Theory Predictions for the CP Asymmetry in the Golden Mode(s)

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Outline

Motivation

- Validate CKM mechanism
- Measurements of angles require nonleptonic decays
- Enormous precision expected from future experiments
- Obstacle: Hadronic matrix elements notoriously difficult
- ➥ Golden Modes almost free of hadronic uncertainties

- Last few years: shift of focus:
  CKM main source of (low energy) CP violation ✔
  - ➥ What about new physics (NP)?

- NP expected at the TeV-scale
- Direct search will be performed at the LHC
- Flavour physics complementary tool

Prediction 0: SM with standard powercounting

- $B \to J/\psi K$: Tree-dominated, governed by a single amplitude ($+\mathcal{O}(\frac{P}{T}\lambda^2) \sim \mathcal{O}(\lambda^3)$, "Gold-plated")

➡ Expected observables (neglecting $\mathcal{O}(\lambda^3)$ terms):
  - Mixing-induced CP-Asymmetry:

$$S_{CP} + \sin(2\beta) \simeq 0$$

  - Direct CP-Asymmetries (up to order $\mathcal{O}(\lambda^5)$):

$$A_{CP}^{dir}(\bar{B}^0) = A_{CP}^{dir}(B^-) \simeq 0$$

  - Averaged Rates:

$$\bar{\Gamma}(B^0) = \bar{\Gamma}(B^-)$$

- $B_s \to J/\psi\phi$: similar pattern, VV mode

Tensions (?)

Experimentally:

Decay	$\Gamma/10^{-4}ps^{-1}$	A_{CP}	S_{CP}
$B^- \to J/\psi K^-$	6.14 ± 0.21	0.017 ± 0.016	–
$\bar{B}^0 \to J/\psi \bar{K}^0$	5.69 ± 0.21	$-0.002 \pm 0.020(*)$	0.657 ± 0.025

Also: Small tensions in $|\Delta S| = |\Delta B| = 1$ - processes:

- $\sin 2\beta$ from $B \to J/\psi K_S$ vs. $\sin 2\beta$ from $|V_{ub}/V_{cb}|$ and $\Delta m_d/\Delta m_s$
- $\sin 2\beta$ from $B \to J/\psi K_S$ vs. $\sin 2\beta$ from $B \to \phi K_S$ (Note: Naive average now compatible with $(\sin 2\beta)_{J/\psi K_S}$)
- CP asymmetry in B_s-mixing
- $B \to \tau\nu$ (?)
- CP asymmetries in $B \to K\pi$ (?)

Problem twofold:

- Understand SM hadronic process
- Determine possible NP influence

Strategies

Problem:
SM corrections to "Prediction 0" cannot be quantified

- QCD Factorization et al. do not work here...
- Estimates hint however towards small effects [Boos et al, Li et al, Gronau et al]

➥ Flavour Symmetries important tool!

Used within different scenarios:

1. "Prediction 0" + NP in amplitude
2. Large hadronic SM effects plus NP mixing phase
3. Large hadronic effects beyond the symmetry limit

Statistical treatment using RFit (CKMfitter)

Strategy I: Prediction 0 + NP in amplitudes

[Th. Feldmann, MJ, Th. Mannel]

Explore $b \to s\bar{q}q$-processes the following way:

- Take SM $|\Delta B| = |\Delta S| = 1$ effective Hamiltonian
- Include NP "operator-wise"
- Determine UT parameters independent of *this* NP
- Determine allowed ranges for NP contributions, using isospin decomposition and "Prediction 0" for SM contributions

Parameterization for $B \to J/\psi K$ with $(\bar{b}s)(\bar{u}u)$ operator:

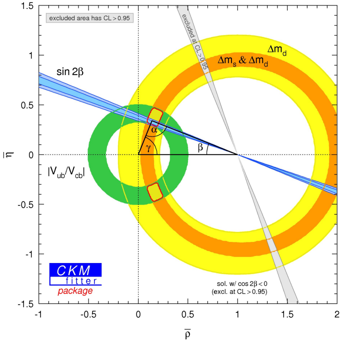
$$\mathcal{A}(B^{0,+} \to J/\psi K^{0,+}) = \mathcal{A}_0 \left[1 + r_0\, e^{i\theta_W} e^{i\phi_0} \pm r_1\, e^{i\theta_W} e^{i\phi_1}\right]$$

"Reparametrisation invariance": Take $\theta_W = \pi - \gamma_{SM}$ as reference → Possible interpretation as (CKM suppressed) SM contributions

UT analysis

Determine β and γ by independent measurements:

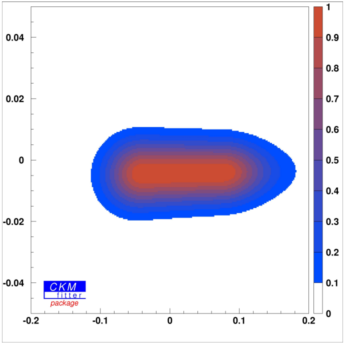
- Use only $|V_{ub}/V_{cb}|$, Δm_d and Δm_s (Moriond '09)



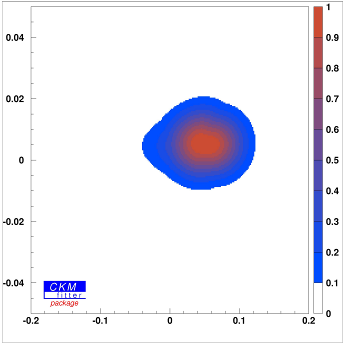
$$\sin 2\beta = 0.746^{+0.014}_{-0.020} \pm 0.081$$
$$\gamma = (65.7^{+1.8}_{-1.7} \pm 5.5)^\circ$$
$$\Delta\phi_d = -(8.7^{+2.6}_{-3.6} \pm 3.8)^\circ$$

- Tension decreased due to larger error for V_{ub}
- $B \to \tau\nu$ not included (avoid f_B/B_{B_d} discussion)
  Inclusion increases tension above the old level
  $\to$ larger $\Delta I = 0$ contributions in the following

$b \to s\bar{u}u, \bar{d}d$ NP operator in $B \to J/\psi K$



$r_0 \cos\phi_0^s vs. r_0 \sin\phi_0^s$



$r_1 \cos\phi_1^s vs. r_1 \sin\phi_1^s$

1σ-ranges:

$$r_0\ \cos\phi_0 = [-0.074 \text{ to } 0.118]\,, \quad r_0\ \sin\phi_0 = [-0.015 \text{ to } 0.003]\,,$$
$$r_1\ \cos\phi_1 = [\ \ 0.014 \text{ to } 0.089]\,, \quad r_1\ \sin\phi_1 = [-0.002 \text{ to } 0.013]\,.$$

Results Strategy I

Details: see Warwick proceedings

- Data for $B \to J/\psi K$, $B \to \phi K$, $B \to \pi K$ point all to a contribution of an operator $(\bar{b}s)(\bar{u}u)$
- Typical order of magnitude larger than expected in the SM, but not significantly, effect decreased lately
- Relative size of effects in $B \to J/\psi K$, $B \to \phi K$ as expected
- Small strong phases preferred

However:

- Reparametrisation invariance: NP indistinguishable from large hadronic SM effects
- Final states not related by symmetry
  ↳ no quantitative relation

- More data needed → LHCb, SuperB
- Reliable SM predictions necessary

Strategy II: Large SM effects + NP in mixing

Find symmetry-related decay $\to$ SU(3)

- Simplest choice: $B_s \to J/\psi K_S$, but not measured yet
- Alternative: $B \to J/\psi \pi^0$ [M. Ciuchini, M. Pierini, L. Silvestrini]

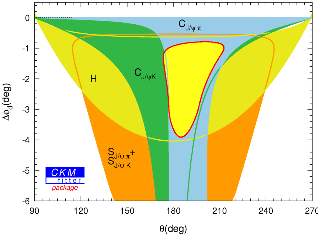
This approach has the following features:

- Not just SU(3), but data confirm smallness of neglected terms
- Cabbibo-suppression of penguins absent
  ➡ high sensitivity to terms suppressed in $J/\psi K$
- Already measured time-dependently
- Additionally fit for NP mixing phase possible [S. Faller, R. Fleischer, MJ, Th. Mannel]
- Discrimination between SM and NP possible if NP breaks SU(3)

Results Strategy II

Performing this program...

- $B \to J/\psi\pi$ data imply a significant shift in $S_{J/\psi K}$ in the right direction, from subleading terms: $\Delta\phi_d \in [-3.9, -0.8]\,(1\sigma)$
- NP phase is small or zero
- Discrimination of SM vs. NP difficult



1σ-ranges (only!) in the $\theta - \Delta\phi_d$ plane

In the future:

- Significant statements with a SuperB factory
- However: for improved data $SU(3)$ breaking crucial!

