New search strategies for well tempered neutralino dark matter

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Roadmap of the talk

- Briefly review WIMP dark matter
- Explain what a well tempered neutralino is
- Astrophysical constraints from Indirect/Direct Detection
- Discuss why well tempered neutrinos are hard to find
- Show example of new strategies
- Parameter space covered with strategies
Dark Matter Overview

Evidence for DM
- Rotation curves
- Gravitational lensing
- Ia supernovae
- Cosmological nucleosynthesis
- CMB anisotropies
Dark Matter Overview

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What do we Know?
- Density
  \[ \Omega_c = \rho \frac{8\pi G}{3H_0^2} = 0.2568 \]
- Interacts with gravity, not photons
Dark Matter Overview

Evidence for DM
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What do we Know?
- Density \( \Omega_c = \frac{8\pi G}{3H_0^2} = 0.2568 \)
- Interacts with gravity, not photons

Still need to know:
- Mass, spin, interactions...
Assume that DM does interact with the SM by means beyond gravity
WIMP Dark Matter

Assume that DM does interact with the SM by means beyond gravity

- DM can be in thermal equilibrium with SM in the early universe
- Expansion leads to freeze-out, "WIMP miracle"

\[
\frac{d(n_X a^3)}{dt} = -(n_X^2 - n_{X,eq}^2)a^3 \langle \sigma v \rangle
\]
WIMP Dark Matter

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\]

\[
x = \frac{m}{T} \text{ (time \rightarrow)}
\]
WIMP Dark Matter

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\[ \frac{d(n_X a^3)}{dt} = -(n_X^2 - n_X^{eq}) a^3 \langle \sigma v \rangle \]

- Allows for search methods
  - Direct Detection
  - Indirect Detection
  - Production at colliders
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  \]

- Allows for search methods
  - Direct Detection
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  - Production at colliders

Use supersymmetry as a WIMP model. Extra particles affect \( \langle \sigma v \rangle \)
Dark matter from supersymmetry

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<tr>
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# Dark matter from supersymmetry

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**Dark matter from supersymmetry**

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**Higgsinos and Gauginos mix to form Neutralinos and Charginos**
Dark matter from supersymmetry

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Higgsinos and Gauginos mix to form Neutralinos and Charginos

\[
(\tilde{B} \ \tilde{W}^3 \ \tilde{H}_d^0 \ \tilde{H}_u^0) \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^3 \\ \tilde{H}_d^0 \\ \tilde{H}_u^0 \end{pmatrix}
\]
Dark matter from supersymmetry

Higgsinos and Gauginos mix to form Neutralinos and Charginos

\[
\langle \sigma v \rangle \text{ determined by } M_1, M_2, \mu, \text{ and } \tan \beta
\]

R parity doesn’t allow LSP to decay
Dark matter from supersymmetry

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Higgsinos and Gauginos mix to form Neutralinos and Charginos

$$\begin{pmatrix}
\tilde{B} & \tilde{W}^3 & \tilde{H}_d^0 & \tilde{H}_u^0
\end{pmatrix}
\begin{pmatrix}
M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\
0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\
-c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\
s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0
\end{pmatrix}
\begin{pmatrix}
\tilde{B} \\
\tilde{W}^3 \\
\tilde{H}_d^0 \\
\tilde{H}_u^0
\end{pmatrix}$$

$\langle \sigma v \rangle$ determined by $M_1, M_2, \mu, \text{ and } \tan \beta$

R parity doesn’t allow LSP to decay

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Isolated EW-inos

What mass is needed to quench relic abundance?
Isolated EW-inos

What mass is needed to quench relic abundance?

**Bino**
- Gauge singlet
- 1 Neutralino, 0 Charginos

![Graph showing relic density vs. Wimp Mass](image)
Isolated EW-inos

What mass is needed to quench relic abundance?

**Bino**
- Gauge singlet
- 1 Neutralino, 0 Charginos

**Higgsinos**
- 2 Gauge doublets
- 2 Neutralinos, 1 Charginos
Isolated EW-inos

What mass is needed to quench relic abundance?

