Search for New Particles at the Fermilab Tevatron

Abstract

Since the discovery of the top quark, there have been a number of exciting hints for new particles beyond the Standard Model of particle physics from the Fermilab Tevatron. In this talk I will present what I believe are some of the most tantalizing hints (e.g. one observed proton anti-proton collision appears so unlikely to be from known sources that of the 3 trillion collisions we observed, we expected $10^{-6}$) and present the results of a recently finished systematic set of model independent searches using the novel Sleuth method to look for other hints. In addition, I will present some very preliminary results from the new Tevatron data and present prospects for a future upgrade which will make us even more sensitive and robust for future observations.

David Toback

Searching for New Particles at the Fermilab Tevatron
Searching for New Particles at the Fermilab Tevatron

Dave Toback
Texas A&M University

Department Colloquium
September, 2002
Overview

• Since the discovery of the 6th and final(?) quark at the Fermilab Tevatron, the field of particle physics continues to progress rapidly

• During that data taking run, and since, there continue to be a number of exciting hints from Fermilab that there are new fundamental particles just around the corner waiting to be discovered

• This talk describes following up on some of what may be some of the best experimental hints
Outline

• Overview: Fermilab and looking for new particles
• A hint?: An unusual event
• Model Independent Search Methods and Results: “Cousins,” Signature Based Searches and Sleuth
• The present and future: Taking more data and improving search robustness
• Conclusions
The Known Particles

The Standard Model of particle physics has been enormously successful

But: • Why do we need so many different particles?
• Why are some so much heavier than the others?
• How do we know we aren’t missing any?
How to attack the problem

Theorists: Theoretical Models

New Particles to Look For

Theoretical Parameters to Measure

Experimenters: Experimental Results

Unexplained Phenomena

Results of Particle Searches and Parameter Measurements

David Toback
Searching for New Particles at the Fermilab Tevatron
Fermi National Accelerator Laboratory
(Fermilab Tevatron)

- The world's highest energy experiment
- Proton Anti-Proton Collisions
- Center of Mass energy of 1.8 TeV
- 1 collision every 3.5μsec (300,000/sec)
- The data presented today corresponds to the study of ~5 trillion \( \bar{p}p \) collisions

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Searching for New Particles at the Fermilab Tevatron
Big Toys: The CDF and DØ Detectors

Surround the collision point with a detector

Two of the ~600 people now on the experiments

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Searching for New Particles at the Fermilab Tevatron
Review: How does one search for new particles at the Tevatron?

- Look at the final state particles from the $\bar{p}p$ collision (an event)
- We know what Standard Model events look like
- Look for events which are “Un-Standard Model Like”
Example Final States:
Two Photons and Supersymmetry

Supersymmetry:
\[ \tilde{P} \rightarrow \tilde{\chi}_1^0 \rightarrow \tilde{G} \]
\[ \tilde{P} \rightarrow \tilde{\chi}_1^0 \rightarrow \tilde{G} \]
\[ \gamma + \text{Supersymmetric Particles in Final State} \]

Standard Model:
\[ \tilde{P} \rightarrow \gamma \rightarrow q \]
\[ \gamma \gamma + \text{No Supersymmetric Particles in Final State} \]
Look at collisions with Two Final State Photons

SUSY particles would leave the detector (not interact)
Use Conservation of Momentum and “observe” the missing momentum/energy
Look for Gravitinos or Neutralinos this way

Note: A number of other models also predict final states with $\gamma\gamma + \text{“Other Stuff”}$
Search for anomalous γγ events at CDF

Example of what might show up:
- Supersymmetry would show up as an excess of events with large Missing Energy

Our observations are consistent with background expectations with one possible exception

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

- In addition to $\gamma\gamma+$Missing Energy this (famous) event has two high energy electron candidates
  - $e$ candidate passes all standard ID cuts, but there is evidence which points away from the $e$ hypothesis. We may never know.
- Very unusual
- Good example of getting an answer which is far more interesting than what you asked for
- How unusual?

Particle Physics Jargon:
Energy imbalance = Missing Energy = $E_T = \text{MET}$
Predicted by the Standard Model?

• Dominant Standard Model Source for this type of event: $WW\gamma\gamma$
  
  – $WW\gamma\gamma \rightarrow (e\nu)(e\nu)\gamma\gamma \rightarrow e\gamma\gamma + \text{MET}$: $8 \times 10^{-7}$ 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

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So what is it? Is it SUSY?

Statistical fluctuation? New physics?

• We’ve been looking for Supersymmetry and the Higgs for a long time. Is it either of those?
  – No model of Higgs I know about predicts this type of event
  – Could be Supersymmetry
  – Technicolor?
  – Others?
Supersymmetry

• This event looks like a natural prediction of the model. (Well…after it was seen by the theoretical community)

• However:
  – However, most models predict additional events with $\gamma\gamma+$Missing Energy. We don’t see those
  – Also, no others seen by the Tevatron or LEP
What to do?

• Our anomaly doesn’t look like the currently favored models of Supersymmetry or the Higgs

• While there are other models which predict this event most have fallen by the wayside, or also predict the same final state of $\gamma\gamma+$Missing Energy.

• Perhaps there is something far more interesting and unpredicted going on! But what? Need more hints…
Outline

A survey of the follow up on what may be some of the best hints in particle physics

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What to do?

