Detecting metastable staus and gravitinos at the ILC

Hans-Ulrich Martyn

RWTH Aachen & DESY

SUSY 2007

The 15th International Conference on Supersymmetry
and the Unification of Fundamental Interactions

July 26 - August 1, 2007
Karlsruhe, Germany

Gravitino in supersymmetry

Gravitino mass set by SUSY breaking scale F of mediating interaction

$m_{3/2} = F/\sqrt{3} \cdot M_P$ reduced Planck scale $M_P = 2.4 \cdot 10^{18}$ GeV

in general free parameter depending on scenario

Typical SUSY scenarios

gauge mediation, gaugino mediation, SUGRA $m_{3/2} \sim$ eV … TeV

most interesting: gravitino LSP, stau NLSP $m_{3/2} = O(10\text{-}100\ \text{GeV})$

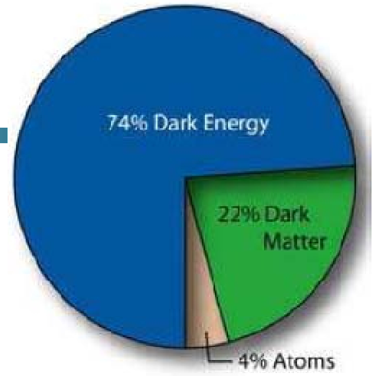
Dominant decay $\tilde{\tau} \to \tau \tilde{G}$ gravitational coupling, lifetime sec - years

$$\Gamma_{\tilde{\tau}\to\tau\tilde{G}} = \frac{1}{48\pi M_P^2} \frac{m_{\tilde{\tau}}^5}{m_{\tilde{G}}^2} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right]^4$$

Observables $m_{\tilde{\tau}},\ t_{\tilde{\tau}},\ m_{\tilde{G}}, J_{\tilde{G}}$

H-U M, Eur. Phys. J. C 48 (2006) 15 [hep-ph/0605257]

Gravitino dark matter



Cold dark matter in Universe $\Omega_{DM} \approx 22\%$

$\Omega_{DM}h^2 = 0.105 \pm 0.008$ WMAP

Formation

freeze out of thermal equilibrium negligible

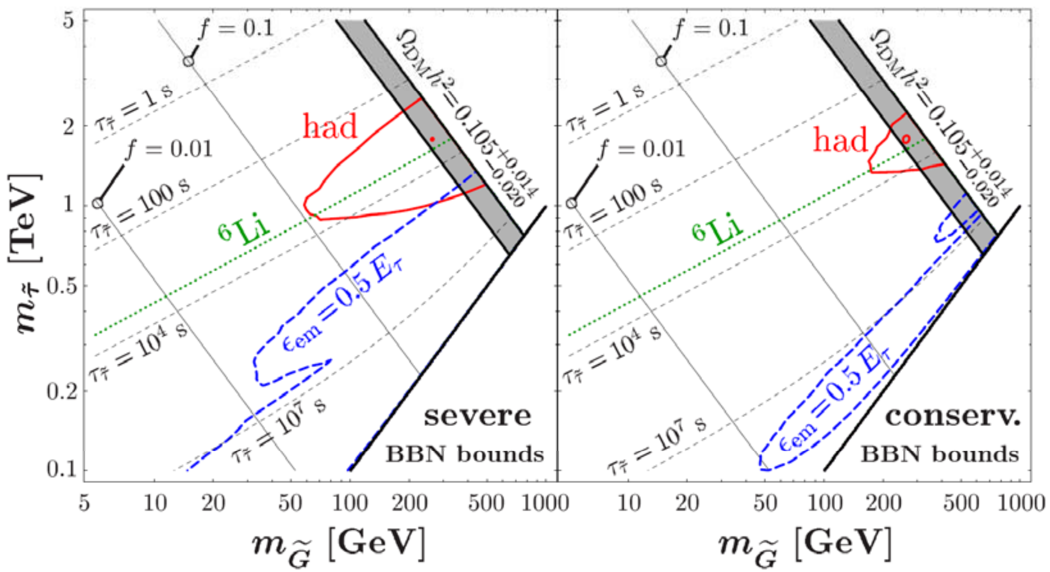
thermal production after reheating (inflation) $g\tilde{g} \to g\tilde{G}, q\tilde{g} \to q\tilde{G} \ldots$

