ICHEP 2018

CP Violation and Polarisation Amplitudes in $B \to VV$ Decays at LHCb

Jeremy Dalseno

on behalf of the LHCb collaboration

J.Dalseno [at] bristol.ac.uk

6 July 2018

Outline

1. Types of CP violation
   - Mixing-induced, direct
   - Triple Product Asymmetries

2. Time-dependent, flavour-tagging principles in $B \to VV$
   - Decay time acceptance
   - Decay time resolution
   - Flavour-tagging calibration
   - Angular analysis

3. $B_s^0 \to \phi\phi$

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

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

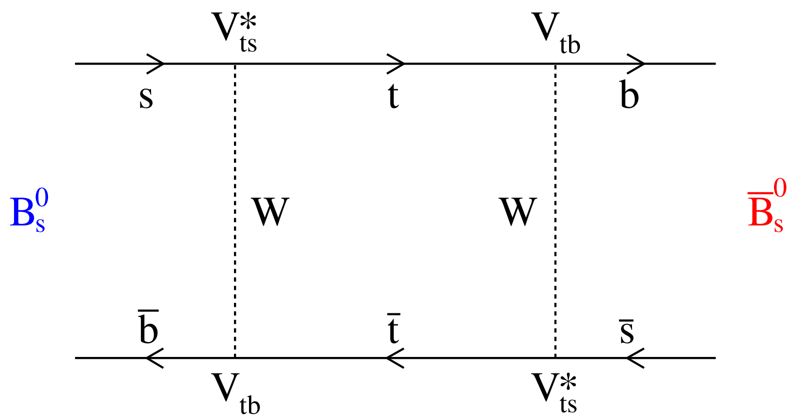
3 mixing physical observables

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

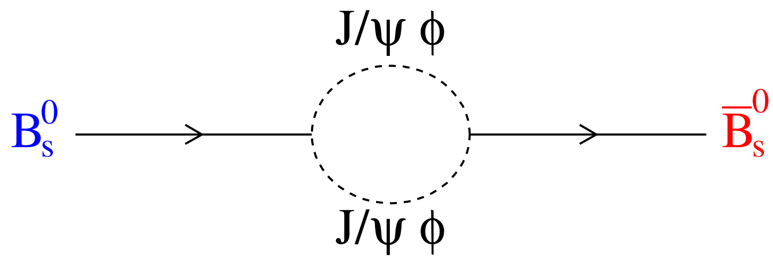
$\Delta\Gamma \equiv \Gamma_H - \Gamma_L$: lifetime difference

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

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

Conditions for Direct CP Violation

In 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

Source of strong phase differences come from short/long distance effects, rescattering *etc.*

Triple Product Asymmetries

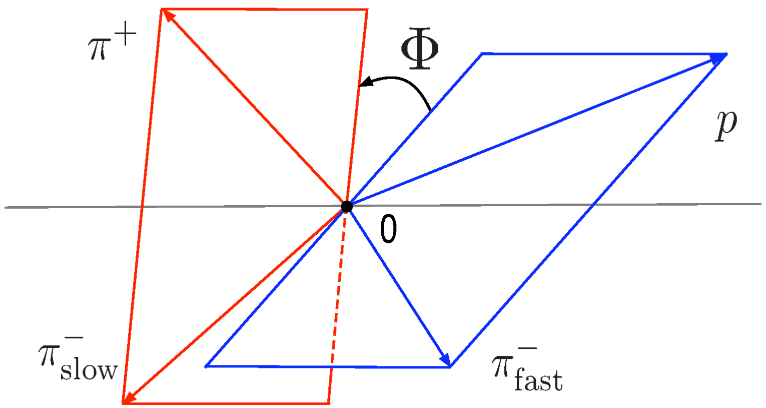
Rich underlying resonant structure

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

P-odd triple products

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

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



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

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

CP-odd observable

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

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

Outline

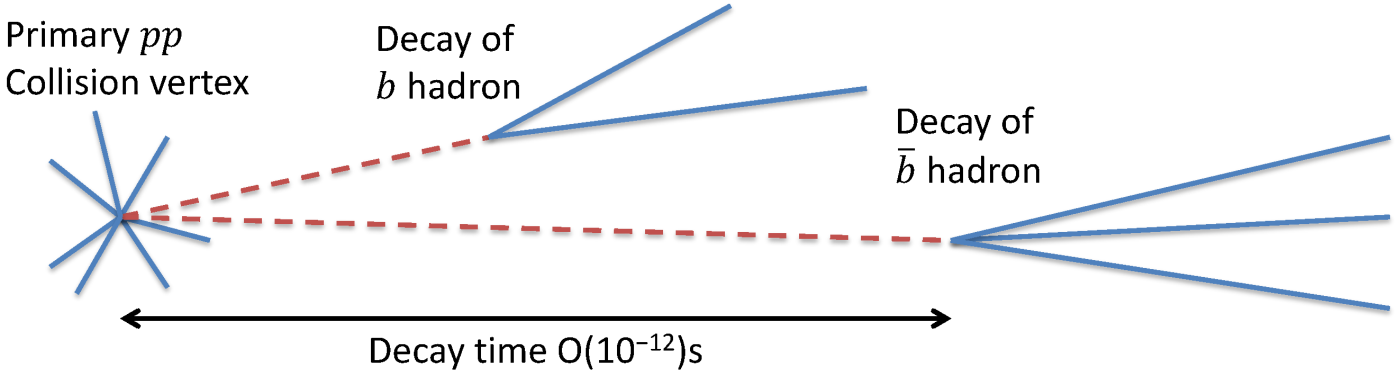
1. Types of CP violation
   - Mixing-induced, direct
   - Triple Product Asymmetries