As experimentalists we decided to do two things:

1. Investigate the predictions of models which predict this type of even
   • No results which followed up on the model predictions yielded additional hints

2. Need to do something new and not based on existing models
Model Independent Search

Need a new method

• Use properties of the event to suggest a more *model independent* search

• Look for “Cousins” of our events
  – I.e., Others with “similar” properties
  – Others of this ‘type’

• In some sense we are looking for many models all at once

(At the time this was a non-standard method of looking for new particles)
Unknown Interactions: Example

These two events would be Cousins
Example of a “Cousin” Search

- *A priori* the $ee\gamma\gamma+\text{MET}$ event is unlikely to be Standard Model $WW\gamma\gamma$ production
  - ($\sim10^{-6}$ Events)
- Guess that the unknown interaction is “Anomalous” $WW\gamma\gamma$ production and decay
- Look for similar unknown interaction with
  - $WW \rightarrow (qq)(qq) \rightarrow jjjj$
  - $\text{Br}(WW \rightarrow jjjj) \gg \text{Br}(WW \rightarrow ee+\text{MET})$

By branching ratio arguments: Given 1 $\gamma\gamma+ll+\text{MET}$ event
  - Expect $\sim30 \, \gamma\gamma+jjj$ “Cousin” events
\( \gamma \gamma + \) Jets Search at CDF

- Look in \( \gamma \gamma \) data to for anomalous production of associated jets from quark decays of W’s

- No Excess

~30 Event excess would show up here

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Searching for New Particles at the Fermilab Tevatron
Generalize: Signature Based Search

- **Generalize the Cousin Search to a full Signature Based Search**
- **Search for an excess of events in the $\gamma\gamma+X$ final state, where $X$ is**
  - **Gauge Boson**
    - W, Z, gluon ($\rightarrow$ jet) or extra $\gamma$
  - **Quarks**
    - Light quarks (up, down, strange or charm $\rightarrow$ jet)
    - b-quarks (jet with long lifetime)
    - t-quarks ($t \rightarrow Wb$)
  - **Leptons**
    - Electrons, muons, taus and neutrinos
    - Leptons from $W \rightarrow l\nu$, $Z \rightarrow l\ell$ or $Z \rightarrow \nu\nu$
- **No rate predictions for new physics, just look for an excess**

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*Searching for New Particles at the Fermilab Tevatron*
# γγ+X Signature Based Search Results

## CDF Run I
All results are consistent with the Standard Model background expectations with no other exceptions

### High Acceptance, Large # of Background Events

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

### Lower Acceptance, Smaller # of Background Events

<table>
<thead>
<tr>
<th>Object</th>
<th>Obs.</th>
<th>Exp.</th>
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</thead>
<tbody>
<tr>
<td>$p_T &gt; 25 \text{ GeV},</td>
<td>\Delta \phi_{\gamma,\text{-jet}}</td>
<td>&gt; 10^\circ$</td>
</tr>
<tr>
<td>$N_{\text{jet}} \geq 3, E^\text{jet} &gt; 10 \text{ GeV},</td>
<td>\eta^\text{jet}</td>
<td>&lt; 2.0$</td>
</tr>
<tr>
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<td>1</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>Central $\tau$, $E_T^\tau &gt; 25 \text{ GeV}$</td>
<td>0</td>
<td>0.03 ± 0.03</td>
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<tr>
<td>$b$-tag, $E_T^b &gt; 25 \text{ GeV}$</td>
<td>0</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>Central $\gamma$, $E_T^\gamma &gt; 25 \text{ GeV}$</td>
<td>0</td>
<td>0.01 ± 0.01</td>
</tr>
</tbody>
</table>

*R. Culbertson, H. Frisch, D. Toback + CDF

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Searching for New Particles at the Fermilab Tevatron
Well...Maybe....μμγγjj

- Another event in the data with similar properties
- Not part of the “official” γγ dataset
- No significant Missing Energy, but the energy resolution isn’t as good
- Not quite as interesting. Background only at the 10^{-4} level
- Again, no good Standard Model explanation

More Particle Physics Jargon
j=jet: Usually from a final state quark or gluon
Another Cousins Search

Unknown Interaction

Similar Unknown Interaction

- P
- P
P
P
P

\[ E_T \]

\[ \gamma \]

\[ e \]

\[ \gamma \]

\[ \gamma \]

\[ \gamma \]

\[ \gamma \]

lepton

Anything

Other final state particles
Lepton+Photon Cousin search

- Finds the $ee\gamma+\text{Met}$ and $mm\gamma\gamma jj$ events
- All the other channels agree with background expectations except $\mu\gamma+\text{Met}$:
  - 11 events on a background of $4.2\pm0.5$
  - No excess in $e\gamma+\text{Met}!?!$ 5 on a background of $3.4\pm0.3$
- Not statistically significant enough to be a discovery, but appears quite similar to other anomalies in that the events combines leptons, photons and Missing Energy
- No other events look all that unusual

*J. Berryhill, H. Frisch, D. Toback + CDF
What to do….

• Not clear what to make of this excess
• Standard Model $W\gamma$ can produce this via $W\gamma \rightarrow (\mu\nu)\gamma \rightarrow \mu\gamma + \text{Met}$

• Anomalous $W\gamma$ production?
  • But why is there no excess in $e\gamma + \text{Met}$
• Really need more data!
• However, we are encouraged that this new model independent method gave us a new hint.
• Take the next step: Expand this search in a larger, systematic and more $a \text{ priori}$ way to find other hints unpredicted by theory. Look at DØ data.
Sleuth

A friend to help us systematically look in our data for experimental clues in model independent ways

B. Knuteson, D. Toback + DØ
PRD 62, 092004 (2000)

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Searching for New Particles at the Fermilab Tevatron
A New Model-Independent Search Method: Sleuth

• Assume nothing about the new particles except that they are high mass/E_T
  – If it were low mass, we most likely would have seen it already

• Systematically look at events by their final state particles: Signature Based Search

• Search for new physics by looking for excesses in multi-dimensional data distributions
Sleuth Algorithm

- *A priori* search prescription to define which regions you can look in to maximize sensitivity
- Find most interesting region (largest excess relative to backgrounds)
- Run hypothetical similar experiments using background expectations and systematic errors
- Measure of interestingness: Fraction of hypothetical similar experiments (from backgrounds alone) which have an excess more significant than the one observed

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*Searching for New Particles at the Fermilab Tevatron*
How well does Sleuth work? Example:

- Both WW and top quark pair production are good examples of high $E_T$ events which might show up at DØ with Sleuth if we didn’t know about them.

