



STCF上陶轻子和粲强 子的CP破坏研究

《CP violation studies at Super tau-charm facility》

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CP破坏研究专题

CP violation studies at Super tau-charm facility

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Abstract

Charge-parity (CP) violation in tau-charm energy region is one of the promising areas to search for. The future tau-charm facility of next generation is designed to operate in a center-of-mass energy from 2.0 to 7.0 GeV with a peak luminosity of $0.5 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$. Huge amount of hadrons or τ leptons will be collected with well kinematic constraint and low-background environment. In this report, possibilities of CP violation studies in tau-charm energy region and at the future tau-charm facility are discussed from various aspects, i.e. in the production and decay of hyperons and τ lepton; in the decay of charmed hadrons. We also study the combined symmetry of CP and time reversal T , CPT invariance test in $K^0 - \bar{K}^0$ mixing.

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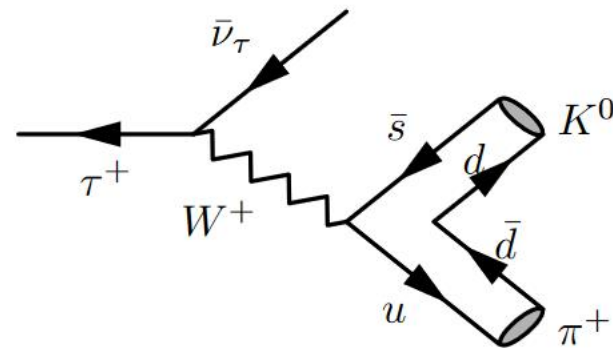
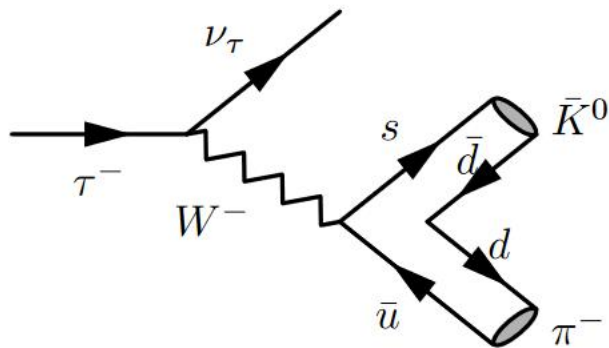
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Not complete overview!

τ 轻子的CP破坏

$$\tau \rightarrow K_S^0 \pi \nu_\tau$$

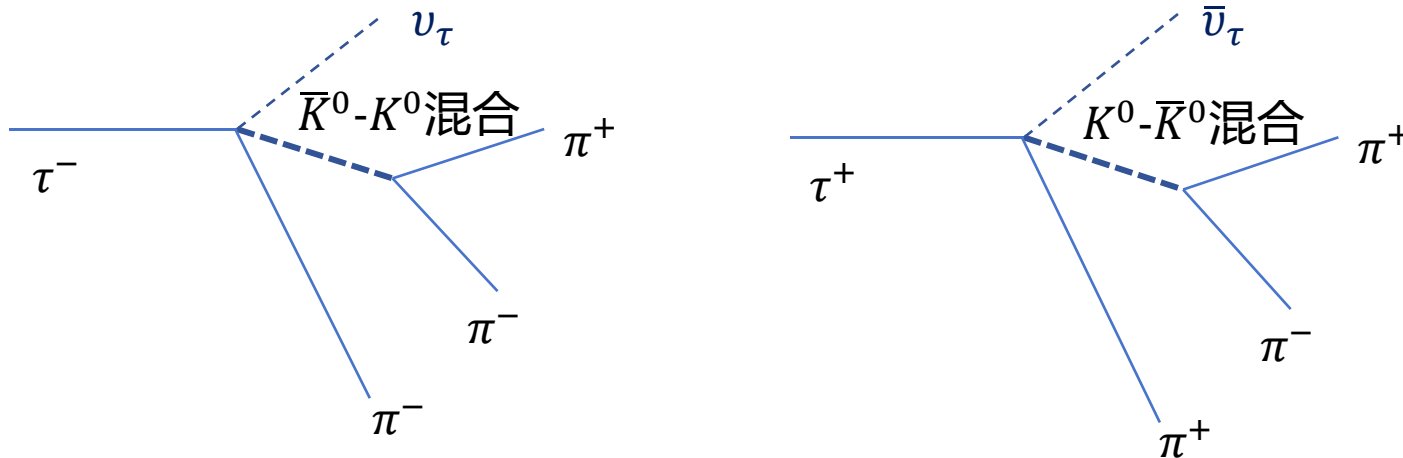
$\tau \rightarrow K^0 \pi \nu_\tau$ 衰变



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- CP不变, V_{us} 为实数且两过程中的强相位相等
- 不存在直接CP破坏: $A(\tau^- \rightarrow \bar{K}^0 \pi^- \nu_\tau) = A(\tau^+ \rightarrow K^0 \pi^+ \bar{\nu}_\tau)$

$\tau \rightarrow K_S^0 \pi \nu_\tau$ 衰变中的CP不对称



$$|\mathcal{T}_-(\tau)|^2 \simeq \frac{B(1 + 2\text{Re}[\epsilon])}{4M_S^2} [e^{-\Gamma_S \tau} + |\epsilon|^2 e^{-\Gamma_L \tau} - 2|\epsilon| e^{-\frac{1}{2}(\Gamma_S + \Gamma_L)\tau} \cos(\Delta m \tau - \phi_{+-})]$$

$$|\mathcal{T}_+(\tau)|^2 \simeq \frac{B(1 - 2\text{Re}[\epsilon])}{4M_S^2} [e^{-\Gamma_S \tau} + |\epsilon|^2 e^{-\Gamma_L \tau} + 2|\epsilon| e^{-\frac{1}{2}(\Gamma_S + \Gamma_L)\tau} \cos(\Delta m \tau - \phi_{+-})],$$

