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Mixing and Time Dependent CPV in Charm Decays

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Outline

- Introduction and formalism
- y_{CP} measurements
- Time dependent $D^0 \to K^+\pi^-$, $K_S\pi^+\pi^-$
- Strong phase $\delta_{K\pi}$
- Triple product asymmetries
- Perspectives
- Outlook

Why Study Mixing and CPV in Charm ?

- Charm is an up-type quark: unique probe complementary to studies in the K and B sectors.
- Precision CKM measurements in B sector need input from charm
- Mixing and CPV are small in the SM(GIM + CKM suppression)
  - Sensitive to New Physics effects
- Long distance contributions are non negligible, precise theoretical predictions are difficult

Mixing and CPV Formalism

D mesons are produced as flavor eigenstates D^0 and $\bar{D}^0$ and decays as mass eigenstates D_1 and D_2

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

$$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}$$

$$|D_1\rangle = p\,|D^0\rangle + q\,|\bar{D}^0\rangle$$
$$|D_2\rangle = p\,|D^0\rangle - q\,|\bar{D}^0\rangle$$

$$|q|^2 + |p|^2 = 1$$

Mixing occurs if

$$\Delta M = M_1 - M_2 \neq 0$$
$$\Delta\Gamma = \Gamma_1 - \Gamma_2 \neq 0$$

Mixing parameters

$$x = \frac{\Delta M}{\Gamma}, \quad y = \frac{\Delta\Gamma}{2\Gamma} \qquad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

DIRECT CPV
Different decay amplitudes for D^0 and $\bar{D}^0$

$$A_f = \langle f|H|D^0\rangle$$
$$\bar{A}_{\bar{f}} = \langle \bar{f}|H|\bar{D}^0\rangle$$
$$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1$$

CPV IN MIXING
Different mixing rates $D^0 \rightarrow \bar{D}^0$ and $\bar{D}^0 \rightarrow D^0$

$$\left|\frac{q}{p}\right| \neq 1$$

CPV IN INTERFERENCE
between mixing and decays

$$\phi = \arg\left(\frac{q\bar{A}_f}{pA_f}\right)$$

y_{CP}, ΔY, and A_Γ

- D mixing manifests into different decay time distributions for D^0 mesons decaying to different CP eigenstates.
- From the average D^0 width Γ and the width of the D^0 ($\overline{D}^0$) to a CP+ eigenstate Γ^+ ($\overline{\Gamma}^+$), it is possible to build the observables:

$$y_{CP} = \frac{\Gamma^+ + \overline{\Gamma}^+}{2\Gamma} - 1 \qquad \Delta Y = \frac{\Gamma^+ - \overline{\Gamma}^+}{2\Gamma} \qquad A_\Gamma = \frac{\overline{\Gamma}^+ - \Gamma^+}{\overline{\Gamma}^+ + \Gamma^+}$$

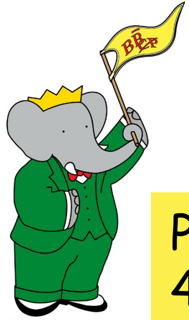
- From the decay time distributions, assuming no direct CPV, small indirect CPV

$$y_{CP} = \frac{1}{2}[ycos\phi(|\frac{q}{p}| + |\frac{p}{q}|) - xsin\phi(|\frac{q}{p}| - |\frac{p}{q}|)]$$

$$A_\Gamma = \frac{1}{2}[ycos\phi(|\frac{q}{p}| - |\frac{p}{q}|) - xsin\phi(|\frac{q}{p}| + |\frac{p}{q}|)]$$

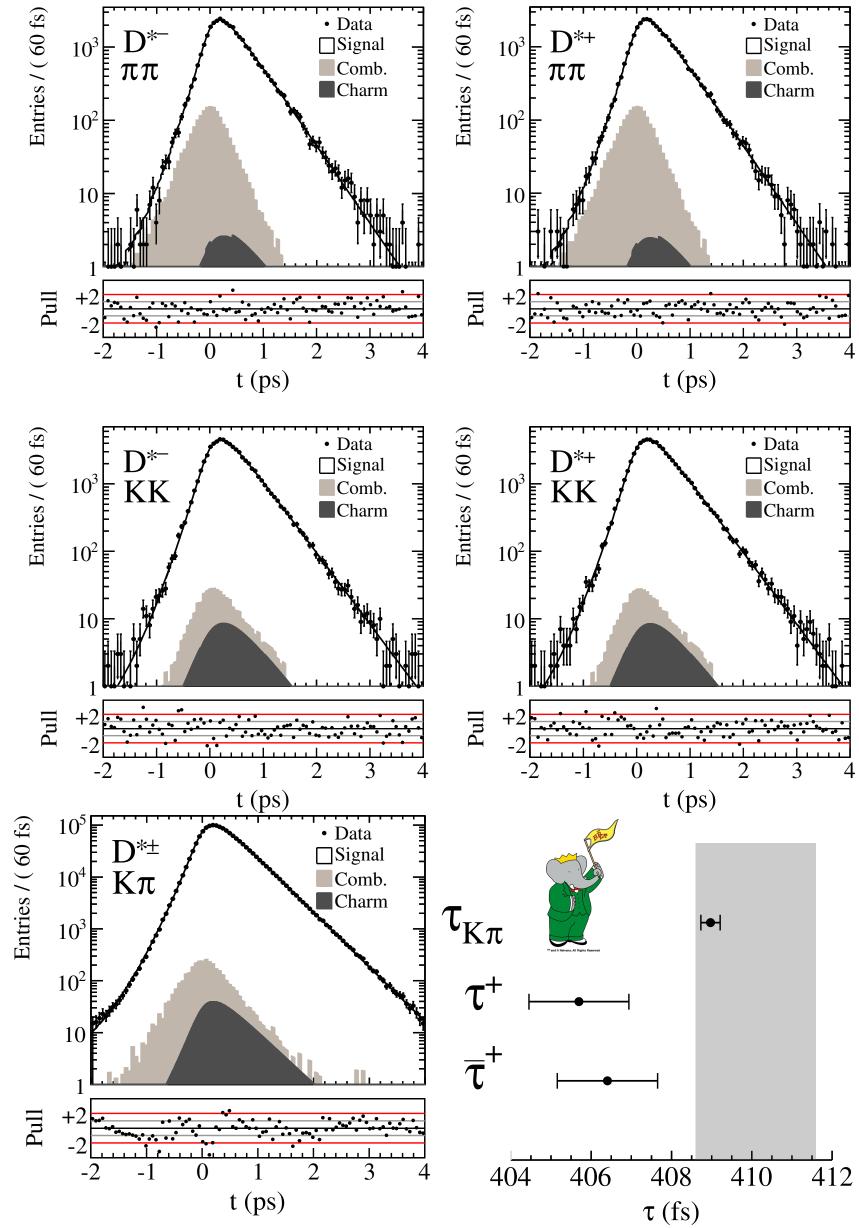
- If no CPV: $y_{CP} = y$; $\Delta Y = A_\Gamma = 0$

Y_{CP} Measurement



PRD 87, 012004 (2013)
468 fb^{-1}

- 5 signal channels
  - Tagged: $D^{*+} \to D^0\pi^+, D^0 \to \pi^+\pi^-$, K^+K^-, $K^-\pi^+$
  - Untagged: $D^0 \to K^+K^-, K\pi$
  - Assume decay width Γ for $K^-\pi^+$ and Γ^+ for CP even $h^+h^- = \pi^+\pi^-$, K^+K^-



- Fit to decay time distributions to extract τ

$$A_\Gamma = \frac{\tau(\overline{D}^0 \to h^+h^-) - \tau(D^0 \to h^+h^-)}{\tau(\overline{D}^0 \to h^+h^-) + \tau(D^0 \to h^+h^-)}$$

$$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(h^+h^-)} - 1 \quad \Delta Y = -(1 + y_{CP})A_\Gamma$$

$$y_{CP} = [0.72 \pm 0.18(\mathrm{stat}) \pm 0.12(\mathrm{syst})]\%$$

$$\Delta Y = [0.09 \pm 0.26(\mathrm{stat}) \pm 0.06(\mathrm{syst})]\%$$

y_{CP} Measurement

- At open charm threshold the D mesons have opposite CP eigenvalues
  - Fully reconstruct a D meson in a CP eigenstate (single tag)
  - Search for single tag events in which the other D decays semileptonically (double tag)
  - The semileptonic BF of a D in a CP eigenstate can be written as:

$$\mathcal{B}_{D_{CP\pm}\to l} \approx \mathcal{B}_{D\to l}(1 \mp y_{CP})$$

  - Extract y_{CP} as:

$$y_{CP} \approx \frac{1}{4}\left(\frac{\mathcal{B}_{D_{CP-}\to l}}{\mathcal{B}_{D_{CP+}\to l}} - \frac{\mathcal{B}_{D_{CP+}\to l}}{\mathcal{B}_{D_{CP-}\to l}}\right)$$

$$\mathcal{B}_{D_{CP\mp}\to l} = \frac{N_{CP\pm;l}}{N_{CP\pm}} \cdot \frac{\varepsilon_{CP\pm}}{\varepsilon_{CP\pm;l}}$$

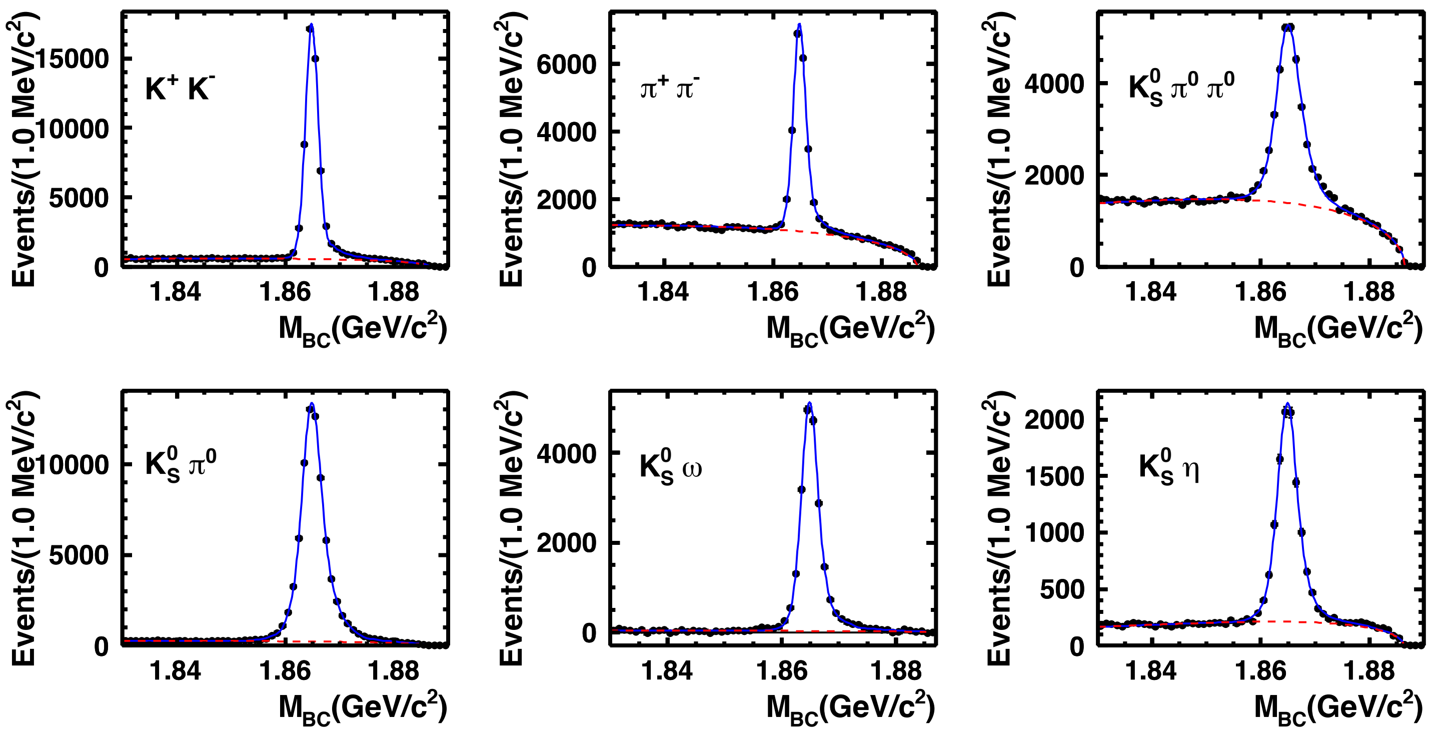
  - Event yields from fit to data, efficiencies from MC

y_{CP} Measurement

- Single tag:
- Cut on $\Delta E \equiv E_D - E_{\text{beam}}$
- Extract yields with fit to

$$M_{\text{BC}} \equiv \sqrt{E^2_{\text{beam}}/c^4 - |\vec{p}_D|^2/c^2}$$

ST Mode	$N_{CP\pm}$	$\varepsilon_{CP\pm}$ (%)
K^+K^-	54494 ± 251	61.32 ± 0.18
$\pi^+\pi^-$	19921 ± 174	64.09 ± 0.18
$K^0_S\pi^0\pi^0$	24015 ± 236	16.13 ± 0.08
$K^0_S\pi^0$	71421 ± 285	40.67 ± 0.14
$K^0_S\omega$	20989 ± 243	13.44 ± 0.07
$K^0_S\eta$	9878 ± 117	34.39 ± 0.13



