Reconstructing SUSY Contribution to Muon g-2 at ILC

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Status of Muon g-2

Precise result from Brookhaven E821 experiment

Dedicated studies on standard model prediction

[Hagiwara,Liao,Martin,Nomura,Teubner;Davier,Hoecker,Malaescu,Zhang]

$$a_\mu^{(\mathrm{exp})} - a_\mu^{(\mathrm{SM})} = \begin{cases} (26.1 \pm 8.0) \times 10^{-10} \\ (28.7 \pm 8.0) \times 10^{-10} \end{cases}$$

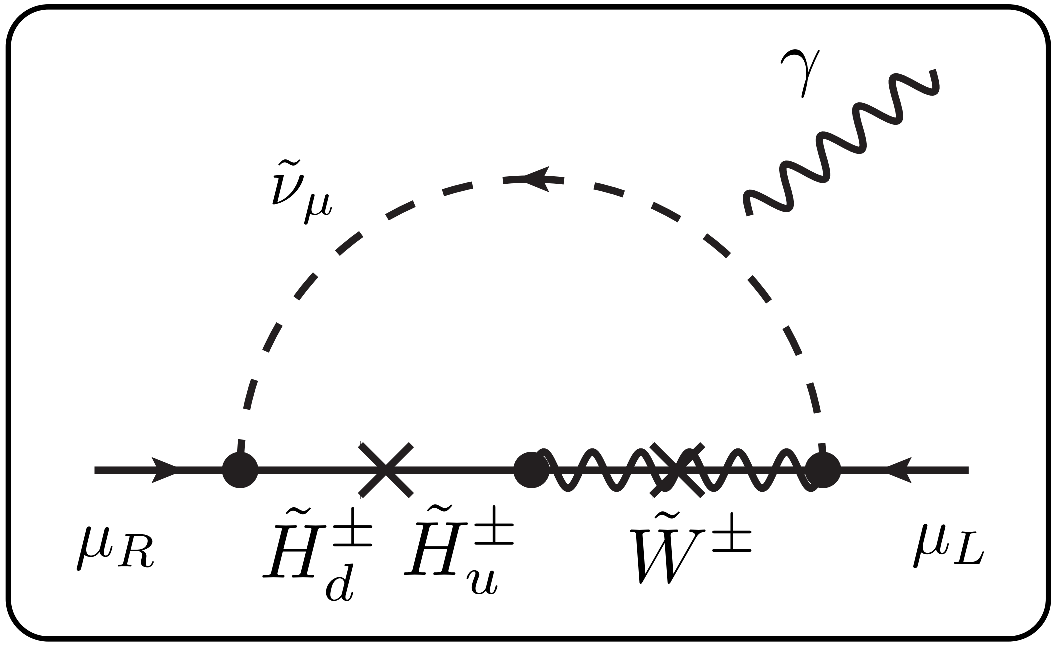
> 3σ deviation

(possibly) a signal of new physics

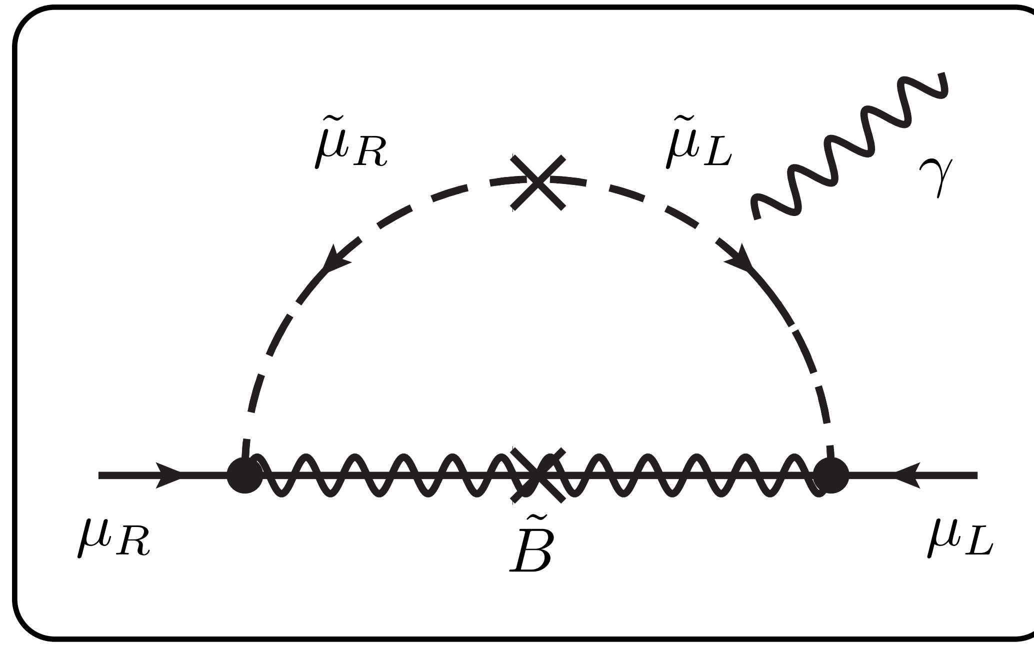
c.f. Electroweak: $a_\mu^{(\mathrm{EW})} = (15.4 \pm 0.1) \times 10^{-10}$

SUSY Solution

chargino-muon sneutrino



neutralino-smuon



$$a_\mu(\mathrm{SUSY}) \sim \frac{\alpha_2(\alpha_Y)}{4\pi} \frac{m_\mu^2}{m_{\mathrm{soft}}^2} \tan\beta \qquad (\tan\beta \sim 10)$$

