

矢量粲介子非轻弱衰变的唯象学研究

学科、专业 : 物理学、粒子物理与原子核物理

申请学位 : 理学硕士

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May 07, 2023

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研究背景与意义

● 事例数

Table: 在未来的实验中, D_s^* 和 D^* 介子的潜在的衰变事例数, 其中 $Br(Z^0 \rightarrow c\bar{c}) \simeq 12\%$, $f(c \rightarrow D_s^*) \simeq 5.5\%$, $f(c \rightarrow D^{*+}) \simeq 25\%$, $f(c \rightarrow D^{*0}) \simeq 23\%$, $Br(Z^0 \rightarrow D^{*0}X/\bar{D}^{*0}X) = Br(Z^0 \rightarrow D^{*\pm}X) = (11.4 \pm 1.3)\%$ 。

experiment	$N_{D_s^*}$	N_{D^*}	remarks
STCF	10^{10}	8×10^{10}	with 10 ab^{-1} data
SuperKEKB	5.5×10^9	2×10^{10}	with 5×10^{10} charm quark pairs
CEPC	1.3×10^{10}	10^{11}	from 10^{12} Z^0 boson decays
FCC-ee	1.3×10^{11}	10^{12}	from 10^{13} Z^0 boson decays
LHCb@HL-LHC	4×10^{13}	2×10^{14}	with 300 fb^{-1} data



X. R. Lyu. (STCF Working Group). PoS BEAUTY2020, 060 (2021).



E. Kou, P. Urquijo, W. Altmannshofer, *et al.* (Belle-II). PTEP 2019, 123C01 (2019); [erratum: PTEP 2020, 029201 (2020)].



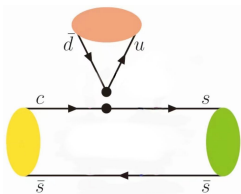
A. Abada, M. Abbrescia, S. S. AbdusSalam, *et al.* (FCC Collaboration). Eur. Phys. J. C 79, 474 (2019).

研究背景与意义

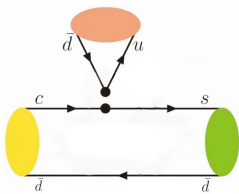
- D_q^* 、 D_s^* 介子主要通过电磁相互作用进行衰变
 - $m_{D^{*0}} = 2010.26 \pm 0.05 \text{ MeV}$
 - $m_{D^{*+}} = 2006.85 \pm 0.05 \text{ MeV}$
 - $m_{D_s^*} = 2112.2 \pm 0.4 \text{ MeV}$
 - $m_{D_{u,d}} + m_K > m_{D_s^*} > m_{D_s} + m_\pi$
- 通过电磁相互作用进行衰变的末态不易被识别

研究背景与意义

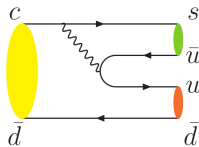
- $D_s^* \rightarrow \phi\pi$, $D^* \rightarrow \bar{K}\pi^+$, $\bar{K}^*\pi^+$, $\bar{K}\rho^+$ 衰变末态容易被探测器识别
- $D_s^* \rightarrow \phi\pi$, $D^* \rightarrow \bar{K}\pi^+$, $\bar{K}^*\pi^+$, $\bar{K}\rho^+$ 衰变不存在Cabibbo 压低
- 费曼图



(a)



(b)



(c)

- 低能有效哈密顿量

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cs}^* V_{ud} \{ C_1 O_1 + C_2 O_2 \} + \text{h.c.}$$

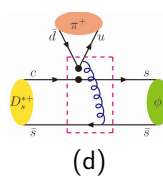
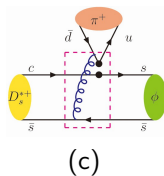
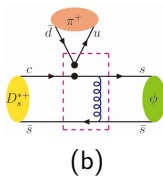
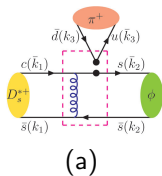
- 衰变振幅

$$\begin{aligned} \mathcal{A}(D_q^* \rightarrow M_1 M_2) &= \langle M_1 M_2 | \mathcal{H}_{\text{eff}} | D_q^* \rangle \\ &= \frac{G_F}{\sqrt{2}} V_{cs}^* V_{ud} \sum_{i=1} C_i(\mu) \langle M_1 M_2 | O_i(\mu) | D_q^* \rangle \end{aligned}$$

- 在 pQCD 方法下, $D_s^* \rightarrow \phi \pi$ 衰变的强子矩阵元一般写为:

$$\langle \phi \pi | O_i | D_s^* \rangle \propto \int dx_1 dx_2 dx_3 db_1 db_2 db_3 H_i(t_i, x_1, x_2, x_3, b_1, b_2, b_3) \\ \phi_{D_s^*}(x_1, b_1) e^{-S_{D_s^*}} \phi_\phi(x_2, b_2) e^{-S_\phi} \phi_\pi(x_3, b_3) e^{-S_\pi}$$

