中性D介子混合和间接CP破坏以及强相位差实验测量

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报告内容

- 中性粲介子混合和间接CP破坏测量（LHCb+Belle II）
  - CP本征态$D \to K^+K^-, \pi^+\pi^-, \pi^+\pi^-\pi^0$
  - 多体自共轭衰变$D \to K^0_S\pi^+\pi^-$
  - 准味道本征态$D \to K^-n\pi$
- $D^0/\overline{D}^0 \to f$衰变中的强相位差测量（BESIII）
  - 准味道本征态$f = Kn\pi\ (\delta_D^f, R_f, r_D^f)$
  - 自共轭衰变$f = K^0_{S,L}\pi^+\pi^-, h^+h^-\pi^+\pi^-\ (c_i, s_i)$
  - 准CP本征态$f = h^+h^-\pi^0 (F^+)$
- 总结与展望

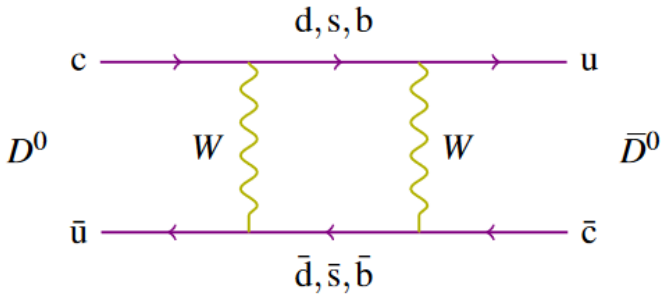
$D^0-\overline{D}^0$混合

- 质量本征态可表示为味道本征态的叠加$|D_{1,2}\rangle = p|D^0\rangle + q|\overline{D}^0\rangle$
- 产生时D介子为味道本征态$D^0/\overline{D}^0$, 随着时间演化为$D^0\overline{D}^0$ 叠加态:
  - $|D^0_{phys}(t)\rangle = g_+(t)|D^0\rangle + \frac{q}{p}g_-(t)|\overline{D}^0\rangle$, $|\overline{D}^0_{phys}(t)\rangle = g_+(t)|D^0\rangle + \frac{q}{p}g_-(t)|\overline{D}^0\rangle$

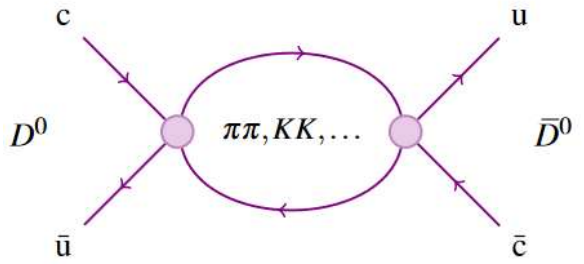
$$g_+(t) = \exp(-(im+\Gamma/2)t)\cosh((i\Delta m-\Gamma/2)t/2) \qquad m \equiv (m_1+m_2)/2, \Delta m \equiv m_2-m_1$$
$$g_-(t) = \exp(-(im+\Gamma/2)t)\sinh((i\Delta m-\Gamma/2)t/2) \qquad \Gamma \equiv (\Gamma_1+\Gamma_2)/2, \Delta\Gamma \equiv \Gamma_1-\Gamma_2$$

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

短程贡献 $(x, y)\sim 10^{-7}$



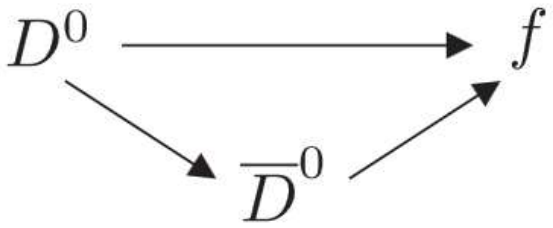
长程贡献 $(x, y)\sim 10^{-3}$



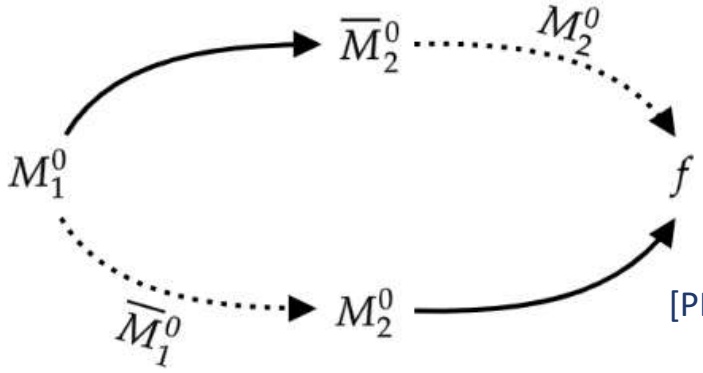
Phys. Lett. B 810 (2020) 135802
Chin. Phys. C 42 (2018) 063101
Phys. Rev. D 81 (2010) 114020
Phys. Rev. D 65 (2002) 054034

Plots from arXiv:1503.00032

混合导致的间接CP破坏



- Type 1. 混合带来的CP破坏$|p| \neq |q|$
  - 质量本征态不是CP本征态
- Type 2. 混合和衰变的干涉带来的CP破坏 $Im\left(\frac{q}{p}\frac{A(\overline{D}^0\to f)}{A(D^0\to f)}\right) \neq Im\left(\frac{p}{q}\frac{A(D^0\to \bar{f})}{A(\overline{D}^0\to \bar{f})}\right)$
  - Non-zero ϕ for $\frac{q}{p} = \left|\frac{q}{p}\right| e^{i\phi}$
- Type 3. charm mixing and kaon mixing之间的干涉



[PRD 110 (2024) L031301]

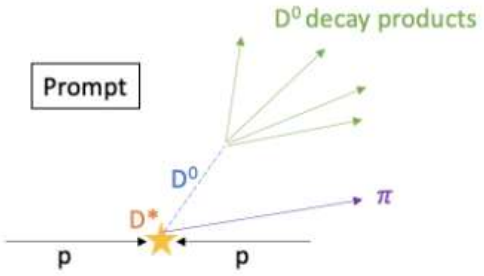
$D^0-\overline{D}^0$混合的另一种参数化形式

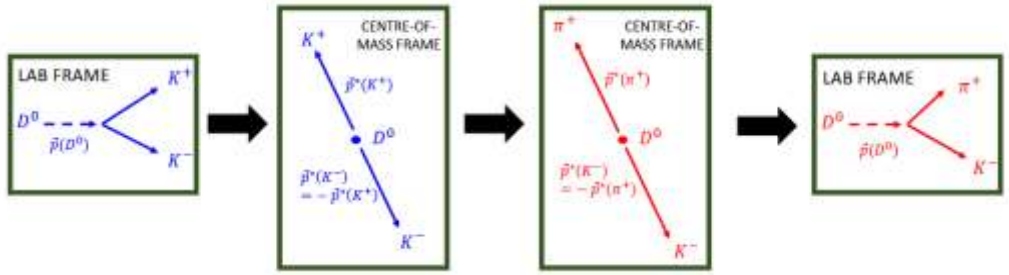
- $y_{CP}^{f}=y_{12}\cos\phi_f^{\Gamma},\ \phi_f^{\Gamma}=\arg(\Gamma_{12}A_f/\bar{A}_f)$
- $x=sign(\cos\phi_{12})\times\left(x_{12}^2-y_{12}^2+\sqrt{(x_{12}^2+y_{12}^2)^2-4x_{12}^2y_{12}^2\sin^2\phi_{12}}\right)^{1/2}$
- $y=\left(y_{12}^2-x_{12}^2+\sqrt{(x_{12}^2+y_{12}^2)^2-4x_{12}^2y_{12}^2\sin^2\phi_{12}}\right)^{1/2}$
- 忽略间接CP破坏时，$y\approx y_{12},x\approx x_{12}$
- $y_{CP}^{K\pi}\approx\sqrt{R_D}\left(x_{12}\cos\phi_2^{M}\sin\delta_{K\pi}+y_{12}\cos\phi_2^{\Gamma}\cos\delta_{K\pi}\right)\approx-0.4\times10^{-3}$
- $\frac{\hat{\Gamma}(D^0\to f)+\hat{\Gamma}(\bar{D}^0\to f)}{\hat{\Gamma}(D^0\to K^-\pi^+)+\hat{\Gamma}(\bar{D}^0\to K^+\pi^-)}-1\approx y_{CP}^{f}-y_{CP}^{K\pi}\ (f=KK/\pi\pi)$

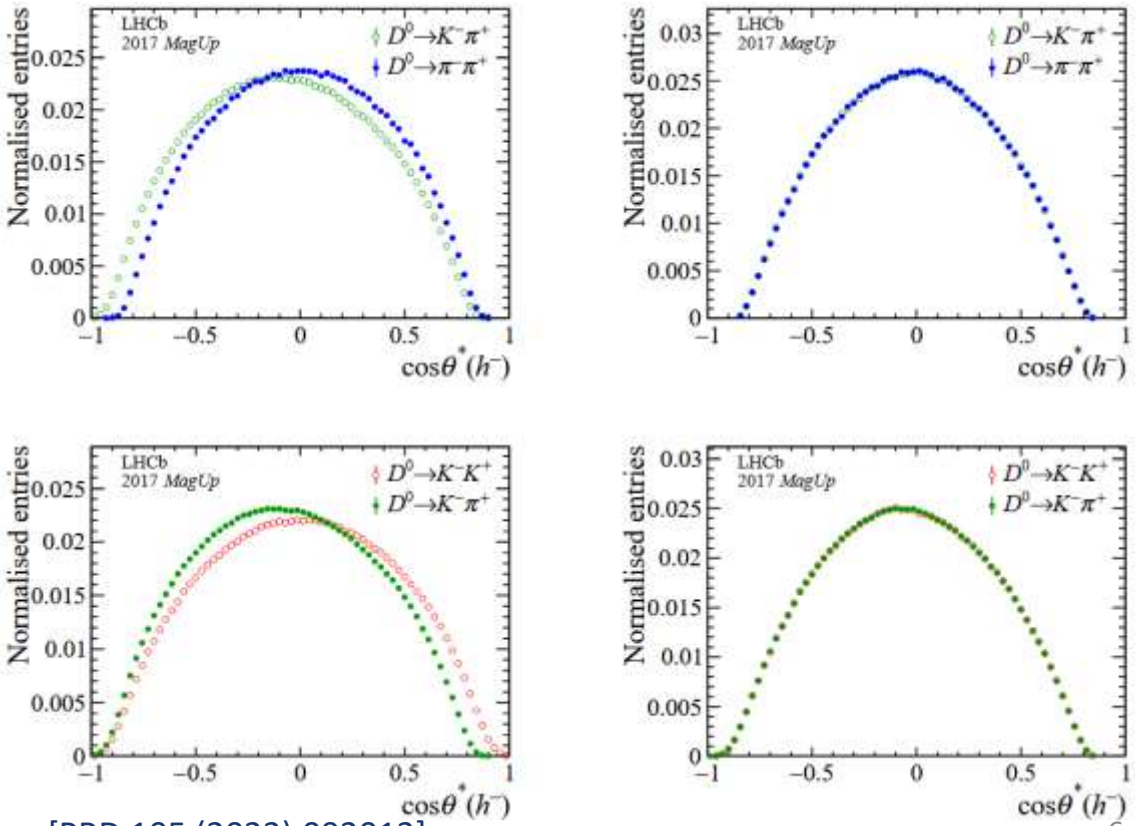
两体CP本征态衰变测量混合参数y

$$R^f(t) = \frac{N(D^0 \to f, t)}{N(D^0 \to K^-\pi^+, t)} \propto e^{-\left(y_{CP}^f - y_{CP}^{K\pi}\right)t/\tau_{D^0}} \frac{\epsilon(f,t)}{\epsilon(K^-\pi^+,t)}$$

