Detecting metastable staus @ ILC

Gravitino dark matter

Felix Sefkow on behalf of **Hans-Ulrich Martyn**

- ▷ **Cold Dark Matter in universe** $\Omega_{DM} = \rho_{DM}/\rho_{crit} \simeq 0.23$
- ▷ **CDM SUSY candidates, neutral LSP**
  - **neutralino** $\tilde{\chi}_1^0$ $m_{\tilde{\chi}^0} = \mathcal{O}(100\ \mathrm{GeV})$
  - **gravitino** $\tilde{G}$ $m_{\tilde{G}} = \mathcal{O}(10 - 100\ \mathrm{GeV})$
  - **axino** $\tilde{a}$ $m_{\tilde{a}} = \mathcal{O}(\mathrm{keV} - \mathrm{MeV})$
- ▷ **Identification of** $\tilde{G}$ **via NLSP decay** $\tilde{\tau}_1 \to \tau \tilde{G}$
  - $\tilde{\tau}$ **may be long-lived** $t \sim \mathcal{O}(10^4 - 10^8\ \mathrm{s})$
  - **Expt challenge** **detectability of metastable** $\tilde{\tau}$ **and** $\tilde{G}$ **at ILC**

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

review: J Feng, ‘Superymmetry and Cosmology’, hep-ph/0405215

$\tilde{G}$ dark matter

- Mass scales set by SUSY breaking scale F and scale M_m of mediating interaction

$$m_{\tilde{G}} = \frac{F}{\sqrt{3}M_P}, \qquad m_{\tilde{f}}, m_\lambda \sim \frac{F}{M_m}, \qquad M_P = (8\pi G_N)^{-1/2} \simeq 2.4 \cdot 10^{18}\ \mathrm{GeV}$$

- Typical SUSY scenarios

mSUGRA	$M_m = M_P$	high $F \sim 10^{21}\mathrm{GeV}^2$	$m_{\tilde{G}} \sim \mathrm{TeV} \ldots \mathrm{GeV}$
GMSB	$M_m \sim 10^5\mathrm{GeV}$	low $F \sim 10^{10}\mathrm{GeV}^2$	$m_{\tilde{G}} \sim \mathrm{keV}$
$\tilde{\chi}$MSB	$M_m \sim 10^{17}\mathrm{GeV}$	high $F \sim 10^{20}\mathrm{GeV}^2$	$m_{\tilde{G}} \sim \mathrm{GeV}$

- $\tilde{G} = LSP \quad \Rightarrow NLSP = \tilde{\ell},\ \tilde{\nu}, \tilde{\chi}^0_1$

- Dominant decay $\tilde{\tau} \to \tau \tilde{G}$ long lifetime

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

$$t_{\tilde{\tau}} \simeq 3.6 \cdot 10^8\ \mathrm{s} \left[\frac{100\ \mathrm{GeV}}{m_{\tilde{\tau}} - m_{\tilde{G}}}\right]^4 \left[\frac{m_{\tilde{G}}}{1\ \mathrm{TeV}}\right]$$

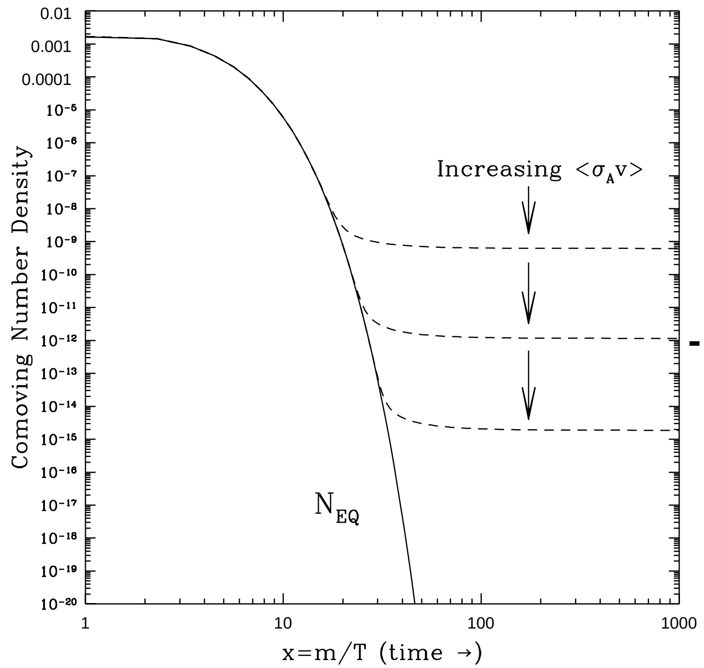
- $\tilde{G}$ interesting dark matter candidate
  freeze out of WIMPs, NLSPs from thermal equilibrium $n_{eq}\langle\sigma_A v\rangle \sim H$
  temperature $T \sim m/30$ $m = 300\,\mathrm{GeV}, T = 10\,\mathrm{GeV}$ time $t \sim 10^{-8}\mathrm{s}$

- Production of metastable $NLSP = \tilde{\tau}$ during inflation density $\Omega_{\tilde{\tau}}$
  delayed $\tilde{\tau}$ decays lead to $\tilde{G}$ dark matter relic density $\Omega_{\tilde{G}} = (m_{\tilde{G}}/m_{\tilde{\tau}})\,\Omega_{\tilde{\tau}}$

- Big Bang Nucleosynthesis ($t \sim 1\,\mathrm{s}$) should not be destroyed during reheating after inflation or by hadronic decays $\tilde{\tau} \to \tau Z \tilde{G}$ $\Rightarrow$ lifetime $M_P^2/M_{\mathrm{weak}}^3 \sim 10^4 - 10^8\mathrm{s}$

