Baryogenesis in a $U(1)$ Gauge Extension of the MSSM

- **Beyond the MSSM**
- **A TeV Scale $U(1)'$**
- **A (string-motivated) model**
- **Electroweak baryogenesis**

Work with Junhai Kang, Tianjun Li, Tau Liu

References

- J. Kang, P. Langacker, T. j. Li and T. Liu, Electroweak baryogenesis in a supersymmetric $U(1)'$ model, Phys. Rev. Lett. 94, 061801 (2005) [arXiv:hep-ph/0402086], and TBP.

- J. Erler, P. Langacker and T. j. Li, The Z - Z' mass hierarchy in a supersymmetric model with a secluded $U(1)'$-breaking sector, Phys. Rev. D 66, 015002 (2002) [arXiv:hep-ph/0205001].

- T. Han, P. Langacker and B. McElrath, The Higgs sector in a $U(1)'$ extension of the MSSM, Phys. Rev. D 70, 115006 (2004) [arXiv:hep-ph/0405244].

Beyond the MSSM

Even if supersymmetry holds, MSSM may not be the full story

Most of the problems of standard model remain, new ones introduced (FCNC, EDM)

μ problem introduced: $W_\mu = \mu \hat{H}_u \cdot \hat{H}_d, \quad \mu = O(\text{electroweak})$

Ingredients of 4d GUTs hard to embed in string, especially large Higgs representations, Yukawa relations

Remnants of GUT/Planck scale physics may survive to TeV scale

Specific string constructions often have extended gauge groups, exotics, extended Higgs/neutralino sectors (Defect or hint?)

Important to explore alternatives/extensions to MSSM

Remnants Physics from the Top-Down

- Z' or other gauge
- Extended Higgs/neutralino (doublet, singlet)
- Quasi-Chiral Exotics
- Non-standard ν mass (enhanced symmetries)
- Quasi-hidden (Strong coupling? SUSY breaking? Composite family?)
- Charge $1/2$ (Confinement?, Stable relic?)
- Time varying couplings
- LED (TeV black holes, stringy resonances)
- CPTV, LIV, VEP (speed, decays, (oscillations) HE γ, e, gravity wave, (ν))

A TeV-Scale Z'

- Strings, GUTs, DSB, little Higgs, LED often involve extra Z'
- Typically $M_{Z'} > 600 - 900$ GeV (Tevatron, LEP 2, WNC); $|\theta_{Z-Z'}| < \text{few} \times 10^{-3}$ (Z-pole)
  (CDF di-electron: 850 (Z_{seq}), 740 (Z_χ), 725 (Z_ψ), 745 (Z_η))
- Discovery to $M_{Z'} \sim 5 - 8$ TeV at LHC, ILC, $(pp \to \mu^+\mu^-, e^+e^-, q\bar{q})$ (depends on couplings, exotics, sparticles)
- Diagnostics to 1-2 TeV (asymmetries, y distributions, associated production, rare decays)

Implications of a TeV-scale $U(1)'$

- **Natural Solution to μ problem** $W \sim hSH_uH_d \rightarrow \mu_{eff} = h\langle S\rangle$
  ("stringy version" of NMSSM)

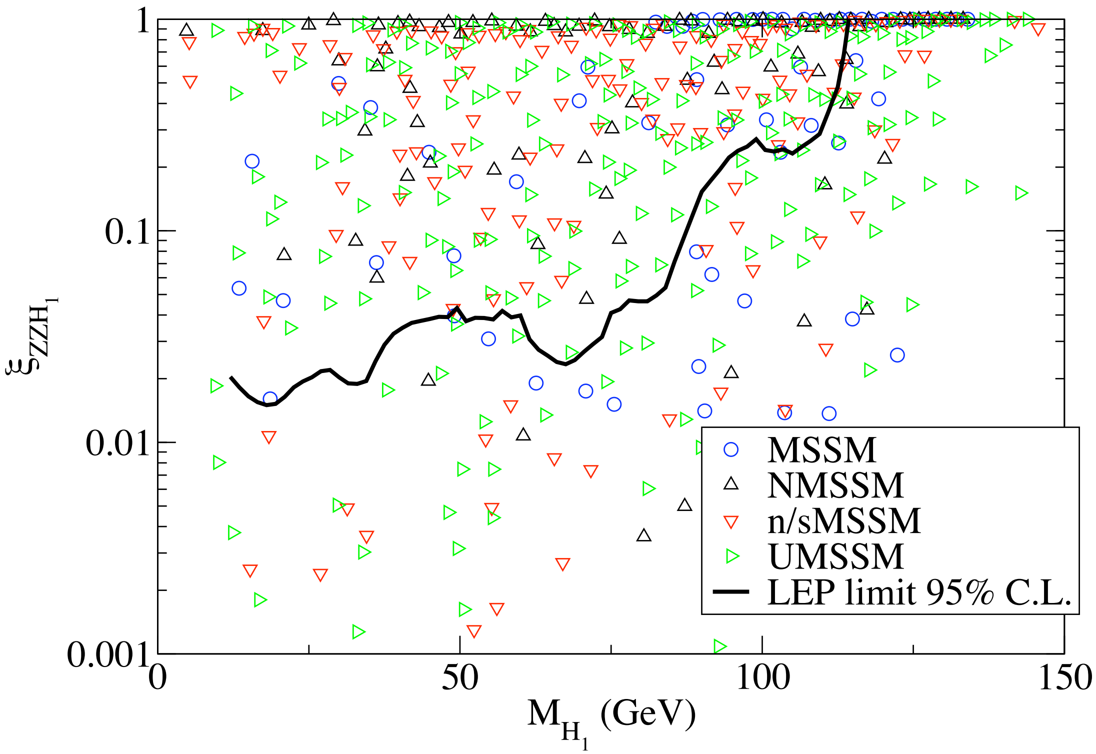
- **Extended Higgs sector**
  - Relaxed upper limits, couplings, parameter ranges (e.g., $\tan\beta$ can be close to 1)
  - Higgs singlets needed to break $U(1)'$
  - Doublet-singlet mixing $\longrightarrow$ highly non-standard collider signatures

- **Large A term and possible tree-level CP violation** (no new EDM constraints) $\longrightarrow$ **electroweak baryogenesis**

- Extended neutralino sector
  - Additional neutralinos, non-standard couplings, e.g., light singlino-dominated, extended cascades
  - Enhanced possibilities for cold dark matter, $g_\mu - 2$ (small $\tan\beta$)
- Exotics (anomaly-cancellation)
  - Decay by mixing; diquark or leptoquark coupling; or quasi-stable
- Constraints on neutrino mass generation
- Z' decays into sparticles/exotics
- Flavor changing neutral currents (for non-universal $U(1)'$ charges)
  - Tree-level effects in B decay competing with SM/MSSM loops
- Z' mediation of supersymmetry breaking (PL, G. Paz, L. T. Wang, I. Yavin, 0710.1632.)

- **Experimental LEP SM and MSSM bounds may be relaxed by singlet-doublet mixing** (also by nonstandard decays)

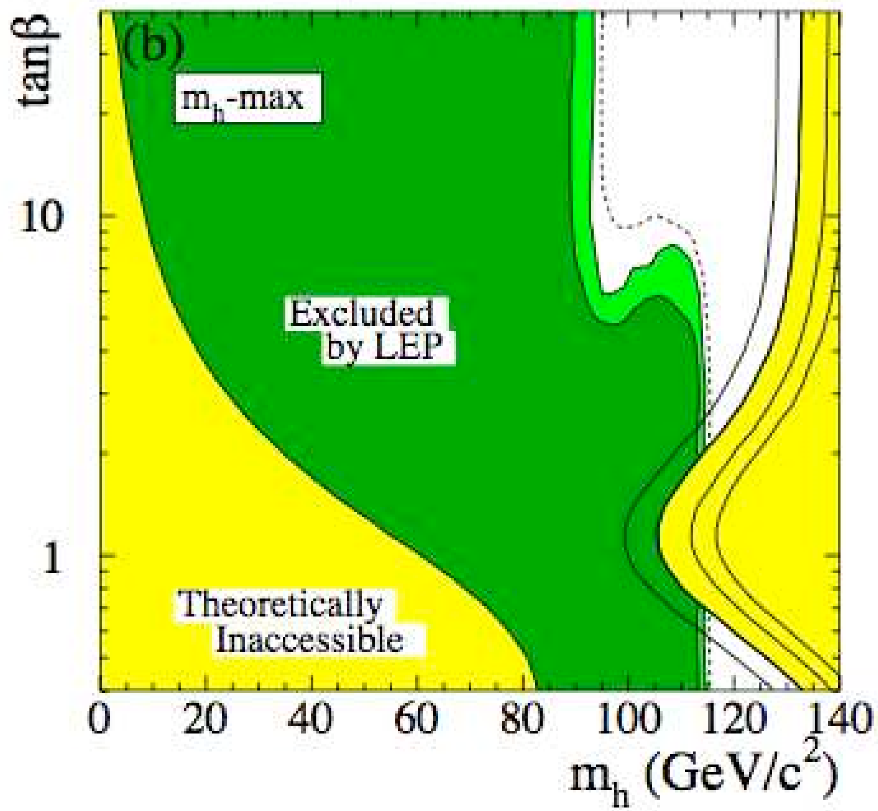
- **Theoretical upper bound ~ 135 GeV relaxed by F and D terms**

