Searching for New Particles at the Fermilab Tevatron

Abstract
Since the discovery of the top quark there have been a number of experimental hints that may be indicative of new, unpredicted particles to be discovered at the Fermilab Tevatron. In this talk I will discuss some of these hints and my program to both follow up on them and systematically uncover other hints. The bulk of the talk will concentrate on the search methodology and the results in the preliminary data. However, I will also discuss the work in progress as well as some of the prospects for next few years when lots of new data comes in.
Searching for New Particles at the Fermilab Tevatron

Dave Toback
Texas A&M University
Department Colloquium
September, 2004
Overview

• Since the discovery of the 6\textsuperscript{th} 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 experimental hints from Fermilab that there may be other, undiscovered, fundamental particles just around the corner

• This talk describes following up on some of these hints and how we are trying to turn up others
Outline

• The Standard Model of Particle Physics, Fermilab and looking for new particles
• The story so far… Some hints of new particles
• Model Independent Search Methods
• What we've learned so far…
  - Results of many searches
  - Some interesting new hints!
• Setting up for the future…
  - The prospects for the next couple of years and beyond…
• Conclusions
The Known Particles*

The Standard Model of particle physics has been enormously successful. **But:**

- Why do we need so many different particles?
- How do we know we aren’t missing any?
- Lots of other unanswered questions...

*Not a review of particle physics"
The Known Particles

Many theories/models attempt to address these issues, but none have been experimentally verified

Many credible reasons to believe there are new fundamental particles out there to be discovered
Review

How does one search for new particles at the Tevatron?

- Bang a proton and an anti-proton together and look at what comes out (an event)
- We know what Standard Model events look like
- Look for events which are "Un-Standard Model Like"
Fermilab Tevatron

The world's highest energy accelerator
- Proton anti-proton collisions
- Center of Mass energy of ~2 TeV
- 1 collision every 395 nsec
- > (2.5 Million/sec)

4 Miles Around
Inside the Accelerator
Big Toys: The CDF detector

Surround the collision point with a detector and look at what pops out... Requires about 600 friends
Big Toys: The CDF detector

Surround the collision point with a detector and look at what pops out...

Requires about 600 friends
The story

• Looking for new particles predicted by theory is, in general, well prescribed
  - not easy... but often straight-forward

• **Goal**: Hope we guess the right theory and that we have sensitivity
  (this worked for the top quark)

*Side benefit*: Sometimes searching in systematic ways uncovers something unexpected and starts a whole new direction
Color coding the recurring themes in the story...

Three recurring themes...

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

2. Null Results or Theory that doesn’t explain the data
   - Mother Nature is fond of teasing those who try to understand her
   - Theories of new particles haven’t helped as much as we would like

3. New ideas or new techniques
The story begins with a search for **Supersymmetry**

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

**Standard Model:**
\[ P \rightarrow \gamma \]
\[ P \rightarrow \gamma \]

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

**Supersymmetry:**
\[ \tilde{P} \rightarrow \tilde{G} \]
\[ \tilde{P} \rightarrow \tilde{G} \]
\[ \tilde{P} \rightarrow \tilde{\chi}_1 \]
\[ \tilde{P} \rightarrow \tilde{\chi}_1 \]

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

- **Standard Model (SM):**
  - $P \rightarrow \gamma$ (No Energy Imbalance)

- **Supersymmetry (SUSY):**
  - $P \rightarrow \tilde{G}$, $\tilde{G} \rightarrow \tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \rightarrow \gamma$ (Energy Imbalance)

SUSY Particles Leave the detector → Energy Imbalance
**Signal Vs. Background**

- Look at each event
- Put its Energy Imbalance in a histogram
- Compare the expected predictions from Standard Model and from SUSY

**Energy Imbalance Per Event**

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Search for anomalous $\gamma\gamma$ events at CDF

Run I Data from CDF

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

One possible exception

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

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

- Dominant Standard Model Source for this type of event: $WW\gamma\gamma$
  - $WW\gamma\gamma \rightarrow (e\nu)(e\nu)\gamma\gamma \rightarrow e\nu e\nu \gamma\gamma + \text{MET}$
    $\rightarrow 8 \times 10^{-7}$ Events
- All other sources (mostly detector mis-identification): $5 \times 10^{-7}$ Events
- Total: $(1 \pm 1) \times 10^{-6}$ Events

Perspective: Look at 5 trillion collisions, expect $10^{-6}$ events with two electrons, two photons and an energy imbalance; observe 1 (expect one like this in 5 quintillion collisions)
Predicted by Supersymmetry?

