# Results on CP violation in the charm sector

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- Motivation
- Data and methodology
- Indirect CP violation
- CP violation in decays
- Summary and outlook

♣ Replacement for N.K. Nisar

# Motivation

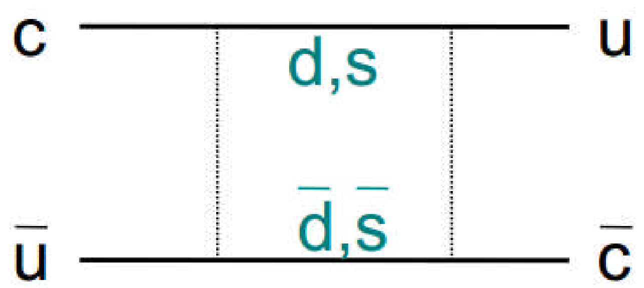
- CP violation in charm decays provides an interesting test bed for new physics as the standard model (SM) expects a small asymmetry owing to
  - Large GIM/CKM suppression
  - Lack of a large hierarchy in the down-type quark masses

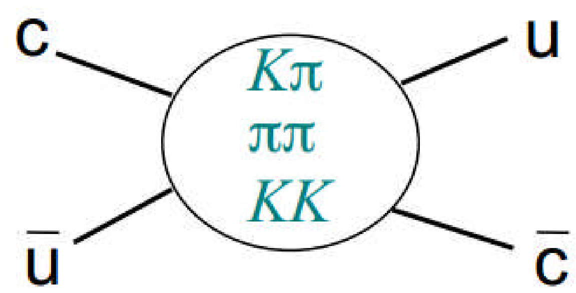
- Typical SM value of the order of $10^{-3}$ ⇨ most promising candidates to study are singly Cabibbo-suppressed (SCS) decays

**Grossman, Kagan and Nir**
**PRD 75, 036008 (2007)**

- While talking about percentage effect, one needs a good control on the SM predictions, something that is in general lacking in this sector due to long-distance effects

An example of "short vs. long"




- Further, with $D^0$-$\bar{D}^0$ mixing being firmly established, could there be any CPV in the mixing or due to interference between mixing and decay?

# Current expectation for direct CP violation

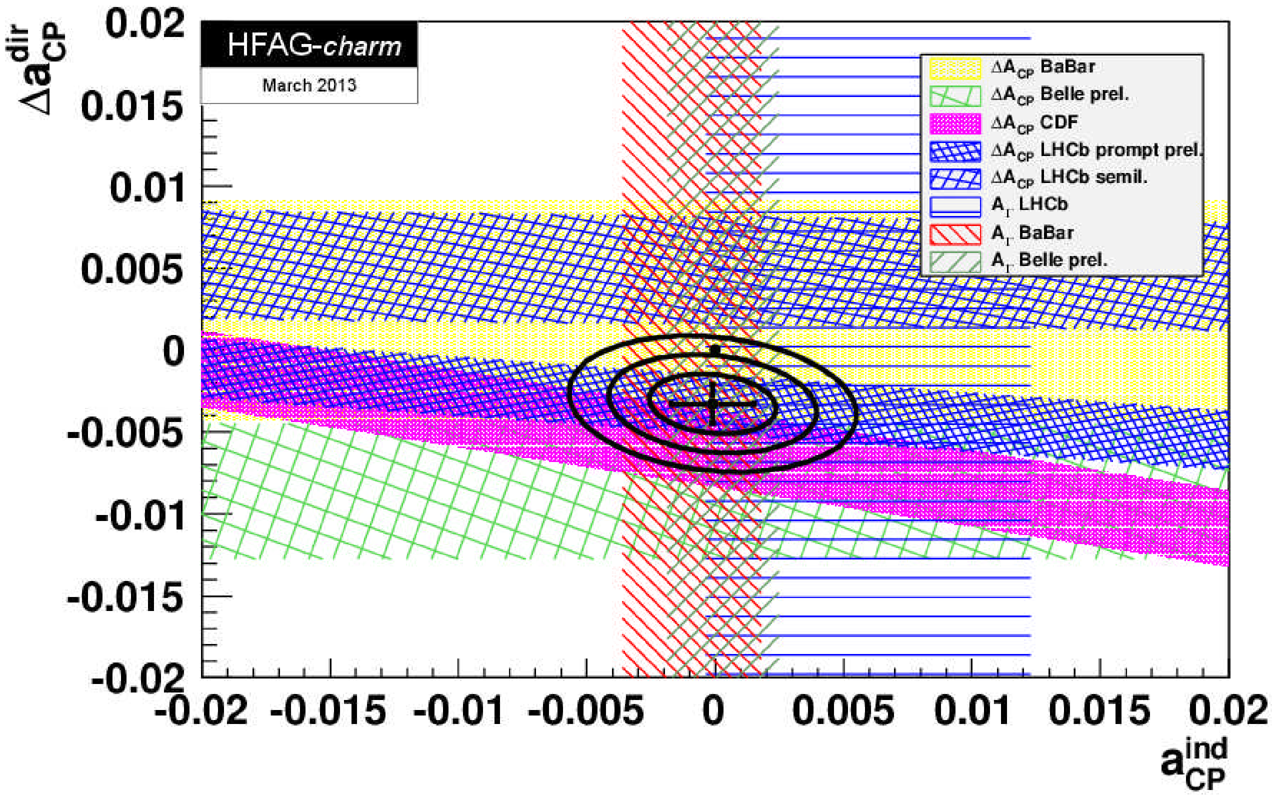
$$A_\Gamma^f \equiv \frac{\tau(\overline{D}^0 \to f) - \tau(D^0 \to f)}{\tau(\overline{D}^0 \to f) + \tau(D^0 \to f)} \approx -a_{CP}^{\text{ind}}$$

$$A_{CP}^f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

**JPG 39, 045005 (2012)**

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = \left(1 + y\cos\phi\frac{\langle t\rangle}{\tau}\right)\Delta a_{CP}^{\text{dir}} + \left(\frac{\Delta\langle t\rangle}{\tau}\right)a_{CP}^{\text{ind}}$$

