Observations in $B \to PP$ Decays

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Implications of LHCb measurements and future prospects

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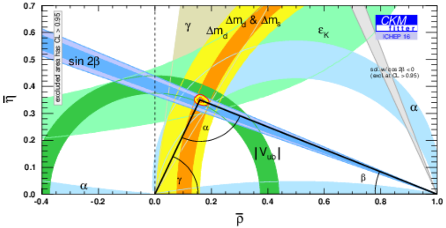
Extracting weak phases in hadronic decays

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

$B \to PP$ Decays:

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

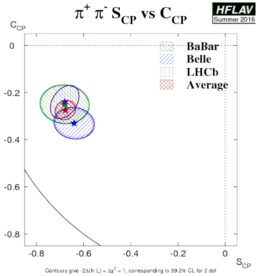
Available data and their treatment

HFLAV: $B \to PP$ 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 effective 14×14 correlation matrix for BRs

BR measurements and isospin violation [MJ 1510.03423]

Detail due to high precision and small NP

➥ Relevant for $\sigma_{\rm BR}/{\rm BR} \sim \mathcal{O}(\%)$

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

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

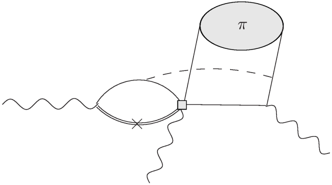
Advantage of LCSRs: Finite Annihilation!

[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)



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]

In $B \to PP$ Decays: "Topological approach"

- Form factors and decay constants dominant source?

➥ Needs testing, partly accessible from data

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": 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 a possible within the analysis

Previous assumptions rendered unfeasible by LHCb data

➥ Penguin annihilation

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)

- typically $\phi_w = \gamma$, not a restriction
- 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+'08]
  - ➥ Extracted phase fully dependent on SU(3) treatment

➥ NP phases in $\mathcal{A}$ not directly visible

➥ NP tests remain possible, dynamical input necessary!

General results

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

➥ MEs determined, predict anything so far not measured

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

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

Recent LHCb measurements: significant penguin annihilation!

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

LCSRs: [Khodamirian'01,Khodjamirian+'03,'05]

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

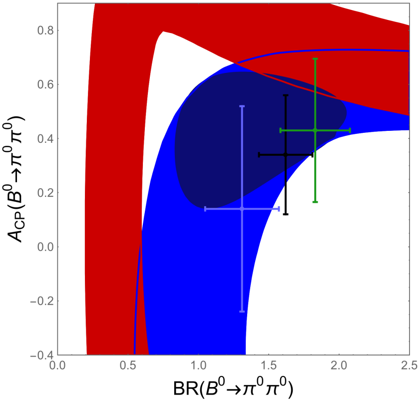
$B \to \pi\pi$

Special isospin-related subclass $\to$ extraction of $\gamma + \beta$ (α)
Dynamical approaches typically two issues:

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

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

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



$B \to \pi K$

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

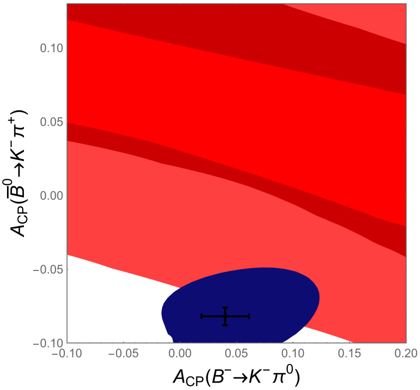
➥ Experimentally: $\Delta A_{\rm CP} = 0.122 \pm 0.022$

LCSRs:

- Individually ok, $\Delta A_{\rm CP}$ difficult
- Large r_E does not help
- Large r_E *and* r_A ok, but conflict with $A_{\rm CP}(B^- \to \pi^- K_S)$

➥ SU(3) breaking not the culprit

SU(3) fit predicts $\Delta A_{\rm CP}$



Where to go?

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

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

Hard spectator scattering not calculable

- Can be extracted from $\rho_E = \frac{BR(B^- \to \pi^- \pi^0)}{BR(B \to \pi \ell \nu)}$ [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

- $B \to PP$ important modes with potential NP sensitivity
- Smallness of NP poses new challenges to CPV interpretation
- Several hierarchies complicate analysis
- Recent LHCb results provide access to PA, previously neglected
  - ➥ Precise measurements of rare modes feed back into theory
- SU(3) provides model-independent analysis, breaking critical

➥ Reparametrization invariance necessitates dynamical input

- LCSRs allow partial access to power-suppressed contributions
  - ➥ Annihilation finite, smaller than expected
- Most observables within predicted ranges
- Induced correlations make fits difficult
- $B \to \pi\pi$ and $B \to \pi K$ indicate missing contributions

➥ QCD understanding critical for NP sensitivity!

Parametrization

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

$$C_1\mathcal{O}_1 + C_2\mathcal{O}_2 = (C_1 + C_2/3)O_1 + 2C_2\tilde{\mathcal{O}}_1 \, .$$

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

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

(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