10th National Conference on Heavy Flavor and CP Violation

Implications on η-η'-glueball mixing from $B_{d/s} \to J\psi\eta^{(\prime)}$ decays

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Based on Phys. Rev. D 86, 011501(R) (2012)

Oct. 25-28, 2012

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- **Motivation and Introduction**
- **Mixing schemes**
- $B_{d/s} \to J\psi\eta^{(\prime)}$ **decays in pQCD approach**
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1. Motivation and Introduction

- **(Feb. 2012) Belle Collaboration reported the first observations of $B_s \to J/\psi\, \eta^{(\prime)}$ decays**

Phys. Rev. Lett. 108, 181808 (2012)

$$\mathrm{BR}(B_s \to J/\psi\, \eta)_{\mathrm{Exp}} = 5.10 \pm 0.50(\mathrm{stat}) \pm 0.25(\mathrm{syst})^{+1.14}_{-0.79}(N_{B_s^{(*)}\bar{B}_s^{(*)}}) \times 10^{-4},$$

$$\mathrm{BR}(B_s \to J/\psi\, \eta')_{\mathrm{Exp}} = 3.71 \pm 0.61(\mathrm{stat}) \pm 0.18(\mathrm{syst})^{+0.83}_{-0.57}(N_{B_s^{(*)}\bar{B}_s^{(*)}}) \times 10^{-4},$$

- **And the relation of the above two branching ratios reads**

$$\mathrm{R}_s^{Exp} = \frac{\mathrm{BR}(B_s \to J/\psi\, \eta')}{\mathrm{BR}(B_s \to J/\psi\, \eta)} = 0.73 \pm 0.14(\mathrm{stat}) \pm 0.02(\mathrm{syst}).$$

Phys. Rev. Lett. 108, 181808 (2012)

- **(Mar. 2012) Belle Collaboration updated their measurements of $B_d \to J/\psi\,\eta^{(\prime)}$ decays**

$$\mathrm{BR}\,(B_d \to J/\psi\,\eta)_{\mathrm{Exp}} = 12.3^{+1.9}_{-1.8} \times 10^{-6},$$

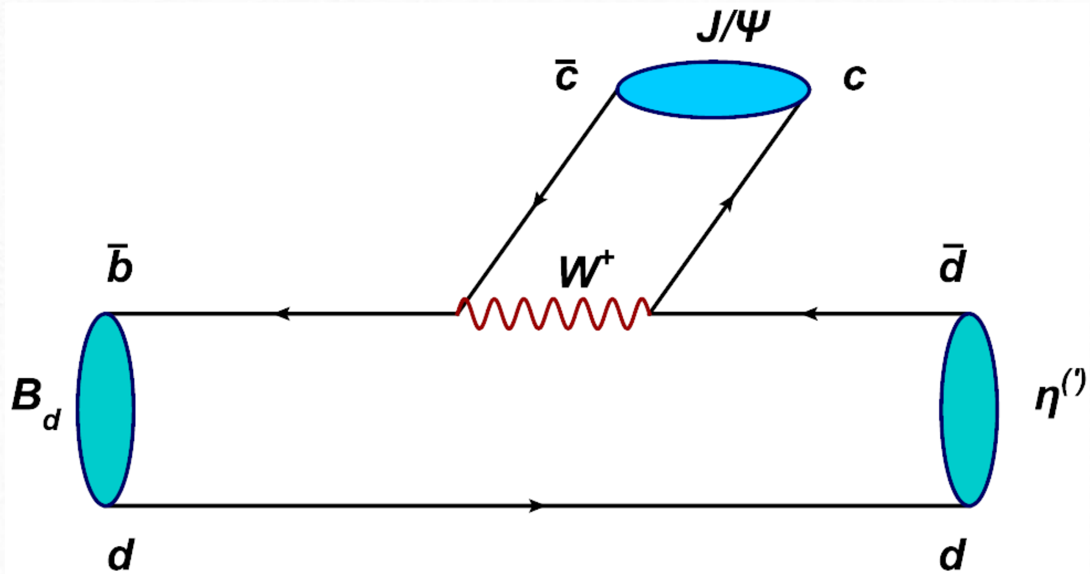
$$\mathrm{BR}\,(B_d \to J/\psi\,\eta')_{\mathrm{Exp}} < 7.4 \times 10^{-6}, \qquad (90\%\mathrm{C.L.})$$