**Bino**
- Gauge singlet
- 1 Neutralino, 0 Charginos

**Higgsinos**
- 2 Gauge doublets
- 2 Neutralinos, 1 Charginos

**Wino**
- 1 Gauge triplet
- 1 Neutralino, 1 Charginos

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Co-annihilations

Why are the relic abundances different for the pure electroweakinos?
Co-annihilations

Why are the relic abundances different for the pure electroweakinos?

\[ \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^+ W^+ \]

\[ \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^+ W^- \]
Co-annihilations

Why are the relic abundances different for the pure electroweakinos?

Annihilation cross section affected by particles near in mass
Co-annihilations

Why are the relic abundances different for the pure electroweakinos?

Annihilation cross section affected by particles near in mass

Well Tempering tunes the values of $M_1, M_2, \mu,$ and $\tan \beta$ to achieve observed relic abundance
The Well Tempered Surface

_Well Tempering_ tunes the values of $M_1, M_2, \mu,$ and $\tan \beta$ to achieve observed relic abundance

- Decouple all supersymmetric scalars (heavy Higgs and sfermions)
- Chose a value for $\tan \beta$ (10)
- Scan over values of $M_1, M_2,$ and $\mu$
  (Spectrum calculated with SUSPECT)
- Keep model point if $\Omega h^2 = 0.12$
  (DM properties calculated with micrOMEGAs)
- Points left over define the **Well Tempered Surface**

The Well Tempered Surface

Mass of the lightest neutralino

\[ m_{\chi^0_1} \]
\[ \tan \beta = 10 \]
The Well Tempered Surface

Mass of the lightest neutralino

$m_{\chi_1^0}$
$tan\beta=10$
The Well Tempered Surface

Mass difference between the lightest two neutralinos
The Well Tempered Surface

Mass difference between the lightest two neutralinos

\[ \Delta m(\chi_1^0, \chi_2^0) \]

\[ \text{tan}\beta = 10 \]
The Well Tempered Surface

Mass difference between the lightest neutralino and chargino

\[ \Delta m(\chi_1^0, \chi_1^\pm) \]

\[ \tan \beta = 10 \]
The Well Tempered Surface

Mass difference between the lightest neutralino and chargino

\[ \Delta m(\chi_1^0, \chi_1^\pm) \]
\[ \tan \beta = 10 \]

\[ M_2 [\text{TeV}] \]
\[ M_1 [\text{TeV}] \]
\[ \mu [\text{TeV}] \]

\[ \leq 2 \text{ GeV} \]
\[ 10 \text{ GeV} \]
\[ 20 \text{ GeV} \]
\[ 30 \text{ GeV} \]
\[ 50 \text{ GeV} \]
\[ \geq m_Z \text{ GeV} \]
What have we learned?

• SUSY with R-parity provides a DM candidate
• Not all SUSY DM candidates give correct DM abundance
• Well tempering leads to small mass splittings
What have we learned?

- SUSY with R-parity provides a DM candidate
- Not all SUSY DM candidates give correct DM abundance
- Well tempering leads to small mass splittings

Modifications and improvements

- Sommerfeld enhancement substantially increases pure Wino annihilation cross section
- Some effect for pure Higgsino
- How is the surface affected?
  - Use DarkSE code by Hruczuk

What is the Sommerfeld enhancement?

“The modification of the wave function of the incoming non-relativistic particles due to their mutual interaction”

Sommerfelded Surface

\[ m_{\chi_1^{\pm}} = 0.1 \text{ TeV}, 0.2 \text{ TeV}, 0.5 \text{ TeV}, 1.0 \text{ TeV}, 1.5 \text{ TeV}, 2.0 \text{ TeV}, 2.5 \text{ TeV} \]

\[ \tan \beta = 10 \]

No Sommerfeld = \[\text{gray}\]
Can entire surface be discovered with current/future experiments?

• Examine indirect/direct detection constraints
• Explore search techniques at high energy colliders
• Complementarity between experiments
Where are we going?

Can entire surface be discovered with current/future experiments?