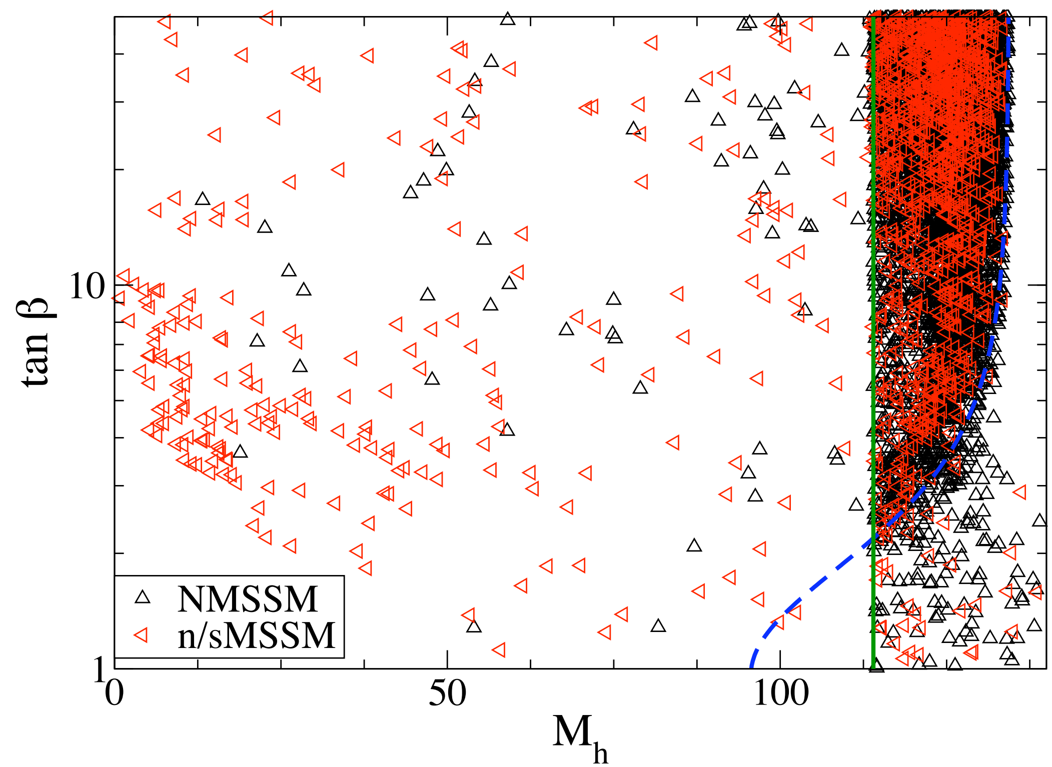


- **Reduced ZZH_i coupling**

$$\xi_{ZZH_i} = (R_+^{i1}\cos\beta + R_+^{i2}\sin\beta)^2$$

- **Also, $Z \to HA$, Z width, $\chi^\pm$ mass, $Z - Z'$ mixing, V minimum, RGE**


tanβ
(b)
m_h-max
Excluded by LEP
Theoretically Inaccessible
10
1
0
20
40
60
80
100
120
140
m_h (GeV/c^2)


tan β
10
1
0
50
100
M_h
NMSSM
n/sMSSM

SUSY-breaking scale models (Demir et al)

- $M_{Z'} \sim M_Z$, leptophobic
- $M_{Z'} \gtrsim 10 M_Z$ by modest tuning

$$\textbf{Superpotential}: \quad W = hSH_uH_d$$

$$\textbf{Potential}: \quad V = V_F + V_D + V_{soft}$$

$$\begin{aligned}
V_F &= h^2\left(|H_d|^2|H_u|^2 + |S|^2|H_d|^2 + |S|^2|H_u|^2\right) \\
V_D &= \frac{G^2}{8}\left(|H_u|^2 - |H_d|^2\right)^2 \\
&+ \frac{g_{Z'}^2}{2}\left(Q_S|S|^2 + Q_{H_d}|H_d|^2 + Q_{H_u}|H_u|^2\right)^2 \\
V_{soft} &= m_{H_d}^2|H_d|^2 + m_{H_u}^2|H_u|^2 + m_S^2|S|^2 - (A_h hSH_uH_d + \text{H.C.})
\end{aligned}$$

where $G^2 = g_1^2 + g_2^2$, $\quad M_{Z'} \sim \sqrt{2} g_{Z'} Q_s \langle S \rangle$

- A_h term can give strong first order EWPT, but no tree-level CP violation in Higgs sector

Flat directions

- Two SM singlets charged under $U(1)'$. If no F terms,

$$V(S_1, S_2) = m_1^2|S_1^2| + m_2^2|S_2^2| + \frac{g'^2 Q'^2}{2}(|S_1^2| - |S_2^2|)^2$$

  Break at EW scale for $m_1^2 + m_2^2 > 0$, at intermediate scale for $m_1^2 + m_2^2 < 0$ (stabilized by loops or HDO)

- Small Dirac neutrino (or other fermion) masses from

$$W \sim \hat{H}_u \hat{L}_L \hat{\nu}_L^c \left(\frac{\hat{S}}{\mathcal{M}}\right)^{P_D}$$

- Secluded sector: lift F-flatness by small (~ 0.05) singlet Yukawa

Secluded sector models (Erler, PL, Li)

- Approximately flat direction, broken by small (~ 0.05) Yukawa
- Z' breaking decoupled from effective μ term
- Four SM singlets: $S, S_{1,2,3}$, doublets $H_{1,2}$
- Off-diagonal Yukawas
- Can be consistent with minimal gauge unification

Superpotential : $W = hSH_uH_d + \lambda S_1S_2S_3$

Potential : $V = V_F + V_D + V_{soft}$

$$
\begin{aligned}
V_F &= h^2\left(|H_d|^2|H_u|^2 + |S|^2|H_d|^2 + |S|^2|H_u|^2\right) \\
&+ \lambda^2\left(|S_1|^2|S_2|^2 + |S_2|^2|S_3|^2 + |S_3|^2|S_1|^2\right)
\end{aligned}
$$

$$
\begin{aligned}
V_D &= \frac{G^2}{8}\left(|H_u|^2 - |H_d|^2\right)^2 \\
&+ \frac{1}{2}g_{Z'}^2\left(Q_S|S|^2 + Q_{H_d}|H_d|^2 + Q_{H_u}|H_u|^2 + \sum_{i=1}^{3} Q_{S_i}|S_i|^2\right)^2
\end{aligned}
$$

where $G^2 = g_1^2 + g_2^2$,

$$
\begin{aligned}
V_{soft} &= m^2_{H_d}|H_d|^2 + m^2_{H_u}|H_u|^2 + m^2_S|S|^2 + \sum_{i=1}^{3} m^2_{S_i}|S_i|^2 \\
&- (A_h h S H_u H_d + A_\lambda \lambda S_1 S_2 S_3 + \text{H.C.}) \\
&- (m^2_{SS_1} S S_1 + m^2_{SS_2} S S_2 + m^2_{S_1 S_2} S_1^\dagger S_2 + \text{H.C.})
\end{aligned}
$$

