SUSY dark matter

—A Collider Physicist's Point of View—

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Jan 5th, 2002

Promising years will come!

Potential to discover "New Physics" is high at ....

- High energy collider experiments (Tevatron, LHC...LC?)
- Dark matter(LSP) search
  $\ll$ existence of dark matter= new physics $\gg$ is now established.

Discovery$\rightarrow$ New frontier

- Physics at very high scale (GUT, string, brane??)
- history of our universe

  component of dark matter(s), production mechanism, structure of halo

earlier? likely LHC but opportunity is open for dark matter searches as well.

A Solid Physics Case will be established within 10 years.

What is dark matter?

for cosmologist:	gravitationally interacting particle which created structure of the universe
for particle physcist:	weakly interacting particle(s) that may be searched for to get <u>Nobel Prize</u>.

What is LSP DM

- neutralino $\tilde{\chi} = \mathrm{N}_{\tilde{\mathrm{B}}}\tilde{\mathrm{B}} + \mathrm{N}_{\tilde{\mathrm{W}}}\tilde{\mathrm{W}} + \mathrm{N}_{\tilde{\mathrm{H}}_1}\tilde{\mathrm{H}}_1 + + \mathrm{N}_{\tilde{\mathrm{H}}_1}\tilde{\mathrm{H}}_1$ (in gravity mediated models)

  $N\chi$ scattering by higgs exchange, pair annihilation...

- gravitino: ψ_μ (in gauge mediated models) Only gravitational interaction

Part I Now searching!

Searching DM around us.. CDMS II started!
(Soudan 2090 mwe, Kg detector, hope to find up to $3 \times 10^{-4}/(\mathrm{Kg} \cdot \mathrm{keV} \cdot \mathrm{day})$)

Cryogenetic detector: measure both phonon and ionization
LSP as halo dark matter with $\sigma(\chi N \to \chi N) > 10^{-8}$pb
GENEUS $> 10^{-9}$pb

LSP dark matter confronts Experiments

“standard” assumption on the “reach”.
flux

- **virialized dark halo**
  LSP: Gaussian velocity distribution,average at rest
  WIMP velocity = Earth velocity
  $\rightarrow$ **annual modulation**

- **non standard**
  non-virialized halo model(Sikivie et al PRD56(1997) 1863)
  annual modulation with opposite phase

Imagine if we have 100 events at CDMS
more info from energy distibution etc...

○ velocity distribution $\leftrightarrow$ energy diposit
(Kamionkowski and Kinkhabwala 1997 Bergstrome)

global density profile of our galaxy and DM search

–Power spectrum problem –

Density profile of DM

$$\rho(\mathrm{r}) \propto \frac{1}{(r/a)^{\gamma}\left[1+(r/a)^{\alpha}\right]^{(\beta-\gamma)/\alpha}} \quad (1)$$

r: radial distance

modified isothermal $(\alpha,\beta,\gamma)=(2,3,0)$

$$\rho_{\mathrm{is}}(\mathrm{r}) = \frac{\rho'_{\mathrm{is}}}{\left[1+(r/a)^{2}\right]^{1.5}} \quad (2)$$

Navarro Frenk White (1996) (1,3,1)

$$\rho_{\mathrm{nfw}}(\mathrm{r}) = \frac{\rho'_{\mathrm{nfw}}}{(r/a)\left[1+r/a\right]^{2}} \quad (3)$$

Moore (1999) (1.5, 3, 1.5)

$$\rho_{\mathrm{moore}} = \frac{\rho'_{\mathrm{moore}}}{(r/a)^{1.5}\left[1+(r/a)^{1.5}\right]} \quad (4)$$

Recent numerical simulations

N body simulation with gravitational interaction

better simulation $\rightarrow$ **higher** γ

'70 $N=400 \rightarrow$ 90' $O(10^5) \rightarrow$ current best $O(10^7)$.

singular distribution (NFW, Moore) and gamma rays from the center of our galaxy

$\chi\chi \to \gamma$.... (terminates at $E = m_\chi$)
$\chi\chi \to \gamma\gamma$ ($\mathrm{E}_\gamma = \mathrm{m}_\chi$ line)

$$\text{(signal rate)} \propto \int_{\text{line of sight}} \rho^2(l) dl(\Psi) \tag{5}$$

$\gamma = 1.5 \to$ **divergent at the center** and **spiky**.
The surface of the singularity emits γ's.
(Moore astro-ph/0010056)

Future γ search

○ **"Space based" GLAST (**2005 $\sim$ **)**

(Gamma-ray large Area space Telescope)

$E_\gamma \sim$ 0.02-300 GeV,δE $\sim$ 10% point source sensitivity

Don't forget EGRET(E $<$ 30 **GeV)**

Hooper and Dingus (not in the group, astro-ph 0210617)

Improved analysis for point source sensitivity(its energy dependence)

○ "Ground Based" ACTs(Airshower Cerenkov Telescopes)

sensitivity is typically

continuum gives very strong constraint but there are also continuous background.

