The Stau-Neutralino Coannihilation Region and Colliders

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Talk Outline

- **Supersymmetry and Cosmology**
- **Available mSUGRA parameter space:**
  We use: (a) Rare decay constraints, (b) Collider bounds, (c) Cosmological constraints.
- $\tilde{\chi}_1^0$-p **cross-section for Dark Matter Detectors.**
- **Signal, backgrounds and measurement of the susy masses at Colliders:**

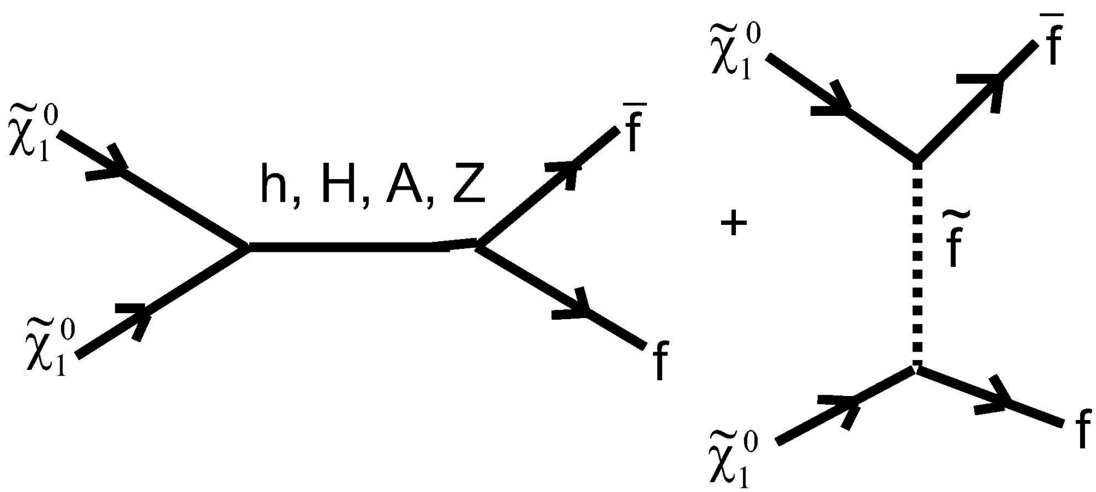
1. **ILC : $\sqrt{s}$=500 GeV and $\sqrt{s}$=800 GeV.**
2. **LHC: $\sqrt{s}$=14 TeV**

- $\tilde{\chi}_1^0$- the lightest neutralino as a stable dark matter candidate (R-parity invariant SUSY model).

- The relic density of these neutralinos is given by:

$$\Omega_{\tilde{\chi}_1^0} h^2 \sim \int_0^{x_f} dx (< \sigma_{ann} v >)^{-1}$$

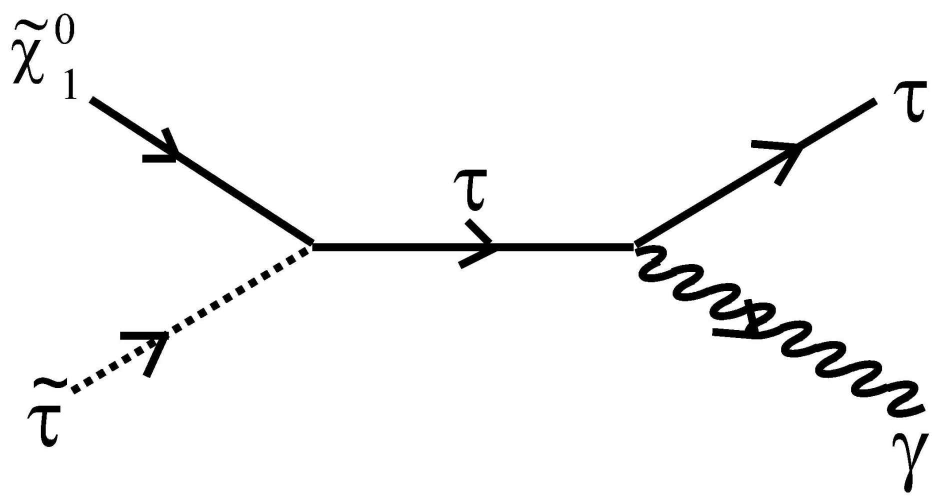
where σ_{ann} is calculated in terms of SUSY model parameters typically using the following annhilation diagrams:



Minimal SUGRA (mSUGRA) Model

- **It is found that a large region of mSUGRA parameter space needs the "coannihilation effect" to be allowed (after including other experimental constraints).**

- **Coannihilation: A second particle becomes nearly degenerate with the $\tilde{\chi}_1^0$.** **[Griest, Seckel:92]**



- **This contribution:** $\Delta M \equiv m_{\tilde{\tau}_1}$-$m_{\tilde{\chi}_1^0}$, **(**$\propto Exp[-\Delta M/20]$ **for** $m_{\tilde{\chi}_1^0}$=400 **GeV .**

Model Parameters

mSUGRA model depends on 4 parameters and 1 sign:

- m_0: **Scalar soft breaking mass at** M_G,
- $m_{1/2}$: **Gaugino mass at** M_G ($m_{\tilde{\chi}_1^0} \simeq 0.4 m_{1/2}$; $m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_2^0} \simeq 0.8 m_{1/2}$),
- A_0: **cubic soft breaking mass at** M_G,
- **tan**β: $< H_2 > / < H_1 >$ **at the electroweak scale,**
- $\frac{|\mu|}{\mu}$: **sign of Higgs mixing parameter** ($W^{(2)} = \mu H_1 H_2$).

Experimental constraints

(i) **Accelerator bounds:**

$m_h \geq 114$ GeV, $m_{\tilde{\chi}^{\pm}} \geq 104$ GeV.

(ii) $b \to s\gamma$ **bounds:**

$2 \times 10^{-4} < BR(b \to s\gamma) < 4.5 \times 10^{-4}$

(iii) **Relic density bounds: :**

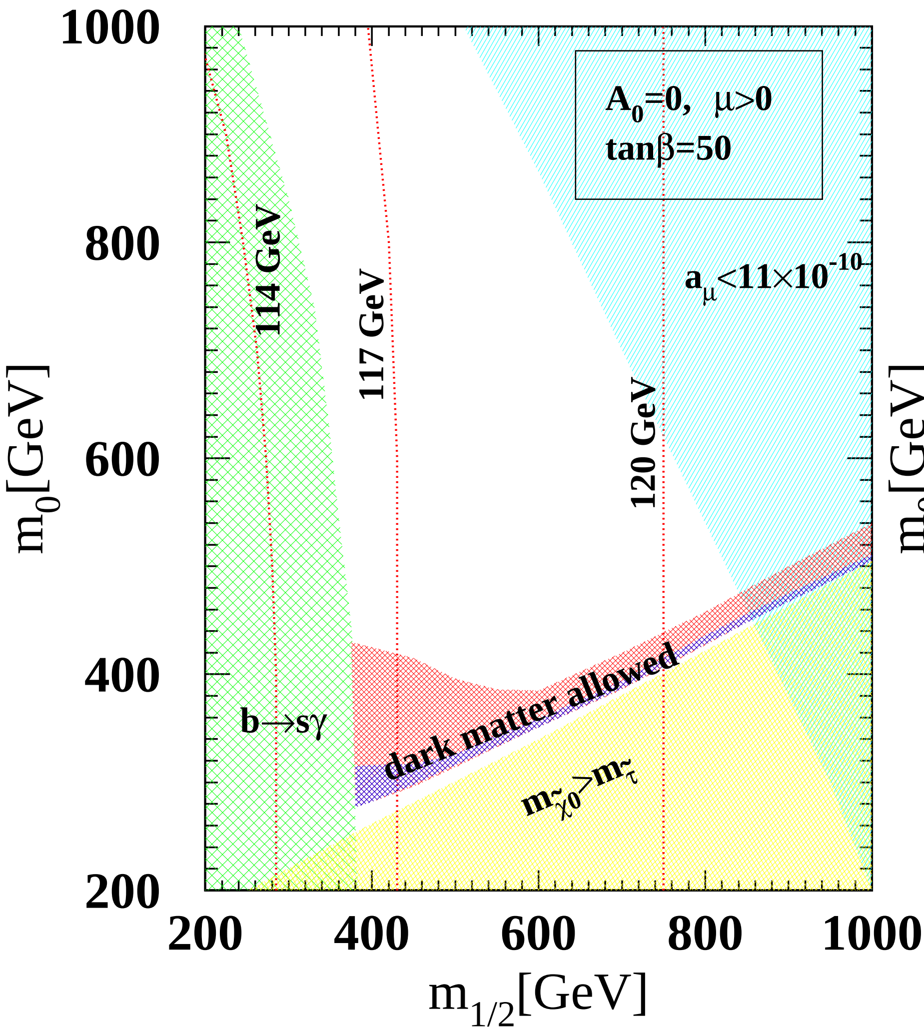
$$0.094 \leq \Omega_{\tilde{\chi}_1^0} h^2 \leq 0.129.$$

