CP violation in the three-body $B^{\pm}$ phase-space

Jorge Alvarenga Nogueira
Instituto Tecnológico de Aeronáutica
São José dos Campos, Brazil
jhan@ita.br

Supervisor: Tobias Frederico (ITA, Brazil)

Collaborators:
Ignacio Bediaga (CBPF, Brazil), Odilon Lourenço (UFRJ, Brazil), Patrícia Magalhães (CBPF, Brazil)

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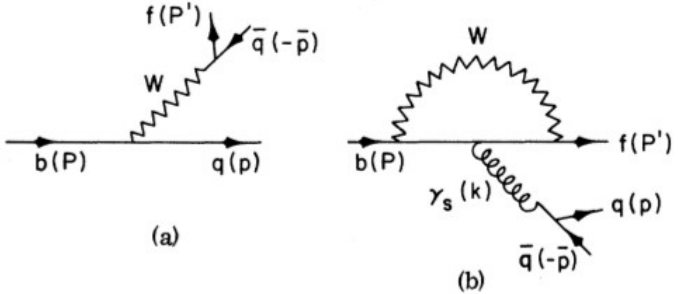
CP noninvariance in charged decays

- CPV: Different decay rates for particle and antiparticle
- Charged systems: First mechanism to CPV by BSS
  - No CPV at tree level – Need to go beyond first Born approximation
  - Absorption from loop-diagrams is needed
  - QCD: "penguin" diagrams with timelike gluon transition
- Writing the decay amplitude in a general form: $\mathcal{M} = \mathcal{D} - (i/2)\mathcal{A}$

$$a_{CP} = \Gamma\,(i \to f) - \Gamma\,(\bar{i} \to \bar{f})\ \alpha\ Im(\mathcal{D}^{*}\mathcal{A})$$



M. Bander, D. Silverman and A. Soni,

Phys. Rev. Lett. 43, 242 (1979)

Basic ingredients to CPV at quark level

- Schematically we can write as an example the b → s amplitude as:

$$\mathcal{M}_{b\to s} = v_u A_u + v_c A_c + v_t A_t \equiv v_u \Delta_{ut} + v_c \Delta_{ct}$$

- The asymmetry for this amlitude is:

$$a_{CP} \propto Im(v^*_u v_c) * Im(\Delta^*_{ut} \Delta_{ct})$$

- This equation shows that we need basically two ingredients to have CPV:

  1) different weak CP violating phases and

  2) absorptive part coming from a loop diagram (hard FSI's);

- Additional terms with respect to CPT;

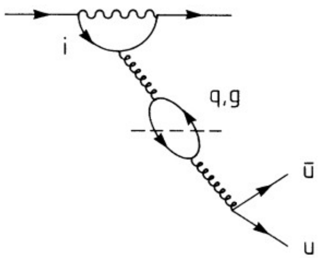


FIG. 2. The extra $O(\alpha_s^2)$ graph needed to satisfy the *CPT* theorem at the $O(\hbar^2)$, $O(\alpha_s^2)$ level. Only the absorptive part, i.e., the cut graph, of the vacuum bubble is needed.

J.M. Gérard and W.S. Hou, Phys. Rev. Lett. 62, 855 (1989)

Soft final state interactions

- Develop a formalism based on CPT invariance and Unitarity;
  - Hadronic FSI replace the absorptive part of the penguin graph;
  - Soft final state interactions do not disappear for large m_b;
  - Soft FSI should have an important effect for CPV;
- Meson-meson inelastic scattering at 5 GeV:
  - Important strong phase effect in B decays;
  - Depends on how probable the state is as a final state;

- L. Wolfenstein, Phys. Rev. D 43, 151 (1991)
- J. F. Donoghue, E. Golowich, A. A. Petrov, and J. M. Soares, Phys. Rev. Lett. 77, 11 (1996))
- M. Suzuki and L. Wolfenstein, Phys. Rev. D 60, 074019 (1999)

