IF YOU LOOK AT WHAT THE UNIVERSE IS MADE OUT OF, LIKE A PIE CHART:

WE HAVE NO IDEA

75%

20%

5%

STUFF WE KNOW

DARK MATTER ??

THE UNIVERSE (AS WE KNOW IT)
If you look at what the universe is made out of, like a pie chart:

- We have no idea
- 75%
- 20%
- 5%

Stuff we know

Dark matter ??

The universe (as we know it)

Dark matter is 5 times as heavy as all the matter we know about,
WE'VE BEEN STUDYING MATTER FOR A COUPLE HUNDRED YEARS...

...AND WE HAVE A FINE UNDERSTANDING OF CHEMICALS, ETC...

AND ALL OF A SUDDEN WE DISCOVER THAT ALL THAT WORK WE'VE BEEN DOING,

IS ONLY ON A TINY FRACTION OF WHAT THE UNIVERSE IS MADE OUT OF!
We've been studying matter for a couple hundred years...

...and we have a fine understanding of chemicals, etc...

...and all of a sudden we discover that all that work we've been doing, is only on a tiny fraction of what the universe is made out of!

It's like you've been studying an elephant's tail for two hundred years and you discover...

It's only the tail!
Motivation

The Standard Model

Can this be right?
Outline

I. Motivation
II. Strategy
III. Results
Our goals:
- Maximize possibility for discovery
- Learn something no matter what we see
Traditional approach

Bet on a specific full theory
Optimize analysis to squeeze out maximal sensitivity to new physics.

(param 3-N fixed at arbitrary choices)
Model independent search

Discard the model
compare data to standard model

“Never listen to theorists. Just go look for it”
–Aaron Pierce, Theorist
Admit the need for a model
New signal requires a coherent physical explanation, even trivial or effective

Generalize your model
Focus on the general experimental sensitivity
Construct simple models that describe classes of new physics

Examples
Simple SM extensions: fourth generation, $Z'$, resonances ($X\rightarrow tt$) etc
Effective Lagrangian

A natural, compact language for communication between theory and experiment.

Experimental data → Limits or measurements on effective Lagrangian parameters → Full Theory
A Theorist’s dream?

- Unfolded cross-sections
- Deconvolution to remove detector effects
- Publish measured differential cross-sections
- Theorists don’t need to know/have detector description

This is hard!
I. Motivation

II. Strategy

III. Results

   a. Heavy resonances ($Z'$)
   b. Heavy quarks ($b'$, $t'$)
   c. Simplified SUSY
Dataset
High mass resonances

Z’ to di-muons
High mass dimuon res.

CDF Run II Preliminary 4.6 fb⁻¹

Events vs. $M_{\mu\mu}$ [GeV/c²]

Data
- $Z/\gamma^*$
- $t\bar{t}$
- WW
- Fakes
- Cosmics

(Obs'd - Exp'd)/Exp'd vs. $M_{\mu\mu}$ [GeV/c²]

PRL 2011, to appear
$P_{Z'}(x_i|M_{Z'}) = \int dq_1 dq_2 |\mathcal{M}_{Z'}(M_{Z'})|^2$

$\times f_{PDF}(x_p)f_{PDF}(x_{\bar{p}})T(p_1, q_1)T(p_2, q_2)P_{PT}(q_1 + q_2, N_{jets})$
Z' to muons

Best Fit Point (•):
- $M_{Z'} = 199 \text{ GeV/c}^2$
- $\sigma_{Z'} = 26 \text{ fb}$
- bkg-only CL = 16%
Z' to muons

CDF Run II Preliminary 4.6 fb^{-1}

\[ \sigma(Z') \times BR(Z' \rightarrow \mu\mu) \text{ [pb]} \]

\[ Z' \text{ mass [GeV/c}^2\text{]} \]

<table>
<thead>
<tr>
<th>Model</th>
<th>Mass Limit (GeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z'_1</td>
<td>817</td>
</tr>
<tr>
<td>Z'_{sec}</td>
<td>858</td>
</tr>
<tr>
<td>Z'_N</td>
<td>900</td>
</tr>
<tr>
<td>Z'_{\psi}</td>
<td>917</td>
</tr>
<tr>
<td>Z'_{\chi}</td>
<td>930</td>
</tr>
<tr>
<td>Z'_{\eta}</td>
<td>938</td>
</tr>
<tr>
<td>Z'_{SM}</td>
<td>1071</td>
</tr>
</tbody>
</table>

PRL 2011, to appear
\[ \int L \, dt = 39 \, \text{pb}^{-1} \]
\[ \sqrt{s} = 7 \, \text{TeV} \]

\[ \int L \, dt = 42 \, \text{pb}^{-1} \]
\[ \sqrt{s} = 7 \, \text{TeV} \]
Limits

