Searches for Supersymmetry at CMS

Alex Tapper
Outline

- Introduction to the LHC and CMS
  - Why you should believe our measurements
- Search strategy
  - What to look for and how to look for it
- Detailed examples
  - Jets + MET
  - Di-photons + MET
  - Long lived stopped particles
- Plans and expectations for 2011
- Interpretation/communication of results
  - How do we tell you what we’ve found or not
The Large Hadron Collider

Overall view of the LHC experiments.

3.5 TeV → p

3.5 TeV ← p
The Large Hadron Collider

\[ p + p \rightarrow \text{3.5 TeV} \]

\[ \sim 35 \text{ pb}^{-1} \text{ in 2010} \]

Will discuss expectations for 2011 run later

Total Integrated Luminosity 2010 (Mar 30 10:00 UTC - Nov 03 00:00 UTC)

Delivered 47.03 pb\(^{-1}\)

Recorded 43.17 pb\(^{-1}\)
The CMS detector

- 4T solenoid magnet
- Silicon detector (pixel, strips)
- Crystal ECAL $\sigma(E)/E=3%/\sqrt{E}+0.003$,
- Brass/sci. HCAL $\sigma(E)/E=100%/\sqrt{E}+0.05$
- Muon chambers $\sigma(p)/p<10\%$ at 1TeV
• Measurements of jet cross sections and MET resolution

• Jets and MET in good shape already
• Measurements of jet cross sections and MET resolution

• Jets and MET in good shape already
Standard Model physics

- Beautiful reconstruction of W and Z bosons
- Leptons and MET reconstruction performing well
Standard Model physics


- Top-quark pair-production and $Z \rightarrow \tau^+ \tau^-$
- b-tagging and $\tau$-tagging performing well already
Re-discovery of the Standard Model

Original discovery


2006 Dec 2009 Jan 2010 Feb Mar Apr May Jun Jul 2010

"Rediscovery" in CMS (dates approximate)
Search strategy (what and how?)

- Production
  - Squark and gluino expected to dominate
  - Strong production so high cross section
  - Cross section depends only on masses
  - Approx. independent of SUSY model
Search strategy (what and how?)

- **Production**
  - Squark and gluino expected to dominate
  - Strong production so high cross section
  - Cross section depends only on masses
  - Approx. independent of SUSY model

- **Decay**
  - Details of decay chain depend on SUSY model (mass spectra, branching ratios, etc.)
  - Assume $R_P$ conserved $\rightarrow$ decay to lightest SUSY particle (LSP)
  - Assume squarks and gluinos are heavy $\rightarrow$ long decay chains

- **Signatures**
  - MET from LSPs, **high-$E_T$ jets** and **leptons** from long decay chain

- **Focus on robust and simple signatures**
  - Common to wide variety of models
  - Let Standard Model background and detector performance define searches not models
Backgrounds

- **Physics**
  - Standard Model processes that give the same signatures as SUSY
  - Cannot rely on Monte Carlo predictions $\rightarrow$ measure in data

- **Detector effects**
  - Detector noise, mis-measurements etc. that generate MET or extra jets
  - Commissioning and calibration $\rightarrow$ good performance shown earlier

- **Beam related**
  - Beam-halo muons (and cosmic-ray muons), beam-gas events
  - Data and simulation already $\rightarrow$ measure in situ too
**Search strategy (what and how?)**

<table>
<thead>
<tr>
<th>0-leptons</th>
<th>2-photons</th>
<th>1-lepton</th>
<th>SSDL</th>
<th>OSDL</th>
<th>≥3 leptons</th>
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<td>Jets + MET</td>
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- Generic searches based on MET
- Categorised by numbers of leptons and photons
- Most include jet requirement → strong production
### Search strategy (what and how?)

- Very challenging due to large amount and wide range of backgrounds
- However most sensitive search for strongly produced SUSY
- CMS pursues several complementary strategies
- In principle ATLAS should be better suited to this than CMS
- Extend this in the future to b-tagged final states (2010 dataset)
- Extension to $\tau$ and top-tagged final states (2011 dataset)
- **Will show you first result from this search**

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### Search strategy (what and how?)

Many gauge mediated models predict photons in final state
- Extend to single photon in future and single photon + lepton
- **Will show you first result from this search**

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Lepton (electron or muon) requirement reduces background considerably

Basically only ttbar left → topological handles
### Search strategy (what and how?)

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- Very small Standard Model backgrounds
- Include all three generations of leptons and all cross channels
Search strategy (what and how?)

