Measurement of the CP-violating phase ϕ_s in the $B_s^0 \to J/\psi\,\phi(1020)$ channel at 13 TeV by CMS

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Introduction

Motivations

$$
\begin{tikzcd}
B_s^0 \arrow[dr, "\phi_{decay}"] \arrow[dd, leftrightarrow, "\phi_{mix}"'] & \\
& J/\psi\,\phi(1020) \\
\overline{B}_s^0 \arrow[ur, "-\phi_{decay}"'] &
\end{tikzcd}
$$

$$\boxed{\phi_s = \phi_{mix} - 2\phi_{decay}}$$

- $\boldsymbol{\phi_s}$: CPV phase arising from interference between direct decays to a CP final state and decays through B_s^0-$\overline{B}_s^0$ mixing
- **SM prediction**: $\phi_s \simeq -2\beta_s = -36.96^{+0.72}_{-0.84}$ mrad [CKMfitter]
    - $\beta_s = \arg\left(-V_{ts}V_{tb}^{*}/V_{cs}V_{cb}^{*}\right)$ is one of the angles of the unitary triangle
- New Physics can change the value of ϕ_s up to ~10 % via new particles contributing to the B_s^0-$\overline{B}_s^0$ mixing [JHEP04(2010)031]
- Current results agree with the SM, but the experimental uncertainty is much higher than the theoretical one
- $\boldsymbol{B_s^0 \rightarrow J/\psi\,\phi(1020)}$ **is a good channel to measure** $\boldsymbol{\phi_s}$**:**
    - No direct CPV
    - Only one CPV phase
    - Easy to reconstruct with high S/B ratio
- **Several other interesting observables** can be measured in the same analysis: Γ_s, $\Delta\Gamma_s$, Δm_s, $|\lambda| = \left|\frac{q}{p}\frac{\overline{A}_f}{A_f}\right|$

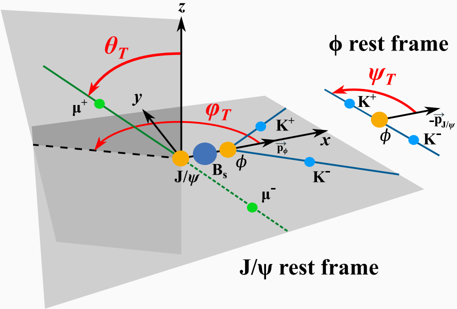
Overview

Angular analysis

- The final state is **not a single CP eigenstate**
- **Time-dependent angular analysis** is needed to disentagle CP-odd and CP-even components in the final state

Needed informations:

- **Angular variables:**
  - **ψ_T:** helicity angle of K^+ in the ϕ rest frame
  - **θ_T:** polar angle of μ^+ in the J/ψ rest frame
  - **φ_T:** azimuthal angle of μ^+ in the J/ψ rest frame
- **Proper decay time** of the meson
  - **Proper decay time uncertainty** is evaluated in each event
- **Accurate flavour tagging** to infer the initial flavour of the B_s^0 meson (the terms most sensitive to ϕ_s in the decay rate depend on this information)



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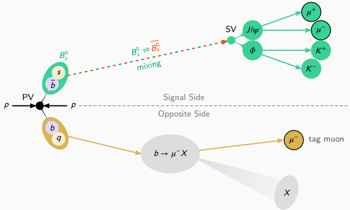
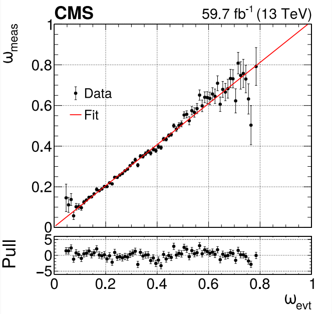
Flavour tagging

- The angular analysis needs an accurate estimation of the initial flavour of the B_s^0 meson
- **Chosen algorithm**: opposite-side (OS) muon
- Exploits **$b \rightarrow \mu X$** decays of the other b in the event
- **Developed** using simulated $B_s^0 \rightarrow J/\psi\ \phi(1020)$ events
- **Mistag probability evaluated on a per-event basis** using a dedicated Neural Network
- The output is **calibrated** in data using $B^{\pm} \rightarrow J/\psi\ K^{\pm}$ self-tagging decays
- The average mistag is found to be ~27 %





