SUSY @ CMS PTDR
for the Flavor in the Era of LHC Workshop

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CERN-PH

October 9, 2006
Outline

Introduction
Comments pertaining to this workshop

Search, Discovery & Characterization
Canonical SUSY program as a function of luminosity
Interplay of inclusive and exclusive measurements
Results from inclusive measurements
Reconstruction
Prospects for Dark Matter

Preparation For First Data
From Detector Projects and Pieces to Physics Data
History
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This talk is a downsized version of the SUSY at LHC talk in “Physics at LHC” 2006, Krakow, contains highlights of the CMS PTDR II SUSY analyses

Models according to how they affect flavor physics

- Constrained Minimal Flavor Violating [CMFV], e.g. mSUGRA with low or moderate $\tan \beta$, UEDs. The only source of quark flavor violation is the CMK
- Minimal Flavor Violation [MFV], same as CMFV with some new relevant operators that contribute to flavor transitions, e.g. SUSY models with large $\tan \beta$
- Next-to-MVF, new operators involving third generation quarks. They help solve problems in little Higgs, topcolor and RS models
- General Flavor Violation, e.g. most of MSSM before you worry about flavor contraints
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CMS PTDR framework
CMVF[mSUGRA], all results with detailed Geant-4 based CMS simulation - N.B. In the context of this workshop and in collaboration with the theory people we try to also move towards MVF e.g. Example tomorrow at WG2 Michael Schmitt, Rick Cavanaugh, Oliver Buchmüller.
Comments pertaining to this workshop

on the constraints front

M. C. et al. hep-ph/0603106

MVF SUSY models outside of the thick solid lines are excluded.
Comments pertaining to this workshop

measurements/theory data assisted calculations

- slightly high SM value for $\Delta M_s$ [used to be lower]
- slightly high SM value for $\text{BR}(B_u \rightarrow \tau \nu)$
- large $\tan \beta$ SUSY gives negative contributions to the above in the correct ballpark [but then $B_s \rightarrow \mu \mu$ must be observed now!]
- The SM values are changing ... e.g $\Delta M_s$ used to be 18 ps$^{-1}$ and became 21.5 ps$^{-1}$
- a very recent example of a new change in the theory calculation of the $\text{Br}(B \rightarrow X_s \gamma)$ [NNLO, hep-ph/0610067, Becher/Neubert] is showing slightly low SM calculation and “open a window for significant new physics contributions in rare radiative $B$ decays”, e.g charged Higgs of 500 GeV is back.
Comments pertaining to this workshop

basics
Since the squarks and sleptons can have significant flavor changing vertices and be complex the connection to collider physics can be subtle indeed– but the main implication is that the superpartners cannot be too heavy and that $\tan \beta$ is larger [which has no direct signature in general].

side remark
there is new tolerance in SM cosmology [e.g. Barenboim hep-ph/0608265] and the WMAP retranslated constraints are opening up the allowed space

remark
For the CMS studies of the past year we were signature driven in anticipation of first data. The analyses can be re-applied and repopimized for SO(10) or MSSM models...Example tomorrow at WG2 Michael Schmitt, Rick Cavanaugh, Oliver Buchmüller.
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The SUSY Search Path

Discovery
Inclusive canonical searches

Characterization
Which other channels show excesses? multileptons? photons (GMSB perhaps)? third generation particles? spin analysis?

Reconstruction
(some) masses and decays: two LSP’s in the final state → no mass peak. But kinematic endpoints (e.g. di-lepton edges) can provide masses of the particles involved.

“Measurement” of the underlying theory
We take more mass combinations, more decay chains, mass peaks once the LSP mass is known, determine the mass hierarchies, spins, &tc model parameters. How many simple measurements do we need to “nail” the theory?
The SUSY Search Path

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**Inclusive**
Inclusive canonical searches: large jet multiplicity, isolated leptons, large missing energy \(\rightarrow\) counting, identifying an excess.

**Exclusive**
Specific decay processes \(\rightarrow\) [modulo reasonable assumptions] measure object combination of invariant masses and determine susy masses and parameters.
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traps and pitfalls?
The SUSY Search Path

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**Exclusive**
Specific decay processes → [modulo reasonable assumptions] measure object combination of invariant masses and determine susy masses and parameters.

