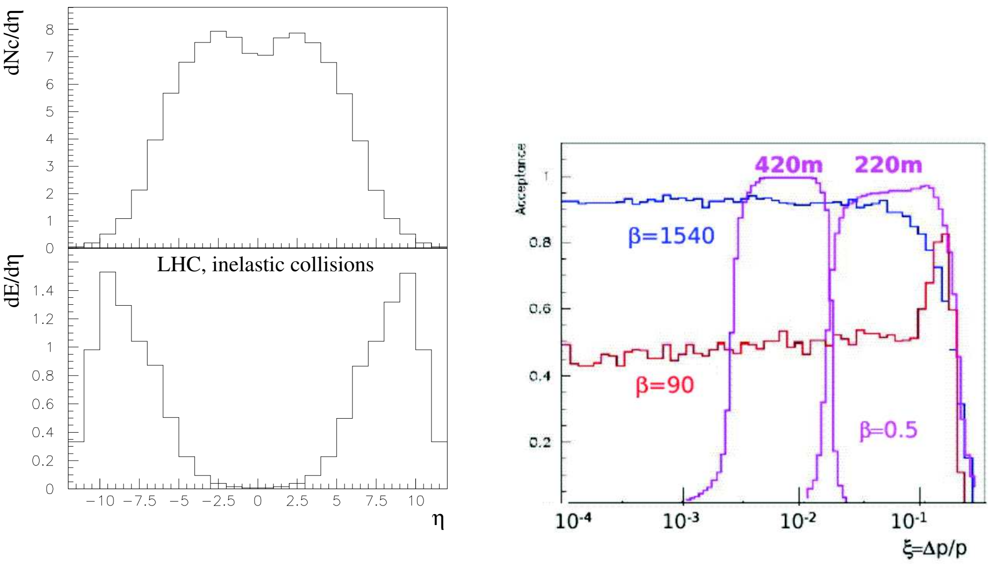

Fig. 2: (Left) Pseudorapidity distribution of the charged particles and of the energy flow at the LHC. The energy is in units of TeV; (Right) ξ acceptance of the Roman Pots of TOTEM and detectors at 420m.

Tevatron. It uses the correlation between the maximum value at which activity (charged tracks or energy) has been measured, η_{max}, and the diffractive variable ξ, the energy lost by the proton in the collision. Obviously this can be used only at low luminosity (perhaps up to 10^{33} cm^{-2} s^{-1} where about 20% of the bunch crossings still contain only one collision), and Monte Carlo corrections are essential. Hence it is important that the detectors have an as large coverage in η as possible.

On the other hand a more direct method is to detect the protons in those collisions where they remain intact (i.e. don't dissociate). This allows to constrain the full kinematics of the scattering. Hence near-beam detectors have been developed and used, the most well known one being the so called Roman Pots. These type of detectors will also be deployed at the LHC.

3 Forward detectors

The central detector of the CMS and ATLAS experiments have an acceptance in pseudorapidity η, of roughly $|\eta| < 2.5$ for tracking information and $|\eta| < 5$ for calorimeter information. Figure 2(left) [4, 5] shows the expected pseudorapidity distribution of the charged particles and of the energy flow at the LHC, demonstrating that with an acceptance limited to $|\eta| < 5$ most of the energy in the collision will not be detected.

Several of the LHC experiments will have so called Zero Degree Calorimeters (ZDCs). These detectors are located at 140m from the interaction point, where the proton beams are separated in their own beampipe. The prime goal of the ZDC is to measure the centrality in AA collisions. So-called ultra-peripheral events can also be tagged. In pp interactions it will allow the study of events with charge exchange and consequently a forward high energy neutron. Its ability to see low energy ($\approx$ 50 GeV) photons is important for exclusive diffractive studies. For cosmic ray physics also the measurement of the high energy π^0 component in pp and pA collisions at the LHC will be very important to tune the air shower models.

The different experiments and their forward detector capabilities are discussed next.