Line is robust... if observed

Possible for Moore profile and wino like LSP

(Anomary mediation)

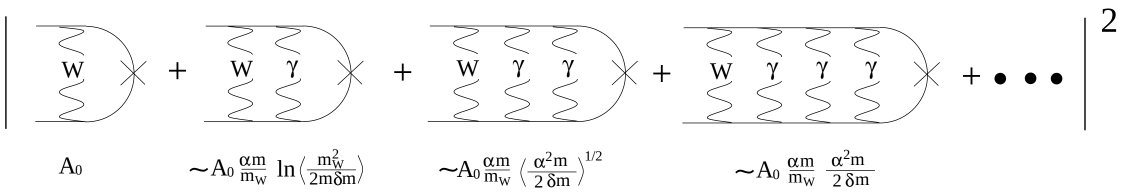
$$\sigma(\chi\chi \to 2\gamma) \sim \frac{\alpha^2\alpha_2^2}{m_W^2} \quad \sigma(\chi\chi \to \gamma X) \sim \frac{1}{m_{\chi^2}}$$

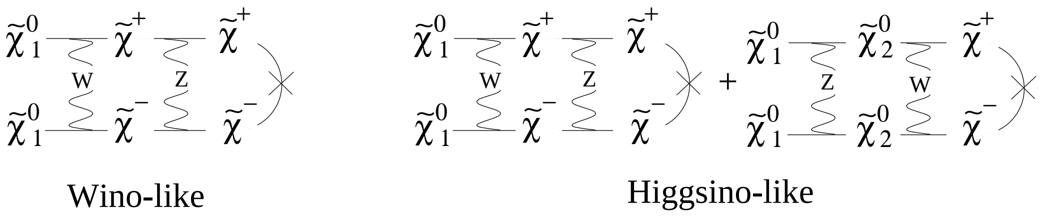
2γ signal: more important for $m_{\tilde{\chi}} \gg m_W$?? but unitarity is broken.

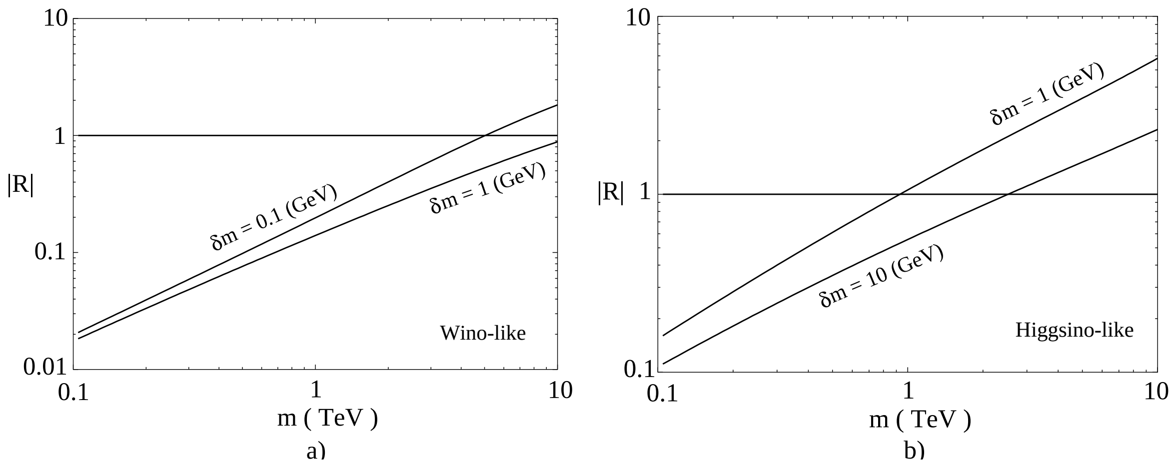
Wino like $\rightarrow$ $m_{\tilde{\chi}^+} = m_{\tilde{\chi}}$ nearly on-shell chargino enhance the amplitude by $m_{\tilde{\chi}}/m_W$

$\rightarrow$ resummation needed !
(Using NRQED techenique)

All order QED effect+ 2 loop effect is calculated (hep-ph/0212022 Hisano, Matsumoto and MMN)







2 loop effect is important 8TeV (1 TeV) for Wino and Higgsino dark matters

Still working....

