Measuring Lepton Flavour Violation at LHC with Long-Lived Slepton in the Coannihilation Region

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Introduction

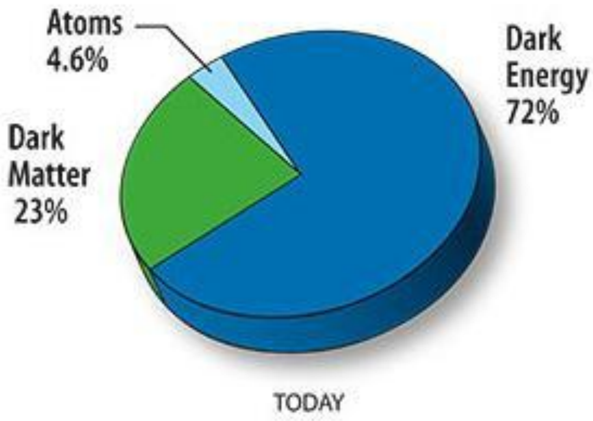
WMAP Experiment

About 23% of the total energy density

Non baryonic matter

No candidate in the SM particles

(not emitting a light = dark matter)



Supersymmetric Standard Model (SSM)

Neutralino LSP **(SUSY+R parity)**

Electrically neutral
Weakly interacting
Massive (O(100) GeV)
Stable

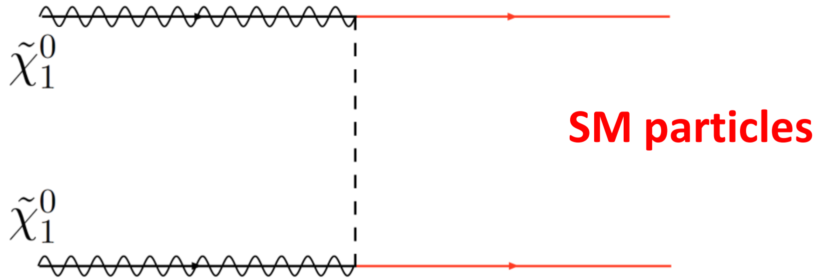
Coannihilation Mechanism

Naively, the neutralino relic abundance is larger than the observed value.

Pair-annihilation process

Too weak

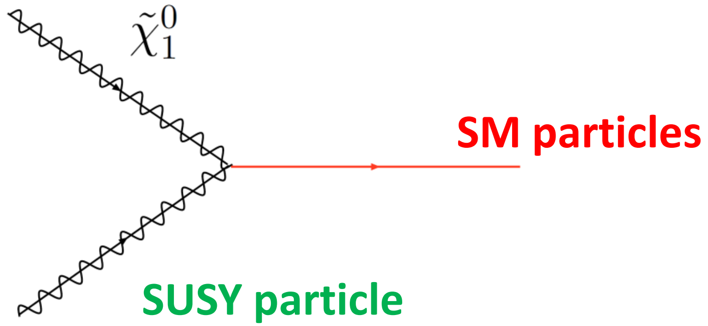
(in most of parameter space)



If a large number of **other SUSY particles** decouples at the same freeze out time,

Coannihilation process

Effectively reduce the neutralino abundance



"Rather tight" degeneracy between neutralino and SUSY particle

$$\frac{\delta m}{m_{LSP}} < \text{a few}\%$$

Degenerate neutralino LSP and slepton NLSP

Constrained Minimal SSM (CMSSM)

LSP	Bino-like neutralino (**pure Bino**)
NLSP	Slepton (**right-handed Stau**)

- If the mass difference is smaller than the tau mass, the stau can not decay into the neutralino and the tau

> ➢ **Stau NLSP becomes long-lived**

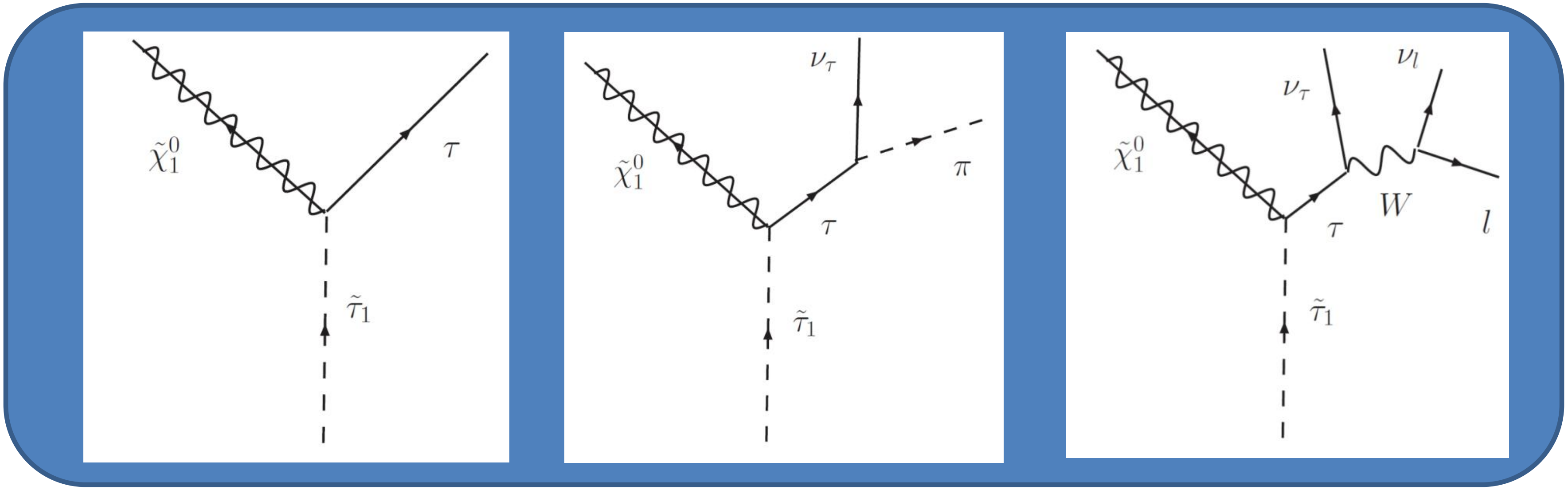
- When Lepton Flavour Violation is present, the slepton can decay into the neutralino and the electron/muon

> ➢ **Slepton lifetimes depend on LFV couplings**

➡ The LFV coupling can be measured through measurements of the lifetime.

Long-Lived Stau in CMSSM (No LFVs)

Decays of Staus



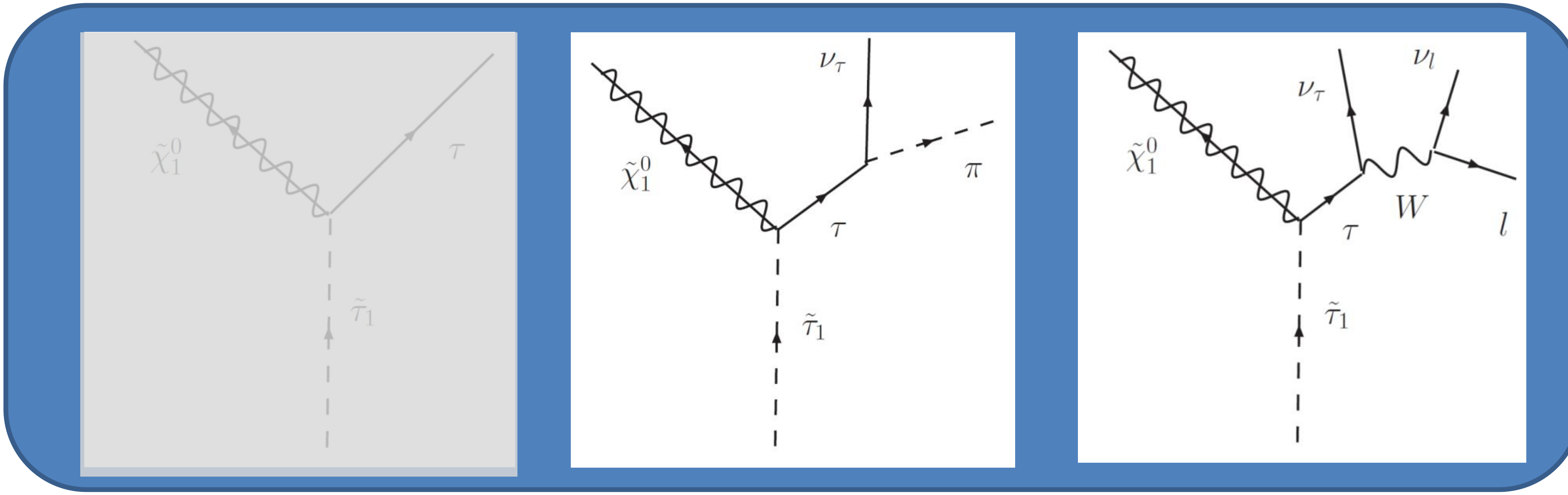
- **When δm > tau mass, two-body decay is dominant**

$$\Gamma_{2-\mathrm{body}} \simeq \frac{g_2^2 \tan^2\theta_W}{2\pi m_{\tilde{\tau}_1}} \delta m \sqrt{(\delta m)^2 - m_\tau^2} \sim \mathcal{O}(10^{-4})\ \mathrm{GeV}$$

$$\delta m \equiv m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$$

Long-Lived Stau in CMSSM (No LFVs)