This event looks like a natural prediction of Supersymmetry

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

Other evidence for this type of Supersymmetry?

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

- We don’t see any other candidates like that
- No others seen by the Tevatron or at CERN
Set limits on the models

- These null results have been combined
- They constrain or exclude most SUSY models which predict the event.
What to do?

- Our anomaly doesn’t look like the currently favored models of Supersymmetry
- While there are other models which predict this event, most have long since fallen by the wayside
- Perhaps there is something far more interesting and unpredicted going on! But what? Need more experimental hints… and new ways of doing things…
Model Independent Searches

This area is where I have played my largest role in the community

**New Systematic Method:** Use properties of the event to suggest a more *model independent* search

- Look for "cousins" of our events
  - Others with "similar" properties
  - Others of this "type"

- To corrupt a famous quote: "I don't know exactly what I'm looking for, but I'd know it if I saw it."
Unknown Interactions: Example

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

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

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

• Look for similar unknown interaction with
  - $WW \rightarrow (qq)(qq) \rightarrow jjjj$
  - $Br(WW \rightarrow jjjj) \gg Br(WW \rightarrow ee+MET)$

By branching ratio arguments: Given 1 $\gamma\gamma+ll+MET$ event
  - Expect $\sim 30 \gamma\gamma+jjj$ “Cousin” events
Look in $\gamma\gamma$ data for anomalous production of associated jets from quark decays of W's

$\sim$30 Event excess would show up here
Repeat many times for $\gamma\gamma + "Something"

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

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

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

Instead of two photons try a photon and a lepton

Unknown Interaction

Similar Unknown Interaction

$E_T$

Other final state particles

David Toback
Sept 2004
Lepton+Photon Cousin Search Results

In general data agrees with expectations. But:

- 11 $\mu\gamma+$Met events on a background of $4.2\pm0.5$ expected
  - Not statistically significant enough to be a discovery, but interesting

- No excess in $e\gamma+$Met?! 5 on a background of $3.4\pm0.3$
  - Not clear what to make of this... In general SM particles have the same ~branching ratio for all leptons

- However, we are encouraged that this new model independent method gave us a new hint
  
  *J. Berryhill, H. Frisch, D. Toback + CDF
Hmmm...Another hint? $\mu\mu\gamma\gamma jj$

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

Unpublished confidential result

M. Contreras, H. Frisch and D. Toback
(CDF Internal 1996)
A friend to help us be more systematic in our search for clues in model independent ways

B. Knuteson, D. Toback + DØ
PRD 62, 092004 (2000)
A New Model-Independent Search Method: Sleuth

- Need a systematic way of finding interesting events, can’t just look for ones that are similar to the ones we stumbled on
- Ought to be better prepared, in general, to search for new physics when we don’t know exactly what we are looking for
- Need a more systematic plan of what to do with interesting events when we find them
  - An *a priori* way of estimating the significance of unexpected events
  - Don’t want to get caught unprepared again
Sleuth

Sleuth is a very complicated algorithm and strategy. Quick overview*

• Systematically look at events by grouping them into their final state particles: “Signature” Based Search

• Search for new physics by looking for excesses in multi-dimensional data distributions where SM backgrounds should be low

• Not looking for a model... just a statistically and systematically significant excess of events

*Gross oversimplification
Testing Sleuth

Mock Experiments

Expectations

% of Mock Experiments

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

Test: Could Sleuth have found the top quark? (remember it doesn’t know where to look)

Yes: ~50% of experiments would give a >2σ excess in at least one channel
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
  - Would find events like the eeγγ+MET naturally
  - Would be sensitive to many SUSY and Higgs signatures (depending on cross section and final state)
- A powerful/natural complement to the standard searches
- Now that we have a powerful tool, apply it to lots of different data sets from Run I using the DØ detector
Look in lots of final states

• Looked at over 40 final states
• Plot the significance of every result in terms of standard deviations
• $1.7\sigma$ excess; 89% of experiments would have given a more interesting excess

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

Each entry in the histogram is a different final state

B. Knuteson, D. Toback + DØ
PRL 86, 3712 (2001), PRD 64, 012004 (2001)
What to do? Results since 2000

Take more data!

