Precision determinations of the weak B meson mixing phases including “penguin pollution”

Martin Jung

DFG Deutsche Forschungsgemeinschaft

Future Challenges in Non-Leptonic B decays:
Theory and Experiment

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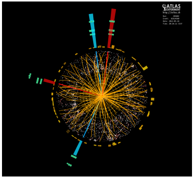
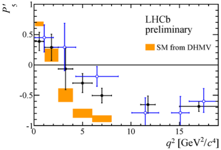
Consequences of the Flavour Problem



Higher precision necessary

- Experimental challenge:
  Control systematics at high luminosities
- Theoretical challenge:
  Reduce hadronic uncertainties



More complex analyses, e.g.

- Inclusion of neglected contributions
- Differential distributions even for rare decays

➥ Possible due to experimental advances!

Combination of many observables

- Use more available information
- Tests of more realistic models
  - ➥ Danger of higher model-dependence
- Model-independent analyses e.g. in HEFT
  - ➥ Rather weak statements regarding flavour

Extracting weak phases in hadronic decays

UT angles extracted from non-leptonic decays

➥ Hadronic matrix elements (MEs) main theoretical difficulty!

Options:

- Lattice: not (yet) feasible for (most) 3-meson MEs [Chris' talk]
- Other non-perturbative methods, e.g. QCDSR: idem, precision
- QCDF/SCET: applicability, power corrections [e.g. Guido's talk]
- Symmetry methods: limited applicability or precision

➥ New/improved methods necessary!

UT angles extracted by avoiding direct calculation of MEs

➥ Revisit approximations for precision analyses [Sebastian's talk]

Here: Improve SU(3) analysis in $B \to J/\psi M$

Flavour SU(3) and its breaking

SU(3) flavour symmetry ($m_u = m_d = m_s$)...

- does not allow to calculate MEs, but relates them (WE theorem)
- provides a model-independent approach
- allows to determine MEs from data
  ➥ improves "automatically"!
- includes final state interactions

flavour octet

SU(3) breaking...

- is sizable, $\mathcal{O}(20 - 30\%)$
- can systematically be included: tensor (octet) $\sim m_s$ [Savage'91,Gronau et al.'95,Grinstein/Lebed'96,Hinchliffe/Kaeding'96]
  ➥ even to arbitrary orders [Grinstein/Lebed'96]

Main questions:

- How large is the SU(3)-expansion parameter?
- Is the number of reduced MEs tractable?

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

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

- Amplitude $A = \lambda_{cs} A_c + \lambda_{us} A_u$
- Clearly 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 [but see Frings+'15]
- Fantastic precision expected at LHC and Belle II

➥ Subleading contributions should be controlled:
Apparent phase $\tilde{\phi} = \phi^{\rm mix}_{\rm SM} + \Delta\phi^{\rm mix}_{\rm NP} + \Delta\phi_{\rm pen\,(SM+NP)}$

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

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

Idea: U-spin-related modes constrain A_u [Fleischer'99, Ciuchini et al.'05,'11, Faller/Fleischer/MJ/Mannel'09, ...]

- Increased relative penguin influence in $b \to d$
- Extract $\phi = \phi_{\rm SM}^{\rm mix} + \Delta\phi_{\rm NP}^{\rm mix}$ and $\Delta\phi_{\rm pen}$
- Issue: Dependence of $\Delta\phi_{\rm pen}$ on SU(3) breaking

Using full SU(3) analysis: [MJ'12]

➥ Determines model-independently SU(3) breaking: $\sim 20\%$

$$\boxed{\text{Improved extraction of } \phi_d (\to \Delta\phi_{\rm NP}^{\rm mix}) \text{ and } \Delta\phi_{\rm pen}!}$$

Power counting

SU(3) breaking typically $\mathcal{O}(20-30\%)$

Several other suppression mechanisms involved:

- CKM structure (λ, but also $R_u \sim 1/3$)
- Topologial suppression: penguins and annihilation
- $1/N_C$ counting

All these effects should be considered!

➥ Combined power counting in $\delta \sim 30\%$ for all effects

➥ Neglect/Constrain only multiply suppressed contributions

➥ Numerically: contribution $x \sim \delta^n \to x \leq \delta^{(2n-1)/2}$

Yields predictive frameworks with weaker assumptions!

