Models with Long-Lived Particles :

A Short Survey

- What are the types of models which predict long-lived particles decaying macroscopically, ie, $d \sim 10^{-3} - 10^{0}$ m ??

- How likely is it the model's parameters allow such lifetimes ?? What are their signatures ??

→ Quick + dirty intro to models

→ Numerics

Summary + Conclusions

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12/03

Gauge Mediation : A Story of 3 Sectors

- A 'secluded' SUSY breaking sector which

communicates $\cancel{SUSY}$ at $\begin{cases} \text{tree} & k \sim g^2 \simeq 1 \\ \text{1-loops} & k \sim \alpha \sim 10^{-2} \\ \text{2-loops} & k \sim \alpha^2 \sim 10^{-4} \end{cases}$

[the scale is $\sqrt{F/k}$]

to the

- Messenger sector : (i) a SM singlet field S

$\langle S \rangle = M + \theta^2 F$ { M, $\sqrt{F}$ are fund. scales }

(ii) messenger fields { anomaly free combos of SM fields } $5+\bar{5}$ / $10+\overline{10}$ in SU(5) language

e.g, q, q^c, ℓ, ℓ^c $W = \lambda_1 S q q^c + \lambda_2 S \ell \ell^c$

$$m^{mess}_{fermion} \simeq \lambda M$$

$$m^2_{\substack{boson \\ mess}} \simeq \begin{pmatrix} \lambda^2 M^2 & \lambda F \\ \lambda F & \lambda^2 M^2 \end{pmatrix}, \rightsquigarrow \frac{\sqrt{F}}{M} \leq 1 \quad \underline{\text{for } m^2 > 0}$$

$\sqrt{F}$, M range from $\lesssim$ 1TeV up to M_{GUT}, in principle ...

→ Lastly ..

· Messenger communicate with ordinary 'sector'

superfields ... via loops

→ gauginos

$$M_i = \begin{Bmatrix} 1 \\ 1 \\ 5/3 \end{Bmatrix} N\, g(x)\, \frac{\alpha_i}{4\pi}\, \Lambda$$

F/M

$O(1)$ loop functions

→ scalars

$$m^2 = 2\Lambda^2 N f(x) \sum_i c_i \left(\frac{\alpha_i}{4\pi}\right)^2$$

$O(1)$ constants from grp theory

of $5+\bar{5}$ messengers ($\lesssim 4$ GUT)

$x = \lambda M^2/F$ (boson/fermion messenger mass ratio)

RGE ($M \to$ electroweak scale)

∴ masses calculable in terms of a few parameters

Measuring masses tells us $\underline{\Lambda}$; we'd like to get $\sqrt{F}$, M + k .... , ($k \sim O(1)$ favored by tuning arguments ??)

So what?

- LSP is gravitino! $\quad m_{3/2} = \dfrac{F/k}{\sqrt{3}\,\bar{M}_{Pl}} = 2.37 \left(\dfrac{\sqrt{F/k}}{100\,\mathrm{TeV}}\right)^2 \underline{\underline{eV}}$

... for $\sqrt{F/k} \gtrsim 3000\,\mathrm{TeV}$, $\tilde{G}$ dominates + over closes universe

- $\underline{\underline{N}}$LSP is typically $\underline{\chi_1}$ or $\underline{\tau_R}$ + decays to $\tilde{G}$:

$$\begin{cases} \chi_1^0 \to \tilde{G}\,\gamma/Z \\ \tilde{\tau} \to \tau\,\tilde{G} \end{cases}$$

