Interplay of the LHC and DM search experiments in unravelling Natural Supersymmetry

Alexander Belyaev

Southampton University & Rutherford Appleton Laboratory

December 8, 2015
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Particle Physics at the Dawn of the LHC13

Organizers: Thanks to the organisers!

Eduardo Pontón (IFT-UNESP & ICTP-SAIFR), Mariano Quirós (IFAE-Barcelona), Rogério Rosenfeld (IFT-UNESP & ICTP-SAIFR)
OUTLINE

- Motivation for BSM
- General approach for SUSY hunt
- DM search interplay
- Beyond MSSM
- Natural SUSY probe at the LHC and DD of DM
- Conclusions
The Standard Model is very successful!

Confirmed to better than 1% precision by 100’s of precision measurements

The last missing particle - Higgs boson with ~125 GeV mass is discovered on the 4th of July 2012
Higgs Boson Status

$\lambda = $ Yukawa coupling for fermions
$\sqrt{g/2v} =$ couplings for W/Z bosons

For the first time, non-universal, mass-dependent couplings observed

CMS

19.7 fb$^{-1}$ (8 TeV) + 5.1 fb$^{-1}$ (7 TeV)

ATLAS Preliminary
$\sqrt{s} = 7$ TeV, 4.5-4.7 fb$^{-1}$
$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

$\frac{\lambda_{\tau}}{(g/2v)^{1/2}}$ or $\frac{m_{\psi}}{\sqrt{v}}$

Particle mass (GeV)

Particle mass [GeV]
SM is empirically incomplete

- The presence of non-baryonic, cold dark matter: DM is neutral, stable, colourless, non-baryonic and massive (cold or warm). Neutrinos are too light, make instead hot DM.

Galactic rotation curves  
CMB: WMAP and PLANCK  
Large Scale Structures

- Dark Energy: 73%  
- Cold Dark Matter: 23%  
- Atoms: 4%
"SM is empirically incomplete"

the presence of non-baryonic, cold dark matter: DM is neutral, stable, colourless, non-baryonic and massive (cold or warm). Neutrinos are too light, make instead hot DM.
SM is empirically incomplete

- the presence of non-baryonic, cold dark matter: DM is neutral, stable, colourless, non-baryonic and massive (cold or warm). Neutrinos are too light, make instead hot DM.
SM is empirically incomplete

- the presence of scale-invariant, Gaussian, and apparently acausal density perturbations: consistent with a period of inflation at early times

The universe, on large scales, is extremely homogeneous and isotropic

The CMB fluctuations are at the $10^{-5} - 10^{-6} \%$ level
SM is empirically incomplete

the observed abundance of matter over anti-matter: note, moreover, that inflation would destroy any asymmetry imposed as an initial condition.

The amount of CP violation in the SM which could lead to baryon-antibaryon asymmetry is too small (would provide BAU orders of magnitude below the observed one)

$$\frac{n_B}{n_\gamma} = (6.1^{+0.3}_{-0.2}) \times 10^{-10}$$

Empirical problems of the SM stated above have been established beyond reasonable doubt.
**SM is aesthetically unacceptable**

- inability to describe physics at planckian scales: General relativity makes perfect sense as a theory of quantum gravity up to planckian scales (as an effective field theory) but beyond that we need a theory of quantum gravity, such as string theory.

- hierarchy between the observed cosmological constant and other scales: the measured energy density associated with the accelerated expansion of the Universe is \((10^{-3} \text{ eV})^4\), but receives contributions of size \(\text{GeV}^4\) and \(\text{TeV}^4\) from QCD and weak scale physics respectively. How is it achieved?

- the hierarchy between the weak and other presumed scales: as above, but now the question is how to get a TeV from the Planck scale.

\[
\delta M_H^2 = \frac{|g_f|^2}{4} \int \frac{d^4k}{(2\pi)^4} \text{tr} \left[ \frac{(k + p + m_f)(k + m_f)}{(k + p)^2 - m_f^2} \right] \left[ k^2 - m_f^2 \right] \\
= \frac{|g_f|^2}{16\pi^2} \left[ -2\Lambda^2 + 6m_f^2 \ln \left( \frac{\Lambda}{m_f} \right) \right]
\]

\[
M_H^2 = M_{H,\text{bare}}^2 + \delta M_H^2
\]

there is a cancellation of over 30 orders of magnitude to have 125 GeV Higgs
Higgs Boson Discovery has completed the puzzle of the Standard model ...
Higgs Boson Discovery has completed the puzzle of the Standard model …
But the SM itself is just a piece of a bigger puzzle - BSM one!

The Nature of Higgs Boson?

