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First Observation 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 high E_T photons with nothing else observed in the CDF detector) on a background of 0.5±0.4 events. The measured cross section for these events is $120\ ^{+120}_{-40}\ (stat) \pm 20\ (sys)$ fb 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 observed are consistent with $\bar{p}p \to \bar{p}\gamma\gamma p$ with a predicted cross section of 40 fb and a factor 3 to 5 uncertainty.
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Contents

[1]Ph.D.Thesis

1 Introduction

In March 2001 some of us submitted a Letter of Intent to the Fermilab Director [1, 2] 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 [3]. 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 $p\bar{p} \to (p)\gamma\gamma(\bar{p})$ as a function of $M(\gamma\gamma)$ and that should give us a reliable estimate of $p\bar{p} \to pH\bar{p}$. ... 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 [3], 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 $gg^{PP} \to \gamma\gamma$ 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 $\sigma(30° < \theta^*_\gamma < 150°) \simeq 0.3(0.04)$ 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 [4]. They calculated a cross section, dominated by the $gg \to \gamma\gamma$ 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 $\gamma\gamma \to \gamma\gamma$ 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 [5] for papers on exclusive processes. There are no other predictions of the fully exclusive process.

This note depends heavily on CDFNOTE 7930 [6], 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 [6] when methodology is the same.

2 Monte Carlo

The Exhume Monte Carlo [11], written by Pilkington and Monk, is based on the Durham calculation. It is the only generator to simulate the exclusive two photon process.

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 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 [6]

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 [6]. For clarity, the central region of Table 1 is copied here from [6].

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 [6].

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 1 to 5. Event display pictures of the 3 events are shown in Figures 6 to 8.

```
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
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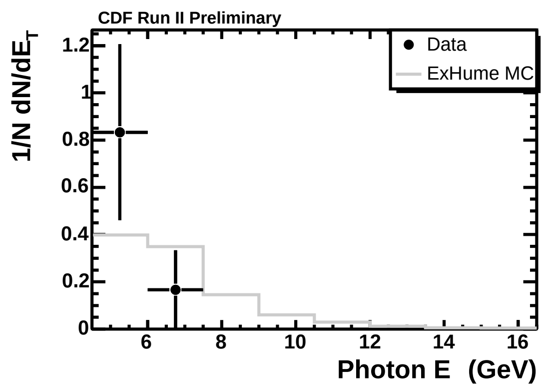

Figure 1: E_T of photons in signal sample (points) compared to Exhume MC (line)

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 9. 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.

4 Efficiencies

Most of the efficiencies for this analysis are the same as [6]. 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.

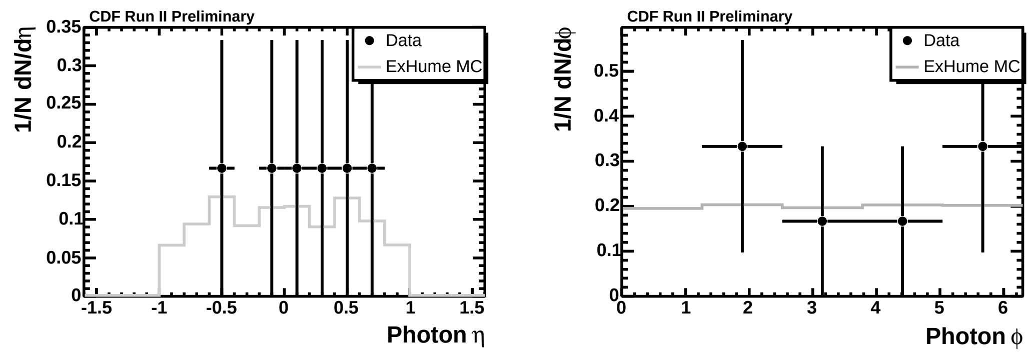

