P2VV measurements from LHCb

Sevda Esen

Heidelberg University

P2VV measurements at LHCb: from Quantum Entanglement perspective
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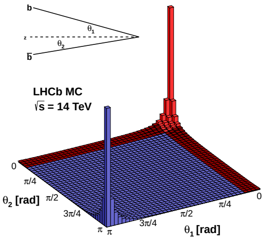
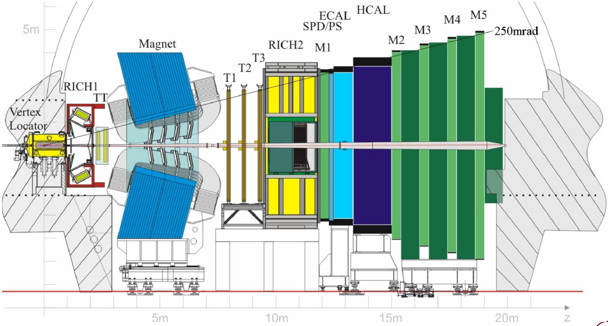
LHCb experiment

- LHCb is an experiment designed for heavy quark flavour physics at CERN,
- The detector is a single-arm forward spectrometer, covering $2 < \eta < 5$;
- Tracking system consists of Vertex Locator ($\sigma_{IP} \approx 20\mu m$ for high pT tracks), followed by one tracking station upstream and three stations downstream of a dipole magnet;
- Particle identification from two RICH detectors, calorimeters and muon system;
- Calorimeter and muon stations provide 40 MHz input to hardware Level-0 trigger, while all other subdetectors are read out at 1 MHz.



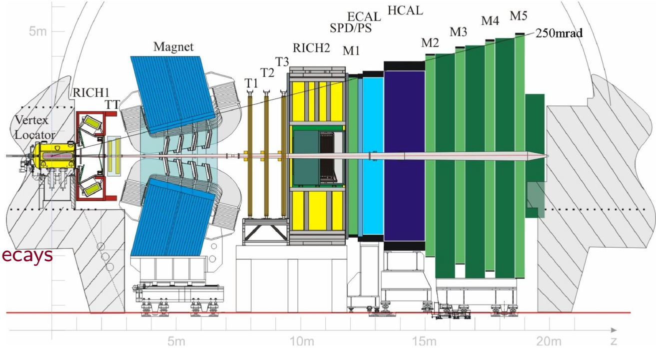


LHCb EXPERIMENT

Momentum resolution:
σ_p/p: 0.4% – 0.6%

Time resolution:
40-50 fs

Mass resolution:
$8\ MeV/c^2$ for $B \to J/\psi X$ decays



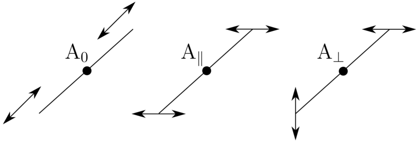
Particle identification:
$\varepsilon(\mu) = 97\%$, mis-id: 0.7%
$\varepsilon(K) > 90\%$, mis-id: 5%

Data sets:

Run1 : 3 fb^{-1} @ 7&8 TeV
Run2 : 6 fb^{-1} @ 13 TeV
Run3: expected 23 fb^{-1}

P2VV decays at LHCb

- Three possible intermediate angular-momentum states



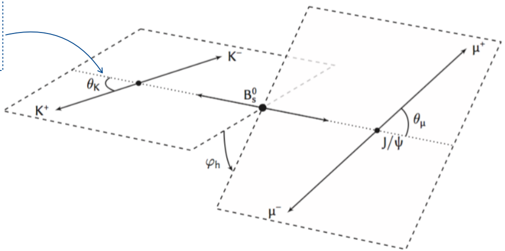
- A typical measurement:
  - Reconstruct mass, subtract the background
  - Reconstruct helicity angles + time if time dependent analysis
  - Estimate acceptances + resolutions if needed, from data if possible
  - Maximum likelihood fit to determine physics parameters
  - Some keys decays:
    $B_s \to J/\psi\phi$, $B_{s,d} \to J/\psi K^*$, $B_s \to \phi\phi$, $B \to J/\psi\rho$, $B \to K^* K^*$

