# The Golden Modes $B_d \to J/\psi K_s$ and $B_s \to J/\psi \phi$

## How can we know *Penguin*/*Tree*?

Thomas Mannel

Theoretische Physik I, Universität Siegen

May 28., 2009, FPCP 2009

# Contents

# Introduction: Some framework

- Look at a decay $B \to f$, ($f$: Some CP eigentstate)

$$A(B^0 \to f) = \mathcal{A}\left[1 + r_f\, e^{i\delta_f}\, e^{i\theta_f}\right]$$

- $\delta_f$: Weak Phase and $\theta_f$: Strong phase
- Penguin-over-Tree ratio:

$$r_f = \lambda_{\rm CKM,f}\, a_f$$

- $a_f$: Modulus of a ratio of hadronic matrix elements
- $\lambda_{\rm CKM,f}$: Modulus of a ratio of CKM matrix elements

- Key Observable: Time-Dependent CP Asymmetries

$$A_{\rm CP}(t;f) \equiv \frac{\Gamma(B^0(t) \to f) - \Gamma(\bar{B}^0(t) \to f)}{\Gamma(B^0(t) \to f) + \Gamma(\bar{B}^0(t) \to f)}$$

- General Expression

$$A_{\rm CP}(t;f) = \frac{A_{\rm D}^f \cos(\Delta M_q t) + A_{\rm M}^f \sin(\Delta M_q t)}{\cosh(\Delta\Gamma_q t/2) - \mathcal{A}_{\Delta\Gamma}^f \sinh(\Delta\Gamma_q t/2)}$$

- Neglecting the lifetime difference (for the $B_d$)

$$A_{\rm CP}(t;f) = A_{\rm D}^f \cos(\Delta M_q t) + A_{\rm M}^f \sin(\Delta M_q t)$$

- In terms of the parameters of the amplitude an the mixing phase $\phi_s$

$$A^f_{\rm D} = -2 r_f \sin\theta_f \sin\delta_f$$
$$A^f_{\rm M} = \left[\sin\phi_s + 2 r_f \cos\theta_f \sin(\phi_s + \delta_f) + r_f^2 \sin(\phi_s + 2\delta_f)\right]$$
$$A^f_{\Delta\Gamma} = \text{.... not needed here}$$

- Golden Modes: For $B_d \to J/\psi K_s$ and $B_s \to J/\psi \phi$:

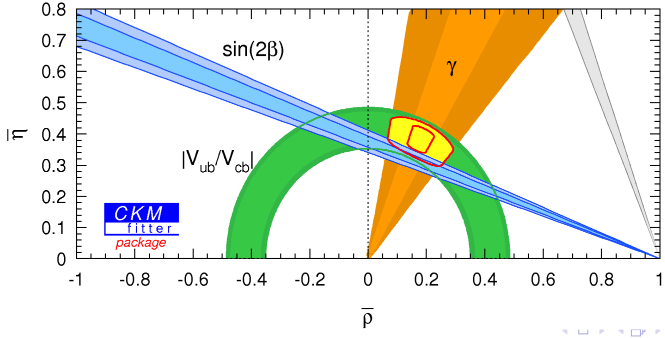
$$\lambda_{\rm CKM,f} = \left| \frac{V_{ub} V^*_{us}}{V_{cb} V^*_{cs}} \right| \sim 5\%$$

(Bigi, Sanda)

- Thus: In the Standard Model $r_{J/\psi K} \leq 5\%$:

$$C(J/\psi K_{\mathrm{S,L}}) \approx 0, \quad S(J/\psi K_{\mathrm{S,L}}) \approx -\eta_{\mathrm{S,L}} \sin 2\beta$$

- Penguin contamination small, suppressed by $\lambda_{\mathrm{CKM}}$
- Is it really small ?



