Dark Matter at the LHC

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Dark Matter

What we know from astrophysical observations:

- From CMB anisotropies (WMAP): \( \Omega_{DM} \sim 0.23 \) (\( \Omega_X = \rho_X / \rho_{\text{crit}} \))
- From nucleosynthesis, only 4% of total matter density baryonic
- From structure formation: most DM "cold" and weakly interacting
- DM candidates must be stable on cosmological time scales, interact very weakly with EM radiation

What we would like to learn:

- Is it a fundamental particle?
- What are its properties?
- How does it interact?
- Is DM composed of one particle species or several?
- How and when it was produced?

Combine info from particle physics experiments with astrophysical observations
Experimental searches for Dark Matter

Very active field: expect stringent tests in the next decade

• Search for dark matter already present in the universe:
  1. Direct: look for elastic scattering of DM particles on nuclei
  2. Indirect: look for annihilation products of DM particles in galactic halo:
     – Ground based
     – Satellite based

• Produce it in accelerator experiments

Concentrate here on DM production at LHC experiments
Explore what kind of information the LHC can produce on Dark Matter candidates
Study complementarity of LHC information with other type of searches and with astrophysics measurements
Particle Dark Matter and new physics

Focus on WIMP (weak interacting massive particles) DM candidates, with mass $O(100) \text{ GeV}$ and electroweak interaction strength. for LHC.

Simplest way of ensuring stability of DM particles is attributing them a conserved quantum number not shared by SM particles.

Models proposed to complete the SM often contain new conserved quantum numbers, from new symmetries, or introduced to avoid large corrections to EWK observables.

Conservation of these quantum numbers implies that models contain a neutral, stable weakly interacting particle.

Examples are SUSY (R-parity), Little Higgs (T-parity), UED (KK number).

All of these models can be studied at the LHC.

The Minimal Supersymmetric Standard Model is the best studied one.
MSSM: Minimal Supersymmetric Standard Model

- Every SM particle has a superpartner with \( \Delta S = 1/2 \), two higgs doublets
- Superpartners have same quantum numbers as SM particles
- SUSY is broken, masses and mixings of sparticles depend on SUSY breaking parametrization. Main examples used in studies:
  - Generic SUSY breaking including all soft terms at electroweak scale and low-energy constraint: 24 Parameters (24-MSSM)
  - Assume supergravity inspired model of SUSY breaking (mSUGRA) defined in term of 5 parameters at SUSY breaking scale
- After SUSY breaking the partners of gauge boson and higgs mix to form 4 neutralinos \((\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0)\) and to charginos \((\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm)\)
- Define absolutely conserved quantum number \( R \)-parity: \( R = (-1)^{3(B-L)+2S} \)
  - LSP (Lightest Supersymmetric Particle) is stable and DM candidate
  - Sparticles produced in pairs, all sparticles decay to LSP
- Lightest neutralino \((\tilde{\chi}_1^0)\) is in many models the LSP
Relic Density and annihilation Cross-Section

At first, when $T \gg m_\chi$ all particles in thermal equilibrium. Universe cools down and expands:

When $T < m_\chi$ is reached only annihilation: density becomes exponentially suppressed

As expansion goes on, particles can not find each other: freeze out and leave a relic density

After freezeout relic density is:

$$\Omega_\chi \equiv \frac{m_\chi n_\chi}{\rho_c} \propto \frac{1}{<\sigma_A v>}$$

where $<\sigma_A v>$ is DM pair annihilation $X$-section times relative velocity

Assuming $\Omega_\chi = 0.2$ gives: $<\sigma_A v> = 1 \text{ pb}$

Using $<\sigma_A v> = \frac{\pi \alpha^2}{8 m_\chi^2}$ we find:

$$m_\chi \sim 100 \text{ GeV}, \text{ scale of EW symmetry breaking}$$

From LHC measurements can evaluate LSP annihilation $X$-section and thence predict relic density and verify agreement with cosmological measurements
The LHC machine

pp Collider, $\sqrt{s}=14$ TeV
LEP tunnel: 27 Km circumference
1232 Superconducting dipoles, field 8.33 T
High and Low luminosity scenarios:

- peak $\sim 10^{33}$ cm$^{-2}$s$^{-1}$ $\int \mathcal{L} dt = 10$ fb$^{-1}$/year
- peak $\sim 10^{34}$ cm$^{-2}$s$^{-1}$ $\int \mathcal{L} dt = 100$ fb$^{-1}$/year

2010/2011 run
Run at $\sqrt{s}=7$ TeV
First 7 TeV collisions expected in the next weeks!
Long run with target integrated luminosity 1 fb$^{-1}$
Thereafter long shutdown to implement protection system for ramping energy up to nominal value

Eight sectors
Point 1: ATLAS General purpose
Point 2: ALICE Heavy ions
Point 5: CMS General purpose
Point 8: LHCb B-physics
ATLAS detector

**Precision Muon Spectrometer,**
\( \sigma / p_T \approx 10\% \) at 1 TeV/c
Fast response for trigger
Good \( p \) resolution
(e.g., \( A/Z' \rightarrow \mu \mu \), \( H \rightarrow 4\mu \))

**EM Calorimeters,**
\( \sigma / E \approx 10\% / \sqrt{E(GeV)} \oplus 0.7\% 
excellent electron/photon identification
Good \( E \) resolution (e.g., \( H \rightarrow \gamma \gamma \))

