

Flavour Symmetries in Non-Leptonic Decays

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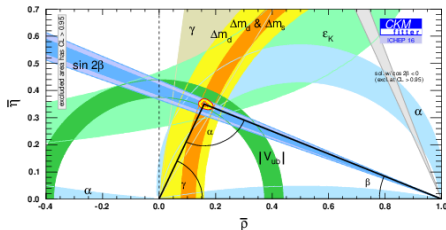
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Extracting weak phases in hadronic decays

UT fit: angles extracted from CPV in non-leptonic decays
 Theory: Hadronic matrix elements (MEs) main difficulty!



➡ UT angles extracted by avoiding direct calculation of MEs

Non-leptonic Decays:

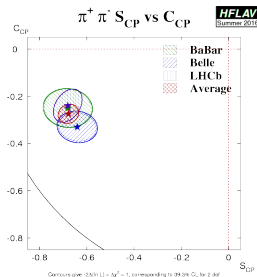
- Sensitive to CKM angles
- Some penguin- or even annihilation-dominated
 - ➡ Sensitivity to NP
- Different approaches available, predictions differ
 - ➡ Testing grounds for QCD

Available data and their treatment

HFLAV: $B \rightarrow PP$ listed under “Rare Decays”

➡ True up to the B factories, not so much anymore

- Absolute BRs: B factories
 - Ratios of BRs: LHCb, Tevatron
Very precise, especially charged final states!
 - CP asymmetries: all of the above
- ➡ Recently: B_s modes and annihilation-dominated modes [LHCb]



Sources of correlations between BRs (accessible to me):

- Common normalization modes (large, up to 50%)
 - For B_s modes: f_s/f_d (soon to be dominant uncertainty)
 - Absolute BRs: production asymmetry from Υ decays
- ➡ Yields e.g. 14×14 correlation matrix for BRs in $B \rightarrow PP$

BR measurements and isospin violation [MJ 1510.03423]

Detail due to high precision and small NP

➡ Relevant for $\sigma_{\text{BR}}/\text{BR} \sim \mathcal{O}(\%)$

Branching ratio measurements require normalization. . .

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

Assumptions entering this normalization:

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

Both approaches problematic:

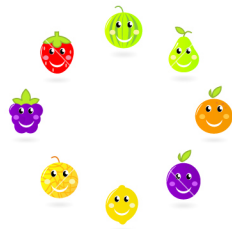
- Potential large isospin violation in $\Upsilon \rightarrow BB$ [Atwood/Marciano'90]
- Measurements in r_{+0}^{HFAG} assume isospin in exclusive decays
➡ This is one thing we want to test!

➡ Avoiding this assumption yields $r_{+0} = 1.035 \pm 0.038$
(potentially subject to change, in contact with Belle members)

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?

Reparametrization invariance and NP sensitivity

Why not just use one decay to extract a weak phase?

➡ **Reparametrization invariance (RI):**

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

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

Transformation changes weak phase, observables remain identical

➡ Sensitivity to (subleading) weak phase lost (presence visible)

- typically $\phi_w = \gamma$, not a restriction even beyond SM
- **RI usually broken** by including symmetry partners
 - ➡ Proposals to extract γ 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 γ observed in [Gronau+'08]

➡ Extracted phase fully dependent on SU(3) treatment

➡ NP phases in \mathcal{A} not directly visible

➡ NP tests remain possible, **dynamical input necessary!**

Size of SU(3) breaking

SU(3) breaking “generically 20 – 30%”

- ➡ What does that mean? Exceptions?
- ➡ Avoid naive SU(3) assumption, understand cases of large breaking

Examples of of large symmetry breaking:

- Kinematically forbidden decays
 - ➡ affect e.g. $D \leftrightarrow \bar{D}$ mixing analysis
- Degeneracy of states
 - ➡ e.g. large M_K/M_π , $\phi + \omega$ not close to SU(3) eigenstate
- Presence of additional (small) scale(s)
 - ➡ e.g. $M_\Upsilon - 2M_B$
- Other effects
 - ➡ BR ratios can become large (~ 3) even for 20 – 30% effect, e.g. $BR(D \rightarrow KK)/BR(D \rightarrow \pi\pi)$
 - ➡ All of these can be included w/o major complications

SU(3) breaking and dynamical input

All-order SU(3) w/o hierarchies usually just reparametrization

- Additional input necessary to control SU(3) breaking
- Required input depends on decay class:
 - Analysis of a subclass
 - $B \rightarrow \pi\pi$ classic example, **isospin**
 - CKM hierarchy
 - Very effective in $b \rightarrow c\bar{c}s$, less so in $B \rightarrow PP$
 - Additional hierarchies
 - Wilson coefficients
 - $\alpha_s(m_b)$ expansion
 - colour suppression
 - loop factors
 - Heavy-quark suppression
- “Topological approach”, i.e. hierarchies among topologies
- (Approximate) absence of specific reduced MEs, e.g. $\Delta I = 3/2$ amplitude $\sim \lambda_{cs}$ in $b \rightarrow c\bar{c}s$