- Run Mock Experiments pretending we don’t know about WW and $t\bar{t}$ production to see if we can find it. Also look in samples with nothing new and interesting.

- 4 Example Samples:
  - $e\mu + 0$ Jets WW
  - $e\mu + 1$ Jet
  - $e\mu + 2$ Jets $t\bar{t}$
  - $e\mu + 3$ Jets

Lots of other examples in other channels as well including Supersymmetry, Leptoquarks etc.
Test Results: $\bar{t}t$ and WW as unknowns

Expectations

~50% of experiments would give a $>2\sigma$ excess in at least one channel

Significance of excess in standard deviations
(All overflows in last bin)

Remember: The top quark discovery required combining MANY different channels and this is just one
Test Results: $\bar{t}t$ and WW as unknowns

Predict that ~50% of experiments would give a $>2\sigma$ excess.

What about our data?

B. Knuteson, D. Toback + DØ
PRD 62, 092004 (2000)

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Run I DØ Data

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Significance in Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\mu E_T$</td>
<td>2.4σ</td>
</tr>
<tr>
<td>$e\mu E_{T,j}$</td>
<td>0.4σ</td>
</tr>
<tr>
<td>$e\mu E_{T,ij}$</td>
<td>2.3σ</td>
</tr>
<tr>
<td>$e\mu E_{T,ijj}$</td>
<td>0.3σ</td>
</tr>
<tr>
<td>Combined Results</td>
<td>1.9σ</td>
</tr>
</tbody>
</table>

Excesses corresponding to WW and $\bar{t}t$ found even though Sleuth didn’t know what it was looking for.
Sleuth cont....

• Sleuth shows that when there is no signal to be observed, it doesn’t predict one
• When there is a significant signal to be observed, even if we didn’t know where to look, Sleuth has a good chance of finding it
• Now that we have a powerful tool, apply it to lots of different data sets from Run I
Sleuth on Run I Data at DØ

Run Sleuth on many sets of DØ data in addition to the photon final states in the hopes of finding an unexpected new hint

- $e\mu + X$
- $W+$Jets “like”
- $Z+$Jets “like”
- $(\ell\gamma)(\ell\gamma)(\ell\gamma)$

**Nothing New**

B. Knuteson, D. Toback + DØ
PRL 86, 3712 (2001), PRD 64, 012004 (2001)

David Toback
Searching for New Particles at the Fermi Lab

<table>
<thead>
<tr>
<th>Final State</th>
<th>Bkg</th>
<th>Data</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\mu X$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e\mu\mu\mu\mu$</td>
<td>48.3±7.6</td>
<td>39</td>
<td>0.14 (+1.08σ)</td>
</tr>
<tr>
<td>$e\mu\mu\mu\mu$</td>
<td>13.2±1.5</td>
<td>13</td>
<td>0.45 (+0.13σ)</td>
</tr>
<tr>
<td>$e\mu\mu\mu\mu$</td>
<td>5.2±0.8</td>
<td>5</td>
<td>0.31 (+0.50σ)</td>
</tr>
<tr>
<td>$e\mu\mu\mu\mu$</td>
<td>1.3±0.3</td>
<td>1</td>
<td>0.71 (-0.55σ)</td>
</tr>
<tr>
<td>$W+$-jets-like</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W_{jjj}$</td>
<td>400.1 ± 53.7</td>
<td>441</td>
<td>0.29 (+0.55σ)</td>
</tr>
<tr>
<td>$W_{ jj}$</td>
<td>77.1 ± 9.9</td>
<td>67</td>
<td>0.23 (+0.74σ)</td>
</tr>
<tr>
<td>$W_{jjj}$</td>
<td>14.3 ± 2.3</td>
<td>15</td>
<td>0.53 (-0.08σ)</td>
</tr>
<tr>
<td>$W_{jj}$</td>
<td>1.8 ± 0.4</td>
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<td>0.81 (-0.88σ)</td>
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<tr>
<td>$W_{ jj}$</td>
<td>0.35 ± 0.07</td>
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<td>0.22 (+0.77σ)</td>
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<tr>
<td>$e_{ jjjj}$</td>
<td>11.6 ± 1.7</td>
<td>7</td>
<td>0.76 (-0.71σ)</td>
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<td>$e_{ jj}$</td>
<td>2.5 ± 0.6</td>
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<td>0.17 (+0.95σ)</td>
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<tr>
<td>$e_{ jjj}$</td>
<td>0.80 ± 0.24</td>
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<td>0.13 (+1.13σ)</td>
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<td>$Z+$-jets-like</td>
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<td></td>
</tr>
<tr>
<td>$Z_{jj}$</td>
<td>98.0 ± 8.9</td>
<td>85</td>
<td>0.52 (-0.05σ)</td>
</tr>
<tr>
<td>$Z_{jj}$</td>
<td>13.2 ± 2.7</td>
<td>12</td>
<td>0.71 (-0.55σ)</td>
</tr>
<tr>
<td>$Z_{jjj}$</td>
<td>1.9 ± 0.5</td>
<td>1</td>
<td>0.83 (-0.95σ)</td>
</tr>
<tr>
<td>$ee_{jj}$</td>
<td>33.1 ± 4.4</td>
<td>32</td>
<td>0.72 (-0.58σ)</td>
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<td>4.5 ± 0.6</td>
<td>4</td>
<td>0.61 (-0.28σ)</td>
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<td>3.7 ± 0.8</td>
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<td>0.68 (-0.47σ)</td>
</tr>
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<td>$ee_{jjj}$</td>
<td>0.45 ± 0.13</td>
<td>1</td>
<td>0.36 (+0.36σ)</td>
</tr>
<tr>
<td>$ee_{jjjj}$</td>
<td>0.061 ± 0.028</td>
<td>1</td>
<td>0.06 (+1.53σ)</td>
</tr>
<tr>
<td>$e\mu_{jj}$</td>
<td>0.50 ± 0.15</td>
<td>2</td>
<td>0.08 (+1.41σ)</td>
</tr>
<tr>
<td>$(\ell\gamma)(\ell\gamma)(\ell\gamma)X$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$ee\gamma$</td>
<td>2.6 ± 1.0</td>
<td>1</td>
<td>0.89 (-1.23σ)</td>
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<tr>
<td>$e\gamma\gamma$</td>
<td>4.3 ± 0.7</td>
<td>3</td>
<td>0.84 (-0.90σ)</td>
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<td>$e\gamma_{jj}$</td>
<td>1.03 ± 0.31</td>
<td>1</td>
<td>0.63 (-0.33σ)</td>
</tr>
<tr>
<td>$e\gamma_{jj}$</td>
<td>2.9 ± 0.4</td>
<td>1</td>
<td>0.88 (-1.17σ)</td>
</tr>
<tr>
<td>$ee\gamma_{jj}$</td>
<td>0.26 ± 0.10</td>
<td>1</td>
<td>0.23 (+0.74σ)</td>
</tr>
<tr>
<td>$e\gamma_{jj}$</td>
<td>10.7 ± 2.1</td>
<td>5</td>
<td>0.66 (-0.41σ)</td>
</tr>
<tr>
<td>$e\gamma_{jj}$</td>
<td>2.3 ± 0.7</td>
<td>4</td>
<td>0.21 (+0.81σ)</td>
</tr>
<tr>
<td>$e\gamma_{jj}$</td>
<td>0.37 ± 0.15</td>
<td>1</td>
<td>0.30 (+0.52σ)</td>
</tr>
<tr>
<td>$W_{\gamma\gamma}$</td>
<td>0.21 ± 0.08</td>
<td>1</td>
<td>0.18 (+0.92σ)</td>
</tr>
<tr>
<td>$\gamma_{\gamma}$</td>
<td>2.5 ± 0.5</td>
<td>2</td>
<td>0.41 (+0.23σ)</td>
</tr>
<tr>
<td>$P$</td>
<td></td>
<td></td>
<td>0.89 (-1.23σ)</td>
</tr>
</tbody>
</table>
Final Run I Results: DØ