$f\bar{f} \leftrightarrow \tilde{\tau}\tilde{\tau}$

freeze out of dark matter particles

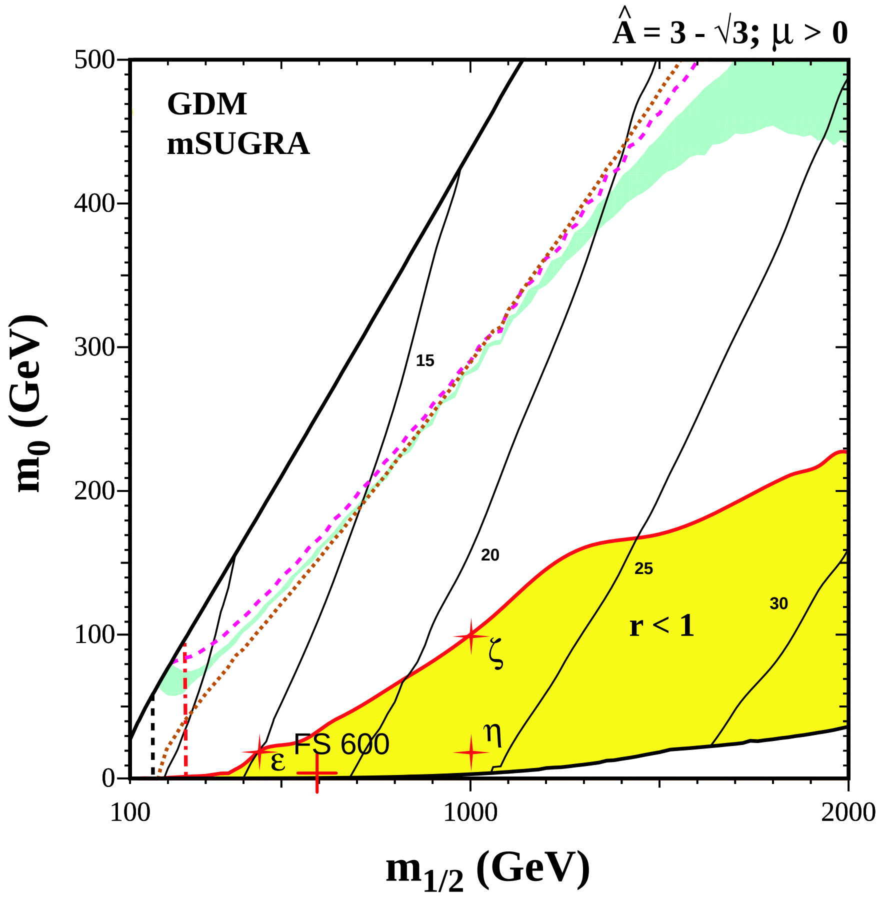


- - - - WIMP ⟶ superWIMP

W Buchmüller et al, hep-ph/0402179, hep-ph/0403203, J Feng et al, hep-ph/0404198, hep-ph/0404231

GDM scenarios

$\tilde{\ell}, \tilde{\chi}$	SPS 7	FS 600	GDM ϵ	GDM ζ	GDM η
$\tilde{\tau}_1$	123.4	219.3	157.6	340.2	322.1
$\tilde{\tau}_2$	264.9	406.5	307.2	659.2	652.2
$\tilde{\nu}_\tau$	249.6	396.4	290.9	649.5	641.5
$\tilde{e}_R$	130.9	227.2	175.1	381.4	368.5
$\tilde{e}_L$	262.8	405.6	303.0	662.7	655.3
$\tilde{\nu}_e$	250.1	397.6	292.8	658.1	650.7
$\tilde{\chi}_1^0$	163.7	243.0	179.4	426.5	426.5
$\tilde{\chi}_2^0$	277.9	469.6	338.2	801.9	801.5
$\tilde{\chi}_1^\pm$	275.5	469.9	338.0	801.9	801.4
$\tilde{G}$			20	100	20



GMSB $\Lambda,\ M_m,\ N_m,\ \tan\beta,\ \mu$

mSUGRA $m_0,\ M_{1/2},\ A_0,\ \tan\beta$, sign μ

in general $m_{3/2} = m_{\tilde{G}}$ free parameter

tighter definition $m_{3/2} = m_0$ in GDM ϵ, ζ, η

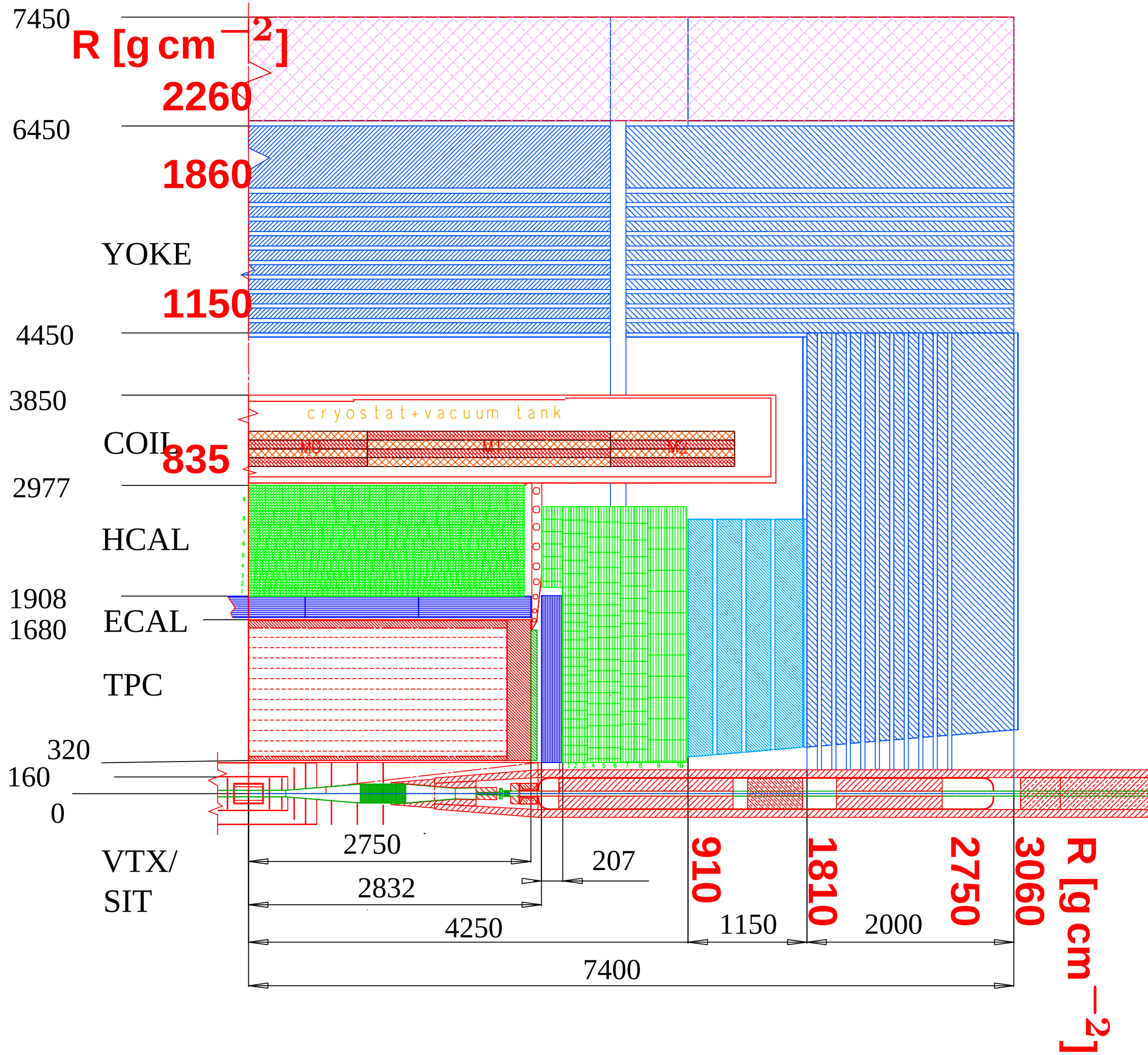
FS 600: J Feng, B Smith hep-ph/0409278

GDM: A De Roeck et al, hep-ph/0508198

$\tilde{\tau}$ ID in LDC detector

$\tilde{\tau}$ identification

1. heavy ionisation in TPC
   $-dE/dx \propto 1/\beta^2$
2. stop $\tilde{\tau}$ in HCAL & instrumented yoke
3. record $\tilde{\tau}$ location & time stamp t_{start}
4. wait until decay $\tilde{\tau} \longrightarrow \tau\tilde{G}$ at t_{decay}
   $\Rightarrow$ $\tilde{\tau}$ lifetime $t_{\tilde{\tau}} = t_{decay} - t_{start}$
5. measure τ decay products
   $\Rightarrow$ gravitino mass $m_{\tilde{G}}$
6. rare radiative decay $\tilde{\tau} \longrightarrow \tau\gamma\tilde{G}$
   $\Rightarrow$ gravitino spin $J_{\tilde{G}}$