The origin of matter/anti-matter asymmetry

Fine-tuning problem

Connection to GUT & couplings unification

Dark Matter problem
Beyond the Higgs discovery

Higgs properties are amazingly consistent with all main compelling underlying theories **(except higgsless ones!)** Some parameter space of BSM theories was eventually excluded.

CPNSH workshop
CERN 2006-009
Beyond the Higgs discovery

Higgs properties are amazingly consistent with all main compelling underlying theories (except higgsless ones!) Some parameter space of BSM theories was eventually excluded.
What do we know about Dark Matter?
What do we know about Dark Matter?

Spin $\square$?
What do we know about Dark Matter?

Spin ?

Mass ?
What do we know about Dark Matter?

- Spin
- Mass
- Stable
  - Yes
  - No

Symmetry behind stability
What do we know about Dark Matter?

- Spin
- Mass
- Stable
  - Yes
  - No
- Symmetry behind stability
- Thermal relic
  - Yes
  - No
What do we know about Dark Matter?

- Spin
- Mass
- Stable
  - Yes
  - No
- Couplings
  - Gravity: Yes
  - Weak: ?
  - Higgs: ?
  - Quarks/gluons: ?
  - Leptons: ?
  - New sector: ?
- Thermal relic
  - Yes: ?
  - No: ?
SUSY
Supersymmetry (SUSY)

boson-fermion symmetry aimed to unify all forces in nature

$$Q |\text{BOSON}\rangle = |\text{FERMION}\rangle, \quad Q |\text{FERMION}\rangle = |\text{BOSON}\rangle$$

extends Poincare algebra to Super-Poincare Algebra:

the most general set of space-time symmetries! (1971-74)

$$\{ f, f \} = 0, \quad [B, B] = 0, \quad \{ Q_\alpha, \bar{Q}_\beta \} = 2\gamma^\mu_{\alpha\beta} P_\mu$$

Golfand and Likhtman'71; Ramond'71; Neveu, Schwarz'71; Volkov and Akulov'73; Wess and Zumino'74
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could give rise the proton decay!
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the absence of proton decay suggests R-parity

\[ R = (-1)^{3(B-L)+2S} \]
Supersymmetry (SUSY)

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could give rise the proton decay!

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\[ R = (-1)^{3(B-L)+2S} \]

R-parity guarantees Lightest SUSY particle (LSP) is stable – DM candidate!
We are still inspired by this beauty …
We are still inspired by this beauty ... after more than 30 year unsuccessful searches ...
Beauty of SUSY

- Provides good DM candidate – LSP
- CP violation can be incorporated – baryogenesis via leptogenesis
- Radiative EWSB
- Solves fine-tuning problem
- Provides gauge coupling unification
- Local supersymmetry requires spin 2 boson – graviton!
- Allows to introduce fermions into string theories

\[ \Delta M_H^2 \sim M_{SUSY}^2 \log(\Lambda/M_{SUSY}) \]

It was not deliberately designed to solve the SM problems!
**SUSY breaking and mSUGRA scenario**

- **SUSY is not observed ⇒ must be broken**

\[
L_{\text{soft}}^{\text{MSSM}} = \sum_{i,j} B_{ij} H_{ij} S_i S_j + \sum_{ij} m_{ij}^2 S_i S_j^\dagger + \sum_{i,j,k} A_{ijk} f_{ijk} S_i S_j S_k + \sum_{A,\alpha} M_{A\alpha} \tilde{\lambda}_A \lambda_{A\alpha}
\]

- **Gravity mediation**
- **Gauge mediation**
- **Anomaly mediation**
- **Gaugino mediation**

**Visible Sector**

**Hidden Sector**

**Messengers**
**SUSY breaking and mSUGRA scenario**

- **SUSY is not observed** $\Rightarrow$ must be broken

\[ L_{\text{soft}}^{\text{MSSM}} = \sum_{i,j} B_{ij} \mu_{ij} S_i S_j + \sum_{ij} m_{ij}^2 S_i S_j^\dagger + \sum_{i,j,k} A_{ijk} f_{ijk} S_i S_j S_k + \sum_{A,\alpha} M_{A\alpha} \tilde{\lambda}_{A\alpha} \lambda_{A\alpha} \]

- **Gravity mediation**
- **Gauge mediation**
- **Anomaly mediation**
- **Gaugino mediation**

**SUGRA**: the hidden sector communicates with visible one via gravity
- all soft terms are non-zero in general ($\sim m_{3/2}$ - gravitino mass)

SUGRA:
\[
M_{\alpha} = f_{\alpha} \frac{\langle F \rangle}{M_P} \quad m_{ij}^2 = k_{ij} \frac{\langle F \rangle^2}{M_P^2} \quad A_{ijk} = y_{ijk} \frac{\langle F \rangle}{M_P}
\]

mSUGRA:
\[
\Rightarrow m_{1/2} \quad \Rightarrow m_0 \quad \Rightarrow A_0
\]

Flat Kähler metric takes care of constraining of Flavor violating processes

- $\text{sign}(\mu)$, $\mu^2$ value is fixed by the minim condition for Higgs potential

- $B$ - parameter – usually expressed via $\tan \beta$

- $\Rightarrow$ mSUGRA parameters: $m_0, m_{1/2}, A_0, \tan \beta, \text{sign}(\mu)$
How do we search/constrain SUSY?

