Charm mixing and indirect CPV studies at STCF

Ying-Hao Wang[1] , Yu Zhang[2], Ying-Rui Hou[3], Pei-Rong Li[1]
Xiao-Rui Lyu[3] , Yang-Heng Zheng[3]

[1]LZU [2]USC [3]UCAS

超级陶粲装置研讨会，兰州，09/07/2024

Outline

- Charm mixing and indirect CPV
- Time-integrated measurement
- Sensitivity study with STCF
- Summary and future plan

Neutral meson mixing

First observation of neutral meson mixing in K^0 mesons.

Evidence for a Long-Lived Neutral Unstable Particle*

W. F. Fry, J. Schneps, and M. S. Swami
Department of Physics, University of Wisconsin, Madison, Wisconsin
(Received July 19, 1956)

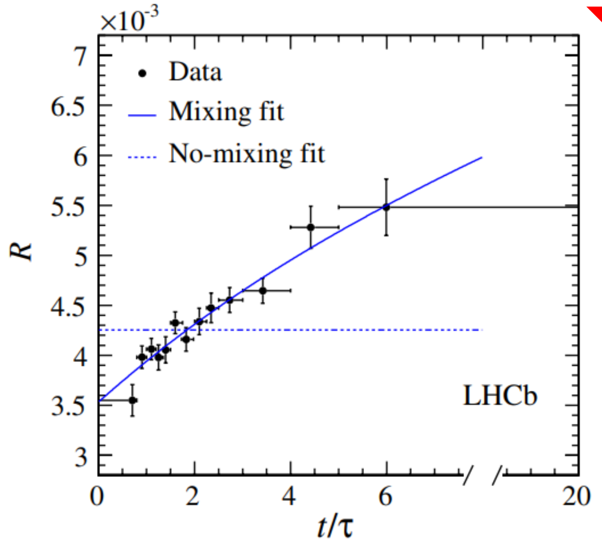
SEARCH FOR B^0–$\bar{B}^0$ OSCILLATIONS AT THE CERN PROTON–ANTIPROTON COLLIDER

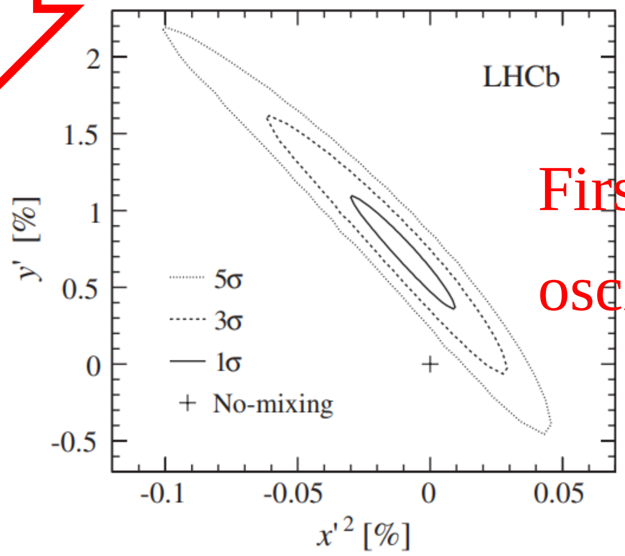
UA1 Collaboration, CERN, Geneva, Switzerland

PRL **97**, 242003 (2006) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER 2006

Observation of $B_s^0 - \bar{B}_s^0$ Oscillations

Search for D^0 meson mixing (Belle, BaBar, CDF and LHCb)

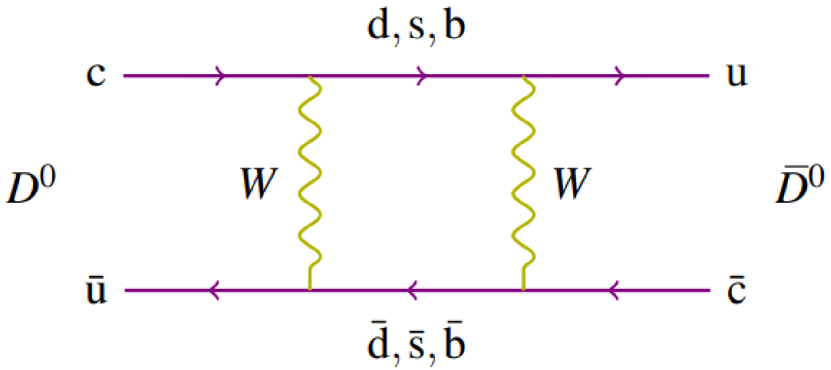


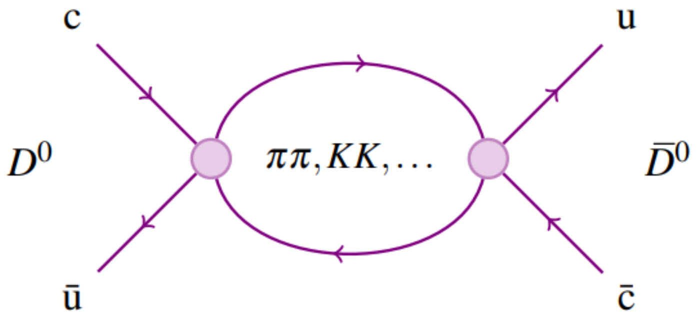


First observation of $D^0\bar{D}^0$ oscillations.

