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Physics and Beam Monitoring with Forward Shower Counters (FSC) in CMS

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Abstract

We propose to add forward shower counters, FSC, to CMS along the beam pipes, with 59 m $\lesssim z \lesssim$ 140 m. These will detect showers from very forward particles with $7 \lesssim \eta \lesssim 11$ interacting in the beam pipe and surrounding material. They increase the total rapidity coverage of CMS to nearly $\Delta\Omega = 4\pi$, thus detecting most of the inelastic cross section σ_{inel}, including low mass diffraction. They will help increase our understanding of all high cross section processes, which is important for understanding the "underlying event" backgrounds to most physics searches. To the extent that the luminosity is well known, they may (together with all of CMS) provide the best measurement of σ_{inel} at the LHC. They are most useful when the luminosity per bunch crossing is still low enough to provide single (no pile-up) collisions. They will allow measurements of single diffraction: $p + p \to p \oplus X$ (where $\oplus$ means a rapidity gap) for lower masses than otherwise possible, and double diffraction: $p + p \to X \oplus X$ with a large central rapidity gap. They can also be used as rapidity gap detectors for double pomeron exchange and central exclusive processes. Studies of exclusive processes such as $\gamma\gamma \to \mu^+\mu^-$ (for luminosity calibration and eventually momentum calibration of forward spectrometers) can be made more cleanly requiring gaps in the FSC counters.

Models of forward particle production can be tested indirectly through simulations of hit patterns in the counters. This may reduce the uncertainty on very high energy ($E \sim 10^{17}$ eV) cosmic ray shower parameters. For heavy ion collisions, the counters act as crude forward calorimeters detecting nuclear fragments (supplementing the ZDC), as well as enabling the study of coherent quasi-elastic scattering e.g. Pb + Pb $\to$ Pb $\oplus X \oplus$ Pb via two-photon interactions.

The counters can also be used for real-time monitoring, and if desired for vetoing in the level 1 trigger,both incoming and outgoing beam halo-generated backgrounds (separated by timing) and beam conditions generally. These counters represent a significant enhancement of the beam monitoring, and will make an invaluable contribution to the understanding of the background environment and its topology. They can also provide an additional luminosity monitor, up to luminosities such that the number of interactions per bunch crossing is $\langle n_X \rangle \sim 5$.

This note discusses mainly the physics issues; more technical details will be presented in another note. Basically we propose a set of scintillation counters at several locations between 59 m and 140 m along the beam pipes (on both sides), and read out by DAQ electronics identical to that of the HF, with some inputs to the level 1 trigger. Bunch-by-bunch information on rates etc. will be provided for LHC operations. The cost is very modest, given the added value to many physics studies in CMS and to our knowledge of beam conditions generally.

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Contents

1 Introduction and summary of physics goals

We propose to add very forward scintillation counters closely surrounding the beam pipes with 59 m $\lesssim |z| \lesssim$ 140 m from IP5 on both plus (+) and minus (-) sides. These locations are upstream of the TAN and the ZDC, and where both incoming and outgoing beams are in a common pipe, which is warm and accessible in some places. We call these counters Forward Shower Counters, FSC; they do not detect primary particles directly from the pp collisions, but showers produced by small angle and high energy ($\sim$ TeV) particles that hit the beam pipes and surrounding material.

This note gives an outline of the physics that will be made possible, or much improved, with a simple set of scintillation counter paddles. The baseline design for the counters is to have two at each of several z locations, one above and one below the beam pipe, with elliptical or circular cut-outs fitting closely around the beam pipe. Refs. [1] and [2] present some of the physics case, included here for completeness. An accompanying note [3] will cover the technical aspects. The counters will cover 7 $\lesssim |\eta| \lesssim$ 11, where $\eta = -\ln \tan\frac{\theta}{2}$ is the pseudorapidity, depending on the particle type and p_T. By nearly completing the rapidity coverage of CMS, the total solid angle approaches $\Delta\Omega \sim 4\pi$, and almost all inelastic collisions will be detected. In the next section we discuss possible locations.

In addition to their giving added value to the CMS physics programme, they will be important for understanding beam-related backgrounds (beam-gas, beam halo-pipe, etc.), complementing other monitors such as the BSC [4]. For this purpose we also propose to add a few (perhaps two on each side of CMS) directional Cherenkov counters (DCC) [5]. These are simply cylindrical rods of cast acrylic plastic, about 5 cm in diameter and 12 cm long, closely adjacent and parallel to the beam pipe. With a PMT at each end, incoming and outgoing particles (or showers) can easily be distinguished by the pulse height asymmetry. Placed close to a scintillator that can distinguish incoming and outgoing showers by timing, each can monitor the performance of the other.

The primary physics use of the FSC is for diffractive physics, both as rapidity gap detectors and to measure very forward showers in low mass diffractive excitation, in both cases when the luminosity per bunch crossing is low enough to have some events without pile-up. They can be used effectively as a pile-up veto in the level 1 trigger for single diffraction, especially for hard diffraction (W, Z, dijets) and central exclusive production (dijets, etc.) resulting from pomeron $I\!\!P$ or photon γ exchanges [6, 7]. Hard single diffraction physics can only be done cleanly with a single interaction in the bunch crossing. If there is more than one (a) there is no rapidity gap and (b) even if the forward proton were to be detected it is usually not possible to match the proton with the correct central event. We use the symbol $\oplus$ to mean a large rapidity gap, with no hadrons. Central exclusive production [6], e.g. $p + p \rightarrow p \oplus \ell^+\ell^- \oplus p$, $p \oplus JJ \oplus p$ (J = jet) and $p \oplus \gamma\gamma \oplus p$, can be studied without forward proton detection by selecting large rapidity gaps. Forward coverage by the FSC will be essential for these studies. Feynman-x, defined as $x_F = p_z/p_{beam} = 2p_L/\sqrt{s}$ is very close to $x_F(p) = 1.0$ for the protons in these reactions. With $\xi = 1 - x_F$, in the central exclusive case $p+p \rightarrow 1 \oplus X \oplus 2$ we have $M(X) \approx \sqrt{\xi_1.\xi_2} \times \sqrt{s}$. In single diffraction $p+p \rightarrow p \oplus X$ we have $M(X) \approx \sqrt{\xi}.\sqrt{s}$.

This proposal is independent of the proposal to install very forward (z = 240 m and 420 m) High Precision Spectrometers (HPS) [8], although there is some overlap in the personnel, and the physics is related. However we expect that they will be useful in combination (FSC+HPS) if there are still some bunch crossings with no pile-up when both are operational.

As this physics program requires no pile-up, it requires not-too-high luminosity *per bunch crossing*, L/X. But the average number of inelastic collisions per bunch crossing, $\langle n_{inel}/X \rangle$, need not be as low as ~ 1. We have:

$$\langle n_{inel}/X \rangle = (L \times \sigma_{inel})/(N_b \times f), \tag{1.1}$$

where L is the luminosity, σ_{inel} the inelastic cross section, N_b the number of bunches and f is the revolution frequency ($f \sim 1.1 \times 10^4$/sec.). The probability of an event of interest having no other pile-up interactions is $P(0) = e^{-\langle n_{inel}/X \rangle}$. Even at $L = 10^{33}$ cm^{-2}s^{-1}, if σ_{inel} = 80 mb and with 50 ns between bunch crossings, $\langle n_{inel}/X \rangle$ = 5, there will still be $\sim 5 \times 10^5$ crossings/second with exactly one inelastic interaction. Therefore the part of the physics program with $\sigma \gtrsim 1\mu$b, which is much of this general diffraction physics programme, will still be possible. The physics processes motivating this proposal have high cross sections, typically μb, so even with small efficiency (due to pile-up) they can be studied. As long as $\langle n_{inel}/X \rangle$ is not *always* $>\sim 5$, even at the end of a store, data can be still be collected with useful statistics.

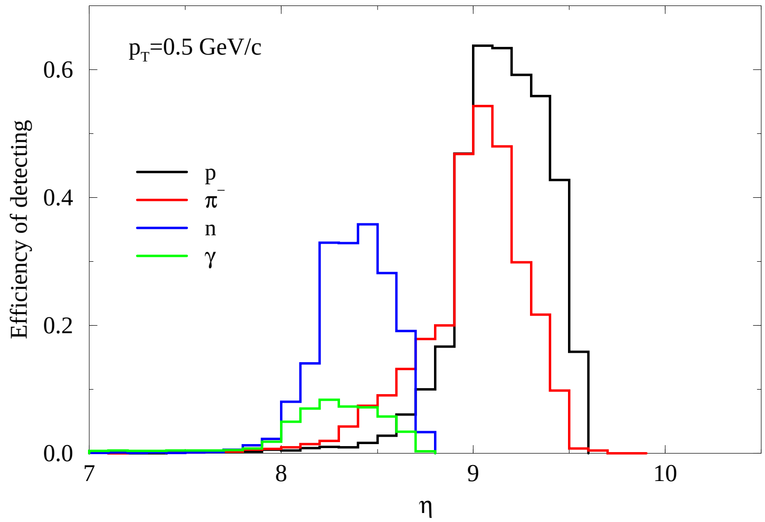

Figure 1: Efficiency (from DPMJET) of detecting different particles produced at p_T = 0.5 GeV/c vs η. Protons and neutrons are the most abundant particles at such large rapidity.

As most of the pile-up events will have forward particles giving showers in the FSC, they can be effectively vetoed at the level 1 trigger. For single diffractive excitation one would require (in addition to other criteria, such as HF gaps) all the counters on one side (in logical OR) to be consistent with noise. Showers will usually give a large pulse height, many times that of a minimum ionizing particle (MIP), and are easily discriminated from noise. Off-line, multiple events in a bunch crossing also usually give more than one primary vertex, as reconstructed from the excellent central tracking capabilities of CMS. However low mass diffractive excitation events can have all the produced particles at small polar angles, and then not have measured tracks, and/or they will not form a reconstructable primary vertex.

