Effects of New Physics on CP violation in B decays

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Outline

- $b \rightleftarrows s$ Phenomena: Current Frontier for NP
- Flavor Models w/ *1 Extra CP Phase* in $b \rightleftarrows s$
    - 4th Generation
    - Large s_R-b_R Mixing w/ SUSY: Light $\widetilde{sb}_{1R}$ Squark
- 4th Generation & $b \to s\ell^+\ell^-$, Δm_{B_s}, $\sin 2\Phi_{B_s}$

  — Does Not Touch EM/Strong Penguins Much
- Light $\widetilde{sb}_{1R}$ and $S_{\phi K_S}$, $S_{\eta' K_S}$, Δm_{B_s}, $\sin 2\Phi_{B_s}$
    - Survive $b \to s\gamma$
    - Tune for $S_{\phi K_S}$, $S_{\eta' K_S}$ Possible
    - Consequences: Δm_{B_s}, $\sin 2\Phi_{B_s}$, wrong γ helicity
- Conclusion

Based on A. Arhrib and WSH, EPJC 27, 555 (2003)
A. Arhrib, C.K. Chua and WSH, PRD 65, 017701 (2001)
C.K. Chua, WSH and M. Nagashima, to appear

$b \rightleftarrows s$ Phenomena: Current NP Frontier

- CP Phase $\sin 2\Phi_{B_d} \cong 0.8$ Agree with CKM Fit

  but $\gamma/\phi_3 \cong 60^\circ$ CKM Fit

  v. $\gamma/\phi_3 \sim 90^\circ$ $B \to K\pi/\pi\pi$ Modes

- Although $\sin 2\Phi_{B_d \to \eta' K_S} \cong \sin 2\Phi_{B_d}$

  but $\sin 2\Phi_{B_d \to \phi K_S}$ Opposite Sign !?

- $b \to s\ell^+\ell^- >$ SM?

- Δm_{B_s} "*Just Around the Corner*"

  but if $\mathbf{\sin 2\Phi_{B_s} \neq 0} \Rightarrow$ NP

- $b \to s\gamma_L$? Wrong Helicity Component

  Test via $B_s \to \phi\gamma$ Mixing-dep CPV

  $\Lambda_b \to \Lambda\gamma$ Λ Polarization

(Near) Future

Models w/ *1 Extra CP Phase* in $b \rightleftarrows s$

- **4th Generation**: In general 3 New CP Phases

  Restrict to $b \rightleftarrows s$ Only: *Just One New CP Phase*

$$\lambda_u + \lambda_c + \lambda_t + \lambda_{t'} = 0 \quad \text{Unitarity,} \quad \lambda_i \equiv V_{is}^* V_{ib}$$

$$\approx O(\lambda^5) + \lambda^2 + \lambda_t + \lambda_{t'} \quad \Rightarrow \quad \lambda_t \approx -\lambda_c - \lambda_{t'} \equiv r_s e^{i\Phi_s}$$

Phase Φ_s Neglected in Literature !

- **Large s_R-b_R Mixing w/ SUSY**: Light $\widetilde{sb}_{1R}$ Squark

$$s_R - b_R \text{ Mixing} \xleftrightarrow{\text{Near Maximal ?}} \nu_\mu - \nu_\tau \text{ Mixing}$$

Flavor Symmetry

⊕ Supersymmetry

Just One New CP Phase

in $\tilde{s}_R - \tilde{b}_R$ Mixing

➤ **Flavor-driven Light *s-b* Flavored Squark** $\widetilde{sb}_{1R}$

4th Generation Effect

Formalism

$$\lambda_{t'} \equiv V^*_{t's} V_{t'b} \equiv r_s e^{i\Phi_s}$$

Phase Φ_s has been Neglected in Literature

$$\lambda_t \approx -\lambda_c - \lambda_{t'} \cong -\lambda^2 - \lambda_{t'} \quad \text{if } |\lambda_{t'}| >> |\lambda_u| \approx O(\lambda^5)$$

$\cong -0.04$ ~ 0.0006

Take Hamiltonian for $b \to s\gamma$

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} \sum_{i=1}^{i=8} [\lambda_t C_i^{\rm SM}(\mu) + \lambda_{t'} C_i^{\rm new}(\mu)] O_i(\mu),$$

usual term

$$\lambda_t C_i^{\rm SM} + \lambda_{t'} C_i^{\rm New} = -\lambda_c C_i^{\rm SM} + \lambda_{t'}(C_i^{\rm New} - C_i^{\rm SM})$$

Satisfies GIM $\begin{cases} \lambda_{t'} \to 0 \\ m_{t'} \to m_t \end{cases}$

Parameters

$$m_{t'};\ r_s,\ \Phi_s$$

popular: absorb $\lambda_{t'}$ in $C_i^{\rm New}$ def.

