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First Evidence of Exclusive Photon Pair Candidates in Hadron-Hadron Collisions

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Abstract

We have observed 3 exclusive $\gamma\gamma$ event candidates (i.e. two photon candidates with *nothing* else observed in the CDF detector) on a background of 0.09 ± 0.04 events. Such events have been predicted to occur through $gg \to \gamma\gamma$ through quark loops, while another gluon exchange cancels the color of the interacting gluons, and leave the (anti-)protons in their ground state. The events are also consistent with exclusive dimeson ($\pi^\circ\pi^\circ$ or $\eta\eta$) production. An upper limit on the cross section of $p\bar{p} \to p + \gamma\gamma + \bar{p}$ production is set with 95% CL at 410 fb. The probability of each event to be either $\gamma\gamma$, $\pi^\circ\pi^\circ$, or $\eta\eta$ is also discussed.

Contents

[1] Ph.D.Thesis

1 Introduction

QCD mediated exclusive interactions have tremendous potential as a method of observing new physics at the LHC. Before detailed conclusions can be drawn, theoretical predictions must be compared against experimental observation. No QCD mediated exclusive interaction has been observed in hadron-hadron collisions since the observation of exclusive $\pi^+\pi^-$ at the ISR [1]. There are many pitfalls in the extrapolation from the ISR to the Tevatron and LHC, so an observation at the Tevatron is critical to the progress of research project investigating exclusive interactions at the LHC (the FP420 project [2]). This is the motivation for the search for exclusive $\gamma\gamma$ interactions. Figure 1 shows the leading order diagram for QCD mediated exclusive $\gamma\gamma$ interactions.

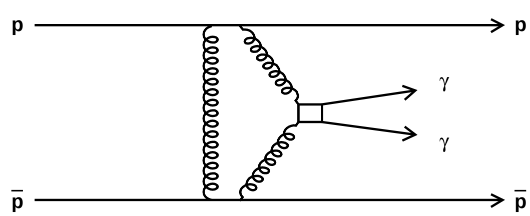

Figure 1: Leading order diagram for QCD mediated $\gamma\gamma$ interactions

In March 2001 some of us submitted a Letter of Intent to the Fermilab Director [3, 4] to add new very forward proton detectors to CDF to search for exclusive production of the Higgs boson, i.e the process $p\bar{p} \to pHp$ and *nothing else*. The observation of the exclusive Higgs process can produce many measurements not available in the inclusive Higgs production processes [5]. The 2001 LOI contains the first suggestion that exclusive $\gamma\gamma$ production might be possible and, if measurable in CDF could "calibrate" the diverse theoretical predictions.

1.1 From the Letter of Intent to the PAC

"Fortunately there is a process that is very closely related to exclusive Higgs production, namely the exclusive production of two photons by gg-fusion through a quark loop.

While in the Higgs case only the top quark loop is significant, in this case all quarks contribute, although the up-type quarks contribute a factor $Q^4 = 16$ more than the down-type quarks. The crucial similarity is that in both cases the final state, H or $\gamma\gamma$, is not strongly interacting. Therefore the non-perturbative parts of the process should be *identical* in exclusive $\gamma\gamma$ and H production. The ratio

$$\frac{d\sigma}{dM_{\gamma\gamma}}(M_{\gamma\gamma}) : \sigma_H(M_H)$$

should be theoretically well predicted (although we cannot measure both at the same Q^2), and related to the inclusive ratio (selecting the gg part of the $\gamma\gamma$ production). A calculation including helicity effects has not yet been done. We can measure $p\bar{p} \rightarrow (p)\gamma\gamma(\bar{p})$ as a function of $M(\gamma\gamma)$ and that should give us a reliable estimate of $p\bar{p} \rightarrow pH\bar{p}$. ... This study will be done without attempting to detect the p and $\bar{p}$, so all t and ϕ values are accepted. We are not likely to find any exclusive $\gamma\gamma$ events with the p and $\bar{p}$ detected.

We are able to start such a study now, without seeing the p and $\bar{p}$ but looking for events that have two photons, fairly well balanced in p_T, and nothing else visible in all the CDF detectors, including the forward Miniplugs and Beam Shower Counters. To do this we will trigger on two electromagnetic towers with $E_T > 5$ GeV (3 GeV if possible) with a Level 1 veto on the Miniplugs and BSC. At Level 2 (or 3) we require zero tracks and no energy in the hadronic calorimeters. These requirements will veto crossings with any additional interaction, so the useful luminosity is reduced by a factor $e^{-<n>}$ where $<n>= L\sigma_{inel}\Delta t, \sigma_{inel} = 60$ mb and $\Delta t = 396$ ns so at $L = 1.0 \times 10^{32}$ cm^{-2} s^{-1} we have $<n> = 2.4$ and $e^{-<n>} = 9\%$. (When we see the p and $\bar{p}$ we will not have to apply this factor.)

We have inclusive $\gamma\gamma$ data from Run 1 and are starting to look for evidence of single diffractive or double pomeron rapidity gap signals. However this is just a "warm up" exercise as we do not expect more than 10^{-2} (and it could be much less) of those events that come from gg fusion (not $q\bar{q}$ annihilation) to be exclusive."