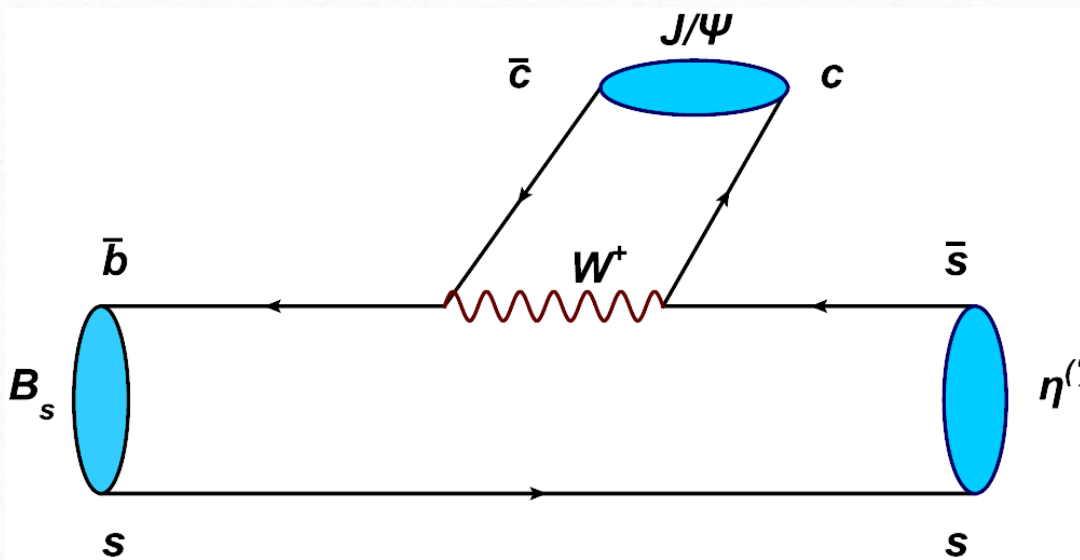
Phys. Rev. D 85, 091102(R) (2012)

- **The first measurement of $B_d \to J/\psi\,\eta$ decay was performed in 2006,**

$$\mathrm{BR}(B_d \to J/\psi\,\eta) = 9.5^{+1.9}_{-1.9} \times 10^{-6},$$

Phys. Rev. Lett. 98, 131803 (2007)





Leading quark-level diagrams for the $B_{d/s} \to J/\psi\, \eta^{(\prime)}$ decays.

The data indicate one point on the branching ratios of $B_{d/s} \to J/\psi\,\eta^{(\prime)}$ decays to be clarified.

$$R_d \equiv \frac{BR(B_d \to J/\psi\,\eta')}{BR(B_d \to J/\psi\,\eta)} \approx \tan^2\phi < 1,$$

$$R_s \equiv \frac{BR(B_s \to J/\psi\,\eta')}{BR(B_s \to J/\psi\,\eta)} \approx \cot^2\phi > 1.$$

Phys. Lett. B 529, 93 (2002), A. Datta *et al.*

Experimentally, the small measured ratio R_s^{Exp} indicates additional flavor-singlet components in the η' meson other than the $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ pairs, or violation of the η-η' mixing scheme.

Phys. Rev. Lett. 108, 181808 (2012)

Theoretically,

- **A. Deandrea** *et al.* Phys. Lett. B 318, 549 (1993)

  Firstly investigated $B_{d/s} \to J/\psi\, \eta^{(\prime)}$ decays without considering the eta-eta' mixing

- **P.Z. Skands** J. High Energy Phys. 01 (2001) 008

  Studied $B_{d/s} \to J/\psi\, \eta$ decays via SU(3) relation to $B_d \to J/\psi\, K^0$ including the eta-eta' mixing

$$\begin{cases} \mathrm{BR}(B_d \to J/\psi\, \eta) = 11.0 \times 10^{-6} \\ \mathrm{BR}(B_s \to J/\psi\, \eta) = 5.0 \times 10^{-4} \end{cases} \qquad \theta = -10^\circ$$

$$\begin{cases} \mathrm{BR}(B_d \to J/\psi\, \eta) = 15.0 \times 10^{-6} \\ \mathrm{BR}(B_s \to J/\psi\, \eta) = 3.3 \times 10^{-4} \end{cases} \qquad \theta = -20^\circ$$

