Phenomenological studies on neutral B-meson decays into $J/\psi f_1$ and $\eta c f_1$

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概述

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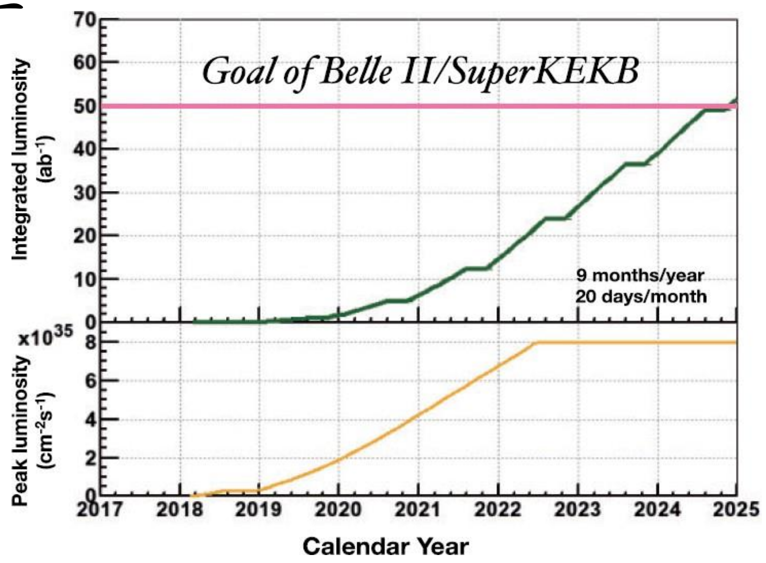
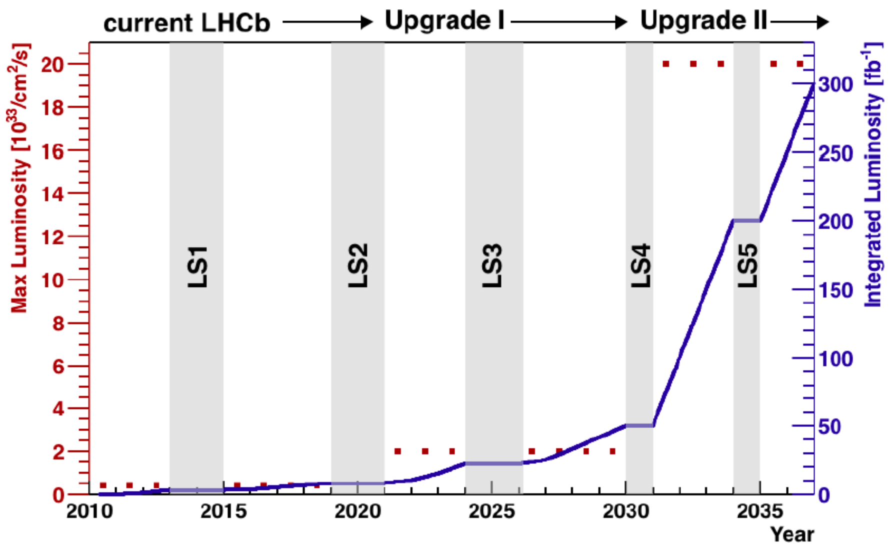
研究动机

1.1 动机一





- 随着探测器的不断升级，未来Belle-ll探测器的亮度将会达到50ab^{-1},LHCb Upgradell 探测器的亮度将会达到300fb^{-1}。
- 探测技术也在不断地提高，探测器的测量精度将会大大提升，并且能够收集更多关于B介子的数据。

研究动机

$$\phi_s = -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{tb}V_{cb}^*}\right) = -0.036 \pm 0.002(\text{rad}).$$ (SM)

$B_s^0 \to J/\psi\,\phi$ or $B_s^0 \to J/\psi\, f_0$

QCD求和规则认为轴矢量介子f_1和矢量介子ϕ的动力学行为相似；

$B_s^0 \to (J/\psi，\eta_c)\, f_1$的衰变中，在夸克层次上也是由$b \to c\bar{c}s$跃迁所控制，

类似于$B_s^0 \to J/\psi\,\phi$衰变道，对于混合相角 ϕ_s 的提取起到一定约束作用。

⇧

$$\begin{cases} B_s^0 \to J/\psi\, f_1(1420) \\ B_s^0 \to \eta_c\, f_1(1420) \end{cases}$$

研究动机

LHCb通过$B \to J/\psi(2\pi^+2\pi^-)_{f_1(1285)}$衰变道得到了$B \to J/\psi f_1(1285)$衰变的分支比和混合角：

[R. Aaij et al. [LHCb Collaboration], Phys. Rev. D, 2013, 112(9):091802.]

$$\begin{cases} \mathcal{B}\left(B_d^0 \to J/\psi\ f_1(1285)\right)_{\text{Exp}} = 8.37^{+2.11}_{-2.09} \times 10^{-6} \\ \mathcal{B}\left(B_s^0 \to J/\psi\ f_1(1285)\right)_{\text{Exp}} = 7.14^{+1.36}_{-1.41} \times 10^{-5}, \end{cases} \qquad \varphi^{\text{Exp}} = \pm\left(24.0^{+3.2}_{-2.7}\right)^{\circ}.$$

理论上从$B_s^0 \to J/\psi f_1(1285)$衰变道抽取出的混合角值为：$\varphi^{\text{Theo}} = \left(15.0^{+1.5}_{-1.5}\right)^{\circ}$.

