SEARCHES FOR SUPERSYMMETRY USING RAZOR VARIABLES AT CMS

SUSY 2016
The University of Melbourne
Melbourne, Australia

JULY 5, 2016

Javier Duarte
Caltech
OUTLINE

• Motivation: expanded natural SUSY
• Why razor variables?
• Searches
  • Inclusive search for squarks and gluinos
  • Exclusive search for anomalous $H \rightarrow \gamma \gamma$ production
• New topological triggers
• Outlook
NATURAL SUSY

- Lightest Higgs boson mass is connected with:
  - Higgsino masses (tree level)
  - stop/sbottom masses (1 loop)
  - gluino mass (2 loop)

- Naturalness = all contributions are of the same order as the physical Higgs mass (no fine-tuning)

- “Acceptable” fine-tuning implies:
  - Higgsinos lighter than \( \sim 300 \) GeV
  - Stops lighter than \( \sim 700 \) GeV
  - Gluinos lighter than \( \sim 1.5 \) TeV

- Possible spectrum:

SUSY SIMPLIFIED MODELS

- One heavy particle (gluino), one invisible particle (neutralino), one possible decay channel (bb)

\[ 100\% = \text{BR}(\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0) \]
NATURAL SUSY SIMPLIFIED MODELS

- Extended "natural" spectrum: allow multiple decay channels to see how it impacts our sensitivity
- Possible gluino decay topologies (depending on branching ratios \(x, y, z\))

\[ x = \text{BR}(\tilde{g} \to b\bar{b}\tilde{\chi}_1^0) \]
\[ y = \text{BR}(\tilde{g} \to t\bar{t}\tilde{\chi}_1^0) \]
\[ z = \text{BR}(\tilde{g} \to t\bar{b}\tilde{\chi}_1^\pm) \]
**INCLUSIVE RAZOR**

- Treat all events as “dijets + MET” by clustering particles into two pseudo-jets, called megajets.

\[ M_R = \sqrt{(|\vec{p}_{j1}| + |\vec{p}_{j2}|)^2 - (p_{z1}^j + p_{z2}^j)^2} \]

\[ R \equiv \frac{M_T^R}{M_R} \quad M_T^R \equiv \sqrt{\frac{E_{\text{miss}}(p_T^j + p_T^{j2}) - E_{\text{miss}}(p_T^{j1} + p_T^{j2})}{2}} \]

- Gluino signal events well-separated from SM background events.

\[ M_R \text{ peaks at char. mass scale } M_{\Delta} = \frac{m_{\tilde{g}}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{g}}} \]

Javier Duarte
Caltech
WHY RAZOR FOR NATURAL SUSY?

- Behavior of razor variables largely invariant under different gluino decay modes
- Slight dependence on the presence of top quarks: More tops $\rightarrow$ lower $M_R$ response, larger $M_R$ resolution

\[ M_\Delta = \frac{m_\tilde{g}^2 - m_{\tilde{\chi}_1^0}^2}{m_\tilde{g}} \]

neglecting mass of $bb$, $tt$, $tbW^*$ systems,
INCLUSIVE RAZOR SEARCHES @ CMS

Javier Duarte
Caltech
DATA-DRIVEN BACKGROUND PREDICTION

\[ f_{\text{Razor}}(x, y) \propto (b[(x-x_0)(y-y_0)]^{1/n} - 1) \exp\{-bn[(x-x_0)(y-y_0)]^{1/n}\} \]

- Fit the 2D distribution of data with an empirical function in a background-enriched sideband, and extrapolate to the signal-sensitive region

- Extensive validation of functional form performed on 2010-2015 data and MC

\[ \log f_j(M_R, R^2) \]
FIT SYSTEMATIC UNCERTAINTIES

- Size of background systematic uncertainty in signal-sensitive region varies between ~40%-100%
- Example from 8 TeV fit shows how variation of shape parameters affects background prediction
TARGET AND STRATEGY

• Same basic strategy as in Run 1 with short-term target of gluino-mediated signal models

• Select and categorize events based on jets and leptons

• Perform maximum likelihood fit in a sideband of $R^2$ and $M_R$ and quantify agreement between SM backgrounds and data

• All-hadronic channel (MultiJet) uses custom razor trigger
2D FIT PROJECTION

- Alternate representation of the data, fit prediction, and their agreement provides greater density of information