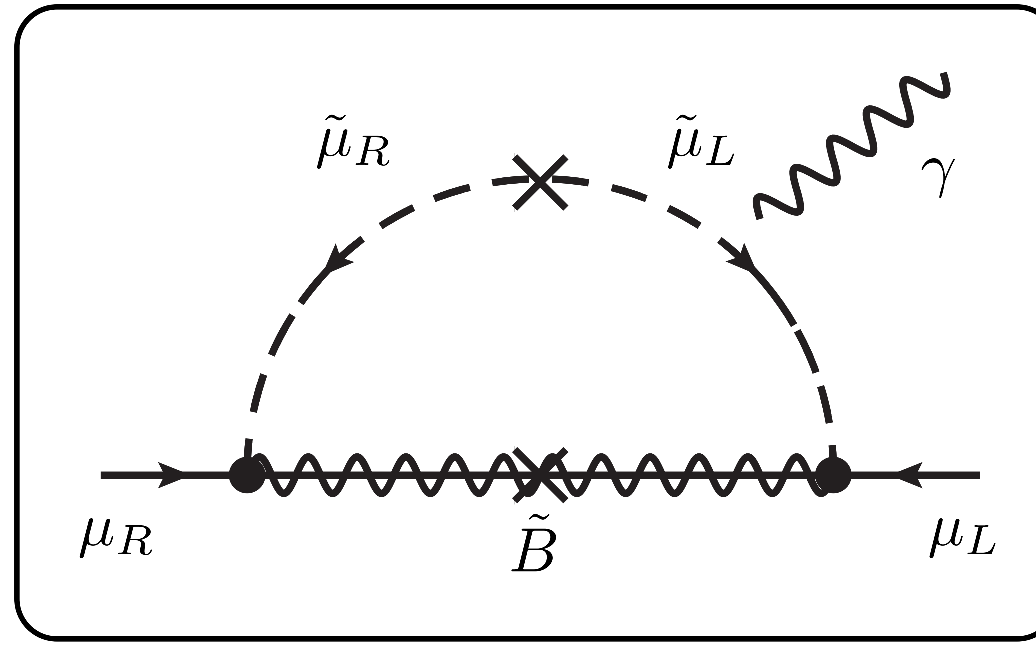
→ Enhanced by tanβ

Question: How to test SUSY solution?

SUSY Solution

chargino-muon sneutrino

neutralino-smuon



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→ Enhanced by tanβ

Question: How to test SUSY solution?

Test of SUSY Solution

Stage 1

discovery of SUSY particles necessary for SUSY contribution to muon g-2

Stage 2

reconstruct SUSY contribution to muon g-2 by information available at colliders (ILC)

Neutralino Contribution

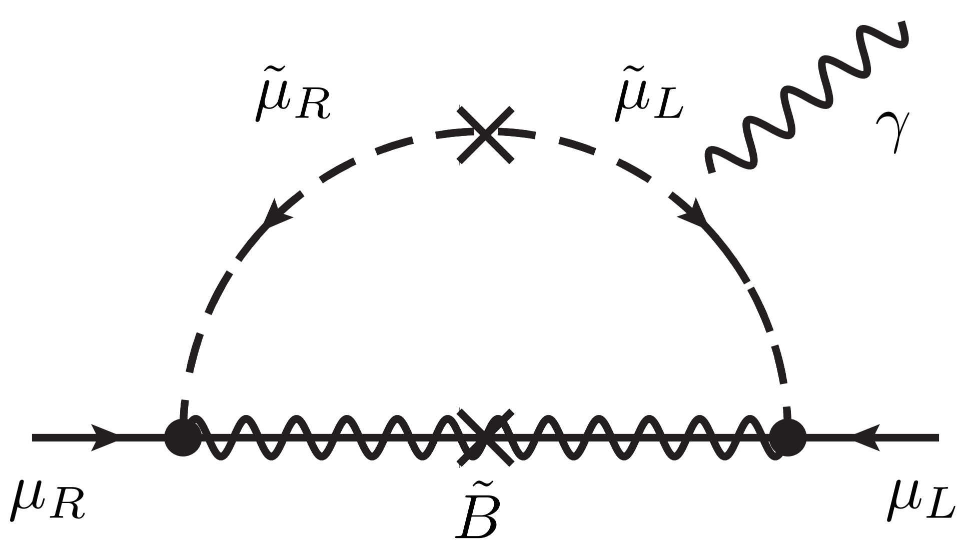
Contribution becomes sizable

✓ Light: left- and right-handed smuons, Bino

✓ large smuon LR mixing parameter ($\propto \mu \tan\beta$)

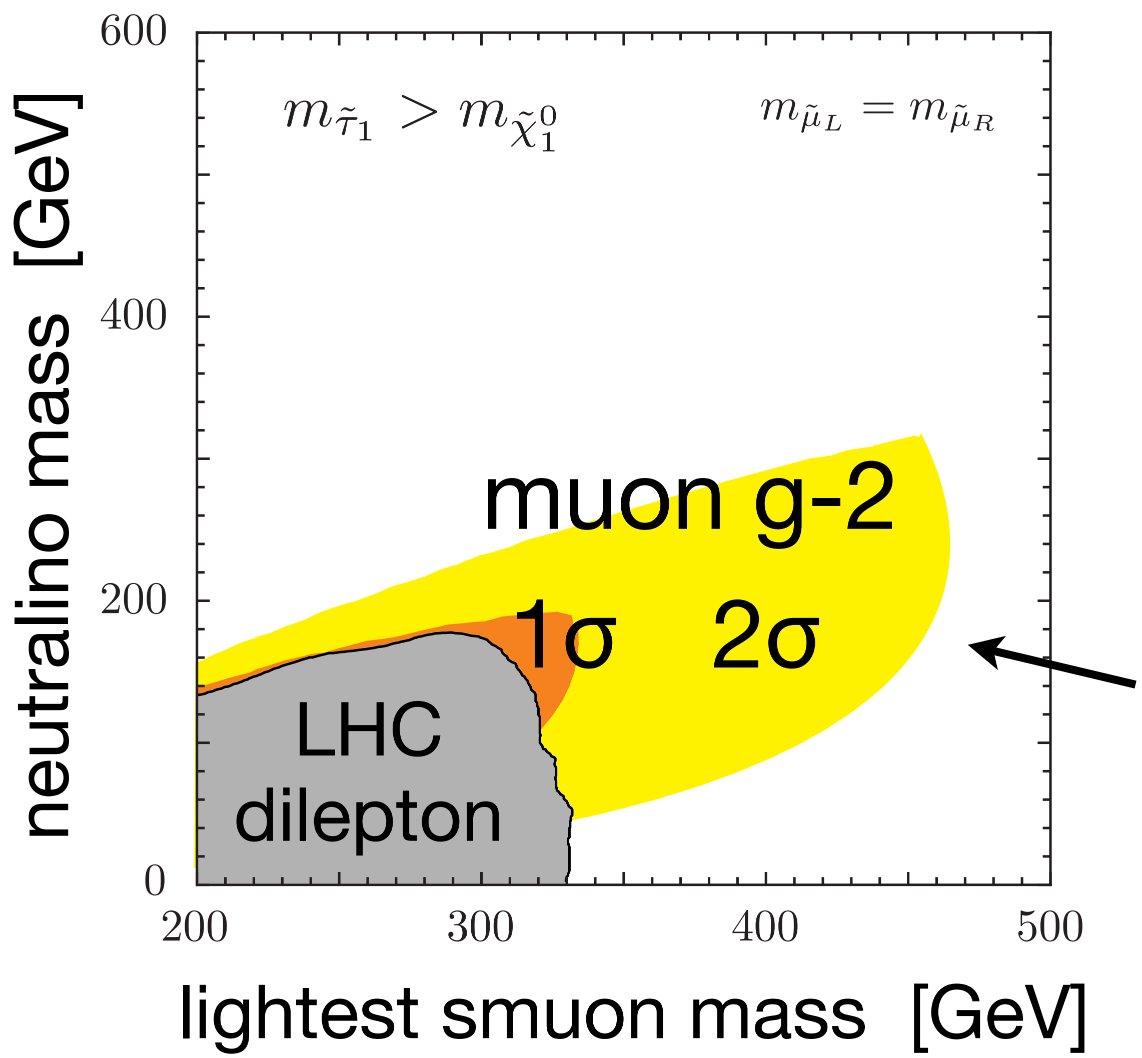
- too large LR mixing spoils vacuum stability

