Supersymmetric Dark Matter:
Direct, Indirect and Collider Searches

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OUTLINE

★ The Standard Model
★ Inconsistencies
★ Supersymmetry
★ Dark matter (DM)
  • neutralino, axion/axino, gravitino
★ The Hunt for DM at LHC
★ direct DM searches
★ indirect DM searches
The Standard Model of Particle Physics

☆ gauge symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow g, W^\pm, Z^0, \gamma$

☆ matter content: 3 generations quarks and leptons

\[
\begin{pmatrix}
  u \\
  d
\end{pmatrix}_L, \ u_R, \ d_R; \ \begin{pmatrix}
  \nu \\
  e
\end{pmatrix}_L , \ e_R
\]  \hspace{1cm} (1)

☆ Higgs sector $\Rightarrow$ spontaneous electroweak symmetry breaking:

\[
\phi = \begin{pmatrix}
  \phi^+ \\
  \phi_0
\end{pmatrix}
\]  \hspace{1cm} (2)

☆ $\Rightarrow$ massive $W^\pm, Z^0$, quarks and leptons

☆ $\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{matter} + \mathcal{L}_{Yuk.} + \mathcal{L}_{Higgs}$: 19 parameters

☆ good-to-excellent description of (almost) all accelerator data!
Shortcomings of SM

Data

- neutrino masses and mixing
- baryogenesis (matter anti-matter asymmetry)
- cold dark matter
- dark energy

Theory

- quadratic divergences in scalar sector $\Rightarrow$ fine-tuning
- origin of generations
- explanation of masses/ mixing angles
- origin of gauge symmetry/ quantum numbers
- unification with gravity
The supersymmetry alternative

Supersymmetry: bosons ⇔ fermions

★ SUSY is a space-time symmetry!
★ space-time $x^\mu \Rightarrow (x^\mu, \theta_i) \ i = 1, \cdots, 4$ superspace
★ fields $\psi \Rightarrow \hat{\phi} \ni (\phi, \psi)$ superfields
★ gauge fields $A^\mu \Rightarrow \hat{W} \ni (\lambda, A^\mu)$ gauge superfields
★ superfield formalism $\Rightarrow$ general form for Lagrangian of (globally) supersymmetric gauge theory: quadratic divergences cancel!
★ SUSY can be broken by soft SUSY breaking terms: maintain cancellation of quadratic divergences
Weak Scale Supersymmetry

HB and X. Tata
Spring, 2006; Cambridge University Press

★ Part 1: superfields/Lagrangians
  – 4-component spinor notation for exp’ts
  – master Lagrangian for SUSY gauge theories

★ Part 2: models/implications
  – MSSM, SUGRA, GMSB, AMSB, · · ·
  – dark matter density/detection

★ Part 3: SUSY at colliders
  – production/decay/event generation
  – collider signatures
  – $R$-parity violation
Minimal Supersymmetric Standard Model (MSSM)

★ Adopt gauge symmetry of Standard Model
  • spin $\frac{1}{2}$ gaugino for each SM gauge boson
★ SM fermions $\in$ chiral scalar superfields: $\Rightarrow$ scalar partner for each SM fermion helicity state
  • electron $\Leftrightarrow \tilde{e}_L$ and $\tilde{e}_R$
★ two Higgs doublets to cancel triangle anomalies
★ add all admissible soft SUSY breaking terms
★ resultant Lagrangian has 124 parameters!
★ Lagrangian yields mass eigenstates, mixings, Feynman rules for scattering and decay processes
★ predictive model!
Supergravity (SUGRA)

- $e^{i\alpha Q}$ with $\alpha(x)$: local SUSY transformation
  - forces introduction of spin 2 graviton and spin $\frac{3}{2}$ gravitino
  - resultant theory $\Rightarrow$ General Relativity in classical limit!

- rules for Lagrangian in supergravity gauge theory: Cremmer et al. (1983)

- fertile ground: supergravity $\cup$ grand unification: LE limit of superstring?

