Search for Supersymmetry in Events with Same-Sign Di-Leptons and Missing Energy with the CMS Detector

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Introduction

• If SUSY exists, it could manifest itself in a variety of ways
  – Numerous particle states become available, diverse phenomenology

• In general we expect:
  – Long cascade decays that begin with colored SUSY particles (squarks/gluinos) and end with an LSP (typically the lightest neutralino)
  – Lots of activity in the event
    • Jets from squark/gluino decays
    • Leptons form intermediate chargino/neutralino decays
    • Missing energy from escaping invisible particles
  – The key is to choose a final state configuration (topology) that is not easily mimicked by the Standard Model
The **Same-Sign Di-Lepton Topology**

- Events containing two isolated leptons of the same electromagnetic charge (same-sign) are highly suppressed in the Standard Model
  - **Much more natural to produce oppositely charged leptons**
- Same-Sign di-lepton events are easily produced in SUSY scenarios as well as other models of new physics
Documentation (CMS-SUS-11-010)

- Four Contributions:
  - Florida (e/µ final states)
  - UCSD/UCSB/FNAL (e/µ final states)
  - ETH/Santander/Oviedo/Tehran (e/µ final states)
  - Imperial/Wisconsin/Perugia/Athens (τ final states)

- Original Analysis Results based on 2010 (35pb$^{-1}$)
  - Published in JHEP 1106:077 (2011) [arxiv:1104.3168]

- Second update based on Summer 2011 (1fb$^{-1}$)
  - Presented at EPS 2011 Conference

- Third update based on full 2011 Data (4.7fb$^{-1}$)
  - PRL submission in preparation
Lepton Selection

Muons ($\mu$), electrons (e), and hadronic taus ($\tau$) up to $|\eta| < 2.4$ are reconstructed using standard techniques on CMS. Analysis is designed to probe models that could feature “soft leptons”:
- $p_T(\mu) > 5$ GeV, $p_T(e) > 10$ GeV, $p_T(\tau) > 15$ GeV

The relative isolation (RelIso) observable is used to distinguish prompt from non-prompt leptons:

$$
\sum_{\Delta R < 0.3} \frac{P_T^{\text{Track}} + E_T^{\text{ECAL}} + E_T^{\text{HCAL}}}{P_T^\ell} < 0.15
$$

A requirement is placed on the transverse impact parameter at $d_0 < 0.02$ cm in order to suppress leptons from heavy-flavor quark decays.

Leptons are “prompt” (signal-like) if they come from W/Z/\chi decays and “non-prompt” (fake) if they come from hadron decays.
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Jets and Missing Energy

Jets and missing transverse energy (MET or $\vec{E}_T$ or $E_T^{\text{Miss}}$) are based on the Particle Flow technique (combined calorimeter + tracking).

- Jet $p_T > 40$ GeV and $|\eta| < 2.5$

The total hadronic activity in the event is characterized by the $H_T$ variable:

$$H_T = \sum_{j} |p_T^j|$$

The $E_T^{\text{Miss}}$ is calculated by summing vectorially over the transverse momenta of all of the reconstructed particle candidates in the event:

$$|\vec{E}_T^{\text{miss}}| = \sum_{j} x(p_T^j \cdot \cos(\varphi)) + y(p_T^j \cdot \sin(\varphi))$$
Datasets and Triggers

- We pursue 3 online event selection strategies
  - Di-Lepton Triggers
    - Allows for low-$H_T$ cuts, but requires *high-$p_T$ leptons*
  - Di-Lepton + $H_T$ Triggers
    - Allows for *low-$p_T$ leptons*, but requires larger $H_T$
  - Lepton + $H_T$ + MET Triggers
    - Allows for *hadronic-tau final states* but requires larger $H_T$ and MET
Baseline Event Selection

- 2 isolated same-sign leptons + 2 jets
- Z-Veto: no OS pair within [76,106] GeV
- Di-lepton Mass \( > 8 \) GeV
  - Reduces pairs from heavy flavor decays
  - Implemented in logic of Dilepton+\( H_T \) triggers

<table>
<thead>
<tr>
<th>Table 1. Baseline Event Selection (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category</td>
</tr>
<tr>
<td>Low-( p_T )</td>
</tr>
<tr>
<td>High-( p_T )</td>
</tr>
<tr>
<td>Tau</td>
</tr>
</tbody>
</table>
Determining the Signal Regions

- In its simplest incarnation, our topology features 3 mass scales, and these can influence our main observables

<table>
<thead>
<tr>
<th>Observable</th>
<th>Influenced By</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\text{prod}}$</td>
<td>$m_B$</td>
</tr>
<tr>
<td>$H_T$</td>
<td>$\Delta m_{BC}$</td>
</tr>
<tr>
<td>$p_T'$</td>
<td>$\Delta m_{CA}$</td>
</tr>
<tr>
<td>MET</td>
<td>$\Delta m_{BA}$</td>
</tr>
</tbody>
</table>

A: LSP [dark-matter motivated; expect $E_{T}^{\text{miss}}$]
B: gluino/squark [large $\sigma$; expect jets]
C: chargino [gives exclusive same-sign leptons]
Signal Regions

- Probe various mass-splitting scenarios by targeting regions in the $H_T$-MET plane

<table>
<thead>
<tr>
<th>Region</th>
<th>$H_T$ (GeV)</th>
<th>MET (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>120</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>120</td>
</tr>
<tr>
<td>3</td>
<td>450</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>450</td>
<td>120</td>
</tr>
</tbody>
</table>

