CP violation and mixing in beauty with LHCb

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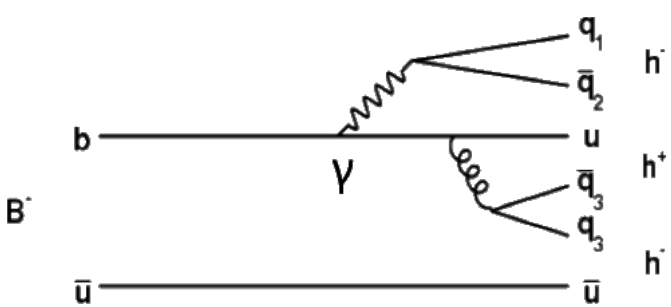
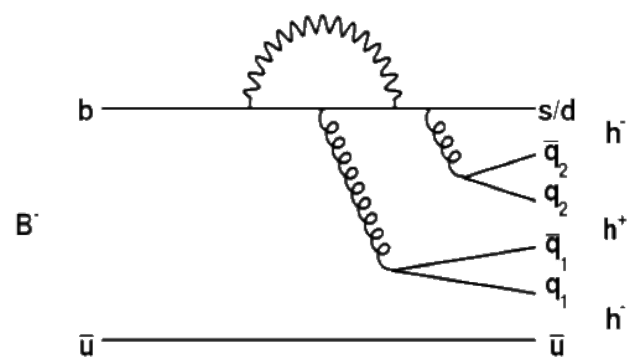
On behalf of the LHCb collaboration

Direct CP violation in 3-body decays

- Direct CPV: only CPV manifestation in charged B mesons.
- At least two interfering amplitudes.
  - Weak phases (flip sign under *CP*).
  - Strong phases (*CP* invariant).
- 3-body charmless decays allow to study strong phases that can originate in:
  - Short distance processes.
  - Long distance processes with hadron-hadron interactions in the final state:
    - Final state $KK \leftrightarrow \pi\pi$ rescattering.
    - Interference between intermediate states.
- Eg.: Analysis of $B^{\pm} \to \pi^{\pm} K^{-} K^{+}$: **[Phys.Rev.D90 (2014) 112004]**
    - CP asymmetry in the phase space: A_{CP}: -0.123 ± 0.022.
    - Large asymmetries in the $\pi\pi \leftrightarrow KK$ rescattering region.





Amplitude analysis of $B^{\pm} \to \pi^{\pm} K^{-} K^{+}$ decays

- $B^{\pm} \to \pi^{\pm} K^{-} K^{+}$ Dalitz Plot separated for B^{+} and B^{-}.
- DP amplitude analysis with Isobar model of seven components.

Complete Run-I, 3.0 fb^{-1}

arXiv:1905.09244

$$\mathcal{A}(m^2_{\pi^+K^-}, m^2_{K^+K^-}) = \sum_{i=1}^{N} c_i \mathcal{M}_{R_i}(m^2_{\pi^+K^-}, m^2_{K^+K^-})$$

- c_i : complex isobar coefficients
- $\mathcal{M}_{R_i}(m^2_{\pi^+K^-}, m^2_{K^+K^-})$: amplitudes for the *i*-th intermediate state.
- Observables:

$$A_{CP} = \frac{|\bar{c}_i|^2 - |c_i|^2}{|\bar{c}_i|^2 + |c_i|^2}$$

$$FF_i = \frac{\int \left(|c_i \mathcal{M}_i|^2 + |\bar{c}_i \overline{\mathcal{M}}_i|^2 \right) \mathrm{d}m^2_{\pi^\pm K^\mp} \mathrm{d}m^2_{K^+K^-}}{\int \left(|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2 \right) \mathrm{d}m^2_{\pi^\pm K^\mp} \mathrm{d}m^2_{K^+K^-}}$$

B^+ yield: 2052 ± 102

B^- yield: 1566 ± 84

	Contribution	Fit Fraction(%)	A_{CP}(%)
$\pi^\pm K^\mp$	$K^*(892)^0$	$7.5 \pm 0.6 \pm 0.5$	$+12.3 \pm 8.7 \pm 4.5$
	$K_0^*(1430)^0$	$4.5 \pm 0.7 \pm 1.2$	$+10.4 \pm 14.9 \pm 8.8$
	Single pole	$32.3 \pm 1.5 \pm 4.1$	$-10.7 \pm 5.3 \pm 3.5$
K^+K^-	$\rho(1450)^0$	$30.7 \pm 1.2 \pm 0.9$	$-10.9 \pm 4.4 \pm 2.4$
	$f_2(1270)$	$7.5 \pm 0.8 \pm 0.7$	$+26.7 \pm 10.2 \pm 4.8$
	Rescattering	$16.4 \pm 0.8 \pm 1.0$	$-66.4 \pm 3.8 \pm 1.9$
	$\phi(1020)$	$0.3 \pm 0.1 \pm 0.1$	$+9.8 \pm 43.6 \pm 26.6$