- **Collider search**
  - strong SUSY particles production, cascade decay: missing PT + jets/leptons
  - EW DM pair production: mono-jet signature

- **Direct/Indirect DM detection experiments**

- **Constraints from Relic Density**

- **Constraints from EW precision measurements and rare decays**
Mass spectrum for mSUGRA scenario

Independent parameters:

- $m_0$: universal scalar mass
- $m_{1/2}$: universal gaugino masses
- $A$: trilinear soft parameter
- $\tan(\beta) = v_1/v_2$

ISASUGRA, SPHENO, SUSPECT, SOFTSUSY
Challenge is to evaluate thousands of annihilation/co-annihilation diagrams. The relic density depends crucially on the thermal equilibrium stage:

\[ n = n_{\text{eq}} \sim e^{-m/T} \]

Neutralinos “freeze-out” at

\[ T > m_\chi, \quad \chi \chi \leftrightarrow f \bar{f} \]

\[ T \lesssim m_\chi, \quad \chi \chi \leftrightarrow f \bar{f} \]

\[ T_F \sim m/25 \]

Time evolution of number density is given by Boltzmann equation:

\[ \frac{dn}{dt} = -3Hn - \langle \sigma_A v \rangle (n^2 - n_{\chi\chi}^2) \]
**Evolution of neutralino relic density**

*Challenge is to evaluate thousands annihilation/co-annihilation diagrams*

\[ \frac{dn}{dt} = -3Hn - \langle \sigma_A v \rangle (n^2 - n_{eq}^2) \]

**Time evolution of number density is given by Boltzmann equation**

- **Thermal equilibrium stage:**
  - Universe cools:
  - \( n = n_{eq} \approx e^{-m/T} \)
  - Neutralinos “freeze-out” at

\[ \Omega_\chi = \frac{10^{-10} \text{GeV}^{-2}}{\langle \sigma_A v \rangle} \]

\[ \langle \sigma_A v \rangle = 1 \text{pb} \]

\[ \langle \sigma_A v \rangle = \frac{\pi \alpha^2}{8m^2} \]

\( m = 100 \text{GeV} \)

---

Packages:
- MicrOMEGAs (Pukhov et al)
- DarkSusy
- ISARED
Neutralino relic density in \textit{mSUGRA}

most of the parameter space is ruled out! $\Omega h^2 \gg 1$
special regions with high $\sigma_A$ are required to get $0.094 < \Omega h^2 < 0.129$

1. bulk region: light sfermions

2. stau coannihilation: degenerate $\chi$ and stau

3. focus point: mixed neutralino, low $\mu$, importance of higgsino-wino component

$$\mu^2 + M_Z^2 / 2 \approx -\epsilon m_0^2 + 2 m_{1/2}^2$$

Baer, A.B., Balazs '02
Neutralino relic density in mSUGRA

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special regions with high $\sigma_A$ are required to get $0.094 < \Omega h^2 < 0.129$

1. bulk region: light sfermions

2. stau coannihilation: degenerate $\chi$ and stau

3. focus point: mixed neutralino, low $\mu$, importance of higgsino-wino component

4. funnel: (large $\tan\beta$) annihilation via $A$, $H$

additional regions: $Z/h$ annihilation stop coannihilation

1. bulk region: light sfermions

Baer, A.B., Balazs '02
Collider signatures in DM allowed regions

DM allowed regions are difficult for the observation at the colliders: stau(stop) co-annihilation, FP region: small visible energy release

\[ m_{\text{Sugra with } \tan \beta = 55, A_\nu = 0, \mu > 0} \]

\[ \Omega h^2 < 0.129 \]

LEP2 excluded

Baer, A.B., Krupovnickas '03

![Graph showing collider signatures and regions](image-url)
Collider signatures in DM allowed regions

DM allowed regions are difficult for the observation at the colliders:
stau(stop) co-annihilation, FP region: small visible energy release

