b-meson decays at LHCb

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Outline

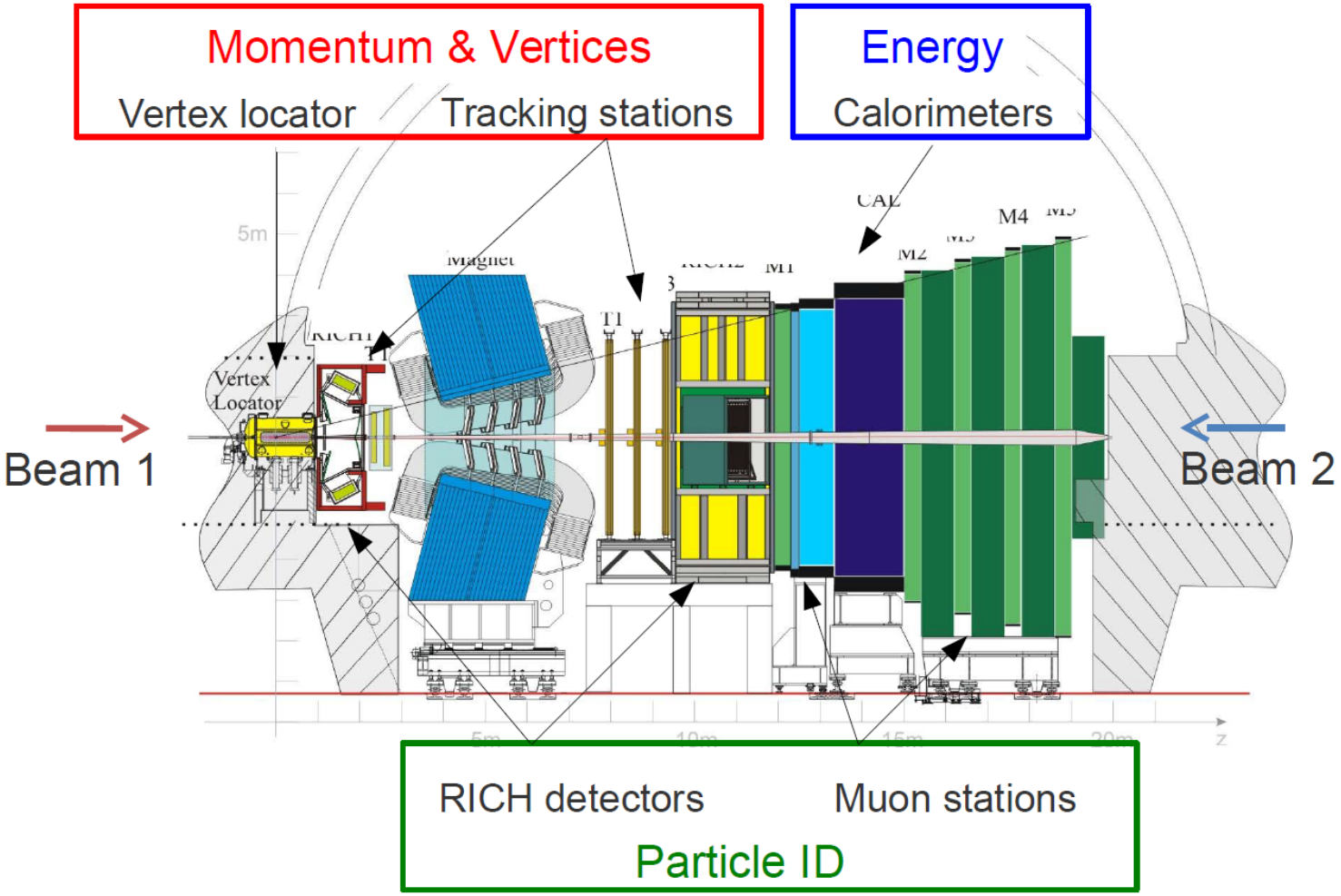
- Introduction

- Latest ϕ_s measurement in b-meson decays
  - $\phi_s^{s\bar{s}s}$ in $B_s^0 \to \phi\phi(\phi \to K^+K^-)$ decay LHCb-CONF-2018-001
  - $\phi_s^{d\bar{d}s}$ in $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ decay JHEP03(2018)140

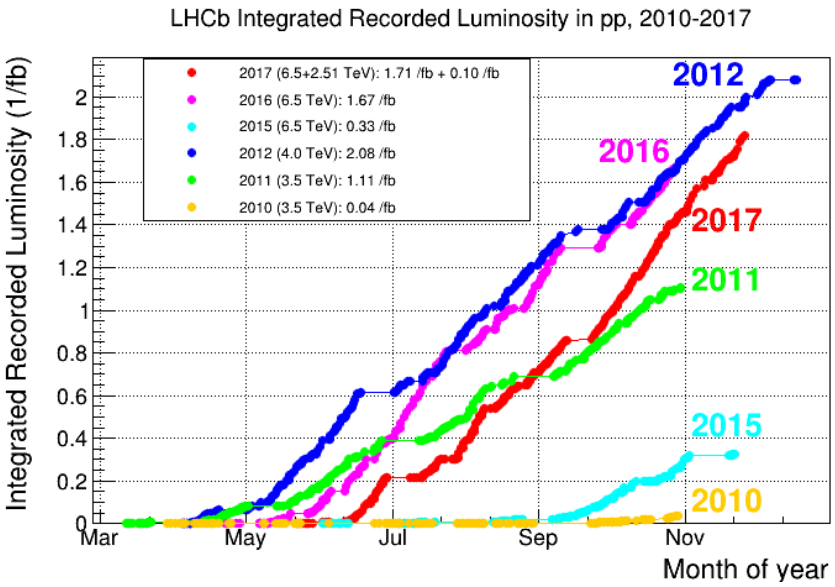
- Summary

LHCb detector

- Designed for beauty and charm physics, $2.0 < \eta < 5.0$



LHCb data



RUN-I

1 fb^{-1} of pp collisions at 7 TeV

2 fb^{-1} of pp collisions at 8 TeV

RUN-II (2015~2018 13 TeV)

2 fb^{-1} of pp collisions (2015~2016)

LHCb: $\boldsymbol{\sigma(pp \to b\bar{b}) \approx 0.3\ \text{mb}\ @7\ \text{TeV}}$

$\boldsymbol{\sigma(pp \to b\bar{b}) \approx 0.5\ \text{mb}\ @13\ \text{TeV}}$

Have large data sample for b physics

b physics

- Rare *B* meson decays

  - $B^0_{(s)} \to \mu^+\mu^-$, $B^0_{(s)} \to e^{\pm}\mu^{\mp}$, $B \to Ke\mu$.....

- *b*-hadrons spectroscopy

  - Ξ_{bc}, Ω^0_{bc}, B^*_c .....

- CP violation in *B* meson decays

  - time-integrated CP measurement (γ measurement)

  - time-dependent CPV (ϕ_s measurement)

Time-dependent decay rate

$$\frac{d\Gamma_{B^{(-)}_{(s)}\to f}(t)}{dt} \propto e^{-\Gamma_{(s)}t}\Big[\cosh(\frac{\Delta\Gamma_{(s)}t}{2}) + A_f^{\Delta\Gamma_{(s)}}\sinh(\frac{\Delta\Gamma_{(s)}t}{2}) \pm C_f\cos(\Delta m_{(s)}t) \mp S_f\sin(\Delta m_{(s)}t)\Big]$$

