Six Femtobarn Photon Searches from CDF

\(\gamma\gamma\text{MET} \cdot \gamma\gamma l \cdot \gamma\gamma \cdot \gamma\gamma\text{ mass} \cdot l\gamma X \cdot l\gamma b\text{MET}\)
## All CDF Photon Results

### Cross sections

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross Section (pb^-1)</th>
<th>Reference / Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td>200</td>
<td>PRL 95, 022003 (2005)</td>
</tr>
<tr>
<td>$\gamma+b$</td>
<td>340/230</td>
<td>see Mario Campanelli's talk</td>
</tr>
<tr>
<td>$W/Z\to lv/\ell+\gamma$</td>
<td>200</td>
<td>PRL 94, 041803 (2004)</td>
</tr>
<tr>
<td>$W/Z\to jets+\gamma$</td>
<td>180</td>
<td>available</td>
</tr>
</tbody>
</table>

### Searches

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross Section (pb^-1)</th>
<th>Reference / Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ MEt</td>
<td>70</td>
<td>available</td>
</tr>
<tr>
<td>$e^*$ in $ee\gamma$</td>
<td>200</td>
<td>PRL 94, 101802 (2005)</td>
</tr>
<tr>
<td>$\mu^*$ in $\mu\mu\gamma$</td>
<td>370</td>
<td>submitted to PRL</td>
</tr>
<tr>
<td>$\gamma\gamma$ mass peaks</td>
<td>1.1</td>
<td>this talk</td>
</tr>
<tr>
<td>$\gamma\gamma$ MEt, $\gamma \ell$, $\gamma \gamma$</td>
<td>1.1</td>
<td>this talk</td>
</tr>
<tr>
<td>$l\gamma+X$</td>
<td>300/930</td>
<td>PRL 97, 031801 (2006)/this talk</td>
</tr>
<tr>
<td>$l\gamma b$ MEt</td>
<td>0.9</td>
<td>this talk</td>
</tr>
<tr>
<td>delayed photons</td>
<td>500</td>
<td>see Max Goncharov's talk</td>
</tr>
</tbody>
</table>
# Photon Triggers and Selections

<table>
<thead>
<tr>
<th><strong>DiPhoton triggers</strong></th>
<th><strong>Photon triggers</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>$2 \times E_t &gt; 12$, w/cal iso</td>
<td>$E_t &gt; 25$, w/cal iso</td>
</tr>
<tr>
<td>$2 \times E_t &gt; 18$, wo/cal iso</td>
<td>$E_t &gt; 50$, wo/cal iso</td>
</tr>
</tbody>
</table>

plus ... photon+muon, photon+b, photon+2jet, triphoton

## Central Cuts ($\eta<1.0$)
- Had/EM <0.055
- Calorimeter Iso, cone 0.4 < 2 GeV
- cluster in shower max, good $\chi^2$
- small leading track Pt < 1 GeV
- track isolation, cone 0.4 < 2 GeV
- second Sh.Max. cluster Et < 2 to 3 GeV

## Forward Cuts (1.2<$\eta$<2.8)
- Had/EM <0.05
- Calorimeter Iso, cone 0.4 < 2 GeV
- cluster in shower max, good shape
- small leading track Pt < 1 GeV
- track isolation, cone 0.4 < 2 GeV
- tower shower shape, good $\chi^2$

MEt search adds anti-cosmic cuts:
- EM TDC times (when available), jet topology, unattached muon stubs

All analyses use $Z \rightarrow \text{ee}$ and minbias to study/correct ID efficiencies
Two Techniques

e→γ fake rate
- almost all due to brem in detector
- Compare:
  Z peak in ee
  Z peak in eγ
- take Et dependence from Monte Carlo

Phoenix Tracking
- seed a track from cal cluster and event vertex
- find forward electrons
- or reject electrons with evidence of an e brem in the Si tracking