实验观测量

$$A_{+-}(\tau) = \frac{|\mathcal{T}_-(\tau)|^2 - |\mathcal{T}_+(\tau)|^2}{|\mathcal{T}_-(\tau)|^2 + |\mathcal{T}_+(\tau)|^2}$$

ϵ 、 ϕ : CP破坏参数

$$\simeq 2\text{Re}[\epsilon] \left[\frac{-\frac{1}{\cos \phi_{+-}} e^{-1/2(\Gamma_S + \Gamma_L)\tau} \cos(\Delta m \tau - \phi_{+-}) + e^{-\Gamma_S \tau} + |\epsilon|^2 e^{-\Gamma_L \tau}}{e^{-\Gamma_S \tau} + |\epsilon|^2 e^{-\Gamma_L \tau}} \right]$$

$\tau \rightarrow K_S^0 \pi \nu_\tau$ 中CP不对称性理论预言

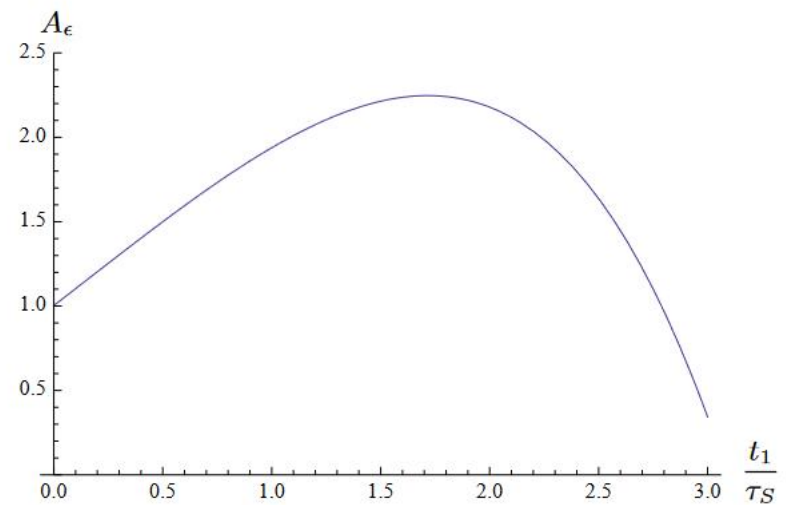
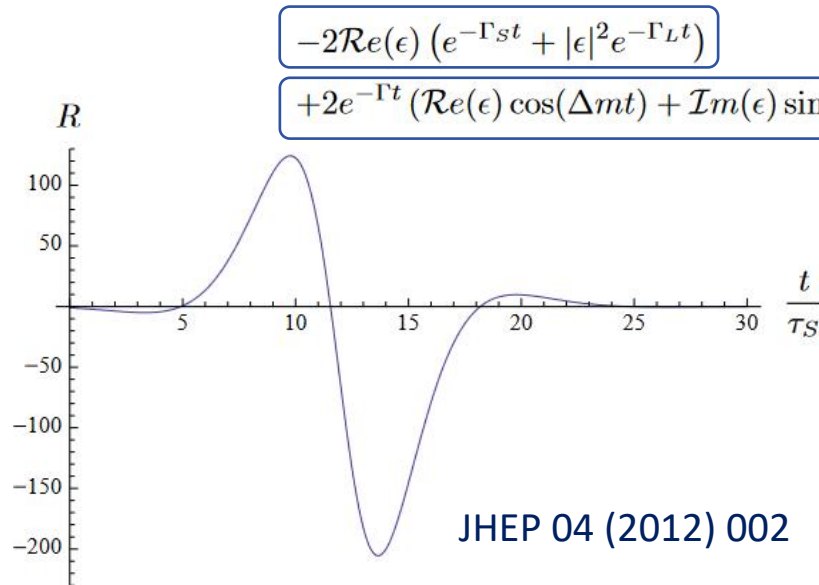
$$A_{CP}^\tau = A_{CP}(\tau^- \rightarrow K_S \pi^- \nu_\tau)$$

$$= \frac{\Gamma(\tau^+ \rightarrow K_S \pi^+ \bar{\nu}_\tau) - \Gamma(\tau^- \rightarrow K_S \pi^- \nu_\tau)}{\Gamma(\tau^+ \rightarrow K_S \pi^+ \bar{\nu}_\tau) + \Gamma(\tau^- \rightarrow K_S \pi^- \nu_\tau)}$$