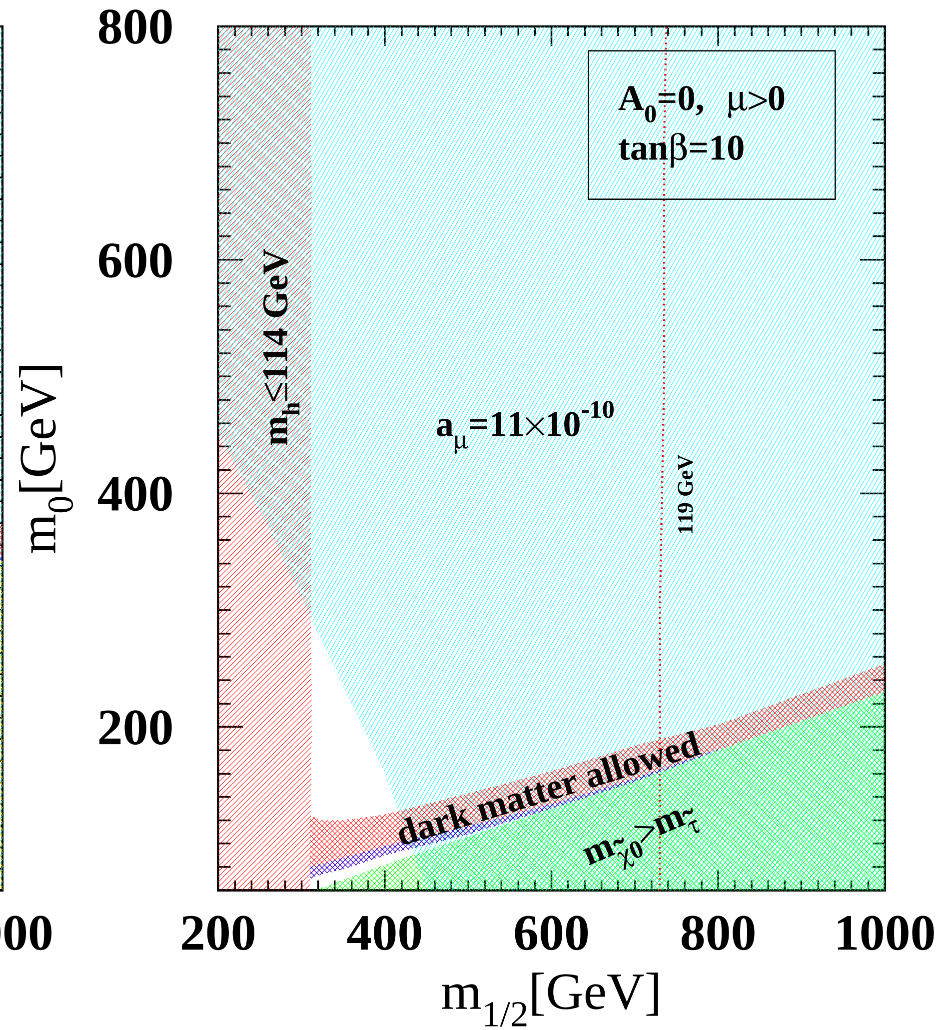
(iv) $a_\mu^{\rm SUGRA}$ **bounds of BNL E821 experiment:**

(e^+e^- data: CMD2, BES and previous data)

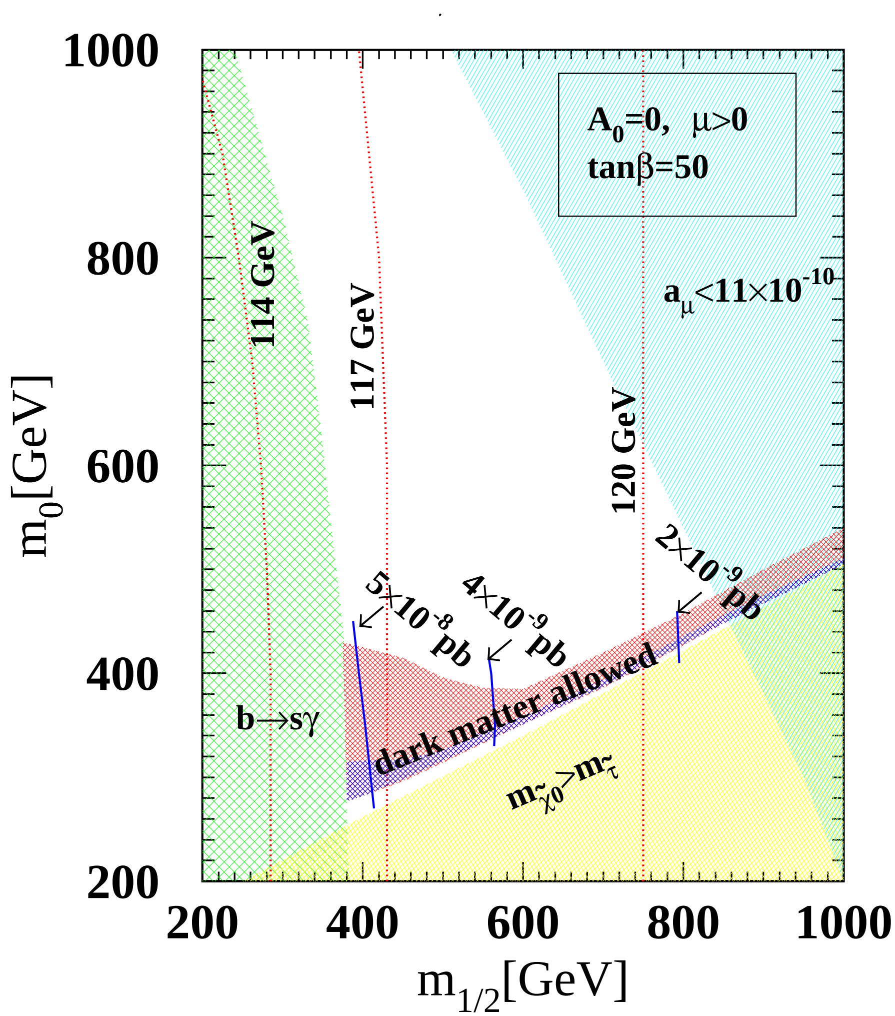
$\Delta a_\mu \times 10^{10} = 27(10)$(Davier et al.),

Allowed Parameter Space (with WMAP)

