Probing SUSY Contributions to Muon g-2 at LHC and ILC

Motoi Endo (Tokyo)

Based on papers in collaborations with
ME, Hamaguchi, Iwamoto, Yoshinaga
ME, Hamaguchi, Kitahara, Yoshinaga
ME, Hamaguchi, Iwamoto, Kitahara, Moroi

"Particle Physics and Cosmology after the Discovery of Higgs Boson," 2013.10.21-25, Tohoku

Muon g-2

Search for BSM based on experimental anomalies

<u>Magnetic moment</u>

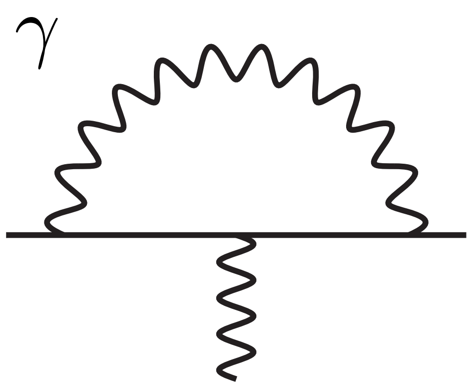
$$\mathcal{H} = -\vec{\mu} \cdot \vec{B}, \qquad \vec{\mu} = g \left(\frac{e}{2m}\right) \vec{S}$$

<u>g-factor</u>

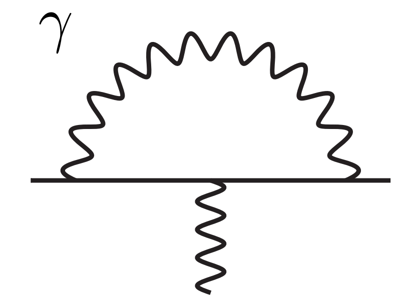
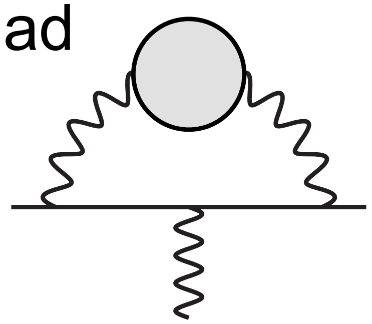
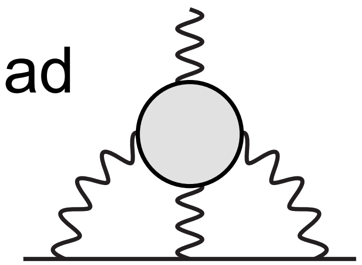
✓ g = 2 at tree level (Dirac equation)

✓ g ≠ 2 by radiative corrections

$$\rightarrow \qquad a = (g-2)/2$$



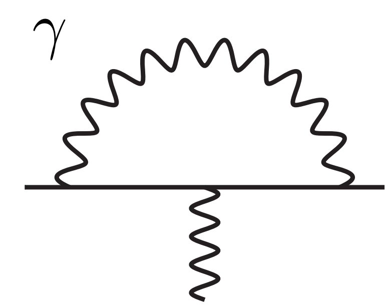
Status of Muon g-2

Experiment (E821)		116 592 089	(63) $[10^{-11}]$	
QED (α^5, Rb)		116 584 718.951	(0.080)	
EW (W/Z/H_{SM}, NLO)		153.6	(1.0)	
Hadronic (leading)	[HLMNT]	6 949.1	(43)	
	[DHMZ]	6 923	(42)	
Hadronic (α higher)		-98.4	(0.7)	
Hadronic (LbL)	[RdRV]	105	(26)*	
	[NJN]	116	(39)	

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = \begin{cases} (261 \pm 80) \times 10^{-11} \\ (287 \pm 80) \times 10^{-11} \end{cases}$$

> 3σ deviation

Status of Muon g-2

Contribution		Value	Error	Diagram
Experiment (E821)		116 592 089	(63) $[10^{-11}]$	
QED (α^5, Rb)		116 584 718.951	(0.080)	
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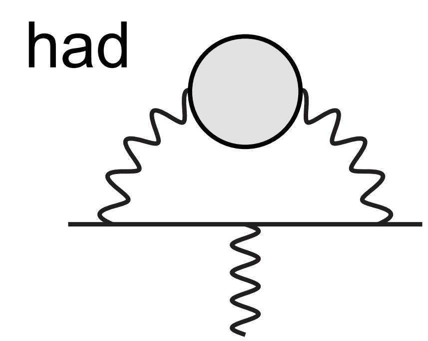
Hadronic (leading)	[HLMNT]	6 949.1	(43)	
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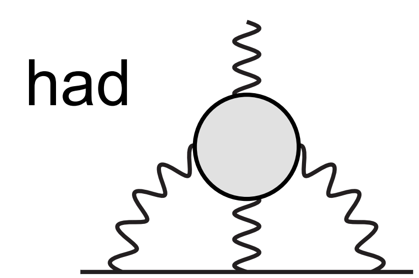
Hadronic (LbL)	[RdRV]	105	(26)*	
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$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = \begin{cases} (261 \pm 80) \times 10^{-11} \\ (287 \pm 80) \times 10^{-11} \end{cases}$$

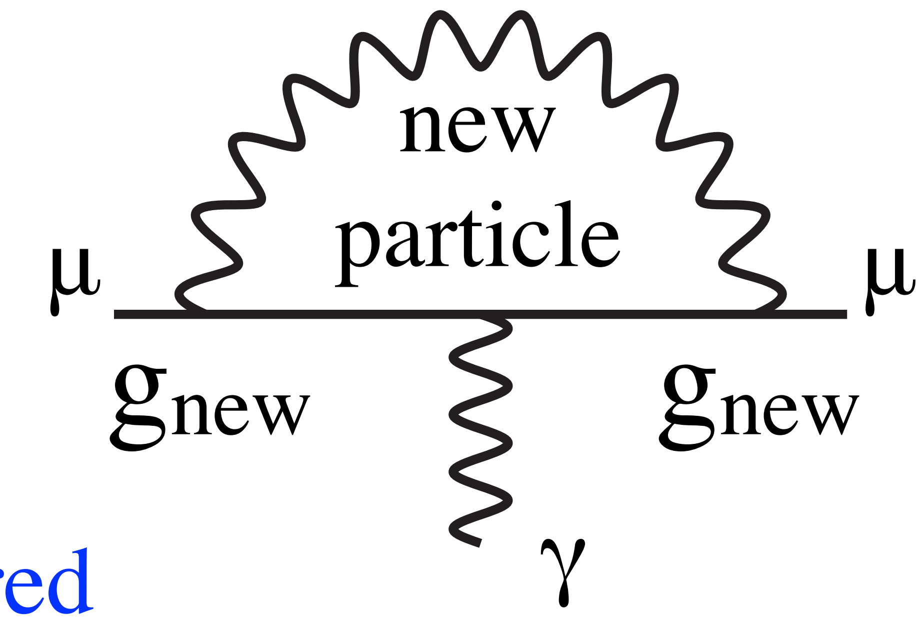
> 3σ deviation

New Physics Contribution

$$\Delta a_\mu \sim \frac{g_{new}^2}{16\pi^2} \frac{(\text{muon mass} \sim 106\text{MeV})^2}{(\text{new particle mass})^2}$$

Discrepancy (~EW) is explained

- g_{new} ~ W boson coupling
- m_{new} ~ W boson mass



No such particles have been discovered

New Physics Contribution

$$\Delta a_\mu \sim \frac{g_{new}{}^2}{16\pi^2} \frac{(\text{muon mass} \sim 106\text{MeV})^2}{(\text{new particle mass})^2}$$

- weak interaction, small mass

  e.g. heavy photon model (~10-100MeV)

- strong interaction, large mass

  → Supersymmetry (~100GeV)

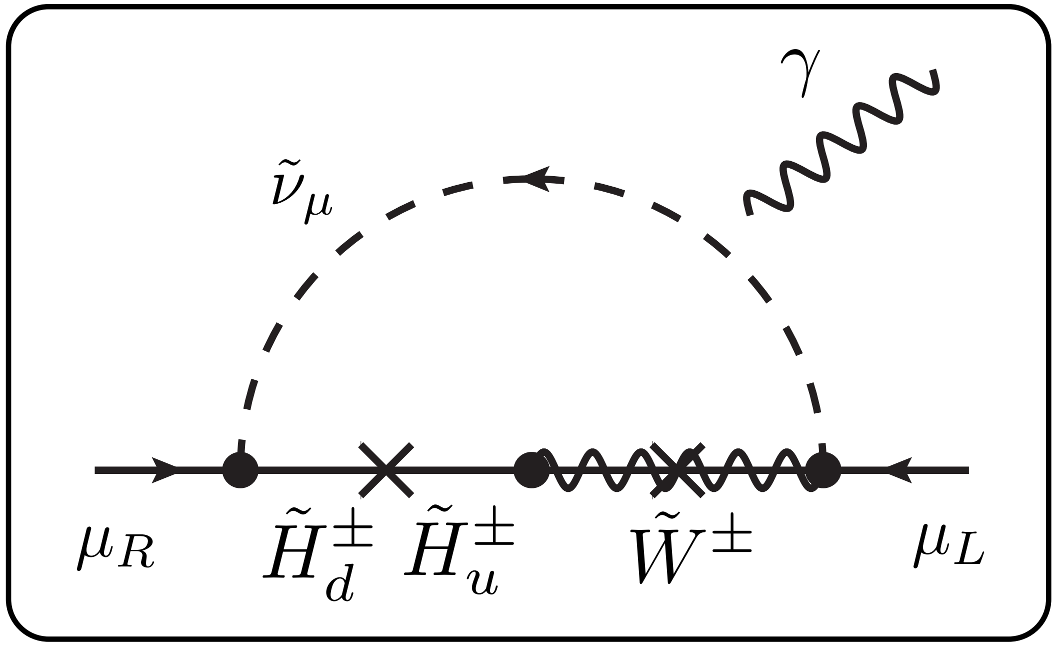
Today's subject: Test of SUSY solution at colliders

Outline

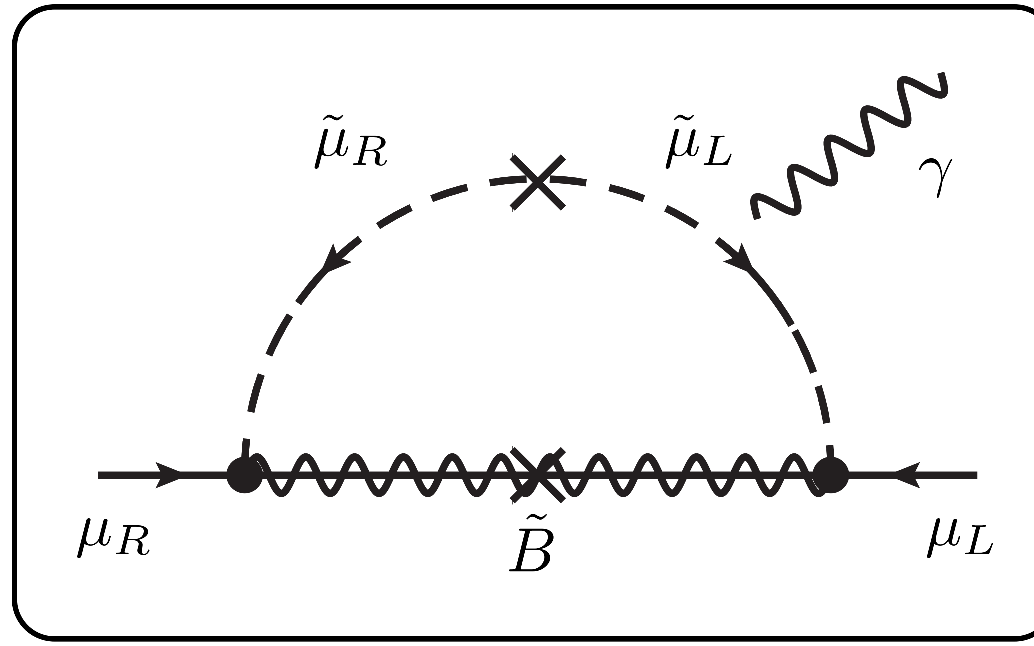
- Status of muon g-2
  - more than 3σ deviation between SM and Exp.
  - can be a sign of low-scale SUSY
- Probing SUSY contributions to muon g-2
  - types of contributions
  - probing the contributions at LHC and ILC
- Summary