- Two analyses here: inclusive and Z peak search
- Not including $\tau$ final states in 2010
- Several techniques including opposite-sign opposite flavour subtraction
- Shape information and mass edges

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Search strategy (what and how?)

- Very clean events with very low Standard Model background
- Include all three generations of leptons and all combinations
- Search inclusively, Z peak, with and without MET
- Some striking Standard Model events observed already

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- **Non-MET based searches**
- **R-parity conserving and “exotic” SUSY**
- **Examples are long lived particles**
- **Will show you first result from stopped gluino search**

### Other Strategies:

<table>
<thead>
<tr>
<th>RPV</th>
<th>“Exotic”</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-Parity violating searches</td>
<td>Long-lived particles etc.</td>
</tr>
</tbody>
</table>
All hadronic search pre-selection

- Loose sample of hadronic events
  - Trigger $H_T$ ($\sum E_{Tjets}$) > 150 GeV (RAW)
  - $H_T$ > 250 GeV
  - Vertex consistent with pp collision
  - At least 2 jets with $E_T$>50 GeV & $|\eta|<3$
  - Leading jet $|\eta|<2.5$
  - $E_{Tj2}>100$ GeV
  - Event veto for isolated electrons and muons with $P_T>10$ GeV
  - Event veto for isolated photons $P_T>25$ GeV

- Dominated by multi-jet QCD

hep-ex/0176391
Final selection

- No dependence on MET ➔ robust for early LHC running
- Originally proposed for di-jet events ➔ generalised up to 6 jets
- $\alpha_T > 0.55$
- $R_{\text{miss}} = H_{\text{Tmiss}} / \text{MET} < 1.25$ (effect of soft jets)
- For $\Delta\phi^* < 0.5$ the $\Delta R_{\text{ECAL}} > 0.3$ (jets pointing to dead CALO cells)
- $H_T > 350$ GeV (beyond previous searches)
Data and Monte Carlo yields

- Data and Monte Carlo expectation in good agreement (errors are stat.)
- QCD is PYTHIA, EWK backgrounds from MADGRAPH
- For \(N_{\text{jets}}=2\) main backgrounds \(Z \rightarrow \nu\bar{\nu}\) and \(W \rightarrow \tau\nu\)
- For \(N_{\text{jets}}>2\) \(t\bar{t}\) also contributes - \(Z/W/ttbar\) approx. equal

<table>
<thead>
<tr>
<th>Selection</th>
<th>Data</th>
<th>SM</th>
<th>QCD multijet</th>
<th>(Z \rightarrow \nu\bar{\nu})</th>
<th>(W + \text{jets})</th>
<th>(t\bar{t})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H_T &gt; 250) GeV</td>
<td>4.68M</td>
<td>5.81M</td>
<td>5.81M</td>
<td>290</td>
<td>2.0k</td>
<td>2.5k</td>
</tr>
<tr>
<td>(E_{T_j} &gt; 100) GeV</td>
<td>2.89M</td>
<td>3.40M</td>
<td>3.40M</td>
<td>160</td>
<td>610</td>
<td>830</td>
</tr>
<tr>
<td>(H_T &gt; 350) GeV</td>
<td>908k</td>
<td>1.11M</td>
<td>1.11M</td>
<td>80</td>
<td>280</td>
<td>650</td>
</tr>
<tr>
<td>(\alpha_T &gt; 0.55)</td>
<td>37</td>
<td>30.5±4.7</td>
<td>19.5±4.6</td>
<td>4.2±0.6</td>
<td>3.9±0.7</td>
<td>2.8±0.1</td>
</tr>
<tr>
<td>(\Delta R_{\text{ECAL}} &gt; 0.3 \lor \Delta \phi^* &gt; 0.5)</td>
<td>32</td>
<td>24.5±4.2</td>
<td>14.3±4.1</td>
<td>4.2±0.6</td>
<td>3.6±0.6</td>
<td>2.4±0.1</td>
</tr>
<tr>
<td>(R_{\text{miss}} &lt; 1.25)</td>
<td>13</td>
<td>9.3±0.9</td>
<td>0.03±0.02</td>
<td>4.1±0.6</td>
<td>3.3±0.6</td>
<td>1.8±0.1</td>
</tr>
</tbody>
</table>
Inclusive background estimate

