Physics with Photons at CDF

Sasha Pronko
Fermilab
Wikipedia: “The Noble Eightfold Path, in the teachings of the Buddha, is used as an instrument of discovery to gradually generate insights unveiling the ultimate truth of things”

① Photon is one of seven objects at colliders

② QCD > QED > EWK
- photons second most frequent objects after jets
There is no deficit of models or signatures!!

- **SUSY**
  \[ \chi^0_1 \to \gamma G \]
  \[ \gamma + \text{MET}, \text{displaced} \gamma + X, \gamma \gamma + j + \text{MET}, \gamma + b + \text{MET}, \gamma + bj + \text{MET}, \]
  \[ \chi^0_2 \to \gamma \chi^0_1 \]
  \[ \gamma + bc + \text{MET}, \gamma + jj + \text{MET}, \gamma + ll + \text{MET}, \gamma \gamma + ll + \text{MET}, \gamma + \text{MET}, jj + \gamma + \text{MET} \]

- **Technicolor**
  \[ \omega_T, \rho_T \pi_T \to \gamma \pi_T \]
  \[ \pi_T \to \gamma \gamma \]

- **Compositeness**
  \[ f^* \to \gamma f \]
  \[ ll + \gamma, ll + \gamma \gamma, jj + \gamma, bb + \gamma, jj + \gamma \gamma, bb + \gamma \gamma \]

- **Extra Dimensions**
  **LED:** \[ G \to \gamma \gamma \]
  \[ \gamma \gamma, \gamma \text{MET} \]
  **UED (6DSM)**
  \[ \gamma \gamma + n^*/l + \text{MET} \]

- **Higgs**
  \[ H \to \gamma \gamma, A \to \gamma \gamma \]
  \[ \gamma \gamma, ll + \gamma, l + \gamma \gamma + \text{MET}, \gamma \gamma + \text{MET}, jj + \gamma \gamma, \gamma \gamma + \gamma \gamma \]

- **4th generation**
  \[ b' \to \gamma b \]
  \[ \gamma \gamma + bb, ll + \gamma + bb, jj + \gamma \gamma + bb \]
"Old" Physics with Photons

- Prompt $\gamma$'s come unaltered (by fragmentation/hadronization) from hard scattering
- Well known coupling to quarks
- Well measured (unlike jets) $P_T^\gamma$
- Can be used to constrain quark PDFs
- $\sigma(\gamma)/\sigma(\text{jets}) \sim 10^{-3}$ → challenging measurement
  - Dominant background: $\pi^0/\eta$ from jets

X-section measurements
- Inclusive photon
- Photon+jets
- Photon+H.F.(c/b-jet)
- Photon+bb
- Inclusive di-photon
- $Z/W+$photon

inclusive photon cross section $0 < |\eta| < 0.9$

Fractional contribution

<table>
<thead>
<tr>
<th>$p_T$ (GeV)</th>
<th>gg</th>
<th>qg</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

(all quark/anti-quark subprocesses)
Tevatron running well
- 5 fb\(^{-1}\) per experiment
- ~1.6 fb\(^{-1}\) in FY08
- Current rate: ~50 pb\(^{-1}\) per week
- Goal by 2009: 5-8 fb\(^{-1}\)
- Running till 2010?

- 36×36 bunches
- Collisions every 396 ns
- Proton-antiproton collisions at \(\sqrt{s}=1.96\) TeV
Muon Chambers
Calorimeters
Silicon Tracker
Wire Chamber (COT)
1.4 T Superconducting Solenoid
**Photons in Central EM Calorimeter**

| Detector | $|\eta|$ range | $\Delta\phi$ | $\Delta\eta$ |
|----------|---------------|--------------|--------------|
| CEM      | 0 - 1.1       | 15°          | ~0.1         |

**Table: Detector Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>$18 X_0, 1\lambda$</td>
</tr>
<tr>
<td>Absorber</td>
<td>Lead</td>
</tr>
<tr>
<td>Scintillator</td>
<td>Polystyrene (SCSN-38)</td>
</tr>
<tr>
<td>Shower Max (CES)</td>
<td>R=184 cm; depth=5.9 $X_0$</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>13.5%/$\sqrt{E}$</td>
</tr>
<tr>
<td>Position resolution</td>
<td>$\pm 2$ mm</td>
</tr>
</tbody>
</table>

**Diagram:**
- CES chamber: one per wedge

**Table: Perpendicular Distance**

<table>
<thead>
<tr>
<th>Chamber section 1</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire readout</td>
<td>6.2 cm $&lt;</td>
</tr>
<tr>
<td>Strip readout</td>
<td>32 pairs $\times$ 1.45 cm</td>
</tr>
<tr>
<td>Chamber section 2</td>
<td>Distance</td>
</tr>
<tr>
<td>Wire readout</td>
<td>121.2 cm $&lt;</td>
</tr>
<tr>
<td>Strip readout</td>
<td>32 pairs $\times$ 1.45 cm</td>
</tr>
</tbody>
</table>

**Diagram:**
- Phototubes
- Light guides
- Wave shift sheets
- Right
- Left

**Diagram Details:**
- Phototubes
- Light guides
- Wave shift sheets
- Right
- Left
CP2 (Preshower) Detector

- CP2 replaced old CPR in 2004
  - Scintillator pads efficiently detect MIPs
  - Design optimized for higher luminosity