$\tilde{\tau}$ range out

Range R of a heavy particle, mass M, due to ionisation loss

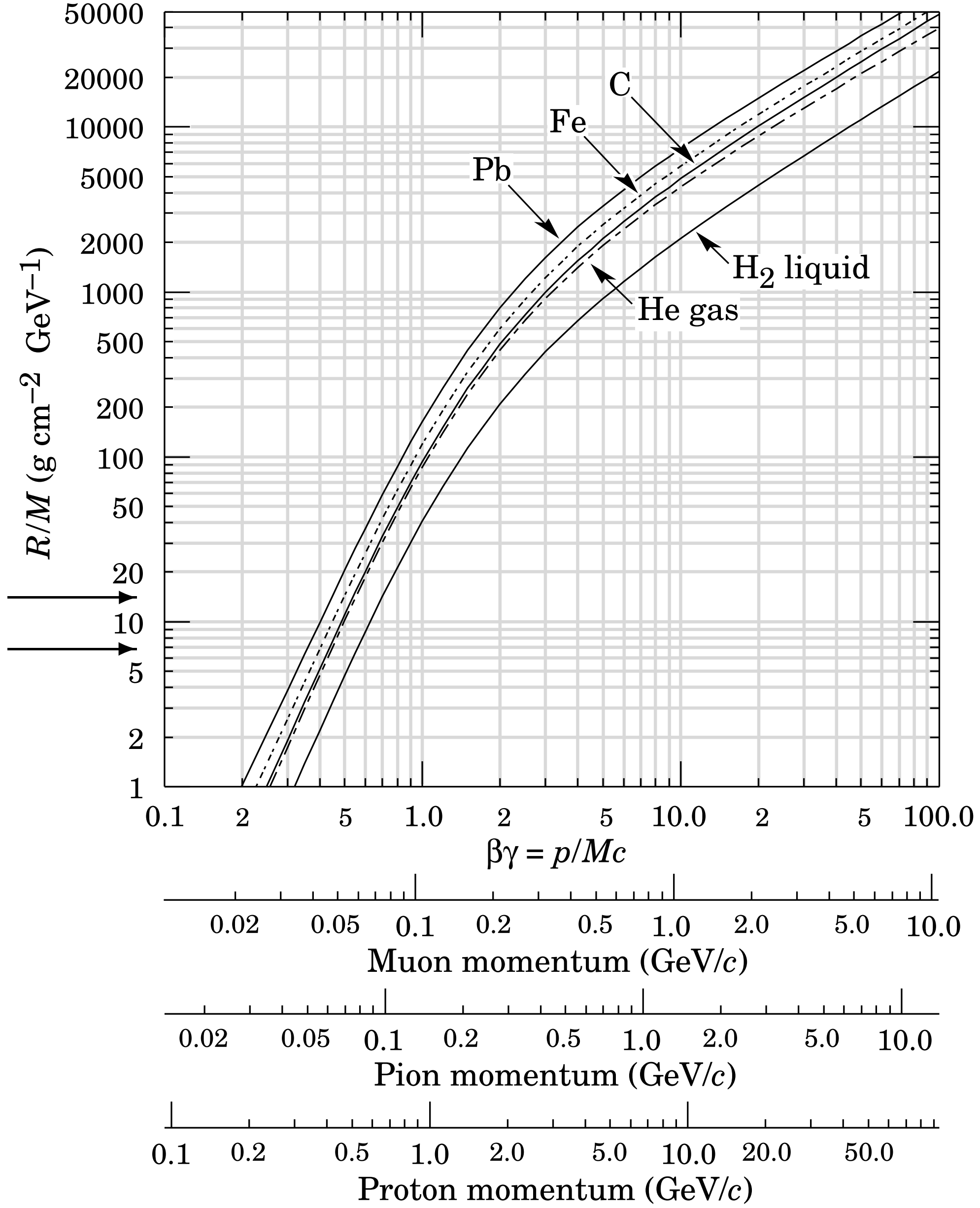
$$R(E') = \int_M^{E'} dE\,(dE/dx)^{-1}$$
$$R/M = f(p/M = \beta\gamma)$$

Max. momentum acceptance for stopping particles $\beta \lesssim 0.5$

barrel

$m_{\tilde{\tau}} = 120$ GeV

$m_{\tilde{\tau}} = 250$ GeV



$\tilde{\tau}$ decays & $\tilde{G}$ detection

$\tau \to e\nu\nu$	$B_e = 17.8\%$
$\tau \to \mu\nu\nu$	$B_\mu = 17.4\%$
$\tau \to \pi\nu$	$B_\pi = 11.1\%$
$\tau \to \rho\nu$	$B_\rho = 25.4\%$
$\tau \to 3\pi\nu$	$B_{3\pi} = 19.4\%$

- **Trigger** isolated $\tilde{\tau}/\tau$ decay in detector
  - any time – not correlated to beam collision
  - origin – associate to list of stopped $\tilde{\tau}'s$
  - spatial resolution, granularity good enough?
- **Lifetime** clean signature: large energy release in HCAL, μ in HCAL & yoke
  - handling detector-off times
- **Gravitino mass** hadronic τ energy spectra (leptonic decays less useful)

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

  - restricted to E/HCAL? iron yoke resolution good enough?
- **Test Planck scale** M_P $m_{\tilde{\tau}}, t_{\tilde{\tau}}, m_{\tilde{G}} \Rightarrow M_P$
- **Gravitino spin** $\gamma - \tau$ correlations in $\tilde{\tau} \to \tau\gamma\tilde{G}$
  - extremely small rate, γ ID & resolution experimental challenge!
- **Background** low & manageable
  - cosmic rays, CC interactions from atmospheric neutrinos

K Hamaguchi et al, hep-ph/0409248, J Feng and B Smith, hep-ph/0409278

mSUGRA scenario GDM ϵ

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

$m_{\tilde{\tau}} = 157.6$ GeV, $m_{\tilde{G}} = 20$ GeV, $t_{\tilde{\tau}} = 2.6 \cdot 10^6$ s