Two Types of Contributions

chargino-muon sneutrino



neutralino-smuon

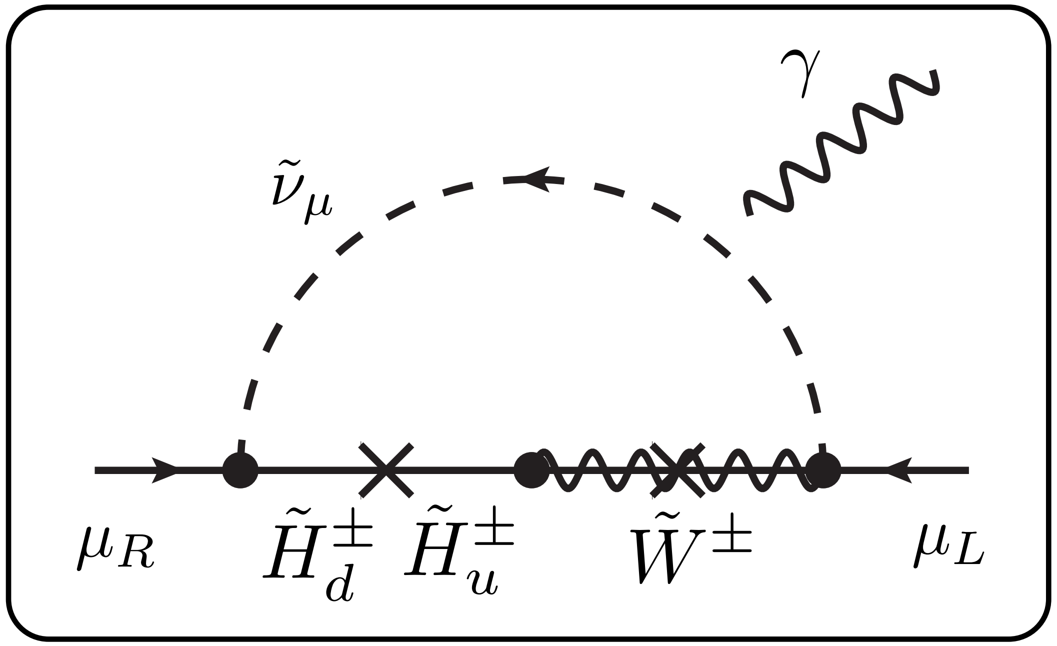


$$a_\mu(\mathrm{SUSY}) \sim \frac{\alpha_2(\alpha_Y)}{4\pi}\frac{m_\mu^2}{m_{\mathrm{soft}}^2}\tan\beta \qquad (\tan\beta \sim 10)$$

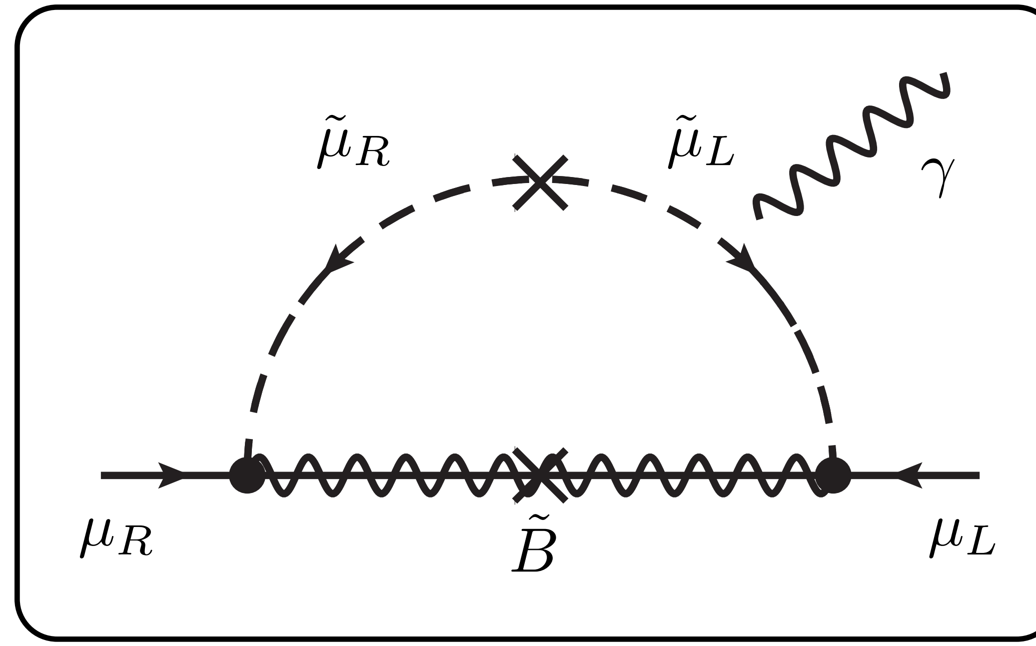
Enhanced by tanβ: $m_{\mathrm{soft}}^2 = \mathcal{O}(100)\mathrm{GeV}$

Two Types of Contributions

chargino-muon sneutrino



neutralino-smuon



light particles
✓ muon sneutrino (smuon)
✓ Wino, Higgsino
large tanβ

light particles
✓ L- and R-smuons
✓ Bino
large smuon LR mixing

"SUSY solution" can be tested, if these particles are discovered

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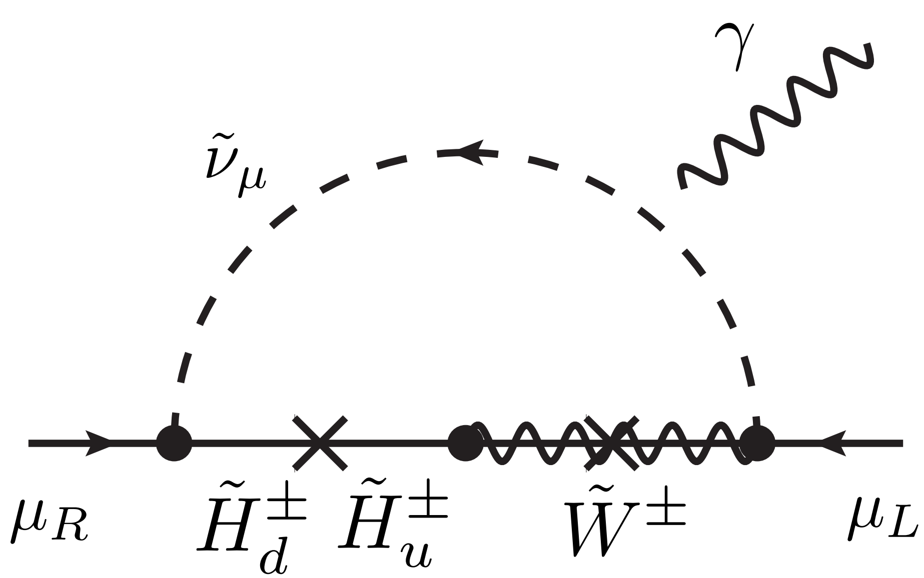
- Status of muon g-2
  - more than 3σ deviation between SM and Exp.
  - can be a sign of low-scale SUSY
- Probing SUSY contributions to muon g-2
  - ▸ types of contributions
  - ▸ probe: status, prospect
    - chargino type
    - neutralino type
- Summary

1. Probing Chargino Contributions



light particles

✓ muon sneutrino (smuon)

✓ Wino, Higgsino

[ME, Hamaguchi, Iwamoto, Yoshinaga]

