CP violation in B decays at LHCb

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on behalf of the LHCb collaboration

Overview

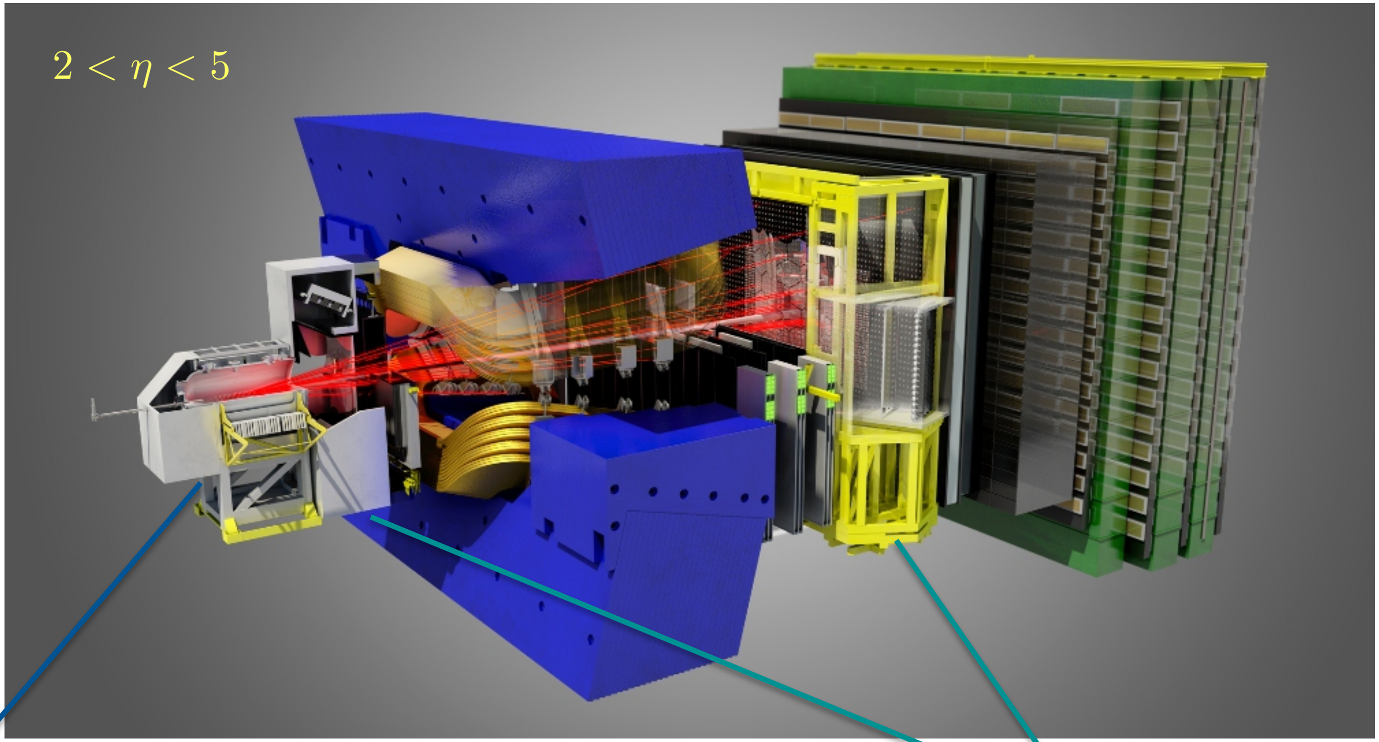
- B decays are an interesting environment to study CP violation: large O(10%) CP violation effects are observed
- Can use CP-violating observables to
  - test the CKM matrix unitarity condition
  - probe New Physics

- Recent LHCb results are presented:

1. Tree-level determination of CKM angle γ
   – $B^{\pm} \to D(K^0_{\mathrm{S}} h^+ h^-) K^{\pm}$ arXiv:1408.2748
2. Inclusive and local direct CP asymmetries
   – three-body charmless $B^{\pm}$ decays arXiv:1408.5373
3. CP violation in interference between mixing and decay
   – $B^0_s \to \phi\phi$ arXiv:1407.2222

LHCb detector

3.0 fb^{-1} of data collected during Run 1 (2011-2012)



VELO
(VErtex LOcater)
Powerful discriminator for B mesons which have flight distance ~1 cm at LHCb
Impact parameter resolution ~ 20 μm: vital for triggers and offline selection

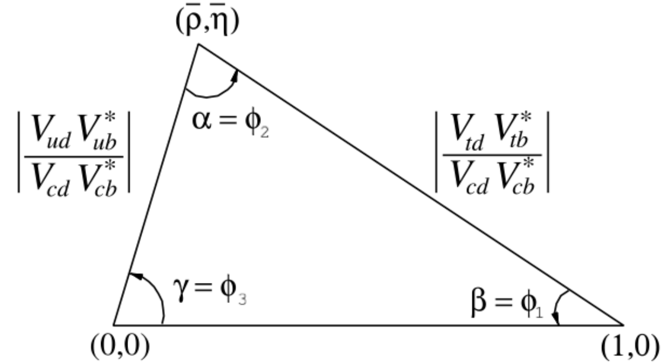
RICH I & II
(Ring Imaging CHerenkov detectors)
Particle Identification: π, K, p
Essential to differentiate B, D final states
Two systems for different momentum ranges

Tree-level determination of γ

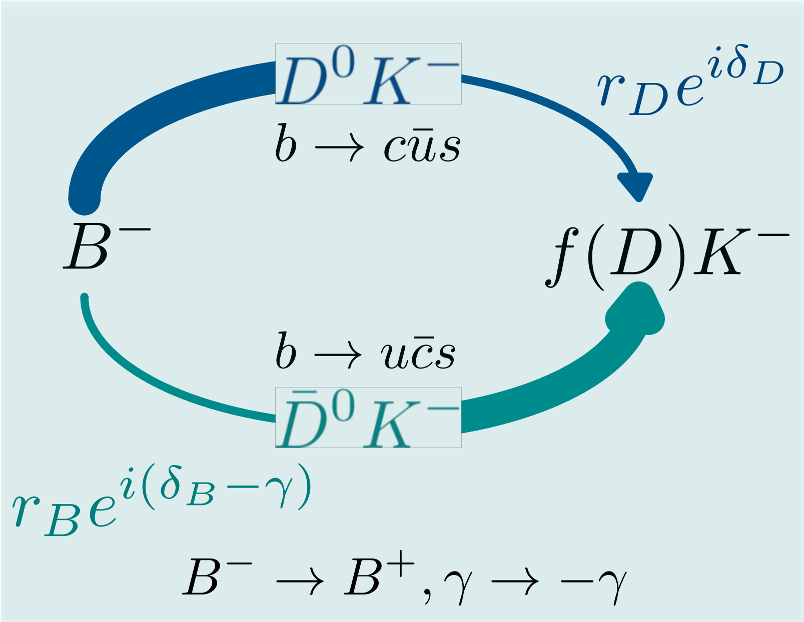
$$B^- \to D(\to K^0_{\mathrm{S}} h^+ h^-) K^-$$

