FERMILAB-PUB-09-049-E

Search for exclusive Z boson production and observation of high mass $p\bar{p} \to p\gamma\gamma\bar{p} \to p\ell^+\ell^-\bar{p}$ events in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

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We present a search for exclusive Z boson production in proton-antiproton collisions at $\sqrt{s} =$ 1.96 TeV, using the CDF II detector at Fermilab. We observe no exclusive $Z \rightarrow \ell^+\ell^-$ candidates and place the first upper limit on the exclusive Z cross section in hadron collisions, $\sigma_{excl}(Z) <$ 0.96 pb at 95% confidence level. In addition, we observe eight candidate exclusive dilepton events from the quantum electrodynamic process $p\bar{p} \rightarrow p\gamma\gamma\bar{p} \rightarrow p\ell^+\ell^-\bar{p}$, and measure the cross section for $M_{\ell\ell} > 40$ GeV/c^2 and $|\eta_\ell| < 4$ to be $\sigma = 0.24^{+0.13}_{-0.10}$ pb, which is the first measurement for this mass range and is consistent with the standard model prediction.

PACS numbers:

At the Tevatron $p\bar{p}$ collider it is possible to produce Z bosons exclusively, in association with no other particles except the p and $\bar{p}$: $p\bar{p} \to pZ\bar{p}$. The colliding hadrons emerge intact with small transverse momenta, p_T [1]. The process is predicted by the standard model (SM) to proceed via photoproduction. A radiated virtual photon fluctuates to a $q\bar{q}$ loop which scatters elastically by two-gluon exchange on the (anti)proton and materializes as a Z, as shown in Figure 1(a). The same mechanism gives

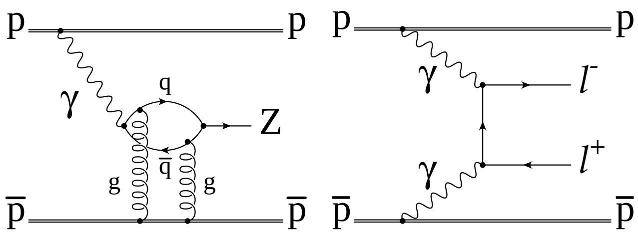

FIG. 1: (a) Exclusive photoproduction of a Z boson and (b) exclusive dilepton production via two-photon exchange at the Tevatron.

photoproduction of the vector mesons $J/\psi, \psi(2S)$ and Υ, which have been studied in ep collisions at HERA [3] and recently observed for the first time in $p\bar{p}$ collisions by CDF [4]. The SM cross section for exclusive Z production is predicted to be $\sigma_{excl}(Z) = 0.3$ fb [5], and is thus below the threshold for detection. An observation at the Tevatron would therefore be evidence for beyond SM (BSM) physics. A BSM theory of the pomeron $I\!P$ [6] predicts a much larger cross section, possibly orders of magnitude larger, but without a quantitative estimate. In this theory the pomeron couples strongly to the electroweak sector through a pair of color sextet quarks which contribute to the quark loop shown in Figure 1(a).

This Letter presents a search for exclusive Z production with the Z decaying to a $\mu^+\mu^-$ or e^+e^- pair, and a measurement of the cross section for exclusive $\mu^+\mu^-$ and e^+e^- production with dilepton invariant mass $M_{\ell\ell} > 40$ GeV/c^2 and $|\eta_\ell| < 4$. We use the CDF II detector at the Tevatron with $p\bar{p}$ collisions at a center of mass energy $\sqrt{s} = 1.96$ TeV. The exclusive dilepton process is expected in quantum electrodynamics (QED) through $p\bar{p} \to p\gamma\gamma\bar{p} \to p\ell^+\ell^-\bar{p}$, as shown in Figure 1(b). For the remainder of this Letter we will refer to this process as $\gamma\gamma \to \ell^+\ell^-$ for convenience. We have previously observed $\gamma\gamma \to e^+e^-$ with $10 < M_{ee} < 40$ GeV/c^2 [7] and $\gamma\gamma \to \mu^+\mu^-$ with $3 < M_{\mu\mu} < 4$ GeV/c^2 [4] and measured cross sections in agreement with expectations. The final state particles in exclusive dilepton events are identical to those in exclusive Z production with leptonic decay, the only difference in the signature being the $M_{\ell\ell}$ distribution and other kinematics. Agreement with the precise theoretical prediction therefore gives us confidence in our sensitivity to selecting exclusive Z bosons.