(1) is decay open? (2) kinematic edges are sensitive to mass differences (3) what other decay chains have the same final state [as the data analysis selection is designed for]? could be higher mass neutralinos or left-hand sleptons involved...
Attempts to Map Measurements to the Parameter Space

Inclusive+Exclusive

Inclusive [counting/cross section] and exclusive [end-point type] of measurements $\rightarrow$ a-posteriori probabilities of mapping back to the parameter space (cf references last slide and “Olympics” series)
Attempts to Map Measurements to the Parameter Space

**Inclusive+Exclusive**

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**Example**

[3] a-posteriori probability distribution of mSUGRA parameters using cross-section + end-point measurements in a Markov Chain Monte Carlo sampling of the parameter space. The two regions reflect the lack of knowledge of which slepton is involved in the decay chain.
Discovery: Inclusive Signatures
Discovery: Inclusive Signatures

squarks and gluinos dominate production
## Discovery: Inclusive Signatures

**Example**

- long decay chains possible
- many high $P_T$ objects: leptons, jets, $b$-jets...
- $R$–parity conservation $\rightarrow$ LSP stable and weakly interacting $\rightarrow$ large missing energy
Discovery: Inclusive Signatures

The closest SM process is $t \rightarrow Wb$
Discovery: Inclusive Signatures

Example

- assuming 600 GeV gluino and MSSM-like SUSY:
- large cross-section [QCD couplings] and coloured particles in the final state (jets)
- Majorana new particles $\rightarrow$ excess of same-sign lepton pairs
- decay of neutral particle into two particles with lepton quantum numbers $\rightarrow$ excess of opposite-sign same-flavor lepton pairs
Inclusive Signatures CMS PTDR2:LCHCC-2006/021

- canonical inclusive
  - jets+ $E_T^{miss}$ (*) includes strategies for beam halo/noise, first data
  - jets+ $\mu$+ $E_T^{miss}$
  - same-sign dimuon
  - opposite-sign same flavor dielectron and dimuon
  - opposite-sign same flavor hadronic ditau
  - trileptons at high $m_0$

- higher reco object inclusive
  - $Z$ + $E_T^{miss}$
  - $t$ hadronic + $E_T^{miss}$
  - $h^0(b\bar{b})$ + $E_T^{miss}$ (*) includes strategies for decay chain separation aka “hemispheres”

- flavor violating
  - opposite-sign different flavor $e\mu$ for FV neutralino decays

[next talk]
SUSY maps

- major production mechanisms in parameter space
SUSY maps

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SUSY maps

- major decays in parameter space
SUSY maps

- major decays in parameter space
Inclusive Signatures CMS PTDR2:LCHCC-2006/021

Discovery map including background systematics

\[ \tan \beta = 10, A_0 = 0, \mu > 0 \]

CMS

\[ m_h = 120 \text{ GeV} \]

\[ m_{\mu} = 114 \text{ GeV} \]

\[ m_{\tau} = 103 \text{ GeV} \]

\[ NO \ EWSB \]
Inclusive Signatures CMS PTDR2:LCHCC-2006/021

Discovery map including background systematics

- interplay of signatures in the parameter space
- including excess of $t$’s, $\tau$’s, $b$’s, $Z$’s and $W$’s
- for fast orientation need to understand very fast and very well lepton efficiencies and $E_T^{miss}$ tails
Inclusive Signatures CMS PTDR2:LCHCC-2006/021

$E_T^{\text{miss}} + \text{jets}$, $m_0 = 60$, $m_{1/2} = 250$, $A_0 = 0$, $\tan(\beta) = 10$, $\text{sgn}(\mu) = +1$ [CMS LM1 test-point]

- fast-track to discovery of low mass SUSY $\mathcal{O}(10)$ pb$^{-1}$ b/c of signal cross section – control of systematics using SM processes (e.g. $Z$+jets, top)
- BUT $\sim$ fb$^{-1}$ needed to reliably do this: the time between $\mathcal{O}(10)$ and $\mathcal{O}(100)$ pb$^{-1}$ of well understood data will be critical for the discovery and characterization of SUSY
Inclusive Signatures CMS PTDR2:LCHCC-2006/021