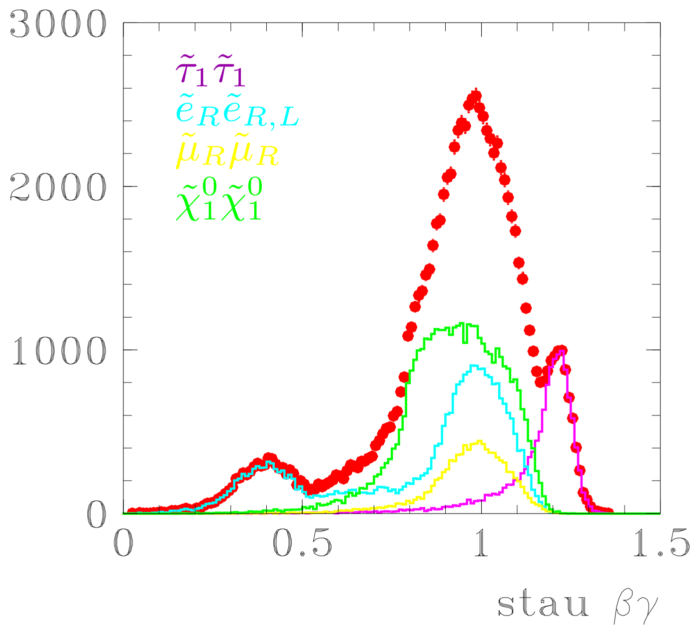
Case study $\mathcal{L} = 100\,\text{fb}^{-1}$ @ $\sqrt{s} = 500$ GeV
$\sigma_{SUSY} = 300$ fb

Clean signature $\sum \vec{p} \simeq 0$ and $\sum E < \sqrt{s}$

High acceptance $\epsilon \longrightarrow 1$

Prolific production of $\tilde{\tau}$ pairs and cascade
$\tilde{\tau}'s$ with similar kinematics

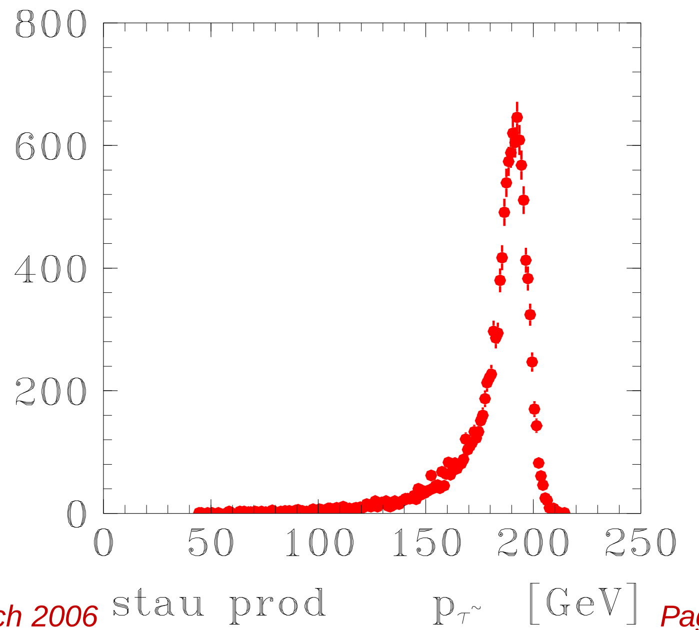
Low $\beta\gamma$: $\tilde{e}_R\tilde{e}_L \rightarrow e\tau^{\mp}\tilde{\tau}_1^{\mp}\; e\tilde{\chi}_1^0$



Pair production $e^+e^- \rightarrow \tilde{\tau}_1\tilde{\tau}_1$

$p_{\tilde{\tau}} = 192.4 \pm 0.2$ GeV $E_{\tilde{\tau}} = \sqrt{s}/2$

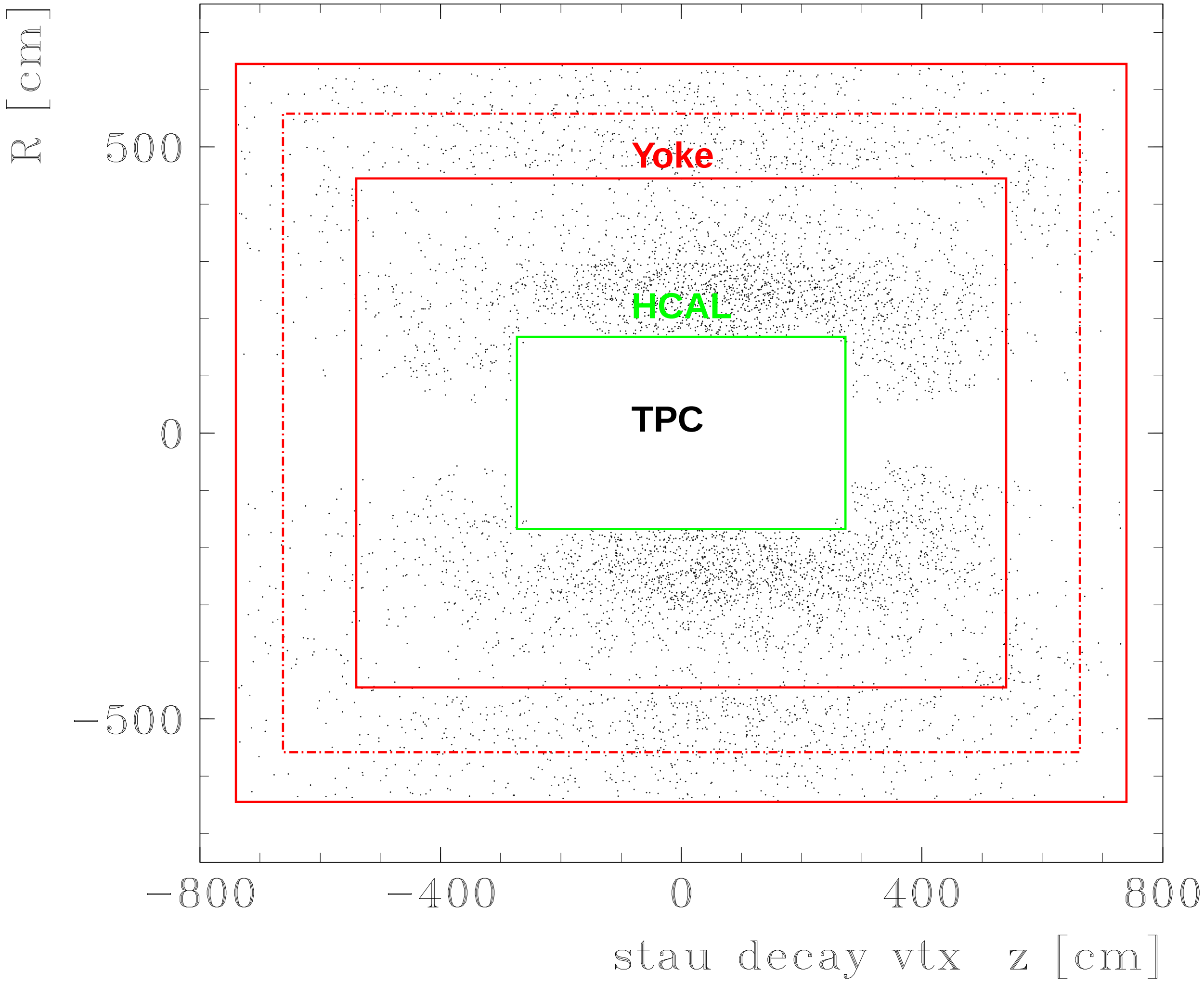
$\Rightarrow$ $\boxed{m_{\tilde{\tau}} = 157.6 \pm 0.2 \text{ GeV}}$



mSUGRA scenario GDM ϵ

Large samples of stopping $\tilde{\tau}$

	barrel	endcap	Sum
HCAL	3038	1055	4093
Plug		428	428
Yoke	1584	256	1840
Fid Vol	4092	1688	5780



