# $CP$ violation in $B \to 3h$: experimental status

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# Outline

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2. Selected results before 2019
   - Evidence for direct CPV in $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ by Belle and BaBar
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   - Amplitude analysis of $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ by LHCb
   - Amplitude analysis of $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ by LHCb
   - Time-dependent CPV in $B^0 \to K_S^0\pi^0\pi^0$ by Belle
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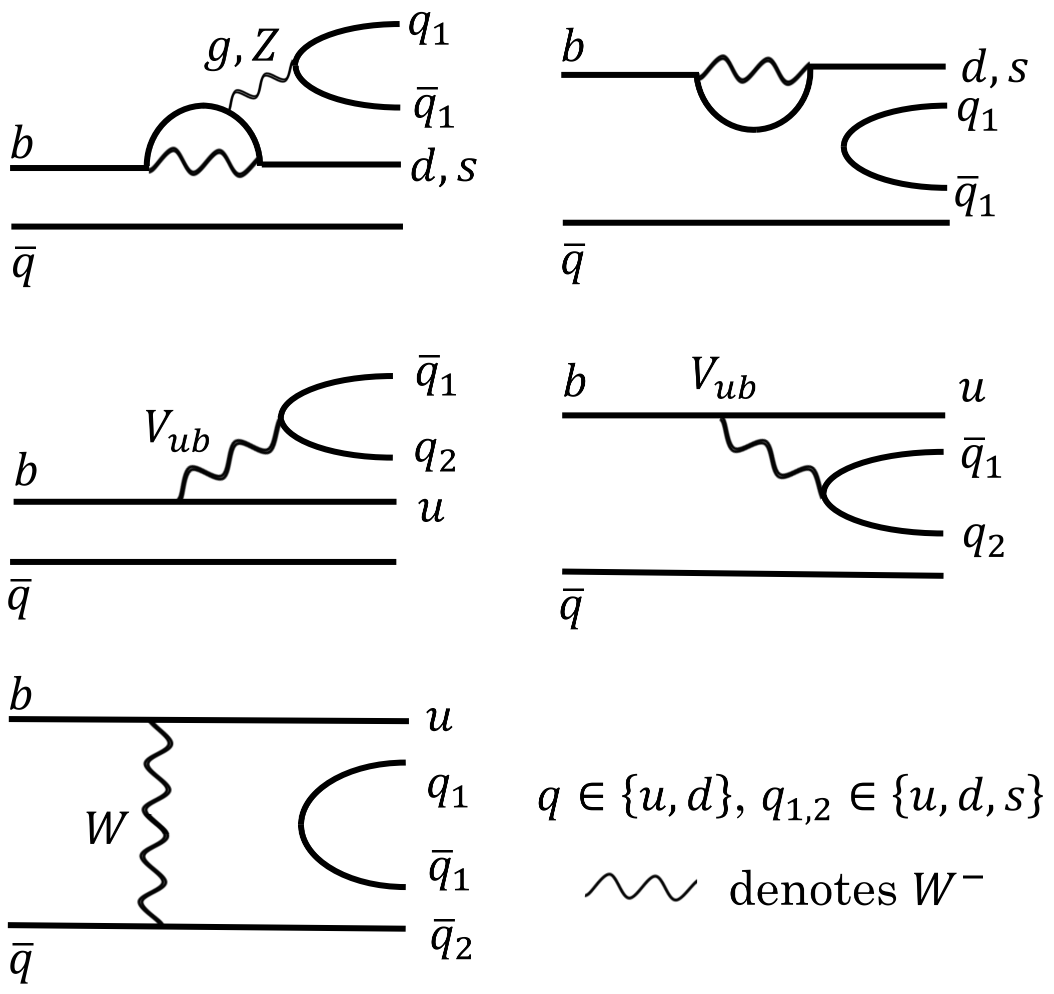
4. UT angle $\phi_3$ from $B \to 3h$
5. Conclusions

# $B \to 3h$ decays

- Scope of this talk
  - $B \in \{B^0, B^\pm\}$
  - $h \in \{\pi^0, \pi^\pm, K_S^0, K^\pm\}$
- Mainly via loop $b \to d, s$ and tree $b \to u$ quark transitions
  - $BF(B \to 3h) \sim 10^{-5}$
  - Sensitive to NP (ex. new heavy states in the loops)
- CP violation in $B \to 3h$
  - In decay (direct)
  - In mixing
  - In interference between mixing and decay



# Phenomenology of CPV in $B \to 3h$

- Three-body decays provide rich phenomenology because of decay dynamics
  - **Time-dependent Dalitz plot analysis**
  - **Phase-space-dependent (local) direct CPV**
- $CKM$ phases with $B \to 3h$
  - $\phi_1^{\text{eff}}$ from $B^0 \to 3h$
  - $\phi_2$ from $B \to \pi\pi\pi$ exploiting isospin symmetry
  - $\phi_3$ relying on isospin and $SU(3)$ symmetry
- Direct CP asymmetry

$$\mathcal{A}_{CP} \equiv \frac{\Gamma(B^- \to f^-) - \Gamma(B^+ \to f^+)}{\Gamma(B^- \to f^-) + \Gamma(B^+ \to f^+)}$$

  - Can be measured in phase-space regions

## Origin of (direct) CPV in $B \to 3h$

- At least two coherent amplitudes with different weak *and* strong phases are required
- Weak phases difference
  - Interference between tree and loop transitions
- Strong phases difference
  - Short-distance QCD
  - Long-distance hadron final-state interactions
  - Final-state $KK \leftrightarrow \pi\pi$ rescattering

# The $B \to 3h$ zoo

Neutral

| 3 kaons | 2 kaons | 1 kaon | No kaons |
|---|---|---|---|
| $K_S^0 K^+ K^-$ | $K_S^0 K^- \pi^+$ | $K_S^0 \pi^+ \pi^-$ | $\pi^0 \pi^+ \pi^-$ |
| $K_S^0 K_S^0 K_S^0$ | $K^+ K^- \pi^0$ | $K^+ \pi^- \pi^0$ | $\pi^0 \pi^0 \pi^0$ |
| | $K_S^0 K_S^0 \pi^0$ | $K^- \pi^+ \pi^0$ | |
| | $K_S^0 K^+ \pi^-$ | $K_S^0 \pi^0 \pi^0$ | |

Charged

| 3 kaons | 2 kaons | 1 kaon | No kaons |
|---|---|---|---|
| $K^+ K^+ K^-$ | $K^+ K^- \pi^+$ | $K^+ \pi^- \pi^+$ | $\pi^+ \pi^+ \pi^-$ |
| $K_S^0 K_S^0 K^+$ | $K_S^0 K_S^0 \pi^+$ | $K^+ \pi^0 \pi^0$ | $\pi^+ \pi^0 \pi^0$ |
| | $K_S^0 K^+ \pi^0$ | $K^- \pi^+ \pi^+$ | |
| | $K^+ K^+ \pi^-$ | $K_S^0 \pi^+ \pi^0$ | |

Not observed

No CPV observed

# Selected results before 2019

# First steps: Belle and BaBar

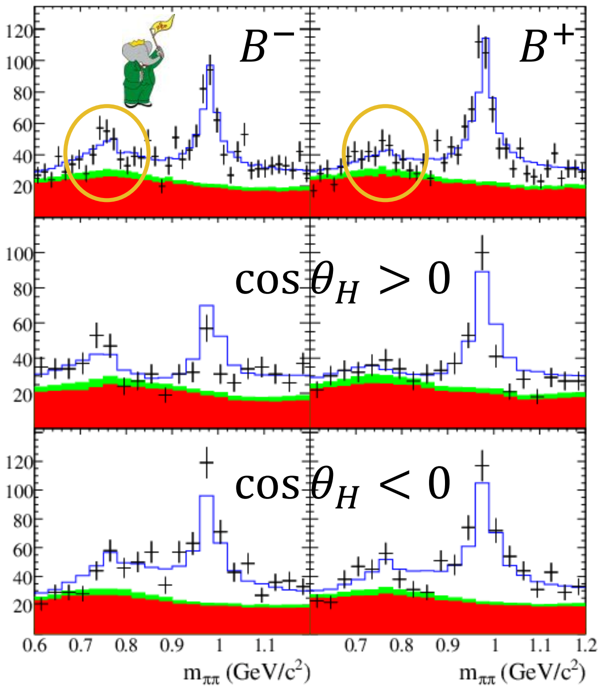
- Amplitude analysis of $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ [1,2]

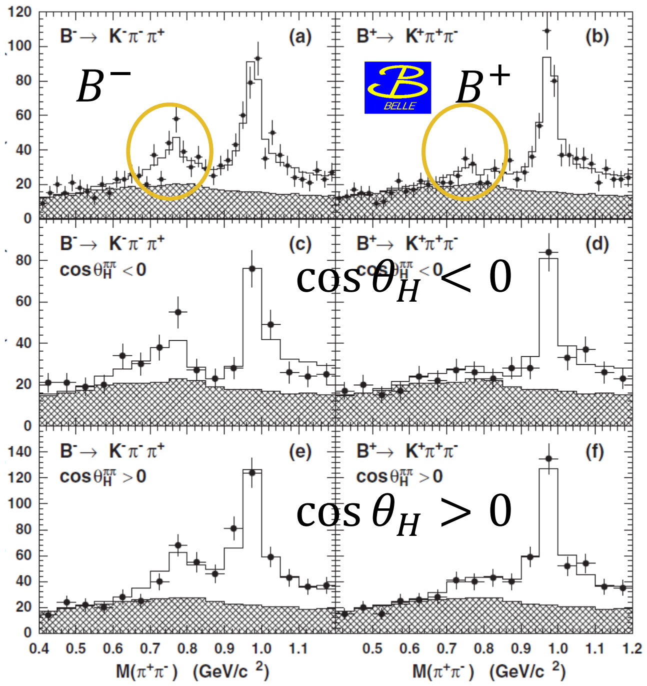
$$\mathcal{A}_{CP}(B^{\pm} \to \rho^{0}(770)K^{\pm}) = (+30 \pm 11 \pm 2^{+11}_{-4})\% \ (\approx 4\sigma)$$

$$\mathcal{A}_{CP}(B^{\pm} \to \rho^{0}(770)K^{\pm}) = \left(+44 \pm 10 \pm 4^{+5}_{-13}\right)\% \ (3.7\sigma)$$