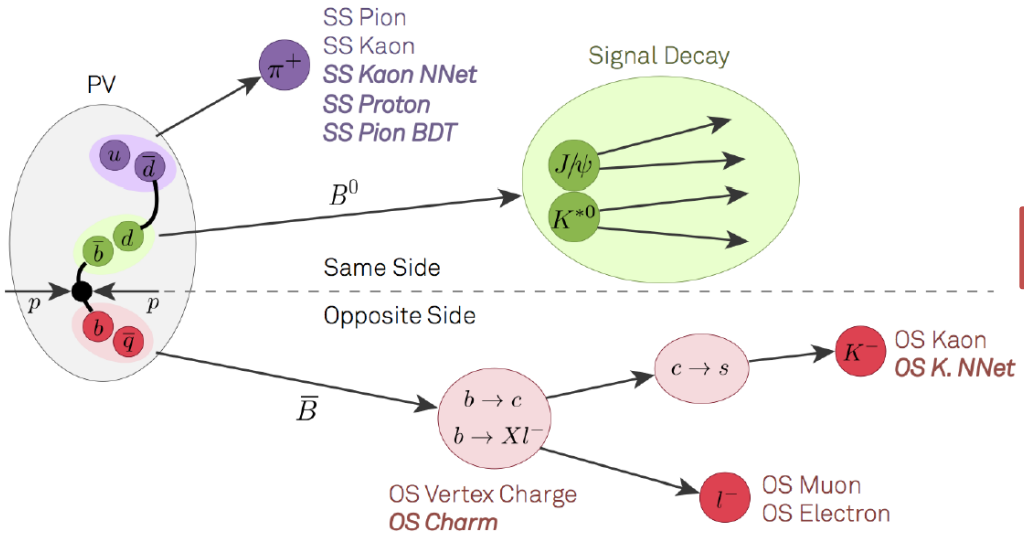
$$A_f^{\Delta\Gamma} \equiv -\frac{2\,\Re(\lambda_f)}{1+|\lambda_f|^2}, \quad C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \quad S_f \equiv \frac{2\,\Im(\lambda_f)}{1+|\lambda_f|^2} \quad \lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

- CPV terms $A_f^{\Delta\Gamma}$, C_f (driect CPV), S_f (mxing induced CPV)
- q, p mixing parameters in $|B_{L(H)}\rangle = p|B^0_{(s)}\rangle \pm q|\bar{B}^0_{(s)}\rangle$

Need identification of initial flavour and precise reconstruction of decay time

Flavour tagging

- Tag the initial flavour
  - Same side(SS) : using charges of particles produced in association with signal B
  - Opposite side(OS) : using charges of decay products of the other B hadron



imperfect taggers

↓

tagging efficiency ε, mistag ratio ω

↓

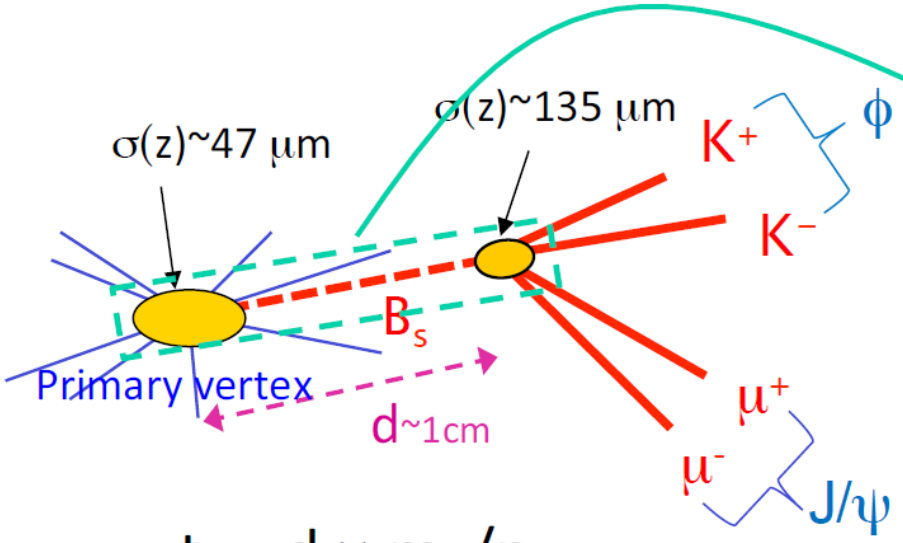
(1) $C_f(S_f) \to (1\text{-}2\omega)C_f(S_f)$
(2) tagging power $\varepsilon(1-2\omega)^2$

