CP Violation in (quasi-)2 body charmless B decays at LHCb

Emmy Gabriel (University of Edinburgh)
on behalf of the LHCb collaboration

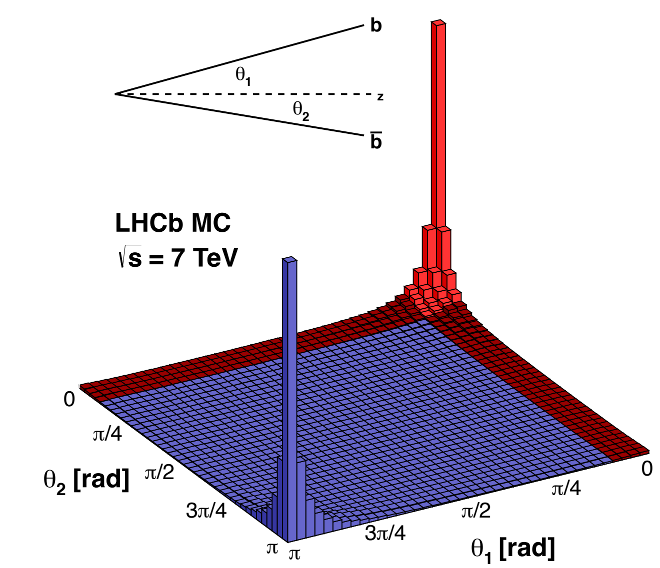
Overview

- *The LHCb Detector*
- ϕ_s *measurements using* $B_s^0 \to \phi\phi$ *and* $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$
- *CPV in* $B_{(s)}^0 \to hh'$
- *Summary and Prospects*

The LHCb detector

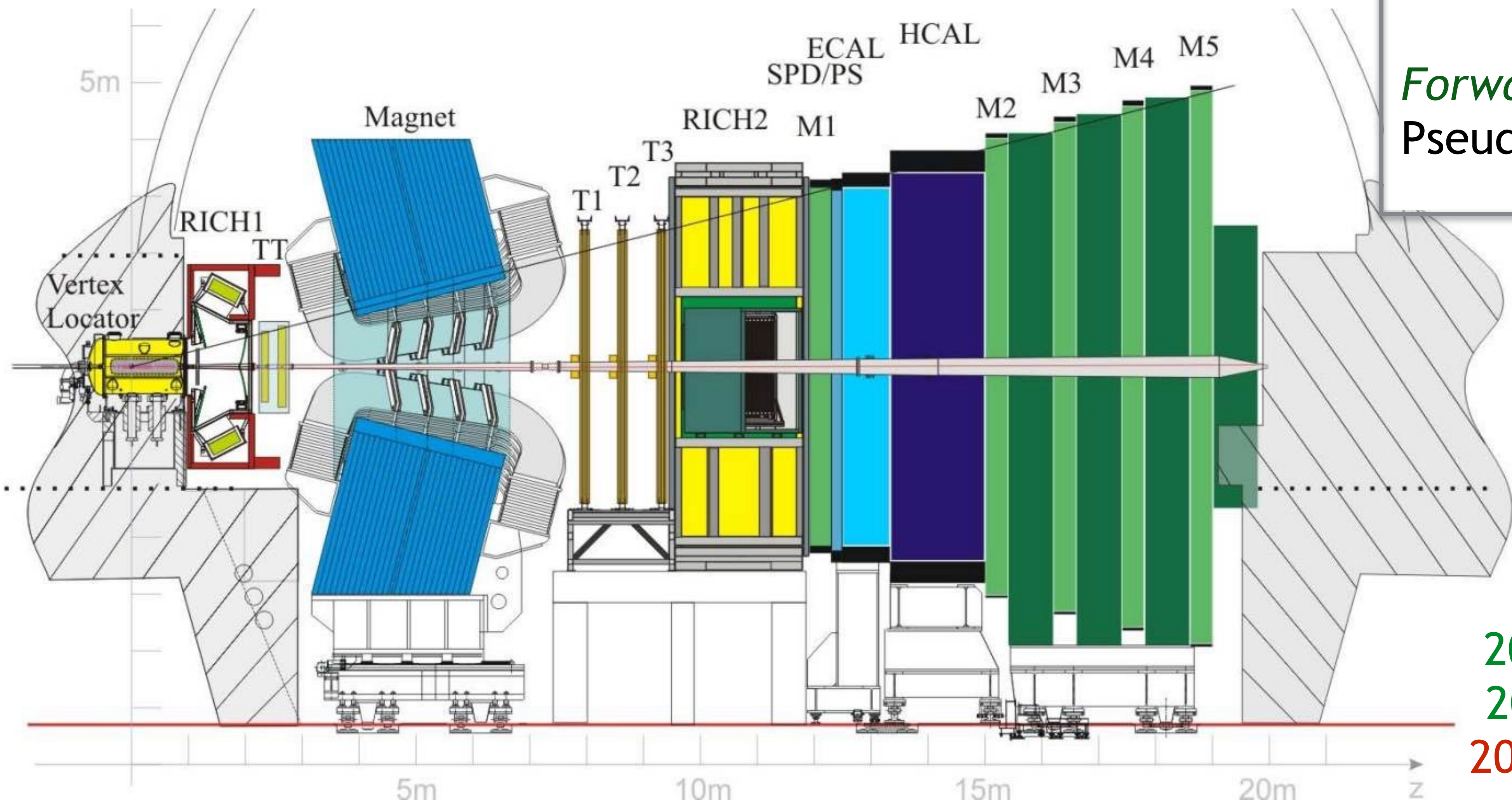
Properties of the LHCb detector

- Good PID and track & vertex reconstruction
- Flavour tagging power ~4-8 %
- Decay time resolution ~45 fs



Forward arm spectrometer

Pseudorapidity $2 < \eta < 5$



Run 1
Run 2

Data samples:

2010-11: 1.1 fb^{-1}(7 Tev)

2012: 2.1 fb^{-1} (8 TeV)

2015-17: 3.6 fb^{-1}(13 TeV)

ϕ_s measurement in

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

Motivation for $\phi_s^{\bar{q}q}$

- Decays are FCNCs, *dominated by a gluonic penguin diagram*
- Sensitive to CP violation in *interference between decay and mixing* (phase $\phi_s = -2\beta_s = \Phi_M - 2\Phi_D$)
- *Direct CPV* possible

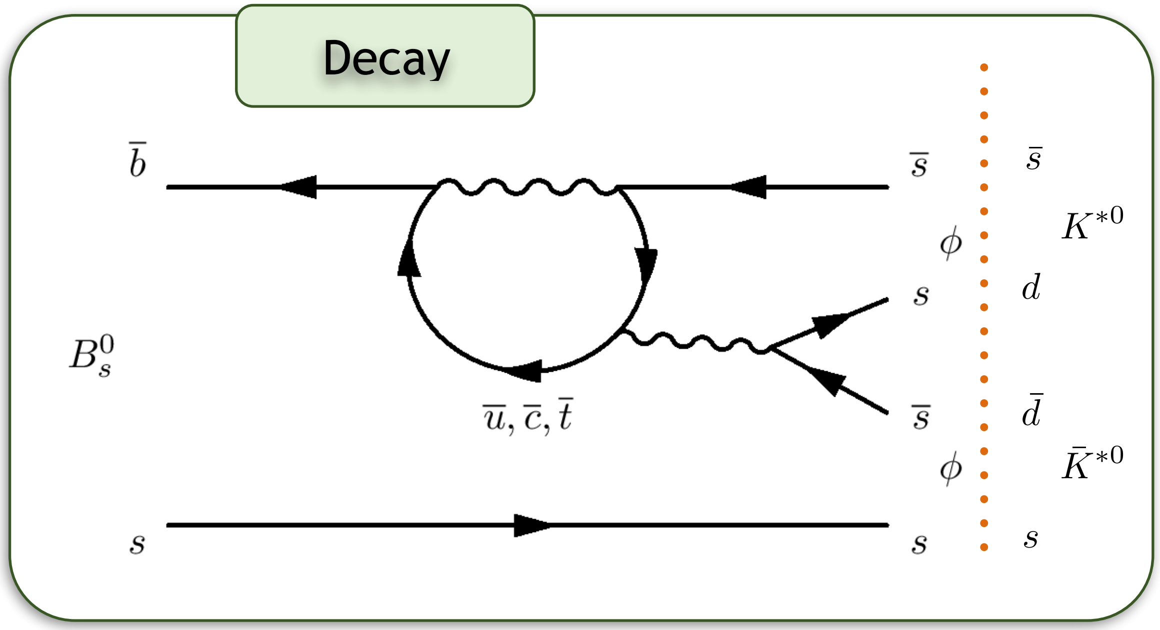
$$|\lambda| = \left|\frac{q}{p}\frac{\bar{A}}{A}\right|$$