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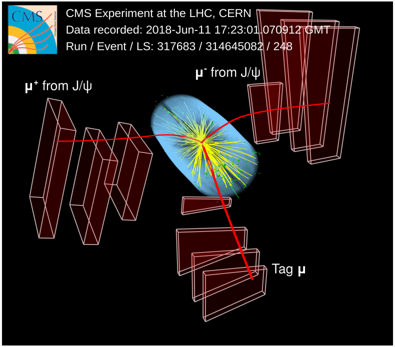
Trigger strategy

A new trigger strategy is developed to enhance tagging efficiency $\epsilon_{tag} = \left(\frac{N_{tagged}}{N_{events}}\right)$

Trigger: $J/\psi \rightarrow \mu^+\mu^-$ candidate plus an additional μ

- The additional muon is used to tag the B_s^0 flavour
- This trigger allows for an **improved tagging efficiency** in the sample, at the cost of a **reduced number of selected signal events**
- The luminosity for this analysis is **96.4 fb^{-1}**, ~ 5 times that of the Run 1 analysis, but the **number of events is similar**
- Thanks to this trigger the tagging efficiency is ~50 %



Maximum likelihood fit and results

Fit model

Event pdf: $P = N_{sig}P_{sig} + N_{bkg}P_{bkg} + N_{peak}P_{peak}$

$$P_{sig} = \epsilon(ct)\,\epsilon(\Theta)\,[\mathcal{F}(\Theta, ct, \alpha) \otimes G(ct, \sigma_{ct})]\,P_{sig}(m_{B_s^0})P_{sig}(\sigma_{ct})\,P_{sig}(\xi)$$

- $\epsilon(ct)\,\epsilon(\Theta)$: efficiency functions
- $\mathcal{F}(\Theta, ct, \alpha)$: differential decay rate
- $G(ct, \sigma_{ct})$: gaussian resolution model
- $P_{sig}(m_{B_s^0})$: signal mass pdf
- $P_{sig}(\sigma_{ct})$: signal σ_{ct} pdf
- $P_{sig}(\xi)$: tag distribution

$$P_{bkg} = P_{bkg}(\Theta)P_{bkg}(ct)P_{bkg}(m_{B_s^0})P_{bkg}(\sigma_{ct})\,P_{bkg}(\xi)$$

- $P_{bkg}(\Theta)P_{bkg}(ct)$: background angular and lifetime PDFs

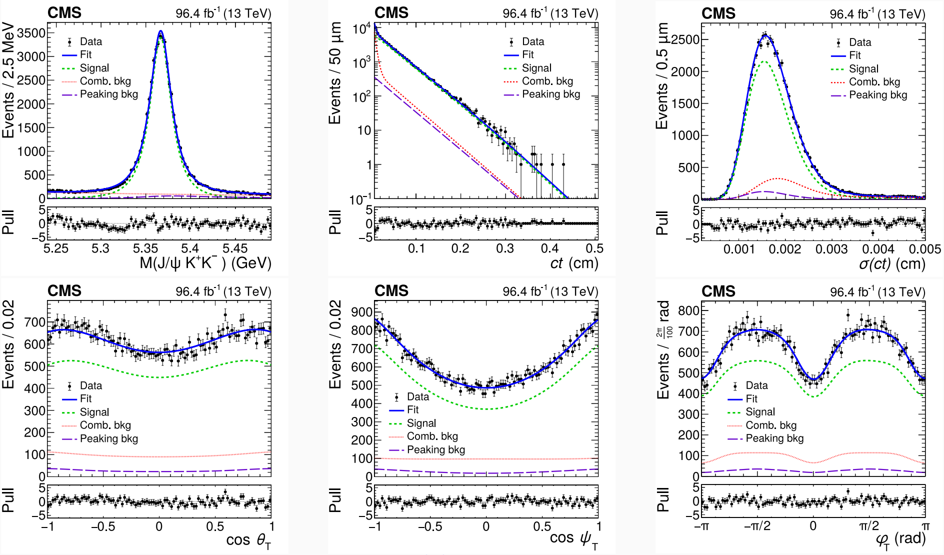
$$P_{peak} = P_{peak}(\Theta)P_{peak}(ct)P_{peak}(m_{B_s^0})P_{peak}(\sigma_{ct})\,P_{peak}(\xi)$$

- P_{peak} models the **peaking background** from $B^0 \to J/\psi\, K^{*0} \to \mu^+\mu^-\, K^\pm\pi^\mp$ where the π is reconstructed as a K
- Background from $\Lambda_b \to J/\psi K^\pm p^\mp$ is estimated to be negligible