  - First evidences for CPV in a charged particle decay

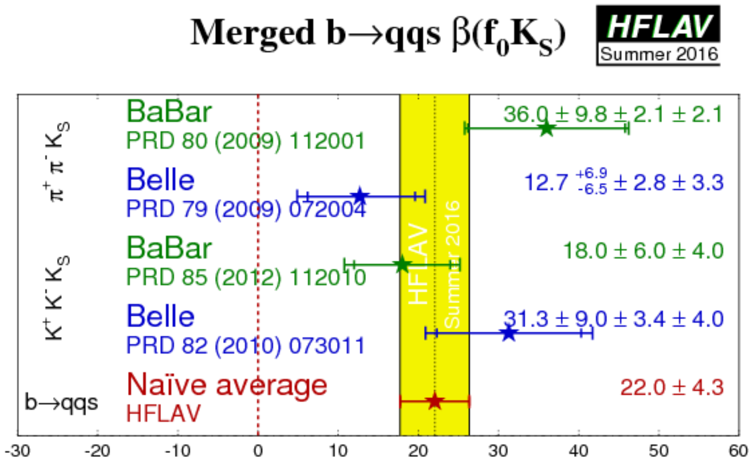
[1] PRL 96 (2006) 251803
[2] PRD 78 (2008) 012004

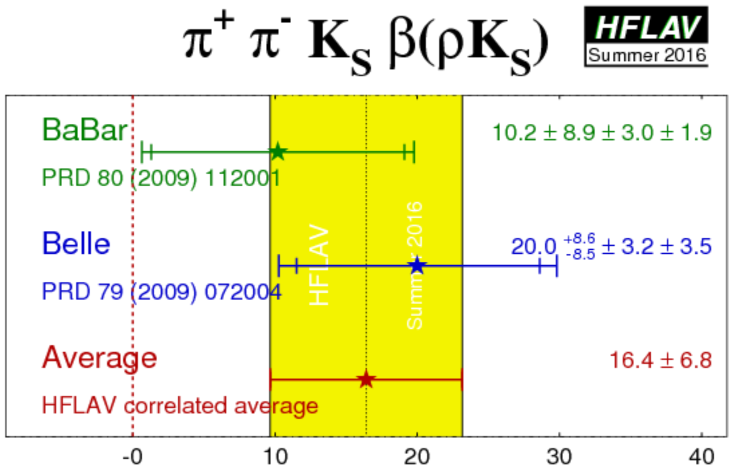


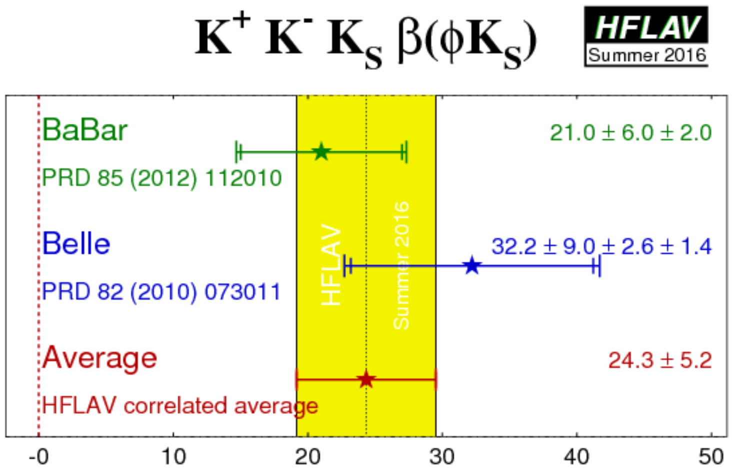



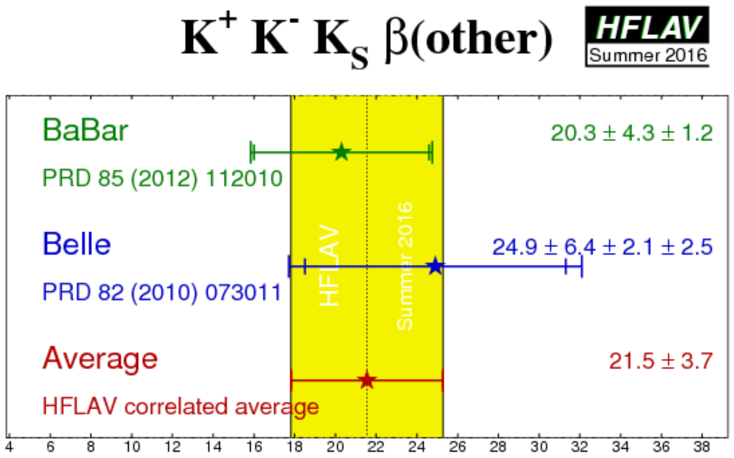
# UT angle $\phi_1^{\mathrm{eff}} \equiv \beta$ from $B^0 \to K_S^0 h^+ h^-$

- Time-dependent amplitude analyses of $B^0 \to K_S^0 h^+ h^-$
  - Variation of the decay amplitude phase over the phase space allows to measure both $\sin 2\phi_1^{\mathrm{eff}}$ and $\cos 2\phi_1^{\mathrm{eff}}$
  - The challenge of *multiple solutions* for the decay model
  - No sign of direct CPV found
- Consistent with $b \to c\bar{c}s$ though less precise



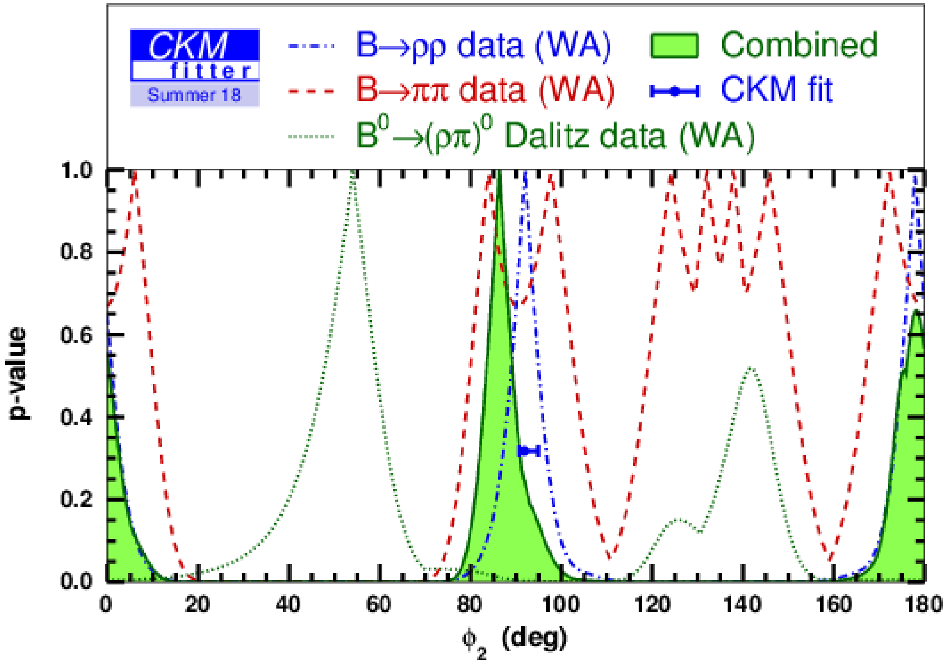



# UT angle $\phi_2 \equiv \alpha$ from $B \to \rho\pi$

- Full time-dependent amplitude analysis of $B^0 \to \pi^+\pi^-\pi^0$ by Belle and BaBar [1,2]
  - 26 amplitude parameters from the data fit
- $\phi_2$ from $SU(2)$ isospin analysis
  - Suggested by Snyder and Quinn [3]
  - Input: branching fractions and $\mathcal{A}_{CP}$ for all five combinations

$$\rho^+\pi^-, \rho^-\pi^+, \rho^0\pi^0, \rho^+\pi^0, \rho^0\pi^+$$

- The constrains on $\phi_2$ obtained are less precise than that from $B \to \pi\pi$ and $B \to \rho\rho$ analyses





[1] PRL 98 (2007) 221602
[2] PRD 88 (2013) 012003
[3] PRD 48 (1993) 2139

PRD 90 (2014) 112004

# Observation of CPV in $B \to h^{\pm}h^{+}h^{-}$

- Inclusive asymmetries with 3 $\text{fb}^{-1}$ (supersedes [1,2])

$$\mathcal{A}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) = (+2.5 \pm 0.4 \pm 0.4 \pm \boxed{0.7})\% \ (2.8\sigma)$$
$$\mathcal{A}(B^{\pm} \to K^{\pm}K^{+}K^{-}) = (-3.6 \pm 0.4 \pm 0.2 \pm \boxed{0.7})\% \ (4.3\sigma)$$
$$\mathcal{A}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = (+5.8 \pm 0.8 \pm 0.9 \pm \boxed{0.7})\% \ (4.2\sigma)$$
$$\mathcal{A}(B^{\pm} \to \pi^{\pm}K^{+}K^{-}) = (-12.3 \pm 1.7 \pm 1.2 \pm \boxed{0.7})\% \ (5.6\sigma)$$

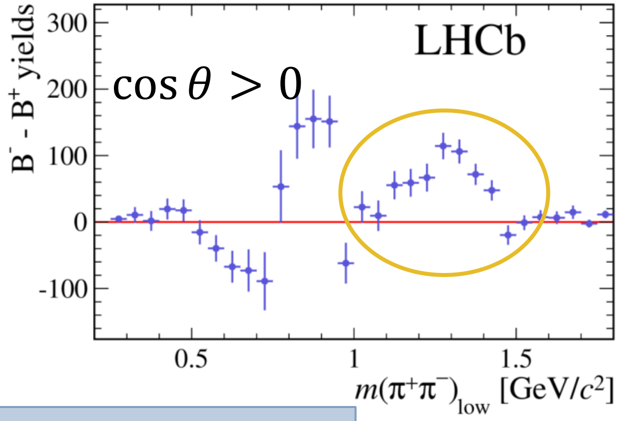
from the $J/\psi\, K^{\pm}$ reference mode

| Decay | $A_{CP}$ |
|---|---|
| $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ | $+0.121 \pm 0.012 \pm 0.017 \pm 0.007$ |
| $B^{\pm} \to K^{\pm}K^{+}K^{-}$ | $-0.211 \pm 0.011 \pm 0.004 \pm 0.007$ |
| $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ | $+0.172 \pm 0.021 \pm 0.015 \pm 0.007$ |
| $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ | $-0.328 \pm 0.028 \pm 0.029 \pm 0.007$ |

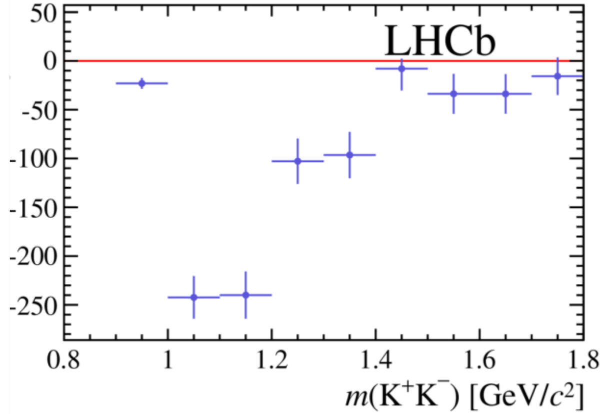
- Significant local CP asymmetry in each channel in the $m(\pi^{+}\pi^{-})$ or $m(K^{+}K^{-})$ region between 1 and 1.5 GeV
  - Positive for the channels with two pions
  - Negative for the channels with two kaons

$KK \leftrightarrow \pi\pi$ rescattering region

$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$




$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$




- Amplitude analysis and study of conjugated channels (ex. $K^{\pm}\pi^{0}\pi^{0}$, $K^{\pm}\bar{K}^{0}K^{0}$, $\pi^{\pm}\pi^{0}\pi^{0}$) are needed for an interpretation.