Production

<table>
<thead>
<tr>
<th>1</th>
<th>( d )</th>
<th>( w^- )</th>
<th>( \tilde{Z}_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u )</td>
<td>( \bar{q} )</td>
<td>( \gamma, Z )</td>
<td>( \tilde{\ell}_{L,R} )</td>
</tr>
</tbody>
</table>

TEV: \( 3\ell + E_T + jets \)

LHC, ILC: \( 2\tau + E_T \)

Decay

<table>
<thead>
<tr>
<th>( \tilde{W}_1 )</th>
<th>( \tilde{Z}_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z, h, H, A )</td>
<td></td>
</tr>
</tbody>
</table>

LHC: \( jets + \ell + E_T \)

LHC and ILC are highly complementary!
Collider signatures in DM allowed regions

$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}$ production dominant for $m \lesssim 1$ TeV

- $E_T + \text{jets}$
- $1\ell + E_T + \text{jets}$
- opposite - sign (OS) $2\ell + E_T + \text{jets}$
- same - sign (SS) $2\ell + E_T + \text{jets}$

$3\ell + E_T + \text{jets}$
$4\ell + E_T + \text{jets}$
$5\ell + E_T + \text{jets}$

<table>
<thead>
<tr>
<th>SUSY event with 3 lepton + 2 Jets signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $\tan\beta = 2$, $A_0 = 0$, $\mu &lt; 0$,</td>
</tr>
<tr>
<td>$m(\tilde{q}) = 686$ GeV, $m(\tilde{g}) = 766$ GeV, $m(\tilde{\chi}_0^2) = 257$ GeV,</td>
</tr>
<tr>
<td>$m(\tilde{\chi}^0_1) = 128$ GeV.</td>
</tr>
</tbody>
</table>

$m_{\tilde{g}}$ reach to $m \tilde{g} \sim 1.8$ (3) TeV for high (low) $m_0$

<table>
<thead>
<tr>
<th>Leptons:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(\mu^-) = 55.2$ GeV</td>
</tr>
<tr>
<td>$E_T(\text{Jet1}) = 237$ GeV</td>
</tr>
<tr>
<td>$p_T(\mu^+) = 44.3$ GeV</td>
</tr>
<tr>
<td>$E_T(\text{Jet2}) = 339$ GeV</td>
</tr>
<tr>
<td>$p_T(e^-) = 43.9$ GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Jets:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged particles with $p_T &gt; 2$ GeV, $</td>
</tr>
<tr>
<td>neutrons are not shown; no pile up events superimposed.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sparticles:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(\tilde{\chi}^0_1) = 95.1$ GeV</td>
</tr>
<tr>
<td>$p_T(\tilde{\chi}^0_1) = 190$ GeV</td>
</tr>
</tbody>
</table>
Limits from LHC8 for mSUGRA scenario

MSUGRA/CMSSM: $\tan(\beta) = 30$, $A_0 = -2m_0$, $\mu > 0$

ATLAS Preliminary

$\int L dt = 20.1 - 20.7 \text{ fb}^{-1}$, $\sqrt{s} = 8 \text{ TeV}$

95% CL limits, $c_{\text{SUSY}}^\text{theory}$ not included.

- Expected
  - 0-lepton, 2-6 jets
  - 0-lepton, 7-10 jets
  - 0-1 lepton, 3 b-jets
  - 1-lepton + jets + MET
  - 1-2 taus + jets + MET
  - 2-SS-leptons, 0 - $\geq$ 3 b-jets

- Observed
  - ATLAS-CONF-2013-047
  - ATLAS-CONF-2013-054
  - ATLAS-CONF-2013-061
  - ATLAS-CONF-2013-062
  - ATLAS-CONF-2013-026
  - ATLAS-CONF-2013-007
Limits from LHC8 for mSUGRA scenario

\[ m_{1/2} \text{ [GeV]} \]

\[ m_0 \text{ [GeV]} \]

CMS

\[ \tilde{\tau} = \text{LSP} \]

\[ m_{\tilde{g}} = 1000 \text{ GeV} \]

\[ m_{\tilde{g}} = 1400 \text{ GeV} \]

\[ m_{\tilde{g}} = 2200 \text{ GeV} \]

\[ m_{\tilde{g}} = 2400 \text{ GeV} \]

\[ m_{\tilde{g}} = 3400 \text{ GeV} \]

\[ m_h = 123 \text{ GeV} \]

\[ m_h = 125 \text{ GeV} \]

\[ m_h = 127 \text{ GeV} \]

\[ M_{\text{top}} = 172.5 \text{ GeV} \]

\[ \tan(\beta) = 30, \quad A_0 = -2\max(m_0,m_{1/2}) \]

\[ \mu > 0; \quad m_{\tilde{g}} = 1000 \text{ GeV} \]

\[ 19.5 \text{ fb}^{-1} (8 \text{ TeV}) \]

\[ \text{observed limit} \pm 1 \sigma_{\text{experiment}} \]

\[ \text{expected limit} \pm 1 \sigma_{\text{theory}} \]

Alexander Belyaev

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No SUSY hint from the experimental searches …

Coloured Sparticles are excluded below 1 TeV for the large enough mass gap with LSP.