$$\approx 2\text{Re}(\epsilon) = 0.003192(26)$$

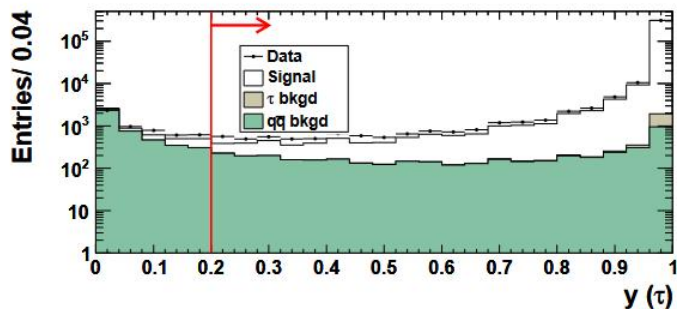
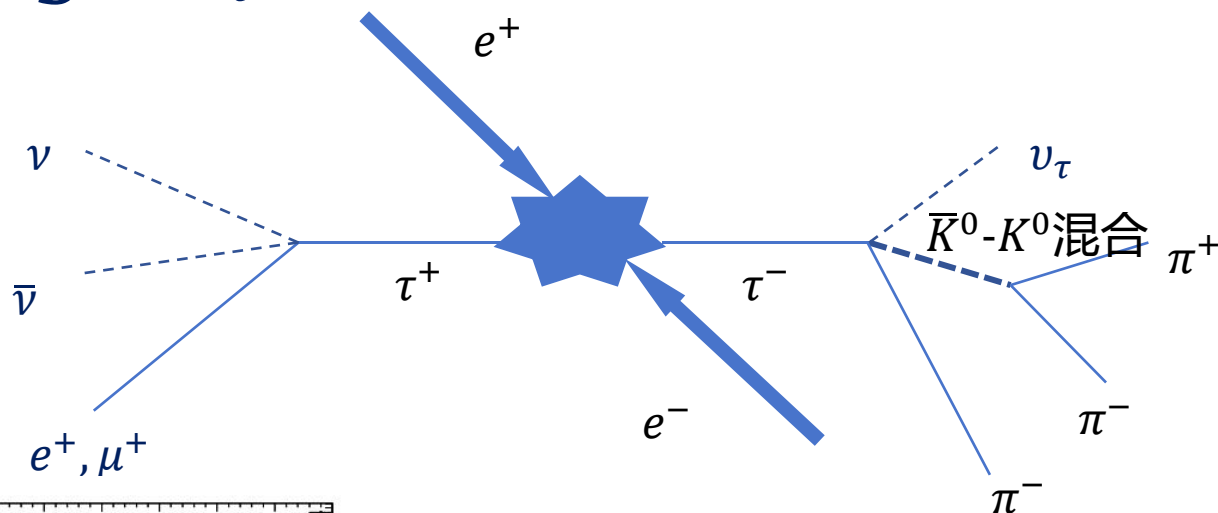
PLB 625 (2005) 47;

PRD 75 (2007) 076001;



实验测量的CP不对称性的大小依赖于 K_S^0 衰变时间
 需要考虑不同 K_S^0 衰变时间的实验探测效率

$\tau \rightarrow K_S^0 \pi \nu_\tau$ 中 CP 不对称性测量



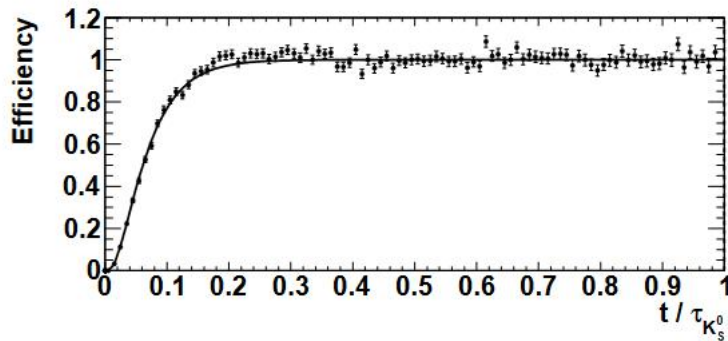
τ 似然函数:
 可见能量
 标记侧中性簇射数目
 Thrust
 横动量

K_S^0 似然函数:
 横向飞行距离
 不变质量
 动量
 极角

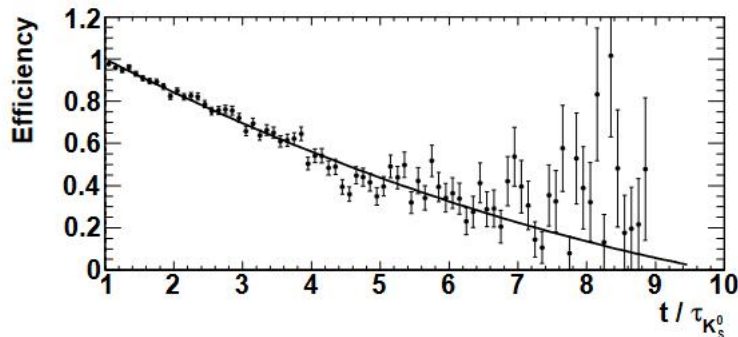


$\tau \rightarrow K_S^0 \pi \nu_\tau$ 中 CP 不对称性测量

	$N(\tau^+)$	$N(\tau^-)$	A_{CP}^τ
e 标记 (78.7%)	99842	99222	$-0.39(23)(13)\%$
μ 标记 (78.4%)	70369	70233	$-0.12(27)(10)\%$



效率修正: 1.08(1)



$$A_{CP,EXP}^\tau = -0.36(23)(11)\%$$

$$A_{CP,SM}^\tau = 0.36(1)\%$$

2.8 σ tension

$\tau \rightarrow K_S^0 \pi \nu_\tau$ 中的角分布

$$d\Gamma_{\tau^-} = \frac{G_F^2}{2m_\tau} \sin^2 \theta_c \frac{1}{(4\pi)^3} \frac{(m_\tau^2 - Q^2)^2}{m_\tau^2} |\vec{q}_1|$$

$$\times \frac{1}{2} \left(\sum_X \bar{L}_X W_X \right) \frac{dQ^2}{\sqrt{Q^2}} \frac{d\cos\theta}{2} \frac{d\alpha}{2\pi} \frac{d\cos\beta}{2}$$