$\varepsilon(1-2\omega)^2$ ~ 3.73 % for $J/\psi K^+K^-$ in Run I analysis

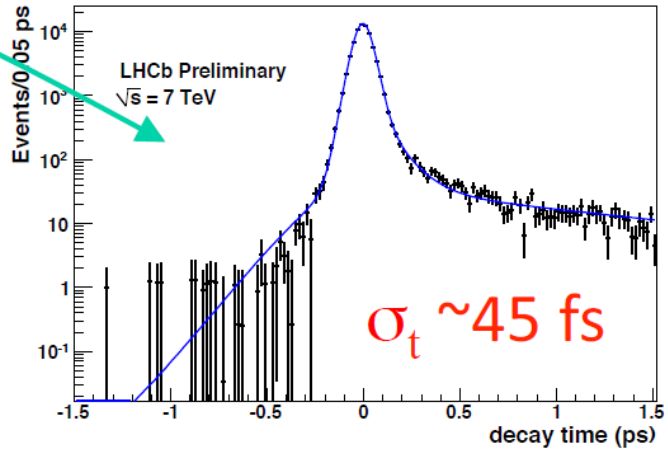
Time resolution

$B_s \rightarrow J/\psi(\mu\mu)\ \phi(KK)$

Calibration with prompt events



$t = d \times m_B / p_B$



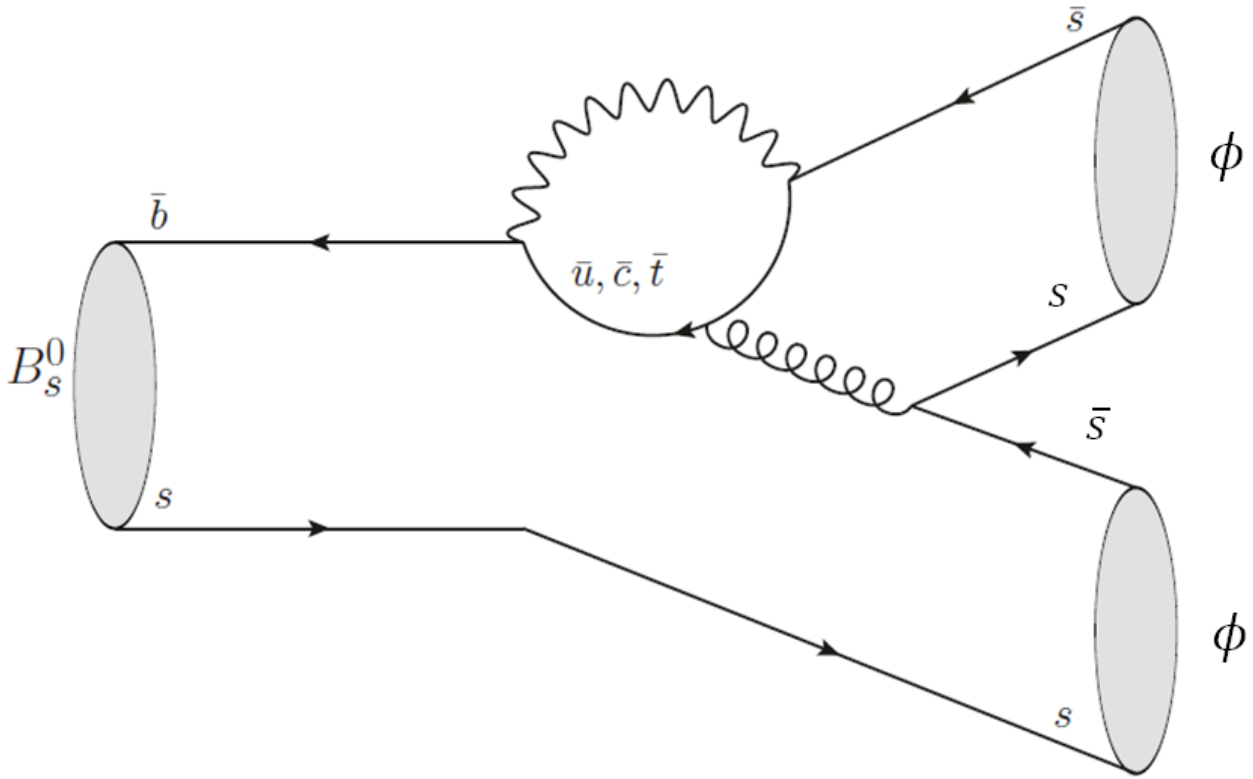
c.f. oscillation period ~ 350 fs

σ_t ~ 45 fs, dilution ~ 0.73 $C_f(S_f)$

$\phi_s^{s\bar{s}s}$ in $B_s^0 \to \phi\phi(\phi \to K^+K^-)$ decay

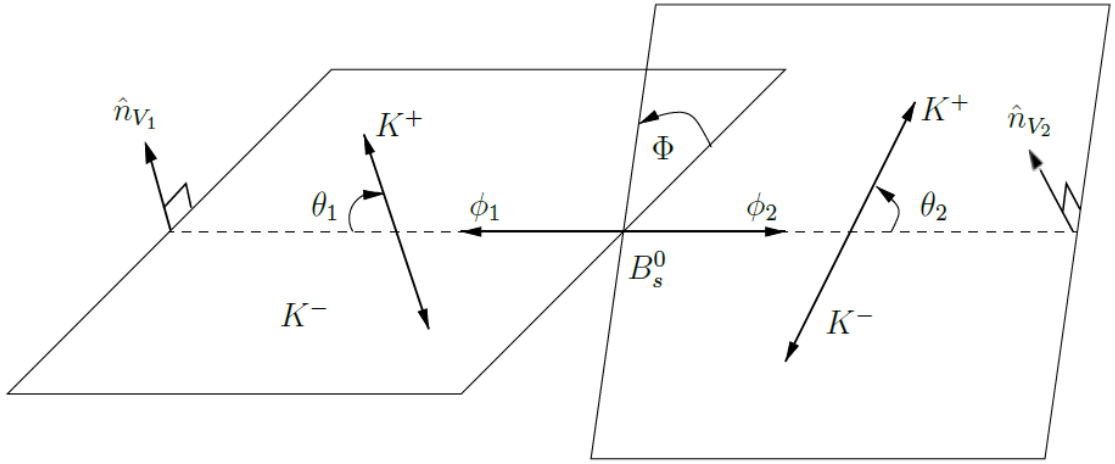
Feynman diagram

Mixing induced CPV phase $\phi_s = \arg(\lambda_f)$
excellent probe for physics beyond the SM



Time-dependent amplitude

- Extract the $\phi_s^{s\bar{s}s}$ from the fit of t and helicity angles



$$\frac{\mathrm{d}\Gamma}{\mathrm{d}t\,\mathrm{d}\cos\theta_1\,\mathrm{d}\cos\theta_2\,\mathrm{d}\Phi} \propto 4|\mathcal{A}(t,\theta_1,\theta_2,\Phi)|^2 = \sum_{i=1}^{15} K_i(t) f_i(\theta_1,\theta_2,\Phi)$$

- $\mathcal{A}$, total amplitude containing P-($\phi(1020)$) & S- (K^+K^-) wave
- $K_i(t)$, decay time model containing CPV terms; Γ_s, $\Delta\Gamma_s$, Δm_s are from previous measurements

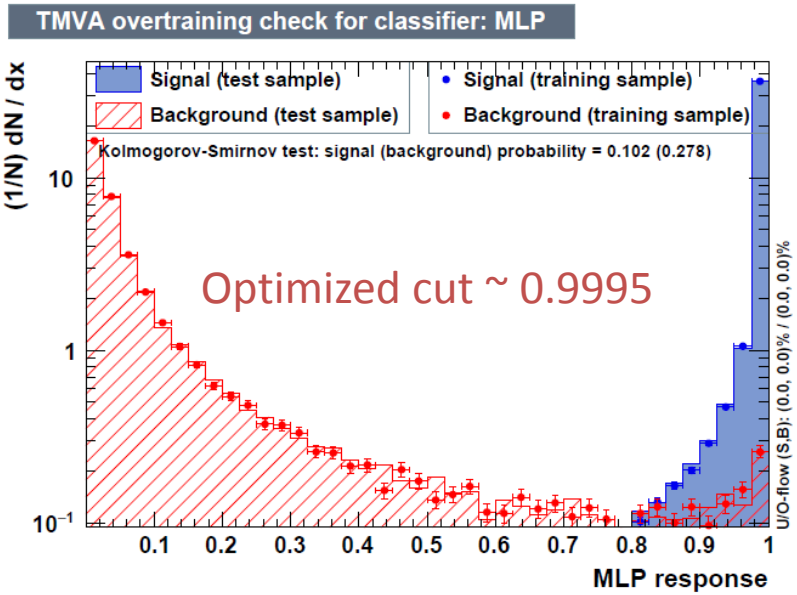
Selection and mass spectrum

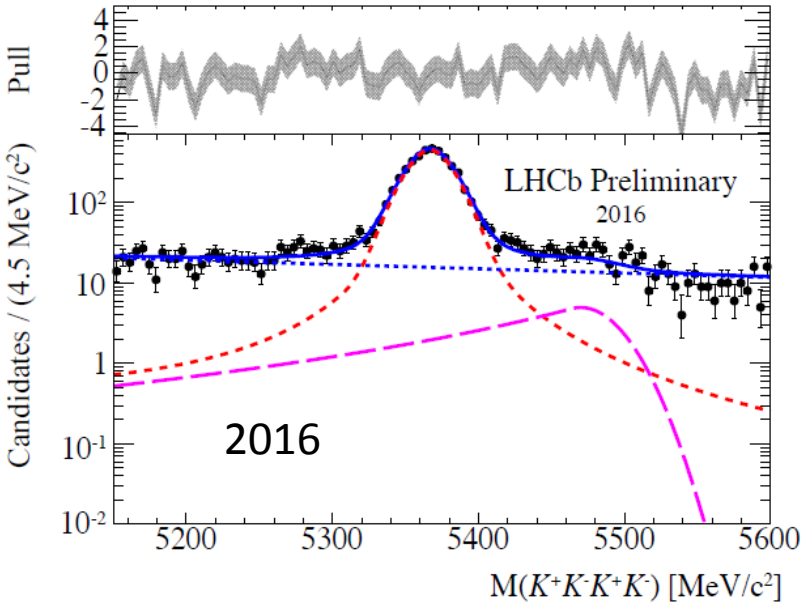
- Run I&2, $5fb^{-1}$

  - reconstructed with requirements on vertex fit quality, *PT*, χ^2_{IP}……

  - MVA training with *PT* of (B,ϕ,K), η of (B,ϕ) …….

  - background : combinatorial, $\Lambda_b^0 \to \phi p K^-$





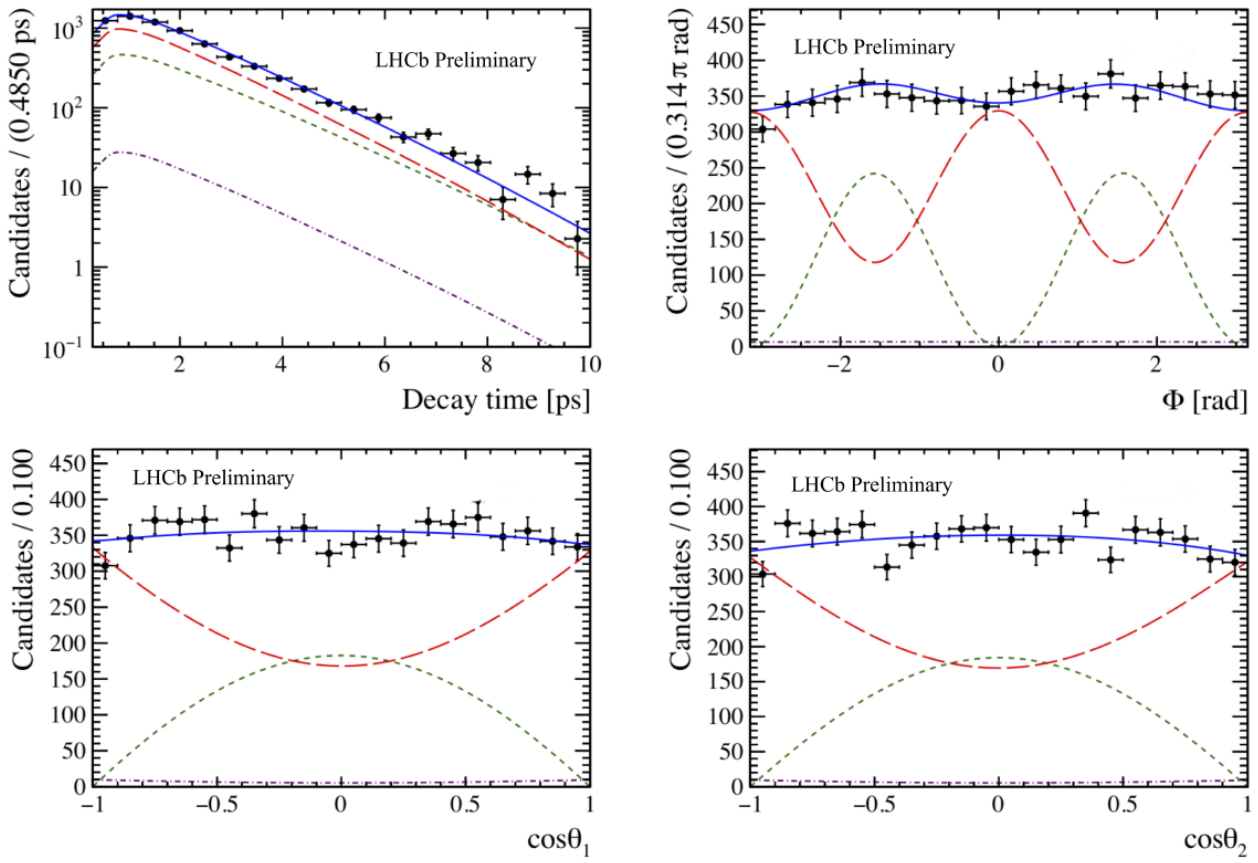
Calculate sWeight to substract background