**Full coverage for \( |\eta| < 2.5 \)**

**Hadron Calorimeters,**
\( \sigma / E \approx 50\% / \sqrt{E(GeV)} \oplus 3\% 
Good jet and \( E_T \) miss performance
(e.g., \( H \rightarrow \tau \tau \))

**Inner Detector:**
Si Pixel and strips (SCT) &
Transition radiation tracker (TRT)
\( \sigma / p_T \approx 5 \times 10^{-4} \ p_T \oplus 0.001 
Good impact parameter res.
\( \sigma(d_0) = 15 \mu m @ 20 GeV \) (e.g. \( H \rightarrow bb \))

**Magnets:**
Solenoid (Inner Detector) 2T, air-core toroids (Muon Spectrometer) \( \sim 0.5T \)
CMS detector

SUPERCONDUCTING COIL

EM Calorimeter,
\( \sigma/E \approx 3\%/\sqrt{E(\text{GeV})} \oplus 0.5\% \)

Hadron Calorimeter,
\( \sigma/E \approx 100\% / \sqrt{E(\text{GeV})} \oplus 5\% \)

Scintillating PbWO4 crystals

Plastic scintillator/brass sandwich

IRON YOKE

MUON BARREL

Muon Spectrometer,
\( \sigma/p_T \approx 5\% \text{ at } 1 \text{ TeV/c} \) (from Tracker)

Drift Tube Chambers (DT)

Resistive Plate Chambers (RPC)

Cathode Strip Chambers (CSC)

Resistive Plate Chambers (RPC)

Silicon Microstrips

Pixels

Trackers

Hadron Calorimeter,
\( V/E \left| V/E \right| 100\% / -E(\text{GeV}) \oplus 5\% \)

EM Calorimeter,
\( V/E \left| V/E \right| 3\% / \sqrt{E(\text{GeV})} \oplus 0.5\% \)

\( \sigma/p_T \approx 1.5 \times 10^{-4} p_T \oplus 0.005 \)

Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

ENDCAPS

CSC

RPC

RPC

V/pT | 5% at 1 TeV/c (from Tracker)
SUSY Dark Matter Strategy at the LHC

- Discovery of deviation from SM in $\not{E}_T + X$ channel:
  7 TeV data if $m(\text{susy}) < 7-800$ GeV

- First inclusive studies: 7 TeV data if $m(\text{susy}) < 7-800$ GeV
  Relevance to DM: verify if discovered signal provides dark matter candidate, possibly first rough evaluation of LSP mass

- First mass measurements based on kinematics of high-BR decays
  Unless SUSY mass very low (4-500 GeV), 14 TeV data, moderate luminosity
  Relevance to DM: Model-independent calculation of LSP mass, comparison with direct detection experiments

- Focus onto the physics of the model: Precision measurements involving branching ratios, angular distributions, rare decays: Need 14 TeV and high luminosity
  Relevance to DM: model-independent calculation of relic density, interaction cross-section, etc.
SUSY production at the LHC

Production dominated by strongly interacting sparticles: $\tilde{q}$, $\tilde{g}$

$\tilde{q}$ and $\tilde{g}$ production cross-section

$\sim$ only function of their masses, $\sim$ independent of model details

LO Cross-sections for two ATLAS benchmark points and NLO for top

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (TeV)</th>
<th>$\sigma_{SUSY}$ (pb)</th>
<th>$\sigma_{SUSY}$ (pb)</th>
<th>$\sigma_{tt}$ (pb)</th>
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</thead>
<tbody>
<tr>
<td>SU3</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>7</td>
<td>1.9</td>
<td>36</td>
<td>148</td>
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<tr>
<td>10</td>
<td>6.5</td>
<td>103</td>
<td>374</td>
</tr>
<tr>
<td>14</td>
<td>18.9</td>
<td>264</td>
<td>827</td>
</tr>
<tr>
<td>SU4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{\tilde{g}}$ (GeV)</td>
<td>717</td>
<td>413</td>
<td>172.5</td>
</tr>
<tr>
<td>$m_{\tilde{q}}$ (GeV)</td>
<td>620</td>
<td>410</td>
<td></td>
</tr>
</tbody>
</table>

SU3: $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $A_0 = -300$ GeV, $\tan \beta = 6$, $\mu > 0$.

SU4: $m_0 = 200$ GeV, $m_{1/2} = 160$ GeV, $A_0 = -400$ GeV, $\tan \beta = 10$, $\mu > 0$.

Squarks and gluinos are typically the heaviest sparticles

$\Rightarrow$ If $R_p$ conserved, complex cascades to undetected LSP, with large multiplicities of jets and leptons produced in the decay.
SUSY discovery: basic strategy

Basic assumption: discovery from squark/gluinos cascading to undetectable LSP

Details of cascade decays are a function of model parameters. Focus on robust signatures covering large classes of models and large rejection of SM backgrounds

- $E_T$: from LSP escaping detection
- High $E_T$ jets: guaranteed if squarks/gluinos if unification of gaugino masses assumed.
- Multiple leptons ($Z$): from decays of Charginos/neutralinos in cascade
- Multiple $\tau$-jets or $b$-jets ($h$): Often abundant production of third generation sparticles

Define basic selection criteria on these variables for RPC SUSY with $\tilde{\chi}_1^0$ LSP

Scan low-dimensional parameter space (mSUGRA) to assess experimental reach
Reach in MSUGRA space: 10 TeV, 200 pb$^{-1}$, 14 TeV 1 fb$^{-1}$

For 10 TeV grid assume 50% uncertainty on all backgrounds.
For 14 TeV grid assume 50% uncertainty on QCD and 20% on other backgrounds
Reach essentially determined by:
- Production cross-section (mass) for squark/gluino
- Level of systematic control on backgrounds. Very difficult experimental challenge.
Main focus of work is development of techniques for background control
Inclusive Studies