Helicity formalism

Definition of helicity angles in $B_s^0 \to J/\psi\ (\mu^+\mu^-)\ K^+K^-$ system
Similar angular systems are used in many other analysis, for example in $B_s^0 \to \varphi\varphi$

θ_K [0; π] angle between direction of the positively charged hadron and helicity axis
θ_μ [0; π] angle between direction of the positively charged muon and helicity axis
φ_h [0;2π] angle between positively charged hadron and helicity axis

Helicity axis
defined by the directions of the J/ψ and $K^+ K^-$ momenta in the B_s^0 rest frame



coefficient	$f(\Omega) \times \frac{32\pi}{9}$
$\lvert c_0\rvert^2$	$2\cos^2\theta_K \sin^2\theta_\mu$
$\lvert c_\parallel\rvert^2$	$\sin^2\theta_K (1 - \sin^2\theta_\mu \cos^2\varphi_h)$
$\lvert c_\perp\rvert^2$	$\sin^2\theta_K (1 - \sin^2\theta_\mu \sin^2\varphi_h)$
$\Re(c_0^* c_\parallel)$	$+\frac{1}{\sqrt{2}} \sin 2\theta_K \sin 2\theta_\mu \cos\varphi_h$
$\Im(c_0^* c_\perp)$	$-\frac{1}{\sqrt{2}} \sin 2\theta_K \sin 2\theta_\mu \sin\varphi_h$
$\Im(c_\parallel^* c_\perp)$	$+\sin^2\theta_K \sin^2\theta_\mu \sin 2\varphi_h$
$\lvert c_S\rvert^2$	$\frac{2}{3}\sin^2\theta_\mu$
$\Re(c_0^* c_S)$	$\frac{4}{3}\sqrt{3}\cos\theta_K \sin^2\theta_\mu$
$\Re(c_\parallel^* c_S)$	$\frac{1}{3}\sqrt{6}\sin\theta_K \sin 2\theta_\mu \cos\varphi_h$
$\Im(c_\perp^* c_S)$	$\frac{1}{3}\sqrt{6}\sin\theta_K \sin 2\theta_\mu \sin\varphi_h$

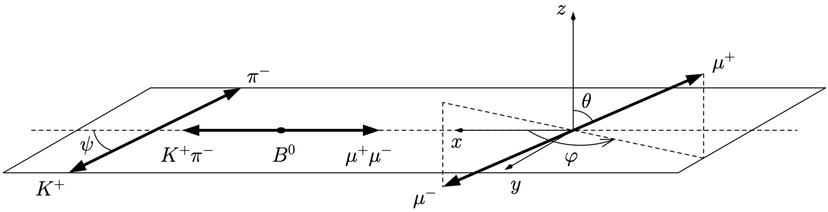
Angular functions for the $B_s^0 \to J/\psi\ K^+K^-$ decay in helicity angles. The coefficients, which depend on the decay time and K^+K^- mass are given by c_i

$B \to J/\psi K^{*0}$ [PAPER-2013-023]

- Measurement of the polarisation amplitudes and phases, separate for $B^0 \to J/\psi K^{*0}(K^+\pi^-)$ and $\bar{B} \to J/\psi \bar{K}^{*0}(K^-\pi^+)$
- Charge of K determines the B flavour
- Using only 2011 data, $\approx$ 61000 signal events

$$\begin{aligned}
|A_\parallel|^2 &= 0.227 \pm 0.004 \text{ (stat.)} \pm 0.011 \text{ (syst.)},\\
|A_\perp|^2 &= 0.201 \pm 0.004 \text{ (stat.)} \pm 0.008 \text{ (syst.)},\\
\delta_\parallel \text{ [rad]} &= -2.94 \pm 0.02 \text{ (stat.)} \pm 0.03 \text{ (syst.)},\\
\delta_\perp \text{ [rad]} &= 2.94 \pm 0.02 \text{ (stat.)} \pm 0.02 \text{ (syst.)}.
\end{aligned}$$