2. Mixing schemes

- **Conventional eta-eta' mixing (FKS)**

Phys. Rev. D 58, 114006 (1998); Phys. Lett. B 449, 339 (1999)

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} \eta_q \\ \eta_s \end{pmatrix}$$

$\eta_q = (u\bar{u} + d\bar{d})/\sqrt{2}$ and $\eta_s = s\bar{s}$ $\phi < 45°$

Phys. Rev. D 85, 013016 (2012), I.I. Bigi *et al.*

- **More complete eta-eta'-G mixing (CLL)**

Phys. Rev. D 79, 014024 (2009), H.Y. Cheng *et al.*

G denoting a pseudoscalar glueball

$$\begin{pmatrix} |\eta\rangle \\ |\eta'\rangle \\ |G\rangle \end{pmatrix} = \begin{pmatrix} \cos\phi + \sin\theta\sin\theta_i\Delta_G & -\sin\phi + \sin\theta\cos\theta_i\Delta_G & -\sin\theta\sin\phi_G \\ \sin\phi - \cos\theta\sin\theta_i\Delta_G & \cos\phi - \cos\theta\cos\theta_i\Delta_G & \cos\theta\sin\phi_G \\ -\sin\theta_i\sin\phi_G & -\cos\theta_i\sin\phi_G & \cos\phi_G \end{pmatrix} \begin{pmatrix} |\eta_q\rangle \\ |\eta_s\rangle \\ |g\rangle \end{pmatrix}$$

$\phi = \theta + \theta_i$ θ_i is the ideal mixing angle with $\theta_i = 54.7°$

the abbreviation $\Delta_G \equiv 1 - \cos\phi_G$

in the $\phi_G \to 0$ limit **CLL mixing approaches to FKS mixing**

$$R_d^{Th} \approx \left(\frac{\sin\phi - \cos\theta \sin\theta_i \Delta_G}{\cos\phi + \sin\theta \sin\theta_i \Delta_G}\right)^2,$$

the ratio R_d^{Th} could remain smaller than unity.

$$R_s^{Th} \approx \left(\frac{\cos\phi - \cos\theta \cos\theta_i \Delta_G}{-\sin\phi + \sin\theta \cos\theta_i \Delta_G}\right)^2,$$

R_s^{Th} might drop from above unity to below unity for a sufficiently large angle ϕ_G.

It has been verified that the contribution from the gluonic distribution amplitudes in the $\eta^{(\prime)}$ meson is negligible for B meson transition form factors

Phys. Rev. D 74, 074024 (2006), H.-n. Li *et al.*

3. $B_{d/s} \to J\psi\eta^{(\prime)}$ decays in pQCD approach

- We calculate the branching ratios of $B_{d/s} \to J/\psi\,\eta^{(\prime)}$ decays in the eta-eta'-G mixing by employing the pQCD approach at NLO of $alpha_s$.

- Assumption: no final state interactions and no isospin violation

- Input parameters can be seen in our paper. We here clarify the choices of the mixing angles.

  ☺ On $\phi = 43.7°$ $\qquad \theta = \phi - \theta_i = -11°,$

  The best fit on the mixing angle θ from experiment data converged in the range of $[-11°, -17°]$

  Phys. Rev. D 63, 054027 (2001), E. Kou

consistent with $\phi = (44^{+6}_{-7})^\circ$ determined from the $B_d \to J/\psi\, \eta/\pi^0$ data

J. High Energy Phys. 10 (2007) 026, C.E. Thomas

☺ **On** $\phi_G = 33^\circ$

varies in a wide range $10^\circ \lesssim \phi_G \lesssim 30^\circ$

Phys. Rev. D 79, 014024 (2009), H.Y. Cheng *et al.*

$$\phi_G = 33^\circ \pm 13^\circ$$

J. High Energy Phys. 10 (2007) 026, C.E. Thomas

Eur. Phys. J. C 65, 467 (2010), R. Escribano

👍 **The CP-averaged branching ratios for $B_{d/s} \to J/\psi\, \eta^{(\prime)}$ decays in the standard model read as**

$$\mathrm{BR}(B_d \to J/\psi\,\eta) = 11.2^{+2.8}_{-2.1}(\omega_{B_d})^{+1.9}_{-1.0}(a_2)^{+1.5}_{-1.4}(f_{J/\psi}) \times 10^{-6},$$

$$\mathrm{BR}(B_d \to J/\psi\,\eta') = 6.5^{+1.6}_{-1.2}(\omega_{B_d})^{+1.1}_{-0.6}(a_2)^{+0.9}_{-0.8}(f_{J/\psi}) \times 10^{-6},$$

