SUSY and Cosmology/Naturalness

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1. SUSY after LHC
   Higgs Mass
   Mini-split SUSY
   Dark Matter

2. Dark Matter Signatures in Mini-split
   Wino
   Gaugino coannihilation
   Long lived particle signatures

3. Summary
Higgs and SUSY at LHC

Higgs Discovered!

SUSY Constrained!
Cornering Higgs and SUSY

\[ m_h = 125.18 \pm 0.16 \text{ GeV} \]

\[ m_{\tilde{q}} > 1550 \text{ GeV} \]
SUSY Higgs

Higgs potential

\[ V(H) = \frac{\lambda}{2} (HH^\dagger - \nu^2)^2 \]

In MSSM

\[ \lambda = \frac{1}{4} (g_1^2 + g_2^2) \cos(2\beta) \]

\[ m_h = m_Z \cos(2\beta) \lesssim 91 \text{ GeV} \]

This is clearly less than observed 125 GeV Higgs!

\[ \lambda = \lambda_{\text{MSSM}} + \lambda_{\text{SUSY breaking}} + \lambda_{\text{new interaction}} \]
SUSY after 125 GeV Higgs

Scalar top

\{ Large mass
A-term \}

“4-th” family

NMSSM

\{ Lambda SUSY
Fat higgs \}

New Gauge Interaction

New Interaction
SUSY after 125 GeV Higgs

- SUSY
  - Scalar top
    - Large mass
    - A-term
  - “4-th” family
- New Interaction
  - NMSSM
    - Lambda SUSY
    - Fat higgs
  - New Gauge Interaction

Simple?  Natural?
Higgs Mass from Stop

125 GeV Higgs OK regions

Theory

Experiment

$\delta \tilde{Q}_L = \delta \tilde{u}_R = 0.9$

$\Delta_3 \tilde{Q}_L = 4$

Scalar Mass

$m_0 [\text{TeV}]$

$\tan \beta$
Benefit and demerit of SUSY

Benefit

- Hierarchy Problem
- GUT unification
- DM

Possible demerit

- Flavor/CP Problem
- Cosmological Gravitino Problem
- Model building
Mini-Split Mass Spectrum

Tree level Gravity Mediation

$$|m_0| \sim |\mu| \sim m_{3/2}$$

Loop suppressed: Anomaly Mediation

$$M_a \sim \frac{\alpha_a}{4\pi} m_{3/2}$$

Randall, Sundrum '98
Giudice, Luty, Murayama, Rattazzi '98
Benefit and demerit of SUSY

Benefit

? • Hierarchy Problem
✓ • GUT unification
✓ • DM

Possible demerit

✓ • Flavor/CP Problem
✓ • Cosmological Gravitino Problem
✓ • Model building
Three Possibilities for DM

Wino DM  Bino-wino coannihilation  Bino-gluino coannihilation
Wino DM case
Wino Spectrum

Radiative correction

Charged slightly heavier

\[ c \tau (\tilde{W}^\pm \rightarrow \tilde{W}^0 \pi^\pm) \simeq 7 \text{ cm} \left( \frac{\Delta m}{165 \text{ MeV}} \right)^{-3} \]
LHC Signals

\[ p \rightarrow \tilde{\chi}^0 \rightarrow \tilde{\chi}^\pm \rightarrow \tilde{\chi}^0 + \pi^\pm \]

Meta-stable track + MET

O(1-10)cm
Current Constraint (wino)

30 cm

3 cm

MET + disappearing track
Tracker for Run1

8 TeV selection

TRT (Transition Radiation)

SCT (Semiconductor)

Pixel

Four layer hits
Tracker for Run2

- TRT (Transition Radiation)
- SCT (Semiconductor)
- Pixel
- IBL (Insertable B-Layer)
Tracker for Run2

TRT (Transition Radiation)

SCT (Semiconductor)

Pixel

IBL (Insertable B-Layer)
Current Constraint (wino)

$\tan\beta = 5, \mu > 0$

$\tau_{\chi^1} [\text{ns}]$

$\chi_1 [\text{GeV}]$

$\sqrt{s} = 13\text{TeV}, 36.1 \text{ fb}^{-1}$

- Observed 95% CL limit ($\pm 1\sigma_{\text{theory}}$)
- Expected 95% CL limit ($\pm 1\sigma_{\text{exp}}$)
- ATLAS (8 TeV, 20.3 fb$^{-1}$, EW prod.)

