Gravitino Dark Matter
and its collider signatures

Koichi Hamaguchi (DESY)

at UK HEP Forum (2005 May, Abingdon,UK)

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based on .....

- W.Buchmüller, KH, M.Ratz, hep-ph/0307181 [PLB574]
- W.Buchmüller, KH, M.Ratz, T.Yanagida, hep-ph/0402179 [PLB588], /0403203
- KH, Y.Kuno, T.Nakaya, M.M.Nojiri, hep-ph/0409248 [PRD70]
- KH, A.Ibarra, hep-ph/0412229 [JHEP0502]
- A.Brandenburg, L.Covi, KH, L.Roszkowski, F.D.Steffen, hep-ph/0501287

PLAN

- Introduction: (What is Gravitino?)
  - Cosmological Gravitino Problems
- Gravitino Dark Matter
- Gravitino at Colliders
- Summary

Introduction

quarks $\boldsymbol{q}$

leptons $\boldsymbol{\ell}$

gauge bosons $\boldsymbol{A_\mu^{(a)}}$

Higgs bosons $\boldsymbol{H}$

Introduction

Supersymmetry

quarks $\boldsymbol{q}$	$\longleftrightarrow$	squarks $\widetilde{\boldsymbol{q}}$
leptons $\boldsymbol{\ell}$	$\longleftrightarrow$	sleptons $\widetilde{\boldsymbol{\ell}}$
gauge bosons $\boldsymbol{A_\mu^{(a)}}$	$\longleftrightarrow$	gauginos $\boldsymbol{\lambda^{(a)}}$
Higgs bosons $\boldsymbol{H}$	$\longleftrightarrow$	higgsinos $\widetilde{\boldsymbol{h}}$

Introduction

Supersymmetry

quarks q	$\longleftrightarrow$	squarks $\widetilde{q}$
leptons ℓ	$\longleftrightarrow$	sleptons $\widetilde{\ell}$
gauge bosons $A_\mu^{(a)}$	$\longleftrightarrow$	gauginos $\lambda^{(a)}$
Higgs bosons H	$\longleftrightarrow$	higgsinos $\widetilde{h}$

graviton e_μ^α

Introduction

Supergravity

Supersymmetry

quarks q	$\longleftrightarrow$	squarks $\widetilde{q}$
leptons ℓ	$\longleftrightarrow$	sleptons $\widetilde{\ell}$
gauge bosons $A_\mu^{(a)}$	$\longleftrightarrow$	gauginos $\lambda^{(a)}$
Higgs bosons H	$\longleftrightarrow$	higgsinos $\widetilde{h}$

graviton e_μ^α	$\longleftrightarrow$	gravitino $\psi_{3/2}$

Introduction: R-parity

- Usually R-parity is imposed to avoid too large baryon/lepton number violation.

$$\boldsymbol{q},\ \boldsymbol{\ell},\ \boldsymbol{A}_{\boldsymbol{\mu}}^{(a)},\ \boldsymbol{H},\ \boldsymbol{e}_{\boldsymbol{\mu}}^{\boldsymbol{\alpha}},\ \cdots \quad \text{R-parity } + \text{ (even)}$$

$$\widetilde{\boldsymbol{q}},\ \widetilde{\boldsymbol{\ell}},\ \boldsymbol{\lambda}^{(a)},\ \widetilde{\boldsymbol{h}},\ \boldsymbol{\psi}_{3/2},\ \cdots \quad \text{R-parity } - \text{ (odd)}$$

$$\text{e.g.,}\quad \underset{(-)}{\overset{\text{squark}}{\widetilde{\boldsymbol{q}}}} \longrightarrow \underset{(+)}{\overset{\text{quark}}{\boldsymbol{q}}} + \underset{(-)}{\overset{\text{gaugino}}{\boldsymbol{\lambda}}}$$

- The lightest SUSY particle (LSP) becomes stable.
- The next-to-lightest SUSY particle (NLSP) can decay only to LSP + SM particle.

Introduction: Setup

We consider a scenario where.....

- LSP $=$ gravitino $\psi_{3/2}$ $\cdots$ stable

..... realized in various SUSY models, e.g., GMSB, mSUGRA, gaugino-MSB....

..... The gravitino mass: $m_{3/2} \sim \mathcal{O}(\text{eV}) \cdots \mathcal{O}(100 \text{ GeV})$.

$\Rightarrow$ NLSP ($=$ for example charged slepton $\tilde{\tau}$) $\cdots$ very long-lived!!

NLSP slepton LSP gravitino

$$\tilde{\tau} \longrightarrow \psi_{3/2} + \tau$$

$$(-) \qquad (-) \qquad (+)$$

..... interaction suppressed by $\sim 1/M_{\text{Planck}}$

(e.g., for $m_{\tilde{\tau}} = 100$ GeV and $m_{3/2} = 10$ GeV,... $\tilde{\tau}$'s lifetime $= 70$ days!)

Gravitino Problems:

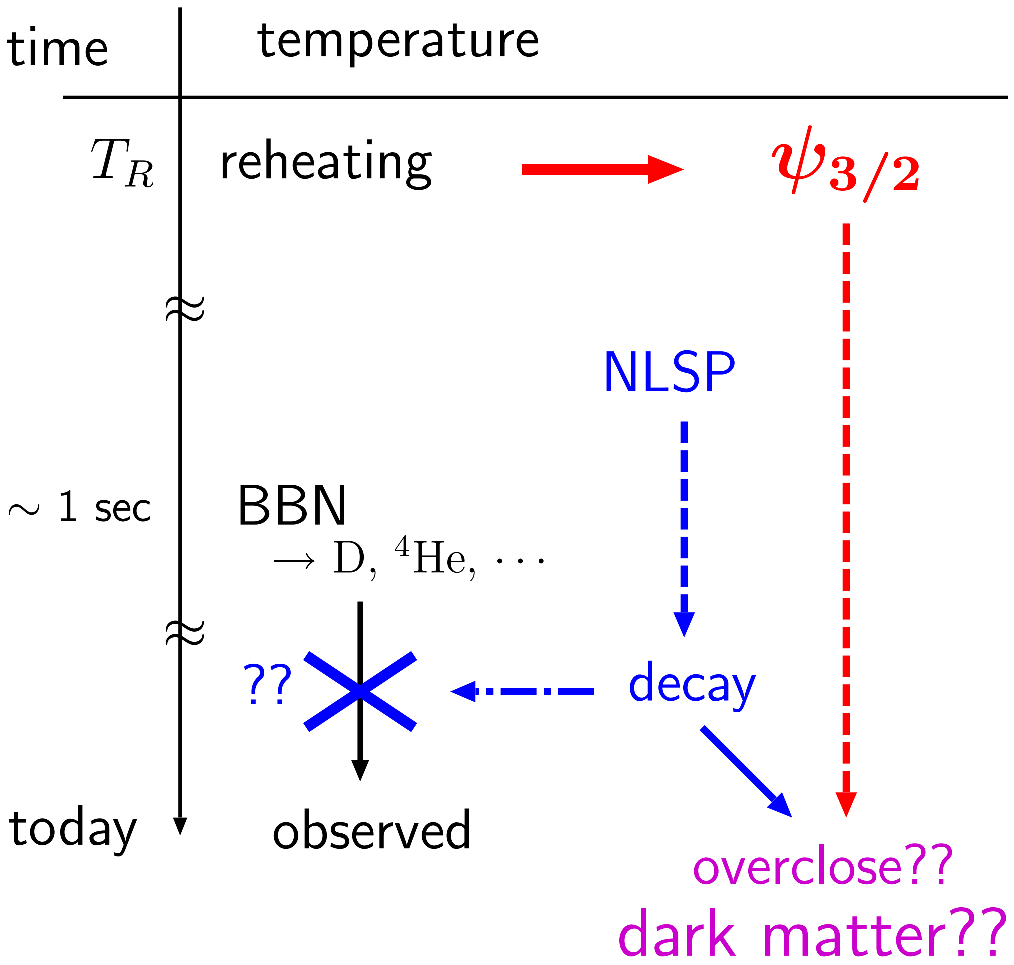
Gravitino Problems:

thermal history

time	temperature	
??	~ 0	inflation
??	T_R	reheating
$\approx$		baryogenesis $\to n_B/s \simeq 10^{-10}$
$\sim$ 1 sec	~ 1 MeV	Big Bang Nucleosynthesis $\to$ D, ^{4}He, $\cdots$
$\approx$		$\downarrow$
14 Gyr	2.7 K	observed

Gravitino Problems:

thermal history with stable gravitino $\psi_{3/2}$



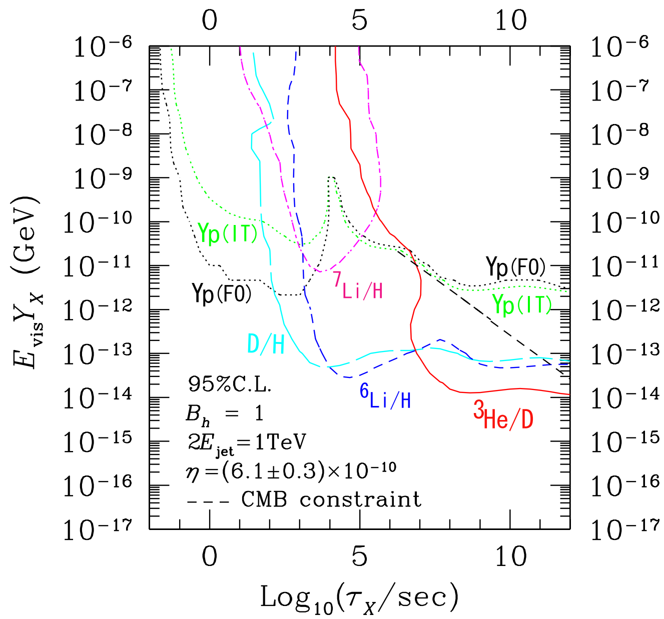
Gravitino Problems: NLSP decay into Gravitino

- Generic BBN constraints on late decaying particle

Recent analysis including hadronic decay:

– M.Kawasaki, K.Kohri, T.Moroi, astro-ph/0408426 [PRD71] $\Longrightarrow$

– cf. K.Jedamzik, astro-ph/0402344 [PRD70]



- Constraints on NLSP decay into Gravitino

Some of recent analyses

– …

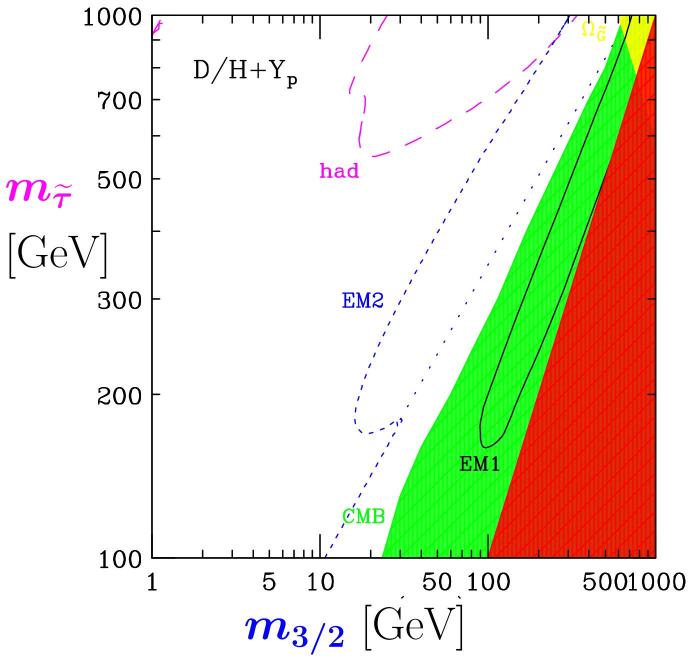
– M.Fujii, M.Ibe, T.Yanagida, hep-ph/0310142 [PLB579]

– J.R.Ellis, K.A.Olive, Y.Santoso, V.C.Spanos, hep-ph/0312262 [PLB588]

– J.L.Feng, S.Su, F.Takayama hep-ph/0404231 [PRD70] $\Longrightarrow$

– L.Roszkowski, R.Ruiz de Austri hep-ph/0408227

– …



Gravitino Dark Matter:

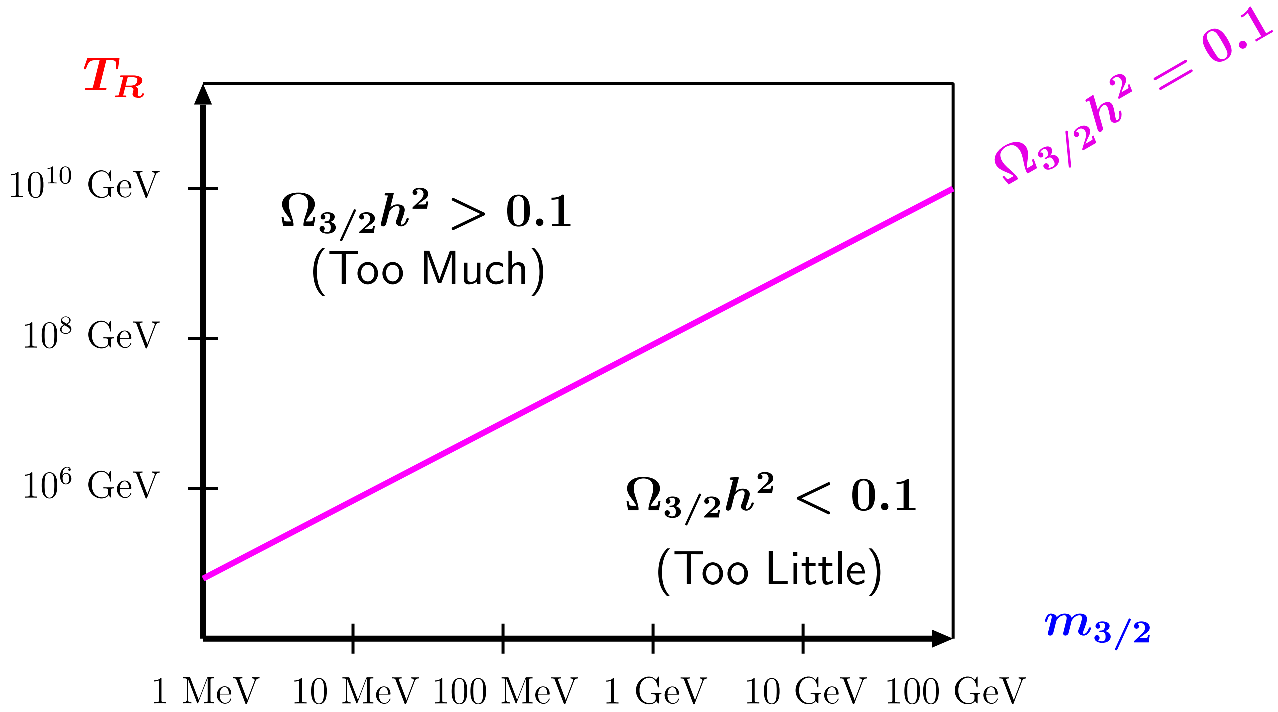
Gravitino Dark Matter: thermal relic density

$\cdots$ depends on the history of the very early Universe

Dominant production occurs just after the Inflation

$$\Omega_{3/2} \propto \frac{T_R}{m_{3/2}} + \mathcal{O}\left(\frac{m_{3/2}}{m_{\tilde{g}}}\right)^2$$

$T_R \cdots$ reheating temperature



(See latest calculation, M. Bolz, A. Brandenburg, W. Buchmüller, NPB**606**, 518 ('01).)

Gravitino Dark Matter:

Several ways to make $\Omega_{3/2}$ independent of T_R

- thermal production + changing gauge coupling

– W.Buchmüller, KH, M.Ratz, hep-ph/0307181 [PLB574]

- thermal production + late time entropy production

e.g., some of recent works $\cdots$

– ...

– M.Fujii, T.Yanagida, hep-ph/0208191 [PLB549]

– M.Fujii, M.Ibe, T.Yanagida, hep-ph/0309064 [PRD69]

– M.Ibe, T.Yanagida, hep-ph/0404134 [PLB597]

– W.Buchmüller, KH, M.Ibe, T.Yanagida, work in progress

– ...

- non-thermal production from NLSP decay ("superWIMP" mechanism)

– J.L.Feng, A.Rajaraman, F.Takayama, hep-ph/0302215 [PRL91], hep-ph/0306024 [PRD68]

– cf. L.Covi, J.E.Kim, L.Roszkowski, hep-ph/9905212 [PRL82]

- non-thermal production from other sources

Gravitino Dark Matter:

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Gravitino Dark Matter:

gauge coupling at high T and gravitino abundance

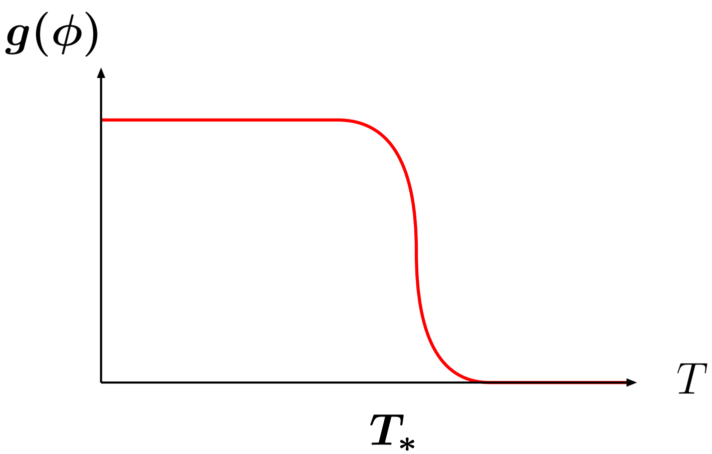
W.Buchmüller, KH, M.Ratz, PLB$\mathbf{574}$('03)

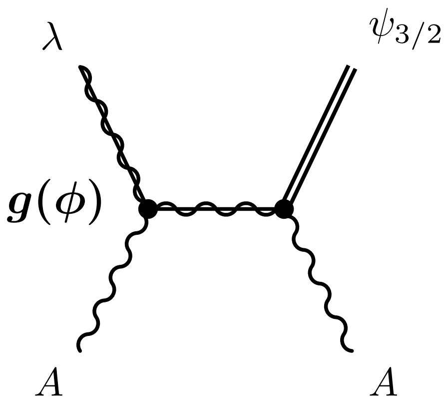
If gauge coupling $g = g(\phi)$, $\cdots$

$V(\phi) \overset{T>0}{\longrightarrow} V(\phi) + a_2\, g^2(\phi) T^4$ (cf. W.Buchmüller, KH, O.Lebedev, M.Ratz, hep-th/0404168)

$\Longrightarrow$ ϕ is shifted

$\Longrightarrow$ $g(\phi)$ decreases at high T.





gravitino production suppressed at $T > T_*$!!

Gravitino Dark Matter:

gauge coupling at high T and gravitino abundance

W.Buchmüller, KH, M.Ratz, PLB**574**('03)

For a simple set-up

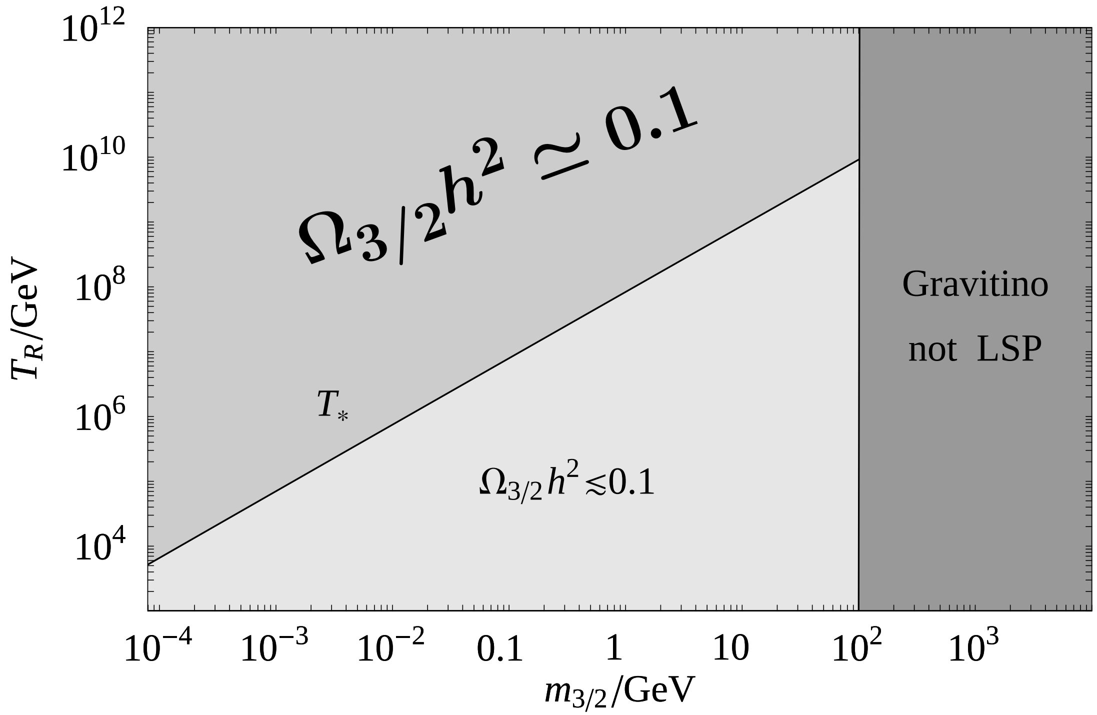
$$\mathcal{L} = \frac{1}{4}\int d^2\theta \left(\frac{1}{g_0^2} + \frac{\phi}{M}\right)\mathcal{W}_\alpha \mathcal{W}^\alpha \quad \Longrightarrow \quad \frac{1}{g_0^2}+\frac{\phi}{M} = \frac{1}{g^2(\phi)}, \quad m_{\widetilde{g}} = g^2 \frac{F_\phi}{2M} \quad \Longrightarrow \quad T_* \sim m_{3/2}\left(\frac{M_{\rm P}}{m_{\widetilde{g}}}\right)^{1/2}$$

$$\Downarrow$$

$$\Omega_{3/2}h^2 \simeq 0.1 \left(\frac{m_{\widetilde{g}}}{1\ \mathrm{TeV}}\right)^{3/2} \left(\frac{\xi}{\eta^2}\right)^{1/4}$$

$$\xi = \frac{m_\phi^2}{m_{3/2}^2} \sim \mathcal{O}(1)\,, \ \eta = \frac{F_{\rm total}}{\sqrt{3}F_\phi} \sim \mathcal{O}(1)\,.$$

without any fine-tuning!!



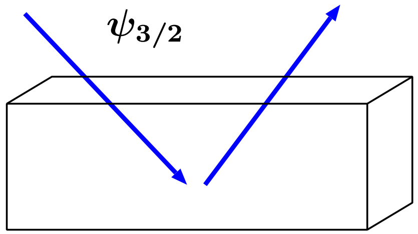
$\cdots$, moduli problem associated with ϕ field $\longrightarrow$ Open Question

Gravitino at Colliders:

Gravitino at Colliders:

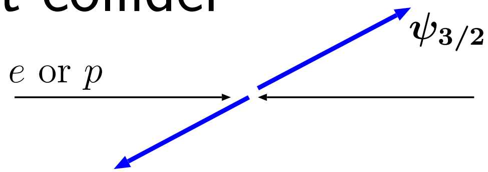
If Gravitino LSP is the Dark Matter, $\cdots$

- direct detection



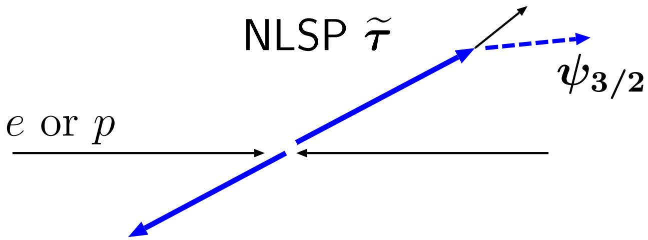
$\cdots$ seems hopeless.

- direct production at collider



$\cdots$ is extremely suppressed.

- indirect production at collider

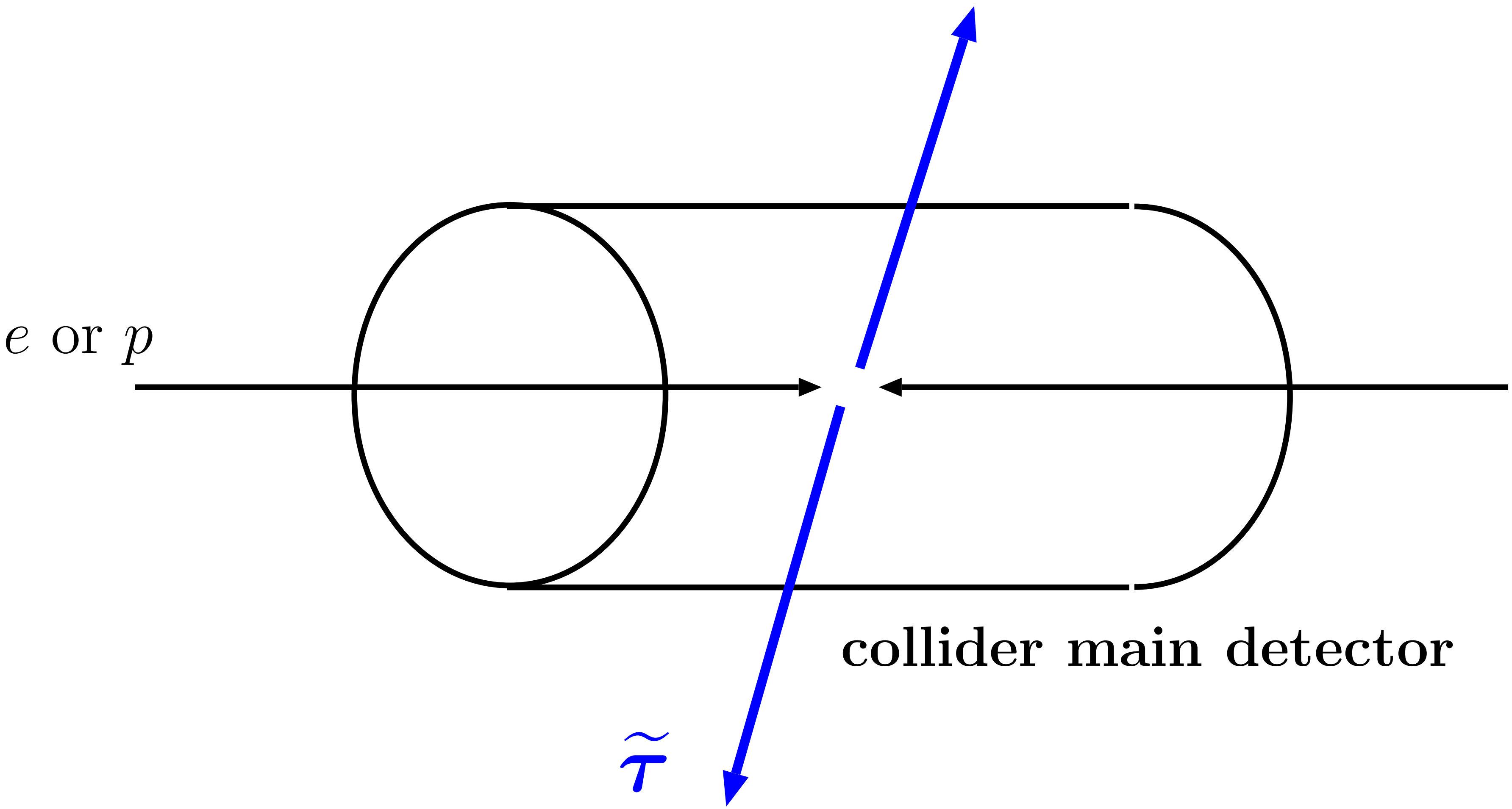


$\cdots$ looks interesting!!