CP2 location: R=170.47 cm
Photons in Plug EM Calorimeter

| Detector | $|\eta| \text{ range}$ | $\Delta \phi$ | $\Delta \eta$ |
|----------|---------------------|--------------|------------|
| PEM      | 1.1 - 1.8           | 7.5°         | ~0.1       |
|          | 1.8 - 2.1           | 7.5°         | ~0.16      |
|          | 2.1 - 3.64          | 15°          | 0.2 - 0.6  |

Thickness | 21 $X_0$, 1$\lambda$
Absorber  | Lead
Scintillator | Polystyrene (SCSN38)
Shower Max (PES) | $Z \sim 184 \text{ cm}$; depth $\sim 6 \times X_0$
Energy resolution | 16%/$\sqrt{E}$; +1% const term

PES: 5 mm pitch
V & U scintillator strips
**Concept of Photon ID**

**Photon signature**
- **No electric charge**
  - no track
- **“Compact” EM cluster**
  - shower contained in EM CAL
- **No color charge**
  - Unlike jets, photon is isolated object

**What fakes a photon?**
- A: another photon...
- $\pi^0/\eta^0 \rightarrow \gamma\gamma$ is two photons in one cluster
  - Copiously produced in jets
  - Surrounded by other particles
- Electron is a “photon” with a track, and it brems in material
- Non-collision sources...
Photon candidate

- Up to 3 towers in $\eta$:
  - seed tower EM $E_T > 3$ GeV; shoulder tower EM $E_T > 0.1$ GeV
  - Had/Em $< 12.5\%$ unless EM $E_T > 100$ GeV
Photon ID: Had/Em

<table>
<thead>
<tr>
<th></th>
<th>Central</th>
<th>Forward</th>
</tr>
</thead>
<tbody>
<tr>
<td>Had/Em</td>
<td>&lt;0.125 or $&lt;0.055 + 0.00045 \times E$</td>
<td>$&lt;0.05$ if $E \leq 100$ GeV, $&lt;0.05 + 0.026 \times \ln(E/100)$ if $E &gt; 100$ GeV</td>
</tr>
</tbody>
</table>
Shower size ~3.5 cm; minimal $\gamma$ separation for $\pi^0$: $50 \text{ [cm GeV]} / E_T$
- Can resolve individual $\gamma$ showers from $\pi^0$ for $E_T(\pi^0) < 15 \text{ GeV}$

$\chi^2 = (\chi_S^2 + \chi_W^2) / 2$

$\chi_{S(W)}^2 = \sum (p_i - y_i)^2 / \sigma_i^2$

$\sigma_i^2 = 4(0.026^2 + 0.096^2 y_i) \times \left( \frac{10 \text{ GeV}}{E} \right)^{0.747}$
Photon ID: Track in CES Cluster

Central Only

<table>
<thead>
<tr>
<th>Number of Tracks in CES cluster</th>
<th>≤1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_T$ of track</td>
<td>&lt;1.0 + 0.005*E_T</td>
</tr>
</tbody>
</table>
Photon ID: Calorimeter Isolation

- **Calorimeter ISO corrections**
  - Photon towers removed;
  - Leakage in \( \phi \)-direction
  - Multiple interaction

### Central & Forward

| Cal ISO (cone R<0.4) | \( E_T < 20 \text{ GeV} \): \(< 0.1 \times E_T \)  
|                     | \( E_T > 20 \text{ GeV} \): \(< 2.0 + 0.02 \times (E_T - 20.0) \) |

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Central & Forward

Track ISO
(cone $R<0.4$; all tracks
with $|\Delta z|<5$ cm)

$<2.0+0.005E_T$
Photon ID: $E_T$ of 2nd CES Cluster

Central Only

| $E_T$ of 2nd CES cluster in same chamber | $E_T < 18$ GeV: $< 0.14 \times E_T$
|                                           | $E_T > 18$ GeV: $< 2.4 + 0.01 \times E_T$ |
Photon ID: PEM 3x3 $\chi^2$

- PEM 3x3 $\chi^2$
  - EM shower profile in 3x3=9 towers
  - Compared to known EM shower shape

Forward Only

<table>
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<th>Forward Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEM 3x3 $\chi^2$</td>
</tr>
</tbody>
</table>
**Photon ID: PES 5x9 Ratio**

- **PES 5x9 Ratio**
  - Ratio of $E(5\text{ strips})/E(9\text{ strips})$ centered on EM cluster
  - For U- & V-layers

<table>
<thead>
<tr>
<th>PES 5x9 Ratio</th>
<th>Forward Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>U &amp; V</td>
<td>&gt;0.65</td>
</tr>
</tbody>
</table>
~15% (~30%) central (forward) photons convert to $e^+e^-$

- Conversions are not used in photon analyses at CDF
- CDF has only one measurement using converted photons
What do you need in order to do an analysis with photons?

