Searches for Dark Matter at CMS

Alex Tapper
Outline

- The LHC and the CMS detector
- Search strategy
- Examples of searches
  - Strong production
  - Weak production
  - Initial state radiation searches
- Summary and outlook
The Large Hadron Collider

Overall view of the LHC experiments.

4 TeV → p

4 TeV ← p

3 Dark Attack 2012 Workshop, 15 - 20 July 2012, Ascona, Switzerland.
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

JINST3:S08004 (2008)
The CMS detector in 2011

- LHC delivered \( \sim 6 \, \text{fb}^{-1} \)
- CMS collected \( \sim 5.6 \, \text{fb}^{-1} \) (93%)
- Results based on \( \sim 5 \, \text{fb}^{-1} \) (83%)

- Average fraction of functional detector channels \( > 98.5\% \)
- Lowest still \( > 95\% \)
Dark Matter @ LHC

- Neutral and weakly interacting so difficult to observe
  - No signal in LHC detectors ➔ missing transverse energy

- Direct production has small cross section and no signal in detector ➔ difficult searches

- Production in conjunction with Standard Model particles easier option for detection

- Design searches based on MET ➔
Search strategy

- **Strong production**
  - Long cascades, hadronic jets, maybe leptons
  - High cross sections

- **Weak production** ➔ no hadronic jets (χ pair-production)
- **Direct production** ➔ QED/QCD initial state radiation
- **More exotic** ➔ stopped gluinos, HSCP…

![Diagram with N_jets and N_{leptons/N_{photons}} axes](image)
Search strategy

- **Strong production**
  - Long cascades, hadronic jets, maybe leptons
  - High cross sections

- **Weak production** → no hadronic jets (\(\chi\) pair-production)

- **Direct production** → QED/QCD initial state radiation

- **More exotic** → stopped gluinos, HSCP…

\[ N_{\text{jets}} \]
\[
\begin{array}{c}
  \vdots \\
  3 \\
  2 \\
  1 \\
  0, 1, 2 (SS/OS), >2
\end{array}
\]

\[ N_{\text{leptons}}/N_{\text{photons}} \]
The key: backgrounds

- **Physics**
  - Standard Model processes that give the same signatures as SUSY
  - Cannot/do not (yet?) rely on Monte Carlo simulations ➔ measure in data

- **Detector effects**
  - Detector noise, mis-measurements etc. that generate MET or extra jets
  - Commissioning and calibration ➔ good performance

- **Other**
  - Beam-halo muons and cosmic-ray muons, beam-gas events
  - Data and simulation already ➔ measure in situ too
Jets + MET

• All hadronic channel, just jets and missing energy in event
  ▪ Very challenging due to large amount and wide range of backgrounds
  ▪ However most sensitive search for strongly produced SUSY
  ▪ CMS pursues several complementary strategies based on kinematics and detector understanding → this analysis the “classic” version

• Selection
  ▪ No leptons (e or μ)
  ▪ At least 3 jets > 50 GeV
  ▪ Δφ between jets and MET
  ▪ Examine data in bins
    • $H_T^{\text{miss}}$ (MET from jets)
    • $H_T$ (sum of jet $p_T$)

Jets + MET

- All background estimates taken from data
- Multi-bin approach in $H_T^{\text{miss}}$ and $H_T$
  - Wide sensitivity
  - Bins combined for final limits

No excess seen in data → set limits

CMS Preliminary
$L = 4.98 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV}$

- Data
- $Z \rightarrow \nu\bar{\nu}+\text{Jets}$
- $W/\ell(t_{\text{had}}+\nu)+\text{Jets}$
- $W/\ell(e/\mu+\nu)+\text{Jets}$
- QCD

Total uncertainty on measured background

$H_T$ [GeV]
$H_T^{\text{miss}}$ [GeV]
- Limit in the usual CMSSM plane ($\tan\beta=10$, $A_0=0$, $\mu>0$)
Interpretation Intermezzo

- **Simplified Model Spectra**
  - Limited set of hypothetical particles and decays
  - Less specific mass patterns and signatures
  - Give acceptance x efficiency and cross-section limit
  - Models proposed at: [http://www.lhcnewphysics.org](http://www.lhcnewphysics.org)

- **Hadronic searches**
  - Squark anti-squark pair production with decay
    - squark → quark + \( \chi^0 \)
  - Kinematics specified by masses
  - Direct case \( m_{\text{squark}} \) vs \( m_{\text{LSP}} \) 2D plot
  - For cascade decays (arbitrary but sensible) slices of intermediate particle
  - “Reference” cross sections (from PROSPINO) given to illustrate limits
● Clean way to communicate results of our searches and compare different channels → no hidden theory dependence
● Reference cross section scaled by 1/3 and 3 to demonstrate differences from spin or branching ration assumptions
● Areas of small mass splittings removed to reduce sensitivity to signal modelling

Photon(s) + MET

**Single photon + jets + MET:**

- $P_{T\gamma} > 80$ GeV
- $H_T (\geq 2$ Jets $) > 450$ GeV
- $\text{MET} > 100$ GeV

- QCD bkgd. dominant $\rightarrow$ shape from control samples - norm. at low MET

- $e \rightarrow \gamma$ fake rate measured on Z peak and used to estimate EWK bkgd.s.

