CP Asymmetries in Supersymmetry

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Why should a B physicist be interested in SUSY?

BIG reasons: Gauge hierarchy problem/finetuning. Understanding electroweak symmetry breaking. Implementing grand unification or string theory. Connection to gravity. Cosmological constant problem. Because it might be right . . .

Pretty big reasons: Not enough CPV in SM to explain why we are here! Maybe SUSY can help . . .

Some still-darn-good reasons: SUSY is a dream (nightmare?) for physicists studying FCNCs and CPV. 33 mixing angles and 28 CP-violating phases in quark/squark sector (vs. 3+1)!

The Unitarity Triangle

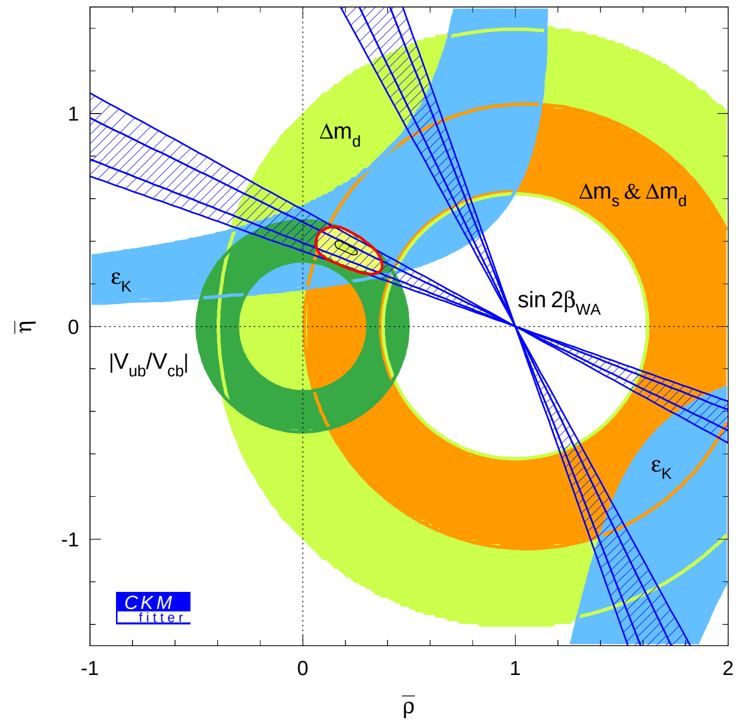
Room for physics BTSM??

The great success of the "unitarity triangle program" begs the question(s):

Is there any room for low-energy physics which is not flavor-blind?

Worse, is there room for any new physics at low energies?

- Success of the CKM picture is strong evidence that all of flavor is adequately and completely described at low energies by Standard Model, which has no explanation of flavor.
- One may be tempted to claim that there can be no new flavor structures near the weak scale, putting hope of understanding flavor beyond experimental reach.



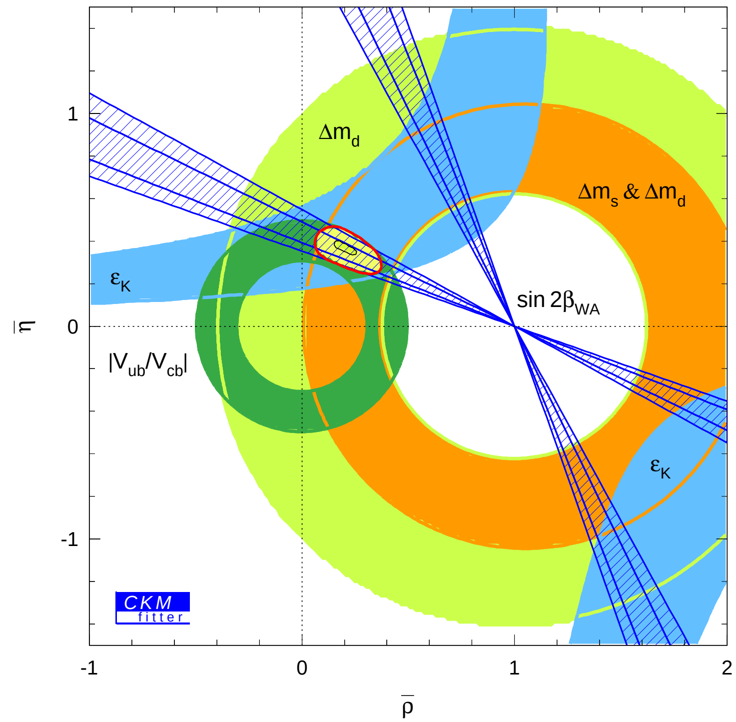
- In BTSM physics, preserving SM flavor successes (CKM unitarity, absence of FCNCs and CPV) is incredibly hard. These are accidents in the SM and they are hard to sustain in most extensions.
- Thus success of CKM program points indirectly to absence of *any* new physics near weak scale!

The Unitarity Triangle

Room for physics BTSM??

Lots of room for new physics, even if it isn't obvious:

- This is only one of six such triangles, chosen because most sensitive to Standard Model CPV.
- Particularly sensitive to new physics which violates CKM unitarity.



- Data going into triangle sensitive to $b \rightarrow d$ and $s \rightarrow d$ transitions, but not particularly $b \rightarrow s$.
- Processes used are used precisely because they are cleanest in SM, so difficult for new physics to compete with them.

THE MINIMAL SUPERSYMMETRIC STANDARD MODEL:
Dream or Nightmare??

⇒ The MSSM is the *minimal* extension of the SM consistent with spontaneously broken SUSY.

⇒ The MSSM is the *most general* theory consistent with particle content and symmetries of the SM and with spontaneously broken SUSY.

Being very general and full of scalars, there are many new parameters.

In squark sector, there are 12 masses, 30 angles and 27 phases *beyond* the SM.

If we set masses at or below TeV scale, and choose angles and phases to be randomly $O(1)$, then MSSM generates huge new FCNC's and CPV.

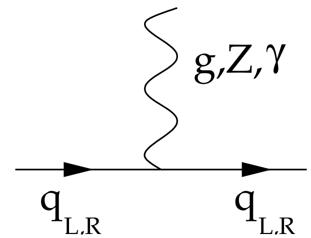
$\Longrightarrow$ Easily ruled out!

Further, LHC only really sensitive to the masses, not angles and phases — that's only 12 out of the 69 parameters!

Reminder of the problem:

For quarks, neutral gauge bosons couplings conserve flavor:

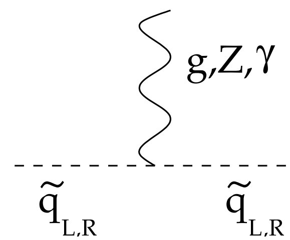
$$\begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} & \mathbf{V_d} & \end{pmatrix} \begin{pmatrix} d^0 \\ s^0 \\ b^0 \end{pmatrix} \implies$$



$$\propto V_d^\dagger V_d = \mathbf{1}.$$

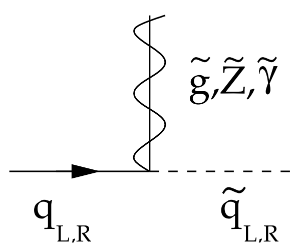
In broken SUSY, similar rotations for the scalars:

$$\begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \end{pmatrix} = \begin{pmatrix} & \widetilde{\mathbf{V}}_{\mathbf{d}} & \end{pmatrix} \begin{pmatrix} \tilde{d}^0 \\ \tilde{s}^0 \\ \tilde{b}^0 \end{pmatrix} \implies$$



$$\propto \tilde{V}_d^\dagger \tilde{V}_d = \mathbf{1}$$

But there are also neutral currents of the form:



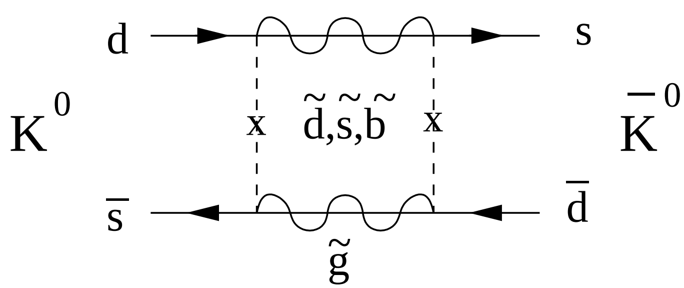
$$\propto \tilde{V}_d^\dagger V_d \neq \mathbf{1}.$$

Squark flavor changing occurs at the gaugino-quark-squark couplings!

How much flavor-changing can there be?

In kaon sector, $\Delta M_{\overline{K}K}$ and ϵ_K constrain flavor-changing angles in the $d-s$ sector to be unnaturally small!

$\Rightarrow$ SUSY flavor and CP problems



Possible Solutions:

Decoupling: Set M_{SUSY} so large that SUSY contributions go away.

But doesn't solve hierarchy problem – SUSY has nothing to do with EWSB!

Alignment: Dynamics set $\tilde{V} = V$ so $\tilde{V}^\dagger V = 1$.

Hard to do in real models. Tends to show up in D-$\overline{D}$ mixing.

Degeneracy: Squarks with same quantum numbers are mass-degenerate at SUSY-breaking scale. Then $\tilde{V}$ is arbitrary.

IMHO, degeneracy is most likely.