• Examine indirect/direct detection constraints
• Explore search techniques at high energy colliders
• Complementarity between experiments
Indirect Detection

- Annihilations still happen in dense regions
- Can do $\chi \chi \rightarrow \gamma \gamma$ ($E_\gamma = m_\chi$)
- Lack of signal leads to constraints

Current

Projection

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Indirect Detection

\[ \frac{1}{2}\sigma_{\chi\chi \rightarrow \gamma Z} + \sigma_{\chi\chi \rightarrow \gamma\gamma} = \begin{cases} >10^{-24} & \text{ cm}^3/s \\ 10^{-25} & \text{ cm}^3/s \\ 10^{-26} & \text{ cm}^3/s \\ 10^{-27} & \text{ cm}^3/s \\ 10^{-29} & \text{ cm}^3/s \\ 10^{-31} & \text{ cm}^3/s \\ <10^{-33} & \text{ cm}^3/s \end{cases} \]

Sommerfeld effect enhances annihilation to photons
Indirect Detection

- Constraint depends on DM profile

**Excluded:** HESS-Burk, HESS-NFW, HESS-Ein

**Projected Exclusion:** CTA-Ein
Indirect Detection

- Constraint depends on DM profile

★ Pure Wino plane excluded
- Wino-Higgsino sheet in future
• Constraint depends on DM profile

★ Pure Wino plane excluded
• Wino-Higgsino sheet in future
Direct Detection

• Look for DM scattering off nucleon in detector material
Direct Detection

- Look for DM scattering off nucleon in detector material
Direct Detection

\[ \tan \beta = 10 \]

\[
\begin{align*}
\sigma(\chi_i^0 n \rightarrow \chi_i^0 n) &= \begin{cases} 
< 10^{-45} & : \text{blind spots} \\
10^{-44} & : \text{blind spots} \\
10^{-43} & : \text{blind spots} \\
10^{-42} & : \text{blind spots} \\
10^{-41} & : \text{blind spots} \\
10^{-40} & : \text{blind spots} \\
> 10^{-39} \text{ cm}^2 & : \text{blind spots}
\end{cases}
\end{align*}
\]

\[ \sigma \propto \text{Coupling to } Z \]
\[ \sigma \propto \text{Coupling to } h \]

Accidental cancelations in coupling of LSP to Z(h) leads to blind spots
Direct Detection

- Spin-independent bounds are much better
- Exclusions depend on $\tan \beta$
Direct Detection

- Spin-independent bounds are much better
- Exclusions depend on \( \tan \, \beta \)

★ Bino-Higgsino and Wino-Higgsino are or will be excluded
★ \( M_1, M_2 \leq 4000 \) GeV not decoupled enough… `Pure’ Higgsino discoverable in future
★ Pure Wino mostly covered

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Where are we going?

Can entire surface be discovered with current/future experiments?

• Examine Direct/Indirect Detection constraints

★ Pure Wino and Wino-Higgsino covered by indirect detection
★ Bino-Higgsino, Wino-Higgsino, `Pure Higgsino’, and some Wino surface covered by direct detection
★ No coverage for Bino-Wino
★ Depend on astrophysical assumptions

• Explore search techniques at high energy colliders

• Complementarity between experiments
Can entire surface be discovered with current/future experiments?

- Examine Direct/Indirect Detection constraints
- Explore search techniques at high energy colliders

- Cover Bino-Wino surface
- Resolve conflicts with pure wino

LHC Detectors can distinguish

- Leptons (electrons and muons)
- Photons
- Anything with quarks seen as ‘jet’
- Neutrinos and dark matter not detected; conservation of transverse momentum

- Complementarity between experiments
What limits exist already?

\[ \tilde{\chi}_2^0 - \tilde{\chi}_1^\pm \text{ production} \]

CMS Preliminary
\[ \sqrt{s} = 8 \text{ TeV} \]
ICHEP 2014

\[ \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow (H \tilde{\chi}_1^0)(W \tilde{\chi}_2^0) \]
\[ \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow (Z \tilde{\chi}_1^0)(W \tilde{\chi}_2^0) \]
\[ \tilde{\chi}_2^0 \tilde{\chi}_1^- (1_L, BF(1^+ \Gamma) = 0.5) \]
\[ \tilde{\chi}_1^+ \tilde{\chi}_1^- (1_L, BF(1^+ \Gamma) = 1) \]
\[ \tilde{\chi}_2^0 \tilde{\chi}_1^- (\tilde{\tau} \tilde{\nu}) \]

SUS-13-006  19.5 fb^{-1}

SUS-14-002  19.5 fb^{-1}

Observed

Expected

neutralino mass = chargino mass [GeV]
What limits exist already?

\[ m_{\chi^0} = m_{\tilde{\chi}_2^0} > m_{\chi_1^0} \]

\[ m_{\chi^0} - m_{\tilde{\chi}_2^0} = m_Z \]

CMS \[ \sqrt{s} = 8 \text{ TeV} \]

L = 19.5 fb\(^{-1}\)

\[ pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm, \ (\text{no} \tilde{\gamma}, \text{BF(WZ)}=1) \]

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What limits exist already?