- Photon ID efficiency & acceptance
- Photon purity & background subtraction
- Fake rates
- Anything else?...
- **Method**
  - Use photon MC for efficiency
  - Data/MC scale factor: compare “unbiased” electron from Z-peak in data and MC

- **Acceptance**
  - ~15% of central photons lost because they have no CES cluster
EM cluster produced by $\pi^0/\eta$ have worse $\chi^2$ (if $E_T<35$ GeV)

- $\epsilon=1$ if $\chi^2<4$; $\epsilon=0$ if $\chi^2>4$
- $\epsilon_{\text{sig}}=N(\chi^2<4)/N(\chi^2<20) \approx 78\%$ (checked in $W/Z+\gamma$ with $\gamma$ FSR in Run II)
- $\epsilon_{\text{bckg}}=N(\chi^2<4)/N(\chi^2<20) \approx 30-40\%$ (checked with $\rho^\pm \rightarrow \pi^\pm \pi^0$ in Run I)
Two photons have higher conversion probability than one photon
- $\epsilon = 1$ if CP2 hit; $\epsilon = 0$ if no CP2 hit
- $\epsilon_{\text{sig}} = \sim 65\%$ (checked with $W/Z+\gamma$ events with $\gamma$ FSR)
- $\epsilon_{\text{bckg}} = \sim 85\%$

$$P = 1 - \exp\left(-\frac{7 \times M \times N_\gamma(E, \sin \theta)}{9 X_0 \sin \theta}\right)$$

$$M = 1.105 X_0$$

$N_\gamma = 1$ for single photon
$N_\gamma \sim 2$ for $\pi^0$
Method

- Signal template from $\gamma$+jet MC
  - Can use Z’s in data and MC for validation

- Background template from large stat. di-jet MC
  - Can use jets with leading $\pi^\pm$ ($P_T/E_T > 0.8$) in data and MC for validation
Method:
- Start from a collection of jets
- Count "photons" in jet collection
- Subtract number of true photons (based on statistical methods)
**Method:**

- Use MC (W, Drell-Yan) to get $E_T$ and $\eta$ dependences
- Compare $e^+\gamma$ and $e^+e^-$ events from Z-peak in data and MC to get MC-to-Data normalization
Reducing $e \rightarrow \gamma$ Fake Rate

- “Phoenix” tracking
  - Seed track from CAL cluster and event vertex
  - Look for Silicon hits along the expected arc
  - Originally developed for “forward” electrons
  - Also used for rejecting fake photons due to electron bremsstrahlung

![Diagram showing Phoenix tracking](image)

### Probability to match Phoenix track and Photon as function of $E_T^{\text{det}}$

- $\chi^2$/ndf: 36.25 / 28
- Prob: 0.687
- $p_0$: $0.4315 \pm 0.0041$
- $p_1$: $0.1159 \pm 0.0074$
- $p_2$: $24.4 \pm 0.3$

Fit function: $p_0 \text{Erfc}(p_1(p_2 - E_T^{\text{det}}))$
How does tau fake a photon?

Dominant: $\tau \rightarrow \rho \rightarrow \pi^+\pi^0 \rightarrow \gamma\gamma \rightarrow \gamma_{\text{fake}}$

- Hard to define and measure the fake rate; need to rely on MC
- Not the same as jet→γ_{fake}
- Can use reconstructed $Z \rightarrow \tau\tau$ in data & MC for normalization

Ratio = $\frac{N_{\tau \rightarrow \gamma}(P_T)}{N_{\tau}(P_T)}$  $\frac{N_{e \rightarrow \gamma}(P_T)}{N_{e}(P_T)}$
Cosmics

- Significant background for $\gamma$+MET and “delayed” photon searches
- Arrives independently of collision time
- Cosmic samples:
  - “$\gamma$+MET” candidate events without reconstructed vertex and tracks
  - “$\gamma$+MET” candidate events from special “no beam” runs

Use $W\rightarrow e\nu$ events to study EM timing in true collision events

EM timing resolution:
- True vertex: $\sigma \sim 0.7$ ns
- Wrong vertex: $\sigma \sim 1.9$ ns
Cosmics can also produce di-photon signature

- Can use $\Delta T_{12}$ cut to remove such events
  - True collision $\sigma_{\Delta T} \sim 1$ ns
  - Cosmics: $\Delta T \sim 5$–10 ns
Beam Halo events can produce $\gamma$+MET or even $\gamma\gamma$+MET signature.

Calorimeter $\eta$-$\phi$ view.
Example of “di-photon” beam halo event.
• Beam Halo samples
  – “γ+MET” candidate events without reconstructed vertex and tracks
• Beam Halo rejection
  – Topological cuts and EM timing
PMT Spikes

- **Central EM CAL:**
  - Spike overlaps with low $E_T$ particle from regular collision and gives fake $\gamma+\text{MET}$
  - 2 PMTs per tower; high PMT spike rate
  - removed by PMT asymmetry cut and EM timing cut

~50 Hz rate
- **Forward EM CAL:**
  - 1 PMT per tower, but much lower PMT spike rate
  - Rejected based on EM timing
Moving on to Physics
Search for Di-Photon Peaks

1155 pb\(^{-1}\) of Data

- Two central-central or central-forward photons
  - \(E_T(\text{photon}) \geq 15\) GeV
  - “tight” photon ID

- Backgrounds
  - SM \(\gamma\gamma\) production
    - DIPHOX MC
  - Fakes: \(\gamma\)-jet, jet-jet events
    - “Loose” \(\gamma\gamma\) events: at least one \(\gamma\) fails “tight” photon ID

