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 0.5×10^{35} cm^{-2}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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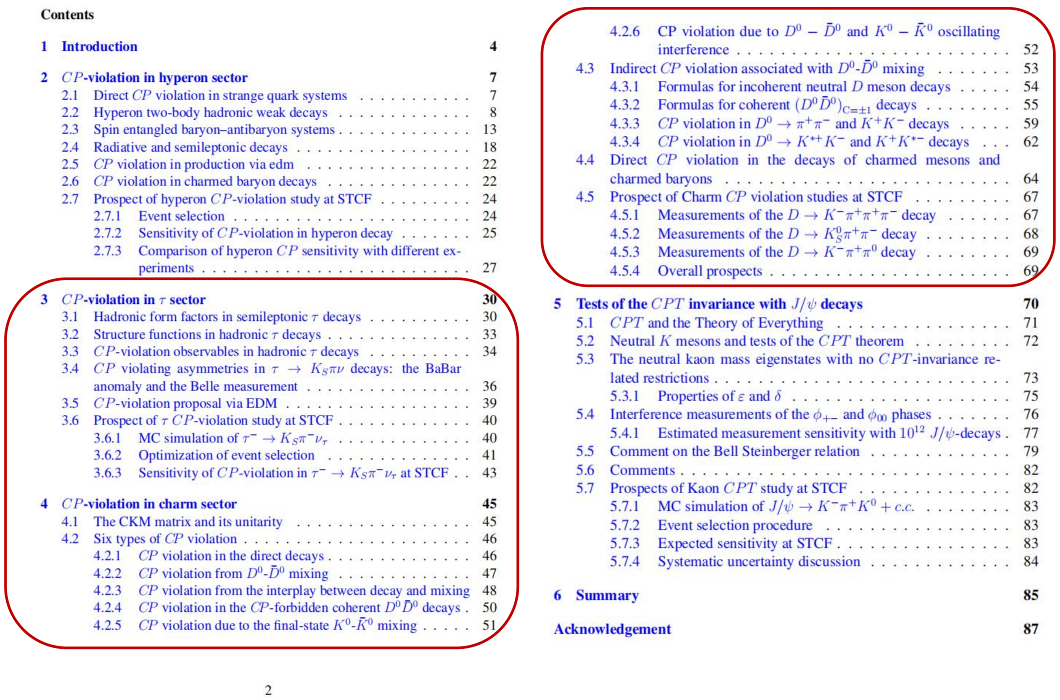

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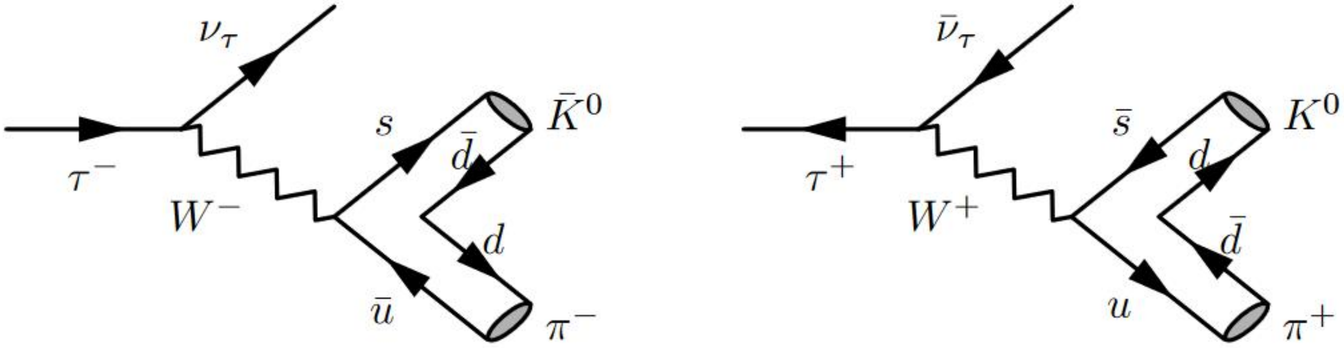
Not complete overview!

