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

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in collaboration with

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Theor. Physik 1

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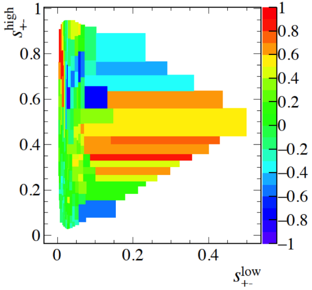
Motivation

- Non-leptonic B meson decays offer an interesting laboratory to search for new sources of CP violation
  - Theoretically challenging
  - Two-body decays well established
- Multibody decays form large part of the non-leptonic decays
- CP violation in multibody decays can provide more information about the strong phase
  - only useful if it can be interpreted

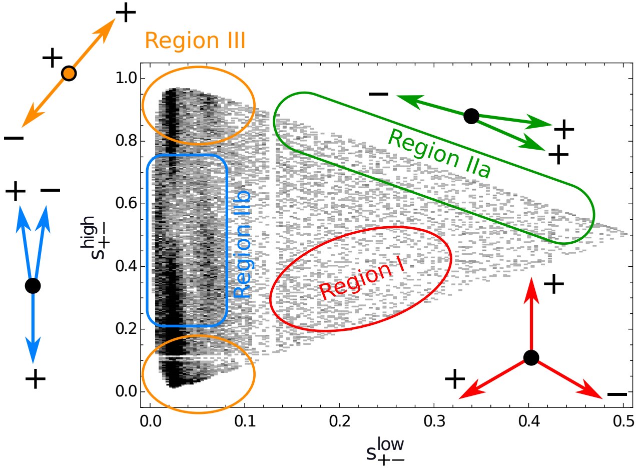
Motivation

- CP violation in multibody decays can provide more information about the strong phase
  - only useful if it can be interpreted
- Study with data-driven model-independent approach
  - using "partial" factorization Kraenkl, Mannel, Virto [2015]
- Rich structure of CP violation
  - Large local CP asymmetries
  - Specifically for $B^+ \to \pi^+\pi^-\pi^+$
- First leading order study



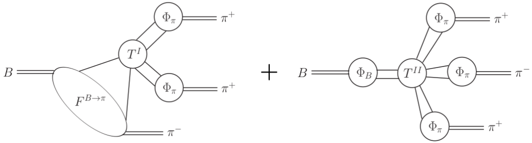
Dalitz distribution - Kinematics

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



Factorization in three-body decays - Central Region

Kraenkl, Mannel, Virto [2015]

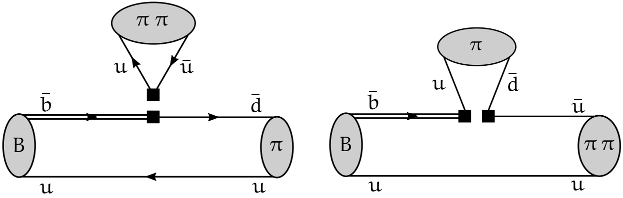


$$\langle \pi^+\pi^+\pi^- | \mathcal{Q}_i | B \rangle_c = T_i^I \otimes F^{B\to\pi} \otimes \Phi_\pi \otimes \Phi_\pi + T_i^{II} \otimes \Phi_B \otimes \Phi_\pi \otimes \Phi_\pi$$

- Hard kernels depend on momentum fractions
- At leading order all convolutions are finite
- $1/m_b^2$ and α_s suppressed compared to two-body

Factorization in three-body decays - Edges

- Resonances only close to the edges — Kraenkl, Mannel, Virto [2015]
- Breakdown of factorization at edges requires new input
- Three-body decays resemble two-body



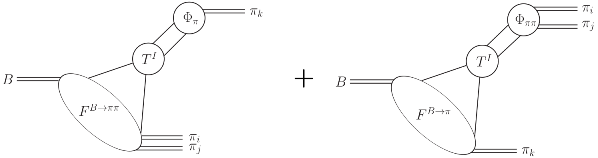
Leading contributions to hard kernels

- 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 New strong phases

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

2π **LCDA**

Polyakov [1999]

$$\phi^q_{\pi\pi}(u,\zeta,s) = \int \frac{dx^-}{2\pi} e^{iu(k^+_{12}x^-)} \langle \pi^+(k_1)\pi^-(k_2)|\bar{q}(x^- n_-)\not{n}_+ q(0)|0\rangle$$

$$s = (k_1+k_2)^2,\ \zeta = k_1/s$$

- Both isoscalar ($I=0$) and isovector ($I=1$) contribute
- At leading order only normalization needed

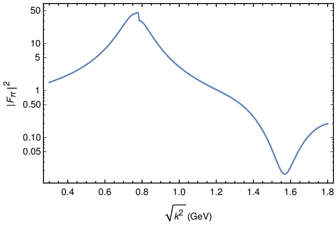
$$\int du\ \phi^{I=1}_{\pi\pi}(u,\zeta,s) = (2\zeta-1)F_\pi(s) \qquad \int du\ \phi^{I=0}_{\pi\pi}(u,\zeta,s) = 0$$