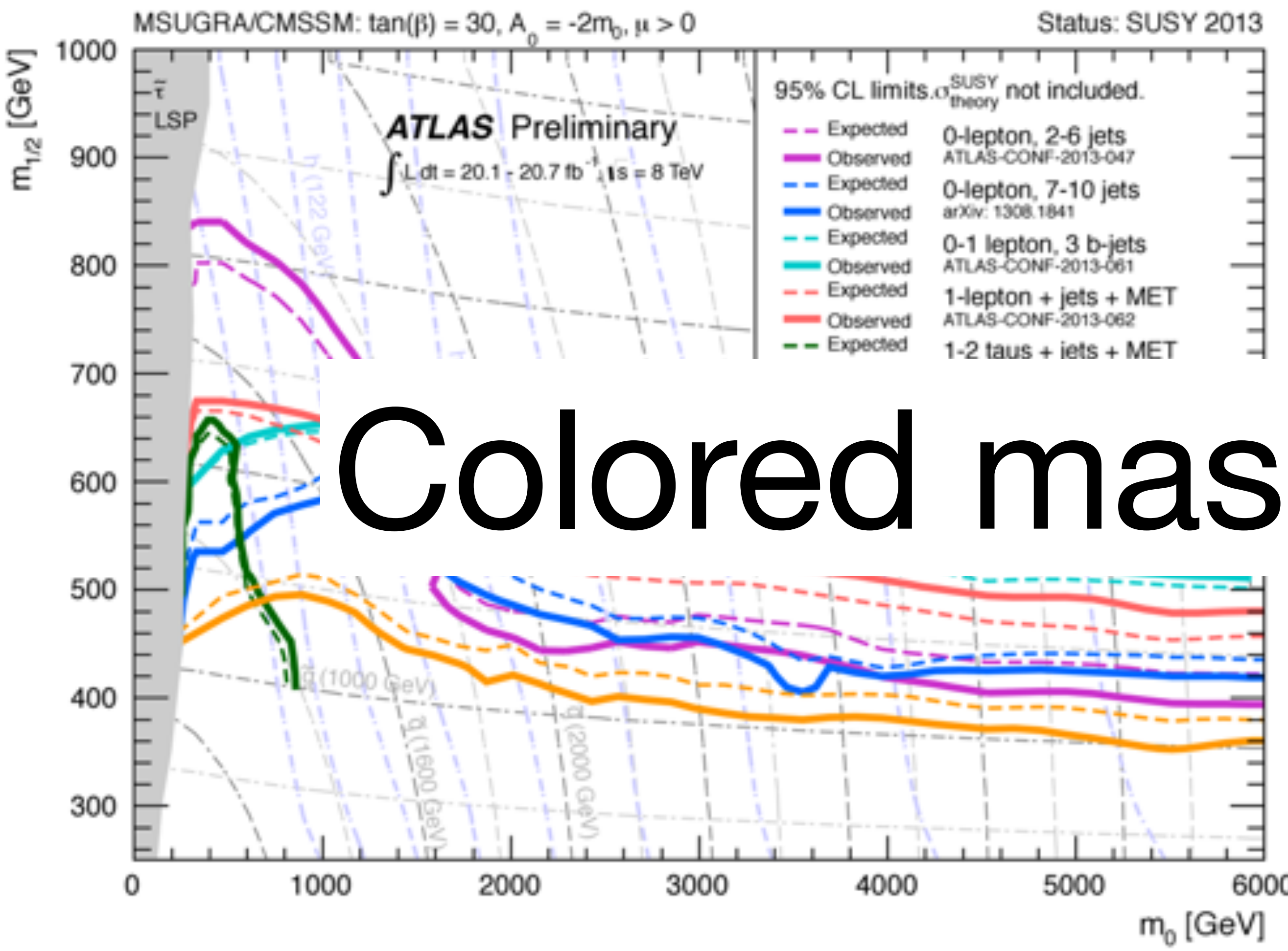
Mass Spectrum

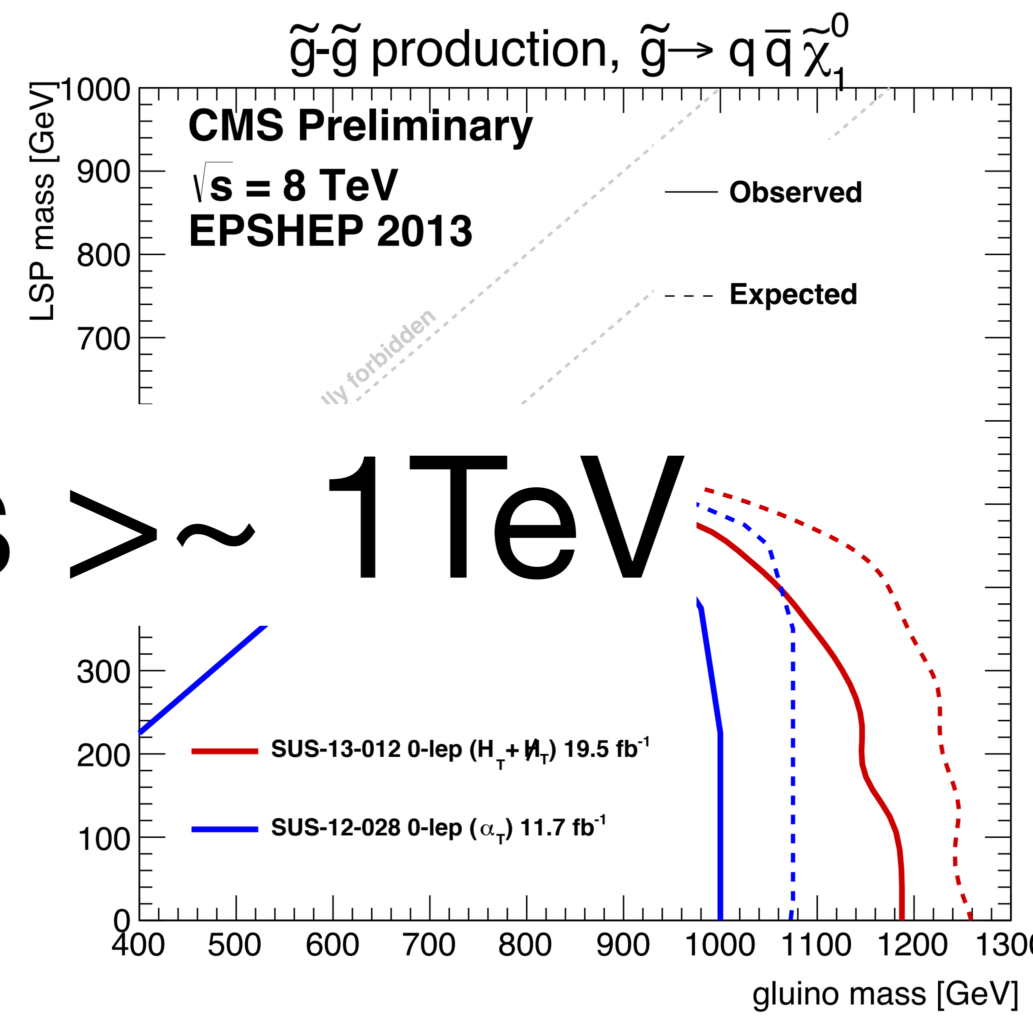
Chargino contributions are sizable:

- light: smuon, Wino, Higgsino + Bino (LSP)
- large $\tan\beta$ (= 40)
- * other SUSY particles are heavy (decoupled)

consistent with

multi-jet search at LHC, Higgs boson mass





Colored mass >~ 1TeV

consistent with

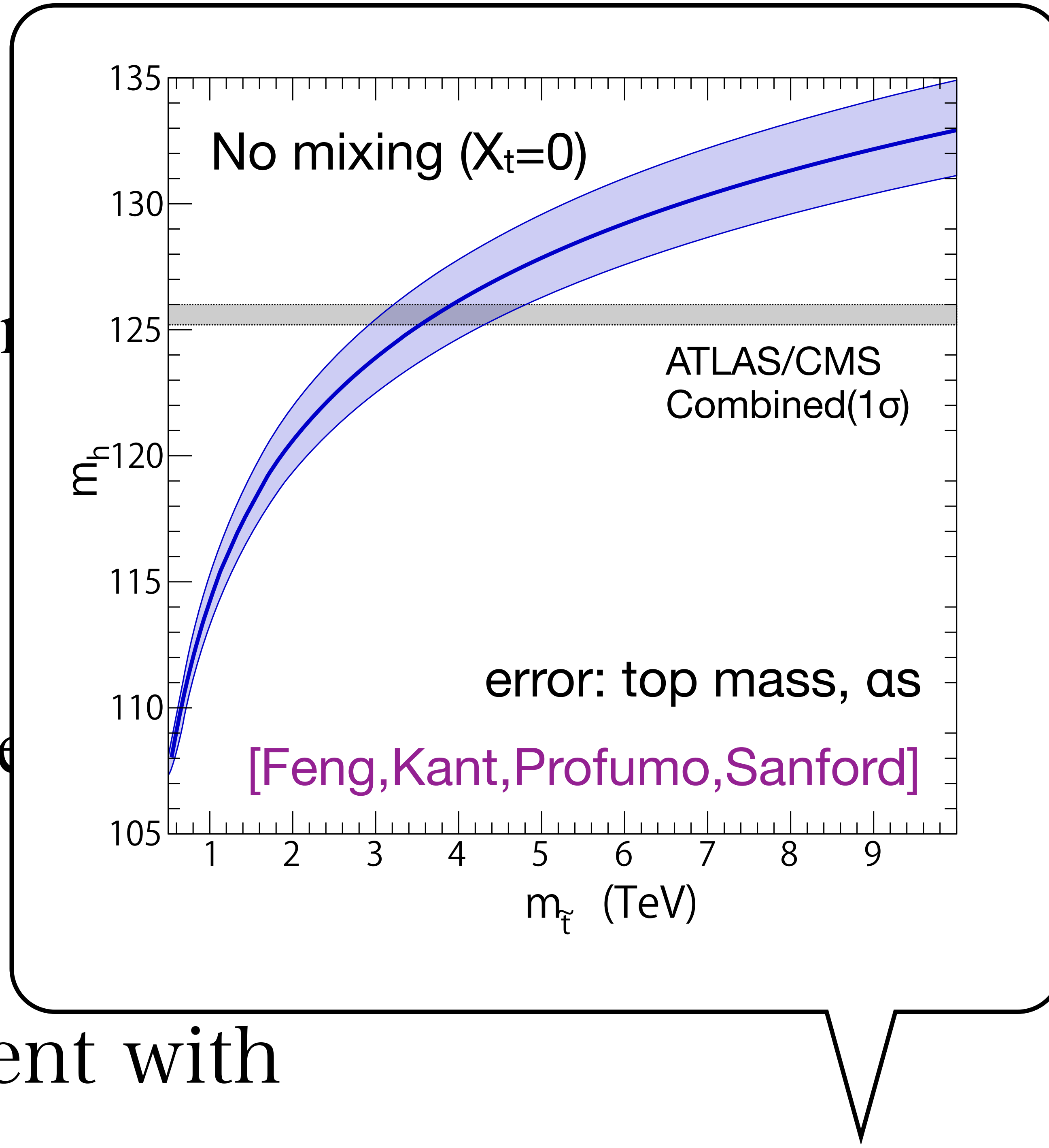
multi-jet search at LHC, Higgs boson mass

Chargino co[…]

light: […] LSP)

large […]

* othe[…] upled)



consistent with

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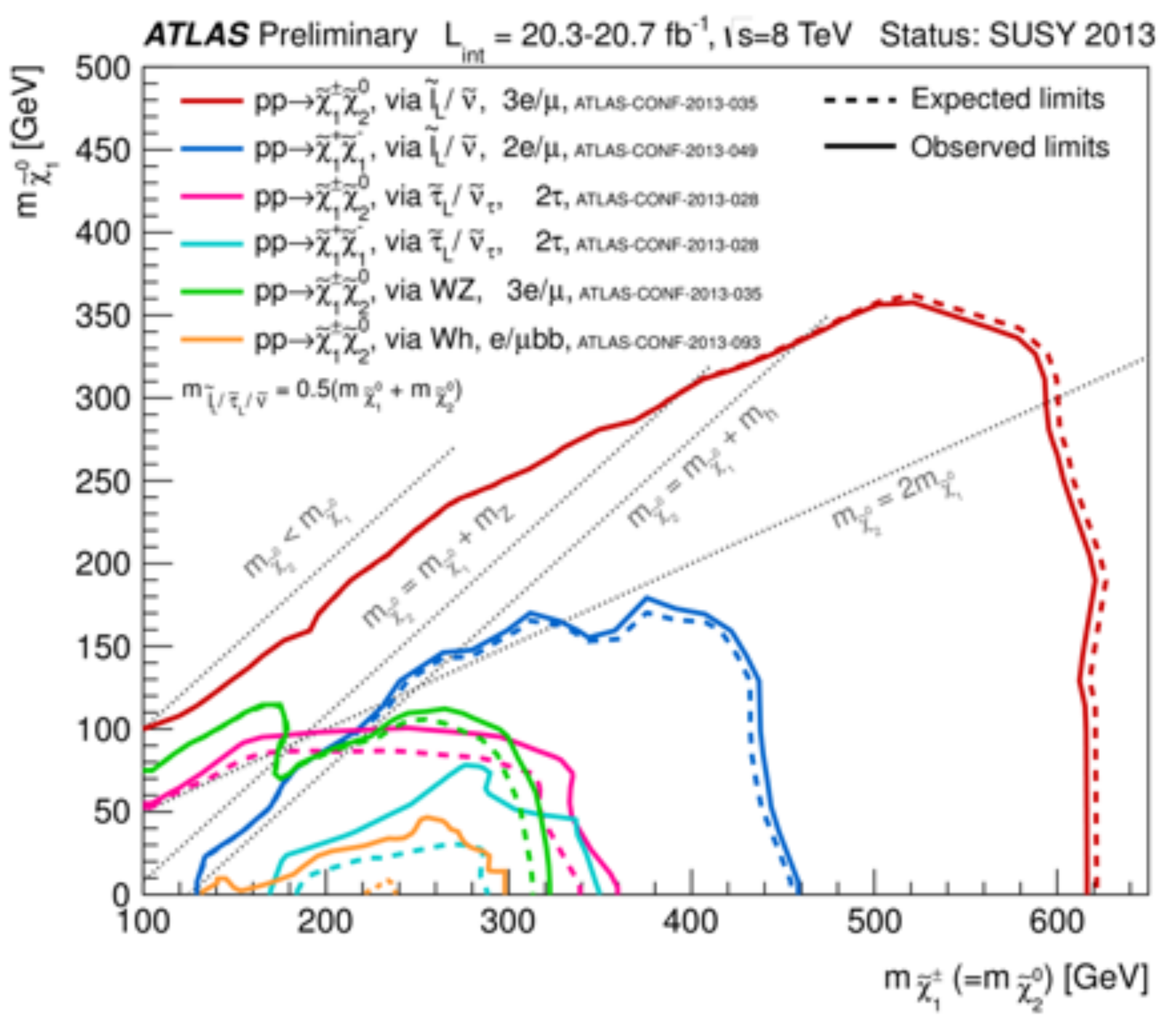
consistent with

multi-jet search at LHC, Higgs boson mass

Mass Spectrum

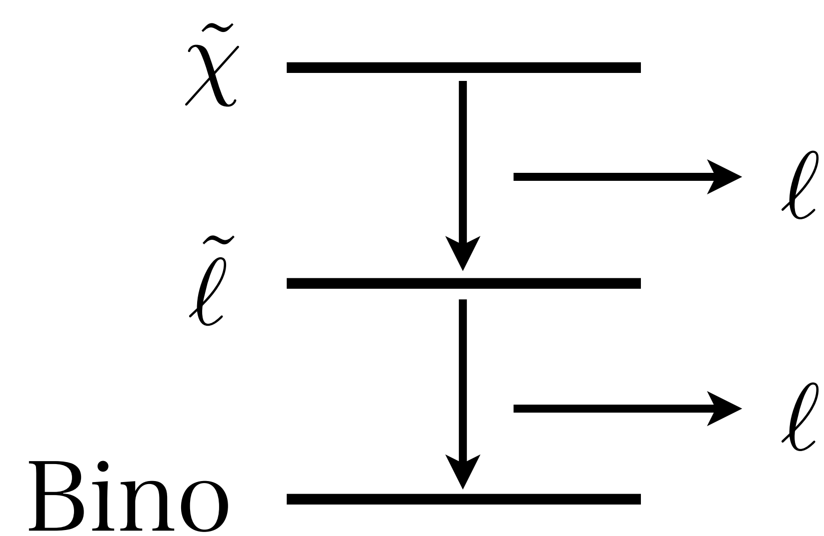
Chargino contributions are sizable: “EWKino” search

light: smuon, Wino, Higgsino + Bino (LSP)



multi-lepton signature

$$pp \to \tilde{\chi}\tilde{\chi} \to \ell\tilde{\ell}\,\ell\tilde{\ell} \to \ell\ell\tilde{\chi}\,\ell\ell\tilde{\chi}$$