8 overlapping regions in total. We do track yields in exclusive $H_T$-MET boxes as well, to be used for combined limit-setting in the future.
# Signal Region Yields

<table>
<thead>
<tr>
<th></th>
<th>80/120</th>
<th>200/120</th>
<th>450/50</th>
<th>450/120</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High-p_T</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ee</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>μμ</td>
<td>7</td>
<td>6</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>eμ</td>
<td>12</td>
<td>11</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Tot</td>
<td>24</td>
<td>21</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td><strong>Low-p_T</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ee</td>
<td>–</td>
<td>4</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>μμ</td>
<td>–</td>
<td>10</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>eμ</td>
<td>–</td>
<td>14</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Tot</td>
<td>28</td>
<td>18</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td><strong>Tau</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>eτ</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td>μτ</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>5</td>
</tr>
<tr>
<td>ττ</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>Tot</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>

![CMS Preliminary](image)

L_{int} = 4.7 fb^{-1}

- μμ
- μτ
- ee
- eτ
- eμ
- ττ

---

Fundamental challenge of the analysis: *Can we predict these event counts using our understanding of the SM?*
**Candidate Signal Event**

$H_T = 579$ GeV  
$MET = 172$ GeV

<table>
<thead>
<tr>
<th></th>
<th>$p_T$</th>
<th>$\eta$</th>
<th>$\phi$</th>
<th>Iso</th>
<th>$d_0$</th>
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<tbody>
<tr>
<td>$\mu^+$</td>
<td>130</td>
<td>0.05</td>
<td>1.6</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$e^+$</td>
<td>79</td>
<td>-0.4</td>
<td>-2.7</td>
<td>0.01</td>
<td>0.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$p_T$</th>
<th>$\eta$</th>
<th>$\phi$</th>
<th>TCHE (hp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet 1</td>
<td>215</td>
<td>-0.85</td>
<td>2.0</td>
<td>0.8</td>
</tr>
<tr>
<td>Jet 2</td>
<td>185</td>
<td>-0.97</td>
<td>-0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>Jet 3</td>
<td>91</td>
<td>-0.92</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Jet 4</td>
<td>83</td>
<td>-0.32</td>
<td>-1.1</td>
<td>10.8</td>
</tr>
</tbody>
</table>

$\text{Mass}(J_2,J_3) = 105$ GeV  
$\text{Mass}(J_2,J_3,J_4) = 188$ GeV
## Background Classification

<table>
<thead>
<tr>
<th>Type</th>
<th>Sources</th>
</tr>
</thead>
</table>
| 2 same-sign prompt leptons: | $N_{p-p}^{SS}$
- small, but irreducible, contribution
- reasonably well understood $\rightarrow$ *taken from MC*
| $qq \rightarrow qqW^+W^-$, $WZ, ZZ, WWW, t\bar{t}W, t\bar{t}Z$
double parton scattering $2 \times (qq \rightarrow W^\pm)$ |
| 2 opposite-sign prompt leptons + charge misidentification (appears as same-sign) | $N_{p-p}^{OS}$
- small contribution
- relying on MC is not safe $\rightarrow$ *derive from data*
| $t\bar{t}, tW$, Drell-Yan,
$W^\pm W^\mp, WZ, ZZ$ |
| 1 prompt lepton + 1 fake lepton | $N_{p-f}^{SS}$
- dominant contribution
- relying on MC is not safe $\rightarrow$ *derive from data*
| $(t\bar{t}, tW, tb) \rightarrow \ell \nu + \text{jets}$
$W + \text{jets}, \text{Drell-Yan} + \text{jets}$
$VV \rightarrow \ell + \text{jets}$ |
| 2 fake leptons | $N_{f-f}^{SS}$
- sub-dominant contribution
- relying on MC is impossible $\rightarrow$ *derive from data*
| $QCD$
$t\bar{t}$ (all-hadronic) |

$$N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}$$
Irreducible Backgrounds

- These backgrounds include:
  - Di-boson production: $q\bar{q} \rightarrow WZ, ZZ$
  - Double “W-sstrahlung”: $qq \rightarrow q'q'W^\pm W^\pm$
  - Double-parton scattering: $2\times(qq \rightarrow W^\pm)$
  - Tri-Boson production: $q\bar{q} \rightarrow WWW, WWZ, WZZ, ZZZ$
  - Top-Antitop+Boson production: $q\bar{q}' \rightarrow t\bar{t}W, t\bar{t}Z$

- Many of these rare SM processes have not been well-measured or established directly at the LHC, so Monte-Carlo—based estimates are necessary
  - Several of these samples produced specifically for this analysis*
  - 50% uncertainty to cover incomplete knowledge of NLO $\sigma$’s
  - Accounts for 12-75% of the total bgd, depending on search region

Expected Contribution for 4.7fb$^{-1}$

<table>
<thead>
<tr>
<th></th>
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<th>450/50</th>
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</tr>
</thead>
<tbody>
<tr>
<td>High-pT</td>
<td>13.4</td>
<td>10.2</td>
<td>6.4</td>
<td>3.0</td>
</tr>
<tr>
<td>Low-pT</td>
<td>11.2</td>
<td>6.8</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>Tau</td>
<td></td>
<td></td>
<td></td>
<td>0.9</td>
</tr>
</tbody>
</table>

*https://indico.cern.ch/contributionDisplay.py?contribId=3&confId=168540
Electron Charge Mis-ID

