Implications of a Heavy Z' Gauge Boson

- Motivations
- Constraints, prospects, diagnostics
- A (string-motivated) model
- Non-standard Higgs sector
- Electroweak baryogenesis
- FCNC and rare B decays
- Neutrino masses

Motivations

- **Strings, GUTs, DSB, little Higgs often involve extra $U(1)'$** (GUTs require extra fine tuning for $M_{Z'} \ll M_{\rm GUT}$)

- **String models**
  - **Extra $U(1)'$ and SM singlets extremely common**
  - **Radiative breaking of electroweak (SUGRA or gauge mediated) often yield EW/TeV scale Z'** (unless breaking along flat direction $\longrightarrow$ intermediate scale)
  - **Breaking due to negative mass^2 for scalar S (driven by large Yukawa) or by A term**

- **Solution to μ problem (string-motivated extension of NMSSM)**

$$W \sim hSH_uH_d,$$

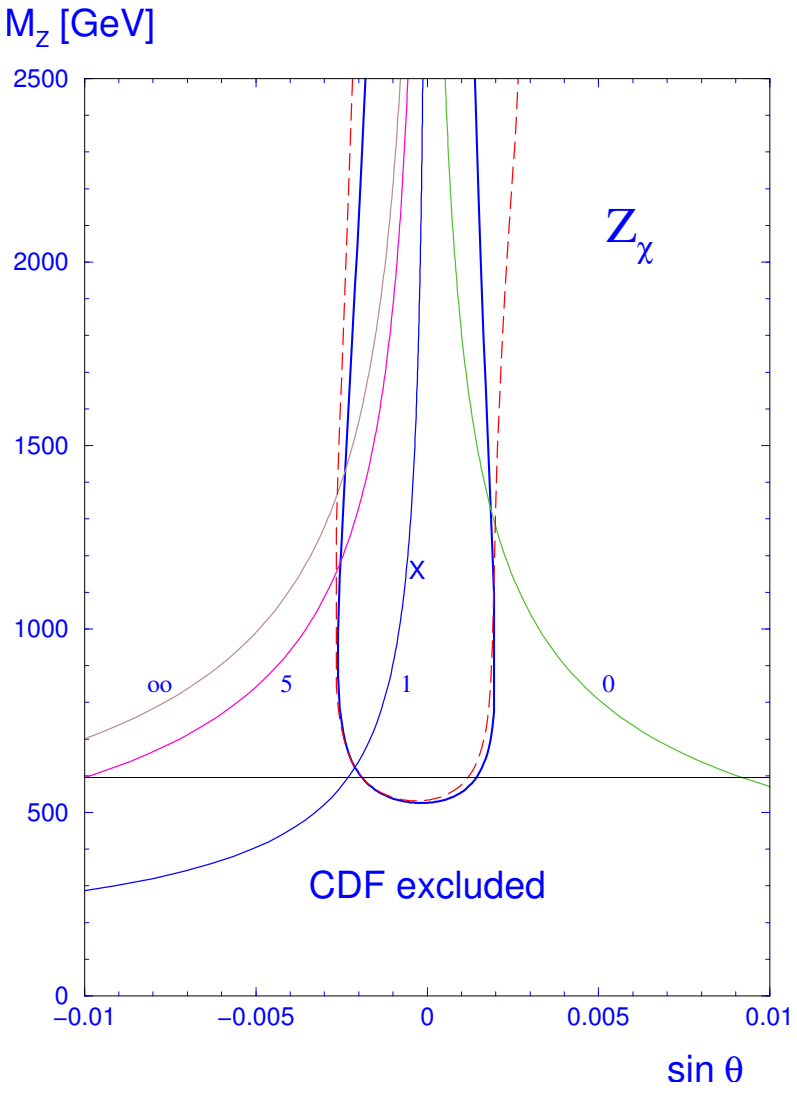
  - $U(1)'$ may forbid elementary μ or term in Kähler
  - S = standard model singlet, charged under $U(1)'$
  - $\langle S \rangle$ breaks $U(1)'$, $\mu_{eff} = h\langle S \rangle$
  - Like NMSSM, but no domain walls
  - Singlets don't have $W \sim \kappa S^3$ (needed in NMSSM) in constructions studied
  - SM-singlets usually have $U(1)'$ charges in constructions studied

Experiment

- Typically $M_{Z'} > 500 - 800$ GeV (Tevatron, LEP 2, WNC), $|\theta_{Z-Z'}| < \text{few} \times 10^{-3}$ (Z-pole)
  (PL, Jens Erler)

- Discovery to $M_{Z'} \sim 5-8$ TeV at LHC, LC

- Diagnostics to 1-2 TeV (asymmetries, y distributions, associated production, rare decays)



Models

- **SUSY-breaking scale models** (Demir et al)
  - $M_{Z'} \sim M_Z$, leptophobic
  - $M_{Z'} \gtrsim 10 M_Z$ by modest tuning
- **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 (string-motivated)
  - Can be consistent with minimal gauge unification

