On long lived staus

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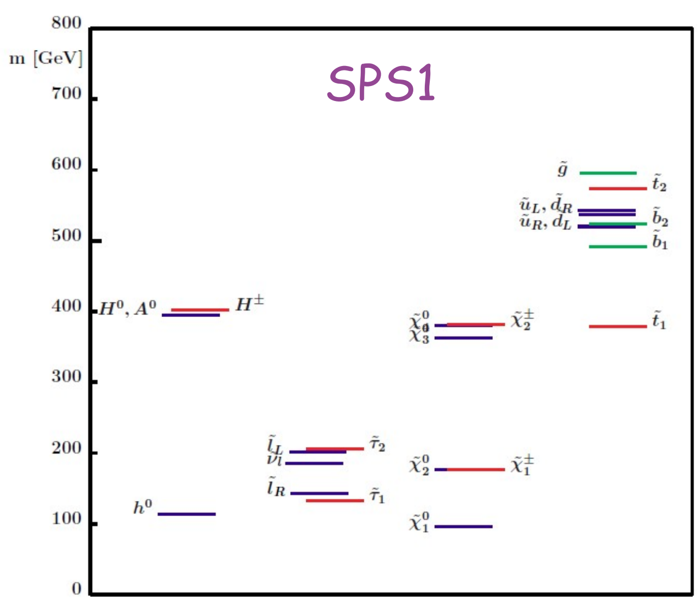
Introduction

Canonical SUSY scenario:

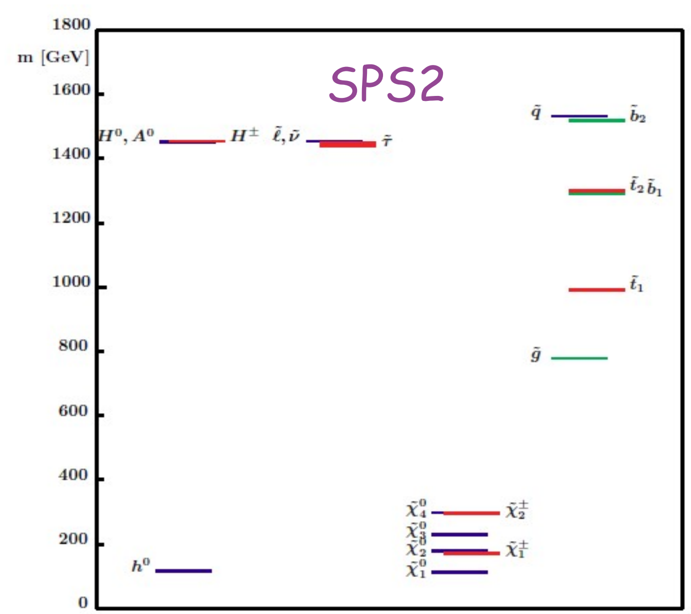
LSP: neutralino

(may provide the dark matter of the Universe if R-parity is almost exactly conserved)

next-to-LSP: lightest stau, chargino (sneutrino, stop)



SPS 1 mass spectrum of ISAJET



SPS 2 mass spectrum of ISAJET

Ghodbane, Martyn

Is this the only possibility?

The LSP could also be a **superweakly interacting particle:**

gravitino: superpartner of the graviton in SUGRA scenarios.
Interactions suppressed by the Planck mass
(or strictly speaking by the SUSY breaking scale)

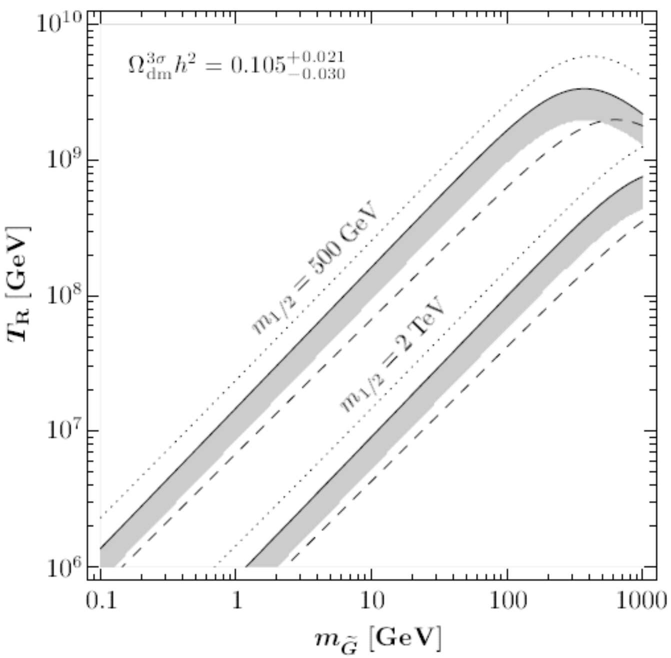
axino: Superpartner of the axion is scenarios implementing the Peccei-Quinn solution to the strong CP problem.
Interactions suppressed by the Peccei-Quinn scale

hidden U(1) gaugino: Superpartner of a hidden U(1) gauge boson which communicates to the observable sector via kinetic mixing.
Interactions suppressed by a small kinetic mixing

Interesting and viable scenarios, which could account for the dark matter of the Universe

The LSP could also be a **superweakly interacting particle:**

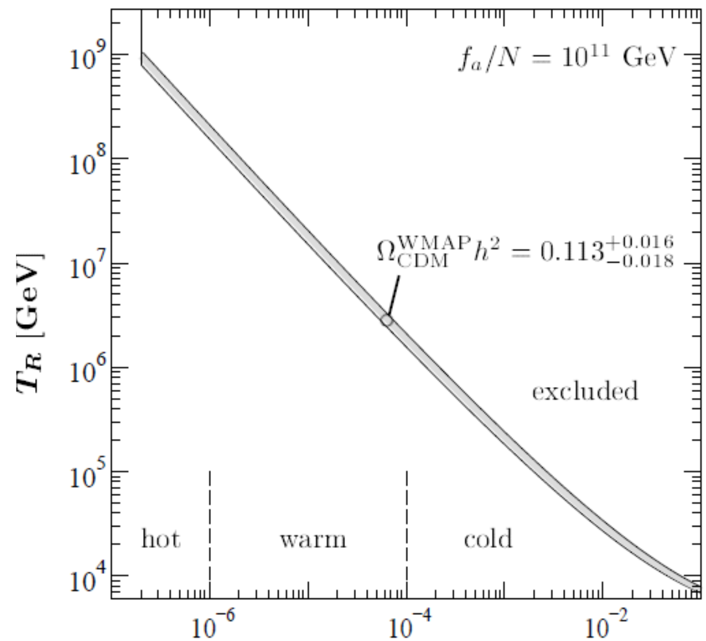
gravitino



$$\Omega_{\tilde G}^{\rm TP} h^2 \simeq 0.32 \left(\frac{10\ \mathrm{GeV}}{m_{\tilde G}}\right)\left(\frac{m_{1/2}}{1\ \mathrm{TeV}}\right)^2\left(\frac{T_{\rm R}}{10^8\ \mathrm{GeV}}\right)$$

Bolz, Brandenbutg,Buchmüller;
Pradler, Steffen;
Rychkov,Strumia

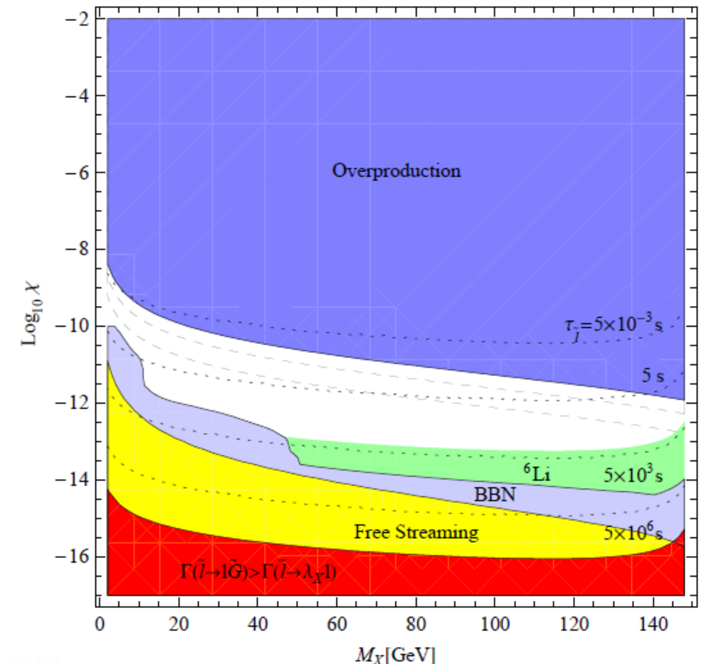
axino



$$\Omega_{\tilde a}^{\rm TP} h^2 \simeq 5.5\, g_s^6(T_{\rm R}) \ln\left(\frac{1.108}{g_s(T_{\rm R})}\right)\left(\frac{10^{11}\ \mathrm{GeV}}{f_a/N}\right)^2 \times \left(\frac{m_{\tilde a}}{0.1\ \mathrm{GeV}}\right)\left(\frac{T_R}{10^4\ \mathrm{GeV}}\right)$$

Asaka, Yanagida;
Covi, Kim, Kim, Roszkowski;
Brandenbutg, Steffen.

Hidden U(1) gaugino

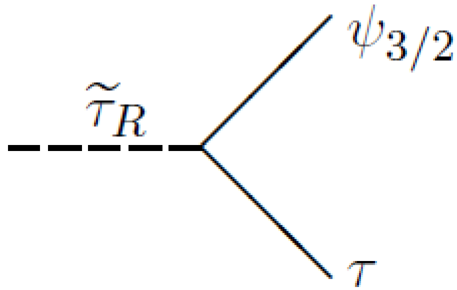


$$\Omega_X h^2 \approx 5.5 \times 10^7 \left(\frac{M_X}{100\ \mathrm{GeV}}\right) \times \int_{T_0}^{T_R} dT \frac{M_P}{T^2}\frac{\gamma_{QCD}(T)\Theta^2(T)}{T^4}$$

AI, Ringwald, Weniger

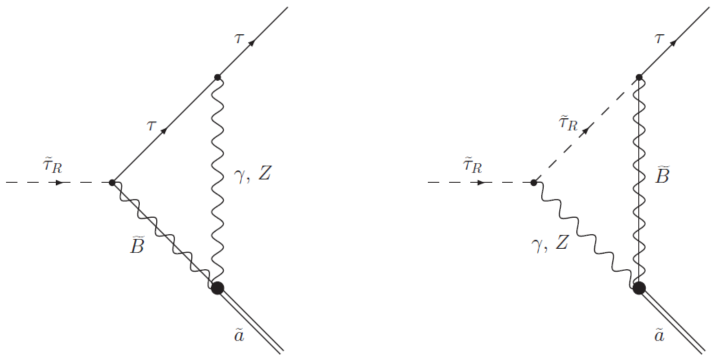
Scenarios with superWIMP LSP share one common feature: if R-parity is conserved, the NLSP is very long lived!

gravitino



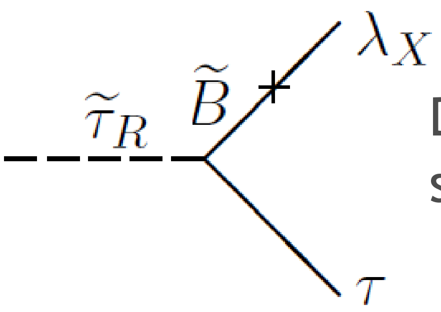
Decay rate suppressed by the Planck mass (or more properly, by the SUSY breaking scale $F=\sqrt{3}\, m_{3/2} M_P$)

axinos



Decay rate suppressed by the Peccei-Quinn scale

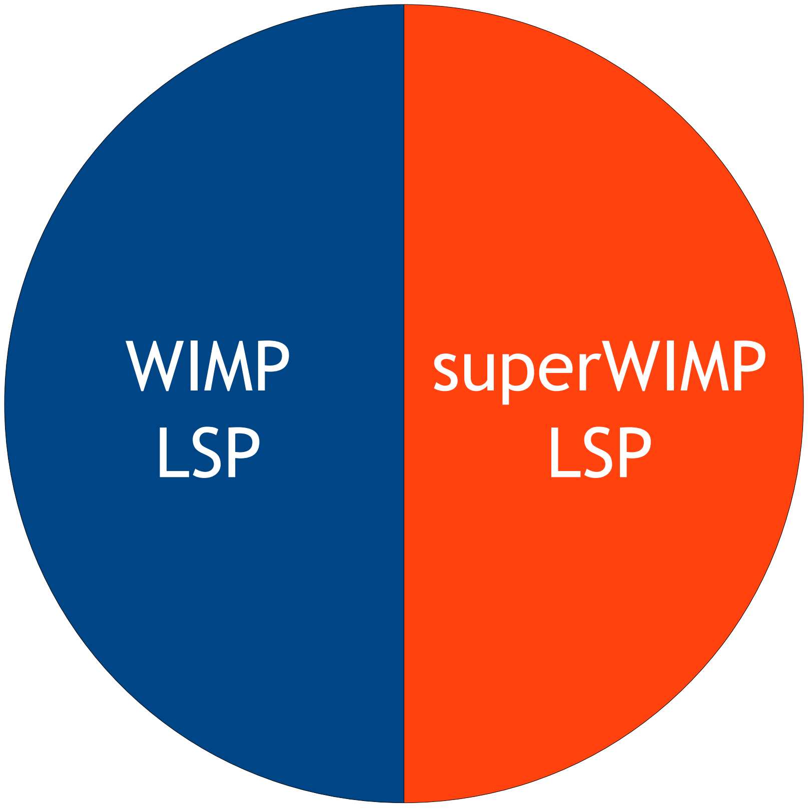
hidden U(1) gauginos



Decay rate suppressed by the small kinetic mixing.

If SUSY is realized in Nature, there exists the possibility that long lived staus exist.