2. Principles of time-dependent, flavour-tagged measurements at LHCb
   - Decay time acceptance
   - Decay time resolution
   - Flavour-tagging calibration
   - Angular analysis

3. $B_s^0 \to \phi\phi$

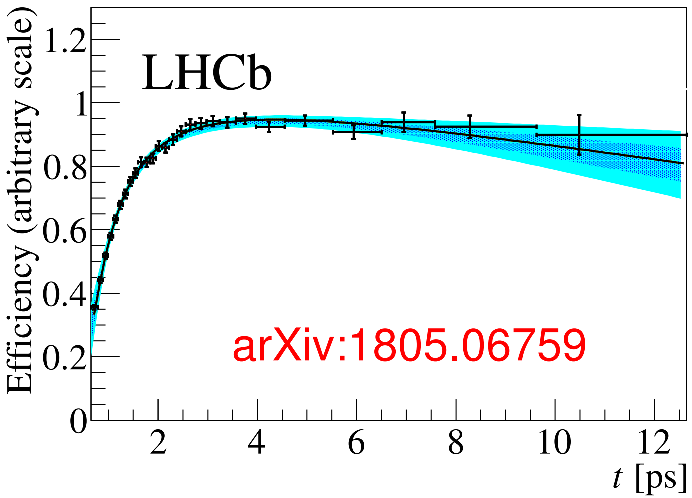
4. $B_s^0 \to K^{*0}\bar{K}^{*0}$

Decay Time Distribution



Decay times precisely measured due to VELO vertex measurements

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



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

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

Perform lifetime fit

Transform back to $B^0 \to \pi^+\pi^-$

Topological weights obtained from simulation

Decay Time Resolution

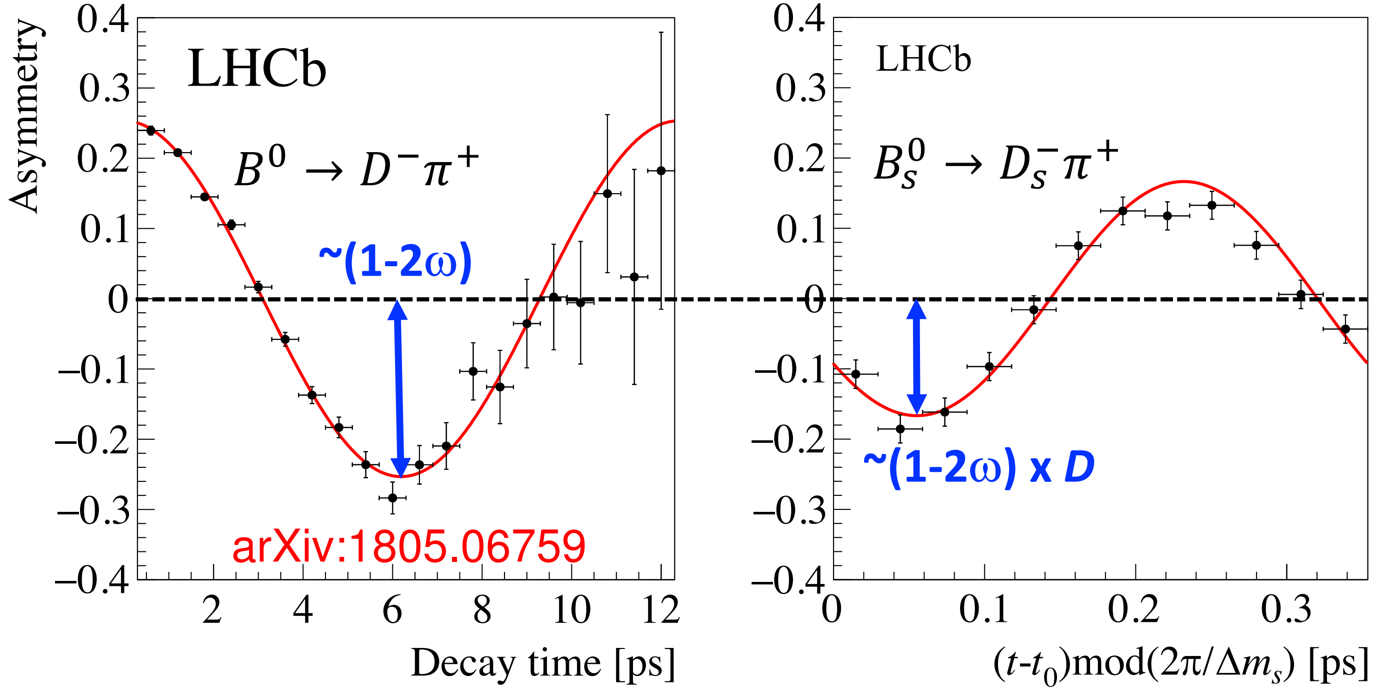
Event-dependent decay time resolution σ_t