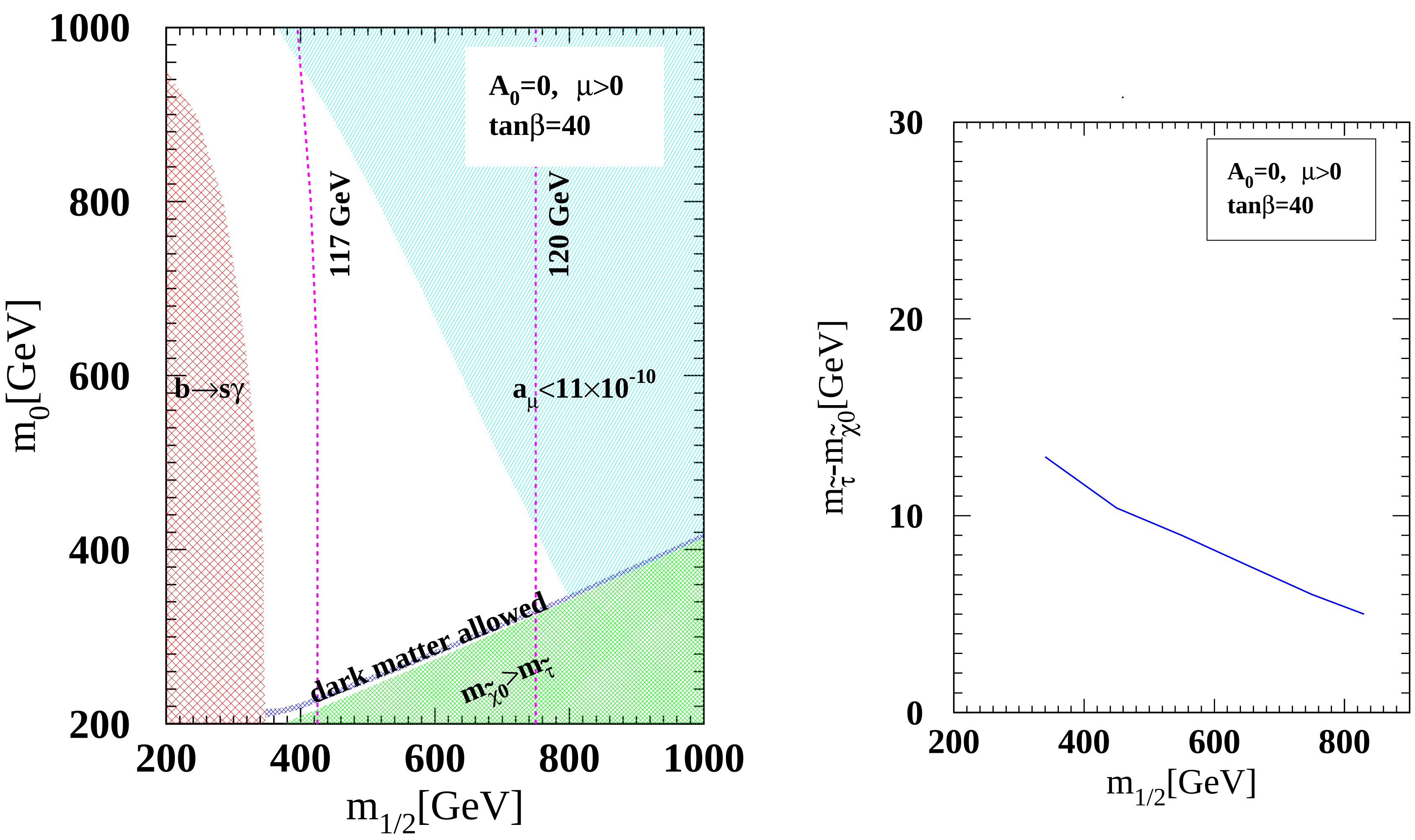




Neutralino-proton cross-section



Narrow Coannihilation Region



Detection of SUSY at Colliders

- **Questions:**

  (1) What are the signals from the narrow coannihilation corridor?

  (2) What is accuracy of the mass measurement (since ΔM is ~ 10 GeV)?

- **Collider experiments:**

  Linear Collider (500 or 800 GeV): e^+e^-

  Large Hadron Collider 14 TeV: pp

(a) The kinematic limit of ILC for $\sqrt{s} = 500$ GeV and $\sqrt{s} = 800$ GeV.

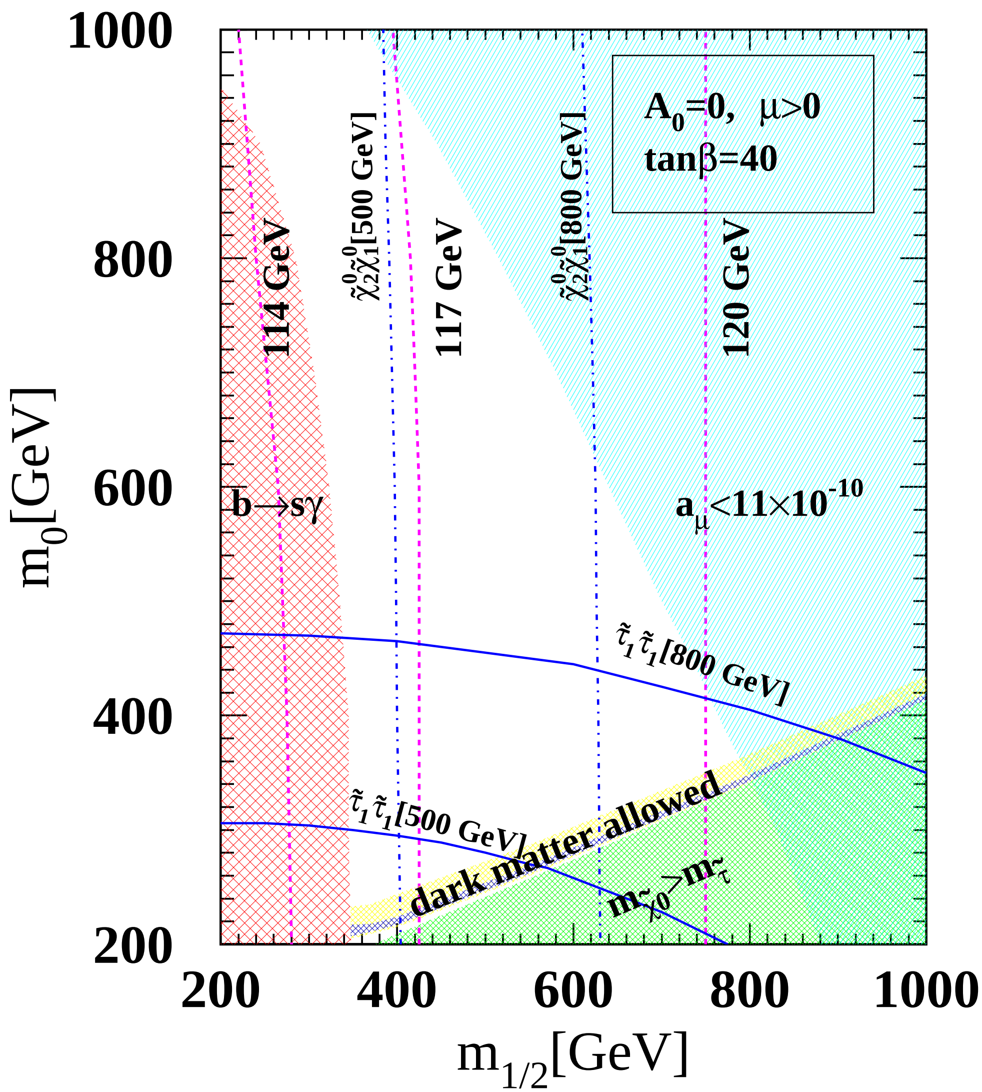
(b) Develop appropriate cuts and extract the signal from the background.

(c) Discovery significance of the parameter space.

(d) Accuracy of measuring the most crucial parameter

$$\Delta M \equiv m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}.$$

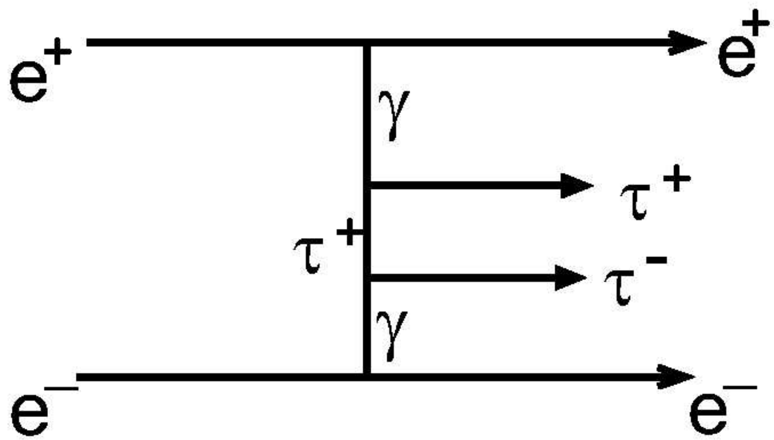
Kinematic Limit



The vertical blue dotted lines: $\sigma_{\tilde{\chi}^0_2\tilde{\chi}^0_1}$ Left:$\sqrt{s} = 500$GeV; Right:$\sqrt{s} = 800$GeV. The slanted blue solid lines: $\sigma_{\tilde{\tau}\tilde{\tau}}$.