Following any discovery next task will be to test broad features of potential Dark Matter candidate

**Question 1:** Do we get a significant $E_T$ signal (stable WIMP from some kind of parity conservation (R,KK,T)?)

- Loophole: LHC experiments sensitive only to lifetimes $\lesssim 1$ ms

**Question 2:** Can we have a glimpse of which decays produces DM candidate: Examples in SUSY:

- Always two photons together with $E_T$, and some of the photons non-pointing (GMSB with light gravitino LSP and $\tilde{\chi}^0_1$ NLSP)
- Always two leptons together with $E_T$ (GMSB with light gravitino LSP and $\tilde{\chi}^0_1$ NLSP)
Mass measurements: start from sequence of two-body decays

Decay chain: $c \rightarrow q b \rightarrow q p a$

$p, q$ massless visible particles:

$a$ invisible LSP:

$$\left(m_{pq}^{max}\right)^2 = \frac{(m_c^2 - m_b^2)(m_b^2 - m_a^2)}{m_b^2}$$

Apply to: $\tilde{\chi}_2^0 \rightarrow \ell^\pm \tilde{\ell}_R^\mp \rightarrow \ell^\pm \ell^\mp \tilde{\chi}_1^0$ for ATLAS SU3 Point

Plot $\ell^+ \ell^-$ invariant mass; Perform flavour subtraction $ee + \mu\mu - e\mu$

Fit smeared triangular function: fitted edge: $99.7 \pm 1.4 \pm 0.3$ GeV (14 TeV, 1 fb$^{-1}$)
Mass determination through kinematic edges

With two decays only single mass combination $\Rightarrow$ only one edge constraint

If a chain of at least three two-body decays can be isolated, enough constraints to measure all involved masses

Example: full reconstruction of squark decays in models with light $\tilde{\ell}_R$ ($m_{\tilde{\ell}_R} < m_{\tilde{\chi}_2^0}$):

Three visible particles: 4 invariant mass combinations: $(\ell_1\ell_2)$, $(q\ell_1)$, $(q\ell_2)$, $(q\ell_1\ell_2)$

For first three minimum value is zero: only $M_{\text{max}}$ constraint. For $(q\ell_1\ell_2)$ combination, if lower limit is set on $(\ell_1\ell_2)$, both $M_{\text{max}}$ and $M_{\text{min}}$ constraint: total 5 constraints
Application to SU3 (14 TeV, 1 fb$^{-1}$)

$m_{\ell\ell q}^{\text{max}} = 517 \pm 30 \pm 10 \pm 13$ GeV

$m_{\ell\ell q}^{\text{min}} = 265 \pm 17 \pm 15 \pm 7$ GeV

$m_{lq(\text{low})}^{\text{max}} = 333 \pm 6 \pm 6 \pm 8$ GeV

$m_{lq(\text{high})}^{\text{max}} = 445 \pm 11 \pm 11 \pm 11$ GeV

$\sim 5\%$ Statistical error, $2\%$ from fit technique, $5\%$ from Jet energy scale
Mass measurement (14 TeV 1 fb$^{-1}$)

Invert algebraical relations defining edges in terms masses through a minuit fit

First error from MIGRAD, second one from lepton energy scale

Much better measurement for mass differences, as the edges are essentially sensitive to the differences

<table>
<thead>
<tr>
<th>Observable</th>
<th>SU3 $m_{\text{meas}}$ (GeV)</th>
<th>$m_{\text{MC}}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\tilde{\chi}_1^0}$</td>
<td>88 ± 60 ± 2</td>
<td>118</td>
</tr>
<tr>
<td>$m_{\tilde{\chi}_2^0}$</td>
<td>189 ± 60 ± 2</td>
<td>219</td>
</tr>
<tr>
<td>$m_{\tilde{q}}$</td>
<td>614 ± 91 ± 11</td>
<td>634</td>
</tr>
<tr>
<td>$m_{\tilde{\ell}}$</td>
<td>122 ± 61 ± 2</td>
<td>155</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Observable</th>
<th>SU3 $\Delta m_{\text{meas}}$ (GeV)</th>
<th>$\Delta m_{\text{MC}}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\tilde{\chi}<em>2^0} - m</em>{\tilde{\chi}_1^0}$</td>
<td>100.6 ± 1.9 ± 0.0</td>
<td>100.7</td>
</tr>
<tr>
<td>$m_{\tilde{q}} - m_{\tilde{\chi}_1^0}$</td>
<td>526 ± 34 ± 13</td>
<td>516.0</td>
</tr>
<tr>
<td>$m_{\tilde{\ell}} - m_{\tilde{\chi}_1^0}$</td>
<td>34.2 ± 3.8 ± 0.1</td>
<td>37.6</td>
</tr>
</tbody>
</table>

Despite low statistics considered, can define absolute mass scale

⇒ Comparison with constraints from direct WIMP detection

Based on this kind of measurements the soft SUSY breaking parameters can be constrained (Sfitter, Fittino)
Neutralino relic density prediction from SUSY parameter measurement

In MSSM the $\tilde{\chi}^0_1$ is a mix of gauginos ($\tilde{B}, \tilde{W}_3$) and higgsinos ($\tilde{h}_u, \tilde{h}_d$).

