Direct CPV in Three-Body Charmless B Decays:

Prospects for a model-independent interpretation of LHCb data

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Just some thoughts based on collaborations with S. Kränkl, T. Mannel, A. Khodjamirian, S. Cheng, T. Huber and K. Vos

:: Direct CP Violation

$$\mathcal{A}(\bar{B} \to f) \equiv \mathcal{A}_f = \underbrace{\lambda_u}_{\sim e^{i\gamma}} \underbrace{(T_f^u - P_f)}_{\mathcal{A}^u} + \underbrace{\lambda_c}_{\simeq \text{real}} \underbrace{(T_f^c - P_f)}_{\mathcal{A}^c} \qquad \lambda_p = V_{pb} V^\star_{p\{d,s\}}$$

$$T_f^p = \sum_{1,2} C_i^p \langle f | Q_i^p | \bar{B} \rangle \quad \text{(current-current operators)}$$

$$P_f = \sum_{3,\ldots,6} C_i \langle f | Q_i^p | \bar{B} \rangle \quad \text{(penguin operators)}$$

- In the SM, C_i contain no phases.
- We write $\mathcal{A}^p = |\mathcal{A}^p| e^{i\delta_p}$. Then:

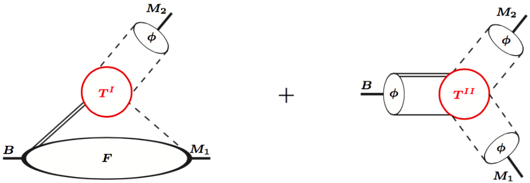
$$\mathcal{A}_{\text{CP}} \equiv \frac{|\mathcal{A}_f| - |\bar{\mathcal{A}}_{\bar{f}}|}{|\mathcal{A}_f| + |\bar{\mathcal{A}}_{\bar{f}}|} \propto \left| \frac{\lambda_u \mathcal{A}^u}{\lambda_c \mathcal{A}^c} \right| \cdot \sin\gamma \cdot \sin(\delta_c - \delta_u)$$

► Look for relative strong phases in interfering amplitudes

:: Two-body decays

To leading power in the heavy-quark expansion Beneke, Buchalla, Neubert, Sachrajda '99

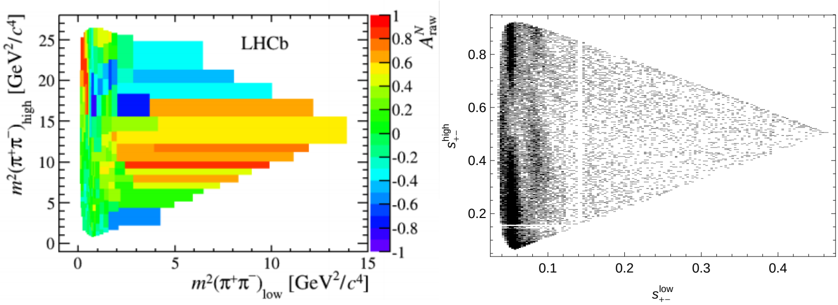
$$\langle M_1 M_2 | \mathcal{O}_i | B \rangle = F^{BM_1} \int du \, T_i^I(u) \phi_{M_2}(u) + \int d\omega \, du \, dv \, T_i^{II}(\omega, u, v) \phi_B(\omega) \phi_{M_1}(u) \phi_{M_2}(v)$$



- Vertex corrections: $T^I(u) = 1 + \mathcal{O}(\alpha_s/\pi)$
- Spectator scattering: $T^{II}(\omega, u, v) = \underbrace{\mathcal{O}(\alpha_s)}_{real} + \mathcal{O}(\alpha_s^2/\pi)$
- $A_{\rm CP} = \mathcal{O}(\alpha_s(m_b)/\pi) + \mathcal{O}(\Lambda/m_b)$ – But ... $\alpha_s(m_b)/\pi \sim \Lambda/m_b$!!