τ轻子的CP破坏

$$\tau \to K_S^0 \pi \upsilon_\tau$$

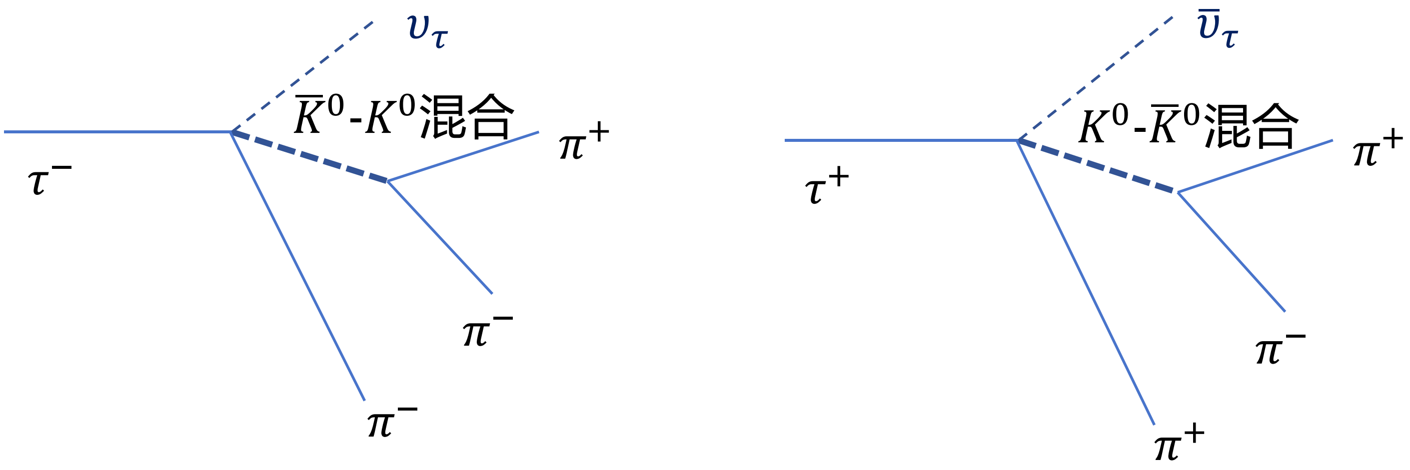
$\tau \rightarrow K^0\pi\upsilon_\tau$衰变



JHEP 01 (2022) 108

- 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：$A(\tau^- \rightarrow \overline{K}^0\pi^-\upsilon_\tau) = A(\tau^+ \rightarrow K^0\pi^+\overline{\upsilon}_\tau)$

$\tau \to K_S^0 \pi \upsilon_\tau$衰变中的CP不对称



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

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

实验观测量

$$\begin{aligned} A_{+-}(\tau) &= \frac{|\mathcal{T}_-(\tau)|^2 - |\mathcal{T}_+(\tau)|^2}{|\mathcal{T}_-(\tau)|^2 + |\mathcal{T}_+(\tau)|^2} \\ &\simeq 2Re[\epsilon]\left[\frac{-\frac{1}{\cos\phi_{+-}}e^{-1/2(\Gamma_S+\Gamma_L)\tau}\cos(\Delta m\tau - \phi_{+-}) + e^{-\Gamma_S\tau} + |\epsilon|^2 e^{-\Gamma_L\tau}}{e^{-\Gamma_S\tau} + |\epsilon|^2 e^{-\Gamma_L\tau}}\right] \end{aligned}$$

ϵ、ϕ：CP破坏参数

PRD 75 (2007) 076001

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

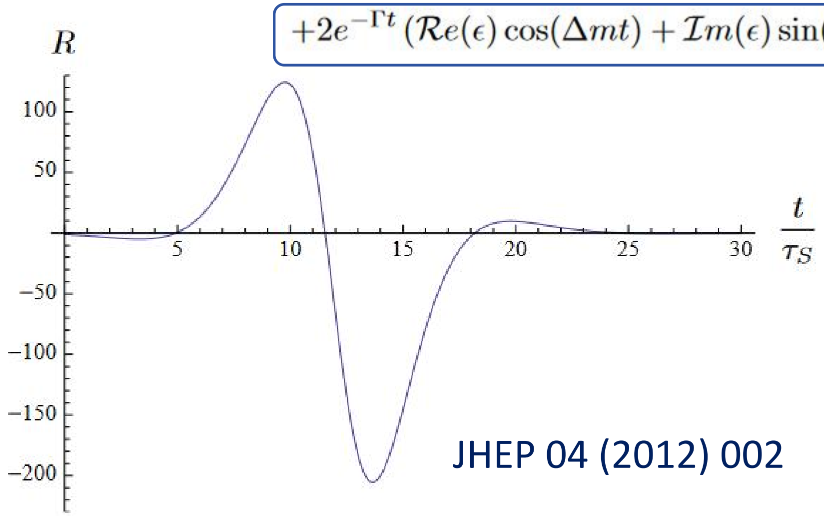
$$A_{CP}^{\tau} = A_{CP}(\tau^- \to K_S\pi^-\nu_\tau)$$
$$= \frac{\Gamma(\tau^+ \to K_S\pi^+\bar{\nu}_\tau) - \Gamma(\tau^- \to K_S\pi^-\nu_\tau)}{\Gamma(\tau^+ \to K_S\pi^+\bar{\nu}_\tau) + \Gamma(\tau^- \to K_S\pi^-\nu_\tau)}$$

