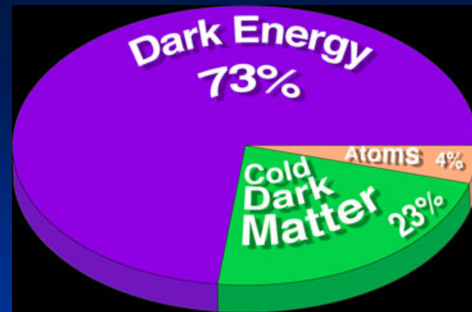

SUSY and beyond …

SUSY Co-annihilation Region at ILC

hep-ph/0503165

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Talk Outline

SUSY and Cosmology

Available mSUGRA parameter space with:

(a) Rare decay constraints

(b) Collider bounds

(c) Cosmological constraints

ILC ($\sqrt{s}$ = 500 and 800 GeV) reach of the mSUGRA parameter space via $\tilde{\tau}_1^+\tilde{\tau}_1^-$ and $\tilde{\chi}_1^0\tilde{\chi}_2^0$

(i) Detailed study of signal and the background processes

(ii) Determination of SUSY masses in the dark matter allowed regions

Conclusion

SUGRA and Cosmology

1. SUGRA models with R parity invariance is used as a benchmark.

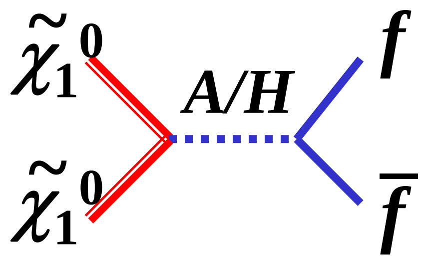
$m_{1/2}$	Common gaugino (spin=1/2) mass (GeV)
m_0	Common scalar (spin=0) mass (GeV)
$\tan\beta$	Ratio of 2 v.e.v.'s (2 Higgs doublets; H_u & H_d)
sign(μ)	Sign of Higgs mixing parameter μ (GeV) → We choose $\mu > 0$
A_0	Trilinear coupling (GeV) → We choose $A_0 = 0$

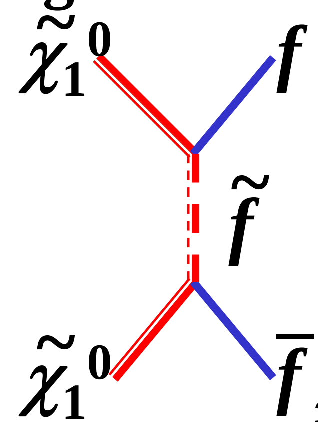
2. $\tilde{\chi}_1^0$ - the lightest neutralino as a stable dark matter candidate.

3. The relic density of these neutralinos is given by:

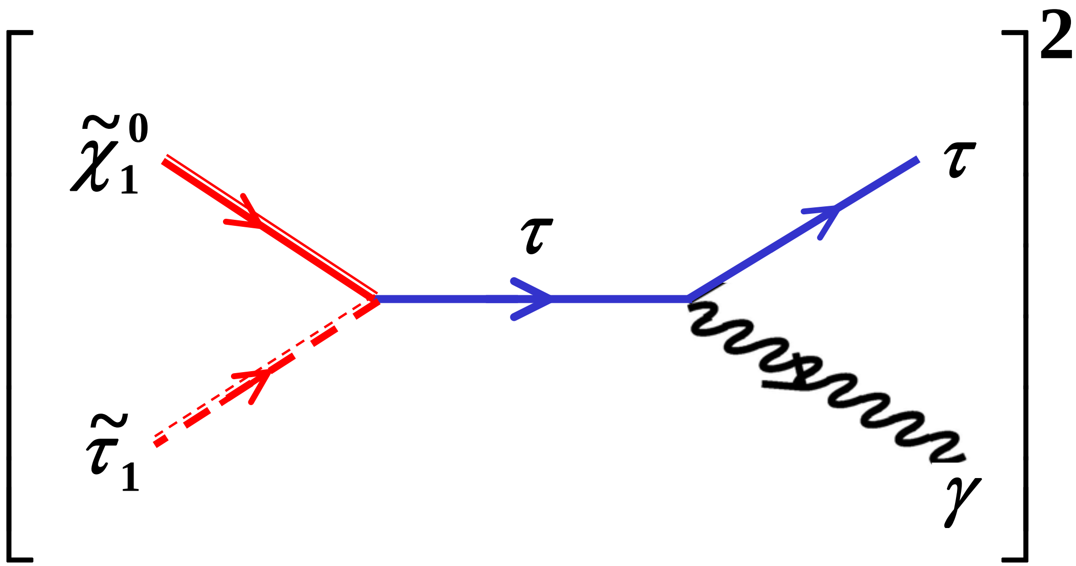
$$\Omega_{\tilde{\chi}_1^0} h^2 \sim \left[\int_0^{x_f} \langle \sigma_{\text{ann}} v \rangle dx \right]^{-1}$$

where σ_{ann} is calculated in terms of SUSY model parameters typically using the following diagrams:





- **Co-annihilation [Griest and Seckel ’92]: An accidental near degeneracy occurs naturally for light stau $\tilde{\tau}_1$ in mSUGRA.**



$$e^{-\frac{20}{M_{\tilde{\chi}}}\Delta M}$$

- **Here $\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0}$. This diagram also contributes to the relic density along with the other neutralino annihilation diagrams. This is a generic feature of any SUSY model.**

Experimental Constraints and Technical Issues

CLEO $b \rightarrow s\ \gamma$

$1.9 \times 10^{-4} < Br < 4.5 \times 10^{-4}$

LEP Higgs Mass

$M_{\mathrm{Higgs}} > 114$ GeV/c^2

LEP Chargino Mass Bounds

$M_{\mathrm{chargino}} > 104$ GeV/c^2

Relic Density Bounds

$0.094 < \Omega_{\chi_1^0} h^2 < 0.129$

[WMAP, Balloon Experiments such as BoomeranG, Maxima, DASI etc., Supernovae data, Radio Galaxy measurements]

$b \rightarrow s\ \gamma$

Large $\tan\beta$ NLO correction [Degrassi *et al.*; Carena *et al.*; Buras *et al.*; D'Ambrosio *et al*.]

Relic Density

Inclusion of co-annihilation $\tilde{\tau}_1$-$\tilde{\chi}_1^0$ effects in relic density calculations [Ellis *et al.*; Arnowitt, Dutta; Gomez *et al.*]

Note: We do not assume Yukawa unification or proton decay as these depend on unknown physics beyond M_G.

Existing Bounds from Experiments

[1] Higgs Mass (M_h):

$M_h > 114$ GeV

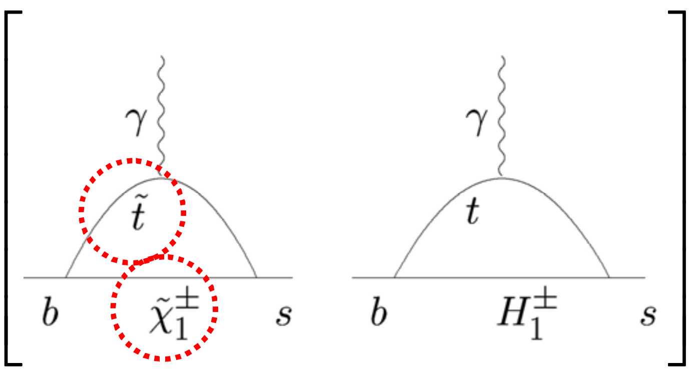
(The Higgs mass depends on the mass parameters m_0 and $m_{1/2}$, and A_0 and $\tan\beta$.)