- Increased the Collision Energy
- Increased the rate at which we take data
- Upgraded the detectors
Preliminary CDF Run II Data

4 years of work in one slide

• Any new excess in two photons + energy imbalance?

• No new official events out here!

*R. Culbertson, D.H. Kim, M.S. Kim, S.W. Lee, D. Toback + CDF (Approved for submission to PRD, 2004, First CDF II SUSY Result)
A new CDF Run IIa Event Candidate

But...

An unofficial interesting event!!
Came in before the "official" data taking period started (will never become public)

Two photons, one electron and Missing Energy

Preliminary background estimate at the 3\times10^{-3} level from W_{\gamma\gamma}

Clearly similar to the other CDF anomalies

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

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

If all “ee$\gamma\gamma$Met” favored SUSY parameter space is nearly excluded, then what is it? Why do we keep getting these events?

Unpublished Result
Last Couple Years → Next Couple Years

- There continue to be interesting events with photons and no good theory to explain them
- Perhaps they are from Cosmic Rays?
- Our studies show that these backgrounds are VERY small
  - For the $ee\gamma\gamma+\text{Met}$ candidate expect about $10^{-9}$ events of this type
We measured an imbalance in Cosmic Ray energy imbalance. 

\[ e\gamma + \text{Big Energy Imbalance} \] 

Arrives "later" in time

David Toback  Sept 2004
Another upgrade: EMTiming

Add "photon" timing:

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

2. Reduces cosmic ray background sources
   - Further improves the sensitivity to important models such as SUSY, Large Extra Dimensions, Anomalous Couplings etc. which produce $\gamma+$Met in the detector

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

- Large system to add to existing (very large) detector
- Effectively put a TDC onto about 2000 phototubes at CDF
- International collaboration led by TAMU
  - INFN-Frascati*
  - Univ. of Michigan*
  - Univ. of Chicago*,**
  - Fermilab**
- ~$1M project (parts and labor)
  - Project fully approved by CDF, Fermilab PAC, DOE, and INFN
  - Equipment support by Italian funding, DOE and Fermilab
  - TAMU funding supported by U.S. DOE

* Engineering support
** Technician support
Preliminary System Sensitivity

- System resolution of ~800 psec
- Finishing installation this fall (2 years ahead of original Run IIb schedule)
- Will start taking data in January 2005

Collision Particles

Beam-Related

Cosmic Rays (Arrive randomly in time)

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

With ~1 nsec resolution, it turns out we can try a NEW type of search
Compare Supersymmetry vs SM

Standard Model

Long-Lived SUSY Particles

Signal can be well separated from SM

David Toback

Sept 2004
Sensitivity vs Timing Resolution

Sensitivity improves as the resolution gets better
Excellent prospects for ~1 nsec resolution
Comparing the sensitivity

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

D. Toback and P. Wagner
Results Submitted to PRD, Summer 2004
The plan for the next ~5 years

Next two years: Pursue best guesses for Run II
  • Dedicated searches
  • Use our new timing system
  • Model Independent Searches
  • Start transition to LHC/CMS

Next five years: Pursue best hints from Run II
  • Full Sleuth searches
  • Search for long-lived neutralinos
  • Higgs signal? Supersymmetry? Twenty $ee\gamma\gamma + \text{MET}$ events?
  • Some other completely unexpected events?
The next 10 or so years: LHC*

Ramp up LHC/Ramp down CDF

- Software/Commissioning
- Trigger electronics upgrades (Super CMS)

Start taking data: 2007(?)

- 2007-2013(?) Discovery, data analysis, completion of hardware upgrades
- 2013?-2017? SCMS era...

Install hardware and prepare for the next round of discoveries

*More speculative
Conclusions

- While LHC will be very exciting, the Fermilab Tevatron continues to be the place to search for new particles for the next many years.
- Many interesting hints in the data with photons; may point the way to the next major discovery.
- *Sleuth* may enable a major discovery even if the theories are wrong.
- New results from CDF are a significant improvement and there are new hints!
- New instrumentation gives us new and exciting sensitivity for the next many years.
- The preparations for the next ~5 and ~10 years at the Tevatron/LHC are underway.
- The prospects are excellent and this should be fun for many years...
Run II Luminosity

- This is some text about the luminosity...
- ~350 on tape
- ~200 analyzed
Fermi National Accelerator Laboratory

- The Fermilab Tevatron is the world's highest energy accelerator
- Currently operating at a Center of Mass energy of ~2 TeV
- 1 collision every 395 nsec (2.5 Million/sec)

~4 Miles in Circumference
Big Toys: The CDF detector

Surround the collision point with a detector and look at what pops out...