Another physics channel that will be made possible by the FSC is low mass double pomeron exchange. Ideally this requires detection of both coherently scattered protons, but that is not possible in CMS (even in combination with TOTEM, except in special high-β running). However we can allow both protons to dissociate into low mass states (e.g. $p \to p\pi^+\pi^-$ or $n\pi^+$) which give hits only in the FSC or ZDC, and can provide a trigger. Pomeron exchange is then selected as having large rapidity gaps between those forward showers and a central state, which may have low mass (a few GeV/c^2).

Simulations of very high energy ($E \gtrsim 10^{17}$ eV) cosmic ray showers differ in important parameters such as the height of shower maximum, X_{max}, from which one attempts to distinguish proton from iron primaries. The various Monte Carlo simulations (e.g. SIBYLL, DPMJET, EPOS, and QCSJET) embody extrapolations from much lower energies; in fact there are no measurements of charged hadron spectra with $0.05 < x_F < 0.85$ at energies higher than $\sqrt{s}$ = 63 GeV (ISR). The FSC cannot directly measure forward charged hadron spectra. However forward particle simulations (in general inelastic collisions) can be passed through beam line and detector simulations and the results compared with data. Even though the information is limited, there are no other detectors at the LHC that cover this region. For example the FSC can detect a π^- with $p_T = 0.5$ GeV/c and $x_F = 0.3$ at $\sqrt{s}$ = 14 TeV; these have η = 9, and their detection efficiency is shown in Fig. 1 for a particular counter configuration (see Section 6).

The FSC can also give added value to the heavy ion program, both by measuring forward nuclear fragments (including protons, and complementing the ZDC which detects only neutrons, K_L^0, and photons), and by selecting coherent nuclear scatters with rapidity gaps (e.g. $\gamma\gamma$ collisions).

The earlier the FSC are installed, the greater will be their benefit to the diffractive physics program and to beam background monitoring. Furthermore, if the FSC are operational in time for physics at $\sqrt{s}$ = 7 TeV, and continue into the $\sqrt{s}$ = 10 TeV-14 TeV periods, we will be able to measure the $\sqrt{s}$ dependence of diffractive cross sections. Therefore an approval in time for an installation during the Winter 2010-2011 shut down is important.

2 Locations in LHC tunnel

A discussion of the possible locations (in z) of FSC counters is presented in the accompanying note [3]. Here we briefly mention seven positions shown in Table 1 (in each of the + and - directions) in front of and behind the MBX magnets, where the warm elliptical beam pipe is accessible, see Fig **??**, and detectors can be placed. Beyond those locations there are further places out to 140 m where the vacuum pipe flares and the TAN is located, but the (circular) beam pipe there has larger diameter, 22.5 cm. There are 3 m concrete shielding blocks at z = 107.2, 118.2 and 131.2 m, and their front face, as well as the front face of the TAN, may be good locations, shielded from incoming particles. Some locations are best placed to distinguish incoming and outgoing beam halo using timing; with 50 ns between bunches the maximum time difference Δt is 25 ns, is easily distinguishable. We will show some MARS simulations of coverage for counters in these MBX locations. Further simulations are now being done to choose z-locations that maximise the forward coverage (e.g. for the total inelastic cross section, and for low mass diffraction). Also, some z-positions may be more useful than others for beam background monitoring. A location closer to the interaction point, e.g. between the quadrupole triplet and the TAS, will also be considered, mainly for background tagging.

Location	z(mm)	Δt (ns)
1	59426	3.8
2	63751	0.0
3	68026	3.5
4	72301	7.0
5	76576	10.5
6	80851	11.0
7	85126	7.5

Table 1: Possible locations of counters on each (+ and -) beam pipe around the MBX magnets, as used in the simulations, and the time difference Δt between incoming and outgoing bunch passes for 25 ns bunch spacing. Additional locations beyond the MBX magnets with 12.5 ns bunch separation are available.

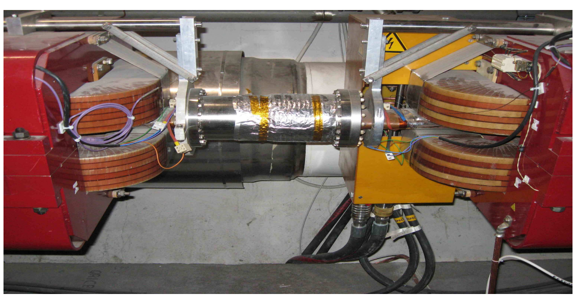

Figure 2: Example of a region between MBX magnets where FSC counters can be placed.

Figure 3: Example of the region in the LSS beyond the MBX magnets where FSC counters could be placed.

The FSC counter locations are close enough (closer than the ZDC) for their signals to be included in level 1 triggers. The minimal (and probably sufficient) trigger signal is a logical-OR of all the FSC on each arm. These will be used both in a positive requirement and as a veto, together with a central signal Y, where Y = central $\sum E_T$, di-leptons, jets, etc., sometimes in combination with E_T or E sums from the HF (again, either positive or in veto). The possibility to use simple logical combinations of these counters is kept open at this time. It is also foreseen to provide a background tag for incoming background from the LHC tunnel to the CMS detector, using hit timing as a discriminant and to be used as a background veto should it be required.

3 Towards 4π coverage for CMS, and σ_{inel}

At present there is no detector at the LHC that has very close to complete coverage for inelastic collisions. Experiments cover a large fraction of the 4π solid angle but not the small polar angles, θ, where the particle density is high, as are their typical energies. At the highest energy at which these cross sections have been measured, the Tevatron with $\sqrt{s}$ = 1800 GeV, $\sigma_{tot} = 72 - 80$ mb, and $\sigma_{elastic}$ = 16-20 mb, implying (although it has not been directly measured) σ_{inel} = 52-64 mb. At $\sqrt{s}$ = 10 - 14 TeV we may expect (approximately) $\sigma_{tot} \sim 110$ mb, $\sigma_{elastic} \sim$ 30 mb, and $\sigma_{inel} \sim$ 80 mb. Although σ_{tot} and $\sigma_{elastic}$ are important, when it comes to understanding cosmic ray interactions (for example) σ_{inel} is at least as important. We believe that the combination of the existing CMS detectors (including CASTOR, T2 and the ZDC) with the FSC presents a unique opportunity to measure this.

The existing detectors of CMS from η = 0 to the forward edge of the HF calorimeter at $|\eta_{HF}(max)|$ = 5.2, are essentially free of cracks and have good efficiency for detecting all events that have particles in that region. Beyond that, CASTOR (on one side only) with $5.2 < \eta < 6.4$ is a deep electromagnetic and hadronic calorimeter. Diffractive events with particles only more forward, on one or both sides, will not be detected, unless they happen to have a neutral particle (γ, K_L^0 or $n/\bar{n}$) very close to $\theta = 0°$ which are detected in the ZDC. The beam (true) rapidity at $\sqrt{s}$ = 7 (10) (14) TeV is 8.9 (9.3) (9.6). A diffractively scattered proton with $p_T \sim 1$ GeV/c has $\eta \sim y_{beam}$ and we will ignore the distinction between η and y in this discussion. Then a rapidity region $\Delta\eta$ = 3.7 (4.1) (4.4) in the forward region at these three energies is not covered (apart from by the ZDC for neutrals) on one side (1.2 units less on the CASTOR side). As a rule of thumb, a diffractive mass M_X covers a rapidity region $\Delta y \sim \ln(M_X^2/s_0)$ with $s_0 \sim 1$ GeV^2, thus diffractive masses $M_X \lesssim$ 6.4 (7.8) (9.0) GeV/c^2 are not detected. The diffractive high-x_F peak in the proton spectrum has the behaviour $\frac{d\sigma}{dM^2} \propto (1/M^2)^{1+\epsilon}$, where $1 + \epsilon \sim 1.1$ is the intercept of the pomeron trajectory: $\alpha_{I\!P}(t) = 1 + \epsilon + \alpha' t$. So the missing low mass diffraction region is a significant part of the total single diffractive cross section, which is $\sigma_{diff} \sim$ 10 mb at the Tevatron and rises with $\sqrt{s}$. It should be included in a measurement of σ_{inel}.

By including a set of counters in this important forward η region we considerably increase the fraction f_{inel} of inelastic collisions that are detected. The missed fraction $1 - f_{inel}$ corresponds to events where *all* the produced particles either went through remaining cracks (only elastic scattering events have *no* particles outside the beam pipes at this distance) or are not detected through detector inefficiencies. Very low-p_T charged particles, even if they do not leave a track stub in the silicon tracker, spiral in the solenoidal field and can hit the forward calorimeters. The overall inefficiency, $1 - f_{inel}$, which we expect to be $\lesssim$ 1% if we have the FSC, can be estimated by simulation of all inelastic events (with programs such as PHOJET and MARS, tuned to reproduce the data after detector simulation). Then if P(0) is the probability that a bunch crossing is found to have no detected particles, σ_{inel} follows from Eqn. 1.1, with $P(0) = e^{-\langle n_{inel}/X \rangle}$. Knowledge of the bunch-by-bunch luminosity may be the biggest uncertainty, but improvements in Van der Meer scanning [9] and other techniques (e.g. the QED process $\gamma + \gamma \to \mu^+\mu^-$) should reduce this to a few percent or better. It is necessary to monitor the *relative* luminosities of all the bunch crossings in this process, as done by the HF and PLT luminosity monitors. Then a systematic uncertainty on the procedure can be derived from the dependence, if any, of the measured σ_{inel} on the bunch luminosity.