In the following we assume NLSP $=$ charges slepton $\widetilde{\tau}$

Gravitino at Colliders:

at LHC/ILC, many (up to $\mathbf{10^5 \sim 10^6}$) $\widetilde{\tau}$ will be produced.

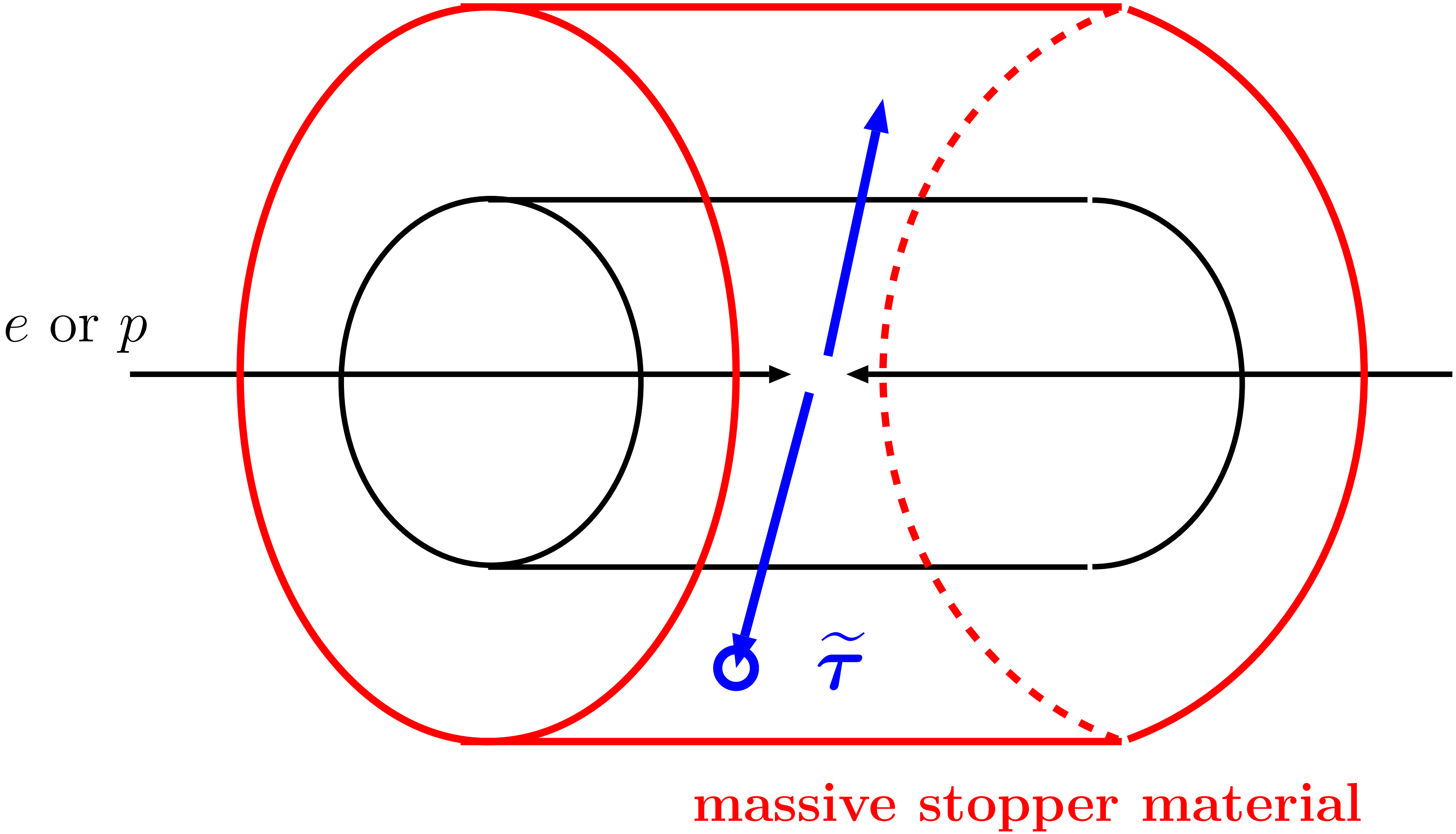


Heavy Charged Particle Track (exciting signature!)

$\cdots$ But they escape the detector — gravitino is not seen

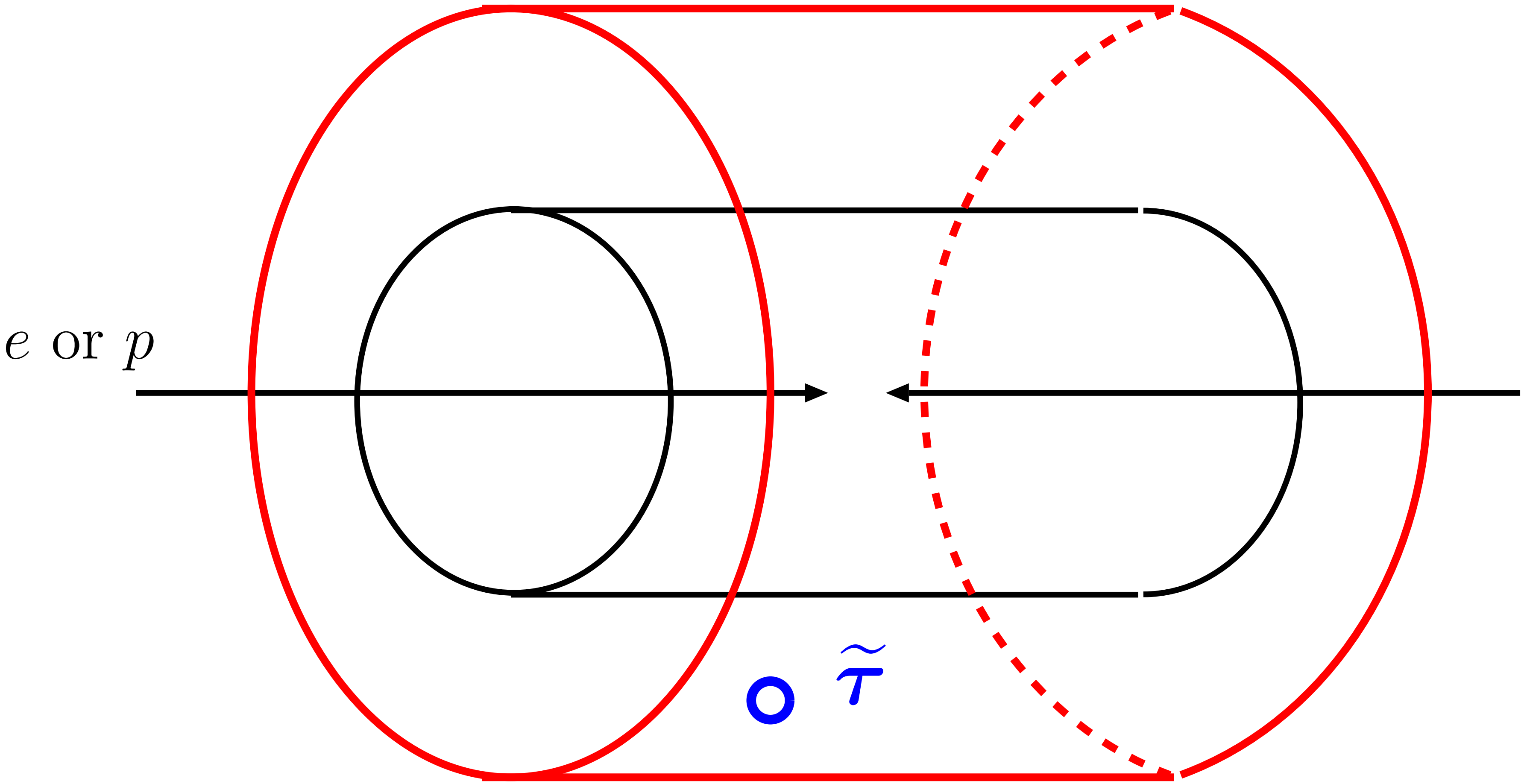
Gravitino at Colliders:

Let's stop the sleptons $\cdots$



Gravitino at Colliders:

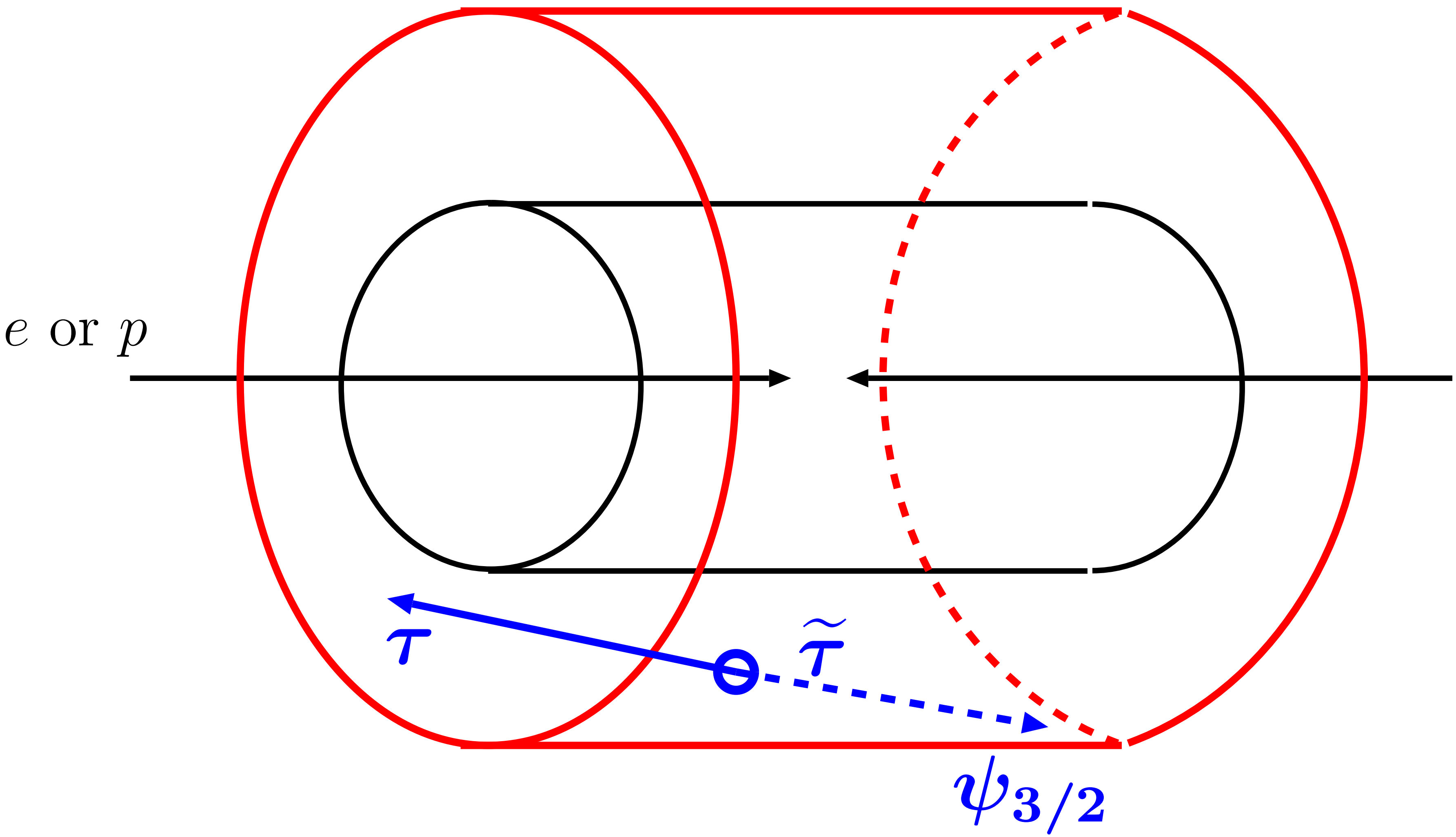
Wait for a while · · ·



· · · recall that NLSP lifetime can be $\mathcal{O}$(sec), $\mathcal{O}$(days), $\mathcal{O}$(years) · · ·

Gravitino at Colliders:

After a while, $\cdots$ Slepton decay into Gravitino!!