• Looked at over 40 final states
• Plot the significance of every result in terms of standard deviations
• No signature has a significant excess

Each entry in the histogram is a different final state

Significance (in \( \sigma \)) of the most anomalous region in a dataset

Data
Expectation

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Searching for New Particles at the Fermilab Tevatron
Summarizing the Sleuth Results

• The most anomalous data set at DØ (according to Sleuth) is $ee+4jets$; excess is 1.7$\sigma$

• However, since we looked at so many places, expected this large an excess.

• Bottom line: Nothing new
Sleuth and the CDF anomalies

• Sleuth certainly finds the CDF anomalies already described to be highly unlikely to be statistical fluctuations when compared to known backgrounds.

• However, it can’t have anything to say about whether we forgot a background or an unknown set of detector malfunctions.

• **Bottom line:** Sleuth doesn’t (can’t) have anything to say about whether the CDF anomalies are real. It doesn’t see any similar anomalies, or new anomalies in DØ.
Outline

A survey of the follow up on what may be some of the best hints in particle physics

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Run II of the Tevatron

Finally taking more data!!!

• Collision Energy: 1.8 TeV → 2.0 TeV
• 1 collision every 396 nsec
• Upgraded detectors
• Better acceptance, more data more quickly
• Started taking new data
  – 20 times the data by the end of 2005
  – 200 times the data by the end of 2009
A new CDF Run IIa Event Candidate

Two photons, one electron and Missing Energy

Preliminary background estimate at the 3x10^{-3} level

Clearly similar to the other CDF anomalies

An $e\gamma\gamma\not{E}_t$ Event

$e^+: E_t \approx 50$ GeV  \quad $\gamma_2: E_t \approx 25$ GeV

$\gamma_1: E_t \approx 90$ GeV

Preliminary confidential result

David Toback
Searching for New Particles at the Fermilab Tevatron
Hmmm...

It’s very encouraging to see this new event. But we’re still left with nagging doubts on our hints:

• Only single (unrelated?) anomalous events and a $2\sigma$ excess

• Events with photons and missing energy continue to be a common theme…

  ➢ However, “Only at CDF” also seems to be a common theme…

• Any differences between CDF and DØ that might explain this?

• Perhaps. The DØ has a “pointing calorimeter” which gives more confidence that photons are from the collision point. CDF does not.
So what?

- Cosmic rays can interact with the CDF detector and produce an additional fake photon with corresponding energy imbalance
- Could the photons in these anomalous events be from cosmic rays on top of an already complicated collision?

We searched the events for any reason to believe that this might be causing the problem.

- We found no evidence that this was the case
- The rate for this as a background is tiny
Powerful Tool: Time of arrival

What we’d really like is a tell-tale affirmative handle that would put this to bed once and for all at CDF...

- Look at the time the photons “arrives” at the detector and compare with the expected time of flight from the collision point
- Cosmics are clearly separated from real events
The down side

Only indirect measurements available in Run I:

• Very inefficient at low energies

• The whole detector isn’t instrumented (e.g. no possibility of timing for second electron candidate)
Run IIa at CDF

• Expected only 1.4 of the 3 e/γ objects in the eγγ+Met event to have timing info: Saw 2
• Same for the eγγ+Met event
• Only half of events in the μγ+Met sample have timing information
• While we’ve expanded the coverage of the timing system in Run IIa, it still has the same lousy efficiency.
An upgrade to CDF: EMTiming

- To solve these problems, we are adding a direct timing measurement of the photons in the electromagnetic calorimeters to the CDF detector.

- ~100% efficient for all photons of useful energy
  - Could get timing for all objects in any new $ee\gamma\gamma$+Met events
  - ~5% effic $\rightarrow$ ~100% effic
Direct Physics Benefits

In addition to confirming that all photons are part of the collision, this would reduce the backgrounds for certain types of high profile searches with photons and MET

- SUSY ($N_2 \rightarrow \gamma N_1$, light gravitinos)
- Large Extra Dimensions
- Excited leptons
- New dynamics (like Technicolor)
- $V+\text{Higgs} \rightarrow V+\gamma\gamma$
- $W/Z+\gamma$ production
- Whatever produced the $e e \gamma\gamma + \text{MET}$ candidate event
- Whatever produced the CDF $\mu \gamma + \text{Met excess}$
How do we do it?

