河南師範大學
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B介子含粲三体半轻衰变的QED非因子化修正

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[1]Eur. Phys. J. C, 2024, 84: 1282

[2]arXiv: 2502.09883 [hep-ph]

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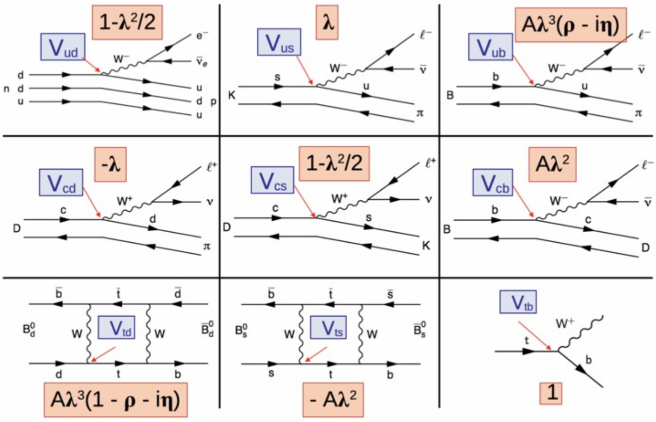
研究动机

1973 年，Kobayashi 和 Maskawa 将 Cabibbo 两代夸克混合和 GIM 机制的思想推广到三代夸克



研究动机

- 通过单举和遍举的B介子半轻衰变得到的$|V_{cb}|$最新值之间的偏差约为3.0σ[3]。

$$
\begin{aligned}
|V_{cb}| &= (42.2 \pm 0.5) \times 10^{-3} \quad \text{(inclusive)}, \\
|V_{cb}| &= (39.8 \pm 0.6) \times 10^{-3} \quad \text{(exclusive)}.
\end{aligned}
$$

- HFLAV最新数值[4]：

$$R(D)_{SM} = 0.296 \pm 0.004, \quad R(D)_{Exp} = 0.342 \pm 0.026.$$

$$R(D^*)_{SM} = 0.254 \pm 0.005, \quad R(D^*)_{Exp} = 0.286 \pm 0.005.$$

在$R(D) - R(D^*)$的联合分布中，测量平均值和标准模型期望值之间的偏差大于 3.0σ。

- 这种现象引起了人们对“轻子味普适性”的关注。

[3]PDG, Phys. Rev. D, 2024, 110: 030001
[4]arXiv: 2411.18639 [hep-ex]

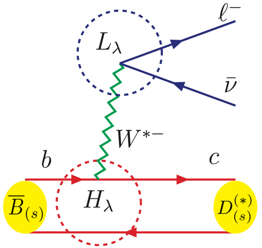


Figure: $\overline{B}_{(s)} \to D^{(*)}_{(s)} + \ell^- + \bar{\nu}_\ell$衰变的费曼图

理论框架

低能有效哈密顿量为：

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb}\, \bar{c}\, \gamma_\mu\, (1-\gamma_5)\, b\, \bar{\ell}\, \gamma^\mu\, (1-\gamma_5)\, \nu_\ell = \frac{G_F}{\sqrt{2}} V_{cb}\, j_{h,\mu}\, j_\ell^\mu,$$

衰变振幅被因子化为两部分，

$$\mathcal{A}_0 = \langle\, D_{(s)}^{(*)}\, \ell^-\, \bar{\nu}_\ell \,|\, \mathcal{H}_{\text{eff}} \,|\, \overline{B}_{(s)} \,\rangle = \frac{G_F}{\sqrt{2}} V_{cb}\, H_\mu\, L^\mu,$$

插入完备性关系：

$$\varepsilon_{W^*}(\lambda) \cdot \varepsilon^*_{W^*}(\lambda') = \varepsilon^\mu_{W^*}(\lambda)\, \varepsilon^{*\,\nu}_{W^*}(\lambda')\, g_{\mu\nu} = g_{\lambda,\lambda'},$$

$$\sum_{\lambda,\lambda'} \varepsilon^\mu_{W^*}(\lambda)\, \varepsilon^{*\,\nu}_{W^*}(\lambda')\, g_{\lambda,\lambda'} = g^{\mu\nu}.$$