Experimental facts

- Significant part of the observed CPV distribution is located in a region where hadronic channels are strongly coupled;
- Events concentrated at low invariant mass;
  - Huge phase-space available;
- Reasonable assumptions:
  - 1) Final states factorize in a two body interacting system plus a bachelor;
  - 2) Rescattering effects in three-body B decays happens in $3 \to 3$ channels;

Cohen, D et al PRD 22 (1980) 2595

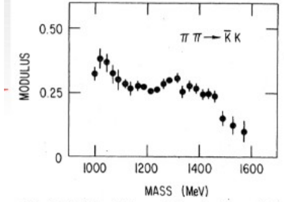
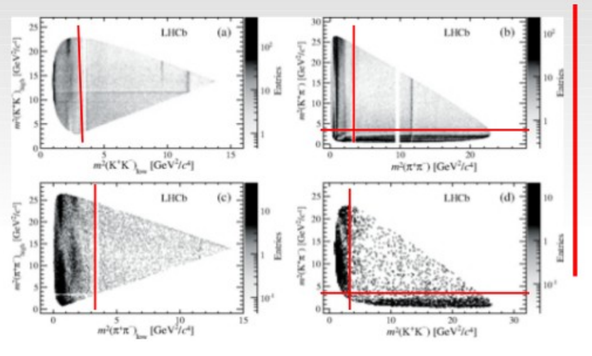
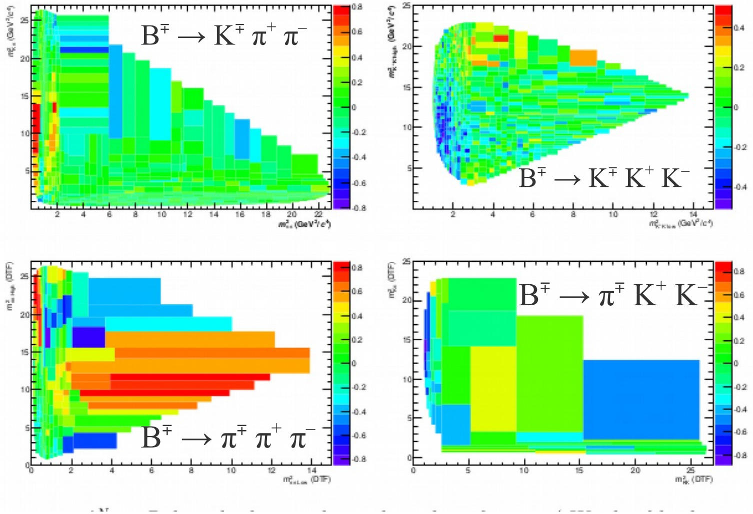


FIG. 27. Modulus of the $\pi\pi \to \bar{K}K$ scattering amplitude $|T(\pi\pi \to \bar{K}K)|$ from solution I(b).





- D. Cohen, D. S. Ayres, R. Diebold, S. L. Kramer, A. J. Pawlicki, and A. B. Wicklund, Phys. Rev. D 22, 2595(1980).
- R. Aaiji et al. (LHCb Collaboration), Phys. Rev. D 90, 112004 (2014).

Model asymmetry

- Split the S-matrix in two parts

$$S = S_0 + S_1,$$

where S_0 is the diagonal part with the elastic scattering and S_1 is perturbatively treated as the first order inelastic transition;

- Factorizes the short-range and long-range contributions in the decay amplitude:

$$\mathcal{A}^{\pm}_{\lambda\,LO} = A_{0\lambda} + e^{\pm i\gamma} B_{0\lambda} + i \sum_{\lambda'} t_{\lambda\lambda'} (A_{0\lambda'} + e^{\pm i\gamma} B_{0\lambda'})$$

$$\Delta\Gamma_{\lambda} = |A^{-}_{\lambda}|^2 - |A^{+}_{\lambda}|^2 = \Gamma\,(h \rightarrow \lambda) - \Gamma\,(\bar{h} \rightarrow \bar{\lambda})$$

$$\Delta\Gamma_{\lambda} = 4\,(sin\,\gamma)\,Im[B^{*}_{0\lambda} A_{0\lambda} + i \sum_{\lambda'} (B^{*}_{0\lambda} t_{\lambda\lambda'} A_{0\lambda'} - B^{*}_{0\lambda'} t^{*}_{\lambda\lambda'} A_{0\lambda})]$$

- Channels coupled by strong interactions implies $\Delta\Gamma_{\alpha} = -\,\Delta\Gamma_{\beta}$
  - I. Bediaga, T. Frederico, and O. Lourenço, Phys. Rev. D 89, 094013 (2014).