Superpotential : $W = hSH_1H_2 + \lambda S_1S_2S_3$

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

$$\begin{aligned} V_F &= h^2\left(|H_1|^2|H_2|^2 + |S|^2|H_1|^2 + |S|^2|H_2|^2\right) \\ &+ \lambda^2\left(|S_1|^2|S_2|^2 + |S_2|^2|S_3|^2 + |S_3|^2|S_1|^2\right) \end{aligned}$$

$$\begin{aligned} V_D &= \frac{G^2}{8}\left(|H_2|^2 - |H_1|^2\right)^2 \\ &+ \frac{1}{2}g_{Z'}^2\left(Q_S|S|^2 + Q_{H_1}|H_1|^2 + Q_{H_2}|H_2|^2 + \sum_{i=1}^{3} Q_{S_i}|S_i|^2\right)^2 \end{aligned}$$

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

$$
\begin{aligned}
V_{soft} &= m_{H_1}^2|H_1|^2 + m_{H_2}^2|H_2|^2 + m_S^2|S|^2 + \sum_{i=1}^{3} m_{S_i}^2|S_i|^2 \\
&- (A_h h S H_1 H_2 + A_\lambda \lambda S_1 S_2 S_3 + \text{H.C.}) \\
&+ (m_{SS_1}^2 S S_1 + m_{SS_2}^2 S S_2 + m_{S_1S_2}^2 S_1^\dagger S_2 + \text{H.C.})
\end{aligned}
$$

- $\langle S_i \rangle \sim m_{S_i}/\lambda$ large for small λ
- Breaking along $D(U(1)') \sim 0$
- Smaller $\langle S \rangle$, $\langle H_i \rangle$, dominated by $hA_h \rightarrow \tan\beta \sim 1, \langle S \rangle \sim \langle H_i \rangle$
- Large doublet-singlet mixing
- Two sectors nearly decoupled
- Tree-level CP breaking in S, S_i sector in general

Implications of $U(1)'$

- Solution to μ problem
- CP phase correlations possible (Demir, Everett)
- Exotics; needed for anomaly cancellation (can be consistent with gauge unification)
- Non-standard sparticle spectrum
- Neutrino implications: Dirac, natural ν_R decoupling, TeV seesaw
- Dirac neutrinos and BBN (Barger, PL, Lee)

- **Non-standard Higgs masses, couplings (doublet-singlet mixing)** **(Han, PL, McElrath)**
- **Enhanced possibility of EW baryogenesis** **(Kang, Liu, PL, Li)**
- **FCNC (especially in string models)** **(PL, Plümacher)**; **rare B decays** **(Barger, Chiang, PL, LI)**

