Observation of *CP* violation in charmless three-body $B^{\pm}$ meson decays at LHCb

LHCb-PAPER-2021-049
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on behalf of the LHCb collaboration

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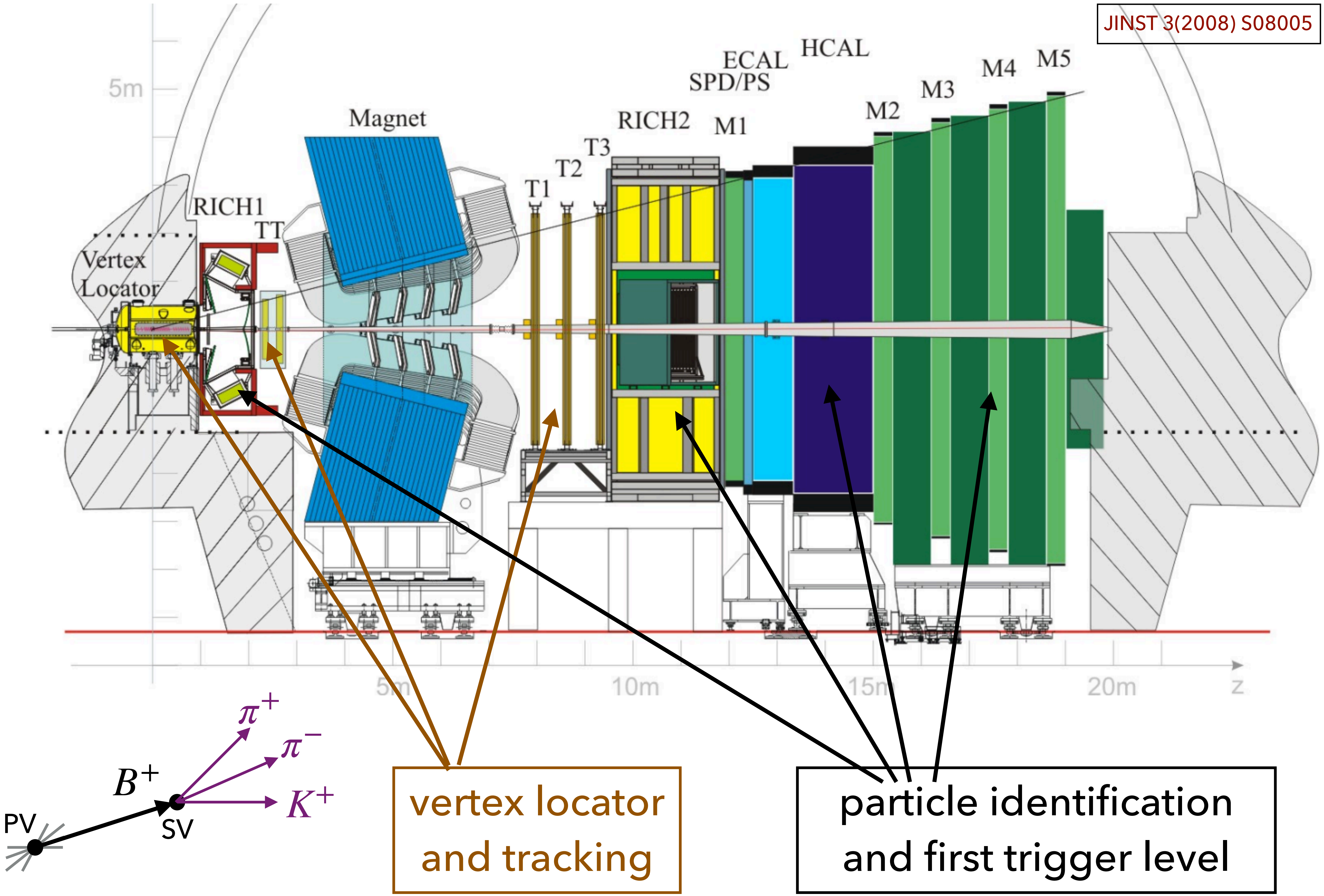
CERN seminar

The LHCb detector



Generalities on *CP* violation

- 1973: *CP* violation can not be explained in a four-quark model

  → Introduction of the Cabibbo-Kobayashi-Maskawa matrix

  → It describes the probability of flavour transition

Wolfenstein parametrisation

Phys. Rev. Lett. 51 (1983) 1945

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ \lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \qquad \lambda \approx 0.23$$

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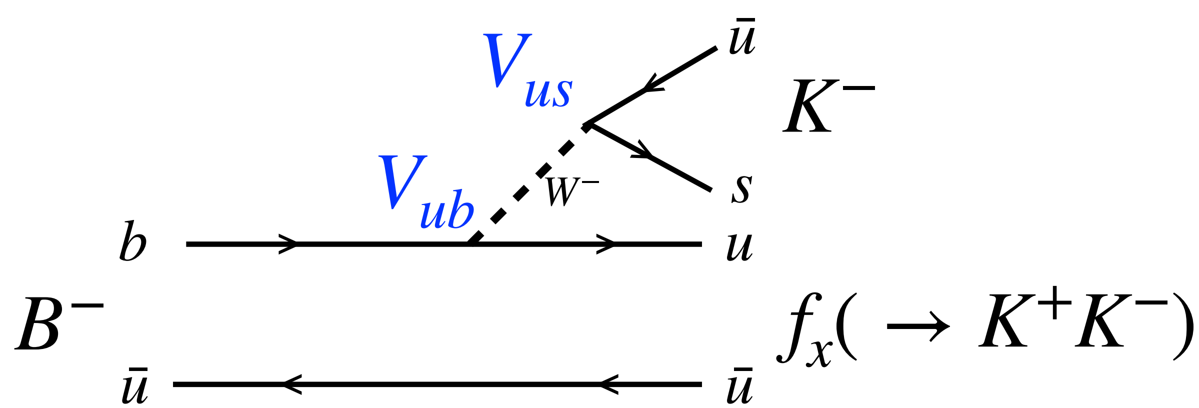
Example: $B^- \to K^- K^+ K^-$



$\propto \lambda^4$

- → complex phase in V_{CKM} are necessary to observe *CP* violation
- → Deviations from SM predictions probe new interactions

Generalities on *CP* violation

To observe *CP* violation: at least 2 interfering amplitudes must contribute to the same final state with different weak and strong phases

$$A_{CP} = \frac{|A(B \to f)|^2 - |A(\bar{B} \to \bar{f})|^2}{|A(B \to f)|^2 + |A(\bar{B} \to \bar{f})|^2} = \frac{2|A_2/A_1|\sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)}{1 + |A_2/A_1|^2 + |A_2/A_1|\cos(\delta_1 - \delta_2)\cos(\phi_1 - \phi_2)}$$

- The size of the *CP* asymmetry depends also on the relative magnitude of the amplitudes
- Weak phases: CKM matrix elements
- Strong phases:

(i) Short distance penguin contributions at quark level

(ii) Final-state interactions (example: hadronic rescattering $\pi\pi \leftrightarrow KK$, 1-1.5 GeV)

Prog. Part. Nucl. Phys. 114 (2020) 103808

CPT contraints on *CP* violation

- *CP* violation: $\Gamma(P \to f) - \Gamma(\bar{P} \to \bar{f}) \neq 0$
- CPT symmetry: total decay widths of P and $\bar{P}$ are the same

$$\Gamma(P \to f_1) + \ldots + \Gamma(P \to f_n) = \Gamma(\bar{P} \to \bar{f}_1) + \ldots + \Gamma(\bar{P} \to \bar{f}_n)$$

→ requires communication between the different decay modes having the same quantum numbers

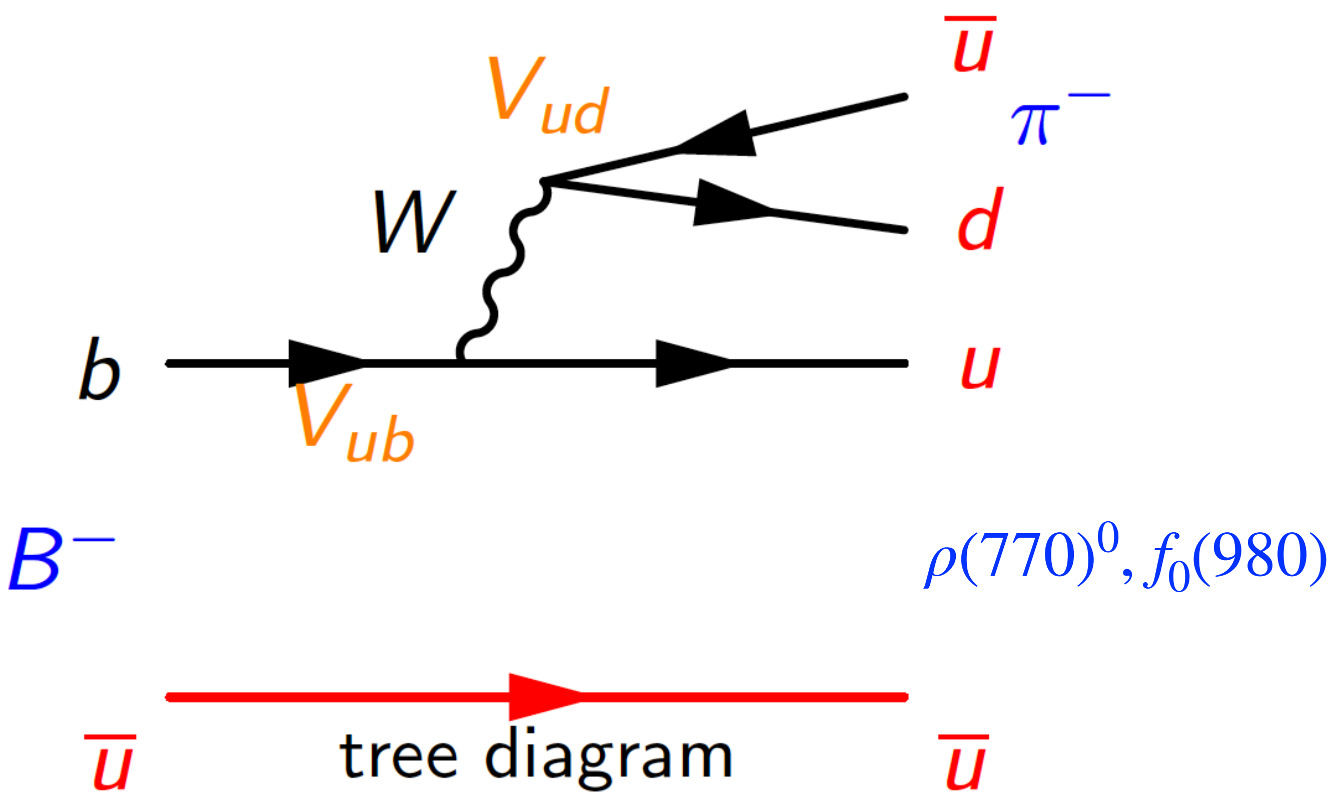
- Final-state hadronic interactions:

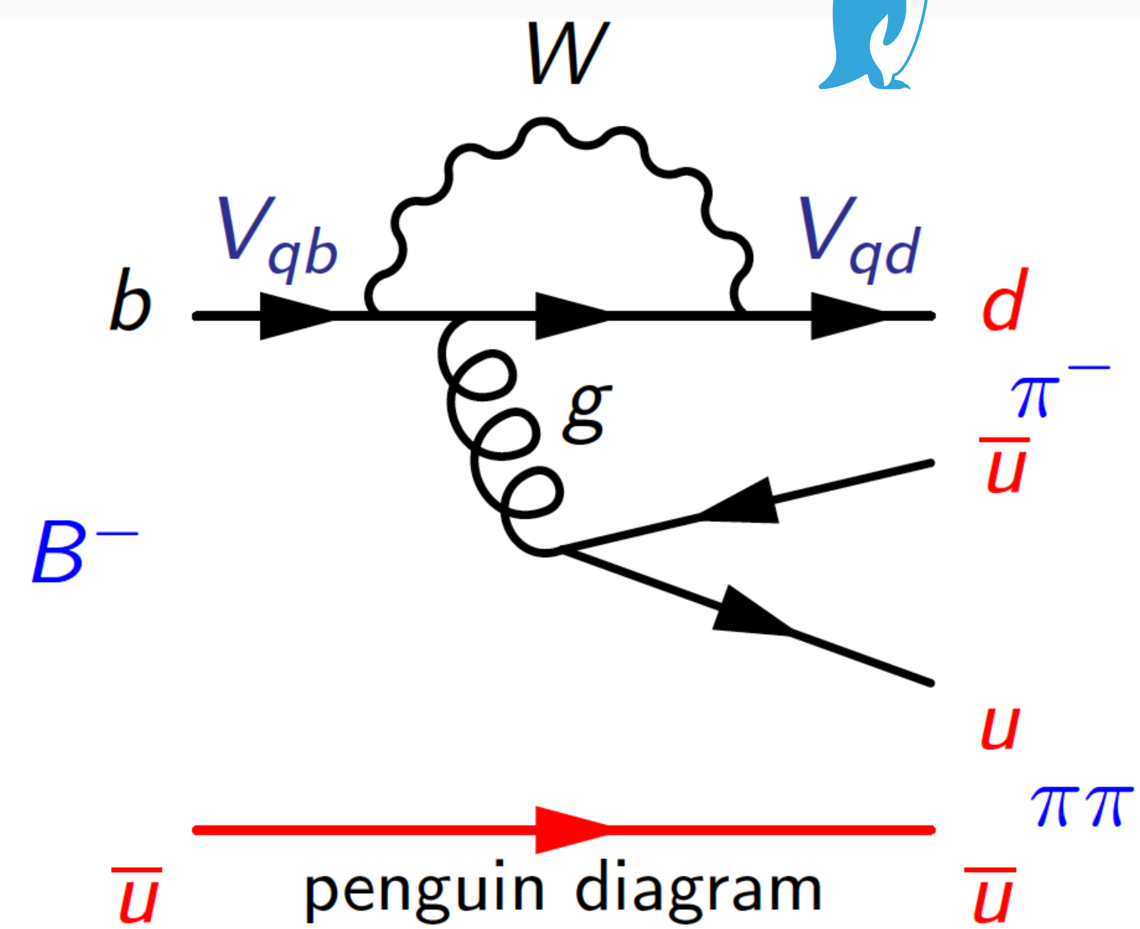
→ provide the strong phases for *CP* violation to be observed

→ is a key ingredient to preserve CPT symmetry

Prog. Part. Nucl. Phys. 114 (2020) 103808

$$B^- \to \pi^-\pi^+\pi^-$$





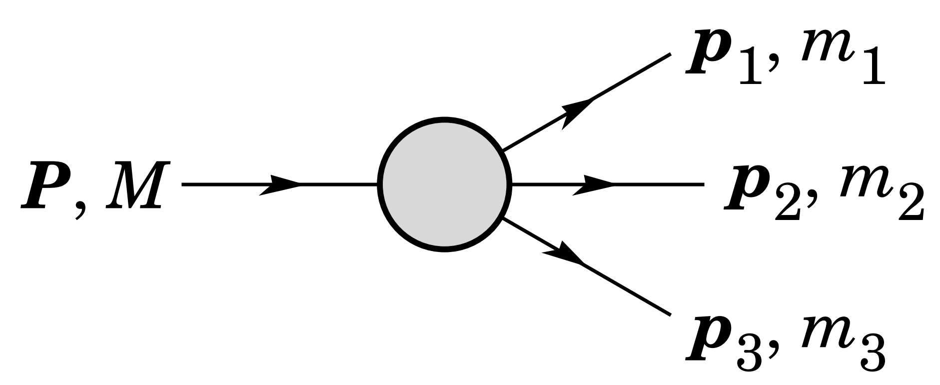
source: Juan Otalora

CP violation from interferences between:

- Tree penguin diagrams
- Resonances in the phase space

Three-body decays in the phase space

- Multi-body decays proceed through several intermediate states which interfere
- Density distribution in a 3-body decay



$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\,|\,\mathscr{M}\,|^2\,\mathrm{d}m_{12}^2\,\mathrm{d}m_{23}^2$$

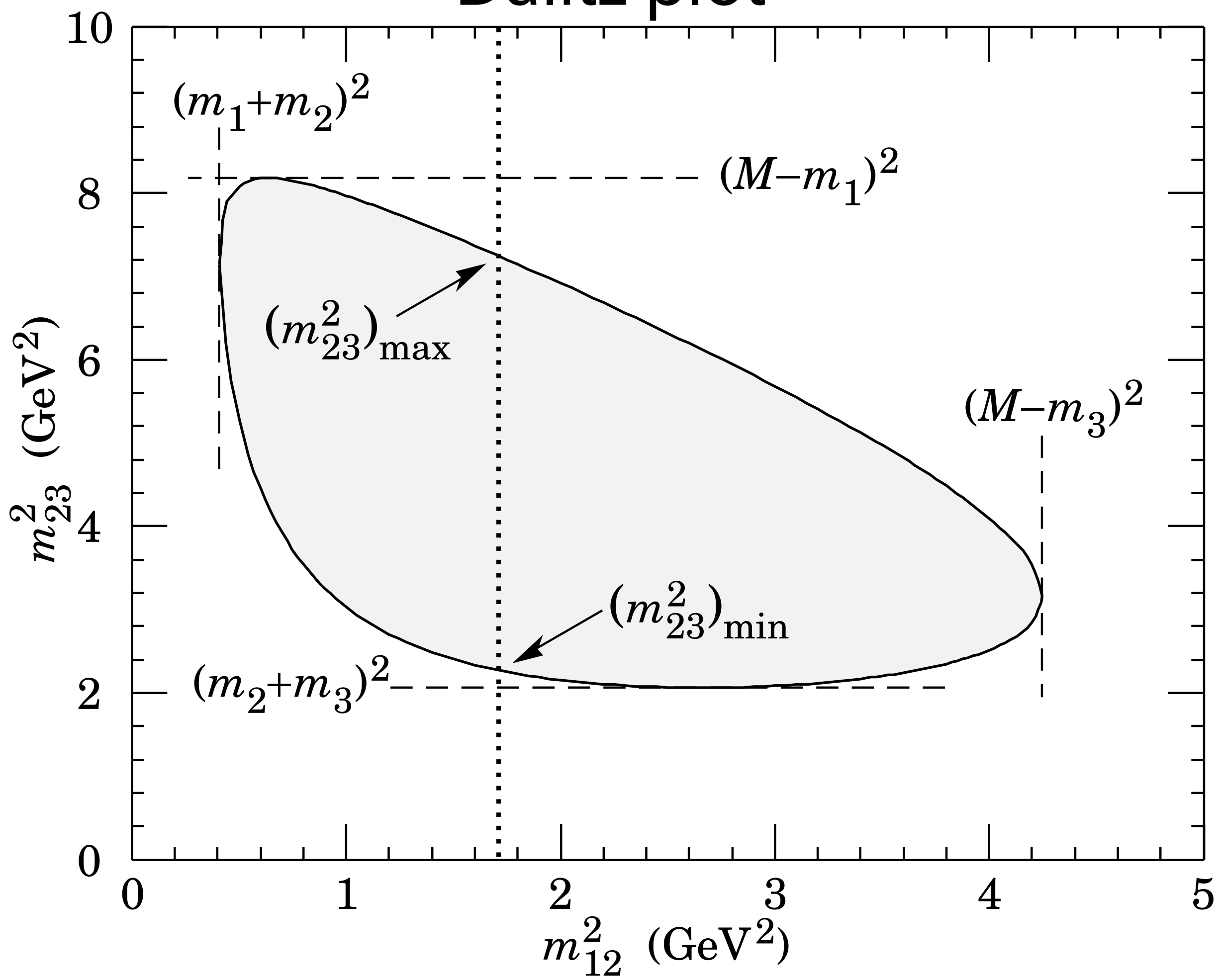
$$m_{ij}^2 = (E_i + E_j)^2 - (p_i + p_j)^2$$

→ m_{12}^2 and m_{23}^2 enough to describe the system

→ Dynamic is contained in the matrix $\mathscr{M}$

→ Information about resonant structure

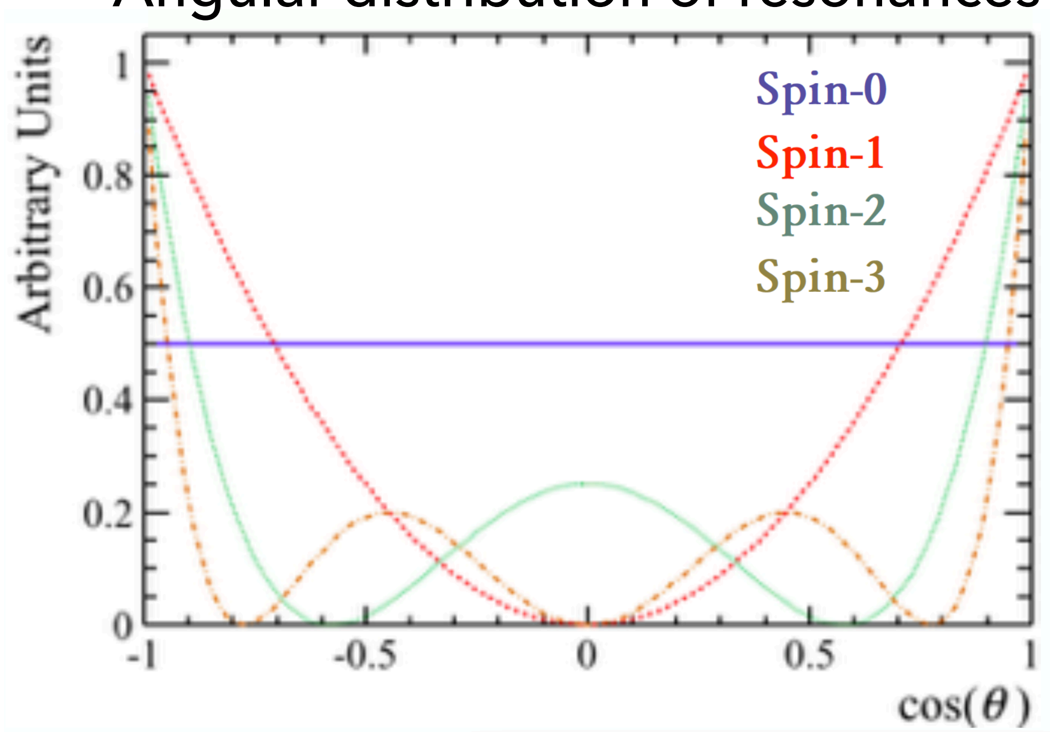
Dalitz plot

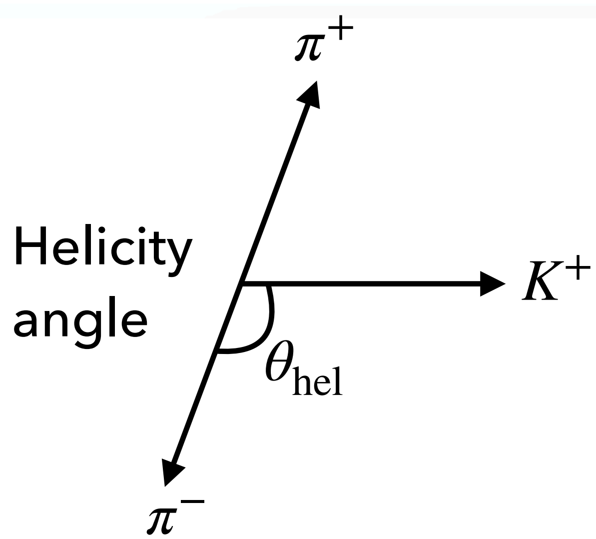


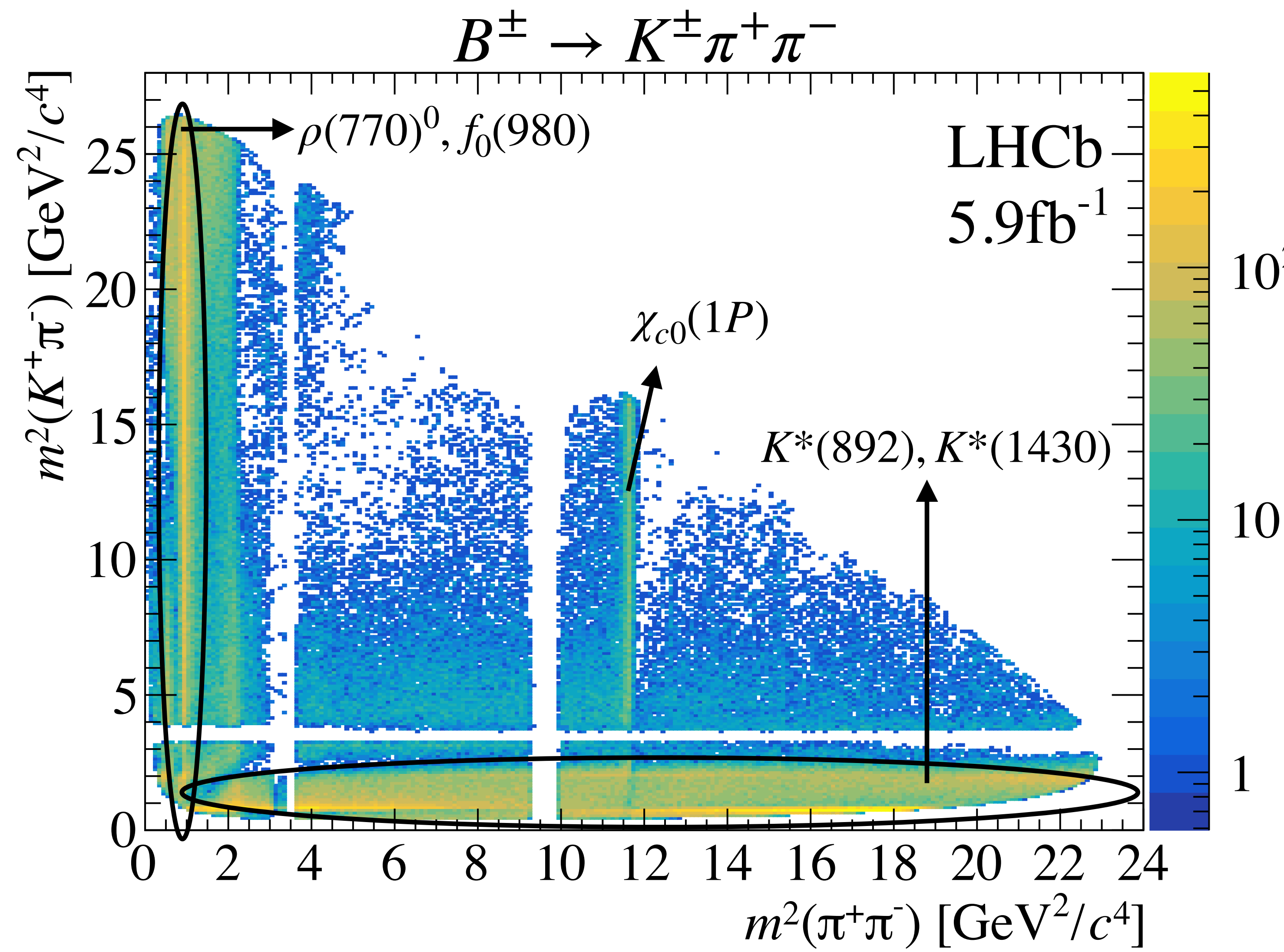
Prog. Theor. Exp. Phys. 2020 (2020) 083C01

- Resonant process: horizontal, vertical, diagonal bands
- Spins: density distribution along bands
- Non-resonant process

Angular distribution of resonances



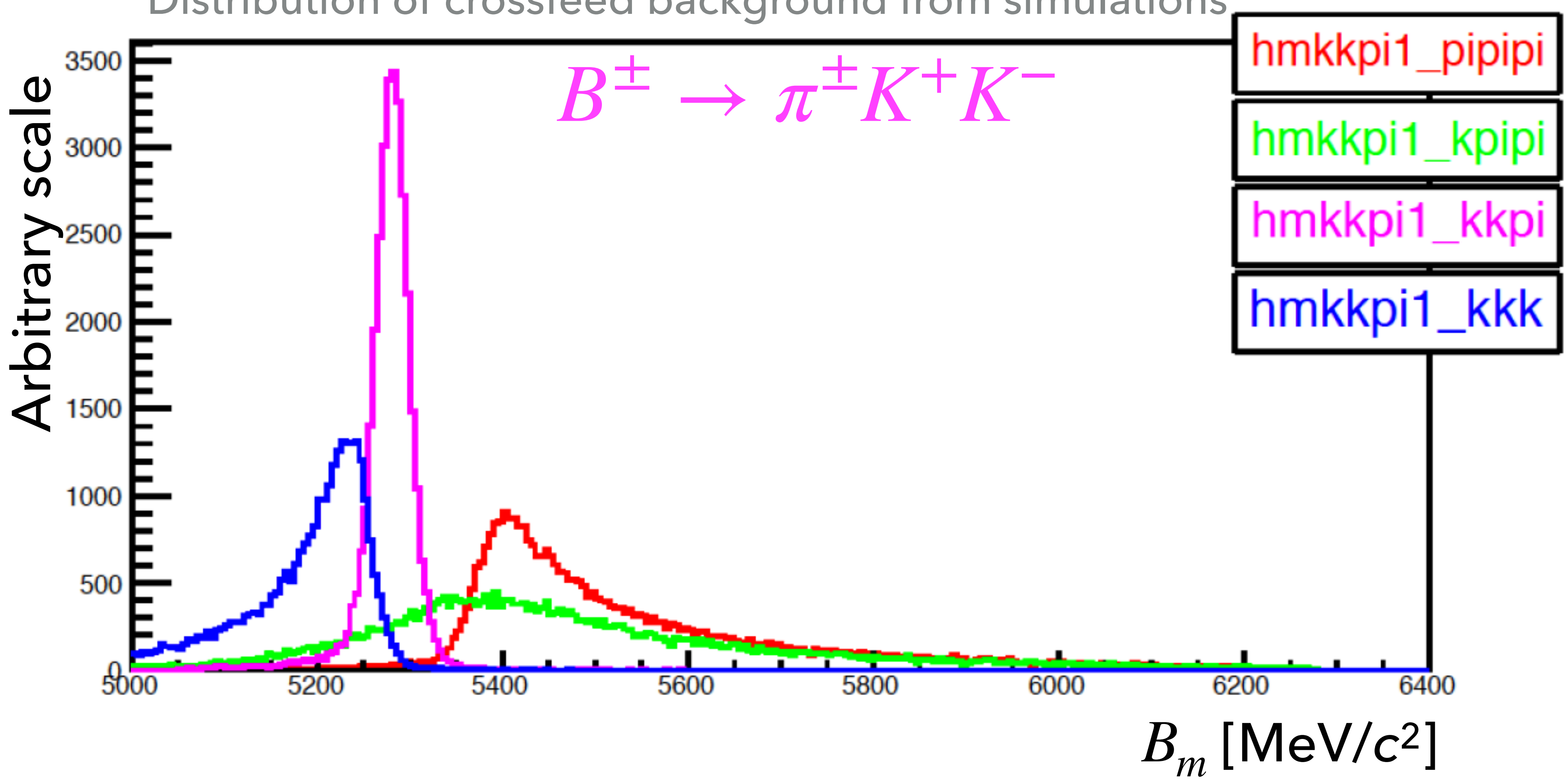




Event selection strategy

- Multivariate analysis selection
  - → Training performed specific for each decay channel
- Final PID selection (crossfeed only)
  - → $B^+ \to \bar{D}^0 K^+(\pi^+)$ to define the cut values
- Charm veto (D^0, J/ψ)

Distribution of crossfeed background from simulations



Fit model

Simultaneous mass fit of B^+ and B^- for each channel

Fit observables

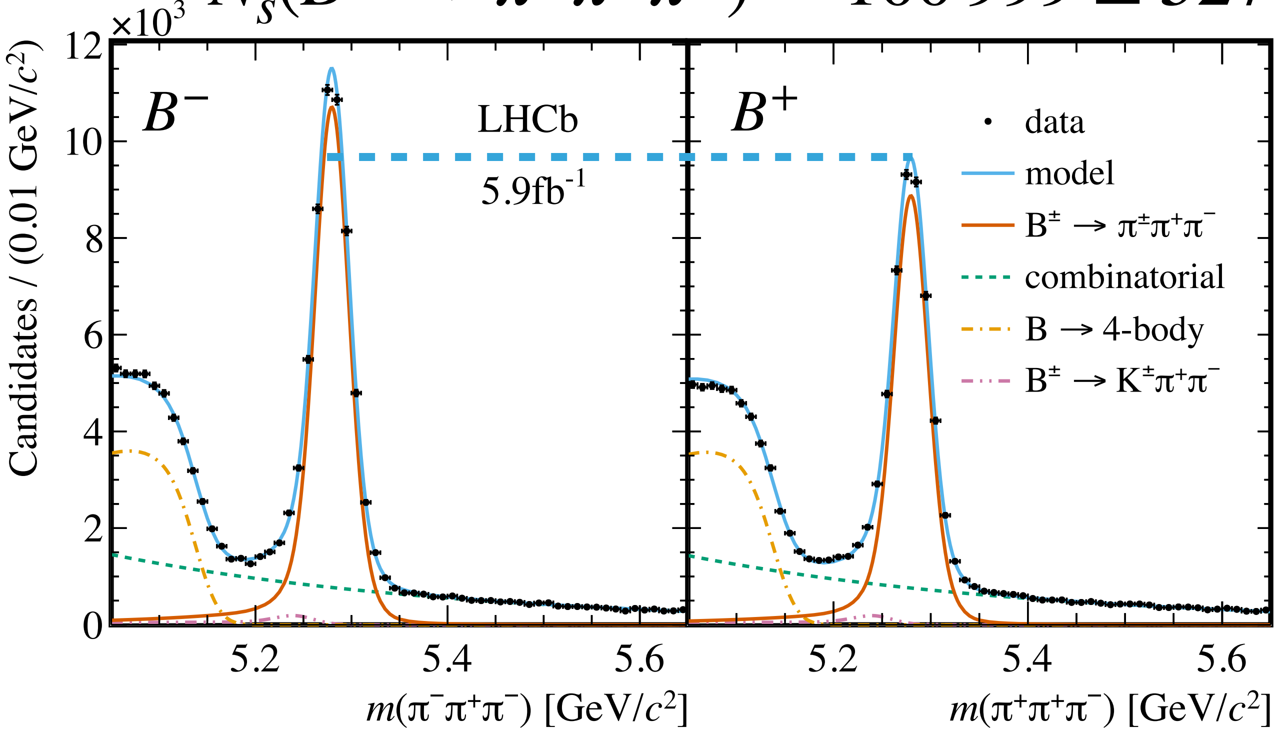
- Signal yield
- Raw asymmetry

$$A_{RAW} = \frac{N^- - N^+}{N^- + N^+}$$

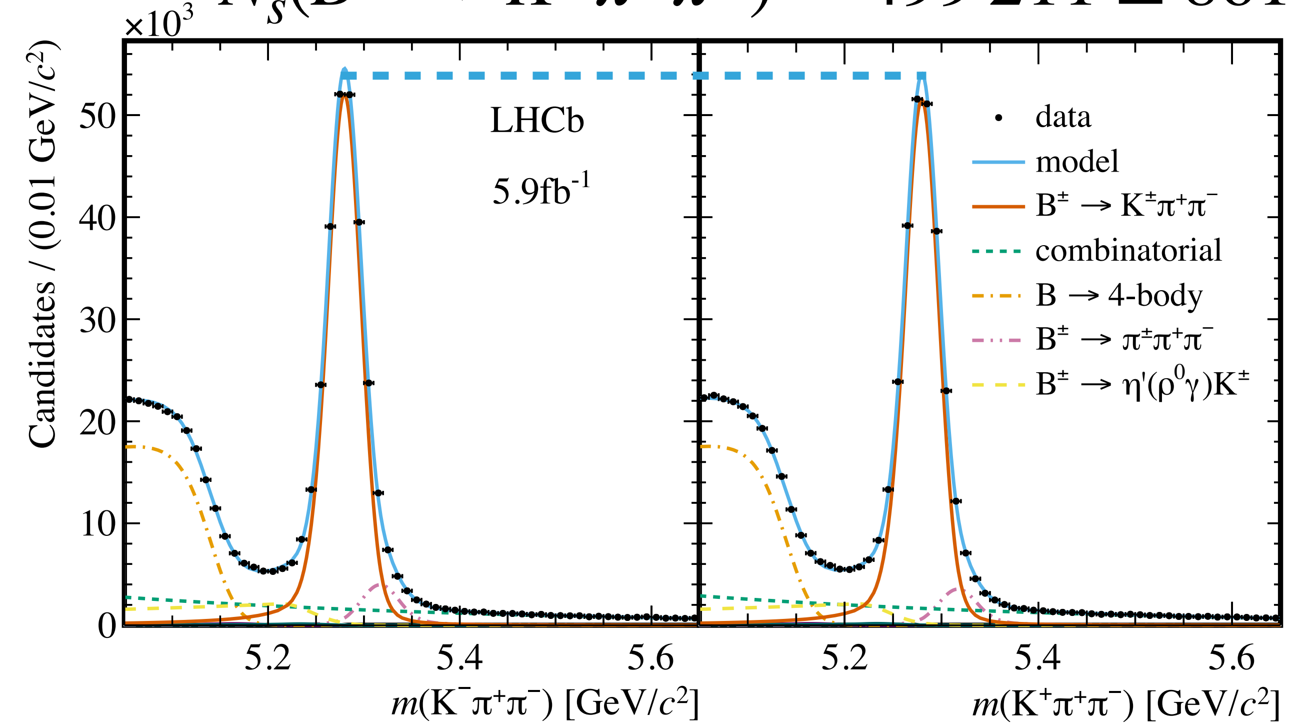
- Signal
  → Two Crystal-Ball + Gaussian. Shape determined by MC
- Combinatorial background
  → Exponential function
- Partially reconstructed background
  → Argus function convolved with a Gaussian
- Crossfeed from other $B^\pm \to h^\pm h^+ h^-$ decays
  → Two Crystal-Ball functions. Shape and fractions determined by MC and fixed in the fit.
  → MC samples with selection cuts and PIDCalib efficiency.