\( \gamma^2 / \text{n.dof} = 24.41 / 15 \)
\( \text{Prob} = 0.05846 \)
\( p_0 = -2.991 \pm 0.143 \)
\( p_1 = -0.04524 \pm 0.00773 \)
\( p_2 = 0.00728 \pm 0.00145 \)

Gen 5 + Gen 6 Drell Yan MC
\( \gamma = e^{p_0 + p_1 x + p_2} \)
Search for Diphoton Peaks

Model
- Randall-Sundrum Gravitons
- Extra dimension is "warped", with parameter k
- $S$-channel Graviton yields $e^+e^-, \mu^+\mu^-, \gamma\gamma, \ldots$ peaks at high-mass
- this search sensitive to any narrow diphoton peak

Analysis
- 2 central-central or central-forward photons
- $E_t > 15$ GeV
- Mass > 30 GeV

central-central and central-forward have complimentary acceptance

October 31, 2006  Ray Culbertson  DPF 2006
Search for Diphotoon Peaks

Data sample
- 1.2 fb$^{-1}$
- Highest mass events:
  central-central: 602 GeV
  central-forward: 454 GeV
- no significant MEt observed in high-mass events
- No sign of cosmics which brem in calorimeters

γγ Mass in bins of 1σ mass resolution
Search for Diphoton Peaks

SM Diphoton Background
- NLO Diphox calculation
- normalized by luminosity

Jets Faking Photons
- mostly hard $\pi^0$'s
- Mass shape from a sample of loose diphoton candidates
- normalized to low mass - DiPhox

*This background is not used in setting limits*
Search for Diphoton Peaks

**Limits**
- Fit spectrum to Diphox + exponentials
- fit central-central and central-forward separately
- no normalization constraints
- limits from binned maximum likelihood with Monte Carlo signal shape times efficiency
Randall-Sundrum Graviton Limits

- for \( k/M_{\text{pl}} = 0.1 \), \( M(G) > 850 \text{ GeV} \)
- combined with \( e^+e^- \) RS search result: \( M(G) > 875 \text{ GeV} \)
- \( \gamma\gamma \) has larger BR, better acceptance due to spin effects
Search in Diphoton and Met

Sample
- 1.2 fb⁻¹
- Two central photons with Et>13
- Signature-based

Remove fake MEt
- remove jets along MEt
- use lowest MEt vertex

Remove Ewk
- W→e→γ by brem rejected by Phoenix

Remove non-collision
- EM timing
- extra muon stubs

Ht = scalar sum of Et from photons, leptons, jets, and MEt
Search in Diphoton and Met

**QCD background**
- MEt Model from control samples
- predict MEt from energy and expected resolution

**Ewk background**
- e+γ sample times e→γ fake rate

**Non-Collision background**
- no-vertex and out-of-time control samples

Total background, MEt>50GeV: 1.6 ± 0.3, 4 observed

Search for γγ+\(\not{E}_T\), Signal sample

CDF Run II Preliminary, 1.2 fb\(^{-1}\)
- Data, \(\not{E}_T\)>20 GeV
- QCD + fake \(\not{E}_T\)
- eγ events
- Non-Collision

Search for γγ+\(\not{E}_T\), Signal sample

CDF Run II Preliminary, 1.2 fb\(^{-1}\)
- Data
- QCD + fake \(\not{E}_T\)
- eγ events
- Non-Collision
Search for Diphotons and Leptons