Penn + other groups

\[ \int L \, dt \sim 40 \, \text{pb}^{-1} \]

\[ \sqrt{s} = 7 \, \text{TeV} \]

\[ Z' \rightarrow \Pi \]

---

Expected limit

Expected ± 1σ

Expected ± 2σ

Observed limit

Z'_{SSM}

Z'_{\chi}

Z'_{\psi}

ATLAS Preliminary

M [TeV]

\[ \sigma B [pb] \]

0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6

10^1 1 10

[Graph showing limits and expected values for a physics experiment]
### Limits

**Penn + other groups**

<table>
<thead>
<tr>
<th>Process</th>
<th>Observed limit</th>
<th>Expected limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z'_{SSM} \rightarrow e^+ e^-$</td>
<td>0.957, 0.155</td>
<td>0.964, 0.148</td>
</tr>
<tr>
<td>$Z'_{SSM} \rightarrow \mu^+ \mu^-$</td>
<td>0.834, 0.297</td>
<td>0.895, 0.206</td>
</tr>
<tr>
<td>$Z'_{SSM} \rightarrow \ell^+ \ell^-$</td>
<td>1.048, 0.094</td>
<td>1.084, 0.082</td>
</tr>
</tbody>
</table>

**ATLAS Preliminary**

![Graph](image.png)
I. Motivation

II. Strategy

III. Results

a. Heavy resonances (Z’)
b. Heavy quarks (b’, t’)
c. Simplified SUSY
4th generation

PDG says it’s ruled out to 6σ....
4th generation

PDG says it’s ruled out to 6σ....

..that’s true if the masses are degenerate

projects.hepforge.org/opucem/
Selection
1 lepton
$pt > 20$ GeV
4 jets
$pt > 20$ GeV
Missing transverse energy
$> 20$ GeV

Sample
4.6/fb
Limit

\[ m_{t'} > 335 \text{ GeV} \]
Selection
2 like-signed leptons
\( pt > 20\) GeV
at least one isolated
2 jets
\( pt > 20\) GeV
\( \geq 1\) btags
Missing transverse energy
\( > 20\) GeV

Sample
2.7/fb

PRL 104 091801 (2010)
b'

Final selection
2 like-signed leptons
2 jets \geq 1 btags
Missing transverse energy

m_{b'} > 338 \text{ GeV}
b' decays

If b' -> Wt

same-sign lepton selection: \sim 2%

consider single-lepton mode
Signal (madgraph)

Eight hard partons, $\sim 6$ jets
**Signal (madgraph)**

**HT**

Scalar sum of transverse energy in the event

Includes jets, lepton and missing transverse energy

Captures soft recoil and unclustered jets

CDF Run II Preliminary
top quark pair background

$tt + 0,1,2,3p$

$p = udscb$

Madgraph+Pythia

MLM matching
CDF Run II Preliminary

Analysis technique

Events

heavy and jetty

Analysis variable

- if \( N_{jets} = 5 \), Jet-\( H_T = H_T \).
- if \( N_{jets} = 6 \), Jet-\( H_T = H_T + 1000 \) GeV.
- if \( N_{jets} \geq 7 \), Jet-\( H_T = H_T + 2000 \) GeV.

normalized to 5/fb
Data, $\geq 1$ b-tag

![Graphs showing data and backgrounds for $b$-tagged events with different jet numbers and $H_T$.](image)
## The numbers

<table>
<thead>
<tr>
<th></th>
<th>Control Region</th>
<th></th>
<th>Signal Region</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>207 ± 125</td>
<td>199</td>
<td>84 ± 65</td>
<td>87</td>
<td>291 ± 190</td>
<td>286</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>43 ± 31</td>
<td>40</td>
<td>18 ± 12</td>
<td>14</td>
<td>61 ± 43</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>≥ 7</td>
<td>11 ± 3.9</td>
<td>5</td>
<td>3.4 ± 3.4</td>
<td>12</td>
<td>14 ± 7.1</td>
<td>17</td>
<td></td>
</tr>
</tbody>
</table>
The limits

![Graph showing the limits for quark mass and cross-section. The graph includes shaded regions for 68% and 95% confidence levels, a line for the median, and a dashed line indicating theoretical expectations. The observed data points are marked with black dots connected by a red line.](image)
Direct searches

\[ m_{b'} > 372 \text{ GeV} \]

\[ m_{t'} > 335 \text{ GeV} \]
Direct searches

\[ m_{b'} > 372 \text{ GeV} \]
If \( BR(b' \rightarrow Wt) = 100\% \)

\[ m_{t'} > 335 \text{ GeV} \]
If \( BR(t' \rightarrow Wq) = 100\% \)
If $m_t' > m_{b'}$
b' and t'

