Phenomenological MSSM interpretation of CMS results

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Road map

- Definition of the pMSSM
- CMS analyses considered
- Posterior density
- Interpretation of CMS 7 and 8 TeV results
- pMSSM points that evaded run 1 analyses
pMSSM

Non-prejudiced submodel of the MSSM that captures most of the phenomenological features of the MSSM

19 Parameters:
- Gaugino mass parameters $M_1$, $M_2$, and $M_3$
- Higgs sector parameters $\tan(\beta)$, $\mu$, and $m_A$
- 10 sfermion mass parameters $m_i$
- Trilinear couplings $A_t$, $A_b$, and $A_\tau$

MCMC scan (20 million points) Simulated events for 7200 points
Probability density

Bayes’ theorem

\[ p(\theta|\text{Data}^{CMS}) \propto L(\text{Data}^{CMS}|\theta)\Pi(\theta) \]
Bayes’ theorem

\[
p(\theta|\text{Data}^{CMS}) \propto L(\text{Data}^{CMS}|\theta) \Pi(\theta)
\]

pre-CMS results

\[
\mathcal{B}(b \to s\gamma), \alpha_s, B_s \to \mu\mu, m_t, \mu_h
\]

[2][3][4][5][6][7][8][9][10][11][12]
Probability density

Bayes' theorem

\[ p(\theta|Data^{CMS}) \propto L(Data^{CMS}|\theta) \Pi(\theta) \]

pre-CMS results

\[ \mathcal{B}(b \rightarrow s\gamma) \quad \alpha_s \quad B_s \rightarrow \mu\mu \]

\[ m_t \quad \mu_h \]

CMS searches

\[ 13,14,15,16,17,18,19,20,21,22,23 \]

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Why this procedure?

Two reasons for Bayesian approach:

1. Result can be interpreted as a probability density for hypotheses of mass patterns

2. We sample interesting regions of the pMSSM subspace with a higher density
Gluino mass

Probability density

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Squark Mass

Probability density

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Lightest colored particle

Probability density

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LSP mass

Probability density

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Processes

CMS

\(|\bar{q}q(q \to qq)| 1
\)

\(|\tilde{\chi}^\pm \tilde{\chi}^0 (\tilde{\chi} \to W^{\pm})| 2
\)

\(|\tilde{\chi}^\pm \chi^- (\tilde{\chi} \to V/h)| 3
\)

\(|\tilde{b}\tilde{b}(\tilde{b} \to b)| 4
\)

\(|\tilde{g}\tilde{g}(g \to qq)| 5
\)

\(|\tilde{g}\tilde{g}(g \to \tilde{q}q)|* 6
\)

\(|\tilde{q}\tilde{q}(\tilde{q} \to \tilde{\chi}^\pm)|* 7
\)

\(|\tilde{g}\tilde{g}(g \to \tilde{b}\tilde{b})| 8
\)

\(|\tilde{q}\tilde{q}(\tilde{q} \to q\tilde{\chi}^0)|* 9
\)

\(|\tilde{\chi}^0 \tilde{\chi}^0| 10
\)

\(|\tilde{t}\tilde{t}(\tilde{t} \to t)| 11
\)

\(|\tilde{\tau}\tilde{\nu}(\tilde{\tau} \to l)| 12
\)

| other |}

fraction of points

\(10^{-3}\)  \(10^{-2}\)  \(10^{-1}\)

\(4.5\text{ fb}^{-1} (7 \text{ TeV}) + 19.7\text{ fb}^{-1} (8 \text{ TeV})\)
Processes

CMS

\begin{align*}
\tilde{q}\tilde{q}(\tilde{q} \rightarrow qq) & \quad 1 \\
\tilde{\chi}^\pm \tilde{\chi}^0 (\tilde{\chi}^\pm \rightarrow W^{\pm}) & \quad 2 \\
\tilde{\chi}^\pm \tilde{\chi}_2 (\tilde{\chi} \rightarrow V/h) & \quad 3 \\
\tilde{b}\tilde{b} (\tilde{b} \rightarrow b) & \quad 4 \\
\tilde{g}\tilde{g} (\tilde{g} \rightarrow q\bar{q}) & \quad 5 \\
\tilde{q}\tilde{q} (\tilde{q} \rightarrow \tilde{\chi}^0) & \quad 6 \\
\tilde{g}\tilde{g} (\tilde{g} \rightarrow b\bar{b}) & \quad 7 \\
\tilde{q}\tilde{q} (\tilde{q} \rightarrow \tilde{\chi}_2) & \quad 8 \\
\tilde{q}\tilde{q} (\tilde{q} \rightarrow \tilde{\chi}_1) & \quad 9 \\
\tilde{g}\tilde{g} (\tilde{g} \rightarrow \tilde{\chi}_0) & \quad 10 \\
\tilde{\chi}_0 \rightarrow q\bar{q} & \quad 11 \\
\tilde{\chi}_0 \rightarrow g\bar{g} & \quad 12 \\
\tilde{\chi}_1 \rightarrow \tilde{\chi}_0 & \quad 13
\end{align*}