- Electronic design is actually quite simple and similar systems already exist on the detector.
- Take photo-tube signal and put it into a TDC and readout.
- Large system to add to existing (very large) detector.
About the project

• To set the scale: adding cabling and readout electronics for about 2000 phototubes at CDF

• Large international collaboration led by TAMU (other institutions such as INFN-Frascati, Univ. of Chicago, Univ. of Michigan, Fermilab and Argonne are contributing components and funding)

• ~$1M project including parts and labor
  – Project fully approved by CDF
  – Italian funding fully approved (buys some of the components)
  – Fermilab PAC Stage 1 project approval
  – Positive feedback from U.S. DOE (project funding review yesterday). Remaining funding is expected by November
  – TAMU funding approved by U.S. DOE
Making the Future Successful

For Run II we have/need:

• More data. (Taking it as we speak…)

• Powerful targeted searches for Supersymmetry and the Higgs

• New search strategies like Sleuth:
  – While it can’t be as sensitive as a dedicated search, it may be our only shot if we guess wrong about where to look in our data in the future.
  – A natural complement to the standard searches

• Working on tools to make any potential discovery more robust
Conclusions

• The Fermilab Tevatron continues to be an exciting place to search for new particles

• There have been a number of interesting hints in the data with photons and we’ve worked hard to follow up on them

• We are well poised to make a major discovery in Run II
Backup Slides

David Toback
Searching for New Particles at the Fermilab Tevatron
• Run I Timing: Problems Cosmic rays, know for sure that the final state particles are part of the event (Robustness)

• Run IIa Timing Preliminary results

• Run IIb EMTiming: Why?
  – Design
  – Estimated results: gg+Met, LED, Zgamma (order?)

• Conclusions:
  – Interesting events to follow up on
  – Have the technology to deal with unexpected events from an analysis point of view
  – Need more data (that’s coming!!!)
  – Need better tools to confirm the robustness of the results.
Run IIa at CDF

- Expected only 1.4 of the 3 e/γ objects in the eeγγ+Met event to have timing info: Saw 2
- Same for the eγγ+Met event
- Only half of events in the μγ+Met sample have timing information
- While we’ve expanded the coverage of the timing system in Run IIa, it still has the same lousy efficiency.
  - E.g. Only ~5% of eeγγ+Met events would have timing for all 4 objects
The plan for the next few years

• Next two years: **Pursue best guesses for Run II**
  – Dedicated searches (Fermilab’s top priority)
    • Higgs Boson, Supersymmetry
  – Signature based “cousins” and Sleuth searches
    • Lepton + Photon + X, Photon+Photon +X, Photon+Met+X
  – Gain full funding for EMTiming project and build

• Next five years: **Pursue best hints from Run II**
  – Higgs signal? Supersymmetry? Twenty eeγγ+MET events?
  – Some other completely unexpected events?
  – Install the EMTiming upgrade and take data
Some thoughts on Sleuth

- Sleuth is sensitive to finding new physics when it is there to be found
- Would find events like the eeγγ+MET naturally
- Would be sensitive to many SUSY and Higgs signatures
- While it can’t be as sensitive as a dedicated search, it may be our only shot if we guess wrong about where to look in our data in the future
- A natural complement to the standard searches
Cosmic Ray backgrounds at CDF

Problem: Cosmic rays enter the detector and fake a photon (+Met)

• Question: Can’t you just get rid of the cosmic ray backgrounds?

• Answer: Photons from the primary event, and photons from cosmic rays look very similar in the CDF calorimeter. Many are real photons.
Where are we and what’s next?

It’s very encouraging to see this new event. But we’re still left with nagging doubts on our tantalizing hints:

- Only single (unrelated?) anomalous events and a $2\sigma$ excess
- There is some evidence that one of the electrons in the $ee\gamma\gamma+$MET event is a fake
  - After extensive study it’s not clear what that object is (we may never know)
  - We’ve entirely replaced that calorimeter for Run II
This event was different than what we were looking for

How many did we expect from background?

- This is a difficult question
- Can’t estimate the probability of a single event (measure zero)
- “How many events of this ‘type’ did we expect to observe in our data set from known Standard Model sources?”
- Try to define a “reasonable” set of criteria to define ‘type’ after the fact
Overview of Sleuth

- Define final state signatures
  - (which particles in the final state)
- *A priori* prescription for defining search parameters and regions in those variables
- A systematic look for regions with an excess (more events than expected) with large Energy
- Find most interesting region
- Compare with the expectations from hypothetical similar experiments using background expectations
- Take into account the statistics of the large number of regions searched and systematics of the uncertainties of the backgrounds
So where are we?

- We have one very interesting event
- Statistically unlikely to be from known Standard Model backgrounds
- No Cousins in the $\gamma\gamma + X$ final state
- What’s next?
Take more data!!!

