

Precision proton spectrometers for CMS

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We plan to add high precision tracking- and timing-detectors at $z = \pm \sim 240\text{m}$ to study central exclusive processes $p + p \rightarrow p \oplus X \oplus p$ at high luminosity. This enables the LHC to be used as a tagged $\gamma\gamma$ collider, with $X = \ell^+\ell^-, W^+W^-$ and as a “tagged” gluon-gluon collider (with a spectator gluon) for QCD studies with jets. A second stage with $z \sim 420\text{m}$ would allow observations of exclusive Higgs boson production.

Adding forward proton spectrometers to CMS, with tracking precision $\sim 10 \mu\text{m}$ and timing precision $\sim 10 \text{ ps}$, enhances the physics potential of CMS by enabling the study of specific clean exclusive reactions, both Standard Model and beyond. A proposal to do this, now called Precision Proton Spectrometers, PPS, (it was previously FP420 [1]) has now been endorsed by the CMS Management and Collaboration Boards. In $p + p \rightarrow p \oplus X \oplus p$ the protons typically have $p_T \lesssim 1 \text{ GeV}$ and $\xi = 1 - (p_z/p_{beam}) \lesssim 0.05$, and they go down the beam pipes. They are deflected out of the beam by LHC magnets, and at 210 m are a few mm to the side. Silicon tracking detectors and timing detectors will be installed there using special movable vacuum chambers, either a sideways-moving beam pipe with a thin flat wall, or a Roman pot.

The four-momentum transfer from the protons can be carried only by a virtual photon, γ , or by a pomeron \mathbb{P} . The pomeron is a feature of Regge theory, a strongly-interacting color-singlet, at leading order a pair of gluons. High- Q^2 processes such as high- E_T jet production can be calculated as perturbative $gg \rightarrow gg$ together with another gluon exchange to cancel the color and allow the protons to emerge intact. The non-perturbative QCD involved (low- x gluon fluxes, Sudakov suppression of soft gluon radiation, rapidity gap survival probability) is tested by such measurements, and the same physics is needed to calculate exclusive H(125) production with $gg \rightarrow H$ through a top loop. Photon-pomeron interactions can produce exclusive Z-bosons through virtual q -loops. The two-photon process $\gamma\gamma \rightarrow W^+W^-$ is a window on BSM physics, being sensitive to triple- and quartic-gauge boson couplings. Indeed CMS has observed two candidate events with $e^\pm\mu^\mp$ and missing E_T and no other tracks, putting stringent limits on these couplings, but without detecting the protons. The PPS will enable much more data, and measuring the protons provides kinematic constraints and kills background.

Pomeron exchange is expected to dominate when the scattered protons have $\xi \lesssim 0.05$, corresponding to central masses (both protons detected): $M(X) = 3 \text{ GeV}$ at the ISR (glueball searches), 100 GeV at the Tevatron (jets) and up to 700 GeV at the LHC(13 TeV). Thus for the first time the LHC gives access to electroweak-scale masses; interesting channels are $X = Z, H, WW, ZZ, \mu\mu$ and of course jets. With only one proton detected, high mass single diffraction can be studied, but probably only in low pile-up runs when one can associate the proton with the right central collision (out of perhaps 40!).

The possibility of seeing exclusive Higgs production was first pointed out in Ref.[2] and

followed with a Letter of Intent [3] to the Fermilab PAC in 2000. At that time there were orders of magnitude differences in the cross section predictions and the LoI was not followed with a proposal; rather we made a series of measurements in CDF of exclusive $\gamma\gamma$ [4], χ_c [5] and dijet production, which reduced the uncertainty on $\sigma(H)|_{excl}$ to a factor about $\times 3$. It is much too small for the Tevatron, but can be a few fb at the LHC. Annual meetings at Manchester led to the FP420 project [1]. After 2006 ATLAS continued to develop it as AFP and CMS as HPS (now PPS).

Traditionally *Roman pots* have been used (since the CERN-Rome ISR experiment in 1971) to place detectors (in air) very close to the beams. Another technique, a sideways *moving beam pipe*, was used at HERA. Although there is less experience with an MBP, it has the advantages of allowing long (e.g. 50 cm) pockets for easily accessible detectors, there are no differential pressure forces, and there is less effect (through impedance) on the beams. In addition, at 420 m the deflected protons are in-between the two beam pipes and only MBPs can fit. Both options are still being pursued, and will (hopefully) be tested with high luminosity in 2015.