Amplitude analysis of $B^{\pm} \to \pi^{\pm} K^{-} K^{+}$ decays

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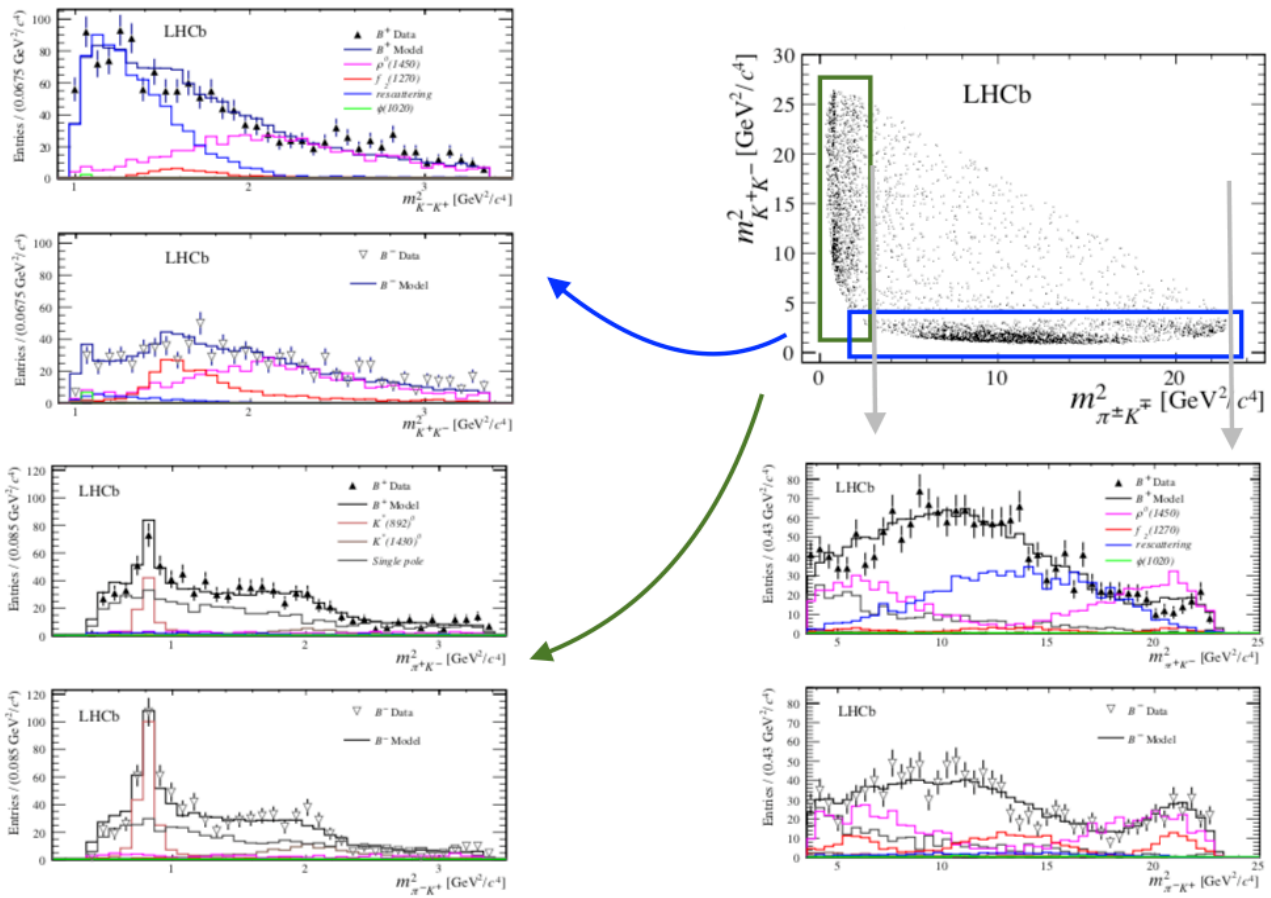


- Main contributions ~30%: non-resonant and $B^{\pm} \to \rho^0(1450)\pi^{\pm}$.
- Large CP asymmetry in K^+K^- rescattering contribution ~66%.
  - In agreement with the inclusive CP asymmetry reported in PRD 90, 112004 (2014).

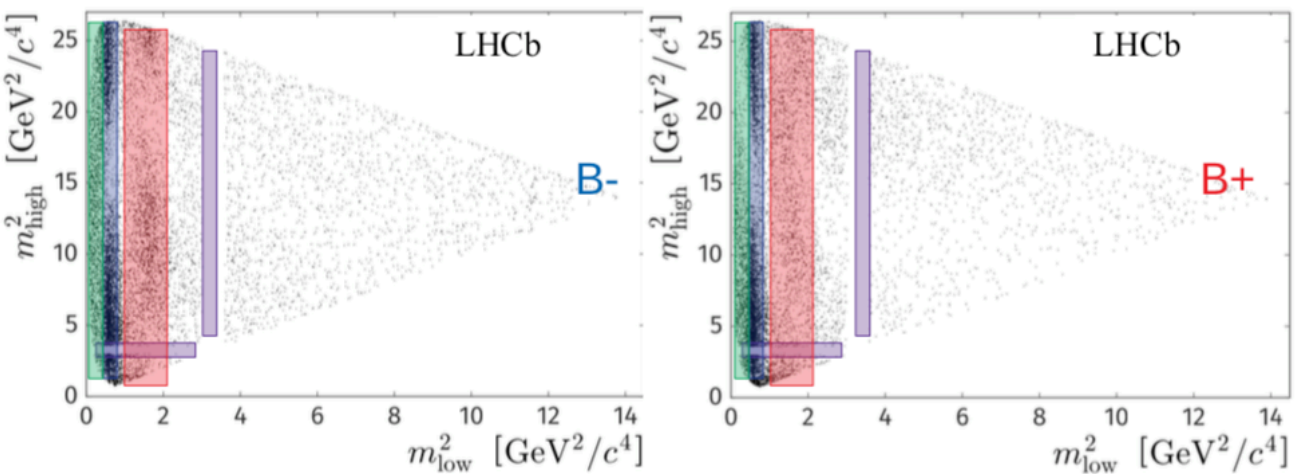
Amplitude analysis of $B^+ \to \pi^+\pi^-\pi^+$ decays