Figure 2: eta (left) and phi (right) of photons in signal sample (points) compared to Exhume MC (line)

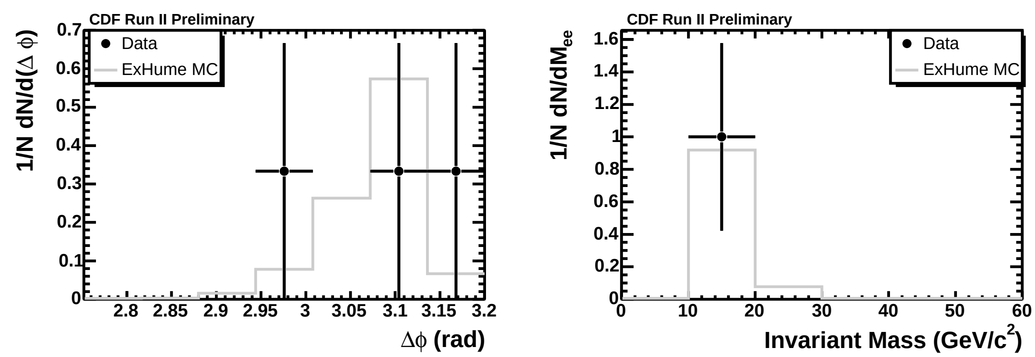

Figure 3: Delta ϕ (left) and invariant mass (right) of photon pairs in signal sample (points) compared to Exhume MC (line)

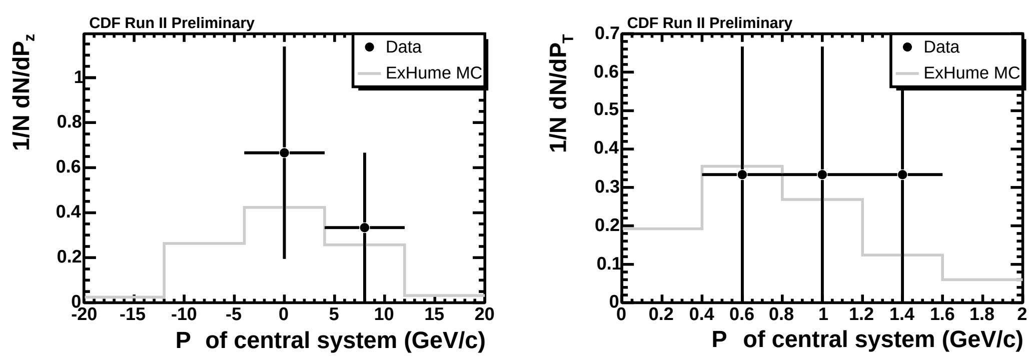

Figure 4: p_z and p_t of photon pairs in signal sample (points) compared to Exhume MC (line)

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.

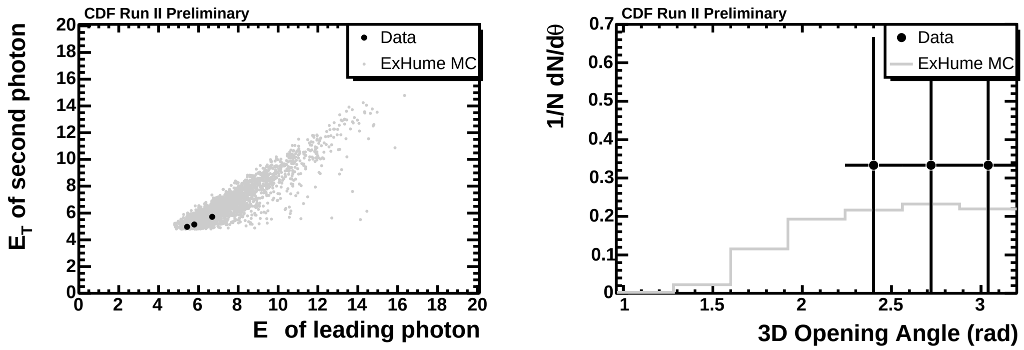

Figure 5: E_T vs E_T (left) and 3d opening angle of photon pairs in signal sample (points) compared to Exhume MC (line)

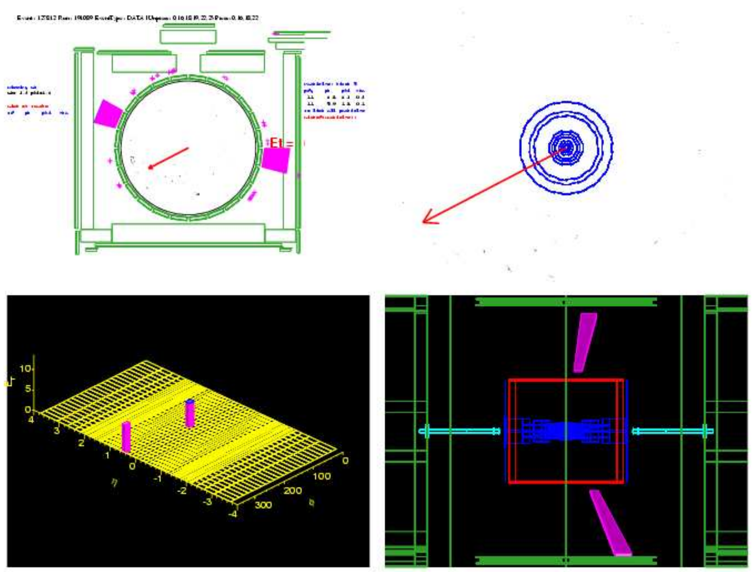

Figure 6: Event display of run 191089 event 127812.

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). 3229 out of 3562 events pass all the exclusive cuts, and 3108 out of the 3229 events pass the tracking cuts. Therefore, the conversion efficiency is $\varepsilon_{conv} = 3108/3562 = 0.87$. The systematic uncertainty on this efficiency is dominated by our knowledge of material in the tracking volume, which I expect would have been applied in 5.3.3. A CDF note for 4.9.1 MC [8] refers to a 30% correction in the material count. I haven't found any notes on 5.3.3 MC, but have

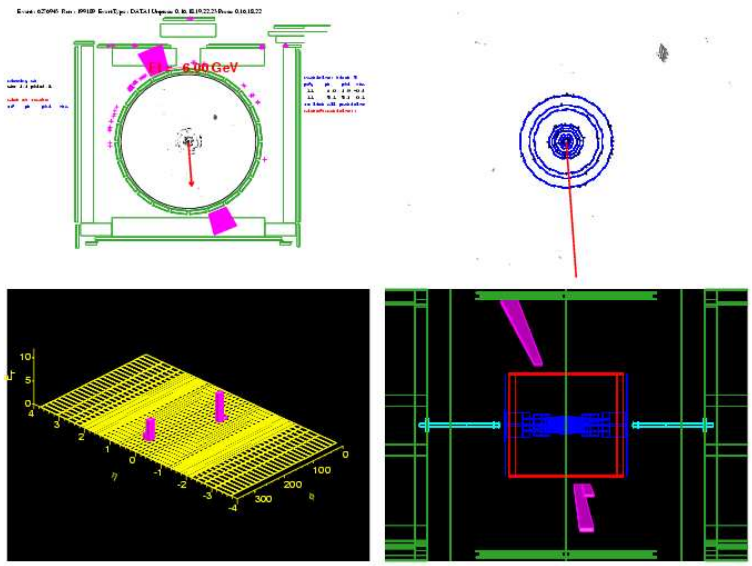

Figure 7: Event display of run 199189 event 6276945.

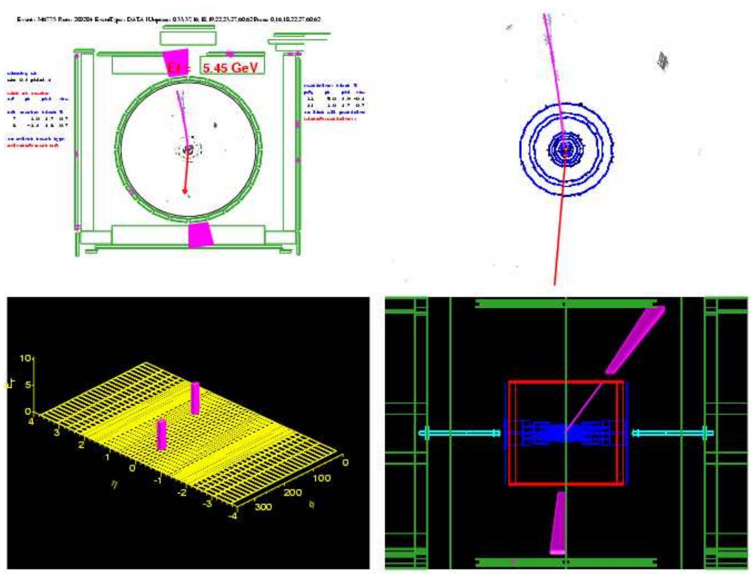

Figure 8: Event display of run 200284 event 346775 (note the conversion).