选择效率：matching
探测效率：reweighting

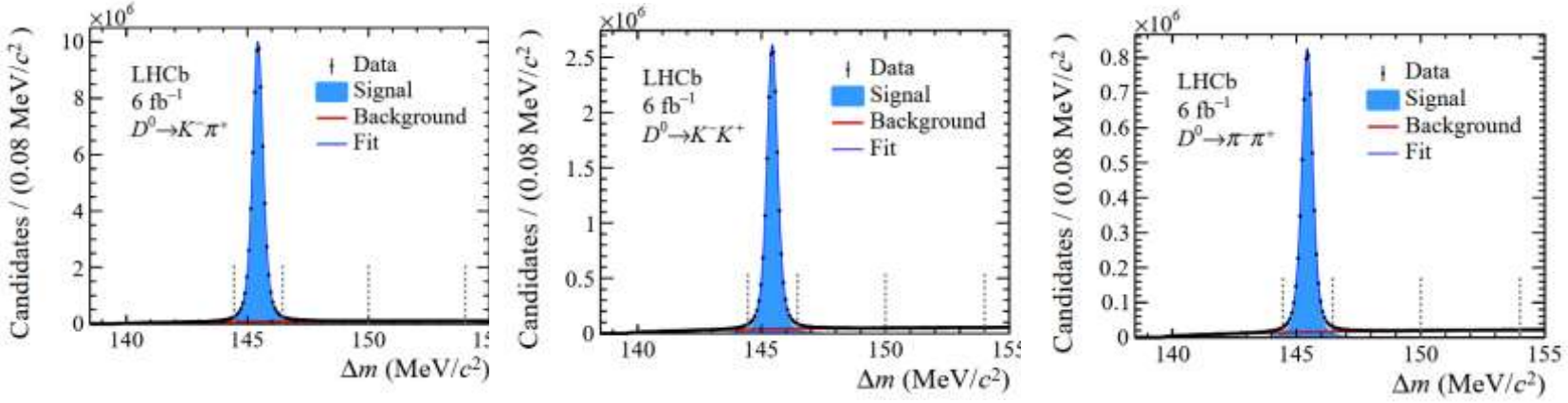




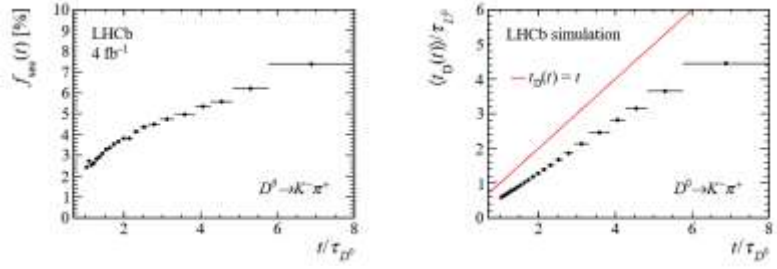


[PRD 105 (2022) 092013]

CP本征态衰变测量混合参数y



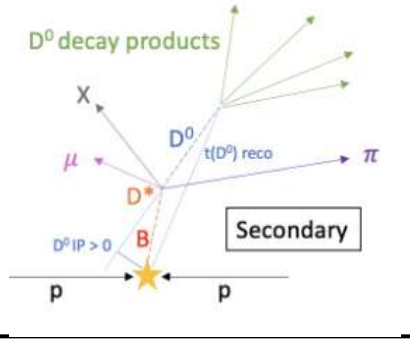
[PRD 105 (2022) 092013]



次级D^{*+}衰变通过数据驱动和模拟得到

$$R_f(t) = \big(1 - f_{sec}(t)\big)R^f_{prompt}(t) + f_{sec}(t)R^f_{sec}(t)$$

$$R^f_{sec}(t) \propto e^{-\left(y^f_{CP} - y^{K\pi}_{CP}\right)\langle t_D(t)\rangle/\tau_{D^0}}$$

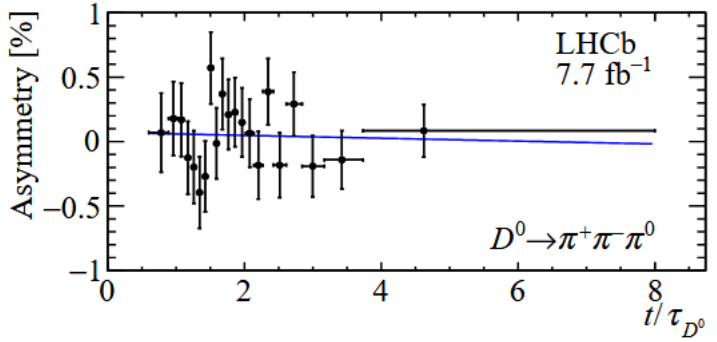


$$y^f_{CP} - y^{K\pi}_{CP} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}$$

$$y = \left(6.46^{+0.24}_{-0.25}\right) \times 10^{-3}$$

$$\delta^{K\pi}_D = (192.1^{+3.7}_{-4.0})^{\circ}$$

目前为止最精确的y参数测量



$$A_{CP} = \frac{\Gamma_{D^0\to f}(t) - \Gamma_{\overline{D}^0\to f}(t)}{\Gamma_{D^0\to f}(t) + \Gamma_{\overline{D}^0\to f}(t)} = a^{dir}_f + \frac{\Delta Y_f t}{\tau_{D^0}}$$

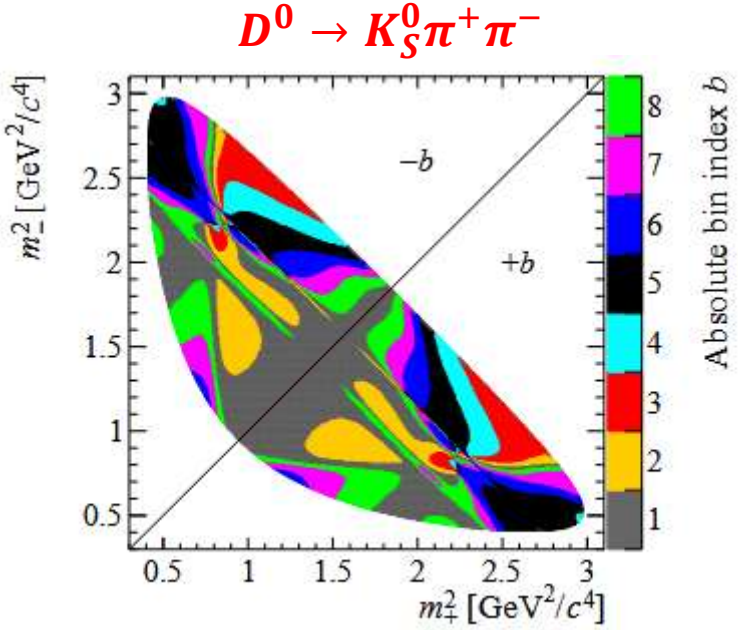
$$\Delta Y_f = \frac{2F_+ - 1}{2}\left[\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)x\sin\phi - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)y\cos\phi\right]$$

$$= (-1.3 \pm 6.3 \pm 2.4) \times 10^{-4}$$

[PRL 133 (2024) 101803]

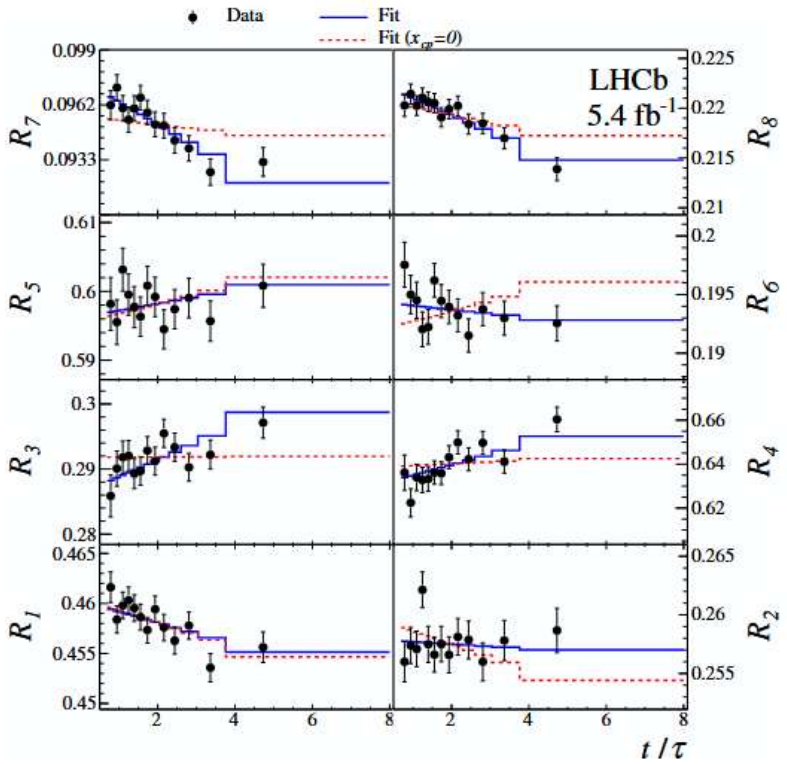
多体自共轭衰变测量混合参数

- $R_{bj}^{\pm} \approx \dfrac{r_b + r_b \frac{\langle t^2 \rangle_j}{4} Re(z_{CP}^2 - \Delta z^2) + \frac{\langle t^2 \rangle_j}{4} |z_{CP} \pm \Delta z|^2 + \sqrt{r_b} \langle t \rangle_j Re[X_b^*(z_{CP} \pm \Delta z)]}{1 + \frac{\langle t^2 \rangle_j}{4} Re(z_{CP}^2 - \Delta z^2) + r_b \frac{\langle t^2 \rangle_j}{4} |z_{CP} \pm \Delta z|^2 + \sqrt{r_b} \langle t \rangle_j Re[X_b(z_{CP} \pm \Delta z)]}$
- $z_{CP} \pm \Delta z \equiv -\left(\frac{q}{p}\right)^{\pm 1} (y + ix)$
- 混合参数$x_{CP} \equiv -Im(z_{CP}), y_{CP} \equiv -Re(z_{CP})$
- CP破坏参数$\Delta x \equiv -Im(\Delta z), \Delta y \equiv -Re(\Delta z)$



多体自共轭衰变测量混合参数

$D \to K^0_S\pi^+\pi^-$



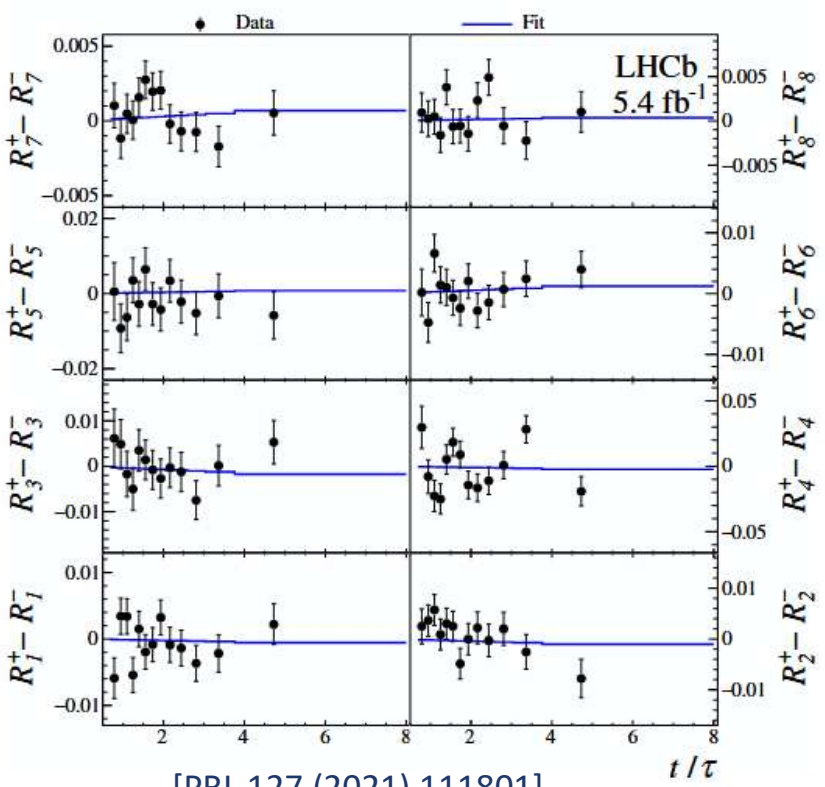
$x = \left(3.98^{+0.56}_{-0.54}\right) \times 10^{-3}$

$y = \left(4.6^{+1.5}_{-1.4}\right) \times 10^{-3}$

$|q/p| = 0.996 \pm 0.052$

$\phi = -0.056^{+0.047}_{-0.051}$

Difference between D^0 and $\bar{D}^0 \to K^0_S\pi^+\pi^-$



[PRL 127 (2021) 111801]