Strategy III: Improve SM predictions

[MJ, Th. Mannel]

- Both previous strategies call for better control of hadronic SM effects
- Started to address this using U-spin, which is the analogue to isospin, but relates d and s:

$$\begin{pmatrix} u \\ d \end{pmatrix} \overset{Isospin}{=} \begin{pmatrix} |1/2,+1/2\rangle \\ |1/2,-1/2\rangle \end{pmatrix}, \; q := \begin{pmatrix} d \\ s \end{pmatrix} \overset{U-spin}{=} \begin{pmatrix} |1/2,+1/2\rangle \\ |1/2,-1/2\rangle \end{pmatrix}$$

- Advantageous because:
  - Simpler structure than full $SU(3)$
  - Electroweak penguins included trivially ($Q_d = Q_s$)
  - Combination with unbroken isospin possible
- Major drawback: Breaking due to strange quark mass,

$$\mathcal{L}_m^{s,d} = m_d\bar{d}d + m_s\bar{s}s = \underbrace{\frac{1}{2}(m_s+m_d)\,\bar{q}q}_{U\text{-spin symmetric}} - \underbrace{\frac{1}{2}\Delta m\,\bar{q}\tau_3 q.}_{\text{breaks } U\text{-spin}}$$

Including breaking corrections

Generally:

- Perform spurion analysis, expand in $\epsilon = m_s/\Lambda_\chi$
- Results almost always in too many parameters ☹
- However,various strategies exist to reduce them ☺
- This re-introduces systematic uncertainties... ☹
  ...but on a subleading level ☺

Possible strategies:

- Use isospin additionally, assumed as unbroken
- For $|A_1/A_2| \sim \delta \ll 1$, neglect $\mathcal{O}(\epsilon^2, \delta\epsilon)$ terms
- For colour-allowed tree amplitudes, factorization might be used
- The first point might be extended to small amplitude combinations

$B^- \to J/\psi(\pi/K)^-$

U-spin limit:

- Only one amplitude, with two CKM structures
- Predicts

$$A_{CP}(J/\psi K^-)BR(J/\psi K^-) \quad + \\ A_{CP}(J/\psi\pi^-)BR(J/\psi\pi^-) \quad \stackrel{!}{=} \quad 0 \stackrel{exp}{=} 0.22 \pm 0.17$$

➥ Not conclusive at the moment, due to uncertainties

- Naive factorization does not describe the breaking well:

$$\frac{BR(B^- \to J/\psi K^-)}{BR(B^- \to J/\psi\pi^-)}\left|\frac{\lambda_{cd}}{\lambda_{cs}}\right|^2 \quad \sim \quad \left(\frac{F^{B\to K}(M^2_{J/\psi})}{F^{B\to\pi}(M^2_{J/\psi})}\right)^2$$
$$\Longleftrightarrow \qquad 1.1 \pm 0.1 \quad \sim \quad 1.8 \pm 0.3$$

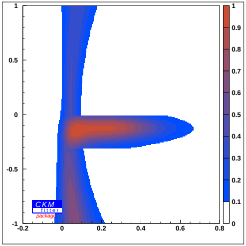
$B \to J/\psi(\pi, K)$

The Golden Mode is included via isospin. The following approximations are used:

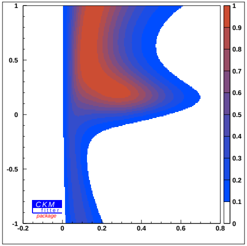
- The U-spin breaking in penguin suppressed amplitudes is neglected
- The $\Delta I = 1, 3/2$ amplitude $\sim \lambda_{cd,s}$ is neglected

This results in the following for the relative U-spin breaking parameter $x_\epsilon = A_\epsilon / A_0$:

$\delta_0 \in [-\pi/2, \pi/2]$



$\delta_0 \in [\pi/2, 3\pi/2]$



Conclusions Strategy III

$B \to J/\psi(\pi/K)$:

- As before, $A_u(\Delta I = 1, 3/2)$ larger than expected
- At present large range for SU(3) breaking allowed from data
- Imaginary part hard to constrain
- Earlier approximation can be implemented, but charged sector in tension with neutral
- Update on BR's by present B factories would be interesting

Generally:

- Statistics of LHCb and a SuperB factory will help to control U-spin breaking model-independently
- Isospin can accompany the U-spin analysis
- However, individual analyses required

Conclusions and outlook

- Nonleptonic B decays and especially the Golden Modes remain a powerful tool in the seach for NP
- Indispensable to determine flavour structure of NP
- However: Control over hadronic uncertainties essential to differentiate between SM and NP
- Three projects have been discussed:
  - $\mathcal{O} = (\bar{b}s)(\bar{u}u)$ contribution preferred in $b \to s$ decay amplitudes. SM explanation possible, but contributions tend to be large.
  - Assuming SM + NP in mixing, $SU(3)$ implies a sizable correction to $S_{J/\psi K}$ in the SM, while no sign for a NP phase is found. NP interpretation possible as well.
  - With high statistics, U-spin breaking may be addressed in a data driven approach. Additional assumptions usually needed, but applied on a sub-leading level.