[Liu X, Xiao Z J. Phys. Rev. D, 2014, 89(9):097503.]

研究动机

1.2 动机二

发现*p*-波介子,这些粒子的分类和内部结构等基本问题还存在诸多争议，轴矢量介子K_{1A}和K_{1B}的混合复杂，实验和理论上对其混合角仍不十分确定。

$n\,^{2s+1}\ell_J$	J^{PC}	I = 1 $u\bar{d}$, $\bar{u}d$, $\frac{1}{\sqrt{2}}(d\bar{d}-u\bar{u})$	I = $\frac{1}{2}$ $u\bar{s}$, $d\bar{s}$; $\bar{d}s$, $-\bar{u}s$	I = 0 f'	I = 0 f	$\theta_{\rm quad}$ [°]	$\theta_{\rm lin}$ [°]
$1\,^1S_0$	0^{-+}	π	K	η	$\eta'(958)$	−11.5	−24.6
$1\,^3S_1$	1^{--}	$\rho(770)$	$K^*(892)$	$\phi(1020)$	$\omega(782)$	38.7	36.0
$1\,^1P_1$	1^{+-}	$b_1(1235)$	$K_{1B}{}^\dagger$	$h_1(1380)$	$h_1(1170)$		
$1\,^3P_0$	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1710)$	$f_0(1370)$		
$1\,^3P_1$	1^{++}	$a_1(1260)$	$K_{1A}{}^\dagger$	$f_1(1420)$	$f_1(1285)$		
$1\,^3P_2$	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2'(1525)$	$f_2(1270)$	29.6	28.0

研究动机

$f_1(1285)$和$f_1(1420)$介子混合：

$$\begin{pmatrix} f_1(1285) \\ f_1(1420) \end{pmatrix} = \begin{pmatrix} \cos\varphi & -\sin\varphi \\ \sin\varphi & \cos\varphi \end{pmatrix} \begin{pmatrix} f_n \\ f_s \end{pmatrix}$$

$$\begin{pmatrix} f_1(1285) \\ f_1(1420) \end{pmatrix} = \begin{pmatrix} \cos\theta_{f_1} & \sin\theta_{f_1} \\ -\sin\theta_{f_1} & \cos\theta_{f_1} \end{pmatrix} \begin{pmatrix} f_1 \\ f_8 \end{pmatrix}$$

混合角关系式：$\varphi = \theta_i - \theta_{f_1}$；

$$\tan^2\theta_{f_1} = \frac{4m_{K_{1A}}^2 - m_{a_1}^2 - 3m_{f_1(1420)}^2}{-4m_{K_{1A}}^2 + m_{a_1}^2 + 3m_{f_1(1285)}^2}, \quad m_{K_{1A}}^2 = m_{K_1(1400)}^2 \cos^2\theta_{K_1} + m_{K_1(1270)}^2 \sin^2\theta_{K_1}$$

$K_1(1270)$ 和 $K_1(1400)$ 混合形式：

$$\begin{pmatrix} K_1(1270) \\ K_1(1400) \end{pmatrix} = \begin{pmatrix} \sin\theta_{K_1} & \cos\theta_{K_1} \\ \cos\theta_{K_1} & -\sin\theta_{K_1} \end{pmatrix} \begin{pmatrix} K_{1A} \\ K_{1B} \end{pmatrix}$$

理论框架

PQCD因子化方法：

基于k_T因子化定理，消除端点发散，所有拓扑结构费曼图均可微扰计算。

$$\frac{1}{l^2(p_b^2-m_B^2)} \sim -\frac{1}{m_B^4 x_1 x_3(1-x_3)} \rightarrow -\frac{1}{((1-x_3)m_B^2+\mathrm{k}_{3T}^2)(x_1x_3m_B^2+(\mathrm{k}_{1T}-\mathrm{k}_{3T})^2)}$$