**Diphoton + jet + MET:**

- $P_{T\gamma} > 40/25$ GeV
- At least one jet
- $\text{MET} > 50$ GeV

---

15 Dark Attack 2012 Workshop, 15 - 20 July 2012, Ascona, Switzerland.
**Photon(s) + MET**

### Table

<table>
<thead>
<tr>
<th></th>
<th>2γ MET &gt; 100 GeV</th>
<th>γ MET &gt; 350 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>SM</td>
<td>17.8 ± 12.4</td>
<td>14.6 ± 6.4</td>
</tr>
</tbody>
</table>

**GGM model (J. Ruderman, D. Shih arXiv:1103.6083)**

- Gravitino LSP
- Neutralino NLSP
- $\chi^0$ (bino/wino-like) gives $> 1$ photon (BR $\gamma$ vs $Z^0$)
- Limit for fixed $\chi^0$ mass of 375 GeV

---

**Single photon**

**Excluded**

**Diphoton**

---

16 Dark Attack 2012 Workshop, 15 - 20 July 2012, Ascona, Switzerland.
Photon(s) + MET

<table>
<thead>
<tr>
<th>2γ MET &gt; 100 GeV</th>
<th>γ MET &gt; 350 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>11</td>
</tr>
<tr>
<td>SM</td>
<td>17.8 ± 12.4</td>
</tr>
<tr>
<td></td>
<td>14.6 ± 6.4</td>
</tr>
</tbody>
</table>

GGM model (J. Ruderman, D. Shih arXiv:1103.6083)

- Gravitino LSP
- Neutralino NLSP
- $\chi^0$ (bino/wino-like) gives $> 1$ photon (BR $\gamma$ vs $Z^0$)
- Limit for fixed $\chi^0$ mass of 375 GeV

Data

- Single photon
- Diphoton
- SUS-12-018
Multileptons

- At least three high $p_T$ leptons e, $\mu$ and $\tau$ (require at least one e or $\mu$)
  - Many signal/control boxes considered:
    - MET (50 GeV)/ no MET, on/off Z peak, high $H_T$ (200 GeV)/no $H_T$, same-sign/opposite-sign/flavour
  - MET threshold determines control/signal for RPC/RPV search
  - Statistically combined for final limit

- Backgrounds
  - Irreducible: WZ+jets, ZZ+jets → estimated from simulation
  - $t\bar{t}$ → simulation with study in control regions
  - Z+jets, WW+jets, W+jets, QCD → data-driven fake rate

arXiv:1204.5341

Events/10 GeV

$\sqrt{s} = 7$ TeV, $L = 4.98$ fb$^{-1}$

Data

VV

$H_T$

$(Z\gamma^*)+Jet$

$(Z\gamma^*) \rightarrow l\gamma$

SM Unc.
Multileptons

GGM inspired model

- Gravitino LSP
- Mass degenerate slepton co-NLSPs
- $\chi^0$ (bino-like) NNLSP

Multilepton signatures from:

$$\chi^0 \rightarrow \tilde{l}^\pm l^\mp \rightarrow l^\mp + l^\pm + \tilde{G}$$
Multileptons

Only tracks with $p_T > 1$ GeV are displayed.
Multilepton searches constrain electroweak pair-production of SUSY particles.

Multileptons


SUS-11-016
Multilepton searches constrain electroweak pair-production of SUSY particles.

![Multilepton diagram]

<table>
<thead>
<tr>
<th>Chargino/Heavy Neutralino Mass [GeV]</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ (95% CL upper limit)</td>
<td>10^4</td>
<td>10^3</td>
<td>10^2</td>
<td>10^1</td>
<td>10^0</td>
</tr>
</tbody>
</table>

CMS Preliminary

m_{LSP} = 0 [GeV] | m_{\tilde{\chi}^0} = 0.5 m_{LSP} + 0.5 m_{\tilde{\chi}_1^0}

SUS-11-016
Multilepton searches constrain electroweak pair-production of SUSY particles

![Multilepton Diagrams](image)

---

Multileptons

Multilepton searches constrain electroweak pair-production of SUSY particles

Multileptons

CMS Preliminary

\[ \sqrt{s} = 7 \text{ TeV} \int \frac{\mathrm{d}t}{\mathrm{d}x} = 4.98 \text{ fb} \]

\[ \text{m}(\tilde{\chi}^0) \geq \text{multilepton(NLO)} \]

\[ \text{m}(\tilde{\chi}^0) = 0 \text{ [GeV]} \]

\[ \text{m}(\tilde{\chi}^0) = 0.5 \text{ m}(\tilde{\chi}^0) + 0.5 \text{ m}(\tilde{\chi}^0) \]

95\% CL upper limit on \( \sigma \)

(pp -> \( \tilde{\chi}^0 \tilde{\chi}^0 \))

L dt = 4.98 fb

\[ \int = 7 \text{ TeV} \]

SUS-11-016
Monojets/monophotons

- Dark matter production at LHC
Monojets/monophotons

- Dark matter production at LHC

- Selection
  - $P_T^{\gamma} > 145 \text{ GeV}$
  - $\text{MET} > 130 \text{ GeV}$
  - Veto on jets ($p_T > 30 \text{ GeV}$)