Upper bounds on masses of SUSY particles



Mass Region

(Lightest) smuon and Bino are within kinematical reach of ILC at $\sqrt{s} = 1\,\mathrm{TeV}$ [Endo,Hamaguchi,Kitahara,Yoshinaga]



$\sigma(\tilde{\mu}_1) \gtrsim 1\,\mathrm{fb}$
$[\sqrt{s} = 1\,\mathrm{TeV}]$

ILC can *probe* neutralino contribution to muon g-2

Test of SUSY Solution

Stage 1

discovery of SUSY particles necessary for SUSY contribution to muon g-2

→ ILC can *probe* neutralino contribution

Stage 2

reconstruct SUSY contribution to muon g-2 by information available at colliders (ILC)

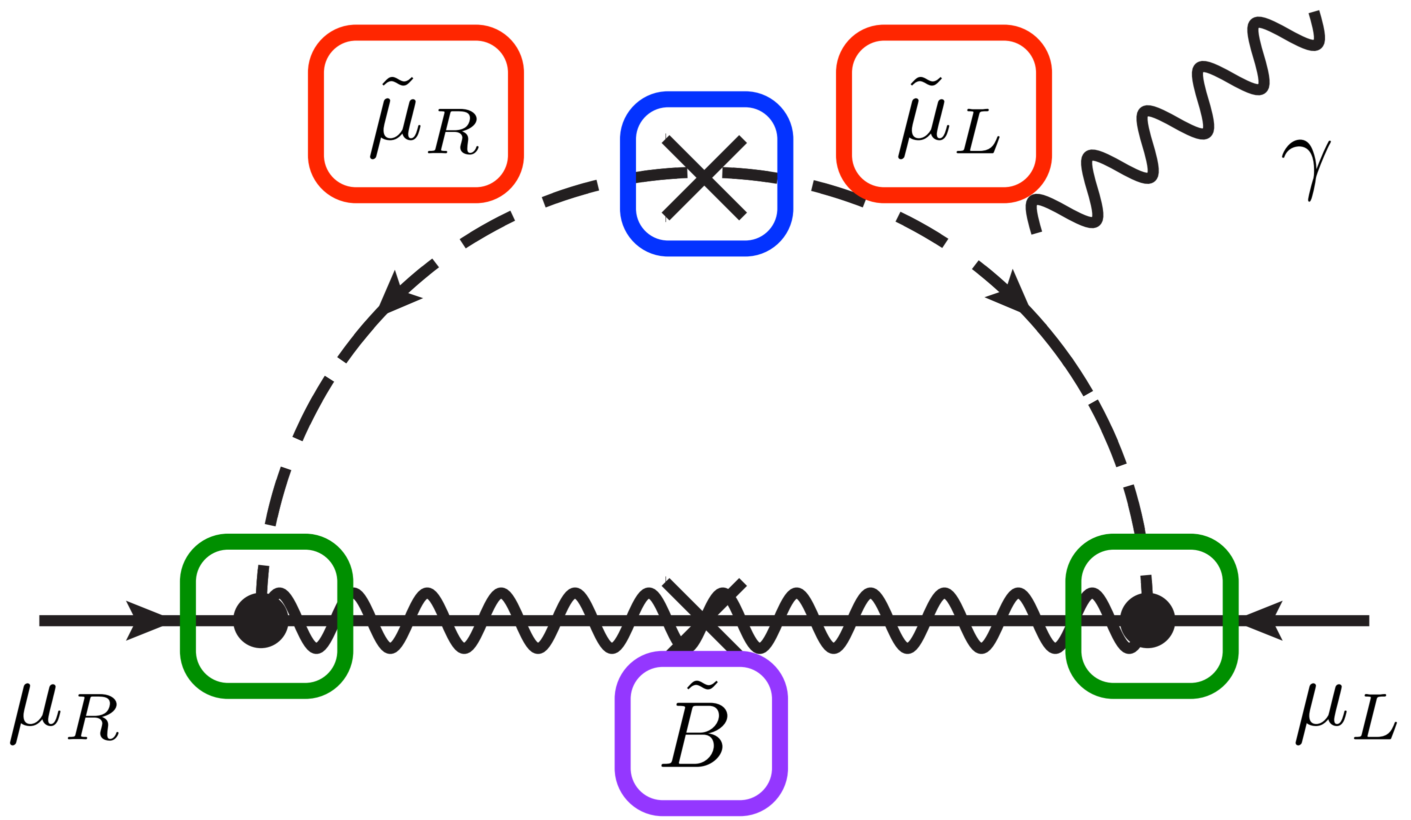
⇩

It is possible to *reconstruct* at ILC under some conditions

Reconstruction

Muon g-2 parameters

$$m_{\tilde{\mu}1},\ m_{\tilde{\mu}2},\ m^2_{\tilde{\mu}LR},\ m_{\tilde{\chi}^0_1},\ \tilde{g}^{(\mathrm{eff})}_{1,L},\ \tilde{g}^{(\mathrm{eff})}_{1,R}$$