CDF II is a general purpose detector which is described in detail elsewhere [8]; here we give a brief summary. Surrounding the collision region is a tracking system consisting of silicon microstrips and a cylindrical drift chamber, the central outer tracker (COT), in a 1.4 Tesla solenoid. The tracking system tracks particles with $p_T \gtrsim 0.3$ GeV/c and pseudorapidity $|\eta| \lesssim 2$ [1]. Central and end-plug calorimeters cover the range $|\eta| < 1.3$ and $1.3 < |\eta| < 3.6$ respectively, with separate electromagnetic (EM) and hadronic (HAD) compartments. Outside the calorimeters, drift chambers measure muons in the region $|\eta| < 1.0$. The regions $3.6 < |\eta| < 5.2$ are covered by lead-liquid scintillator calorimeters called the miniplugs [9]. At higher pseudorapidities, $5.4 < |\eta| < 7.4$, scintillation counters called beam shower counters (BSC) are located along the beam pipe. Gas Čerenkov detectors covering $3.7 < |\eta| < 4.7$ measure the luminosity with a 6% uncertainty by counting inelastic interactions [10]. Tracking detectors in a Roman pot spectrometer [11], located 57 meters from the interaction point, can detect antiprotons with small p_T and $0.03 \lesssim \xi(\bar{p}) \lesssim 0.08$, where $\xi(\bar{p})$ is the fractional momentum loss of the antiproton [2]. These detectors were operational for approximately 30% of the data set used in this analysis.

For the $\gamma\gamma \to \ell^+\ell^-$ event selection we select a sample of $\ell^+\ell^-$ pairs in a kinematic region where this process has not previously been observed, with $M_{\ell\ell} > 40$ GeV/c^2 and lepton transverse momenta $p_T^\ell > 20$ GeV/c. For the exclusive Z search we select a subsample with an invariant mass close to the Z mass, $82 < M_{\ell\ell} < 98$ GeV/c^2, and $p_T^\ell > 25$ GeV/c. The $\mu^+\mu^-$ events are collected with a trigger requiring one muon with $p_T > 18$ GeV/c. Offline we require two candidate muons. One muon must be detected in the COT, the central calorimeter, and the muon chambers, and therefore has $|\eta_\mu| < 1.0$. To increase acceptance the second muon is only required to be detected in the COT and therefore has $|\eta_\mu| < 1.5$. Events consistent with cosmic rays are eliminated with an identification algorithm [12] that uses the timing of the COT drift chamber hits. The muon kinematics are found from the COT track momentum measurement. The e^+e^- events are collected with a trigger requiring one central electron with $p_T > 18$ GeV/c. Offline we require one candidate electron reconstructed in the central EM calorimeter and matched to a COT track, and a second electron reconstructed either in the same way or in the end-plug EM calorimeter where no matching COT track is required,

*Deceased

since the tracking efficiency is lower in this region. The central electrons have $|\eta_e| < 1.3$ and the end-plug electrons have $1.3 < |\eta_e| < 3.6$. The electron kinematics are found from the calorimeter energy measurement, but if a track is matched to the calorimeter cluster it is used to determine the electron direction. If no track is matched the z position of the interaction is measured from the other electron track, and is used to determine the kinematics. Events with two central electrons are denoted CC e^+e^- events, and those with one central and one end-plug electron are denoted CP e^+e^- events. The $\mu^+\mu^-$, CC e^+e^-, and CP e^+e^- events are each treated as separate final states which are ultimately combined together. With an integrated luminosity of 2.20(2.03) fb^{-1} in the electron(muon) channels we find a total of 317,712 candidate dileptons with $M_{\ell\ell} > 40$ GeV/c^2, of which 183,332 are in the Z region $82 < M_{\ell\ell} < 98$ GeV/c^2.