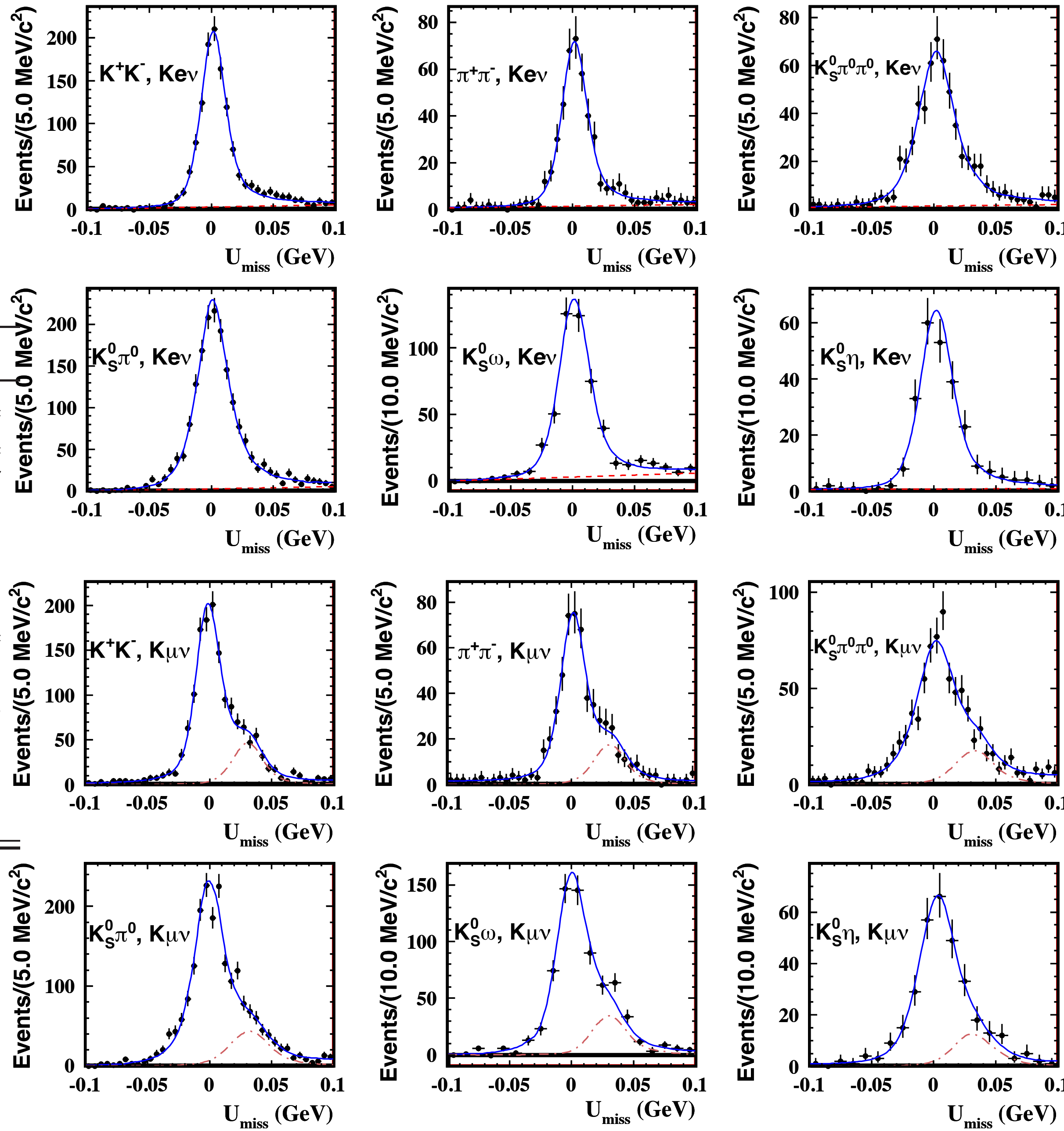
y_{CP} Measurement

PLB 744, 339 (2015)
2.92 fb-1

- Double tag:
- Extract yields with fit to

$$U_{\text{miss}} \equiv E_{\text{miss}} - c|\vec{p}_{\text{miss}}|$$

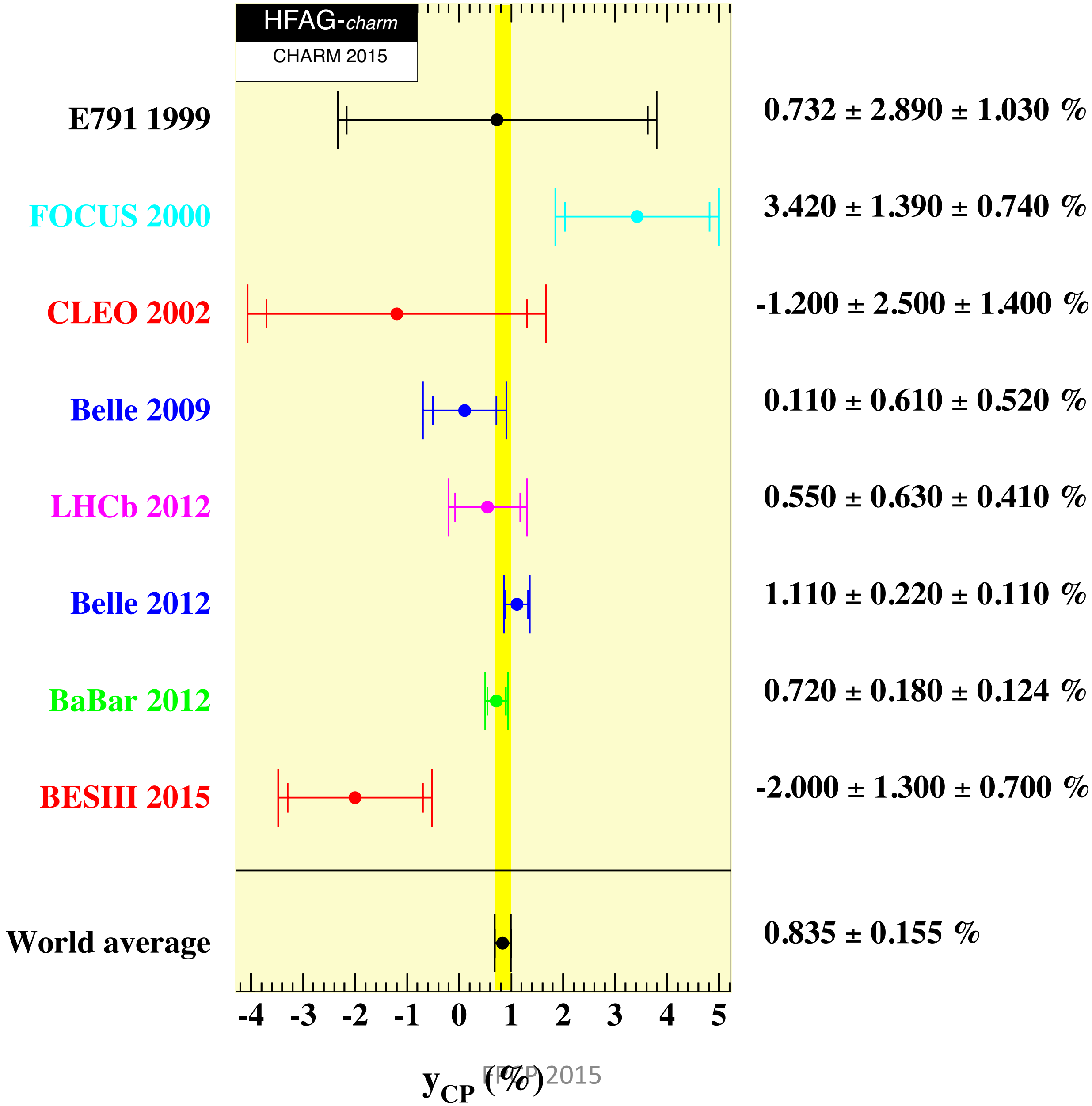
DT Mode	$N_{CP\pm;l}$	$\varepsilon_{CP\pm;l}$ (%)
K^+K^-, $Ke\nu$	1216 ± 40	39.80 ± 0.14
$\pi^+\pi^-$, $Ke\nu$	427 ± 23	41.75 ± 0.14
$K^0_S\pi^0\pi^0$, $Ke\nu$	560 ± 28	11.05 ± 0.07
$K^0_S\pi^0$, $Ke\nu$	1699 ± 47	26.70 ± 0.12
$K^0_S\omega$, $Ke\nu$	481 ± 30	9.27 ± 0.07
$K^0_S\eta$, $Ke\nu$	243 ± 17	22.96 ± 0.11
K^+K^-, $K\mu\nu$	1093 ± 37	36.89 ± 0.14
$\pi^+\pi^-$, $K\mu\nu$	400 ± 23	38.43 ± 0.15
$K^0_S\pi^0\pi^0$, $K\mu\nu$	558 ± 28	10.76 ± 0.08
$K^0_S\pi^0$, $K\mu\nu$	1475 ± 43	25.21 ± 0.12
$K^0_S\omega$, $K\mu\nu$	521 ± 27	8.75 ± 0.07
$K^0_S\eta$, $K\mu\nu$	241 ± 18	21.85 ± 0.11



$K\pi\pi^0$ background shape from data

y_{CP}=(-2.0±1.3±0.7)%

y_{CP} Measurement: HFAG Summary

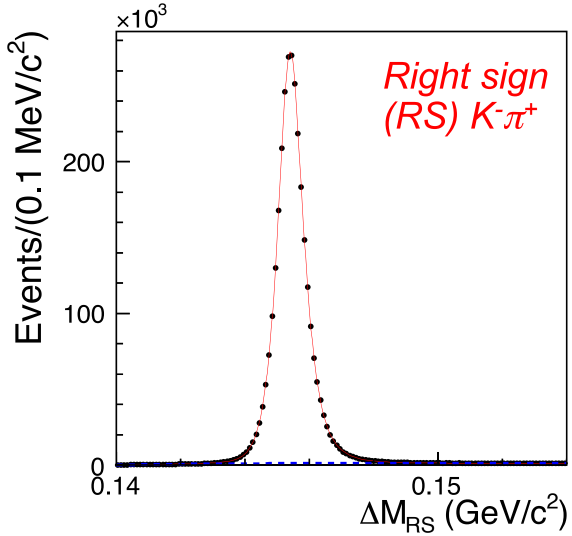


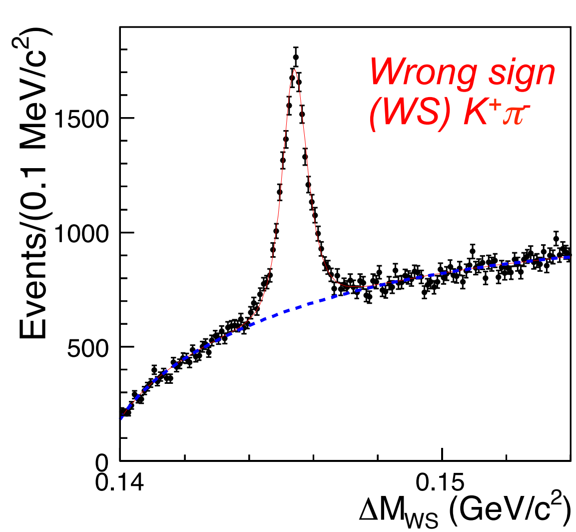
Time Dependent $D^0 \rightarrow K^+\pi^-$

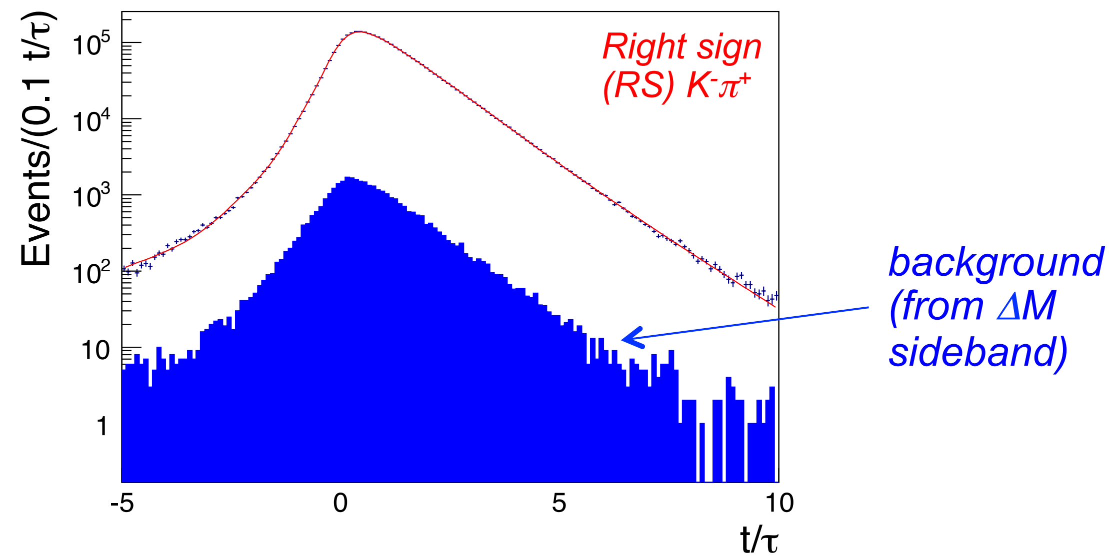
PRL 112, 111801 (2014)
976 fb-1

Method:

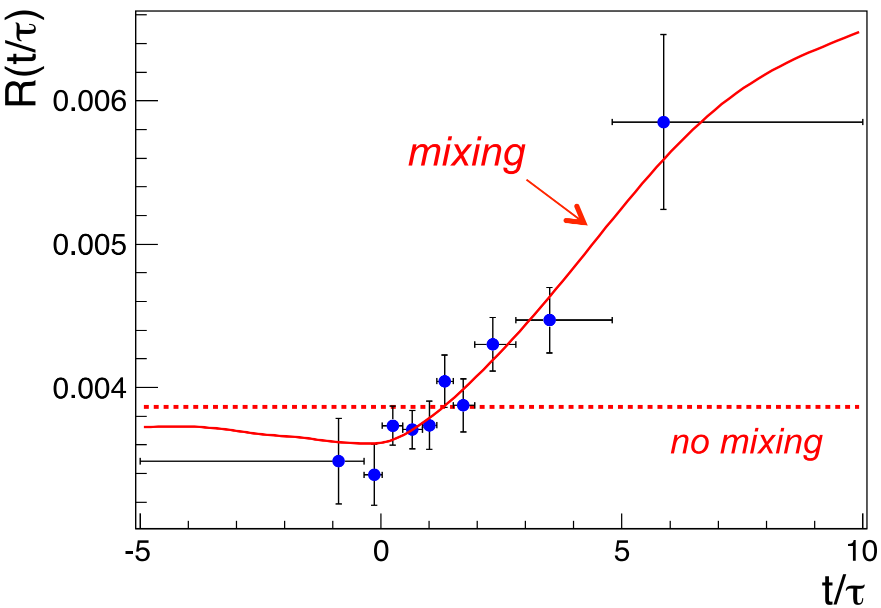
- Tag WS ($K^+\pi^-$) and RS ($K^-\pi^+$) decays using $D^{*+} \rightarrow D^0(K^{+-}\pi^{-+})\pi_s^+$
- Select WS and RS samples: $|M_{K\pi} - M_D| < 20$ MeV/c^2
- Divide samples into 10 bins of decay time. For each bin, determine event yields by fitting $\Delta M = M_{K\pi\pi} - M_{K\pi}$ distribution
- Fit to ratio of WS to RS events yields to extract R_D, x'^2, y'
- Fitting ratio events yields reduces sensitivity on resolution function

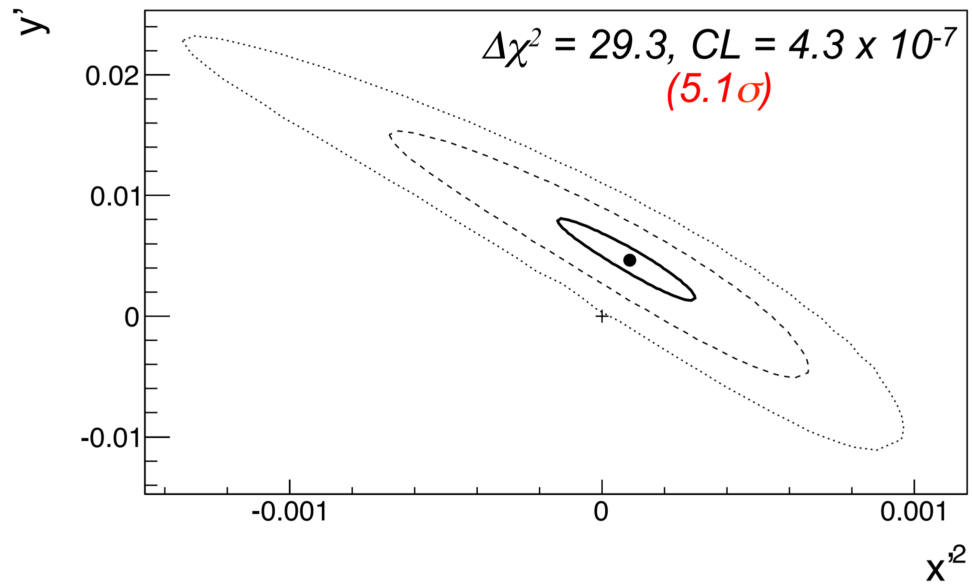






Time Dependent $D^0 \to K^+\pi^-$





Test hypothesis (χ^2/d.o.f.)	Parameters	Fit results (10^{-3})
Mixing (4.2/7)	R_D	3.53 ± 0.13
	y'	4.6 ± 3.4
	x'^2	0.09 ± 0.22
No Mixing (33.5/9)	R_D	3.864 ± 0.059

$$R(\tilde{t}/\tau) = \frac{\Gamma_{\rm WS}(\tilde{t}/\tau)}{\Gamma_{\rm RS}(\tilde{t}/\tau)} \approx R_D + \sqrt{R_D}y'\frac{\tilde{t}}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{\tilde{t}}{\tau}\right)^2$$

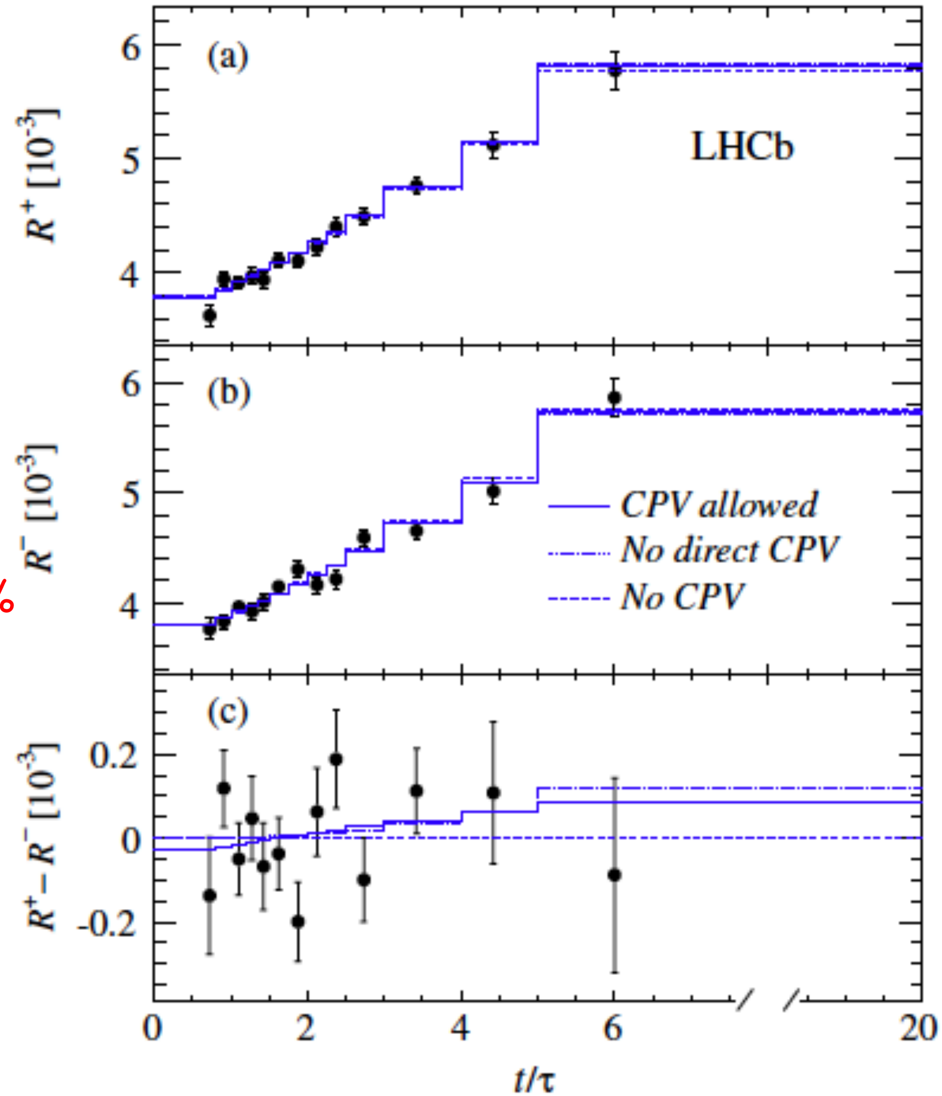
$$x' = x\cos\delta + y\sin\delta,$$
$$y' = y\cos\delta - x\sin\delta,$$

δ is the strong phase between DCS and CF amplitudes

Time Dependent $D^0 \to K^+\pi^-$

PRL 111 (2013) 251801

- Search of CP violation in $D^0 - \overline{D}^0$ mixing by comparing the decay- time-dependent ratio of D^0 and $\overline{D}^0$
  - Difference in $R^{\pm}_D$ => direct CPV
  - Difference in (x'^2, y') => indirect CPV
- 3 fit scenario considered: CPV allowed, no direct CPV and no CPV allowed
- Results for CPV allowed scenario:
- Direct CPV if $A_D \neq 0$
  - $A_D = (R^+_D - R^-_D)/(R^+_D + R^-_D) = (-0.7 \pm 1.9)\%$
- Indirect CPV if $|q/p| \neq 1$ or $\varphi \neq 0$
  - $0.75 < |q/p| < 1.24$ at 68.3% C.L.
  - $0.67 < |q/p| < 1.52$ at 95.5% C.L.
- $R^+_D = (3.545 \pm 0.082 \pm 0.048) \times 10^{-3}$
- $R^-_D = (3.591 \pm 0.081 \pm 0.048) \times 10^{-3}$
- $y'^+ = (5.1 \pm 1.2 \pm 0.7) \times 10^{-3}$
- $Y'^- = (4.5 \pm 1.2 \pm 0.7) \times 10^{-3}$
- $x'^{2+} = (4.9 \pm 6.0 \pm 3.6) \times 10^{-5}$
- $x'^{2-} = (6.0 \pm 5.8 \pm 3.6) \times 10^{-5}$

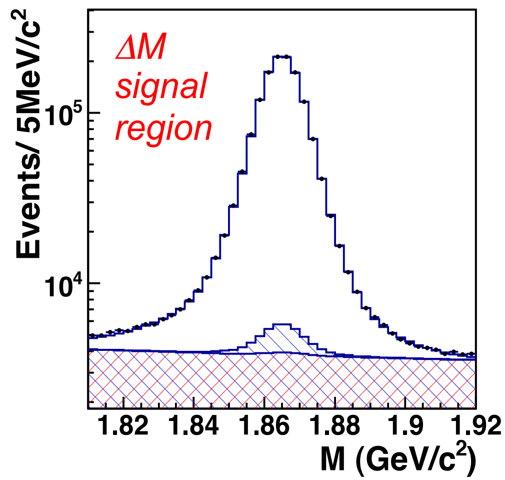


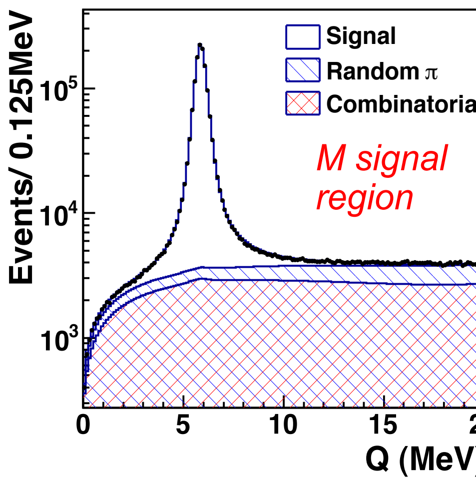
Time Dependent $D^0 \to K_S\pi^+\pi^-$

BELLE

PRD 89, 091103(R) (2014)
976 fb^{-1}

- Signal yield determined from 2-dim. fit to $M_{K\pi\pi}$ and $\Delta M = M_{K\pi\pi\pi} - M_{K\pi\pi}$. Yield is 1.2 x 10^6 events with a purity of 96%.
- Select events in signal region $|M_{K\pi\pi} - M_D| < 15$ MeV/c^2 and $5.75 < \Delta M < 5.95$ MeV.
- For events in signal region, do unbinned ML fit to $m_+ = M_{K\pi+}{}^2$, $m_- = M_{K\pi-}{}^2$, and decay time t.
- Fit parameters are x, y, τ, resolution function parameters, and decay model.
- Fit separately (and simultaneous D^0 and $\overline{D}^0$ samples with (and without) fixing to zero the CPV parameters.