- Analysis in high and low ($\pi^+\pi^-$) pairs mass .
- Bose-symmetric amplitude.
- Isobar model of Non S-wave and S-wave cont.
- Non S-wave cont.: $\rho(770)^0$-$\omega(782)$, $f_2(1270)$, $\rho(1450)^0$ and $\rho_3(1690)^0$.
- S-wave cont.: $f_0(500)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$.
- Three S-wave approaches:
  - Isobar Approach.
    - Includes rescattering component and pole for $f_0(500)$.
  - K-matrix Approach.
    - Unitary by construction.
  - QMI Approach.
    - Fit magnitude and phase in regions of the DP.
- General agreement between the three S-wave approaches.

Complete Run-I, 3.0 fb^{-1}

Combined signal yield 20600 ± 1600 events

LHCb-PAPER-2019-017
LHCb-PAPER-2019-018



- Charm veto.
- $f_2(1270)$ region.
- $\rho(770)$ region.
- low scalar m($\pi\pi$).

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Amplitude analysis of $B^+ \to \pi^+\pi^-\pi^+$ decays

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Phases:

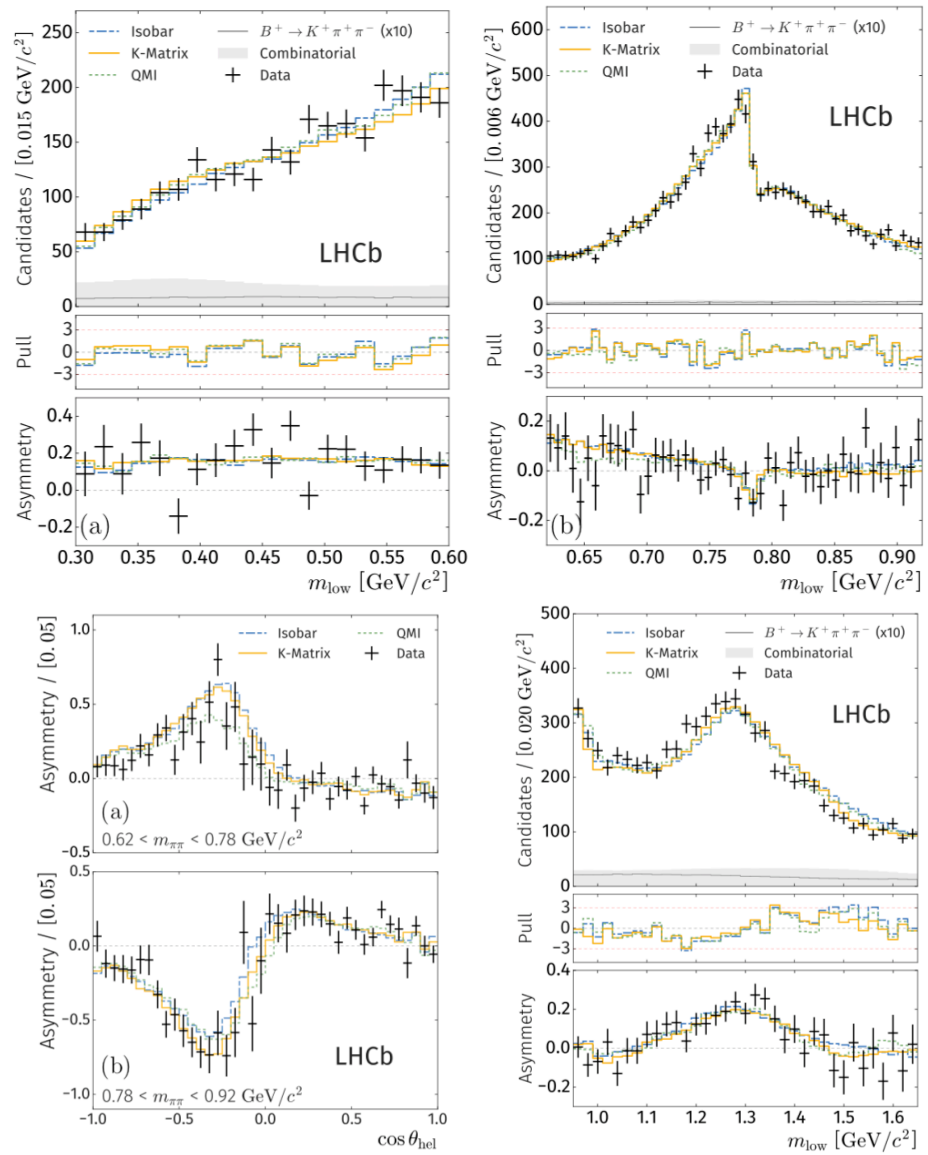
- Largest difference between B^- and B^+ in $f_2(1270)$ (~55°).
- Originates some large CPV in DP.

