HQL 2018

Charmless b Decays

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on behalf of the LHCb collaboration

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Outline

1. Types of CP violation
   - Direct, mixing-induced

2. 2-body
   - $B^0 \to K^+\pi^-, \pi^+\pi^-, B_s^0 \to K^+K^-$

3. 3-body
   - $B^0 \to K_S^0\pi^+\pi^-$

4. 4-body
   - $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$, $\Lambda_b^0 \to pK^-h^+h^-$ New!, $\Xi_b^0 \to pK^-\pi^+K^-$ New!
   - $B_s^0 \to \phi\phi$, $K^*\bar{K}^*$

Conditions for Direct CP Violation

In charged B decays, presence of multiple amplitudes may lead to direct CP violation

$A(B \to f) = \sum_i |A_i| e^{i(\delta_i + \phi_i)}$

$\bar{A}(\bar{B} \to \bar{f}) = \sum_i |A_i| e^{i(\delta_i - \phi_i)}$

Strong phase (δ) invariant under CP, while weak phase (ϕ) changes sign under CP

$$\mathcal{A}_{CP}(B \to f) \equiv \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} \propto \sum_{i,j} |A_i||A_j| \sin(\delta_i - \delta_j) \sin(\phi_i - \phi_j)$$

3 conditions required for direct CP violation

- At least 2 amplitudes
- Non-zero strong phase difference, $\delta_i - \delta_j \neq 0$
- Non-zero weak phase difference, $\phi_i - \phi_j \neq 0$

Source of weak phase differences come from different CKM phases of each amplitude

Short-Distance Contributions

Multiple sources of strong phase

1. Short-distance contributions (quark level)

    BSS mechanism, PRL **43** 242 (1979)

    Tree contribution (a)

    Penguin diagram (b) contains 3 quark generations in loop

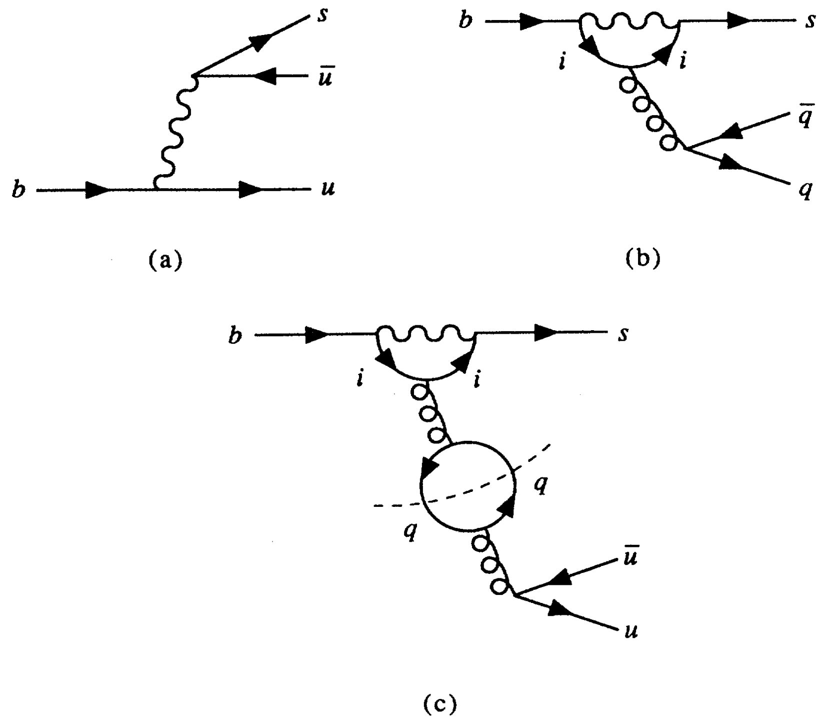
    S-matrix unitarity, CPT require absorptive amplitude

    If gluon in penguin is timelike (on-shell)

    - Momentum transfer $q^2 > 4m_i^2$ where $i = u, c$
    - Imaginary part depends on quark masses
    - Particle rescattering (c) generates a phase difference

    CP violation in 2-body processes caused by this effect

    - eg. $B^0 \to K^+\pi^-$



Long-Distance Contributions

Remaining sources endemic to multibody decays

Long-distance contributions ($q\bar{q}$ level)

2. Breit-Wigner phase

   Propagator represents intermediate resonance states

$$F_R^{\rm BW}(s) = \frac{1}{m_R^2 - s - i m_R \Gamma_R(s)}$$

   Phase varies across the Dalitz plot

3. Relative CP-even phase in the isobar model

$$A(B \to f) = \sum_i |A_i| e^{i(\delta_i + \phi_i)}$$
$$\bar{A}(\bar{B} \to \bar{f}) = \sum_i |\bar{A}_i| e^{i(\delta_i - \phi_i)}$$

   Related to final state interactions between different resonances

Neutral Meson Mixing

Mixing arises from a difference between the mass and flavour eigenstates

$$|P_H\rangle = p|P^0\rangle + q|\bar{P}^0\rangle, \qquad |P_L\rangle = p|P^0\rangle - q|\bar{P}^0\rangle$$

p, q are complex mixing parameters

Mixing can be described by the effective 2x2 Hamiltonian

$$H_{ij} = M_{ij} - i\Gamma_{ij}/2$$

M is the mass term

Γ provides the decay term due to the $-i$

Solving the Schrödinger Equation

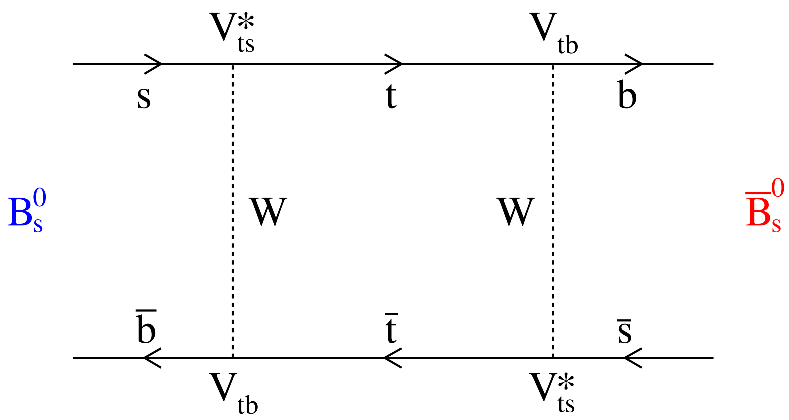
3 mixing physical observables

$\Delta m \equiv m_H - m_L$: mixing frequency in time evolution

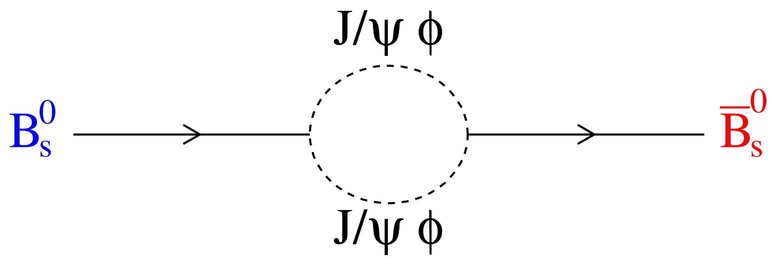
$\Delta\Gamma \equiv \Gamma_H - \Gamma_L$: lifetime difference

$\phi_{\text{mix}} = -\arg(M_{12}/\Gamma_{12})$: CP-violating mixing phase

M_{12}: short-distance (off-shell)



$-i\Gamma_{12}/2$: long-distance (on-shell)



CP Violation in Neutral Mesons

CP violation in neutral meson system governed by complex parameter

$$\lambda_{CP} \equiv \frac{q}{p}\frac{\bar{A}(\bar{P}^0 \to f_{CP})}{A(P^0 \to f_{CP})}$$

Access experimentally through time-dependent rate asymmetry in neutral mesons

$$a_{CP}(t) \equiv \frac{\Gamma(\bar{P}^0 \to f_{CP}) - \Gamma(P^0 \to f_{CP})}{\Gamma(\bar{P}^0 \to f_{CP}) + \Gamma(P^0 \to f_{CP})} = \frac{-\mathcal{C}_{CP}\cos(\Delta m t) + \mathcal{S}_{CP}\sin(\Delta m t)}{\cosh(\Delta\Gamma t/2) + \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma t/2)}$$