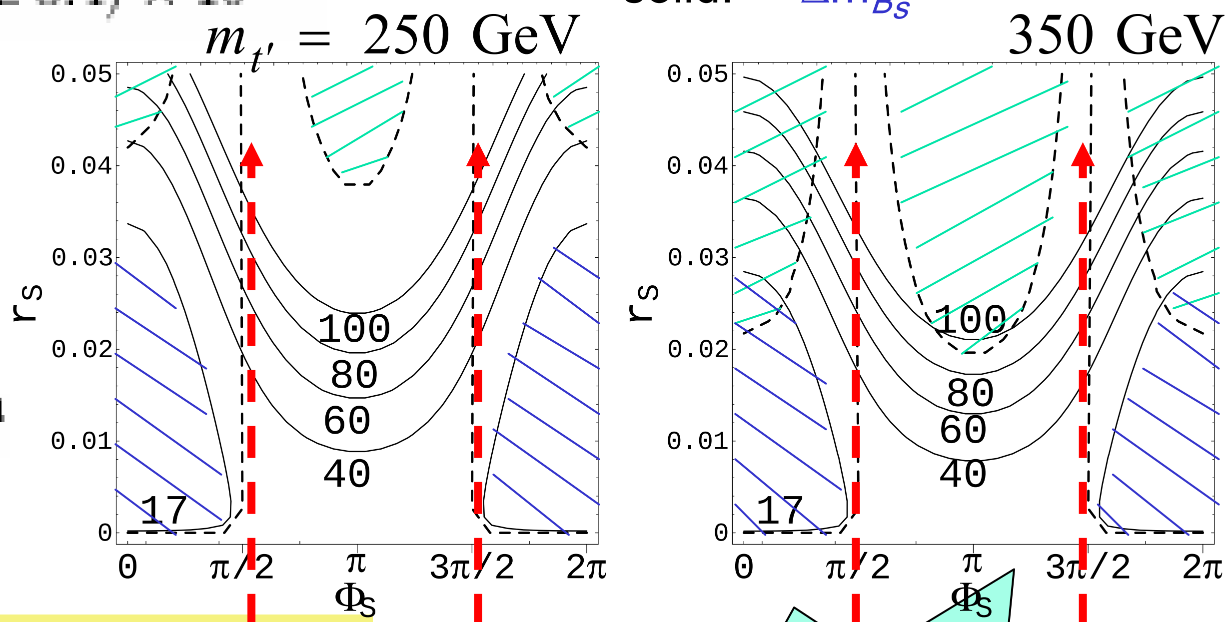
Constraints: $b \to s\gamma$, Δm_{B_s}

Expt.

$$\begin{cases} \mathcal{B}(B \to X_s\gamma) = (3.3 \pm 0.4) \times 10^{-4} \\ \Delta m_{B_s} > 14.9\,\mathrm{ps}^{-1} \end{cases}$$

dashed: $b \to s\gamma$,

solid: Δm_{B_s}



Choose param.

⇨ SM Values

$\mathcal{B}(B \to X_s\gamma) \simeq 3.26 \times 10^{-4}$

$\Delta m_{B_s}^{\rm SM} \simeq 17.0\,\mathrm{ps}^{-1}$

- $b \to s\gamma$, Δm_{B_s} Complementary
  - $b \to s\gamma$ **Weak $m_{t'}$–dep**

    ⇨ Not So Constraining
  - Δm_{B_s} **Strong $m_{t'}$–dep**

    ⇨ Not Constructive Interf.

