Determining Weak Phases from $B \to J/\psi P$ Decays

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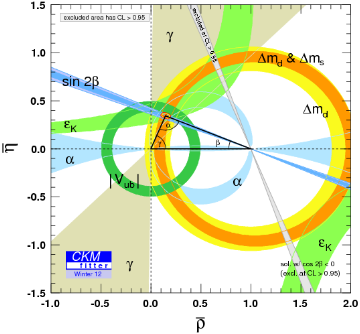
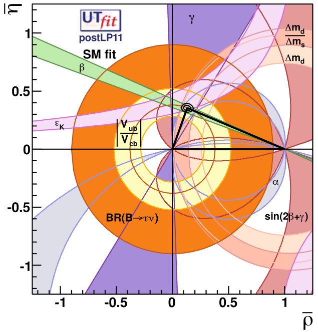
Outline

Motivation

Flavour sector of the SM established:





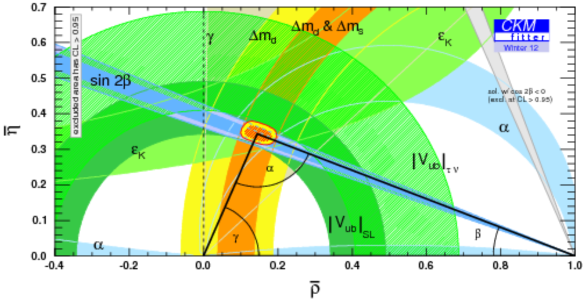
Furthermore B_s seems now basically SM-like

- NP influence constrained to be “small”
- LHC and NGB(s) will reach immense precision

Subleading SM contributions important

A closer look

Tension(s) in direct vs indirect determination of $\sin 2\beta$:



Main issue: $B \to \tau\nu$

- $\Delta \sin 2\beta \neq 0$ @ 2.8σ
- Tree-level process
- However sensitive to NP

Additionally:

- $|V_{ub}^{B\to\tau\nu}| \gtrsim |V_{ub}^{sl}| \gtrsim |V_{ub}^{\sin 2\beta}|$
- $|V_{ub}^{sl}|$ inclusive vs exclusive
- ϵ_K largish (input-dependent)

Increased interest in sources for $\Delta \sin 2\beta$

$B \to J/\psi M$ decays - basics

$B_d \to J/\psi K$, $B_s \to J/\psi \phi$:

- Amplitude $A = \lambda_{cs} A_c + \lambda_{us} A_u$
- Completely dominated by A_c [Bigi/Sanda '81]
- Very clear experimental signature
- Subleading terms:
  - Doubly Cabibbo suppressed
  - Penguin suppressed
  - ➥ Estimates $|\lambda_{us} A_u| / |\lambda_{cs} A_c| \lesssim 10^{-3}$ [Boos et al.'03, Li/Mishima '04, Gronau/Rosner '09]

The golden modes of B physics: $S = \sin \phi$

However:

- Quantitative calculation still unfeasible
- Fantastic precision expected at LHC and SFFs
- Indications of $\Delta \sin \phi \neq 0$

➥ Subleading contributions should be controlled

Including $|A_u| \neq 0$ – Penguin Pollution

$$A_u \neq 0 \;\Rightarrow\; S \neq \sin\phi,\; A_{\rm CP}^{\rm dir} \neq 0$$

Idea: U-spin-related modes constrain A_u

[Fleischer'99, Ciuchini et al.'05,'11, Faller/Fleischer/MJ/Mannel'09, ...]