$x_{\mathrm{CP}} = (3.97 \pm 0.46 \pm 0.29) \times 10^{-3}$

$y_{CP} = (4.59 \pm 1.20 \pm 0.85) \times 10^{-3}$

$\Delta x = (-0.27 \pm 0.18 \pm 0.01) \times 10^{-3}$

$\Delta y = (0.20 \pm 0.36 \pm 0.13) \times 10^{-3}$

强相位差误差贡献小于统计误差：

$\sigma_{x_{CP}} = 0.23 \times 10^{-3}$

$\sigma_{y_{CP}} = 0.66 \times 10^{-3}$

$\sigma_{\Delta x} = 0.04 \times 10^{-3}$

$\sigma_{\Delta y} = 0.08 \times 10^{-3}$

Include secondary D^* [PRD 108 (2023) 052005]

$x_{CP} = (4.01 \pm 0.45 \pm 0.20) \times 10^{-3}$

$y_{CP} = (5.51 \pm 1.16 \pm 0.59) \times 10^{-3}$

$\Delta x = (-0.29 \pm 0.18 \pm 0.01) \times 10^{-3}$

$\Delta y = (0.31 \pm 0.35 \pm 0.13) \times 10^{-3}$

目前为止精度最高的x参数测量和间接CP破坏参数测量

多体自共轭衰变测量粲介子混合参数

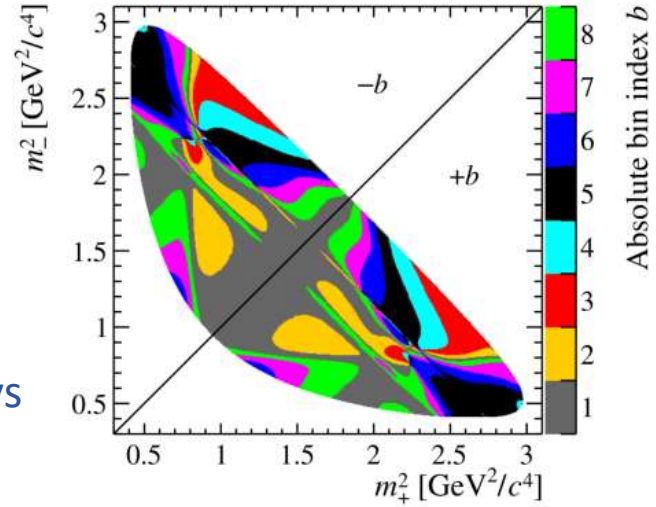
- Flavour-tagged D mesons from $D^* \to D\left(K_S^0\pi^+\pi^-\right)\pi$ decays
- Time-dependent distribution of decay rate

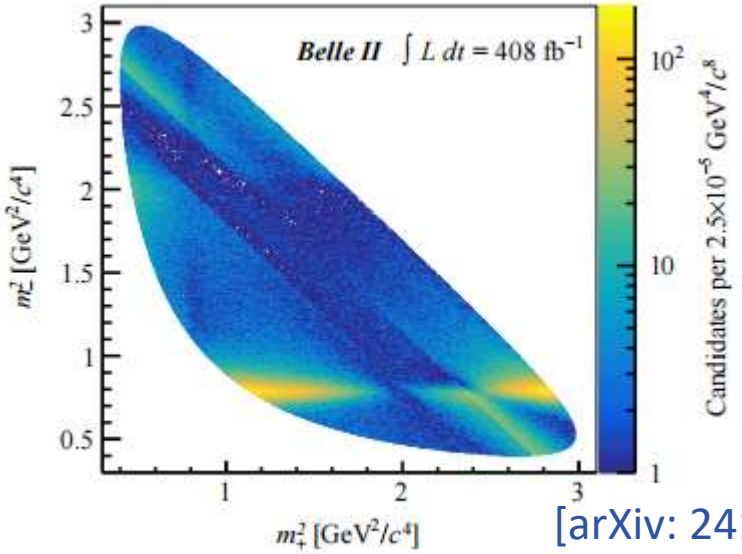
$$p_{\pm b}(t) \propto g_{\pm}^2(t) + r_b g_{\mp}^2(t) + 2\sqrt{r_b} Re[X_{\pm b} g_+^*(t) g_-(t)]$$

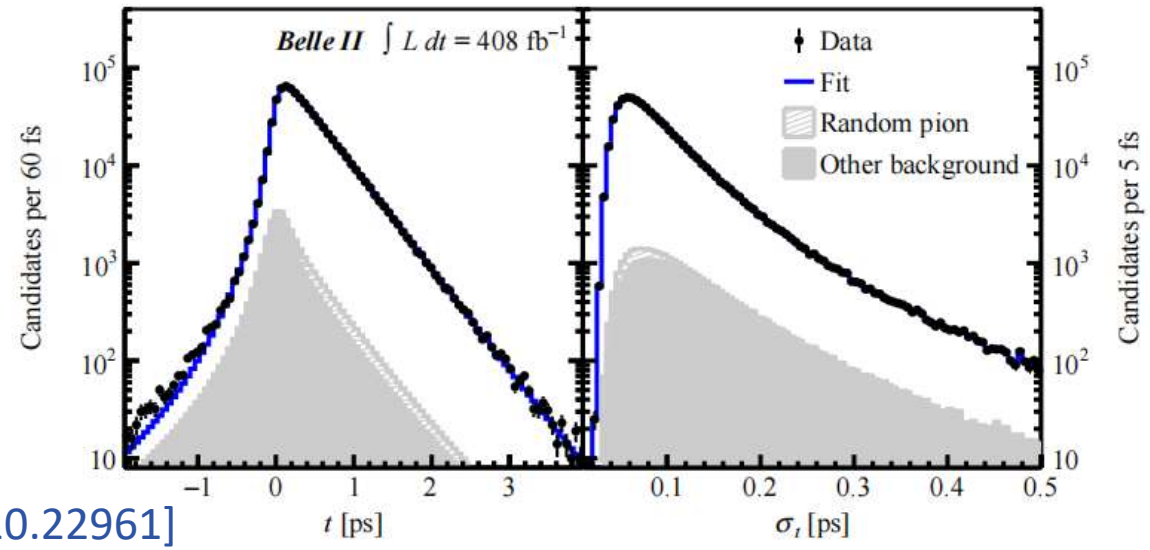
Charm mixing

$X_{\pm b}$: Strong-phase difference between D^0 and $\overline{D}^0$ decays

r_b: Ratio of D^0 and $\overline{D}^0$ decay amplitude square

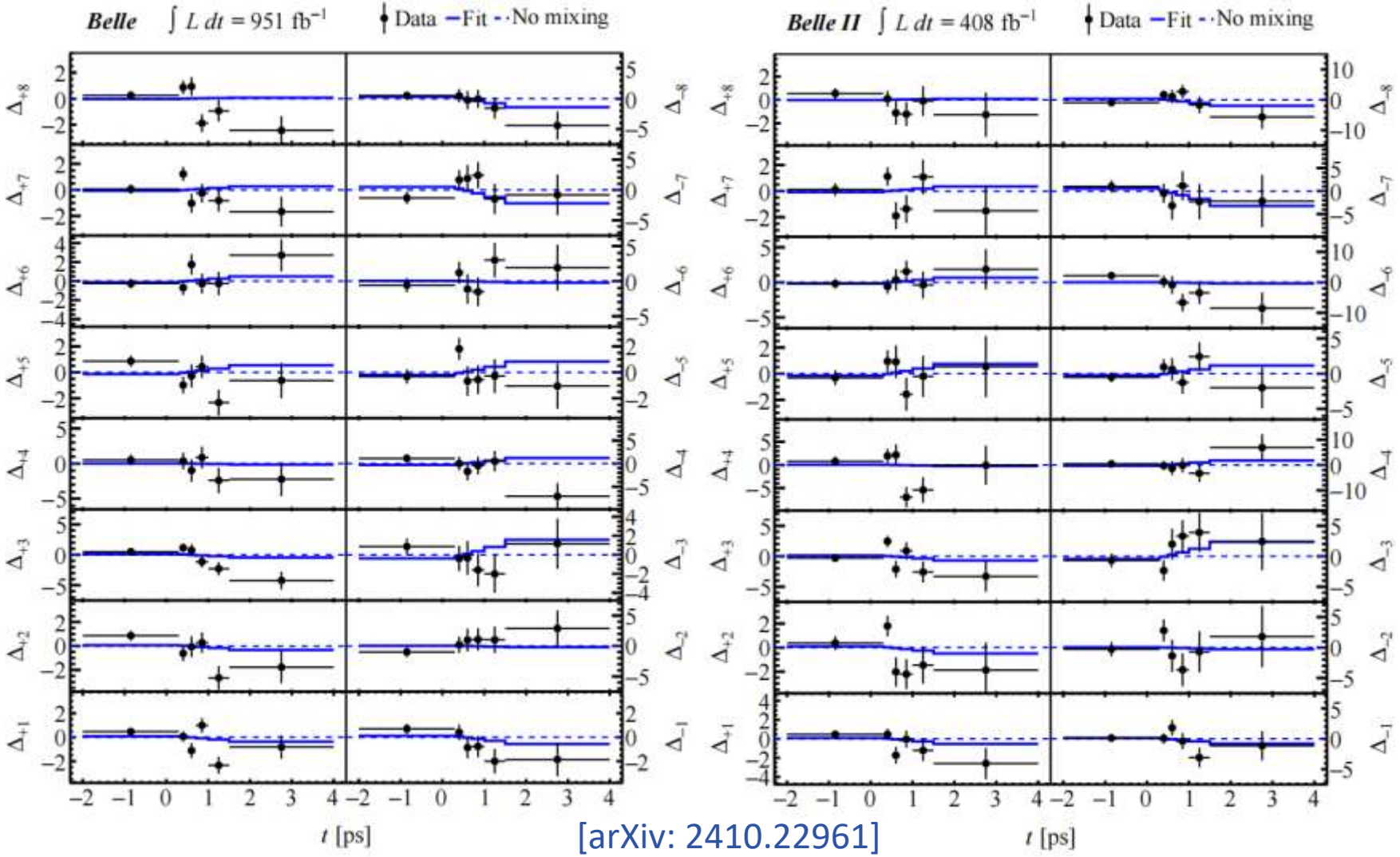






[arXiv: 2410.22961]

多体自共轭衰变测量粲介子混合参数



[arXiv: 2410.22961]

假设不存在CP破坏

$x = (4.0 \pm 1.7 \pm 0.4) \times 10^{-3}$

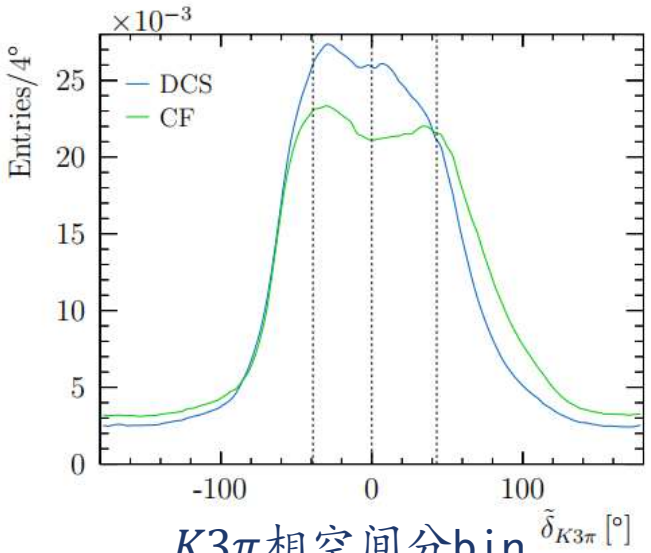
$y = (2.9 \pm 1.4 \pm 0.3) \times 10^{-3}$