Cross section for $\tilde{\chi}^0_1$ annihilation depends on its composition (gaugino or higgsino) and on the masses of lighter sfermions and higgses. Main mechanisms:

Names correspond to the regions the mSUGRA parameter space where each of the mechanisms appear

(1) Annihilation through sfermion exchange

One sfermion light and $\tilde{\chi}^0_1$ mostly gaugino

"bulk" region

(2) Co-annihilation: $\tilde{\chi}^0_1$ mostly gaugino,

a sfermion almost degenerate with $\tilde{\chi}^0_1$

Example: $\tilde{\chi}^0_1 \tau \rightarrow \tilde{\tau} \gamma$, $\tilde{\tau} \tilde{\chi}^+_1 \rightarrow \tau W^+$ "coannihilation" region
(3) Annihilation into $W(Z)$ through $Z$ or $h$ exchange

$\tilde{\chi}^0_1$ mostly higgsino

“focus point” region

(4) Resonant annihilation into higgs boson

$m(H/A) \sim 2 \times m(\tilde{\chi}^0_1)$ “funnel” region

Benchmark points are typically chosen in one of this regions

Discuss today full analysis of LHC constraints for two configurations for which detailed studies available in literature:

**Bulk Region:** SPS1a, SPA, ATLAS SU3 (shown above), CMS LM1, Peskin LCC1

$m(\tilde{g}) \gtrsim m(\tilde{q}) \sim 700 \text{ GeV}$. Significant BR for $\tilde{\chi}^0_2 \rightarrow \ell \tilde{\ell}_R$

**Focus point region:** ATLAS SU2, CMS LM7, Peskin LCC2

Very heavy sfermions (Multi-TeV), light gluinos (6-800 GeV)

Can study gaugino spectrum from gluino decays
From LHC measurements to relic density

Discuss two detailed studies addressing LHC (ultimate luminosity, O(100) fb$^{-1}$).

Assume unconstrained MSSM as template model.

**Nojiri, G.P., Tovey:** JHEP 0603:063,2006 (hep-ph/0512204)

- Only SPA point (bulk), only relic density, only LHC. Use micrOMEGAs
  - Build MonteCarlo experiments from constraints from detailed studies
  - For each experiment constrain soft MSSM parameters, and from them calculate relic density

**Requires careful “a posteriori” consideration of unconstrained parameters**


- All four main annihilation processes. Studies LHC, ILC-500, ILC-1000
- Use DarkSUSY program, several different DM variables
  - Scan on MSSM 24-parameter space using a Markov chain technique

**Final distribution may depend on priors for scan**

Two independent methods, good agreement of results
Bulk region: inputs

From the chain $\tilde{q}_L \rightarrow q\tilde{\chi}_2^0 \rightarrow \ell\tilde{\ell}_R \rightarrow \ell\tilde{\chi}_1^0$ measure $m(\tilde{q}_L)$, $m(\tilde{\chi}_2^0)$, $m(\tilde{\ell}_R)$, $m(\tilde{\chi}_1^0)$

From the decay $\tilde{\chi}_4^0 \rightarrow \ell\tilde{\ell}_L$ measure $m(\tilde{\chi}_4^0)$

In this region dominant $\tilde{\chi}_1^0$ annihilation process through $\tilde{\tau}_1$ exchange

Need precise measurement of $\tilde{\tau}_1$ mass and mixing parameters

Measure $\tilde{\tau}_1$ mass from edge in di-tau invariant mass from $\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1\tau \rightarrow \tilde{\chi}_1^0\tau^\pm\tau^\mp$

Invariant mass of visible decay products of two $\tau$

No sharp end-point because of escaping neutrinos

Measured end-point:

$$m_{EP} = (70 \pm 6.5^{\text{stat}} \pm 5^{\text{syst}}) \text{ GeV}$$

Stat is for $1 \text{ fb}^{-1}$, systematic is from fitting procedure

Use measurement of ratio $BR(\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1\tau)/BR(\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_R\ell)$ to constrain $\tilde{\tau}_1$ mixing
Bulk region: relic density prediction

Use the soft parameters as extracted from the mass and BR measurements.

\[ \tan \beta, m(A), m(\tilde{\tau}_2) \] badly constrained

Assume limits on \( m(A) - \tan \beta \) from direct higgs searches: \( \tan \beta < 7.0(m(A)/200) \)

Assume \( m(A) > 300 \) GeV from its non-appearance in SUSY cascade decays

Uncertainty dominated by error on on \( \tau\tau \) edge position

For \( \Delta(m_{\tau\tau}) = 5 \) GeV:
\[ \Delta \Omega_{\chi^h} \sim 20\% \]

For \( \Delta(m_{\tau\tau}) = 1 \) GeV:
\[ \Delta \Omega_{\chi^h} \sim 11\% \]

Next most important uncertainty: \( \tilde{\chi}_1^0 \) mass, known only to a few GeV at the LHC

Errors on \( \tan \beta, m(A), m(\tilde{\tau}_2) \) subdominant
Focus point: inputs

Scalars 2-3 TeV, put a limit from non-observation of $\tilde{q}\tilde{q}$ and $\tilde{\ell}\tilde{\ell}$ production

Main observable process at the LHC: gluino production

Three-body gluino decay: $\tilde{g} \rightarrow qq\tilde{\chi}$, with $\tilde{\chi}$ chargino or neutralino

ATLAS study for SU2 Point: De Sanctis et al. ATLAS-PHYS-PUB-2006-023

Produce both $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$ in $\tilde{g} \rightarrow qq\tilde{\chi}_i^0$ decays

Study lepton-lepton invariant mass for decays

$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\ell^+\ell^-$

$\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^0\ell^+\ell^-$

From fit of three-body shape: (300 fb$^{-1}$)