Fit results

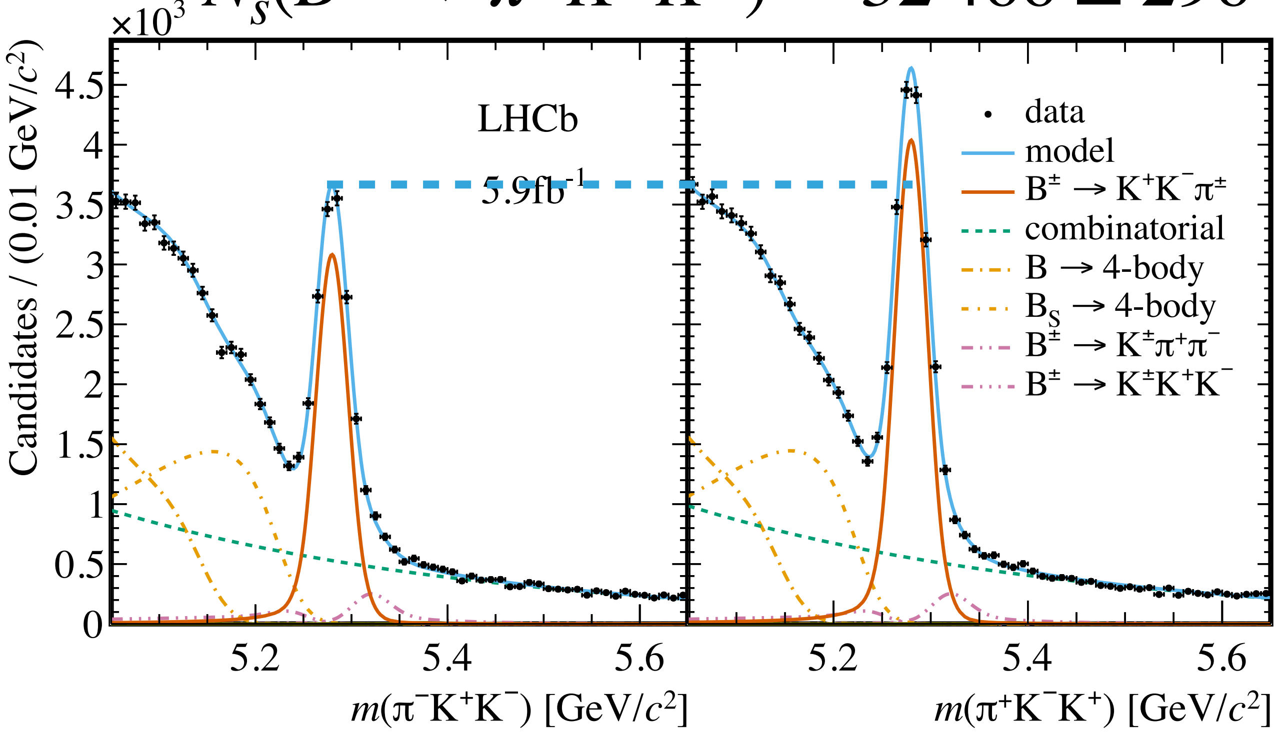
$N_s(B^\pm \to \pi^\pm\pi^+\pi^-) = 100\,999 \pm 527$



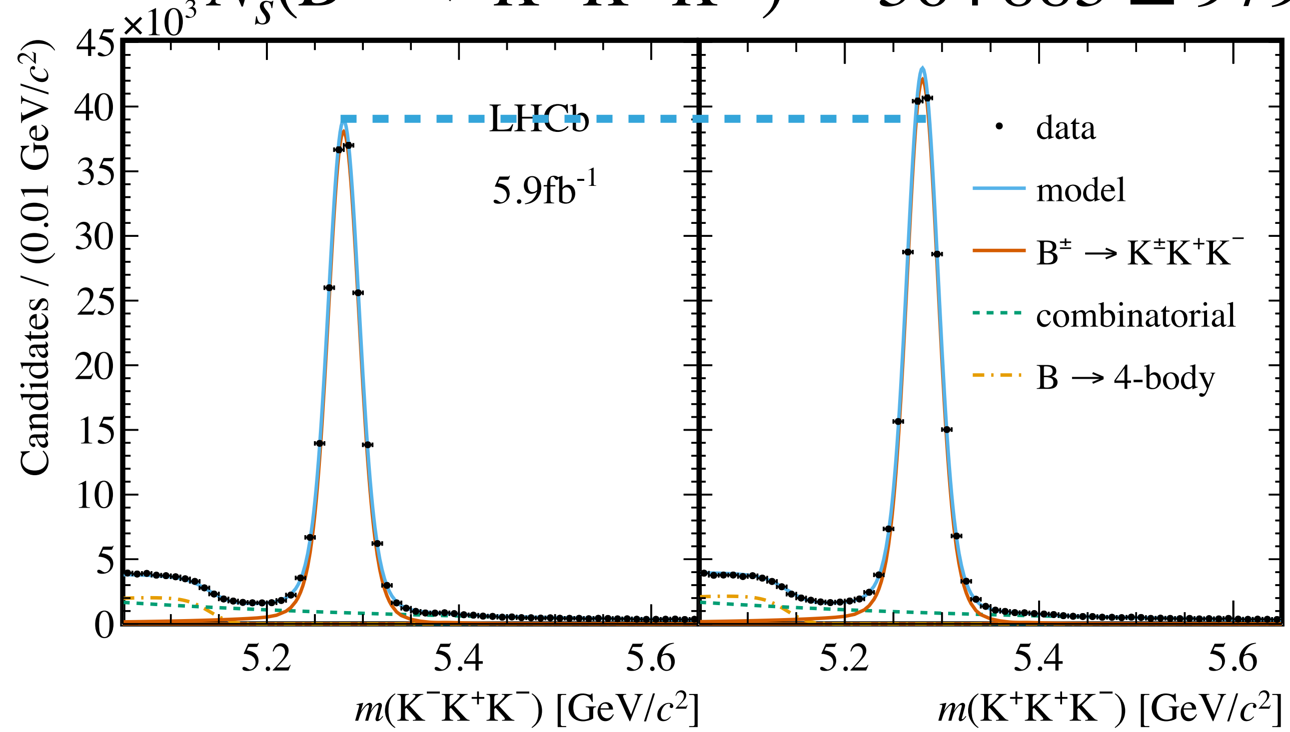
$N_s(B^\pm \to K^\pm\pi^+\pi^-) = 499\,211 \pm 861$



$N_s(B^\pm \to \pi^\pm K^+K^-) = 32\,466 \pm 296$



$N_s(B^\pm \to K^\pm K^+K^-) = 364\,883 \pm 979$



Phase-space integrated asymmetries

$$A_{CP} = \frac{A_{RAW}^{ACC} - A_P}{1 - A_{RAW}^{ACC} A_P}$$

$$A_P = A_{CP}(B^\pm \to J/\psi K^\pm)_{\text{data}} - A_{CP}(B^\pm \to J/\psi K^\pm)_{\text{PDG}}$$
$$= -\,0.0070 \pm 0.0008^{+0.0007}_{-0.0008} \pm 0.0030$$

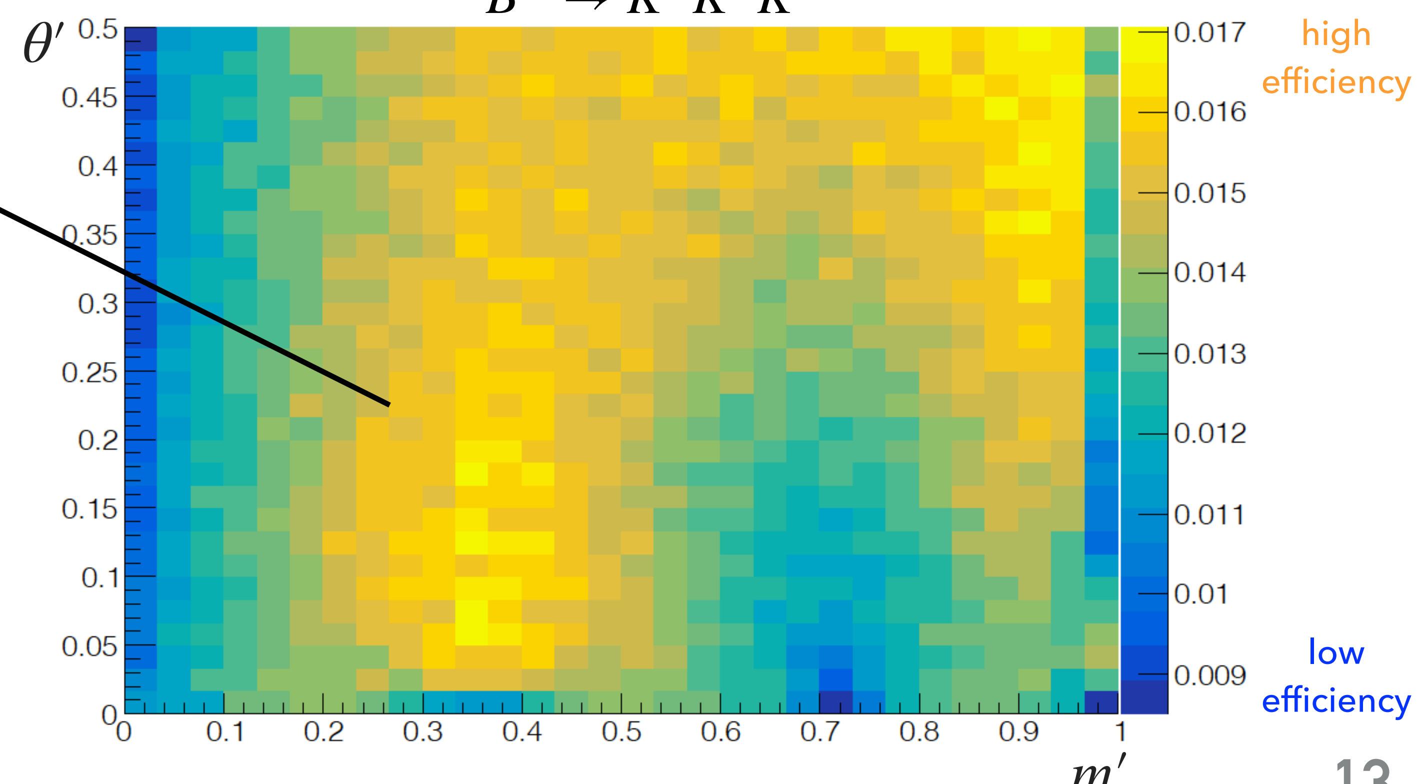
$$< \varepsilon^\pm > = \frac{\sum_{i'=1}^{events'} 1}{\sum_{i'=1}^{events'} \frac{1}{acc'_i}}$$

$$R = \frac{< \varepsilon^- >}{< \varepsilon^+ >}$$

$$A_{RAW}^{ACC} = \frac{1 + A_{RAW} - R + A_{RAW} . R}{1 + A_{RAW} + R - A_{RAW} . R}$$

Square Dalitz plot

$B^\pm \to K^\pm K^+ K^-$



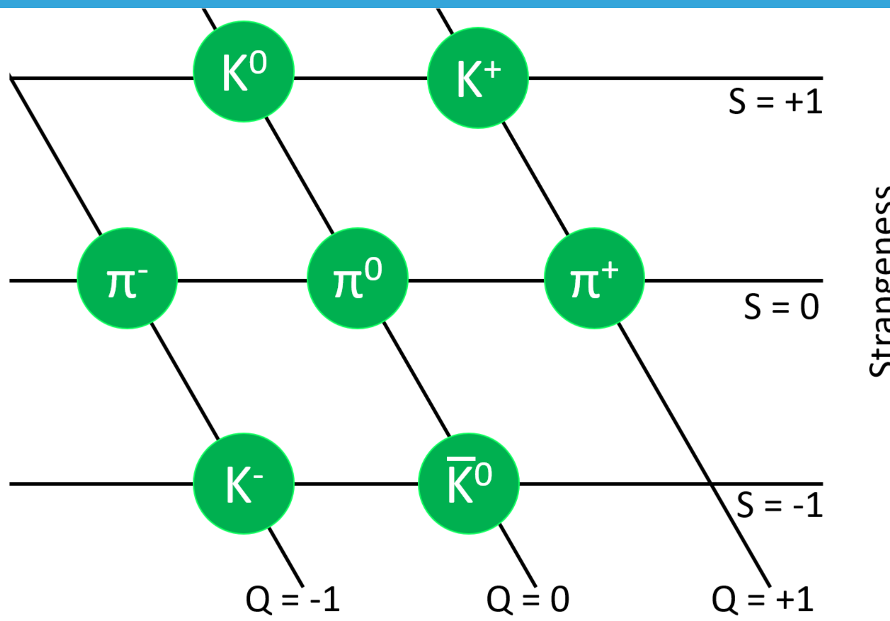
U-spin symmetry

- *CP* asymmetries of partial decay widths in $B^\pm \to h^\pm h^+ h^-$ decays related to U-spin symmetry

Phys. Lett. B824 (2022) 136824

Phys. Lett. B726 (2013) 337

Phys. Lett. B564 (2003) 90



- Theoretical prediction:

$$\frac{\Delta\Gamma(B^\pm \to \pi^\pm K^+ K^-)}{\Delta\Gamma(B^\pm \to K^\pm \pi^+ \pi^-)} = \frac{\Delta\Gamma(B^\pm \to \pi^\pm \pi^+ \pi^-)}{\Delta\Gamma(B^\pm \to K^\pm K^+ K^-)} = -1$$

Phys. Rev. D102 (2020) 112010

$$\Delta\Gamma_{CP}(h_1^\pm h_2^+ h_3^-) = \Gamma(h_1^- h_2^+ h_3^-) - \Gamma(h_1^+ h_2^- h_3^+) = \frac{A_{CP}(B^\pm \to h_1^\pm h_2^+ h_3^-)\mathscr{B}(B^+ \to h_1^+ h_2^+ h_3^-)}{\tau(B^+)}$$

Results:

$$\frac{\Delta\Gamma(B^\pm \to \pi^\pm K^+ K^-)}{\Delta\Gamma(B^\pm \to K^\pm \pi^+ \pi^-)} = \frac{A_{CP}(B^\pm \to \pi^\pm K^+ K^-)\mathscr{B}(B^+ \to \pi^+ K^+ K^-)}{A_{CP}(B^\pm \to K^\pm \pi^+ \pi^-)\mathscr{B}(B^+ \to K^+ \pi^+ \pi^-)} = -0.92 \pm 0.18$$

$$\frac{\Delta\Gamma(B^\pm \to \pi^\pm \pi^+ \pi^-)}{\Delta\Gamma(B^\pm \to K^\pm K^+ K^-)} = \frac{A_{CP}(B^\pm \to \pi^\pm \pi^+ \pi^-)\mathscr{B}(B^+ \to \pi^\pm \pi^+ \pi^-)}{A_{CP}(B^\pm \to K^\pm K^+ K^-)\mathscr{B}(B^+ \to K^+ K^+ K^-)} = -1.06 \pm 0.08$$

In agreement with the predictions

CP asymmetry in the phase space

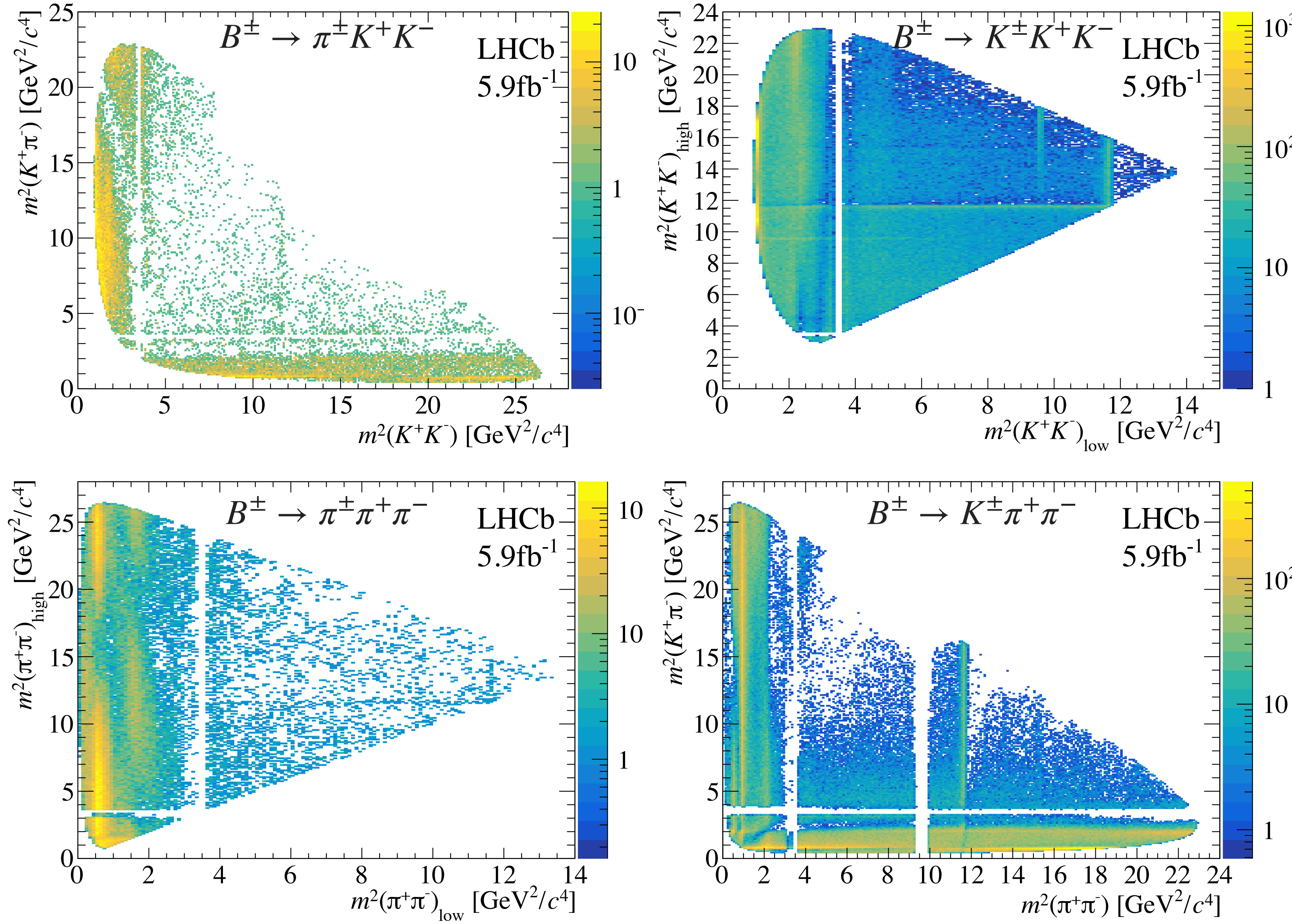
- $B^{\pm} \to h^{\pm}h^{+}h^{-}$ decays: rich environment for the study of CP violation
- Large phase-space available
- Different sources contributing to the asymmetries

→ interferences between tree and penguin diagrams

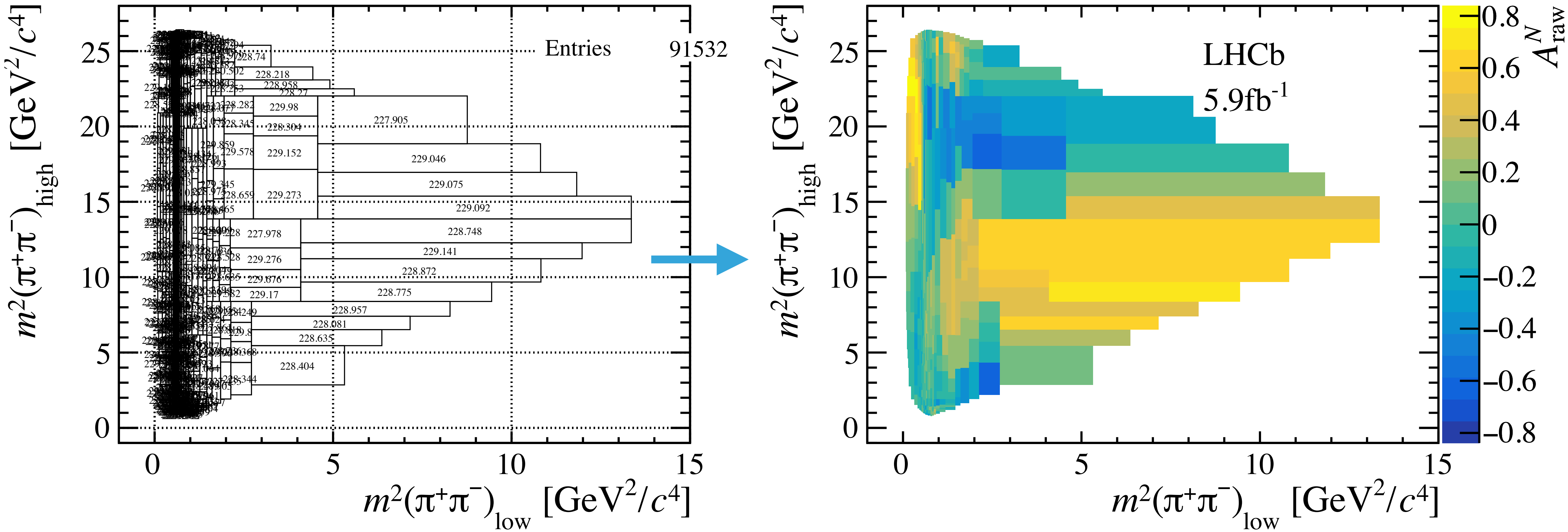
→ interferences involving quasi-two-body resonances

→ hadronic final-state interactions

Distribution of events over the phase space



CP asymmetry in the phase space



$$A_{CP}^{bin} = \frac{N^- - N^+}{N^- + N^+}$$

Phys. Rev. D86 (2012) 036005

- Histogram created by an adaptative binning algorithm
- Each bin contains the same number of events ($N^- + N^+$)
- The vertical color scale tells us the asymmetry value

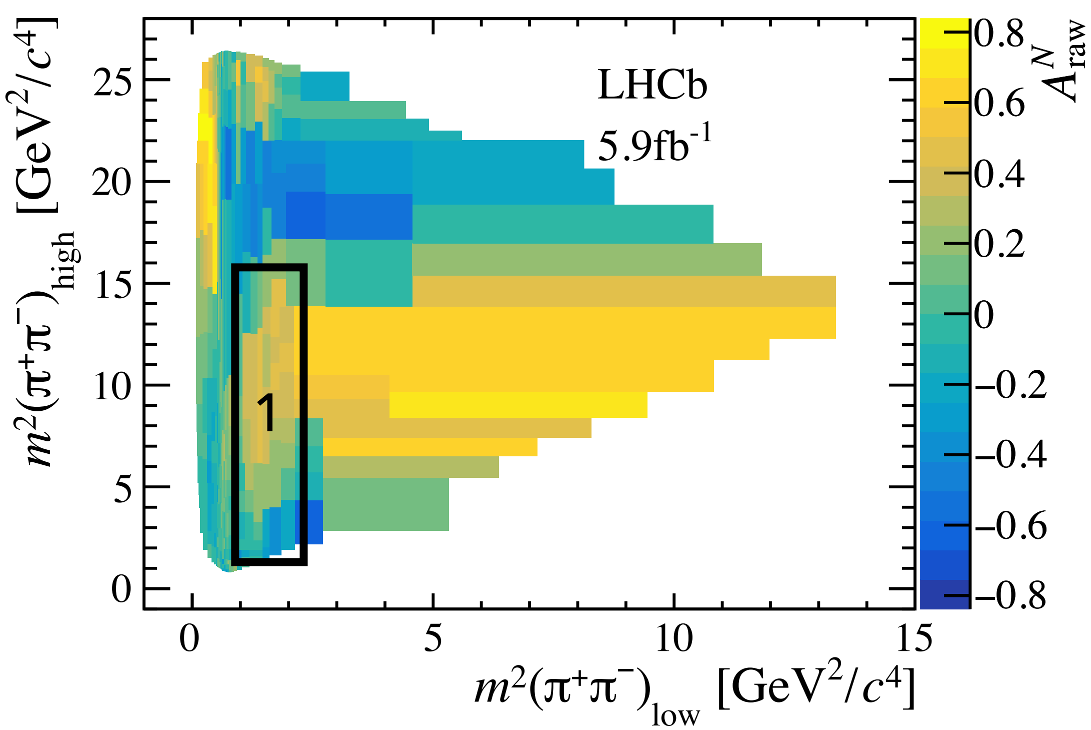
CP asymmetry in the phase space

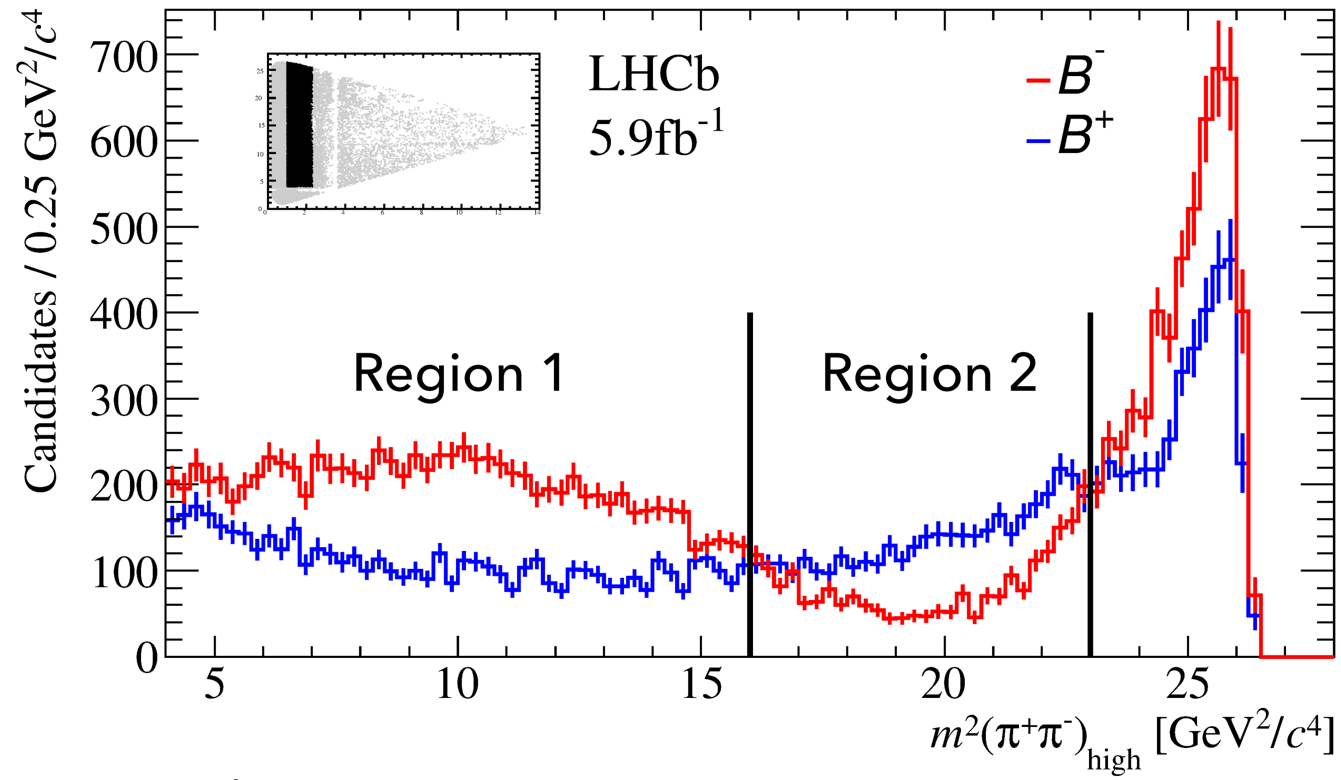
$$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$$