2.7σ统计显著性

“味道本征态”衰变测量混合参数

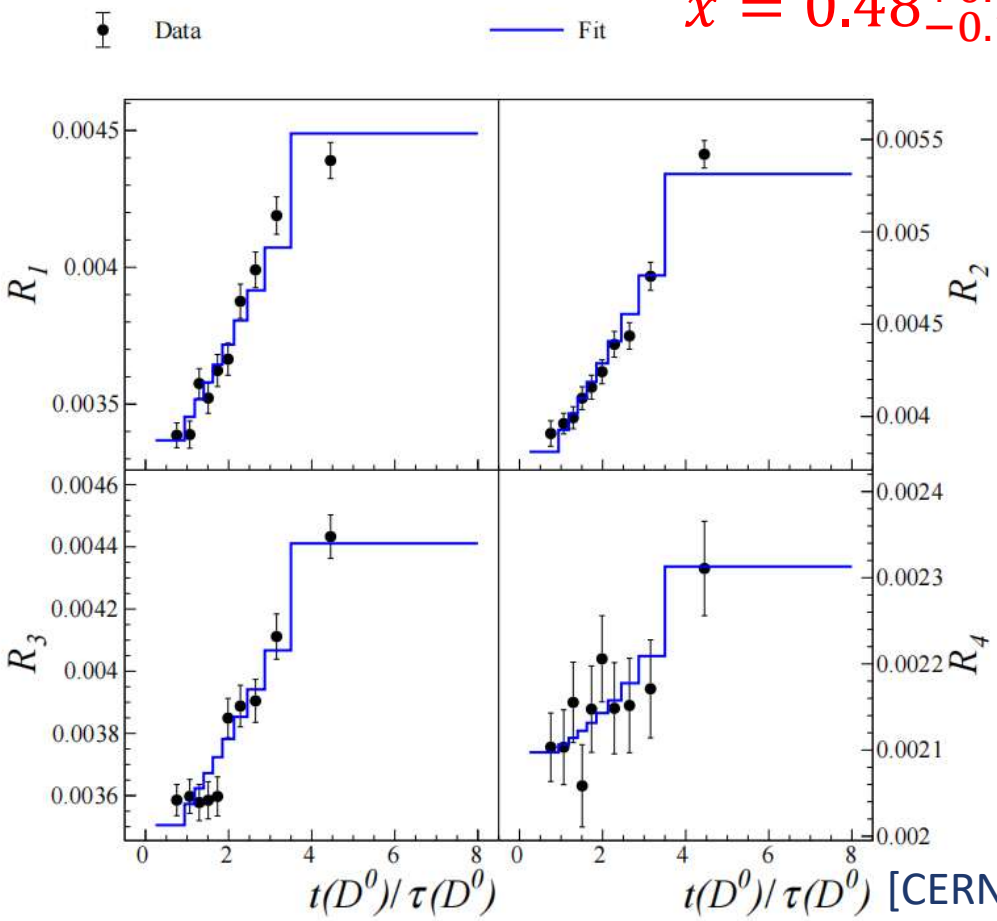
- $R_{ij} = \frac{N_{ij}^{WS}}{N_{ij}^{RS}} = r_i^2 - r_i(R^{Kn\pi}y')_i \left\langle \frac{t_{ij}}{\tau_{D^0}} \right\rangle + \frac{x^2+y^2}{4} \left\langle \left(\frac{t_{ij}}{\tau_{D^0}}\right)^2 \right\rangle$
- WS: $D^{*+} \to (K^+n\pi)\pi^+$; RS: $D^{*+} \to (K^-n\pi)\pi^+$
- $y' = y\cos\delta_D^{Kn\pi} - x\sin\delta_D^{Kn\pi}$
- i: 相空间bin, j: 时间bin

$$y = 0.48^{+0.14}_{-0.13}$$
$$x = 0.48^{+0.11}_{-0.13}$$



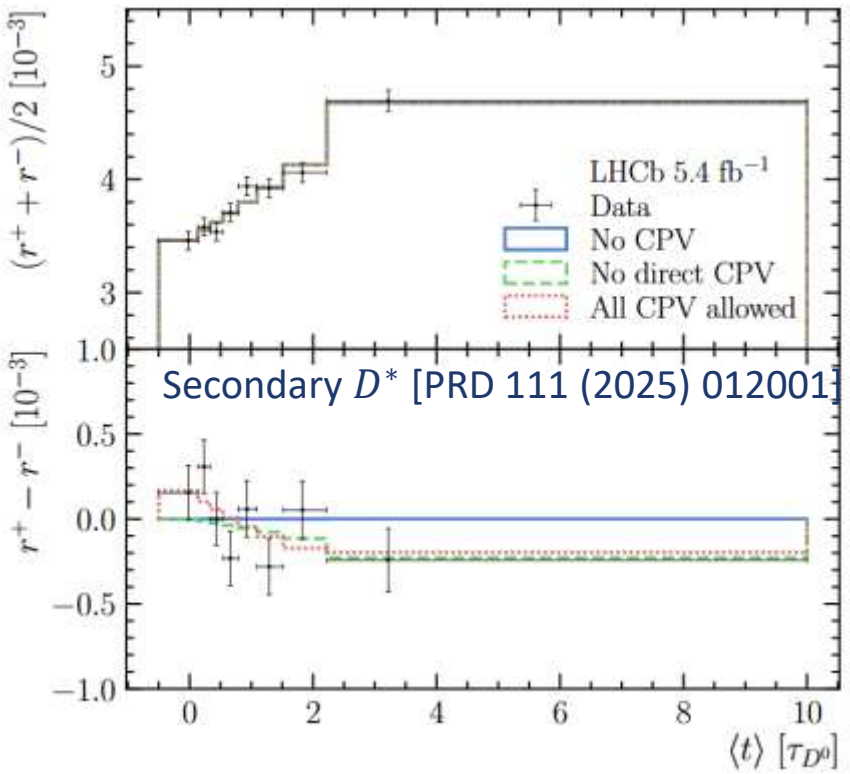
$K3\pi$相空间分bin

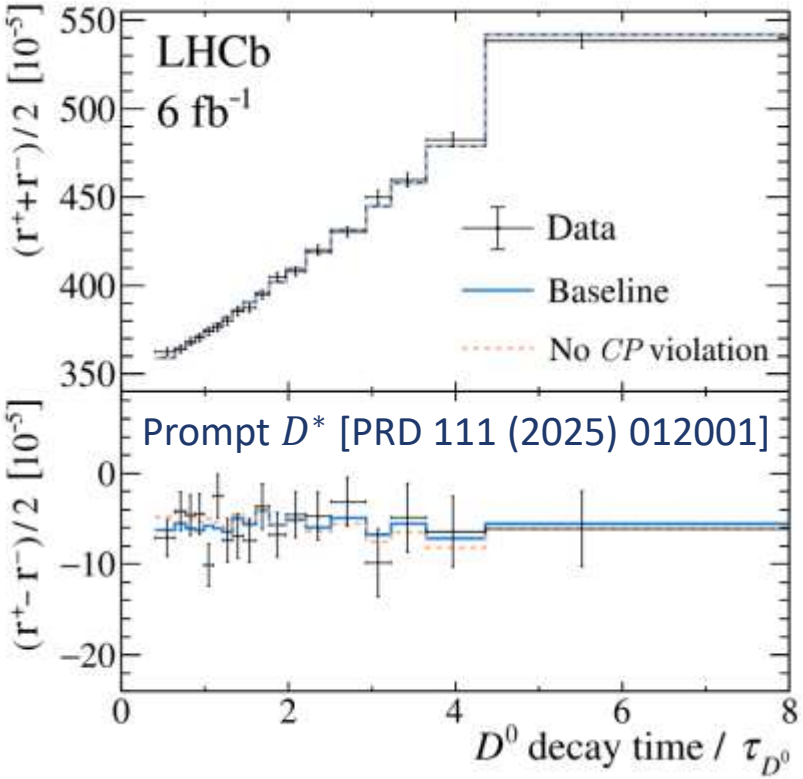
[PLB 802 (2020) 135188]



[CERN-THESIS-2023-252]

“味道本征态”衰变测量混合参数





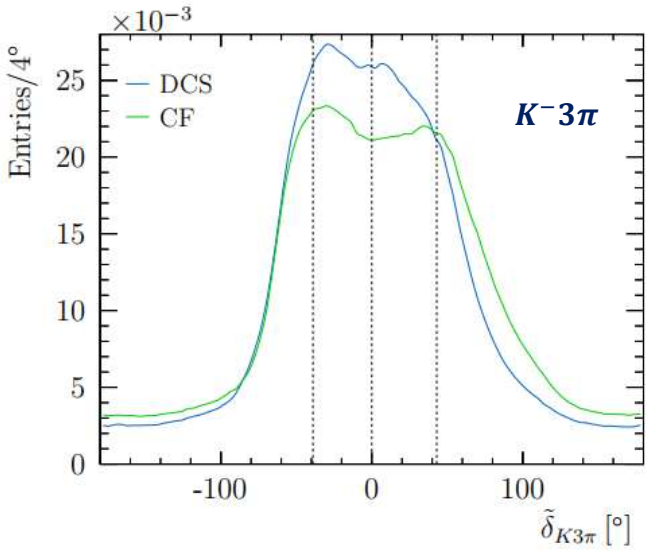
$$y'^{+} = (3.6 \pm 2.2 \pm 0.3) \times 10^{-3}$$
$$(x'^{+})^2 = (1.1 \pm 1.6 \pm 0.1) \times 10^{-4}$$
$$y'^{-} = (8.1 \pm 2.3 \pm 0.3) \times 10^{-3}$$
$$(x'^{+})^2 = (-1.1 \pm 1.9 \pm 0.1) \times 10^{-4}$$

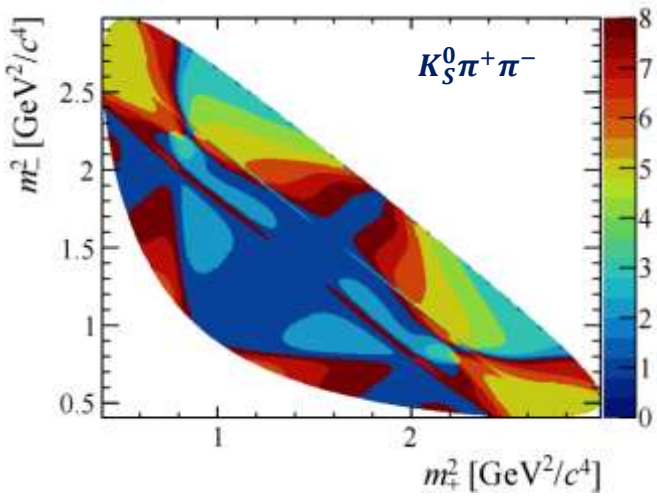
$$\begin{pmatrix} x'^{\pm} \\ y'^{\pm} \end{pmatrix} = |q/p|^{\pm 1} \begin{pmatrix} \cos[\delta \pm \phi] & \sin[\delta \pm \phi] \\ -\sin[\delta \pm \phi] & \cos[\delta \pm \phi] \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

$$c_{K\pi} = y_{12} \cos\phi_f^{\Gamma} \cos\delta_D^f + x_{12} \cos\phi_f^M \sin\delta_D^f$$
$$= (51.4 \pm 3.5) \times 10^{-4}$$
$$\Delta c_{K\pi} = -y_{12} \sin\phi_f^{\Gamma} \sin\delta_D^f + x_{12} \sin\phi_f^M \cos\delta_D^f$$
$$= (3.0 \pm 3.6) \times 10^{-4}$$
$$c'_{k\pi} = \frac{1}{4}(x_{12}^2 + y_{12}^2) = (13.1 \pm 3.7) \times 10^{-6}$$
$$\Delta c'_{k\pi} = \frac{1}{2} x_{12} y_{12} \sin(\phi_f^M - \phi_f^{\Gamma}) = (-1.9 \pm 3.8) \times 10^{-6}$$

强相位差的定义

- 味道本征态$K^-n\pi$
  - $r_D^F \exp(-i\delta_D^F) = \left(\frac{A_{\bar{F}}}{A_F}\right), R_F \exp(-i\delta_D^F) = \frac{\int \mathrm{d}X\, A_F^*(X)A_F(X)}{A_F\bar{A}_F}$
- CP本征态
  - $\delta_D^{CP\pm} = 0$（CP正），π（CP负）
- 准CP本征态
  - $F_+ = \frac{\Gamma_+}{\Gamma_+ + \Gamma_-} = \frac{\int \mathrm{d}X\,(|A_F|^2 + |\bar{A}_F|^2 + 2|A_F||\bar{A}_F|\cos\delta_D^F(X))}{\int \mathrm{d}X\, 2(|A_F|^2 + |\bar{A}_F|^2)} = \frac{1 + \int \mathrm{d}X \cos\delta_D^F(X)}{2}$
- 自共轭衰变
  - $c_i = \frac{1}{\sqrt{F_i F_{-i}}} \int_i \mathrm{d}X |A(X)||\bar{A}(X)| \cos[\delta_D(X)]$
  - $s_i = \frac{1}{\sqrt{F_i F_{-i}}} \int_i \mathrm{d}X |A(X)||\bar{A}(X)| \sin[\delta_D(X)]$
  - $F_i = \frac{\int_i \mathrm{d}X\, |A_F|^2}{\int \mathrm{d}X\, |A_F|^2}$