PQCD因子化方法的中心思想是将QCD参与的过程中可微扰部分分离出来用微扰论处理，而非微扰部分用普适的强子波函数表示。

理论框架

1. B介子波函数：
$$\Phi_B=\frac{i}{\sqrt{2N_C}}\{(\not{P}+m_B)\gamma_5\phi_B(x,k_T)\}_{\alpha\beta}$$

2. 矢量介子J/ψ和赝标介子η_c的波函数：

$$\Phi^L_{J/\psi}(x)=\frac{1}{\sqrt{2N_C}}\left\{m_{J/\psi}\not{\epsilon}_L\phi^L_{J/\psi}(x)+\not{\epsilon}_L\not{P}\phi^t_{J/\psi}(x)\right\}_{\alpha\beta}$$

$$\Phi^T_{J/\psi}(x)=\frac{1}{\sqrt{2N_C}}\left\{m_{J/\psi}\not{\epsilon}_T\phi^v_{J/\psi}(x)+\not{\epsilon}_T\not{P}\phi^T_{J/\psi}(x)\right\}_{\alpha\beta}$$

$$\Phi_{\eta_c}=\frac{i}{\sqrt{2N_C}}\gamma_5\left\{\not{P}\phi^v_{\eta_c}(x)+m_{\eta_c}\phi^s_{\eta_c}(x)\right\}_{\alpha\beta}$$

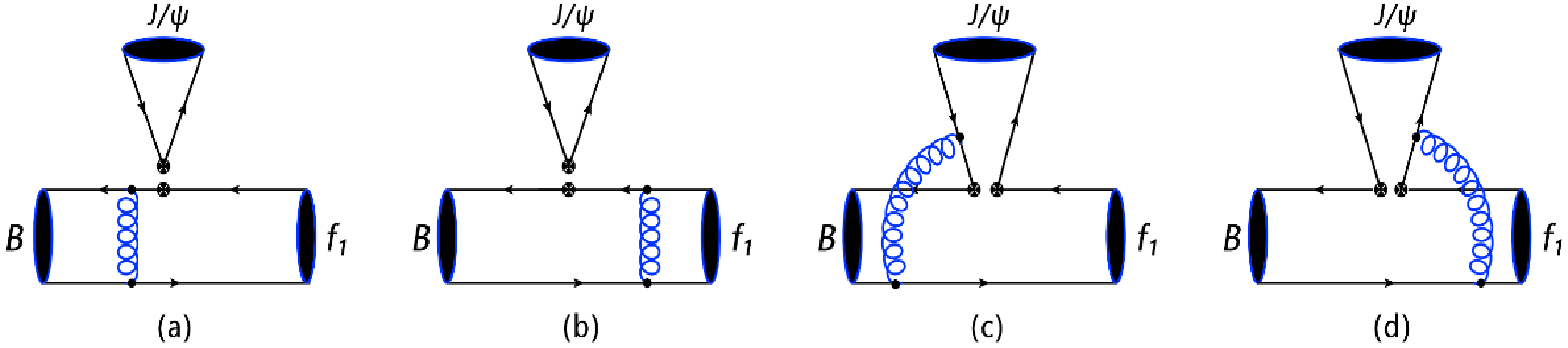
3. 轴矢量介子夸克-味态$f_q(q=n,s)$的波函数：

$$\Phi^L_{f_q}=\frac{1}{\sqrt{2N_c}}\gamma_5\left\{m_{f_q}\not{\epsilon}_L\phi_{f_q}(x)+\not{\epsilon}_L\not{P}\phi^t_{f_q}(x)+m_{f_q}\phi^s_{f_q}(x)\right\}_{\alpha\beta}$$

$$\Phi^T_{f_q}=\frac{1}{\sqrt{2N_C}}\gamma_5\left\{m_{f_q}\not{\epsilon}_T\phi^v_{f_q}(x)+\not{\epsilon}_T\not{P}\phi^T_{f_q}(x)+m_{f_q}i\epsilon_{\mu\nu\rho\sigma}\gamma_5\gamma^\mu\not{\epsilon}^\nu_T n^\rho v^\sigma\phi^a_{f_q}(x)\right\}_{\alpha\beta}$$