- **Green** illustrates sideband bins

SUS-15-004

Javier Duarte
Caltech
SELECTED RESULTS IN DATA

- No significant deviation observed in any data category
- Scattered $\sim 2\sigma$ “local” deviations consistent with fluctuations

**P-VALUE= 34%**

**P-VALUE= 85%**
• Simulated signal injection for $m_{\tilde{g}} = 1400$ GeV, $m_{\tilde{\chi}_1^0} = 100$ GeV illustrates how an excess consistent with SUSY would appear.
• For a massless LSP, gluino is excluded below 1650 GeV with 2.1 fb$^{-1}$ at 13 TeV in four-bottom-quark final state
RUN 2 LIMITS

- For a massless LSP, gluino is excluded below 1650 GeV with 2.1 fb$^{-1}$ at 13 TeV in four-bottom-quark final state.

- Compare with Run 1 limit 1400 GeV with 19.3 fb$^{-1}$ at 8 TeV.
BRANCHING RATIOS

- Scan the triangular branching ratio phase space in \((x,y)\)

\[
x = \text{BR}(\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0)
\]
\[
y = \text{BR}(\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0)
\]
\[
z = \text{BR}(\tilde{g} \rightarrow t\bar{b}\tilde{\chi}_1^{\pm})
\]

\[
x = \text{BR}(\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0)
\]
\[
y = \text{BR}(\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0)
\]
\[
z = \text{BR}(\tilde{g} \rightarrow t\bar{b}\tilde{\chi}_1^{\pm})
\]
• For generic branching ratio, gluino is excluded below ~1600 GeV

• First branching-ratio independent gluino limit from LHC!
SEARCHES @ CMS
RAZOR H $\rightarrow \gamma\gamma$

Javier Duarte
Caltech
RAZOR \( H \to \gamma \gamma \) SEARCH

- Search for electroweak SUSY production (Higgsinos, Winos, Binos)
- Selection:
  - Tag events using \( H \to \gamma \gamma \)
  - Categorize using Higgs \( p_T \) and photon resolution
- Discriminating variables \( M_R \) and \( R^2 \)
- Background prediction in \( R^2 - M_R \) plane by interpolating from \( m_{\gamma \gamma} \) sidebands
- Look bin-by-bin in \( R^2 - M_R \) plane for an excess

\[ \gamma \gamma \in [103, 118] \cup [133, 164] \]
2.9σ local excess is 1.6σ after look-elsewhere effect

excess not consistent with standard EWK SUSY models
RAZOR TRIGGERS

- 4 triggers designed for different aspects of SUSY/DM/Higgs phase space

- Dijet trigger (squark pair production)
- Quadjet trigger (gluino pair production)
- $R^2$ trigger (DM direct production / large transverse imbalance)
- $H \rightarrow bb$ trigger (Higgs-aware SUSY à la $H \rightarrow \gamma \gamma$ 8 TeV excess)

Hardware-based triggers on hadronic activity

- Tracker-only b-tagging
  - 2 b-tags
  - PF $R^2 > 0.02$, $M_R > 300$

Calo jets

- 3 Calo jets, $p_T > (70,50,30)$

Calo MET

- 3 PF jets, $p_T > (80,60,40)$
- Particle Flow MET

Particle Flow jets

- 2 PF b-tags
- $60 < m_{bb} < 200$, $p_T^b > (50,30)$

Particle Flow b-tagging

- Calo $M_R > 200$

Calo MET

- Calo $M_R > 200$

~10 kHz

10 kHz

10 Hz
SUMMARY AND OUTLOOK

• The CMS SUSY search program at 13 TeV has produced stringent limits on many natural SUSY scenarios
  • gluinos excluded below ~1600 GeV for generic BR
  • Interesting excess seen in razor $H \rightarrow \gamma \gamma$ analysis, so we developed a trigger to search in the $H \rightarrow b \bar{b}$ channel
  • Forthcoming razor $H \rightarrow \gamma \gamma$ analysis of 2015+2016 13 TeV data as well as inclusive razor analysis of 2016 13 TeV data: stay tuned!
GLUINO PAIR PRODUCTION

- Gluino pair production cross section at the 13 TeV LHC is **10x-50x** greater than 8 TeV in the accessible phase space.
Stop pair production cross section at the 13 TeV LHC is \textbf{5x-15x} greater than 8 TeV in the accessible phase space.
Without SUSY, the Higgs mass would “naturally” be enormous, unless certain parameters are delicately fine-tuned to 1 part in 10,000,000,000,000,000,000.