[2] Branching Ratio $b \to s\gamma$:

CLEO: $(3.21 \pm 0.47) \times 10^{-4}$

SM : $(3.62 \pm 0.33) \times 10^{-4}$

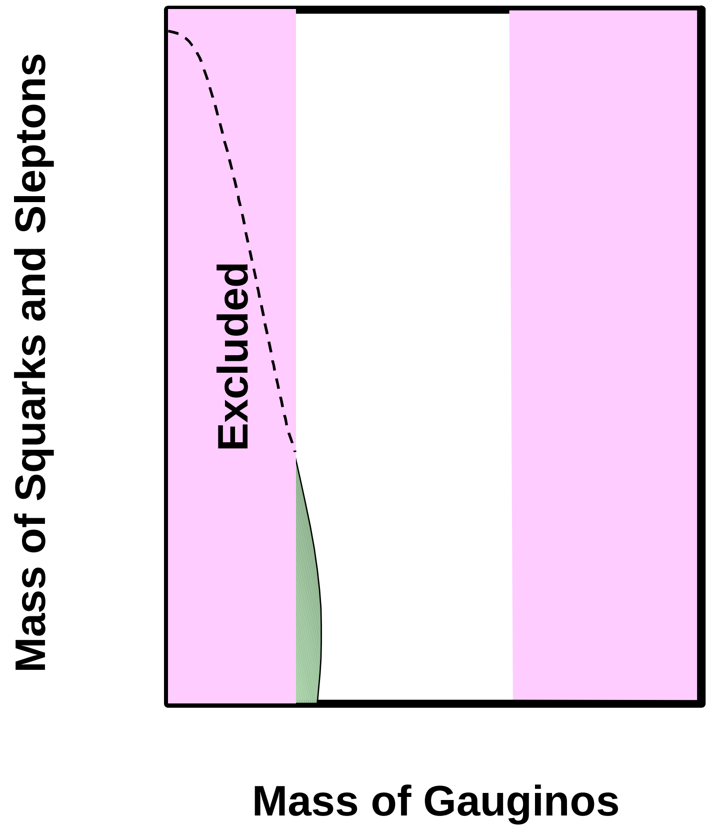
Br



$$\propto \frac{1}{m_{\mathrm{SUSY}}^2}$$

- Excluding parameter space based on the SUSY particle masses.

Excluded Region in SUSY World



Existing Bounds from Experiments

[3] Magnetic Moment of Muon:

$$\mu = g\frac{eh}{2m}s$$

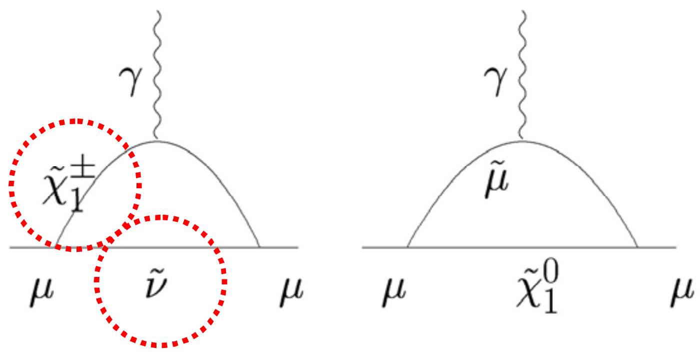
- In the Supersymmetric SM:

$$g = 2(1+a)$$

a is the anomalous magnetic moment.

- The latest BNL result:

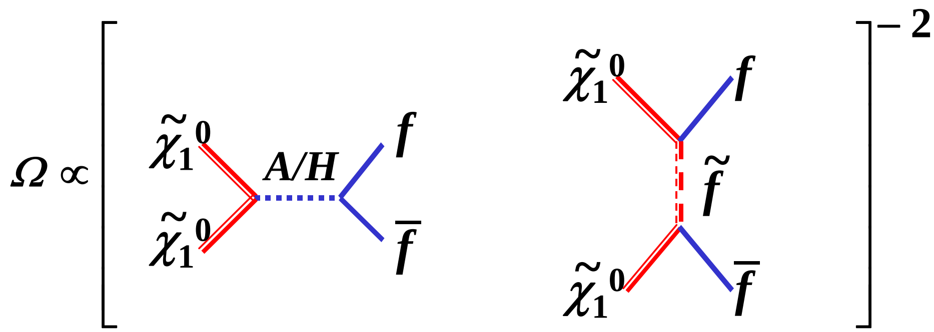
$$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (27 \pm 10) \times 10^{-10}$$



Existing Bounds from Experiments

[4] Dark Matter: Allowed region

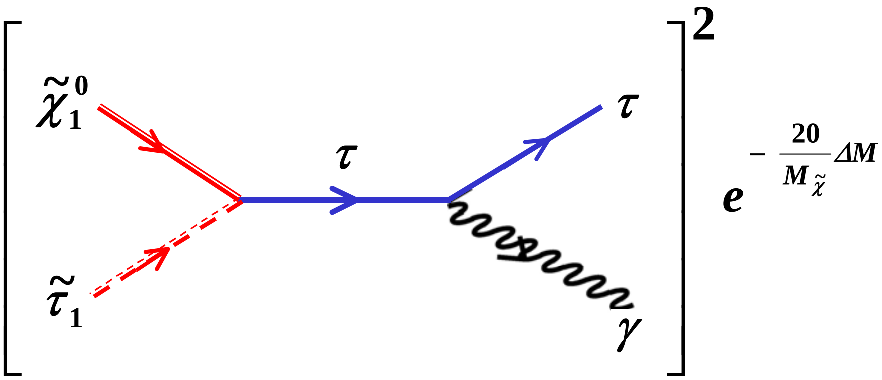
- **The relic density is expressed as Ω where $\Omega_{\mathrm{CDM}} = 0.23 \pm 0.04$.**
- **Neutralino ($\tilde{\chi}_1^0$) constitutes the dark matter in this model. It is the lightest and stable particle in our model.**
- **In order to calculate Ω_{CDM}, we need to know the density of the remaining neutralinos when they stopped annihilating each other, "neutralino annihilation," i.e.**



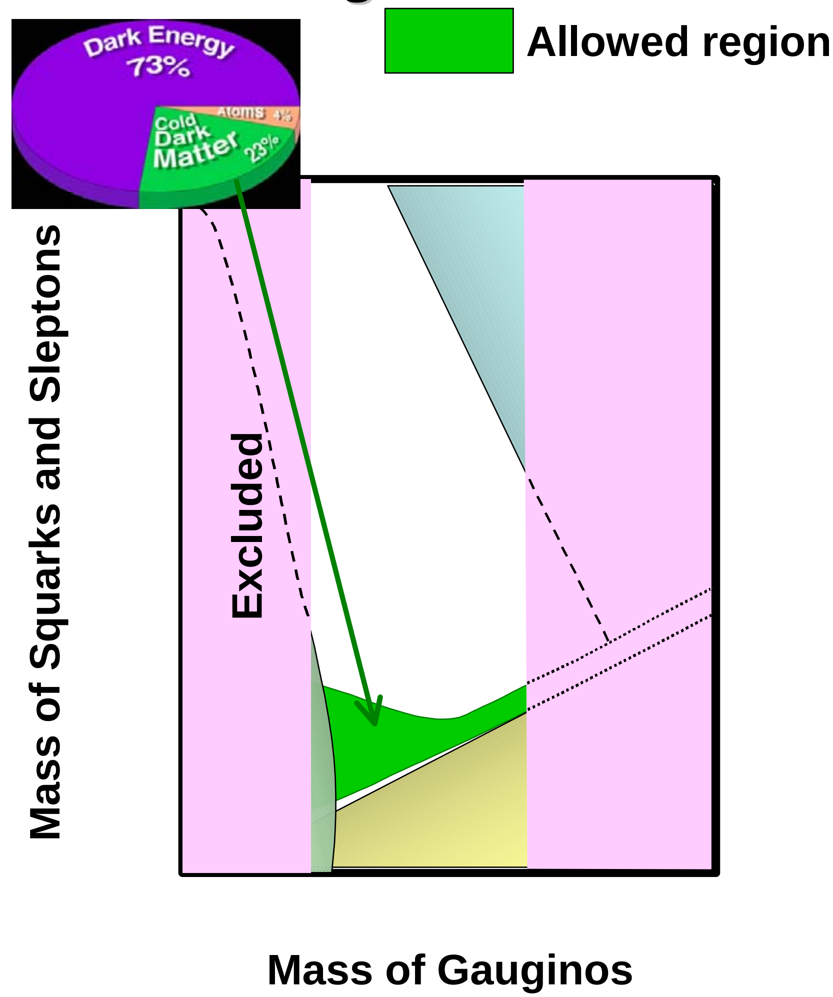
- **$\Omega_{\mathrm{CDM}} \propto m_{\mathrm{SUSY}}^2$**
- **Ω_{CDM} can be expressed in terms of our mSUGRA parameters.**

Excluded Region in SUSY World

- **Co-annihilation [Griest and Seckel '92]: An accidental near degeneracy occurs naturally for light stau $\tilde{\tau}_1$ in mSUGRA.**