30 cm

3 cm
Tracking shorter

SCT (Semiconductor) 51 cm 30 cm

TRT (Transition Radiation) 108 cm 55 cm

Pixel 12 cm 5 cm

IBL (Insertable B-Layer) 3 cm

Three hits
Tracking shorter

TRT
(Transition Radiation)

SCT
(Semiconductor)

Pixel

IBL
(Insertable B-Layer)

108 cm
55 cm
51 cm
30 cm
12 cm
5 cm
3 cm

Two layer+
One primary vertex
Tracker for Run???

TRT (Transition Radiation)

SCT (Semiconductor)

Pixel

IBL (Insertable B-Layer)
Prospects for Wino

![Graph showing prospects for Wino with regions for MET>400 GeV and MET>600 GeV.]
Bino-Gluino Coannihilation
Bino-Gluino Coannihilation 1

Dark matter abundance

Gluino-bino mass difference

1 TeV bino

Observed DM
Gluino Coannihilation

\[ M_{\tilde{g}} - M_B \ [\text{GeV}] \]

\[ M_B \ [\text{GeV}] \]

\[ \Omega h^2 = 0.12 \]
LHC Signals

\begin{figure}
\centering
\includegraphics[width=\textwidth]{diagram}
\caption{Diagram of LHC Signals}
\end{figure}
Prompt Decay Case

$\tilde{g}\tilde{g}$ production, $B(\tilde{g} \rightarrow qq\tilde{\chi}_1^0) = 100\%$

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

0-leptons, 2-6 jets
MEff or RJR (Best Expected)
All limits at 95% CL

Mass diff. = 100 GeV
Bino-Gluino Interaction

Bino-gluino interaction is suppressed by sfermion mass

Long-lived gluino

\[ c\tau \tilde{g} = O(1) \left( \frac{\Delta m}{100 \text{ GeV}} \right)^{-5} \left( \frac{M_s}{100 \text{ TeV}} \right)^4 \text{ cm} \]
Bino-Gluino Interaction

**ATLAS**

$\sqrt{s}=13$ TeV, $L=32.8$ fb$^{-1}$

All limits at 95% CL

$\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$, $\Delta m=100$ GeV

**Upper limit on cross section [pb]**

$\sqrt{s}=13$ TeV, $L=32.8$ fb$^{-1}$

All limits at 95% CL

$\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$, $\tau = 1$ ns
Prospects
Bino-Wino Coannihilation
Bino-Wino Coannihilation

A few tens of GeV mass diff.

Required mass difference

\( \Omega_{DM} h^2 = 0.12 \)
LHC Signals

Mass diff. 30 GeV
Wino Decay (tree)

\[ \tilde{W}^0 \rightarrow H \rightarrow \bar{b}b \]

- Suppressed by Higgsino mass
- Small Yukawa

Long-lived neutral wino
Wino Decay

- Prompt charged Wino decay: \( \tilde{W}^\pm \rightarrow W^\pm \tilde{B} \propto \mu^{-1} \)
- Displaced neutral Wino decay: \( \tilde{W}^0 \rightarrow \gamma \tilde{B} \propto \frac{\alpha}{4\pi} \mu^{-2}, \left(\frac{\alpha}{4\pi}\right)^2 \mu^{-1} \)
Wino Decay

Bino = 400 GeV
Wino = 430 GeV

Decay length of neutral wino

Higgs mass OK
LHC Signals

Low mass \sim 10 \text{ GeV} \text{ DV } + \text{ MET}
Summary

- Mini-split is simplest SUSY model with 125 GeV Higgs
- DM in mini-split likely provide *meta-stable* particles
  - Wino DM: disappering track
  - Gluino-bino DM: long-lived R-hadron
  - Wino-bino DM: long-lived neutral wino
- Improvement of LLP detection
Indirect Search @LHC
DM Search

