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

Takashi Shimomura
Departament de Física Teòrica
Universitat de València

In collaboration with

S. Kaneko (CFTP, Portugal)
J. Sato and M. Yamanaka (Saitama Univ., Japan)
O. Vives (Univ. Valencia, Spain)

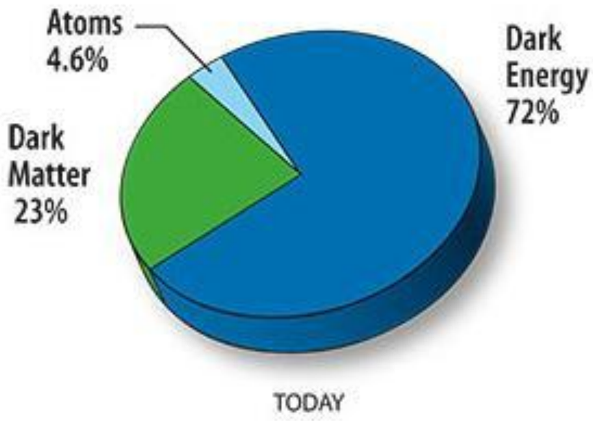
WMAP Experiment

About 23% of the total energy density

Non baryonic matter

No candidate in the SM particles

(not emitting a light = dark matter)



Dark matter candidate

Neutralino LSP (SUSY+R parity)

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

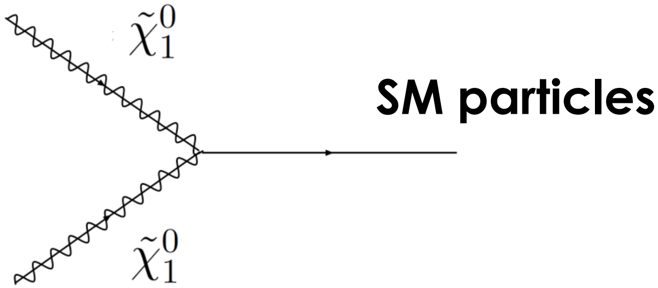
Coannihilation Mechanism

Naively, neutralino relic abundance is larger

Pair-annihilation process

Too weak

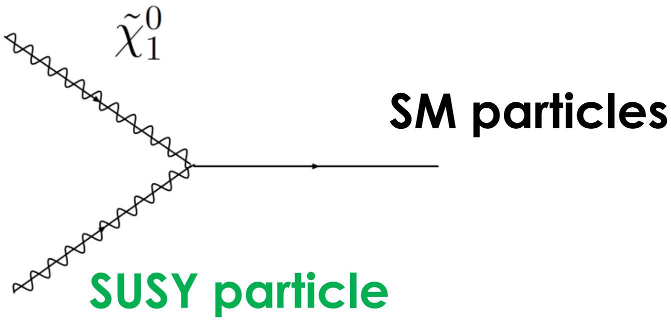
(in most of parameter space)



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

Coannihilation process

Effectively reduce the abundance



"Rather tight" degeneracy between neutralino and SUSY particle

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

Degenerate neutralino LSP and slepton NLSP

Constrained MSSM

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

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

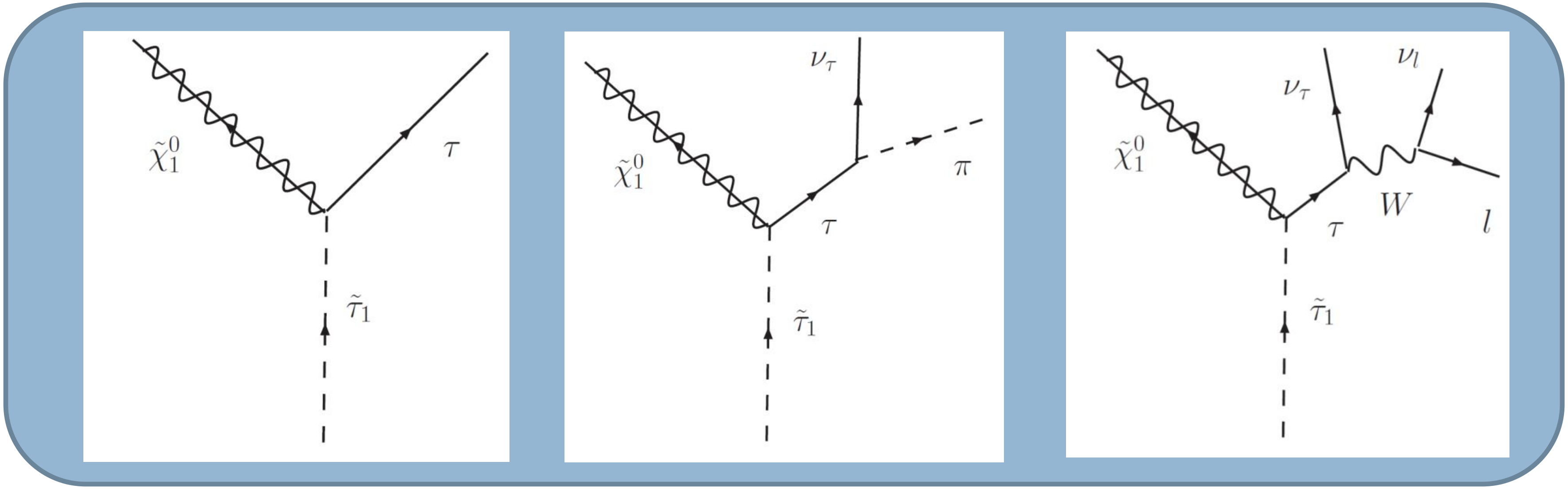
- **Stau NLSP becomes long-lived**

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

- **Slepton lifetime is sensitive to small LFV couplings**

2. Long-Lived Stau in CMSSM (No LFVs)

NLSP stau decays



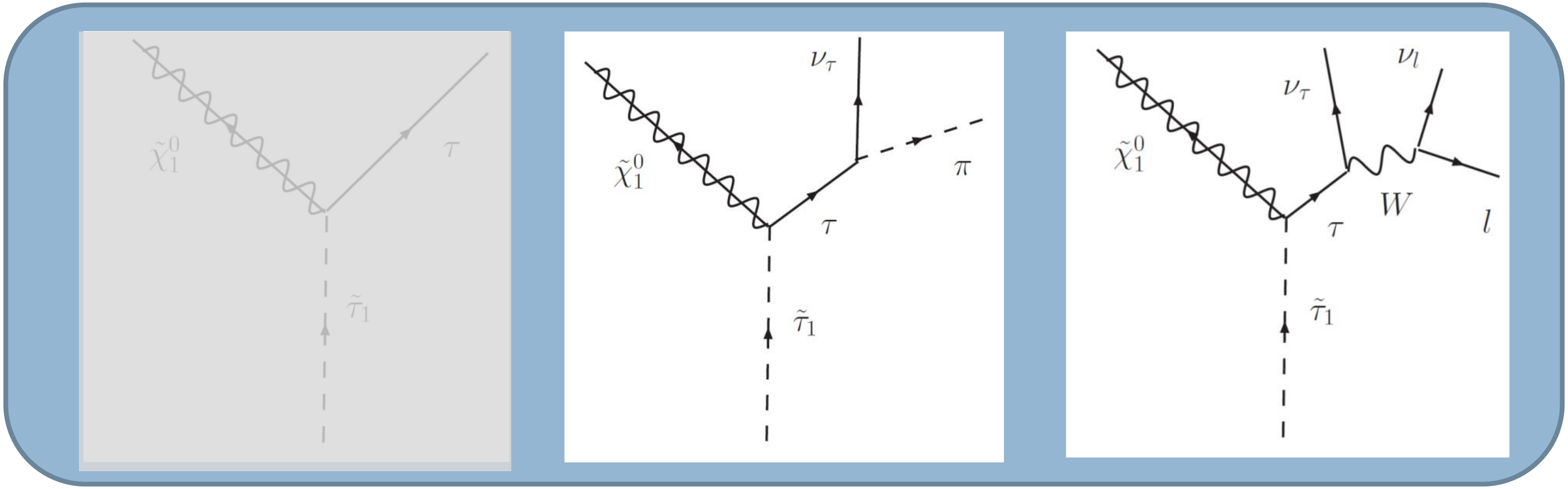
- **When δm > tau mass, two-body decay is dominant**

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

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

2. Long-Lived Stau in CMSSM (No LFVs)

NLSP stau decays



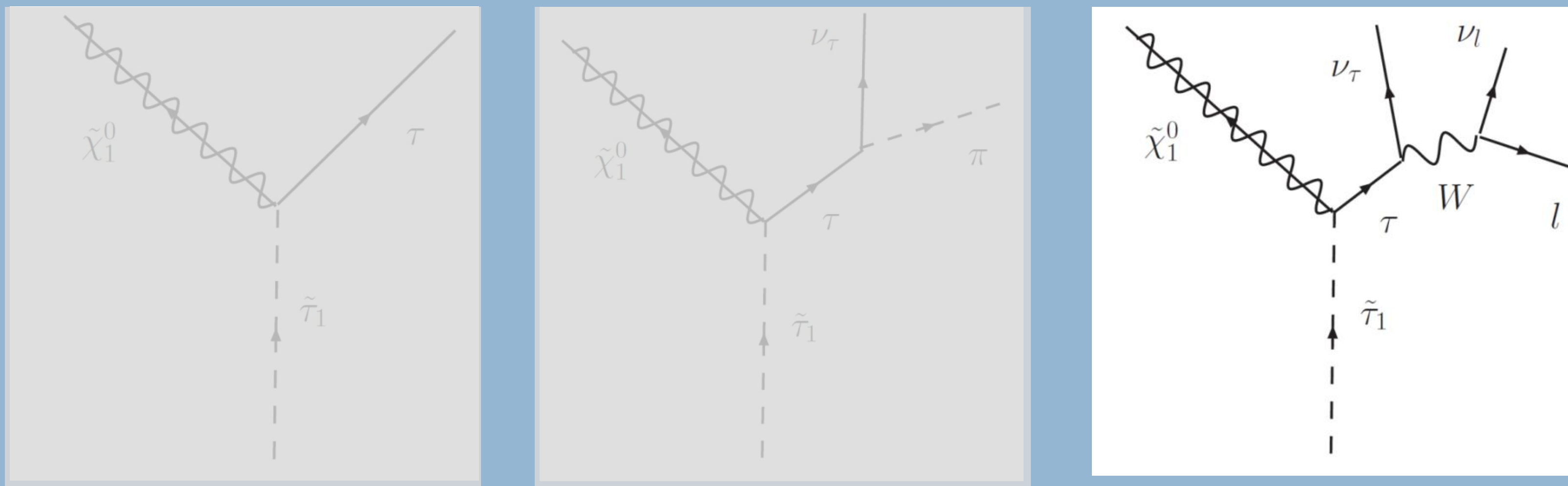
- **When δm < tau mass, two-body decay channel is close.**
- **Three body decay is dominant**

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

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

13 order smaller !

NLSP stau decays



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

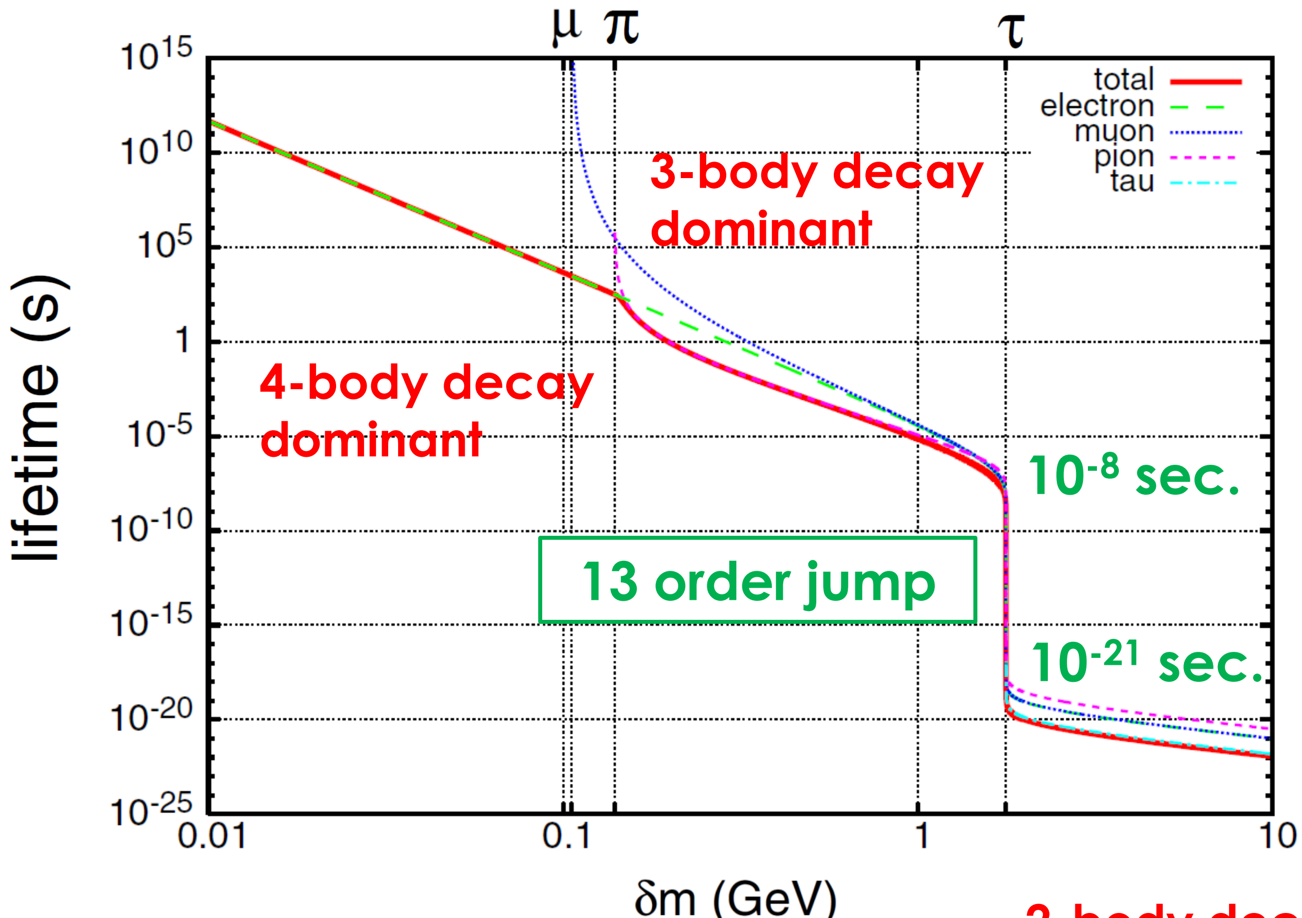
$$\Gamma_{4-\mathrm{body}} \simeq \frac{2}{3}\frac{g_2^2 G_F^2 \tan^2\theta_W}{5^3(2\pi)^5 m_{\tilde{\tau}_1} m_\tau^2}\delta m\left((\delta m)^2 - m_l^2\right)^{5/2}\left(2(\delta m)^2 - 23 m_l^2\right)$$

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

13 order smaller !