The main uncertainty in the σ_{inel} measurement, apart from the luminosity, is likely to be calorimeter detector noise, rather than inefficiency. This can be well measured in crossings at low luminosity (with a zero-bias trigger) with no tracks and (e.g.) with the FSC on both sides empty. Nearly every event (and certainly almost every detector region) is then only showing noise. There are other ways of measuring the noise spectrum in the FSC themselves, such as the luminosity dependence of rates, and short single beam runs. One could also make the noise in the FSC negligible by doubling the counters (in z) and demanding a coincidence, but this is probably not necessary. In the similar CDF counters, described next, it was found that of the two counters at the same z (but not overlapping), when one detected a shower it was nearly always also seen in the other. We expect a measurement of σ_{inel} at the few % level after these studies.

Similar forward shower counters have been used in ZEUS [10] and elsewhere. The Collider Detector at Fermilab, CDF, included a similar set of counters (called Beam Shower Counters, BSC) used in veto at level 1 for some physics (central exclusive production). These were pairs of scintillation counters, closely surrounding the beam pipe, at locations up to 56.4 m from the intersection point. The closest counters had acceptance for primary particles with $5.4 < |\eta| < 5.9$, and were preceded by two radiation lengths of lead to convert photons. The other counters were behind quadrupoles, electrostatic separators and (for the last counter) a dipole magnet. These only detected showers produced by particles in the beam pipe and surrounding material. Together they covered 5.4 $< |\eta| <$ 7.4 (the Tevatron beam has $y(p)$ = 7.65, where rapidity $y(p)$ = ln $\frac{\sqrt{s}}{m(p)}$. They were used effectively to veto pile-up and trigger on rapidity gaps in level 1 triggers, and to tag events with proton dissociation. CDF also had a set of Roman pot detectors, with tracking, to measure diffractively scattered antiprotons. It was found that high mass single diffraction studies of dijets, W, and Z with a $\bar{p}$ track are dominated by pile-up (the $\bar{p}$ and the hard central state being from different collisions) even when $\langle n_{inel} \rangle < 1$, unless a forward rapidity gap is required. The requirement of a rapidity gap is usually necessary (and sufficient) to select events dominated by diffraction. Note however that in central *exclusive* production with *both* protons measured ($p + p \rightarrow p \oplus X \oplus p$) four-momentum conservation and precision (relative) timing of the protons enable physics to be done with no gap requirement even with $\langle n/X \rangle \gtrsim$ 25 [11].

CDF published papers on exclusive e^+e^- [12, 13], $\mu^+\mu^-$ [14] and $\gamma\gamma$ [15] production that would not have been possible without their BSC. See Ref. [16] for a discussion of exclusive lepton pairs and photoproduction in CMS.

4 Single and double diffractive excitation

A major goal of the early programme of forward physics is the measurement of the main characteristics of diffractive interactions. These processes are very significant in their own right to better understand QCD in the non-perturbative regime, and they form a large fraction of the total cross section. In addition, they are valuable because of their intimate connection to the rapidity gap survival probability $\hat{S}^2$, which determines the rate of suppression of central exclusive processes caused by additional parton interactions and rescattering effects. These detectors will allow the measurement of low mass single diffractive dissociation, $p + p \rightarrow p + p^* \rightarrow p \oplus X$, where X is a system of particles with typically $M(X) \sim$ few GeV/c^2. This physics is not possible with the central detectors, as the hadrons coming from the fragmentation of X have forward (longitudinal) momenta $\sim$ TeV/c and transverse momenta $p_T \lesssim$ 1 GeV/c. The FSC cannot *reconstruct* these very forward primary hadrons, but the patterns of their signals can be compared with simulations of soft diffraction to test the models. Such data are important, as they will strongly constrain existing models of diffractive processes.

Different behaviours of the diffractive cross sections are predicted for different asymptotic behaviours of the total cross section σ_{tot}. It is therefore important to study diffractive dissociation processes at the LHC. The experimental results available at present are fragmentary, and of course at lower $\sqrt{s}$. To further constrain the parameters of the models of soft diffraction one needs to make measurements at LHC energies of the single diffractive dissociation cross section for low masses, and of central diffractive production, $\frac{d\sigma}{d\eta_1 d\eta_2}$, where η_1 and η_2 define the pseudorapidity range of the central system.

None of the major LHC detectors (ALICE, ATLAS, CMS, and LHCb) have the coverage necessary to measure forward rapidity gaps. We have performed simulations of several reactions to establish the efficiency of an example FSC detector arrangement. The results presented here correspond to seven locations around the MBX dipole magnets, with 59 m $< z <$ 85 m. Larger z locations are possible up to 140 m, but the beam pipe diameters are larger (22.5 cm). The actual optimal locations in z of the counters will be established in conjunction with the technical issues, but the physics arguments in this note are general.

4.1 Single diffraction, SDE: $p + p \rightarrow p \oplus X$

The FSCs cover a key rapidity region between the zero degree calorimeters, ZDC, in CMS (which detect neutral particles produced close to $\theta = 0°$), CASTOR, and the TOTEM detectors T2. Single diffractive excitation, SDE, is the process $p + p \rightarrow p \oplus X$. The dependence of $M(X)$ on rapidity gap size $\Delta\eta$ is $\frac{M(X)}{\sqrt{s}} \sim e^{-\Delta\eta}$, which can be used to estimate the mass spectrum, after correcting for the more detailed relationship using Monte Carlo expectations. Strictly, true rapidity y should be used, but for practical reasons η is usually considered to be an acceptable approximation, especially in the central region. In the very forward region of the FSC the difference diverges, and as $\theta \rightarrow 0°, \eta \rightarrow \infty$, while $y_{beam} \rightarrow 8.6$ at $\sqrt{s} = 10$ TeV. Furthermore the FSC are beyond the MBX bending magnets, so the angular coverage of a detector does not correspond exactly to an η-region, and is different

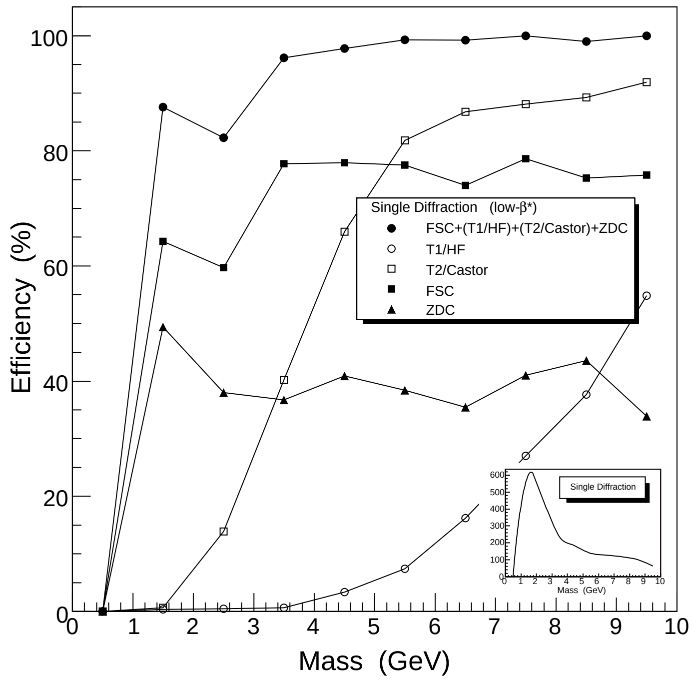

Figure 4: The detection efficiencies for single diffractive events simulated by PYTHIA6.2 as a function of the diffractive mass. We required at least five hits in any of the forward shower counters, or at least one track in the η region covered by T1/HF or T2/CASTOR, or a minimum energy deposit in the ZDC (see text).

for charge $Q = +1$ and $Q =$ -1 particles. So the coverage is a function of (Q, y, p_T). While these distinctions are taken into account in our simulations, for the purpose of discussion we sometimes ignore them.

Fig 4 shows results of a simulation, using PYTHIA6.2, of the efficiency of detecting low mass ($M(X) <$ 10 GeV/c^2) single diffractive excitation with different combinations of detectors. The ZDC are quite efficient for detecting the $\sim$ 50% of dissociations with a small angle neutron. The other events, especially with $M(X) \lesssim$ 4 GeV/c^2, require the FSC to be detected.

At present, without detecting diffractively scattered protons and without the possibility of detecting very forward rapidity gaps (over $\Delta y \sim y_{beam} - 3$) we are unable to distinguish events dominated by diffraction from non-diffractive events. The FSC, perhaps in combination with CASTOR and the HF, will allow us to address questions such as the heavy flavour, jet and W/Z content of events with large forward rapidity gaps and those with no such gaps. Such hard diffractive processes have been observed at the Tevatron, and in a model where the exchanged pomeron has a quark/gluon content, together they probe its composition. Although even with full $\Delta\Omega = 4\pi$ coverage one can only classify inelastic events as diffractive or non-diffractive in a model-dependent way, all would agree that an event with a rapidity gap of $\gtrsim$ 5 units is dominated by diffraction and one with no gap exceeding 2 units is certainly not. But without detecting $x_F \gtrsim$ 0.95 protons or the $\Delta y \gtrsim$ 3 gaps adjacent to them (as at present) it is not possible to distinguish between diffraction-dominated and non-diffraction-dominated events $^{*)}$.

