Isolated leptons in Higgs and SUSY: the forgotten background from heavy flavor decays

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Based on Z.S., E. Berger, PRD 74, 033008 (06); PRD 78 034030 (08);
and PRD 82, 014001 (10).
Thanks

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The Argonne Laboratory Computing Resource Center for 5 CPU-years of time on the JAZZ cluster.
Isolated leptons play a central role in searches for new physics
Higgs production — the excitement

The search for the Higgs boson has driven the field of high energy physics for a long time. Now we approach the Age of Discovery.

The Tevatron is in a race to find a SM Higgs before LHC first reports, while the LHC promises an “easy” observation if the Higgs is there.

\[ P = \otimes \rightarrow H \rightarrow WW \rightarrow l^+ l^- \mathbb{E}_T \]  

depends on a sophisticated understanding of low-momentum leptons and their backgrounds.
SUSY trilepton production — the “golden channel”

The measurement of trileptons plus missing energy is expected to be a clean probe of chargino and neutralino production.

DØ and CDF (PRD77,052002(08)) hope to both discover supersymmetry in an excess of trilepton events, and extract mass information. CMS and ATLAS hope to do the same.
Higgs and SUSY — the main LHC searches!

\[ H \rightarrow WW^* \rightarrow l^+l^-E_T \]

Common thread: multi-leptons + \( E_T \)

Trilepton SUSY

CDF & DØ, hep-ex/1007.4587

Experimentalist RULE of THUMB: All jet signals fake leptons at \( 10^{-4} \).

Is this really true? The real physical processes below do not matter?

\[
\begin{align*}
P &= \otimes \quad j^d \quad b \not\rightarrow \overline{B} = \mu/e^+ \\
\overline{P} &= \otimes \quad \overline{b} \not\rightarrow \overline{B} = \mu^+/e^+ \\
P &= \otimes \quad W^+ \quad \mu^+/e^- \\
\overline{P} &= \otimes \quad \overline{W} \quad \overline{\mu^-}/e^- \\
P &= \otimes \quad Z \quad \overline{e}^+ / \mu^+ \\
\overline{P} &= \otimes \quad \overline{b} \not\rightarrow \overline{B} = e/\mu
\end{align*}
\]

Zack Sullivan, Illinois Institute of Technology – p.6/43
Outline

1. The Physics
   • The underlying physics of isolated leptons from heavy flavors \((b/c) \Rightarrow\) isolation is a band pass filter

2. The Evidence
   • Measurement of \(b\bar{b}\) to isolated muons (CDF)

3. Dileptons
   • \(H \rightarrow WW\) vs. leptons from heavy flavors at the LHC (ATLAS)

4. Trileptons
   • \(\tilde{\chi}^{\pm} \tilde{\chi}^{0}\) (The “Golden” SUSY channel) vs. leptons from heavy flavors at LHC (CMS)

5. The Verdict
   • A new rule-of-thumb: \(1/200\) of all \(b/c\) look like \(\mu\) or \(e\)
The physics of isolated leptons from heavy-flavor decays

Physics of isolated leptons from $b$ decay

Normalized Probability

$p_T$ (GeV) vs. $\mu_1 > 10$ GeV
Physics of isolated leptons from $b$ decay

![Normalized Probability](image)

**Prob. isolated muon**

\[
\text{Prob. isolated muon} = \text{Prob. producing muon} \times \text{Prob. } B \text{ remnants missed}
\]

- **Muons that pass isolation take large fraction of $p_T$**

- **Many isolated muons point back to primary vertex.**

  C. Wolfe, CDF internal

- **Isolation leaves $\sim 1/200 \mu/b$**

  $\gg 10^{-4}$ per light jet
**Physics of isolated leptons from $b$ decay**

Probs. isolated muon

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  C. Wolfe, CDF internal

- Isolation leaves $\sim 1/200 \mu/b$
  
  $\gg 10^{-4} \text{ per light jet}$

Harder $b$'s can give isolated $e$'s, because $e$ cuts must allow more energy in the calorimeter.

It is difficult to reduce this without losing efficiency for primary $e$.

Isolation is not extremely effective for leptons from $b$ decay.
Fold in $\bar{b}b$ production.

Old focus: 1/2 of all 10 GeV isolated $\mu$ come from threshold, $b$ with $p_Tb < 20$ GeV.

It is common for analyses to start simulations with $p_Tb > 20$ GeV.

New focus: Isolation acts as a narrow band-pass filter!

*Isolated* muons of a given energy come from $bs$ of barely more energy.
Isolated leptons from $b/c$ production & decay

Fold in $b\bar{b}$ production.
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New focus: Isolation acts as a narrow band-pass filter!

*Isolated* muons of a given energy come from $b$s of barely more energy.

Fold in $c\bar{c}$ production.
The story repeats for $c$ decays

1 twist: $D$ decays have many pions $\pi^\pm$ fake $e$ at $\sim 10^{-4}$

$\Rightarrow$ Large “$e_{iso}$” rate
What does ATLAS $H \rightarrow ZZ \rightarrow 4\ell$ tell us?