CKM angle γ

- **Unitarity Triangle:** visualises one of the off-diagonal unitarity conditions of the CKM quark-mixing matrix
- Of the three angles, it is the **least well known** and **the only one that can be measured at tree-level**
- Current world average from CKMfitter Winter '14
  - direct measurements: $\gamma = (70.0^{+7.7}_{-9.9})^\circ$
  - indirect measurements: $\gamma = (66.5^{+1.3}_{-2.5})^\circ$
- Can be measured with $B^- \to DK^-$, where D is an admixture of D^0 and $\overline{D}^0$ decaying to same final state
- Hadronic terms enter and need to be experimentally determined
  - r = ratio of amplitude moduli
  - δ = strong phase difference
- Many D final states to be exploited

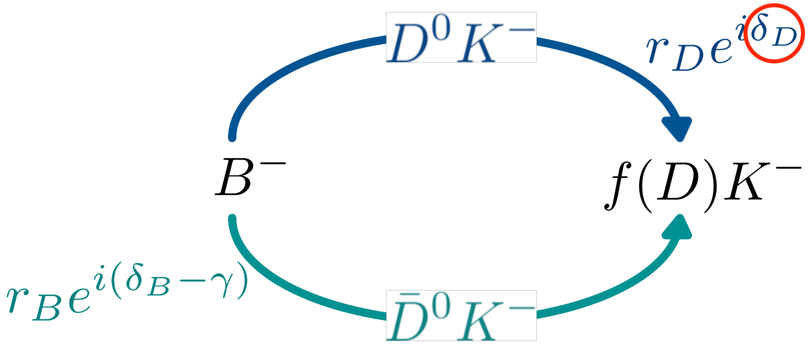


$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$



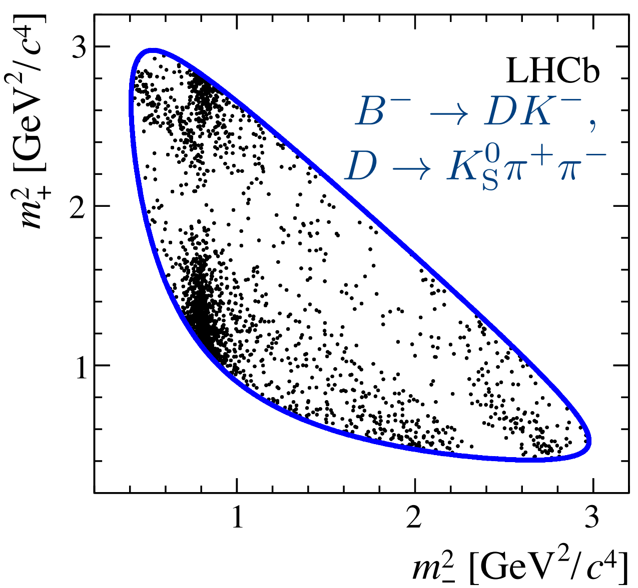
**CPV and mixing in the D system are ignored*

'GGSZ': $f(D) = K^0_S\pi^+\pi^-, K^0_S K^+ K^-$



Multi-body decay

- δ_D (and hence decay rate) varies with final-state kinematics
- Parameterise in phase space of **Dalitz plot:**
  $(m^2_-, m^2_+) \equiv (m^2(K^0_S h^-), m^2(K^0_S h^+))$



Two methods pursued at LHCb

Model-dependent method
Fit the data to an amplitude model to provide δ_D

arXiv:1407.6211

Model-independent method
Use external measurements of δ_D averaged in binned regions of Dalitz plot

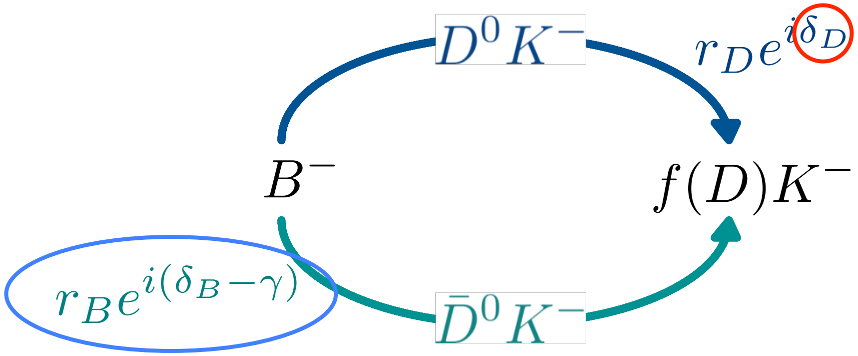
Measurements from quantum-correlated $\psi(3770) \to D\overline{D}$ decays by CLEO experiment

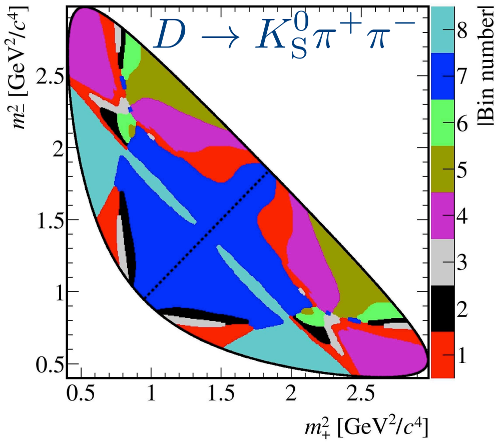
PRD 82, 112006 (2010)

Key advantages
1. systematics remain robust as statistics grow
2. reduces to a counting experiment

However, lose some statistical sensitivity as the phase space is binned.

Model-independent method





Decay rate to bin *i*:

$$N_{\pm i}(B^-) \propto \left(F_{\pm i} + (x_-^2 + y_-^2)F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_- c_i \pm y_- s_i)\right)$$

$$N_{\pm i}(B^+) \propto \left(F_{\mp i} + (x_+^2 + y_+^2)F_{\pm i} + 2\sqrt{F_i F_{-i}}(x_+ c_i \pm y_+ s_i)\right)$$

c_i, s_i amplitude-weighted cosine, sine δ_D integrated over bin	F_i fractional yield of flavour-tagged $D^0 \to K^0_S h^+ h^-$ in bin	$x_\pm = r_B \cos(\delta_B \pm \gamma)$ $y_\pm = r_B \sin(\delta_B \pm \gamma)$
External input from CLEO-c	Measure with a flavour-tagged control mode which has same efficiency profile as signal	Extract from simultaneous fit to all bins

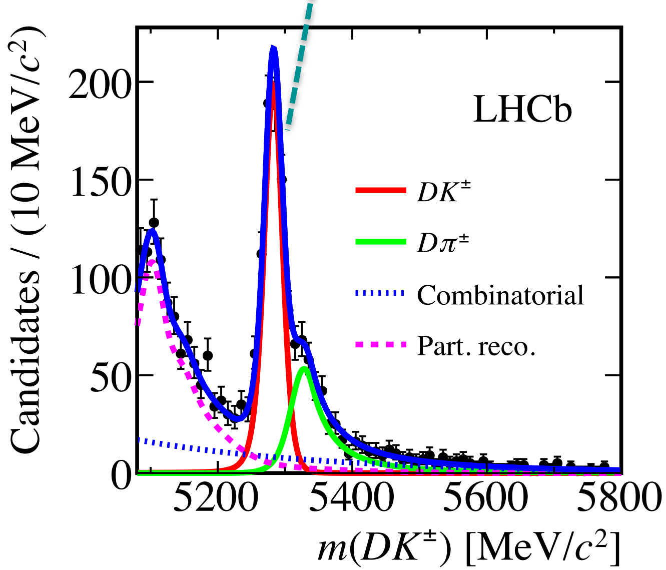
all we need to know are the relative yields of the signal and control mode in each bin!

