Searching for New Particles at the Fermilab Tevatron

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Physics Department Colloquium
Texas A&M University
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Outline

• Why look for new particles?
• The standard way to search for new particles: A supersymmetric example
• Fermilab Tevatron, CDF and DØ detectors
• New methods:
  – Searching for “Cousins” of interesting events
  – Sherlock: A quasi-model independent method
• The future and conclusions
The Domain of Particle Physics

Matter  Molecule  Atom  Nucleus

10^{-9}m  10^{-10}m  10^{-14}m

Chemistry  Atomic Physics  Nuclear Physics

Baryon  Quark

Hadron

10^{-15}m  <10^{-19}m
protons, neutrons, mesons, etc. top, bottom, charm, strange, up, down

Electron

(Lepton)

<10^{-18}m

Mass
proton ~ 1 GeV/c^2

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Overview of the Standard Model

• The Standard Model of particle physics is a description of the known particles and their interactions

• An excellent description of physical processes at energies probed by experiments
  – Accelerator experiments
  – Measurements of, or bounds on, rare processes

• Consistent with all current data
The Known Particles of the Standard Model and their Interactions

Example Interaction:

\[ e^{-} + W^{-} \rightarrow u, \bar{d}, \nu_{e} \]
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

Theoretical Parameters to Look For

New Particles to Look For

Theorists: Theoretical Models

Experimenters: Experimental Results

Unexplained Phenomena

Results of Particle Searches

Theorists: Theoretical Models

Experimenters: Experimental Results

Unexplained Phenomena

Results of Particle Searches
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?

#### SM Particles | Superpartners
--- | ---
Glues (g) | Gluino (g̅)
Charged Higgs ($H^\pm$) | Chargino ($\chi_i^\pm$) ($i = 1,2$)
Weak Charged Boson ($W^\pm$) | Neutralino ($\chi_i^0$) ($i = 1,2,3,4$)
Neutral Higgs ($h, H, A$) |  
Neutral Weak Boson ($Z$) |  
Photon ($\gamma$) |  
Quark (q), Lepton (l) | Squark ($\tilde{q}_{R,L}$), Sleptons ($\tilde{l}_{R,L}$)
Graviton | Gravitino ($\tilde{G}$)

Other New Particles:
- Higgs Boson

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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
Example with Supersymmetry

Supersymmetry:

Standard Model:

Supersymmetric Particles in Final State

No Supersymmetric Particles in Final State
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
Fermi National Accelerator Laboratory
(Fermilab Tevatron)

• Proton Anti-Proton Collisions
  – (An Event)

• Center of Mass energy is 1.8 TeV

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

• Data taking from 1992 to 1996
  – Roughly $5\times10^{12}$ \(\bar{p}p\) collisions
The Fermilab Accelerator

~4 Miles in Circumference
The CDF and DØ Detectors

Surround the collision point with a detector
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 \( \bar{q}q \) pairs pop from the vacuum creating a spray of particles in the Detector.
Long Lived Particles in the Detector

Long lived Supersymmetric particles do not interact in the detector
Very much like neutrinos
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
Search for Supersymmetry*

A number of models predict final states with $\gamma\gamma$+Missing Transverse Energy

Look at a sample of events with two high energy photons in the final state

Unbiased sample in which to search for evidence of Gravitinos (MET)

*Work done at University of Chicago with Henry Frisch and Ray Culbertson on CDF
Results published in PRL & PRD

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Predictions and Comparisons

Supersymmetric Predictions

Standard Model Predictions

Select events above threshold or

Look for excess of events with large MET
Search for $\gamma\gamma$ events with large MET

- High Acceptance
- Large # of Background Events

$E_T^{\gamma}>12$ GeV, MET$>35$ GeV
Expect 0.5±0.1 Events
Observe 1 Event

$E_T^{\gamma}>25$ GeV, MET$>25$ GeV
Expect 0.5±0.1 Events
Observe 2 Events

Our observations are consistent with background expectations with one possible exception (we’ll come back to this event.)
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.
The interesting event on the tail

- In addition to $\gamma\gamma + \text{MET}$ the event has two high energy electron candidates
- Unexpected from Standard Model predictions
- Hint of new physics?
- Lots of discussion between theoretical and experimental communities
How many of these 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 $WW\gamma\gamma$
  
  $WW\gamma\gamma \uparrow (ev)(ev)\gamma\gamma \uparrow ee\gamma\gamma + \text{MET}: \uparrow 8\times 10^{-7}$ Events

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

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

• What is it?