S and P-wave resonant interferences

- Two resonant intermediate states, with different weak phases, share the same kinematical region and hadronic final state;

- CP asymmetry from S and P wave interference in same hadronic final state.

  - Resonant interferences ($\rho(770)$ and $f_0(980)$ resonances) + hadronic inelastic rescattering

$$\mathcal{A}^{\pm}_{0\lambda} = A_0^{\rho} F_{\rho}^{BW} k(s) \cos\theta + A_0^{f0} F_{f0}^{BW} + A_0^{NR},$$

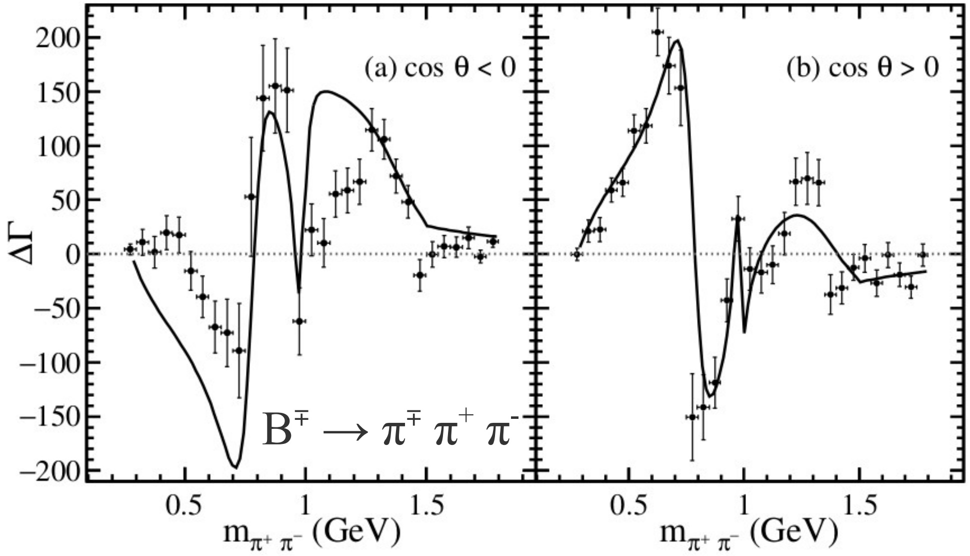
$$\text{where } A_0^{i} = a_0^{i} + b_0^{i} e^{\pm i\gamma} \; (i = \rho, f_0, NR)$$

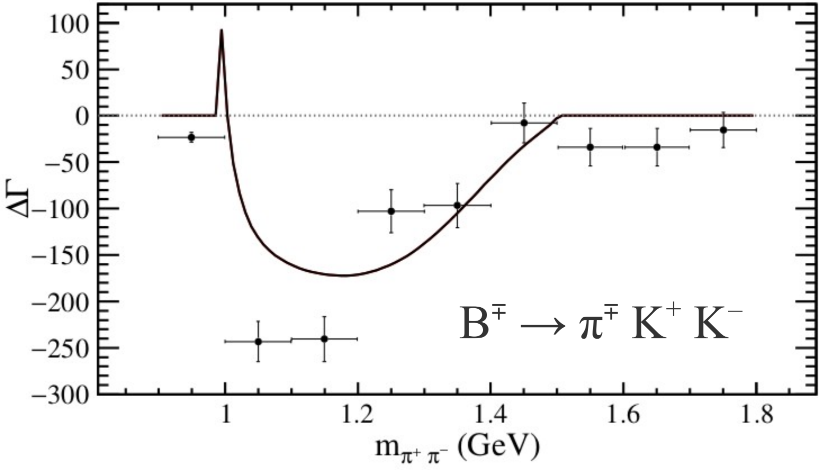
$$\text{S-matrix: } S_{\lambda,\lambda'} = \delta_{\lambda,\lambda'} + i\, t_{\lambda,\lambda'} \, , \; t_{\pi\pi\to KK} = \sqrt{1-\eta^2 (s)}\, e^{i(\delta KK + \delta\pi\pi)} \quad (\text{using } \delta_{KK} \approx \delta_{\pi\pi})$$