Charm mixing

- Mixing amplitudes governed by two contributions:
  - Short distance:
    - ✓ Via box diagrams, $(x, y) \sim 10^{-7}$
    - ✓ Suppressed by GIM cancellation





  - Long distance:
    - ✓ re-scattering diagram, $(x, y) \sim 10^{-3}$
    - ✓ Theoretical prediction of x and y very challenging

Plots from arXiv:1503.00032

Charm mixing

- Mass eigenstates of D^0 and $\overline{D}^0$ mesons can be written as superpositions of flavor eigenstates:

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle \qquad |p|^2+|q|^2=1$$

- Time evolution of a initially flavor eigenstates of D^0 and $\overline{D}^0$ mesons:

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

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

- Practically, it is more popular to use the following two dimensionless parameters for describing D^0-$\overline{D}^0$ mixing:

$$x\equiv\frac{\Delta m}{\Gamma}, y\equiv\frac{\Delta\Gamma}{2\Gamma}$$

Indirect charm CPV

- CPV in mixing:

  Probability of $|D^0_{phy}(t)\rangle \to |\bar{D}^0\rangle \neq |\bar{D}^0_{phy}(t)\rangle \to |D^0\rangle$: $|q/p| \neq 1$.

- CPV in mixing/decay interference:

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

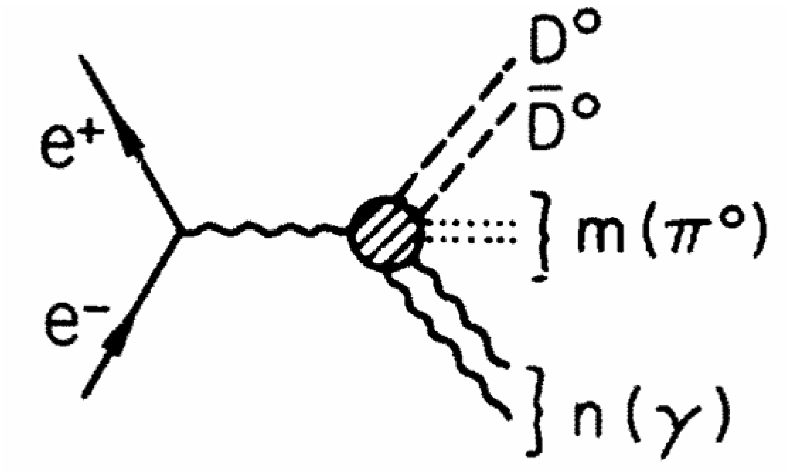
  Decay rates: $$R(D^0_{\rm phys}(t)\to f) \propto |A_f|^2 \exp(-\Gamma t)\Big[1+\tfrac{1}{4}(x_D^2+y_D^2)|\lambda_f|^2\Gamma^2t^2 - \tfrac{1}{4}(x_D^2-y_D^2)\Gamma^2t^2-(y_D{\rm Re}\lambda_f+x_D{\rm Im}\lambda_f)\Gamma t\Big]$$

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

  Phys. Rev. D 55 (1997) 196

- Currently, the mixing and CPV parameters are usually measured with the time-dependent analysis in B factory.

Quantum correlated $D^0\bar{D}^0$



Phys. Rev. D 15 (1977) 1254

- $D^0\bar{D}^0$ pairs produced by e^+e^- annihilations near threshold are in quantum correlated state with $C = (-1)^{n+1}$.
- @3770 MeV
  - $C = -1, e^+e^- \to D^0\bar{D}^0$
- @>4009 MeV
  - $C = +1$ for $e^+e^- \to D^{*0}\bar{D}^0 + c.c, D^{*0} \to \gamma D^0$
  - $C = -1$ for $e^+e^- \to D^{*0}\bar{D}^0 + c.c, D^{*0} \to \pi^0 D^0$

Exploring the QC in $D^0\bar{D}^0$ allows to extract the mixing and CPV parameters with time-integrated decay rates.