Fit function: \(y = \left( x^{0.1} + \alpha_5 x^{\alpha_6} \right) \left( e^{x/\alpha_0} + \alpha_1 e^{x/\alpha_2} + \alpha_3 e^{x/\alpha_4} \right),\quad x = M_{\gamma\gamma} - 30\)
Limit for $k/M_{pl}=0.1$
- Di-photons: $M(G)>850$ GeV
- Combined with $e^+e^-$: $M(G)>875$ GeV

Total efficiency for $G \rightarrow \gamma \gamma$

Graviton Mass (GeV/c²)

Graviton Mass (GeV/c²)

CDF Run II Preliminary

\[ \int L \, dt = 0.8 - 1.2 \text{ fb}^{-1} \]
Models with exclusive $\gamma$+MET signature
- Large Extra Dimensions: $q + \bar{q} \rightarrow G + \gamma$
- Anomalous $Z\gamma$ coupling
- Heavy right-handed neutrinos

Analysis
- $E_T(\gamma) > 50$ GeV & MET > 50 GeV;
- veto $E_T$(jet)>15 GeV & $P_T$(track)>10 GeV
- Require at least 3 tracks

New invisible particle

photon
Non-collision background rejection is critical
  - EM timing: $|T_\gamma|<3.2$ ns
  - Track requirements
  - Relevance Vector Machine: train on $\gamma+$jet and out-of-time cosmic events
  - Cosmic rejection: x600

EWK backgrounds
  - Fake rates; data based

<table>
<thead>
<tr>
<th></th>
<th>$E_T^{\gamma}&gt;50$ GeV</th>
<th>$E_T^{\gamma}&gt;90$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W(e/\tau\rightarrow\gamma)$</td>
<td>24.7%</td>
<td>7.7%</td>
</tr>
<tr>
<td>$W_\gamma$</td>
<td>21%</td>
<td>11%</td>
</tr>
<tr>
<td>$\gamma\gamma\rightarrow\gamma$ (lost $\gamma$)</td>
<td>6.6%</td>
<td>4.9%</td>
</tr>
<tr>
<td>cosmics</td>
<td>13%</td>
<td>21%</td>
</tr>
<tr>
<td>$Z\gamma\rightarrow\nu\nu\gamma$</td>
<td>35.6%</td>
<td>54%</td>
</tr>
<tr>
<td>Total Bckg</td>
<td>280.5±15.7</td>
<td>46.3±3.0</td>
</tr>
<tr>
<td>Data</td>
<td>280</td>
<td>40</td>
</tr>
</tbody>
</table>
**Optimization for LED: $E_T(\gamma) > 90$ GeV**

- Signal acceptance: 2.7%
Search for Anomalous Production of $\gamma\gamma+X$

Why $\gamma\gamma+X$? Why model-independent

**SUSY**: $\gamma\gamma + E_T$, $\gamma\gamma + jets + E_T$, $\gamma\gamma + ll + E_T$

**Technicolor**: $\gamma\gamma + ll + E_T$

**Higgs**: $\gamma\gamma + E_T$, $\gamma\gamma + l + E_T$

**UED(6DSM)**: $\gamma\gamma + m^* l + E_T$

Rare $\gamma\gamma+X$ events at Tevatron
- Infamous CDF Run I “ee$\gamma\gamma$+MET” event
  - Dominant SM: $WW\gamma\gamma \Rightarrow 8 \times 10^{-7}$ events
  - Total: $\sim 10^{-6}$ events
- CDF & D0 Run II “e$\gamma\gamma$+MET” event
Three $\gamma\gamma+X$ analyses: $X=$MET, $\tau$, e/\(\mu\)

**Signal region**
- Two “tight” central photons
- Photon candidate $E_T>13$ GeV
- ~25% $\gamma\gamma$ pure events

**Control region**
- Two “loose” central photons, at least one photon must fail “tight” photon ID
- Photon candidate $E_T>13$ GeV
- ~5% $\gamma\gamma$ pure events
- Same backgrounds as in signal region

**Results**
- Event count; background predictions; kinematic distributions
Search for Anomalous $\gamma\gamma$+MET

- Two photons in time with collision
- Select events with MET-sig>3, 4, 5
- Backgrounds
  - QCD with fake MET ($\gamma\gamma$, $\gamma j$, $jj$)
    - MET Resolution Model
      - fake MET p.d.f for each event based on energy resolution (for jets and soft unclustered energy)
  - EWK with true MET
    - $W/Z+\gamma$, $W/Z$+jet, $Z\rightarrow\tau\tau\rightarrow\gamma\text{fake}\gamma \text{fake}$
    - shapes from MC; normalized to data $e+\gamma$
  - Non-collision
    - Beam Halo, Cosmics, PMT spikes
    - EM timing, topological cuts
**MET Resolution & Significance Model**

- Takes into account individual jet resolution
- Accounts for relative direction of MET and jet
- Eliminates need for Δφ(MET-jet) cuts

**New MET-sig=−log(P) for fake MET:**

Simple shape for any distribution F(x)