In degenerate case, easier to move FC/CPV to squark propagators/mass matrices:

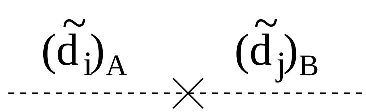
- Diagonalize the gaugino vertices
- This generates off-diagonal squark mass mixing: we must diagonalize two 6×6 squark mass matrices: (similar in up sector)

$$\begin{pmatrix} m^2_{\tilde{d}_L} & m_d(A_d - \mu \tan\beta) & (\Delta^d_{12})_{LL} & (\Delta^d_{12})_{LR} & (\Delta^d_{13})_{LL} & (\Delta^d_{13})_{LR} \\ & m^2_{\tilde{d}_R} & (\Delta^d_{12})_{RL} & (\Delta^d_{12})_{RR} & (\Delta^d_{13})_{RL} & (\Delta^d_{13})_{RR} \\ & & m^2_{\tilde{s}_L} & m_s(A_s - \mu \tan\beta) & (\Delta^d_{23})_{LL} & (\Delta^d_{23})_{LR} \\ & & & m^2_{\tilde{s}_R} & (\Delta^d_{23})_{RL} & (\Delta^d_{23})_{RR} \\ & & & & m^2_{\tilde{b}_L} & m_b(A_b - \mu \tan\beta) \\ & & & & & m^2_{\tilde{b}_R} \end{pmatrix}$$

Assuming all Δ's small and squarks nearly degenerate, we can use mass insertion approximation (MIA):

$$(\delta^d_{ij})_{AB} = \frac{(\Delta^d_{ij})_{AB}}{\tilde{m}^2}$$

with new Feynman rule:



$$\longrightarrow (\Delta^d_{ij})_{AB} = \tilde{m}^2 (\delta^d_{ij})_{AB}$$

What are current constraints on squark δ^q_{ij}'s?

(compiled by Masiero)

CP-Conserving Processes:

12	$(\delta^d_{12})_{LL} < 4 \times 10^{-2}$	$(\delta^d_{12})_{LR} < 4 \times 10^{-3}$	from	Δm_K
	$(\delta^u_{12})_{LL} < 10^{-1}$	$(\delta^u_{12})_{LR} < 3 \times 10^{-2}$		Δm_D
13	$(\delta^d_{13})_{LL} < 10^{-1}$	$(\delta^d_{13})_{LR} < 3 \times 10^{-2}$		Δm_B
23	$(\delta^d_{23})_{LL}$ unbounded	$(\delta^d_{23})_{LR} < 2 \times 10^{-6}$		$\Delta b \to s\gamma$

for $m_{\tilde{q}} = m_{\tilde{g}} = 500\,\text{GeV}$.

CP-Violating Processes:

12	$\sqrt{\text{Im}\,(\delta^d_{12})^2_{LL}} < 3 \times 10^{-3}$	$\sqrt{\text{Im}\,(\delta^d_{12})^2_{LR}} < 3 \times 10^{-4}$	from	ϵ_K
	$\left|\text{Im}\,(\delta^d_{12})_{LL}\right| < 0.5$	$\left|\text{Im}\,(\delta^d_{12})_{LR}\right| < 2 \times 10^{-5}$		ϵ'_K
		$\left|\text{Im}\,(\delta^d_{12})_{LR}\right| < 10^{-6}$		d_n

"Flavors" of SUSY

We can impose external structure on SUSY (or other BTSM models) to yield agreement with current FCNC/CPV bounds. Three broad classes:

"Minimal Flavor Violation" or "Strong Flavor Blindness": (MFV)

(See D'Ambrosio, Giudice, Isidori, Strumia)

— SUSY broken at scale Λ in flavor-blind way.

— RGE's from Λ to M_W *with a minimal spectrum* generates $\delta_{ij} \neq 0$:

$$\begin{aligned} \frac{d}{d\log Q}\left(m^2_{\tilde{Q}}\right)_{ij} &= \frac{1}{16\pi^2}\Big\{-\frac{2}{15}g_1^2 M_1^2 - 6g_2^2 M_2^2 - \frac{32}{3}g_3^2 M_3^2 \\ &\quad +2\Big(Y_u^\dagger m^2_{\tilde{Q}} Y_u + Y_d m^2_{\tilde{Q}} Y_d^\dagger + Y_u^\dagger m^2_{\tilde{U}} Y_u + Y_d m^2_{\tilde{D}} Y_d^\dagger \\ &\quad +Y_u^\dagger Y_u m^2_{H_u} + Y_d Y_d^\dagger m^2_{H_d} + A_u^\dagger A_u + A_d A_d^\dagger\Big)\Big\}_{ij} \end{aligned}$$

Since Y_u and Y_d can't be simultaneously diagonalized, off-diagonal Δ_{ij}'s appear.

— But Δ_{ij}'s proportional to CKM elements:

$$(\delta m^2_{\tilde{Q}})_{ij} \simeq \frac{1}{8\pi^2}\log(M_X/M_{\rm SUSY}) \times (V^\dagger_{\rm KM} V_{\rm KM})_{ij}.$$

— SUSY contributions to FC/CPV processes have same CKM structure as SM contributions $\Rightarrow$ same weak phases!

"Minimal Flavor Violation": *(con't)*

— SUSY merely changes some decay rates (usually by $O(1)$ or less) but does not contribute to CP asymmetries.

— Unitarity triangle is expected to look just like SM.

— Example: Anomaly mediation (all $\delta_{ij} = 0$), low-scale gauge mediation (all $\delta_{ij} \simeq 0$), or mSUGRA models (all $\delta_{ij} \propto V_{\mathrm{KM},ij}$)

Where do we look for this?

Small to moderate $\tan\beta$: $b \to s\gamma$ is best constraint to date. Must measure strength of FCNC interactions!

Large $\tan\beta$: can also use $B_{(s)} \to \mu\mu, \tau\tau$ (more later ...)

This is a very attractive possibility, since it naturally solves the SUSY flavor and CP problems.

⇒ But then CPV asymmetries are not interesting.

⇒ Need a machine to do precision FCNC's, like a SuperB factory!

"Nearly Minimal Flavor Violation" or "Weak Flavor Blindness":

— SUSY-breaking mechanism at Λ is flavor-blind as in MFV.

— Running with a *non-minimal* spectrum produces flavor mixing which is not proportional to CKM elements.

— Attractive examples:

RH Neutrinos: If RH neutrinos sit at a scale $M_W < M_R < \Lambda$, then above M_R unknown Y_ν alters running of slepton masses. Since $\theta_{\mu\tau} \sim 45^\circ$, this can be large effect, leading to $\tau \to \mu\gamma$ at observable rates.

GUT effects: If flavor violation is seeded above GUT scale, then lepton and quark FCNCs are related. Example: In SU(5), (See Masiero et al)

$$\mathbf{\overline{5}}: \quad (\delta^d_{ij})_{RR} \simeq (m_{\tilde{\ell}}/m_{\tilde{d}})^2 (\delta^\ell_{ij})_{LL},$$

$$\mathbf{10}: \quad (\delta^{u,d}_{ij})_{LL} \simeq (m_{\tilde{u}}/m_{\tilde{Q}})^2 (\delta^u_{ij})_{RR} \simeq (m_{\tilde{e}}/m_{\tilde{Q}})^2 (\delta^\ell_{ij})_{RR}.$$

— Correlations between lepton and quark flavor changing would be strong evidence for scenario.

Good reason to believe in large $\tau \to \mu\gamma$ and other leptonic effects from RH neutrino at intermediate scales.

$\Rightarrow$But additional, less motivated, assumptions necessary to move these to quark sector.

(More) General MSSM:

— Uncouple SUSY flavor breaking from SM Yukawas/CKM matrix.

— Generates a host of problems known as SUSY flavor and CP problems. *This would appear to be a very bad idea!*

— Need some additional flavor symmetry to avoid disaster.

— But reasonable flavor symmetries often treat third generation differently.

— Reasonable for FCNCs to be observable in the 3rd generation while small in all others. Example:

U(2) Flavor Symmetry: First two generations in a U(2) doublet, third is a singlet (very different!). Break symmetry in two stages: $U(2) \to U(1) \to$ nothing, which sets up a Yukawa hierarchy like that seen in CKM matrix.

In models like these, effects at a super B factory can be huge!

Two important notes about CP violation in SUSY models:

- Even with *complete* degeneracy/minimal flavor violation, there are still new CPV phases in the MSSM. At a minimum, two phases cannot be removed and they show up in EDM measurements.

  $\Longrightarrow$ Dipole moment experiments are crucially important for testing and constraining SUSY!

- THERE ARE NO GUARANTEES!
  We need more CPV in order to explain baryon asymmetry, but SUSY has ways to get B asymmetry at high scales, in sectors partially removed from the MSSM.

  At its "worst" SUSY can completely hide flavor physics behind a wall of weak-scale degeneracy!

THE $b \to \bar{s}ss$ TRANSITION

Appearance of any $(\delta_{23}^{u,d})_{AB} \neq 0$ generates non-SM $b \to \bar{s}ss$ transitions through chargino or gluino loops.

