CP-Violation in Three-body B Decays
A Model Ansatz

Kevin Olschewsky
based on arXiv:2003.12053
with K. Vos and T. Mannel

Universität Siegen

Young Scientist Forum

Motivation

- Non-leptonic three-body B decays offer a wide range of phenomenological interpretations

  $\rightarrow$ Many different decay channels observed

- CP-violation in B-decays has already reached a high level of precision and will further increase in the future

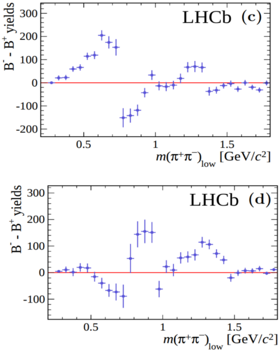
- Fully hadronic final states make theoretical description challenging

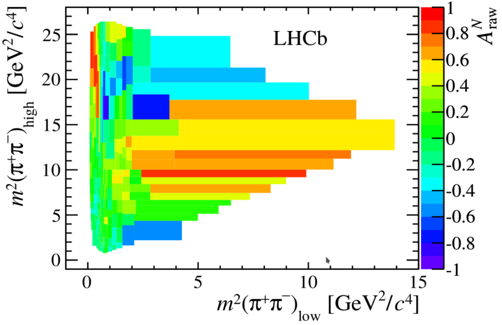
- Strong phases are not constant throughout Dalitz

  $\rightarrow$ New sources of CP-violation

CP-Violation in $B \to \pi\pi\pi$

- Rich structure of CP-violation, especially in $B \to \pi\pi\pi$
  $\to$ Strongly local with rapid changes
- Inclusion of charm-effects might be necessary





LHCb collaboration,'14

CP-Violation

- Direct CP-violation if $\Gamma(B \to f) \neq \Gamma(\bar{B} \to \bar{f})$
- $\Gamma(B \to f) \propto |A(B \to f)|^2 \equiv |\langle B|\mathcal{H}_{\text{eff}}|f\rangle|^2$
- Effective Hamiltonian for $\Delta B = 1$

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}}(\lambda_u \mathcal{O}_u + \lambda_c \mathcal{O}_c)$$

- $\lambda_q = V_{qb} V_{qd}^*$ are CKM-factors and $\mathcal{O}_q$ contain current-current and penguin operators
- λ_u carries CP-phase, but λ_c does not
- $\mathcal{O}_u$ and $\mathcal{O}_c$ both carry strong phase

Direct CP-violation in B-decays is caused by interference of $\mathcal{O}_u$ and $\mathcal{O}_c$!

Amplitude Convention

- Currently isobar (inspired) models are often used to parametrize three-body-decays

$$A_{\pm}(s_{12}) = \sum_k \frac{c_k^{\pm} P_k^{(\ell)}(s_{12})}{s_{12} - m_k^2 + i m_k \Gamma_k}$$

- Fit parameters $c_k^{\pm}$ are complex and constant throughout Dalitz
$\rightarrow$ Dynamical dependence of phases arises only from BW-form

- Underlying physics effects are better reflected when parameterizing amplitudes in A_u and A_c

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- We propose to perform amplitude analysis in $A_{u/c}$ instead

$$A_{\pm}(s_{12}) = \sum_k \frac{(a_k^{(u)} e^{\mp i\gamma} + a_k^{(c)}) P_k^{(\ell)}(s_{12})}{s_{12} - m_k^2 + i m_k \Gamma_k}$$

Charm resonances and the Isobar Model

- Currently residues of resonances are parameterized as

$$c_k^{\pm} = x_k \pm \delta x_k + i(y_k \pm \delta y_k) = a_k^{(u)} e^{\mp i\gamma} + a_k^{(c)}$$

- Parameterizations are related and contain the same information
- However assignment to matrix elements is not evident anymore
- Transforming to our parameterization gives [LHCb, '20]

$$\frac{|a_\rho^{(u)}|}{|a_\rho^{(c)}|} \simeq \delta x_\rho \simeq \mathcal{O}(10^{-3})$$

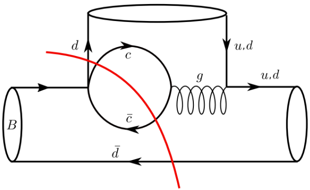
- Indicates that ρ-meson is dominated by contribution of A_c
  $\rightarrow$ In contradiction with expectations!
  $\rightarrow$ Might be an artefact of missing charm-resonances

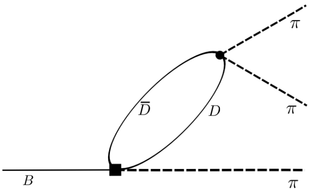
A new Model Ansatz

Why a new Model Ansatz?