其中，本文所采用的波函数的分布振幅和Gegenbauer矩是由QCD求和规则得到。

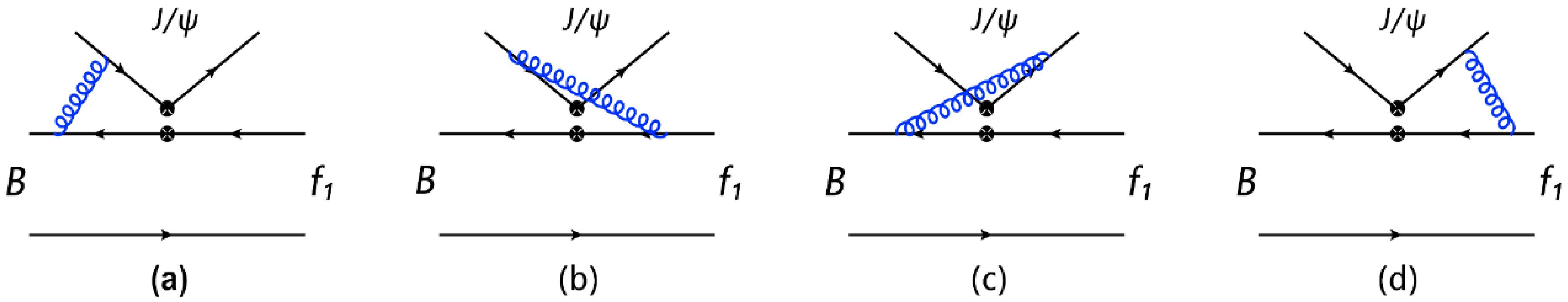
理论框架



可因子化发射图　　　　　　不可因子化发射图

$$
\begin{aligned}
F^{L}_{J/\psi} = {} & 8\pi C_F f_{J/\psi} m_B^4 \int_0^1 dx_1 dx_3 \int_0^\infty b_1 db_1 b_3 db_3 \phi_B(x_1,b_1) \Big\{ \Big[\sqrt{1-r_2^2} \Big(r_3 \Big(\sqrt{1-r_2^2}\,(2x_3-1) \\
& \times \phi^s_{f_q}(x_3) - \phi^t_{f_q}(x_3)\big(2x_3(r^2-1)+r^2+1\big)\Big) + \phi_{f_q}(x_3)\big((r^2-1)x_3-1\big)\Big)\Big] \\
& \times h_{fe}(x_1,x_3,b_1,b_3) E_{fe}(t_a) - \big[2r_3(1-r^2)\phi^s_{f_q}(x_3) \big] h_{fe}(x_3,x_1,b_3,b_1) E_{fe}(t_b) \Big\},
\end{aligned}
$$

理论框架



次领头阶顶角修正费曼图

$$a_2 \to \tilde{a}_2^h = a_2 + \frac{\alpha_s}{4\pi}\frac{C_F}{N_c}C_2\left(-18+12\ln\frac{m_b}{\mu}+f_I^h\right),\quad a_7 \to \tilde{a}_7^h = a_7 + \frac{\alpha_s}{4\pi}\frac{C_F}{N_c}C_8\left(6-12\ln\frac{m_b}{\mu}-f_I^h\right),$$

$$a_3 \to \tilde{a}_3^h = a_3 + \frac{\alpha_s}{4\pi}\frac{C_F}{N_c}C_4\left(-18+12\ln\frac{m_b}{\mu}+f_I^h\right),\quad a_9 \to \tilde{a}_9^h = a_9 + \frac{\alpha_s}{4\pi}\frac{C_F}{N_c}C_{10}\left(-18+12\ln\frac{m_b}{\mu}+f_I^h\right),$$

$$a_5 \to \tilde{a}_5^h = a_5 + \frac{\alpha_s}{4\pi}\frac{C_F}{N_c}C_6\left(6-12\ln\frac{m_b}{\mu}-f_I^h\right),$$

其中，函数 $f_I^0 = f_I + g_I\left(1-r_2^2\right)$，$f^{\pm} = f_I$.

[Cheng H Y, Keum Y Y, Yang K C. Phys. Rev. D, 2002, 65(9):094023.]

数值结果

3.1 分支比

混合角$\varphi^{\mathrm{Theo}} \sim 15.0^{\circ}$：

f_q Gegenbauer

$$\mathcal{B}\left(B_d^0 \to J/\psi f_1(1285)\right) = 3.05^{+0.73+0.22+1.51+0.42+1.01+0.02+0.09+0.01+0.04}_{-0.56-0.20-1.08-0.40-0.77-0.02-0.12-0.00-0.04}\left[3.05^{+2.02}_{-1.51}\right]\times 10^{-5}$$

$$\mathcal{B}\left(B_d^0 \to J/\psi f_1(1420)\right) = 1.99^{+0.47+0.14+0.99+0.28+0.64+0.01+0.06+0.00+0.41}_{-0.37-0.13-0.71-0.26-0.49-0.01-0.08-0.00-0.37}\left[1.99^{+1.37}_{-1.05}\right]\times 10^{-6}$$

$$\mathcal{B}\left(B_s^0 \to J/\psi f_1(1285)\right) = 0.89^{+0.25+0.07+0.08+0.13+0.32+0.01+0.04+0.00+0.19}_{-0.18-0.06-0.06-0.12-0.24-0.00-0.04-0.00-0.16}\left[0.89^{+0.48}_{-0.37}\right]\times 10^{-4}$$

$$\mathcal{B}\left(B_s^0 \to J/\psi f_1(1420)\right) = 1.14^{+0.32+0.08+0.10+0.17+0.40+0.02+0.05+0.00+0.02}_{-0.23-0.07-0.08-0.15-0.30-0.01-0.05-0.00-0.01}\left[1.14^{+0.56}_{-0.42}\right]\times 10^{-3}$$