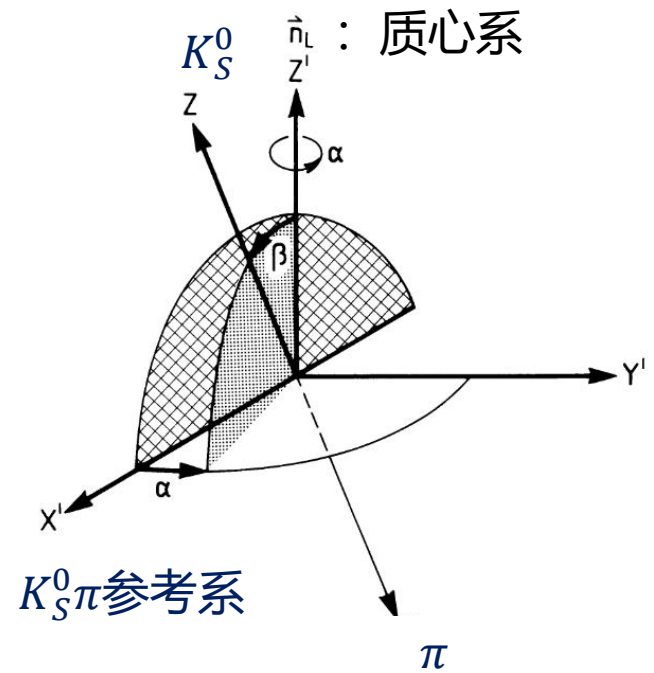
$$\cos\theta = \frac{2xm_\tau^2 - m_\tau^2 - Q^2}{(m_\tau^2 - Q^2)\sqrt{1 - 4m_\tau^2/s}}, \quad x = 2\frac{E_h}{\sqrt{s}}$$

τ 参考系中 $e\bar{e}$ 质心系与 $K_S^0 \pi$ 夹角

实验观测量:

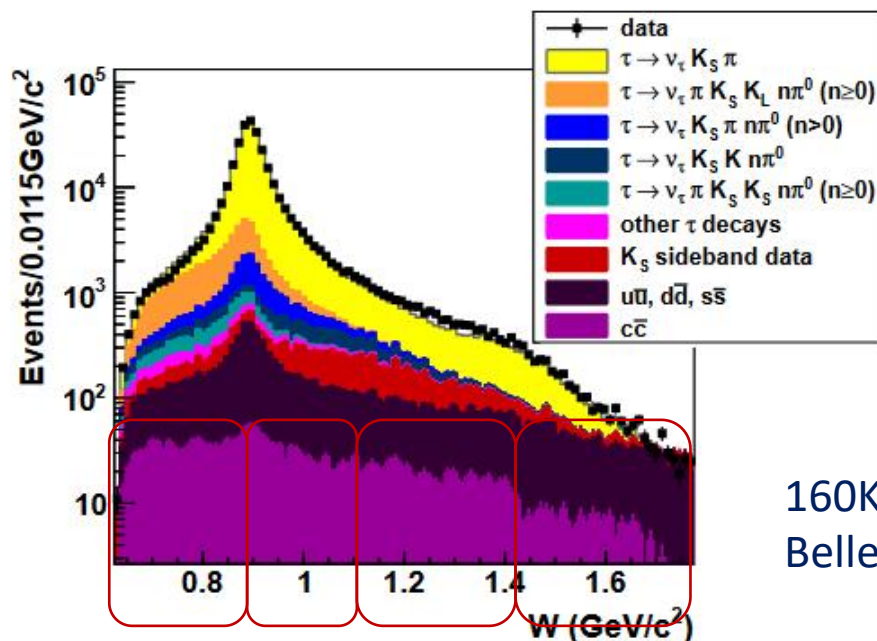
$$A_i^{\text{cp}} = \frac{\iiint_{Q_{1,i}^2}^{Q_{2,i}^2} \cos\beta \cos\psi \left(\frac{d\Gamma_{\tau^-}}{d\omega} - \frac{d\Gamma_{\tau^+}}{d\omega} \right) d\omega}{\frac{1}{2} \iiint_{Q_{1,i}^2}^{Q_{2,i}^2} \left(\frac{d\Gamma_{\tau^-}}{d\omega} + \frac{d\Gamma_{\tau^+}}{d\omega} \right) d\omega}$$

$$\simeq \langle \cos\beta \cos\psi \rangle_{\tau^-}^i - \langle \cos\beta \cos\psi \rangle_{\tau^+}^i$$



see ZPC 56 (1992) 661&PLB 398 (1997) 407 for detail

$\tau \rightarrow K_S^0 \pi \nu_\tau$ 中的角分布测量



160K τ^+/τ^- 事例 (纯度78%)
Belle, PRL 107 (2011) 131801

W (GeV/c^2)	$A^{\text{CP}} (10^{-3})$			$n_i/N_s (\%)$
	Observed	Corrected	Backgr. subtr.	
0.625–0.890	-0.1 ± 2.1	5.2 ± 2.1	$7.9 \pm 3.0 \pm 2.8$	36.53 ± 0.14
0.890–1.110	-2.7 ± 1.7	1.6 ± 1.7	$1.8 \pm 2.1 \pm 1.4$	57.85 ± 0.15
1.110–1.420	-5.1 ± 4.7	-3.5 ± 4.7	$-4.6 \pm 7.2 \pm 1.7$	4.87 ± 0.04
1.420–1.775	9.3 ± 12.1	9.6 ± 12.1	$-2.3 \pm 19.1 \pm 5.5$	0.75 ± 0.02

没有观测到CP不对称

STCF精度预研

STCF快模拟软件

1 ab^{-1} @ 4.26 GeV

$e^+e^- \rightarrow \tau^+\tau^-$ 产生子: KKMC+TAUOLA

$$\tau \rightarrow K_S^0 \pi \nu_\tau: \frac{d\Gamma}{d\sqrt{s}} \propto \frac{1}{s} \left(1 - \frac{s}{m_\tau^2}\right)^2 \left(1 + \frac{2s}{m_\tau^2}\right) P(s) \times \left\{ P^2(s) |F_V|^2 + \frac{3(m_{K_S}^2 - m_\pi^2)^2 |F_S|^2}{4s(1 + \frac{2s}{m_\tau^2})} \right\}$$

$$P(s) = \frac{\sqrt{(s - (m_{K_S} + m_\pi)^2)(s - (m_{K_S} - m_\pi)^2)}}{2\sqrt{s}}$$

$$F_S = a_{K_0^*(800)} \cdot BW_{K_0^*(800)},$$

考虑了标量/矢量形状因子

$$F_V = \frac{BW_{K^*(892)} + a_{K^*(1410)} \cdot BW_{K^*(1410)}}{1 + a_{K^*(1410)}},$$