- We estimate the probability $f^e_{q}$ to mis-assign the charge for electrons using $Z\rightarrow ee$ events (i.e., look for SS events in the $Z$-peak).
- Mis-Id rate agrees well with simulation
  - $0.02\%$ in the barrel and $0.28\%$ in endcaps
- Estimate contribution to signal regions by inverting charge requirement and multiplying by the probability

\[
N(e^\pm e^\pm) = 2f^e_q \cdot N(e^\pm e^\mp)
\]
\[
N(e^\pm \mu^\pm) = f^e_q \cdot N(e^\pm \mu^\mp)
\]

Accounts for $\sim 1\%$ to $5\%$ of total background

$\text{CMS Preliminary, } \sqrt{s} = 7 \text{ TeV}$

$\text{CMS Simulation, } \sqrt{s} = 7 \text{ TeV}$

$\text{MC}$

$\text{data}$

$N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}$
Fake Leptons (single & double)

- Dominant background for most search regions
- Main source (e/μ): Heavy-Flavor decays
  - ~95% of our non-prompt muons
  - ~80% of our non-prompt electrons
- Main source (τ): Hadronic jets
- Important to derive these estimates from data as simulation does not model these well enough
- We present a diverse set of approaches to measuring contributions from fakes
- All methods rely on some type of a loose-to-tight extrapolation in the respective lepton selection variables
  - Measure loose-to-tight probabilities in well-defined control region in data
  - Apply to sideband next to signal region
- Systematic uncertainties on various methods ~50%
Notation

The conditional probability for a lepton candidate to pass the tight selection criteria given that it has passed some loose selection criteria is called a “Tight-To-Loose” ratio or the T/L ratio.

Consider the RelIso selection variable. Depending on the value of this parameter a lepton may either be classified as:

I. Loose [a.k.a. the sideband]
II. Tight [a.k.a. the signal region]
III. Neither Loose, nor Tight [a.k.a. junk]

\[ N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS} \]
Diversified Approaches

Each group chooses a different collection of *extrapolation variables* and varying lengths for the sideband. The T/L ratio must be derived from a *control region*. This region may need to be transformed to the signal region. This is achieved by *binning* the T/L ratio as a function of *appropriate observables*. Additionally, some groups assume *universality* of the T/L ratio (i.e., the origin of the lepton does not influence the T/L ratio).

\[
N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}
\]

<table>
<thead>
<tr>
<th>Group</th>
<th>Extrapolation Variables</th>
<th>Transformation Variables</th>
<th>T/L Universality Assumption</th>
<th>Sideband Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Florida</td>
<td>RelIso, MET</td>
<td>(p_T^\ell, \text{NJets})</td>
<td>No</td>
<td>Large</td>
</tr>
<tr>
<td>ETH, et. al.</td>
<td>RelIso, e-ID</td>
<td>None</td>
<td>Yes</td>
<td>Medium</td>
</tr>
<tr>
<td>UCSD, et. al.</td>
<td>RelIso, e-ID, (d_0, \chi^2)</td>
<td>(p_T^\ell, \eta^\ell)</td>
<td>Yes</td>
<td>Small</td>
</tr>
<tr>
<td>Imperial, et. al.</td>
<td>RelIso, (\tau)-ID</td>
<td>(p_T^\ell, \eta^\ell)</td>
<td>Yes</td>
<td>Medium</td>
</tr>
</tbody>
</table>

Control regions are selected independently by each group. Most feature inverted cuts on MET and \(M_T\) in order to suppress events w/ signal leptons.
T/L Algebra and Application

Notation: T/L Ratio = Probability for loose lepton to also pass tight selection

- General Formula, assuming true cut efficiencies $f$ and $p$ for fake and prompt leptons respectively:

\[
\begin{align*}
N_{pf} &= \frac{pf}{(p-f)^2} \left[ -2fpN_{ll} + [f(1-p) + p(1-f)]N_{tl} - 2(1-p)(1-f)N_{tt} \right] \\
N_{ff} &= \frac{f^2}{(p-f)^2} \left[ p^2N_{ll} - p(1-p)N_{tl} + (1-p)^2N_{tt} \right]
\end{align*}
\]

- If one assumes no prompt leptons in the sideband, then $p \rightarrow 1$

\[
\begin{align*}
N_{pf} &\approx \frac{f}{(1-f)^2} \left[ -2fN_{ll} + (1-f)N_{tl} \right] \\
N_{ff} &\approx \frac{f^2N_{ll}}{(1-f)^2}
\end{align*}
\]

- Each group uses some variation of this formula
- **Universality assumption:** $f$ is the same in $N_{pf}$ and $N_{ff}$
**T/L Ratios from Data (e/µ)**

Notation: T/L Ratio = Probability for loose lepton to also pass tight selection

Measure T/L ratio in events with Jets + “away” lepton

"Short Sideband"  
UCSD/UCSB/FNAL

"Medium Sideband"  
ETH, et. al.

\[ N_{\text{bkgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS} \]
Non-Universal T/L Ratios (e/\mu) 

- Use knowledge that \textit{single-fake} events primarily come from \textit{top events} and \textit{double-fakes} come from QCD.