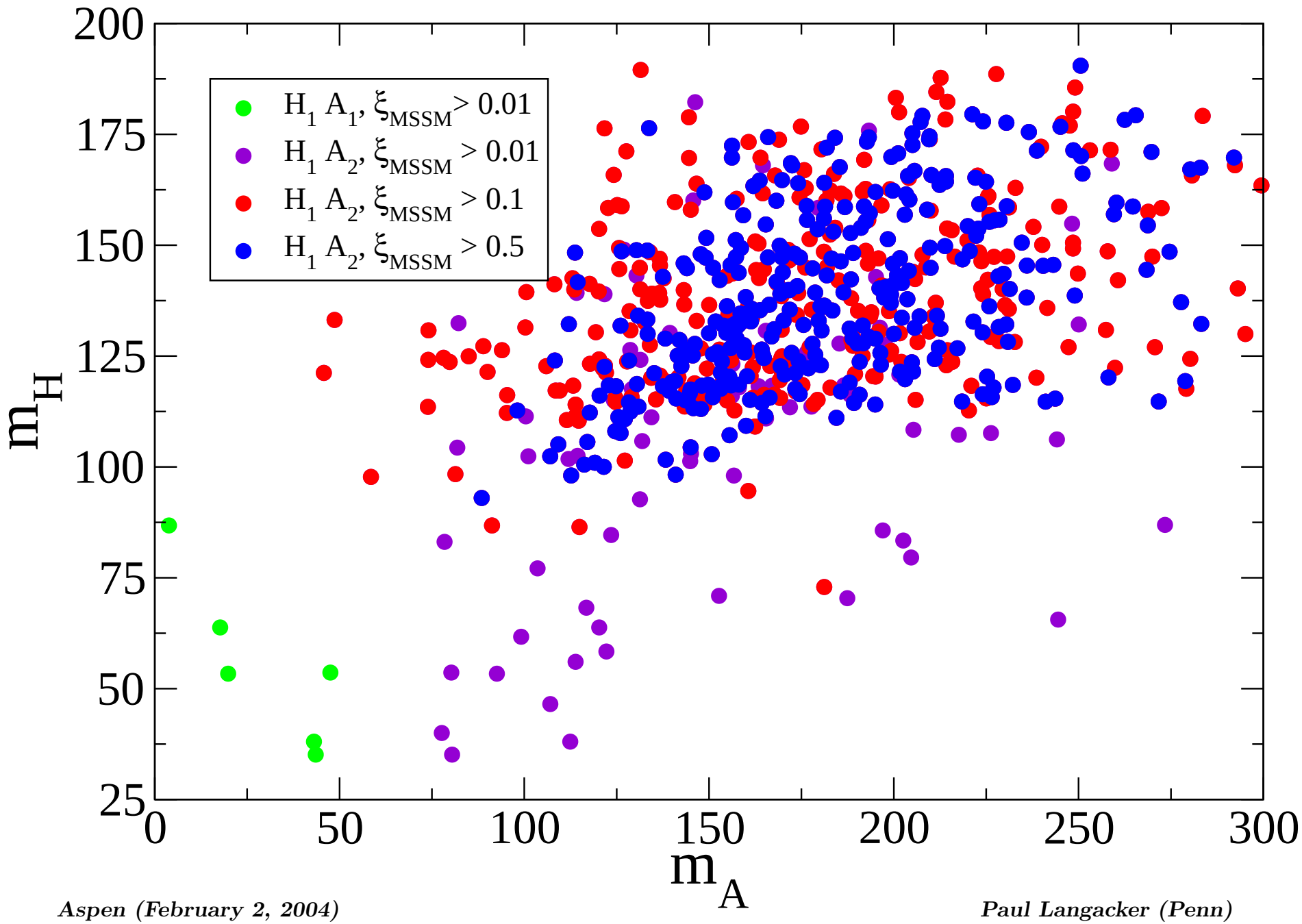
Nonstandard Higgs

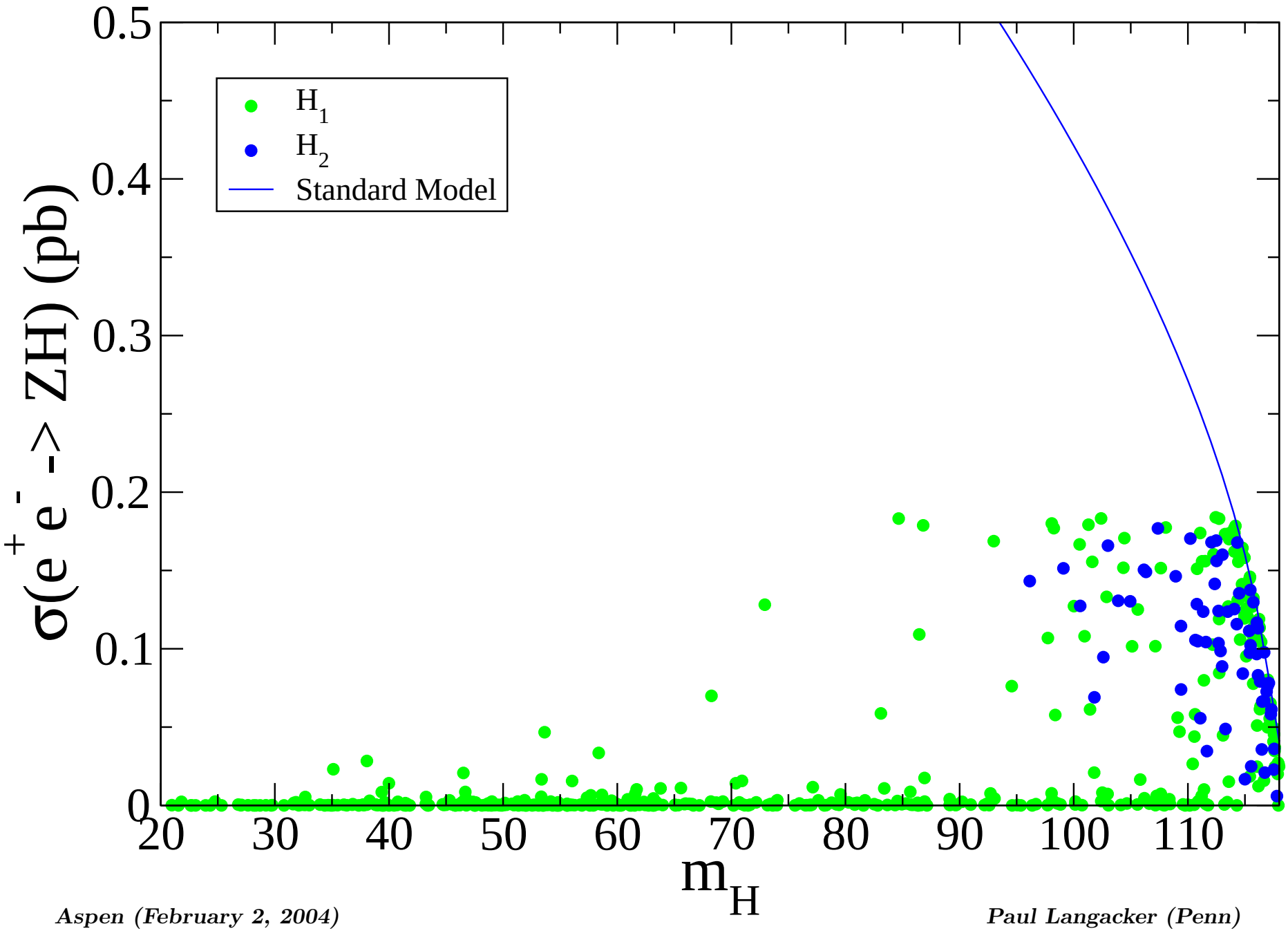
(T. Han, PL, B. McElrath)