- 费曼图



研究方法

- 分支比

$$Br(D_s^* \rightarrow \phi \pi) = \frac{1}{24 \pi} \frac{p_{\text{c.m.}}}{m_{D_s^*}^2 \Gamma_{D_s^*}} \{ |\mathcal{M}_0|^2 + |\mathcal{M}_{\parallel}|^2 + |\mathcal{M}_{\perp}|^2 \}$$

$$\Gamma(D_s^* \rightarrow D_s \gamma) = \frac{4}{3} \alpha_{\text{em}} k_{\gamma}^3 \mu_{D_s^* D_s}^2 \approx 0.36 \text{ keV}$$

Table: $D_s^* \rightarrow \phi \pi$ 衰变过程的分支比数值结果

	<i>PQCD</i>	<i>NF</i>
$D_s^* \rightarrow \phi \pi$	$(1.51) \times 10^{-7}$	$(2.6) \times 10^{-7}$

研究方法

- 衰变振幅

$$\begin{aligned}\mathcal{A}(D_s^* \rightarrow \phi\pi) &= \langle \phi\pi | \mathcal{H}_{\text{eff}} | D_s^* \rangle \\ &= \frac{G_F}{\sqrt{2}} V_{cs}^* V_{ud} a_1 \langle \phi\pi | (\bar{s}c)_{V-A} (\bar{u}d)_{V-A} | D_s^* \rangle \\ &= \frac{G_F}{\sqrt{2}} V_{cs}^* V_{ud} a_1 \langle \pi | (\bar{u}d)_{V-A} | 0 \rangle \langle \phi | (\bar{s}c)_{V-A} | D_s^* \rangle\end{aligned}$$

- 衰变常数

$$\langle 0 | \bar{d}\gamma_\mu u | \pi^+(p) \rangle = 0$$

$$\langle 0 | \bar{d}\gamma_\mu \gamma_5 u | \pi^+(p) \rangle = if_\pi p_\mu$$

● 形状因子

$$\begin{aligned}
 & \langle \phi(\epsilon_2, p_2) | \bar{s} \gamma_\mu c | D_s^*(\epsilon_1, p_1) \rangle \\
 = & -(\epsilon_1 \cdot \epsilon_2^*) \left\{ P_\mu V_1(q^2) - q_\mu V_2(q^2) \right\} - (\epsilon_1 \cdot q) \epsilon_{2,\mu}^* V_5(q^2) + (\epsilon_2^* \cdot q) \epsilon_{1,\mu} V_6(q^2) \\
 & + \frac{(\epsilon_1 \cdot q)(\epsilon_2^* \cdot q)}{m_{D_s^*}^2 - m_\phi^2} \left\{ \left[P_\mu - \frac{m_{D_s^*}^2 - m_\phi^2}{q^2} q_\mu \right] V_3(q^2) + \frac{m_{D_s^*}^2 - m_\phi^2}{q^2} q_\mu V_4(q^2) \right\}, \\
 & \langle \phi(\epsilon_2, p_2) | \bar{s} \gamma_\mu \gamma_5 c | D_s^*(\epsilon_1, p_1) \rangle \\
 = & -i \varepsilon_{\mu\nu\alpha\beta} \epsilon_1^\alpha \epsilon_2^{*\beta} \left\{ \left[P^\nu - \frac{m_{D_s^*}^2 - m_\phi^2}{q^2} q^\nu \right] A_1(q^2) + \frac{m_{D_s^*}^2 - m_\phi^2}{q^2} q^\nu A_2(q^2) \right\} \\
 & - \frac{i \varepsilon_{\mu\nu\alpha\beta} P^\alpha q^\beta}{m_{D_s^*}^2 - m_\phi^2} \left\{ (\epsilon_2^* \cdot q) \epsilon_1^\nu A_3(q^2) - (\epsilon_1 \cdot q) \epsilon_2^{*,\nu} A_4(q^2) \right\},
 \end{aligned}$$

结果与分析

Table: 在极点 $q_2 = 0$ 处的衰变常数和形状因子的数值。

$f_\pi = 130.2 \pm 1.2 \text{ MeV}$	$f_K = 155.7 \pm 0.3 \text{ MeV}$	$f_\rho = 207.7 \pm 1.6 \text{ MeV}$	$f_{K^*} = 202.5^{+6.5}_{-6.7} \text{ MeV}$
$V_1^{D^*\rho} = 0.65$	$V_2^{D^*\rho} = 0.51$	$V_3^{D^*\rho} = 0.29$	$V_5^{D^*\rho} = 1.42$
$V_6^{D^*\rho} = 0.68$	$A_1^{D^*\rho} = 0.59$	$A_3^{D^*\rho} = 0.22$	$A_4^{D^*\rho} = 0.24$
$V_1^{D^*K^*} = 0.74$	$V_2^{D^*K^*} = 0.43$	$V_3^{D^*K^*} = 0.26$	$V_5^{D^*K^*} = 1.50$
$V_6^{D^*K^*} = 0.78$	$A_1^{D^*K^*} = 0.69$	$A_3^{D^*K^*} = 0.15$	$A_4^{D^*K^*} = 0.22$
$V^{D^*\pi} = 0.92$	$A_0^{D^*\pi} = 0.68$	$A_1^{D^*\pi} = 0.74$	$A_2^{D^*\pi} = 0.61$
$V^{D^*K} = 1.04$	$A_0^{D^*K} = 0.78$	$A_1^{D^*K} = 0.85$	$A_2^{D^*K} = 0.68$
$V_1^{D_s^*\phi} = 0.71$	$V_2^{D_s^*\phi} = 0.38$	$V_3^{D_s^*\phi} = 0.28$	$V_5^{D_s^*\phi} = 1.54$
$V_6^{D_s^*\phi} = 0.86$	$A_1^{D_s^*\phi} = 0.65$	$A_3^{D_s^*\phi} = 0.16$	$A_4^{D_s^*\phi} = 0.27$