Anti-particle searches (BESS, BESS-polar, AMS, PAMERA)

- Anti-proton produced at center of our galaxy (window below $E_{kin} \sim 1$GeV)

- Positron does not survive long
–sensitive to local clump
astro-ph/0109318 (Baltz et al)
Excess(? HEAT)

Experiments coming ....

- Bess $\rightarrow$ Bess Polar
(flight: 2004/1, 2006/2-solar minimum)
improved flight time($\sim$ 20 days)
sensitive down to $E_{kin} \sim 100$ MeV.

- AMS-02(2004/3 for 3 to 5 years) Use ISS
$E_{kin} > 300$ MeV

target
New understanding Solar Modulation (plot)
(Need long term operations)
Inprove propagation models
PBH, domain wall, SUSY + clumpy halo

washing out clumps

observed galaxies (baryons) do not have cusps

solution?
1) Problem in Numerical simulation
calculate big scale structure $\rightarrow$ passed to smaller subscale

Is the predictuion to the small scale structure reliable? no radiation etc ...OK??

2)warm dark matter (Free Streaming scale $R_f \sim 0.1$ Mpc)

- **gravitino dark matter** $m_{3/2} \sim 1$ **keV** (Ω_{th} is too large!)

$$\mathrm{R_f} = 0.2(\Omega_\mathrm{W}\mathrm{h}^2)^{1/3}\left(\frac{\mathrm{m}_{3/2}}{\mathrm{KeV}}\right)^{-4/3}\mathrm{Mpc} \tag{6}$$

- **non-thermal production of LSP**

  From topological defect(Lin et al PRL 86, 950) or moduli(or heavy gravitino) decay

  Need 10 TeV initial neutralino energy and very lage decay $T_I < 5$MeV
  (Hisano, Kohri and M.M.N. Phys.Lett. B505, 169)

3) Tune density perturbation

(Kamionkowski and Liddle PRL 2000, J. Yokoyama PRD 62 123509(2000))

We need a density perturbation at small scale. $m_{3/2} > 750$ eV (Narayanan et al astro-ph/0005095 constraint from Lyman- α forest)

4) **It's dead already??**
radio Sgr A^*(Gondolo and Silk 83(1999) 1719, Bertone et al 2001, 2002)

- black hole at the center of our galaxy (criticized Ullio et al PRD 64(2001) 043504)

- deformation of ρ_{halo} around the black hole $\rightarrow$ even higher rate for pair annihilation

- existence of strong magnetic field.

then much of SUSY parameter space for LSP dak matter is excluded already...

Summary

This is a Field with

Many Ideas, and Discussions ......

Need First Step (Discoverly)

$\boxed{\text{Part II Quantitative understanding of DM}}$

Basic numbers we need to know

- theraml relic density Ω_{th}

  dark matter pair annihilation cross section at T_{dec}

  $\sigma(\chi\chi \to \mathrm{f\bar{f}}, \mathrm{WW}, \mathrm{etc})$ (pair annihilation)
  $\sigma(\chi\tilde{\tau} \to \tau\gamma)$ (coannihilation; $\tilde{\mathrm{t}}$, $\tilde{\chi}_1^+$ also)

  $\Omega^{-1} \propto \sum \sigma(\chi\chi \to)$ at $\mathrm{T_{dec}}$

- direct detection

  $\sigma(\chi \mathrm{N} \to \chi \mathrm{N})$ at $\mathrm{T} = 0$

- searching for exisotic cosmic ray
  $\sigma \mathrm{v}(\chi\chi \to \mathrm{WW} \to \gamma'\mathrm{s})$

  $\sigma \mathrm{v}(\chi\chi \to 2\gamma)$(radiative process)

  $\sigma \mathrm{v}(\chi\chi \to \bar{\mathrm{P}}, \mathrm{e}^+ ...)$

Collider Physcist's View

They would be measured "precisely" once supersymmetric particles are discovered by collider experiments.