3.1 TOTEM

The TOTEM experiment [6, 7] will measure the pp elastic cross section as a function of t, –the square of the exchanged four-momentum–, the total cross section with a precision of approximately 1%, and diffractive dissociation at $\sqrt{s}$ = 14 TeV. The TOTEM experimental set-up consists of 2 tracking telescopes T1 and T2, as well as Roman Pot (RP) stations, on both sides of interaction point IP5. The T1 and T2 telescopes consist of CSC (Cathode Strip Chambers) and GEM (Gas Electron Multipliers) chambers respectively, and will detect charged particles in the η regions $3.2 < |\eta| < 5$ and $5 < |\eta| < 6.6$. The latter overlaps in acceptance with CASTOR of CMS.

The TOTEM RP stations will be placed at a distance of $\pm$147m and $\pm$220m from IP5. These stations can measure protons with a momentum loss $\xi = \Delta p/p$ in the range $0.02 < \xi < 0.2$ for the nominal collision optics. For other optics with larger β^*, and hence lower luminosity, much smaller values of ξ can be reached.

3.2 CMS

Presently there are two planned additions to extend the coverage in the forward region of CMS:

- Add two calorimeters on either side of the interaction region which will cover higher $|\eta|$ values, called CASTOR ($5.1 < |\eta| < 6.5$) and the Zero Degree Calorimeter (ZDC). Both have an electromagnetic and hadronic section. These calorimeters are of interest for measurements in pp, pA and AA collisions.
- Capitalize on the opportunity to have common runs with the TOTEM experiment, which uses the same interaction region as CMS (IP5). This common physics programme has recently been reported in a document, released by the CMS/TOTEM working group [8].

CASTOR is an electromagnetic/hadronic calorimeter, azimuthally symmetric around the beam and divided into 16 sectors. It is situated in the collar shielding at the very forward region of CMS, starting at 1437 cm from the interaction point, as shown in Figure 3. The pseudorapidity

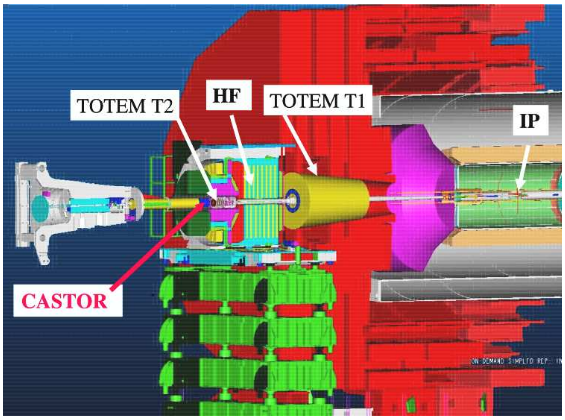

Fig. 3: Schematics of the CMS forward region.

range covered is $5.3 < |\eta| < 6.5$ for the EM-section and $5.1 < |\eta| < 6.4$ for the hadronic section. This η-coverage closes hermetically the CMS pseudorapidity range over almost 13 units. The ZDCs consist of tungsten absorber/quartz fibers.

The Roman Pot detectors of TOTEM aim to detect the protons in diffractive interactions of the type $pp \rightarrow p + X$ and $pp \rightarrow p + X + p$. When used in conjunction with the central CMS detector interesting phenomena such as hard diffractive scattering can be studied, where the system X can consist of jets, W, Z bosons, high E_T photons, top quark pairs or even the Higgs particle, as discussed recently in [9, 10].

The combination of T2 and CASTOR will allow the study of phenomena at lower Bjorken-x than otherwise reachable. Drell-Yan measurements will enable the parton distributions to be probed down to $x \approx 10^{-6} - 10^{-7}$. The energy and particle flows in the forward region are also of prime interest for tuning Monte Carlo simulation programs used in cosmic ray studies. CASTOR is designed especially to hunt for "strangelets" in AA collisions, which are characterized by very atypical fluctuations in hadronic showers.

It is expected that one CASTOR and two ZDC's will be available for the LHC data taking run in 2008.

3.3 ATLAS

ATLAS plans for its own Roman Pots for luminosity measurements, the ALFA project. Detectors, consisting of scintillating fibres will be placed at 240m in Roman pots. These detectors, in the present design, are not suited for diffractive physics studies at the nominal high luminosity. Instead the option is studied to put radiation hard detectors in Roman Pots or other near beam detector mechanics at 220m, the so called RP220 project.