late decays of NLSP = WIMP $\tilde{\tau}_1 \to \tau\tilde{G}$

Cosmological constraint

BBN (t~1s) should not be destroyed during reheating or by NLSP decays

stau bound states enhance Nucleon, Li production Pospelov 06

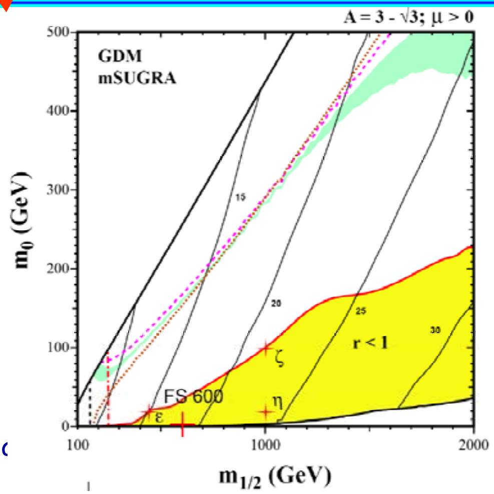


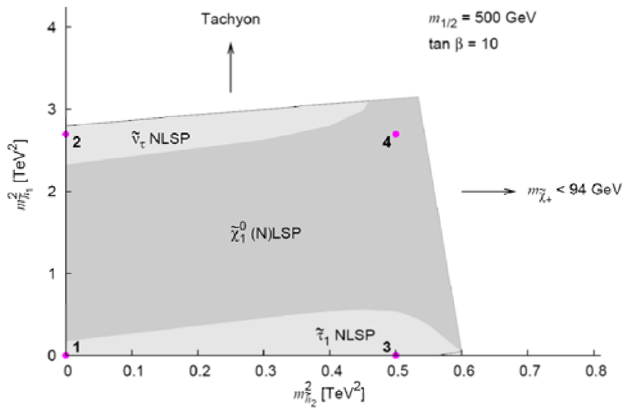
Steffen 06

GDM scenarios & spectra

	1	2	3	4	5	6	7
$\tilde{\ell}, \tilde{\chi}, \tilde{G}$	SPS 7	FS 600	GDM ϵ	GDM ζ	GDM η	$\tilde{\chi}$MSB P1	$\tilde{\chi}$MSB P3
$\tilde{\tau}_1$	123.4	219.3	157.6	340.2	322.1	185.2	102.5
$\tilde{\tau}_2$	264.9	406.5	307.2	659.2	652.2	341.5	356.9
$\tilde{\nu}_\tau$	249.6	396.4	290.9	649.5	641.5	327.7	346.9
$\tilde{e}_R$	130.9	227.2	175.1	381.4	368.5	192.9	109.5
$\tilde{e}_L$	262.8	405.6	303.0	662.7	655.3	340.1	357.4
$\tilde{\nu}_e$	250.1	397.6	292.8	658.1	650.7	328.0	247.4
$\tilde{\chi}_1^0$	163.7	243.0	179.4	426.5	426.5	203.6	189.2
$\tilde{\chi}_2^0$	277.9	469.6	338.2	801.9	801.5	385.5	263.8
$\tilde{\chi}_1^\pm$	275.5	469.9	338.0	801.9	801.4	388.2	251.5
$\tilde{G}$	0.1	50	20	100	20	50	25

details of analysis





1	GMSB, Snowmass 02
2	mSUGRA, J Feng, B Smith 04
3 – 5	mSUGRA, A De Roeck et al 05
6, 7	$\tilde{\chi}$MSB, W Buchmüller et al 05

Detecting staus & gravitinos

Identify & record stopping stau → stau mass

dE/dx ~ $1/\beta^2$ in TPC

record location & time stamp

Wait until decay → stau lifetime

$\tilde{\tau} \rightarrow \tau \tilde{G}$ huge energy release

Measure τ recoil spectra → gravitino mass

$$E_\tau = (m^2_{\tilde{\tau}} - m^2_{\tilde{G}})/2\, m_{\tilde{\tau}}$$

Rare radiative decays → gravitino spin

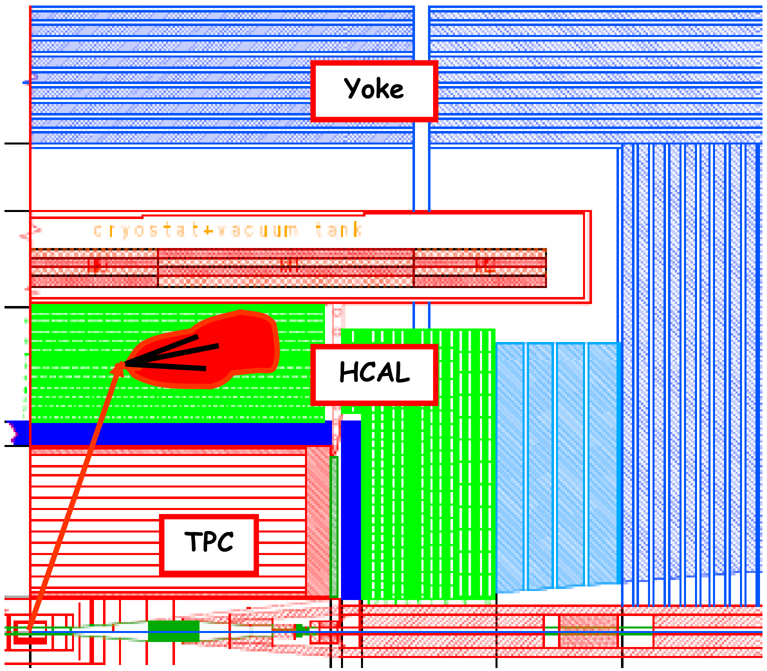
γ-τ correlations in $\tilde{\tau} \rightarrow \tau \gamma \tilde{G}$

Momentum acceptance for stopping particles

$\beta\gamma = p/m \lesssim 0.5$

$m_{\tilde{\tau}}$	$\beta\gamma$ (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