Reconstruction

<u>Muon g-2 parameters</u>

$$m_{\tilde{\mu}1},\ m_{\tilde{\mu}2},\ m^2_{\tilde{\mu}LR},\ m_{\tilde{\chi}^0_1},\ \tilde{g}^{(\mathrm{eff})}_{1,L},\ \tilde{g}^{(\mathrm{eff})}_{1,R}$$

Reconstruct neutralino contribution:

$$a_\mu = \frac{1}{16\pi^2}\frac{m_\mu^2}{m_{\tilde{\mu}}^2}\left[-\frac{1}{12}\left[(\hat{N}^\mu_L)^2 + (\hat{N}^\mu_R)^2\right] F^N_1(x) - \frac{m_{\tilde{\chi}^0_1}}{3m_\mu}\hat{N}^\mu_L \hat{N}^\mu_R F^N_2(x)\right]$$

$$(\hat{N}^\mu_L)_i = \frac{1}{\sqrt{2}}\tilde{g}^{(\mathrm{eff})}_{1,L}(U_{\tilde{\mu}})_{iL}, \quad (\hat{N}^\mu_R)_i = -\sqrt{2}\tilde{g}^{(\mathrm{eff})}_{1,R}(U_{\tilde{\mu}})_{iR},$$

* Winos and Higgsinos are decoupled

Reconstruction

Parameter	Process	Result
$m_{\tilde{\mu}1},\ m_{\tilde{\mu}2},\ m_{\tilde{\chi}_1^0}$		
$m^2_{\tilde{\mu}LR}$		
$\tilde{g}^{(\text{eff})}_{1,L},\ \tilde{g}^{(\text{eff})}_{1,R}$		

Setup

Sample point

Parameters	$m_{\tilde{\ell}1}$	$m_{\tilde{\ell}2}$	$m_{\tilde{\tau}1}$	$m_{\tilde{\tau}2}$	$m_{\tilde{\chi}_1^0}$	$\sin\theta_{\tilde{\mu}}$	$\sin\theta_{\tilde{\tau}}$	$a_\mu^{(\mathrm{ILC})}$
Values	126	200	108	210	90	0.027	0.36	2.6×10^{-9}

$(\tilde{\ell} = \tilde{e},\ \tilde{\mu})$

* other SUSY particles [Wino,Higgsino,colored] are decoupled.

- All of selectrons, smuons and staus are within kinematical reach of ILC at $\sqrt{s} = 500\,\mathrm{GeV}$
- Close to SPS1a('): [left-handed sleptons are lighter]

  - avoid LHC/LEP limits

  - previous studies of ILC can be applied

Mass Measurement

Smuon and neutralino masses are measured precisely by studying endpoints or by threshold scans

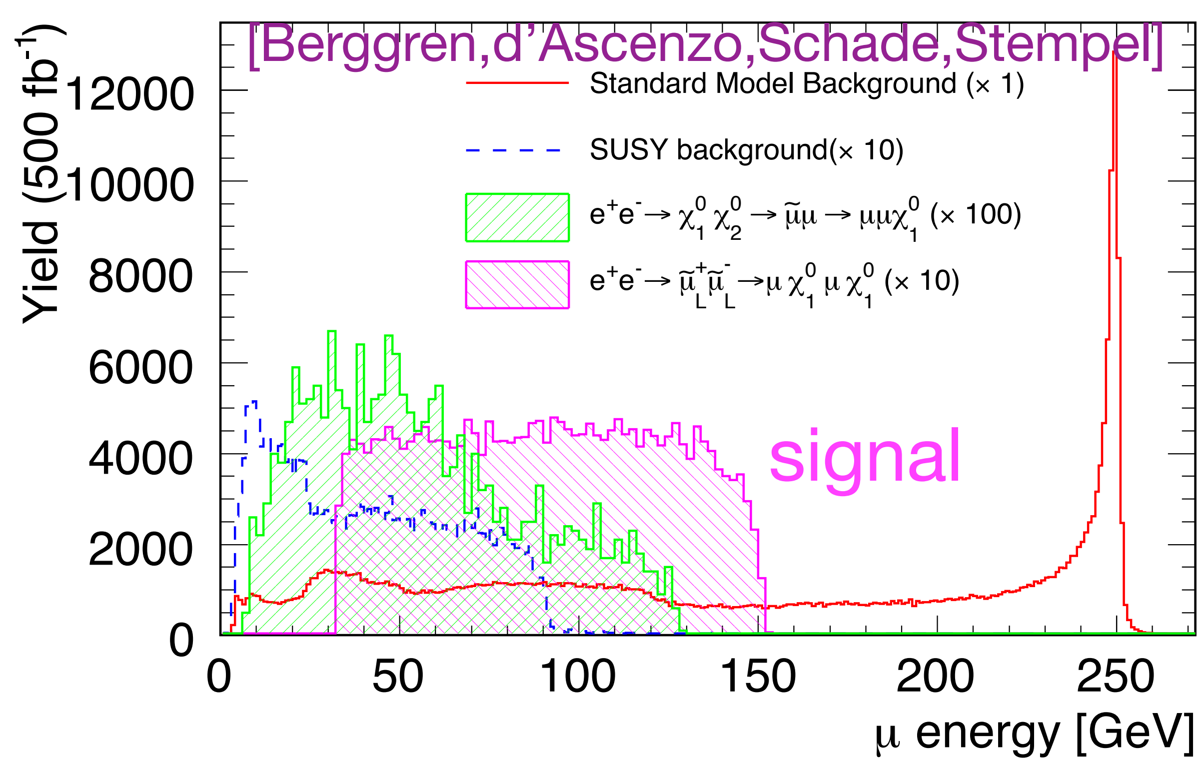
$$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-, \quad e^+e^- \to \tilde{e}^+\tilde{e}^-$$