---

<table>
<thead>
<tr>
<th>Source</th>
<th>Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Mimics Photon</td>
<td>11.2 ± 2.8</td>
</tr>
<tr>
<td>Beam Halo</td>
<td>11.1 ± 5.6</td>
</tr>
<tr>
<td>Electron Mimics Photon</td>
<td>3.5 ± 1.5</td>
</tr>
<tr>
<td>$W\gamma$</td>
<td>3.0 ± 1.0</td>
</tr>
<tr>
<td>$\gamma$ + jet</td>
<td>0.5 ± 0.2</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>0.6 ± 0.3</td>
</tr>
<tr>
<td>$Z(\nu\bar{\nu})\gamma$</td>
<td>45.3 ± 6.9</td>
</tr>
<tr>
<td>Total Background</td>
<td>75.1 ± 9.5</td>
</tr>
<tr>
<td>Total Observed Candidates</td>
<td>73</td>
</tr>
</tbody>
</table>
Monojets/monophotons

- Dark matter production at LHC

- Selection
  - One or two jets with $p_T > 100$ (30) GeV
  - MET $> 200$ GeV
  - $\Delta\phi$ between jets $< 2.4$

<table>
<thead>
<tr>
<th>$E_{\text{miss}}$ (GeV) $\rightarrow$</th>
<th>$\geq 250$</th>
<th>$\geq 300$</th>
<th>$\geq 350$</th>
<th>$\geq 400$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>Events</td>
<td>Events</td>
<td>Events</td>
<td>Events</td>
</tr>
<tr>
<td>$Z(\nu\nu)+$jets</td>
<td>5106 ± 271</td>
<td>1908 ± 143</td>
<td>900 ± 94</td>
<td>433 ± 62</td>
</tr>
<tr>
<td>$W+$jets</td>
<td>2632 ± 237</td>
<td>816 ± 83</td>
<td>312 ± 35</td>
<td>135 ± 17</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>69.8 ± 69.8</td>
<td>22.6 ± 22.6</td>
<td>8.5 ± 8.5</td>
<td>3.0 ± 3.0</td>
</tr>
<tr>
<td>$Z(t\bar{t})+$jets</td>
<td>22.3 ± 22.3</td>
<td>6.1 ± 6.1</td>
<td>2.0 ± 2.0</td>
<td>0.6 ± 0.6</td>
</tr>
<tr>
<td>Single t</td>
<td>10.2 ± 10.2</td>
<td>2.7 ± 2.7</td>
<td>1.1 ± 1.1</td>
<td>0.4 ± 0.4</td>
</tr>
<tr>
<td>QCD Multijets</td>
<td>2.2 ± 2.2</td>
<td>1.3 ± 1.3</td>
<td>1.3 ± 1.3</td>
<td>1.3 ± 1.3</td>
</tr>
<tr>
<td>Total SM</td>
<td>7842 ± 367</td>
<td>2757 ± 167</td>
<td>1225 ± 101</td>
<td>573 ± 65</td>
</tr>
<tr>
<td>Data</td>
<td>7584</td>
<td>2774</td>
<td>1142</td>
<td>522</td>
</tr>
<tr>
<td>Expected upper limit non-SM</td>
<td>779</td>
<td>325</td>
<td>200</td>
<td>118</td>
</tr>
<tr>
<td>Observed upper limit non-SM</td>
<td>600</td>
<td>368</td>
<td>158</td>
<td>95</td>
</tr>
</tbody>
</table>

arXiv:1206.5663

$\bar{q}$ \rightarrow \chi \rightarrow q \chi$
- Interpret searches in contact interaction model (Bai et al. JHEP 1012:048(2010))
- Independent of astrophysical experiments
- CMS results extend to lower masses
- Strong constraints on spin-dependent cross section
Results at a glance

Hadronic searches

CMS Preliminary

<table>
<thead>
<tr>
<th>Search</th>
<th>Signal Region</th>
<th>Mass Scales [GeV]</th>
<th>Cross Section</th>
<th>Decay Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1: $\tilde{g} \rightarrow q\bar{q}X^0$</td>
<td>$E_T + jets$, 1.1 fb$^{-1}$, gluino</td>
<td>0 - 1000</td>
<td>1.1 fb$^{-1}$</td>
<td>gluino</td>
</tr>
<tr>
<td>T1: $\tilde{g} \rightarrow q\bar{q}X^0$</td>
<td>$E_T + b$, 1.1 fb$^{-1}$, gluino</td>
<td>0 - 1000</td>
<td>1.1 fb$^{-1}$</td>
<td>gluino</td>
</tr>
<tr>
<td>T1: $\tilde{g} \rightarrow q\bar{q}X^0$</td>
<td>MT2, 1.1 fb$^{-1}$, gluino</td>
<td>0 - 1000</td>
<td>1.1 fb$^{-1}$</td>
<td>gluino</td>
</tr>
<tr>
<td>T2: $\tilde{g} \rightarrow q\bar{q}X^0$</td>
<td>$E_T + jets$, 1.1 fb$^{-1}$, squark</td>
<td>0 - 1000</td>
<td>1.1 fb$^{-1}$</td>
<td>squark</td>
</tr>
<tr>
<td>T2: $\tilde{g} \rightarrow q\bar{q}X^0$</td>
<td>$E_T + b$, 1.1 fb$^{-1}$, squark</td>
<td>0 - 1000</td>
<td>1.1 fb$^{-1}$</td>
<td>squark</td>
</tr>
<tr>
<td>T5zz: $\tilde{g} \rightarrow q\bar{q}X^0$</td>
<td>$E_T + jets$, 1.1 fb$^{-1}$, gluino</td>
<td>0 - 1000</td>
<td>1.1 fb$^{-1}$</td>
<td>gluino</td>
</tr>
</tbody>
</table>