1.2 Comments on LOI

Table II (not reproduced here) gave an estimate of 72 events with $M(\gamma\gamma) > 10$ GeV per fb^{-1}, *assuming* that 10^{-3} of inclusive pairs are exclusive. This is likely to be an over-estimate; we now know that the rule-of-thumb is that 10^{-3} of similar states have two large rapidity gaps (a classical "Double Pomeron Exchange" $D\mathbb{P}E$ signature), however only a fraction of these would be exclusive. But we might expect to see a few events.

The trigger we finally used had a L1 veto on the BSC but not on the Miniplugs, and (fortunately) we did not make any track requirement.

1.3 Theoretical Developments

The first theoretical published work, by the Durham group [5], on exclusive $\gamma\gamma$ production was stimulated by a discussion we had with Valery Khoze. The paper is mainly concerned with exclusive Higgs, dijet, $t\bar{t}$ and SUSY particles. About exclusive $\gamma\gamma$ production (in section 3.3) they say:

"At first sight, the subprocess $gg^{PP} \rightarrow \gamma\gamma$ appears attractive to serve as an alternative gg^{PP} luminosity monitor for the exclusive double diffractive processes. However it turns out that the event rate is too small" They find $\sigma(30^\circ < \theta^*_\gamma < 150^\circ) \simeq 0.3(0.04)$ pb for $M_{\gamma\gamma} \sim 50(120)$ GeV. They did not give estimates for the lower masses of relevance here.

Later the Durham Group made a refined calculation of fully exclusive $\gamma\gamma$ production [6]. They calculated a cross section, dominated by the $gg \rightarrow \gamma\gamma$ process, of $\sigma_{\gamma\gamma}(E_T(\gamma) > 5$ GeV, $|\eta(\gamma)| < 1.0(2.0)) = 38$ fb (90 fb). The probability of events with proton dissociation passing our forward rapidity cuts (especially the BSC) is said to be small, "the admixture of processes with incoming proton dissociation is not expected to exceed 0.1%". They also calculate that the contribution from quark exchange diagrams is $< 5\%$ and from $\gamma\gamma \rightarrow \gamma\gamma$ is $< 1\%$. They say "Therefore indeed this process (exclusive $\gamma\gamma$) can be used as a "standard candle" to check and to monitor the exclusive gg^{PP} luminosity that has been used for the prediction of the Higgs cross section." See also Refs [7] for papers on exclusive processes. There are no other predictions of the fully exclusive process.

This note depends heavily on CDFNOTE 7930 [8], the observation of exclusive electron pairs. Both notes use essentially the same data set, event selection, efficiencies, and very similar background estimation techniques. We will summarize the essentials of the analysis here, but refer to [8] when methodology is the same.

2 Monte Carlo

The Exhume Monte Carlo [9], written by Pilkington and Monk, is based on the Durham calculation. It is the only generator to simulate the exclusive two photon process.

3 Event Selection

3.1 Trigger and Good Run Lists

The DIFF_DIPHOTON trigger and good run lists used for this analysis are explained in see Ref. [8]

3.2 Photon ID Cuts

The exclusive ee analysis uses both the central and plug regions. Because the tracking efficiency drops in the plug region, ee events with no tracks would become an additional background to the $\gamma\gamma$ events. In order to minimize background this analysis will only include the central region. Other than the η range and the tracking requirements, the ID cuts in this analysis are identical to the ID cuts used in [8]. For clarity, the central region of Table 1 is copied here from [8].

3.3 Cosmic Ray Cut

The cosmic rays cuts are the same as the ee analysis.

3.4 Exclusivity Cuts

The choice of cuts to define empty regions of the detector is described in Ref [8].

Cut	Threshold
Energy (GeV)	$E_t > 5.0$
Shower Shape	CES χ^2 <20
Had/Em Ratio	< 0.055 + 0.00045*E
CES Fiducial	$\|x\|$ <21.0, 9.0<z<230.0

Table 1: Details of central photon ID cuts (energy units are GeV).

Cut	Threshold
$\Delta\cot(\theta)$	<0.1
XY Separation	<0.9 cm

Table 2: Conversion Cuts.

3.5 Track Cut

Since photons have a non-neglibible probability of converting into an ee pair, the tracking cut accounts for this possibility. The tracking cut requires that there either 0 or 2 tracks associated with each photon candidate, and when there are 2 tracks they must be a conversion pair, see Table 2. An additional requirement that there be no other tracks in the event is imposed. 3 events pass this selection criteria

3.6 Signal Sample

The 3 candidate events are listed below. Comparison of the properties of these three events to Exhume MC expectations is shown in Figures 2 to 6. Event display pictures of the 3 events are shown in Figures 7 to 9.

```
Run: 191089 Event: 127812
 Electron 1: (Q)Pt=(0)n/a Et=6.825 det eta=0.4429 eta=0.4429 phi=6.111
 Electron 2: (Q)Pt=(0)n/a Et=5.864 det eta=0.1948 eta=0.1948 phi=2.827
 dphi=2.999 angle=2.487 mass=12.7 xiP=0.009058 xiPbar=0.004698
Run: 200284 Event: 346775
 Electron 1: (Q)Pt=(1)3.003  Et=5.414 det eta=0.6686 eta=0.6686 phi=1.66
 Electron 2: (Q)Pt=(0)n/a    Et=5.002 det eta=-0.06527 eta=-0.06527 phi=4.858
 dphi=3.085 angle=2.604 mass=11.2 xiP=0.007781 xiPbar=0.004139
Run: 199189 Event: 6276945
 Electron 1: (Q)Pt=(0)n/a  Et=5.999 det eta=-0.4429 eta=-0.4429 phi=1.912
 Electron 2: (Q)Pt=(0)n/a  Et=5.123 det eta=0.2188 eta=0.2188 phi=5.054
 dphi=3.141 angle=2.962 mass=11.76 xiP=0.005218 xiPbar=0.006866
```