For 10,000 events:
- Cut on Sig>1 ⇒ ∼1,000 events pass
- Cut on Sig>2 ⇒ ∼100 events pass
- Cut on Sig>3 ⇒ ∼10 events pass
- Cut on Sig>4 ⇒ ∼1 event pass

\[ x_0 = \frac{E_T}{E_T^{\text{jet}}} - 1 \]

\[ \text{\(E_T\)-significance} = -\log(P) \]

\[ P = \int_{x_0}^{\infty} F(x) \, dx \]

\[ F(x) = \ln(10) e^{x \ln(10)} \]
$\gamma\gamma + \text{MET}: \text{ Results}$

**Efficiency for $W_\gamma \rightarrow e\nu\gamma$**

<table>
<thead>
<tr>
<th>MetSig &gt; 3.0</th>
<th>MetSig &gt; 4.0</th>
<th>MetSig &gt; 5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>84%</td>
<td>74%</td>
<td>67%</td>
</tr>
</tbody>
</table>

- Total number of $\gamma\gamma$ events: 31,116

<table>
<thead>
<tr>
<th></th>
<th>MetSig &gt; 3.0</th>
<th>MetSig &gt; 4.0</th>
<th>MetSig &gt; 5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>EWK</td>
<td>47%</td>
<td>75%</td>
<td>84%</td>
</tr>
<tr>
<td>Background</td>
<td>67.9 $\pm$ 7.5</td>
<td>35.8 $\pm$ 3.0</td>
<td>27.3 $\pm$ 2.3</td>
</tr>
<tr>
<td>Data</td>
<td>82</td>
<td>31</td>
<td>23</td>
</tr>
</tbody>
</table>

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Results for $\gamma\gamma+\text{MET}$: After Metsig>5 Cut

- Top left: $\text{MET}$
- Top right: $H_T$
- Bottom: $M_{\gamma\gamma}$
Visible “hadronic” tau $E_T > 15$ GeV
- jet→τ fake rate from di-jet events
- $\gamma\gamma$+jet × fake rate
- Test technique in control sample

Backgrounds
- Dominant: $\gamma\gamma$+jet fake
- Real τ from $W\gamma$ or $Z\gamma$
  - From MC
Search for Anomalous $\gamma\gamma + \tau$
Search for Anomalous $\gamma\gamma+e/\mu$

- Central or forward electron with $E_T > 20$ GeV
- Central muon with $P_T > 20$ GeV
- Backgrounds
  - $W\gamma\gamma+Z\gamma\gamma$ (from MC)
  - $\gamma+\text{lepton}+\text{ele} \rightarrow \text{fake } \gamma$ (dominant for $\gamma\gamma e$)
  - $\gamma+\text{fake lepton}$
  - $\gamma+\text{lepton}+\text{jet} \rightarrow \text{fake } \gamma$

From data
Using fake rates

<table>
<thead>
<tr>
<th></th>
<th>$\gamma\gamma+e$</th>
<th>$\gamma\gamma+\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data, 1 fb$^{-1}$</strong></td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td><strong>Bckg</strong></td>
<td>6.82±0.75</td>
<td>0.79±0.11</td>
</tr>
<tr>
<td>$W\gamma\gamma+Z\gamma\gamma$</td>
<td>16%</td>
<td>81%</td>
</tr>
<tr>
<td>$\gamma l+e \rightarrow \gamma$</td>
<td>75%</td>
<td>2%</td>
</tr>
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<th>$\gamma\gamma+e$</th>
<th>$\gamma\gamma+\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data, 1 fb$^{-1}$</strong></td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td><strong>Bckg</strong></td>
<td>3.79±0.54</td>
<td>0.71±0.10</td>
</tr>
<tr>
<td>$W\gamma\gamma+Z\gamma\gamma$</td>
<td>26%</td>
<td>81%</td>
</tr>
<tr>
<td>$\gamma l+e \rightarrow \gamma$</td>
<td>60%</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>

Before Phoenix rejection

After Phoenix rejection

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Search for Anomalous $\gamma\gamma + e$
"Delayed" Photons

- **Gauge-Mediated SUSY**
  - $\chi^0 \to \gamma + G$ decays can occur with finite lifetime
  - **Signature:** at least one "delayed" photon, MET, jet (from $\tau$'s)
"Delayed" Photons: Analysis Technique

Selection
- $E_T(\gamma)>30$ GeV; MET$>40$ GeV; $E_T$(jet$)>35$ GeV; $\Delta \Phi$(MET-jet$)>1.0$ rad
- Signal region: $2$ ns$<T_{\gamma}<10$ ns

Analysis feature
- All backgrounds estimated from purely data
- Don't need to consider different sources of SM backgrounds

It is all about timing distribution shapes!!

W→ev events
Cosmic events
Beam Halo

10/28/08
Sasha Pronko, HEP seminar, Univ. of Pennsylvania
“Delayed” Pho+Jet+MET

0 Result

- Data: 2 events
- Background: 1.3±0.7;
  - SM=0.71;
  - Cosmics=0.46;
  - Beam Halo=0.07
Follow up on Gauge-Mediated SUSY models
- Renewed interest motivated by Run I ee+γγ+MET event

Technicolor models, but without MET

Event selection
- Central photon $E_T > 25$ GeV
- 2 jets: $E_T > 15$ GeV & $|\eta| < 2$
- MET > 25 GeV
- $\Delta \phi (\text{jet, MET}) > 0.3$
- At least 1 b-tag (SecVtx)

Background categories

<table>
<thead>
<tr>
<th></th>
<th>Real $\gamma$</th>
<th>Fake $\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real b-tag</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Fake b-tag</td>
<td>C</td>
<td>D</td>
</tr>
</tbody>
</table>
**γ+jet+b+MET: Backgrounds**