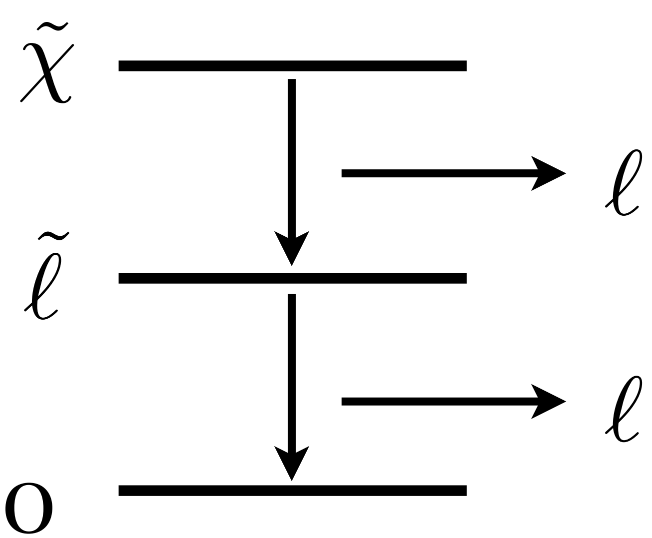


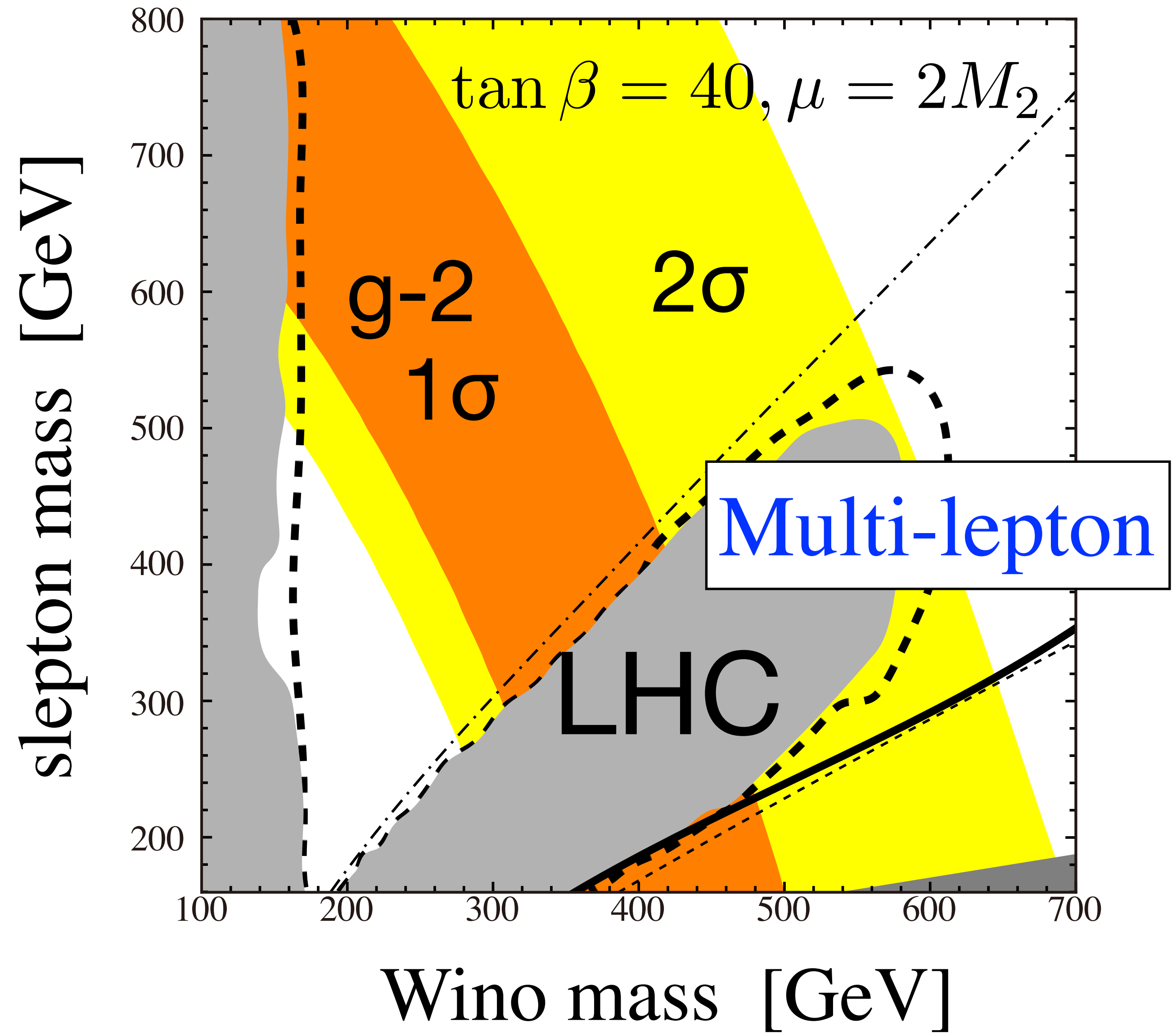
LHC: Chargino Type [status]

Multi-lepton signature:

sleptons lighter than Winos

Wino three-body decays





ATLAS 3 leptons + MET
[ATLAS-CONF-NOTE-2012-154]

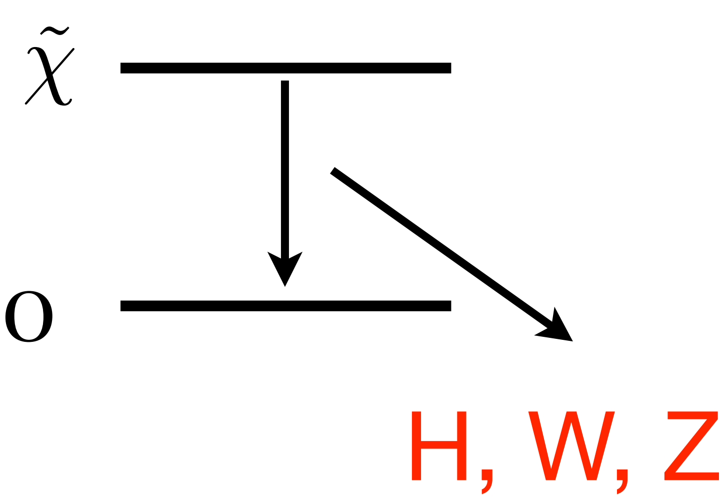
[Endo,Hamaguchi,Iwamoto,Yoshinaga]

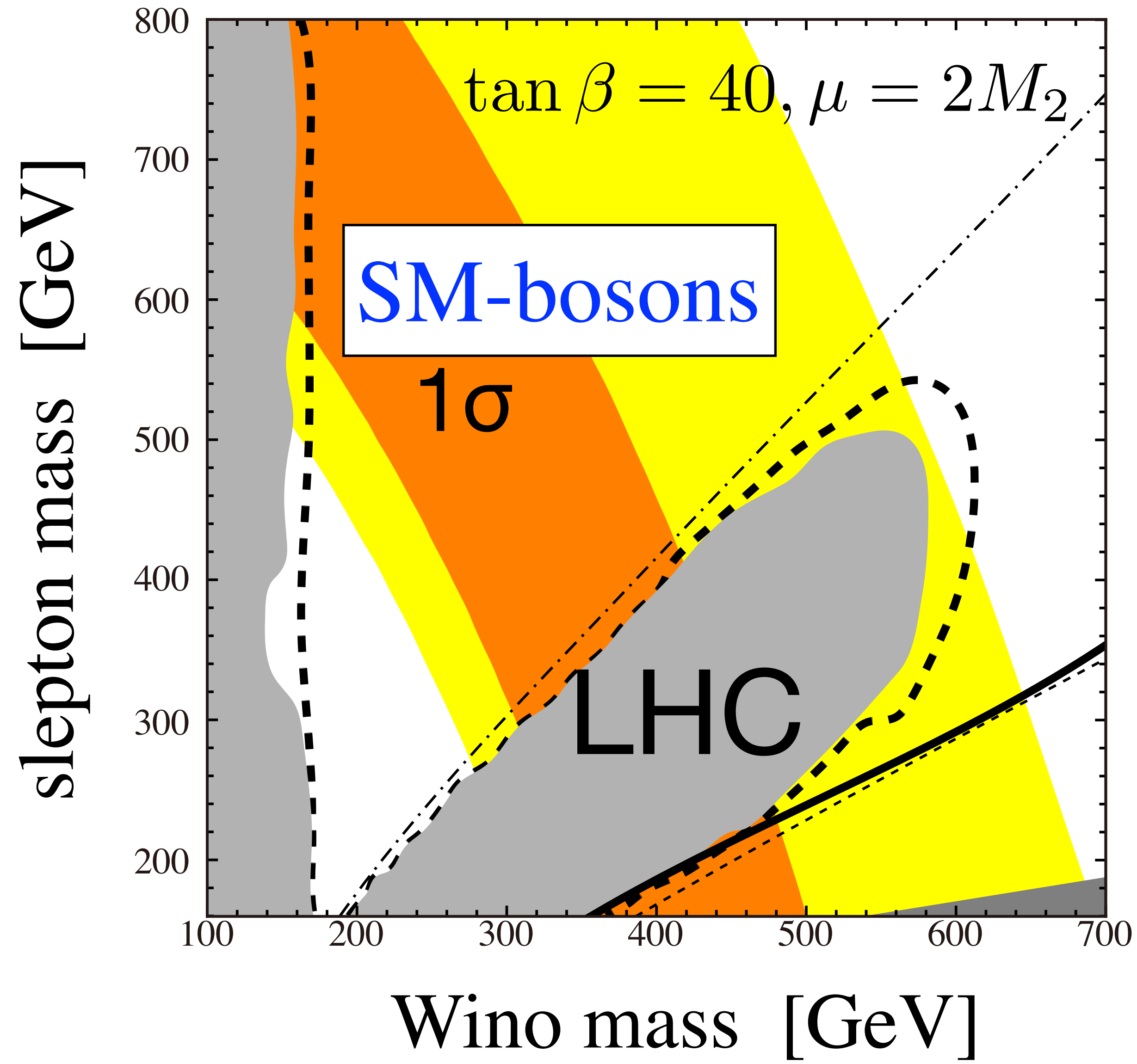
LHC: Chargino Type [status]

SM-boson signatures:

sleptons heavier than Winos

currently very weak





ATLAS-CONF-2013-035, 093

CMS-PAS-SUS-13-017

[Endo,Hamaguchi,Iwamoto,Yoshinaga]

LHC: Chargino Type [prospect]