Fit fractions:

- Dominant $\rho(770)^0$ (~0.56) and S-wave (~0.26).
- Significant $f_2(1270)$ (~0.09).

CP asymmetries:

- No asymmetry observed in ρ-ω mixing.
- Clear asymmetry in $m(\pi^+\pi^-)$ below $\rho(770)^0$ mass.
  - Flips sign at K^+K^- threshold.
- Large asymmetry in helicity angle.
  - Reveals CPV in S-P waves interference.
  - **First observation** (>25σ) of CPV in a quasi-two-body interference.
- Large asymmetry ~40% in $f_2(1270)$.
  - **First observation** (>10σ) of CPV involving a tensor.



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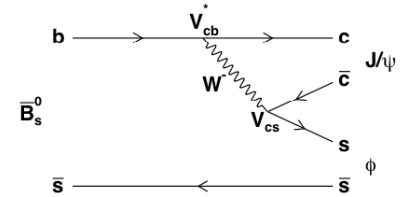
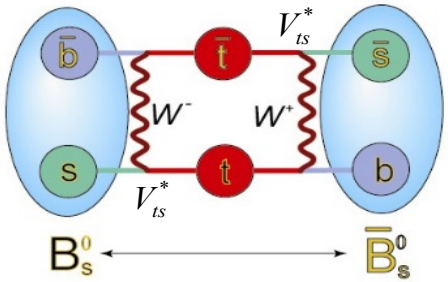
$B_s^0 \to VV$ time dependent analyses

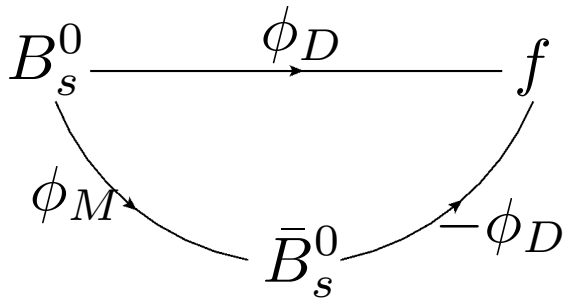
[CKM fitter]

$$\phi_s^{c\bar{c}s} \equiv \arg\lambda \overset{\text{1st order}}{\approx} \arg\left(\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -36.8^{+1.0}_{-0.8}\ \text{mrad}$$

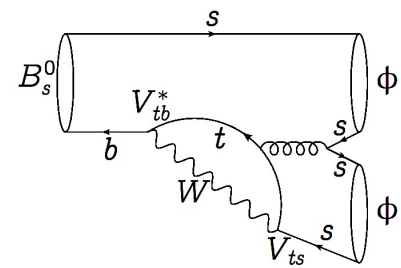
- $B_s^0 - \overline{B}_s^0$ mixing interference between:
  - Decay.
  - Decay after mixing.





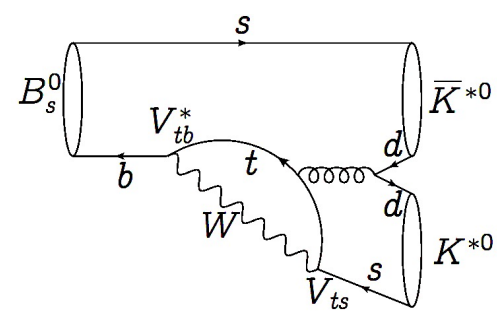


$$\phi_s^{s\bar{s}s} \equiv \arg\lambda \overset{\text{1st order}}{\approx} \arg\left(\frac{V_{tb}^*V_{ts}}{V_{tb}V_{ts}^*}\frac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}}\right) = 0$$



- Observable phase $\phi_s = \Phi_M - 2\,\Phi_D$.
- Different decays → different ϕ_s.
- NP can appear in Φ_M.
- *Tree* decays (no NP in Φ_D): b→ scc transitions.
- *Loop* decays (potential NP in Φ_D): b→sss and b→sdd transitions.

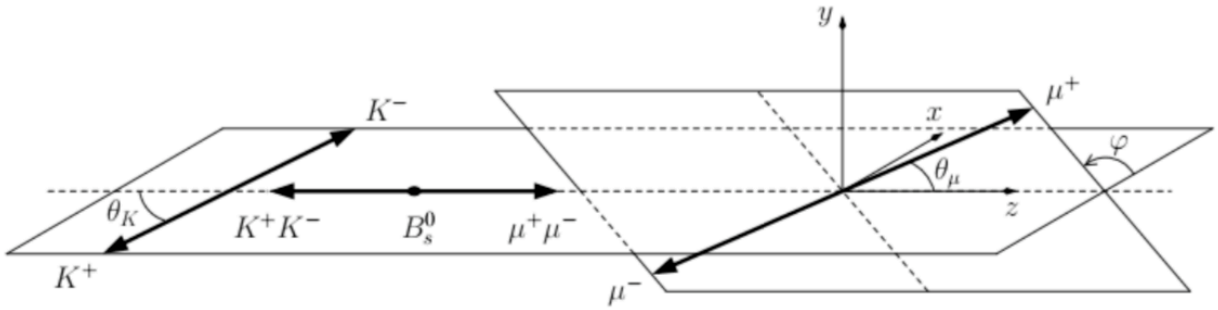
$$\phi_s^{d\bar{d}s} \equiv \arg\lambda \overset{\text{1st order}}{\approx} \arg\left(\frac{V_{tb}^*V_{ts}}{V_{tb}V_{ts}^*}\frac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}}\right) = 0$$