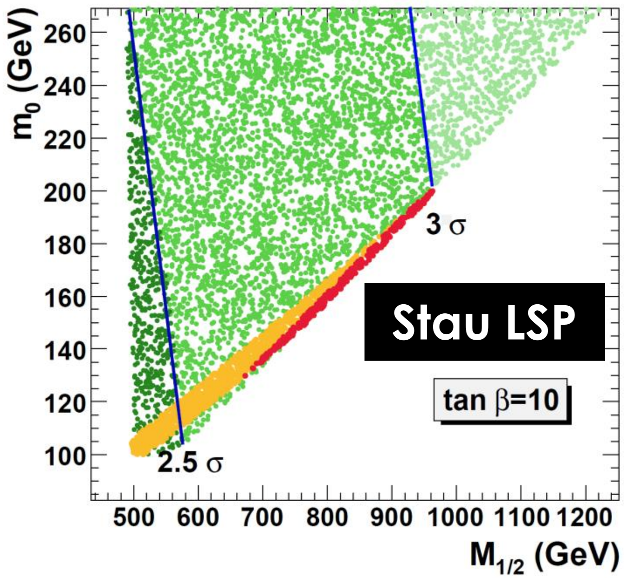
δm dependence of stau lifetime

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

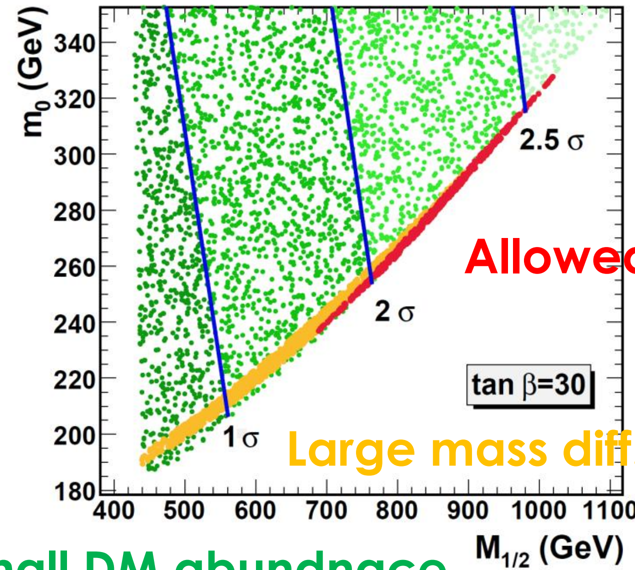


2-body decay dominant

Allowed parameter space in CMSSM



Large DM abundance

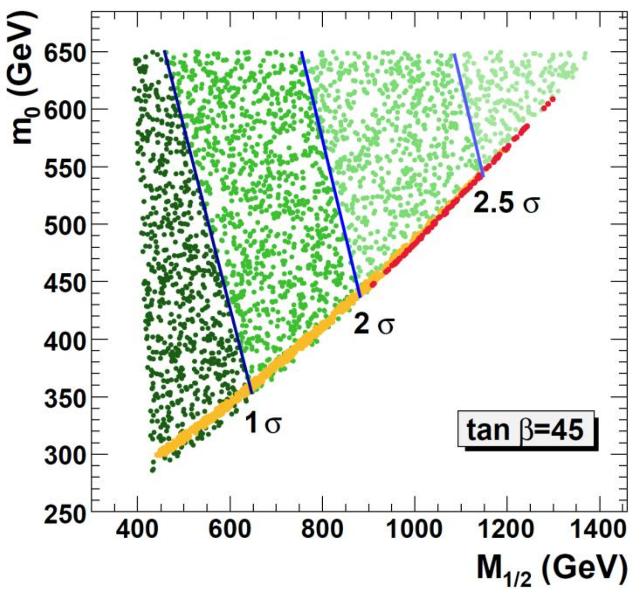


Muon (g-2)

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 $(g-2)_\mu$

3. LFV and Long-Lived Slepton

kaneko, Sato, T.S., Vives, Yamanaka, arXiv:0811.0703

Lepton flavour violation in slepton sector is naturally expected to exist

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

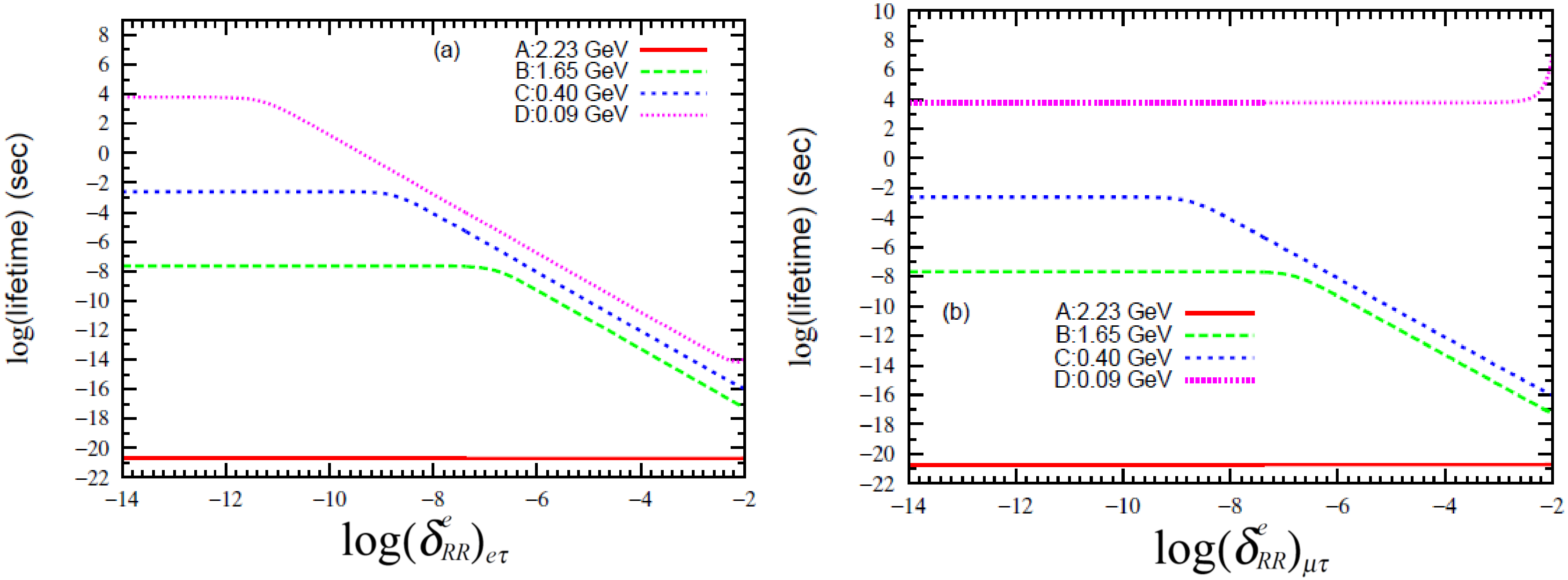
2-body decay channel is open even if $\delta m < m_\tau$

- **LFV decays becomes dominant decays**
- **Lepton Flavour Conserving processes are suppressed**

The lifetime of the slepton shows a good sensitivity to small LFV parameters

Lifetime in right-handed slepton mixing case

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



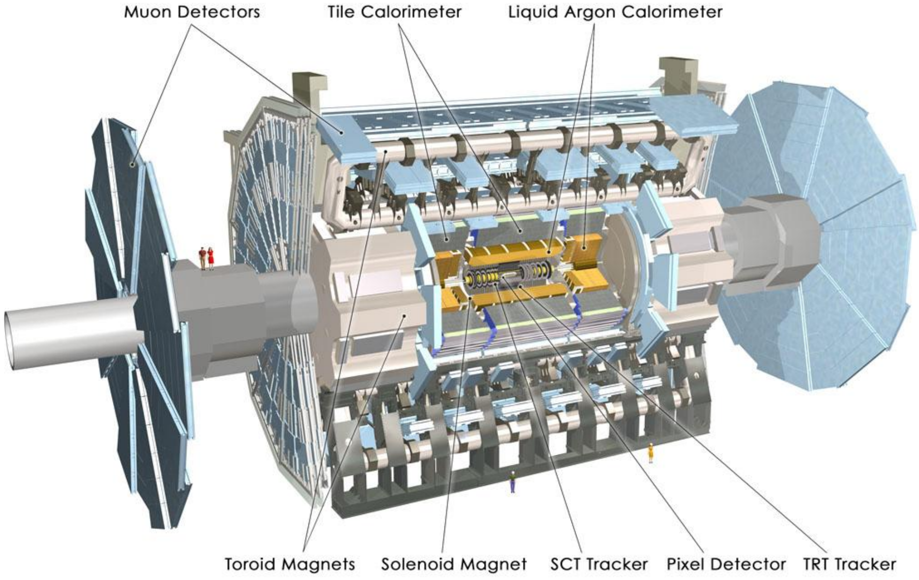
No.	δm (GeV)	$m_{\tilde{\chi}^0_1}$ (GeV)	$m_{\tilde{l}_1}$ (GeV)	$\Omega_{\tilde{\chi}^0_1} h^2$	a_μ ($\times 10^{-10}$)
A	2.227 ($> m_\tau$)	323.1549	325.3817	0.110	10.32
B	1.650 ($< m_\tau$)	325.5601	326.2147	0.102	10.25
C	0.407	327.6294	328.0365	0.085	10.09
D	0.092 ($< m_\mu$)	328.4060	328.4981	0.081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

4. 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 — $\sigma_{\rm SUSY} = 130$ fb.
  P. Z. Skands, Eur. Phys. J. C 23, 173 (2002)
- ✓ Integrated Luminosity — $\mathcal{L}_{\rm int} = 30\ {\rm fb}^{-1}$
  $\mathcal{L} = 10^{33}\ {\rm cm}^{-2}\ {\rm s}^{-1}$, 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

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

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
10^{-12} sec.	4290.0	4290.0	4290.0	4290.0	4290.0

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

Almost all the slepton would decay inside the inner detector

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

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

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

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

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

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

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

5. 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 lifetime of stau can be very long.
   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).

$$240 \lesssim m_0 \lesssim 260 \text{ GeV and } 700 \lesssim M_{1/2} \lesssim 800 \text{ GeV at } \tan\beta = 30$$

5. Summary

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.
If the lifetime is beteen 10^{-10} to10^{-9} sec., LFV couplings could be determined.