:: Three-body decays

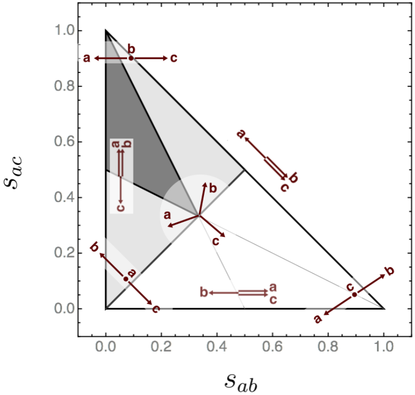
- ▷ Richer dynamics
- ▷ May have non-perturbative strong phases not suppressed by Λ/m_b

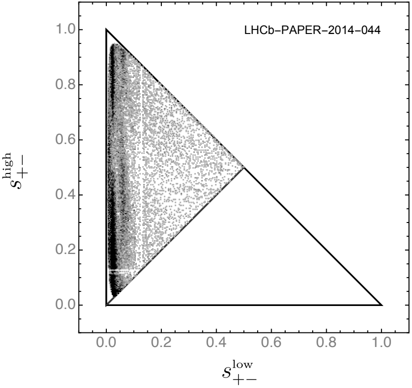


- ▷ We **do not** want just *a model* that fits well.
- ▷ Instead we want to **know** if CKM+QCD is compatible with the data.

:: Three-body decays – kinematics

- ▷ $\bar{B} \to M_a(p_a)M_b(p_b)M_c(p_c)$
- ▷ Two independent invariants, *e.g.* $s_{ab} = \frac{(p_a+p_b)^2}{m_B^2}$ and $s_{ac} = \frac{(p_a+p_c)^2}{m_B^2}$

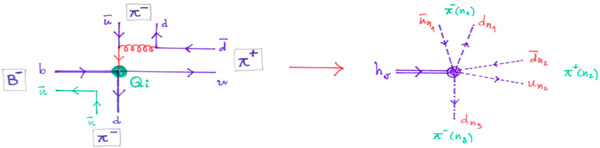




:: Central region

Krankl, Mannel, JV '15

⋆ Three collinear directions n_1, n_2, n_3, disconnected at the leading power.



$$\langle \pi^- \pi^+ \pi^- | \mathcal{O}_i | \bar{B} \rangle = F^{B\to\pi} \int du\, dv\; T_i^{I}(u,v)\; \phi_\pi(u)\; \phi_\pi(v)$$
$$+ \int d\omega\, du\, dv\, dy\; T_i^{II}(\omega,u,v,y)\; \phi_B(\omega)\; \phi_\pi(u)\; \phi_\pi(v)\; \phi_\pi(y)$$

▷ Power ($1/m_b^2$) & α_s suppressed with respect to two-body.

▷ At leading order/power/twist all convolutions are finite → factorization ✓

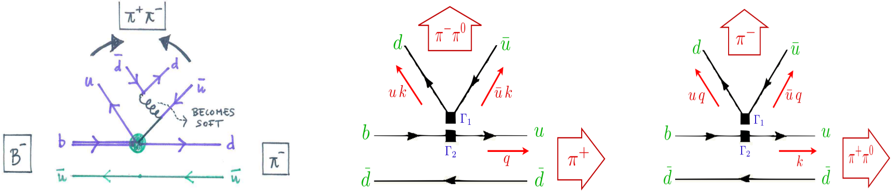
▷ Some pieces proven at NLO: Factorization of $B \to \pi\pi$ form factors [Böer, Feldmann, van Dyk '16] and 2π LCDAs [Diehl, Feldmann, Kroll, Vogt '99]

► $A_{\rm CP} = \mathcal{O}(\alpha_s(m_b)/\pi) + \mathcal{O}(\Lambda/m_b)$ – Like two-body !

► But this region might not exist for $m_B = 5$ GeV Krankl, Mannel, JV '15

:: Edges

- Breakdown of factorization at resonant edges requires new NP functions.
- 3-body decay remsembles 2-body, but with new $(\pi\pi)$ "compound object":



- Operators are the same as in 2-body, but final states different:

$$\begin{aligned}\langle \pi^-_{\bar n}\pi^+_{\bar n}\pi^-_n|\mathcal{O}|B\rangle &= \langle \pi^-_n|\bar h_v\Gamma\xi_n|B\rangle \times \int dz\; T_1(z)\langle \pi^-_{\bar n}\pi^+_{\bar n}|\bar\chi_{\bar n}(z\bar n)\Gamma'\chi_{\bar n}(0)|0\rangle \\ &+ \langle \pi^-_{\bar n}\pi^+_{\bar n}|\bar h_v\Gamma\xi_{\bar n}|B\rangle \times \int dz\; T_2(z)\langle \pi^-_n|\bar\chi_{\bar n}(zn)\Gamma'\chi_n(0)|0\rangle \\ &= F^{B\to\pi}\; T_1\star\phi_{\pi\pi} + F^{B\to\pi\pi}\; T_2\star\phi_\pi\end{aligned}$$

- New non-perturbative input: (Contains NP strong phases!!)
  - Generalized Distribution Amplitudes (GDAs) [Diehl, Polyakov, Gousset, Pire, Grozin...]
  - Generalized Form Factors (GFFs) [Faller, Feldmann, Khodjamirian, Mannel, van Dyk...]