- Use kinematics and control regions to estimate all backgrounds
  - Use lower $H_T$ bins 250-300 GeV and 300-350 GeV to extrapolate into signal region 350 GeV
  - Adjust cuts in control regions to preserve kinematics
  - Define $R_{\alpha_T} = N(\alpha_T>x)/N(\alpha_T<x)$
  - For QCD (mismeasurement) expect this to fall as resolution improves with increasing $H_T$
  - For EWK (real MET) expect flat behaviour. Check with $W/\text{ttbar}$ control sample
  - Indicates final selection is QCD free
  - Extrapolate for low to high $H_T$
  - Result is $9.4^{+4.8}_{-4.0}$ (stat.) $\pm 1.0$ (syst.)
W+jets and ttbar backgrounds

- Select a high $P_T$ muon sample (same as ttbar cross section)
  - Same cuts as signal region excluding muon in calculations ($H_{T\text{miss}} > 140$ GeV)
  - $M_T > 30$ GeV to ensure pure W/ttbar sample - no QCD
  - Use MC efficiencies and acceptances with this muon samples
    - Estimate number of semi-leptonic decays that are not vetoed due to low $P_T$ leptons or leptons out of acceptance
    - Estimate number of hadronic $\tau$ decays which end up in the signal sample
  - Result is $6.1^{+2.8}_{-1.9}$ (stat.) ± 1.8 (syst.)
  - Systematic (~30%) is conservative
• Data-driven background estimates
• $Z \rightarrow \nu\nu + \text{jets} \rightarrow$ irreducible background
  ☐ Replacement technique

$Z \rightarrow ll + \text{jets}$
Strength: very clean
Weakness: low statistics

$W \rightarrow l\nu + \text{jets}$
Strength: larger statistics
Weakness: background from SM and SUSY

$\gamma + \text{jets}$
Strength: large statistics and clean at high $E_T$
Weakness: background at low $E_T$, theoretical errors
Using $\gamma + \text{jets}$ events

- Select very clean $\gamma + \text{jets}$ sample
- $P_T^{\gamma} > 100$ GeV
- $|\eta^{\gamma}| < 1.45$
- $\Delta R(\gamma,\text{jet}) > 1.0$
- $H_{\text{miss}} > 140$ GeV
- Yields 7 events in data
- Use MC to scale $\gamma \rightarrow Z$
- Result is $4.4^{+2.3}_{-1.6}$ (stat.) $\pm 1.8$ (syst.)
- Largest systematic from $\gamma \rightarrow Z$ theory

Cross check with W sample

- Result is $4.9^{+2.6}_{-1.8}$ (stat.) $\pm 1.5$ (syst.)
- ttbar contamination in muon sample

100 pb$^{-1}$ at 14 TeV CMS
Observed data events

- Background summary
  - Inclusive $9.4^{+4.8}_{-4.0}$ (stat.) $\pm 1.0$ (syst.)
  - EWK $10.5^{+3.6}_{-2.5}$

- Examine events selected in data
  - $M_{\text{eff}} = H_T + H_{\text{Tmiss}}$ scale of event
  - $\Delta\phi^*$ distribution not peaked

- Events consistent with EWK background
Interpretation in CMSSM

- Signal acceptance uncertainty dominated by luminosity error (11%)
- Use Feldman-Cousins method to set 95% CL, using Profile-Likelihood to deal with nuisance parameters
- Upper limit on signal events is 13.4
- $p$ value for SM only = 0.3
- Very weak dependence on $\tan\beta$
- Significant extension of excluded region over Tevatron experiments

Production mechanism | Yields for 35 pb$^{-1}$ | $\epsilon_{\text{total}}$ (%) | $\epsilon_{\text{signature}}$ (%) |
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>$q\bar{q}$</td>
<td>9.7 ± 0.1</td>
<td>16.0 ± 0.1</td>
<td>22.2 ± 0.4</td>
</tr>
<tr>
<td>$q\bar{g}$</td>
<td>8.8 ± 0.1</td>
<td>14.4 ± 0.1</td>
<td>23.0 ± 0.5</td>
</tr>
<tr>
<td>$g\bar{g}$</td>
<td>0.71 ± 0.02</td>
<td>12.0 ± 0.4</td>
<td>22.5 ± 2.0</td>
</tr>
</tbody>
</table>

$L_{\text{int}} = 35$ pb$^{-1}$, $\sqrt{s} = 7$ TeV
Search with di-photon events

- **Pre-selection**
  - Trigger: single photon $P_{T\gamma} > 30$ GeV
  - Require two photons with $P_{T\gamma} > 30$ GeV and $|\eta\gamma| < 1.4$
  - Shower shape ID cuts
  - Veto if H/E>5%
  - Isolation$^{\text{TRK}} < 0.001x E_T + 2$ GeV
  - Isolation$^{\text{ECAL}} < 0.006x E_T + 4.2$ GeV
  - Isolation$^{\text{HCAL}} < 0.0025x E_T + 2.2$ GeV