- If there is new physics in $B^0$–$\bar{B}^0$ mixing:

$$\phi_d = 2\beta + \phi_d^{\rm NP}$$

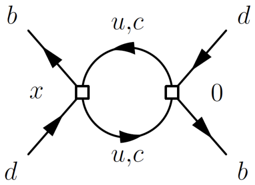
- "True value" of $\beta$ from $|V_{ub}/V_{cb}|$ and $\gamma$

$$(\sin 2\beta)_{\rm true} = 0.76^{+0.02+0.04}_{-0.04-0.05} \quad \text{and}$$
$$(\phi_d)_{J/\psi K^0} - 2\beta_{\rm true} = -(8.7^{+2.6}_{-3.6} \pm 3.8)^\circ$$

- Reliable Calculation needed:
- Is this "new physics" or is it ony "funny penguins"?

# Precise predictions I: Theoretical Attempt 1

- Try to calculate the relevant matrix elements for $r_f$
- Corrections to the mixing phase from charm loops

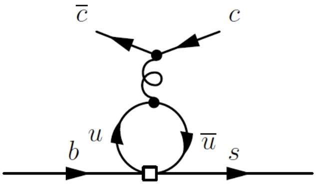


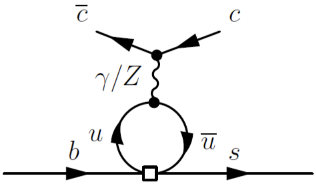

$$\Delta \Im \left[ \frac{M_{12}}{|M_{12}|} \right] \approx -2 \frac{m_c^2}{m_t^2} \ln \left( \frac{m_c^2}{M_W^2} \right) \approx -4 \times 10^{-4}$$

- These are calculable and safely small

(see eg. H. Boos,T.M., J. Reuter, Phys. Rev. **D70**:036006, 2004.)

- Up quark penguin corrections to the decay rate
- Very difficult to compute!
- Perturbative try: (M. Bander, D. Silverman, A. Soni, Phys. Rev. Lett. **44** (1980).)




$$\mathcal{H}_{\text{eff}}^{\text{Peng.}}(b \to c\bar{c}s) = -\frac{G_F}{\sqrt{2}} \left\{ \frac{\alpha}{3\pi} (\bar{s}b)_{V-A} (\bar{c}c)_V \cdot \left[ 1 + \mathcal{O}\left( \frac{M_\Psi^2}{M_Z^2} \right) \right] + \frac{\alpha_s(k^2)}{3\pi} (\bar{s}T^a b)_{V-A} (\bar{c}T^a c)_V \right\} \cdot \left( \frac{5}{3} - \ln\left( \frac{k^2}{\mu^2} \right) + i\pi \right)$$

- Use $\mu = m_b$ and $k^2 = M^2_{J/\psi}$:
  This yields a tiny number

$$S(J/\Psi\, K_S) = (\sin 2\beta)_0 - (2.16 \pm 2.23) \times 10^{-4}$$
$$C(J/\Psi\, K_S) = (5.0 \pm 3.8) \times 10^{-4}$$

(H. Boos,T.M., J. Reuter, Phys. Rev. **D70**:036006, 2004.)

- This is far beyond the current experimental accuracy
- Hard to asess the uncertainties of this estimate

# Precise predictions I: Theoretical Attempt 2

- Try to compute the $\bar{u}u \to \bar{c}c$ backscattering in terms of hadronic states M. Gronau, J. Rosner, Phys. Lett. B **672**, 349 (2009)
- $S_0$: Strong interaction Scattering,
  $T = T^\dagger$: Weak interaction $\boxed{T = S_0 T S_0}$
  $T = T^c + T^u$ with $T^c \sim V_{cb} V_{cs}^*$ and $T^u \sim V_{ub} V_{us}^*$
- Insert a set of (hadronic) states

$$\langle J/\psi K^0 | T^u | B \rangle = \sum_f \langle J/\psi K^0 | S_0 | f \rangle \langle f | T^u | B \rangle$$

- Need an estimate for $\langle f | T^u | B \rangle$ for $f = K^* \pi, K^{**} \pi, \dots$