4.2 The odderon

The odderon is, at leading order, triple-gluon colour-singlet exchange with charge-parity C = -1, which distinguishes it from the pomeron with C = +1, and which is to leading order a pair of gluons. There is no clear evidence for the odderon yet, although it is possible that it can be discovered in CMS or TOTEM. The FSC could in principle make that possible. A central exclusive $J^{PC} = 1^{--}$ state such as the $\phi, J/\psi$ or Υ between large rapidity gaps (say $\Delta\eta \gtrsim$ 4) cannot result from $\gamma\gamma$ exchange or $I\!PI\!P$ exchange in the t-channel, which give only J = even and $PC = ++$ states. They normally result from photoproduction, $\gamma I\!P$, as measured at HERA and recently at the

$^{*)}$ When we publish a result classifying events as "diffractive" or "non-diffractive" it is important to state the criteria used, as in Nature there is no absolute distinction.

Tevatron [14] and RHIC [17]. However they could be produced by odderon + pomeron exchange ($O\mathbb{P}$), which results in a different cross section from that expected by photoproduction as measured at HERA, where there is no odderon exchange. There is a spread in the predictions, but e.g. Szymanowski [18] quotes a "central value" for exclusive Υ production at the LHC (at 14 TeV) of 31 pb for $\gamma\mathbb{P}$ production and 5 pb for $O\mathbb{P}$ production. The processes could in principle be distinguished by the t-distribution of the scattered proton, but in CMS we cannot detect that. What we *can* do is trigger on hits from showers produced by proton diffractive dissociation products on both sides, with $|\eta| \gtrsim 5$, and an empty detector with $-5 < \eta < +5$ apart from the vector meson V (e.g. $\phi \to K^+K^-, \Upsilon \to \mu^+\mu^-$). Evidence for odderon exchange would then be a higher than expected cross section, together with a higher than expected $\langle p_T(V)\rangle$, because on average $p_T(O) \sim p_T(\mathbb{P}) \gg p_T(\gamma)$. This is clearly marginal, and not a main objective for the FSC, but apart from the odderon search, photoproduced $\Upsilon \to \mu^+\mu^-$ should be observable.

4.3 Double diffractive excitation, DDE: $p + p \to X \oplus X$ and double pomeron exchange $p + p \to X \oplus Y \oplus X$

We can compare the forward detector information in $p + p \to p + X$ events, e.g. detectors with $|\eta| > 3$ on one side having hits when the rest of CMS is empty, with the same information in $p + p \to X + G + X$ events, having hits on both sides, but no particles in $-3 < \eta < +3$, to test *factorisation* in single and double diffraction. Making the comparisons also when the central gap covers $-4 < \eta < +4$ and $-5 < \eta < +5$ gives the mass dependence. Note that the SDE-DDE comparison can be done without full reconstruction of the states X; simply the information in the FSC hit/energy distributions can be compared.

Selecting events with hits in FSC- and FSC+ corresponding to low mass diffractive excitations also can enable the study of low mass double pomeron exchange $D\mathbb{P}E$. Rather than requiring *no* particles in the central $\Delta y = 8$ (or similar) units, we can select events with rapidity gaps $\Delta y \gtrsim 3$ on each side of a central state: $p + p \to X \oplus Y \oplus X$, where X are hits in the FSC's and Y is a central state with all particles in $-2 < |\eta| < +2$ or so (which can be of low mass, $\sim$ GeV/c^2). The $\mathbb{P}\mathbb{P} \to X$ cross section is of course much higher than the $\gamma\gamma$ and $\gamma\mathbb{P}$ cross sections (unless purely leptonic or C = -1 central states are selected). Ideally double pomeron processes should be studied with detection of both forward protons, and thus measuring their $\xi = 1 - x_F, t$, and ϕ. While we cannot do this (except possibly in combination with TOTEM detectors) $\mathbb{P}\mathbb{P}$ studies are still possible with proton dissociation. One can study the central state Y in terms of its mass distribution, charged and neutral multiplicity distribution and their mass dependence, particle correlations (including Bose-Einstein), particle types e.g. K/π ratios, K^0_s, and $\Lambda/\bar{\Lambda}$ (which should be identical), event shapes (sphericity S and thrust T etc.) and jet content to probe parton scattering in these events. In fact any generic high cross-section studies already done in pp and $p\bar{p}$ collisions can be redone in these $\mathbb{P}\mathbb{P}$ interactions or, if that terminology is not considered appropriate, in between two large rapidity gaps in hadron-hadron collisions (probably the type of colliding hadron is irrelevant). A start at such a study was done using the UA1 [19] and UA8 [20] detectors at the CERN $Sp\bar{p}S$ collider.

4.4 Elastic and inelastic π^+p and $\pi^+\pi^+$ scattering

As discussed in Ref. [21], very forward, high-x_F neutrons result from (virtual, or Regge) pion exchange, and the "tagged" pions can interact inelastically or elastically on the other proton. If a high-x_F neutron is detected on both sides $\pi^+\pi^+$ scattering can be studied. In the case of (quasi-real) $\pi^+\pi^+$ elastic scattering, the outgoing pions typically have $x_F(\pi) \sim$ 100's of GeV and small p_T, and can give signals in the FSC. This improves the study of pion interactions compared with what is possible with the ZDC alone.

5 Central exclusive production: jets, lepton pairs, $\gamma\gamma$, Υ, χ_b, etc.

Central exclusive [†)] production processes, CEP, are specifically $p + p \to p \oplus X \oplus p$ where X is a simple state completely measured, and the protons have high Feynman x_F and small $p_T \lesssim$ 1 GeV/c, and therefore remain in the beam pipe for hundreds of metres. They may only be detected by special "edgeless" detectors, such as those

[†)] Exclusive means no other particles are produced.

in TOTEM or the proposed HPS (High Precision Spectrometers) [8]. It has been shown, especially by CDF at the Tevatron, that even without detecting the scattered protons a valuable physics programme can be done using forward rapidity gap detectors. The $x_F = 1 - \xi$ (ξ is the fractional momentum loss) of a scattered proton is highly correlated with the size of an adjacent rapidity gap Δy, by the approximate relation $\Delta y = \ln(\frac{1}{\xi})$. Thus a gap Δy = 3 (4) implies a leading proton with $x_F \gtrsim$ 0.95 (0.98). Of course measuring the forward protons would provide more information, but much physics can be done integrating over these variables by simply requiring large gaps.

Four-momentum exchanges from coherently scattered protons over rapidity gaps $\Delta y \gtrsim$ 3 units can only be due to photon, γ, or pomeron, $I\!P$ exchange [‡)], so we only consider $\gamma + \gamma, \gamma + I\!P$ and $I\!P + I\!P$ interactions. A review of central exclusive production processes at pp and $p\bar{p}$-colliders is given in Ref. [6]. Two reactions of particular interest are $p + p \to p \oplus \gamma\gamma \oplus p$ [22] and $p + p \to p \oplus \mu^+\mu^- \oplus p$. The former is a valuable test of the calculations of exclusive Higgs boson production, as the QCD diagrams are identical, exchanging a t-loop with a q-loop and H with $\gamma\gamma$. It can probably only be studied with no other inelastic interactions in the bunch crossing [§)], hence at low luminosity. The forward protons are at too small ξ to be detected (in low-β running). The level 1 trigger is basically two central EM showers at large $\Delta\phi$, with no forward activity. Requiring FSC in veto (on both sides) reduces pile-up and cleans up the exclusivity requirements in the analysis. CDF have recently done such a study [15] and report three candidate events compared to the theoretical prediction [22] of $0.8^{+1.6}_{-0.5}$ events. The predicted cross section at the LHC for $E_T(\gamma) > 5$ GeV and $|\eta(\gamma)| < 2.0$ is 600 fb. Even though the *"effective single interaction luminosity"* [¶)] through the LHC luminosity growth period will probably only be a few hundred pb^{-1}, this still allows a statistically useful measurement, provided we have FSC-veto in the trigger.

The $p + p \to p \oplus \mu^+\mu^- \oplus p$ reaction [14, 16] can be used even in the presence of pile-up, thanks to there being no other tracks on the $\mu^+\mu^-$ vertex, $p_T(\mu^+\mu^-)$ being very small, and $\Delta\phi(\mu^+\mu^-) \sim \pi$. This is an important method of calibrating the forward proton spectrometers e.g. in the HPS [11] (the proton momenta are both well known from the measurement of the two central muons). $\Upsilon \to \mu^+\mu^-$ is not likely to be useful for this, because an unknown fraction are the products of χ_b radiative decays, and also the p_T and $\Delta\phi$ constraints are weaker. A level 1 trigger, based on two muons and vetoing on the FSC counters, ZDC, T1 and T2 detectors and the HF calorimeters, will select interactions with very large rapidity gaps and no pile-up. The rate of such events will be acceptable even with a low ($\sim$ 4 GeV/c) p_T threshold for muons, thus including $\Upsilon \to \mu^+\mu^-$ (for low p_T Υ). The CDF observations of exclusive lepton pairs and charmonium states [14] have been made possible thanks to their beam shower counters (BSCs). Having a "superclean" subsample with no pile-up is very useful to show experimentally what the $p_T(\mu^+\mu^-)$ distribution is for truly exclusive events. The experience in CDF on both these reactions is that beam shower counters, equivalent to our proposed FSC, are very important.

The physics programme may include a search for the production of mesonic states, such as heavy quarkonia χ_c [14], and χ_b in double pomeron, $I\!PI\!P$, reactions as well as photoproduction: $\gamma I\!P \to J/\psi, \psi(2S)$ [14], Υ [16]. Low mass states in $DI\!PE$ are interesting for glueball and hybrid meson searches [6]. A trigger based on energy in both FSC+ and FSC-, adjacent to rapidity gaps in HF calorimeters together with some energy deposition in the central region could be used for this study. Simulation results with the existing CMS detectors exist [23] for Υ photoproduction.