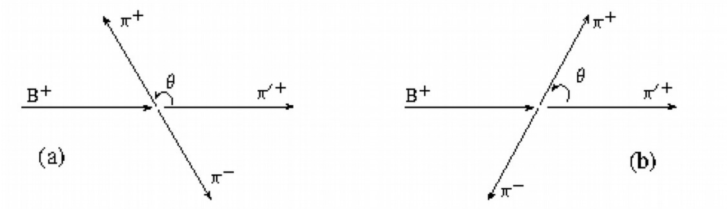
- $$\Delta\Gamma_{\lambda} = \mathcal{B}\sqrt{1-\eta^2 (s)} \cos[2\delta_{\pi\pi}(s)] + |F_{\rho}^{BW}(s)|^2 k(s) \cos\theta \, \{\mathcal{D}(m_{\rho}^{2} - s) + \mathcal{E} m_{\rho} \Gamma_{\rho}(s)\} + \mathcal{G}|F_{\rho}^{BW}(s)|^2 |F_{f0}^{BW}(s)|^2 k(s) \cos\theta \, [(m_{\rho}^{2} - s) m_{f0} \Gamma_{f0}(s) + m_{\rho}\Gamma_{\rho}(s) (m_{f0}^{2} - s)]$$

- I. Bediaga, T. Frederico, and O. Lourenço, Phys. Rev. D 89, 094013 (2014).
- J.H.A.N., I. Bediaga, A.B.R. Cavalcante, T. Frederico, O. Lourenço. Phys.Rev. D 92, 054010 (2015)
- I.B., I.I. Bigi, A. Gomes, G. Guerrer, J. Miranda and A.C. Dos Reis-Phys. Rev. D80, 096006 (2009)
- J.R. Pelaez and F.J. Ynduráin, Phys. Rev. D 71, 074016 (2005)