- Use rescattering fomula for $T^c \sim V_{cb} V_{cs}^*$

$$\langle f | T^c | B \rangle = \sum_k \langle f | S_0 | k \rangle \langle k | T^c | B \rangle$$

- Saturate the sum by a single state

$$|\langle f | T | B \rangle| \geq |\langle f | S_0 | D^* D_s \rangle| \, |\langle D^* D_s | T | B \rangle|$$

- Obtain an inequality

$$\xi_f = \frac{|\langle J/\psi K^0 | S_0 | f \rangle \langle f | T^u | B \rangle|}{|\langle J/\psi K^0 | T | B \rangle|} \leq \frac{1}{3} \frac{|\langle f | T^u | B \rangle|}{|\langle f | T^c | B \rangle|} \left( \frac{|\langle f | T | B \rangle|}{\langle J/\psi K^0 | T | B \rangle|} \right)^2$$

Table II: Branching ratios [17], center-of-mass momenta [12], parameters $r_f$ and upper bounds on $\xi_f$ for seven charmless intermediate $VP$ states.

| Mode $f$ | $\mathcal{B}$ $(10^{-6})$ | $p^*$ (MeV) | $r_f$ | Upper bound on $\xi_f$ $(10^{-4})$ |
|---|---|---|---|---|
| $K^{*+}\pi^-$ | 10.3±1.1 | 2563 | 0.31±0.03 | 7.9±1.1 |
| $\rho^- K^+$ | 8.6±1.0 | 2559 | 0.26±0.03 | 5.6±1.0 |
| $K^{*0}\pi^0$ | 2.4±0.7 | 2562 | 0.09±0.04 | 0.6±0.3 |
| $\rho^0 K^0$ | 5.4±1.0 | 2558 | 0.04±0.03 | 0.5±0.4 |
| $\omega K^0$ | 5.0±0.6 | 2557 | 0.04±0.03 | 0.5±0.4 |
| $K^{*0}\eta$ | 15.9±1.0 | 2534 | 0.04±0.02 | 1.6±0.7 |
| $K^{*0}\eta'$ | 3.8±1.2 | 2471 | 0.08±0.04 | 0.8±0.4 |

- Conclusion: $r_{J/\psi K}$ is at most few $\times 10^{-3}$ (Gronau, Rosner)

# Precise predictions II: Using Data

(M. Ciuchini, M. Pierini and L. Silvestrini, Phys. Rev. Lett. **95**, 221804 (2005),
S. Faller, R. Fleischer, M. Jung and T. M., Phys. Rev. **D79**:014030,2009.)

- Use of data: Using Flavour Symmetries
- Problem: Flavour $SU(3)$ is severely broken
- Two Strategies:
  - Assume $SU(3)$ relations, but leave (generous) uncertainties
  - Try to get a hand on $SU(3)$ breaking (in progress)
- In the case at hand:
  Compare $b \to s\bar{c}c$ with its $SU(3)$ friend $b \to d\bar{c}c$

# Penguins in $B_d \longrightarrow J/\psi K_s$

- Remember

$$A(B^0 \to J/\psi K^0) = \mathcal{A}\left[1 + \lambda_{\rm CKM} e^{i\gamma} a\, e^{i\theta}\right]$$

- Parametrize ($\phi_d$ = $B - \overline{B}$ Mixing phase)

$$S(J/\Psi\, K_S) = \sin(\phi_d + \Delta\phi_d)$$

$$\boxed{\tan\Delta\phi_d = \frac{2\lambda_{\rm CKM} a \cos\theta \sin\gamma + \lambda_{\rm CKM}^2 a^2 \sin 2\gamma}{1 + 2\lambda_{\rm CKM} a \cos\theta \cos\gamma + \lambda_{\rm CKM}^2 a^2 \cos 2\gamma}}$$

- “Control Channel” for $B^0 \to J/\psi K^0$: $B^0 \to J/\psi \pi^0$

$$\sqrt{2} A(B^0 \to J/\psi \pi^0) = \mathcal{A}' \left[ 1 - a' e^{i\theta'} e^{i\gamma} \right]$$

- Measurements (HFAG Uncertainties!):

$$C(J/\psi \pi^0) = -0.10 \pm 0.13, \quad S(J/\psi \pi^0) = -0.93 \pm 0.15$$

- $SU(3)$ limit: Identify the hadronic amplitudes

$$\mathcal{A}' = \frac{V_{cd}}{V_{cs}} \mathcal{A} \quad a' = a \quad \theta' = \theta$$

- Of course, this is debatable ....