ATLAS also plans a Cerenkov detector for relative luminosity measurements (LUCID with an acceptance of $5.4 < \eta < 6.1$) and ZDCs at a position of 140m. The ZDCs are made of tungsten absorber and quartz fibres. LUCID could be used to help to define a rapidity gap in the event, at low luminosity.

LUCID and the ZDC should be operational for the 2008 run but ALFA and RP220 (still to be approved) will be installed only after 2009.

3.4 ALICE

The ALICE detector has (on one side) a muon spectrometer that covers the region $2.4 < \eta < 4$ and a ZDC. Thus the forward muon acceptance of ALICE is larger than for the ATLAS and CMS experiments, allowing for a more forward acceptance for the detection of heavy flavors.

Since some time ALICE has a program for the study of minimum bias pp collisions (see e.g [11]). Recently [12] ALICE also studies specific diffractive channels.

3.5 LHCb

LHCb is a collider experiment but with the set-up of a fixed target experiment, namely a single side forward spectrometer covering the range $1.9 < \eta < 4.9$. In particular very forward heavy flavour production can be studied in LHCb. So far LHCb has no specific diffractive program.

3.6 LHCf

The LHCf has recently been approved for forward physics, consisting only of two forward electromagnetic calorimeters at zero degrees, hence positioned at 140m. The aim is to measure the very forward π^0 and γ energy spectrum for pp collisions with an equivalent E_{lab} of 10^{17} eV. LHCf also plans to take data during heavy ion runs. These measurements will help calibrating high energy cosmic ray spectra.

The detectors used will be based on a Tungsten absorber with scintillating fibres (one side) or silicon μstrips (the other side) as active elements. The detectors should measure energy and position of the γ's from the π^0 decays.

3.7 FP420

The FP420 project proposes to complement the experiments CMS and ATLAS by installing additional near-beam detectors at 420m away from the interaction region [13]. The presence of these detectors will allow to measure exclusive production of massive particles, such as the Higgs particle, as discussed in the next section.

The aims of the FP420 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 and 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 for the FP420 setup.
- 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, with 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 [14].

4 Forward physics

The forward physics program is very diverse. Examples are:

Soft and Hard diffraction

- Total cross section and elastic scattering, single diffraction (SD).
- Gap survival dynamics, multi-gap events; proton light cone studies ($pp \to 3jets + p$), Odderon studies.
- Diffractive structure: Production of jets, W, J/ψ, b, top quarks, hard photons; Generalized Parton Distributions.
- Double Pomeron exchange (DPE) events as a gluon factory (anomalous W, Z production?).

Exclusive production of new mass states

- Exclusive Higgs production, Exclusive Radion production...
- SUSY and other (low mass) exotics, long lived gluinos.

Low-x dynamics

- Parton saturation, BFKL/CCFM dynamics, proton structure, multi-parton scattering.

New forward physics phenomena

- New phenomena such as DCCs, incoherent pion emission, Centauros.

Strong interest from cosmic rays community, and heavy ions

- Forward energy and particle flows/minimum bias event structure.
- Two-photon interactions and peripheral collisions.
- Forward physics in pA and AA collisions.
- Use QED processes to determine the luminosity to O(1%) ($pp \to ppee, pp\mu\mu$).

Many of these topics can be best studied at start-up luminosities. As mentioned, the forward detectors are of special interest for cosmic ray studies since these measure the production of high energy particles, an important component in the air shower simulations. To better tune such simulations collider data at the highest energies and over an as large acceptance range as possible, are critical.

4.1 Diffraction and QCD

The acceptance for diffractive physics with tagged protons is given in Fig. 2, for TOTEM and for detectors at 420m. Similar numbers hold for the ATLAS RPs. It shows that special runs with high β^* optics allow to detect protons over essentially the whole ξ range, but this corresponds essentially to luminosities below 10^{31} cm^{-1} s^{-1}. At the nominal high luminosity β^* detectors at 220m (TOTEM or RP220) and detectors at 420m are complementary on the region they cover. Physics topics include QCD and diffraction. Detectors at 220/420m can tag and measure protons which have lost 10% to 0.1% of there initial momentum, and study in detail diffractive reactions in that range.