Leptonic searches

CMS Preliminary

<table>
<thead>
<tr>
<th>Search</th>
<th>Signal Region</th>
<th>Mass Scales [GeV]</th>
<th>Cross Section</th>
<th>Decay Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1tttt: $\tilde{g} \rightarrow t\bar{t}X^0$</td>
<td>SS+b, 4.98 fb$^{-1}$, gluino</td>
<td>0 - 1000</td>
<td>4.98 fb$^{-1}$</td>
<td>gluino</td>
</tr>
<tr>
<td>T3w: $\tilde{g} \rightarrow qq(W)\chi^0$</td>
<td>$e/\mu$ spectrum, 4.98 fb$^{-1}$, gluino</td>
<td>0 - 1000</td>
<td>4.98 fb$^{-1}$</td>
<td>gluino</td>
</tr>
<tr>
<td>T3Lh: $\tilde{g} \rightarrow qqX^0\chi^0_2$</td>
<td>$l^\pm l^\mp$ edge, 4.98 fb$^{-1}$, gluino</td>
<td>0 - 1000</td>
<td>4.98 fb$^{-1}$</td>
<td>gluino</td>
</tr>
<tr>
<td>T3Lh: $\tilde{g} \rightarrow qqX^0\chi^0_2$</td>
<td>$l^\pm + E_T$, 4.98 fb$^{-1}$, gluino</td>
<td>0 - 1000</td>
<td>4.98 fb$^{-1}$</td>
<td>gluino</td>
</tr>
<tr>
<td>T5zz: $\tilde{g} \rightarrow qqX^0\chi^0_2$</td>
<td>$Z+E_T$, 4.98 fb$^{-1}$, gluino</td>
<td>0 - 1000</td>
<td>4.98 fb$^{-1}$</td>
<td>gluino</td>
</tr>
<tr>
<td>T5zz: $\tilde{g} \rightarrow qqX^0\chi^0_2$</td>
<td>JZB, 4.98 fb$^{-1}$, gluino</td>
<td>0 - 1000</td>
<td>4.98 fb$^{-1}$</td>
<td>gluino</td>
</tr>
<tr>
<td>T5Lnu: $\tilde{g} \rightarrow qq\chi^\pm_2 \to ll\chi^0_2\chi^0_0$</td>
<td>$l^\pm l^\mp$, 4.98 fb$^{-1}$, gluino</td>
<td>0 - 1000</td>
<td>4.98 fb$^{-1}$</td>
<td>neutralino/chargino</td>
</tr>
<tr>
<td>TChiSlep: $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm \rightarrow lll\chi^0_1$</td>
<td>multilepton, 4.98 fb$^{-1}$, neutralino/chargino</td>
<td>0 - 1000</td>
<td>4.98 fb$^{-1}$</td>
<td>neutralino/chargino</td>
</tr>
</tbody>
</table>

SUS-11-016

29 Dark Attack 2012 Workshop, 15 - 20 July 2012, Ascona, Switzerland.
Summary

- Wide range of MET based searches performed with 5 fb$^{-1}$ 2011 data
  - No significant deviation from the Standard Model
- Larger data samples
  - Weak production modes
  - More exclusive channels
- 14 TeV collisions
  - Larger reach
- LHC running well in 2012

