Searches for New Physics Using Photons at the Tevatron

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The next big discovery in particle physics may well come from looking at samples with Final State Photons
Motivation

There are two types of reasons to look for new physics in final states with photons at the Tevatron

1. Well motivated theories
   - Most importantly Supersymmetry

2. Follow up on some of the anomalies from CDF in Run I
Outline

- Supersymmetry and Photons
- Run I Results
  - The search for SUSY
  - The CDF $ee\gamma\gamma$ candidate event
  - Model-independent follow-up and other interesting hints
- Run II Results
  - New limits
  - Exciting new hints
  - Recently installed hardware
  - Prospects for the future
- Conclusions
Color coding the recurring themes in the story...

Three recurring themes...

1. Golden Events
   • Individual events which don’t look SM-like and thus could be “hints” of new particles in the data

2. Null Results or Theories that don’t explain the hints
   • Theories of new particles haven’t helped as much as we would like

3. New ideas or new techniques
Supersymmetry

- One of the most promising theories of new particles (for MANY reasons not discussed here)
  - Well developed and motivated
  - Potential for helping with Grand Unified Theories
  - Cold Dark Matter candidate/Cosmology connections
  - Etc...
- The fermion/boson symmetry provides a Supersymmetric partner for each Standard Model particle
Example Final States for one Model: Two photons and Supersymmetry

Compare SM and SUSY Collisions at the Tevatron

**Standard Model:**

\[ \overline{P} \rightarrow \gamma \]

\[ P \rightarrow \gamma \]

\[ \gamma \gamma + \text{No Supersymmetric Particles in Final State} \]

**Supersymmetry:**

\[ \overline{P} \rightarrow \tilde{G} \]

\[ P \rightarrow \tilde{\chi}_1^0, \tilde{\chi}_1^0 \]

\[ \gamma \gamma + \text{Supersymmetric Particles in Final State} \]
**Standard Model:**

$\gamma$

**Supersymmetry:**

$\tilde{P} \rightarrow \tilde{G}$

Collision End view:

**Standard Model:**

No Energy Imbalance

**Supersymmetry:**

SUSY Particles Leave the detector

Energy Imbalance
Background Expectations

What SUSY would look like

Search for events here

Energy Imbalance Per Event

- Look at each γγ data event
- Put its Energy Imbalance in a histogram
- Compare to the expected predictions from the Standard Model and from SUSY
Search for anomalous $\gamma \gamma$ events at CDF

Data is consistent with background expectations (gives us confidence we got that part right)

One possible exception

* R. Culbertson, H. Frisch, D. Toback + CDF
The interesting event on the tail

- In addition to $\gamma\gamma^+$ Energy Imbalance this (famous) event has two high energy electron candidates
  - Both are unexpected
- Very unusual
- Good example of getting an answer which is far more interesting than what you asked for
- How unusual?

David Tobac
Predicted by the Standard Model?

- Dominant Standard Model Source for this type of event: $WW_{\gamma\gamma}$
  
  - $WW_{\gamma\gamma} \rightarrow (e\nu)(e\nu)_{\gamma\gamma} \rightarrow ee_{\gamma\gamma} + \text{Energy Imbalance:}$
    
    - $8 \times 10^{-7}$ Events

- All other sources (mostly detector mis-identification): $5 \times 10^{-7}$ Events

- Total: $(1 \pm 1) \times 10^{-6}$ Events

Perspective: Look at ~5 trillion collisions, expect $10^{-6}$ events with two electrons, two photons and an energy imbalance; observe 1 (expect one like this in 5 quintrillion collisions)
This event looks like a natural prediction of Supersymmetry

(Well...this was pointed out after it was seen by the theory community... Gauge Mediated Supersymmetry has since been revived and become an important theme in the field)
Other evidence for this type of Supersymmetry?

Theory Prediction: Models which predict this event predict additional events with $\gamma\gamma + \text{Energy Imbalance}$

- We don't see any other candidates like that
- No others seen by CDF or DØ in Run I, or in the high energy data taking at LEP
Set limits on the models

- These null results have been combined
- They constrain or exclude most SUSY models which predict the event

ALEPH DELPHI L3 OPAL
\[ e^+ e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \tilde{g}\tilde{g}W \]
\[ 130 \leq \sqrt{s} \leq 209 \text{ GeV} \]

SUSY Theory region favored by \( e\gamma+\text{Met} \) candidate

Excluded at 95% C.L.
What to do?

