CP violation in charmless hadronic B decays

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Charmless $b$ decays

- No charm quark in final state particles
- $\sim 1\%$ of $b$ decay

Large CPV from mixing and decay or with other diagrams from different resonant structures over Dalitz plot

\[
\begin{align*}
  b & \rightarrow s\bar{u}u \\
  b & \rightarrow s\bar{d}d \\
  b & \rightarrow s\bar{s}s \\
  b & \rightarrow d\bar{u}u \\
  b & \rightarrow d\bar{s}s \\
  b & \rightarrow d\bar{d}s
\end{align*}
\]

U-spin related
**CPV in charmless B decays**

\[ |V_{td}|e^{i\beta} \text{ or } -|V_{ts}|e^{-i\beta_s} \quad |V_{ub}|e^{-i\gamma} \]

➢ **CPV appears when there are two competitive contributions:**

\[ A = a_1 e^{i(\delta_1 + \phi_1)} + a_2 e^{i(\delta_2 + \phi_2)} \]
\[ \bar{A} = a_1 e^{i(\delta_1 - \phi_1)} + a_2 e^{i(\delta_2 - \phi_2)} \]

\[ A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} \propto \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2) \]

➢ **Additional weak phase through mixing**

➢ **QCD plays an important role in the game**

\[ |V_{td}|^2 e^{-2i\beta} \text{ or } |V_{ts}|^2 e^{2i\beta_s} \]
Two body charmless $B$ decays

- Main contributions for $B^0 \rightarrow K^+K^-$ and $B_s \rightarrow \pi^+\pi^-$, $\pi^0\pi^0$: PA/E processes, very rare decay; two charged modes have been found by LHCb recently
  
  \textit{PRL} 118 (2017) 081801, \textit{JHEP} 10 (2012) 037

- While $B_s \rightarrow K_s\pi^0$, $\pi^0\pi^0$ not observed yet, other decay modes are extensively studied by B factories and LHCb

- $B \rightarrow \pi\pi$ system: extract CKM angle $\alpha$ through Isospin relationship
  
  \textit{arXiv:1705.02981}

- $B \rightarrow \pi\pi$, $B_s \rightarrow K^+K^-$ system: extract CKM angle $\gamma$ and $2\beta_s$ through U-spin and U-spin + Isospin analyses
  
  \textit{PLB} 741 (2015) 1 and references therein

- Recently, Belle has updated the Branching fraction and $A_{CP}$ measurements on $B^0 \rightarrow \pi^0\pi^0$ and LHCb on $B^0 \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$
Measurements on $B^0 \rightarrow \pi^0 \pi^0$ from Belle

$\Delta E = E_B^* - E_{\text{BEAM}}$

$M_{bc} = \sqrt{E_{\text{BEAM}}^2 - p_B^{*2}}$

Fisher + angle info.

Measurements with $752 \times 10^6$ $B\bar{B}$ (693 fb$^{-1}$) to replace previous results; Time-integrated measurements; initial flavor from the other $B$.

Projects in signal enhanced areas of other two variables.

arXiv: 1705.02083

Continuum background

Signal

$B^+ \rightarrow \rho^+ \pi^0$ and others
Results from $B^0 \rightarrow \pi^0 \pi^0$

$\mathcal{B}(B^0 \rightarrow \pi^0 \pi^0) = (1.31 \pm 0.19 \pm 0.18) \times 10^{-6}$

$A_{CP} = +0.14 \pm 0.36 \pm 0.12$

Some recent Predictions:

$Br(B^0 \rightarrow \pi^0 \pi^0) = [0.23^{+0.08}_{-0.05} (\omega_b)^{+0.05}_{-0.04} (f_B)^{+0.04}_{-0.03} (a_2^\pi)] \times 10^{-6}$,

$\mathcal{B}(B_d \rightarrow \pi^0 \pi^0)|_{PMC} = \left(0.98^{+0.44}_{-0.31}\right) \times 10^{-6}$,

$Br(B^0(B^0) \rightarrow \pi^0 \pi^0) = (1.17^{+0.11}_{-0.12}) \times 10^{-6}$.