- $\langle S_i \rangle \sim m_{S_i}/\lambda$ large for small λ, along $D(U(1)') \sim 0$
- Smaller $\langle S \rangle$, $\langle H_i \rangle$, dominated by hA_h: $\tan\beta \sim 1, \langle S \rangle \sim \langle H_i \rangle$
- Large doublet-singlet mixing
- Two sectors nearly decoupled
- Mixed soft terms break two global symmetries (constrains charges)
- Tree-level CP breaking in S, S_i sector in general (Important for baryogenesis; little effect on EDMs)

Electroweak Baryogenesis

(J. Kang, PL, T. Li, T. Liu)

- Secluded model implemented in anomaly-free E_6-type $U(1)'$ model, consistent with gauge unification

$$E_6 \rightarrow SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi \qquad (1)$$

$$Q' = \cos\theta \, Q_\chi + \sin\theta \, Q_\psi, \qquad \tan\theta = \frac{\sqrt{15}}{9} \qquad (2)$$

$$(S_{1,2} \rightarrow S^*, \, S_3 \rightarrow \bar{N}^*)$$

- $U(1)'$ charges of all quarks, leptons, Higgs, exotics specified

$SO(10)$	$SU(5)$	$2\sqrt{10}Q_\chi$	$2\sqrt{6}Q_\psi$	$2\sqrt{15}Q'$
16	$10\ (u, d, \bar{u}, \bar{e})$	–1	1	$-1/2$
	$\bar{5}\ (\bar{d}, \nu, e)$	3	1	4
	$1\bar{N}$	–5	1	–5
10	$5\ (D, H'_u)$	2	–2	1
	$\bar{5}\ (\bar{D}, H'_d)$	–2	–2	$-7/2$
1	$1\ S_L$	0	4	$5/2$

Decomposition of the E_6 fundamental 27 representation under $SO(10)$, $SU(5)$, and the $U(1)_\chi$, $U(1)_\psi$ and $U(1)'$ charges.

h	A_h	λ	A_λ	$m^2_{SS_1}$	$m^2_{SS_2}$	$m^2_{S_1S_2}$	$m^2_{H_u^0}$
0.8	4	0.06	3.1	0.02	0.1	5.6D-4	2 / 4 / 6
$m^2_{H_d^0}$	m^2_S	$m^2_{S_1}$	$m^2_{S_2}$	$m^2_{S_3}$	M'_1	M_1	M_2
-0.5	0.5	0.03	0.03	-0.01	6.4	6.4	6.4

Three sets of typical parameter values (a,b,c). The energy units are 65 GeV, 80 GeV and 93 GeV, corresponding to $m^2_{H_u^0} = 2$, 4 and 6, respectively.