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

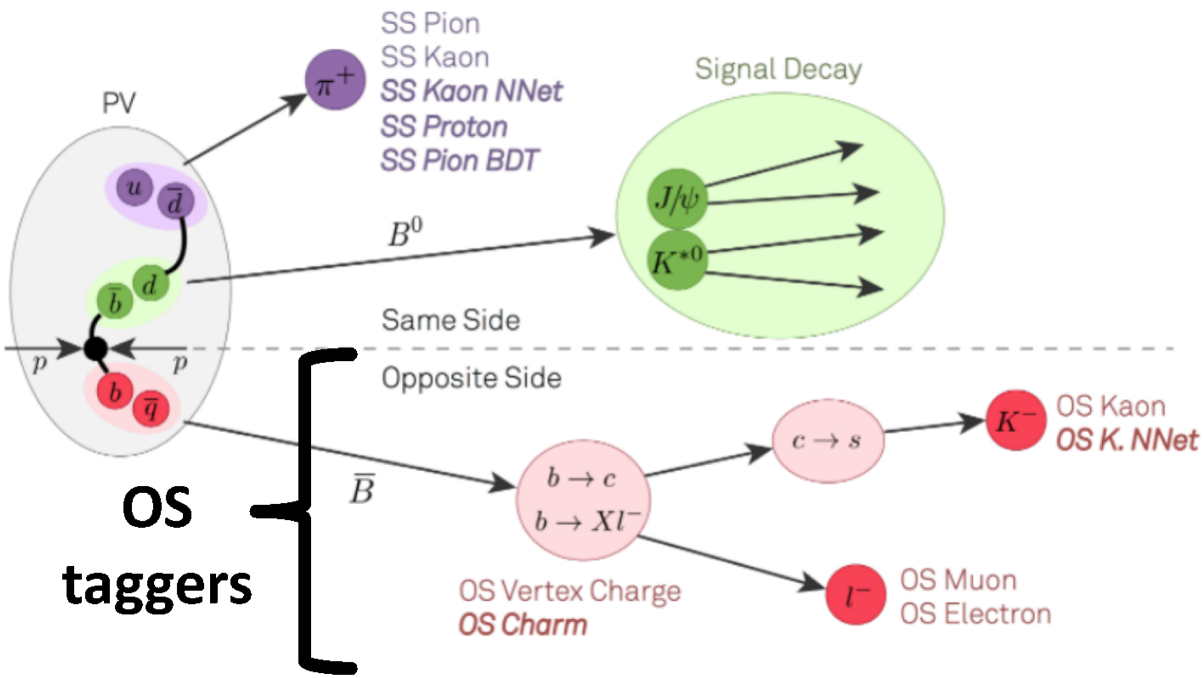
Negligible in B^0 decays due to small Δm_d, critical for B_s^0, however

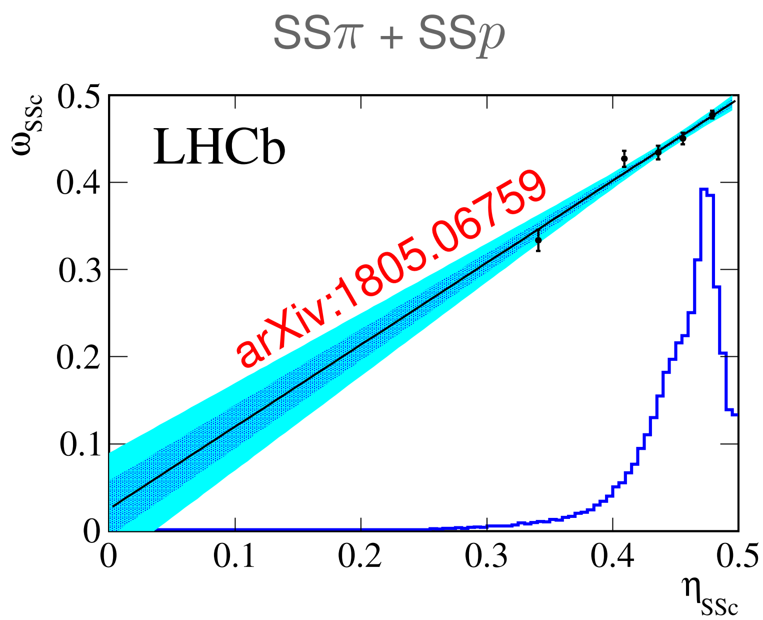
Linearly dependent on per-event decay time error