螺旋度振幅：

$$H_\lambda = \varepsilon^{*\mu}_W(\lambda)\, H_\mu, \quad L_\lambda = \varepsilon^\nu_W(\lambda)\, L_\nu.$$

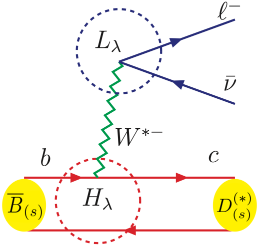


Figure: $\overline{B}_{(s)} \to D_{(s)}^{(*)} + \ell^- + \bar{\nu}_\ell$ 衰变的费曼图

$\overline{B}\to D+\ell^- +\bar{\nu}_\ell$衰变：

$$\langle D\,|\,V^\mu\,|\,B\,\rangle = f_+(q^2)\left[(p_B^\mu+p_D^\mu)-\frac{m_B^2-m_D^2}{q^2}\,q^\mu\right]+f_0(q^2)\,\frac{m_B^2-m_D^2}{q^2}\,q^\mu,$$

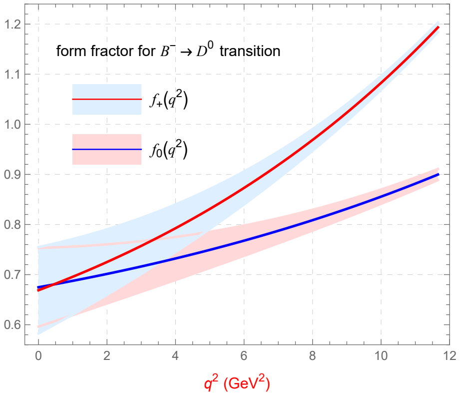
BGL形状因子的参数化[5]为：

$$f_i(z) = \frac{1}{P_i(z)\,\phi_i(z)}\sum_n a_{i,n}\,z^n,$$

螺旋度振幅可表示为：

$$H_\pm = 0,$$
$$H_0 = \frac{2\,m_B\,|\mathbf{p}|}{\sqrt{q^2}}\,f_+(q^2),$$
$$H_t = \frac{m_B^2-m_D^2}{\sqrt{q^2}}\,f_0(q^2).$$

[5]Phys. Rev. D, 2015, 92: 034506



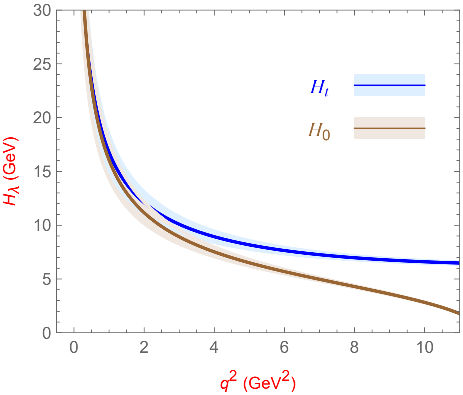


Figure: 形状因子（左边）和螺旋度振幅（右边）随 q^2 变化的形状曲线。

$\overline{B} \to D^* + \ell^- + \bar{\nu}_\ell$衰变:

$$\begin{aligned} \langle D^* | V_\mu | B \rangle &= -i\, \varepsilon_{\mu\nu\alpha\beta}\, \varepsilon_D^{*\,\nu}\, p_B^\alpha\, p_{D^*}^\beta\, g(z), \\ \langle D^* | A_\mu | B \rangle &= \varepsilon_{D^*}^{*\,\nu}\, f(z) + (\varepsilon_D^* \cdot p_B)\{(p_B^\mu + p_{D^*}^\mu)\, a_+(z) + (p_B^\mu - p_{D^*}^\mu)\, a_-(z)\}, \end{aligned}$$

形状因子的组合是:

$$\begin{aligned} 2\, m_{D^*}\, \mathcal{F}_1 &= (m_B^2 - m_{D^*}^2 - q^2)\, f(z) + 4\, m_B^2\, |\mathbf{p}|^2\, a_+(z), \\ m_{D^*}\, \mathcal{F}_2 &= f(z) + (m_B^2 - m_{D^*}^2)\, a_+(z) + q^2\, a_-(z). \end{aligned}$$

