Model Independent Searches using Final State Photons at CDF and DØ

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Outline

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

- Overview: Fermilab and looking for new particles
- Run I hint: The $ee\gamma\gamma+\text{Met}$ candidate event
- “Cousins,” Signature Based Searches and Sleuth
- Sleuth: Full DØ Run I results
- CDF II and Photon “Timing”: Taking more data and improving search robustness
- Conclusions
Run I

• Proton Anti-Proton Collisions
  Center of Mass energy of 1.8 TeV

• 1 collision every 3.5µsec
  – (300,000/sec)

• Took data from 1992 to 1996
  – Roughly 5x10^{12} āp collisions (~100 pb^{-1})
Run II of the Tevatron

• Energy: 1.8 TeV → 2.0 TeV
• 1 collision every 396 nsec
  – (eventually a collision every 132 nsec)
• Upgraded detectors
• Better acceptance, more data more quickly
• Started taking new data
  – 20 times the data by 2005
  – 200 times the data by 2007
The CDF and DØ Detectors

Surround the collision point with a detector
Review: How does one search for new particles at the Tevatron?

- Look at the final state particles from the collision
- We know what Standard Model events look like
- Look for events which are "Un-Standard Model Like"
Example with Supersymmetry

Supersymmetry: Standard Model:

Supersymmetric Particles in Final State

No Supersymmetric Particles in Final State
Two Photon Final States*

A number of models 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 Henry Frisch and Ray Culbertson on CDF. Results published in PRL & PRD
Search for $\gamma\gamma$ events with large MET

Supersymmetry would show up as an excess at large MET

$E_T^{\gamma}>12$ GeV, $\text{MET}>35$ GeV

Expect 0.5±0.1 Events

→ Observe 1 Event

$E_T^{\gamma}>25$ GeV, $\text{MET}>25$ GeV

Expect 0.5±0.1 Events

→ Observe 2 Events

Our observations are consistent with background expectations with one possible exception.
The interesting event on the tail

- In addition to $\gamma\gamma^+\text{MET}$ the 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.

- Unexpected from Standard Model predictions

- Hint of new physics?

- Lots of discussion between theoretical and experimental communities
How many did we expect?

• 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
Known Standard Model Sources

• Standard Model $WW\gamma\gamma$
  \[ WW\gamma\gamma \rightarrow (ev)(ev)\gamma\gamma \rightarrow e\nu e\nu + MET: \]
  \[ \rightarrow 8 \times 10^{-7} \text{ Events} \]

• All other sources: $5 \times 10^{-7}$ Events

• Total: $(1 \pm 1) \times 10^{-6}$ Events
Still left with many questions…

• What is it?
• Statistical fluctuation?
• Lots of theoretical interpretations:
  – Supersymmetry?
  – Technicolor?
  – Others?
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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 event
   - E.g. Supersymmetry which also predicts events with $\gamma\gamma$+MET
   - But, no others seen by Tevatron or LEP in $\gamma\gamma$+MET

2. Need to do something a little less standard just in case...
Model Independent Search

What if none of the theories are right?

• Need a new method
• Use properties of the event to suggest a more *model independent* search
• Look for “Cousins” of the event
  – I.e., Others with “similar” properties
  – Others of this ‘type’
• Possibility of looking for many models all at once

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

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

• *A priori* the event is unlikely to be Standard Model WWγγ production (~10⁻⁶ Events)
  – WWγγ → (ev)(ev)γγ → eeγγ+MET

• Guess that the unknown interaction is “Anomalous” WWγγ production and decay

• Look for similar unknown interaction with
  – WW → (qq)(qq) → jjjj
  – Note: Br(WW → jjjj) >> Br(WW → ee+MET)

• Given 1 γγ+ll+MET event
  ➢ Expect ~30 γγ+jjj “Cousin” events
\( \gamma \gamma + \text{Jets Search at CDF} \)

- Look in \( \gamma \gamma \) data to for anomalous production of associated jets
  - \( E_T^\gamma > 12 \text{ GeV}, \geq 4 \text{ Jets} \)
    - Expect \( 1.6 \pm 0.4 \) background events
    - Observe 2 Events
  - \( E_T^\gamma > 25 \text{ GeV}, \geq 3 \text{ Jets} \)
    - Expect \( 1.7 \pm 1.5 \) background events
    - Observe 0 Events
- No Excess
  - \(~30 \) Event excess would show up here
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 $W \rightarrow l\nu$, $Z \rightarrow ll$ or $Z \rightarrow \nu\nu$

• No rate predictions for new physics, just look for an excess
**CDF Run I**

All results are consistent with the Standard Model background expectations with our one possible exception.

