# Moscow International School of Physics 2024

## Voronovo, 28 February – 6 March 2024

# Measurement of the $B_s^0$ effective lifetime in the decay $B_s^0 \to J/\psi K_s^0$ using full Run-II CMS data


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# Outline

- Introduction
- Selections
- Lifetime validation
- Unblinded fit
- Systematics
- Summary

# Introduction to lifetime

From the decay law, the decay probability of an unstable particle defined as,

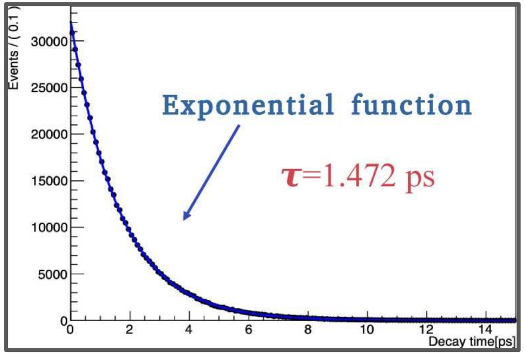
$$P \alpha\, e^{-t/\tau}$$

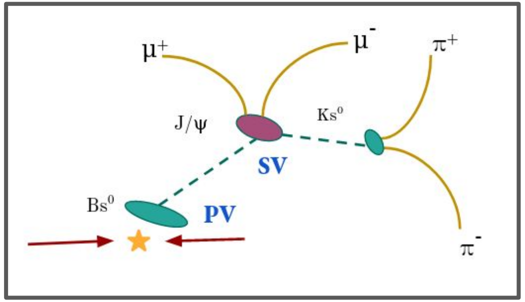
$\tau$ = lifetime of the particle, t = decay time of the particle.

Decay time is defined as,

$$\boxed{t = \frac{L_{xy} M_{B_s^0}}{p_T}}$$

Where $M_B$ is the mass of the B candidate. (Reconstructed mass)
Lxy is the length difference between the PV (primary vertex) and SV (secondary vertex) in transverse plane.
$p_T$ is the transverse momentum of the B candidate.




The effective lifetime is obtained by performing 2D UML fit to the $J/\psi K_s^0$ invariant mass and the decay time.

# Cont.

➔ Signal decay mode - $B_s^0 \rightarrow J/\Psi K_s^0$

➔ Control channel - $B^0 \rightarrow J/\Psi K_s^0$

➔ Related through interchanging all d quarks with s quarks.

The $B_s^0 \rightarrow J/\Psi Ks^0$ effective lifetime is defined as,

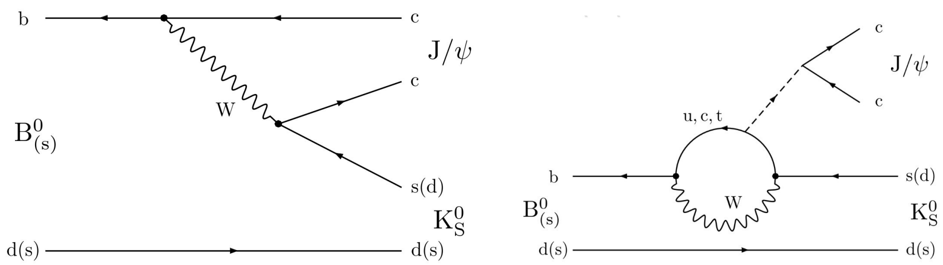
$$\tau_{J/\psi K_s^0} = \frac{\int_0^\infty t[\Gamma(B_s^0(t) \to J/\psi K_s^0) + \Gamma(\overline{B_s^0}(t) \to J/\psi K_s^0)]dt}{\int_0^\infty [\Gamma(B_s^0(t) \to J/\psi K_s^0) + \Gamma(\overline{B_s^0}(t) \to J/\psi K_s^0)]dt}$$

Can be rewritten as,

$$\tau_{J/\psi K_s^0} = \frac{\tau_{B_s^0}}{1 - {y_s}^2}\left(\frac{1 + 2A_{\Delta\Gamma}y_s + {y_s}^2}{1 + A_{\Delta\Gamma}.y_s}\right)$$ , where $y_s = \tau_{B_s^0}\frac{\Delta\Gamma}{2}$

➔ The advantage of effective lifetime study is that it allows an efficient extraction of $A_{\Delta\Gamma}$.