$x \equiv \Delta m/\overline{\Gamma}$, $y \equiv \Delta\Gamma/2\overline{\Gamma}$ and $\phi \equiv \text{Arg}(q/p)$, where $\Delta m$ and $\Delta\Gamma$ are the mass and width difference between two D-meson mass eigenstates, $\overline{\Gamma}$ is their average width and (p, q) are the two complex coefficients that relate mass with flavor eigenstates

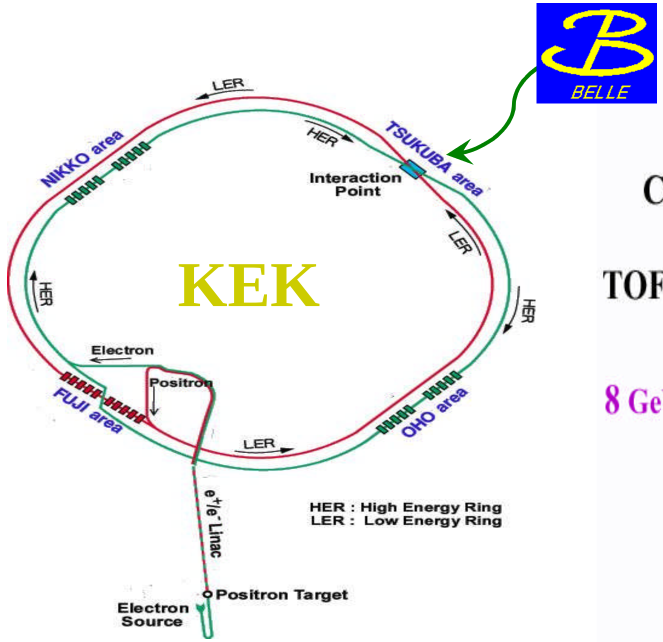


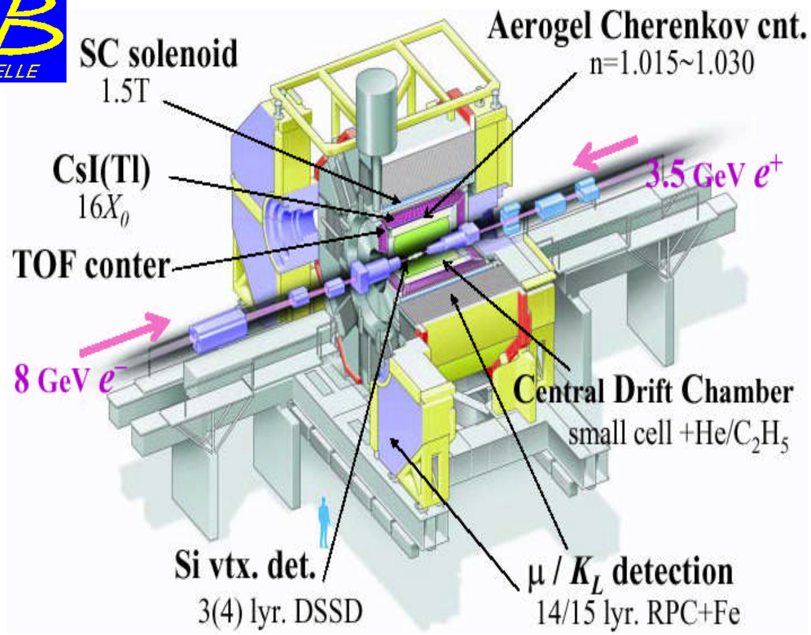

$$a_{CP}^{\text{ind}} = (+0.015 \pm 0.052)\%$$

$$\Delta a_{CP}^{\text{dir}} = (-0.333 \pm 0.120)\%$$

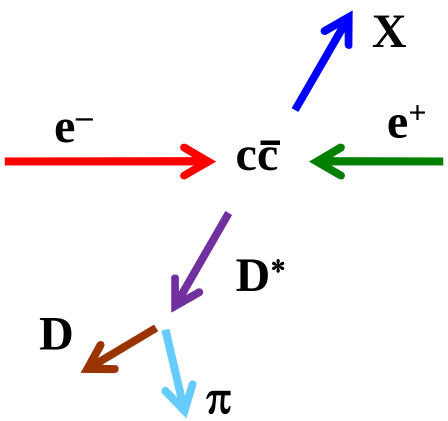
- No CPV (0,0) point: $\Delta\chi^2 = 7.8$, CL = 2% (excluded at $2\sigma$)