Model-independent method

$$N_{\pm i}(B^-) \propto \left(F_{\pm i} + (x_-^2 + y_-^2) F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_- c_i \pm y_- s_i) \right)$$

2580 signal decays selected

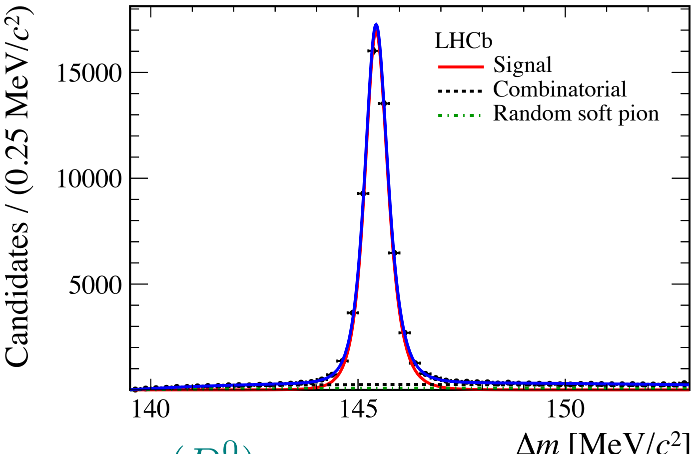
$D \to K^0_S \pi^+ \pi^-, K^0_S K^+ K^-$



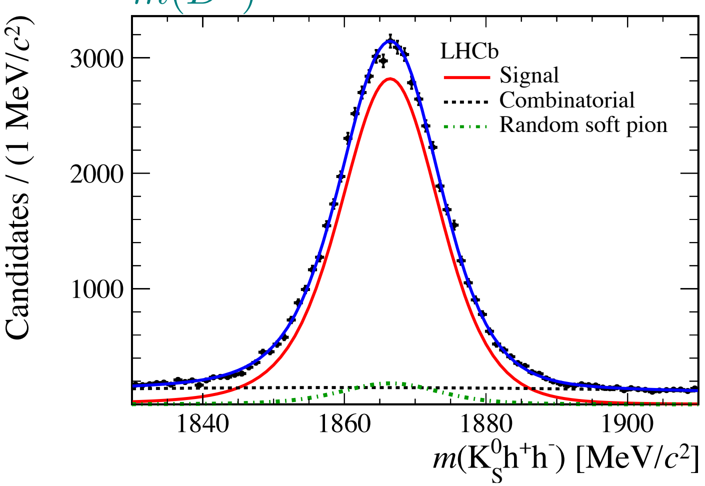
low level of $B \to D\pi$ cross-feed and other backgrounds

Also from LHCb data: $B \to D^{*+}\mu^-\bar{\nu}_\mu, D^{*+} \to D^0\pi^+$

$m(D^{*\pm}) - m(D^0)$



$m(D^0)$



High yield

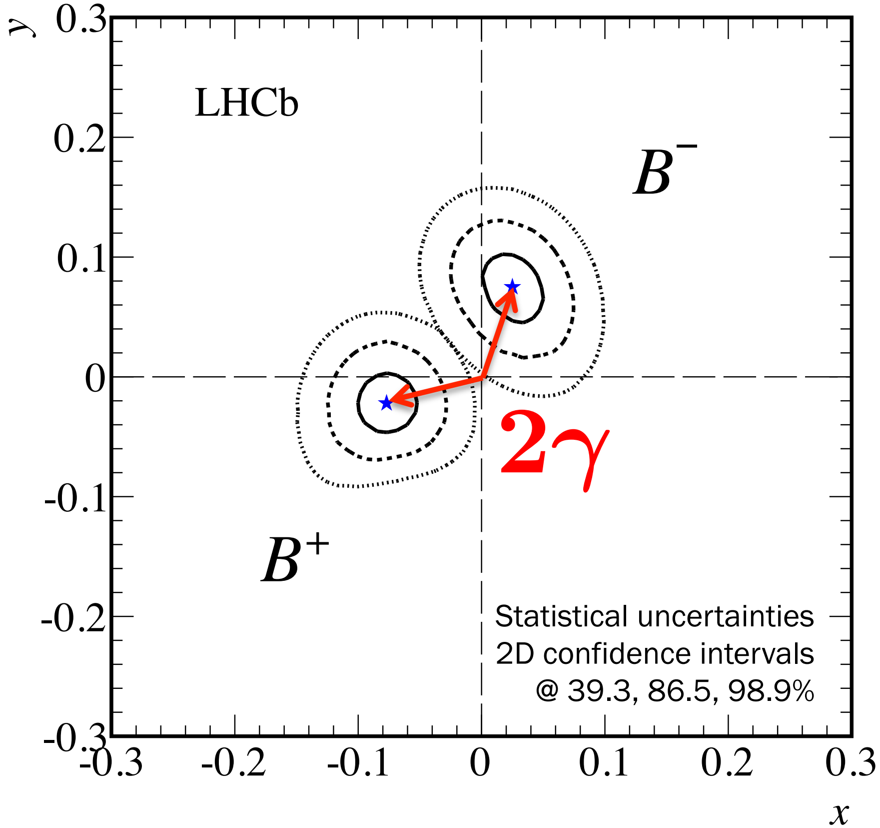
(~ 40×signal yield)

High purity

Negligible mistag rate

Fit to CP observables

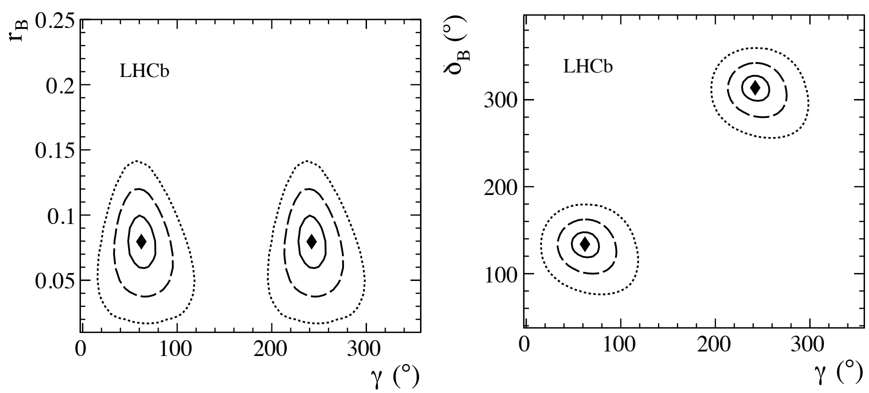
$$x_\pm = r_B \cos(\delta_B \pm \gamma)$$
$$y_\pm = r_B \sin(\delta_B \pm \gamma)$$



Most accurate measurement of these *CP* observables to date

$$x_+ = (-7.7 \pm 2.4 \pm 1.0 \pm 0.4) \times 10^{-2}$$
$$y_+ = (-2.2 \pm 2.5 \pm 0.4 \pm 1.0) \times 10^{-2}$$
$$x_- = (2.5 \pm 2.5 \pm 1.0 \pm 0.5) \times 10^{-2}$$
$$y_- = (7.5 \pm 2.9 \pm 0.5 \pm 1.4) \times 10^{-2}$$