SUSY models



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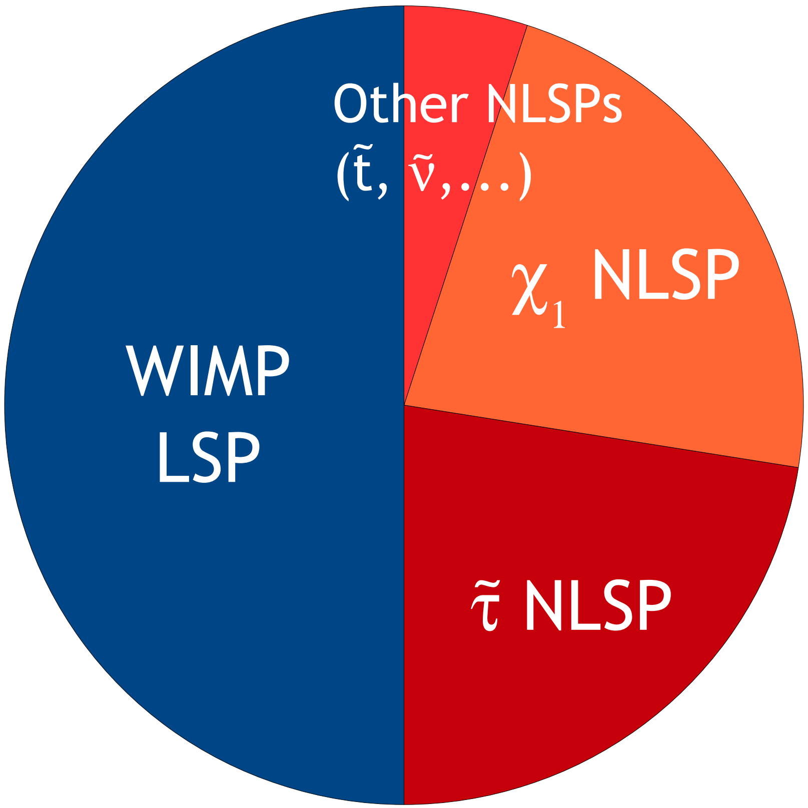
SUSY models



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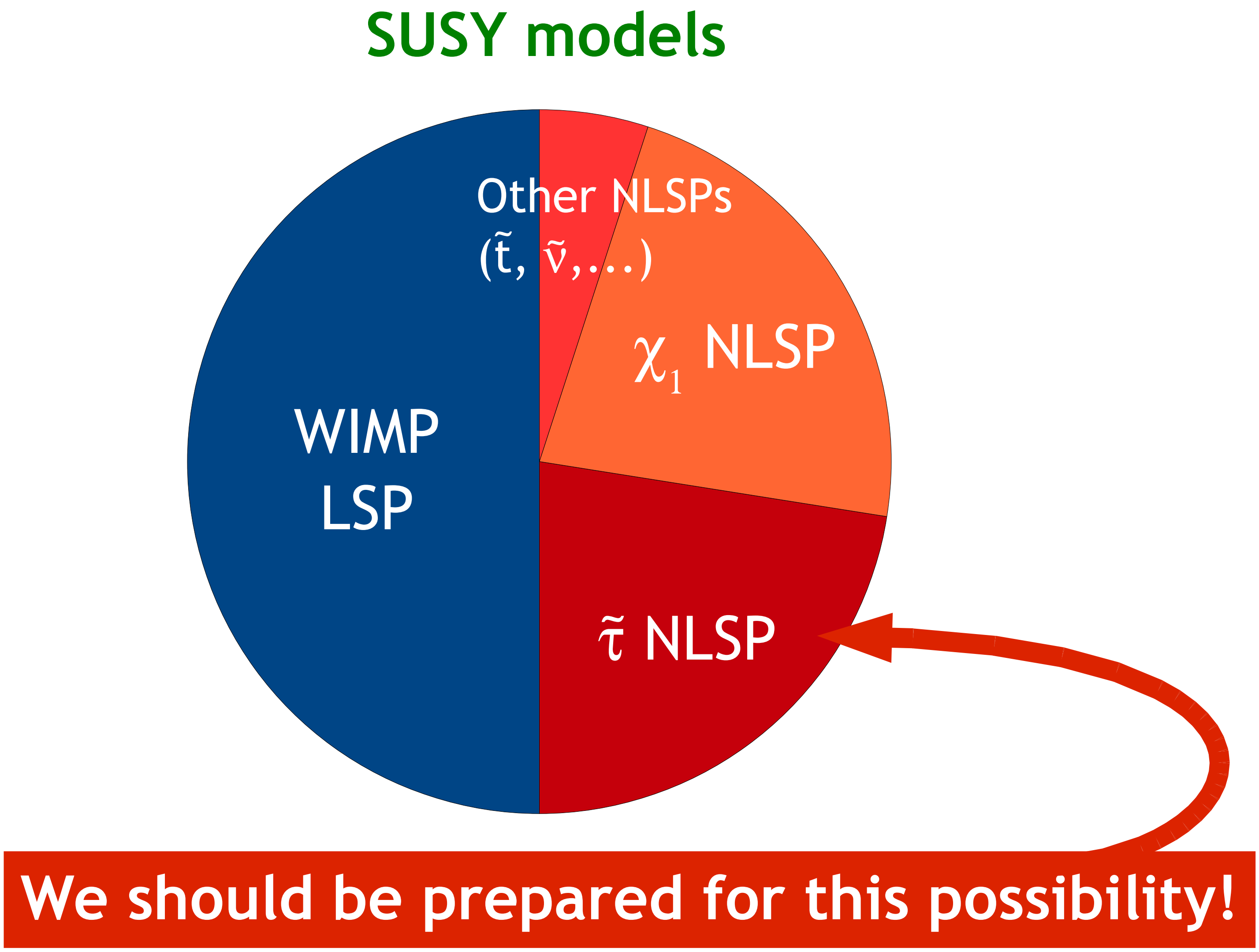
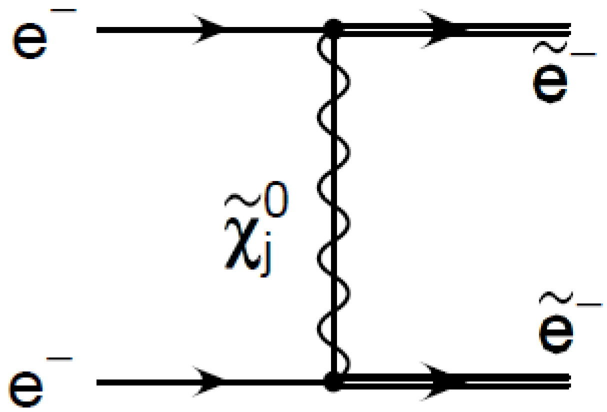


Outline

- Production and detection of long lived staus at linear colliders.
- Physics opportunities.
- Trapping of long lived staus.
- Physics opportunities with trapped staus.
- R-parity violation.
- Conclusions.

Production of long lived staus

e⁻e⁻ collider



The selectron decays producing staus:

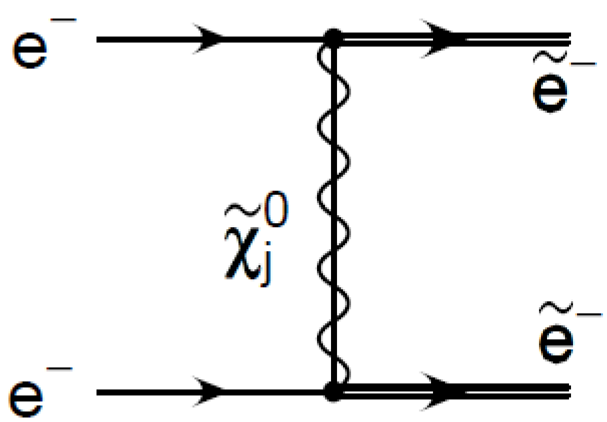
$$\tilde{e}_R^- \longrightarrow e^- \ \tau^\pm \ \tilde{\tau}_1^\mp$$

$$\tilde{e}_L^- \longrightarrow e^- \ \tau^\pm \ \tilde{\tau}_1^\mp$$

$$\tilde{e}_L^- \longrightarrow \nu_e \ \bar{\nu}_\tau \ \tilde{\tau}_1^-$$

Production of long lived staus

$e^- e^-$ collider



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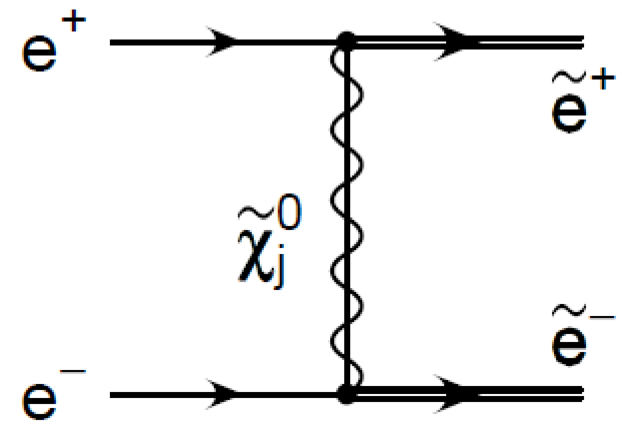
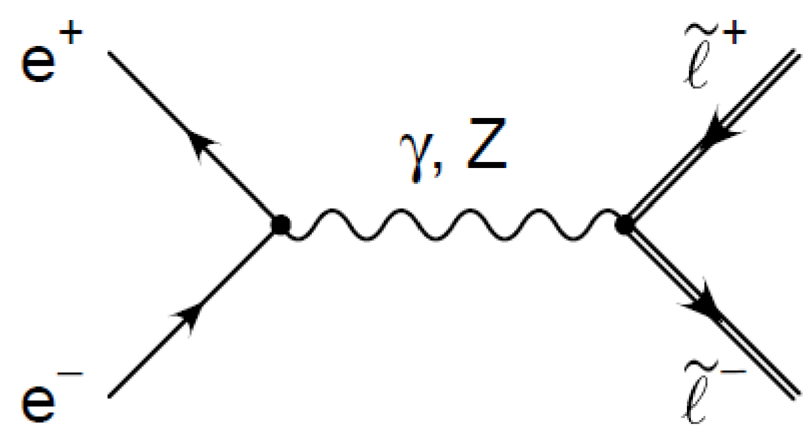
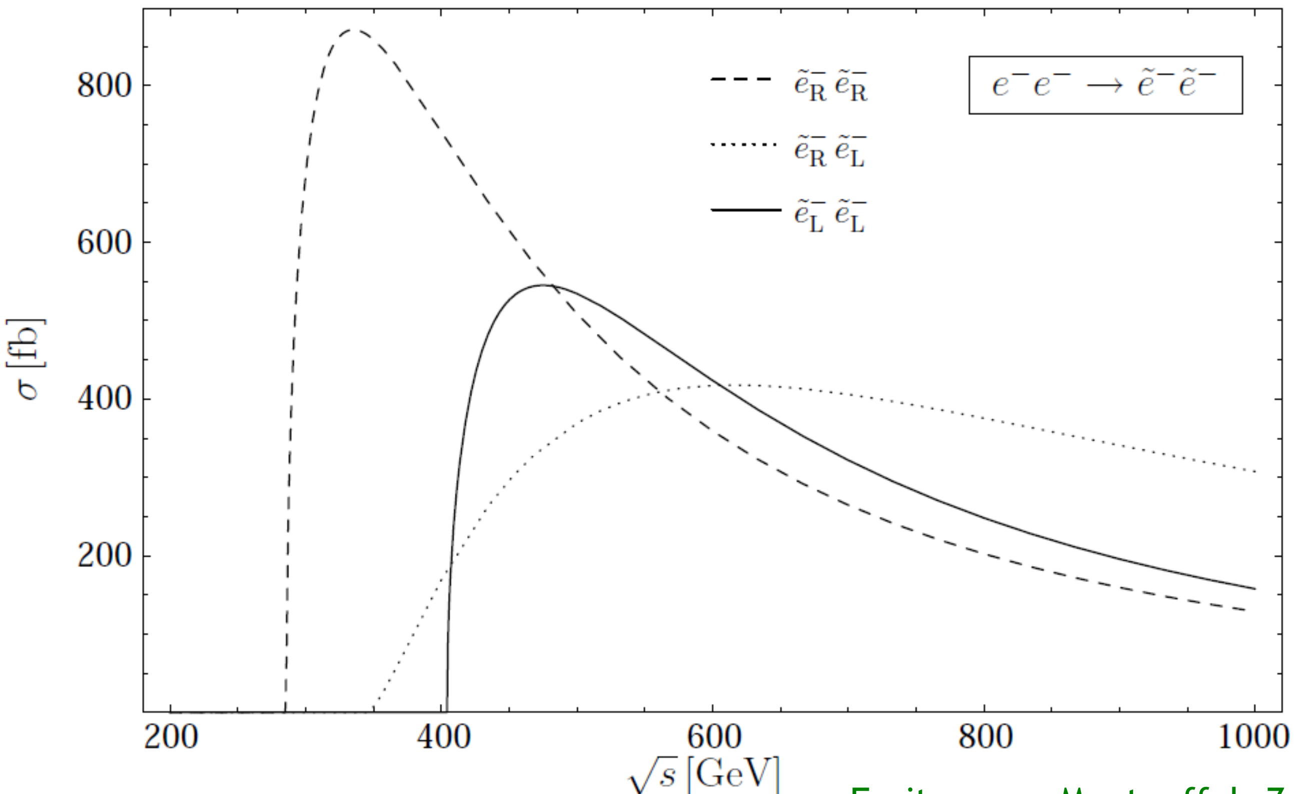
$e^+ e^-$ collider