Power counting

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

Several other suppression mechanisms involved:

- CKM structure (λ , but also $R_u \sim 1/3$)
 - “Topological”: penguins and annihilation (α_s , loop, $1/m_b$)
 - $1/N_C$ counting
- ➡ Only their combination decides size of a contribution
- ➡ Importantly, SU(3) breaking can e.g. mimic EWPs

Goal: predictive framework with weaker assumptions

- Uses full set of observables for related decays
- Check assumptions as much as possible **within** the analysis

Previous assumptions rendered unfeasible by LHCb data

➡ Penguin annihilation in $B \rightarrow PP$

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

Annihilation is important!

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

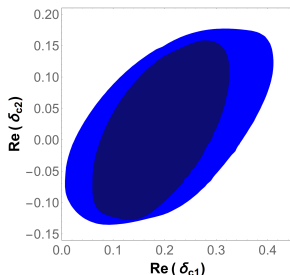
In $B \rightarrow J/\psi M$ three annihilation contributions:

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

$SU(3)$ breaking in $B \rightarrow J/\psi P$ [MJ('19), preliminary]

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

- PDG uncertainties applied
 - ➔ Experimental issue: $R_{\pi K}$
- Excellent fit ($\chi^2/\text{dof} \leq 1$)
 - ➔ 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!)
- $A(B_s \rightarrow J/\psi \pi^0) = 0$: testable (challenging)

General results in $B \rightarrow PP$

Topological fit with (almost) arbitrary MEs works (CL 25%)

➡ MEs determined, predict everything so far not measured

Largest χ^2 contribution from $B_s \rightarrow K^+K^-$, two reasons:

1. Tension in $S_{CP}, C_{CP}, A_{\Delta\Gamma}$ ($S^2 + C^2 + A^2 = 1$)
2. Non-factorizable SU(3) breaking (U -spin $\leftrightarrow B_d \rightarrow \pi^+\pi^-$)

Recent LHCb measurements: significant penguin annihilation!

➡ $B_s \rightarrow \pi^+\pi^-$, PA previously neglected, but $\lambda_{cs}PA \sim \lambda_{us}T$
PA not calculable, neither QCDf nor LCSRs \rightarrow fit parameters

LCSR: [Khodamirian'01, Khodjamirian+'03, '05, Alex' talk]

- BRs typically fine (after including PA)
- CP asymmetries mostly in 1D ranges as well
 - ➡ Exception: $A_{CP}(B^0 \rightarrow \pi^+\pi^-)$ (similar in QCDf)
- Good overlap between fitted parameters + predictions
- Global fit doesn't work \rightarrow **correlations**, e.g. $A \sim E$

$B \rightarrow \pi\pi$

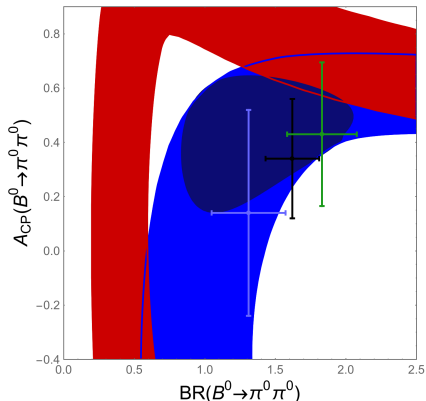
Special isospin-related subclass \rightarrow extraction of $\gamma + \beta$ (α)

Dynamical approaches typically two issues:

- $A_{\text{CP}}(B^0 \rightarrow \pi^+\pi^-)$ sizable and positive
- $BR(B^0 \rightarrow \pi^0\pi^0)$ much larger than expected
 - \rightarrow the latter is often considered an experimental issue

$B \rightarrow \pi^0\pi^0$ (removed from fits):

- Isospin: $BR > 0.5 \times 10^{-6}$
- SU(3): $BR > 0.8 \times 10^{-6}$
- \rightarrow Does not look like an exp. issue!
- LCSR: weakly restricted, but tension with $BR(B^- \rightarrow \pi^-\pi^0)$
- $B \rightarrow \pi\pi$ data: r_E not enough!
- \rightarrow Indicates missing piece(s)
- \rightarrow Better understanding of QCD could reveal NP