Detect and measure gravitino via decays

$$\tilde{\tau} \to \tau \tilde{G}$$

and subsequent τ decays

mSUGRA scenario GDM ϵ

$\tilde\tau$ lifetime measurement

Trigger isolated $\tilde\tau/\tau$ decay in detector

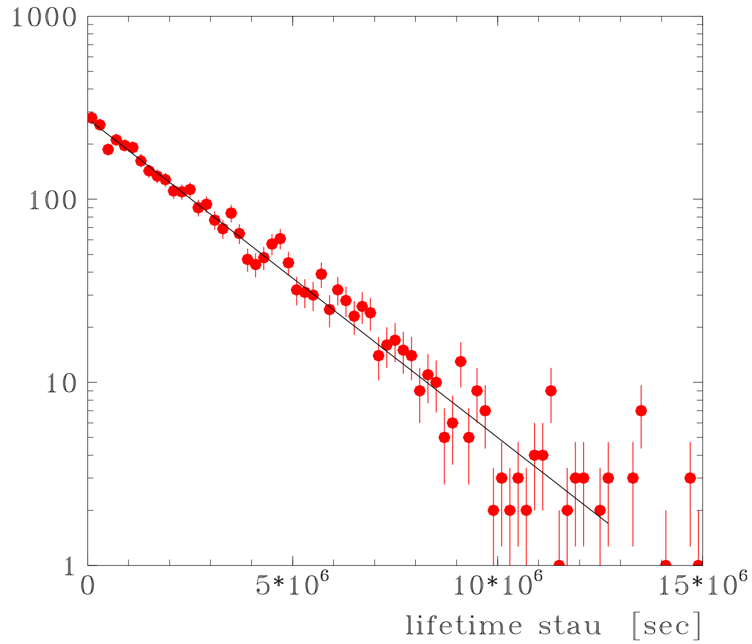
any time – not correlated to beam collision

origin – associate to list of stopped $\tilde\tau's$

muons in HCAL and yoke $E_\mu > 5$ GeV

electrons, hadrons in HCAL $E_{e,h} > 10$ GeV

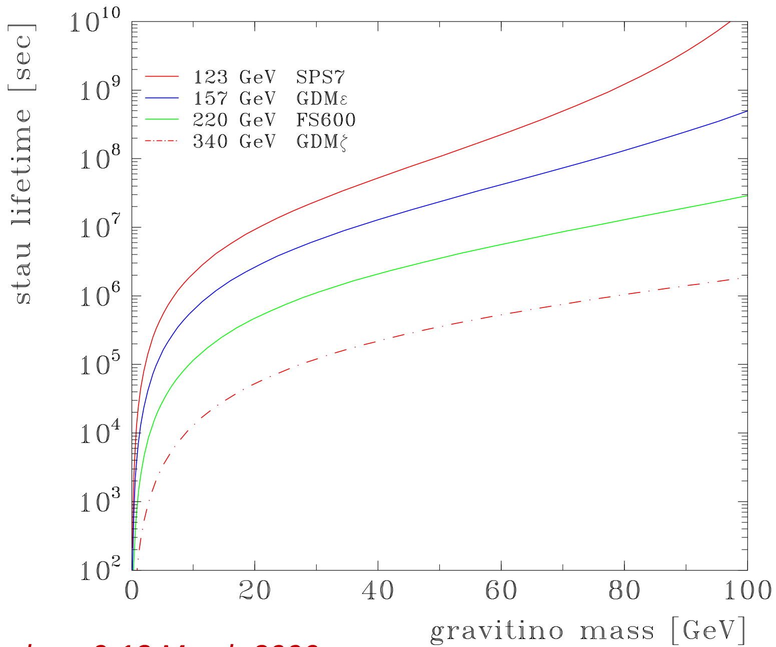
$$t_{\tilde\tau} = (2.59 \pm 0.05) \cdot 10^6 \text{ s}$$



$\tilde G$ mass from decay rate

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

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



mSUGRA scenario GDM ϵ

τ decay spectra

Max. energy of τ candidate

$$E^{max}_{\tau\to h\nu} = (m^2_{\tilde\tau} - m^2_{\tilde G})/2\, m_{\tilde\tau}$$
$$= 77.5 \text{ GeV}$$

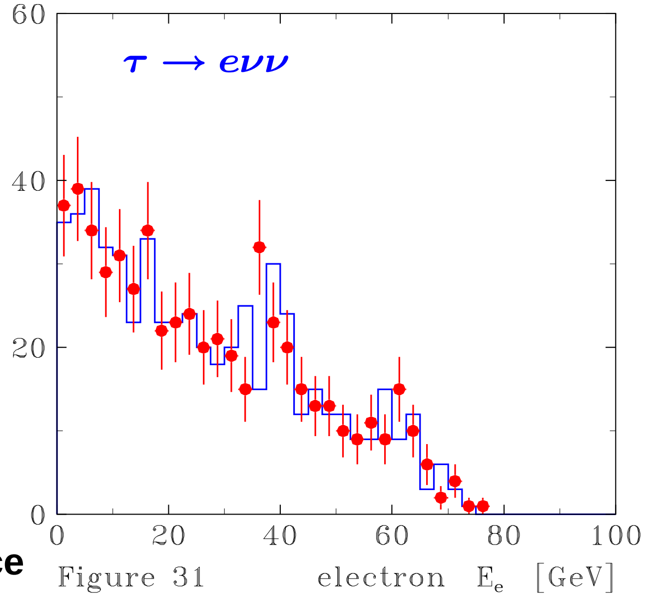
$\Rightarrow$ lepton spectra not very useful

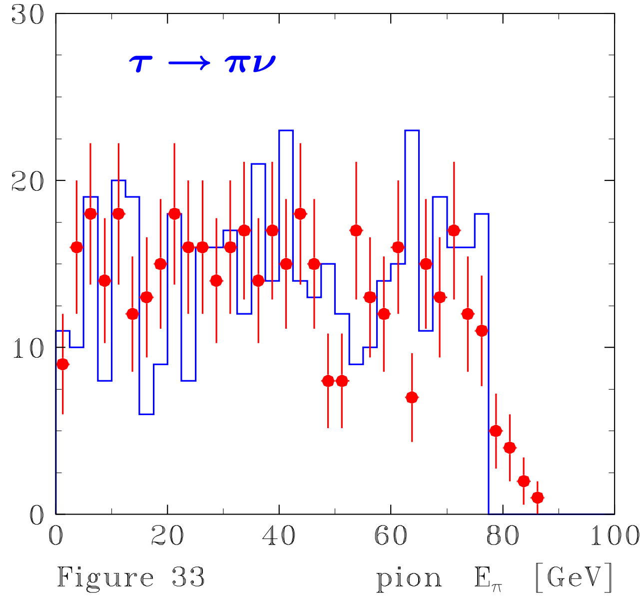
Resolution & containement

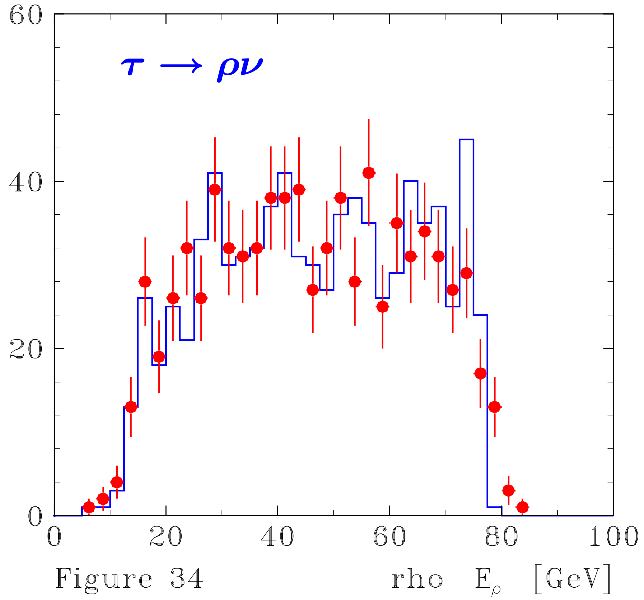
depend on shower start and incidence wrt absorber plates