With special optics and rather short running time (perhaps a week) processes with cross sections of μbarns are accessible, while with high luminosity processes with nbarn and pbarn cross sections can be studied. As an example for jet events, generator studies show that with about 300 nb^{-1} about 60000 SD events and 2000 DPE events are produced with jets having an E_T larger than 20 GeV. With 100 pb^{-1} we have 500000 and 30000 events with jets with an E_T larger than 50 GeV. Low luminosities will allow initial studies while high luminosity samples will allow for detailed t, M_x, p_T dependence studies.

A measurement of particular interest for this conference is the total and elastic pp cross section. The total cross section can be measured via the luminosity independent measurement as detailed in [15, 16]. TOTEM opts to use a β^* of 1500m in order to achieve a precision of 1% on the total cross section. While TOTEM may be ready from the start in 2008, this special optics is not expected to come very early on in the LHC running. As a compromise and easier achievable β^* of 90m would allow this measurement as well, but with a precision of O(5%). ATLAS opts for a β^* optics of 2625 m, which would allow to reach smaller $|t|$ values and allow to measure the ρ parameter as well. It has been often emphasized that ρ is an important quantity to measure as it is sensitive to new strong physics at higher energies, beyond the c.m.s. energy of the collisions.

An extensive program of two photon physics and photon-proton physics becomes accessible as well. In particular the study of the processes $\gamma\gamma \to WW$ and ZZ is of interest and can give precise measurements of the anomalous couplings. The QED processes $\gamma\gamma \to \mu\mu, ee$ can be precise monitors of the luminosity. Two photon processes can also be used to search for chargino pair production.

Other processes where forward detectors play a significant role are eg. in the study of low-x processes and the access to the gluon distribtution in the proton via Drell-Yan, jet or heavy flavor production. Values in Bjorken-x down to $10^{-6} - 10^{-7}$ in the perturbative regime can be reached. Adding forward detectors such as CASTOR to CMS will also allow to study forward-central correlations between particles, which are measurements that are very sensitive to for example multiple interactions and the way they are modeled.

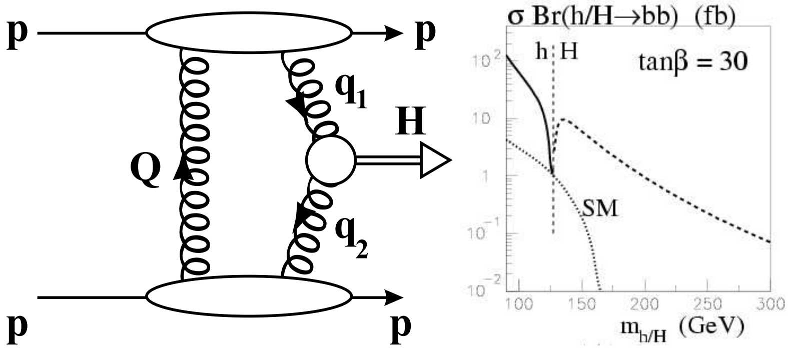

Fig. 4: (Left) Diagram for the CEP process; (Right) Cross section for SM and MSSM exclusive Higgs production.