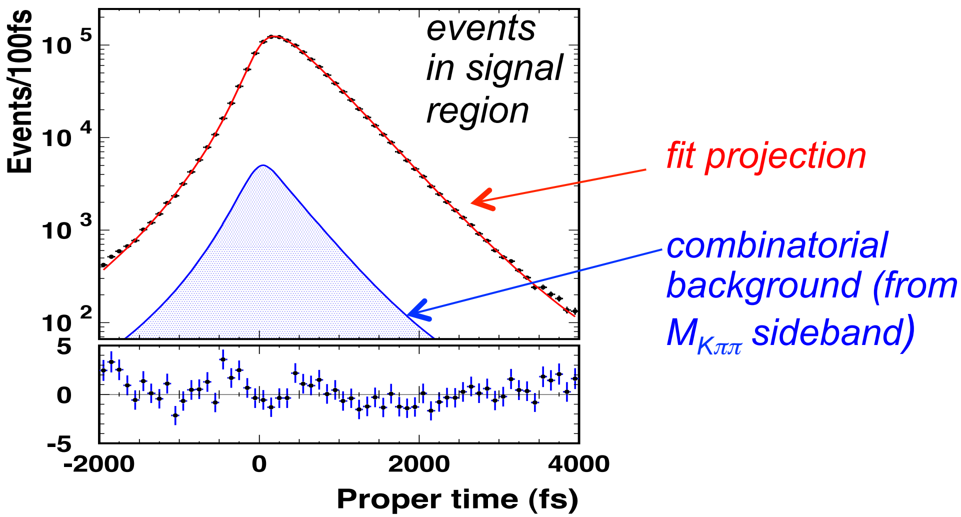


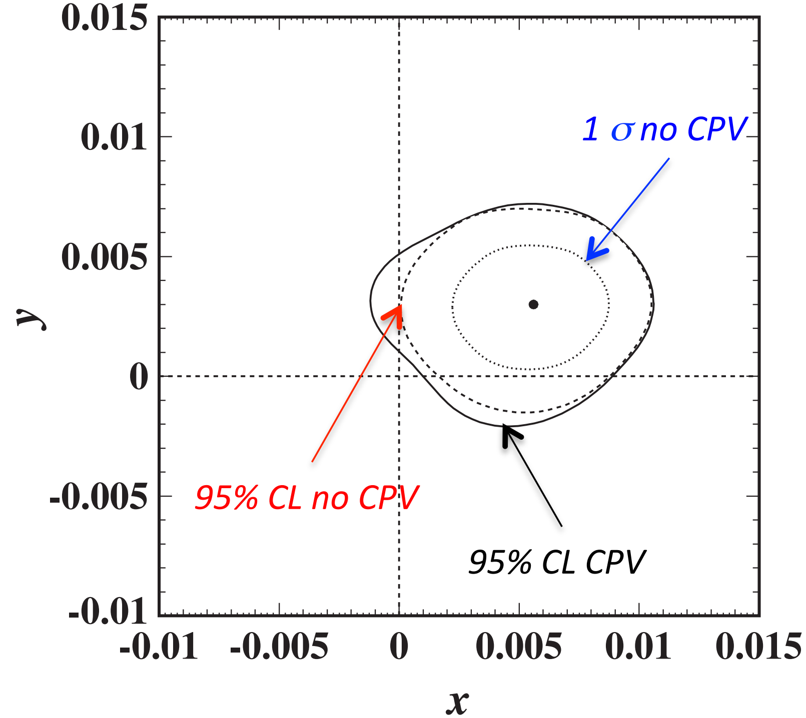
$$R_{D^0} = \frac{e^{-\Gamma t}}{2}\left\{\left(|\mathcal{A}_f|^2 + \left|\frac{q}{p}\right|^2 |\overline{\mathcal{A}}_f|^2\right)\cosh(yt) + \left(|\mathcal{A}_f|^2 - \left|\frac{q}{p}\right|^2 |\overline{\mathcal{A}}_f|^2\right)\cos(xt) + 2\mathrm{Re}\left(\frac{q}{p}\overline{\mathcal{A}}_f\mathcal{A}_f^*\right)\sinh(yt) - 2\mathrm{Im}\left(\frac{q}{p}\overline{\mathcal{A}}_f\mathcal{A}_f^*\right)\sin(xt)\right\}$$

$$R_{\overline{D}^0} = \frac{e^{-\Gamma t}}{2}\left\{\left(|\overline{\mathcal{A}}_f|^2 + \left|\frac{p}{q}\right|^2 |\mathcal{A}_f|^2\right)\cosh(yt) + \left(|\overline{\mathcal{A}}_f|^2 - \left|\frac{p}{q}\right|^2 |\mathcal{A}_f|^2\right)\cos(xt) + 2\mathrm{Re}\left(\frac{p}{q}\mathcal{A}_f\overline{\mathcal{A}}_f^*\right)\sinh(yt) - 2\mathrm{Im}\left(\frac{p}{q}\mathcal{A}_f\overline{\mathcal{A}}_f^*\right)\sin(xt)\right\}$$

$$\text{If no } CPV: \quad \mathcal{A}_f(m_+^2, m_-^2) = \overline{\mathcal{A}}_f(m_-^2, m_+^2)$$

Time Dependent $D^0 \to K_S\pi^+\pi^-$: results





Fit type	Parameter	Fit result
No *CPV*	$x(\%)$	$0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06}$
CPV	$x(\%)$	$0.56 \pm 0.19^{+0.04+0.06}_{-0.08-0.08}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.07}$
	$\|q/p\|$	$0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$
	$\arg(q/p)(°)$	$-6 \pm 11 \pm 3^{+3}_{-4}$

Mixing significance = 2.5 σ
No evidence for indirect or direct CPV

Third error is systematic due to the amplitude model

Measurement of the Strong Phase $\delta_{K\pi}$

PLB 734, 227 (2014)
2.92 fb^{-1}

- $\delta_{K\pi}$ is the strong phase difference between the DCS and CF amplitudes:

$$\frac{\langle K^-\pi^+|\overline{D}^0\rangle}{\langle K^-\pi^+|D^0\rangle} = -re^{-i\delta_{K\pi}} \qquad r = \left|\frac{\langle K^-\pi^+|\overline{D}^0\rangle}{\langle K^-\pi^+|D^0\rangle}\right|$$

- At threshold D meson pairs are produced in a quantum coherent state
- They have opposite CP eigenvalues
- The asymmetry of CP tagged (S_+ (S_-) denotes the CP even (odd)) decay rate is:

$$\mathcal{A}^{CP}_{K\pi} \equiv \frac{\mathcal{B}_{D^{S-}\to K^-\pi^+} - \mathcal{B}_{D^{S+}\to K^-\pi^+}}{\mathcal{B}_{D^{S-}\to K^-\pi^+} + \mathcal{B}_{D^{S+}\to K^-\pi^+}}$$

- At the lowest order in the mixing parameters:

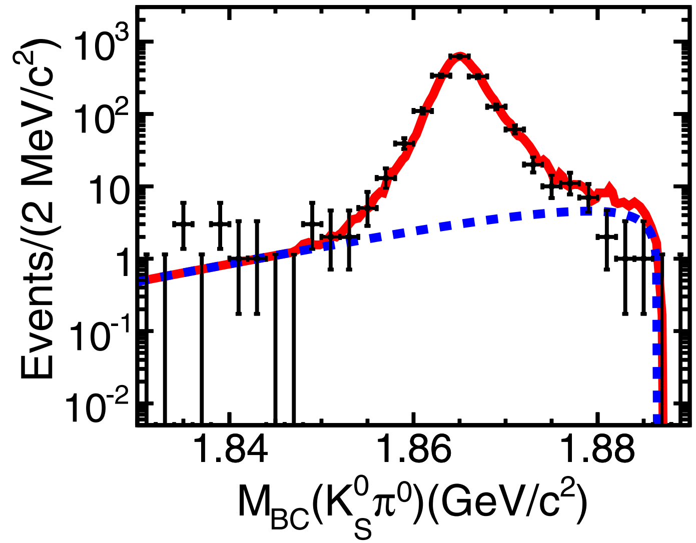
$$2r\cos\delta_{K\pi} + y = (1 + R_{\mathrm{WS}}) \cdot \mathcal{A}^{CP}_{K\pi}$$

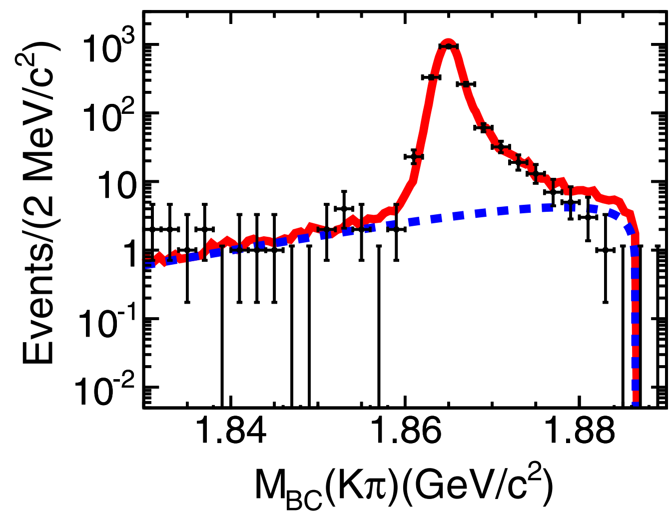
- R_{ws} is the decay rate ratio of WS (DCS + Mixing followed by CF decay) over RS (CF decay) processes
- BES III measures A^{CP}_{Kp} and uses external input for r, y and R_{WS} to determine cos $\delta_{K\pi}$

BESIII Measurement of the Strong Phase $\delta_{K\pi}$

- Reconstructed modes:
  - Flavor tags: $K^+\pi^-$, $K^-\pi^+$
  - CP even tags: K^+K^-, $\pi^+\pi^-$, $K_s\pi^0\pi^0$, $\pi^0\pi^0$, $\rho^0\pi^0$
  - CP odd tags: $K_s\pi^0$, $K_s\eta$, $K_s w$
- Strategy:
  - Single tag: CP tag
  - Double tag: $K\pi$ + CP tag
  - Extract the number of double tag $n_{K\pi,S}$ and of single tag n_s from a M_{BC} fit
  - Efficiencies from MC
  - Compute:

$$\mathcal{B}_{D^{S\pm}\to K^-\pi^+} = \frac{n_{K^-\pi^+,S\pm}}{n_{S\pm}} \cdot \frac{\varepsilon_{S\pm}}{\varepsilon_{K^-\pi^+,S\pm}}$$





$$M_{\rm BC} \equiv \sqrt{E^2_{\rm beam}/c^4 - |\vec{p}_D|^2/c^2}$$

Measurement of the Strong Phase $\delta_{K\pi}$

- BES III measures:

$$\mathcal{A}_{CP\to K\pi} = (12.7 \pm 1.3 \pm 0.7) \times 10^{-2}$$

- With external input from HFAG and PDG:

$r^2_{K\pi}=(3.50\pm0.04)\times10^{-3}$; $y_{CP}=(6.7\pm0.9)\times10^{-3}$; $R_{WS}=(3.80\pm0.05)\times10^{-3}$

$$\cos\delta_{K\pi} = 1.02 \pm 0.11 \pm 0.06 \pm 0.01$$

Error from input parameters

CLEO-c results ***[Phys. Rev. D 86 (2012) 112001]***

$$\cos\delta_{K\pi} = 0.81^{+0.22+0.07}_{-0.18-0.05}$$

$$\cos\delta_{K\pi} = 1.15^{+0.19+0.00}_{-0.17-0.08} \quad \text{(globalfit)}$$

- With 10 fb^{-1} at open charm threshold, BESIII expects to reach a precision on $\cos\delta_{K\pi}$ at the level of 0.06

Triple Product Asymmetries

- Define a T-odd observable in the 4 body decay M -> 1 2 3 4:

$$C_T = (\vec{p}_1 \times \vec{p}_2) \cdot \vec{p}_3$$

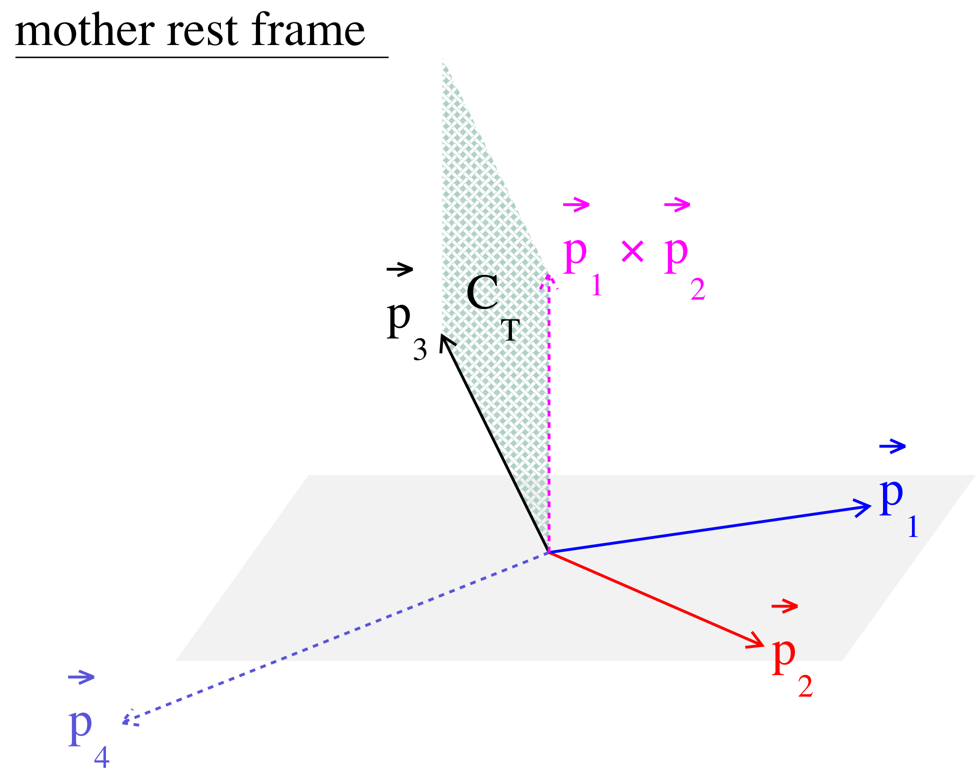
- Construct the asymmetries for M and $\overline{M}$ decays:

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma}$$

$$\bar{A}_T = \frac{\bar{\Gamma}(-\overline{C}_T > 0) - \bar{\Gamma}(-\overline{C}_T < 0)}{\bar{\Gamma}}$$

- The CP violating asymmetry is:

$$a_{CP}^{T-\mathrm{odd}} = \frac{1}{2}(A_T - \bar{A}_T)$$



Complementary to direct CPV mesurements:

$$a_{CP} \propto \sin\Delta\delta \sin\Delta\phi$$

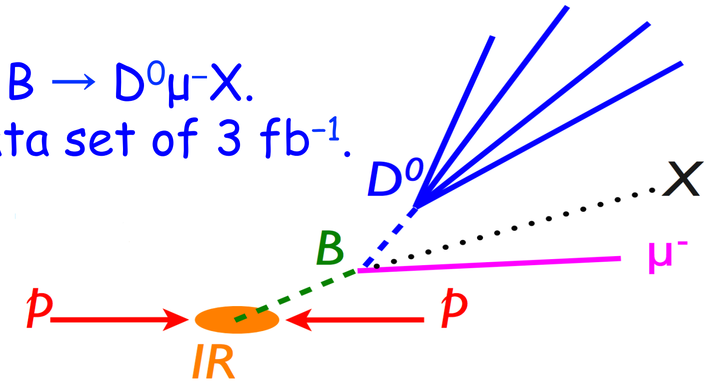
$$a_{CP}^{T-\mathrm{odd}} \propto \cos\Delta\delta \sin\Delta\phi$$