- Uses full set of observables for related decays
- Assumptions can be checked within the analysis

BR measurements and isospin violation [MJ'16]

Again: detail due to high precision and small NP

➥ Not specific to $B \to J/\psi M$!

Branching ratio measurements require normalization. . .

- B factories: depends on $\Upsilon \to B^+B^-$ vs. $B^0\bar{B}^0$
- LHCb: normalization mode, usually obtained from B factories

Assumptions entering this normalization:

- PDG: assumes $r_{+0} \equiv \Gamma(\Upsilon \to B^+B^-)/\Gamma(\Upsilon \to B^0\bar{B}^0) \equiv 1$
- LHCb: assumes $f_u \equiv f_d$, uses $r_{+0}^{\mathrm{HFAG}} = 1.058 \pm 0.024$

Both approaches problematic:

- Potential large isospin violation in $\Upsilon \to BB$ [Atwood/Marciano'90]
- Measurements in r_{+0}^{HFAG} assume isospin in exclusive decays
  - ➥ This is one thing we want to test!

➥ Avoiding this assumption yields $r_{+0} = 1.027 \pm 0.037$

➥ Isospin asymmetry $B \to J/\psi K$: $A_I = -0.009 \pm 0.024$

Factorization in $B \to J/\psi M$

$B \to J/\psi M$ *formally* factorizes for $m_{c,b} \to \infty$... [BBNS'00]

➡ ... but corrections are large: $\Lambda_{\mathrm{QCD}}/(\alpha_s m_{c,b})$

$B \to J/\psi M$ *formally* factorizes for $N_C \to \infty$... [Buras+'86]

➡ ... but corrections are large: $A_c \sim C_0 v_0 + C_8(v_8 - a_8)$ [Frings+'15]
Non-factorizable $a_8, v_8 \sim v_0/N_C$, but $C_8 \sim 17 C_0$!

$BR(B \to J/\psi M)$ remains uncalculable
N.B.: No reason to assume $F_{B\to K}/F_{B\to\pi}$ for $SU(3)$ breaking

Factorization for P/T: [Frings+'15 → see Uli's talk this morning]

- $\mathcal{A}(B \to J/\psi M) = \lambda_{cs} A_c + \lambda_{us} A_u$, A_u "penguin pollution"

➡ $A_u \sim p + a$, includes penguin and annihilation contributions
No annihilation in $B_d \to J/\psi K$, but in $B_s \to J/\psi \phi$

- $p = \sum_j \langle J/\psi M|\mathcal{O}_j^u|B\rangle = \sum_k \langle J/\psi M|\mathcal{O}_k^c|B\rangle + \mathcal{O}(\Lambda/m_{J/\psi})$
- Estimating $\langle J/\psi M|\mathcal{O}_k^c|B\rangle$ in $1/N_C$ yields $\Delta\phi_{d,s}|_p \lesssim 1^\circ$

A word on meson mixing

Neutral singlets and octets can mix under QCD

- Complicates SU(3) analysis

$B \to J/\psi P$: η, η' not necessary to determine ϕ_d
$B \to J/\psi V$: ϕ central mode

- Meson mixing has to be dealt with

For $N_C \to \infty$ in the SU(3) limit: degenerate $P_{1,8}$ and $V_{1,8}$

- Relative size of corrections determines mixing angle
- Large mixing does not mean breakdown of SU(3)!

η, η': large correction to $1/N_C$ from anomaly (singlet)

- η, η' remain approximate SU(3) eigenstates

ϕ, ω: $1/N_C$ effects small (OZI) → SU(3) breaking dominant

- eigenstates according to strangeness content, large mixing

Only the octet part can be controlled by K^* and ρ!

- Data for ω necessary to control singlet in SU(3)

Annihilation contributions in $B \to J/\psi M$

Annihilation is important!