$\Phi_s = \pi/2, 3\pi/2$

Most Forgiving

∵ Add in quadrature

Constraint/Test: $b \to s\ell^+\ell^-$ Rate

EW Penguin has Strong $m_{t'}$–dep., Just Like B_s Mixing

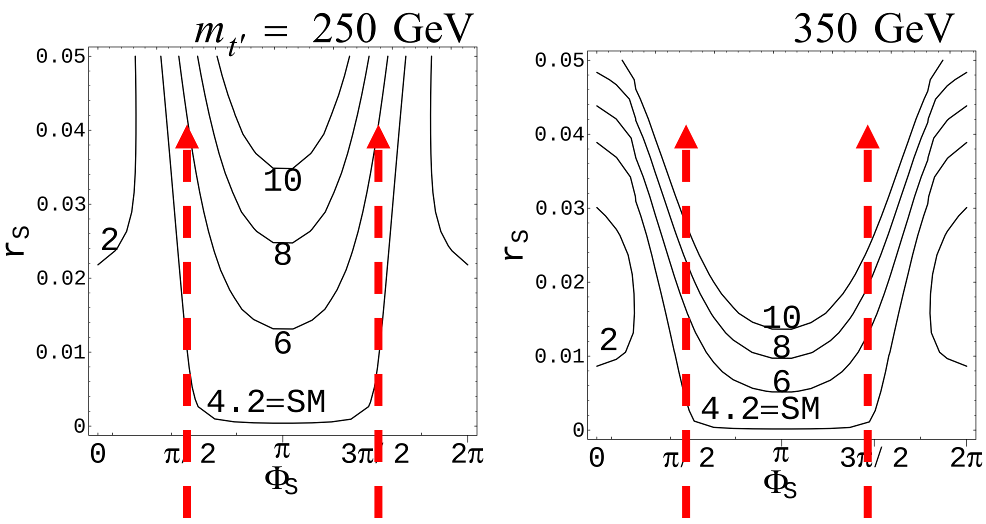
$\mathcal{B}(B \to K\ell^+\ell^-)$ ~ (0.5–0.8) x 10^{-6}

$\mathcal{B}(B \to K^*\ell^+\ell^-)$ ~ (0.8–1.7) x 10^{-6}

} Yet to Settle (a bit high)

$$\mathcal{B}(B \to X_s\ell^+\ell^-) = (6.1 \pm 1.4^{+1.3}_{-1.1}) \times 10^{-6}$$

Less hadronic uncertainty
Maybe high vs. NNLO



SM ~ NNLO SM3

- More Stringent than Δm_{B_s}
  ⇨ *Improve Soon* !
- Φ_s ~ π/2, 3π/2
  Allow Larger r_s
- May be Needed If
  NNLO Remains Low
- No Further Info in $m^2(\ell\ell)$
- Constrained by BR
  ⇨ A_{FB} ~ SM

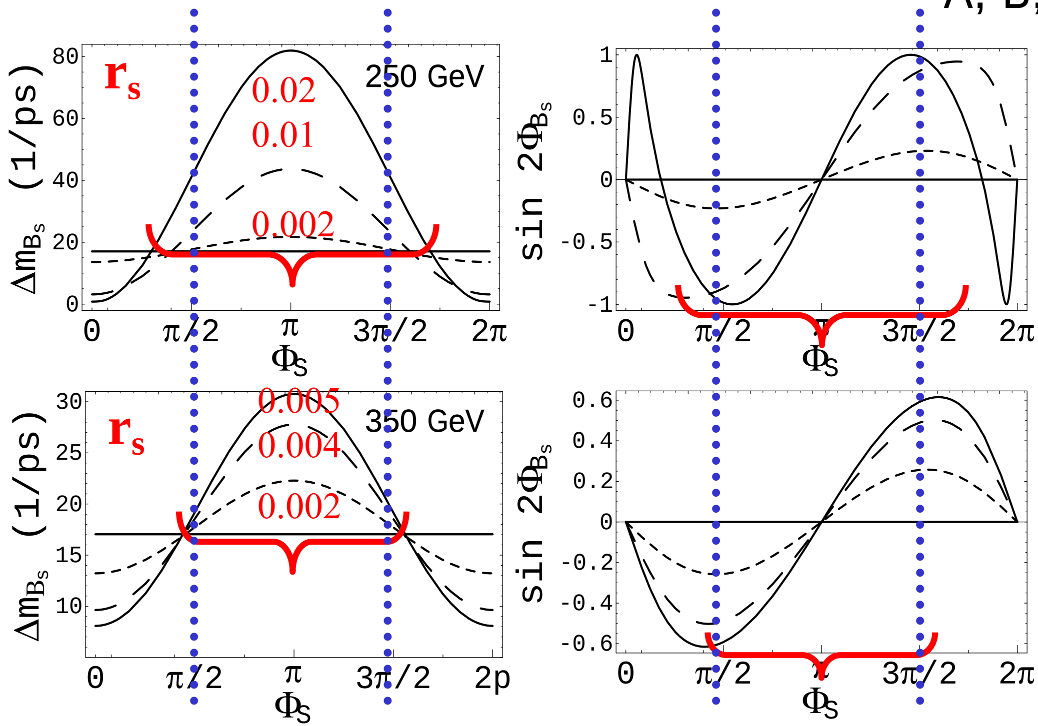
The Highlight: Large $\sin 2\Phi_{B_s} \neq 0$

- $\sin 2\Phi_{B_d}$ Agree with SM3, but May be Affected by $V^*_{t'd} V_{t'b}$
- $\sin 2\Phi_{B_s}$ = 0 Strictly in SM3 ⇨ Any $\sin 2\Phi_{B_s} \neq 0$ Implies NP !!