$\Rightarrow$ $\mathrm{R}_{\mathrm{d}}^{\mathrm{Th}} \approx 0.58$

$$\mathrm{BR}(B_s \to J/\psi\,\eta) = 5.14^{+1.45}_{-1.10}(\omega_{B_s})^{+1.10}_{-0.77}(a_2)^{+0.71}_{-0.64}(f_{J/\psi}) \times 10^{-4},$$

$$\mathrm{BR}(B_s \to J/\psi\,\eta') = 3.68^{+1.04}_{-0.78}(\omega_{B_s})^{+0.78}_{-0.55}(a_2)^{+0.51}_{-0.46}(f_{J/\psi}) \times 10^{-4},$$

$\Rightarrow$ $\mathrm{R}_{\mathrm{s}}^{\mathrm{Th}} \approx 0.72$

$\omega_B = 0.40 \pm 0.04$ GeV $\quad \omega_{B_s} = 0.50 \pm 0.05$ GeV

$f_{J/\psi} = 0.405 \pm 0.014$ GeV $\quad a_2 = 0.44 \pm 0.22$

4. Phenomenological discussion

- The theoretical branching ratios are in agreement with the existing data and the upper bound after considering the eta-eta'-G mixing.

- In fact, $B_s \to J/\psi\, \eta^{(\prime)}$ decays have been proposed by R. Fleischer *et al.* to explore the eta-eta'-G mixing with KLOE's parameterization for the mixing matrix.

Eur. Phys. J. C 71, 1798 (2011), **R. Fleischer** *et al.*

$$\begin{pmatrix} \eta \\ \eta' \\ G \end{pmatrix} = \begin{pmatrix} \cos\phi' & -\sin\phi' & 0 \\ \sin\phi' \cos\phi_G & \cos\phi' \cos\phi_G & \sin\phi_G \\ -\sin\phi' \sin\phi_G & -\cos\phi' \sin\phi_G & \cos\phi_G \end{pmatrix} \begin{pmatrix} \eta_q \\ \eta_s \\ g \end{pmatrix}$$

the angles $\phi' \approx 40^\circ$ and $\phi_G \approx 20^\circ$ determined by KLOE lead to $R_s \approx 1$

- Our parameterization is close to that in [J. High Energy Phys. 10 (2007) 026, Eur. Phys. J. C 65, 467 (2010)]. So the extracted larger $\phi_G = 33^\circ$ is chosen. Then $R_s < 1$ is obtained naturally.

- When $\phi_G = 22^\circ$, the central values of the branching ratios become

$$\mathrm{BR}(B_d \to J/\psi\,\eta) = 11.7 \times 10^{-6},$$
$$\mathrm{BR}(B_d \to J/\psi\,\eta') = 8.2 \times 10^{-6},$$

$$\mathrm{BR}(B_s \to J/\psi\,\eta) = 5.00 \times 10^{-4},$$
$$\mathrm{BR}(B_s \to J/\psi\,\eta') = 4.28 \times 10^{-4},$$

the consistency with the data deteriorates

- **By comparison, one can observe that** $\mathrm{BR}(B_{d/s} \to J/\psi\,\eta)$ **are less sensitive to** ϕ_G than $\mathrm{BR}(B_{d/s} \to J/\psi\,\eta')$ **: A smaller glueball component involved in the eta meson.**

- **As far as the** $B_d \to J/\psi\,\eta^{(\prime)}$ **decays are concerned, their branching ratios can be accommodated in the conventional eta-eta' mixing by tuning the mixing angle phi.**

our predictions yields $\phi \approx 37.3°$, close to $\phi = 39.3° \pm 1.0°$

- **A larger phi$_G$ also makes an impact on the** $B \to K\eta^{(\prime)}$ **branching ratios in the** η-η'-G-η_c **tetramixing formalism.**