3.7 Signal Sample Discussion

There is one interesting event that did not make it into the signal sample. The event is shown in Figure 10. This event looks like exclusive $\gamma\gamma$, but is excluded from the signal sample by the tracking cut. The tracks appear to be from an ee pair produced in the photon's interaction with the material of the SVX.

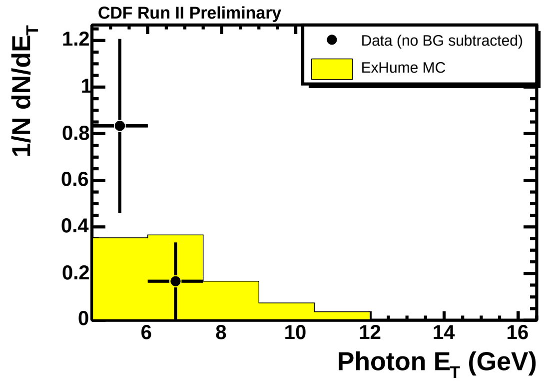

Figure 2: E_T of photons in signal sample (points) compared to Exhume MC (line)

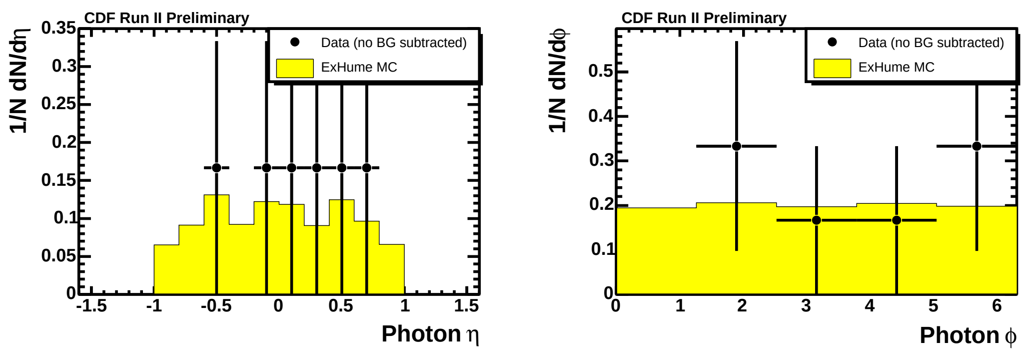

Figure 3: eta (left) and phi (right) of photons in signal sample (points) compared to Exhume MC (line)

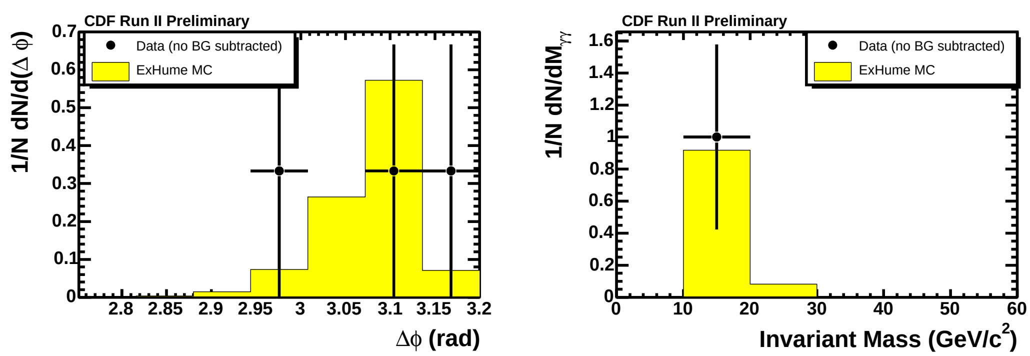

Figure 4: Delta ϕ (left) and invariant mass (right) of photon pairs in signal sample (points) compared to Exhume MC (line)

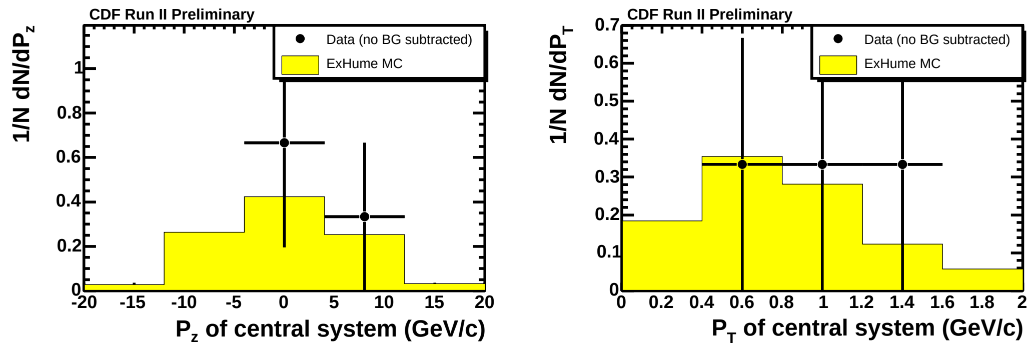

Figure 5: p_z and p_t of photon pairs in signal sample (points) compared to Exhume MC (line)