The PPS has to reach small cross sections (fb) and therefore to run with high pile-up conditions, with 30-40 interactions per bunch crossing (every 25 ns). There will be a large pile-up background in which two single diffractive protons from different collisions in the same bunch crossing are detected. Kinematic constraints can be applied, e.g. the missing mass from the incoming and outgoing protons must be consistent with the central mass, there should be no extra tracks $N(ass) = 0$ on the vertex (exactly two charged leptons for W^+W^- , no large k_T tracks to jet axes, etc.), and the longitudinal momentum (p_z) difference between the protons should equal the p_z of the central state. However a reduction factor $\sim \times 25$ can come from precision timing [2, 3]. If we can measure the *time difference* Δt between the protons with $\sigma(\Delta t) = \sqrt{2} \times \sigma_t = 15$ ps we have $\sigma(z_{pp}) = 2.25$ mm, to be matched with z_{vertex} . We have developed quartz Cherenkov counters (QUARTIC) [6] that satisfy the requirements of being edgeless on the beam side, radiation hard (quartz), segmented in 24 $3 \text{ mm} \times 3 \text{ mm}$ cells, and covering the needed area (18 mm in x and 12 mm in y). For the PPS we developed the *L-bar* QUARTIC, with an array of 24 bars with SiPMs. We have demonstrated $\sigma_t = 30$ ps in the test beam; the plan is to have four modules in line to have $\sigma_t = 15$ ps, with improvements possible. A 24-channel module is being prepared for beam tests in November.

To give an idea of the acceptance in ξ, t of a small detector at $z = +240$ m, Fig. 1a shows contours at several fixed t and ξ values in x, y . The inner edge is shown at 2 mm from the beam. At $\xi = 0.05$ one has 100% acceptance (all ϕ) out to $t = 2 \text{ GeV}^2$. Coulomb-scattered protons (e.g. photoproduction of $Z, \gamma\gamma \rightarrow W^+W^-$) have very small $|t|$ and thus $y \sim 0$, which could be used in a trigger. At $z = +250$ m the figure is slightly different, as angles θ_x, θ_y are important, so we plan two stations about 10 m apart to give $\sim 1\mu\text{rad}$ angular precision. Fig.1b shows the approximate acceptance, assuming 3 mm from the beam, in $M(X)$ for small $|t|$ for three cases: detector stations at $z = 240$ m on both sides (Stage 1), and together with additional stations at 420 m (Stage 2). Stage 1 is good for W^+W^- , other massive states and high E_T jet physics, while 420 m stations are needed to see H(125) with both protons. The configuration 420+240 is best for acceptance; 420+420 has the best mass resolution because of the 120 m of 8T dipoles between 240 m and 420 m. In Stage 1 we will study both QCD and EWK physics.

QCD: Exclusive di-jets and tri-jets with $M(JJ, JJJ)$ up to $\sim 800 \text{ GeV}$ can be studied. The dijets should be pure gluon jets (the LHC as a “gluon jet factory”), with a small component of $b\bar{b}$. Both jets can be b -tagged; this is an important test of the $J_z = 0$ rule which states that exclusive $q\bar{q}$ -dijets are forbidden for massless quarks. The rule is important in keeping the background to exclusive $H \rightarrow b\bar{b}$ small. The exclusive $q\bar{q}$ -dijet spectrum is important as it constitutes

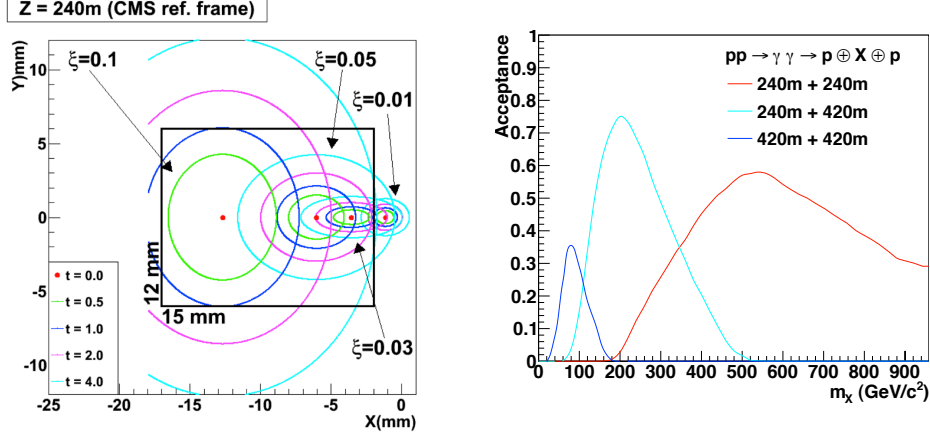


Figure 1: (a) Contours at fixed t and ξ in the x, y -plane at $z = 240$ m, low- β . (b) Acceptance in $M(X)$ for $p + X + p$ with Stage 1 detectors. It is shown for two-photon interactions (very small $|t|$).