$\Delta(m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)) = 0.4$ GeV

$\Delta(m(\tilde{\chi}_3^0) - m(\tilde{\chi}_1^0)) = 1.4$ GeV

Constraint from direct production cross-section $pp \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^\pm \rightarrow 3\ell$

$(\sigma \times BR \approx 40$ fb) may constrain $\tilde{\chi}_2^0$ mass scale to $\sim 10$ GeV
Focus point: MSSM scan results for relic density

Assume (extrap. from ILC analyses):

• $\Delta (m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)) = 1$ GeV
• $\Delta (m(\tilde{\chi}_3^0) - m(\tilde{\chi}_1^0)) = 1$ GeV
• $\Delta (m(\tilde{\chi}_1^0)) = 10$ GeV

For LHC data three different solution islands in $(M_1, \mu)$ plane, corresponding to bino-, wino-, and higgsino-like neutralino.

Wrong solutions responsible for peak at zero in relic density estimate
Focus point: solving the ambiguities

Measurement of three neutralino masses not enough to fix gaugino mixing

Try to use ratios of BR's, also sensitive to mixing

Recent work by White and Feroz (hep-ph/1002.1922).

Propose to use the measurement of:

\[
\frac{BR(\tilde{g} \rightarrow \tilde{\chi}^0_2) \times BR(\tilde{\chi}^0_2 \rightarrow \ell^+\ell^-\tilde{\chi}^0_1)}{BR(\tilde{g} \rightarrow \tilde{\chi}^0_3) \times BR(\tilde{\chi}^0_3 \rightarrow \ell^+\ell^-\tilde{\chi}^0_1)}
\]

Ratio measured as $1.4 \pm 0.3$ in ATLAS-PHYS-PUB-2006-023

24-parameter MSSM scan with new constraint: discrimination among possible solutions and prediction of $\Omega h^2$
Conclusions

Already in first 7 TeV run LHC might discover SUSY up to a scale of 7-800 GeV, and give first hints about particle DM.

With the 14 TeV run the LHC will be able to measure through kinematic analysis part of the mass spectra and some ratios of couplings for models of new physics. In two test regions with favourable kinematics, it has been shown through detailed studies that LHC information might be able to constrain $\tilde{\chi}_1^0$ relic density.

Main LHC weakness is in region of intermediate $\tan \beta$ with heavy Higgs bosons of mass $\gtrsim 300$ GeV, where $\tan \beta$ and heavy Higgs masses undetermined.

Situation greatly improved with high energy lepton Collider.

Combination of results of Collider and DM experiments necessary to achieve global understanding of DM issue.
Backup
Large annihilation sross-section required by WMAP data

Boost annihilation via quasi-degeneracy of a sparticle with $\tilde{\chi}_1^0$, or large higgsino content of $\tilde{\chi}_1^0$

Regions in mSUGRA ($m_{1/2}, m_0$) plane with acceptable $\tilde{\chi}_1^0$ relic density (e.g. Ellis et al.):

- **SU3:** Bulk region. Annihilation dominated by slepton exchange, easy LHC signatures from $\tilde{\chi}_2^0 \to \tilde{\ell}\ell$
- **SU1:** Coannihilation region. Small $m(\tilde{\chi}_1^0) - m(\tilde{\tau})$ (1-10 Gev). Dominant processes $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \tau\tau, \tilde{\chi}_1^0 \tilde{\tau} \to \tau\gamma$
  Similar to bulk, but softer leptons!
- **SU6:** Funnel region. $m(\tilde{\chi}_1^0) \approx m(H/A)/2$ at high $\tan\beta$
  Annihilation through resonant heavy Higgs exchange.
  Heavy higgs at the LHC observable up to $\sim 800$ GeV
- **SU2:** Focus Point high $m_0$, large higgsino content, annihilation through coupling to W/Z
  Sfermions outside LHC reach, study gluino decays.
- **SU4:** Light point. Not inspired by cosmology. Mass scale $\sim 400$ GeV, at limit of Tevatron reach
Parameters and cross-sections of benchmark Points

**SU1:** \( m_0 = 70 \text{ GeV}, \ m_{1/2} = 350 \text{ GeV}, \ A_0 = 0, \ \tan \beta = 10, \ \mu > 0. \)

**SU2:** \( m_0 = 3550 \text{ GeV}, \ m_{1/2} = 300 \text{ GeV}, \ A_0 = 0, \ \tan \beta = 10, \ \mu > 0. \)

**SU3:** \( m_0 = 100 \text{ GeV}, \ m_{1/2} = 300 \text{ GeV}, \ A_0 = -300 \text{ GeV}, \ \tan \beta = 6, \ \mu > 0. \)

**SU4:** \( m_0 = 200 \text{ GeV}, \ m_{1/2} = 160 \text{ GeV}, \ A_0 = -400 \text{ GeV}, \ \tan \beta = 10, \ \mu > 0. \)

**SU6:** \( m_0 = 320 \text{ GeV}, \ m_{1/2} = 375 \text{ GeV}, \ A_0 = 0, \ \tan \beta = 50, \ \mu > 0. \)

<table>
<thead>
<tr>
<th>Signal</th>
<th>( \sigma^{LO} ) (pb)</th>
<th>( \sigma^{NLO} ) (pb)</th>
<th>N</th>
</tr>
</thead>
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<tr>
<td>SU1</td>
<td>8.15</td>
<td>10.86</td>
<td>200 K</td>
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<tr>
<td>SU2</td>
<td>5.17</td>
<td>7.18</td>
<td>50 K</td>
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<tr>
<td>SU3</td>
<td>20.85</td>
<td>27.68</td>
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<tr>
<td>SU4</td>
<td>294.46</td>
<td>402.19</td>
<td>200 K</td>
</tr>
<tr>
<td>SU6</td>
<td>4.47</td>
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<tr>
<td>Particle</td>
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<td>SU2</td>
<td>SU3</td>
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<tr>
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<tr>
<td>$\tilde{u}_L$</td>
<td>760.42</td>
<td>3563.24</td>
<td>631.51</td>
</tr>
<tr>
<td>$\tilde{b}_1$</td>
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<td>2924.80</td>
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Study of SPA point. Step 1: solving neutralino matrix

Use measured masses for $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_4^0$.