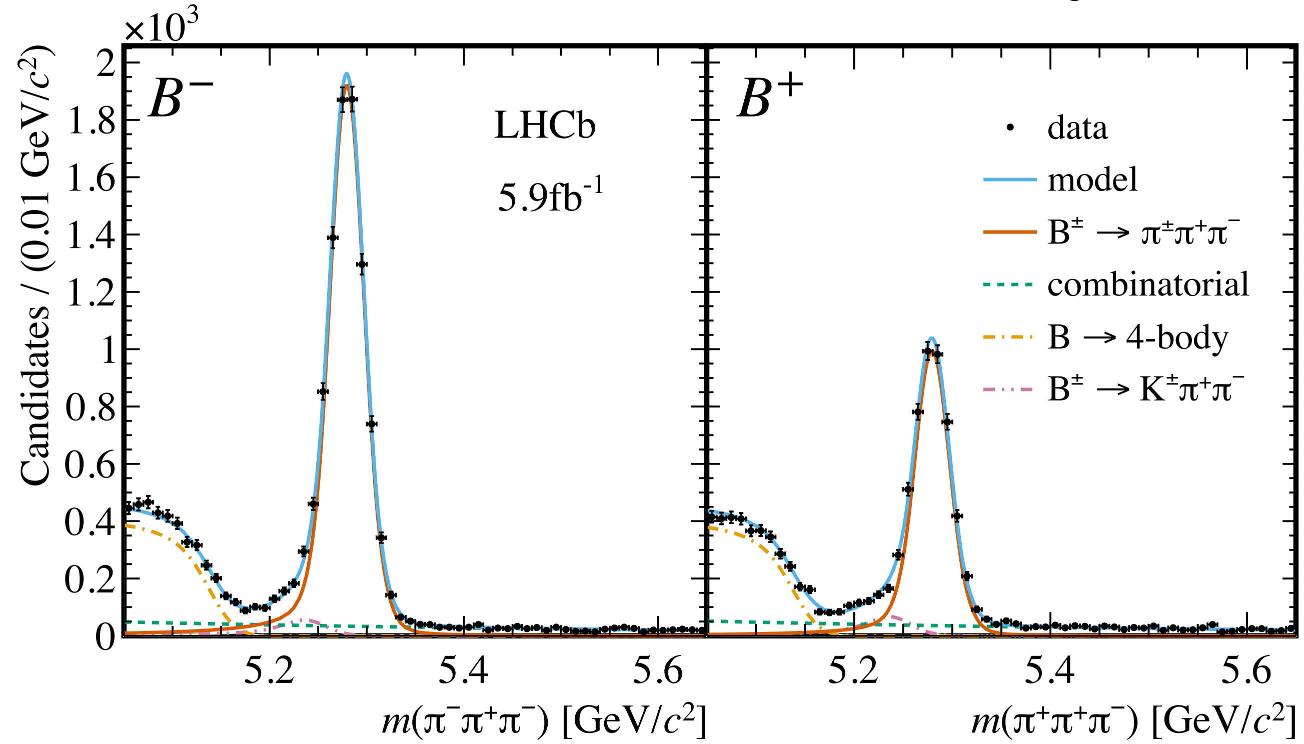
Region 1

$1 < m^2(\pi^+\pi^-)_{\text{low}} < 2.25$

$3.5 < m^2(\pi^+\pi^-)_{\text{high}} < 16$







$$A_{CP} = +0.303 \pm 0.009$$

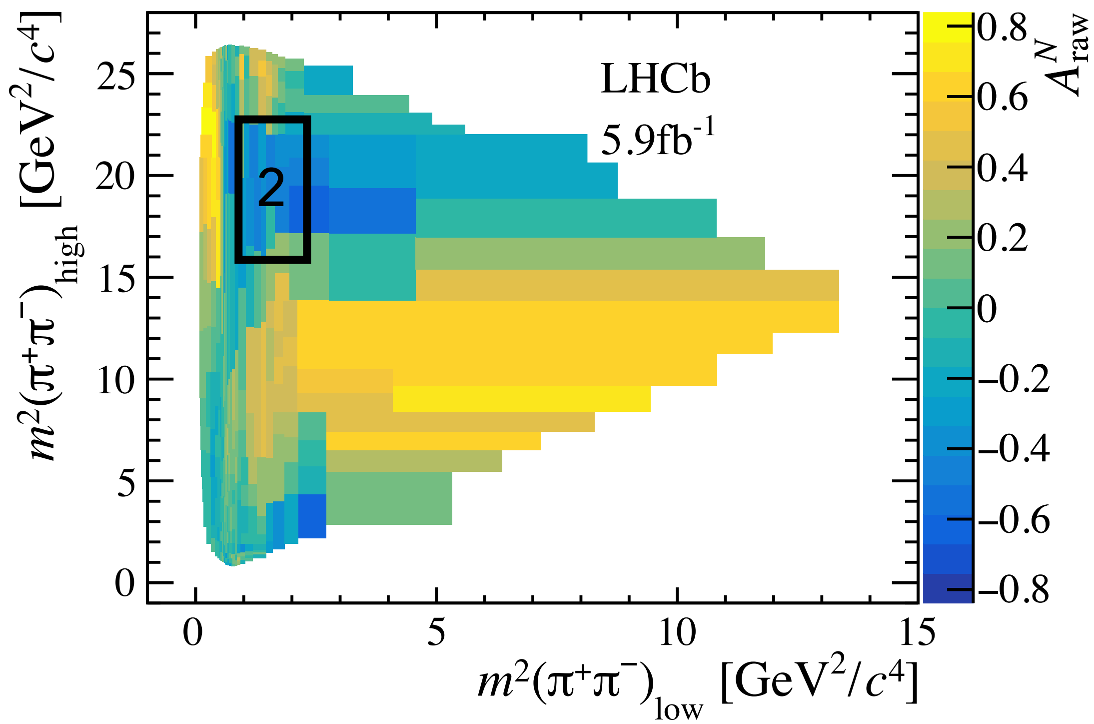
CP asymmetry in the phase space

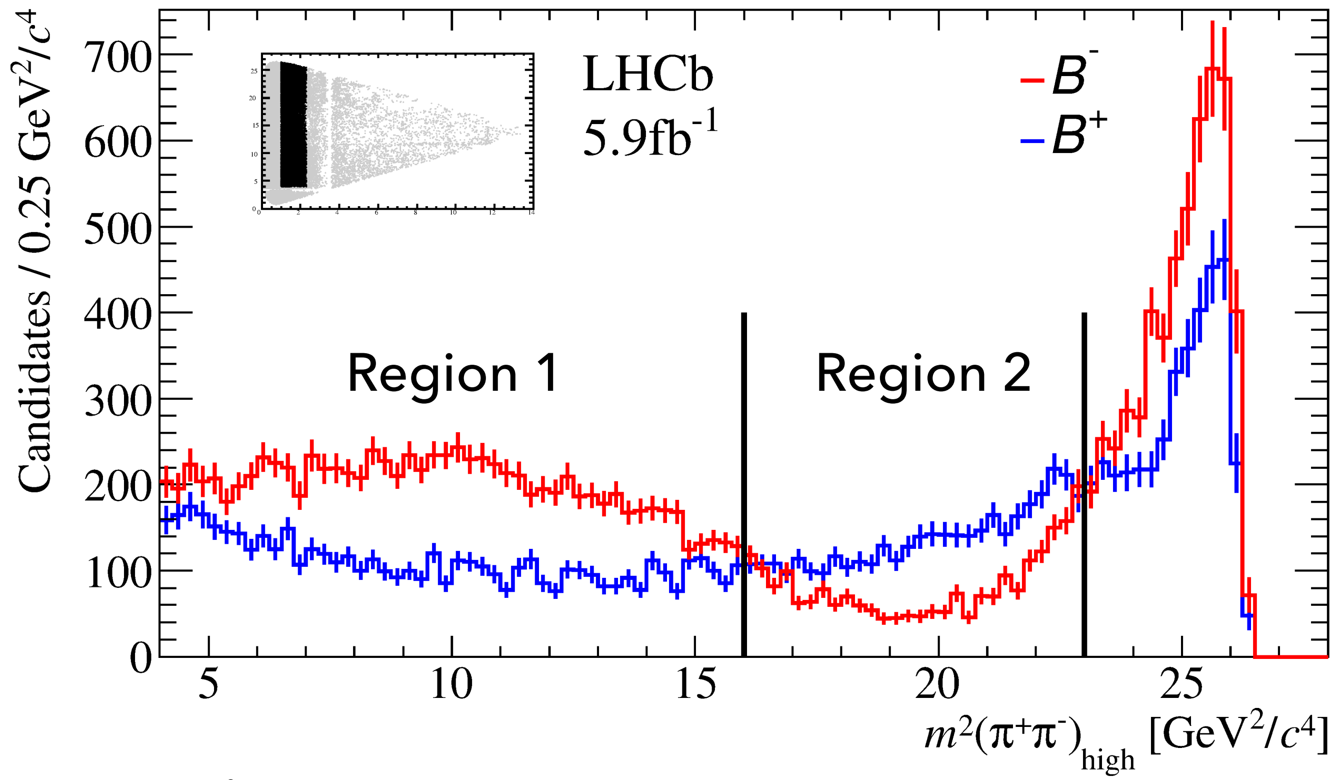
$$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$$

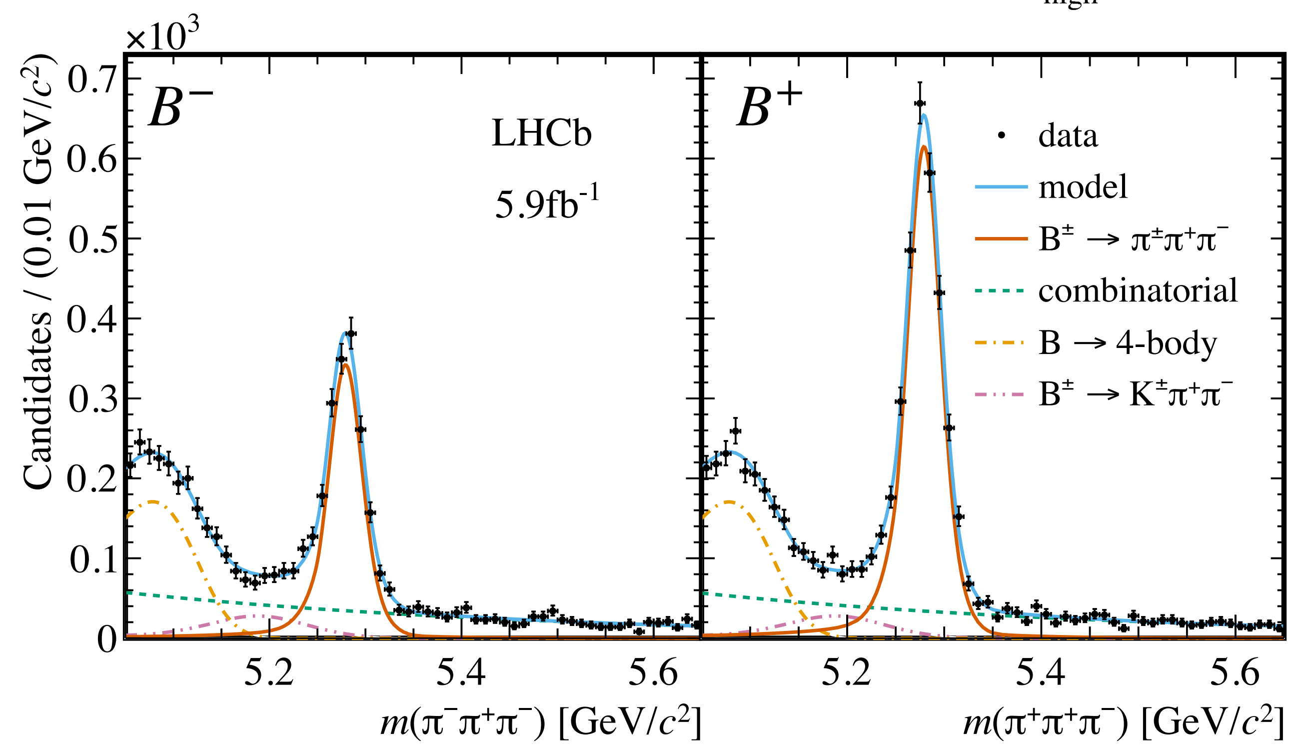
Region 2

$1 < m^2(\pi^+\pi^-)_{\text{low}} < 2.25$

$16 < m^2(\pi^+\pi^-)_{\text{high}} < 23$







$$A_{CP} = -0.284 \pm 0.017$$

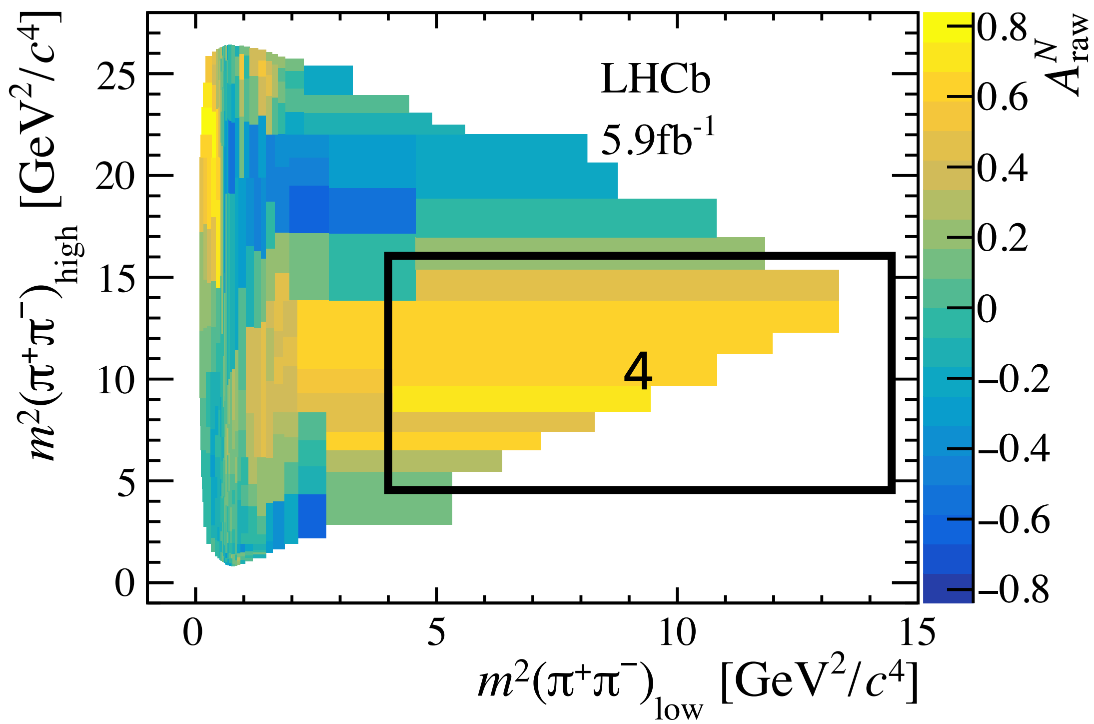
CP asymmetry in the phase space

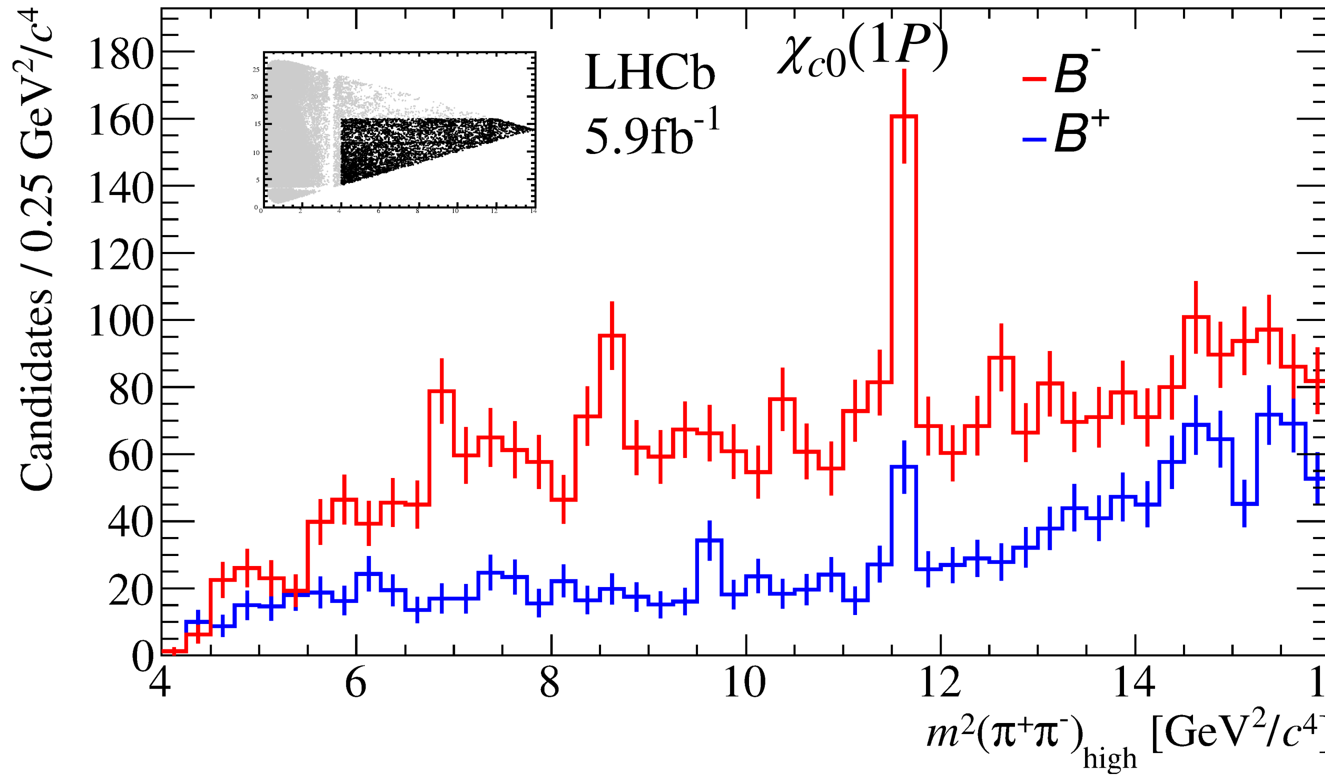
$$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$$

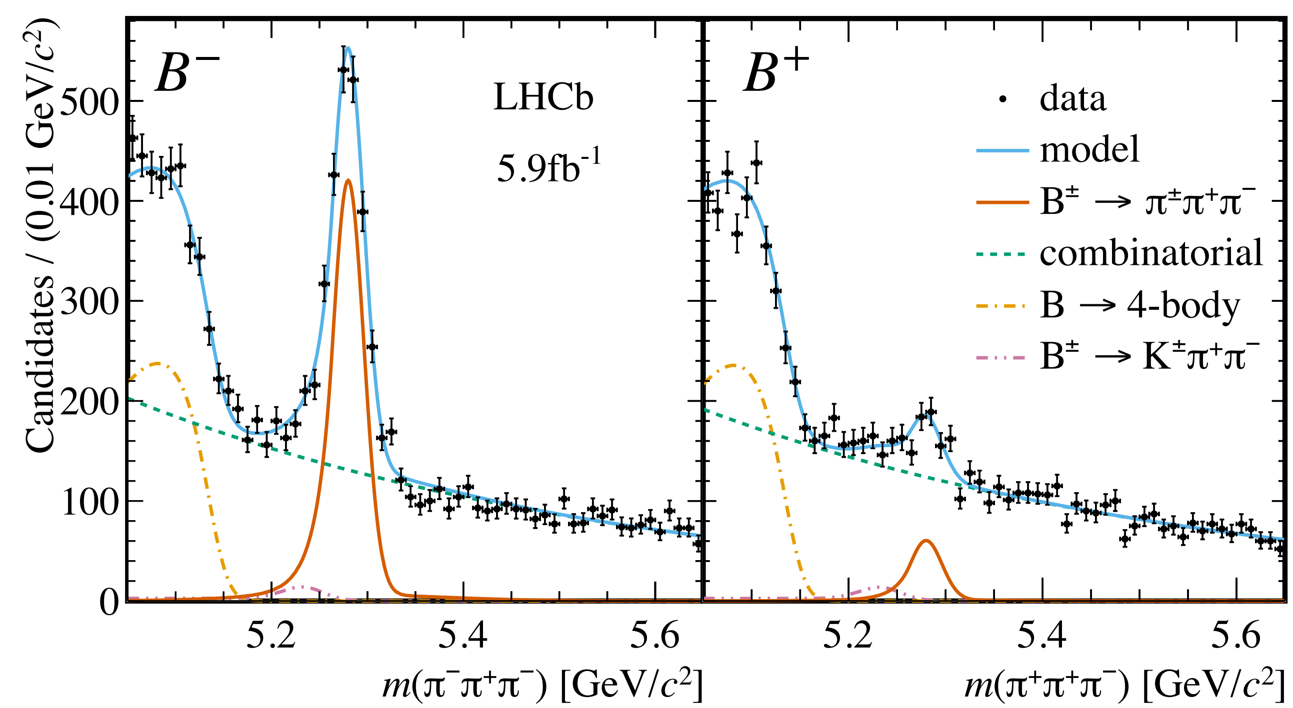
Region 4

$4 < m^2(\pi^+\pi^-)_{\text{low}} < 15$

$4 < m^2(\pi^+\pi^-)_{\text{high}} < 16$







- **No *CPV* expected in $\chi_{c0}(1P)$ in SM**
- *CPV* could arise from interference with a non-resonant decay amplitude

Phys. Rev. Lett. 74 (1995) 4984

$$A_{CP} = +0.745 \pm 0.027$$

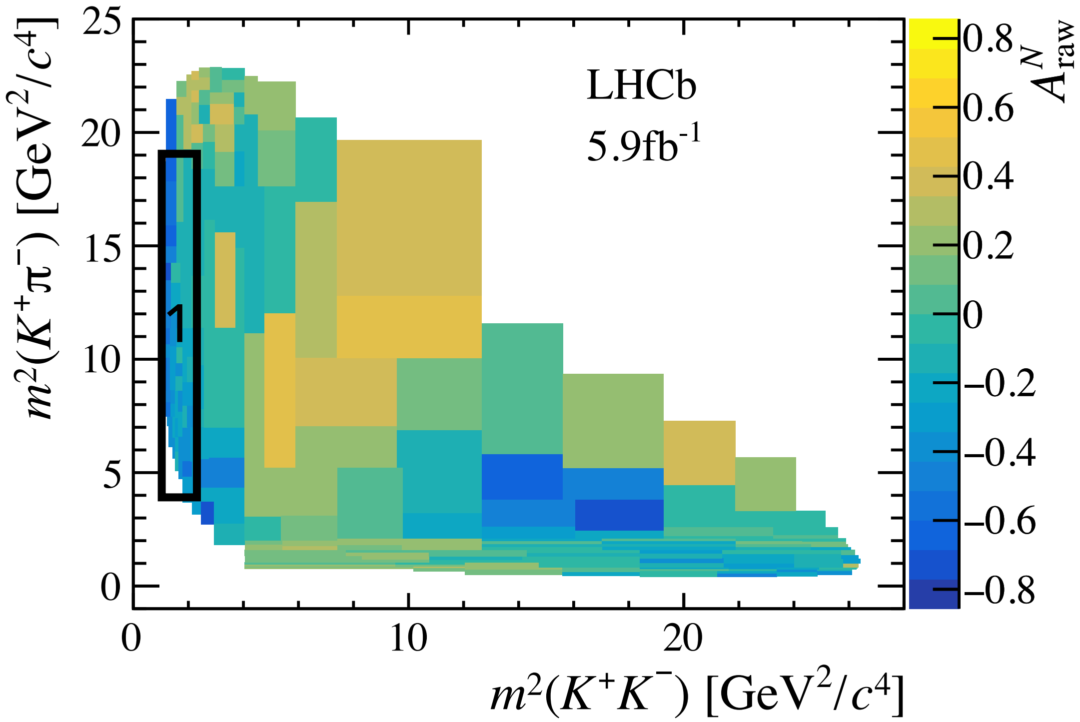
CP asymmetry in the phase space

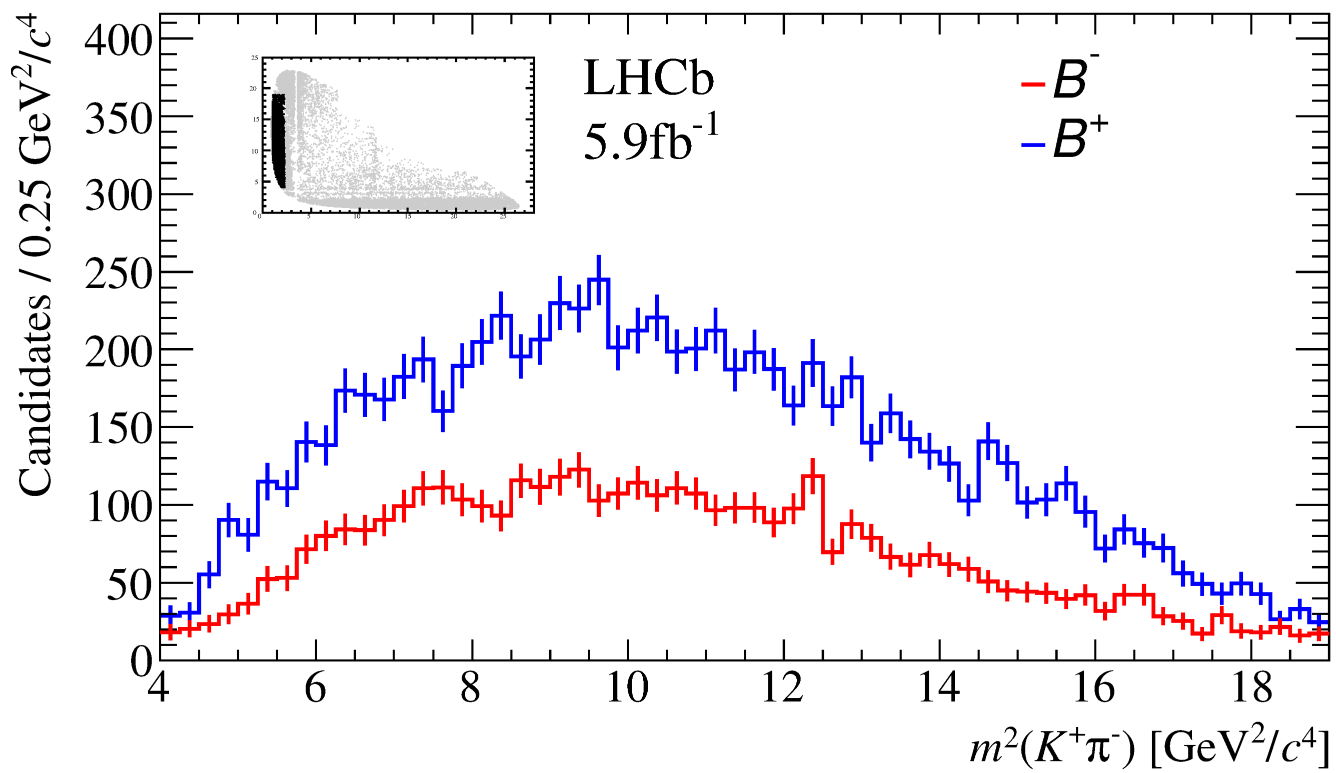
$$B^{\pm} \rightarrow \pi^{\pm} K^{+} K^{-}$$

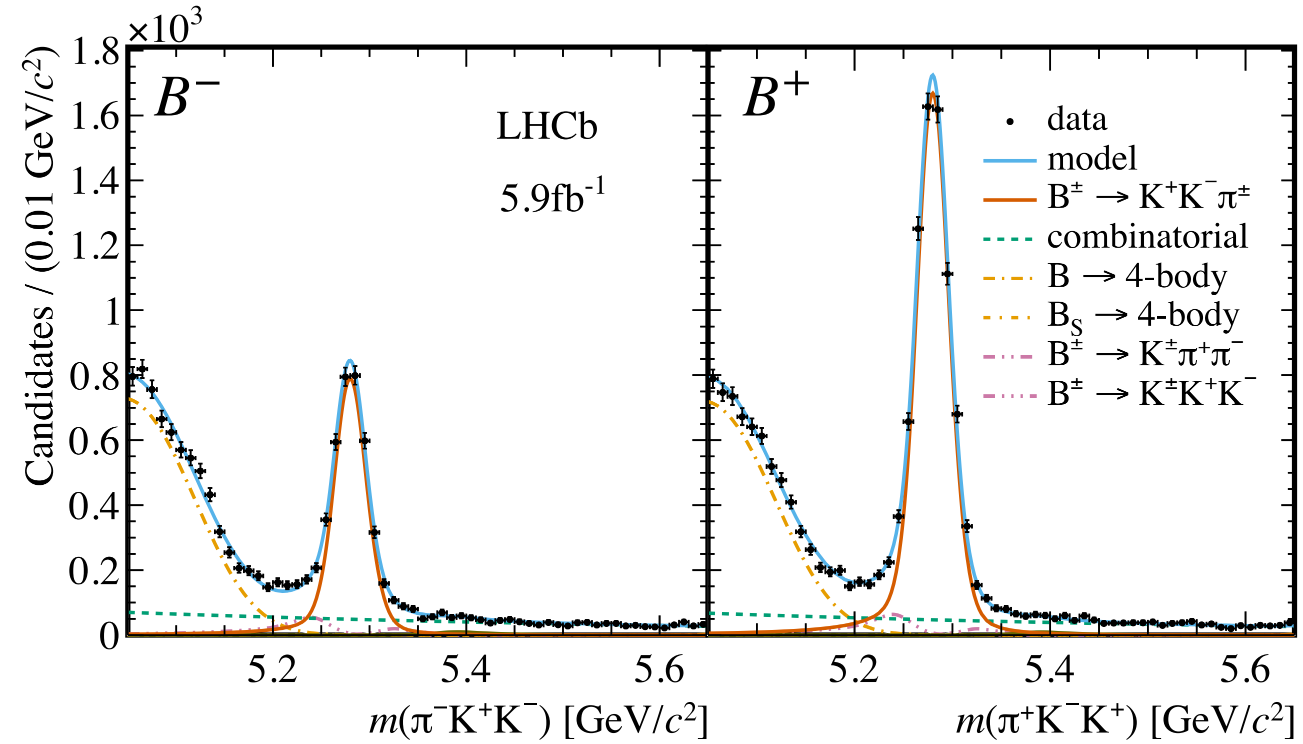
Region 1

$1 < m^2(K^+K^-) < 2.25$

$4 < m^2(K^+\pi^-) < 19$







$B^{\pm} \rightarrow \pi^{\pm} K^{+} K^{-}$ amplitude analysis:

A_{CP}(rescattering) = $(-66.4 \pm 3.8 \pm 1.9)\,\%$

Relative size contribution = $(16.4 \pm 0.8 \pm 1.0)\,\%$

Phys. Rev. Lett. 123 (2019) 231802

$$A_{CP} = -\,0.358 \pm 0.010$$

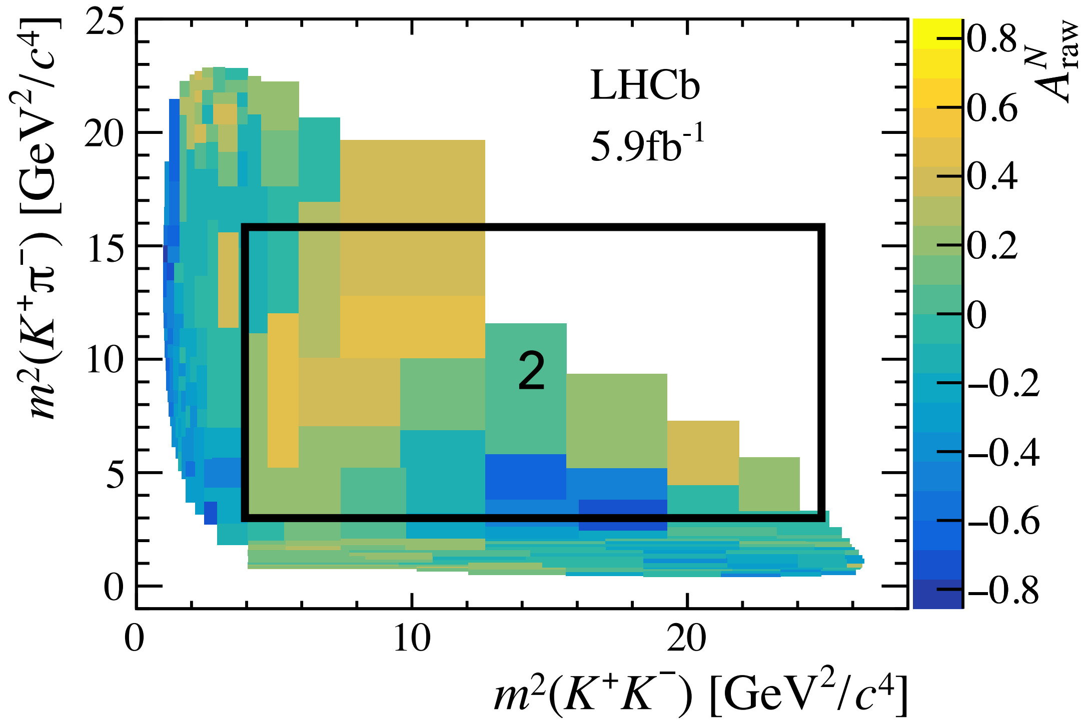
CP asymmetry in the phase space

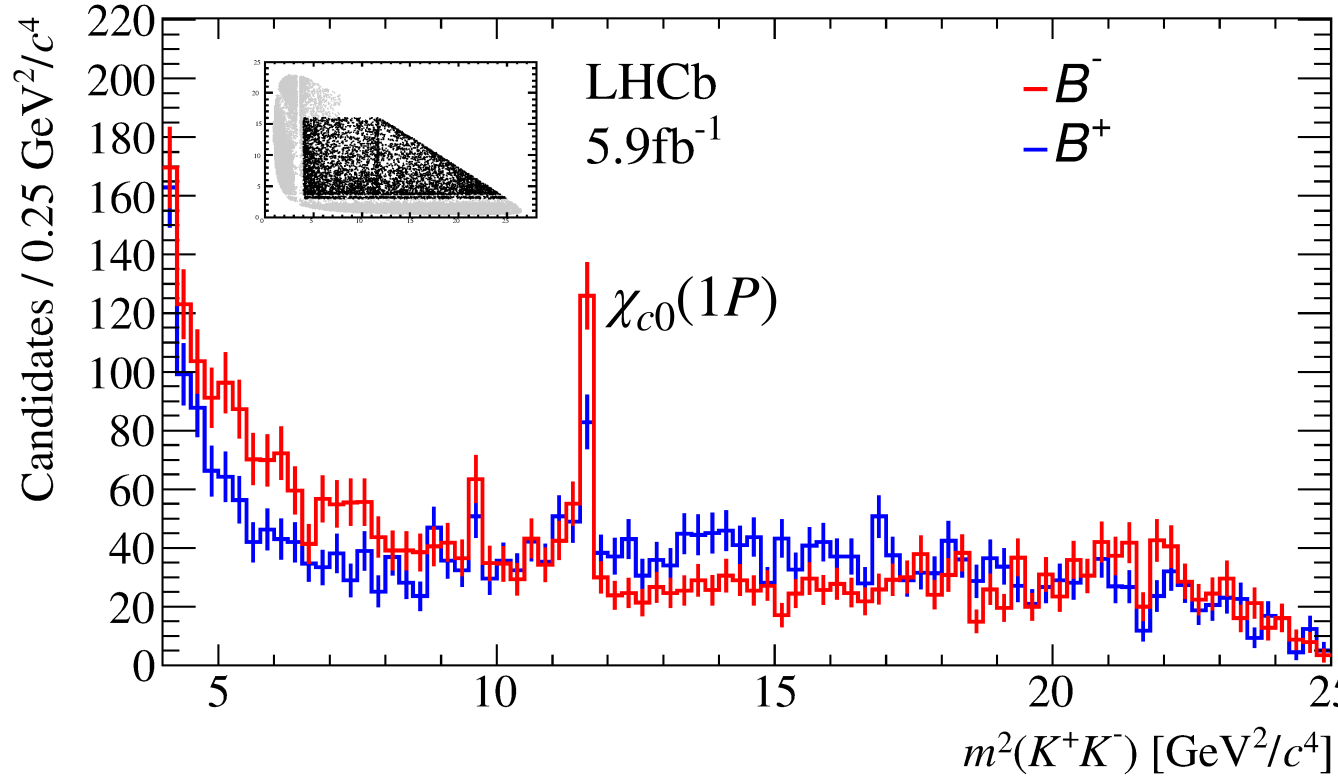
$$B^{\pm} \to \pi^{\pm} K^{+} K^{-}$$

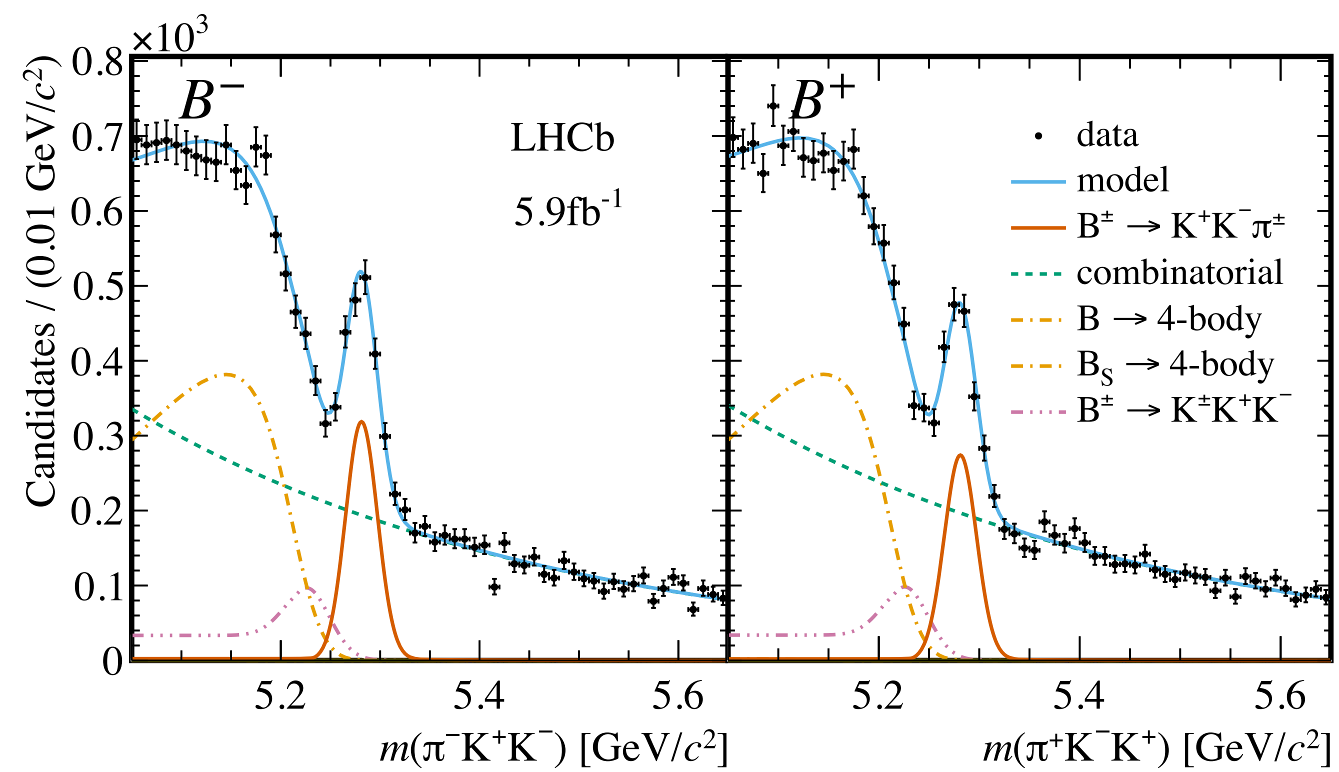
Region 2

$4 < m^2(K^+K^-) < 25$

$3 < m^2(K^+\pi^-) < 16$







$$A_{CP} = +0.097 \pm 0.031$$

Systematic uncertainties

- Mass fit models
  - → Combinatorial background model: Exponential → polynomial
  - → Peaking background asymmetry: Fixed to zero → fixed to Phys. Rev. D90 (2014) 112004
  - → Peaking background model: Varying $\pm 1\sigma$ obtained from MC
  - → Signal model: 1 Gauss + 2 Crystal Ball → 1 Gauss + 2 RooGaussExp
- Dalitz plot efficiency
  - → Distribution of the R factor by randomizing the efficiency map bins
  - → Different binning for the efficiency maps
- Control channel
  - → Fit parameters float
  - → Split regions in bins of momentum, magnet polarity