Time-dependent amplitude fit

- Multidimensional fit to t and helicity angles

  - time resolution [41,44] fs, tagging power ~ 5.74 %

  - data point, total fit, CP-even P-wave, CP-odd P-wave, S- & double S-wave



Systematic

AA, TA & TR : angular acceptance, time acceptance & time resolution

Parameter	Mass model	AA	TA	TR	Fit bias	Total
$\phi_s^{s\bar{s}s}$ (rad)	0.0119	0.0072	0.0077	0.0035	0.0126	0.0206
$\lvert\lambda\rvert$	0.0063	0.0217	0.0023	0.0053	0.0097	0.0253

Parameters	Run 1&2, 5 fb^{-1}	Run 1, 3 fb^{-1}
$\phi_s^{s\bar{s}s}$	$-0.07 \pm 0.13 \pm 0.02$ rad	$-0.17 \pm 0.15 \pm 0.03$ rad
$\lvert\lambda\rvert$	$-1.02 \pm 0.05 \pm 0.03$	$-1.04 \pm 0.07 \pm 0.03$

$\phi_s^{d\bar{d}s}$ in $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ decay

Feynman diagram

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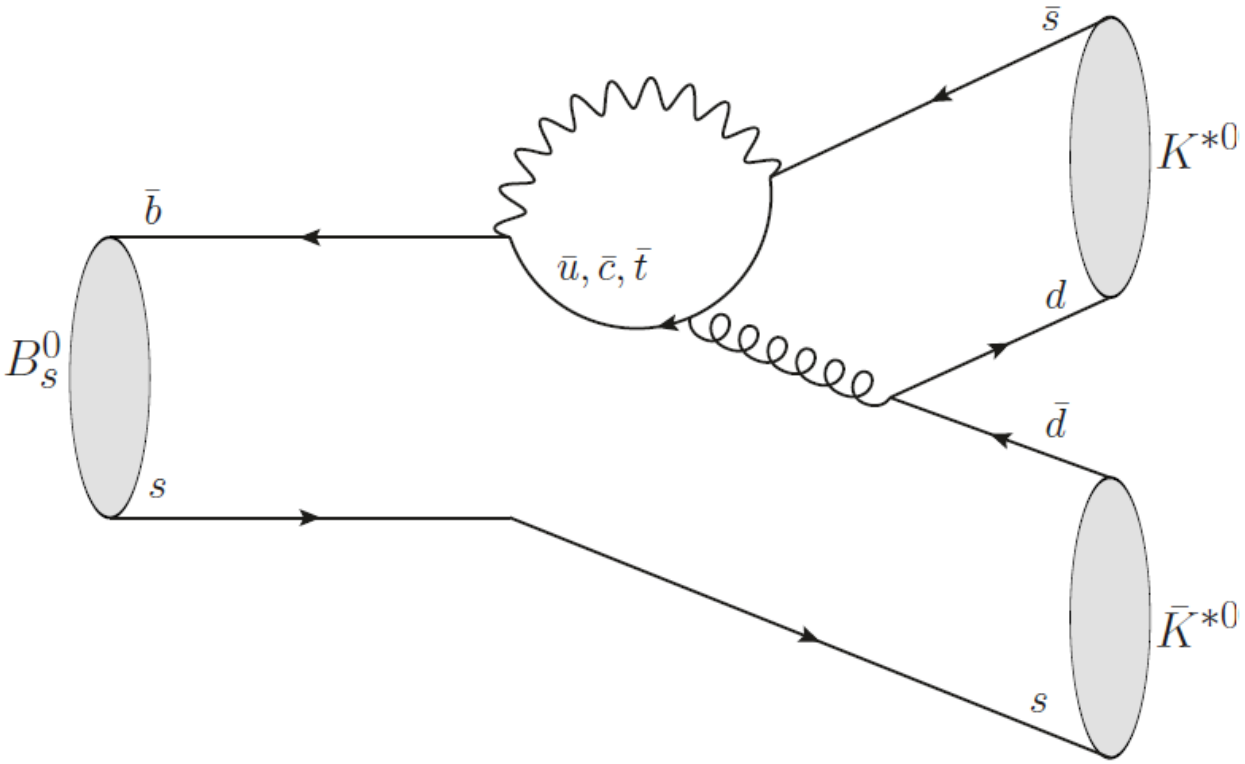
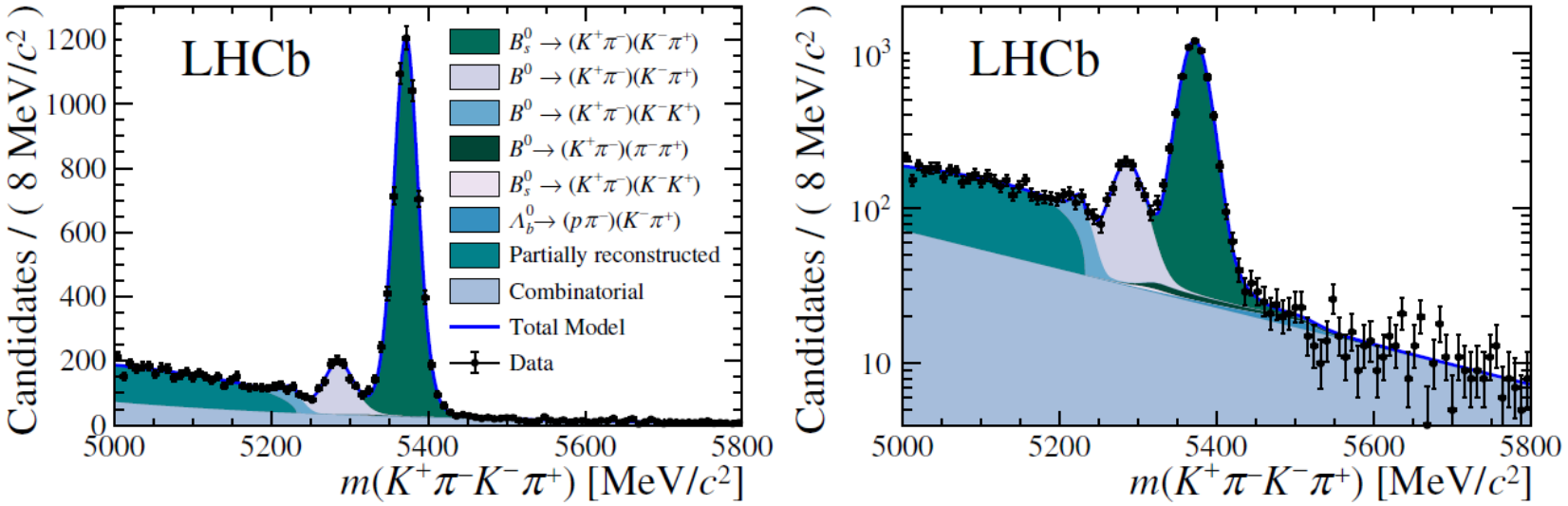