- Suppression unclear for heavy final states
  - ➥ $\sim 20\%$ in $A_c(B \to DD)$ [MJ/Schacht'15]
- Determines singlet contributions in $B_s \to J/\psi\phi$
- Affects extraction of $\eta - \eta'$ mixing angle from $B_{d,s} \to J/\psi\eta^{(\prime)}$
- Its neglect in A_u correlates e.g. $B^- \to J/\psi\pi^-$ and $B^0 \to J/\psi K^0$ directly
  - ➥ Overly "precise" predictions for CP asymmetries

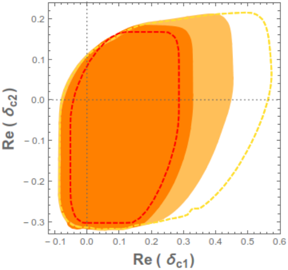
In $B \to J/\psi M$ three annihilation contributions:

- Annihilation in A_c, taken into account where appropriate
- Two annihilation contributions in A_u, $a_2 \sim a_1/N_C$
  - ➥ $a_2 \ll 1 \to BR(B_s \to J/\psi\pi^0, \rho^0) \approx 0$
$BR(B_s \to J/\psi\rho) \leq 3.6 \times 10^{-6}\,(90\%\mathrm{CL})$
  - ➥ No improvement from inclusion (unlike [Ligeti/Robinson'15])
  - ➥ Only leading contribution included later

$SU(3)$ breaking in $B \to J/\psi P$ [MJ/Knegjens('16), preliminary]

Fit to $\mathbf{B_{d,u,s} \to J/\psi(K,\pi)}$ data (including correlations)

- PDG uncertainties applied
  - Experimental issue: $R_{\pi K}$
- Excellent fit $(\chi^2/\mathrm{dof} \leq 1)$
  - Bad fit w/o SU(3) breaking
- SU(3) breaking $\leq 55\%$ allowed
  - Real SU(3) breaking $\lesssim 30\%$



1. $SU(3)$-breaking parameters perfectly within expectations
2. Strong correlation between $Re(\delta C_1)$ and $Re(P)$:
   - Cancellations for large P
   - Assumption on SU(3) breaking affects penguin shift

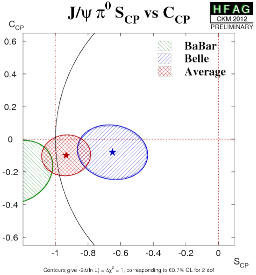
Remaining weaker approximations:

- SU(3) breaking for A_c, only (but to all orders for $P = \pi, K$!)
- EWPs with $\Delta I = 1, 3/2$ neglected in $\mathcal{A}_c$ (tiny!)
- $A(B_s \to J/\psi\pi^0) = 0$: testable (challenging)

“Penguins” in $B \to J/\psi P$ [MJ/Knegjens(’16), preliminary]

Fit to $\mathbf{B_{d,u,s} \to J/\psi(K,\pi)}$ data (including correlations)

- PDG uncertainties applied
  - ➥ Experimental issue: $S(B \to J/\psi\pi^0)$
- Annihilation included
  - ➥ $P/T, A/T \leq (100, 55, 16)\%$
- Pen. + Ann. consistent with 0



1. No significant $\mathcal{A}_u$ anywhere
   - ➥ no motivation for enhanced P, A
2. ϕ_d stable even with enhancements
3. Large CP asymmetries in $B_s \to J/\psi K$ possible with cancellations
   - ➥ Exp. progress important!

$\lvert P, A/T\rvert$	$\phi/^\circ$
100% (PDG)	22.2 ± 0.9
55% (PDG)	22.1 ± 0.8
55% (Belle)	22.0 ± 0.7
16% (PDG)	22.0 ± 0.8
0	21.7 ± 0.7

Conclusions

- Smallness of NP poses new challenges to CPV interpretation
- SU(3) with breaking enables model-independent analyses
- Combined power counting of small effects necessary

- High precision → Control penguins *and* annihilation
  - ➥ Possible for ϕ_d by $B \to J/\psi P$ $|\Delta\phi| \leq 0.6^\circ$ (95% CL)
  - ➥ $B \to J/\psi\pi^0$ and $B_s \to J/\psi K$ central
- Interplay with SU(3) breaking
  - ➥ careful interpretation of BR data necessary
- Results will improve with coming data, penguins tamed

- QCD-mixing of mesons complicates $B \to J/\psi V$ analysis
  - ➥ Nevertheless possible, work in progress

$b \to c\bar{c}s$ modes remain "golden"!

