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

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

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based on work with H. Boos, J. Reuter, S. Faller, R. Fleischer and M. Jung,
hep-ph/0403085, arXiv:0809.0842 [hep-ph], arXiv:0810.4248 [hep-ph], SI-HEP-2009-01

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Contents

Introduction

- Key Observable: Time-Dependent CP Asymmetries

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

- In case we can neglect the lifetime difference

$$A_{\rm CP}(t;f) = C(f)\cos(\Delta M_d t) - S(f)\sin(\Delta M_d t),$$

- Theory Prediction of $C(f)$ and $S(f)$ in general difficult

Some “Theory” ...

- The decay amplitude for $B^0 \to J/\psi K^0$

$$A(B^0 \to J/\psi K^0) = (V_{cb} V_{cs}^*) A_{\mathrm{T}}^{(c)} + (V_{ub} V_{us}^*) A_{\mathrm{P}}^{(u)} + (V_{cb} V_{cs}^*) A_{\mathrm{P}}^{(c)} + (V_{tb} V_{ts}^*) A_{\mathrm{P}}^{(t)}$$

- CKM Unitarity yields

$$V_{tb} V_{ts}^* = -V_{cb} V_{cs}^* - V_{ub} V_{us}^*$$

- Eliminate $V_{tb} V_{ts}^*$

$$A(B^0 \to J/\psi K^0) = (V_{cb} V_{cs}^*) A_{\mathrm{T}}^{(c)} + (V_{ub} V_{us}^*)[A_{\mathrm{P}}^{(u)} - A_{\mathrm{P}}^{(t)}] + (V_{cb} V_{cs}^*)[A_{\mathrm{P}}^{(c)} - A_{\mathrm{P}}^{(t)}]$$

$$A(B^0 \to J/\psi K^0) = (V_{cb} V_{cs}^*)[A_{\rm T}^{(c)} + A_{\rm P}^{(c)} - A_{\rm P}^{(t)}] + (V_{ub} V_{us}^*)[A_{\rm P}^{(u)} - A_{\rm P}^{(t)}]$$

- Identify the contributions with different weak phases

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

- with

$$\mathcal{A} = (V_{cb} V_{cs}^*)[A_{\rm T}^{(c)} + A_{\rm P}^{(c)} - A_{\rm P}^{(t)}] \text{ and}$$

$$a\, e^{i\theta} = \left[\frac{A_{\rm P}^{(u)} - A_{\rm P}^{(t)}}{A_{\rm T}^{(c)} + A_{\rm P}^{(c)} - A_{\rm P}^{(t)}}\right] \qquad \epsilon e^{i\gamma} = \frac{V_{ub} V_{us}^*}{V_{cb} V_{cs}^*}$$

- $\epsilon \sim 5\%$: This is why the mode is golden!

Impact of Penguins

- In general we have (r = Penguin over Tree ratio)

$$A(B^0 \to f) = \mathcal{A}_f \left[1 + e^{i\gamma} r \, e^{i\theta}\right]$$
$$A(\overline{B}^0 \to \bar{f}) = \mathcal{A}_{\bar{f}} \left[1 + e^{-i\gamma} r \, e^{i\theta}\right]$$

- Insert the time dependent B^0 state and $f = \bar{f}$

$$\Gamma[f,t] = |A_f(t)|^2 + |\overline{A}_f(t)|^2 = R_{\mathrm{L}}^f \, e^{-\Gamma_{\mathrm{L}}^{(s)} t} + R_{\mathrm{H}}^f \, e^{-\Gamma_{\mathrm{H}}^{(s)} t}$$
$$|A_f(t)|^2 - |\overline{A}_f(t)|^2 = 2\, e^{-\overline{\Gamma} t} \left[A_{\mathrm{D}}^f \cos(\Delta M_s t) + A_{\mathrm{M}}^f \sin(\Delta M_s t)\right]$$

- In terms of the params of the amplitude

$$\Gamma[f, t=0] = R_{\rm L}^f + R_{\rm H}^f = 2|\mathcal{A}_f|^2 \left[1 + 2 r_f \cos\theta_f \cos\gamma + r_f^2\right]$$

$$A_{\rm D}^f = -2|\mathcal{A}_f|^2 r_f \sin\theta_f \sin\gamma$$

$$A_{\rm M}^f = |\mathcal{A}_f|^2 \left[\sin\phi_s + 2 r_f \cos\theta_f \sin(\phi_s + \gamma) + r_f^2 \sin(\phi_s + 2\gamma)\right]$$