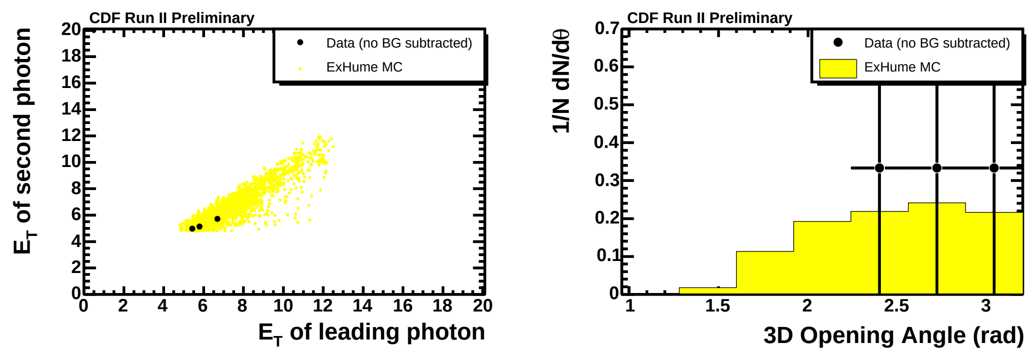

Figure 6: E_T vs E_T (left) and 3d opening angle of photon pairs in signal sample (points) compared to Exhume MC (line)

4 Efficiencies

Most of the efficiencies for this analysis are the same as [8]. The two differences are the tracking efficiency is not applied, and the final state radiation efficiency is changed to the conversion efficiency, ε_{conv} because photons do not undergo bremsstrahlung but they do convert to electron pairs and interact with the material in the tracking volume.

4.1 Conversion Efficiency

The conversion efficiency accounts for events that convert to ee pairs as well as events that produce electrons in the detector by Compton scattering off the tracking material. The conversion efficiency is measured by applying the exclusivity cuts to the Exhume MC events that have been put through cdfSim version 5.3.3 and ntuplized with stntuple dev_243. Table 3 shows the number of events that pass each exclusive cut (starting from the number of events with 2 central photons). 2340 out of 2577 events pass all the exclusive cuts, and 2249 out of the 2340 events pass the tracking cuts. Therefore, the conversion efficiency is $\varepsilon_{conv} = 2249/2577 = 0.87$. The systematic uncertainty on this

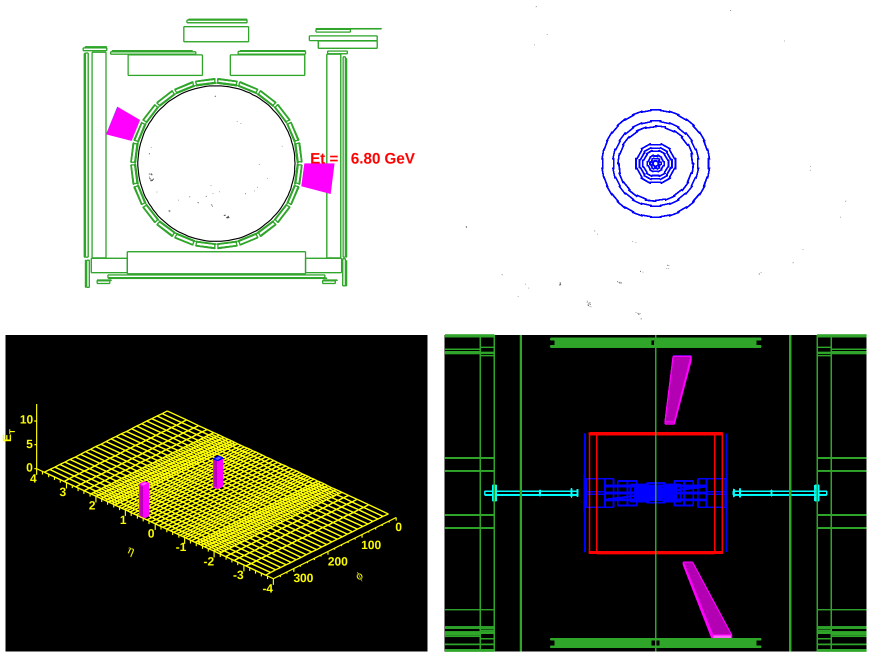

Figure 7: Event display of run 191089 event 127812.