基于无CP不对称假设

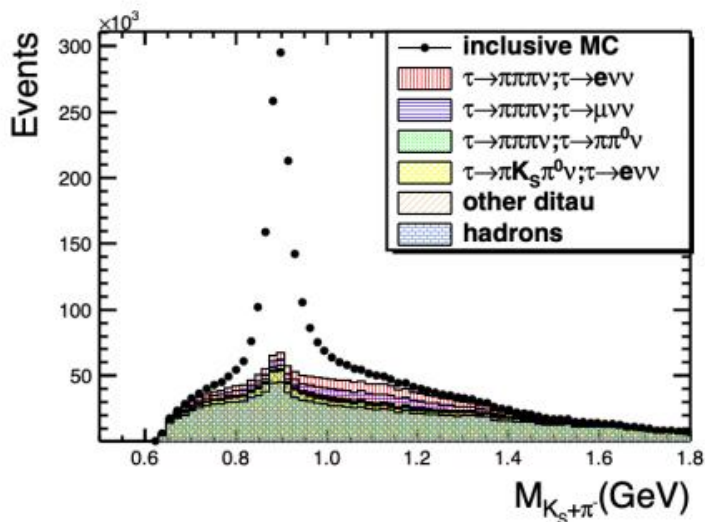
STCF精度预研

• 信号事例重建

$$y_L(\vec{x}) = \frac{L_S(\vec{x})}{L_S(\vec{x}) + L_B(\vec{x})},$$

$$L_{S/B} = \prod_{k=1}^{n_{\text{var}}} P_{S/B,k}(x_k),$$

似然函数比：
 中性簇射数目
 K_S^0 子粒子动量
 K_S^0 飞行距离
 $\pi^+\pi^-$ 不变质量
 K_S^0 顶点拟合优度
 电子E/P
 μ 子极角
 π 动量, $K_S^0\pi$ 动量



~3.7 million τ^+/τ^- 信号事例

$$\delta(A_{CP,EXP}^\tau) \sim 9.7 \times 10^{-4}$$

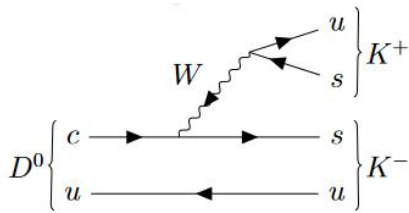
10 ab^{-1} 数据: $\delta(A_{CP,EXP}^\tau) \sim 3 \times 10^{-4}$

$$\delta(A_{CP,SM}^\tau) \sim 1 \times 10^{-4}$$

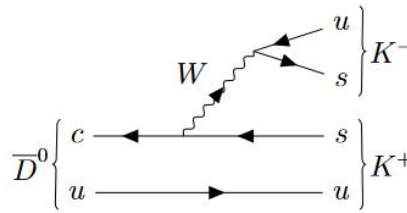
粲强子的CP破坏

直接CP破坏

$$\begin{aligned}
 A(D^0 \rightarrow f) &= A_1 e^{i(\delta_1 + \phi_1)} + A_2 e^{i(\delta_2 + \phi_2)}, & \mathcal{A}_f &\equiv \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow \bar{f})}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow \bar{f})} \\
 A(\bar{D}^0 \rightarrow \bar{f}) &= A_1 e^{i(\delta_1 - \phi_1)} + A_2 e^{i(\delta_2 - \phi_2)}, & &= \frac{-2A_1 A_2 \sin(\delta_2 - \delta_1) \sin(\phi_2 - \phi_1)}{|A_1|^2 + |A_2|^2 + 2A_1 A_2 \cos(\delta_2 - \delta_1) \cos(\phi_2 - \phi_1)}.
 \end{aligned}$$

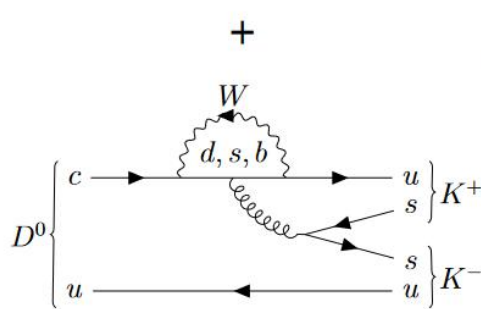


$$A_1 = |A_1| e^{i\delta_1} e^{i\phi_1}$$

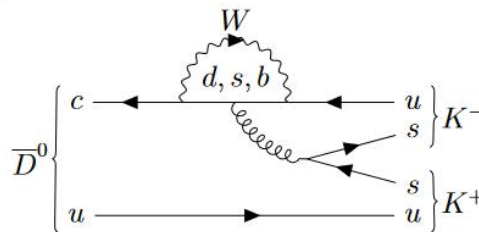


$$\bar{A}_1 = |A_1| e^{i\delta_1} e^{-i\phi_1}$$

CP守恒强相位: $\delta_1 \neq \delta_2$
 CP破缺弱相位: $\phi_1 \neq \phi_2$



$$A_2 = |A_2| e^{i\delta_2} e^{i\phi_2}$$



$$\bar{A}_2 = |A_2| e^{i\delta_2} e^{-i\phi_2}$$

中性粲介子混合

质量本征态: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$

Time evolution of a initially flavour eigenstate D :