$E_T^{miss} + \text{jets}$ candidate event display

$E_T^{miss} = 360 \text{ GeV}, \ E_T(1) = 330 \text{ GeV}, \ E_T(2) = 140 \text{ GeV}, \ E_T(3) = 60 \text{ GeV}$
First Mass Clues (dileptons)
First Mass Clues (dileptons)

- SFOS dilepton+jets+$E_T^{miss}$
- $t\bar{t}$:WW+j:Z+j:other $\sim 6:1:1:1$
- Flavor subtraction ($e^-\mu^+ + e^+\mu^-$) to suppress chargino, $W$, $t\bar{t}$, $WW$, “other”
- L1+HLT trigger path required
- Overall systematic on the background 20% (JES dominated)
- $5\sigma$ discovery with $\sim 20$ pb$^{-1}$ (of data understood as expected with 1 fb$^{-1}$).
First Mass Clues (dileptons)

\[ M_{\ell\ell}^{\text{max}} = M(\tilde{\chi}_0^2) \sqrt{1 - \frac{M^2(\ell_R)}{M^2(\tilde{\chi}_0^0)}} \sqrt{1 - \frac{M^2(\tilde{\chi}_1^0)}{M^2(\ell_R)}} \]

- \( M_{\ell\ell}^{\text{max}} = 80.42 \pm 0.48 \text{ GeV/c}^2 \), cfr

\( M_{\ell\ell}^{\text{max}} \) (meas) = 80.42 ± 0.48 GeV/c², cfr with

- expected \( M_{\ell\ell}^{\text{max}} = 81 \text{ GeV/c}^2 \) [given \( M(\tilde{\chi}_1^0) = 95, M(\tilde{\chi}_2^0) = 180 \) and \( M(\ell_R) = 119 \text{ GeV/c}^2 \)]
First Mass Clues (dileptons)

\(m_0 = 185\), \(m_{1/2} = 350\), \(A_0 = 0\), \(\tan(\beta) = 35\)

\(\text{sgn}(\mu) = +1\) [CMS LM2 test-point]

Selection uses 1-prong/3-prong OS hadronic \(\tau\), two jets, \(E_T^{\text{miss}}\)

\(M^{\text{max}}_{\tau\tau}\) (meas) \(95 \pm 5\) with 40 fb\(^{-1}\)

difficult due to (soft) \(\tau\) decays and energy scale
First Mass Clues ($b\bar{b}$)
First Mass Clues ($b\bar{b}$)

- $b\bar{b}$ width to be extracted from SM control processes
- $5\sigma$ excess with 1.5 fb$^{-1}$
- background here 5th order polynomial, signal Gaussian of fixed width
- cascade chain separation using 2 axis (aka “hemisphere”)
- 2 $b$’s required in the same hemisphere and closest in $\Delta R$
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First Mass Clues (adding the jets)
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Combine measurements of thresholds and edges from different jet/lepton mass combinations to obtain mass measurements:

CMS PTDR [1]
First Mass Clues (adding the jets)

CMS PTDR [1]
First Mass Clues (adding the jets)

CMS PTDR [1]

<table>
<thead>
<tr>
<th>LM2 test point</th>
<th>measured</th>
<th>theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M(\tilde{\chi}_1^0)$ (GeV)</td>
<td>147 ± 23(stat) ± 19(sys)</td>
<td>138.2</td>
</tr>
<tr>
<td>$M(\tilde{\chi}_2^0)$ (GeV)</td>
<td>265 ± 10(stat) ± 25(sys)</td>
<td>265.5</td>
</tr>
<tr>
<td>$M(\tilde{\tau})$ (GeV)</td>
<td>165 ± 10(stat) ± 20(sys)</td>
<td>153.9</td>
</tr>
<tr>
<td>$M(\tilde{q})$ (GeV)</td>
<td>763 ± 33(stat) ± 58(sys)</td>
<td>753-783 (light $\tilde{q}$)</td>
</tr>
</tbody>
</table>
stop: inclusive top excess
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\[ \tilde{t} \] sources (LM1)