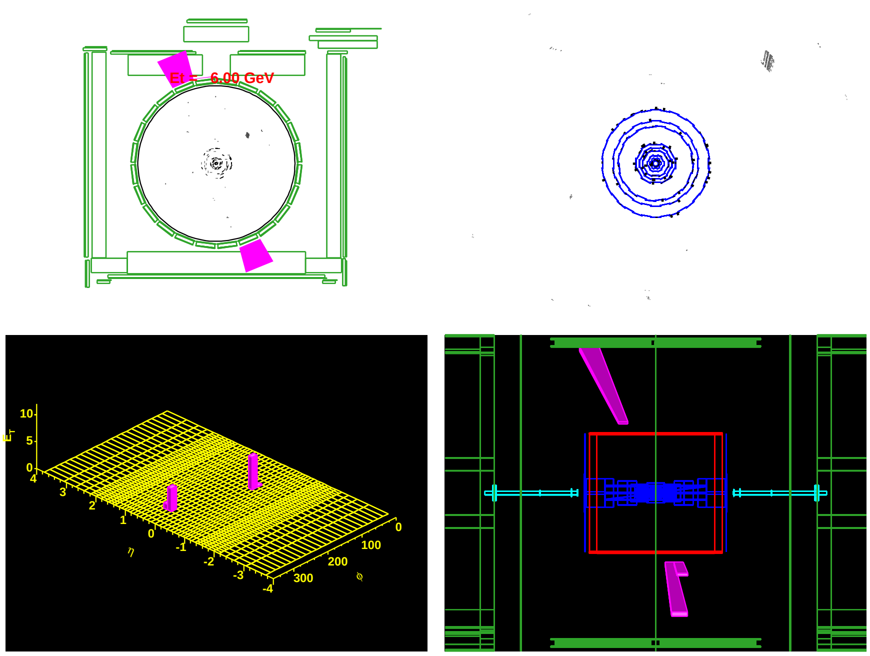

Figure 8: Event display of run 199189 event 6276945.

efficiency is dominated by our knowledge of material in the tracking volume, which is

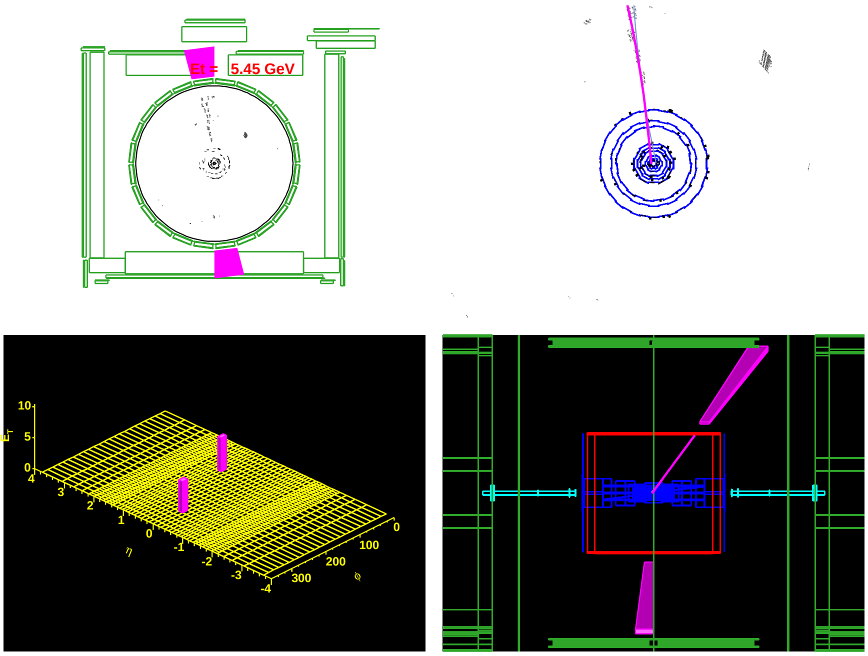

Figure 9: Event display of run 200284 event 346775 (note the conversion).

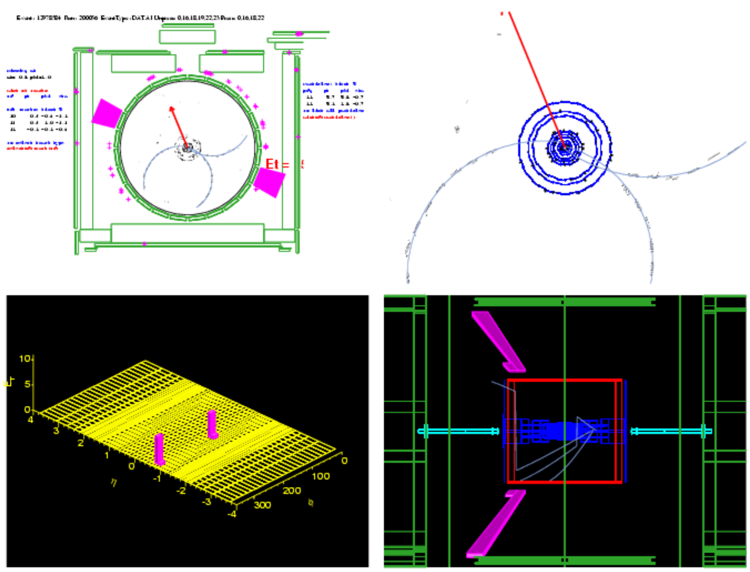

Figure 10: Event display of run 2000056 event 12978584 (not part of signal sample).

