“Penguin Pollution” in $B \to J/\psi X$ Decays

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Implications of LHCb measurements and future prospects

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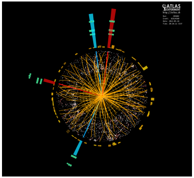
Consequences of the Flavour Problem

Higher precision necessary

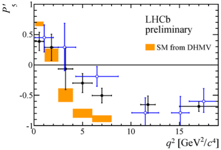
- Experimental challenge:
  Control systematics at high luminosities
- Theoretical challenge:
  Reduce hadronic uncertainties



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) three-meson MEs
- Other non-perturbative methods: idem, precision
- QCDF/SCET: applicability, power corrections
- Symmetry methods: limited applicability or precision

➥ New/improved methods necessary!

UT angles extracted by avoiding direct calculation of MEs

➥ Revisit approximations for precision analyses

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

$B \to J/\psi M$ 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 $\tilde{\phi} = \phi_{\rm SM}^{\rm mix} + \Delta\phi_{\rm NP}^{\rm mix} + \Delta\phi_{\rm pen}$

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?

Power counting

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

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

Yields predictive frameworks with weaker assumptions!

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

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: $\sim 20\%$

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

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 (tiny!)
- $A(B_s \to J/\psi\pi^0) = 0$: testable (challenging)

BR measurements and isospin violation [MJ 1510.03423]

Again: detail due to high precision and small NP

➥ Not specific to $B \to J/\psi K^{(*)}$!

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 $r_{+0}^{\rm HFAG} = 1.058 \pm 0.024$

Both approaches problematic:

- Potential large isospin violation in $\Upsilon \to BB$ [Atwood/Marciano'90]
- Measurements in $r_{+0}^{\rm HFAG}$ 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 $m_{c,b} \to \infty \ldots$ [BBNS'00]

➥ …but corrections are large: $\Lambda_{\rm QCD}/(\alpha_s m_{c,b})$

$B \to J/\psi M$ *formally* factorizes for $N_C \to \infty \ldots$ [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]

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

$N_C \to \infty$ and 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 strange 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 correlates e.g. A_u in $B^- \to J/\psi\pi^-$ and $B^0 \to J/\psi K^0$‘ directly
  - ➥ Overly “precise” predictions for CP asymmetries

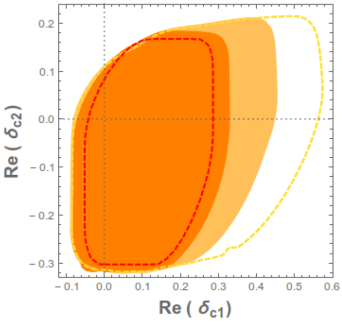
In $B \to J/\psi M$ three annihilation contributions:

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

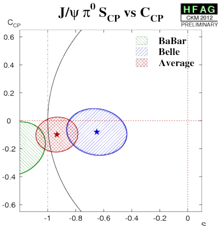
PRELIMINARY results for $B \to J/\psi P$ [Beaujean/MJ/Knegjens('15)]

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

- PDG uncertainties applied
- Annihilation included
- SU(3) breaking $\leq 55\%$ allowed
- $P/T, A/T \leq (100, 55, 16, 0)\%$
- Excellent fit $(\chi^2/\mathrm{dof} \leq 1)$
- SU(3) breaking $\lesssim 30\%$
- Pen. + Ann. consistent with 0
- Issues: $R_{\pi K}$, $S_{\mathrm{CP}}(B \to J/\psi\pi^0)$



$\lvert P, A/T \rvert$	$\phi/°$	$\Delta\phi/°(95\%)$
100%	22.2 ± 0.9	$[-0.5, 1.0]$
55%	22.1 ± 0.8	$[-0.5, 0.6]$
16%	22.0 ± 0.8	$[-0.2, 0.2]$



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)
- 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	$f_s/f_d = f_s/f_d\|_{\mathrm{LHCb}}$
$\frac{\mathrm{BR}(\bar{B}_s \to J/\psi K_S)}{\mathrm{BR}(\bar{B}^0 \to J/\psi K_S)}$	0.038 ± 0.009	uses $f_s/f_d = f_s/f_d\|_{\mathrm{Tev}}$
$\frac{1}{c_0}\mathrm{BR}(\bar{B}^0 \to J/\psi \eta)$	$0.123 \pm 0.019 \times 10^{-4}$	
$\mathrm{BR}(\bar{B}_s \to J/\psi \eta)$	$(5.1 \pm 1.1) \times 10^{-4}$	
$R_s = \frac{\mathrm{BR}(\bar{B}_s \to J/\psi \eta')}{\mathrm{BR}(\bar{B}_s \to J/\psi \eta)}$	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

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