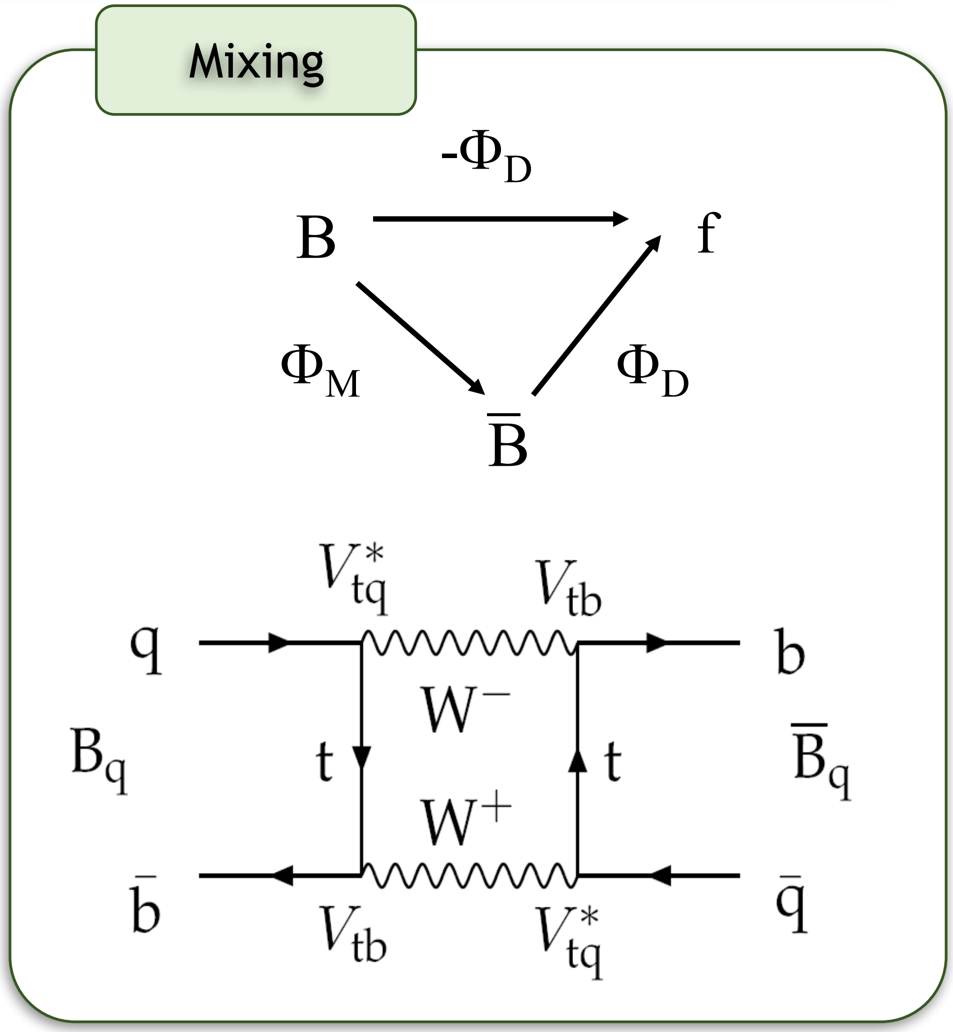
- SM prediction of ϕ_s small

LMU-ASC-43-08
Phys.Rev.D80:114026,2009

- Larger values possible in certain BSM models

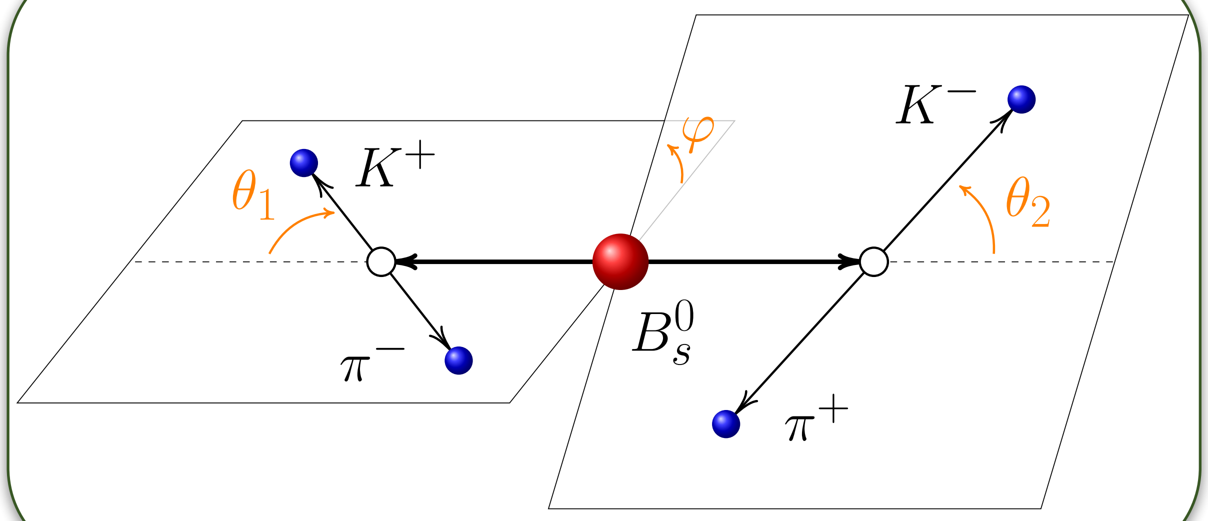
Phys.Lett. B671 (2009)
arXiv:1212.6486v1
Phys.Lett. B493 (2000)
J.Phys. G32 (2006)





Observables

Run 1 data $(3fb^{-1})$



- 9 different quasi-2 body decays are considered, requiring *time-dependent angular analysis*
- $m(K\pi)$ window analysed from 750 -1600 MeV/c^2

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

Parameters in the fit:

- CP-averaged fractions of amplitudes, f_i
- CP conserving strong phases, δ_i
- CP violating phase, ϕ_s
- Direct CPV through $|\lambda|$

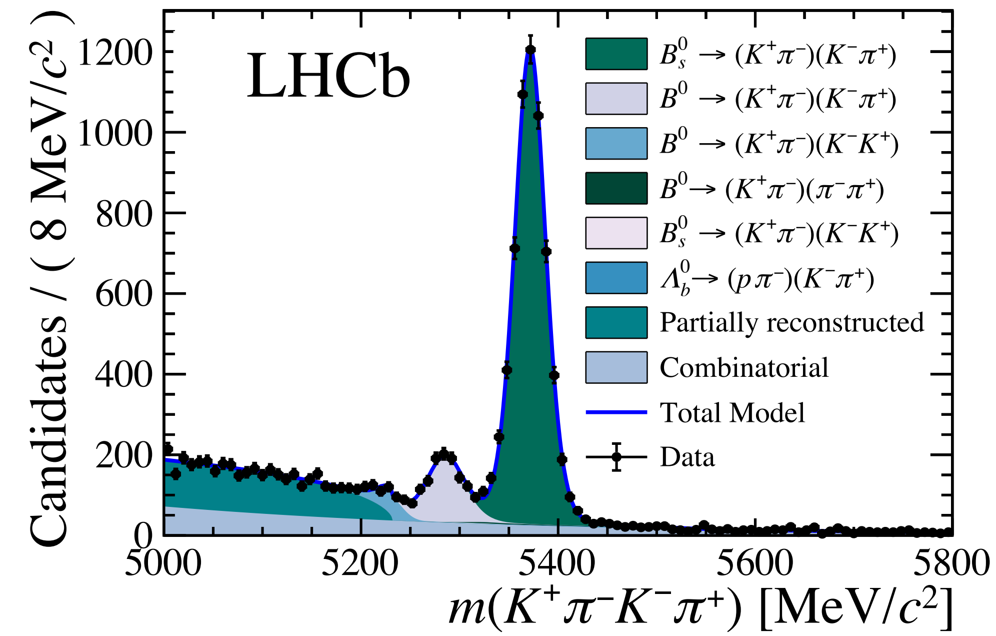
$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$

JHEP 03(2018)140

Run 1 data
$(3fb^{-1})$

Analysis Ingredients

- Cut-based *selection* including a BDT to remove background
- *Complex fit* to the data
- Include the *decay time resolution, flavour tagging input (~5.15%), angular acceptance and decay time acceptance.*



Time-dependent decay rate of B_s^0

$$\frac{d\Gamma}{dt} \propto \sum_{i,j} e^{-\Gamma_s t} \times \left[a_{ij} \cosh\left(\frac{1}{2}\Delta\Gamma_s t\right) + b_{ij} \sinh\left(\frac{1}{2}\Delta\Gamma_s t\right) + c_{ij} \cos(\Delta m_s t) + d_{ij} \sin(\Delta m_s t) \right]$$

$$\boxed{\begin{aligned}
a_{ij} &= \mathcal{A}_i(0)\mathcal{A}_j^*(0) + \eta_i\eta_j\bar{\mathcal{A}}_i(0)\bar{\mathcal{A}}_j^*(0) \\
b_{ij} &= -(\eta_j e^{i\phi_M}\mathcal{A}_i(0)\bar{\mathcal{A}}_j^*(0) + \eta_i e^{-i\phi_M}\bar{\mathcal{A}}_i(0)\mathcal{A}_j^*(0)) \\
c_{ij} &= \mathcal{A}_i(0)\mathcal{A}_j^*(0) - \eta_i\eta_j\bar{\mathcal{A}}_i(0)\bar{\mathcal{A}}_j^*(0) \\
d_{ij} &= -i(\eta_j e^{i\phi_M}\mathcal{A}_i(0)\bar{\mathcal{A}}_j^*(0) - \eta_i e^{-i\phi_M}\bar{\mathcal{A}}_i(0)\mathcal{A}_j^*(0))
\end{aligned}}$$

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

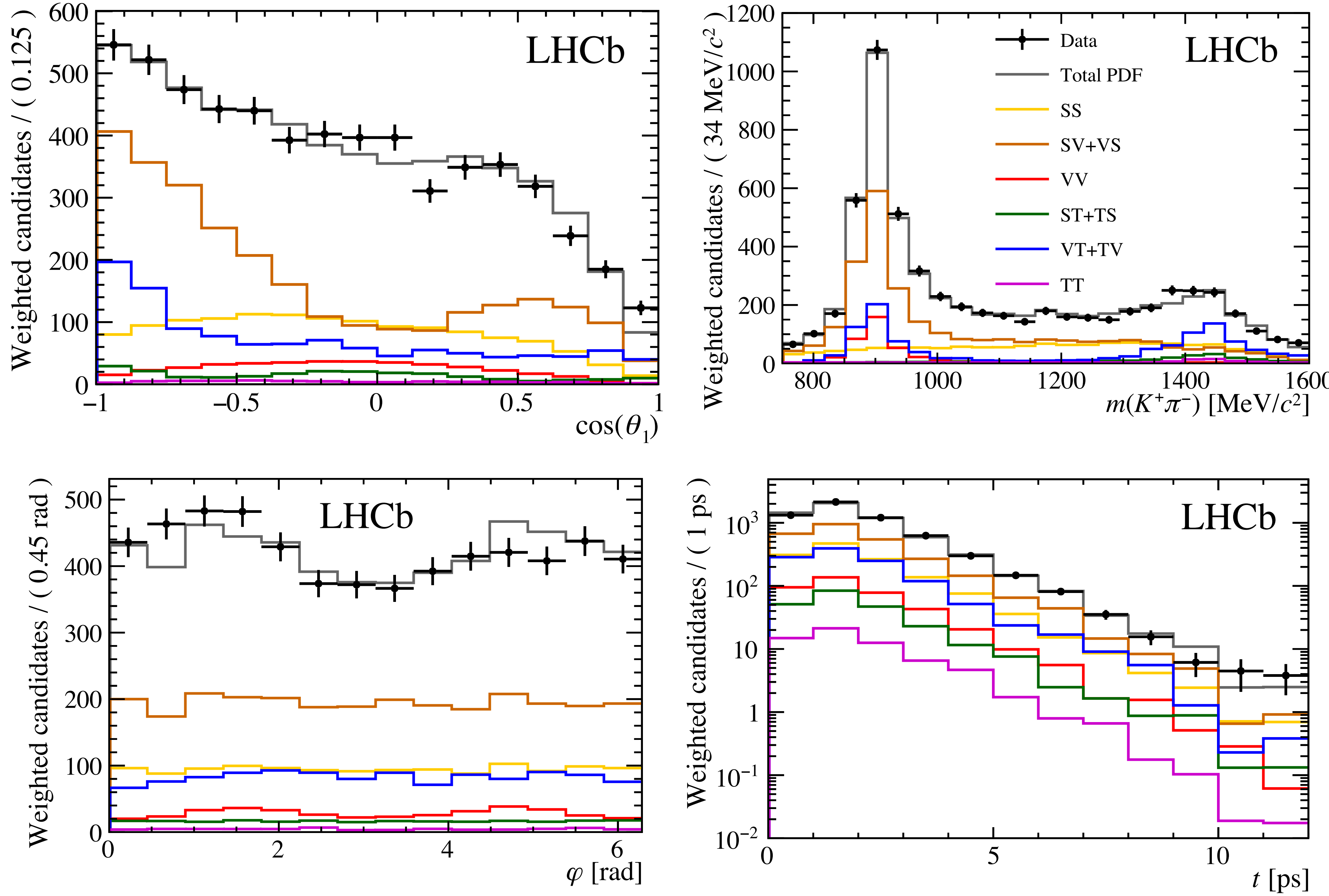
Run 1 data
$(3fb^{-1})$

JHEP 03(2018)140

+2 dimensions not shown

$$\phi_s^{d\bar{d}}[\text{rad}] = -0.10 \pm 0.13 \pm 0.14$$
$$|\lambda| = 1.035 \pm 0.034 \pm 0.089$$

+ more results of fractions/phases for other amplitudes



First time the weak phase in $b \to d\bar{d}s$ transitions has been measured.