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

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

Back up slides

SUSY particles' spectrum

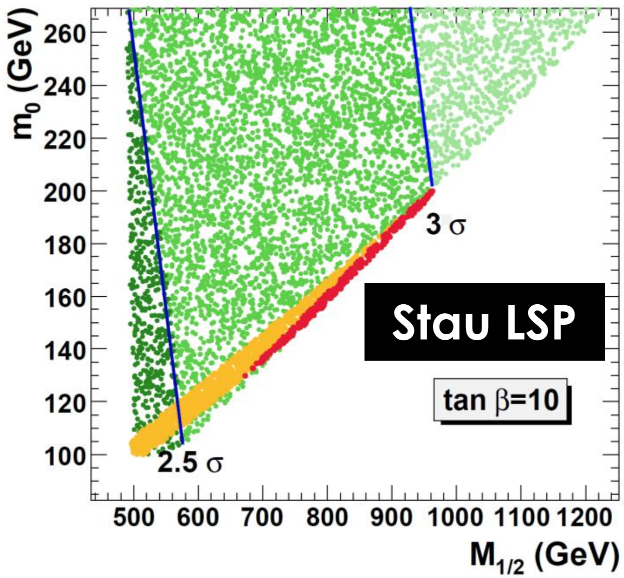
	mass (GeV)		mass (GeV)
$\tilde{\chi}_1^0$	290 – 320	$\tilde{\chi}_2^0$	540 – 600
$\tilde{\chi}_3^0$	750 – 820	$\tilde{\chi}_4^0$	770 – 830
$\tilde{\chi}_1^\pm$	540 – 600	$\tilde{\chi}_2^\pm$	770 – 830
$\tilde{g}$	1540 – 1680		
$\tilde{t}_1$	1150 – 1260	$\tilde{t}_2$	1330 – 1460
$\tilde{b}_1$	1300 – 1420	$\tilde{b}_2$	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

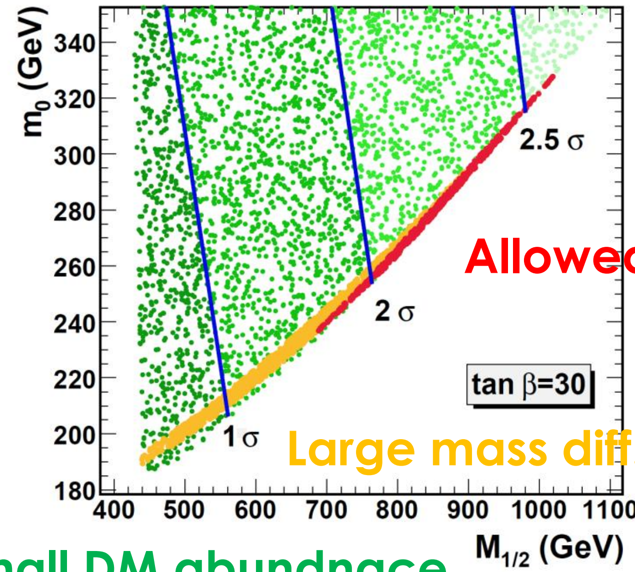
Dark matter abundance	$0.08 < \Omega_{\rm DM} h^2 < 0.14,$
Higg mass limit	$m_h \gtrsim 114\ {\rm GeV}$
Bound on ${\rm Br}(b \to s\gamma)$	$2.5 \times 10^{-4} < {\rm Br}(b \to s\gamma) < 4.5 \times 10^{-4}$
Muon $(g-2)_\mu$	$\Delta a_\mu = a_\mu^{(\rm exp)} - a_\mu^{(SM)} = (27.5 \pm 8.4) \times 10^{-10}$

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

Allowed parameter space in mSUGRA MSSM



Large DM abundance



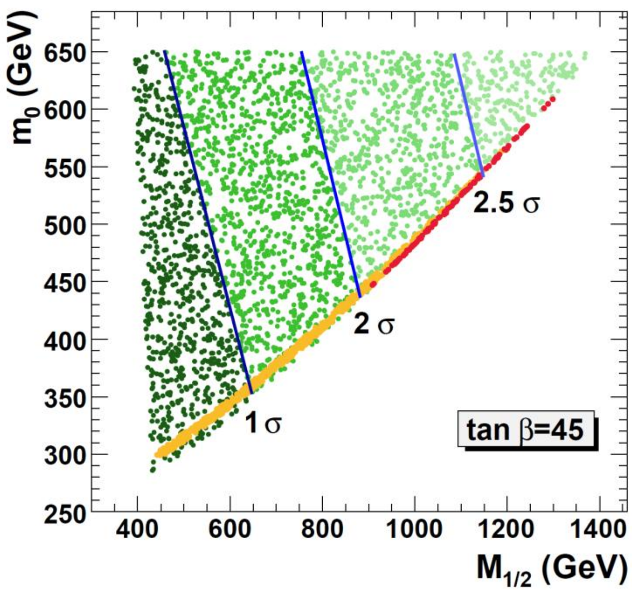
Muon (g-2)

Allowed region

Large mass diff.

Small DM abundnace

(allowed if other DM components exist)

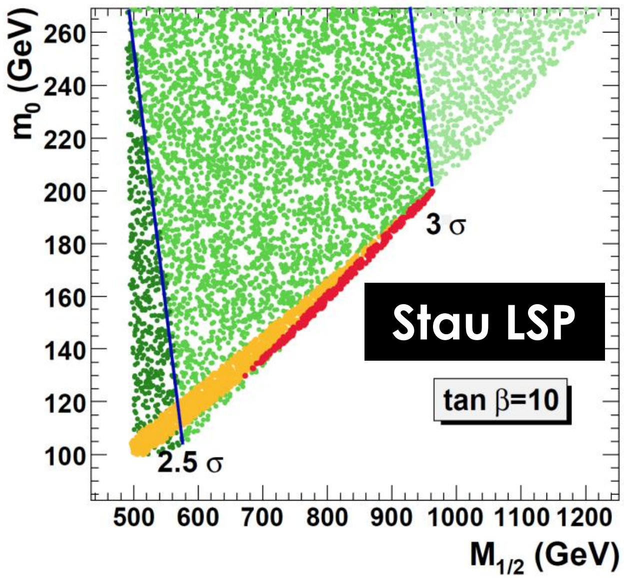


Sign(μ) > 0

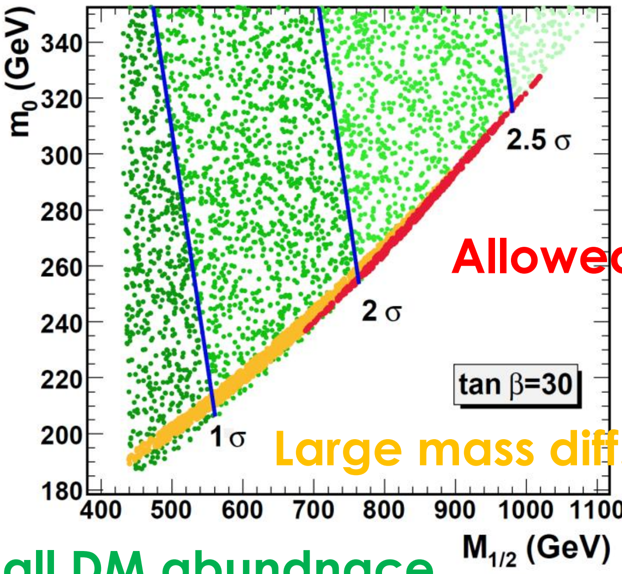
A_0 – large & positive

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

Allowed parameter space in mSUGRA MSSM



Large DM abundance

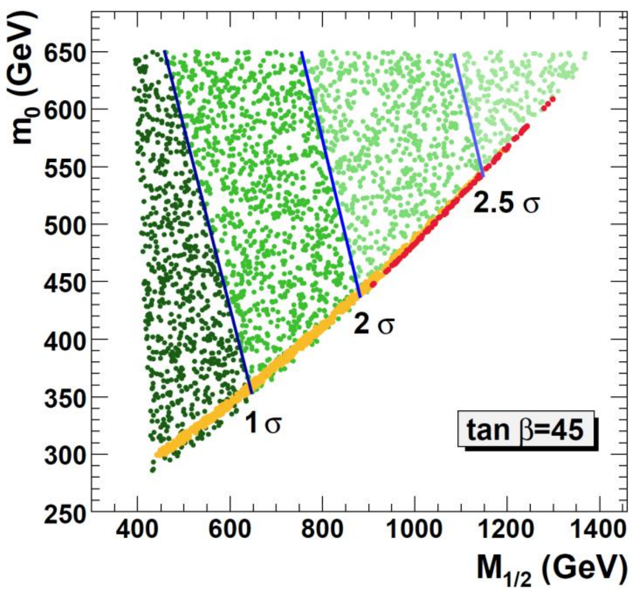


Muon (g-2)

Allowed region

Large mass diff.

Small DM abundnace
(allowed if other DM components exist)



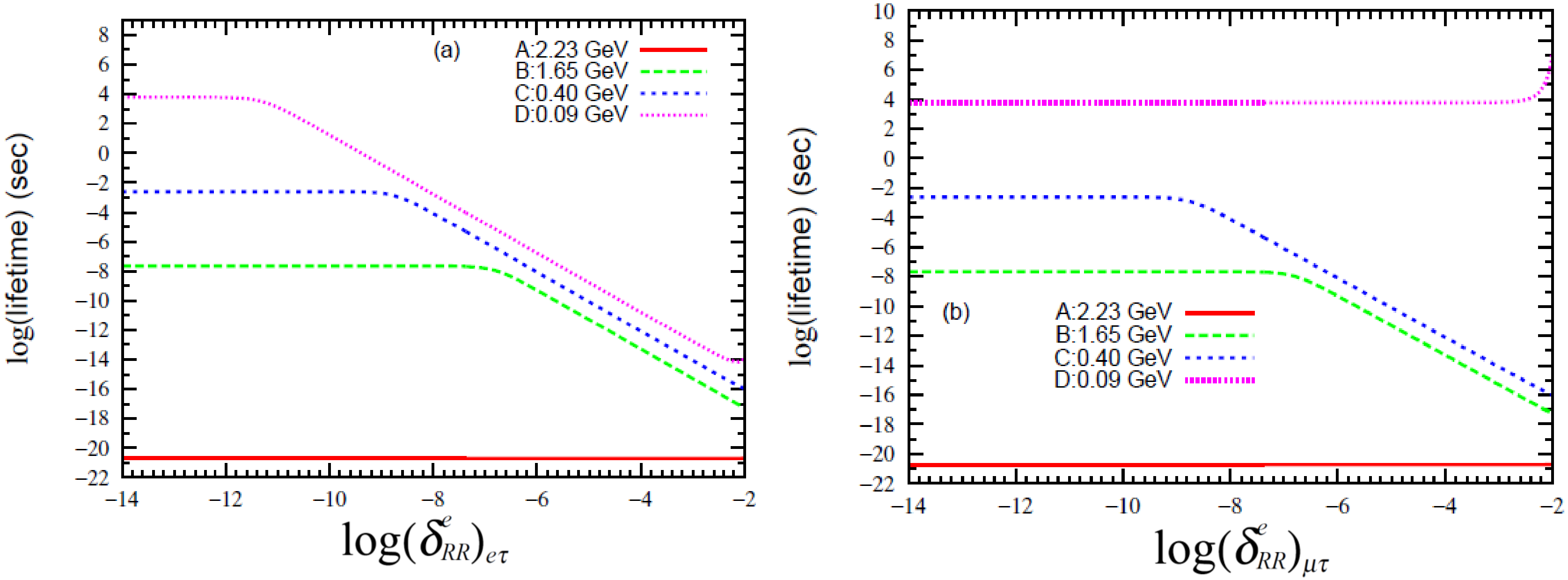
$\delta m < m_\tau$ region

- ✓ relatively large $M_{1/2}$

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

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

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



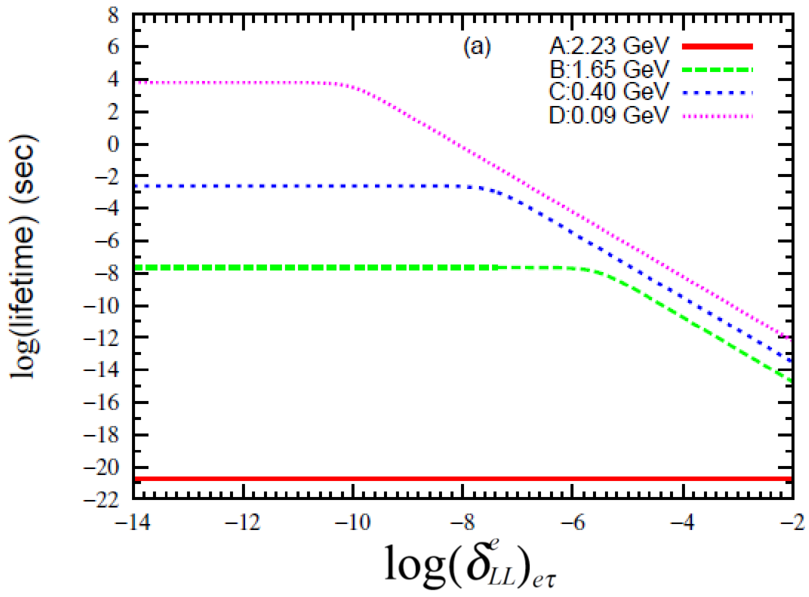
Present bound on δ's (m_0=260 GeV, $M_{1/2}$=750 GeV)