Indirect Search from SM precision

Exotic tracks:
- Disappearing track
- Displaced soft track
Indirect Probe at LHC

Interference between SM and BSM gives correction
Observed Data
Correction from DM

Relative correction from 300 GeV Wino
Correction from DM

Relative correction from 300 GeV Wino

gauge running. \sim \log(s)

\Delta \sim - \left( \frac{n}{3} \right)^3$

\begin{align*}
\dim. 6 & \sim s/m^2 \\
\end{align*}
Indirect Probe at LHC
Indirect Probe at LHC

# of SU(2) representation

![Graph showing the expected and observed values for the number of SU(2) representations as a function of mass. The graph includes lines for mass, 5% systematics, 2% systematics, statistical only, 5plet MDM, wino, and "Higgsino". The observed data is marked with 36 fb⁻¹, and the expected data is marked with 3 ab⁻¹.](image)
LHC DM Search Summary

- LLP signals are great help for DM search
- Prevision measurements can also probe DM: as powerful as mono-jet + MET search
Indirect Search @ILC
Effective Operator

Case of beam energy < 2 x mass. Integrating out of MDM leads effective operators

\[-\frac{1}{\Lambda_{2W}^2}(D_\mu W^a_{\mu\nu})^2 - \frac{1}{\Lambda_{2B}^2}(\partial_\mu B_{\mu\nu})^2 + \frac{g}{\Lambda_{3W}} W^3 \ldots\]

\[
\frac{1}{\Lambda_{2W}^2} = \frac{g^2}{16\pi^2} \frac{1}{15m^2} \frac{n(n-1)(n+1)}{6}
\]

\[
\frac{1}{\Lambda_{2B}^2} = \frac{g'^2}{16\pi^2} \frac{2nY^2}{15m^2}
\]

\[
\frac{1}{\Lambda_{3W}^2} = -\frac{1}{12\Lambda_{2W}^2}
\]

(Dirac Fermion)

Correction to gauge boson propagator and self-coupling
On-Z Observables

Heavy DM cannot be produced at collider, but affects SM processes

Case 1: Oblique correction to electroweak precision observables (EWPO)
weak boson mass and so on
Current Constraints from EWPO

# of SU(2) representation

Corrections are roughly proportional to $\frac{n^3}{m^2}$
ILC250 for MDM

Case 2: Correction to di-fermion process at ILC.

See Suehara’s talk
ILC250 for Heavy MDM

![Graph showing the comparison between (BSM-SM)/(SM)% and dσ_{SM}/d(cosθ) for different masses: 220 GeV wino, 150 GeV Higgsino, and 300 GeV MDM.]
Reach of ILC250 for Higgsinos

mu, e, b, c sys. Ratios: 2 : 1.5 : 5 : 10 assumed
Reach of ILC250

\[ n \quad vs \quad m \quad [\text{GeV}] \]

- \( e^+ e^- \rightarrow \mu^+ \mu^- (0.2\% \text{sys.}) \)
- \( e^+ e^- \rightarrow \mu^+ \mu^- (\text{stat. only}) \)
- all mode (stat. only)
- 5plet MDM
- Wino
- "Higgsino"
ILC250 for MDM

Case 3: Correction to diboson process at ILC.
ILC250 for MDM

\[ \delta \sigma_{WW}/\sigma_{WW} = -10^{-4} \]

95% sensitivity (stat only)

\[ n = 10^{-2}, 10^{-3} \]

Mass [GeV]

5plet MDM

Wino

“Higgsino”
Indirect Probe Summary

# of SU(2) representation

- $\text{EWPO (observed)}$
- $\text{EWPO (GigaZ)}$
- $\text{ILC250 (0.2\% sys.)}$
- Expected 3 $\text{ab}^{-1}$
- 5\% sys
- 2\% sys
- Stat. only
- $\text{5plet MDM}$
- $\text{Wino}$
- “Higgsino”
Indirect Search Summary

• MDM can be indirectly tested at LHC and ILC
• As powerful as mono-jet + MET search
• This method uses only EW gauge interaction
  • Any EW interacting particle
Bino-Gluino Interaction