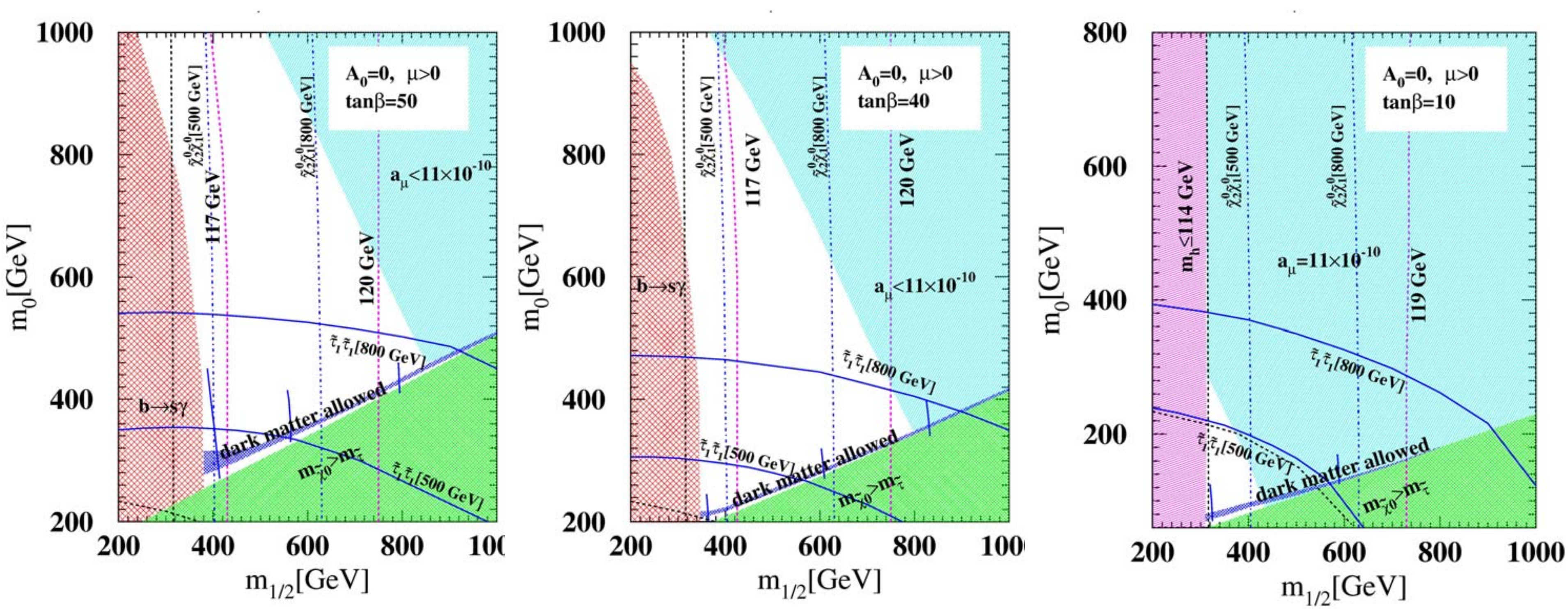


Here $\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0}$. This diagram also contributes to the relic density along with the other neutralino annihilation diagrams. This is a generic feature of any SUSY model.



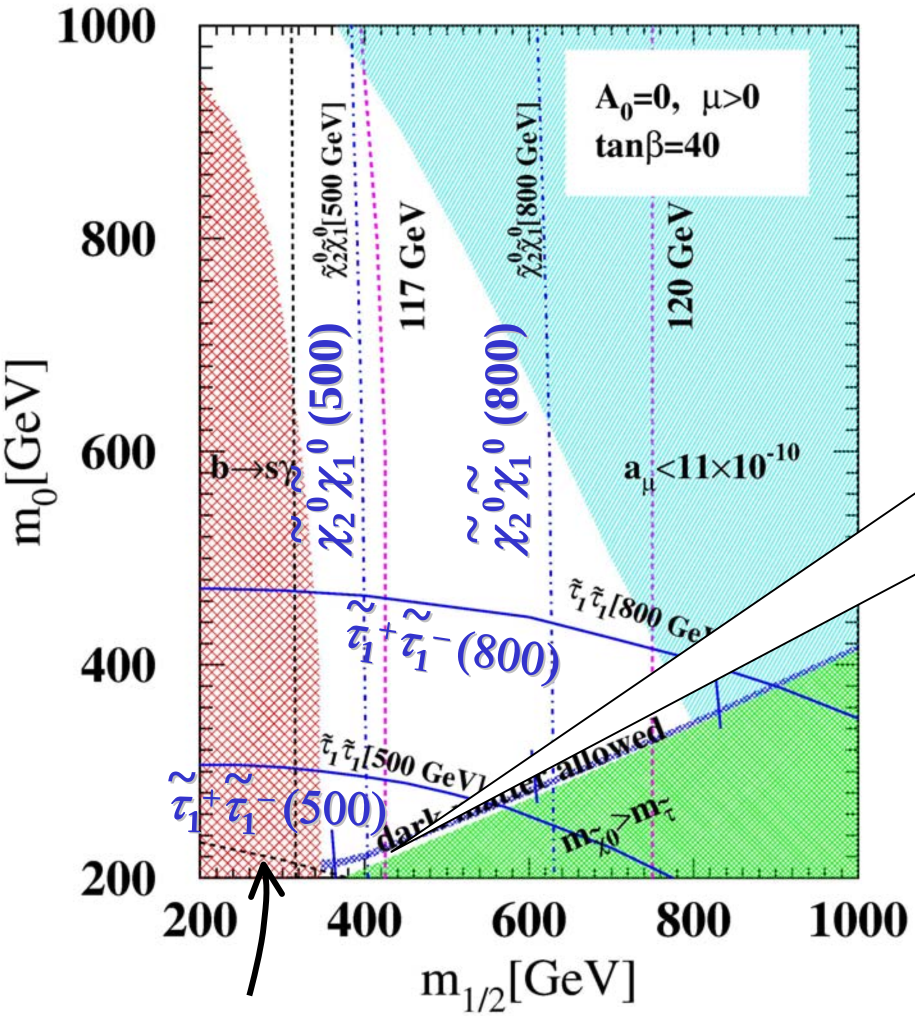
CDM Allowed Region and Kinematical Reach for $\tilde{\tau}_1^+\tilde{\tau}_1^-$ & $\tilde{\chi}_2^0\tilde{\chi}_1^0$

tanβ=50 **tanβ=40** **tanβ=10**

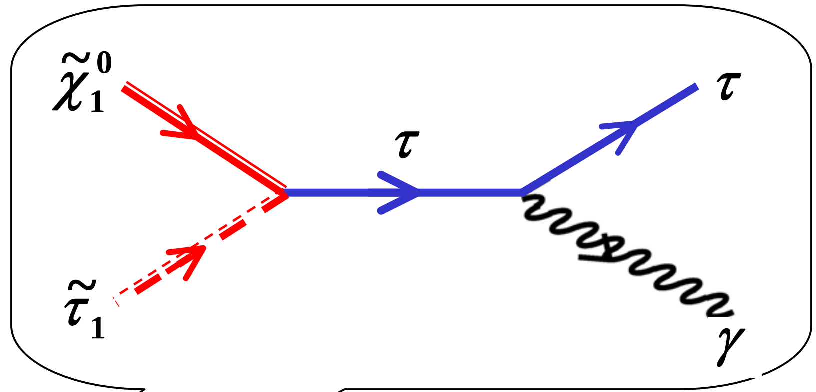


Study of SUSY Signals at ILC

m_0 vs. $m_{1/2}$ ($\tan\beta = 40$, $A_0 = 0$)