Decays of Staus



- **When δm < tau mass, two-body decay channel is close.**
- **Three body decay is dominant**

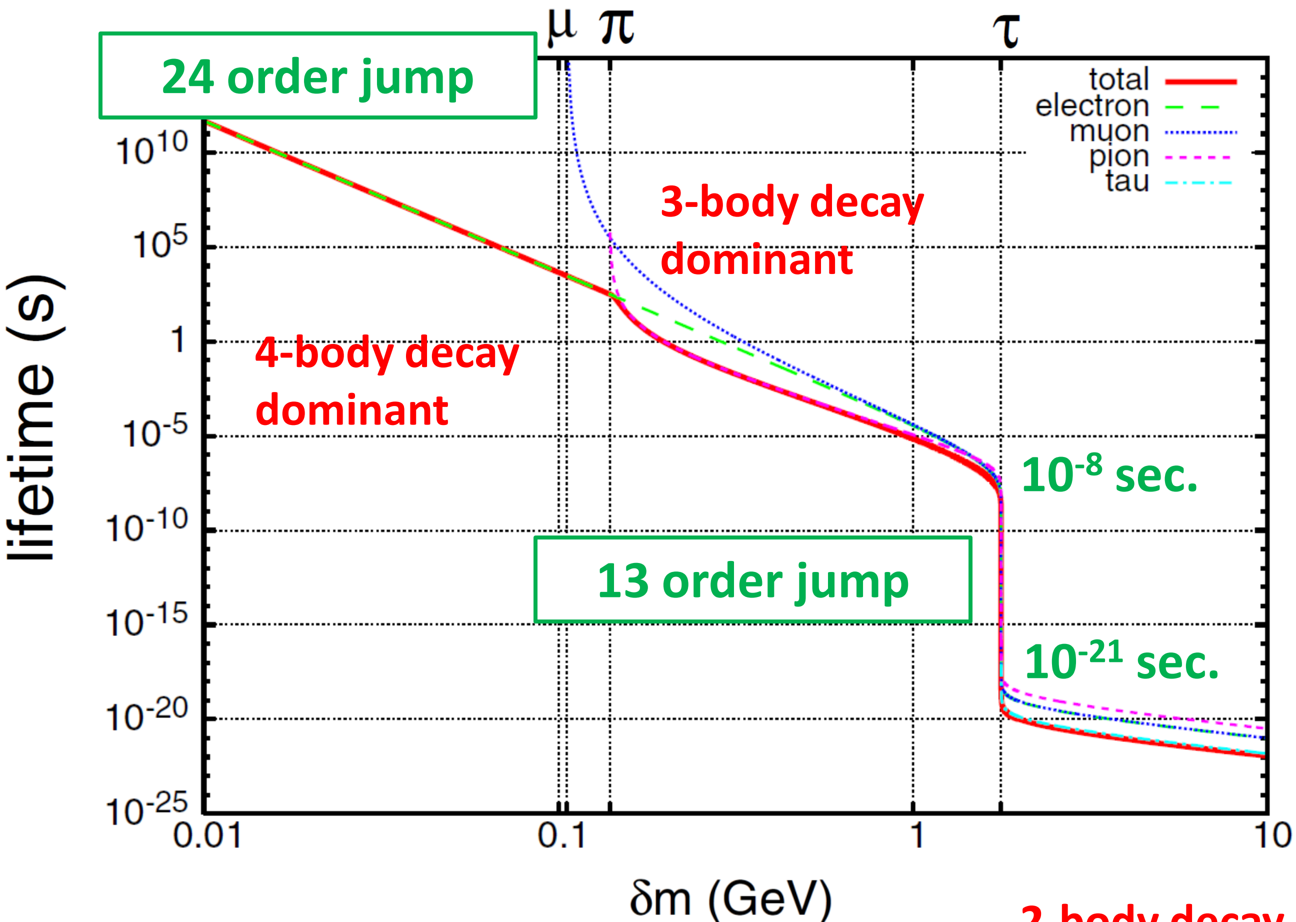
$$\Gamma_{3-\text{body}} \simeq \frac{g_2^2 G_F^2 f_\pi^2 \cos^2\theta_c \tan^2\theta_W}{30(2\pi)^3 m_{\tilde{\tau}_1} m_\tau^2}\, \delta m\left((\delta m)^2 - m_\pi^2\right)^{5/2}$$

$$\sim \mathcal{O}(10^{-17})\ \text{GeV}$$

13 order smaller !

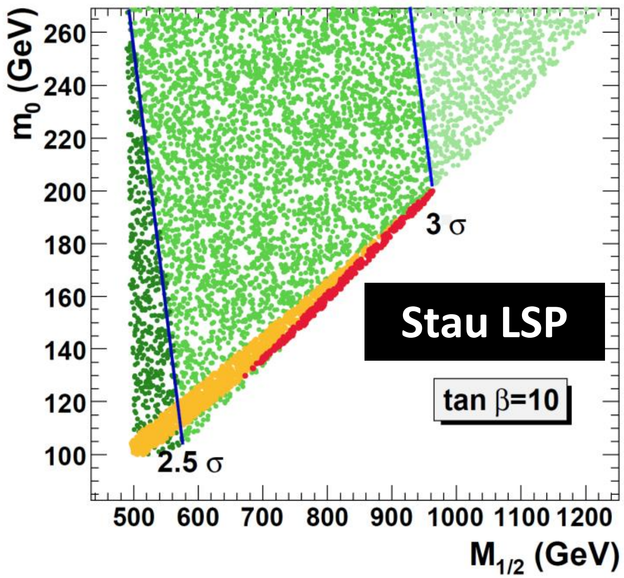
δm dependence of stau lifetime

T. Jittoh, J. Sato, T.S., M. Yamanaka, PRD, 73, 055009 (2006)



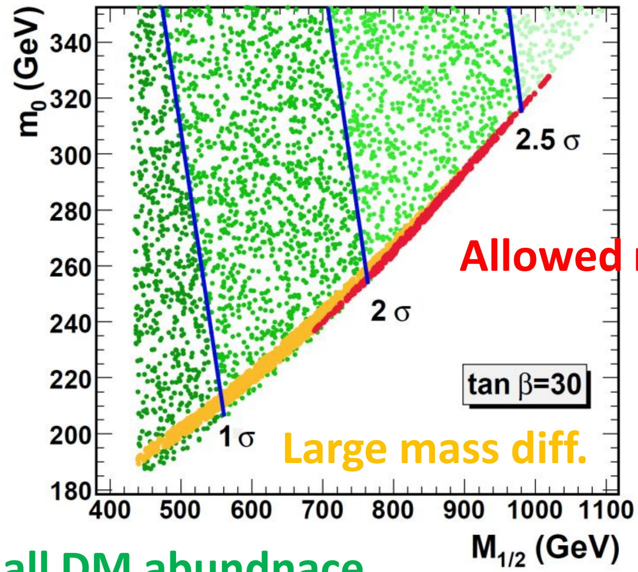
2-body decay
dominant

Allowed parameter space in CMSSM



Large DM abundance

Muon (g-2)

