CP Violation in Non-Leptonic Three-Body B decays

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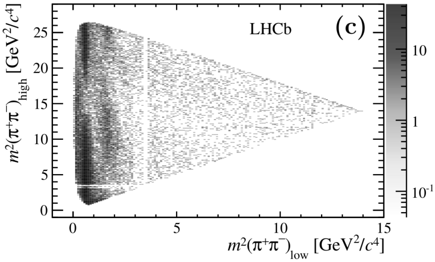
Motivation

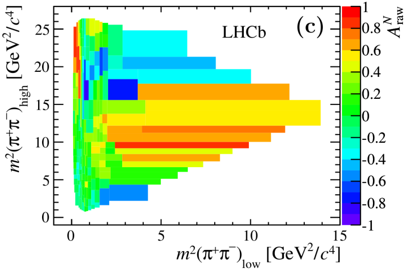
- Multibody decays form large part of the non-leptonic decays
  - offer more information than two-body decays
- Study three-body B decays using "partial" factorization S. Kraenkl *et al.* [2015]
- Rich structure of CP violation
  - Large local CP asymmetries

Motivation

- Rich structure of CP violation
  - Large local CP asymmetries
  - Specifically for $B^+ \to \pi^+\pi^-\pi^+$



Dalitz distribution



CP asymmetry

- Study with data-driven model-independent approach

Direct CP Violation

$$\mathcal{A} \propto e^{i\gamma}|\mathcal{A}_1|e^{i\phi_1} + e^{i\gamma'}|\mathcal{A}_2|e^{i\phi_2}$$

- $\mathcal{A}_1$ and $\mathcal{A}_2$ from current-current and penguin operators
- γ, γ' weak phase from CKM, ϕ_1, ϕ_2 strong phases

$$A_{CP} \equiv \frac{|\mathcal{A}|^2 - |\bar{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\bar{\mathcal{A}}|^2} = \frac{2|\mathcal{A}_1||\mathcal{A}_2| \sin(\Delta\phi) \sin \Delta\gamma}{|\mathcal{A}_1|^2 + |\mathcal{A}_2|^2 + 2|\mathcal{A}_1||\mathcal{A}_2| \cos(\Delta\phi) \cos \Delta\gamma}$$

- Strong phase difference in interfering amplitudes

Three-body decays

- $B(p_B) \to P_1(k_1)P_2(k_2)P_3(k_3)$
- Two independent kinematic variables $m_{ij} = (k_i + k_j)^2$

Quasi-two-body decay

$$B \to P_1 P_2 P_3 = B \to V P_3 \text{ and } V \to P_1 P_2$$

V vectormeson resonance

- Historical "isobar" model
  - Dalitz plot filled with quasi-two-body resonances (and non-resonant background)

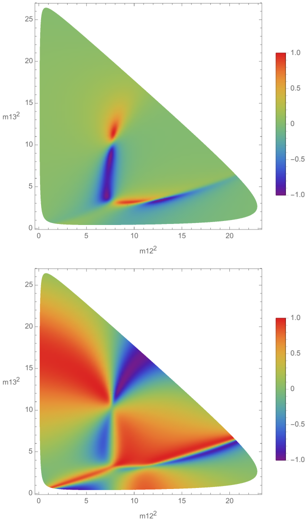
Quasi-two-body decay

- Study CP violation in simplified quasi-two-body model
  - Resembles QCD factorization findings details later
  - Resonances parametrized by Breit-Wigner distribution $\frac{1}{q^2 - m_V^2 + i m_V \Gamma}$
  - Strong phase $\Delta\phi$ depends on kinematics

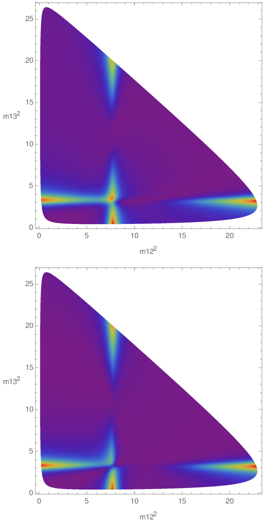
$$\mathcal{A}(B \to (P_1 P_2) P_3 + P_1 (P_2 P_3)) = A_1(m_{12}, m_{23}) e^{i\Delta\phi + \delta} e^{i\Delta\gamma} + A_2(m_{12}, m_{23})$$