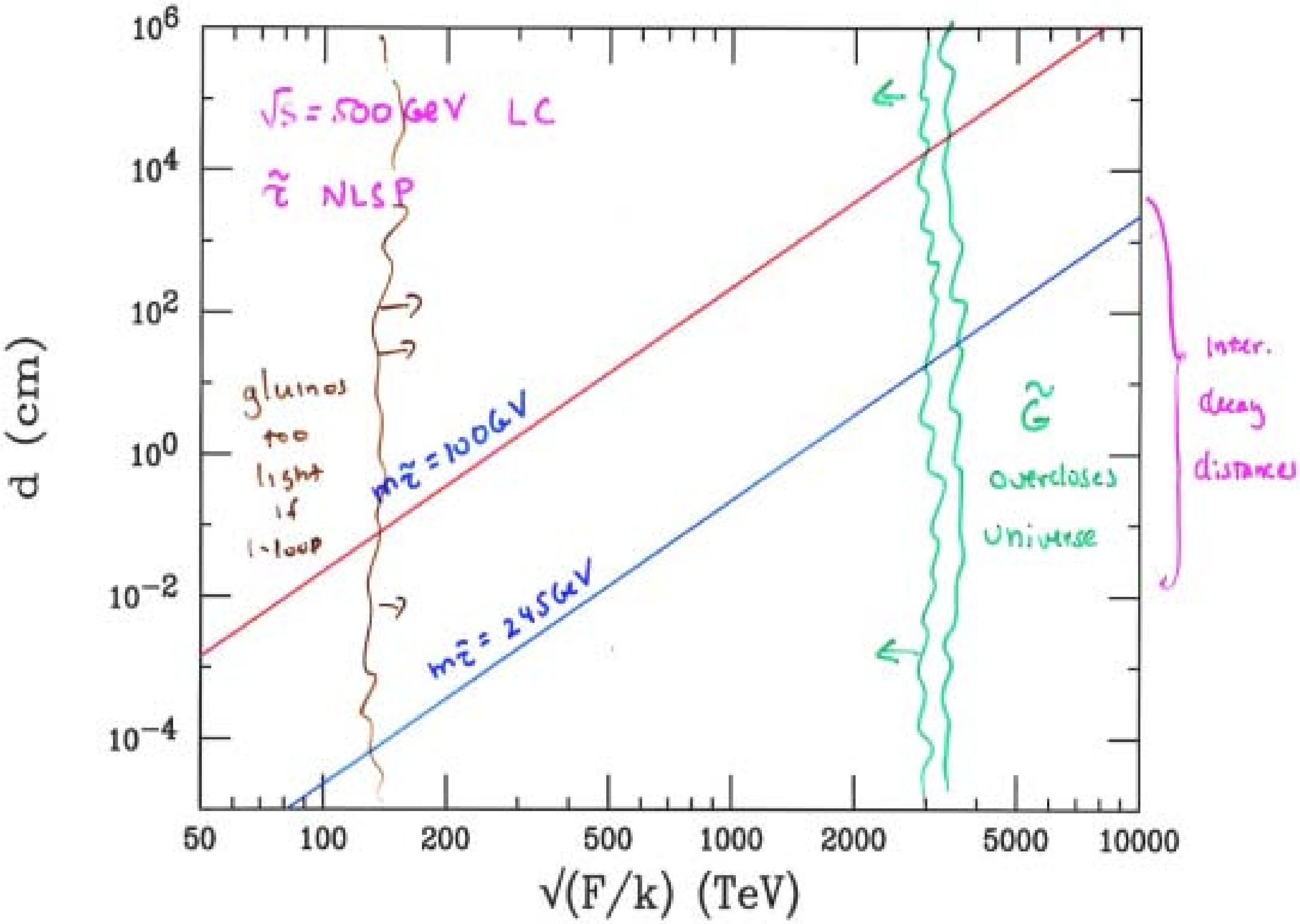
Clebschs $\sim O(1)$

$$\Gamma\left(\underset{(\tilde{\tau})}{\chi_1^0}\right) = \left(k/F\right)^2 \frac{m_{\chi_1,\tilde{\tau}}^5}{16\pi} \left(\kappa_{\gamma,Z}\right)$$

$$d\,[\mathrm{cm}] = \overbrace{\left(1/\kappa_{\gamma,Z}\right)}^{\text{absent for } \tilde{\tau}\text{'s}} \left(\frac{100\,\mathrm{GeV}}{m}\right)^5 \left(\frac{\sqrt{F/k}}{100\,\mathrm{TeV}}\right)^4 \left[\frac{s}{4m^2} - 1\right]^{1/2} \cdot \left(4.92 \cdot 10^{-3}\,\mathrm{cm}\right)$$