Previous studies: SPS1a('), $\sqrt{s} = 400, 500\,\mathrm{GeV},\ \mathcal{L} = 200\text{–}500\,\mathrm{fb}^{-1}$

ILC can provide

$$\begin{cases} \delta m_{\tilde{\mu}1} \sim 200\,\mathrm{MeV} \\ \delta m_{\tilde{\mu}2} \sim 200\,\mathrm{MeV} \\ \delta m_{\tilde{\chi}_1^0} \sim 100\,\mathrm{MeV} \end{cases}$$

or better



Reconstruction

Parameter	Process	Result
$m_{\tilde{\mu}1},\ m_{\tilde{\mu}2},\ m_{\tilde{\chi}_1^0}$	$e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-$ $(\tilde{\ell} = \tilde{e},\ \tilde{\mu})$	very precise
$m^2_{\tilde{\mu}LR}$	too small to measure directly	
$\tilde{g}^{(\text{eff})}_{1,L},\ \tilde{g}^{(\text{eff})}_{1,R}$		

Smuon LR Mixing

smuon LR mixing parameter is measured by the relation:

$$m^2_{\tilde{\mu}LR} = \frac{m_\mu}{m_\tau} m^2_{\tilde{\tau}LR}, \quad m^2_{\tilde{\tau}LR} = \frac{1}{2}(m^2_{\tilde{\tau}1} - m^2_{\tilde{\tau}2}) \sin 2\theta_{\tilde{\tau}}$$

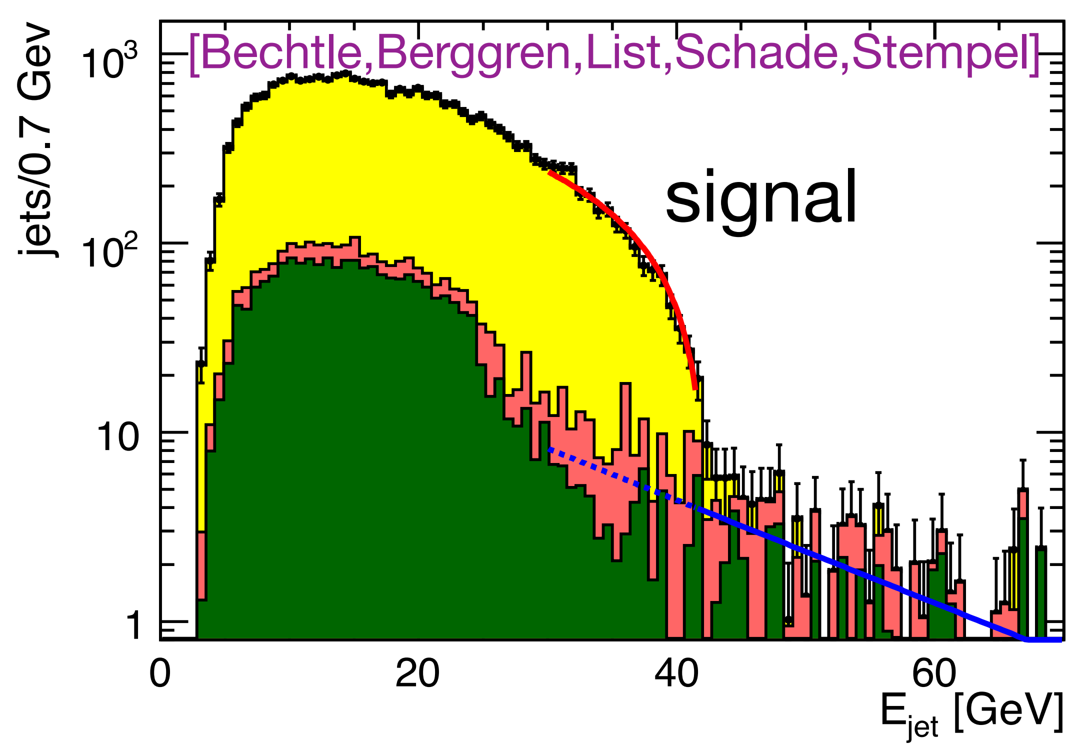
stau masses: endpoint of tau (-jet) energy

$$e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^-, \quad e^+e^- \to \tilde{\tau}_2^+\tilde{\tau}_2^-$$

$$\text{ILC} \begin{cases} \delta m_{\tilde{\tau}1}/m_{\tilde{\tau}1} \sim 0.1\,\% \\ \delta m_{\tilde{\tau}2}/m_{\tilde{\tau}2} \sim 3\,\% \end{cases}$$

Based on detailed study at SPS1a'

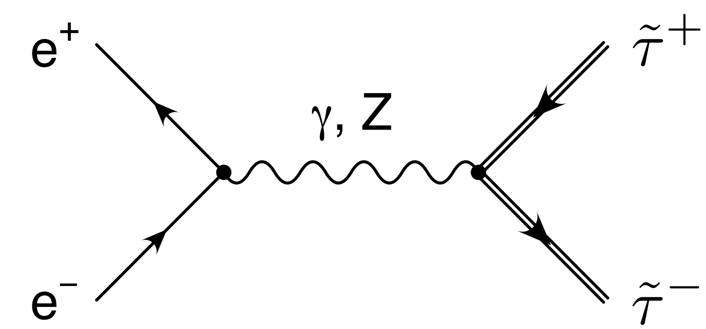
with $\sqrt{s} = 500\,\text{GeV},\ \mathcal{L} = 500\,\text{fb}^{-1}$



Smuon LR Mixing contd.