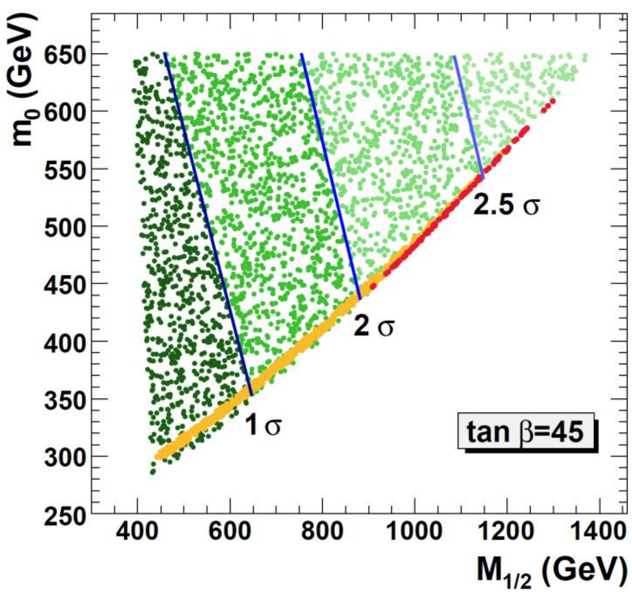


Allowed region

Large mass diff.

Small DM abundnace

(allowed if other DM components exist)



Sign(μ) > 0

A_0 – large & positive

to optimize SUSY contribution to $(g-2)_\mu$

LFV and Long-Lived Slepton

kaneko, Sato, T.S., Vives, Yamanaka, **Phys.Rev.D78:116013,2008**.

Lepton flavour violation in the slepton sector is naturally expected to exist

- ✓ **CMSSM + Right-handed neutrino**
- ✓ **SUSY GUTs (SO(10), SU(5))**
- ✓ **Flavour symmetry**

2-body decay channels are open even if $\delta m < m_\tau$

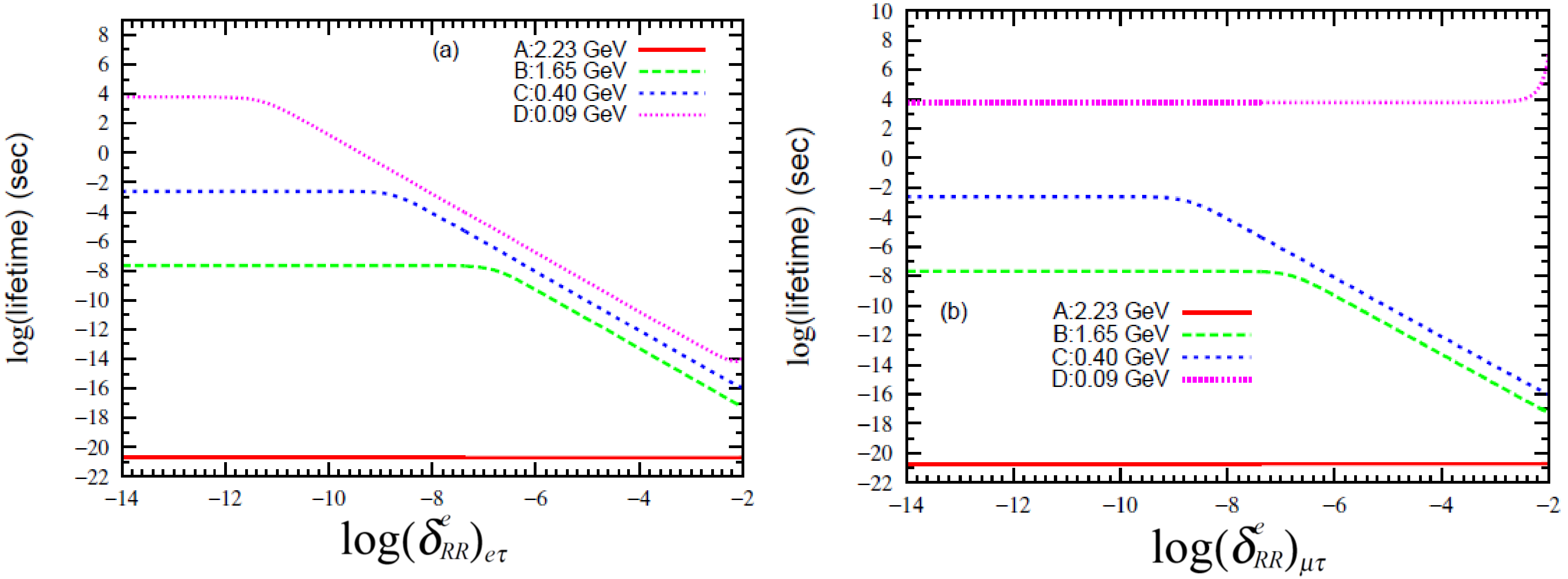
- ➢ The slepton decays into the neutralino and e/mu
- ➢ Lepton Flavour Conserving processes are suppressed

$$(\delta^e)^2 \Gamma_2 \sim \Gamma_3 \text{ or } \Gamma_4 \quad \Rightarrow \quad \delta^e \sim 10^{-7} \text{ or } 10^{-12}$$

The lifetime shows a good sensitivity to small LFV parameters

Lifetime in right-handed slepton mixing case

$$(m_0 = 260\ \text{GeV},\quad \tan\beta = 30)$$



No.	δm (GeV)	$m_{\tilde{\chi}_1^0}$ (GeV)	$m_{\tilde{l}_1}$ (GeV)	$\Omega_{\tilde{\chi}_1^0} h^2$	a_μ ($\times 10^{-10}$)
A	2.227 ($> m_\tau$)	323.1549	325.3817	0.110	10.32
B	1.650 ($< m_\tau$)	325.5601	326.2147	0.102	10.25
C	0.407	327.6294	328.0365	0.085	10.09
D	0.092 ($< m_\mu$)	328.4060	328.4981	0.081	10.06

Lifetime in right-handed slepton mixing case

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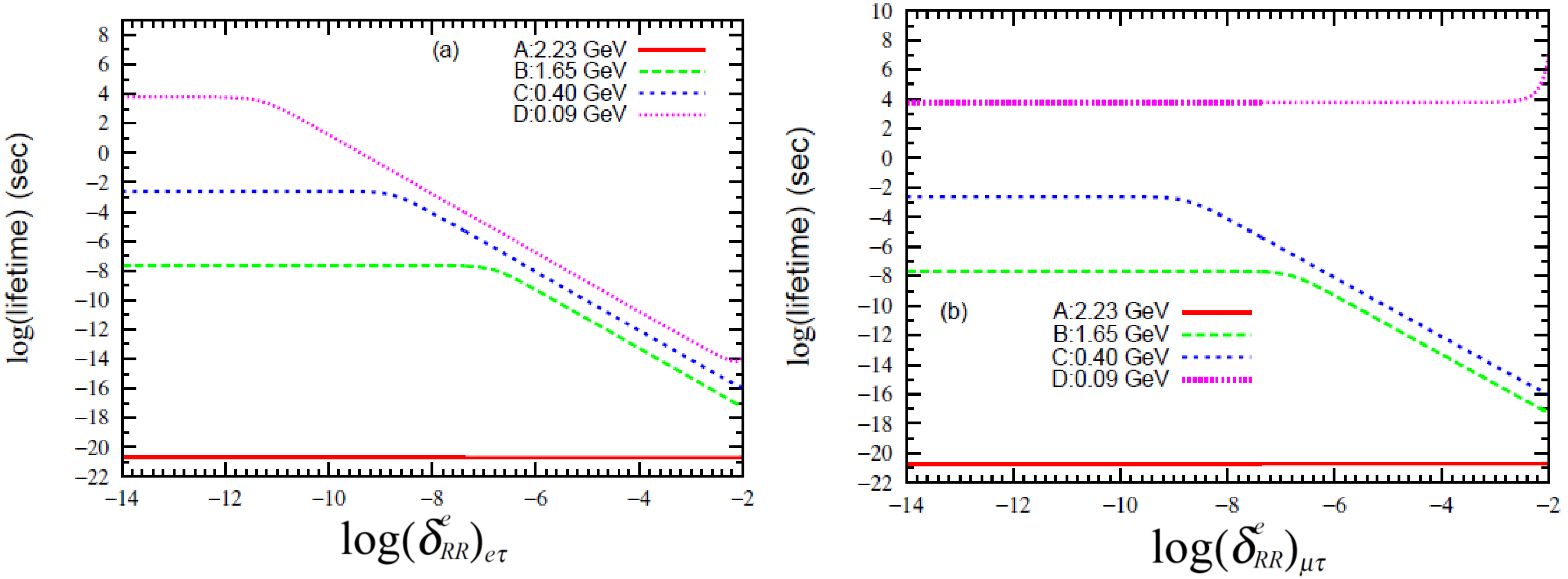