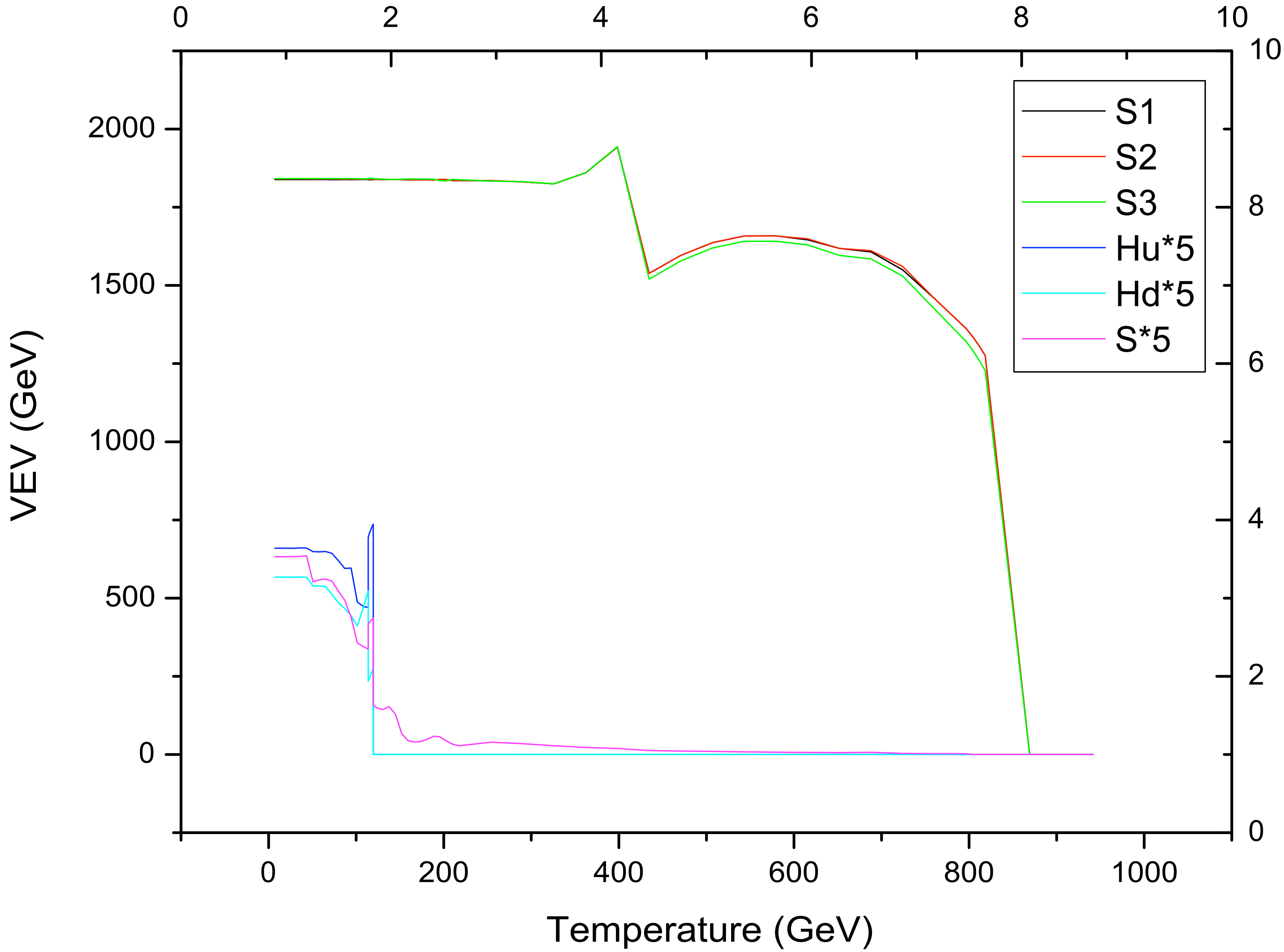
The Electroweak Phase Transition

- Effective potential at finite T

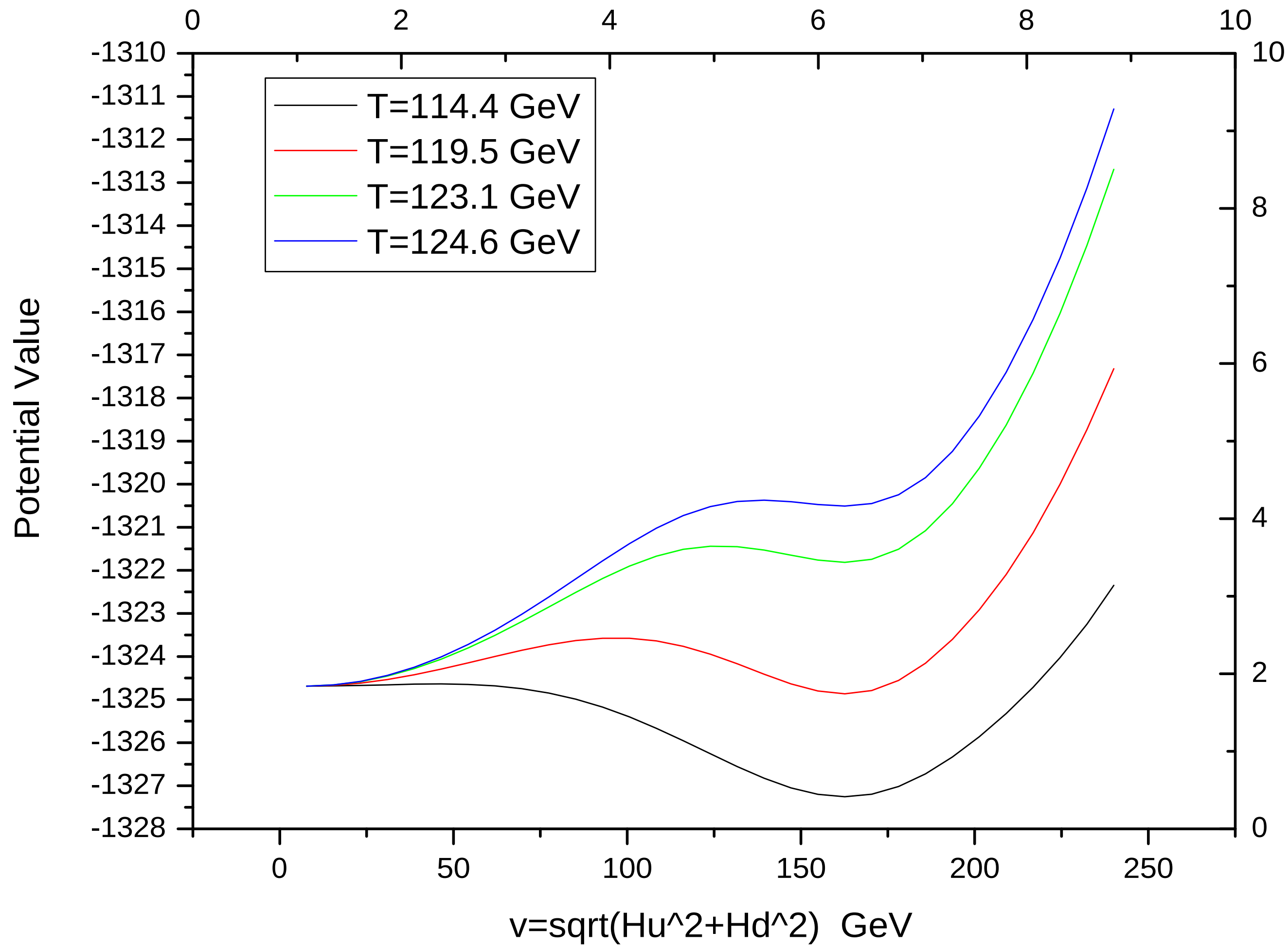
$$V_{\text{eff}}(\phi, T) = V_0(\phi) + V_1(\phi, 0) + \Delta V_1(\phi, T) + \Delta V_{\text{daisy}}(\phi, T)$$

- Assume no charge/color breaking$\longrightarrow$ 10 physical variables
  (complex VEVs of $H^0_{1,2}$, S, $S_{1,2,3}$ minus 2 gauge dof)

- $M_{Z'} \sim 1$ TeV $\gg M_Z \Rightarrow$
  - $S_{1,2,3}$ VEVs $\gg$ those of $H_{1,2}, S$
  - First phase transition breaks $U(1)'$, second breaks $SU(2)\times U(1)$
  - Magnitude of S VEV changes during $SU(2)\times U(1)$ transition, inducing phase changes



The Higgs VEVs versus temperature. The VEVs of $H^0_{u,d}$ and S are multiplied by 5.



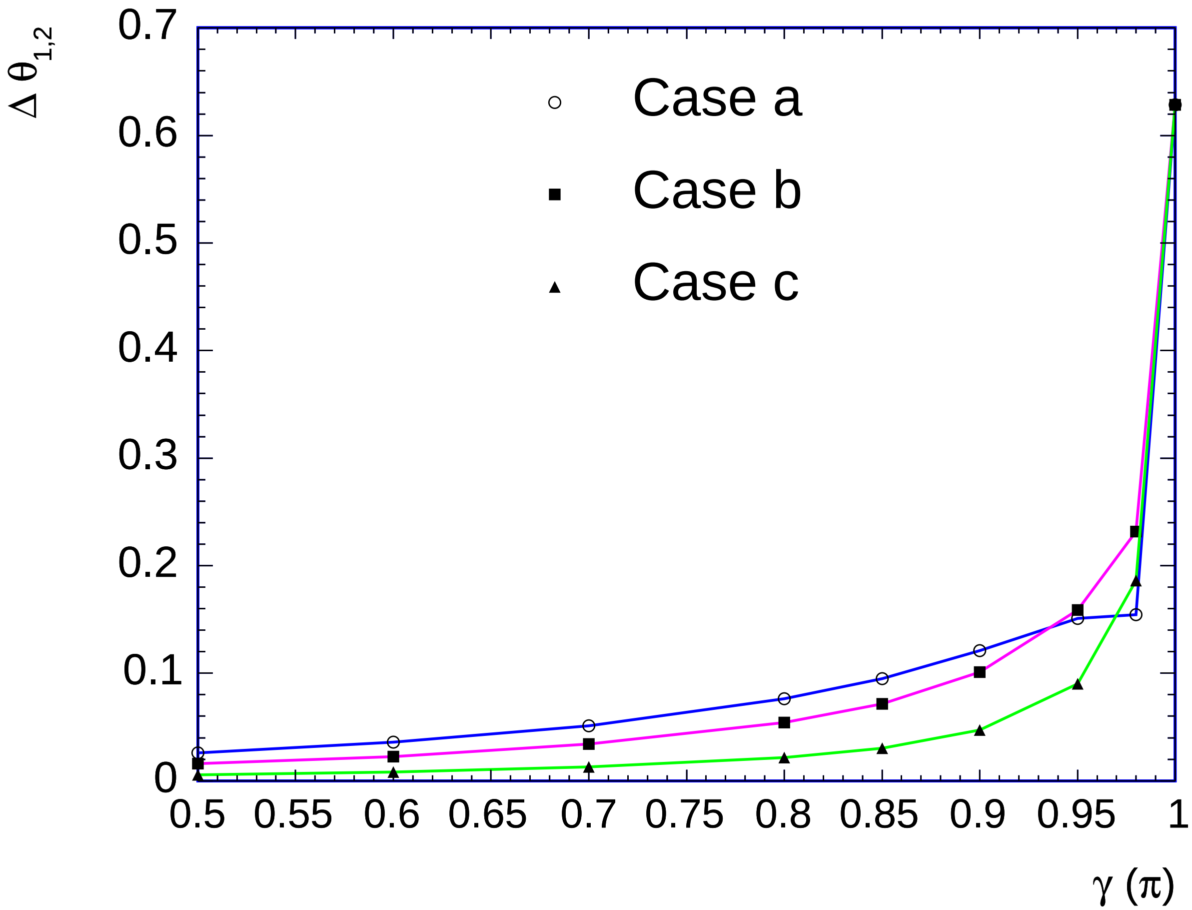
- **Can obtain strong first order transition, even with large $\tilde{t}$ masses, e.g., $v(T_c)/T_c = 1.3$ with $T_c = 120$ GeV**

Tree-Level CP Violation in Higgs Sector

- 6 neutral Higgs, 4 gauge invariant phases $\longrightarrow$ can choose $A_h h, A_\lambda \lambda, m^2_{SS_1}, m^2_{SS_2}$ real and positive, and $m^2_{S_1S_2} = |m^2_{S_1S_2}|e^{i\gamma}$

$$\begin{aligned} V^H_{soft} \;=\; & m^2_{H_d^0}|H_d^0|^2 + m^2_{H_u^0}|H_u^0|^2 + m^2_S|S|^2 + \sum_{i=1}^{3} m^2_{S_i}|S_i|^2 \\ & -2A_h h|S||H_d^0||H_u^0|\cos\beta_3 - 2A_\lambda\lambda|S_1||S_2||S_3|\cos\beta_4 \\ & -2m^2_{SS_1}|S||S_1|\cos\beta_1 - 2m^2_{SS_2}|S||S_2|\cos\beta_2 \\ & -2|m^2_{S_1S_2}||S_1||S_2|\cos(-\beta_1+\beta_2+\gamma) \end{aligned}$$

- Tree-level: minimum for $\beta_{3,4} = 0$, $\beta_{1,2} \neq 0$
- EWPT: $S_i \sim$ constant, $H^0_{u,d}$ change $\longrightarrow$ S changes $\longrightarrow$ $\beta_{1,2}$ change