- Three-body B decays are much more difficult to describe theoretically
  $\rightarrow$ Strong phases are not constant
  $\rightarrow$ Central region of Dalitz is difficult to describe
- First attempts to study in a QCD-based method [Kränkl, Mannel, Virto,'15; Mannel, Klein, Vos, '17]
- Lack of knowledge about power-corrections and non-perturbative input impedes description with QCDF
- Experimental amplitude analysis still in the stage of modelling (Isobar, K-Matrix,...)

Parameterization of Threshold effects





- Assume difference between $\mathcal{O}_u$ and $\mathcal{O}_c$ is mainly driven by states with valence charm quarks
- In three-body decays $D\bar{D}$ generates non-perturbative strong phase once threshold $q > 2m_D$ is crossed
- A_c will contain additional threshold like contributions

$$A_c = \langle B^+|\mathcal{O}_c|R_{c\bar{c}}\pi\rangle \langle R_{c\bar{c}}\pi|\pi\pi\pi\rangle + \langle B^+|\mathcal{O}_c|D\bar{D}X\rangle \langle D\bar{D}X|\pi\pi\pi\rangle$$

Parameterization of Threshold effects

- Threshold contribution is challenging to calculate
  $\rightarrow$ We propose a simple model ansatz to describe these effects

- Intermediate states can be described by a modified propagator

$$T_R(s_{12}) = \frac{1}{s_{12} - m_R^2 + [\Sigma_R(s_{12}) - \text{Re}\,\Sigma_R(m_R^2)]}$$

- Self-energy Σ_R must account for threshold effects
  $\rightarrow$ We focus on open-charm-loops

$$\Sigma_R(s_{12}) = g_R m_R \sqrt{s_{\text{thres}} - s_{12}}\, \arctan\left(\frac{1}{\sqrt{\frac{s_{\text{thres}}}{s_{12}} - 1 + i\epsilon}}\right)$$

- Generates dynamical width above the open-charm-threshold s_{thres}

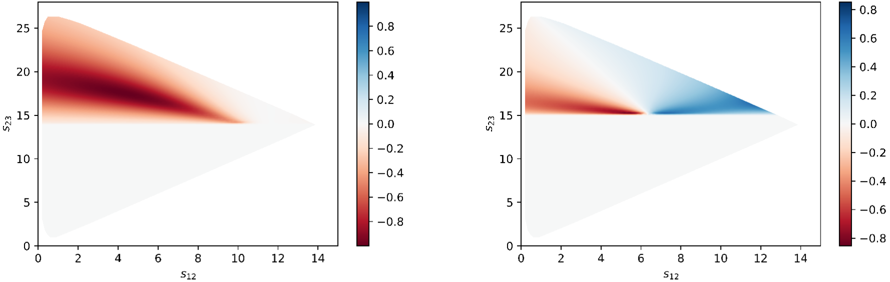
Parameterization of Threshold effects

- Include threshold effects in A_c

$$A_c(s_{12}) = \sum_R a_R e^{i\phi_R} P_R^{(\ell)}(s_{12})\, T_R(s_{12}) + \ldots$$