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

30 Dark Attack 2012 Workshop, 15 - 20 July 2012, Ascona, Switzerland.
## Jets + MET Results

<table>
<thead>
<tr>
<th>Selection $H_T$ (GeV)</th>
<th>$p_T$ (GeV)</th>
<th>$Z \rightarrow \nu \bar{\nu}$ from $\gamma +$ jets</th>
<th>$t\bar{t}/W \rightarrow e, \mu + X$</th>
<th>$t\bar{t}/W \rightarrow \tau_{had} + X$</th>
<th>QCD multijets</th>
<th>Total background</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>500–800</td>
<td>200–350</td>
<td>359.2 ± 82.2</td>
<td>326.5 ± 47.0</td>
<td>348.5 ± 40.1</td>
<td>118.6 ± 76.9</td>
<td>1152.8 ± 128.4</td>
<td>1269</td>
</tr>
<tr>
<td>500–800</td>
<td>350–500</td>
<td>112.3 ± 27.4</td>
<td>47.8 ± 9.2</td>
<td>62.5 ± 8.7</td>
<td>2.2 ± 2.2</td>
<td>224.8 ± 30.3</td>
<td>236</td>
</tr>
<tr>
<td>500–800</td>
<td>500–600</td>
<td>17.6 ± 5.6</td>
<td>5.0 ± 2.2</td>
<td>8.7 ± 2.5</td>
<td>0.0 ± 0.1</td>
<td>31.3 ± 6.5</td>
<td>22</td>
</tr>
<tr>
<td>500–800</td>
<td>&gt;600</td>
<td>5.5 ± 3.1</td>
<td>0.8 ± 0.8</td>
<td>2.0 ± 1.8</td>
<td>0.0 ± 0.0</td>
<td>8.3 ± 3.6</td>
<td>6</td>
</tr>
<tr>
<td>800–1000</td>
<td>200–350</td>
<td>48.4 ± 19.1</td>
<td>57.7 ± 15.3</td>
<td>56.3 ± 8.3</td>
<td>34.6 ± 24.0</td>
<td>197.0 ± 35.3</td>
<td>177</td>
</tr>
<tr>
<td>800–1000</td>
<td>350–500</td>
<td>16.0 ± 7.3</td>
<td>5.4 ± 2.3</td>
<td>7.2 ± 2.0</td>
<td>1.2 ± 1.3</td>
<td>29.8 ± 8.0</td>
<td>24</td>
</tr>
<tr>
<td>800–1000</td>
<td>500–600</td>
<td>7.1 ± 4.5</td>
<td>2.4 ± 1.5</td>
<td>1.3 ± 0.6</td>
<td>0.0 ± 0.2</td>
<td>10.8 ± 4.8</td>
<td>6</td>
</tr>
<tr>
<td>800–1000</td>
<td>&gt;600</td>
<td>3.3 ± 2.0</td>
<td>0.7 ± 0.7</td>
<td>1.0 ± 0.3</td>
<td>0.0 ± 0.1</td>
<td>5.0 ± 2.2</td>
<td>5</td>
</tr>
<tr>
<td>1000–1200</td>
<td>200–350</td>
<td>10.9 ± 5.5</td>
<td>13.7 ± 3.8</td>
<td>21.9 ± 4.6</td>
<td>19.7 ± 13.3</td>
<td>66.2 ± 15.5</td>
<td>71</td>
</tr>
<tr>
<td>1000–1200</td>
<td>350–500</td>
<td>5.5 ± 3.5</td>
<td>5.0 ± 4.4</td>
<td>2.9 ± 1.3</td>
<td>0.4 ± 0.7</td>
<td>13.8 ± 5.8</td>
<td>12</td>
</tr>
<tr>
<td>1000–1200</td>
<td>&gt;500</td>
<td>2.2 ± 2.9</td>
<td>1.6 ± 1.2</td>
<td>2.3 ± 1.0</td>
<td>0.0 ± 0.2</td>
<td>6.1 ± 3.3</td>
<td>4</td>
</tr>
<tr>
<td>1200–1400</td>
<td>200–350</td>
<td>3.1 ± 2.0</td>
<td>4.2 ± 2.1</td>
<td>6.2 ± 1.8</td>
<td>11.7 ± 8.3</td>
<td>25.2 ± 9.0</td>
<td>29</td>
</tr>
<tr>
<td>1200–1400</td>
<td>&gt;350</td>
<td>2.3 ± 2.3</td>
<td>2.3 ± 1.4</td>
<td>0.6 ± 0.8</td>
<td>0.2 ± 0.6</td>
<td>5.4 ± 2.9</td>
<td>8</td>
</tr>
<tr>
<td>&gt;1400</td>
<td>&gt;200</td>
<td>3.2 ± 2.4</td>
<td>2.7 ± 1.6</td>
<td>1.1 ± 0.5</td>
<td>12.0 ± 9.1</td>
<td>19.0 ± 9.6</td>
<td>16</td>
</tr>
</tbody>
</table>
## Multilepton results