- The T/L ratios may not be identical in QCD events and top events:
  - Different Heavy-Flavor proportions
  - Different jet multiplicities
  - Different kinematics

- Goal: Measure two sets of T/L ratios
  - \textit{BTag-And-Probe Method} (measures single-fakes ttbar/single-top)
  - \textit{Factorization Method} (measures double-fakes from QCD)

- Use both methods together to derive the total contribution from fake leptons.
T/L Ratios for top events

Measure T/L ratios in B-enriched control sample (B-tagged jet + “away” lepton)

First bin represents the T/L ratio

03/02/12  R. Remington, Univ. of Florida
The QCD (double-fake) prediction requires one to extrapolate in three observables sequentially: \( \text{Iso}(\ell_1) \times \text{Iso}(\ell_2) \times \text{MET} \). This can only be done if the three are factorizable (i.e., the T/L ratios are uncorrelated). We demonstrate this in data using QCD-dominated regions of our baseline selection.
**Fake Lepton Predictions in Baseline (e/µ)**

\[
N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}
\]

<table>
<thead>
<tr>
<th></th>
<th>High-(p_T)</th>
<th>Low-(p_T)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HT &gt; 80, ME_T &gt; 30</strong></td>
<td>ETH</td>
<td>UCSD/SB/FNAL</td>
</tr>
<tr>
<td>ee Single-Fake</td>
<td>41.3 ± 21.7</td>
<td>64.6 ± 33.2</td>
</tr>
<tr>
<td>Double-Fake</td>
<td>11.8 ± 6.0</td>
<td>6.8 ± 3.6</td>
</tr>
<tr>
<td>µµ Single-Fake</td>
<td>65.9 ± 33.3</td>
<td>57.1 ± 28.9</td>
</tr>
<tr>
<td>Double-Fake</td>
<td>10.5 ± 5.3</td>
<td>4.4 ± 2.3</td>
</tr>
<tr>
<td>eµ Single-Fake</td>
<td>109 ± 55</td>
<td>114 ± 58</td>
</tr>
<tr>
<td>Double-Fake</td>
<td>13.0 ± 6.5</td>
<td>10.6 ± 5.4</td>
</tr>
</tbody>
</table>

|                | FLORIDA      | UCSD/SB/FNAL | \(N_{\text{obs}} - N_{p-p}^{SS} - N_{p-p}^{OS}\)  |
|----------------|---------------|--------------|
| **HT > 200, ME_T > 30** | ETH | UCSD/SB/FNAL | \(N_{\text{obs}} - N_{p-p}^{SS} - N_{p-p}^{OS}\)  |
| ee Single-Fake  | 12.7 ± 8.7   | 22.9 ± 12.0 | 17.5  |
| Double-Fake     | 3.0 ± 3.0    | 2.4 ± 1.3   |       |
| µµ Single-Fake  | 58.1 ± 27.6  | 53.1 ± 27.6 | 70.8  |
| Double-Fake     | 26.1 ± 9.6   | 25.5 ± 12.9 |       |
| eµ Single-Fake  | 64.6 ± 26.3  | 82.5 ± 41.8 | 67.2  |
| Double-Fake     | 18.5 ± 16.3  | 11.5 ± 5.9  |       |

**Good agreement between methods and with observations**
Summary of Backgrounds

- Combine methods by taking avg of predictions and most conservative uncerts.
- Observations in good agreement with predictions in all regions
- Single-Fakes (ttbar) and rare SM processes dominate (ttW and WZ)
- Proceed with limit calculations on signal rate

<table>
<thead>
<tr>
<th>Region</th>
<th>Mode or $p_T$ threshold</th>
<th>Total</th>
<th>UL 95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p_T^{1,2} &gt; 20, 10$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>ee $6.7 \pm 2.7$ 8.3 $\pm 3.1$ 18.3 $\pm 6.9$</td>
<td>33.2 $\pm 12.0$</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>ee $5$ 7 $12$</td>
<td>24</td>
<td>14.0</td>
</tr>
<tr>
<td>3</td>
<td>ee $4$ 6 $11$</td>
<td>21</td>
<td>16.3</td>
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<tr>
<td>4</td>
<td>ee $4$ 2 $11$</td>
<td>11</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td>ee $1$ 0 $3$</td>
<td>4</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td>$p_T^{e,\mu} &gt; 10, 5$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>ee $4.3 \pm 1.7$ 13.9 $\pm 6.0$ 16.1 $\pm 6.2$</td>
<td>34.3 $\pm 13.2$</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>ee $4$ 10 $14$</td>
<td>28</td>
<td>17.4</td>
</tr>
<tr>
<td>4</td>
<td>ee $4$ 6 $8$</td>
<td>18</td>
<td>14.3</td>
</tr>
<tr>
<td></td>
<td>ee $1$ 2 $3$</td>
<td>6</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>$p_T^{e,\mu} &gt; 15, 10, 5$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>ee $t\tau$ $2.6 \pm 1.0$ 4.4 $\pm 2.2$ 0.0 $\pm 0.1$</td>
<td>7.1 $\pm 2.8$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ee $t\tau$ $1$ 5 $0$</td>
<td>6</td>
<td>7.1</td>
</tr>
</tbody>
</table>
Systematics & Interpretation of Results

<table>
<thead>
<tr>
<th>Systematics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>e/µ selection (trigger, id, iso)</td>
<td>6-10%</td>
</tr>
<tr>
<td>Tau selection (trigger, id, iso)</td>
<td>10%</td>
</tr>
<tr>
<td>Isolation dependence on H_T</td>
<td>10%</td>
</tr>
<tr>
<td>Jet energy scale (7.5%)</td>
<td>3-30%</td>
</tr>
<tr>
<td>PDF (Acceptance)</td>
<td>2%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>4.5%</td>
</tr>
</tbody>
</table>