Statistical **Experimental** **strong phase measurements**



3D confidence intervals @ 19.9, 74.9, 98.1% projected onto 2D

$$\boxed{\begin{aligned} \gamma &= \left(62\,^{+15}_{-14}\right)^\circ \\ \delta_B &= \left(134\,^{+14}_{-15}\right)^\circ \\ r_B &= \left(8.0\,^{+1.9}_{-2.1}\right) \times 10^{-2} \end{aligned}}$$

Precision matches that of B-factory γ combinations

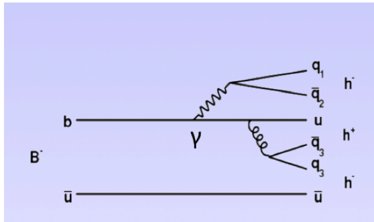
Inclusive and local direct CP asymmetries

three-body charmless $B^{\pm}$ decays

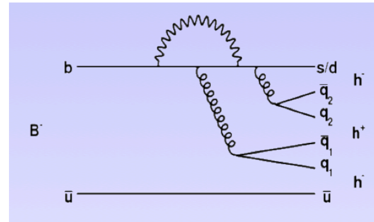
$B^{\pm} \to h^{(\prime)\pm} h^{+} h^{-}$ decays

Interference between tree- and loop-level contributions:

$$\Gamma(B \to f) = \Bigg|$$



$$+$$



$$\Bigg|^2 = |Ae^{i(s_A+w_A)} + Be^{i(s_B+w_B)}|^2$$

$$\begin{aligned} A_{CP} &\propto \Gamma(B \to f) - \Gamma(\overline{B} \to \bar{f}) \\ &= |Ae^{i(s_A+w_A)} + Be^{i(s_B+w_B)}|^2 - |Ae^{i(s_A-w_A)} + Be^{i(s_B-w_B)}|^2 \\ &= 4AB \sin(\underline{w_A - w_B}) \sin(\underline{s_A - s_B}) \end{aligned}$$

Direct CP violation requires at least two amplitudes with $\boxed{\text{weak}}$ *and* $\boxed{\text{strong}}$ phase differences

different CKM matrix elements involved in tree and loop

- **Short-distance process:** Gluon in penguin diagram
- **Long-distance processes**

a) Amplitudes of intermediate resonances

Breit-Wigner propagator: phase varies with resonant mass

Final-state interactions: constant phase difference

CP violation from interference

b) Rescattering $\pi\pi \leftrightarrow KK$

Occurs between final states with same quantum numbers

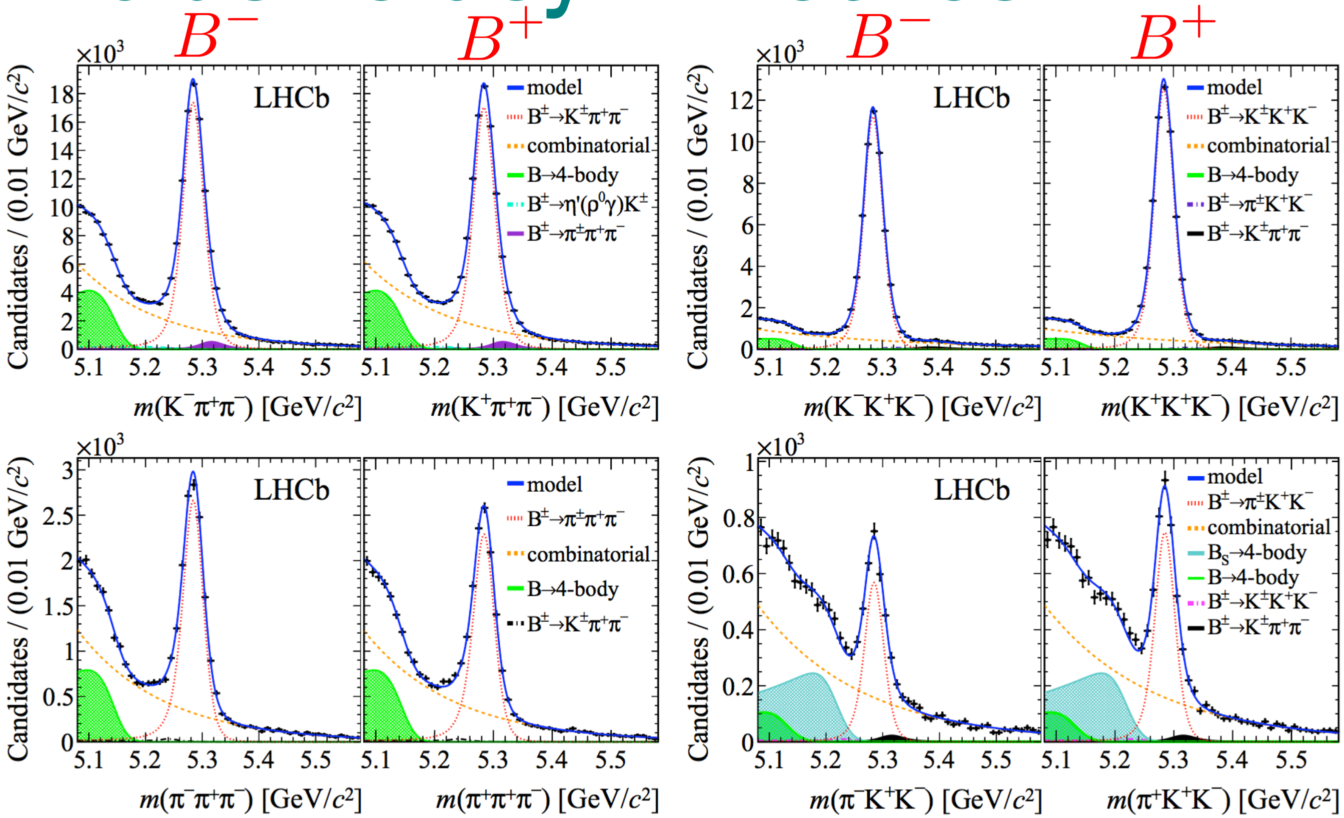
$\Rightarrow$ Expect large asymmetries in the rescattering region

$\Rightarrow$ CPT requires opposite-sign asymmetries for $\pi\pi, KK$

CP violation from rescattering

The processes inducing strong phase differences can be studied with local asymmetries

Inclusive asymmetries



$$A_{\text{raw}} = \frac{N_{B^-} - N_{B^+}}{N_{B^-} + N_{B^+}}$$

Raw asymmetries corrected for:

- detection asymmetry
- production asymmetry
- kaon matter-interaction asymmetry

$$\begin{aligned}
A_{CP}(B^\pm \to K^\pm\pi^+\pi^-) &= +0.025 \pm 0.004 \pm 0.004 \pm 0.007\,, & 2.8\sigma \\
A_{CP}(B^\pm \to K^\pm K^+K^-) &= -0.036 \pm 0.004 \pm 0.002 \pm 0.007\,, & 4.3\sigma \\
A_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-) &= +0.058 \pm 0.008 \pm 0.009 \pm 0.007\,, & 5.6\sigma \\
A_{CP}(B^\pm \to \pi^\pm K^+K^-) &= -0.123 \pm 0.017 \pm 0.012 \pm 0.007\,, & 4.2\sigma
\end{aligned}$$

stat. syst.