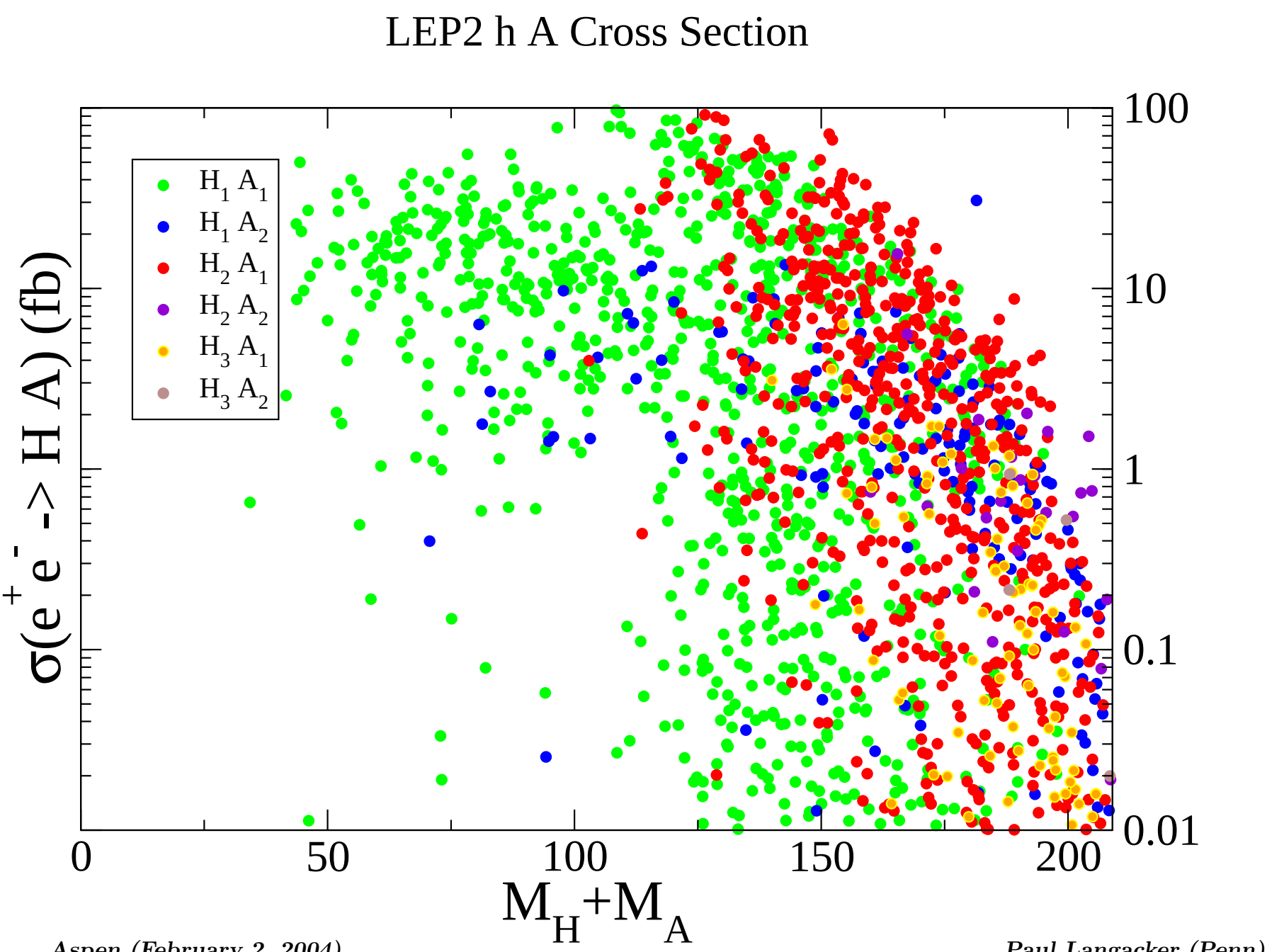
- **Complex Higgs, neutralino spectrum and decays, very different from MSSM and NMSSM because of mixing and D terms**

- **6 scalars and 4 pseudoscalars**
  - **Can have tree level CP breaking $\Rightarrow$ mixing**
  - **Separate into two sectors, one decoupled**
  - **Often light scalars with significant doublet admixture, but reduced coupling due to singlet admixture; $M_A < 65$ GeV**
  - **Can have lightest Higgs up to 185 GeV with all couplings perturbative to M_P because of D terms**

$$\begin{aligned} M_h^2 &\leq h^2 v^2 + (M_Z^2 - h^2 v^2)\cos^2 2\beta \\ &+ 2 g_{Z'}^2 v^2 (Q_{H_2}\cos^2\beta^2 + \sin^2\beta Q_{H_1})^2 \\ &+ \frac{3}{2}\frac{\cos^2\beta m_t^4}{v^2\pi^2}\log\frac{m_{\tilde{t_1}} m_{\tilde{t_2}}}{m_t^2}. \end{aligned}$$


200
175
150
125
100
75
50
25
0
50
100
150
200
250
300
m_H
m_A
H_1 A_1, $\xi_{MSSM} > 0.01$
H_1 A_2, $\xi_{MSSM} > 0.01$
H_1 A_2, $\xi_{MSSM} > 0.1$
H_1 A_2, $\xi_{MSSM} > 0.5$


