Study of exclusive decays of $B_s \to \psi(1S,2S)K_s$ and $B_s \to \eta_c(1S,2S)K_s$ in the framework of Relativistic Independent Quark Model

(Based on- arXiv:2404.14267v2 [hep-ph])
(Accepted by Phys. Rev. D)

17TH INTERNATIONAL CONFERENCE ON INTERCONNECTIONS BETWEEN PARTICLE PHYSICS AND COSMOLOGY

PPC 2024

14 -18 October 2024, Hyderabad, India

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राष्ट्रीय विज्ञान शिक्षा एवं अनुसंधान संस्थान
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భారతీయ సాంకేతిక విజ్ఞాన సంస్థ హైదరాబాద్
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Outline

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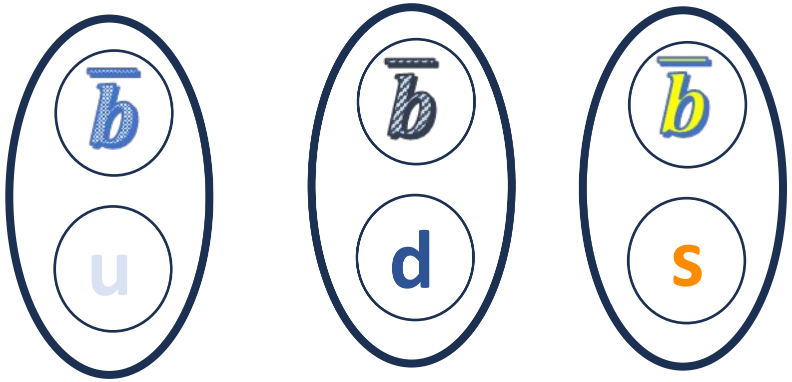
Introduction



- Heavy ~ (5-6) GeV
- Long lifetime ~1.5 ps.
- B mesons decay via weak interactions
- Involve in flavor changing processes
- CP violating effects

Motivation

- B_s meson is involved in rare decay processes.
- The B_s mesons show the effect of mixing.
- This oscillation from matter to antimatter can be used to measure fundamental parameters of the Standard Model.
- In addition, it is closely related to CP violation and might have far reaching effects, such as the matter-antimatter asymmetry observed in the universe.
- $B_s \rightarrow J/\psi K_s$ is used as the control channel to handle phase shift $\Delta\varphi_d$.
- The decay $B_d \rightarrow J/\psi K_s$ is considered as the "golden mode" for measuring the CKM angle sin 2β.
- The decay $B_s \rightarrow J/\psi K_s$ is related to $B_d \rightarrow J/\psi K_s$ through the U-spin symmetry of strong interaction.

Literature

Extracting γ from $B(s/d) \to J/\psi K_S$ and $B(d/s) \to D^+(d/s)D^-(d/s)$ #6

Robert Fleischer (CERN) (Mar, 1999)

Published in: *Eur.Phys.J.C* 10 (1999) 299-306 • e-Print: hep-ph/9903455 [hep-ph]

itations

Penguin Effects in $\phi_{d,s}$ Determinations #1

Robert Fleischer (NIKHEF, Amsterdam and Vrije U., Amsterdam) (Dec, 2012)

Contribution to: CKM 2012 • e-Print: 1212.2792 [hep-ph]

e search   8 citations

A Roadmap to Control Penguin Effects in $B_d^0 \to J/\psi K_S^0$ and $B_s^0 \to J/\psi\phi$ #1

Kristof De Bruyn (NIKHEF, Amsterdam), Robert Fleischer (NIKHEF, Amsterdam and Vrije U., Amsterdam) (Dec 21, 2014)

Published in: *JHEP* 03 (2015) 145 • e-Print: 1412.6834 [hep-ph]

pdf   DOI   cite   claim   reference search   93 citations

Literature

Observation of $B_s^0 \to J/\psi K^{*0}(892)$ and $B_s^0 \to J/\psi K_S^0$ Decays

CDF Collaboration • T. Aaltonen (Helsinki Inst. of Phys.) Show All(514)