Dominant contributions

Phase space integrated asymmetries

	(stat)	(syst)	$(J/\psi K^{\pm})$	
$A_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) = +0.011$	$\pm\, 0.002$	$\pm\, 0.003$	$\pm\, 0.003$	(2.4σ)
$A_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-}) = -0.037$	$\pm\, 0.002$	$\pm\, 0.002$	$\pm\, 0.003$	(8.5σ)
$A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = +0.080$	$\pm\, 0.004$	$\pm\, 0.003$	$\pm\, 0.003$	(14.1σ)
$A_{CP}(B^{\pm} \to \pi^{\pm}K^{+}K^{-}) = -0.114$	$\pm\, 0.007$	$\pm\, 0.003$	$\pm\, 0.003$	(13.6σ)

First observation of CPV in $B^{\pm} \to K^{\pm}K^{+}K^{-}$ and $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$, $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ confirmed

Comparison with run1 results

Phys. Rev. D90 (2014) 112004

	(stat)	(syst)	$(J/\psi K^{\pm})$
$A_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) = +0.025$	$\pm\, 0.004$	$\pm\, 0.004$	$\pm\, 0.007$
$A_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-}) = -0.036$	$\pm\, 0.004$	$\pm\, 0.002$	$\pm\, 0.007$
$A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = +0.058$	$\pm\, 0.008$	$\pm\, 0.009$	$\pm\, 0.007$
$A_{CP}(B^{\pm} \to \pi^{\pm}K^{+}K^{-}) = -0.123$	$\pm\, 0.017$	$\pm\, 0.012$	$\pm\, 0.007$

Final results

Regions of the phase space

$B^\pm \to \pi^\pm\pi^+\pi^-$	N_{sig}	A_{raw}	A_{CP}	
Region 1	$14\,340 \pm 150$	$+0.309 \pm 0.009$	$+0.303 \pm 0.009 \pm 0.004 \pm 0.003$	(29.9σ)
Region 2	$4\,850 \pm 130$	-0.287 ± 0.017	$-0.284 \pm 0.017 \pm 0.007 \pm 0.003$	(15.2σ)
Region 3	$4\,730 \pm 170$	$+0.196 \pm 0.019$	$+0.211 \pm 0.019 \pm 0.043 \pm 0.003$	(4.5σ)
Region 4	$2\,270 \pm 60$	$+0.747 \pm 0.027$	$+0.745 \pm 0.027 \pm 0.018 \pm 0.003$	(23.0σ)
$B^\pm \to K^\pm\pi^+\pi^-$				
Region 1	$41\,980 \pm 280$	$+0.201 \pm 0.005$	$+0.217 \pm 0.005 \pm 0.005 \pm 0.003$	(27.3σ)
Region 2	$27\,040 \pm 250$	-0.149 ± 0.007	$-0.145 \pm 0.007 \pm 0.006 \pm 0.003$	(15.0σ)
$B^\pm \to \pi^\pm K^+K^-$				
Region 1	$11\,430 \pm 170$	-0.363 ± 0.010	$-0.358 \pm 0.010 \pm 0.014 \pm 0.003$	(20.2σ)
Region 2	$2\,600 \pm 120$	$+0.075 \pm 0.031$	$+0.097 \pm 0.031 \pm 0.005 \pm 0.003$	(3.1σ)
$B^\pm \to K^\pm K^+K^-$				
Region 1	$76\,020 \pm 350$	-0.189 ± 0.004	$-0.178 \pm 0.004 \pm 0.004 \pm 0.003$	(28.3σ)
Region 2	$37\,440 \pm 320$	$+0.030 \pm 0.005$	$+0.043 \pm 0.005 \pm 0.004 \pm 0.003$	(6.3σ)

Huge localised asymmetry of ~75% in $B^\pm \to \pi^\pm\pi^+\pi^-$

Regions of the phase space

$B^\pm \to \pi^\pm\pi^+\pi^-$	N_{sig}	A_{raw}	A_{CP}	
Region 1	$14\,340 \pm 150$	$+0.309 \pm 0.009$	$+0.303 \pm 0.009 \pm 0.004 \pm 0.003$	(29.9σ)
Region 2	$4\,850 \pm 130$	-0.287 ± 0.017	$-0.284 \pm 0.017 \pm 0.007 \pm 0.003$	(15.2σ)
Region 3	$4\,730 \pm 170$	$+0.196 \pm 0.019$	$+0.211 \pm 0.019 \pm 0.043 \pm 0.003$	(4.5σ)
Region 4	$2\,270 \pm 60$	$+0.747 \pm 0.027$	$+0.745 \pm 0.027 \pm 0.018 \pm 0.003$	(23.0σ)
$B^\pm \to K^\pm\pi^+\pi^-$				
Region 1	$41\,980 \pm 280$	$+0.201 \pm 0.005$	$+0.217 \pm 0.005 \pm 0.005 \pm 0.003$	(27.3σ)
Region 2	$27\,040 \pm 250$	-0.149 ± 0.007	$-0.145 \pm 0.007 \pm 0.006 \pm 0.003$	(15.0σ)
$B^\pm \to \pi^\pm K^+K^-$				
Region 1	$11\,430 \pm 170$	-0.363 ± 0.010	$-0.358 \pm 0.010 \pm 0.014 \pm 0.003$	(20.2σ)
Region 2	$2\,600 \pm 120$	$+0.075 \pm 0.031$	$+0.097 \pm 0.031 \pm 0.005 \pm 0.003$	(3.1σ)
$B^\pm \to K^\pm K^+K^-$				
Region 1	$76\,020 \pm 350$	-0.189 ± 0.004	$-0.178 \pm 0.004 \pm 0.004 \pm 0.003$	(28.3σ)
Region 2	$37\,440 \pm 320$	$+0.030 \pm 0.005$	$+0.043 \pm 0.005 \pm 0.004 \pm 0.003$	(6.3σ)

Change of sign in the rescattering region

$\to$ strong phases

$B^{\pm}$ decays into a vector resonance

$S_{||} \equiv (p_{h^+} + p_{h^-})^2$
$S_{\perp} \equiv (p_{h_b} + p_{h^{\pm}})^2$
$\theta \equiv$ helicity angle

- Few $B^{\pm} \to PV$ measurements in the literature and huge theoretical interest
- $B^{\pm} \to h^{\pm}(V \to h^+h^-)$ contributions
- Total amplitudes for B^+ and B^-

$$\mathcal{M}_{\pm} = a^V_{\pm} e^{i\delta^V_{\pm}} F^{\rm BW}_V \cos\theta(s_{\perp}, s_{||}) + a^S_{\pm} e^{i\delta^S_{\pm}} F^{\rm BW}_S$$

- Asymmetry ∝ to square modulus of amplitude difference

$$\left|\mathcal{M}_{\pm}\right|^2 = (a^V_{\pm})^2(\cos\theta)^2 |F^{\rm BW}_V|^2 + (a^S_{\pm})^2 |F^{\rm BW}_S|^2 + 2a^V_{\pm}a^S_{\pm}\cos\theta |F^{\rm BW}_V|^2 |F^{\rm BW}_S|^2$$
$$\times \{\cos(\delta^V_{\pm} - \delta^S_{\pm})[(m^2_V - s_{||})(m^2_S - s_{||}) + (m_V\Gamma_V)(m_S\Gamma_S)]$$
$$+\sin(\delta^V_{\pm} - \delta^S_{\pm})[(m_S\Gamma_S)(m^2_V - s_{||}) - (m_V\Gamma_V)(m^2_S - s_{||})]\} .$$

Direct vector A_{cp} — Direct NR A_{cp} — NR and vector interference

Phys. Rev. D94 (2016) 054028

$B^{\pm}$ decays into a vector resonance

$S_{||} \equiv (p_{h^+} + p_{h^-})^2$

$S_{\perp} \equiv (p_{h_b} + p_{h^{\pm}})^2$

$\theta \equiv$ helicity angle

- Mass window chosen as the nominal resonance width
  - → 150 MeV/c² for $\rho(770)^0$
  - → 50 MeV/c² for $K^*(892)$
  - → 5 MeV/c² for $\phi(1020)$

Direct NR A_{cp} | NR and vector interference | Direct vector A_{cp}

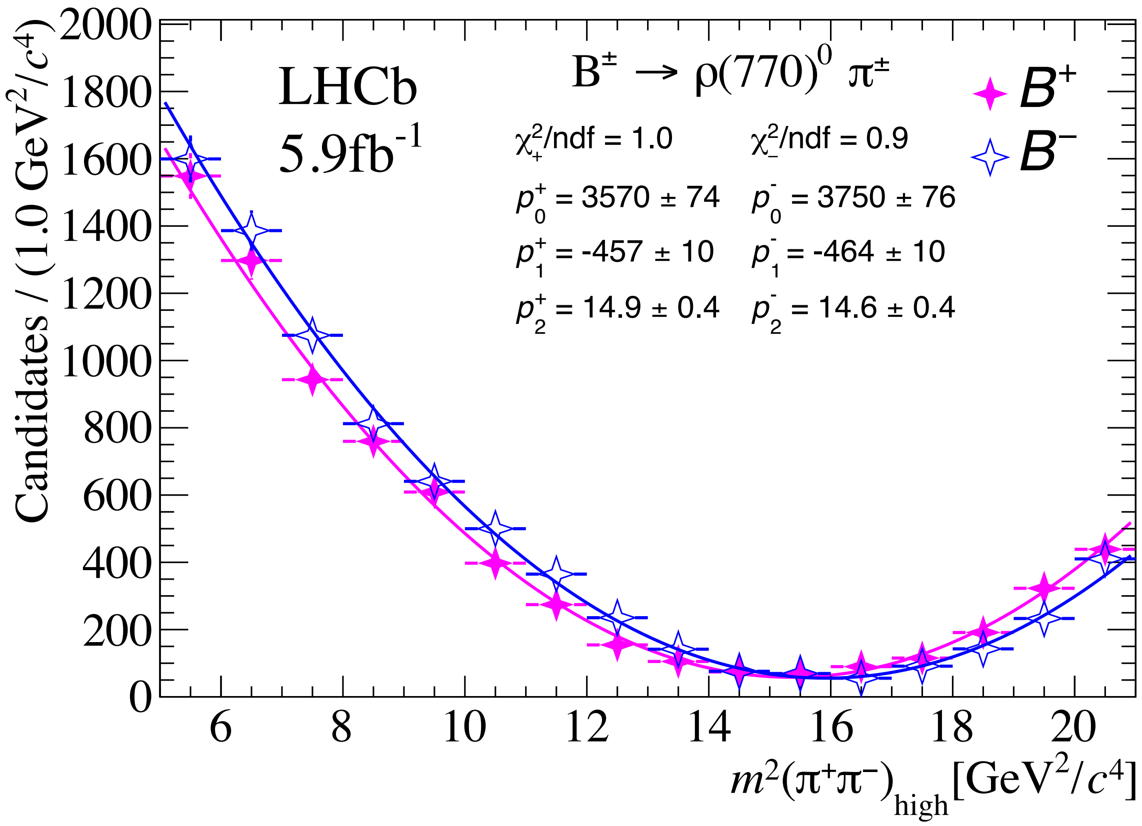
$$|\mathcal{M}_{\pm}|^2 = f(\cos\theta(m_V^2, s_\perp)) = p_0^{\pm} + p_1^{\pm}\cos\theta(m_V^2, s_\perp) + p_2^{\pm}\cos^2\theta(m_V^2, s_\perp)$$

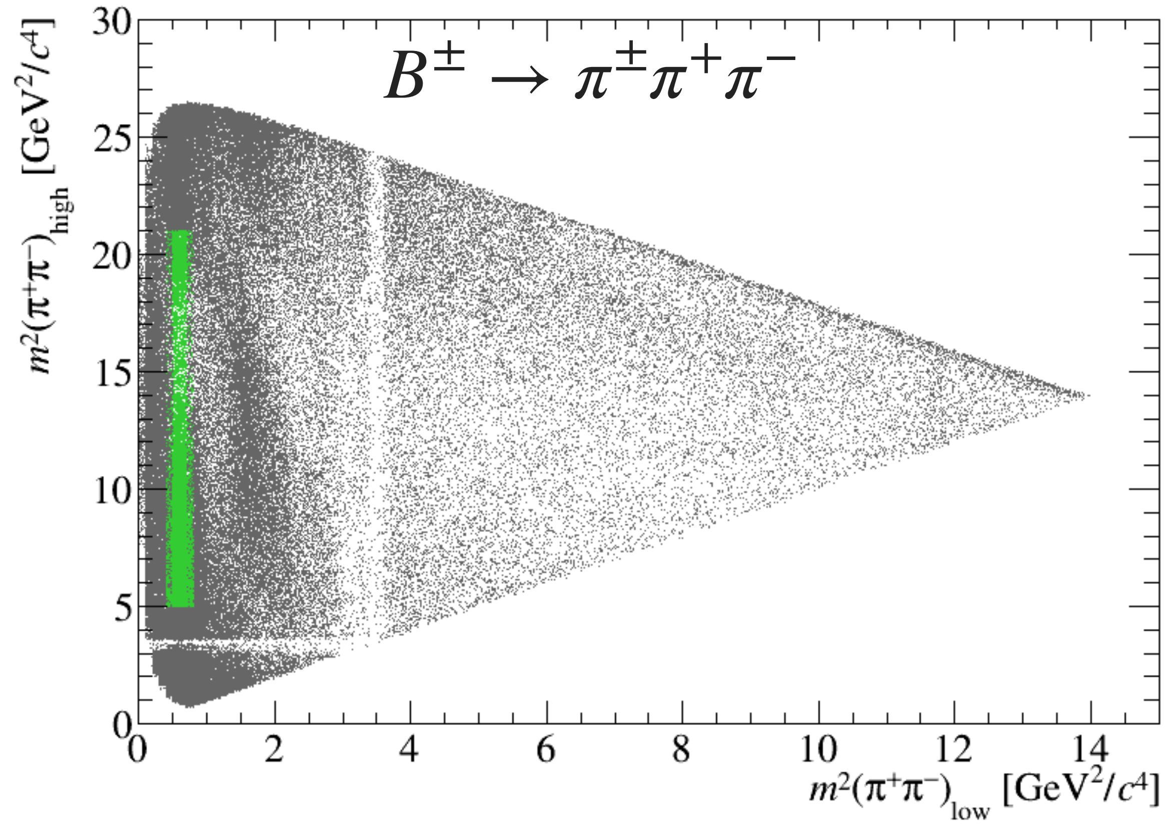
- Quadratic function to get amplitude parameters
  - → $f(x) = p_0 + p_1 x + p_2 x^2$

$$A_{CP}^V = \frac{|\mathcal{M}_-|^2 - |\mathcal{M}_+|^2}{|M_-|^2 + |\mathcal{M}_+|^2} = \frac{p_2^- - p_2^+}{p_2^- + p_2^+}$$

Phys. Rev. D94 (2016) 054028

$B^{\pm} \to \rho(770)^0\pi^{\pm}$



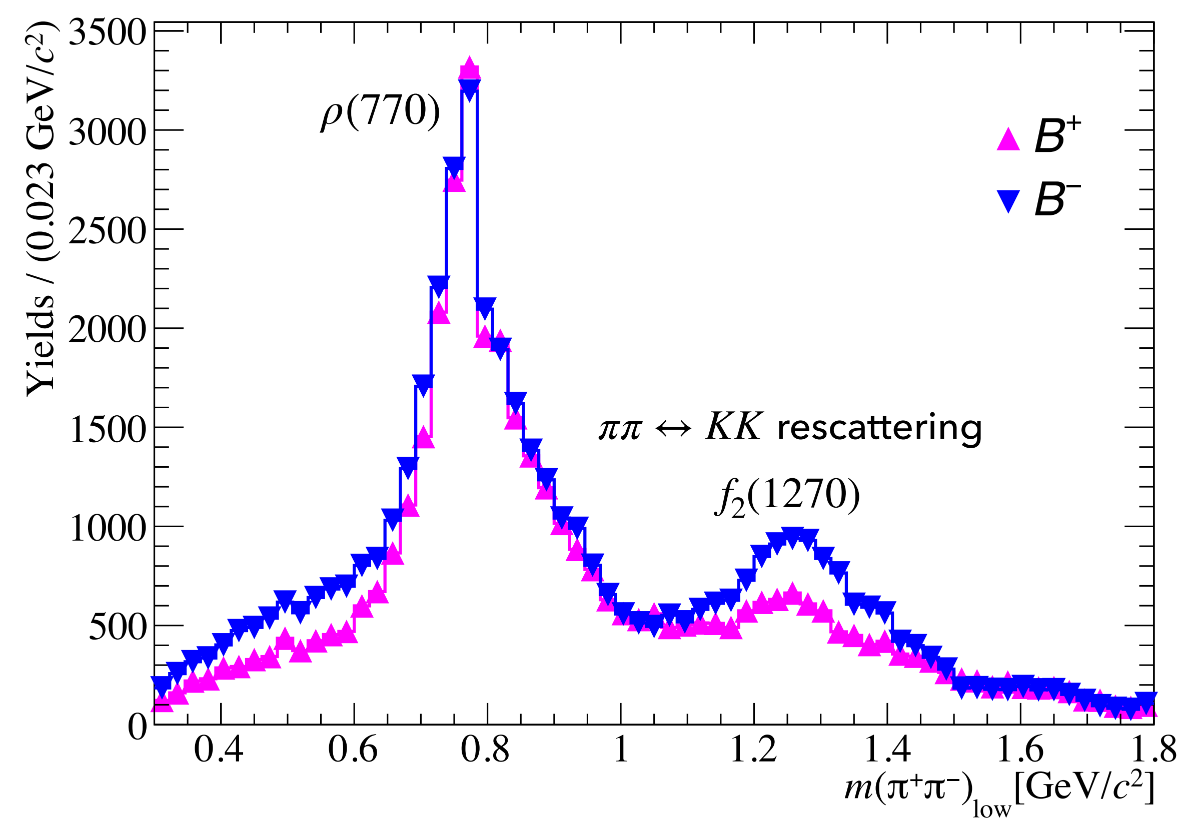


◆ Measurement of $\rho - \omega$ mixing

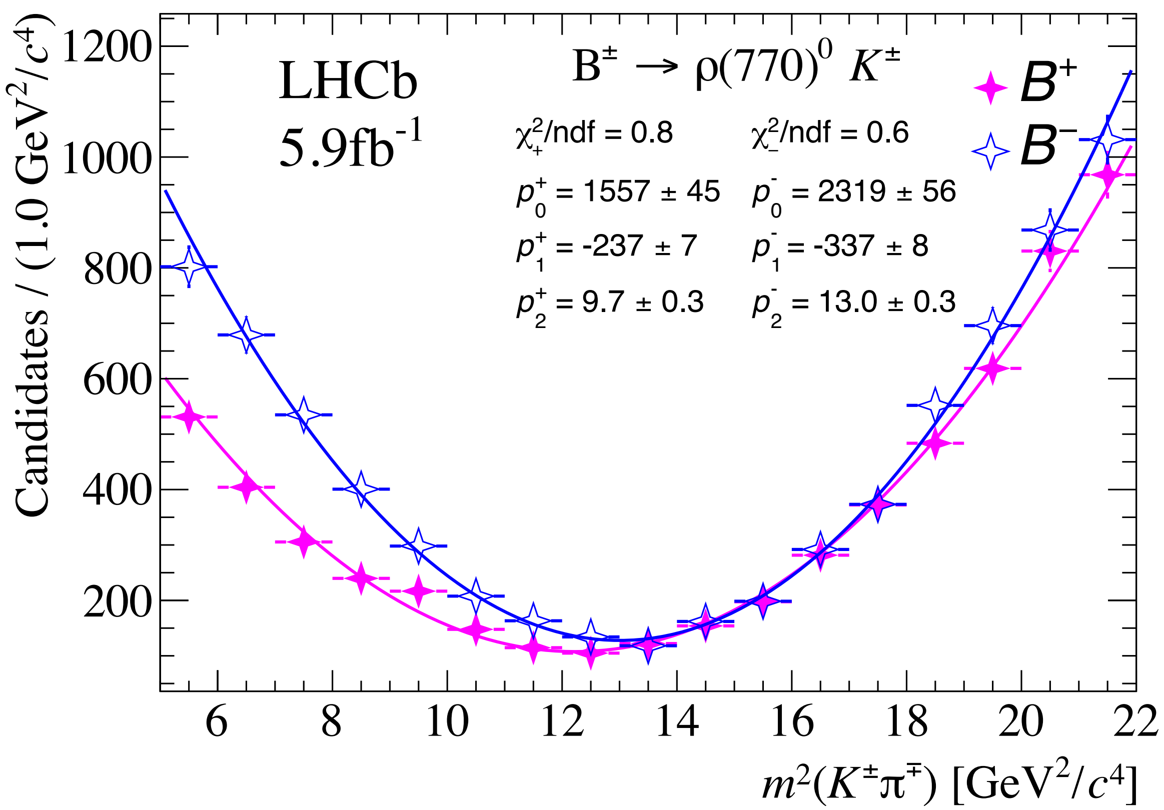
$$A_{CP} = -0.004 \pm 0.017$$

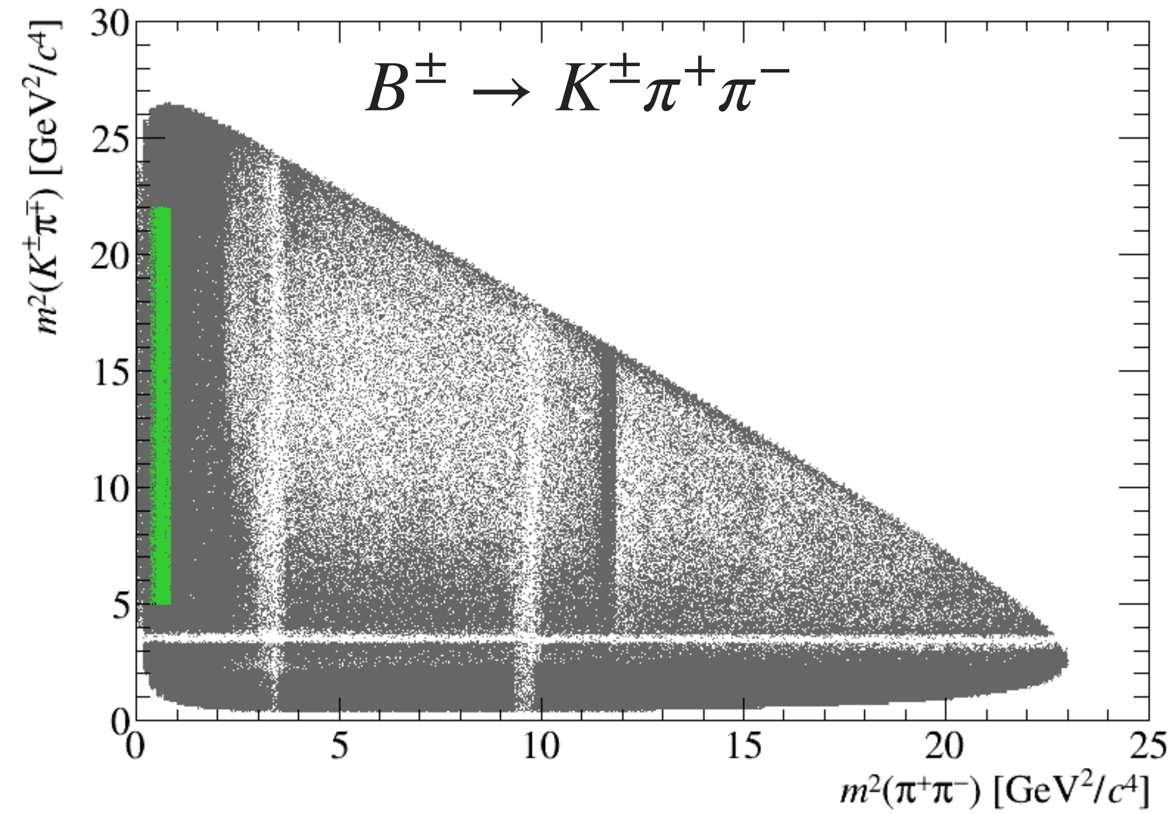
$$A_{CP} = 0.007 \pm 0.011 \pm 0.016$$

LHCb
Phys. Rev. Lett. 124 (2020) 031801



$B^\pm \to \rho(770)^0 K^\pm$





First time observed!

$$A_{CP} = 0.150 \pm 0.019$$

$$A_{CP} = 0.44 \pm 0.10 \pm 0.04^{+0.05}_{-0.13}$$

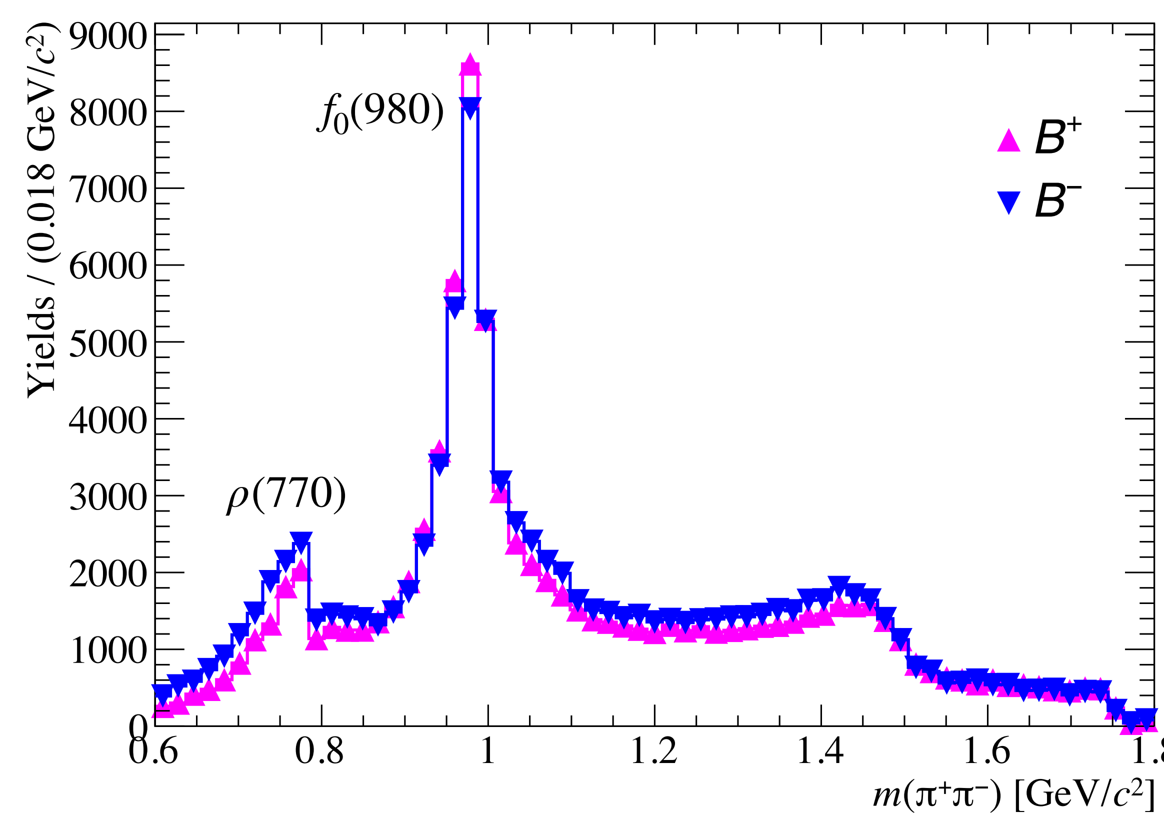
BaBar

Phys. Rev. D78 (2008) 012004

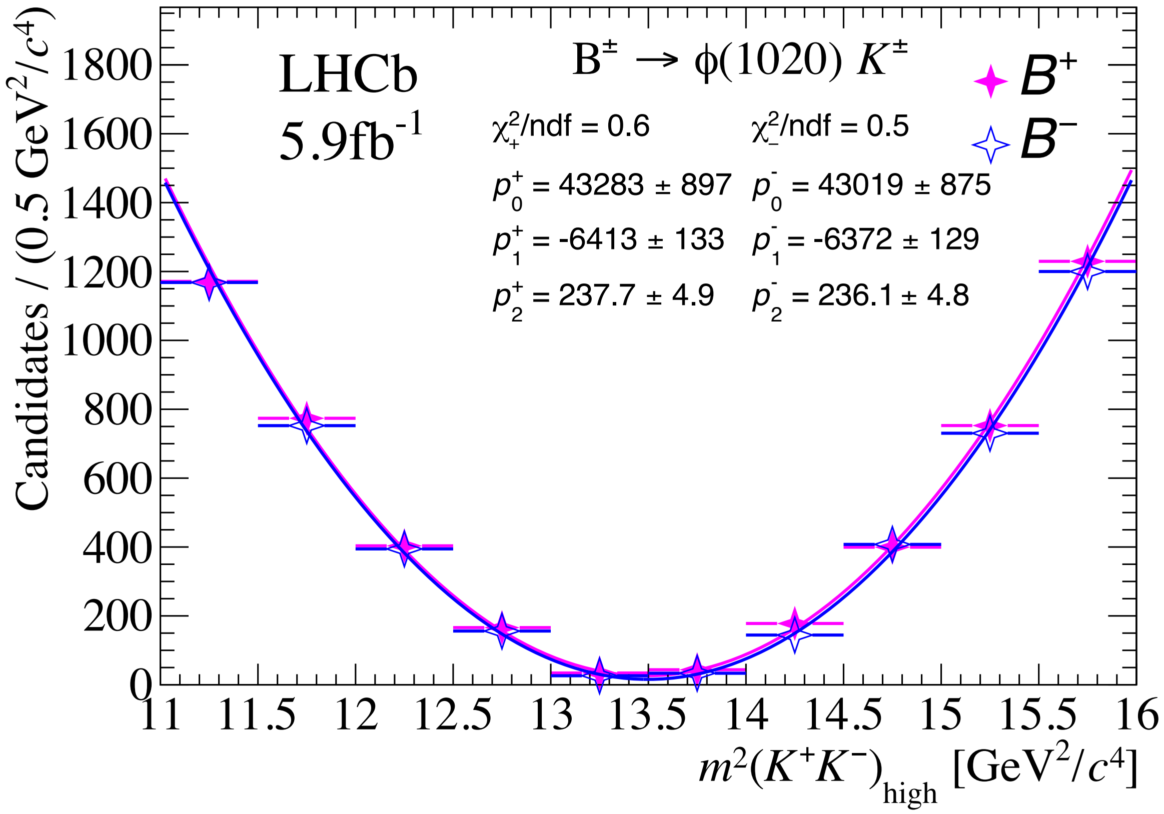
$$A_{CP} = 0.30 \pm 0.11 \pm 0.02^{+0.11}_{-0.04}$$