The diagram illustrates the probabilities of various particle interactions:

- $b' \rightarrow WWb$
- $t' \rightarrow WWq$
- $b' \rightarrow WWb$
- $t' \rightarrow Wq$
- $b' \rightarrow Wq$
- $t' \rightarrow Wq$

The axes represent different combinations of $B(t' \rightarrow Wb')$ and $B(b' \rightarrow Wt)$.
b' and t'

CDF limits

B(t'\rightarrow Wq)

B(b'\rightarrow Wt)

B(t'\rightarrow Wb')

B(b'\rightarrow W{u,c})

(0, 1)  (1, 1)

(t' \rightarrow Wq)

(b' \rightarrow WWb)

(t' \rightarrow WWb)

(0, 0)  (1, 0)

(t' \rightarrow Wq)

(b' \rightarrow Wq)

PRL 2010, PRD 2011
b' and t'

No direct limits!

PRL 2010, PRD 2011
$m_{t'} = m_{b'} + 100$

$m_{t'} = m_{b'} + 50$

PRL 2010, PRD 2011
Limits

\[ V_{CKM4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix} \]

\[ \begin{align*}
V_{ud} &= 0.97418 \pm 0.00027 \quad \text{Nuclear Beta decay} \\
V_{us} &= 0.2255 \pm 0.0019 \quad \text{Semileptonic K-decay} \\
V_{ub} &= 0.00393 \pm 0.00036 \quad \text{Semileptonic B-decay} \\
V_{cd} &= 0.230 \pm 0.011 \quad \text{Semileptonic D-decay} \\
V_{cs} &= 1.04 \pm 0.06 \quad \text{Semi- /Leptonic D-decay} \\
V_{cb} &= 0.0412 \pm 0.0011 \quad \text{Semileptonic B-decay} \\
V_{tb} &> 0.74 \quad \text{Single Top-production} 
\end{align*} \]
heavy quarks

If the lifetime is short enough so the decay is in the central detector:

$$m_{Q'} > 290 \text{ GeV}$$
Selection
2 OS leptons
$pt>20$ GeV
2 jets
$pt>20$ GeV
Missing transverse energy
$>20$ GeV

Sample
35/pb
topology

Boosted tops
topology

Boosted Ws!
Lepton-neutrino angles

Heavy $t'$

SM top

More $W_p T$ means smaller opening angle
Mass reconstruction

Assume lepton and neutrino are ~collinear
No sign of heavy quarks...
Limit

\[ m_{t'} > 275 \text{ GeV} \]
Limit

\[ m_{t'} > 275 \text{ GeV} \]
Dark Matter

Need long lived dark matter X
Need long lived dark matter $X$
Give it some dark charge that is conserved
(eg R-parity for susy LSP)
Need long lived dark matter X
Give it some dark charge that is conserved (eg R-parity for susy LSP)

X can’t be light (\(< 10 \) GeV) and carry SM charges to be consistent with relic density.
Need long lived dark matter X

Produce Y, decay as $Y \rightarrow f X$
Look for $tt\bar{t} + \text{invisible X}$

$T' \rightarrow t + X$

$stop \rightarrow t + \text{LSP}$
Transverse mass

$T'T' \rightarrow t\bar{t}XX$

- $m_{T'} = 300$ GeV/$c^2$, $m_\chi = 80$ GeV/$c^2$
- $m_{T'} = 330$ GeV/$c^2$, $m_\chi = 80$ GeV/$c^2$
- $m_{T'} = 360$ GeV/$c^2$, $m_\chi = 1$ GeV/$c^2$

Events/bin

- $t\bar{t}$
- QCD
- W+jets
- Z+jets
- Diboson
- Single top
- Data
Limits
I. Motivation
II. Strategy
III. Results
   a. Heavy resonances (Z’)
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**Goal**
Set limits on SUSY-like processes

_in as general a fashion as possible_

**Approach**
Use effective lagrangian, explicitly set particle masses (EW scale):

_simple to handle, easy to interpret_

Set limits as functions of these masses, not parameters of specific models:

_can be easily translated into arbitrary models_
How many particles & parameters needed?
Want leptons
  needs Ws and Zs, so *chargino/neutralinos* and *sleptons*

Want strong production
  so *squarks* and *gluinos*

R-Parity conserving
  need *LSP*

Large sections of this space are 3 or 4-dimensional
SUSY simplified

UCI postdoc
Ning Zhou
SS SUSY simplified

UCI postdoc
Ning Zhou
CDF
Still producing world-class physics

ATLAS
Working well, much more to come