Input Values for $B \to J/\psi P$ Decays: BRs

Observable	Value	Ref./Comments
$\frac{1}{c_-}\mathrm{BR}(B^- \to J/\psi K^-)$	$(10.27 \pm 0.31) \times 10^{-4}$	
$\frac{1}{c_-}\mathrm{BR}(B^- \to J/\psi \pi^-)$	$(0.38 \pm 0.07) \times 10^{-4}$	
$\frac{\mathrm{BR}(B^- \to J/\psi \pi^-)}{\mathrm{BR}(B^- \to J/\psi K^-)}$	0.040 ± 0.004	scaling factor 3.2
	0.0386 ± 0.0013	Excluding BaBar
	0.052 ± 0.004	Excluding LHCb
$\frac{1}{c_0}\mathrm{BR}(\bar{B}^0 \to J/\psi \bar{K}^0)$	$(8.73 \pm 0.32) \times 10^{-4}$	
$r\,\frac{\mathrm{BR}(B^- \to J/\psi K^-)}{\mathrm{BR}(\bar{B}^0 \to J/\psi \bar{K}^0)}$	1.090 ± 0.045	correlations neglected
$\frac{1}{c_0}\mathrm{BR}(\bar{B}^0 \to J/\psi \pi^0)$	$(0.176 \pm 0.016) \times 10^{-4}$	scaling factor 1.1
$\frac{f_s}{f_d}\,\frac{\mathrm{BR}(\bar{B}_s \to J/\psi K_S)}{\mathrm{BR}(\bar{B}^0 \to J/\psi K_S)}$	0.0112 ± 0.0006	$f_s/f_d = f_s/f_d\vert_{\mathrm{LHCb}}$
$\frac{\mathrm{BR}(\bar{B}_s \to J/\psi K_S)}{\mathrm{BR}(\bar{B}^0 \to J/\psi K_S)}$	0.038 ± 0.009	uses $f_s/f_d = f_s/f_d\vert_{\mathrm{Tev}}$
$\frac{1}{c_0}\mathrm{BR}(\bar{B}^0 \to J/\psi \eta)$	$0.123 \pm 0.019 \times 10^{-4}$	
$\mathrm{BR}(\bar{B}_s \to J/\psi \eta)$	$(5.1 \pm 1.1) \times 10^{-4}$	
$R_s = \frac{\mathrm{BR}(\bar{B}_s \to J/\psi \eta')}{\mathrm{BR}(\bar{B}_s \to J/\psi \eta)}$	0.73 ± 0.14	$\rho(BR, R_s) = -23\%$
R_s	0.902 ± 0.084	$\rho(R_s, R) = 1\%$
$R = \frac{\mathrm{BR}(\bar{B}^0 \to J/\psi \eta')}{\mathrm{BR}(\bar{B}^0 \to J/\psi \eta)}$	1.11 ± 0.48	$\rho(R, R_\eta) = -73\%$
$\frac{f_d}{f_s} R_\eta = \frac{f_d}{f_s}\,\frac{\mathrm{BR}(\bar{B}^0 \to J/\psi \eta)}{\mathrm{BR}(\bar{B}_s \to J/\psi \eta)}$	0.072 ± 0.024	$\rho(R_\eta, R_s) = 9\%$

Input Values for $B \to J/\psi P$ Decays: CP Asymmetries

Observable	Value	Ref./Comments
$\mathcal{A}_{\rm CP}(B^- \to J/\psi K^-)$	0.003 ± 0.006	
$\mathcal{A}_{\rm CP}(B^- \to J/\psi \pi^-)$	0.001 ± 0.028	
$-\eta_{\rm CP}\mathcal{S}_{\rm CP}(\bar{B}^0 \to J/\psi K_{S,L})$	0.687 ± 0.019	
$\mathcal{A}_{\rm CP}(\bar{B}^0 \to J/\psi K_{S,L})$	0.016 ± 0.017	$\rho(\mathcal{S}_{\rm CP}, \mathcal{A}_{\rm CP}) = -15\%$
$\mathcal{S}_{\rm CP}(\bar{B}^0 \to J/\psi \pi^0)$	-0.94 ± 0.29	
	-0.65 ± 0.22	Belle only
$\mathcal{A}_{\rm CP}(\bar{B}^0 \to J/\psi \pi^0)$	0.13 ± 0.13	
	0.08 ± 0.17	Belle only
$\mathcal{S}_{\rm CP}(\bar{B}_s \to J/\psi K_S)$	-0.08 ± 0.41	
$\mathcal{A}_{\rm CP}(\bar{B}_s \to J/\psi K_S)$	0.28 ± 0.42	
$\mathcal{A}_{\Delta\Gamma}(\bar{B}_s \to J/\psi K_S)$	$0.49^{+0.77}_{-0.65} \pm 0.06$	
$f_s/f_d\|_{\rm LHCb}$	0.259 ± 0.015	
y_s	0.0611 ± 0.0037	
$r = f_{+-}/f_{00}$	1.027 ± 0.037	