Def. $$M_{12} = |M_{12}| e^{2i\Phi_{B_s}} \approx r_s^2 e^{2i\Phi_s} A + r_s e^{i\Phi_s} B + C$$

$$\Delta m_{B_s} = 2|M_{12}|$$

A, B, C are quadratic fns of m_t, $m_{t'}$



- Even for Small r_s
  $\sin 2\Phi_{B_s}$ **Can be Large**
- Both Signs Possible
- Largest If Δm_{B_s}
  "Just Around Corner"
  i.e. when $\Phi_s \sim \pi/2, 3\pi/2$
  Δm_{B_s} Quite Measurable
  $\sin 2\Phi_{B_s} \sim \pm 1$

Good at Tevatron !

But, ...

4th Generation Not Effective on EM & Strong Penguins

- $b \to s\gamma$ affected only when r_s (and $m_{t'}$) gets large

  No Mixing CPV because (L) Chirality Same as SM

- $b \to sg^*$ Even Less Affected

  ⇨ Cannot Touch $S_{\phi K_S}$, $S_{\eta' K_S}$ etc.

⇨ Turn to one that Can

Light $\widetilde{sb}_{1R}$ & $S_{\phi K_S}$, $S_{\eta' K_S}$, Δm_{B_S}, $\sin 2\Phi_{B_S}$

Mass/Mixing Hierarchy

$$\hat{M}_u = \frac{M_u}{m_t} \sim \begin{bmatrix} \lambda^7 & \lambda^5 & \lambda^3 \\ ? & \lambda^4 & \lambda^2 \\ ? & ? & 1 \end{bmatrix}, \quad \hat{M}_d = \frac{M_d}{m_b} \sim \begin{bmatrix} \lambda^4 & \lambda^3 & \lambda^3 \\ ? & \lambda^2 & \lambda^2 \\ ? & ? & 1 \end{bmatrix}$$

Abelian Flavor Symmetry $\quad M_{ij} M_{ji} \approx M_{ii} M_{jj}$ *Commuting* Charges

$$\hat{M}_u \sim \begin{bmatrix} \lambda^7 & \lambda^5 & \lambda^3 \\ \lambda^6 & \lambda^4 & \lambda^2 \\ \lambda^4 & \lambda^2 & 1 \end{bmatrix}, \quad \hat{M}_d \sim \begin{bmatrix} \lambda^4 & [\lambda^3] & [\lambda^3] \\ [\lambda^3] & \lambda^2 & \lambda^2 \\ [\lambda] & 1 & 1 \end{bmatrix}$$

Prominent **but right-handed**

Nir-Seiberg, PLB'93; Leurer-Nir-Seiberg, NPB'94

N.B. Need 4 Texture Zeros (Chua-WSH, PRL'01) : Set [..] = 0

Arhrib-Chua-WSH, PRD'01 *Decouple d flavor*

Alternative Picture:

$$\nu_\mu - \nu_\tau \text{ Mixing} \xrightarrow{\text{Near Maximal ?}} s_R - b_R \text{ Mixing}$$

Chang, Masiero, Murayama

Right-handed Quarks Inert in SM

→ Right-handed **S**quarks

$\tilde{d}_{iR}$-d_{jR}-$\tilde{g}$ *Dynamics*

SUSY

Assume
- Squarks $\approx \tilde{m}$, almost degenerate
- AFS not far above SUSY Scale

also important

$$\left(\tilde{M}_q^2\right)_{RL} = \left(\tilde{M}_q^2\right)_{LR}^{*T} \approx M_q \tilde{m}, \qquad \frac{m_q}{\tilde{m}} \text{ suppressed}$$

$$\left(\tilde{M}_Q^2\right)_{LL} \approx \tilde{m}^2 V_{\mathrm{CKM}}, \qquad \text{CKM suppressed}$$

$$\text{but} \quad \left(\tilde{M}_d^2\right)_{RR} \approx \tilde{m}^2 \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{bmatrix}$$