Fitting the data

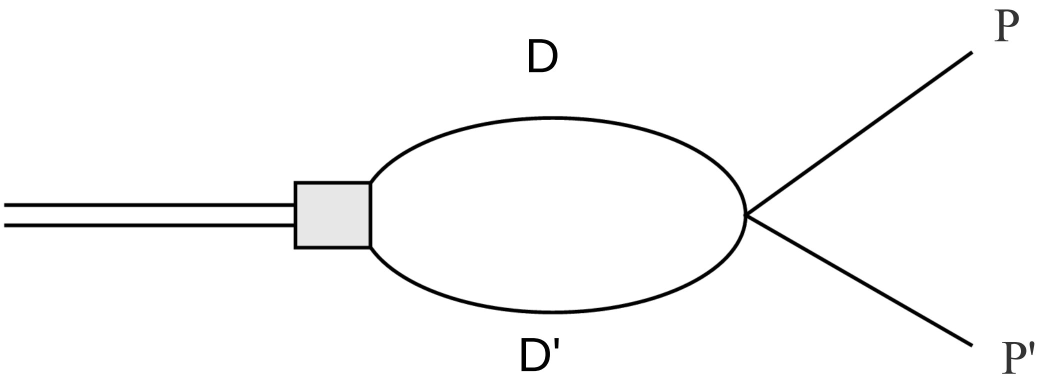






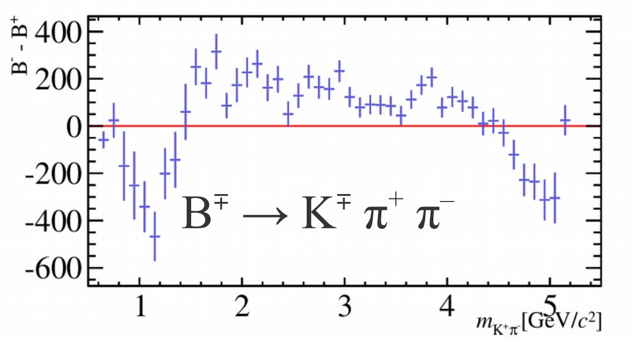
- Only region cos θ > 0 of $B^{\mp} \rightarrow \pi^{\mp}\pi^{+}\pi^{-}$ is fitted
  - J.H.A.N., I. Bediaga, A.B.R. Cavalcante, T. Frederico, O. Lourenço, Phys.: Conf. Ser. 706 042010 (2016)
- Same study was done for $B^{\mp} \rightarrow K^{\mp}\pi^{+}\pi^{-}$ (obtaining $B^{\mp} \rightarrow K^{\mp}K^{+}K^{-}$ as output) in J.H.A.N., I. Bediaga, A.B.R. Cavalcante, T. Frederico, O. Lourenço. Phys.Rev. D 92, 054010 (2015)

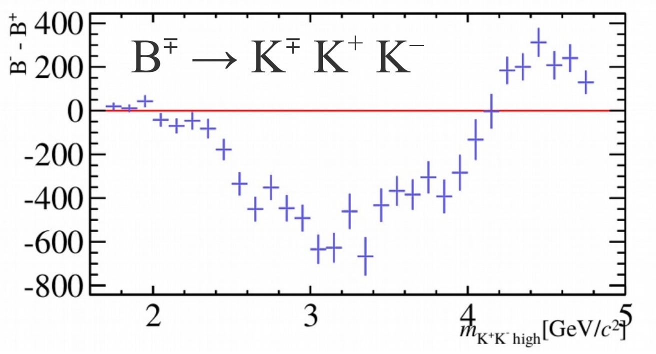
High mass CP distribution

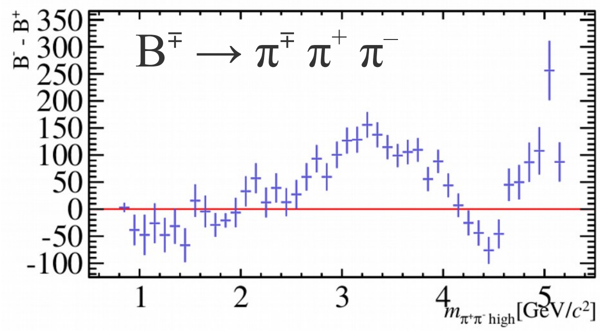


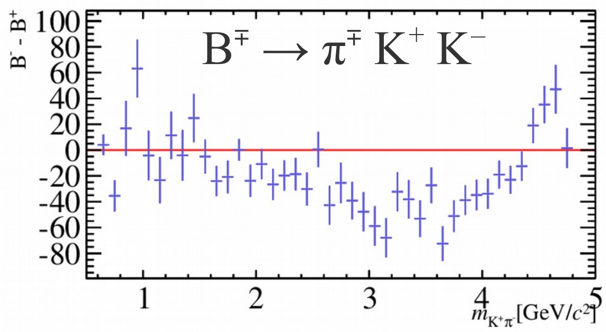
- Involving two-body coupling between light mesons (PP') and heavy mesons (double charm DD');
  - P and P' can be kaon or pion;

CP asymmetry in the high mass region









- R. Aaiji et al. (LHCb Collaboration), Phys. Rev. D 90, 112004 (2014).
  New LHCb results: available at https://cds.cern.ch/record/1751517?ln=en

