CPV measurements in B2VV decays at LHCb

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Charge-Parity Violation: why the interest?

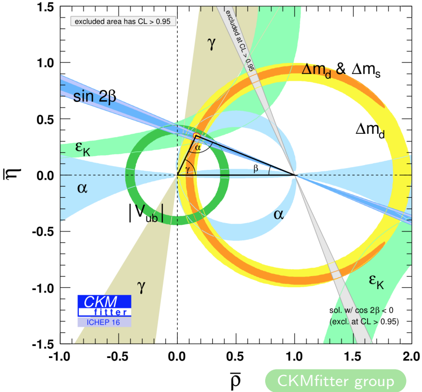
The Standard Model (SM) of particle physics **despite** being very successful in its predictions **fails to explain matter anti-matter differences** in our universe.

New sources of these asymmetries (CPV) are therefore **expected** in any satisfactory SM extension!

Flavour transitions in the quark sector are parametrised by the **CKM matrix**

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

CKM matrix: unitary, 3×3 matrix describing quark mixing (3 angles, one phase).
(A, λ, ρ, η) are not predicted by the SM.
They need to be measured!



CKMfitter group

These parameters are over constrained in the SM → great scenario to search for incompatibilities and small deviations due to New Physics (NP) effects

Why b hadrons? related unitary triangles are less squeezed hence expect larger sensitivity to any CP violation effect.

CPV phenomenology

How: measure interfering amplitudes with different CKM phases
Conditions: at least two amplitudes, non-zero strong phase difference and non-zero weak phase difference

Mixing

$$|X_{L,H}\rangle = q\,|X^0\rangle \pm p\,|\overline{X}^0\rangle$$

- $|q/p| \neq 1$
- **Neutral meson mixing**: $\mathcal{P}(X \to \overline{X}) \neq \mathcal{P}(\overline{X} \to X)$
- *Ex.:* $a_{sl}^{s,d} = \frac{R(\overline{B}^0 \to \bar{\ell}X) - R(B^0 \to \ell X)}{R(\overline{B}^0 \to \bar{\ell}X) + R(B^0 \to \ell X)}$

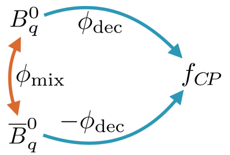
Decay

$$\mathcal{A}(X \to f) \neq \mathcal{A}(\overline{X} \to \bar{f})$$

- Amplitudes for **CP conjugates differ**
- Possible also for charged hadrons
- *Ex.:* $B^0 \to K^+\pi^-$ vs $\overline{B}^0 \to K^-\pi^+$

Interference Mixing and Decay

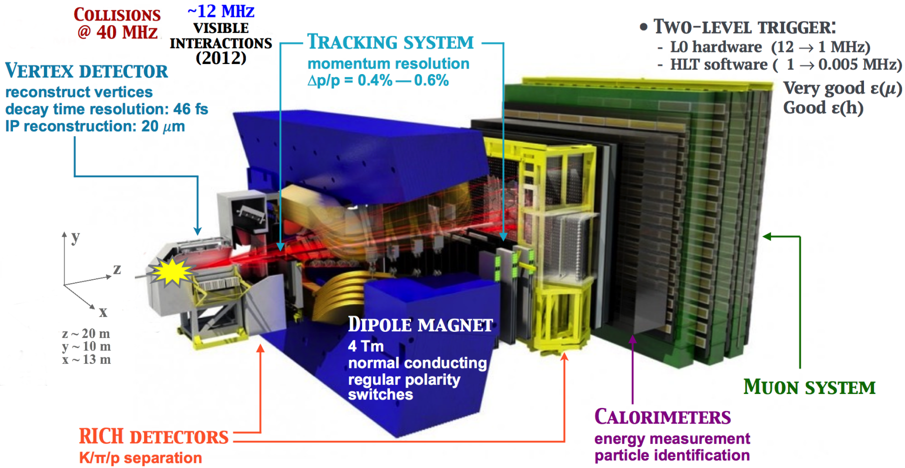
- **Interference of direct decay and decay after mixing**
- Partial decay widths are sensitive to $\phi_q = \phi_{mix} - 2\phi_{dec}$
- Decay-time dependent CP asymmetry:
  $a_{CP} = \frac{\Gamma(\overline{B}(t) \to f) - \Gamma(B(t) \to f)}{\Gamma(\overline{B}(t) \to f) + \Gamma(B(t) \to f)} = \frac{C_f \cos(\Delta M t) - S_f \sin(\Delta M t)}{\cosh(\frac{\Delta\Gamma t}{2}) + A_f^{\Delta\Gamma} \sinh(\frac{\Delta\Gamma t}{2})}$
- *Ex.:* $B^0 \to J/\Psi K_s^0$