Of course heavy-flavor background to $H \rightarrow ZZ \rightarrow 4\ell$ is small, but . . .

<table>
<thead>
<tr>
<th>Selection cut</th>
<th>$4e$</th>
<th>$4\mu$</th>
<th>$2e2\mu$</th>
<th>$4e$</th>
<th>$4\mu$</th>
<th>$2e2\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>1</td>
<td>96.6</td>
<td>96.6</td>
<td>91.4</td>
<td>91.4</td>
<td>91.4</td>
</tr>
<tr>
<td>Preselection</td>
<td>2</td>
<td>13.8</td>
<td>17.6</td>
<td>31.4</td>
<td>2.6</td>
<td>9.4</td>
</tr>
<tr>
<td>Lepton quality and $p_T$</td>
<td>3</td>
<td>7.3</td>
<td>16.0</td>
<td>21.9</td>
<td>$1.1\times10^{-1}$</td>
<td>2.1</td>
</tr>
<tr>
<td>Z mass cuts</td>
<td>4</td>
<td>6.9</td>
<td>14.8</td>
<td>20.2</td>
<td>$4.7\times10^{-2}$</td>
<td>1.1</td>
</tr>
<tr>
<td>Calo Isolation</td>
<td>5</td>
<td>6.9</td>
<td>13.9</td>
<td>19.5</td>
<td>$4.7\times10^{-2}$</td>
<td>8.5$\times10^{-2}$</td>
</tr>
<tr>
<td>Track Isolation</td>
<td>6</td>
<td>6.8</td>
<td>13.6</td>
<td>19.2</td>
<td>$1.3\times10^{-2}$</td>
<td>3.3$\times10^{-2}$</td>
</tr>
<tr>
<td>IP cut</td>
<td>7</td>
<td>6.2</td>
<td>13.0</td>
<td>17.8</td>
<td>$5.6\times10^{-3}$</td>
<td>1.1$\times10^{-2}$</td>
</tr>
<tr>
<td>H Mass window</td>
<td>8</td>
<td>$5.2\times10^{-2}$</td>
<td>$11.3\times10^{-2}$</td>
<td>$12.0\times10^{-2}$</td>
<td>$1.6\times10^{-3}$</td>
<td>$1.2\times10^{-3}$</td>
</tr>
</tbody>
</table>

ATLAS, hep-ex/0901.0512

Isolation and impact parameter do NOT help much.
Summary: Isolation cuts have limited impact

For the isolated leptons, our simulations suggest:

- $\sim 1/2$ of the events pass the usual isolation cuts, because the remnant is just outside whatever “cone” is used for tracking/energy cuts.
- $\sim 1/2$ of the events pass because the lepton took nearly all of the energy. Hence, there is nothing left to reject on.

Estimating efficiency (from ATLAS or us):

- Branching fraction gives a factor of 1/10 (to $e$ or $\mu$).
- Isolation ONLY buys another factor of 1/5 (we saw 1/10).
- Impact parameter only buys another factor of 1/2.

Other simulations (and data) point to $\sim 1/200$ of every $c$ and $b$ produce an isolated $e$ or $\mu$.

Nature of the problem: $\sigma_{b\bar{b}}^{\text{inclusive}} \sim 5 \times 10^8$ pb at LHC.
Dimuons from $b \bar{b}$ decays in the CDF data

The foil:
A Trilepton search at CDF (PRD 79, 052004 (09))

Z.S., E. Berger, PRD 82, 014001 (2010)
CDF Motivation: SUSY Trileptons

CDF is looking for the golden signature of supersymmetry,
\[ \tilde{\chi}_1 \tilde{\chi}_2^0 \rightarrow l^+ l^- l^\pm + E_T \]
Specifically, they are looking for anomalous \( \mu \mu + e/\mu + E_T \).

CDF, PRD 79, 052004 (09)

Is this SUSY or background?
In our dilepton study (PRD 74, 033008 (06)) we recommended measuring the production of isolated muons from $b\bar{b}$ production by varying isolation cuts to extract the $\mu_{iso}$ fraction.
Searching the data — is this real?

In our dilepton study (PRD 74, 033008 (06)) we recommended measuring the production of isolated muons from $b\bar{b}$ production by varying isolation cuts to extract the $\mu_{iso}$ fraction.

That is exactly what CDF has now done!

ALL previous trilepton studies at the Tevatron had ignored heavy-flavors as a source of isolated leptons.

CDF established several control regions in the $E_T - M_{\mu\mu}$ plane.
—Dimuons are used because the the signal is large and clean.
Each component of background is measured explicitly.
CDF result

CDF, PRD 79,052004 (2009)

Looking in the dimuon sample, CDF varies the impact parameter cut, and fits for $b\bar{b}$ in both opposite-sign and same-sign channels.