Feb 2011

Measurement of the $B_s^0 \to J/\psi K_S^0$ branching fraction

LHCb Collaboration • R Aaij (NIKHEF, Amsterdam) Show All(596)

Measurement of the time-dependent CP asymmetries in $B_s^0 \to J/\psi K_S^0$

LHCb Collaboration • Roel Aaij (NIKHEF, Amsterdam) Show All(703)

Measurement of the effective $B_s^0 \to J/\psi K_S^0$ lifetime

LHCb Collaboration • R Aaij (NIKHEF, Amsterdam) Show All(632)

Apr 16, 2013

Eur. Phys. J. C (2022) 82:499
https://doi.org/10.1140/epjc/s10052-022-10315-y

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

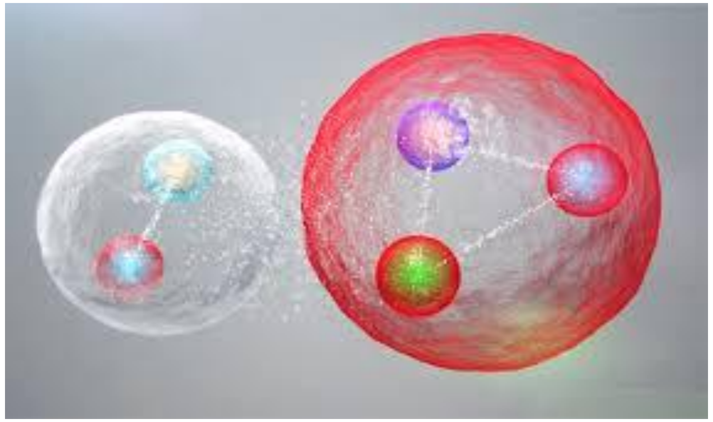
Observation of $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ and $B_s^0 \to \psi(2S)K_S^0$ decays

CMS Collaboration*
CERN, 1211 Geneva 23, Switzerland

Relativistic Independent Quark(RIQ) Model

- ***In this model a hadron is considered as a colour singlet core of relativistic independent quark and antiquark, surrounded by cloud of pions.***
- ***The quark constituents in this model are believed to interact with the potential in the form :***

$$U(r) = \frac{1}{2}(1 + \Upsilon_0)(ar^2 + V_0)$$



- ***The potential represents phenomenologically the confining interaction expected in QCD to be generated by non-perturbative multigluon mechanism.***

We incorporate this interaction potential in the lagrangian density to obtain in the form :

$$\pounds = \overline{\psi_q}[\frac{1}{2}i\Upsilon^{\mu}\partial_{\mu} - U(r) - m_q]\,\psi_q(r)$$

The Dirac Equation:

$$(\alpha.p + \beta m_q + U(r))\psi_q(r) = E\,\psi_q(r)$$

where, $\alpha = \frac{\Upsilon_i}{\Upsilon_0}$ and $\beta = \Upsilon_0$

Solving the Dirac equations we get positive and negative energy solutions known as quark and antiquark orbitals respectively in the general form:

$$\boldsymbol{\psi^{+}_{nlj}(\vec{r})} = \begin{pmatrix} \dfrac{i g_{nlj}(r)}{r} \\ \overrightarrow{(\sigma.\hat{r})}\,\dfrac{f_{nlj}(r)}{r} \end{pmatrix} \varphi_{ljm_j}(\hat{r}) \qquad \boldsymbol{\psi^{-}_{nlj}(\vec{r})} = \begin{pmatrix} i\vec{\sigma}.\dfrac{\hat{r}\, f_{nj}(r)}{r} \\ g_{nlj}(r)/r \end{pmatrix} (-1)^{j+m_j-l}\, \varphi_{ljm_j}(\hat{r})$$