LDC detector



LHC detectors not appropriate

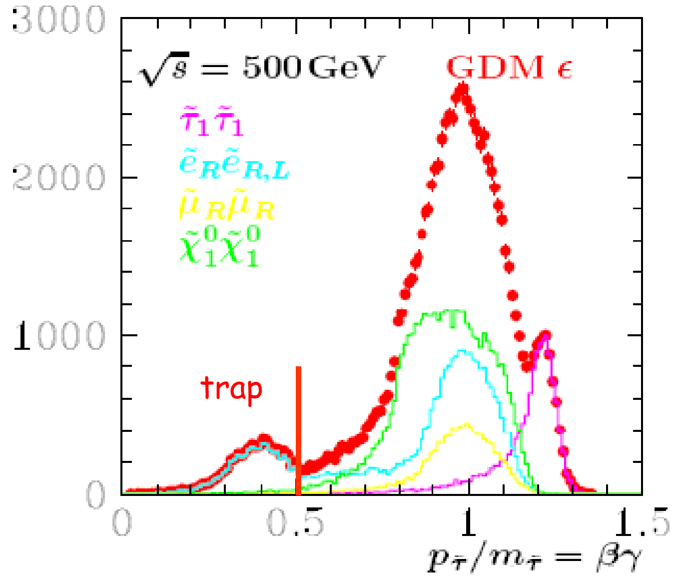
additional absorber, calorimeter required

Gravitino not detectable in astrophysical expts

mSUGRA scenario GDM ε

$m_0 = 20$ GeV	$\tan\beta = 15$
$M_{1/2} = 440$ GeV	sign $\mu+$
$A_0 = 25$ GeV	

- **Case study** L=100 fb[-1] @ 500 GeV
  σ_{SUSY}=300 fb (< 1 year data taking)
  $m_{\tilde\tau} = 157.6$ GeV, $m_{\tilde G} = 20$ GeV, $t_{\tilde\tau} = 2.6 \cdot 10^6$ s

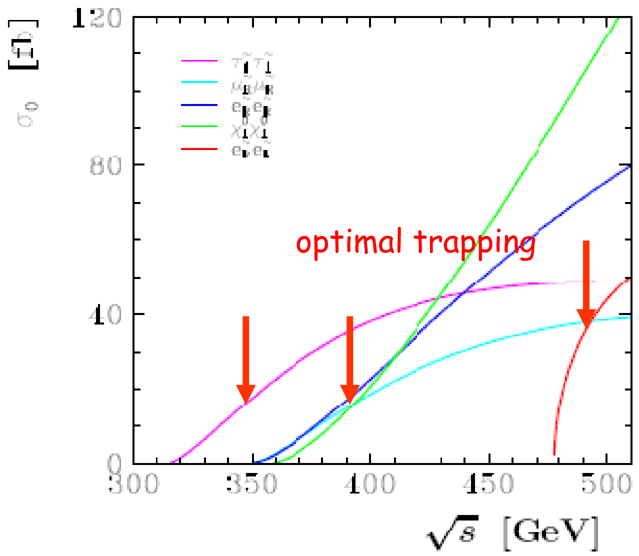


- **Clean signature** $\sum \vec p \simeq 0$ and $\sum E < \sqrt{s}$
  completely reconstructed SUSY evts,
  no SM bkg

- **Prolific stau production**
  pairs & cascade decays

HCAL	4100
Yoke	1800

$$\tilde e_R \tilde e_R \rightarrow e\tau\tilde\tau_1 \; e\tau\tilde\tau_1 \qquad \sigma \sim \beta^3$$
$$\tilde\mu_R \tilde\mu_R \rightarrow \mu\tau\tilde\tau_1 \; \mu\tau\tilde\tau_1 \qquad \sigma \sim \beta^3$$
$$\tilde\chi^0_1 \tilde\chi^0_1 \rightarrow \tau\tilde\tau_1 \; \tau\tilde\tau_1 \qquad \sigma \sim \beta^3$$
$$\tilde e_R \tilde e_L \rightarrow e\tau\tilde\tau_1 \; e\tilde\chi^0_1 \qquad \sigma \sim \beta$$