Affected processes include:

- $\mathrm{Br}(B \to \phi K_S) = 8.4^{+2.5}_{-2.1} \times 10^{-6}$
- $A_{\mathrm{CP}}(B \to \phi K_S)$, including $S_{\phi K}$ and $C_{\phi K}$
- Br (and A_{CP}) of $B \to \eta^{(\prime)} K_S$, $B \to K^+ K^- K_S$

But other transitions are also correlated, including $b \to s\gamma$ and $b \to s\bar{q}q$:

- $\mathrm{Br}(B \to X_s\gamma) = (3.34 \pm 0.38) \times 10^{-4}$ and $A_{\mathrm{CP}}(B \to X_s\gamma) = -0.02 \pm 0.04$.
- $\mathrm{Br}(B \to X_s\ell^+\ell^-) = (6.1 \pm 1.9) \times 10^{-6}$ (and related observables)
- $\mathrm{Br}(B_s \to \ell^+\ell^-) < 2.6 \times 10^{-6}$
- B_s–$\overline{B}_s$ mixing ($\Delta M_s > 14.4\,\mathrm{ps}^{-1}$) and other processes that rely on it, like $B_s \to D_s^+ K^-$.
- and others . . .

$B \to \psi K_S$ vs. $B \to \phi K_S$

BaBar vs. Belle??

Strong agreement on phase in $B \to \psi K_S$:

$$\sin 2\beta_{\psi K} = \begin{cases} 0.741 \pm 0.075 & \text{(Babar)} \\ 0.733 \pm 0.064 & \text{(Belle)} \end{cases} \implies 0.736 \pm 0.049 \quad \text{(average)}$$

"Old" published data showed discrepancy between $\beta_{\psi K}$ and $\beta_{\phi K}$, but not convincing:

$$\sin 2\beta_{\phi K} = \begin{cases} -0.18 \pm 0.51 & \text{(Babar)} \\ -0.73 \pm 0.68 & \text{(Belle)} \end{cases}$$

LP03 results are more complicated:

$$\sin 2\beta_{\phi K} = \begin{cases} 0.45 \pm 0.44 & \text{(Babar)} \\ -0.96 \pm 0.51 & \text{(Belle)} \end{cases}$$

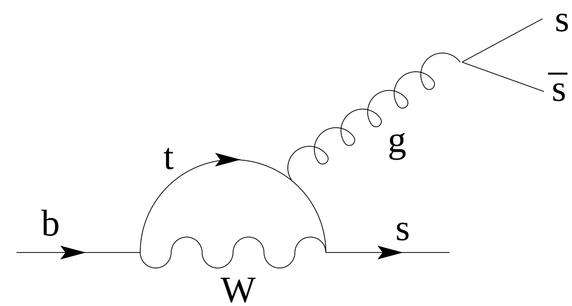
Belle data shows a 3.3σ discrepancy, but Babar within 1σ. Data disagree at 2.7σ.

But other $b \to \bar{s}ss$ transitions also give low $S_{\phi K}$, including $B \to K^+ K^- K_S$ and $B \to \eta' K_S$. For all $b \to \bar{s}ss$ processes,

$$S_{\phi K} = 0.24 \pm 0.15 \quad \Leftarrow \; 3.1\sigma \text{ below } b \to c\bar{s}s \text{ modes}$$

$B \to \phi K_S$: the Basics

In Standard Model, $b \to \bar{s}ss$ transition through penguin, has no CPV phase in decay (clear in Wolfenstein parametrization), so phase comes from B^0–$\overline{B}^0$ mixing.



Compare to $B \to \psi K_S$: tree level in SM, but also gets phase from mixing.

$\Longrightarrow$ Phases of ψK_S and ϕK_S should match!

$\Longrightarrow$ $B \to \phi K_S$ more sensitive to new physics that doesn't violate CKM unitarity!

Two interesting observables:

- $\mathrm{Br}(B \to \phi K_S)$, subject to large long-distance corrections.
- $A_{\mathrm{CP}}(B \to \phi K_S)$, many systematics drop out.

Define:

$$A_{\rm CP}[B^0 \to \phi K_S](t) \equiv \frac{\Gamma(\overline{B}^0_{\rm phys}(t) \to \phi K_S) - \Gamma(B^0_{\rm phys}(t) \to \phi K_S)}{\Gamma(\overline{B}^0_{\rm phys}(t) \to \phi K_S) + \Gamma(B^0_{\rm phys}(t) \to \phi K_S)} = -C_{\phi K}\cos(\Delta M t) + S_{\phi K}\sin(\Delta M t),$$

where

$$C_{\phi K} = \frac{1-|\lambda_{\phi K}|^2}{1+|\lambda_{\phi K}|^2} \quad \text{and} \quad S_{\phi K} = \sin 2\beta_{\phi K} = \frac{2\,{\rm Im}\lambda_{\phi K}}{1+|\lambda_{\phi K}|^2},$$

with

$$\lambda_{\phi K} \equiv -\underbrace{e^{-2i(\beta+\theta_d)}}_{\text{indirect}}\underbrace{\frac{\overline{\mathcal{A}}(\overline{B}^0 \to \phi K_S)}{\mathcal{A}(B^0 \to \phi K_S)}}_{\text{direct}}$$

where β is SM phase in B^0–$\overline{B}^0$ mixing.

θ_d is contribution of new physics to mixing phase.
→ Take to be zero since no evidence for non-zero value.
→(Would be generated by δ_{13} mixings, not δ_{23}.)

DATA: (SM predicts $C_{\phi K} = -0.008$)

$$\left.\begin{array}{ll} \text{Babar:} & C_{\phi K} = -0.80 \pm 0.40 \\ \text{Belle:} & C_{\phi K} = 0.56 \pm 0.44 \end{array}\right\} -0.19 \pm 0.30$$

Amplitudes $\mathcal{A}$ and $\overline{\mathcal{A}}$ can depend on several separate channels (labelled m), each with own strong (δ_m) and weak (φ_m) phases:

$$\begin{aligned} \mathcal{A} &= \sum_m a_m e^{+i\varphi_m} e^{+i\delta_m} \\ \overline{\mathcal{A}} &= \sum_m a_m e^{-i\varphi_m} e^{+i\delta_m} \end{aligned}$$

For one new amplitude a_{new} only: $(r \equiv a_{\text{new}}/a_{\text{SM}})$

$$\lambda_{\phi K} \simeq -e^{-2i\beta} \frac{1 + re^{i(\delta-\varphi)}}{1 + re^{i(\delta+\varphi)}}$$

Then given $r \gg 1$ (*i.e.*, $a_{\text{new}} \gg a_{\text{SM}}$),

$$\lambda_{\phi K} \simeq -e^{-2i(\beta+\varphi)} \quad \longrightarrow \quad \text{strong phase drops out!} \quad \longrightarrow \quad C_{\phi K} \to 0$$

However many authors use this approximation even when $r \sim 1$.

For $r \sim 1$ must get strong phase from factorization calculation.

Lots of work on $B \to \phi K_S$ in SUSY of late:

- T. Moroi, Phys. Lett. B **493**, 366 (2000) [arXiv:hep-ph/0007328].
- E. Lunghi and D. Wyler, Phys. Lett. B **521**, 320 (2001) [arXiv:hep-ph/0109149].
- D. Chang, A. Masiero and H. Murayama, arXiv:hep-ph/0205111.
- M. B. Causse, arXiv:hep-ph/0207070.

$\Longleftarrow$ Babar/Belle $S_{\phi K}$ results $\Longrightarrow$

- G. Hiller, arXiv:hep-ph/0207356.
- A. Datta, Phys. Rev. D **66**, 071702 (2002) [arXiv:hep-ph/0208016].
- M. Ciuchini and L. Silvestrini, arXiv:hep-ph/0208087.
- M. Raidal, Phys. Rev. Lett. **89**, 231803 (2002) [arXiv:hep-ph/0208091].
- B. Dutta, C. S. Kim and S. Oh, arXiv:hep-ph/0208226.
- G. L. Kane, P. Ko, H. b. Wang, C. Kolda, J. H. Park and L. T. Wang, arXiv:hep-ph/0212092 and Phys. Rev. Lett. **90**, 141803 (2003) [arXiv:hep-ph/0304239].
- R. Harnik, D. T. Larson, H. Murayama and A. Pierce, arXiv:hep-ph/0212180.
- M. Ciuchini, E. Franco, A. Masiero and L. Silvestrini, Phys. Rev. D **67**, 075016 (2003) [arXiv:hep-ph/0212397].
- S. Baek, Phys. Rev. D **67**, 096004 (2003) [arXiv:hep-ph/0301269].
- J. Hisano and Y. Shimizu, Phys. Lett. B **565**, 183 (2003) [arXiv:hep-ph/0303071].
- K. Agashe and C. D. Carone, Phys. Rev. D **68**, 035017 (2003) [arXiv:hep-ph/0304229].
- D. Chakraverty, E. Gabrielli, K. Huitu and S. Khalil, arXiv:hep-ph/0306076.
- T. Goto, Y. Okada, Y. Shimizu, T. Shindou and M. Tanaka, arXiv:hep-ph/0306093.

Factorization

IR

Use technique of Beneke, Buchalla, Neubert and Sachradja (BBNS) to evaluate matrix element for $B \to M_1 M_2$.

$C_{\phi K}$ particularly sensitive to choice of scheme.

BBNS scheme does not properly address subleading power corrections to annihilation channels, or from hard scattering with spectator quarks. These corrections are IR-divergent – prescription for controlling divergence introduces new parameters.