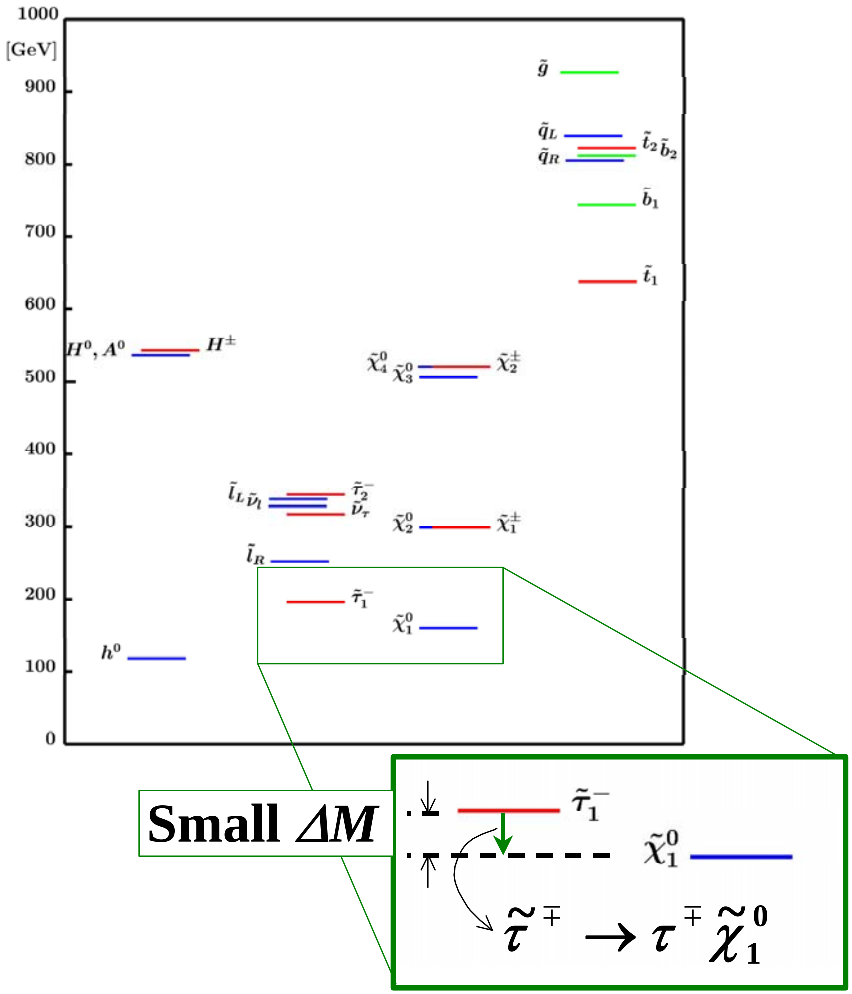
$m_{\tilde e} = 250$ GeV



- **Develop event selection cuts and extract signal from the background**
- **Discovery significance of the parameter space**
- **ΔM = Accuracy of measuring the most crucial parameter**

Collider Experiments

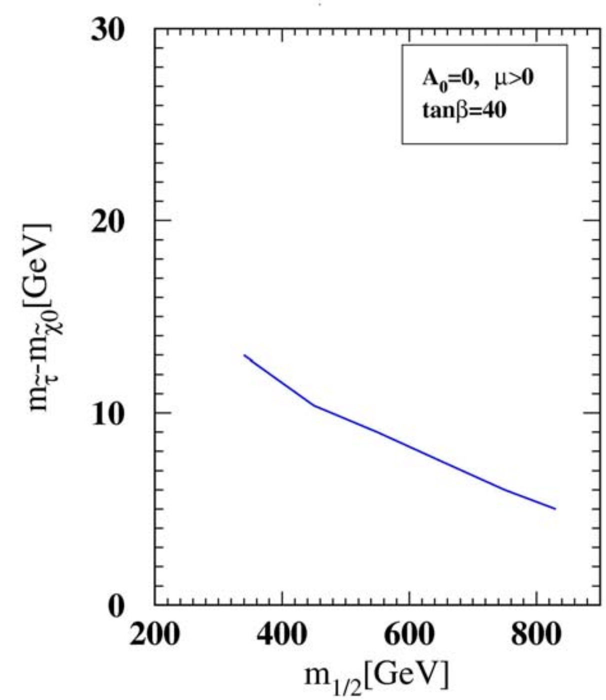
- **Questions:**
  - **a. What are the signals from the narrow co-annihilation corridor?**



Collider Experiments

- **Questions:**
  - **b. ΔM - How small?**

$$\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} = 5 \sim 15 \text{ GeV}$$

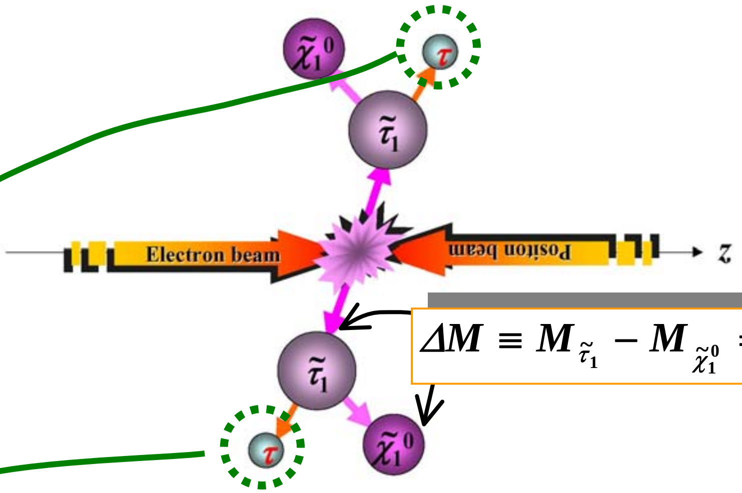


  - **c. What is the accuracy of the measurement on ΔM?**

- **We will discuss c) at ILC.**

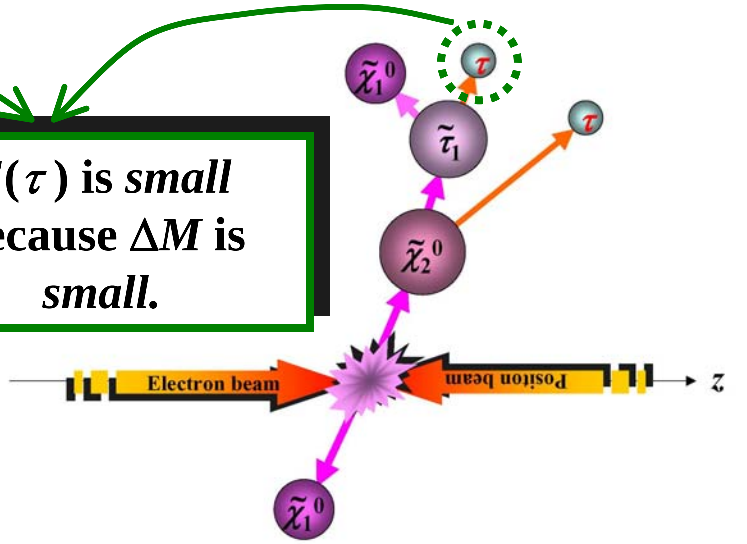
SUSY Signals at LC

- **Stau-pair production** $\tau^+\tau^-\tilde{\chi}_1^0\tilde{\chi}_1^0$



$\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} = 5 \sim 15$ GeV

- **Neutralino-pair production** $\tau^+\tau^-\tilde{\chi}_1^0\tilde{\chi}_1^0$

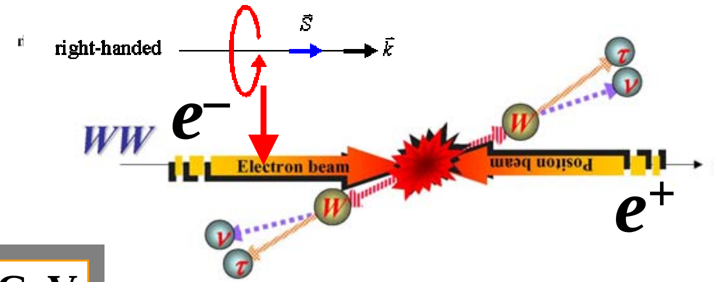


E*(τ) is *small* because Δ*M* is *small.

SM Backgrounds at LC

- **4-fermion *WW, ZZ, Zνν* production**

  e.g., $e^+e^- \to W^+W^- \to \tau^+\nu\,\tau^-\bar{\nu}$

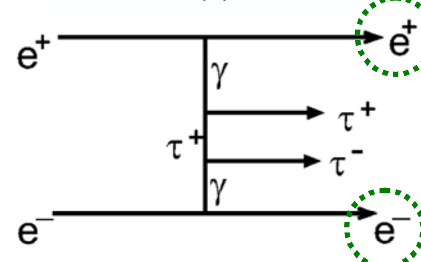


Suppressed by RH polarized electron beams

N_{4f}(500 fb^{-1}) ≈ 10k @ 90% RH

- **Two-photon (*γγ*) process**

  $e^+e^- \to \gamma\gamma\, e^+e^- \to \tau^+\tau^- e^+e^-$



Lower energy τ's

$N_{2\gamma}$(500 fb^{-1}) ≈ 13M events*!*

We need to detect e⁻ and e⁺ going very close to the beam direction (down to 2° or 1°).