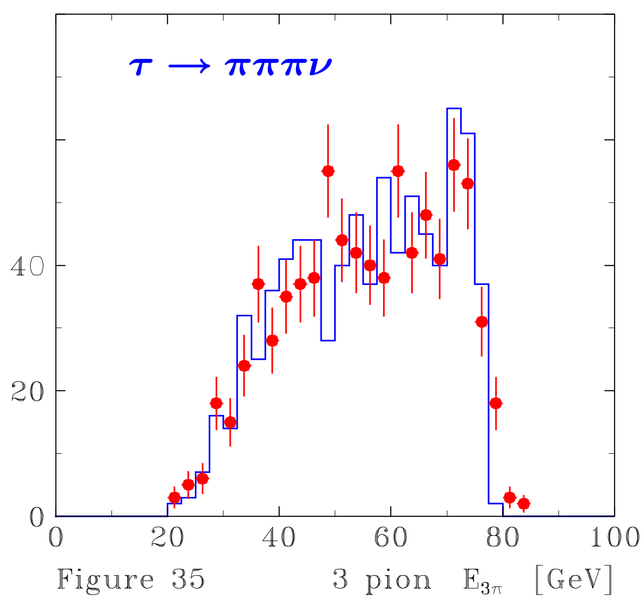
assume

$$\sigma_{em} = 0.2\sqrt{E} \oplus 0.01E$$
$$\sigma_{had} = 0.5\sqrt{E} \oplus 0.04E$$









mSUGRA scenario GDM ϵ

$\tilde{G}$ mass measurement

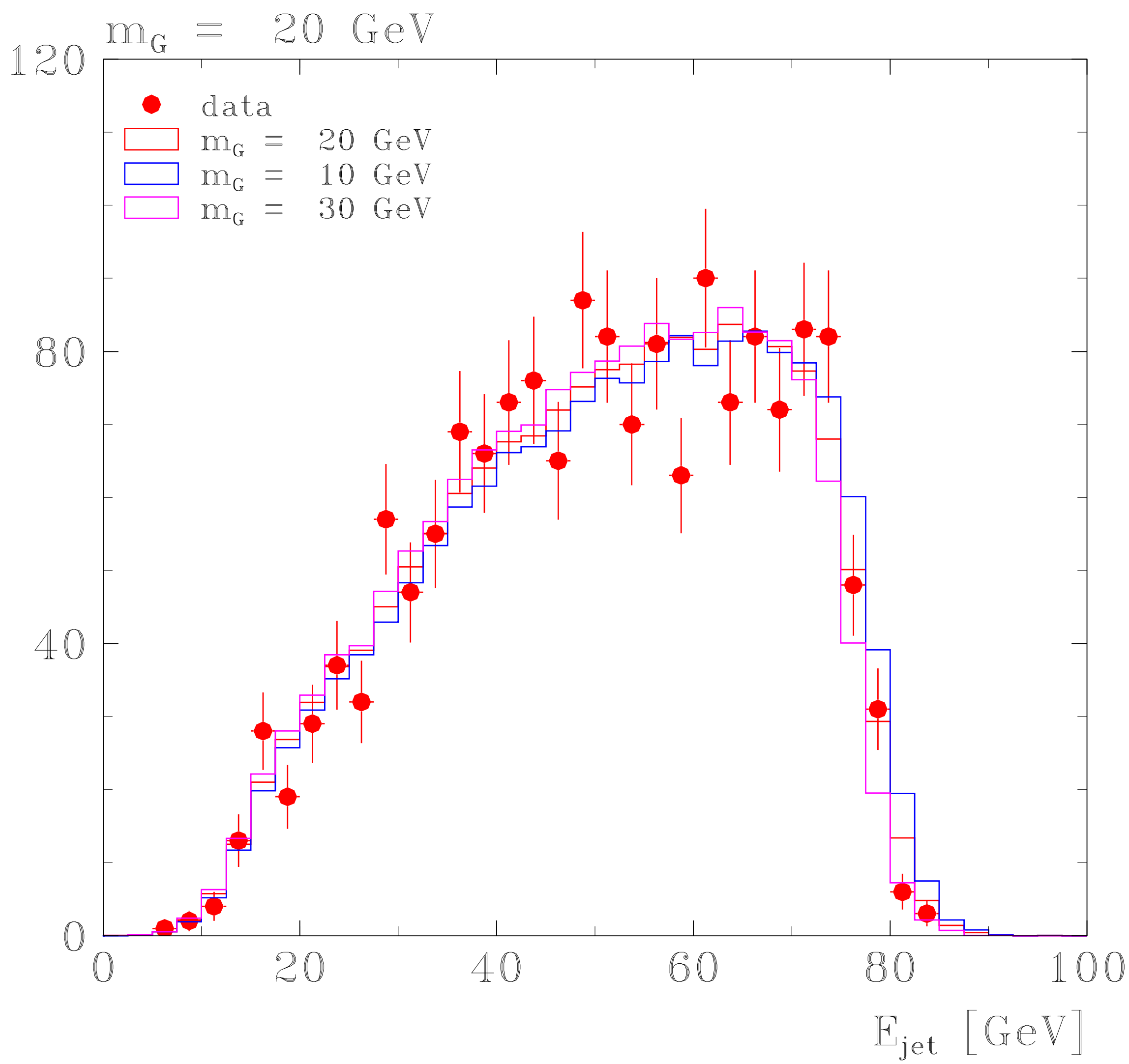
Fits to spectra E_ρ and $E_{3\pi}$

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

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

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

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



$m_{\tilde{\tau}}$ [GeV]	$t_{\tilde{\tau}}$ [s]	$m_{\tilde{G}}(\Gamma_{\tilde{\tau}})$	$m_{\tilde{G}}(E_\tau)$
157.6 ± 0.2	$(2.59 \pm 0.05)\ 10^6$	20 ± 0.2	20 ± 4