0.5
0.4
0.3
0.2
0.1
0
20
30
40
50
60
70
80
90
100
110
m_H
$\sigma(e^+e^- \to ZH)$ (pb)
H_1
H_2
Standard Model


LEP2 h A Cross Section
σ(e+ e- -> H A) (fb)
H1 A1
H1 A2
H2 A1
H2 A2
H3 A1
H3 A2
100
10
1
0.1
0.01
0
50
100
150
200
MH+MA

Electroweak Baryogenesis

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

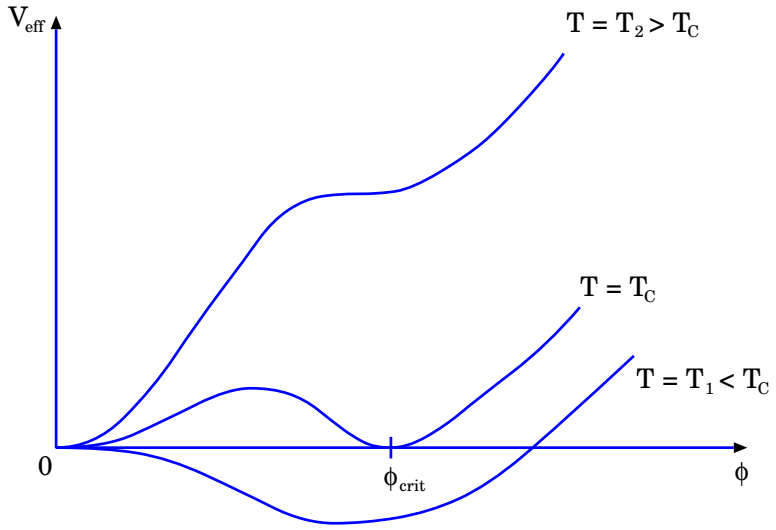
- Baryon asymmetry $n_B/n_\gamma \sim 6 \times 10^{-10}$
- Basic ideas worked out by Sakharov in 1967, but no concrete model
- Possible mechanisms
  - Affleck-Dine baryogenesis
  - GUT baryogenesis (wiped out by sphalerons for $B - L$=0)
  - Leptogenesis
  - Electroweak baryogenesis

Electroweak baryogenesis

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

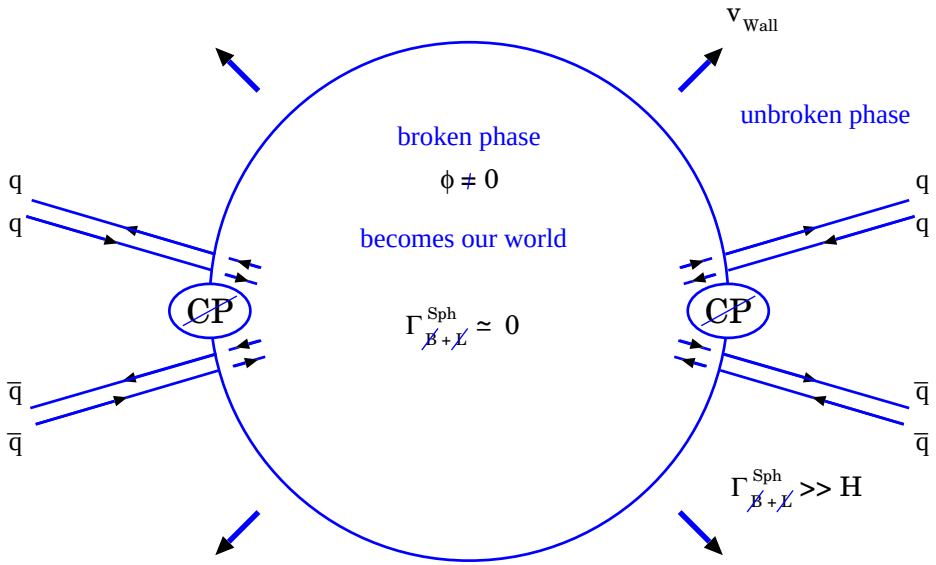
Off the wall scenario (Cohen, Kaplan, Nelson)

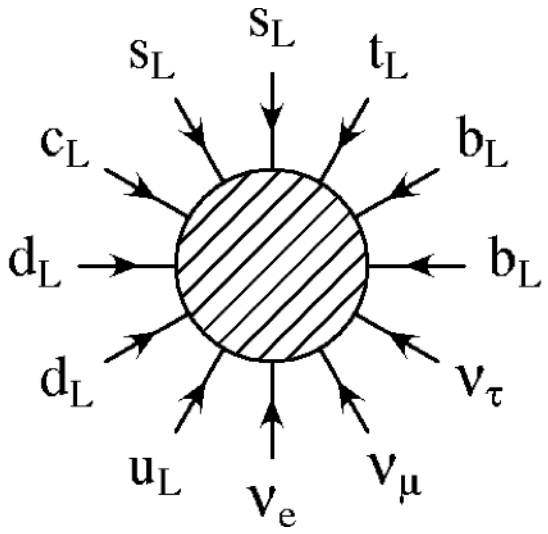
- **Strong first order phase transition from electroweak symmetry unbroken (massless W, Z, fermions) to broken phase (massive W, Z, fermions) proceeds by nucleation and expansion of bubbles**