BESIII强相位差参数的测量

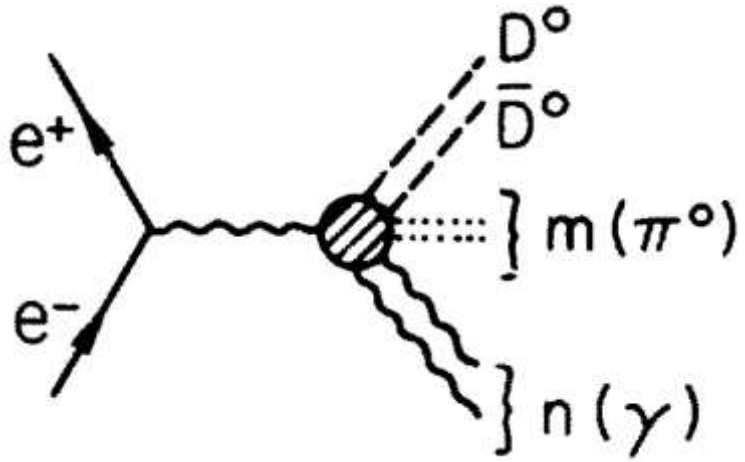
@3770 MeV

C odd for $e^+e^- \to D^0\overline{D}^0$

@Higher energy points

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

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



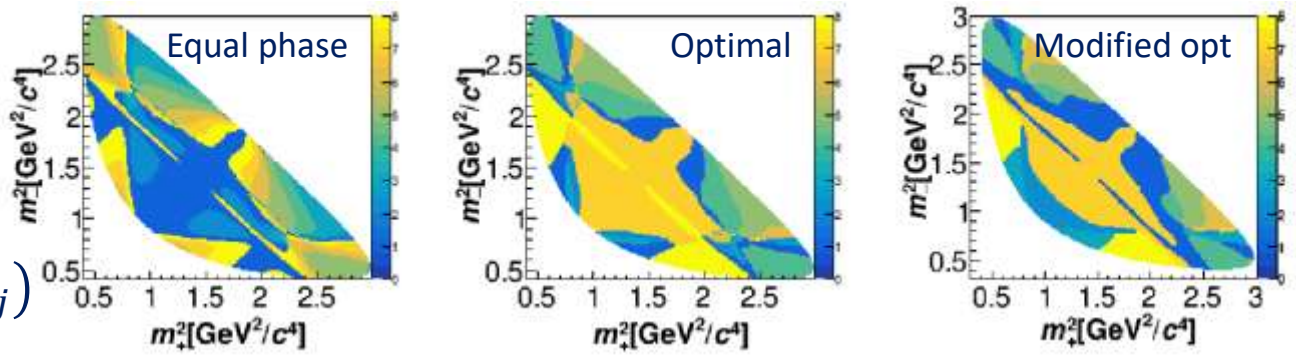
- C宇称负关联，$(e^+e^-)_{\psi(3770)} \to [S]_D[T]_{\overline{D}}$
  - $\Gamma \propto A_S^2A_T^2\left[(r_D^S)^2+(r_D^T)^2-2R_SR_Tr_D^Sr_D^T\cos(\delta_D^S-\delta_D^T)\right]$
- C宇称正关联，$(e^+e^-)_{4009-4230} \to \gamma(\pi^0)[S]_D[T]_{\overline{D}}$
  - $\Gamma \propto A_S^2A_T^2\left[(r_D^S)^2+(r_D^T)^2+2R_SR_Tr_D^Sr_D^T\cos(\delta_D^S-\delta_D^T)-2y\left(R_Sr_D^S\cos\delta_D^S+R_Tr_D^T\cos\delta_D^T\right)+4x\left(R_Sr_D^S\sin\delta_D^S+R_Tr_D^T\sin\delta_D^T\right)\right]$
- 通过不同衰变标记重建信号衰变

		标记侧	分支比
味道本征态		$K^-e^+\nu_e$、$K^-\pi^+$、$K^-\pi^+\pi^0$、$K^-\pi^+\pi^+\pi^-$	10^{-2}
CP本征态	正	K^+K^-、$\pi^+\pi^-$、$\pi^0\pi^0$、$K_L^0\pi^0$、$K_L^0\omega$、$K_S^0\pi^0\pi^0$、$K_S^0\pi^0\eta$、$\pi^+\pi^-\pi^0$	10^{-3}~10^{-2}
	负	$K_S^0\pi^0$、$K_S^0\omega$、$K_S^0\eta$、$K_S^0\eta'$、$K_L^0\pi^0\pi^0$	10^{-3}~10^{-2}
CP共轭		$K_{S,L}^0\pi^+\pi^-(\pi^0)$、$\pi^+\pi^-\pi^+\pi^-$	10^{-3}~10^{-2}

$D \to K^0_{S,L}\pi^+\pi^-$ 衰变中的 $c_i^{(\prime)}, s_i^{(\prime)}$

- CP本征态标记
  - $M_i \propto K_i + K_{-i} - 2c_i\sqrt{K_iK_{-i}}$
  - $M_i' \propto K_i' + K_{-i}' + 2c_i'\sqrt{K_i'K_{-i}'}$
- 自共轭标记
  - $M_{ij} \propto K_iK_{-j} + K_{-i}K_j - 2\sqrt{K_iK_{-i}K_jK_{-j}}(c_ic_j + s_is_j)$
  - $M_{ij} \propto K_iK_{-j}' + K_{-i}K_j' + 2\sqrt{K_iK_{-i}K_j'K_{-j}'}(c_ic_j' + s_is_j')$
- 味道标记
  - $M_i \propto K_i + (r_D^F)^2K_{-i} - 2R_Dr_D^F\sqrt{K_iK_{-i}}(\cos\delta_D^Fc_i - \sin\delta_D^Fs_i)$
  - $M_i' \propto K_i' + (r_D^F)^2K_{-i}' + 2R_Dr_D^F\sqrt{K_i'K_{-i}'}(\cos\delta_D^Fc_i' - \sin\delta_D^Fs_i')$
- $K_L^0\pi^+\pi^-$ is used to improve the measurement

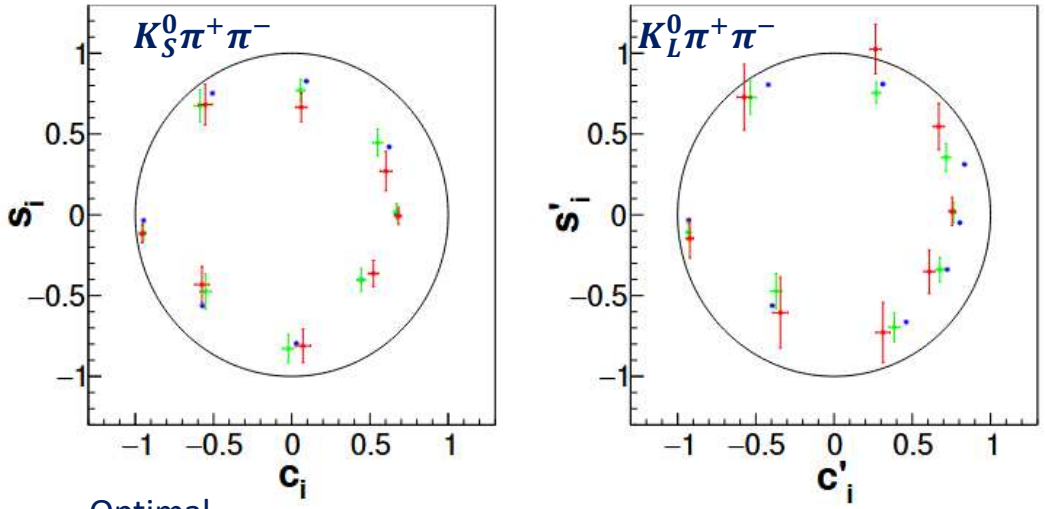
$K^0_{S,L}\pi^+\pi^-$



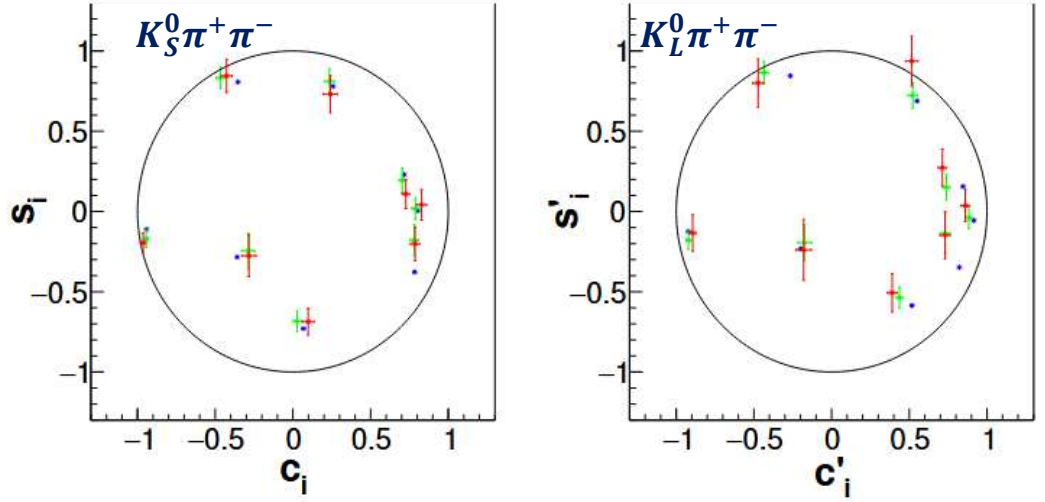
$D \to K^0_{S,L}\pi^+\pi^-$衰变中的$c_i^{(\prime)}, s_i^{(\prime)}$