$$\approx 2Re(\varepsilon) = 0.003192(26)$$

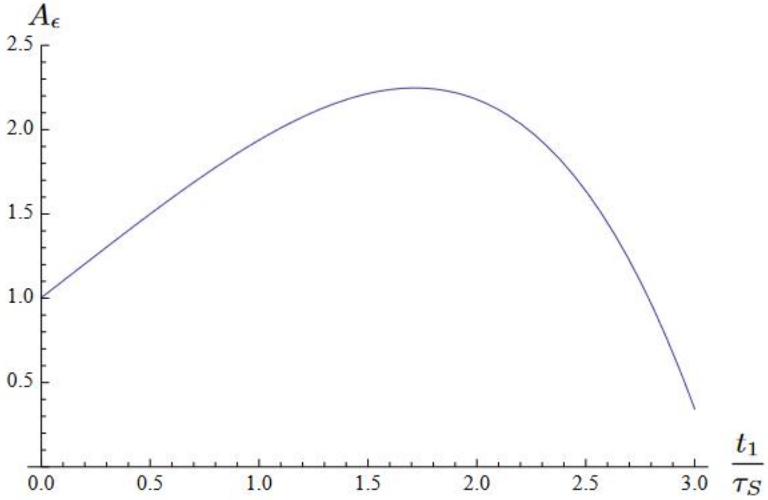
PLB 625 (2005) 47;
PRD 75 (2007) 076001;

$$\boxed{-2\mathcal{R}e(\epsilon)\left(e^{-\Gamma_S t} + |\epsilon|^2 e^{-\Gamma_L t}\right)}$$

$$\boxed{+2e^{-\Gamma t}\left(\mathcal{R}e(\epsilon)\cos(\Delta m t) + \mathcal{I}m(\epsilon)\sin(\Delta m t)\right)}$$