Selection and mass spectrum

- Run 1, 3 fb^{-1}

  - consider $K^{\pm}\pi^{\mp}\epsilon$ [750,1600] MeV
  - reconstructed with requirements on vertex fit quality, *PT*, χ^2_{IP}……
  - MVA training with kinematic and geometric quantities…..
  - combinatorial, misID, partial reconstructed and physical background



Calculate sWeight to substract background

Time-dependent amplitude

- $K^{\pm}\pi^{\mp}$ combination with spin 0,1,2

  - dominated by $K_0^*(800)^0$, $K_0^*(1430)^0$, $K^*(892)^0$ and $K_2^*(1430)^0$

Decay	Mode	j_1	j_2	Allowed values of h	Number of amplitudes
$B_s^0 \to (K^+\pi^-)_0^*(K^-\pi^+)_0^*$	scalar-scalar	0	0	0	1
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}^*(892)^0$	scalar-vector	0	1	0	1
$B_s^0 \to K^*(892)^0(K^-\pi^+)_0^*$	vector-scalar	1	0	0	1
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}_2^*(1430)^0$	scalar-tensor	0	2	0	1
$B_s^0 \to K_2^*(1430)^0(K^-\pi^+)_0^*$	tensor-scalar	2	0	0	1
$B_s^0 \to K^*(892)^0\overline{K}^*(892)^0$	vector-vector	1	1	$0, \parallel, \perp$	3
$B_s^0 \to K^*(892)^0\overline{K}_2^*(1430)^0$	vector-tensor	1	2	$0, \parallel, \perp$	3
$B_s^0 \to K_2^*(1430)^0\overline{K}^*(892)^0$	tensor-vector	2	1	$0, \parallel, \perp$	3
$B_s^0 \to K_2^*(1430)^0\overline{K}_2^*(1430)^0$	tensor-tensor	2	2	$0, \parallel_1, \perp_1, \parallel_2, \perp_2$	5

- Time-dependent amplitude

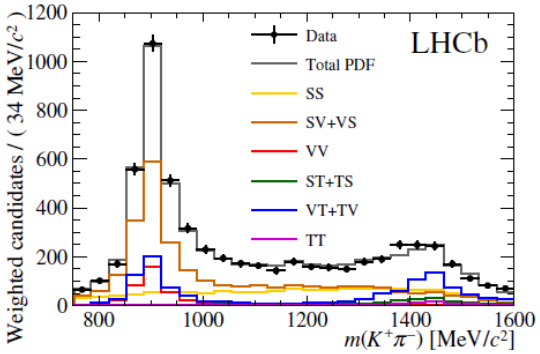
$$\mathrm{PDF}(t,\Omega) = \frac{\sum_{\alpha=1}^{19}\sum_{\beta\le\alpha}\Re e[K_{\alpha\beta}(t)F_{\alpha\beta}(\Omega)]}{\sum_{\alpha'=1}^{19}\sum_{\beta'\le\alpha'}\Re e[(\int dt'\, K^{\mathrm{untag}}_{\alpha'\beta'}(t')\epsilon_t(t'))\xi_{\alpha'\beta'}]}$$

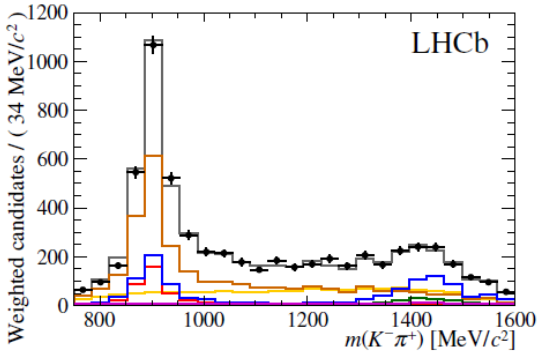
$$\Omega = (m_1, m_2, \cos\theta_1, \cos\theta_2, \varphi)$$

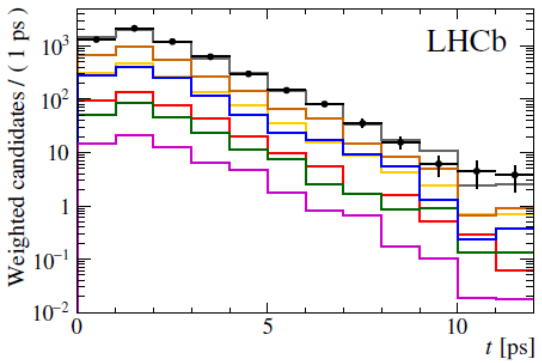
Time-dependent amplitude fit

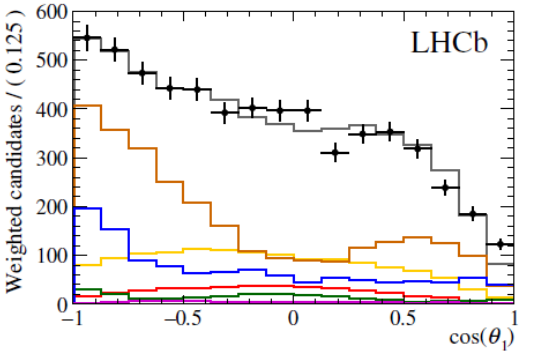
- Multidimensional fit to t, $K^{\pm}\pi^{\mp}$ mass and helicity angles

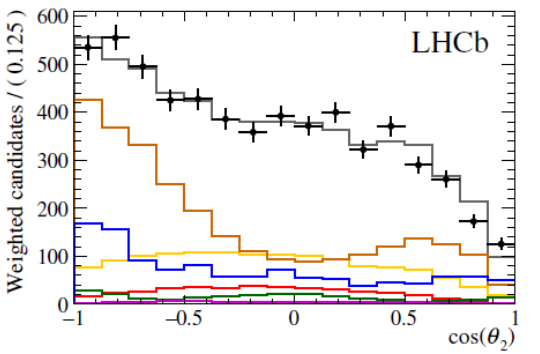
  - tagging power ~ 5.15 %

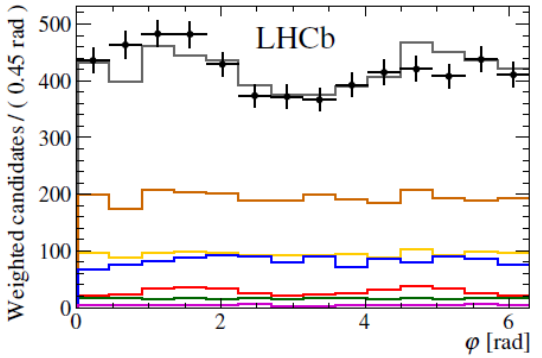












Systematic

Parameter	$\phi_s^{d\bar{d}}$ [rad]	$\lvert\lambda\rvert$
Yield and shape of mass model	0.012	0.001
Signal weights of mass model	0.012	0.007
Decay-time-dependent fit procedure	0.006	0.002
Decay-time-dependent fit parameterisation	0.049	0.013
Acceptance weights (simulated sample size)	0.106	0.078
Other acceptance and resolution effects	0.063	0.008
Production asymmetry	0.002	0.002
Total	0.141	0.089

First measurement in b $\rightarrow d\bar{d}s$ trainsitions

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

$|\lambda| = -1.035 \pm 0.034(stat) \pm 0.089(\text{syst})$

Statistical precision with more data

ϕ_s precision

Decay mode	σ(stat.) [rad] Run 1 (3 fb^{-1})	Run 1-3 (23 fb^{-1})	Run 1-6 (300 fb^{-1})
$B_s^0 \to \phi\phi$	0.154	0.039	0.011
$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ (inclusive)	0.129	0.033	0.009

The statistical precision will be improved ~ 4 times for Run 1-3 and ~14 times for Run 1-6