<table>
<thead>
<tr>
<th></th>
<th>Real γ</th>
<th>Fake γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real b-tag</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Fake b-tag</td>
<td>C</td>
<td>D</td>
</tr>
</tbody>
</table>

- **Background A:**
  - MadGraph MC: γ+b+jets, γ+c+jets
  - Normalized based on photon purity & H.F. fractions

- **Backgrounds B & D:**
  - Fake photon subtraction based on CES/CP2 method
  - Photon purity: 81%±12%

- **Background C:**
  - γ+jet+jet × mis-tag rate
  - CES/CP2 method to subtract fake photon contribution

---

Data: 617  
Background: 637±139
\(\gamma + \text{jet} + b + \text{MET}:\) Kinematic Distributions

CDF Run II Preliminary 2.0 fb\(^{-1}\) \(\gamma b\bar{b} \pT\) Search

- **Data**
- Fake \(\gamma\), Real + fake b
- Real \(\gamma\), Fake b
- \(\gamma c\)
- \(\gamma b\)
- Background Uncertainty

CDF Run II Preliminary 2.0 fb\(^{-1}\) \(\gamma b\bar{b} \pT\) Search

- **Data**
- Fake \(\gamma\), Real + fake b
- Real \(\gamma\), Fake b
- \(\gamma c\)
- \(\gamma b\)
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CDF Run II Preliminary 2.0 fb\(^{-1}\) \(\gamma b\bar{b} \pT\) Search

- **Data**
- Fake \(\gamma\), Real + fake b
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CDF Run II Preliminary 2.0 fb\(^{-1}\) \(\gamma b\bar{b} \pT\) Search

- **Data**
- Fake \(\gamma\), Real + fake b
- Real \(\gamma\), Fake b
- \(\gamma c\)
- \(\gamma b\)
- Background Uncertainty

10/28/08

Sasha Pronko, HEP seminar, Univ. of Pennsylvania
**Search for New Physics in $\ell\gamma\not{E}_T b$ Events and $\sigma_{tt\gamma}$ measurement**

**Motivation**
- Extension of $\ell\gamma\not{E}_T$
- Signature with $b$ and $t$, $W$ and $\gamma$
- $tt\gamma$: control sample for $ttH$ (LHC), $Q$(top)

**Results**

<table>
<thead>
<tr>
<th>$\ell\gamma\not{E}_T b$</th>
<th>$e\gamma\not{E}_T b$</th>
<th>$\mu\gamma\not{E}_T b$</th>
<th>$(e+\mu)\gamma\not{E}_T b$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expected</strong></td>
<td>16.8 ± 2.2</td>
<td>11.1 ± 1.4</td>
<td>27.9 ± 3.5</td>
</tr>
<tr>
<td><strong>Observed</strong></td>
<td>16</td>
<td>12</td>
<td>28</td>
</tr>
</tbody>
</table>

The CDF Run II Preliminary, 1.9fb$^{-1}$

The probability, assuming no true $tt\gamma$ Standard Model (SM) signal, for the background alone to produce at least as many events (16) as observed in data, is 1% (2.3 $\sigma$). Assuming SM $tt\gamma$ production, we calculate the $tt\gamma$ cross-section to be $\sigma_{\text{semileptonic}}^{tt\gamma} = 0.15 \pm 0.08$ pb. SM prediction is $\sigma_{\text{semileptonic}}^{tt\gamma}^{\text{SM}} = 0.080 \pm 0.011$ pb.
CDF has very reach program of searches for new physics in final states with photons
- Many channels: photon+ leptons, jets, b-jets, MET
- New techniques developed and applied
- Unfortunately, no signs of new physics... just yet

Physics with photons is both fun and challenging
- LHC experiments should be prepared for surprises

Most interesting times are still ahead!!
Backup Slides
Gauss+Landau fits JER well at any $E_{\text{jet}}$ and $\eta$

$$\frac{C \cdot G(y) + L(y)}{1 + C},$$

where $y = \frac{-x}{1 + x}$,

$$x = \frac{E_{\text{had}}}{E_{\text{det}}} - 1$$

✓ Smooth parameterization of JER as a function of $E_{\text{jet}}$ in bins of $\eta_{\text{det}}$ (bin size of 0.2)
Met Model gives a PDF of possible MET values due to energy mis-measurements (also available in XY)

- This is done by smearing un-clustered and each jet energy according to their resolution
- Met Model successfully describes MET in Pythia $\gamma\gamma$ and Z events where there is no real MET
- Just as expected, it doesn’t describe MET in Baur $W\gamma$ events with real MET
“New” MET Significance Example

- **“Old” Metsig**
  - Sig = MET/\(\sum E\)

- **Event-1**
  - largest MET
  - MET = 165.1 GeV
  - METsig
    - Met Model: 1.76
    - “Old” Metsig: 7.65

- **Event-2**
  - MET = 57.1 GeV
  - METsig
    - Metmodel: >18.0
    - “Old” Metsig: 5.45
**γγ+e+MET**

