Factorization in multibody B decays

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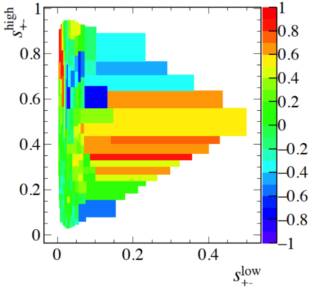
Motivation

Multibody decays form a large part of the non-leptonic decays

- Rich structure of CP violation
- May contain non-perturbative strong phases not suppressed by Λ/m_b



At the stage of modelling; historic isobar model

- Sum of Breit-Wigner shapes and non-resonant background

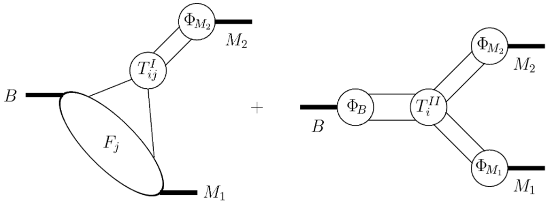
$$\frac{1}{q^2 - m_R^2 + i\Gamma_R m_R}$$

Requires a QCD-based factorization approach [Kraenkl, Mannel, Virto '15]

QCD Factorization in two-body decays

Beneke, Buchalla, Neubert, Sachrajda [1999]; Beneke, Neubert [2003]

At leading order in the heavy-quark expansion (Λ/m_b)



Hard scattering kernels $T^{I,II}$ perturbatively calculable

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

Form factors and LCDAs universal non-perturbative objects

- Vertex corrections $T^I = 1 + \mathcal{O}(\alpha_s/\pi)$
- Spectator scattering $T^{II} = \mathcal{O}(\alpha_s)$ and real

NNLO penguin contractions of current-current operators computed Beneke, Bell, Huber, Li

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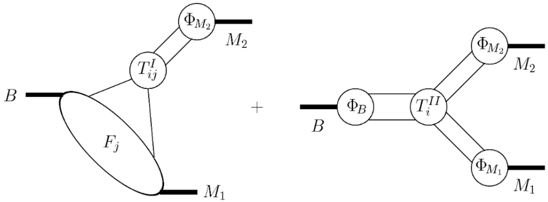

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$$\langle M_1 M_2|\mathcal{O}_i|\bar{B}\rangle = F^{B\to M_1}\int du\,T_i^I(u)\Phi_{M_2}(u) + \int d\omega\,du\,dv\,T_i^{II}\phi_B(\omega)\Phi_{M_1}(u)\Phi_{M_2}(v)$$

Form factors and LCDAs universal non-perturbative objects

$$A_{\rm CP} = \mathcal{O}(\alpha_s/\pi) + \mathcal{O}(\Lambda/m_b)$$

Indications for the presence of subleading terms

Factorization in three-body B decays

Kraenkl, Mannel, Virto [2015]; Klein, Mannel, Virto, KKV [2018]

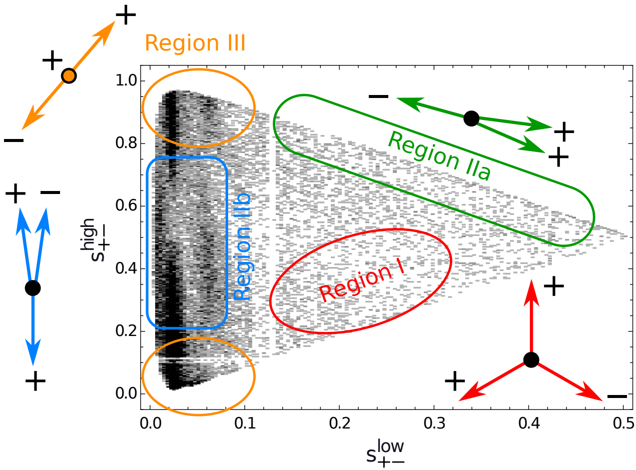
Data-driven model-independent factorization approach

- Improvement over quasi-two body interpretation
- Introduces new non-perturbative strong phases
- Focuss here on $B \to \pi\pi\pi$ but similar for $B \to hhh$

(First) Challenge: Reach the same level as two-body QCDF

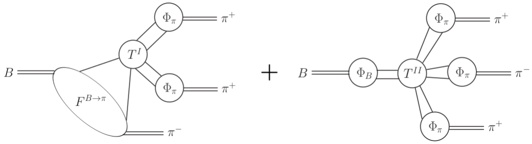
Dalitz distribution - Kinematics

- $B^+ \to \pi^+(k_1)\pi^-(k_2)\pi^+(k_3)$ Symmetric Dalitz plot
- Kinematic variables $s_{+-}^{\text{low}} = \frac{(k_1+k_2)^2}{m_B^2}$ and $s_{+-}^{\text{high}} = \frac{(k_2+k_3)^2}{m_B^2}$