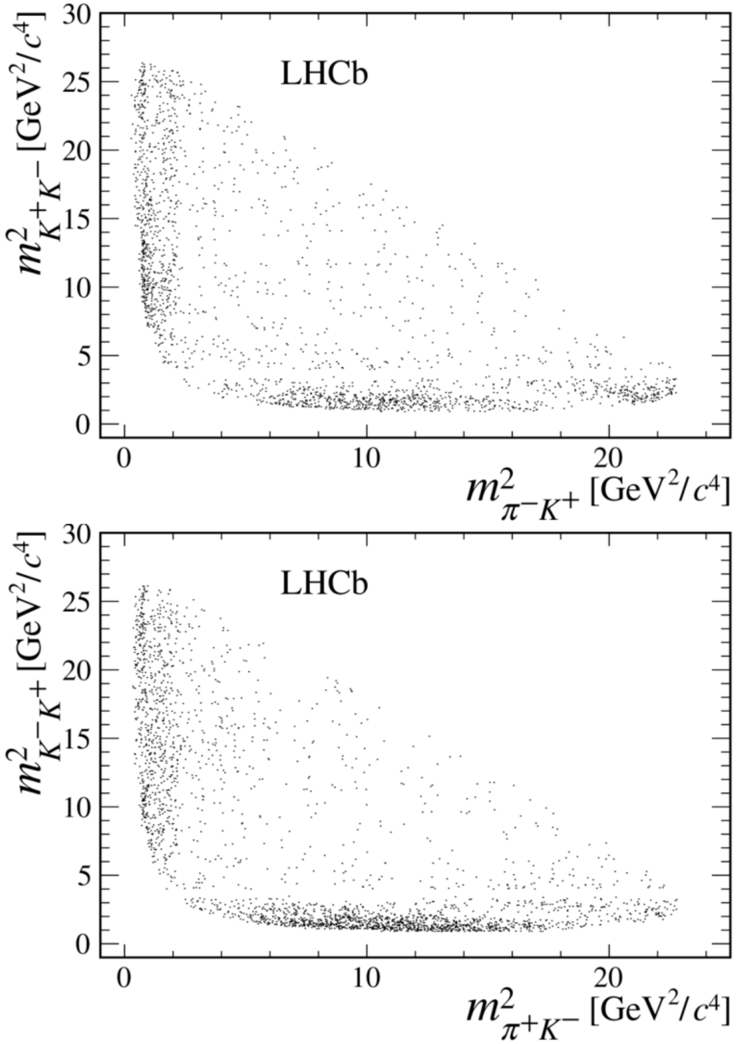
[1] PRL 111 (2013) 101801 (1 $\text{fb}^{-1}$)
[2] PRL 112 (2014) 011801 (1 $\text{fb}^{-1}$)

# 2019-2020 results

PRL 123 (2019) 231802

# Amplitude analysis of $B^{\pm} \to \pi^{\pm} K^{+} K^{-}$

- First full amplitude analysis of $B^{\pm} \to \pi^{\pm} K^{+} K^{-}$ with 2011 and 2012 LHCb data (3 fb$^{-1}$)
- Signal yields
    - $2052 \pm 102\ K^{+}K^{-}\pi^{+}$
    - $1566 \pm 84\ K^{+}K^{-}\pi^{-}$
- Background
    - Combinatorial (27%)
    - Cross feed ($B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$) (2.7%)
- Production via rescattering with $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ can be essential



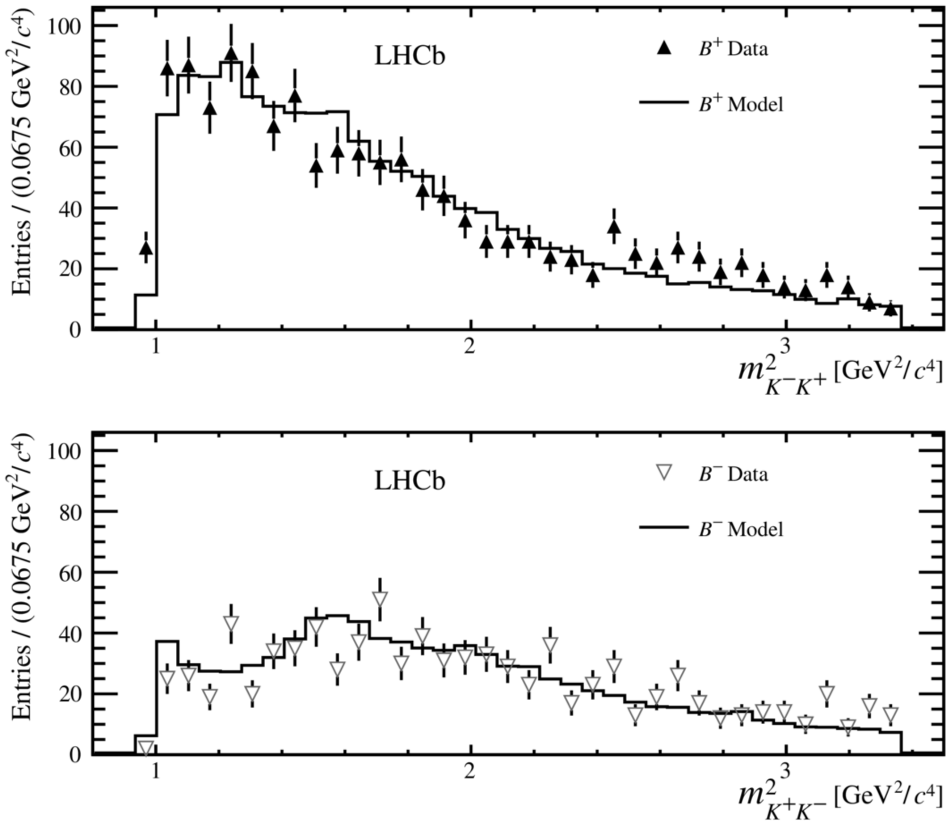
# Amplitude analysis of $B^{\pm} \rightarrow \pi^{\pm} K^{+} K^{-}$

- Decay amplitude model includes
  - NR $\pi^{\pm}K^{\mp}$ w/ single-pole form factor
  - $K^{*}(892)^{0}$, $K_0^{*}(1430)^{0}$
  - $K$-matrix $\pi\pi \leftrightarrow KK$ rescattering amplitude
  - $\rho(1450)^{0}$, $f_2(1270)$, $\phi(1020)$

$\pi^{\pm}K^{\mp}$

$K^{+}K^{-}$

- NR component is dominant in $\pi^{\pm}K^{\mp}$ system
- $\rho(1450)^{0}$ component is dominant in $K^{+}K^{-}$ system
- Large destructive interference between $\rho(1450)^{0}$ and $f_2(1270)$ in $m^2_{K^{+}K^{-}}$ between 0.8 and 3.3 GeV$^2$
- The $K^{+}K^{-}$ mass region between 0.95 and 1.42 GeV$^2$ contains concentration of events and exhibits local CPV: the region of $S$-wave $\pi\pi \leftrightarrow KK$ rescattering



PRL 123 (2019) 231802

# Amplitude analysis of $B^{\pm} \to \pi^{\pm} K^{+} K^{-}$

$$\mathcal{A}(m^2_{\pi^+K^-}, m^2_{K^+K^-}) = \sum c_i \mathcal{M}_i(m^2_{\pi^+K^-}, m^2_{K^+K^-})$$

$$\bar{\mathcal{A}}(m^2_{\pi^-K^+}, m^2_{K^+K^-}) = \sum \bar{c}_i \bar{\mathcal{M}}_i(m^2_{\pi^-K^+}, m^2_{K^+K^-})$$

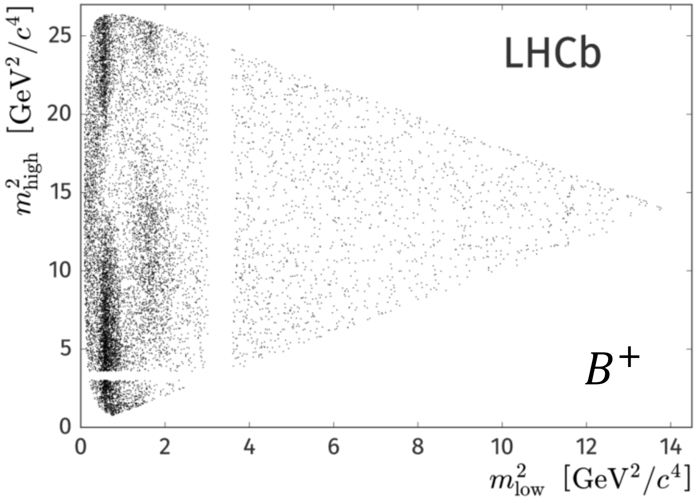
$$A_{CP\,i} \equiv \frac{|c_i|^2 - |\bar{c}_i|^2}{|c_i|^2 + |\bar{c}_i|^2}$$

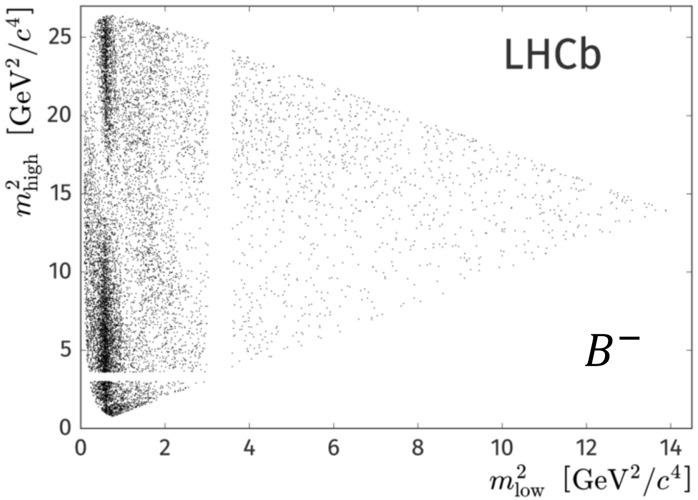
- CPV in the rescattering channel is the largest CPV observed from a single channel
- No significant CPV is observed in the other contributions

| Contribution | Fit Fraction(%) | $A_{CP}$(%) |
|---|---|---|
| $K^*(892)^0$ | $7.5 \pm 0.6 \pm 0.5$ | $+12.3 \pm 8.7 \pm 4.5$ |
| $K_0^*(1430)^0$ | $4.5 \pm 0.7 \pm 1.2$ | $+10.4 \pm 14.9 \pm 8.8$ |
| Single pole | $32.3 \pm 1.5 \pm 4.1$ | $-10.7 \pm 5.3 \pm 3.5$ |
| $\rho(1450)^0$ | $30.7 \pm 1.2 \pm 0.9$ | $-10.9 \pm 4.4 \pm 2.4$ |
| $f_2(1270)$ | $7.5 \pm 0.8 \pm 0.7$ | $+26.7 \pm 10.2 \pm 4.8$ |
| Rescattering | $16.4 \pm 0.8 \pm 1.0$ | $-66.4 \pm 3.8 \pm 1.9$ |
| $\phi(1020)$ | $0.3 \pm 0.1 \pm 0.1$ | $+9.8 \pm 43.6 \pm 26.6$ |