CMS \( \sqrt{s} = 8 \text{ TeV} \) \( \mathbf{L} = 19.5 \text{ fb}^{-1} \)

- \( pp \to \tilde{\chi}^0 \tilde{\chi}_1^\pm \), (no \( \tilde{\tau} \), BF(WZ)=1)
- \( pp \to \tilde{\chi}^0 \tilde{\chi}_2^\pm \), (no \( \tilde{\tau} \), BF(WH)=1)

LEP: \( m_{\chi^+} > 94 \text{ GeV} \)
What limits exist already?

Reminder of mass splittings
What limits exist already?

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

- \( pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \), (no \( \tilde{\gamma} \), BF(WZ)=1)
- \( pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \), (no \( \tilde{\gamma} \), BF(WH)=1)

\[ m_{\tilde{\chi}^0_{\chi_1}} = m_{\tilde{\chi}^0_{\chi_2}} \succ m_{\chi_0} \]

\[ m_{\tilde{\chi}^0_{\chi_2}} - m_{\tilde{\chi}^0_{\chi_1}} = m_Z \]

LEP: \( m_{\chi^+} > 94 \text{ GeV} \)
What limits exist already?

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

- \( pp \rightarrow \tilde{\chi}^{0}_2 \tilde{\chi}^{\pm}_1 \), (no\( \tilde{\tau} \), BF(WZ)=1)
- \( pp \rightarrow \tilde{\chi}^{0}_2 \tilde{\chi}^{\pm}_1 \), (no\( \tilde{\tau} \), BF(WH)=1)

Surface: \( m_{\chi^+}, m_{\chi^0_2} \lesssim m_{\chi^0_1} + 30 \)

LEP: \( m_{\chi^+} > 94 \text{ GeV} \)
Need new methods

• Few SUSY searches so far use photons
• Can light be used to search for dark matter?

\[ pp \rightarrow \gamma + \ell^+ \ell^- + \not{E}_T \]
Neutral current aimed at production of \( \chi_2^0 \chi_3^0 \)
• J. Bramante, A. Delgado, F. Elahi, A. Martin and BO, “Catching sparks from well-forged neutralinos,”

\[ pp \rightarrow \gamma + \ell^\pm + \not{E}_T \]
Charged current aimed at production of \( \chi_2^0 \chi_1^+ \)
• J. Bramante, P. J. Fox, A. Martin, BO, T. Plehn, T. Schell and M. Takeuchi, “Relic neutralino surface at a 100 TeV collider,”
• J. Bramante, N. Desai, P. Fox, A. Martin, BO, and T. Plehn, “Towards the Final Word on Neutralino Dark Matter,”
  arXiv:1510.03460 [hep-ph]
How to get a photon

- 2-body phase space
- Loop factor \( \sim 1/16\pi^2 \)
How to get a photon

\[
\begin{align*}
\chi_{2,3}^{0} & \rightarrow W^{\pm} \rightarrow \chi_{1}^{\pm} \rightarrow \chi_{1}^{0} \\
\chi_{3,2}^{0} & \rightarrow Z^{*} \rightarrow \ell^{-} \rightarrow \ell^{+} \rightarrow \chi_{1}^{0}
\end{align*}
\]

- 2-body phase space
- Loop factor $\sim 1/16\pi^2$

- 3-body phase space
  $\sim 2\text{BPS} \ast \frac{1}{(2\pi)^3} \frac{1}{2} \frac{d^3p}{E_p}$
- Z propagator $\sim \frac{1}{p_Z^2 - m_Z^2}$
- BR($Z \rightarrow \ell^+\ell^-$) $\sim 7\%$
\[ pp \rightarrow \chi_2^0 \chi_3^0 \rightarrow \gamma + \ell^+ \ell^- + E_T \]
Only works in the Bino-Higgsino part of the surface

\[ pp \rightarrow \chi_2^0 \chi_3^0 \rightarrow \gamma + \ell^+ \ell^- + \not{E}_T \]
Only works in the Bino-Higgsino part of the surface

\[ pp \rightarrow \chi_2^0 \chi_3^0 \rightarrow \gamma + \ell^+ \ell^- + E_T \]