**Sample**
- Same diphotons
- 1.0 to 1.1 fb$^{-1}$
- top-like leptons:

**Backgrounds:**
- Ewk $l\gamma\gamma$ (MadGraph)

**Electrons**
- Central $e$ Et>20 GeV
- Forward $e$ Et>20 GeV, including Phoenix tracks

**Muons**
- Central $\mu$ Pt>20 GeV
- Forward (CMX) $\mu$ Pt>20 GeV

<table>
<thead>
<tr>
<th>Source</th>
<th>Before applying Phoenix rejection electron</th>
<th>Before applying Phoenix rejection muon</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z\gamma\gamma$</td>
<td>$0.904 \pm 0.023 \pm 0.083$</td>
<td>$0.552 \pm 0.017 \pm 0.050$</td>
</tr>
<tr>
<td>$W\gamma\gamma$</td>
<td>$0.170 \pm 0.012 \pm 0.016$</td>
<td>$0.086 \pm 0.008 \pm 0.008$</td>
</tr>
<tr>
<td>Fake $l+\gamma\gamma$</td>
<td>$0.131 \pm 0.004 \pm 0.053$</td>
<td>$0.004 \pm 0.003 \pm 0.002$</td>
</tr>
<tr>
<td>$l\gamma + \text{jet} \rightarrow \gamma$</td>
<td>$0.475 \pm 0.025 \pm 0.312$</td>
<td>$0.133 \pm 0.013 \pm 0.090$</td>
</tr>
<tr>
<td>$l\gamma + e \rightarrow \gamma$</td>
<td>$5.140 \pm 0.340 \pm 0.584$</td>
<td>$0.017 \pm 0.017 \pm 0.002$</td>
</tr>
<tr>
<td>Total</td>
<td>$6.82 \pm 0.75$</td>
<td>$0.79 \pm 0.11$</td>
</tr>
<tr>
<td>Data</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>
Search for Diphotons and Leptons

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Ray Culbertson
DPF 2006
**Search for Triphotons**

**Sample**
- 1155 pb⁻¹
- Start with same diphotons
- Add a third central photon with Et>13 GeV

**Backgrounds**
S.M. Triphotons from MadGraph: $0.8 \pm 0.15$
At least one fake: $1.4 \pm 0.6$
Total: $2.2 \pm 0.6$
Observed: 4
Search for Lepton+Photon+X

- In Run I, in $\mu \gamma \text{MET}$, expected 4 and observed 11
- Repeat the Run I analysis, so kinematics are completely \textit{a priori}

\textbf{Sample}

- 930 pb$^{-1}$
- Require:
  - tight central electron or muon, $E_T (P_T) > 25$ GeV
  - central photon, $E_T > 25$ GeV
- Look for
  - More Photons
  - Loose central or plug electron
  - Loose central muons
  - $\text{MET} > 25$ GeV

\textbf{Backgrounds}

- $W/Z\gamma$, $W/Z\gamma\gamma$ Baur and MadGraph Monte Carlo
- $e \rightarrow \gamma$ fake rate
- $\text{jet} \rightarrow \gamma$
  - iso method (see next)
- $\text{jet} \rightarrow l$ fake rate
Search for Lepton+Photon+X

**Iso technique**
- Find isolated shower isolation distribution from $Z \rightarrow e^-e^+$
- From non-isolated shape from jets
- Fit candidates calorimeter isolation distribution to the two shapes

![Graph showing Photon IsoEt distribution with statistical parameters](image)
**Search for Lepton+Photon+X**

**eγMET**
Expect $94.2 \pm 8.1$
Observe 96

**μγMET**
Expect $53.9 \pm 7.1$
Observe 67
Search for Lepton+Photon+X

\(e\gamma\)
Expect \(39.0 \pm 4.8\)
Observe 53

\(\mu\gamma\)
Expect \(26.0 \pm 3.1\)
Observe 21

\(e\mu\gamma\)
0 observed,
1.0 \(\pm 0.3\) expected

\(l\gamma\) \(\text{MET}>25\) \(\text{GeV}\)
3 observed,
0.6 \(\pm 0.1\) expected

\(l\gamma\gamma\)
0 observed
0.5 \(\pm 0.1\) expected
Search for $l\gamma\not{E}_T$.