BGL形状因子的参数化[6]为:

$$f_i(z) = \frac{1}{P_i(z)\, \phi_i(z)} \sum_n a_{i,n}\, z^n, \quad (f_i = f,\, g,\, \mathcal{F}_1,\, \mathcal{F}_2),$$

螺旋度振幅可表示为:

$$\begin{aligned} H_\pm &= f(z) \mp m_B\, |\mathbf{p}|\, g(z), \\ H_0 &= \frac{1}{\sqrt{q^2}}\, \mathcal{F}_1(z), \\ H_t &= \frac{m_B\, |\mathbf{p}|}{\sqrt{q^2}}\, \mathcal{F}_2(z). \end{aligned}$$

[6]Phys. Rev. D, 2024, 109: 074503

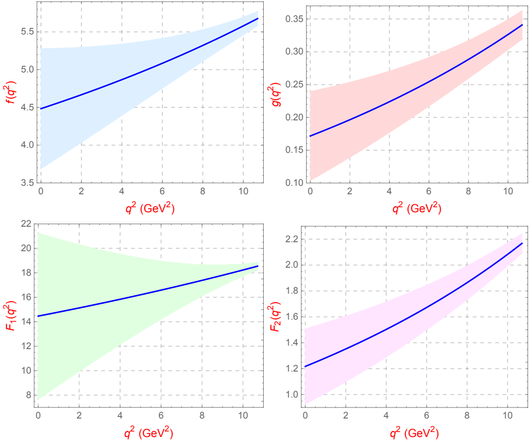


Figure: 形状因子随 q^2 变化的形状曲线

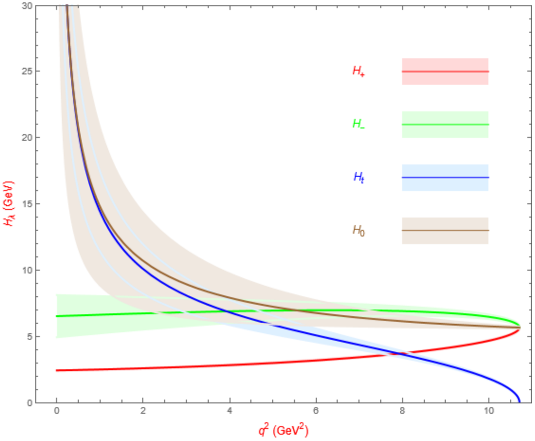


Figure: 螺旋度振幅随 q^2 变化的形状曲线

$\overline{B}_{(s)} \to D_{(s)}^{(*)} + \ell^- + \bar{\nu}_\ell$衰变的微分宽度[7]：

$$\frac{d\,\Gamma}{d\,q^2\;d\cos\theta} = |\eta_{\rm EW}|^2\,\frac{G_F^2\,|V_{cb}|^2\,|\mathbf{p}|\,q^2}{256\,\pi^3\,m_B^2}\left(1-\frac{m_\ell^2}{q^2}\right)^2\Big\{\big[H_U\,(1+\cos^2\theta)+2\,H_L\,\sin^2\theta+2\,H_P\,\cos\theta\big] + \frac{m_\ell^2}{q^2}\,\big[2\,H_S+2\,H_L\,\cos^2\theta+4\,H_{SL}\,\cos\theta+H_U\,\sin^2\theta\big]\Big\},$$

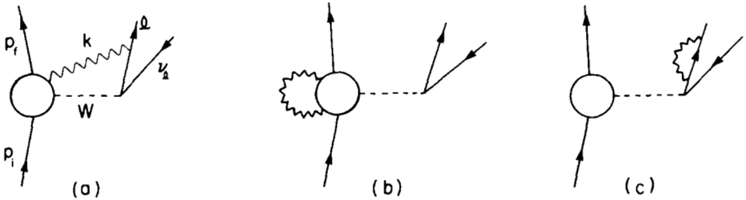
其中：

$$\begin{aligned} H_U &= |H_+|^2+|H_-|^2, \\ H_P &= |H_+|^2-|H_-|^2, \\ H_L &= |H_0|^2, \\ H_S &= |H_t|^2, \\ H_{SL} &= \mathrm{Re}(H_t\,H_0^*). \end{aligned}$$