Example:Thermal relic density:

1. LSP and slepton mass

   $\Omega \propto \frac{m_{\tilde{\chi}}^4}{m_{\tilde{\chi}}^2} \rightarrow \mathrm{m}_{\tilde{\chi}}$, $\mathrm{m}_{\tilde{\mathrm{l}}}$,

2. ratio of higgsino and gaugino component of LSP

   coupling to higgs: $\mathrm{N}_{\tilde{\mathrm{H}}}\mathrm{N}_{\tilde{\mathrm{B}}(\tilde{\mathrm{W}})}$
   coupling to W: $\mathrm{N}_{\tilde{\mathrm{H}}}^2$ or $\mathrm{N}_{\tilde{\mathrm{W}}}^2$
   Large higgsino gaugino mixing $\rightarrow$ small Ω_{th}

3. higgs bosons with mass close to $2m_{\tilde{\chi}}$

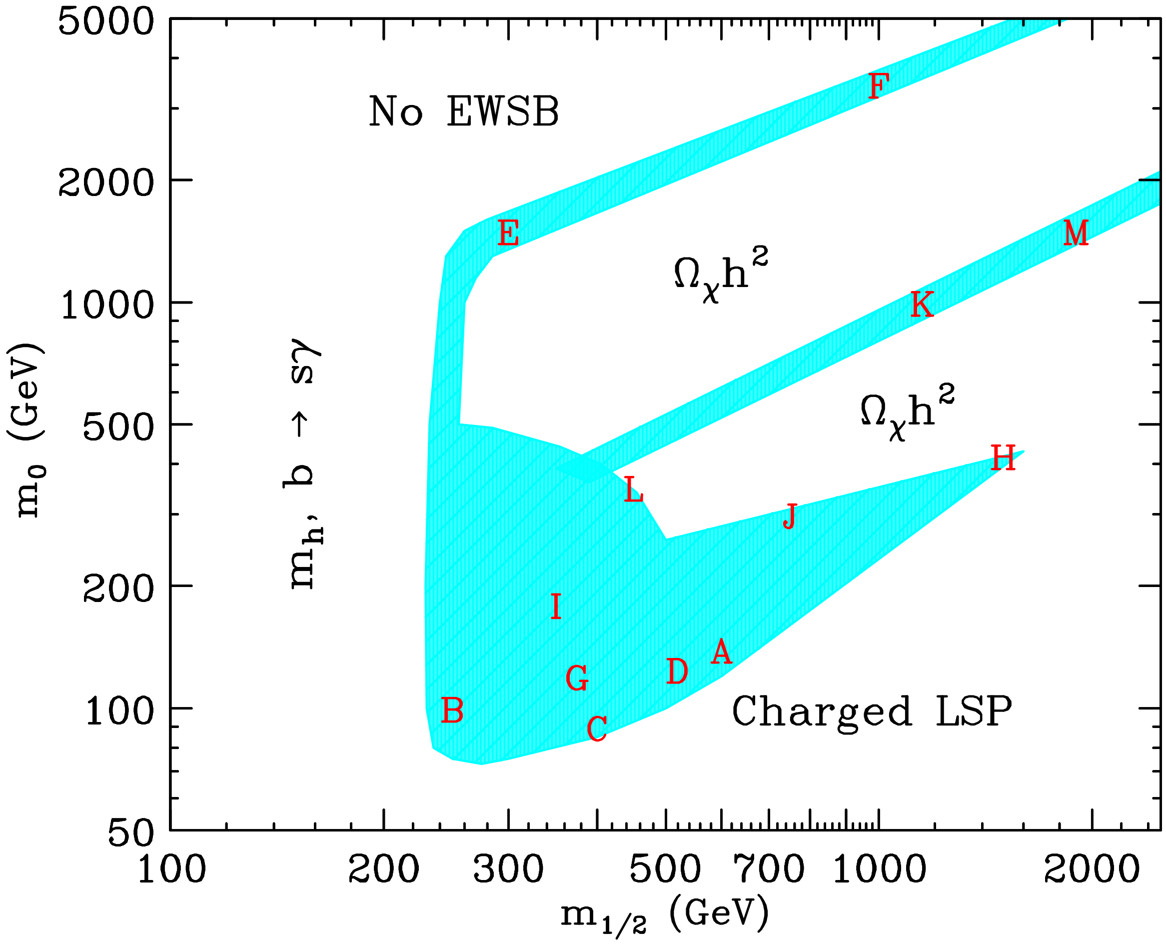
   $\mathcal{M} \propto 1/(4\mathrm{m}_{\tilde{\chi}}^2 - \mathrm{m}_{\mathrm{P}}^2)$