CPV at LHCb

The LHCb detector

LHCb Detector Performance

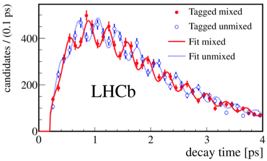


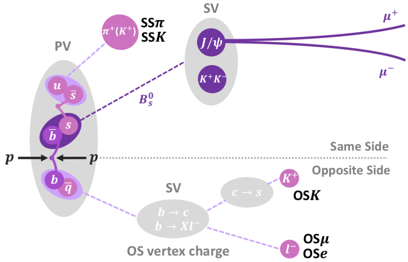
Experimental challenges

To **measure TD CPV** an experiment **needs**:

- Excellent **vertexing:**
  to separate primary from secondary vertexes
  to resolve fast oscillations
- Very good **PID** performance:
  to distinguish between topologically identical events
  to tag the initial flavour content
- Very **large sample sizes** to be sensitive to tiny variations
- **Control** over known CP asymmetries/effects

New J. Phys. 15 (2013) 053021



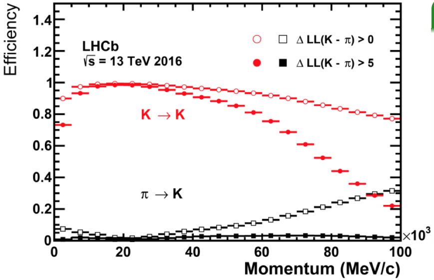


To help with these, the **LHCb:**

- runs at **lower instantaneous luminosity** than ATLAS or CMS
- **levels the luminosity**, making trigger conditions constant throughout the runs
- takes data with **different magnet polarities**

A word on PID and tagging

LHCb RICH Performance

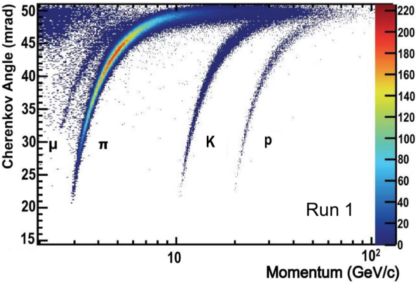


Particle Identification

- π/K separation: $\varepsilon_K \sim 90\%, \pi \to K$ misID $\sim 5\%$
- π/μ separation: $\varepsilon_\mu \sim 97\%, \pi \to \mu$ misID $\sim 1-3\%$
- Calibrated via **data driven** methods
- Good control and understanding of the **PID performance is critical** to our analyses.

Flavour tagging

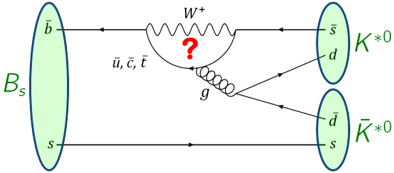
- Efficiency: $\varepsilon_{tag} = \frac{N_{tag}}{N_{tag}+N_{untag}}$
- Mistag: $\omega = \frac{N_{wrong}}{N_{right}+N_{wrong}}$
- Tagging power: $\varepsilon_{eff} = \varepsilon_{tag}\langle(1-2\omega)^2\rangle$ (~3 - 5%)
- Statistical uncertainty: $\sigma_{stat} \propto \frac{1}{\sqrt{\varepsilon_{eff} N}}$



Amplitude analyses of charmless b decays

FCNC, forbidden at tree level in the Standard Model (SM)

$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ and $B_s^0 \to \phi\phi$



Rich scenario to search for New Physics (NP) effects:

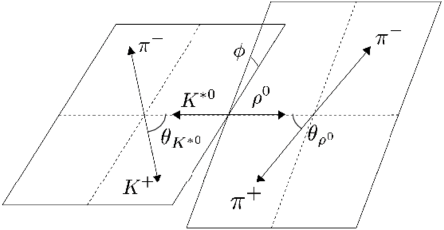
- **New particles** may contribute in the **loops**
- Rare modes, sensitive to **variations** of $\mathcal{B}$ w.r.t. SM predictions
- **NP** could also provide **additional sources** of **CP violation**
- **Flavour symmetries** can be exploited to **deal with QCD**

Formalism

$B \to (p_1 p_2)(p_3 p_4)$ decays

Can be **fully described** in terms of:

- **Three helicity angles**: $\theta_{12}, \theta_{34}, \phi$
- **Two invariant masses**: m_{12}, m_{34}
- **Decay time**: t