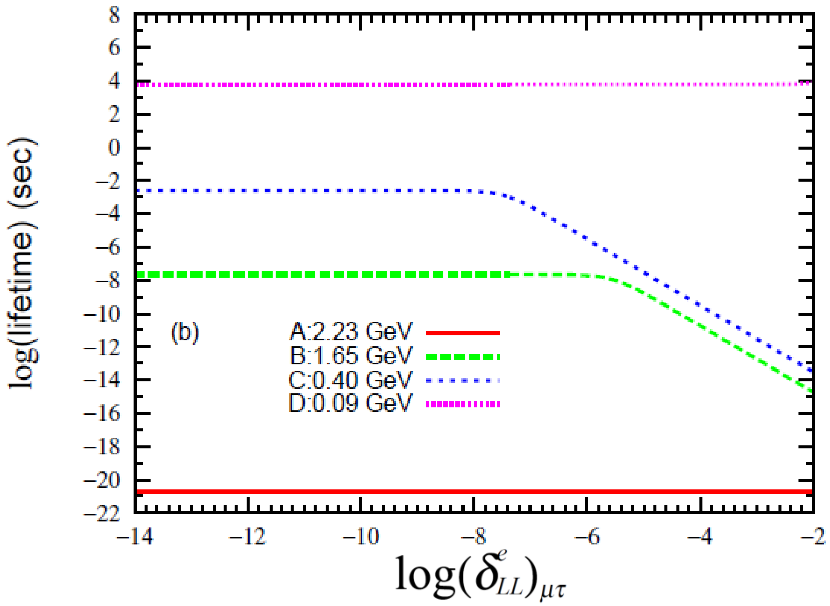
	$\tan\beta = 10$			$\tan\beta = 30$			$\tan\beta = 45$		
	$\delta^e_{e\mu}$	$\delta^e_{e\tau}$	$\delta^e_{\mu\tau}$	$\delta^e_{e\mu}$	$\delta^e_{e\tau}$	$\delta^e_{\mu\tau}$	$\delta^e_{e\mu}$	$\delta^e_{e\tau}$	$\delta^e_{\mu\tau}$
LL	0.0014	0.33	0.21	0.00047	0.10	0.068	0.00030	0.067	0.043
RR	0.0060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

Thanks to J. Jones-Perez

Lifetime in left-handed slepton mixing case

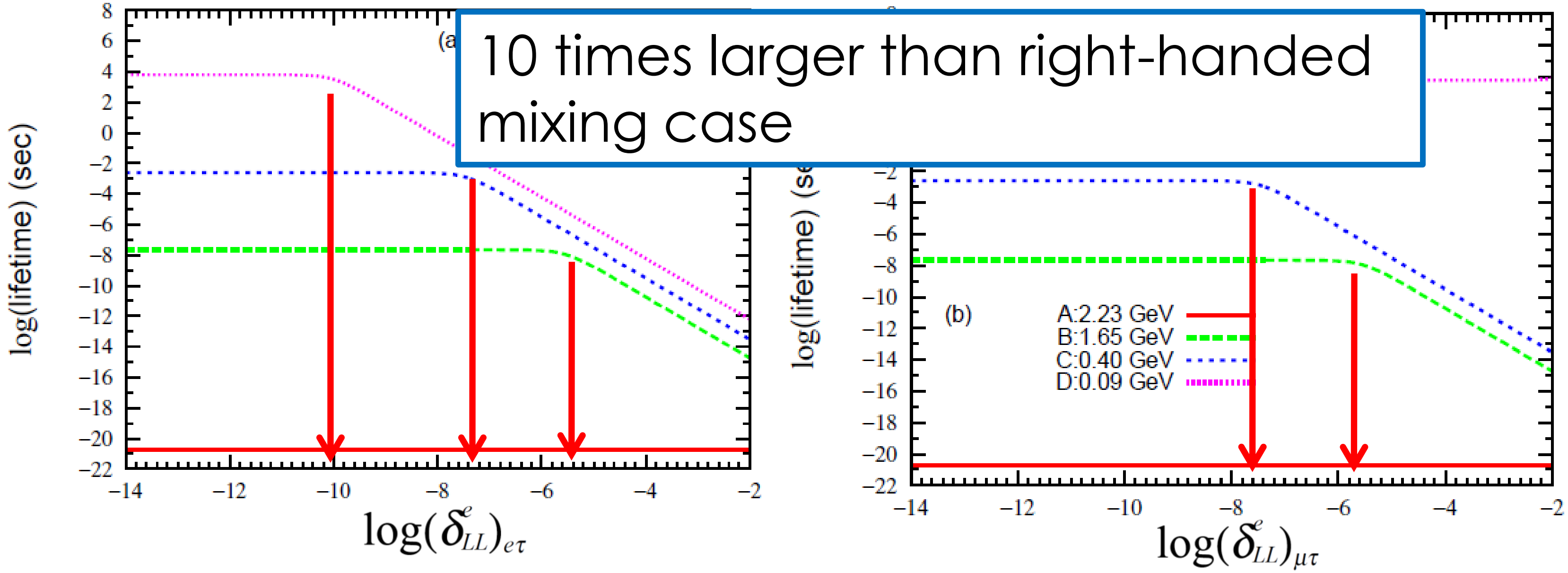
$$(m_0 = 260\ \mathrm{GeV},\quad \tan\beta = 30)$$

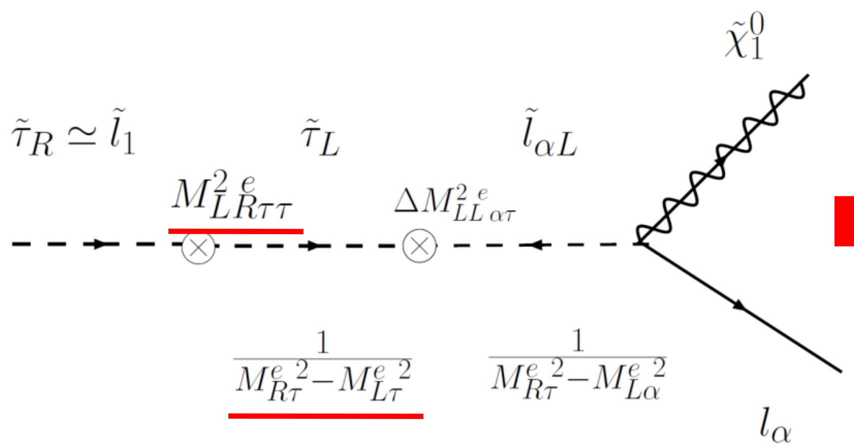




Lifetime in left-handed slepton mixing case

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

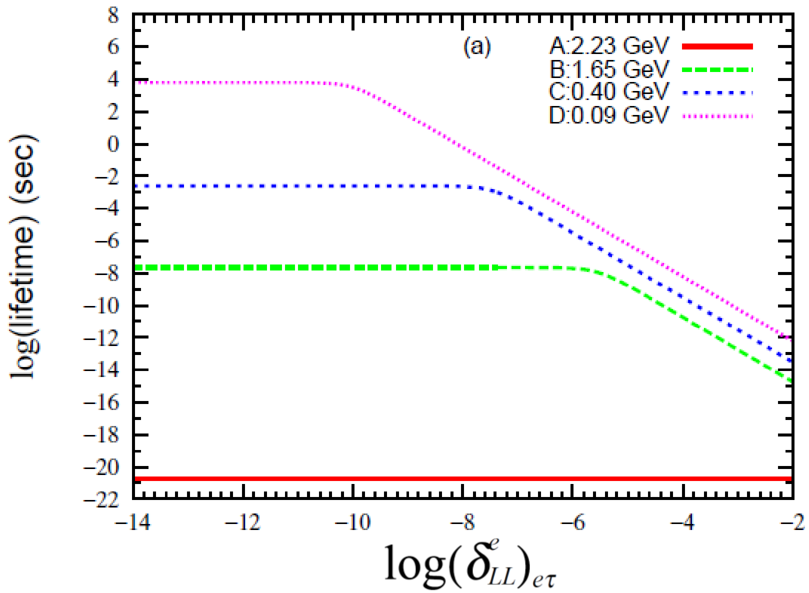


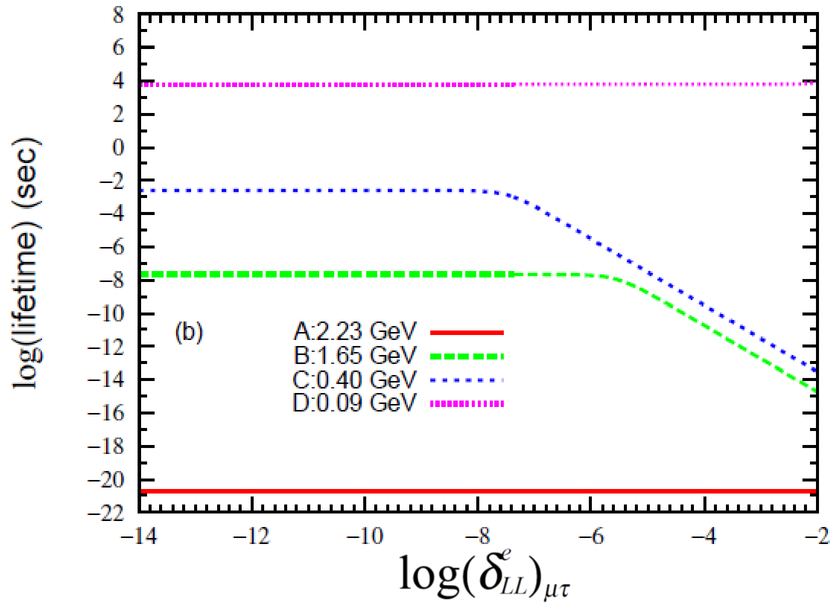


$$\frac{M^{2\ e}_{LR\tau\tau}}{M^{e\ 2}_{R\tau} - M^{e\ 2}_{L\tau}} \approx 0.1$$

Lifetime in left-handed slepton mixing case

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





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

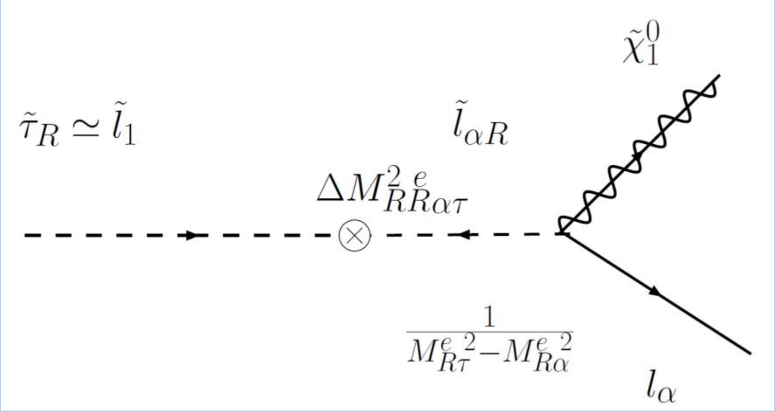
	$\tan\beta = 10$			$\tan\beta = 30$			$\tan\beta = 45$		
	$\delta^e_{e\mu}$	$\delta^e_{e\tau}$	$\delta^e_{\mu\tau}$	$\delta^e_{e\mu}$	$\delta^e_{e\tau}$	$\delta^e_{\mu\tau}$	$\delta^e_{e\mu}$	$\delta^e_{e\tau}$	$\delta^e_{\mu\tau}$
LL	0.0014	0.33	0.21	0.00047	0.10	0.068	0.00030	0.067	0.043
RR	0.0060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

Thanks to J. Jones-Perez

MI approximation of decay width

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

Proportional to the square of Mass Insertions



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

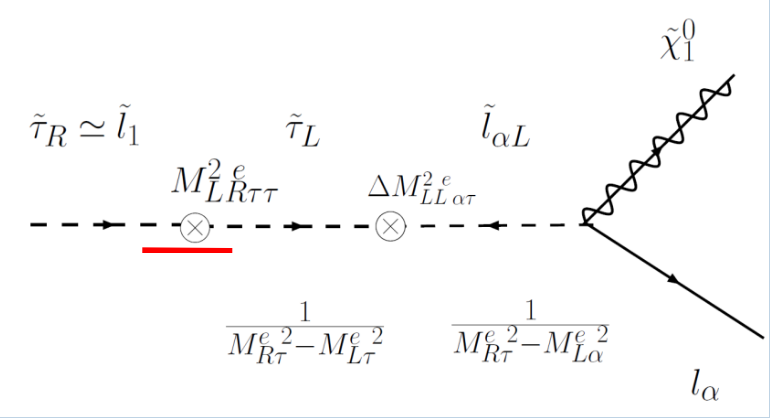
$$g^L_{1\alpha 1} \simeq 0, \quad g^R_{1\alpha 1} \simeq \tan\theta_W \frac{M^e_{R\tau} M^e_{R\alpha}}{M^{e\,2}_{R\tau} - M^{e\,2}_{R\alpha}} (\delta^e_{RR})_{\alpha\tau},$$

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

MI approximation of decay width

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

Proportional to the square of Mass Insertions



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

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

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

Expected Number of the lightest slepton

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

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

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
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

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

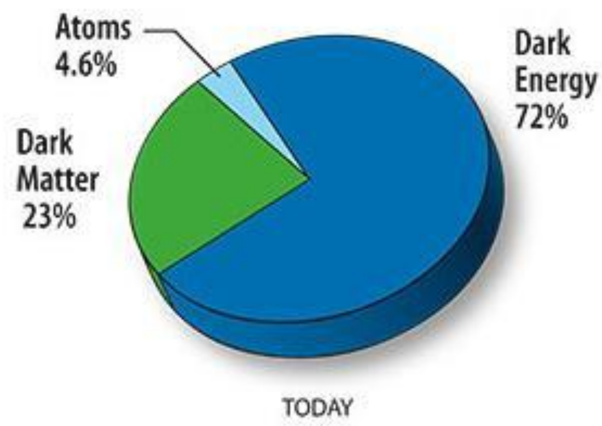
WMAP Experiment

Only 4.6% of the total energy density
Baryonic matter

About 23% of the total energy density

Non baryonic matter
(not emitting a light = dark matter)

No candidate in the SM particles



http://map.gsfc.nasa.gov/

Nature of the Dark matter

- ✓ **Electrically (and color) neutral**
- ✓ **massive (>100 GeV)**
- ✓ **Weakly Interacting**
- ✓ **(Almost) Stable**