Change in phases of $H^0_{u,d}$

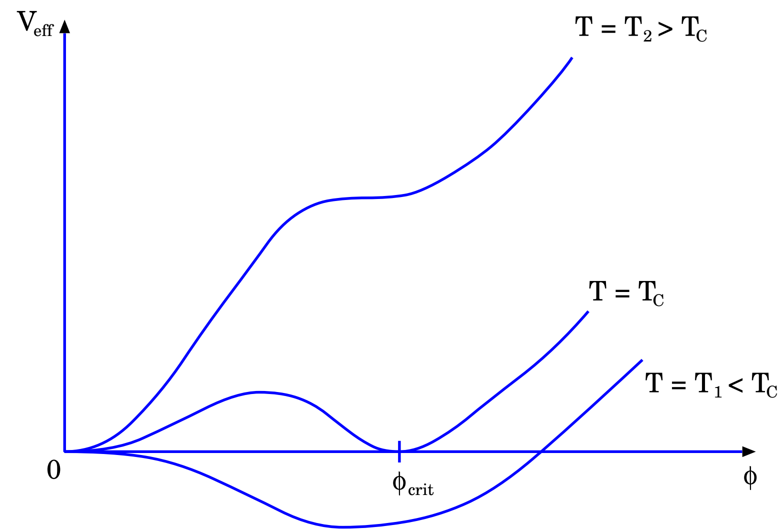
- **New contributions to quark, electron, atomic EDMs negligible** (need 3 Yukawas and 3 soft mass-squares)

Electroweak baryogenesis

Utilize the electroweak (B-violating) tunneling to *generate* the asymmetry at time of electroweak phase transition (Kuzmin, Rubakov, Shaposhnikov)

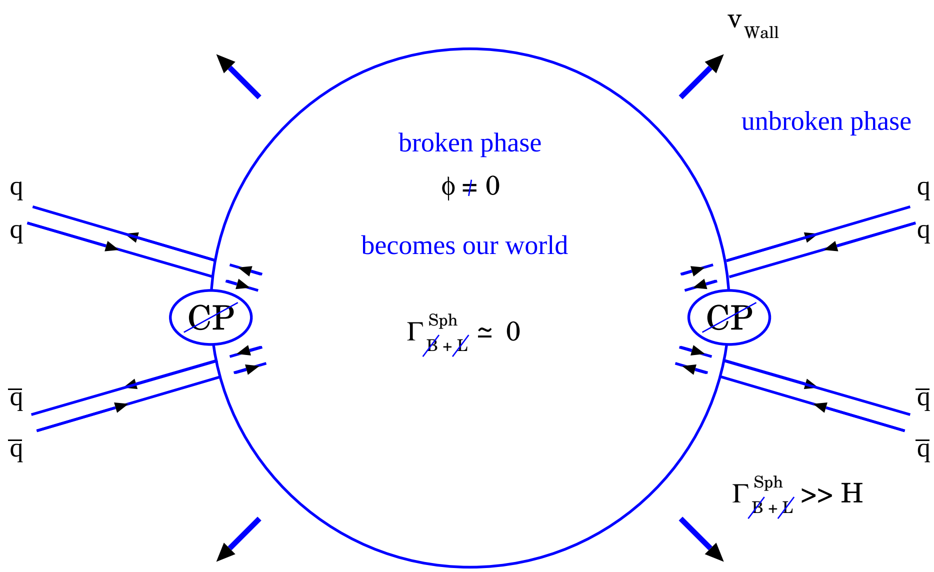
Off the wall scenario (Cohen, Kaplan, Nelson)

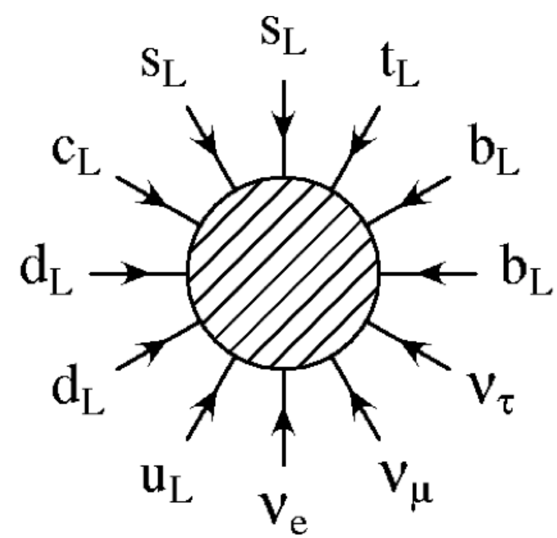
- Strong first order phase transition from electroweak symmetry unbroken (massless W, Z, fermions) to broken phase (massive W, Z, fermions) proceeds by nucleation and expansion of bubbles



(Figures: W. Bernreuther, hep-ph/0205279)

- **CP violation by asymmetric reflection of quarks and leptons (or squarks/charginos/neutralinos) from the wall**
- **Electroweak B violation in unbroken phase outside wall**
- **Scenario requires strong first order transition, $v(T_c)/T_c \gtrsim 1-1.3$ and adequate CP violation in expanding bubble wall**

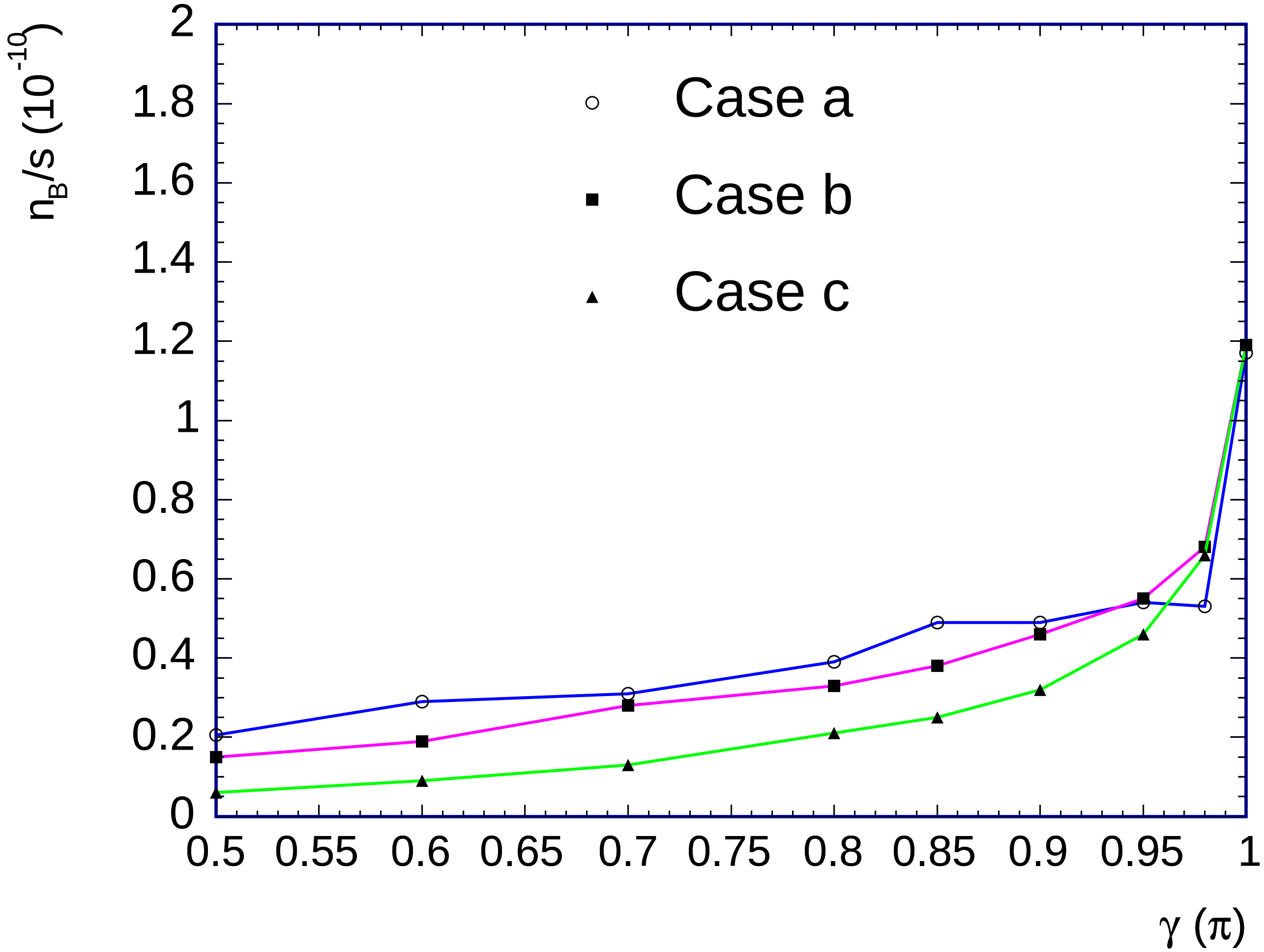




- For τ lepton use thin wall approximation (justified)

- For reasonable parameters, can obtain adequate asymmetry, even for large $\tilde{t}$ mass, from τ alone

$$\frac{n_B}{s} = 540\gamma^3(\langle v_{\tau_L}\rangle + v_w)\frac{D_{\tau_L} m_\tau(\infty)^2 \delta \Delta\theta_1 h(\delta, T_c)\Gamma_{ws}}{(2\pi)^4 v_w g_* T_c^3}$$



γ = explicit CP phase; $v_w = 0.02$, $m_\tau = 10^{-2}T_c$. Exp: $n_B/s \sim 0.9\times10^{-10}$.