Monte Carlo

Event Generator plus Beam Bremsstruhlung

SUSY: ISAJET v7.69

$$e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^0 \rightarrow \tilde{\tau}_1\tau + \tilde{\chi}_1^0 \rightarrow \tau\,\tau + E^{\mathrm{miss}}$$

$$e^+e^- \rightarrow \tilde{\tau}_1^+\tilde{\tau}_1^- \rightarrow \tau\,\tau + E^{\mathrm{miss}}$$

SM : WPHACT v2.02pol

(all 4 fermion final states (SM4f) and $\gamma\gamma$ process with e^+/e^- polarization)

$$e^+e^- \rightarrow \nu_e\nu_e\tau\tau,\ \nu_\mu\nu_\mu\tau\tau,\ \nu_\tau\nu_\tau\tau\tau\,;\ ee\tau\tau,\ eeqq\ (\gamma\gamma\ \text{process})$$

Ref: E. Accomando and A. Ballestrero, Comput. Phys. Commun. 99, 270 (1997)

E. Accomando, A. Ballestrero, and E. Maina, Comput. Phys. Commun. 150, 166 (2003)

Tau Decay: TAUOLA v2.6

Detector Simulation & Event Analysis:

Package LCD Root v3.5

FAST MC using LD Mar01 detector parameterization, Jet Finder, …

mSUGRA Points

ISAJET 7.69 $\mu > 0,\ \tan\beta = 40,\ A_0 = 0$

MCPt	Mass (GeV)						
	m_0	$m_{1/2}$	$M\tilde{\tau}_1$	$M\tilde{\chi}_1^0$	$M\tilde{\chi}_2^0$	$M\tilde{\tau}_1 - M\tilde{\chi}_1^0$	$M\tilde{\chi}_1^0 + M\tilde{\chi}_2^0$
P1	210	360	147.2	142.5	274.2	4.75	390
P2	215	360	152.0	142.5	274.2	9.53	390
P3	225	360	161.6	142.6	274.3	19.0	390

$\sigma \times Br(\tau \rightarrow \tau_h)^2$ [fb]

ISAJET 7.69 $\sqrt{s} = 500$ GeV

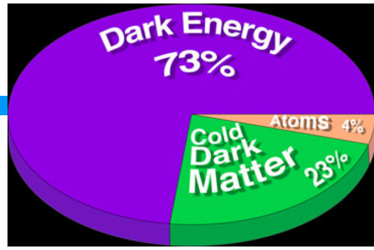
	$Pol(e^-) = -0.9$		$Pol(e^-) = 0$		$Pol(e^-) = +0.9$	
SM4f	7.84		48.9		89.8	
SUSY	$\tilde{\chi}_1^0\tilde{\chi}_2^0$	$\tilde{\tau}_1\tilde{\tau}_1$	$\tilde{\chi}_1^0\tilde{\chi}_2^0$	$\tilde{\tau}_1\tilde{\tau}_1$	$\tilde{\chi}_1^0\tilde{\chi}_2^0$	$\tilde{\tau}_1\tilde{\tau}_1$
P1	0.41	28.3	3.39	19.6	6.09	13.2
P2	0.40	26.6	3.31	18.4	6.00	12.4
P3	0.38	23.0	3.15	15.8	5.68	10.6

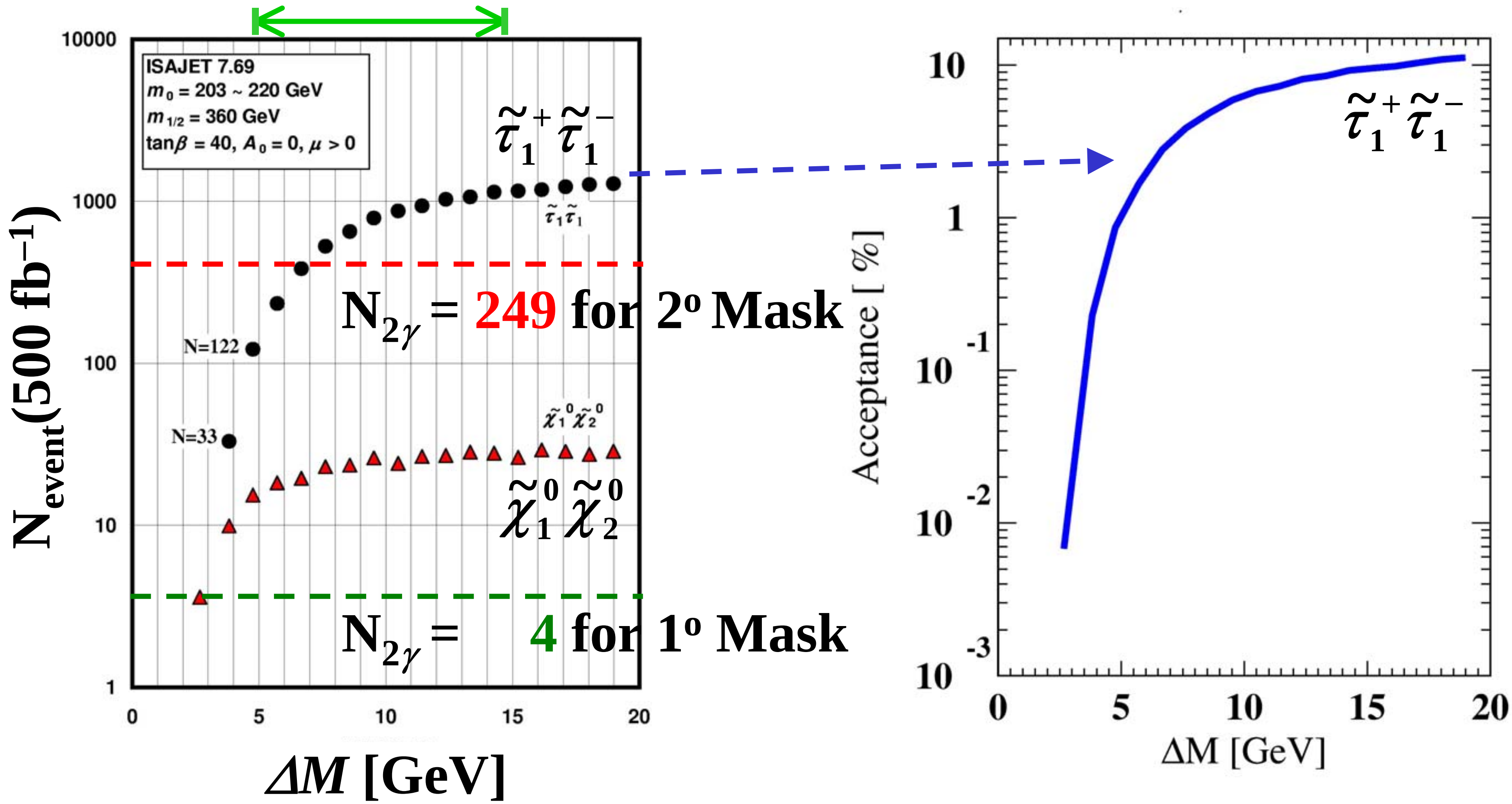
Event Selection Cuts

$\tilde{\chi}_1^0 \tilde{\chi}_2^0$ at $Pol = +0.9$(LH)	$\tilde{\tau}_1^+ \tilde{\tau}_1^-$ at $Pol = -0.9$(RH)
$N_{jet} \geq 2$ ($E_{jet} > 3$ GeV; JADE $Y \geq 0.0025$)	
τ_h ID ($N_{track}=1, 3$; $q=\pm1$; $M_{track} < 1.8$ GeV)	
$-q \times \cos\theta_{jet} < 0.7$	$\lvert \cos\theta_{jet} \rvert < 0.65$
Missing $P_T > 5$ GeV	
$-0.8 < \cos\theta(j_2, P_{vis}) < 0.7$	$-0.6 < \cos\theta(j_2, P_{vis}) < 0.6$
Acoplanarity > 40^o	
No EM clusters in $5.8^o < \theta < 25.8^o$ with $E > 2$ GeV	
No electrons in $\theta > 25.8^o$ with $P_T > 1.5$ GeV	
Beam mask: $2^o(1^o) - 5.8^o$ No EM clusters with $E > 100$ GeV	