Signals and Backgrounds at ILC

- $e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$: **Key process to study the coannihilation band.**
- **2 τ+ 2 $\tilde{\chi}_1^0 \Rightarrow$ 2 τ+ Missing energy**
- **Small $\Delta M \equiv (m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0})$: Low energy τs.**
- **SM Background:**
- $e^+e^- \to W^+W^-, ZZ \to \tau^+\tau^-\nu\nu$
- **Two photon background becomes crucial:**



Analysis

We analyze the $\tilde{\tau}_1$ pair at ILC.

We choose three scenarios

$$(\tan\beta = 40,\ \mu > 0,\ A_0 = 0)$$

MC point	$m_{1/2}$	m_0
1.	360	205
2.	360	210
3.	360	220

MC Point	$M(\tilde{\chi}_2^0)$	$M(\tilde{\tau}_1)$	$M(\tilde{\chi}_1^0)$	ΔM
1.	274	147.24	142.48	4.76
2.	274	152	142.51	9.5
3.	274	161.55	142.57	19

MC Simulation

- $\tilde{\tau}_1$-$\tilde{\tau}_1$ and $\tilde{\chi}_2^0$-$\tilde{\chi}_1^0$ productions at ILC.
- $\sigma_{\tau_h \tau_h}$ (fb) for different polarizations:

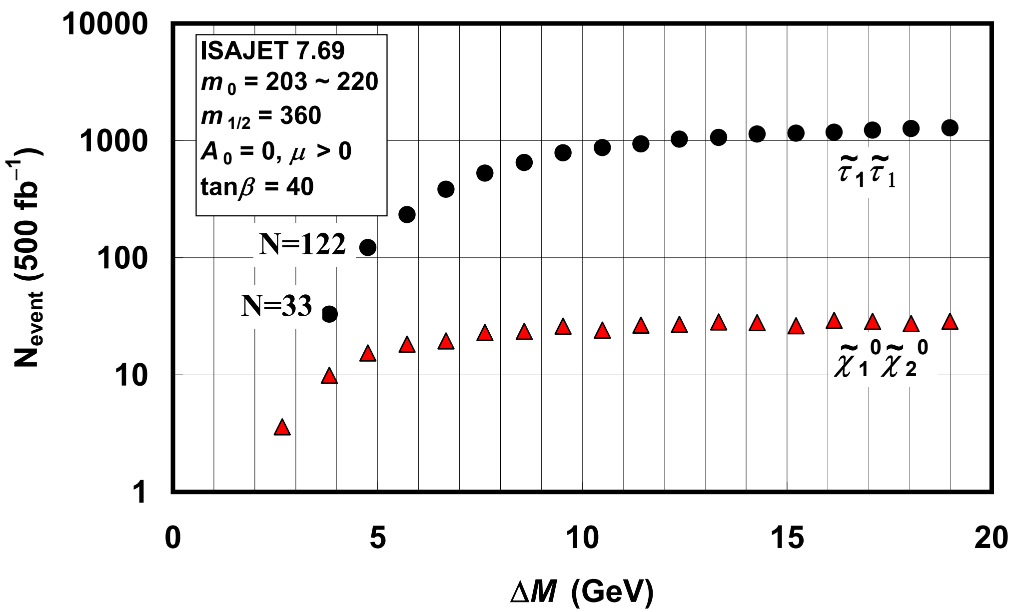
P(e$^-$)	-0.9(RH)	0	0.9(LH)
SM	7.84	48.9	89.8
SUSY	$\tilde{\chi}_2^0\tilde{\chi}_1^0$, $\tilde{\tau}_1\tilde{\tau}_1$		
1.	0.43, 28.25	3.39, 19.6	7.10, 12.8
2.	0.39, 25.85	3.31, 18.4	6.91, 11.8
3.	0.38, 22.9	3.15, 15.8	6.62, 10.3

- **Monte Carlo and Analysis tools**: Event generator: ISAJET 7.69, SM: WPHACT v2.02pol (all fermion final states with e^+/e^- polarization): (Ballestrero etal). Tau decay: Tauola v2.6, Detector Simulation and event analysis: Package LCD Root v3.5, FAST MC using LD Mar01 detector paramterization, Jet Finder,...

Event SelectionCuts

RH ((e^-) = $-$0.9) ($\tilde{\tau}_1$-$\tilde{\tau}_1$)
$N_{jet} \geq 2$($E_{jet} > 3$ GeV) τ_h ID : 1, 3 tracks; $M_{tracks} <$ 1.8 GeV
$\lvert\cos\theta_{jet}\rvert < 0.65$ $\lvert\cos\theta(j_2, p_{vis})\rvert < 0.6$
Missing $p_T > 5$ GeV
Acoplanarity $> 40^\circ$
No EM cluster in $5.8^\circ < \theta < 28^\circ$($E > 2$ GeV)
No electrons: $\theta > 28^\circ$ with $p_T > 1.5$ GeV
(1°(2°) - 5.8°) No EM cluster:$E > 100$ GeV

No. of events vs ΔM



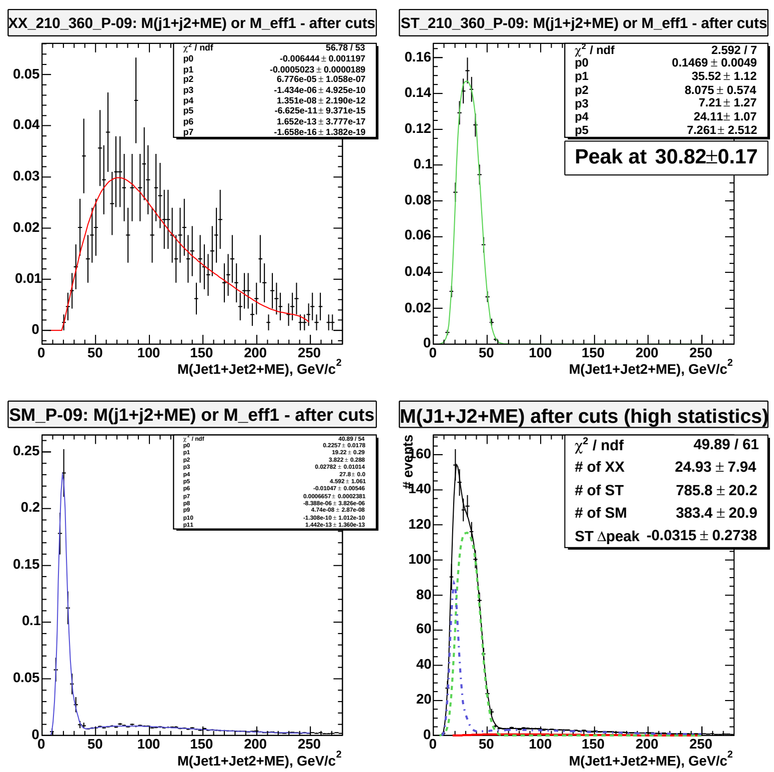
- **Number of events for 500 fb^{-1} of luminosity for $m_0 = 203 - 220$ GeV with 2° (1°) mask in the RH polarization case.**
- **Numbers of 2 photon events: 249(4) for 2° (1°) mask.**

Measurement of ΔM at ILC

- $M_{\rm eff} \equiv M(j_1, j_2, \not{E})$: an invariant mass of two τ-jets and missing energy is used as a key discriminator .