<table>
<thead>
<tr>
<th>m(mother) - m(LSP)</th>
<th>SUSY Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUS 13.019 L=19.5 fb</td>
<td>SUS 13.011 SUS 13.019 L=19.5 fb</td>
</tr>
<tr>
<td>SUS 13.007 SUS 13.013 L=19.5 fb</td>
<td>SUS 13.007 SUS 13.013 L=19.5 fb</td>
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<td>SUS 13.007 SUS 13.013 L=19.5 fb</td>
</tr>
</tbody>
</table>

*Observed limits, theory uncertainties not included. Only a selection of available mass limits.
Probe "up to" the others.

CMS Preliminary
For decays with intermediate mass,
\[ m_{\text{intermediate}} = x m_{\text{mother}} + (1-x) m_{\text{LSP}} \]
What is about DM mass?

CMS Preliminary, 19.5 fb\(^{-1}\), \(\sqrt{s} = 8\) TeV

**Interplay of the LHC and DM search in unravelling Natural SUSY**
What is about DM mass?

There is no limit on the LSP mass if the mass of strongly interacting SUSY particles above ~ 1 TeV
Complementarity of DM searches (from 2004)

**DM direct detection:**
neutralino scattering off nuclei

Correct relic density $\rightarrow$ Efficient annihilation

Efficient annihilation now (Indirect detection)
Efficient scattering now (Direct detection)

Stage 1: CDMS1(2), Edelweiss, Zeplin(2)
Stage 2: LUX, XENON 100, ...
Stage 3: XENON 1 ton, WARP

**DM indirect detection:**
signatures from neutralino annihilation in halo, core of the Earth and Sun
photons, anti-protons, positrons, neutrinos

*Neutrino telescopes: Amanda, Icecube, Antares*
pMSSM combined results

ArXiv:1305.6921: Cahill-Rowley, Cotta, Drlica-Wagner, Funk, Hewett

dark matter can be discovered
- in DD experiments
- in ID experiments
- in both, DD and ID
- may be discovered at the upgraded LHC, but escape detection in future DD or ID detection experiments

XENON 1T
The EW measure of Fine Tuning

\[ \mathcal{L}_{\text{MSSM}} = \mu \tilde{H}_u \tilde{H}_d + \text{h.c.} + (m_{\tilde{H}_u}^2 + |\mu|^2) |H_u|^2 + (m_{\tilde{H}_d}^2 + |\mu|^2) |H_d|^2 + \ldots \]

The EW measure requires that there be no large/unnatural cancellations in deriving \( m_Z \) from the weak scale scalar potential:

\[
\frac{m_Z^2}{2} = \frac{(m_{\tilde{H}_d}^2 + \Sigma_d^d) - (m_{\tilde{H}_u}^2 + \Sigma_u^u) \tan^2 \beta}{(\tan^2 \beta - 1)} - \mu^2 \simeq -m_{H_u}^2 - \mu^2
\]

using fine-tuning definition which became standard

Ellis, Enqvist, Nanopoulos, Zwirner '86; Barbieri, Giudice '88

\[ \Delta_{FT} = \max [c_i], \quad c_i = \left| \frac{\partial \ln m_Z^2}{\partial \ln p_i} \right| = \left| \frac{p_i}{m_Z^2} \frac{\partial m_Z^2}{\partial p_i} \right| \]

one finds \( \Delta_{FT} \simeq \Delta_{EW} \) which requires as well as

\[
|\mu^2| \simeq M_Z^2 \quad |m_{H_u}^2| \simeq M_Z^2
\]

The last one is GUT model-dependent, so we consider the value \( |\mu^2| \) as a measure of the minimal fine-tuning
"Compressed Higgsino" Scenario (CHS)

Chargino-neutralino mass matrices

- In \((\tilde{W}^-, \tilde{H}^-)\) basis:
  \[
  \begin{pmatrix}
  M_2 & \sqrt{2}m_W c_\beta \\
  \sqrt{2}m_W s_\beta & \mu
  \end{pmatrix}
  \]

- In \((\tilde{B}^0, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0)\) basis:
  \[
  \begin{pmatrix}
  M_1 & 0 & -m_Z c_\beta s_w & m_Z s_\beta s_w \\
  0 & M_2 & m_Z c_\beta c_w & 0 \\
  -m_Z c_\beta s_w & m_Z c_\beta c_w & 0 & -\mu \\
  m_Z s_\beta s_w & -m_Z s_\beta c_w & -\mu & 0
  \end{pmatrix}
  \]

- \(M_2\) real, \(M_1 = |M_1| e^{-\Phi_1}\), \(\mu = |\mu| e^{i\Phi_\mu}\)

- Case of \(\mu \ll M_1, M_2\): \(\chi_{1,2}^0\) and \(\chi^\pm\) become quasi-degenerate and acquire large higgsino component. This provides a naturally low DM relic density via gaugino annihilation and co-annihilation processes into SM V's and H.