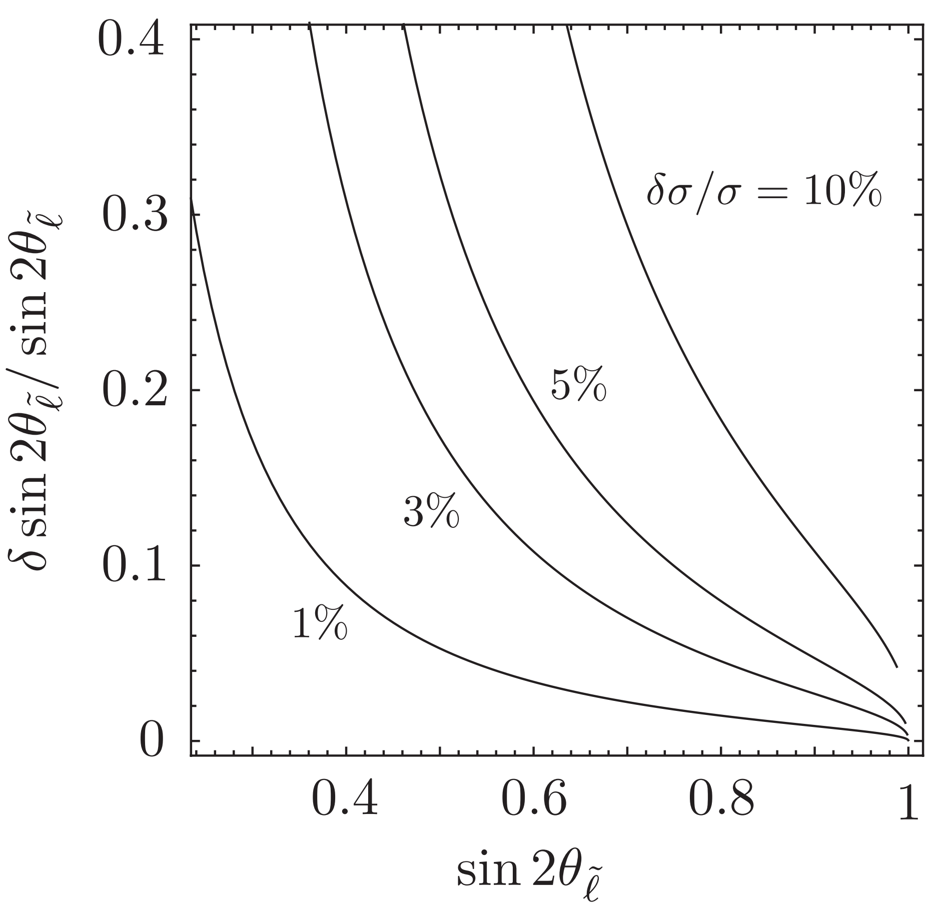
stau mixing angle: stau production cross section

Cross section depends on the angle via s-channel Z exchange



$$\sigma(e^+e^- \to \tilde{\tau}_1\tilde{\tau}_1^*) = \underbrace{\alpha}_{\gamma} + \underbrace{\beta \cos 2\theta_{\tilde{\tau}}}_{\text{Z-exchange}} + \cdots$$

Mixing angle is determined, once the cross section and the model point are given.



[ME,Hamaguchi,Iwamoto,Kitahara,Moroi]

Smuon LR Mixing contd.

stau mixing angle: stau production cross section

Based on detailed study at SPS1a' w/. $\sqrt{s} = 500\,\mathrm{GeV},\ \mathcal{L} = 500\,\mathrm{fb}^{-1}$
and with some discussions [Bechtle,Berggren,List,Schade,Stempel]

$$\delta\sigma(\tilde{\tau}_1)/\sigma(\tilde{\tau}_1) = 3.4\,\%$$

$$\longrightarrow \quad \delta \sin 2\theta_{\tilde{\tau}} / \sin 2\theta_{\tilde{\tau}} = 9\,\% \qquad \text{for } \sin 2\theta_{\tilde{\tau}} = 0.67$$

<u>As a result, stau production processes yield</u> [500fb^{-1}]

$$m^2_{\tilde{\mu}LR} = \frac{m_\mu}{m_\tau} m^2_{\tilde{\tau}LR} \longrightarrow \boxed{\delta m^2_{\tilde{\mu}LR}/m^2_{\tilde{\mu}LR} = 12\,\%}$$

Reconstruction

Parameter	Process	Result
$m_{\tilde{\mu}1},\ m_{\tilde{\mu}2},\ m_{\tilde{\chi}_1^0}$	$e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-$ $(\tilde{\ell} = \tilde{e},\ \tilde{\mu})$	very precise
$m^2_{\tilde{\mu}LR}$	$e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$ $[\tilde{\tau}_1^+\tilde{\tau}_1^-,\ \tilde{\tau}_2^+\tilde{\tau}_2^-]$	12% at model point
$\tilde{g}^{(\mathrm{eff})}_{1,L},\ \tilde{g}^{(\mathrm{eff})}_{1,R}$		