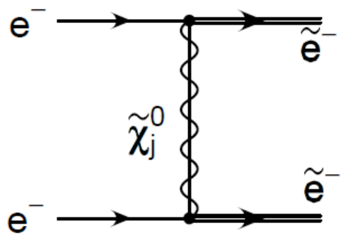
Direct production of staus



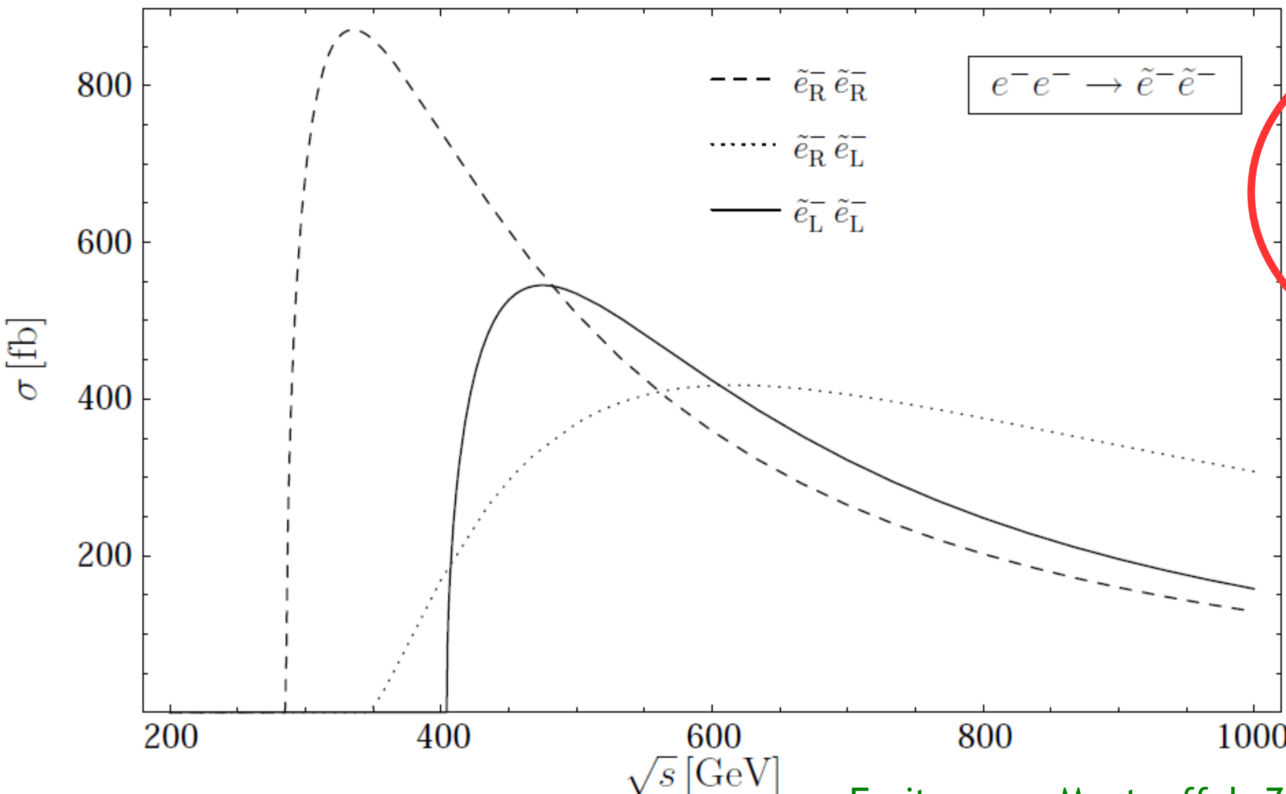
For SPS1a
m_{χ^0}=96 GeV
$m_{\tilde{e}_R}$=143 GeV
$m_{\tilde{e}_L}$=202 GeV
$\sqrt{s}$=500GeV

Freitas, von Manteuffel, Zerwas

Benchmark point with neutralino LSP!



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 M_1^2}{2\cos^4\theta_W}\left(\frac{1}{t - M_1^2} + \frac{1}{u - M_1^2}\right)^2$$



Freitas, von Manteuffel, Zerwas

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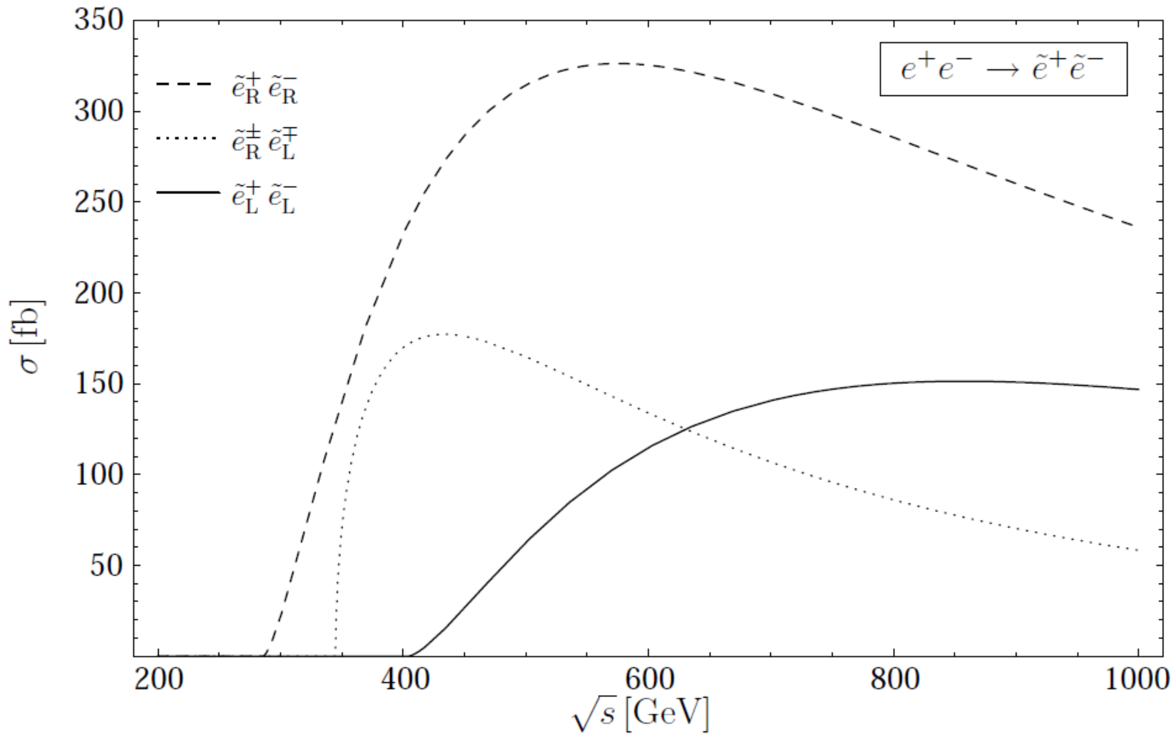
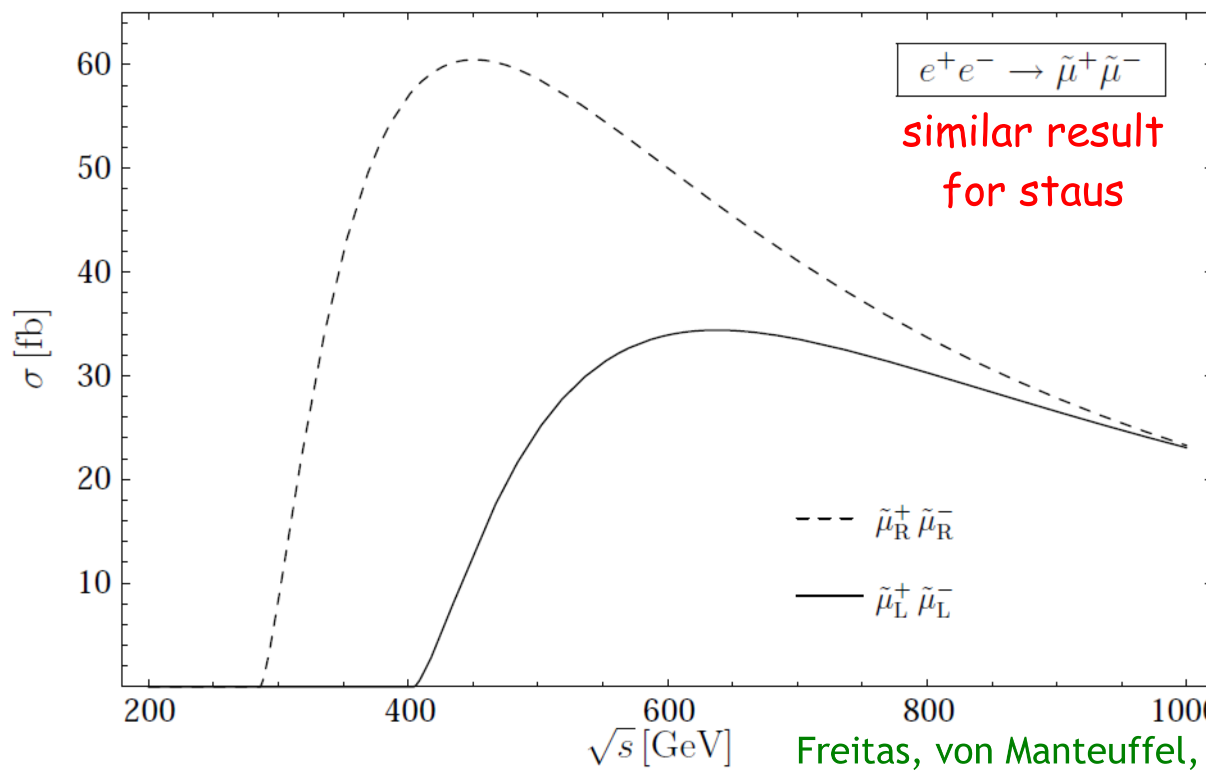




Freitas, von Manteuffel, Zerwas

Detection of long lived staus

Charged track in the detector. Very similar to a muon, but with some differences:

- Large mass. Use kinematical cuts.
- Slow. Use a good Time of Flight (ToF) device.

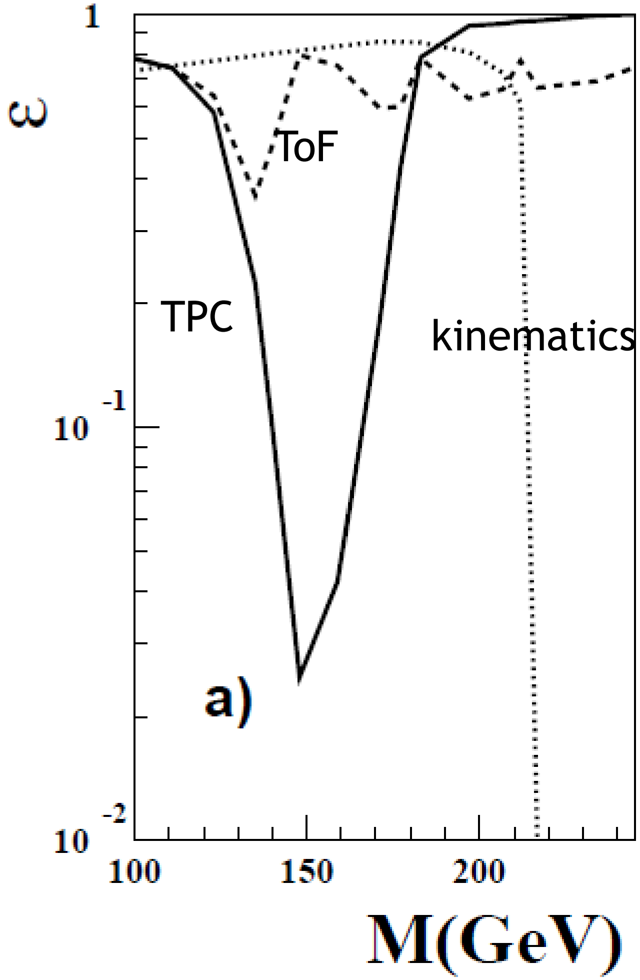
  In a large detector (r=2m), the mean time of flight of a muon (β=1) is 6.7 ns. A heavy particle (β<1) will reach the detector later. Assuming a time of flight measurement with an error of 50ps, the cut Δt>0.13 ns removes 99% of the muon background.
  $\Rightarrow$ Efficiency in the identification 60-80% for stau masses 140-250 GeV

- Ionizing particle. Use a good Time Projection Chamber (TPC)

  In contrast to muons (which lose energy mostly by radiation), heavy charged particles lose energy by ionization. Assuming a 5% resolution in the measurement of dE/dx, the cut $\frac{dE/dX - dE/dX(\mathrm{muon})}{\sigma(dE/dX)} > 3$ provides an efficiency in the identification >90% for stau masses larger than 180 GeV.

Efficiency

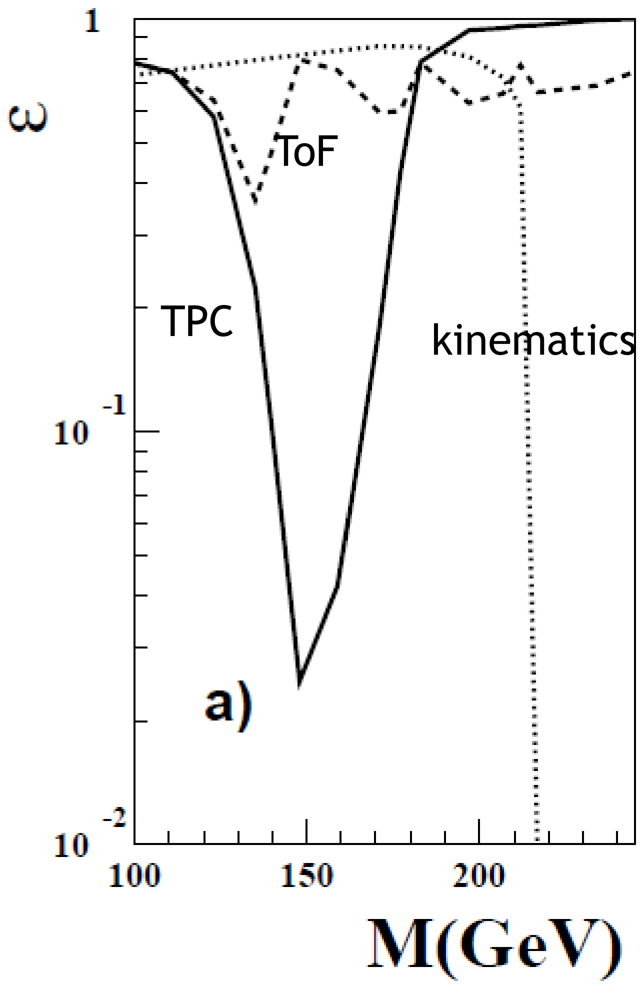
$\sqrt{s}$=500GeV



Mercadante, Mizukoshi, Yamamoto

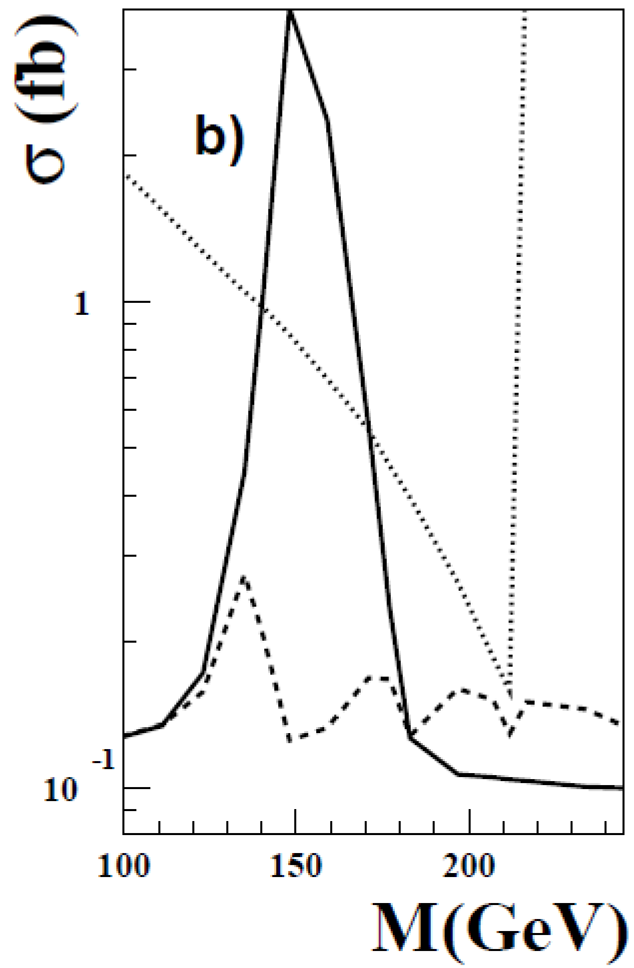
Efficiency

$\sqrt{s}$=500GeV



Mercadante, Mizukoshi, Yamamoto

Reach in cross section



for typical SUSY parameters the production cross sections are $\mathcal{O}$(100fb).