Factorization in three-body decays - Central Region

Kraenkl, Mannel, Virto [2015]



$$\langle \pi^+\pi^+\pi^-|\mathcal{O}_i|\bar{B}\rangle = F^{B\to\pi}\int du\, dv T_i^I(u,v)\Phi_\pi(u)\Phi_\pi(v)$$
$$+\int du\, dv\, dz\, d\omega\, T_i^{II}(u,v,z,\omega)\Phi_B(\omega)\Phi_\pi(u)\Phi_\pi(v)\Phi_\pi(z)$$

- Hard kernels depend on momentum fractions
- At leading order all convolutions are finite
- $1/m_b^2$ and α_s suppressed compared to the edge
- $A_{\rm CP} = \mathcal{O}(\alpha_s/\pi) + \mathcal{O}(\Lambda/m_b)$

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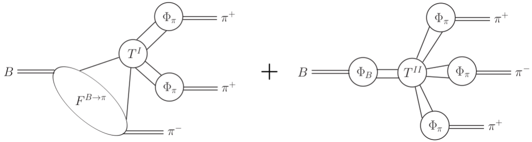


$$\langle \pi^+\pi^+\pi^- | \mathcal{O}_i | \bar{B} \rangle = F^{B\to\pi} \int du\, dv T_i^I(u,v)\Phi_\pi(u)\Phi_\pi(v)$$
$$+ \int du\, dv\, dz\, d\omega\, T_i^{II}(u,v,z,\omega)\Phi_B(\omega)\Phi_\pi(u)\Phi_\pi(v)\Phi_\pi(z)$$

Perturbatively calculable region might not exist for $m_B = 5$ GeV

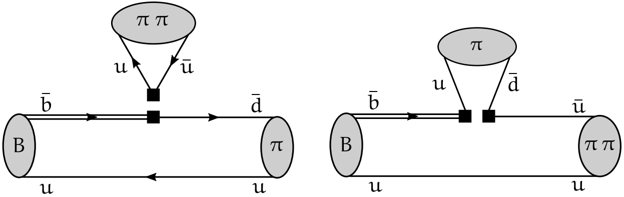
- Interesting to study QCD factorization properties
- Study power-corrections/weak annihilation? Bediaga, Frederico, Magalhaes [2017]

Factorization in three-body decays - Edges

Kraenkl, Mannel, Virto [2015]; Klein, Mannel, Virto, KKV [2018]

Breakdown of factorization at edges requires new input

- Resonances only close to the edges
- Three-body decays resemble two-body



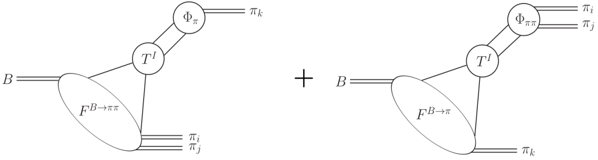
Leading contributions to hard kernels

Same operators as in two-body case, different final states

- Always an improvement over quasi-two-body decays
- Reduces to $B \to \rho\pi$ for ρ dominance and zero-width approximation

Factorization in three-body decays - Edges

Kraenkl, Mannel, Virto [2015]



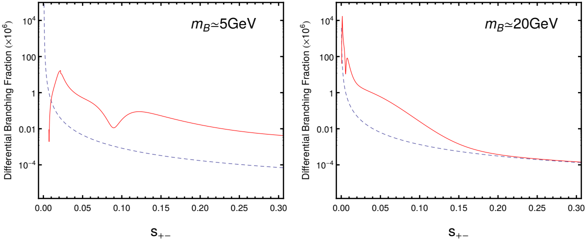
$$\langle \pi^+\pi^+\pi^- | \mathcal{Q}_i | B \rangle_{s_{+-}\ll 1} = T_i^I \otimes F^{B\to\pi^+} \otimes \Phi_{\pi^+\pi^-} + T_i^I \otimes F^{B\to\pi^+\pi^-} \otimes \Phi_{\pi^+}$$

New non-perturbative input $\rightarrow$ new strong phases

- Two-pion light-cone distribution amplitude Polyakov, Diehl, Gousset, Pire, Gozin, ...
- Generalized Form Factor Feldmann, Khodjamirian, Faller, Mannel, van Dyk, ...