- Signal acceptance and uncertainties are model dependent
- Based on LM6 mSUGRA model uncerts range from 14%-20%
- Theory errors have to be applied (model dependent)

3 approaches to hypothesis testing all based on standard formula:

\[
\sigma \times \text{BR} \times \text{Acceptance} = \frac{N_{\text{events}}}{\int L \cdot dt} \geq \frac{N_{\text{UL}}}{\int L \cdot dt}
\]

1. cMSSM + FastSim determines LHS as fcn of \(m_0, m_{1/2}\) and we compare to \(N_{\text{UL}}\)
2. SMS + FastSim determine Acceptance as fcn of mass parameters and we absorb \(\sigma \times \text{BR}\) into the upper limit
3. We parameterize Acceptance = \(\text{Acc}(H_T, \text{MET}, p_T^\tau)\) with parton-level information so that results can be interpreted beyond the models we care to simulate
CMSSM Interpretation

- High-\(p_T\) search with \(\text{MET} > 120\ GeV\) and \(H_T > 450\ GeV\) gives the best expected limits everywhere

- Point-by-point systematics are evaluated and these influence the calculated UL to a small degree

Gluino masses constrained above \(~950\ GeV\) for \(m_0 < 700\ GeV\)
Simplified Model Interpretation

\[ pp \rightarrow \tilde{g}\tilde{g} \rightarrow qqqq\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow qqq\tau^+\tau^-\nu\nu\tilde{\chi}_1^0\tilde{\chi}_1^0 \]

Model: T1-TauNu

- Assume 100% BR to taus
- 50% BR to SS; 50% BR to OS
- Relevant for Higgsino-like chargino scenarios
Acceptance Parameterization

Derived from representative mSUGRA benchmark point using the CMS Full Simulation. Gives agreement to within ~15%.
Summary

- A robust analysis strategy has been developed to search for new physics signal using the same-sign di-lepton topology with 4.7 fb$^{-1}$
- Multiple groups contributing and multiple cross-checks are performed
- Major backgrounds are successfully derived from data using thoroughly-validated and well-established methods
- No excesses above Standard Model predictions observed
- Competitive limits on the signal rate are presented for the CMSSM and Simplified Models
- A succinct and user-friendly parameterization of the signal acceptance is provided to guide model-builders
Backup
(Supporting Material)
Fake Tau Prediction in Control Region

- Baseline region for taus already comes with aggressive cuts from the triggers, so to achieve a fake tau control region in data we go to MuHad/ElHad
  - Impose \( H_T > 150 \text{ GeV} \) and invert \( \text{MET} < 50 \text{ GeV} \)
  - Bgds from SS prompt-prompt leptons are negligible here

\[
N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}
\]

<table>
<thead>
<tr>
<th></th>
<th>e(\tau)</th>
<th>(\mu\tau)</th>
<th>(\tau\tau)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted</td>
<td>221 ± 19</td>
<td>271 ± 24</td>
<td>61 ± 19</td>
</tr>
<tr>
<td>Observed</td>
<td>205</td>
<td>233</td>
<td>69</td>
</tr>
</tbody>
</table>

**Good agreement observed**
Tau Charge Mis-ID

- Estimate the probability to mis-assign the charge for taus using $Z \rightarrow \tau \tau \rightarrow \mu \tau_h$
- Large background contribution from $W$ +jets/QCD in control region makes measurement challenging
- Simultaneous fits to visible mass($\mu, t$) spectrum and muon charge are used to extract the mis-ID rate: $f=(0.9\pm2.4)\%$

\[ N_{\text{tot}}^{\text{bkg}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS} \]
Plots

CMS Preliminary

Non-prompt Electrons

CMS Preliminary

Non-prompt Muons

Electrons

Muons

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T/L Ratios from Data (e/$\mu$)

Notation: $T/L$ Ratio = Probability for loose lepton to also pass tight selection

- Measure T/L ratio in a QCD control region

\[
N_{\text{bkgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}
\]
Single-Fake Control Regions

- Measure T/L ratio in B-enriched control sample (B-jet + away lepton)
- Suppress prompt leptons: $M_T < 15$ GeV, $\text{MET} < 15$ GeV
- $\sim 50\%$ systematic uncertainty from closure test precision and control region definition

\[ N_{\text{tot}}^{\text{bkgd}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS} \]

Re-weighted isolation templates for muons and electrons

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Double-Fake Control Regions

Data-Driven verification of $\text{Iso}_1 \times \text{Iso}_2 \times \text{MET}$ factorization in QCD

Measure RelIso and MET Efficiencies in QCD-dominated subset of baseline region. Multiply together to obtain QCD predictions

$\sim 65\%$ systematics based on closure tests and estimates of prompt lepton contamination.

NOTE: All T/L methods assume that extrapolated observables factorize similarly
Double-Fake Control Regions

Data-Driven verification of $\text{Iso}_1 \times \text{Iso}_2 \times \text{MET}$ factorization in QCD

- Single-e efficiency: $\epsilon_\text{e}$
- Single-\(\mu\) efficiency: $\epsilon_\mu$
- $\text{e+}\mu$ efficiency: $\epsilon_\text{e+}\mu$
- Predicted $\text{e+}\mu$ efficiency: $\epsilon_\text{e+}\mu$