$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ $B_s^0 \to K^{*0}\bar{K}_2^*(1430)^0$

$B_s^0 \to K^{*0}\bar{K}^{*0}$ $B_s^0 \to (K^+\pi^-)\bar{K}_2^*(1430)^0$

$B_s^0 \to (K^+\pi^-)\bar{K}^{*0}$ $B_s^0 \to K_2^*(1430)^0\bar{K}_2^*(1430)^0$

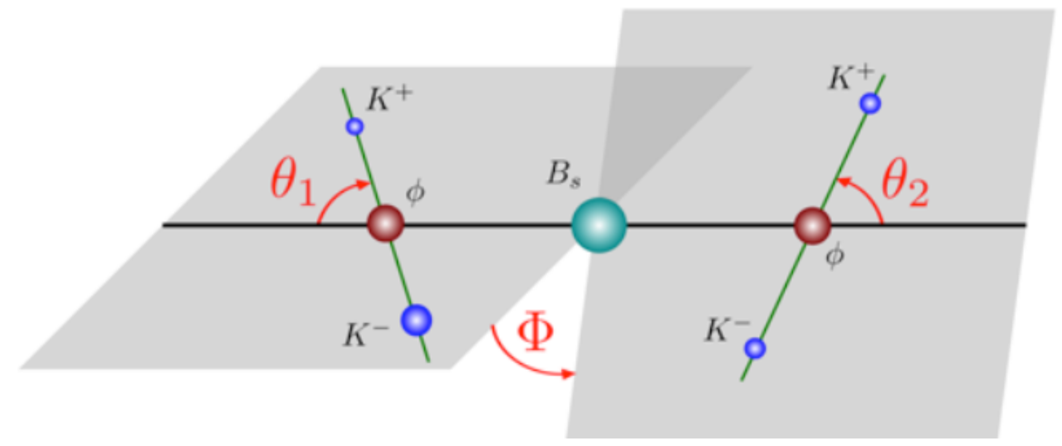
Results are consistent with SM predictions

ϕ_s measurement in $B_s^0 \to \phi\phi$

Observables

Run 1 + 2015 + 2016 data

- Pseudovector $\to$ Vector Vector decay, so requires *time-dependent angular analysis*



i	K_i	f_i
1	$\lvert A_0(t)\rvert^2$	$4\cos^2\theta_1\cos^2\theta_2$
2	$\lvert A_\parallel(t)\rvert^2$	$\sin^2\theta_1\sin^2\theta_2(1+\cos 2\Phi)$
3	$\lvert A_\perp(t)\rvert^2$	$\sin^2\theta_1\sin^2\theta_2(1-\cos 2\Phi)$
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	$\lvert A_{SS}(t)\rvert^2$	$\frac{4}{9}$
8	$\lvert A_S(t)\rvert^2$	$\frac{4}{3}(\cos\theta_1+\cos\theta_2)^2$
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	$Im(A_\perp(t)A_S^*(t))$	$-\frac{4\sqrt{2}}{\sqrt{3}}\sin\theta_1\sin\theta_2(\cos\theta_1+\cos\theta_2)\sin\Phi$

P-wave (ϕϕ)

CP-even S-wave (f0f0)

CP-odd S-wave (ϕf0)

f0f0– ϕf0 interference

ϕϕ-f0f0 interference

ϕϕ-ϕf0 interference

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

Parameters in time-dependent fit:

- Polarisation amplitudes $A_\parallel, A_\perp, A_0, A_s, A_{ss}$
- CP conserving strong phases $\delta_1, \delta_2, \delta_s, \delta_{ss}$
- CP violating phase ϕ_s
- Direct CPV through λ

Triple Product Asymmetries

Can probe for T-violation in a decay time integrated untagged method with the use of *triple product asymmetries* (A_U and A_V).

- *Simultaneous fitting* of separate datasets according to the sign of the U(V) observable.

Definitions

$$U = \cos\Phi \times \sin\Phi$$
$$V = \eta_\theta \times \sin\Phi$$

$$A_U = \frac{N(U>0) - N(U<0)}{N(U>0) + N(U<0)}$$
$$A_V = \frac{N(V>0) - N(V<0)}{N(V>0) + N(V<0)}$$

Run 2 result

$$A_U = 0.3 \pm 1.6\,(\text{stat}) \pm 0.5\,(\text{syst})\ \%$$
$$A_V = 1.0 \pm 1.6\,(\text{stat}) \pm 0.5\,(\text{syst})\ \%$$

Run 1 result

$$A_U = -0.3 \pm 1.7\,(\text{stat}) \pm 0.6\,(\text{syst})\ \%$$
$$A_V = -1.7 \pm 1.7\,(\text{stat}) \pm 0.6\,(\text{syst})\ \%$$

Phys.Rev.D90:052011,2014

Weighted average

$$A_U = 0.0 \pm 1.2\,(\text{stat}) \pm 0.4\,(\text{syst})\ \%$$
$$A_V = -0.3 \pm 1.2\,(\text{stat}) \pm 0.4\,(\text{syst})\ \%$$

Run 1 + 2015 + 2016 data

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External Inputs

- B_s^0 decay widths Gaussian constrained
  PRL 114 (2015) 041801
- B_s^0 oscillation frequency
  New J. Phys. 15 (2013) 053021

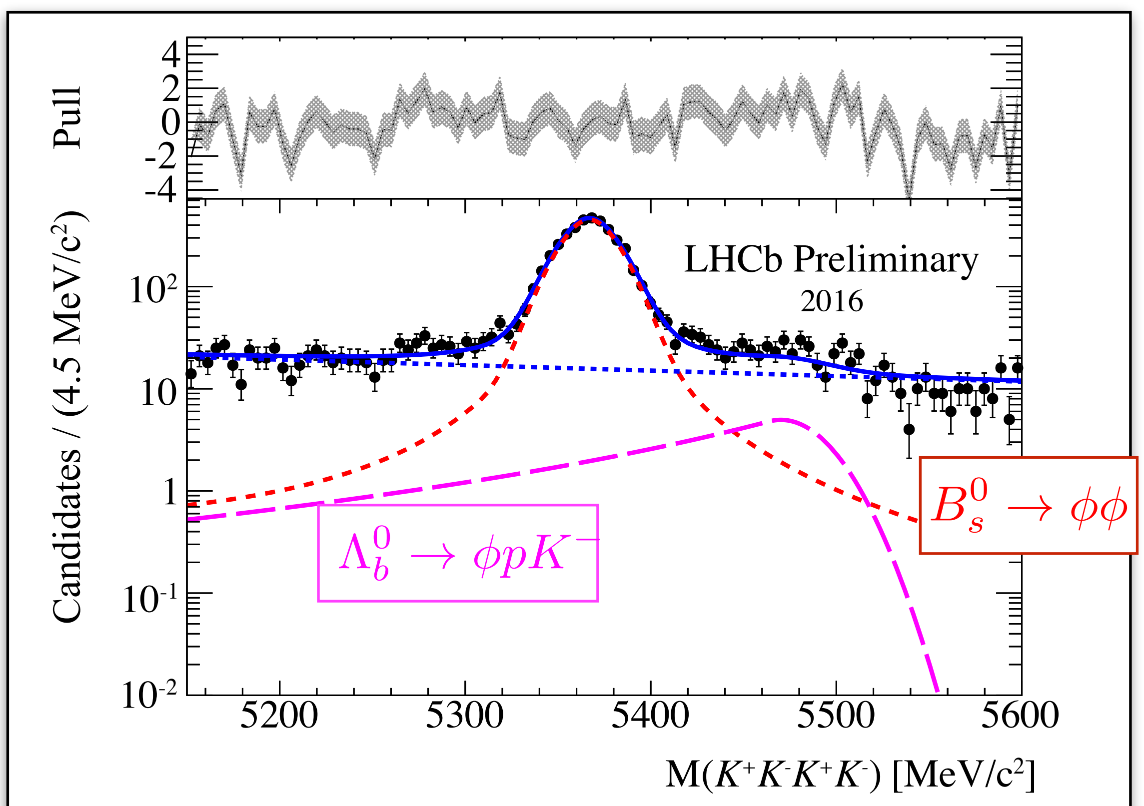
Flavour-tagging

B_s oscillation frequency

$$\Im(A_{\|}(t)^* A_{\perp}(t)) = |A_{\|}||A_{\perp}|\{(1-2\omega)e^{-\Gamma_s t}[\sin\delta_1\cos(\Delta m_s t) - \cos\delta_1\sin(\Delta m_s t)\cos\phi_s] - \frac{1}{2}\cos\delta_1(e^{-\Gamma_{\rm H}t} - e^{-\Gamma_{\rm L}t})\sin\phi_s\}$$

B_s decay rates

Analysis Ingredients



- Cut-based *data selection* and a neural net to remove background
- *Mass model* consisting of a Crystal Ball + Student-T
- Include the *decay time resolution, flavour tagging input (~5.8%), angular acceptance and decay time acceptance.*