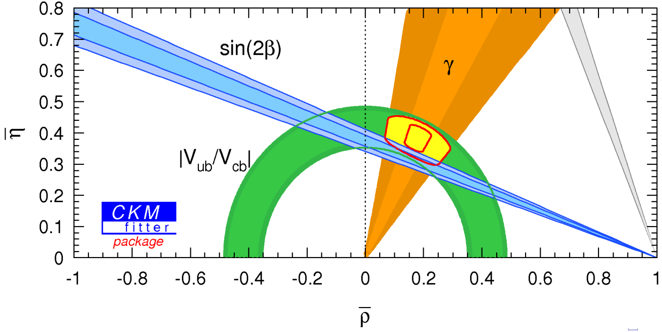
$$\boxed{\frac{|A_f(t)|^2 - |\overline{A}_f(t)|^2}{|A_f(t)|^2 + |\overline{A}_f(t)|^2} = \frac{A_{\rm D}^f \cos(\Delta M_s t) + A_{\rm M}^f \sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s t/2) - \mathcal{A}_{\Delta\Gamma}^f \sinh(\Delta\Gamma_s t/2)}}$$

$$A_{\rm D}^f = C(f) \quad \text{and} \quad A_{\rm M}^f = S(f) \qquad \Delta\Gamma \sim 0$$

- Back to $J/\Psi K$: In the Standard Model $r_{J/\Psi K} \leq 5\%$:

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

- Penguin contamination small, suppressed by ϵ
- Is it really small ?



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

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

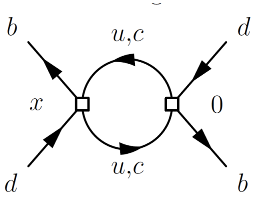
- "True value" of β from $|V_{ub}/V_{cb}|$ and γ

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

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

Precise predictions I: Theoretical Attempts

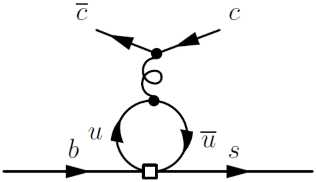
- Try to calculate the relevant matrix elements for r_f
- Corrections to the mixing phase from charm loops

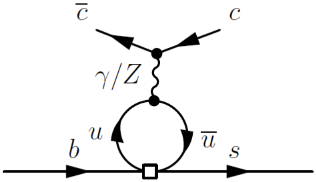


$$\Delta \Im \left[\frac{M_{12}}{|M_{12}|} \right] \approx -2 \frac{m_c^2}{m_t^2} \ln \left(\frac{m_c^2}{M_W^2} \right) \approx -4 \times 10^{-4}$$

- These are calculable and safely small

- Up quark penguin corrections to the decay rate
- Almost impossible to compute!
- Perturbative (un)reasoning:





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

$$\left. + \frac{\alpha_s(k^2)}{3\pi} (\bar{s}T^a b)_{V-A} (\bar{c}T^a c)_V \right\} \cdot \left(\frac{5}{3} - \ln\left(\frac{k^2}{\mu^2} \right) + i\pi \right)$$

- Use $\mu = m_b$ and $k^2 = M^2_{J/\psi}$:
  This yields a tiny number
- As a rule of thumb:
  Perturbative Estimates tend to underestimate ....

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

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

Precise predictions II: Using Data

- 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 (see below)
- 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 $B_d \to J/\psi K_s$

- Remember

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

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

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

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

- "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 (Φ: Phase Space Corrections)

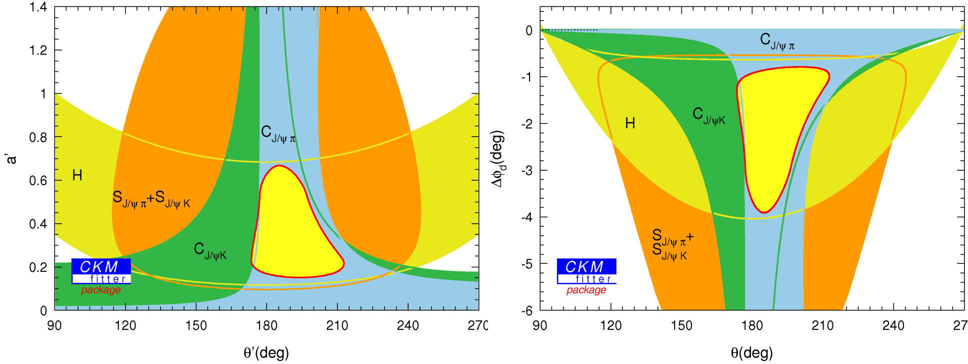
$$H \equiv \frac{2}{\epsilon}\left[\frac{\mathrm{BR}(B_d \to J/\psi\pi^0)}{\mathrm{BR}(B_d \to J/\psi K^0)}\right]\left|\frac{V_{cd}\mathcal{A}}{V_{cs}\mathcal{A}'}\right|^2 \frac{\Phi_{J/\psi K^0}}{\Phi_{J/\psi\pi^0}}$$
$$= \frac{1 - 2a'\cos\theta'\cos\gamma + a'^2}{1 + 2\epsilon a\cos\theta\cos\gamma + \epsilon^2 a^2},$$