Multi-lepton:

most sensitive

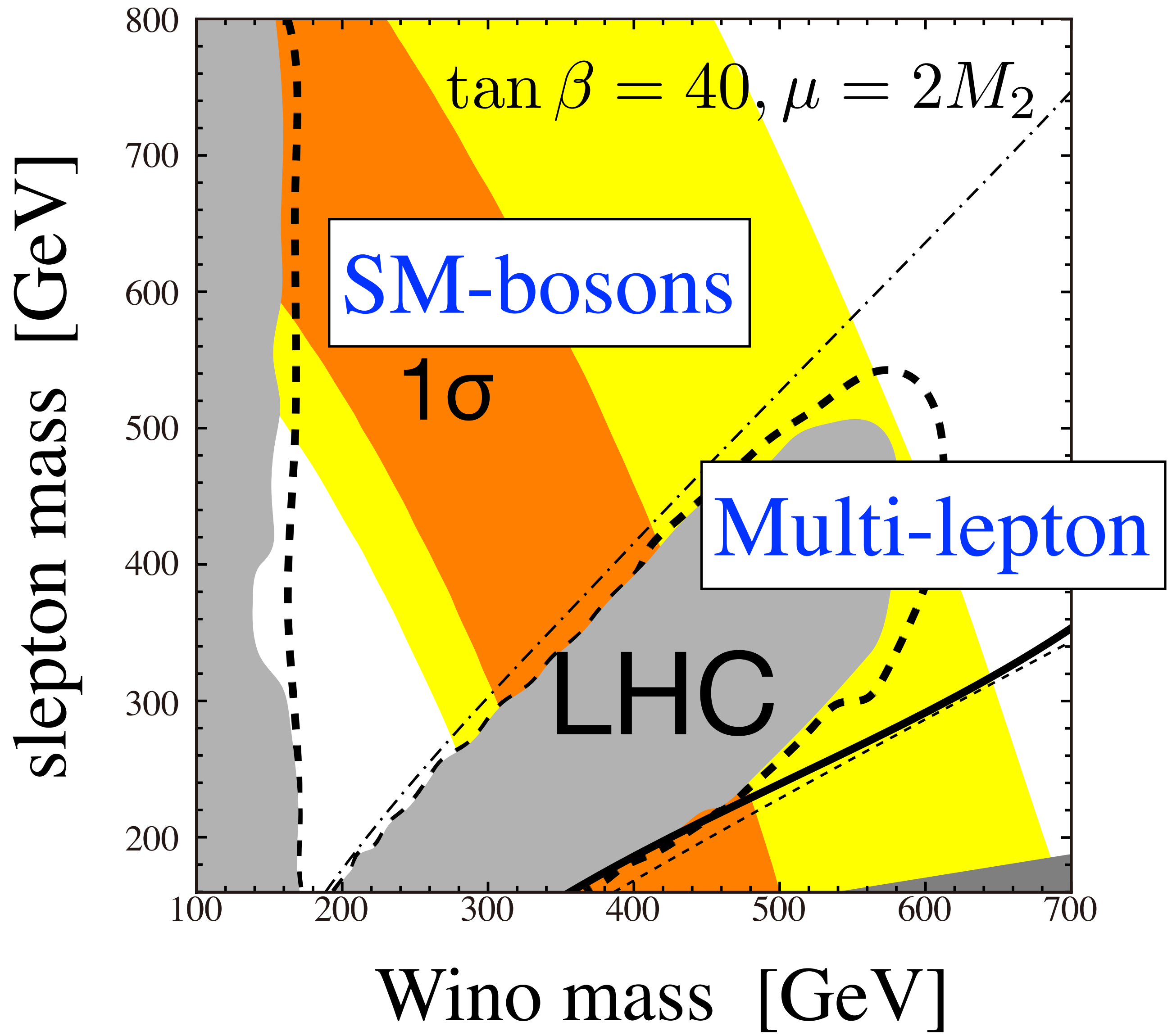
(expect) improved well

SM-bosons:

Wh: Wino, Higgsino mass
~ 250-400GeV
at 14TeV, 300fb^{-1}
[Berggren,et.al., 1309.7342]

WZ: Wino mass ~ 800GeV
(1TeV) for 300(3000)fb^{-1}

[ATLAS-PHYS-PUB-2013-007
,CMS-NOTE-13-002]



[Endo,Hamaguchi,Iwamoto,Yoshinaga]

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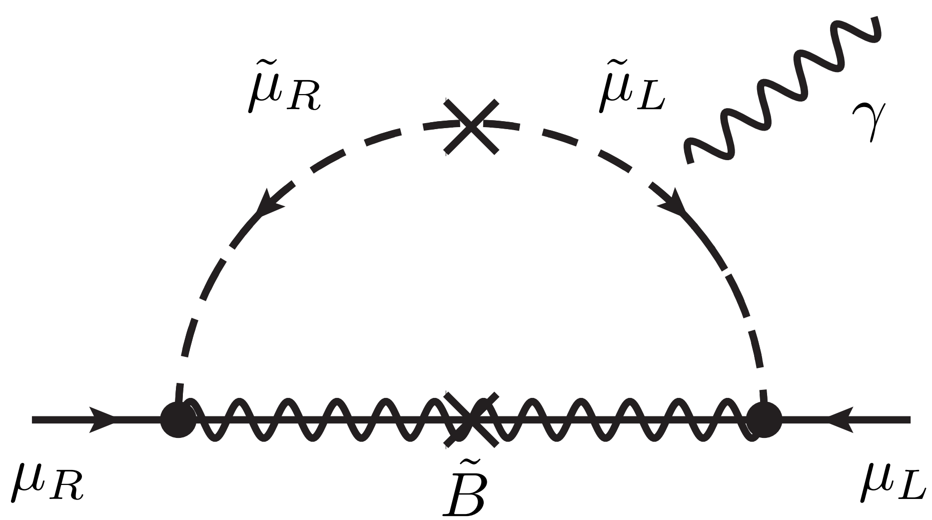
  - types of contributions
  - probe: status, prospect
    - chargino type: LHC w/ multi-lepton, SM bosons
    - neutralino type
- Summary

2. Probing Neutralino Contributions



light particles

✓ L- and R-smuons

✓ Bino

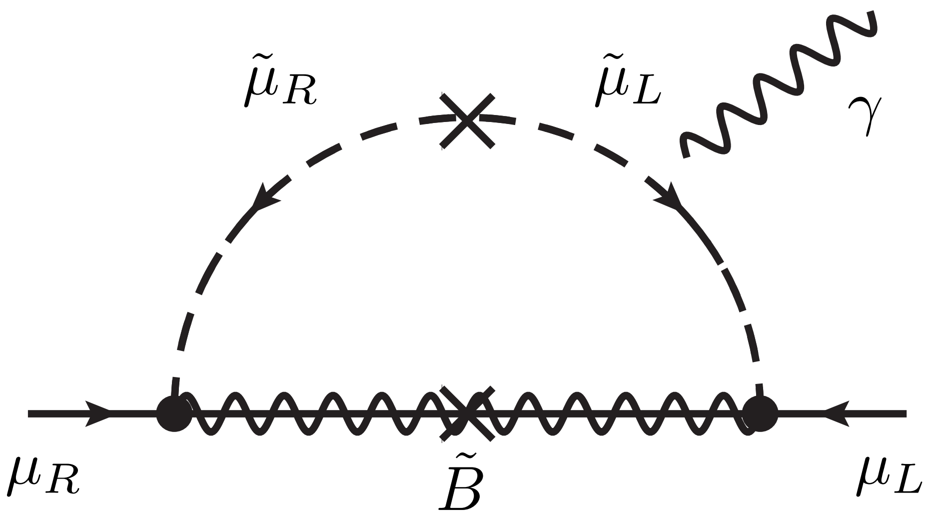
large smuon LR mixing

[ME, Hamaguchi, Kitahara, Yoshinaga,
ME, Hamaguchi, Iwamoto, Kitahara, Moroi]

Mass Spectrum

Neutralino contributions are sizable:

- light: left- and right-handed smuons, Bino
- large LR mixing parameter (∝ μ tanβ)
- * other SUSY particles (Winos, Higgsinos) are heavy



$$a_\mu(\tilde{B}) \simeq \frac{\alpha_Y}{24\pi}\frac{m_\mu^2}{m_{\rm soft}^3}\,\mu\tan\beta$$

consistent w/ multi-jet search at LHC, Higgs boson mass

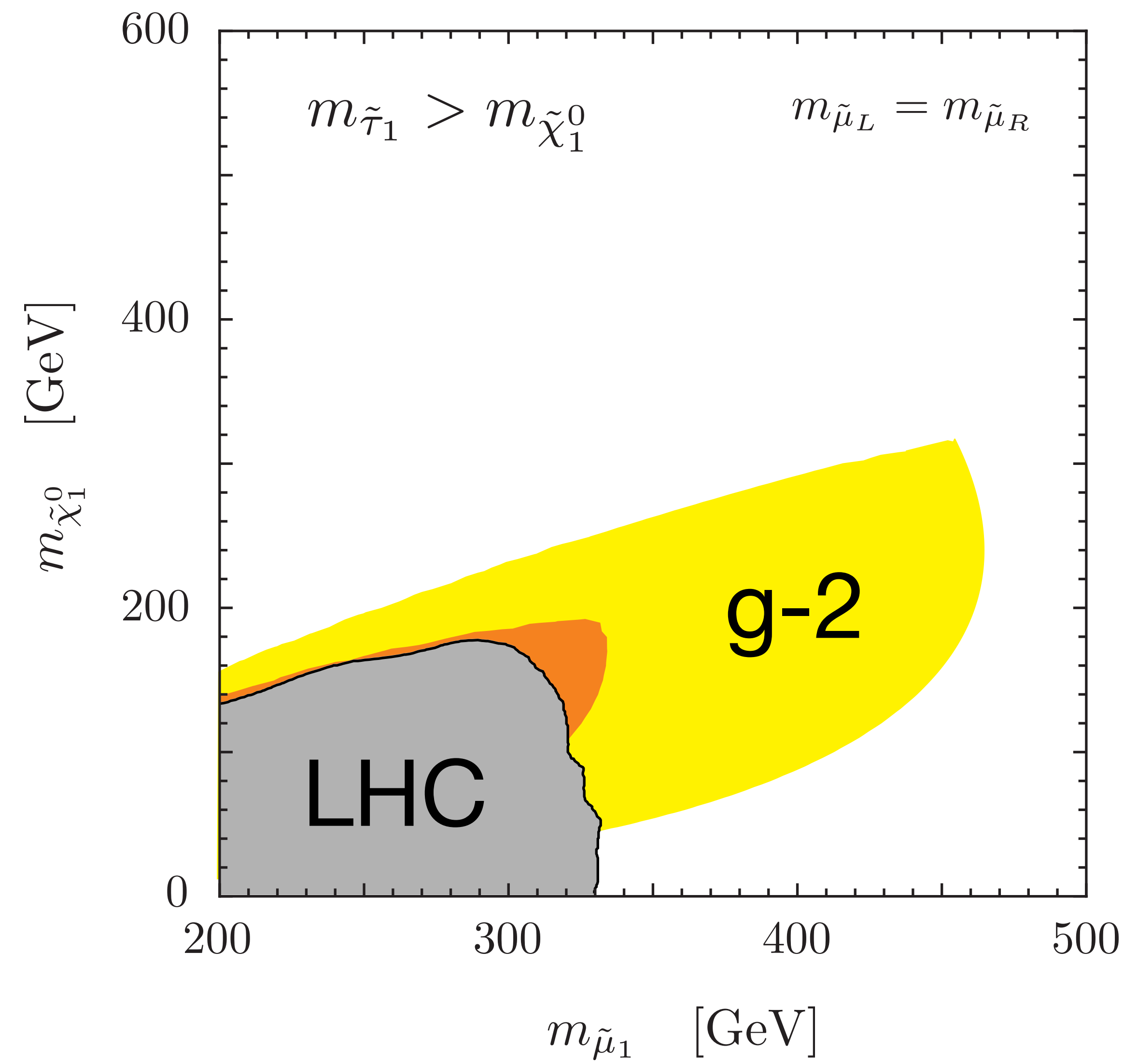
Mass Spectrum

Muon g-2 is explained when smuon mass < 330/460GeV

- vacuum stability (stau-H)
- slepton mass degeneracy to avoid FCNC/CP
- stau searches at LEP, LHC

LHC di-lepton search

$$pp \longrightarrow \tilde{\ell}\tilde{\ell} \longrightarrow \ell\ell + \tilde{\chi}_1^0\tilde{\chi}_1^0$$



[ATLAS-CONF-2013-049,CMS-PAS-SUS-13-006]