Direct CPV also possible if $|\lambda| = \left|\frac{q}{p}\cdot\frac{\overline{A}}{A}\right| \neq 1.$

$B_s^0 \rightarrow VV$ time dependent analyses

- Deviation of ϕ_s from SM would imply NP.
- Decay rate depends on ϕ_s, $\Delta\Gamma_s$ and Δm_s.
- Vector and S-wave final states: admixture of CP-even and CP-odd eigensates.
- Full amplitude analyses applied with dependencies on:
  - Mass.
  - Helicity angles.
  - Time.
- Require tagging.
- Time resolution and tagging power enter in the experimental PDF.
- Unbinned maximum likelihood fits.



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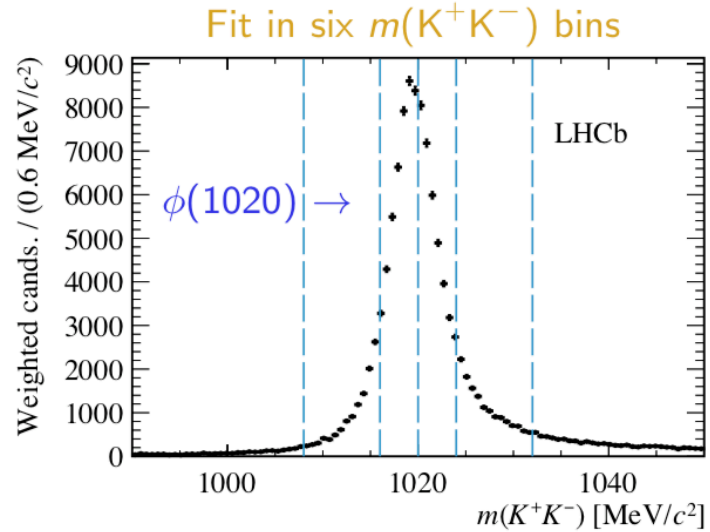
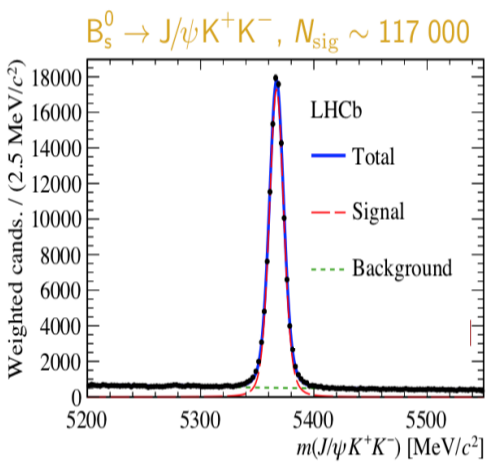
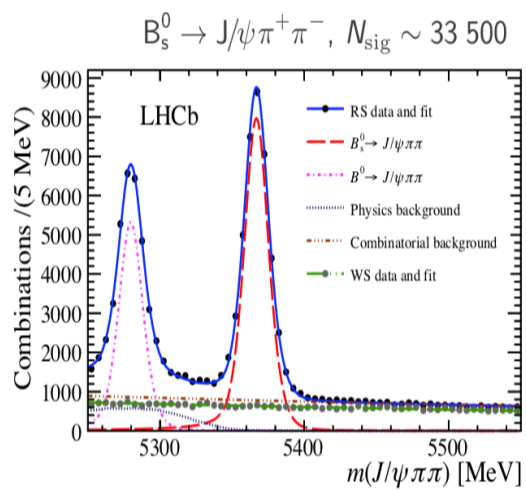
$B^0_s \to J/\psi K^+K^-$ and $B^0_s \to J/\psi \pi^+\pi^-$

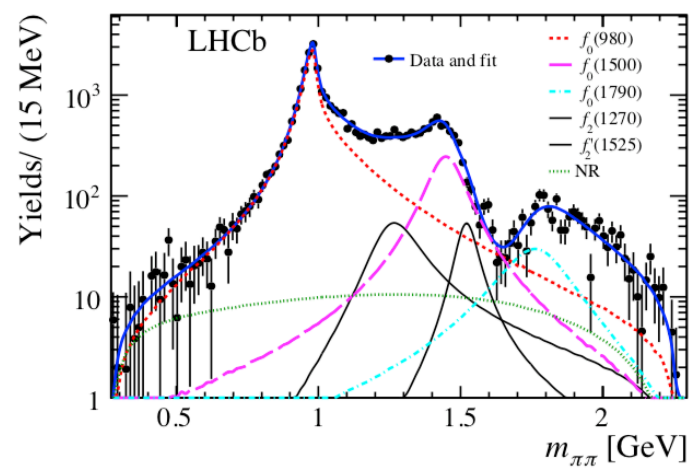
arXiv:1906.08356
arXiv:1903.05530

- 1.9 fb^{-1} (2015: 0.3 fb^{-1} & 2016: 1.6 fb^{-1}) Run-II data.
- $B^0_s \to J/\psi K^+K^-$ around $\phi(1020)$.
  - Modest S-wave contribution.
- $B^0_s \to J/\psi \pi^+\pi^-$: mainly $B^0_s \to J/\psi f_0(980)$.
- Decay-time resolution
  - $\sigma_{eff}(B^0_s \to J/\psi K^+K^-) \approx 45.5$ fs,
  - $\sigma_{eff}(B^0_s \to J/\psi \pi^+\pi^-) \approx 41.5$ fs.
- Decay-time and angular efficiencies
  - Estimated with simulation.
  - Corrected with data methods.
- Flavour tagging
  - 30% higher tagging power than Run-1.