Measured values lower and predicted values higher, though still have tensions

$\alpha$ excluded at 95% for [15.5°, 75°]

Including new results

+ Belle results on $B^0 \rightarrow \pi^+ \pi^-$

Previous from Belle

PRD 88 (2013) 092003
PRL 94 (2005) 181803 (253 fb$^{-1}$)
PRD 87 (2013) 031103(R)
$B^0 \rightarrow \pi^+\pi^-$ \hspace{1cm} $28652 \pm 226$

$B_s \rightarrow K^+K^-$ \hspace{1cm} $36840 \pm 222$

➢ Time-dependent analysis with 3 fb$^{-1}$ data;

➢ Production asymmetries of $B_{d(s)}$ determined from $B_{d(s)} \rightarrow K\pi$
Time dependent asymmetries

\[ \Delta m_{d(s)}, \Delta \Gamma_{d(s)} \text{ and } \Gamma_{d(s)} \text{ fixed from measured values} \]

\[ A(t) = \frac{\Gamma_{\bar{B}^0_{(s)}} - \Gamma_{B^0_{(s)}}}{\Gamma_{\bar{B}^0_{(s)}} + \Gamma_{B^0_{(s)}}} = -C_f \cos(\Delta m_{d,s} t) + S_f \sin(\Delta m_{d,s} t) \cosh\left(\frac{\Delta \Gamma_{d,s}}{2} t\right) + A_f \Gamma \sinh\left(\frac{\Delta \Gamma_{d,s}}{2} t\right) \]

\[ B^0 \rightarrow \pi^+ \pi^- \]

\[ B_s \rightarrow K^+ K^- \]

\[ B_{(s)} \rightarrow K \pi \text{ used for calibration channels of flavor tagging} \]
Results from $B^0 \rightarrow \pi\pi$ and $B_s \rightarrow KK$ measurements

$LHCb$-CONF-2016-018

\[
\begin{align*}
C_{\pi^+\pi^-} &= -0.24 \pm 0.07 \pm 0.01, \\
S_{\pi^+\pi^-} &= -0.68 \pm 0.06 \pm 0.01, \\
C_{K^+K^-} &= 0.24 \pm 0.06 \pm 0.02, \quad 3.6\sigma \\
S_{K^+K^-} &= 0.22 \pm 0.06 \pm 0.02, \quad 3.3\sigma \\
A_{K^+K^-} &\Delta \Gamma = -0.75 \pm 0.07 \pm 0.11,
\end{align*}
\]

Evidence of CPV for $B_s$ mode at 4.6$\sigma$

> Recent updates into paper ongoing (3 fb$^{-1}$):

BDT selections re-optimized to gain more statistic power

Adding SS flavor taggers

$\pi^+ \pi^- S_{CP}$ vs $C_{CP}$

$\text{Contours give } -2\Delta(L) = \Delta \chi^2 = 1, \text{ corresponding to 39.3% CL for 2 dof}$

$arXiv:1612.07233$
Three body charmless B decays

➢ Three body $B_{d(s)}$ charmless decays involve one or more neutral final state ($\pi^0$ or $K_s$): extensively studied by B factories with limited statistics; $\pi^0$ mode hard for LHCb but not fully impossible

➢ Three body $B^-$ charmless decays with charged final states much easier experimentally; increasing interests after LHCb’s CPV measurements over Dalitz plot

➢ Amplitude analyses needed to extract CPV information; $B \rightarrow \pi\pi\pi$, $K\pi\pi$ and $KKK$ have been performed by B factories

➢ Large data set collected by LHCb will show more interesting results
Resonant effect over Dalitz plot

➢ Full version of $A_{CP}$ in slide 3 (also including angular distributions)

\[ A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} = \frac{2a_1 a_2 h_1(\theta)h_2(\theta) \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2)}{a_1^2 h_1^2(\theta) + a_2^2 h_2^2(\theta) + 2a_1 a_2 h_1(\theta)h_2(\theta) \cos(\delta_1 - \delta_2) \cos(\phi_1 - \phi_2)} \]

\[ h_1(\theta)h_2(\theta) \]

\[ \theta : \text{helicity angle} \quad h(\theta) : \text{angular distribution of resonance} \]

➢ 180° phase changing for Breit-Wigner $\Rightarrow$ CPV sign flip

➢ CPV sign flip when different wave (S-P, S-D, P-D etc) components interference
An Example: P-S interference

\[ A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} = \frac{2a_1a_2h_1(\theta)h_2(\theta)\sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)}{a_1^2h_1^2(\theta) + a_2^2h_2^2(\theta) + 2a_1a_2h_1(\theta)h_2(\theta)\cos(\delta_1 - \delta_2)\cos(\phi_1 - \phi_2)} \]