Starting with the dilepton samples we select events that are consistent with arising from exclusive production, by requiring that no other particles are produced in the collision. We veto events where any additional tracks are reconstructed in the COT or the silicon tracker, or where any of the calorimeters have a total energy deposition above that expected from noise. For this purpose the calorimeters are divided into five sub-detectors and the energy of all towers is summed, excluding those traversed by and surrounding the charged leptons, to give five ΣE values. Each ΣE is required to be less than a threshold, which is determined by studying two control samples: (1) events selected with a random bunch-crossing (zero bias) trigger with no tracks in the event, which should give distributions dominated by noise and (2) $W \to \ell\nu$ events with no detected tracks other than one from the charged lepton, which should give the distributions expected for non-exclusive $Z \to \ell^+\ell^-$ events with no additional tracks. The production mechanism for non-exclusive W bosons is very similar to that for Z bosons and the cross section for exclusive W production ($p\bar{p} \to n\,W\bar{p}$) is negligible, making them an excellent control sample. The chosen energy cuts are $\Sigma E < 3$ GeV in each of the East and West miniplugs, < 5 GeV in both EM plugs, < 7 GeV in both HAD plugs, and < 0.35 GeV in the central EM calorimeter.

These exclusivity cuts reject exclusive events that are in coincidence with additional inelastic $p\bar{p}$ collisions. It is therefore necessary to define an *effective integrated luminosity* $\int \mathcal{L}_{eff}$. The fraction of bunch crossings, selected from the zero bias trigger, that pass the exclusivity cuts is used to establish that $\int \mathcal{L}_{eff}$ is 20.6% of the total integrated luminosity. The efficiency is found from distributions reweighted to account for the difference in the instantaneous luminosity profiles between the zero bias events and the Z events. As a cross check we also estimate $\int \mathcal{L}_{eff}$ using Poisson statistics and the mean number of expected interactions per bunch crossing as a function of instantaneous luminosity to be 18.7% of the total integrated luminosity. Since the method using the zero bias data properly takes into account events with no interactions that fail the cuts due to noise in the calorimeters and fake reconstructed tracks, and events with a very soft interaction that pass the exclusivity cuts, we use 20.6% to determine $\int \mathcal{L}_{eff}$, and take the 9% difference between the two methods as a systematic uncertainty. We find $\int \mathcal{L}_{eff} = (403 \pm 45)$ pb^{-1} and (467 ± 50) pb^{-1} for the $\mu^+\mu^-$ and e^+e^- samples, respectively, where the uncertainty includes contributions from the difference between the two methods and the 6% uncertainty on the CDF luminosity measurement.

In order to reduce the background from $\gamma\gamma \to \ell^+\ell^-$ events where the proton dissociates into forward-going hadrons, we also make cuts on hits in the BSC detectors. An event is vetoed if any photomultiplier has hits above threshold, which occurs in 76% of zero bias events that pass all the other exclusivity cuts. This inefficiency is included in the acceptance.

A total of eight events pass the $\gamma\gamma \to \ell^+\ell^-$ selection criteria and no events pass the tighter exclusive $Z \to \ell^+\ell^-$ criteria. We use these events to measure the cross section for the $\gamma\gamma \to \ell^+\ell^-$ process and we set an upper limit on the cross section for exclusive Z production. To do this we need to determine the acceptance for reconstructing the events and the expected number of background events.

We calculate the acceptance for reconstructing $\gamma\gamma \to \ell^+\ell^-$ events using the LPAIR [13] Monte Carlo (MC) event generator together with a GEANT [14] simulation of the CDF detector. We apply corrections to account for changes in the acceptance due to internal Bremsstrahlung from the leptons, using the PHOTOS [15] MC event generator. The acceptance for the exclusive Z search is found from the PYTHIA [16] MC event generator, which simulates non-exclusive $Z/\gamma^* \to \ell^+\ell^-$ events. Corrections are applied to account for the difference in kinematics between non-exclusive and exclusive production. We consider the Z p_T distribution, which is assumed to be between 0 and 2 GeV/c for exclusive Z production, the Z rapidity y_Z distribution, obtained from Ref. [5], and the angular distribution of the leptons. The latter is assumed to be that for the decay of a spin-1 boson into two spin-1/2 fermions, which has the form $(1 + \cos^2\theta^*)$, where θ^* is the polar angle between the outgoing lepton and the proton direction in the boson rest frame.