$B \rightarrow \pi K$

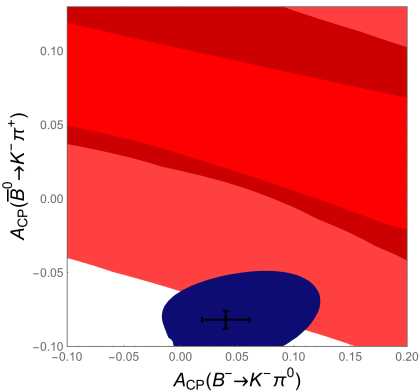
Long-standing puzzle: expect $A_{\text{CP}}(B^- \rightarrow K^- \pi^0) \sim A_{\text{CP}}(\bar{B}^0 \rightarrow K^- \pi^+)$

➡ Experimentally: $\Delta A_{\text{CP}} = 0.122 \pm 0.022$

LCSRs:

- Individually ok, ΔA_{CP} difficult
 - Large r_E does not help
 - Large r_E and r_A ok, but conflict with $A_{\text{CP}}(B^- \rightarrow \pi^- K_S)$
- ➡ SU(3) breaking not the culprit

SU(3) fit predicts ΔA_{CP}



Where to go in $B \rightarrow PP$?

Idea: combine “the best of two worlds” (see also e.g.

[Descotes-Genon+'06, Cheng/Oh'11, Bobeth+'15] for combination w/ QCDF)

Important ratio: $r_E \equiv \frac{\langle P_1 P_2 | \tilde{O}_1^{u,(D)} | \bar{B}_{(s)} \rangle_E}{\langle P_1 P_2 | O_1^{u,(D)} | \bar{B}_{(s)} \rangle_{E, fact}}$.

➡ Soft gluon exchange calculable in LCSR, sizable [Khodjamirian'01]

Hard spectator scattering not calculable

➡ Can be extracted from $\rho_E = \frac{BR(B^- \rightarrow \pi^- \pi^0)}{BR(B^- \rightarrow \pi \ell \nu)}$ [Beneke+'01]

First step: assume r_E to be SU(3) invariant

➡ Infrared sensitivity? BBNS: Cut-off $\Lambda_h \sim 500$ MeV

➡ Testable with data

For PA, so far only extraction from data possible

➡ Limited predictivity, but effect included in larger modes

LCSRs: Calculable SU(3) breaking for P (and A)

➡ Distinguish SU(3) breaking from other effects

Conclusions and Outlook

- Symmetry methods important for SM-parameter extractions
 - ↳ Precision extractions typically avoid direct calculation
 - ↳ **Future challenge in non-leptonic B decays**
- Smallness of NP poses new challenges to CPV interpretation
- Correlations and small effects in exp. data important
- New data show importance of previously neglected contributions
 - ↳ Precise measurements of rare modes feed back into theory
- Reparametrization invariance necessitates dynamical input
- Understanding SU(3) breaking essential for reducing uncertainties
 - ↳ Several hierarchies complicate analysis
 - ↳ Data-driven determination possible to some extent
- $b \rightarrow c\bar{c}s$: precision analysis of $\phi_{d,s}$ possible, SU(3) breaking critical
- $B \rightarrow PP$: $B \rightarrow \pi\pi$ and $B \rightarrow \pi K$ indicate missing contributions
 - ↳ QCD understanding critical for NP sensitivity!

Parametrization

Operators written as colour-singlet and -octet, e.g.,

$$C_1 \mathcal{O}_1 + C_2 \mathcal{O}_2 = (C_1 + C_2/3) \mathcal{O}_1 + 2C_2 \tilde{\mathcal{O}}_1.$$

Factorize where appropriate, parametrize rest as, e.g.,

$$r_E \equiv \frac{\langle P_1 P_2 | \tilde{\mathcal{O}}_1^{u,(D)} | \bar{B}_{(s)} \rangle_E}{\langle P_1 P_2 | \mathcal{O}_1^{u,(D)} | \bar{B}_{(s)} \rangle_{E, fact}}.$$

(r_E includes hard scattering contributions)

Calculations of r_T (T=A,E,P,...) taken from [\[Khodjamirian+'05\]](#)

➡ Convenient interface between LCSRs and other approaches

Light-cone sum rules

Method to calculate hadronic matrix elements non-perturbatively

- Start from suitable correlation function
 - ➡ Theory object, some freedom to choose
- Calculate two representations, **hadronic** and **partonic**
 - ➡ based on **Quark-Hadron-Duality** ($3\times \rightarrow$ systematic error)
 - ➡ matched in dispersion relation (using unitarity+analyticity)
- Expansion in $1/m_B$ (OPE), α_s

Advantage of LCSRs: Finite Annihilation!

[Khodjamirian+'05]

- ➡ one main uncertainty in QCDF
- ➡ Soft + hard pieces largely cancel \rightarrow small
Hard-scattering not feasible (so far)
- ➡ For high precision combined with data
- ➡ Uses SU(3), breaking calculable (wip)