对$\cos\theta$积分

$$\begin{aligned} \frac{d\,\Gamma}{d\,q^2} &= |\eta_{\rm EW}|^2\,\frac{G_F^2\,|V_{cb}|^2\,|\mathbf{p}|\,q^2}{96\,\pi^3\,m_B^2}\left(1-\frac{m_\ell^2}{q^2}\right)^2\Big\{(H_U+H_L)\left(1+\frac{m_\ell^2}{2\,q^2}\right)+\frac{3\,m_\ell^2}{2\,q^2}\,H_S\Big\} \\ &= |\eta_{\rm EW}|^2\,\frac{G_F^2\,|V_{cb}|^2\,|\mathbf{p}|\,q^2}{96\,\pi^3\,m_B^2}\left(1-\frac{m_\ell^2}{q^2}\right)^2\Big\{(|H_+|^2+|H_-|^2+|H_0|^2)\left(1+\frac{m_\ell^2}{2\,q^2}\right)+\frac{3\,m_\ell^2}{2\,q^2}\,|H_t|^2\Big\}. \end{aligned}$$

[7]Z. Phys. C, 1990, 46: 93-109



$$\eta_{\rm EW} = 1 + \frac{3\alpha_{em}}{4\pi}(1+2\bar{Q})\ln\frac{m_Z}{\mu}.$$

[8]Nucl. Phys. B,1982, 196: 83-92.

QED辐射修正

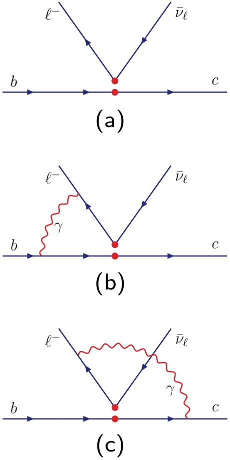


Figure: $b \to c + \ell^- + \bar{\nu}_\ell$衰变的费曼图。

振幅可以修改为：

$$\begin{aligned} \mathcal{A} &= \mathcal{A}_0\, \eta_{\rm EW}, \\ \mathcal{A} &= \mathcal{A}_0\, \tilde{\eta}_{\rm EW} = \mathcal{A}_0\,(1+\alpha_{\rm em}\,\eta) = \mathcal{A}_0\{1+\alpha_{\rm em}\,(\eta_b+\eta_c)\}. \end{aligned}$$

$$\mathcal{M}_{(b)} = j_{h,\mu}\, j_\ell^\mu \left\{ \frac{Q_b\, Q_\ell\, \alpha_{\rm em}}{4\,\pi} \left[\frac{1}{\epsilon_{\rm uv}} - \frac{t_b+s_b}{t_b-s_b} \ln\left(\frac{t_b}{s_b}\right) \frac{1}{\varepsilon_{\rm ir}} \right] + \alpha_{\rm em}\, \eta_b \right\}.$$

$$\eta_b: \quad \ln\left(\frac{t_b}{s_b}\right) = \ln\left(\frac{t_b^2}{s_b t_b}\right) \propto \ln\left(\frac{m_b^2}{m_\ell^2}\right)$$

- $\tilde{\eta}_{\rm EW}$ 是轻子质量、q^2和$\cos\theta$的函数

Table: 不同螺旋度振幅对$B^- \to D^{*0} + \ell + \nu$ 衰变的贡献（以百分比为单位），其中Γ_B 是B^-介子的总宽度，Γ 是所关注的半轻衰变的分宽度，Γ_i，$i = U, L, P, S$。$f_\perp = \Gamma_U/\Gamma, f_L = \Gamma_L/\Gamma, f_S = \Gamma_S/\Gamma$。

case	$f_\perp$	f_L	f_S	$f_L^{\text{exp.}[9]}$
$\ell = e$	49.1	50.9	~ 0	50.5±2.8
$\ell = \mu$	49.1	50.4	0.5	52.2±2.6
$\ell = \tau$	55.4	36.1	8.4	

