Signature-Based Searches for New Physics Involving Photons at the Tevatron

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Motivation

- As rare phenomenon are observed theorists get ever more creative in devising new possibilities for why
  - why limit ourselves to the current crop of TOE
  - review the exotic signatures and see if anything sticks out
- Photons are a good candidate since they don't add a big mass burden to the event and are reasonably rare
- Cautionary note
  - looking for rare phenomenon sometimes succeeds in finding fluctuations
    - one such fluctuation is the eeγγ missing $E_T$ event described in the 1995 $\bar{P}P$ workshop at FNAL
    - we've been looking for another for 15 years
- Perhaps because of the above event this has been a popular CDF sport
- D0 has a dark photon & GMSB search but nothing that fits this description so all the results here are from CDF
Where might you look?

- Searches described here include
  - $\gamma\gamma$ plus
    - $\tau$
    - $e$
    - $\mu$
    - Missing $E_T$
  - $\gamma$+jet+b+missing $E_T$
  - $\gamma$+b+missing $E_T$+lepton (e or $\mu$)
    - this one is of particular interest because it includes $t\bar{t}\gamma$ events

- Numerous as yet unconfirmed theories lead to such signatures
  - SUSY, Technicolor, associated Higgs production...
Diphoton + X searches

- Two triggered photons
  - 2 photon candidates
    - both isolated with $E_T > 12$ GeV
    - no isolation requirement but both with $E_T > 18$ GeV

- Candidate events have:
  - 2 candidates with $E_T > 13$ GeV & $0.05 < |\eta| < 1.05$
    - shower maximum lateral profile consistent with single shower
    - no high $P_T$ tracks pointing at the candidate
    - isolation (track and calorimeter) in a cone of $\Delta\eta, \Delta\phi$ with $R<0.4$
      - calorimeter $0.1X E_T$ for $E_T < 20$ GeV or $2.0$ GeV + $0.02X(E_T - 20$ GeV) above 20 GeV
      - track:: $2.0$ GeV +0.005 X $E_T$

- Sample of $\gamma\gamma$ from $2.0 \pm 0.1$ fb$^{-1}$
  - 31,116 candidates (~30% true diphotons)
  - 42,708 control events with at least one failed $\gamma$
**γγ** plus **τ** results

- **τ** reconstruction using calorimeter and shower max. for **π⁰** plus tracking
  - Mass <1.8 GeV/c²
  - Reconstruction in cone with size dependent on **E_T**
    - \( \theta < 0.17 \) for 30 GeV
    - \( \theta < 0.05 \) for 100 GeV
  - Isolation annulus with outer radius of 0.52
    - Track \( P_T < 1.0 \) GeV
    - \( \pi^0 E_T < 0.6 \) GeV

- 34 events observed in \( 2.0 \pm 0.1 \) fb⁻¹
  - Expect \( 46 \pm 10 \)
**γγ plus τ results**

- Fake $\tau$ dominates the background (44 out of 46 events)
**γγ plus lepton results**

- 1.1±0.1 fb⁻¹
- $E_T > 20$ GeV
- SM sources estimated using Madgraph+Pythia for $Z/Wγγ$ K factor of 1.4 for LO->NLO
- Background estimates come from event sample plus rates of jet or $e$ to fake gamma
- Table includes a cut on silicon hits pointing at $γ$ (events plotted don't have this cut which adds 2 such events)

<table>
<thead>
<tr>
<th>Source</th>
<th>electron</th>
<th>muon</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Zγγ$</td>
<td>0.82±0.08</td>
<td>0.50±0.05</td>
</tr>
<tr>
<td>$Wγγ$</td>
<td>0.15±0.02</td>
<td>0.08±0.01</td>
</tr>
<tr>
<td>$lγ+e→γ$</td>
<td>2.26±0.46</td>
<td>0.004±0.004</td>
</tr>
<tr>
<td>$lγ+jet→γ$</td>
<td>0.44±0.26</td>
<td>0.12±0.08</td>
</tr>
<tr>
<td>Fake $l+γγ$</td>
<td>0.12±0.05</td>
<td>0.004±0.004</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3.79±0.54</strong></td>
<td><strong>0.71±0.10</strong></td>
</tr>
<tr>
<td><strong>Observed</strong></td>
<td><strong>1</strong></td>
<td><strong>0</strong></td>
</tr>
</tbody>
</table>
\( \gamma \gamma \) plus electron results