<table>
<thead>
<tr>
<th>Mother $\rightarrow$ Daughters</th>
<th>B.R(%)</th>
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</thead>
<tbody>
<tr>
<td>$\tilde{g} \rightarrow t + t_1$</td>
<td>6.16</td>
<td>$\tilde{g} \rightarrow \tilde{b} + b_1$</td>
<td>18.09</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow \tilde{b} + b_2$</td>
<td>12.67</td>
<td>$t_2 \rightarrow Z^0 + t_1$</td>
<td>12.17</td>
</tr>
<tr>
<td>$\tilde{t}_2 \rightarrow h_0 + t_1$</td>
<td>2.62</td>
<td>$\tilde{b}_2 \rightarrow W^- + t_1$</td>
<td>16.33</td>
</tr>
<tr>
<td>$\tilde{b}_1 \rightarrow W^- + t_1$</td>
<td>6.64</td>
<td>$\tilde{t}_1 \rightarrow \chi_2^0 + t$</td>
<td>12.53</td>
</tr>
<tr>
<td>$t_1 \rightarrow \chi_1^0 + t$</td>
<td>17.70</td>
<td>$t_2 \rightarrow \chi_{all}^0 + t$</td>
<td>40.58</td>
</tr>
<tr>
<td>$b_1 \rightarrow \chi_1^+ + t$</td>
<td>48.36</td>
<td>$b_2 \rightarrow \chi_1^+ + t$</td>
<td>23.85</td>
</tr>
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</table>
stop: inclusive top excess

- excess of reconstructed hadronic top
- $m(jj)$ consistent with $W$ mass and $m(jjb)$ consistent with top mass
- 2C kinematic fit
- additional $b$’s can be used to start reconstruction
- excess of $t$’s in LM1 used inclusively
Dark Matter

use extracted model parameters to estimate LSP DM properties (using Micromegas [8], DarkSUSY[9])

annihilation to gauge bosons:
large higgsino component to LSP
"Focus point" region
Case study

co-annihilation signatures

• $m_0 = 70$, $m_{1/2} = 350$, $A_0 = 0$, $\tan \beta = 10$, $\text{sgn}(\mu) = +1$

• $\chi^0_2 \rightarrow \tilde{\ell} L, R \rightarrow \ell \ell \chi^0_1 \rightarrow$ double dilepton invariant mass edge

• small slepton-neutralino mass difference $\rightarrow$ one soft lepton

• large $E_T^{\text{miss}}$, 1 hard jet, dileptons (with flavor subtraction OSSF-OSOF)

• measure edges/thresholds in $q\ell\ell, q\ell$
knowledge, ignorance, enlightenment and temptation

- we know something about dark/B matter
- we think we know something about SUSY
- we think we will measure it at the LHC

Note
Efforts to put all what we know, what we think we know and what we know we don’t know, into one coherent picture: tough without the LHC data in hand but preparative value is huge.
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Integration-Commissioning-Start-up Physics

**test beams/cosmics/single beam/collisions**

**Definition (commissioning & physics)**

- test beams-cosmics-one beam-collisions:
  1. commissioning data (alignment/calibration/synchronization)
  2. commissioning data (trigger)
  3. physics data
  4. first analyses
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- $\eta$ distribution of charged particles 1990
- $K_s$ production 1990

Jets

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- Inclusive jet cross section 1989
- Two-jet inv-mass distributions 1990
- Jet fragmentation 1990
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First Data and SUSY

At start-up

- understand detectors and SM backgrounds
- control/understand: trigger, initial calibrations, scales, resolutions, efficiencies...
- minimize poorly estimated standard model backgrounds
- use SM “candle”/control samples (W/Z/top) to estimate backgrounds as possible (this afternoon)
- adapt methods for background extraction as a function of luminosity
- have in place MC tools
First Data and SUSY

General Strategy

- Choose signatures identifying well defined decay chains
- Extract constraints on masses, couplings, spin from decay kinematics/rates (especially for spin, need clever ideas!)
- try to match emerging pattern to tentative template models
- having adjusted template models to measurements, try to find additional signatures to discriminate different options
**Introduction**

SUSY Search, Discovery and Characterization

- CMS PTDR, LHCC-2006-021
- ATLAS PTDR, LHCC-1999-015
- Allanach *et al* hep-ph/0507283
- Baltz *et al* hep-ph/0602187
- Belanger *et al* hep-ph/0405253
- Gondolo *et al* astro-ph/0406204