Summary

Presents ϕ_s measurement in $B_s^0 \to \phi\phi$ and $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ decay

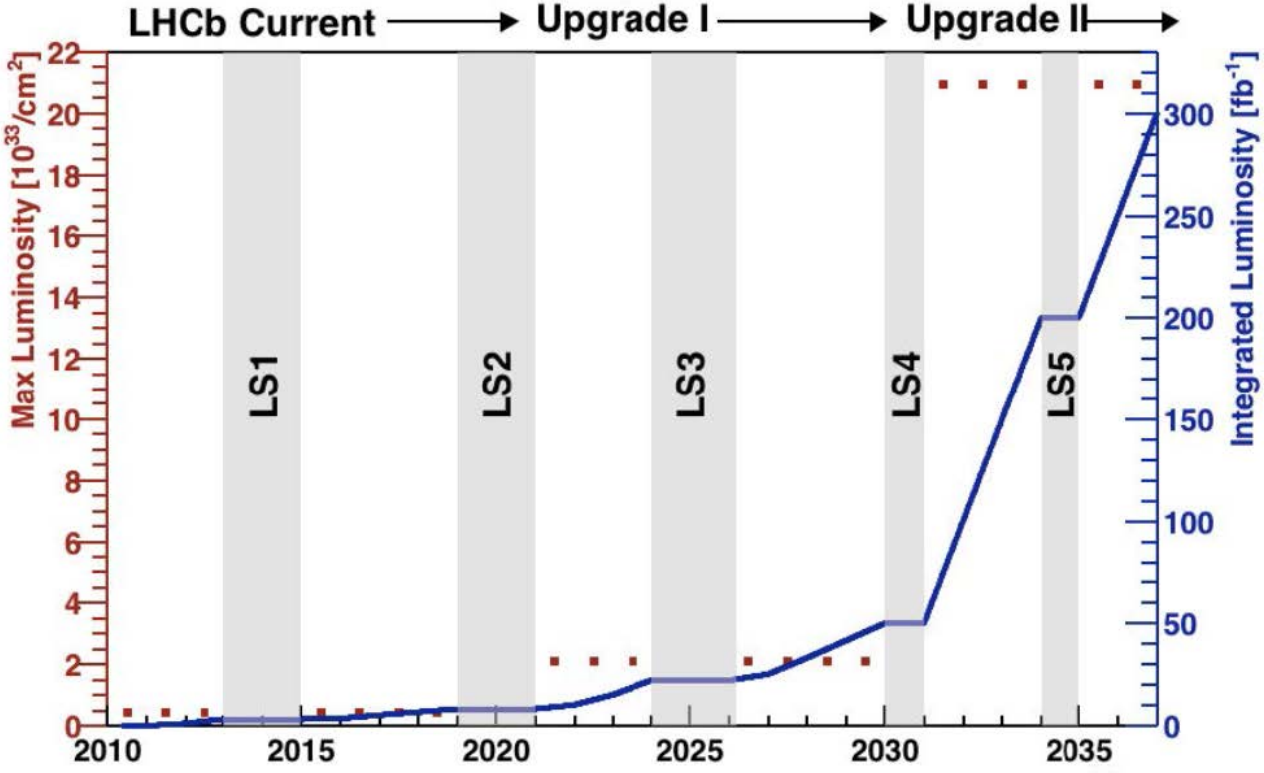
$$\phi_s^{s\bar{s}s} = -0.07 \pm 0.13(stat) \pm 0.03(\text{syst}) \text{ rad}$$
$$\phi_s^{d\bar{d}s} = -0.10 \pm 0.13(stat) \pm 0.14(\text{syst}) \text{ rad}$$

No significant CPV is found

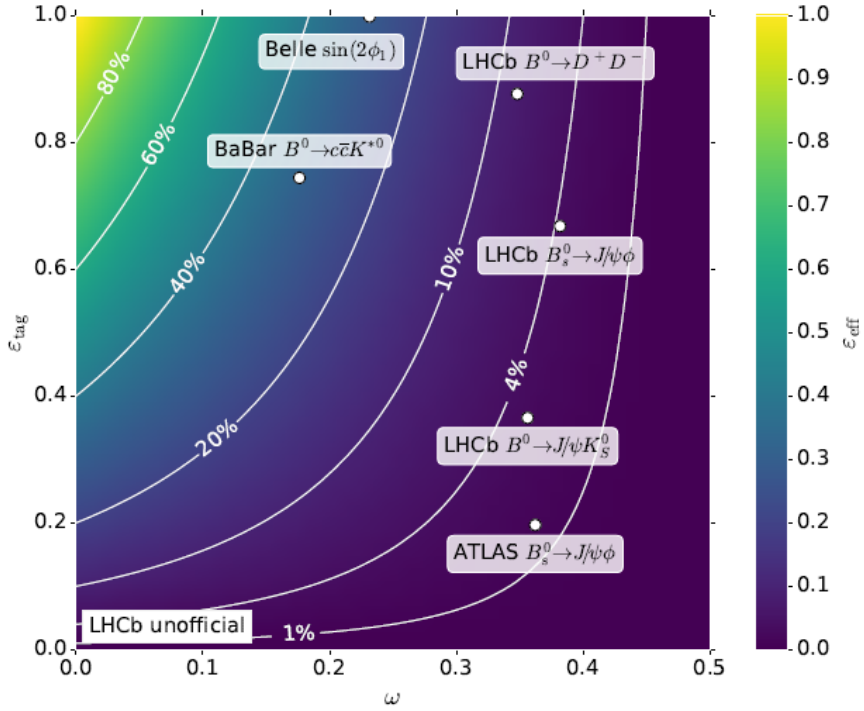
Thank you !