- This is the case of relatively light higgsinos-electroweakinos compared to the other SUSY particles.

- This scenario is not just motivated by its simplicity, but also by the lack of evidence for SUSY to date, indicating that a weak scale SUSY spectrum is likely non-universal.
CHS Mass Spectrum and Challenge for the LHC

- The most challenging case takes place when only $\chi^0_{1,2}$ and $\chi^\pm$ are accessible at the LHC, and the mass gap between them is not enough for any leptonic signature as happen in FFP scenario.
- The only way to probe FFP is a mono-jet signature [Where the Sidewalk Ends? ... Alves, Izaguirre, Wacker '11], which has been used in studies on compressed SUSY spectra, e.g. Dreiner, Kramer, Tattersall '12; Han, Kobakhidze, Liu, Saavedra, Wu'13; Han, Kribs, Martin, Menon '14.
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Note that $W^*$ decay products do not get large boost – it is proportional to the mass of $W^*$ which is much smaller than the mass of the LSP.
Analysis Setup

MSSM
- SPHENO for mass spectrum, cross checked with ISAJET
- micrOMEGAs for DM relic density, DM DD and ID
- MadGraph for parton level simulations, cross checked with CalcHEP
- PYTHIA6 for hadronization and parton-showering
- Delphes3 for fast detector simulation
- CTEQ6L1 PDF

Main backgrounds for $p_T$ jet + high MET signature
- Irreducible $Z$ + jet → $\nu \nu$ + jet (Zj)
- Reducible $W$ + jet → $\ell \nu$ + jet (Wj) when $\ell$ is missed
Spectrum and Decays in CHS

For $|\mu| \ll |M1|$, $|M2|$ one has

$$m_{\tilde{\chi}^0_{1,2}} \simeq |\mu| \mp \frac{m_Z^2}{2} (1 \pm s_{2\beta}) \left( \frac{s_W^2}{M_1} + \frac{c_W^2}{M_2} \right)$$

$$m_{\tilde{\chi}^\pm_1} \simeq |\mu| \left( 1 + \frac{\alpha(m_Z)}{\pi} \left( 2 + \ln \frac{m_Z^2}{\mu^2} \right) \right) - s_{2\beta} \frac{m_W^2}{M_2}$$

$$\Delta m_o = m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} \approx \frac{m_Z^2}{2} \left( \frac{s_W^2}{M_1} + \frac{c_W^2}{M_2} \right)$$

$$\Delta m_\pm = m_{\tilde{\chi}^\pm_1} - m_{\tilde{\chi}^0_1} \approx \frac{\Delta m_0}{2} + \mu \frac{\alpha(m_Z)}{\pi} \left( 2 + \ln \frac{m_Z^2}{\mu^2} \right)$$

$$\Gamma(\tilde{\chi}^\pm_1, \tilde{\chi}^0_2 \rightarrow f f' \tilde{\chi}^0_1) = \frac{C^4 \Delta m^5}{120 \pi^3 \Lambda^4}$$

$$C^4 \simeq \frac{1}{4} \frac{g^4}{c_W^4} (s_w^2 - 1/2)^2$$

$$L = c\tau \simeq 0.01 \text{ cm} \left( \frac{\Delta m}{1 \text{ GeV}} \right)^{-5} \tilde{\chi}^0_2 \rightarrow f f' \tilde{\chi}^0_1 \text{ (Z-exchange)}$$

$$L = c\tau \simeq 0.006 \text{ cm} \left( \frac{\Delta m}{1 \text{ GeV}} \right)^{-5} \tilde{\chi}^\pm_1 \rightarrow f f' \tilde{\chi}^0_1 \text{ (W-exchange)}$$

for $\Delta m < 1 \text{ GeV}$ we expect to start seeing displaced vertices $\sim 0.1 \text{ mm}$
\[ \Delta M = m_{\chi^\pm} - m_{\chi^0} \text{ VS } M_1 \text{ plane} \]
$\Delta M$ pattern for $M_1 > 0$ and $M_1 < 0$ cases
Dark Matter Relic Density

\[ M_1 > 0 \]

\[ M_1 < 0 \]

\[ \Omega_X h^2 \]

\[ \mu \text{ [GeV]} \]
Dark Matter Relic Density

\[ \Omega_x h^2 \]

\[ M_1 > 0 \]

\[ M_1 = \mu \]

\[ M_1 = \mu + 600 \]

\[ \tan \beta = 5 \]

\[ \mu [\text{GeV}] \]

\[ \Omega_x h^2 \]

\[ M_1 < 0 \]

\[ M_1 = -\mu \]

\[ M_1 = -\mu - 600 \]

\[ \mu [\text{GeV}] \]