$\Longrightarrow$ Note: $\sqrt{F} \simeq M$, $N = 4$, $k = 1$, $\alpha_s \simeq 0.11$, $m_{\tilde{g}} > 200\,\mathrm{GeV}$

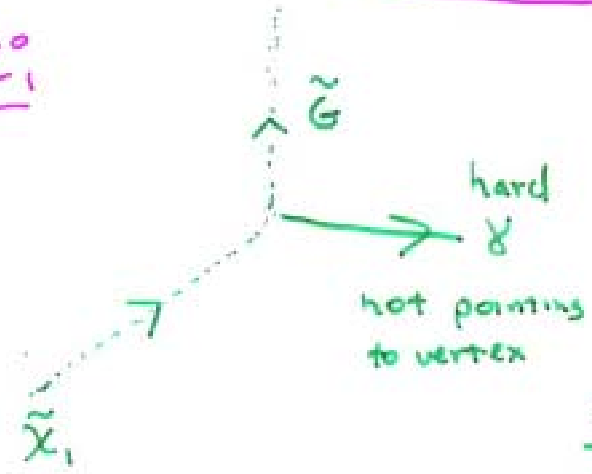
$\to \sqrt{F} \gtrsim$ few TeV $\quad$ more naturally $\gtrsim 50\,\mathrm{TeV}$ or more



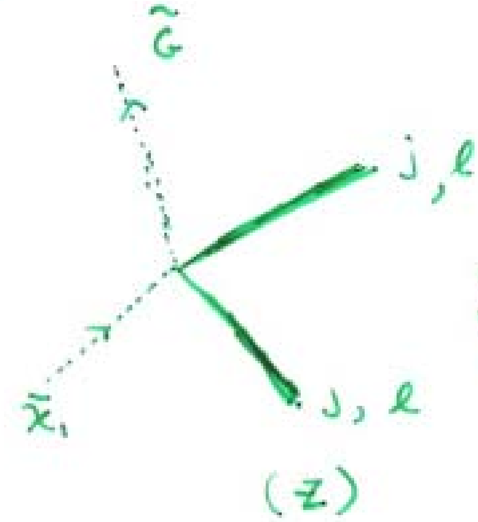
d (cm)
√(F/k) (TeV)
√s = 500 GeV LC
τ̃ NLSP
gluinos too light if 1-loop
mτ̃ = 100 GeV
mτ̃ = 245 GeV
G̃ overcloses Universe
Inter. decay distances

Signatures

χ_1^0



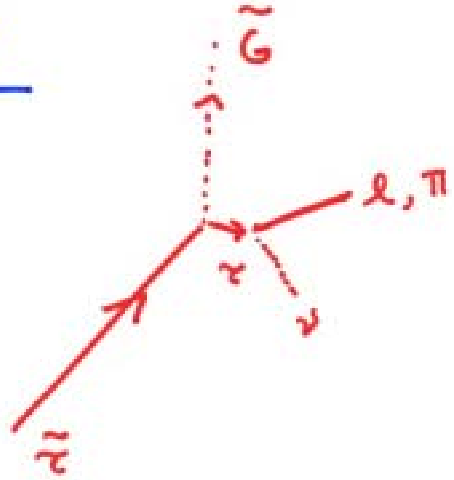
or



inv. mass is m_Z

again, traces not pointing to vertex

$\tilde{\tau}$



MIP $\rightarrow$ tau $\rightarrow$ ℓ, π + $\not{E}$
+
$\not{E}$

as above

Refs

- Chen + Gunion - hep-ph/9802252
- Mercadante, Mizukoshi + Yamamoto, hep-ph/0010067
- Giudice + Rattazzi, hep-ph/9801271