Q. Chang, L. T. Wang and X. N. Li. JHEP 12, 102 (2019).

结果与分析

- 分支比

$$Br = \frac{G_F^2}{48\pi} |V_{cs}|^2 |V_{ud}|^2 \frac{p_{cm}}{m_{D_q^*}^2 \Gamma_{D_q^*}} \sum_{s_i} \mathcal{M} \mathcal{M}^\dagger$$

Table: $D^* \rightarrow PP$ PV 衰变过程的分支比数值结果

mode	Br	mode	Br
$D^{*+} \rightarrow \bar{K}^0 \pi^+$	1.6×10^{-10}	$D^{*+} \rightarrow \bar{K}^{*0} \pi^+$	4.4×10^{-10}
$D^{*+} \rightarrow \bar{K}^0 \rho^+$	8.3×10^{-10}		
$D^{*0} \rightarrow K^- \pi^+$	7.3×10^{-10}	$D^{*0} \rightarrow K^{*-} \pi^+$	2.0×10^{-9}
$D^{*0} \rightarrow K^- \rho^+$	2.9×10^{-9}		

结果与分析

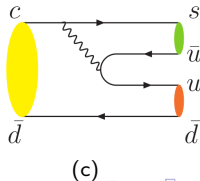
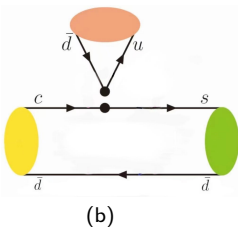
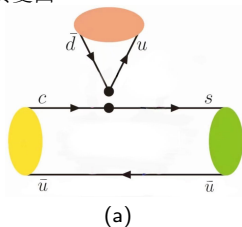
● 衰变宽度

$$\Gamma_{D^{*+}} = 83.4 \pm 1.8 \text{ keV}$$

$$\frac{\Gamma(D^{*0} \rightarrow D^0 \pi^0)}{\Gamma(D^{*+} \rightarrow D^+ \pi^0)} = \frac{p_{\text{cm} D^0 \pi^0}^3}{p_{\text{cm} D^+ \pi^0}^3} \frac{m_{D^{*+}}^2}{m_{D^{*0}}^2}$$

$$\Gamma_{D^{*0}} = \Gamma_{D^{*+}} \frac{\text{Br}(D^{*+} \rightarrow D^+ \pi^0)}{\text{Br}(D^{*0} \rightarrow D^0 \pi^0)} \frac{p_{\text{cm} D^0 \pi^0}^3}{p_{\text{cm} D^+ \pi^0}^3} \frac{m_{D^{*+}}^2}{m_{D^{*0}}^2} = 55.9_{-5.4}^{+5.9} \text{ keV}$$

● 费曼图



总结与展望

● 事例数

Table: 在未来实验中, $D^* \rightarrow \bar{K}\pi^+$ 、 $\bar{K}\rho^+$ 、 $\bar{K}^*\pi^+$, $D_s^* \rightarrow \phi\pi$ 衰变的事例数。

experiment	SuperKEKB	STCF	CEPC	FCC-ee	LHCb@HL-LHC
N_{D^*}	2×10^{10}	8×10^{10}	10^{11}	10^{12}	2×10^{14}
$N_{D_s^*}$	5.5×10^9	10^{10}	1.3×10^{10}	1.3×10^{11}	4×10^{13}
$N_{D^{*+} \rightarrow \bar{K}^0 \pi^+}$	3	13	16	160	3.2×10^4
$N_{D^{*+} \rightarrow \bar{K}^{*0} \pi^+}$	9	35	44	440	8.8×10^4
$N_{D^{*+} \rightarrow \bar{K}^0 \rho^+}$	17	66	83	830	1.66×10^5
$N_{D^{*0} \rightarrow K^- \pi^+}$	14	58	72	720	1.44×10^5
$N_{D^{*0} \rightarrow K^{*-} \pi^+}$	40	160	200	2000	4.0×10^5
$N_{D^{*0} \rightarrow K^- \rho^+}$	57	230	287	2870	5.74×10^5
$N_{D_s^* \rightarrow \phi \pi^+}$	800	1500	2000	1.0×10^4	6.0×10^6

感谢各位老师和同学！