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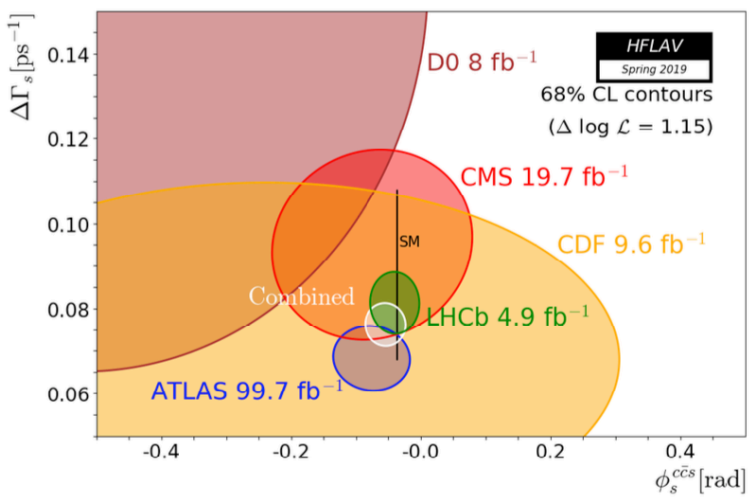
$B^0_s \to J/\psi K^+K^-$ and $B^0_s \to J/\psi \pi^+\pi^-$

Results in agreement with previous measurements and SM prediction.

Exp. unc. of ϕ_s average: 31→21 mrad.

Exp. unc. of $\Delta\Gamma_s$ average: 0.005 → 0.0034 ps^{-1}.



Average LHCb

$$\phi_s = -41 \pm 25 \text{ mrad}$$
$$|\lambda| = 0.093 \pm 0.010$$
$$\Gamma_s = 0.6562 \pm 0.0021 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.0816 \pm 0.0048 \text{ ps}^{-1}$$

HFLAV combination

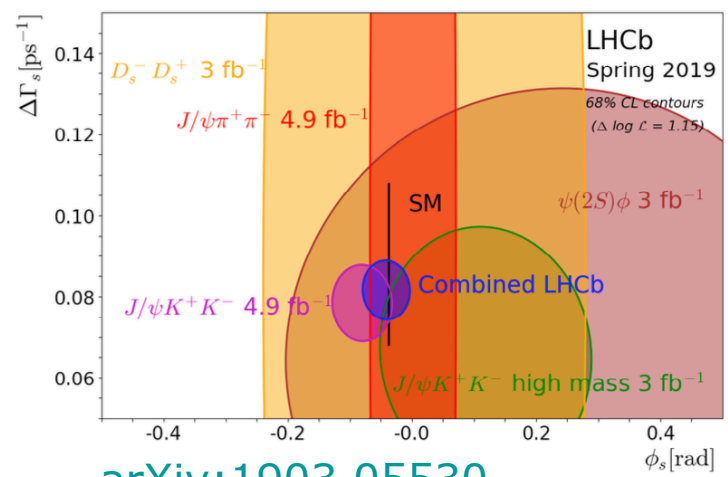
$$\phi_s = -55 \pm 21 \text{ mrad}$$
$$\Delta\Gamma_s = 0.0764 \pm 0.0024 \text{ ps}^{-1}$$

$B^0_s \to J/\psi K^+K^-$

$$\phi_s = -83 \pm 41 \pm 6 \text{ mrad}$$
$$|\lambda| = 1.012 \pm 0.016 \pm 0.006$$
$$\Gamma_s - \Gamma_d = -0.0041 \pm 0.0024 \pm 0.0015 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.077 \pm 0.008 \pm 0.003 \text{ ps}^{-1}$$

$B^0_s \to J/\psi \pi^+\pi^-$

$$\phi_s = -57 \pm 60 \pm 11 \text{ mrad}$$
$$|\lambda| = 1.01^{+0.08}_{-0.06} \pm 0.03$$
$$\Gamma_H - \Gamma_d = -0.050 \pm 0.004 \pm 0.004 \text{ ps}^{-1}$$