Sample	Number of Events
Two-candidate events	2577
Pass BSC (offline)†	2577
Pass MiniPlug†	2577
Pass FwdPlug	2564
Pass MidPlug	2563
Pass EndWall	2503
Pass Central	2340
Pass Tracking	2249

Table 3: Number of Exhume MC events with both photons in $|\eta| < 1$ passing exclusive cuts (sequential). †MP and BSC are not yet simulated in cdfSim.

estimated to be 10% [10].

5 Backgrounds

The backgrounds considered are: exclusive e^+e^- production, exclusive dimeson ($\pi^\circ\pi^\circ$ and $\eta\eta$) production, cosmic rays, non-exclusive events, and dissociation. The cosmic background is negligible as in the ee case, the remaining backgrounds are discussed in the following sections. Since the exclusive dimeson production background can not be reliably determined, it is discussed in greater detail in Section 7

5.1 Exclusive e^+e^- Production

Exclusive e^+e^- events could be misidentified as $\gamma\gamma$ events if both charged electron-tracks are not detected or both the electrons undergo hard bremsstrahlung. This contribution is estimated by applying a 5% electron mis-identification rate to the exclusive e^+e^- sample from [8], which contains 8 events that have both electrons within $|\eta| < 1$. This results in a background of 0.02 ± 0.02 events. For 5 of the 6 shower candidates the COT shows not only no tracks but no hits in line with the showers. In the sixth case an e^+e^- pair from a photon conversion is seen, with the sum of the two momenta equal to the calorimeter shower energy.

5.2 Non-Exclusive Background

Non-exclusive events where some particle(s) passed through the cracks in the calorimetry coverage or below the noise thresholds, are a background to the exclusive signature. The same methodology as the ee analysis is applied here, except that the requirement that there be no tracks (other than conversions) virutally eliminates all background events. Figure 11 shows that there are the three exclusive signal events, and only one potential background event (shown in Figure 12). The background in the zero bin is estimated by assuming the same shape of the background shape in the exclusive e^+e^- analysis [8], but normalized $\gamma\gamma$ distribution, resulting in 0.06 ± 0.03 background events. An estimation using a flat distribution over the smallest range containing any events (1-14) yeilds a similar result.

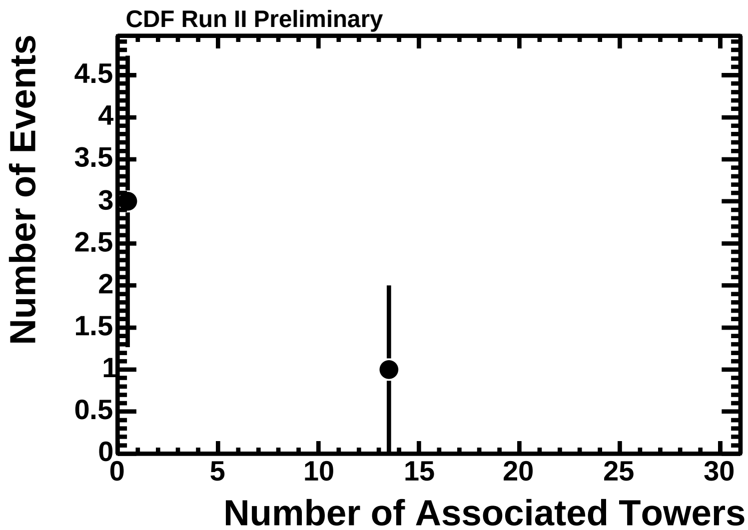

Figure 11: Number of associated clusters in two-candidate events after tracking cut is applied.

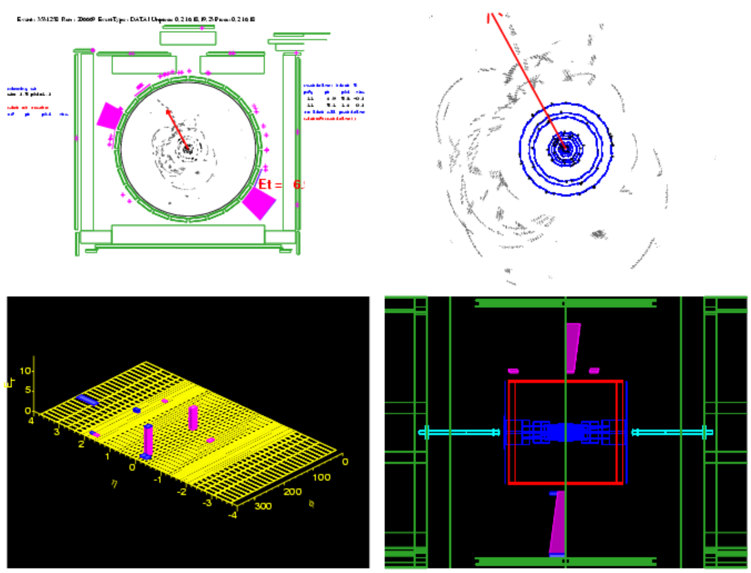

Figure 12: Event display of run 206669 event 3531258. This is the single background event in Figure 11, and looks like a $\gamma\gamma$ event with a soft interaction (exactly what the exclusivity cut is expected to eliminate).