Quantum correlated decay rates

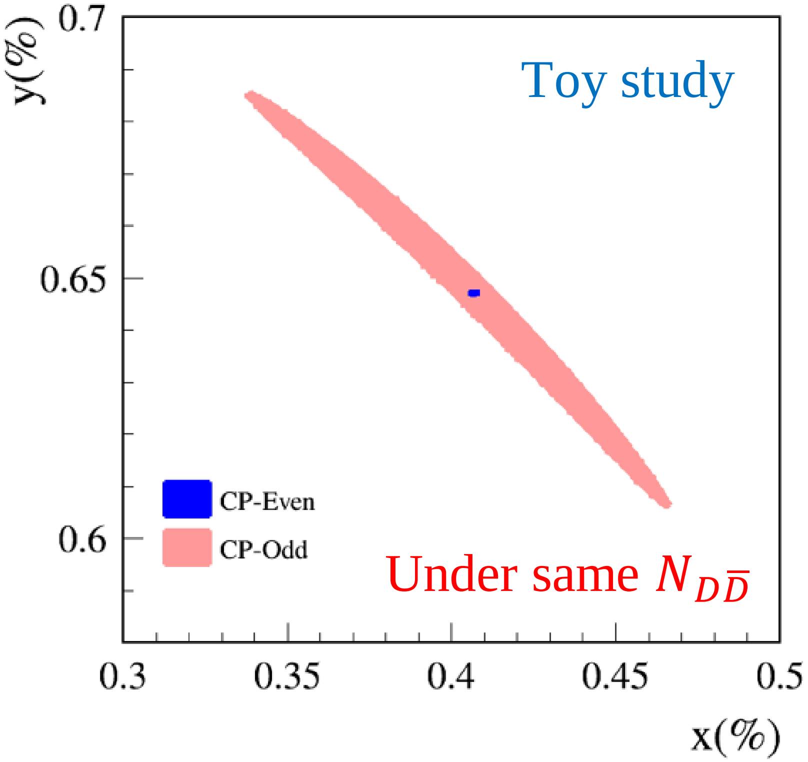
$\mathcal{C} = +1$

$$W(f_1, f_2) = 3(x^2 + y^2)(|\lambda_{D^0}|^2 + |\lambda_{\bar{D}^0}|^2 + 2R_{D^0}R_{\bar{D}^0}\lambda_{D^0}\lambda_{\bar{D}^0}) + (2 - 3(x^2 - y^2))(1 + 2R_{D^0}R_{\bar{D}^0}\mathrm{Re}(\lambda_{D^0}\lambda_{\bar{D}^0}) + |\lambda_{D^0}\lambda_{\bar{D}^0}|^2) - 4y[R_{\bar{D}^0}(1 + |\lambda_{D^0}|^2)\mathrm{Re}(\lambda_{\bar{D}^0}) + R_{D^0}(1 + |\lambda_{\bar{D}^0}|^2)\mathrm{Re}(\lambda_{D^0})] - 4x[R_{\bar{D}^0}(1 - |\lambda_{D^0}|^2)\mathrm{Im}(\lambda_{\bar{D}^0}) + R_{D^0}(1 - |\lambda_{\bar{D}^0}|^2)\mathrm{Im}(\lambda_{D^0})]$$

$\mathcal{C} = -1$

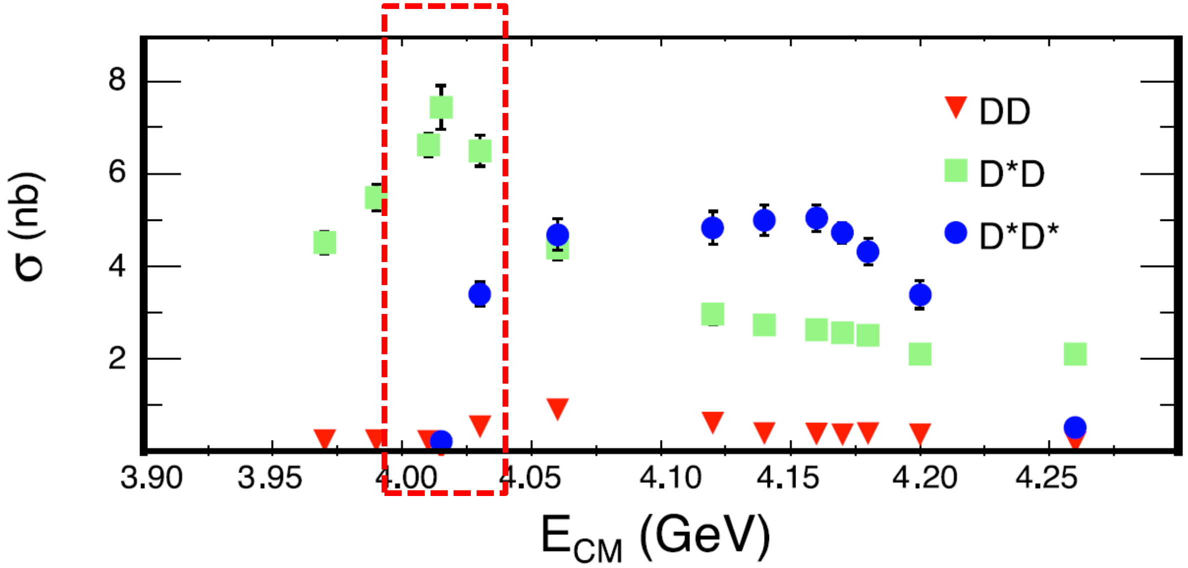
$$W(f_1, f_2) = (x^2 + y^2)(|\lambda_{D^0}|^2 + |\lambda_{\bar{D}^0}|^2 - 2R_{D^0}R_{\bar{D}^0}\mathrm{Re}(\lambda_{D^0}\lambda_{\bar{D}^0})) + (2 - (x^2 - y^2))(1 - 2R_{D^0}R_{\bar{D}^0}\mathrm{Re}(\lambda_{D^0}\lambda_{\bar{D}^0}) + |\lambda_{D^0}\lambda_{\bar{D}^0}|^2)$$