UV

Calculate SUSY contributions to $B \to \phi K_S$ in basis of 4-quark operators. Four major classes:

Charged current: Such as
$(\overline{u}b)_{V-A}(\overline{s}u)_{V-A}$
which is relevant at NLO.

Electroweak penguins: Such as
$(\overline{s}b)_{V-A}\sum_q(\overline{q}q)_{V-A}$

Gluonic penguins: Similar to EW, but enhanced by α_s.

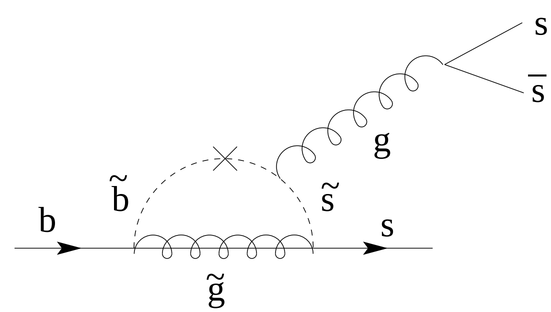
(Chromo)magnetic moments:
Such as $\overline{s}_L\sigma_{\mu\nu}b_R G^{\mu\nu}$
Requires a helicity flip.

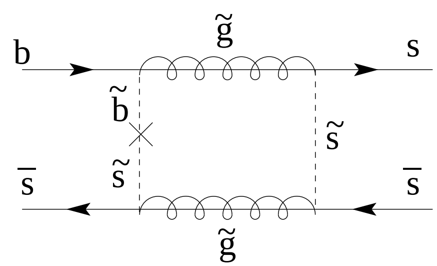
At LO, only keep last two classes.

GLUINO-MEDIATED FCNC'S

Rules for next few slides:

- Work in mass insertion approximation.
- Use BBNS for long distance, with no annihilation/hard scattering corrections.
- Examine only contributions from gluino penguins and boxes.
- Consider only one $(\delta^d_{23})_{AB}$ at a time.
  $\Longrightarrow$ 4 cases: LL, RR, LR, RL
- Ignore possible problems created in other charmless modes, like $B \to \pi\pi$, $B \to \pi K$. Why?
  - Techniques known for large $B \to VP$ corrections with vanishing $B \to VV$ corrections: $(\delta^d_{23})_{LL} = (\delta^d_{23})_{RR}$ [Kagan]
  - Only one SM diagram contributes to $B \to \phi K_S$, while many contribute to $B \to \pi\pi$. How sure are we of SM predictions?





Constraints & Correlations

Mixing of $\tilde{s}$-$\tilde{b}$ implies more than a new CPV phase in $B \to \phi K_S$:

Br($B \to \phi K$): Currently measured to be $8.4^{+2.5}_{-2.1} \times 10^{-6}$
We require prediction to be $< 16 \times 10^{-6}$ using BBNS.
(Aside: In SM, BBNS predicts Br $\simeq 5 \times 10^{-6}$.)

Br($B \to X_s\gamma$): Requires helicity flip, so only a strong constraint on LR or RL, suppressing $(\delta^d_{23})_{LR,RL} \lesssim 10^{-2}$ in typical models. We require:

$$2.0 \times 10^{-4} < \text{Br}(B \to X_s\gamma) < 4.5 \times 10^{-4}$$

Generous range because NLO corrections in SUSY not complete.

$A_{\text{CP}}^{\text{direct}}(B \to X_s\gamma)$**:** Only useful for LR models (RL lacks interference with SM). Current bounds weak:

$$A_{\text{CP}} = (-7.9 \pm 11.0)(1.0 \pm 0.03)\%$$

SM predicts $\sim 0.5\%$, so a signal would be significant!

B_s-$\overline{B}_s$ mixing: As constraint, demand $\Delta M_s > 14.9\,\mathrm{ps}^{-1}$.

Correlation: In SM, $\Delta M_s < 20\,\mathrm{ps}^{-1}$, but LL and RR models can increase that significantly $\longrightarrow$ bad news for Run II!

$\mathrm{Im}(\delta^d_{23})_{LL,RR}$ also shifts mixing phase β_s. Shows up in $A_{\mathrm{CP}}(B_s \to \psi\phi)$, which is about zero in SM.

Dilepton charge asymmetry: At hadron colliders:

$$A_{\ell\ell} = \frac{N(\ell^+\ell^+) - N(\ell^-\ell^-)}{N(\ell^+\ell^+) + N(\ell^-\ell^-)} = \frac{N(BB) - N(\overline{BB})}{N(BB) + N(\overline{BB})} \simeq \mathrm{Im}\left(\frac{\Gamma_{12}(B_s)}{M_{12}(B_s)}\right)$$

In SM, $\arg M_{12} \simeq \arg \Gamma_{12}$, so $A_{\ell\ell} \simeq 10^{-4}$ (or 10^{-3} for B). SUSY can change $\arg M_{12}$ considerably.

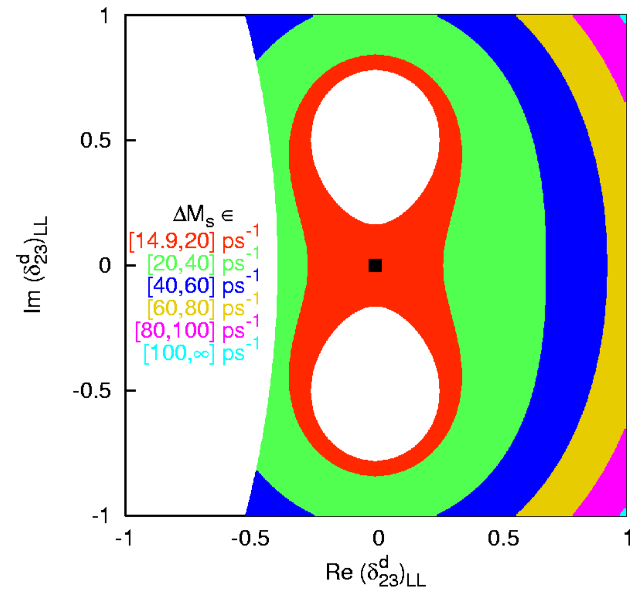
LL — Best motivated, even in degenerate models. Natural for $(\delta^d_{23})_{LL} \sim V_{ts}$.

Vary over $|\mathrm{Re,Im}\,(\delta^d_{23})_{LL})| \leq 1$ for $m_{\tilde{q}} = m_{\tilde{g}} = 400\,\mathrm{GeV}$.

Apply constraints:

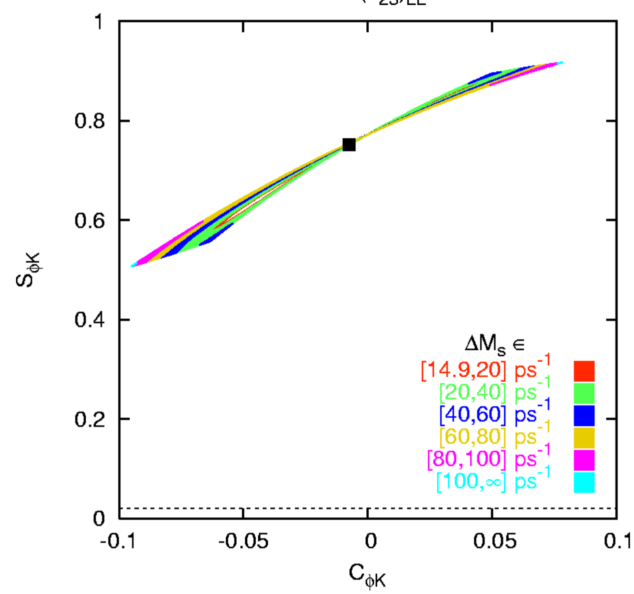
- No significant constraint from $\mathrm{Br}(B \to \phi K)$. (Cannot relieve discrepancy between BBNS and experiment!)
- $\mathrm{Br}(B \to X_s\gamma)$ rules out $\mathrm{Re}\,(\delta^d_{23})_{LL} \lesssim -\frac{1}{2}$
- ΔM_s rules out $\frac{1}{4} \lesssim |\mathrm{Im}\,(\delta^d_{23})_{LL}| \lesssim \frac{3}{4}$ for $|\mathrm{Re}\,(\delta^d_{23})_{LL}| \lesssim \frac{1}{4}$.

Shading is ΔM_s — can be as large as $100\,\mathrm{ps}^{-1}$!