RR Sector
Impact ***b* ⇄ *s***
thru **SUSY**

Level Splitting by Large Mixing → Drive One State Light

$$\left(\widetilde{M}_q^2\right)_{RR} \approx \widetilde{m}^2 \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{bmatrix} \Rightarrow \left(\widetilde{M}_{RR}^{2(sb)} = \begin{bmatrix} \widetilde{m}_{22}^2 & \widetilde{m}_{23}^2 e^{-i\sigma} \\ \widetilde{m}_{23}^2 e^{i\sigma} & \widetilde{m}_{33}^2 \end{bmatrix} = R \begin{bmatrix} \widetilde{m}_1^2 & 0 \\ 0 & \widetilde{m}_2^2 \end{bmatrix} R^\dagger\right.$$

$$R = \begin{bmatrix} c_\theta & s_\theta \\ -s_\theta e^{i\sigma} & c_\theta e^{i\sigma} \end{bmatrix}$$

1 *CP* Phase

- Near Maximal Mixing: $s_\theta \sim 1/\sqrt{2}$
- $\sigma = \arg(\widetilde{M}_d^2)_{RR}^{32}$ similar footing as $\phi_3 \equiv \arg V_{ub}^*$

Light $\widetilde{sb}_1$ w/ Some Tuning: set $\widetilde{m}_{22}^2 = \widetilde{m}_{33}^2 = \widetilde{m}^2$,

With $\widetilde{m}_{23}^2/\widetilde{m}^2 \equiv 1 - \delta \simeq 1$,

$$\widetilde{m}_1^2 \cong \delta\, \widetilde{m}^2, \quad \widetilde{m}_2^2 \cong (2-\delta)\widetilde{m}^2$$

Tunings: take $\widetilde{m} = 2\ (1)$ TeV

$$\delta = \lambda^2,\ \lambda^3,\ \lambda^4 \qquad (\lambda,\ \lambda^2,\ \lambda^3)$$

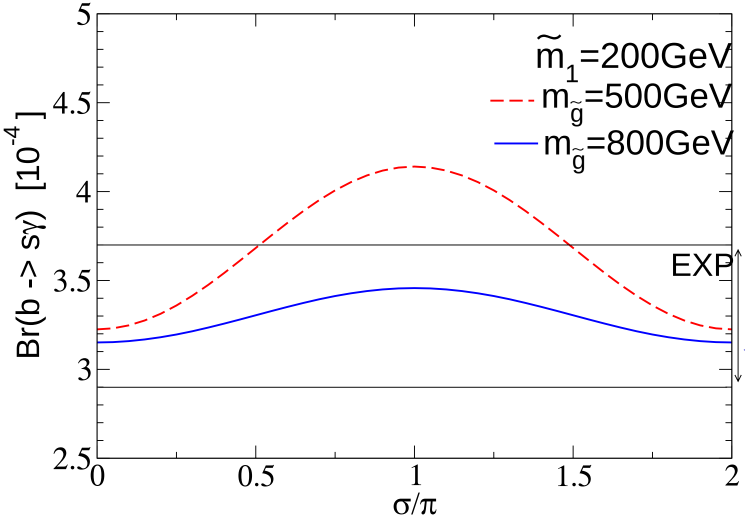
$$\Rightarrow \widetilde{m}_1 = 440,\ 206,\ 97\ \text{GeV} \qquad (470,\ 220,\ 103\ \text{GeV})$$