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

- **CP violation by asymmetric reflection of quarks and leptons 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**





Implementation of "off the wall"

Standard model: no strong first order for $M_h > 114.4$ GeV; CP violation too small

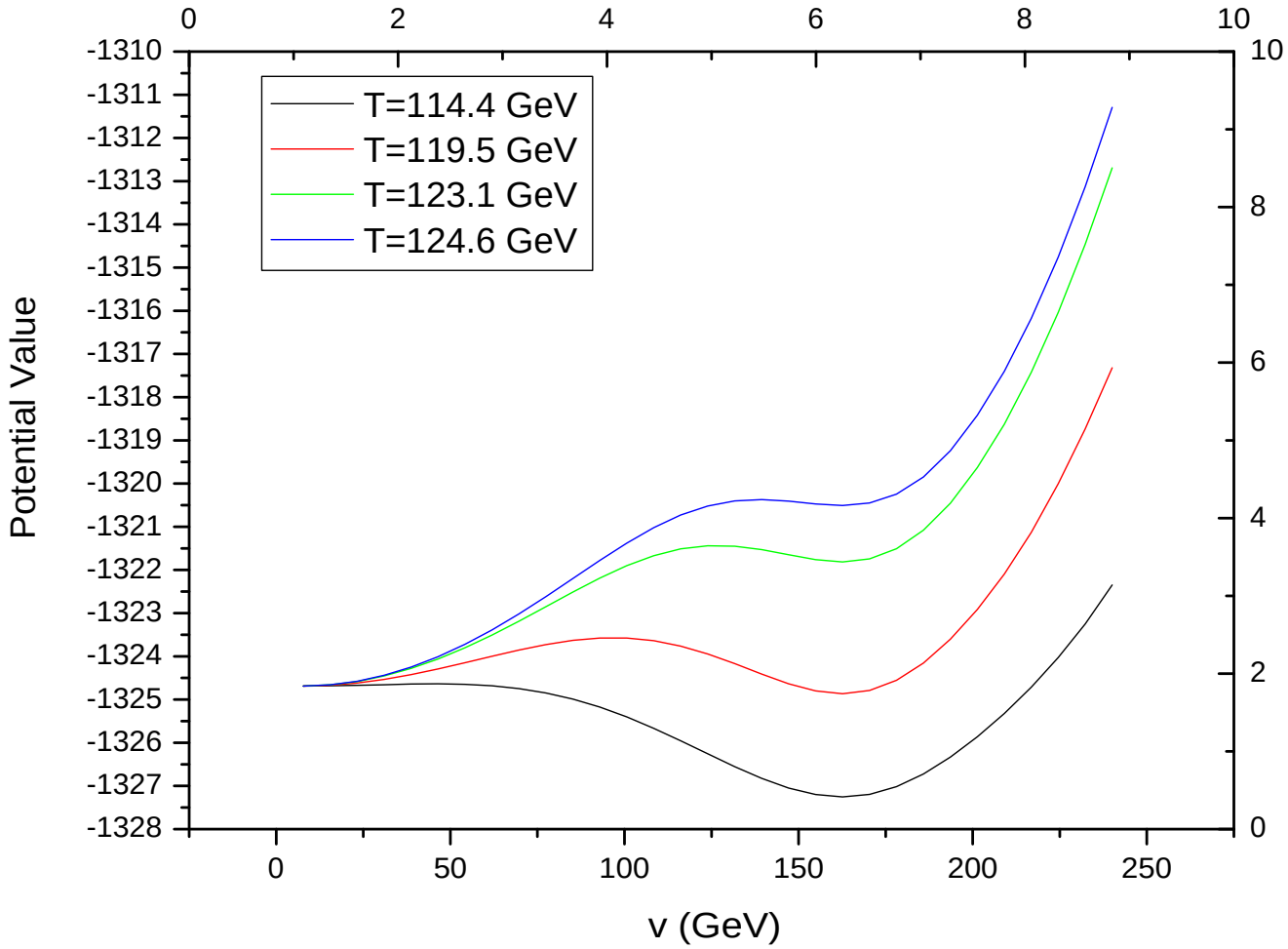
Minimal supersymmetric extension (MSSM): small parameter space for light Higgs and stop; new sources for CP violation

NMSSM (extension to include extra Higgs fields): can have strong first order for large $hA_hSH_1H_2$ *but* cosmological domain walls