:: Edges

This is **always** an improvement w.r.t. quasi-two-body decays:

$$\mathcal{A}(B^- \to \pi^-[\pi^+\pi^-]) = F^{B\to\pi}\ T_1 \star \phi_{\pi\pi} + F^{B\to\pi\pi}\ T_2 \star \phi_\pi$$

$$\Big\downarrow \quad \rho \text{ dominance} + \text{zero-width limit}$$

$$\mathcal{A}(B^- \to \pi^-\rho) = F^{B\to\pi}\ T_1 \star \phi_\rho + F^{B\to\rho}\ T_2 \star \phi_\pi$$

This limit can be checked analytically.

- ▷ Factorization is at the same level of theoretical rigour for quasi-two-body and 3-body.
- ▷ Any model for $\phi_{\pi\pi}$ and $F^{B\to\pi\pi}$ satisfying axiomatic constraints and compatible with data (e.g. $e^+e^- \to \pi\pi$) replaces any notion of "ρ".

:: 2π GDAs

Krankl, Mannel, JV '15

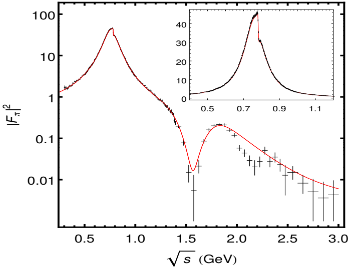
- Definition: $[s = (k_1 + k_2)^2,\ k_1 = \zeta k_{12},\ k_2 = (1-\zeta)k_{12}]$

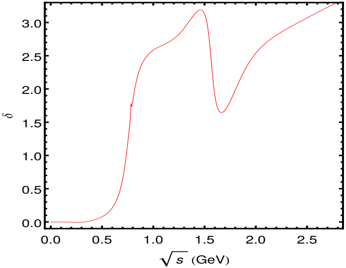
$$\phi^q_{\pi\pi}(z,\zeta,s) = \int \frac{dx^-}{2\pi} e^{iz(k^+_{12}x^-)} \langle \pi^+(k_1)\pi^-(k_2)|\bar{q}(x^- n_-)\not{n}_+ q(0)|0\rangle$$

- Normalization (local correlator):

$$\int dz\, \phi_{\pi\pi}(z,\zeta,s) = (2\zeta - 1)F_\pi(s) \quad \text{(pion vector FF)}$$

- $F_\pi(s)$: Data ($e^+e^- \to \pi\pi(\gamma)$ [BaBar])





:: $B \to \pi\pi$ form factors from B-meson LCSRs

Cheng, Khodjamirian, JV '16?

▷ **Correlation function**

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

▷ **Unitarity relation**

$$2\mathrm{Im}F_\mu(k,q) = m_b\int d\tau_{2\pi}\underbrace{\langle 0|\bar d\gamma_\mu|\pi(k_1)\pi(k_2)\rangle}_{F_\pi^\star(s)}\underbrace{\langle\pi(k_1)\pi(k_2)|\bar u\gamma_5 b|\bar B^0(q+k)\rangle}_{F_t(s,q^2,\cos\theta_\pi)}+\cdots$$

$$= q_\mu\frac{s\sqrt{q^2}\beta_\pi(s)^2}{4\sqrt{6}\pi\sqrt{\lambda}}\,F_\pi^\star(s)\,F_t^{(\ell=1)}(s,q^2)+\cdots$$

Corollary: $F_\pi^\star(s)\,F_t^{(\ell=1)}(s,q^2)$ is real for all $s<16m_\pi^2 \Rightarrow$

$$\mathrm{Phase}(F^{B\to\pi\pi}) = \mathrm{Phase(pion\ form\ factor)}$$

Important for CP violation!!! [See also Kang, Kubis, Hanhart, Meissner '13]

:: $B \to \pi\pi$ form factors from B-meson LCSRs

Cheng, Khodjamirian, JV '16?