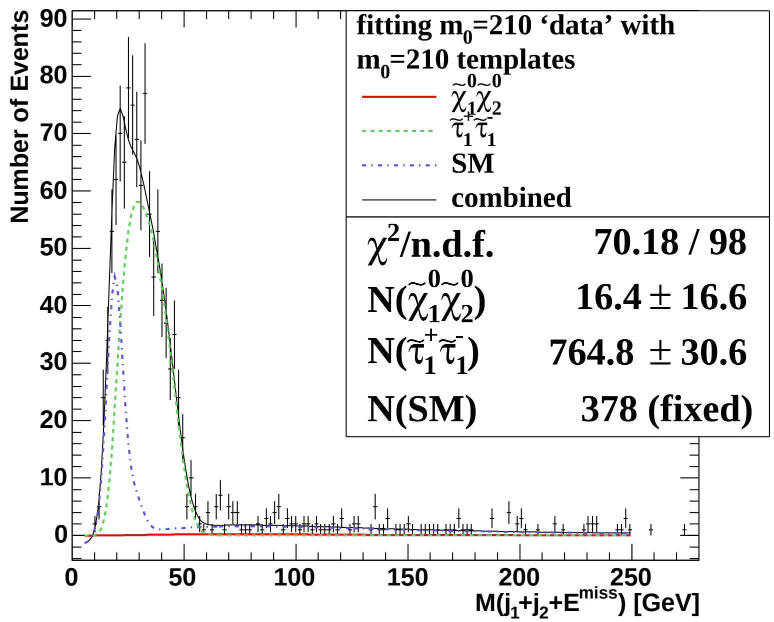
- The peak of the SUSY signal and the background separates as ΔM increases.

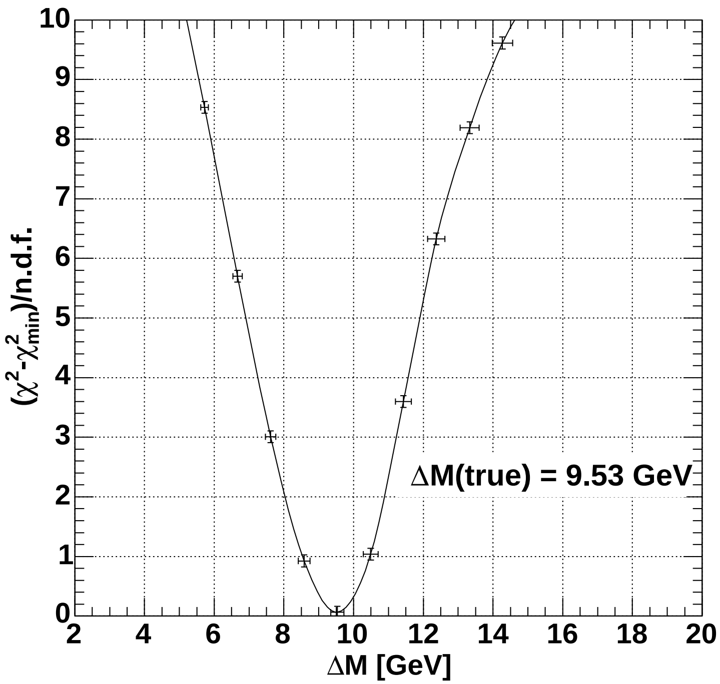
$$m_0 = 210, m_{1/2} = 360, \tan\beta = 40, \mu > 0, A_0 = 0$$ **:RH**



Determination of ΔM

- **500 fb^{-1} data for $m_0 = 210$, $m_{1/2}$=360 GeV, $\Delta M = 9.53$ GeV.**
- **Templates of M_{eff} shapes in the range of m_0 =203-220 GeV is used to fit the data.**





$\Delta M = 9.5 \pm 1$ GeV.(The true value: 9.53 GeV)

Accuracy of Mass Determination

Accuracy of the determination of ΔM for different beam mask.

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

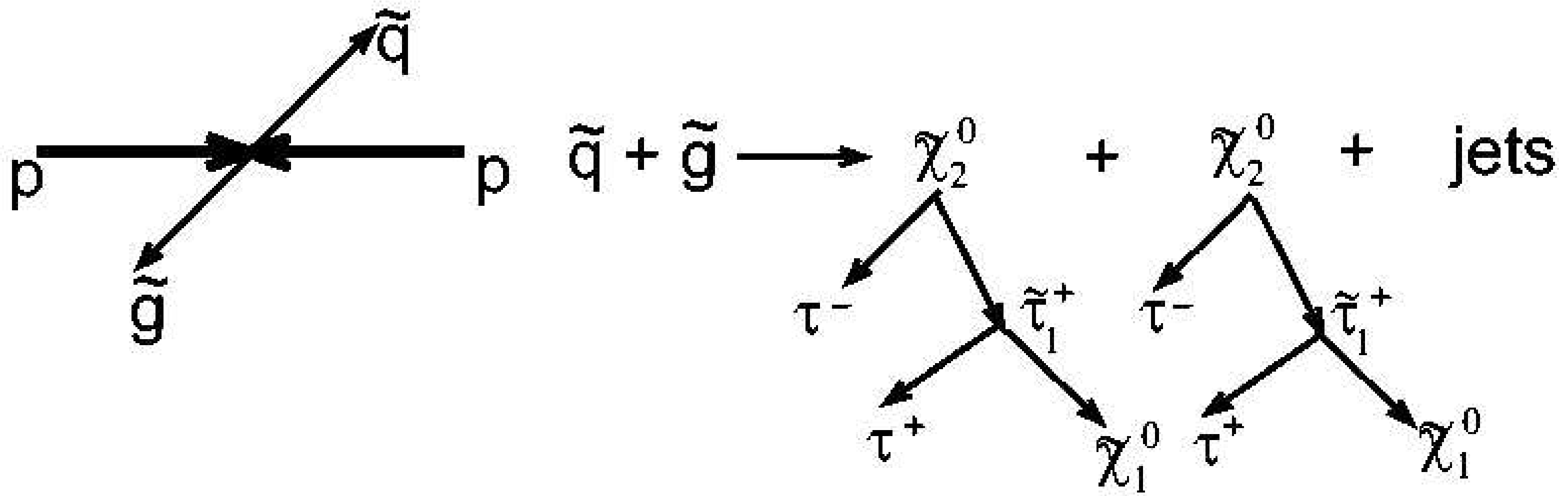
- x$^\circ$ Mask: indicates the angular proximity to the beam direction one can probe. 1° Mask is possible for LC.
- $\frac{\delta\Delta M}{\Delta M}$ is about 10%

[R. Arnowitt, B.D., T. Kamon,V. Khotilovich, PLB,05]

Signals and Measurements at LHC

- **Squark-gluino production cross section is very large.**

- **The Squark, Gluino decays, e.g.**



- **We have**

  4 τ (2 low energy and 2 high energy)+ jets+missing energy.