➔ An effective lifetime for a $B_s^0$ decay channel is obtained in practice by fitting a single exponential function to its untagged rate.

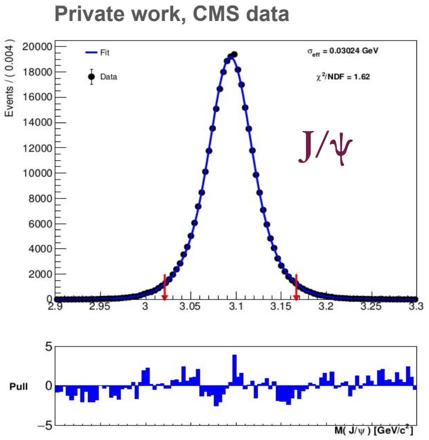


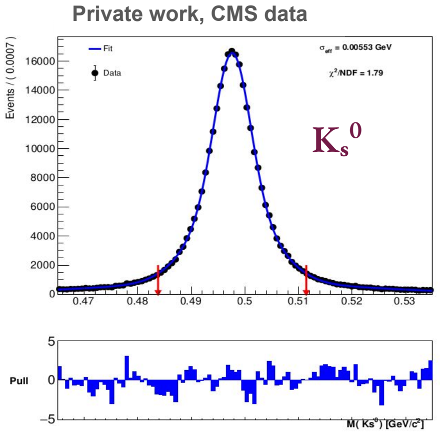

LHCb lifetime results : 1.75 ± 0.12 (stat) ± 0.07 (syst) ps

SM lifetime results : 1.619 ± 0.019 ps

# Signal selection and background rejection

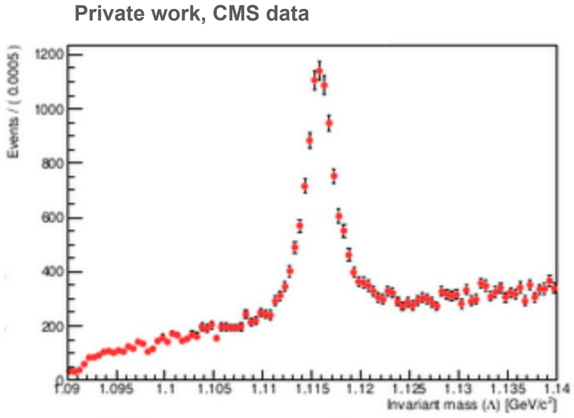
- Selection on $J/\psi$ and $K_s^0$ invariant mass.
- $J/\psi$ and $K_s^0$ mass distribution is fitted with double Gaussian with common mean.
- $\pm\,2.5\sigma_{eff}$ selection cut on $J/\psi$ (1st column) and $K_s^0$ (2nd column) invariant mass.




## $\Lambda^0$ rejection

- Proton from the $\Lambda^0$ is faked as $\pi$, which may peak in the $K_s^0$ invariant mass.
- The Armenteros-Podolanski method is followed to reject this background.



# Cont.

- Flight length (distance between B-decay vertex to di-track vertex) significance cut is applied >5$\sigma$.

- To suppress the combinatorial backgrounds we used MVA (BDT) followed by initial selections.