	$\vert A_\parallel\vert^2$	$\vert A_\perp\vert^2$	$\delta_\parallel$	$\delta_\perp$
$\vert A_\parallel\vert^2$	1.00	-0.70	0.12	0.04
$\vert A_\perp\vert^2$		1.00	-0.14	-0.01
$\delta_\parallel$			1.00	0.64
$\delta_\perp$				1.00



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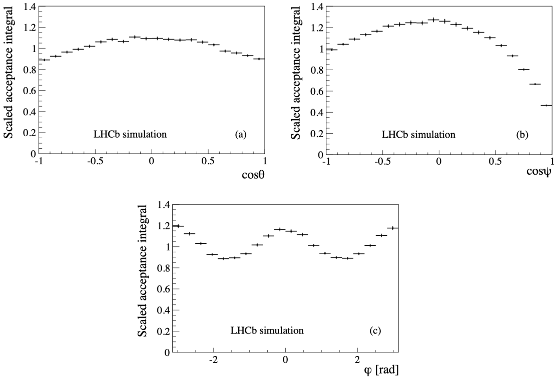
Source	$\lvert A_\parallel \rvert^2$	$\lvert A_\perp \rvert^2$	$\delta_\parallel$[rad]	$\delta_\perp$[rad]
Mass model	0.000	0.001	0.00	0.00
Background treatment	0.002	0.001	0.00	0.00
Misreconstructed background	0.002	0.000	0.00	0.01
Angular acceptance	0.009	0.007	0.03	0.01
Statistical uncertainty on acceptance	0.001	0.001	0.01	0.01
Other resonances	0.005	0.004	0.00	0.01
Total systematic uncertainty	0.011	0.008	0.03	0.02
Statistical uncertainty	0.004	0.004	0.02	0.02

Angular acceptance and resolution

- Angular resolution has negligible effect for most analyses so far
- Detector geometry and selection criteria introduce non-uniform angular efficiency
- Effects of the angular acceptance included with 10 normalization weights obtained from simulation

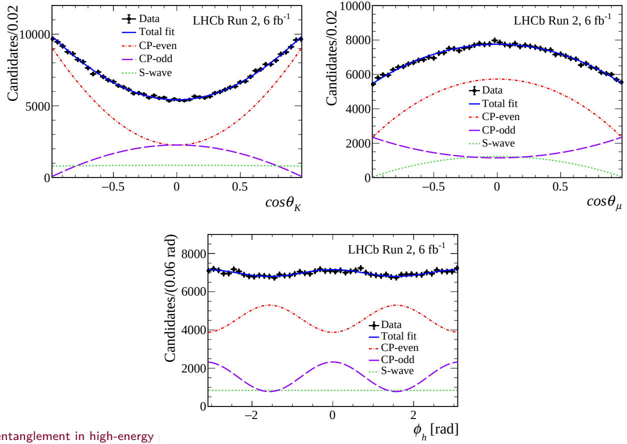


Angular acceptance and resolution

- Angular resolution has negligible effect for most analyses so far
- Detector geometry and selection criteria introduce non-uniform angular efficiency
- Effects of the angular acceptance included with 10 normalization weights obtained from simulation
- Iterative procedure to correct the difference between possible data/simulation differences:
  - poorly modeled detector effects
  - s-wave events are not simulated
  - kinematical dependence on the physics parameters to be measured
- Most kinematic distributions in simulation agree well with data after reweighting
- Remaining discrepancies taken as systematic uncertainty

$B_s \to J/\psi\phi$ [PAPER-2023-016]

- Measurement of the polarisation amplitudes and phases, CPV and mixing parameters
- Flavor non-specific, needs flavor tagging
- Using full run2 data, $\approx$ 349000 signal events