Input fixed value for $\tan \beta$, and get numerically the values of $M_1$, $M_2$, $\mu$.

Annihilation X-section determined by components of the lightest neutralino:

$$\tilde{\chi}_1^0 = Z_{11} \tilde{B} + Z_{12} \tilde{W}_3^3 + Z_{13} \tilde{H}_1^0 + Z_{14} \tilde{H}_2^0$$

Experimental spread is 0.03% for bino component and 1-2% for other components.

Study dependence of the values of the neutralino components from assumed value of $\tan \beta$.

Little dependence for the bino component, larger variation for subdominant component.

For any $\tan \beta$ neutralino is essentially pure bino, annihilation will be dominated by sfermion exchange/co-annihilation.

Squarks, including stop measured to be much heavier than $\tilde{\chi}_1^0$, need to address slepton sector.
Step 2: stau sector

\( \tilde{\tau}_1 \) and \( \tilde{\tau}_2 \) produced from the mixing of \( \tilde{\tau}_L \) and \( \tilde{\tau}_R \) through a mixing angle \( \theta_\tau \)

Assume no mixing in the sleptons sector for the first two generations

From the knowledge of the neutralino mixing matrix, \( m(\tilde{\tau}_1) \), and \( BR(\tilde{\chi}^0_2 \rightarrow \ell_R \ell)/BR(\tilde{\chi}^0_2 \rightarrow \tilde{\tau}_1 \ell) \)

can extract the value of \( \theta_\tau \)

Show distribution of calculated \( \theta_\tau \) for the MonteCarlo experiments

Uncertainty from experimental error is \( \sim 2\% \)

Large uncertainty (25-30%) from \( \tan \beta \) spread

\( \tilde{\tau} \) sector not fully solved, need one more parameter, \( m(\tilde{\tau}_2) \) or \( m(\tilde{\tau}_R) \)

\( m(\tilde{\tau}_2) > m(\tilde{\chi}^0_2) \), otherwise it would be seen in \( \tilde{\chi}^0_2 \) decay

For \( \tan \beta = 10 \), if require \(|A_\tau| < 5 \text{ TeV}, m(\tilde{\tau}_2) < 250 \text{ GeV} \)
Constraints from higgs sector

\( h \) can be discovered over the whole parameter space

For high \( \tan \beta \) little info on \( \tan \beta \) from \( m(h) \)

Can assume approx \( \tan \beta > 5 \), \( m(A) > 200 \) GeV.

Need detailed study of stop sector for better limits

Heavy higgses can not be discovered at the LHC in their SM decay modes for the selected model:

\( m(A) \sim 425 \) GeV, \( \tan \beta = 10 \).

Constraints from SUSY sector:

- Detection of \( A/H \rightarrow bb \) in chargino/neutralino decays

  Kinematically closed: can probably put a limit \( m(A/H) < m(\tilde{\chi}_4^0) - m(\tilde{\chi}_1^0) \sim 300 \) GeV from non-observation of \( H/A \rightarrow bb \) peak in cascade decays. Detailed analysis needed

- Detection of \( A/H \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow 4\ell\ell \)

  Very small rate: \( \sim 40 \) events/experiment for 300 fb\(^{-1}\). Need detailed background study
Calculation of relic matter density

Use the soft parameters as extracted from the mass and BR measurements.

The stop can be observed in this point in the gluino decay, and $m(t_{\tilde{1}}) > m(\tilde{\chi}_{1}^{\pm}) \rightarrow$ no impact of light stop on relic density prediction

$tan \beta, m(A), m(\tilde{\tau}_{2})$ affect the relic density measurement and are badly constrained

Fix them at nominal value, calculate relic density for each MonteCarlo experiment with Micromegas 1.36

Uncertainty dominated by error on $\tau \tau$ edge position

If the error on $m_{\tau \tau}$, better than 1 GeV measurement error, of 10% on $\Omega\chi h^2$

Next most important error source from uncertainty on $\tilde{\chi}_{1}^{0}$ mass, constrained only to a few GeV by LHC measurements
Uncertainty from badly constrained parameters

Method: vary concerned parameter in relevant range, and recalculate all other soft SUSY breaking parameters such that measurable masses and BR are kept at measured value

\[ m(A) \] dependency.

Three scenarios:

- No handle on \( m(A/H) \): only upper limit on \( \Omega h^2 \)
- Can set \( m(A/H) > 300 \text{ GeV} \): \( \Delta \Omega h^2 \sim 1\% \)
- \( H/A \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \) observed: \( \Delta \Omega h^2 \) negligible

\( \tan \beta \) dependency

All dependency coming from \( \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \tau\tau \), caused by dependency of \( \theta_\tau \) on \( \tan \beta \)

\( \Delta \Omega \chi h^2 \sim 11\% \), depends on the lower limit one can assume on \( \tan \beta \) from the higgs sector.