Present bound on δ's (m_0=260 GeV, $M_{1/2}$=750 GeV)

	$\tan\beta = 10$			$\tan\beta = 30$			$\tan\beta = 45$		
	$\delta^e_{e\mu}$	$\delta^e_{e\tau}$	$\delta^e_{\mu\tau}$	$\delta^e_{e\mu}$	$\delta^e_{e\tau}$	$\delta^e_{\mu\tau}$	$\delta^e_{e\mu}$	$\delta^e_{e\tau}$	$\delta^e_{\mu\tau}$
LL	0.0014	0.33	0.21	0.00047	0.10	0.068	0.00030	0.067	0.043
RR	0.0060	1.7	1.1	0.0019	0.44	0.29	0.0012	0.28	0.18

Lifetime in left-handed slepton mixing case

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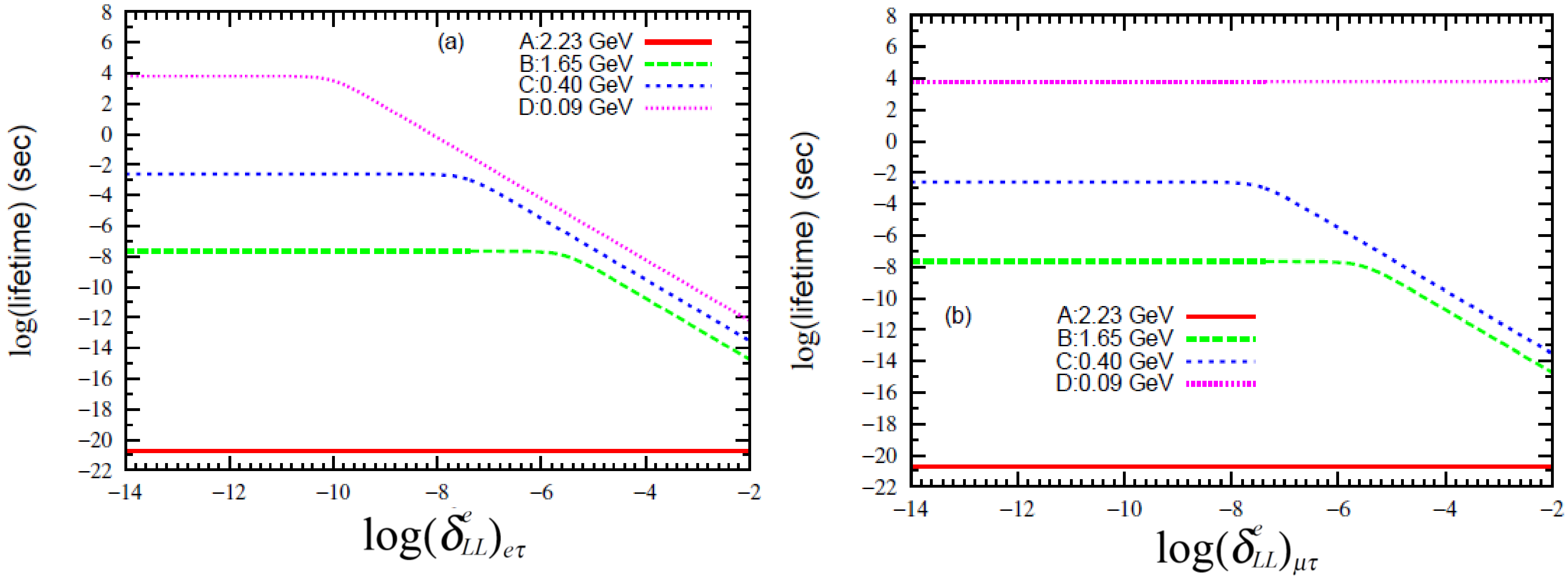

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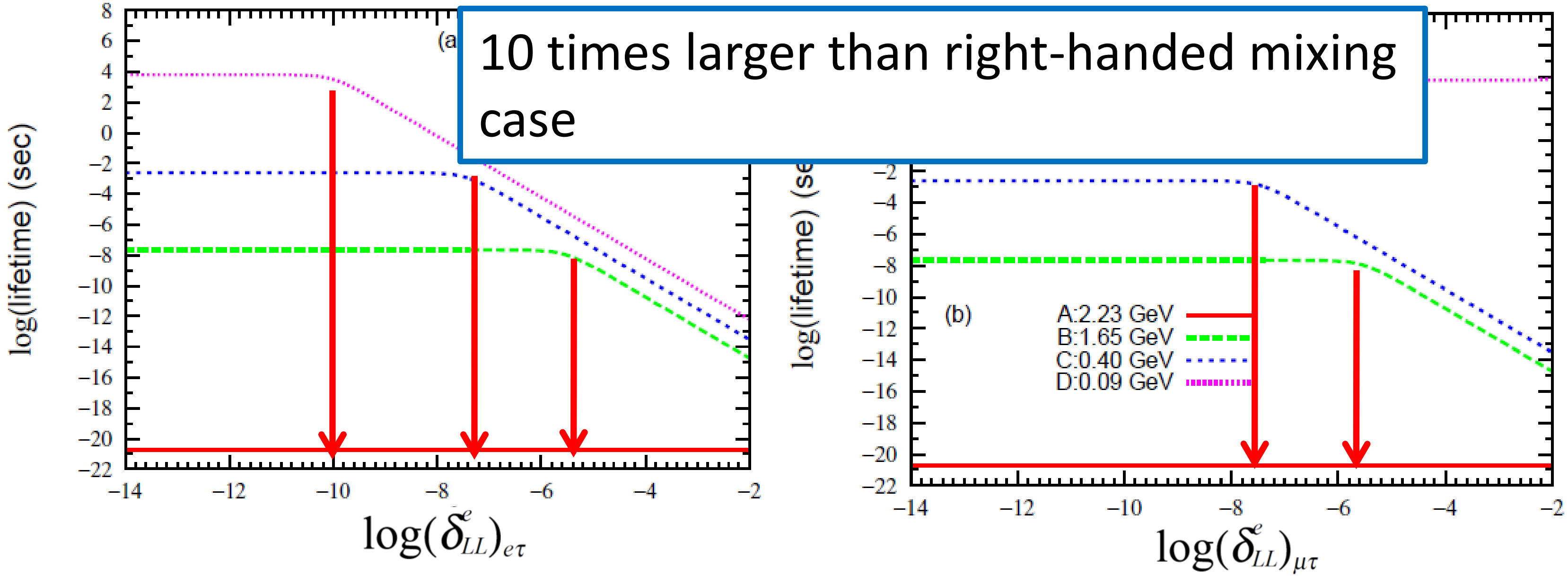

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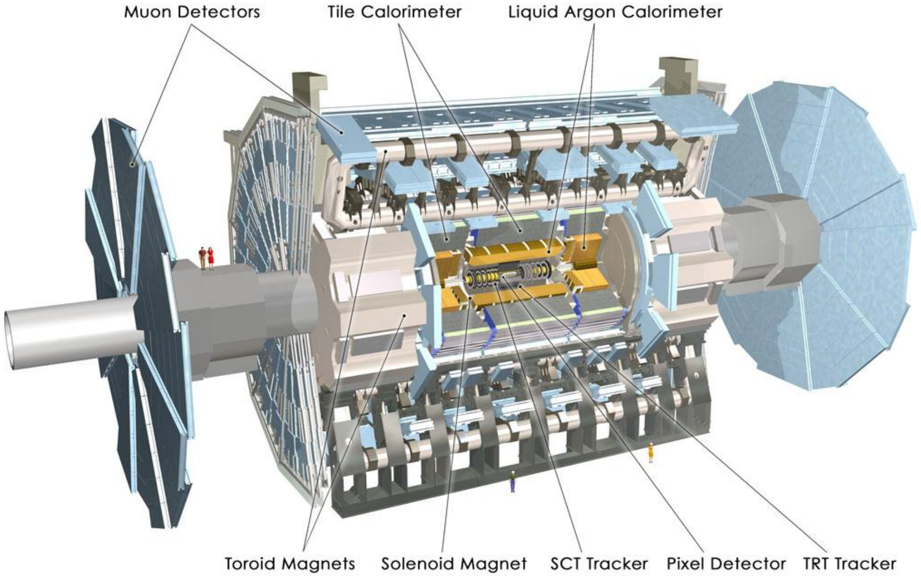
Expected Phenomenology at LHC