Maximum likelihood fit

- The model parameters are estimated using an **unbinned maximum likelihood fit**
- **Input observables:** $\cos\theta_T$, $\cos\psi_T$, φ_T, ct, $\sigma(ct)$, $m_{B_s^0}$, tag decision, ω_{tag}
- **Physics parameters:** ϕ_s, $\Delta\Gamma_s$, Γ_s, Δm_s, $|\lambda|$, $|A_0|^2$, $|A_\perp|^2$, $|A_S|^2$, $\delta_\parallel$, $\delta_\perp$, $\delta_{S\perp}$

Fit results: 1D projections



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Systematic uncertainties

	ϕ_s [mrad]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [$\hbar$ps^{-1}]	$\lvert\lambda\rvert$	Γ_s [ps^{-1}]	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	$\lvert A_S\rvert^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	$\delta_{S\perp}$ [rad]
Model bias	**7.9**	0.0019	—	0.0035	0.0005	0.0002	0.0012	0.001	0.020	0.016	0.006
Angular efficiency	**3.8**	0.0006	0.007	**0.0057**	0.0002	0.0008	0.0010	0.002	0.006	0.015	0.015
Proper decay length efficiency	0.3	**0.0062**	0.001	0.0002	**0.0022**	0.0014	0.0023	0.001	0.001	0.002	0.002
Proper decay length resolution	2.5	0.0008	**0.015**	0.0009	0.0005	0.0007	0.0009	0.007	0.006	0.025	0.022
Data/simulation difference	0.6	0.0008	0.004	0.0003	0.0003	0.0044	0.0029	0.007	0.007	0.007	0.028
Flavor tagging	0.1	$<10^{-4}$	0.001	0.0002	$<10^{-4}$	0.0003	$<10^{-4}$	$<10^{-3}$	0.001	0.003	0.001
Sig./bkg. ω_{evt} difference	3.0	—	—	—	0.0005	—	0.0008	—	—	—	0.006
Model assumptions	—	0.0008	—	**0.0046**	0.0003	—	0.0013	0.001	0.017	0.019	0.011
Peaking background	0.3	0.0008	**0.011**	$<10^{-4}$	0.0002	0.0005	0.0002	0.003	0.005	0.007	0.011
S-P wave interference	—	0.0010	0.019	—	0.0005	0.0005	—	0.013	—	0.019	0.019
Total systematic uncertainty	9.6	0.0067	0.028	0.0082	0.0024	0.0048	0.0044	0.016	0.028	0.045	0.047

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In red are the leading systematic uncertainties for the main parameters:

- $\boldsymbol{\phi_s}$: model bias and angular efficiency
- $\boldsymbol{\Delta\Gamma_s, \Gamma_s}$: lifetime efficiency
- $\boldsymbol{\Delta m_s}$: lifetime resolution and peaking background
- $\boldsymbol{\lvert\lambda\rvert}$: angular efficiency and model assumption

Results

Parameter	Fit value	Stat. uncer.	Syst. uncer.
ϕ_s [mrad]	**−11**	**± 50**	**± 10**
$\Delta\Gamma_s$ [ps^{-1}]	**0.114**	**± 0.014**	**± 0.007**
Δm_s [$\hbar$ps^{-1}]	**17.51**	**$^{+0.10}_{-0.09}$**	**± 0.03**
Γ_s [ps^{-1}]	**0.6531**	**± 0.0042**	**± 0.0024**
$\lvert\lambda\rvert$	**0.972**	**± 0.026**	**± 0.008**
$\lvert A_0\rvert^2$	0.5350	± 0.0047	± 0.0048
$\lvert A_\perp\rvert^2$	0.2337	± 0.0063	± 0.0044
$\lvert A_S\rvert^2$	0.022	$^{+0.008}_{-0.007}$	± 0.016
$\delta_\parallel$ [rad]	3.18	± 0.12	± 0.03
$\delta_\perp$ [rad]	2.77	± 0.16	± 0.04
$\delta_{S\perp}$ [rad]	0.221	$^{+0.083}_{-0.070}$	± 0.048

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- **ϕ_s and $\Delta\Gamma_s$ are in agreement with the SM (CKMfitter, arXiv:1912.07621):**

$$\phi_s^{SM} = -36.96^{+0.72}_{-0.84} \text{ mrad}$$

$$\Delta\Gamma_s^{SM} = 0.091 \pm 0.013 \text{ ps}^{-1}$$

- **Γ_s and Δm_s are consistent with the world average (Phys. Rev. D 98 (2018) 030001):**