Matching of the two approaches

Kraenkl, Mannel, Virto [2015]



Full 2πLCDA (red) and perturbative contribution (dashed)

Two approaches do not merge for realistic B meson mass

- Power-corrections not suppressed enough
- No part of the Dalitz plot is really center-like

New non-perturbative inputs

Focus on $B \to \pi\pi\pi$ but can be adapted for $B \to hhh$ decays

2π LCDA

Polyakov, Diehl, Gousset, Pire, Teryaev

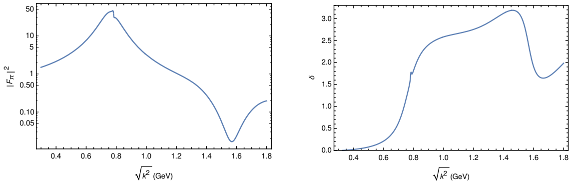
Reduces at leading order to the normalization

- Both isoscalar ($I = 0$) and isovector ($I = 1$) contribute

$$\int du\, \phi_{\pi\pi}^{I=1}(u,\zeta,s) = (2\zeta - 1) F_\pi(s) \qquad \int du\, \phi_{\pi\pi}^{I=0}(u,\zeta,s) = 0$$

Time-like pion formfactor $F_\pi(s)$: Babar data on $e^+e^- \to \pi\pi(\gamma)$

Hanhart, Kubis, Shekhovtsova, Roig, Was, Predzinski



$B \to \pi\pi$ form factor

Only vector form factor relevant [Faller, Feldmann, Khodjamirian, Mannel, van Dyk '14]

- Partial wave expansion: P wave always $I = 1$ and S wave has $I = 0$

$$k_{3\mu} \langle \pi^+(k_1)\pi^-(k_2)|\bar{b}\gamma^\mu\gamma^5 u|B^+(p)\rangle = -\sqrt{k_3^2} F_t(s, \zeta)$$

Theory efforts: [Boër, Feldmann, van Dyk '17, Feldmann, van Dyk, KKV '18]

- $B \to \pi\pi$ form factors factorize at large k^2
- Relevant kinematics in regime of Light-Cone Sum Rules
- P-wave studied with B-meson and dipion LCSRs [Khodjamirian, Virto, Cheng '17]
- S-wave in progress! [Descotes-Genon, Khodjamirian, Virto, KKV [in progress]]

$B \to \pi\pi$ form factor from B-meson LCSRs

Correlation function with pseudoscalar heavy-light current

$$F_\mu(k,q) = i \int d^4x e^{ik\cdot x} \langle 0| T \bar{d}(x)\gamma_\mu u(x), i m_b \bar{u}(0)\gamma_5 b(0)|\bar{B}^0(q+k)\rangle$$

Light-cone OPE in terms of B-meson LCDA and dispersive relation:

$$F_\mu^{OPE}(k^2,q^2) = \frac{1}{\pi}\int_{s_{th}}^{\infty} ds \frac{2\mathrm{Im}F_\mu}{s-q^2}$$

Unitarity Relation [Kang, Kubis, Hanhart, Meissner '14, Khodjamirian, Virto, Cheng [2017]]

$$\begin{aligned} 2\mathrm{Im}F_\mu &= m_b \int d\tau \langle 0|\bar{d}\gamma_\mu u|\pi(k_1)\pi(k_2)\rangle \langle \pi\pi|\bar{u}\gamma_5 b|\bar{B}^0(q+k)\rangle + \dots \\ &\propto F_\pi^*(s) F_t^{l=1}(s,q^2) + \dots \end{aligned}$$

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$$\propto F_\pi^*(s) F_t^{l=1}(s,q^2) + \dots$$

Phase F_π = Phase $F_t^{l=1}$

Study of CP violation in $B^+ \to \pi^+\pi^-\pi^+$

R. Klein, Th. Mannel, J. Virto, KKV

JHEP 1710(1017) 117 [arXiv:1708.020407]

$B \to \pi\pi\pi$ decay amplitude

At leading order, leading twist

$$\mathcal{A}_{s_\pm^{\rm low}<<1} = \frac{G_F}{\sqrt{2}} m_B^2 \left[f_\pi \frac{m_\pi}{m_B^2} (\lambda_u (a_1 + a_4^u) + \lambda_c a_4^c) F_t(s_\pm^{\rm low}, \zeta) \right.$$
$$\left. + (\lambda_u (a_2 - a_4^u) - \lambda_c a_4^c)(2\zeta - 1) F_\pi(s_\pm^{\rm low}) f_0(s_\pm^{\rm low}) \right] ,$$