Data in both tables: PDG, HFAG, LHCb, Belle, BaBar

Topological amplitudes in $B \to J/\psi P$

Mode	C	E^c	$\tilde{P}_2$	A^u	PA	E^u
$\bar{B}^0 \to J/\psi \bar{K}^0$	1	0	1	0	0	0
$\bar{B}^0 \to J/\psi \pi^0 \times\sqrt{2}$	1	0	1	0	0	-1
$B^- \to J/\psi K^-$	1	0	1	1	0	0
$B^- \to J/\psi \pi^-$	1	0	1	1	0	0
$\bar{B}_s \to J/\psi K^0$	1	0	1	0	0	0
$\bar{B}_s \to J/\psi \pi^0 \times\sqrt{2}$	0	0	0	0	0	-1
$\bar{B}^0 \to J/\psi \eta_8 \times\sqrt{6}$	-1	0	-1	0	0	-1
$\bar{B}^0 \to J/\psi \eta_1 \times\sqrt{3}$	1	$\sqrt{3}$	1	0	3	1
$\bar{B}_s \to J/\psi \eta_8 \times\sqrt{6}$	2	0	2	0	0	-1
$\bar{B}_s \to J/\psi \eta_1 \times\sqrt{3}$	1	$\sqrt{3}$	1	0	3	1

Table : Topological amplitudes contributing to $B \to J/\psi P$ in the $SU(3)$ limit.

Power counting explicit

Contribution	CKM	$1/N_C$	Pen.	Ann.	Π
C	1	1	1	1	1
A^c	1	δ	1	δ	δ^2
$\tilde{P}_2$	R_u	δ	δ	1	$R_u \times \delta^2$
$\tilde{P}_4$	R_u	δ^2	δ	δ	$R_u \times \delta^4$
A_1^u	R_u	1	1	δ^2	$R_u \times \delta^2$
A_2^u	R_u	δ	1	δ^2	$R_u \times \delta^3$

Table : Relative power counting for the contributions to $B \to J/\psi P$ decays with $b \to d$ transitions ($b \to s$ transitions receive an additional factor of λ^2 in the contributions to $\mathcal{A}_u$). There is an additional factor of δ for the SU(3) corrections to a given amplitude.

Reparametrization invariance and NP sensitivity

$$\mathcal{A} = \mathcal{N}(1 + r\, e^{i\phi_s} e^{i\,\phi_w}) \to \tilde{\mathcal{N}}(1 + \tilde{r}\, e^{i\tilde{\phi}_s} e^{i\tilde{\phi}_w})$$

Reparametrization invariance:

[London et al.'99,Botella et al.'05,Feldmann/MJ/Mannel'08]

Transformation changes weak phase, but not form of amplitude

- ➜ Sensitivity to (subleading) weak phase lost (presence visible)
  - $\phi_w = \gamma$ in given analyses
  - Usually broken by including symmetry partners
    - ➜ Proposals to extract γ in $B \to J/\psi P$ or $B \to DD$
  - However: partially restored when including SU(3) breaking! [MJ/Schacht'14]
    - ➜ Reason for large range for γ observed in [Gronau et al.'08]
    - ➜ Extracted phase fully dependent on SU(3) treatment
- ➜ NP phases in $\mathcal{A}$ not directly visible
- ➜ NP tests remain possible
- ➜ Addition of new terms, e.g. $A_c^{\Delta I=1}$ additional option