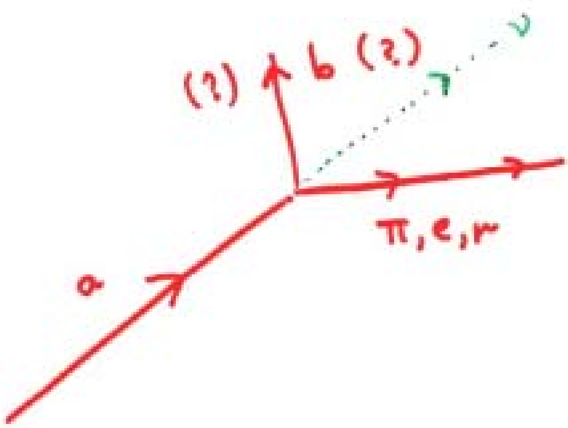
Close-Mass Fermions $\begin{pmatrix} a \\ b \end{pmatrix}_{L,R}$

$$a \Rightarrow b\,W^*, \quad W^* \rightarrow \{\pi,\ e\nu,\ \mu\nu\}$$

Degenerate†, vector like fermions split by R.C.

$\lesssim$ 1 GeV, e.g.,

$$\Delta m \simeq \frac{\alpha}{4\pi}\, m \simeq 120\ \text{MeV}\ \left(m/200\,\text{GeV}\right)$$



Signal depends somewhat on what b does — probably decaying via mixing w/ SM fields

+ would be short-lived

Recall: $\begin{pmatrix} a \\ b \end{pmatrix}$ may be quarks or leptons ...!!

$\Rightarrow$ And $Q(a) = 0$ is possible $\Rightarrow$ multiple signatures!

† Vector-like fermions are naturally degenerate avoiding STU bounds on oblique parameters

$$\Gamma(a \to b\,\pi) = \frac{G_F^2 f_\pi^2}{8\pi} \frac{(E_\pi^2 - m_\pi^2)^{1/2}}{m_a} \left\{ 2 m_a E_\pi (m_a E_\pi - m_\pi^2) - m_\pi^2 (m_a^2 - m_a E_\pi) \right\}$$

$$E_\pi \equiv \frac{m_a^2 + m_\pi^2 - m_b^2}{2 m_a}$$

$$\Gamma(a \to b e \nu) = \frac{G_F^2 m_a^5}{192\pi^3} \left\{ (1-y^2)(1-8y+y^2) - 12 y^2 \ln y \right\}$$