Focus on 200 GeV

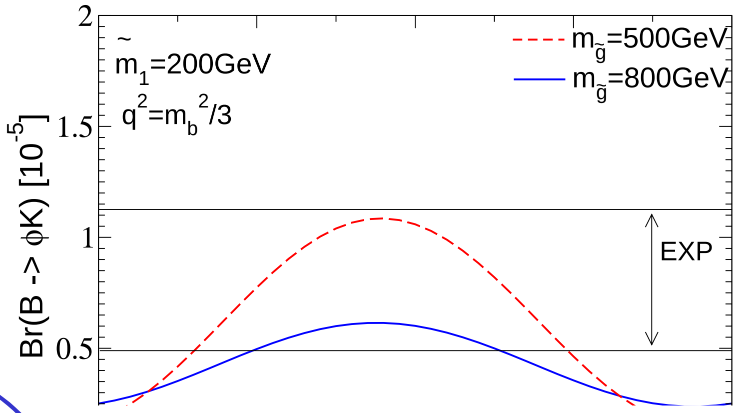
100 GeV possible

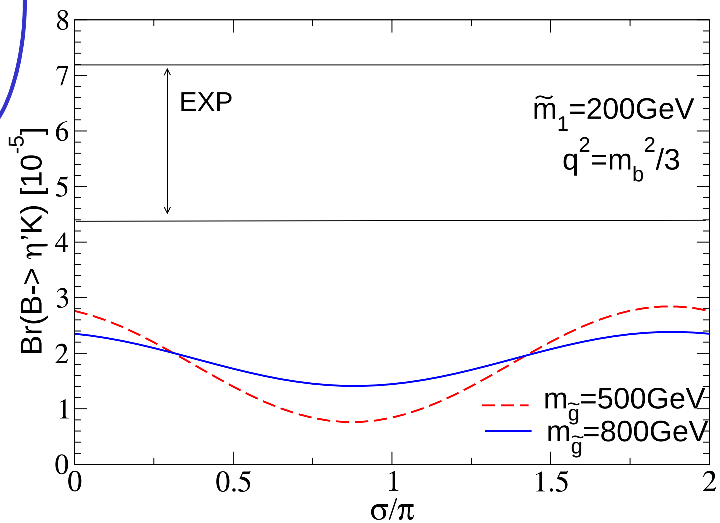
Rates

- Survive $b \to s\gamma$ Constraint



- $B \to \phi K_s,\ \eta' K_s$ Rates





$$\tilde{m} = 2\ \text{TeV} \quad \Rightarrow \quad m_{\tilde{g}} = 800\ \ \text{GeV}$$

More Conservative

Cannot Account of $\eta' K_s$ Rate
ϕK_s Rate also a bit Low
But, Not New Problems

A Little Note on Formalism ...

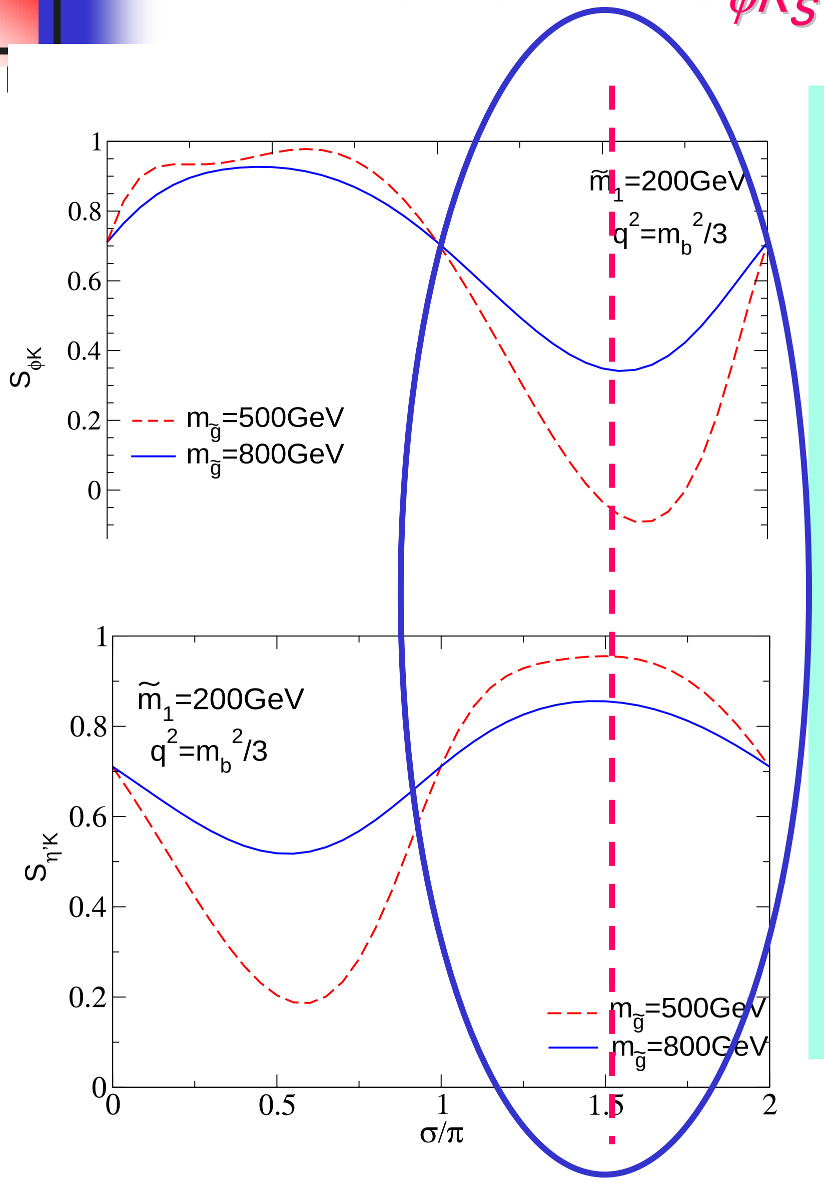
- Besides $O_{1,2}$ Tree

  $O_{3\text{-}6}$ Strong Penguin $\xrightarrow{\text{Right-handed Coupling}}$ O_i'