JHEP 06 (2025) 086

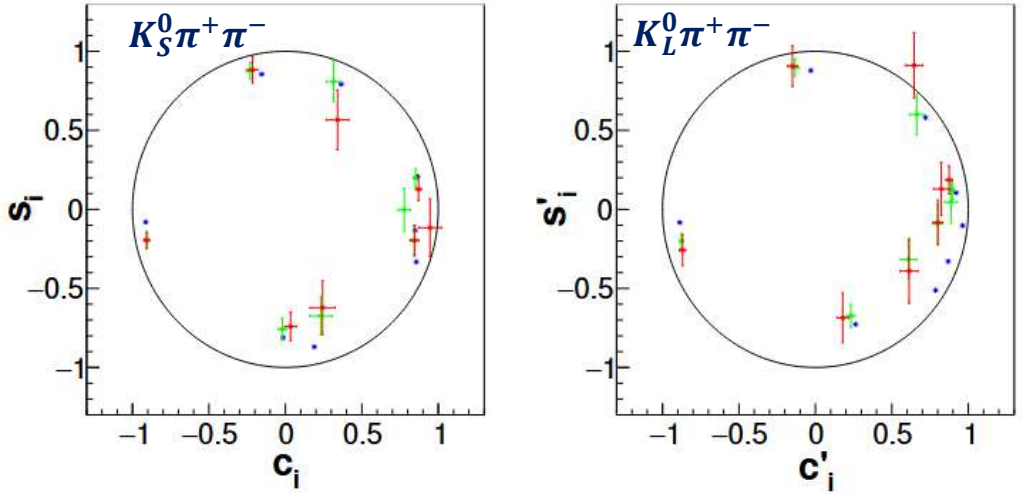
Equal phase



Modified optimal



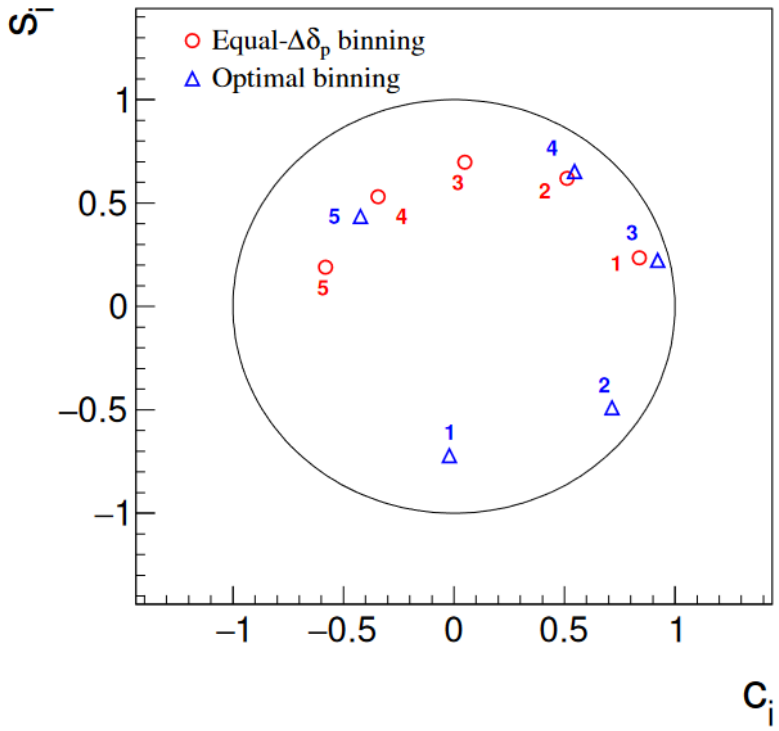
Optimal



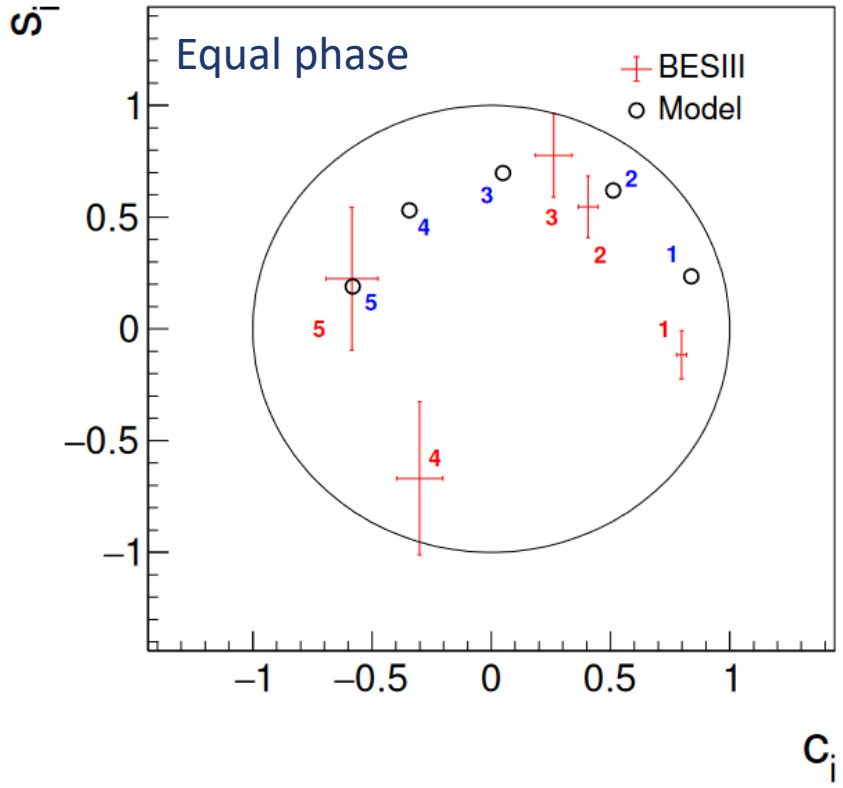
- 改进了模拟样本中的量子关联效应的模拟
  - 信号$K^0_{S,L}\pi^+\pi^-$和本底$2(\pi^+\pi^-)$等衰变的振幅模型
- 不同数据的测量结果基本一致
- 对charm mixing参数/γ角误差贡献改善1.4倍

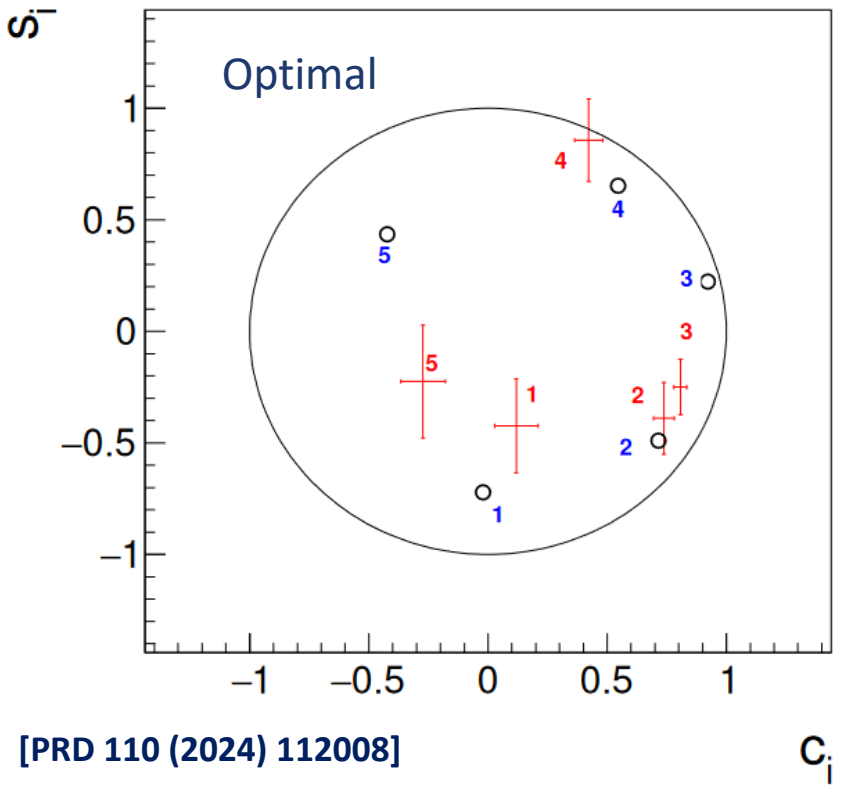
$D \to \pi^+\pi^-\pi^+\pi^-$衰变中的$c_i, s_i$

- 分bin方法
  - 5维相空间$m_+, m_-, \cos\theta_+, \cos\theta_-, \phi$
  - BESIII振幅模型Chin. Phys. C 48, 083001 (2024)
  - Equal phase binning & optimal binning
- CP本征态标记
  - $M_i \propto K_i + K_{-i} - 2c_i\sqrt{K_i K_{-i}}$
  - $M_i' \propto K_i' + K_{-i}' + 2c_i'\sqrt{K_i' K_{-i}'}$
- 自共轭标记
  - $M_{ij} \propto K_i K_{-j} + K_{-i} K_j - 2\sqrt{K_i K_{-i} K_j K_{-j}}\left(c_i c_j + s_i s_j\right)$
  - $M_{ij} \propto K_i K_{-j}' + K_{-i} K_j' + 2\sqrt{K_i K_{-i} K_j' K_{-j}'}\left(c_i c_j' + s_i s_j'\right)$
- 味道标记
  - $M_i \propto K_i + (r_D^F)^2 K_{-i} - 2R_D r_D^F \sqrt{K_i K_{-i}}(\cos\delta_D^F c_i - \sin\delta_D^F s_i)$
  - $M_i' \propto K_i' + (r_D^F)^2 K_{-i}' + 2R_D r_D^F \sqrt{K_i' K_{-i}'}(\cos\delta_D^F c_i' - \sin\delta_D^F s_i')$



$D \to \pi^+\pi^-\pi^+\pi^-$ 衰变中的 c_i, s_i



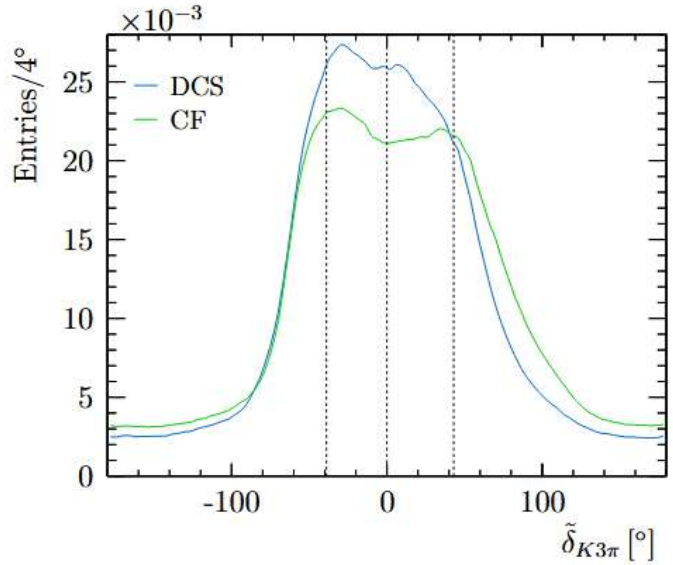


[PRD 110 (2024) 112008]

$D \to K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-, K^-\pi^+$

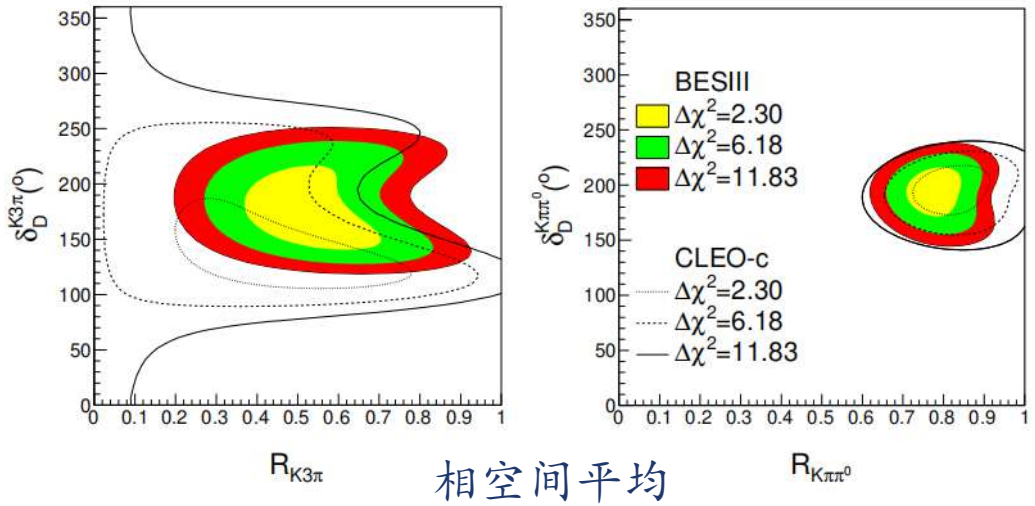
- 味道本征态（同号）标记
  - $\Gamma = \Gamma_0|A_S|^2|\bar{A}_S|^2[1 - R_S^2]$
  - $\Gamma = \Gamma_0|A_S|^2|A_T|^2\left[\left(r_D^S\right)^2 + (r_D^T)^2 - 2R_SR_Tr_D^Sr_D^T\cos\left(\delta_D^T - \delta_D^S\right)\right]$
- CP标记
  - $\Gamma = \Gamma_0|A_S|^2|A_{CP}|^2\left[1 + \left(r_D^S\right)^2 - 2(2F_+ - 1)R_Fr_D^F\cos(\delta_D^F)\right]$
- CP共轭标记
  - $Y_i^{K_S^0\pi\pi} = H_F\left(K_i + \left(r_D^S\right)^2K_{-i} - 2R_Fr_D^F\sqrt{K_iK_{-i}}[c_i\cos\delta_D^F - s_i\sin\delta_D^F]\right)$
  - $Y_i^{K_L^0\pi\pi} = H_F'\left(K_i' + \left(r_D^S\right)^2K_{-i}' + 2R_Fr_D^F\sqrt{K_i'K_{-i}'}[c_i'\cos\delta_D^F - s_i'\sin\delta_D^F]\right)$

$K3\pi$相空间分bin
[PLB 802 (2020) 135188]