the irreducible background to $H \rightarrow b\bar{b}$, as well as being a good test of the QCD mechanisms involved. Exclusive tri-jets can be ggg or $gq\bar{q}$, distinguishable (statistically) by kinematics (the former are more Mercedes-like), democratic between the five light-quark flavours. A foretaste is shown in Fig.2, one out of a few dozen events with both protons detected in TOTEM Roman pots and two jets with $E_T > 20$ GeV in CMS, and very little else. One week of dedicated low pile-up running could increase that data sample by a factor $>1000!$ Most QCD events will not be “golden” exclusive jets, but high mass $\mathbb{P} + \mathbb{P} \rightarrow$ hadrons, which is unexplored territory, not to be neglected. Study event shapes (spherical, very high multiplicity or ...), double parton scattering, heavy flavour production, etc. Developing event generators. like PYTHIA but for X in $p + X + p$ events is a challenge for theory and phenomenology and should lead to a better understanding of the strong interaction.

EWK: Searches for central exclusive production of MSSM Higgs are on the agenda [7]. It is also very interesting to measure $\gamma\gamma \rightarrow W^+W^-$. This uses the LHC as a photon-photon collider, with reach up to about 1 TeV, much higher than LEP and unique for the foreseeable future. Two W^+W^- candidates have been seen by CMS in the $e + \mu + \cancel{E}_T$ channel without the protons, with $N(ass) = 0$. With proton tagging other W -decay channels can be used, proton-dissociation can be excluded, and a few hundred events obtained. The two observed events already put much more stringent limits on anomalous quartic gauge couplings than previous experiments (LEP); this is a unique study. What about exclusive ZZ production, negligible in the Standard Model? Any exotic heavy states with vacuum quantum numbers (and even spin) that couple even indirectly (like H) to gluons may be visible. Even in Stage 1 there is some acceptance for $H(125)$ if only one proton is accepted (and the Higgs is boosted). But without both protons we do not have the kinematic constraints or Δt_{pp} to kill background. The background is very small in $H \rightarrow WW^*$ (leptonic decays) and $H \rightarrow \tau^+\tau^-$ but unfortunately the signals are tiny. So exclusive $H(125)$ studies need Stage 2. It seem obvious that we should

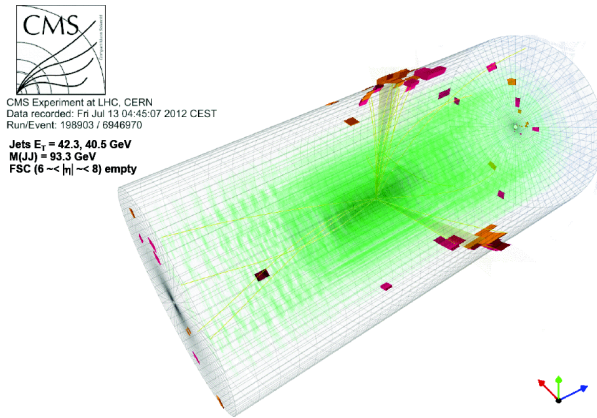


Figure 2: Dijet event recorded by TOTEM and CMS in low pile-up (90 m β^*) run at $\sqrt{s} = 8$ TeV. Two leading protons and two jets with $E_T > 20$ GeV were required.

study this particle every way we can, which should be enough justification for the modest outlay, even if its mass, spin and other properties will be already established. However its parity, which must be $P = +1$, may not have been measured without assuming CP-conservation in the Higgs sector. Even seeing it exclusively demonstrates $P = +1$ unambiguously. (If it has mixed parity that would be *very* interesting! The direct coupling $Hb\bar{b}$ is measurable in a clean way. Stage 1 can also measure Z -photoproduction in e^+e^- , $\mu^+\mu^-$ and $\tau^+\tau^-$, together with the continuum in these channels from $\gamma\gamma$. No surprises are expected, but these channels are good “tools” for calibrating the momentum scales of the PPS trackers as both proton momenta are predicted from the $\mu^+\mu^-$.

To conclude, the addition of small but very precise tracking and timing detectors far along the beams, PPS at CMS, opens up a whole new field in both QCD and electroweak physics for a very modest cost. We have developed suitable detectors, state-of-the-art but very small (cm^2) to cope with pile-up around 30 interactions per crossing, more for W^+W^- .

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