- C-even quantum correlation samples are better at measuring mixing and CPV parameters.



Fake data study at STCF

- $E_{cms} = 4009\text{MeV}, 4015\text{ MeV}$ and 4030 MeV, $\int L = 1\text{ab}^{-1}$ for each energy point.
- Coherent samples: $e^+e^- \to D^{*0}\bar{D}^0 + c.c.$ and $e^+e^- \to D^{*0}\bar{D}^{*0}$.
- Incoherent samples: $e^+e^- \to D^{*+}D^- + c.c.$ and $e^+e^- \to D^{*+}D^{*-}$.
- Sim and reconstruction framework is based on FastSim software.



	Component	Final State	$\mathcal{C}(D^0\bar{D}^0)$
Coherent	$D^0\bar{D}^0$	$D^0\bar{D}^0$	Odd
	$D^{*0}\bar{D}^0$	$\gamma D^0\bar{D}^0$	Even
		$\pi^0 D^0\bar{D}^0$	Odd
	$D^{*0}\bar{D}^{*0}$	$\gamma\pi^0 D^0\bar{D}^0$	Even
		$\gamma\gamma(\pi^0\pi^0)D^0\bar{D}^0$	Odd
Incoherent	$D^{*+}D^{*-}$	$\pi^+\pi^- D^0\bar{D}^0$	-
	$D^{*+}D^-$	$\pi^+ D^0 D^-$	-

QC correction for MC samples

- QCMC package is developed for both $C-\mathrm{odd/even}\ D^0\bar{D}^0$.
- For each event, QC weight is determined by the ratio of decay rate with or without QC effect.
- Input of amplitude models for multibody decays, mixing and CPV parameters from HFLAV.

C-even

$$W(f_1,f_2) = 3(x^2+y^2)(|\lambda_{D^0}|^2+|\lambda_{\bar{D}^0}|^2+2R_{D^0}R_{\bar{D}^0}\lambda_{D^0}\lambda_{\bar{D}^0}) + (2-3(x^2-y^2))(1+2R_{D^0}R_{\bar{D}^0}\mathrm{Re}(\lambda_{D^0}\lambda_{\bar{D}^0})+|\lambda_{D^0}\lambda_{\bar{D}^0}|^2) -4y[R_{\bar{D}^0}(1+|\lambda_{D^0}|^2)\mathrm{Re}(\lambda_{\bar{D}^0})+R_{D^0}(1+|\lambda_{\bar{D}^0}|^2)\mathrm{Re}(\lambda_{D^0})] -4x[R_{\bar{D}^0}(1-|\lambda_{D^0}|^2)\mathrm{Im}(\lambda_{\bar{D}^0})+R_{D^0}(1-|\lambda_{\bar{D}^0}|^2)\mathrm{Im}(\lambda_{D^0})]$$

C-odd

$$W(f_1,f_2) = (x^2+y^2)(|\lambda_{D^0}|^2+|\lambda_{\bar{D}^0}|^2-2R_{D^0}R_{\bar{D}^0}\mathrm{Re}(\lambda_{D^0}\lambda_{\bar{D}^0})) +(2-(x^2-y^2))(1-2R_{D^0}R_{\bar{D}^0}\mathrm{Re}(\lambda_{D^0}\lambda_{\bar{D}^0})+|\lambda_{D^0}\lambda_{\bar{D}^0}|^2)$$

Analysis strategy: signal modes

- Decay modes: $D^0 \to K\pi\pi\pi$, $K\pi\pi^0$ and $K_S\pi\pi$.
- For the coherent samples, the double tag method is performed.
  - Flavor tag: $K\pi\pi\pi$, $K\pi\pi^0$, $K\pi$ (like-sign and opposite sign for $Kn\pi$).
  - CP-even tag: KK, $\pi\pi$, $\pi\pi\pi^0$, $K_S\pi^0\pi^0$.
  - CP-odd tag: $K_S\pi^0$, $K_S\eta$, $K_S\omega$, $K\eta'$.
  - Self-conjugate tag: $K_S\pi\pi$.
- For the incoherent samples, the flavor tag method is adopted.