### CDF Run II Preliminary, γγ+X, 2 fb⁻¹

#### Object

<table>
<thead>
<tr>
<th>Object</th>
<th>$E_T$, GeV</th>
<th>$\varphi$</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pho-1</td>
<td>85.2</td>
<td>5.93</td>
<td>-0.303</td>
</tr>
<tr>
<td>Pho-2</td>
<td>24.7</td>
<td>2.22</td>
<td>-0.845</td>
</tr>
<tr>
<td>Electron</td>
<td>49.6</td>
<td>3.20</td>
<td>1.07</td>
</tr>
<tr>
<td>MET</td>
<td>15.1</td>
<td>2.56</td>
<td>N/A</td>
</tr>
<tr>
<td>$H_T$</td>
<td>174.6</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>
Results for $\gamma\gamma$+MET: Signal Sample

- Signal sample
  - two “tight” photons;
  - ~25% true $\gamma\gamma$ events

- $\gamma\gamma$ events before MetSig cut: 31,116

<table>
<thead>
<tr>
<th></th>
<th>MetSig&gt;3.0</th>
<th>MetSig&gt;4.0</th>
<th>MetSig&gt;5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-collision</td>
<td>0.89 ± 0.32</td>
<td>0.84 ± 0.30</td>
<td>0.77 ± 0.27</td>
</tr>
<tr>
<td>“No $\gamma\gamma$ Vertex”</td>
<td>4.4 ± 2.0</td>
<td>2.5 ± 1.0</td>
<td>1.5 ± 0.7</td>
</tr>
<tr>
<td>$\gamma\gamma\gamma$ (lost $\gamma$)</td>
<td>2.9 ± 1.0</td>
<td>2.2 ± 1.0</td>
<td>1.6 ± 1.0</td>
</tr>
<tr>
<td>Fake Met (MetModel)</td>
<td>28.1 ± 6.8</td>
<td>3.6 ± 1.8</td>
<td>0.60 ± 0.83</td>
</tr>
<tr>
<td>EWK real MET</td>
<td>31.6 ± 2.0</td>
<td>26.7 ± 1.9</td>
<td>22.8 ± 1.7</td>
</tr>
<tr>
<td>Total</td>
<td>67.9 ± 7.5</td>
<td>35.8 ± 3.0</td>
<td>27.3 ± 2.3</td>
</tr>
<tr>
<td>Observed</td>
<td>82</td>
<td>31</td>
<td>23</td>
</tr>
</tbody>
</table>
Results for $\gamma\gamma$+MET: Control Sample

- Control sample
  - Two “loose” photons; at least one photon fails “tight” ID cuts;
  - ~5% true $\gamma\gamma$ events

$\gamma\gamma$ events before MetSig cut: 42,708

<table>
<thead>
<tr>
<th></th>
<th>MetSig&gt;3.0</th>
<th>MetSig&gt;4.0</th>
<th>MetSig&gt;5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-collision</td>
<td>1.29 ± 0.47</td>
<td>1.18 ± 0.42</td>
<td>1.03 ± 0.36</td>
</tr>
<tr>
<td>“No $\gamma\gamma$ Vertex”</td>
<td>1.35 ± 0.62</td>
<td>0.78 ± 0.30</td>
<td>0.45 ± 0.22</td>
</tr>
<tr>
<td>$\gamma\gamma\gamma$ (lost $\gamma$)</td>
<td>4.4 ± 1.5</td>
<td>3.2 ± 1.4</td>
<td>2.4 ± 1.4</td>
</tr>
<tr>
<td>Fake Met (MetModel)</td>
<td>38.5 ± 11.0</td>
<td>5.7 ± 1.3</td>
<td>0.80 ± 0.36</td>
</tr>
<tr>
<td>EWK real MET</td>
<td>43.7 ± 5.4</td>
<td>35.4 ± 4.7</td>
<td>32.2 ± 7.8</td>
</tr>
<tr>
<td>Total</td>
<td>89.2 ± 12.4</td>
<td>46.2 ± 5.1</td>
<td>36.9 ± 8.0</td>
</tr>
<tr>
<td>Observed</td>
<td>103</td>
<td>50</td>
<td>28</td>
</tr>
</tbody>
</table>
### CDF Run II Preliminary, 1.9fb⁻¹