Where ,

$$g_{nlj}(r) = \mathrm{N_q} \left(\frac{r}{r_{nl}}\right)^{l+1} e^{-r^2/2r_{nl}^2}\; L_{n-1}^{l+1/2}\left(\frac{r^2}{r_{nl}^2}\right)$$

and $f_{nlj}(r) = -\mathrm{N_q}\, \frac{1}{r_{nl}\lambda_{nl}} \left(\frac{r}{r_{nl}}\right)^{l+2} e^{-r^2/2r_{nl}^2}\; \left[\, L_{n-2}^{l+3/2}\left(\frac{r^2}{r_{nl}^2}\right) + L_{n-1}^{l+3/2}\left(\frac{r^2}{r_{nl}^2}\right) \right]$

MOMENTUM PROBABILITY AMPLITUDE

- For n=1 and l=0 (ground state)
- $G_s(\overrightarrow{p_s}) = \frac{i\pi N_s}{2\alpha_s\lambda_s}\sqrt{\frac{(E_{p_s}+m_s)}{E_{p_s}}}(E_{p_s}+E_s)exp\left(-\frac{\overrightarrow{p_s}^2}{4\alpha_s}\right)$

- $\tilde{G}_b(\overrightarrow{p_b}) = \frac{i\pi N_b}{2\alpha_b\lambda_b}\sqrt{\frac{(E_{p_b}+m_b)}{E_{p_b}}}(E_{p_b}+E_b)exp\left(-\frac{\overrightarrow{p_b}^2}{4\alpha_b}\right)$

Using the momentum probability amplitudes for quarks and antiquarks we construct the momentum profile function for the meson state as:

$$\mathcal{G}_{B_s}(\vec{p}_b, \vec{p}_s) = \sqrt{\tilde{G}_b(\vec{p}_b)G_s(\vec{p}_s)}$$

MOMENTUM DISTRIBUTION FUNCTION

MESON STATE AND MESON NORMALIZATION

The meson state at definite momentum $\vec{P}$ and spin projection S_{B_s} is taken as:

$| B_s(\vec{P}, S_{B_s}) \rangle = \hat{\Lambda}_{Bs} (\vec{P}, S_{B_s}) \; | (\vec{p_b}, \lambda_b);(\vec{p_s}, \lambda_s) \rangle$

where $| (\vec{p_b}, \lambda_b); (\vec{p_s}, \lambda_s)\rangle = \tilde{b}_b^{\dagger}(\vec{p_b}, \lambda_b)\hat{b}_s^{\dagger}(\vec{p_s}, \lambda_s) \, |0\rangle$