- a_i as in two-body decay, contain perturbative strong phases $\mathcal{O}(\alpha_s)$
- $\lambda_u = |\lambda_u| e^{i\gamma}$ weak phase

Only 4 inputs that can be obtained from data

- $B \to \pi$ form factor f_0
- Single pion DA gives the pion decay constant f_π
- $B \to \pi\pi$ form factor F_t
- 2π LCDA gives F_π

$B \to \pi\pi\pi$ decay amplitude

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$$\left. + (\lambda_u (a_2 - a_4^u) - \lambda_c a_4^c)(2\zeta - 1) F_\pi(s_\pm^{\rm low}) f_0(s_\pm^{\rm low}) \right],$$

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CP violation requires two strong phases $F_t \neq F_\pi$

- Both isoscalar (S-wave) and isovector (P-wave) contribute

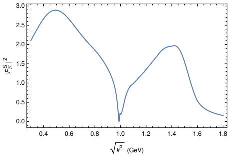
$$F_t = F_t^{I=0} + F_t^{I=1}$$

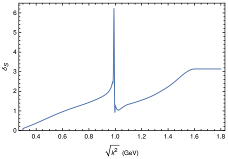
Daub, Hanhart, Kubis, Passemar, Cirigliano

F_π^S scalar pion form factor (analogous to F_π)

$$\langle \pi^-(k_1)\pi^+(k_2)|m_u\bar{u}u + m_d\bar{d}d|0\rangle = m_\pi^2 F_\pi^S(k^2)\ .$$

- Dispersion theory, coupled Omnes-equations (only non-strange)
- Only reliable* up to about 1.3 GeV





LCSR inspired model similar to $F_t^{I=1}$: not necessary in future!

β constant fit parameter

$$F_t^{I=0}(q^2) = \frac{m_B^2}{m_\pi f_\pi}\beta F_\pi^S(q^2)$$

$B \to \pi\pi$ form factor: Isoscalar contribution

Daub, Hanhart, Kubis, Passemar, Cirigliano

F_π^S scalar pion form factor (analogous to F_π)

$$\langle \pi^-(k_1)\pi^+(k_2)| m_u \bar{u}u + m_d \bar{d}d |0\rangle = m_\pi^2 F_\pi^S(k^2) \ .$$

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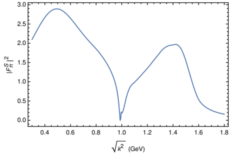

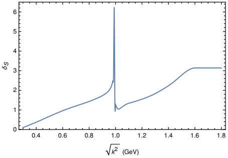

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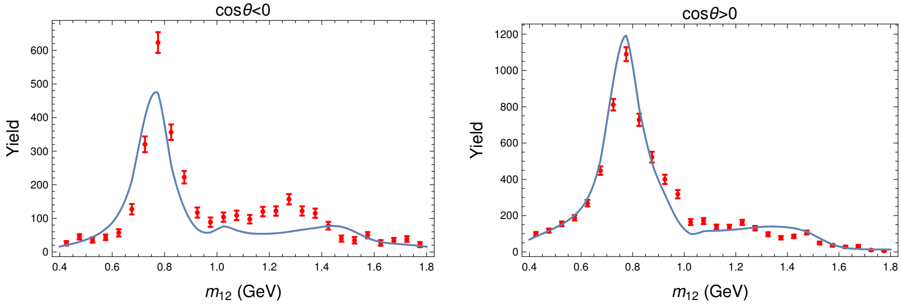
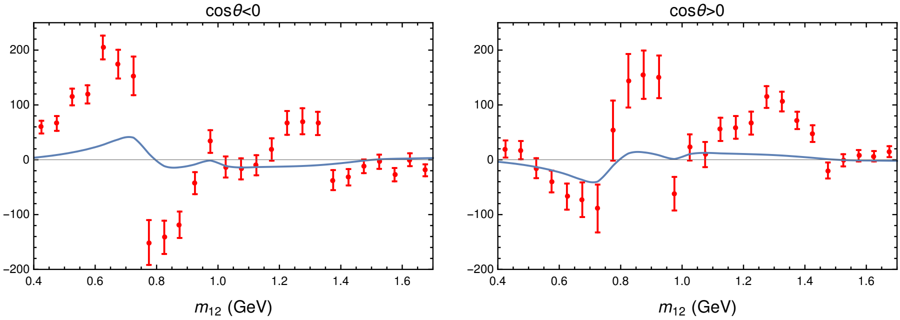
Dalitz Distribution

KKV, Virto, Mannel, Klein



- Cannot be reproduced with our <u>current</u> inputs
- Full Dalitz distribution preferred over projections

Dalitz and CP Distributions



$$A_{\rm CP} \propto \beta \sin\gamma \sin\phi \cos\theta_\pi$$

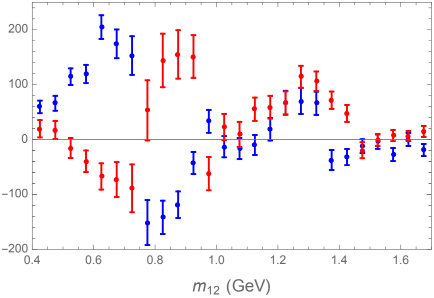
Only vector-scalar interferences (at this order!)