<table>
<thead>
<tr>
<th>Region</th>
<th>DY</th>
<th>HF</th>
<th>Fakes</th>
<th>Diboson</th>
<th>$t\bar{t}$</th>
<th>Total SM expected</th>
<th>SUSY expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control a</td>
<td>6419 ± 709</td>
<td>-</td>
<td>10 ± 11</td>
<td>2.4 ± 0.2</td>
<td>1.18 ± 0.14</td>
<td>6433 ± 712</td>
<td>0.30 ± 0.07</td>
<td>6347</td>
</tr>
<tr>
<td>Control A</td>
<td>14820 ± 2242</td>
<td>9344 ± 1612</td>
<td>2294 ± 1148</td>
<td>1.03 ± 0.09</td>
<td>0.12 ± 0.03</td>
<td>26459 ± 1429</td>
<td>0.9 ± 0.2</td>
<td>26295</td>
</tr>
<tr>
<td>Control b</td>
<td>217 ± 25</td>
<td>-</td>
<td>9 ± 7</td>
<td>1.7 ± 0.2</td>
<td>0.27 ± 0.05</td>
<td>227 ± 26</td>
<td>0.5 ± 0.1</td>
<td>253</td>
</tr>
<tr>
<td>Control c</td>
<td>5770 ± 1043</td>
<td>2238 ± 384</td>
<td>466 ± 234</td>
<td>0.49 ± 0.07</td>
<td>0.02 ± 0.01</td>
<td>8474 ± 857</td>
<td>0.7 ± 0.2</td>
<td>8205</td>
</tr>
<tr>
<td>Control d</td>
<td>7.8 ± 1.5</td>
<td>9 ± 4</td>
<td>0.3 ± 0.3</td>
<td>0.21 ± 0.07</td>
<td>4.1 ± 0.4</td>
<td>22 ± 5</td>
<td>1.8 ± 0.4</td>
<td>23</td>
</tr>
<tr>
<td>Signal Reg.</td>
<td>169 ± 30</td>
<td>90 ± 20</td>
<td>49 ± 25</td>
<td>6.5 ± 0.4</td>
<td>0.96 ± 0.11</td>
<td>315 ± 37</td>
<td>17 ± 3</td>
<td>297</td>
</tr>
</tbody>
</table>

Conclusion: Leptons from heavy-flavor decays are comparable to Drell-Yan at low $M_{ll}$ and low $E_T$. 
Comparing to CDF

Z.S., E. Berger, PRD 82, 014001 (2010)

We feed MadEvent events through PYTHIA and into the same detector simulation we used before to predict a signal for each control region. Our results are normalized to the $Z$ peak. Our DY and $b\bar{b}$ include NLO $K$-factors.

<table>
<thead>
<tr>
<th>Region</th>
<th>CDF</th>
<th>Our study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DY</td>
<td>$b\bar{b}$</td>
</tr>
<tr>
<td>Control Z</td>
<td>6419 ± 709</td>
<td>—</td>
</tr>
<tr>
<td>Control A</td>
<td>14820 ± 2242</td>
<td>9344 ± 1621</td>
</tr>
<tr>
<td>Control C</td>
<td>5770 ± 1043</td>
<td>2238 ± 384</td>
</tr>
</tbody>
</table>

Conclusions:

- We consistently underestimate the real background from $b\bar{b}$.
- We believe our results have been conservative.
- Isolated leptons from heavy flavor decays are a significant fraction of ALL low-$p_T$ data samples.
Dileptons at the LHC

The foil:
Higgs production and decay to $WW$

Higgs decays through $W^+W^-$ to opposite-sign dileptons is expected to give the largest significance signal for $135 < M_H < 219$ GeV.

CDF, DØ, ATLAS, and CMS have devoted substantial effort to this channel. With 6 fb$^{-1}$ each, CDF, DØ claim to exclude at 95% CL a SM Higgs boson with $M_H \sim 158$–175 GeV. 

arXiv:1007.4587
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In addition to continuum $WW$, $Z/\gamma^*$, and $t\bar{t}$ contributions, many other QCD and EW processes can provide backgrounds. These include processes with heavy flavors:

- $b\bar{b} + X$, $c\bar{c} + X$, $Wc$, $Wc\bar{c}$, $Wb\bar{b}$, single-top

We redid (old) DØ and ATLAS analyses, including full detector simulations, but included isolated leptons from heavy flavor ($b$, $c$) decays.
Detailed simulations for Tevatron and LHC

- DØ: Has published data, has ongoing analyses, with $S/B \sim 1/30$.
- ATLAS: Has simulations and expects $S/B \sim 1$.

There are two classes of backgrounds with heavy-flavor leptons:

1. $W_c, Wb\bar{b}, Wc\bar{c}, Wb$, single-top — All have 1 real $W$ plus 1 HFL.

2. $b\bar{b}, c\bar{c}$ — Both have 2 HFL.
   Both have mb cross sections, w/ only $10^4$ suppression from isolation.