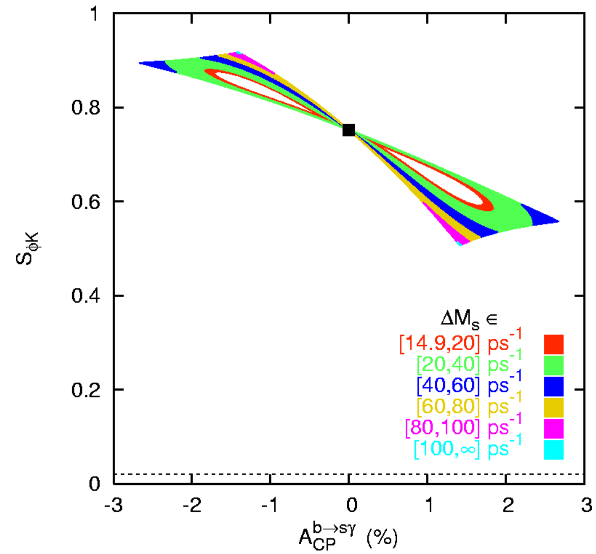


Observables:

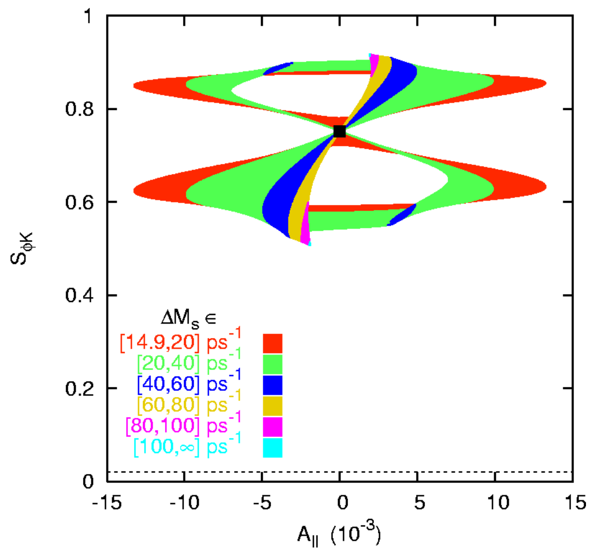
$A_{\mathrm{CP}}(B \to \phi K_S)$: $S_{\phi K}$ can shift from SM, but only as low as 0.5.
$C_{\phi K}$ can be as large as ± 0.1.
Large shifts in $S_{\phi K}$ imply somewhat smaller shifts in $C_{\phi K}$.
(N.B. Vary $\tilde{m}$'s in a moment...)



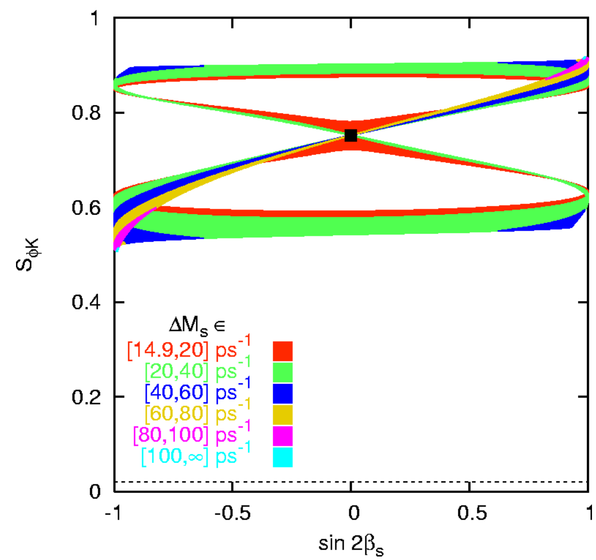
$A_{\mathrm{CP}}(B \to X_s\gamma)$: Large changes in $S_{\phi K}$ imply changes here of few %. Correlation pretty clean. Need $10\mathrm{ab}^{-1}$ to measure!



$A_{\ell\ell}$: Can easily generate asymmetries 1 or 2 orders above SM predictions. But correlation with $S_{\phi K}$ not clear.



$\sin 2\beta_s$: All over the place! Opportunity for a major deviation from SM, but correlation with $S_{\phi K}$ not clean at all.



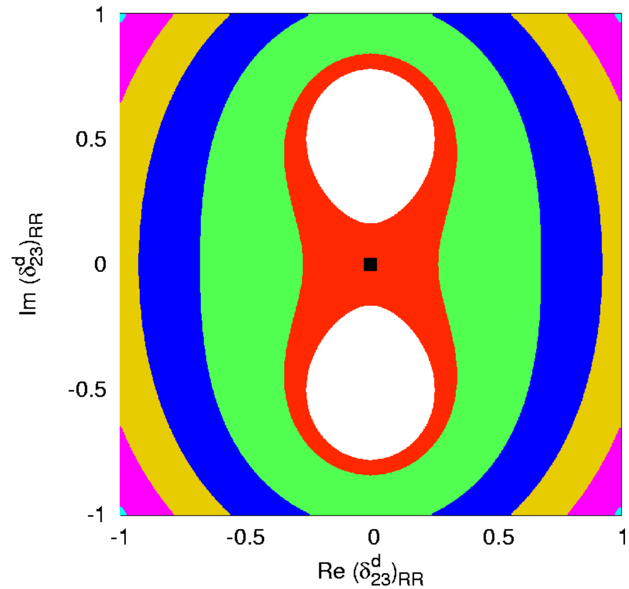
RR

Motivated in models with flavor physics at or above GUT scale – connects large ν mixing to large $(\delta^d_{23})_{RR}$.

Apply constraints:

- No significant constraint from $\mathrm{Br}(B \to \phi K)$. (Cannot relieve discrepancy between BBNS and experiment!)
- No significant constraint from $\mathrm{Br}(B \to X_s \gamma)$. (RR doesn't interfere at amplitude level.)
- ΔM_s rules out $\frac{1}{4} \lesssim |\mathrm{Im}\,(\delta^d_{23})_{LL}| \lesssim \frac{3}{4}$ for $|\mathrm{Re}\,(\delta^d_{23})_{LL}| \lesssim \frac{1}{4}$.

Shading is ΔM_s — can be as large as $100\,\mathrm{ps}^{-1}$!

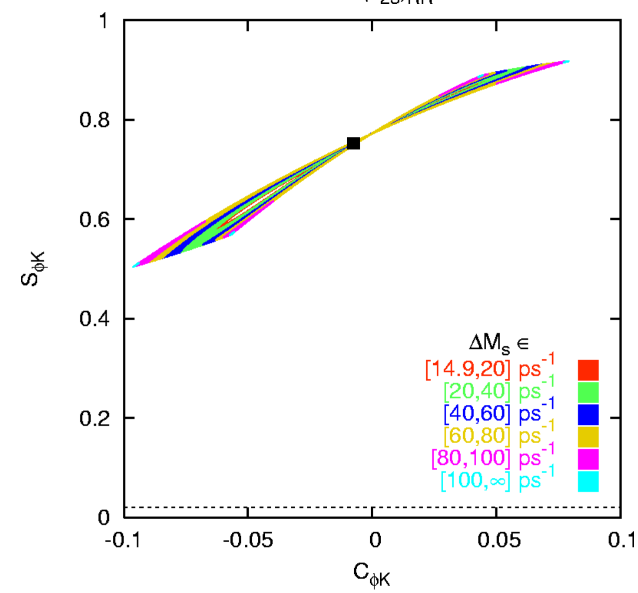


Observables:

$A_{\mathrm{CP}}(B \to \phi K_S)$: $S_{\phi K}$ can shift from SM, but only as low as 0.5. $C_{\phi K}$ can be as large as ± 0.1.

Large shifts in $S_{\phi K}$ imply somewhat smaller shifts in $C_{\phi K}$.

Essentially same as LL case!



$A_{\rm CP}(B \to X_s \gamma)$**:** Very different from LL case.

No interference with SM, so no new CPV phase.

No deviation from SM expected!

$A_{\ell\ell}$**:** Same as LL case.

Can easily generate asymmetries 1 or 2 orders above SM predictions.

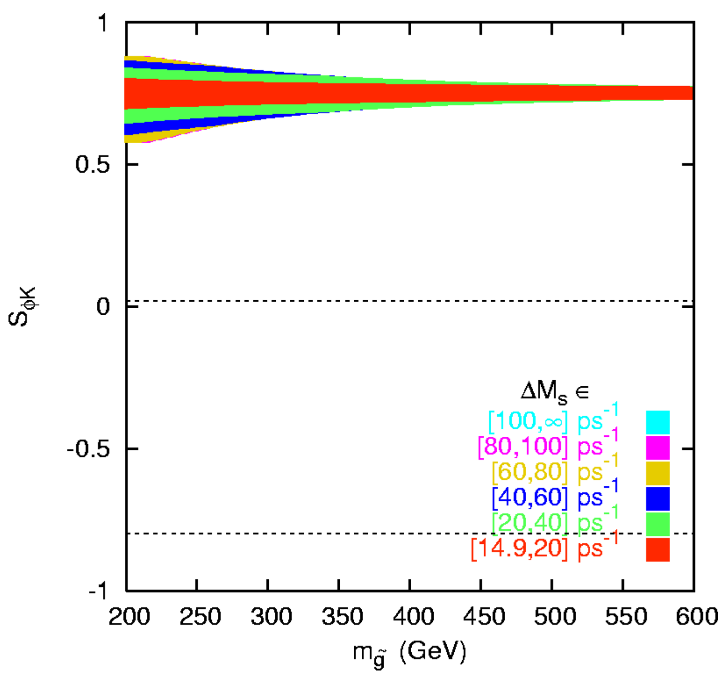
But correlation with $S_{\phi K}$ not clear.

$\sin 2\beta_s$**:** Same as LL case.