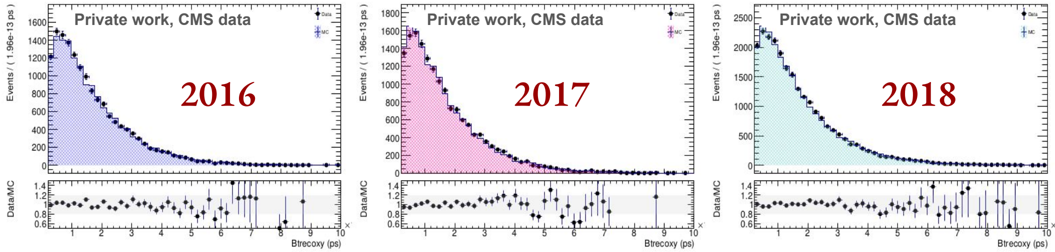
  - ➔ 8 different discriminating variables which are less correlated with decay time used as Input variables.
  - ➔ Input variables - alpha_xy, Ks $p_{T,}$ pvips, B_vtxprob, Ks_vtxprob, J/$\Upsilon$ $p_{T,}$ $\eta_{B,}$ Ks_alphaxy
  - ➔ Optimization is based on least lifetime error. For this, toy study has been performed.
  - ➔ For each BDT values, toys have been generated and fitted like data fit. 2D UML fit to individual years is performed for BDT optimization.

  The optimized BDT cut values: 2016 - 0.61, 2017 - 0.60 and 2018 - 0.61.

➔ Data-Simulation comparison for the control channel ($B^0 \rightarrow J/\Upsilon K_s^0$) are verified.

➔ The comparisons are in agreement.

## Decay time Data-simulation comparison



# Efficiency

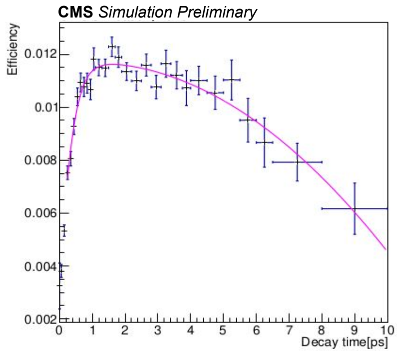


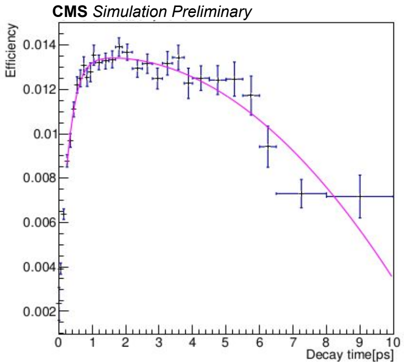
➔ The generator level decay time for B mesons is a simple exponential function.

➔ However, trigger and other selection cuts distort this exponential function. This distortion is measured by efficiency.

➔ The function used to describe the efficiency distribution (range: 0.2ps - 10 ps).

$$\epsilon(t; p_0, p_1, p_2, p_3, p_4) = p_0 + p_1 t + p_2 t^2 + \frac{p_3}{1 + exp(-p_4 t)}$$




Efficiency plot for $B_s^0$ (top), $B^0$ (bottom)

# Validation with signal MC



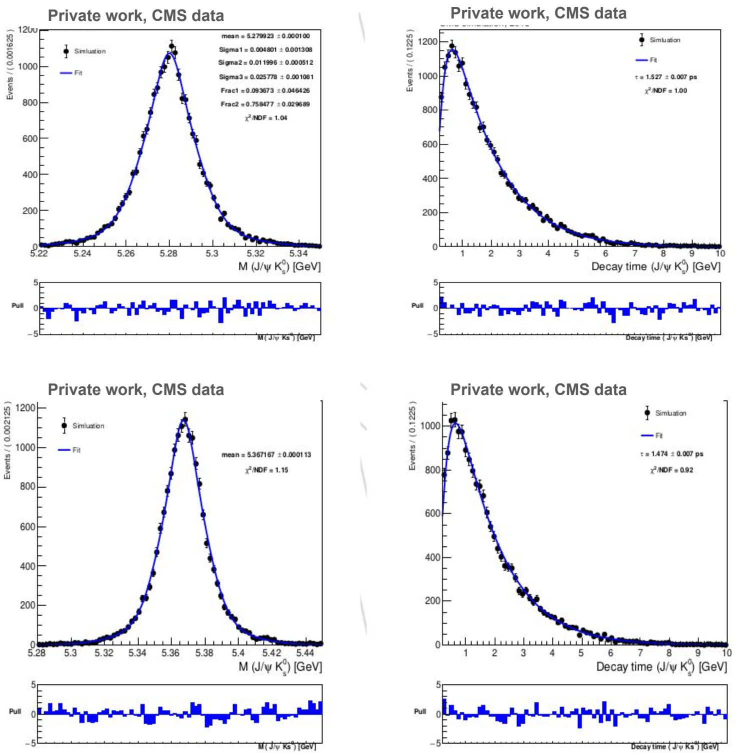
➔ Effective lifetime is extracted after performing a simultaneous fit over three year signal MC using 2D UML method