With SUSY, the Higgs mass matches what we see without excessive fine tuning.

\[
\Delta m_H^2 = \frac{|\lambda_f|^2}{8\pi^2} \Lambda_{UV}^2 + \cdots
\]

\[
\Delta m_H^2 = \frac{\lambda_S}{16\pi^2} \Lambda_{UV}^2 + \cdots
\]
<table>
<thead>
<tr>
<th>$M_R$ region</th>
<th>$R^2$ region</th>
<th>observed events</th>
<th>expected background</th>
<th>$p$-value</th>
<th>significance ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 - 250</td>
<td>0.00 - 0.05</td>
<td>363</td>
<td>$357.6^{+9.6}_{-9.4}$ (syst.)</td>
<td>0.40</td>
<td>0.3</td>
</tr>
<tr>
<td>150 - 250</td>
<td>0.05 - 0.10</td>
<td>149</td>
<td>$139.4^{+5.6}_{-5.4}$ (syst.)</td>
<td>0.23</td>
<td>0.7</td>
</tr>
<tr>
<td>150 - 250</td>
<td>0.10 - 0.15</td>
<td>35</td>
<td>$32.5^{+3.4}_{-3.1}$ (syst.)</td>
<td>0.34</td>
<td>0.4</td>
</tr>
<tr>
<td>150 - 250</td>
<td>0.15 - 1.00</td>
<td>7</td>
<td>$8.0^{+1.7}_{-1.4}$ (syst.)</td>
<td>0.40</td>
<td>-0.3</td>
</tr>
<tr>
<td>250 - 400</td>
<td>0.00 - 0.05</td>
<td>218</td>
<td>$207.9^{+7.0}_{-6.8}$ (syst.)</td>
<td>0.27</td>
<td>0.6</td>
</tr>
<tr>
<td>250 - 400</td>
<td>0.05 - 0.10</td>
<td>20</td>
<td>$14.7^{+2.5}_{-2.1}$ (syst.)</td>
<td>0.13</td>
<td>1.1</td>
</tr>
<tr>
<td>250 - 400</td>
<td>0.10 - 1.00</td>
<td>3</td>
<td>$2.7^{+0.8}_{-0.6}$ (syst.)</td>
<td>0.43</td>
<td>0.2</td>
</tr>
<tr>
<td>400 - 1400</td>
<td>0.00 - 0.05</td>
<td>109</td>
<td>$101.6^{+5.0}_{-4.8}$ (syst.)</td>
<td>0.26</td>
<td>0.7</td>
</tr>
<tr>
<td>400 - 1400</td>
<td>0.05 - 1.00</td>
<td>5</td>
<td>$0.5^{+0.4}_{-0.2}$ (syst.)</td>
<td>0.002</td>
<td>2.9</td>
</tr>
<tr>
<td>1400 - 3000</td>
<td>0.00 - 1.00</td>
<td>0</td>
<td>$0.9^{+0.5}_{-0.3}$ (syst.)</td>
<td>0.44</td>
<td>-0.1</td>
</tr>
</tbody>
</table>

### 2.9σ local excess

is 1.6σ after

**look elsewhere effect**
**RUN 2 SIGNAL SYSTEMATICS**

- Updated Run 2 signal systematic uncertainties

<table>
<thead>
<tr>
<th>SYSTEMATIC UNCERTAINTIES</th>
<th>Uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEPTON SELECTION EFFICIENCY</td>
<td>2%</td>
</tr>
<tr>
<td>LEPTON TRIGGER EFFICIENCY</td>
<td>3%</td>
</tr>
<tr>
<td>LUMINOSITY</td>
<td>4.6%</td>
</tr>
<tr>
<td>JET ENERGY SCALE</td>
<td>15-30%, VARIES WITH ENERGY &amp; ETA</td>
</tr>
<tr>
<td>B-TAGGING EFFICIENCY</td>
<td>5-15%</td>
</tr>
<tr>
<td>FASTSIM LEPTON EFFICIENCY</td>
<td>0-10%, VARIES WITH ENERGY &amp; ETA</td>
</tr>
<tr>
<td>FASTSIM B-TAGGING EFFICIENCY</td>
<td>0-10%</td>
</tr>
<tr>
<td>ISR</td>
<td>UP TO 30%</td>
</tr>
<tr>
<td>PARTON DENSITY FUNCTIONS</td>
<td>10%</td>
</tr>
<tr>
<td>REN. AND FAC. SCALES</td>
<td>3-5%</td>
</tr>
<tr>
<td>PILEUP REWEIGHTING</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>MC STATISTICS</td>
<td>POISSON</td>
</tr>
</tbody>
</table>
BASELINE SELECTION