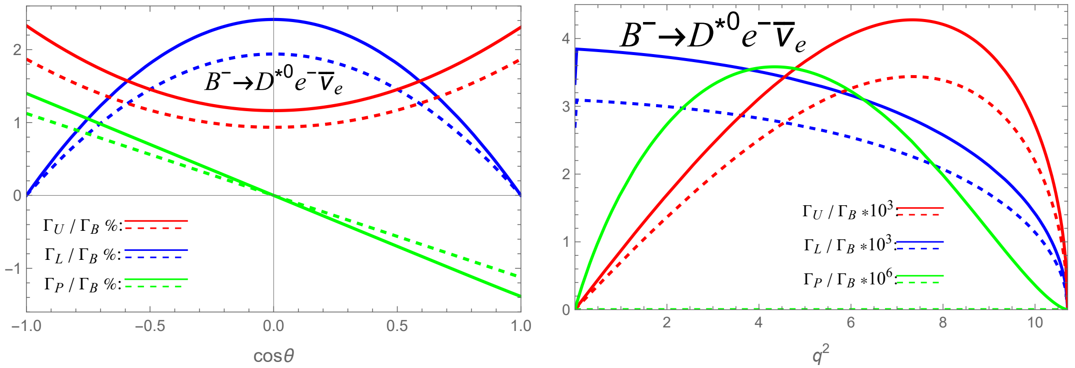


Figure: 不同螺旋度振幅对 $B^- \to D^{*0} + \ell + \nu$ 衰变的贡献，其中实线（虚线）对应于 $\tilde{\eta}_{\text{EW}}$ (η_{EW})的情况。

[9]Phys. Rev. D, 2023, 108: 012002

数值结果与分析

Table: $\overline{B}_{(s)} \to D_{(s)}^{(*)} + \ell^- + \bar{\nu}_\ell$ 半轻衰变的分支比（以百分比为单位）。

decay mode	$\eta_{EW} = 1.0066$	$\tilde{\eta}_{EW}$ (this work)	PDG data
$B^- \to D^0 + e^- + \bar{\nu}$	$2.29^{+0.33}_{-0.31}$	$2.85^{+0.42}_{-0.38}$	2.29 ± 0.08
$B^- \to D^0 + \mu^- + \bar{\nu}$	$2.28^{+0.33}_{-0.30}$	$2.38^{+0.35}_{-0.32}$	2.29 ± 0.08
$B^- \to D^0 + \tau^- + \bar{\nu}$	0.69 ± 0.04	0.69 ± 0.04	0.77 ± 0.25
$\overline{B}^0 \to D^+ + e^- + \bar{\nu}$	$2.14^{+0.31}_{-0.28}$	$2.67^{+0.39}_{-0.35}$	2.25 ± 0.08
$\overline{B}^0 \to D^+ + \mu^- + \bar{\nu}$	$2.13^{+0.31}_{-0.28}$	$2.22^{+0.32}_{-0.29}$	2.25 ± 0.08
$\overline{B}^0 \to D^+ + \tau^- + \bar{\nu}$	0.64 ± 0.04	0.64 ± 0.04	0.99 ± 0.21
$\overline{B}_s^0 \to D_s^+ + e^- + \bar{\nu}$	2.23 ± 0.12	2.77 ± 0.15	−−
$\overline{B}_s^0 \to D_s^+ + \mu^- + \bar{\nu}$	2.22 ± 0.12	$2.31^{+0.13}_{-0.12}$	2.31 ± 0.21
$\overline{B}_s^0 \to D_s^+ + \tau^- + \bar{\nu}$	0.66 ± 0.04	0.67 ± 0.04	−−
$B^- \to D^{*0} + e^- + \bar{\nu}$	$5.08^{+1.73}_{-1.34}$	$6.32^{+2.15}_{-1.67}$	5.58 ± 0.26
$B^- \to D^{*0} + \mu^- + \bar{\nu}$	$5.06^{+1.70}_{-1.33}$	$5.27^{+1.78}_{-1.38}$	5.58 ± 0.26
$B^- \to D^{*0} + \tau^- + \bar{\nu}$	$1.28^{+0.19}_{-0.17}$	$1.28^{+0.19}_{-0.17}$	1.88 ± 0.20
$\overline{B}^0 \to D^{*+} + e^- + \bar{\nu}$	$4.85^{+1.64}_{-1.28}$	$6.04^{+2.05}_{-1.59}$	5.11 ± 0.15
$\overline{B}^0 \to D^{*+} + \mu^- + \bar{\nu}$	$4.83^{+1.62}_{-1.26}$	$5.04^{+1.69}_{-1.31}$	5.11 ± 0.15
$\overline{B}^0 \to D^{*+} + \tau^- + \bar{\nu}$	$1.22^{+0.18}_{-0.16}$	$1.22^{+0.18}_{-0.16}$	1.48 ± 0.18
$\overline{B}_s^0 \to D_s^{*+} + e^- + \bar{\nu}$	$5.09^{+2.24}_{-1.64}$	$6.33^{+2.79}_{-2.04}$	−−
$\overline{B}_s^0 \to D_s^{*+} + \mu^- + \bar{\nu}$	$5.06^{+2.20}_{-1.62}$	$5.28^{+2.30}_{-1.69}$	5.20 ± 0.50
$\overline{B}_s^0 \to D_s^{*+} + \tau^- + \bar{\nu}$	$1.26^{+0.26}_{-0.23}$	$1.26^{+0.26}_{-0.23}$	−−