# Amplitude analysis of $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$

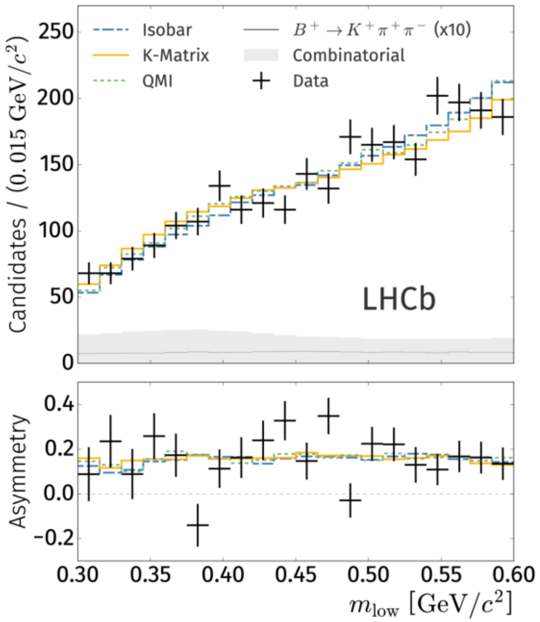
- Amplitude analysis of $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ with 2011 and 2012 LHCb data (3 $\mathrm{fb}^{-1}$)
- Yields
  - $20600 \pm 1600$ signal
  - $4400 \pm 1600$ combinatorial background
  - $143 \pm 11$ $B^{+} \to K^{+}\pi^{+}\pi^{-}$ miss ID
- $\rho(770)^{0}$ resonance is the dominant channel



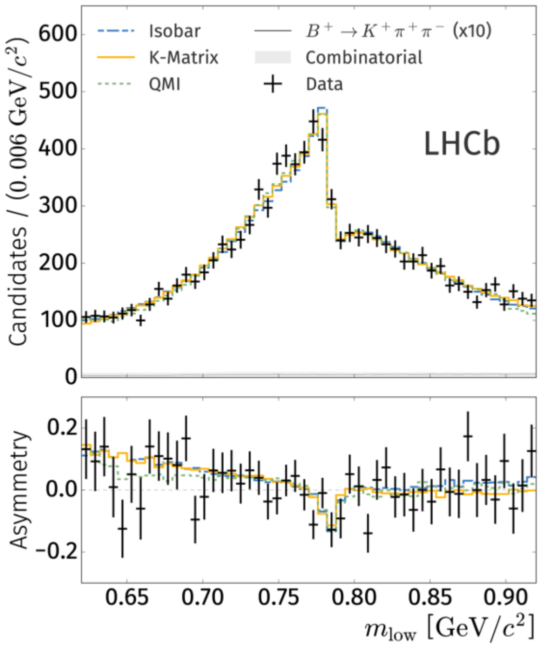



PRL 124 (2020) 031801

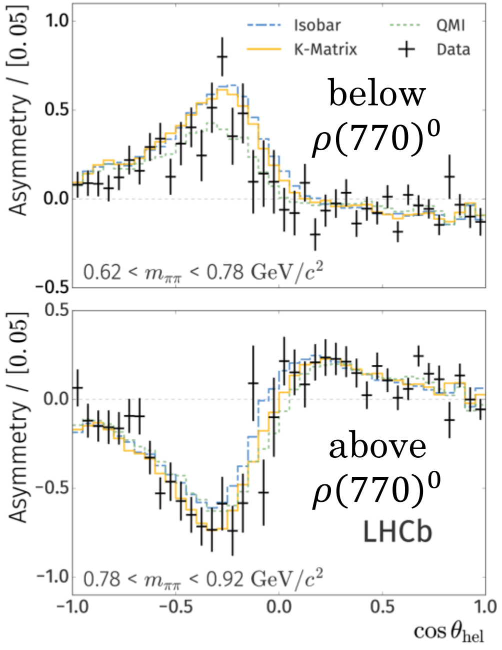
# Amplitude analysis of $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$



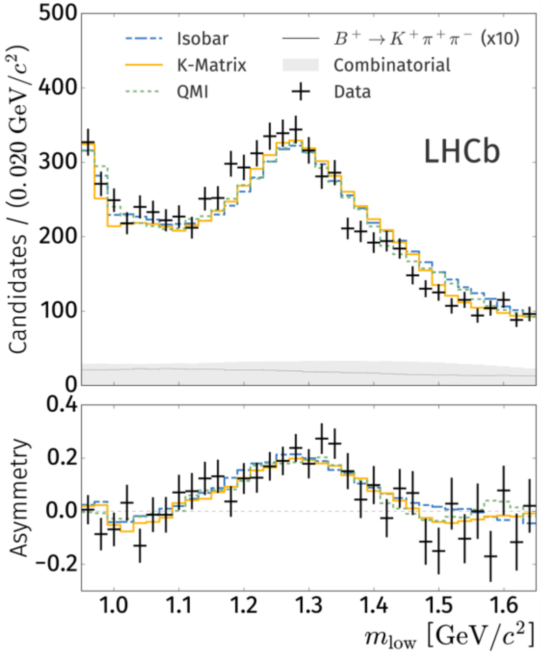

CPV in the $S$-wave amplitude




No CPV from $\rho$-$\omega$ mixing is observed




CPV via interference of $S$- and $P$-waves




CPV in tensor resonance $f_2(1270)$

PRL 124 (2020) 031801

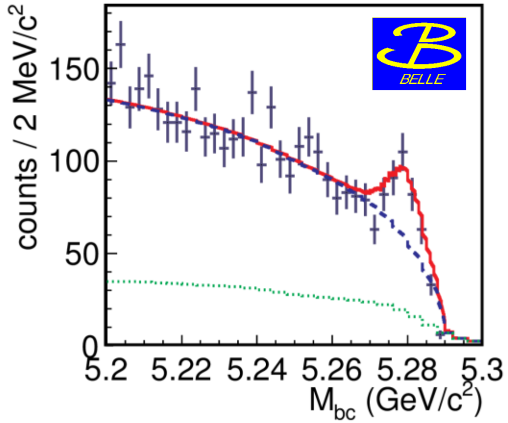
# Amplitude analysis of $B^\pm \to \pi^\pm\pi^+\pi^-$

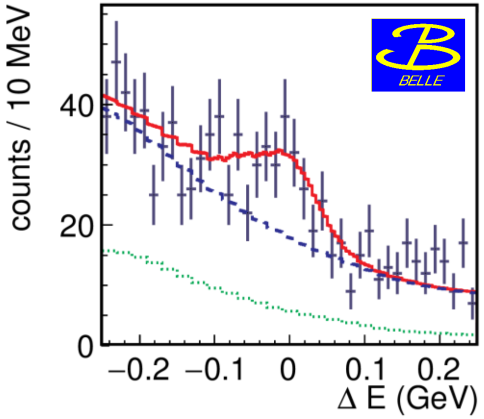
- Three complementary approaches adopted for the S-wave amplitude description
  - Isobar with scalar $\sigma$ and $\pi\pi \leftrightarrow KK$ rescattering term
  - $K$-matrix with fixed parameters
  - Quasi model-independent (QMI)
- Good agreement is found between all three models
- CPV observed is associated with
  - $f_2(1270)$ resonance (first observation of CPV in tensor amplitude)
  - low-mass $S$-wave amplitude
  - interference of $S$-wave and $\rho(770)^0$ amplitudes

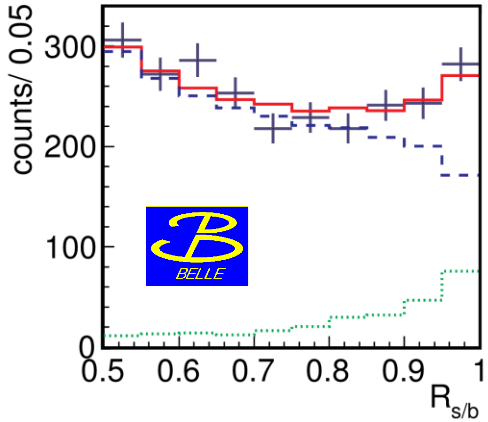
| Contribution | Fit fraction $(10^{-2})$ | $A_{CP}$ $(10^{-2})$ |
|---|---|---|
| Isobar model | | |
| $\rho(770)^0$ | $55.5 \pm 0.6 \pm 2.5$ | $+0.7 \pm 1.1 \pm 1.6$ |
| $\omega(782)$ | $0.50 \pm 0.03 \pm 0.05$ | $-4.8 \pm 6.5 \pm 3.8$ |
| $f_2(1270)$ | $9.0 \pm 0.3 \pm 1.5$ | $+46.8 \pm 6.1 \pm 4.7$ |
| $\rho(1450)^0$ | $5.2 \pm 0.3 \pm 1.9$ | $-12.9 \pm 3.3 \pm 35.9$ |
| $\rho_3(1690)^0$ | $0.5 \pm 0.1 \pm 0.3$ | $-80.1 \pm 11.4 \pm 25.3$ |
| S-wave | $25.4 \pm 0.5 \pm 3.6$ | $+14.4 \pm 1.8 \pm 2.1$ |
| Rescattering | $1.4 \pm 0.1 \pm 0.5$ | $+44.7 \pm 8.6 \pm 17.3$ |
| $\sigma$ | $25.2 \pm 0.5 \pm 5.0$ | $+16.0 \pm 1.7 \pm 2.2$ |
| K-matrix | | |
| $\rho(770)^0$ | $56.5 \pm 0.7 \pm 3.4$ | $+4.2 \pm 1.5 \pm 6.4$ |
| $\omega(782)$ | $0.47 \pm 0.04 \pm 0.03$ | $-6.2 \pm 8.4 \pm 9.8$ |
| $f_2(1270)$ | $9.3 \pm 0.4 \pm 2.5$ | $+42.8 \pm 4.1 \pm 9.1$ |
| $\rho(1450)^0$ | $10.5 \pm 0.7 \pm 4.6$ | $+9.0 \pm 6.0 \pm 47.0$ |
| $\rho_3(1690)^0$ | $1.5 \pm 0.1 \pm 0.4$ | $-35.7 \pm 10.8 \pm 36.9$ |
| S-wave | $25.7 \pm 0.6 \pm 3.0$ | $+15.8 \pm 2.6 \pm 7.2$ |
| QMI | | |
| $\rho(770)^0$ | $54.8 \pm 1.0 \pm 2.2$ | $+4.4 \pm 1.7 \pm 2.8$ |
| $\omega(782)$ | $0.57 \pm 0.10 \pm 0.17$ | $-7.9 \pm 16.5 \pm 15.8$ |
| $f_2(1270)$ | $9.6 \pm 0.4 \pm 4.0$ | $+37.6 \pm 4.4 \pm 8.0$ |
| $\rho(1450)^0$ | $7.4 \pm 0.5 \pm 4.0$ | $-15.5 \pm 7.3 \pm 35.2$ |
| $\rho_3(1690)^0$ | $1.0 \pm 0.1 \pm 0.5$ | $-93.2 \pm 6.8 \pm 38.9$ |
| S-wave | $26.8 \pm 0.7 \pm 2.2$ | $+15.0 \pm 2.7 \pm 8.1$ |