Sensitive to 3 physical observables

$\mathcal{C}_{CP}$: CP violation in the decay, $|\bar{A}| \neq |A|$

$$\mathcal{C}_{CP} \equiv \frac{|\lambda_{CP}|^2 - 1}{|\lambda_{CP}|^2 + 1}$$

$\mathcal{S}_{CP}$: Mixing-induced CP violation, $\arg(\lambda_{CP}) \neq 0$

$$\mathcal{S}_{CP} \equiv -\eta_{CP}\frac{2\Im(\lambda_{CP})}{|\lambda_{CP}|^2 + 1}$$

$\mathcal{A}_{\Delta\Gamma}$: Admixture of P_H and P_L that decay to final state

$$\mathcal{A}_{\Delta\Gamma} \equiv -\frac{2\Re(\lambda_{CP})}{|\lambda_{CP}|^2 + 1}$$

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   - $B_s^0 \to \phi\phi, K^*\bar{K}^*$

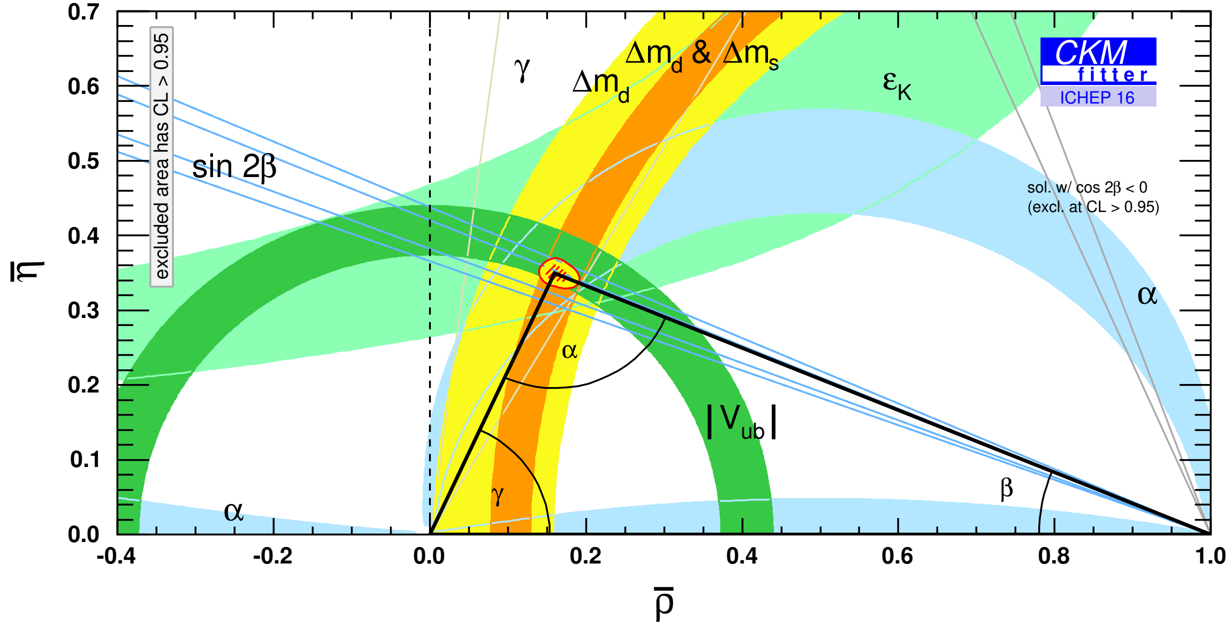
$B \to h^+ h^{-\prime}$

Simultaneous analysis includes $B^0 \to K^-\pi^+$, $\pi^+\pi^-$ and $B_s^0 \to K^+K^-$

Based on 2011+2012 data (3.0 fb^{-1})

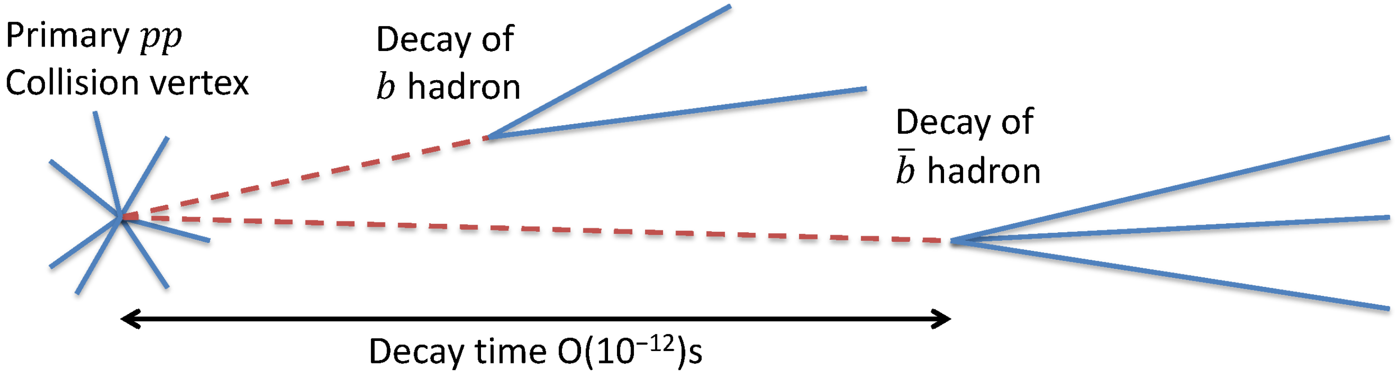
Sensitive to direct and mixing-induced CP violation

Constrain α, γ and $-2\beta_s$



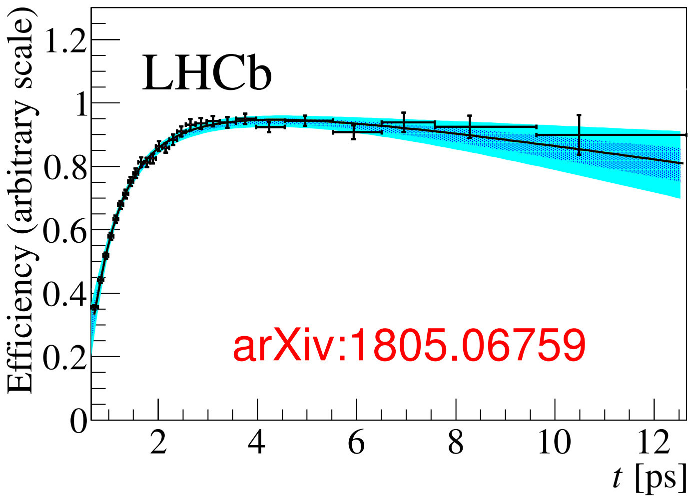
Requires time-dependent and flavour-tagged analysis

Decay Time Distribution



Decay times precisely measured due LHCb VELO vertex measurements

Time distribution affected by acceptance effects due to trigger and selection criteria



Shape determined from $B^0 \to K^+\pi^-$ data

Transformation to other final states from simulation

Decay Time Resolution

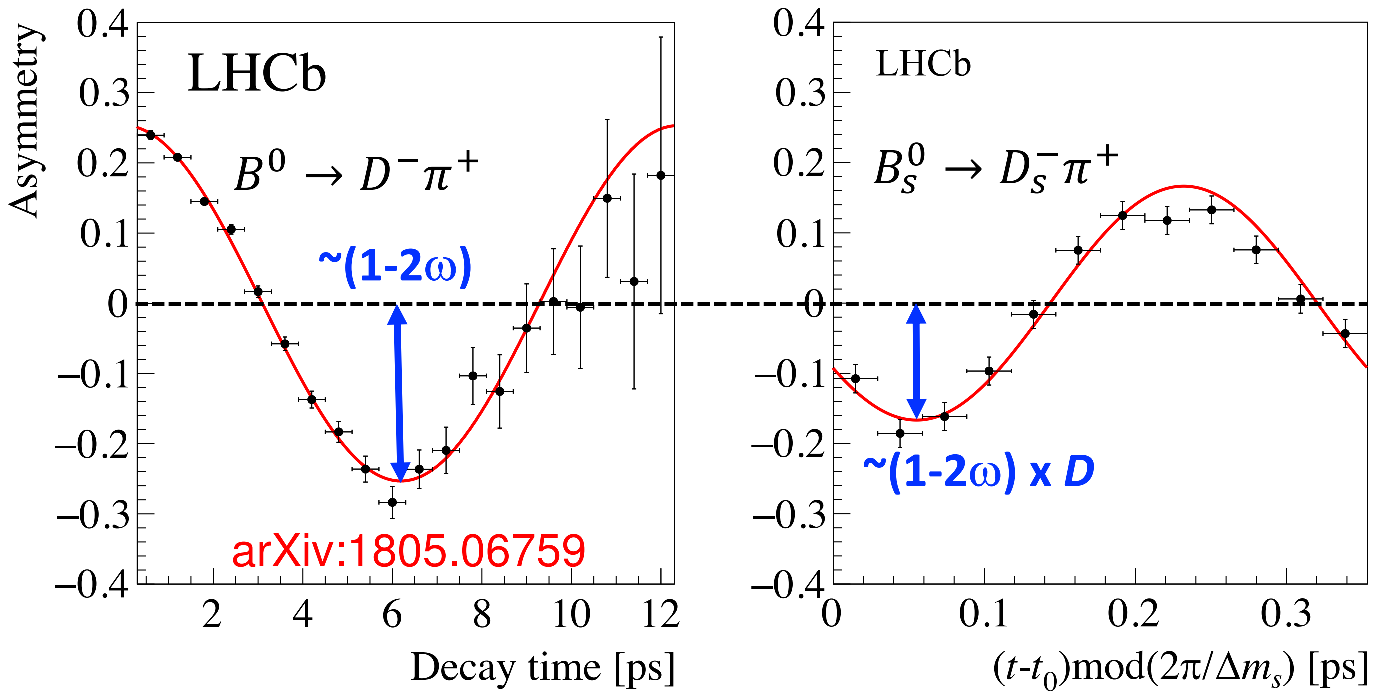
Event-dependent decay time resolution σ_t