Dark Matter Candidates in SUSY

Supersymmetric Models with conserved R parity

→ Lightest Supersymmetric Particle (LSP) is **stable**

neutralino → **dark matter candidate**

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

LSPs

Bino-like neutralino	(Supergravity mediation)
Gravitino	(Gauge mediation)
Wino-like neutralino	(Anomaly mediation)

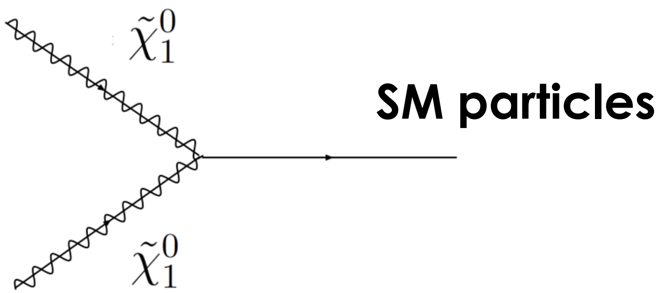
Coannihilation Mechanism

Naively, neutralino relic abundance is larger

Pair-annihilation process

Too weak

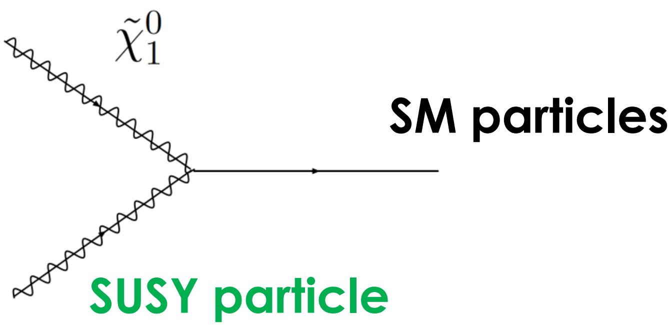
(in most of parameter space)



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

Coannihilation process

Effectively reduce the abundance



"Rather tight" degeneracy between neutralino and SUSY particle

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

Degenerate neutralino LSP and slepton NLSP

Next Lightest Supersymmetric Particle (NLSP) in most of mSUGRA parameter space

NLSP = the lightest slepton
(right-handed stau)

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

- **Very good sensitivity to small LFV couplings**

  (Main Part of Today's Talk)

- **A solution to ^{7}Li problem**

  Jittoh, Kohri, Koike, Sato, **T.S.**, Yamanaka, PRD, 76, 125023 (2007) & PRD, 78, 055007 (2008)

  (One of motivation)

Table of Talk

1. Introduction
2. **Long-Lived Stau in MSSM**
3. **Lepton Flavour Violation**
4. **LHC phenomenology**
5. **Summary**
6. **Future Work**

2. Long Lived Stau in MSSM

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**)

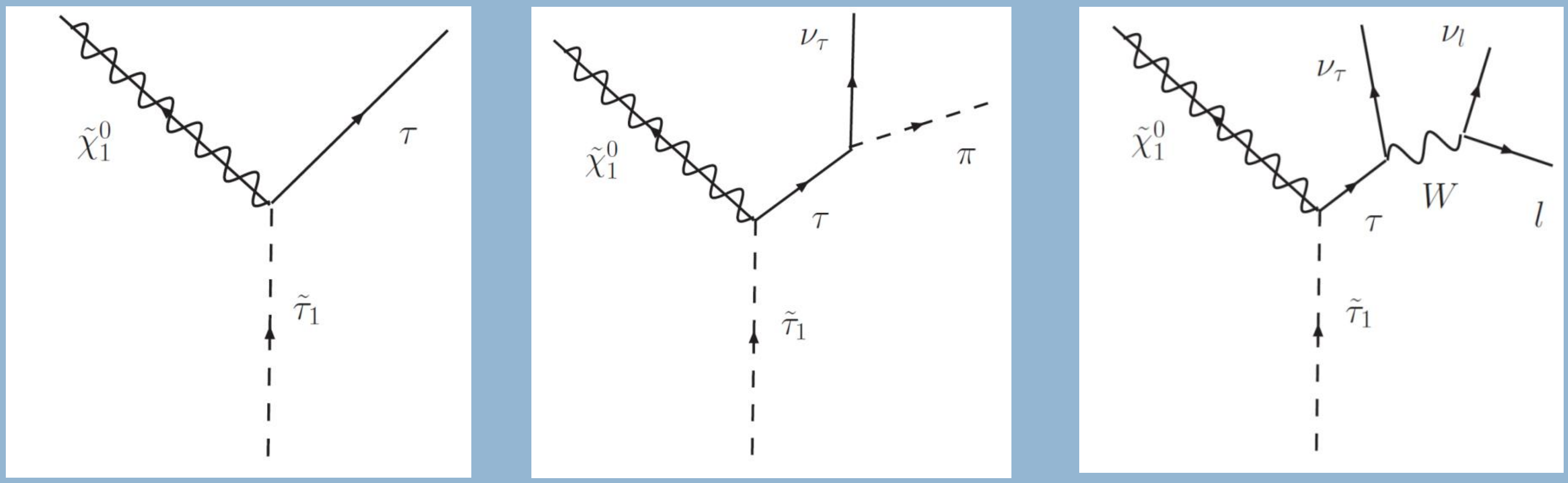
$$\tilde{\tau}_1 = \cos\theta_{\tilde{\tau}} \tilde{\tau}_L + \sin\theta_{\tilde{\tau}} e^{-i\gamma_{\tilde{\tau}}} \tilde{\tau}_R$$

Mass difference smaller than tau mass

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

2. Long-Lived Stau in CMSSM

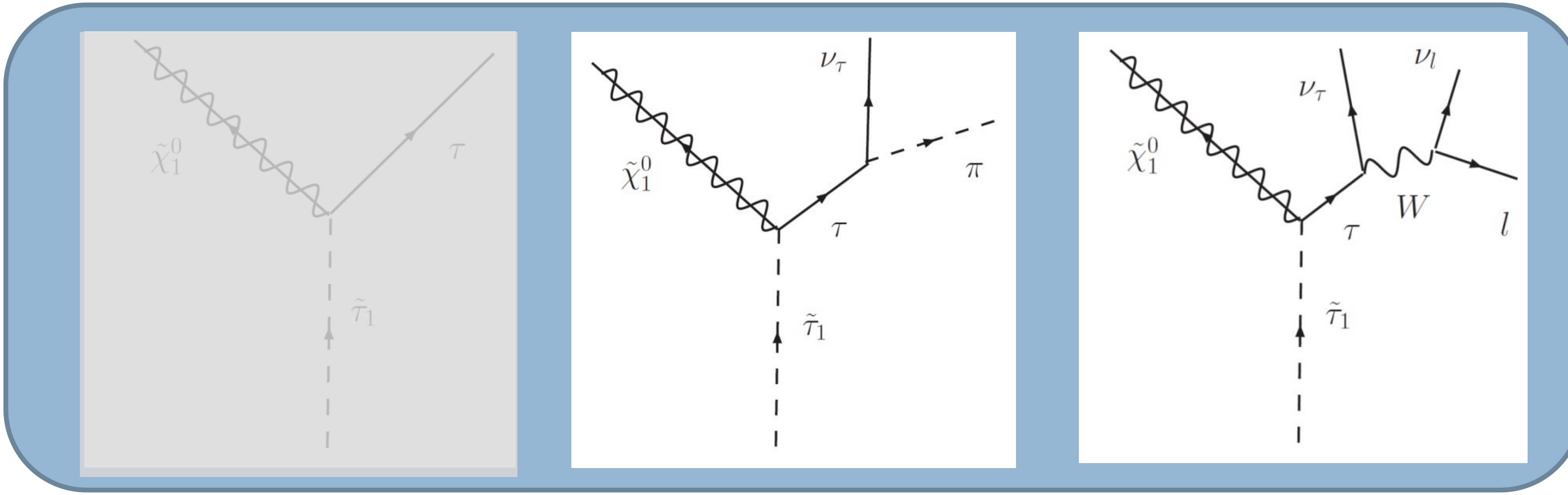
NLSP stau decays



- **When δm > tau mass, all three decay channels are open.**
- **Two-body decay is dominant**

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

NLSP stau decays



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

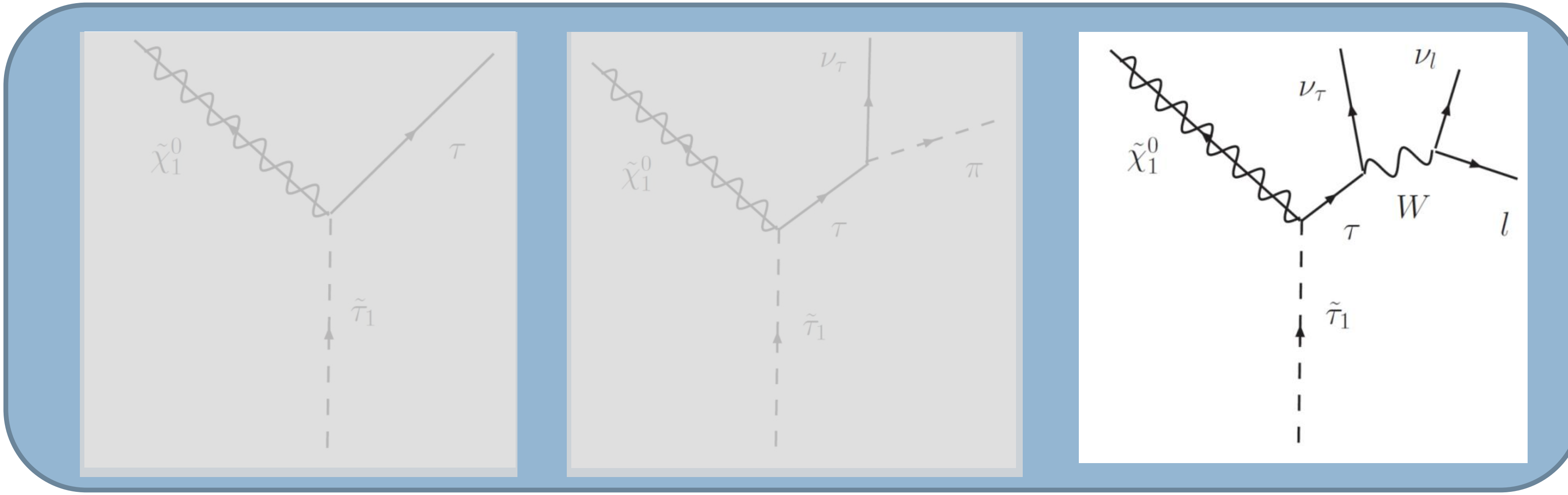
$$\Gamma_{3-\text{body}} \simeq \frac{g_2^2 G_F^2 f_\pi^2 \cos^2\theta_c \tan^2\theta_W}{30(2\pi)^3 m_{\tilde{\tau}_1} m_\tau^2}\, \delta m\left((\delta m)^2 - m_\pi^2\right)^{5/2}$$

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

13 order smaller !

2. Long-Lived Stau in CMSSM

NLSP stau decays



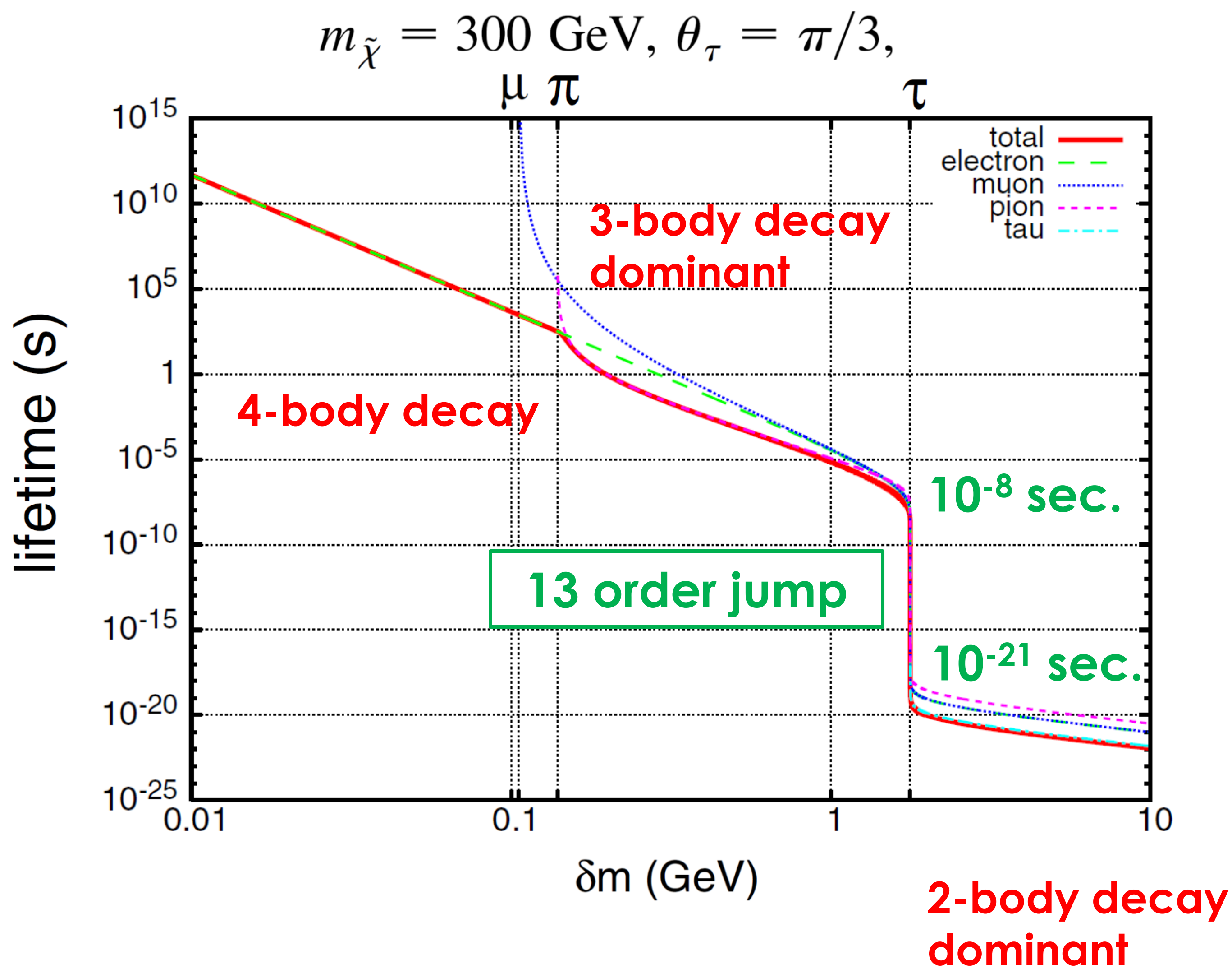
- **When δm < pion mass, three body decay is also close.**
- **Four body decays are dominant**

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

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

13 order smaller !