- minimal supergravity model (mSUGRA)

- $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$, $\text{sign}(\mu)$
  - $m_0 = \text{mass of all scalars at } Q = M_{\text{GUT}}$
  - $m_{1/2} = \text{mass of all gauginos at } Q = M_{\text{GUT}}$
  - $A_0 = \text{trilinear soft breaking parameter at } Q = M_{\text{GUT}}$
  - $\tan \beta = \text{ratio of Higgs vevs}$
  - $\mu = \text{SUSY Higgs mass term; magnitude determined by REWSB!}$
Some successes of SUSY GUT theories

★ SUSY divergence cancellation maintains hierarchy between GUT scale $Q = 10^{16}$ GeV and weak scale $Q = 100$ GeV

★ gauge coupling unification!
Gauge coupling evolution

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    width=\textwidth,
    height=\textwidth,
    log basis y={10},
    xlabel={Q (GeV)},
    ylabel={\(\alpha_i^{-1}\)},
    yticklabels={60,50,40,30,20,10,0},
    ytick={60,50,40,30,20,10,0},
    xtick={10^3,10^6,10^9,10^{12},10^{15}},
    xticklabels={,},
    legend pos=north west
]
\addplot[red, thick, mark=none] coordinates {
(10^3,50) (10^6,40) (10^9,30) (10^{12},20) (10^{15},10)
};
\addplot[blue, thick, mark=none] coordinates {
(10^3,40) (10^6,30) (10^9,20) (10^{12},10) (10^{15},0)
};
\addplot[green, thick, mark=none] coordinates {
(10^3,30) (10^6,20) (10^9,10) (10^{12},0) (10^{15},-10)
};
\legend{a) SM, b) MSSM-2HD, c) MSSM-4HD}
\end{axis}
\end{tikzpicture}
\end{center}
Some successes of SUSY GUT theories

★ SUSY divergence cancellation maintains hierarchy between GUT scale $Q = 10^{16}$ GeV and weak scale $Q = 100$ GeV

★ gauge coupling unification!

★ Lightest Higgs mass $m_h \sim 135$ GeV as indicated by radiative corrections!
Precision electroweak data and the Higgs mass:

Experimental errors 68% CL:
- LEP2/Tevatron (today)
- Tevatron/LHC

Light SUSY
Heavy SUSY

SM
MSSM

Heinemeyer, Hollik, Stockinger, Weber, Weiglein '08

S. Heinemeyer et al.
Some successes of SUSY GUT theories

★ SUSY divergence cancellation maintains hierarchy between GUT scale $Q = 10^{16}$ GeV and weak scale $Q = 100$ GeV

★ gauge coupling unification!

★ Lightest Higgs mass $m_h \lesssim 130$ GeV as indicated by radiative corrections!

★ radiative breaking of EW symmetry if $m_t \sim 100 - 200$ GeV!
Soft term evolution and radiative EWSB
Some successes of SUSY GUT theories

★ SUSY divergence cancellation maintains hierarchy between GUT scale $Q = 10^{16}$ GeV and weak scale $Q = 100$ GeV

★ gauge coupling unification!

★ Lightest Higgs mass $m_h \sim 130$ GeV as indicated by radiative corrections!

★ radiative breaking of EW symmetry if $m_t \sim 100 - 200$ GeV!

★ dark matter candidate: lightest neutralino $\tilde{Z}_1$

★ stabilize neutrino see-saw scale vs. weak scale

★ $SO(10)$ SUSY GUT: baryogenesis via leptogenesis

★ can give dark energy via CC $\Lambda$ (but need huge fine-tuning...)
  • SUGRA = low energy limit of superstring?
  • stringy multiverse: anthropic selection of small CC?
Evidence for dark matter in the universe