Triple Product Asymmetries: $D^0 \to K^+K^-\pi^+\pi^-$

JHEP 1410 (2014) 5

- D^0 flavor tagged using semileptonic B decays $B \to D^0\mu^-X$.
- 171k $D^0 \to K^+K^-\pi^+\pi^-$ reconstructed using a data set of 3 fb^{-1}.
- Triple-products:

$$C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}), \text{ for } D^0$$
$$\bar{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}), \text{ for } \bar{D}^0$$

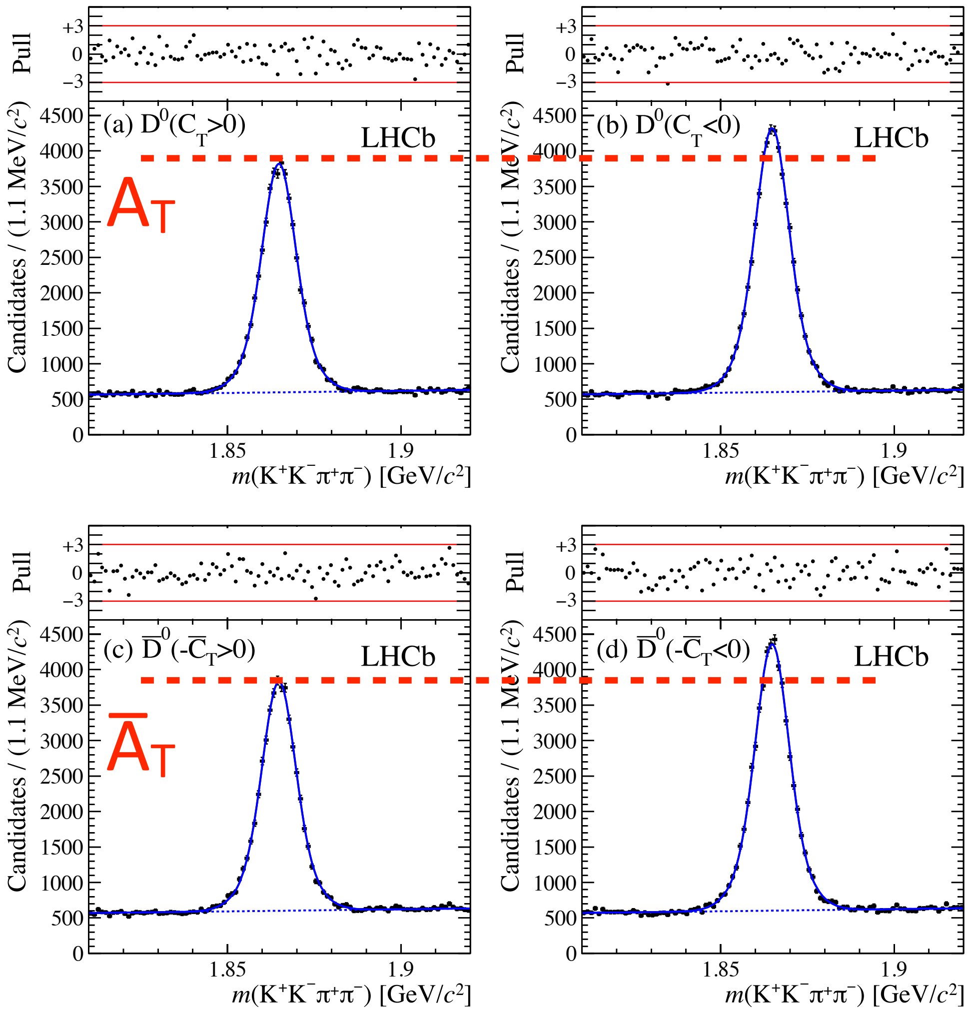


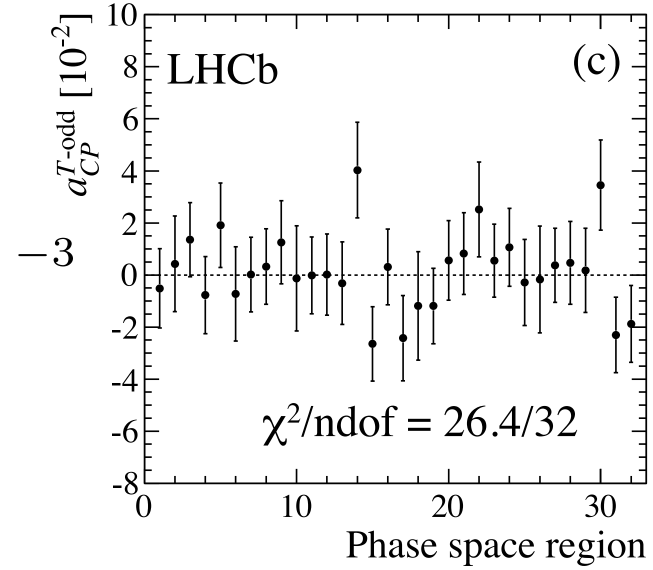
- Dataset divided into 4 samples depending on D^0 flavor and C_T value.
- Simultaneous fit to the four distributions of $m(K^+K^-\pi^+\pi^-)$ to extract event yields and the asymmetry parameters A_T and A_T.

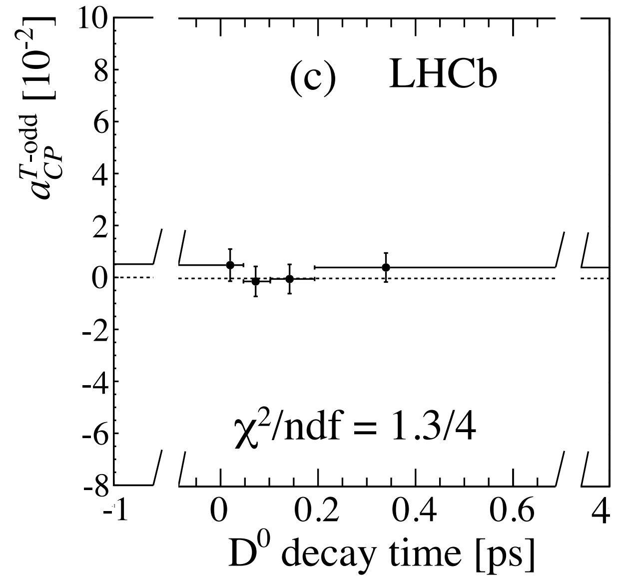
$$N_{D^0,C_T>0} = \frac{1}{2}N_{D^0}(1 + A_T),$$
$$N_{D^0,C_T<0} = \frac{1}{2}N_{D^0}(1 - A_T),$$
$$N_{\bar{D}^0,-\bar{C}_T>0} = \frac{1}{2}N_{\bar{D}^0}(1 + \bar{A}_T)$$
$$N_{\bar{D}^0,-\bar{C}_T<0} = \frac{1}{2}N_{\bar{D}^0}(1 - \bar{A}_T)$$

- Three measurements:
  - Measurement integrated in the phase space.
  - Measurement in different regions of the phase space.
  - Measurement as a function of D^0 proper time (sensitive to indirect CPV).

Triple Product Asymmetries: $D^0 \to K^+K^-\pi^+\pi^-$







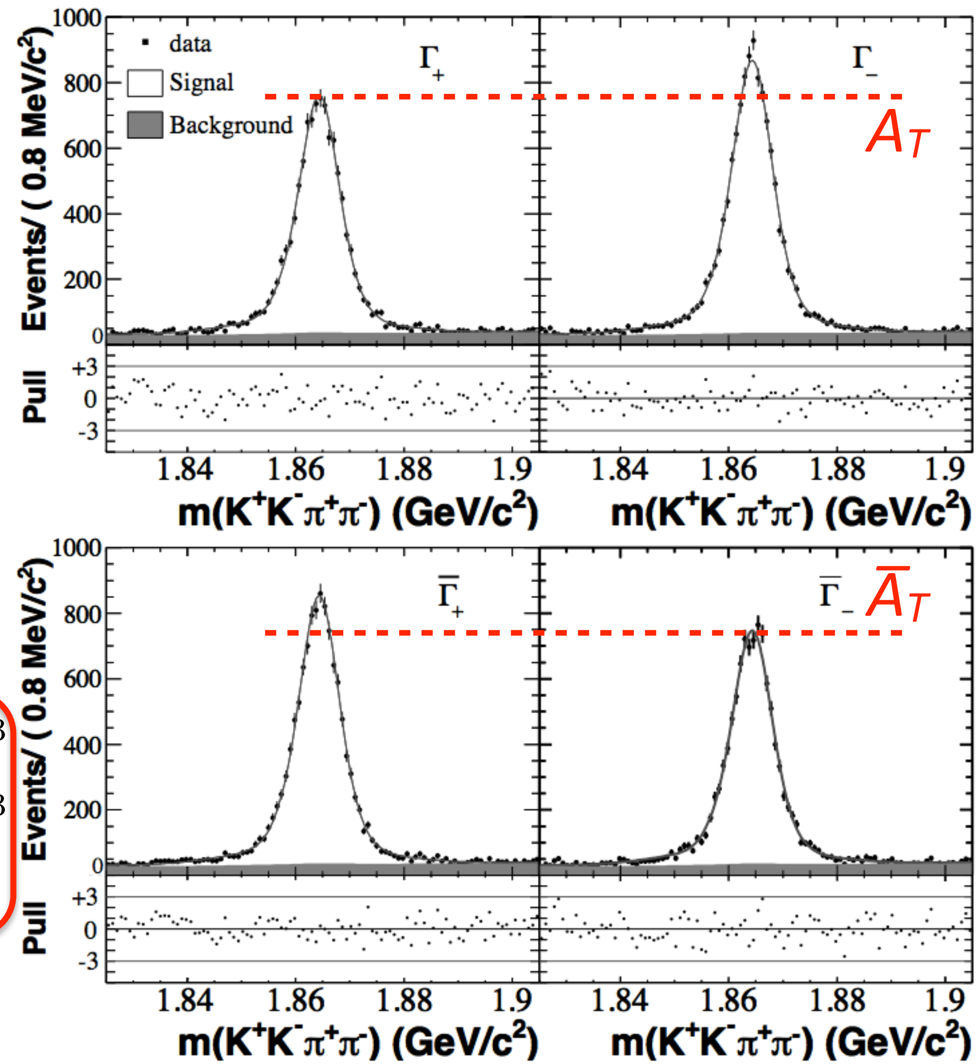
$$a_{CP}^{T-\mathrm{odd}}(D^0) = (1.8 \pm 2.9(\mathrm{stat}) \pm 0.4(\mathrm{syst})) \times 10^{-3}$$

Triple Product Asymmetries: $D^0 \to K^+K^-\pi^+\pi^-$

Phys. Rev. D81 (2010) 111103(R)

- Tag D^0 flavor from $D^{*+} \to D^0\pi^+$ decays
- 47K events
- 2D fit to $m(K^+K^-\pi^+\pi^-)$ and $\Delta m = m(K^+K^-\pi^+\pi^-\pi_s^+) - m(K^+K^-\pi^+\pi^-)$
- Results:

$$A_T(D^0) = (-68.5 \pm 7.3_{\rm stat} \pm 5.8_{\rm syst}) \times 10^{-3}$$
$$\bar{A}_T(\overline{D}^0) = (-70.5 \pm 7.3_{\rm stat} \pm 3.9_{\rm syst}) \times 10^{-3}$$
$$a_{CP}^{T-{\rm odd}}(D^0) = (1.0 \pm 5.1_{\rm stat} \pm 4.4_{\rm syst}) \times 10^{-3}$$

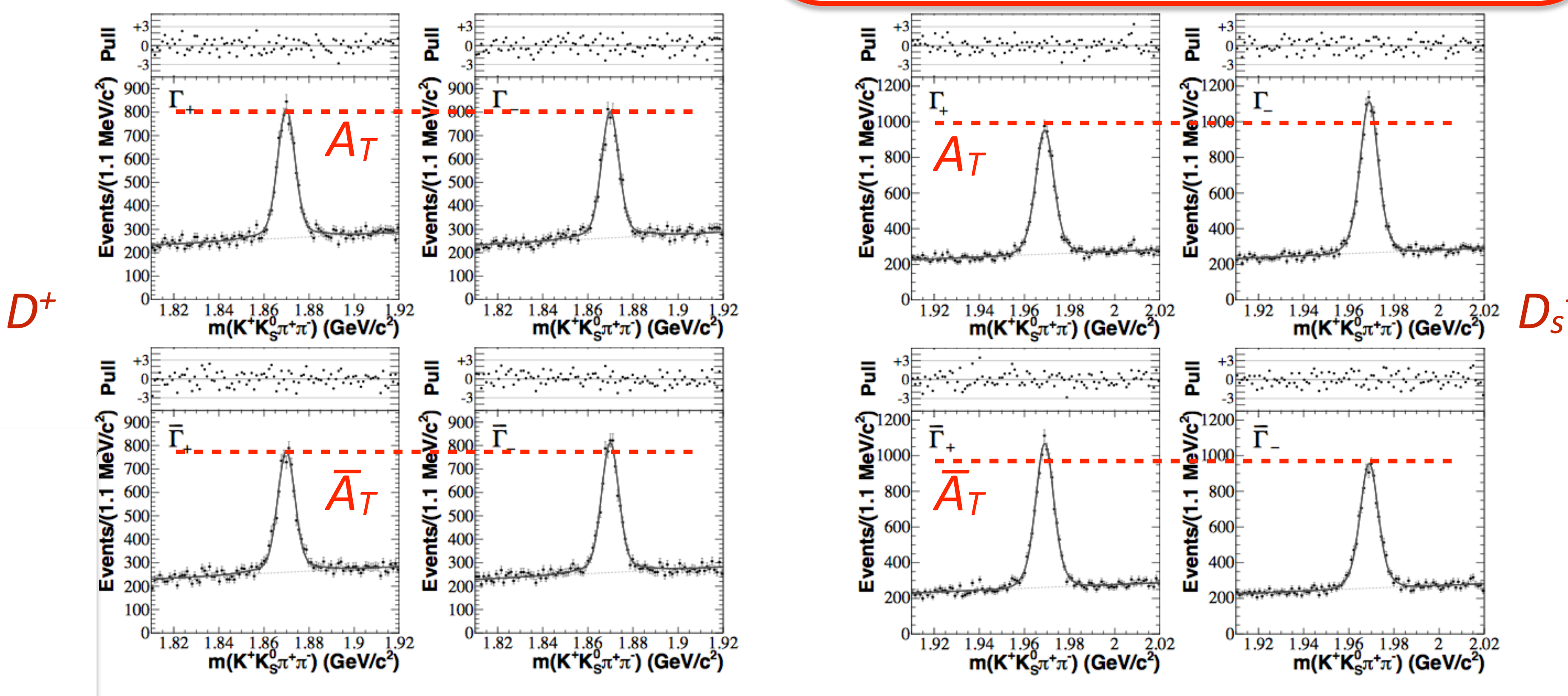


Triple Product Asymmetries: $D^+_{(S)} \to K_s K^+ \pi^+ \pi^-$

Phys. Rev. D84 (2011) 031103(R)