▷ **Dispersion relation + LCOPE + Borel + duality**

$$-\int_{4m_\pi^2}^{s_0^{2\pi}} ds\; e^{-s/M^2}\, \frac{s\,\sqrt{q^2}\,[\beta_\pi(s)]^2}{4\sqrt{6}\pi^2\sqrt{\lambda}}\, F_\pi^\star(s)\, F_t^{(1)}(s,q^2) = f_B m_B^2 m_b \left\{ \int_0^{\sigma_0^{2\pi}} d\sigma\; e^{-s(\sigma,q^2)/M^2} \times \right.$$

$$\left. \times \left[\frac{\sigma}{\bar\sigma}\phi_+^B(\sigma m_B) - \frac{\sigma}{\bar\sigma}\left[\phi_+^B(\sigma m_B) - \phi_-^B(\sigma m_B)\right] - \frac{1}{\bar\sigma m_B}\bar\Phi_\pm^B(\sigma m_B)\right] + \Delta A_0^{BV}(q^2, \sigma_0^{2\pi}, M^2) \right\}$$

▷ **ρ-dominance + zero-width limit:**

$$F_\pi^\star(s) \simeq \frac{f_\rho g_{\rho\pi\pi} m_\rho/\sqrt{2}}{m_\rho^2 - s + i\sqrt{2}\Gamma_\rho(s)} \quad , \quad F_t^{(1)}(s,q^2) \simeq -\frac{\beta_\pi(s)\sqrt{\lambda}}{\sqrt{3q^2}}\, \frac{m_\rho g_{\rho\pi\pi} A_0^{B\rho}(q^2)}{m_\rho^2 - s - i\sqrt{2}\Gamma_\rho(s)}$$

$$LHS = 2 f_\rho m_\rho A_0^{B\rho}(q^2) \int_{4m_\pi^2}^{s_0^{2\pi}} ds\; e^{-s/M^2} \underbrace{\left[\frac{\sqrt{s}\;\Gamma_\rho(s)/\pi}{(m_\rho^2 - s)^2 + s\Gamma_\rho^2(s)}\right]}_{\xrightarrow{\Gamma_\rho\to 0}\ \delta(s - m_\rho^2)} \xrightarrow{\Gamma_\rho\to 0} 2 f_\rho m_\rho A_0^{B\rho}(q^2)\, e^{-s/m_\rho^2}$$

hep-ph/0611193 ✓

:: Edges – recap

⋆ Leading order amplitude: Krankl, Mannel, JV '15

$$\mathcal{A}|_{s_{+-}\ll 1} = \frac{G_F}{\sqrt{2}}\Big[4m_B^2 f_0(s_{+-})(2\zeta - 1)F_\pi(s_{+-})(a_2 + a_4) + f_\pi m_\pi (a_1 - a_4) F_t(\zeta, s_{+-})\Big]$$

- ▷ The Wilson coefficients a_1, a_2 have weak phase $\sim \lambda_u$, and a_4 has weak phase $\sim \lambda_c$.
- ▷ Everything here is LO, so all perturbative strong phases are ignored.
- ▷ $F_\pi(s_{+-})$ and the P-wave contribution to $F_t(\zeta, s_{+-})$ have the same strong phase.
- ▷ S-wave contributions to $F_t(\zeta, s_{+-})$ can generate a strong phase (S- and P-wave interference).
- ▷ The corresponding "scalar-penguin" amplitude (power-suppressed but chirally enhanced) is in this case proportional to the scalar pion form factor. Its interference with the P-wave contribution to the F_t part may also potentially contribute a large strong phase.
- ▷ All these issues are under study.

:: Outlook

- ▷ Soft corners of Dalitz plot contain interference of crossed resonances: potentially important DCPV. But difficult for QCDF. New ideas?

- ▷ Central "perturbative" region boring, but it might not exist.

- ▷ Edges: how large are they? Promising prospects for data-driven understanding of large local asymmetries. Need to improve hadronic input, including vector and scalar (pion) form factors. Study also LCSRs for S-wave $B \to \pi\pi$ form factors.

- ▷ $B \to \pi\pi$ Form factors: the same approach can be applied to $B \to K\pi$ form factors: Important for $B \to K^*\ell\ell$!!!

- ▷ Distribution amplitudes: $B^- \to D^0(\pi^-\pi^0)$ and $\bar{B}^0 \to D^+(\pi^-\pi^0)$. What can be done? can we measure phases?