Time-like pion formfactor $F_\pi(s)$

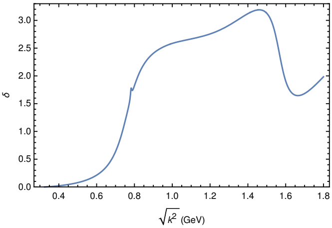
- Asymptotic u and ζ dependence known Not needed at tree-level
- Experimentally from $e^+e^- \to \pi\pi(\gamma)$ data BaBar

Time-like pion formfactor $F_\pi(s)$

Hanhart, Kubis, Shekhovtsova, Roig, Was, Predzinski



Vector form factor



Phase

- No experimental data on the phase available

$B \to \pi\pi$ Form factor

- Only vector form factor relevant

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

- Here both isoscalar (S-wave) and isovector (P-wave) contributions

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

- Isovector part studied with Light-Cone Sume Rules Khodjamirian, Virto, Cheng
  - $F_\pi F_t^{I=1}$ real for $s < 16 m_\pi^2$

$$\text{Phase } F_\pi = \text{Phase } F_t^{I=1}$$

- Experimental information on $F_t^{I=0}$?

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

Direct CP Violation

$$\mathcal{A} \propto e^{i\gamma}|\mathcal{A}_u|e^{i\phi_u} + |\mathcal{A}_c|e^{i\phi_c}$$

- γ weak phase from CKM
- $\mathcal{A}_u$ and $\mathcal{A}_c$ from current-current and penguin operators with

$$\langle\pi\pi\pi|(\bar{b}u)(\bar{u}d)|B\rangle \text{ and } \langle\pi\pi\pi|(\bar{b}c)(\bar{u}c)|B\rangle$$

- CPV induced by non-perturbative phases in matrix elements
  - $B \to \pi\pi$ form factor (isoscalar and isovector)
  - 2π LCDA (isovector only)

$$A_{CP} \equiv \frac{|\mathcal{A}|^2 - |\bar{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\bar{\mathcal{A}}|^2} = \frac{2|\mathcal{A}_u||\mathcal{A}_c|\sin(\Delta\phi)\sin\Delta\gamma}{|\mathcal{A}_u|^2 + |\mathcal{A}_c|^2 + 2|\mathcal{A}_u||\mathcal{A}_c|\cos(\Delta\phi)\cos\Delta\gamma}$$

$B \to \pi\pi$ Form factor: Isovector contributions

- Light-Cone Sume Rule Khodjamirian, Virto, Cheng

$$F_t(q^2,\zeta)^{I=1} = \frac{6m_b^2(2\zeta-1)F_\pi(q^2)}{m_\pi f_B m_B^2}\int_{u_0}^{1}\frac{du}{u}\,\bar{u}\,e^{\frac{m_B^2-s(u)}{M^2}}(m_b^2-m_\pi^2+u^2q^2)$$

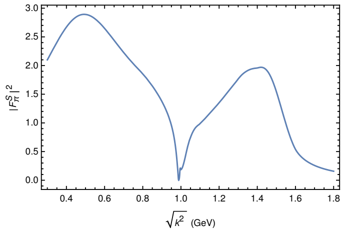
$$s(u) \equiv \frac{m_b^2-\bar{u}m_\pi^2+u\bar{u}q^2}{u}$$

- Reduces to $B \to \rho$ form factor in ρ-dominace, zero-width approximation

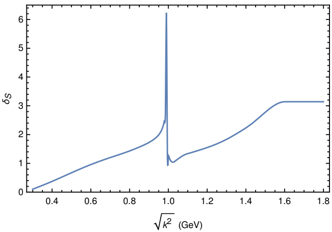
$$F_t^{I=1} \propto (2\zeta-1)A_0^{B\rho}\frac{g_{\rho\pi\pi}m_\rho}{\sqrt{2}(m_\rho^2-s-im_\rho\Gamma_\rho)} \propto (2\zeta-1)F_\pi A_0^{B\rho}$$

Isoscalar contribution

Daub, Hanhart, Kubis, Passemar, Cirigliano



Scalar form factor



Phase

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

- F_π^S scalar pion form factor (analogous to F_π)
  - Dispersion theory, coupled Omnes-equations

Isoscalar contribution

Daub, Hanhart, Kubis, Passemar, Cirigliano

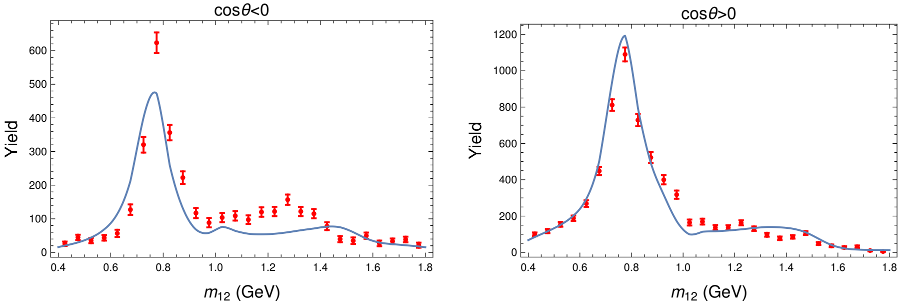
- Similar as to the ρ case, we may now express