Dilutes oscillation amplitudes $D = \exp(\frac{1}{2}\Delta m^2 \sigma_t^2)$

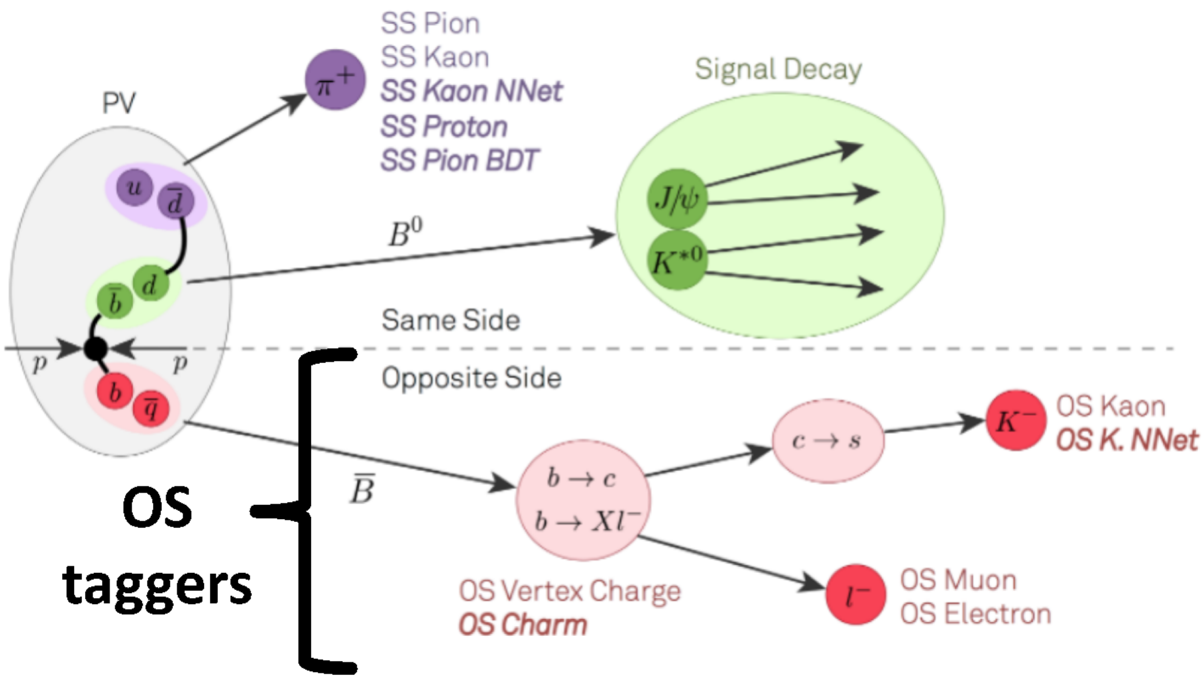
Negligible in B^0 decays due to small Δm_d

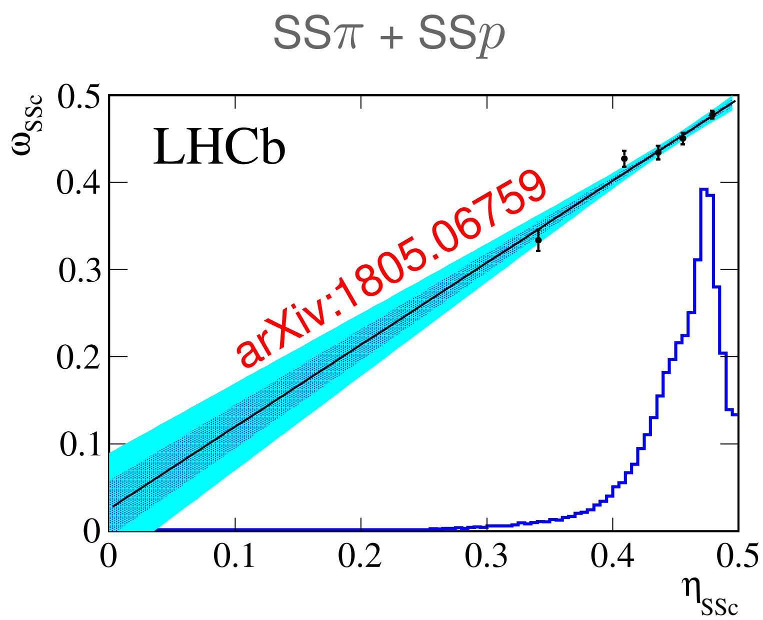
Linearly dependent on per-event decay time error

Calibrated from time-dependent asymmetry of $B \to D\pi$ control samples



Flavour Tagging





Calibrated vs Uncalibrated mistag

Employs Opposite Side (OS) and Same Side (SS) taggers

Algorithm produces per-event tagging decision and associated wrong tag probability

Wrong tag probability linearly calibrated with various control samples

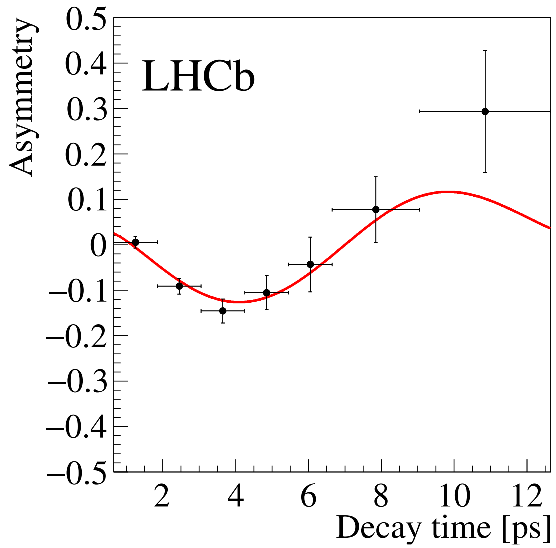
B^0 tagging power: $(4.08 \pm 0.20)\%$, B^0_s tagging power: $(3.65 \pm 0.21)\%$

$B \to h^+h^{-\prime}$ Results

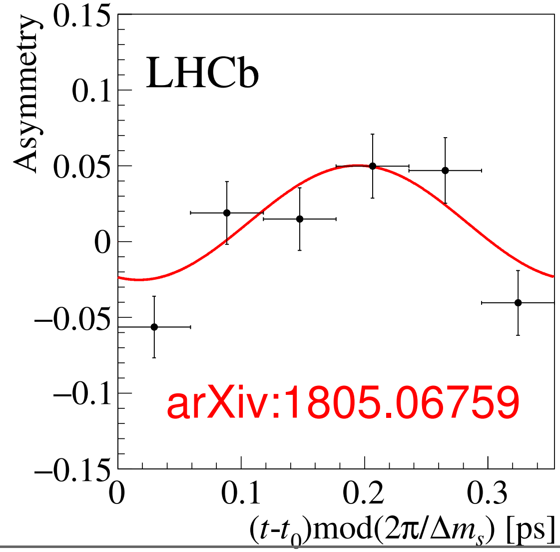
First error statistical, second systematic

$$\begin{aligned}
\mathcal{C}_{\pi^+\pi^-} &= -0.34 \pm 0.06 \pm 0.01, \\
\mathcal{S}_{\pi^+\pi^-} &= -0.63 \pm 0.05 \pm 0.01, \\
\mathcal{C}_{K^+K^-} &= +0.20 \pm 0.06 \pm 0.02, \\
\mathcal{S}_{K^+K^-} &= +0.18 \pm 0.06 \pm 0.02, \\
A^{\Delta\Gamma}_{K^+K^-} &= -0.79 \pm 0.07 \pm 0.10, \\
\mathcal{A}_{CP}^{B^0\to K^+\pi^-} &= -0.084 \pm 0.004 \pm 0.003, \\
\mathcal{A}_{CP}^{B_s^0\to K^-\pi^+} &= +0.213 \pm 0.015 \pm 0.007
\end{aligned}$$