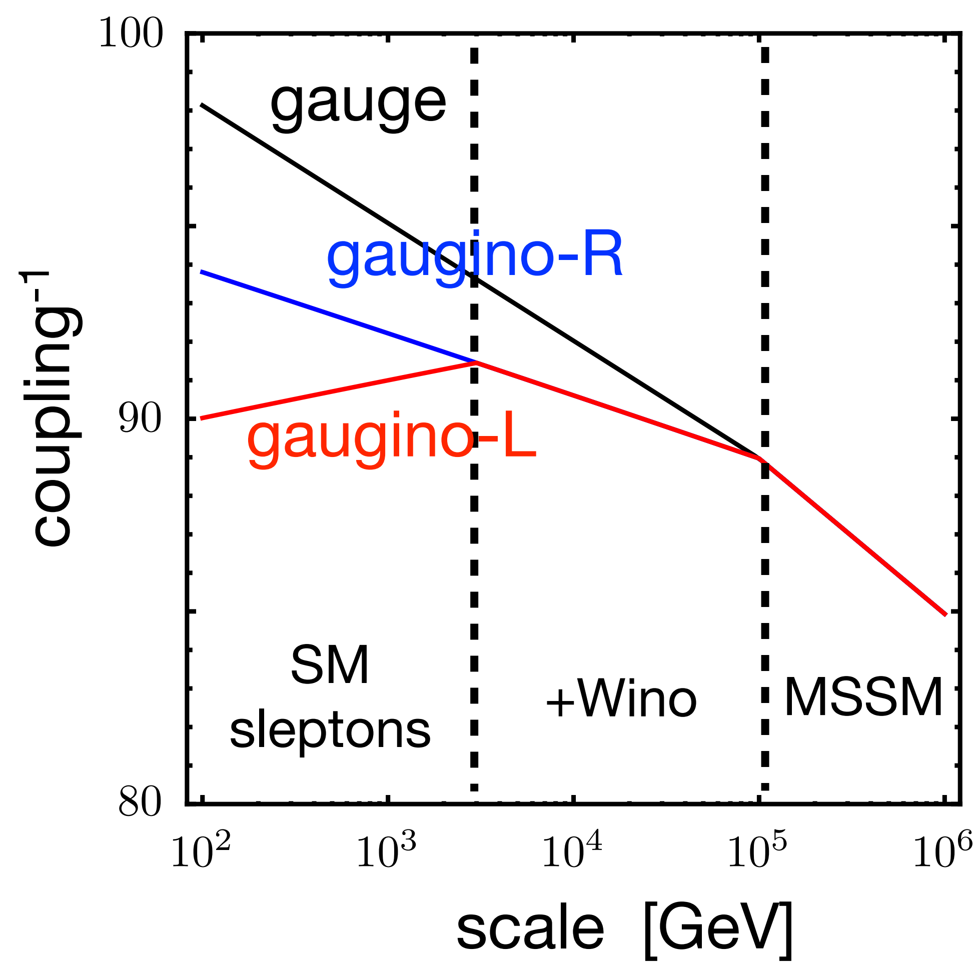
Gaugino Couplings

$$\mathcal{L}_{\rm int} = \bar{\chi}_1^0 \, (N_L P_L + N_R P_R) \, \ell \, \tilde{\ell}^\dagger + \text{h.c.}$$

$$N_L \equiv \frac{1}{\sqrt{2}} \, \tilde{g}_{1,L}^{(\rm eff)} (U_{\tilde{\ell}})_{iL}, \;\; N_R \equiv -\sqrt{2} \, \tilde{g}_{1,R}^{(\rm eff)} (U_{\tilde{\ell}})_{iR}$$

- LO is approximated by $U(1)_Y$ gauge coupling
- Deviate due to mixing with (heavy) Winos/Higgsinos and by radiative corrections

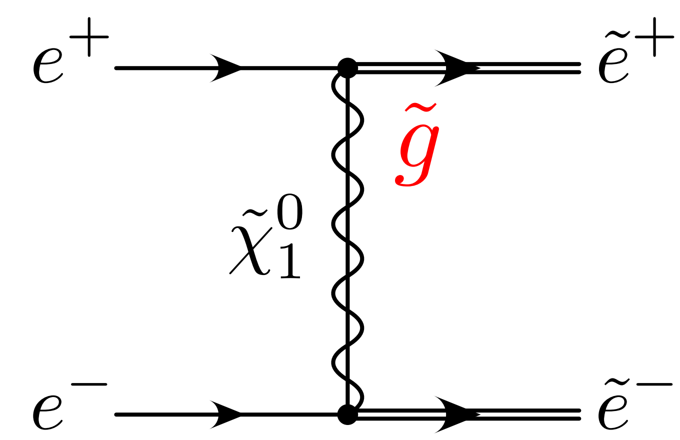
→ O(1-10)% correction



Gaugino Couplings

Selectron productions involve neutralino contributions

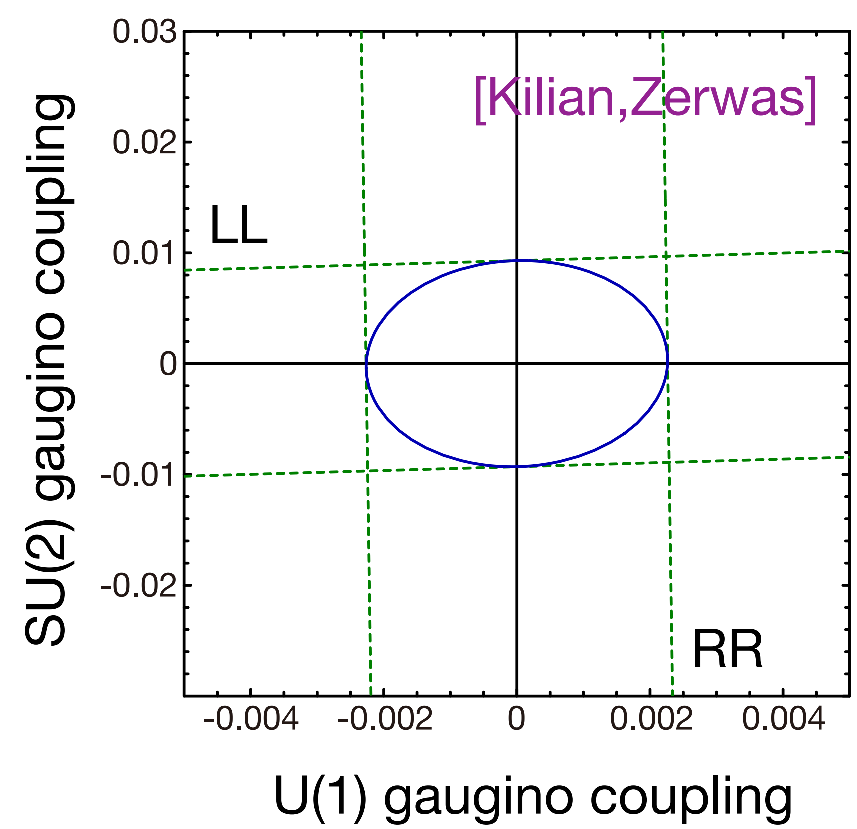
Right-handed coupling: $\tilde{g}_{1,R}^{(\mathrm{eff})}$



$$\sigma(e^+e^- \to \tilde{e}_R^+\tilde{e}_R^-) \sim (\tilde{g}_{1,R}^{(\mathrm{eff})})^4$$

Based on previous study at SPS1a
with $\sqrt{s} = 500\,\mathrm{GeV},\ \mathcal{L} = 500\,\mathrm{fb}^{-1}$
with discussions [Freitas,Manteuffel,Zerwas]

$$\delta\tilde{g}_{1,R}^{(\mathrm{eff})}/\tilde{g}_{1,R}^{(\mathrm{eff})} \lesssim 1\,\%$$



including contaminations from
(unobserved) Winos and Higgsinos

Gaugino Couplings

Left-handed coupling: $\tilde{g}_{1,L}^{(\mathrm{eff})}$

$$\sigma(e^+e^- \to \tilde{e}_L^+ \tilde{e}_R^-) \sim (\tilde{g}_{1,L}^{(\mathrm{eff})})^2 \ (\tilde{g}_{1,R}^{(\mathrm{eff})})^2$$