$B_s \to J/\psi\phi$ [PAPER-2023-016]

- Measurement of the polarisation amplitudes and phases, CPV and mixing parameters
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Parameter	Values		
ϕ_s [rad]	-0.039	± 0.022	± 0.006
$\lvert\lambda\rvert$	1.001	± 0.011	± 0.005
$\Gamma_s - \Gamma_d$ [ps^{-1}]	-0.0056	$^{+0.0013}_{-0.0015}$	± 0.0014
$\Delta\Gamma_s$ [ps^{-1}]	0.0845	± 0.0044	± 0.0024
Δm_s [ps^{-1}]	17.743	± 0.033	± 0.009
$\lvert A_\perp\rvert^2$	0.2463	± 0.0023	± 0.0024
$\lvert A_0\rvert^2$	0.5179	± 0.0017	± 0.0032
$\delta_\perp - \delta_0$ [rad]	2.903	$^{+0.075}_{-0.074}$	± 0.048
$\delta_\parallel - \delta_0$ [rad]	3.146	± 0.061	± 0.052

$B_s \to J/\psi\phi$ [PAPER-2023-016]

* Uncertainties ($\times 0.01$) Dominant sys. Sub-dominant sys. Stat. limited

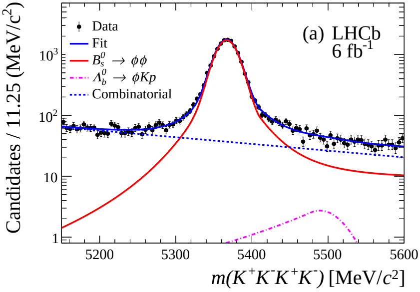
Source	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	ϕ_s [rad]	$\lvert\lambda\rvert$	$\delta_\perp - \delta_0$ [rad]	$\delta_\parallel - \delta_0$ [rad]	$\Gamma_s - \Gamma_d$ [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [ps^{-1}]
Mass parametrization	0.04	0.03	0.03	0.02	0.15	0.12	0.02	0.04	0.03
Mass: shape statistical	0.04	0.04	0.05	0.09	0.62	0.33	0.02	0.01	0.11
Mass factorization	0.11	0.10	0.42	0.19	0.54	0.60	0.12	0.16	0.18
B_c^+ contamination *	0.04	0.05	—	0.02	—	0.17	(0.07)	(0.03)	—
D–wave component	0.04	0.04	0.02	—	0.07	0.13	0.01	0.03	0.02
Ghost tracks	0.07	0.04	0.02	0.10	0.18	0.18	0.02	—	0.01
Multiple candidates	0.01	—	0.27	0.22	0.90	0.41	0.01	0.01	0.24
Particle identification	0.06	0.09	0.27	0.27	1.31	0.51	0.05	0.15	0.46
C_{SP} factors	—	0.01	0.01	0.03	0.73	0.41	—	0.01	0.04
DTR model portability	—	—	0.08	0.03	0.26	0.09	—	—	0.09
DTR calibration	—	—	0.03	0.02	0.11	0.07	—	—	0.05
Time bias correction	0.04	0.05	0.06	0.05	0.77	0.11	0.03	0.05	0.44
Angular efficiency	0.05	0.14	0.25	0.32	0.42	0.44	0.01	0.02	0.13
Angular resolution	0.01	0.01	0.02	0.01	0.02	0.08	—	0.01	0.02
Kinematic weighting	0.24	0.09	0.01	0.01	0.98	0.86	0.02	0.03	0.31
Momentum uncertainty	0.08	0.04	0.04	—	0.07	0.11	0.01	—	0.13
Longitudinal scale	0.07	0.04	0.04	—	0.10	0.09	0.02	—	0.31
Neglected correlations	—	—	—	—	4.20	4.96	—	—	—
Total sys. unc.	0.32	0.24	0.6	0.5	4.8	5.2	0.14	0.24	0.9
Stat. unc.	0.17	0.23	2.2	1.1	7.5	6.0	0.14	0.44	3.3

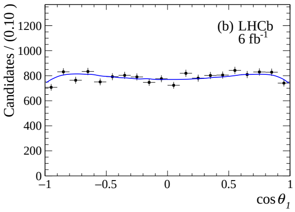
*The uncertainty of the B_c^+ contamination for $\Delta\Gamma_d^s$ and $\Delta\Gamma_s$ is included in the fit to data and does not contribute to the quoted total systematic uncertainty.