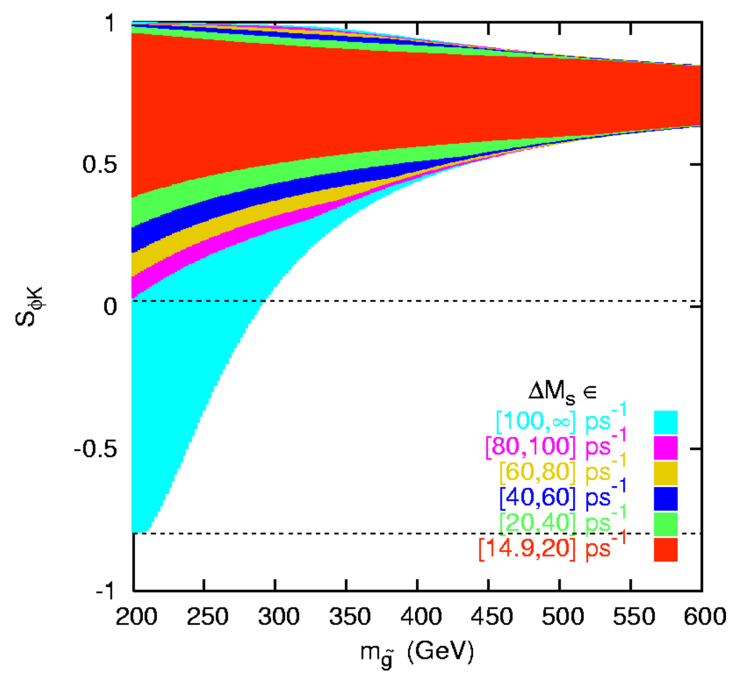
All over the place! Opportunity for a major deviation from SM, but correlation with $S_{\phi K}$ not clean at all.

What if we vary the SUSY masses away from $m_{\tilde{g}} = m_{\tilde{q}} = 400\,\text{GeV}$?? (Ex: RR case)

$m_{\tilde{g}}^2 = 3m_{\tilde{q}}^2$



$m_{\tilde{g}}^2 = 0.5m_{\tilde{q}}^2$:



In order for LL or RR insertions to explain $S_{\phi K} < 0$ need squarks and gluinos below 300 GeV.

⇒ Either good news for experimentalists or bad news for the LL and RR cases.

LR

Of form $\tilde{s}_L^\dagger \tilde{b}_R$. Requires flavor-mixing and EW-breaking. Should be smaller than LL or RR by $\sim m_W^2/M_{\rm SUSY}^2$.

Does not contribute to penguin operators, but only to chromomagnetic operators.

Lacks helicity suppression of SM diagrams $\longrightarrow$ enhanced over SM by $m_{\tilde{g}}/m_b$!

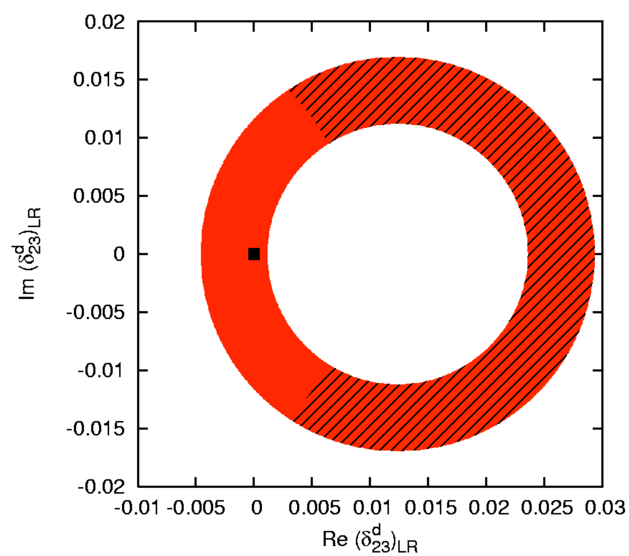
Constrained by charmless, nonleptonic B decays, but especially by $b \to s\gamma$.

Apply constraints:

- $\mathrm{Br}(B \to X_s\gamma)$ rules out large regions of parameter space!
  (Not centered because of interference.)

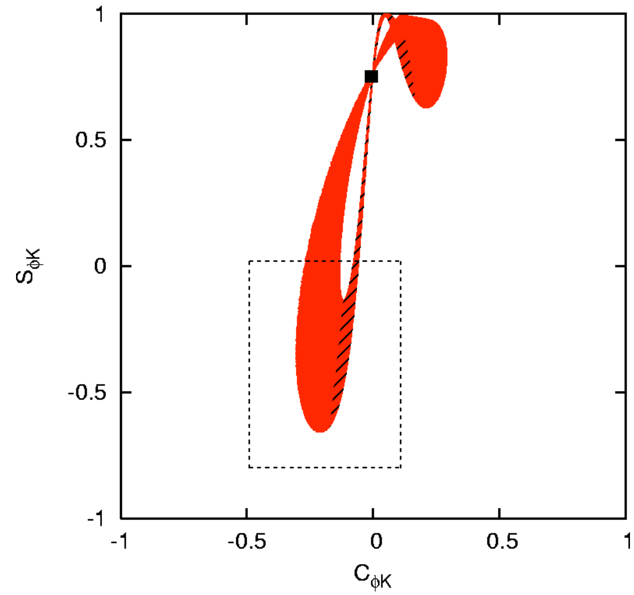
- $\mathrm{Br}(B \to \phi K)$ can be much larger than SM prediction or observation!
  Regions with Br$> 16 \times 10^{-6}$ hatched out.
  $\Longrightarrow$ This is a new & important constraint on SUSY models!

- No sizable contribution to ΔM_s.

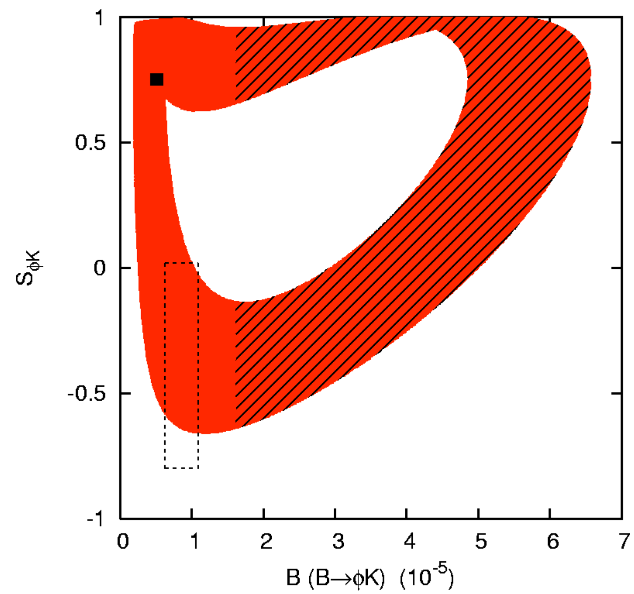


Observables:

$A_{\rm CP}(B \to \phi K_S)$**:** $S_{\phi K}$ can shift from SM, can become significantly negative.
$C_{\phi K}$ can be as large as ± 0.3.
Clean correlation between $S_{\phi K}$ and $C_{\phi K}$.
(Both negative or both positive.)



BR$(B \to \phi K)$**:** Can bring BBNS calculation back into line with experiment (dashed box).

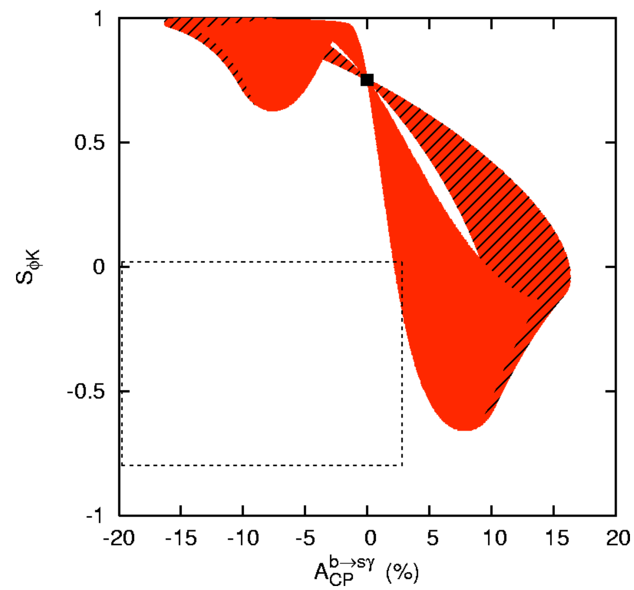


$A_{\rm CP}(B \to X_s\gamma)$**:**

Large changes in $S_{\phi K}$ imply asymmetries as large as 10–15%.

Correlation pretty clean.

Negative $S_{\phi K}$ prefers positive $A_{\rm CP}^{B\to X_s\gamma}$.



$A_{\ell\ell}$**:** Only small effects – very difficult to measure.

$\sin 2\beta_s$**:** Miniscule effects – will appear SM-like.

RL

Of form $\tilde{s}_R^\dagger \tilde{b}_L$. Requires flavor-mixing and EW-breaking. Should be smaller than LL or RR by $\sim (m_s/m_b)(m_W^2/M_{\rm SUSY}^2)$. But perhaps not ...