- **SM Background: top-anti top pair.**

- **Event selection: select 3 out of 4 τs from $\tilde{\chi}_2^0$-$\tilde{\chi}_2^0$ (or 3 τs from $\tilde{\chi}_2^0$-$\tilde{\chi}_1^{\pm}$) Two with high threshold and one with low threshold taus are chosen, All jets and τs are selected with: E_T(1st τ)$>$40 GeV; E_T(2nd τ)$>$40 GeV; E_T(3rd τ)$>$20 GeV; $E_T(J_1)$+$\not{E}_T>$400 GeV**

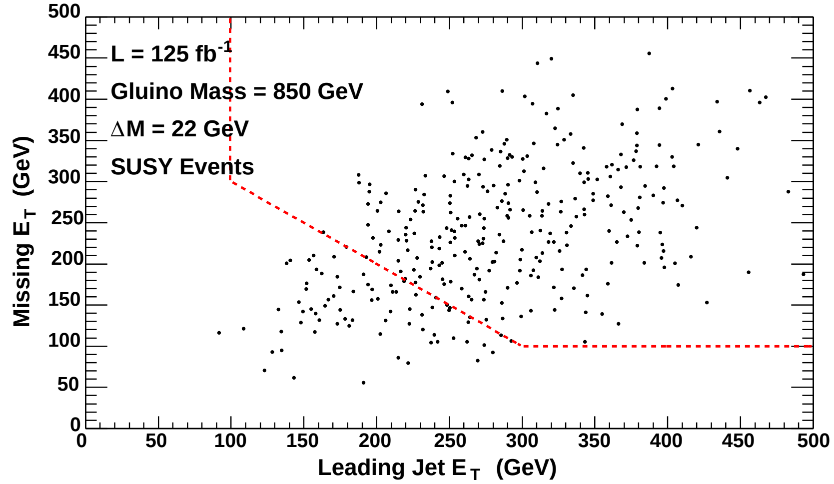
- **Each event has many jets [Due to cascades] $\tilde{g} \to q\tilde{q} \to qq\tilde{\chi}_2^0 \to 2q\,2\tau$+missing energy**

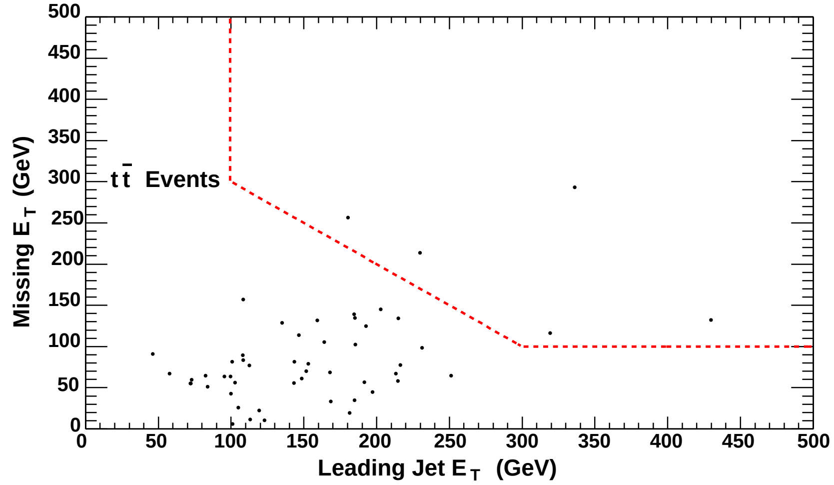
- **The above jets can fake taus and the nos. of signal events increase.**

- **1% fake rate with 20% variation is assumed [CDF].**

- **ATLFAST detector simulation is used.**

SUSY vs $t\bar{t}$ Background





All SM Backgrounds are ignored in this study.

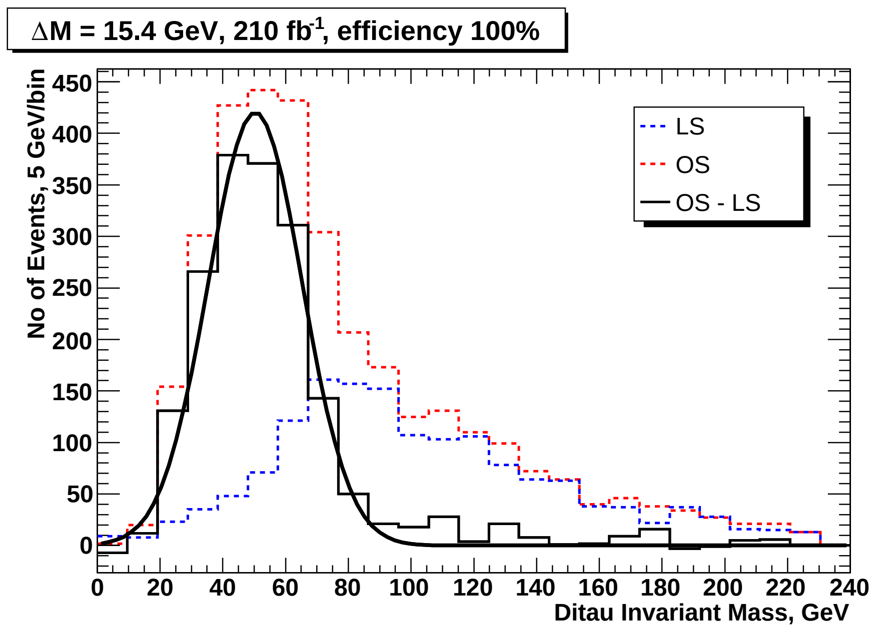
Choose: $E_T(J_1)+\not{E}_T>$**400** **GeV,** $E_T(J_1) > 100$ **GeV and** $\not{E}_T > 100$ **GeV**

Analysis

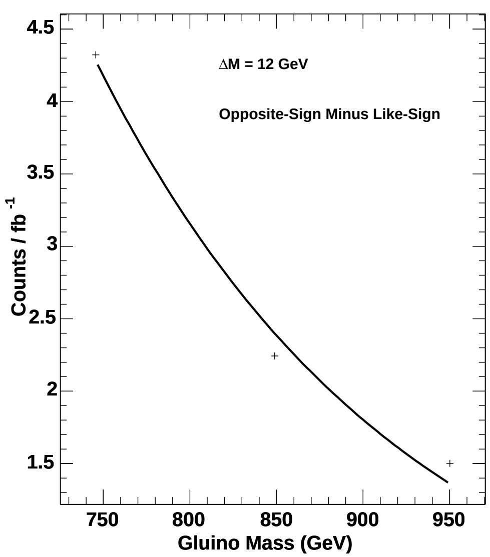
$$\tilde{\chi}_2^0 \Rightarrow \tau(\mathrm{hard})(1) + \tau(\mathrm{soft})(3) \ + \ \not{E}$$

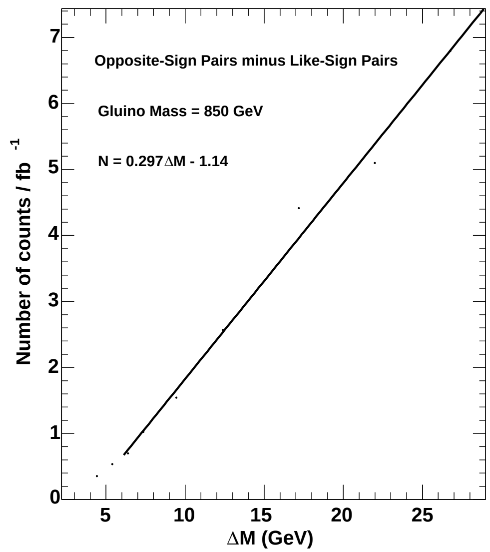
$$\tilde{\chi}_2^0 \Rightarrow \tau(\mathrm{hard})(2) + \tau(\mathrm{soft})(4) \ + \ \not{E}$$

- **Calculate invariant masses of two tau-jets between 1 and 3 or 4; between 2 and 4 or 3**
- **Use "OS-LS" technique to subtract the wrong combination.**
- **Study N_{OS-LS}, $M_{\tau\tau}^{\mathrm{peak}}$ as a function of ΔM, $M_{\tilde{g}}$ and f.**

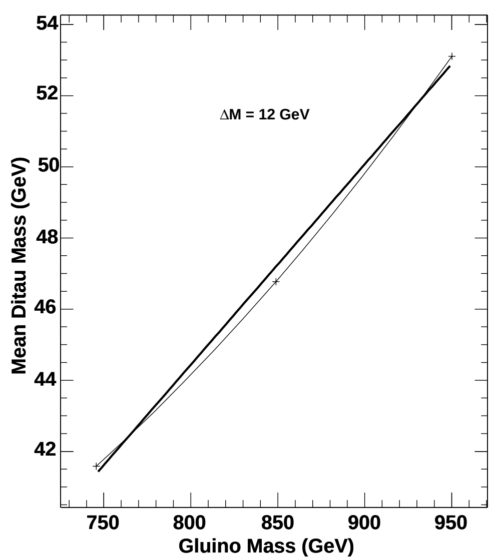


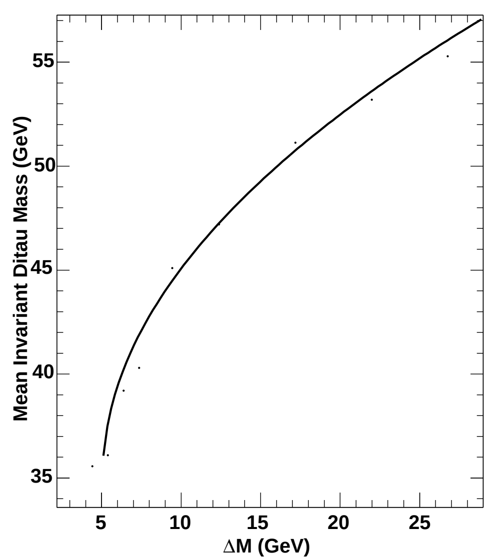
Analysis





The number of 3τ events N_{OS-LS} as function of $M_{\tilde{g}}$ and ΔM (without fake)