Analysis strategy: fitting method of coherent sample

- The charm mixing parameters are extracted in a ratio between C-even and C-odd $D^0\overline{D}$ production processes.
- In quantum correlations:

$$N_{sig}^{C-even} = N_{D^{*0}\overline{D}^0} \cdot R^{C-even} \cdot \mathcal{B}(D^{*0} \to D^0\gamma) \cdot \varepsilon_{sig}$$

decay rate

$$N_{sig}^{C-odd} = N_{D^{*0}\overline{D}^0} \cdot R^{C-odd} \cdot \mathcal{B}(D^{*0} \to D^0\pi^0) \cdot \varepsilon_{sig}$$

$$\frac{N_{sig}^{C-even}}{N_{sig}^{C-odd}} = \frac{R^{C-even} \cdot \mathcal{B}(D^{*0} \to D^0\gamma)}{R^{C-odd} \cdot \mathcal{B}(D^{*0} \to D^0\pi^0)}$$

$$\begin{aligned} R^{C-even}(K^-\pi^+\pi^-\pi^+;K^+\pi^-) \propto A_{K3\pi}^2 A_{K\pi}^2 \{&3(x^2+y^2)[K_i(r_{CP}^{-1})^2(r_D^{K\pi})^2 + \bar{K}_i(r_{CP})^2(r_D^{K3\pi})^2 \\ &+ 2\sqrt{K_i\bar{K}_i}R_{K3\pi}^i r_D^{K3\pi} r_D^{K\pi}\cos(\delta_D^{i,K3\pi} - \delta_D^{K\pi} - 2\phi)] \\ &+ [2-3(x^2-y^2)][K_i + \bar{K}_i(r_D^{K\pi})^2(r_D^{K3\pi})^2 \\ &+ 2\sqrt{K_i\bar{K}_i} r_D^{K\pi} R_{K3\pi}^i r_D^{K3\pi}\cos(\delta_D^{i,K3\pi} + \delta_D^{K\pi})] \\ &- 4y[r_D^{K\pi}(K_i r_{CP}^{-1} + \bar{K}_i r_{CP}(r_D^{K3\pi})^2)\cos(\delta_D^{K\pi} + \phi) \\ &+ \sqrt{K_i\bar{K}_i}R_{K3\pi}^i r_D^{K3\pi}(r_{CP} + r_{CP}^{-1}(r_D^{K\pi})^2)\cos(\delta_D^{i,K3\pi} - \phi)] \\ &- 4x[r_D^{K\pi}(K_i r_{CP}^{-1} - \bar{K}_i r_{CP}(r_D^{K3\pi})^2)\sin(\delta_D^{K\pi} + \phi) \\ &+ \sqrt{K_i\bar{K}_i}R_{K3\pi}^i r_D^{K3\pi}(r_{CP} - r_{CP}^{-1}(r_D^{K\pi})^2)\sin(\delta_D^{i,K3\pi} - \phi)]\} \end{aligned}$$

$$\begin{aligned} R^{C-odd}(K^-\pi^+\pi^-\pi^+;K^+\pi^-) \propto A_{K3\pi}^2 A_{K\pi}^2 \{&(x^2+y^2)[K_i(r_{CP}^{-1})^2(r_D^{K\pi})^2 + \bar{K}_i(r_{CP})^2(r_D^{K3\pi})^2 \\ &- 2\sqrt{K_i\bar{K}_i}R_{K3\pi}^i r_D^{K3\pi} r_D^{K\pi}\cos(\delta_D^{i,K3\pi} - \delta_D^{K\pi} - 2\phi)] \\ &+ [2-(x^2-y^2)][K_i + \bar{K}_i(r_D^{K\pi})^2(r_D^{K3\pi})^2 \\ &- 2\sqrt{K_i\bar{K}_i} r_D^{K\pi} R_{K3\pi}^i r_D^{K3\pi}\cos(\delta_D^{i,K3\pi} + \delta_D^{K\pi})] \end{aligned}$$

- This will cancel the reconstruction efficiencies and the number of $D^0\overline{D}^0$ pairs.
- Cancel out some systematic uncertainty.

➢ Similar treatment in $D^{*0}\overline{D}^{*0}$ sample.

Strong phase parameters are fixed.