However...
Don’t want to get caught unprepared again

- Having to estimate the background for an interesting event *a posteriori* is not good
- Need a systematic way of finding more interesting events
- Need a more systematic plan of what to do when we find them
- Need a systematic way of estimating the significance of unexpected events
Towards a model independent solution

• Many believe Supersymmetry is correct, but what if we haven’t gotten the details right and we’re just looking at the wrong final states
  – Looking for photons in the final state in 1994 was not even considered as a Supersymmetry discovery channel

• Ought to be better prepared to search for new physics when we don’t know what we are looking for

• Design a system which should also find the kinds of things we know to look for
The Fermilab Accelerator

~4 Miles in Circumference
Identifying the Final State Particles

• Many particles in the final state
  – Want to identify as many as possible
  – Determine the 4-momentum

• Two types: short lived and long lived
  – Long lived: electrons, muons, photons…
  – Short lived: quarks, W, Z…“decay” into long lived particles

• Observe how long lived particles interact with matter
  – Detection
Short Lived Particles in the Detector

The qq pairs pop from the vacuum creating a spray of particles.
Long Lived Particles in the Detector

Long lived Supersymmetric particles do not interact in the detector
Very much like neutrinos

Muon Chamber
Steel/Iron
Muon Chamber
Hadronic Layers
Calorimeter
EM Layers
Tracking Chamber
Beam Axis

David Toback
Searching for New Particles at the Fermilab Tevatron
Event with energy balance in transverse plane

Event with energy imbalance in transverse plane

Energy in direction transverse to the beam:

\[ E_T = E \sin(\theta) \]

Missing \( E_T \): MET

David Toback

Searching for New Particles at the Fermilab Tevatron
An attractive theoretical solution

• One of the most promising theories is Supersymmetry which is an attempt to solve these (and other) problems

• Each Standard Model particle has a Supersymmetric partner
### Supersymmetric Particles?

<table>
<thead>
<tr>
<th>SM Particles</th>
<th>Superpartners</th>
</tr>
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<tbody>
<tr>
<td>gluon ((g))</td>
<td>gluino ((\tilde{g}))</td>
</tr>
<tr>
<td>charged higgs ((H^\pm))</td>
<td>Chargino ((\chi_i^\pm))</td>
</tr>
<tr>
<td>weak charged boson ((W^\pm))</td>
<td>((i = 1, 2))</td>
</tr>
<tr>
<td>neutral higgs ((h, H, A))</td>
<td>Neutralino ((\chi_i^0))</td>
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<tr>
<td>neutral weak boson ((Z))</td>
<td>((i = 1, 2, 3, 4))</td>
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<tr>
<td>photon ((\gamma))</td>
<td></td>
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<tr>
<td>quark ((q)), lepton ((l))</td>
<td>squark ((\tilde{q}<em>{R,L})), sleptons ((\tilde{l}</em>{R,L}))</td>
</tr>
<tr>
<td>Graviton</td>
<td>Gravitino ((\tilde{G}))</td>
</tr>
</tbody>
</table>

Other New Particles:
- Higgs Boson

David Toback

*Searching for New Particles at the Fermilab Tevatron*
Predictions and Comparisons

Supersymmetric Predictions

Select events above threshold

Look for excess of events with large MET

Standard Model Predictions

David Toback

Searching for New Particles at the Fermilab Tevatron
Example with Supersymmetry

Look for Regions where the backgrounds are small and the predictions for Supersymmetry are large

- Background Expectations from Standard Model
- How the data might look

Prediction from Supersymmetry

David Toback
Searching for New Particles at the Fermilab Tevatron
How we might observe evidence of Supersymmetry in a laboratory

Proton Anti-Proton Collision
(Actually the quarks inside)

Example* Final State:
Two electrons, two photons and two Gravitinos

*Gauge Mediated Supersymmetry Breaking

David Toback
Searching for New Particles at the Fermilab Tevatron
Look at collisions with Two Final State Photons

A number of other models also predict final states with $\gamma\gamma+\text{"Other Stuff"}$
Good reason to believe a sample of events with two high energy photons in the final state can be an unbiased sample in which to search for evidence of New Particles
(Gravitinos? Neutralinos?)

*Work done at University of Chicago with H. Frisch and R. Culbertson on CDF. Results published in PRL & PRD

David Toback

Searching for New Particles at the Fermilab Tevatron
Typical Search for New Particles

• Look at the final state particles from a Proton Anti-Proton collision

• Use a computer (Monte Carlo) to simulate the interaction
  – Probability a collision might produce Supersymmetric particles
  – Properties of the final state particles

• Same for known Standard Model interactions which might produce similar results

• Compare
Example Final States:
Two Photons and Supersymmetry

Supersymmetry: Standard Model:

\[ \gamma \gamma + \text{Supersymmetric Particles in Final State} \]

\[ \gamma \gamma + \text{No Supersymmetric Particles in Final State} \]
Set limits on one of the models

- Since counting experiment is consistent with expectations we set limits on the new physics production at the 95% Confidence Level
- This constrains/excludes some theoretical models
- Gives feedback to theoretical community

Example Limit

Excluded this side
Unexcluded this side
Example Theory

Lightest Chargino Mass
Quantitative Estimate

• Use a computer simulation of Standard Model $WW\gamma\gamma$ production and decay

• Use known $W$ decay branching ratios and detector response to the various decays of $W$’s

• Result: Given 1 $\gamma\gamma+ll+MET$ event
  ➢ Expect $\sim 30 \gamma\gamma+jjj$ events
Take more data

• The Fermilab Tevatron is being upgraded
• The detectors are being upgraded
• Already started taking data this year
• Should be able to answer the question with 20 times the data:
  – Scenario 1: We see more than a couple cousins
    • Study the sample for more clues for its origins
  – Scenario 2: We see very few or none
    • Most likely a fluctuation (of whatever it was).
Labeling Final State Signatures

• Final State particles:
  – e, μ, τ, γ, j, b, c, MET, W or Z

• Each event is uniquely identified:
  – All events which contain the same number of each of these objects belong to the same final state
Using Sleuth on Run I Data

• Look in events with an electron and a muon for a excess which might indicate a new heavy particle(s)

• Why eμ? (why not?)
  – Lots of theory models
  – Supersymmetry? Anomalous Top quarks?

• Backgrounds include good example of heavy particles to look for
  – Top quarks, W bosons
\( \bar{t}t \) and WW production

\[ \text{High } E_T \text{ relative to other backgrounds} \]

\[ e\mu + 0 \text{ Jets} \]

\[ e\mu + 2 \text{ Jets} \]

David Toback
Searching for New Particles at the Fermilab Tevatron
Fraction of hypothetical similar experiments (from backgrounds alone) which have an excess more significant than the one observed.