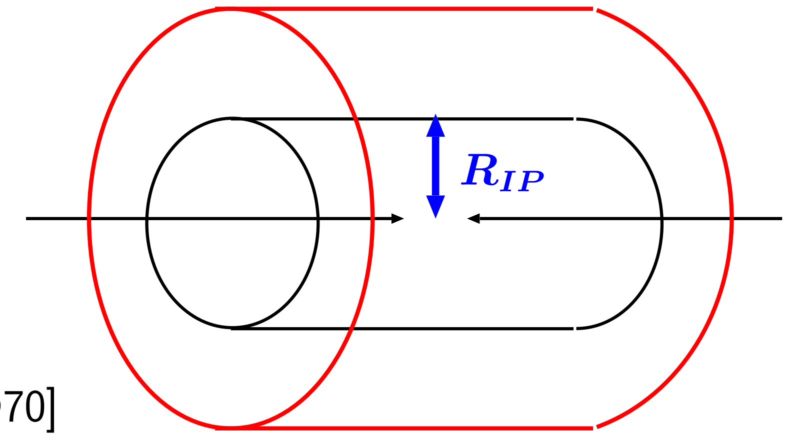


Gravitino at Colliders:

How many sleptons can we collect ?

Here we assumed 1000g/cm^2 main detector
and 2000g/cm^2 stopping material.

For details,
see KH, Kuno, Nakaya, Nojiri, hep-ph/0409248 [PRD70]
cf. Feng, Smith, hep-ph/0409278 [PRD71]



at LHC

$$\text{Number of collected } \widetilde{\tau} \simeq 5000 \times \left[\frac{M_{\text{total}}/1 \text{ kton}}{(R_{IP}/10 \text{ m})^2} \right]$$

for G2b point of GMSB model ($m_{\widetilde{\tau}} = 100$ GeV etc) and $\mathcal{L} = 300$ fb^{-1} (= 3 years high luminosity).

at ILC

$$\text{Number of collected } \widetilde{\tau} \simeq 0.9 \times 10^5 \times \left[\frac{M_{\text{total}}/1 \text{ kton}}{(R_{IP}/10 \text{ m})^2} \right]$$

for $m_{\widetilde{\tau}_R} = 100$ GeV, $m_{\widetilde{e}_R} = 103$ GeV, and $m_{\widetilde{B}} = 110$ GeV,
$e^- e^-$ mode with $E_{\text{cm}} = 229$ GeV, $\mathcal{L} = 100$ fb^{-1} ($\simeq$ 250 days run)

Stopper = Detector??

It's better if the stopper simultaneously serves as a real-time detector

- to identify the stopping position $\vec{x}_{\rm stop}$
- to record the stopping time $t_{\rm stop}$
- to record the decay time $t_{\rm decay}$
- and to study the decay products

for each NLSP event.

It's encouraging that some existing detectors can serve as a realistic stopper-detector!!

e.g. Soudan II (fine-grained tracking calorimeter for proton decay, with drift tubes sandwiched between steel sheets.)

- total mass 0.96 kton
- track resolution 0.18 cm $\times$ 0.18 cm $\times$ 1cm.
- dead time of each tube $<$ (back ground μ rate)$^{-1}$

Neutrino backgrounds from atmospheric/collider events are also small enough.

Gravitino at Colliders:

3 methods to test (discover?) the gravitino LSP

W.Buchmüller, KH, M.Ratz, T.Yanagida, hep-ph/0402179 [PLB588], hep-ph/0403203

Method ①

Measurement of the Planck scale M_P.

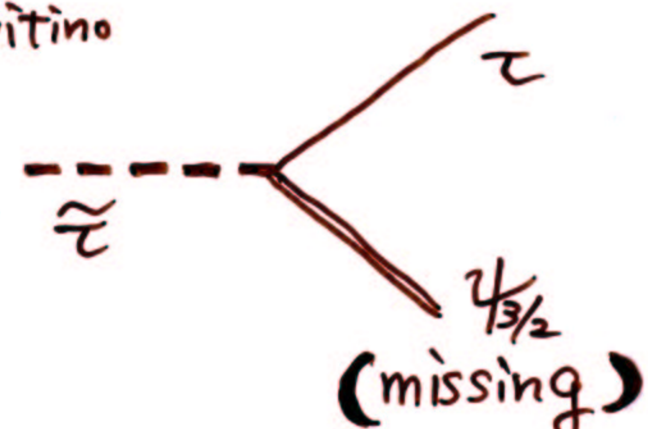
microscopic

(W. Buchmüller, KH, M. Ratz, T. Yanagida
hep-ph/0402179 (PLB 588))

slepton   lepton

$$\mathcal{L}_{\text{supergravity}} \supset \frac{-1}{\sqrt{2}\,M_P}\,\partial_\nu \tilde{\tau}_R^{*}\,\psi^{\mu}\gamma^{\nu}\gamma_{\mu}P_R\,\tau + \text{h.c.} + \cdots$$

gravitino



$$\Gamma_{\tilde{\tau}} = \Gamma_{\tilde{\tau}}(\tilde{\tau} \to \tau + \psi_{3/2}) = \frac{m_{\tilde{\tau}}^5}{48\pi m_{3/2}^2 M_P^2}\left(1 - \frac{m_{3/2}^2}{m_{\tilde{\tau}}^2}\right)^4$$

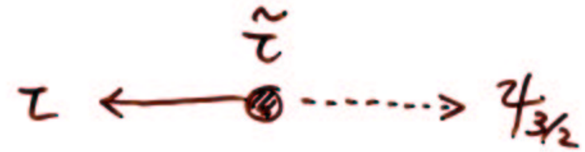
prediction of supergravity

$$\Longleftrightarrow \quad M_P^2(\text{supergravity}) = \frac{1}{48\pi}\,\frac{1}{\Gamma_{\tilde{\tau}}}\,\frac{m_{\tilde{\tau}}^5}{m_{3/2}^2}\left(1 - \frac{m_{3/2}^2}{m_{\tilde{\tau}}^2}\right)^4$$

will be measured ($\Gamma_{\tilde{\tau}}$, $m_{\tilde{\tau}}$)

can be "measured" by kinematics ($m_{3/2}$)

$$\left(m_{3/2}^2 = m_{\tilde{\tau}}^2 - m_{\tau}^2 - 2 m_{\tilde{\tau}} E_{\tau} \right)$$



consistency check!!

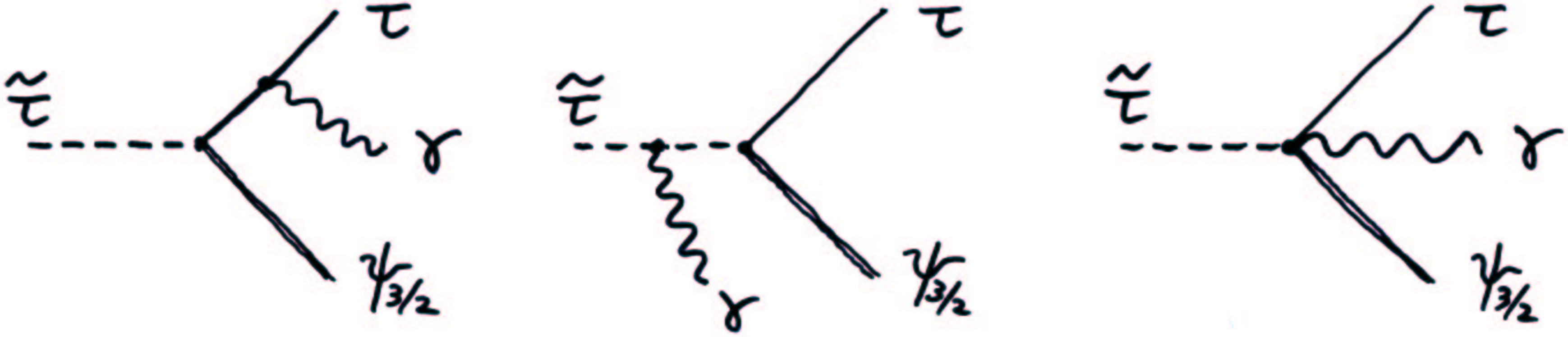
$$M_P^2(\text{gravity}) = (8\pi G_N)^{-1} = (2.44 \times 10^{18}\,\text{GeV})^2$$

Newton const

Method ②

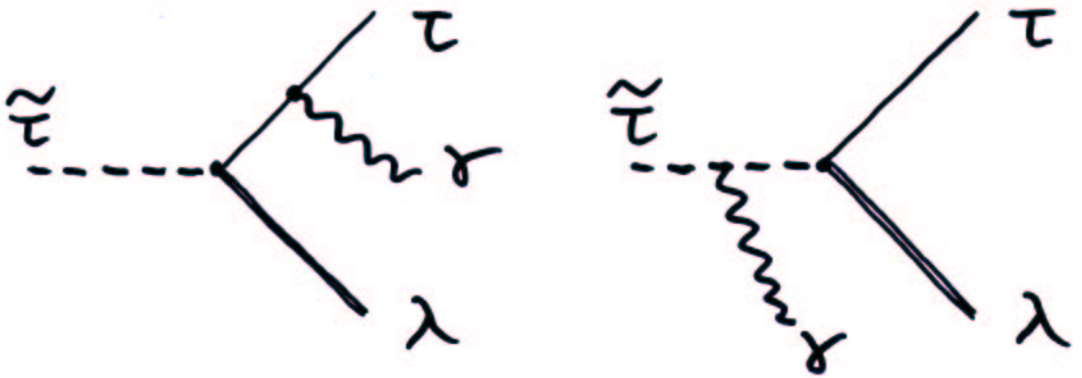
Test of particular gravitino couplings by 3-body decay

$$\mathcal{L} = \frac{-1}{\sqrt{2}M_P}(\partial_\nu + ieA_\nu)\tilde{\tau}_R^* \bar{\Psi}^\mu \gamma^\nu \gamma_\mu P_R \tau + \cdots$$

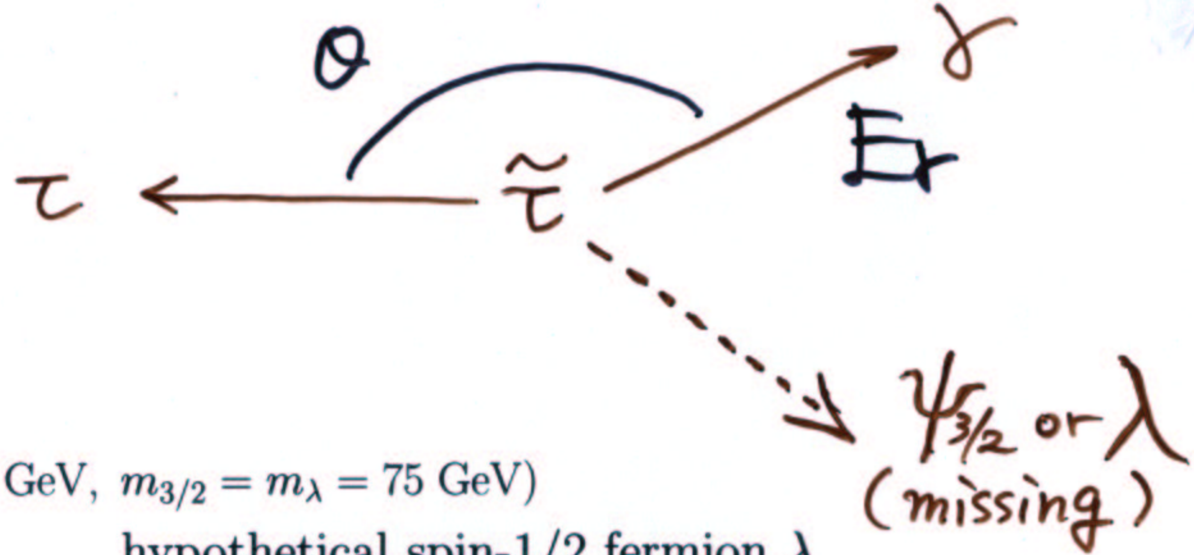


Compare with hypothetical spin-½ fermion λ.

$$\mathcal{L} = y(\tilde{\tau}_R^* \bar{\lambda} P_R \tau + \tilde{\tau}_L^* \bar{\lambda} P_L \tau) + h.c. \qquad y \ll 1$$



angular and energy distributions of τ and γ



Results (for right-handed $\tilde{\tau}_R$, $m_{\tilde{\tau}} = 150$ GeV, $m_{3/2} = m_\lambda = 75$ GeV)