**SM Backgrounds**
- \( \gamma tt \)\_dilepton
- \( \gamma \gamma^* / Z (\tau^+ \tau^-) \)\_dilepton
- \( \gamma VV \)\_dilepton
\[ pp \rightarrow \chi_2^0 \chi_3^0 \rightarrow \gamma + \ell^+ \ell^- + E_T \]

Only works in the Bino-Higgsino part of the surface

**SM Backgrounds**

- \( \gamma t\bar{t} \)\textsubscript{dilepton}
- \( \gamma \gamma^*/Z(\tau^+ \tau^-) \)\textsubscript{dilepton}
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\[ pp \rightarrow \chi_2^0 \chi_3^0 \rightarrow \gamma + \ell^+ \ell^- + E_T \]

**SM Backgrounds**

- \( \gamma tt \)\textsubscript{dilepton}
- \( \gamma \gamma^*/Z(\tau^+ \tau^-) \)\textsubscript{dilepton}
- \( \gamma VV \)\textsubscript{dilepton}

- Angle between leptons
- Transverse mass
- Angle between leptons and photon
- \( p_T(\gamma) \), Total \( E_T \)

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\[ pp \rightarrow \chi_2^0 \chi_3^0 \rightarrow \gamma + \ell^+ \ell^- + \not{E}_T \]

Most discriminating cut is \(m_{ll}\)
Most discriminating cut is \( m_{ll} \)
$pp \rightarrow \chi^{0}_2 \chi^{0}_3 \rightarrow \gamma + \ell^+ \ell^- + E_T$

Most discriminating cut is $m_{ll}$

Search cuts are optimal for smaller mass splittings*

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\[ pp \rightarrow \chi_2^0 \chi_3^0 \rightarrow \gamma + \ell^+ \ell^- + E_T \]

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<th>Benchmark points</th>
<th>( \mu )</th>
<th>( M_1 )</th>
<th>( \tan \beta )</th>
<th>( m_{\widetilde{\chi}_1^0} )</th>
<th>( m_{\widetilde{\chi}_2^0} )</th>
<th>( m_{\widetilde{\chi}_3^0} )</th>
<th>((\sqrt{s} = 14 \text{ TeV}) \int \mathcal{L} \text{ needed [fb}^{-1}\text{]})</th>
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<td>Point A</td>
<td>-150 GeV</td>
<td>125 GeV</td>
<td>2</td>
<td>124.0 GeV</td>
<td>156.9 GeV</td>
<td>157.4 GeV</td>
<td>430</td>
</tr>
<tr>
<td>Point C</td>
<td>-145 GeV</td>
<td>120 GeV</td>
<td>10</td>
<td>105 GeV</td>
<td>150 GeV</td>
<td>163 GeV</td>
<td>4300</td>
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Small mass splitting is good for cuts, bad for triggering

we were using 8-TeV di-lepton trigger, small efficiency

What if the system is boosted off a hard ISR jet to trigger on?
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\[ pp \to \chi_{2}^{0}\chi_{1}^{+} \to \gamma + \ell^{+} + E_{T} \]
What if the system is boosted off a hard ISR jet to trigger on?

\[ pp \rightarrow \chi_2^0 \chi_1^+ \rightarrow \gamma + \ell^+ + \not{E}_T \]

Bino-Wino
What if the system is boosted off a hard ISR jet to trigger on?

\[ pp \rightarrow \chi_2^0 \chi_1^+ \rightarrow \gamma + \ell^+ + E_T \]

Bino-Wino

- \[ E_T \propto p_T(j) \]
- \[ p_T(\gamma) \propto \Delta(m_{\chi_2^0}, m_{\chi_1^0}) \]
- \[ p_T(\ell) \propto \Delta(m_{\chi_1^\pm}, m_{\chi_1^0}) \]
What if the system is boosted off a hard ISR jet to trigger on?