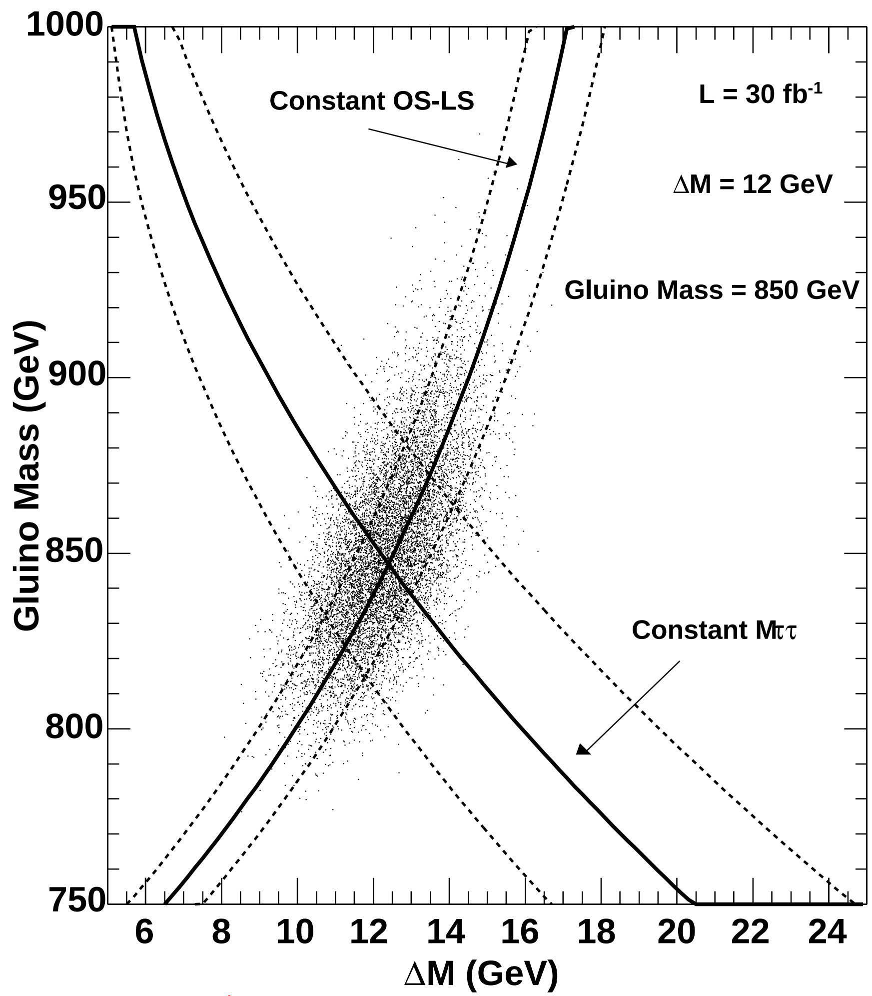


The measurement of $M_{\tau\tau}$ (OS-LS) peak as function of $M_{\tilde{g}}$ and ΔM (without fake)

The ΔM and its uncertainty can be determined from above measurements.

Determination of ΔM and $M_{\tilde{g}}$

Constant events: $N \pm \sqrt{N}$ and Constant $M_{\tau\tau}$ peak $\pm\, \sigma_{M_{\tau\tau}}/\sqrt{N}$ are plotted for ΔM=12 GeV for 30 fb^{-1} luminosity (without fake rate).



The Gluino mass measured here can be compared with the direct measurement. We determine ΔM, $M_{\tilde{g}}$ simultaneously.

The uncertainty of ΔM is of the order of a GeV.

“fake” effects

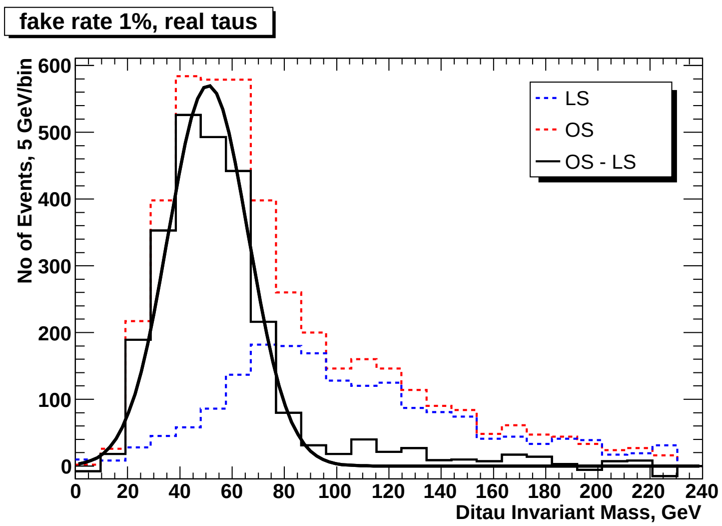
- **Assume an event with X real τs and Y jets(j_1,...,j_Y), where each jet can fake τ.**
- **Use ϵ_τ=50%(100%) and fake=1%**
- **Re-label X+Y objects: e.g. τ_1,τ_2,$\tau_3(j)$,...τ_X, and j_1...,j_6(τ),...j_Y, where**

  τ_3(j) means a object misidentified as τ.

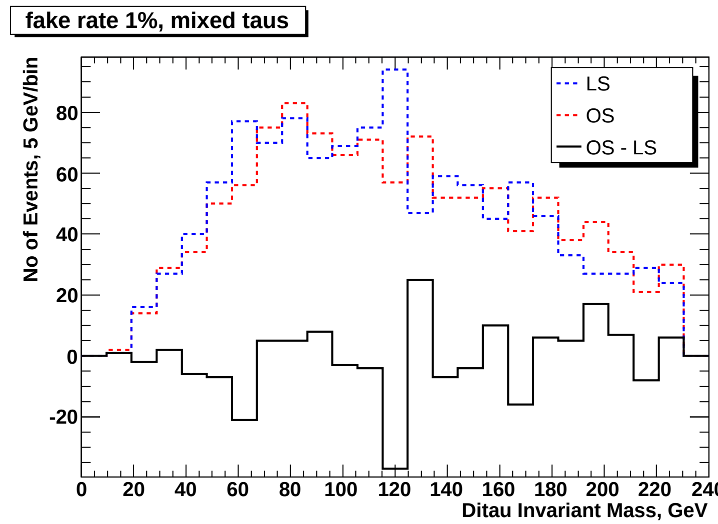
  j_6(τ) means a τ misidentified as jet with 6th leading E_T.
- **Apply our event selection cuts-3τ s+ 1 jet +$\not{E}_T$**
- **Number of events $N_{\rm OS-LS}$ increases with fake rate.**