# Dataset and Methodology



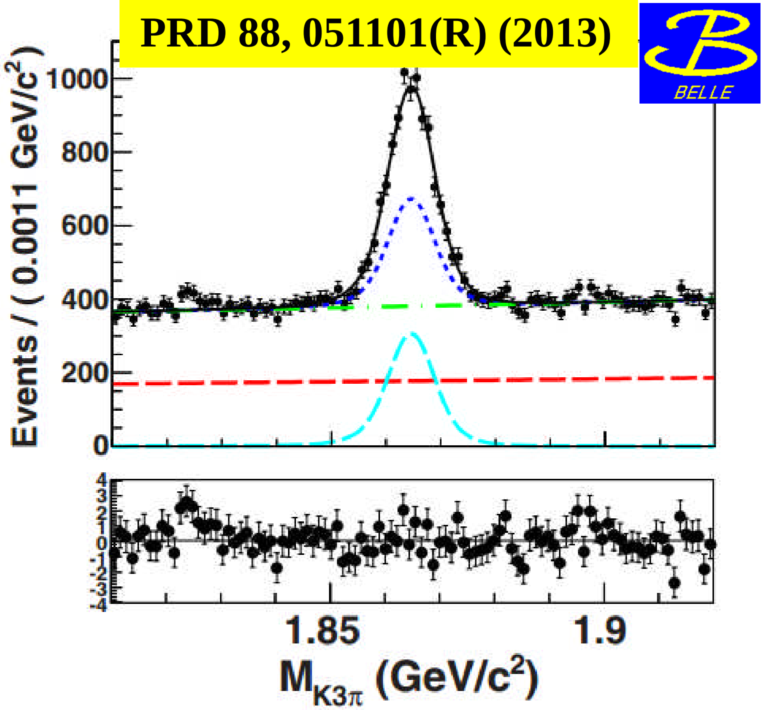

| Dataset | $\mathcal{L}_{\rm int}(\rm fb^{-1})$ |
|---|---|
| $\Upsilon(1S)$ | 6 |
| $\Upsilon(2S)$ | 25 |
| $\Upsilon(3S)$ | 3 |
| $\Upsilon(4S)$ | 711 |
| $\Upsilon(5S)$ | 121 |
| Off-res. | 100 |
| Total | 966 |

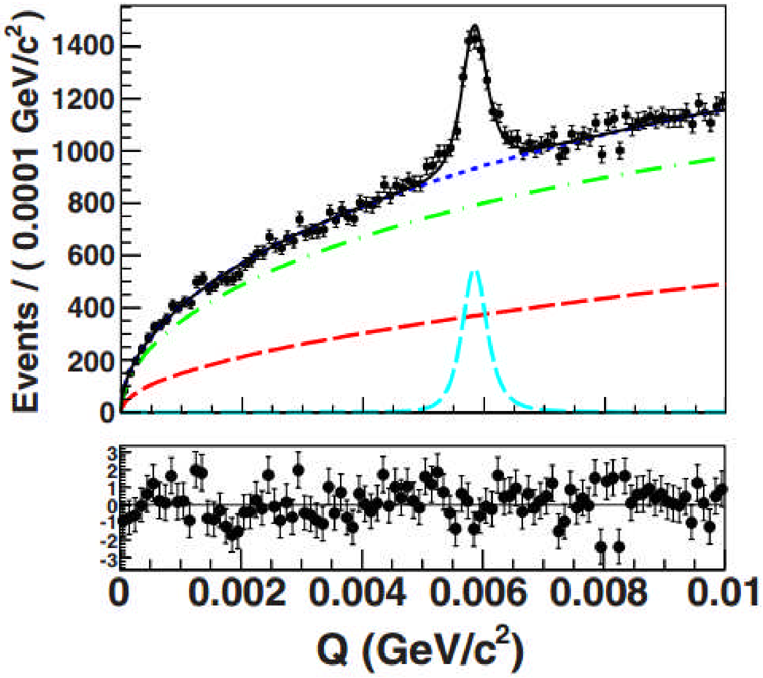



- Charge of the slow pion in the $D^*$ decay ($D^{*+} \rightarrow D^0\pi^+$ or $D^{*-} \rightarrow \bar{D}^0\pi^-$) can tell us flavor of the D meson
- For a CP study, we need to keep in mind a) $D^*$ production and b) the kinematics of the accompanying charged pion

# Study of the wrong-sign decay $D^0 \to K^+\pi^-\pi^+\pi^-$

PRD 88, 051101(R) (2013)




- Contributions from both a doubly-Cabibbo suppressed (DCS) decay and $D^0$-$\overline{D}^0$ mixing followed by a Cabibbo favored (CF) decay
- Measurement performed relative to the CF decay $D^0 \to K^-\pi^+\pi^+\pi^-$

$$R_{WS} = \frac{\Gamma(D^0 \to K^+\pi^-\pi^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+\pi^+\pi^-)} = R_D + \alpha\, y' \sqrt{R_D} + 1/2(x^2 + y^2)$$

$R_D$: ratio of the DCS to CF decay amplitude squared
α: coherence factor that accounts for strong phase variation over the phase space ($0 \le \alpha \le 1$)
$y' = y \cos\delta - x \sin\delta$ where δ is strong-phase difference between DCS and CF decays

- A 2D binned maximum likelihood fit to the $M_{K3\pi}$ and $Q = M_{D^*\pi} - M_D$ distributions

$$R_{WS} = (0.324 \pm 0.008 \pm 0.007)\%$$
$$\mathcal{B}_{WS} = (2.61 \pm 0.06^{+0.09}_{-0.08}) \times 10^{-4}$$