4.2 Central exclusive Higgs production

Central exclusive Higgs (CEP) production $pp \to p + H + p$ is of special interest. The diagram is shown in Fig. 4 (left). One of the key advantages of CEP is that the $gg \to b\bar{b}$ process is strongly suppressed in LO, hence the decay $H \to b\bar{b}$ has less background and becomes potentially observable. The Higgs to b-quark Yukawa coupling is otherwhise very difficult to access at the LHC. The inclusive $H \to bb$ channel is not accessible due to the too large QCD backgrounds. Recently, the ttH channel was analysed with detailed simulation in [17] 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 CEP of Higgs bosons has been subject of many discussions over the last years, in particular during the HERA/LHC workshops [18], but now generally the calculations of [19] are taken as a reference. Note that there are still some issues and concerns on the CEP soft survival probability at the LHC and the uncertainties in the PDFs. 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. 4. Generator level calculations, including detector and trigger cuts, and estimates of selection efficiencies, show that the decay channels $H \to bb$ and $H \to WW$ are accessable. Eg. $M_H = 120$ GeV/c^2 gives about 11 events with O(10) events background for 30 fb^{-1} in the bb decay mode. For M_H above 140 GeV/c^2 about 5-6 events with no appreciable background for 30 fb^{-1} in the WW decay mode [10] will be observed, using channels with at least one leptonic 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 the 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. But in any case, studies both using detailed [8] and fast [20] 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. 4 (right), 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 [21]. A typical result is shown in Fig. 5 (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. 5 (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_h^{max} scenario [22], with $m_A = 120$ GeV and $\tan\beta = 40$. A clear signal over background is observable.

A detailed study of the backgrounds to this diffractive process was presented in [8]. At high luminosity, ie. 10^{33} cm^{-2}s^{-1} and higher, the pile-up is considerable, coming mainly from soft single diffractive interactions. Several techniques such as correlations between the detectors at 420/220m, 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.

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 [23]. Hence this is a way to get information on the spin of the Higgs, and is added value to the LHC measurements.

It was pointed out recently [24] that in case of CPV models the h, A, H may mix into states h_1, h_2, h_3 which may be quasi-degenerated 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 a structure that is sensitive to the underlying parameters. Analyzing the three-way mixing scenario [24] 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.

Other searches for new physics in the 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 [25]. More spectacular are the predictions presented in [26], where a very high cross section of CEP WW and ZZ events is expected, in a color sextet quark model.

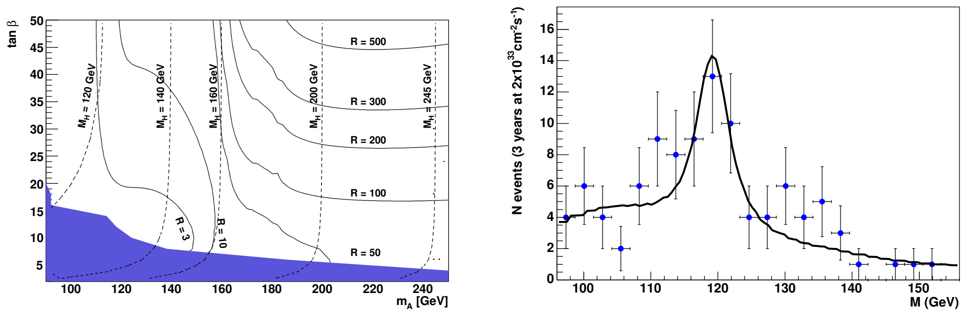

Fig. 5: (Left) Contours for the ratio of signal events in the MSSM to those in the SM in the $H \to bb$ channel in CEP production in the M_A–$\tan\beta$ plane. The ratio is shown in the no-mixing scenario with $\mu = +200$ GeV. The values of the mass of the heavier CP-even Higgs boson, m_H, are indicated by dashed contour lines. (Right) A typical mass fit for 3 years of data taking at 2×10^{33} cm^{-2} s^{-1} (60 fb^{-1}). The significance of the fit is 3.5σ and uses only events with both protons tagged at 420m.

5 Conclusion

The LHC is coming on line, with the first 14 TeV collisions to be expected in summer 2008.

Forward physics at the LHC came a long way during the last years. Two forward physics experiments got approved (TOTEM, LHCf). ATLAS and CMS plan to extend the detector coverage in the forward direction, with ZDCs, CASTOR (CMS) and LUCID (ATLAS). ATLAS also plans to add RPs at 240m and studies additional near beam detectors at 220m. CMS and TOTEM have common physics program on diffraction.

The R&D for FP420 is nearing its completion. Discussions with the ATLAS and CMS managment have started. The earliest date for data taking with these detectors is 2010.

In all, forward physics is now well in the blood of the LHC experiments.

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