- binding of galactic clusters (Zwicky, 1930s)
- galactic rotation curves
- large scale structure formation
- inflation $\Rightarrow \Omega = \rho/\rho_c = 1$
- gravitational lensing
- anisotropies in cosmic MB (WMAP)
- surveys of distant galaxies via SN (DE)
- Big Bang nucleosynthesis
  - $\Omega_A \simeq 0.7$
  - $\Omega_{CDM} \simeq 0.25$
  - $\Omega_{baryons} \simeq 0.045$ (dark baryons $\simeq 0.040$
  - $\Omega_\nu \simeq 0.005$
SUSY dark matter

★ R-parity conservation $\Rightarrow$ conserved $B$ and $L \Rightarrow$ proton stability
  • $R(particle) = 1$; $R(sparticle) = -1$

★ Naturally occurs in $SO(10)$ SUSY GUT theories

★ Some consequences:
  • Sparticles are produced in pairs
  • Sparticles decay to other sparticles
  • Lightest SUSY particle (LSP) is absolutely stable (good candidate for dark matter)

★ LSP must be charge, color neutral (bound on cosmological relics)

★ Sneutrino would have been detected in direct detection experiments

★ lightest neutralino $\tilde{\chi}_1$ is LSP in wide range of models

★ $\tilde{\chi}_1$ is weakly interacting, massive particle (WIMP)
Calculating the relic density of neutralinos

★ At very high $T$, neutralinos in thermal equilibrium with cosmic soup

★ As universe expands and cools, expansion rate exceeds interaction rate (freeze-out)

★ number density is governed by Boltzmann eq. for FRW universe

- $\frac{dn}{dt} = -3Hn - \langle \sigma v_{rel} \rangle (n^2 - n_0^2)$

- $\Omega \tilde{\chi}_1^2 h^2 = \frac{s_0}{\rho_c h^2} \left( \frac{45}{\pi g_*} \right)^{1/2} \frac{x_f}{m_{Pl}} \frac{1}{\langle \sigma v \rangle}$

- $\Omega_{CDM} h^2 \sim 0.1 \Rightarrow \langle \sigma v \rangle \sim 0.9 \text{ pb!}$

- $\langle \sigma v \rangle = \pi \alpha^2 / 8m^2 \Rightarrow m \sim 100 \text{ GeV}$

★ “The WIMP miracle!”: cosmic motivation for new physics at weak scale

★ SUSY: 1722 annihilation/co-annihilation reactions; 7618 Feynman diagrams

★ IsaReD program (HB, A. Belyaev, C. Balazs)
Results of $\chi^2$ fit using $\tau$ data for $a_\mu$:

$m_{\text{Sugra with } \tan \beta = 10, A_0 = 0, \mu > 0}$

$m_{\text{Sugra with } \tan \beta = 54, A_0 = 0, \mu > 0}$

Axions

★ PQ solution to strong CP problem in QCD
★ pseudo-Goldstone boson from PQ breaking at scale $f_a \sim 10^9 - 10^{12}$ GeV
★ non-thermally produced via vacuum mis-alignment as cold DM
  - $m_a \sim \frac{\Lambda^2_{QCD}}{f_a} \sim 10^{-6} - 10^{-1}$ eV
  - $\Omega_a h^2 \sim \frac{1}{2} \left[ \frac{6 \times 10^{-6} \text{eV}}{m_a} \right]^{7/6} h^2$
  - astro bound: stellar cooling $\Rightarrow m_a < 10^{-1}$ eV
  - $a$ couples to EM field: $a - \gamma - \gamma$ coupling (Sikivie)
  - axion microwave cavity searches

Howie Baer, Oklahoma State University colloquium, April 16, 2009
Axion microwave cavity searches

- ongoing searches: ADMX experiment
  - Livermore ⇒ U Wash.
  - Phase I: probe KSVZ for $m_a \sim 10^{-6} - 10^{-5}$ eV
  - Phase II: probe DFSZ for $m_a \sim 10^{-6} - 10^{-5}$ eV
  - beyond Phase II: probe higher values $m_a$
Axions + SUSY $\Rightarrow$ Axino $\tilde{a}$ dark matter