Large CP in \( f_2(1270) \), but dividing w.r.t \( \cos \theta = 0 \) may not be ideal as shown in previous slide

\[ \cos \theta < 0 \quad \theta : \text{helicity angle} \]

\[ \cos \theta > 0 \]
Amplitude analysis of $B \rightarrow \pi \pi \pi$ from LHCb

RUN 1 LHCb data: ~21K signals with 4.4K background vs Babar: 1219 signals with 2.3K background

Resonant contributions:
- $\rho-\omega$, $f_0(500)$, $f_0(980)$ region: S-P wave interference
- $f_2(1270)$ region: D-S, P wave interference
- High mass: $KK-\pi\pi$ rescattering

Plots from PRD 90, 112004 (2014) for instruction
\[ \pi\pi \ S\text{-wave description} \]

➢ General agreed descriptions (RBW, GS) for \(\pi\pi\) P- and D-waves;

➢ More complicated \(\pi\pi\) S-wave, modeled in three different approaches:

➢ Isobar model: different S-wave contributions are explicitly modeled:

\(f_0(500)\): RBW, complex pole parameterization

\(f_0(980)\): Flatte parametrization

non-resonant: flat, Belle model, re-scattering model etc

\[ T_{\sigma}(m_{13}) = \frac{1}{m_{\sigma}^2 - m_{13}^2}, \]

\[ T_{nr}(m_{13}, m_{23}) = c_{nr}(e^{-\alpha_{nr}m_{13}^2}e^{i\delta_{1n}} + e^{-\alpha_{nr}m_{23}^2}e^{i\delta_{2n}}), \]

\[ T_{nr}(m_{13}) = \frac{a^{nr}}{1 + \frac{m_{13}^2}{\Lambda^2}}e^{i\delta^{nr}} \]

PRL 96 (2006) 251803


➢ K-Matrix approach: 5 poles and 5 decay channels; parameters from global fit to previous data while production vector parameters from fit to data

EPJA 16 (2003) 229

➢ Model independent approach (QMI): \(\pi\pi\) S-wave binned into 13 bins; amplitudes in each bin obtained from fit to data (26 free parameters)
**ππ S-wave from data**

Very preliminary, un-official results

Similar pictures between different models over broad range
CPV modeling and results

- Amplitude over Dalitz plot will be expressed as:

\[
A \equiv A(m^2_{\text{max}}, m^2_{\text{min}}) = \sum_j c_j F_j(m^2_{\text{max}}, m^2_{\text{min}}),
\]

\[
\bar{A} \equiv \bar{A}(m^2_{\text{max}}, m^2_{\text{min}}) = \sum_j \bar{c}_j \bar{F}_j(m^2_{\text{max}}, m^2_{\text{min}}).
\]

- Results on \( c_i \), \( A_{CP} \) and fit fractions will be given

\[
A_{CP} = -2 \left[ \frac{x \delta_x + y \delta_y}{x^2 + \delta_x^2 + y^2 + \delta_y^2} \right],
\]

- A fit example of \( \rho-\omega \) region

\[
c_i = (x_i + \Delta x_i) + i(y_i + \Delta y_i)
\]

\[
\bar{c}_i = (x_i - \Delta x_i) + i(y_i - \Delta y_i)
\]
Measurements with $B \rightarrow KK\pi$

- Previous LHCb $A_{CP}$ measurement with 6k signals:
  PRD 90, 112004 (2014)
  arXiv:1705.02640

- Belle join the game recently with around 660 signal events: results consistent with LHCb
  arXiv:1705.02640

- LHCb is also working on amplitude analysis; reasonable fit has already achieved

  - $K\pi$ resonances: $K^*(800)$, $K^*(892)$, $K_0^*(1430)$
  - $KK$ resonances: $f_0(980)$, $f_0(1370)$, $f_2(1270)$, $\rho^0(1450)$, possible P-wave contribution

  Alternative models also tried: like rescattering model for $KK$ S-wave

Branching fraction updates for $B_{d(s)} \to K_{s}hh^{(*)}$

- Previous LHCb measurements with 1 fb$^{-1}$ data observes $B_{s} \to K_{s}K\pi$, $K_{s}\pi\pi$ and confirms $B^{0} \to K_{s}K\pi$

- Updates performed with full Run 1 data, aiming at finding $B_{s} \to K_{s}KK$; though a bit unlucky, only 2.5$\sigma$ significance