Yield
$181\,074 \pm 556$
$109\,240 \pm 354$
$24\,907 \pm 222$
$6\,161 \pm 172$

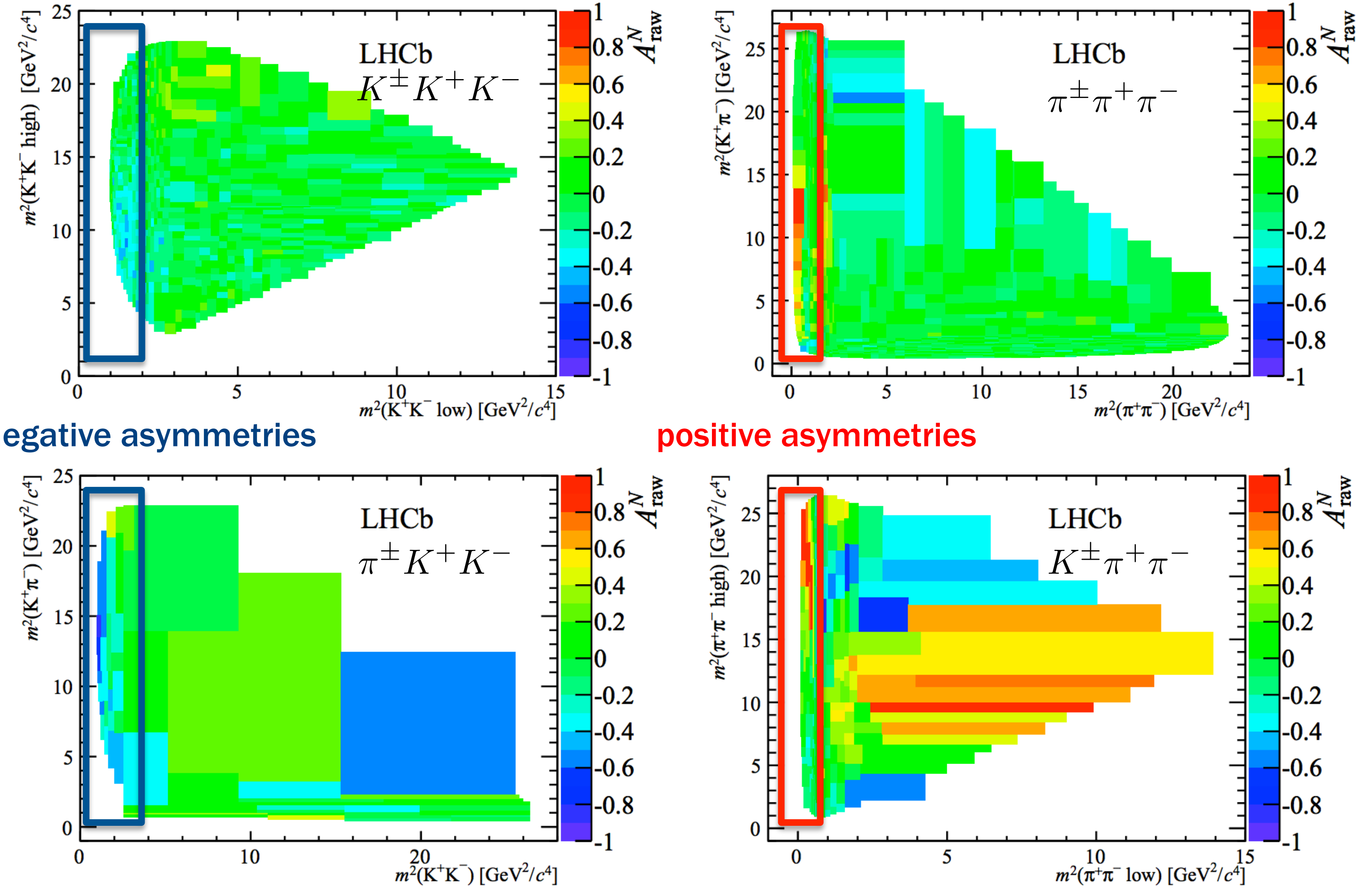
syst. due to $A_{CP}(B^\pm \to J/\psi K^\pm) = (0.1 \pm 0.7)\%$

Asymmetries incompatible with $A_{CP} = 0$

Local asymmetries

$$A_{\rm raw} = \frac{N_{B^-} - N_{B^+}}{N_{B^-} + N_{B^+}}$$

Background-subtracted and acceptance-corrected asymmetries
Adaptive binning: ~ equal statistics in each bin

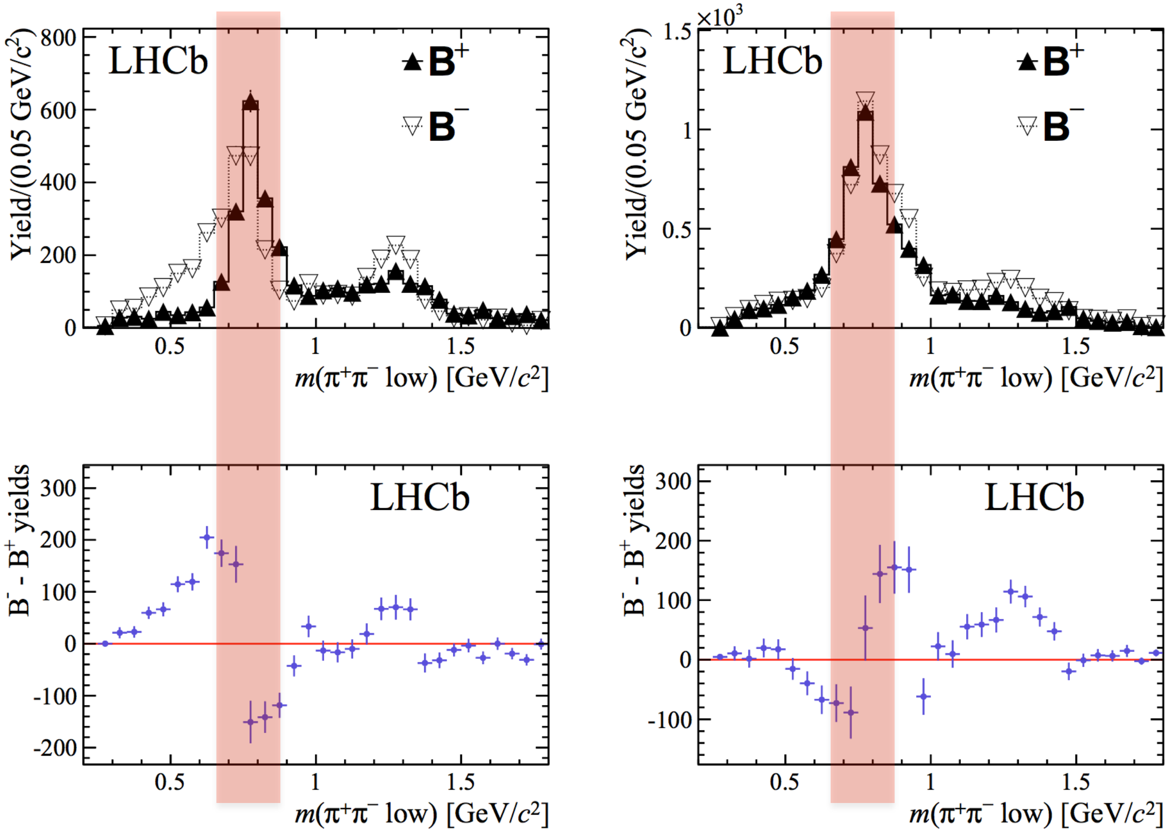


Large differences in asymmetries across the Dalitz plot => study projections

CPV from interference

$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ $\cos\theta$: $\pi^{\pm}$ helicity angle with same-sign daughter