- axino is spin-$\frac{1}{2}$ element of axion supermultiplet ($R$-odd; can be LSP)
- $m_{\tilde{a}}$ model dependent: keV $\rightarrow$ GeV
- $\tilde{Z}_1 \rightarrow \tilde{a}\gamma$
- non-thermal $\tilde{a}$ production via $\tilde{Z}_1$ decay:
- axinos inherit neutralino number density
- $\Omega^{NTP}_{\tilde{a}} h^2 = \frac{m_{\tilde{a}}}{m_{\tilde{Z}_1}} \Omega_{\tilde{Z}_1} h^2$:
Thermally produced axinos

- If $T_R < f_a$, then axinos never in thermal equilibrium in early universe
- Can still produce $\tilde{a}$ thermally via radiation off particles in thermal equilibrium
- Brandenberg-Steffen calculation:

$$\Omega_{\tilde{a}}^{TP} h^2 \simeq 5.5 g_s^6 \ln \left( \frac{1.108}{g_s} \right) \left( \frac{10^{11} \text{ GeV}}{f_a/N} \right)^2 \left( \frac{m_{\tilde{a}}}{0.1 \text{ GeV}} \right) \left( \frac{T_R}{10^4 \text{ GeV}} \right)$$  \hspace{1cm} (3)
Gravitinos: spin-$\frac{3}{2}$ partner of graviton

- gravitino problem in generic SUGRA models: overproduction of $\tilde{G}$ followed by late $\tilde{G}$ decay can destroy successful BBN predictions: upper bound on $T_R$

(see Kawasaki, Kohri, Moroi, Yotsuyanagi; Cybert, Ellis, Fields, Olive)
Gravitinos as dark matter: again the gravitino problem

- neutralino production in generic SUGRA models: followed by late time $\tilde{Z}_1 \rightarrow \tilde{G} + X$ decays can destroy successful BBN predictions:

(see Kawasaki, Kohri, Moroi, Yotsuyanagi)
Gravitino dark matter: if one can avoid gravitino problem

* \( m_{\tilde{G}} = \frac{F}{\sqrt{3} M_*} \sim \text{TeV} \) in Supergravity models
  * if \( \tilde{G} \) is LSP, then calculate NLSP abundance as a thermal relic: \( \Omega_{NLSP} h^2 \)
  * \( \tilde{Z}_1 \rightarrow h\tilde{G}, \ Z\tilde{G}, \ \gamma\tilde{G} \) or \( \tilde{\tau}_1 \rightarrow \tau\tilde{G} \) possible
    * lifetime \( \tau_{NLSP} \sim 10^4 - 10^8 \) sec
    * also produce \( \tilde{G} \) thermally (depends on re-heat temp. \( T_R \))
    * DM relic density is then \( \Omega_{\tilde{G}} = \frac{m_{\tilde{G}}}{m_{NLSP}} \Omega_{NLSP} + \Omega_{TP}^{\tilde{G}} \)
    * Feng et al.; Ellis et al.; Brandenberg+Steffen; Buchmuller et al.
  * \( \tilde{G} \) undetectable via direct/indirect DM searches
  * unique collider signatures are possible:
    * \( \tilde{\tau}_1=\text{NLSP}: \) stable charged tracks
    * can collect NLSPs in e.g. water (slepton trapping)
    * monitor for \( NLSP \rightarrow \tilde{G} \) decays
Production of sparticles at CERN LHC

Howie Baer, Oklahoma State University colloquium, April 16, 2009
Sparticle cascade decays

\[
\begin{align*}
\tilde{g} &\sim (2060) \\
\tilde{q}_L &\sim (1857) \\
\tilde{q}_R &\sim (1770) \\
\tilde{b}_L &\sim (1690) \\
\tilde{b}_R &\sim (1619) \\
\tilde{t}_L &\sim (1449) \\
\tilde{t}_R &\sim (1380) \\
\tilde{W}^+ &\sim (1067) \\
\tilde{Z} &\sim (1056) \\
\tilde{t}_L &\sim (754) \\
\tilde{t}_R &\sim (726) \\
M_n &\sim (712) \\
\end{align*}
\]