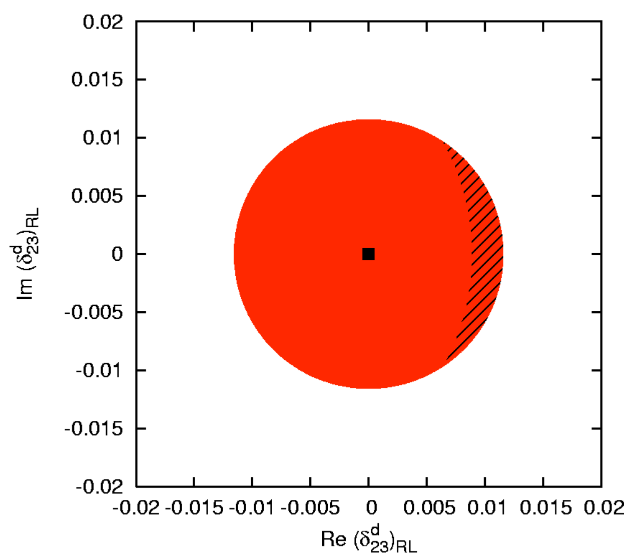
Does not contribute to penguin operators, but only to chromomagnetic operators.

Lacks helicity suppression of SM diagrams $\longrightarrow$ enhanced over SM by $m_{\tilde{g}}/m_b$!

Does not interfere with SM amplitudes thanks to unusual helicity stucture
$\longrightarrow$ not much like LR case!

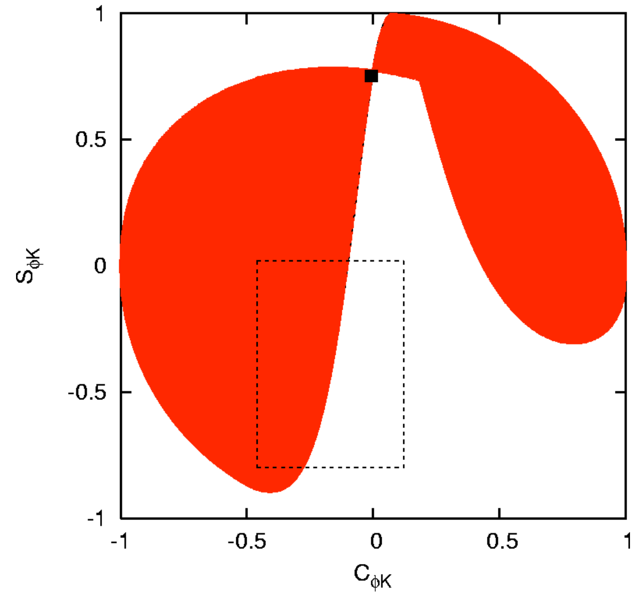
Apply constraints:

- $\mathrm{Br}(B \to X_s\gamma)$ rules out large regions of parameter space.
  Centered about origin because no interference.
- $\mathrm{Br}(B \to \phi K)$ can be much larger than SM prediction or observation!
  Regions with $\mathrm{BR} > 16 \times 10^{-6}$ hatched out.
  $\Longrightarrow$ This is a new & important constraint on SUSY models! (as in LR case)
- No sizable contribution to ΔM_s.

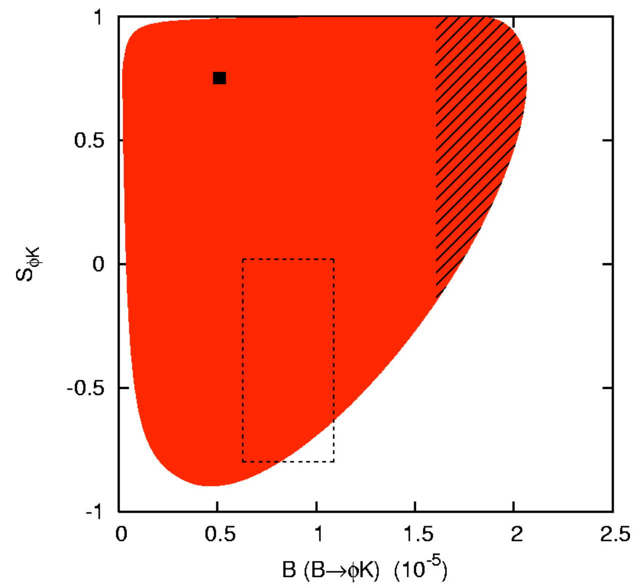


Observables:

$A_{\text{CP}}(B \to \phi K_S)$**:** $S_{\phi K}$ can shift from SM, can become significantly negative.
$C_{\phi K}$ can be as large as ± 0.3.
Not a clean correlation between $S_{\phi K}$ and $C_{\phi K}$!



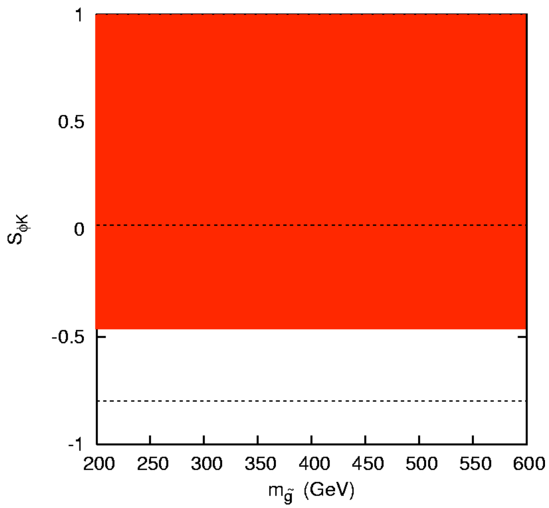
BR$(B \to \phi K)$**:** Can bring BBNS calculation back into line with experiment (dashed box).

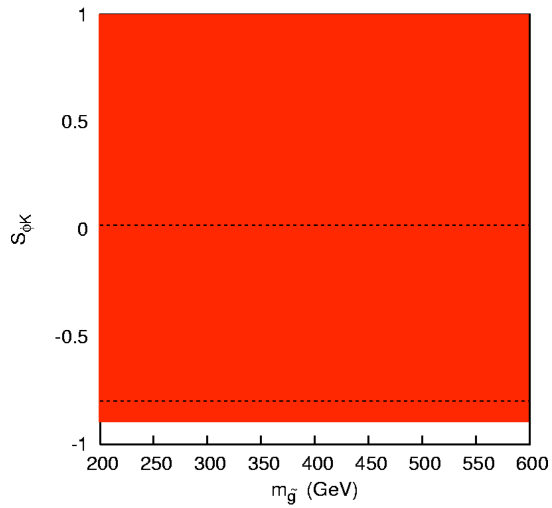


And that's it! Nothing new happens in $A_{\text{CP}}(B \to X_s\gamma)$, or $A_{\ell\ell}$, or in $\sin 2\beta_s$!
Only observable consequence is in BR and A_{CP} of $B \to \phi K$!

Varying the squark and gluinos masses . . .

$$m_{\tilde{g}}^2 = 3m_{\tilde{q}}^2 :$$

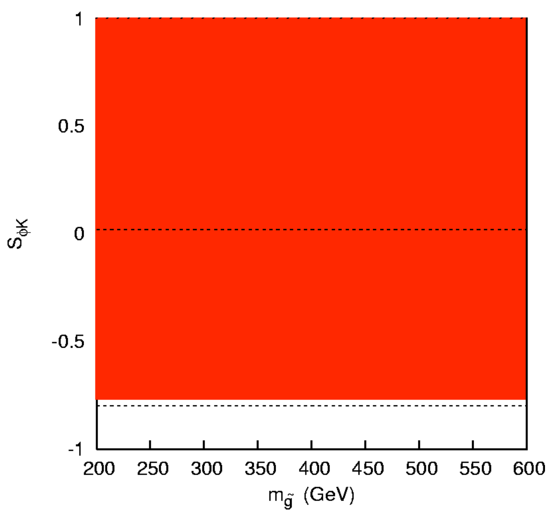
LR: 

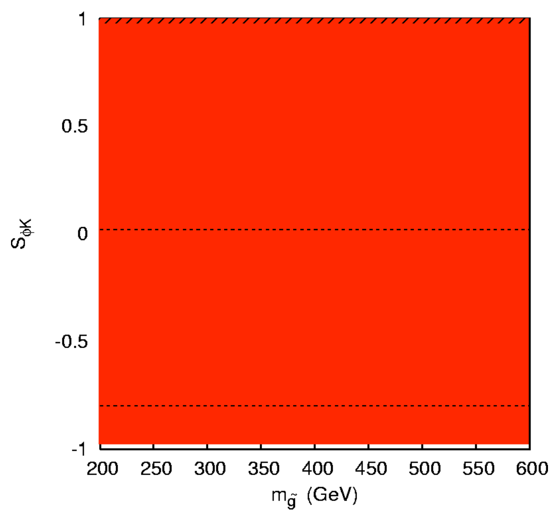
RL: 

What happened to decoupling?!?

As $m \to \infty$, constraints decouple at same rate as signal.

$$m_{\tilde{g}}^2 = 0.5m_{\tilde{q}}^2 :$$

LR: 

RL: 

So δ increases to offset increasing masses.

By $\tilde{m} \gtrsim 1\,\text{TeV}$, δ can't keep increasing, so signal does fall away.

What can we conclude??

Lots of room left for interesting SUSY flavor physics which is consistent with everything we currently know!!