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

- First study: β and ϕ parameters of our model
- Data on F_π^S only available up to 1.8 GeV
- Information on β, ϕ from fit to Dalitz projections

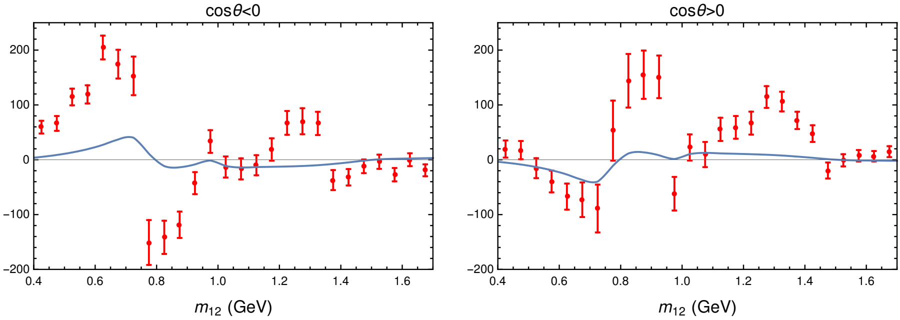
Isoscalar contribution

KKV, Virto, Mannel, Klein



- Difficult to reproduce with our current inputs
- Full Dalitz distribution preferred over projections

Dalitz and CP Distributions



$$A_{CP} \propto \beta \sin\gamma \sin\phi \cos\theta$$

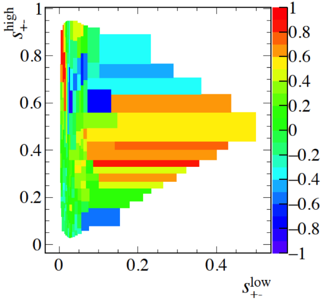
- Our model only gives Vector-Scalar interferences
- Several extensions of our framework possible

Discussion

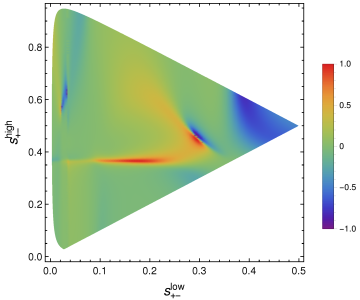
- Difficult to generate rich structure in CP asymmetry
  - QCDF framework and form factors only reliable close to the edges
  - Simple scenarios to get qualitative picture
- Additional strong phases generated above charm threshold
- Scenario: Breit-Wigner shape

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

Charm model scenario



Scenario



Experimental Data

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

Outlook

- Study CPV in three-body decays in QCD factorization approach
  - Improve description of the unknown (isoscalar) inputs
  - Include $\mathcal{O}(\alpha)$ corrections
  - Include higher-partial waves
  - Apply to $B \to K\pi\pi, B \to D\pi\pi$
- Devise "optimal" observables
- Improved experimental data needed
  - Dalitz distributions with background and efficiency correction
  - Data in different kinematic regions
  - Connection with $B \to \pi\pi\ell\nu$ or $B \to \pi\pi\ell\ell$
  - Updated $B \to \rho\pi$ measurements

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Thank you for your attention

S-wave form factor model

$$\left\langle \pi^-(k_1)\pi^+(k_2)|\bar{u}u|0\right\rangle = \left\langle \pi^-(k_1)\pi^+(k_2)|S^0\right\rangle \mathrm{BW}_S \left\langle S^0|\bar{u}u|0\right\rangle$$

$$\left\langle S^0|\bar{u}u|0\right\rangle = f_S m_S \ , \ \left\langle \pi^-(k_1)\pi^+(k_2)|S^0\right\rangle = g_{S\pi^-\pi^+} m_S$$

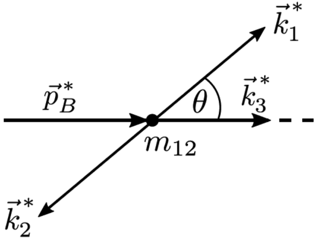
$$F_\pi^S(q^2) = \frac{2m_u}{m_\pi^2}\frac{f_S m_S^2 g_{S\pi^-\pi^+}}{m_S^2 - q^2 - i\sqrt{q^2}\Gamma_S}$$

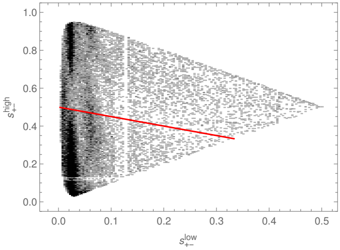
$$\left\langle \pi^-(k_1)\pi^+(k_2)|J_\nu|B^-(p)\right\rangle$$
$$= \left\langle \pi^-(k_1)\pi^+(k_2)|S^0\right\rangle \mathrm{BW}_S \left\langle S^0(q)|J_\nu|B^-(p)\right\rangle$$

Finally

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

Helicity Angle





$$k_3 \cdot (k_1 - k_2) = \frac{\beta_\pi}{2}\sqrt{\lambda}\cos\theta$$