4. nature of sparticles with mass close to $m_{\tilde{\chi}}$

Compare Ω_{CDM} and Ω_{th} to reveal exotic thermal history

- entropy production after $\mathrm{T}_{\mathrm{dec}}$ $\Omega_{\mathrm{CDM}} < \Omega\mathrm{th}$
- Moduli decays after T_{dec} (say, Moroi& Randall (1999)) $\Omega_{\mathrm{CDM}} > \Omega_{\mathrm{th}}$
- other dark matters: $\Omega_{\mathrm{CDM}} > \Omega_{\mathrm{th}}$

Even in MSUGRA model ($m, M, A_0, \tan\beta$) all four cases are relevant



Model may be extended as far as it is consistent to current experiment

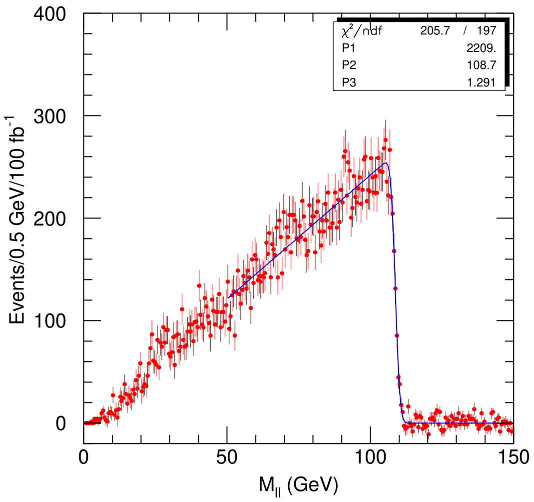
- non-universal GUT scale higgs mass $\rightarrow$ arbitrary higgsino mass μ
- GUT scale D term contribution
- intermediate scale susy breaking

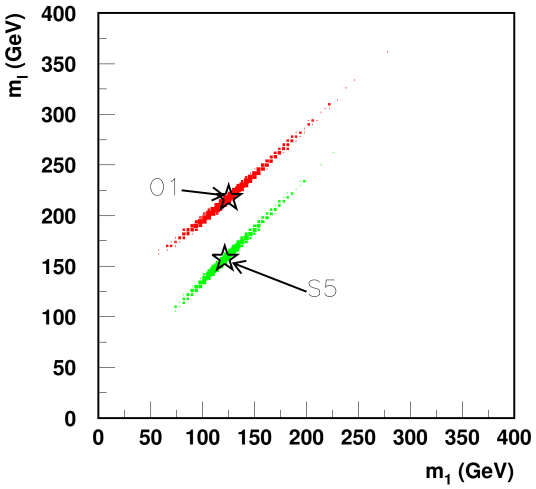
—in LHC—

mostly $\tilde{q}\tilde{g}$ production $\rightarrow$ cascade decay $\rightarrow$ jets (+ leptons) + some missing momentum.

Identify cascade decay chains $\rightarrow$ mass reconstruction

Especially jll reconstruction ($\tilde{q} \rightarrow j\tilde{\chi}^0_2 \rightarrow \tilde{l}jl \rightarrow \tilde{\chi}^0_1 jll$) is known to be useful. (Hinchliffe et al PRD 55 (1997) 5520)



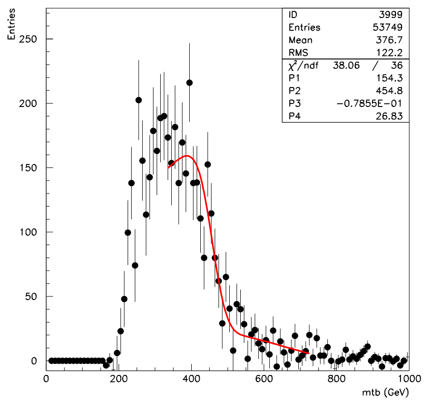


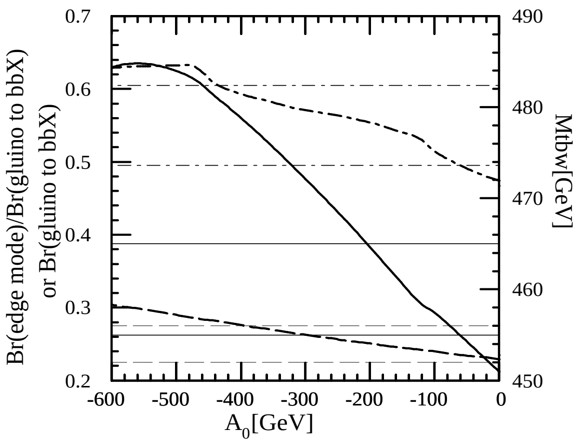
mass precision is typically 10% for electroweak partilces for the channel

So for the case 1, Ω_{th} within 20%? But how to distingush it from the others?