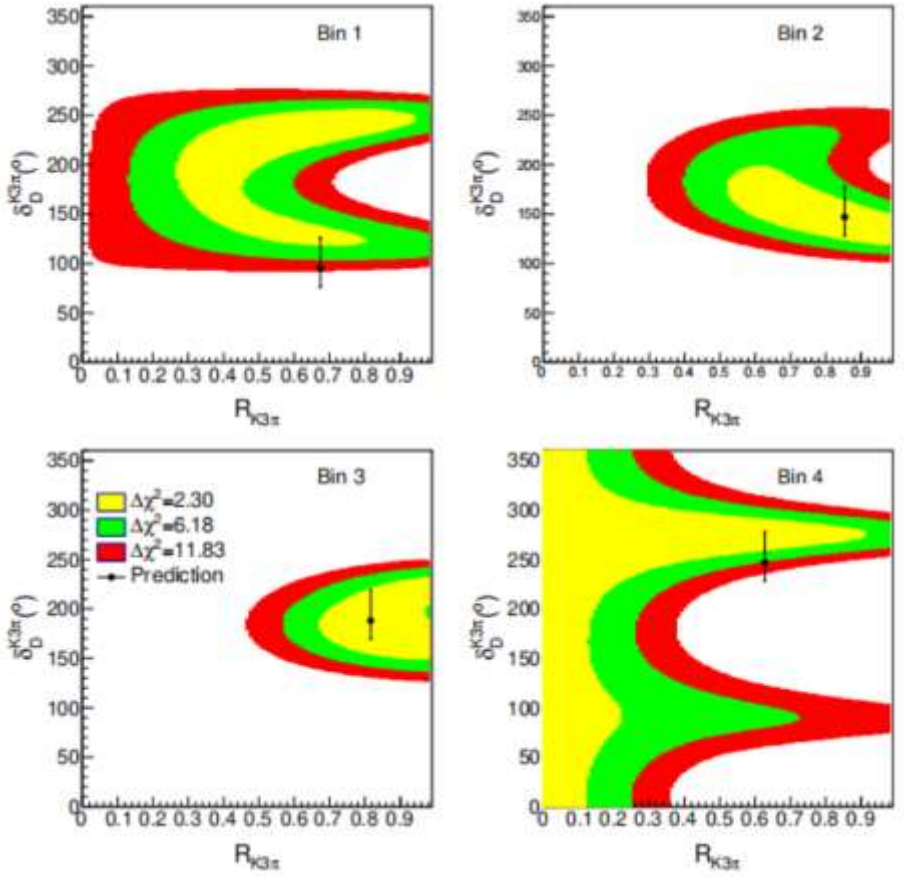
$D \to K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$

Parameter	Global fit	Binned fit			
		Bin 1	Bin 2	Bin 3	Bin 4
$R_{K3\pi}$	$0.52^{+0.12}_{-0.10}$	$0.58^{+0.25}_{-0.33}$	$0.78^{+0.50}_{-0.21}$	$0.85^{+0.15}_{-0.12}$	$0.45^{+0.33}_{-0.37}$
$\delta_D^{K3\pi}$	$\left(167^{+31}_{-19}\right)^\circ$	$\left(131^{+124}_{-16}\right)^\circ$	$\left(150^{+37}_{-39}\right)^\circ$	$\left(176^{+57}_{-21}\right)^\circ$	$\left(274^{+19}_{-30}\right)^\circ$
$r_D^{K3\pi}$ $(\times 10^{-2})$	5.46 ± 0.09	$5.44^{+0.45}_{-0.14}$	$5.80^{+0.14}_{-0.13}$	$5.75^{+0.41}_{-0.14}$	$5.09^{+0.14}_{-0.14}$
$R_{K\pi\pi^0}$	0.78 ± 0.04	0.80 ± 0.04			
$\delta_D^{K\pi\pi^0}$	$\left(196^{+14}_{-15}\right)^\circ$	$(200\pm11)^\circ$			
$r_D^{K\pi\pi^0}$ $(\times 10^{-2})$	4.40 ± 0.11	4.41 ± 0.11			



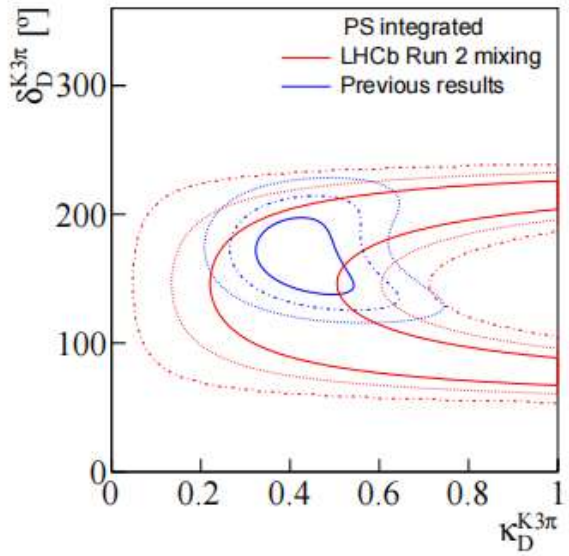
相空间平均

$K3\pi$相空间分bin

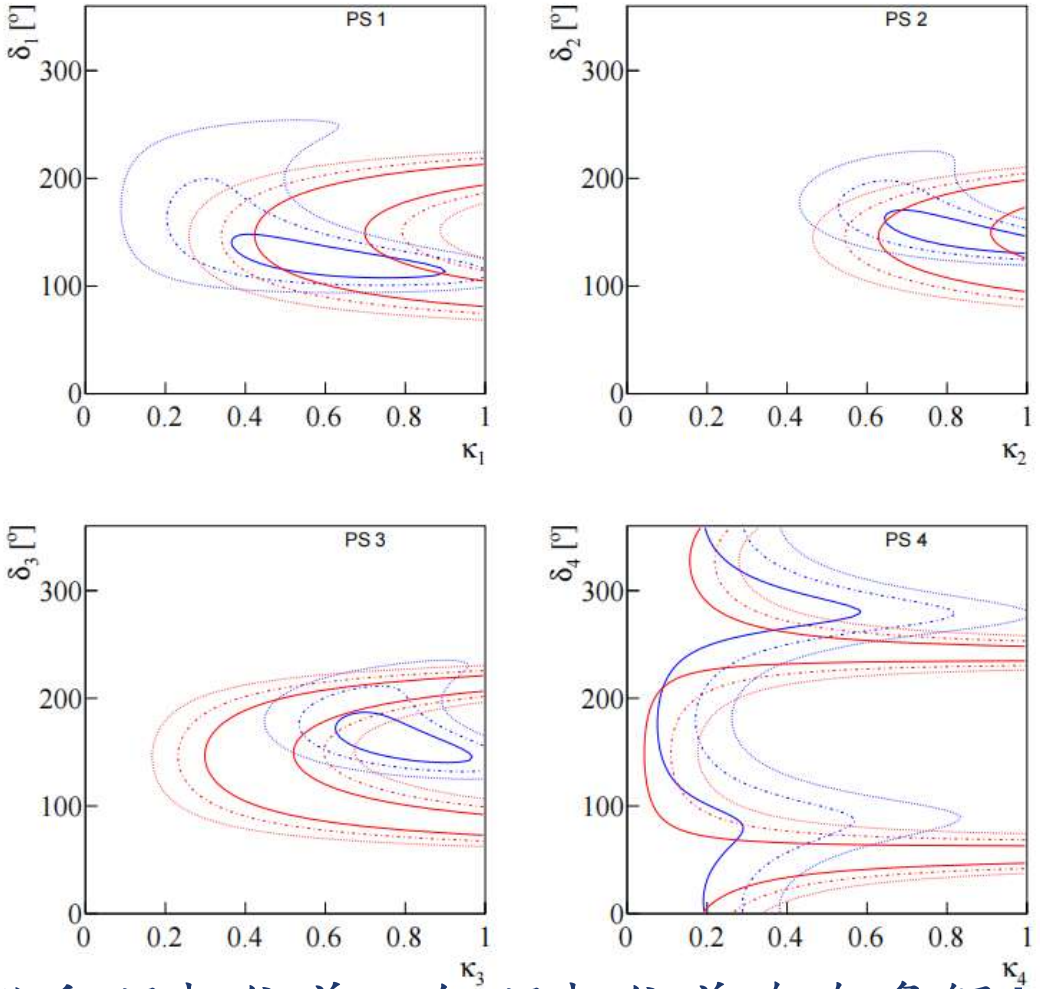


JHEP 05 (2021) 164

$D \to K^-\pi^+\pi^+\pi^-$衰变的强相位差



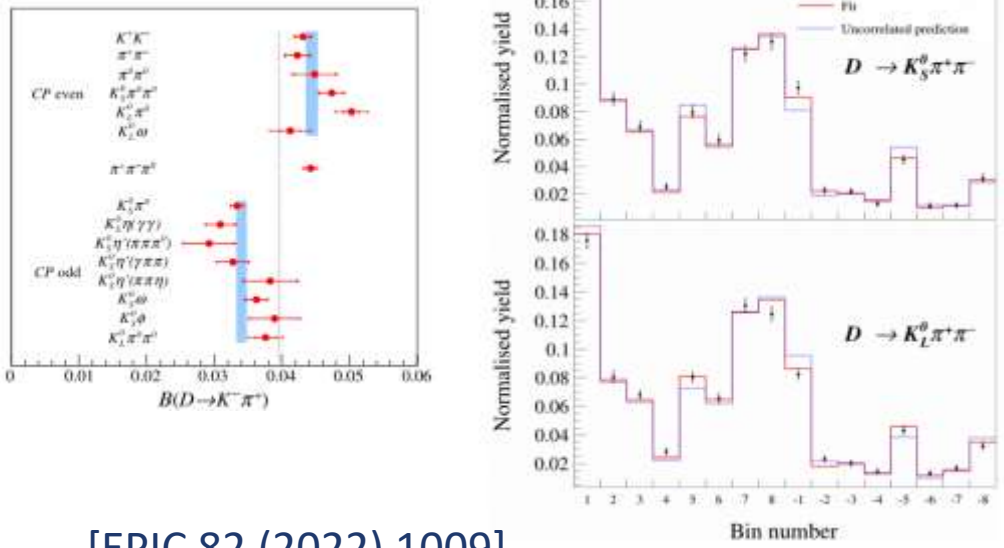
[CERN-THESIS-2023-252]



B工厂含时测量可同时测量混合参数和强相位差，但强相位差存在多解！

粲介子工厂上量子关联的$D\overline{D}$数据提供不可或缺的输入

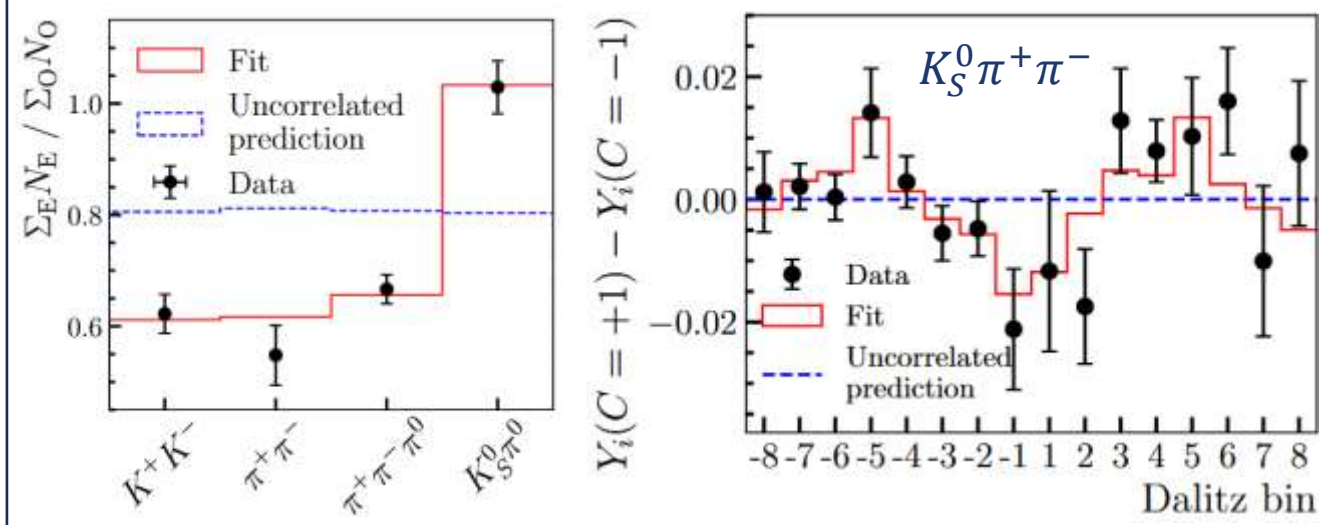
$D \to K^-\pi^+$



[EPJC 82 (2022) 1009]

$\psi(3770)$数据，C宇称负关联

$\delta_D^{K\pi} = \left(187.6^{+8.9+5.4}_{-9.7-6.4}\right)^o$



[arXiv: 2506.07906]