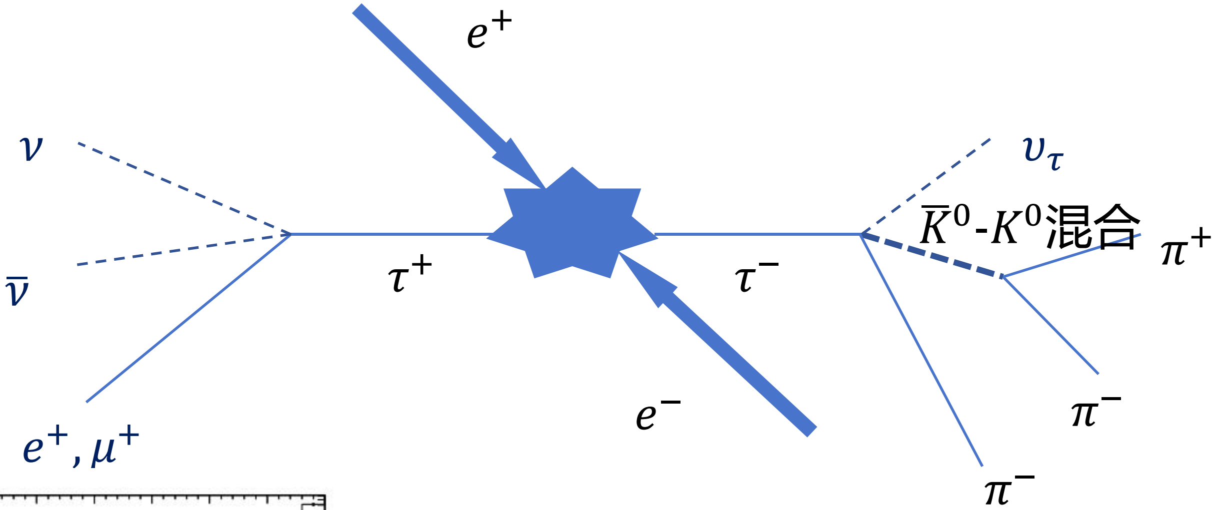


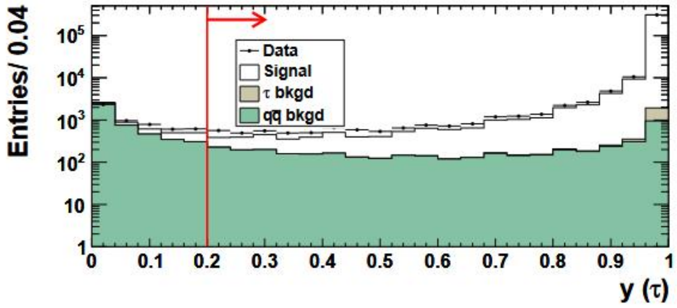
JHEP 04 (2012) 002

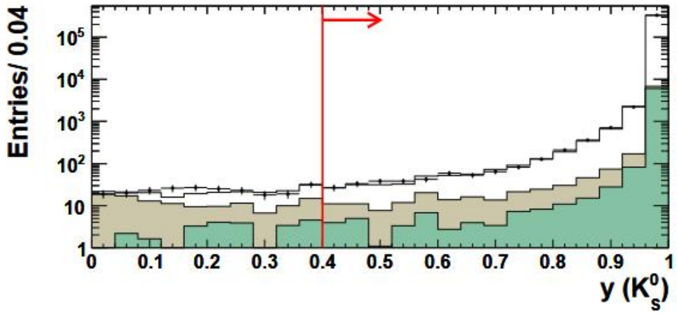


实验测量的CP不对称性的大小依赖于K_S^0衰变时间
需要考虑不同K_S^0衰变时间的实验探测效率

$\tau \to K_S^0 \pi \upsilon_\tau$中CP不对称性测量







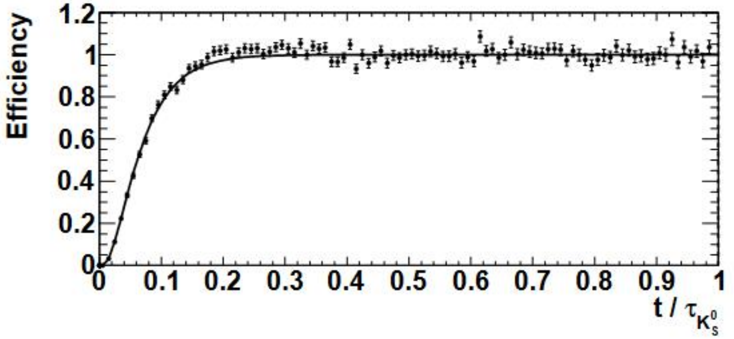
τ似然函数:
可见能量
标记侧中性簇射数目
Thrust
横动量

K_S^0似然函数:
横向飞行距离
不变质量
动量
极角

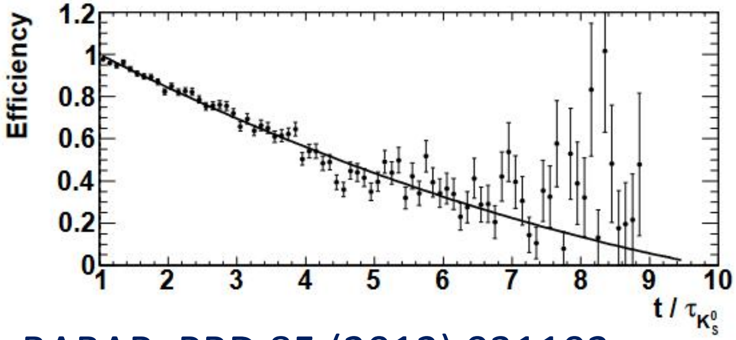
BABAR, PRD 85 (2012) 031102

$\tau \to K_S^0 \pi \upsilon_\tau$中CP不对称性测量

	$\mathrm{N}(\tau^+)$	$\mathrm{N}(\tau^-)$	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)



$$A_{CP,\mathrm{EXP}}^{\tau} = -\ 0.36(23)(11)\%$$
$$A_{CP,\mathrm{SM}}^{\tau} = 0.36(1)\%$$
2.8σ tension

BABAR, PRD 85 (2012) 031102

$\tau \to K_S^0 \pi \upsilon_\tau$中的角分布

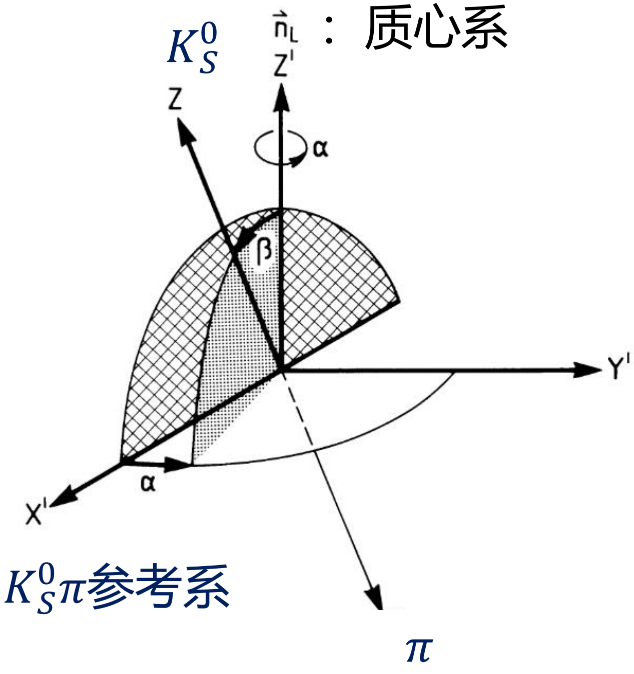
$$d\Gamma_{\tau^-} = \frac{G_F^2}{2m_\tau} \sin^2\theta_c \frac{1}{(4\pi)^3} \frac{(m_\tau^2 - Q^2)^2}{m_\tau^2} |\vec{q}_1|$$
$$\times \frac{1}{2} \boxed{\left(\sum_X \bar{L}_X W_X \right)} \frac{dQ^2}{\sqrt{Q^2}} \frac{d\cos\theta}{2} \frac{d\alpha}{2\pi} \frac{d\cos\beta}{2}$$