OS: $\pi^+\pi^-$



OS: K^+K^-

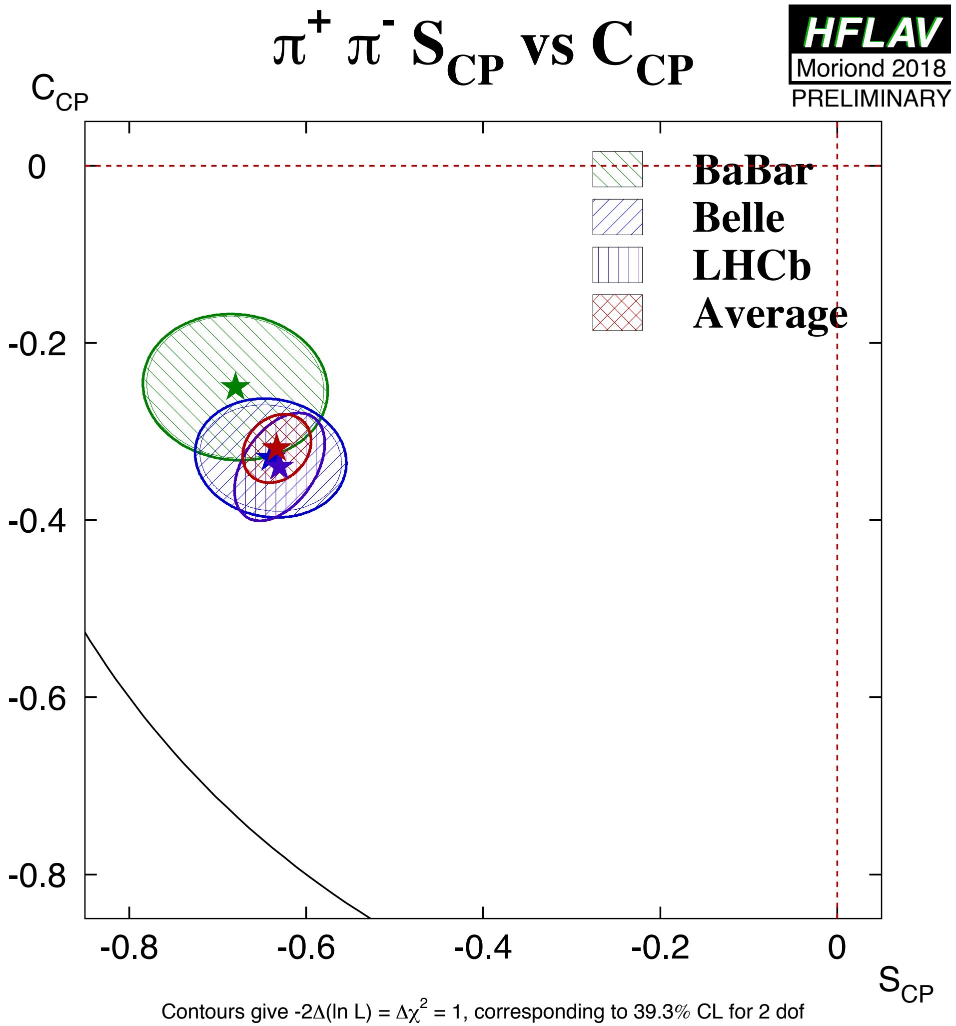


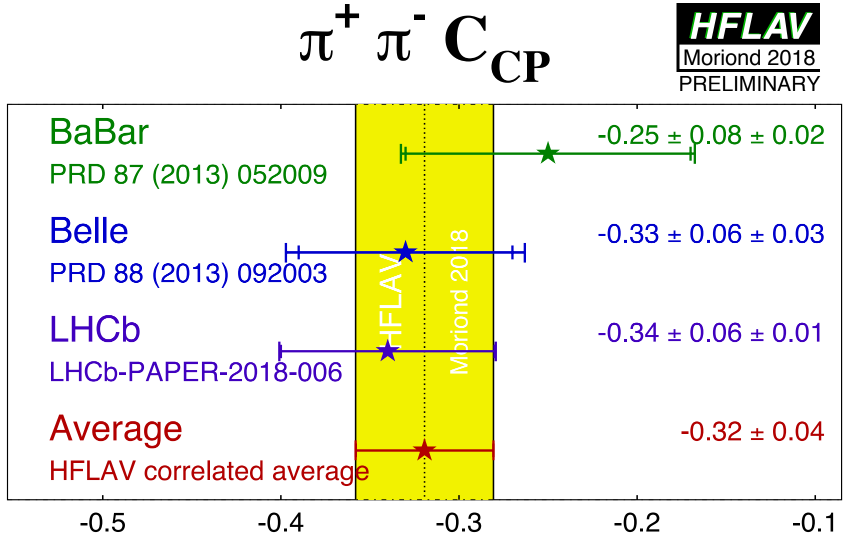
Most precise single measurement

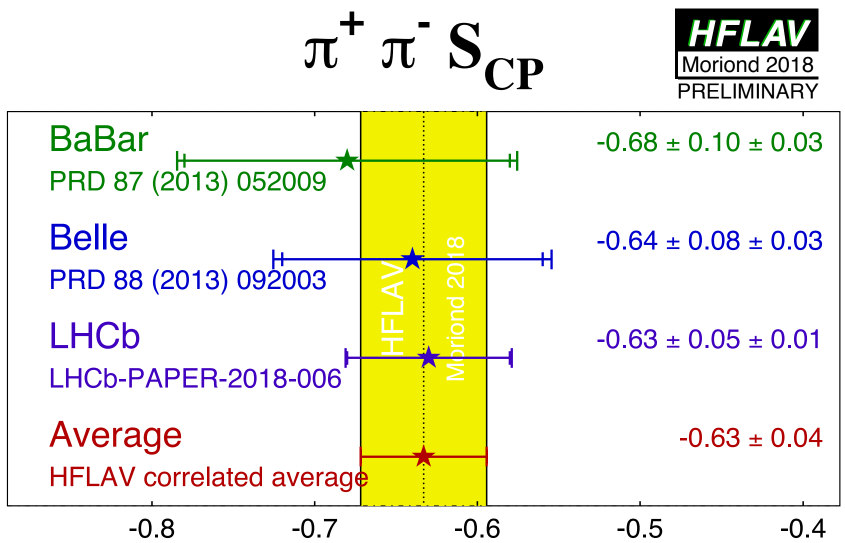
First determination of $A^{\Delta\Gamma}_{K^+K^-}$