**Lepton + Photon + E_T + b Events, Isolated Leptons**

<table>
<thead>
<tr>
<th>Standard Model Source</th>
<th>eγbE_T</th>
<th>µγbE_T</th>
<th>(e + µ)γbE_T</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttγ semileptonic</td>
<td>2.06 ± 0.38</td>
<td>1.52 ± 0.28</td>
<td>3.58 ± 0.65</td>
</tr>
<tr>
<td>ttγ dileptonic</td>
<td>1.30 ± 0.23</td>
<td>1.02 ± 0.18</td>
<td>2.32 ± 0.41</td>
</tr>
<tr>
<td>W±cγ</td>
<td>0.75 ± 0.16</td>
<td>0.72 ± 0.15</td>
<td>1.47 ± 0.26</td>
</tr>
<tr>
<td>W±cγ</td>
<td>0.08 ± 0.04</td>
<td>0.22 ± 0.06</td>
<td>0.30 ± 0.08</td>
</tr>
<tr>
<td>W±bbγ</td>
<td>0.62 ± 0.11</td>
<td>0.42 ± 0.08</td>
<td>1.04 ± 0.17</td>
</tr>
<tr>
<td>Z(ττ)γ</td>
<td>0.13 ± 0.09</td>
<td>0.11 ± 0.08</td>
<td>0.24 ± 0.12</td>
</tr>
<tr>
<td>WZ</td>
<td>0.08 ± 0.04</td>
<td>0.01 ± 0.01</td>
<td>0.00 ± 0.04</td>
</tr>
<tr>
<td>τ → γ fake</td>
<td>0.12 ± 0.01</td>
<td>0.10 ± 0.01</td>
<td>0.22 ± 0.01</td>
</tr>
<tr>
<td>Jet faking τ (ejE_Tb, j → γ)</td>
<td>4.56 ± 1.92</td>
<td>3.02 ± 1.19</td>
<td>7.58 ± 3.11</td>
</tr>
<tr>
<td>MisTags</td>
<td>4.11 ± 0.41</td>
<td>3.54 ± 0.37</td>
<td>7.65 ± 0.70</td>
</tr>
<tr>
<td>QCD(Jets faking ℓ and E_T)</td>
<td>1.49 ± 0.77</td>
<td>0 ± 1</td>
<td>1.49 ± 1.30</td>
</tr>
<tr>
<td>eeE_Tb, e → γ</td>
<td>1.50 ± 0.28</td>
<td>–</td>
<td>1.50 ± 0.28</td>
</tr>
<tr>
<td>µeE_Tb, e → γ</td>
<td>–</td>
<td>0.45 ± 0.10</td>
<td>0.45 ± 0.10</td>
</tr>
<tr>
<td>Total SM Prediction</td>
<td>16 ± 2.2 ttot</td>
<td>11.1 ± 1.7 ttot</td>
<td>27.9 ± 3.6 ttot</td>
</tr>
<tr>
<td>Observed in Data</td>
<td>16</td>
<td>12</td>
<td>28</td>
</tr>
</tbody>
</table>

**ttγ, Isolated Leptons**

<table>
<thead>
<tr>
<th>Standard Model Source</th>
<th>eγbE_T</th>
<th>µγbE_T</th>
<th>(e + µ)γbE_T</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttγ (semileptonic)</td>
<td>1.97 ± 0.36</td>
<td>1.47 ± 0.27</td>
<td>3.44 ± 0.62</td>
</tr>
<tr>
<td>ttγ (dileptonic)</td>
<td>0.52 ± 0.10</td>
<td>0.43 ± 0.08</td>
<td>0.95 ± 0.17</td>
</tr>
<tr>
<td>W±cγ</td>
<td>0.00 ± 0.02</td>
<td>0.01 ± 0.01</td>
<td>0 ± 0.03</td>
</tr>
<tr>
<td>W±bbγ</td>
<td>0.00 ± 0.02</td>
<td>0.01 ± 0.01</td>
<td>0.00 ± 0.02</td>
</tr>
<tr>
<td>W±cγ</td>
<td>0.06 ± 0.03</td>
<td>0.01 ± 0.01</td>
<td>0.07 ± 0.03</td>
</tr>
<tr>
<td>WZ</td>
<td>0.02 ± 0.02</td>
<td>0.01 ± 0.01</td>
<td>0.02 ± 0.02</td>
</tr>
<tr>
<td>τ → γ fake</td>
<td>0.08 ± 0.01</td>
<td>0.02 ± 0.01</td>
<td>0.10 ± 0.01</td>
</tr>
<tr>
<td>Jet faking τ (ejE_Tb, j → γ)</td>
<td>2.37 ± 1.22</td>
<td>1.42 ± 0.70</td>
<td>3.79 ± 1.92</td>
</tr>
<tr>
<td>MisTags</td>
<td>0.78 ± 0.20</td>
<td>0.83 ± 0.22</td>
<td>1.61 ± 0.31</td>
</tr>
<tr>
<td>QCD(Jets faking ℓ and E_T)</td>
<td>0.53 ± 0.46</td>
<td>0 ± 1</td>
<td>0.53 ± 1.10</td>
</tr>
<tr>
<td>eeE_Tb, e → γ</td>
<td>0.34 ± 0.11</td>
<td>–</td>
<td>0.34 ± 0.11</td>
</tr>
<tr>
<td>µeE_Tb, e → γ</td>
<td>–</td>
<td>0.20 ± 0.06</td>
<td>0.20 ± 0.06</td>
</tr>
<tr>
<td>Total SM Prediction</td>
<td>6.7 ± 1.4 ttot</td>
<td>4.4 ± 1.3 ttot</td>
<td>11.1 ± 2.3 ttot</td>
</tr>
<tr>
<td>Observed in Data</td>
<td>8</td>
<td>8</td>
<td>16</td>
</tr>
</tbody>
</table>

10/28/08

Sasha Pronko, HEP seminar, Univ. of Pennsylvania

- Central photon: E_T > 10 GeV
- Lepton: E_T > 20 GeV
- B-jet: E_T > 15 GeV
- MET > 20 GeV
- ttγ: H_T > 200 GeV
ISO ideas

![Graph showing particle flow in arbitrary units vs. angle with respect to cone axis. Red line represents Jet Cone and blue line represents Photon Cone.](image)
Photons in Central EM Calorimeter

CMU - Central Muon
CHA - Central Hadron Towers 0-7
CEM - Central E-M Towers 0-9
WHA - Wall Hadron Towers 6-71
PHA - Plug Hadron Towers 12-21

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