- Distinguish electrons and photons by track in pixel detector
- At least one jet $E_T > 30$ GeV (cleans up beam and cosmic backgrounds)

- **Define two control samples for later**
  - fake-fake (ff) - fail track isolation or shower shape
  - Z (ee) - two electrons and Z mass window cut (90 $\pm$ 20 GeV)
Electroweak backgrounds

- Irreducible SM backgrounds $Z\gamma\gamma$ and $W\gamma\gamma$ negligible

- Main electroweak background
  - $W \rightarrow e\nu$ where $e$ is mis-ID as a $\gamma$ and also a real or fake $\gamma$ in the event
  - Measure mis-ID rate $f_{e\rightarrow\gamma}$ from the number of $Z \rightarrow ee$ events in the $ee$ and $e\gamma$ samples
  - Result is $1.4 \pm 0.4\%$
  - Apply this to $e\gamma$ sample to get prediction
QCD backgrounds

- ECAL resolution much better than HCAL
- MET resolution dominated by HCAL
- Reweight ff and ee control samples to signal $\gamma\gamma E_T$ spectrum
- Normalise at low MET (<20 GeV)
Proof that if a signal is was there we would have seen it
• “Discover” Standard Model $W\gamma$ events by switching to $e\gamma$ sample
Interpretation in a GGM model

- Observe 1 event MET >50 GeV consistent with 1.2 ± 0.8 background

<table>
<thead>
<tr>
<th>Type</th>
<th>Number of Events</th>
<th>stat error</th>
<th>reweight error</th>
<th>normalization error</th>
</tr>
</thead>
<tbody>
<tr>
<td>γγ events</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fake-fake QCD background est.</td>
<td>0.49 ± 0.40</td>
<td>±0.36</td>
<td>±0.06</td>
<td>±0.07</td>
</tr>
<tr>
<td>Z → ee QCD background est.</td>
<td>1.67 ± 0.64</td>
<td>±0.46</td>
<td>±0.38</td>
<td>±0.23</td>
</tr>
<tr>
<td>background from eγ</td>
<td>0.04 ± 0.15</td>
<td>±0.15</td>
<td>±0.0</td>
<td>±0.01</td>
</tr>
<tr>
<td>Total Background ≥ 50 GeV (using ff)</td>
<td>0.53 ± 0.40</td>
<td></td>
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<td>Total Background ≥ 50 GeV (using ee)</td>
<td>1.71 ± 0.68</td>
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- Only three “light” particles: neutralino, gluino, and squark

- Gluino decays: Two jets and gaugino. Can be 3-body or cascade depending on m(squark)-m(gluino)

- Squark decays: If heavier then gluinos: quark + gluino gives three jets + gaugino. If lighter then gluino: quark and gaugino gives one jet + gaugino

- Each event has: Two gauginos ➔ in our simple model neutralinos ➔ two Photons + MET and between two and six jets from SUSY cascades
Interpretation in a GGM model

- 95% CL upper limit for simple model for neutralino mass = 150 GeV
- Upper limits between 0.3 and 1.1 pb depending on masses
- Factor of ~10 better than Tevatron could do with 6 fb$^{-1}$
Long-lived particle searches

- Long-lived particles possible in many theories
  - For example many SUSY models with stau NLSP with Gravitino LSP

- Long-lived charged particles with lifetimes of $O(100-1000)$s could explain the discrepancy between Li abundance and BBN

- Two complementary approaches:
  - High momentum tracks with large dE/dx E loss (high $\beta > 0.4$)
  - **Stopped particles** may decay any time $\rightarrow$ signal out-of-time with LHC beam
Stopped particle searches

- Long-lived particles produced in pp collisions
- Particles stop in detector in brass absorber in barrel hadronic calorimeter
- Search for decays during non-collision times (between bunches, orbits and fills)

- Trigger is simple jet trigger in HCAL with $E_T > 20$ GeV
- Fight against HCAL noise and cosmic muons
Stopped particle searches

- **Background determination**
  - Noise rate is measured from 95 hours taken at $2-7 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}$
  - Data was taken with 62 hours at higher intensities with 312 proton bunches per beam.