Possible NP in mixing: $\phi = \phi^{\rm SM} + \phi^{\rm NP}$

Advantages:

- Data-driven method, avoids calculating matrix elements
- Penguin influence in $b \to d$ modes much larger, $|\lambda_{ud}| \sim |\lambda_{cd}|$
- Allows to extract $\Delta\phi_{\rm pen}$, yields more reliable $\Delta\phi_{\rm NP}$

Problems:

- $BR(b \to d) \sim \lambda^2 BR(b \to s)$
- $SU(3)$ breaking affects the analysis

➥ Relatively large range of $\Delta\phi_{\rm pen}$ remains allowed

Refining the analysis

Some of these problems can be addressed: [MJ'12, arXiv: 1206.2050]

- Cabibbo-suppressed modes well accessible at LHC/SFFs
- Perform $SU(3)$ analysis of $B \to J/\psi P$ [Zeppenfeld'81]
  - ➡ Inclusion of 5 accessible modes ($B_{u,d,s} \to J/\psi(\pi, K)$)
- Treat SU(3) breaking model-independently
  [Subsets considered in Gronau et al.'95, MJ/Mannel '09]

Assumptions used:

- $SU(3)$ breaking only for the leading amplitude
- MEs of EW penguins with $\Delta I = 1, 3/2$ neglected in A_c (yields tiny corrections to observables!)
- $A_u(B \to J/\psi\pi^0) - A_u(B \to J/\psi K^0) = 0$ (checkable within the analysis)

Data include recent updates from Belle, LHCb, and CDF

Improved extraction of $\phi_d(\to \phi_d^{\mathrm{NP}}), \Delta\phi_d^{\mathrm{pen}}$

Resulting framework

This analysis allows in principle to:

- extract the B_d mixing-phase ϕ_d,
- extract the shift $\Delta\phi_{\mathrm{pen}}$, and
- model-independently analyze $SU(3)$ breaking in $B \to J/\psi P$,

using available data, improvable with LHCb and SFFs.

Less restrictive assumptions than in previous analyses

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In addition, it provides:

- sensitivity to NP in mixing,
- some sensitivity to NP in the decay amplitudes,
- some sensitivity to the CKM angle γ(?)
  [Fleischer '99, Fleischer et al. '10]

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In addition, it provides:

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- some sensitivity to NP in the decay amplitudes.

Parametrization

$$
\begin{aligned}
A(\bar{B}^0 \to J/\psi \bar{K}^0) &= \mathcal{N}\left[1 + 2R_{\epsilon 1} + \bar{\lambda}^2 e^{-i\gamma}\left(R_{u1} + 3R_{u2}\right)\right] \\
\sqrt{2}A(\bar{B}^0 \to J/\psi \pi^0) &= -\bar{\lambda}\mathcal{N}\left[1 - R_{\epsilon 1} - R_{\epsilon 2} - e^{-i\gamma}\left(R_{u1} + 3R_{u2}\right)\right] \\
A(B^- \to J/\psi K^-) &= \mathcal{N}\left[1 + 2R_{\epsilon 1} + \bar{\lambda}^2 e^{-i\gamma}\left(R_{u1} - 5R_{u2}\right)\right] \\
A(B^- \to J/\psi \pi^-) &= -\bar{\lambda}\mathcal{N}\left[1 - R_{\epsilon 1} - R_{\epsilon 2} - e^{-i\gamma}\left(R_{u1} - 5R_{u2}\right)\right] \\
A(\bar{B}_s \to J/\psi K^0) &= -\bar{\lambda}\mathcal{N}\left[1 - R_{\epsilon 1} + R_{\epsilon 2} - e^{-i\gamma}\left(R_{u1} + 3R_{u2}\right)\right]
\end{aligned}
$$

- $\mathcal{N}$: Leading amplitude
- $R_{u1,2}$: $\sim P/T$, includes $\sqrt{\bar{\rho}^2 + \bar{\eta}^2}$ and numerical factors
- $R_{\epsilon 1,2}$: SU(3)-breaking ME combinations, normalized to $\mathcal{N}$
- $\bar{\lambda} = \lambda(1 + \lambda^2/2)$ for brevity

Expected orders of magnitude:
$|R_{u1}|, |R_{\epsilon 1,2}| \lesssim 10 - 15\%$, $|R_{u2}| \lesssim 1.7\%$,
corresponding to SU(3) breaking $\lesssim 40\%$, $P/T \lesssim 50\%$