Phys. Rev. D 85, 034002 (2012), Tsai, Li, and Zhao

$$\begin{pmatrix} |\eta\rangle \\ |\eta'\rangle \\ |G\rangle \\ |\eta_c\rangle \end{pmatrix} = \begin{pmatrix} c\theta c\theta_i - s\theta c\phi_G s\theta_i & -c\theta s\theta_i - s\theta c\phi_G c\theta_i & -s\theta s\phi_G c\phi_Q & -s\theta s\phi_G s\phi_Q \\ s\theta c\theta_i + c\theta c\phi_G s\theta_i & -s\theta s\theta_i + c\theta c\phi_G c\theta_i & c\theta s\phi_G c\phi_Q & c\theta s\phi_G s\phi_Q \\ -s\phi_G s\theta_i & -s\phi_G c\theta_i & c\phi_G c\phi_Q & c\phi_G s\phi_Q \\ 0 & 0 & -s\phi_Q & c\phi_Q \end{pmatrix} \begin{pmatrix} |\eta_q\rangle \\ |\eta_s\rangle \\ |g\rangle \\ |\eta_Q\rangle \end{pmatrix}$$

☺ **Updated result:**

$$\mathrm{BR}(B^0 \to K^0\eta') = (59.7^{+22.6}_{-16.4}) \times 10^{-6}$$

☺ **In NLO pQCD with conventional mixing:**

$$\mathrm{BR}(B^0 \to K^0\eta') = 50 \times 10^{-6}$$

Phys. Rev. D 78, 114001 (2008), Z.J. Xiao *et al.*

☺ **The data:**

$$\mathrm{BR}(B^0 \to K^0\eta') = (66.1 \pm 3.1) \times 10^{-6}$$

Phys. Rev. D 86, 010001 (2012)

HFAG2012, arXiv: 1207.1158[ex]

On the other hand, $\mathrm{BR}(B^0 \to K^0\eta)$ is insensitive to the variation of ϕ_G, which remains as around 2×10^{-6}

Phys. Rev. D 85, 034002 (2012)

It is also interesting to examine whether D, D_s decays into eta(prime) mesons, such as $D,\ D_s \to \eta^{(\prime)}\ell^+\nu$ reveal the similar implication on the mixing mechanism.

Phys. Rev. D 80, 055023 (2009), **M.V. Carluccia** *et al.*

Eur. Phys. J. C 69, 133 (2010), **Ke, Li, and Wei**

Phys. Rev. D 85, 013016 (2012), **I.I. Bigi** *et al.*

$$R_d^{\prime} \equiv \frac{BR(D^+ \to \eta^{\prime}\ell^+\nu)}{BR(D^+ \to \eta\ell^+\nu)} = \tilde{R}_D \tan^2\phi,$$

$$R_s^{\prime} \equiv \frac{BR(D_s \to \eta^{\prime}\ell^+\nu)}{BR(D_s \to \eta\ell^+\nu)} = R_D \cot^2\phi,$$

the factors $\tilde{R}_D \approx R_D$ collect the information on the $D_{d/s} \to \eta_{q/s}$ transition form factors and the corresponding phase space

R_D depends on how to model

the q^2 dependence of the form factor, q^2 being the lepton-pair invariant mass squared, and suffers theoretical uncertainty

☺ **Taking conventional approximation $R_D \approx 0.28$**

Phys. Lett. B 404, 166 (1997), V.V. Anisovich ***et al.***

$$R_d^{\prime Exp} \approx 0.19 \pm 0.05 < R_D$$

[CLEO Collaboration] Phys. Rev. D 84, 032001 (2011)

$$R_s^{\prime Exp} = 0.37 \pm 0.10 > R_D$$

[Particle Data Group] J. Phys. G 37, 075021 (2010)

exhibit a pattern in agreement with the conventional η-η' mixing

☺ **However,**

- ❐ **Viewing the potential uncertainties in the estimate of R_D and in the assumption of $\tilde{R}_D \approx R_D$ we stress that the above observation is not in conflict with the eta-eta'-G mixing formalism.**

- ❐ **It is not sure that the contributions from the D, D_s transitions to pseudoscalar glueballs are negligible as in the $B_{d/s}$ meson decays.**

5. Summary

✍ The recent $B_{d/s} \to J/\psi\, \eta^{(\prime)}$ data provided a strong implication on the sizable pseudoscalar glueball contents in the eta(prime) mesons.