数值结果与分析

Table: $\overline{B}_{(s)} \to D_{(s)}^{(*)} + \ell^- + \bar{\nu}_\ell$ 半轻衰变的分支比（以百分比为单位）。

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$\overline{B}^0 \to D^+ + \tau^- + \bar{\nu}$	0.64 ± 0.04	0.64 ± 0.04	0.99 ± 0.21
$\overline{B}_s^0 \to D_s^+ + e^- + \bar{\nu}$	2.23 ± 0.12	2.77 ± 0.15	$--$
$\overline{B}_s^0 \to D_s^+ + \mu^- + \bar{\nu}$	2.22 ± 0.12	$2.31^{+0.13}_{-0.12}$	2.31 ± 0.21
$\overline{B}_s^0 \to D_s^+ + \tau^- + \bar{\nu}$	0.66 ± 0.04	0.67 ± 0.04	$--$
$B^- \to D^{*0} + e^- + \bar{\nu}$	$5.08^{+1.73}_{-1.34}$	$6.32^{+2.15}_{-1.67}$	5.58 ± 0.26
$B^- \to D^{*0} + \mu^- + \bar{\nu}$	$5.06^{+1.70}_{-1.33}$	$5.27^{+1.78}_{-1.38}$	5.58 ± 0.26
$B^- \to D^{*0} + \tau^- + \bar{\nu}$	$1.28^{+0.19}_{-0.17}$	$1.28^{+0.19}_{-0.17}$	1.88 ± 0.20
$\overline{B}^0 \to D^{*+} + e^- + \bar{\nu}$	$4.85^{+1.64}_{-1.28}$	$6.04^{+2.05}_{-1.59}$	5.11 ± 0.15
$\overline{B}^0 \to D^{*+} + \mu^- + \bar{\nu}$	$4.83^{+1.62}_{-1.26}$	$5.04^{+1.69}_{-1.31}$	5.11 ± 0.15
$\overline{B}^0 \to D^{*+} + \tau^- + \bar{\nu}$	$1.22^{+0.18}_{-0.16}$	$1.22^{+0.18}_{-0.16}$	1.48 ± 0.18
$\overline{B}_s^0 \to D_s^{*+} + e^- + \bar{\nu}$	$5.09^{+2.24}_{-1.64}$	$6.33^{+2.79}_{-2.04}$	$--$
$\overline{B}_s^0 \to D_s^{*+} + \mu^- + \bar{\nu}$	$5.06^{+2.20}_{-1.62}$	$5.28^{+2.30}_{-1.69}$	5.20 ± 0.50
$\overline{B}_s^0 \to D_s^{*+} + \tau^- + \bar{\nu}$	$1.26^{+0.26}_{-0.23}$	$1.26^{+0.26}_{-0.23}$	$--$