Analysis strategy: fitting method of incoherent sample

- The time-independent decay rates turn out to be:

$$R(D^0 \to K^-\pi^+\pi^+\pi^-) \propto A^2_{K3\pi}[K_i + \frac{1}{2}(x^2+y^2)(r_{CP})^2(r_D^{K3\pi})^2\bar{K}_i - \frac{1}{2}(x^2-y^2)K_i - \sqrt{K_i\bar{K}_i}r_{CP}r_D^{K3\pi}R^i_{K3\pi}(y\cos(\delta_D^{i,K3\pi}-\phi)+x\sin(\delta_D^{i,K3\pi}-\phi))]$$

$$R(\bar{D}^0 \to K^-\pi^+\pi^+\pi^-) \propto A^2_{K3\pi}[\bar{K}_i(r_D^{K3\pi})^2 + \frac{1}{2}(x^2+y^2)(r_{CP}^{-1})^2K_i - \frac{1}{2}(x^2-y^2)\bar{K}_i(r_D^{K3\pi}) - \sqrt{K_i\bar{K}_i}r_{CP}^{-1}r_D^{K3\pi}R^i_{K3\pi}(y\cos(\delta_D^{i,K3\pi}-\phi)-x\sin(\delta_D^{i,K3\pi}-\phi))]$$

$$R(D^0 \to K^+\pi^-\pi^-\pi^+) \propto A^2_{K3\pi}[\bar{K}_i(r_D^{K3\pi})^2 + \frac{1}{2}(x^2+y^2)(r_{CP})^2K_i - \frac{1}{2}(x^2-y^2)\bar{K}_i(r_D^{K3\pi})^2 - \sqrt{K_i\bar{K}_i}r_{CP}r_D^{K3\pi}R^i_{K3\pi}(y\cos(\delta_D^{i,K3\pi}+\phi)+x\sin(\delta_D^{i,K3\pi}+\phi))]$$

$$R(\bar{D}^0 \to K^+\pi^-\pi^-\pi^+) \propto A^2_{K3\pi}[K_i + \frac{1}{2}(x^2+y^2)(r_{CP}^{-1})^2(r_D^{K3\pi})^2\bar{K}_i - \frac{1}{2}(x^2-y^2)K_i - \sqrt{K_i\bar{K}_i}r_{CP}^{-1}r_D^{K3\pi}R^i_{K3\pi}(y\cos(\delta_D^{i,K3\pi}+\phi)-x\sin(\delta_D^{i,K3\pi}+\phi))]$$

- The charm mixing parameters are extracted by:

$$N_{sig} = \mathcal{L}\cdot\sigma^{obs}_{D^{*+}D^-}\cdot R\cdot\mathcal{B}(D^{*+}\to D^0\pi^+)\cdot\varepsilon_{sig}$$

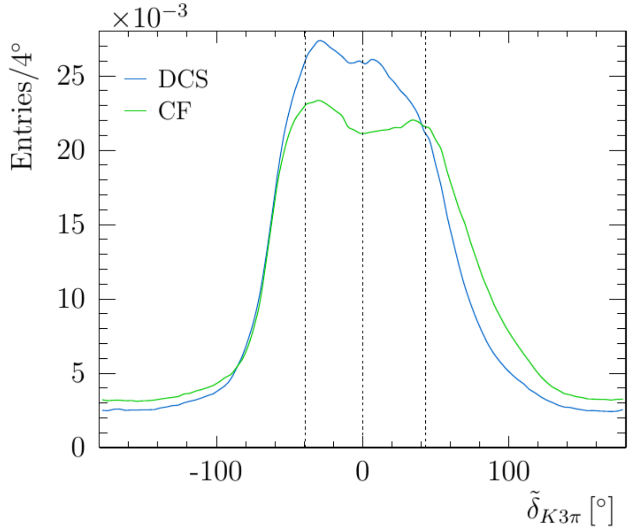
➢ Similar treatment in $D^{*+}D^{*-}$ sample.