\[ pp \rightarrow \chi_2^0 \chi_1^+ \rightarrow \gamma + \ell^+ + E_T \]

**Bino-Wino**

Dominant Background

- \( E_T \propto p_T(j) \)
- \( p_T(\gamma) \propto \Delta(m_{\chi_2^0}, m_{\chi_1^0}) \)
- \( p_T(\ell) \propto \Delta(m_{\chi_1^\pm}, m_{\chi_1^0}) \)

- \( E_T \propto p_T(j) \)
- \( p_T(\gamma) \propto p_T(j) \)
- \( p_T(\ell) \propto p_T(j) \)
Parameter space for $pp \rightarrow \chi_2^0 \chi_1^+ \rightarrow \gamma + \ell^+ + \not{E_T}$

**CLSP-LSP mass splitting**

$m_{\chi_1^0} - m_{\chi_1^0} = \begin{cases} <0.15 & \text{red} \\ 0.25 & \text{orange} \\ 0.35 & \text{yellow} \\ 1 & \text{blue} \\ 20 & \text{green} \\ >40 & \text{purple} \end{cases}$

**NLSP-LSP mass splitting**

$m_{\chi_2^0} - m_{\chi_1^0} = \begin{cases} <1 & \text{red} \\ 10 & \text{orange} \\ 20 & \text{yellow} \\ 30 & \text{blue} \\ 40 & \text{green} \\ >60 & \text{purple} \end{cases}$
$pp \rightarrow \chi_2^0 \chi_1^+ \rightarrow \gamma + \ell^+ + E_T$

Larger $p_T(j)$ yields more separation from background
$pp \rightarrow \chi_2^0 \chi_1^+ \rightarrow \gamma + \ell^+ + E_T$

Larger $p_T(j)$ yields more separation from background

Higher Energy Collider
$pp \rightarrow \chi_2^0 \chi_1^+ \rightarrow \gamma + \ell^+ + E_T$

Larger $p_T(j)$ yields more separation from background

Higher Energy Collider

$m_{\chi_2^0} = m_{\chi_1^\pm} = 200\text{ GeV}; m_{\chi_1^0} = 190\text{ GeV}$

$p_T(j) > 100(600)\text{ GeV}$
\[ pp \rightarrow \chi_2^0 \chi_1^+ \rightarrow \gamma + \ell^+ + E_T \]  Results

\[ p_{T,j} > 0.8 \text{ TeV} \quad |\eta_j| < 2.5 \]
\[ E_T > 1.2 \text{ TeV} \]
\[ p_{T,\ell} = [10 - 60] \text{ GeV} \quad |\eta_\ell| < 2.5 \]
\[ p_{T,\gamma} = [10 - 60] \text{ GeV} \quad |\eta_\gamma| < 2.5 \]
\[ M_{\gamma,\ell}^{T_2} < 10 \text{ GeV} \quad \Delta R_{\ell\gamma} > 0.5 \]
\[ pp \rightarrow \chi_2^0 \chi_1^+ \rightarrow \gamma + \ell^+ + \not{E}_T \] Results

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Cover most of the Bino-Wino plane!
Can entire surface be discovered with current/future experiments?

- Examine Direct/Indirect Detection constraints
- Explore search techniques at high energy colliders
  - Cover Bino-Wino surface
  - Resolve conflicts with pure wino
- Complementarity between experiments
Where are we going?

Can entire surface be discovered with current/future experiments?

- Examine Direct/Indirect Detection constraints
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- Complementarity between experiments
Resolve conflicts with pure wino

- Pure Wino mass splittings come at loop level
- Small mass splitting $\rightarrow$ little phase space $\rightarrow$ large lifetimes
- Look for chargino traveling a macroscopic distance then decaying to pions (soft and undetected). i.e. *disappearing track*
What process gives a background for a disappearing track?