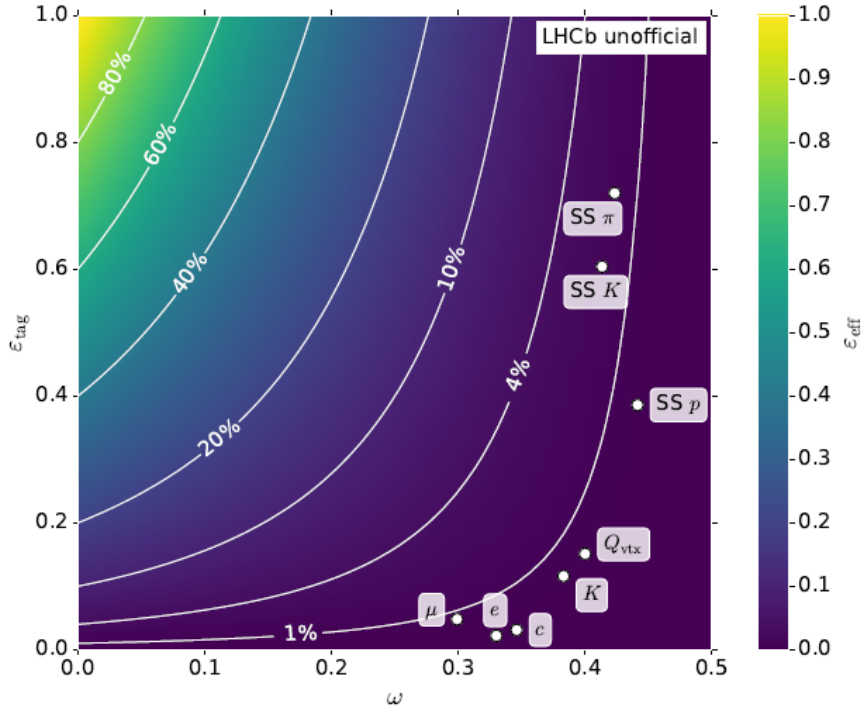
Backup

LHCb data taking



Tagging performance





$\phi_s^{s\bar{s}s}$ in $B_s^0 \to \phi\phi(\phi \to K^+K^-)$ decay

- Punzi figure

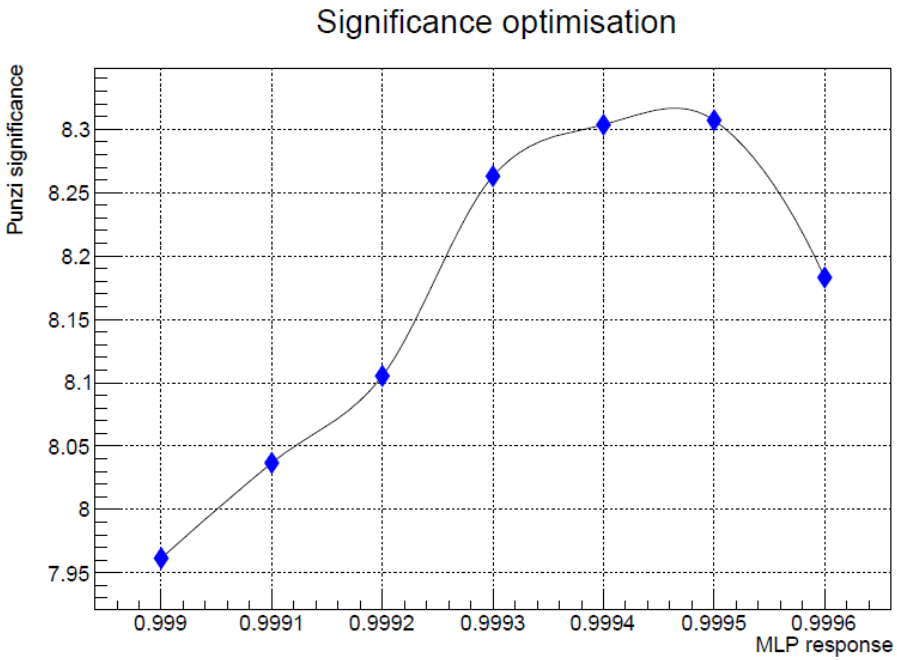


Figure 4: Significance optimisation using Punzi figure of merit for the $B^0 \to \phi\phi$ selection as a function of MVA response requirement for the full Run 1 and Run 2 dataset classifiers. Note the suppressed scale.

$\phi_s^{s\bar{s}s}$ in $B_s^0 \to \phi\phi(\phi \to K^+K^-)$ decay

- Coefficients of time-dependent terms and angular functions

Table 1: Coefficients of the time-dependent terms and angular functions used in Eq. 2. Amplitudes are defined at $t = 0$.

i	N_i	a_i	b_i	c_i	d_i	f_i
1	$\lvert A_0\rvert^2$	1	D	C	$-S$	$4\cos^2\theta_1\cos^2\theta_2$
2	$\lvert A_\parallel\rvert^2$	1	D	C	$-S$	$\sin^2\theta_1\sin^2\theta_2(1+\cos 2\Phi)$
3	$\lvert A_\perp\rvert^2$	1	$-D$	C	S	$\sin^2\theta_1\sin^2\theta_2(1-\cos 2\Phi)$
4	$\lvert A_\parallel\rvert\lvert A_\perp\rvert$	$C\sin\delta_1$	$S\cos\delta_1$	$\sin\delta_1$	$D\cos\delta_1$	$-2\sin^2\theta_1\sin^2\theta_2\sin 2\Phi$
5	$\lvert A_\parallel\rvert\lvert A_0\rvert$	$\cos(\delta_{2,1})$	$D\cos(\delta_{2,1})$	$C\cos\delta_{2,1}$	$-S\cos(\delta_{2,1})$	$\sqrt{2}\sin 2\theta_1\sin 2\theta_2\cos\Phi$
6	$\lvert A_0\rvert\lvert A_\perp\rvert$	$C\sin\delta_2$	$S\cos\delta_2$	$\sin\delta_2$	$D\cos\delta_2$	$-\sqrt{2}\sin 2\theta_1\sin 2\theta_2\sin\Phi$
7	$\lvert A_{SS}\rvert^2$	1	D	C	$-S$	$\frac{4}{9}$
8	$\lvert A_S\rvert^2$	1	$-D$	C	S	$\frac{4}{3}(\cos\theta_1+\cos\theta_2)^2$
9	$\lvert A_S\rvert\lvert A_{SS}\rvert$	$C\cos(\delta_S-\delta_{SS})$	$S\sin(\delta_S-\delta_{SS})$	$\cos(\delta_{SS}-\delta_S)$	$D\sin(\delta_{SS}-\delta_S)$	$\frac{8}{3\sqrt{3}}(\cos\theta_1+\cos\theta_2)$
10	$\lvert A_0\rvert\lvert A_{SS}\rvert$	$\cos\delta_{SS}$	$D\cos\delta_{SS}$	$C\cos\delta_{SS}$	$-S\cos\delta_{SS}$	$\frac{8}{3}\cos\theta_1\cos\theta_2$
11	$\lvert A_\parallel\rvert\lvert A_{SS}\rvert$	$\cos(\delta_{2,1}-\delta_{SS})$	$D\cos(\delta_{2,1}-\delta_{SS})$	$C\cos(\delta_{2,1}-\delta_{SS})$	$-S\cos(\delta_{2,1}-\delta_{SS})$	$\frac{4\sqrt{2}}{3}\sin\theta_1\sin\theta_2\cos\Phi$
12	$\lvert A_\perp\rvert\lvert A_{SS}\rvert$	$C\sin(\delta_2-\delta_{SS})$	$S\cos(\delta_2-\delta_{SS})$	$\sin(\delta_2-\delta_{SS})$	$D\cos(\delta_2-\delta_{SS})$	$-\frac{4\sqrt{2}}{3}\sin\theta_1\sin\theta_2\sin\Phi$
13	$\lvert A_0\rvert\lvert A_S\rvert$	$C\cos\delta_S$	$-S\sin\delta_S$	$\cos\delta_S$	$-D\sin\delta_S$	$\frac{8}{\sqrt{3}}\cos\theta_1\cos\theta_2$ $\times(\cos\theta_1+\cos\theta_2)$
14	$\lvert A_\parallel\rvert\lvert A_S\rvert$	$C\cos(\delta_{2,1}-\delta_S)$	$S\sin(\delta_{2,1}-\delta_S)$	$\cos(\delta_{2,1}-\delta_S)$	$D\sin(\delta_{2,1}-\delta_S)$	$\frac{4\sqrt{2}}{\sqrt{3}}\sin\theta_1\sin\theta_2$ $\times(\cos\theta_1+\cos\theta_2)\cos\Phi$
15	$\lvert A_\perp\rvert\lvert A_S\rvert$	$\sin(\delta_2-\delta_S)$	$-D\sin(\delta_2-\delta_S)$	$C\sin(\delta_2-\delta_S)$	$S\sin(\delta_2-\delta_S)$	$-\frac{4\sqrt{2}}{\sqrt{3}}\sin\theta_1\sin\theta_2$ $\times(\cos\theta_1+\cos\theta_2)\sin\Phi$

$\phi_s^{d\bar{d}s}$ in $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ decay

- Decay-time-dependent amplitude fit results

Parameter	Value
Common parameters	
$\phi_s^{d\bar{d}}$ [rad]	$-0.10 \pm 0.13 \pm 0.14$
$\lvert\lambda\rvert$	$1.035 \pm 0.034 \pm 0.089$
Vector/Vector (VV)	
f^{VV}	$0.067 \pm 0.004 \pm 0.024$
$f_{\rm L}^{VV}$	$0.208 \pm 0.032 \pm 0.046$
$f_{\parallel}^{VV}$	$0.297 \pm 0.029 \pm 0.042$
$\delta_{\parallel}^{VV}$ [rad]	$2.40 \pm 0.11 \pm 0.33$
$\delta_{\perp}^{VV}$ [rad]	$2.62 \pm 0.26 \pm 0.64$
Scalar/Vector (SV and VS)	
f^{SV}	$0.329 \pm 0.015 \pm 0.071$
f^{VS}	$0.133 \pm 0.013 \pm 0.065$
δ^{SV} [rad]	$-1.31 \pm 0.10 \pm 0.35$
δ^{VS} [rad]	$1.86 \pm 0.11 \pm 0.41$
Scalar/Scalar (SS)	
f^{SS}	$0.225 \pm 0.010 \pm 0.069$
δ^{SS} [rad]	$1.07 \pm 0.10 \pm 0.40$
Scalar/Tensor (ST and TS)	
f^{ST}	$0.014 \pm 0.006 \pm 0.031$
f^{TS}	$0.025 \pm 0.007 \pm 0.033$
δ^{ST} [rad]	$-2.3 \pm 0.4 \pm 1.7$
δ^{TS} [rad]	$-0.10 \pm 0.26 \pm 0.82$