δm dependence of stau lifetime



3. LFV with Long-Lived Slepton

3. LFV and Long-Lived Slepton

kaneko, Sato, **T.S.**, Vives, Yamanaka, arXiv:0811.0703

Lepton flavour violation in slepton sector is naturally expected to exist

Examples)

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

2-body decay channel is open even if $\delta m < m_\tau$

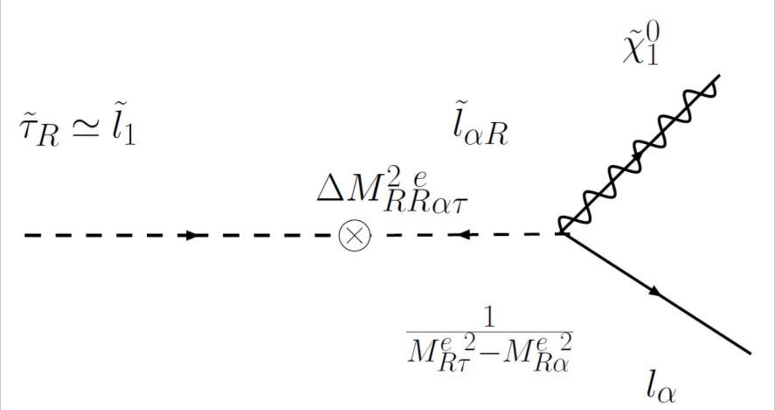
- **LFV decays becomes dominant decays**
- **Lepton Flavour Conserving processes are suppressed**

The lifetime of the slepton shows a good sensitivity to small LFV parameters

MI approximation of decay width

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

Proportional to the square of Mass Insertions



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

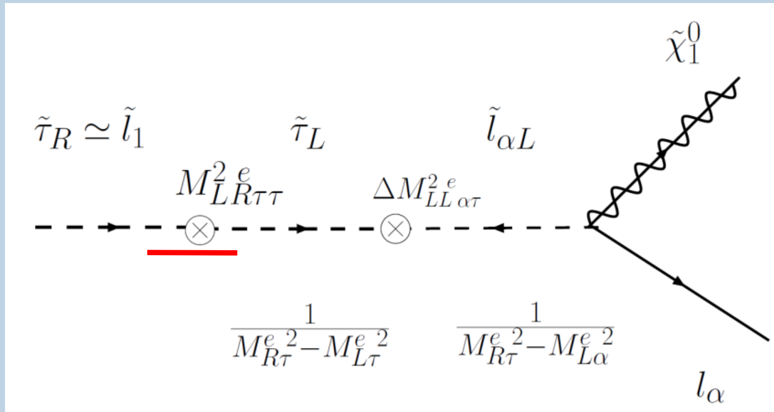
$$g^L_{1\alpha 1} \simeq 0, \quad g^R_{1\alpha 1} \simeq \tan\theta_W \frac{M^e_{R\tau} M^e_{R\alpha}}{M^{e\ 2}_{R\tau} - M^{e\ 2}_{R\alpha}} (\delta^e_{RR})_{\alpha\tau},$$

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

MI approximation of decay width

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

Proportional to the square of Mass Insertions



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

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

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

Setup

Model independent analysis of the lifetime of the slepton

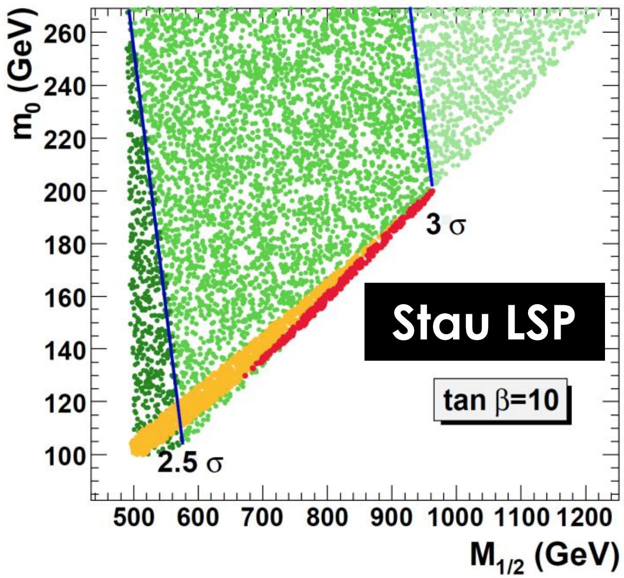
- **CMSSM with mSUGRA SUSY breaking including LFV**
- **the mass difference smaller than tau mass**

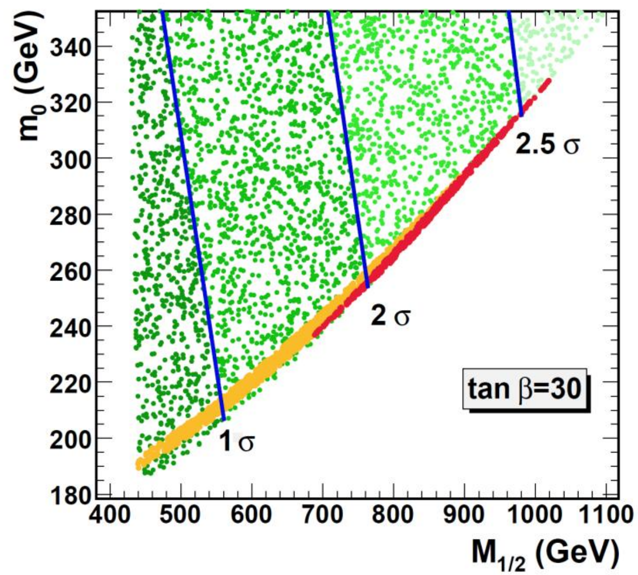
Is there a small δm region consistent with experimental constraints ?

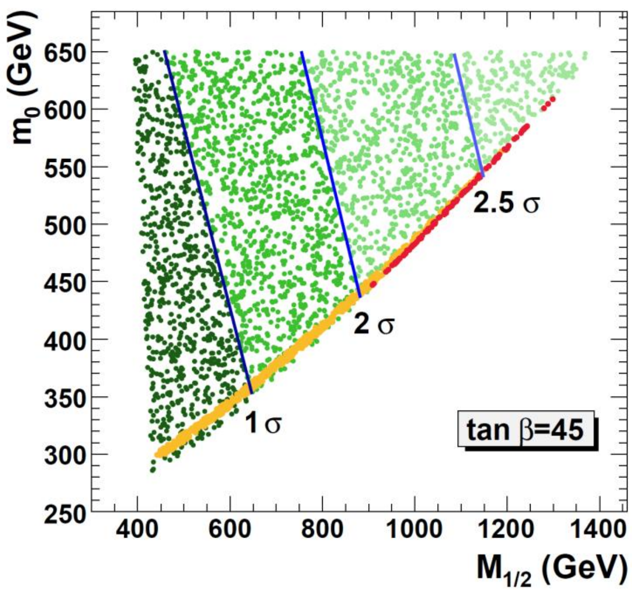
Dark matter abundance	$0.08 < \Omega_{\rm DM} h^2 < 0.14,$
Higg mass limit	$m_h \gtrsim 114 \text{ GeV}$
Bound on $\mathrm{Br}(b \to s\gamma)$	$2.5 \times 10^{-4} < \mathrm{Br}(b \to s\gamma) < 4.5 \times 10^{-4}$
Muon $(g-2)_\mu$	$\Delta a_\mu = a_\mu^{(\rm exp)} - a_\mu^{(SM)} = (27.5 \pm 8.4) \times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