- **Under investigation**
  - **Contributions from squarks/neutralinos/charginos** (may be large but very sensitive to spectrum)
  - **Full spectrum with all experimental constraints**
  - **Cold Dark Matter** (light singlino-Higgsino LSP)
  - **First ($U(1)'$) transition** (gravity waves?)

Conclusions

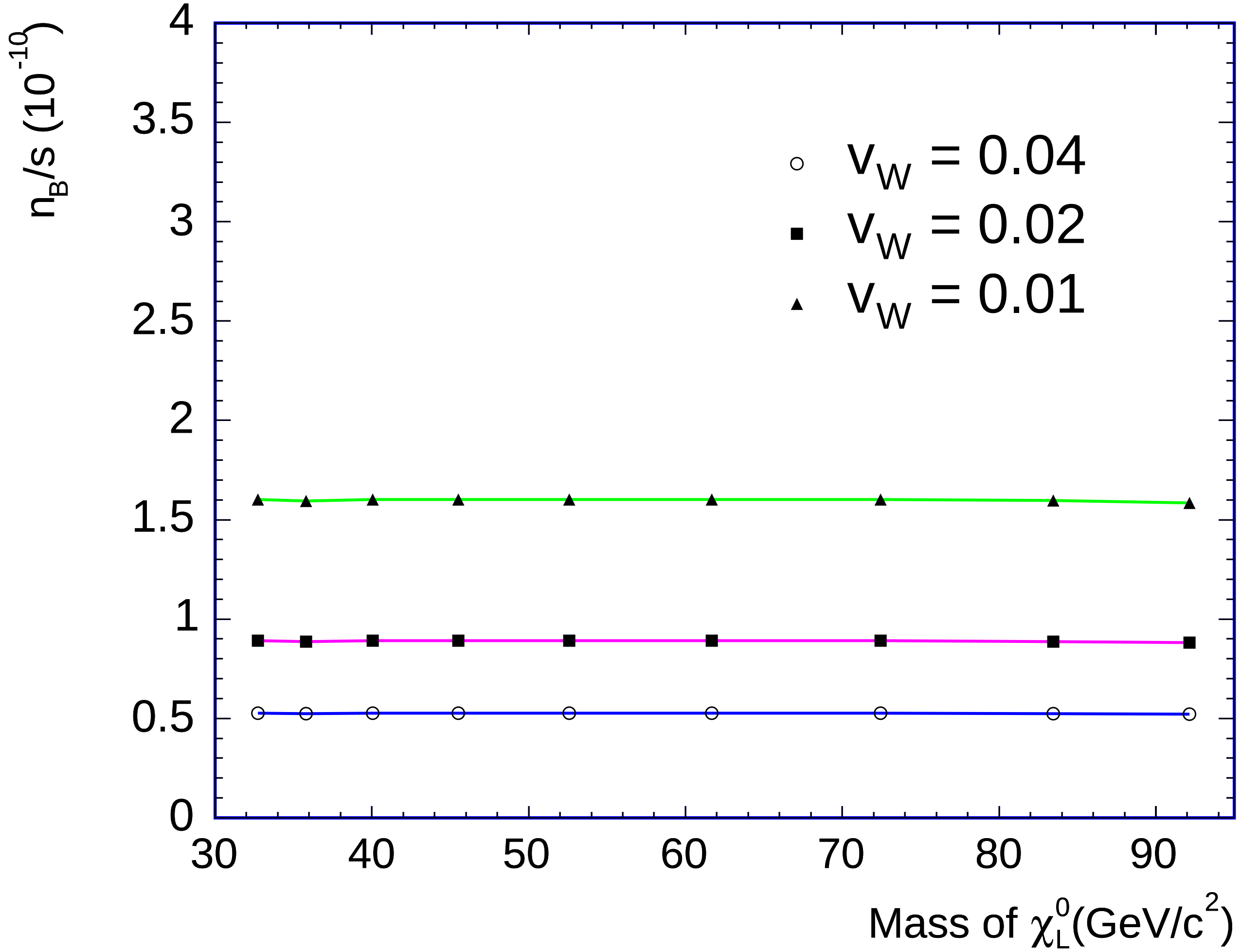
- Important to explore alternatives to MSSM

- Top-down string constructions very often contain extra Z' and SM singlets S

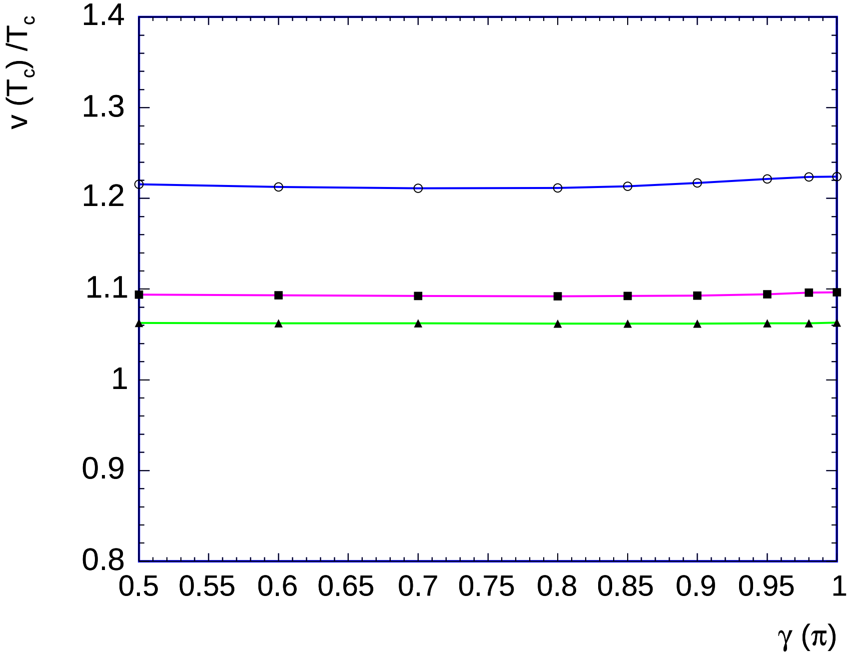
- Elegant solution to μ problem (string-motivated version of NMSSM)

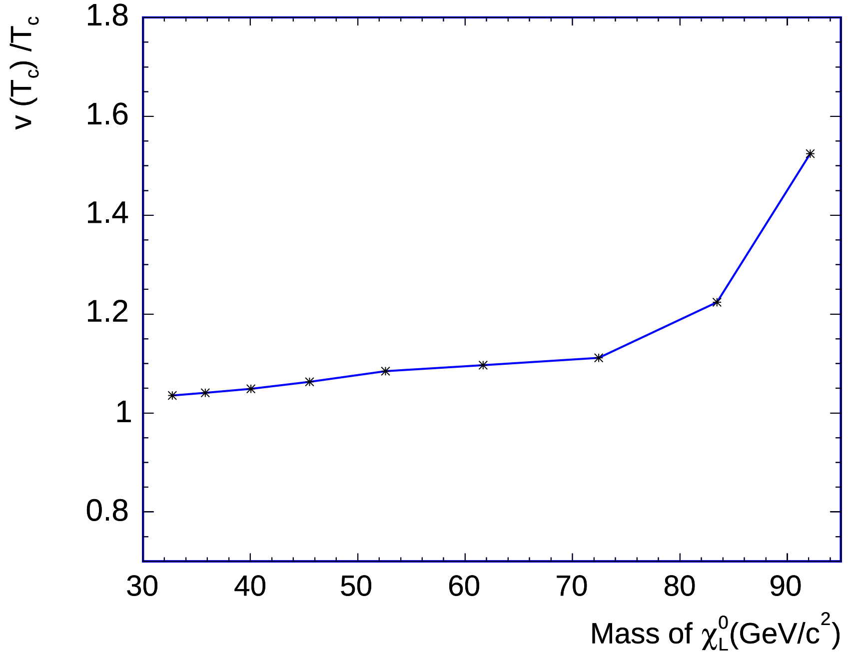
- Many implications, including nonstandard Higgs spectrum/couplings, CDM, $g_\mu - 2$, efficient EW baryogenesis, $B_s - \bar{B}_s$ mixing, rare B decays, neutrino masses