Simulation method

- for $H \rightarrow WW$ and continuum $WW$ use PYTHIA with NLO $K$ factors.
- $Wc/Wb$ use MadEvent fed through PYTHIA with NLO $K$ factors.
- Single-top, $Wb\bar{b}, Wc\bar{c}$, normalized to ZTOP/MCFM differential NLO.

PYTHIA output is fed through **modified** PGS simulation that reproduces DØ and ATLAS full detector results to 10%.
### ATLAS-like search for 160 GeV Higgs

The biggest difference between analysis and a Tevatron analysis is that cross sections are bigger, so the cuts are tighter.

- After the $E_T$ cut, all real power comes from the $M_{ll}^T$ cut. **Warning**: Numbers can be deceptive!

- $S/B \sim 1$ at LHC, but let’s look at $M_{ll}^T$ distribution.

<table>
<thead>
<tr>
<th>Cut level</th>
<th>$H \rightarrow WW$</th>
<th>$WW$</th>
<th>$b\bar{b}j^*$</th>
<th>$Wc$</th>
<th>single-top</th>
<th>$Wb\bar{b}$</th>
<th>$Wc\bar{c}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolated $l^+l^- &gt; 10$ GeV</td>
<td>336</td>
<td>1270</td>
<td>&gt; 35700</td>
<td>12200</td>
<td>3010</td>
<td>1500</td>
<td>1110</td>
</tr>
<tr>
<td>$E_{Tl_1} &gt; 20$ GeV</td>
<td>324</td>
<td>1210</td>
<td>&gt; 5650</td>
<td>11300</td>
<td>2550</td>
<td>1270</td>
<td>963</td>
</tr>
<tr>
<td>$E_T &gt; 40$ GeV</td>
<td>244</td>
<td>661</td>
<td>&gt; 3280</td>
<td>2710</td>
<td>726</td>
<td>364</td>
<td>468</td>
</tr>
<tr>
<td>$M_{ll} &lt; 80$ GeV</td>
<td>240</td>
<td>376</td>
<td>&gt; 3270</td>
<td>2450</td>
<td>692</td>
<td>320</td>
<td>461</td>
</tr>
<tr>
<td>$\Delta\phi &lt; 1.0$</td>
<td>136</td>
<td>124</td>
<td>&gt; 1670</td>
<td>609</td>
<td>115</td>
<td>94</td>
<td>131</td>
</tr>
<tr>
<td>$</td>
<td>\theta_{ll}</td>
<td>&lt; 0.9$</td>
<td>81</td>
<td>83</td>
<td>&gt; 1290</td>
<td>393</td>
<td>68</td>
</tr>
<tr>
<td>$</td>
<td>\eta_l_1 - \eta_l_2</td>
<td>&lt; 1.5$</td>
<td>76</td>
<td>71</td>
<td>&gt; 678</td>
<td>320</td>
<td>48</td>
</tr>
<tr>
<td>Jet veto</td>
<td>41</td>
<td>43</td>
<td>&gt; 557</td>
<td>175</td>
<td>11</td>
<td>12</td>
<td>7.4</td>
</tr>
<tr>
<td>$130 &lt; M_{ll}^T &lt; 160$ GeV</td>
<td>18</td>
<td>11</td>
<td>—</td>
<td>0.21</td>
<td>1.3</td>
<td>0.04</td>
<td>0.09</td>
</tr>
</tbody>
</table>
Transverse mass distribution after cuts

- Cannot reconstruct a Higgs boson mass peak from $H \rightarrow WW^* \rightarrow l^+ l^- \nu \bar{\nu}$; use ‘transverse mass’ as an estimator;

$$M_{TT}^H = \sqrt{2p_T^H E_T (1 - \cos(\Delta \phi))}$$

- Heavy flavor background is more than 50 times previous background estimates when $M_{TT}^H < 110$ GeV; a tail extends through the entire signal region
Most variations of cuts do not help much.

One could try to raise the cut on $p_T l_1$.

- No help vs. anything with a $W$.
- Even $\bar{b}b$ does not decrease fast enough.

Recall, an “isolated lepton” from a $B$ is usually not soft compared to the $B$.

However, the second lepton $p_T$ falls exponentially.

So raise the cut: $p_T l_2 > 10$ GeV $\Rightarrow p_T l_2 > 20$ GeV.
One very effective new cut . . .

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• No help vs. anything with a $W$.

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  Recall, an “isolated lepton” from a $B$ is usually not soft compared to the $B$.

However, the second lepton $p_T$ falls exponentially.

So raise the cut: $p_T l_2 > 10$ GeV $\Rightarrow p_T l_2 > 20$ GeV.

Leading edge 20 GeV lower!

$H \rightarrow WW$ survives!

$b\bar{b} \rightarrow b\bar{b}/30$, $W + X \rightarrow W + X/10$, $t + X \rightarrow t + X/5$
Effect of isolation on $H \rightarrow WW \rightarrow l^+l^-E_T$

Why does this new background have a hard right edge?