arXiv:1903.05530

arXiv:1906.08356

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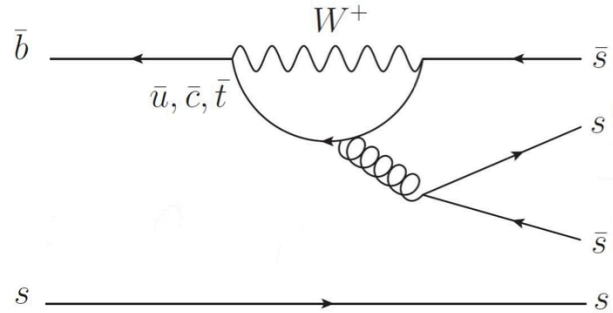
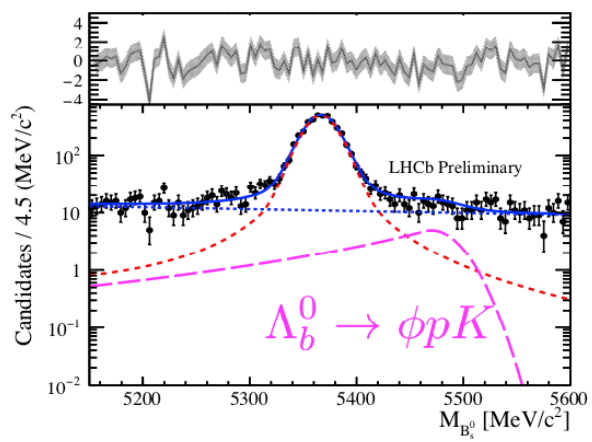
$B_s^0 \to \phi\phi$

arXiv:1907.10003



- Run 1 (3 fb^{-1}) + part. Run 2 (2 fb^{-1}) data
- 4-dimension: 3 angles + time:
  - Γ_s and $\Delta\Gamma_s$ and Δm_s from external input (PDG and HFLAV).
- CP-even and CP-odd S-wave contributions.
- Detector efficiency and decay-time resolution determined with simulated events.
- Decay-time efficiency determined with data method.
- Angular observables measured.
  - Pure penguin decays show small longitudinal polarisation (A_0 or f_L) with one exception.

~8500 signal events.



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$B_s^0 \to \phi\phi$

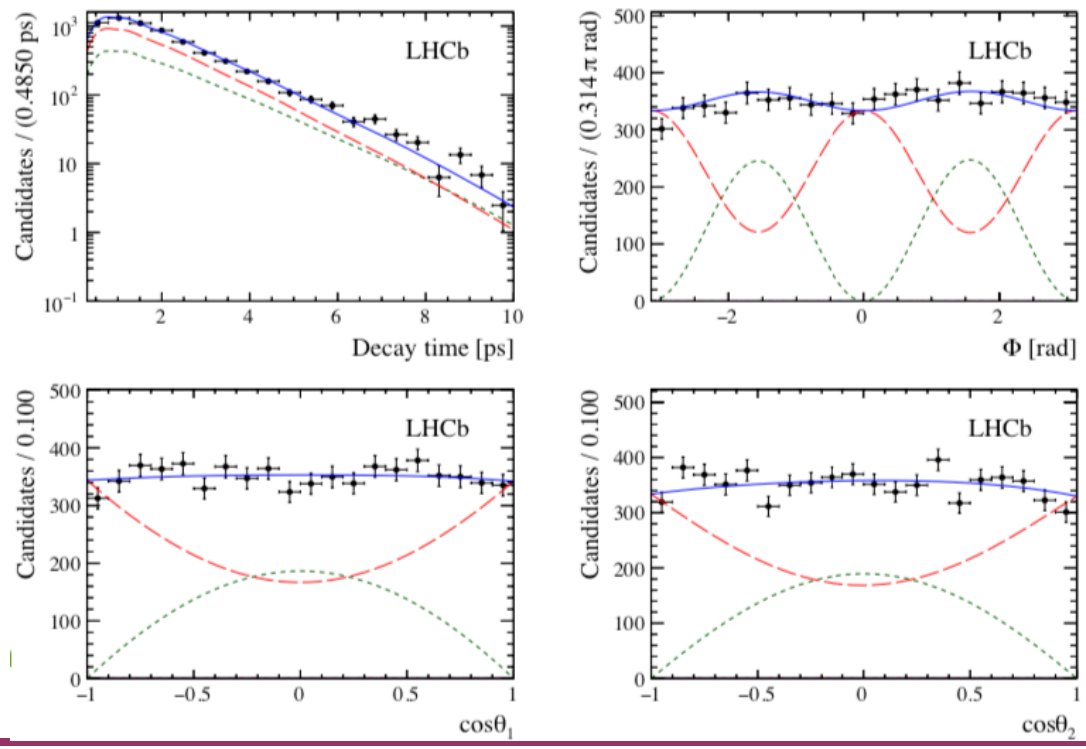
arXiv:1907.10003

$$|A_0|^2 = 0.381 \pm 0.007\,(\text{stat}) \pm 0.012\,(\text{syst}),$$
$$\phi_s^{s\bar{s}s} = -0.073 \pm 0.115\,(\text{stat}) \pm 0.027\,(\text{syst})\ \text{rad},$$
$$|\lambda| = 0.99 \pm 0.05\,(\text{stat}) \pm 0.01\,(\text{syst}).$$

Stat. unc. of ϕ_s : 15→11.5 mrad.