CMS (8 TeV)\(-1\)

CMS (7 TeV)\(+19.7\) fb\(^{-1}\)

4.5 fb\(^{-1}\) (7 TeV) \(+ 19.7\) fb\(^{-1}\) (8 TeV)

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pMSSM interpretation of CMS searches
Process with the highest significance

\[ \Delta m(\tilde{\chi}_1^0, \tilde{\chi}_1'^{\pm}) \sim 3 \text{ GeV} \]
\[ m_{\tilde{\chi}_1^0} \sim 200 \text{ GeV} \]

8 TeV signed significance: +3.6
Gluino vs LSP mass

Probability density

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Gluino vs LSP mass

Survival probability

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Gluino vs LSP mass

CMS probed heavy gluinos
Gluino vs LSP mass

CMS probed heavy gluinos

Combined, 7 TeV
Combined, 7 + 8 TeV
Combined, 7 + 8 TeV, Higgs data

Survival probability
Gluino vs LSP mass

Can we characterize this region?

Survival probability
2nd lightest surviving gluino

Scenario 1

\[
m_{\tilde{g}} = 644 \text{ GeV} \\
m_{\tilde{\chi}^\pm_2} = 400.8 \text{ GeV} \\
m_{\tilde{\chi}^0_1} = 400.4 \text{ GeV}
\]

8 TeV signed significance: +1.8
Lightest surviving gluino

Scenario 2

8 TeV signed significance: +2.3

\[ m_{\tilde{g}} = 581 \text{ GeV} \]
\[ m_{\tilde{\chi}_2^0} = 533 \text{ GeV} \]
\[ m_{\tilde{\chi}_1^0} = 528 \text{ GeV} \]
Observables

Scenario 1

Scenario 2

$H_T$

$E_{\text{miss}}$

Typical threshold

$\sqrt{s} = 13$ TeV, $L = 2.3$ fb$^{-1}$
Summary

• Much knowledge has been gained about the possible masses of gluinos, light-flavor squarks

• Gluinos as light as 600 GeV survived Run 1 due to compressed spectra, intermediate sparticle decays

• Second-most prevalent diagram predicts events that fail typical supersymmetry triggers

• Low-HT, monojet+X event signatures describe many surviving scenarios

References


[6] Tevatron Electroweak Working Group, CDF and D0 Collaborations. Combination of CDF and D0 results on the mass of the top quark using up to 8.7 fb\(^{-1}\) at the Tevatron. 2013.


References


[16] Serguei Chatrchyan et al. Search for new physics in the multijet and missing transverse momentum final state in proton-proton collisions at $\sqrt{s} = 8$ TeV. *JHEP*, 06:055, 2014.


References


Backup (assumptions)

A realization of the R-parity conserving MSSM with

* no new sources of CP violation
* no flavor changing neutral currents
* 1st and 2nd generation squarks are degenerate
* lightest supersymmetric particle is the neutralino
### pMSSM interpretation of CMS searches

| $i$ | Observable | Constraint $D_j^{\text{preCMS}}$ | Likelihood function $L(D_j^{\text{preCMS}} | \mu_j(\theta))$ |
|-----|------------|-----------------------------------|----------------------------------------------------------|
| 1   | $BR(b \rightarrow s\gamma)$ [28, 29] | $(3.55 \pm 0.23^{\text{stat}} \pm 0.24^{\text{th}} \pm 0.09^{\text{sys}}) \times 10^{-4}$ | Gaussian |
| 2a  | $BR(B_s \rightarrow \mu\mu)$ [30] | observed CLs curve from [30] | $d(1 - \text{CLs})/dx$ 2-sided Gaussian |
| 2b  | $BR(B_s \rightarrow \mu\mu)$ [31] | $3.2_{-1.2}^{+1.5} \times 10^{-9}$ | Gaussian |
| 3   | $R(B_u \rightarrow \tau\nu)$ [32] | $1.63 \pm 0.54$ | Gaussian |
| 4   | $\Delta a_\mu$ [33] | $(26.1 \pm 8.0^{\exp} \pm 10.0^{\text{th}}) \times 10^{-10}$ | Gaussian |
| 5   | $m_t$ [34] | $173.3 \pm 0.5^{\text{stat}} \pm 1.3^{\text{sys}}$ (GeV) | Gaussian |
| 6   | $m_b$ ($m_b$) [32] | $4.19_{-0.06}^{+0.18}$ GeV | Two-sided Gaussian |
| 7   | $\alpha_s(M_Z)$ [32] | $0.1184 \pm 0.0007$ | Gaussian |
| 8a  | $m_h$ | pre-LHC: $m_h^{\text{low}} = 112$ | 1 if $m_h \geq m_h^{\text{low}}$
0 if $m_h < m_h^{\text{low}}$
1 if $m_h^{\text{low}} \leq m_h \leq m_h^{\text{up}}$
0 if $m_h < m_h^{\text{low}}$ or $m_h > m_h^{\text{up}}$ |
| 8b  | $m_h$ | LHC: $m_h^{\text{low}} = 120$, $m_h^{\text{up}} = 130$ | 1 if allowed
0 if excluded |
| 9   | sparticle masses | LEP [35] (via micrOMEGAs [24]) | 1 if allowed
0 if excluded |
| 10  | prompt $\tilde{\chi}_1^\pm$ | $ct(\tilde{\chi}_1^\pm) < 10$ mm | 1 if allowed
0 if excluded |
## Backup