Good prospects of detection!!

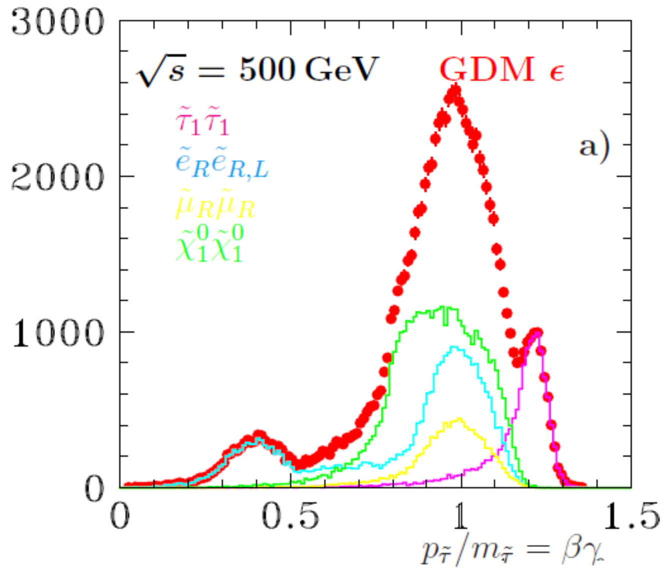
Physics opportunities with long lived staus

1- Mass measurements

Consider a e^+e^- collider, with E_{CM}=500 GeV and $\mathcal{L}$=100 fb^{-1} and SUSY parameters as in the ε benchmark point:

$m_{\tilde{\tau}}$=157.6 GeV, $\tau_{\tilde{\tau}}$= 2.6×10^6 s, $m_{3/2}$=20 GeV

From the stau momentum in $e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$



$$\langle p_{\tilde{\tau}} \rangle = 192.4 \pm 0.2 \text{ GeV}$$
$$m_{\tilde{\tau}} = 157.6 \pm 0.2 \text{ GeV}$$

Martyn

Masses of other SUSY particles can be determined using the standard techniques (with a stau at the end of the chain instead of a neutralino)

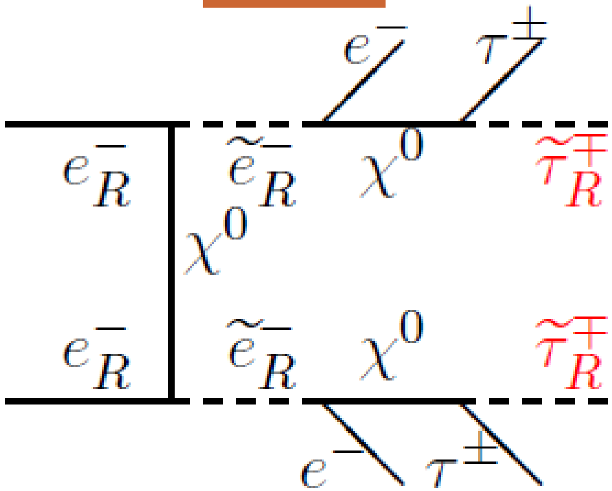
Physics opportunities with long lived staus

2- Searches for lepton flavour violation

Al, Roy

At the e⁻e⁻ collider, if $m_{\tilde{\tau}_R} < m_{\tilde{e}_R} < m_{\tilde{\chi}^0}$, stau production proceeds as:

LFC



- Four charged fermions in the final state and two heavily ionizing tracks

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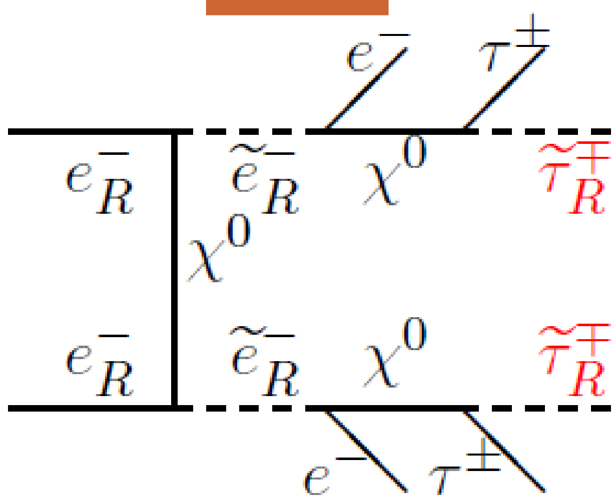
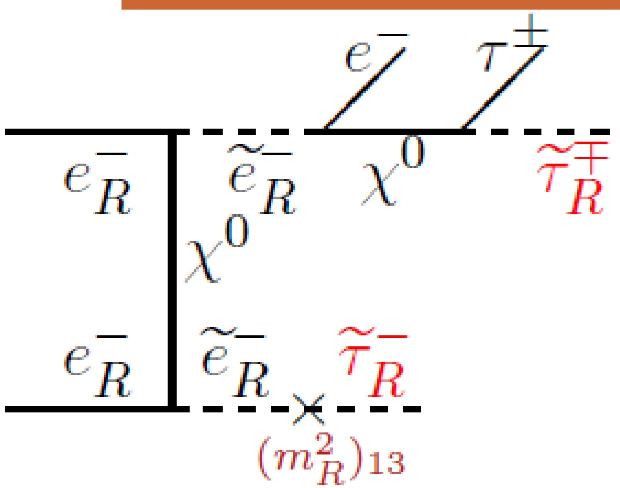


LFV in τ–e sector



- Four charged fermions in the final state and two heavily ionizing tracks

- Two charged fermions and two heavily ionizing tracks

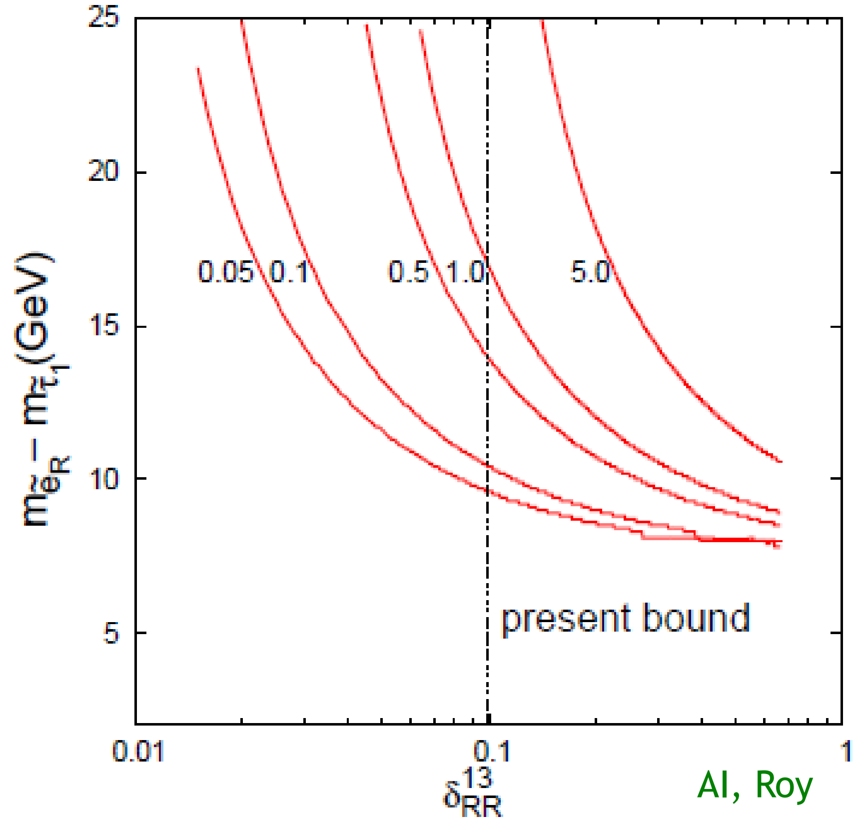
Essentially no SM background, but SUSY backgrounds exist, e.g.

$$e^- \, e^- \to \tilde{e}^-_R \, \tilde{e}^-_L \to (e^- \, \tau^\pm \, \tilde{\tau}^\mp_R)(\nu_e \, \bar{\nu}_\tau \, \tilde{\tau}^-_R)$$

However, it can be kept under control by choosing appropriate cuts.

Contours of constant cross section (in fb) for the process

$$e^- e^- \longrightarrow \tilde{e}_R^- \tilde{\tau}_1^- \longrightarrow e^- \tau^+ \tilde{\tau}_1^- \tilde{\tau}_1^- + e^- \tau^- \tilde{\tau}_1^+ \tilde{\tau}_1^-$$



$$\delta_{RR}^{13} = \frac{(m_R^2)_{13}}{m_R^2}$$

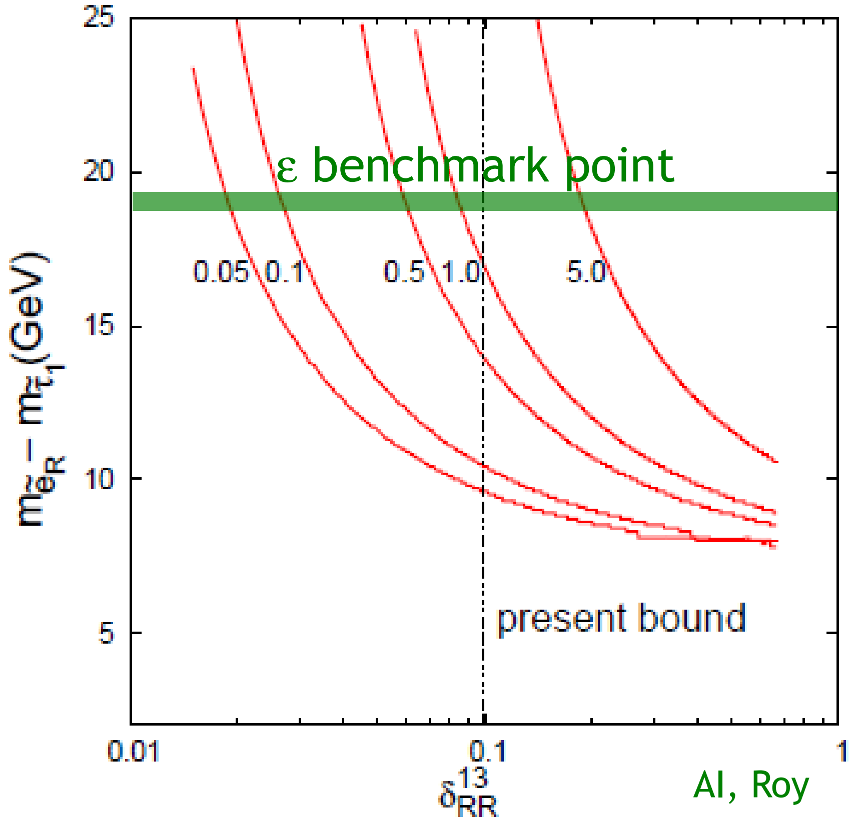
$\sqrt{s} = 500$ GeV

$m_{\tilde{e}_R} = 169$ GeV

$m_{\chi_1^0} = 183$ GeV

Contours of constant cross section (in fb) for the process

$$e^- e^- \longrightarrow \tilde{e}_R^- \tilde{\tau}_1^- \longrightarrow e^- \tau^+ \tilde{\tau}_1^- \tilde{\tau}_1^- + e^- \tau^- \tilde{\tau}_1^+ \tilde{\tau}_1^-$$