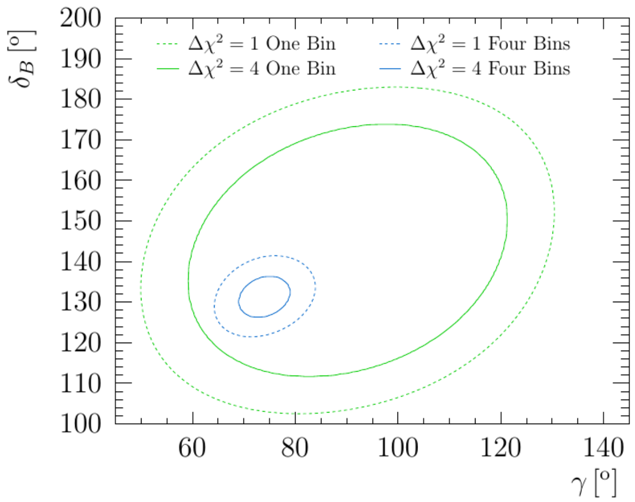
Binning scheme of $K^-\pi^+\pi^+\pi^-$

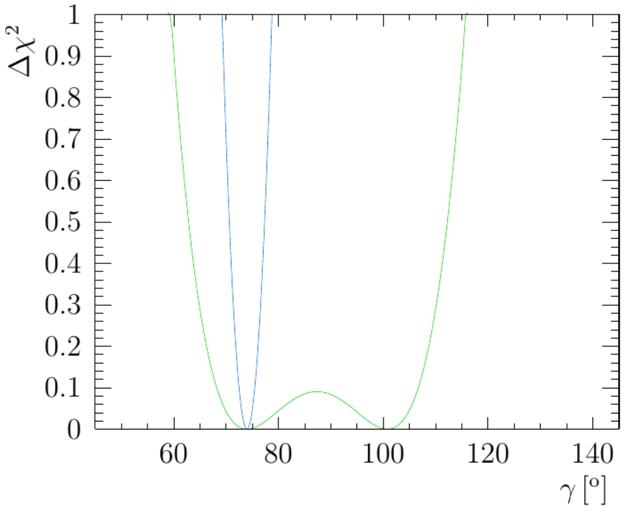
- Local strong phase has been divided into 4 bins with approximately equal population of CF decay events.

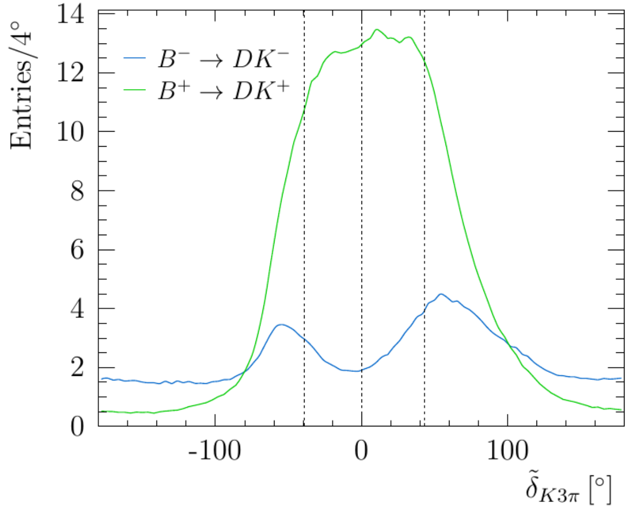
$$\tilde{\delta}_D^{K3\pi} = \arg(A_{\bar{D}^0\to K^+3\pi}(\mathbf{x})A^*_{D^0\to K^+3\pi}(\mathbf{x})) - \arg(\int A_{\bar{D}^0\to K^+3\pi}(\mathbf{x}')A^*_{D^0\to K^+3\pi}(\mathbf{x}')\mathrm{d}\mathbf{x}')$$

- Binned parameters $R_{K3\pi,i}$ and $\delta_D^{K3\pi,i}$ in each bin has been calculated by the amplitude model.









Phys. Lett. B 802 (2020) 135188

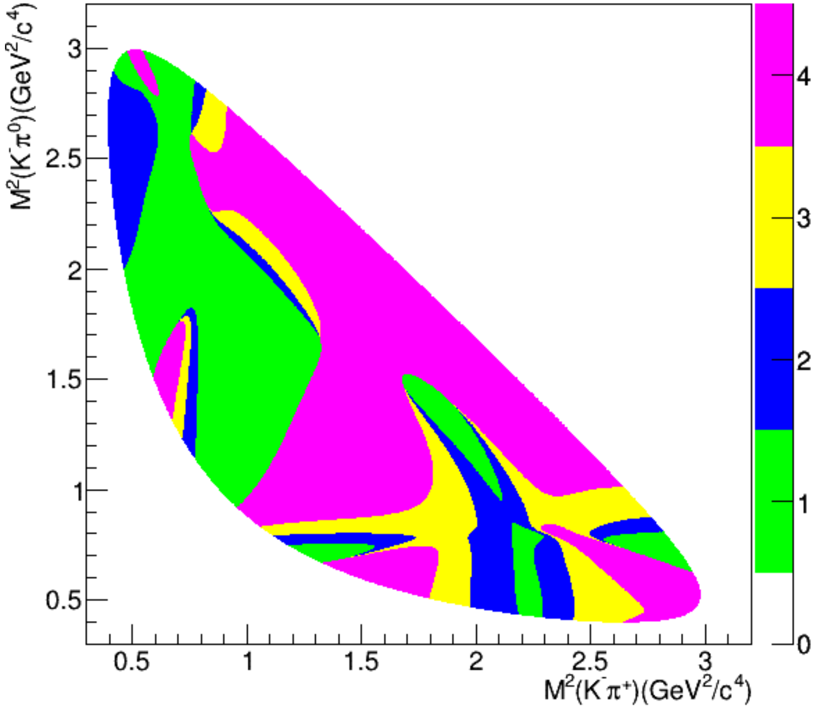
Binning scheme of $K^-\pi^+\pi^0$

- The phase space of the D meson decay is divided into disjoint regions using the model predictions for the strong-phase difference between the CF(BESIII) and DCS(*BABAR*) amplitudes.

$$\Delta\delta_{K\pi\pi^0} = \arg(A_{\bar{D}^0\to K^+\pi^-\pi^0}A^*_{D^0\to K^+\pi^-\pi^0})$$

- Similar to the binning scheme for the decay $D^0 \to K\pi\pi\pi$, we initially categorize the decay $D^0 \to K\pi\pi^0$ into four bins.