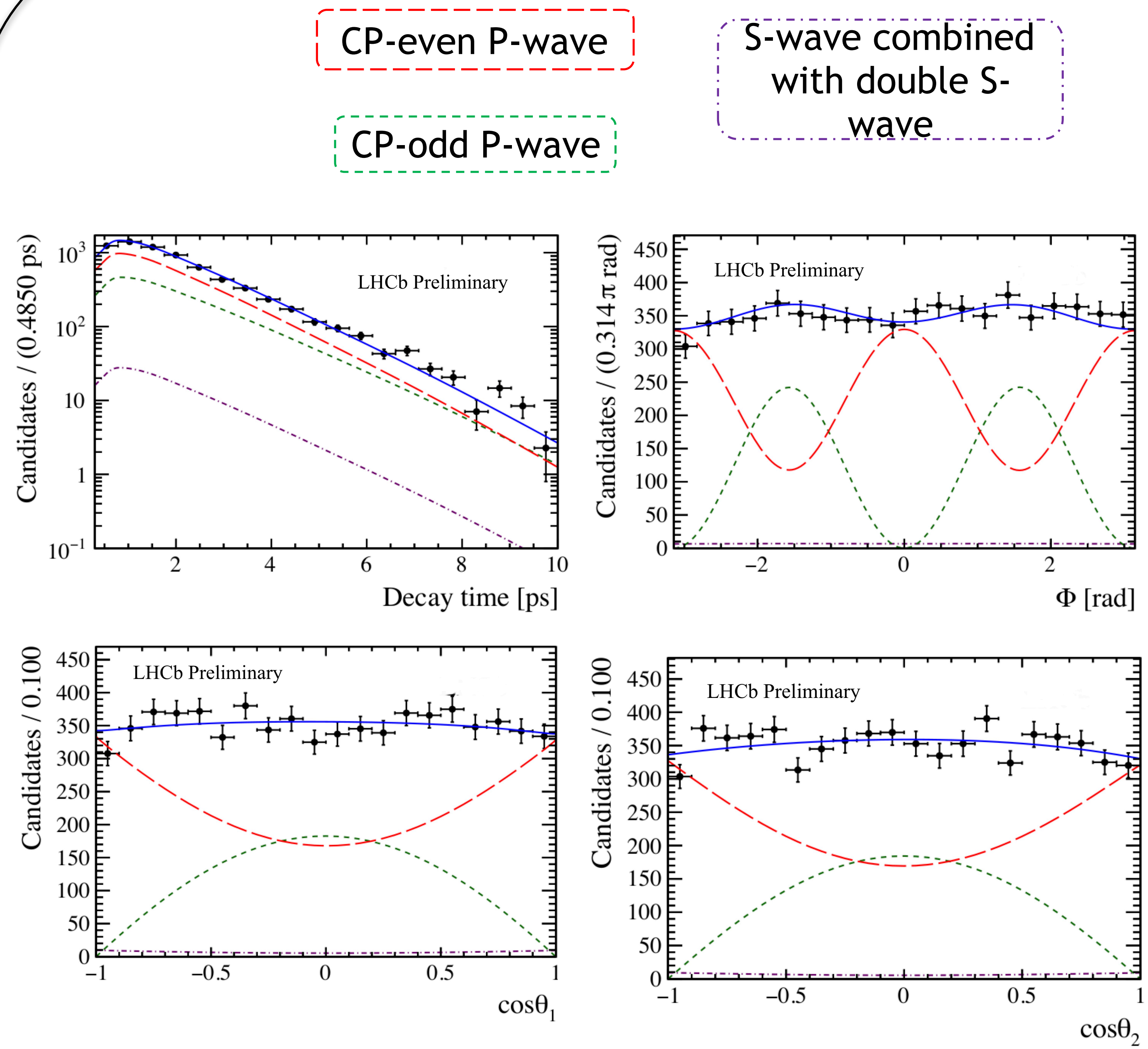
Fit

Run 1 + 2015 + 2016 data

Parameterisation estimation from *minimisation of negative log likelihood.*

Each of the data samples have:

- Independent signal weights
- Decay time and angular acceptances
- Separate Gaussian constraints to decay time resolution parameters.



Summary of Results

Run 1+2 $B_s^0 \to \phi\phi$

Preliminary!

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

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All measurements of CP-violating phases and CP violating parameters *are in agreement with previous measurements and the SM predictions*.

Measurements *supersede* previous LHCb measurements.

First time the weak phase in $b \to d\bar{d}s$ transitions has been measured.

Run 1 $B_s^0 \to K^{*0}\bar{K}^{*0}$

$\phi_s^{d\bar{d}}$ [rad]	-0.10	± 0.13	± 0.14
$\lvert\lambda\rvert$	1.035	± 0.034	± 0.089

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$$B^0_{(s)} \to hh'$$

arXiv:1805.06759

Motivation

Run 1 data
$(3fb^{-1})$

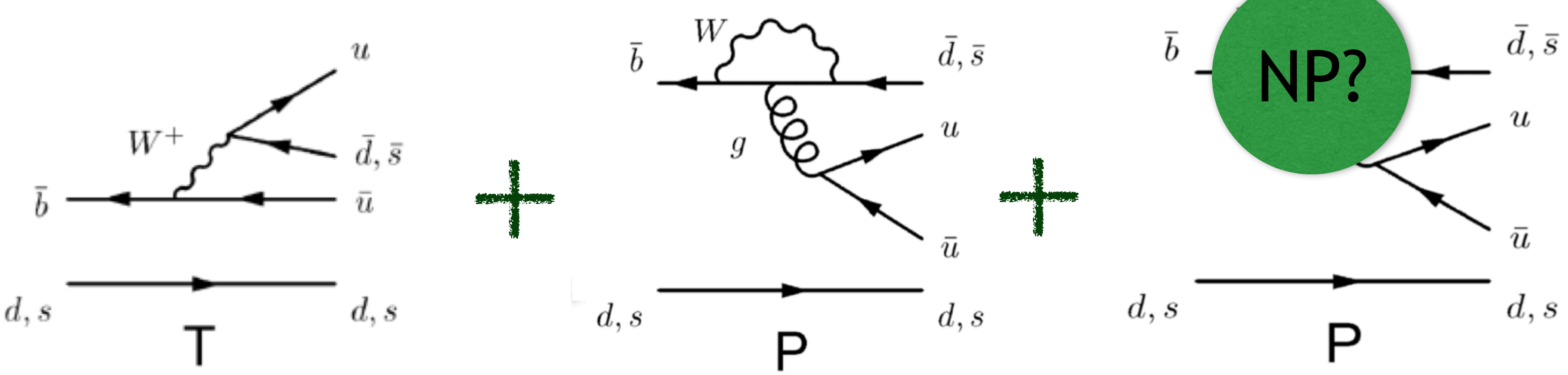
- Analysis allows for measurement of the CP asymmetries as a function of decay time.

Decays considered:

$$\left.\begin{array}{l} B^0_s \to K^+K^- \\ B^0 \to \pi^+\pi^- \end{array}\right\} \text{Time-dependent measurement}$$

$$\left.\begin{array}{l} B^0 \to K^+\pi^- \\ B^0_s \to \pi^+K^- \end{array}\right\} \text{Time-integrated measurement}$$

Tree contributions *Penguin contributions*



arXiv:1805.06759

Run 1 data
$(3fb^{-1})$

Analysis Ingredients

- *Preselection cuts* and *PID* requirements + *BDT* to remove background.
- Simultaneous fit to $\pi\pi, KK, K\pi$ categories, using a *flavour-tagged, decay-time and hh'-mass dependent fit*.
- Inclusion of *decay-time acceptance and resolution*.

Decays considered:

$B^0_s \to K^+K^-$, $B^0 \to \pi^+\pi^-$ } Time-dependent measurement

$B^0 \to K^+\pi^-$, $B^0_s \to \pi^+K^-$ } Time-integrated measurement

Observables

time-dependent measurement

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

$$C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad S_f \equiv \frac{2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2} \qquad A_f^{\Delta\Gamma} \equiv -\frac{2\mathrm{Re}\lambda_f}{1+|\lambda_f|^2} \qquad \lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

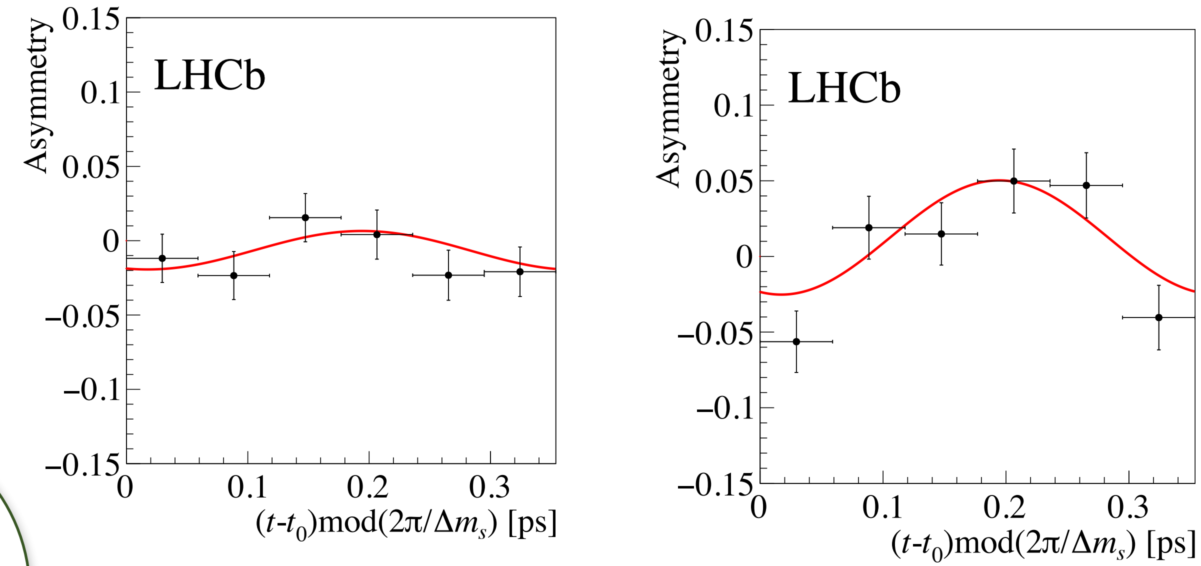
Observables time-integrated measurement

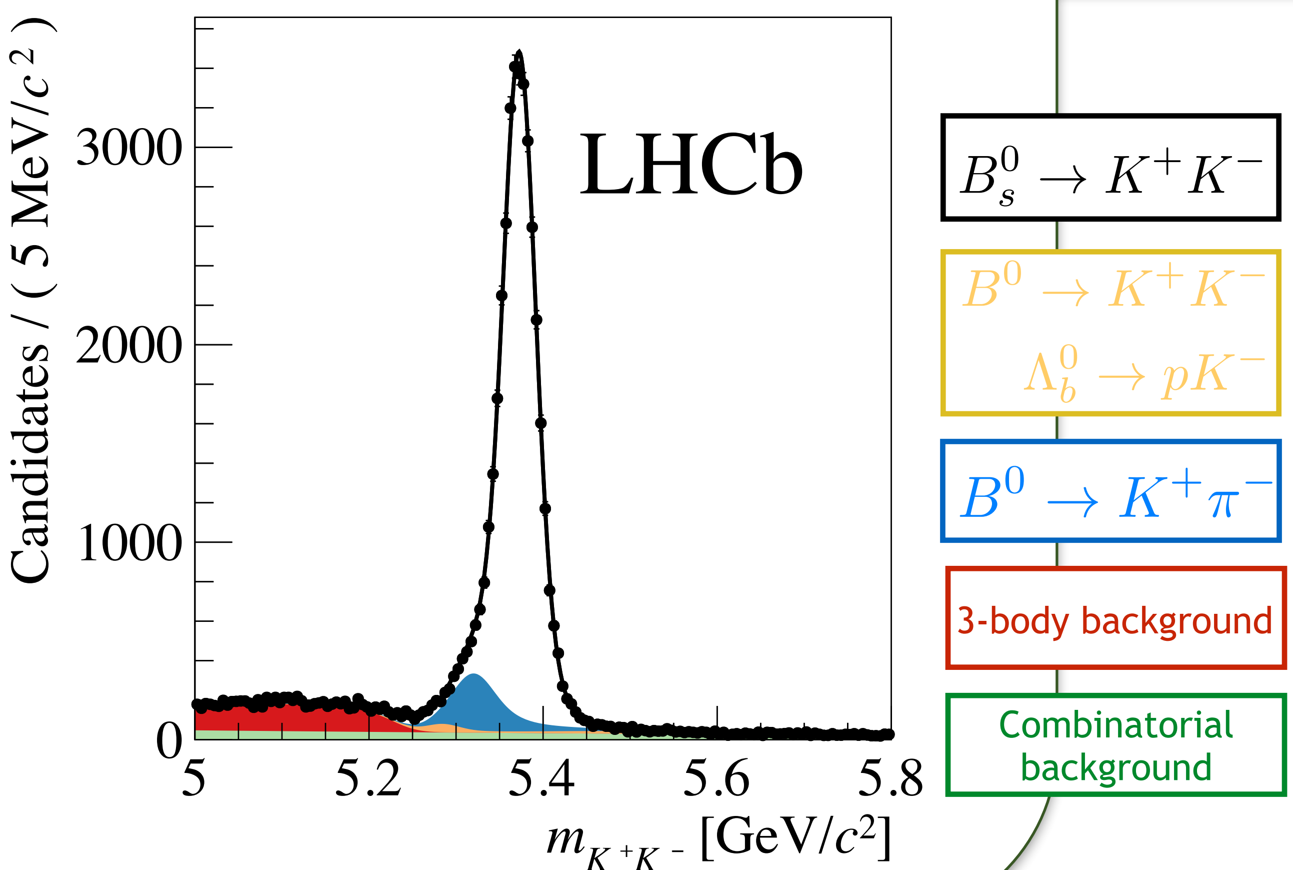
$$A_{CP} = \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2}$$