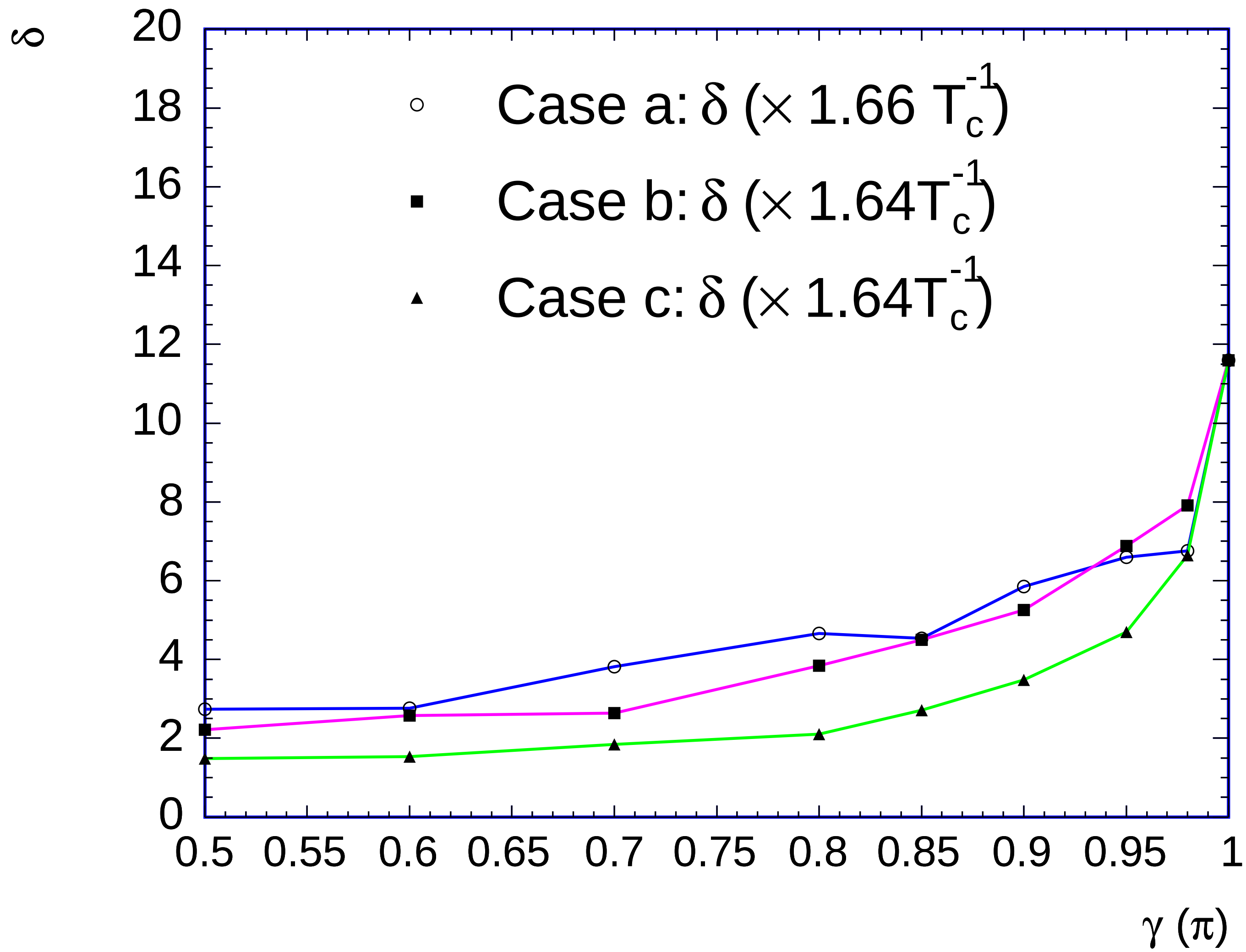
- But, must observe Z'



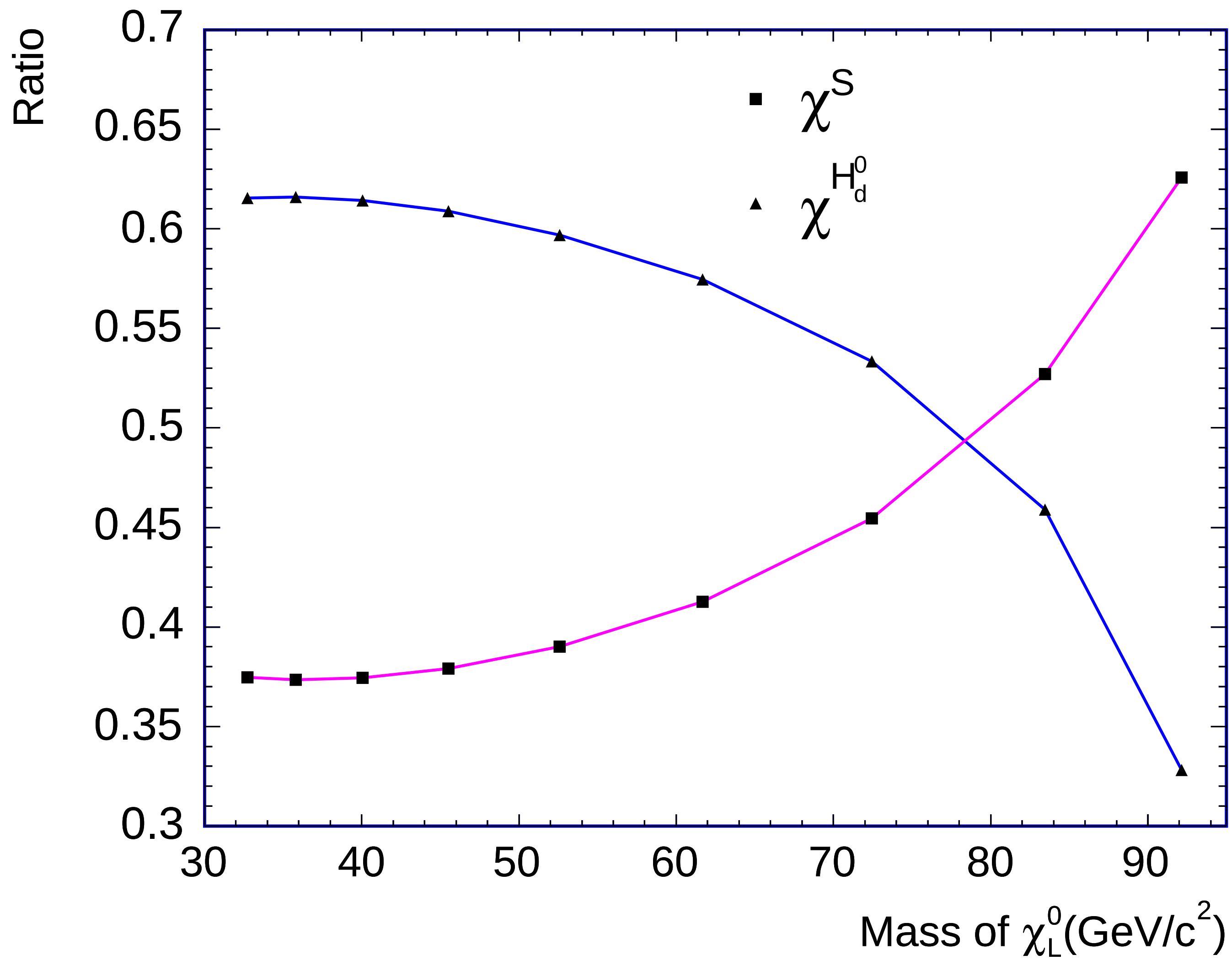
$\chi_L^0 =$ **LSP. Exp:** $n_B/s \sim 0.9 \times 10^{-10}$.