In addition to low mass exclusive central states (with all particles reconstructed, and mass $M(X) \lesssim$ 10 GeV/c^2), the same trigger will collect high mass double pomeron events, with $M(X)$ up to above 100 GeV/c^2. The jet content of such events, and in particular the subset of exclusive di-jets, is important as a probe of partons in the pomeron. Most such jets should be gluon jets. One can compare $I\!PI\!P$ collisions at $M(X)$ with pp and e^+e^- collisions at $\sqrt{s} = M(X)$. Some differences may be a larger content of η and η' mesons, and a smaller baryon fraction from the higher gluon content. Pomerons should have a smaller transverse size than protons, and this may manifest itself in an increase in double parton scattering ($2 \times (gg \to JJ)$) and perhaps in different (than

‡) Neglecting the odderon.

§) Using a tight $\Delta\phi(\gamma\gamma) = \pi$ and $p_T(\gamma_1) = p_T(\gamma_2)$ it might be possible to include events with one or two additional collisions.

¶) I.e. the integrated luminosity when only no-pile-up interactions can be used.

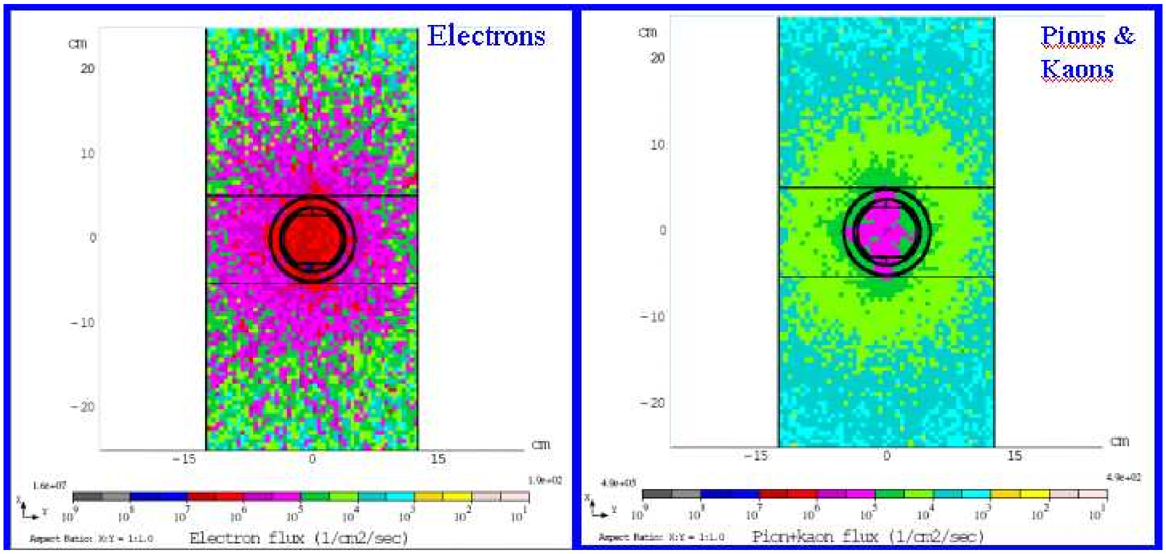

Figure 5: Transverse (x, y) view of deposited energy at a luminosity of 10^{32}cm^{-2}s^{-1}. Electrons and photons (left) and pions and kaons (right).

pp) Bose-Einstein correlations, which measure the size of the pion emission region. Double parton scattering, seen in 4-jet events having two pair-wise balancing dijets, is a probe of the unintegrated two-gluon density $G_2(x_i, x_j)$.

6 Simulations (MARS)

We have used the MARS simulation [24] for the generation of forward particles in pp collisions, as well as of beam halo and beam losses in the region, with a detailed simulation of particle showering in all materials (beam pipe, collimators, magnets etc.). This enables us to predict particle fluxes in the FSC detectors from both incoming and outgoing beam-generated showers, and to calculate the probability that non-diffractive and diffractive pp collisions have counts in this region, i.e. their efficiency at rejecting pile-up and their efficiency at detecting rapidity gaps.

The dimensions of the counters used in the simulation were ±12.5 cm horizontally (x) and ± 25 cm vertically (y) centred on the beam pipe, and at the z locations given in Table 1, around the MBX magnets.

Figure 5 shows (colour) a map of energy deposition in fluxes (cm^{-2}s^{-1}) for electrons (left) and hadrons (right) in showers. Figure 6 shows the average deposited energy per pp-collision for the seven locations; it is higher above and below the beam because of the elliptical pipe together with a strong dependence on the distance from the beams. The spectra of different particle types in the showers is shown in Figure 7 on the inside of the LHC ring (i.e. towards the LHC centre; up and down and outside are similar).

The radiation levels are calculated to be about 1750 Gy/fb^{-1} for the left and right detectors, and about 730 Gy/fb^{-1} for the up and down detectors. However the absorbed dose is a factor $\approx$ 25 higher close to the beam pipe than at the outer edges, as shown in Figure 5. Radiation hard scintillators can survive up to about 10^4 Gy, so they may need replacing after a few fb^{-1}. However these detectors are probably not very useful once $\langle n_X \rangle \gtrsim 5$ even at the end of a store.

6.1 Particles from collisions, non-diffractive and diffractive

DPMJET simulations have been done of particles created in non-diffractive (ND) collisions, defined for this purpose as having no particle with $x_F > 0.95$, for nominal low-β conditions. Forward particles were tracked through the magnetic fields until they hit the beam pipe and other material and shower, and the probability of

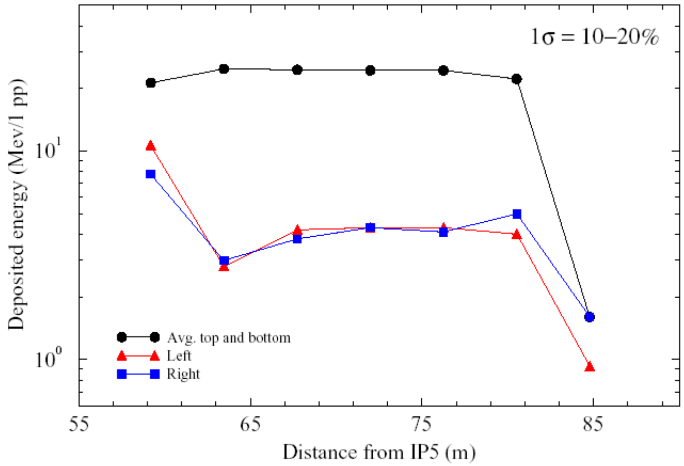

Figure 6: Average deposited energy, in MeV per pp-collision, at the seven locations simulated and separately for the inside (L) and outside (R) of the ring, and up and down (averaged).

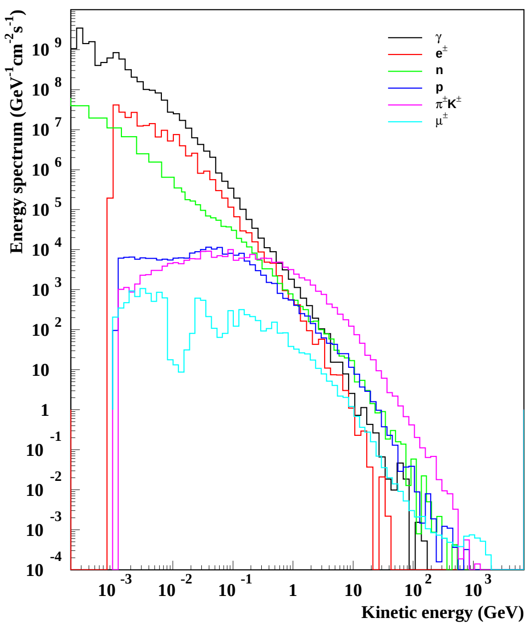

Figure 7: (Colour) Rate of different particles above 1 keV in showers generated by different particles at location 1, on the inside of the ring.

having hits in the FSC was determined. Figure 1 shows the detection efficiency for primary particles with p_T = 0.5 GeV/c as a function of η. For this p_T we have $x_F = \frac{1}{2}\frac{p_T}{p_{beam}}.e^\eta$ = 0.29 at η = 9 and 0.79 at η = 10. Studying the distributions of hits in these counters for single no-pile-up interactions will provide an approximate (but unique) test of forward particle production in DPMJET and other generators.

For pile-up vetoing at level 1 for diffractive collisions, one is more interested in the probability that a non-diffractive event is detected by one or more primary particles interacting. The simulation shows that a ND event has a probability of $\approx$ 0.68 of being detected on either side. Neglecting long-range correlations between the sides, we have the following probabilities per ND collision: P[00] = 0.325, P[10] = P[01] = 0.245, and P[11] = 0.185. (P[00] is the probability of having no signal in both arms, etc.) These numbers can probably be improved by adding counters between z = 85 m and 140 m. They are also quite sensitive to the generator; we are in the process of studying other generators, which will give an idea of the systematic uncertainty on these predictions.