• Our anomalous event isn’t consistent with the currently favored models of Supersymmetry

• While there are other models which predict this event, most have long since fallen by the wayside

• Perhaps there is something far more interesting and unpredicted going on! But what? Need more experimental hints... and new ways of doing things...
New Systematic Method: Use properties of the event to suggest a more model independent search

• Look for “cousins” of our events
  - Others with “similar” properties
  - Others of this “type”

• To corrupt a famous quote: “I don’t know exactly what I’m looking for, but I’d know it if I saw it”
Unknown Interactions: Example

These two events would be "cousins"
Example “cousins” Search

- A priori the $e e \gamma \gamma + \text{Energy Imbalance}$ event is unlikely to be Standard Model $W W \gamma \gamma$ production
  - (~$10^{-6}$ Events)

- Guess that the unknown interaction is “Anomalous” $W W \gamma \gamma$ production and decay

- Look for similar unknown interaction with
  - $W W \rightarrow (q q)(q q) \rightarrow jjjj$
  - $\text{Br}(W W \rightarrow jjjj) \gg \text{Br}(W W \rightarrow ee+\text{EnergyImb})$

By branching ratio arguments: Given 1 $\gamma \gamma + ll + \text{Energy Imbalance}$ event

$\rightarrow$ Expect ~30 $\gamma \gamma + jjj$ “cousin” events
\[ \gamma \gamma + \text{Jets Search at CDF} \]

- Look in \( \gamma \gamma \) data for anomalous production of associated jets from quark decays of \( W \)'s
- \(~30\) Event excess would show up here

\[ \text{Number of Jets} \]

\[ \text{Events} \]

Run I Data from CDF

\[ *R. Culbertson, H. Frisch, D. Toback + CDF \]

\[ \text{PRL 81, 1791 (1998), PRD 59, 092002 (1999)} \]

\[ \text{David Toback, Texas A&M University, May 2005} \]

\[ \oplus \gamma \gamma \text{ Data (85 pb}^{-1}) \]
CDF Run I

All results are consistent with the Standard Model background expectations with no other exceptions

<table>
<thead>
<tr>
<th>Signature (Object)</th>
<th>Obs.</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T &gt; 35$ GeV, $</td>
<td>\Delta \phi_{\tau,\text{jet}}</td>
<td>&gt; 10^\circ$</td>
</tr>
<tr>
<td>$N_{\text{jet}} \geq 4$, $E_T^{\text{jet}} &gt; 10$ GeV, $</td>
<td>\eta^{\text{jet}}</td>
<td>&lt; 2.0$</td>
</tr>
<tr>
<td>Central $e$ or $\mu$, $E_T^{e,\mu} &gt; 25$ GeV</td>
<td>3</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>Central $\tau$, $E_T^{\tau} &gt; 25$ GeV</td>
<td>1</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>$b$-tag, $E_T^b &gt; 25$ GeV</td>
<td>2</td>
<td>1.3 ± 0.7</td>
</tr>
<tr>
<td>Central $\gamma$, $E_T^\gamma &gt; 25$ GeV</td>
<td>0</td>
<td>0.1 ± 0.1</td>
</tr>
</tbody>
</table>

*R. Culbertson, H. Frisch, D. Toback + CDF
Another Cousins Search

Instead of two photons try a photon and a lepton
In general data agrees with expectations. But:

- 11 $\mu\gamma+\text{Met}$ events on a background of $4.2\pm0.5$ expected
  - Not statistically significant enough to be a discovery, but interesting
- No excess in $e\gamma+\text{Met}$?! 5 on a background of $3.4\pm0.3$
  - Not clear what to make of this... In general SM particles have roughly the same branching ratio for all leptons
- However, we are encouraged that this new model independent method gave us a new hint

*J. Berryhill, H. Frisch, D. Toback + CDF
Hmmm...Another hint? $\mu\gamma\gamma jj$

- Another event in the data with properties “similar” to the $ee\gamma\gamma+\text{Energy Imbalance}$ candidate
- Not part of the “official” $\gamma\gamma$ dataset
- No significant energy imbalance
- Not quite as interesting. Background only at the $10^{-4}$ level
  - 1 in 10 quadrillion
- Again, no good Standard Model explanation
  Need to keep looking...

Unpublished confidential result

M. Contreras, H. Frisch and D. Toback
(CDF Internal 1996)
Half-Way Point Summary

- Theory not confirmed by experiment
- “cousins” model provides interesting hints, but doesn’t point to a theory
- The logical next steps are:
  1. Look in many more places using new systematic model-independent search methods
     - “Sleuth” Method
     - Whole separate talk… bottom line: no new hints in DØ photon data or otherwise
       - B. Knuteson, D. Toback + DØ, PRL 86, 3712 (2001)
       & PRD 64, 012004 (2001)

  2. Improve the detectors and take more data
Take more data!

- Increase the Collision Energy
- Increase the rate at which we take data
- Upgrade the detectors
4 years of work in one slide

• Any new excess in two photons + energy imbalance?
• No new official events out here!