### High Acceptance, Large # of Background Events

<table>
<thead>
<tr>
<th>Signature (Object)</th>
<th>Obs.</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\not{E}_T &gt; 35$ GeV, $</td>
<td>\Delta \phi_{\gamma - \text{jet}}</td>
<td>&gt; 10^\circ$</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>$0.3 \pm 0.1$</td>
</tr>
<tr>
<td>Central $\tau$, $E_T^\tau &gt; 25$ GeV</td>
<td>1</td>
<td>$0.2 \pm 0.1$</td>
</tr>
<tr>
<td>$b$-tag, $E_T^b &gt; 25$ GeV</td>
<td>2</td>
<td>$1.3 \pm 0.7$</td>
</tr>
<tr>
<td>Central $\gamma$, $E_T^\gamma &gt; 25$ GeV</td>
<td>0</td>
<td>$0.1 \pm 0.1$</td>
</tr>
</tbody>
</table>

### Lower Acceptance, Smaller # of Background Events

<table>
<thead>
<tr>
<th>Object</th>
<th>Obs.</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\not{E}_T &gt; 25$ GeV, $</td>
<td>\Delta \phi_{\gamma - \text{jet}}</td>
<td>&gt; 10^\circ$</td>
</tr>
<tr>
<td>$N_{\text{jet}} \geq 3$, $E_T^{\text{jet}} &gt; 10$ 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>1</td>
<td>$0.1 \pm 0.1$</td>
</tr>
<tr>
<td>Central $\tau$, $E_T^\tau &gt; 25$ GeV</td>
<td>0</td>
<td>$0.03 \pm 0.03$</td>
</tr>
<tr>
<td>$b$-tag, $E_T^b &gt; 25$ GeV</td>
<td>0</td>
<td>$0.1 \pm 0.1$</td>
</tr>
<tr>
<td>Central $\gamma$, $E_T^\gamma &gt; 25$ GeV</td>
<td>0</td>
<td>$0.01 \pm 0.01$</td>
</tr>
</tbody>
</table>

Number of observed and expected $\gamma\gamma$ events with additional objects in $85 \text{ pb}^{-1}$.
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
Sleuth*

A friend to help us look in our data for experimental clues

*Work done at University of Maryland with Bruce Knuteson (Grad Student at Berkeley-Now at University of Chicago) on DØ. Results published in PRL & PRD
Quasi-Model-Independent Search at DØ: 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
  – High Mass assumption $\rightarrow$ Quasi-Model Independent

• 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
Overview of Sleuth

• Define final state signatures
  – (which particles in the final state)
• \textit{A priori} prescription for defining variables and regions of space in those variables
• A systematic look for regions with an excess (more events than expected) with large $E_T$
• 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
Sleuth Algorithm

- Look at various regions
- Find most interesting region (largest excess)
- 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

Example signal events

Background expectation
How well does Sleuth work?

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

• Run Mock Experiments pretending we don’t know about WW and $\bar{t}t$ production

• 4 Samples:
  – $e\mu + 0$ Jets WW
  – $e\mu + 1$ Jet
  – $e\mu + 2$ Jets $\bar{t}t$
  – $e\mu + 3$ Jets
Test Results: $\bar{t}t$ and WW as unknowns

Expectations

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

Significance of excess in standard deviations

(All overflows in last bin)
Test Results: $\bar{t}t$ and WW as unknowns

Predict that ~50% of experiments would give a $>2\sigma$ excess. What about our data?

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>2.4$\sigma$</td>
</tr>
<tr>
<td>$e\mu E_{Tj}$</td>
<td>0.4$\sigma$</td>
</tr>
<tr>
<td>$e\mu E_{Tjj}$</td>
<td>2.3$\sigma$</td>
</tr>
<tr>
<td>$e\mu E_{Tjjj}$</td>
<td>0.3$\sigma$</td>
</tr>
<tr>
<td>Combined Results</td>
<td>1.9$\sigma$</td>
</tr>
</tbody>
</table>

Excesses corresponding to WW and $\bar{t}t$ found
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

- eµ + X
- W+Jets “like”
- Z+Jets “like”
- (l/γ) (l/γ) (l/γ)

<table>
<thead>
<tr>
<th>Final</th>
<th>Bkg</th>
<th>Data</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>eµX</td>
<td>48.5±7.6</td>
<td>39</td>
<td>0.44 ± 0.08σ</td>
</tr>
<tr>
<td>eµFj</td>
<td>13.2±1.5</td>
<td>13</td>
<td>0.45 ± 0.13σ</td>
</tr>
<tr>
<td>eµFj-jj</td>
<td>5.2±0.8</td>
<td>5</td>
<td>0.8±0.50σ</td>
</tr>
<tr>
<td>eµFj-jjj</td>
<td>1.3±0.3</td>
<td>1</td>
<td>0.71 ± 0.55σ</td>
</tr>
</tbody>
</table>