- Aside from the CP Observables we have ($\Phi$: Phase Space Corrections)

$$H \equiv \frac{2}{\epsilon}\left[\frac{\mathrm{BR}(B_d \to J/\psi \pi^0)}{\mathrm{BR}(B_d \to J/\psi K^0)}\right]\left|\frac{V_{cd}\mathcal{A}}{V_{cs}\mathcal{A}'}\right|^2 \frac{\Phi_{J/\psi K^0}}{\Phi_{J/\psi \pi^0}}$$

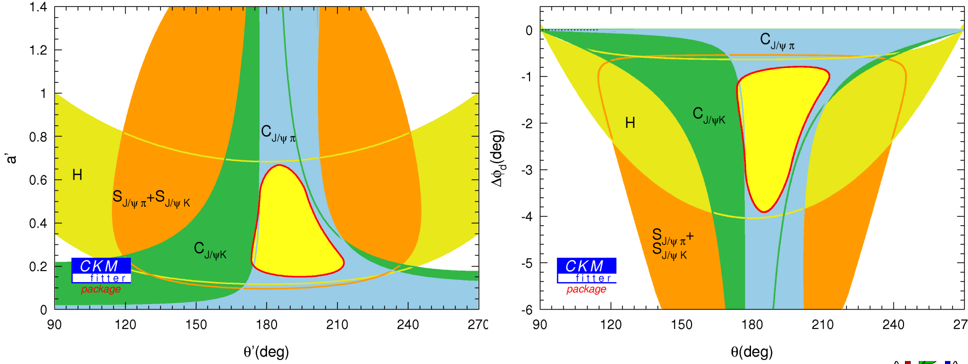
$$= \frac{1 - 2a' \cos\theta' \cos\gamma + a'^2}{1 + 2\epsilon a \cos\theta \cos\gamma + \epsilon^2 a^2},$$

- Note that in the $SU(3)$ Limit: $\left|\frac{V_{cd}\mathcal{A}}{V_{cs}\mathcal{A}'}\right|^2 = 1$
- Include "some $SU(3)$ breaking effects" by assuming

$$\left|\frac{V_{cd}\mathcal{A}}{V_{cs}\mathcal{A}'}\right| = \frac{f^+_{B\to K}(M^2_{J/\psi})}{f^+_{B\to\pi}(M^2_{J\psi})} = 1.34 \pm 0.12.$$

(Values from QCD Sum rules and from pole extrapolation)

- This yields $H = 1.53 \pm 0.16_{\rm BR} \pm 0.27_{\rm FF}$
- Use $C$, $S$ and $H$ to extract $a' \to a$ and $\theta' \to \theta$
- Extract $\Delta\phi_d$