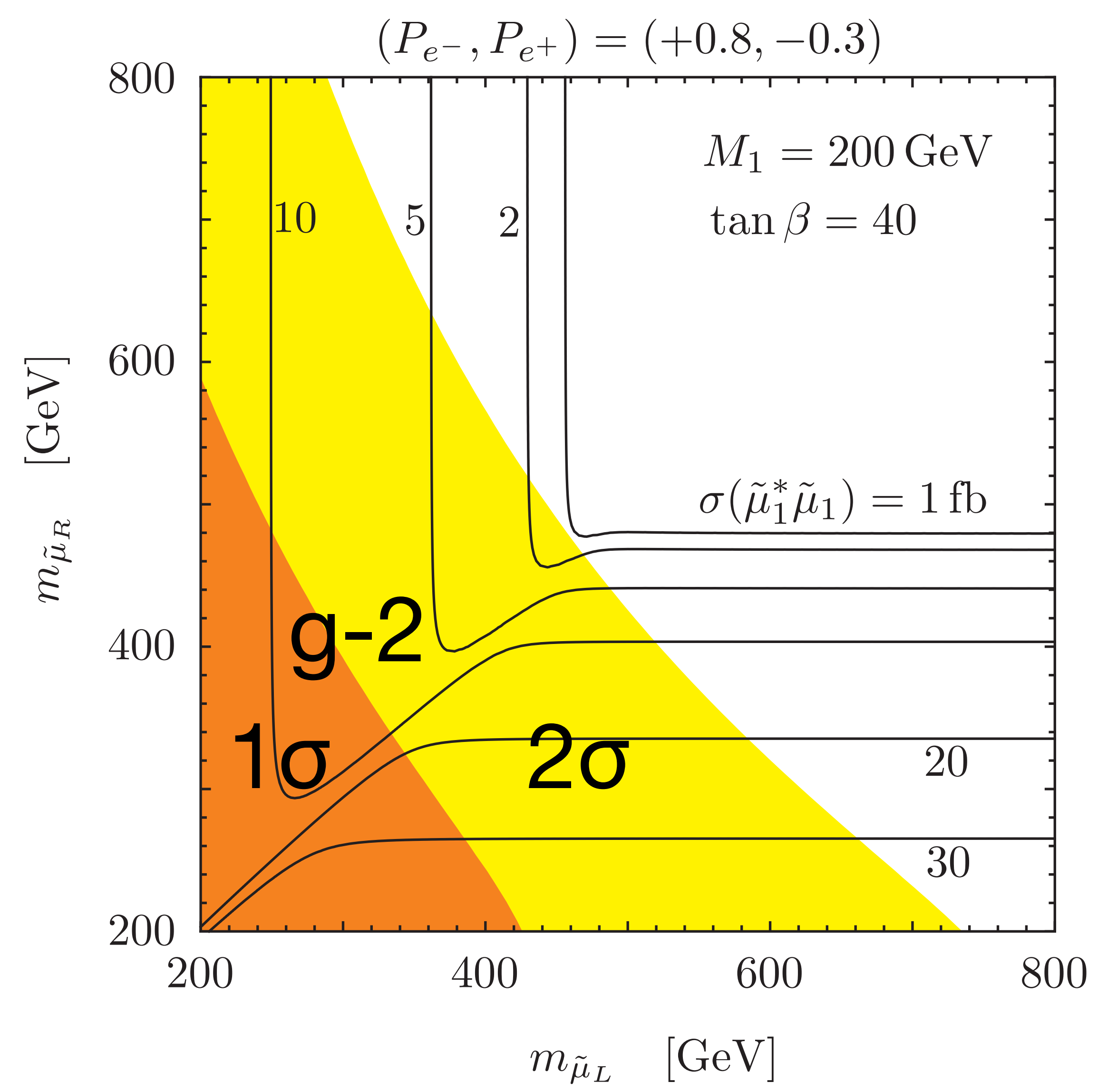
[Endo,Hamaguchi,Kitahara,Yoshinaga]

Neutralino contribution at ILC

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

- lightest smuon is within kinematical reach of ILC
- cross section >~ 1fb

$$\left[\sqrt{s} = 1\,\mathrm{TeV}\right]$$

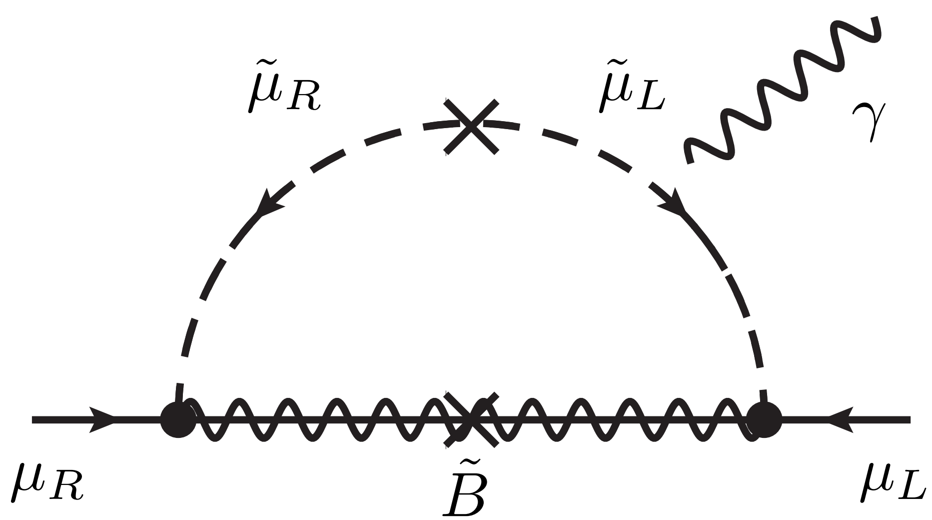


It is possible to *reconstruct* at ILC under some conditions

[Endo,Hamaguchi,Kitahara,Yoshinaga]

Reconstructing

2. ~~Probing~~ Neutralino Contributions



light particles

✓ L- and R-smuons

✓ Bino

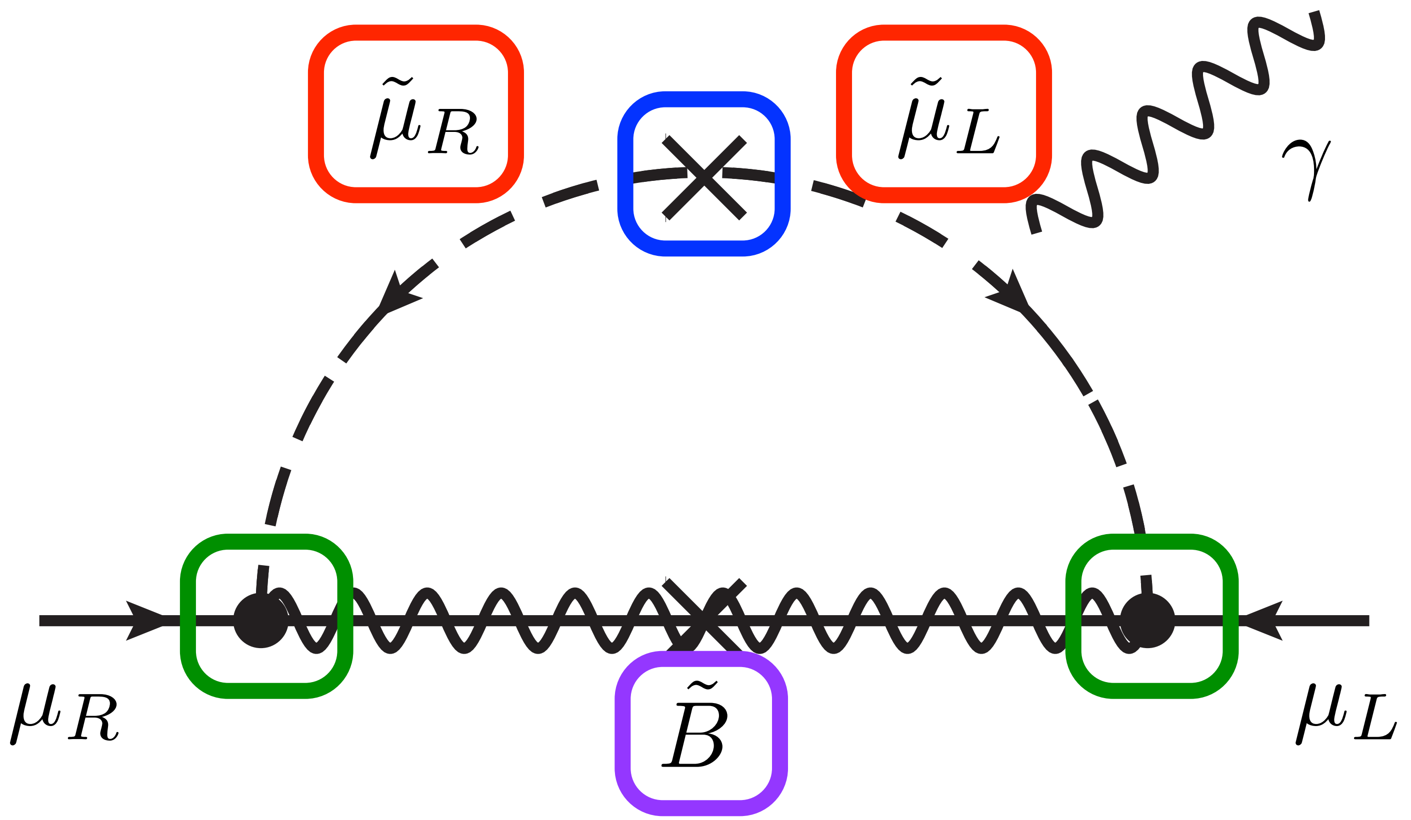
large smuon LR mixing

[ME, Hamaguchi, Iwamoto, Kitahara, Moroi]

Reconstruction at ILC

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 at ILC

Muon g-2 parameters:

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

Neutralino contribution is reconstructed

$$a_\mu = \frac{1}{16\pi^2}\frac{m_\mu^2}{m_{\tilde{\mu}}^2}\left[-\frac{1}{12}\left[(\hat{N}^\mu_L)^2 + (\hat{N}^\mu_R)^2\right]F_1^N(x) - \frac{m_{\tilde{\chi}^0_1}}{3m_\mu}\hat{N}^\mu_L\hat{N}^\mu_R F_2^N(x)\right]$$

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

* Winos and Higgsinos are decoupled

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}

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

others 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

Overview

$m_{\tilde{\mu}1},\ m_{\tilde{\mu}2},\ m_{\tilde{\chi}_1^0}$ $\quad e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-\ (\tilde{\ell} = \tilde{e},\ \tilde{\mu})$

precise by studying endpoints or by threshold scans

$m^2_{\tilde{\mu}LR}$ $\quad e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$

too small to measure directly → stau productions

[most uncertain, strongly depend on model point]