\( m(\tilde{\tau}_2) \) dependency

\( \Delta \Omega \chi h^2 \sim 7\% \), for the assumed range of \( \tilde{\tau}_2 \) mass, i.e. \( m(\tilde{\tau}_2) > m(\tilde{\chi}_2^0) \) and \( A_\tau < 5 \text{ TeV} \)
Minimal Supersymmetric Standard Model

SUSY model with soft breaking of SUSY and minimal particle content:

\[ \mathcal{L}^{\text{MSSM}}_{\text{soft}} = -\frac{1}{2} \left( M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B} \right) + \text{c.c.} \]

\[ - \left( \tilde{u} a_u \tilde{Q} H_u - \tilde{d} a_d \tilde{Q} H_d - \tilde{e} a_e \tilde{L} H_d \right) + \text{c.c.} \]

\[ - \tilde{Q}^\dagger m_Q^2 \tilde{Q} - \tilde{L}^\dagger m_L^2 \tilde{L} - \tilde{u} m_u^2 \tilde{u}^\dagger - \tilde{d} m_d^2 \tilde{d}^\dagger - \tilde{e} m_e^2 \tilde{e}^\dagger \]

\[ - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + \text{c.c.}) . \]  

1. Gaugino mass terms. Parameters: \( M_1, M_2, M_3 \)
2. Trilinear \( \tilde{f} \tilde{f} H \) terms. Parameters \( a_u, a_d, a_e \)
3. Sfermion mass terms. Parameters \( m_Q^2, m_L^2, m_u^2, m_d^2, m_e^2 \)
4. SUSY breaking contributions to Higgs potential. Parameters: \( m_{H_u}^2, m_{H_d}^2, b \)

\( a_f \) and \( m_f^2 \) complex \( 3 \times 3 \) matrices \( \Rightarrow \) model has 105 parameters!
The SUSY Zoo

quarks → squarks \( \tilde{q}_L, \tilde{q}_R \)

leptons → sleptons \( \tilde{\ell}_L, \tilde{\ell}_R \)

\( W^\pm \) → winos \( \tilde{\chi}^\pm_{1,2} \) charginos

\( H^\pm \) → charged higgsinos \( \tilde{\chi}^\pm_{1,2} \) charginos

\( \gamma \) → photino \( \tilde{\chi}^0_{1,2,3,4} \) neutralinos

\( Z \) → zino \( \tilde{\chi}^0_{1,2,3,4} \) neutralinos

\( h,H \) → higgsinos \( \tilde{\chi}^0_{1,2,3,4} \) neutralinos

\( g \) → gluino \( \tilde{g} \)

For each fermion \( f \) two partners \( \tilde{f}_L \) and \( \tilde{f}_R \) corresponding to the two helicity states.

The SUSY partners of the \( W \) and of the \( H^\pm \) mix to form 2 charginos.

The SUSY partners of the neutral gauge and higgs bosons mix to form 4 neutralinos.

Phenomenology determined by the mixing in gaugino sector and by sfermion left-right mixing.
Neutralino mixing

Gauginos and higgsinos \((\tilde{B}, \tilde{W}^3, \tilde{H}^0_d, \tilde{H}^0_u)\) mix to form mass eigenstates: \(\chi^0_i\) 
\((i=1,2,3,4)\) through matrix:

\[
\mathcal{M} = \begin{pmatrix} 
M_1 & 0 & -m_Zc_\beta s_W & m_Zs_\beta s_W \\
0 & M_2 & m_Zc_\beta c_W & -m_Zs_\beta c_W \\
-m_Zc_\beta s_W & m_Zc_\beta c_W & 0 & -\mu \\
m_Zs_\beta s_W & -m_Zs_\beta c_W & -\mu & 0 
\end{pmatrix} \tag{3}
\]

- Entries \(M_1\) and \(M_2\) come from the soft breaking terms in lagrangian
- Entries \(\mu\) are supersymmetric higgsino mass terms
- Terms proportional to \(m_Z\) arise from EW symmetry breaking

Diagonalize \(\mathcal{M}\) by unitary matrix \(N\): \(\mathcal{M}^{\text{diag}}_N = N^* \mathcal{M} \tilde{N} N^{-1}\)

Each of the neutralino states is a linear combination of gauginos and higgsinos:

\[
\tilde{\chi}^0_i = N_{i1} \tilde{B} + N_{i2} \tilde{W}^3 + N_{i3} \tilde{H}^0_d + N_{i4} \tilde{H}^0_u
\]

With \(m(\tilde{\chi}^0_1) < m(\tilde{\chi}^0_2) < m(\tilde{\chi}^0_3) < m(\tilde{\chi}^0_4)\)
Sfermion mixing

(mass)$^2$ terms in Lagrangian mix the gauge-eigenstates ($\tilde{f}_L$, $\tilde{f}_R$) through matrix:

$$m_F^2 = \begin{pmatrix} m_Q^2 + m_q^2 + L_q & m_q X_q^* \\ m_q X_q & m_R^2 + m_q^2 + R_q \end{pmatrix}$$

$$X_q \equiv A_q - \mu^* (\cot \beta)^2 T_{3q}.$$  \hspace{1cm} (4)