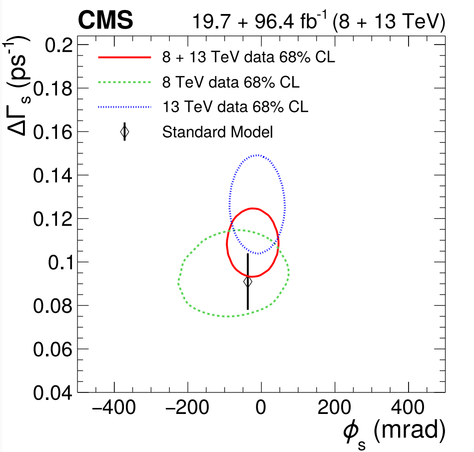
$$\Gamma_s^{WA} = 0.6624 \pm 0.0018 \text{ ps}^{-1}$$

$$\Delta m_s^{WA} = 17.757 \pm 0.021\ \hbar\text{ps}^{-1}$$

- **$\lvert\lambda\rvert$ is consistent with no direct CP violation ($\lvert\lambda\rvert = 1$)**
- **This is the first measurement by CMS of Δm_s and $\lvert\lambda\rvert$**

Combination with 8 TeV results

- The results are **combined** with those from the previous analysis at $\sqrt{s}$ = 8 TeV (Phys. Lett. B 757 (2016) 97)



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- The combination is in agreement with the SM

$$\boldsymbol{\phi_s = -21 \pm 45\,\mathrm{mrad}}$$

$$\boldsymbol{\Delta\Gamma_s = 0.1073 \pm 0.0097\,\mathrm{ps}^{-1}}$$

- ϕ_s uncertainty is greatly improved thanks to the increase in tag accuracy due to the new trigger strategy
- $\Delta\Gamma_s$ on the other hand is not sensitive to the tagging performance and its precision is similar in the two analyses

Conclusions

Summary

- The **CPV phase ϕ_s** and the **decay width difference $\Delta\Gamma_s$** are measured using 48500 $B_s^0 \rightarrow J/\psi\,\phi(1020) \rightarrow \mu^+\mu^-K^+K^-$ signal events, collected by CMS at $\sqrt{s} = 13\,\text{TeV}$, corresponding to $\mathcal{L}_{\text{int}} = 96.4\,\text{fb}^{-1}$
- A **novel** opposite-side muon tagger based on deep neural networks has been developed to directly predict the mistag probability on per-event basis, leading to improved precision in the ϕ_s measurement
- The results are **combined** with those from the $\sqrt{s} = 8\,\text{TeV}$ analysis, yielding

$$\boldsymbol{\phi_s = -21 \pm 45\,\text{mrad}}$$

$$\boldsymbol{\Delta\Gamma_s = 0.1073 \pm 0.0097\,\text{ps}^{-1}}$$

- Results are consistent with the **Standard Model** predictions:

$$\phi_s^{SM} = -36.96^{+0.72}_{-0.84}\,\text{mrad} \qquad \Delta\Gamma_s^{SM} = 0.091 \pm 0.013\,\text{ps}^{-1}$$

- Article CMS-BPH-20-001 is available at arXiv:2007.02434

Outlook

Comparison with other LHC experiments in the $B_s^0 \to J/\psi\,\phi(1020)$ channel

	ϕ_s [mrad]	$\Delta\Gamma_s$ [ps^{-1}]	Reference
CMS	-21 ± 45	0.1073 ± 0.0097	CMS-BPH-20-001
ATLAS	-87 ± 41	0.0641 ± 0.0049	CERN-EP-2019-218
LHCb	-81 ± 32	0.0777 ± 0.0062	EUR.PHYS.J.C79(2019)706
SM	$-36.96^{+0.72}_{-0.84}$	0.091 ± 0.013	CKMfitter, arXiv:1912.07621

Future plans

- CMS plans to analyze the **full Run-2 dataset**, adding a complementary trigger that requires a displaced J/ψ plus two charged tracks
    - To achieve an even better tagging performance an electron- and jet-based taggers will be used together with the current muon-based one
- The precision in the measurement is expected to improve by 30 % for ϕ_s and by a factor ~ 2 for $\Delta\Gamma_s$

Thanks for your attention!