- Quantities a_R and Φ_R together with m_R and g_R are fit parameters

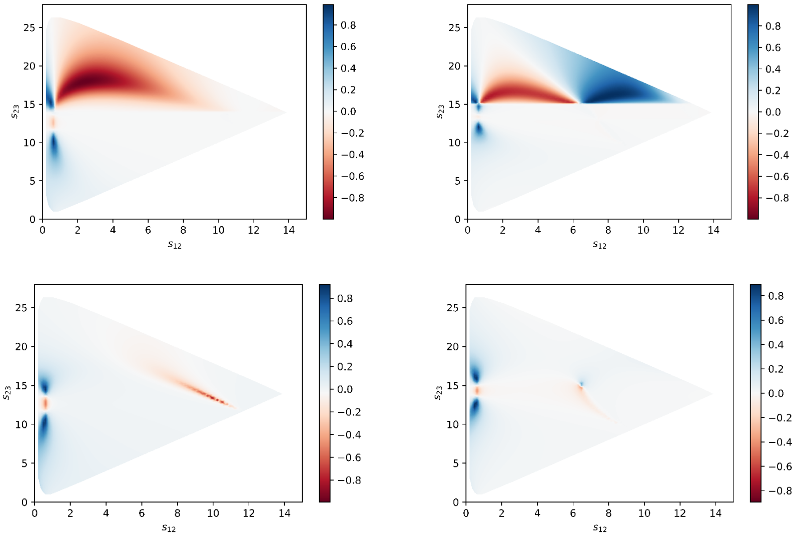
- Dots indicate low-lying resonances, parameterized in the usual way



- Structures are much larger than in usual CP-asymmetry

Comparison with Breit-Wigner Parameterization

- Interference of a ρ meson with *s*- and *p*-wave resonance



Conclusion and Outlook

- Proposed a new model to study three-body B decays
  - Usage of A_u and A_c in amplitude analysis is natural and helps understand physical interpretation and causes of CP-violation
  - Inclusion of threshold-effects can create large and quickly changing structures in CP-distribution
- Updated data will be very interesting, especially for $B \to \pi\pi\pi$
  $\to$ Full CP-plot from experimental amplitude analysis is very desirable
- Threshold effects should be included in the experimental analysis!

Conclusion and Outlook

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Thanks for your attention!

Backup

CP-Violation

- Interference of intermediate quark-states also introduces CP-invariant strong phases
- Decay amplitude

$$A(B \to f) = \mathrm{e}^{\mathrm{i}\gamma}|A_u|\mathrm{e}^{\mathrm{i}\theta_1} + |A_c|\mathrm{e}^{\mathrm{i}\theta_2}$$

with strong phases θ_i and weak phase γ

- Define direct CP-violation as

$$A_{\mathrm{CP}} = \frac{|A(B \to f)|^2 - |A(\bar{B} \to \bar{f})|^2}{|A(B \to f)|^2 + |A(\bar{B} \to \bar{f})|^2} = \frac{2|A_u||A_c| \sin\gamma \sin\Delta\theta}{|A_u|^2 + |A_c|^2 + 2|A_u||A_c| \cos\gamma \cos\Delta\theta}$$

Direct CP-violation only occurs with strong <u>and</u> weak phase difference

Parameterization of Threshold effects

- Concentrate on the current-current part of the operator $\mathcal{O}_c$

$$\langle B^+|\mathcal{O}_c|\pi\pi\pi\rangle = \sum_n \langle B^+|\mathcal{O}_c|n\rangle \langle n|\pi\pi\pi\rangle$$

- Assume difference between $\mathcal{O}_u$ and $\mathcal{O}_c$ is mainly driven by states with valence charm quarks

$$\langle\mathcal{O}_c\rangle = \frac{1}{N_c} \underbrace{\langle\bar{b}\gamma_\mu(1-\gamma_5)d\rangle\langle\bar{c}\gamma_\mu(1-\gamma_5)c\rangle}_{\text{Color-singlet}} + \underbrace{\langle\bar{b}\gamma_\mu T^a(1-\gamma_5)d\rangle\langle\bar{c}\gamma_\mu T^a(1-\gamma_5)c\rangle}_{\text{Color-octet}}$$

- Color-singlet contribution generates tower of $J/\psi(1^{--})$-states
  $\rightarrow$ Only very small branching fraction to $\pi\pi$ final state

- Color-octet contribution arises through intermediate $D^{(*)}\bar{D}^{(*)}$ pairs