With α and δ from CLEOc: $R_D = (0.327\,^{+0.019}_{-0.016})\%$

# Search for CP violation in $D^+ \to K_S K^+$

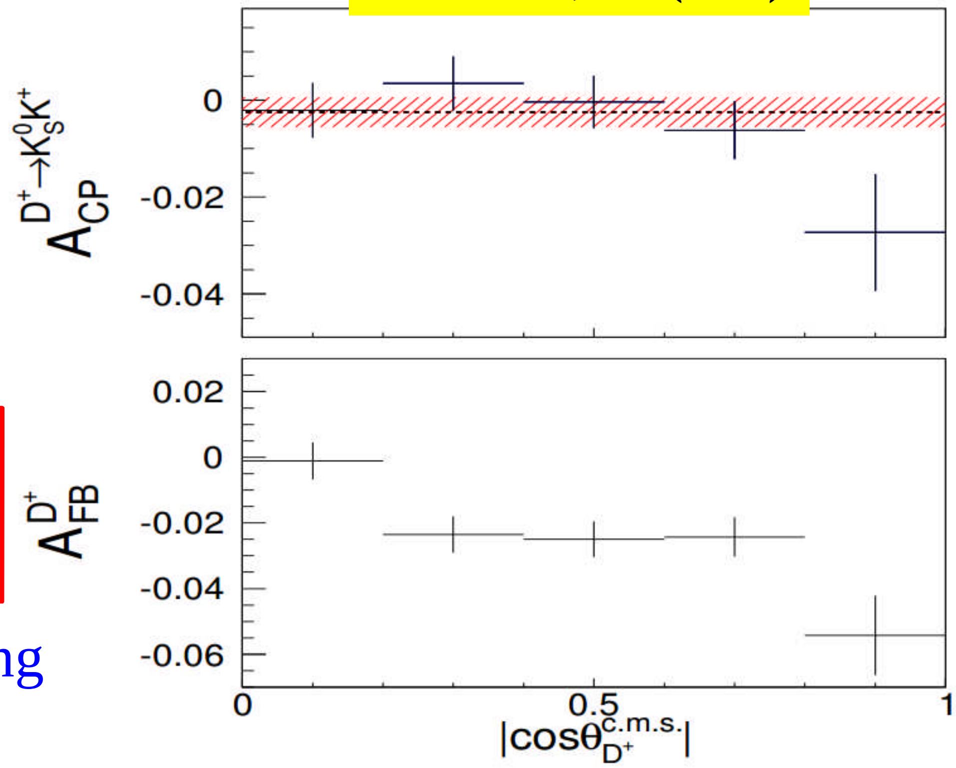
- We measure here: $$A_{\rm rec}^{K_S K^+} = A_{CP}^{K_S K^+} + A_{FB} + A_\varepsilon^{K^+} + A_{K^0}$$

  Worry about the detection efficiency asymmetry for charged kaons and the asymmetry owing to difference in interactions of $K^0$ and $\overline{K}^0$ inside detector

- Obtain the charged kaon detection asymmetry using the self-tagged decay channels $D^0 \to K^-\pi^+$ ($\overline{D}^0 \to K^+\pi^-$) and $D_s^+ \to \phi\pi^+$ ($D_s^- \to \phi\pi^-$)

$$A^{K\pi} = A_{FB} + A_\varepsilon^{K^-} + A_\varepsilon^{\pi^+}$$
$$A^{\phi\pi} = A_{FB} + A_\varepsilon^{\pi^+}$$

JHEP 1302, 098 (2013)




- Take symmetric and antisymmetric combinations in $\cos\theta^*$ to calculate $A_{CP}$ and $A_{FB}$ respectively ($f \equiv K_S K^+$)

$$A_{CP}^f = 1/2[A_{\rm rec}^{f,\rm cor}(\cos\theta^*) + A_{\rm rec}^{f,\rm cor}(-\cos\theta^*)]$$
$$A_{FB} = 1/2[A_{\rm rec}^{f,\rm cor}(\cos\theta^*) - A_{\rm rec}^{f,\rm cor}(-\cos\theta^*)]$$

- After considering CPV due to $K^0$-$\overline{K}^0$ mixing

$$A_{CP} = (+0.08 \pm 0.28 \pm 0.14)\%$$

# Search for CP violation in $D^+ \to K_S\pi^+$

- We measure here: $$A_{\rm rec}^{K_S\pi^+} = A_{CP}^{K_S\pi^+} + A_{FB} + A_{\varepsilon}^{\pi^+} + A_{K^0}$$

  Complication arises due to difference in interactions of $K^0$ and $\overline{K}^0$ inside the detector

- Obtain the charged pion detection asymmetry using $D \to K\pi\pi$ decays

$$A(D^+ \to K^-\pi^+\pi^+) = A_{FB} + A_{\varepsilon}^{K^-\pi^+} + A_{\varepsilon}^{\pi^+}$$
$$A(D^0 \to K^-\pi^+\pi^0) = A_{FB} + A_{\varepsilon}^{K^-\pi^+}$$