A **$B \to VV$ final state is an admixture of three amplitudes**
$\to$ three allowed **spin configurations**: CP-odd $S_{VV} = 1$ and CP-even $S_{VV} = 0, 2$:

$$J_B = 0 \text{ Angular Momentum Conservation } \Rightarrow \mathrm{J_{VV}} = 0, \text{ thus } \mathrm{S_{VV}} = \mathrm{L_{VV}}$$

Generalising to i amplitudes and taking into account the **time**, **masses** and **angles** factorisation:

$$d^6\Gamma \propto \sum_{ij} A(t)_{ij} \cdot g_{ij}(\cos\theta_{12}, \cos\theta_{34}, \phi) \cdot M_{ij}(m_{12}, m_{34})$$

An amplitude analysis disentangles the final state!

$A_i(t)$: **physical parameter**

$g_i(\theta_{12}, \theta_{34}, \phi)$: **spherical harmonics**

$M_i(m_{12}, m_{34})$: **mass prop.**

Observables

Polarisation fractions and phase differences

- CP-averaged polarisation fractions:
  $f_i = \frac{|A_i|^2}{\sum_\lambda |A_\lambda|^2}$, $\lambda = L, ||, \perp$
- CP-averaged strong phase differences $(\delta_0 - \delta_\perp)$
- CP-violating ϕ_s phase
- Direct CPV through $|\lambda|$

SM expectations:

- $\to$ (naïve factorisation) $f_L = 1 - \mathcal{O}(m_V^2/m_B^2)$, only holds for tree-dominated decays
- $\Delta(\delta_{||} - \delta_\perp) \sim 0$
- $|\lambda| \sim 1$, $\phi_s \sim 0$

HFLAV,arXiv:1612.07233

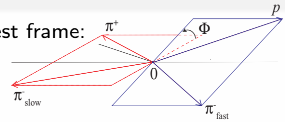
Nuclear Physics B 774 (2007) 64–101

Triple Product Asymmetries

Triple product definitions in the B candidate rest frame:

$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h^-} \times \vec{p}_{h^+}) \propto \sin\Phi$$

$$\overline{C}_{\hat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h^+} \times \vec{p}_{h^-}) \propto \sin\overline{\Phi}$$



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

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

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

CP-odd observable:

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

P-odd observable:

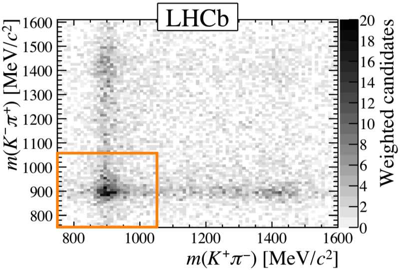
$$a_{P}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} + \overline{A}_{\hat{T}})$$

The $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ decay channel

$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$

JHEP 03 (2018) 140

- First analyses (1 fb^{-1}) by LHCb PLB 709 (2012) 50–58 (discovery) and JHEP 07 (2015) 166 (time-integrated amplitude analysis)



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JHEP 03 (2018) 140

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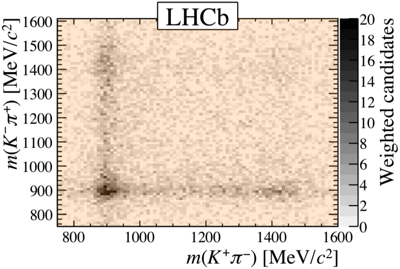
- First flavour-tagged, time-dependent amplitude analysis JHEP 03 (2018) 140, using full LHCb Run I data sample (3 fb^{-1})



Decay	Polarization Amplitudes
$B_s^0 \to (K^+\pi^-)_0^*(K^-\pi^+)_0^*$	SS
$B_s^0 \to (K^+\pi^-)_0^*\bar{K}^*(892)^0$	SV
$B_s^0 \to K^*(892)^0(K^-\pi^+)_0^*$	VS
$B_s^0 \to (K^+\pi^-)_0^*\bar{K}_2^*(1430)^0$	ST
$B_s^0 \to K_2^*(1430)^0(K^-\pi^+)_0^*$	TS
$B_s^0 \to K^*(892)^0\bar{K}^*(892)^0$	VV0, VV$\parallel$, VV$\perp$
$B_s^0 \to K^*(892)^0\bar{K}_2^*(1430)^0$	VT0, VT$\parallel$, VT$\perp$
$B_s^0 \to K_2^*(1430)^0\bar{K}^*(892)^0$	TV0, TV$\parallel$, TV$\perp$
$B_s^0 \to K_2^*(1430)^0\bar{K}_2^*(1430)^0$	TT0, TT$\parallel_1$, TT$\perp_1$, TT$\parallel_2$, TT$\perp_2$