W+jets-like

| Wj  | 400.1 ± 52.7 | 441 | 0.29 ± 0.55σ |
| W'j | 77.1±9.9    | 67  | 0.28 ± 0.74σ |
| W"j | 14.3±2.3    | 15  | 0.63 ± 0.08σ |
| W 5j | 1.8±0.4    | 1   | 0.81 ± 0.08σ |
| W 6j | 0.25±0.07   | 1   | 0.22 ± 0.77σ |
| eFj-jj | 11.6±1.7  | 7   | 0.47 ± 0.71σ |
| eFj-jjj | 2.5±0.6    | 5   | 0.47 ± 0.95σ |
| eFj-jjjj | 0.80±0.24  | 2   | 0.47 ± 0.13σ |

Z+jets-like

| Zj  | 98.0±18.9 | 85  | 0.62 ± 0.05σ |
| Z'j | 13.2±2.7  | 12  | 0.71 ± 0.55σ |
| Z"j | 1.9±0.5   | 1   | 0.83 ± 0.95σ |
| jeej | 32.1±4.4  | 32  | 0.72 ± 0.58σ |
| jeej | 4.5±0.6   | 4   | 0.61 ± 0.28σ |
| jeej | 0.64±0.20 | 3   | 0.04 ± 0.75σ |
| eeFj-jj | 3.7±0.8  | 2   | 0.68 ± 0.47σ |
| eeFj-jjj | 0.45±0.13 | 1   | 0.86 ± 0.36σ |
| eeFj-jjjj | 0.66±0.028 | 1  | 0.66 ± 0.55σ |
| jµµj | 0.50±0.15 | 2   | 0.08 ± 0.41σ |

(ℓ/γ)/(ℓ/γ)/(ℓ/γ)X

| eee  | 2.6±1.0    | 1   | 0.89 ± 1.23σ |
| Zγ   | 4.3±0.7    | 3   | 0.84 ± 0.99σ |
| Zγ   | 1.03±0.31  | 1   | 0.63 ± 0.33σ |
| eegγ | 2.2±0.4    | 1   | 0.88 ± 1.17σ |
| eeegγ | 0.26±0.10 | 1   | 0.23 ± 0.74σ |
| γγγ  | 10.7±2.1   | 6   | 0.66 ± 0.41σ |
| jγγ  | 2.3±0.7    | 4   | 0.24 ± 0.81σ |
| jjγγ  | 0.37±0.15  | 1   | 0.89 ± 0.52σ |
| Wγ   | 0.21±0.08  | 1   | 0.48 ± 0.92σ |
| γγγγ | 2.5±0.5    | 2   | 0.44 ± 3.48σ |

p  | 0.89 ± 1.23σ |
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

Significance (in $\sigma$) of the most anomalous region in a dataset
Summarizing the Sleuth Results

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

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

• Bottom line: If we had an ensemble of Run I data sets, would expect 89% of them would give a larger “excess”
Some thoughts on Sleuth

• Sleuth is sensitive to finding new physics when it is there to be found
• Would find events like the $ee\gamma\gamma +\text{MET}$ naturally
• Would be sensitive to many SUSY 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.
• A natural complement to the standard searches
Sleuth and the $e\gamma\gamma + Met$ event

• Sleuth certainly finds the event to be highly unlikely to be a statistical fluctuation 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 event is real
Where are we and what’s next?

Still left with nagging doubts:

• Only one event…

• There is some evidence that one of the electrons 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

• Is it even a single collision which produced two electrons, two photons and something(s) which left the detector?

• Could the photons be from cosmic rays?

• We don’t see anything in DØ? Why not just let it go?
Any reason to push further?

• Other possible anomalies in the CDF data:
  ➢ Recently published CDF excess in the $\mu\gamma+\text{Met}$ data
  ➢ 11 events on a background of $4.2\pm0.5$

• Photons and Met are a common theme…
  ➢ “Only at CDF” also seems to be a theme…

• Since cosmics produce Photons + Met, and cosmics are harder to reject at CDF, we would really would like to put this to bed once and for all…
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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.
Powerful Tool: Time of arrival

- Look at “leakage” of photon candidate energy into hadronic calorimeter where there is timing information.
- Cosmics are clearly separated from real events.
- But only one electron and one photon from $ee\gamma\gamma + \text{Met}$ have information.
The down side

Limitations in Run I:

• Very inefficient at low energies

• No timing for large $\eta$ (where second electron candidate is)

• Expected 1.4 of the 3 central EM clusters to be “tagged”

• Got lucky: saw 2
Run IIa at CDF

- We’ve replaced the Hadron TDC system for the central calorimeter
- Added a TDC system for the plug hadron calorimeter
- Both still lousy for photons since they use leakage
- Only ~5% of eeγγ+Met events would have timing for all 4 objects
Run IIb Proposal: EMTiming

• Add timing information into the readout of the electromagnetic calorimeters

• ~100% efficient for all photons of useful $E_T$ in all detectors
  – Could get timing for all objects in any new $ee\gamma\gamma+\text{Met}$ events ($\sim 5\%$ effic $\rightarrow \sim 100\%$ effic)

• Unique handle that solves both problems:
  – Gets rid of cosmics (and allows us to measure the residual background)
  – Tells us if our events are robust
How do we do it?