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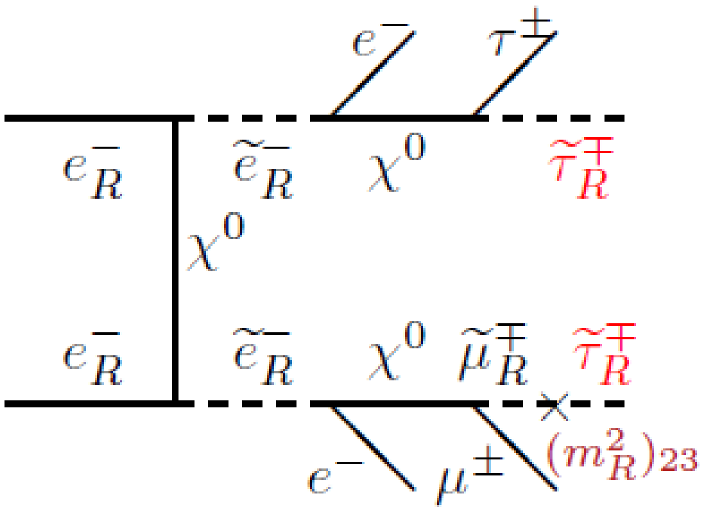
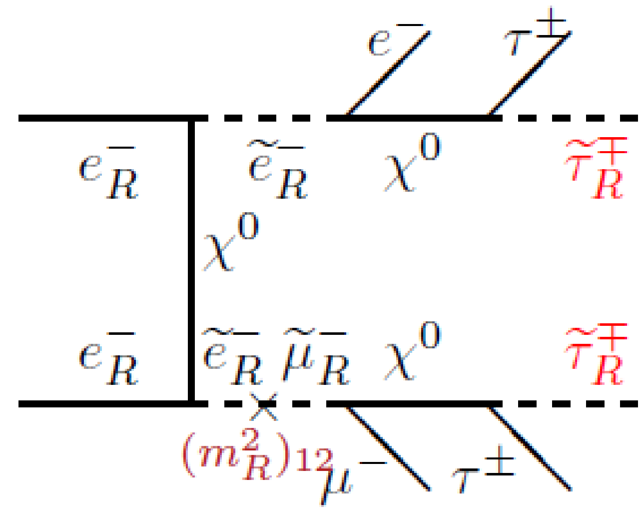
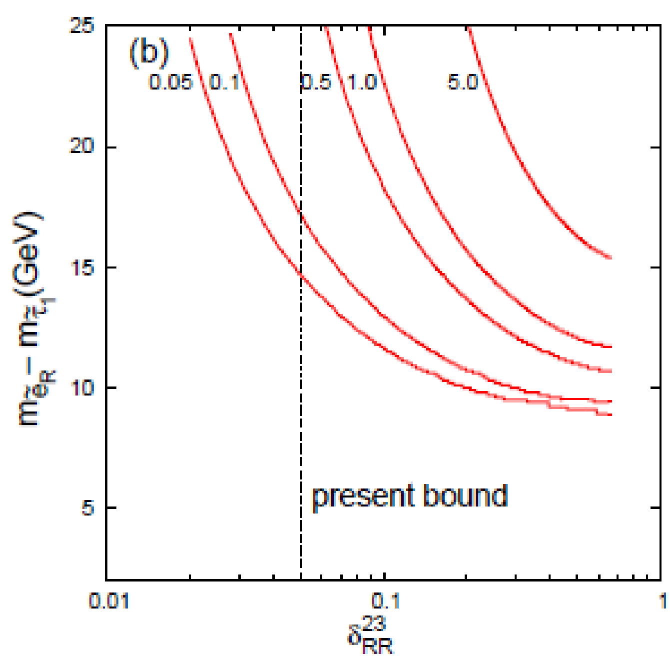
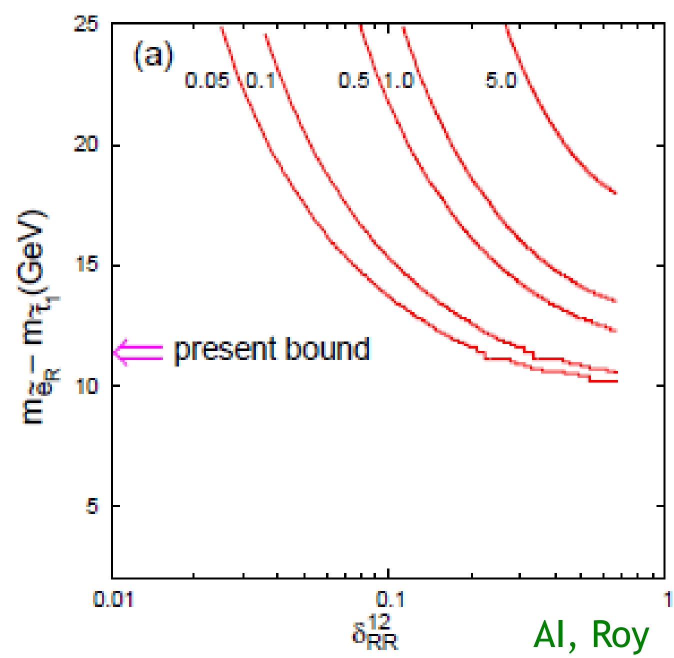
$$\delta_{RR}^{13} = \frac{(m_R^2)_{13}}{m_R^2}$$

Lepton flavour violation in the τ–μ and μ–e sectors



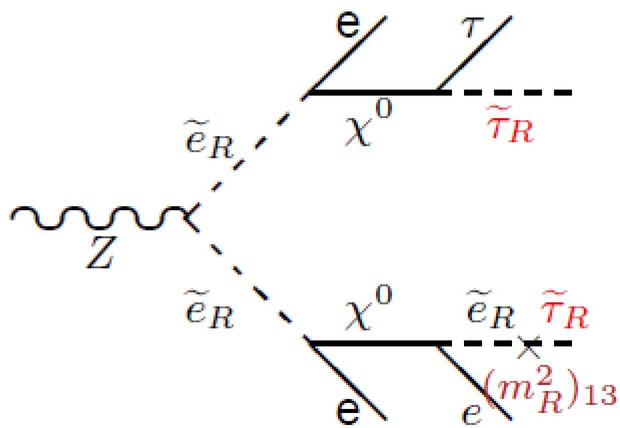




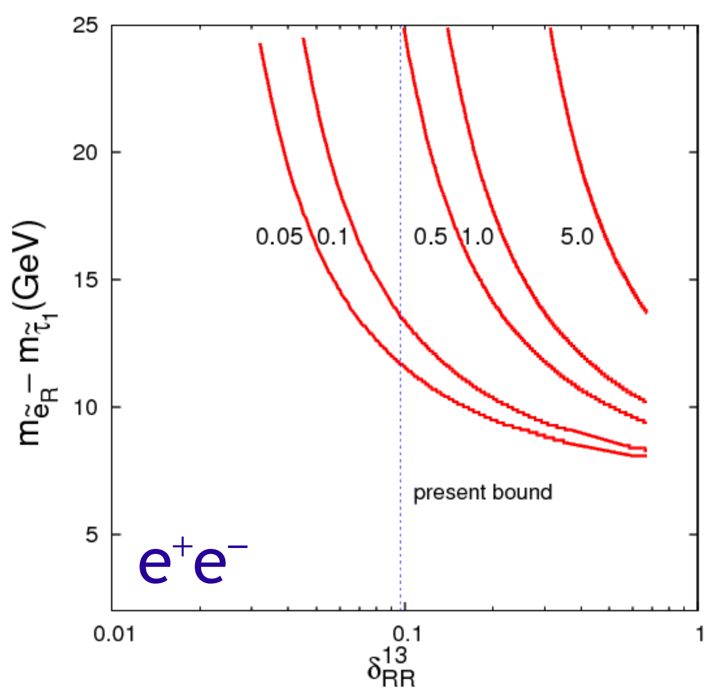


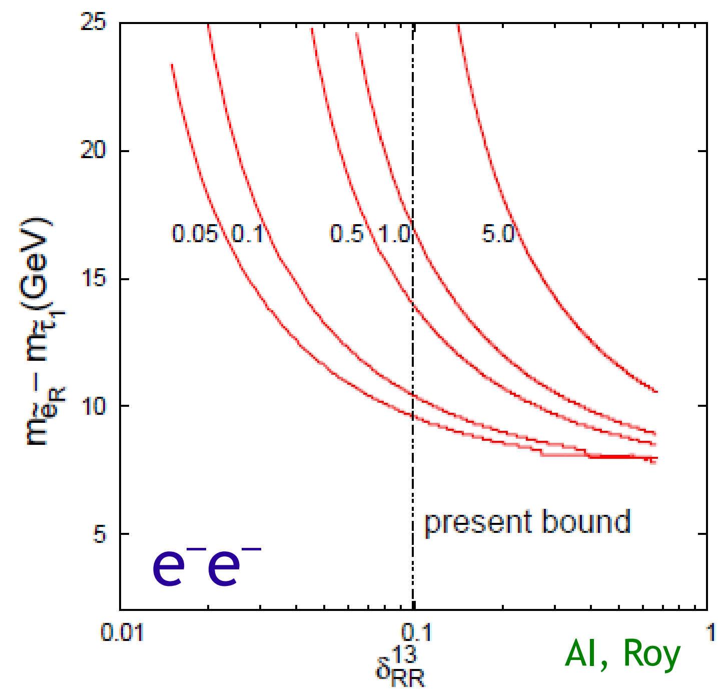
Al, Roy

At a e^+e^- collider there are new channels, but the analysis is similar. For example, if lepton flavour is violated in the τ–e sector



The sensitivity to LFV turns to be slightly worst than in the e^-e^- mode, due to a smaller production cross section.



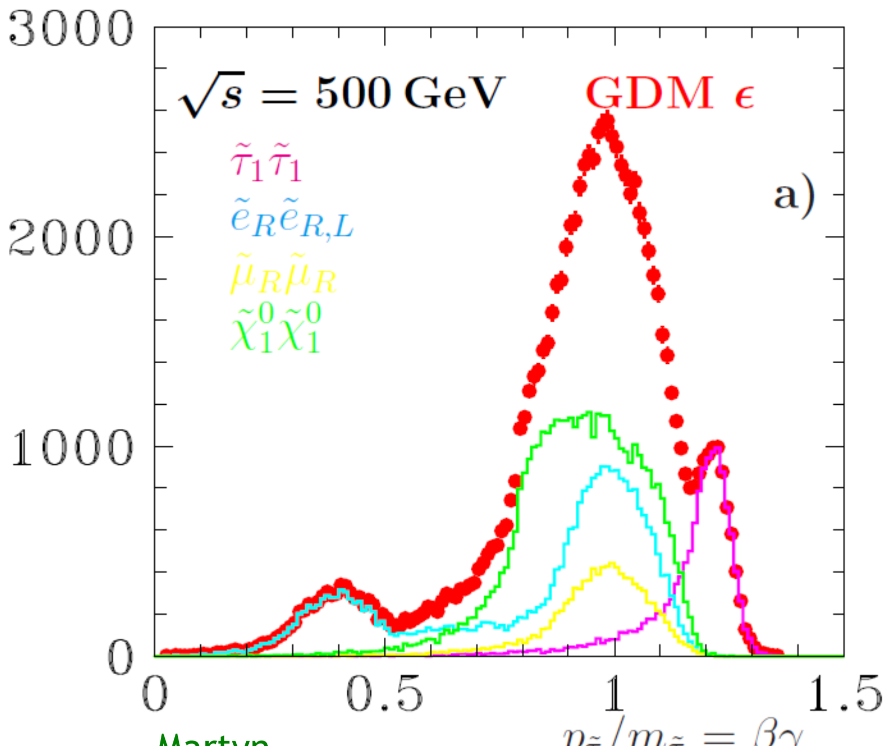


AI, Roy

Trapping long lived staus

Staus lose energy as they propagate in the hadronic calorimeter and the iron yoke. They can get trapped if they are slow enough.

$m_{\tilde{\tau}}$	$\beta\gamma$ (HCAL)	$\beta\gamma$ (Yoke)
125 GeV	0.41 – 0.46	0.52 – 0.59
250 GeV	0.33 – 0.37	0.42 – 0.48
375 GeV	0.29 – 0.33	0.37 – 0.41



Martyn

$\tilde{\ell}, \tilde{\chi}, \tilde{G}$	GDM ϵ
$\tilde{\tau}_1$	157.6
$\tilde{\tau}_2$	307.2
$\tilde{\nu}_\tau$	290.9
$\tilde{e}_R$	175.1
$\tilde{e}_L$	303.0
$\tilde{\nu}_e$	292.8
$\tilde{\chi}^0_1$	179.4
$\tilde{\chi}^0_2$	338.2
$\tilde{\chi}^\pm_1$	338.0
$\tilde{G}$	20

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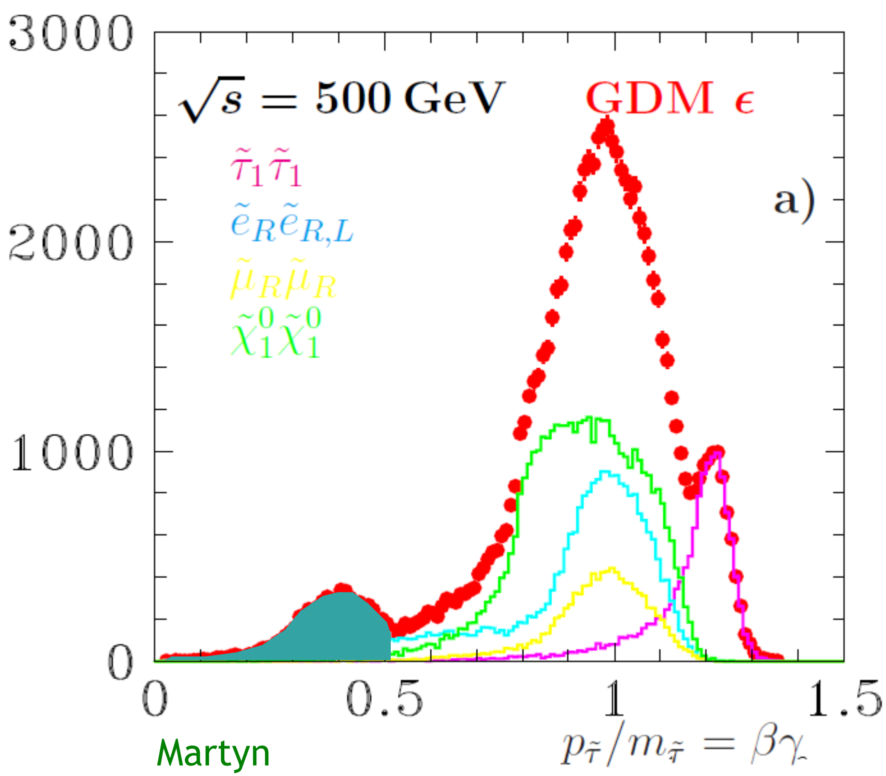


Martyn

Number of trapped staus:

HCAL: 4100

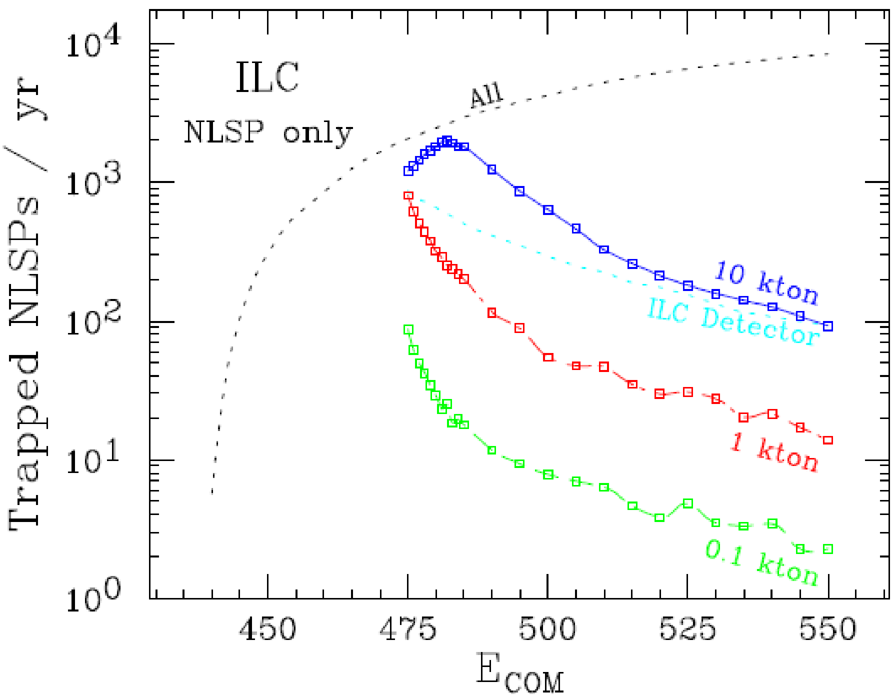
yoke: 1850

Trapping even more long lived staus

More staus could be trapped by placing a stopping material around the detectors

Water

Feng, Smith



$\mathcal{L}$=300 fb^{-1}, $m_{\tilde{\tau}}$=219 GeV

Iron

Hamaguchi, Kuno, Nakaya, Nojiri

	total		1000 g/cm^2		3000 g/cm^2		5000 g/cm^2	
	$\times 10^4$	$\times 10^4$	$\times 10^4$	$\times 10^4$	$\times 10^4$	$\times 10^4$	$\times 10^4$	$\times 10^4$
$\beta_{\tilde{e}} = 0.2$	1.47 $\tilde{\tau}^-$	1.83 $\tilde{\tau}^+$	1.11 $\tilde{\tau}^-$	1.38 $\tilde{\tau}^+$	1.11 $\tilde{\tau}^-$	1.38 $\tilde{\tau}^+$	1.11 $\tilde{\tau}^-$	1.38 $\tilde{\tau}^+$
$\beta_{\tilde{e}} = 0.3$	2.06 $\tilde{\tau}^-$	2.56 $\tilde{\tau}^+$	1.30 $\tilde{\tau}^-$	1.78 $\tilde{\tau}^+$	1.54 $\tilde{\tau}^-$	1.90 $\tilde{\tau}^+$	1.54 $\tilde{\tau}^-$	1.90 $\tilde{\tau}^+$
$\beta_{\tilde{e}} = 0.4$	2.47 $\tilde{\tau}^-$	3.08 $\tilde{\tau}^+$	0.49 $\tilde{\tau}^-$	0.48 $\tilde{\tau}^+$	1.71 $\tilde{\tau}^-$	2.22 $\tilde{\tau}^+$	1.81 $\tilde{\tau}^-$	2.25 $\tilde{\tau}^+$
$\beta_{\tilde{e}} = 0.5$	2.67 $\tilde{\tau}^-$	3.33 $\tilde{\tau}^+$	0 $\tilde{\tau}^-$	0 $\tilde{\tau}^+$	0.60 $\tilde{\tau}^-$	0.65 $\tilde{\tau}^+$	1.38 $\tilde{\tau}^-$	1.95 $\tilde{\tau}^+$

$\mathcal{L}$=10 fb^{-1}, $m_{\tilde{\tau}}$=150 GeV, $m_{\tilde{e}}$=170 GeV, M_1=180 GeV

For $\mathcal{L}$=100 fb^{-1} and a 10 kton stopper

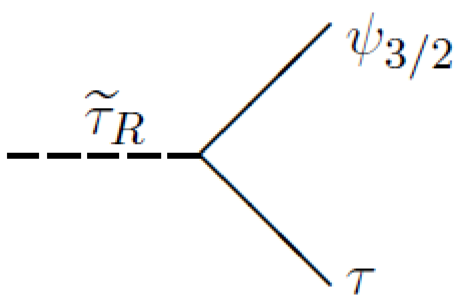
$$N = 1.2 \times 10^5 \left(\frac{M_T/10\text{kton}}{(R_{\text{IP}}/10\text{m})^2} \right)$$

Physics opportunities with trapped staus

1- If the LSP is the gravitino, measure the Planck mass

Buchmüller, Hamaguchi, Ratz, Yanagida

If R-parity is conserved, the stau can only decay gravitationally



$$t_{\widetilde{\tau}}^{-1} = \Gamma_{\widetilde{\tau} \to \tau\, \psi_{3/2}} = \frac{1}{48\pi M_P^2} \frac{m_{\widetilde{\tau}}^5}{m_{3/2}^2} \left[1 - \frac{m_{3/2}^2}{m_{\widetilde{\tau}}^2}\right]^4$$

In principle, the Planck mass could be determined from experiments

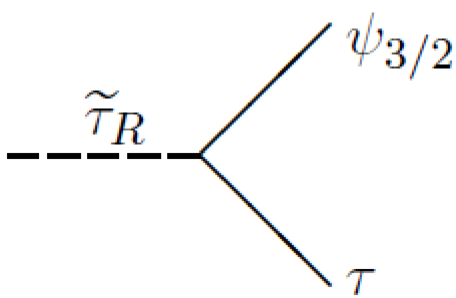
$$M_P = \sqrt{\frac{t_{\widetilde{\tau}}\, m_{\widetilde{\tau}}}{48\pi} \frac{m_{\widetilde{\tau}}^2}{m_{3/2}} \left[1 - \frac{m_{3/2}^2}{m_{\widetilde{\tau}}^2}\right]^2}$$

Physics opportunities with trapped staus

1- If the LSP is the gravitino, measure the Planck mass

Buchmüller, Hamaguchi, Ratz, Yanagida

If R-parity is conserved, the stau can only decay gravitationally



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stau mass

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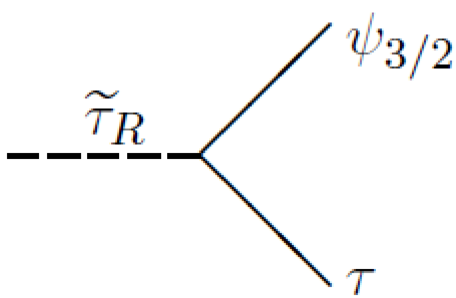

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stau lifetime

Physics opportunities with trapped staus

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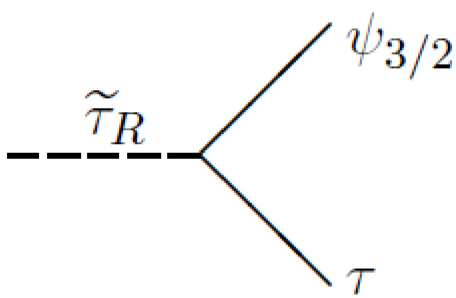

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gravitino mass

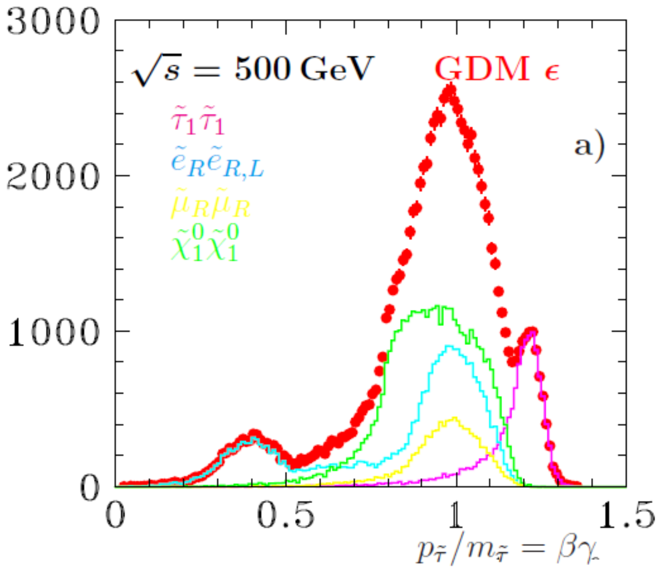
Consider a e^+e^- collider, with E_{CM}=500 GeV and $\mathcal{L}$=100 fb^{-1} and SUSY parameters as in the ε benchmark point:

$m_{\tilde{\tau}}$=157.6 GeV, $\tau_{\tilde{\tau}}$= 2.6×10^6 s, $m_{3/2}$=20 GeV

- Stau mass measurement:

From the stau momentum in $e^+e^- \rightarrow \tilde{\tau}^+\tilde{\tau}^-$

$$\langle p_{\tilde{\tau}} \rangle = 192.4 \pm 0.2 \text{ GeV}$$
$$m_{\tilde{\tau}} = 157.6 \pm 0.2 \text{ GeV}$$



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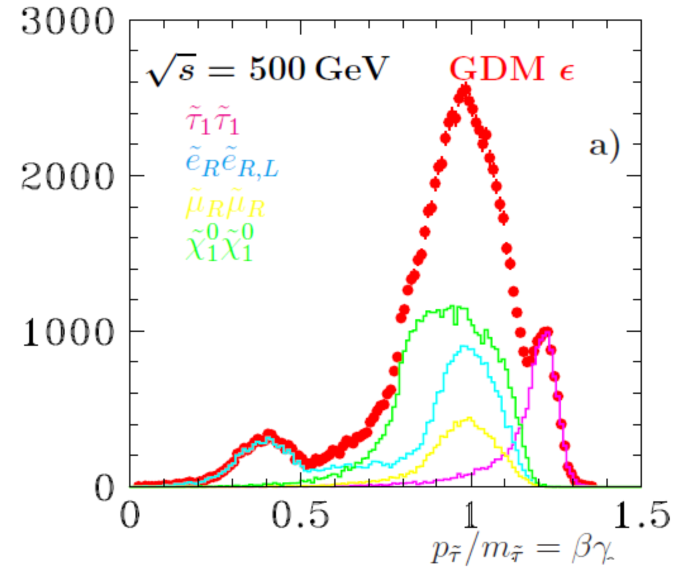
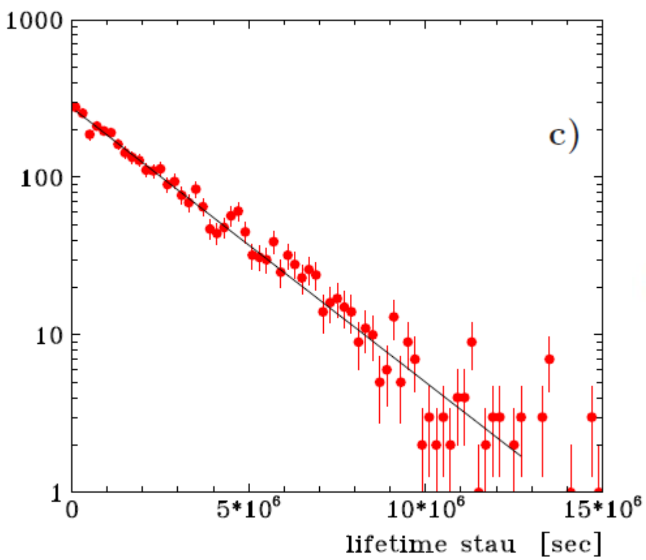


- **Stau lifetime**

$$t_{\tilde{\tau}} = (2.6 \pm 0.05)\cdot 10^6 \text{ s}$$



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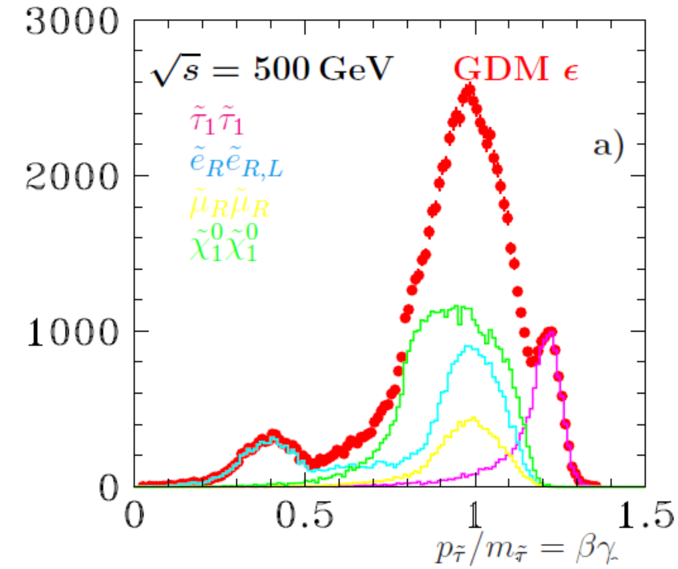