Lots to do for a SuperB factory!

Backupslides

- Experimental data
- Which input to use?
- Reparametrisation invariance
- Powercounting in $B \to J/\psi K, \phi K$

Experimental data for $b \to s\bar{q}q$ transitions

Decay	BR	A_{CP}	S_{CP}
$B^- \to J/\psi K^-$	$(10.07 \pm 0.35)10^{-4}$	$0.017 \pm 0.016(*)$	–
$\bar{B}^0 \to J/\psi \bar{K}^0$	$(\ 8.71 \pm 0.32)10^{-4}$	$-0.002 \pm 0.020(*)$	0.657 ± 0.025
$B^- \to \phi K^-$	$(8.3 \pm 0.65)10^{-6}$	0.034 ± 0.044	–
$\bar{B}^0 \to \phi \bar{K}^0$	$(8.3^{+1.2}_{-1.0})10^{-6}$	0.23 ± 0.15	$-(0.44^{+0.17}_{-0.18})$
$B^- \to \pi^0 K^-$	$(12.9 \pm 0.6)10^{-6}$	0.050 ± 0.025	–
$B^- \to \pi^- \bar{K}^0$	$(23.1 \pm 1.0)10^{-6}$	0.009 ± 0.025	–
$\bar{B}^0 \to \pi^+ K^-$	$(19.4 \pm 0.6)10^{-6}$	$-0.098^{+0.012}_{-0.011}$	–
$\bar{B}^0 \to \pi^0 \bar{K}^0$	$(\ 9.8 \pm 0.6)10^{-6}$	-0.01 ± 0.10	-0.57 ± 0.17

Which input to use?

Recent analyses of $B \to \pi K$ puzzle come to different conclusions. Schematically:

- No NP needed in $B \to \pi K$ [Ciuchini et al. '08]
- Puzzle reduced, mod. EWP do not help much [Baek et al. '09]
- Discrepancy in $S_{CP} - A_{CP}(B \to \pi^0 K^0)$ plane, mod. EWP help [Fleischer et al. '08]

Inputs are:

- QCDF + large non-factorizable corrections
- Fleischer/Neubert/Rosner relations (both)
- Neubert/Rosner relation I, $BR(B \to \pi^+\pi^0)$ (fixes mainly $\epsilon_{3/2}$, large phase)

Reparametrisation invariance

The amplitude is invariant under the transformations

$$
\begin{aligned}
\mathcal{A}_0 &\rightarrow \mathcal{A}_0\,(1+\xi\, r_0\, e^{i\phi_s^0})\,,\\
r_0\, e^{i\phi_s^0} &\rightarrow \frac{r_0\, e^{i\phi_s^0}\sqrt{1-2\,\xi\,\cos\phi_w^0+\xi^2}}{1+\xi\, r_0\, e^{i\phi_s^0}}\\
e^{i\phi_w^0} &\rightarrow \sqrt{\frac{e^{i\phi_w^0}-\xi}{e^{-i\phi_w^0}-\xi}}\,,\\
r_1\, e^{i\phi_s^1} &\rightarrow \frac{r_1\, e^{i\phi_s^1}}{1+\xi\, r_0\, e^{i\phi_s^0}}\,,
\end{aligned}
$$

as long as the leading SM-matrix-element $\mathcal{A}_0$ is not fixed.

$B \to J/\psi K$

SM and NP contributions and suppression factors:

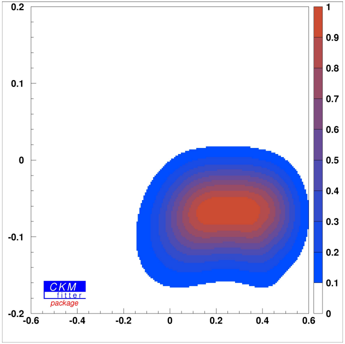
Contr.	**Suppression factors**					**Comment**
	Op.	Dyn.	CKM	NP	Π	
$\lambda_c^s T$	1	1	1	-	$\boldsymbol{1}$	$\mathcal{O}(1) \longrightarrow \lambda_c^s A_c^0$
$\lambda_c^s P^{\bar{c}c}$	λ	1	1	-	$\boldsymbol{\lambda}$	
$\lambda_c^s P^{\bar{q}q}_{I=0}$	λ	λ	1	-	$\boldsymbol{\lambda^2}$	
$\lambda_c^s P^{\bar{q}q}_{I=1}$	λ^2	λ	1	-	$\boldsymbol{\lambda^3}$	$\leq \mathcal{O}(\lambda^3) \times \lambda_c^s A_c^0 \longrightarrow$ "gold-plated mode"
$\lambda_u^s T$	1	λ	λ^2	-	$\boldsymbol{\lambda^3}$	
$\lambda_u^s P^{\bar{c}c}$	λ	1	λ^2	-	$\boldsymbol{\lambda^3}$	
$\lambda_u^s P^{\bar{q}q}_{I=0}$	λ	λ	λ^2	-	$\boldsymbol{\lambda^4}$	
$\lambda_u^s P^{\bar{q}q}_{I=1}$	λ^2	λ	λ^2	-	$\boldsymbol{\lambda^5}$	
$P^{\bar{c}c}_{0/c}$	1	1	1	λ	$\boldsymbol{\lambda}$	$\mathcal{O}(\lambda) \times \lambda_c^s A_c^0$
$P^{\bar{q}q}_{0/c,I=0}$	1	λ	1	λ	$\boldsymbol{\lambda^2}$	
$P^{\bar{q}q}_{c,I=1}$	1	λ	1	λ	$\boldsymbol{\lambda^2}$	$\mathcal{O}(\lambda^2) \times \lambda_c^s A_c^0$

$B \to \phi K$

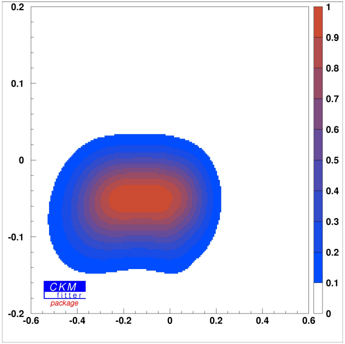
SM and NP contributions and suppression factors:

Contr.	Suppression factors					Comment
	Op.	Dyn.	CKM	NP	Π	
$\lambda_c^s T$	1	λ	1	-	$\boldsymbol{\lambda}$	$\mathcal{O}(\lambda) \longrightarrow \lambda_c^s A_c^0$
$\lambda_c^s P^{\bar{s}s}$	λ	1	1	-	$\boldsymbol{\lambda}$	
$\lambda_c^s P^{\bar{q}q}_{I=0}$	λ	λ	1	-	$\boldsymbol{\lambda^2}$	
$\lambda_c^s P^{\bar{q}q}_{I=1}$	λ^2	λ	1	-	$\boldsymbol{\lambda^3}$	$\leq \mathcal{O}(\lambda^2) \times \lambda_c^s A_c^0$
$\lambda_u^s T$	1	λ	λ^2	-	$\boldsymbol{\lambda^3}$	
$\lambda_u^s P^{\bar{s}s}$	λ	1	λ^2	-	$\boldsymbol{\lambda^3}$	
$\lambda_u^s P^{\bar{q}q}_{I=0}$	λ	λ	λ^2	-	$\boldsymbol{\lambda^4}$	
$\lambda_u^s P^{qq}_{I=1}$	λ^2	λ	λ^2	-	$\boldsymbol{\lambda^5}$	
$P^{\bar{s}s}_{0/c}$	1	1	1	λ	$\boldsymbol{\lambda}$	$\mathcal{O}(1) \times \lambda_c^s A_c^0$
$P^{\bar{q}q}_{0/c,I=0}$	1	λ	1	λ	$\boldsymbol{\lambda^2}$	
$P^{\bar{q}q}_{c,I=1}$	1	λ	1	λ	$\boldsymbol{\lambda^2}$	$\mathcal{O}(\lambda) \times \lambda_c^s A_c^0$

$b \to s\bar{u}u, \bar{d}d$ NP operator in $B \to \phi K$



$r_0 \cos\phi_0^s vs. r_0 \sin\phi_0^s$



$r_1 \cos\phi_1^s vs. r_1 \sin\phi_1^s$

1σ-ranges:

$$r_0 \ \cos\phi_0 = [\ \ 0.03 \text{ to } 0.48] \ , \quad r_0 \ \sin\phi_0 = [-0.11 \text{ to } -0.03] \ ,$$
$$r_1 \ \cos\phi_1 = [-0.35 \text{ to } 0.10] \ , \quad r_1 \ \sin\phi_1 = [-0.09 \text{ to } -0.01] \ .$$