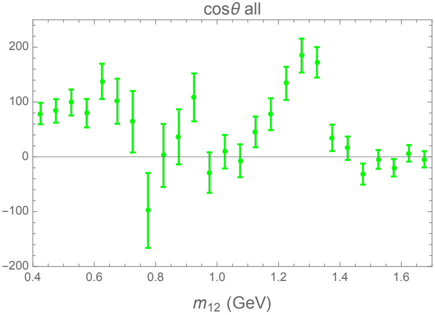
CP Distributions

Data from LHCb

$$A_{CP} \propto \beta \sin\gamma \sin\phi \cos\theta + \beta' \sin\phi' \cos^2\theta + \beta'' \sin\phi'' \cos^4\theta$$

- Distinguish between region above and below $m_{12} = 1.0$ GeV
- Include higher-twist and $\mathcal{O}(\alpha)$ corrections



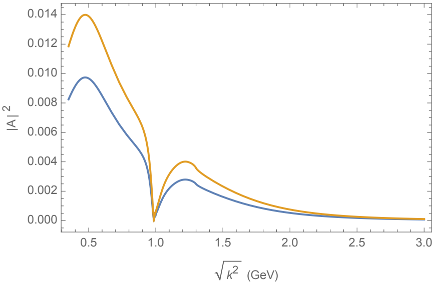


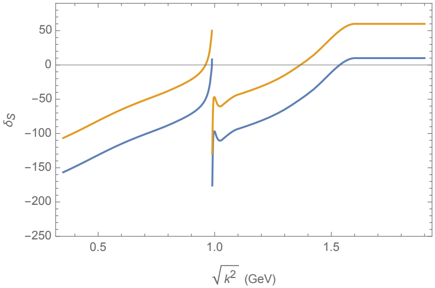
Scalar CP violation (example)

Example to show importance of perturbative phases

$$A_S^+ = (a_T e^{i\gamma} + a_P e^{i\delta}) F_\pi^S$$
$$A_S^- = (a_T e^{-i\gamma} + a_P e^{i\delta}) F_\pi^S$$

- Include $\mathcal{O}(\alpha)$ strong phases from QCD penguins
- Can give large CP violation in S-wave that agrees with data





Outlook

First challenge: [in progress]

- QCD sum rules for scalar form factors
- Study QCDF using SCET and $B^0 \to D^-(\pi^+\pi^0)$
- Apply to all $B \to hhh$; $SU(3)$ analysis
- Include $\mathcal{O}(\alpha)$ corrections and higher-twist corrections
- Merge low and high-s descriptions of the Dalitz plot

Experimental inputs required:

- Dalitz distributions with background and efficiency correction
- Data in different kinematic regions
- Connection with $B \to \pi\pi\ell\nu, B \to \pi\pi\ell\ell$ and $B \to K^*\ell\ell$!
- Updated $B \to \rho\pi$ measurements

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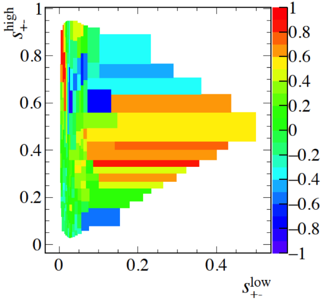
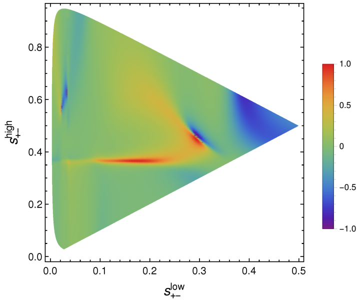
Thank you for your attention

Charm model scenario



Scenario



Experimental Data

$$\mathcal{A}_c = \mathcal{A}_c^{(0)} + g\,\frac{4m_c^2}{m_B^2 s_{+-}^{\mathrm{low}} - 4m_c^2 + i m_c \Gamma}$$

Inspired by strong phases generated above the charm threshold: Final-state-interactions

Edge versus Center