- Interfering resonances may have additional strong phase difference δ
  - CP distribution gives insights into the strong phases
- For example 0 and 90° additional strong phase

Quasi-two-body decay



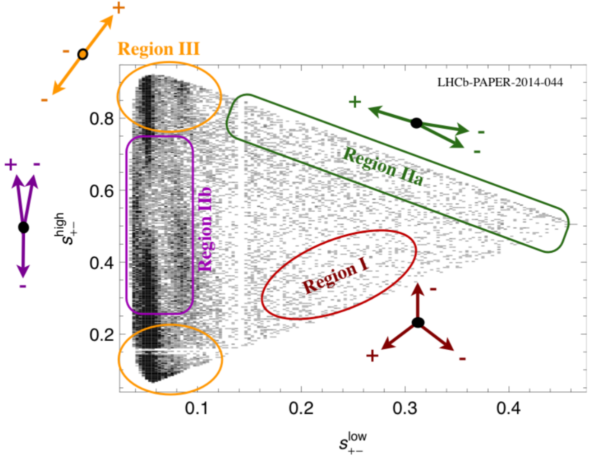
CP asymmetry



Dalitz Distribution

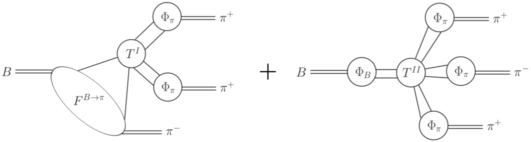
Dalitz distribution - Kinematics

- $B^+ \to \pi^+(k_1)\pi^-(k_2)\pi^+(k_3)$ Symmetric Dalitz plot
- Kinematic variables $s_{12} \equiv s_{+-}^{\mathrm{low}} = \frac{(k_1+k_2)^2}{m_B^2}$ and $s_{23} \equiv s_{+-}^{\mathrm{high}} = \frac{(k_2+k_3)^2}{m_B^2}$



Factorization in three-body decays - Central Region

S. Kraenkl *et al.* [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

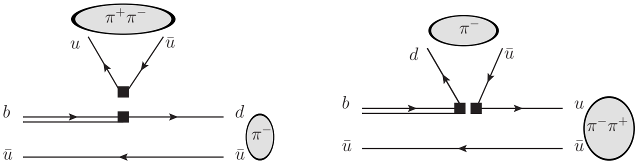
Perturbatively calculable central region might not exist for realistic *B*-meson masses

Factorization in three-body decays - Edges

- Dalitz plot consists only of edges

S. Kraenkl *et al.* [2015]

- Breakdown of factorization at edges requires new input
- Three-body decays resemble two-body



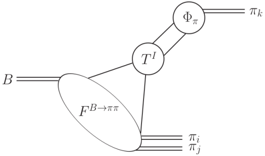
Leading contributions to hard kernels

- 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

S. Kraenkl *et al.* [2015]



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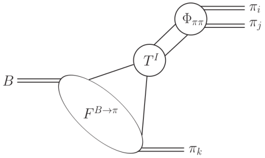


$$\langle \pi^+\pi^+\pi^- | \mathcal{Q}_i | B \rangle_{s_{+-}\ll 1} = T_i^I \otimes F^{B\to\pi^+} \otimes \Phi_{\pi^+\pi^-} + T_i^I \otimes F^{B\to\pi^+\pi^-} \otimes \Phi_{\pi^+}$$

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]

$$\phi_{\pi\pi}(u,\zeta,s) = \int \frac{dx^-}{2\pi} e^{iz(k_{12}^+ x^-)} \left\langle \pi^+(k_1)\pi^-(k_2) | \bar{q}(x^- n_-) \not{n}_+ q(0) | 0 \right\rangle$$