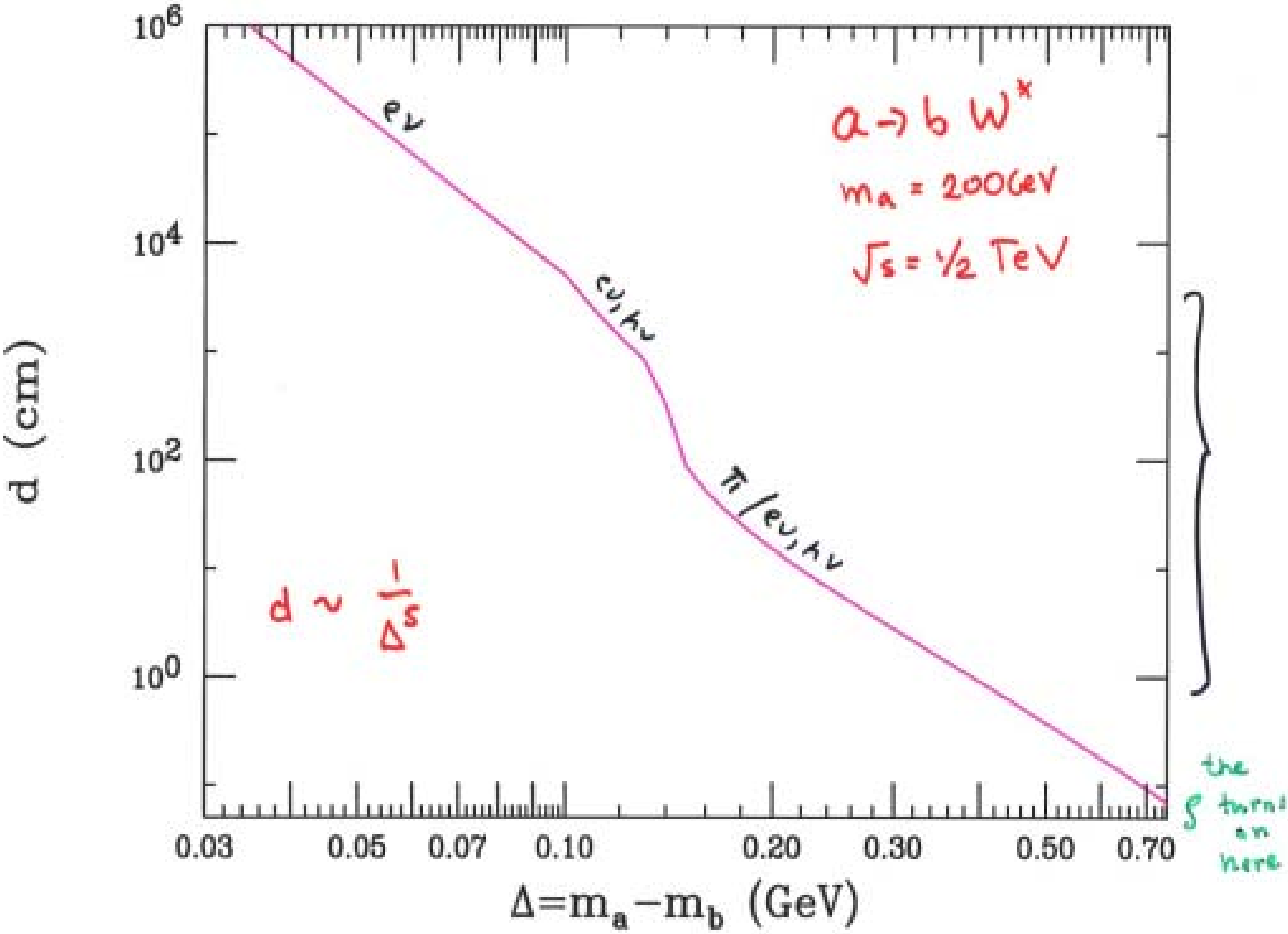
$$y \equiv m_b^2 / m_a^2$$

$(m_a - m_b \gg m_e)$

→ enormous PS suppression

leads to long lifetime !

$\Gamma(a) \gtrsim (m_a - m_b)^5$!

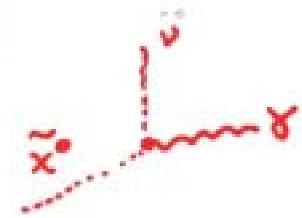


natural mass splitting range

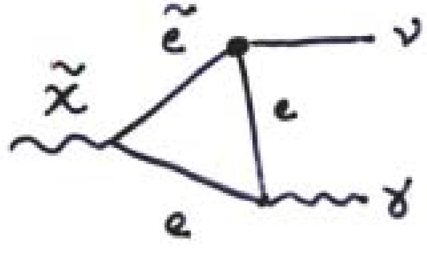
$\rightarrow$ detector decays

$\not{R}$ decay of LSP ††

$$W = \lambda L L E^c + \lambda' L Q D^c + \lambda'' U D^c D^c$$

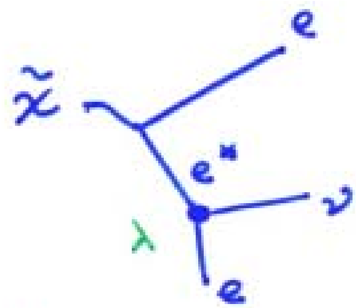


loop decay

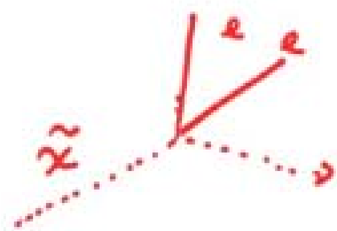


$B \gtrsim 5\text{-}10\%$
(for $\lambda, \lambda' \neq 0$)

tree level decay dominant!