Bin	Range
1	$-180^\circ < \Delta\delta_{K\pi\pi^0} < -18^\circ$
2	$-18^\circ < \Delta\delta_{K\pi\pi^0} < 0^\circ$
3	$0^\circ < \Delta\delta_{K\pi\pi^0} < 22^\circ$
4	$22^\circ < \Delta\delta_{K\pi\pi^0} < 180^\circ$



Sensitivity study results

- The results of the charm mixing and CPV parameters are summarized in the following table, where the uncertainty is only statistical.

$K^-\pi^+\pi^0$	4009 MeV	4015 MeV	4030 MeV
$x(\%)$	0.044	0.041	0.040
$y(\%)$	0.017	0.016	0.016
r_{CP}	0.034	0.032	0.030
$\phi(°)$	2.51	2.34	2.25

The most accurate results will be obtained at $E_{cms} = 4030$ MeV, as more samples are available at this energy point.

$K^-\pi^+\pi^+\pi^-$	4009 MeV	4015 MeV	4030 MeV	LHCb($50fb^{-1}$)
$x(\%)$	0.047	0.043	0.043	-
$y(\%)$	0.025	0.021	0.021	-
r_{CP}	0.042	0.038	0.038	0.005
$\phi(°)$	3.10	2.85	2.83	0.30

$K_S\pi\pi$	4009 MeV	4015 MeV	4030 MeV	LHCb($50fb^{-1}$)	Belle II($50ab^{-1}$)
$x(\%)$	0.069	0.064	0.063	0.012	0.030
$y(\%)$	0.050	0.046	0.046	0.013	0.020
r_{CP}	0.077	0.071	0.070	0.011	0.022
$\phi(°)$	4.57	4.24	4.19	0.48	1.50

Summary and to do list

Summary:

- Precision measurement of charm mixing is an important goal in heavy flavor physics for the next decade.
- Time-integrated measurements with C-even $D\bar{D}$ and incoherent $D\bar{D}$ at STCF are essential contributions.
- The most accurate results will be obtained at $E_{cms} = 4030$ MeV, as more samples are available at this energy point.

Plan:

- Study of more double tag channels, such as $K_S\pi^+\pi^-\pi^0$ and $K^-\pi^+\pi^0\pi^0$.
- Sensitivity of direct CPV at STCF with K^+K^-, $\pi^+\pi^-$ and some CP eigenstates.

Thanks!

Backup

量子关联$D^0\bar{D}^0$

$$\psi(3770) \rightarrow D^0\bar{D}^0$$

$\psi(3770)$：$I^G(J^{PC}) = 0^-(1^{--})$

D^0：$I(J^P) = \frac{1}{2}(0^-)$

角动量守恒 → $D^0\bar{D}^0$轨道角动量$L=1$， $D^0\bar{D}^0$可看作全同玻色子。

两玻色子体系的总波函数：　$\psi = \psi(r_1, r_2) \cdot \chi_{s,s_z} \cdot \chi_{I,I_3} \cdot \psi(D^0, \bar{D}^0)$

空间波函数，自旋波函数，同位旋波函数，态函数

$L=1$	空间波函数满足反对称关系
两末态粒子总自旋为0	自旋波函数是对称的
两末态粒子总同位旋为0	同位旋波函数是对称的
母粒子为玻色子，满足玻色对称关系	态函数必须满足反对称关系

- 由于对称性关系的要求，$D^0\bar{D}^0$不可能出于相同的量子态，例如$D^0 \rightarrow K^-\pi^+$ vs $\bar{D}^0 \rightarrow K^-\pi^+$ 在奇C宇称关联的$D^0\bar{D}^0$样本中是完全禁戒的。

量子关联$D^0\overline{D}^0$

$$e^+e^- \rightarrow \gamma^* \rightarrow \gamma D^0\overline{D}^0$$

γ^*： $J^P = 1^-$

γ： $J = 1$

D^0： $I(J^P) = \frac{1}{2}(0^-)$

角动量守恒 → $D^0\overline{D}^0$轨道角动量$L = 0$。

两玻色子体系的总波函数： γ^*： $J^P = 1^-$

空间波函数，自旋波函数，同位旋波函数，态函数

$L = 0$ — 空间波函数满足对称关系

两末态粒子总自旋为0 — 自旋波函数是对称的

两末态粒子总同位旋为0 — 同位旋波函数是对称的

母粒子为玻色子，满足玻色对称关系 — 态函数必须满足对称关系

$e^+e^- \rightarrow n\gamma m\pi^0 D^0\overline{D}^0$，当n为奇数时，态函数满足交换对称关系，n为偶数时，态函数满足交换反对称关系。