混合角 $\varphi^{\mathrm{Exp}} \sim 24.0^{\circ}$：

$$\mathcal{B}\left(B_d^0 \to J/\psi f_1(1285)\right) = 2.73^{+0.65+0.19+1.35+0.38+0.90+0.02+0.08+0.01+0.11}_{-0.50-0.18-0.97-0.36-0.69-0.02-0.11-0.00-0.14}\left[2.73^{+1.80}_{-1.36}\right]\times 10^{-5}$$

$$\mathcal{B}\left(B_d^0 \to J/\psi f_1(1420)\right) = 4.92^{+1.16+0.34+2.43+0.68+1.58+0.03+0.14+0.00+1.29}_{-0.91-0.34-1.75-0.65-1.22-0.04-0.20-0.01-1.00}\left[4.92^{+3.47}_{-2.64}\right]\times 10^{-6}$$

$$\mathcal{B}\left(B_s^0 \to J/\psi f_1(1285)\right) = 2.21^{+0.61+0.15+0.18+0.31+0.79+0.02+0.09+0.00+0.58}_{-0.46-0.15-0.17-0.30-0.60-0.02-0.10-0.00-0.45}\left[2.21^{+1.22}_{-0.96}\right]\times 10^{-4}$$

$$\mathcal{B}\left(B_s^0 \to J/\psi f_1(1420)\right) = 1.02^{+0.28+0.08+0.08+0.15+0.36+0.01+0.04+0.00+0.04}_{-0.21-0.07-0.08-0.14-0.27-0.01-0.04-0.00-0.05}\left[1.02^{+0.50}_{-0.39}\right]\times 10^{-3}$$

数值结果

混合角 $\varphi^{\text{Theo}} \sim 15.0^{\circ}$：

$$\mathcal{B}\left(B_d^0 \to \eta_c f_1(1285)\right) = 7.64^{+2.42+1.92+3.77+0.92+4.08+0.10+0.58+0.01+0.10}_{-1.78-1.71-2.71-0.86-3.03-0.10-0.66-0.02-0.11}\left[7.64^{+6.45}_{-4.88}\right]\times 10^{-6}$$

$$\mathcal{B}\left(B_d^0 \to \eta_c f_1(1420)\right) = 5.16^{+1.64+1.31+2.56+0.63+2.77+0.07+0.40+0.02+1.06}_{-1.20-1.16-1.83-0.58-2.04-0.06-0.44-0.01-0.96}\left[5.16^{+4.51}_{-3.61}\right]\times 10^{-7}$$

$$\mathcal{B}\left(B_s^0 \to \eta_c f_1(1285)\right) = 2.15^{+0.81+0.54+0.17+0.26+1.28+0.04+0.18+0.00+0.44}_{-0.58-0.48-0.17-0.25-0.92-0.04-0.18-0.00-0.40}\left[2.15^{+1.71}_{-1.30}\right]\times 10^{-5}$$

$$\mathcal{B}\left(B_s^0 \to \eta_c f_1(1420)\right) = 2.84^{+1.07+0.71+0.22+0.35+1.69+0.05+0.24+0.00+0.03}_{-0.77-0.64-0.22-0.33-1.22-0.06-0.25-0.00-0.05}\left[2.84^{+2.18}_{-1.65}\right]\times 10^{-4}$$

混合角 $\varphi^{\text{Exp}} \sim 24.0^{\circ}$：

$$\mathcal{B}\left(B_d^0 \to \eta_c f_1(1285)\right) = 6.83^{+2.16+1.72+3.38+0.83+3.66+0.09+0.52+0.02+0.28}_{-1.59-1.53-2.42-0.77-2.71-0.09-0.58-0.01-0.35}\left[6.83^{+5.79}_{-4.37}\right]\times 10^{-6}$$

$$\mathcal{B}\left(B_d^0 \to \eta_c f_1(1420)\right) = 1.28^{+0.40+0.32+0.63+0.15+0.68+0.01+0.09+0.00+0.33}_{-0.30-0.29-0.46-0.15-0.51-0.02-0.11-0.01-0.26}\left[1.28^{+1.12}_{-0.87}\right]\times 10^{-6}$$

$$\mathcal{B}\left(B_s^0 \to \eta_c f_1(1285)\right) = 5.31^{+2.00+1.13+0.42+0.65+3.16+0.10+0.45+0.00+1.39}_{-1.43-1.19-0.41-0.62-2.28-0.11-0.46-0.01-1.08}\left[5.31^{+4.24}_{-3.26}\right]\times 10^{-5}$$

$$\mathcal{B}\left(B_s^0 \to \eta_c f_1(1420)\right) = 2.54^{+0.96+0.64+0.20+0.31+1.51+0.05+0.22+0.00+0.10}_{-0.69-0.57-0.20-0.30-1.09-0.05-0.22-0.00-0.13}\left[2.54^{+1.95}_{-1.48}\right]\times 10^{-4}$$