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



Flavour Tagging





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

Calibrated vs Uncalibrated mistag

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

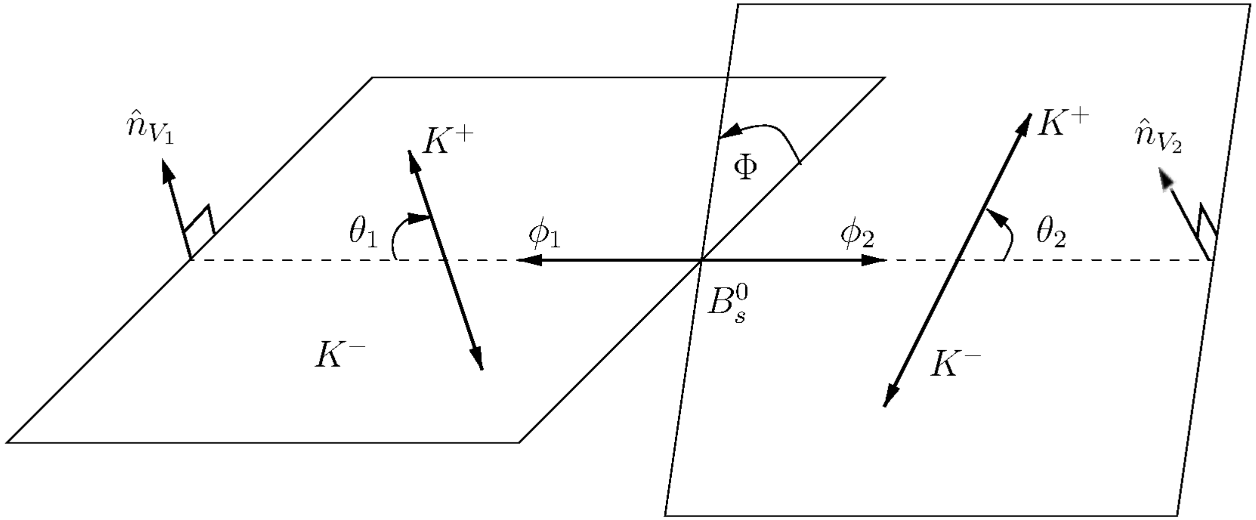
Wrong tag probability w, linearly calibrated with various control samples

Effective tagging power for particular category, $\epsilon_{\text{Tag}}(1-2w)^2$

Angular Analysis in $B \to VV$

3 polarisations in main topology of interest: S, P, D

Transform phase space to convenient "transversity basis": 0, $\perp$, $\parallel$



Fraction of longitudinal polarisation

$$f_L = \frac{|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$$

Naive Standard Model:

$$f_L \sim 1 - \mathcal{O}(m_V^2/m_B^2)$$

Breaks down for penguin dominated decays

New Physics proposed, however mainly attributed to poor understanding of strong interaction

Sufficient degrees of freedom to constrain amplitude through angular analysis

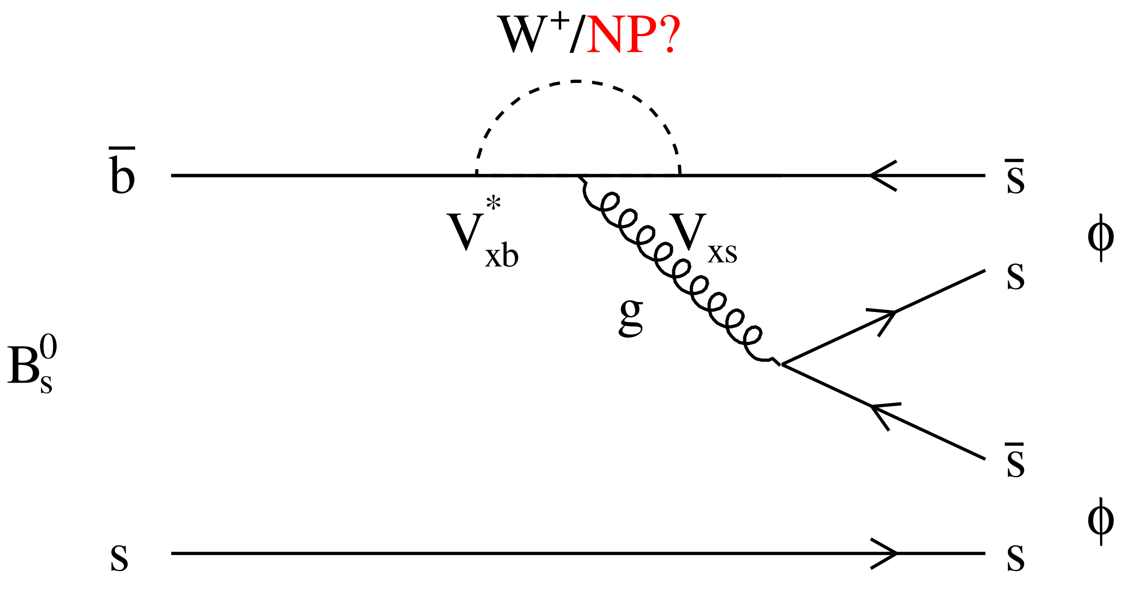
Separate interfering topologies *eg.* SS, SV, ST, VT, TT