- 20(30)k $D_{(s)}$ decays reconstructed
- One-D fit
- Main systematics from Particle ID and selection criteria

$$A_T(D^+) = (+11.2 \pm 14.1_{\text{stat}} \pm 5.7_{\text{syst}}) \times 10^{-3}$$
$$\bar{A}_T(D^-) = (+35.1 \pm 14.3_{\text{stat}} \pm 7.2_{\text{syst}}) \times 10^{-3}$$
$$A_T(D_s^+) = (-99.2 \pm 10.7_{\text{stat}} \pm 8.3_{\text{syst}}) \times 10^{-3}$$
$$\bar{A}_T(D_s^-) = (-72.1 \pm 10.9_{\text{stat}} \pm 10.7_{\text{syst}}) \times 10^{-3}$$
$$a_{CP}^{T-\text{odd}}(D^+) = (-12.0 \pm 10.0_{\text{stat}} \pm 4.6_{\text{syst}}) \times 10^{-3}$$
$$a_{CP}^{T-\text{odd}}(D_s^+) = (-13.6 \pm 7.7_{\text{stat}} \pm 3.4_{\text{syst}}) \times 10^{-3}$$



Triple Product Asymmetries: Reinterpretation (1)

A. Bevan, hep-ph/1408.3813

- A_T interpreted as a P-odd (A_P) rather than T-odd observable since time-reversal test is not possible

$$P(C_T) = P(\vec{p}_{K^+} \cdot \vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) = -\vec{p}_{K^+} \cdot \vec{p}_{\pi^+} \times \vec{p}_{\pi^-} = -C_T$$

- Defining:

$$\Gamma_+ = \Gamma(C_T > 0) \qquad \bar{\Gamma}_+ = \bar{\Gamma}(\overline{C}_T > 0)$$

$$\Gamma_- = \Gamma(C_T < 0) \qquad \bar{\Gamma}_- = \bar{\Gamma}(\overline{C}_T < 0)$$

- One gets:

$$A_P = \frac{\Gamma_+ - \Gamma_-}{\Gamma_+ + \Gamma_-}; \quad \bar{A}_P = \frac{\bar{\Gamma}_+ - \bar{\Gamma}_-}{\bar{\Gamma}_+ + \bar{\Gamma}_-}$$

- Considering that $C(A_P) = \bar{A}_P$ and $CP(A_P) = -\bar{A}_P$ the following asymmetries testing C and CP can be extracted:

$$a_C^P = \frac{1}{2}\left(A_P - \bar{A}_P\right) \qquad a_{CP}^P = \frac{1}{2}\left(A_P + \bar{A}_P\right) = a_{CP}^{T-\mathrm{odd}}$$

Triple Product Asymmetries: Reinterpretation (2)

- Same exercise with C:

$$C(C_T) = C(\vec{p}_{K^+} \cdot \vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) = \vec{p}_{K^-} \cdot \vec{p}_{\pi^-} \times \vec{p}_{\pi^+} = \bar{C}_T$$

$$A_C = \frac{\bar{\Gamma}_- - \Gamma_-}{\bar{\Gamma}_- + \Gamma_-}; \quad \bar{A}_C = \frac{\bar{\Gamma}_+ - \Gamma_+}{\bar{\Gamma}_+ + \Gamma_-}$$

- Given that $P(A_c) = \bar{A}_c$ and $CP(A_c) = -\bar{A}_c$ one can define:

$$a_P^C = \frac{1}{2}(A_C - \bar{A}_C) \qquad a_{CP}^C = \frac{1}{2}(A_C + \bar{A}_C)$$

- And for CP:

$$CP(C_T) = CP(\vec{p}_{K^+} \cdot \vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) = -\vec{p}_{K^-} \cdot \vec{p}_{\pi^-} \times \vec{p}_{\pi^+} = -\bar{C}_T$$

$$A_{CP} = \frac{\bar{\Gamma}_+ - \Gamma_-}{\bar{\Gamma}_+ + \Gamma_-}; \quad \bar{A}_{CP} = \frac{\bar{\Gamma}_- - \Gamma_+}{\bar{\Gamma}_- + \Gamma_+}$$

- $P(A_{CP}) = \bar{A}_{CP}$ and $CP(A_{CP}) = -\bar{A}_{CP}$

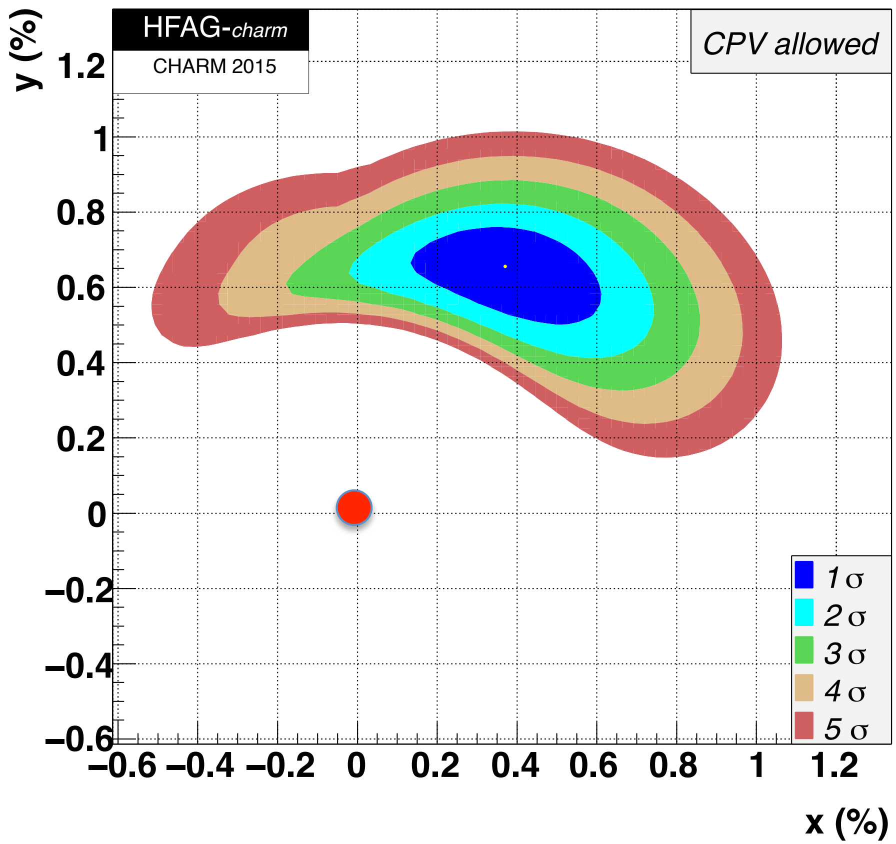
$$a_P^{CP} = \frac{1}{2}(A_{CP} - \bar{A}_{CP}) \qquad a_C^{CP} = \frac{1}{2}(A_{CP} + \bar{A}_{CP})$$

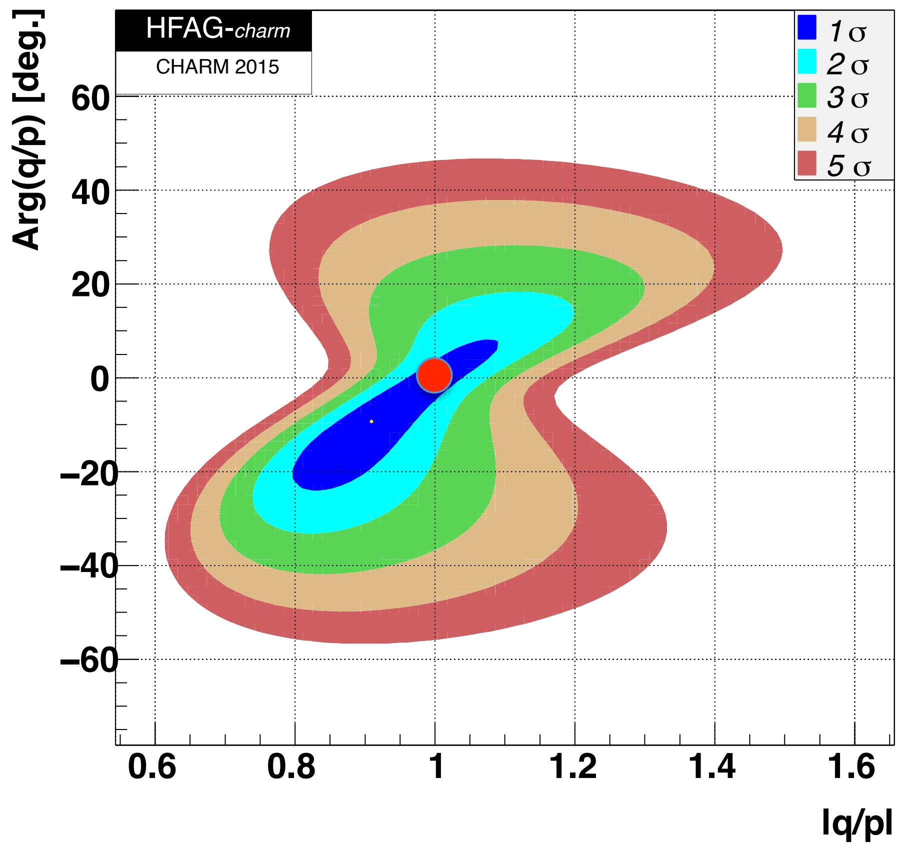
Triple Product Asymmetries: Reanalysis (Preliminary)

	Asymmetry	$D^0 \to K^+K^-\pi^+\pi^-$	$D^+ \to K^0_S K^+\pi^+\pi^-$	$D^+_s \to K^0_S K^+\pi^+\pi^-$
$\not{P}$, FSI	A_P	$-0.069 \pm 0.007 \pm 0.006\,(7.5)$	$0.011 \pm 0.014 \pm 0.006\,(0.7)$	$-0.099 \pm 0.011 \pm 0.008\,(7.3)$
	$\overline{A}_P$	$0.071 \pm 0.007 \pm 0.004\,(8.8)$	$-0.035 \pm 0.014 \pm 0.007\,(2.2)$	$0.072 \pm 0.011 \pm 0.011\,(4.6)$
$\not{C}$, FSI	a_C^P	$-0.070 \pm 0.005 \pm 0.001\,(13.5)$	$0.023 \pm 0.011 \pm 0.002\,(2.1)$	$-0.086 \pm 0.009 \pm 0.002\,(9.3)$
	a_{CP}^P	$0.001 \pm 0.005 \pm 0.004\,(0.2)$	$-0.012 \pm 0.010 \pm 0.005\,(1.1)$	$-0.014 \pm 0.008 \pm 0.003\,(1.6)$
$\not{C}$	A_C	$0.060 \pm 0.007 \pm 0.001\,(8.3)$	$-0.026 \pm 0.016 \pm 0.005\,(1.6)$	$0.080 \pm 0.013 \pm 0.005\,(5.7)$
$\not{C}$	$\overline{A}_C$	$-0.079 \pm 0.007 \pm 0.001\,(10.8)$	$0.020 \pm 0.016 \pm 0.005\,(1.2)$	$-0.092 \pm 0.012 \pm 0.005\,(7.1)$
$\not{P}$	a_P^C	$0.070 \pm 0.005 \pm 0.001\,(13.5)$	$-0.023 \pm 0.011 \pm 0.002\,(2.1)$	$0.086 \pm 0.009 \pm 0.002\,(9.3)$
	a_{CP}^C	$-0.009 \pm 0.005 \pm 0.000\,(1.8)$	$-0.004 \pm 0.011 \pm 0.010\,(0.3)$	$-0.006 \pm 0.009 \pm 0.010\,(0.4)$
	A_{CP}	$-0.008 \pm 0.007 \pm 0.004\,(1.0)$	$-0.016 \pm 0.016 \pm 0.008\,(0.9)$	$-0.020 \pm 0.012 \pm 0.008\,(1.4)$
	$\overline{A}_{CP}$	$-0.010 \pm 0.008 \pm 0.004\,(1.1)$	$0.008 \pm 0.016 \pm 0.008\,(0.5)$	$0.008 \pm 0.013 \pm 0.009\,(0.5)$
	a_P^{CP}	$0.001 \pm 0.005 \pm 0.004\,(0.2)$	$-0.012 \pm 0.011 \pm 0.006\,(1.0)$	$-0.014 \pm 0.009 \pm 0.006\,(1.3)$
	a_C^{CP}	$-0.009 \pm 0.005 \pm 0.000\,(1.8)$	$-0.004 \pm 0.011 \pm 0.010\,(0.3)$	$-0.006 \pm 0.009 \pm 0.010\,(0.4)$