数值结果

根据窄宽度近似：

$$\mathcal{B}\left(B_d^0 \to J/\psi\left(\eta\pi^+\pi^-\right)_{f_1(1285)}\right) \equiv \mathcal{B}\left(B_d^0 \to J/\psi\ f_1(1285)\right)\cdot\mathcal{B}\left(f_1(1285)\to\eta\pi^+\pi^-\right) \approx \begin{cases} 1.07^{+0.84}_{-0.70}\times10^{-5} \\ 0.96^{+0.75}_{-0.63}\times10^{-5} \end{cases}$$

$$\mathcal{B}\left(B_d^0 \to \eta_c\left(\eta\pi^+\pi^-\right)_{f_1(1285)}\right) \equiv \mathcal{B}\left(B_d^0 \to \eta_c f_1(1285)\right)\cdot\mathcal{B}\left(f_1(1285)\to\eta\pi^+\pi^-\right) \approx \begin{cases} 2.67^{+2.54}_{-2.06}\times10^{-6} \\ 2.39^{+2.27}_{-1.84}\times10^{-6} \end{cases}$$

$$\mathcal{B}\left(B_s^0 \to J/\psi\left(K_S^0K^+\pi^-\right)_{f_1(1420)}\right) \equiv \mathcal{B}\left(B_s^0 \to J/\psi\ f_1(1420)\right)\cdot\mathcal{B}\left(f_1(1420)\to K_S^0K^+\pi^-\right) \approx \begin{cases} 0.73^{+0.36}_{-0.28}\times10^{-3} \\ 0.65^{+0.33}_{-0.25}\times10^{-3} \end{cases}$$

$$\mathcal{B}\left(B_s^0 \to \eta_c\left(K_S^0K^+\pi^-\right)_{f_1(1420)}\right) \equiv \mathcal{B}\left(B_s^0 \to \eta_c f_1(1420)\right)\cdot\mathcal{B}\left(f_1(1420)\to K_S^0K^+\pi^-\right) \approx \begin{cases} 1.82^{+1.40}_{-1.07}\times10^{-4} \\ 1.63^{+1.26}_{-0.96}\times10^{-4} \end{cases}$$

数量级较大，有望在LHCb和Belle-II实验中被探测到

数值结果

3.2 分支比比值

从实验的角度，分支比的比值通常比单个分支比测得的精度要高，定义了多组分支比比值：

$$R_d^{J/\psi} \equiv \left.\frac{\mathcal{B}\left(B_d^0 \to J/\psi\ f_1(1285)\right)}{\mathcal{B}\left(B_d^0 \to J/\psi\ f_1(1420)\right)}\right|_{\mathrm{PQCD}} = \frac{\Phi_{d,J/\psi}^{f_1(1285)}}{\Phi_{d,J/\psi}^{f_1(1420)}} \cdot \cot^2\varphi \approx \begin{cases} 15.33_{-0.14}^{+0.15} \\ 5.55_{-0.04}^{+0.06} \end{cases}$$

$$R_s^{J/\psi} \equiv \left.\frac{\mathcal{B}\left(B_s^0 \to J/\psi\ f_1(1420)\right)}{\mathcal{B}\left(B_s^0 \to J/\psi\ f_1(1285)\right)}\right|_{\mathrm{PQCD}} = \frac{\Phi_{s,J/\psi}^{f_1(1420)}}{\Phi_{s,J/\psi}^{f_1(1285)}} \cdot \cot^2\varphi \approx \begin{cases} 12.81_{-0.18}^{+0.17} \\ 4.62_{-0.03}^{+0.08} \end{cases}$$

$$R_d^{\eta_c} \equiv \left.\frac{\mathcal{B}\left(B_d^0 \to \eta_c\, f_1(1285)\right)}{\mathcal{B}\left(B_d^0 \to \eta_c\, f_1(1420)\right)}\right|_{\mathrm{PQCD}} = \frac{\Phi_{d,\eta_c}^{f_1(1285)}}{\Phi_{d,\eta_c}^{f_1(1420)}} \cdot \cot^2\varphi \approx \begin{cases} 14.81_{-2.36}^{+3.12} \\ 5.34_{-0.92}^{+1.02} \end{cases}$$

$$R_s^{\eta_c} \equiv \left.\frac{\mathcal{B}\left(B_s^0 \to \eta_c\, f_1(1420)\right)}{\mathcal{B}\left(B_s^0 \to \eta_c\, f_1(1285)\right)}\right|_{\mathrm{PQCD}} = \frac{\Phi_{s,\eta_c}^{f_1(1420)}}{\Phi_{s,\eta_c}^{f_1(1285)}} \cdot \cot^2\varphi \approx \begin{cases} 13.21_{-2.13}^{+2.73} \\ 4.78_{-0.84}^{+0.91} \end{cases}$$