Bino-gluino interaction is suppressed by sfermion mass

Long-lived gluino

Too heavy sfermion prevents coannihilation

\[ c \tau \tilde{g} = O(1) \left( \frac{\Delta m}{100 \text{ GeV}} \right)^{-5} \left( \frac{M_s}{100 \text{ TeV}} \right)^4 \text{ cm} \]

\[ M_s \lesssim 250 \left( \frac{M_{bino}}{1 \text{ TeV}} \right)^{3/4} \text{ TeV} \]
Bino-Gluino Coannihilation 2

E.g.,

For 100 TeV sfermion,

Mass diff. ~ 100 GeV

Decay length ~ cm
EW interacting DM

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</table>
Higgsino Spectrum

\[
\left( \begin{array}{c} H_u^+ \\ \tilde{H}_u^0 \\ H_u^0 \end{array} \right), \quad \left( \begin{array}{c} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{array} \right) \quad \rightarrow \quad \tilde{\chi}_1^0, \quad \tilde{\chi}_2^0, \quad \tilde{\chi}^{\pm}
\]

\[
c\tau(\tilde{\chi}^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm) = 1.1 \text{ cm} \left( \frac{\Delta m_+}{300 \text{ MeV}} \right)^{-3} \left[ 1 - \frac{m_{\pi^\pm}^2}{\Delta m_+^2} \right]^{-1/2}
\]
Prospects for Higgsino

![Graph showing the prospects for Higgsino with different background rates (BG=0, BG=10) and MET thresholds (MET>400 GeV, MET>600 GeV). The graph plots cτ [cm] against Higgsino mass [GeV] with colored bands representing different detection scenarios.]

- **BG=0**: MET>400 GeV
  - 5 cm
  - MET>600 GeV
  - 3 cm

- **BG=10**: MET>400 GeV
  - 5 cm
  - MET>600 GeV
  - 3 cm
Gaugino Mass

\[ M_1 = \frac{3}{5} \frac{\alpha_1}{4\pi} (11m_{3/2} + L), \]
\[ M_2 = \frac{\alpha_2}{4\pi} (m_{3/2} + L), \]
\[ M_3 = \frac{\alpha_3}{4\pi} (-3m_{3/2})(1 + c_{\tilde{g}}). \]
Gaugino Mass

\[
M_1 = \frac{3}{5} \frac{\alpha_1}{4\pi} \left( \frac{11m_3/2 + L}{\alpha_2} \right),
\]

\[
M_2 = \frac{\alpha_2}{4\pi} \left( \frac{m_3/2 + L}{\alpha_3} \right),
\]

\[
M_3 = \frac{\alpha_3}{4\pi} \left( -\frac{3m_3/2}{\alpha_3} (1 + c_\tilde{g}) \right).
\]

+ High energy sector, such as Axion, also affects
Gaugino Mass

\[
M_1 = \frac{3}{5} \frac{\alpha_1}{4\pi} \left( 11 \frac{m_3}{2} + L \right),
\]

\[
M_2 = \frac{\alpha_2}{4\pi} \left( \frac{m_3}{2} + L \right).
\]

\[
M_3 = \frac{\alpha_3}{4\pi} \left( -3 \frac{m_3}{2} \right) \left( 1 + c_{\tilde{g}} \right).
\]

+ High energy sector, such as Axion, also affects

Free gaugino mass relation
Bino DM 1

Bino interactions are tiny; suppression by heavy higgsinos and sfermions

\[ \Omega_{\tilde{B}}^{\text{Higgsino}} h^2 \sim \mathcal{O}(100) \times \left( \frac{\tan \beta}{10} \right)^2 \left( \frac{\mu}{1 \text{ TeV}} \right)^2 \]

\[ \Omega_{\tilde{B}}^{\text{sfermion}} h^2 \sim \mathcal{O}(10) \times \left( \frac{100 \text{ GeV}}{M_{\tilde{B}}} \right)^2 \left( \frac{M_s}{1 \text{ TeV}} \right)^4 \]
Bino DM 2

Bino interactions are tiny; suppression by heavy higgsinos and sfermions

Too much abundance without coannihilation

Tiny constraints from CRs and direct detection.

Astrophysical probe is hard

LHC search is most important!