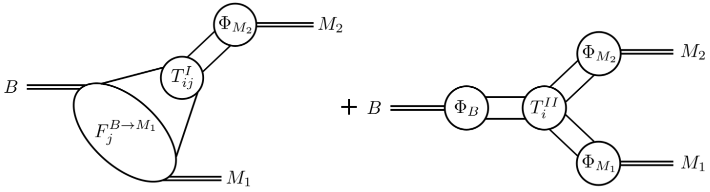
Intermezzo: Exotic States

- Exotic states do not fit in the usual quark model
  $\rightarrow$ Often conjectured to consist of 4 quarks (tetraquarks, hadronic molecules)
- Many such states were found in charm region
- Often lie remarkably close to a two-particle-threshold
  $\rightarrow X(3872) \leftrightarrow D\bar{D}$, $Y(4260) \leftrightarrow D\bar{D}_1$
- Often decay predominantly in their constituents
- Conjectured to be bound states of two mesons (hadr. molecules)
- Threshold effects might play an important role in their description

QCD-Factorization for Two-Body-Decays

- At leading order in Heavy-Quark Expansion

$$\langle M_1 M_2 | \mathcal{O}_i | \bar{B} \rangle = F^{B\to M_1} \int \mathrm{d}u T_i^I(u) \Phi_{M_2}(u) + \int \mathrm{d}\omega \mathrm{d}u \mathrm{d}v T_i^{II} \Phi_B(\omega) \Phi_{M_1}(u) \Phi_{M_2}(v)$$



- $T^{I/II}$: scattering kernels perturbatively calculable
- Formfactors and LCDA's non-perturbative objects
- $B \to \pi\pi$ well understood here; subleading terms might be important

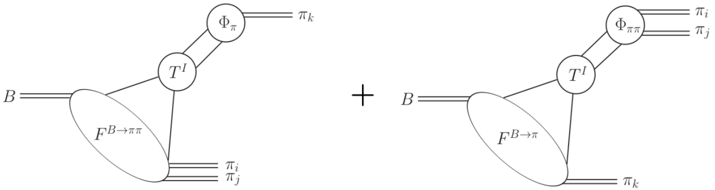
[Beneke, Buchalla, Neubert, Sachrajda, 1999]

QCDF for Three-Body-Decays

- Perturbatively calculable central region might not exist for realistic B meson masses

- Factorization formula can be found for the edges

$$\langle \pi\pi\pi|\mathcal{O}|B\rangle_{s_{+-}\ll 1} = T_1^I \otimes F^{B\to\pi\pi} \otimes \Phi_\pi + T_2^I \otimes F^{B\to\pi} \otimes \Phi_{\pi\pi}$$



- Contains several non-perturbative inputs

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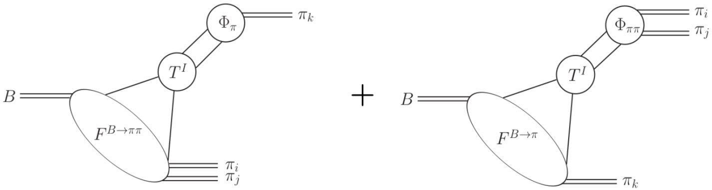

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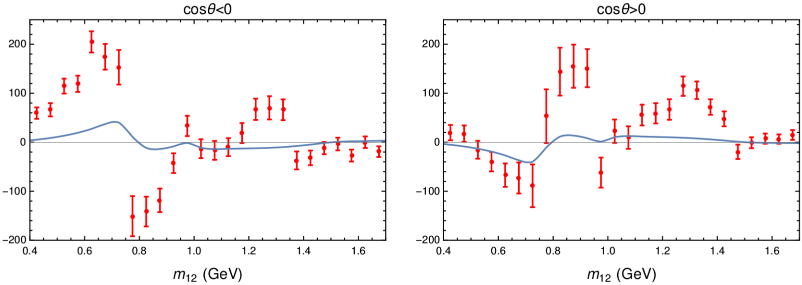
QCDF for Three-Body-Decays

- Results for projection of CP-asymmetry general shape of distribution

  → Strong phases are not large enough to explain the large differences in CP-asymmetry

- Higher orders of non-perturbative input might be needed



- QCDF struggles in description of <u>some</u> three-body decays

[Klein, Vos, Mannel, '17]