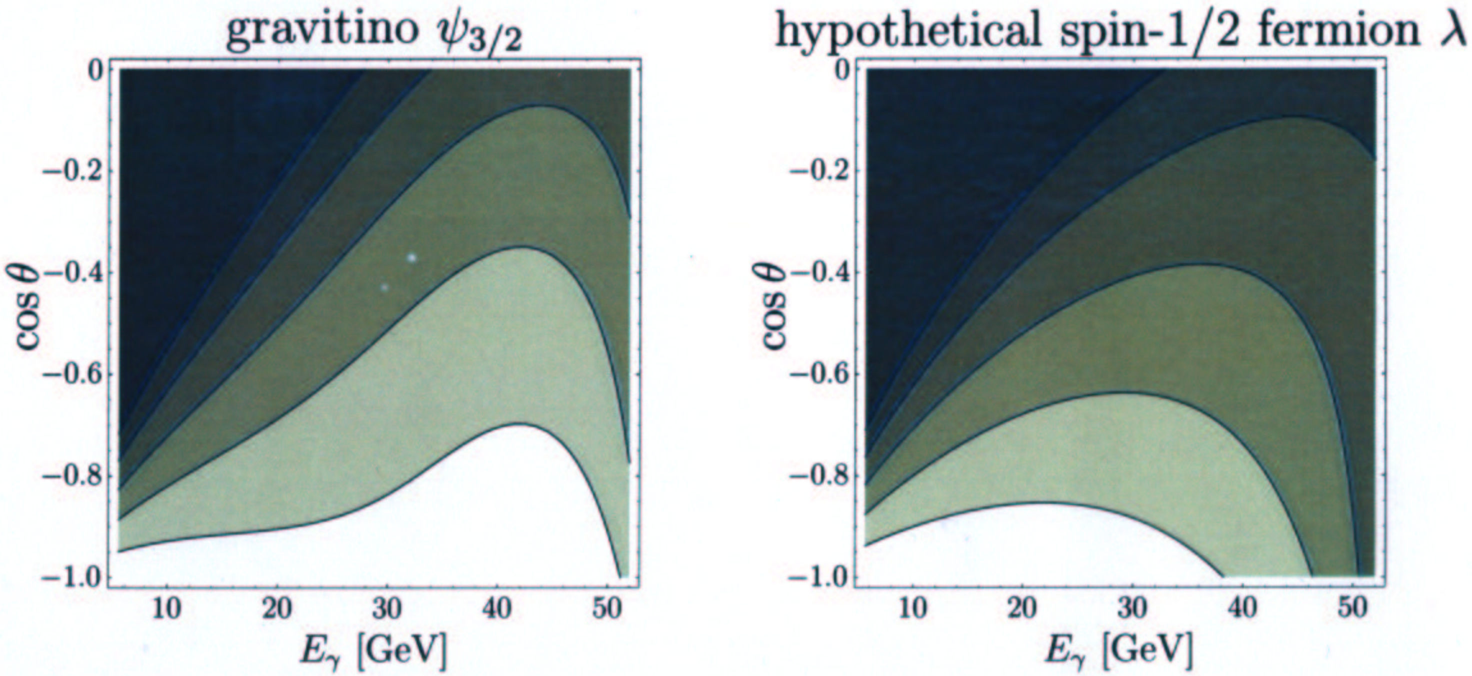
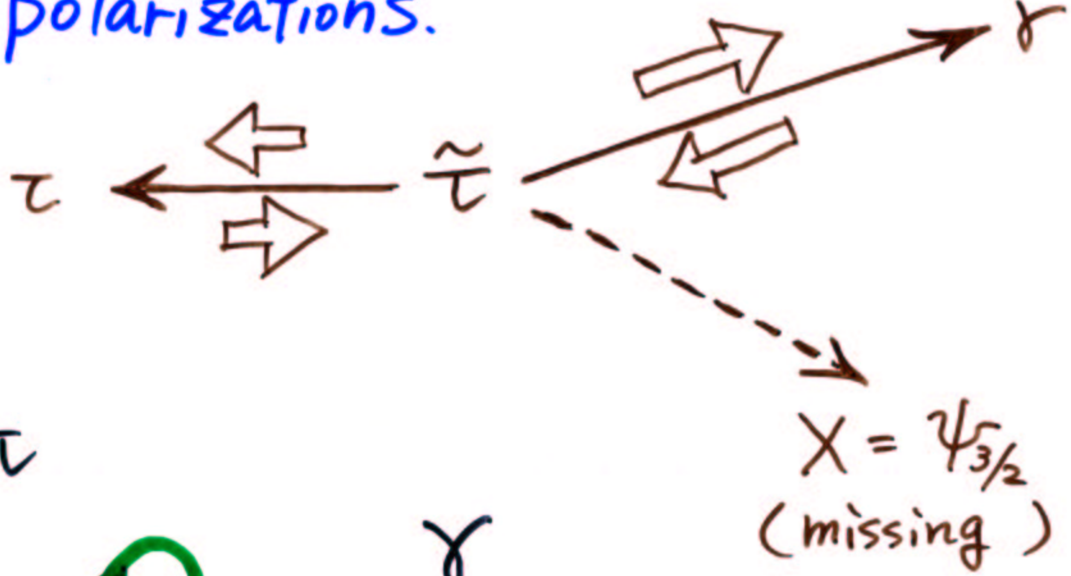


Figure: Contour plots of $\dfrac{d^2 B_r}{dE_\gamma d\cos\theta} = \dfrac{1}{\Gamma_{\tilde{\tau}}} \dfrac{d^2\Gamma_{\tilde{\tau}}(\tilde{\tau} \to \tau + \gamma + X)}{dE_\gamma d\cos\theta}$ for $X = \psi_{3/2}$ and λ.

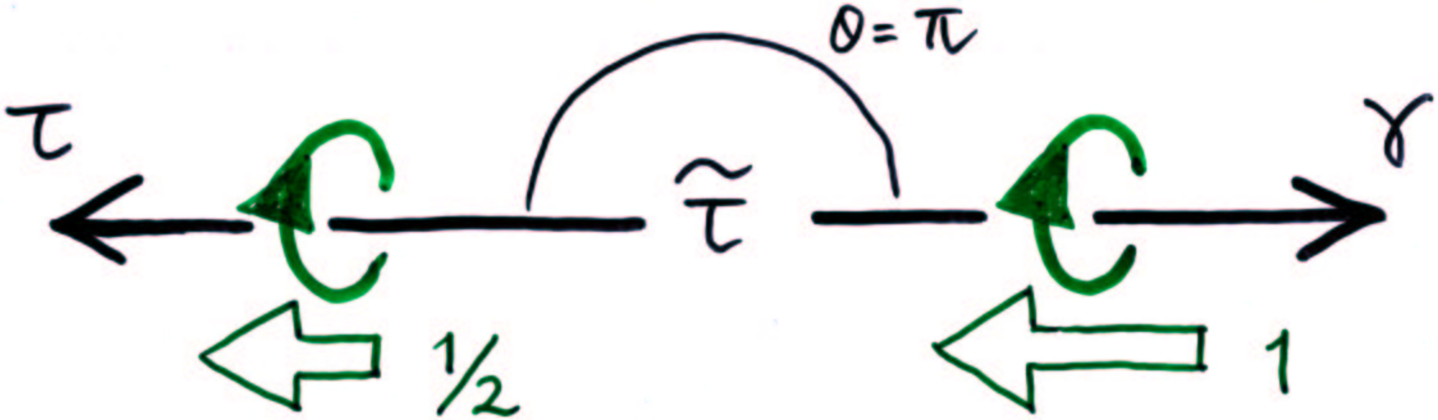
Darker shading = larger rate. (Boundaries are [1, 2, 3, 4, and 5] $\times 10^{-3}\alpha$ [GeV^{-1}].)

Method ③

Measurement of the gravitino spin $(= 3/2)$
by 3-body decay + polarizations.

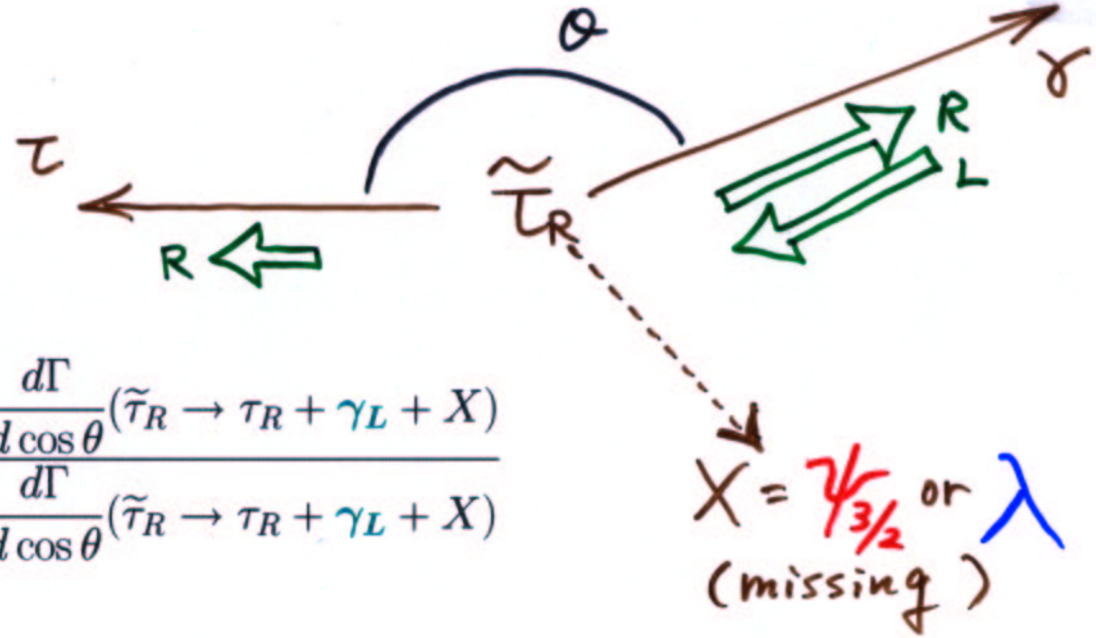


In particular, ...



$\tilde{\tau} \rightarrow \tau_R + \gamma_L + X$ at $\theta = \pi$ is possible only if the missing particle X has spin $3/2$.

angular distribution and polarizations of τ & γ



$$A_{RL}\,(\cos\theta\,) = \frac{\frac{d\Gamma}{d\cos\theta}(\tilde{\tau}_R \to \tau_R + \gamma_R + X) - \frac{d\Gamma}{d\cos\theta}(\tilde{\tau}_R \to \tau_R + \gamma_L + X)}{\frac{d\Gamma}{d\cos\theta}(\tilde{\tau}_R \to \tau_R + \gamma_R + X) + \frac{d\Gamma}{d\cos\theta}(\tilde{\tau}_R \to \tau_R + \gamma_L + X)}$$

Results (for right-handed $\tilde{\tau}_R$, $m_{\tilde{\tau}} = 150$ GeV)

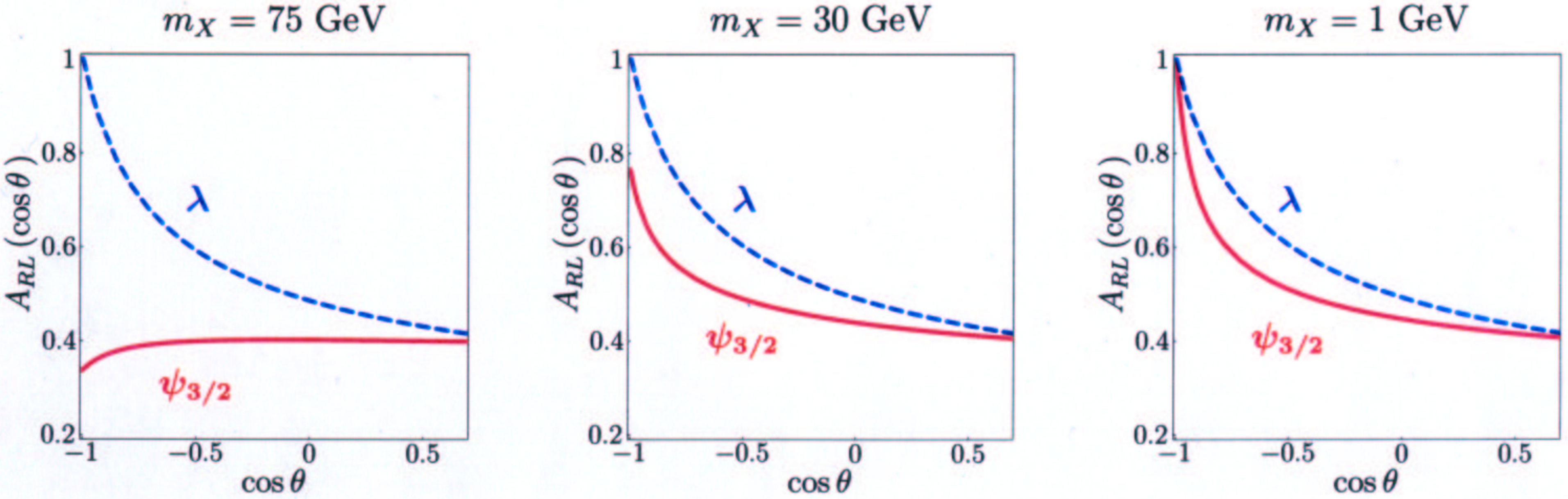


Figure: $A_{RL}\,(\cos\theta\,)$.

We cut the soft photon (energy below 10% of maximal photon energy, $E_\gamma^{\max} = (m_{\tilde{\tau}}^2 - m_{3/2}^2)/2m_{\tilde{\tau}}$).