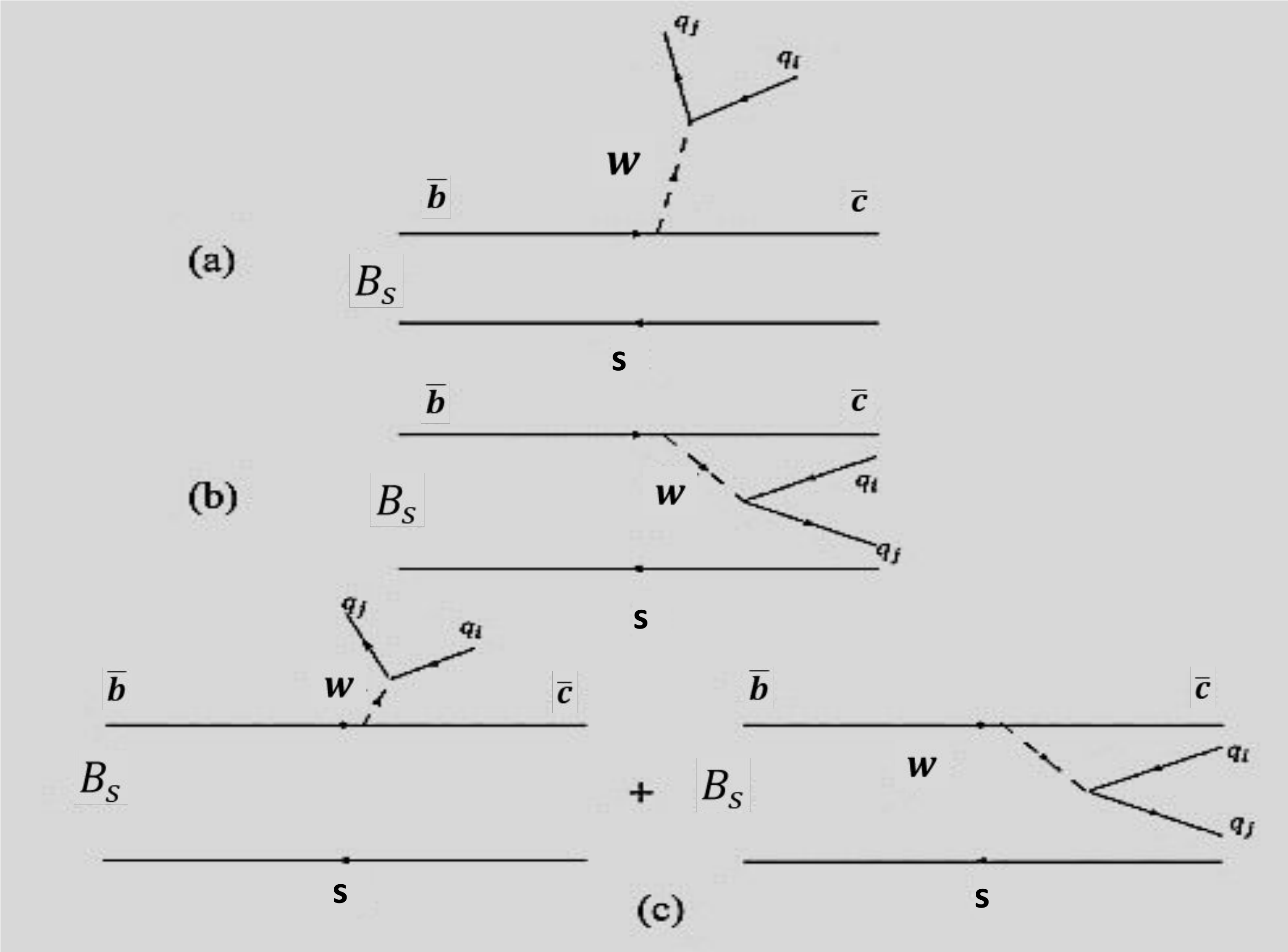
$$\hat{\Lambda}_{B_s}(\vec{P},S_{B_s}) = \frac{\sqrt{3}}{\sqrt{N_{B_s}(\vec{P})}} \sum_{\delta_b,\delta_s} \varsigma_{b,s}^{B_s} \, (\lambda_b,\lambda_s) \int d^3\vec{p_b} \, d^3\vec{p_s} \;\; \delta^{(3)}\left(\vec{p}_b + \vec{p}_s - \vec{P}\right) \mathcal{G}_{B_s}(\vec{p}_b,\vec{p}_s)$$

Imposing Normalisation condition

$$\left\langle B_s\left(\vec{P'}\right) \middle| B_s(\vec{P})\right\rangle = \delta^3(\vec{P} - \vec{P}')$$

Where $N(\vec{P}) = \int d\vec{p_b} \;\; | \, G(\vec{p}_b \, , \vec{P} - \vec{p}_b \,)|^2$