$\cos\theta < 0$ $\cos\theta > 0$



- In all channels the charge asymmetry changes sign near a resonance (here $\rho(770)$)
- Long-distance interference term for vector resonance $\propto \cos\theta$
  Short-distance term $\propto \cos^2\theta$
- Asymmetry is opposite sign in the two $\cos\theta$ ranges: long-distance interference is dominant

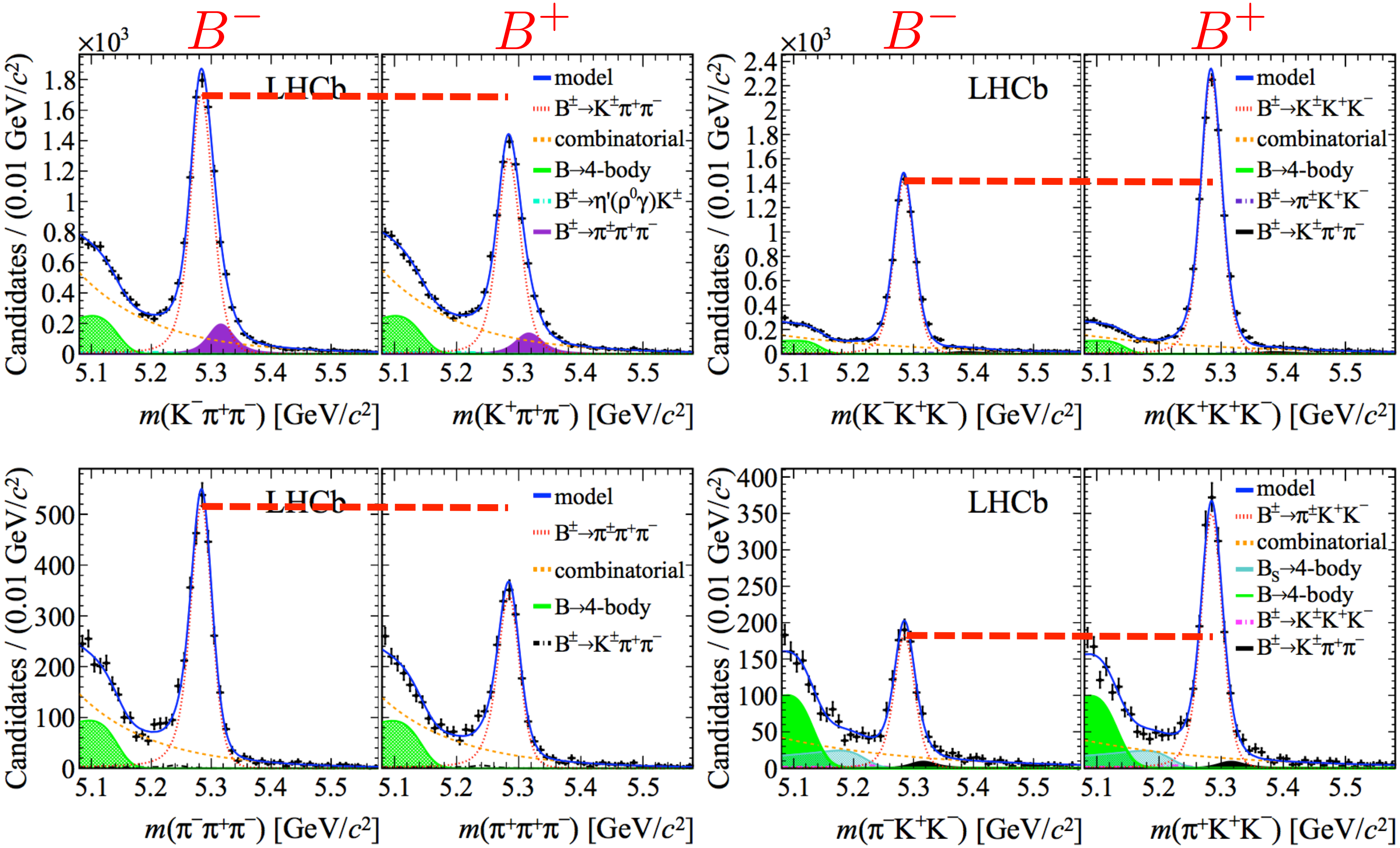
Smaller yield Larger CP asymmetry	Larger yield Smaller CP asymmetry

Possible explanation: relative tree and penguin contributions vary across phase space

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

CPV from rescattering

Rescattering region $m(\pi^+\pi^-), m(K^+K^-) \in [1.0, 1.5]\,\mathrm{GeV}/c^2$



10-30% CP asymmetries with >5σ significance observed

Oppositely-signed asymmetries for $\pi^+\pi^-$ and K^+K^- pairs, as required by CPT symmetry

Rescattering plays an important role in CP violation in these channels!

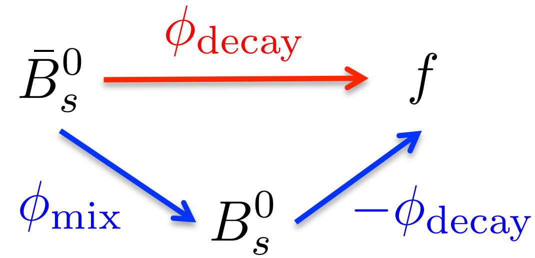
CP violation in loop-level decays

$$B_s^0 \to \phi\phi$$

$B_s^0 \to \phi\phi$

- FCNC decay, proceeds via loop diagrams

$$\phi_s = \phi_{\mathrm{mix}} - 2\phi_{\mathrm{decay}}$$

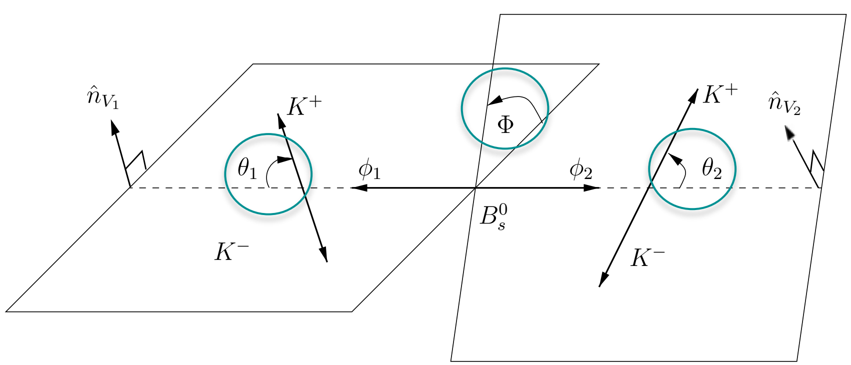


- **CP violation enters:**
  - primarily through phase difference between decays with and without mixing: ϕ_s
  - assume no CPV in mixing
  - small amount of direct CPV to be measured $|\lambda| \equiv (\overline{A}/A) \sim 1$
- **Angular analysis** needed to separate CP-eigenstates, which have different lifetime distributions
  - $\phi\phi$ final state: linear combination of CP-even and CP-odd eigenstates
  - each K^+K^- pair: P-wave ϕ, S-wave resonant $f_0(980)$, non-resonant, interference terms

