Probing Dark Matter at the LHC

Alex Tapper
Outline

• The LHC and ATLAS and CMS detectors

• Detector performance and Standard Model physics

• Status of Dark Matter searches at the LHC
  ▪ MET based searches
  ▪ Long-lived particle searches

• Future prospects and connection to cosmology

• Summary and outlook
The Large Hadron Collider

Overall view of the LHC experiments.

3.5 TeV  3.5 TeV

CMS

ATLAS

ALICE

LEP/LHC

T1 8

SPS

T1 2

LHC - B

Point 8

CERN

Point 1

ATLAS

Point 2

ALICE

Point 2

CMS

Point 5

LHC - B

Point 8

CERN

Point 1

ATLAS

Point 2

ALICE

Point 2

CMS

Point 5

International Workshop on Linear Colliders, 18-22 October 2010, Geneva, Switzerland.
The Large Hadron Collider

3.5 TeV p 3.5 TeV

So far 20 pb$^{-1}$

Another ~ week to go in 2010 pp run

Search results from 70-230 nb$^{-1}$
ATLAS and CMS detectors

- 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


- 2T solenoid & toroid magnets
- Silicon detector (pixel, strips) & TRT
- LAr ECAL $\sigma(E)/E = 10%/\sqrt{E} + 0.007$
- Tile/sci. HCAL $\sigma(E)/E = 50%/\sqrt{E} + 0.03$
- Muon chambers $\sigma(p)/p < 10\%$ at 1TeV

JINST3:S08004 (2008)
ATLAS and CMS detectors

- Muon chambers
- Solenoid magnet
- Transition radiation tracker
- Pixel detector
- LAr electromagnetic calorimeters
- Tile calorimeters
- LAr hadronic end-cap and forward calorimeters
- Toroid magnets
- Semiconductor tracker

International Workshop on Linear Colliders, 18-22 October 2010, Geneva, Switzerland.
• 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
• 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

CMS PAS-TOP-10-004

CMS PAS-PFT-10-004

Events / 9.0 GeV/c²

CMS Preliminary 2010
$L_{\text{int}} = 1.7 \text{ pb}^{-1}, \sqrt{s} = 7 \text{ TeV}$

Jet multiplicity

visible Mass[GeV/c²]
What can we search for?
- Detectors designed for discovery of particles in GeV to TeV range
- Luminosities give lower bound production cross sections

WIMP dark matter
- Neutralinos, KK particles, Little Higgs…
- Missing energy signatures
- Difficult to distinguish between different types of candidate

Gravitinos/axinos...
- Hints possible from long-lived particles
- Distinctive signatures in detector

WIMP dark matter

- WIMPS neutral and weakly interacting so difficult to observe
- Direct production has small cross section and no signal in detector
- Production in conjunction with Standard Model particles better option for detection
- Design searches
MET based searches

- Production
  - Pair-produce new heavy particles
  - Strong production so high cross section
  - Cross section depends only on masses
  - Approx. independent of model
**MET based searches**

- **Production**
  - Pair-produce new heavy particles
  - Strong production so high cross section
  - Cross section depends only on masses
  - Approx. independent of model

- **Decay**
  - Details of decay chain depend on model (mass spectra, branching ratios, etc.)
  - Some conserved quantum number needed for dark matter (R-parity, T-parity, KK-parity…)
  - Assume original particles are heavy (since we haven’t detected them) ➔ long decay chains

- **Signatures**
  - MET from dark matter candidate, high-\(E_T\) jets and leptons from long decay chain

- **Focus on robust and simple signatures**
  - Common to wide variety of models
Jets + MET searches

- All-hadronic search highly sensitive, but suffers from many backgrounds
- Reach beyond Tevatron with 2010 data
- Reach up to masses of ~800 GeV with 1 fb$^{-1}$
Jets + MET searches