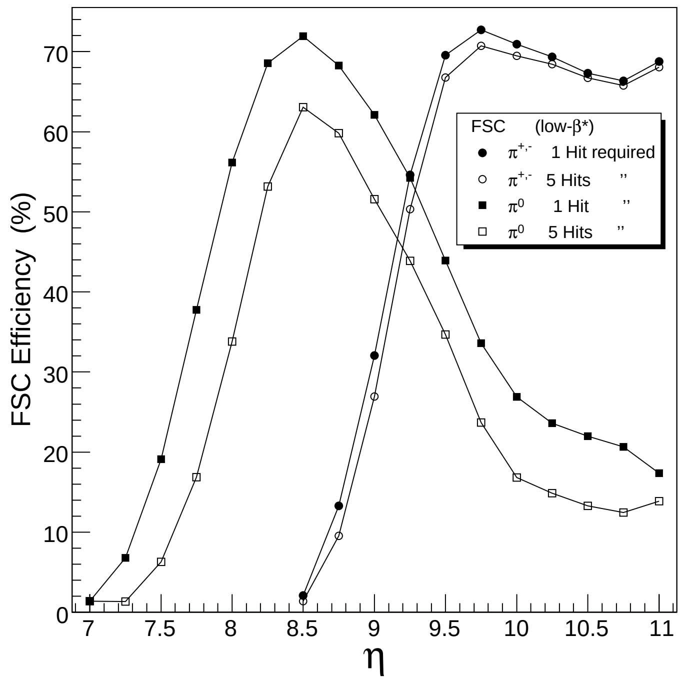

Figure 8: The efficiency (%) of the forward shower counters (FSC) for registering particle showers induced by primary $\pi^{\pm}$ and π^0 as a function of their pseudorapidity η (low β^* conditions).

Thus if the diffractive proton is accompanied by 1 (2,3,...) other inelastic collisions the probability of it passing a level 1 trigger which includes a FSC-veto (the OR of both sides) is 0.32 (0.10,0.03, ...). Additional counters at larger z will increase these efficiencies.

6.2 Tests of the simulations and refining production models

Data on very forward particle production at hadron collider energies is sparse, despite its intrinsic importance and value for understanding very high energy cosmic ray showers, for example. Small-angle spectrometers at the ISR measured π, K, p, Λ, etc. spectra for the full range $0 < x_F < 1$ up to $\sqrt{s}$ = 63 GeV, but this was not done at any higher energy hadron-hadron collider. The simulations we have used, DPMJET and MARS, and other simulation programs of pp collisions or the interactions and showering of particles along the beam line, have of course never been tested with collisions or forward particles at LHC energies (or even at the Sp$\bar{\text{p}}$S or Tevatron). Measuring rates and pulse height distributions and their correlations in the different FSC counters can provide tests of these models, uniquely in this very forward region (together with the ZDC for neutrals). The counters will be calibrated before installation to know the signals for one MIP.

These studies can make an invaluable and unique contribution to understand the magnitude and structure of the LHC machine backgrounds, which is essential if the nominal luminosity is to be achieved. Studies can also give an insight into the relative contributions (p-p, p-O, p-C, etc.) to the beam gas background rates [25], which may be important if the beam gas background becomes large or the vacuum is degraded.

7 Efficiencies

7.1 Efficiency for detecting rapidity gaps and for rejecting background

Together with the FSC we have included in our efficiency calulations the T1, T2, HF, CASTOR (one side only) and ZDC detectors. The TOTEM tracker T1 and the forward calorimeter HF span the region $3 < |\eta| < 5$. Tracker T2 and the CASTOR calorimeter cover $5 < |\eta| < 7$. The Zero Degree Calorimeter, ZDC, is between the two beam pipes just beyond their separation, and detects only neutral particles (mainly γ and neutrons) with $|\eta| > 8.5$. The program GEANT [26] has been used to simulate the beam line, including the beam pipes, beam screens, and magnetic elements. The running condition is for the standard low-β configuration, $\beta^* = 0.55$ m at $\sqrt{s}$ = 14 TeV. Simulations are being done for $\sqrt{s}$ = 7 TeV and 10 TeV.

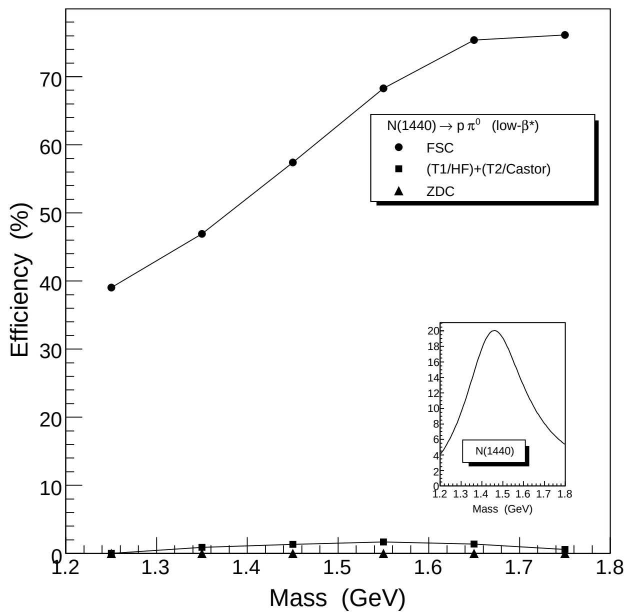

Figure 9: The detection efficiency for single diffractive events with $N^*(1440) \to p + \pi^0$ as a function of diffractive mass. We required at least five hits in any of the forward shower counters, or at least one track in the η region covered by T1/HF or T2/CASTOR, or a minimum energy deposit in the ZDC (see text).

7.2 Single particle efficiency of FSCs

The FSC detection efficiency for incident particles ($\pi^{\pm}, \pi^0$) was calculated as a function of pseudorapidity η. The requirement was at least one hit (alternatively at least five hits) in any of the FSC counters. A transverse momentum (p_T) distribution of the form $e^{-6.7p_T^2}.dp_T^2$ was assumed for the incident primary particles, corresponding to that obtained from PYTHIA 6.2 [27]. The efficiency of the FSCs for detecting charged particles from showers induced by the primary $\pi^{\pm}$ and π^0 is shown in Figure 8. For charged pions the efficiency is ~70% for $|\eta| > 9.5$, and it is nearly independent of the number of hits, for 1 - 5 hits per detector plane. For π^0 between 8 $< |\eta| < 9.3$ the efficiency exceeds 65% (50%) when at least 1 (5) hits are required. From the results presented in the following sections, this is sufficient for most anticipated physics studies.

7.3 Single diffraction detection efficiency

The detection efficiencies for single diffractive excitation, as simulated with PYTHIA 6.2, were calculated as a function of the diffractive mass. They were also calculated with PHOJET 1.1 [28] and found to approximately agree with those from PYTHIA. We required at least five hits in any FSC counter, or a track or signal in the $|\eta|$ region covered by T1, T2, HF, CASTOR or the ZDC. A "signal" in HF or CASTOR is defined as an energy deposit above 15 GeV, or above 500 GeV in the ZDC. The 500 GeV is nominal. Once data are obtained at low luminosity with a zero-bias (bunch crossing) trigger, it will be possible to optimise the cuts, for each detector, that provide the best separation between events with a true gap (no particles) and with particles. As in the CDF analysis, one can divide the zero-bias events into two classes: those apparently empty (no tracks and no large electromagnetic clusters) and those with interactions. For such studies it is very important to have zero-bias data recorded. The efficiency with FSC included is >90% for the lower mass region, and approximately 100% for masses above 10 GeV. Approximately 25% of the single diffractive cross section is for masses below 10 GeV (at $\sqrt{s}$ = 14 TeV, and scaling as $M(X) \propto \sqrt{s}$).

Simulations have also been made for exclusive diffractive baryon resonance production, such as $p + p \to p + N^*(1440)$ with $N^* \to p + \pi^0, n + \pi^+$, or $\Delta^{++} + \pi^-$. The efficiencies for detecting these final states are shown as functions of the diffractive mass in the following figures. For $N^* \to p + \pi^0$ the average efficiency is 70% (Figure 9), for $N^* \to n + \pi^+$ it is close to 100% (Figure 10), and for $N^* \to \Delta^{++} + \pi^-$ it is about 70%

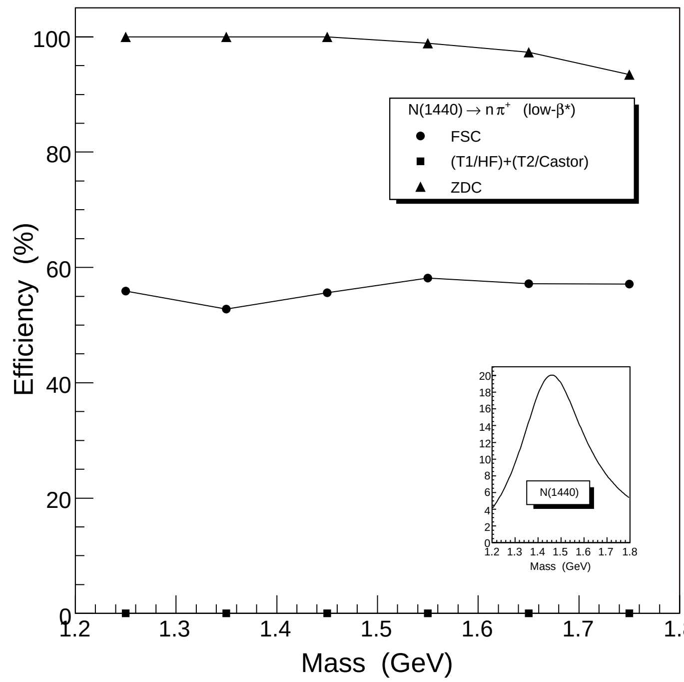

Figure 10: As Figure 9 for $N^*(1440) \to n + \pi^+$. The neutrons are detected in the ZDC and the π^+ on the FSC.

(Figure 11).