![Graphs showing results of \( \gamma \gamma \) and electron data]

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Expected muon distributions
\[ \gamma \gamma \text{ plus } E_T \]

- Missing \( E_T \) modeled using detailed understanding of jet resolution and underlying event contribution
  - Significance constructed to estimate log likelihood of a given event missing \( E_T \)

- Several other sources estimated
  - Incorrect vertex
    - Other vertices considered and if one produces less missing \( E_T \) it is used instead
    - Leaves cases where other vertex is not reconstructed (this contribution is estimated)
  - Three gamma events with a missing gamma (this is estimated from the data)
  - Non collision events (cosmic rays) TDC's used to estimate this
$\gamma \gamma$ plus missing $E_T$
\( \gamma \gamma \) plus missing \( E_T \)

<table>
<thead>
<tr>
<th></th>
<th>signif.&gt;3</th>
<th>signif.&gt;4</th>
<th>signif.&gt;5</th>
</tr>
</thead>
<tbody>
<tr>
<td>EWK</td>
<td>35.4±2.2</td>
<td>29.9±2.0</td>
<td>25.9±1.9</td>
</tr>
<tr>
<td>Total exp.</td>
<td>71.7±7.5</td>
<td>39.0±3.1</td>
<td>30.4±2.4</td>
</tr>
<tr>
<td>Observed</td>
<td>82</td>
<td>31</td>
<td>23</td>
</tr>
</tbody>
</table>
\[ \gamma + \text{jet} + b + \text{missing } E_T \]  

**PRD 80, 052003 (2009)**

- Photon candidate with \( E_T > 25 \text{ GeV} \) and \(|\eta|<1.1\)
- Two jets with \( E_T > 15 \text{ GeV} \) and \(|\eta|<2.0\)
- \( \Delta R>0.4 \) for all of the above (\( \gamma \) and jets)
- Missing \( E_T > 25 \text{ GeV} \)
- \( \Delta \phi(\text{jet and met})>0.3 \)
- 1 SECondary VerTeX (SECVTX) b tag
  - 617 events satisfy above
  - Expect 607 ± 74(stat.) ± 86(syst.)
  - This includes 115 ± 49 ± 54 fake \( \gamma \) and 141 ± 6 ± 30 true \( \gamma \) fake b
  - \( \gamma \) b \((341±18±91)\) dominates
- Veto events with track (\( P_T > 20 \text{ GeV} \)) carrying > 90% track \( \Sigma P_T \) in \( \Delta R<0.4 \)
  - 17 events eliminated by this cut
- 600 events satisfy all cuts in 2.0 fb\(^{-1}\) sample
$\gamma + \text{jet} + b + \text{missing } E_T$
$\gamma + b + \text{missing } E_T + \text{lepton (e or } \mu \text{)}$

**PRD 80, 011102(R) (2009)**

- $\gamma + b + \text{missing } E_T + \text{lepton (e or } \mu \text{)} \ 1.9 \text{ fb}^{-1} \ (\text{trigger on high } P_T \text{ lepton})$
  - Central photon with $E_T > 10 \text{ GeV}$
  - B tagged jet with $E_T > 15 \text{ GeV}$
  - Missing $E_T > 20 \text{ GeV}$
  - e or $\mu$ with $E_T > 20 \text{ GeV}$

- 28 events observed
  - Expect $31.0 (+4.1 - 3.9)$
  - Dominated by jets faking $\gamma$ and mistagged b jets ($7.58 \pm 3.11 \ & \ 7.65 \pm 0.70$ respectively)
  - Top plus gamma come in next (semileptonic: $3.58 \pm 0.65$ & dilepton: $2.32 \pm 0.41$)

- Subsample rich in $t\bar{t}\gamma$
  - require $H_T > 200 \text{ GeV}$
  - require $N_{\text{jets}} \geq 3$
$\gamma + b + \text{missing } E_T + \text{lepton (e or } \mu)$