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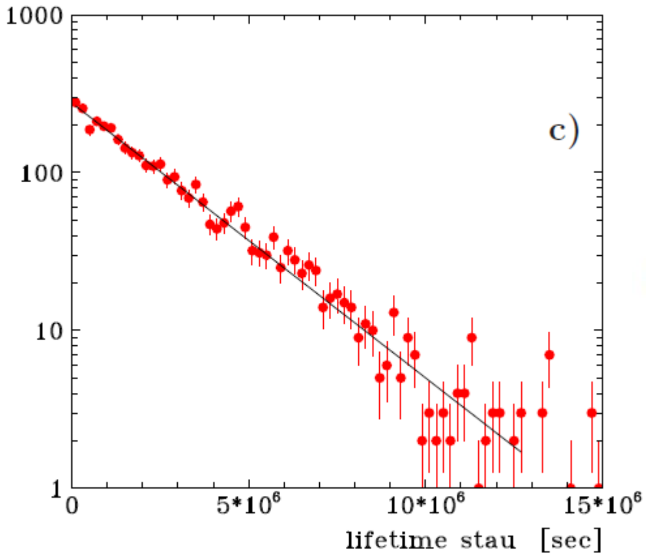
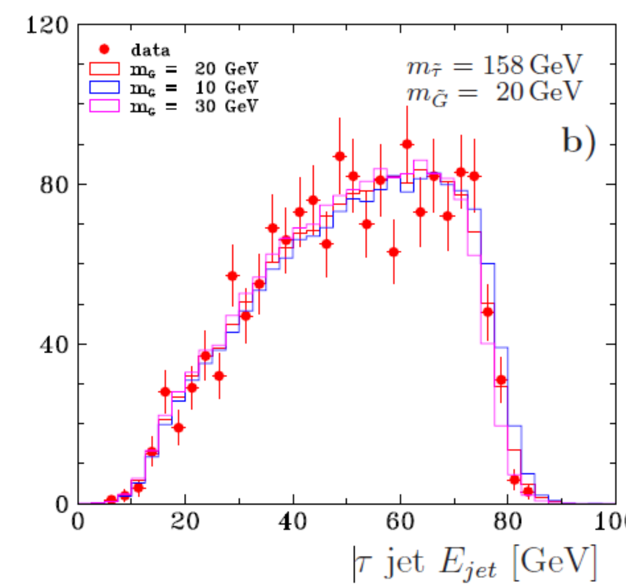


- Gravitino mass:

From the τ recoil energy in $\tilde{\tau}_1\rightarrow\tau\,\psi_{3/2}$

$$m_{3/2} = 20 \pm 4 \text{ GeV}$$



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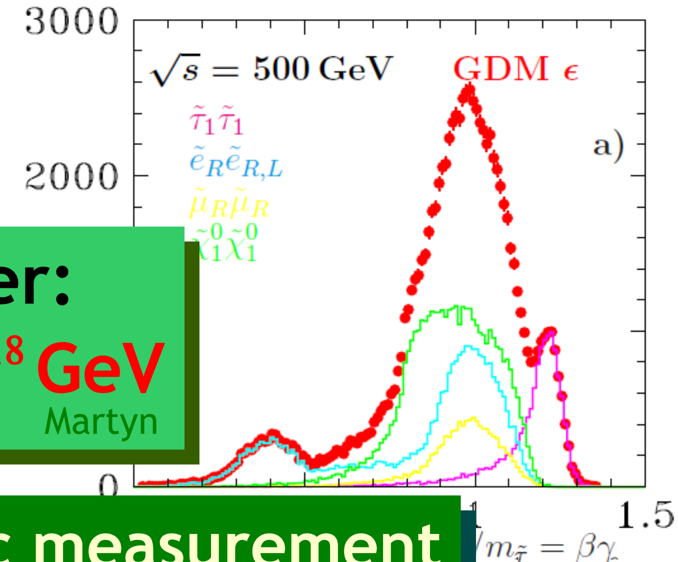
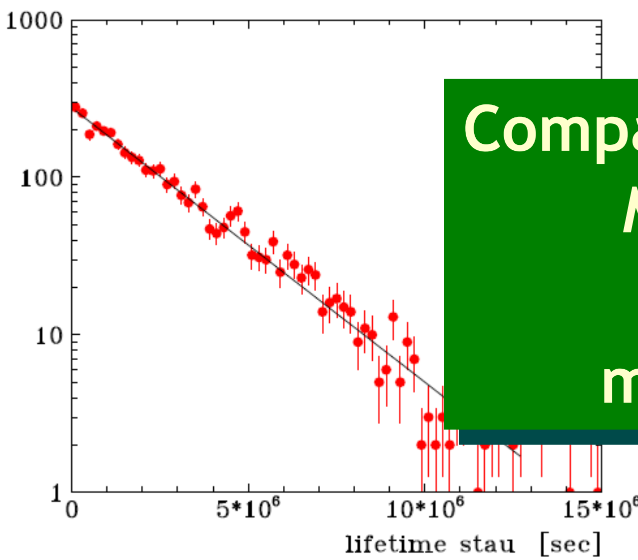


Putting all together:

$M_p=(2.4 \pm 0.5)\times10^{18}$ GeV

Martyn



Compare to the macroscopic measurement
$M_p=(8\pi G_N)^{-1/2}=2.436(2)\times10^{18}$ GeV
Rather accurate *microscopic* measurement of the Planck mass!

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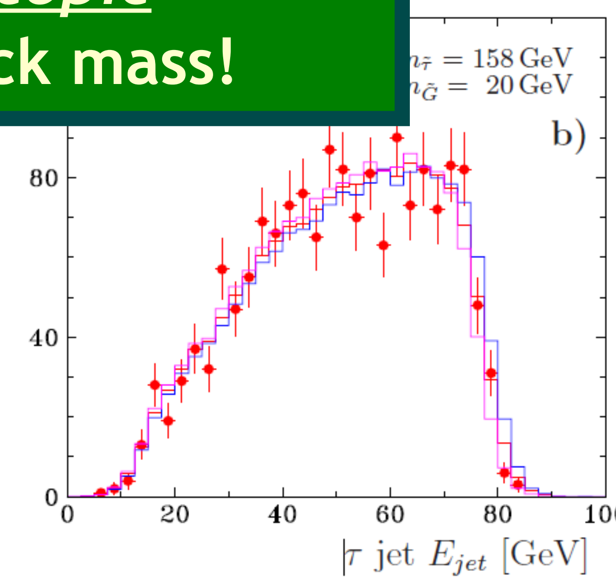

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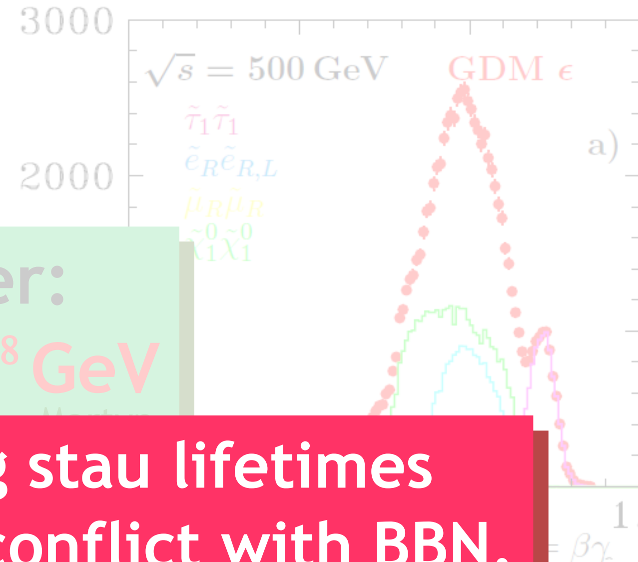


Putting all together:

M_P=(2.4 ± 0.5)×10^{18} GeV

WARNING!

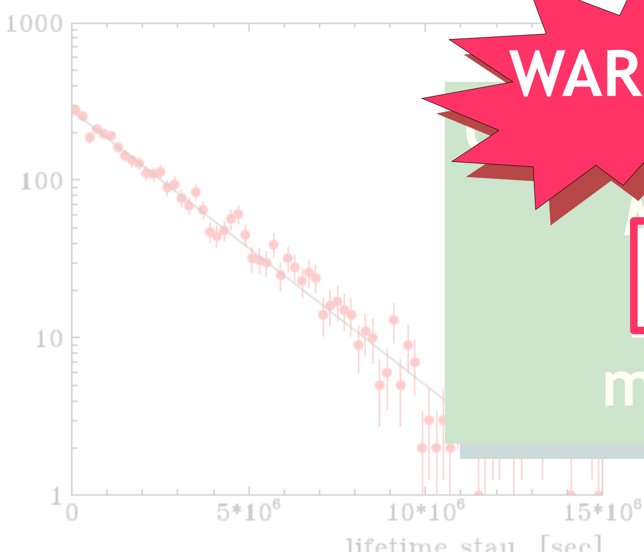
These long stau lifetimes could be in conflict with BBN.

$M_P=(8\pi G_N)^{-1/2}$=2.436(2)×10^{18} GeV

$$t_{\tilde{\tau}} = (2.6 \pm 0.05) \cdot 10^6\,\mathrm{s}$$

croscopic

measurement of the Planck mass!



- Gravitino mass:

From the τ recoil energy in $\tilde{\tau}_1 \to \tau\,\psi_{3/2}$

$$m_{3/2} = 20 \pm 4\ \mathrm{GeV}$$

Consistency with BBN typically requires a stau lifetime shorter than 1000 s ⇒ $m_{3/2}<0.3$ GeV. Too small to be measured through the τ recoil energy.

The measurement of the Planck mass in collider experiments is not guaranteed, however, the SUSY breaking scale, $F=\sqrt{3}\, m_{3/2}M_P$, could be measured.

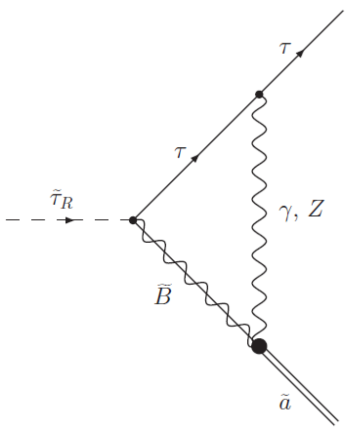
$$t_{\tilde{\tau}}^{-1} = \Gamma_{\tilde{\tau}\to\tau\,\psi_{3/2}} = \frac{m_{\tilde{\tau}}^5}{16\pi F^2}\left[1-\frac{m_{3/2}^2}{m_{\tilde{\tau}}^2}\right]^4$$

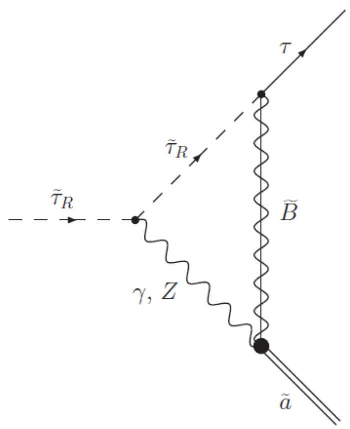
$$F \simeq \left[\frac{t_{\tilde{\tau}}\, m_{\tilde{\tau}}^5}{16\pi}\right]^{1/2}$$

2- If the LSP is the axino, estimate the Peccei-Quinn scale

Brandenburg et al

The stau can only decay via a one loop diagram:





$$\Gamma(\tilde{\tau}_{\mathrm{R}} \rightarrow \tau\, \tilde{a}) \simeq \xi^2\, (25\ \mathrm{sec})^{-1} C^2_{\mathrm{aYY}} \left(1 - \frac{m^2_{\tilde{a}}}{m^2_{\tilde{\tau}}}\right) \times \left(\frac{m_{\tilde{\tau}}}{100\,\mathrm{GeV}}\right) \left(\frac{10^{11}\ \mathrm{GeV}}{f_a}\right)^2 \left(\frac{m_{\tilde{B}}}{100\,\mathrm{GeV}}\right)^2$$

$$f_a^2 \simeq \left(\frac{\tau_{\tilde{\tau}}}{25\ \mathrm{sec}}\right) \xi^2\, C^2_{\mathrm{aYY}} \left(1 - \frac{m^2_{\tilde{a}}}{m^2_{\tilde{\tau}}}\right) \left(\frac{m_{\tilde{\tau}}}{100\,\mathrm{GeV}}\right) \left(\frac{m_{\tilde{B}}}{100\,\mathrm{GeV}}\right)^2 \left(10^{11}\ \mathrm{GeV}\right)^2$$

ξ and C_{aYY} are $\mathcal{O}(1)$ parameters, and $m_{\tilde{a}}$ is typically $\ll m_{\tilde{\tau}}$.

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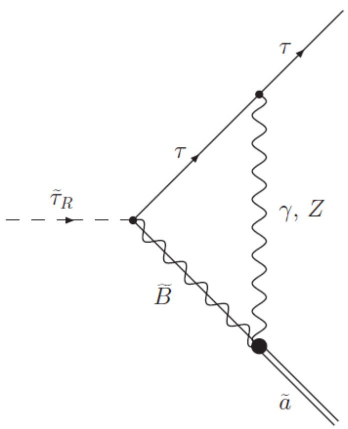

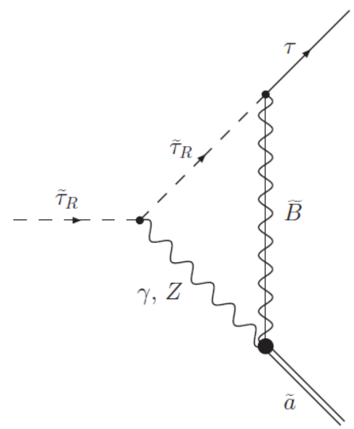

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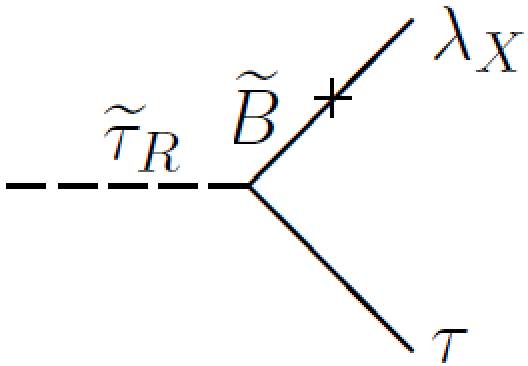
ξ and C_{aYY} are $\mathcal{O}(1)$ parameters, and $m_{\tilde{a}}$ is typically $\ll m_{\tilde{\tau}}$.

The measurement of the bino mass as well as the stau mass and lifetime leads to an estimate of the PQ scale.