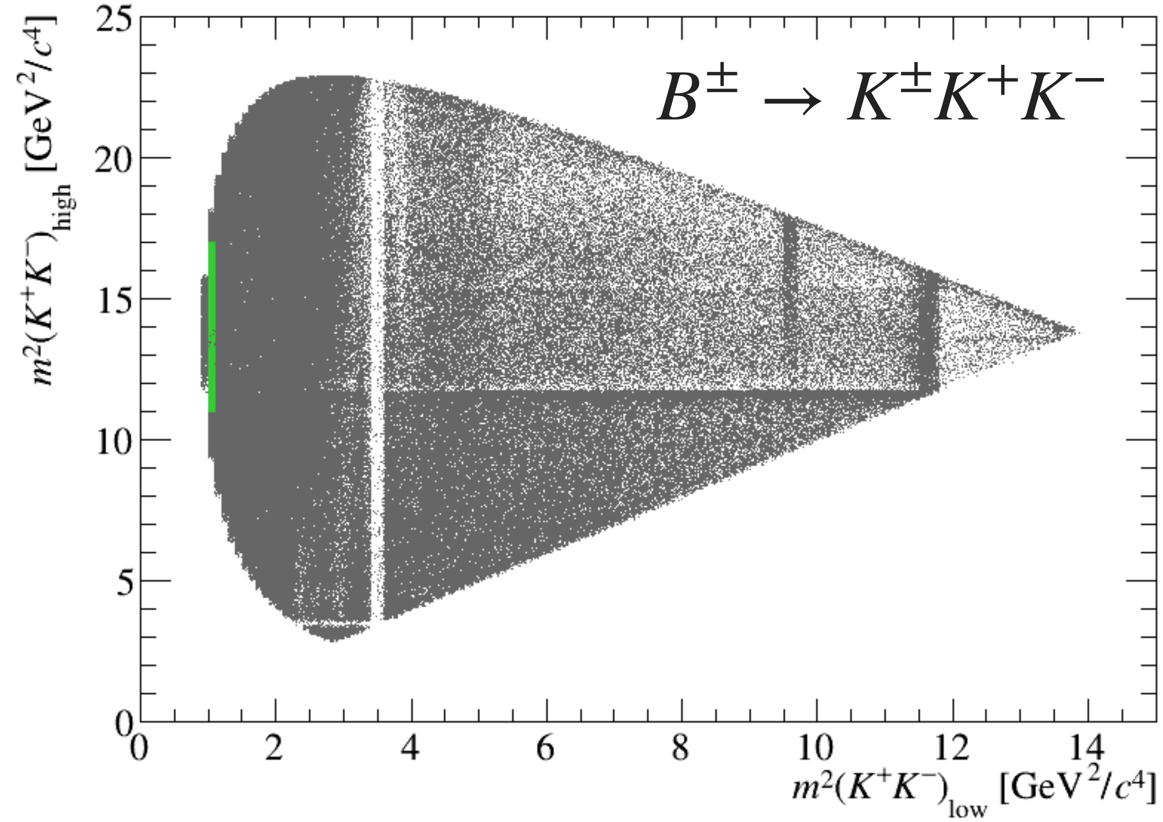
Belle

Phys. Rev. Lett. 96 (2006) 251803



$B^{\pm} \to \phi(1020)K^{\pm}$



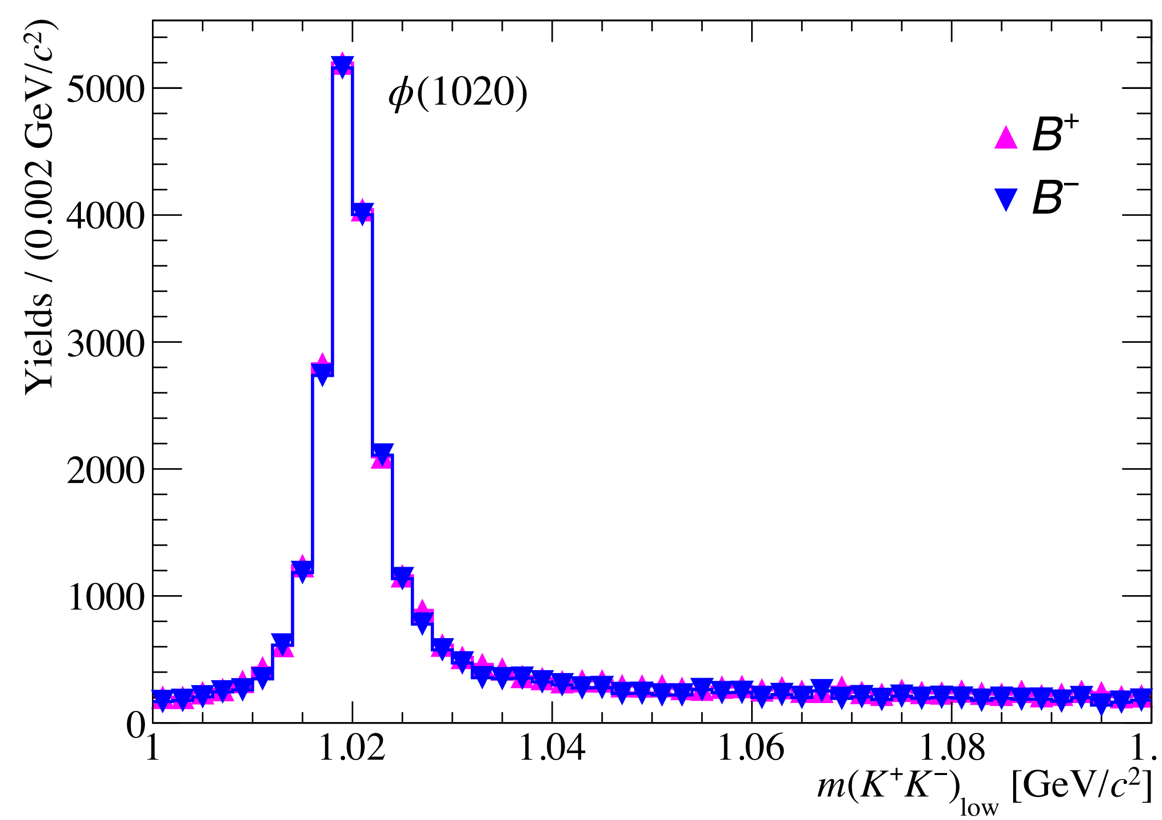


$$A_{CP} = 0.004 \pm 0.010$$

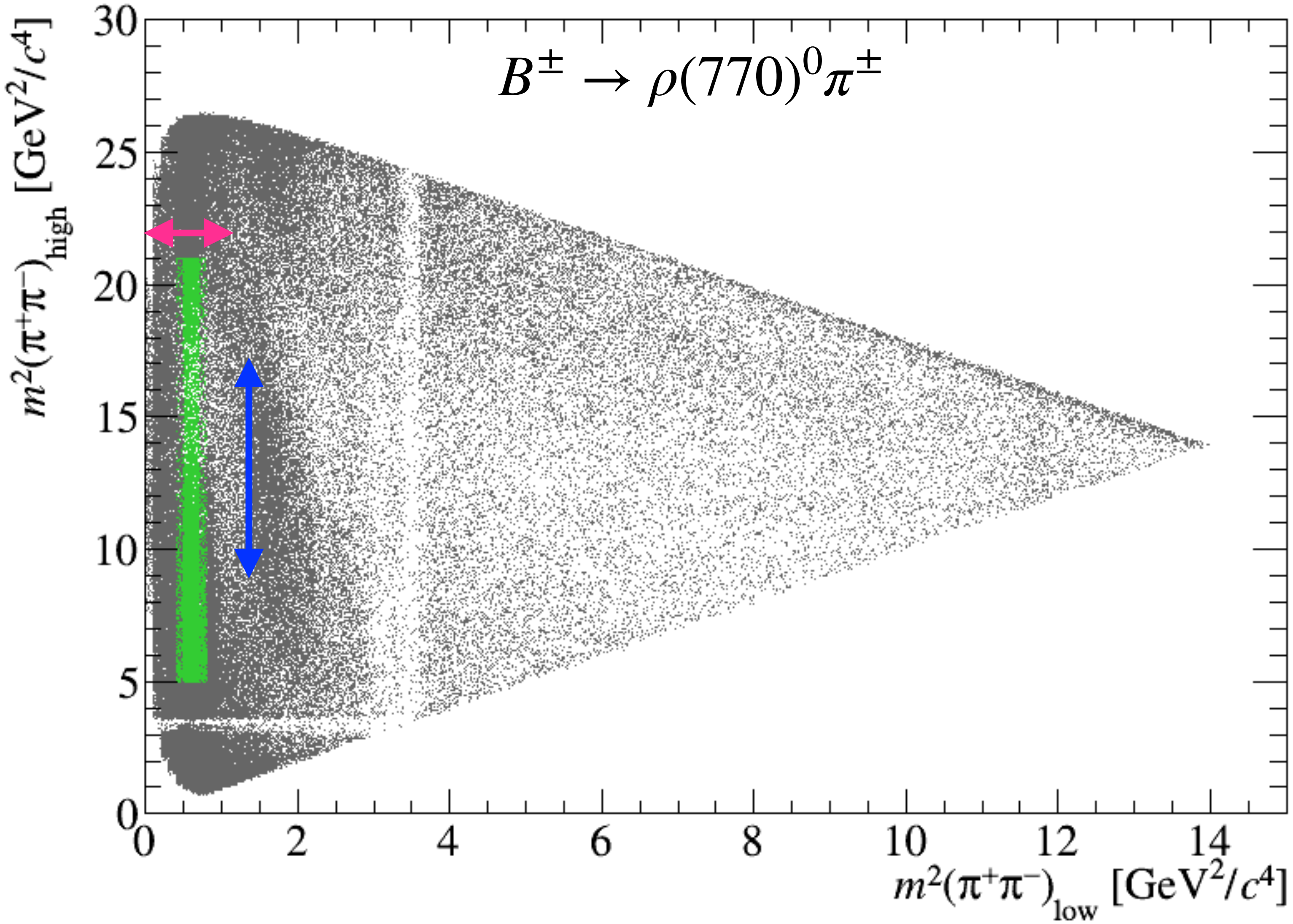
$$A_{CP} = 0.128 \pm 0.044 \pm 0.013$$

BaBar

Phys. Rev. D85 (2012) 112010



- $B^{\pm} \to PV$ decays
  - → Variation of the resonance mass window
  - → Variation of the fit regions
  - → Projection over $\cos(\theta_{hel})$ instead of $m^2_{(31,23)}$



Final results

Results for full run2 dataset

Decay channel	Vector Resonance	$\mathcal{A}_{CP}^{V} \pm \sigma_{\text{stat}} \pm \sigma_{\text{syst}}$
$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$	$\rho(770)^{0} \to \pi^{+}\pi^{-}$	-0.004 ± 0.017 ± 0.009
$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$	$\rho(770)^{0} \to \pi^{+}\pi^{-}$	+0.150 ± 0.019 ± 0.011 (6.8σ)
	$K^{*}(892)^{0} \to K^{\pm}\pi^{\mp}$	-0.015 ± 0.021 ± 0.012
$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$	$K^{*}(892)^{0} \to K^{\pm}\pi^{\mp}$	+0.007 ± 0.054 ± 0.032
$B^{\pm} \to K^{\pm}K^{+}K^{-}$	$\phi(1020) \to K^{+}K^{-}$	+0.004 ± 0.010 ± 0.007

First observation of CPV in $B^{\pm} \to \rho(770)^{0}K^{\pm}$

Conclusions (1)

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

- Phase space integrated asymmetries confirmed

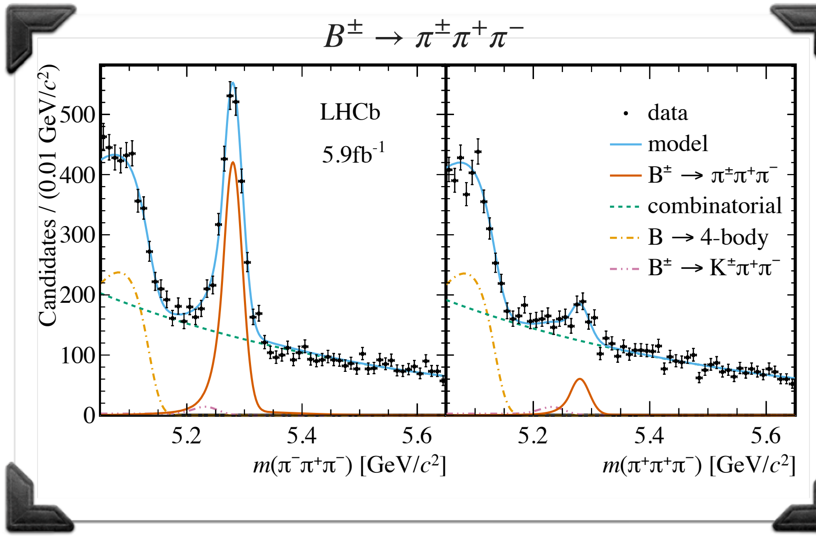
	(stat)	(syst)	$(J/\psi K^{\pm})$	
$A_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) = +0.011$	$\pm\, 0.002$	$\pm\, 0.003$	$\pm\, 0.003$	(2.4σ)
$A_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-}) = -0.037$	$\pm\, 0.002$	$\pm\, 0.002$	$\pm\, 0.003$	(8.5σ)
$A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = +0.080$	$\pm\, 0.004$	$\pm\, 0.003$	$\pm\, 0.003$	(14.1σ)
$A_{CP}(B^{\pm} \to \pi^{\pm}K^{+}K^{-}) = -0.114$	$\pm\, 0.007$	$\pm\, 0.003$	$\pm\, 0.003$	(13.6σ)

First observation of CPV in $B^{\pm} \to K^{\pm}K^{+}K^{-}$ and $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$, $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ confirmed

Conclusions (2)

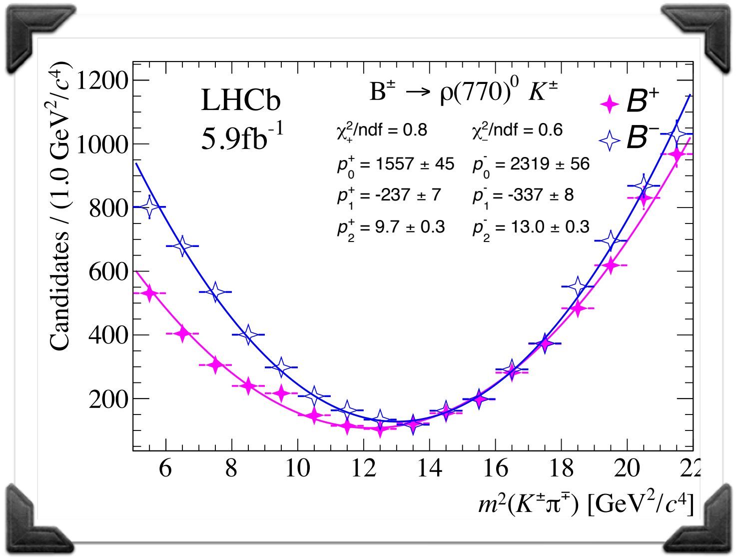
$$B^{\pm} \to h^{\pm}h^{+}h^{-}$$

- Non-uniform asymmetries in the phase space observed
- Significant *CP* violation in the $\pi\pi \leftrightarrow KK$ rescattering region
- Indication of CPV in the region of the $\chi_{c0}(1P)$ resonance
- Ongoing amplitude analysis will provide further details



$$B^{\pm} \to PV$$

- Measurement of asymmetries in $B^{\pm} \to PV$ decays
- Observation for the first time of CPV in $B^{\pm} \to \rho(770)^0 K^{\pm}$
- Significant improvement compared to Belle and BaBar

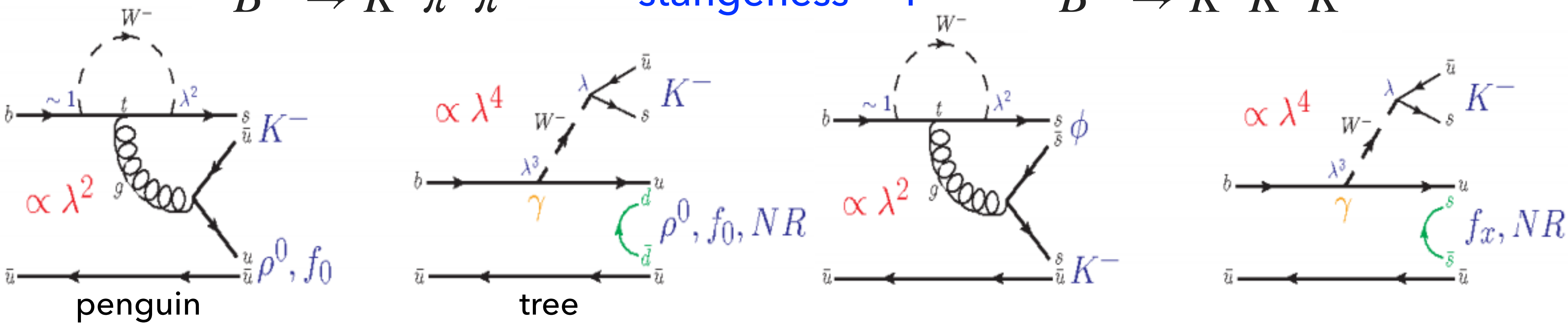


Run3 starting soon!

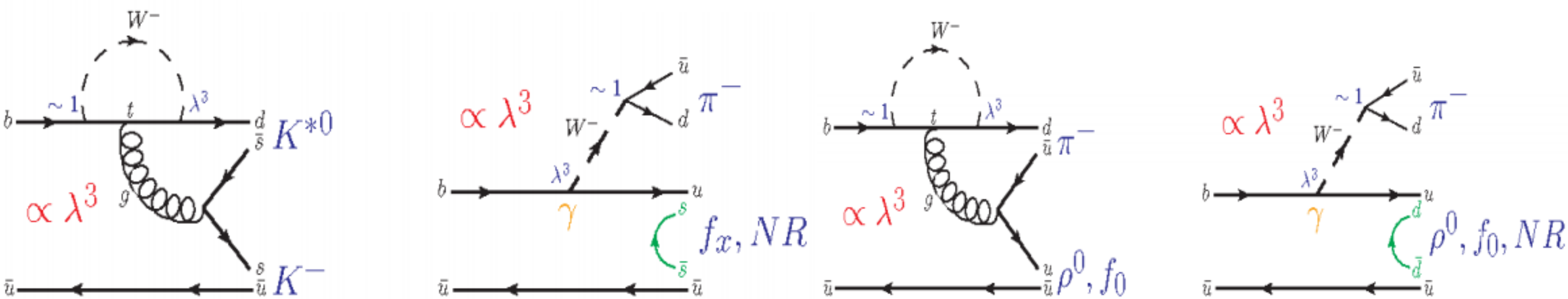
Backup

Generalities on *CP* violation

$B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}$ stangeness = 1 $B^{\pm} \rightarrow K^{\pm}K^{+}K^{-}$



$B^{\pm} \rightarrow \pi^{\pm}K^{+}K^{-}$ stangeness = 0 $B^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$



CP violation from interferences between:

- penguin and tree diagrams
- resonances in the phase space

Event selection strategy

Trigger requirements

- L0 Trigger
  - B_L0HadronDecision_TOS > 0 || B_L0Global_TIS > 0
- HLT Trigger
  - B_Hlt1TrackAllMVADecision_TOS>0 > 0
  - Hlt2Topo(2-,3-, or 4-Body)_TOS

Stripping selection

- Data selected using StrippingBu2hhh_KKK_inclLine

Full run2 data sample (5.9 fb^{-1})

Stripping requirements

Table 5: `StrippingBu2hhh_KKK_inclLine` stripping line selection criteria for charmless $B^{\pm}$ decays to three light hadrons.

Variables	Selection cuts
Tracks $\mathrm{P_T}$	$>$ 0.1 GeV/c
Tracks P	$>$ 1.5 GeV/c
Tracks IPχ^2	$>$ 1
Tracks χ^2/n.d.f.	$<$ 3
Tracks GhostProb	$<$ 0.5
Sum of $\mathrm{P_T}$ of tracks	$>$ 4.5 GeV/c
Sum of P of tracks	$>$ 20. GeV/c
Sum of IPχ^2 of tracks	$>$ 500
$\mathrm{P_T}$ of the highest-$\mathrm{P_T}$ track	$>$ 1.5 GeV/c
Maximum DOCA	$<$ 0.2 mm
$B^{\pm}$ candidate M_{KKK}	5.05 – 6.30 GeV/c^2
$B^{\pm}$ candidate M_{KKK}^{COR}	4 – 7 GeV/c^2
$B^{\pm}$ candidate IP χ^2	$<$ 10
$B^{\pm}$ candidate $\mathrm{P_T}$	$>$ 1. GeV/c
Distance from SV to any PV	$>$ 3 mm
Secondary Vertex χ^2	$<$ 12
$B^{\pm}$ candidate $\cos(\theta)$	$>$ 0.99998
$B^{\pm}$ Flight Distance χ^2	$>$ 500

BACKUP

Full run2 data samples (2015 - 2018)

Year	Luminosity	Stripping	Reco
2015	$0.33\,\text{fb}^{-1}$	Stripping24r1	Reco15a
2016	$1.67\,\text{fb}^{-1}$	Stripping28r1	Reco16a
2017	$1.71\,\text{fb}^{-1}$	Stripping29r2	Reco17
2018	$2.19\,\text{fb}^{-1}$	Stripping34	Reco18

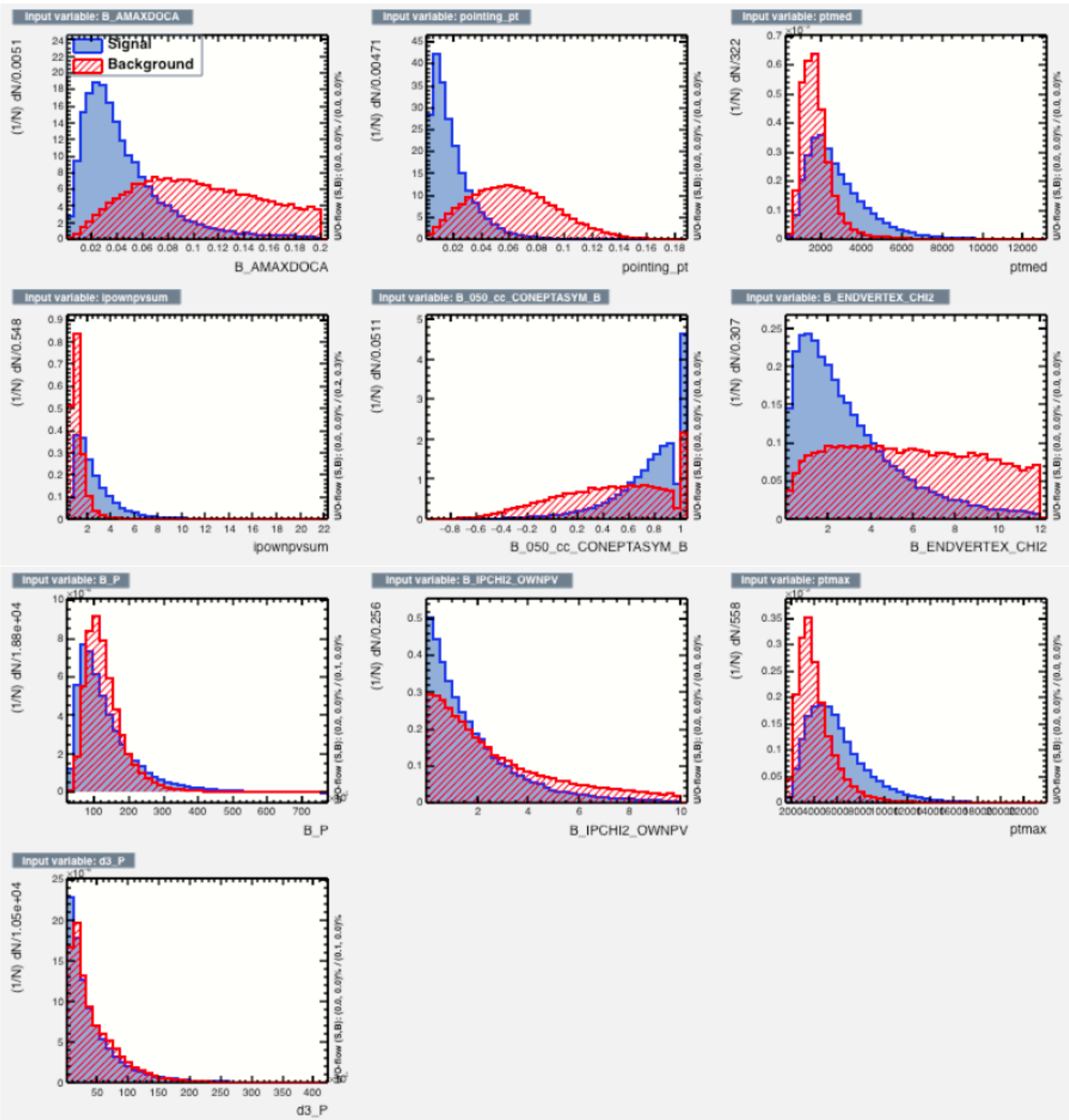
run2 = 5.9 fb^{-1}

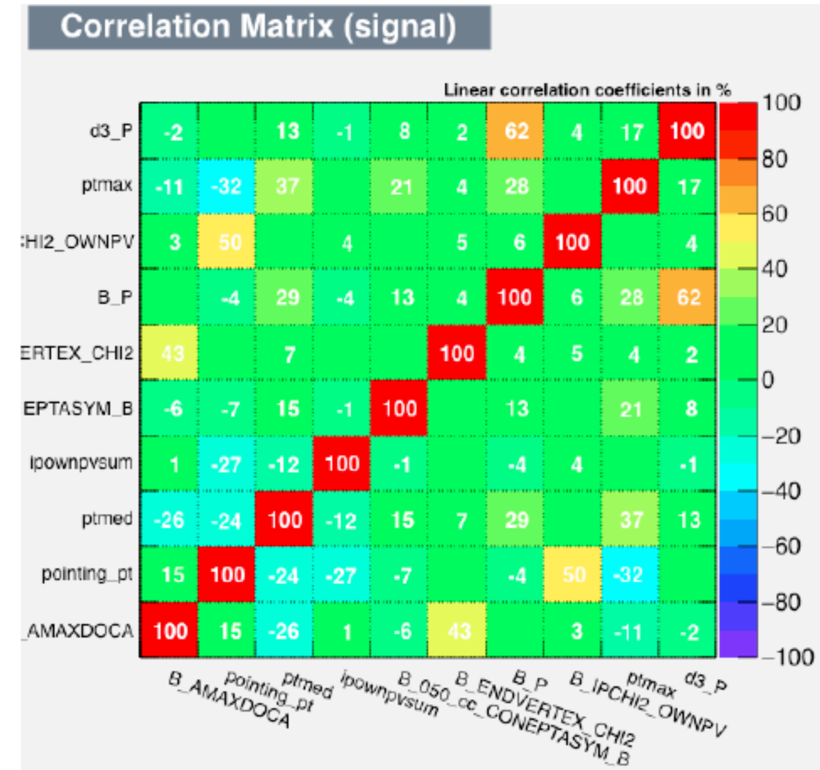
MC samples (2015 - 2017)

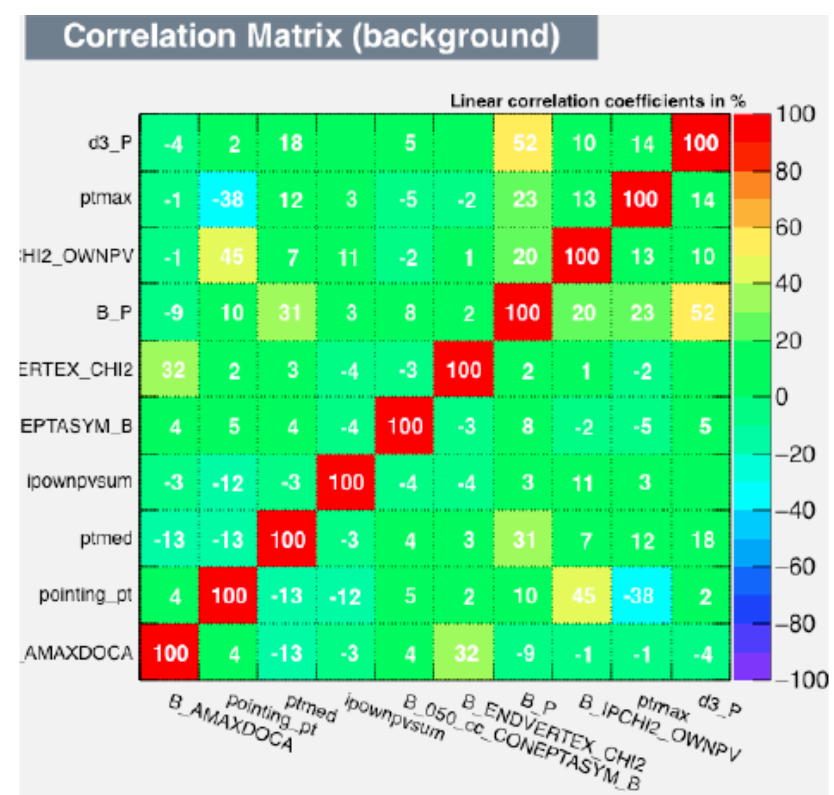
- Generated flat in the square Dalitz plot without CPV
- Small MC for MVA, PID selection and background studies
- Large MC for efficiency maps and mass fits

ANA address: https://twiki.cern.ch/twiki/bin/viewauth/LHCbPhysics/Bu2hhhAcpPaperRun2

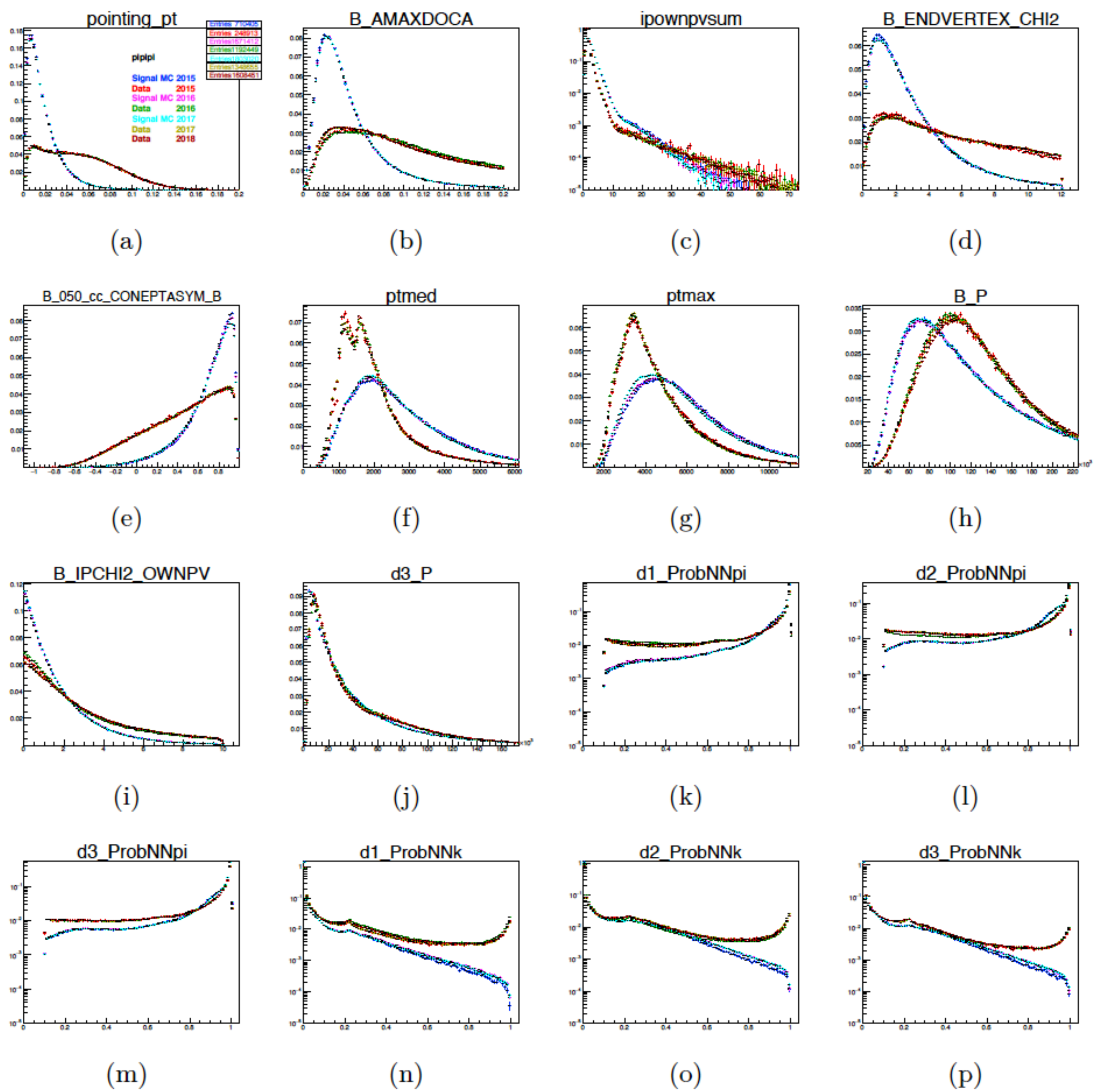
$$B^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$$