5.3 Dissociation Background

The dissociation background for $\gamma\gamma$ events is expected to be lower than that of ee events because there are fewer (and higher mass) excitation states available to the proton in the exclusive QCD mechanism. Almost all N and Δ resonances are available for excitation in the QED mediated exclusive processes, while only $N(1440)$, $N(1710)$, and $N(2100)$ are available to the QCD mediated exclusive processes due to the spin selection rule [11]. The KMR estimation is that there should be on the order of 0.1% dissociation background, which is ≤ 0.01 events in the three candidate sample. We take this background to be 0.01 ± 0.01

A study analogous to the ee dissociation background study was done by Sergei Striganov using the DPMJET MC (written by S, Roesler, R. Engel and J. Ranft). The conclusion of the study was that the fraction of dissociation background events in Pomeron exchange events is 1.5%. Since DPMJET does not simulate exclusive $\gamma\gamma$, applying this study to this analysis requires that we assume there is a factorization between the dissociation of the proton and the content of the central system. We know this assumption is incorrect at some level, because the exclusive process has the additional requriment of spin-selection. This will yeild an overestimate in the DPMJET result. The DPMJET estimation corresponds to 0.05 events in the 3 event signal sample. Since the DPMJET result is known to be an overestimate, and is in the order as the KMR estimate, we take the more relieable KMR estimate as the background.

5.4 Indistinquishable Physics Processes

There are physics process other than $gg \rightarrow \gamma\gamma$ that can produce an exclusive $\gamma\gamma$ final state. KMR calculates that the contribution from quark exchange diagrams is $< 5\%$ and from $\gamma\gamma \rightarrow \gamma\gamma$ is $< 1\%$ [6]. These processes are not experimental backgrounds, and thus, will not be treated as such.

5.5 Dimeson Background

Backgrounds to diphoton production arise from exclusive pair production of neutral mesons $\pi^\circ\pi^\circ$ and $\eta\eta$ ($\pi^\circ \rightarrow \gamma\gamma$ or $\eta \rightarrow \gamma\gamma$)[2]. These processes cannot be distinguished on an event-by-event basis from diphoton production. Since the cross sections are unknown we cannot directly calculate these backgrounds. Thus we cannot rule out the possibility that all events are from such a background source. We can use the CES χ^2 and number of CES clusters to evaluate the probability that each event comes from a γ or meson, but the statistical uncertainty on this evaluation is huge with only three events. Therefore, we calculate an upper limit on the cross section for $p\bar{p} \rightarrow p + \gamma\gamma + \bar{p}$ based on the assumption that all three events are $\gamma\gamma$, and then we discuss the probability that each event comes from $\gamma\gamma$ or dimeson production. It should be noted that the exclusive production of dimesons would also an interesting observation.

5.6 Background Summary

The sum of all calculable (*not including dimeson production*) backgrounds discussed above is 0.06 ± 0.03. A summary of the backgrounds is shown in Table 4.

[2]Note that π° η is forbidden by both Isospin and G-parity, and exclusive $p\bar{p} \rightarrow p + \gamma\pi^\circ(\eta) + \bar{p}$ cross section is negligible on theoretical grounds [12].

Background	Value
Cosmic	neglibible
Exclusive e^+e^-	0.02 ± 0.02 (sys)
Non-exclusive Events	0.06 ± 0.03 (sys)
Dissociation	0.01 ± 0.01 (sys)
Total	0.09 ± 0.04 (sys)

Table 4: Summary of calculable backgrounds

Quantity	Value
N_{sig}	3
N_{bkgd}	0.06 ± 0.03
$\mathscr{L}$ (pb^{-1})	532 ± 32
ε_{total}	0.040 ± 0.007

Table 5: Summary of numbers put into the cross section upper limit calculation.

6 Cross Section Upper Limit

Assuming that all three signal candidates are exclusive $\gamma\gamma$, the cross section upper limit for exclusive $\gamma\gamma$ production within E_T >5 GeV and $\eta < 1$ can be calculated. The relevant numbers are summarized in Table 5.

Using a Bayesian approach, assuming a flat prior for the cross section and Gaussian distribution for the uncertainties, the 95% confidence level upper limit corresponds to 8.8 events:

$$\sigma_{exc,\gamma\gamma}^{E_t>5\ GeV,\eta<1} < \frac{8.8}{\varepsilon_{total}\mathscr{L}} = 410 \text{ fb} \qquad (1)$$

While this is an order of magnitude above the theoretical cross section from the Durham group of 40 fb (uncertainty factor of 3 to 5), it does put severe constraints on some of the earlier predictions for exclusive Higgs production which were much higher.

We can calculate the probability that the 3 candidate events come from something other than $\gamma\gamma$ or dimeson production. The fraction of a Poisson distribution with a mean of 0.09 ± 0.04 background events (Gaussian error assumed) that have $\geq$3 events is 1.7×10^{-4}, corresponding to 3.7 σ [13].

7 Discussion of $\gamma\gamma$ vs. Dimeson Events

We now discuss the three candidate events as possible $\gamma\gamma$ or dimeson production. The selection efficiency for a π° is only 13% lower than that of a photon while the selection efficiency of an η meson is about 35% lower.