Z-resonance

H-resonance

WW-threshold

LEP

Planck
DM relic density is below the measured one because of intense LSP annihilation and co-annihilation processes.
Dark Matter Relic Density

- The pattern is independent of $\tan \beta$
Direct Detection Prospects

- DD cross section rescaled with the relic density is low in the small $\Delta M$ region. Chance for the LHC?
Direct Detection Prospects

Interplay of the LHC and DM search in unravelling Natural SUSY
DD in $M_1-\mu$ plane

$m_{\chi_1^0}$ and $m_{\chi_1^\pm}-m_{\chi_1^0}$ [GeV]

$m_{\chi_1^0}$ and $m_{\chi_1^\pm}-m_{\chi_1^0}$ [GeV]
LHC potential to probe NSUSY space through the \( pp \to \chi \chi j : \chi = \chi^0_{1,2}, \chi^\pm_1 \) process
LHC sensitivity to FFP through the $pp \rightarrow \chi \chi j : \chi = \chi^0_{1,2}, \chi^\pm_1$ process

$\sigma$(fb) vs. $\mu$(GeV) for $pp \rightarrow \chi \chi$

$\sigma$(fb) vs. $\mu$(GeV) for $pp \rightarrow \chi \chi j$ with $P_T^j > 50$ GeV and $P_T^j > 600$ GeV
Signal vs Background analysis

difference in rates is quite pessimistic ...

$pp \rightarrow \nu\nu j$ vs. $pp \rightarrow \chi\chi j$
Signal vs Background analysis

but the difference in shapes is quite encouraging!

$pp \rightarrow vvj$ vs. $pp \rightarrow \chi \chi j$

![Graph showing signal vs background analysis](image)
the lack of the perfect $p_T^{j1}$ vs MET correlations leads to a visible difference of the S/B ratio and significance, and should be taken into account.
There is a strong tension between S/B and signal significance.

- S/B pushes $E_T^{\text{miss}}$ cut up towards an acceptable systematic.
- Significance requires comparatively low (below 500 GeV) $E_T^{\text{miss}}$ cut.
What is the minimal S/B is accessible?

- the respected systematic error has been studies by **ATLAS and CMS LHC@8 collaborations**

  sources of systematic uncertainty and their contributions (in %) to the total uncertainty on the $Z(\nu\nu)$ background from CMS PAS EXO-12-048

<table>
<thead>
<tr>
<th>$E_T^{\text{miss}}$ (GeV)</th>
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<td>Statistics ($N^{\text{obs}}$)</td>
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<td>0.0</td>
<td>0.0</td>
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<td>2.2</td>
<td>2.4</td>
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<td>2.4</td>
<td>2.7</td>
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- So, the realistic (or even optimistic!) S/B one should be looking at is \( \sim 5\% \) or more.
Interpreting LHC@8TeV results (CMS EXO-12-048)

<table>
<thead>
<tr>
<th>Selection</th>
<th>W+jets</th>
<th>Z+j</th>
<th>Z(\nu\nu)+j</th>
<th>tt</th>
<th>QCD</th>
<th>Single top</th>
<th>Total</th>
</tr>
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<tr>
<td>Cross section (pb)</td>
<td>229.0</td>
<td>34.1</td>
<td>588.3</td>
<td>225.2</td>
<td>1904.8</td>
<td>113.5</td>
<td></td>
</tr>
<tr>
<td>(E_T^{miss}&gt;550) GeV</td>
<td>136</td>
<td>1</td>
<td>429</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>569</td>
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LHC8 \(L=19.6\) fb\(^{-1}\) \(E_T^{miss}>250\) GeV

LHC8 \(L=19.6\) fb\(^{-1}\) \(E_T^{miss}>550\) GeV

- Both S/B and Significance are too low – so LHC@8 is unfortunately not sensitive to NSUSY space …
LHC@13 TeV potential to probe NSUSY

\[ m_{X_1^0} = 105 \text{ GeV} \quad \Delta M = 3 \text{ GeV} \quad \text{LHC13 100 fb}^{-1} \]

\[ m_{X_1^0} = 203 \text{ GeV} \quad \Delta M = 3 \text{ GeV} \quad \text{LHC13 100 fb}^{-1} \]

- \( S/B \) vs significance tension requires very high luminosity to allow high (~1 TeV) missing \( E_T \) cut and keep \( \alpha \) above 2 at the same time!
Optimisation of the $E_T^{\text{miss}}$ cut

LHC13  $L=3000$ fb$^{-1}$

- The shapes of $S/B$ and $\alpha$ contours are correlated.
- The idea is to choose $E_T^{\text{miss}}$ which brings $S/B$ and $\alpha$ iso-contours together.