Outline

1. Types of CP violation
   - Mixing-induced, direct
   - Triple Product Asymmetries
2. Time-dependent, flavour-tagging principles in $B \to VV$
   - Decay time acceptance
   - Decay time resolution
   - Flavour-tagging calibration
   - Angular analysis
3. $B_s^0 \to \phi\phi$
4. $B_s^0 \to K^{*0}\bar{K}^{*0}$

$B_s^0 \to \phi\phi$

Penguin dominated final state



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

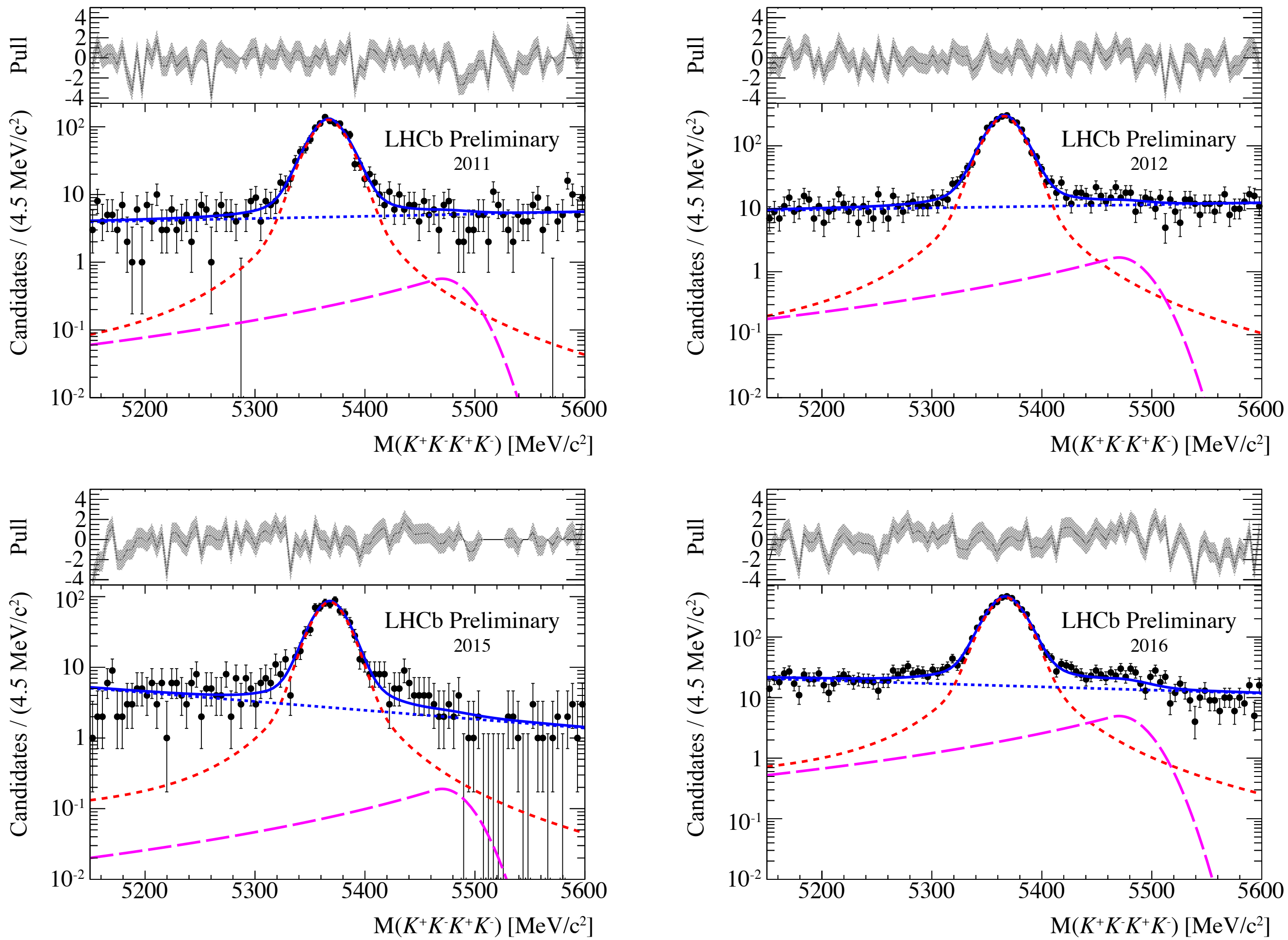
QCD Factorisation (QCDf) predictions: $|\phi_s^{s\bar{s}s}| < 0.02\ \mathrm{rad}$, $\mathcal{A}_{CP} = (0.2^{+0.6}_{-0.4})\%$, $f_L = 0.36^{+0.23}_{-0.18}$