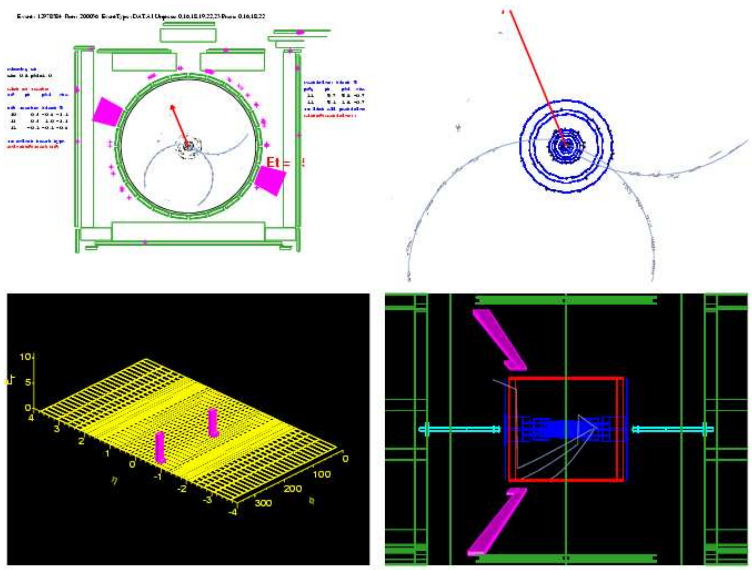

Figure 9: Event display of run 2000056 event 12978584 (not part of signal sample).

Sample	Number of Events
Two-candidate events	3562
Pass BSC (offline)†	3562
Pass MiniPlug†	3562
Pass FwdPlug	3540
Pass MidPlug	3537
Pass EndWall	3454
Pass Central	3229
Pass Tracking	3108

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.

emailed the authors of [8] to find out the current status of the material count. For now I have set the systematic uncertainty to 10%.

5 Backgrounds

The $\gamma\gamma$ and ee events are subject to the similar backgrounds. Jet fake, cosmic, exclusivity, and dissociation backgrounds all need to be accounted for. All but the cosmic background are slightly different than the ee case and are discussed in the following sections. Additional indistingushable physics backgrounds are also discussed and accounted for.

5.1 Jet Fake Background

The jet fake rate (F_{jet}) is the probability that a neutral hadron fakes a photon by passing the photon cuts. The most likely physics background producing this background is exclusive π^o,π^o where both π^o's pass the photon cuts. Since the cross section for exclusive $\pi^o\pi^o$ is not well known, the background is estimated from data, which will take into account all physics processes producing neutral hadrons. The jet fake rate for this analysis is defined as the probability that a trackless jet[2] passes the photon cuts.

$$F_{jet} \equiv \frac{N_{jets}^{pass\ photon\ cuts}(|\eta| < 1,\ NTracks = 0)}{N_{jets}(|\eta| < 1,\ NTracks = 0)} \tag{1}$$

Where the denominator, $N_{jets}(|\eta| < 1,\ NTracks = 0)$ is the number of jets in GAP_GAP_ST5 trigger data (the same good run list as the signal sample) with $|\eta| < 1,\ NTracks = 0$. The numerator, $N_{jets}^{pass\ photon\ cuts}(|\eta| < 1,\ NTracks = 0)$ is the number of denominator jets that pass the photon cuts listed in Table 1 plus the trackless cut requirement. Figure 10 shows F_{jet} is <3%[3], and does not have significant dependence on E_T .