When the lightest slepton is enough long-lived

the slepton decays will be seen at LHC

The ATLAS detector (25 m high & 44 m length)



http://atlasexperiment.org/index.html

S. Bentvelsen et al, JINST 3 (2008) S08003

Inner detector ($\pm$3.51 m length)

- **Pixel detector**
  - **5, 9, 12 cm radii barrels**
- **SemiConductor Tracker (SCT)**
  - **30, 37, 44, 52 cm radii barrels**
- **Transition Radiation Tracker (TRT)**
  - **56 to 107 cm radii**

Calorimeter

- **4m radius and 8.4 m length**

Muon detector

- **Outer surface of detector**

Expected Number of the lightest slepton

the number of the lightest slepton **produced at LHC**

- ✓ SUSY pair production cross section

$$\sigma_{\mathrm{SUSY}} = 130 \text{ fb.}$$

P. Z. Skands, Eur. Phys. J. C 23, 173 (2002)

- ✓ Integrated Luminosity

$$\mathcal{L}_{\mathrm{int}} = 30 \text{ fb}^{-1}$$

$\mathcal{L} = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, for 3 year

- ✓ Branching Ratios

$\tilde{q}_L$	0.86	$\tilde{t}_1$	0.72	$\tilde{b}_1$	0.87
		$\tilde{t}_2$	0.90	$\tilde{b}_2$	0.67

M. Battaglia et al, Eur. Phys. J. C 33, 273 (2004)

The number of Slepton produced

$$N_{\tilde{l}_1} = 4290$$

Estimation of the number of the lightest slepton **decay**

- ✓ Lorentz factor

$$1.53 \lesssim \beta\gamma \lesssim 2.75$$

Expected number of decay within the distance, l

$$N_{\mathrm{dec}}(l) = N_{\tilde{l}_1} P_{\mathrm{dec}}(l) = N_{\tilde{l}_1} \left(1 - \exp\left(-\frac{l}{\beta\gamma c\tau_{\tilde{l}_1}}\right)\right)$$

Expected decays in the ATLAS detector

	Pixel detector	SCT	TRT	Calori-meter	Muon detector
	5 cm	50 cm	3.1 m	5.8 m	25.0 m
10^{-5} sec.	0.04	0.36	2.2	4.1	17.8
10^{-6} sec.	0.36	3.6	22.1	41.3	175.1
10^{-7} sec.	3.6	35.6	216.0	395.3	1461.9
10^{-8} sec.	35.6	343.0	1731.0	2658.3	4223.5
10^{-9} sec.	343.0	2425.6	4265.5	4289.7	4290.0
10^{-10} sec.	2425.6	4289.0	4290.0	4290.0	4290.0
10^{-11} sec.	4289.0	4290.0	4290.0	4290.0	4290.0
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Almost all the slepton would decay inside the inner detector

When the mass difference is fixed, δ's are determined

$$10^{-7} < (\delta^e_{RR})_{e\tau} < 10^{-4} \qquad 10^{-7} < (\delta^e_{RR})_{\mu\tau} < 10^{-5}$$

$$4 \times 10^{-6} < (\delta^e_{LL})_{e\tau} < 10^{-3} \qquad 4 \times 10^{-6} < (\delta^e_{LL})_{\mu\tau} < 10^{-4}$$

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A few to hundred sleptons would decay inside the inner detector and most of them would escape

- ✓ **The lifetime would be measured**
- ✓ **Mass and momentum of the slepton could be determined with muon detector**

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Almost all of the slepton would escape the detector

- ✓ **Lower bound on the lifetime would be put**
  → **stringent upper bound on δ's**
- ✓ **Mass and momentum of the slepton could be determined with muon detector**

Summary

In the CMSSM (absence of LFV) in which stau is the NLSP and bino-like neutralino is the LSP, if δm < tau mass

1. The stau can be long-lived.
   Due to phase suppression and the weak int.
   Typically from 10^{-8} sec to 10^{10} sec.
2. There exists the small δm region consistent with the dark matter abundance, b->s gamma, Higgs mass limit and muon (g-2).

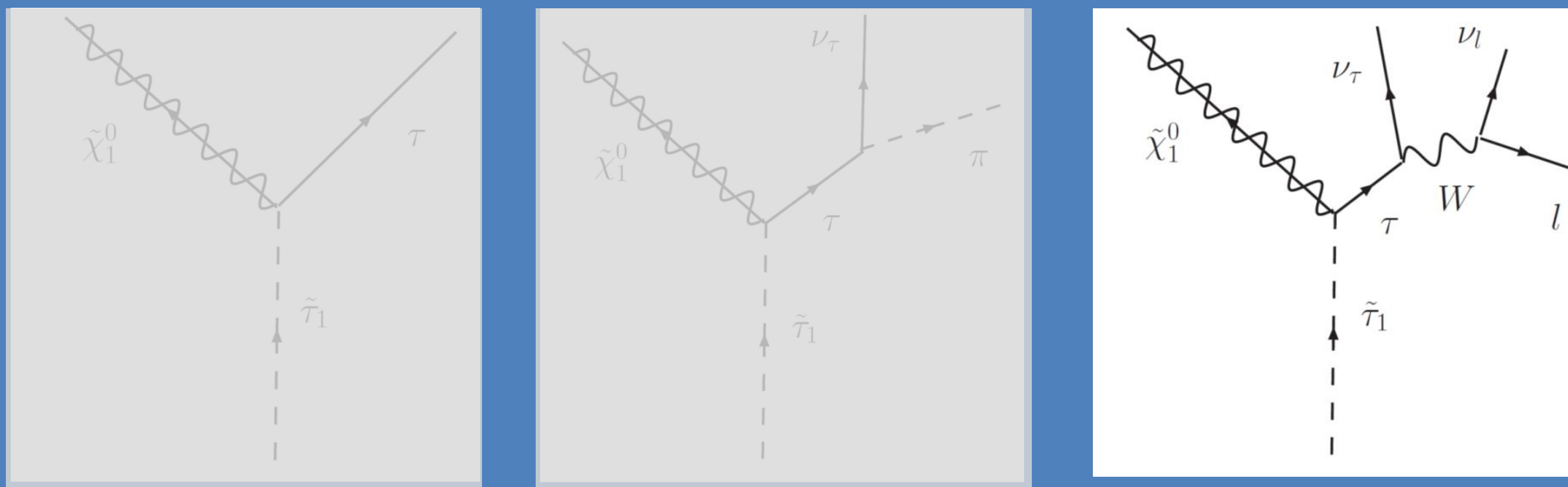
In the CMSSM with LFV

1. The slepton lifetime is sensitive to δ^e up to 10^{-5} to 10^{-11} depending on the mass difference.
2. The ATLAS detector would measure lifetime in the range of 10^{-11} to10^{-5} sec.
3. If the lifetime is beteen 10^{-10} to10^{-9} sec., LFV couplings could be determined.

Back up slides

Long-Lived Stau in CMSSM (No LFVs)

Decays of Staus



- **When δm < pion mass, three body decay is also close.**
- **Four body decays are dominant**

$$\Gamma_{4-\text{body}} \simeq \frac{2}{3}\frac{g_2^2 G_F^2 \tan^2\theta_W}{5^3(2\pi)^5 m_{\tilde{\tau}_1} m_\tau^2}\delta m\left((\delta m)^2 - m_l^2\right)^{5/2}\left(2(\delta m)^2 - 23 m_l^2\right)$$

$$\sim \underline{\mathcal{O}(10^{-28})\ \text{GeV}}$$

24 order smaller !