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

τ参考系中ee质心系与$K_S^0\pi$夹角

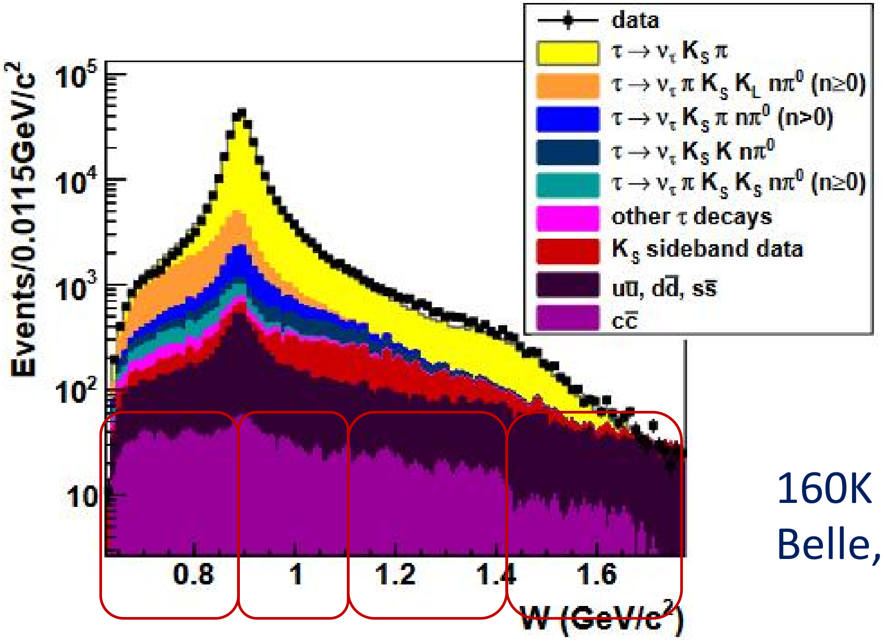
实验观测量：

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

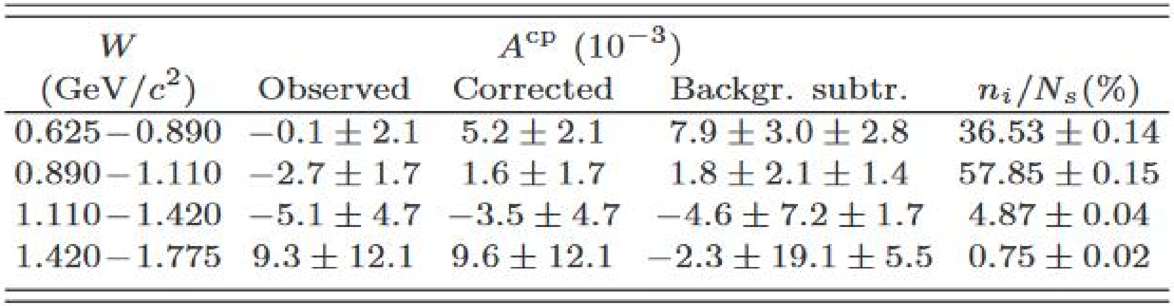


see ZPC 56 (1992) 661&PLB 398 (1997) 407 for detail

$\tau \to K_S^0 \pi \upsilon_\tau$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^{cp} (10^{-3}) Observed	Corrected	Backgr. subtr.	n_i/N_s(%)
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
$1\ ab^{-1}$@4.26GeV
$e^+e^- \to \tau^+\tau^-$产生子: KKMC+TAUOLA

$\tau \to K_S^0 \pi \upsilon_\tau$:

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

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

考虑了标量/矢量形状因子

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

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

基于无CP不对称假设

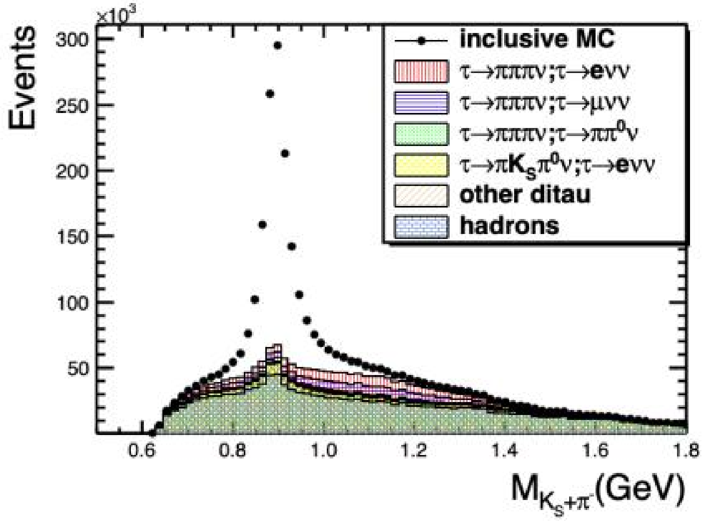
STCF精度预研

- 信号事例重建

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

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

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

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

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

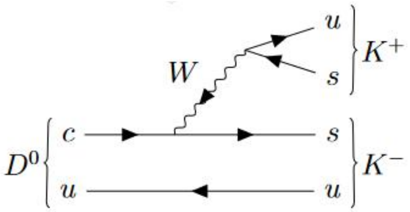
$$\delta(A_{CP,\rm SM}^{\tau}) \sim 1 \times 10^{-4}$$