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Branching Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tilde{Z})_{qq}</td>
<td>(27.9 %)</td>
</tr>
<tr>
<td>(\tilde{Z})_{\tau\nu Wbb}</td>
<td>(12.1 %)</td>
</tr>
<tr>
<td>(\tilde{Z})_{\tau\nu Wbb}</td>
<td>(8.4 %)</td>
</tr>
<tr>
<td>(\tilde{Z})_{WWbb}</td>
<td>(7.4 %)</td>
</tr>
<tr>
<td>(\tilde{Z})_{\tau\nu qq}</td>
<td>(5.9 %)</td>
</tr>
<tr>
<td>(\tilde{Z})_{\tau\nu WWbb}</td>
<td>(2.9 %)</td>
</tr>
<tr>
<td>(\tilde{Z})_{\tau\nu ZWbb}</td>
<td>(2.8 %)</td>
</tr>
<tr>
<td>(\tilde{Z})_{\tau\nu hWbb}</td>
<td>(2.6 %)</td>
</tr>
</tbody>
</table>
Event generation in LL - QCD

1) Hard scattering / convolution with PDFs
2) Initial / final state showers
3) Cascade decays
4) Hadronization
5) Beam remnants
Isajet v7.79 for sparticle event generation

★ Isajet (1979), by F. Paige and S. Protopopescu
★ Isajet 7.0 (1993) -7.75: FP, SP, HB and X. Tata
  • Isasugra subprogram: SUGRA models (and others) ⇒ sparticle masses, mixings, decay rates
★ SUSY and SM event generation for hadron colliders
★ $e^+e^-$ colliders
  • polarized beams
  • bremsstrahlung/ beamstrahlung
★ IsaTools: $\Omega \tilde{Z}_1^2$, $(g - 2)_\mu$, $BF(b \rightarrow s\gamma)$, $BF(B_s \rightarrow \mu^+\mu^-)$, $\sigma(\tilde{Z}_1 p)$
★ Les Houches event output: 7.78
Simulated sparticle production event at LHC

GEANT figure

mSUGRA: $m_{h} = 1000$ GeV, $m_{1/2} = 500$ GeV, $A_{0} = 0$, $\tan \beta = 35$, $\mu > 0$

- $\tilde{g} \rightarrow \tilde{t}_{1} \tilde{t}_{1}^{c}$
- $\tilde{u}_{L} \rightarrow \tilde{Z}_{2} + u$ (jet 4, $E_{T} = 113$ GeV)
- $W^{+} + h$ (jet 5, $E_{T} = 79$ GeV) + $\tilde{c}$
- $W^{+} + Z = u^{+}$ (jet 6, $E_{T} = 526$ GeV)
- $\tilde{Z}_{1} + W = \tilde{c}^{+}$
- $E_{T}^{miss} = 380$ GeV

$m_{g} = 1266$ GeV
$m_{\tilde{g}} = 1450$ GeV
$m_{\tilde{t}_{1}} = 1826$ GeV
$m_{\tilde{t}_{1}} = 410$ GeV
$m_{\tilde{Z}_{1}} = 214$ GeV
$m_{h} = 119$ GeV

jet 1, $E_{T} = 1196$ GeV
jet 2, $E_{T} = 206$ GeV
jet 3, $E_{T} = 320$ GeV
$e^+e^- \rightarrow \tilde{W}_1^+\tilde{W}_1^- \rightarrow (q\bar{q}'\tilde{Z}_1) + (e\bar{\nu}_e\tilde{Z}_1)$ at linear collider
Sparticle reach of all colliders with relic density

$m_{\text{Sugra}}$ with $\tan \beta = 10$, $A_0 = 0$, $\mu > 0$

$m_{\text{Sugra}}$ with $\tan \beta = 45$, $A_0 = 0$, $\mu < 0$

HB, Belyaev, Krupovnickas, Tata: JHEP 0402, 007 (2004)
Early SUSY discovery at LHC with just $0.1 \text{ fb}^{-1}$?