The backgrounds to $\gamma\gamma \to \ell^+\ell^-$ events are non-exclusive $Z/\gamma^* \to \ell^+\ell^-$ events that pass the exclusivity cuts, and $\gamma\gamma \to \ell^+\ell^-$ events where the proton or antiproton dissociates and the products are not detected in the forward detectors. The former is found to be 0.28 ± 0.19 events by assuming the fraction of non-exclusive $Z/\gamma^* \to \ell^+\ell^-$ events passing the exclusivity cuts to be the same as that for non-exclusive $W \to \ell\nu$ events. This fraction is found from $W \to \ell\nu$ data samples, selected by requiring a high p_T lepton and large missing transverse energy, to be $(9 \pm 6) \times 10^{-7}$, where the uncertainty comes from the statistics of the samples. The latter is found from the LPAIR event generator, which also simulates $\gamma\gamma \to \ell^+\ell^-$ events where one or both (anti)proton dissociate. We use the minimum bias Rockefeller MC [17], which fragments the excited (anti)proton into a nucleon and pions, to predict the fraction of dissociation events that fail our exclusivity cuts due to particles in the region $|\eta| < 7.4$, which is the edge of the BSC acceptance. We predict a total background of 1.45 $\pm$ 0.61 events, where the uncertainty comes from varying the exclusivity cuts and observing how the number of events changes.

The backgrounds to exclusive Z events are non-exclusive $Z/\gamma^* \to \ell^+\ell^-$ events that pass the exclusivity cuts and exclusive $\gamma\gamma \to \ell^+\ell^-$ events that have $M_{\ell\ell}$ in the Z mass window. The former is found to be 0.163 $\pm$ 0.099 events using the method described above, and the latter is found from the LPAIR MC samples to be 0.492 $\pm$ 0.061 events. We do not include a dissociation background for the exclusive Z search; instead we quote an upper limit on the cross section for a Z produced with no other particles with $|\eta| < 7.4$.

There is no evidence of cosmic ray contamination after using the tagger described above. This is verified by inspecting distributions such as the timing of the COT drift chamber hits and the acolinearity of the lepton tracks. None of the candidate events are consistent with cosmic rays in any of the distributions.

We calculate a cross section for each final state ($\mu^+\mu^-$, CC e^+e^- and CP e^+e^-) using the formula

$$\sigma = \frac{N - N_{bck}}{\alpha \times \int \mathcal{L}_{eff}},$$

where N is the number of candidate events, N_{bck} is the expected number of background events, and α is the acceptance. Assuming equal rates for the $\mu^+\mu^-$ and e^+e^- processes, a combined cross section is found by forming a joint likelihood for the three final states, which is the product of the Poisson probabilities to observe N events in each final state. The joint likelihood is a function of the signal cross section, and all the systematic uncertainties are nuisance parameters. The likelihood is maximized as a function of the signal cross section, and the uncertainty is obtained by multiplying this likelihood by a prior that is flat for positive cross sections and finding the shortest interval containing 68% of the integral. We treat the background and luminosity systematics as correlated and the acceptance systematics as uncorrelated. The combined cross section for one lepton flavor is found to be $\sigma(p\bar{p} \to p\gamma\gamma\bar{p} \to p\ell^+\ell^-\bar{p}) = 0.24^{+0.13}_{-0.10}$ pb for $M_{\ell\ell} > 40$ GeV/c^2 and $|\eta_\ell| < 4$, which is in good agreement with the LPAIR prediction of 0.256 pb.

Some of the kinematic properties of the candidate events are given in Table I, where $p_T^\ell(1)$ and $p_T^\ell(2)$ are the lepton transverse momenta, $\Delta\phi_{\ell\ell}$ is the difference in the azimuthal lepton angles (i.e. 180° minus $\Delta\phi_{\ell\ell}$ is the deviation from back-to-back in the transverse plane) and $p_{\rm T}(\ell\ell)$ is the p_T of the lepton pair. The resolution of the lepton transverse momenta is approximately 3.5(1.4)% for electrons(muons). All of the events have lepton pairs that are back-to-back in azimuth with low $p_{\rm T}(\ell\ell)$ values, which is expected for $\gamma\gamma \to \ell^+\ell^-$ events. Figures 2(a) and 2(b) show the dilepton invariant mass and 180° minus $\Delta\phi_{\ell\ell}$ distributions for the data together with the QED spectrum from LPAIR and the GEANT detector simulation. A good agreement with the data is observed.