4σ evidence for CP violation in $B_s^0 \to K^+K^-$

$B \to h^+h^{-\prime}$ World Average







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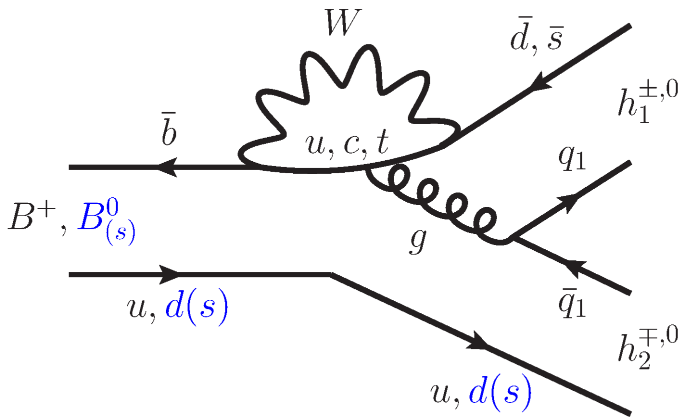
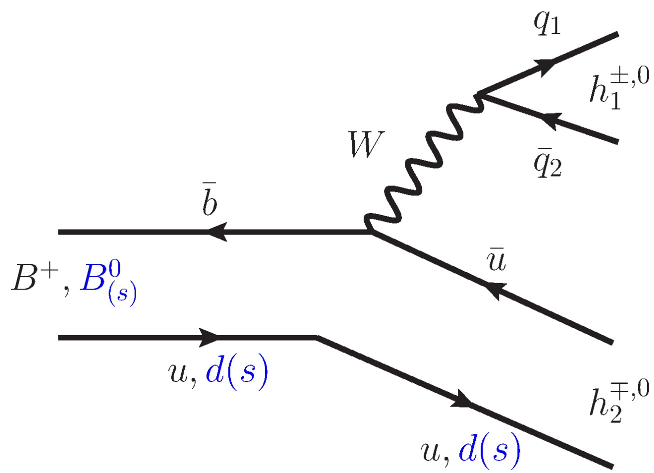
$B^0 \to K_S^0 \pi^+ \pi^-$

Mediated by penguin and tree processes





Time-independent amplitude analysis (today)

Sensitive to direct CP violation for intermediate states

Time-dependent amplitude analysis (long-term plan)

Direct measurement of CP violating phase β from CP eigenstate intermediates states

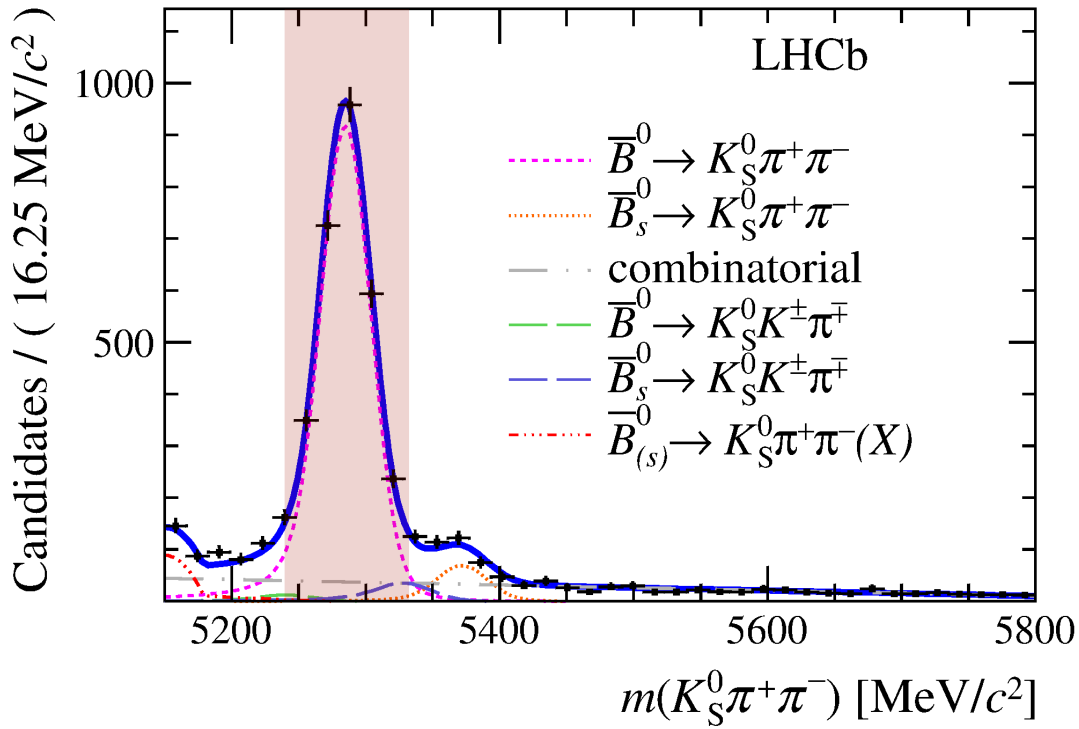
Flavour-specific intermediate states contribute information towards γ measurement

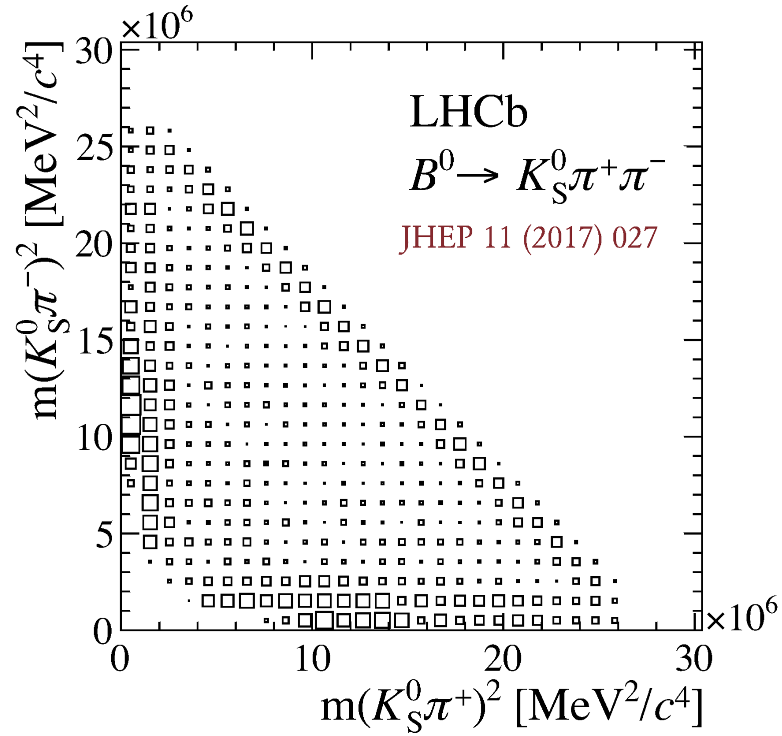
$B^0 \to K^0_S \pi^+ \pi^-$ Yield

Analysis performed with 2011+2012 data (3.0 fb^{-1})

Around 3200 signal events in signal region with $\sim$ 90% purity

arXiv:1712.09320





$B^0 \to K_S^0 \pi^+ \pi^-$ Amplitude

Isobar approach

$$A = \sum_i c_i F_i(m_{12}^2, m_{23}^2)$$

$F_i(m_{12}^2, m_{23}^2)$: strong dynamics form factor

Contains lineshape and spin density

c_i: CP-violating complex fit coefficients

$$\mathcal{A}_{CP}^{\mathrm{Raw},i} = \frac{|\bar{c}_i|^2 - |c_i|^2}{|\bar{c}_i|^2 + |c_i|^2}$$