$\sqrt{s} = 7 \text{ TeV}, \mathcal{L} = 4.70 \text{ fb}^{-1}$

Electron-Muon RelIso Factorization

Di-Electron Factorization

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Background Summary

CMS preliminary $L_{\text{int}}=4.7$ fb$^{-1}$, $\sqrt{s}=7$ TeV

Low-pT : HT > 200, MET > 30

High-pT : HT > 200, MET > 30

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Baseline Yields

**High pT**

**Low pT**

**Tau**

CMS Preliminary

$L_{\text{int}} = 4.7 \text{ fb}^{-1}$

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# Object Definitions

## Muons

<table>
<thead>
<tr>
<th>Observable</th>
<th>Value or Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Id</td>
<td>Tracker and Global</td>
</tr>
<tr>
<td>$p_T$</td>
<td>$&gt; 5$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>$\chi^2$/ndof</td>
<td>$&lt; 10$</td>
</tr>
<tr>
<td>$\sigma(p_T)/p_T$</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td># Valid Si Hits</td>
<td>$&gt; 10$</td>
</tr>
<tr>
<td># Valid SA Hits</td>
<td>$&gt; 0$</td>
</tr>
<tr>
<td>$</td>
<td>d_{0,PU}</td>
</tr>
<tr>
<td>Ecal/Hcal Non-MIP Veto</td>
<td>$&lt; 4/6$ GeV</td>
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<tr>
<td>RelIso</td>
<td>$&lt; 0.15$</td>
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</table>

## Electrons

<table>
<thead>
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</thead>
<tbody>
<tr>
<td>Missing pixel hits</td>
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<tr>
<td>$</td>
<td>\Delta \cot</td>
</tr>
<tr>
<td>$</td>
<td>dist</td>
</tr>
<tr>
<td>$\sigma_{inj}$ (B/E)</td>
<td>$&lt; 0.01/0.03$</td>
</tr>
<tr>
<td>$\Delta \phi_{inj}$ (B/E)</td>
<td>$&lt; 0.06/0.03$</td>
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<tr>
<td>$\Delta \eta_{inj}$ (B/E)</td>
<td>$&lt; 0.004/0.007$</td>
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<td>$H/E$ (B)</td>
<td>$&lt; 0.04$</td>
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<td>Seed</td>
<td>Ecal-Driven</td>
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<tr>
<td>$p_T$</td>
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</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>$</td>
<td>d_{0,PU}</td>
</tr>
<tr>
<td>RelIso</td>
<td>$&lt; 0.15$</td>
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<tr>
<td>$\Delta R(e,\mu)$</td>
<td>$&gt; 0.1$</td>
</tr>
<tr>
<td>$f_{brem} &gt; 0.15$</td>
<td>$\left</td>
</tr>
<tr>
<td>charge consistency among CTF, GSF and SuperCluster</td>
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## AK5 PFJets

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Id</td>
<td>Loose</td>
</tr>
<tr>
<td>$\Delta R(jet,\ell)$</td>
<td>$&gt; 0.4$</td>
</tr>
</tbody>
</table>
**T/L Control Regions** *(e/μ)*

*Notation: T/L Ratio = Probability for loose lepton to also pass tight selection*

- Measure Fake T/L ratio in a **QCD control region** (jet + away lepton)
- Prompt leptons are suppressed by inverting $M_T < 20$ GeV, MET < 20 GeV
  - Avg: $T/L(e) = 9.8\%$, $T/L(\mu) = 20.8\%$
- Measure Prompt T/L ratio in **Z-events**
- 50% systematic error from closure tests

\[ N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS} \]

**CMS Preliminary**  

- **T/L(e)**
- **T/L(μ)**

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Details on Each Approach

Notation: \( T/L \) Ratio = Probability for loose lepton to also pass tight selection

- **UCSD/USCB/FNAL [short sideband]**
  - Relax RelIso, \( d_0 \), and \( \chi^2/\text{ndof} \) (for \( \mu \))
  - T/L Ratios range from 20-40\% [\( p_T/\eta \)-dependent]

- **ETH, et. al. [med sideband]**
  - Relax RelIso for muons, RelIso & ID for electrons
  - T/L Ratios \( \sim 10\% (\mu), \sim 20\% (e) \)
  - Also employ T/L-ratios for prompt leptons: \( \sim 90\% \)

- **Florida [long sideband]**
  - Completely invert RelIso cut
  - Ratios vary between 1\%-5\% and are derived in unique control samples for single-fake (ttbar) and double-fake (QCD) backgrounds
  - Apply the BTag-And-Probe Method (ttbar) and Factorization Method (QCD)

- **Imperial, et. al [taus]**
  - Relax HPS tau discriminators (Iso, decay-mode reconstruction)
  - T/L Ratios between 1\% and 20\% [\( p_T/\eta \) dependent]

\[ N_{\text{tot}}^{\text{bgd}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS} \]
T/L Details : ETH

- Loose $\mu$ (tight in parenthesis):
  - $\text{RelIso} < 1.0$ (0.15)

- Loose $e$ (tight in parenthesis):
  - $\text{RelIso} < 0.6$ (0.15)
  - $\text{EcalRecHitSumE}_{T}/p_{T} < 0.2$, $\text{HcalTowerSumE}_{T}/p_{T} < 0.2$, $\text{TrackSumP}_{T}/p_{T} < 0.2$

- $\sigma_{\text{ieta}_{\text{ieta}}} < 0.011$ (0.01) in barrel, < 0.031 (0.03) in endcap
- $|\Delta \Phi| < 0.15$ (0.06) in barrel, < 0.10 (0.03) in endcap
- $|\Delta \eta| < 0.007$ (0.004) in barrel, < 0.009 (0.007) in endcap
- $H/E < 0.10$ (0.04) in barrel only