数值结果

$$R_{d,f_1(1285)}^{s,f_1(1420)}[J/\psi] \equiv \left.\frac{\mathcal{B}\left(B_s^0 \to J/\psi\ f_1(1420)\right)}{\mathcal{B}\left(B_d^0 \to J/\psi\ f_1(1285)\right)}\right|_{\text{PQCD}} = \frac{\tau_{B_s^0}}{\tau_{B_d^0}} \cdot \left(\frac{m_{B_s^0}}{m_{B_d^0}}\right)^7 \frac{\Phi_{s,J/\psi}^{f_1(1420)}}{\Phi_{d,J/\psi}^{f_1(1285)}} \cdot \frac{\left|\mathcal{A}\left(B_s^0 \to J/\psi\ f_s\right)/m^2_{B_s^0}\right|^2}{\left|\mathcal{A}\left(B_d^0 \to J/\psi\ f_n\right)/m^2_{B_d^0}\right|^2} \approx 37.47_{-10.50}^{+16.22}$$

$$R_{d,f_1(1420)}^{s,f_1(1285)}[J/\psi] \equiv \left.\frac{\mathcal{B}\left(B_s^0 \to J/\psi\ f_1(1285)\right)}{\mathcal{B}\left(B_d^0 \to J/\psi\ f_1(1420)\right)}\right|_{\text{PQCD}} = \frac{\tau_{B_s^0}}{\tau_{B_d^0}} \cdot \left(\frac{m_{B_s^0}}{m_{B_d^0}}\right)^7 \frac{\Phi_{s,J/\psi}^{f_1(1285)}}{\Phi_{d,J/\psi}^{f_1(1420)}} \cdot \frac{\left|\mathcal{A}\left(B_s^0 \to J/\psi\ f_s\right)/m^2_{B_s^0}\right|^2}{\left|\mathcal{A}\left(B_d^0 \to J/\psi\ f_n\right)/m^2_{B_d^0}\right|^2} \approx 44.92_{-12.64}^{+19.47}$$

$$R_{d,f_1(1285)}^{s,f_1(1420)}[\eta_c] \equiv \left.\frac{\mathcal{B}\left(B_s^0 \to \eta_c f_1(1420)\right)}{\mathcal{B}\left(B_d^0 \to \eta_c f_1(1285)\right)}\right|_{\text{PQCD}} = \frac{\tau_{B_s^0}}{\tau_{B_d^0}} \cdot \left(\frac{m_{B_s^0}}{m_{B_d^0}}\right)^7 \cdot \frac{\Phi_{s,\eta_c}^{f_1(1420)}}{\Phi_{d,\eta_c}^{f_1(1285)}} \cdot \frac{\left|\mathcal{A}\left(B_s^0 \to \eta_c f_s\right)/m^2_{B_s^0}\right|^2}{\left|\mathcal{A}\left(B_d^0 \to \eta_c f_n\right)/m^2_{B_d^0}\right|^2} \approx 37.13_{-10.66}^{+16.19}$$

$$R_{d,f_1(1420)}^{s,f_1(1285)}[\eta_c] \equiv \left.\frac{\mathcal{B}\left(B_s^0 \to \eta_c f_1(1285)\right)}{\mathcal{B}\left(B_d^0 \to \eta_c f_1(1420)\right)}\right|_{\text{PQCD}} = \frac{\tau_{B_s^0}}{\tau_{B_d^0}} \cdot \left(\frac{m_{B_s^0}}{m_{B_d^0}}\right)^7 \cdot \frac{\Phi_{s,\eta_c}^{f_1(1285)}}{\Phi_{d,\eta_c}^{f_1(1420)}} \cdot \frac{\left|\mathcal{A}\left(B_s^0 \to \eta_c f_s\right)/m^2_{B_s^0}\right|^2}{\left|\mathcal{A}\left(B_d^0 \to \eta_c f_n\right)/m^2_{B_d^0}\right|^2} \approx 41.60_{-11.94}^{+18.14}$$