  $O_{7\text{-}10}$ EM/EW Penguin

  also $O_{11,12}$ γ/g Dipole

Tune for $S_{\phi K_S}$, $S_{\eta' K_S}$ Possible



- $S_{\phi K_S} \lesssim 0$ prefers lower σ-plane
  ⇨ $S_{\eta' K_S} \cong \sin 2\Phi_{B_d}$ as well !
- Lower gluino mass lowers $S_{\phi K_S}$
- Hadronic Parameters
  CP phase enters $B \to \phi K_S$ via

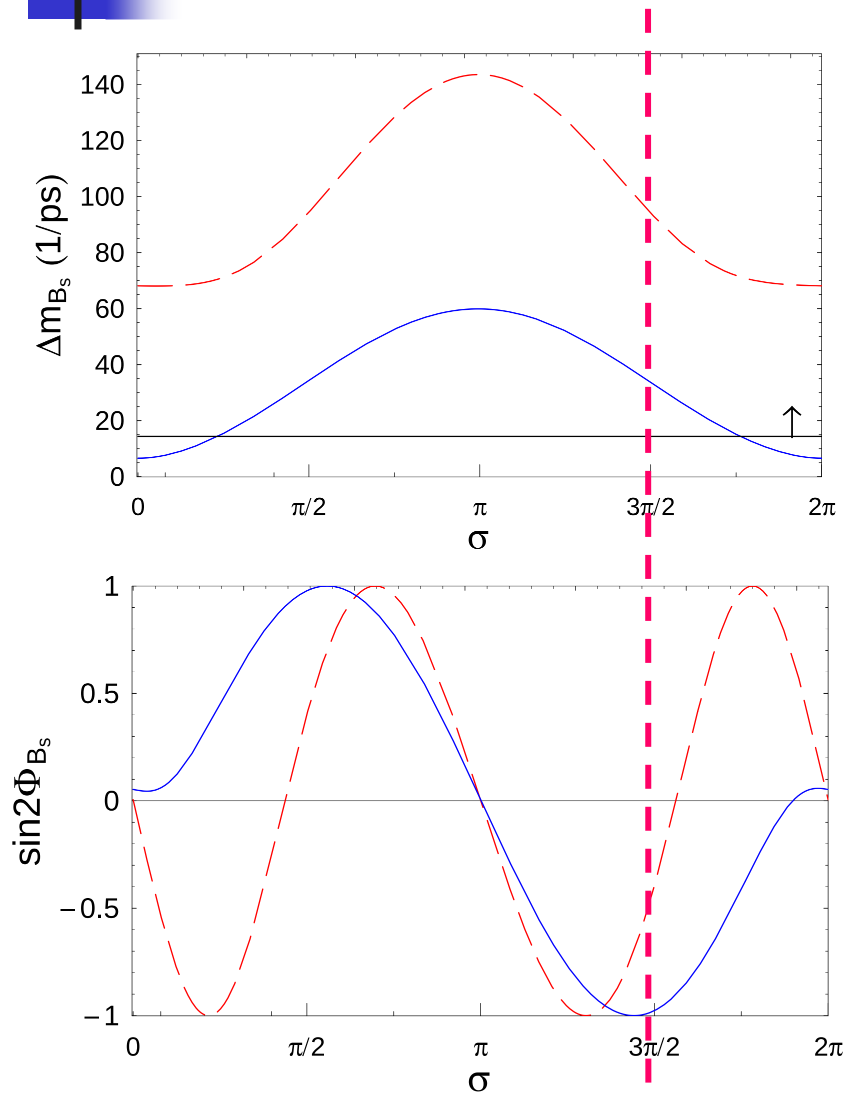
$$\frac{\alpha_s}{4\pi}\frac{m_b^2}{q^2}(C_{12}+C'_{12})\tilde{S}_{\phi K_s}$$

Lower q², larger $\tilde{S}_{\phi K_s}$
⇨ Larger $|S_{\phi K_S}|$

- If $B \to \eta' K_S$ rate due to (SM)
  QCD Effect ⇨ $S_{\eta' K_S}$ drops a bit
- Could $\sigma \simeq 3\pi/2$ be it?

noticed also by Khalil & Kou
Murayama et al.