- No cut on $f_{\text{brem}}$, $|\eta_{\text{SC}}|$ or $E/P_{\text{in}}$, was:
  - $f_{\text{brem}} > 0.15$ OR ($|\eta_{\text{SC}}| < 0.1$ AND $E/P_{\text{in}} > 0.95$)

- Control region:
  - $M_{E_{T}} < 20$ GeV, $m_{T} < 20$ GeV ($m_{T}$ between lepton and $M_{E_{T}}$)
  - Additional lepton veto
  - At least one jet with $p_{T} > 50$ GeV
T/L Details: UCSD/UCSB/FNAL

- **Loose μ (tight in parenthesis):**
  - $\text{Chi}^2/N_{\text{Dof}}$ (global fit) < 50 (10)
  - $|d_0| < 0.2 \text{ cm} (0.02 \text{ cm})$
  - $\text{RelIso} < 0.4 (0.15)$

- **Loose e (tight in parenthesis):**
  - No $d_0$ cut (0.02 cm)
  - $\text{RelIso} < 0.6 (0.15)$

- **Control region:**
  - $\text{ME}_T < 20 \text{ GeV}$
  - $m_T < 25 \text{ GeV} (m_T$ between lepton and ME$_T$)
  - Z veto: $m_{ll}$ not in (71 - 111 GeV), only if both $p_T > 20 \text{ GeV}$
  - Opposite side jet with $p_T > 40 \text{ GeV, } \Delta R(l, \text{ jet}) > 1.0$

- Electron fake-ratios measured separately for different trigger level cuts
Fake-Fake Same-Sign Di-Leptons:

(aka “the QCD background”)

- The background from QCD events can be estimated by exploiting the fact that the 3 variables used in the final selection are uncorrelated

(i) RelIso($\ell_1^\pm$) < 0.15

(ii) RelIso($\ell_2^\pm$) < 0.15

(iii) $E_T^{\text{miss}}$ < 50 GeV (120 GeV)

- Qualitatively, for QCD events we expect
  - The two fake leptons to come from different jets
    - RelIso calculations should involve different tracks and calorimeter deposits
  - The missing energy (if any) should come from jet mis-measurement and not from neutrino activity

- The 3 selection efficiencies should factorize:

$$\varepsilon_{\text{total}}(\ell_1, \ell_2, E_T^{\text{miss}}) = \varepsilon(\ell_1) \cdot \varepsilon(\ell_2) \cdot \varepsilon(E_T^{\text{miss}})$$

- This background estimation method is aptly named: “The Factorization Method”
• Deriving the Prediction via Tag-And-Probe
  – Select a \textbf{bb control} sample using a high-purity \textit{b}-jet tagging algorithm
    • Tag = \textit{b}-tagged jet
    • Probe = lepton on opposite side of the event
  – Parameterize the isolation of probe-leptons as a function of lepton-$p_T$ and jet multiplicity ($N_{jets}$)
  – Use simulated top-quark events to re-weight the templates
    • Simulation should model $p_T$ and $N_{jets}$
  – Obtain the probability for fake leptons in top events to survive the isolation cut using these re-weighted templates
  – Multiply probability by the number of events in the \textit{sideband region}

\[
N_{\text{bgd}}^{\text{tot}} = N_{p-p}^{SS} + N_{p-p}^{OS} + N_{f-f}^{SS} + N_{p-f}^{SS}
\]

\textit{sideband region} : all final selection requirements imposed except for RelIso on the least isolated lepton
Interpretation of Results

- Signal acceptance and uncertainties are model dependent
- Based on LM6 uncertainties range from 14%-20%

<table>
<thead>
<tr>
<th></th>
<th>HT80 MET120</th>
<th>HT200 MET120</th>
<th>HT450 MET50</th>
<th>HT450 MET120</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-p_{T}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pred.</td>
<td>33.2</td>
<td>22.1</td>
<td>12.5</td>
<td>4.6</td>
</tr>
<tr>
<td>ΔPred</td>
<td>12.0</td>
<td>9.8</td>
<td>4.7</td>
<td>2.0</td>
</tr>
<tr>
<td>Obs.</td>
<td>24</td>
<td>21</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>N_{Sig} &lt;</td>
<td>14.0</td>
<td>16.3</td>
<td>9.9</td>
<td>6.1</td>
</tr>
<tr>
<td>Low-p_{T}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pred.</td>
<td></td>
<td></td>
<td>34.3</td>
<td>18.2</td>
</tr>
<tr>
<td>ΔPred</td>
<td></td>
<td></td>
<td>13.2</td>
<td>6.9</td>
</tr>
<tr>
<td>Obs.</td>
<td></td>
<td></td>
<td>28</td>
<td>18</td>
</tr>
<tr>
<td>N_{Sig} &lt;</td>
<td></td>
<td></td>
<td>17.4</td>
<td>14.3</td>
</tr>
<tr>
<td>Tau</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pred.</td>
<td></td>
<td></td>
<td></td>
<td>7.1</td>
</tr>
<tr>
<td>ΔPred</td>
<td></td>
<td></td>
<td></td>
<td>2.8</td>
</tr>
<tr>
<td>Obs.</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>N_{Sig} &lt;</td>
<td></td>
<td></td>
<td></td>
<td>7.1</td>
</tr>
</tbody>
</table>

For the reported limits we assume a flat 20% uncertainty on signal acceptance.