Observables

- Define power counting to identify leading contributions: $\bar{\lambda}, |R_{u1,\epsilon 1,2}| \sim \xi \sim 0.1 \ldots 0.2,\ |R_{u2}| \sim \xi^2$
- Find combinations sensitive to single parameters at "LO"
- Direct CP asymmetries $A_{\rm CP}^{\rm dir} \sim \mathrm{Im}(R_{u1,2})$
- $\Delta S \equiv \eta_f S + \sin\phi \sim \mathrm{Re}(R_{u1})$
- Important rate combination:

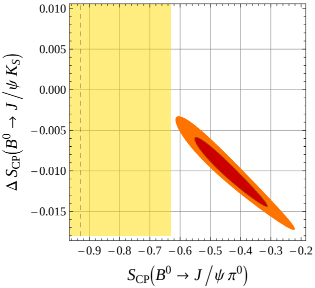
$$
\begin{aligned}
R_\Sigma &\equiv \frac{1}{\bar{\lambda}^2}\left(\frac{\bar{\Gamma}(B^- \to J/\psi\pi^-)}{\bar{\Gamma}(B^- \to J/\psi K^-)} + \frac{\bar{\Gamma}(B_s \to J/\psi \bar{K}^0)}{\bar{\Gamma}(B^0 \to J/\psi K^0)}\right) - 2 \\
&= -4(3\mathrm{Re}(R_{\epsilon 1}) + \cos\gamma\,\mathrm{Re}(R_{u1}))
\end{aligned}
$$

Results with present data – $SU(3)$ limit

Two datasets: $R_{\pi K} = \frac{BR(B^- \to J/\psi \pi^-)}{BR(B^- \to J/\psi K^-)} = \begin{cases} (4.9 \pm 0.4)\% \,(\mathrm{WA}) \\ (3.8 \pm 0.1)\% \,(\mathrm{LHCb}) \end{cases}$

Including *only* penguins:

- Yields bad fit, $\chi^2_{\min}/\mathrm{d.o.f.} \gtrsim 5$
- $S(B \to J/\psi \pi^0)_{\mathrm{fit}} < \mathrm{exp.}$
- No help from neglected amplitude
- Correction ΔS negative
  ➥Result worsens CKM fit
- Driving force:
  $R_\Sigma \overset{\mathrm{exp.}}{=} -0.32 \pm 0.14(-0.52 \pm 0.12)$

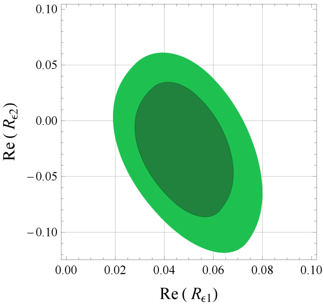


Necessity to go beyond $SU(3)$ limit
"Factorizable breaking" does not help

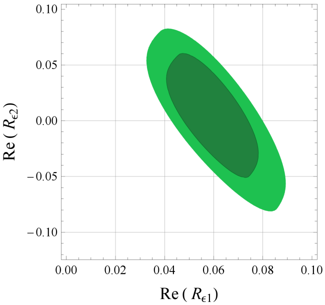
Results with present data – vanishing penguins

Setting $R_{ui} \equiv 0$ works rather well:

$R_{\pi K}$ from WA



$R_{\pi K}$ from LHCb



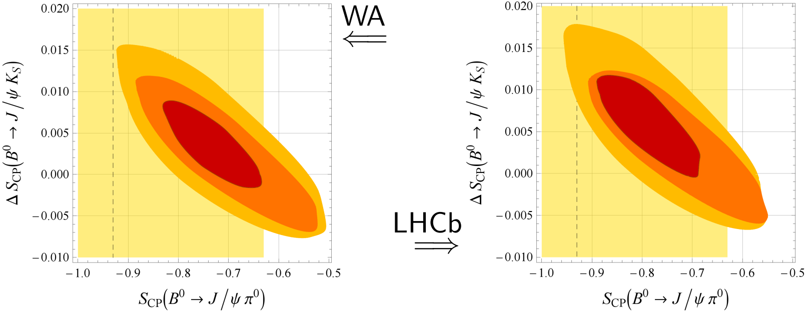
- Order of $\mathrm{Re}(R_{\epsilon i})$ as expected, $\sim 20\%$ $SU(3)$ breaking
- $\mathrm{Im}(R_{\epsilon i})$ not constrained
- $\chi^2 = 9.4(6.0)$ for 7 *effective degrees of freedom*

➥ $SU(3)$ breaking main ingredient to understand data

Results with present data – full fit I

Inclusion of penguins:

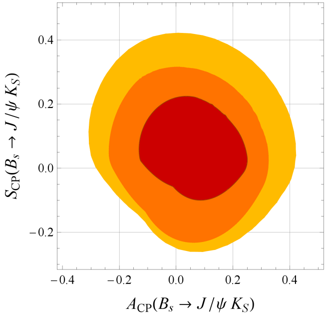
- Fits data well, $R_{\pi K}^{\mathrm{LHCb}}$ preferred
- Remaining tension due to $\Gamma(B^0 \to J/\psi K^0) - \Gamma(B^- \to J/\psi K^-)$
- Predicts $|S(B \to J/\psi\pi)|$ smaller than present central value
- $|\Delta S| \lesssim 0.01$ for $r_{SU(3)} \leq 40\%$ and $r_{\mathrm{pen}} \leq 50\%$



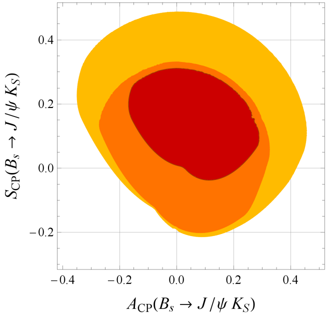
Results with present data – full fit II

Predictions for CP asymmetries in $B_s \to J/\psi K_S$:

$R_{\pi K}$ from WA



$R_{\pi K}$ from LHCb



- Present bound: $|A_{\rm CP}|, |S_{\rm CP}| \lesssim 20\%$
  - Measurement will add important information
  - Remaining theory input reduced!

Projections for data to come

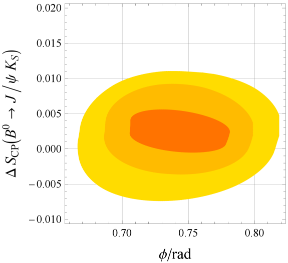
With future data (scenarios 1-3):

- Remaining theory input reduced
- $\delta\phi_d$ follows $\delta S_{\text{exp}}(B \to J/\psi K_S)$

Error due to $\Delta\phi_{\text{pen}}$ reducible!

What about $B \to J/\psi V$?

- In principle method transferable
- Technical complications:
  - 3 amplitudes/decay
  - ϕ has singlet component
- Experimentally more involved: final states $f = J/\psi\{\phi, K^*, \rho, \omega\}$
  ↳Work in progress



Sc.1	5 fb^{-1} LHCb
Sc.2	+5 ab^{-1} SFF
Sc.3	50 ab^{-1} SFF + 100 fb^{-1} SLHCb

Conclusions and outlook

- $B \to J/\psi M$ decays remain most important source for $\phi_{d,s}$
- Controlling penguins is necessary for very high precision
- $SU(3)$-breaking corrections are important
- Presented method allows for inclusion with present data
- $\Delta S \lesssim 0.01$ for conservative assumptions
- Results will improve with LHCb/SFF data, penguins tamed
- $B \to J/\psi V$ more complicated, work in progress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What about $J/\psi V$ modes?