<table>
<thead>
<tr>
<th>Selection</th>
<th>N(τ)=0</th>
<th>N(τ)=1</th>
<th>N(τ)=2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>obs</td>
<td>expect</td>
<td>obs</td>
</tr>
<tr>
<td>4f (DY0) S(τ)(High)</td>
<td>0 0.0010 ± 0.0009</td>
<td>0 0.01 ± 0.09</td>
<td>0 0.18 ± 0.07</td>
</tr>
<tr>
<td>4f (DY0) S(τ)(Mid)</td>
<td>0 0.004 ± 0.002</td>
<td>0 0.28 ± 0.10</td>
<td>0 2.5 ± 1.2</td>
</tr>
<tr>
<td>4f (DY0) S(τ)(Low)</td>
<td>0 0.04 ± 0.02</td>
<td>0 2.98 ± 0.48</td>
<td>0 3.5 ± 1.1</td>
</tr>
<tr>
<td>4f (DY1, no Z) S(τ)(High)</td>
<td>1 0.009 ± 0.004</td>
<td>0 0.10 ± 0.07</td>
<td>0 0.12 ± 0.05</td>
</tr>
<tr>
<td>4f (DY1, Z) S(τ)(High)</td>
<td>1 0.09 ± 0.01</td>
<td>0 0.51 ± 0.15</td>
<td>0 0.43 ± 0.15</td>
</tr>
<tr>
<td>4f (DY1, no Z) S(τ)(Mid)</td>
<td>0 0.07 ± 0.02</td>
<td>1 0.88 ± 0.26</td>
<td>1 0.94 ± 0.29</td>
</tr>
<tr>
<td>4f (DY1, Z) S(τ)(Mid)</td>
<td>0 0.45 ± 0.11</td>
<td>5 4.1 ± 1.2</td>
<td>3 3.4 ± 0.9</td>
</tr>
<tr>
<td>4f (DY1, no Z) S(τ)(Low)</td>
<td>0 0.09 ± 0.04</td>
<td>7 5.5 ± 2.2</td>
<td>19 13.7 ± 6.4</td>
</tr>
<tr>
<td>4f (DY1, Z) S(τ)(Low)</td>
<td>2 0.80 ± 0.34</td>
<td>19 17.7 ± 4.9</td>
<td>95 60 ± 31</td>
</tr>
<tr>
<td>4f (DY2, no Z) S(τ)(High)</td>
<td>0 0.02 ± 0.01</td>
<td>– – – –</td>
<td>– – – –</td>
</tr>
<tr>
<td>4f (DY2, Z) S(τ)(High)</td>
<td>0 0.89 ± 0.34</td>
<td>– – – –</td>
<td>– – – –</td>
</tr>
<tr>
<td>4f (DY2, no Z) S(τ)(Mid)</td>
<td>0 0.20 ± 0.09</td>
<td>– – – –</td>
<td>– – – –</td>
</tr>
<tr>
<td>4f (DY2, Z) S(τ)(Mid)</td>
<td>3 7.9 ± 3.2</td>
<td>– – – –</td>
<td>– – – –</td>
</tr>
<tr>
<td>4f (DY2, no Z) S(τ)(Low)</td>
<td>1 2.4 ± 1.1</td>
<td>– – – –</td>
<td>– – – –</td>
</tr>
<tr>
<td>4f (DY2, Z) S(τ)(Low)</td>
<td>29 29 ± 12</td>
<td>– – – –</td>
<td>– – – –</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Selection</th>
<th>N(τ)=0</th>
<th>N(τ)=1</th>
<th>N(τ)=2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>obs</td>
<td>expect</td>
<td>obs</td>
</tr>
<tr>
<td>3f (DY0) S(τ)(High)</td>
<td>2 1.14 ± 0.43</td>
<td>17 11.2 ± 3.2</td>
<td>20 22.5 ± 6.1</td>
</tr>
<tr>
<td>3f (DY0) S(τ)(Mid)</td>
<td>5 7.4 ± 3.0</td>
<td>113 97 ± 31</td>
<td>157 181 ± 24</td>
</tr>
<tr>
<td>3f (DY0) S(τ)(Low)</td>
<td>17 13.5 ± 4.1</td>
<td>522 419 ± 63</td>
<td>1631 2018 ± 253</td>
</tr>
<tr>
<td>3f (DY1, no Z) S(τ)(High)</td>
<td>6 3.5 ± 0.9</td>
<td>10 13.1 ± 2.3</td>
<td>– – – –</td>
</tr>
<tr>
<td>3f (DY1, Z) S(τ)(High)</td>
<td>17 18.7 ± 6.0</td>
<td>35 39.2 ± 4.8</td>
<td>– – – –</td>
</tr>
<tr>
<td>3f (DY1, no Z) S(τ)(Mid)</td>
<td>32 25.5 ± 6.6</td>
<td>159 141 ± 27</td>
<td>– – – –</td>
</tr>
<tr>
<td>3f (DY1, Z) S(τ)(Mid)</td>
<td>32 25.5 ± 6.6</td>
<td>159 141 ± 27</td>
<td>– – – –</td>
</tr>
<tr>
<td>3f (DY1, no Z) S(τ)(Low)</td>
<td>126 150 ± 36</td>
<td>3721 2983 ± 418</td>
<td>– – – –</td>
</tr>
<tr>
<td>3f (DY1, Z) S(τ)(Low)</td>
<td>727 815 ± 192</td>
<td>17631 15758 ± 2452</td>
<td>– – – –</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Selection</th>
<th>N(τ)=0</th>
<th>N(τ)=1</th>