SUSY particles' spectrum

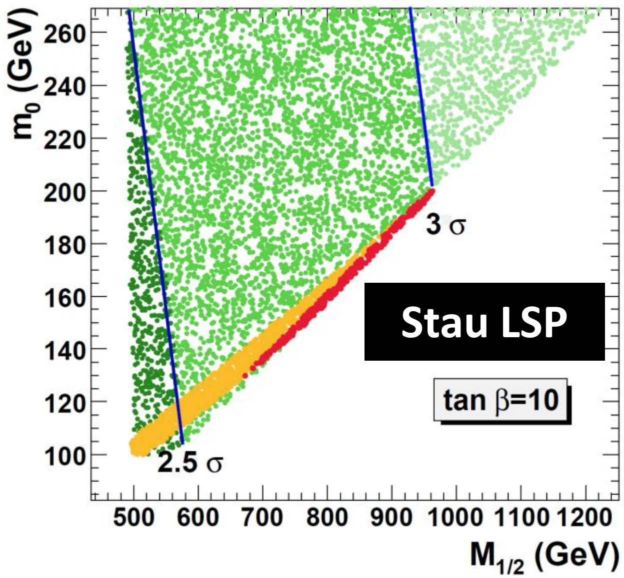
	mass (GeV)		mass (GeV)
$\tilde{\chi}_1^0$	290 – 320	$\tilde{\chi}_2^0$	540 – 600
$\tilde{\chi}_3^0$	750 – 820	$\tilde{\chi}_4^0$	770 – 830
$\tilde{\chi}_1^\pm$	540 – 600	$\tilde{\chi}_2^\pm$	770 – 830
$\tilde{g}$	1540 – 1680		
$\tilde{t}_1$	1150 – 1260	$\tilde{t}_2$	1330 – 1460
$\tilde{b}_1$	1300 – 1420	$\tilde{b}_2$	1340 – 1460
$\tilde{u}_R$	1370 – 1500	$\tilde{u}_L$	1430 – 1560
$\tilde{d}_R$	1370 – 1500	$\tilde{d}_L$	1430 – 1560
$\tilde{\tau}_1$	290 – 320	$\tilde{\tau}_2$	510 – 560
$\tilde{e}_R$	350 – 385	$\tilde{e}_L$	520 – 570
$\tilde{\nu}_1$	500 – 550	$\tilde{\nu}_3$	510 – 560
h	116 – 118	H	800 – 900
A	800 – 900	$H^\pm$	800 – 900

Experimental Constraints

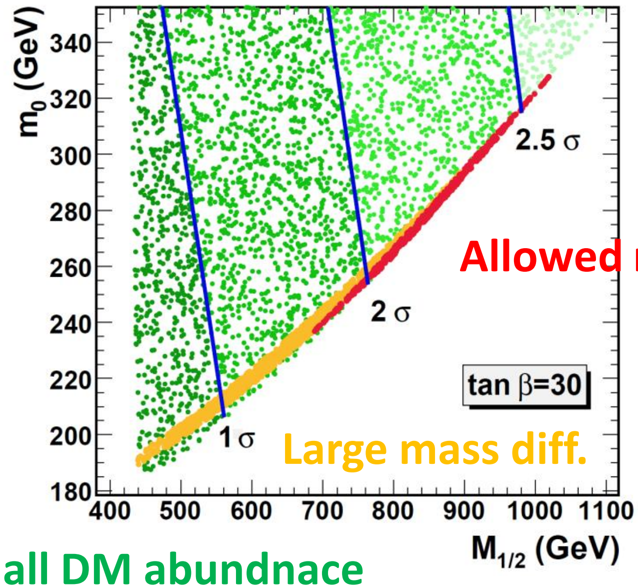
Dark matter abundance	$0.08 < \Omega_{\rm DM} h^2 < 0.14,$
Higg mass limit	$m_h \gtrsim 114 \text{ GeV}$
Bound on $\mathrm{Br}(b \to s\gamma)$	$2.5 \times 10^{-4} < \mathrm{Br}(b \to s\gamma) < 4.5 \times 10^{-4}$
Muon $(g-2)_\mu$	$\Delta a_\mu = a_\mu^{(\exp)} - a_\mu^{(SM)} = (27.5 \pm 8.4) \times 10^{-10}$

M. Davier, NP. Proc. Suppl, 169, 288 (2007)

Allowed parameter space in mSUGRA MSSM



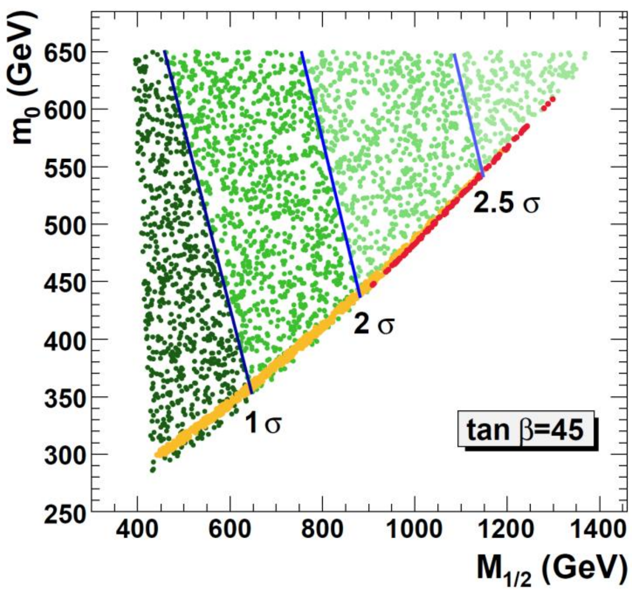
Large DM abundance



Muon (g-2)

Allowed region

Large mass diff.



Small DM abundnace

(allowed if other DM components exist)

Sign(μ) > 0

A_0 – large & positive

to optimize SUSY contribution to $(g-2)_\mu$

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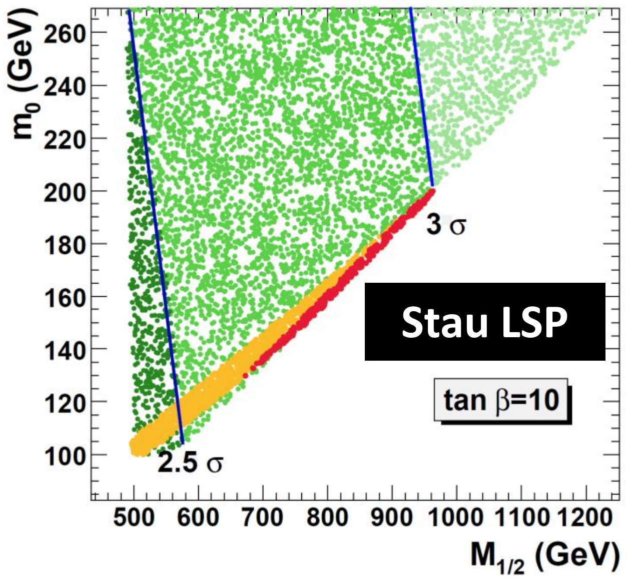

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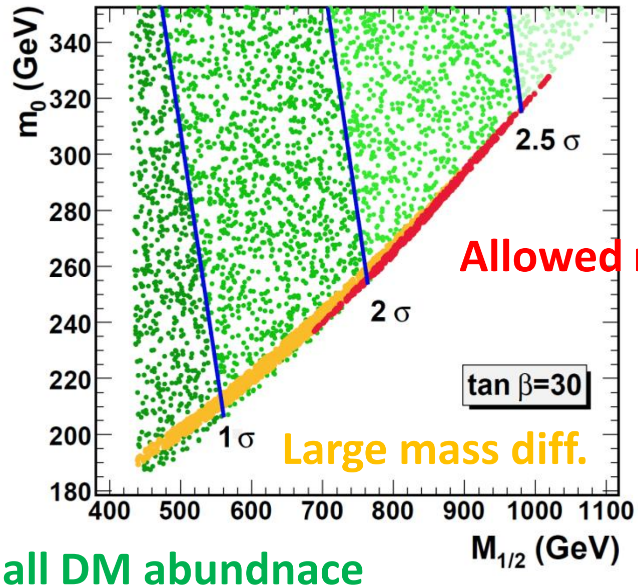