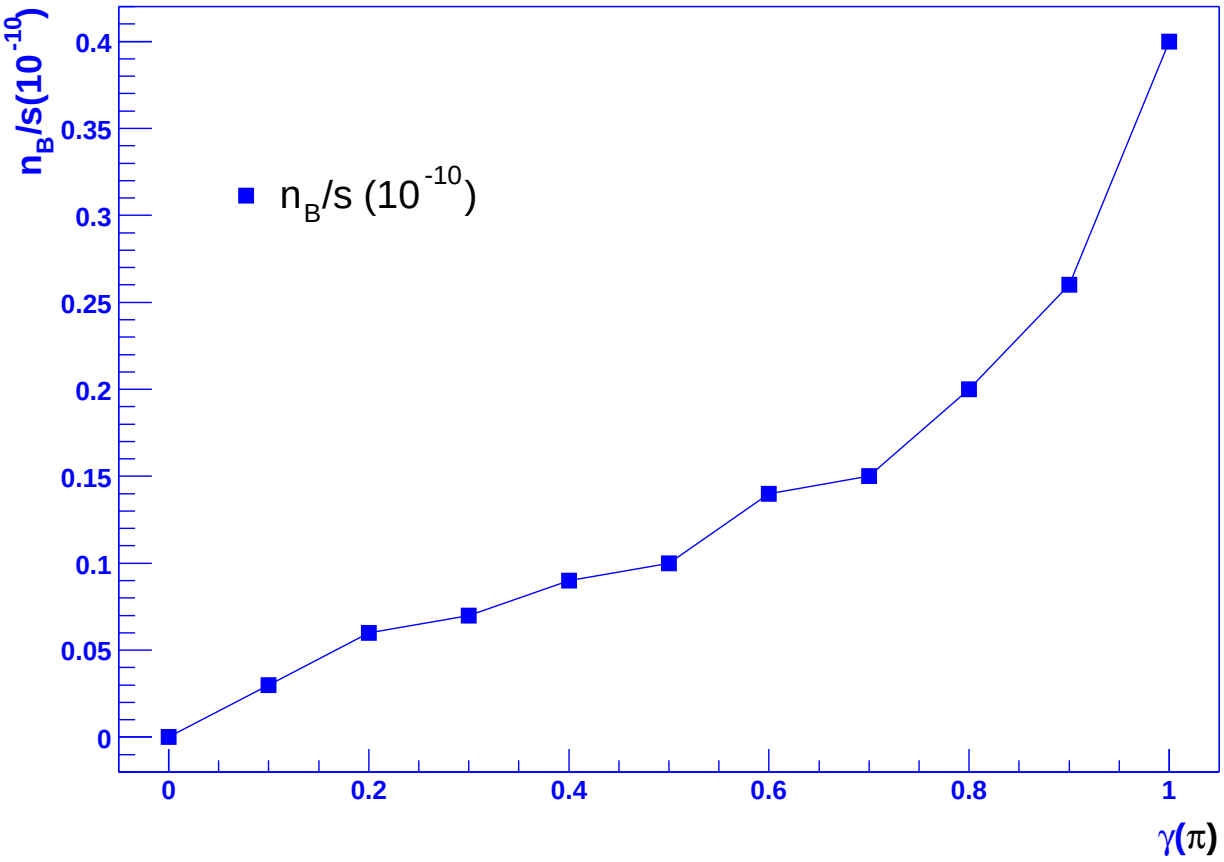
Secluded sector $U(1)'$:

- Symmetry breaking driven by large $hA_h SH_1H_2$
- Tree level CP breaking in Higgs sector associated with soft SM singlet terms
- New contributions to electric dipole moments small
- First phase transition breaks $U(1)'$, second breaks $SU(2)\times U(1)$

- Phase transition strongly first order
- We only consider the τ lepton and use thin wall approximation (justified)
- For reasonable parameters, can obtain adequate asymmetry, even for large $\tilde{t}$ mass



Transition at $T_c = 120$ GeV, $v(T_c)/T_c = 1.31$



$\gamma =$ **explicit CP phase. Exp:** $n_B/s \sim (0.8 - 0.9) \times 10^{-10}$.

FCNC and rare B decays

- $U(1)'$ couplings often family-nonuniversal in string constructions $\Rightarrow$ FCNC (Z' and Z from $Z - Z'$ mixing) after family mixing (GIM breaking) (also from exotic mixing)

- Depends on $V_{\psi L}$ and $V_{\psi R}$, $\psi = u, d, e, \nu$, but only $V_{\rm CKM} = V_{u_L} V_{d_L}^\dagger$ and $V_{\rm MNS} = V_{\nu_L} V_{e_L}^\dagger$ known from exp

- K and μ decays $\Rightarrow$ first two families are universal (PL, Plümacher)

- Third family could be nonuniversal
  - A_{FB}^{0b} (Erler, pl)
  - Rare B decays, especially in competition with SM loops, e.g. $B \to \phi K, \eta' K$ or $B_s \to \mu^+ \mu^-$ (Leroux, London; Barger, Chiang, PL, Lee)