TABLE I: Properties of the eight exclusive dilepton events, in order of $M_{\ell\ell}$.

Final state	$M_{\ell\ell}$ (GeV/c^2)	$p_T^\ell(1)$ (GeV/c)	$p_T^\ell(2)$ (GeV/c)	180° - $\Delta\phi_{\ell\ell}$ (degrees)	$p_{\rm T}(\ell\ell)$ (GeV/c)
e^+e^-(CC)	40.9	20.4	20.1	0.38	0.26
e^+e^-(CC)	49.3	24.5	24.6	0.37	0.21
e^+e^-(CP)	50.4	20.5	20.2	0.05	0.31
e^+e^-(CP)	56.3	24.8	24.9	0.48	0.24
$\mu^+\mu^-$	58.6	24.1	24.4	0.17	0.32
$\mu^+\mu^-$	66.0	31.8	31.3	0.75	0.65
e^+e^-(CP)	67.1	24.1	24.0	0.51	0.24
e^+e^-(CP)	75.6	34.1	33.1	0.23	1.01

No events pass our exclusive $Z \to \ell^+\ell^-$ selection criteria, therefore we place an upper limit on the cross section of exclusive Z production at the Tevatron. We sum the three final states to give $\sum N = 0$, $\sum N_{bck} = 0.66 \pm 0.11$, and $\alpha \times \int \mathcal{L}_{eff} \times \mathrm{BR}(\ell^+\ell^-) = 3.22 \pm 0.38$ pb^{-1}. Here we have used $\mathrm{BR}(\ell^+\ell^-) = 3.37\%$ as the branching fraction of the Z to decay to one lepton flavor pair. We use a Bayesian limit technique to set an upper limit on the exclusive Z cross section of $\sigma_{excl}(Z) < 0.96$ pb at 95% confidence level. We also set an upper limit on the differential cross section with respect to y_Z at y_Z=0 ($\frac{d\sigma}{dy}|_{y=0}$) using the theoretical prediction of the y_Z distribution [5]. We take 0.257 as the ratio of $\frac{d\sigma}{dy}|_{y=0}$ to $\sigma_{excl}(Z)$ and find $\frac{d\sigma}{dy}|_{y=0} < 0.25$ pb at 95% confidence level.

At hadron colliders the lepton kinematics in $\gamma\gamma \to \ell^+\ell^-$ events determine the momenta of the forward (anti)protons through the relation $\xi(p_{1(2)}) = \frac{1}{\sqrt{s}} \sum_{i=1,2} p_T^{\ell_i} e^{+(-)\eta^{\ell_i}}$ [1, 2], where $\xi(p_{1(2)})$ is the fractional momentum loss of the forward (backward) hadron. In principle this relation could be used to calibrate both the momentum scale and resolution of forward proton spectrometers. In our eight candidate events, only one - that with $M_{\mu\mu} = 66.0$ GeV/c^2 - was from a period when the Roman pot spectrometer was operational and with $\xi(\bar{p})$ in its acceptance; a track is observed, as expected for exclusive dilepton production. This is an encouraging