Angular momentum conservation
$0^{-1} \rightarrow 1^{-1}\ 1^{-1}$

Final state: CP even (L = 0, 2) and CP odd (L = 1)

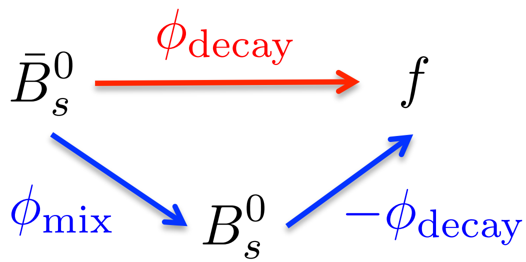
3 polarisation amplitudes
$\Rightarrow$ different angular distributions studied in helicity angle basis



$B_s^0 \to \phi\phi$

Two complementary probes of CPV

ϕ_s



$$\phi_s = \phi_{\rm mix} - 2\phi_{\rm decay}$$

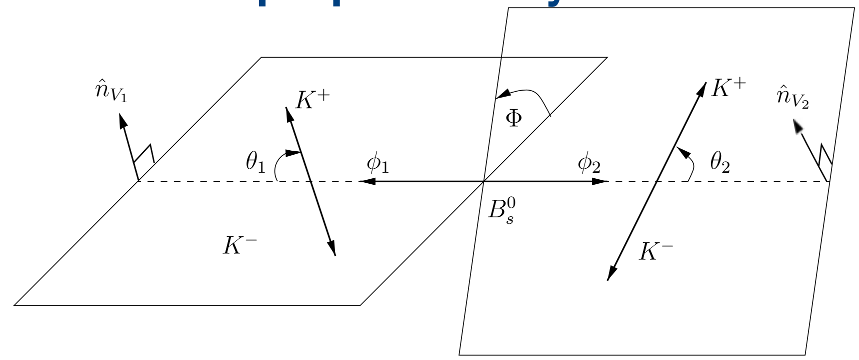
Interference between oscillation and direct decay amplitudes

SM expectation: small
$|\phi_s| < 0.02$ rad

Potentially large enhancement from NP

Improve sensitivity by tagging initial B_s^0 flavour

T-odd triple-product asymmetries



T-odd triple-products $\sin\Phi = (\hat{n}_{V_1} \times \hat{n}_{V_2}) \cdot \hat{p}_{V_1}$

$$\sin 2\Phi = 2(\hat{n}_{V_1} \cdot \hat{n}_{V_2})(\hat{n}_{V_1} \times \hat{n}_{V_2}) \cdot \hat{p}_{V_1}$$

$$U \equiv \sin\Phi\cos\Phi \qquad V \equiv \sin(\pm\Phi)$$

Triple-product asymmetries

$$A_{\alpha=U,V} \equiv \frac{\Gamma(\alpha>0) - \Gamma(\alpha<0)}{\Gamma(\alpha>0) + \Gamma(\alpha<0)}$$

SM expectation: close to zero

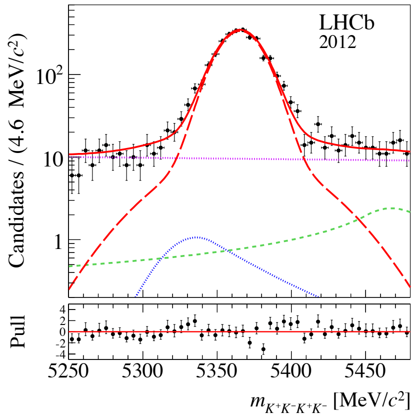
Counting experiment, independent of decay time or initial B_s^0 flavour

ϕ_s measurement

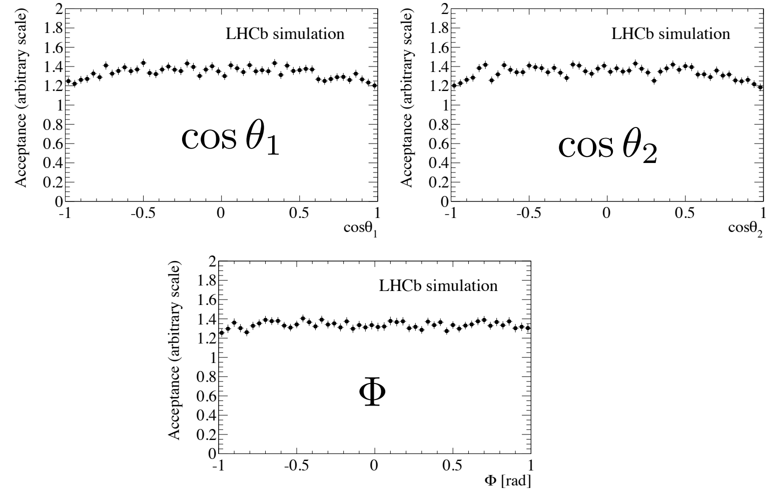
Background subtraction

Obtain per-event signal weights by fitting the invariant mass spectrum

3950 signal events



Angular acceptance (simulation)



Flavour-tagging

'Opposite Side' algorithm

Reconstruct other *b* quark that was produced with signal

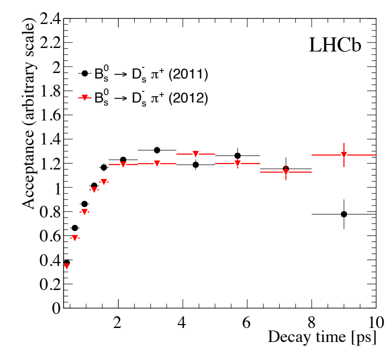
'Same Side Kaon' algorithm

Associated $\bar{s}$ quark formed in hadronisation of signal B_s^0 meson which forms a charged kaon

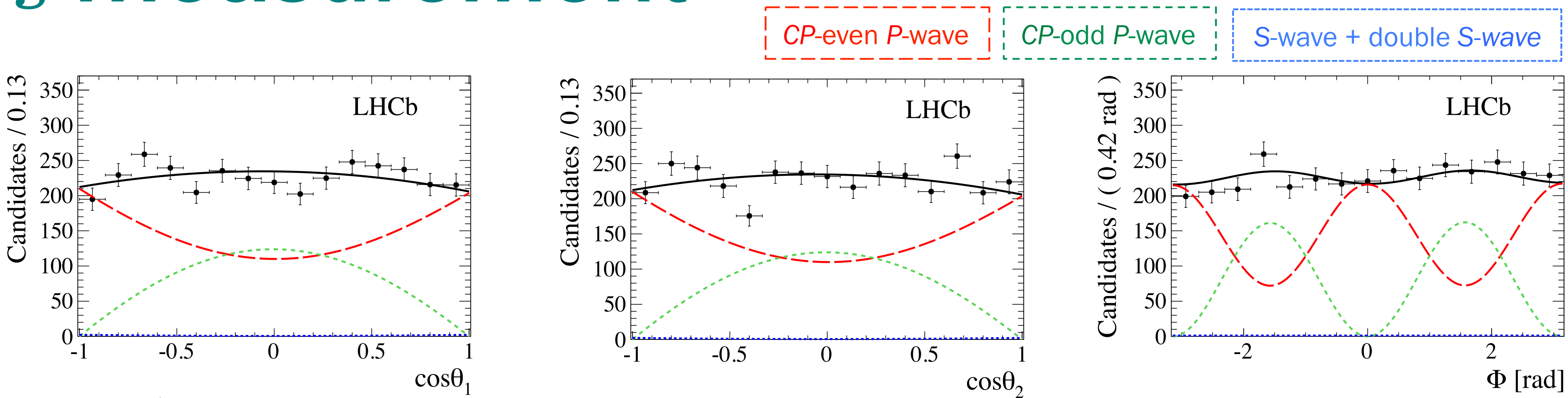
Combined tagging efficiency of ~26%, with ~33% mistag rate