FEYNMAN DIAGRAM

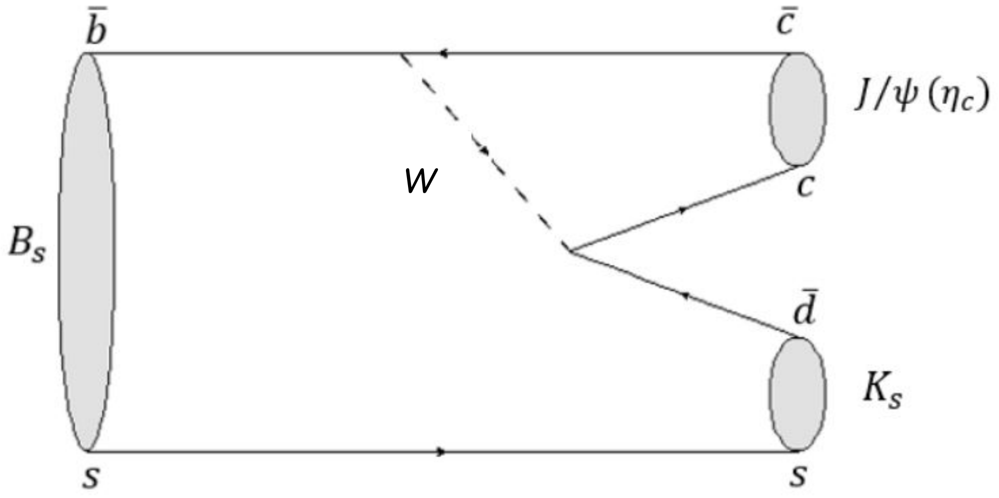


⇨ Class I

⇨ Class II

⇨ Class III

$B_s \to \psi(1S,2S) K_s$ and $B_s \to \eta_c(1S,2S) K_s$



$$\langle m_1 m_2 | \mathcal{H}_{\text{eff}} | M \rangle = \frac{G_F}{\sqrt{2}} V_{q_{1(2)} q'_{1(2)}} V_{q_3 q'_3} [a_1(\mu) \langle m_2 | J^\mu | 0 \rangle \langle m_1 | J_\mu | M \rangle + a_2(\mu) \langle m_1 | J^\mu | 0 \rangle \langle m_2 | J_\mu | M \rangle],$$

The nonvanishing part of the matrix elements of the current J^μ between the vacuum and final meson states in covariant form are parameterized by meson decay constants $f_{P,V}$

$$\langle P | \bar{q}'_i \gamma^\mu \gamma_5 q_j | 0 \rangle = i f_P p_P^\mu$$

$$\langle V | \bar{q}'_i \gamma^\mu q_j | 0 \rangle = e^{*\mu} f_V m_V$$

$$\langle P(p_P) | \bar{q}_c \gamma_\mu q_b | B_s(p) \rangle = \left[(p + p_P)_\mu - \frac{M^2 - m_P^2}{q^2} q_\mu \right] F_1(q^2) + \frac{M^2 - m_P^2}{q^2} q_\mu F_0(q^2) = (p + p_P)_\mu f_+(q^2) + (p - p_P)_\mu f_-(q^2),$$

FORM FACTOR EXPRESSION

$$f_{\pm}(q^2) = \frac{1}{2}\int d\vec{p}_b C(\vec{p}_b)\left\{ \left[E_b(\vec{p}_b) + m_b\right]\left[E_d(\vec{p}_b + \vec{k}) + m_d\right] + \vec{p}_b^{\,2} \pm \left[E_b(\vec{p}_b) + m_b\right]\left[M \mp E_{P_1}\right] \right\}$$

$$C(\vec{p}_b) = \frac{\mathcal{G}_{B_s}(\vec{p}_b, -\vec{p}_b)\mathcal{G}_{K_s}(\vec{p}_b + \vec{k}, -\vec{p}_b)}{\sqrt{N_{B_s}(0)N_{K_s}(\vec{k})}}$$

$$\sqrt{\frac{\left[E_b(\vec{p}_b) + E_s(-\vec{p}_b)\right]\left[E_d(\vec{p}_b + \vec{k}) + E_s(-\vec{p}_b)\right]}{E_b(\vec{p}_b)E_d(\vec{p}_b + \vec{k})\left[E_b(\vec{p}_b) + m_b\right]\left[E_d(\vec{p}_b + \vec{k}) + m_d\right]}}$$