500 GeV close to optimal energy for stau trapping

mSUGRA scenario GDM ε

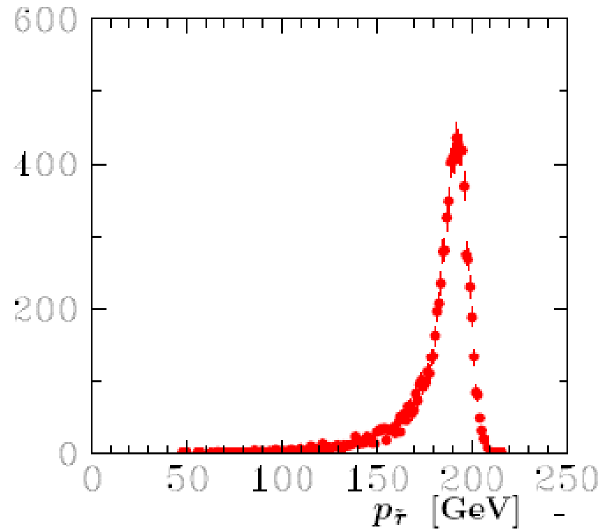
- **Stau mass measurement**

  pair production $e^+e^- \to \tilde{\tau}_1\tilde{\tau}_1$

  m² = E$_b$² - p²

  $p_{\tilde{\tau}} = 192.4 \pm 0.2$ GeV

  $\Rightarrow$ $m_{\tilde{\tau}} = 157.6 \pm 0.2$ GeV



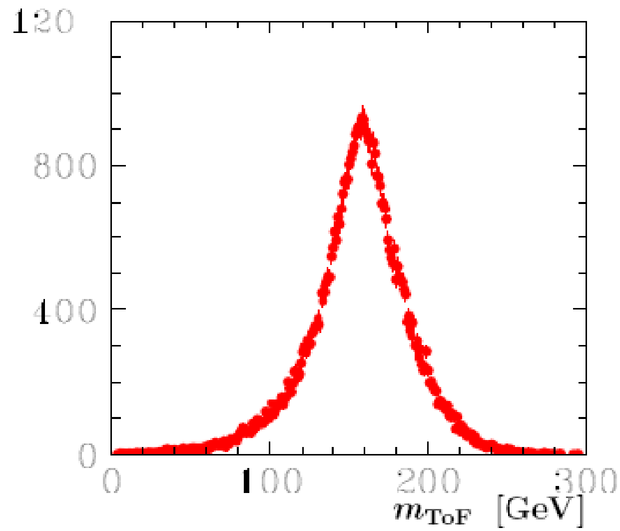
- **Time of flight**

  time resolution at calorimeter *δt = 1 ns*

  all candidates, large sample from cascades

  m² = (1/β² - 1)·p²

  ➔ **δm_{ToF} = 0.15 GeV**



mSUGRA scenario GDM ε

- **Stau lifetime measurement**

  trigger isolated τ decay in detector

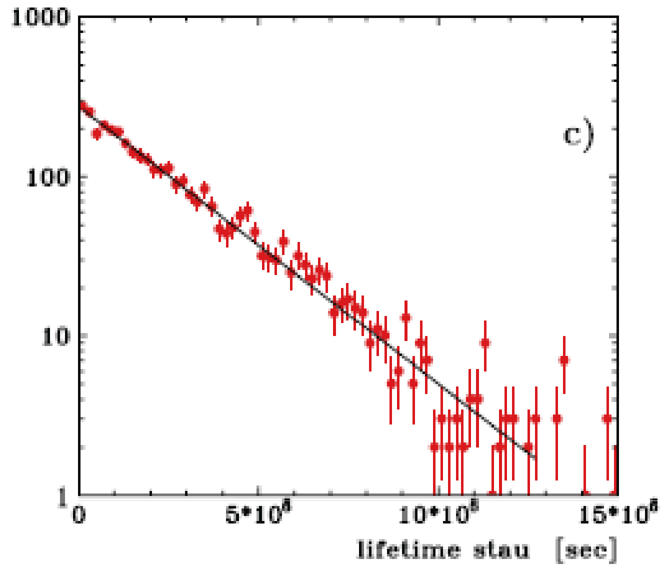
  any time - not correlated to beam collision

  origin - associate to list of stopped staus

  e, μ, h in HCAL E > 10 GeV

  μ, h in yoke E > 10 GeV

$$t_{\tilde\tau} = (2.59 \pm 0.05) \cdot 10^6 \text{ s}$$

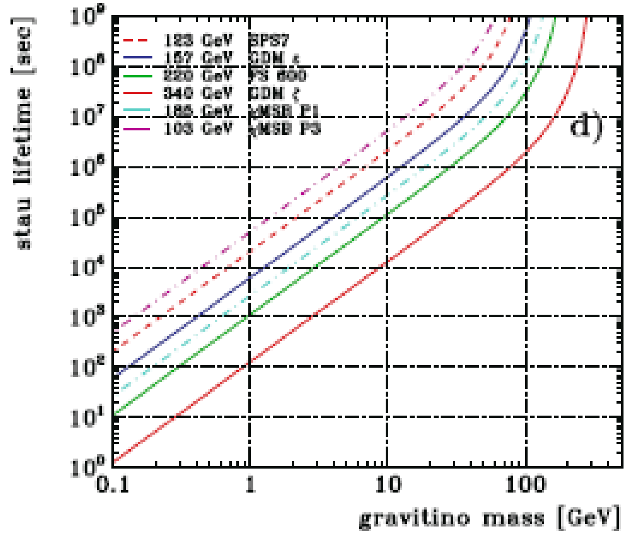


- **Gravitino mass from decay rate**

  assuming gravitational coupling

$$\Gamma_{\tilde\tau} = t_{\tilde\tau}^{-1} = \frac{1}{48\pi M_P^2}\frac{m_{\tilde\tau}^5}{m_{\tilde G}^2}\left[1 - \frac{m_{\tilde G}^2}{m_{\tilde\tau}^2}\right]^4$$