Raw $\mathcal{A}_{CP}$ corrections

B^0/ $\bar{B}^0$ production asymmetry

$(-0.35 \pm 0.81)\%$

π^+/ π^- detection asymmetry

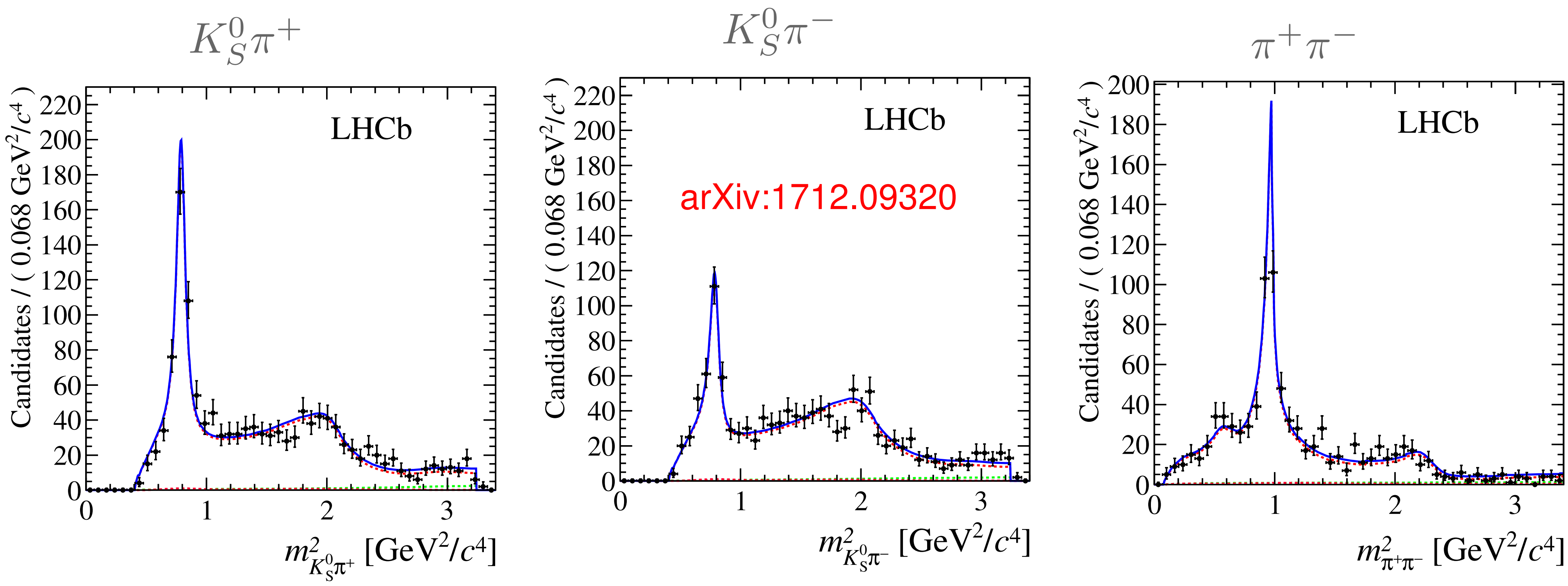
$(0.00 \pm 0.25)\%$

Resonance	Parameters	Lineshape
$K^*(892)^-$	$m_0 = 891.66 \pm 0.26$ $\Gamma_0 = 50.8 \pm 0.9$	RBW
$(K\pi)_0^-$	$\mathcal{R}e(\lambda_0) = 0.204 \pm 0.103$ $\mathcal{I}m(\lambda_0) = 0$ $\mathcal{R}e(\lambda_1) = 1$ $\mathcal{I}m(\lambda_1) = 0$	EFKLLM
$K_2^*(1430)^-$	$m_0 = 1425.6 \pm 1.5$ $\Gamma_0 = 98.5 \pm 2.7$	RBW
$K^*(1680)^-$	$m_0 = 1717 \pm 27$ $\Gamma_0 = 332 \pm 110$	Flatté
$f_0(500)$	$\mathrm{m}_0 = 513 \pm 32$ $\Gamma_0 = 335 \pm 67$	RBW
$\rho(770)^0$	$m_0 = 775.26 \pm 0.25$ $\Gamma_0 = 149.8 \pm 0.8$	GS
$f_0(980)$	$m_0 = 965 \pm 10$ $g_\pi = 0.165 \pm 0.025$ GeV $g_K = 0.695 \pm 0.119$ GeV	Flatté
$f_0(1500)$	$m_0 = 1505 \pm 6$ $\Gamma_0 = 109 \pm 7$	RBW
χ_{c0}	$m_0 = 3414.75 \pm 0.31$ $\Gamma_0 = 10.5 \pm 0.6$	RBW
Nonresonant (NR)		Phase space

EFKLLM: $(K\pi)^0$ form factor from QCDf

Phys. Rev. D **79**, 094005 (2009)

$B^0 \to K_S^0\pi^+\pi^-$ Amplitude



$$\mathcal{A}_{CP}(K^*(892)^-\pi^+) = -0.308 \pm 0.060 \pm 0.011 \pm 0.012$$
$$\mathcal{A}_{CP}((K\pi)_0^-\pi^+) = -0.032 \pm 0.047 \pm 0.016 \pm 0.027$$
$$\mathcal{A}_{CP}(K_2^*(1430)^-\pi^+) = -0.29 \pm 0.22 \pm 0.09 \pm 0.03$$
$$\mathcal{A}_{CP}(K^*(1680)^-\pi^+) = -0.07 \pm 0.13 \pm 0.02 \pm 0.03$$
$$\mathcal{A}_{CP}(f_0(980)K_S^0) = 0.28 \pm 0.27 \pm 0.05 \pm 0.14$$

First observation of CP violation in $B^0 \to K^{*+}(892)\pi^-$ (6σ significance)

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   - $B_s^0 \to \phi\phi, K^*\bar{K}^*$

4-body Baryonic Decays

Rich underlying resonant structure

Probe CP violation with integrated and scalar triple-product asymmetry measurements

P-odd triple products

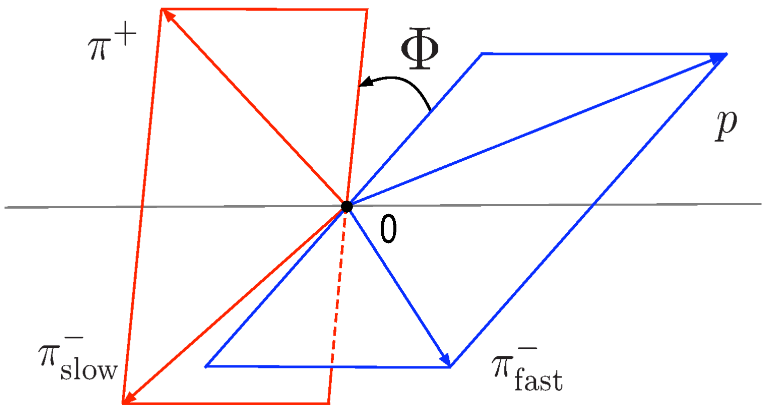
$$\Lambda_b^0\colon C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}) \propto \sin\Phi$$

$$\bar{\Lambda}_b^0\colon \bar{C}_{\hat{T}} = \vec{p}_{\bar{p}} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-}) \propto \sin\bar{\Phi}$$

P-odd asymmetries of $\hat{T}$ operator

$$A_{\hat{T}} = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$$

$$\bar{A}_{\hat{T}} = \frac{\bar{N}(-\bar{C}_{\hat{T}} > 0) - \bar{N}(-\bar{C}_{\hat{T}} < 0)}{\bar{N}(-\bar{C}_{\hat{T}} > 0) + \bar{N}(-\bar{C}_{\hat{T}} < 0)}$$



P-odd observable

$$a_P^{\hat{T}-\text{odd}} = \frac{1}{2}(A_{\hat{T}} + \bar{A}_{\hat{T}})$$

CP-odd observable

$$a_{CP}^{\hat{T}-\text{odd}} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}})$$

Sensitive to interference between P-even and P-odd amplitudes

$\Lambda_b^0 \to p\pi^- h^+ h^-$ Results

Based on 2011-12 data (3.0 fb^{-1})

Nature Physics 13 (2017) 391

No CP violation in integrated phase space

Divide into bins

Scheme A:

Based on dominant resonant structure

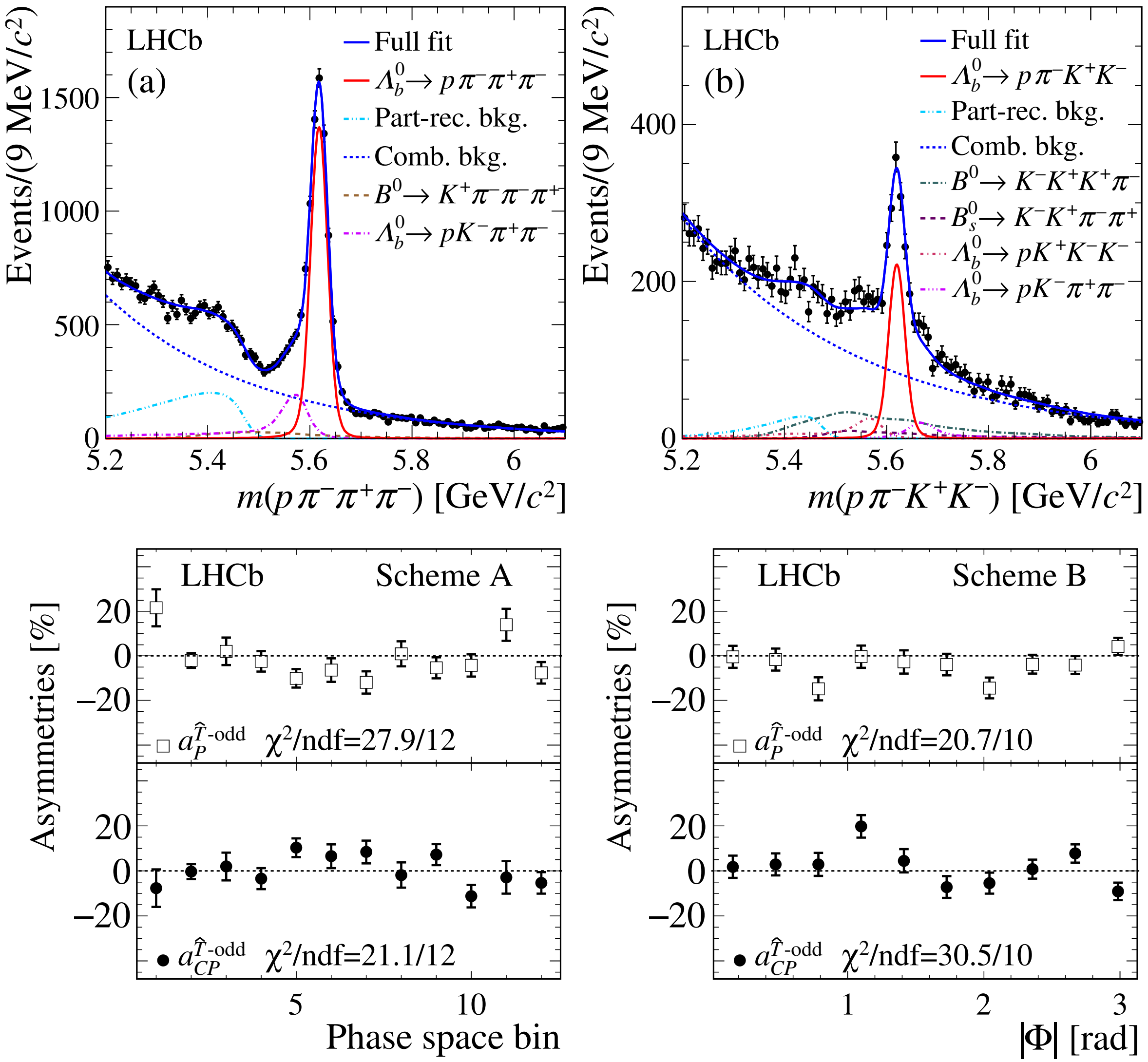
eg. Δ^{++}, N^*, $\rho(770)$

Scheme B:

Function of angle between decay planes

First evidence for CP violation (3.3σ)

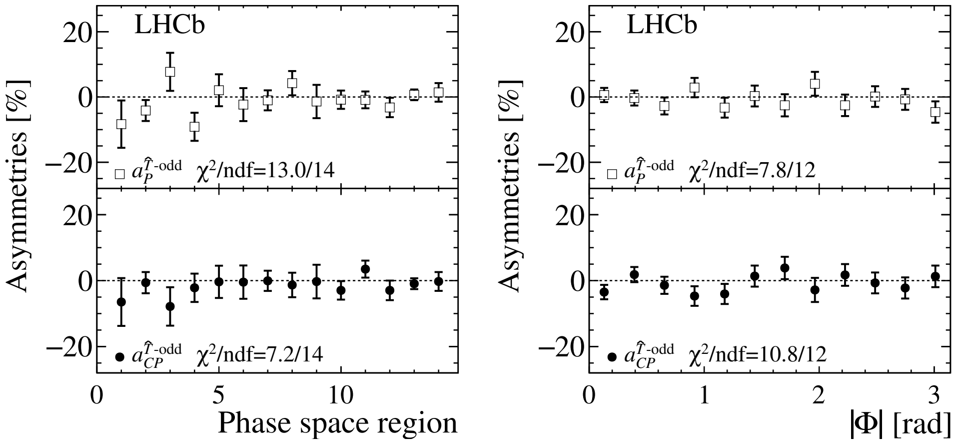
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ $\Lambda_b^0 \to p\pi^- K^+ K^-$



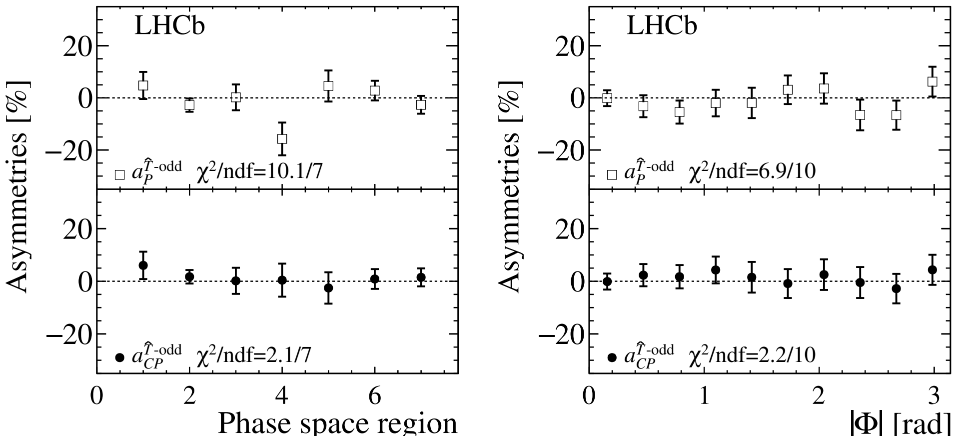
$\Lambda_b^0 \to pK^-h^+h^-, \Xi_b^0 \to pK^-\pi^+K^-$

New preliminary result based on 3.0 fb^{-1} ($p\pi^-h^+h^{-\prime} \to pK^-h^+h^{-\prime}$)

$\Lambda_b^0 \to pK^-\pi^+\pi^-$



$\Lambda_b^0 \to pK^-K^+K^-$



$\Lambda_b^0 \to pK^-\pi^+\pi^-$ Yield: 19877 ± 195

$\Lambda_b^0 \to pK^-K^+K^-$ Yield: 5297 ± 83

$\Xi_b^0 \to pK^-\pi^+K^-$ Yield: 709 ± 45

Left: Sceme A, Right: Scheme B

Scheme A: Binned in dominant resonances

Scheme B: Binned in Φ

Additional binned search in mass combinations

No significant asymmetries found

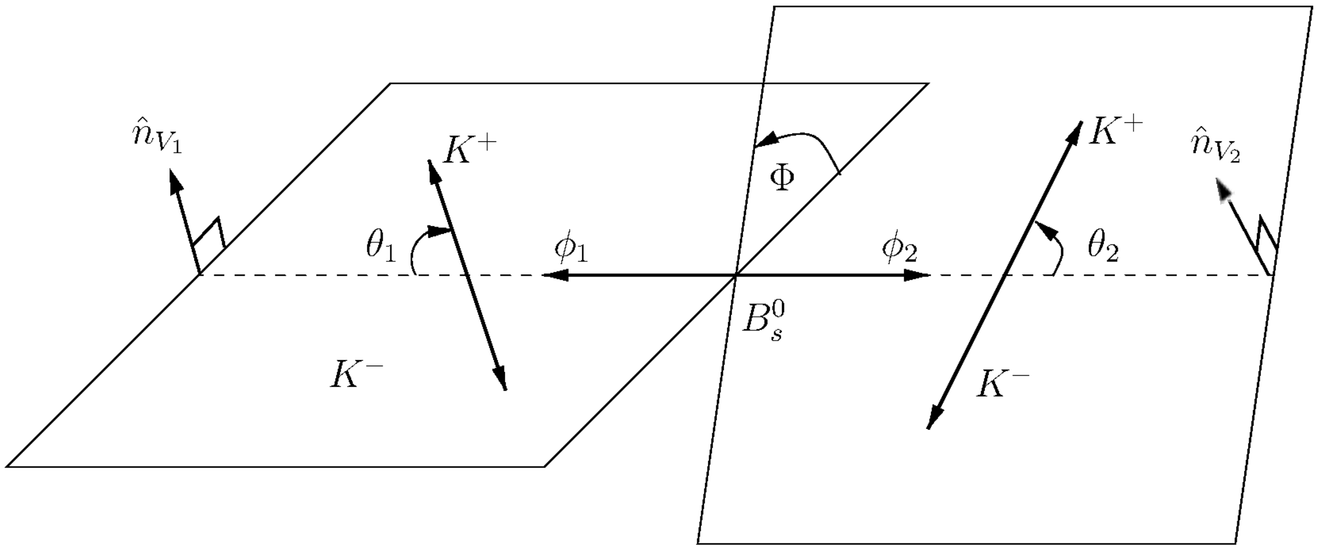
arXiv:1805.03941

Time-dependent VV Final States

$B_s^0 \to \phi\phi$ ($b \to s\bar{s}s$), $K^*\bar{K}^*$ ($b \to s\bar{d}d$) penguin dominated final states