Decay time acceptance

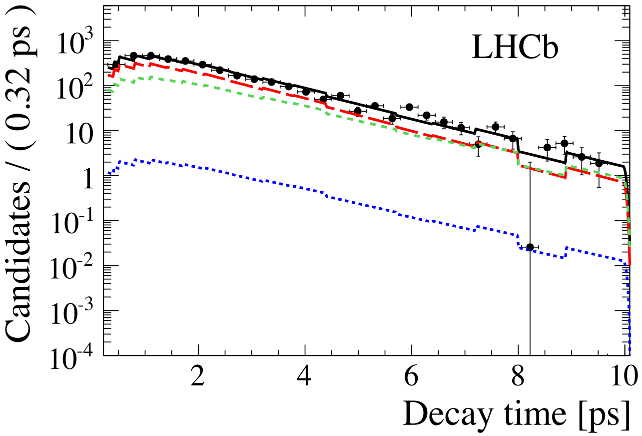
$B_s \to D_s\pi$ data and simulation passing same selection requirements and kinematically weighted to signal



ϕ_s measurement



$$\frac{d^4\Gamma}{dt\, d\cos\theta_1\, d\cos\theta_2\, d\Phi} \propto \sum_i \boxed{K_i(t)} f_i(\theta_1, \theta_2, \Phi)$$



Time evolution of the polarisation states:

Polarisation amplitudes, strong phases

B_s^0 mixing parameters (constrained to LHCb measurements)

CPV parameters $\phi_s, |\lambda|$

Flavour tagging parameters

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

$$|\lambda| = 1.04 \pm 0.07\,(\text{stat.}) \pm 0.03\,(\text{syst.})$$

In agreement with SM theory predictions

No direct CP violation observed

Comparison to ϕ_s in $B_s^0 \to J/\psi\pi^+\pi^-, J/\psi K^+K^-$:

No large CP violation in B_s mixing

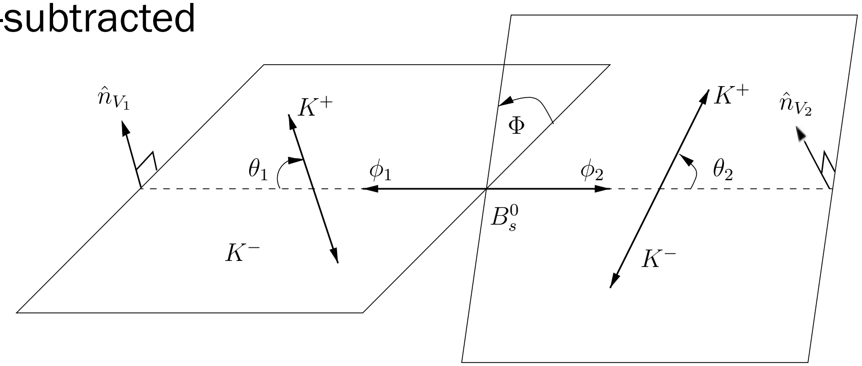
No large CP violation in decay amplitude

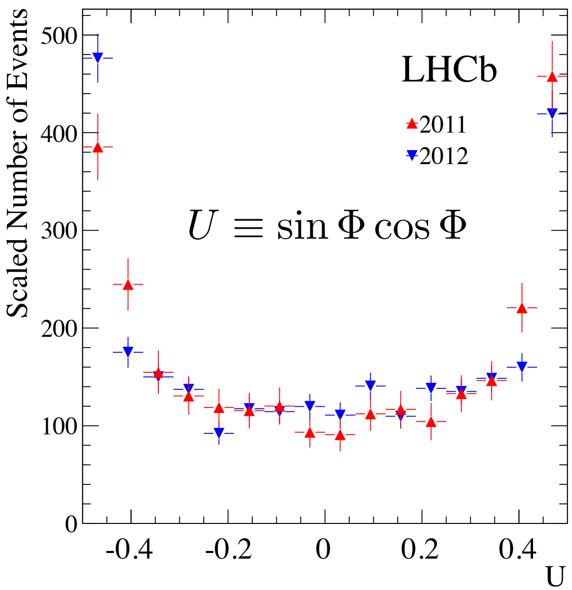
PRD 87, 112010 (2013)

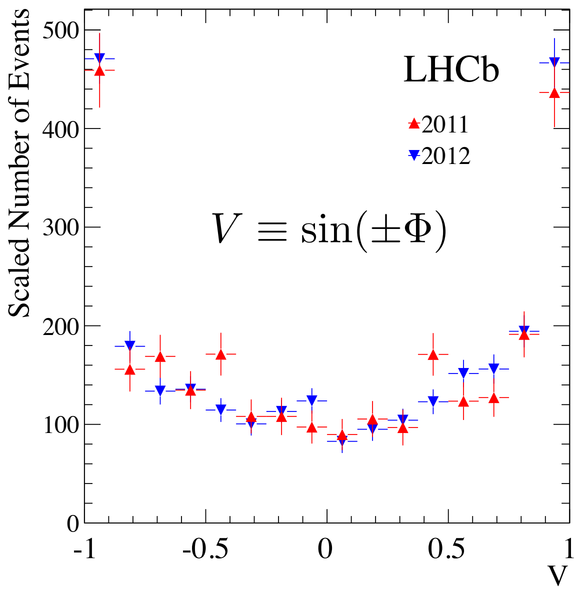
T-odd triple product asymmetries

Counting experiment, data points are background-subtracted

$$A_{\alpha=U,V} \equiv \frac{\Gamma(\alpha>0)-\Gamma(\alpha<0)}{\Gamma(\alpha>0)+\Gamma(\alpha<0)}$$







Non-zero asymmetries indicate either CPV or final state interactions

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

$$A_V = -0.017 \pm 0.017\,(\text{stat.}) \pm 0.006\,(\text{syst.})$$

Results are consistent with CP conservation hypothesis

Summary and outlook

- Latest measurements of γ $(B^{\pm} \to DK^{\pm})$, local asymmetries in $B \to 3h$, and ϕ_s $(B_s^0 \to \phi\phi)$ presented

- Many other LHCb measurements of these parameters!

$\gamma : B \to (D \to hh)K^*$	arXiv:1407.8136
$B_s \to D_s K$	arXiv:1407.6127
$\phi_s : B_s \to J/\psi\pi\pi$	PLB 736 (2014) 186
$\text{local } A_{CP} : B \to p\bar{p}K$	arXiv:1407.5907

- Measurements of CP violation in the B-sector have been found to be compatible with the Standard Model

- Many results still statistically-limited: Run 2 will deliver a further 5 fb^{-1} of data to provide further constraints on the CKM matrix and on New Physics

EXTRA SLIDES

Local asymmetries

- Exploit angular analysis & local asymmetries in Dalitz phase space to better understand different sources of strong phase difference