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

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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: \( M = \mathcal{D} - (i/2)\mathcal{A} \)

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

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

Basic ingredients to CPV at quark level

➢ Schematically we can write as an example the $b \rightarrow s$ amplitude as:

$$M_{b\rightarrow s} = v_u A_u + v_c A_c + v_t A_t \equiv v_u \Delta_{ut} + v_c \Delta_{ct}$$

➢ The asymmetry for this amplitude is:

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

➢ 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;

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;

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 $3 \rightarrow 3$ channels;

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:
  \[
  \mathcal{A}^\pm_{\lambda, \text{LO}} = A_{0\lambda} + e^{\pm i\gamma} B_{0\lambda} + i \sum_{\lambda'} t_{\lambda \lambda'} (A_{0\lambda'} + e^{\pm i\gamma} B_{0\lambda'})
  \]
  \[
  \Delta \Gamma_{\lambda} = |A^-_{\lambda}|^2 - |A^+_{\lambda}|^2 = \Gamma (h \to \lambda) - \Gamma (\bar{h} \to \bar{\lambda})
  \]
  \[
  \Delta \Gamma_{\lambda} = 4 (\sin \gamma) \text{Im}[B^*_{0\lambda} A_{0\lambda} + i \sum_{\lambda'} (B^*_{0\lambda} t_{\lambda \lambda'} A_{0\lambda'} - B^*_{0\lambda'} t^*_{\lambda \lambda'} A_{0\lambda})]
  \]

- Channels coupled by strong interactions implies \( \Delta \Gamma_\alpha = - \Delta \Gamma_\beta \)
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

$$\mathcal{A}_{0\lambda}^{\pm} = A_0^\rho F_{\rho}^{BW} k(s) \cos \theta + A_0^{f_0} F_{f_0}^{BW} + A_0^{NR},$$

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

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

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

$$G |F_{\rho}^{BW}(s)|^2 |F_{f_0}^{BW}(s)|^2 k(s) \cos \theta [(m_\rho^2 - s) m_{f_0} \Gamma_{f_0}(s) + m_\rho \Gamma_\rho(s) (m_{f_0}^2 - s)]$$

Fitting the data

- Only region $\cos \theta > 0$ of $B^\pm \rightarrow \pi^\mp \pi^+ \pi^-$ is fitted

- Same study was done for $B^\pm \rightarrow K^\mp \pi^\mp \pi^+$ (obtaining $B^\pm \rightarrow K^\mp K^+ K^-$ 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

  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 $D \bar{D} \, h$, $h = K, \pi$;
  - 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;
- $D D_s \rightarrow K \pi$ 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;

CP asymmetry in the high mass region

➢ Preliminary result (using $t_{K\pi \rightarrow DD_s}$ from chiral lagrangian model):

➢ Two-channel unitary S-matrix parametrization:
  
  - $|S_{LL\rightarrow HH}|^2 = \sqrt{1-\eta^2(s)} = \Lambda (s/s_{\text{th}} - 1)^{1/2}/(s/s_{\text{th}})^{2.5}$
  
  $S_\lambda = (k \cot \delta_\lambda + i k_\lambda)/(k \cot \delta_\lambda - i k_\lambda), \quad k_\lambda = (s - s_{\text{th} \lambda})^{1/2}/2$

  - $\lambda$=LL channel with a pole above the HH threshold:
    
    $k \cot \delta_{LL} = -c/(1-k_{LL}/k_{0LL}), \quad k_{0LL} = (s_0 - s_{\text{th LL}})^{1/2}/2$

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

Our parametrization agrees with this result.

Summary and Outlook

➢ CPT must be a practical constraint in the analysis 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 interferences with particular features;
➢ The decay channels $B^\mp \rightarrow \pi^\mp \pi^+ \pi^-$ and $B^\mp \rightarrow \pi^\mp K^+ K^-$ (also $B^\mp \rightarrow K^\mp \pi^+ \pi^-$ and $B^\mp \rightarrow K^\mp K^+ K^-$) presents asymmetries that seems to be related by the CPT constraint;
➢ PP → HH ($P = \pi, K$ and $H = D, D_s$) scattering seems to be related with the high mass CP distribution;
➢ Understand hadron-hadron scattering below 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;
Thank you!