- No evidence of CP violation
- No evidence of C and P violation in D^+ decay
- C and P violation observed in $D^0 \to K^+K^-\pi^+\pi^-$ and $D^+_S \to K_s K^+\pi^+\pi^-$

Putting Everything Together: HFAG Averages



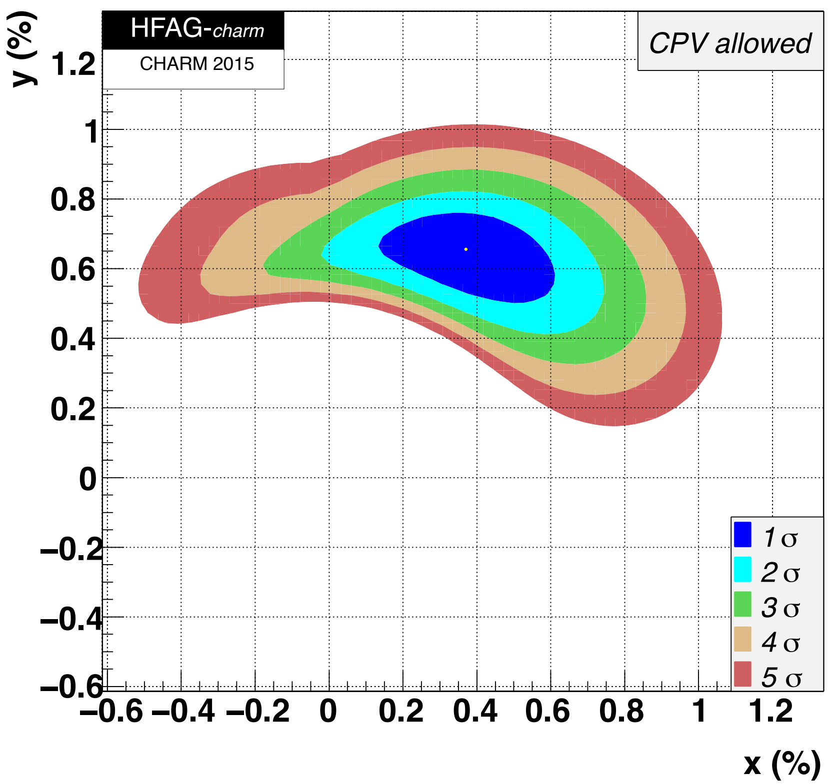


- Mixing in charm decays is firmly established (> 12 σ)
- No evidence for direct or indirect CPV

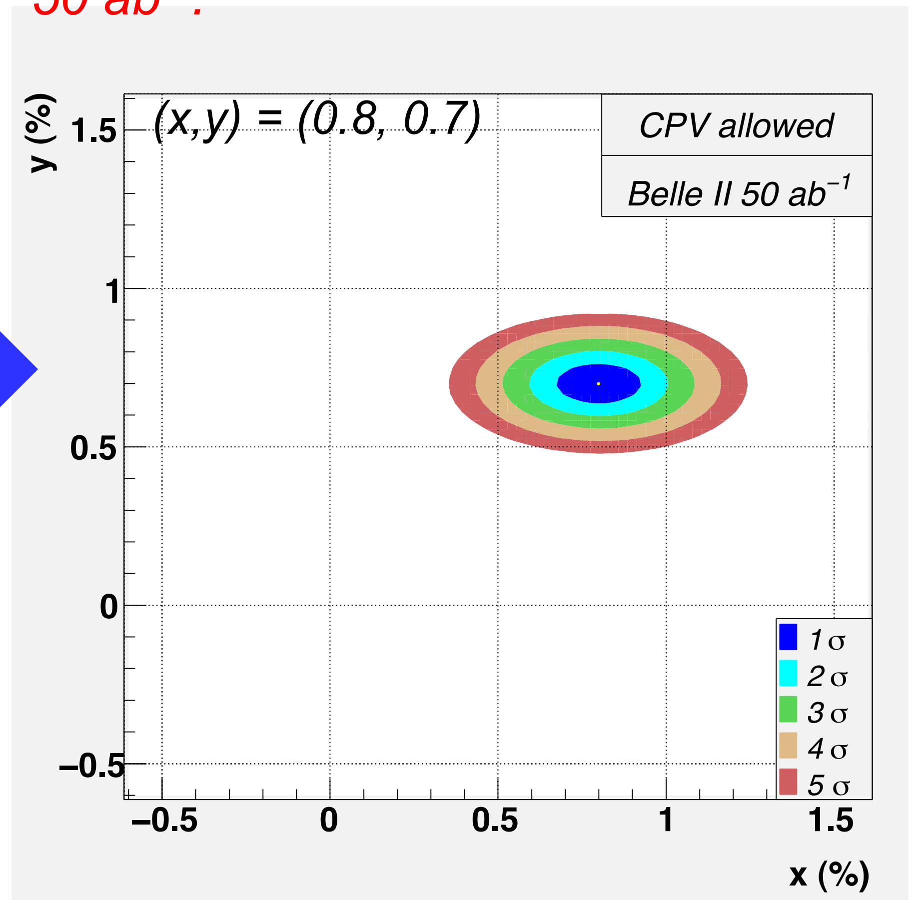
Belle II expectations on Mixing

A. J. Schwartz at CKM 2014 Workshop

Now:



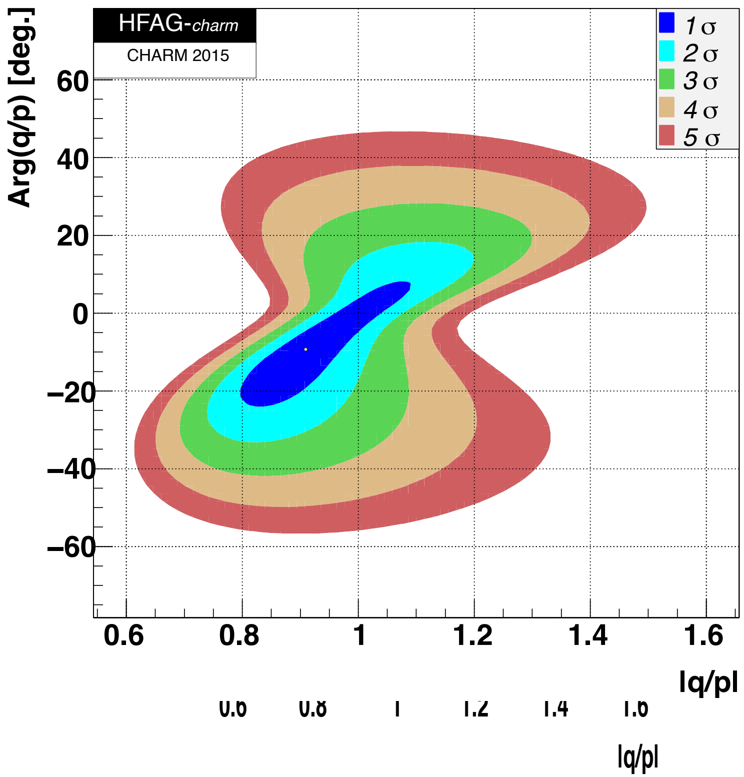
50 ab^{-1}:



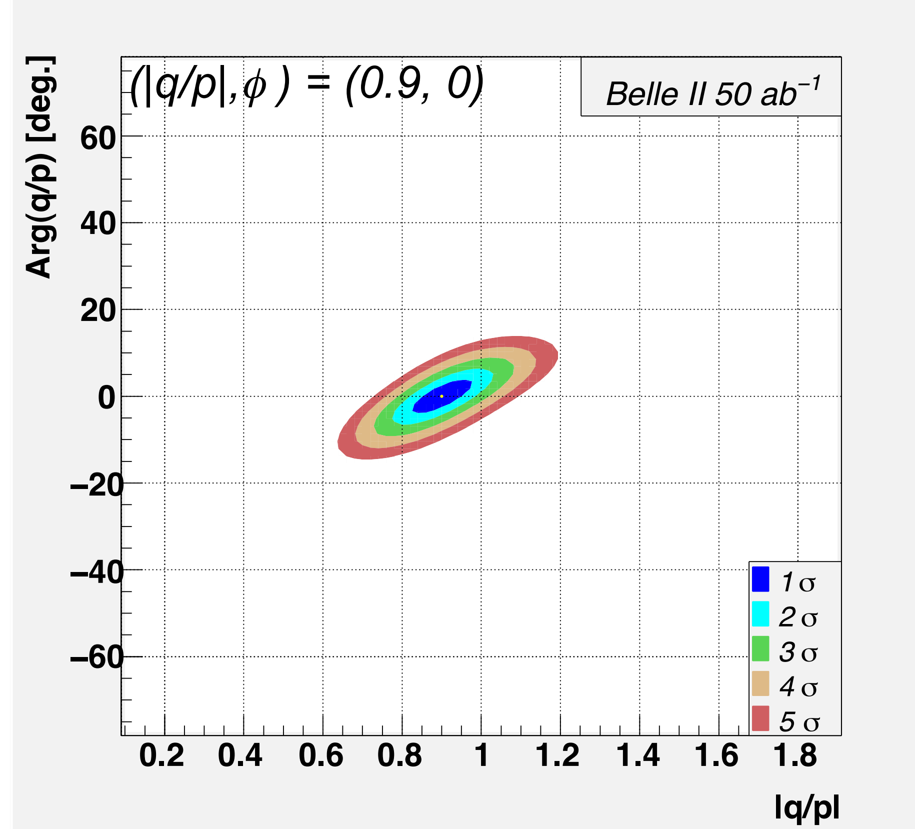
Belle II expectations on CPV

A. J. Schwartz at CKM 2014 Workshop

Now:



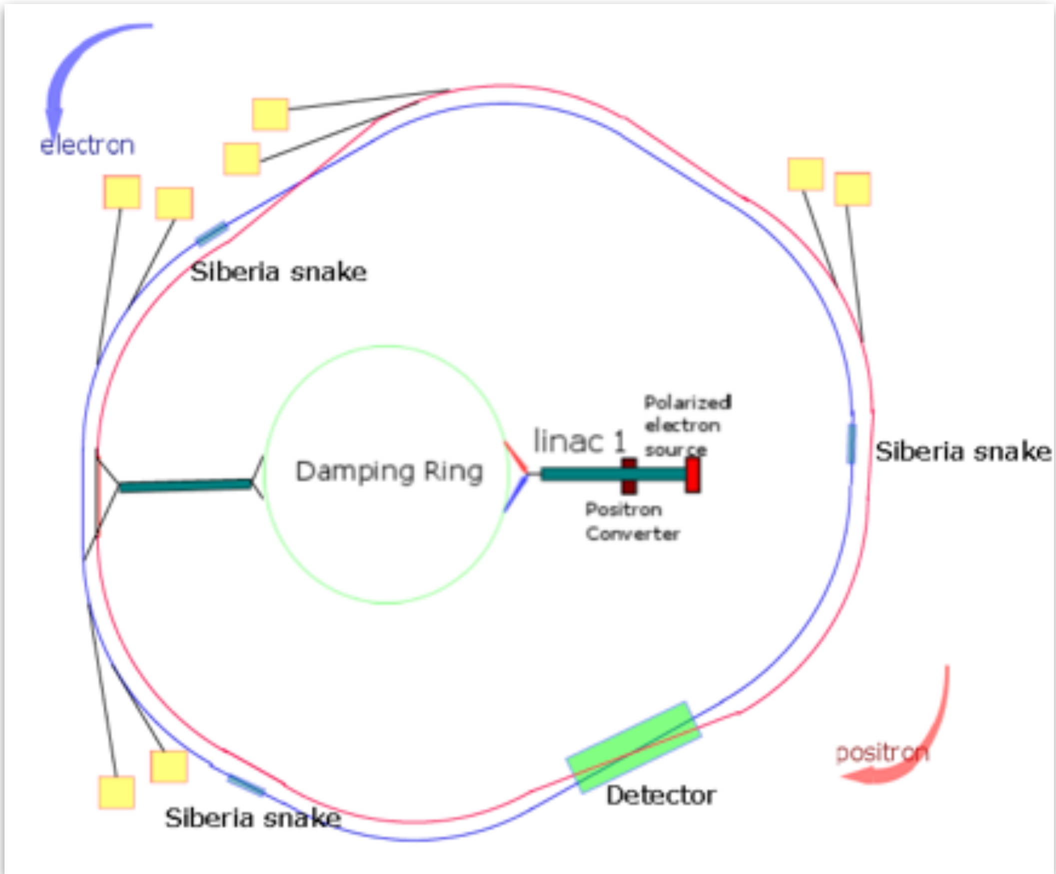
50 ab^{-1}:



- LHCb will dominate most of these measurements, but Belle II should be competitive in y_{CP} and possibly in x'^2, y', $|q/p|$, ϕ
- If LHCb sees new physics it will be important to confirm it

High Intensity Electron Positron Accelerator (HIEPA)

- China is proposing a future super tau-charm factory: HIEPA
- Peak luminosity: 1×10^{35} cm^{-2} s^{-1} at 4 GeV for physics in the tau-charm sector, covering E_{cm} = 2-7 GeV.



with $1ab^{-1}$ data @HIEPA

- ✓ Direct CP violation in $D^+ \to hh$ sensitivity: $10^{-3} \sim 10^{-4}$
- ✓ $\Delta(\cos\delta_{K\pi}) \sim 0.007$; $\Delta(\delta_{K\pi}) \sim 2^o$
- ✓ $R_M = (x^2+y^2)/2 \sim 10^{-5}$ in $K\pi$ and $Ke\nu$ channels
- ✓ Probe y: $\Delta y_{CP} < 0.1\%$