- Simple (ignoring lots of things) jet cuts (anti-\(k_T\) R=0.4)
  - Leading jet \(E_T>70\) GeV
  - Other jets \(E_T>30\) GeV
- Veto isolated leptons (\(P_T>10\) GeV)
- QCD MC normalised to data in two jet channel (uncertainty neglected)
Jets + MET searches

- **Further selection**
  - MET > 40 GeV
  - \( \text{MET}/M_{\text{eff}} > 0.3(0.2) \)

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<td>Data</td>
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<td>23 000</td>
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<td>( ^{+3100}_{-25000} )</td>
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<td>( E_T^{\text{miss}} ) cut</td>
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<td>46 ( ^{+22}_{-14} )</td>
<td>650</td>
<td>450 ( ^{+190}_{-120} )</td>
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<td>( \Delta\phi ) and ( E_T^{\text{miss}} ) cuts</td>
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<td>–</td>
<td>280</td>
<td>200 ( ^{+110}_{-65} )</td>
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<td>4</td>
<td>6.6 ( ^{+3}_{-3} )</td>
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**Integral over 50 GeV**

- **Two Jet Channel**
  - *ATLAS Preliminary*
  - Data 2010 \( \sqrt{s} = 7 \text{ TeV} \)
  - Monte Carlo
  - QCD
  - W+jets
  - Z+jets
  - \( t\bar{t} \) (x10)

- **Four Jet Channel**
  - *ATLAS Preliminary*
  - Data 2010 \( \sqrt{s} = 7 \text{ TeV} \)
  - Monte Carlo
  - QCD
  - W+jets
  - Z+jets
  - \( t\bar{t} \) (x10)

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17 International Workshop on Linear Colliders, 18-22 October 2010, Geneva, Switzerland.
Single-lepton + MET search

- Requiring one lepton (e or μ) suppresses QCD background powerfully
- Highly sensitive to SUSY
- Backgrounds come from Standard Model processes with neutrinos → real MET
- In particular top and W decays
Simple cuts (once again too lazy to list cleaning, triggers...)

- One isolated lepton with $P_T > 20$ GeV
- At least two jets $E_T > 30$ GeV

QCD MC normalised to data at MET < 40 GeV and $M_T < 40$ GeV

Uncertainty 50% from fake rate study comparison with data
Single-lepton + MET search

- **Further selection**
  - MET $> 30$ GeV
  - $M_T > 100$ GeV

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<th>Muon channel Monte Carlo</th>
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<td>157 $\pm$ 85</td>
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<td>37 $\pm$ 14</td>
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<tr>
<td>$E_T^{\text{miss}} &gt; 30$ GeV</td>
<td>13</td>
<td>16 $\pm$ 7</td>
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<td>15 $\pm$ 7</td>
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<tr>
<td>$\cap m_T &gt; 100$ GeV</td>
<td>2</td>
<td>3.6 $\pm$ 1.6</td>
<td>1</td>
<td>2.8 $\pm$ 1.2</td>
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</table>

**ATLAS** Preliminary

$E_T^{\text{miss}} > 30$ GeV & $m_T > 100$ GeV

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Di-lepton + MET searches

- Low yields but very interesting properties
- Same sign searches
  - Very low Standard Model background rate
  - Backgrounds from charge mis-identified top events (QCD in $\tau$ channel)
- Opposite sign
  - Use opposite-sign, opposite-flavour sample to subtract SM background
First look at the MET distributions for di-leptons.

At least two muons $P_T^1 > 20$ GeV $P_T^2 > 10$ GeV $M_{ll} > 5$ GeV.

Normalise QCD MC to data in $5 < M_{ll} < 15$ GeV and MET < 15 GeV.

100% uncertainty assumed on W and QCD backgrounds and 60% for Z.