<th>N(τ)=2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>obs</td>
<td>expect</td>
<td>obs</td>
</tr>
<tr>
<td>4f &gt;50,&gt;200, no Z</td>
<td>0 0.018 ± 0.005</td>
<td>0 0.09 ± 0.06</td>
<td>0 0.7 ± 0.7</td>
</tr>
<tr>
<td>4f &gt;50,&gt;200, Z</td>
<td>0 0.22 ± 0.05</td>
<td>0 0.27 ± 0.11</td>
<td>0 0.8 ± 1.2</td>
</tr>
<tr>
<td>4f &gt;50,&gt;200, no Z</td>
<td>1 0.20 ± 0.07</td>
<td>3 0.59 ± 0.17</td>
<td>1 1.5 ± 0.6</td>
</tr>
<tr>
<td>4f &gt;50,&gt;200, Z</td>
<td>1 0.70 ± 0.21</td>
<td>4 2.3 ± 0.7</td>
<td>0 11 ± 0.7</td>
</tr>
<tr>
<td>4f &gt;50,&gt;200, no Z</td>
<td>0 0.006 ± 0.001</td>
<td>0 0.14 ± 0.08</td>
<td>0 0.25 ± 0.07</td>
</tr>
<tr>
<td>4f &gt;50,&gt;200, Z</td>
<td>1 0.83 ± 0.33</td>
<td>0 0.55 ± 0.21</td>
<td>0 1.14 ± 0.42</td>
</tr>
<tr>
<td>4f &lt;50,&gt;200, no Z</td>
<td>1 2.6 ± 1.1</td>
<td>5 3.9 ± 1.2</td>
<td>17 10.6 ± 3.2</td>
</tr>
<tr>
<td>4f &lt;50,&gt;200, Z</td>
<td>33 37 ± 15</td>
<td>20 17.0 ± 5.2</td>
<td>62 43 ± 16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Selection</th>
<th>N(τ)=0</th>
<th>N(τ)=1</th>
<th>N(τ)=2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>obs</td>
<td>expect</td>
<td>obs</td>
</tr>
<tr>
<td>3f &gt;50,&gt;200,no-OSSF</td>
<td>2 1.5 ± 0.5</td>
<td>33 30.4 ± 9.7</td>
<td>15 13.5 ± 2.6</td>
</tr>
<tr>
<td>3f &gt;50,&gt;200,no-OSSF</td>
<td>7 6.6 ± 2.3</td>
<td>159 143 ± 37</td>
<td>82 106 ± 16</td>
</tr>
<tr>
<td>3f &lt;50,&gt;200,no-OSSF</td>
<td>1 1.2 ± 0.7</td>
<td>16 16.9 ± 4.5</td>
<td>18 31.9 ± 4.8</td>
</tr>
<tr>
<td>3f &lt;50,&gt;200,no-OSSF</td>
<td>14 11.7 ± 3.6</td>
<td>446 356 ± 55</td>
<td>1006 1026 ± 171</td>
</tr>
<tr>
<td>3f &gt;50,&gt;200, no Z</td>
<td>8 5.0 ± 1.3</td>
<td>16 31.7 ± 9.6</td>
<td>– – – –</td>
</tr>
<tr>
<td>3f &gt;50,&gt;200, no Z</td>
<td>14 11.7 ± 3.6</td>
<td>446 356 ± 55</td>
<td>1006 1026 ± 171</td>
</tr>
<tr>
<td>3f &gt;50,&gt;200, no Z</td>
<td>30 27.0 ± 7.6</td>
<td>114 107 ± 27</td>
<td>– – – –</td>
</tr>
<tr>
<td>3f &gt;50,&gt;200, no Z</td>
<td>11 4.5 ± 1.5</td>
<td>45 51.9 ± 6.2</td>
<td>– – – –</td>
</tr>
<tr>
<td>3f &gt;50,&gt;200, no Z</td>
<td>141 134 ± 50</td>
<td>107 114 ± 16</td>
<td>– – – –</td>
</tr>
<tr>
<td>3f &lt;50,&gt;200, no Z</td>
<td>15 19.2 ± 4.8</td>
<td>166 244 ± 24</td>
<td>– – – –</td>
</tr>
<tr>
<td>3f &lt;50,&gt;200, no Z</td>
<td>123 144 ± 36</td>
<td>3721 2907 ± 412</td>
<td>– – – –</td>
</tr>
<tr>
<td>3f &lt;50,&gt;200, no Z</td>
<td>657 764 ± 183</td>
<td>17857 15519 ± 2421</td>
<td>– – – –</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Selection</th>
<th>N(τ)=0</th>
<th>N(τ)=1</th>
<th>N(τ)=2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>obs</td>
<td>expect</td>
<td>obs</td>
</tr>
<tr>
<td>Total 4f</td>
<td>37 42 ± 15</td>
<td>32.0 24.9 ± 5.4</td>
<td>80 59 ± 16</td>
</tr>
<tr>
<td>Total 3f</td>
<td>1029 1138 ± 193</td>
<td>22693 19545 ± 2457</td>
<td>1121 1177 ± 172</td>
</tr>
<tr>
<td>Total 3f</td>
<td>1066 1180 ± 194</td>
<td>22725 19570 ± 2457</td>
<td>1201 1236 ± 173</td>
</tr>
</tbody>
</table>