Consequences: Δm_{B_s}, $\sin 2\Phi_{B_s}$



Take $\sigma \simeq 3\pi/2$ as example

- 800 GeV gluino "preferred"
  - Δm_{B_s} ~ 20-40 ps^{-1} "Easy"
  - $\sin 2\Phi_{B_s}$ ~ −1 Super
- Lighter gluino at 500 GeV
  - Δm_{B_s} > 60 ps^{-1} Tougher
  - $\sin 2\Phi_{B_s}$ ~ −1 - 0
- For lighter gluino, periodicity change

  $\because$
  $$M_{12} \equiv |M_{12}| e^{2i\Phi_{B_s}} \cong a e^{-2i\sigma} + b e^{-i\sigma} + c$$

  a-term dominant (two $\widetilde{sb}_{1R}$ exch.)
- 100 GeV $\widetilde{sb}_{1R}$ ~ 200 GeV case

  Except, Direct Detection !

More: Wrong Helicity Photon in $b \to s\gamma_L$

- Strength of Mixing-dep. CPV

$$\sin 2\theta = \frac{2\,|C_7 C_7'|}{(|C_7|^2 + |C_7'|^2)}$$

in, e.g. $B_s \to \phi\gamma$

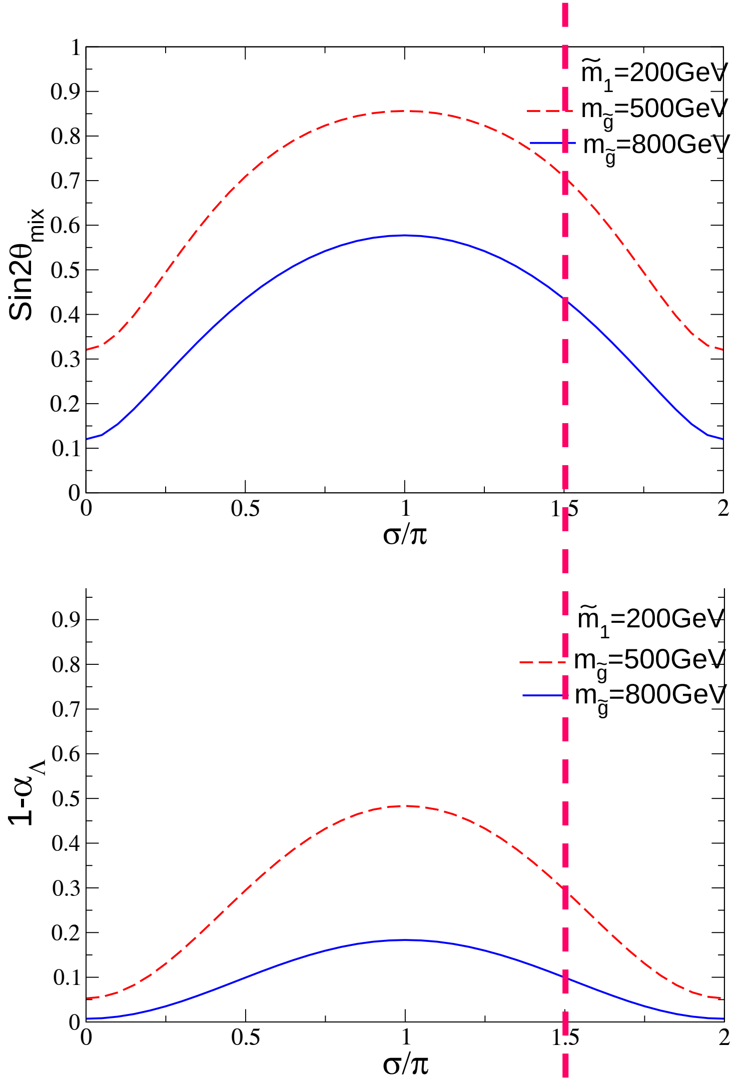
Test γ_L component

(Atwood, Gronau, Soni, 1997)

- Can also test γ_L comp. via Λ Polarization in $\Lambda_b \to \Lambda\gamma$

(Mannel, Recksiegel, 1997)

All Testable at Tevatron and Beyond



Conclusion

- Impact of 4th Generation (Emphasized **New CP Phase**)

  Prominent in - B_s Mixing & CPV

  - EW $b \to s$ Penguin

  Mild in EM/Strong Penguin

- A Light Flavor-mixed $\widetilde{sb}_{1R}$ Squark?
  - Survive $b \to s\gamma$
  - Can Account for $S_{\phi K_S}$, $S_{\eta' K_S}$
  - Strong Impact on: Δm_{B_s}, $\sin 2\Phi_{B_s}$, $b \to s\gamma_L$

⇨ **Study at B Factories, Tevatron, and ...**