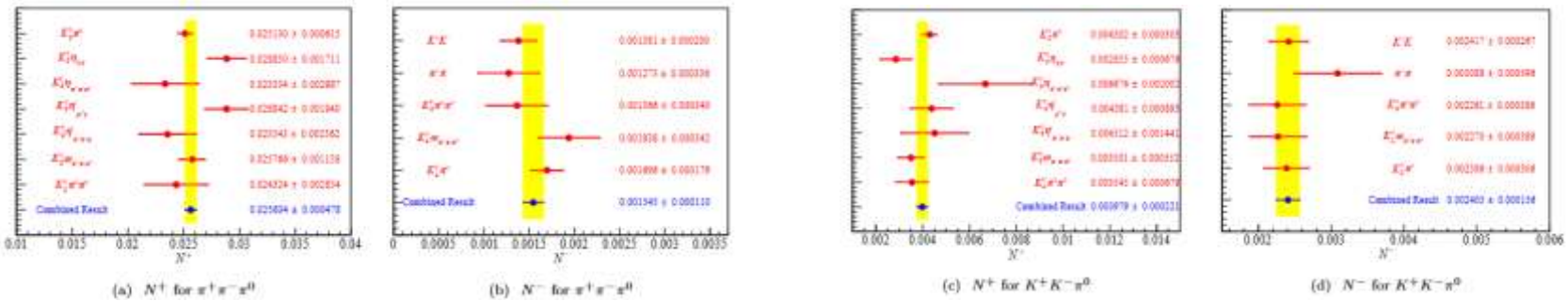
高能量点数据，C宇称负关联+正关联

$\delta_D^{K\pi} = (192.8^{+11.0+1.9}_{-12.4-2.4})^o$

首次采用C宇称正关联的$D\bar{D}$样本测量

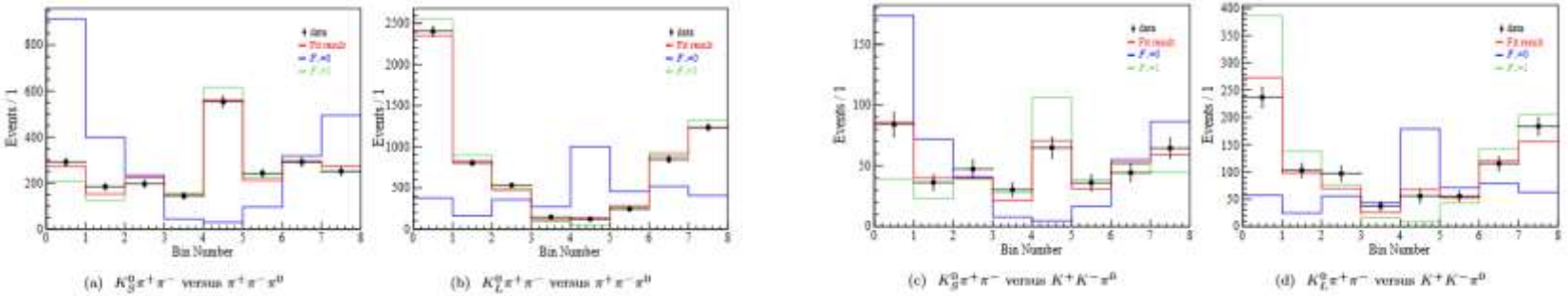
$\pi^+\pi^-\pi^0, K^+K^-\pi^0$衰变中的偶$CP$比分

- CP本征态标记
  - $\Gamma = A_S^2 A_T^2\left[1-(2F_+-1)\cos\delta_D^{CP\pm}\right]$



(a) N^+ for $\pi^+\pi^-\pi^0$ (b) N^- for $\pi^+\pi^-\pi^0$ (c) N^+ for $K^+K^-\pi^0$ (d) N^- for $K^+K^-\pi^0$

- CP共轭标记
  - $\Gamma_i = A_S^2 A_T^2\left[K_i + K_{-i} - 2\sqrt{K_i K_{-i}}c_i(2F_+-1)\right]$
  - $\Gamma_i' = A_S^2 A_T^2\left[K_i' + K_{-i}' + 2\sqrt{K_i' K_{-i}'}c_i'(2F_+-1)\right]$



(a) $K_S^0\pi^+\pi^-$ versus $\pi^+\pi^-\pi^0$ (b) $K_L^0\pi^+\pi^-$ versus $\pi^+\pi^-\pi^0$ (c) $K_S^0\pi^+\pi^-$ versus $K^+K^-\pi^0$ (d) $K_L^0\pi^+\pi^-$ versus $K^+K^-\pi^0$

Tag mode	$F_+^{\pi^+\pi^-\pi^0}$	$F_+^{K^+K^-\pi^0}$
Pure CP	$0.9432 \pm 0.0040 \pm 0.0022$	$0.623 \pm 0.020 \pm 0.008$
$K^+K^-\pi^0$	$1.0060 \pm 0.0675 \pm 0.0379$	$0.649 \pm 0.125 \pm 0.025$
$\pi^+\pi^-\pi^0$	$0.9472 \pm 0.0139 \pm 0.0081$	$0.631 \pm 0.030 \pm 0.020$
$2(\pi^+\pi^-)$	$0.9948 \pm 0.0230 \pm 0.0267$	$0.667 \pm 0.058 \pm 0.033$
$K_{S,L}^0\pi^+\pi^-$	$0.9065 \pm 0.0116 \pm 0.0073$	$0.652 \pm 0.033 \pm 0.023$
Combined	$0.9406 \pm 0.0036 \pm 0.0021$	$0.631 \pm 0.014 \pm 0.011$
PDG Scale	$0.9406 \pm 0.0055 \pm 0.0033$	—

[PRD 111 (2025) 012007]

$F_+^{\pi\pi\pi^0}$	$F_+^{KK\pi^0}$
0.973 ± 0.017	0.732 ± 0.055

[Phys. Lett. B 747 (2015) 9]

Status and prospects of BESIII measurements

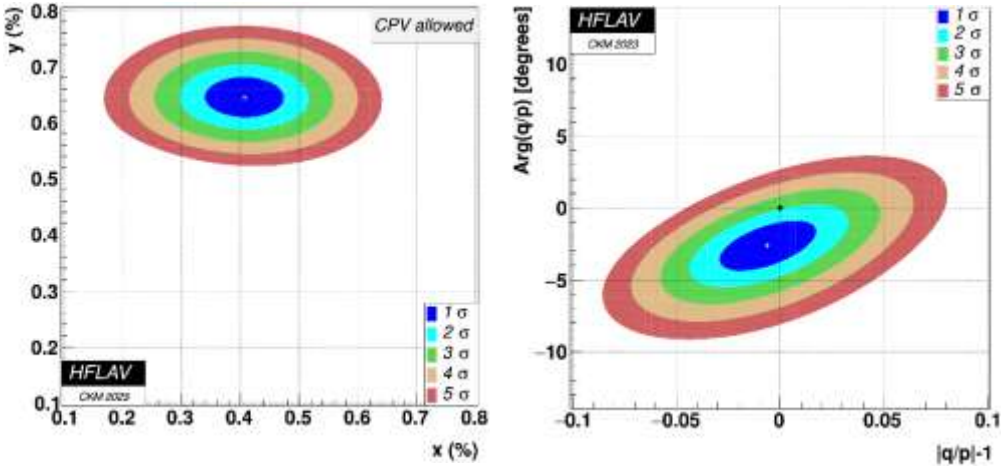
自共轭衰变

味道本征态

准CP本征态

Decay	Strong-phase parameters	2.93 fb^{-1} $\psi(3770)$ data	Prospects
$K^0_{S,L}\pi^+\pi^-$	c_i, s_i	PRL 124 (2020) 241802 PRD 101 (2020) 112002	8 fb^{-1} JHEP 06 (2025) 086 20 fb^{-1} ongoing Unbinned: ongoing
$K^0_{S,L}K^+K^-$	c_i, s_i	PRD 102 (2020) 052008	20 fb^{-1} ongoing Unbinned: ongoing
$\pi^+\pi^-\pi^+\pi^-$	F^+/c_i, s_i	PRD 106 (2022) 092004 PRD 110 (2024) 112008	20 fb^{-1} ongoing
$K^+K^-\pi^+\pi^-$	F^+/c_i, s_i	PRD 107 (2023) 032009	20 fb^{-1} arXiv: 2502.12873
$K^0_{S,L}\pi^+\pi^-\pi^0$	F^+/c_i, s_i	PRD 108 (2023) 032003	c_i, s_i: ongoing
$K^\pm\pi^\mp\pi^+\pi^-$	δ_D, R_D	JHEP 05 (2021) 164	8 and 20 fb^{-1} ongoing $D^*\bar{D}^{(*)}$ ongoing (x, y)
$K^\pm\pi^\mp\pi^0$	δ_D, R_D	JHEP 05 (2021) 164	8 and 20 fb^{-1} ongoing $D^*\bar{D}^{(*)}$ ongoing (x, y)
$K^\pm\pi^\mp$	δ_D	EPJC 82 (2022) 1009	20 fb^{-1} ongoing $D^*\bar{D}^{(*)}$: 2506.07906
$K^0_S K^\pm\pi^\mp$	δ_D, R_D	–	20 fb^{-1} ongoing
$\pi^+\pi^-\pi^0$、 $K^+K^-\pi^0$	F^+/c_i, s_i	–	8 fb^{-1} PRD 111 (2025) 012007 20 fb^{-1} ongoing

Summary



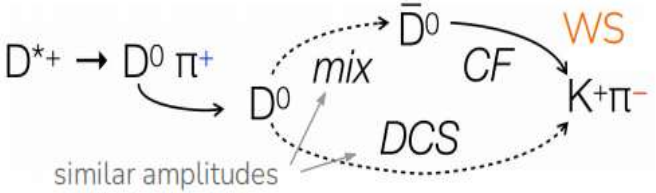
$x = (4.07 \pm 0.44) \times 10^{-3}$

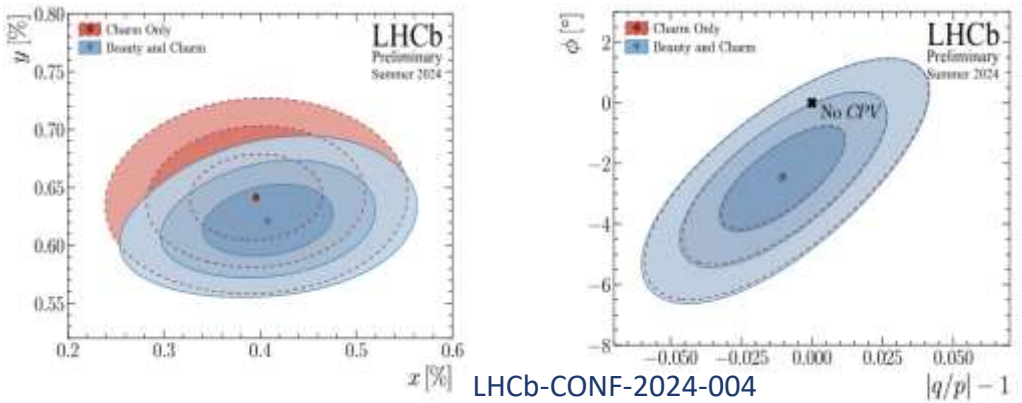
$y = (6.45^{+0.024}_{-0.023}) \times 10^{-3}$

$|q/p| = 0.994^{+0.016}_{-0.015}$

$\phi = (-2.6^{+1.1}_{-1.2})^o$

包含了LHCb, Belle, BESIII等实验测量结果





LHCb-CONF-2024-004

$x = (4.1 \pm 0.5) \times 10^{-3}$

$y = (6.21^{+0.022}_{-0.021}) \times 10^{-3}$

$|q/p| = 0.989 \pm 0.015$

$\phi = (-2.5 \pm 1.2)^o$

包含了LHCb, BESIII等实验测量结果

- 中性粲介子混合和间接CP破坏
  - LHCb+Belle II: $D^{*+} \to D^0\pi^+$
  - BESIII/未来陶粲能区e^+e^-对撞机: C-even关联的$D^0\overline{D}^0$对数据

- 依赖强相位差参数提供关键输入
  - BESIII/未来陶粲能区 e^+e^- 对撞机: C-odd/even关联的$D^0\overline{D}^0$对数据
  - 可满足未来混合和间接CP破坏测量的精度要求