BUT, if $S_{\phi K}$ is indeed negative, then:

	LL	RR	LR	RL
(δ^d_{23})	$O(1)$	$O(1)$	$O(10^{-2})$	$O(10^{-2})$
Masses	$\lesssim 300\,\text{GeV}$	$\lesssim 300\,\text{GeV}$	$\lesssim$ TeV	$\lesssim$ TeV
$C_{\phi K}$	neg, $O(\frac{1}{10})$	neg, $O(\frac{1}{10})$	neg, $O(\frac{1}{10})$	$\pm$, up to $O(1)$
$A_{\text{CP}}^{b\to s\gamma}$	pos, few %	SM-like	pos, $\lesssim 15\%$	SM-like
ΔM_s	can be large	can be large	SM-like	SM-like
$A_{\ell\ell}$	can be large	can be large	SM-like	SM-like
$A_{\text{CP}}(B_s \to \psi\phi)$	can be large	can be large	SM-like	SM-like
$\text{BR}(B \to \phi K)$	SM-like	SM-like	varies	varies

N.B. Any observable which is SM-like can be made to differ by a small admixture of a different insertion. For example, can get negative $S_{\phi K}$ from RL and large ΔM_s from LL or RR.

A change of pace . . .

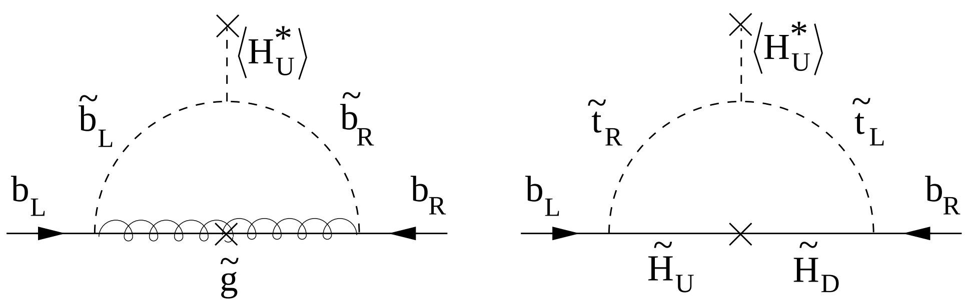
The Rare Decays $B \to \ell^+\ell^-$

In the SM, the decays $B \to \ell^+\ell^-$ are doubly cursed: GIM-suppressed electroweak boxes and penguins which are helicity suppressed.
Prediction:

$$\mathrm{Br}\,(B \to \mu\mu) \simeq 1.6 \times 10^{-10} \qquad \mathrm{Br}\,(B_s \to \mu\mu) \simeq 4.3 \times 10^{-9}$$
$$\mathrm{Br}\,(B \to \tau\tau) \simeq (2-4) \times 10^{-8} \qquad \mathrm{Br}\,(B_s \to \tau\tau) \simeq (0.8-1.2) \times 10^{-6}$$

In MSSM, boxes and penguins contribute at order of SM.
But Higgs bosons can contribute at 2-3 orders of magnitude above SM!! (So-called "Higgs penguins".)

Why? Because at loop level, MSSM is not really a type-II two-Higgs doublet model — H_u couples to d-quarks and gives them a fraction of their mass!



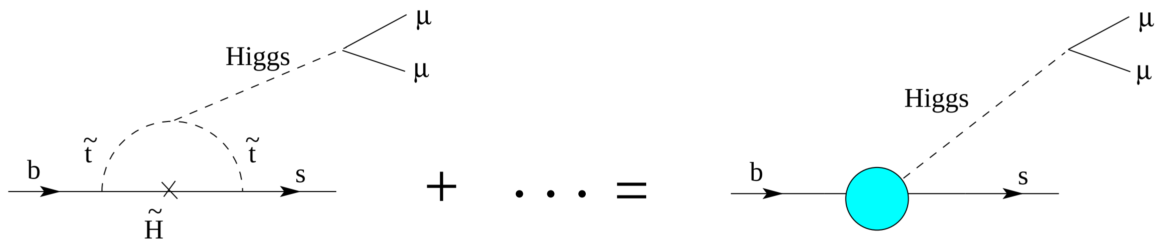
Resulting contributions to d-masses scales as $\frac{\tan\beta}{16\pi^2} \times O(1)$. At large $\tan\beta$, this can itself be $O(1)$! [Hall, Rattazzi, Sarid]

When SUSY partners integrated out, effective Lagrangian contains flavor-changing Higgs couplings.

This happens even for minimal flavor violation (this is totally a CKM effect)

AND even for heavy superpartners (this is a non-decoupling effect).

Opportunity exists to observe this effect in rare B decays. [Babu & Kolda]



$$\mathrm{BR} \propto \frac{\tan^6\beta}{m_A^4}$$

Since this is a Higgs effect, amplitudes $\propto$ Yukawas of final states:

$$\Longrightarrow \quad \frac{\mathrm{Br}(B \to \tau\tau)}{\mathrm{Br}(B \to \mu\mu)} = \left(\frac{m_\tau}{m_\mu}\right)^2 \simeq 300$$

Since this is a CKM effect, amplitude $\propto$ CKM elements

$$\Longrightarrow \quad \frac{\mathrm{Br}(B_s \to \ell\ell)}{\mathrm{Br}(B_d \to \ell\ell)} = \left(\frac{V_{ts}}{V_{td}}\right)^2 \simeq 25$$

How large can this be effect be?

At large $\tan\beta$ CDF bound $\mathrm{Br}(B_s \to \mu\mu) < 10^{-6}$ is already a non-trivial constraint on the mSUGRA parameter space.

In non-MFV models, one expects (much) larger branching ratios. One can even have observable $B_s \to \mu\mu$ with $\tan\beta$ as low as 5. (Kane, Kolda, Lennon)

The Future:

With $2\,\text{fb}^{-1}$ of data, CDF/D0 can probe $\text{BR}(B_s \to \mu\mu)$ down to about 10^{-7}. In MFV models, this is equivalent to:

$$\text{BR}\,(B \to \mu\mu) \;=\; \left(\tfrac{V_{td}}{V_{ts}}\right)^2 \times\; \text{BR}\,(B_s \to \mu\mu) \;\; \simeq 5 \times 10^{-9}$$

$$\text{BR}\,(B \to \tau\tau) \;=\; \left(\frac{m_\tau}{m_\mu}\right)^2 \times\; \text{BR}\,(B \to \mu\mu) \;\; \simeq 1.4 \times 10^{-6}$$

With $10\,\text{ab}^{-1}$ of data, SuperB can probe:

$$\text{BR}\,(B \to \mu\mu) \;\gtrsim\; 5 \times 10^{-9}$$

$$\text{BR}\,(B \to \tau\tau) \;\gtrsim\; 2 \times 10^{-6} \quad \text{(requires tagged } B \text{ sample)}$$

Thus SuperB will have similar sensitivity to Tevatron, but in completely different channels. Could provide important check of MFV!

And with $1\,\text{ab}^{-1}$ on the $\Upsilon(5s)$, sensitivity to $B_s \to \mu\mu$ should be at the 10^{-8} level. Tevatron would need 10 to $20\,\text{fb}^{-1}$ to match this!

(LHC will have enough B/B_s to do $B_{(s)} \to \mu\mu$, but tagging efficiencies are unknown at present. Will never be able to study the τ mode.)

Any other observables due to SUSY Higgs effects?

$B \to X_s \ell\ell$: Same basic physics, just harder to extract. [Huang & Liao]
Hiller and Krüger showed ratio $\mathrm{Br}(B \to X_s \mu\mu)/\mathrm{Br}(B \to X_s ee)$ can be every bit as powerful as $B_s \to \ell\ell$ in probing Higgs effects.

$\tau \to 3\ell$: Rare decays tied to presence of neutrino seesaw in MSSM, [Babu & Kolda]
like $\tau \to \mu\gamma$. Final states tell us about form of neutrino Yukawa matrix.

$\tau \to \eta\ell$: Same physics as above. Slightly better rate. [Sher]

$A_{\mathrm{CP}}(B \to \ell\ell)$: May be fanciful, but there has been work in this direction. [Huang & Liao]

$B_{(s)} \to \ell\ell'$: Should be there, but at very small rates. Probably impossible to observe.
[Dedes, Ellis & Raidal]

$A_{\mathrm{CP}}(B \to \phi K_S)$: In general MSSM models, Higgs exchange may also be able to give $S_{\phi K} < 0$. But are they consistent with everything else we know??

Not all SUSY-breaking models created equal. mSUGRA gives sizable Higgs effects, while GMSB models are completely negligible. So observation would also yield clues to SUSY-breaking sector.

Conclusions

There is no reason to view success of unitarity triangle picture as evidence against new & interesting physics in the B sector, particularly in $b \to s$ transitions.

If there is new physics in the $b \to sss$ transitions, what will we need to measure??

- As precise a measurement of $S_{\phi K}$ as possible.
- Need to know $C_{\phi K}$ at least to $\sigma \simeq 0.1$ level.
- Need to measure $A_{\rm CP}^{b \to s\gamma}$ at the level of 1 to 2%.
- Must be prepared for $\Delta M_s \gg 20\,{\rm ps}^{-1}$.
- A measurement of $A_{\rm CP}(B_s \to \psi\phi)$ with uncertainties at the 0.2 level at least.

So we need three experiments/machines to understand angles and phases of MSSM:
— Tighter measurements of EDMs
— A B_s factory (BTeV, LHCb, Super-B at $\Upsilon(5s)$?) for ΔM_s and $B_s \to \psi\phi$
— And we need a Super-B factory to complete the B measurements

As a bonus, Super-B factory would be able to match Tevatron's ability to search for $B \to \ell\ell$ decays, and will do it in channels unavailable elsewhere.