# Time-dependent CPV in $B^0 \to K_S^0 \pi^0 \pi^0$

- $772 \times 10^6$ $B\bar{B}$ sample
- CP-even final state
- Loop $b \to sd\bar{d}$ and DCS tree $b \to u\bar{u}s$ amplitudes
- 3D $(M_{\text{bc}}, \Delta E, R_{s/b})$ fit to data:
  - Signal
  - $q\bar{q}$ background (dominant)
  - $B\bar{B}$ background
- $335 \pm 37$ signal events




$M_{\text{bc}} \equiv \sqrt{E_{\text{beam}}^2 - |p_B|^2}$

$\Delta E \equiv E_B - E_{\text{beam}}$

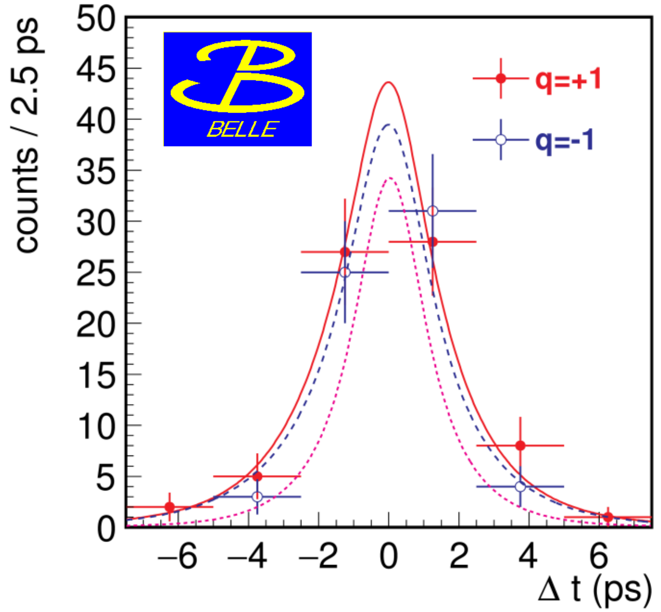
$R_{s/b}$ is the likelihood ratio discriminator between $B\bar{B}$ and $q\bar{q}$ events

# Time-dependent CPV in $B^0 \to K_S^0\pi^0\pi^0$

$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \times (1 + q[\mathcal{S}\sin(\Delta m_d \Delta t) + \mathcal{A}\cos(\Delta m_d \Delta t)])$$

$\mathcal{S} = -\sin 2\phi_1^{\mathrm{eff}}$, $\mathcal{A} = 0$ if there is no direct CPV

- $\Delta t$ fit of 964 events with 11.4% purity
- There are no primary tracks. $K_S^0$ momentum is extrapolated to the interaction region to obtain the $B$ vertex
- $K_S^0$ is slower than in $K_S^0\pi^0$ leading to better vertex and time resolution (more decays inside the vertex detector)
- Effective flavor tagging efficiency is $(29.8 \pm 0.4)\%$



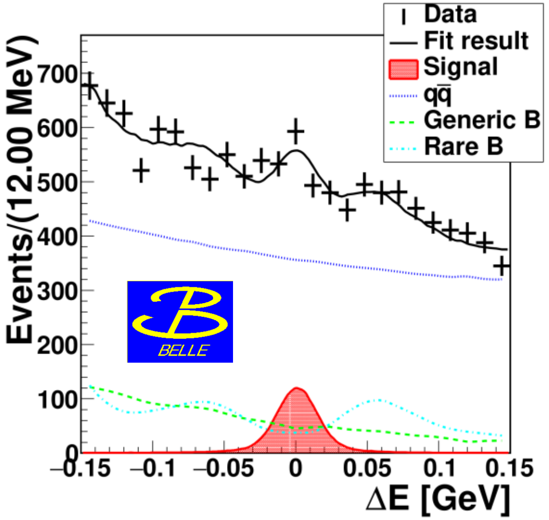

$$\sin 2\phi_1^{\mathrm{eff}} = 0.92^{+0.27}_{-0.31} \pm 0.11$$
$$\mathcal{A} = 0.28 \pm 0.21 \pm 0.04$$

PRD 100 (2019) 011101(R)

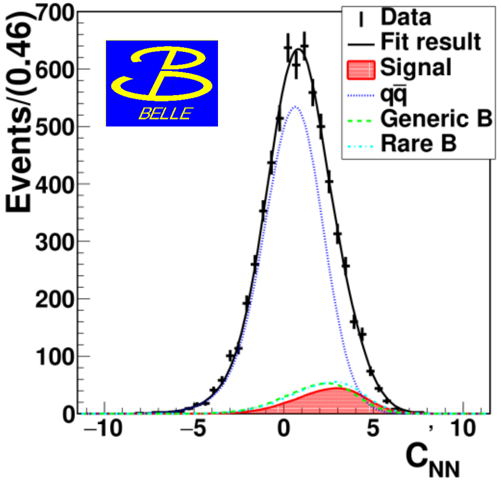
# Final-state asymmetry in $\bar{B}^0 \to K_S^0 K^{\mp}\pi^{\pm}$

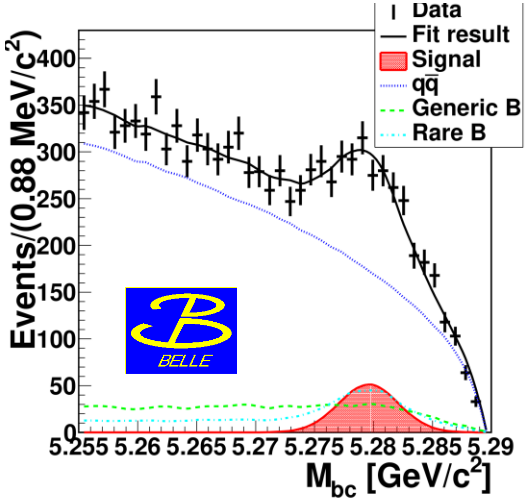
$$\mathcal{A}_{\rm fs} \equiv \frac{N(K_S^0 K^-\pi^+) - N(K_S^0 K^+\pi^-)}{N(K_S^0 K^-\pi^+) + N(K_S^0 K^+\pi^-)} = (-8.5 \pm 8.9 \pm 0.2)\%$$

where $N(X)$ is the $X$ signal yield for both $B^0$ and $\bar{B}^0$ (not $CP$-asymmetry $\mathcal{A}_{CP}$!)




- Final-state $\mathcal{A}_{\rm fs}$ can be measured more precisely then $\mathcal{A}_{CP}$. Non-zero $\mathcal{A}_{\rm fs}$ would be an indirect manifestation of CPV
- $772 \times 10^6$ $B\bar{B}$ sample
- 3D ($M_{\rm bc}, \Delta E, C'_{NN}$) fit to data
- Signal yield $490^{+46}_{-45}$
- Branching fraction measured
  $BF(B^0 \to K_S^0 K^-\pi^+) = (6.2 \pm 0.7) \times 10^{-6}$
- No localized $\mathcal{A}_{\rm fs}$ is observed

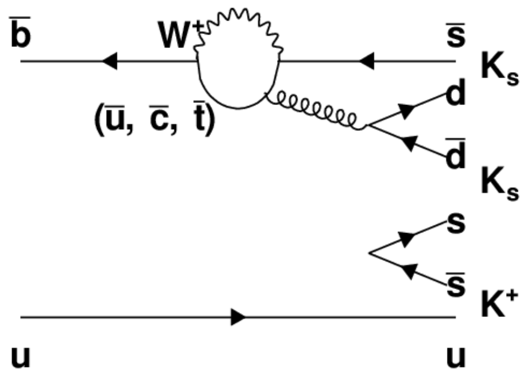


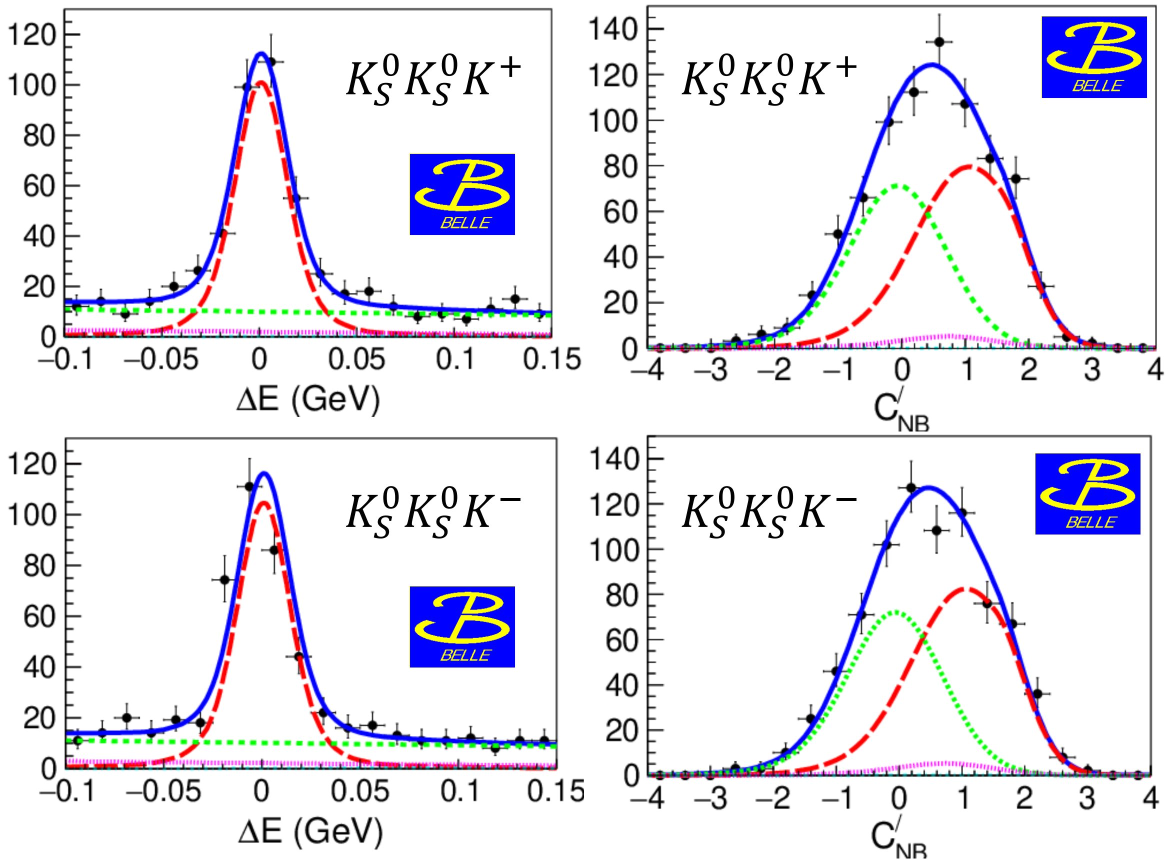



PRD 99 (2019) 031102(R)