➔ The lifetime obtained from simultaneous fit (to three years) to the $B^0$ signal MC samples is 1.527 ± 0.007ps (generated lifetime value is 1.525ps) and to the $B_s^0$ signal MC samples is 1.474 ± 0.007ps (generated lifetime is 1.472ps).

## Mass and decay time projection plots from MC :

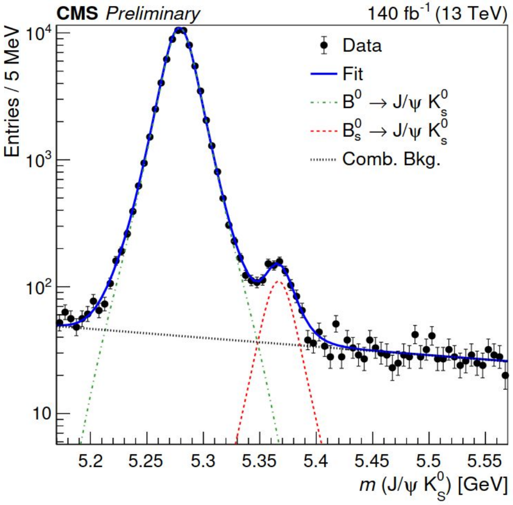
$B^0$

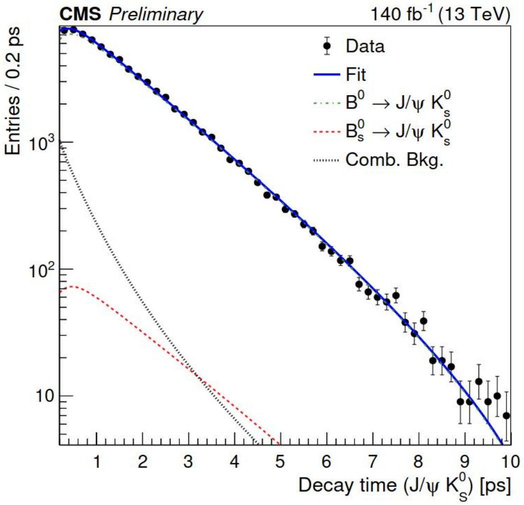
$B_s^0$

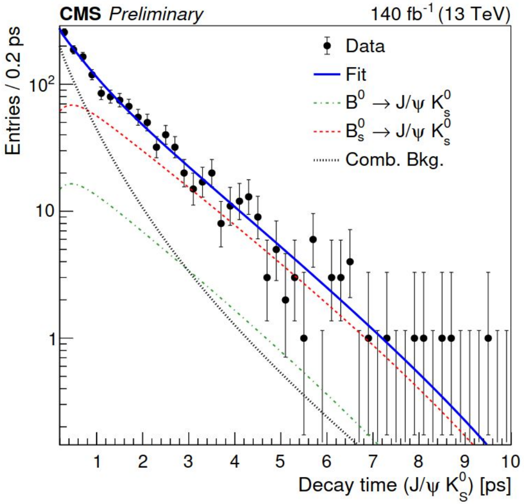


# Final fit to full Run-2 data






The measured lifetime of the $B^0$ meson **1.521 ± 0.007 ps** is in accordance with the value reported by the PDG (**1.519 ± 0.004 ps**). The consistency in the $B^0$ lifetime value implies that there is no bias in the $B_s^0$ lifetime measurement. The effective lifetime for $B_s^0$ meson is measured as - **1.59 ± 0.07 ps.**