BACKUP

Decay rate model

$$\boxed{\frac{d^4\Gamma(B_s^0(t))}{d\Theta dt} = \mathcal{F}(\Theta, t, \alpha) = \sum_{i=1}^{10} \mathcal{O}_i(\alpha, t) \cdot g_i(\Theta)}$$

$$\mathcal{O}_i = N_i e^{-t/\tau}\left[a_i \cosh\left(\frac{1}{2}\Delta\Gamma_s t\right) + b_i \sinh\left(\frac{1}{2}\Delta\Gamma_s t\right) + c_i \xi(1-2\omega)\cos(\Delta m_s t) + d_i \xi(1-2\omega)\sin(\Delta m_s t)\right]$$

i	$g_i(\theta_T, \psi_T, \varphi_T)$	N_i	a_i	b_i	c_i	d_i
1	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_0\rvert^2$	1	D	C	$-S$
2	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\varphi_T)$	$\lvert A_\parallel\rvert^2$	1	D	C	$-S$
3	$\sin^2\psi_T\sin^2\theta_T$	$\lvert A_\perp\rvert^2$	1	$-D$	C	S
4	$-\sin^2\psi_T\sin 2\theta_T\sin\varphi_T$	$\lvert A_\parallel\rvert\lvert A_\perp\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\varphi_T$	$\lvert A_0\rvert\lvert A_\parallel\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\cos\varphi_T$	$\lvert A_0\rvert\lvert A_\perp\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_S\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\varphi_T$	$\lvert A_S\rvert\lvert A_\parallel\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\varphi_T$	$\lvert A_S\rvert\lvert A_\perp\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_S\rvert\lvert A_0\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2}, \qquad S = -\frac{2|\lambda|\sin\phi_s}{1+|\lambda|^2}, \qquad D = -\frac{2|\lambda|\cos\phi_s}{1+|\lambda|^2}, \qquad \lambda = \frac{q}{p}\frac{\bar{A}_f}{A_f}.$$

Conventions: $|A_\parallel|^2 = 1 - |A_0|^2 - |A_\perp|^2$, $\delta_{S\perp} = \delta_S - \delta_\perp$, $\delta_0 = 0$.

Lifetime efficiency

- The reconstruction efficiency is **not** independent from the decay length
- To accurately model the signal PDF we need to parametrize this effect
- Efficiency is evaluated in simulated samples and fitted separately for the two years of data taking
- Fit function is $\epsilon(ct) = e^{-a \cdot ct} \cdot \mathrm{Chebyshev4}(ct)$

Angular efficiency

- Angular efficiency is first evaluated on a 3D grid
  - Numerator from a simulated $\Delta\Gamma_s = 0$ sample where we applied the full reconstruction
  - Denominator from a special GEN-only sample
  - the grid has 70 bins in $\cos\theta_T$ and $\cos\psi_T$, 30 in φ_T
- Efficiency histogram is projected on an orthornomal basis, defined as

$$b_{lkm}(\Theta) = P_l^m(\cos\theta_T) \cdot P_k^m(\cos\psi_T) \cdot \begin{cases} \sin(m\varphi_T) & \text{if } m < 0 \\ \cos(m\varphi_T) & \text{if } m > 0 \\ 1/2 & \text{if } m = 0 \end{cases}$$

- P_l^m are the Legendre polynomials
- k and l are allowed to go up to order 6
- efficiency is

$$\epsilon(\Theta) = \sum_{l,k,m} c_{lkm} b_{lkm}(\Theta)$$

where c_{lkm} is the projection coefficient

S/P wave interfence

- The fit model does not take into account the difference in the invariant mass dependence between the P-wave from the $B_s^0 \to J/\psi\, \phi(1020)$ decay and the S-wave
- This adds an additional factor k_{SP} to their interference
- The k_{SP} factor is computed by integrating the P and S-wave interference term in the ϕ candidate mass range, assuming that the P-wave amplitude is describedby a relativistic Breit–Wigner distribution and the S-wave amplitude by a constant, and found to be $k_{SP} = 0.54$
- The systematic is evaluated generating 1000 pseudo-experiments using the model with the correct factor and fitting each of them with the main model
- For each fit the pull is evaluated
- The distribution of the pulls is fitted to a gaussian
- The mean of the gaussian, if significantly different from 0 (1-sigma) is used to compute the systematic error
- The error was found to have little effects in all parameters save for the S-wave strong phase and amplitude