**Sample**
- 929 pb$^{-1}$
- Lepton: central, $E_T>20$ GeV
- Photon: central, $E_T>10$ GeV
- Standard secondary vertex tag, $E_T>15$ GeV, $|\eta|<2$
- $M_E T > 20$ GeV

$H_T =$ scalar sum of $E_T$ from photons, leptons, jets, and $M_E T$.
Search for $l \gamma \not{E}_T b$

**Backgrounds**
- Mostly fakes
- Especially tags
- 15 observed, $11.37 \pm 1.52$ expected

<table>
<thead>
<tr>
<th>Standard Model Source</th>
<th>$e \gamma b \not{E}_T$</th>
<th>$\mu \gamma b \not{E}_T$</th>
<th>$(e + \mu) \gamma b \not{E}_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}\gamma$</td>
<td>$0.32 \pm 0.036$</td>
<td>$0.21 \pm 0.025$</td>
<td>$0.53 \pm 0.058$</td>
</tr>
<tr>
<td>$W^\pm c\gamma$</td>
<td>$0.14 \pm 0.031$</td>
<td>$0.14 \pm 0.029$</td>
<td>$0.28 \pm 0.048$</td>
</tr>
<tr>
<td>$W^\pm c\gamma$</td>
<td>$0.023 \pm 0.010$</td>
<td>$0.048 \pm 0.014$</td>
<td>$0.071 \pm 0.018$</td>
</tr>
<tr>
<td>$W^\pm b\gamma$</td>
<td>$0.14 \pm 0.024$</td>
<td>$0.099 \pm 0.018$</td>
<td>$0.24 \pm 0.035$</td>
</tr>
<tr>
<td>$WZ$</td>
<td>$0.029 \pm 0.014$</td>
<td>$0.0 \pm 0.0075$</td>
<td>$0.029 \pm 0.016$</td>
</tr>
<tr>
<td>$Z(\tau\tau)\gamma$</td>
<td>$0.041 \pm 0.041$</td>
<td>$0.11 \pm 0.063$</td>
<td>$0.15 \pm 0.076$</td>
</tr>
</tbody>
</table>

| ee $\not{E}_T b$, $e \rightarrow \gamma$ | $1.04961 \pm 0.21$ | -- | $1.04961 \pm 0.21$ |
| $\mu e \not{E}_T b$, $e \rightarrow \gamma$ | -- | $0.24 \pm 0.08$ | $0.24 \pm 0.08$ |
| Jet faking $\gamma$ ($e j \not{E}_T b$, $j \rightarrow \gamma$) | $0.73 \pm 0.34$ | $0.46 \pm 0.20$ | $1.19 \pm 0.028$ |
| MisTags | $2.85 \pm 0.35$ | $1.89 \pm 0.26$ | $4.74 \pm 0.51$ |
| QCD(Jets faking $\ell$ and $\not{E}_T$) | $2.85 \pm 1.32$ | $0.0 \pm 0.50$ | $2.85 \pm 1.41$ |

Total SM Prediction: $8.17 \pm 1.43 (\text{tot})$, $3.20 \pm 0.60 (\text{tot})$, $11.37 \pm 1.52 (\text{tot})$

Observed in Data: 7, 8, 15
Search for $l \gamma \not{E}_T b$

**ttbar Selection**
- create a subsample
- related to $t \bar{t} h^0$
- sensitive to $t$ charge
- require $H_t > 200$ GeV 
  *(a priori top-like cut)*

**Results**
- 10 observed,
  $4.7 \pm 1.0$ expected
- $tt\gamma$ is still out of reach
Ultimate Signature-based Search

- Several of these photon results were “signature-based”
- This idea, taken to the logical conclusion is Sleuth
- Automate searches to all high-Pt regions, all signatures
- Fit efficiencies, fake rates and k-factors to the data,

Apply these to a complete Monte Carlo description of the data

(See talk by Georgios Choudalakis on Wednesday)

Distributions for photon+2jets+MEt:

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DPF 2006
CDF has released recently, shown here:

\[ \gamma\gamma \text{MET} \quad \gamma\gamma \text{mass} \quad \gamma\gamma l \]
\[ l\gamma X \quad \gamma\gamma \quad l\gamma \text{bMET} \]

Also Appearing Now at DPF

\[ \gamma \text{b Cross section} \]
\[ \text{delayed photons} \]
\[ \text{Sleuth} \]

CDF photon program is going strong...