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$\sqrt{s}$ [TeV]</th>
<th>L [fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic HT + MHT search</td>
<td>7</td>
<td>4.98</td>
</tr>
<tr>
<td>Hadronic HT + MET + $b$-jets search</td>
<td>7</td>
<td>4.98</td>
</tr>
<tr>
<td>Leptonic search for EW prod. of $\tilde{\chi}^0$, $\tilde{\chi}^\pm$, $\tilde{\nu}$</td>
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<td>4.98</td>
</tr>
<tr>
<td>Hadronic HT + MHT search</td>
<td>8</td>
<td>19.5</td>
</tr>
<tr>
<td>Hadronic $M_{T2}$ search</td>
<td>8</td>
<td>19.5</td>
</tr>
<tr>
<td>Hadronic HT + MET + $b$-jets search</td>
<td>8</td>
<td>19.4</td>
</tr>
<tr>
<td>Monojet searches</td>
<td>8</td>
<td>19.7</td>
</tr>
<tr>
<td>Hadronic stop search</td>
<td>8</td>
<td>19.4</td>
</tr>
<tr>
<td>Opposite sign di-lepton (OS ll) search</td>
<td>8</td>
<td>19.4</td>
</tr>
<tr>
<td>(count experiment only)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Like-sign di-lepton (LS ll) search</td>
<td>8</td>
<td>19.5</td>
</tr>
<tr>
<td>(only channels w/o 3rd lepton veto)</td>
<td></td>
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</tr>
<tr>
<td>(only ss, 3l, and 4l channels)</td>
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</tr>
</tbody>
</table>
Non-excluded points, properties

CMS

principal process $\sigma_{\text{tot}}^{8 \text{ TeV}}$

$\tilde{q}\tilde{q}(\tilde{q} \to \chi^\pm)^*$

$\tilde{b}\tilde{b}(\tilde{b} \to b)$

$\chi\chi_2(\chi \to V/h)$

$\chi\chi (\chi \to W^\pm)$

$\tilde{q}\tilde{q}(\tilde{q} \to q\bar{q})$

CMS (8 TeV) -1

$4.5 \text{ fb}^{-1} (7 \text{ TeV}) + 19.7 \text{ fb}^{-1} (8 \text{ TeV})$

CMS (7 TeV) + 19.7 fb^{-1} (8 TeV)

$\tilde{0}\tilde{0}$

$10 \text{ fb}$

$10000 \text{ fb}$

$500 \text{ GeV}$

$3$

$1$

$6$

$500 \text{ GeV}$

$30$

$pMSSM$ interpretation of CMS searches
Non-excluded points, properties

CMS

4.5 fb⁻¹ (7 TeV) + 19.7 fb⁻¹ (8 TeV)

principal process  

<\text{miss}_{E_T}>  

\text{\sigma}_f(\text{miss}_{E_T}>100)  

\text{\sigma}_f(\text{miss}_{E_T}>200)  

\text{\sigma}_f(\text{miss}_{E_T}>300)
Non-excluded points, properties

CMS

\[ \overline{\chi} \sim q \rightarrow q\tilde{\chi}_1^0 \]

\[ \overline{\chi} \sim \pm \rightarrow W^\pm \tilde{\chi}_1^0 \]

\[ \overline{\chi} \sim \chi_2 \rightarrow V/h\tilde{\chi}_1^0 \]

\[ \overline{\chi}_1\overline{\chi}_2 \rightarrow \chi \sim b \rightarrow b\tilde{\chi}_1^0 \]

\[ \overline{\chi}_1\overline{\chi}_2 \rightarrow \chi \sim \chi \rightarrow \chi \sim (\chi_2 \rightarrow \chi_2) \]

Principal process

\[ <H_T> \]

\[ \sigma_f(H_T > 300) \]

\[ \sigma_f(H_T > 500) \]

\[ \sigma_f(H_T > 1000) \]

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