Good description by Monte Carlo.
Long-lived particle searches

- Long-lived particles possible in many theories
  - Indirect support for some dark matter candidates
  - For example many SUSY models with stau NLSP with Gravitino LSP
    - Gravitino LSP could be contribution to dark matter

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

- Two complementary approaches:
  - High momentum tracks with large $dE/dx$ E loss
  - Stopped particles may decay any time $\Rightarrow$ signal out-of-time with LHC beam
HSCP searches

- Heavy stable charged particles (HSCP) escape detector
  - Muon-like signature in muon chambers
- Slow moving, high momentum particles
  - Large ionisation energy loss
- $dE/dx$ (TOF in future)

**Figure:**
- CMS Preliminary 2010 $\sqrt{s} = 7$ TeV, $198$ nb$^{-1}$
- Graph showing $dE/dx$ estimator vs. $P$ (GeV/c) for different stop masses (Stop130, Stop200, Stop600)
HSCP searches

- Exclusion limits for stau, stop and gluino
  - Tracker only and tracker & muon chambers covers different models

![Graphs showing cross-sections vs. HSCP mass for different scenarios.]
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)

- Counting experiment in lifetime bins
So far limits on stopped gluinos \( \rightarrow \) technique could be used to set limits on stopped staus with more data.
Future prospects

• Taken the first steps towards searches ➔ What might happen?

• Discovery with 2010-2011 data sample if M<800 GeV
  ▪ First inclusive studies and indication of mass scale
  ▪ Constraint within models example coming up ➔

• High luminosity required for “precision” measurements
  ▪ Masses, spins, cross sections, branching ratios
  ▪ As more parameters are determined, relax model assumptions to achieve more general results for dark matter

• Will always need direct detection measurements
Mass determination example

- Two undetected LSPs per event
  - No mass peaks
  - Constraints from edges and endpoints in kinematic distributions

- Two-body

\[
(m_{l_i}^{\text{max}})^2 = \frac{(m_{\tilde{\chi}_2}^0 - m_{\tilde{l}}^2)(m_{\tilde{l}}^2 - m_{\tilde{\chi}_1}^0)}{m^2}
\]

- Three-body

\[
S(m_{l_i}) = \frac{1}{\sqrt{2\pi}\sigma} \int_0^{m_{\text{cut}}} dy \cdot y \sqrt{y^4 - y^2 (m^2 + M^2) + (m M)^2} \frac{1}{(y^2 - m_{\tilde{\chi}_2}^2)^2} \\
\times \left( -2y^4 - y^2 (m^2 + 2M^2) + (m M)^2 \right) e^{-\frac{(m_{l_i}^0 - y)^2}{2\sigma^2}}
\]

- Simplest example - many others with endpoints, thresholds and other variables (\(M_{T2}\) and friends)
- Vast literature (recommended review Barr & Lester arXiv:1004.2732)
**Mass determination example**

- **Fit ee, μμ and eμ distributions simultaneously**
  - Resolution function and efficiencies from data
  - Monte Carlo study for 200 pb$^{-1}$ @ 10 TeV (600-700 pb$^{-1}$ @ 7 TeV)
  - Di-leptonic end-point $m_{ll,\text{max}}=51.3 \pm 1.5 \text{ (stat.)} \pm 0.9 \text{ (syst.)} \text{ GeV}$ [52.7 GeV]

- **Nice example of what could be done with modest dataset**
Interpreting mass example

JHEP 0809:117, 2008

- Including current limits, precision EW HEP data and WMAP constraints in constrained SUSY model
- Include opposite-sign di-lepton edge measurement
- 1 fb⁻¹ @ 14 TeV with 3 GeV experimental and theoretical uncertainties

• R. Lafaye, M. Rauch, T. Plehn, D. Zerwas (SFITTER)
• H. Flächer, M. Goebel, J. Haller, A. Höcker, K. Mönig, J. Stelzer (GFITTER)
• P. Bechtle, K. Desch, M. Uhlenbrock, P. Wienemann (FITTINO)
• L. Roszkowski, R. Ruiz de Austri, R. Trotta (SuperBayes)
• S.S. AbdusSalam, B.C. Allanach, M.J. Dolan, F. Feroz, M.P. Hobson
Spin-independent elastic cross section per nucleon (old plot sorry...)
Convenient illustration of direct and indirect WIMP searches
Summary and outlook

- Searches for dark matter at the LHC have begun!