Results

Run 1 data $(3fb^{-1})$

Time-dependent asymmetries for candidates K^+K^-





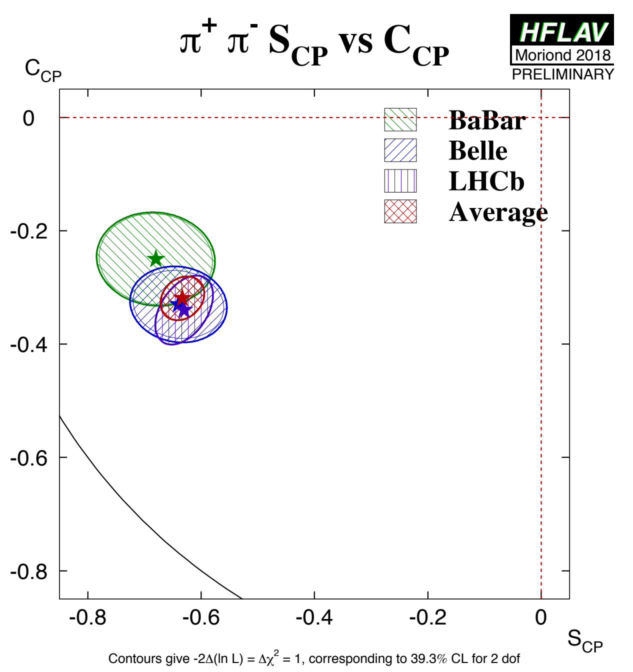
Flavour Tagging Performance

Flavour tagger	Tagging power (%)
OS	2.94 ± 0.17
SSπ	0.81 ± 0.13
SSp	0.42 ± 0.17
SSc	1.17 ± 0.11
SSK	0.71 ± 0.12
Total $B^0 \to \pi^+\pi^-$	4.08 ± 0.20
Total $B^0_s \to K^+K^-$	3.65 ± 0.21

Results

Run 1 data $(3fb^{-1})$

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



- $C_{\pi\pi}, S_{\pi\pi}, A^{B^0}_{CP}, A^{B^s_0}_{CP}$ are the *most precise measurements from a single experiment*.
- C_{KK}, S_{KK} in agreement with previous results.
- 4.0σ deviation of $(C_{KK}, S_{KK}, A^{\Delta\Gamma}_{KK})$ from $(0, 0, -1)$ is the *strongest evidence of CPV* in the B^0_s meson sector to date.
- Measurements presented allow for *improved constraints on CKM CP-violating phases*.

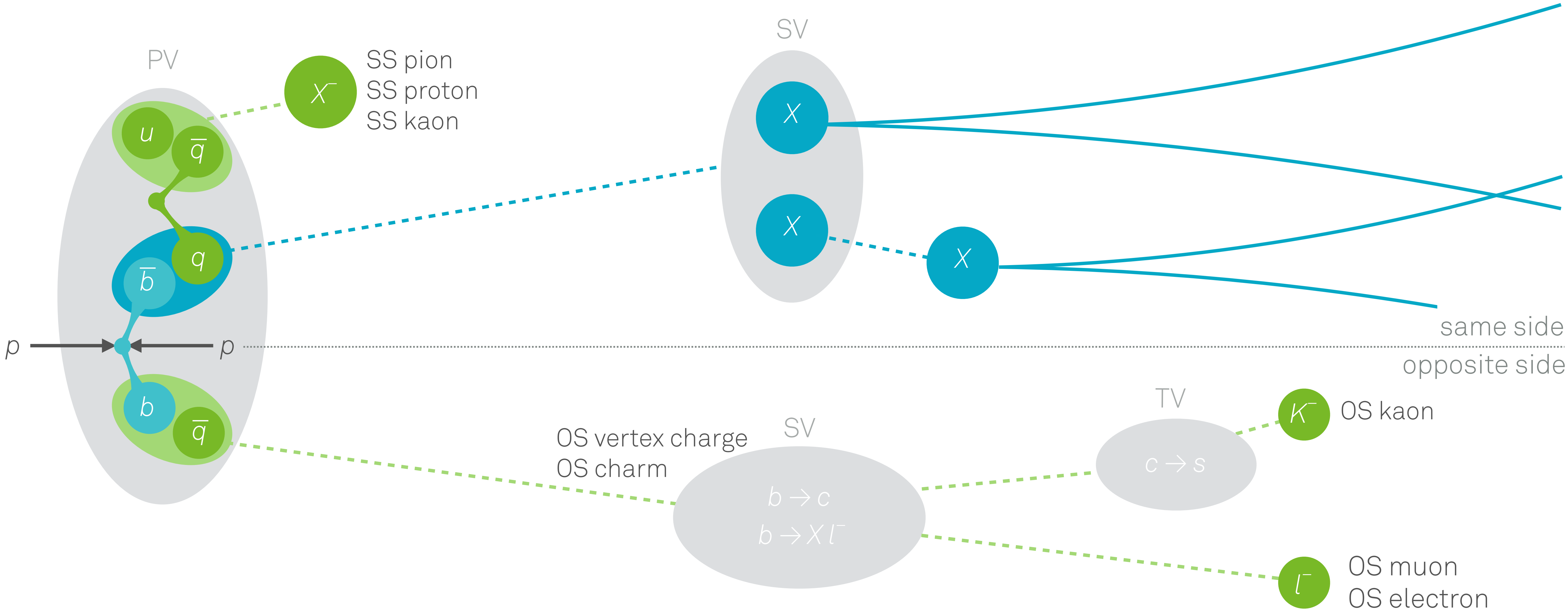
Conclusion & Prospects

- Many interesting CPV results in charmless B physics at LHCb.
- LHCb leads the *world sensitivity* in several of these measurements.
- Results obtained so far are in *agreement with SM predictions*.
- Interesting future ahead: with more data and the LHCb Upgrade, the precision will improve further.

Thank you for your attention!

Backup Slides

Flavour Tagging



Preliminary

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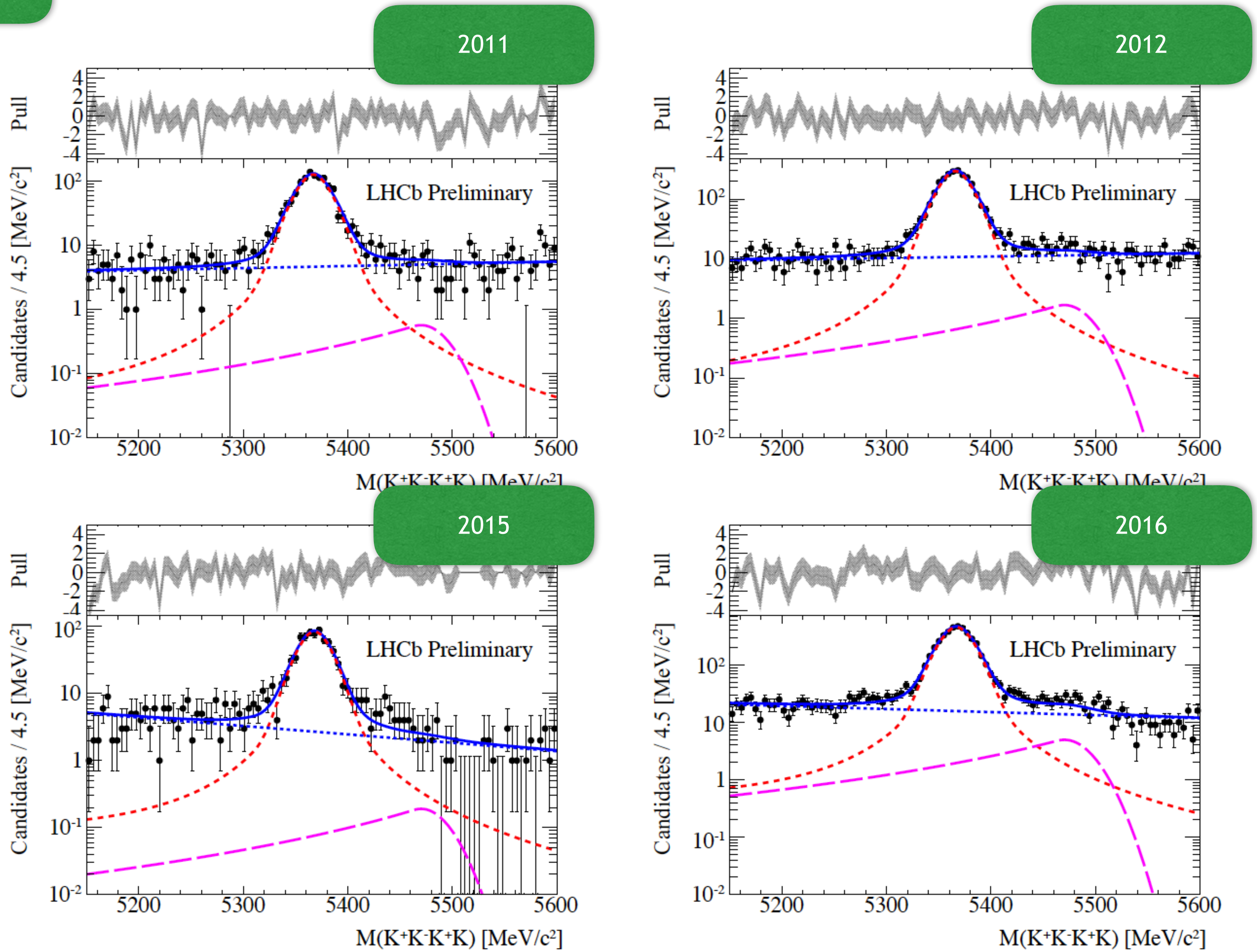
Run 1 + 2015 + 2016 data



Preliminary LHCB-CONF-2018-001

Run 1 + 2015 + 2016 data

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

Coefficients of the time dependent terms and angular functions . Amplitudes are defined at t=0.