Decay Width

$B_s \to \eta_c K_s$

$$\Gamma(B_s \to \eta_c K_s) = \frac{|\vec{k}|}{8\pi M^2}|A_1|^2|F_0(q^2)|^2$$

$$|A_1| = \frac{G_F}{\sqrt{2}} V_{bc} V_{cd} a_2 (M^2 - m_{K_s}^2) f_{\eta_c}$$

$$F_0(q^2) = \left[\frac{q^2}{(M^2 - m_{K_s}^2)}\right] f_-(q^2) + f_+(q^2)$$

$B_s \to J/\psi K_s$

$$\Gamma(B_s \to J/\psi K_s) = \frac{|\vec{k}|^3}{8\pi m_{J/\psi}^2}|A_2|^2|F_1(q^2)|^2$$

$$|A_2| = \frac{G_F}{\sqrt{2}} V_{bc} V_{cd} 2 a_2 m_{J/\psi} f_{J/\psi}$$

$$F_1(q^2) = f_+(q^2) = \frac{1}{2}\int d\vec{p}_b C(\vec{p}_b) \left\{ [E_b(\vec{p}_b) + m_b][E_d(\vec{p}_b + \vec{k}) + m_d] + \vec{p}_b^{\,2} + [E_b(\vec{p}_b) + m_b][M - E_P] \right\}$$

Numerical Analysis

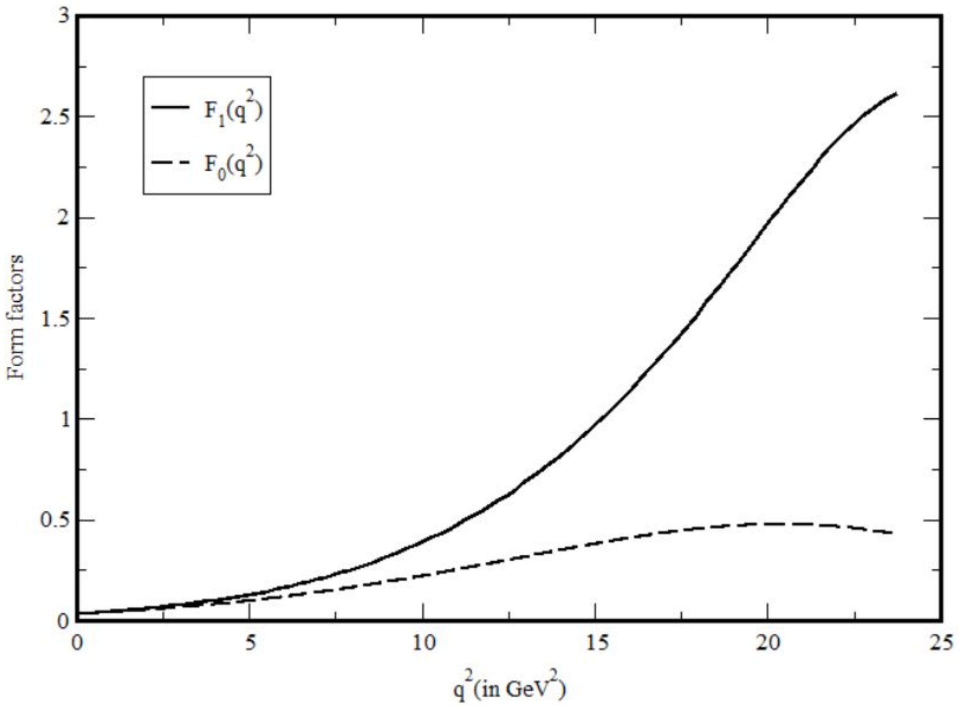
INPUT PARAMETERS

For ground state we take the quark masses, corresponding binding energies and potential parameters:

$(a, V_0) \equiv (0.017166\ GeV^3, -0.1375\ GeV)$

$$m_d = 0.07875 \qquad E_d = 0.47125$$
$$m_s = 0.31575 \qquad E_s = 0.591$$
$$m_c = 1.49275 \qquad E_c = 1.57951$$
$$m_b = 4.77659 \qquad E_b = 4.76633$$

RESULTS



Decays	Our work	Exp. results
$B_s \to J/\psi K_s$	$2.023^{+0.325}_{-0.295}$	1.92 ± 0.14[PDG]
$B_s \to \eta_c K_s$	$1.192^{+0.184}_{-0.162}$	-
$B_s \to \psi(2S) K_s$	$0.515^{+0.89}_{-0.506}$	$0.97 \pm 0.20(stat) \pm 0.03(syst)$ $\pm 0.22(\frac{f_s}{f_d})$[CMS2022]
$B_s \to \eta_c(2S)$	$0.0573^{+0.0638}_{-0.0375}$	-