<table>
<thead>
<tr>
<th></th>
<th>Systematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>e/μ selection (trigger, id, iso)</td>
<td>6-10%</td>
</tr>
<tr>
<td>Tau selection (trigger, id, iso)</td>
<td>10%</td>
</tr>
<tr>
<td>Isolation dependence on H_{T}</td>
<td>10%</td>
</tr>
<tr>
<td>Jet energy scale (7.5%)</td>
<td>3-30%</td>
</tr>
<tr>
<td>PDF (Acceptance)</td>
<td>2%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>4.5%</td>
</tr>
</tbody>
</table>
CMSSM Template Validation


If no convergence appears, then SOFTSUSY is indicating that it didn’t achieve the accuracy of TOLERANCE within less than 40 iterations. The output of the code is therefore to be considered unreliable and it is not clear from the output whether the point is allowed or disallowed, despite the presence or absence of other warning messages. This error flag often appears near the boundary of electroweak symmetry breaking, (where \( \mu(M_{SUSY}) = 0 \)), where the iterative algorithm is not stable. To calculate the position of the electroweak symmetry boundary, one should interpolate between regions a small distance away from it.
Simplified Model Interpretation

\[ pp \rightarrow \tilde{g}\tilde{g} \rightarrow qqqq\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow qqqq\ell^+\ell^- \nu\tilde{\chi}_1^0\tilde{\chi}_1^0 \]

Model: T1lnu

\[ M(\tilde{\chi}_1^+) = \frac{M(\tilde{g}) + M(\tilde{\chi}_1^0)}{2} \]

- Update version for 4.7 fb-1 in progress
Simplified Model Interpretation

\[ pp \rightarrow \tilde{g}\tilde{g} \rightarrow q\bar{q}q\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow q\bar{q}q\tau^+\tau^- \nu\bar{\nu}\tilde{\chi}_1^0\tilde{\chi}_1^0 \]

Model: T1-TauNu

Selection Efficiency: $e^{-}\tau$ channel

Selection Efficiency: $\mu^{-}\tau$ channel

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Simplified Model Interpretation

- Updated version for 4.7 fb-1 in progress

**Model: T1tttt**
The Large Hadron Collider

A proton-proton collider

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design</th>
<th>Achieved in 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$</td>
<td>14 TeV</td>
<td>7 TeV</td>
</tr>
<tr>
<td>Luminosity (L)</td>
<td>$10^{34}$ cm$^{-2}$ s$^{-1}$</td>
<td>$3.5 \times 10^{33}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Bunches per beam</td>
<td>2808</td>
<td>1380</td>
</tr>
</tbody>
</table>

The design $\sqrt{s}$ is 7x higher than the Tevatron collider, while the design L is ~70x greater. The LHC is performing wonderfully but has still yet to reach its full potential.
Importance of High Luminosity

- All particles in the SM are able to be produced, but their production is not equiprobable. 
  - determined by their cross-sections ($\sigma$)

- Small cross-sections correspond to rare processes:
  - Heavy particles (e.g., top quark, SUSY)
  - Particles blind to the strong force (Z/W/higgs)

- In order to produce these particles you need a machine that can "roll the dice" very rapidly 
  - This means "high-luminosity"

- The LHC rolls the dice (by design) at a rate of 40 million hz.
Integrated Luminosity

- The total amount of data produced by a collider is measured by the time-integrated luminosity:

\[ \int L \cdot dt \]

- The total expected events produced for process \( X \) in the data:

\[ N^{\text{events}} = \sigma(pp \rightarrow X) \cdot \int L \cdot dt = \text{probability} \times \text{trials} \]

- In 2011 the CMS Detector recorded 5.2 fb\(^{-1}\) of good data

<table>
<thead>
<tr>
<th>Process</th>
<th>( \sigma ) (pb)</th>
<th>( &lt;N\text{events}&gt; )</th>
</tr>
</thead>
<tbody>
<tr>
<td>light quarks</td>
<td>( &gt; 8e+10 )</td>
<td>( &gt; 4.2e+16 )</td>
</tr>
<tr>
<td>bottom quarks</td>
<td>( &gt; 8e+9 )</td>
<td>( &gt; 4.2e+13 )</td>
</tr>
<tr>
<td>top quarks</td>
<td>157.5</td>
<td>820,000</td>
</tr>
<tr>
<td>W</td>
<td>( \approx 9.2e+4 )</td>
<td>( \approx 4.8e+8 )</td>
</tr>
<tr>
<td>Z</td>
<td>( \approx 2.7e+4 )</td>
<td>( \approx 1.4e+8 )</td>
</tr>
<tr>
<td>ZZ</td>
<td>( \approx 4.3 )</td>
<td>22,000</td>
</tr>
<tr>
<td>Higgs (m~120)</td>
<td>( \approx 5-20 )</td>
<td>26,000-100,000</td>
</tr>
<tr>
<td>SUSY</td>
<td>Model dependent</td>
<td>Discussed Later!</td>
</tr>
</tbody>
</table>
The Compact Muon Solenoid (CMS)

A general purpose particle detector capable of directly detecting all species of stable particles known to exist, except for the weakly interacting neutrino.

- 14,000 tons
- 15 meters in diameter
- 21 meters long
- 3.8 Tesla B-Field
- 100 meters underground
- 3,600 collaborators
- 180 institutions
- 38 countries

Most common particles that live long enough to directly interact with the CMS detector: $\mu^\pm$, $e^\pm$, $\gamma$, $n$, $p^\pm$, $\pi^\pm$, $K^\pm$, $K^0$

R. Remington, Univ. of Florida