Note: $\cos(25.8^o)=0.9$, $\cos(5.8^o)=0.995$

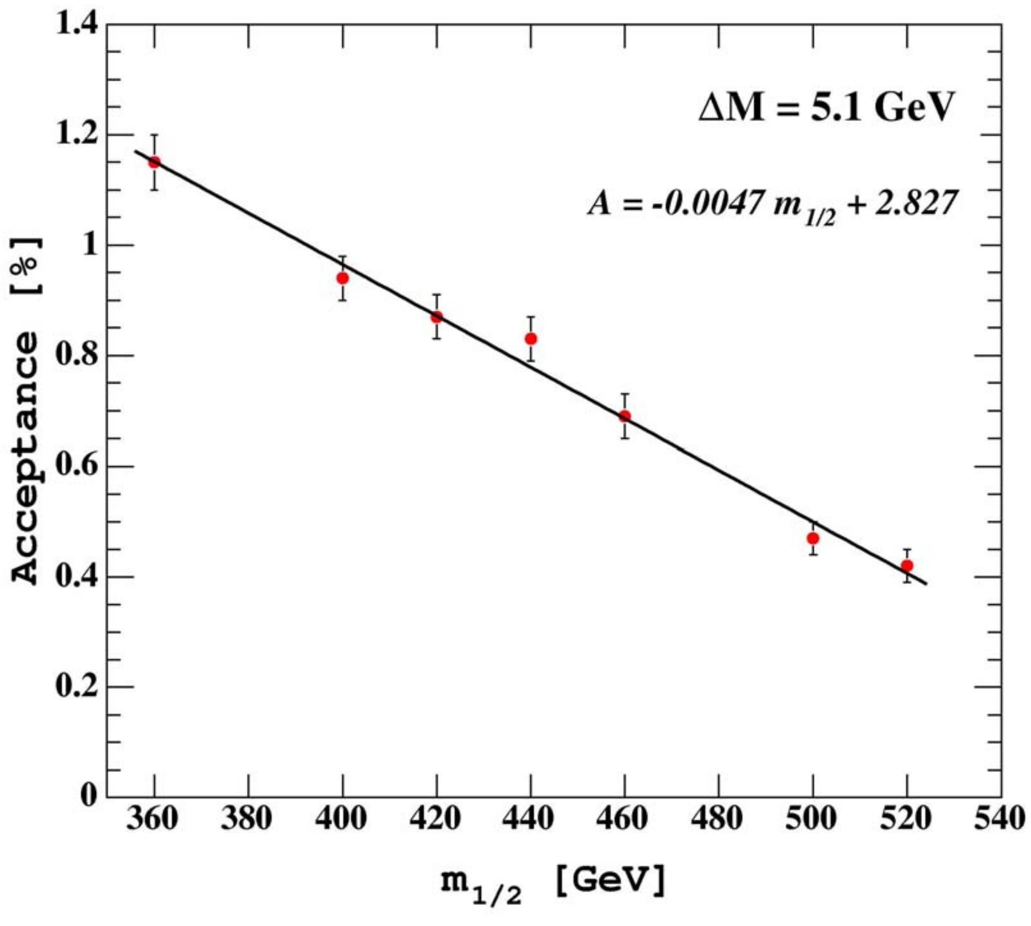
N_{event} vs. ΔM





- **We need 1° to access to small *ΔM* at 500 GeV ILC*!***

Acceptance vs. $m_{1/2}$



Mass Determination

- **Choose an effective mass of j_1, j_2 and E^{miss}, $M(j_1,j_2,E^{miss})$, as a discriminator.**
- **Prepare three templates of the distribution of the effective mass for $\tilde{\chi}_1^0\tilde{\chi}_2^0$, $\tilde{\tau}_1\tilde{\tau}_1$ and SM.**
- **Fit a MC sample of 500 fb^{-1} with the three templates to extract each contribution.**

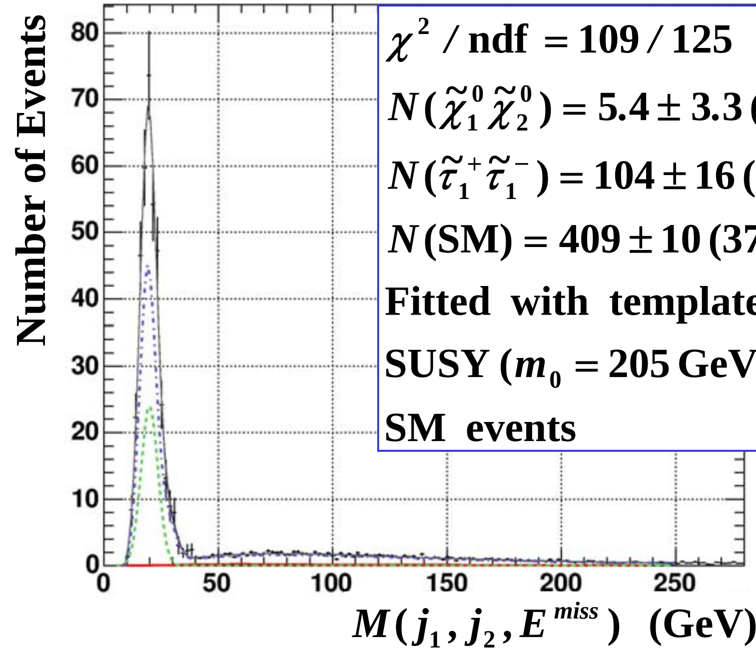
Validation of Templates

2° Mask

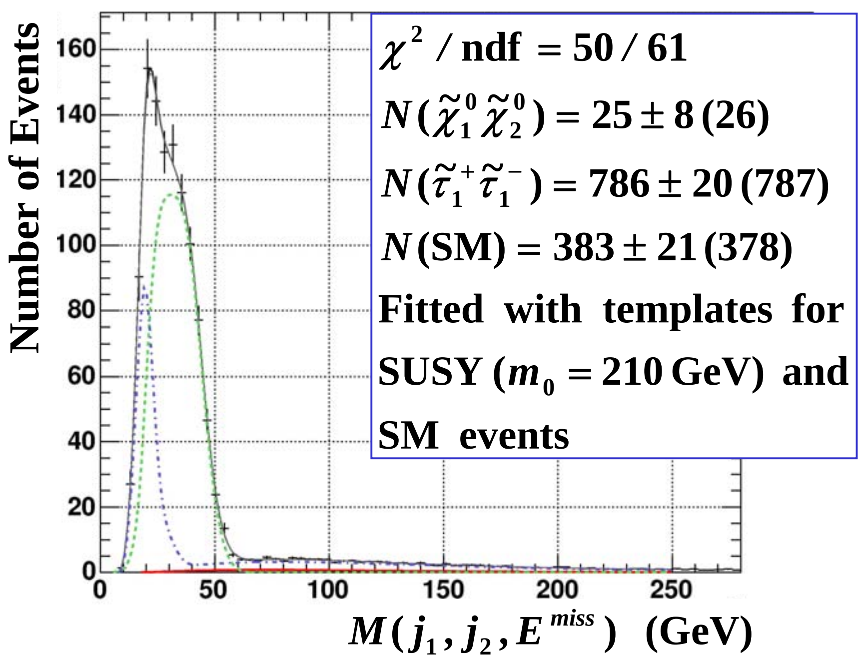
High Stat. "Data"
SM + SUSY

Test, Okay!