- In principle, the approach is transferable to $B_s \to J/\psi V$
- Angular distribution measurements necessary
  ➥separate $SU(3)$ amplitudes $\to$ three analyses
- Corresponding $SU(3)$ partners are $B_{u,d,s} \to J/\psi\{\phi, K^*, \rho, \omega\}$
- Subsets may be useful to keep number of parameters finite...
- Experimentally challenging modes
  ➥Talk to me about the prospects
- Other modes sensitive to these contributions:
  - Can be used for qualitative statements
  - Quantitative analysis extremely difficult

$B \to J/\psi K$

SM and NP contributions and suppression factors:

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

Experimental data

Decay	$BR/10^{-4}$	$A_{\mathrm{CP}}/\%$	S_{CP}
$\bar{B}^0 \to J/\psi \bar{K}^0$	8.71 ± 0.32	1.0 ± 1.2	0.673 ± 0.016
$\bar{B}^0 \to J/\psi \pi^0$	0.176 ± 0.016	10 ± 13	-0.93 ± 0.29
$B^- \to J/\psi K^-$	10.13 ± 0.34	0.1 ± 0.7	—
$B^- \to J/\psi \pi^-$	0.50 ± 0.04	1 ± 7	—
set 2 (LHCb)	0.39 ± 0.02	0.5 ± 2.9	—
$\bar{B}^s \to J/\psi K^0$	0.34 ± 0.05		

Power counting explictly

Observable	LO expression	Experiment
A_I^K	$8\bar{\lambda}^2 \cos\gamma\,\mathrm{Re}(R_{u2})$	-0.037 ± 0.025
A_I^π	$-8\cos\gamma\,\mathrm{Re}(R_{u2})$	-0.13 ± 0.06
		-0.01 ± 0.05
ΔA_{CP}^K	$16\bar{\lambda}^2 \sin\gamma\,\mathrm{Im}(R_{u2})$	0.009 ± 0.014
$\sum A_{\mathrm{CP}}^K$	$4\bar{\lambda}^2 \sin\gamma\,\mathrm{Im}(R_{u1})$	0.011 ± 0.015
$\Delta A_{\mathrm{CP}}^\pi$	$-16\sin\gamma\,\mathrm{Im}(R_{u2})$	0.09 ± 0.15
		0.10 ± 0.13
$\sum A_{\mathrm{CP}}^\pi$	$-4\sin\gamma\,\mathrm{Im}(R_{u1})$	0.11 ± 0.15
		0.11 ± 0.13
$\Delta S(B \to J/\psi K)$	$-2\bar{\lambda}^2 \sin\gamma\cos(\phi)\,\mathrm{Re}(R_{u1})$	—
$\Delta S(B \to J/\psi \pi)$	$2\sin\gamma\cos(\phi)\,\mathrm{Re}(R_{u1})$	—
$\frac{\tilde{R}_{\pi K} - \tilde{R}_{KK}}{\bar{\lambda}^2}$	$-4\,\mathrm{Re}(R_{\epsilon 2})$	0.17 ± 0.13
		-0.03 ± 0.11
$\frac{\tilde{R}_{\pi K} + \tilde{R}_{KK}}{\bar{\lambda}^2} - 2$	$-4(3\,\mathrm{Re}(R_{\epsilon 1}) + \cos\gamma\,\mathrm{Re}(R_{u1}))$	-0.32 ± 0.14
		-0.52 ± 0.12

Structure of fit in the SU(3) limit

The following observations determine the fit:

- Direct CP asymmetries restrict $\mathrm{Im}(R_{u1,2})$ as expected
- $A_I^K \neq 0@1.5\sigma$ only, but c.v. huge compared to expectation
  ➥$\mathrm{Re}(R_{u2})$ larger than expected
- A_I^π ok (for LHCb result) / with "wrong" sign (former WA)
  Both cases: does not fit to A_I^K (worsens χ^2)
- Rate combination R_Σ: yields large $\mathrm{Re}(R_{u1})$
  ➥ΔS larger than expected