- Reject real collisions
- Reject if either beam monitor fired (beam monitor 175m either side)
- Reject if in beam crossing within -2 to 1 of collision BX
- Reject if has reconstructed vertex
- Beam halo filter
- Cosmic filter

- Monitor stability of $N_{-1}$ filters to set uncertainty
Two ways to search

- Counting experiment - need to measure and normalise background absolutely (big systematic on normalisation)

<table>
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<tr>
<th>Lifetime [s]</th>
<th>Expected Background (± stat. ± syst.)</th>
<th>Observed</th>
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<tr>
<td>$1 \times 10^{-7}$</td>
<td>0.8 ± 0.2 ± 0.2</td>
<td>2</td>
</tr>
<tr>
<td>$1 \times 10^{-6}$</td>
<td>1.9 ± 0.4 ± 0.5</td>
<td>3</td>
</tr>
<tr>
<td>$1 \times 10^{-5}$</td>
<td>4.9 ± 1.0 ± 1.3</td>
<td>5</td>
</tr>
<tr>
<td>$1 \times 10^{6}$</td>
<td>4.9 ± 1.0 ± 1.3</td>
<td>5</td>
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- Time-profile analysis - build a PDF for gluino decay for a given mass and lifetime - compare shapes with CMS data (no need to normalise)
stopped particle searches

- Under some assumptions lifetimes from 10µs to 1000s excluded
- So far limits on stopped gluinos → technique could be used to set limits on stopped staus with more data
Expectations for 2011

- Will know much more after the LHC Chamonix workshop
- Could be 8 TeV centre-of-mass energy and running in 2012?

D. Acosta
Plans for 2011

- Analyses are designed for discovery not limits
  - Data-driven background estimates
  - Multiple methods and cross-checks built in
  - Analyses categorised by topology, not by model
  - Analyses designed for maximum coverage, not necessarily best model sensitivity

- We will continue to develop our programme in 2011
  - Run current searches until they are no longer appropriate
  - In parallel develop and evolve techniques for higher luminosity
  - More use of shapes with more data, in 2010 just counting experiments
  - Weak production can come into the game (so far only strong)
  - Challenges with triggers, pile-up.....
Reach in 2011

- Expect us to do better than this!
- Expect our results expressed in less constrained models →
Interpretation/communication

● A moving (evolving) target ➔ we need feedback

● First papers
  ▪ mSUGRA/CMSSM to connect to previous generations of experiments
  ▪ Cross sections x BR and information on efficiencies

● Under discussion now between ATLAS/CMS/Theory
  ▪ Common simple/less constrained models
  ▪ A few slides on this coming up ➔

● Bit further down the line
  ▪ Full likelihoods in some computer format (RooStats?)
  ▪ Some more elaborate solution?
Simplified Models

- Workshops at CERN and SLAC
  - Models proposed at: [http://www.lhcnewphysics.org](http://www.lhcnewphysics.org)
  - Agreed on reference topologies for early searches
  - Cover what one might see in the first $\sim 50 \text{ pb}^{-1}$
  - All initiated by strong production
  - Inspired by SUSY and SUSY-like New Physics (all involve MET)

- Increasing order of complexity
  - Hadronic decays
  - Decays with one or two leptons
  - Decays with heavy flavours
  - Photon and multi-leptons (based on GGM models as di-photon search)
Simplified Models

- Proposal for all-hadronic search
  - Squark anti-squark pair production with decay squark → q + χ
  - Gluino pair production with decay gluino → qqbar + χ
  - χ can be the LSP or an intermediate state, decaying to W + LSP
  - Kinematics specified by masses
  - Direct case \( m_{\text{gluino}}(m_{\text{squark}}) \) vs \( m_{\text{LSP}} \) 2D plot
  - For cascade decays (arbitrary) slices of intermediate particle
  - Given “reference” cross section set limits

- Currently under discussion at CMS
Conclusions

- First SUSY limits from CMS in 2010 are being published
- Preparing programme for 2011/12 run
- Wide range of searches underway
- Need to work closely together to have efficient exchange of information
- Thanks for the invitation to speak today!
Backup: Links

- **ATLAS latest results**
  - [https://twiki.cern.ch/twiki/bin/view/Atlas/AtlasResults](https://twiki.cern.ch/twiki/bin/view/Atlas/AtlasResults)

- **ATLAS Physics TDR**

- **CMS latest results**
  - [https://twiki.cern.ch/twiki/bin/view/CMS/PhysicsResults](https://twiki.cern.ch/twiki/bin/view/CMS/PhysicsResults)

- **CMS Physics TDR**
## Backup: Benchmark points

### Low mass (LM) mSUGRA benchmarks

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### High mass (HM) mSUGRA benchmarks

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