- With the 7 TeV run might already make a discovery with impact on dark matter

- Future data will allow the LHC experiments to determine some of the properties of any discovery but will be a huge challenge requiring the ultimate performance of the accelerator and detectors

- Complementary measurements necessary to reveal the true nature of dark matter in detail
Documents for ICHEP on preparations for SUSY searches at LHC

- ATLAS Collab., Early supersymmetry searches in channels with jets and missing transverse momentum with the ATLAS Detector (ATLAS-CONF-2010-065)
- ATLAS Collab., Early supersymmetry searches with jets, missing transverse momentum and one or more leptons with the ATLAS Detector (ATLAS-CONF-2010-066)
- CMS Collab., Performance of Methods for Data-Driven Background Estimation in SUSY Searches (CMS-SUS-10-001)
- Early supersymmetry searches in events with missing transverse energy and b-jets with the ATLAS detector (ATLAS-CONF-2010-079)
- Prospects for Supersymmetry discovery based on inclusive searches at a 7 TeV centre-of-mass energy with the ATLAS detector (ATL-PHYS-PUB-2010-010)
- The CMS physics reach in searches at 7 TeV (CMS-NOTE-2010-008)
Backup: Links

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

- **ATLAS Physics TDR**

- **CMS latest results**
  - https://twiki.cern.ch/twiki/bin/view/CMS/PhysicsResults

- **CMS Physics TDR**
  - http://cmsdoc.cern.ch/cms/cpt/tdr/
### Backup: Benchmark points

#### Low mass (LM) mSUGRA benchmarks

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>m0</th>
<th>m1/2</th>
<th>A0</th>
<th>tanb</th>
<th>sgn(mu)</th>
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<td>-400</td>
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#### High mass (HM) mSUGRA benchmarks

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#### GMSB (GM) benchmarks

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**Backup: Mass determination**

### Transverse mass

The $m_{T2}$ variable is the generalization of the transverse mass to pair decays [32]. For a final state consisting of two visible objects with transverse momenta $p_T^{(1)}$ and $p_T^{(2)}$ respectively, and with missing transverse momentum $p_T$, it is defined by

$$m_{T2}(p_T^{(1)}, p_T^{(2)}, p_T) = \min_{q_T^{(1)}, q_T^{(2)}} \left\{ \max \left( m_T\left(p_T^{(1)}, q_T^{(1)}\right), m_T\left(p_T^{(2)}, q_T^{(2)}\right) \right) \right\}$$

where $m_T$ is the transverse mass [51]

$$m_T\left(p_T^{(i)}, q_T^{(i)}\right) = 2|p_T^{(i)}||q_T^{(i)}| - 2p_T^{(i)} \cdot q_T^{(i)},$$

and the minimization is over all values of the two undetectable particles’ possible missing transverse momenta $q_T^{(1,2)}$ consistent with the $E_T^{\text{miss}}$ constraint. This variable represents an event-by-event lower bound on the mass of any pair-produced semi-invisibly decaying particle which could have resulted in the observed state [34].

### Contransverse mass

This variable is useful in events in which a pair of identical parent particles has decayed semi-invisibly producing visible daughters (with momenta $j^{(1,2)}$). The contransverse mass is defined by [55]

$$m_{C_T}\left(j^{(1)}, j^{(2)}\right) = 2E_T\left(E_T^{(1)} + E_T^{(2)}\right).$$

It is invariant under back-to-back boosts of the parent particles, and provides a lower bound on a combination of the masses of the parent and undetectable daughter particles. The contransverse mass is sensitive to the boost of the centre-of-momentum frame of the parent particles in the laboratory transverse plane and must therefore be corrected using the procedure described in [36].