<table>
<thead>
<tr>
<th>SM Source</th>
<th>$e\gamma b E_T$</th>
<th>$\mu\gamma b E_T$</th>
<th>$(e + \mu)\gamma b E_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tt\gamma$ semileptonic</td>
<td>$2.06 \pm 0.38$</td>
<td>$1.52 \pm 0.28$</td>
<td>$3.58 \pm 0.65$</td>
</tr>
<tr>
<td>$tt\gamma$ dileptonic</td>
<td>$1.30 \pm 0.23$</td>
<td>$1.02 \pm 0.18$</td>
<td>$2.32 \pm 0.41$</td>
</tr>
<tr>
<td>$W^{\pm} c\gamma$</td>
<td>$0.75 \pm 0.16$</td>
<td>$0.72 \pm 0.15$</td>
<td>$1.47 \pm 0.26$</td>
</tr>
<tr>
<td>$W^{\pm} c\gamma$</td>
<td>$0.08 \pm 0.04$</td>
<td>$0.22 \pm 0.06$</td>
<td>$0.30 \pm 0.08$</td>
</tr>
<tr>
<td>$W^{\pm} bb\gamma$</td>
<td>$0.62 \pm 0.11$</td>
<td>$0.42 \pm 0.08$</td>
<td>$1.04 \pm 0.17$</td>
</tr>
<tr>
<td>$Z(\tau\tau)\gamma$</td>
<td>$0.13 \pm 0.09$</td>
<td>$0.11 \pm 0.08$</td>
<td>$0.24 \pm 0.12$</td>
</tr>
<tr>
<td>$WZ$</td>
<td>$0.08 \pm 0.04$</td>
<td>$0.01 \pm 0.01$</td>
<td>$0.09 \pm 0.04$</td>
</tr>
<tr>
<td>$\tau \rightarrow \gamma$ fake</td>
<td>$0.12 \pm 0.01$</td>
<td>$0.10 \pm 0.01$</td>
<td>$0.22 \pm 0.01$</td>
</tr>
<tr>
<td>Jet faking $\gamma$</td>
<td>$4.56 \pm 1.92$</td>
<td>$3.02 \pm 1.19$</td>
<td>$7.58 \pm 3.11$</td>
</tr>
<tr>
<td>Mistags</td>
<td>$4.11 \pm 0.41$</td>
<td>$3.54 \pm 0.37$</td>
<td>$7.65 \pm 0.70$</td>
</tr>
<tr>
<td>QCD</td>
<td>$1.49 \pm 0.77$</td>
<td>$0^{+1}_{-0}$</td>
<td>$1.49^{+1.30}_{-0.77}$</td>
</tr>
<tr>
<td>$e\gamma E_T b, e \rightarrow \gamma$</td>
<td>$1.50 \pm 0.28$</td>
<td>$0.45 \pm 0.10$</td>
<td>$1.50 \pm 0.28$</td>
</tr>
<tr>
<td>$\mu e E_T b, e \rightarrow \gamma$</td>
<td>$-\gamma$</td>
<td>$-\gamma$</td>
<td>$-\gamma$</td>
</tr>
</tbody>
</table>

| Predicted | $16.8 \pm 2.2$ (tot) | $11.1^{+1.7}_{-1.4}$ (tot) | $27.9^{+3.6}_{-3.5}$ (tot) |
| Observed  | 16                   | 12                        | 28                         |
$\gamma + b + \text{missing } E_T + \text{lepton (e or } \mu \text{)}$
Require $H_T > 200$ GeV and $N_{jets} > 2$

16 events with ~ 4 expected top plus gamma (11.2+2.3-2.1 expected total)
\[ \gamma + b + \text{missing } E_T + \text{lepton (e or } \mu) \]

- Subtracting non-top sources yields \(0.15 \pm 0.08 \text{pb} \) for \(t\bar{t}_\gamma\)
Conclusion

- No surprises so far.
- Tevatron physics is going strong!
  - Sensitive to processes that are two orders of magnitude rarer than top production
  - Lots more data to come