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

Update of LHCb Run 1 analysis, JHEP **10**, 053 (2015)

$B_s^0 \to \phi\phi$

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

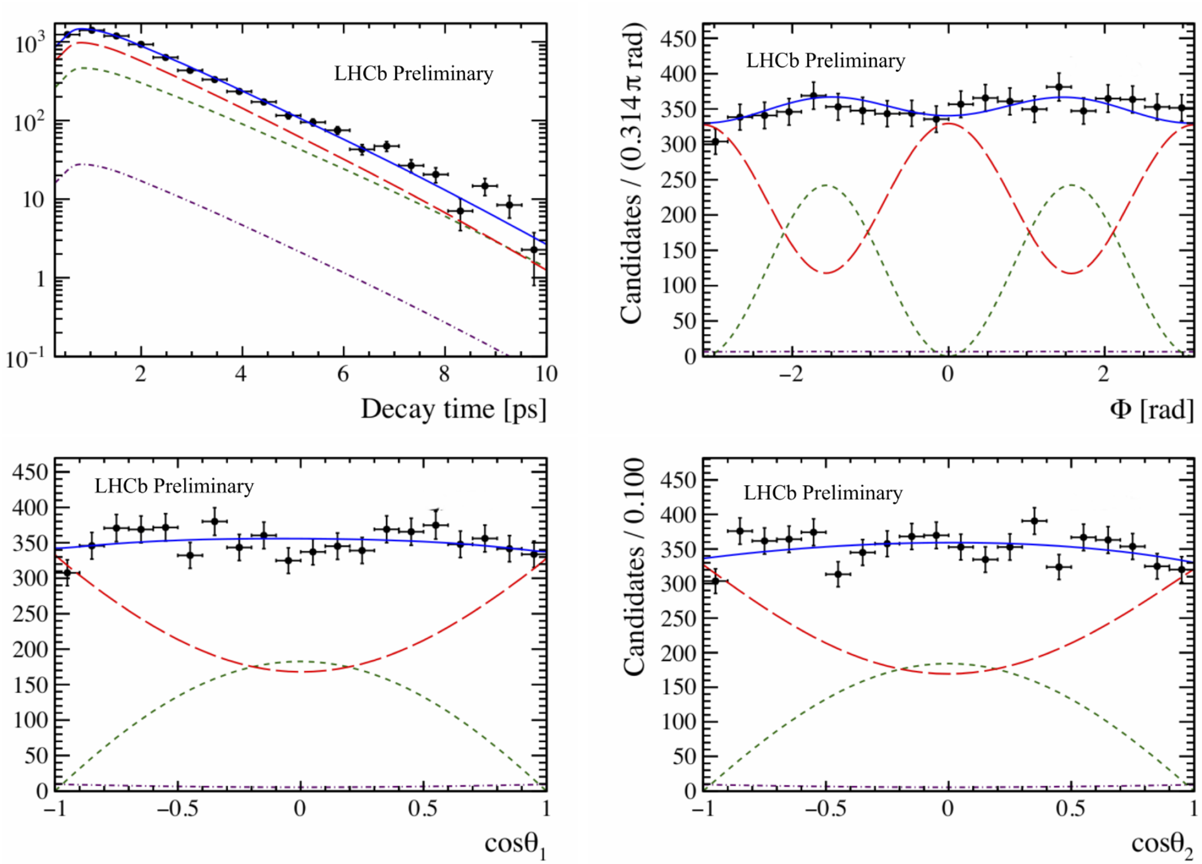


Mass projections by year

Pink: $\Lambda_b^0 \to \phi p K^-$

Yield: 8481 ± 101

$B_s^0 \to \phi\phi$



LHCb-CONF-2018-001

Effective tagging efficiency

$$(5.74 \pm 0.43)\%$$

Red: CP-even VV

Green: CP-odd VV

Purple: SV + SS

$$\phi_s^{s\bar{s}s} = -0.07 \pm 0.13\ (\text{stat}) \pm 0.03\ (\text{syst})\ \text{rad}$$
$$|\lambda_{CP}| = 1.02 \pm 0.05\ (\text{stat}) \pm 0.03\ (\text{syst})$$
$$f_L = 0.382 \pm 0.008\ (\text{stat}) \pm 0.011\ (\text{syst})$$