- 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 $B \to J/\psi K$

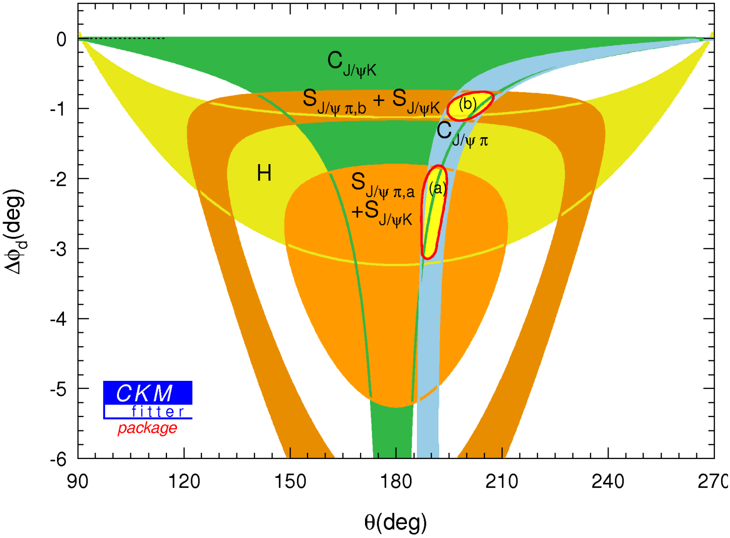
- Using $SU(3)$ for a and θ: $\boxed{\Delta\phi_d \in [-3.9, -0.8]^\circ}$
- Allowing 50% $SU(3)$ breaking in a and $\theta, \theta' \in [90, 270]^\circ$ indepedently: $\boxed{\Delta\phi_d \in [-6.7, 0.0]^\circ}$
- Hints at negative $\Delta\phi_d$
- Softens the tension with the SM fit
- However, still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

Future possibilites

- Assme a future reduction of uncertainties on CP observables by a factor of 2
- Assume a reduction of the uncertainty of γ 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

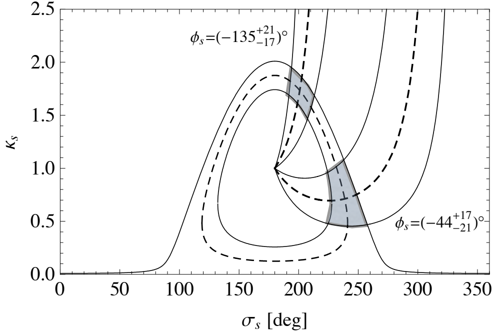
$B_s \to J/\psi\phi$

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

"New Physics" in the mixing

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

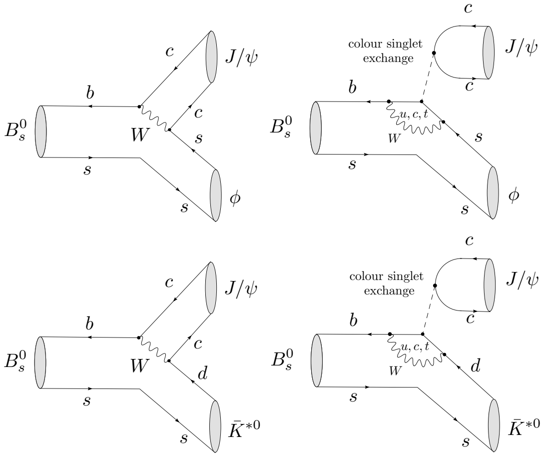
$$M_{12}^{s} = M_{12}^{s,\mathrm{SM}} \left(1 + \kappa_s e^{i\sigma_s}\right)$$