Gravitino at Colliders:

Gravitino signal

would prove the existence of supergravity in nature!!

• What would prove the supergravity ?

Standard Model

=

spontaneously broken
local (gauge) symmetry

$\Downarrow$ Higgs mechanism

massive gauge (spin-1) bosons

Z & $W^{\pm}$

..... discovered in 1983.

• What would prove the supergravity ?

Standard Model

||

spontaneously broken local symmetry.

⇓ Higgs mechanism

massive gauge (spin-1) bosons

Z & $W^{\pm}$

..... discovered in 1983

Supergravity

||

spontaneously broken local supersymmetry

⇓ super-Higgs mechanism

massive spin-3/2 fermion

gravitino $\psi_{3/2}$

..... needs to be discovered!

Summary

- Cold Dark Matter may be the Gravitino LSP.

- Then NLSP is long-lived, and
  (if charged) can be collected in future colliers.

- By looking at NLSP slepton decay, we can $\cdots$
  — measure the Planck scale M_P,
  — test the gravitino coupling,
  — measure the gravitino spin.

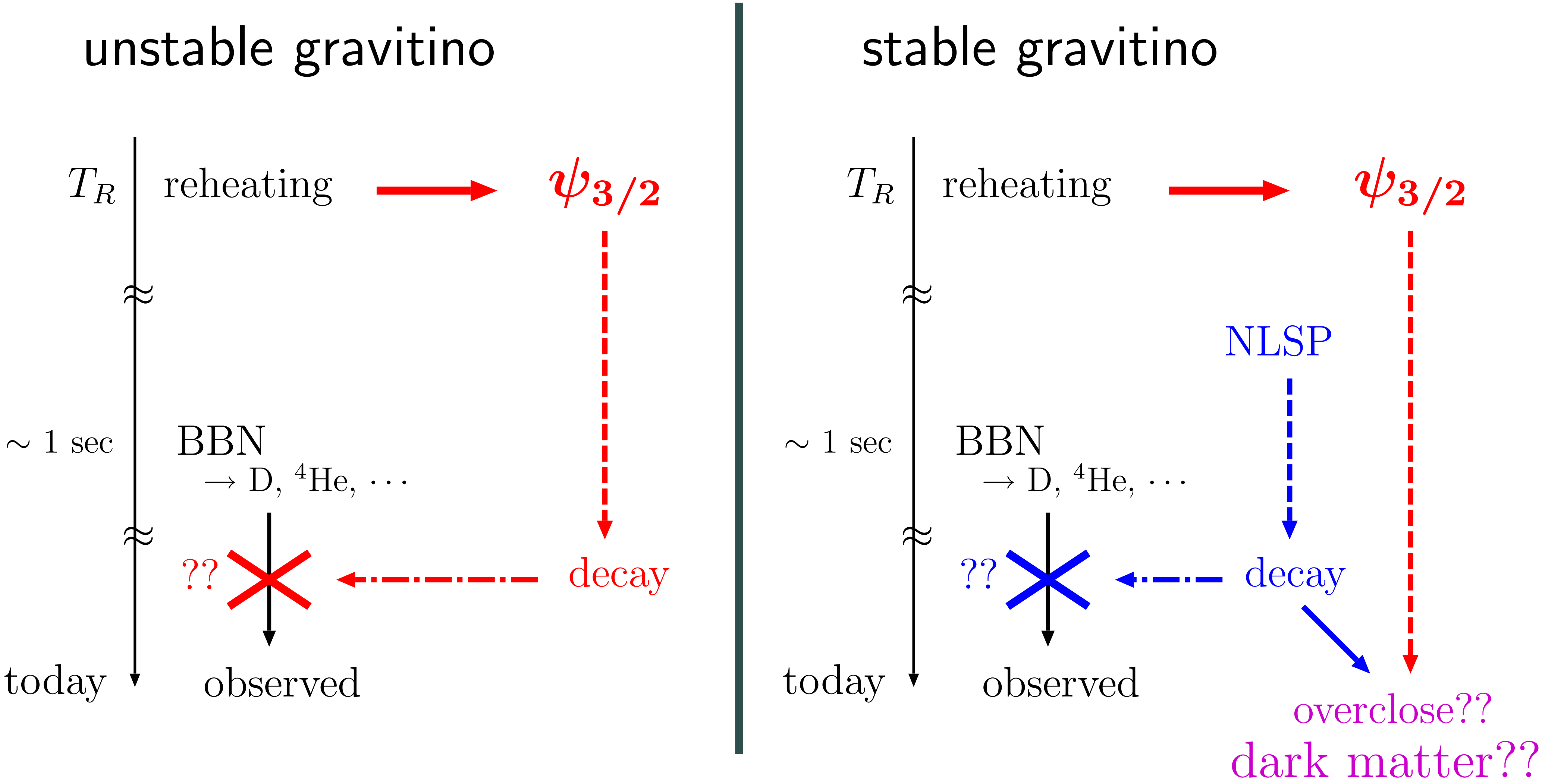
Discussion: in addition $\cdots$

– can probe Lepton Flavour Violation, KH, A.Ibarra, hep-ph/0412229 [JHEP0502]

– can test the axino LSP scenario
A.Brandenburg, L.Covi, KH, L.Roszkowski, F.D.Steffen, hep-ph/0501287

For Questions and Comments

thermal history with gravitino $\psi_{3/2}$

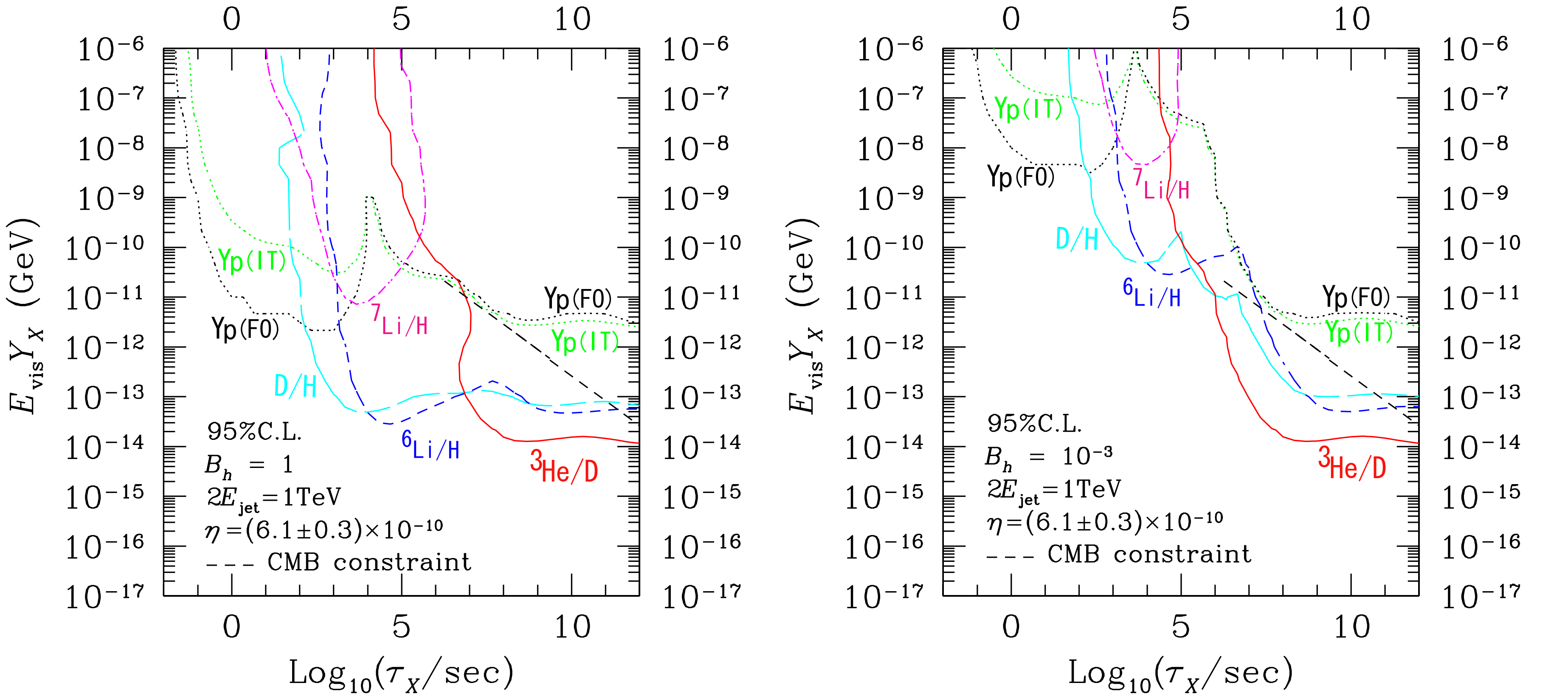


BBN constraints: in general

for a late-decaying particle X $\longrightarrow$ constraints on $(\tau_X,\ m_X Y_X)$.

latest detailed analysis including hadronic decay modes:

M. Kawasaki, K. Kohri and T. Moroi, astro-ph/0402490 + 0408426. (cf. K. Jedamzik, astro-ph/0402344)



$\mathrm{Br}(X \to \mathrm{hadron}) = 1$ $\qquad$ $\mathrm{Br}(X \to \mathrm{hadron}) = 10^{-3}$

unstable gravitino

BBN constraints: late decaying particle $\boldsymbol{X} = \boldsymbol{\psi_{3/2}}$

$m_{3/2} Y_{3/2}$	$\propto$	$m_{3/2} T_R$	$+ \mathcal{O}(m_{\tilde{g}}/m_{3/2})^2$ + log.corr.
$\tau_{3/2}$	$\propto$	${m_{3/2}}^{-3}$	$+ \mathcal{O}(m_{\rm soft}/m_{3/2})^2$

$\longrightarrow$ upper bounds on $\boldsymbol{T_R}$ for a given $\boldsymbol{m_{3/2}}$

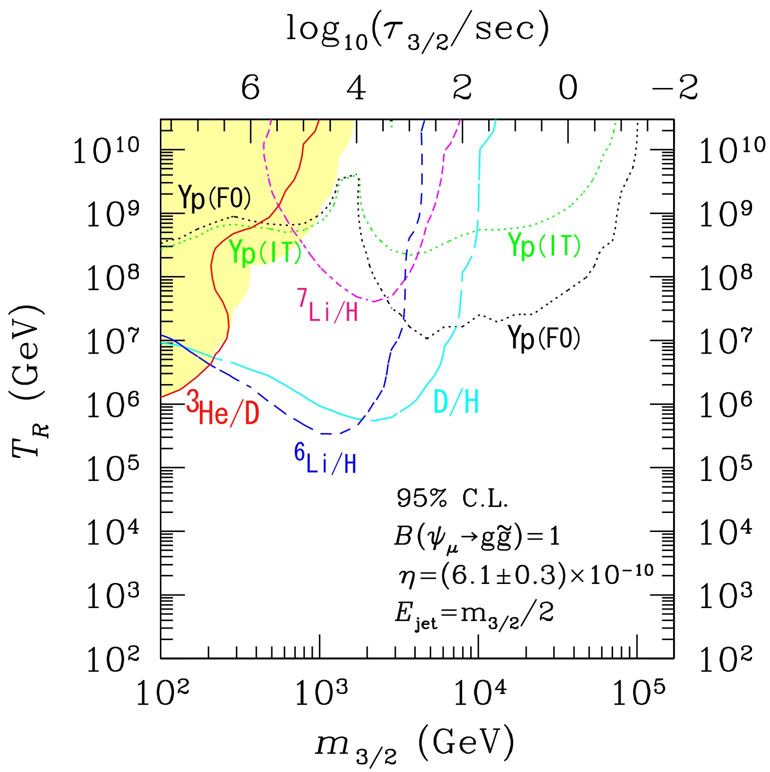


Fig. $Br(\text{gravitino} \to \text{gluino}) = 1$ from Kawasaki et.al. astro-ph/0408426

Solutions

- very heavy gravitino (anomaly mediation)

  cf. M.Ibe, R.Kitano, H.Murayama, T.Yanagida, hep-ph/0403198.
- low scale inflation + baryogenesis

  e.g. Affleck–Dine, EW baryogenesis, non–thermal/resonant/soft leptogenesis, · · ·
- late-time entropy production

  e.g. by moduli. but cf. K.Kohri, M.Yamaguchi, J.Yokoyama, hep-ph/0403043.
- decays only into harmless particle

  e.g. into axion and axino, T.Asaka, T.Yanagida, PLB494('00)
- · · · · · ·

stable gravitino: NSP decay into gravitino

BBN constraints: late decaying particle $\boldsymbol{X}$ = NSP

$$m_{\rm NSP} Y_{\rm NSP} \propto m_{\rm NSP}^{\ 2} \qquad \text{(roughly)}$$
$$\tau_{\rm NSP} \propto m_{3/2}^{\ 2}\, m_{\rm NSP}^{\ -5} \qquad + \mathcal{O}(m_{3/2}/m_{\rm NSP})^2$$