Additional search with triple product asymmetries shows no CP violation

Outline

1. Types of CP violation
   - Mixing-induced, direct
   - Triple Product Asymmetries

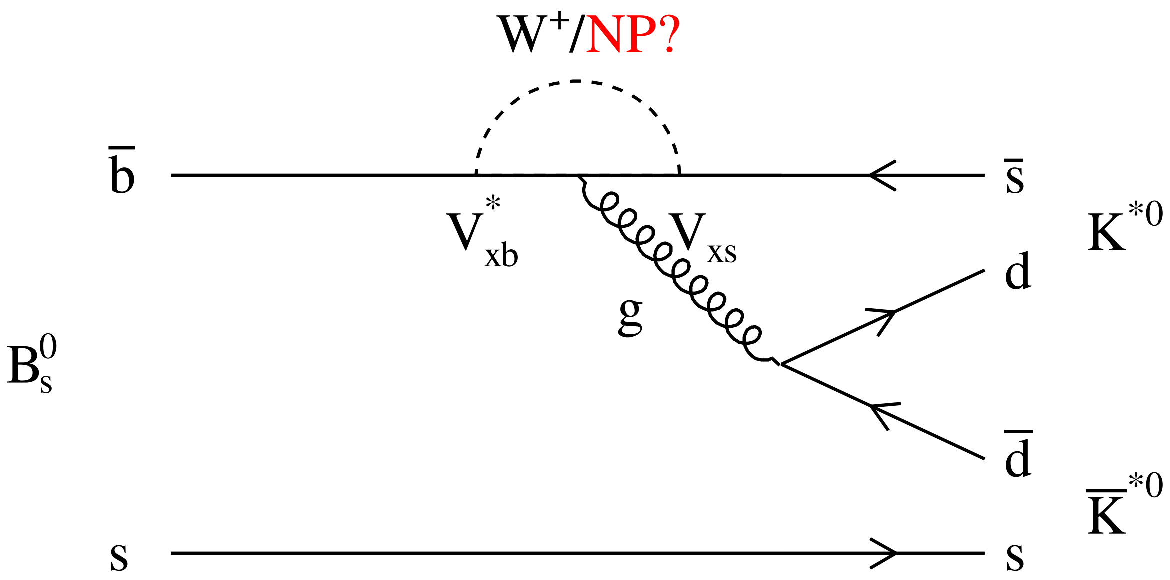
2. Time-dependent, flavour-tagging principles in $B \to VV$
   - Decay time acceptance
   - Decay time resolution
   - Flavour-tagging calibration
   - Angular analysis

3. $B_s^0 \to \phi\phi$

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

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

Penguin dominated final state



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

Additional complication of finite K^* width

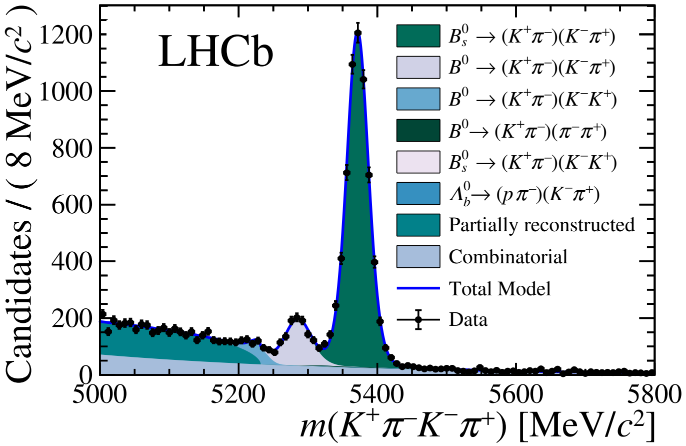
QCDf predictions: $\mathcal{A}_{CP} = (0.4^{+1.0}_{-0.6})\%$, $f_L = 0.56^{+0.22}_{-0.27}$

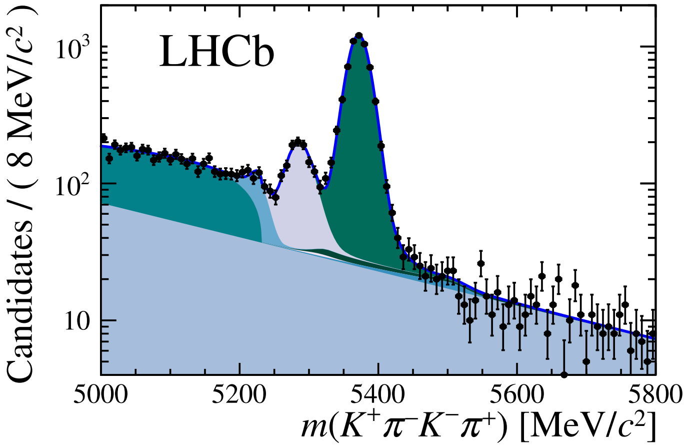
Phys. Rev. D **80**, 114026 (2009)

First observed at LHCb PLB **50**, 709 (2012), first angular measurement JHEP **07**, 166 (2015)