$L_q$, $R_q$ Electroweak correction terms $\sim M_Z^2$

After diagonalization have mass eigenstates $\tilde{f}_1$, $\tilde{f}_2$ with $m_{\tilde{f}_1}^2 < m_{\tilde{f}_2}^2$

$$\begin{pmatrix} \tilde{f}_1 \\ \tilde{f}_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_{\tilde{f}} & \sin \theta_{\tilde{f}} \\ -\sin \theta_{\tilde{f}} & \cos \theta_{\tilde{f}} \end{pmatrix} \begin{pmatrix} \tilde{f}_L \\ \tilde{f}_R \end{pmatrix}$$  \hspace{1cm} (5)

All fermion masses $\ll M_Z$ except $b$, $\tau$, $t$: $\Rightarrow L - R$ mixing only for third generation

• Consider in phenomenology mass autostates ($\tilde{t}_1$, $\tilde{t}_2$), ($\tilde{b}_1$, $\tilde{b}_2$), ($\tilde{\tau}_1$, $\tilde{\tau}_2$)

• $\tilde{t}_1$, $\tilde{b}_1$ lighter than other squarks, $\tilde{\tau}_1$ lighter than other sleptons

• mixing of left and right components changes coupling with gauginos. e.g.:

$$BR(\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_R \ell) < BR(\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \ell)$$

Because of left component in $\tilde{\tau}_1$
Sparticle decays

Sfermion decays: two possibilities: gauge interactions and Yukawa interactions

Yukawa interactions $\propto m^2$ of corresponding fermions: only third generation

For gauge interactions same couplings as corresponding SM vertexes. For squarks:

$$\tilde{q}_L \rightarrow \tilde{q}_L^* \tilde{W}^3 \sqrt{2} g T^3$$

$$\tilde{q}_L \rightarrow \tilde{q}_L^* g \tilde{W}^\pm$$

Decay to $\tilde{\chi}^0_1$ always kinematically favoured, but decays into heavier gauginos may dominate because of the chargino/neutralino composition $\Rightarrow$ Cascade decays

If $\tilde{q} \rightarrow \tilde{g} q$ open: dominates because of $\alpha_s$ coupling, otherwise weak decays

Case: $m_Z \ll M_1 < M_2 < \mu m_Z$; gaugino composition is:

$$\tilde{\chi}^0_1 \sim \tilde{B}, \quad \tilde{\chi}^0_2 \sim \tilde{W}^3, \quad \tilde{\chi}^\pm_1 \sim \tilde{W}^\pm$$

From the vertexes above one easy sees:

$$BR(\tilde{q}_L \rightarrow \tilde{\chi}^0_2 q) = 30\% \quad BR(\tilde{q}_L \rightarrow \tilde{\chi}^\pm_1 q') = 60\% \quad BR(\tilde{q}_R \rightarrow \tilde{\chi}^0 q) = 100\%$$
SUSY breaking models

MSSM agnostic approach, one would like to have a model for SUSY breaking. Spontaneous breaking not possible in MSSM, need to postulate hidden sector.

Phenomenological predictions determined by messenger field:

Three main proposals, sparticle masses and couplings function of few parameters

- Gravity: mSUGRA. Parameters $m_0$, $m_{1/2}$, $A_0$, $\tan\beta$, $\text{sgn}\,\mu$

- Gauge interactions: GMSB. Parameters $\Lambda = F_m/M_m$, $M_m$, $N_5$ (number of messenger fields) $\tan\beta$, $\text{sgn}(\mu)$, $C_{\text{grav}}$

- Anomalies: AMSB: Parameters: $m_0$, $m_{3/2}$, $\tan\beta$, $\text{sign}(\mu)$
SUSY breaking structure

SUSY breaking communicated to visible sector at some high scale

\[ m_0, \, m_{1/2}, \, A_0, \, \tan \beta, \, \text{sgn} \, \mu \, (\text{mSUGRA}) \]

Evolve down to \( EW \) scale through Renormalization Group Equations (RGE)

\[ M_1, \, M_2, \, M_3, \, m(\tilde{f}_R), \, m(\tilde{f}_L), \, A_t, \, A_b, \, A_\tau, \, m(A), \, \tan \beta, \, \mu \]

From 'soft' terms derive mass eigenstates and sparticle couplings.

\[ m(\tilde{\chi}_j^0), \, m(\tilde{\chi}_j^\pm), \, m(\tilde{q}_R), \, m(\tilde{q}_L), \, m(\tilde{b}_1), \, m(\tilde{b}_2), \, m(\tilde{t}_1), \, m(\tilde{t}_2) \ldots \]

Structure enshrined in Monte Carlo generators (e.g. ISAJET)

Task of experimental SUSY searches is to go up the chain, i.e. to measure enough sparticles and branching ratios to infer information on the SUSY breaking mechanism
RGE for $m_{1/2}$ give for soft gaugino terms $M_3 : M_2 : M_1 : m_{1/2} \approx = 7 : 2 : 1 : 2.5$

$m(\tilde{g}) \approx M_3$. In mSUGRA $m(\tilde{\chi}^0_1) \approx M_1$, $m(\tilde{\chi}^0_2) \approx m(\tilde{\chi}^\pm_1) \approx M_2$

Sfermion mass determined by RGE running of $m_0$ and coupling to gauginos:

$m(\tilde{\ell}_L) \approx \sqrt{m_0^2 + 0.5m_{1/2}^2}$; \hspace{1cm} $m(\tilde{\ell}_R) \approx \sqrt{m_0^2 + 0.15m_{1/2}^2}$; \hspace{1cm} $m(\tilde{q}) \approx \sqrt{m_0^2 + 6m_{1/2}^2}$

$A$ and $\tan \beta$: significant contribution only to $3^{rd}$ generation RGE and mixing