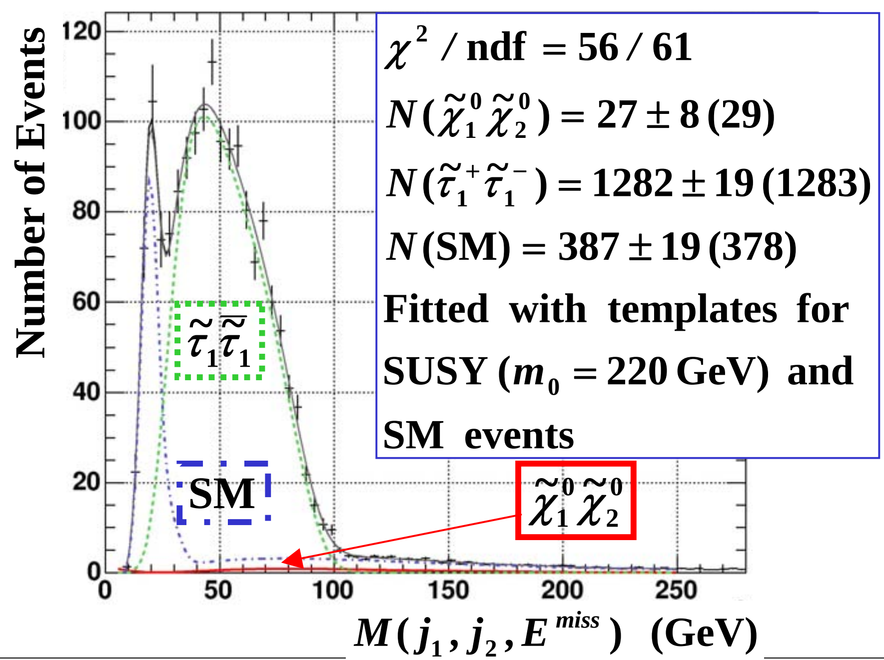
(m_0 = 205, ΔM = 4.76 GeV)



(m_0 = 210, ΔM = 9.53 GeV)



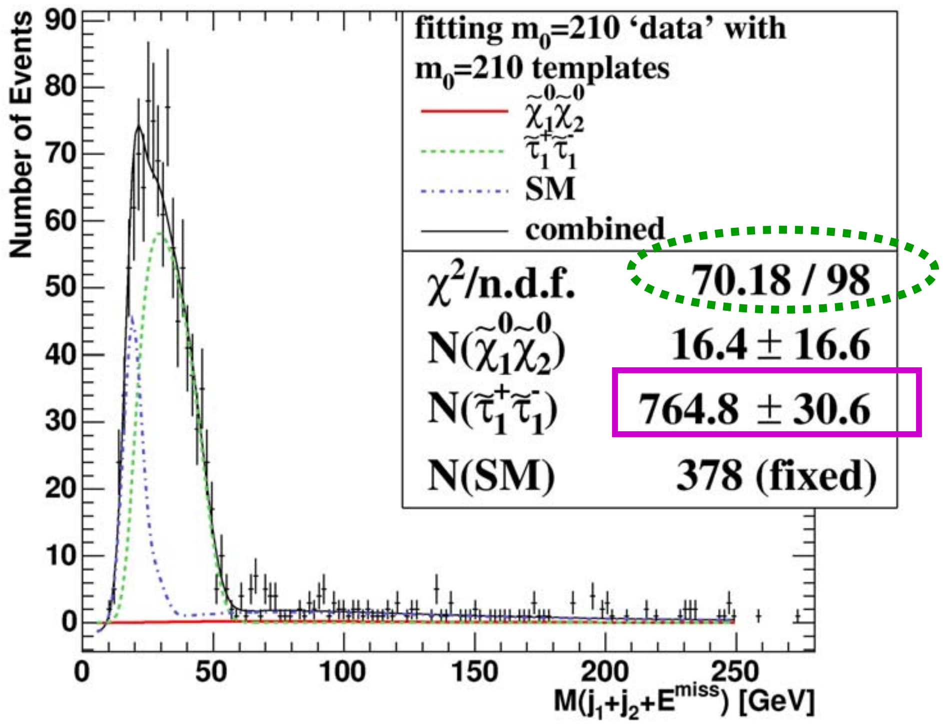
(m_0 = 220, ΔM = 18.98 GeV)

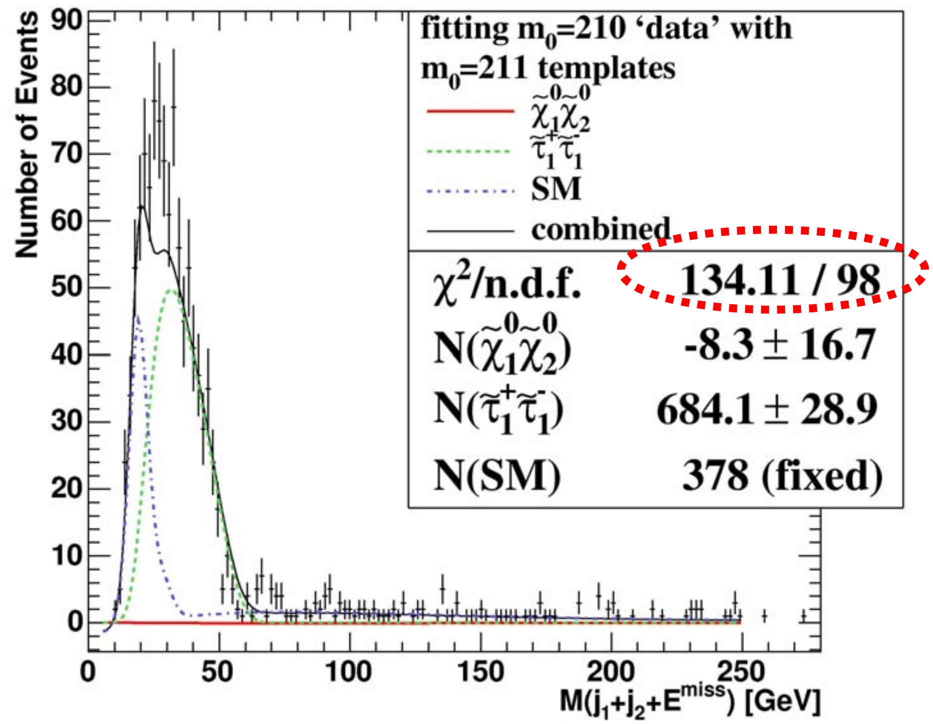


χ^2

2° Mask

"Experimental Data" (500 fb^{-1})
m_0 = 210 (ΔM = 9.53 GeV)





Small χ^2 value suggests the data sample likely contains "m_0 = 210" SUSY events.

$\delta\sigma/\sigma \sim 4\%$
(same for 1° mask)

Finding χ^2 (minimum)

2° Mask

***"Experimental Data"* (500 fb^{-1})**

m_0 = 210 (ΔM = 9.53 GeV)

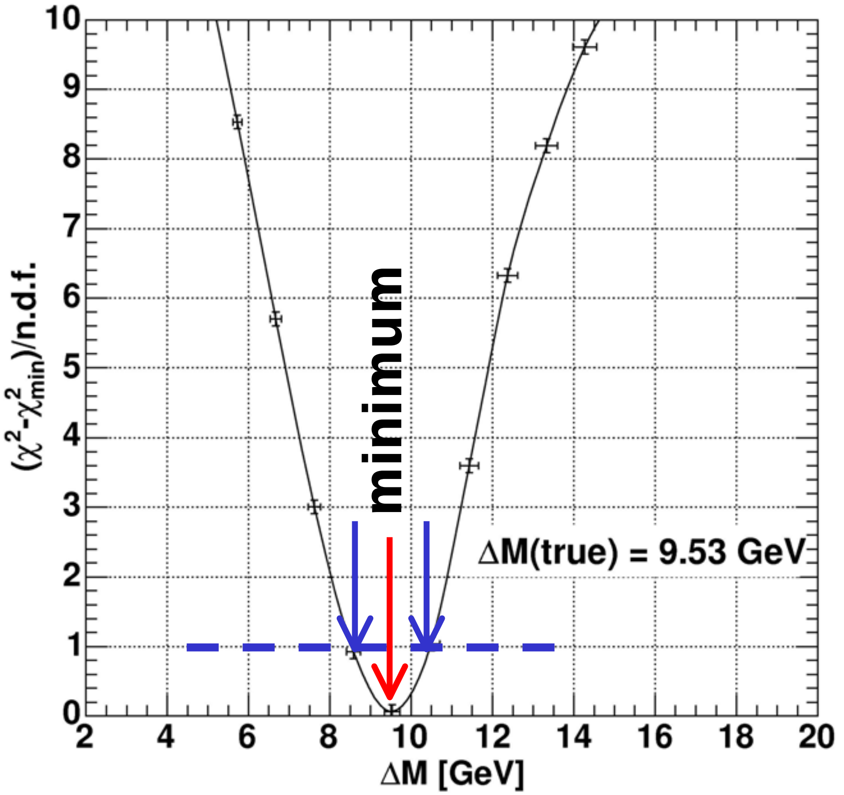
$m_{1/2}$ = 360

Compared to

Templates (high statistics samples)