**Why this?**

[Graph showing missing backgrounds for $H \rightarrow WW$ at ATLAS]

**Why NOT this?**

[Graph showing $WcJ \rightarrow \ell \bar{\nu}e$]
Effect of isolation on $H \rightarrow WW \rightarrow l^+l^- E_T$

Why does this new background have a hard right edge?

Why this?

Why NOT this?

Answer: This is a direct consequence of the band-pass filter of isolation cutting off the high-$p_T$ leptons.

Without the filter of isolation, the critical transverse mass distribution would be swamped by QCD background!

With isolation, the background to isolated $\mu$ (and $e$) from heavy flavor ($b$ and $c$) decays is much softer. The less well-modeled high-$M_T$ tail of the background is suppressed.
Dileptons and $H \rightarrow WW$: Summary

(Z.S. and E. Berger, PRD 74, 033008 (2006))

Isolation cuts do not generally remove leptons from heavy flavors as a background to multi-lepton searches. A sequence of complex physics cuts is needed.

1. A full treatment of all physics processes with $b$ and $c$ should be performed in multi-lepton analyses.

2. Heavy-flavor lepton backgrounds cannot be easily extrapolated from more general samples. The interplay between isolation and various cuts tends to emphasize small corners of phase space, rather than the bulk. Measure the background close to the final cuts.

3. Raising the $p_T$ cut on additional leptons suppresses the heavy flavor backgrounds. $H \rightarrow WW$ signal is barely touched, so this technique should work at the LHC, for $M_H > 130$ GeV. Trileptons, or other Higgs channels may be sensitive as well...
Trileptons at the LHC

The foil:
SUSY chargino/neutralino production

Motivation: Trileptons at LHC

\[ \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow l^+ l^- l^\pm + E_T \] is a golden signature of supersymmetry.

CMS and ATLAS have analyses designed to observe this signal.

CMS TDR V.2&Note 2006/113; ATLAS CSC 7

\[ WZ \] is thought to be the largest source of low-\( p_T \) trileptons at LHC.

\( W \gamma^* \) is not always included but it should be
Motivation: Trileptons at LHC

\[ P = \chi \rightarrow l^+ l^- l^\pm + E_T \]

is a golden signature of supersymmetry.

CMS and ATLAS have analyses designed to observe this signal.

CMS TDR V.2&Note 2006/113; ATLAS CSC 7

There are MANY processes with heavy flavors:

- \( bZ/\gamma \), \( b\bar{b}Z/\gamma \), \( cZ/\gamma \), \( c\bar{c}Z/\gamma \), \( b\bar{b}W \), \( c\bar{c}W \), \( t\bar{t} \), \( tW \), \( t\bar{b} \)

How important are leptons from heavy flavor (\( b, c \)) decays?

NOTE: All photons are virtual, and split to \( l^+ l^- \)
SUSY particle masses

We examined the trilepton SUSY signal and the SM backgrounds for 4 SUSY points (all masses in GeV units):

<table>
<thead>
<tr>
<th></th>
<th>$\tilde{\chi}_1^0$</th>
<th>$\tilde{\chi}_2^0$</th>
<th>$\tilde{\chi}_1^\pm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM1</td>
<td>96.8</td>
<td>178.3</td>
<td>178.1</td>
</tr>
<tr>
<td>LM7</td>
<td>90.5</td>
<td>154.8</td>
<td>154.8</td>
</tr>
<tr>
<td>LM9</td>
<td>68.7</td>
<td>121.7</td>
<td>122.3</td>
</tr>
<tr>
<td>SU2</td>
<td>112.5</td>
<td>171.3</td>
<td>164.0</td>
</tr>
</tbody>
</table>

- LM1, LM7, and LM9 are the SUSY points investigated by CMS. They are a subset that exhibits a large trilepton signature from $\tilde{\chi}_1^+ \tilde{\chi}_2^0$ decay.

- ATLAS point SU2 is in the focus point region of mSUGRA parameter space.

- These may already be excluded by WMAP, $b \rightarrow s\gamma$, or other data. We use them to make contact with the CMS and ATLAS simulations.
Event simulations

We reproduced the analysis chains described in

1. CMS: CMS TDR V.2&Note 2006/113

2. ATLAS: ATLAS CSC 7

but we included, in addition, the contributions from processes with heavy flavors: $bZ/\gamma, \bar{b}bZ/\gamma, cZ/\gamma, \bar{c}cZ/\gamma, b\bar{b}W, c\bar{c}W, t\bar{t}, tW, t\bar{b}$

Simulation method

- Matrix elements computed in MadEvent (spin correlations included)
- MadEvent results fed through PYTHIA showering.

PYTHIA output is fed through a modified PGS detector simulation that reproduces CMS and ATLAS full detector results to 10%.