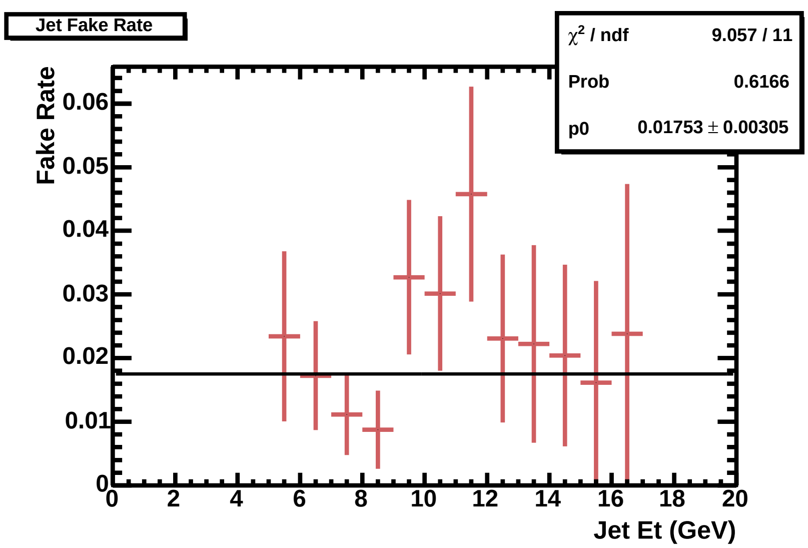

Figure 10: Jet fake rate (F_{jet}) is <3%

Similarly to the ee analysis, there are 0 events in the GAP_GAP_ST5 trigger data with two track-less jets passing the exclusive cuts for $|\eta| > 1$. Therefore, to 95% CL, there are less than 3.1 events with two track-less jets and pass the exclusive

[2] a trackless jet is any jet with zero tracks

[3] the numerator 'jets' could actually be photons

cuts. However, there is a factor 100 prescale on the GAP_GAP_ST5 trigger, therefore $N_{jj}^{pass\ all\ exc\ cuts} < 310$. Applying F_{jet} to each jet, gives $310 \cdot (0.03)^2 = 0.3 \pm 0.3$ background events. This estimate is an upper limit, so the systematic uncertainty accounts for the possibility of no background.

5.2 Exclusivity Background

The exclusivity background accounts for non-exclusive events where some particle(s) passed through the cracks in the calorimetry coverage or below the noise thresholds, causing them to appear exclusive. 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). Using the same methodology as the exclusive ee analysis, the background is estimated by taking the average number of events between bins 1 and 20. This produces a background of 0.05 ± 0.05 events.

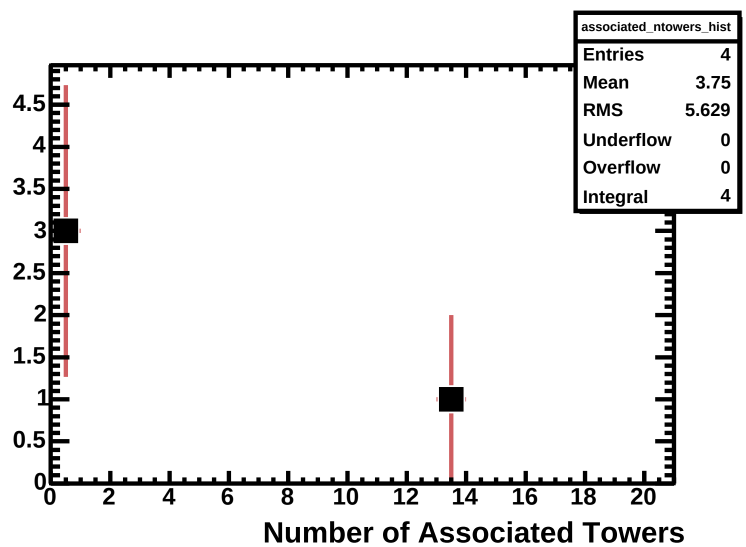

Figure 11: Number of associated towers in two-candidate events after tracking cut is applied.