Red: $\alpha=2$
Blue: $S/B=3\%$
Dashed: $E_T^{\text{miss}}=850$ GeV
Solid: $E_T^{\text{miss}}=900$ GeV
LHC@13 Reach for NSUSY

- 3% and 5% cases for S/B are taken
- 3 ab\(^{-1}\) and 100 fb\(^{-1}\) cases
- LUX and XENON1T are sensitive to the upper end of NSUSY
- assuming S/B \approx 3\% (based on ATLAS studies) the sensitivity of the LHC could extend up to 250 GeV LSP mass (95\% CL) for 3 ab\(^{-1}\) luminosity
- mass gap above 250 GeV requires further attention
3% and 5% cases for S/B are taken

- 3 ab$^{-1}$ and 100 fb$^{-1}$ cases
- LUX and XENON1T are sensitive to the upper end of NSUSY
- Assuming S/B ≈ 3% (based on ATLAS studies) the sensitivity of the LHC could extend up to 200 GeV LSP mass (5σ) for 3 ab$^{-1}$ luminosity
LHC@13 Reach for NSUSY

LHC13  2σ contour  (M1>0)

LHC13  5σ contour  (M1>0)

\[ \Delta M \text{ [GeV]} \]

\[ m_{\chi_1^0} \text{ [GeV]} \]

LUX

XENON1T

LEP

LHC13  3 ab^{-1} (3%)

LHC13  100 fb^{-1} (3%)

LHC13  3 ab^{-1} (5%)

LHC13  3 ab^{-1} (5%)
LHC@13 Reach for NSUSY

![Diagram showing LHC@13 reach for neutralinos](image-url)
Discussion

- **Similar recent studies:**
  - Han, Kobakhidze, Liu, Saavedra, Wu, Yang '13:
    - “NSUSY can be probed up to 200 GeV at 5 sigma level with 1.5 ab⁻¹”
    - but S/B < 1% for 200 GeV LSP – not quite realistic to probe
  - Baer, Mustafayev, Tata '14:
    - “NSUSY can not be probed at the LHC, since S/B ~ 1%”
    - may be bit too conservative, since S/B can be improved with high \( P_T \) cuts, this however requires high luminosity to keep statistics up
  - Han, Kribs, Martin, Menon '14
    - interpreted LHC@8TeV results, found sensitivity up to 70-90 GeV
    - study was done at the parton level, while at the detector level we have found that both S/B and significance are too low for LHC@8TeV to be sensitive to NSUSY

- **How important is the jet matching for this study?**
  - we have performed simulation starting from the hard \( P_T \) cut (500 GeV) to gain as much statistics as possible
  - we have checked that matching (up to the 3 jet) does not have visible effect
Conclusions

• NSUSY with light Higgsinos is well-motivated but hard to test - is not excluded (!)

• so far we have ~ 100 GeV limit from LEP

• We have shown that in reality LHC@13 has potential to probe light Higgsinos up to about 250 GeV if S/B ~ 3% (or better) control is possible

• DDM search experiments - LUX and XENON1T are very complementary for $\Delta M > 5$ GeV

• $M_{DM}$ above 250 GeV requires further exploration (ILC?)
Conclusions

- FFP with light Higgsinos is well-motivated but hard to test - is not excluded (!)

- so far we have ~ 100 GeV limit from LEP, and it is very important not to miss this scenario

- We have shown that in reality LHC@13 has potential to probe light Higgsinos up to about 130 GeV if S/B ~ 5% (or better) control is possible

- DDM search experiments - LUX and XENON1T are very complementary (from about 320 GeV)

- Mass gap 130-320 GeV requires a further exploration (ILC)
Final remarks

- SUSY cannot be experimentally ruled out!
  - It can only be discovered (optimists).
  - Or abandoned (pessimists)

Lets be optimists!

Original statement from Leszek Roszkowski: “Low energy SUSY cannot be experimentally ruled out. It can only be discovered. Or else abandoned.”
Thank you!
Obrigado!