⟶ constraints on $(\, \boldsymbol{m_{3/2}} \,,\, \boldsymbol{m_{\rm NSP}} \,)$

relic gravitino abundance (from NSP decay):

$$\Omega_{3/2} \propto m_{3/2}\, m_{\rm NSP} \qquad \text{(roughly)}$$

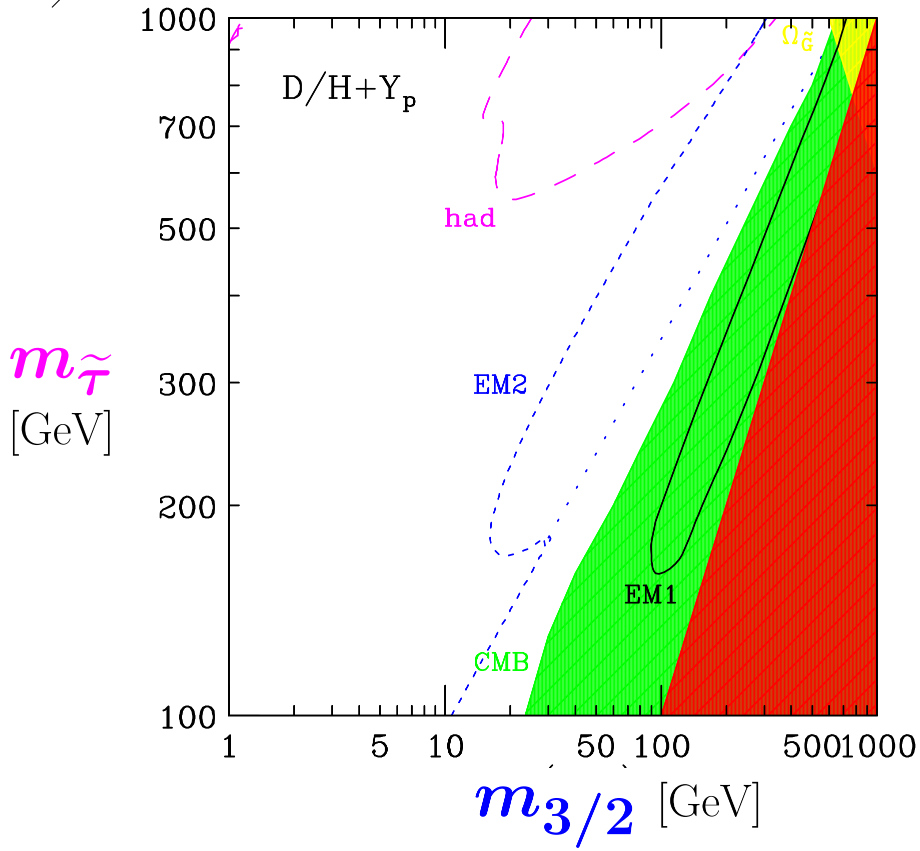
latest detailed analysis including

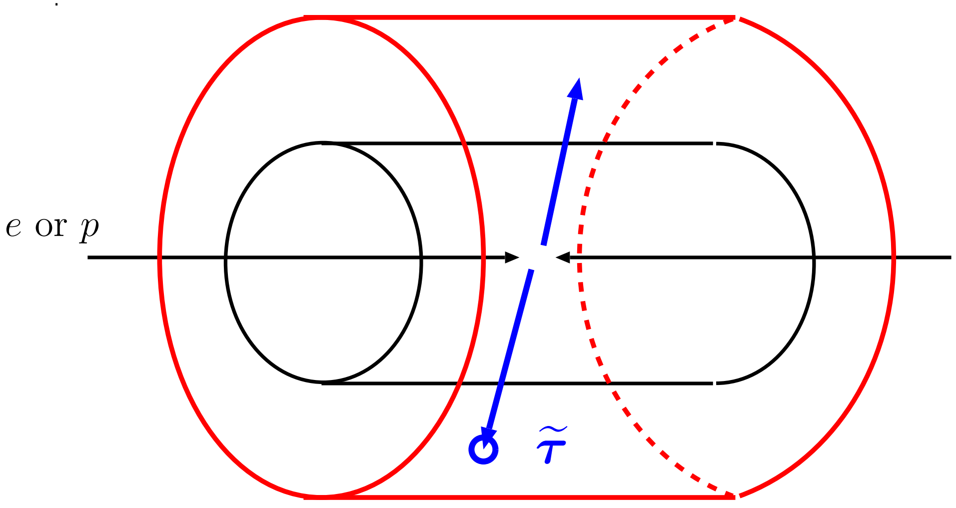
- hadronic decay modes in 3-body decays
- the CMB constraint

J. L. Feng, S. Su, F. Takayama, hep-ph/0404231.

e.g., for NSP $= \widetilde{\tau}$, ⟶

(^{6}Li and ^{3}He not included here)





How thick should the stopping material be?

Stopping range R strongly depends on the velocity $\beta_{\widetilde{\tau}}$: $R =$ mass $\times f(\beta)$.

e.g., for $m_{\widetilde{\tau}} = 150$ GeV,

- $\beta_{\widetilde{\tau}} = 0.37 \quad \Longrightarrow \quad R = 1000$ g/cm^2 $= 10$ m/ water
- $\beta_{\widetilde{\tau}} = 0.48 \quad \Longrightarrow \quad R = 3000$ g/cm^2 $= 30$ m/ water
- $\beta_{\widetilde{\tau}} = 0.54 \quad \Longrightarrow \quad R = 5000$ g/cm^2 $= 50$ m/ water

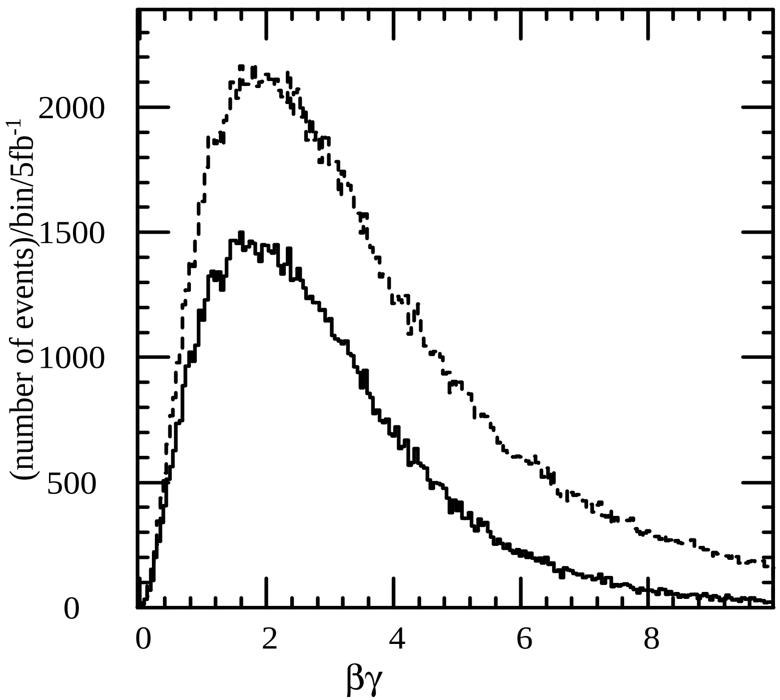
$\Longrightarrow$ Sleptons must be sufficiently slow.

How many sleptons can we collect at LHC ???

(gluino) squark chargino neutralino slepton

$$(\widetilde{g}) \Longrightarrow \widetilde{q} \Longrightarrow \widetilde{\chi}^{\pm}, \quad \widetilde{\chi}^{0} \Longrightarrow \widetilde{\tau},$$

$m_{\widetilde{q}} \gg m_{\widetilde{\tau}} \quad \rightarrow \quad$ Most of the $\widetilde{\tau}$s are too rapid to stop.



But a few % of the $\widetilde{\tau}$s have sufficiently small velocity.

How many sleptons can we collect at LC ???

At LC one can restrict the velocity β by adjusting the beam energy!

- $\sigma(e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-) \;\propto\; \beta_{\tilde{\tau}}^3$ ..... suppressed for small $\beta_{\tilde{\tau}}$.

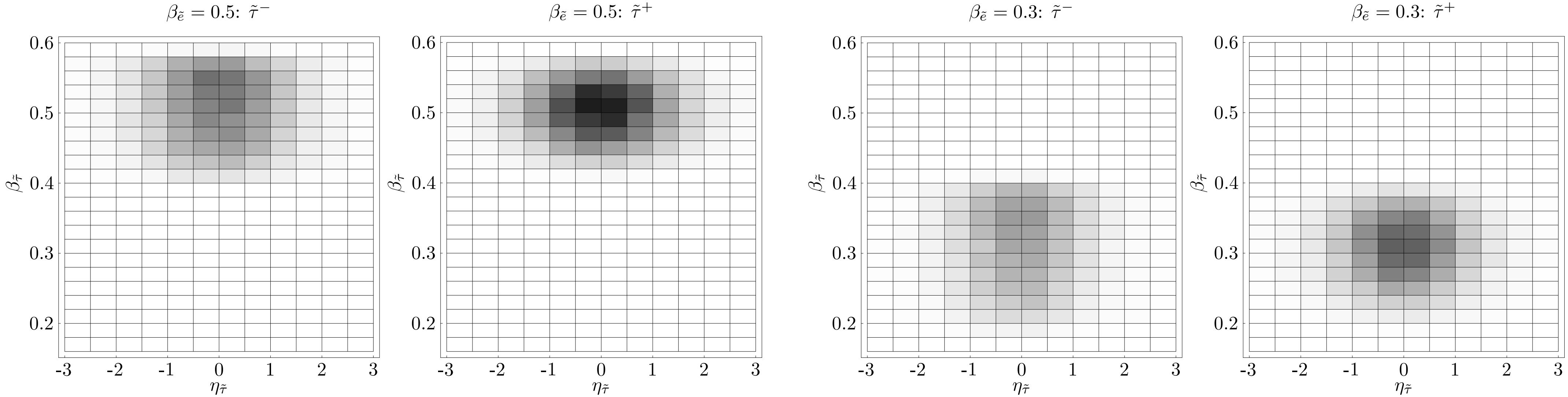
On the other hand,

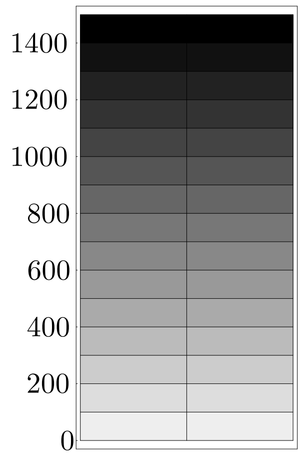
- $\sigma(e^-e^- \to \tilde{e}^-\tilde{e}^-) \;\propto\; \beta_{\tilde{e}}$ then $\tilde{e}^- \to \tilde{\tau}^\mp\tau^\pm e^-$

For small velocity e^-e^- is better than e^+e^-.

How many sleptons can we collect at LC ???

distributions of $\widetilde{\tau}^+$ and $\widetilde{\tau}^-$ from $\quad e^- e^- \to \widetilde{e}^- \widetilde{e}^-;\ \widetilde{e}^- \to \widetilde{\tau}^\mp \tau^\pm e^-$





$(\eta,\ \beta)$ distributions of $\widetilde{\tau}^\pm$ at the laboratory frame,

for $m_{\widetilde{\tau}} = 150$ GeV, $m_{\widetilde{e}} = 170$ GeV, and $m_{\widetilde{B}} = 180$ GeV.

$\beta_{\widetilde{e}} = 0.5$ ($E_{\rm cm} = 392$ GeV) for left figures and $\beta_{\widetilde{e}} = 0.3$ ($E_{\rm cm} = 356$ GeV) for right figures.

Total number of events are normalized so that it corresponds to integrated luminosity 10 fb^{-1}.

Comment:

Very light gravitino $\simeq$ goldstino (spin 1/2 fermion)
$(m_{3/2} \ll m_{\tilde{\tau}})$

2-body decay

→ measurement of M_P is difficult.

$E_\tau \simeq \frac{1}{2} m_{\tilde{\tau}}$

$(m_{3/2}^2 = m_{\tilde{\tau}}^2 + m_\tau^2 - 2m_{\tilde{\tau}} E_\tau \simeq 0)$

3-body decay

→ measurement of gravitino spin is difficult.

→ But we can still see the peculiar coupling. → See Fig.s

NOTE:

If $m_{3/2} \ll 10$ keV, $\tilde{\tau}$ can decay inside the detector!