- For all boxes, we select events that have at least four jets with $p_T > 40$ GeV and $|\eta|<3$

- In the MultiJet box, we also require at least two jets with $p_T > 80$ GeV and $|\eta|<3$

- Within each box, we categorize events which have 0, 1, 2, $\geq 3$ b-tags

<table>
<thead>
<tr>
<th>Event category</th>
<th>B-Tag bins</th>
<th>Selection cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron + Multijet</td>
<td>0 b-tag, 1 b-tag, 2 b-tag, 3 or more b-tags</td>
<td>single electron triggered events, one tight electron, $p_T(e) &gt; 25$ GeV, $M_T &gt; 120$ GeV, $\geq 4$ jets with $p_T &gt; 40$ GeV, $M_R &gt; 400$ GeV, $R^2 &gt; 0.15$</td>
</tr>
<tr>
<td>Muon + Multijet</td>
<td>0 b-tag, 1 b-tag, 2 b-tag, 3 or more b-tags</td>
<td>single muon triggered events, one tight muon, $p_T(\mu) &gt; 20$ GeV, $M_T &gt; 120$ GeV, $\geq 4$ jets with $p_T &gt; 40$ GeV, $M_R &gt; 400$ GeV, $R^2 &gt; 0.15$</td>
</tr>
<tr>
<td>Multijet</td>
<td>0 b-tag, 1 b-tag, 2 b-tag, 3 or more b-tags</td>
<td>hadronic razor triggered events, $\Delta\phi &lt; 2.8$, no veto electrons or muons, $\geq 4$ jets with $p_T &gt; 40$ GeV, $\geq 2$ jets with $p_T &gt; 80$ GeV, $M_R &gt; 500$ GeV, $R^2 &gt; 0.25$</td>
</tr>
</tbody>
</table>
RAZOR VARIABLES (SCALING)

• Empirically we found that, for each background, the tail of the MR distribution is well-modeled by a falling exponential for different R cuts

• The exponents follow a linear relation with respect to the cut position, allowing for an analytic description of the tail
Function satisfying (1) and (2) is:

\[ f_{th}(x, y) = (b(x - x_0)(y - y_0) - 1)e^{-b(x-x_0)(y-y_0)} \]

- As you increase the cut on R2, the exponential slope on MR becomes steeper
- Exp. slope increases linearly with the R2 cut
- Same thing for MR ↔ R2

\[
\begin{align*}
(1) & \quad \int_{y_{min}}^{\infty} dy f(x, y) \propto e^{-kx}, \quad k = by_{min} + c \\
(2) & \quad \int_{x_{min}}^{\infty} dx f(x, y) \propto e^{-ky}, \quad k = bx_{min} + c
\end{align*}
\]
SENSITIVITY WITH B-TAGGING

- For 8 TeV, majority of background is tt+jets, which populates 1b-tag and 2b-tag
- b-tagging based on “combined secondary vertex” algorithm
- The large mass, relatively long lifetimes and hard daughters of bottom hadrons can be used to identify the hadronic jets into which the b quarks fragment
- Discriminator uses secondary vertex and the kinematic variables associated with this vertex, such as flight distance and direction
- b-tagging has dependence on pT, so we expect the MR shape to have some dependence on the b-tag bin (so we allow the ≥2b-tag shape to differ from the 1b-tag shape)
After tight single lepton selection, optimize different multivariate boosted decision trees (BDTs) for different regions of phase space based on signal-sensitive observables.
1 LEPTON DETAILS

- Define a multivariate boosted decision tree (BDT) based on several signal sensitive observables, e.g. $E_T^{\text{miss}}, M_{T2}^W$

- $M_{T2}^W =$ minimum mother particle mass consistent with observed and assumed kinematic constraints

\[ M_{T2}^W = \min\left\{ m_y \text{ consistent with: } \left[ \vec{p}_1^T + \vec{p}_2^T = E_T^{\text{miss}}, p_1^2 = 0, (p_1 + p_\ell)^2 = p_2^2 = M_W^2, (p_1 + p_\ell + p_{b1})^2 = (p_2 + p_{b2})^2 = m_y^2 \right] \right\} \]