- Previous studies ignore the differences between left- and right-handed gaugino couplings.
- No info. of selectron LR production cross section.

$$\delta \tilde{g}_{1,L}^{(\mathrm{eff})} / \tilde{g}_{1,L}^{(\mathrm{eff})} = \mathrm{a\ few}\,\%\,(\mathrm{exp}) + 1\,\%\,(\mathrm{th})$$

exp: measurement of cross section
th: (unobserved) Winos, Higgsinos

For instance, $\delta\sigma(\tilde{e}_L\tilde{e}_R)/\sigma(\tilde{e}_L\tilde{e}_R) = 4\% \quad \to \quad \delta \tilde{g}_{1,L}^{(\mathrm{eff})} / \tilde{g}_{1,L}^{(\mathrm{eff})} = 2\%$

Reconstruction

Parameters	Processes	Result
$m_{\tilde{\mu}1},\ m_{\tilde{\mu}2},\ m_{\tilde{\chi}_1^0}$	$e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-$ $(\tilde{\ell} = \tilde{e},\ \tilde{\mu})$	very precise
$m^2_{\tilde{\mu}LR}$	$e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$ $[\tilde{\tau}_1^+\tilde{\tau}_1^-,\ \tilde{\tau}_2^+\tilde{\tau}_2^-]$	12% at model point
$\tilde{g}_{1,L}^{(\mathrm{eff})},\ \tilde{g}_{1,R}^{(\mathrm{eff})}$	$e^+e^- \to \tilde{e}^+\tilde{e}^-$ $[\tilde{e}_R^+\tilde{e}_R^-,\ e_L^+\tilde{e}_R^-]$	O(1)%

Reconstruction at ILC

Neutralino contribution to muon g-2 is reconstructed by measuring all the sleptons

$$\delta a_\mu^{(\mathrm{ILC})}/a_\mu^{(\mathrm{ILC})} \simeq 13\,\%$$

at the sample point with $\sqrt{s} = 500\,\mathrm{GeV},\ \mathcal{L} \sim 500\mathrm{fb}^{-1}$

[ME,Hamaguchi,Iwamoto,Kitahara,Moroi]

Comments

- Effects of (heavy) Winos and Higgsinos
  - Direct contributions to muon g-2
  - No signals in future LHC can reduce uncertainties
- Largest uncertainty is from smuon LR mixing
  - Relation between smuon and stau LR mixings can be affected by slepton trilinear couplings (A-terms)
    → a few percents if A-term ~ slepton masses
  - $\sigma(\tilde{\tau}_1 \tilde{\tau}_2)$ is very sensitive to the stau mixing angle, though there are no such studies.

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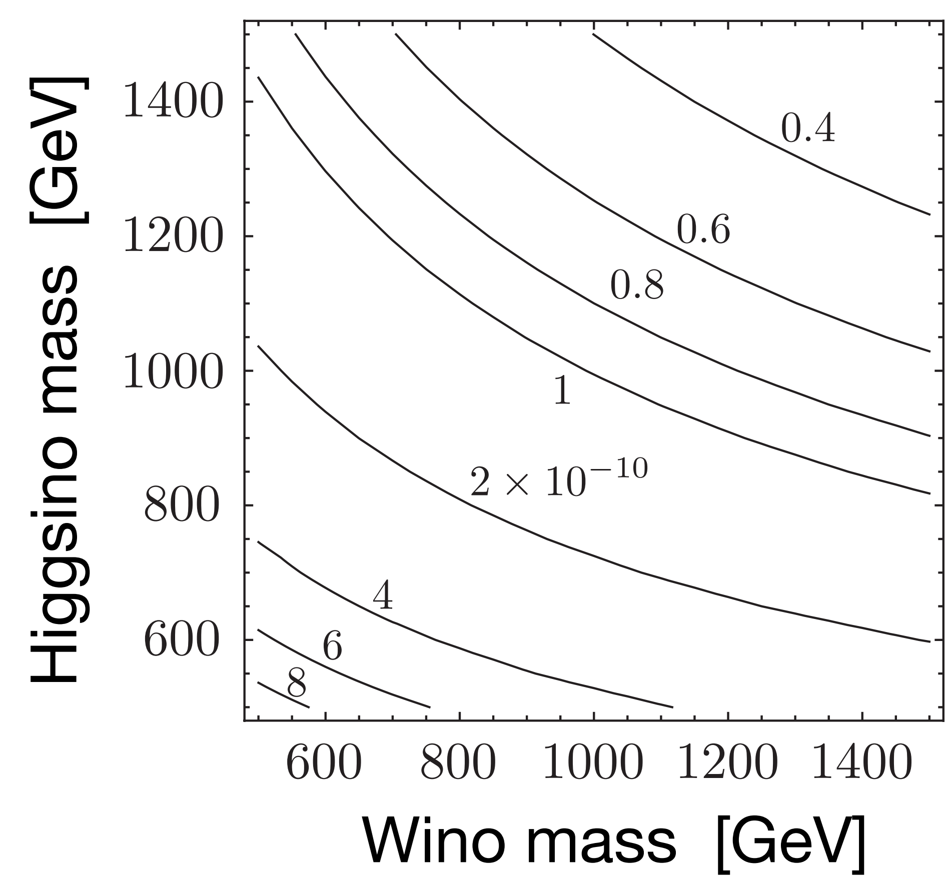
Extra contribution
to muon g-2, Δa_μ

[Winos, Higgsinos]



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Summary

- Muon g-2 has >3σ deviation between SM prediction and experimental value.
- SUSY is a good candidate to solve the anomaly.
- We discussed how to test the SUSY contributions.

✓ Neutralino contribution can be probed at ILC.

  - Sleptons are within kinematical reach.
  - It is possible to reconstruct the contribution, if all the sleptons (selectrons, smuons and staus) are measured.

$\longrightarrow \quad \delta a_\mu^{(\mathrm{ILC})} / a_\mu^{(\mathrm{ILC})} \simeq 13\,\%$ at the sample point