- Measurements normalized to $B^{0} \to K_{s}\pi\pi$ channel

\[
\begin{align*}
\mathcal{B}(B^{0} \to \overline{K}^{0} K^{\pm} \pi^{\mp}) &= (6.1 \pm 0.5 \pm 0.7 \pm 0.3) \times 10^{-6}, \\
\mathcal{B}(B^{0} \to K^{0} K^{+} K^{-}) &= (27.2 \pm 0.9 \pm 1.6 \pm 1.1) \times 10^{-6}, \\
\mathcal{B}(B_{s}^{0} \to K^{0} \pi^{+} \pi^{-}) &= (9.5 \pm 1.3 \pm 1.5 \pm 0.4) \times 10^{-6}, \\
\mathcal{B}(B_{s}^{0} \to \overline{K}^{0} K^{\pm} \pi^{\mp}) &= (84.3 \pm 3.5 \pm 7.4 \pm 3.4) \times 10^{-6}, \\
\mathcal{B}(B_{s}^{0} \to K^{0} K^{+} K^{-}) &\in [0.4 - 2.5] \times 10^{-6} \text{ at 90\% C.L.},
\end{align*}
\]

- Dalitz-plot analyses of $B^{0} \to K_{s}\pi\pi$, $K_{s}KK$ and $B_{s} \to K_{s}K\pi$ underway

\begin{tabular}{|c|c|}
\hline
Decay outside/inside VELO & \\
\hline
2766$\pm$66 & 1411$\pm$45 \\
261$\pm$24 & 160$\pm$17 \\
1133$\pm$39 & 685$\pm$29 \\
146$\pm$19 & 74$\pm$11 \\
1100$\pm$41 & 568$\pm$28 \\
12$\pm$6 & 7$\pm$4 \\
\hline
\end{tabular}
CPV in charmless baryon decays

> Similar as $B^+$ mode, only direct CPV in baryon sector expected

> Two body charmless baryon decays have small Br; only one CPV measurement from CDF where no clear CPV found; Potential large CPV expected in $b \to su\bar{u}$ and $b \to du\bar{u}$


> Several CPV measurements have been performed on three body charmless baryon decays by LHCb and no clear CPV found


> CPV measurements in baryon sectors limited by statistics; Unlike meson decays, baryon decays tend to have larger Br for final states with more tracks (4 body > 3 body > 2 body); rich resonant interference and strong phase variation over phase space offer larger chance to have large CPV and interesting CPV pattern

> CPV measurement in four body baryon decays can be performed either similarly as those for $B \to hhh$ (ongoing) or using technics like triple product; ultimate procedure is full amplitude analysis
**CPV in \( \Lambda_b \rightarrow p\pi hh \) decays from LHCb**

Nature Physics 13 (2017) 391

- **p\pi\pi\pi**: 6.6k signals
- **pK\pi\pi**: 1k signals
- **vs**
- **three body decays**: less than 1k signals

**Phase space integrated CPV:**

\[
\begin{align*}
C_T &= \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}) \propto \sin \Phi, \text{ for } \Lambda_b^0 \\
\overline{C}_T &= \vec{p}_p \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-}) \propto \sin \overline{\Phi}, \text{ for } \overline{\Lambda}_b^0
\end{align*}
\]

**CP violation observable**

\[
a_{\hat{C}^\text{odd}} = \frac{1}{2} (A_T - \overline{A}_T)
\]

**P-violating observable**

\[
a_{\hat{P}^\text{odd}} = \frac{1}{2} (A_T + \overline{A}_T)
\]

\[
A_T(C_T) = \frac{N(C_T>0) - N(C_T<0)}{N(C_T>0) + N(C_T<0)}, \text{ for } \Lambda_b^0
\]

\[
\overline{A}_T(C_T) = \frac{N(-C_T>0) - N(-C_T<0)}{N(-C_T>0) + N(-C_T<0)}, \text{ for } \overline{\Lambda}_b^0
\]

\[
a_{\hat{P}^\text{odd}} = (-3.71 \pm 1.45 \pm 0.32)\% \\
a_{\hat{C}^\text{odd}} = (1.15 \pm 1.45 \pm 0.32)\%
\]
CPV in different regions