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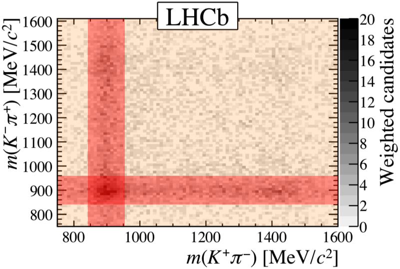

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$B_s^0 \to K_2^*(1430)^0(K^-\pi^+)_0^*$	TS
$B_s^0 \to K^*(892)^0\bar{K}^*(892)^0$	VV0, VV∥, VV⊥
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$B_s^0 \to K_2^*(1430)^0\bar{K}^*(892)^0$	TV0, TV∥, TV⊥
$B_s^0 \to K_2^*(1430)^0\bar{K}_2^*(1430)^0$	TT0, TT$\|_1$, TT$\perp_1$, TT$\|_2$, TT$\perp_2$

- ◇ Accounts for 19 polarisation amplitudes
- ◇ Describing scalar, vector and tensor resonances
- ◇ ϕ_s phase shared among all the channels
- ◇ Simultaneous fit in 4 kinematic categories (different acceptances)

$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$

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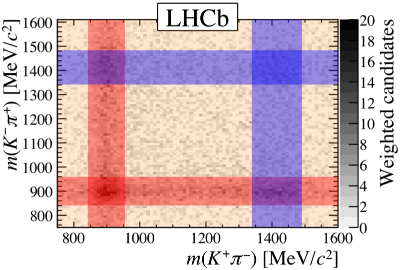

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$B_s^0 \to (K^+\pi^-)_0^*\bar{K}_2^*(1430)^0$	ST
$B_s^0 \to K_2^*(1430)^0(K^-\pi^+)_0^*$	TS
$B_s^0 \to K^*(892)^0\bar{K}^*(892)^0$	VV0, VV$\parallel$, VV$\perp$
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- ◇ Accounts for 19 polarisation amplitudes
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Signal candidates

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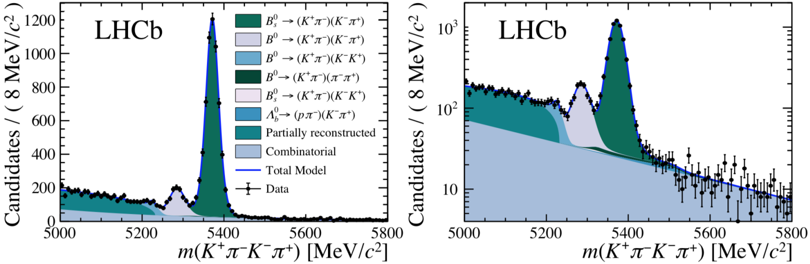

$N_{signal} = 6080 \pm 83$ events
(all signal channels, 4 categories combined)

Remove unwanted backgrounds:

- Use **particle identification** requirements and **BDT** against combinatorial background
- **Mass vetoes** for unwanted contributions
- Use ***s*Plot** procedure to subtract background

Fit results

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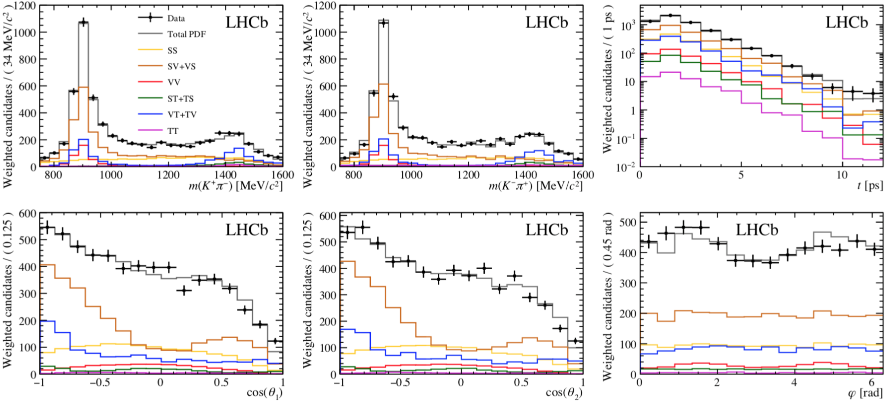
Remarks:

- Detector geometry and selection criteria introduce non-uniform **acceptance** → modelled with **full simulation**
- High dimensional fit, many free parameters → **parallel computation** of the likelihood function, working with **GPUs** using the Ipanema framework.