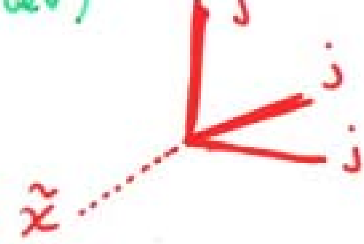


$$\Gamma \sim (\lambda^2 g^2 / m_{\tilde{x}}^4)\, m_x^5$$



$$\frac{\Gamma}{\Gamma_r} \simeq \underbrace{\left(\frac{\lambda g}{g^2/8}\right)^2 \left(\frac{M_W^2}{m_{\tilde{e}}^2}\right)^2}\ \underbrace{\left(\frac{m_x}{m_\mu}\right)^5}_{\simeq (10^4)^5}$$

$$= (\lambda/g)^2 \underbrace{\left(\frac{2\sqrt{2}\, m_W}{m_x}\right)^4}_{\simeq 1} \cdot 10^{20} \cdot \left(m_x/100\,\text{GeV}\right)^5$$



$$\simeq 10^{20} (\lambda/g)^2 (m_x/100\,\text{GeV})^5$$

interesting if $(\lambda/g) \sim 10^{-7} - 10^{-8}$

natural size ??

Possible, not likely!

†† Baltz + Gondolo hep-ph/9709445

Universal Extra Dimensions

- All SM fields in extra dimension of size $R^{-1} \gtrsim 300$ GeV [RC bound / $b \to s\gamma$ etc]

• At tree level the masses of the first KK excitations are

$$m_n^2 = m_0^2 + n^2/R^2 \qquad (n \geq 1)$$

e.g, $\left\{ \begin{array}{l} m_{1e}^2 = m_e^2 + 1/R^2 \\ m_{1\gamma}^2 = 1/R^2 \end{array} \right]$ almost degenerate!

• 1 loop radiative corrections <u>split</u> these KK levels ...

• <u>Important</u> in calculating $\Gamma(e_1 \to e_0 + \gamma_1)$

→ at tree level there is almost <u>NO PS</u>!

→ γ_1 is DM candidate + <u>stable</u> (LKP)

→ will e_1 decay in the 'bulk' of the detector?

†

$$\delta_B = -\frac{39}{2}\, \frac{g'^2}{16\pi^4}\, \frac{\zeta(3)}{R^2} - \frac{1}{6}\, m_n^2\, \frac{g'^2}{16\pi^2} \ln \Lambda^2 R^2$$

$$\delta_W = -\frac{5}{2}\, \frac{g^2}{16\pi^4}\, \frac{\zeta(3)}{R^2} + \frac{15}{2}\, m_n^2\, \frac{g^2}{16\pi^2} \ln \Lambda^2 R^2$$

$$\delta_L = m_n \left(\frac{27}{16}\, \frac{g^2}{16\pi^2} + \frac{9}{16}\, \frac{g'^2}{16\pi^2} \right) \ln \Lambda^2 R^2$$

$$\delta_e = m_n\, \frac{9}{4}\, \frac{g'^2}{16\pi^2} \ln \Lambda^2 R^2$$

note cutoff dependence

$$\begin{pmatrix} n^2/R^2 + \delta_B + m_W^2\, g'^2/g^2 & m_W^2\, g'/g \\ m_W^2\, g'/g & n^2/R^2 + \delta_W + m_W^2 \end{pmatrix}$$