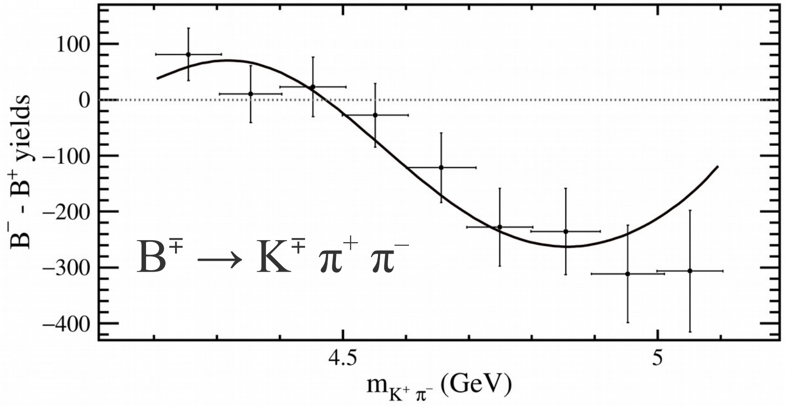
CP asymmetry in the high mass region

- Three light pseudoscalar mesons can couple with channels like $D\bar{D}$ h, h = K, π;
  - Rescattering can contribute to CPV in regions of large two-body invariant mass above the $D\bar{D}$ threshold;
- Final state interactions in hadronic B decays involving transitions from heavy to light mesons in the literature;
- $DD_s \to K\pi$ rescattering computed within chiral Lagrangian based models;
- Or parametrized using an effective expansion for the S-matrix;
- Branching ratio to double charm channels is bigger than to light mesons channels;
  - Even if the coupling is small, the BR is a factor of 10-100 bigger;

- H.-Y. Cheng, C.-K. Chua, and A. Soni, Phys. Rev. D 71, 014030 (2005).
- J.A. Oller, E. Oset, Phys. Rev. D 60, 074023 (1999).
- D. Gamermann, E. Oset, D. Strottman and M. J. Vicente Vacas, Phys. Rev. D 76, 074016 (2007).

CP asymmetry in the high mass region

- Preliminary result (using $t_{K\pi\to DDs}$ from chiral
- lagrangian model):



- Two-channel unitary S-matrix parametrization:
  - $|S_{LL\to HH}|^2 = \sqrt{1-\eta^2(s)} = \Lambda\,(s/s_{th}-1)^{1/2}/(s/s_{th})^{2.5}$

$$S_\lambda = (k\, cot\, \delta_\lambda + i\, k_\lambda)/(k\, cot\, \delta_\lambda - i\, k_\lambda), \qquad k_\lambda = (s - s_{th\,\lambda})^{1/2}/2$$

- λ=LL channel with a pole above the HH threshould:

$$k\, cot\, \delta_{LL} = - c/(1-k_{LL}/k_{0LL}), \qquad k_{0LL} = (s_0 - s_{th\,LL})^{1/2}/2$$

- λ=HH channel with a virtual bound state: $k\, cot\, \delta_{HH} = -1/a$

Our parametrization agrees with this result.

|S| parametrization similar to the one in J.R. Pelaez and F.J. Ynduráin, Phys. Rev. D 71, 074016 (2005)

Summary and Outlook

- CPT must be a practical constraint in the analisys of the three-body B meson decays;
- Formalism is based on CPT invariance and Unitarity;
- Soft FSI is explicitly factorized and shows to be essential in our study;
- The B meson phase space presents resonant interterferences with particular features;
- The decay channels $B^{\mp} \to \pi^{\mp} \pi^{+} \pi^{-}$ and $B^{\mp} \to \pi^{\mp} K^{+} K^{-}$ (also $B^{\mp} \to K^{\mp} \pi^{+} \pi^{-}$ and $B^{\mp} \to K^{\mp} K^{+} K^{-}$) presents asymmetries that seems to be related by the CPT constraint;
- $PP \to HH$ ($P = \pi, K$ and $H = D, D_s$) scattering seems to be related with the high mass CP distribution;
- Understand hadron-hadron scattering bellow 5 GeV using CPV data;
- Next steps:
  - Include the three-body rescattering effects with the spectator meson;
  - Address the quark-level processes as source amplitudes for the hadronic rescattering;

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Thank you!