Fit results

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- **CP-averaged:** best, sometimes first, measurement of **19 polarisation amplitudes**. Of particular relevance: $f_L^{VV} = 0.208 \pm 0.032 \pm 0.046$.
- **CP-violating:** $\phi_s^{d\bar{d}} = -0.10 \pm 0.13 \pm 0.14$ rad and $|\lambda| = 1.035 \pm 0.034 \pm 0.089$.

Parameter	Value
Common parameters	
$\phi_s^{d\bar{d}}$ [rad]	$-0.10 \pm 0.13 \pm 0.14$
$\lvert\lambda\rvert$	$1.035 \pm 0.034 \pm 0.089$
$B_s^0 \to K^*(892)^0 \bar{K}^*(892)^0$ (VV)	
f^{VV}	$0.067 \pm 0.004 \pm 0.024$
f_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]	$2.62 \pm 0.26 \pm 0.64$
Single S-wave(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]	$1.86 \pm 0.11 \pm 0.41$

Parameter	Value
Double S-wave(SS)	
f^{SS}	$0.225 \pm 0.010 \pm 0.069$
δ^{SS} [rad]	$1.07 \pm 0.10 \pm 0.40$
Single D-wave(VT and TV)	
f^{VT}	$0.160 \pm 0.016 \pm 0.049$
f_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_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]	$0.2 \pm 0.4 \pm 1.1$

Parameter	Value
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]	$-0.10 \pm 0.26 \pm 0.82$
Double D-wave(TT)	
f_{TT}	$0.011 \pm 0.003 \pm 0.007$
f_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]	$0.7 \pm 0.6 \pm 1.3$

Dominant systematic uncertainty in $\phi_s^{d\bar{d}}$ from the **multidimensional acceptance** $\to$ **reducible**

The $B_s^0 \to \phi\phi$ decay channel

$B_s^0 \to \phi\phi$

Preliminary!

LHCb-CONF-2018-001

- Update of LHCb Run I analysis, Phys. Rev. D 90, 052011 (2014), adding data recorded during 2015 and 2016 (total of 5fb^{-1}).
- Flavour-tagged, time-dependent angular analysis, accounting for 5 polarisation amplitudes
- Includes **vector** and scalar waves

i	K_i	f_i
1	$\|A_0(t)\|^2$	$4\cos^2\theta_1\cos^2\theta_2$
2	$\|A_\parallel(t)\|^2$	$\sin^2\theta_1\sin^2\theta_2(1+\cos 2\Phi)$
3	$\|A_\perp(t)\|^2$	$\sin^2\theta_1\sin^2\theta_2(1-\cos 2\Phi)$
4	$Im(A_\parallel^*(t)A_\perp(t))$	$-2\sin^2\theta_1\sin^2\theta_2\sin 2\Phi$
5	$Re(A_\parallel^*(t)A_0(t))$	$\sqrt{2}\sin 2\theta_1\sin 2\theta_2\cos\Phi$
6	$Im(A_0^*(t)A_\perp(t))$	$-\sqrt{2}\sin 2\theta_1\sin 2\theta_2\sin\Phi$
7	$\|A_{SS}(t)\|^2$	$\frac{4}{9}$
8	$\|A_S(t)\|^2$	$\frac{4}{3}(\cos\theta_1+\cos\theta_2)^2$
9	$Re(A_S^*(t)A_{SS}(t))$	$\frac{8}{3\sqrt{3}}(\cos\theta_1+\cos\theta_2)$
10	$Re(A_0(t)A_{SS}^*(t))$	$\frac{8}{3}\cos\theta_1\cos\theta_2$
11	$Re(A_\parallel(t)A_{SS}^*(t))$	$\frac{4\sqrt{2}}{3}\sin\theta_1\sin\theta_2\cos\Phi$
12	$Im(A_\perp(t)A_{SS}^*(t))$	$-\frac{4\sqrt{2}}{3}\sin\theta_1\sin\theta_2\sin\Phi$
13	$Re(A_0(t)A_S^*(t))$	$\frac{8}{\sqrt{3}}\cos\theta_1\cos\theta_2(\cos\theta_1+\cos\theta_2)$
14	$Re(A_\parallel(t)A_S^*(t))$	$\frac{4\sqrt{2}}{\sqrt{3}}\sin\theta_1\sin\theta_2(\cos\theta_1+\cos\theta_2)\cos\Phi$
15	$Im(A_\perp(t)A_S^*(t))$	$-\frac{4\sqrt{2}}{\sqrt{3}}\sin\theta_1\sin\theta_2(\cos\theta_1+\cos\theta_2)\sin\Phi$