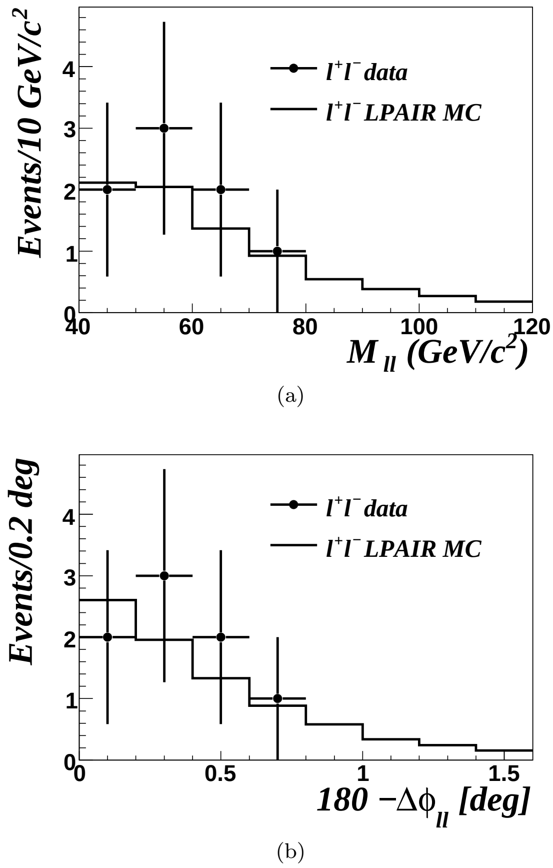

FIG. 2: (a) The dilepton invariant mass distribution, and (b) the distribution of 180° minus the difference in the azimuthal lepton angles for the data and the LPAIR prediction with the GEANT detector simulation, scaled to account for acceptance and luminosity.

sign that if enough exclusive dilepton events are observed at the large hadron collider (LHC), they may be used to calibrate forward proton spectrometers [18].

In conclusion, we have observed exclusive production of high mass ($M_{\ell\ell} > 40$ GeV/c^2) e^+e^- and $\mu^+\mu^-$ pairs and measured a cross section that agrees with QED expectations. We observe no candidates for exclusive Z production and put an upper limit on the photoproduction of Z at a level $\approx 3,000$ times higher than SM predictions. It should be noted that an observation at the LHC, where the SM cross section is predicted to be 13 fb [5], is more promising.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

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[1] A cylindrical coordinate system is used with the z-axis along the proton beam direction; θ is the polar angle and ϕ is the azimuthal angle. The transverse momentum p_T is the momentum perpendicular to the z-axis. We define rapidity as $y = \frac{1}{2}\ln(\frac{E+p_z}{E-p_z})$ where E and p_z are the energy and momentum parallel to the z-axis, pseudorapidity as $\eta = -\ln\tan(\theta/2)$ and transverse energy as $E_T = E\sin\theta$.

[2] A forward $\bar{p}$ has fractional momentum loss $\xi(\bar{p}) = 1 - \frac{p_z}{p_{beam}}$, where p_{beam} is 980 GeV/c and p_z is the $\bar{p}$ momentum after an elastic interaction.

[3] C. Adloff *et al.* (H1 Collaboration), Phys. Lett. B **541**, 251 (2002); S. Chekanov *et al.* (ZEUS Collaboration), Eur. Phys. J. C **24**, 345 (2002).

[4] T. Aaltonen *et al.* (CDF Collaboration), submitted to Phys. Rev. Lett., arXiv:0902.1271 [hep-ex].

[5] L. Motyka and G. Watt, Phys. Rev. D **78**, 014023 (2008).

[6] A. R. White, Phys. Rev. D **72**, 036007 (2005).

[7] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **98**, 112001 (2007).

[8] D. E. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 032001 (2005); D. E. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 052003 (2005). T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **77**, 112001 (2008).

[9] M. Gallinaro *et al.*, IEEE Trans. Nucl. Sci. **52**, 879 (2005).

[10] D. Acosta *et al.*, Nucl. Instrum. Meth. A **494**, 57 (2002).

[11] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **77**, 052004 (2008).

[12] A. V. Kotwal, H. K. Gerberich and C. Hays, Nucl. Instrum. Meth. A **506**, 110 (2003).

[13] J. A. M. Vermaseren, Nucl. Phys. B **229**, 347 (1983); S. P. Baranov, O. Duenger, H. Shooshtari and J. A. M. Vermaseren, *In *Hamburg 1991, Proceedings, Physics at HERA, vol. 3* 1478-1482 (see HIGH ENERGY PHYSICS INDEX 30 (1992) No. 12988).*

[14] R. Brun and F. Carminati, CERN Program Library Long Writeup, W5013 (1993) [unpublished].

[15] E. Barberio and Z. Was, Comput. Phys. Commun. **79**, 291 (1994); E. Barberio, B. van Eijk, and Z. Was, *ibid.* **66**, 115 (1991).

[16] T. Sjostrand *et al.*, Comput. Phys. Commun. **135**, 238 (2001).

[17] F. Abe *et al.* (CDF Collaboration), Phys. Rev. D **50**, 5535 (1994).

[18] M. G. Albrow *et al.* (FP420 R&D Collaboration) submitted to J. Inst., arXiv:0806.0302 [hep-ex].