$$m_{\tilde G} = 20.0 \pm 0.2 \text{ GeV}$$



mSUGRA scenario GDM ε

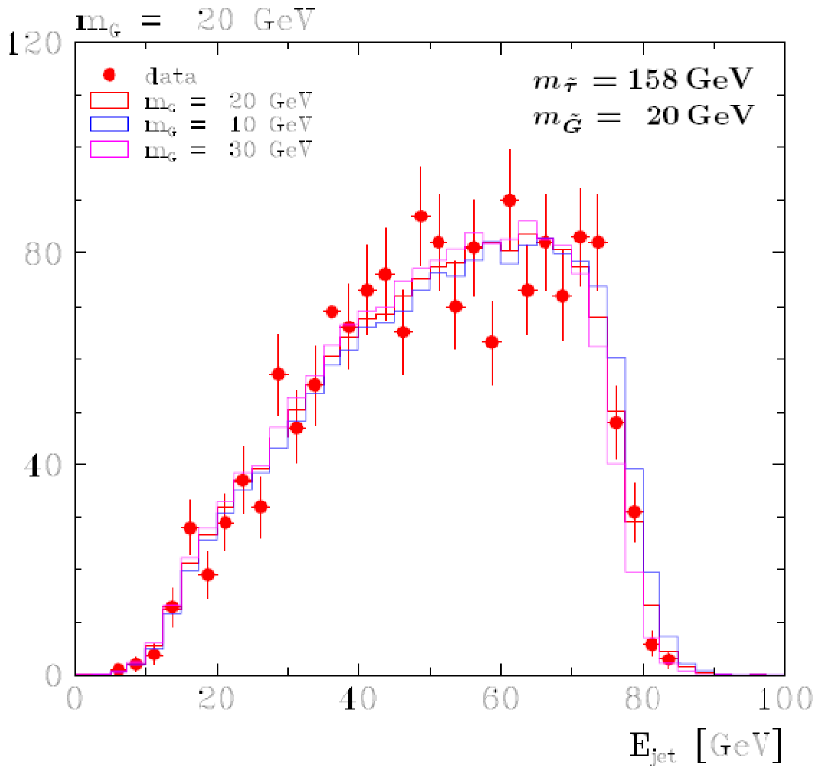
- **Gravitino mass measurement**

τ decay spectra τ → ρν & 3πν

$$E^{max}_{\tau\to h\nu} = (m^2_{\tilde\tau} - m^2_{\tilde G})/2\, m_{\tilde\tau}$$

feasible if $m_{gravitino}$ > ~0.1 m_{stau}

$$m_{\tilde G} = 20 \pm 4 \text{ GeV}$$



Planck scale using $t_{\tilde\tau}$, $m_{\tilde\tau}$ and $m_{\tilde G}$

$$M_P^2 = \frac{t_{\tilde\tau}}{48\pi} \frac{m^5_{\tilde\tau}}{m^2_{\tilde G}} \left[1 - \frac{m^2_{\tilde G}}{m^2_{\tilde\tau}}\right]^4$$