- At large $p_T$ dominated by $p_T$ mismeasured tracks
- Fit by $p_T^{-a}$ with $a=1.78\pm0.05$

**Extrapolation**
- Assume same shape
- Scale total background @ 8 TeV to ratio of $pp \rightarrow \nu\bar{\nu} + j$
- Same detector size

$\text{Isolated track (with largest } p_T \text{) with}$
$30 \text{ cm} < L_T < 80 \text{ cm}$

$\sqrt{s} = 8 \text{ TeV, } \int L dt = 20.3 \text{ fb}^{-1}$

$\vec{p}_{T,j} > 90 \text{ GeV}, \quad E_T > 90 \text{ GeV}, \quad \Delta \phi^\text{jet}_{\text{min}} - E_T^\text{miss} > 1.5$
Disappearing Track

\[ p_{T,j} > 1 \text{ TeV}, \quad E_T > 1.4 \text{ TeV}, \quad \Delta \phi_{\text{min}}^{\text{jet}-E_{\text{T}}^{\text{miss}}} > 1.5 \]

\[ p_{T,j_2} > 500 \text{ GeV}, \quad p_{T,\text{track}} > 2.1 \text{ TeV} \]

Isolated track (with largest \( p_T \)) with \( 30 \text{ cm} < L_T < 80 \text{ cm} \)


Bryan Ostdiek
Where are we going?

Can entire surface be discovered with current/future experiments?

- Examine Direct/Indirect Detection constraints
- Explore search techniques at high energy colliders

- Cover Bino-Wino surface
- Resolve conflicts with pure wino

- Complementarity between experiments
More soft objects in energetic events

Extend methodology of the $j+\gamma+l^{\pm}$ search to soft dileptons

\[ p_{T,\ell} = [10 - 50] \text{ GeV}, \quad p_{T,j} > 100 \text{ GeV}, \]
\[ m_{\ell\ell} < m_{\ell\ell}^{\text{max}}, \quad \not{E}_T > 500 \text{ GeV} \]

Relic neutralino 5\(\sigma\) discovery with soft dileptons (3 ab\(^{-1}\))
More soft objects in energetic events

Extend methodology of the $j+\gamma+l^\pm$ search to soft dileptons

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\[ m_{\ell\ell} < m_{\ell\ell}^{\text{max}}, \quad \slashed{E}_T > 500 \text{ GeV} \]

Relic neutralino $5\sigma$ discovery with soft dileptons (3 ab$^{-1}$)

Soft dileptonic decay of $\chi_2^0$ allows for discovery of much of Bino-Higgsino and some Bino-Wino
Where are we going?

Can entire surface be discovered with current/future experiments?

• Examine Direct/Indirect Detection constraints
• Explore search techniques at high energy colliders
• Complementarity between experiments
Putting the searches together

\[ \tan \beta = 10 \]

2σ Exclusions

- Direct
- Direct + Indirect
- Indirect
- Tracks
- Compr. + Direct
- Compr.
• Well tempering uses co-annihilation of electroweakinos to set the observed relic abundance
  • Does not have to be supersymmetric
  • Small mass splittings result
  • Weak LHC limits (hard to trigger)
  • Searching for soft objects recoiling off hard jet allow for collider coverage of most of the surface

• A few holes remain
• `Pure Higgsino’ needs much more decoupled Wino and Bino
Questions?


<table>
<thead>
<tr>
<th>Benchmark points</th>
<th>Point A</th>
<th>Point B</th>
<th>Point C</th>
<th>Point D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>-150 GeV</td>
<td>-180 GeV</td>
<td>-145 GeV</td>
<td>150 GeV</td>
</tr>
<tr>
<td>$M_1$</td>
<td>125 GeV</td>
<td>160 GeV</td>
<td>120 GeV</td>
<td>125 GeV</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>2</td>
<td>2</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$m_{\tilde{\chi}_1^0}$</td>
<td>124.0 GeV</td>
<td>157 GeV</td>
<td>105 GeV</td>
<td>103 GeV</td>
</tr>
<tr>
<td>$m_{\tilde{\chi}_2^0}$</td>
<td>156.9 GeV</td>
<td>186 GeV</td>
<td>150 GeV</td>
<td>153 GeV</td>
</tr>
<tr>
<td>$m_{\tilde{\chi}_3^0}$</td>
<td>157.4 GeV</td>
<td>188 GeV</td>
<td>163 GeV</td>
<td>173 GeV</td>
</tr>
<tr>
<td>$\sigma(pp \to \tilde{\chi}_2^0 \tilde{\chi}_3^0)$</td>
<td>394 fb</td>
<td>200 fb</td>
<td>345 fb</td>
<td>287 fb</td>
</tr>
<tr>
<td>$BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma)$</td>
<td>0.0441</td>
<td>0.0028</td>
<td>0.0017</td>
<td>0.0014</td>
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<tr>
<td>$BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-)$</td>
<td>0.0671</td>
<td>0.0712</td>
<td>0.0702</td>
<td>0.0700</td>
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<tr>
<td>$BR(\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 \gamma)$</td>
<td>0.0024</td>
<td>0.0767</td>
<td>0.0115</td>
<td>0.0102</td>
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<tr>
<td>$BR(\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-)$</td>
<td>0.0714</td>
<td>0.0613</td>
<td>0.0447</td>
<td>0.0304</td>
</tr>
<tr>
<td>$\sigma(pp \to \tilde{\chi}_2^0 \tilde{\chi}_3^0 \to \gamma \ell^+ \ell^- \tilde{\chi}_1^0 \tilde{\chi}_1^0)$</td>
<td>1.297 fb</td>
<td>1.125 fb</td>
<td>0.279 fb</td>
<td>0.205 fb</td>
</tr>
</tbody>
</table>
Scan over all possibilities for each cut (not $m_{\ell\ell}$)