---

33 Dark Attack 2012 Workshop, 15 - 20 July 2012, Ascona, Switzerland.
### Monophoton/monojet results

<table>
<thead>
<tr>
<th>$M_X$ [GeV]</th>
<th>Vector $\sigma$ [fb]</th>
<th>$\Lambda$ [GeV]</th>
<th>Axial-Vector $\sigma$ [fb]</th>
<th>$\Lambda$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.3 (14.7)</td>
<td>572 (568)</td>
<td>14.9 (15.4)</td>
<td>565 (561)</td>
</tr>
<tr>
<td>10</td>
<td>14.3 (14.7)</td>
<td>571 (567)</td>
<td>14.1 (14.5)</td>
<td>573 (569)</td>
</tr>
<tr>
<td>100</td>
<td>15.4 (15.3)</td>
<td>558 (558)</td>
<td>13.9 (14.3)</td>
<td>554 (550)</td>
</tr>
<tr>
<td>200</td>
<td>14.3 (14.7)</td>
<td>549 (545)</td>
<td>14.0 (14.5)</td>
<td>508 (504)</td>
</tr>
<tr>
<td>500</td>
<td>13.6 (14.0)</td>
<td>442 (439)</td>
<td>13.7 (14.1)</td>
<td>358 (356)</td>
</tr>
<tr>
<td>1000</td>
<td>14.1 (14.5)</td>
<td>246 (244)</td>
<td>13.9 (14.3)</td>
<td>172 (171)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$M_X$ (GeV/c²)</th>
<th>Spin-dependent $\sigma_{YN}$ (cm²)</th>
<th>Spin-independent $\sigma_{YN}$ (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>754 $1.03 \times 10^{-42}$</td>
<td>749 $2.90 \times 10^{-41}$</td>
</tr>
<tr>
<td>1</td>
<td>755 $2.94 \times 10^{-41}$</td>
<td>751 $8.21 \times 10^{-40}$</td>
</tr>
<tr>
<td>10</td>
<td>765 $8.79 \times 10^{-41}$</td>
<td>760 $2.47 \times 10^{-39}$</td>
</tr>
<tr>
<td>100</td>
<td>736 $1.21 \times 10^{-40}$</td>
<td>764 $2.83 \times 10^{-39}$</td>
</tr>
<tr>
<td>200</td>
<td>677 $1.70 \times 10^{-40}$</td>
<td>736 $3.31 \times 10^{-39}$</td>
</tr>
<tr>
<td>300</td>
<td>602 $2.73 \times 10^{-40}$</td>
<td>690 $4.30 \times 10^{-39}$</td>
</tr>
<tr>
<td>400</td>
<td>524 $4.74 \times 10^{-40}$</td>
<td>631 $6.15 \times 10^{-39}$</td>
</tr>
<tr>
<td>700</td>
<td>341 $2.65 \times 10^{-39}$</td>
<td>455 $2.28 \times 10^{-38}$</td>
</tr>
<tr>
<td>1000</td>
<td>206 $1.98 \times 10^{-38}$</td>
<td>302 $1.18 \times 10^{-37}$</td>
</tr>
</tbody>
</table>
CMSSM event topologies

Anatomy of CMSSM, jets + $H_T$

- Charginos/neutralinos
- Squarks
- Associate production
- Gluinos

$m_{1/2}$ vs. $m_0$
Multilepton co-NLSP Model

- Right-handed sleptons are flavour degenerate and NLSP
- Neutralino (bino-like) NNLSP
- Chargino mass twice neutralino mass
- Higgsinos are decoupled
- SUSY production proceeds mainly through pairs of squarks and/or gluinos.
- Cascade decays of these states eventually pass sequentially through the lightest neutralino ($g\tilde{\gamma}, q\tilde{\gamma} \rightarrow \chi^0 + X$)
- Decays into a slepton and a lepton ($\chi^0 \rightarrow \tilde{l}^\pm l^\mp$).
- Each of the degenerate right-handed sleptons decays to the Goldstino component of the massless and non-interacting gravitino and a lepton ($\tilde{l} \rightarrow G\tilde{l}$)
Photon GGM Model

- Gravitino LSP
- Neutralino NLSP
  - Bino-like gives \( \text{BR}(\gamma) \gg \text{BR}(Z) \rightarrow \) two photons \( \gg \gamma + Z \) (\( \rightarrow \) jets, leptons)
  - Wino-like gives \( \text{BR}(Z) \gg \text{BR}(\gamma) \rightarrow \gamma + Z \) (\( \rightarrow \) jets, leptons)
  - Wino-like NLSP also chargino co-NLSP \( \rightarrow \gamma + W \) (\( \rightarrow \) jets, leptons)
  - Higgsino gives \( h^0 \) or \( Z \rightarrow \) BR depends on \( \tan\beta \) and sign(\( \mu \))

![Bino and Neutral Wino NLSP Decays](attachment:image.png)
EWKino Model

Haber & Kane Physics Report Volume 117, pages 75-265 (1985)
[from Frank Wuerthwein]

(a) \[ W^+ \rightarrow \tilde{\chi}_i^+ \tilde{\chi}_j^0 \]
\[ \frac{i}{2} \gamma^\mu \left[ O^L_{ij}(1-\gamma_5) + O^R_{ij}(1+\gamma_5) \right] \]

Couples to all neutralino and chargino mass eigenstates

(c) \[ Z^0 \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0 \]
\[ \frac{i}{2 \cos \theta_w} \gamma^\mu \left[ O^L_{ij}(1-\gamma_5) + O^R_{ij}(1+\gamma_5) \right] \]

Couples to Higgsino neutralino mass eigenstates

- For WZ maximal Wino couplings (pure wino-like) and maximal Higgsino couplings (even split of two electroweak eigenstates)
- For ZZ maximal Higgsino couplings (even split of two electroweak eigenstates)
- Set chargino/heavy neutralino masses equal, light neutralino=0 and slepton mass in between
Monophoton/monojet Model

- Pair production of DM contact interaction with operators

\[ \mathcal{O}_V = \frac{\bar{\chi} \gamma \mu \chi}{\Lambda^2} \]  
vector → spin independent

\[ \mathcal{O}_{AV} = \frac{\bar{\chi} \gamma \mu \gamma_5 \chi}{\Lambda^2} \]  
axial-vector → spin dependent

- Cross sections depend on mass \( m_\chi \) and scale \( \Lambda \) (couplings)

\[ \sigma_{SI} = 9 \frac{\mu^2}{\pi \Lambda^4} \]
\[ \sigma_{SD} = 0.33 \frac{\mu^2}{\pi \Lambda^4} \]

\[ \Lambda = M / \sqrt{g_\chi g_q} \]
\[ \mu = \frac{m_\chi m_p}{m_\chi + m_p} \]

- \( M=10(40) \) TeV for monophoton(jet) analysis