v (T_c) /T_c
1.4
1.3
1.2
1.1
1
0.9
0.8
0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95 1
γ (π)

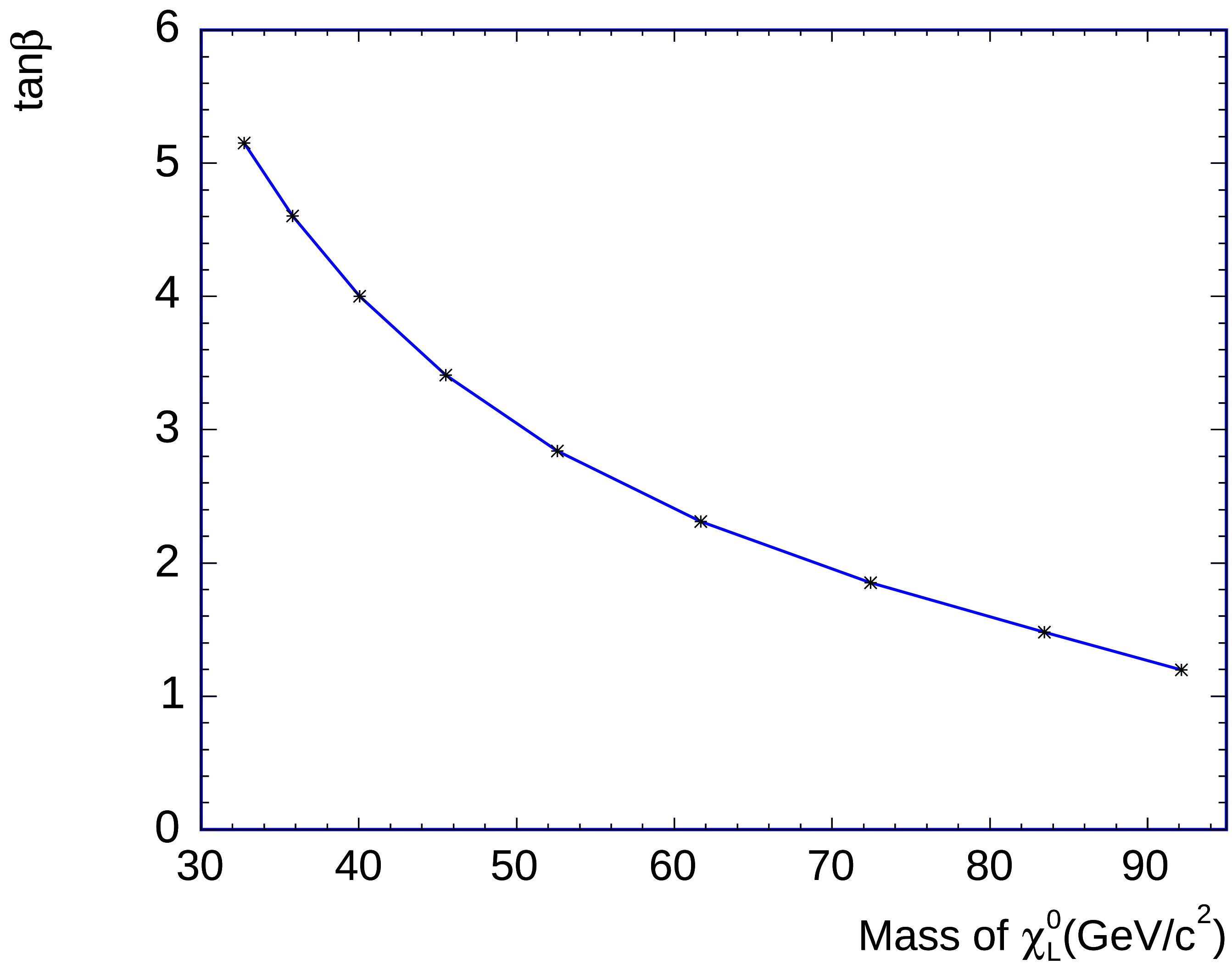

v (T_c) /T_c
1.8
1.6
1.4
1.2
1
0.8
30 40 50 60 70 80 90
Mass of χ_L^0(GeV/c^2)



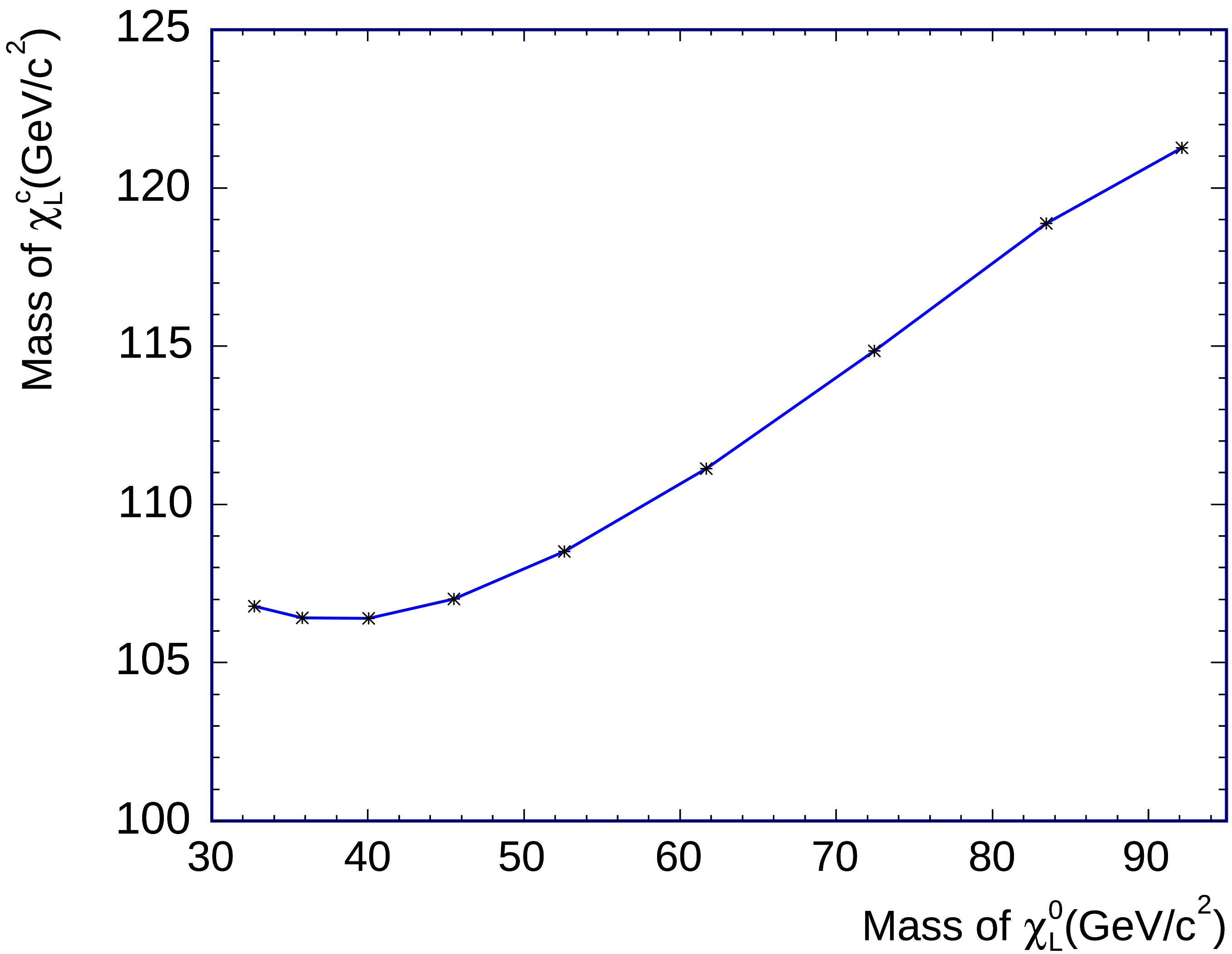
Wall thickness δ



Composition of LSP



$$\tan\beta = \langle H_u^0 \rangle / \langle H_d^0 \rangle$$



Lightest chargino mass