Comparison of data 2015-2018 and MC 2015-2017 after loose requirements

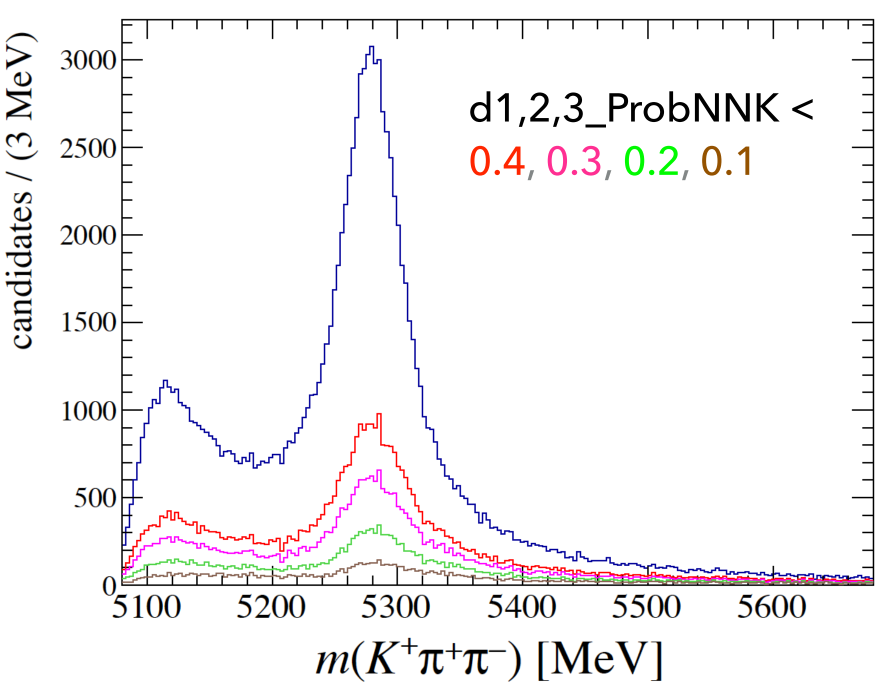


- Selection to control the cross-feed background
- Positive and negative requirements on ProbNNk(pi) variables
- $B^+ \to \bar{D}^0 K^+(\pi^+)$, with $\bar{D}^0 \to K^+\pi^-/K^+K^-/\pi^+\pi^-$ to define the cut values
- isMuon == 0 and ProbNNe < 0.4 to all tracks in all modes

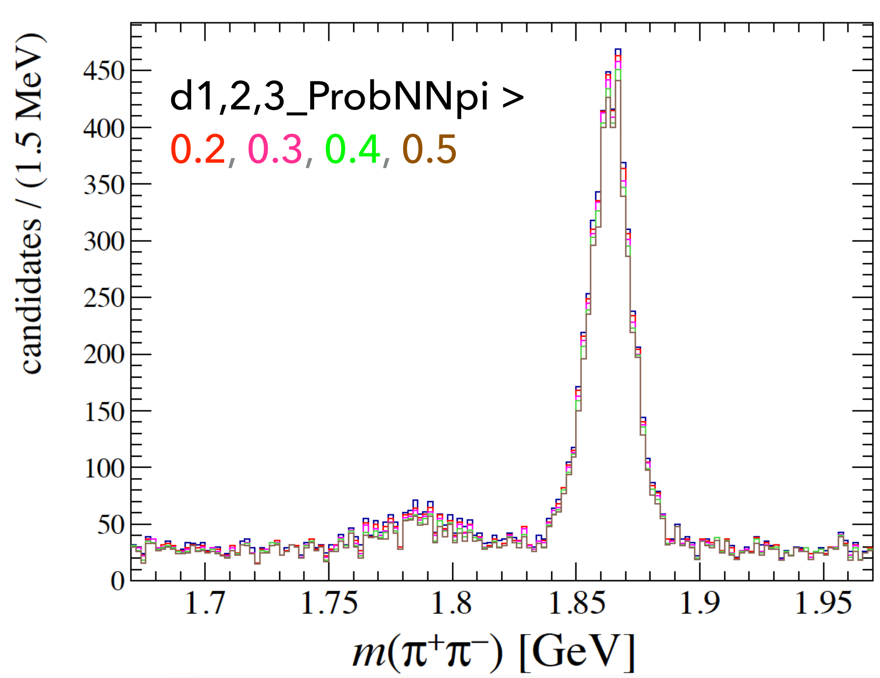
Example: PID requirement of $B^\pm \to \pi^\pm\pi^+\pi^-$

$B^+ \to \bar{D}^0(\to \pi^- K^+)\pi^+$

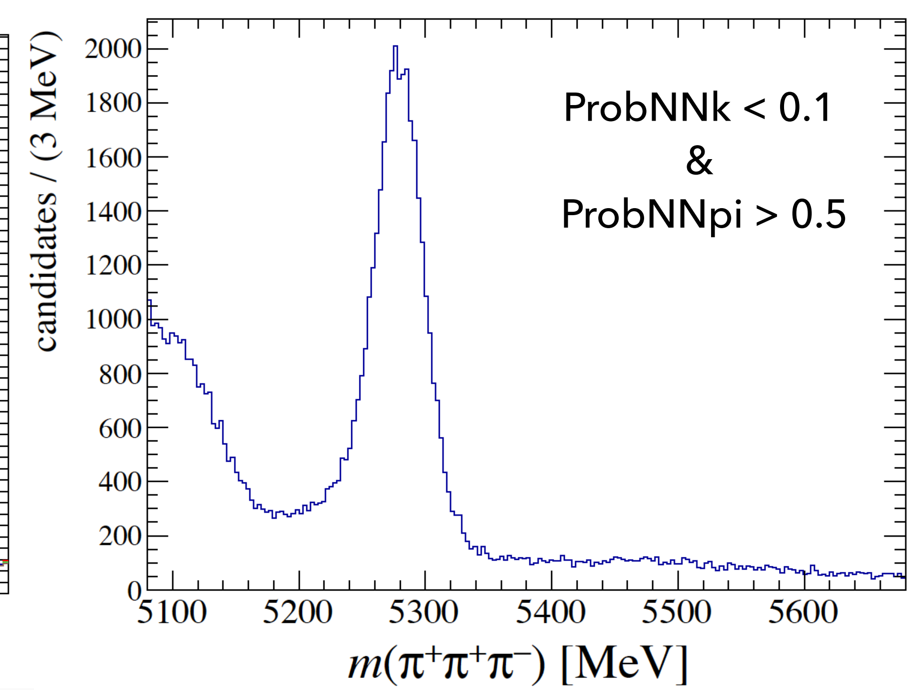
requiring $K^+\pi^-$ mass within 35 MeV from D^0 mass



$\bar{D}^0 \to \pi^+\pi^-$



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



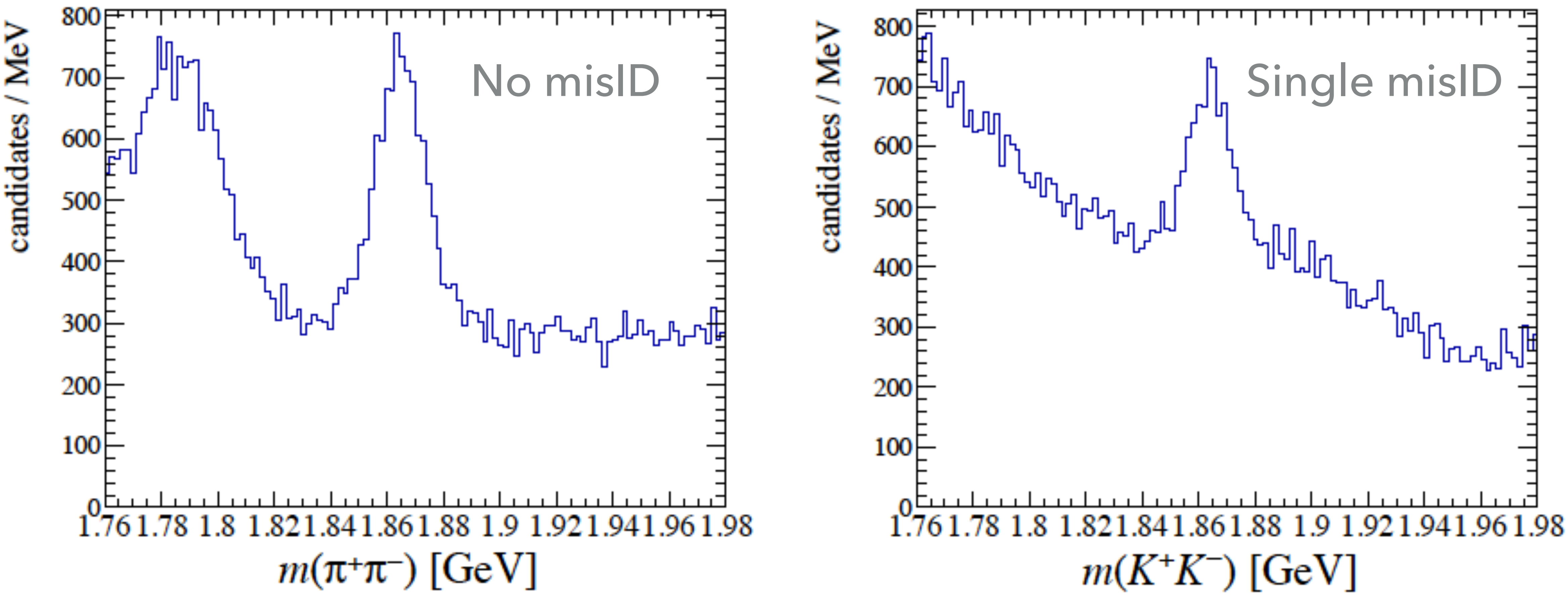
→ After applying negative PID requirements, positive identification becomes very efficient

Charm veto

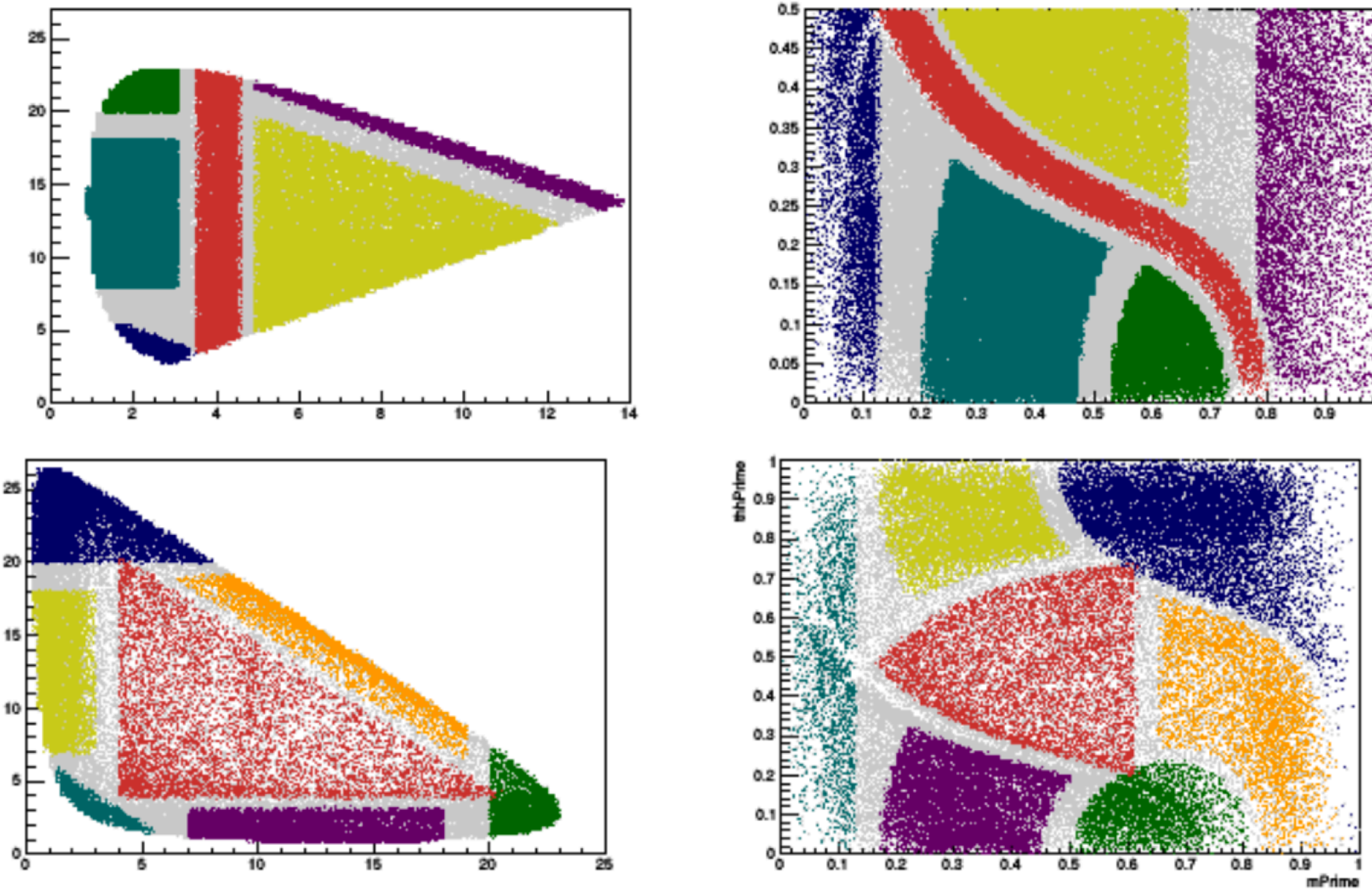
- Veto applied ± 35 MeV around D^0 mass
- misID contributions also removed. Example: $\pi^+ K^+ \pi^-$ final state

→ $B^+ \to \bar{D}^0(\to K^+\pi^-)\pi^+$ and $B^+ \to \bar{D}^0(\to \pi^+\pi^-)K^+$ (no misID)

→ $B^+ \to \bar{D}^0(\to K^+K^-/\pi^+\pi^-)\pi^+$ (single $K-\pi$ misID)



Efficiency



Efficiency correction

- From simulated samples (2015 + 2016 + 2017)
- Square Dalitz plot coordinates $\{m_{12}, \theta_{12}\}$
- Separately by polarity, trigger and year

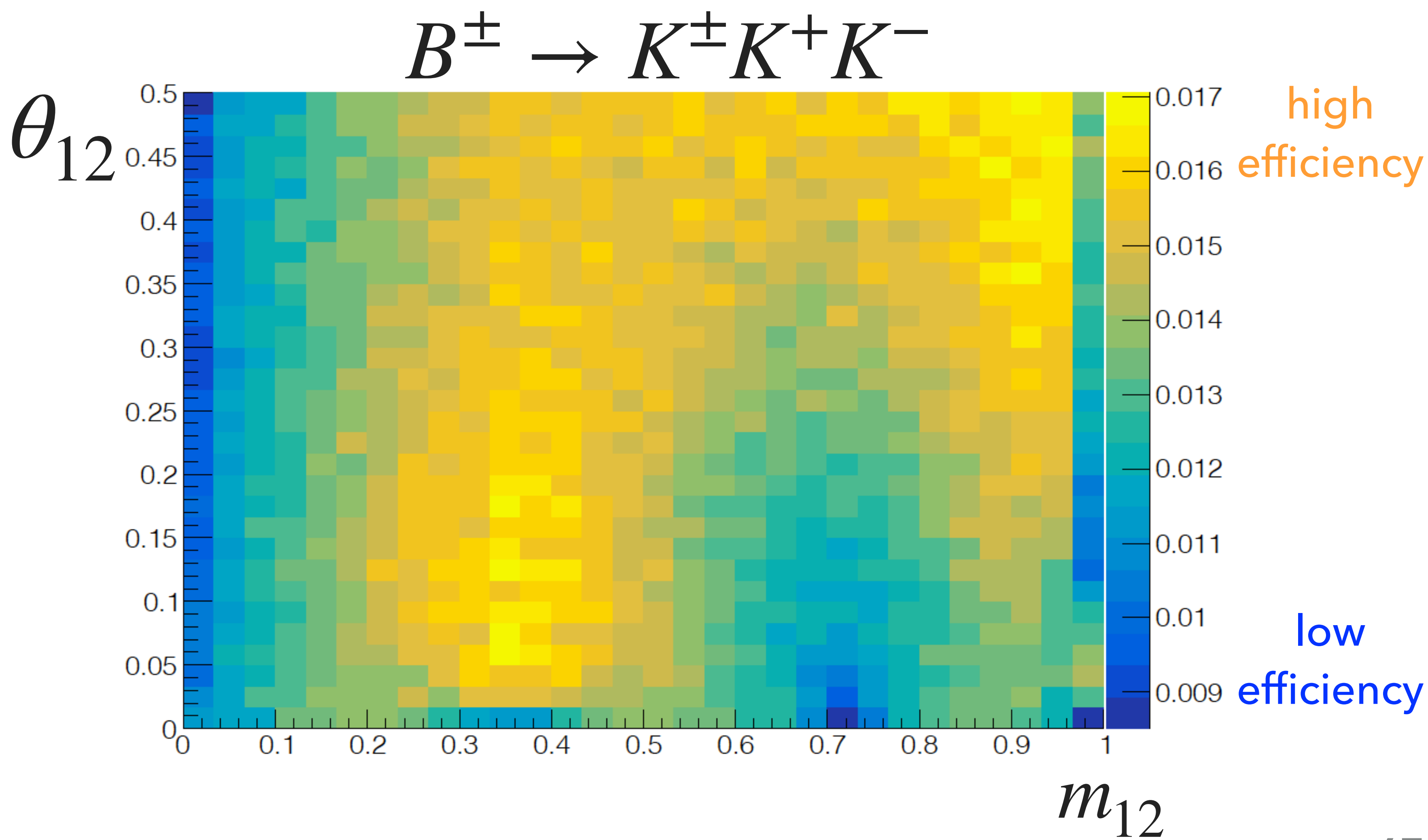
→ Maps are combined by using weights from data

Efficiency map

B+ and B- separately

$$\varepsilon_{B^\pm} = \frac{Histo_{B^\pm}^{final}}{Histo_{B^\pm}^{Gen}}$$

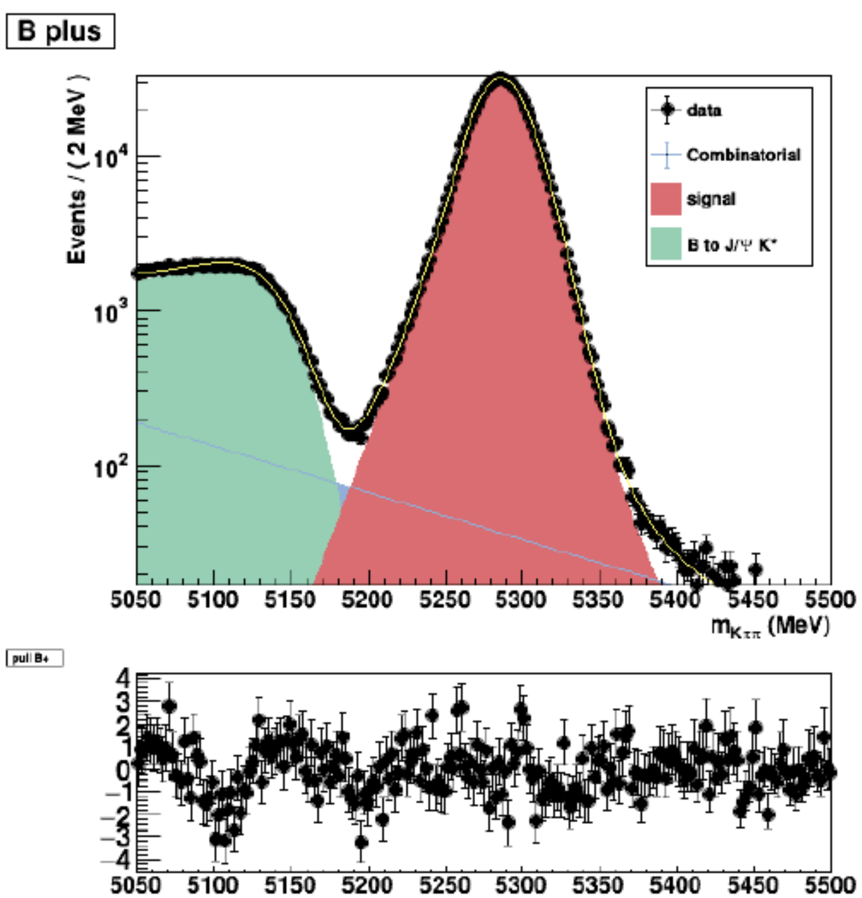
- Selection cuts
- Detection asymmetry
- PID efficiency from PIDcalib
- Trigger correction

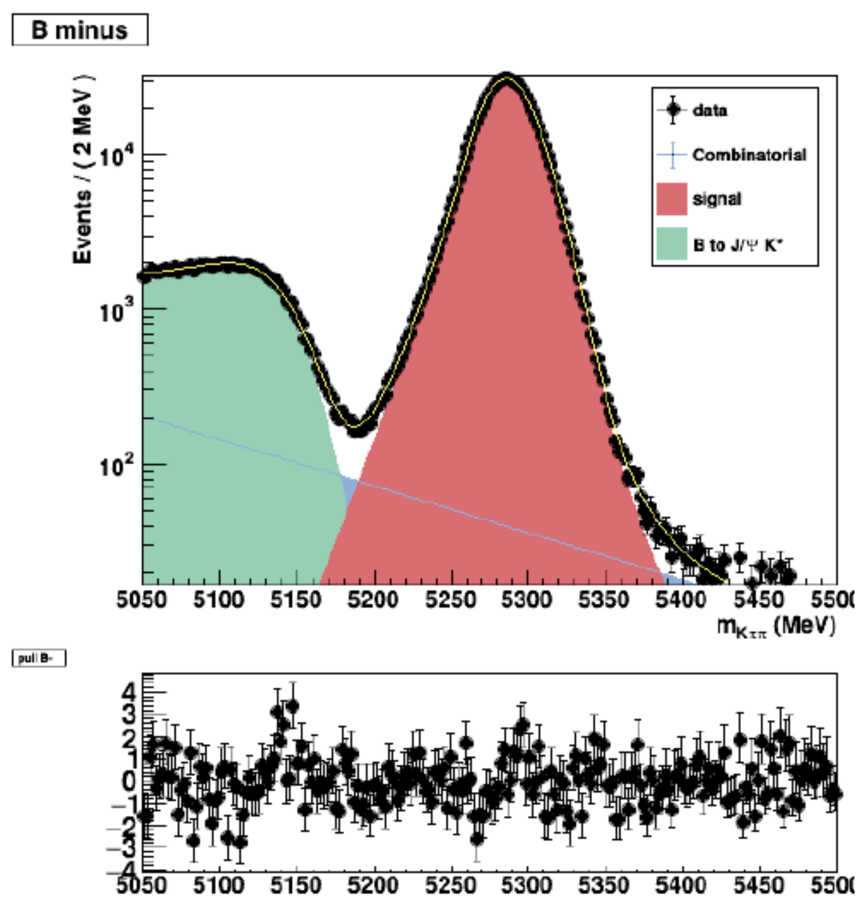


Control channel: $B^{\pm} \to J/\psi K^{\pm}$

- $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ data sample
- $A_{CP}(B^{\pm} \to J/\psi K^{\pm}) = 0.0018 \pm 0.0030$ (PDG)
- 2 CB + 1 gaussian parametrization

$$A_P = A_{CP}(B^{\pm} \to J/\psi K^{\pm})_{\text{data}} - A_{CP}(B^{\pm} \to J/\psi K^{\pm})_{\text{PDG}}$$



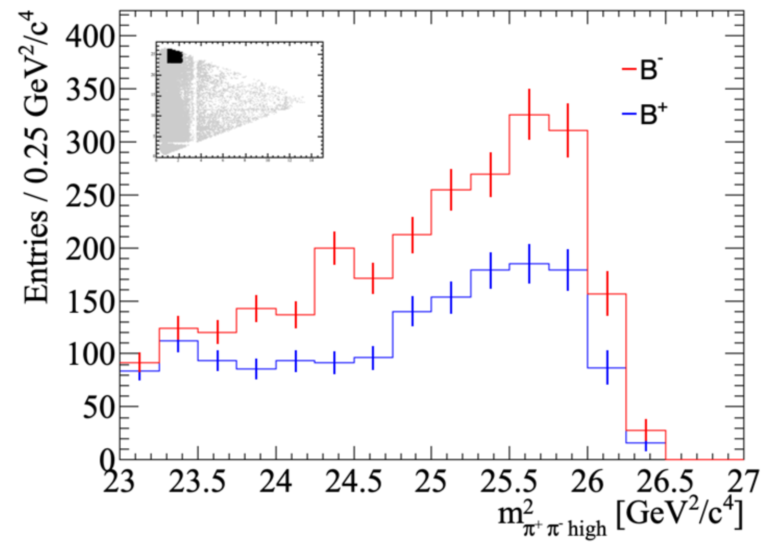


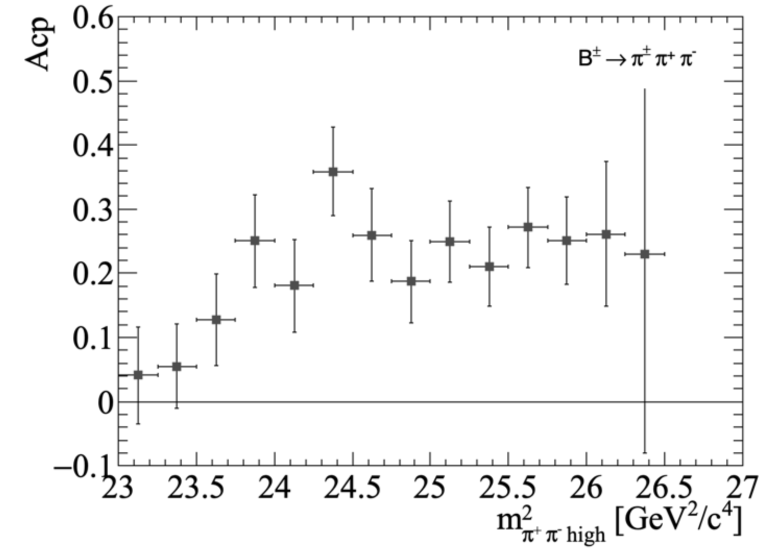
Signal component	
$N(B^{\pm} \to J/\psi K^{\pm})$	1438776 ± 1424
$B^{\pm}_{asymmetry}$	-0.011814 ± 0.000815
B_{mass} [MeV/c^2]	5286.3000 ± 0.0174
B_{width} [MeV/c^2]	20.2440 ± 0.0409
$B_{gausswidth}$ [MeV/c^2]	13.4640 ± 0.0738
f_{gauss}	0.26260 ± 0.00481
$f_{CB1,CB2}$	0.7145 ± 0.0104
n1	145.9 ± 74.5
n2	10.27 ± 1.05
4-body background component	
N^{-}_{4-body}	85143 ± 1494
N^{+}_{4-body}	87633 ± 1470
a1	1.27150 ± 0.00999
a2	-1.6399 ± 0.0201
$d1a_1$	5141 (fixed)
$d1b_1$	-6.59 ± 2.12
$d2a_1$	-0.10000 ± 0.00191
$mean_{conv\ resolution}$	0.0 (fixed)
combinatorial background component	
N^{-}_{comb}	14128 ± 1962
N^{+}_{comb}	13029 ± 1953
slope	-0.006934 ± 0.000530
shift	5050 (fixed)

$$A_p = -0.0070 \pm 0.0008^{+0.0007}_{-0.0008} \pm 0.0030$$

(stat) (syst) (PDG)

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

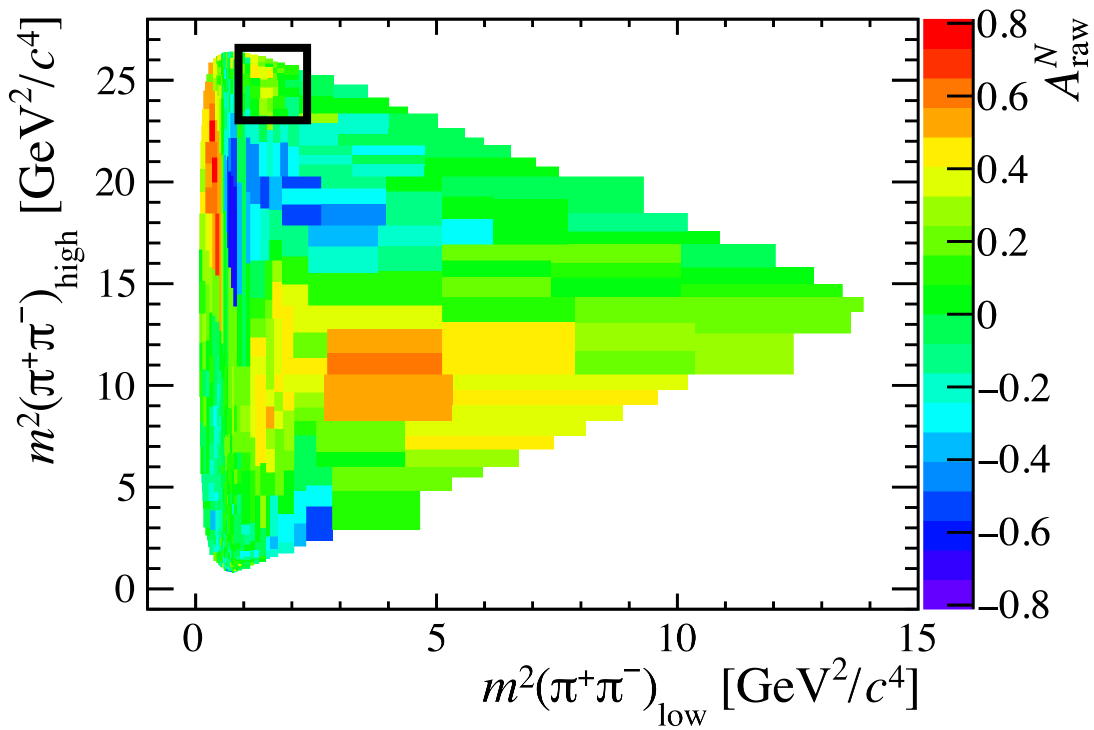


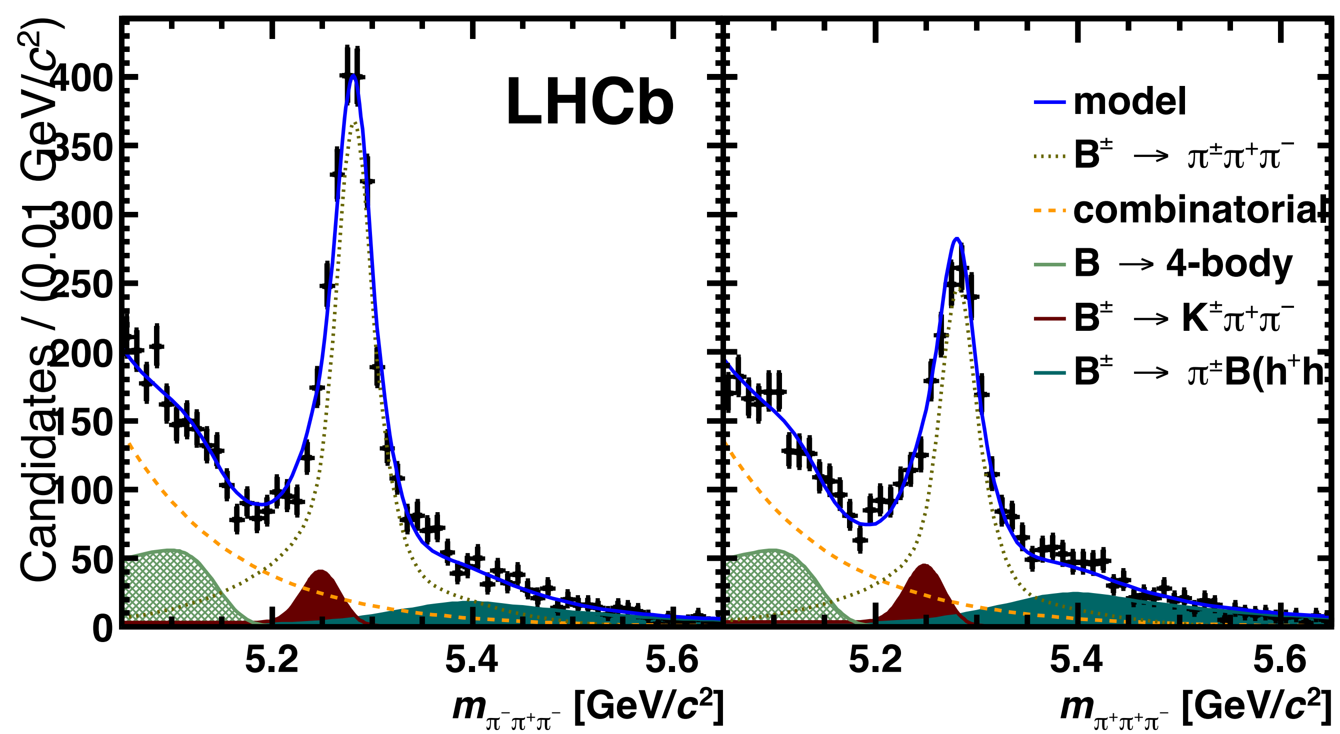


Rescattering

1 < Low [GeV²/c⁴] < 2.25

23 < High [GeV²/c⁴] < 26.5





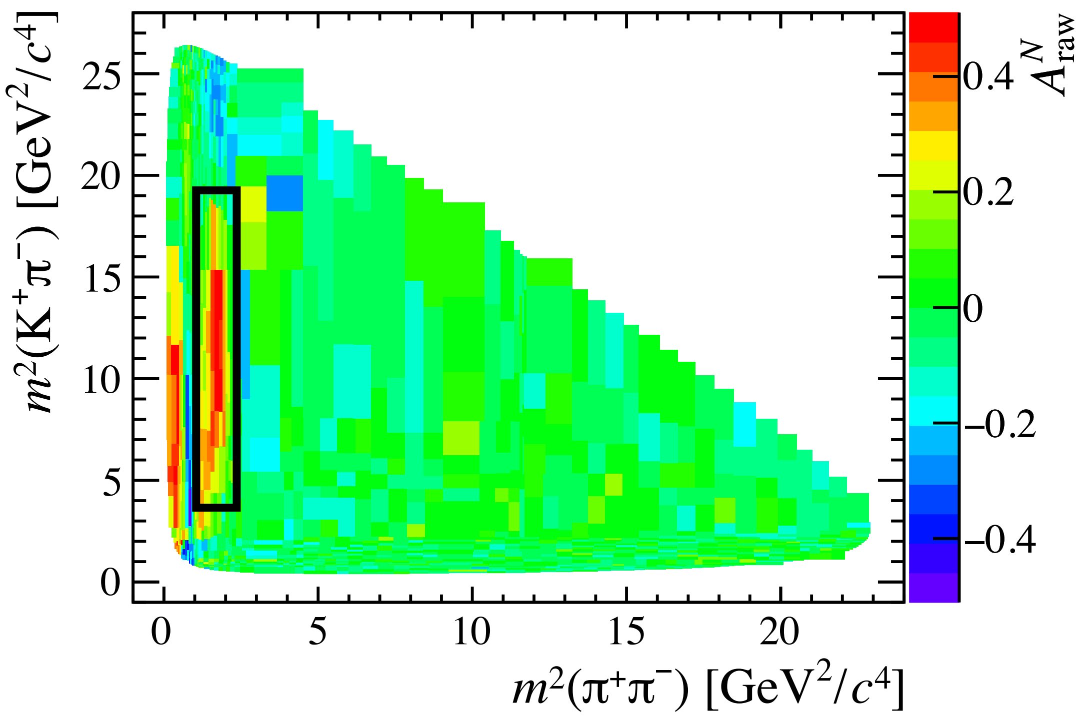
$A_{CP} = 0.211 \pm 0.019$

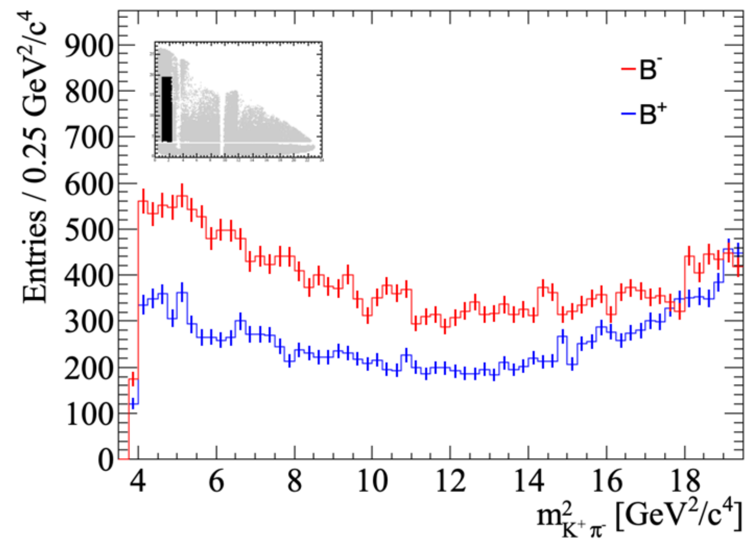
$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$