# Search for CPV in $B^{\pm} \to K_S^0 K_S^0 K^{\pm}$

- Decay mainly via $b \to \mathrm{s}$ loops
- $K_S^0 K_S^0$ cannot form a vector resonance, in contrast with $K^+K^-$ in $B^{\pm} \to K^+K^-K^{\pm}$ decay
- $772 \times 10^6\ B\overline{B}$ sample
- 2D $(\Delta E, C'_{\mathrm{NB}})$ fit to data
  - Signal yield: ~2000 events
  - Dominant background is from $e^+e^- \to q\bar{q}$



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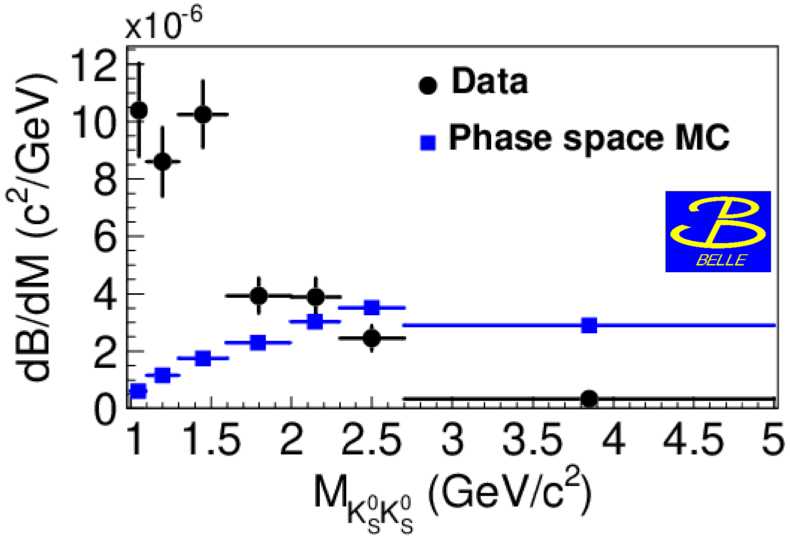
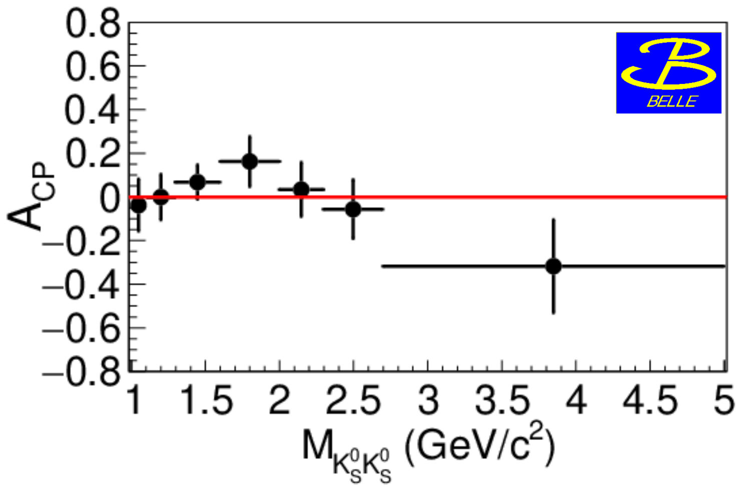
# Search for CPV in $B^{\pm} \to K_S^0 K_S^0 K^{\pm}$

- Resonances in the low $m_{K_S^0 K_S^0}$ region: $f_0(980)$, $f_0(1500)$, $f_2'(1525)$
- Local CP asymmetries are not significant
- Inclusive CP asymmetry

$$\mathcal{A}_{CP} = (+1.6 \pm 3.9 \pm 0.9)\%$$

| $M_{K_S^0 K_S^0}$ (GeV/$c^2$) | $\mathcal{A}_{CP}$ (%) |
|---|---|
| 1.0–1.1 | $-3.9 \pm 10.9 \pm 0.9$ |
| 1.1–1.3 | $-0.1 \pm 9.3 \pm 0.9$ |
| 1.3–1.6 | $+6.6 \pm 6.9 \pm 0.9$ |
| 1.6–2.0 | $+16.1 \pm 10.3 \pm 0.9$ |
| 2.0–2.3 | $-3.3 \pm 11.3 \pm 0.9$ |
| 2.3–2.7 | $-5.7 \pm 12.2 \pm 1.0$ |
| 2.7–5.0 | $-31.9 \pm 19.7 \pm 1.2$ |



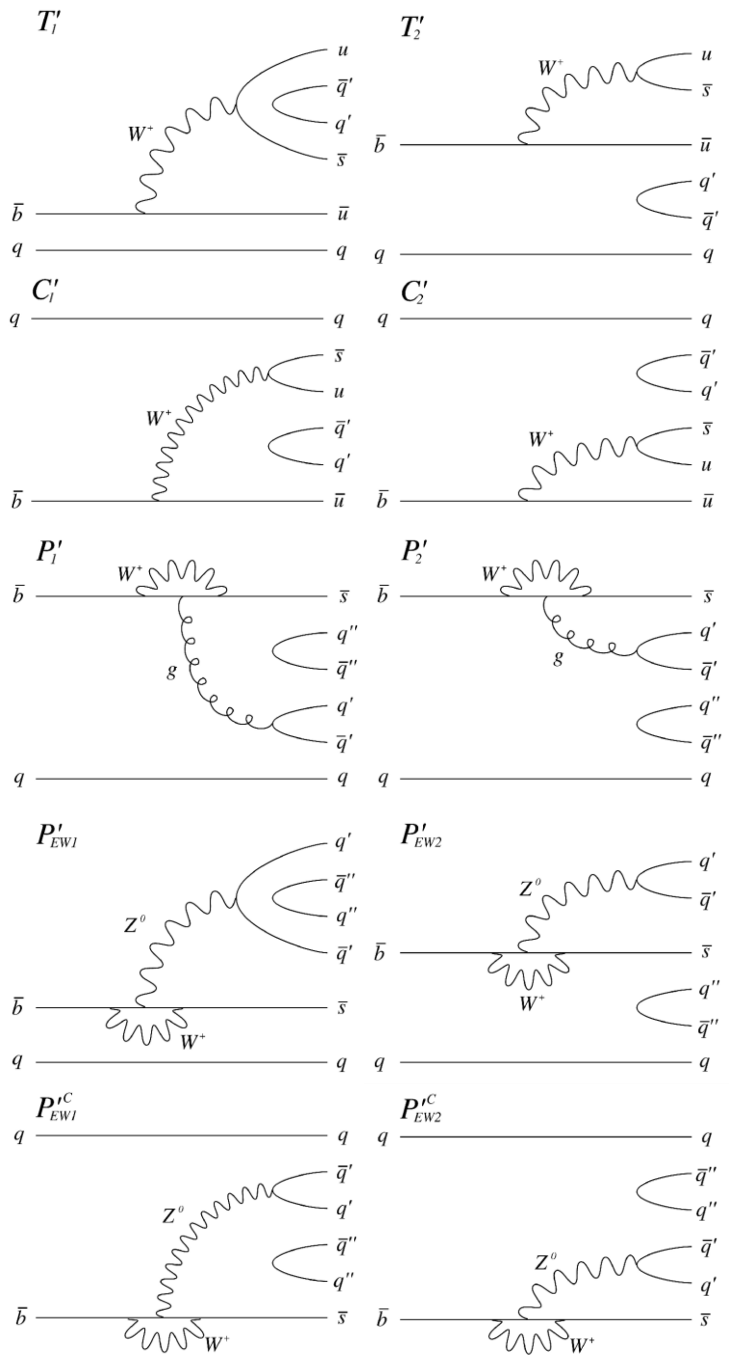
E. Bertholet et al., PRD 99 (2019) 031102(R)

# UT angle $\phi_3$ from $B \to 3h$

- Diagrammatic analysis of $B \to 3h$ [PRD 84 (2011) 034040]
- $B^{0,+} \to K^{0,+}\pi^+\pi^-$, $B^0 \to K^+\pi^0\pi^-$, $B^0 \to K^+K^0K^-$, $B^0 \to K^0K^0\overline{K}^0$ decays considered
- Relations between the *fully symmetric* amplitudes from flavor $SU(3)$
  - $SU(3)$ braking is small when averaged over the phase space and is included in systematic uncertainty
- 6 solutions with BaBar data. Third one is a SM-consistent

$$\phi_3^{(3)} = (68.9^{+8.6}_{-8.6} \pm 2.4)^\circ$$

  - Compare with the world average $\phi_3 = \left(73.5^{+4.2}_{-5.1}\right)^\circ$
- Does this approach survive in the view of large local CPV observed and significant large-distance dynamics (like $\pi\pi \leftrightarrow KK$ rescattering)?