粲强子的CP破坏

直接CP破坏

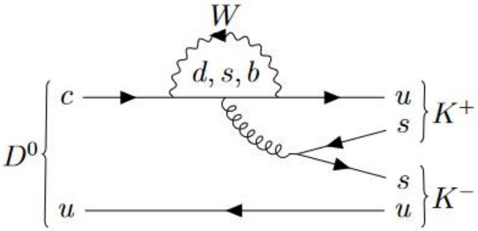
$$A(D^0 \to f) = A_1 e^{\mathrm{i}(\delta_1+\phi_1)} + A_2 e^{\mathrm{i}(\delta_2+\phi_2)} \,,$$
$$A(\bar{D}^0 \to \bar{f}) = A_1 e^{\mathrm{i}(\delta_1-\phi_1)} + A_2 e^{\mathrm{i}(\delta_2-\phi_2)} \,,$$

$$\mathcal{A}_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})} = \frac{-2A_1A_2\sin(\delta_2-\delta_1)\sin(\phi_2-\phi_1)}{|A_1|^2+|A_2|^2+2A_1A_2\cos(\delta_2-\delta_1)\cos(\phi_2-\phi_1)} \,.$$



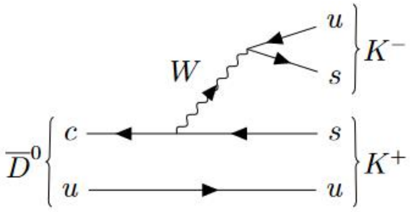
$$A_1 = |A_1| e^{i\delta_1} e^{i\phi_1}$$

+



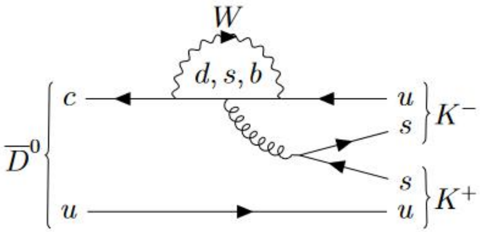
$$A_2 = |A_2| e^{i\delta_2} e^{i\phi_2}$$

$$\xrightarrow{CP}$$



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

+



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

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

中性粲介子混合

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

Time evolution of a initially flavour eigenstate *D*:

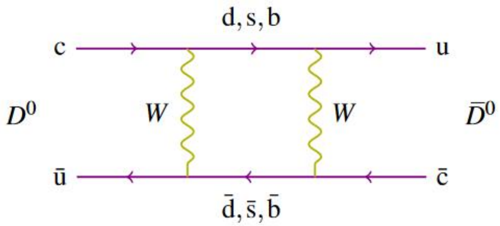
$$\left|D^0_{phys}(t)\right\rangle = g_+(t)\left|D^0\right\rangle + \frac{q}{p} g_-(t)\left|\overline{D}^0\right\rangle \qquad g_+(t) = \exp\left(-(im+\frac{\Gamma}{2})t\right)\cosh\left((i\Delta m - \frac{\Delta\Gamma}{2})\frac{t}{2}\right) \qquad m \equiv \frac{m_1+m_2}{2}, \Delta m \equiv m_2 - m_1$$

$$\left|\overline{D}^0_{phys}(t)\right\rangle = g_+(t)\left|\overline{D}^0\right\rangle + \frac{q}{p} g_-(t)\left|D^0\right\rangle \qquad g_-(t) = \exp\left(-(im+\frac{\Gamma}{2})t\right)\sinh\left((i\Delta m - \frac{\Delta\Gamma}{2})\frac{t}{2}\right) \qquad \Gamma \equiv \frac{\Gamma_1+\Gamma_2}{2}, \Delta\Gamma \equiv \Gamma_1 - \Gamma_2$$

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

Short distance contributions

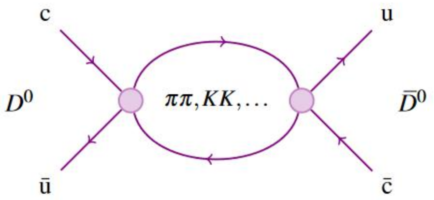
loop level $(\mathbf{x}, \mathbf{y}) \sim \mathbf{10^{-7}}$



Long distance contributions

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

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

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

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

Type 1. 混合CP破坏

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

Type 2. 混合和衰变振幅的干涉

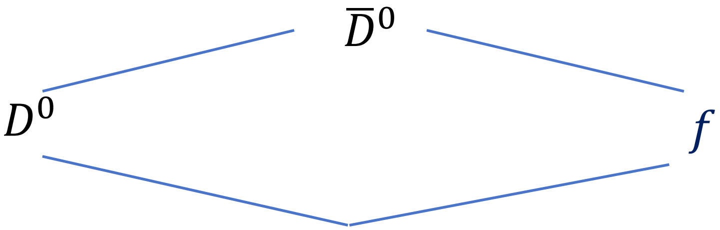
Non-vanishing ϕ in $\frac{q}{p} = \left|\frac{q}{p}\right| e^{i\phi}$

含时衰变率:

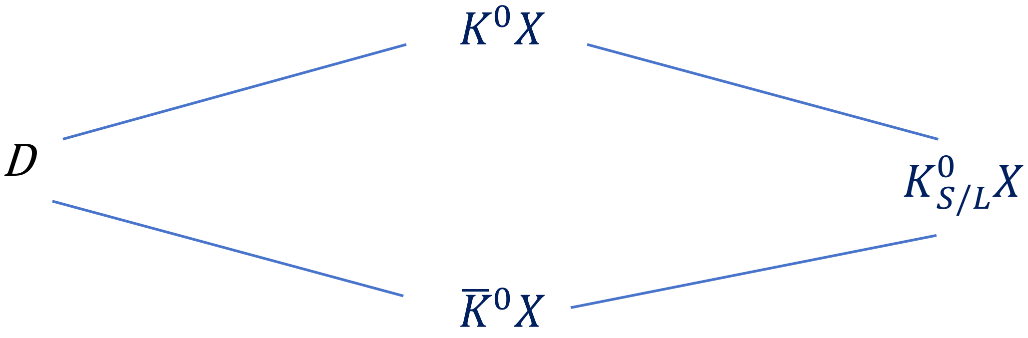
$$\begin{aligned} R(D^0_{\mathrm{phys}}(t) \to f) \;\propto\; & |A_f|^2 \exp(-\Gamma t) \left[1 + \frac{1}{4}\left(x_D^2 + y_D^2\right)|\lambda_f|^2\Gamma^2 t^2 \right. \\ & \left. - \frac{1}{4}\left(x_D^2 - y_D^2\right)\Gamma^2 t^2 - (y_D \mathrm{Re}\lambda_f + x_D \mathrm{Im}\lambda_f)\Gamma t \right] \end{aligned}$$

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

Phys. Rev. D 55 (1997) 196



$D \to K^0_{S,L} X$中的$K^0 - \overline{K}^0$混合



$K^0 X$

D

$K^0_{S/L} X$

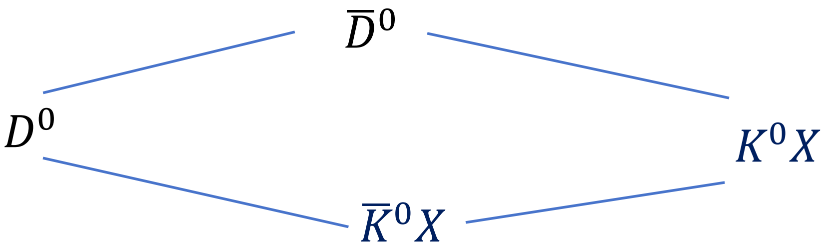
$\overline{K}^0 X$

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

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

$$\begin{aligned}\mathcal{A}_{X^\pm K_S} &\equiv \frac{\Gamma(D^- \to X^- K_S) - \Gamma(D^+ \to X^+ K_S)}{\Gamma(D^- \to X^- K_S) + \Gamma(D^+ \to X^+ K_S)} \\ &= 2\frac{\mathrm{Re}\epsilon_K\left(T_2^2 - T_1^2\right) + 2\mathrm{Im}\epsilon_K T_1 T_2 \cos\left(\phi_2-\phi_1\right)\sin\left(\delta_2-\delta_1\right)}{T_1^2 + T_2^2 + 2T_1T_2\cos\left(\phi_2-\phi_1\right)\cos\left(\delta_2-\delta_1\right)} \\ &\quad + 2\frac{T_1T_2\sin\left(\phi_2-\phi_1\right)\sin\left(\delta_2-\delta_1\right)}{T_1^2 + T_2^2 + 2T_1T_2\cos\left(\phi_2-\phi_1\right)\cos\left(\delta_2-\delta_1\right)},\end{aligned}$$

K介子混合和粲介子混合的干涉



$\overline{D}^0$

D^0

K^0X

$\overline{K}^0X$

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

$$\begin{aligned} S_h(t_K) &= -\sin\left(\Delta m_K t_K\right)\sin\Phi_{DK} + \frac{1}{2}\sinh\frac{\Delta\Gamma_K t_K}{2}\left(\left|\frac{q_D}{p_D}\frac{p_K}{q_K}\right| - \left|\frac{p_D}{q_D}\frac{q_K}{p_K}\right|\right)\cos\Phi_{DK} \\ &\approx -\sin\left(\Delta m_K t_K\right)\sin\Phi_{DK} + 2\sinh\frac{\Delta\Gamma_K t_K}{2}{\rm Re}(\epsilon_K - \epsilon_D)\cos\Phi_{DK}\ , \\ S_n(t_K) &= \sinh\frac{\Delta\Gamma_K t_K}{2}\sin\Phi_{DK} + \frac{1}{2}\sin\left(\Delta m_K t_K\right)\left(\left|\frac{q_D}{p_D}\frac{p_K}{q_K}\right| - \left|\frac{p_D}{q_D}\frac{q_K}{p_K}\right|\right)\cos\Phi_{DK} \\ &\approx \sinh\frac{\Delta\Gamma_K t_K}{2}\sin\Phi_{DK} + 2\sin\left(\Delta m_K t_K\right){\rm Re}(\epsilon_K - \epsilon_D)\cos\Phi_{DK}\ , \end{aligned} \tag{77}$$