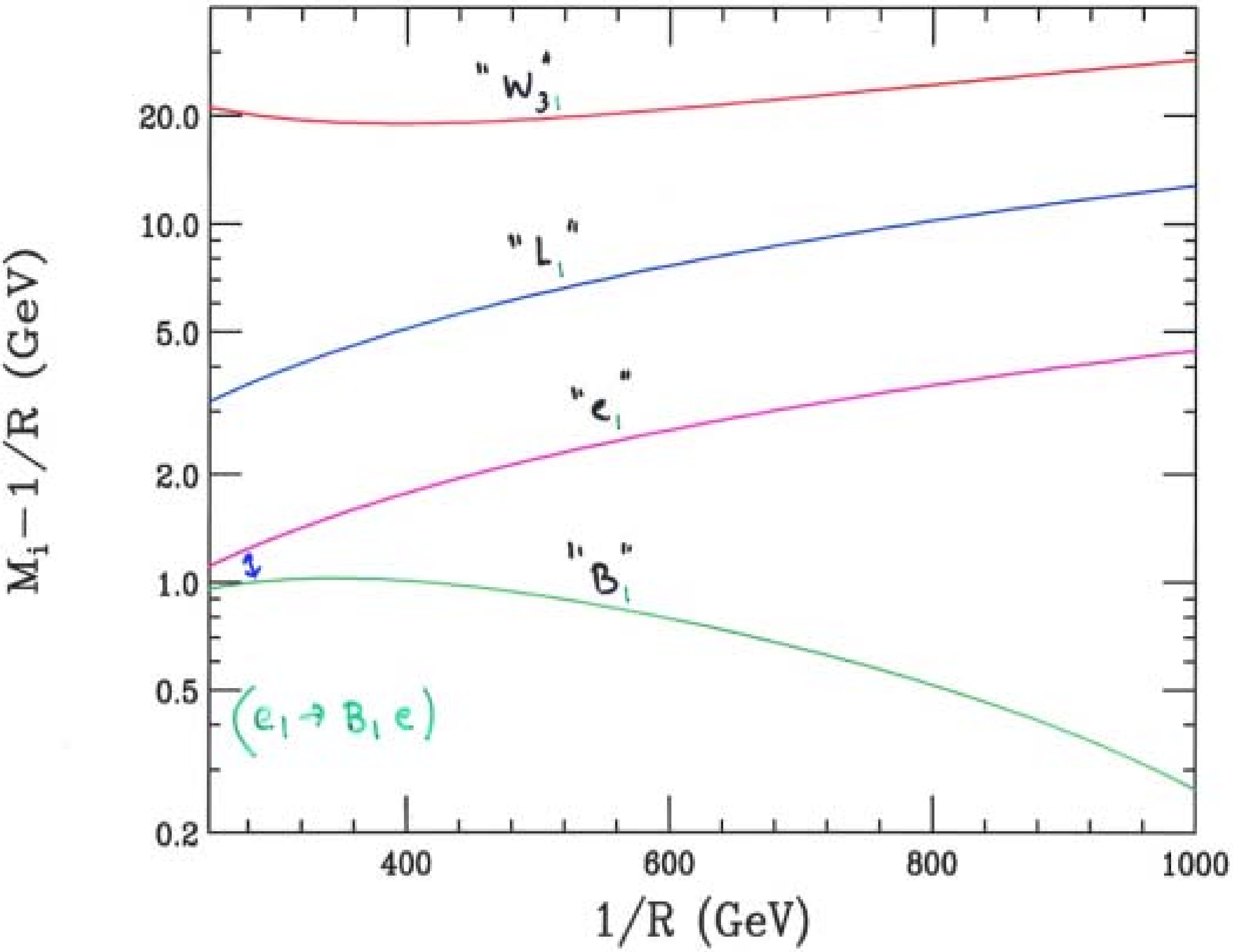
$$\begin{pmatrix} n/R + \delta_L & m_e \\ m_e & -(n/R + \delta_e) \end{pmatrix}$$

Then diagonalise mass matrices (level by level)

- These loop contributions are quite significant !

† Cheng, Matchev + Schmaltz PRD66 036005 '02

Radiative Mass Splittings UED



Inverse compactification radius

$$\Gamma(e_1 \to e_0 B_1) \simeq \frac{\alpha}{4} m_1 \cdot \epsilon \quad , \quad \begin{array}{l} \epsilon \equiv 1-\delta \\ \delta \equiv m_{B_1}^2 / m_{e_1}^2 \simeq 1 \end{array}$$

$$\simeq 750 \, \mathrm{keV} \left(\frac{m_1}{250\, \mathrm{GeV}}\right) \quad !!$$ Narrow but...

This is a <u>very</u> short lifetime for us....

* In this case the RC are BIG ENOUGH to induce splittings leading to <u>short</u> lifetimes!

No finite track length decays in this model...

<u>too bad.</u>

Just because near degeneracy exist we do not <u>necessarily</u> get a long lifetime...

Summary

- There are a wide variety of models that can lead to long-lived particles that can decay inside the detector $d \simeq 10^{-3} - 10^{0}$ m ...

- The signatures are also widely varying
  - → jets, leptons, π's ... appearing from nowhere
  - → track-kinks, γ's ... etc etc

- This is not an exhaustive survey and many other possibilities exist...

- Impact on detectors ??