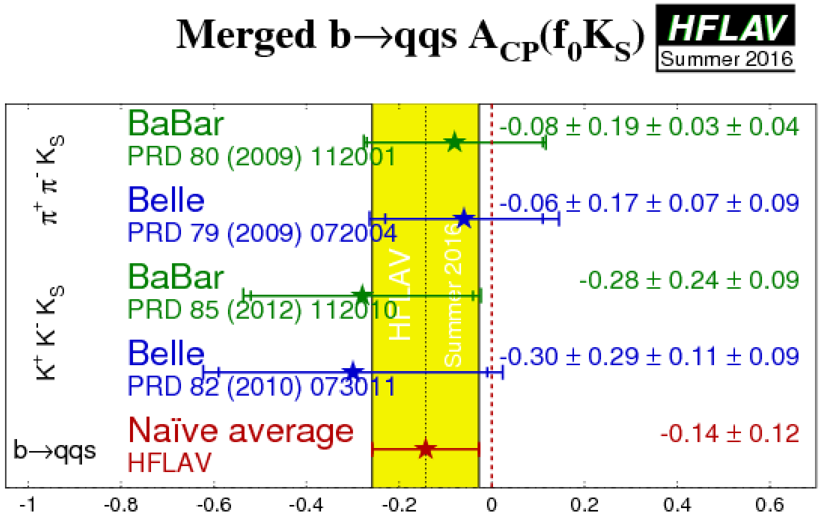


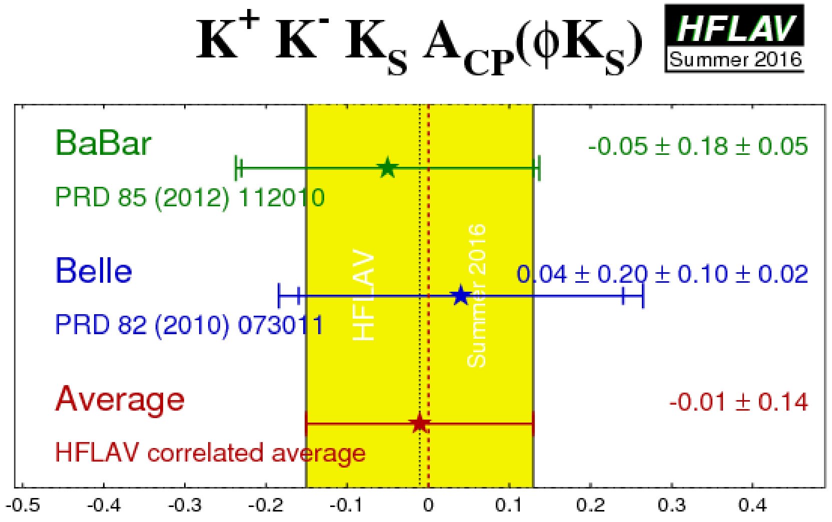
# Conclusions

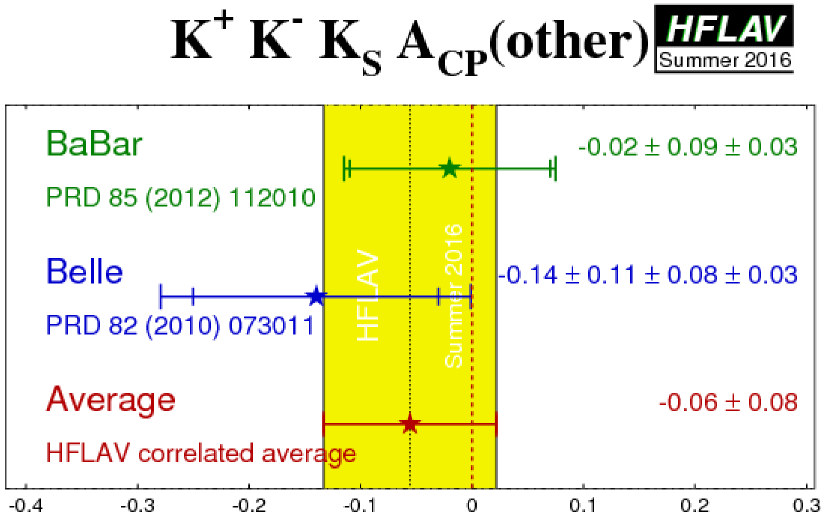
1. A proper study of CPV in $B \to 3h$ is challenging and requires amplitude analysis
2. Significant global and local CPV are observed in all $B^{\pm} \to h^{\pm}h^{+}h^{-}$ modes
   - Several sources of CPV are observed in the $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decay
   - CPV via $\pi^{+}\pi^{-} \leftrightarrow K^{+}K^{-}$ rescattering is confirmed in the $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ decay
3. Setting constraints on CKM matrix elements from CPV in $B \to 3h$ is not straightforward. A coherent analysis of several channels is required in some cases.
4. Study of CPV in the $B \to 3h$ decays should be continued at LHCb and Belle II
5. Belle II will be able to explore channels with final-state neutrals that are hardly accessible at LHCb

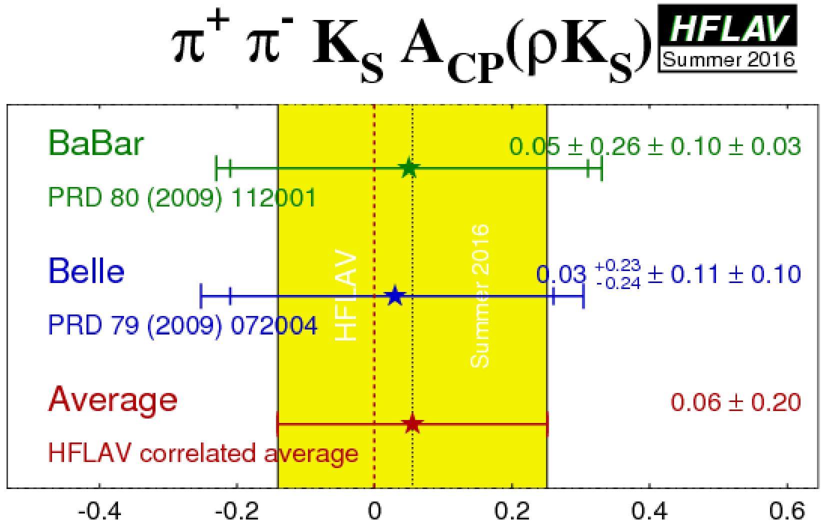
# Backup

# Direct CPV in $B^0 \to K_S^0 h^+ h^-$



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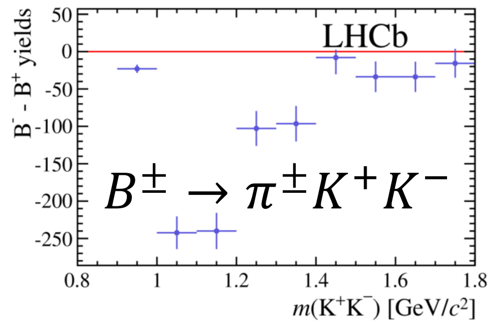
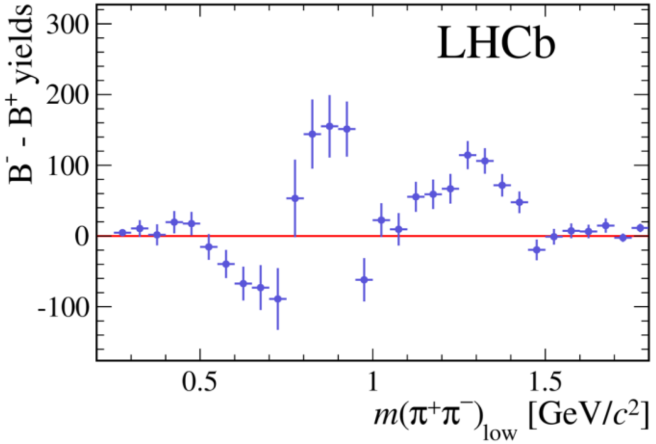
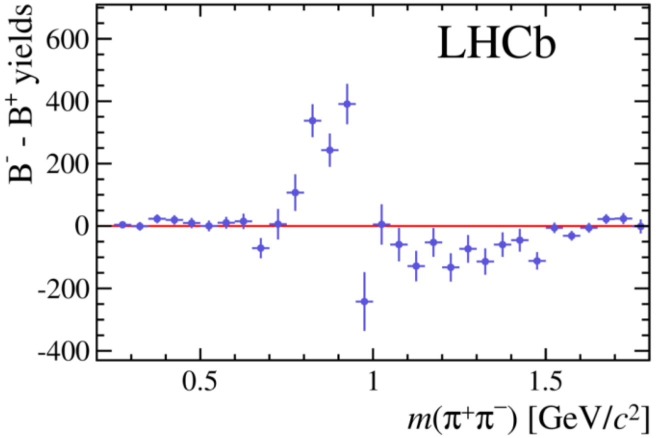
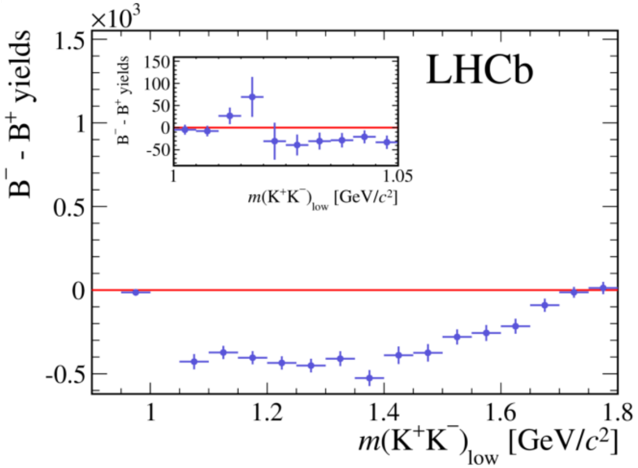
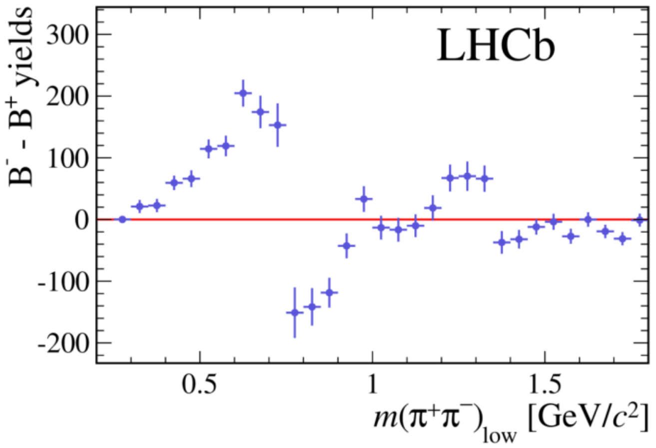
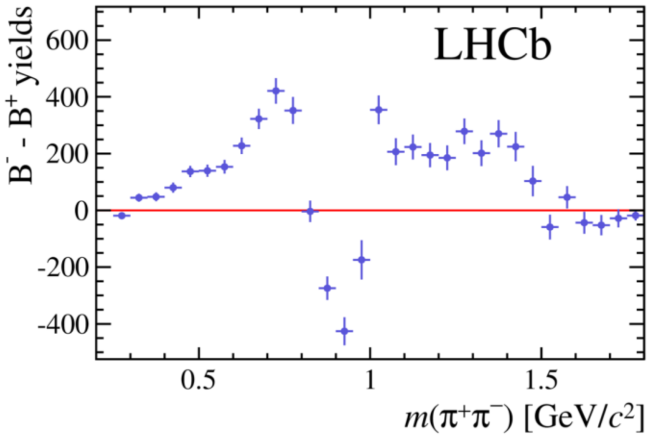
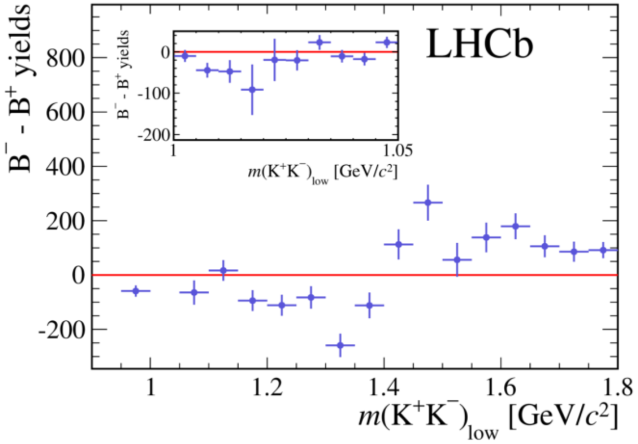
# CPV in $B \to h^{\pm}h^{+}h^{-}$




| | $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ | $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ | $B^{\pm} \to K^{\pm}K^{+}K^{-}$ |
|---|---|---|---|
| $\cos\theta > 0$ |   |   |   |
| $\cos\theta < 0$ |   |   |   |