数值结果

实验数据【PDG2020】:

$$\mathcal{B}\left(B_s^0 \to J/\psi\,\phi\right) = 1.07^{+0.28+0.07+0.04+0.14+0.05+0.03+0.05+0.00}_{-0.22-0.08-0.05-0.13-0.06-0.04-0.07-0.00}\left[1.07^{+0.33}_{-0.29}\right]\times 10^{-3} \qquad \left[1.08^{+0.08}_{-0.08}\right]\times 10^{-3}$$

$$\mathcal{B}\left(B_d^0 \to J/\psi\,\rho^0\right) = 2.98^{+0.67+0.21+0.10+0.35+0.08+0.14+0.09+0.00}_{-0.53-0.20-0.10-0.32-0.07-0.13-0.13-0.00}\left[2.98^{+0.81}_{-0.69}\right]\times 10^{-5} \Leftrightarrow \left[2.55^{+0.18}_{-0.16}\right]\times 10^{-5}$$

$$\mathcal{B}\left(B_s^0 \to \eta_c\phi\right) = 3.57^{+1.39+0.91+0.29+0.26+0.25+0.56+0.00}_{-0.96-0.80-0.27-0.23-0.23-0.50-0.00}\left[3.57^{+1.81}_{-1.41}\right]\times 10^{-4} \qquad \left[5.00^{+0.90}_{-0.90}\right]\times 10^{-4}$$

$$\mathcal{B}\left(B_d^0 \to \eta_c\rho^0\right) = 7.92^{+2.63+1.99+0.57+0.81+0.52+1.15+0.01}_{-1.92-1.78-0.55-0.76-0.50-1.13-0.02}\left[7.92^{+3.67}_{-3.04}\right]\times 10^{-6}$$

$$R_d^{J/\psi}\left[f_1(1285)/\rho^0\right] \equiv \left.\frac{\mathcal{B}\left(B_d^0 \to J/\psi f_1(1285)\right)}{\mathcal{B}\left(B_d^0 \to J/\psi\rho^0\right)}\right|_{\text{PQCD}} \approx \begin{cases} 1.02^{+0.55}_{-0.42} \\ 0.92^{+0.49}_{-0.37} \end{cases}$$

$$R_s^{\eta_c}\left[f_1(1420)/\phi\right] \equiv \left.\frac{\mathcal{B}\left(B_s^0 \to \eta_c f_1(1420)\right)}{\mathcal{B}\left(B_s^0 \to \eta_c\phi\right)}\right|_{\text{PQCD}} \approx \begin{cases} 0.80^{+0.08}_{-0.08} \\ 0.71^{+0.06}_{-0.06} \end{cases}$$

$$R_s^{J/\psi}\left[f_1(1420)/\phi\right] \equiv \left.\frac{\mathcal{B}\left(B_s^0 \to J/\psi f_1(1420)\right)}{\mathcal{B}\left(B_s^0 \to J/\psi\phi\right)}\right|_{\text{PQCD}} \approx \begin{cases} 1.07^{+0.34}_{-0.25} \\ 0.95^{+0.31}_{-0.23} \end{cases}$$

$$R_d^{\eta_c}\left[f_1(1285)/\rho^0\right] \equiv \left.\frac{\mathcal{B}\left(B_d^0 \to \eta_c f_1(1285)\right)}{\mathcal{B}\left(B_d^0 \to \eta_c\rho^0\right)}\right|_{\text{PQCD}} \approx \begin{cases} 0.96^{+0.39}_{-0.31} \\ 0.86^{+0.35}_{-0.27} \end{cases}$$

总结展望

- 中性B介子衰变到$J/\psi f_1$和$\eta_c f_1$的大分支比易被实验探测到。在两个参考角度下得到的理论结果在误差范围内基本一致，这表明混合角仍然需要更多不同视角的约束。

- 定义了$B_{d,s}^0 \to (J/\psi, \eta_c) f_1$衰变分支比之间多个有意义的比值，可用于精确确定夸克-味态f_n和f_s之间的混合角φ和研究其中所包含的$SU(3)_F$对称破缺效应。

- 对于含有粲偶素过程的QCDF研究发现，粲偶素中重夸克对色八重态贡献很大，这应该对应于一些幂次修正贡献，接下来工作可以考虑这一部分贡献。

谢谢各位老师、同学的聆听！

理论框架

$B \to M_2 M_3$衰变振幅的因子化形式为：

$$A(B \to M_2 M_3) \sim \int dx_1 dx_2 dx_3 b_1 db_1 b_2 db_2 b_3 db_3$$

$$\cdot \mathrm{Tr}\left[C(t) \Phi_B(x_1, b_1) \Phi_{M_2}(x_2, b_2) \Phi_{M_3}(x_3, b_3) H(x_i, b_i, t) S_t(x_i) e^{-S(t)} \right].$$

- 第二行的第一项表示Wilson系数；第二到四项表示初末态介子的波函数，属于非微扰部分。
- 第二行的第五项表示可微扰计算的“硬核部分”；最后两项是喷注函数和Sudakov因子，二者一起确保了PQCD方法微扰计算的可靠性。

夸克–味混合方案下，其中非奇异和奇异夸克–味态：

$$\begin{cases} f_n = \dfrac{u\bar{u} + d\bar{d}}{\sqrt{2}} \\ f_s = s\bar{s} \end{cases}$$