“fake” effects on Peaks

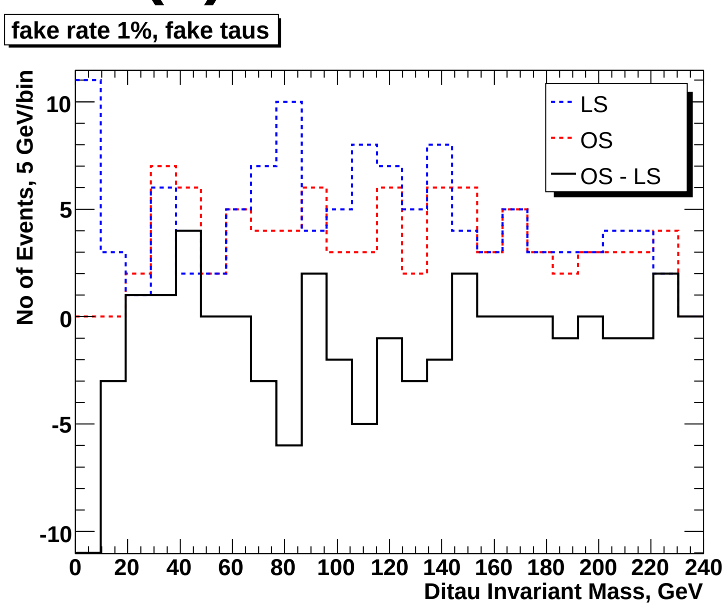
case (a)



case(c)

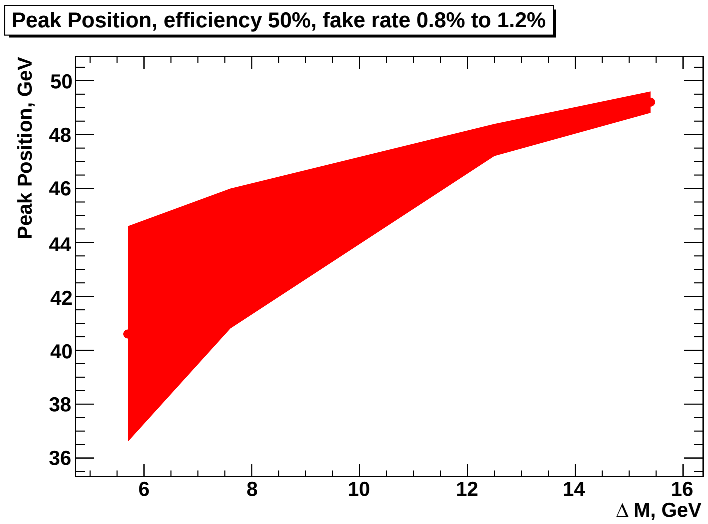


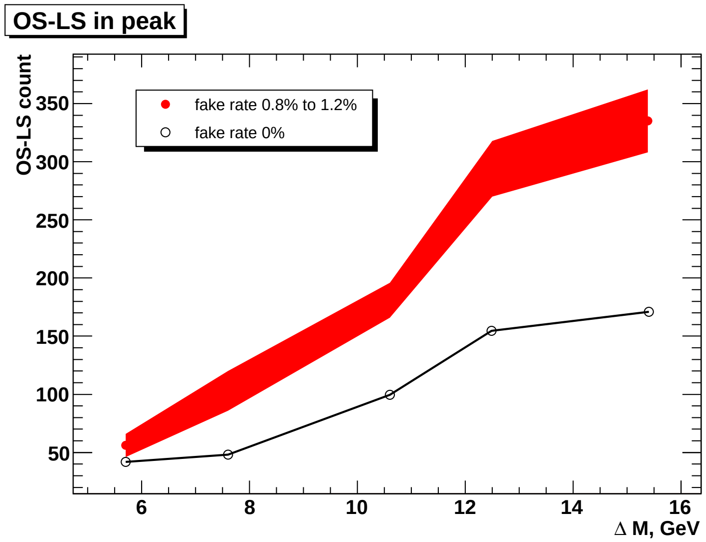
case(b)



(a) Both τs are real, (b)one real and one fake, (c)Both τs are fake. Cancellation in (b) and (c) [Both real taus in (a) come from same $\tilde{\chi}_2^0$]

Analysis(ATLFAST)





- **Consistent with previous analysis.**
- **The band is drawn for fake rate 0.8% to 1.2%.**
- ΔM **could be measured. Work is in progress.**

Conclusion

- **The cosmologically allowed mSUGRA parameter space is examined.**
  The $\tilde{\tau}$ pair and the $\tilde{\chi}_2^0\tilde{\chi}_1^0$ productions have the maximum reach at ILC.

- **The importance of "active mask" to suppress $\gamma\gamma$ events especially for small ΔM.**
  1° mask will be effective at 500 GeV LC.

- **$\frac{\delta\Delta M}{\Delta M}$ is about 10% with**
  (a)shape analysis using $M(j_1, j_2, \not{E})$discriminator.
  (b)a beam mask of 1°.

Conclusion...

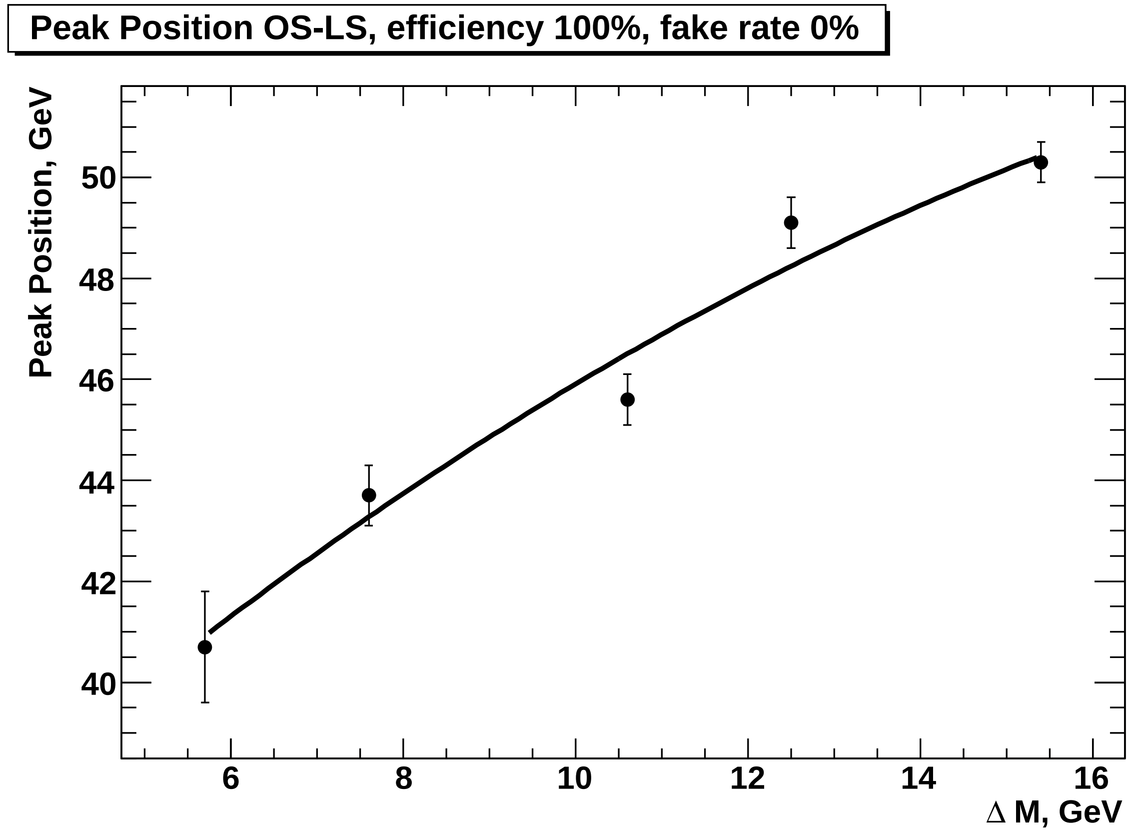
- **The signal (3τ+missing energy) has been studied at LHC The N_{OS-LS} events and the position of the ditau mass distribution peaks are good variables to measure ΔM (and $M_{\tilde{g}}$ for comparison)..**

- **ΔM is determined with an uncertainty of about 2 GeV (without fake rate).**

- **Inclusion of the fake rate increases the error of ΔM. Work is in progress.**

Back-up

- We use ATLFAST to study the shift of the peak with ΔM



- The ΔM can be measured with an uncertainty of ± 2 GeV