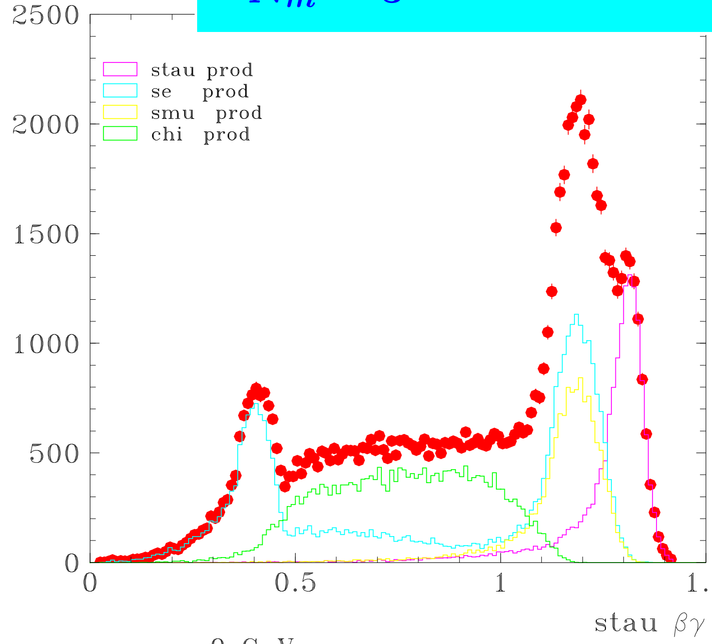
GMSB scenario SPS 7

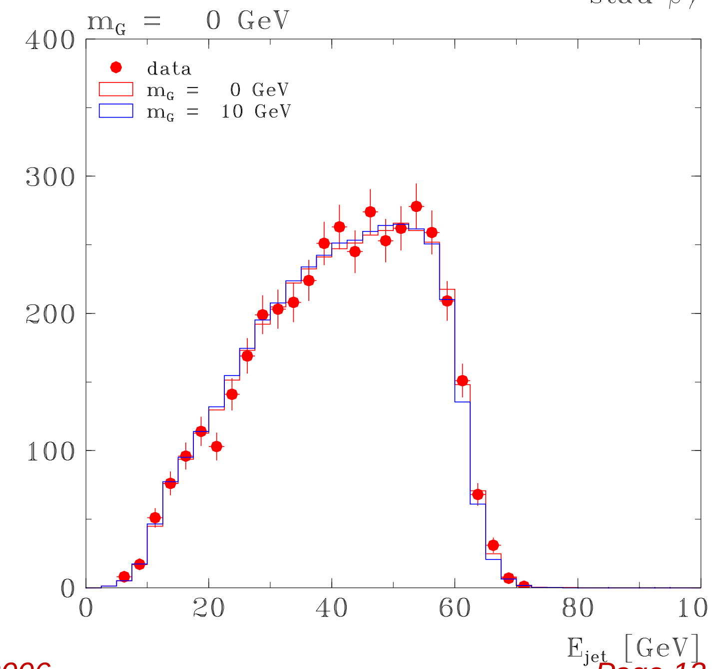
$\Lambda = 40$ TeV $\quad \tan\beta = 15$
$M_m = 80$ TeV $\quad$ sign $\mu+$
$N_m = 3$

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

Case study $\quad \mathcal{L} \sim 100\,\mathrm{fb}^{-1}$ @ $\sqrt{s} = 410$ GeV
$\sigma_{SUSY} = 500\,\mathrm{fb}$

	Barrel	Endcap	Sum
HCAL	7737	2305	10042
Plug		674	674
Yoke	4320	588	4908
Fid Vol	10071	3406	13477





$m_{\tilde{\tau}}$ [GeV]	$t_{\tilde{\tau}}$ [s]	$m_{\tilde{G}}(\Gamma_{\tilde{\tau}})$	$m_{\tilde{G}}(E_\tau)$
124.3 ± 0.1	209.3 ± 2.4	0.1 ± 0.001	< 9
	$(2.1 \pm 0.02)\, 10^6$	10 ± 0.1	10 ± 5

mSUGRA scenario FS 600

$m_0 = 0$ GeV $\tan\beta = 10$

$M_{1/2} = 600$ GeV   sign $\mu +$

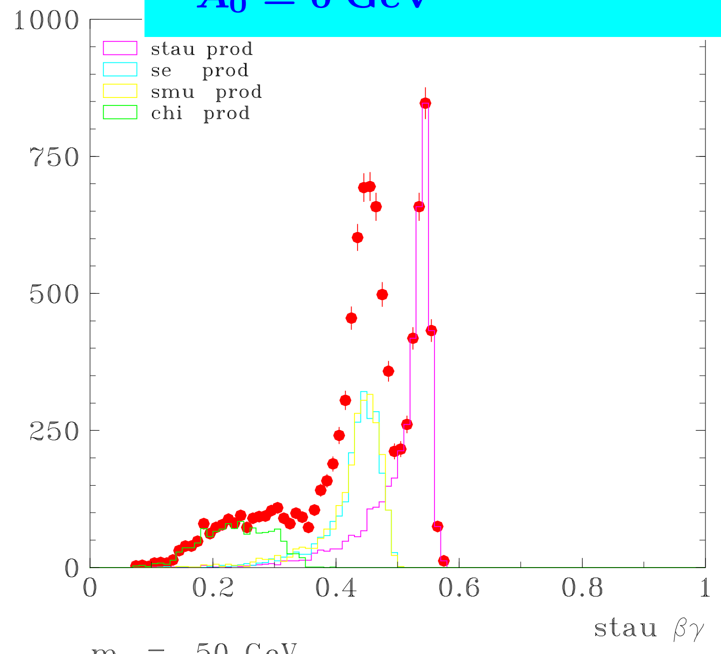
$A_0 = 0$ GeV

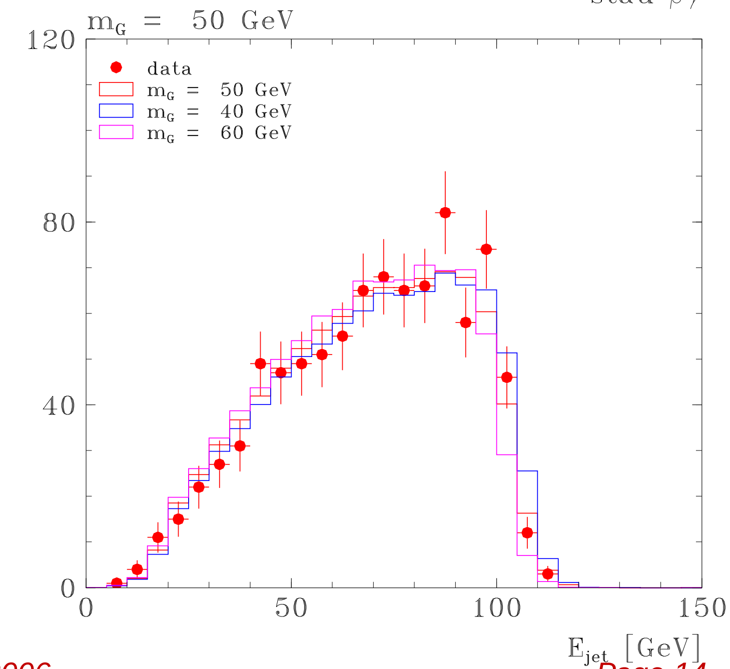
$m_{\tilde\tau} = 219.3$ GeV, $m_{\tilde G} = 50$ GeV, $t_{\tilde\tau} = 3.6\, 10^6$ s