$$M_P = (2.4 \pm 0.5) \cdot 10^{18} \text{ GeV}$$

SUSY breaking scale $F \sim m_{\tilde G} M_P$

$$F = (8.3 \pm 0.1) \cdot 10^{19} \text{ GeV}^2$$

Test of Supergravity

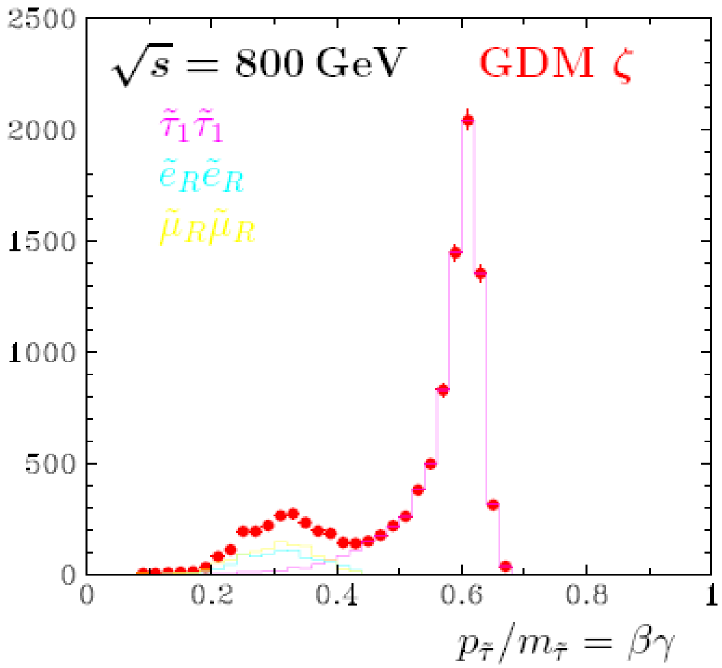
gravitino = superpartner of graviton

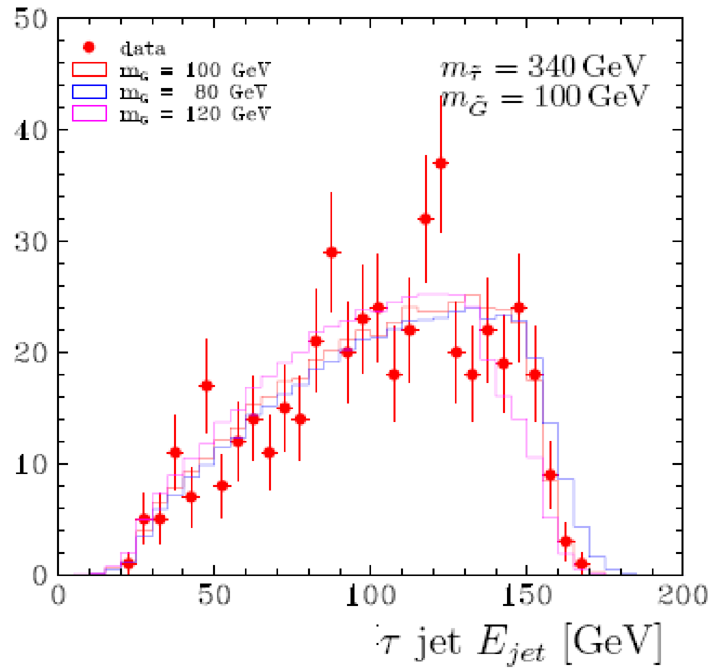
mSUGRA scenario GDM ς

- **Case study** L = 1000 fb^{-1} @ 800 GeV, σ_{SUSY} = 5 fb

$$m_{\tilde{\tau}} = 340.2 \text{ GeV},\ m_{\tilde{G}} = 100 \text{ GeV},\ t_{\tilde{\tau}} = 1.8\,10^6 \text{ s}$$

HCAL	1350
Yoke	770





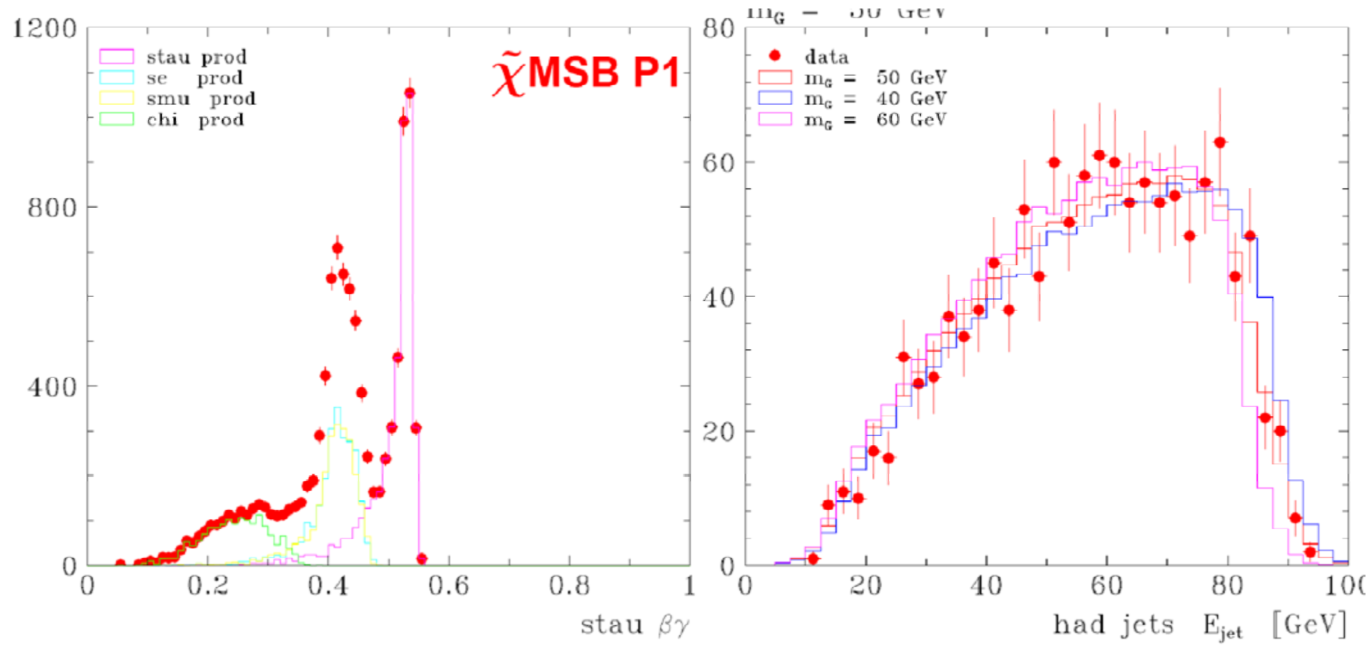
$m_{\tilde{\tau}}$ [GeV]	$t_{\tilde{\tau}}$ [s]	$m_{\tilde{G}}(E_\tau)$
340.2 ± 0.2	$(1.8 \pm 0.1)\,10^6$	100 ± 10

Gaugino mediation scenario P1

- **Case study** L = 200 fb^{-1} @ 420 GeV , σ_{SUSY} = 27 fb

$$m_{\tilde\tau} = 185.2\ \text{GeV},\ m_{\tilde G} = 50\ \text{GeV},\ t_{\tilde\tau} = 9.1\,10^6\ \text{s}$$