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

Allowed parameter space in mSUGRA MSSM





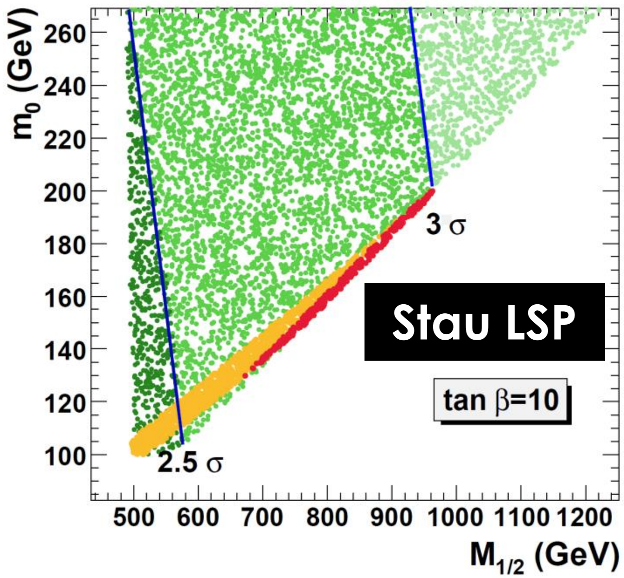


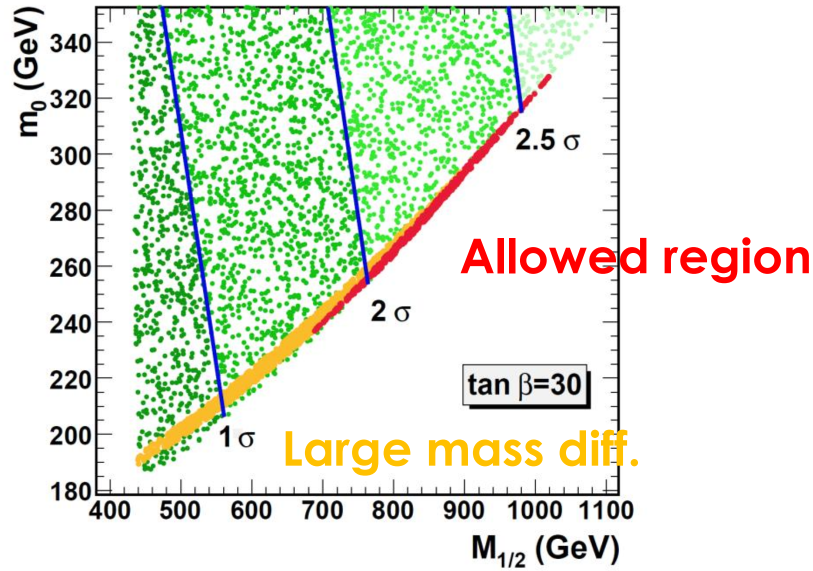
Sign(μ) > 0

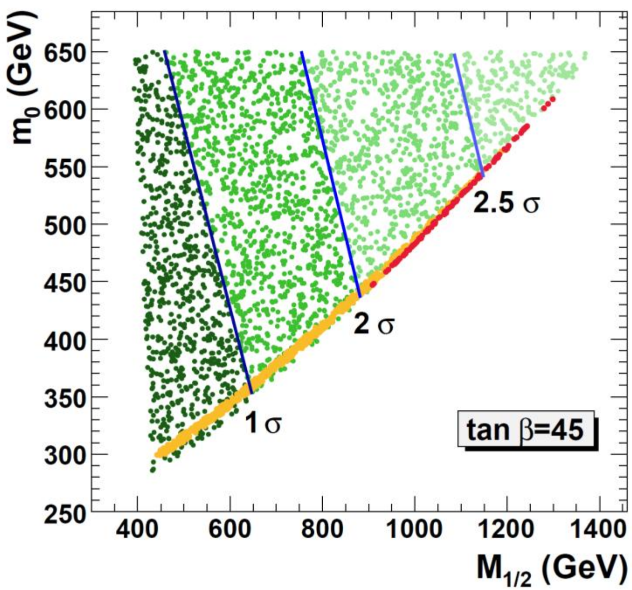
A_0 – large & positive

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

Allowed parameter space in mSUGRA MSSM





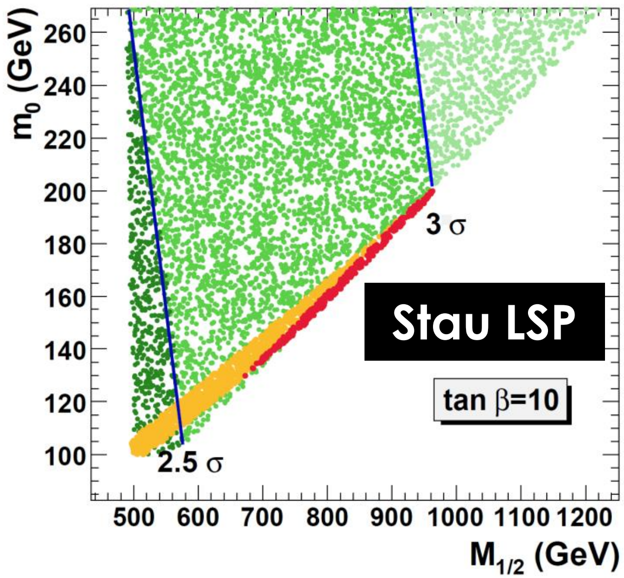


Sign(μ) > 0

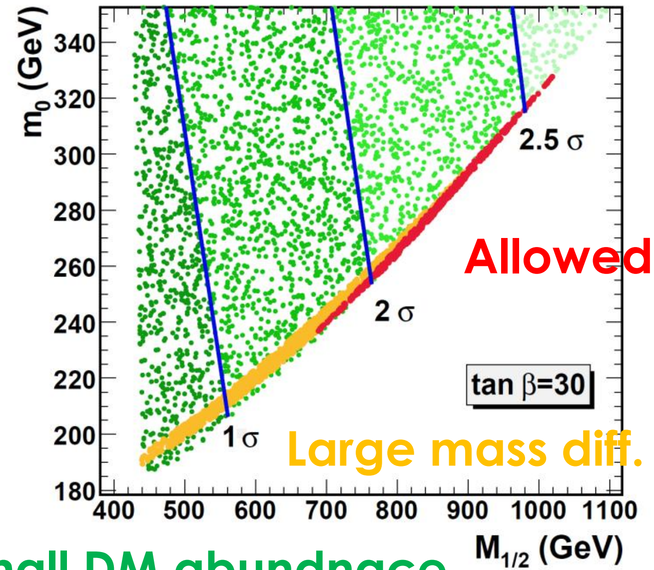
A_0 – large & positive

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

Allowed parameter space in mSUGRA MSSM



Large DM abundance

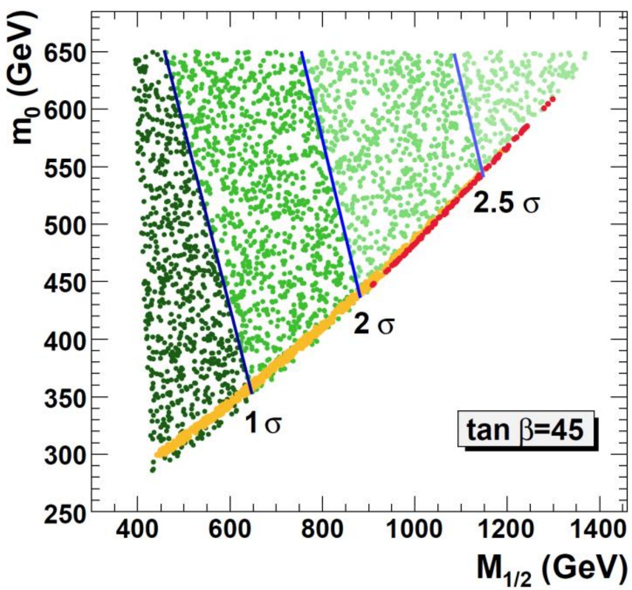


Muon (g-2)

Allowed region

Large mass diff.

Small DM abundnace
(allowed if other DM components exist)

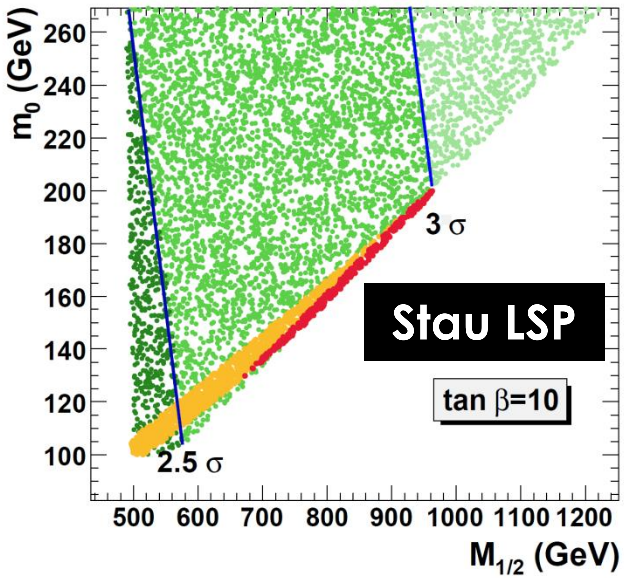


Sign(μ) > 0

A_0 – large & positive

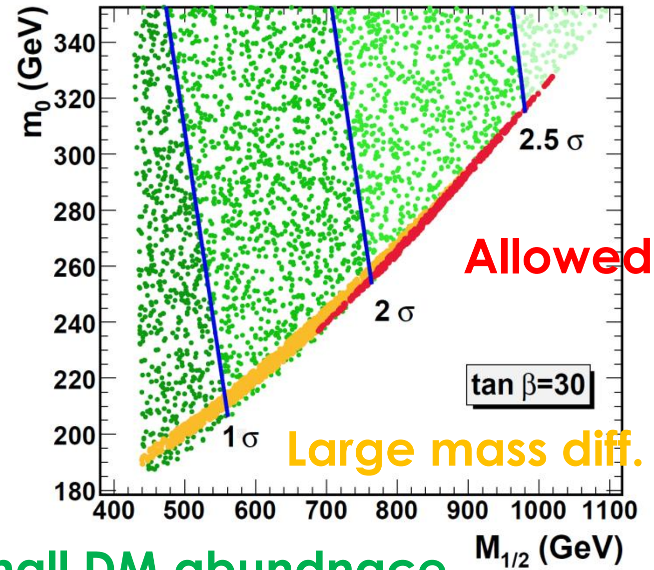
to optimize SUSY contribution to $(g-2)_\mu$

Allowed parameter space in mSUGRA MSSM



Large DM abundance

Muon (g-2)

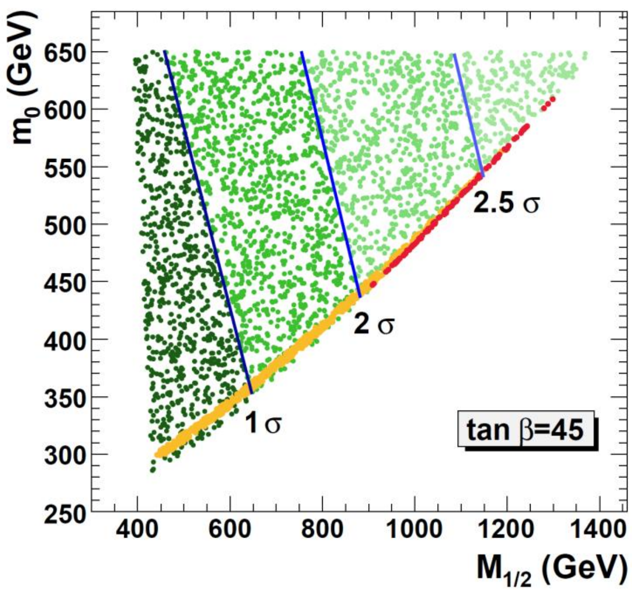


Allowed region

Large mass diff.

Small DM abundnace

(allowed if other DM components exist)



$\delta m < m_\tau$ region

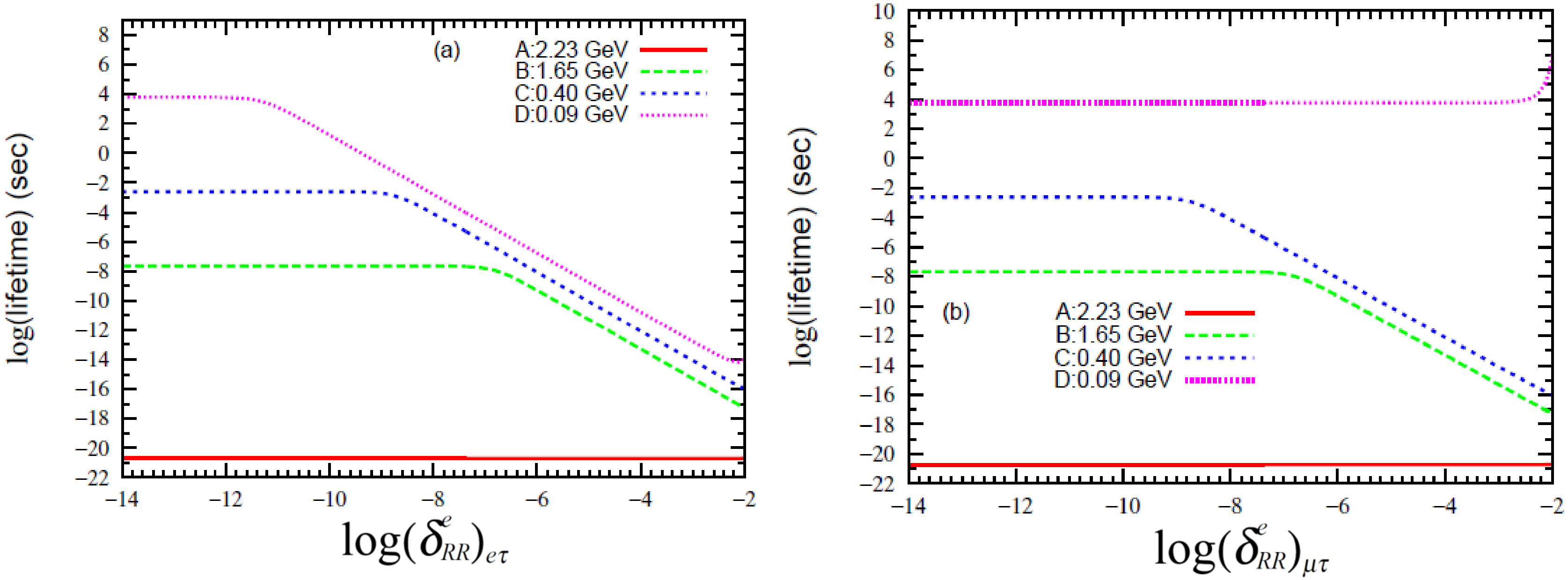
- ✓ relatively large $M_{1/2}$

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

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

Lifetime in right-handed slepton mixing case

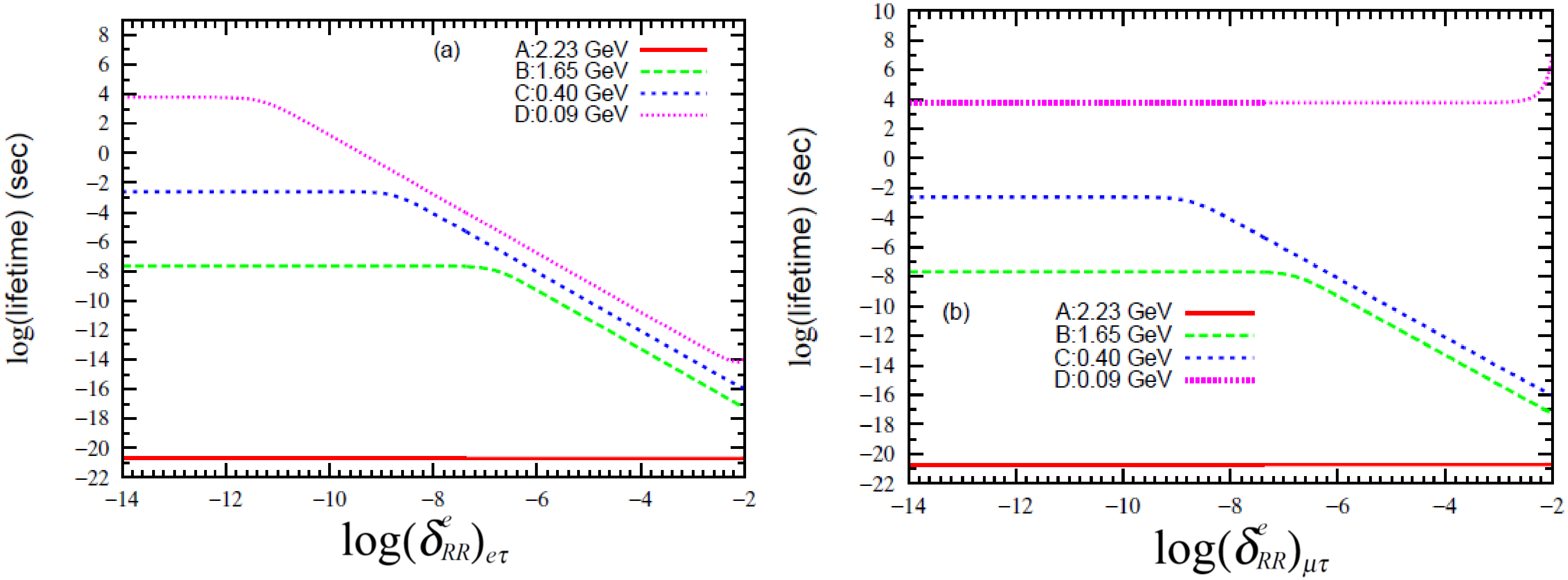
$$(m_0 = 260 \text{ GeV}, \quad \tan\beta = 30)$$