- Rows 1–6: P-wave (ϕϕ)
- Row 7: CP-even S-wave (f0f0)
- Row 8: CP-odd S-wave (ϕf0)
- Row 9: f0f0– ϕf0 interference
- Rows 10–12: ϕϕ-f0f0 interference
- Rows 13–15: ϕϕ-ϕf0 interference

Triple Products
$(\to A_\perp, A_{||})$
U **= sin × cos**

$(\to A_\perp, A_0)$
$V = \sin(\pm\phi)$

$$A_k = \frac{\Gamma(k>0)-\Gamma(k<0)}{\Gamma(k>0)+\Gamma(k<0)}$$

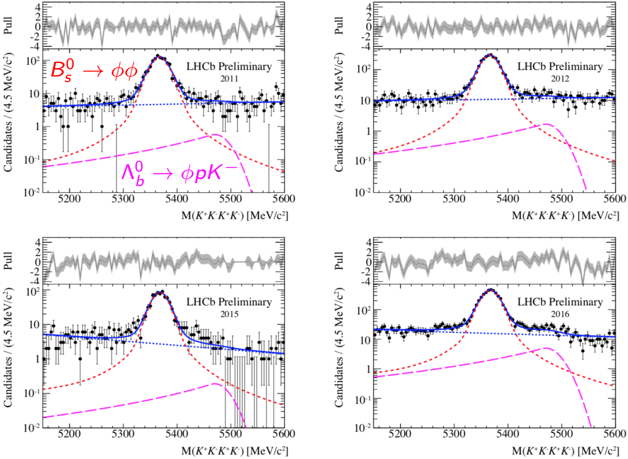
TPA≠0 imply
CP-violating phase or
final-state interactions
(long distance strong interaction effects C, P and CP conserving)

Signal candidates

Preliminary!

LHCb-CONF-2018-001

Invariant mass projections by year, total **signal yield 8481±101**

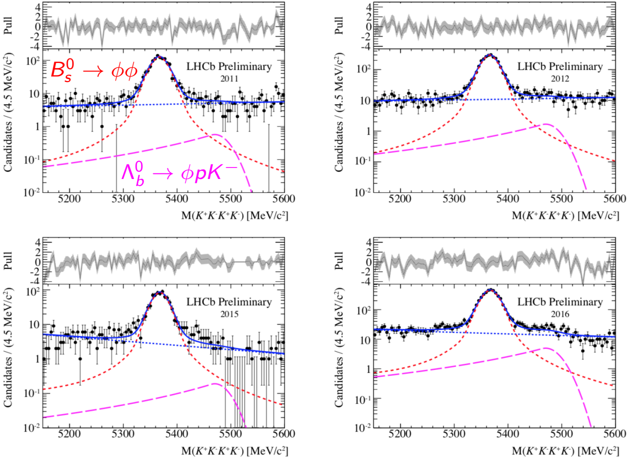


Signal candidates

Preliminary!

LHCb-CONF-2018-001

Invariant mass projections by year, total **signal yield 8481±101**



- **Cut-based** data selection and a **neural network** to remove combinatorial background

Signal candidates

Preliminary!

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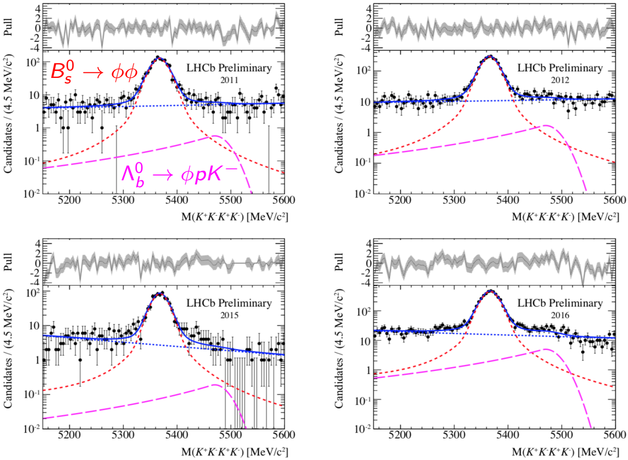