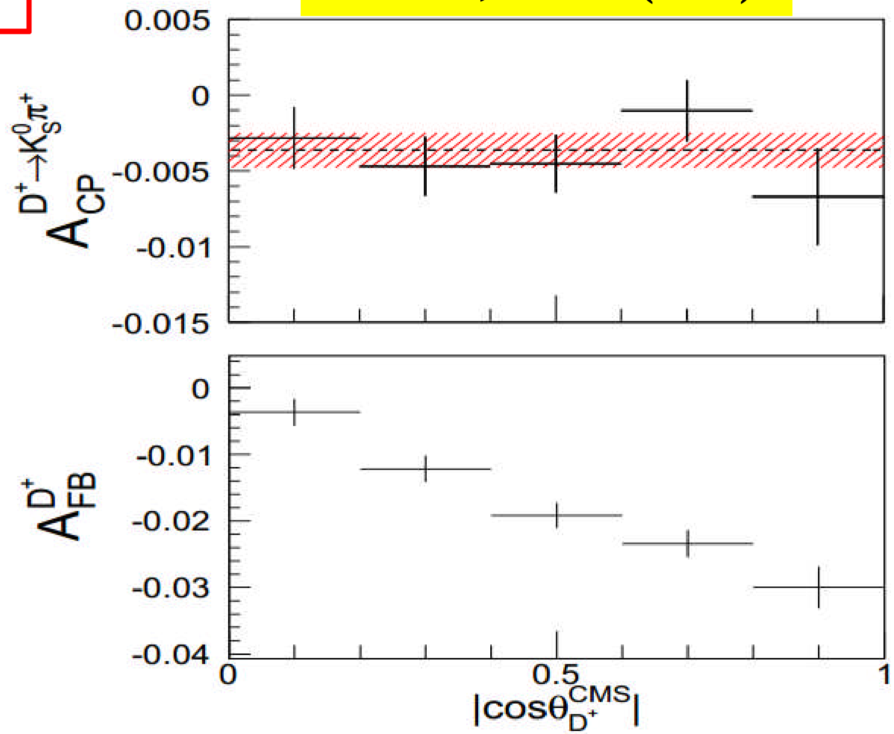
- Calculate $A_{CP}$ and $A_{FB}$ from the symmetric and antisymmetric combinations in $\cos\theta^*$ ($f \equiv K_S\pi^+$)

$$A_{CP}^{f} = 1/2[A_{\rm rec}^{f,{\rm cor}}(\cos\theta^*) + A_{\rm rec}^{f,{\rm cor}}(-\cos\theta^*)]$$
$$A_{FB} = 1/2[A_{\rm rec}^{f,{\rm cor}}(\cos\theta^*) - A_{\rm rec}^{f,{\rm cor}}(-\cos\theta^*)]$$

- After considering CPV due to $K^0$-$\overline{K}^0$ mixing

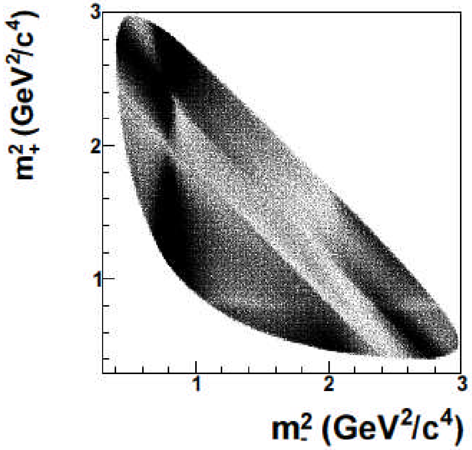
$$A_{CP} = (-0.024 \pm 0.094 \pm 0.067)\%$$

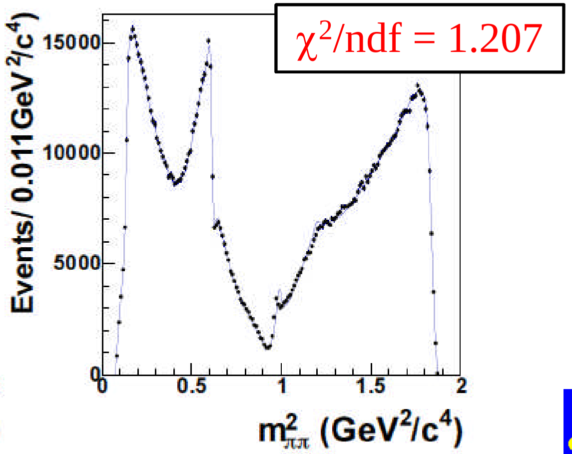
**PRL 109, 021601 (2012)**

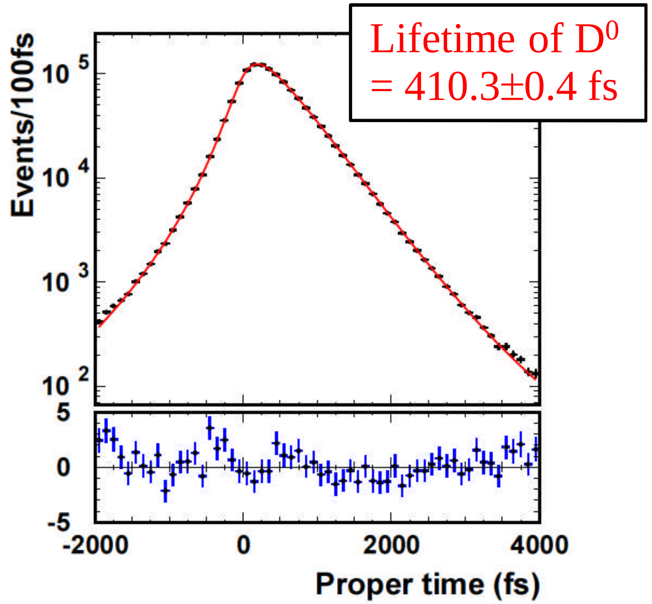


# Mixing and CPV results from $D^0 \to K_S\pi^+\pi^-$

- Time-dependent fit to the Dalitz plot (shown below together with one of its projections)