Important CMS Analysis Cuts

- Require 3 isolated leptons
- Require no jets with $E_T > 30$ GeV
- Require $M_{\text{OSSF}}^{ll} < 75$ GeV
**Trileptons: SUSY & SM at CMS w/ 30 fb⁻¹**

<table>
<thead>
<tr>
<th>Channel</th>
<th>NoJets</th>
<th>$M_{ll}^{\text{OSSF}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM9</td>
<td>248</td>
<td>243</td>
</tr>
<tr>
<td>LM7</td>
<td>126</td>
<td>123</td>
</tr>
<tr>
<td>LM1</td>
<td>46</td>
<td>44</td>
</tr>
</tbody>
</table>

### Analysis cuts:
- 3 leptons
- No jets ($E_{T,j} > 30$ GeV)
- Remove $Z$ peak (demand $M_{ll}^{\text{OSSF}} < 75$ GeV)

$Z$ + heavy flavor decays are $\times WZ/\gamma + \bar{t}t!$
Two additional cuts: $E_T$ and angular correlations

Leptons from SUSY decays are SOFT ⇒ Cannot raise $p_Tl$ cut.

**Missing $E_T$**

$Z/\gamma+\text{heavy flavors} – \text{no intrinsic } E_T$

Comes from misreconstruction,
energy lost down beam pipe

Natural $E_T$ in SUSY points low as well
$	ilde{\chi}_1^0$'s partially balance out

A $E_T$ cut demanding
$E_T > 30$–$40$ GeV is very effective
Two additional cuts: $E_T$ and angular correlations

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Natural $E_T$ in SUSY points low as well

$\tilde{\chi}_1^0$'s partially balance out

A $E_T$ cut demanding

$E_T > 30$–$40$ GeV is very effective

$E_T$ is poorly measured

**Angular correlations**

Angles measured extremely well

All combinations different ($\theta_{12}^{CM}$ shown)

Demand $\theta_{12}^{CM} > 45^\circ$, $\theta_{13}^{CM} > 40^\circ$, $\theta_{23}^{CM} < 160^\circ$

Reduces $B$ by 30% for 5% loss of $S$

Not optimized
### Trileptons: SUSY & SM at CMS (+new cuts)

<table>
<thead>
<tr>
<th>Channel</th>
<th>$N^l = 3$, NoJets</th>
<th>$M^{\text{OSSF}}_{ll}$ &lt; 75 GeV</th>
<th>$E_T &gt; 30$ GeV</th>
<th>Angular cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM9</td>
<td>248</td>
<td>243</td>
<td>160</td>
<td>150</td>
</tr>
<tr>
<td>LM7</td>
<td>126</td>
<td>123</td>
<td>89</td>
<td>85</td>
</tr>
<tr>
<td>LM1</td>
<td>46</td>
<td>44</td>
<td>33</td>
<td>32</td>
</tr>
<tr>
<td>$WZ/\gamma$</td>
<td>1880</td>
<td>538</td>
<td>325</td>
<td>302</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>1540</td>
<td>814</td>
<td>696</td>
<td>672</td>
</tr>
<tr>
<td>$tW$</td>
<td>273</td>
<td>146</td>
<td>123</td>
<td>121</td>
</tr>
<tr>
<td>$t\bar{b}$</td>
<td>1.1</td>
<td>1.0</td>
<td>0.77</td>
<td>0.73</td>
</tr>
<tr>
<td>$bZ/\gamma$</td>
<td>14000</td>
<td>6870</td>
<td>270</td>
<td>177</td>
</tr>
<tr>
<td>$cZ/\gamma$</td>
<td>3450</td>
<td>1400</td>
<td>45</td>
<td>35</td>
</tr>
<tr>
<td>$b\bar{b}Z/\gamma$</td>
<td>8990</td>
<td>2220</td>
<td>119</td>
<td>103</td>
</tr>
<tr>
<td>$c\bar{c}Z/\gamma$</td>
<td>4680</td>
<td>1830</td>
<td>69</td>
<td>35</td>
</tr>
<tr>
<td>$b\bar{b}W$</td>
<td>9.1</td>
<td>7.6</td>
<td>5.6</td>
<td>5.3</td>
</tr>
<tr>
<td>$c\bar{c}W$</td>
<td>0.19</td>
<td>0.15</td>
<td>0.12</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Zack Sullivan, Illinois Institute of Technology – p.32/43
Significance of SUSY point LM9 in 30 fb$^{-1}$

1. Our calculations are LO.
   NLO $K$-factors are large (1.5–2) on most processes,
   BUT, jet veto will reduce this.

2. ISR is not well determined
   The rate of $>30$ GeV jets can be changed by a factor of 4 depending on assumptions in PYTHIA about ISR.