Stat unc. of $|A_0|^2$ 0.012 →0.007

Total CP–even CP–odd S–wave



$B^0 \to K^{*0}\overline{K}^{*0}$

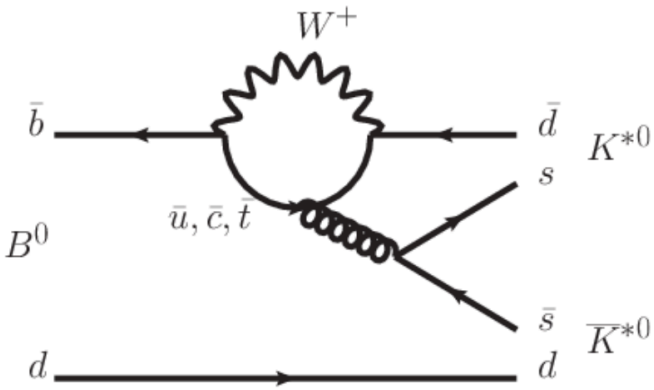
JHEP 07 (2019) 032

- TD 2018 analysis of $B^0_s \to K^{*0}\overline{K}^{*0}$ determined **[JHEP 1803 (2018) 140]:**

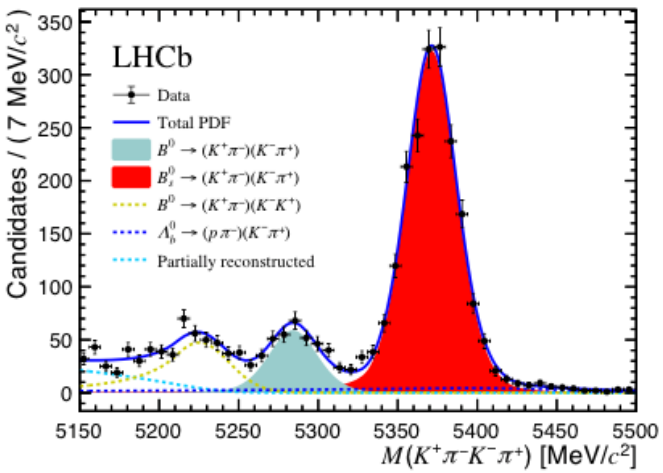
$$\phi_s^{d\bar{d}s} = -0.10 \pm 0.13\ (\text{stat.}) \pm 0.14\ (\text{syst.})\ [\text{rad}]$$

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

- **Prospects**: repeat the study with Run 2 (6 fb^{-1}) and upgraded LHCb data.



Decay mode	σ(stat.) [rad]			
	3 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^0_s \to \phi\phi$	0.154	0.039	0.026	0.011
$B^0_s \to (K^+\pi^-)(K^-\pi^+)$ (inclusive)	0.129	0.033	0.022	0.009
$B^0_s \to K^*(892)^0\overline{K}^*(892)^0$	–	0.127	0.086	0.035



- $B^0 \to K^{*0}\overline{K}^{*0}$ U-spin partner of $B_s^0 \to K^{*0}\overline{K}^{*0}$ decay.
  - Can be used to control penguin pollution from subleading amplitudes.
- First LHCb analysis of $B^0 \to K^{*0}\overline{K}^{*0}$.
- High f_L compared with $B_s^0 \to K^{*0}\overline{K}^{*0}$.
- Complete Run-I (3 fb^{-1}) data.
- Untagged and time-integrated analysis.
- Assuming $\Delta\Gamma \sim 0$ and negligible CPV in the mixing and in the decay.

$B^0 \to K^{*0}\overline{K}^{*0}$

JHEP 07 (2019) 032

- Large longitudinal polarisation: f_L = 0.724 ± 0.051 (stat) ± 0.016 (syst).
  - S–wave fraction: 0.408 ± 0.050 (stat) ± 0.023 (syst).
- Parallel study of the $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ performed.
  - Small f_L = 0.240 ± 0.031 (stat) ± 0.025 (syst).
  - Large S–wave contribution: 0.694 ± 0.016 (stat) ± 0.012 (syst).
  - Compatible with LHCb time dependent study.

$B^0 \to K^{*0}\overline{K}^{*0}$ branching fraction measured

$$\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0}) = (8.04 \pm 0.87\,(\text{stat}) \pm 0.41\,(\text{syst})) \times 10^{-7}$$

- Compatible with QCDF prediction [Nucl.Phys.B774 (2007) 64]. Smaller than measurement from BaBar [Phys.Rev.Lett.100 (2008) 081801], due to S–wave contribution.
- Using averages $y = \Delta\Gamma_s/(2\Gamma_s)$ = 0.064 ± 0.005 and ϕ_s = −0.021 ± 0.031

$$R_{sd} = \frac{\mathcal{B}(B_s^0 \to K^{*0}\overline{K}^{*0}) f_L(B_s^0 \to K^{*0}\overline{K}^{*0})}{\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0}) f_L(B^0 \to K^{*0}\overline{K}^{*0})} \frac{1-y^2}{1+y\cdot\cos\phi_s}$$

found to be R_{sd} = 3.43 ± 0.38.

- There is a theoretical prediction:

$$R_{sd}^{\text{theory}} = 16.4 \pm 5.2$$ [Phys.Rev.D76 (2007) 074005]

Conclusions

- Very large direct CPV effects are observed in DP regions of charmless 3-body decays.
  - Possibly due to strong phases originated in rescattering.

- In particular, in $B^+ \to \pi^+\pi^-\pi^+$ decays, large asymmetry in helicity angle.
  - First observation of CPV in the interference of S and P waves contributions.
  - Large asymmetry ~40% in $f_2(1270)$ which is the first observation of CPV involving a tensor.

- TD analyses compatible with the SM and produce the strongest constraints in the different ϕ_s.

- The B → VV longitudinal polarisation puzzle continues with the very different f_L values of of $B^0 \to K^{*0}\overline{K}^{*0}$ and $B_s^0 \to K^{*0}\overline{K}^{*0}$.
  - Questions U-spin symmetry.