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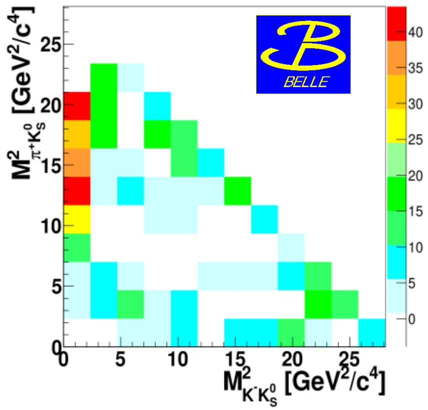
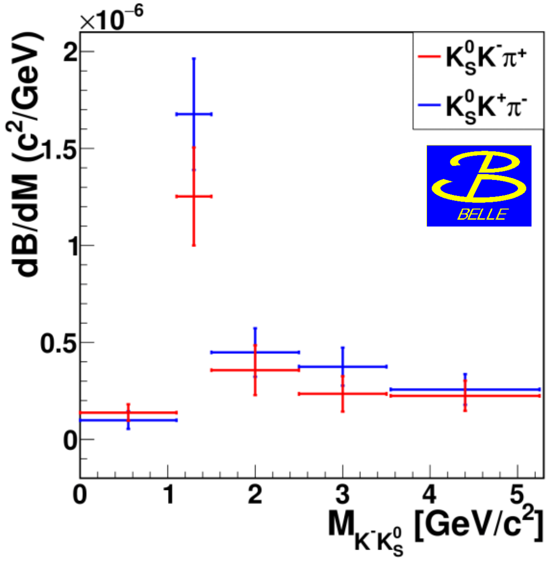
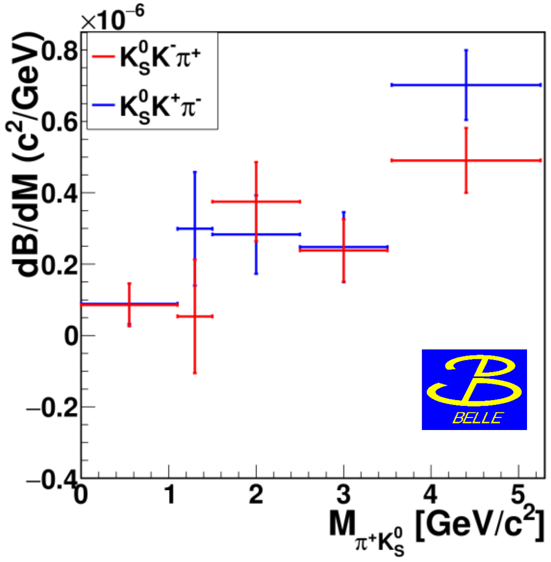
# Final-state asymmetry in $\bar{B}^0 \to K_S^0 K^{\mp}\pi^{\pm}$

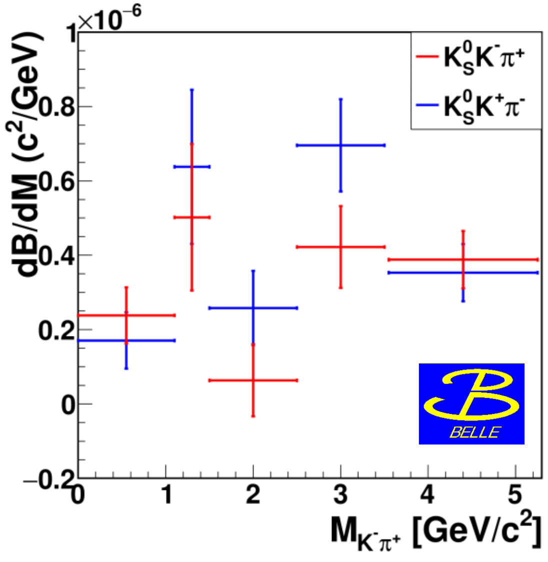
$$\mathcal{A}_{\rm fs} = (-8.5 \pm 8.9 \pm 0.2)\%$$

- No localized final-state asymmetry is observed
- Dalitz distributions:
  - Peaking structures near $m_{K_S^0 K^-} = 1.2$ GeV and $m_{K_S^0\pi^+} = 4.2$ GeV
  - No obvious $K^*$ in both $m_{K^-\pi^+}$ and $m_{K_S^0\pi^+}$

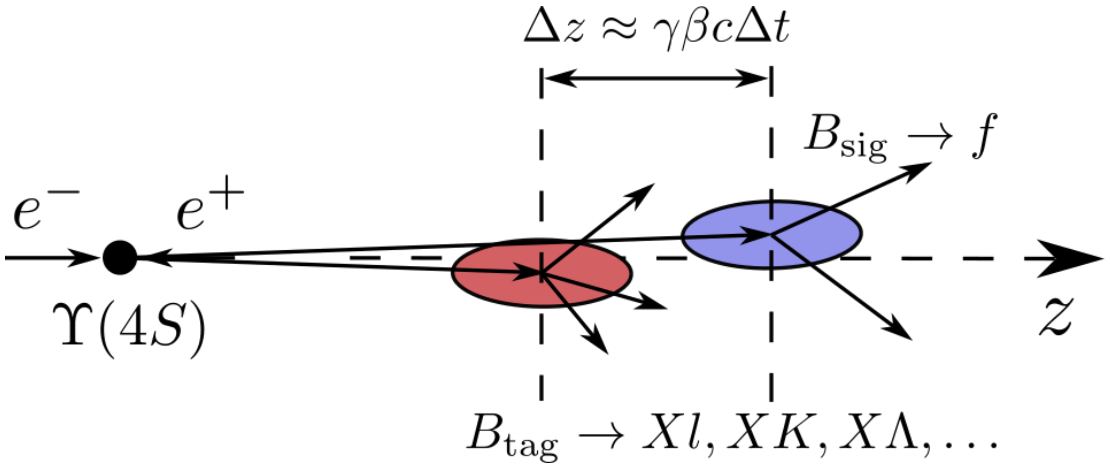


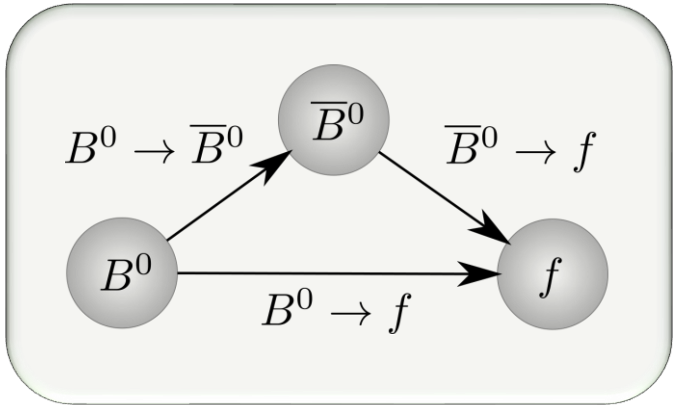



# Time-dependent measurements at an asymmetric $B$-factory




- Flight distance $\Delta z \approx 200\ \mu\text{m}$
- Vertex resolution $\sigma(\Delta z) \approx 130\ \mu\text{m}$
- Correct flavor tagging for $\approx 80\%$ events
- Boost factor:
  - Belle $\beta\gamma = 0.425$
  - BaBar $\beta\gamma = 0.56$




**Time-dependent $B$ decay rate**

$$g(\Delta t) = \frac{1}{4\tau_B} e^{-\frac{|\Delta t|}{\tau_B}} (1 + q[A \sin(\Delta m \Delta t) - B \cos(\Delta m \Delta t)])$$

- $q = \pm 1$ denotes the initial flavor of signal $B$ meson
- Standard model predicts $A = -\eta_f \sin(2\beta)$ and $B = 0$ for a $\mathcal{CP}$-specific final state with $\mathcal{CP}$ parity $\eta_f$

# Branching fractions as in PDG

| 3 kaons | 2 kaons | 1 kaon | Only pions |
|---|---|---|---|
| $K_S^0 K_S^0 K_S^0$ $(6.0 \pm 0.5) \times 10^{-6}$ | $K_S^0 K^- \pi^+$ $(6.2 \pm 0.7) \times 10^{-6}$ | $K_S^0 \pi^+ \pi^-$ $(4.94 \pm 0.18) \times 10^{-5}$ | $\pi^0 \pi^+ \pi^- (2.30 \pm 0.23) \times 10^{-5}$ |
| $K_S^0 K^+ K^-$ $(2.67 \pm 0.11) \times 10^{-5}$ | $K_S^0 K^+ \pi^-$ | $K_S^0 \pi^0 \pi^0$ | $\pi^0 \pi^0 \pi^0$ |
| | $K^+ K^- \pi^0$ $(2.2 \pm 0.6) \times 10^{-6}$ | $K^+ \pi^- \pi^0$ $(3.78 \pm 0.32) \times 10^{-5}$ | |
| | $K_S^0 K_S^0 \pi^0 < 9 \times 10^{-7}$ | $K^- \pi^+ \pi^0$ | |

| 3 kaons | 2 kaons | 1 kaon | Only pions |
|---|---|---|---|
| $K^+ K^+ K^-$ $(3.40 \pm 0.14) \times 10^{-5}$ | $K_S^0 K_S^0 \pi^+ < 5.1 \times 10^{-7}$ | $K^+ \pi^0 \pi^0$ $(1.62 \pm 0.19) \times 10^{-5}$ | $\pi^+ \pi^+ \pi^-$ $(1.52 \pm 0.14) \times 10^{-5}$ |
| $K_S^0 K_S^0 K^+$ $(1.08 \pm 0.06) \times 10^{-5}$ | $K^+ K^- \pi^+$ $(5.2 \pm 0.4) \times 10^{-6}$ | $K^+ \pi^- \pi^+$ $(5.10 \pm 0.29) \times 10^{-5}$ | $\pi^+ \pi^0 \pi^0$ $(1.09 \pm 0.14) \times 10^{-5}$ |
| | $K_S^0 K^+ \pi^0 < 2.4 \times 10^{-5}$ | $K^- \pi^+ \pi^+ < 4.6 \times 10^{-5}$ | |
| | $K^+ K^+ \pi^- < 8.79 \times 10^{-5}$ | $K_S^0 \pi^+ \pi^0 < 6.6 \times 10^{-5}$ | |