✍ We have verified this implication by computing explicitly the $B_{d/s} \to J/\psi\, \eta^{(\prime)}$ branching ratios in the NLO PQCD approach: the outcomes from a large angle $\phi_G \approx 30^\circ$ were found to be well consistent with the current measurements and upper bounds.

- **The abnormally large observed $B \to K\eta'$ branching ratios were also accommodated in the η-η'-G-η_c tetramixing formalism with the same ϕ_G.**

- **Our work suggests that complete understanding of dynamics in $\eta^{(\prime)}$-involved processes demands the η-η'-G mixing scheme. The resultant predictions for other $B_{d/s} \to \eta^{(\prime)}$ decays could be tested by future data of LHCb and/or Super-B factories.**

谢谢！

BACKUP SLIDES

arXiv:1210.2631

LHCb collaboration

$$\mathcal{R}^{B_s^0,\eta'}_{B_s^0,\eta} = \frac{\mathcal{B}(B_s^0 \to J/\psi\,\eta')}{\mathcal{B}(B_s^0 \to J/\psi\,\eta)} = 0.90 \pm 0.09\,(\text{stat})\,^{+0.06}_{-0.02}\,(\text{syst})$$

This result is consistent with the previous Belle measurement of $\mathcal{R}^{B_s^0,\eta'}_{B_s^0,\eta} = 0.73 \pm 0.14$ but is more precise.

the contribution from the purely gluonic component is negligible,

this ratio corresponds to a value of the $\eta - \eta'$ mixing phase of $\phi_P = \left(45.5\,^{+1.8}_{-1.5}\right)^\circ$

$$\frac{\mathcal{B}(B_s^0 \to J/\psi\,\eta)}{\mathcal{B}(B^0 \to J/\psi\,\rho^0)} = 14.0 \pm 1.2\,(\text{stat})\,^{+1.1}_{-1.5}\,(\text{syst})\,^{+1.1}_{-1.0}\left(\frac{f_d}{f_s}\right)$$

$$\frac{\mathcal{B}(B_s^0 \to J/\psi\,\eta')}{\mathcal{B}(B^0 \to J/\psi\,\rho^0)} = 12.7 \pm 1.1\,(\text{stat})\,^{+0.5}_{-1.3}\,(\text{syst})\,^{+1.0}_{-0.9}\left(\frac{f_d}{f_s}\right)$$

arXiv:1210.2631

LHCb collaboration

$$\mathcal{B}(\mathrm{B_s^0} \to \mathrm{J/\psi\,\eta}) = \left(3.79 \pm 0.31\,(\mathrm{stat})\,^{+0.20}_{-0.41}\,(\mathrm{syst})\,^{+0.29}_{-0.27}\left(\frac{f_\mathrm{d}}{f_\mathrm{s}}\right) \pm 0.56\,(\mathcal{B}_{\mathrm{B^0}\to\mathrm{J/\psi\,\rho^0}})\right) \times 10^{-4},$$

$$\mathcal{B}(\mathrm{B_s^0} \to \mathrm{J/\psi\,\eta'}) = \left(3.42 \pm 0.30\,(\mathrm{stat})\,^{+0.14}_{-0.35}\,(\mathrm{syst})\,^{+0.26}_{-0.25}\left(\frac{f_\mathrm{d}}{f_\mathrm{s}}\right) \pm 0.51\,(\mathcal{B}_{\mathrm{B^0}\to\mathrm{J/\psi\,\rho^0}})\right) \times 10^{-4}.$$

arXiv:0912.1434

Belle Collaboration

$$\mathcal{B}(B_s^0 \to J/\psi\eta) = (3.32 \pm 0.87(\mathrm{stat.})^{+0.32}_{-0.28}(\mathrm{syst.}) \pm 0.42(f_s)) \times 10^{-4}$$

$$\mathcal{B}(B_s^0 \to J/\psi\eta') = (3.1 \pm 1.2(\mathrm{stat.})^{+0.5}_{-0.6}(\mathrm{syst.}) \pm 0.38(f_s)) \times 10^{-4}$$