MSUGRA analysis (assume universality, detemine $m_0, M, A_0, \tan\beta$, then cross check.)

· m_0 and M: slepton and LSP masses.
· $\tan\beta, A_0$: $\tilde{\tau}$ +Higgs sector
· Pseudoscalar higgs mass: $\mu\mu$ or bb invariant masses
cross check:
(ex.reconstruction of $\mathbf{\tilde{g} \to (\tilde{t} \text{ or } \tilde{b}) \to tb\tilde{\chi}^+}$
sensitive to A_0: MMN for this conference)





Off MSUGRA
– small μ

more higgsino gaugino mixing for all chargino and neutralino, then $\tilde{q} \to \chi_4^0$, χ_2^+ is enhanced.

More cascade information than MSUGRA.

(Drees et al PRD 2000)

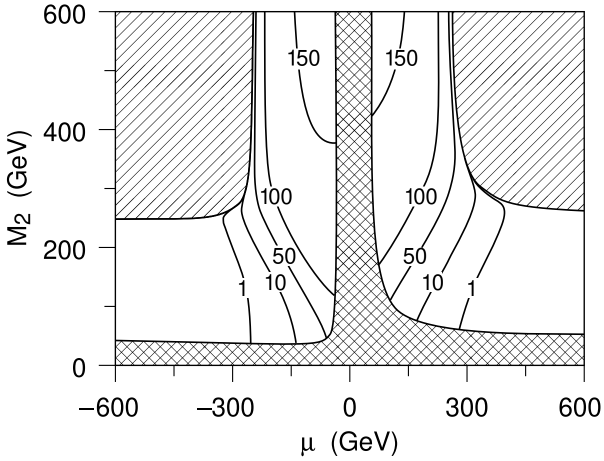
—in e^+e- Linear Collider—

Ultra Precise measurement of masses and interactions for all kinematically accessible particles $\rightarrow \Delta\Omega \sim 1\%$

○ Mass precision by threshold scans

$$\begin{aligned} \Delta m_{\tilde{\chi}^{\pm 0}} &\sim 0.3\text{GeV} \\ \Delta m_{\tilde{l}} \sim \Delta m_{\tilde{\nu}} &\sim 0.1\text{GeV} \\ \Delta m_{\tilde{\tau}} &\sim 0.6\text{GeV} \end{aligned} \tag{7}$$

○ Determination of ino mixings by cross section measurements.



(from Feng et al PRD (1997))

○ Higgs precision study

○ Degenerated case may be studied by producing heavier sparticles

Gravitino and Collider Physics

mass density of gravitino

$$\Omega_{\psi}\mathrm{h}^2 = 0.5\mathrm{m}_{3/2}(\mathrm{KeV}) \qquad (8)$$

(without dilution)

neutralino life time τ

$$c\tau(\chi \to \psi) \sim 24\mathrm{m}\left(\frac{100\mathrm{GeV}}{m_\chi}\right)^5\left(\frac{m_{3/2}}{1\mathrm{keV}}\right)^2 \qquad (9)$$

Front detector at LHC also would be useful to determine gravitino and axino lifetime (Maki and Orito Phys. Rev D57 554(1998))

For LC (Ambrosanio and Blair Euro Phys. J. C12 287 (2000))

τ between $O(10)\mu m < c\tau < O(10)m$ can be measuremed within 10%

MSSM model

$\updownarrow$

collider study of MSSM parameter

$\swarrow \qquad \searrow$

Thermal relic density $\qquad$ LSP-N scattering

$\Updownarrow \qquad \Updownarrow$

CDM density

Dark matter detection

$\searrow\nwarrow \qquad \swarrow\nearrow$

Astrophysical and cosmological inputs

Feng and Nojiri hep-ph 0210390 for “LC book”