Highly sensitive to New Physics amplitudes in the mixing and decay processes

Final state is CP admixture, time-dependent angular analysis to disentangle



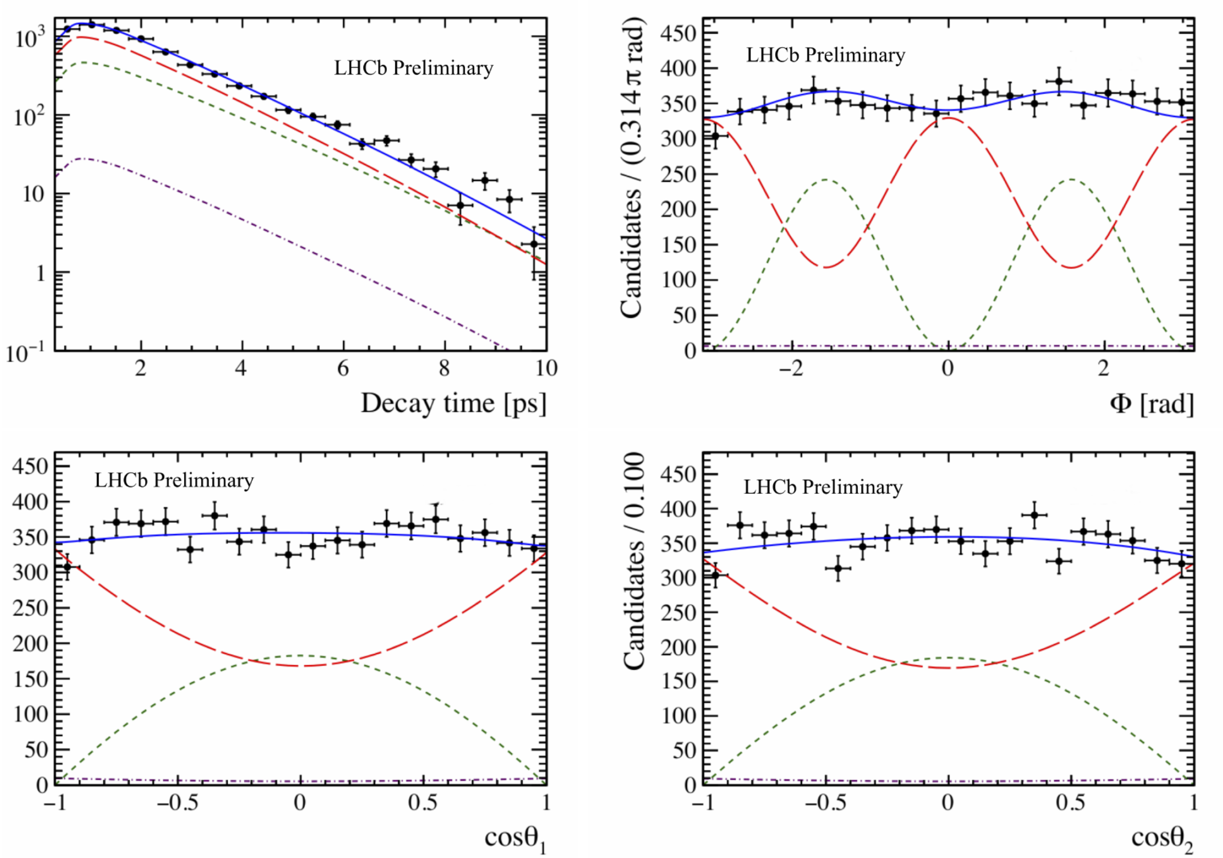
Measure CP-violating mixing phase $\phi_s^{s\bar{s}s}$, $\phi_s^{s\bar{d}d}$

Theory: $|\phi_s^{s\bar{s}s}| < 0.02\ \mathrm{rad}$

arXiv:0810.0249, Nucl. Phys. B **774**, 64 (2007), Phys. Rev. D **80**, 114026 (2009)

$B_s^0 \to \phi\phi$

Analysis based on Run 1 and 2015+16 data ($5\ fb^{-1}$), LHCb-CONF-2018-001



Effective tagging efficiency

$(5.74 \pm 0.43)\%$

Red: CP-even VV

Green: CP-odd VV

Purple: SV + SS

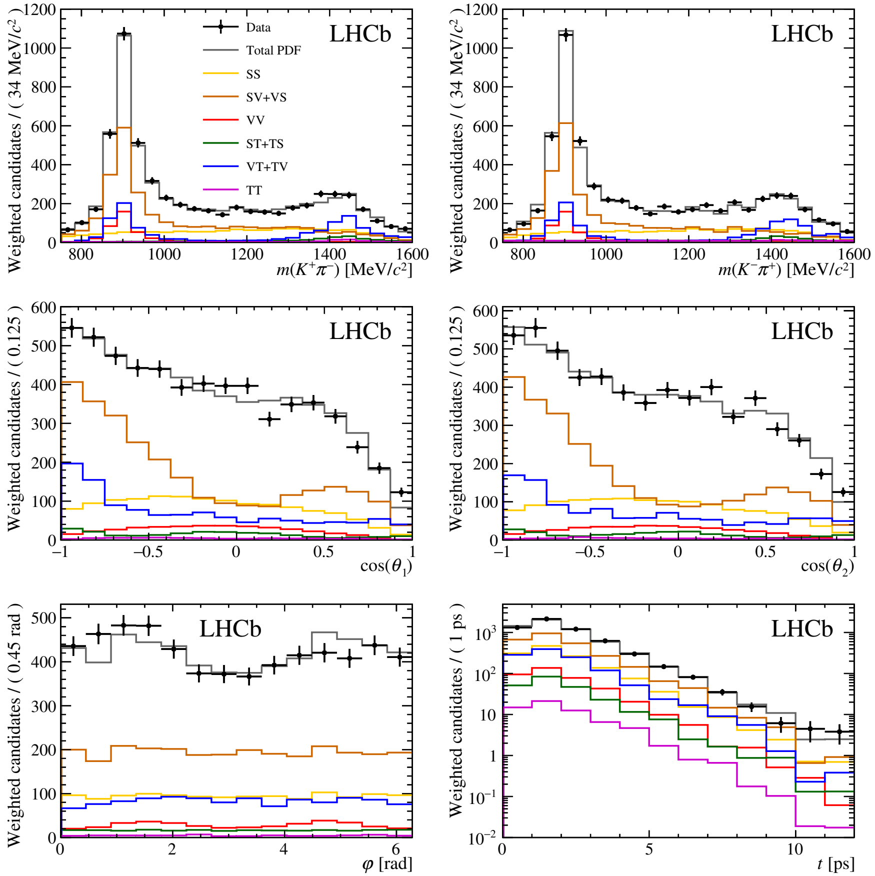
$$\phi_s^{s\bar{s}s} = -0.07 \pm 0.13\ (\text{stat}) \pm 0.03\ (\text{syst})\ \text{rad}$$

$$|\lambda_{CP}| = 1.02 \pm 0.05\ (\text{stat}) \pm 0.03\ (\text{syst})$$

Additional search with triple product asymmetries shows no CP violation

$B_s^0 \to K^* \bar{K}^*$

Analysis based on 2011+12 data ($3\ fb^{-1}$)



World's first measurement

JHEP 03 (2018) 140

$K\pi$ mass distribution modelled

Effective tagging efficiency: $(5.17 \pm 0.17)\%$

Systematics dominated by multi-dimensional acceptance

No evidence for CP violation

Results consistent with $B_s^0 \to \phi\phi$

$$\phi_s^{s\bar{d}d} = -0.10 \pm 0.13\ (\text{stat}) \pm 0.14\ (\text{syst})\ \text{rad}$$

$$|\lambda_{CP}| = 1.035 \pm 0.034\ (\text{stat}) \pm 0.089\ (\text{syst})$$

Summary

LHCb provides a rich environment to search for various manifestations of CP violation

Time-dependent measurement of CP violation in $B \to h^+ h^{-\prime}$

- Most precise single measurement

Amplitude analysis of $B^0 \to K^0_S \pi^+ \pi^-$

- First observation of CP violation in $B^0 \to K^{*+} \pi^-$

Search for CP violation in 4-body baryonic b decays

- First evidence of CP violation in $\Lambda^0_b \to p\pi^-\pi^+\pi^-$ with triple product constructs

Time-dependent measurements of ϕ_s with $B^0 \to VV$ channels

- $B^0_s \to \phi\phi$ consistent with SM predictions
- First measurement with $B^0_s \to K^* \bar{K}^*$