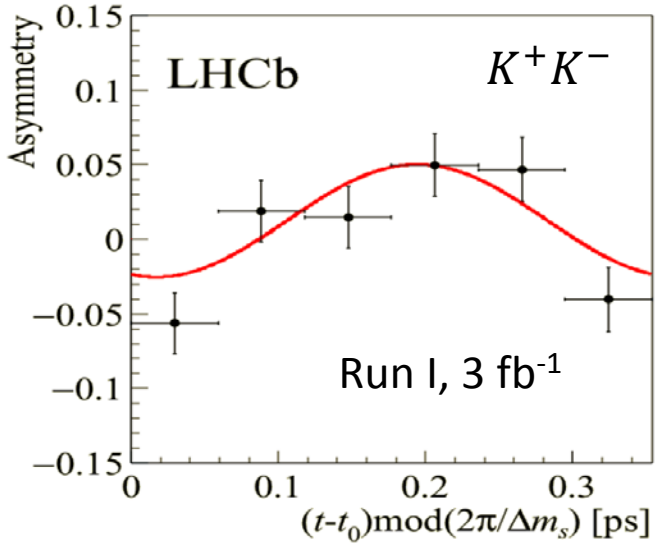
Parameter	Value
Vector/Tensor (VT and TV)	
f^{VT}	$0.160 \pm 0.016 \pm 0.049$
$f_{\rm L}^{VT}$	$0.911 \pm 0.020 \pm 0.165$
$f_{\parallel}^{VT}$	$0.012 \pm 0.008 \pm 0.053$
f^{TV}	$0.036 \pm 0.014 \pm 0.048$
$f_{\rm L}^{TV}$	$0.62 \pm 0.16 \pm 0.25$
$f_{\parallel}^{TV}$	$0.24 \pm 0.10 \pm 0.14$
δ_0^{VT} [rad]	$-2.06 \pm 0.19 \pm 1.17$
$\delta_{\parallel}^{VT}$ [rad]	$-1.8 \pm 0.4 \pm 1.0$
$\delta_{\perp}^{VT}$ [rad]	$-3.2 \pm 0.3 \pm 1.2$
δ_0^{TV} [rad]	$1.91 \pm 0.30 \pm 0.80$
$\delta_{\parallel}^{TV}$ [rad]	$1.09 \pm 0.19 \pm 0.55$
$\delta_{\perp}^{TV}$ [rad]	$0.2 \pm 0.4 \pm 1.1$
Tensor/Tensor (TT)	
f^{TT}	$0.011 \pm 0.003 \pm 0.007$
$f_{\rm L}^{TT}$	$0.25 \pm 0.14 \pm 0.18$
$f_{\parallel_1}^{TT}$	$0.17 \pm 0.11 \pm 0.14$
$f_{\perp_1}^{TT}$	$0.30 \pm 0.18 \pm 0.21$
$f_{\parallel_2}^{TT}$	$0.015 \pm 0.033 \pm 0.107$
δ_0^{TT} [rad]	$1.3 \pm 0.5 \pm 1.8$
$\delta_{\parallel_1}^{TT}$ [rad]	$3.00 \pm 0.29 \pm 0.57$
$\delta_{\perp_1}^{TT}$ [rad]	$2.6 \pm 0.4 \pm 1.5$
$\delta_{\parallel_2}^{TT}$ [rad]	$2.3 \pm 0.8 \pm 1.7$
$\delta_{\perp_2}^{TT}$ [rad]	$0.7 \pm 0.6 \pm 1.3$

CP asymmetry in $B^0_{(s)} \to h^+h^-$ decay

- Time-dependent *CP* asymmetry

  - mixing $|q/p| = 1$, measure C_f, S_f & $A_f^{\Delta\Gamma}$ and A_{CP}^B with $K^+\pi^-$ and $K^-\pi^+$ final states

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f \cos(\Delta m_{d,s} t) + S_f \sin(\Delta m_{d,s} t)}{\cosh\left(\frac{\Delta\Gamma_{d,s}}{2}t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d,s}}{2}t\right)}, \quad A_{CP} = \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2}$$



$$C_{\pi^+\pi^-} = -0.34 \pm 0.06 \pm 0.01$$
$$S_{\pi^+\pi^-} = -0.63 \pm 0.05 \pm 0.01$$
$$C_{K^+K^-} = 0.20 \pm 0.06 \pm 0.02$$
$$S_{K^+K^-} = 0.18 \pm 0.06 \pm 0.02$$
$$A^{\Delta\Gamma}_{K^+K^-} = -0.79 \pm 0.07 \pm 0.10$$
$$A^{B^0}_{CP} = -0.084 \pm 0.004 \pm 0.003$$
$$A^{B^0_s}_{CP} = 0.213 \pm 0.015 \pm 0.007$$

(1) $A_{CP}^{B_s^0}$, evidence of CPV is found in $B_s^0 \to K^+K^-$ for the first time

(2) 4.0 σ deviation of $(C_{K^+K^-}, S_{K^+K^-}, A^{\Delta\Gamma}_{K^+K^-})$ from (0,0,-1)

CP asymmetry in $B^0_{(s)} \to h^+h^-$ decay

- Time-dependent asymmetry

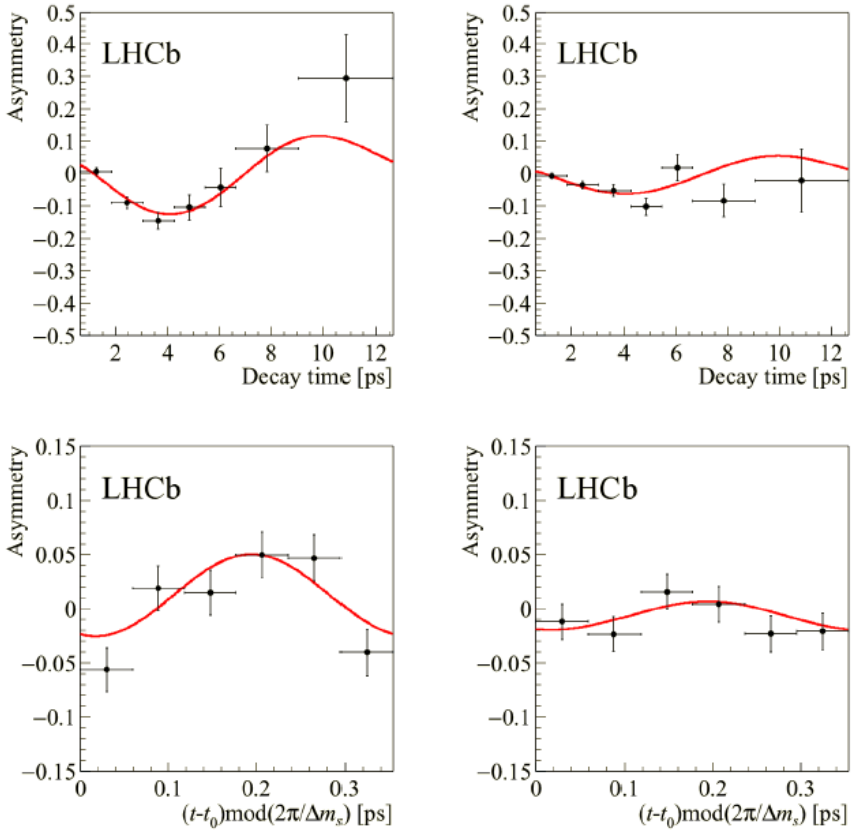


Figure 8: Time-dependent asymmetries for (top) $\pi^+\pi^-$ and (bottom) K^+K^- candidates with mass values in the intervals $5.20 < m < 5.35\,\mathrm{GeV}/c^2$ and $5.30 < m < 5.44\,\mathrm{GeV}/c^2$, respectively: (left) using the OS-tagging decision and (right) using either the SSc-tagging decision (for the $\pi^+\pi^-$ candidates) or the SSK-tagging decision (for the K^+K^- candidates). The result of the simultaneous fit is overlaid.