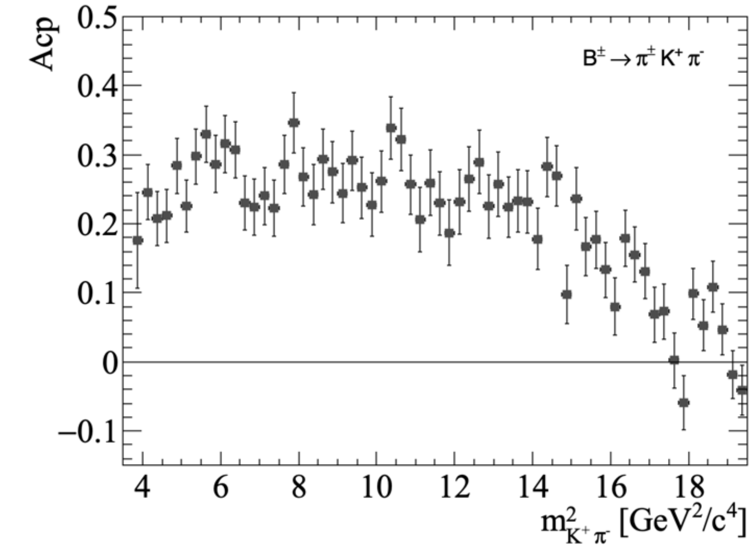
Rescattering

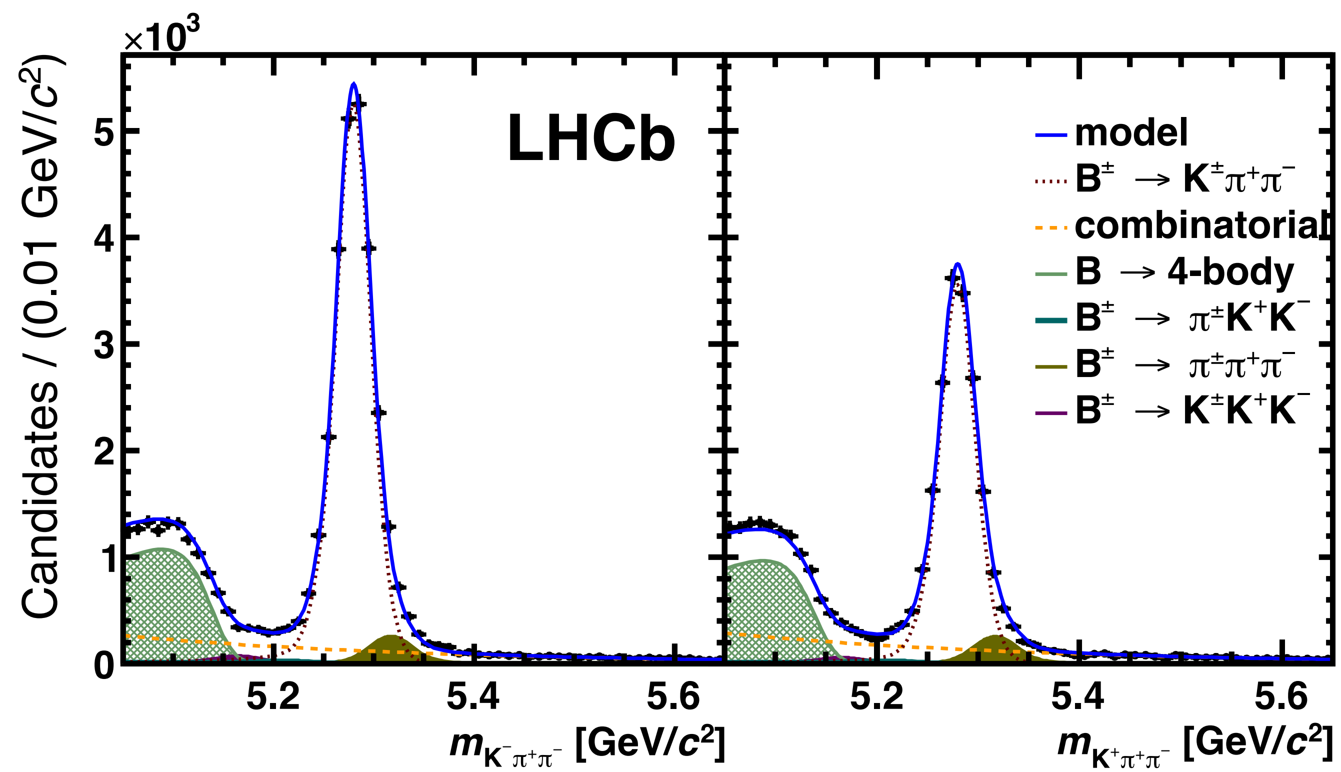
$1 < \pi^{+}\pi^{-}$ [GeV²/c⁴] < 2.25

$3.5 < K^{+}\pi^{-}$ [GeV²/c⁴] < 19.5









$A_{CP} = 0.217 \pm 0.005$

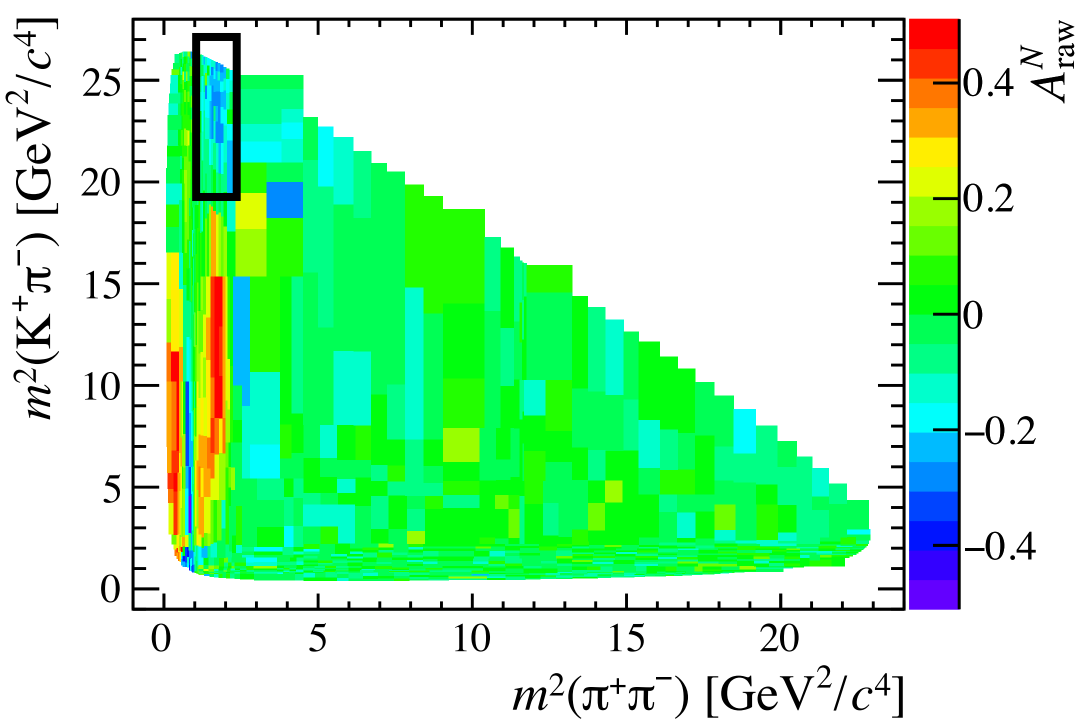
BACKUP

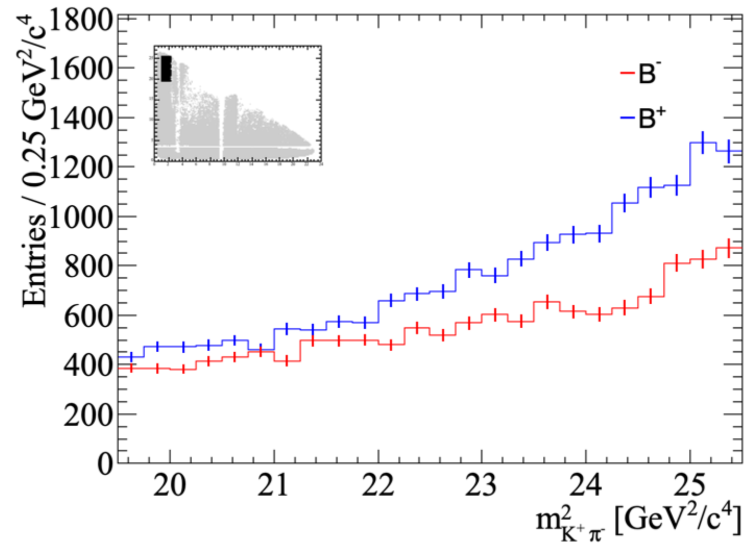
$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$

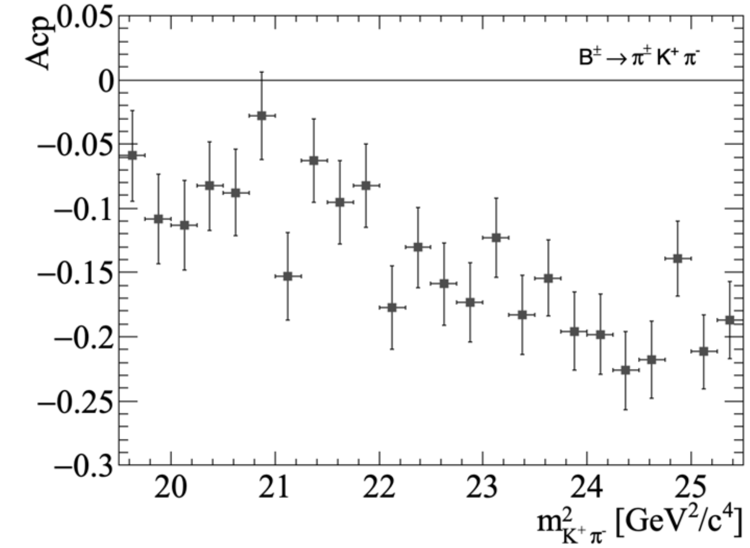
Rescattering

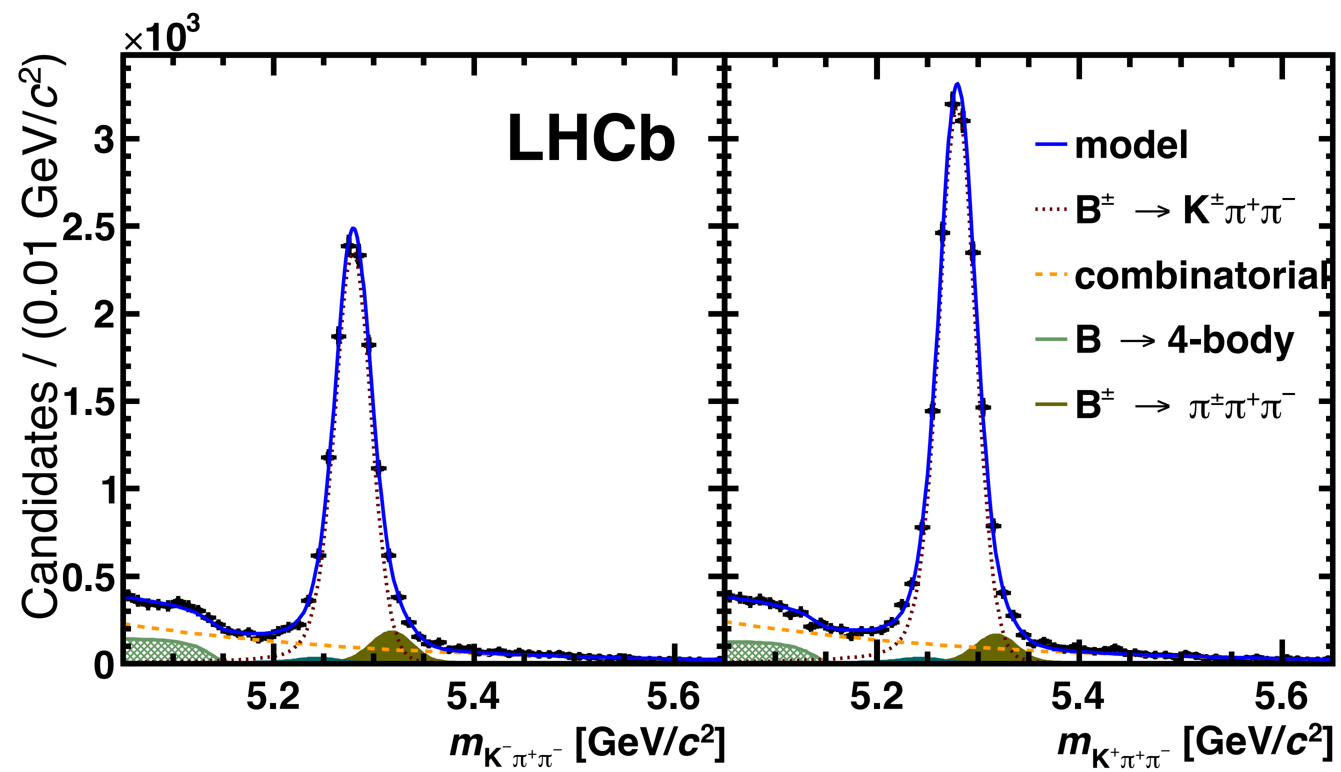
$1 < \pi^{+}\pi^{-}$ [GeV²/c⁴] < 2.25

$19.5 < K^{+}\pi^{-}$ [GeV²/c⁴] < 25.5









$A_{CP} = -0.145 \pm 0.007$

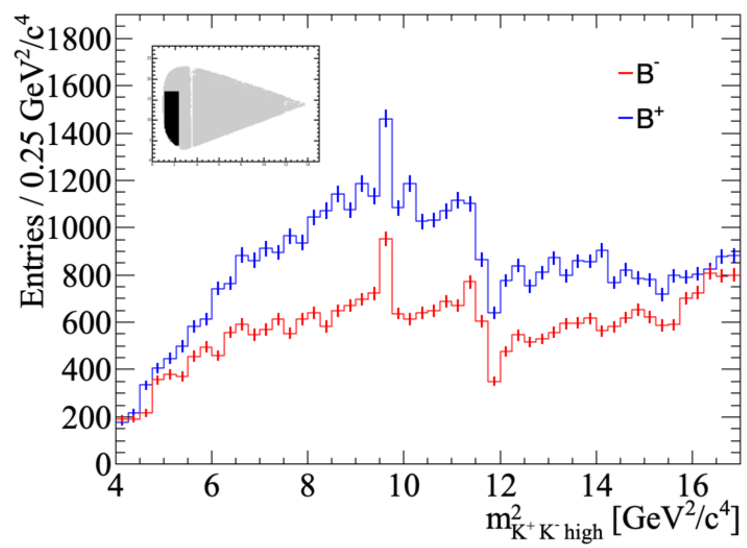
BACKUP

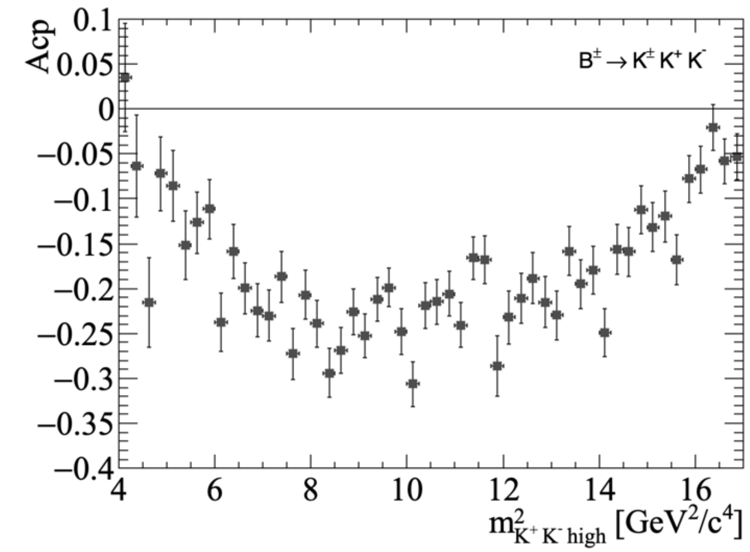
$B^{\pm} \rightarrow K^{\pm}K^{+}K^{-}$

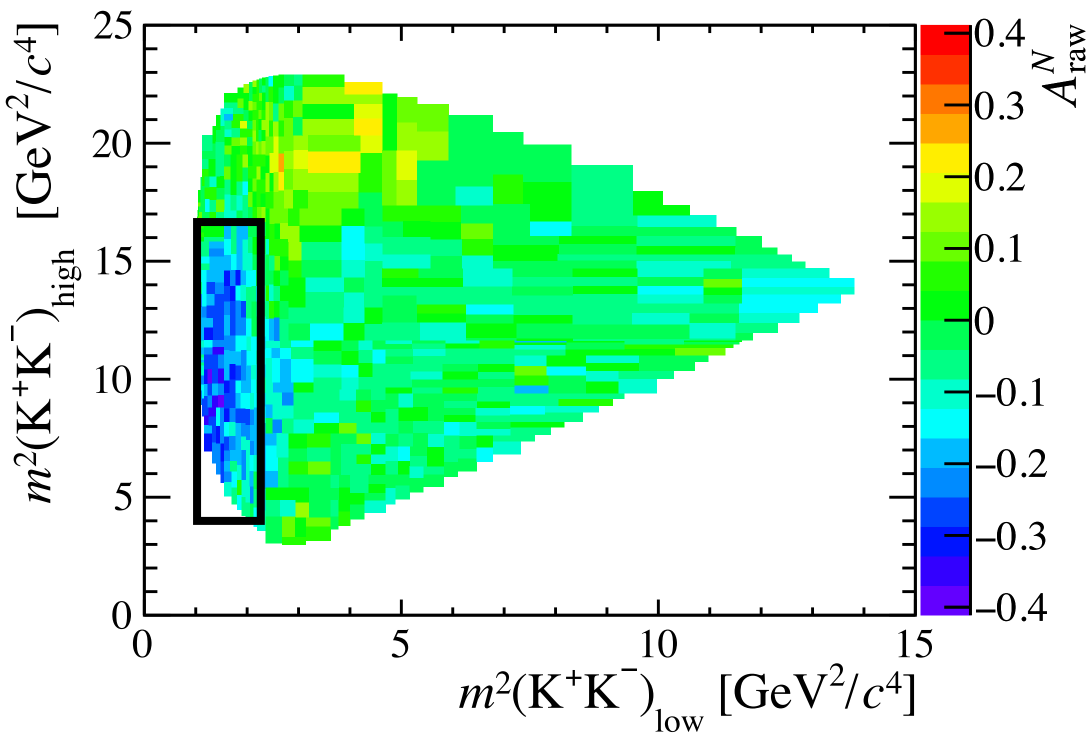
Rescattering

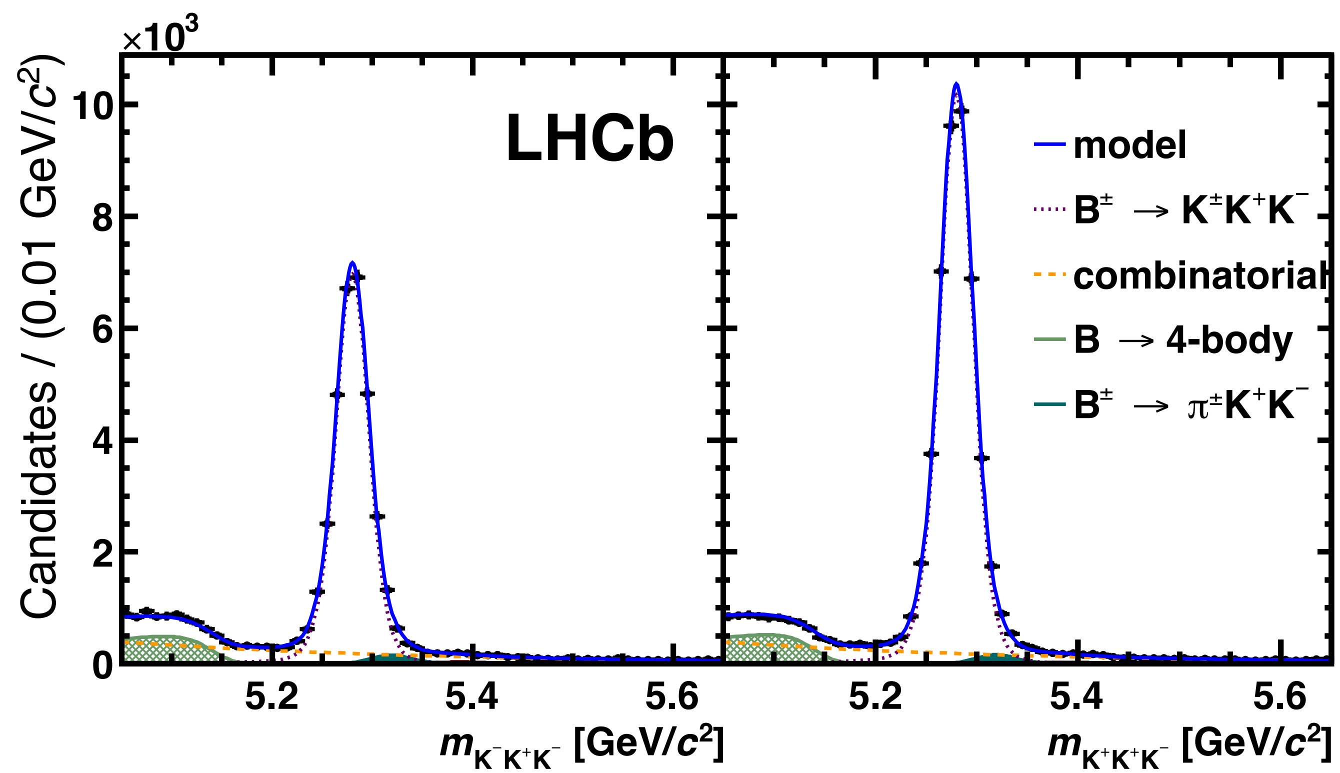
1.1 < Low [GeV²/c⁴] < 2.25

4 < High [GeV²/c⁴] < 17









$A_{CP} = -0.178 \pm 0.004$

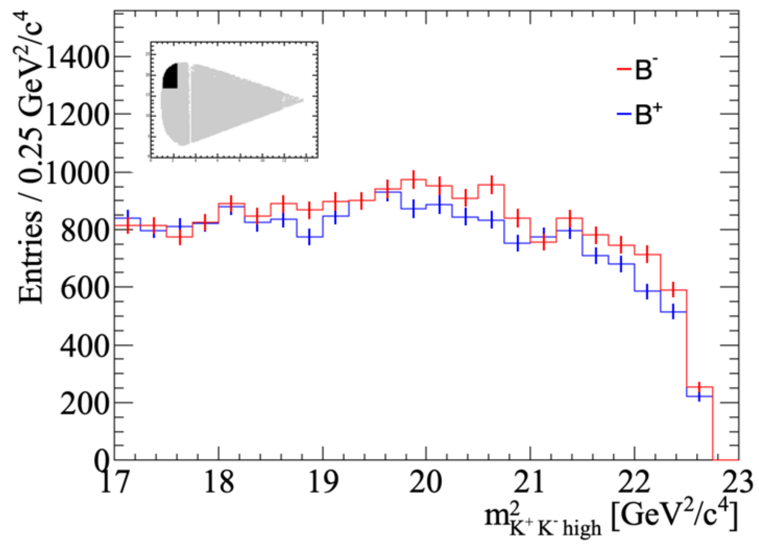
BACKUP

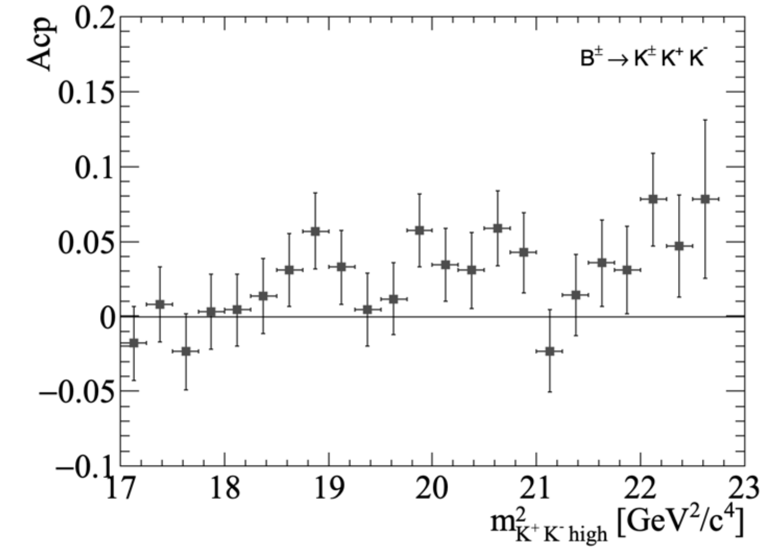
$B^{\pm} \rightarrow K^{\pm}K^{+}K^{-}$

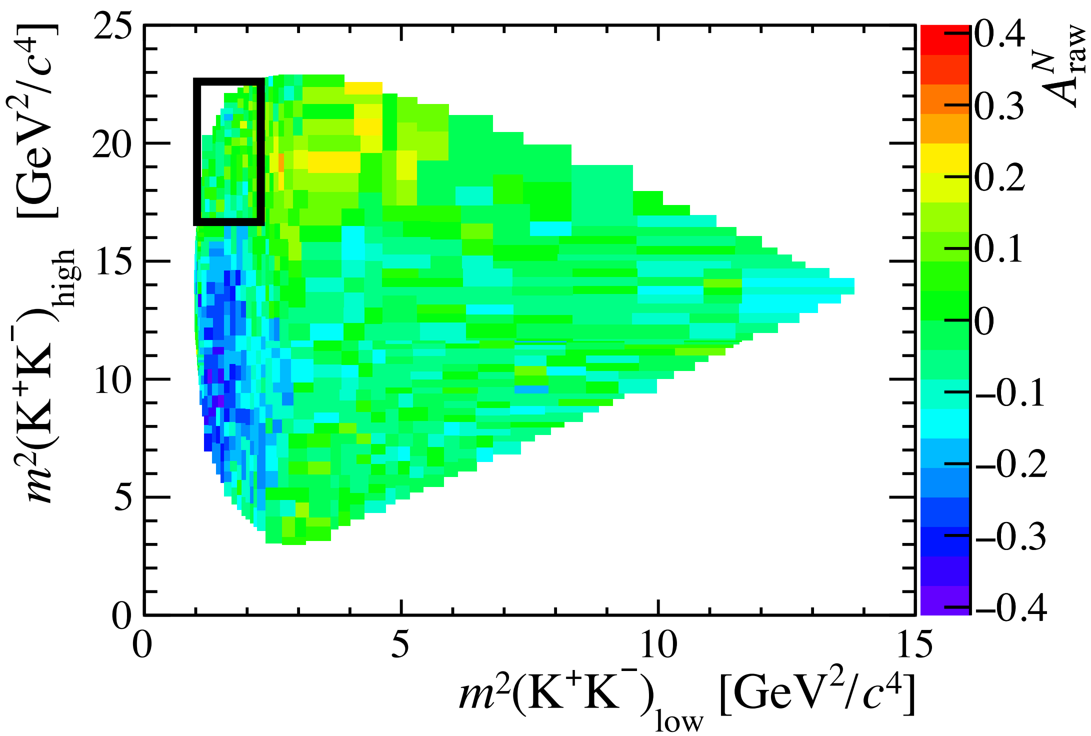
Rescattering

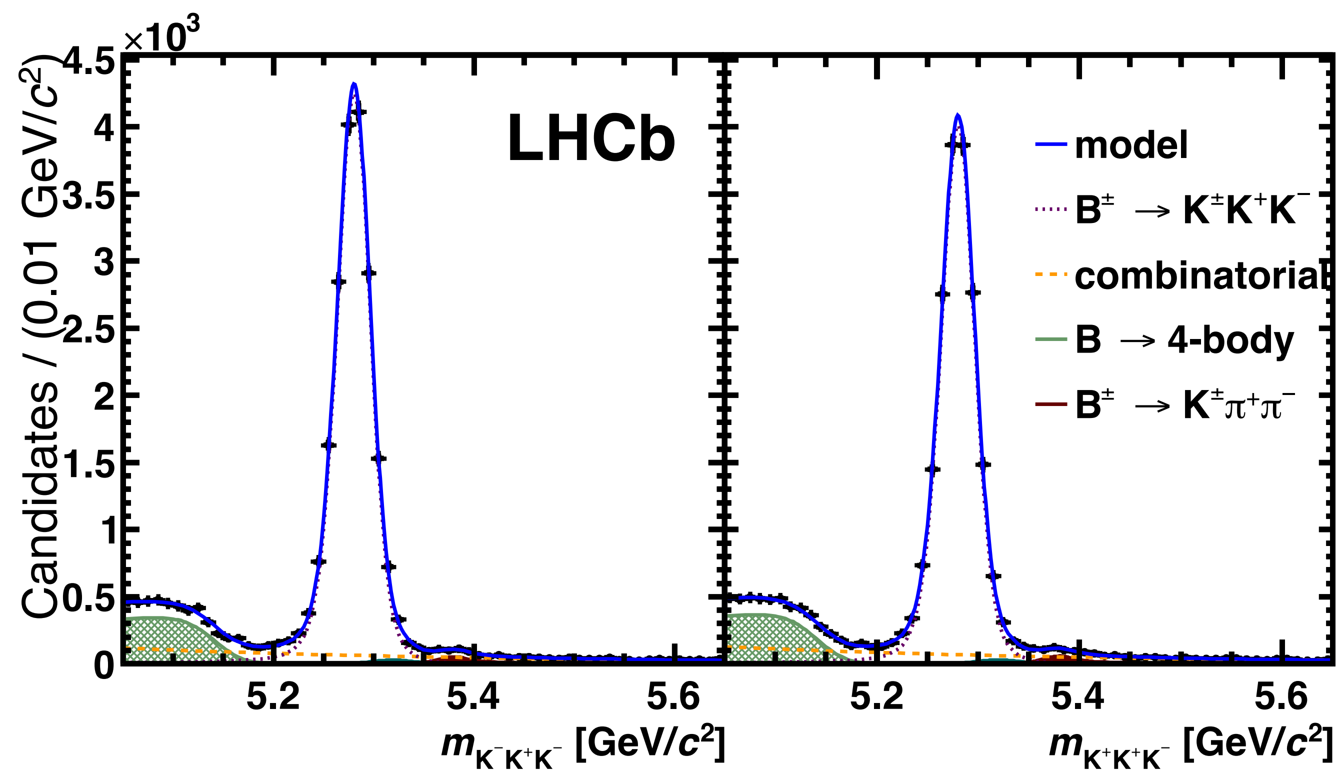
$1.1 < \text{Low}\ [\text{GeV}^2/c^4] < 2.25$