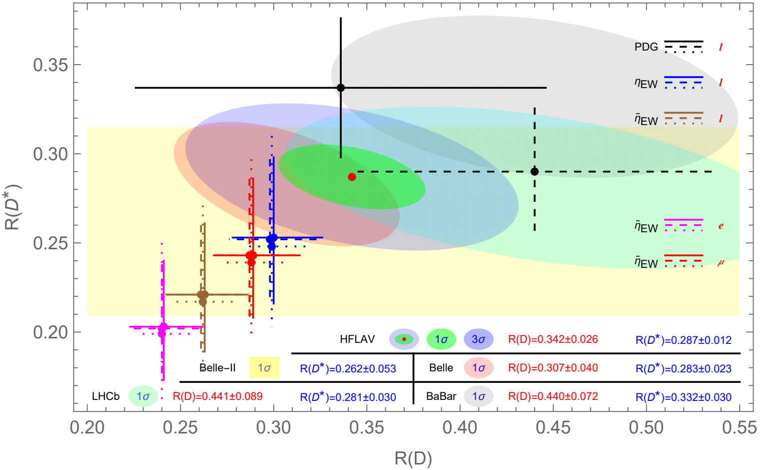

Figure: $R(D)$-$R(D^*)$的联合分布，其中的点和线分别对应于中心值和误差。实线（虚线、点线）分别对应于从$\overline{B}^0$(B^-、$\overline{B}_s^0$)介子半轻衰变中得到的比值。$R(D^{(*)})_\ell$的下标$\ell = e$和μ。

总结和展望

- $\tilde{\eta}_{\text{EW}}$ 是与轻子质量、转移动量 q^2 和角变量 $\cos\theta$ 相关的函数，这导致在没有引入新物理的情况下有效耦合自然地依赖于具体的衰变过程。
- $\tilde{\eta}_{\text{EW}}$ 对分支比的贡献会随着带电轻子的质量而发生变化。带电轻子质量越小，对分支比的增强效果就越大，对于含陶子的半轻衰变，$\tilde{\eta}_{\text{EW}}$ 效果可以忽略不计。这就导致了 $R(D^{(*)})$ 的减小，并有关系 $R(D^{(*)})_e < R(D^{(*)})_\mu$。
- 分支比的主要理论不确定性来自 $B_{(s)} \to D_{(s)}^{(*)}$ 跃迁形状因子。

感谢各位老师、同学
批评指正！

Table: $\overline{B}_{(s)} \to D_{(s)}^{(*)} + \ell^- + \bar{\nu}_\ell$ 半轻衰变的分支比比值，其中理论不确定性仅来自形状因子。

ratios	$\eta_{\rm EW} = 1.0066$	$\tilde{\eta}_{\rm EW}$ (this work)	PDG data	HFLAV
$R(D^0)_e$	$0.300^{+0.026}_{-0.022}$	$0.241^{+0.021}_{-0.018}$		
$R(D^0)_\mu$	$0.301^{+0.026}_{-0.022}$	$0.289^{+0.025}_{-0.021}$	0.336 ± 0.110	
$R(D^0)_\ell$	$0.300^{+0.026}_{-0.022}$	$0.263^{+0.023}_{-0.019}$		
$R(D^+)_e$	$0.298^{+0.025}_{-0.022}$	$0.240^{+0.020}_{-0.018}$		
$R(D^+)_\mu$	$0.299^{+0.025}_{-0.022}$	$0.287^{+0.024}_{-0.021}$	0.440 ± 0.095	0.342 ± 0.026
$R(D^+)_\ell$	$0.298^{+0.025}_{-0.022}$	$0.261^{+0.022}_{-0.019}$		
$R(D_s^+)_e$	$0.298^{+0.019}_{-0.016}$	$0.240^{+0.015}_{-0.013}$		
$R(D_s^+)_\mu$	$0.299^{+0.018}_{-0.016}$	$0.288^{+0.017}_{-0.016}$	$--$	
$R(D_s^+)_\ell$	$0.299^{+0.018}_{-0.016}$	$0.262^{+0.016}_{-0.015}$		
$R(D^{*0})_e$	$0.252^{+0.046}_{-0.037}$	$0.203^{+0.037}_{-0.030}$		
$R(D^{*0})_\mu$	$0.253^{+0.045}_{-0.036}$	$0.243^{+0.043}_{-0.035}$	0.337 ± 0.039	
$R(D^{*0})_\ell$	$0.253^{+0.045}_{-0.037}$	$0.221^{+0.040}_{-0.032}$		
$R(D^{*+})_e$	$0.251^{+0.045}_{-0.037}$	$0.202^{+0.036}_{-0.029}$		
$R(D^{*+})_\mu$	$0.252^{+0.045}_{-0.036}$	$0.243^{+0.043}_{-0.035}$	0.290 ± 0.036	0.287 ± 0.012
$R(D^{*+})_\ell$	$0.252^{+0.045}_{-0.036}$	$0.221^{+0.039}_{-0.032}$		
$R(D_s^{*+})_e$	$0.248^{+0.063}_{-0.046}$	$0.199^{+0.051}_{-0.037}$		
$R(D_s^{*+})_\mu$	$0.249^{+0.061}_{-0.045}$	$0.239^{+0.058}_{-0.043}$	$--$	
$R(D_s^{*+})_\ell$	$0.248^{+0.062}_{-0.045}$	$0.217^{+0.054}_{-0.040}$		