Binning based on resonant structures, e.g. ρ(770), N^*, Δ^{++}

Binning based on ϕ angle

First evidence for CPV with 3.3σ
Search for $\Xi_b, \Omega_b \rightarrow \phi h(\gamma)$

> Decays interesting CPV measurement from P and T interference

82.9 ± 10.4 (8.7σ)

59.6 ± 16.0 (3.4σ)

> Interesting resonant structures over m(pK) and amplitude analysis with Run 2 data is planned
Baryonic B decays

➢ First baryonic B decay (p̅pK) has been observed in 2002 by B factories

➢ First CPV evidence seen in 2013 by LHCb also in p̅pK decay

➢ More interesting baryonic B decays found recently, potential place for CPV studies

LHCb-PAPER-2017-022

B(ℓs)→pΛK

Candidates / (10 MeV/c²)
m(p̅ΛK) [MeV/c²]

B(ℓs)→p̅p

Candidates / (10 MeV/c²)
m(p̅p) [MeV/c²]

B(ℓs)→p̅pℓℓ

Candidates / (5 GeV/c²)
m(p̅pℓℓ) [GeV/c²]

B(ℓs)→p̅pℓℓ

Data

Total fit

B^0 → p̅pℓℓ

B^0 → p̅pℓℓ

B^0 → p̅pℓℓ

B^0 → p̅pℓℓ

Comb. bkgd.

PRL 119 (2017) 041802

PRL 88 (2002) 181803

PRL 113 (2014) 141801

arXiv:1704.08497
Conclusion

➢ Many interesting CPV measurements/searches have been performed by LHCb (Run 1 data) and B factories

➢ Already put useful information in determining CKM angle precisely and in constraining new physics

➢ More new/interesting results are in the pipeline from LHCb (including Run 2 data) and from Belle (Belle II soon)

➢ Stay tuned!!!

Many Thanks
Measurement on $B_s \rightarrow \phi \phi$

- $B_s \rightarrow \phi \phi$ decay dominated by $b \rightarrow s\bar{s}\bar{s}$ penguin contribution: no large direct CPV expected; weak phase from mixing and decay cancels $\rightarrow$ excellent place for new physics search

- Time dependent amplitude analysis performed with 3 fb$^{-1}$ LHCb data

- Using 4000 signal events, the CPV phase is measured to be

$$\phi_s = -0.17 \pm 0.15 \text{ (stat)} \pm 0.03 \text{ (syst)} \text{ rad}$$

- Triple-product asymmetries offered complementary information; the measurement is consistent with CP conservation

$$A_U \equiv \frac{\Gamma(U > 0) - \Gamma(U < 0)}{\Gamma(U > 0) + \Gamma(U < 0)} \quad U = \sin \phi \cos \phi \quad \sin \Phi = (\hat{n}_{V_1} \times \hat{n}_{V_2}) \cdot \hat{p}_{V_1}$$

$$A_V \equiv \frac{\Gamma(V > 0) - \Gamma(V < 0)}{\Gamma(V > 0) + \Gamma(V < 0)} \quad V = \sin(\pm \phi)$$

+ for $\cos \theta_1 \cos \theta_2 \geq 0$

- for $\cos \theta_1 \cos \theta_2 \leq 0$

$$A_V = -0.017 \pm 0.017 \text{ (stat)} \pm 0.006 \text{ (syst)} \quad A_U = -0.003 \pm 0.017 \text{ (stat)} \pm 0.006 \text{ (syst)}$$

- Updates with RUN1 + 2015 + 2016 data ongoing and at least twice signal expected
Other recent studies in $B_s \rightarrow \phi X$ sector by LHCb

➢ Search on $B_s \rightarrow \phi \eta'(\pi \pi \gamma)$ performed with full Run 1 data:

$$B(B_s^0 \rightarrow \eta' \phi) < 0.82 (1.01) \times 10^{-6} \quad \text{at} \quad 90\% \ (95\%) \ \text{CL}$$

➢ Observation of $B_s \rightarrow \phi \pi \pi$ and evidence for $B^0 \rightarrow \phi \pi \pi$ with Run 1 data

- Time-independent amplitude analysis performed
- and resonance structures like $\rho(770)$, $f_0(980)$, $f_2(1270)$ and $f_0(1500)$ identified

➢ Studies also expands to higher KK mass and a time-independent amplitude analysis ongoing with Run 1 3 fb$^{-1}$ data in LHCb

➢ New quasi-two body decays observed in higher mass region could be interesting for future CPV measurements