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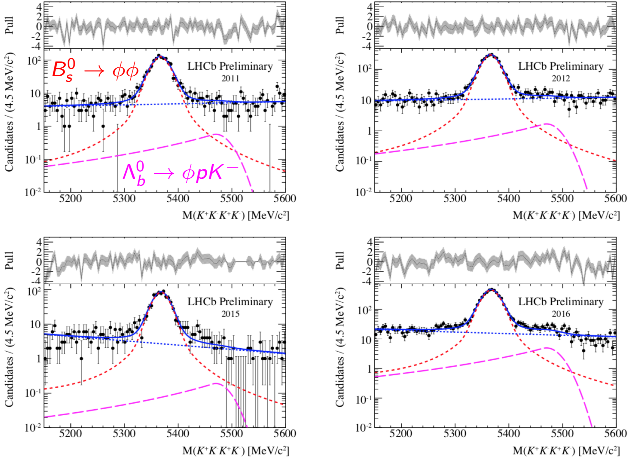

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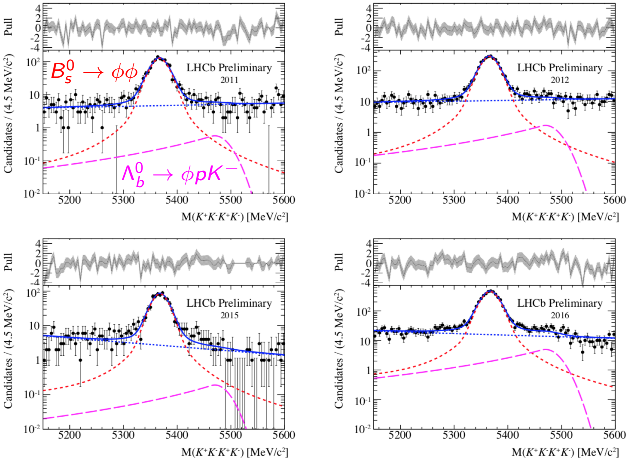

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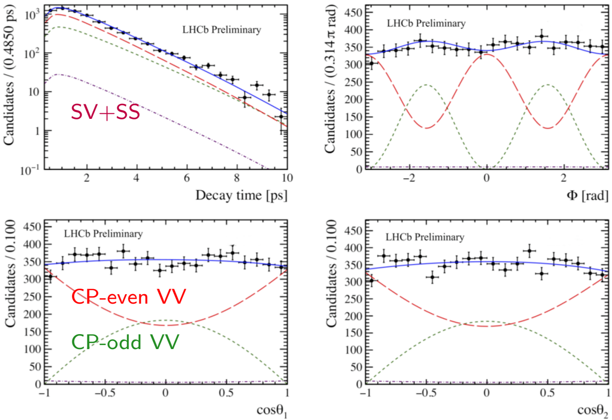
- ***s*Plot** technique is used to subtract the backgrounds

Fit results

Preliminary!

LHCb-CONF-2018-001

Fit projections in the **decay time** and the **three helicity angles**



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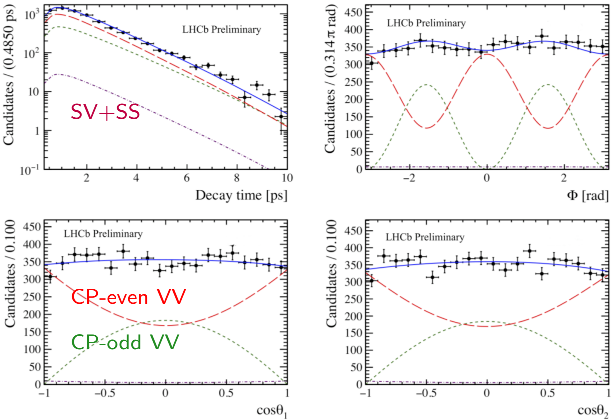

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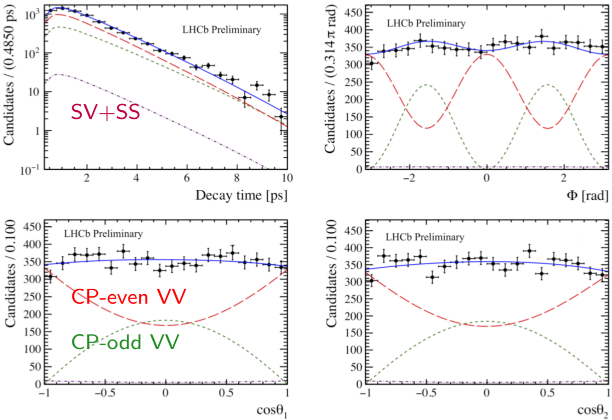