Requires about 600 friends

Photograph instead??
What to do?

As experimentalists we decided to do two things:

1. Investigate the predictions of models which predict this type of even

2. Need to do something new and not based on existing models
Strategy Today

There are two types of strategy for looking for new physics

1. Specific models
   - Most importantly Supersymmetry

2. Model independent searches

My contribution has largely been standardizing model independent searching and using it to make progress since Theory hasn’t done a good job of predicting the anomalies I see in the data...

We need both... This will be a recurring theme...
Models with Photons

Types of high $P_T$ physics with photons and/or MET

- SUSY with $\chi_1 \rightarrow \gamma G$
- SUSY with $\chi_2 \rightarrow \gamma N_1$

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)
- $V+Higgs \rightarrow V+\gamma\gamma$
- $W/Z+\gamma$ production
- Whatever produced the $e\gamma\gamma+MET$ candidate event
- Whatever produced the CDF $\mu\gamma+Met$ excess

Standard Model background estimate of $10^{-6}$
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: Nothing new

If we had an ensemble of Run I data sets, would expect 89% of them would give a larger "excess"
So where are we?

- We have a few interesting events which are “unlikely” to be from known Standard Model backgrounds
- No Cousins in the $\gamma\gamma + X$ final state, some in $l\gamma$, Nothing Sleuthed at DZero
- There is some evidence that one of the electrons in the eegg+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
- 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 2s 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.
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.

- **eeγγ+Met candidate events**
  - 5% of Run II events would have all EM cluster with timing.
  - With EMTiming would go to ~100%

Robustness of discovery potential

- 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

- 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.
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 eeγγ+Met events
  - ~5% effic → ~100% effic
Hardware for EMTiming Project

- Large system to add to existing (very large) detector
- Effectively put a TDC on to about 2000 phototubes at CDF
- International collaboration led by TAMU
  - INFN-Frascati*
  - Univ. of Michigan*
  - Univ. of Chicago*, **
  - Fermilab**
- ~$1M project including parts and labor
  - Project fully approved by CDF, Fermilab PAC, DOE, and INFN
  - Equipment support by Italian funding, DOE and Fermilab
  - TAMU funding supported by U.S. DOE

CDF EM Timing Project

Data Acquisition System (DAQ)

VME Crate (upstairs)

Time-to-Digital Converter (TDC)

Energy Output

Timing Output

220 ft

1st Floor

On Detector

VME Crate (detector)

Transition Board

Amplifier Shaper Discriminator (ASD)

* Engineering support
** Technician support
2000 Phototubes

~2000 Phototubes

Readout path

• Production of all components completed in Fall of 2003, well ahead of schedule.
• Partial installation in Fall 2003.
• Finished this fall.

*Installation team: M. Goncharov, S. Krutelyov, S.W. Lee, D. Allen, P. Wagner, V. Khotilovich & D.T.
Timing distributions

- System resolution of ~800 psec

![Graph showing timing distributions with labels for Beam-halo, Primary Collision Particles, and Cosmic Rays (Arrive randomly in time).]
Fun check: Time of arrival of Beam-Halo vs. Position

Measure speed of beam-halo to be $\sim 2 \times 10^8$ m/s

Primary Collision
Beam-halo

To be submitted
to NIM
(Jan 2005)

David Toback
Sept 2004
Search for Long-Lived Particles?

• With ~1 nsec resolution, we can consider looking for long-lived particles which decay to photons

• GMSB-SUSY predicts $\chi_1 \rightarrow \gamma G$ with nsec lifetimes
  • All Tevatron searches assume ~0 lifetimes

• Photons would arrive delayed in time relative to SM backgrounds
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. 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.
Compare GMSB vs. SM in $\gamma\gamma+\text{Met}$

GMSB-SUSY

SM

Signal can be well separated from SM
(backgrounds estimate from CDF $\gamma\gamma+\text{Met}$ analysis)