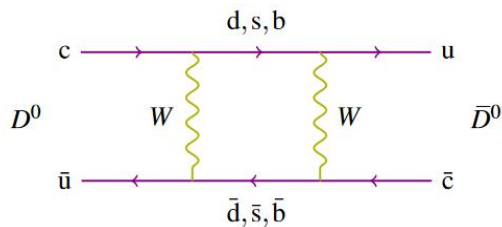
$$\begin{aligned}
 |D_{phys}^0(t)\rangle &= g_+(t)|D^0\rangle + \frac{q}{p}g_-(t)|\bar{D}^0\rangle & g_+(t) &= \exp\left(-\left(im + \frac{\Gamma}{2}\right)t\right) \cosh\left(\left(i\Delta m - \frac{\Delta\Gamma}{2}\right)\frac{t}{2}\right) & m &\equiv \frac{m_1 + m_2}{2}, \Delta m \equiv m_2 - m_1 \\
 |\bar{D}_{phys}^0(t)\rangle &= g_+(t)|\bar{D}^0\rangle + \frac{q}{p}g_-(t)|D^0\rangle & g_-(t) &= \exp\left(-\left(im + \frac{\Gamma}{2}\right)t\right) \sinh\left(\left(i\Delta m - \frac{\Delta\Gamma}{2}\right)\frac{t}{2}\right) & \Gamma &\equiv \frac{\Gamma_1 + \Gamma_2}{2}, \Delta\Gamma \equiv \Gamma_1 - \Gamma_2
 \end{aligned}$$

粲介子混合参数: $x \equiv \frac{\Delta m}{\Gamma}, y \equiv \frac{\Delta\Gamma}{2\Gamma}$

Short distance contributions

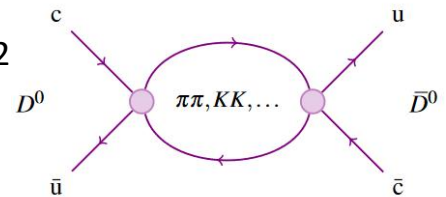
Long distance contributions

loop level $(x, y) \sim 10^{-7}$



$(x, y) \sim 10^{-3}$

Phys. Lett. B 810 (2020) 135802
 Chin. Phys. C 42 (2018) 063101
 Phys. Rev. D 81 (2010) 114020
 Phys. Rev. D 65 (2002) 054034



Plots from arXiv:1503.00032

间接CP破坏

Type 1. 混合CP破坏

$$|D_{phys}^0(t)\rangle = g_+(t)|D^0\rangle + \frac{q}{p}g_-(t)|\bar{D}^0\rangle$$

$$|\bar{D}_{phys}^0(t)\rangle = g_+(t)|\bar{D}^0\rangle + \frac{q}{p}g_-(t)|D^0\rangle$$

Probability of $|D_{phys}^0(t)\rangle \rightarrow |\bar{D}^0\rangle \neq |\bar{D}_{phys}^0(t)\rangle \rightarrow |D^0\rangle$: $\left|\frac{q}{p}\right| \neq 1$

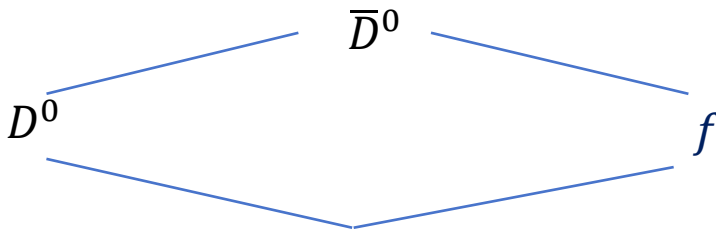
Type 2. 混合和衰变振幅的干涉

Non-vanishing ϕ in $\frac{q}{p} = \left|\frac{q}{p}\right| e^{i\phi}$

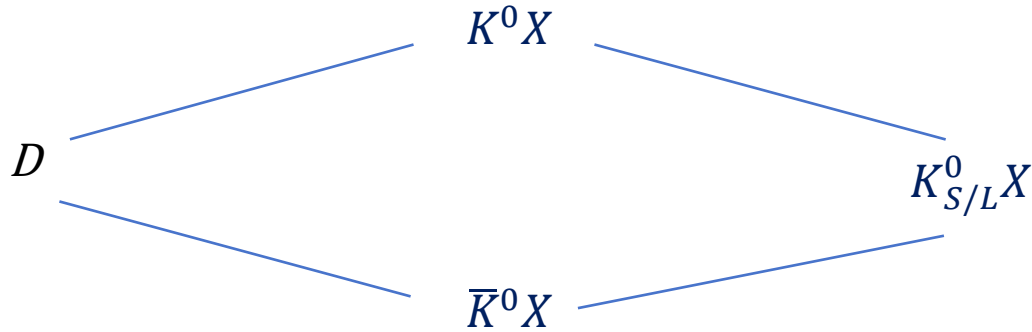
含时衰变率: $R(D_{phys}^0(t) \rightarrow f) \propto |A_f|^2 \exp(-\Gamma t) \left[1 + \frac{1}{4}(x_D^2 + y_D^2)|\lambda_f|^2 \Gamma^2 t^2 - \frac{1}{4}(x_D^2 - y_D^2)\Gamma^2 t^2 - (y_D \text{Re}\lambda_f + x_D \text{Im}\lambda_f)\Gamma t \right]$