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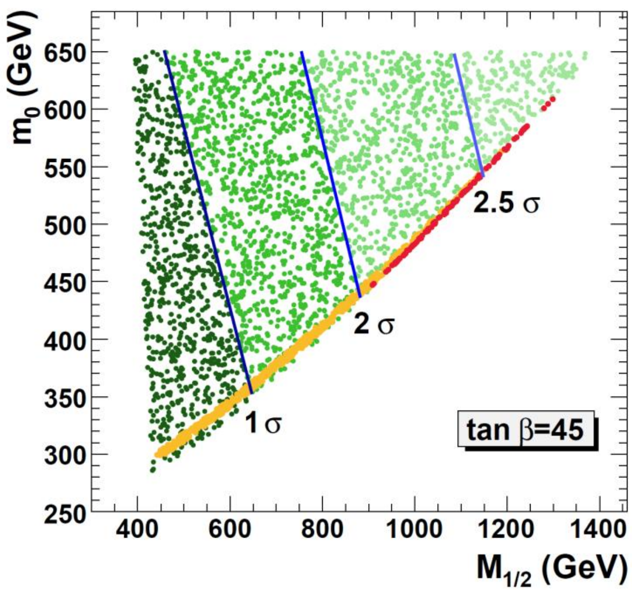


$\delta m < m_\tau$ region

- ✓ relatively large $M_{1/2}$

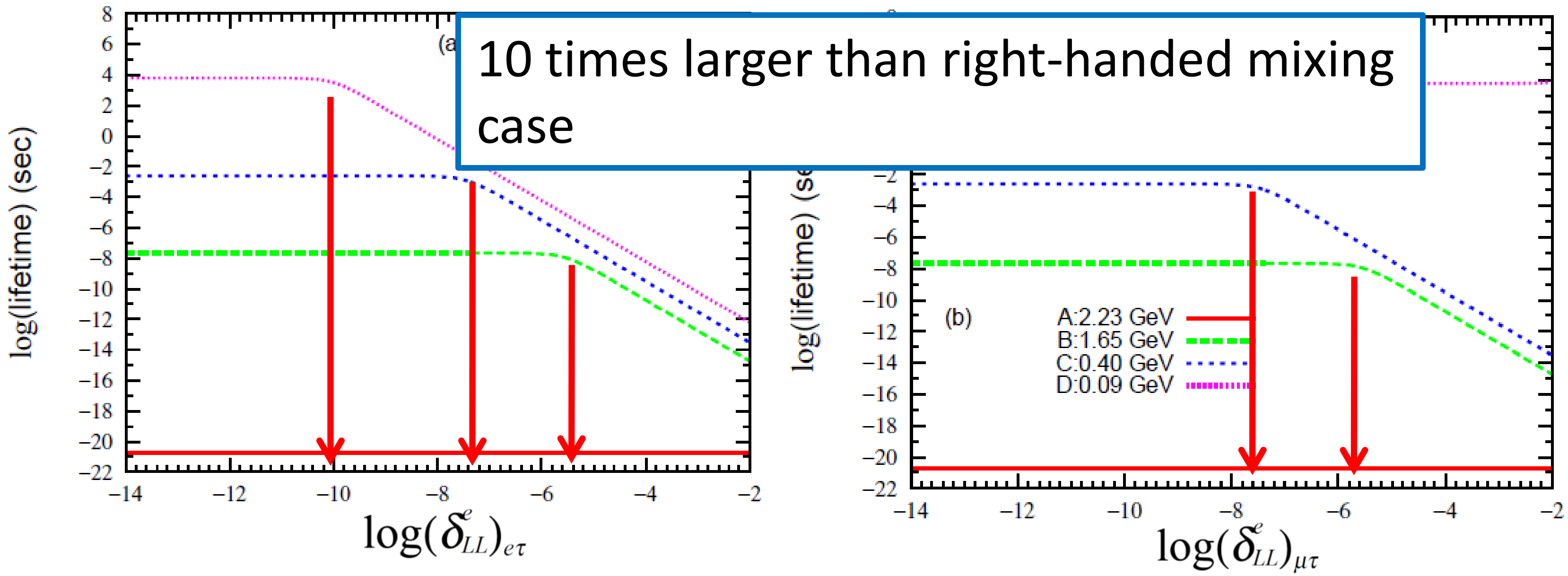
$(g-2)_\mu$ favored region

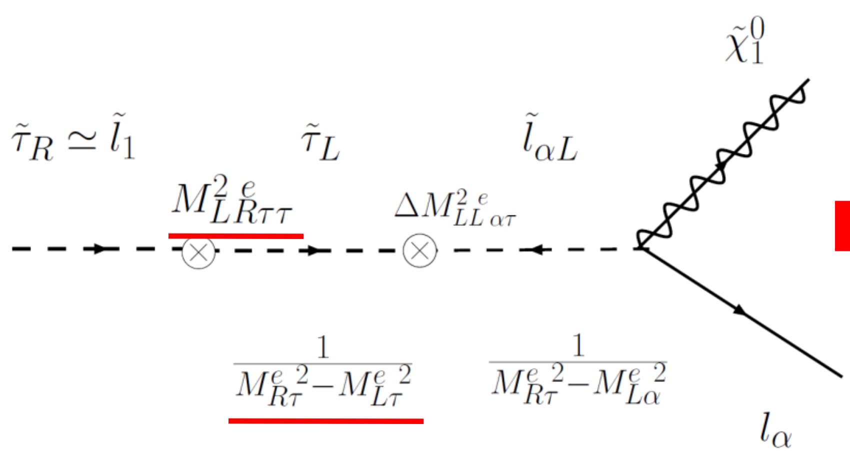
- ✓ proportional to $\tan\beta / m^2_{\tilde{\chi}^0_1}$
- ✓ maximal at $\tan\beta = 30$

Lifetime in left-handed slepton mixing case

$$(m_0 = 260\ \text{GeV},\ \ \tan\beta = 30)$$

10 times larger than right-handed mixing case





$$\frac{M^{2\ e}_{LR\tau\tau}}{M^{e\ 2}_{R\tau} - M^{e\ 2}_{L\tau}} \approx 0.1$$

Expected Number of the lightest slepton

$$\tilde{q}_L \longrightarrow \tilde{\chi}_1^{\pm} + q \quad (0.63),$$
$$\tilde{\chi}_1^{\pm} \longrightarrow \tilde{l}_1 + \nu_\tau \quad (0.64), \quad \tilde{\nu}_\tau + \tau \quad (0.27),$$
$$\tilde{\nu}_\tau \longrightarrow \tilde{l}_1 + W \quad (0.82),$$
$$\tilde{q}_L \longrightarrow \tilde{\chi}_2^{0} + q \quad (0.36),$$
$$\tilde{\chi}_2^{0} \longrightarrow \tilde{l}_1 + \tau \quad (0.66), \quad \tilde{\nu}_\tau + \nu_\tau \quad (0.25),$$

$$\tilde{t}_{1,2} \longrightarrow \tilde{\chi}_1^{\pm} + b, \quad (0.20,\ 0.25)$$
$$\tilde{\chi}_1^{\pm} \longrightarrow \tilde{l}_1 + \nu_\tau,$$
$$\tilde{t}_{1,2} \longrightarrow \tilde{\chi}_2^{0} + t, \quad (0.10,\ 0.10)$$
$$\tilde{\chi}_2^{0} \longrightarrow \tilde{l}_1 + \nu_\tau,$$
$$\tilde{b}_{1,2} \longrightarrow \tilde{\chi}_1^{\pm} + t, \quad (0.36,\ 0.12)$$
$$\tilde{\chi}_1^{\pm} \longrightarrow \tilde{l}_1 + \nu_\tau,$$
$$\tilde{b}_{1,2} \longrightarrow \tilde{\chi}_2^{0} + b, \quad (0.20,\ 0.10)$$
$$\tilde{\chi}_2^{0} \longrightarrow \tilde{l}_1 + \nu_\tau.$$

2. Long-Lived Stau in MSSM

T. Jittoh, J. Sato, **T.S.**, M. Yamanaka, PRD, 73, 055009 (2006)

Minimal Supersymmetric Standard Model (MSSM)

