“Penguin Pollution” in $B \rightarrow J/\psi X$ 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 $B \rightarrow J/\psi M$
**$B \to J/\psi M$ 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]

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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 $\tilde{\phi} = \phi_{\text{SM}}^{\text{mix}} + \Delta \phi_{\text{NP}}^{\text{mix}} + \Delta \phi_{\text{pen}}$
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

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]
  
  \(\rightarrow\) 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 $O(30\%)$

Several other suppression mechanisms involved:

- CKM structure ($\lambda$, but also $R_u \sim 1/3$)
- Topological 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

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


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

Using full SU(3) analysis: [MJ’12]

\[ \text{Determines model-independently SU(3) breaking: } \sim 20\% \]

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

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)
Introduction

Penguin pollution in the golden modes

Conclusions

**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 $r^{\text{HFAG}}_{+0} = 1.058 \pm 0.024$

Both approaches problematic:

- Potential large isospin violation in $\Upsilon \to B B$ [Atwood/Marciano’90]
- Measurements in $r^{\text{HFAG}}_{+0}$ 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: $\Lambda_{QCD}/(\alpha_s m_{c,b})$

$B \to J/\psi M$ 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]

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

- $A_u \sim p + a$, includes penguin and annihilation contributions

- No annihilation in $B_d \to J/\psi K$, but in $B_s \to J/\psi \phi$

- $p = \sum_j \langle J/\psi M | O^u_j | B \rangle = \sum_k \langle J/\psi M | O^c_k | B \rangle + O(\Lambda/m_{J/\psi})$

- Estimating $\langle J/\psi M | O^c_k | B \rangle$ 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

\[ B \rightarrow J/\psi P: \eta, \eta' \text{ not necessary to determine } \phi_d \]
\[ B \rightarrow J/\psi V: \phi \text{ central mode} \]

- Meson mixing has to be dealt with

\[ N_C \rightarrow \infty \text{ and in the SU(3) limit: degenerate } P_{1,8} \text{ and } V_{1,8} \]

- Relative size of corrections determines mixing angle

- Large mixing does not mean breakdown of SU(3)!

\[ \eta, \eta': \text{ large correction to } 1/N_C \text{ from anomaly (singlet)} \]

- \( \eta, \eta' \) remain approximate SU(3) eigenstates

\[ \phi, \omega: 1/N_C \text{ effects small (OZI)} \rightarrow \text{SU(3) breaking dominant} \]

- eigenstates according to strange content, large mixing

Only the octet part can be controlled by \( K^* \) and \( \rho \)!

- Data for \( \omega \) 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 $B_{d,s} \to J/\psi\eta^{(s)}$
- 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 $A_u$, $a_2 \sim a_1/N_C$
  - $a_2 \ll 1 \to BR(B_s \to J/\psi\pi^0, \rho^0) \approx 0$, $A_I(B \to J/\psi K) \approx 0$
  - $BR(B_s \to J/\psi\rho) \leq 3.6 \times 10^{-6} (90\% \text{CL})$
  - No improvement from inclusion (unlike [Ligeti/Robinson'15])
  - Only leading contribution included later
**PRELIMINARY results for** $B \rightarrow J/\psi P$ [Beaujean/MJ/Knegjens('15)]

**Fit to** $B_{d,u,s} \rightarrow J/\psi (K, \pi)$ 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 ($\chi^2$/dof $\leq 1$)
- SU(3) breaking $\lesssim 30\%$
- Pen. + Ann. consistent with 0
- Issues: $R_{\pi K}, S_{CP}(B \rightarrow J/\psi \pi^0)$

| $|P, A/T|$ | $\phi/^{\circ}$ | $\Delta\phi/^{\circ}$ (95%) |
|-----------|----------------|----------------------------|
| 100%      | 22.2 $\pm$ 0.9 | $[-0.5, 1.0]$              |
| 55%       | 22.1 $\pm$ 0.8 | $[-0.5, 0.6]$              |
| 16%       | 22.0 $\pm$ 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 \( \phi_d \) by \( B \rightarrow J/\psi P \) \( |\Delta \phi| \leq 0.6^\circ \) (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 \( B \rightarrow J/\psi V \) analysis
  - Nevertheless possible, work in progress

\[
b \rightarrow c\bar{c}s \text{ modes remain “golden”!}\
\]
### Input Values for $B \to J/\psi P$ Decays: BRs