• Statistical fluctuation?

• Lots of theoretical interpretations:
  – Supersymmetry?
  – Technicolor?
  – Others?
What to do?

• As experimentalists we decided to do two things:
  – Investigate the predictions of models which predict this type of event
    • Previous search for $\gamma\gamma+$MET is a good example
  – Also do something a little less standard just in case...
Model Independent Search

- What if none of the theories are right?
- Use properties of the event to suggest a model independent search
- Look for “Cousins” of the event
  - I.e, Others with “similar” properties, or of this ‘type’
- Possibility of looking for many models all at once
- This is a non-standard method of looking for new particles
Unknown Interactions

Unknown Interaction

Similar Unknown Interaction

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

• *A priori* the event is unlikely to be Standard Model $WW\gamma\gamma$ production ($\sim 10^{-6}$ Events)
  – $WW\gamma\gamma \uparrow (ev)(ev)\gamma\gamma \uparrow ee\gamma\gamma +\text{MET}$

• Guess that the unknown interaction is “Anomalous” $WW\gamma\gamma$ production and decay

• Similar unknown interaction could be with
  – $WW \uparrow (qq)(qq) \uparrow jjjj$
  – Note: $\text{Br}(WW \uparrow jjjj) \gg \text{Br}(WW \uparrow ee +\text{MET})$

• Look for “Cousins” of $WW\gamma\gamma$ where
  – $WW\gamma\gamma \uparrow (qq)(qq) \gamma\gamma \uparrow jjjj\gamma\gamma$
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
γγ + Jets Search at CDF

- Use same γγ data set and look for jets
  - $E_T^{\gamma} > 12$ GeV, $\geq 4$ Jets
    - Expect $1.6 \pm 0.4$ Events
    - Observe 2 Events
  - $E_T^{\gamma} > 25$ GeV, $\geq 3$ Jets
    - Expect $1.7 \pm 1.5$ Events
    - Observe 0 Events
- No Excess
  ~30 Event excess would show up here

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Generalized Cousin Search: $\gamma\gamma+X$

- **Generalize the Cousin Search**
- **Search for an excess of events in the $\gamma\gamma+X$ final state, where X is**
  - **Gauge Boson**
    - W, Z, gluon (jet) or extra $\gamma$
  - **Quarks**
    - Light quarks (up, down, strange or charm jet)
    - b-quarks (jet with long lifetime)
    - t-quarks (t Wb)
  - **Leptons**
    - Electrons, muons, taus and neutrinos
    - Leptons from $W$ l v, $Z$ ll or $Z$ vv
- **No rate predictions, just look for an excess**
## Final Results of $\gamma \gamma$ Cousin Search

### High Acceptance, Large # of Background Events

<table>
<thead>
<tr>
<th>Signature (Object)</th>
<th>Obs.</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T &gt; 35$ GeV, $</td>
<td>\Delta \phi_{\gamma, \gamma-jet}</td>
<td>&gt; 10^\circ$</td>
</tr>
<tr>
<td>$N_{jet} \geq 4$, $E_T^{jet} &gt; 10$ GeV, $</td>
<td>\eta^{jet}</td>
<td>&lt; 2.0$</td>
</tr>
<tr>
<td>Central $e$ or $\mu$, $E_T^e$ or $\mu &gt; 25$ 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>$E_T &gt; 25$ GeV, $</td>
<td>\Delta \phi_{\gamma, \gamma-jet}</td>
<td>&gt; 10^\circ$</td>
</tr>
<tr>
<td>$N_{jet} \geq 3$, $E_T^{jet} &gt; 10$ GeV, $</td>
<td>\eta^{jet}</td>
<td>&lt; 2.0$</td>
</tr>
<tr>
<td>Central $e$ or $\mu$, $E_T^e$ or $\mu &gt; 25$ 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 pb$^{-1}$

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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

• The Fermilab Tevatron is being upgraded
• The detectors are being upgraded
• Plans to start taking data in 2001
• 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).
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 two photons 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
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) on DØ
Results to be submitted to PRD by the end of the spring
Quasi-Model-Independent Search at DØ: Sherlock

• 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 \& Quasi-Model Independent

• Systematically look at events by their final state particles

• Search for new physics by looking for excesses in multi-dimensional data distributions
Overview of Sherlock