HCAL	3700
Yoke	4100



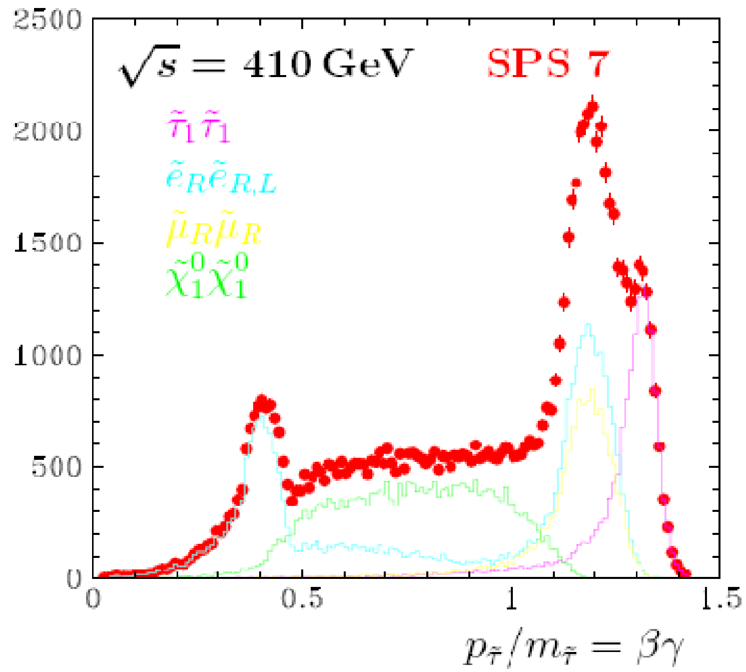
$m_{\tilde\tau}$ [GeV]	$t_{\tilde\tau}$ [s]	$m_{\tilde G}(E_\tau)$
185.2 ± 0.1	$(9.1 \pm 0.2)\,10^6$	50 ± 3

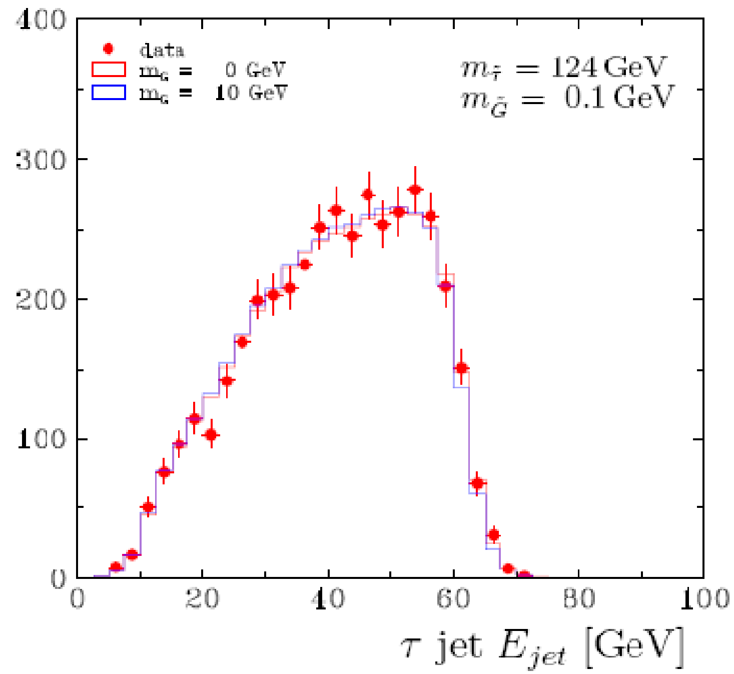
Gauge mediation scenario SPS 7

- **Case study** L =1 00 fb^{-1} @ 410 GeV, σ_{SUSY} = 500 fb

HCAL	10000
Yoke	4900

$$m_{\tilde{\tau}} = 124.3 \text{ GeV}, \; m_{\tilde{G}} = 0.1 \text{ GeV}, \; t_{\tilde{\tau}} = 210 \text{ s}$$





$m_{\tilde{\tau}}$ [GeV]	$t_{\tilde{\tau}}$ [s]	$m_{\tilde{G}}(E_\tau)$
124.3 ± 0.1	209.3 ± 2.4	< 9

Gravitino - or something else?

If direct mass measurement is not feasible, e.g. too light, the nature of the decay particle remains undetermined, the $t_{\tilde{\tau}} - m_{\tilde{G}}$ relation may not be applicable