<table>
<thead>
<tr>
<th>Observable</th>
<th>Value</th>
<th>Ref./Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{1}{c_-} \text{BR}(B^- \to J/\psi K^-)$</td>
<td>$(10.27 \pm 0.31) \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$\frac{1}{c_-} \text{BR}(B^- \to J/\psi \pi^-)$</td>
<td>$(0.38 \pm 0.07) \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$\text{BR}(B^- \to J/\psi \pi^-)$</td>
<td>$0.040 \pm 0.004$</td>
<td>scaling factor 3.2</td>
</tr>
<tr>
<td>$\text{BR}(B^- \to J/\psi K^-)$</td>
<td>$0.0386 \pm 0.0013$</td>
<td>Excluding BaBar</td>
</tr>
<tr>
<td>$\frac{1}{c_0} \text{BR}(\bar{B}^0 \to J/\psi \bar{K}^0)$</td>
<td>$(8.73 \pm 0.32) \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$r \frac{\text{BR}(B^- \to J/\psi K^-)}{\text{BR}(\bar{B}^0 \to J/\psi K^0)}$</td>
<td>$1.090 \pm 0.045$</td>
<td>correlations neglected</td>
</tr>
<tr>
<td>$\frac{1}{c_0} \text{BR}(\bar{B}^0 \to J/\psi \pi^0)$</td>
<td>$(0.176 \pm 0.016) \times 10^{-4}$</td>
<td>scaling factor 1.1</td>
</tr>
<tr>
<td>$\frac{f_s}{f_d} \frac{\text{BR}(\bar{B}_s \to J/\psi K_S)}{\text{BR}(\bar{B}^0 \to J/\psi K^0)}$</td>
<td>$0.0112 \pm 0.0006$</td>
<td>$f_s/f_d = f_s/f_d</td>
</tr>
<tr>
<td>$\frac{f_s}{f_d} \frac{\text{BR}(\bar{B}_s \to J/\psi K_S)}{\text{BR}(\bar{B}_s \to J/\psi \pi^0)}$</td>
<td>$0.038 \pm 0.009$</td>
<td>uses $f_s/f_d = f_s/f_d</td>
</tr>
<tr>
<td>$\frac{1}{c_0} \text{BR}(\bar{B}^0 \to J/\psi \eta)$</td>
<td>$0.123 \pm 0.019 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$\text{BR}(\bar{B}_s \to J/\psi \eta)$</td>
<td>$(5.1 \pm 1.1) \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$R_s = \frac{\text{BR}(\bar{B}_s \to J/\psi \eta')}{\text{BR}(\bar{B}_s \to J/\psi \eta)}$</td>
<td>$0.73 \pm 0.14$</td>
<td>$\rho(BR, R_s) = -23%$</td>
</tr>
<tr>
<td>$R_s$</td>
<td>$0.902 \pm 0.084$</td>
<td>$\rho(R_s, R) = 1%$</td>
</tr>
<tr>
<td>$R = \frac{\text{BR}(\bar{B}^0 \to J/\psi \eta')}{\text{BR}(\bar{B}^0 \to J/\psi \eta)}$</td>
<td>$1.11 \pm 0.48$</td>
<td>$\rho(R, R_\eta) = -73%$</td>
</tr>
<tr>
<td>$\frac{f_d}{f_s} R_\eta = \frac{f_d}{f_s} \frac{\text{BR}(\bar{B}^0 \to J/\psi \eta)}{\text{BR}(\bar{B}_s \to J/\psi \eta)}$</td>
<td>$0.072 \pm 0.024$</td>
<td>$\rho(R_\eta, R_s) = 9%$</td>
</tr>
</tbody>
</table>
## Input Values for $B \to J/\psi P$ Decays: CP Asymmetries

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

Data in both tables: PDG, HFAG, LHCb, Belle, BaBar
Reparametrization invariance and NP sensitivity

\[ A = N(1 + r e^{i\phi_s} e^{i\phi_w}) \rightarrow \tilde{N}(1 + \tilde{r} e^{i\tilde{\phi}_s} e^{i\tilde{\phi}_w}) \]

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 \( \gamma \) in \( B \rightarrow J/\psi P \) or \( B \rightarrow DD \)
    - However: partially restored when including SU(3) breaking!
      - [MJ/Schacht'14]
      - Reason for large range for \( \gamma \) observed in [Gronau et al.'08]
      - Extracted phase fully dependent on SU(3) treatment

- NP phases in \( A \) not directly visible
- NP tests remain possible
- Addition of new terms, e.g. \( A_c^{\Delta I=1} \) additional option