An approximate calculation of the diffractive mass can be made through its relation to the size of the rapidity gap adjacent to the scattered proton, although this has some model dependance. The relation depends on the p_T distribution (and hence $\langle p_T \rangle$) of the produced particles. The "adjacent rapidity gap" is defined as the gap between the scattered proton (close to the beam rapidity, $y_{beam} = 9.6$ at $\sqrt{s}$ = 14 TeV) and the nearest neighbour particle in rapidity. Larger rapidity gaps correspond to smaller diffractive masses. The approximate correspondence between the diffractive mass $M(X)$ and the pseudorapidity gap $\Delta\eta$ is $M(X) \sim e^{-\Delta\eta}$. It is instructive to consider the distribution $\frac{d\sigma_{SD}}{d\eta'}$, where η' is the position of the edge of the gap. To provide a more

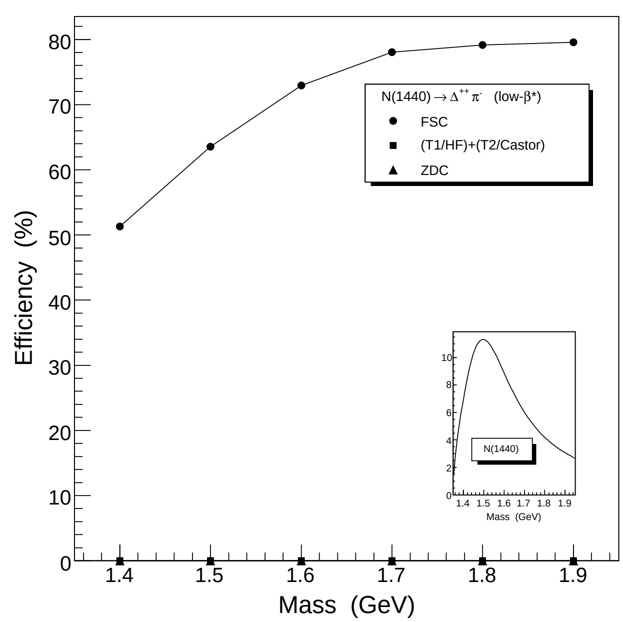

Figure 11: As Figure 9 for $N^* \to \Delta^{++} + \pi^-$.

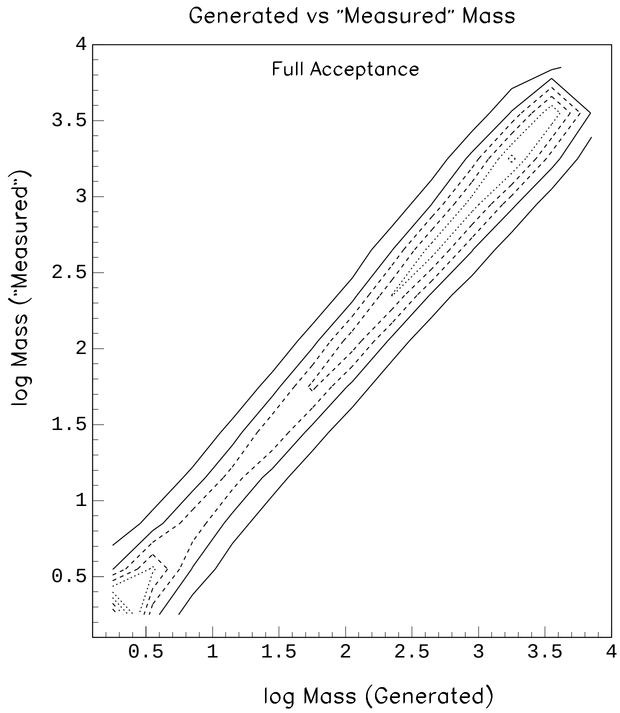

Figure 12: The diffractive mass (GeV/c^2) reconstructed ("measured") from the width of the rapidity gaps vs. the true (generated) mass. The lines show contours of equal density. All forward detectors including the FSC are assumed.

precise (although model dependent) measurement, the PYTHIA program has been used to determine the correlation between the diffractive mass and the size of the rapidity gap. Figure 12 shows the true diffractive mass $M(X)$ versus $\Delta\eta$ as determined by this method. To account for the measurement resolution, a Gausssian spread with $\sigma = 10\%$ has been added to the actual rapidity value. This is more than one unit at the largest values considered, and is considered to be an overestimate. Figure 13 shows the actual (generated) diffractive mass together with that calculated by the above method, for two cases: (a) for full η coverage, and (b) for the limited η range $|\eta| < 4.7$, i.e. the nominal CMS coverage. Clearly the wider the range of rapidity covered, the more accurately the diffractive mass can be determined from the rapidity gap size $\Delta\eta$.

Determination of the diffractive mass on an event-by-event basis from the dependence on $\Delta\eta$ is imprecise for low masses, $M(X) \lesssim$ 5 GeV/c^2. For single diffraction one relies largely on the FSC in this mass range. For central exclusive production the central detectors measure the mass with relatively good precision.

The efficiency of the FSC for detecting forward diffractive systems is high. However it is not 100%, and as a result the SDE and CEP studies will contain some background. A subtraction technique can be used to estimate this background and remove it. Data can be taken (a) with, and (b) without the use of the FSC for rapidity gap detection, with T1/HF and T2/CASTOR in veto in both cases. Case (b) includes increased background and characterises the FSC inefficiency. One can also (off-line) measure the content of individual FSC counters, which cover different η-ranges; this provides more differential tests of the diffractive event simulation. Measuring the various rates, with knowledge of the FSC efficiencies, the background contributions can be estimated and subtracted for different situations (e.g. different $M(X)$). Correlations between the counters can be determined and compared with expectations. An important check will be the independence of all the measured cross sections on the instantaneous luminosity.

7.4 Central exclusive production detection efficiency

Central exclusive production has two leading protons (assumed to be not detected in this programme) adjacent to rapidity gaps of $\gtrsim$ 4 units. Double pomeron exchange will dominate over γ exchanges. Central exclusive production was simulated using PHOJET1.1 [28] to generate the central diffractive mass, and PYTHIA to decay the central system into a gluon-gluon dijet. The detection efficiencies for central diffractive events were calculated as functions of the central mass $M(X)$. We required less than five hits in any FSC counter and no tracks

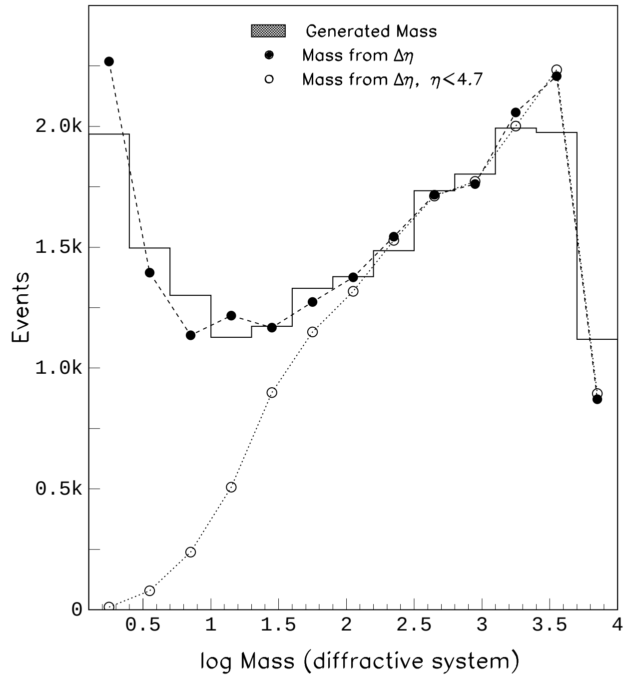

Figure 13: Distribution of the actual (generated) diffractive mass, log $M(X)$ (M in GeV/c^2), together with that calculated using the rapidity gap measurement for two cases: (a) full η coverage, and (b) for a limited η range, $|\eta| < 4.7$. Below $\sim$ 10 GeV/c^2 the FSC contain most of the particles.

in the η regions covered by the T1/HF and T2/CASTOR detectors. For central inclusive events, we studied the probability of having at least five hits in the FSC and the probability of having at least one track in the T1/HF or T2/CASTOR regions, as a function of the central mass $M(X)$. Requiring a FSC veto is seen to be very efficient, and requiring a T2/CASTOR veto is efficient for central masses $M(X) \gtrsim$ 120 GeV/c^2. Higher central masses often give hits in T1 and HF. However if one is interested only in the subset of central diffractive production with no particles beyond $|\eta|$ = 3, the T1/HF veto would be included.

We have also made simulations of the reactions $p + p \rightarrow p \oplus X \oplus p^*$ and $p + p \rightarrow p^* \oplus X \oplus p^*$, where p^* is a forward diffractive system. These reactions are similar to the "quasi-elastic" case where the protons do not dissociate, and the study shows similar results. The cross section of central diffractive production $\frac{d\sigma_{CD}}{d\eta_1 d\eta_2}$ (where η_1 and η_2 are the edges of the rapidity gaps) is particularly sensitive to the models of soft diffraction, and these measurements will provide valuable information on the parton content and sizes of various diffractive states. Measurement of the rapidity gap survival probability, $\hat{S}^2$, which determines the diffractive cross sections, is very important for understanding strong interaction processes. The present estimates of $\hat{S}^2$ are based on model calculations and must be experimentally measured.