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

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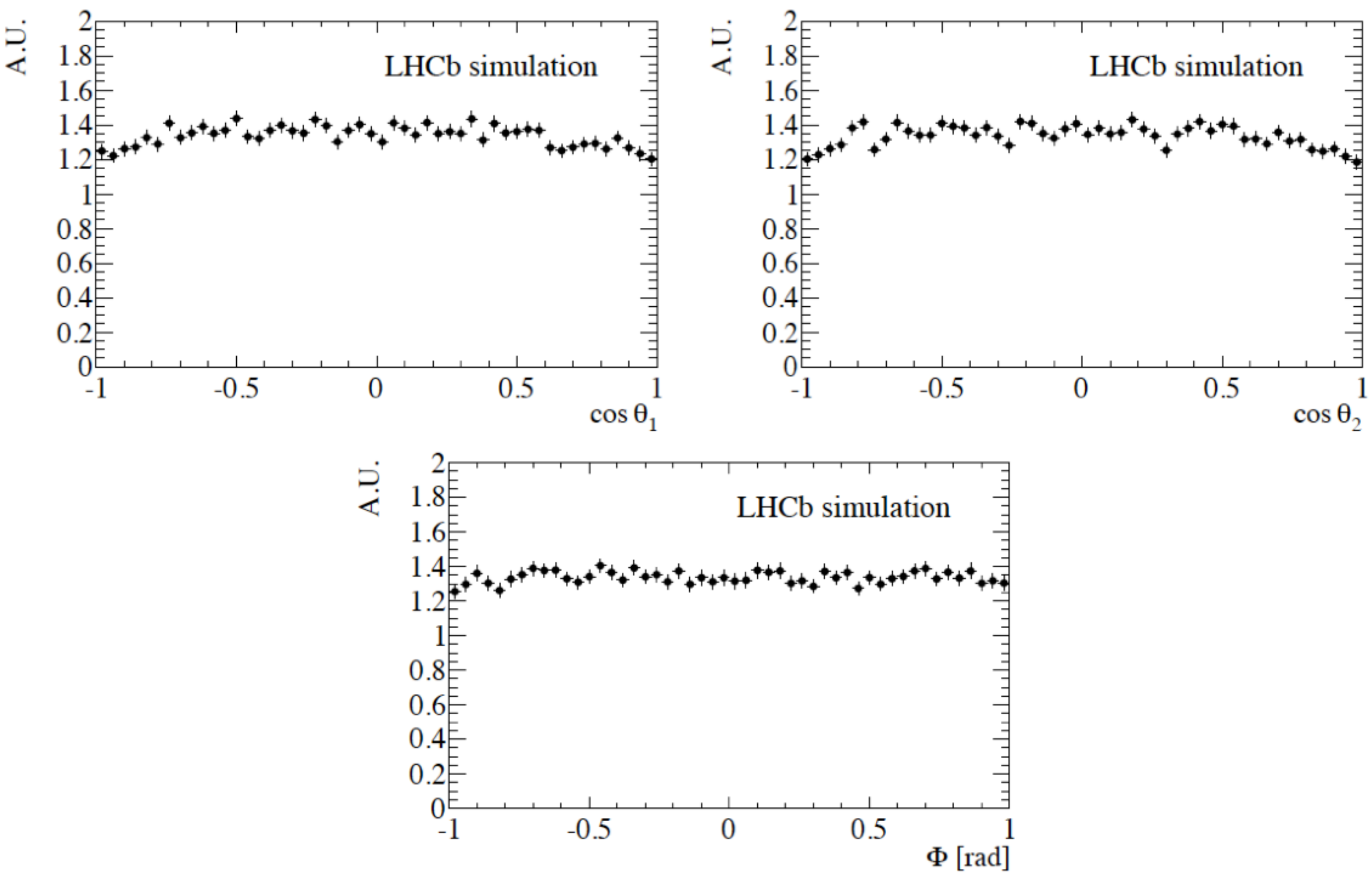
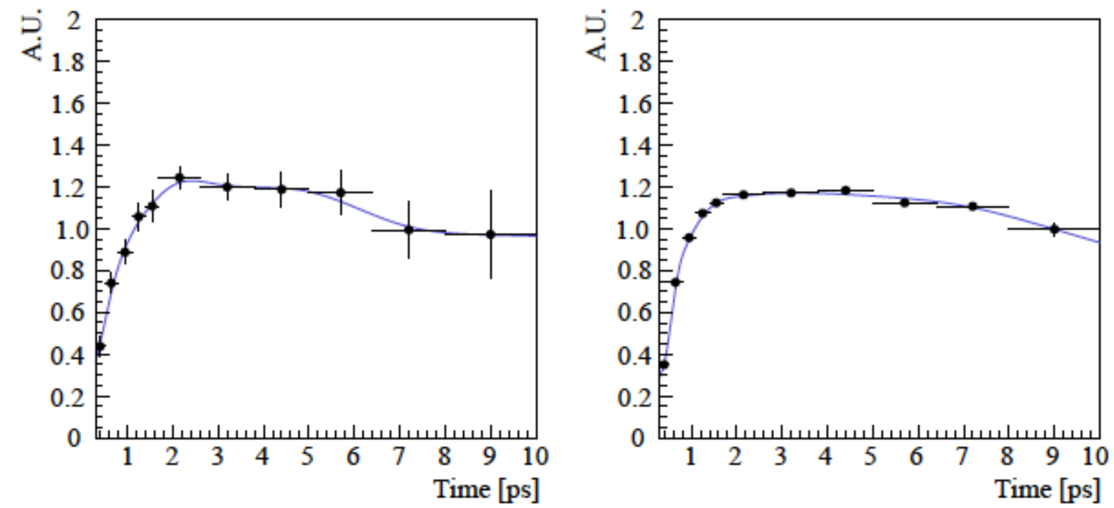
Run 1 + 2015 + 2016 data





Angular acceptance:

Simulated events with the same selection criteria as those applied to $B_s^0 \to \varphi\varphi$ data events used to determine the efficiency correction

Corrections for the differences between data and simulated events are taken into account.

Decay Time acceptance

Efficiency as a function of decay time taken from:

$B_s^0 \to D_s^- \pi^+$ for 2011-2012 data

$B^0 \to J/\psi K^{*0}$ for 2015-2016 data

Control modes are re-weighted according to kinematic and topological information to more closely match the $B_s^0 \to \phi\phi$ decay

Run 1 + 2015 + 2016 data

Table 6: Summary of systematic uncertainties for physics parameters in the decay time dependent measurement, where AA denotes angular acceptance, TA denotes time acceptance, and TR time resolution.

Parameter	Mass model	AA	TA	TR	Fit bias	Total
$\|A_0\|^2$	0.0035	0.0098	0.0008	0.0001	0.0018	0.0106
$\|A_\perp\|^2$	0.0021	0.0046	0.0007	0.0002	0.0012	0.0052
$\delta_\parallel$ (rad)	0.0128	0.0653	0.0049	0.0031	0.0179	0.0692
$\delta_\perp$ (rad)	0.0640	0.0100	0.0085	0.0064	0.0701	0.0960
$\phi_s^{s\bar{s}s}$ (rad)	0.0119	0.0072	0.0077	0.0035	0.0126	0.0206
$\|\lambda\|$	0.0063	0.0217	0.0023	0.0053	0.0097	0.0253

Flavour tagging

Flavour Tagging Performance

Category	Faction(%)	$\varepsilon(\%)$	D^2	$\varepsilon D^2(\%)$
OS-only	16.29	12.51	0.098	1.23 $\pm$0.10
SSK-only	53.39	40.99	0.044	1.80 $\pm$0.42
OS&SSK	30.31	23.27	0.119	2.76 $\pm$0.22
Total	100	76.76	0.075	5.79 $\pm$0.48

Flavour Tagging Performance

Tagging algorithm	$\epsilon_{\rm tag}$ [%]	$\epsilon_{\rm eff}$ [%]
SS	62.0 ± 0.7	1.63 ± 0.21
OS	37.1 ± 0.7	3.70 ± 0.21
Combination	75.6 ± 0.6	5.15 ± 0.14

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Summary

ϕ_s measurements

- Results *agree with theory predictions*.
- Current LHCb results, including $B_s^0 \to J/\psi K^+ K^-$ and $B_s^0 \to J/\psi \pi^+ \pi^-$ decays show *no large CPV* in either $B_s^0 - \bar{B}_s^0$ mixing or $b \to \bar{s} s \bar{s}$ decay amplitudes.
- Results presented *supersede* previous LHCb measurement.

$B^0_{(s)} \to hh'$

- $C_{\pi\pi}, S_{\pi\pi}, A_{CP}^{B^0}, A_{CP}^{B_0^s}$ are the *most precise measurements from a single experiment*.
- C_{KK}, S_{KK} in agreement with previous results.
- 4.0σ deviation of $(C_{KK}, S_{KK}, A_{KK}^{\Delta\Gamma})$ from SM $(0, 0, -1)$ is the *strongest evidence of CPV* in the B_s^0 meson sector to date.
- Measurements presented allow for *improved constraints on CKM CP-violating phases*.