![Data/MC comparison](image1.png)

![Entries / 25 GeV](image2.png)
**LHC CL$_S$ LIMIT SETTING**

\[ \mathcal{L}(\text{data}|\sigma, \hat{\theta}_\sigma) \pi(\hat{\theta}_\sigma) \geq \mathcal{L}(\text{data}|\sigma, \theta) \pi(\theta) \quad \forall \theta, \text{ fixed } \sigma \]

\[ \mathcal{L}(\text{data}|\hat{\sigma}, \hat{\theta}) \pi(\hat{\theta}) \geq \mathcal{L}(\text{data}|\sigma, \theta) \pi(\theta) \quad \forall \theta, \sigma \]

\[ \tilde{q}_\sigma = -2 \log \left( \frac{\mathcal{L}(\text{data}|\sigma, \theta_{\sigma})}{\mathcal{L}(\text{data}|\hat{\sigma}, \hat{\theta})} \right), \quad 0 \leq \hat{\sigma} \leq \sigma \]

\[ \text{CL}_{s+b}(\sigma) = \int_{\tilde{q}_{\sigma}^{\text{obs}}}^{\infty} d\tilde{q}_\sigma \ f(\tilde{q}_\sigma|\sigma, \hat{\theta}_{\sigma}^{\text{obs}}) \]

\[ \text{CL}_b = \int_{\tilde{q}_{\sigma}^{\text{obs}}}^{\infty} d\tilde{q}_\sigma \ f(\tilde{q}_\sigma|\sigma, \hat{\theta}_{0}^{\text{obs}}) \]

- b-only (s+b) full fit on data => best fit for b-only (s+b) nuisance parameters
- All nuisances fixed to ML estimators at toy generation
- Profile Likelihood ratio (s+b vs. best-fit s+b) test statistic re-fit in the full region

Javier Duarte
Caltech
• Protons collide, producing two squarks, which then decay to two quarks and two invisible particles.
WHAT WE SEE

• We can’t directly observe the invisible particles, but we observe **missing transverse momentum**

How can discriminate signal from background?  How can we estimate the hidden masses of the super particles?

$\Phi$
RAZOR VARIABLES

Transform to a more symmetric frame where the visible momenta are equal:

\[ |\vec{p}_{q1}| = |\vec{p}_{q2}| \]

In this frame, we compute the razor variables, functions of the visible and missing momenta:

\[ M_R \equiv 2|\vec{p}_{q1}| \]
\[ R \equiv \frac{M_T^R}{M_R} \]

\[ M_T^R \equiv \sqrt{E_T^{\text{miss}}(p_T^{q1} + p_T^{q2}) - E_T^{\text{miss}}(\vec{p}_{T}^{q1} + \vec{p}_{T}^{q2})} \]

So in order to make predictions, we always need some input from experiment.
**SLHA FOR NATURAL SUSY**

- **SLHA file can be found at:**


- **Chargino decay branching fractions are:**

<table>
<thead>
<tr>
<th>#</th>
<th>BR</th>
<th>NDA</th>
<th>ID1</th>
<th>ID2</th>
<th>ID3</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.51024479E-01</td>
<td>3</td>
<td>1000022</td>
<td>2</td>
<td>-1</td>
<td>BR(~chi_1+ -&gt; ~chi_10 u   db)</td>
</tr>
<tr>
<td>3.51024479E-01</td>
<td>3</td>
<td>1000022</td>
<td>4</td>
<td>-3</td>
<td>BR(~chi_1+ -&gt; ~chi_10 c   sb)</td>
</tr>
<tr>
<td>1.17008160E-01</td>
<td>3</td>
<td>1000022</td>
<td>-11</td>
<td>12</td>
<td>BR(~chi_1+ -&gt; ~chi_10 e+  nu_e)</td>
</tr>
<tr>
<td>1.17008160E-01</td>
<td>3</td>
<td>1000022</td>
<td>-13</td>
<td>14</td>
<td>BR(~chi_1+ -&gt; ~chi_10 mu+ nu_mu)</td>
</tr>
<tr>
<td>6.39347234E-02</td>
<td>3</td>
<td>1000022</td>
<td>-15</td>
<td>16</td>
<td>BR(~chi_1+ -&gt; ~chi_10 tau+ nu_tau)</td>
</tr>
</tbody>
</table>