Assume no Lepton Flavour Violation

LSP Bino-like neutralino (**pure Bino**)

NLSP Lighter Stau (**mixture of left- and right-handed components**)

$$\tilde{\tau}_1 = \cos\theta_{\tilde{\tau}}\tilde{\tau}_L + \sin\theta_{\tilde{\tau}} e^{-i\gamma_{\tilde{\tau}}}\tilde{\tau}_R$$

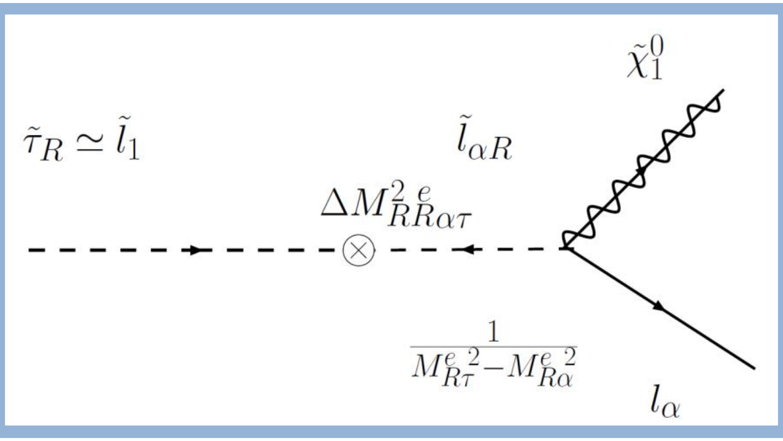
Mass difference smaller than tau mass

$$\delta m \equiv m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0} < m_\tau$$

MI approximation of decay width

2-body decay width (right-handed slepton mixing)

Proportional to the square of Mass Insertions



$$\Gamma_{2-\text{body}} = \frac{g_2^2}{2\pi m_{\tilde{\tau}_1}} (\delta m)^2 (|g^L_{1\alpha 1}|^2 + |g^R_{1\alpha 1}|^2),$$

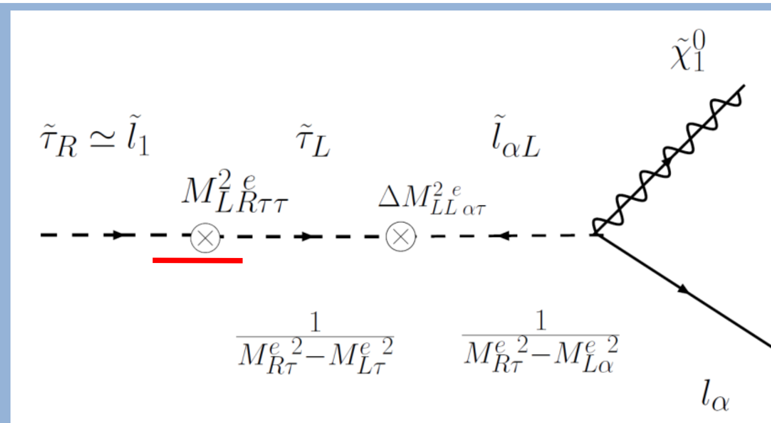
$$g^L_{1\alpha 1} \simeq 0, \quad g^R_{1\alpha 1} \simeq \tan\theta_W \frac{M^e_{R\tau} M^e_{R\alpha}}{M^{e\,2}_{R\tau} - M^{e\,2}_{R\alpha}} (\delta^e_{RR})_{\alpha\tau},$$

$$(\delta^e_{RR/LL})_{\alpha\beta} = \frac{\Delta M^{e\,2}_{RR/LL\,\alpha\beta}}{M^e_{R/L\alpha} M^e_{R/L\beta}},$$

MI approximation of decay width

2-body decay width (left-handed slepton mixing)

Proportional to the square of Mass Insertions



$$\Gamma_{2-\mathrm{body}} = \frac{g_2^2}{2\pi m_{\tilde{\tau}_1}} (\delta m)^2 (|g^L_{1\alpha 1}|^2 + |g^R_{1\alpha 1}|^2),$$

$$g^L_{1\alpha 1} \simeq \frac{1}{2} \tan\theta_W \frac{m_\tau (A_0 - \mu \tan\beta)}{M^{e\;2}_{R\tau} - M^{e\;2}_{L\tau}} \frac{M^e_{L\alpha} M^e_{R\tau}}{M^{e\;2}_{R\tau} - M^{e\;2}_{L\alpha}} (\delta^e_{LL})_{\alpha\tau}, \quad g^R_{1\alpha 1} \simeq 0.$$

$$(\delta^e_{RR/LL})_{\alpha\beta} = \frac{\Delta M^{e\;2}_{RR/LL\,\alpha\beta}}{M^e_{R/L\alpha} M^e_{R/L\beta}},$$

Typical size of δ^e's in various models

- Supersymmetric Seesaw mechanism

  Induced δ^e depends on the neutrino Yukawa couplings

  Large (MNS-like) mixing with $y_3 \simeq y_t \simeq 1$

  $$(\delta^e_{LL})_{e\tau} \simeq 0.1\ U_{e3} \qquad (\delta^e_{LL})_{\mu\tau} \simeq 0.05$$

  $\tau_{\tilde{l}_1} \sim 10^{-10}$ to 10^{-13} sec.

  Small (CKM-like) mixing

  $$(\delta^e_{LL})_{e\tau} \simeq 0.0008 \qquad (\delta^e_{LL})_{\mu\tau} \simeq 0.004$$

  $\tau_{\tilde{l}_1} \sim 10^{-12}$ to 10^{-14} sec.

- SU(3) flavour symmetry in SUSY

  $$(\delta^e_{RR})_{e\tau} \simeq 0.001,\ (\delta^e_{RR})_{\mu\tau} \simeq 0.02$$

  $$(\delta^e_{LL})_{e\tau} \simeq 0.0008 \quad (\delta^e_{LL})_{\mu\tau} \simeq 0.004$$

  $\tau_{\tilde{l}_1} \sim 10^{-10}$ to 10^{-16} sec.

Expected decays in the ATLAS detector

	Pixel detector	SCT	TRT	Calori-meter	Muon detector
	5 cm	50 cm	3.1 m	5.8 m	25.0 m
10^{-5} sec.	0.04	0.36	2.2	4.1	17.8
10^{-6} sec.	0.36	3.6	22.1	41.3	175.1
10^{-7} sec.	3.6	35.6	216.0	395.3	1461.9
10^{-8} sec.	35.6	343.0	1731.0	2658.3	4223.5
10^{-9} sec.	343.0	2425.6	4265.5	4289.7	4290.0
10^{-10} sec.	2425.6	4289.0	4290.0	4290.0	4290.0
10^{-11} sec.	4289.0	4290.0	4290.0	4290.0	4290.0
10^{-12} sec.	4290.0	4290.0	4290.0	4290.0	4290.0

All of the slepton would decay before they reach the inner detector

No signal of heavy charged-particle track would be observed

Expected decays in the ATLAS detector

	Pixel detector	SCT	TRT	Calori-meter	Muon detector
	5 cm	50 cm	3.1 m	5.8 m	25.0 m
10^{-5} sec.	0.04	0.36	2.2	4.1	17.8
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10^{-11} sec.	4289.0	4290.0	4290.0	4290.0	4290.0
10^{-12} sec.	4290.0	4290.0	4290.0	4290.0	4290.0

Half of the slepton would decay inside the inner detector and the other half would decay inside calorimeter and muon detector

When δm is close to tau mass, it is important to identify two-body decay to determine the values of LFV parameters

Expected decays in the ATLAS detector

	Pixel detector	SCT	TRT	Calori-meter	Muon detector
	5 cm	50 cm	3.1 m	5.8 m	25.0 m
10^{-5} sec.	0.04	0.36	2.2	4.1	17.8
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10^{-11} sec.	4289.0	4290.0	4290.0	4290.0	4290.0
10^{-12} sec.	4290.0	4290.0	4290.0	4290.0	4290.0

A few to hundred sleptons would decay inside the inner detector and most of them would escape

- ✓ The lifetime would be measured
- ✓ Mass and momentum of the slepton could be determined with muon detector