(BF in 10^{-5})

$\mathcal{R}$	Our Result	Exp. Result
$\frac{\mathcal{B}(B_s \to J/\psi K_s)}{\mathcal{B}(B_d \to J/\psi K_s)}$	$0.0454^{+0.006}_{-0.0057}$	$0.0431 \pm 0.0017\ (stat) \pm 0.0012\ (syst) \pm 0.0025$[LHCb2015]
$\frac{\mathcal{B}(B_s \to \psi(2S) K_s)}{\mathcal{B}(B_d \to \psi(2S) K_s)}$	$0.0177^{+0.0269}_{-0.0173}$	$0.033 \pm 0.0069\ (stat) \pm 0.0011 (syst)$[CMS2022]

Summary

- The resulting BFs of $B_s \to \psi(1S,2S)K_s$ obtained from our work align with experimental results, as reported by the LHCb and CMS Collaboration.
- Our predictions for $B_s \to \eta_c(1S,2S)K_s$ will become a key reference for both experimentalists and theorists.
- To ensure thoroughness, additionally, we compute the ratio of BF of B_s to B_d for the same final states, $\psi(nS)$ with K_s.
- Our predictions in this analysis, achieved through a parameter-free unification within our model framework, aim to strengthen confidence in SM predictions and contribute to valuable discussions on the crucial B_s sector in flavor physics.

Thank You!

Back up

$$\langle P(p_P)|\bar{q}_c\gamma_\mu q_b|B_s(p)\rangle$$
$$= \left[(p+p_P)_\mu - \frac{M^2-m_P^2}{q^2}q_\mu\right]F_1(q^2) + \frac{M^2-m_P^2}{q^2}q_\mu F_0(q^2)$$
$$= (p+p_P)_\mu f_+(q^2) + (p-p_P)_\mu f_-(q^2),$$

$$f_+(q^2) = F_1(q^2)$$
$$f_-(q^2) = \frac{M^2-m_P^2}{q^2}\left[F_0(q^2) - F_1(q^2)\right]$$

Numerical Analysis

INPUTS

Mesons	Mass(in MeV) ★	Decay constant (in MeV)
B_s	5366.92 ± 0.10	-
K_s	497.61 ± 0.013	-
J/ψ	3096.9 ± 0.006	$418 \pm 8 \pm 5$ ★ (teal)
η_c	2983.9 ± 0.04	$387 \pm 7 \pm 2$ ★ (teal)
$\psi(2S)$	3686.1 ± 0.06	143 ± 81 ★ (orange)
$\eta_c(2S)$	3637.7 ± 1.1	$56 \pm 21 \pm 3$ ★ (orange)

★ PDG 2022

★ "Radiative transitions in charmonium from lattice QCD," Phys. Rev. D 73 (2006) 074507, arXiv:hep-ph/0601137.

★ "Charmonia decay constants from the QCD lattice and QCD sum rules," Nucl. Part. Phys. Proc. 273-275 (2016) 1611–1617

MESON	MESON MASS (GeV)	
	Prediction	**Experiment**
$D^{\pm *}$	2.0149	2.0101
$D^{\pm}$	1.8538	1.8694
$D_s^{\pm *}$	2.0731	2.1103
$D_s^{\pm}$	1.9149	1.9690
$B^{\pm *}$	5.3292	5.3246
$B^{\pm}$	5.2643	5.2786
$B_s^{0 *}$	5.3720	5.4256
B_s^{0}	5.3055	5.3786
$B_c^{\pm *}$	6.3142	-
$B_c^{\pm}$	6.2707	6.2749

Published by Barik and Dash

(i) *Phys.Rev.*D 33, 1925 (1986a)

(ii) Pramana-J. Phys.29(6), 543-557 (1987)