(for comparison) define

"pseudo-goldstino" χ, which has .....

goldstino interactions

$$\mathcal{L}_{goldstino} = \left(\frac{m_{\tilde{\tau}}^2}{\sqrt{3}\, m_{3/2} M_P}\right)\left(\tilde{\tau}_R^* \bar{\chi} P_R \tau + h.c\right) - \frac{m_{\tilde{\gamma}}}{4\sqrt{6}\, m_{3/2} M_P} \bar{\chi} [\gamma^\mu, \gamma^\nu] \tilde{\gamma} F_{\mu\nu}$$

($\tilde{\gamma}$ ← photino)

+

a mass

m_χ → explicit breaking of global SUSY.

gravitino $\psi_{3/2}$ vs. (pseudo) goldstino χ vs. hypothetical spin-1/2 fermion λ

$$A_{RL}(\cos\theta) = \frac{\frac{d\Gamma}{d\cos\theta}(\tilde{\tau}_R \to \tau_R + \gamma_R + X) - \frac{d\Gamma}{d\cos\theta}(\tilde{\tau}_R \to \tau_R + \gamma_L + X)}{\frac{d\Gamma}{d\cos\theta}(\tilde{\tau}_R \to \tau_R + \gamma_R + X) + \frac{d\Gamma}{d\cos\theta}(\tilde{\tau}_R \to \tau_R + \gamma_L + X)}$$

$X = \psi_{3/2}, \chi$ or λ

Results (for right-handed $\tilde{\tau}_R$, $m_{\tilde{\tau}} = 150$ GeV)

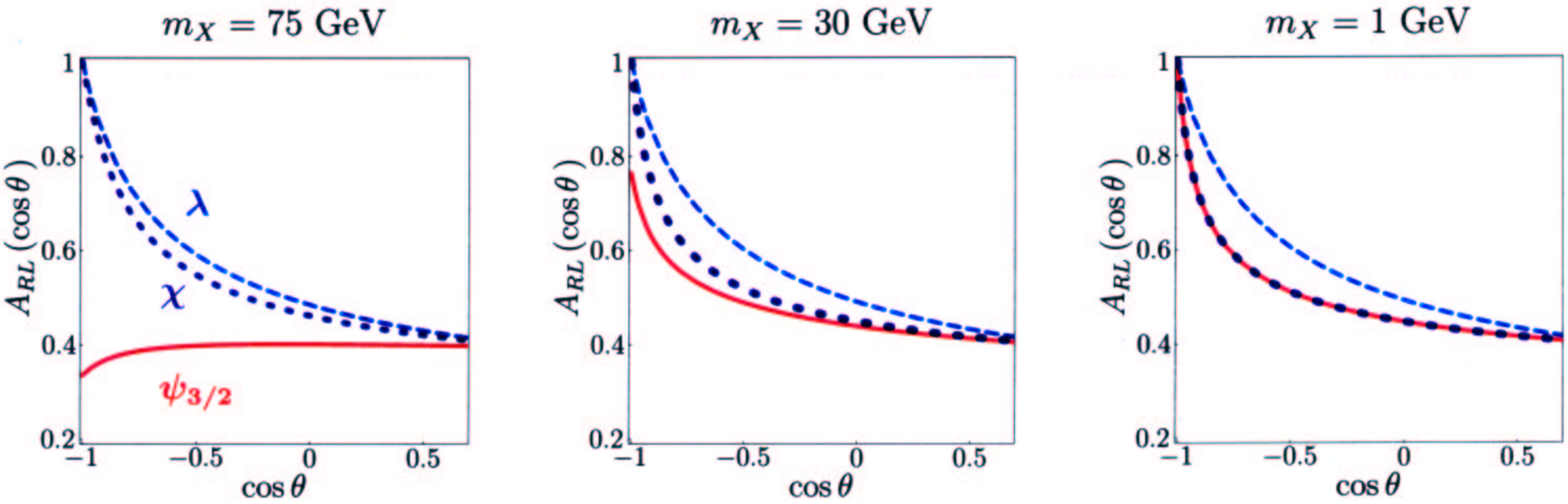
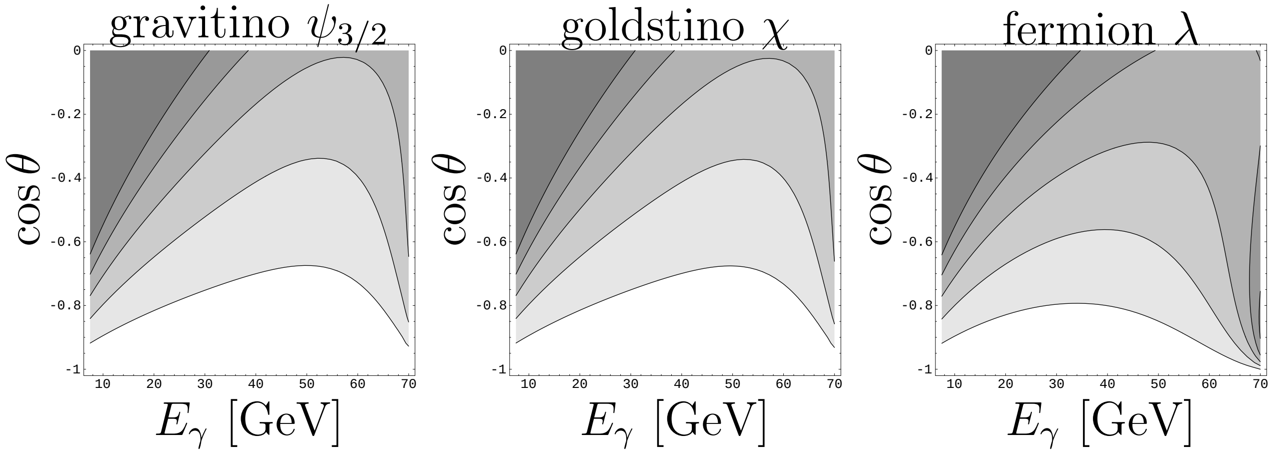
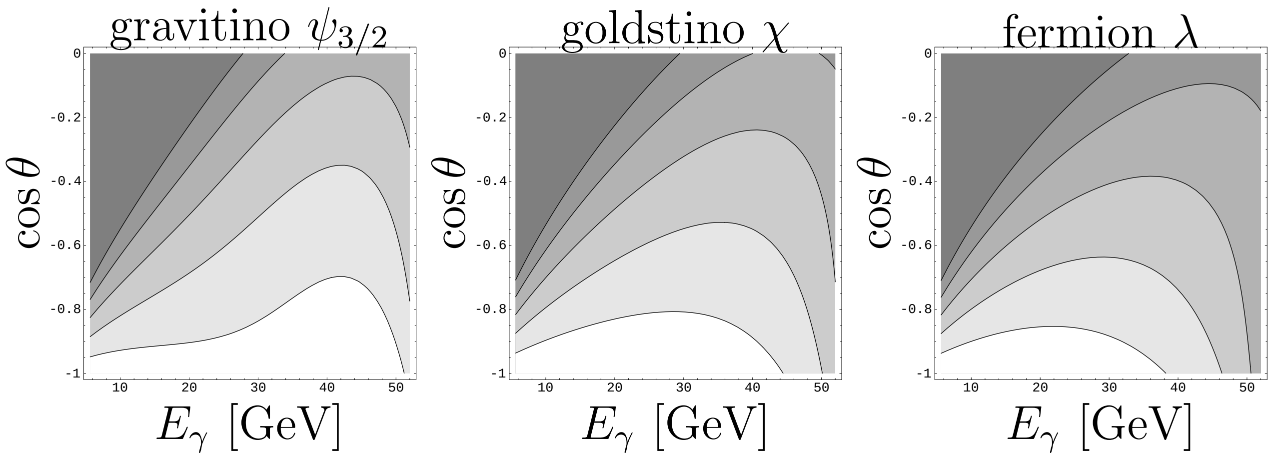


Figure: $A_{RL}(\cos\theta)$.

We cut the soft photon (energy below 10% of maximal photon energy, $E_\gamma^{\max} = (m_{\tilde{\tau}}^2 - m_{3/2}^2)/2m_{\tilde{\tau}}$).



$m_{\tilde{\tau}} = 150$ GeV, $m_X = 10$ GeV.



$m_{\tilde{\tau}} = 150$ GeV, $m_X = 75$ GeV.

Probing Lepton Flavour Violation

KH, A.Ibarra, hep-ph/0412229 [JHEP0502]

$$\tilde{\tau} \longrightarrow \psi_{3/2} + \tau$$

If there is a lepton flavour violation,

$$\tilde{\tau} \longrightarrow \psi_{3/2} + e \qquad \text{or} \qquad \tilde{\tau} \longrightarrow \psi_{3/2} + \mu$$

For instance, if we observe no electron event for 10000 stopped staus,

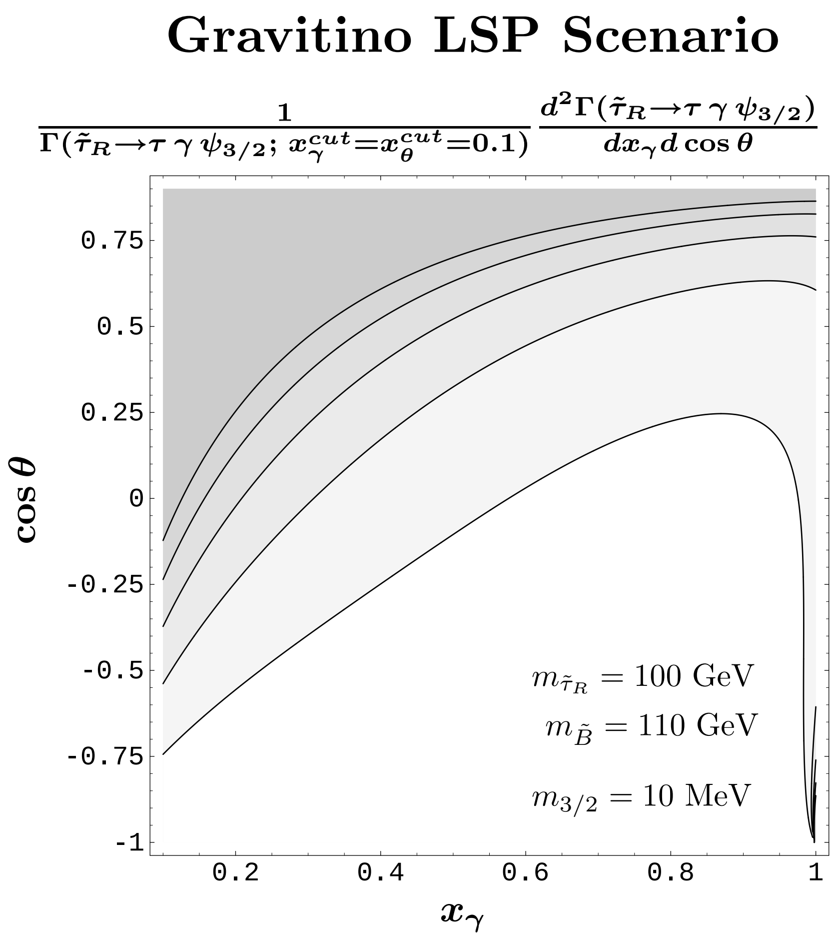
$Br(\tilde{\tau} \rightarrow \psi_{3/2} + e) < 2.3 \times 10^{-4}$ at 90% c.l.

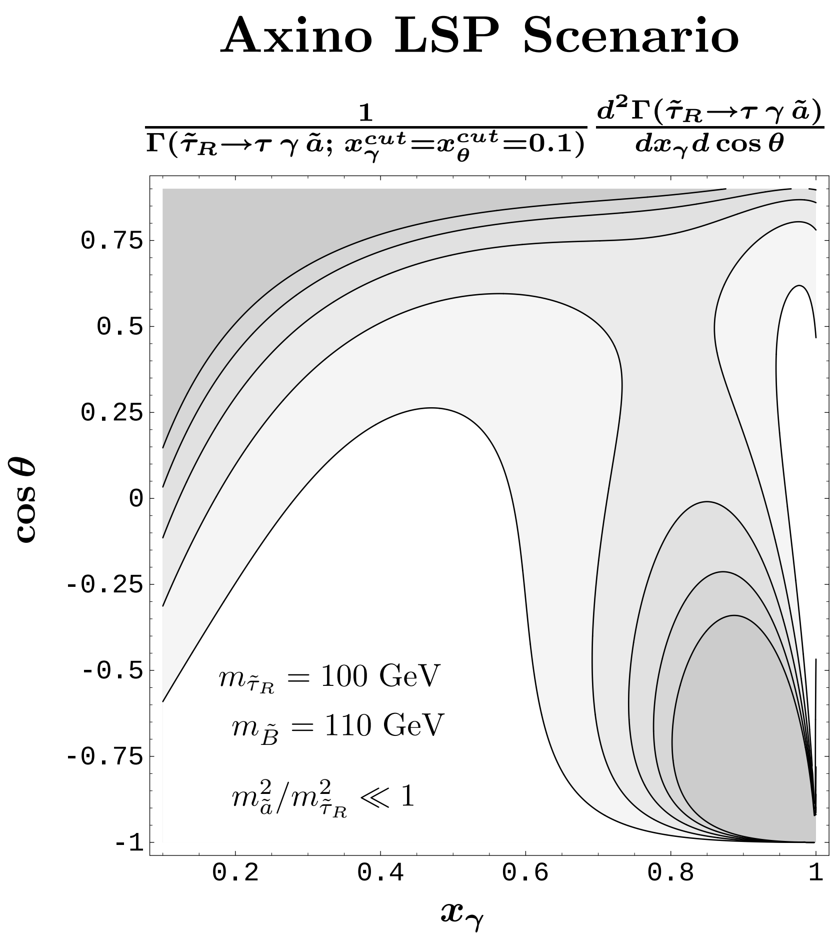
$$|U_{\tilde{\tau}e}|^2 \; < \; 2.3 \times 10^{-4}$$

Severe bounds on the slepton flavour mixings!!

Gravitino LSP vs Axino LSP

A.Brandenburg, L.Covi, KH, L.Roszkowski, F.D.Steffen, hep-ph/0501287





Gravitino LSP vs Axino LSP

A.Brandenburg, L.Covi, KH, L.Roszkowski, F.D.Steffen, hep-ph/0501287