$\tilde{g}^{(\text{eff})}_{1,L},\ \tilde{g}^{(\text{eff})}_{1,R}$ $\quad e^+e^- \to \tilde{e}^+\tilde{e}^-$

theoretically uncertain because of radiative corr. and mixing

involved in t-channel neutralino exchanges of the processes

Mass Measurement

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

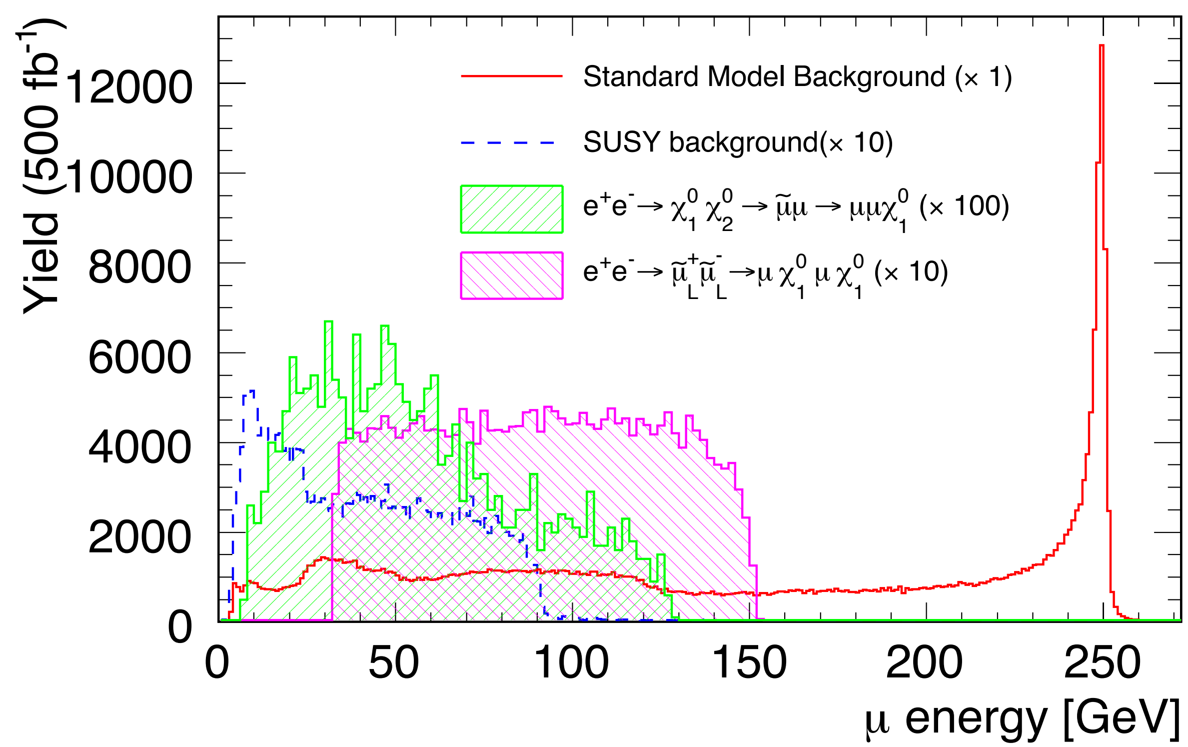
Studies at SPS1a(') with polarized beams,

$$\sqrt{s} = 400, 500\,\mathrm{GeV},\ \ \mathcal{L} = 200\text{–}500\,\mathrm{fb}^{-1}$$

ILC can provide

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

or better



[Berggren,d'Ascenzo,Schade,Stempel]

Smuon LR Mixing

LR mixing is measured by the relation:

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

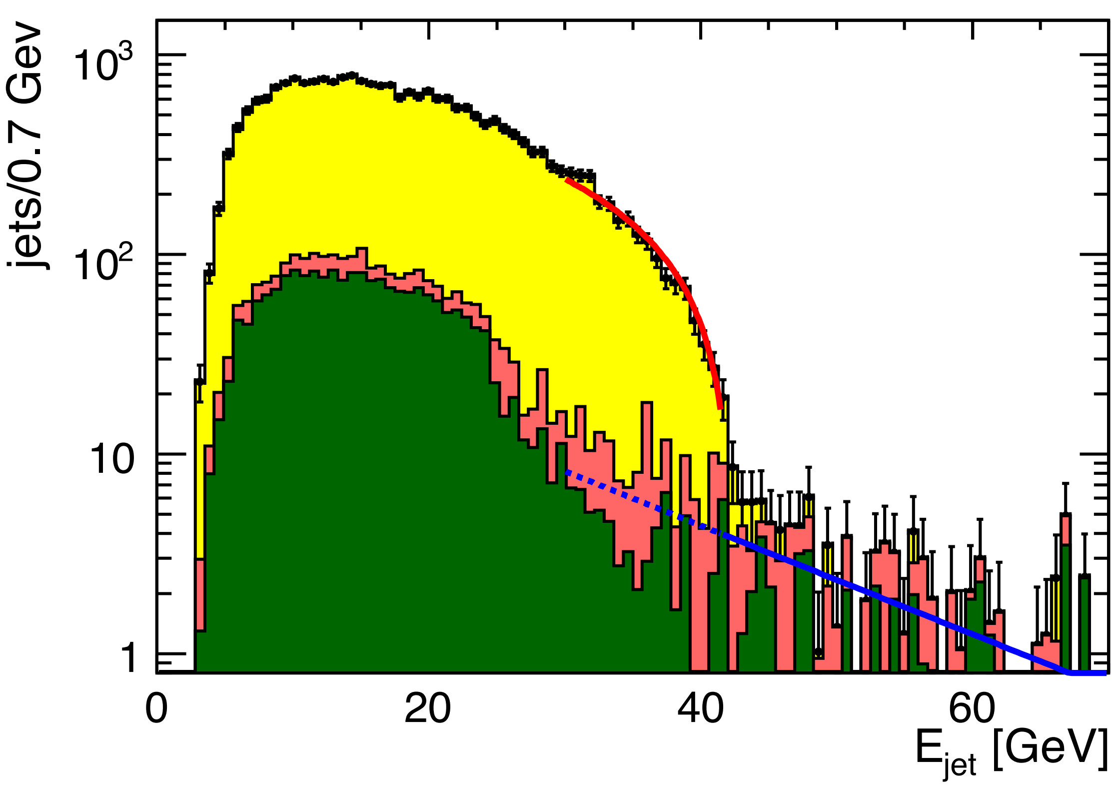
Measurement of stau mass: endpoint of tau (-jet) energy

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

Based on detailed study at

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

$$(P_{e+}, P_{e-}) = (-0.3, +0.8)$$

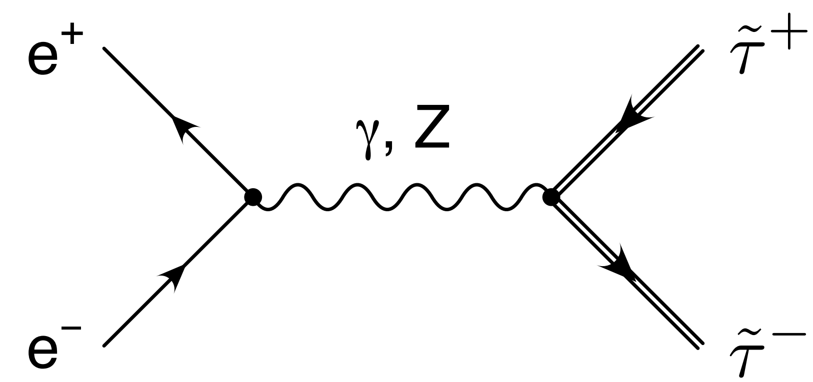


[Bechtle,Berggren,List,Schade,Stempel]

Smuon LR Mixing contd.

Measurement of stau mixing angle: cross section of stau

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



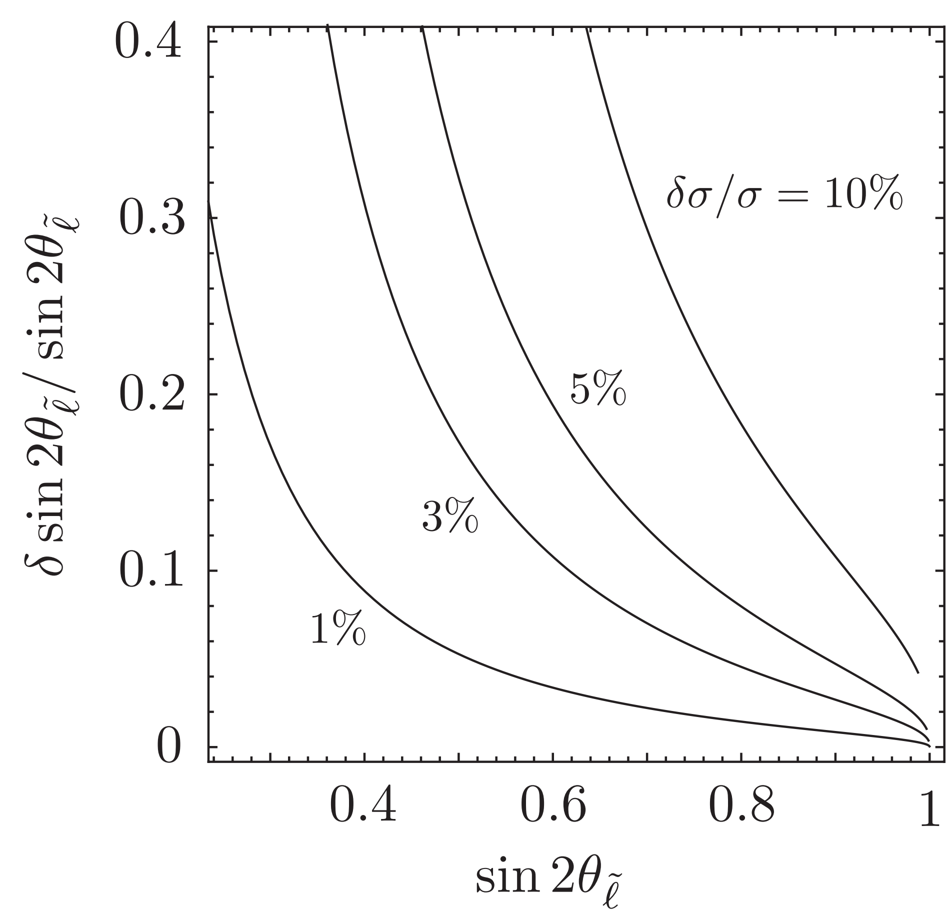
$\longrightarrow$ $\sigma(e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^-)$

$\delta\sigma(\tilde{\tau}_1)/\sigma(\tilde{\tau}_1) = 3.4\,\%$ $[500\mathrm{fb}^{-1}]$

after some discussions

$$\delta \sin 2\theta_{\tilde{\tau}} / \sin 2\theta_{\tilde{\tau}} = 9\,\%$$

at $\sin 2\theta_{\tilde{\tau}} = 0.67$



Smuon LR Mixing contd.

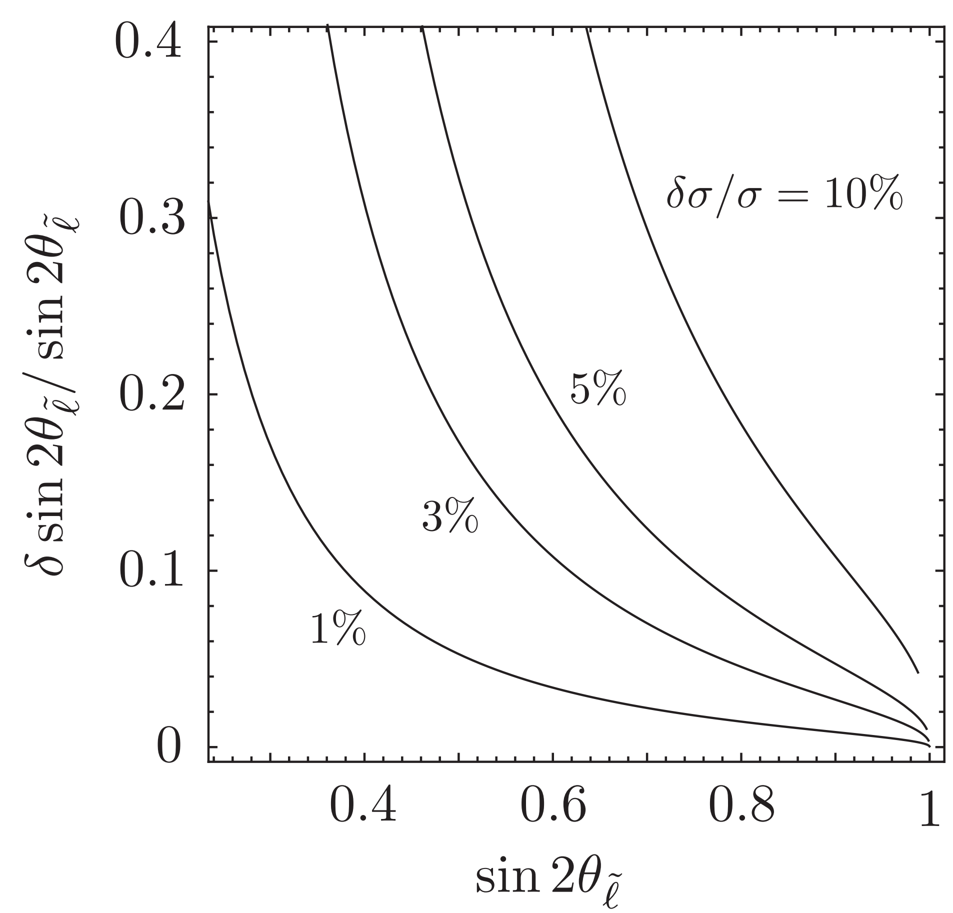
LR mixing is measured by the relation:

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

From stau productions, [500fb^{-1}]

$$\delta m^2_{\tilde{\mu}LR} / m^2_{\tilde{\mu}LR} = 12\,\%$$

Note that $\sigma(e^+e^- \to \tilde{\tau}_1\tilde{\tau}_2)$ is very sensitive to mixing, though there is no study



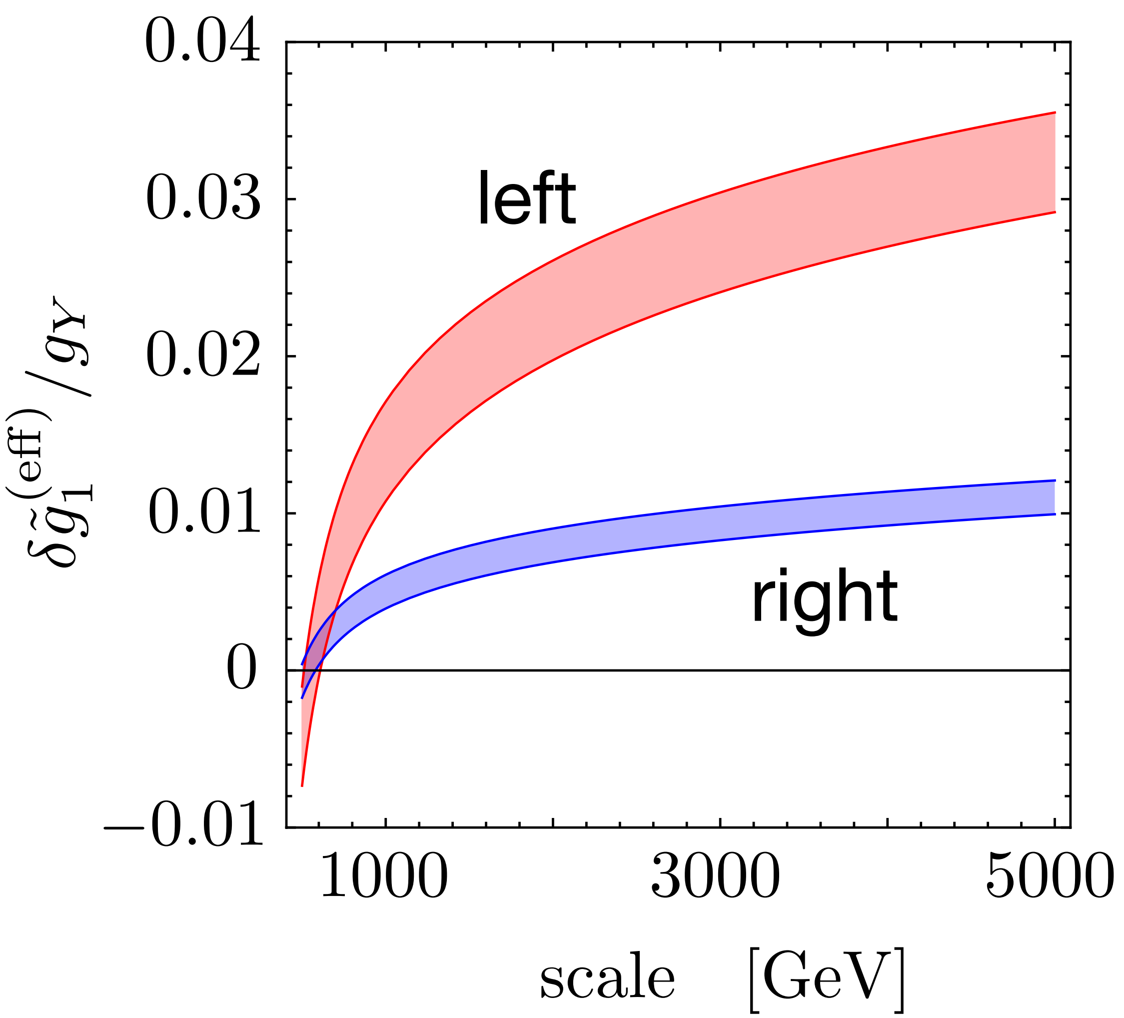
Gaugino Couplings

Couplings of Neutralino-Slepton-Lepton

- equal to gauge coupling constant at LO
- deviate due to radiative corrections as well as mixing with (unobserved) Winos and Higgsinos

  → 1-10% correction

- The couplings should be determined directly at ILC

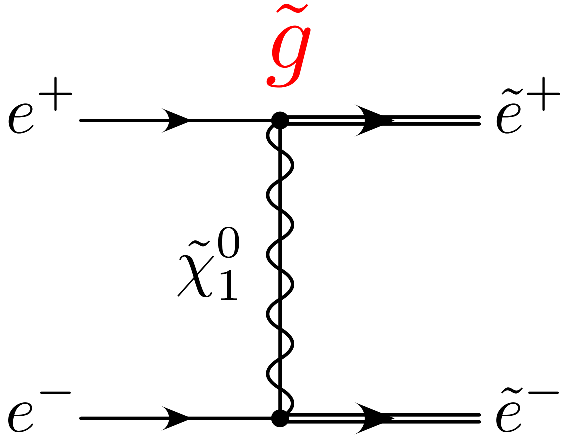


$[\mathrm{scale} = M_{\mathrm{color}},\ M_{\tilde{H}},\ M_{\tilde{W}}]$

Gaugino Couplings

Selectron productions involve t-channel neutralino exchanges

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



$$\longrightarrow \quad \delta\tilde{g}_{1,R}^{(\mathrm{eff})}/\tilde{g}_{1,R}^{(\mathrm{eff})} \lesssim 1\,\% \quad [500\mathrm{fb}^{-1}]$$

contamination of (unobserved) Winos and Higgsinos
is less than 0.4%

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

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

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

exp: measurement of cross section, th: Winos, Higgsinos

Reconstruction at ILC

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

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

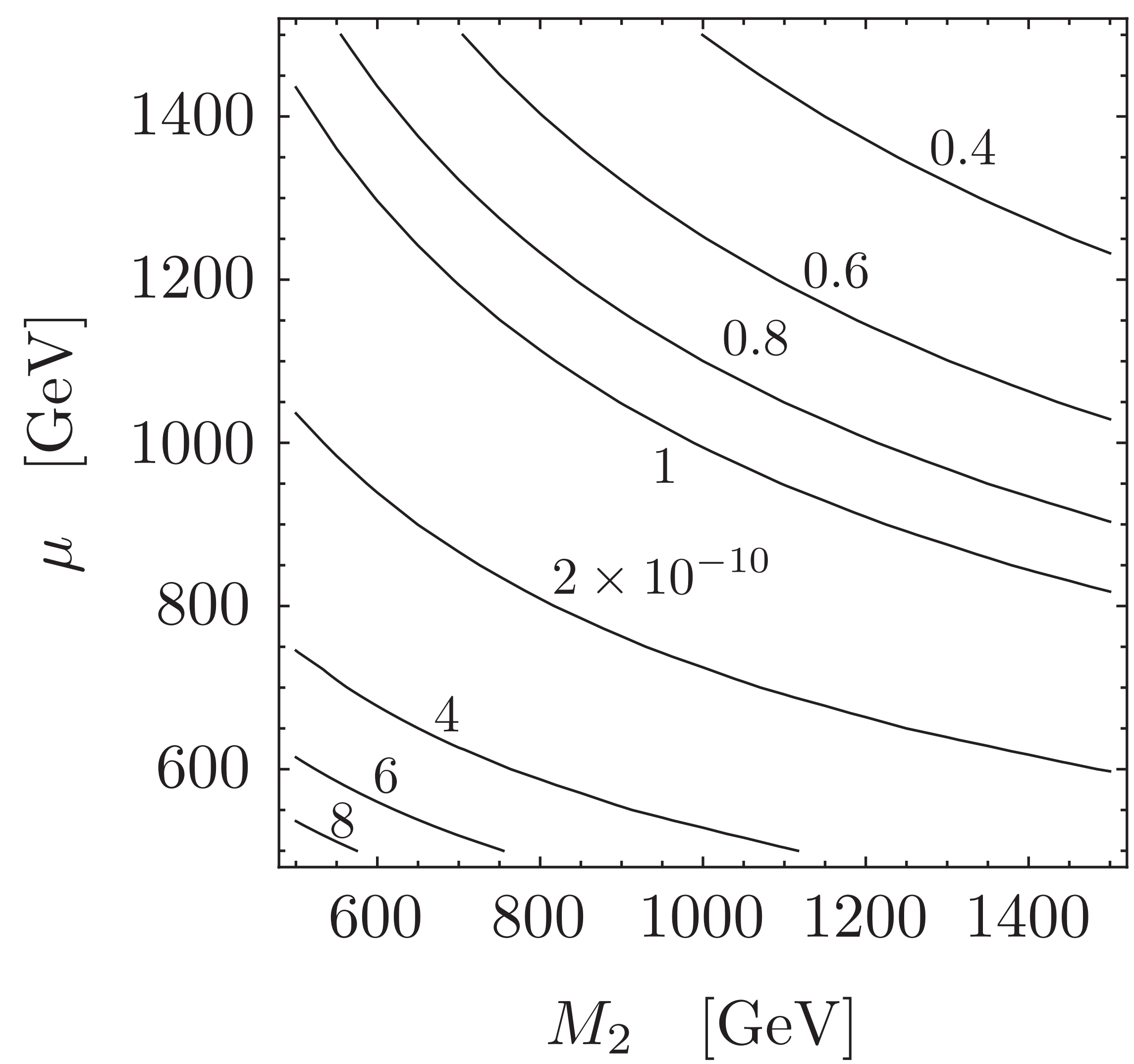
at the sample point with $\sqrt{s} = 500\,\mathrm{GeV},\ \mathcal{L} \sim 500\mathrm{fb}^{-1}$

+ correction from Winos, Higgsinos is 4% (1%) for >1TeV (1.5TeV)

X	δX	$\delta_X a_\mu^{(\mathrm{ILC})}$	Process	
$m^2_{\tilde{\mu}LR}$	$12\,\%$	$13\,\%$	$e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$	(cross section, endpoint)
$(\sin 2\theta_{\tilde{\tau}})$	$(9\,\%)$	$-$	$e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^-$	(cross section)
$(m_{\tilde{\tau}2})$	$(3\,\%)$	$-$	$e^+e^- \to \tilde{\tau}_2^+\tilde{\tau}_2^-$	(endpoint)
$m_{\tilde{\mu}1},\ m_{\tilde{\mu}2}$	$200\,\mathrm{MeV}$	$0.3\,\%$	$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$	(endpoint)
$m_{\tilde{\chi}_1^0}$	$100\,\mathrm{MeV}$	$< 0.1\,\%$	$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-/\tilde{e}^+\tilde{e}^-$	(endpoint)
$\tilde{g}_{1,L}^{(\mathrm{eff})}$	a few+1 %	a few+1 %	$e^+e^- \to \tilde{e}_L^+\tilde{e}_R^-$	(cross section)
$\tilde{g}_{1,R}^{(\mathrm{eff})}$	$1\,\%$	$0.9\,\%$	$e^+e^- \to \tilde{e}_R^+\tilde{e}_R^-$	(cross section)

Extra Contribution to Muon g-2

a_μ(SUSY; total) - a_μ(SUSY; ILC)



Null signal of Winos/Higgsinos reduces theoretical uncertainties

Summary

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

✓ chargino contribution can be probed at LHC

- EWKino search: multi-lepton, SM bosons

✓ 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