# Results for $B \to J/\psi K$

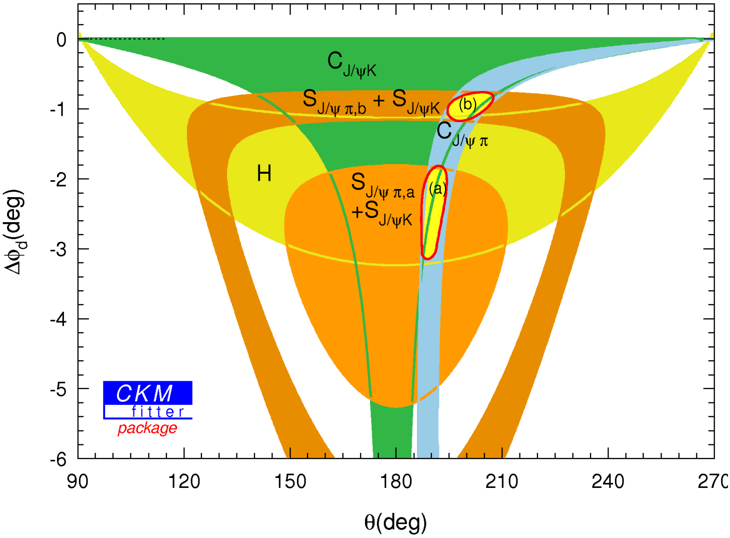
- Using $SU(3)$ for $a$ and $\theta$: $\Delta\phi_d \in [-3.9, -0.8]^\circ$
- Allowing 50% $SU(3)$ breaking in $a$ and $\theta, \theta' \in [90, 270]^\circ$ indepedently: $\Delta\phi_d \in [-6.7, 0.0]^\circ$
- Hints at negative $\Delta\phi_d$
- Softens the tension with the SM fit
- However, still quite debatable $SU(3)$ assumptions
- This is likely much larger then the perturbative estimate! (Ala Boos, Reuter M.)
- Also significantly larger than the Gronau Rosner estimate

# Future possibilites

- Assme a future reduction of uncertainties on CP observables by a factor of 2
- Assume a reduction of the uncertainty of $\gamma$ and on the BR's by a factor of 5
- Scenario (a): "High $S$":

  $C(J/\psi\pi^0) = -0.10 \pm 0.03$, $H = 1.53 \pm 0.03 \pm 0.27$, $S = -0.98 \pm 0.03$
- Scenario (b): "Low $S$":

  $C(J/\psi\pi^0) = -0.10 \pm 0.03$, $H = 1.53 \pm 0.03 \pm 0.27$, $S = -0.85 \pm 0.03$


0
-1
-2
-3
-4
-5
-6
90
120
150
180
210
240
270
θ(deg)
Δφd(deg)
CJ/ψK
SJ/ψ π,b + SJ/ψK
(b)
CJ/ψ π
H
SJ/ψ π,a
+SJ/ψK
(a)
CKM
fitter
package

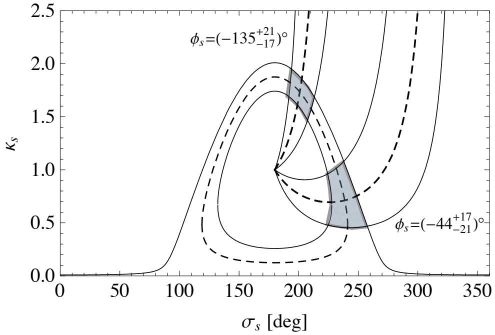
# $B_s \to J/\psi\phi$

- Theory is practically the same, except:
  - Final State is Vector-Vector
  - $\longrightarrow$ Project out the various CP components
  - $\phi_s = -2\lambda^2\eta$: Small
- Experiment:
  - $\Delta M_s = \begin{cases} (18.56 \pm 0.87)\mathrm{ps}^{-1} & \text{(D0 coll.)}, \\ (17.77 \pm 0.10 \pm 0.07)\mathrm{ps}^{-1} & \text{(CDF coll.)}. \end{cases}$
  - $\phi_s = \left(-44^{+17}_{-21}\right)^\circ \vee \left(-135^{+21}_{-17}\right)^\circ$ (HFAG)
- $\phi_s$ could be sizable?