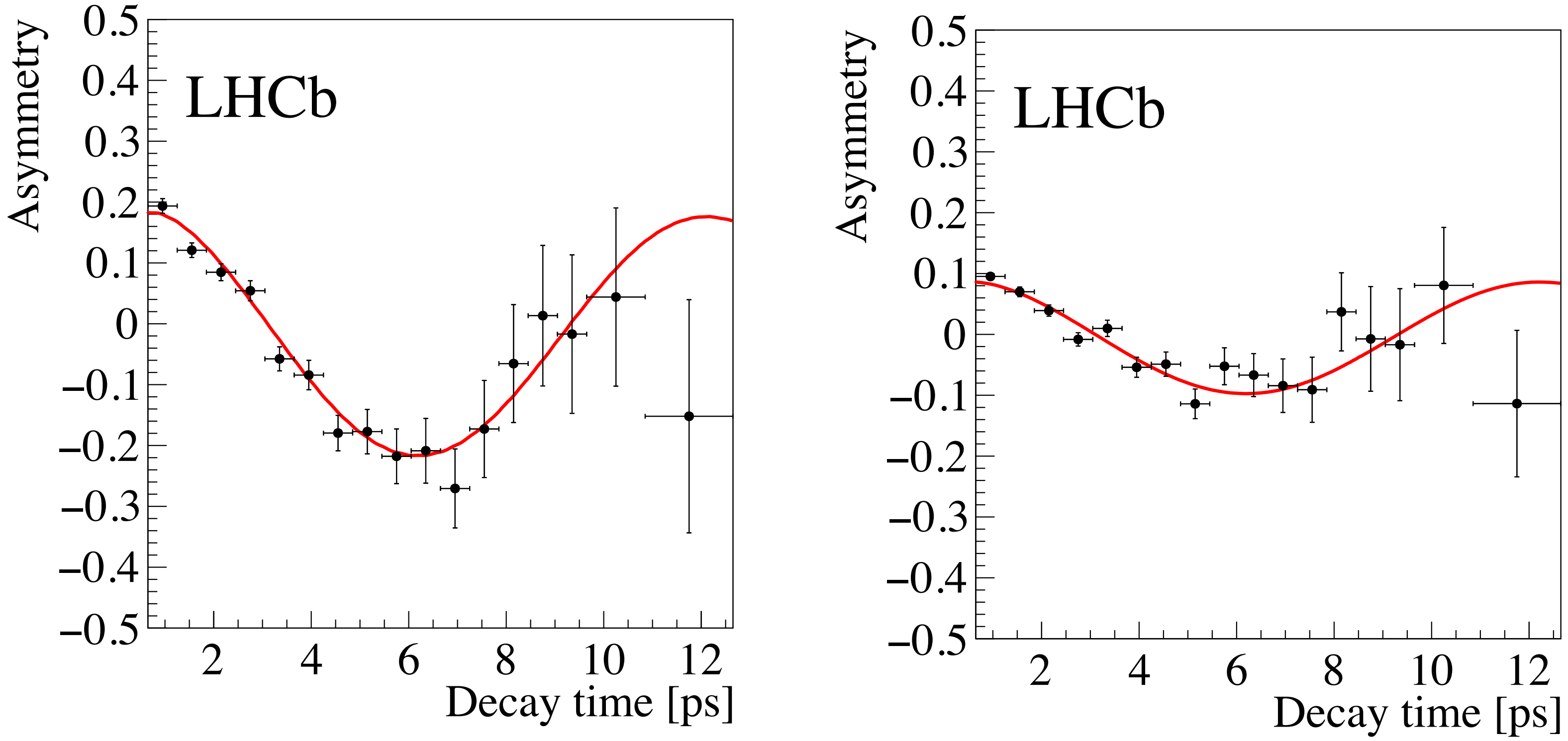
Current experimental knowledge on the CP parameters:

Reference	$C_{\pi^+\pi^-}$	$S_{\pi^+\pi^-}$	$\rho\,(C_{\pi^+\pi^-}, S_{\pi^+\pi^-})$
BaBar [22]	$-0.25 \pm 0.08 \pm 0.02$	$-0.68 \pm 0.10 \pm 0.03$	-0.06
Belle [23]	$-0.33 \pm 0.06 \pm 0.03$	$-0.64 \pm 0.08 \pm 0.03$	-0.10
LHCb [17]	$-0.38 \pm 0.15 \pm 0.02$	$-0.71 \pm 0.13 \pm 0.02$	0.38
HFLAV average [19]	-0.31 ± 0.05	-0.66 ± 0.06	0.00
	$C_{K^+K^-}$	$S_{K^+K^-}$	$\rho\,(C_{K^+K^-}, S_{K^+K^-})$
LHCb [17]	$0.14 \pm 0.11 \pm 0.03$	$0.30 \pm 0.12 \pm 0.04$	0.02

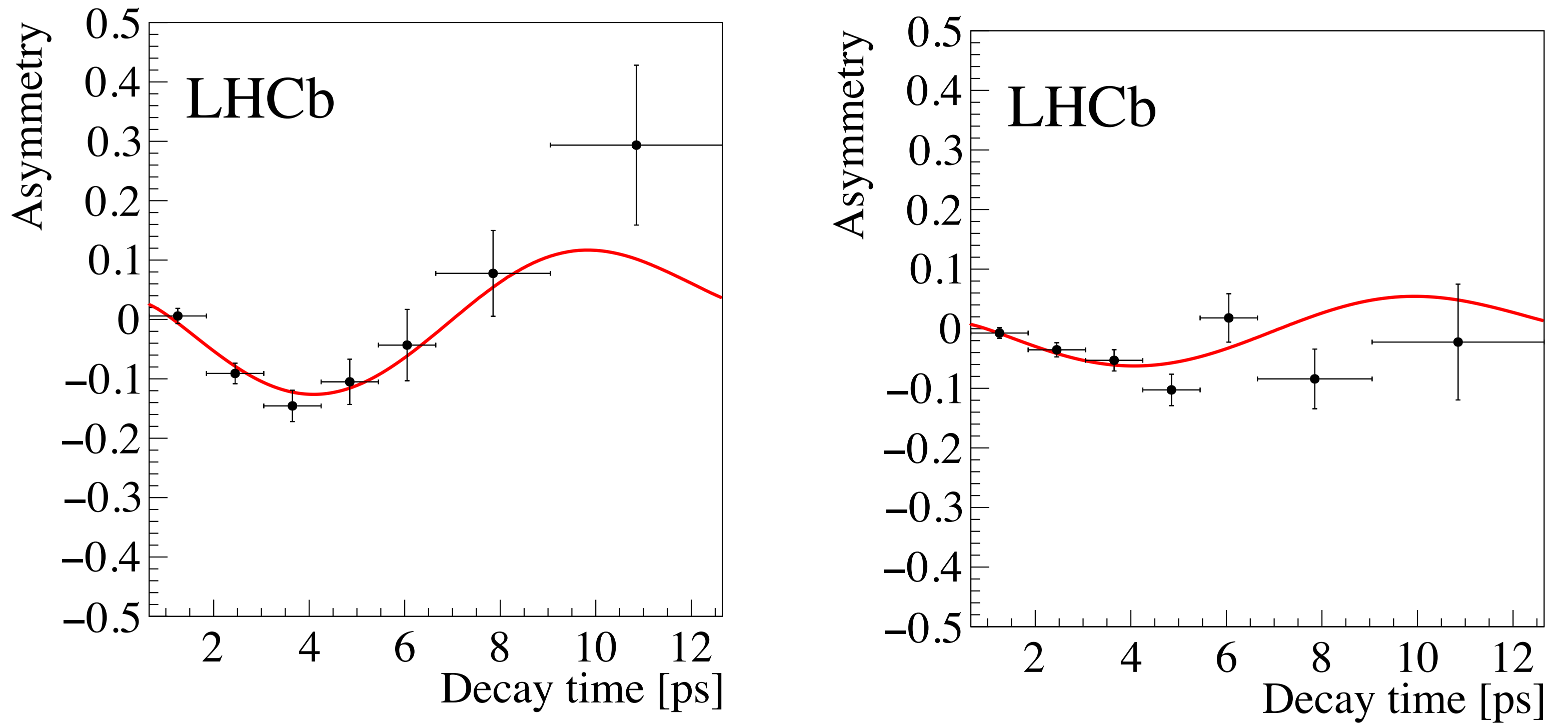
Experiment	$A_{CP}^{B^0}$	$A_{CP}^{B^0_s}$
BaBar [22]	$-0.107 \pm 0.016 \,^{+\,0.006}_{-\,0.004}$	–
Belle [24]	$-0.069 \pm 0.014 \pm 0.007$	–
CDF [25]	$-0.083 \pm 0.013 \pm 0.004$	$0.22 \pm 0.07 \pm 0.02$
LHCb [18]	$-0.080 \pm 0.007 \pm 0.003$	$0.27 \pm 0.04 \pm 0.01$
HFLAV average [19]	-0.082 ± 0.006	0.26 ± 0.04

$B^0_{(s)} \to hh'$

arXiv:1805.06759



Time dependent asymmetries for the $K\pi$ candidates using OS-tagging (left) and SS-tagging (right)



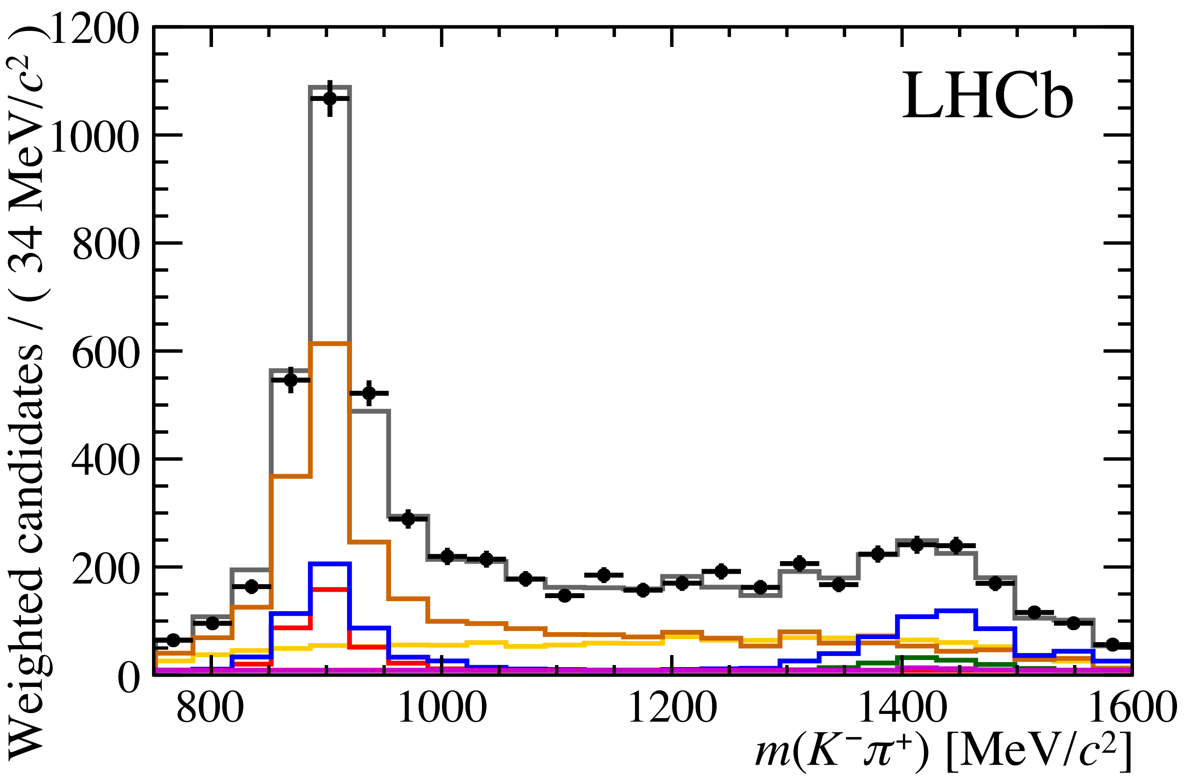
Time dependent asymmetries for the $\pi\pi$ candidates using OS-tagging (left) and SSc-tagging (right)