Table: 不同螺旋度振幅对$B^- \to D^{*0} + \ell + \nu$ 衰变的贡献（以百分比为单位），其中Γ_B 是B^-介子的总宽度，Γ 是所关注的半轻衰变的分宽度，Γ_i，$i = U, L, P, S$。$f_\perp = \Gamma_U/\Gamma$,$f_L = \Gamma_L/\Gamma$,$f_S = \Gamma_S/\Gamma$。

case		Γ_U/Γ_B	Γ_L/Γ_B	Γ_P/Γ_B	Γ_S/Γ_B	Γ/Γ_B	$f_\perp$	f_L	f_S	$f_L^{\text{exp.}}$
$\ell = e$	$\eta_{\rm EW}$	2.494	2.587	—	~ 0	5.081	49.1	50.9	~ 0	50.5±2.8
	$\tilde{\eta}_{\rm EW}$	3.100	3.218	0.0025	~ 0	6.320	49.1	50.9	~ 0	
$\ell = \mu$	$\eta_{\rm EW}$	2.485	2.551	—	0.023	5.059	49.1	50.4	0.5	52.2±2.6
	$\tilde{\eta}_{\rm EW}$	2.588	2.658	0.0019	0.024	5.272	49.1	50.4	0.5	
$\ell = \tau$	$\eta_{\rm EW}$	0.710	0.463	—	0.108	1.281	55.4	36.1	8.4	
	$\tilde{\eta}_{\rm EW}$	0.711	0.464	~ 0	0.108	1.283	55.4	36.2	8.4	

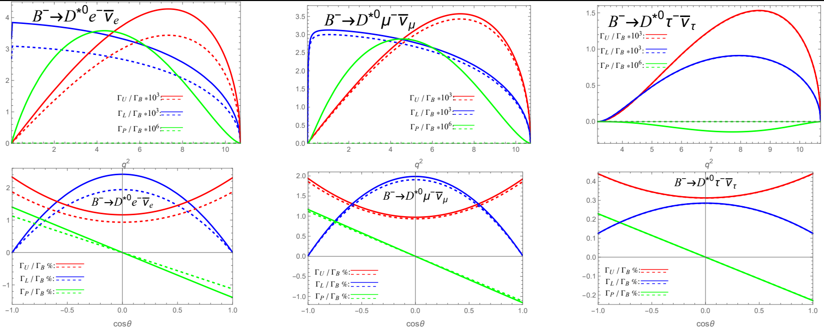

Figure: 不同螺旋度振幅对 $B^- \to D^{*0} + \ell + \nu$ 衰变的贡献，其中实线（虚线）对应于 $\tilde{\eta}_{\rm EW}$ ($\eta_{\rm EW}$)的情况。