$$\lambda_f = r_f \left|\frac{q}{p}\right| e^{-i(\delta_D^f + \phi)}$$

Phys. Rev. D 55 (1997) 196



$D \rightarrow K_{S,L}^0 X$ 中的 $K^0 - \bar{K}^0$ 混合

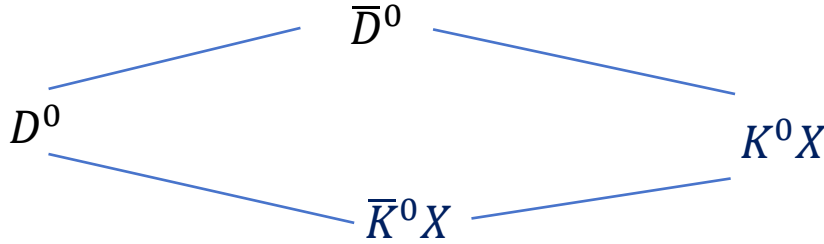


$$A(D^+ \rightarrow X^+ K_S) = \frac{1}{\sqrt{2(1+|\epsilon_K|^2)}} \left[(1 + \epsilon_K^*) T_1 e^{i(\delta_1 + \phi_1)} + (1 - \epsilon_K^*) T_2 e^{i(\delta_2 + \phi_2)} \right]$$

$$A(D^- \rightarrow X^- K_S) = \frac{1}{\sqrt{2(1+|\epsilon_K|^2)}} \left[(1 - \epsilon_K^*) T_1 e^{i(\delta_1 - \phi_1)} + (1 + \epsilon_K^*) T_2 e^{i(\delta_2 - \phi_2)} \right]$$

$$\begin{aligned} \mathcal{A}_{X^\pm K_S} &\equiv \frac{\Gamma(D^- \rightarrow X^- K_S) - \Gamma(D^+ \rightarrow X^+ K_S)}{\Gamma(D^- \rightarrow X^- K_S) + \Gamma(D^+ \rightarrow X^+ K_S)} \\ &= 2 \frac{\operatorname{Re} \epsilon_K (T_2^2 - T_1^2) + 2 \operatorname{Im} \epsilon_K T_1 T_2 \cos(\phi_2 - \phi_1) \sin(\delta_2 - \delta_1)}{T_1^2 + T_2^2 + 2 T_1 T_2 \cos(\phi_2 - \phi_1) \cos(\delta_2 - \delta_1)} \\ &\quad + 2 \frac{T_1 T_2 \sin(\phi_2 - \phi_1) \sin(\delta_2 - \delta_1)}{T_1^2 + T_2^2 + 2 T_1 T_2 \cos(\phi_2 - \phi_1) \cos(\delta_2 - \delta_1)}, \end{aligned}$$

K介子混合和粲介子混合的干涉



$$A_{\text{CP}}^{\text{dm}}(t_1, t_2) \propto e^{-\Gamma_D t_D - \Gamma_K t_K} \left[\sinh \frac{\Delta\Gamma_D t_D}{2} S_h(t_K) + \sin(\Delta m_D t_D) S_n(t_K) \right]$$

$$S_h(t_K) = -\sin(\Delta m_K t_K) \sin \Phi_{DK} + \frac{1}{2} \sinh \frac{\Delta\Gamma_K t_K}{2} \left(\left| \frac{q_D p_K}{p_D q_K} \right| - \left| \frac{p_D q_K}{q_D p_K} \right| \right) \cos \Phi_{DK}$$

$$\approx -\sin(\Delta m_K t_K) \sin \Phi_{DK} + 2 \sinh \frac{\Delta\Gamma_K t_K}{2} \text{Re}(\epsilon_K - \epsilon_D) \cos \Phi_{DK},$$

$$S_n(t_K) = \sinh \frac{\Delta\Gamma_K t_K}{2} \sin \Phi_{DK} + \frac{1}{2} \sin(\Delta m_K t_K) \left(\left| \frac{q_D p_K}{p_D q_K} \right| - \left| \frac{p_D q_K}{q_D p_K} \right| \right) \cos \Phi_{DK}$$

$$\approx \sinh \frac{\Delta\Gamma_K t_K}{2} \sin \Phi_{DK} + 2 \sin(\Delta m_K t_K) \text{Re}(\epsilon_K - \epsilon_D) \cos \Phi_{DK}, \quad (77)$$

STCF上测量D介子CP破坏

See Ying-Hao's talk

- $D^0\bar{D}^0$ 的量子关联性质

- @3770 MeV

$$C\text{-odd, } e^+e^- \rightarrow D^0\bar{D}^0$$

- @4009 MeV

$$C\text{-even for } e^+e^- \rightarrow D^0\bar{D}^{*0} + c.c., \bar{D}^{*0} \rightarrow \gamma\bar{D}^0$$

$$C\text{-odd for } e^+e^- \rightarrow D^0\bar{D}^{*0} + c.c., \bar{D}^{*0} \rightarrow \pi^0\bar{D}^0$$

准味道标记衰变

$$\Gamma(K^-\pi^+; K^-\pi^+)_{C=+1} \propto 2|A(D^0 \rightarrow K^-\pi^+)|^4 \left\{ 3r \left| \frac{p}{q} \right|^2 + 4\lambda^4 h_{K\pi}^2 - 4\lambda^2 h_{K\pi} \left| \frac{p}{q} \right| [y \cos(\delta_{K\pi} + \phi) + x \sin(\delta_{K\pi} + \phi)] \right\}$$

$$\Gamma(K^+\pi^-; K^+\pi^-)_{C=+1} \propto 2|A(\bar{D}^0 \rightarrow K^+\pi^-)|^4 \left\{ 3r \left| \frac{q}{p} \right|^2 + 4\lambda^4 h_{K\pi}^2 - 4\lambda^2 h_{K\pi} \left| \frac{q}{p} \right| [y \cos(\delta_{K\pi} - \phi) + x \sin(\delta_{K\pi} - \phi)] \right\}$$

$$\Gamma(K^-\pi^+; K^-\pi^+)_{C=-1} \propto 2|A(D^0 \rightarrow K^-\pi^+)|^4 r \left| \frac{p}{q} \right|^2$$