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

Controlling the Penguins

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



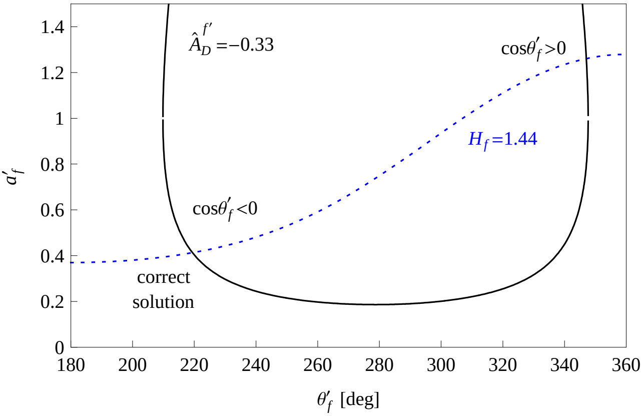
- Measure
  $B_s^0 \to J/\psi[\to \ell^+\ell^-]\phi[\to K^+K^-]$
  $B_s^0 \to J/\psi[\to \ell^+\ell^-]\bar{K}^{*0}[\to \pi^+K^-]$
- However, $B_s^0 \to J/\psi \bar{K}^{*0}$ is flavour specific!

$\longrightarrow$ No mixing induced CP Asymmetry

$\longrightarrow$ less observables

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

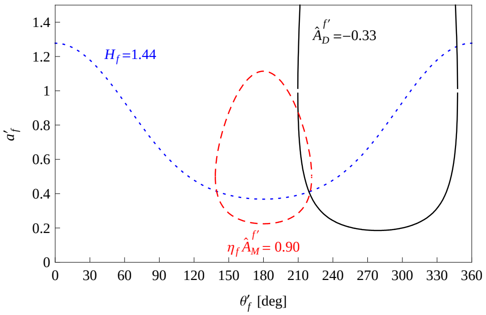
- Numercal example: $H = 1.44$ and $A_D = -0.33$



Still a twofold ambiguity ...

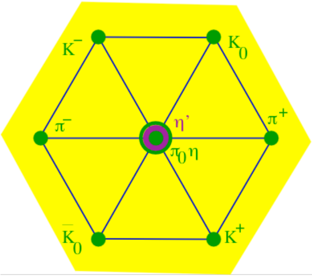
- More Control Channels: $B_d^0 \to J/\psi \rho^0$
- Very much the same as $B_d^0 \to J/\psi \phi$

$\longrightarrow$ The same set of observables



Controlling *SU*(3) Breaking

- *SU*(3) has *SU*(2) Subgroup: Either *I*, *U* or *V* spin



- Pattern of *SU*(3) breaking:
  I Spin is a very good symmetry
  U Spin and *V* Spin are equally bad

U Spin and U Spin breaking

- U Spin: d and s form the fundamental doublet
- Parametrizing U Spin breaking

$$
\begin{aligned}
\mathcal{L}_m^{s,d} &= m_d \bar{d} d + m_s \bar{s} s \\
&= \frac{1}{2}(m_s + m_d)(\bar{s}s + \bar{d}d) + \frac{1}{2}(m_s - m_d)(\bar{s}s - \bar{d}d) \\
&= \frac{1}{2}(m_s + m_d)\,\bar{q}q + \frac{1}{2}\Delta m\,\bar{q}\tau_3 q
\end{aligned}
$$

- Structure of the breaking: Triplett $(j = 1, j_z = 0)$, $\mathcal{H}_{break} = \frac{1}{2}\Delta m\,\bar{q}\tau_3 q = \epsilon B_0^{(1)}$

- Advantage: s and d have the same charge: Electroweak Penguins are singlet
- Hadronic B-decays: $\mathcal{H}_{eff}$ doublet under U-spin
- Relatively simple goup theory
- ... Currently under investgation ...

- To first order in U-spin breaking:

$$\langle\tilde{f}|\mathcal{O}(0)|\tilde{i}\rangle = \langle f|\mathcal{O}(0)|i\rangle + (-i)\int d^4x\,\langle f|T[\mathcal{O}(0)H_{\rm break}(x)]|i\rangle$$

$\mathcal{O}(x)$:	(Irreducible U Spin tensor) operator
$\vert i\rangle, \vert f\rangle$:	U-spin symmetric states
$\vert\tilde{i}\rangle, \vert\tilde{f}\rangle$:	States including U-spin breaking

- Classify the states
- Use Wigner Eckart Theorem ...

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

Interesting because:

- Related to the golden modes
- Factorization does not work (neither naive nor QCDF)
- All observables measured

Decay	$BR/10^{-4}$	A_{CP}
$B^- \to J/\psi K^-$	10.26 ± 0.37	$0.017 \pm 0.016(*)$
$B^- \to J/\psi \pi^-$	$0.48 \pm 0.04(*)$	0.09 ± 0.08

Table 1: Data taken from the PDG. (*): Inconsistent measurements, error enhanced by the PDG.