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) exciatation 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 [10]. A study analagous to the ee dissociation background study was done by Sergei Striganov using the DPMJET MC (written by S, Roesler, R. Engel and J.

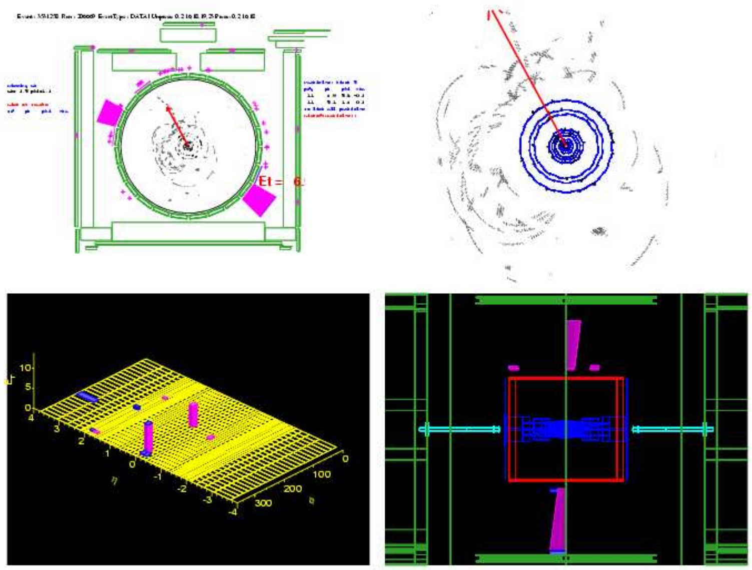

Figure 12: Event display of run 206669 event 3531258. This is the single background event in Figure 11, and looks like a $\gamma\gamma$ event with a soft interaction (exactly what the exclusivity cut is expected to eliminate).

Ranft). The conclusion of the study was that the fraction of dissociation background events in Pomeron exchange events is 1.5%[4] This is similar to the KMR estimation that there should be on the order of 0.1% dissociation background. The DPMJET estimation corresponds to 0.05 events in the 3 event signal sample.

5.4 Indistinquishable Physics Processes

There are physics process other than $gg \to \gamma\gamma$ that can produce an exclusive $\gamma\gamma$ final state. KMR calculates that the contribution from quark exchange diagrams is $< 5\%$ and from $\gamma\gamma \to \gamma\gamma$ is $< 1\%$. [**?**]

5.5 Background Summary

The dominant background in this analysis is the 0.3 event jet fake background. The sum of all backgrounds is 0.5±0.4 events.

[4]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.

Quantity	Value	Uncertainty
N_{sig}	3	-1, +3 (stat)[5]
N_{bkgd}	0.5	0.4 (sys)
$\mathscr{L}$	522	32 (sys)
ε_{exc}	0.0856	n/a
ε_{cos}	0.93	0.03 (sys)
ε_{conv}	0.87	0.09 (sys)
$\varepsilon_{\gamma\gamma}^{\dagger}$	0.57	0.07 (sys)

Table 4: Summary of numbers put into the cross section calculation. † is from version 2 of exclusive ee note (CDF 7930)

6 Cross Section

The cross section for exclusive $\gamma\gamma$ (E_T >5 GeV, $\eta < 1$) is evaluated (using Equation 2 and Table 4) to be 120 $^{+120}_{-40}$ $(stat)$ $\pm$ 20 (sys) fb. This is to be compared with a theoretical cross section from the Durham group of 40 fb with an uncertainty factor of 3 to 5. The measured value is consistent with the Durham calculation.

$$\sigma_{exc,\gamma\gamma}^{E_t>5\ GeV,\eta<1} = \frac{N_{sig} - N_{bkgd}}{\varepsilon_{conv}\varepsilon_{cos}\varepsilon_{\gamma\gamma}\varepsilon_{exc}\mathscr{L}} \tag{2}$$

7 Acknowledgements

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