• To make $E_T$ cut, complete knowledge of detector needed
  – dead regions
  – “hot” cells
  – cosmic rays
  – calorimeter mis-measurement
  – beam-gas events

• Can we make early discovery of SUSY at LHC without $E_T$?

• Expect SUSY events to be rich in jets, $b$-jets, isolated $\ell$s, $\tau$-jets,....

• These are detectable, rather than inferred objects

• Answer: YES! See HB, Prosper, Summy, arXiv:0801.3799
D0 saga with missing $E_T$
Simple cuts: \( \geq 4 \) jets plus isolated leptons

- \( \slashed{E}_T \) not really necessary
Cuts C1' plus $\geq 2$ OS/SF $\ell$
Precision measurements at LHC: Atlas and CMS

- \( M_{\text{eff}} = \not{E}_T + E_T(j1) + \cdots + E_T(j4) \) sets overall \( m_\tilde{g}, m_\tilde{q} \) scale
- \( m(\ell\bar{\ell}) < m_{Z_2} - m_{Z_1} \) mass edge
- \( m(\ell\bar{\ell}) \) distribution shape
- combine \( m(\ell\bar{\ell}) \) with jets to gain \( m(\ell\bar{\ell}j) \) mass edge: info on \( m_\tilde{q} \)
- further mass edges possible e.g. \( m(\ell\bar{\ell}jj) \)
- Higgs mass bump \( h \rightarrow b\bar{b} \) likely visible in \( \not{E}_T + jets \) events
- in favorable cases, may overconstrain system for a given model
  - methodology very p-space dependent
  - some regions are very difficult e.g. HB/FP
International linear $e^+e^-$ collider (ILC)

★ A linear $e^+e^-$ collider with $\sqrt{s} = 0.5 - 1$ TeV is highest priority project for HEP beyond LHC! Why?

- All beam energy $\Rightarrow$ collision (aside from brem/beamstrahlung losses)
- Beam energy known
- Clean collision environment
- Low (electroweak) background levels
- Adjustable beam energy (threshold scans)
- $e^-$ and possibly $e^+$ beam polarization

★ ILC will be ideal machine to perform precision spectroscopy of any new (EW interacting) matter states (provided they are kinematically accessible)!

★ Timeline: decision-2012; ready-2025?
Precision sparticle measurements at a $e^+e^-$ linear collider

a) $e^+e^- \rightarrow \tilde{\mu}^+_R \tilde{\mu}^-_R$

$\sqrt{s} = 350$ GeV

20 fb$^{-1}$

$P_L(e^-) = -0.9$

b) $\Delta \chi^2 = 1.00$  

= 2.28 

= 4.61

Input

min. $\chi^2$
Direct detection of SUSY DM

Direct search via neutralino-nucleon scattering

\[ q \rightarrow q_{L,R} \rightarrow \tilde{q}_1 \rightarrow \tilde{z}_1 \rightarrow q \]

\[ \tilde{z}_1 \rightarrow h, H \rightarrow q \]

\[ g \rightarrow h, H \rightarrow t \]

\[ \tilde{z}_1 \rightarrow h, H \rightarrow g \]
Direct detection of neutralino DM: the race is on!

Cross-section [pb] (normalised to nucleon)

DATA listed top to bottom on plot
Edelweiss I final limit, 62 kg-days Ge 2000+2002+2003 limit
DAMA 2000 58k kg-days NaI Ann. Mod. 3sigma w/DAMA 1996
WARP 2.3L, 96.5 kg-days 55 keV threshold
CDMS 2008 Ge
CDMS: 2004+2005 (reanalysis) +2008 Ge
XENON10 2007 (Net 136 kg-d)
CDMS Soudan 2007 projected
SuperCDMS (Projected) 2-ST@Soudan
WARP 140kg (proj)
SuperCDMS (Projected) 25kg (7-ST@Snomab)
XENON100 (150 kg) projected sensitivity
LUX 300 kg LXe Projection (Jul 2007)
XENON1T (proj)
Baer et. al 2003