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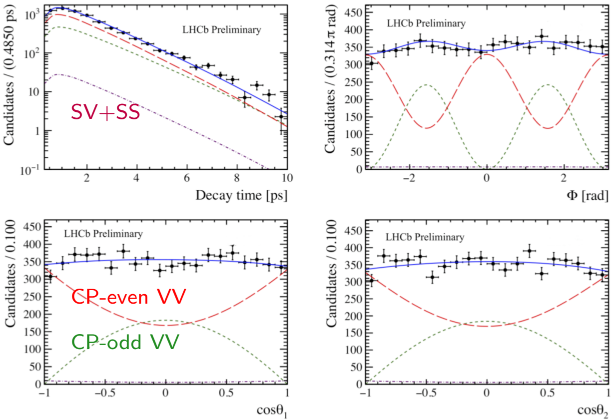

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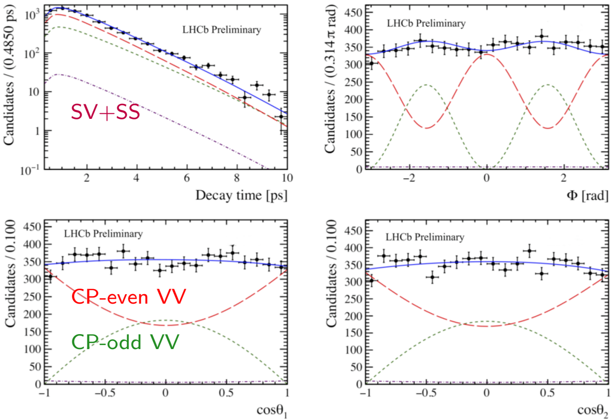

- **Acceptance effects** modelling obtained from **simulated data**, parameterised with Legendre polynomials
- **Decay-time acceptance** parameterised with cubic splines
- **External inputs** used to Gaussian-constraint B_s^0 decay widths and oscillation frequency
- **Separate fit** to the U and V observables to obtain the TPAs

Fit results

Preliminary!

LHCb-CONF-2018-001

Time-dependent fit results

Polarisations, $|\lambda|$ and **phase differences**

$$\phi_s^{s\bar{s}s} = -0.06 \pm 0.13(\text{stat.}) \pm 0.03(\text{syst.})\text{rad}$$
$$|\lambda| = 1.02 \pm 0.05(\text{stat.}) \pm 0.03(\text{syst.})$$
$$|A_0|^2 = 0.382 \pm 0.008(\text{stat.}) \pm 0.011(\text{syst.})$$
$$|A_\perp|^2 = 0.287 \pm 0.008(\text{stat.}) \pm 0.005(\text{syst.})$$
$$\delta_\perp = 2.81 \pm 0.21(\text{stat.}) \pm 0.10(\text{syst.})\text{rad}$$
$$\delta_{||} = 2.52 \pm 0.05(\text{stat.}) \pm 0.07(\text{syst.})\text{rad}$$

Previous measurement Phys. Rev. D 90, 052011 (2014) in agreement with **new results** and both results **compatible with SM expectations**

Triple Product Asymmetries

TPAs measured in **2015+2016 data sample:**

$$A_U = 0.003 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$$
$$A_V = 0.010 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$$

TPAs measured in **Run I analysis:**

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

Weighted average:

$$A_U = 0.000 \pm 0.012(\text{stat}) \pm 0.004(\text{syst})$$
$$A_V = -0.003 \pm 0.012(\text{stat}) \pm 0.004(\text{syst})$$

Summary and conclusions

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

2. **Amplitude analyses** have proven to be a **powerful method** to scrutinise these phenomena

3. With the **statistics** achieved by **LHCb** during the Run I & II, many new analyses have become **feasible** and **high precision measurements are being perfomed**
   - New amplitude analyses $B^0 \to K^*(892)^0 \bar{K}^*(892)^0$, $B^0 \to \pi^+\pi^-\phi$, $B^0 \to \rho^0 K^*(892)^0$ expected soon
   - More Run II updates of Run I analyses on their way

4. Stay tuned for many interesting new results!

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...questions

$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ main systematic uncertainties

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Parameter	$\phi_s^{d\bar{d}}$ [rad]	$\lvert\lambda\rvert$	f^{VV}	f_L^{VV}
Yield and shape of mass model	0.012	0.001	0.001	0.004
Signal weights of mass model	0.012	0.007	0.002	0.006
Time-dependent fit procedure	0.006	0.002	0.001	0.006
Time-dependent fit parameterisation	0.049	0.013	0.021	0.025
Acceptance weights (simulated sample size)	0.106	0.078	0.004	0.031
Other acceptance and resolution effects	0.063	0.008	0.005	0.018
Production asymmetry	0.002	0.002	0.000	0.000
Total	0.141	0.089	0.024	0.046