| Fit case | Parameter | Preliminary (921 fb$^{-1}$) | PRL 99, 131803 (2007) |
|---|---|---|---|
| Assuming no CPV | $x(\%)$ | $0.56 \pm 0.19^{+0.03}_{-0.09}{}^{+0.06}_{-0.09}$ | $0.80 \pm 0.29^{+0.09}_{-0.07}{}^{+0.10}_{-0.14}$ |
| | $y(\%)$ | $0.30 \pm 0.15^{+0.04}_{-0.05}{}^{+0.03}_{-0.06}$ | $0.33 \pm 0.24^{+0.08}_{-0.12}{}^{+0.06}_{-0.08}$ |
| No DCPV | $\lvert q/p \rvert$ | $0.90^{+0.16}_{-0.15}{}^{+0.05}_{-0.04}{}^{+0.06}_{-0.05}$ | $0.86^{+0.30}_{-0.29}{}^{+0.06}_{-0.03} \pm 0.08$ |
| | $\phi(^\circ)$ | $-6 \pm 11^{+3}_{-3}{}^{+3}_{-4}$ | $-14^{+16}_{-18}{}^{+5}_{-3}{}^{+2}_{-4}$ |

No DCPV $\Rightarrow$ $A_f = \bar{A}_f$ when f is a self-conjugate mode such as $K_S\pi^+\pi^-$

- 2.5σ away from the no-mixing hypothesis
- No evidence for indirect CP violation

# Search for CP violation in $D^0 \to \pi^0\pi^0$

- Large CP asymmetries expected in this decay for NP scenarios having large penguin contributions and large chromo-magnetic dipole operators

| Decay mode | Large penguins | Large c.d.o. |
|---|---|---|
| $D^0 \to \pi^+\pi^-$ | 3.96 (4.40) | 5.18 (3.70) |
| $D^0 \to \pi^0\pi^0$ | 0.93 (1.01) | 8.63 (6.19) |
| … | … | … |

$\times 10^{-3}$

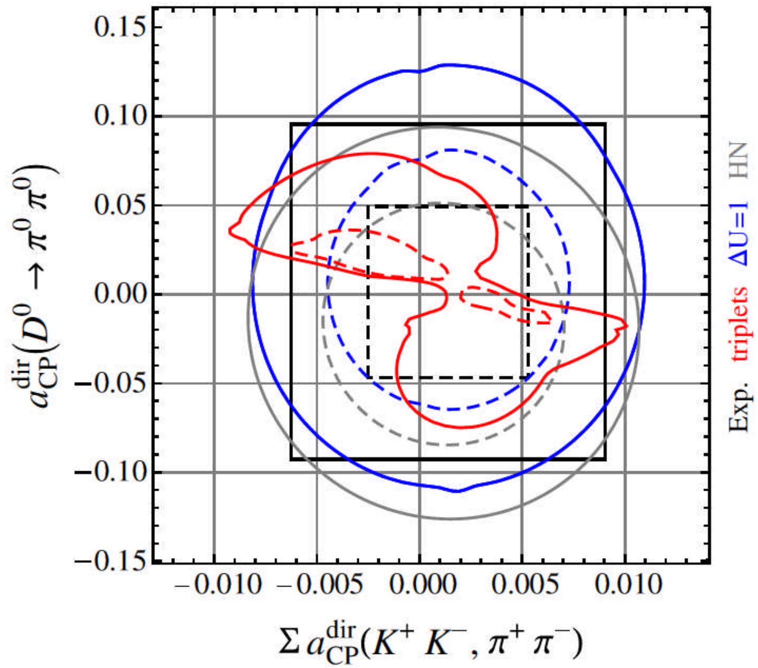
**Cheng and Chiang, PRD 86, 014014 (2012)**