**Decay time projection plot only for signal region [5.34-5.42 GeV]**

## Sources of systematic uncertainties and total systematic uncertainties:

| Sources | Uncertainty (in ps) |
|---|---|
| Limited MC statistics | 0.006 |
| Efficiency modeling | 0.002 |
| Deviation in control channel lifetime | 0.002 |
| Signal and background mass model | 0.022 |
| Background decay time model | 0.014 |
| Mass shape variation | 0.007 |
| Different fit strategy | 0.006 |
| Total | 0.028 |

- The effective lifetime for $B_s^0$ meson with the decay $B_s^0 \rightarrow J/\Psi K_s^0$ has been measured.
- Control channel lifetime is well in line with PDG ➡ No obvious bias in the $B_s^0$ lifetime measurement.
- The measured effective lifetime from the simultaneous fit for $B_s^0$ is

$$\tau_{B_s^0 \rightarrow J/\Psi K_s^0} = 1.59 \pm 0.07\,(\text{stat}) \pm 0.03\,(\text{syst})\ \text{ps}.$$

- The result is in agreement with the standard model prediction and ~60% improvement compared to LHCb results.

**Thank you!**

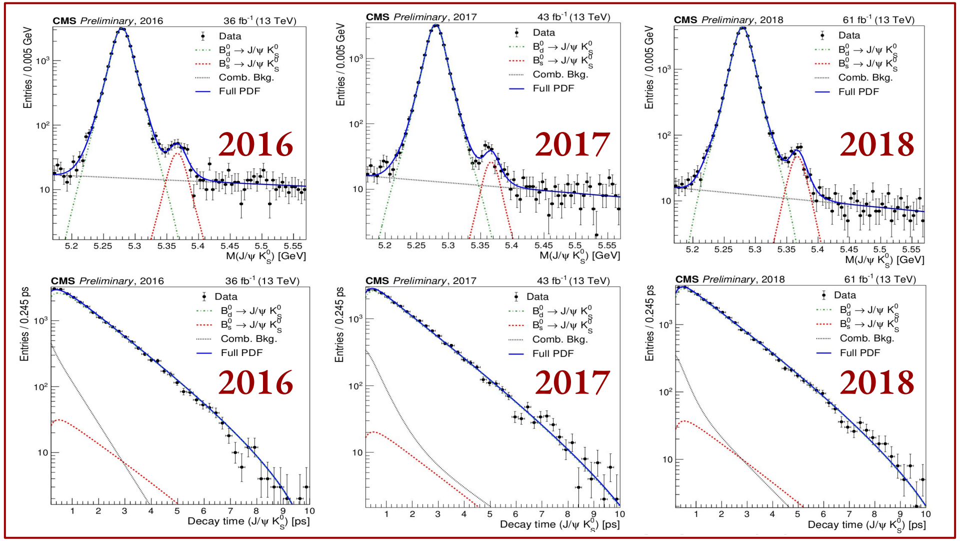
# Backup

# Final fit to full Run-2 data

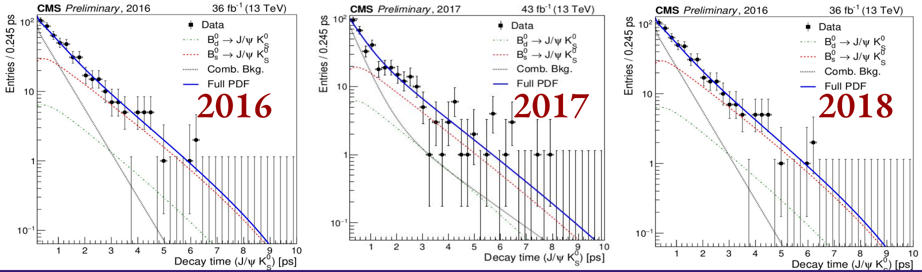
CMS-PAS-BPH-22-001

| Parameters | Values |
|---|---|
| $B^0$ combined yield | 68456 ± 265 |
| $B_s^0$ combined yield | 727 ± 35 |
| $B^0$ lifetime | 1.521 ± 0.007 ps |
| $B_s^0$ lifetime | 1.59 ± 0.07 ps |

The measured lifetime of the $B^0$ meson is in accordance with the value reported by the PDG (1.519 ± 0.004 ps). $B_s^0$ lifetime is in agreement with the SM predicted value (1.619 ± 0.019 ps).