- Define final state signatures
  - (which particles in the final state)
- *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
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
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 $\land$ High $E_T$
• Look at $E_T$ of the final state particles
Sherlock Algorithm

- Look at various regions
- Find most interesting region (largest excess)
- Run hypothetical similar experiments using background expectations
- Fraction of hypothetical similar experiments (from backgrounds alone) which have an excess more significant than the one observed
Using Sherlock on Run I Data

• Look in events with an electron and a muon for an 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

- High \( E_T \) relative to other backgrounds

**e\( \mu \) + 0 Jets**

**e\( \mu \) + 2 Jets**
Testing Sherlock

• Both WW and top quark pair production are good examples of high \( E_T \) events which might show up with Sherlock

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

• 4 Samples:
  – \( e\mu + 0 \text{ Jets} \) WW
  – \( e\mu + 1 \text{ Jet} \)
  – \( e\mu + 2 \text{ Jets} \) \( \bar{t}t \)
  – \( e\mu + 3 \text{ Jets} \)
Mock data with no signal

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

Small P is interesting
Smallest bin is <5%
No indication of anything interesting

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Sherlock 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
0 Jets (WW production)
2 Jets ($t\bar{t}$ production)
in the mock trials

Remember:
Small P is interesting
Smallest bin is <5%

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Combining Results

Pick most significant excess
Take into account that we looked in 4 datasets

Mock Experiments

All overflows in last bin

Significance of excess in standard deviations

[DØ Preliminary]

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Significance in Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>eµET</td>
<td>2.4σ</td>
</tr>
<tr>
<td>eµETjj</td>
<td>0.4σ</td>
</tr>
<tr>
<td>eµETjjj</td>
<td>2.3σ</td>
</tr>
<tr>
<td>eµETjjjj</td>
<td>0.3σ</td>
</tr>
<tr>
<td>Combined Results</td>
<td>1.9σ</td>
</tr>
</tbody>
</table>

Excesses corresponding to WW and tt found

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Sherlock \( \bar{t}t \)

Include WW as a background

Expect an excess in 2 Jets only

\( \bar{t}t \) production

Exercise on \( e\mu X \)

Backgrounds: Fakes, \( Z/\gamma' \rightarrow \tau \tau, WW \)

Mock Samples: Fakes, \( Z/\gamma' \rightarrow \tau \tau, WW, \bar{t}t \)

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Finding $\bar{t}t$ alone

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

DØ Preliminary

<table>
<thead>
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</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>

Mock Experiments

Significance of excess in standard deviations

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Final Sherlock Results

Use all backgrounds and look for excesses

DØ Preliminary

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Significance in Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>eμE_T</td>
<td>1.1σ</td>
</tr>
<tr>
<td>eμE_Tj</td>
<td>0.1σ</td>
</tr>
<tr>
<td>eμE_Tjj</td>
<td>0.5σ</td>
</tr>
<tr>
<td>eμE_Tjjj</td>
<td>-0.5σ</td>
</tr>
<tr>
<td>Combined Results</td>
<td>-0.1σ</td>
</tr>
</tbody>
</table>

We see no evidence for new physics at high $P_T$ in the eμX data
Some thoughts on Sherlock

• Sherlock is sensitive to finding new physics when it is there to be found
  – Would have pointed out either WW or \( \bar{t}t \) if we didn’t know about them
• Would find events like the ee\( \gamma \gamma \) + MET naturally
• Should 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
The Future at Fermilab

• Upgraded Fermilab Tevatron (Run II)
  – Higher energy: 1.8 TeV $\uparrow$ 2.0 TeV

• Upgraded detectors

• Better acceptance, more data more quickly

• Start taking data in March 2001
  – 20 times the data by 2003
  – 200 times the data by 2005-2006
The plan for the next few years

• Next Year:
  – Finish off other final states from Run I (ee+Jets, μμ+Jets etc)
  – Prepare to take data (Run II)

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

• Next five years: **Pursue best hints from Run II**
  – Higgs signal? Supersymmetry? Twenty eeγγ+MET events?
  – Some other completely unexpected events?
Conclusions

- The Fermilab Tevatron continues to be an exciting place to search for new particles
- Interesting hints in the Run I data
- “Cousins” Searches and Sherlock provide powerful new search tools
- Provide an important complement to the standard searches
- Hopefully, between the two we’ll find something interesting in Run II