$17 < \text{High}\ [\text{GeV}^2/c^4] < 23$









$A_{CP} = 0.043 \pm 0.005$

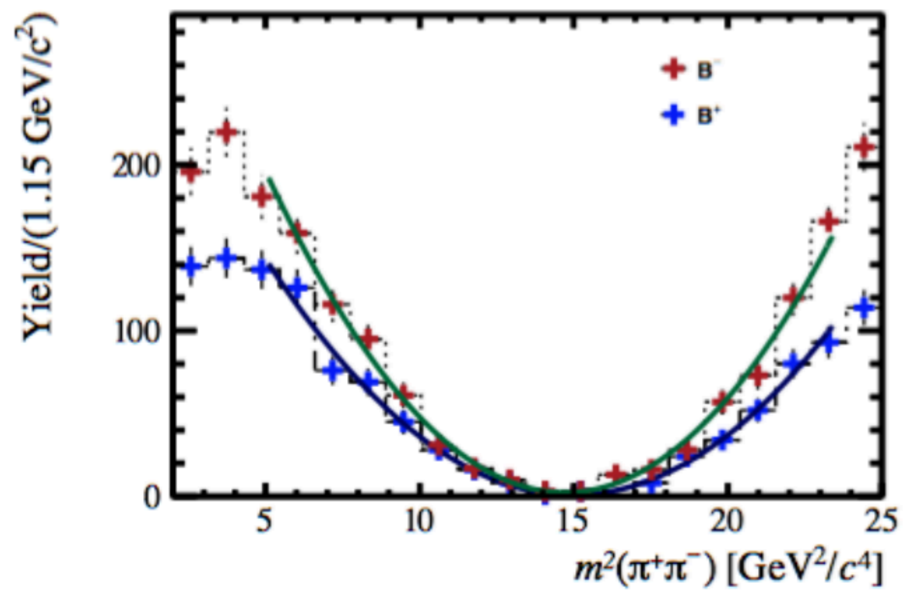
Validation of $B \to PV$ method

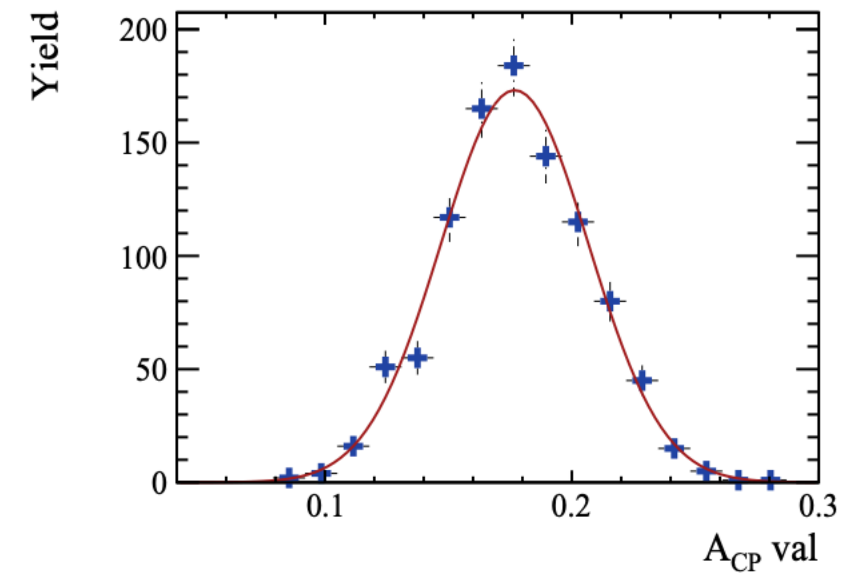
1000 samples simulated, 20000 events each

BaBar inputs for magnitude and phase

$A_{CP}^{\rho(770)} = 18\% \pm 7\ \%$

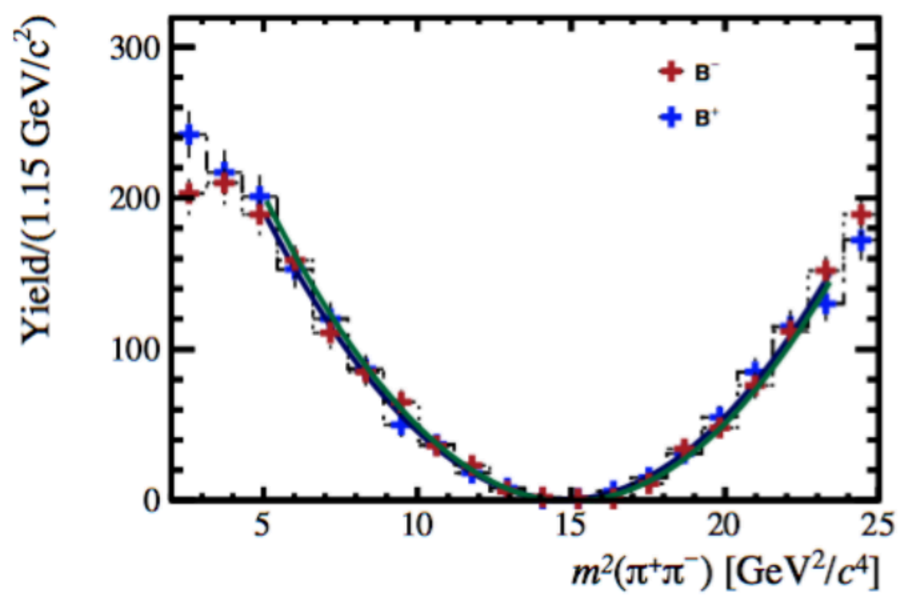
Phys. Rev. D79 (2009) 072006

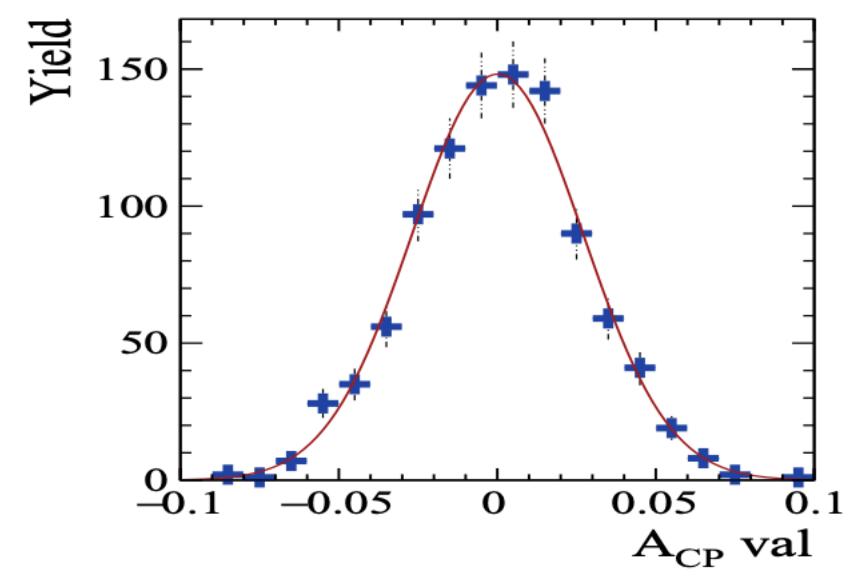




Magnitude modified to obtain

$A_{CP}^{\rho(770)} = 0$





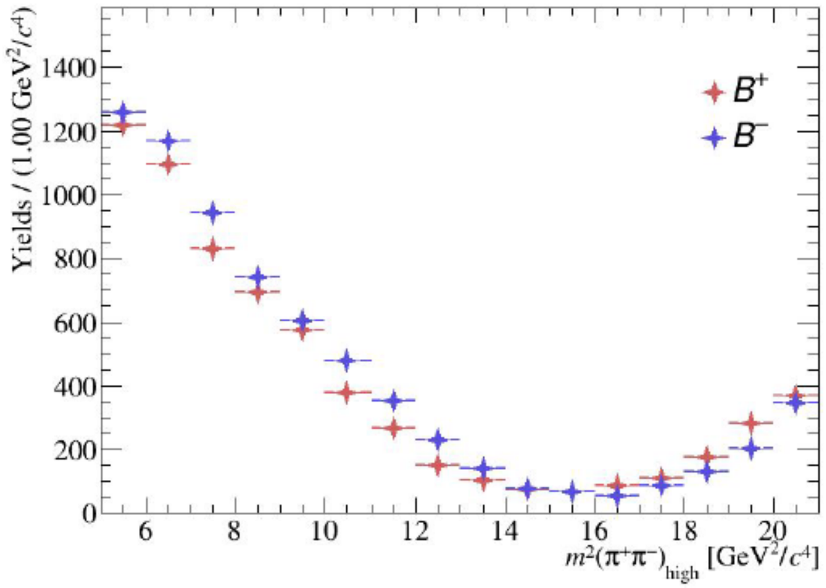
This work: $A_{CP}^{\rho(770)} = 17.7\% \pm 3\ \%$

Phys. Rev. D94 (2016) 054028

Efficiency correction - example for $\rho(770)$ in $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$

- Accounts for overall non-uniform signal efficiencies

→ Dividing B^{+} and B^{-} yields distributions by the scaled efficiency histograms



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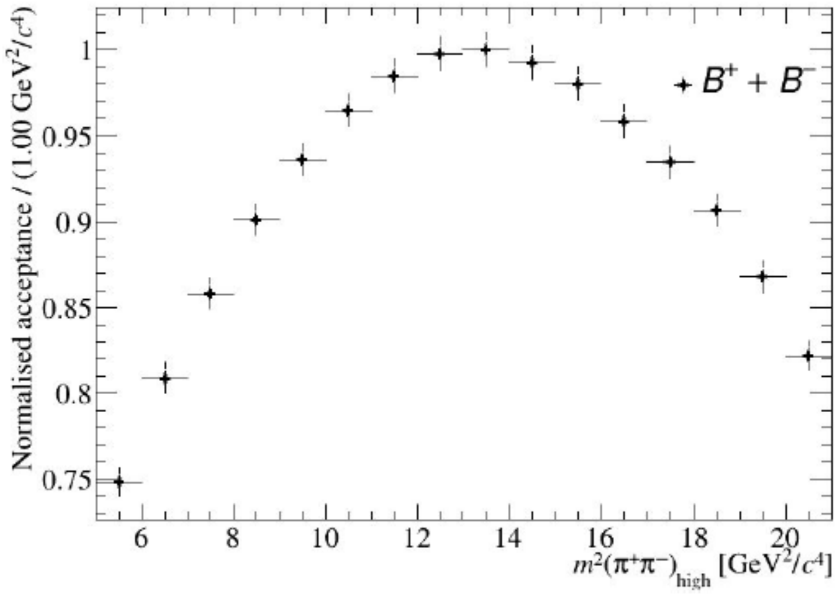

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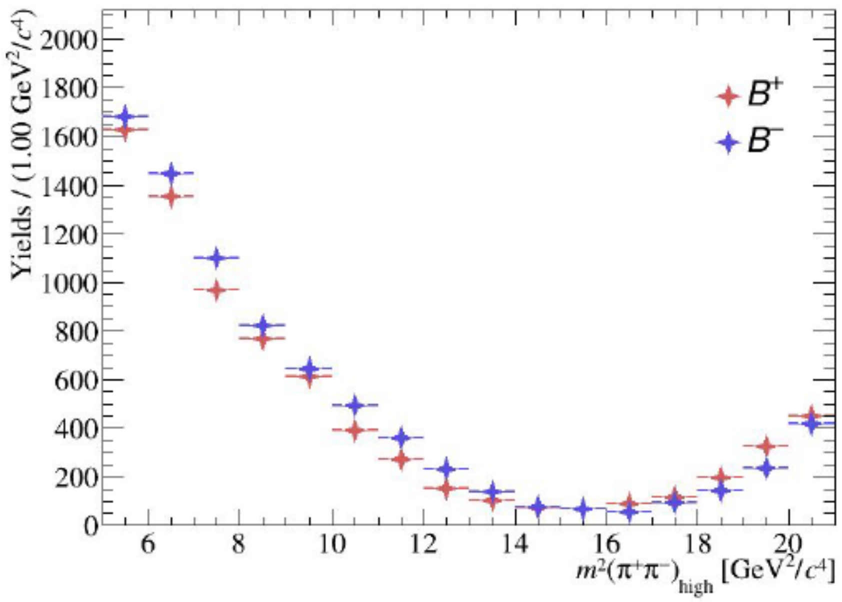
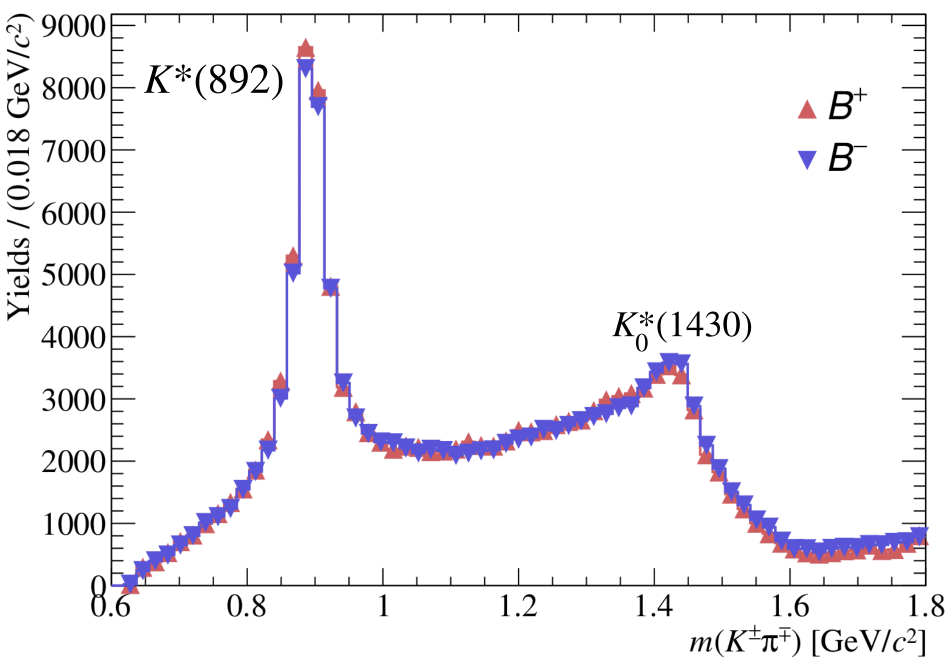
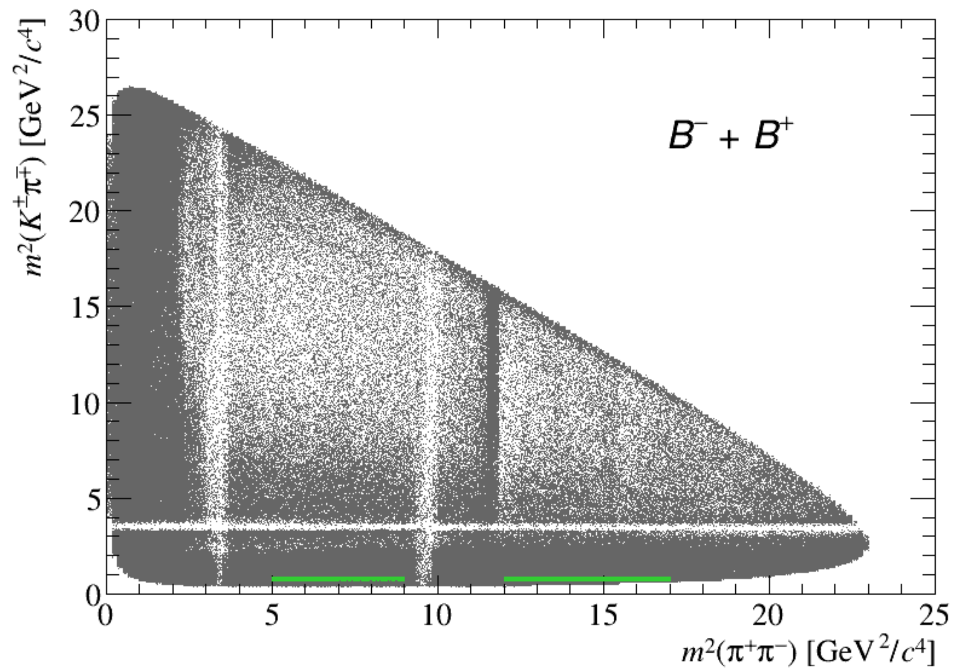


$K^*(892)$ in $B^\pm \to K^\pm\pi^+\pi^-$





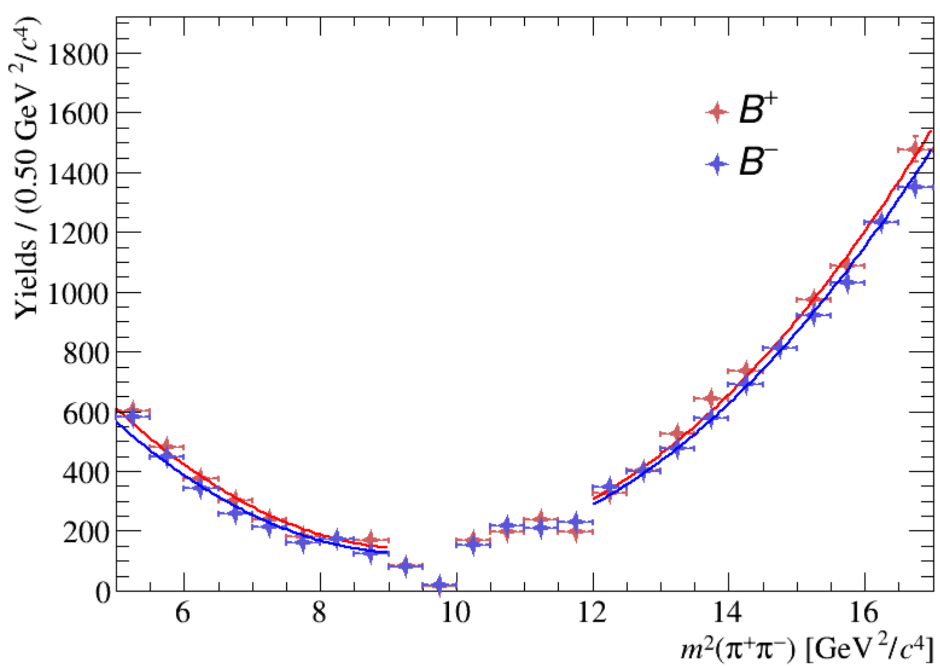
Skipped fit region

- J/ψ mass fit
- χ_{c0} interference

This work

$A_{CP} = (-1.5 \pm 2.1)\,\%$

Fit Parameter	B^+	B^-
p_0	2272 ± 73	2144 ± 70
p_1	-450 ± 15	-429 ± 14
p_2	23.85 ± 0.70	22.82 ± 0.66
χ^2/ndf	1.08	1.38

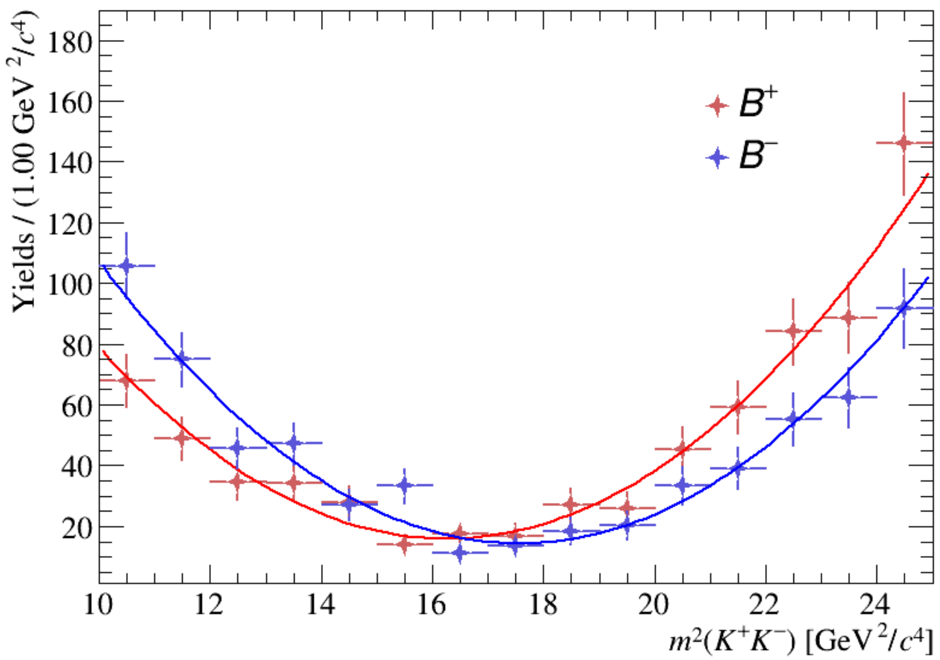


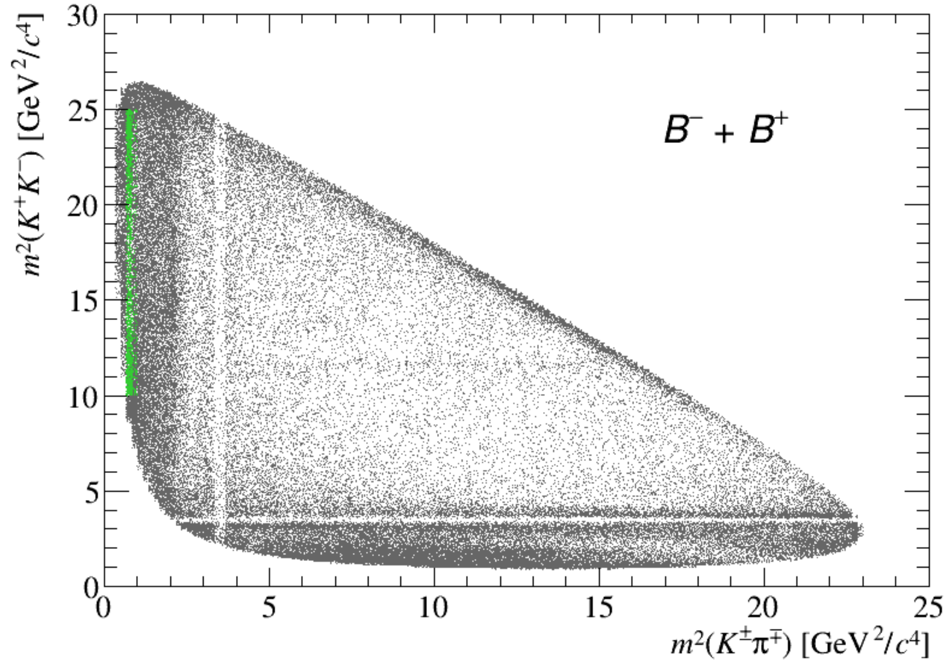
$A_{CP} = (3.2 \pm 5.2 \pm 1.1)\,\%$

BaBar

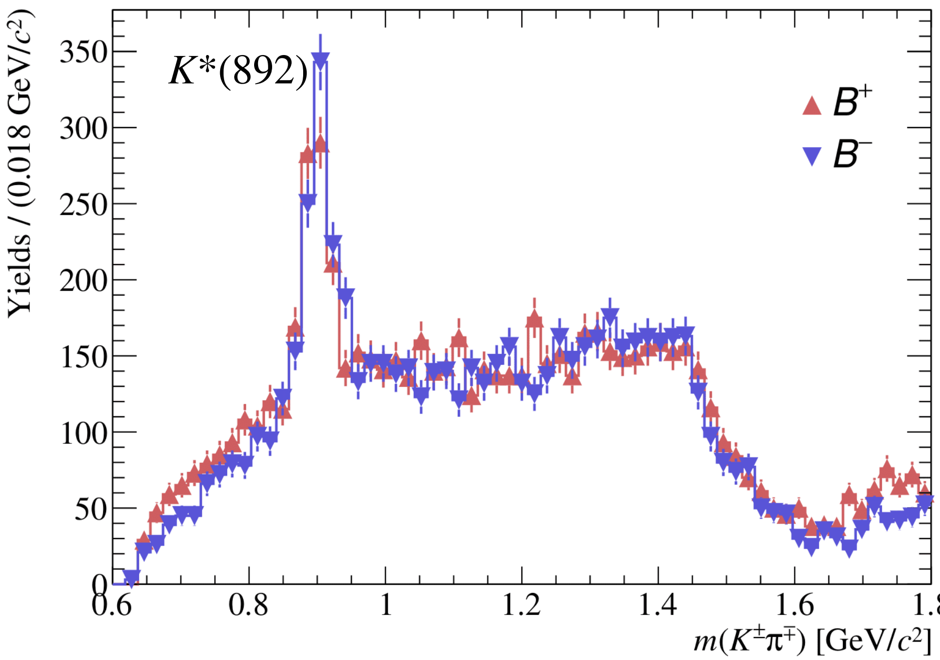
Phys. Rev. D78 (2008) 012004

$K^*(892)$ in $B^\pm \to \pi^\pm K^+ K^-$





Fit Parameter	B^+	B^-
p_0	226 ± 18	262 ± 19
p_1	-26.8 ± 2.2	-29.0 ± 2.2
p_2	0.82 ± 0.06	0.82 ± 0.06
χ^2/ndf	0.91	0.86



This work

$A_{CP} = (0.7 \pm 5.4)\,\%$

$A_{CP} = (12.3 \pm 8.7 \pm 4.5)\,\%$

LHCb

Phys. Rev. Lett. 123 (2019) 231802

BACKUP

variant	R	A_{RAW}	A_{P}
`MuonTOS`			
central		-0.011810 ± 0.000815	-0.006951 ± 0.000827
MagUp		-0.01104 ± 0.00115	-0.00618 ± 0.00116
MagDown	0.986767 ± 0.000274	-0.01204 ± 0.00118	-0.00718 ± 0.00119
GaussExp		-0.011810 ± 0.000843	-0.006951 ± 0.000854
background		-0.011840 ± 0.000763	-0.006981 ± 0.000775
`DiMuonTOS`	0.989947 ± 0.000374	-0.010880 ± 0.000899	-0.007630 ± 0.000918
`TIS`	0.987192 ± 0.000574	-0.01199 ± 0.00147	-0.007344 ± 0.000981

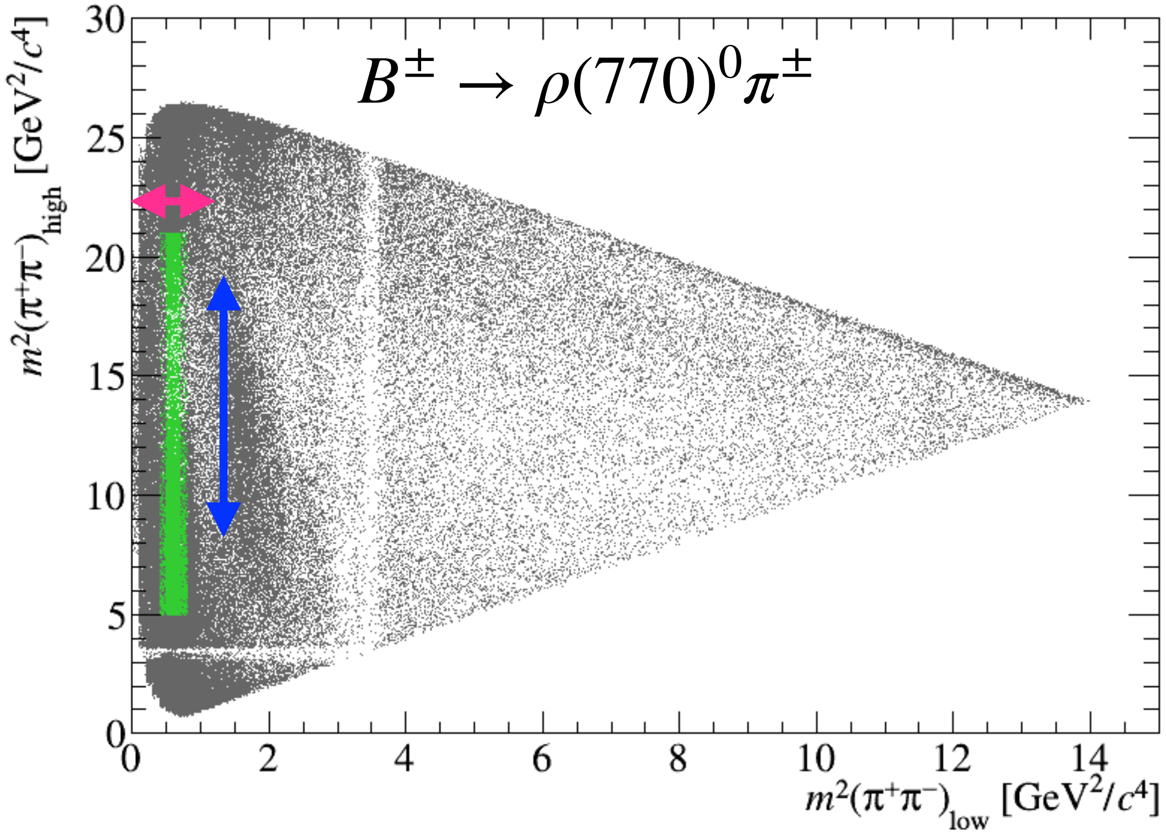
$$A_{\mathrm{P}} = -0.006951 \pm 0.000827^{+0.00068}_{-0.00077}$$

BACKUP

Component	Region	$\pi^{\pm}\pi^{+}\pi^{-}$	$K^{\pm}\pi^{+}\pi^{-}$	$\pi^{\pm}K^{+}K^{-}$	$K^{\pm}K^{+}K^{-}$
Acceptance	All Dalitz plot	0.00181	0.00140	0.00195	0.00164
	Region 1	0.00321	0.00407	0.00302	0.00242
	Region 2	0.00457	0.00497	0.00226	0.00332
	Region 3	0.00560	-	-	-
	Region 4	0.00125	-	-	-
Mass fit (Peaking bkg fraction)	All phase space	0.00017	0.00046	0.00040	0.00099
	Region 1	0.00005	0.00185	0.00406	0.00003
	Region 2	0.00006	0.00024	0.00020	0.00000
	Region 3	0.00483	-	-	-
	Region 4	0.00861	-	-	-
Mass fit (Peaking bkg asymmetry)	All phase space	0.00054	0.00218	0.00068	0.00010
	Region 1	-	-	-	-
	Region 2	-	-	-	-
	Region 3	-	-	-	-
	Region 4	-	-	-	-
Mass fit (Combinatorial model)	All phase space	0.00154	0.00021	0.00253	0.00054
	Region 1	0.00010	0.00212	0.00055	0.00273
	Region 2	0.00177	0.00240	0.00467	0.00050
	Region 3	0.01678	-	-	-
	Region 4	0.01483	-	-	-
Mass fit (Signal model)	All phase space	0.00004	0.00037	0.00013	0.00071
	Region 1	0.00102	0.00191	0.01332	0.00023
	Region 2	0.00506	0.00199	0.00007	0.00030
	Region 3	0.02499	-	-	-
	Region 4	0.00418	-	-	-
Mass fit (Spectrum range)	All phase space	-	-	-	
	Region 1	-	-	-	-
	Region 2	-	-	-	-
	Region 3	0.03000	-	-	-
	Region 4	-	-	-	-
Total	All phase space	0.002	0.003	0.003	0.002
	Region 1	0.003	0.005	0.014	0.004
	Region 2	0.007	0.006	0.005	0.003
	Region 3	0.043	-	-	-
	Region 4	0.018	-	-	-

$B \to PV$ decays

- → Variation of the resonance mass window
- → Variation of the fit regions
- → Projection over $\cos(\theta_{hel})$ instead of $m^2_{(31,23)}$



Decay channel	Vector Resonance	Mass window (MeV/c^2)	Variation (MeV/c^2)	σ
$B^{\pm} \to \pi^{\pm}\pi^+\pi^-$	$\rho(770)^0 \to \pi^+\pi^-$	150	140-160	0.0012
$B^{\pm} \to K^{\pm}\pi^+\pi^-$	$\rho(770)^0 \to \pi^+\pi^-$ $K^*(892)^0 \to K^{\pm}\pi^{\mp}$	150 50	140-160 45-55	0.0012 0.0035
$B^{\pm} \to \pi^{\pm}K^+K^-$	$K^*(892)^0 \to K^{\pm}\pi^{\mp}$	50	45-55	0.0151
$B^{\pm} \to K^{\pm}K^+K^-$	$\phi(1020) \to K^+K^-$	5	4.5-5.5	0.0030

Decay channel	Vector Resonance	Projection range (GeV^2/c^4)	Variation (GeV^2/c^4)	σ
$B^{\pm} \to \pi^{\pm}\pi^+\pi^-$	$\rho(770)^0 \to \pi^+\pi^-$	5-21	4-20 → 6-22	0.0071
$B^{\pm} \to K^{\pm}\pi^+\pi^-$	$\rho(770)^0 \to \pi^+\pi^-$ $K^*(892)^0 \to K^{\pm}\pi^{\mp}$	5-22 5-17	4-21 → 6-23 4-16 → 6-18	0.0076 0.0061
$B^{\pm} \to \pi^{\pm}K^+K^-$	$K^*(892)^0 \to K^{\pm}\pi^{\mp}$	10-25	9-24 → 11-26	0.0235
$B^{\pm} \to K^{\pm}K^+K^-$	$\phi(1020) \to K^+K^-$	11-16	10.5-15.5 → 11.5-16.5	0.0053

Decay channel	Vector Resonance	$A_{CP}(m^2(h^+h^-))$	$A_{CP}(\cos\theta_{hel})$	σ
$B^{\pm} \to \pi^{\pm}\pi^+\pi^-$	$\rho(770)^0 \to \pi^+\pi^-$	-0.0035 ± 0.0171	$+0.0014 \pm 0.0183$	0.0049
$B^{\pm} \to K^{\pm}\pi^+\pi^-$	$\rho(770)^0 \to \pi^+\pi^-$ $K^*(892)^0 \to K^{\pm}\pi^{\mp}$	$+0.1501 \pm 0.0189$ -0.0151 ± 0.0206	$+0.1578 \pm 0.0223$ -0.0054 ± 0.0220	0.0077 0.0097
$B^{\pm} \to \pi^{\pm}K^+K^-$	$K^*(892)^0 \to K^{\pm}\pi^{\mp}$	$+0.0073 \pm 0.0543$	$+0.0225 \pm 0.0651$	0.0153
$B^{\pm} \to K^{\pm}K^+K^-$	$\phi(1020) \to K^+K^-$	$+0.0035 \pm 0.0104$	$+0.0067 \pm 0.0117$	0.0032

BACKUP

Background subtraction method