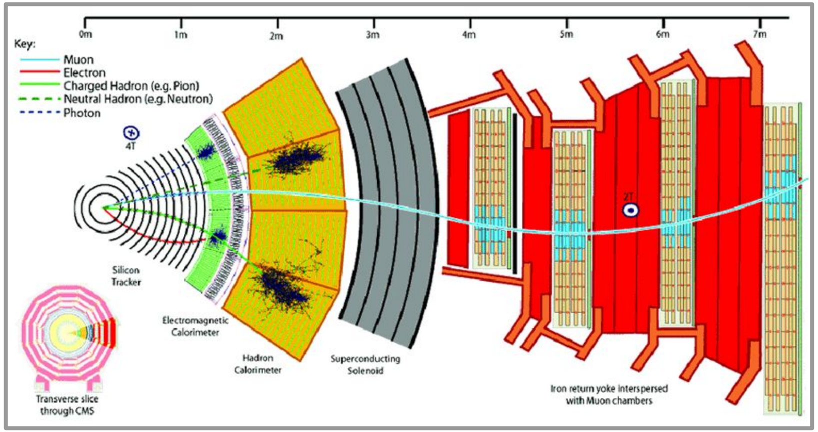



Decay time projection plot only for signal region [5.34-5.42 GeV]



# CMS - The 14,000-tonne detector

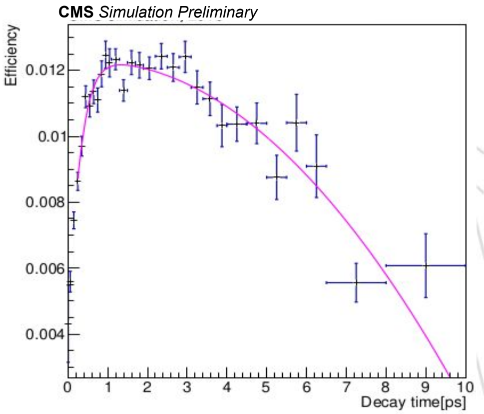
- At 15 metres high and 21 metres long, it really is quite compact for all the detector material it contains.
- It is designed to detect particles known as muons very accurately.
- It has the most powerful solenoid magnet ever made.

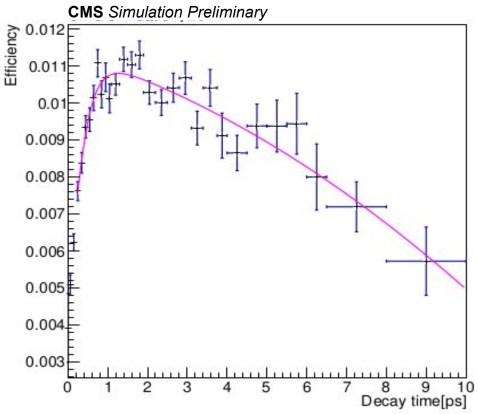


# Input variables

- $\alpha_{xy}$ : Angle in the transverse plane between the $B_s^0$ momentum and the separation between the $B_s^0$ vertex and the primary vertex.
- B Prob : B vertex probability.
- $K_s^0$ Prob : $K_s^0$ vertex probability.
- J/$\psi$ $p_T$ : Transverse momentum of J/$\psi$ candidate.
- $K_s^0$ $p_T$ : Transverse momentum of $K_s^0$ candidate.
- B pvips : Impact parameter significance of B candidate.
- B eta ($\eta_B$) : $\eta$ of B candidate.
- $K_s^0\alpha_{xy}$ : Angle between vector joining $B_s^0$ and $K_s^0$ vertices and $K_s^0$ momentum

# Efficiency




Efficiency plot for $B_s^0$

Efficiency plot for $B^0$