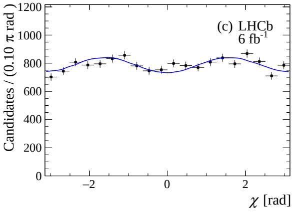
$B_s \to \phi\phi$ [PAPER-2023-001]

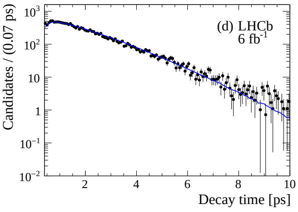
- Penguin dominated decay
- Similar analysis to $\mathrm{B}_s^0 \to J/\psi K^+K^-$
- Run 2 results, 15840 candidates

Parameter	Result
$\phi_s^{s\bar{s}s}$ [rad]	$-0.042 \pm 0.075 \pm 0.009$
$\lvert\lambda\rvert$	$1.004 \pm 0.030 \pm 0.009$
$\lvert A_0\rvert^2$	$0.384 \pm 0.007 \pm 0.003$
$\lvert A_\perp\rvert^2$	$0.310 \pm 0.006 \pm 0.003$
$\delta_\parallel - \delta_0$ [rad]	$2.463 \pm 0.029 \pm 0.009$
$\delta_\perp - \delta_0$ [rad]	$2.769 \pm 0.105 \pm 0.011$









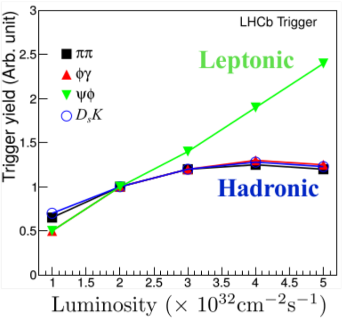
$B_s \to \phi\phi$ [PAPER-2019-019]

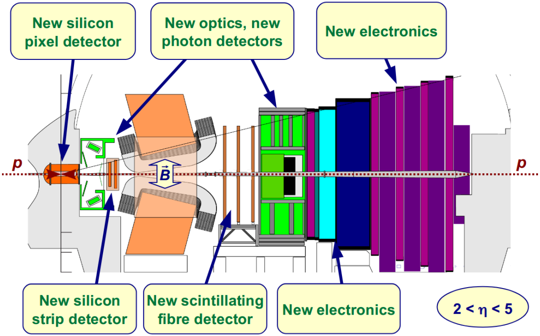
- Correlation matrix with statistical and systematic uncertainties for run 2 data

	$\phi_s^{s\bar{s}s}$	$\lvert\lambda\rvert$	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	$\delta_\parallel - \delta_0$	$\delta_\perp - \delta_0$
$\phi_s^{s\bar{s}s}$	1	-0.037	-0.005	0.058	0.013	-0.005
$\lvert\lambda\rvert$		1	0.033	0.018	-0.008	-0.006
$\lvert A_0\rvert^2$			1	-0.342	-0.007	0.064
$\lvert A_\perp\rvert^2$				1	0.140	0.088
$\delta_\parallel - \delta_0$					1	0.179
$\delta_\perp - \delta_0$						1

A new day has come

- Hardware trigger removed, expect significant benefit for hadronic final states
- 150 pb^{-1} data collected in 2023 pp collision run at 13.6 TeV
- Expected to collect 50 pb^{-1} in run 3+4





THANK YOU