*C. Culbertson, D.H. Kim, M.S. Kim, S.W. Lee, D. Toback + CDF
PRD 71, 031104 (2005). First CDF II direct SUSY Result
David Toback Texas A&M University May 2005
Combined Limits

- DØ has a similar null result
- CDF and DØ have combined their results to create the world's most stringent limits on GMSB SUSY

*R. Culbertson, Y. Gerstein, M.S. Kim, S.W. Lee, S. Mrenna, D. Toback + Tevatron New Phenomena Working Group
hep-ex/0505043, First FNAL Run II Combined Result
A New CDF Run IIa Event Candidate

But...

Another unofficial interesting event!!

Came in before the “official” data taking period started (will never become public)

Two photons, one electron and energy imbalance

Preliminary background estimate at the $3 \times 10^{-3}$ level from $W\gamma\gamma$

Clearly similar to the other CDF anomalies

Unpublished confidential result

R. Culbertson, H. Frisch, B. Heinemann, P. Merkel & D. Toback
(CDF Internal 2002)
Yet Another Event...

- DØ finally has an event like this
- $W_{\gamma\gamma}$? Same background level
- Cousin of CDF events?

If all "ee$\gamma\gamma$+Energy Imbalance" favored SUSY parameter space is nearly excluded, then what is it? Why do we keep getting these events?

Unpublished Result
For the last quarter of the talk focus on the future:

• There continue to be interesting events with photons and no good theory to explain them

• Perhaps they are from Cosmic Rays?

• Our studies show that these backgrounds are VERY small
  
  - Example: For the $ee\gamma\gamma+\text{Energy Imbalance}$ candidate expect about $10^{-9}$ events of this type
$\gamma^+ \gamma^-$ Big Energy Imbalance

Cosmic Ray "Measured" Imbalance

Arrives "later" in time

Real Imbalance
Recent CDF upgrade: EMTiming

Add “photon” timing:

1. Provides a vitally important handle that could confirm or deny that all the photons in unusual events are from the primary collision

2. Reduces cosmic ray background sources
   • Improves the sensitivity to SUSY, Large Extra Dimensions, Anomalous Couplings etc.

3. Allows for direct searches for long-lived particles (A few words on this in a moment)
Hardware for EMTiming Project

• Effectively put a TDC onto about 2000 phototubes at CDF
• Finished full installation in October 2004 (2 years ahead of original Run IIb schedule)
• Started taking data in January 2005
System Sensitivity

- ~100% Efficient for all high $P_T$ photons
- System resolution of ~650 psec

Collision Particles

Beam-Related

Cosmic Rays (Arrive randomly in time)

M. Goncharov, D. Toback et al, to be submitted to NIM (July 2005)
Can we Search for Long-Lived Particles that decay to photons?

With ~1 nsec resolution, it turns out we can try a NEW type of search.

Arrives “later” in time

Energy Imbalance

Heavy & Slow...
Long-Lived SUSY Particles

Signal can be well separated from SM
Comparing the sensitivity

- Exclusions from LEP experiments
- Favored theory region due to cosmological constraints
  - Line is Gravitino mass = 1 keV
- Our prospects for ~3 years of data taking

D. Toback and P. Wagner
PRD 70, 114032 (2004)
David Toback Texas A&M University May 2005
The plan for the next couple years at the Tevatron

Next two years:
• Dedicated SUSY searches
• Model-Independent Searches
• Use our new timing system for both

Next five years:
• Pursue new hints from Run II
• Full Sleuth searches
• Search for long-lived particles
• Higgs Bosons? Supersymmetry? Twenty $e^+e^-\gamma\gamma$+Energy Imbalance events?
• Some other completely unexpected events?
The LHC era is rapidly approaching
Start taking data in 2007
• 2007–2013(?) Discovery of Supersymmetry?
• Model-independent searches will be especially exciting at the new energy frontier
• 2013?–2017? Precision measurements of the properties of our new physics
The next big discovery in particle physics may well come from looking at samples with final state photons

- Many interesting hints in the data with photons; may well point the way
- Model Independent search techniques (*Sleuth*) may enable a major discovery even if the current theory predictions are wrong
- Run II results from the Tevatron have a significant sensitivity improvement and there are new hints!
- New instrumentation at CDF and the immanent turn-on of LHC provides new and exciting sensitivity for the next many years