STCF上测量D介子CP破坏

See Ying-Hao’s talk

- $D^0\overline{D}^0$的量子关联性质
- @3770 MeV

  C-odd, $e^+e^- \to D^0\overline{D}^0$
- @4009 MeV

  C-even for $e^+e^- \to D^0\overline{D}^{*0} + c.c., \overline{D}^{*0} \to \gamma\overline{D}^0$

  C-odd for $e^+e^- \to D^0\overline{D}^{*0} + c.c., \overline{D}^{*0} \to \pi^0\overline{D}^0$

准味道标记衰变

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

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

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

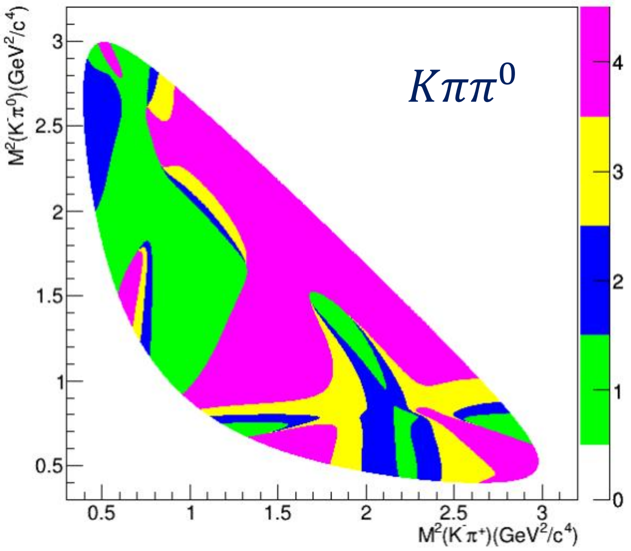
$$\Gamma(K^+\pi^-;K^+\pi^-)_{\mathrm{C=-1}} \propto 2|A(D^0\to K^-\pi^+)|^4 r\left|\frac{q}{p}\right|^2$$

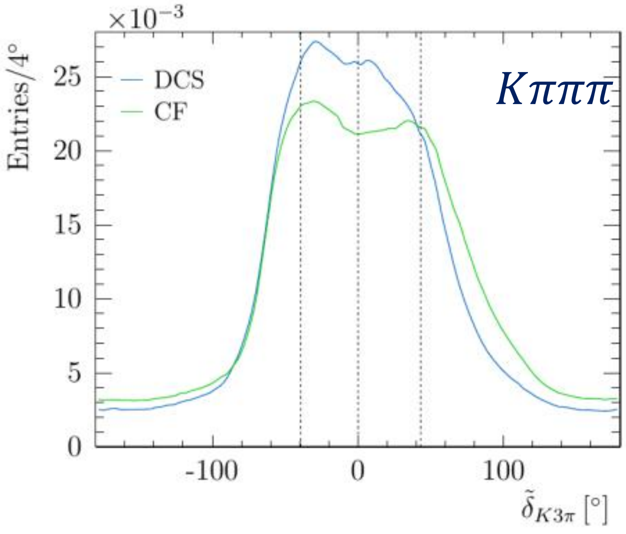
采用Like-sign衰变模式具有最佳敏感度

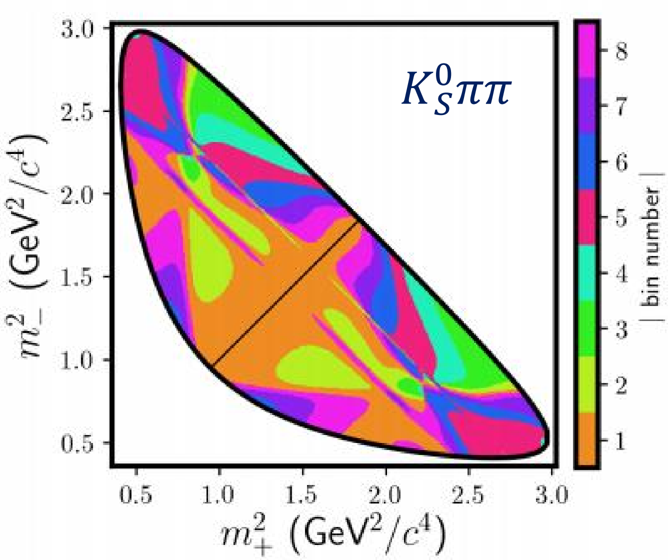
C-even 量子关联可用于测量混合参数x,y以及间接CP破坏参数$\left|\frac{q}{p}\right| e^{i\phi}$

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

	$\boldsymbol{\delta(x)/0.01}$	$\boldsymbol{\delta(y)/0.01}$	$\boldsymbol{\delta(\lvert \frac{q}{p} \rvert)}$	$\boldsymbol{\delta(arg(\frac{q}{p}))/^{\circ}}$
$K\pi\pi^0(\mathrm{STCF})$	0.044	0.017	0.034	2.51
$K\pi\pi\pi(\mathrm{STCF})$	0.047	0.025	0.042	3.10
$K_S^0\pi\pi(\mathrm{STCF})$	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