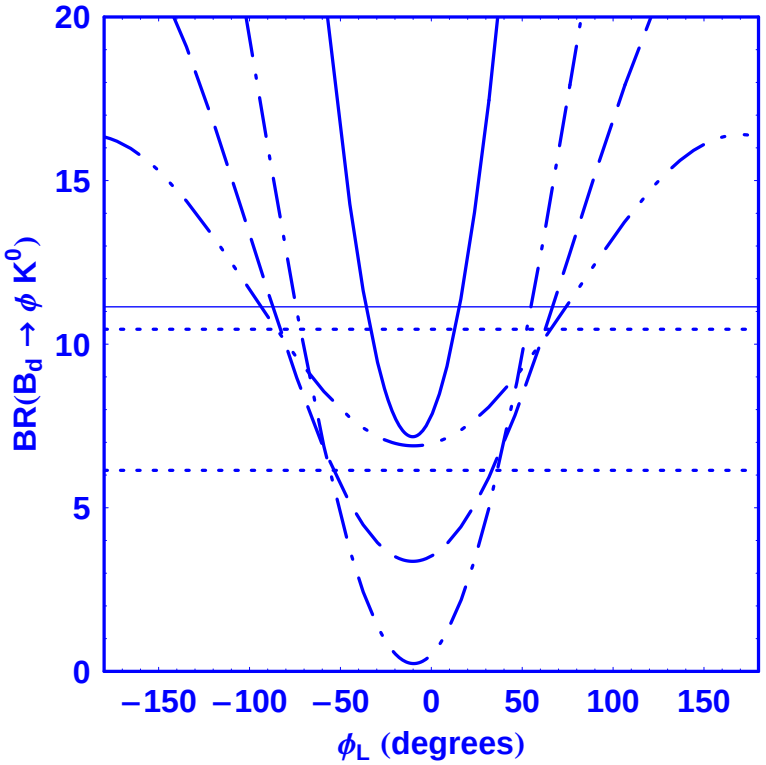
Possible Belle anomaly in $B \to \phi K_s$ asymmetry

$$\begin{aligned} a_{\phi K_S}(t) &= \frac{\Gamma(\bar{B}^0(t) \to \phi K_S) - \Gamma(B^0(t) \to \phi K_S)}{\Gamma(\bar{B}^0(t) \to \phi K_S) + \Gamma(B^0(t) \to \phi K_S)} \\ &= A_{\phi K_S} \cos(\Delta M_{B_d} t) + S_{\phi K_S} \sin(\Delta M_{B_d} t), \end{aligned}$$

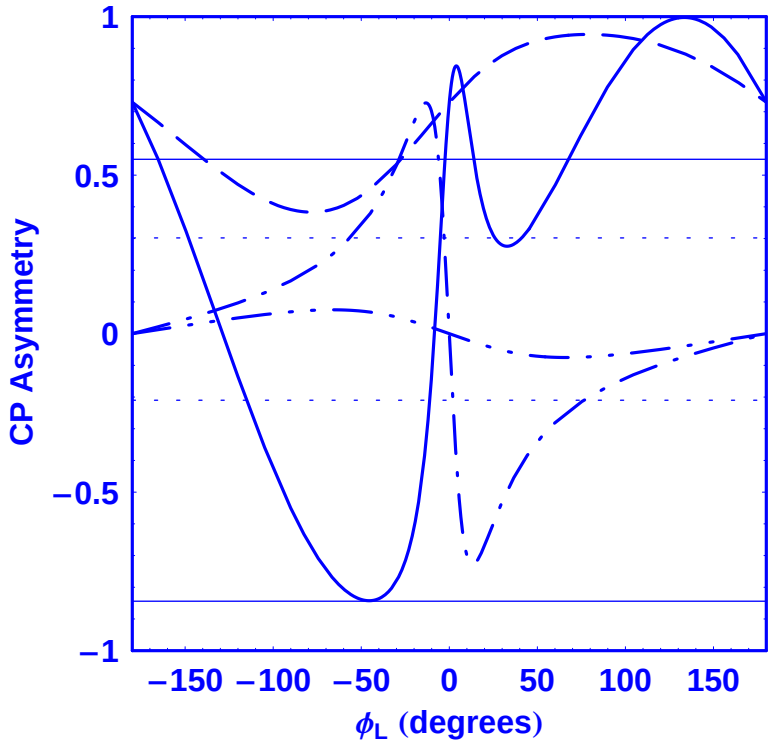
$A_{\phi K_S}$ and $S_{\phi K_S}$ represent direct and indirect CP breaking (SM: $A \sim 0$; $S \sim 0.73$ mainly from QCD penguin)

	BaBar	Belle	SM
$S_{\phi K_S}$	$0.45 \pm 0.43 \pm 0.07$	$-0.96 \pm 0.50^{+0.09}_{-0.11}$	0.73
$A_{\phi K_S}$	$0.38 \pm 0.37 \pm 0.12$	$-0.15 \pm 0.29 \pm 0.07$	0

Weighted average $S_{\phi K_S} = -0.147 \pm 0.697$ $(S = 2.11)$ with scale factor.



Thick solid and dashed curves: $\xi^{LL} = \xi^{LR} = 0.02$ and 0.005. Single-dot-dashed and double-dot-dashed curves: $\xi^{LL} = 0.02$ and 0.005, with $\xi^{LR} = 0$.



$S_{\phi K_S}$ and $A_{\phi K_S}$. Thin horizontal solid and dotted lines: experiment. SM: 0.73,0. Thick solid and dashed curves: $S_{\phi K_S}$ for $\xi^{LL} = 0.02$ and 0.005, with $\xi^{LR} = 0$. Single-dotted and double-dotted dashes: $A_{\phi K_S}$.

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 extension of NMSSM)
- Many implications, including nonstandard Higgs spectrum/couplings, efficient EW baryogenesis, FCNC in B decays, neutrinos
- But, must observe Z'