- Large penguin contribution is predicted for $D^0 \to \pi^0\pi^0$

**Bhattacharya, Gronau and Rosner, PRD 85, 014014 (2012)**

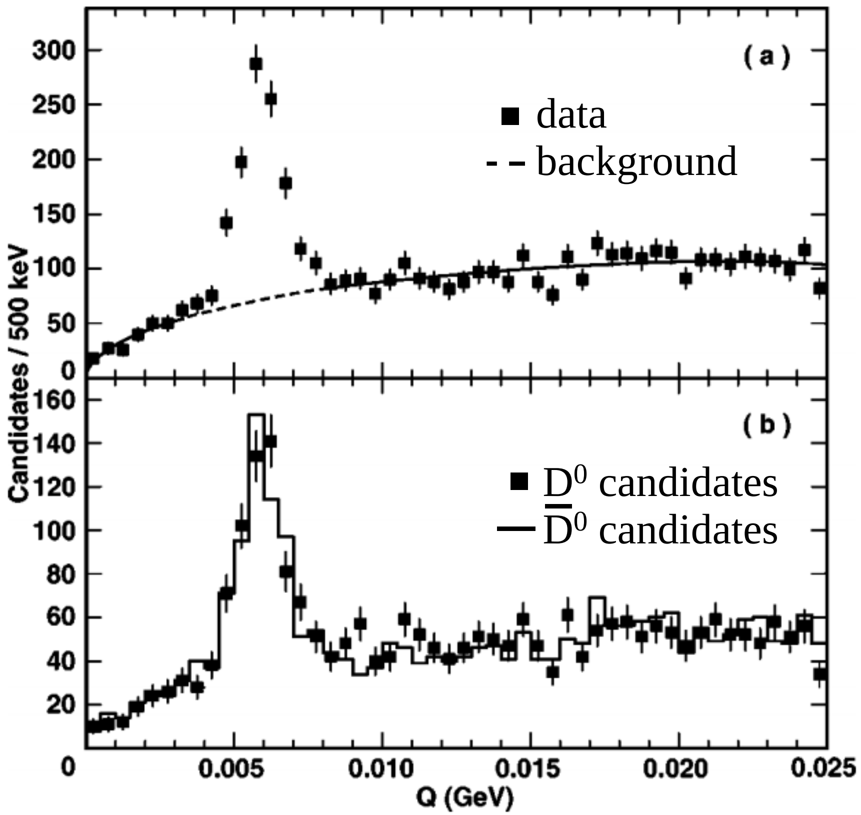
- Some NP models e.g., triplet model, predict a sizeable CP asymmetry in $D^0 \to \pi^0\pi^0$

**Hiller, Jung and Schacht, PRD 87, 014024 (2013)**

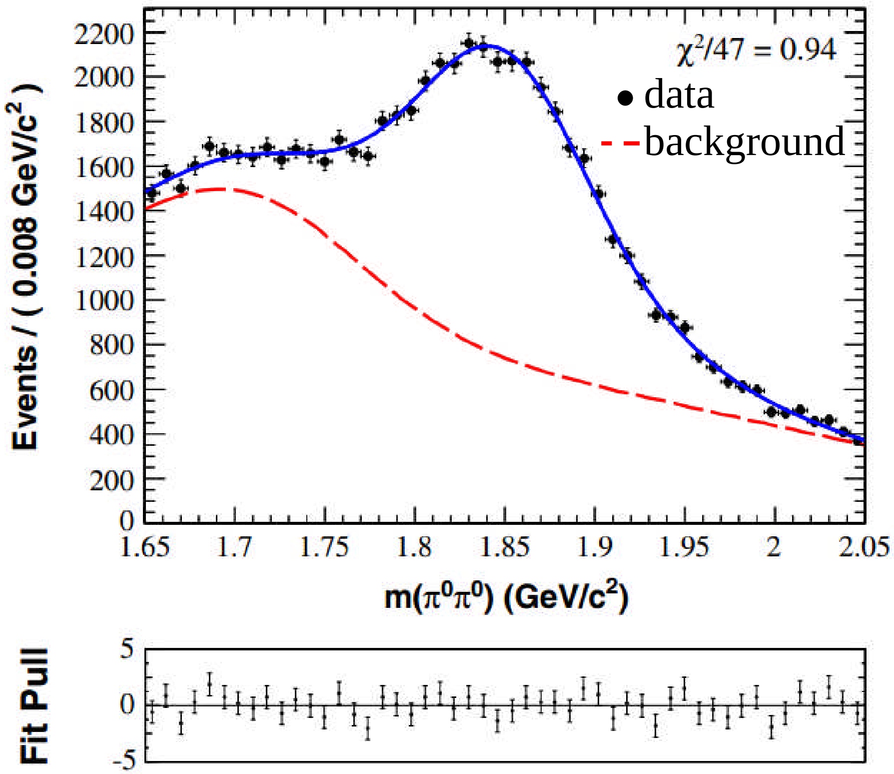



- Need a precise measurement that can only be done at the $e^+e^-$ flavor factories