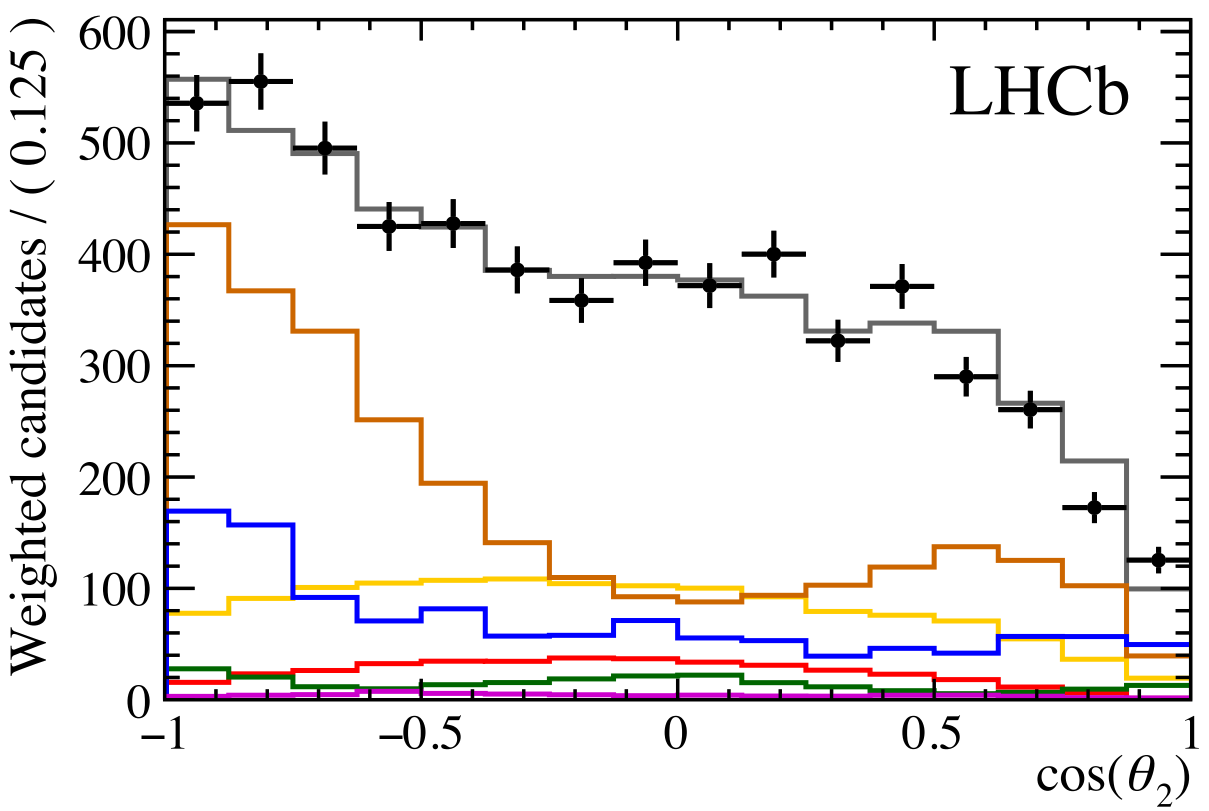
Systematic uncertainties on the CPV parameters

Source of uncertainty	$C_{\pi^+\pi^-}$	$S_{\pi^+\pi^-}$	$C_{K^+K^-}$	$S_{K^+K^-}$	$A^{\Delta\Gamma}_{K^+K^-}$	$A^{B^0}_{CP}$	$A^{B^0_s}_{CP}$
Time-dependent efficiency	0.0011	0.0004	0.0020	0.0017	0.0778	0.0004	0.0002
Time-resolution calibration	0.0014	0.0013	0.0108	0.0119	0.0051	0.0001	0.0001
Time-resolution model	0.0001	0.0005	0.0002	0.0002	0.0003	negligible	negligible
Input parameters	0.0025	0.0024	0.0092	0.0107	0.0480	negligible	0.0001
OS-tagging calibration	0.0018	0.0021	0.0018	0.0019	0.0001	negligible	negligible
SS K -tagging calibration	—	—	0.0061	0.0086	0.0004	—	—
SSc-tagging calibration	0.0015	0.0017	—	—	—	negligible	negligible
Cross-feed time model	0.0075	0.0059	0.0022	0.0024	0.0003	0.0001	0.0001
Three-body bkg.	0.0070	0.0056	0.0044	0.0043	0.0304	0.0008	0.0043
Comb.-bkg. time model	0.0016	0.0016	0.0004	0.0002	0.0019	0.0001	0.0005
Signal mass model (reso.)	0.0027	0.0025	0.0015	0.0015	0.0023	0.0001	0.0041
Signal mass model (tails)	0.0007	0.0008	0.0013	0.0013	0.0016	negligible	0.0003
Comb.-bkg. mass model	0.0001	0.0003	0.0002	0.0002	0.0016	negligible	0.0001
PID asymmetry	—	—	—	—	—	0.0025	0.0025
Detection asymmetry	—	—	—	—	—	0.0014	0.0014
Total	0.0115	0.0095	0.0165	0.0191	0.0966	0.0030	0.0066

Correlations between statistical uncertainties on the CPV parameters

	$C_{\pi^+\pi^-}$	$S_{\pi^+\pi^-}$	$C_{K^+K^-}$	$S_{K^+K^-}$	$A^{\Delta\Gamma}_{K^+K^-}$	$A^{B^0}_{CP}$	$A^{B^0_s}_{CP}$
$C_{\pi^+\pi^-}$	1	0.448	−0.006	−0.009	0.000	−0.009	0.003
$S_{\pi^+\pi^-}$		1	−0.040	−0.006	0.000	0.008	0.000
$C_{K^+K^-}$			1	−0.014	0.025	0.006	0.001
$S_{K^+K^-}$				1	0.028	−0.003	0.000
$A^{\Delta\Gamma}_{K^+K^-}$					1	0.001	0.000
$A^{B^0}_{CP}$						1	0.043
$A^{B^0_s}_{CP}$							1


LHCb
Weighted candidates / (34 MeV/c^2)
1200
1000
800
600
400
200
0
800
1000
1200
1400
1600
$m(K^-\pi^+)$ [MeV/c^2]


LHCb
Weighted candidates / (0.125)
600
500
400
300
200
100
0
−1
−0.5
0
0.5
1
$\cos(\theta_2)$

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Parameter	Value
Common parameters	
$\phi_s^{d\bar{d}}$ [rad]	$-0.10 \pm 0.13 \pm 0.14$
$\|\lambda\|$	$1.035 \pm 0.034 \pm 0.089$
Vector/Vector (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]	$2.62 \pm 0.26 \pm 0.64$
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_{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]	$0.2 \pm 0.4 \pm 1.1$
Tensor/Tensor (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]	$0.7 \pm 0.6 \pm 1.3$

Introduction

The large matter/antimatter asymmetry in the Universe is inconsistent with the small amount of CP violation seen in the SM:

Search for new sources of CPV

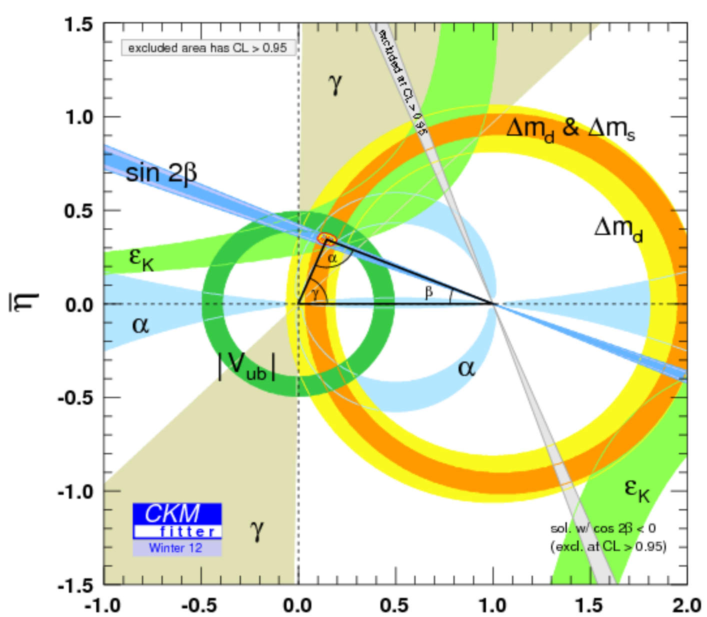
Diagrams including a loop can create sources of CPV when new heavy particles enter the loop.

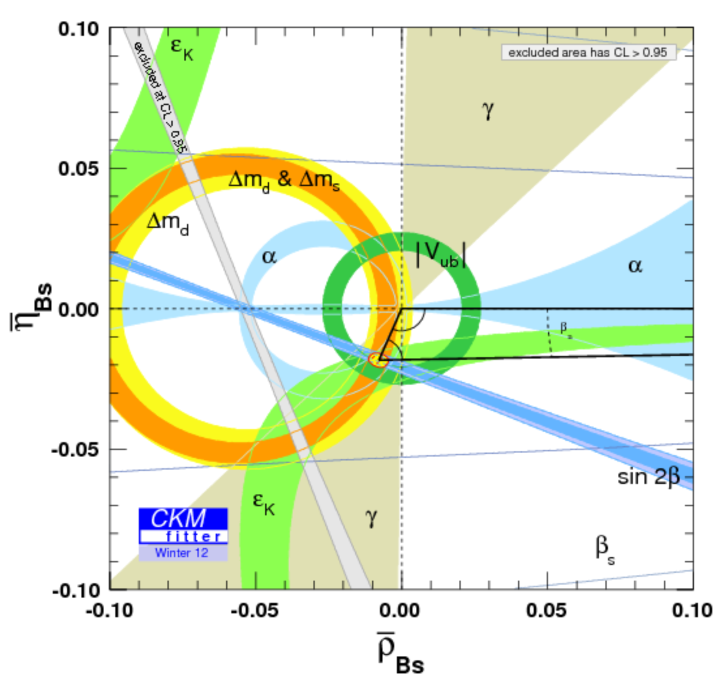
Charmless B decays can occur two ways:

- b $\rightarrow$ u transitions from tree diagrams
- b $\rightarrow$ s,d transitions from penguin diagrams including loops

Due to the CKM matrix element $|V_{ub}|$,the *size of the amplitude of these two transitions is similar*. Within the SM, the relative weak phase difference between these diagrams is given by γ_{CKM} . This allows for *precision measurements of CPV*.

The CKM Matrix





CPV in SM comes from the CKM matrix.

$$
\begin{array}{cc}
 & \begin{array}{ccc} d & s & b \end{array} \\
V = & \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \begin{array}{c} u \\ c \\ t \end{array}
\end{array}
$$

Unitarity of the matrix gives the unitary triangles with angles α, β, γ

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

Experimentally the least known angle

$$\alpha = \mathrm{abs}\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\beta_s = \mathrm{abs}\left(-\frac{V_{cs}V_{cb}^*}{V_{ts}V_{tb}^*}\right)$$

Determined from the $b \to c\bar{c}s$ mixing angle, $\phi_s^{c\bar{c}s}$