8 Heavy ion collisions

The FSC should be very useful in heavy ion collisions, covering the forward rapidity regions where nuclear fragments from dissociation will make showers. In Pb-Pb running the luminosity per bunch crossing will be low enough that pile-up will not be an issue, even though the inelastic (hadronic) cross section will be $\sigma_{inel} \sim$ 7.7 barns. The electromagnetic photon-induced cross sections are about 30$\times$ larger: about 280 barns for e^+e^- production and 220 barns for single or double Coulomb dissociation with forward neutron emission. The total energy of the Pb-ions is huge ($\gtrsim$ 1000 TeV for the nominal 2.76 TeV/nucleon beam energy) and most of it emerges at small angles, through the beam hole in the HF. With such a high flux of very energetic nuclear fragments we can think of the FSC counters together with the upstream showering material as a sampling calorimeter; even with a few scintillator samples the energy resolution will be at a useful level. Together with the ZDC, which will measure mostly fragmentation neutrons, this fills the gap between CASTOR/HF and the ZDC. It will allow measurements of correlations between forward energy flow on the "+" and "$-$" sides and central event characteristics, and of course correlations between the "+" and "$-$" sides.

In addition to the inelastic Pb-Pb collisions with nuclear break-up, the coherent nuclear scattering with (one or both) nuclei emerging intact has a large cross section and interesting properties. The t-channel exchange can be photons (Coulomb scattering) which goes like Z^4 , or pomeron exchange which goes like A^2. However the $p_T, (t)$ of the scattered nuclei is extremely small (conjugate to the size of the nuclei) and not even Roman pot devices could detect them. Therefore elastic scattering cannot be measured, but central exclusive ultraperipheral processes [29, 30], Pb + Pb $\rightarrow$ Pb $\oplus X \oplus$ Pb, *can* be measured, using the FSC, ZDC, and perhaps CASTOR and HF(forward) on one or both sides in veto, together with central activity. This uses the heavy ions as intense sources of photons for photon-photon collisions. As we will not detect the coherently scattered nuclei, but integrate over t, $\gamma\gamma$ collisions will dominate over the other possible Pb $\oplus X \oplus$ Pb processes ($\gamma I\!P$ and $I\!P I\!P$). Events with a gap on only one side will be due to single Coulomb dissociation: Pb + Pb $\rightarrow$ Pb $\oplus X \oplus$ Pb* (where Pb* $\rightarrow$ nuclear fragments).

Therefore for a very modest additional cost, a substantial additional heavy ion physics program can be carried out. The optimal placement and number of scintillation counters may be different for a "heavy ion fragment calorimeter" than for a rapidity gap detector in pp running. This needs to be studied further, but there is some flexibility in the locations beyond the MBX magnets (at least until the cabling is specified). The FSC cannot be implemented in time for the November 2010 heavy ion run, but could be in for the next heavy ion run planned for late 2011.

9 An additional luminosity monitor

It is clearly advantageous for CMS to have several independent luminosity monitors, whose rates should always track each other, with any relative variations being understood. The pixel luminosity telescopes, PLT, detect a small fraction of the inelastic cross section and therefore have a rate that is relatively insensitive to pile-up, and thus is approximately linear in instantaneous luminosity. A coincidence between FSC+ (i.e. the "OR" of all counters on the "+" side) and FSC$-$ sees $\approx$ 20% of $\sigma_{\rm inel}$ (see section 6.1). That rate is therefore non-linear and saturates, and includes some coincidences between single diffractive events on the + and $-$ sides. It is better to consider the rate of completely empty bunch crossings, $R(0) = P(0) \times n_{\rm bunches}$, where $n_{\rm bunches}$ is the number of bunch crossings per second, and $P(0)$ is the probability that an inelastic collision is not detected in CMS. This method works best when the detector coverage is maximal, so that nearly all inelastic collisions give signals. Statistically, this can still work up to high (but not the highest) luminosities. Thus at $L = 2 \times 10^{33}$ cm^{-2}s^{-1} with $\sigma_{\rm inel}$ = 80 mb and 25 (50) ns bunch spacing, we expect $\langle n_x \rangle$ = 5 (10) inelastic collisions per crossing, and P(0) = $e^{-\langle n \rangle} = 6.7 \times 10^{-3} (4.54 \times 10^{-5})$, therefore $R(0)$ = 209,000/s (1420/s). We have $L = -\ln P(0) \times n_{\rm bunches}/\varepsilon\sigma_{\rm inel}$ where ε is the fraction of $\sigma_{\rm inel}$ detected (close to 100% with the FSC). So statistics is not an issue; rather it is a question of distinguishing inelastic collisions from empty crossings that have noisy detectors. This can be studied in data at more modest luminosities where the fraction of empty crossings is not very small. Thus we can use the FSC as a luminosity *monitor* by counting crossings with FSC+ and FSC$-$ empty, supplementing other luminosity monitors.

10 Monitoring of beam conditions

The FSC will have several other uses, including real-time beam halo monitoring of both incoming and outgoing beams, which are both in the same pipe at these locations. The separation of incoming and outgoing beams can be done by timing the scintillation counter signals at a few locations where their time separation is a few ns (the maximum being 12.5 ns, or 50 ns with 1404 bunches). The existing BSC in CMS has a time resolution of a few ns, with RG58 signal cables. This is likely to be a useful beam diagnostic. We are not yet in a position to know what rates to expect from incoming (or outgoing) showering beam halo particles. The outgoing halo monitoring is of course "contaminated" by particles from the pp collisions, but for CMS "protection" the incoming flux is more important. Measurements can be done of the rates with one beam in the machine, and of correlations rates with other monitors. Having some small directional Cherenkov counters [5] at the same z-location(s) gives an independent measure of incoming and outgoing fluxes separately, bunch-by-bunch if flagged by bunch number, and we propose to add these.

It goes without saying that it is crucial that the main central detectors are protected from unwanted beam in every way possible, and the FSC can join other monitors such as the BSC in providing prompt feedback. Rates in the monitors test beam halo simulations and can provide feedback to tune them. Recent studies [31] show that the dominant contribution to the beam-related background in CMS is expected to be beam-gas in the long straight section (LSS) 20 m - 200 m upstream of the interaction point, which is the proposed region for the FSCs. There are no other monitors in this region. They will give access to the rates in the IP5 LSS, giving a handle on the relative background contributions as a function of z, the distance from the IP, in a similar fashion to studies done by ZEUS [25]. They therefore will give an indication of the location of the beam gas interactions. They also offer the possibility of vetoing, or at least flagging, background events in CMS.

A present concern is out-of-time particles (sometimes called *albedo* or *afterglow*) [31]. Good timing of both the FSC and DCC counters should provide a useful diagnostic. Additional DCC can be added at locations where they would be most useful, if required.

11 Installation issues and schedule

These counters are probably most useful for diffractive physics while single interactions are still frequent ($L \lesssim 10^{33}$ cm^{-2}s^{-1} for 25 ns between bunches), and most useful for understanding beam halo and conditions "immediately", i.e. as soon as they can be installed. Their background monitoring function is of course not dependent on no-pile-up conditions, and this is especially true of the directional Cherenkov counters. If approved quickly they could be ready for an installation in a short ($\sim$ 4-6 weeks) shutdown in early 2011. They offer the possibility of vetoing backgrounds already during 2011 running if required.

The counters are a low risk activity for installation. The only items required for installation in the tunnel are HV and signal cables, the scintillation counters and their supports. Neither gas nor cooling is required, and there should be no maintenance required on shorter than annual time scales. Once installed and checked out, such photomultiplier-based systems usually need no access. The supports will be simple and safe, requiring no special tooling, and will be designed for easy, fast access. It is foreseen that the supports will be based on structures already used by beam instrumentation in the LHC tunnel. The readout will be standard and identical to that used already by HF, ZDC and BRM, and the trigger logic is simple (based on YES/NO logic).

We therefore ask the CMS Management Board to approve the addition of FSC and DCC as soon as possible. Even if final approval has to wait for the September meeting, an earlier statement of support would enable us to proceed with funding requests and preparation of purchase orders, etc.

12 Summary and Conclusions

Because of limited forward detector coverage, measurements of single diffractive and central diffractive cross sections in hadron-hadron collisions are very limited at higher $\sqrt{s}$ values than that of the CERN ISR ($\sqrt{s} \leq$ 63 GeV). The published single diffractive cross sections at the S$\mathrm{p\bar{p}}$S and Tevatron were obtained by extrapolation from the data collected in limited p_T and η regions. At the LHC, diffractive cross sections can be measured with the addition of forward shower counters, FSC, to the present CMS or ATLAS detectors to cover the lowest diffractive masses, below $\sim$ 5 GeV/c^2. With the proposed detector arrangement, important new data can be obtained by tagging single and central diffractive processes. The efficiency of the FSC system for detecting rapidity gaps is shown to be adequate for the proposed studies of single- and central-diffraction.

The FSC could also serve as a luminosity monitor by measuring the fraction of bunch crossings with no inelastic collisions, as well as monitoring beam conditions.

To summarise, we propose the addition to CMS of simple detectors in the very forward direction along both outgoing beam pipes, upstream of the ZDC. These are called Forward Shower Counters, FSC, as they detect showers produced by particles with $7 \lesssim |\eta| \lesssim 11$ hitting the beam pipe and surrounding material. This is an $|\eta|$ region in which we (as well as the other experiments) presently have no coverage for charged particles. The detectors proposed are simple scintillator paddles. They can be used in the level 1 trigger, either in veto as rapidity gap triggers or requiring hits for low-mass diffraction triggers. They will increase the total coverage of CMS close to $\Delta\Omega = 4\pi$, and improve the efficiency of the CMS diffractive, photon-photon, ultra-high energy cosmic ray and heavy ion physics programmes, both at the trigger level and in analysis, for events with no pile-up. They will give added value to the heavy ion program, both by measuring forward energy flow and forward rapidity gaps in coherent scattering. In addition they can be used as independent luminosity monitors, and beam condition (halo) monitors. They are relatively inexpensive, and can be prepared for installation in early 2011 if approved by Summer 2010.

This note has focused mainly on the physics issues. Technical aspects will be presented in more detail in Ref. [3].

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