# Current experimental status




**CLEO, PRD 63, 071101 (2001)**

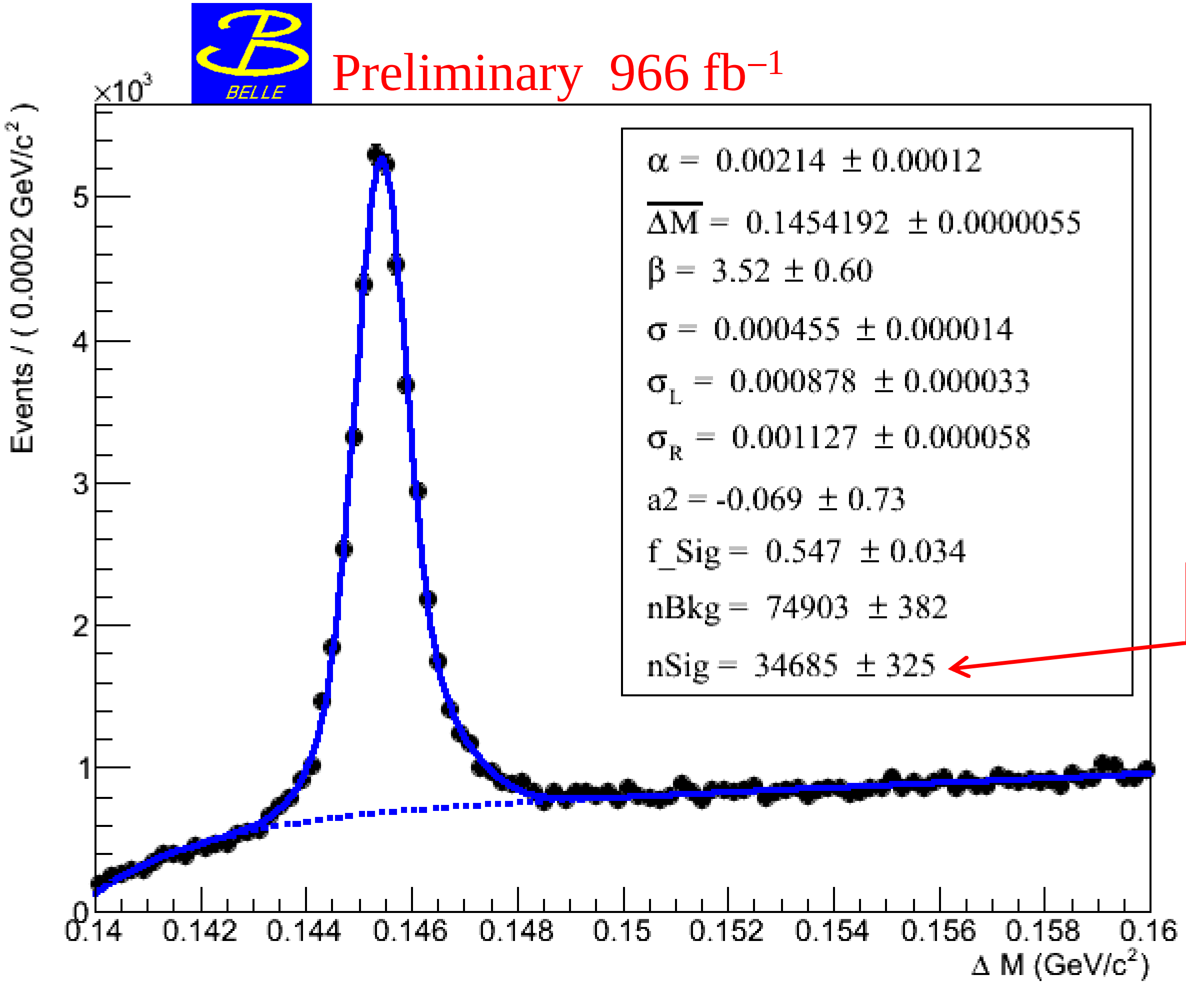



**BABAR, PRD 85, 091107 (2012)**

- Based on a 13.7fb$^{-1}$ data, CLEO has measured $A_{CP} = (+0.1 \pm 4.8)\%$

- Using 470.5fb$^{-1}$ of data BABAR found the branching fraction $BF(D^0 \to \pi^0\pi^0)$ = $[8.4 \pm 0.1(\text{stat.}) \pm 0.4(\text{syst.}) \pm 0.3(\text{norm.})] \times 10^{-4}$, no attempt is made for $A_{CP}$

# Ongoing study from Belle




$N(D^0 \to \pi^0\pi^0) = 35k$

- Signal component is parametrized as a sum of Gaussian and an asymmetric Gaussian function with common mean, while the background as a threshold function $f(x) = (x-m_0)^\alpha \exp[-\beta(x-m_0)]$
- Expected statistical error on $A_{CP}$ is 0.64% (an order of magnitude better than CLEO)

# Summary and Outlook

- presented a sample of results related to CP violation in charm from Belle

1) Measured the rate for "wrong-sign" decay $D^0 \to K^+\pi^-\pi^+\pi^-$ relative to the "right-sign" decay $D^0 \to K^-\pi^+\pi^+\pi^-$ decays

$$R_{WS} = (0.324 \pm 0.008 \pm 0.007)\%$$
$$\mathcal{B}_{WS} = (2.61 \pm 0.06^{+0.09}_{-0.08}) \times 10^{-4}$$

2) Searched for CP violation in $D^+ \to K_S K^+$ ➡ consistent with no CPV

3) Story is same for $D^+ \to K_S\pi^+$ as well as $D^0 \to K_S\pi^+\pi^-$ (indirect CP violation)

4) Conducting the most precise measurement of CP violation in the decay $D^0 \to \pi^0\pi^0$, which can be only done at $e^+e^-$ flavor factories

- Many other related studies are ongoing with the data recorded with Belle

- With Belle ⟶ Belle II being on track, the future looks bright for this exciting area in flavor physics

# Bonus slides

# Systematic uncertainties in $D^0 \to K_S \pi^+ \pi^-$

| Source | $\Delta x (\times 10^{-4})$ | $\Delta y (\times 10^{-4})$ |
|---|---|---|
| Best candidate selection | $+1.05$ | $+1.87$ |
| Signal and background yields | $\pm 0.30$ | $\pm 0.27$ |
| Wrong tagged event fraction | $-0.67$ | $-0.45$ |
| Time resolution of signal | $-1.39$ | $-0.92$ |
| Efficiency | $-1.13$ | $-2.09$ |
| Combinatorial PDF | $^{+1.90}_{-4.82}$ | $^{+2.28}_{-3.88}$ |
| $K^\star(892)$ DCS/CF fraction | $-7.28$ | $+2.29$ |
| $K_2^\star(1430)$ DCS/CF fraction | $+1.71$ | $-0.67$ |
| Total | $^{+2.78}_{-8.94}$ | $^{+3.74}_{-4.58}$ |

- Improved systematic uncertainties together with statistical with respect to the previous publication

**Belle, PRL 99, 131803 (2007)**