3- If the LSP is the hidden gaugino, measure the kinetic mixing

AI, Ringwald, Weniger

The stau decays via the small kinetic mixing:



$$t^{-1}_{\widetilde{\tau}_R} = \Gamma_{\widetilde{\tau}_R \to \lambda_X \tau} \simeq \frac{g'^2}{2\pi} \Theta^2 m_{\widetilde{\tau}} \left(1 - \frac{M_X^2}{m_{\widetilde{\tau}}^2}\right)^2$$

The kinetic mixing parameter could be determined from experiments

$$\Theta = \sqrt{\frac{2\pi t^{-1}_{\widetilde{\tau}_R}}{g'^2 m_{\widetilde{\tau}}} \left(1 - \frac{M_X^2}{m_{\widetilde{\tau}}^2}\right)^{-1}}$$

4- Determine the spin of the invisible particle

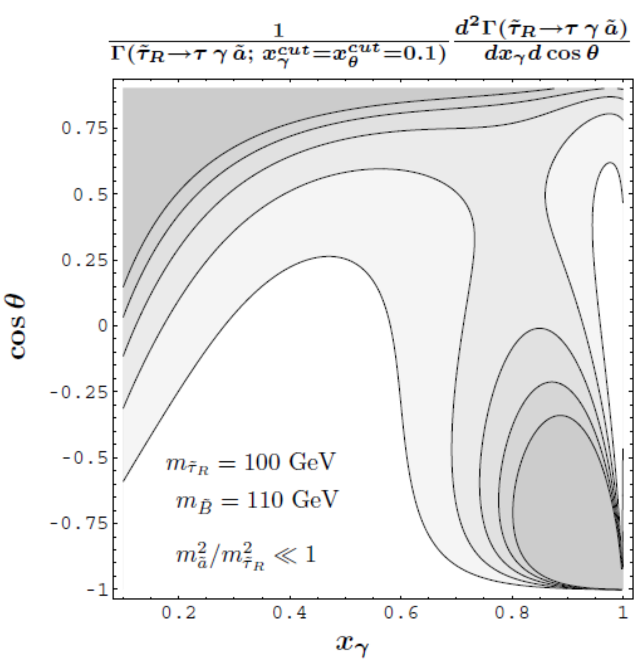
Buchmuller et al.
Brandenburg et al

In experiments, the signal is $\tilde{\tau} \to \tau$ + missing energy.

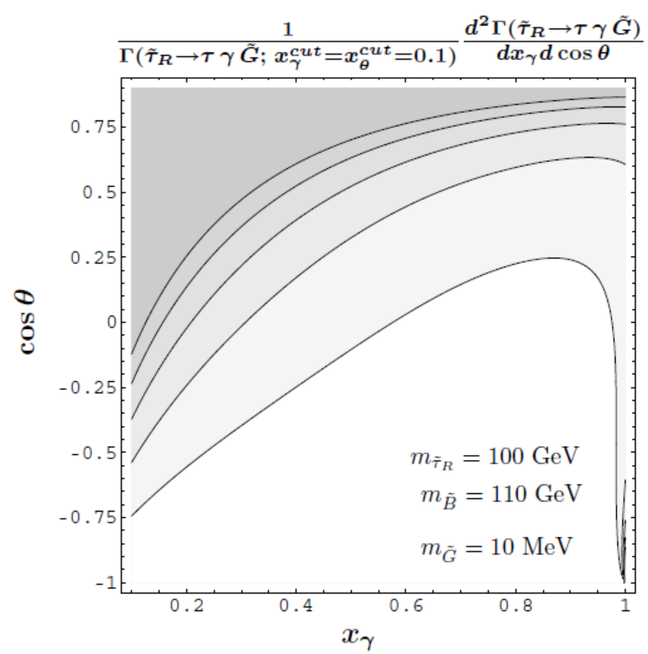
Which particle carries the missing energy:
gravitinos, axinos, hidden gauginos, neutrinos?

Search for the three body decay $\tilde{\tau} \to \tau + \gamma$ + missing energy
And analyze the angular and energy distribution of photons

Axino LSP Scenario



Gravitino LSP Scenario

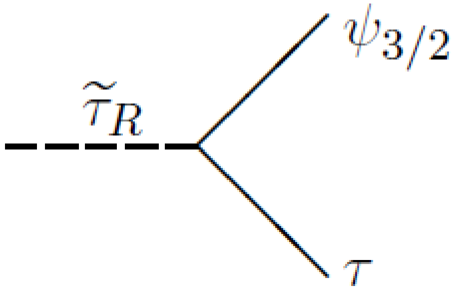


In principle possible, but very difficult!

5- Search for lepton flavour violation

Hamaguchi, AI

LFC



If lepton flavour is conserved,
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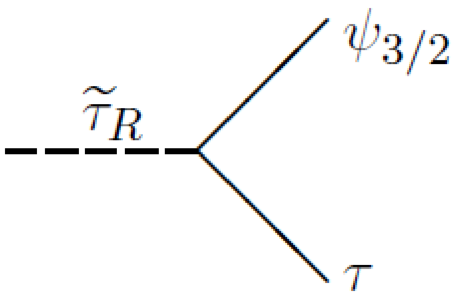
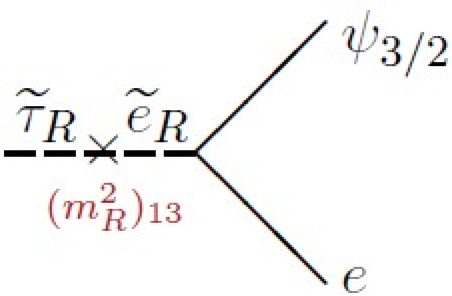


If lepton flavour is conserved, the NLSP can only decay into taus

LFV



If lepton flavour is violated, the NLSP can also decay into electrons or muons

Potential sources of background:

- Flavour conserving tau decays involving neutrinos:

$$\tau^- \longrightarrow e^- \; \bar{\nu}_e \; \nu_\tau \qquad \mathrm{BR} \simeq 18\%$$

$$\widetilde{\tau}_R \longrightarrow \tau \; \psi_{3/2} \longrightarrow \quad \tau^- \longrightarrow \mu^- \; \bar{\nu}_\mu \; \nu_\tau \qquad \mathrm{BR} \simeq 17\%$$

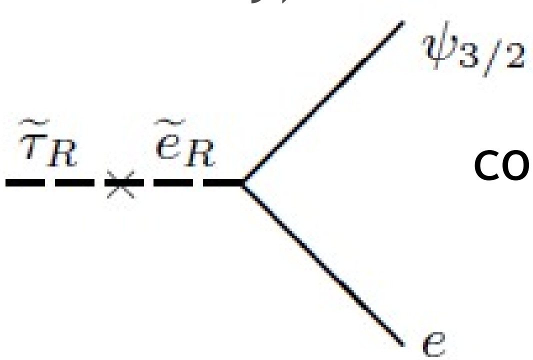
$$\tau^- \longrightarrow \pi^- \; \bar{\nu}_\tau \qquad \mathrm{BR} \simeq 11\%$$

$$\hookrightarrow \mu^- \bar{\nu}_\mu \qquad \mathrm{BR} \simeq 100\%$$

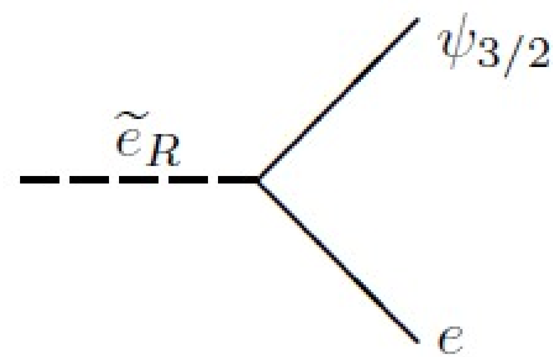
Can be suppressed using appropriate kinematical cuts

- Selectron pollution, when selectrons are also long lived

(when the mass splitting between the selectron and the stau is smaller than the tau mass, so that $\widetilde{e}_R \longrightarrow \widetilde{\tau}_R \tau e$ is forbidden kinematically)



could be confused with



SIGNAL

BACKGROUND

Potential sources of background:

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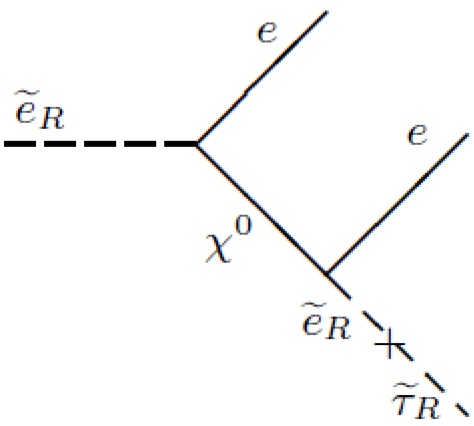
- Selectron pollution, when selectrons are also long lived

(when the mass splitting between the selectron and the stau is smaller than the tau mass, so that $\widetilde{e}_R \to \widetilde{\tau}_R \tau e$ is forbidden kinematically)

But if LFV exists, the selectrons decay very fast ⇒ no pollution



If LFV exists in Nature, backgrounds in this experiments are essentially negligible and all the electrons have to come from the LFV $\tilde{\tau}_R$ decays.

If no electron is observed

$$N_{\tilde{\tau}}(\text{init.}) = N_{\tilde{\mu}}(\text{init.}) = N_{\tilde{e}}(\text{init.}) = 1000$$

$$(m^2_{\tilde{l}_R})_{13}/m^2_{\tilde{\tau}} \lesssim 3 \times 10^{-2} \text{ @ } 90\% \text{ c.l.}$$

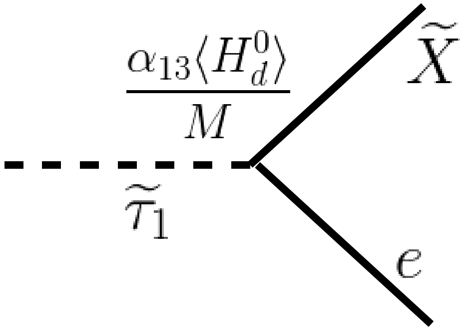
$$N_{\tilde{\tau}}(\text{init.}) = 0, \;\; N_{\tilde{\mu}}(\text{init.}) = 0, \;\; N_{\tilde{e}}(\text{init.}) = 10000$$

$$(m^2_{\tilde{l}_R})_{13}/m^2_{\tilde{\tau}} \lesssim 2 \times 10^{-2} \text{ @ } 90\% \text{ c.l.}$$

Note: in some scenarios the LFV in stau decay can be large, while being the rates for $\ell_i \to \ell_j \gamma$ small:

E.g. Hidden sector chiral superfield, X, that interacts with the MSSM via a higher dimensional operator

$$W \supset \frac{\alpha_{ij}}{M} L_i H_d e^c_{Rj} X$$



De Simone, Garny, AI, Weniger

R-parity non-conservation

The Minimal Supersymmetric extension of the Standard Model introduces new sources of lepton and baryon number violation.

$$
\begin{aligned}
W_{MSSM} = {} & \mathbf{Y}^e_{ij} e^c_{Ri} L_j H_d + \mathbf{Y}^d_{ij} d^c_{Ri} Q_j H_d + \mathbf{Y}^u_{ij} u^c_{Ri} Q_j H_u + \mu H_u H_d + \\
& \frac{1}{2}\lambda_{ijk} L_i L_j e^c_k + \lambda'_{ijk} L_i Q_j d^c_k + \frac{1}{2}\lambda''_{ijk} u^c_i d^c_j d^c_k + \mu'_i L_i H_u .
\end{aligned}
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$$\frac{1}{2}\lambda_{ijk} L_i L_j e^c_k + \lambda'_{ijk} L_i Q_j d^c_k + \frac{1}{2}\lambda''_{ijk} u^c_i d^c_j d^c_k + \mu_i L_i H_u.$$

R-parity is introduced by hand to guarantee proton stability.

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$$W_{MSSM} = \mathbf{Y}^e_{ij} e^c_{Ri} L_j H_d + \mathbf{Y}^d_{ij} d^c_{Ri} Q_j H_d + \mathbf{Y}^u_{ij} u^c_{Ri} Q_j H_u + \mu H_u H_d +$$
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R-parity is introduced by hand to guarantee proton stability.

Strictly speaking this is **not** the minimal SUSY extension of the SM!!

The general MSSM (without imposing R-parity) is viable as long as:

$\lambda'_{11k}\,\lambda''_{11k} < 10^{-27}$ (proton stability).

$\lambda, \lambda', \lambda'' < 10^{-7}$ (baryogenesis)

The neutralino LSP cannot be dark matter. Interestingly, superWIMP LSP (gravitino, axino, hidden U(1) gaugino) can be long lived enough to constitute the dark matter.

(Or the dark matter could be something else, *e.g.* axions.)

In the general MSSM (without R-parity conservation) very spectacular signatures are expected at colliders if the stau is the NLSP (and the LSP is a superWIMP) Buchmüller, Covi, Hamaguchi, AI, Yanagida
Ishiwata, Ito, Moroi

- Main decay: $\tilde{\tau}_R \to \tau\, \nu_\mu,\ \mu\, \nu_\tau$ (through $\lambda L L e^c$)

$$c\tau_{\tilde{\tau}}^{lep} \sim 30 \text{ cm} \left(\frac{m_{\tilde{\tau}}}{200\text{GeV}}\right)^{-1} \left(\frac{\lambda_{323}}{10^{-8}}\right)^{-2}$$

Long heavily ionizing charged track followed by a muon track or a jet (with identical probability).

- Also, the small left-handed component induces $\tilde{\tau}_L \to b^c\, t$ (through $\lambda' Q L d^c$)

$$c\tau_{\tilde{\tau}}^{had} \sim 8 \text{ m} \left(\frac{m_{\tilde{\tau}}}{200\text{GeV}}\right)^{-1} \left(\frac{\lambda_{323}}{10^{-8}}\right)^{-2} \left(\frac{\cos\theta_{\tau}}{0.1}\right)^{-2}$$

Long heavily ionizing charged track followed by three jets.

Conclusions

- Scenarios with long lived staus are common in SUSY models, especially if the lightest supersymmetric particle (the dark matter particle?) is superweakly interacting.
  - Gravitinos
  - Axinos
  - Hidden U(1) gauginos
- Long lived staus could be abundantly produced at future linear colliders. Many physics opportunities:
  - Measure SUSY parameters.
  - Searches for lepton flavour violation.
  - Measure fundamental constants of Nature (Planck mass or Peccei-Quinn scale or kinetic mixing parameter).