The CES χ^2 and number of clusters can be used to discriminate between prompt photons and π° / $\eta \to \gamma\gamma$ showers. A CES cluster is formed using 11 adjacent strips or wires in the CES. The distribution of energies of the wires/strips within this cluster is used to form a χ^2 by comparing it to the expectation from test beam electrons. We

Event	S	E_T (GeV)	(η,ϕ)	N_{CES}	χ^2	P(π°)	P(η)	P(γ)
A	1	6.8	(0.44,6.11)	1	1.0	0.14	0.14	0.26
	2	5.9	(0.19,2.83)	1	1.3	0.19	0.20	0.36
B	1	5.4	(0.67,1.66)	2	n.a.	n.a.	n.a.	n.a.
	2	5.0	(-0.07,4.86)	1	1.4	0.21	0.21	0.39
C	1	6.0	(-0.44,1.66)	1	13.4	0.89	0.88	0.98
	2	5.1	(0.22,5.05)	2	2.2	0.33	0.33	0.57

Table 6: Properties of the three candidate events and their calorimeter showers (S): given are the E_T , the η and ϕ location, the χ^2 value and the total number of CES clusters inside the same calorimeter tower, N_{CES}. Also given are the probabilities that a photon, π° and η have a χ^2 value smaller or equal to that observed from simulation.

use the average value of the calculation baesed on strip and that based on wires. A distribution of χ^2 is shown for simulation for photons, π° , and η mesons in Fig. 13. It is seen that there is no clear discrimination that can be made on event by event basis. Note, that this includes the cases where one of the photons from a meson decay goes into an uninstrumented region. Using the distributions in Fig. 13 the probability that a shower has a value equal to or larger than the observed value can be calculated for the 5 non-conversion candidates.

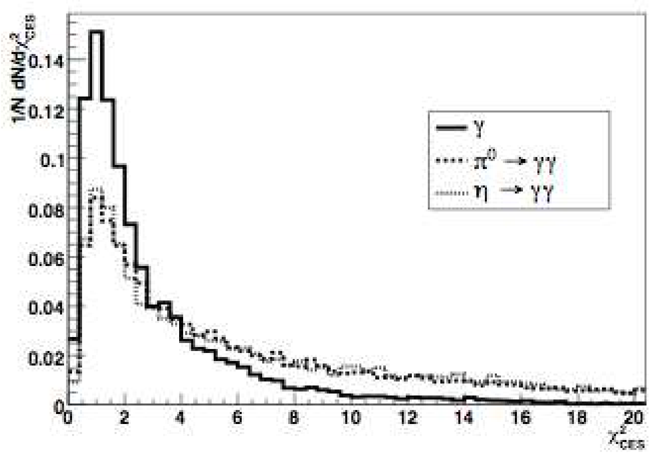

Figure 13: Simulated distribution for χ^2 for prompt photons (solidhistogram), and $\pi^\circ \rightarrow\gamma\gamma$ (dashedhistogram) and $\eta \rightarrow\gamma\gamma$ (dotted histogram) decays. In all cases E_T is required to be between 5 and 7 GeV.

Table 6 lists the kinematic properties and the CES based measurements for the six showers in the three observed events. These probabilities are also given in the table for photons, π° , and η mesons. For event A, both showers have a small value for

χ^2 and are more consistent with originating from photons, while for event C one of the showers has a rather large value making it more likely to originate from a π° or η decay. It is also seen that it is difficult to distinguish between a π° and η hypothesis. For event/shower B/1, the $\gamma \to e^+e^-$ conversion, two separated showers are seen in the CES, separated as expected in ϕ but not in η, and the χ^2 method cannot be used. The sum of the two track momenta is 5.40 GeV, and the calorimeter energy is 5.45 GeV, so if there was a second photon from a π° it must have been very soft, with a probability $\leq 6\%$ from π° decay (photons from π° or η decay have a flat energy spectrum).

The other discriminating variable is the number of CES clusters: while for photons only 12% have a 2nd CES cluster for π° and η mesons 28% and 46% have a 2nd CES cluster, respectively. Out of the 5 candidate showers only C2 has an additional CES cluster. This, together with the large χ^2 value of C1, further increases the evidence that event C is a dimeson event. Within the present statistical limitation of the sample we can only say that the candidates are consistent with being all from diphoton production but also with all being from π° and η production. Probably they are a mixture of both, with event A and B favoring the diphoton hypothesis and events C favoring the dimeson hypothesis. No theoretical calculation of exclusive $\pi^\circ\pi^\circ$ or $\eta\eta$ production has been published; however the Durham group estimates the $\pi^\circ\pi^\circ$ cross section to be about 25% of the diphoton process and the $\eta\eta$ production to be of the same size in the kinematic range of the candidate events. The $\eta \to \gamma\gamma$ branching ratio is only 40%, thus only 16% of the exclusive $\eta\eta$ production cross section will contribute as a background. This is consistent with our observations.

If we assumed that two of the three candidates are indeed diphoton events, we obtain a cross section of 90^{+120}_{-30}(stat.)$\pm$16(syst.) fb. This is consistent with the Durham prediction of 40 fb (uncertainty factor of 3 to 5).

8 Acknowledgements

We would like to thank the members of the Rockefeller group for their contributions to this analysis. We are also very grateful to Valery Khoze, Misha Ryskin and the rest of the Durham theory group for their calculations of the cross sections and valuable insight.

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