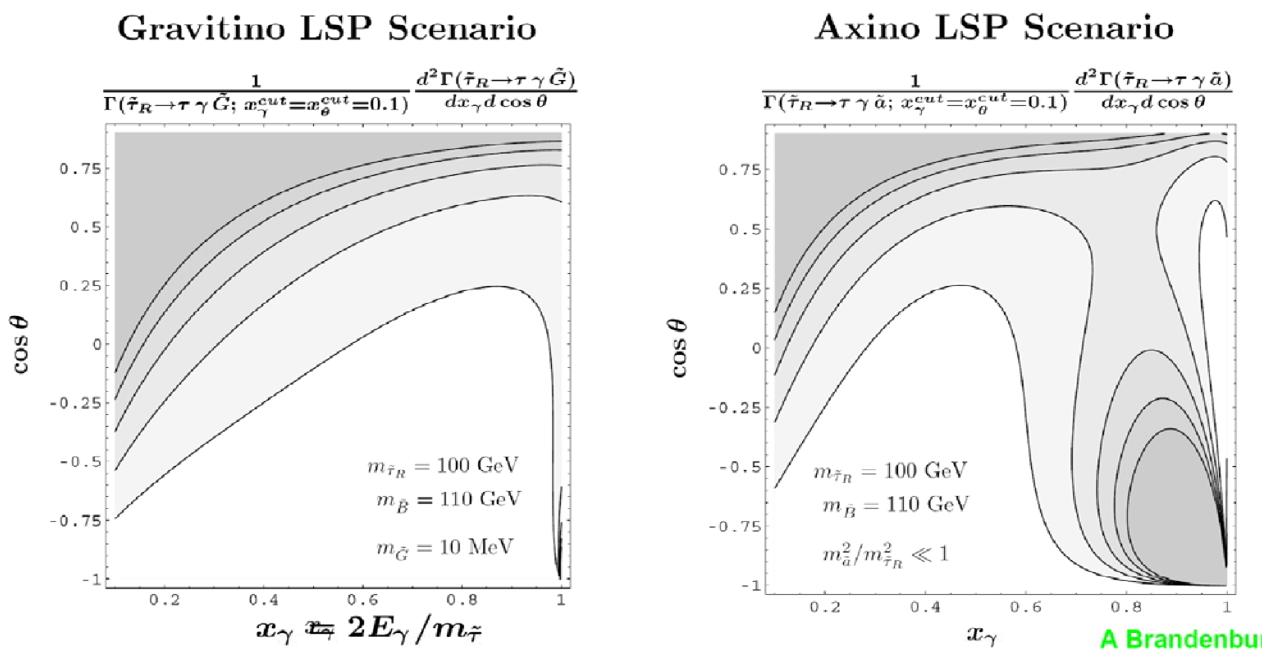
Alternative: axino $\tilde{\tau} \to \tau \tilde{a}$ lifetime not related to axino mass

Discrimination via radiative decay

$\tilde{\tau} \to \tau \gamma \tilde{a} / \tilde{G}$ $\mathcal{B} \sim \mathcal{O}(0.01),\ \mathcal{B}_{\tilde{a}} > \mathcal{B}_{\tilde{G}}$

$\tau - \gamma$ correlations sensitive to spin

LSP $\tilde{G}$: collinear, soft γ's LSP $\tilde{a}$: collinear soft and back-to-back energetic γ's



A Brandenburg et al, hep-ph/0501267

GDM scenario results

	$m_{\tilde{\tau}}$ [GeV]	$t_{\tilde{\tau}}$ [s]	$m_{\tilde{G}}(\Gamma_{\tilde{\tau}})$	$m_{\tilde{G}}(E_\tau)$	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [fb^{-1}]
SPS 7	124.3 ± 0.1	209.3 ± 2.4	0.1 ± 0.001	< 9	410	100
FS 600	219.3 ± 0.2	$(3.6 \pm 0.1)\, 10^6$	50 ± 0.7	50 ± 9	500	250
GDM ϵ	157.6 ± 0.2	$(2.6 \pm 0.05)\, 10^6$	20 ± 0.2	20 ± 4	500	100
GDM ζ	340.2 ± 0.2	$(1.8 \pm 0.06)\, 10^6$	100 ± 2	100 ± 10	800	1000
GDM η	322.1 ± 0.2	$(6.9 \pm 0.3)\, 10^4$	20 ± 0.4	20 ± 25	800	1000
$\tilde{\chi}$MSB P1	185.2 ± 0.1	$(9.1 \pm 0.2)\, 10^6$	50 ± 0.6	50 ± 3	420	200
$\tilde{\chi}$MSB P3	102.5 ± 0.2	$(4.2 \pm 0.1)\, 10^7$	25 ± 0.3	25 ± 1.5	500	100

Large statistics samples with moderate integrated luminosity and proper choice of cm energy (and beam polarisations)

stau mass O (0.1 %)

stau lifetime O (1 %)

gravitino mass O (10 %) provided $m_{Grav} > 0.1\ m_{stau}$

➔ coupling: Supergavity if consistent with Planck, Newton constant
SUSY breaking scale

Experimental challenges

- **ILC timing structure**

  5 buchtrains per second, each 1 ms long

- **LDC detector**

  readout of all ~2600 bunches, software trigger guarantees recording of slow particles

  pulsed operation of calorimeters foreseen (electronic heat consumption)

  HV, readout structure: 2 ms sensitive - 198 ms idle - 2 ms sensitive …

  designed for usual beam-correlated physics scenarios, not for late decays

➢ **Concept has to be revised to be prepared for long-lived particles !!!**

Yoke - no problem, pulsed mode doesn't seem necessary

→ lifetime measurement feasible, at expense of lower statistics

HCAL - R&D needed to increase duty cycle of readout electronics

Conclusions

- A heavy gravitino is an interesting dark matter candidate,
  no chance for direct detection in astrophysical experiments

- If kinematically accessible, a gravitino should be observable at future colliders via decays of metastable sleptons

  $\tilde{\tau}_1 \longrightarrow \tau \tilde{G}$ (and similar $\tilde{e}$, $\tilde{\mu}$)

- The ILC and its proposed detectors offer excellent possibilities to determine the gravitino properties

  mass, coupling, spin

  with high precision, thus providing a unique test of supergravity

  - **ILC environment superior to LHC**