No.	δm (GeV)	$m_{\tilde{\chi}^0_1}$ (GeV)	$m_{\tilde{l}_1}$ (GeV)	$\Omega_{\tilde{\chi}^0_1} h^2$	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

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



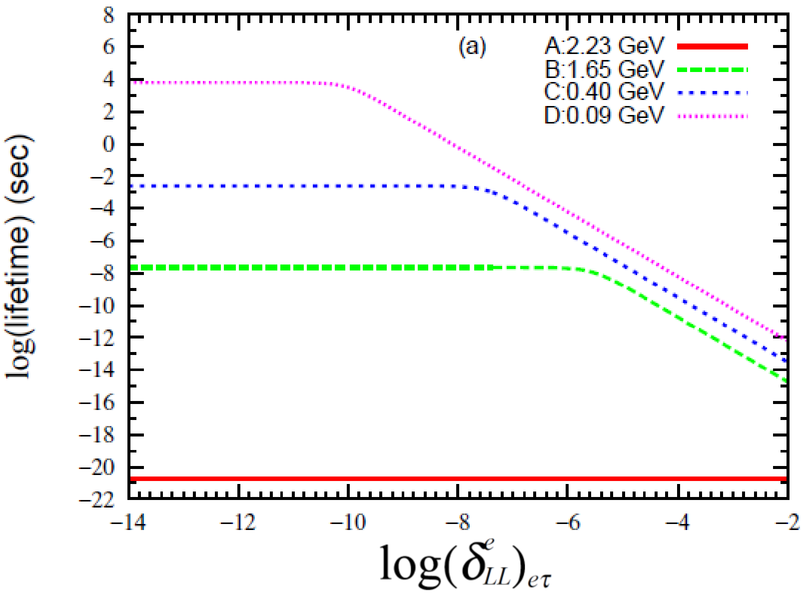
Present bound on δ's (m_0=260 GeV, $M_{1/2}$=750 GeV)

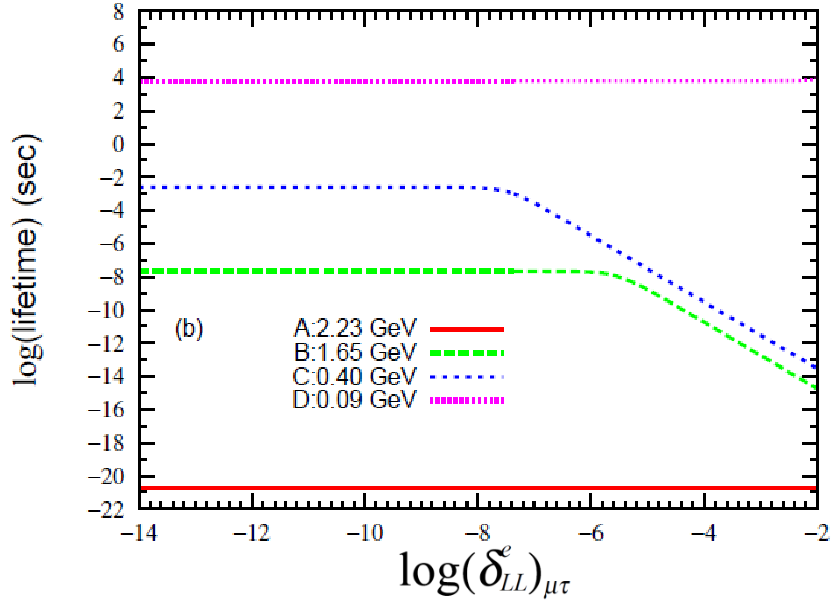
	$\tan\beta = 10$			$\tan\beta = 30$			$\tan\beta = 45$		
	$\delta^e_{e\mu}$	$\delta^e_{e\tau}$	$\delta^e_{\mu\tau}$	$\delta^e_{e\mu}$	$\delta^e_{e\tau}$	$\delta^e_{\mu\tau}$	$\delta^e_{e\mu}$	$\delta^e_{e\tau}$	$\delta^e_{\mu\tau}$
LL	0.0014	0.33	0.21	0.00047	0.10	0.068	0.00030	0.067	0.043
RR	0.0060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

Thanks to J. Jones-Perez

Lifetime in left-handed slepton mixing case

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





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

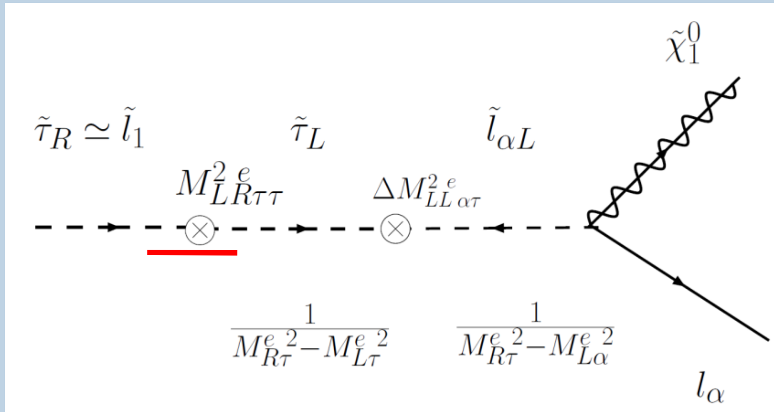
	$\tan\beta = 10$			$\tan\beta = 30$			$\tan\beta = 45$		
	$\delta^e_{e\mu}$	$\delta^e_{e\tau}$	$\delta^e_{\mu\tau}$	$\delta^e_{e\mu}$	$\delta^e_{e\tau}$	$\delta^e_{\mu\tau}$	$\delta^e_{e\mu}$	$\delta^e_{e\tau}$	$\delta^e_{\mu\tau}$
LL	0.0014	0.33	0.21	0.00047	0.10	0.068	0.00030	0.067	0.043
RR	0.0060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

Thanks J. Jones-Perez

MI approximation of decay width

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

Proportional to the square of Mass Insertions



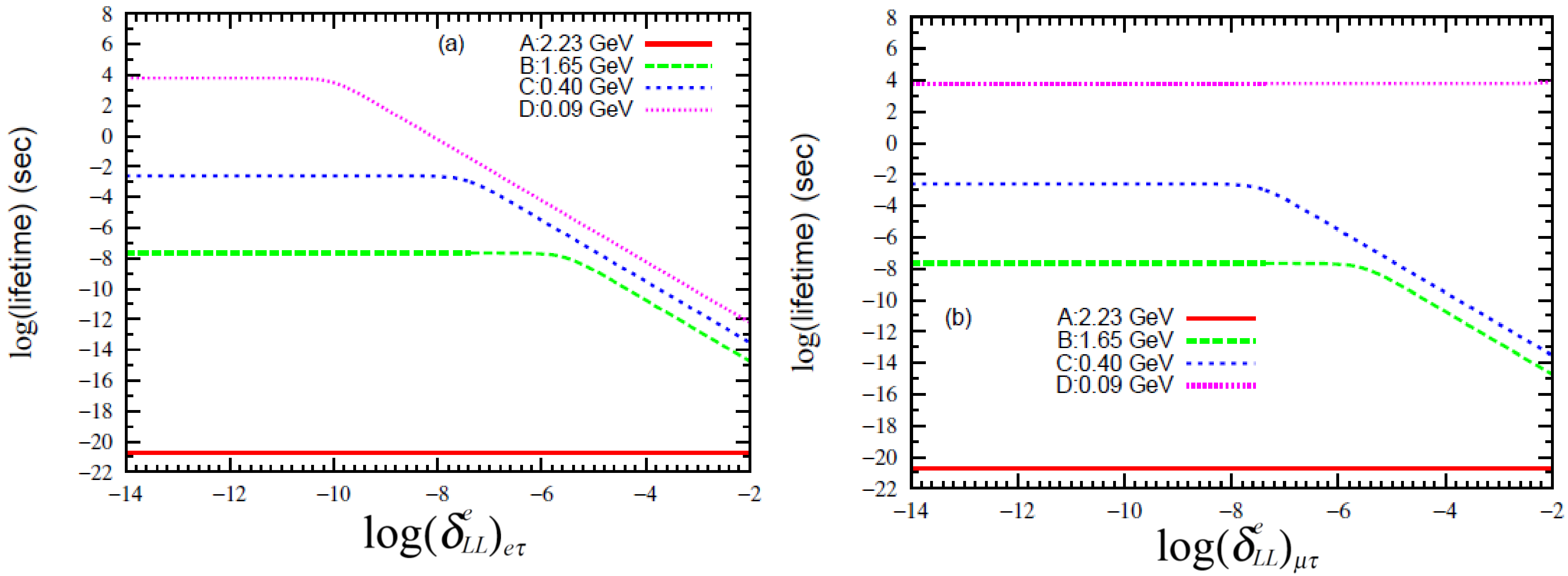
$$\Gamma_{2-\mathrm{body}} = \frac{g_2^2}{2\pi m_{\tilde{\tau}_1}}(\delta m)^2(|g^L_{1\alpha 1}|^2 + |g^R_{1\alpha 1}|^2),$$

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

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

Lifetime in left-handed slepton mixing case

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



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

Thanks J. Jones-Perez

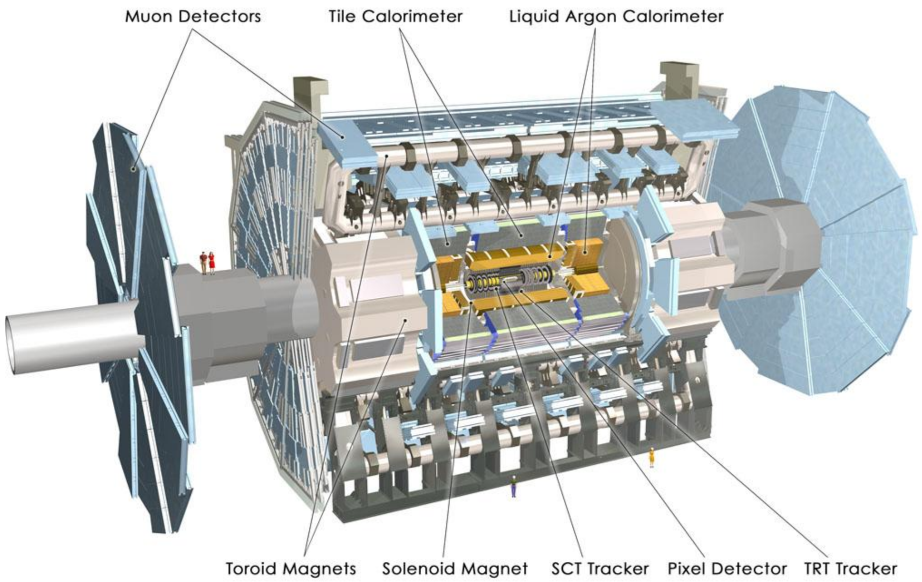
4. LHC Phenomenology

4. 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 $\sigma_{\mathrm{SUSY}} = 130\ \mathrm{fb}.$
  P. Z. Skands, Eur. Phys. J. C 23, 173 (2002)
- ✓ Integrated Luminosity $\mathcal{L}_{\mathrm{int}} = 30\ \mathrm{fb}^{-1}$
  $\mathcal{L} = 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, 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
10^{-12} sec.	4290.0	4290.0	4290.0	4290.0	4290.0

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
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

Almost all the slepton would decay inside the inner detector

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

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

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

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

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
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

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

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

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

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 $y_3 \simeq y_t \simeq 1$

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

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

  Small (CKM-like) mixing

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

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

- ✓ SU(3) flavour symmetry in SUSY

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

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

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

5. Summary and Discussions

5. Summary

In the MSSM (absence of LFV) in which stau is the NLSP and bino-like neutralino is the LSP, if $\delta m < m_\tau$

1. The lifetime of stau can be very long.
   Due to phase suppression and the weak int.
   Typically from 10^{-7} sec to 10^{10} sec.

2. Discrepancy between prediction and observation of ^{7}Li primordial abundance is solved.
   Internal conversion destruct ^{7}Li/^{7}Be efficiently

5. Summary

In the CMSSM with LFV

1. There exists this small δm region consistent with the dark matter abundance, b->s gamma, Higgs mass limit and muon (g-2).

$$240 \lesssim m_0 \lesssim 260 \text{ GeV and } 700 \lesssim M_{1/2} \lesssim 800 \text{ GeV at } \tan\beta = 30$$

2. The slepton lifetime is sensitive to δ^e upto 10^{-5} to 10^{-11} depending on the mass difference.

3. The ATLAS detector will measure lifetime in the range of 10^{-11} to10^{-5} sec.
   If the lifetime is beteen 10^{-10} to10^{-9} sec., LFV couplings could be determined.

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

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

Future Work

Full analyses with Monte-Carlo sim. is needed to obtain the precise number of the decay in the detector.

1. More precise analysis of branching ratios of SUSY particles.
2. Monte-Carlo simulation of the momentum distribution of sleptons.