Mock data with no signal

Probability is flat as expected

Small P is interesting
Smallest bin is <5%

No indication of anything interesting

David Toback
Searching for New Particles at the Fermilab Tevatron
Pretend we don’t know about WW and $\bar{t}t$

Mock experiments with WW and $\bar{t}t$ as part of the sample

Observe an excess in

- 0 Jets (WW production)
- 2 Jets ($\bar{t}t$ production)

in the mock trials

Remember:
Small $P$ is interesting
Smallest bin is $<5\%$
Include WW as a background

Expect an excess in 2 Jets only

\( \bar{t}t \) production
Finding $\bar{t}t$ alone

Use all backgrounds except $\bar{t}t$ and look for excesses

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Significance in Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\mu E_T$</td>
<td>1.0$\sigma$</td>
</tr>
<tr>
<td>$e\mu E_{Tj}$</td>
<td>0.1$\sigma$</td>
</tr>
<tr>
<td>$e\mu E_{Tjj}$</td>
<td>1.9$\sigma$</td>
</tr>
<tr>
<td>$e\mu E_{Tjjj}$</td>
<td>0.2$\sigma$</td>
</tr>
<tr>
<td>Combined Results</td>
<td>1.2$\sigma$</td>
</tr>
</tbody>
</table>

Significance of excess in standard deviations

Excess corresponding to $\bar{t}t$
The $e\mu X$ Sleuth Results

Use all backgrounds and look for excesses

<table>
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<tr>
<td>$e\mu E_T$</td>
<td>1.1$\sigma$</td>
</tr>
<tr>
<td>$e\mu E_{T,j}$</td>
<td>0.1$\sigma$</td>
</tr>
<tr>
<td>$e\mu E_{T,jj}$</td>
<td>0.5$\sigma$</td>
</tr>
<tr>
<td>$e\mu E_{T,jjj}$</td>
<td>-0.5$\sigma$</td>
</tr>
<tr>
<td>Combined Results</td>
<td>-0.1$\sigma$</td>
</tr>
</tbody>
</table>

We see no evidence for new physics at high $P_T$ in the $e\mu X$ data

David Toback
Searching for New Particles at the Fermilab Tevatron
Warning:

• If you are looking for an overview and/or current status of the important theoretical models we’re looking for at the Tevatron, you’ve come to the wrong talk. I won’t spend much time interpreting my results in terms of how they restrict the currently favored models.

• I don’t have much to say about prospects for Higgs or Supersymmetry at the Tevatron; same thing.

• If you’ve come to hear about latest results from the Tevatron, I’m afraid I don’t have much to show.
General rule for picking variables

• Looking for new high mass particles

• Mass-Energy Relationship
  – Decay to known Standard Model particles
    • light in comparison
  – High energy long lived particles in final state
    • High Mass \( \propto \) High \( E_T \)

• Look at \( E_T \) of the final state particles
The EMTiming Project

Dave Toback
Texas A&M University
(for the CDF Collaboration)
Why do we need EMTiming?

Two primary reasons to add timing to the EM Calorimeter:

1. Reduces cosmic ray background sources: Improved sensitivity for high-$P_T$ physics such as SUSY, LED, Anomalous Couplings etc. which produce $\gamma+\text{Met}$ in the detector.

2. Provide a vitally important handle that could confirm or deny that all the photons in unusual events (e.g. CDF $ee\gamma\gamma+\text{Met}$ candidate event) are from the primary collision.
Types of high $P_T$ physics with photons and MET

- SUSY ($N_2 \not\in \gamma N_1$, light gravitinos)
- Large Extra Dimensions
- Excited leptons
- New dynamics
- $V+Higgs \not\in V+\gamma$
- $W/Z+\gamma$ production
- Whatever produced the $ee\gamma\gamma+MET$ candidate event
- Whatever produced the CDF $\mu\gamma+Met$ excess
Cosmic Ray Backgrounds

Example Problem:
Backgrounds in photon+MET analysis dominated by cosmic rays in Run I at high $E_T$.
SUSY would also show up at high $E_T$. 

David Toback
Searching for New Particles at the Fermilab Tevatron
Real photons vs. Cosmics

**Problem:** Cosmic rays enter the detector and fake a photon (+Met)

- **Question:** Can’t you just make ID cuts and get rid of the cosmic ray backgrounds?

- **Answer:** Photons from the primary event, and photons from cosmic rays look very similar in the CDF calorimeter. Many are real photons.
Timing in the Calorimeter

Run I showed that Timing in the Hadronic Calorimeter (HADTDC system) can help distinguish between photons produced promptly and from cosmic rays.
An EM shower needs to leak into the hadronic section of the calorimeter to have timing.

- **HADTDC system is very inefficient for low $E_T$.**
- Requiring timing for a photon gives a bias toward fake photons from jets.

**In Run I:** Expected $\sim 1.4$ of the 4 EM objects in $ee\gamma\gamma+\text{Met}$ to have timing. Only 2 did (both were in time).

**In Run IIa:** Only $\sim 5\%$ of $ee\gamma\gamma+\text{Met}$ events would have timing for all objects.

David Toback

Searching for New Particles at the Fermilab Tevatron
How EMTiming Would Help

Give timing for all useful photons at ~100% efficiency

Zγ Example

SUSY Example

David Toback
Searching for New Particles at the Fermilab Tevatron
More on how EMTiming Would help

Example using known physics $Z\gamma$:

- Old system:
  Not fully efficiency until above 55 GeV

- EMTiming:
  Use all events from the 25 GeV trigger

$$\Rightarrow \frac{\text{EMTiming Acceptance}}{\text{Old Acceptance}} = \frac{\text{Events above 25 GeV}}{\text{Events above 55 GeV}} \approx 30$$

David Toback

Searching for New Particles at the Fermilab Tevatron
 Improved Physics Sensitivity

- EMTiming would allow us to reduce the photon+MET $E_T$ thresholds.
- Factor of two cross section improvement
Improved Confidence

Convince us that all the clusters are from the primary collision

- Lepton+Photon excess in Run I:
  - 25 GeV threshold, only ½ of the events have timing, lowering the threshold doesn’t add much
    - With EMTiming would, by reducing to 10 GeV photons, add a factor of 10 in timed-event rate.