Howie Baer, Oklahoma State University colloquium, April 16, 2009
Indirect detection (ID) of SUSY DM: $\nu$-telescopes

- $\tilde{Z}_1 \tilde{Z}_1 \rightarrow b\bar{b}, etc.$ in core of sun (or earth): $\Rightarrow \nu_\mu \rightarrow \mu$ in $\nu$ telescopes
  - Amanda, Icecube, Antares

\[
\begin{align*}
\tilde{Z}_1 & \rightarrow b\bar{b} \\
\tilde{Z}_1 & \rightarrow \mu^+ \nu_\mu
\end{align*}
\]
ID of SUSY DM: $\gamma$ and anti-matter searches

- $\tilde{Z}_1 \tilde{Z}_1 \rightarrow q\bar{q}, etc. \rightarrow \gamma$ in galactic core or halo
- $\tilde{Z}_1 \tilde{Z}_1 \rightarrow q\bar{q}, etc. \rightarrow e^+$ in galactic halo
- $\tilde{Z}_1 \tilde{Z}_1 \rightarrow q\bar{q}, etc. \rightarrow \bar{p}$ in galactic halo
- $\tilde{Z}_1 \tilde{Z}_1 \rightarrow q\bar{q}, etc. \rightarrow \bar{D}$ in galactic halo
Direct and indirect detection of neutralino DM

HB, Belyaev, Krupovnickas, O’Farrill: JCAP 0408, 005 (2004)
Impact of DM direct/indirect detection on LHC program

• Extend reach in $\sigma_{SI} \sim 10^{-9} - 10^{-10}$ pb
  – explore thoroughly region of MHDM, possibly MWDM

• after discovery, extract $m_{wimp}$?
  – $m_{\tilde{Z}_1}$ sets absolute mass scale for SUSY particles-
  – combine with LHC mass edges to gain LHC absolute sparticle masses
  – learn if $\tilde{Z}_1$ is absolutely stable: $R$-conservation

• IceCube turn-on can discover/verify especially MHDM

• knowledge of LHC spectra, $\sigma_{SI}$, $\sigma_{SD}$ combined with possible gamma ray signals may allow map of dark matter distribution in the galaxy

• role of $\bar{p}$, $e^+$, $\bar{D}$ signals
Models beyond mSUGRA

★ Normal scalar mass hierarchy
  – split scalar generations $m_0(1) \simeq m_0(2) \ll m_0(3)$
  – resolves $BF(b \to s\gamma)$ and $(g - 2)_{\mu}$

★ Non-universal Higgs scalars
  – motivated by $SO(10)$ and $SU(5)$ SUSY GUTs
  – allow $A$-funnel at low $\tan \beta$; higgsino DM at low $m_0$
  – enhanced DD/ ID rates

★ DM in models with $t - b - \tau$ Yukawa unification ($SO(10)$)

★ Mixed wino DM

★ Bino-wino co-annihilation (BWCA) DM

★ Low $M_3$ mixed higgsino DM

★ KKLT mixed moduli/AMSB DM
Conclusions

★ Supersymmetry is very compelling BSM theory
★ Irrefragable case for CDM has emerged
★ Some reach for SUSY at Tevatron
★ Huge reach for SUSY at CERN LHC
★ Possible early SUSY discovery at LHC: leptons instead of $E_T$
★ $e^+e^-$ LC necessary for precision sparticle spectroscopy
★ Direct search for WIMP/axion DM is underway
★ Indirect search for WIMP DM via Icecube $\nu$ telescope
★ Indirect search via $\gamma$, $\bar{p}$, $e^+$, $\bar{D}$ detection from galactic core/halo WIMP annihilations
★ Solution of mystery of CDM is near if $CDM =$ lightest SUSY particle!