- Model system after current Hadron system
- Take photo-tube signal and put it into a TDC and readout
- No new system designs, no technical risks
More on how EMTiming Would help

Example using known physics $Z\gamma$:

- **HADTDC**: Not fully efficiency until above 55 GeV
- **EMTiming**: Use all events from the 25 GeV trigger

$$\frac{\text{EMTiming Acceptance}}{\text{HADTDC Acceptance}} \approx \frac{\text{Events above 25 GeV}}{\text{Events above 55 GeV}} \sim 20$$
Bottom line:

For a small cost and no technical risk we get:

- Big acceptance gains for certain types of searches for new physics with photons
- Excellent rejection against cosmic ray sources which produce events with final state photons and missing $E_T$
- Added confidence that any new events, (e.g. $ee\gamma\gamma+\text{Met}$ events), are really from the primary collision
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 F(i)NAL approval for EMTiming project and build

- **Next five years:** Pursue best hints from Run II
  - Higgs signal? Supersymmetry? Twenty $e\gamma\gamma$+MET events?
  - Some other completely unexpected events?
  - Install the EMTiming upgrade and take data
Conclusions

• The Fermilab Tevatron continues to be an exciting place to search for new particles
• Interesting hints in the Run I data with photons
• For Run II we have/need:
  – More data. (Taking it as we speak…) \(^3\)
  – New technology to deal with unexpected events in an unbiased way/Powerful new search tools: Signature based “Cousins” Searches and Sleuth: \(^3\)
  – Working on more robust tools to measure events.
• We are well poised to find something interesting in Run II, and moving towards being able to believe it
• **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.
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 $q\bar{q}$ pairs pop from the vacuum creating a spray of particles

In the Detector
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
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>
</thead>
<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>
</tr>
<tr>
<td>neutral weak boson ((Z))</td>
<td>((i = 1,2,3,4))</td>
</tr>
<tr>
<td>photon ((\gamma))</td>
<td></td>
</tr>
<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
Predictions and Comparisons

Supersymmetric Predictions

Standard Model Predictions

Select events above threshold

Look for excess of events with large MET
Example with Supersymmetry

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

Prediction from Supersymmetry

Look for Regions where the backgrounds are small and the predictions for Supersymmetry are large
Particles of the Standard Model

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

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

63
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
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
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

![Graph showing cross section vs. lightest Chargino mass with limits and examples.](image-url)
Quantitative Estimate

• Use a computer simulation of Standard Model WWγγ production and decay
• Use known W decay branching ratios and detector response to the various decays of W’s
• Result: Given 1 γγ+ll+MET event
  ➢ Expect ~30 γγ+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

\( \rightarrow \) High \( E_T \) relative to other backgrounds

- **eμ + 0 Jets**
  - \( \bar{P} \rightarrow W \rightarrow \mu + \nu \)
  - \( P \rightarrow W \rightarrow e + \nu \)

- **eμ + 2 Jets**
  - \( \bar{P} \rightarrow W \rightarrow t + \nu \)
  - \( P \rightarrow W \rightarrow b + \nu \)
  - Jet

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Mock data with no signal

Fraction of hypothetical similar experiments (from backgrounds alone) which have an excess more significant than the one observed

Probability is flat as expected

Small P is interesting
Smallest bin is <5%
No indication of anything interesting
Sleuth with WW and $\bar{t}t$

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 $\mu + 0$ Jets (WW production), $\mu + 2$ Jets (tt production) in the mock trials.

Remember:
Small P is interesting
Smallest bin is <5%
Sleuth $\bar{t}t$

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>$e\mu E_Tjj$</td>
<td>0.1$\sigma$</td>
</tr>
<tr>
<td>$e\mu E_Tjjj$</td>
<td>1.9$\sigma$</td>
</tr>
<tr>
<td>$e\mu E_Tjjjj$</td>
<td>0.2$\sigma$</td>
</tr>
<tr>
<td>Combined Results</td>
<td>1.2$\sigma$</td>
</tr>
</tbody>
</table>

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

Use all backgrounds 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>1.1$\sigma$</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
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 → High $E_T$
• Look at $E_T$ of the final state particles