We present our calculation, and one that scales down $B$ by 4 to show the range of possible significances

<table>
<thead>
<tr>
<th>$N^l = 3$, $M_{ll}^{OS SF}$</th>
<th>NoJets $&lt; 75$ GeV</th>
<th>$E_T &gt; 30$ GeV</th>
<th>Angular cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S/\sqrt{B}_{LM9}$</td>
<td>1.33</td>
<td>2.07(1.79)</td>
<td>3.93(3.74)</td>
</tr>
<tr>
<td>$S/\sqrt{B}_{CMS j}$</td>
<td>2.63</td>
<td>4.09(3.54)</td>
<td>7.78(7.39)</td>
</tr>
</tbody>
</table>

(Parentheses include leptons from fakes from CMS Table 6, Note 2006/113)

We will not know which ISR estimate is correct until we measure it at LHC.
Summary of trileptons

(Z.S. and E. Berger, PRD 78, 034030 (2008))

1. Heavy-flavor (b, c) decays to leptons dominate low-$p_T$ isolated leptons at LHC
   Trileptons from $Z/\gamma^* +$ heavy flavors (HF) $\sim 10 \times$ all other backgrounds

2. Raising minimum $p_T$ is not viable for SUSY signal, but other cuts work:
   • Require $E_T > 30$ GeV, $Z/\gamma^* +$ HF $\rightarrow Z/\gamma^* +$ HF/30 Challenging
   • Impose cuts on well-measured angles, $Z/\gamma^* +$ HF reduced by 30%

3. Overall normalization is dominated by assumptions regarding ISR
   Large uncertainty in the effectiveness of jet veto
   If large ISR exists, may want to loosen jet veto to recover SUSY signal
   ISR questions should be resolved with initial data from LHC

4. Any signal that has low-$p_T$ leptons MUST consider the background from heavy flavor (b, c) decays. Analyses of SUSY exclusion limits should include this (neglected) background.

Overall lesson: Precise understanding of all SM physics processes will enable confident discovery claims.
The verdict

Z.S., E. Berger, PRD 74, 033008 (06); PRD 78, 034030 (08); PRD 82, 014001 (10)

There is unambiguous evidence of dimuons from $b\bar{b}$ decay in the CDF data. CDF, PRD 79, 052004 (2009)

Isolated leptons ($\mu$ or $e$) from heavy flavor decays ($b$ or $c$) will play an important role in the extraction of Higgs decays, trilepton SUSY, or any process with modest-$p_T$ leptons.

The band-pass filter effect of isolation allows us to introduce:

A new “rule-of-thumb”

• Replace 1/200 of every produced $b$ or $c$ quark with a muon, and 1/200 with an electron having the same momentum as the $b$ or $c$.

If the resulting background is more than 10% of the signal, it should be simulated more carefully, and eventually measured in situ.

THANK YOU
Comparing invariant mass distributions

Fig. 6c, CDF, PRD 79, 052004 (2009)

Our distributions

Conclusion: Our shapes are very similar!
\[
H \rightarrow W^+W^- \rightarrow e^+e^-E_T / e^\pm \mu^\mp E_T / \mu^+\mu^- E_T
\]

Taken from 1/3 fb\(^{-1}\) study, \(D\emptyset, \text{PRL 96, 011801 (2006)}\)

<table>
<thead>
<tr>
<th>(M_H) (GeV)</th>
<th>120</th>
<th>140</th>
<th>160</th>
<th>180</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H \rightarrow WW(*))</td>
<td>0.125 ± 0.002</td>
<td>0.398 ± 0.008</td>
<td>0.68 ± 0.01</td>
<td>0.463 ± 0.009</td>
<td>0.210 ± 0.004</td>
</tr>
<tr>
<td>(Z/\gamma^*)</td>
<td>7.5 ± 1.0</td>
<td>3.8 ± 0.6</td>
<td>4.0 ± 0.7</td>
<td>6.6 ± 0.9</td>
<td>9.9 ± 1.1</td>
</tr>
<tr>
<td>Diboson</td>
<td>8.1 ± 0.2</td>
<td>11.7 ± 0.3</td>
<td>12.3 ± 0.3</td>
<td>11.6 ± 0.3</td>
<td>9.6 ± 0.3</td>
</tr>
<tr>
<td>(t\bar{t})</td>
<td>0.11 ± 0.02</td>
<td>0.29 ± 0.02</td>
<td>0.47 ± 0.03</td>
<td>0.66 ± 0.05</td>
<td>0.72 ± 0.05</td>
</tr>
<tr>
<td>(W+\text{jet}/\gamma)</td>
<td>14.2 ± 2.1</td>
<td>5.8 ± 1.2</td>
<td>2.8 ± 0.9</td>
<td>0.7 ± 0.5</td>
<td>0.7 ± 0.5</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>0.3 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>0.3 ± 0.1</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>Bknd sum</td>
<td>30.1 ± 2.3</td>
<td>21.8 ± 1.4</td>
<td>19.7 ± 1.2</td>
<td>19.8 ± 1.1</td>
<td>21.2 ± 1.2</td>
</tr>
<tr>
<td>Data</td>
<td>21</td>
<td>20</td>
<td>19</td>
<td>19</td>
<td>14</td>
</tr>
</tbody>
</table>

So the relevant backgrounds are:

\(D\emptyset\): \(WW\), small Drell-Yan, small rate from \(\pi^\pm\) faking \(e^\pm\)

\(\text{ATLAS}\): \(WW\), some \(Wt\), small \(tt\)

Is that the end of the story?...
### Breakdown of LS/OS leptons at DØ

<table>
<thead>
<tr>
<th>( \sigma_{ll} ) (fb):</th>
<th>ee</th>
<th>e(\mu)</th>
<th>(\mu\mu)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LS</td>
<td>OS</td>
<td>LS</td>
</tr>
<tr>
<td>( H \rightarrow WW )</td>
<td>—</td>
<td>0.73 ± 0.04</td>
<td>—</td>
</tr>
<tr>
<td>( WW )</td>
<td>—</td>
<td>12 ± 1</td>
<td>—</td>
</tr>
<tr>
<td>( b\bar{b}(j) )</td>
<td>—</td>
<td>2.1</td>
<td>—</td>
</tr>
<tr>
<td>( WC )</td>
<td>0.8 ± 0.4</td>
<td>2.3 ± 1.1</td>
<td>1.1 ± 0.4</td>
</tr>
<tr>
<td>( Wb\bar{b} )</td>
<td>0.4 ± 0.2</td>
<td>0.4 ± 0.1</td>
<td>2.1 ± 1.6</td>
</tr>
<tr>
<td>( Wc\bar{c} )</td>
<td>1.4 ± 0.5</td>
<td>1.1 ± 0.4</td>
<td>1.0 ± 0.2</td>
</tr>
<tr>
<td>all else</td>
<td>0.1</td>
<td>1.6</td>
<td>0.3</td>
</tr>
</tbody>
</table>

\( b\bar{b} \) more than doubles the background to \( \mu^+ \mu^- \).
Other channels see 50% increases.
Is this consistent with the DØ result?
### Breakdown of LS/OS leptons at DØ

<table>
<thead>
<tr>
<th>( \sigma_{ll} ) (fb):</th>
<th>ee</th>
<th>eµ</th>
<th>µµ</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \to WW )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.73 ± 0.04</td>
<td>1.26 ± 0.05</td>
<td>0.60 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>( WW )</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>12 ± 1</td>
<td>20 ± 1</td>
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</tr>
<tr>
<td>( b\bar{b}(j) )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>5.6</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>( Wc )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<tr>
<td>all else</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>1.6</td>
<td>3.0</td>
<td></td>
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</table>

\( b\bar{b} \) more than doubles the background to \( \mu^+ \mu^- \).

Other channels see 50% increases.

Is this consistent with the DØ result? Yes! to within 1–2\( \sigma \).

Should they see it? The experiments do not have absolute normalized predictions. Instead, they fit \( WW \) and Drell-Yan, etc. to data.

The leptons are there, just misclassified.

What we want is to understand all of the physical processes at play. For that, we have to measure the backgrounds...
Importance of the virtual photon

Simulations of $WZ$ based on PYTHIA do not include virtual photons.

Nearly 1/2 of the trilepton background from $WZ/\gamma$ is from $W\gamma^*$ alone.

Matrix elements that include virtual photons are important for studies of low-$p_T$ leptons.

$(p_Tl$ spectra after $M_{ll}^{\text{OSSF}}$ cut)
Pure QCD background to trileptons

CMS estimates $jjj \rightarrow lll < 5$ events in 30 fb$^{-1}$

What about $b\bar{b}bb$, $b\bar{b}cc$, $c\bar{c}cc$?

We cannot simulate this directly in our lifetimes ($\sim 10^3$ CPU years)

Estimate 3 sources of $b\bar{b}b$ for 30 fb$^{-1}$

1. **Direct $b\bar{b}bb$:** $\sim 500$ events
   
   Use $Wb\bar{b}$ to estimate $P(b \rightarrow \mu_{iso})$: $\sigma_{b\bar{b}bb} \times (7.5 \times 10^{-3})^3$

2. **Multiple interactions:** $\sim 600$ events
   
   10 interactions $\times \sigma_{bb}^2 / \sigma_{\text{inelastic}}$

3. **Multiple scattering, gluon splitting:** $\sim 10^3$ events

Note that $K$ factors could be as high as 5.5

A. Del Fabbro, D. Treleani, PRD 66, 074012 (02)

Scaling results from Z.S., E.L. Berger, PRD 74, 033008 (06), the $E_T$ cut should remove nearly all of these.
Other angular correlations

Angles are well-measured, and defined in the trilepton CM frame.

Suggested cut: $\theta_{13}^{\text{CM}} > 40^\circ$  
Suggested cut: $\theta_{23}^{\text{CM}} < 160^\circ$

These cuts are almost free, and not optimized. 
5% signal decrease, but 30% background decrease
CMS SUSY points LM1, LM7

Representative opposite-sign same-flavor (OSSF) invariant masses

**LM1**

Signal endpoint above \( Z \)-peak cut and signal is small

**LM7**

LM7 similar to LM9, but smaller