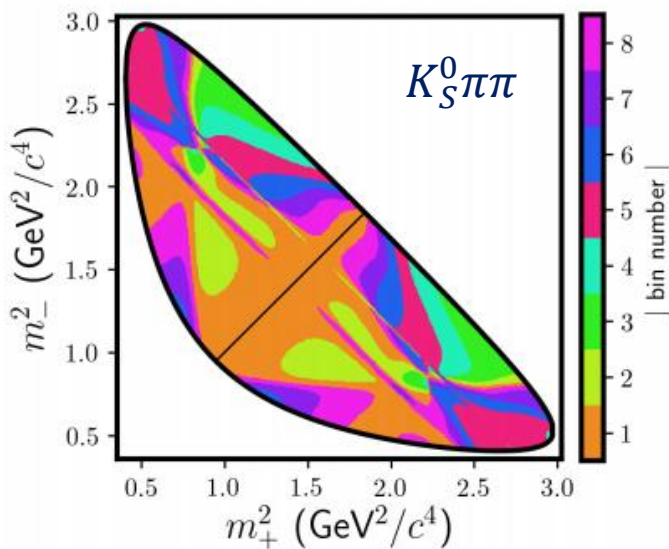
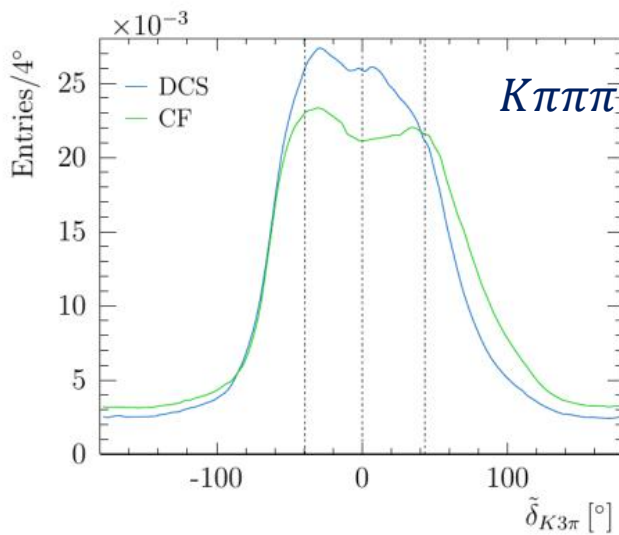
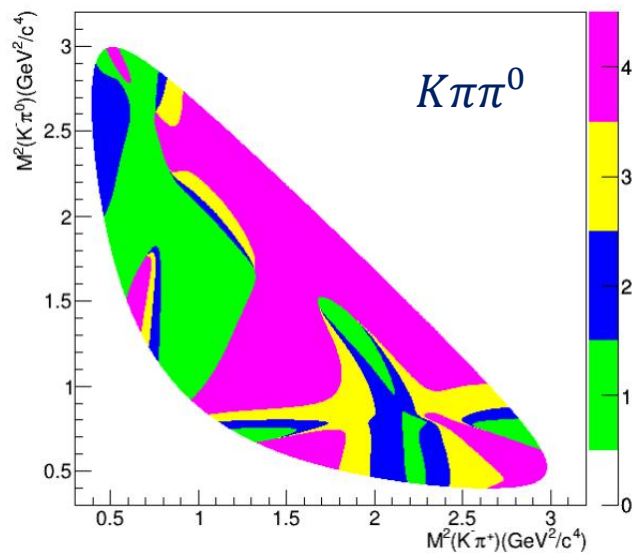
$$\Gamma(K^+\pi^-; K^+\pi^-)_{C=-1} \propto 2|A(D^0 \rightarrow K^-\pi^+)|^4 r \left| \frac{q}{p} \right|^2$$

采用Like-sign衰变模式具有最佳敏感度

C-even 量子关联可用于测量混合参数 x, y 以及间接CP破坏参数 $\left| \frac{q}{p} \right| e^{i\phi}$

需要C-odd 量子关联确定CP不变的强相位

STCF上量子关联测量



利用多体衰变相空间分bin方法
有助于提高实验精度

STCF上量子关联测量精度

$1 ab^{-1}$ @4009MeV

信号重建效率: STCF快模拟软件

	$\delta(x)/0.01$	$\delta(y)/0.01$	$\delta(\frac{q}{p})$	$\delta(\arg(\frac{q}{p}))/^\circ$
$K\pi\pi^0$ (STCF)	0.044	0.017	0.034	2.51
$K\pi\pi\pi$ (STCF)	0.047	0.025	0.042	3.10
$K_S^0\pi\pi$ (STCF)	0.069	0.050	0.077	4.57
LHCb current best	0.056	0.026	0.052	2.9
HFLAV average	0.044	0.024	0.016	1.1

- 未考虑系统误差, 由强相位贡献的系统误差将可忽略
- STCF可以在 10^{-4} 量级测量粲介子 (间接) CP破坏
- 直接CP破坏精度有待进一步研究

总结

- 在陶轻子和粲介子中，STCF可在 10^{-4} 量级精确检验标准模型中的CP破坏
- 陶轻子CP破坏测量精度可达到世界领先水平
- 粲介子CP破坏测量利用独特量子关联性质，与B介子工厂上的测量互补
- 理论家提供的潜在物理课题仍需进一步研究
 - 陶轻子EDM
 - 粲重子CP破坏
 - 粲介子直接CP破坏等