Pick cut which maximizes $S/\sqrt{B}$

Repeat until no gain in significance or each cut has been used

<table>
<thead>
<tr>
<th>'small mass splitting' cuts</th>
<th>Cross section [ab]</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut</td>
<td>Signal A</td>
<td>Signal B</td>
</tr>
<tr>
<td>0) Basic Selection</td>
<td>281</td>
<td>169</td>
</tr>
<tr>
<td>1) $N_{jets} = 0$</td>
<td>181</td>
<td>108</td>
</tr>
<tr>
<td>2) $</td>
<td>\Delta \phi_{\ell_1,\ell_2}</td>
<td>&lt; 1.0$</td>
</tr>
<tr>
<td>3) $15 \text{ GeV} &lt; m_T(\ell_2) &lt; 50 \text{ GeV}$ &amp; 52.4</td>
<td>38.2</td>
<td>93.3</td>
</tr>
<tr>
<td></td>
<td>$m_T(\ell_1) &lt; 60 \text{ GeV}$</td>
<td>49.9</td>
</tr>
<tr>
<td>4) $</td>
<td>\Delta \phi_{\ell\ell-\gamma}</td>
<td>&gt; 1.45$</td>
</tr>
<tr>
<td></td>
<td>$E_T$ cuts</td>
<td>26.8</td>
</tr>
<tr>
<td>7) $m_{\ell\ell} &lt; 24 \text{ GeV}$</td>
<td>23.3</td>
<td>19.3</td>
</tr>
</tbody>
</table>

Discover ‘A’ with $430 \text{ fb}^{-1}$ (125 GeV DM particle)

Discover ‘B’ with $620 \text{ fb}^{-1}$ (157 GeV DM particle)
• Points ‘C’ and ‘D’ have larger mass splittings
• Cuts not as effective
• More possibility of ‘Alternative Signal’

<table>
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<th>Cross section [ab]</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut</td>
<td>Signal C</td>
<td>Signal D</td>
</tr>
<tr>
<td>0) Basic Selection</td>
<td>256</td>
<td>411</td>
</tr>
<tr>
<td>1) N_{jets} = 0</td>
<td>157</td>
<td>227</td>
</tr>
<tr>
<td>2) \left</td>
<td>\Delta \phi_{\ell_1, \ell_2} \right</td>
<td>&lt; 1.05</td>
</tr>
<tr>
<td>3) { 10 \text{ GeV} &lt; m_T(\ell_1) &lt; 100 \text{ GeV} }</td>
<td>47.9</td>
<td>72.2</td>
</tr>
<tr>
<td>4) 10 \text{ GeV} &lt; m_T(\ell_2) &lt; 95 \text{ GeV}</td>
<td>45.8</td>
<td>69.4</td>
</tr>
<tr>
<td>5) m_{\ell\ell} &lt; 39 \text{ GeV}</td>
<td>42.8</td>
<td>64.0</td>
</tr>
</tbody>
</table>

• Discover ‘C’ with 4300 fb\(^{-1}\) (105 GeV DM particle)
• Discover ‘D’ with 1900 fb\(^{-1}\) (103 GeV DM particle)