- ee\gamma\gamma+Met candidate events
  - 5% of Run II events would have all EM cluster with timing.
    - With EMTiming would go to ~100%
Hardware for EMTiming Project

Add TDC readout to CEM and PEM

- Hardware is virtually identical to HADTDC system
- Small R&D costs
- Small technical risks
Project Tasks and Hardware

- Add splitters to 960 CEM channels:
  - PEM bases already readout-ready
- Build more Transition boards/ASD’s
  - Space in crates on first floor already exists
- Recycle small-via TDC’s
  - Recycle crate and tracer, purchase new off the shelf power supply and processor
- Cables and connectors
Splitters for the CEM

- CEM energy readout cards measure charge. Splitter is purely inductive so it doesn’t change the charge collected in any noticeable way.
- ~15% of voltage goes on the secondary to the ASD to fire the TDC.
Splitter characteristics

- ASDs fire with 100% efficiency at high $E_T$
- Timing resolution is 1.1 nsec (1.0 from TDC)
- No evidence of TDC misfiring from noise
- No evidence of noise going to ADMEM’s

![Graph showing EM Timing resolution](image)
Parts and Cost

• M&S costs for this project would be covered by outside sources/grants
  – Texas A&M (TAMU)
  – University of Chicago
  – INFN

• Will recycle much of the parts
  – Small-via TDC’s
  – PMT Base Transition board cables (many connectors)
  – Spare crate and Tracer
  – Much of the PEM Transition board connectors
Assembly and Installation

Responsibilities:

• Overall system, R&D, testing and readout: TAMU
• Splitters and cables: INFN, TAMU and UC w/FNAL technicians
• ASD and Transition boards: INFN
• TDC/Crates: TAMU and w/assistance from UM
Activities before Run IIB

• Prior to Run IIB Shutdown
  – Finish R&D
  – Collect parts for cables and assemble (TAMU and FNAL)
  – Construct transition boards and ASD’s (INFN)
  – Assemble upstairs TDC crate (TAMU)
  – Test production components

• During RunIIB shutdown
  – Install PMT Transition board cables
  – Install transition boards, ASD and dress cables
  – Install cables going upstairs
  – Test
Summary

• EMTiming would significantly enhance searches for new high $P_T$ physics in photon final states

• EMTiming would give a vital handle indicating if high $E_T$ photons are from the primary collision in unusual events

• Small costs which are well understood
  – No hardware costs to FNAL
  – Significant percentage of cost is in recycled parts
  – Simply following existing designs

• Minimal R&D and technical risk
Backup Slides
How EMTiming Would help

• Give timing for all useful photons at ~100% efficiency
• Example using known physics $Z\gamma$:
  – HADTDC: Not fully efficiency until above 55 GeV
  – EMTiming: Use all events from the 25 GeV trigger

$$\text{EMTiming Acceptance} / \text{HADTDC Acceptance} = \frac{\text{Events above 25 GeV}}{\text{Events above 55 GeV}} \approx 30$$

David Toback
Searching for New Particles at the Fermilab Tevatron
Splitter Schematic

EMTiming Splitter

20'-40' of RG174

Secondary Output:
-0.15 x Input Signal

Primary Output

Connects to original ADMEM line LEMO

Connects to ASD transition board

4'' of RG174

5 Turns

Front of PCB

Back of PCB

Primary Output

Male LEMO

Female LEMO

Input Signal

David Toback
Searching for New Particles at the Fermilab Tevatron
Splitter Picture

- Male LEMO to ASD transition board
- Female LEMO to ADMEM input (on back)
- Male LEMO to PMT anode

David Toback
Searching for New Particles at the Fermilab Tevatron
Splitter results at 10 GeV

- No Splitter (solid) — Mean = 3575 ± 3.5, Sigma = 106 ± 2.8
- Splitter (dashed) — Mean = 3579 ± 3.5, Sigma = 107 ± 2.7
Run II $e\gamma\gamma$+Met Candidate

Two photons. One had timing, would have been nice to know if the other was from a cosmic or other beam related background…
Other models results

![Graphs showing events expected from SUSY GGY and Large Extra Dimensions with timing information.](image)

**David Toback**

*Searching for New Particles at the Fermilab Tevatron*
Splitter Characteristics

David Toback

*Searching for New Particles at the Fermilab Tevatron*
Splitter misfires in TDC system

CEM LED input to splitter and WHA/TDC system

Signal from CEM LED data

Noise from background

Events/nsec

TDC Time (nsec)
Benefits vs. Cost/Risk

• Benefits: Important improvements in acceptance and robustness for difficult photon searches
• Costs: Small project costs (<0.5% of Run IIb budget), no M&S outlay from FNAL
• Risks: Primary risk is currently the schedule. What if we don’t finish the installation on time? Modular design of system make it such that we can make the system exactly as it was before we installed; I.e., doesn’t affect the current readout. If we don’t finish on time, we will simply not hook up the system so we don’t affect the rest of the physics program.
Parts, costs and who pays add Labor!!!!!! Need this? Out of date...

<table>
<thead>
<tr>
<th>CEM</th>
<th>Parts &amp; Spares</th>
<th>TAMU</th>
<th>Chicago</th>
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<th>Recycled</th>
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David Toback
Searching for New Particles at the Fermilab Tevatron
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<td>Assemble Splitter and PEM harness prototype</td>
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Search for $\gamma\gamma$ events with large MET

Supersymmetry would show up as an excess at large MET $E_T^\gamma>12$ GeV, $MET>35$ GeV
Expect $0.5\pm0.1$ Events
→ Observe 1 Event

$E_T^\gamma>25$ GeV, $MET>25$ GeV
Expect $0.5\pm0.1$ Events
→ Observe 2 Events

Our observations are consistent with background expectations with one possible exception.