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

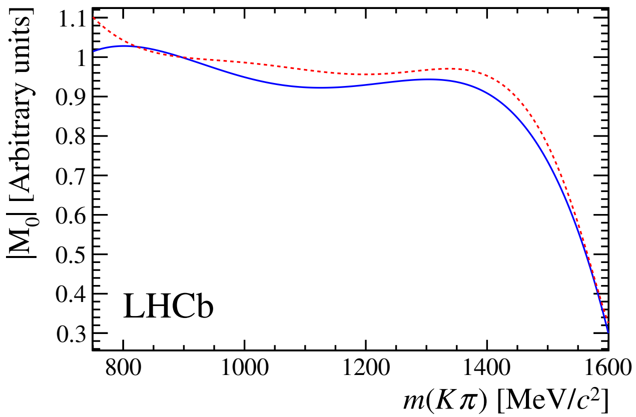
Analysis based on 2011+12 data (3 fb^{-1}), JHEP 03 (2018) 140

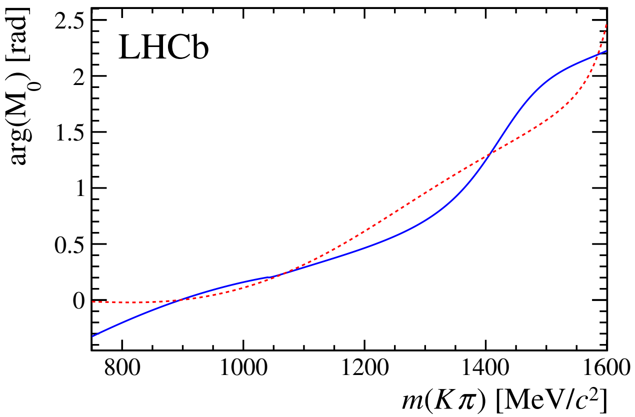




Yield: 6080 ± 83

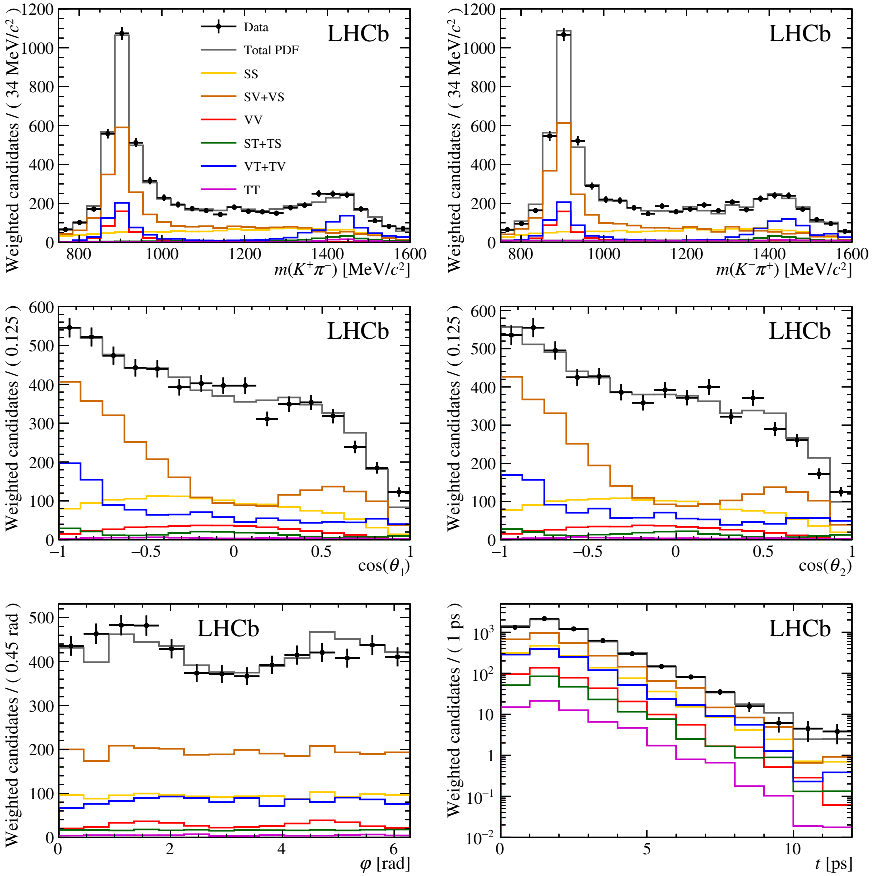
$(K\pi)_0$ S-wave treatment: magnitude from data, phase from scattering PRD **93**, 074025 (2016)





Blue: nominal model, Red: Alternative data-driven quasi-model-independent

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



World's first time-dependent 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 $B_s^0 \to \phi\phi$ and QCDf

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

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

$$f_L = 0.208 \pm 0.032\ (\text{stat}) \pm 0.046\ (\text{syst})$$

Summary

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

- Mixing-induced, direct and triple-product asymmetries

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

Penguin dominated highly sensitive to New Physics

Fraction of longitudinal polarisation another avenue to better understand QCD

Future polarisation-dependent measurement of CP violation will be interesting

Precision dominated by statistical uncertainties, room for New Physics

$B_s^0 \to \phi\phi$

- Consistent with SM predictions

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

- World's first measurement