Case study $\mathcal{L} \sim 250\,\mathrm{fb}^{-1}$ @ $\sqrt{s} = 500$ GeV

$\sigma_{SUSY} = 20\,\mathrm{fb}$

	Barrel	Endcap	Sum
HCAL	1883	217	2100
Plug		140	140
Yoke	3934	253	4187
Fid Vol	3649	568	4217





$m_{\tilde\tau}$ [GeV]	$t_{\tilde\tau}$ [s]	$m_{\tilde G}(\Gamma_{\tilde\tau})$	$m_{\tilde G}(E_\tau)$
219.3 ± 0.2	$(3.6 \pm 0.1)\, 10^6$	50 ± 0.7	50 ± 9

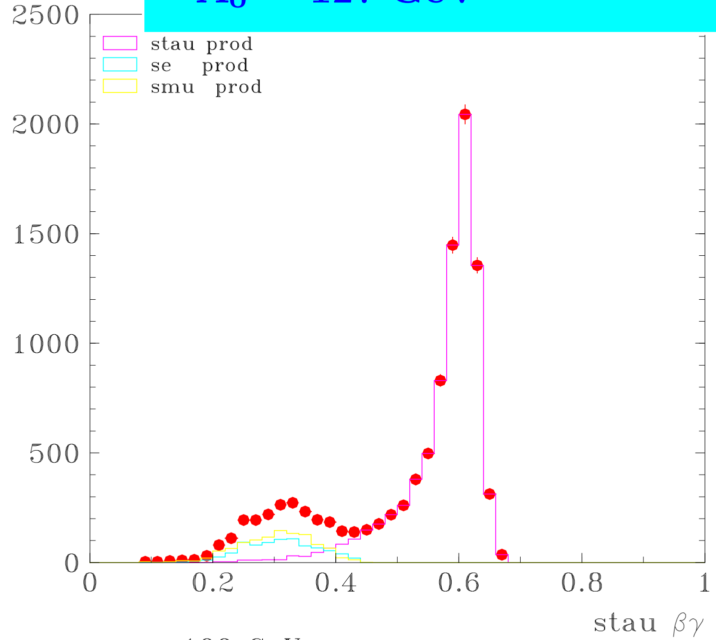
mSUGRA scenario GDM ζ

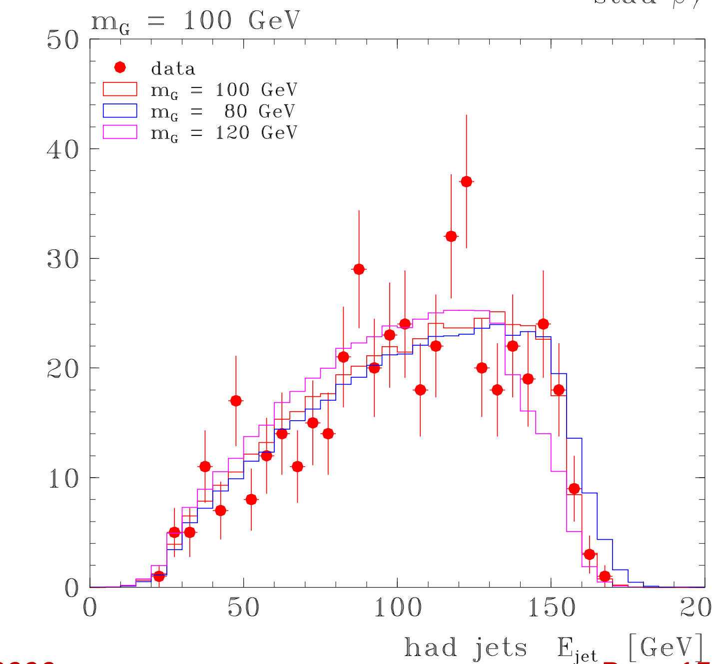
$m_0 = 100$ GeV	$\tan\beta = 21.5$
$M_{1/2} = 1$ TeV	sign $\mu+$
$A_0 = 127$ GeV	

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

Case study $\mathcal{L} \sim 1000\,\text{fb}^{-1}$ @ $\sqrt{s} = 800$ GeV
$\sigma_{SUSY} = 5$ fb

	Barrel	Endcap	Sum
HCAL	1154	181	1335
Plug		61	61
Yoke	740	30	770
Fid Vol	1623	266	1889





$m_{\tilde\tau}$ [GeV]	$t_{\tilde\tau}$ [s]	$m_{\tilde G}(\Gamma_{\tilde\tau})$	$m_{\tilde G}(E_\tau)$
340.2 ± 0.2	$(1.8 \pm 0.06)\,10^6$	100 ± 1	100 ± 10

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

▷ Abundant $\tilde{\tau}$ production at ILC directly and via cascade decays
— accurate measurement of $m_{\tilde{\tau}}$ with moderate luminosity

▷ Proper choice of $\sqrt{s}$
— large samples of stopping $\tilde{\tau}'s$ in HCAL & yoke
— accurate determination of $\tilde{\tau}$ lifetime $\longrightarrow$ $\tilde{G}$ mass at percent level
degrading for $t_{\tilde{\tau}}$ larger than a few years
— direct measurement of $\tilde{G}$ mass at 10% level in HCAL may be feasible

Calorimeter requirements

HCAL absorber material Fe $\lambda_I = 16.6$ cm, $X_0 = 1.76$ cm 2 cm plates: $0.12\,\lambda_I,\ 1.14\,X_0$

- **Trigger & DAQ**
  $\tilde{\tau}$ decay within / out of bunch train
  threshold?
  must be permanently sensitive

- **Energy resolution**
  inclined particles wrt absorber plates
  apply weighting techniques

- **Containement & acceptance**
  decay vertex anywhere in HCAL
  fiducial volume and directional cuts?
  leaving and reentering particles?

- **Particle ID**
  $\pi^{\pm}$ vs e vs γ
  charge meas. to reject cosmics?

- **Spatial resolution of vertex position**
  lateral & longitudinal
  cosmics rejection, overlapping vertices

- **Iron yoke instrumentation**
  doubling the stopping power
  useful for trigger $\longrightarrow$ $\tilde{\tau}$ lifetime measurement
  ok for muons
  hadron energy measurement?

▷ **Calorimeter designs should be prepared to detect metastable sleptons**

Summary

- A heavy gravitino $\tilde{G}$ 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 $\tilde{e}$, $\tilde{\mu}$)
  ILC environment superior to LHC

- Abundant $\tilde{\tau}$ production at ILC directly or via cascades

- Excellent experimental potential already with modearte luminosities
  - identifying & stopping heavy $\tilde{\tau}$'s $\quad \delta m_{\tilde{\tau}} \sim \mathcal{O}(10^{-3})$
  - measuring lifetime of metastable $\tilde{\tau}$'s $\quad \delta t_{\tilde{\tau}} \sim \mathcal{O}(10^{-2})$
  - determining $\tilde{G}$ mass from τ recoil spectra $\quad \delta m_{\tilde{G}} \sim \mathcal{O}(10^{-1})$

▷ Access to Planck's resp Newton's constant!