U-spin limit:

- Only one amplitude, with two CKM structures
- Predicts

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

- Not conclusive at the moment, due to uncertainties
- Naive factorization does not describe the breaking well:

$$\frac{BR(B^- \to J/\psi K^-)}{BR(B^- \to J/\psi \pi^-)} \left| \frac{\lambda_{cd}}{\lambda_{cs}} \right|^2 \sim \left(\frac{F^{B\to K}(M^2_{J/\psi})}{F^{B\to \pi}(M^2_{J/\psi})} \right)^2$$

$$\Longleftrightarrow \qquad 1.1 \pm 0.1 \sim 1.8 \pm 0.3$$

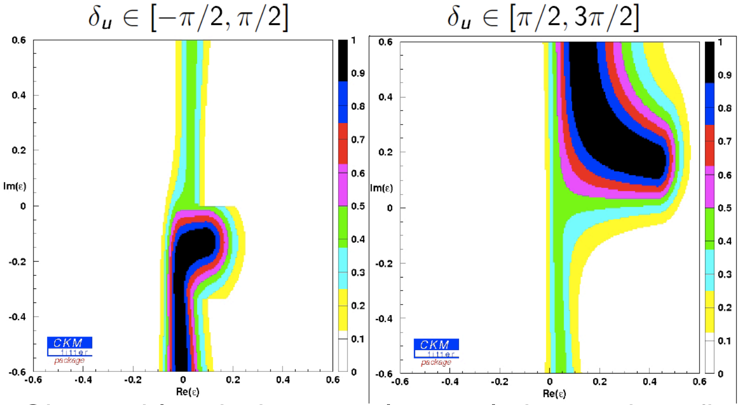
U-spin breaking:

- $|J/\psi \frac{\pi^-}{K^-}\rangle = |1/2, \pm 1/2\rangle \Rightarrow$ no $\Delta U = 3/2$ breaking
- Results in

$$\left\langle B^+ | \mathcal{H}_{eff} | J/\psi \frac{K^+}{\pi^+} \right\rangle = \sum_{q=u,c} \lambda_{qs} \left(A_{q,1/2} \pm A^{\epsilon}_{q,1/2} \right)$$

- Doubling of amplitudes, 7 hadronic parameters
- Possible strategy: $A_{u,1/2} < A_{c,1/2}$ expected
  - consider $A^{\epsilon}_{c,1/2}$ only $\Rightarrow$ 5 parameters, 4 observables
  - not fully determined, study correlations in 2D-plots

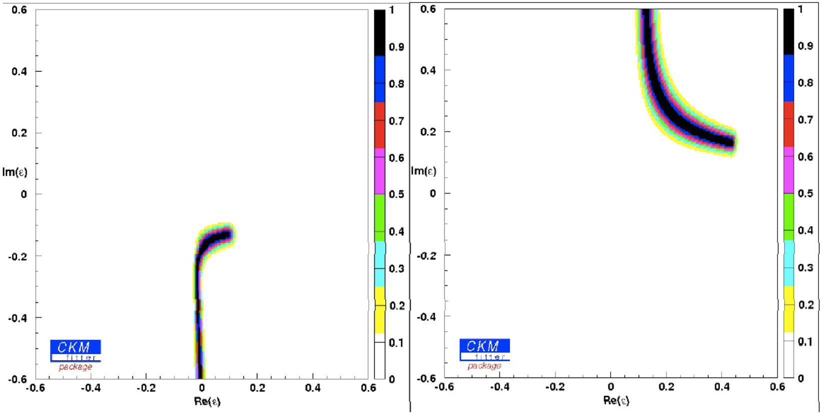
PRELIMINARY fit results. Plotted: $\epsilon = A^{\epsilon}_{c,1/2}/A_{c,1/2}$.



- Observable missing $\Rightarrow$ only correlation, no best fit s
- Real part finite, Imaginary part $\sim$ 100% correlated with $|A_{u,1/2}|$

PRELIMINARY: A simple future scenario ($\sigma_{exp}/5$). Plotted: $\epsilon = A^{\epsilon}_{c,1/2}/A_{c,1/2}$.

$\delta_u \in [-\pi/2, \pi/2]$ $\delta_u \in [\pi/2, 3\pi/2]$



Conclusion

- Perturbative Estimates may be misleading!
(typically underestimate the effects)
- If there are large non-perturbative contributions, SCET/PQCD/QCDF Ansätze will not yield precise results for an SM test
$\longrightarrow$ may be an interesting lab for QCD studies.
- 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"