# "New Physics" in the mixing

- Modify $\Delta B = 2$ matrix element of the mass matrix:

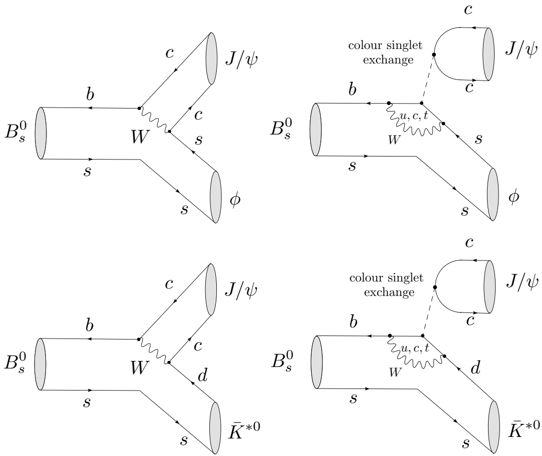
$$M_{12}^s = M_{12}^{s,\mathrm{SM}} \left(1 + \kappa_s e^{i\sigma_s}\right)$$




- However, What, if we have "oversized penguins"?

# Controlling the Penguins

- Pick a control channel: $B_s^0 \to J/\psi \bar{K}^{*0}$



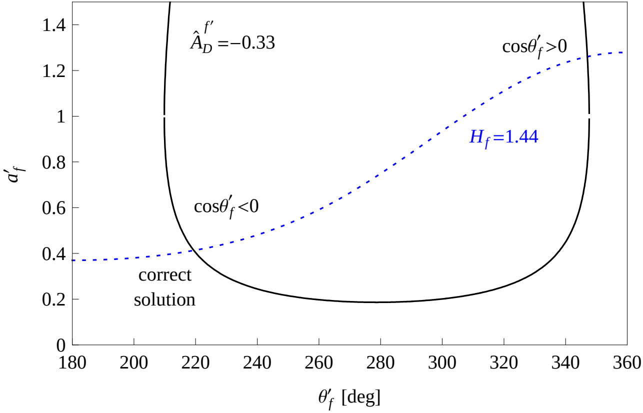
- Measure
  $B_s^0 \to J/\psi[\to \ell^+\ell^-]\phi[\to K^+K^-]$
  $B_s^0 \to J/\psi[\to \ell^+\ell^-]\bar{K}^{*0}[\to \pi^+K^-]$
- However, $B_s^0 \to J/\psi \bar{K}^{*0}$ is flavour specific!

$\longrightarrow$ No mixing induced CP Asymmetry

$\longrightarrow$ less observables

- One still can extract $\theta'$ and $a'$ from data
  (using $H$ and the direct CP Asymmetry)

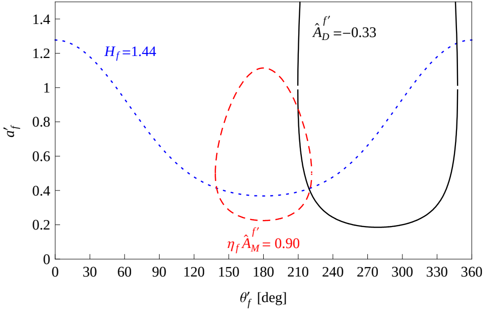
- Numercal example: $H = 1.44$ and $A_D = -0.33$




Still a twofold ambiguity ...

- More Control Channels: $B_d^0 \to J/\psi\rho^0$
- Very much the same as $B_d^0 \to J/\psi\phi$

$\longrightarrow$ The same set of observables



- In case the hadronic $P/T$ parameter $a$ is of similar size as in $B_d \to J/\psi K_s$:

$$\Delta\phi_s \sim \Delta\phi_d$$

- Shift as large as the SM value of $\phi_s$ or even larger
- Values of $\phi_s$ as large as $5^\circ - 10^\circ$ cannot be excluded
- ... this is still far from $40^\circ$

# Conclusion

- The situation is not (yet) conclusive
  - Perturbative Estimates may be too small
    (see eg. Boos, M. Reuter)
  - Estimates based on hadronic rescattering hint at small effects (see Gronau, Rosner)
  - Use of data?
- With sufficient ammount of data (LHC-b and SFF): (Approximate) Flavour Symmetries will be the way to test the SM
- ... and possibly identify "new physics"