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

- At tree-level only normalization needed

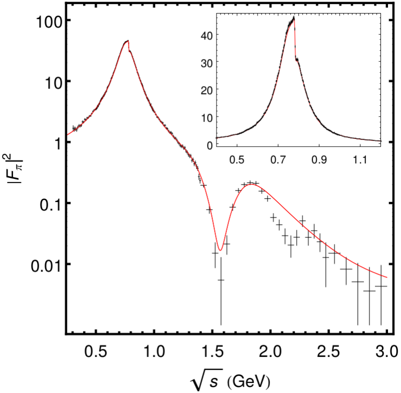
$$\int du\ \phi_{\pi\pi}(u,\zeta,s) = (2\zeta - 1) F_\pi(s)$$

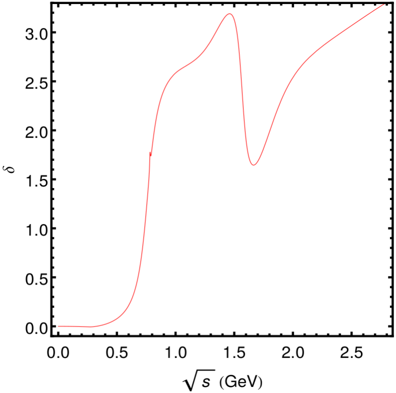
Time-like pion formfactor $F_\pi(s)$

- Asymptotic z 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, ...





- No experimental data on the phase available

$B \to \pi\pi$ Form factor

- Only vector form factor relevant

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

- Can be related to F_π using a Light-Cone Sume Rule Khodjamirian *et. al*

$$F_t(q^2,\zeta) = -\frac{3\sqrt{2}m_b^2(2\zeta-1)F_\pi(q^2)}{m_\pi f_B m_B^2}\int_{u_0}^1 \frac{du}{u}\,\bar{u}\,e^{\frac{m_B^2-s(u)}{M^2}}(m_b^2-m_\pi^2+u^2q^2)$$

Preliminary

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

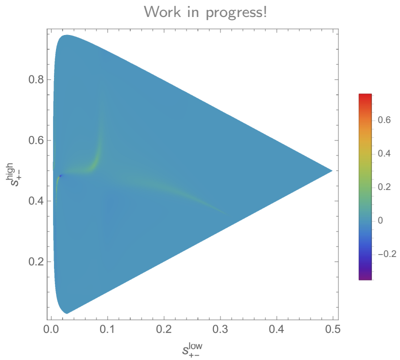
- Unitarity relation: Phase of F_π = Phase of F_t
- Important for CP violation

Decay amplitude

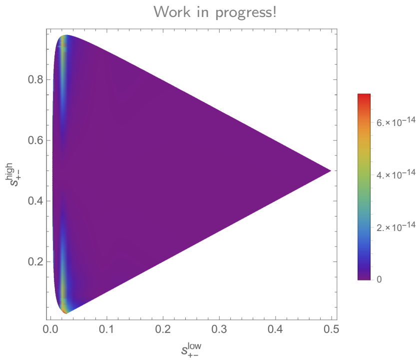
$$\mathcal{A} = \frac{G_F}{\sqrt{2}} m_B^2 \left[f_\pi \frac{m_\pi}{m_B^2} (\lambda_u (a_1 + a_4^u) + \lambda_c a_4^c)(F_t(q^2, \zeta) + F_t(q'^2, \zeta')) \right.$$
$$\left. + (\lambda_u (a_2 - a_4^u) - \lambda_c a_4^c) \left[(2\zeta - 1) F_\pi(q^2) f_0(q^2) + (2\zeta' - 1) F_\pi(q'^2) f_0(q'^2) \right]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

- f_0 is $B \to \pi$ form factor
- a_i as in two-body decay, contain perturbative strong phases $\mathcal{O}(\alpha_s)$
- $\lambda_u = |\lambda_u| e^{i\gamma}$ weak phase
- F_t, F_π contain non-perturbative strong phases

Dalitz and CP Distributions



CP asymmetry



Dalitz Distribution

- Dalitz distribution only shows events near ρ resonances
- CP violation has interesting structure

Recap & Outlook

- Study three-body decays in QCD factorization approach
- No central region $\rightarrow$ whole Dalitz plot is made out of edges
- New non-perturbative quantities generate CP violation in the empty region (?)

Work in Progress...

- Improve hadronic input, include scalar form factors
- Study QCD sum-rule
- Dependence on $B \rightarrow \pi$ form factor
- Apply to $B \rightarrow K\pi$
- CP violation in the central region (?)