m_0 = 203 - 220

$m_{1/2}$ = 360



$9.5^{+1.0}_{-1.0}$ GeV

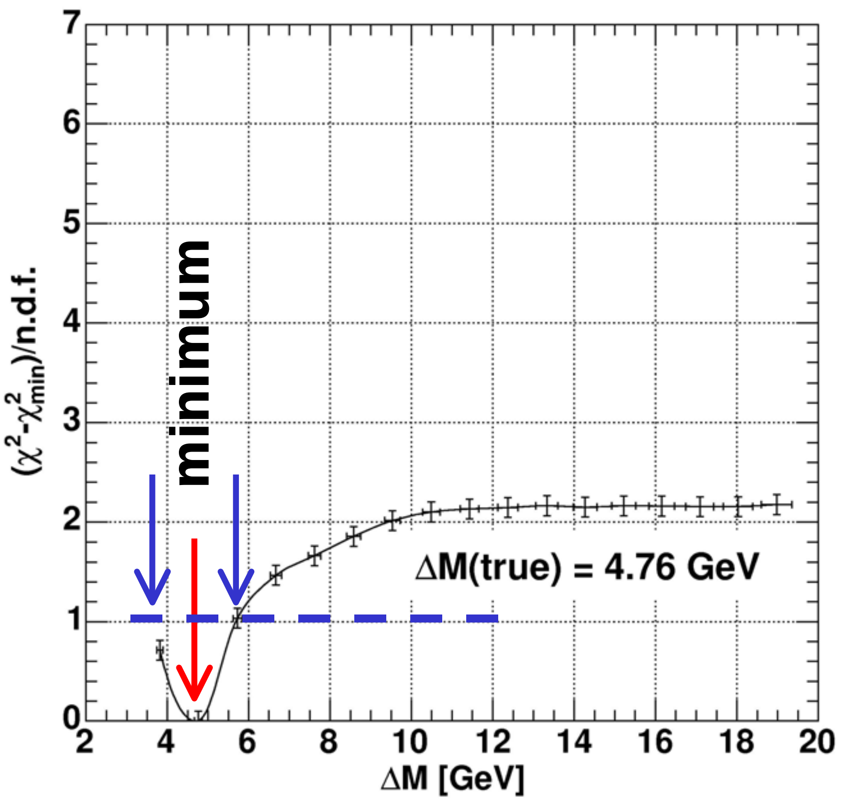
Finding χ^2 (minimum)

1° Mask

***"Experimental Data"* (500 fb^{-1})**
$m_0 = 205$ ($\Delta M = 4.76$ GeV)
$m_{1/2} = 360$

Compared to

Templates (high statistics samples)
$m_0 = 203 - 220$
$m_{1/2} = 360$



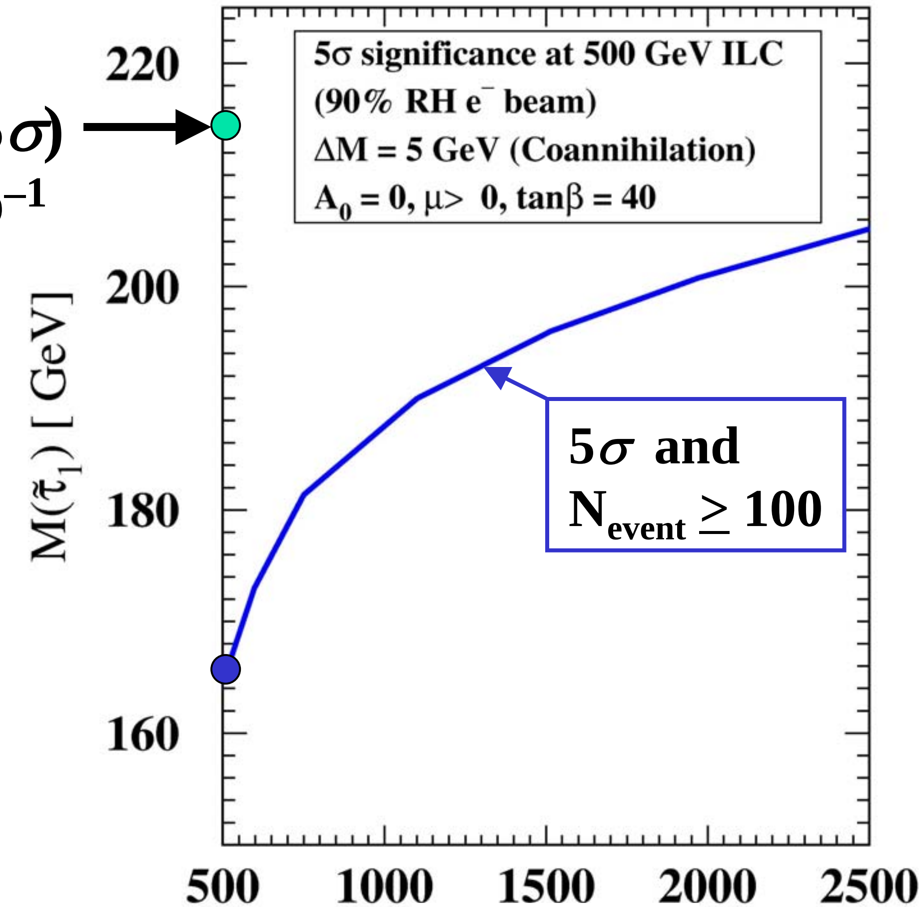
$4.74^{+0.97}_{-1.03}$ GeV

500 GeV ILC Performance

m_0 (ΔM)	(500 fb^{-1}) $N_{\tilde{\tau}_1\tilde{\tau}_1}$	ΔM("500 fb^{-1} experiment")	
		2° Mask	1° Mask
205 (4.76 GeV)	122	Not determined	$4.74^{+0.97}_{-1.03}$ GeV
210 (9.53 GeV)	787	$9.5^{+1.1}_{-1.0}$ GeV	$9.5^{+1.0}_{-1.0}$ GeV
213 (12.37 GeV)	1027	$12.5^{+1.4}_{-1.4}$ GeV	$12.5^{+1.1}_{-1.4}$ GeV
215 (14.27 GeV)	1138	$14.5^{+1.1}_{-1.4}$ GeV	$14.5^{+1.1}_{-1.4}$ GeV

Stau Mass Reach vs. $\mathcal{L}$

215 GeV (5σ) with 500 fb^{-1}



$\mathcal{L}$ [fb^{-1}]

Future Work

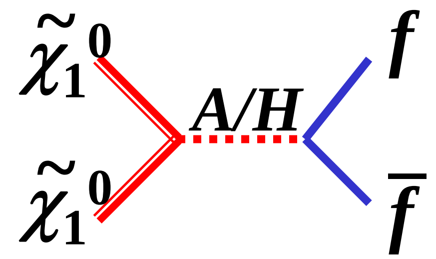
How do we know the stau-neutralino co-annihilation is responsible for the relic density?

(1)No large higgssino component of neutralino – otherwise it will lower the relic density further.

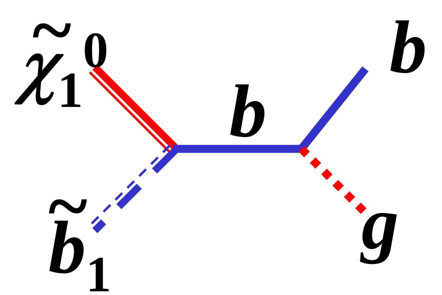
Small μ → Check chargino …

(2)No *A* or *H* annihilation channel – it will lower the relic density.

$$M_{A,H} = 2M_{\tilde{\chi}_1^0}$$



(3)No other co-annihilation channels such as stop, sbottom, chargino.



All these criteria will have their unique signatures...

Conclusion

[1] The cosmologically allowed mSUGRA parameter space is examined using other possible experimental constraints, e.g., collider bounds, rare decay bounds.

[2] The SUSY mass reaches are maximized via the $\tilde{\tau}_1\tilde{\tau}_1$ and $\tilde{\chi}_1^0\tilde{\chi}_2^0$ production.

[3] The importance of 1° "active mask" to detect forward electron/positron to suppress $\gamma\gamma$ events especially for small ΔM.

[4] $\delta(\Delta M)/\Delta M$ ~ 10% with

→Shape analysis using $M(j_1,j_2,E^{\text{miss}})$

→1° active beam mask (e.g., TESLA detector design)

→500 fb^{-1} with RH polarization for e^-