- CDR sometime in 2016
- Complementary to Belle II and LHCb

Workshop in January 2015: http://cicpi2011.lcg.ustc.edu.cn/hiepa2015/

Outlook

- The present:
  - Charm mixing is firmly established
  - No evidence of either direct or indirect CPV

- The future looks bright for charm:
  - More results can be extracted from BaBar and Belle final datasets.
  - More data from BESIII and LHCb are coming and Belle II will start data taking in 2018
  - And then there is the LHCb upgrade
  - And may be a super tau-charm factory in China

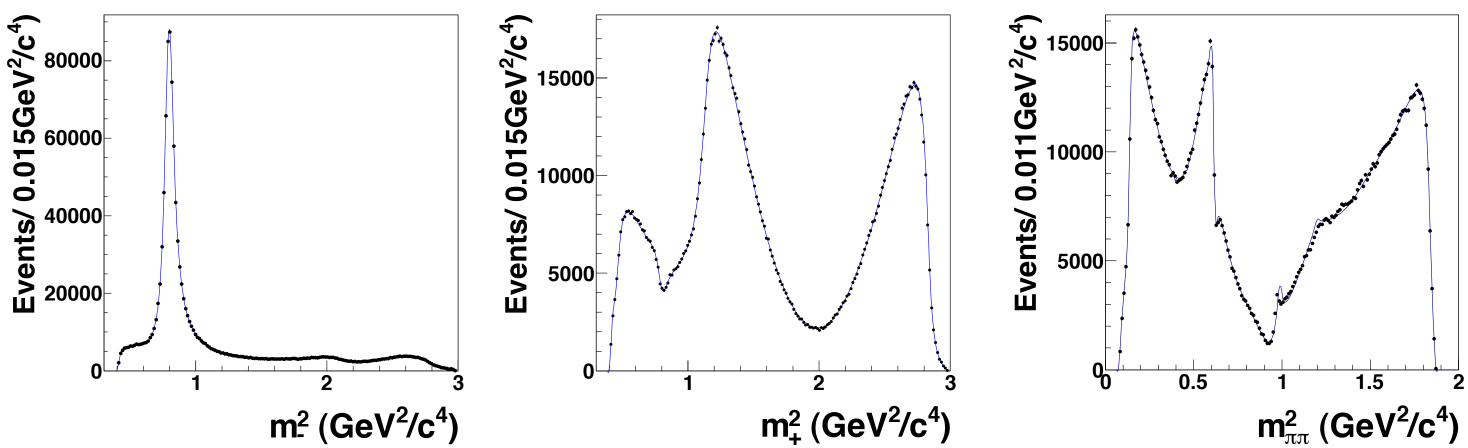
Backup

Time Dependent $D^0 \to K_S\pi^+\pi^-$ Dalitz Plot Fit

Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.590 ± 0.003	131.8 ± 0.2	0.6045
$K_0^*(1430)^-$	2.059 ± 0.010	-194.6 ± 1.7	0.0702
$K_2^*(1430)^-$	1.150 ± 0.009	-41.5 ± 0.4	0.0221
$K^*(1410)^-$	0.496 ± 0.011	83.4 ± 0.9	0.0026
$K^*(1680)^-$	1.556 ± 0.097	-83.2 ± 1.2	0.0016
$K^*(892)^+$	0.139 ± 0.002	-42.1 ± 0.7	0.0046
$K_0^*(1430)^+$	0.176 ± 0.007	-102.3 ± 2.1	0.0005
$K_2^*(1430)^+$	0.077 ± 0.007	-32.2 ± 4.7	0.0001
$K^*(1410)^+$	0.248 ± 0.010	-145.7 ± 2.9	0.0007
$K^*(1680)^+$	1.407 ± 0.053	86.1 ± 2.7	0.0013
$\rho(770)$	1 (fixed)	0 (fixed)	0.2000
$\omega(782)$	0.0370 ± 0.0004	114.9 ± 0.6	0.0057
$f_2(1270)$	1.300 ± 0.013	-31.6 ± 0.5	0.0141
$\rho(1450)$	0.532 ± 0.027	80.8 ± 2.1	0.0012

Resonance	Amplitude	Phase (deg
$\pi\pi$ S-wave		
β_1	4.23 ± 0.02	164.0 ± 0.2
β_2	10.90 ± 0.02	15.6 ± 0.2
β_3	37.4 ± 0.3	3.3 ± 0.4
β_4	14.7 ± 0.1	-8.9 ± 0.3
f_{11}^{prod}	12.76 ± 0.05	$-161.1 \pm 0.$
f_{12}^{prod}	14.2 ± 0.2	$-176.2 \pm 0.$
f_{13}^{prod}	10.0 ± 0.5	$-124.7 \pm 2.$
$K\pi$ S-wave	**Parameters**	
M(MeV/c^2)	1461.7 ± 0.8	
Γ(MeV/c^2)	268.3 ± 1.1	
F	0.4524 ± 0.005	
$\phi_F(rad)$	0.248 ± 0.003	
R	1(fixed)	

Fit projections:
(fitted function describes the data well)



Time Dependent $D^0 \to K_S \pi^+ \pi^-$: Systematics

TABLE III. Summary of the contributions to experimental systematic uncertainty on the mixing and *CPV* parameters. The positive and negative errors are added in quadrature separately.

Source	No *CPV* $\Delta x/10^{-4}$	No *CPV* $\Delta y/10^{-4}$	*CPV* $\Delta x/10^{-4}$	*CPV* $\Delta y/10^{-4}$	*CPV* $\lvert q/p\rvert/10^{-2}$	*CPV* $\arg(q/p)/°$
Best candidate selection	+1.0	+1.9	+1.3	+2.0	−2.3	+2.2
Signal and background yields	±0.3	±0.3	±0.4	±0.4	±1.2	±0.8
Fraction of wrong-tagged events	−0.7	−0.4	−0.5	+0.4	+1.1	+0.8
Time resolution of signal	−1.4	−0.9	−1.2	−0.8	+0.8	−1.2
Efficiency	−1.1	−2.1	−1.4	−2.2	+3.1	+1.3
Combinatorial PDF	$^{+1.9}_{-4.8}$	$^{+2.3}_{-3.9}$	$^{+2.4}_{-4.1}$	$^{+2.0}_{-4.4}$	$^{+1.2}_{-2.9}$	$^{+2.8}_{-2.3}$
$K^*(892)$ DCS/CF reduced by 5%	−7.3	+2.3	−6.9	+3.1	+3.3	−1.4
$K_2^*(1430)$ DCS/CF reduced by 5%	+1.7	−0.7	+2.2	−0.2	+1.1	+0.4
Total	$^{+2.8}_{-8.9}$	$^{+3.7}_{-4.6}$	$^{+3.6}_{-8.3}$	$^{+4.3}_{-5.1}$	$^{+5.0}_{-4.0}$	$^{+3.3}_{-3.0}$

TABLE IV. Summary of contributions to the modeling systematic uncertainty on the mixing and *CPV* parameters. The positive and negative errors are added in quadrature separately.

Source	No *CPV* $\Delta x/10^{-4}$	No *CPV* $\Delta y/10^{-4}$	*CPV* $\Delta x/10^{-4}$	*CPV* $\Delta y/10^{-4}$	*CPV* $\lvert q/p\rvert/10^{-2}$	*CPV* $\arg(q/p)/°$
Resonance M & Γ	±1.4	±1.2	±1.2	±1.3	±2.1	±1.0
$K^*(1680)^+$ removal	−1.8	−3.0	−2.2	−2.8	+2.1	−1.2
$K^*(1410)^\pm$ removal	−1.2	−3.6	−1.7	−3.9	−1.3	+1.4
$\rho(1450)$ removal	+2.1	+0.3	+2.1	+0.5	−1.9	+0.9
Form factors	+4.0	+2.4	+4.3	+2.0	−2.4	−1.0
$\Gamma(q^2) = $ constant	+3.3	−1.6	+4.1	−2.3	−1.6	+1.3
Angular dependence	−8.5	−3.9	−7.4	−3.6	+5.6	−3.2
K-matrix formalism	−2.2	+1.8	−3.5	+2.4	−3.6	+1.1
Total	$^{+5.8}_{-9.1}$	$^{+3.2}_{-6.4}$	$^{+6.4}_{-8.4}$	$^{+3.4}_{-6.9}$	$^{+6.4}_{-5.1}$	$^{+2.5}_{-3.7}$

Triple Product Asymmetries: $D^0 \rightarrow K^+K^-\pi^+\pi^-$ Systematics

Reconstruction Efficiency ☺

- **Does not affect at all the result: A_T and $\bar{A}_T$ asymmetries are calculated separately on the same final state**

Particle Identification ☺

- **The same considerations apply to particle identification**

Systematic uncertainty estimates

Contribution	$\Delta A_T(\%)$	$\Delta \bar{A}_T(\%)$	$\Delta a_{CP}^{T\text{-odd}}(\%)$
Prompt background	± 0.09	± 0.08	± 0.00
Detector bias	± 0.04	± 0.04	± 0.04
C_T resolution	± 0.02	± 0.03	± 0.01
Fit Model	± 0.01	± 0.01	± 0.01
Flavor misidentification	± 0.08	± 0.07	± 0.00
Total	± 0.13	± 0.12	± 0.04

C_T Resolution ✌

- **Estimated accurately from Monte Carlo, almost cancels in a_{CP}^{Todd}**

Peaking Backgrounds under $D^0/\bar{D}^0$ signal ✌

- **Any contamination affects the asymmetry as $A \rightarrow A(1 - f) + f A^d$** ← very small effect

  f - contamination fraction; A^d - asymmetry of the contamination sample

Flavour Mistag ✌

- **Considering the events with flavour mistag as a contamination $a_{CP}^{T\text{-odd}} \rightarrow a_{CP}^{T\text{-odd}} - \Delta\omega/2(A_T+\bar{A}_T)$**

  $\Delta\omega = \omega^+ - \omega^-$ — difference among the mistag probabilities, measured from control samples $B \rightarrow D^{*+}\mu^- X$, $(D^{*+} \rightarrow D^0\pi^+, D^0 \rightarrow K^+K^-\pi^+\pi^-)$; $B \rightarrow D^0\mu^- X$ $(D^0 \rightarrow K^-\pi^+\pi^+\pi^-)$

Detector bias ✌

- **Conservative estimate from control sample of CF $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$**

Perspectives at Belle II

Observable	Statistical	Systematic red.	Systematic irred.	Total	Observable	Statistical	Systematic red.	Systematic irred.	Total
y_{CP} $[10^{-2}]$					$A_{CP}^{K^+K^-}$ $[10^{-2}]$				
976 fb^{-1}	0.22	0.07	0.07	0.24	976 fb^{-1}	0.21	0.07	0.06	0.23
5 ab^{-1}	0.10	0.03-0.04	0.07-0.04	0.11-0.12	5 ab^{-1}	0.09	0.03	0.06	0.11
50 ab^{-1}	0.03	0.01	0.07-0.04	0.05-0.08	50 ab^{-1}	0.03	0.01	0.06	0.06
A_Γ $[10^{-2}]$					$A_{CP}^{\pi^+\pi^-}$ $[10^{-2}]$				
976 fb^{-1}	0.20	0.07	0.04	0.22	976 fb^{-1}	0.38	0.09	0.02	0.37
5 ab^{-1}	0.09	0.03-0.04	0.04-0.01	0.10	5 ab^{-1}	0.16	0.04	0.02	0.17
50 ab^{-1}	0.03	0.01	0.04-0.01	0.03-0.05	50 ab^{-1}	0.05	0.01	0.02	0.06
$A_{CP}^{K_SK^+}$ $[10^{-2}]$					$A_{CP}^{\phi\gamma}$ $[10^{-2}]$				
976 fb^{-1}	0.28	0.12-0.14	0.05-0.00	0.31	976 fb^{-1}	5.6	0.2	0.06	5.6
5 ab^{-1}	0.12	0.06	0.05-0.00	0.14	5 ab^{-1}	2.5	0.1	0.06	2.5
50 ab^{-1}	0.04	0.02	0.05-0.00	0.04-0.07	50 ab^{-1}	0.8	0.03	0.06	0.8
$x^{K_S\pi^+\pi^-}$ $[10^{-2}]$					$y^{K_S\pi^+\pi^-}$ $[10^{-2}]$				
976 fb^{-1}	0.19	0.06	0.11	0.20	976 fb^{-1}	0.15	0.06	0.04	0.16
5 ab^{-1}	0.08	0.03	0.11	0.14	5 ab^{-1}	0.06	0.03	0.04	0.08
50 ab^{-1}	0.03	0.01	0.11	0.11	50 ab^{-1}	0.02	0.01	0.04	0.05
$\lvert q/p\rvert^{K_S\pi^+\pi^-}$ $[10^{-2}]$					$\phi^{K_S\pi^+\pi^-}$ $[^\circ]$				
976 fb^{-1}	15.5	5.2-5.6	7.0-6.7	17.8	976 fb^{-1}	10.7	4.4-4.5	3.8-3.7	12.2
5 ab^{-1}	6.9	2.3-2.5	7.0-6.7	9.9-10.1	5 ab^{-1}	4.7	1.9-2.0	3.8-3.7	6.3-6.4
50 ab^{-1}	2.2	0.7-0.8	7.0-6.7	7.0-7.4	50 ab^{-1}	1.5	0.6	3.8-3.7	4.0-4.2
$A_{CP}^{\pi^0\pi^0}$ $[10^{-2}]$					$A_{CP}^{K_S^0\pi^0}$ $[10^{-2}]$				
996 fb^{-1}	0.64	0.10	0.01	0.65	976 fb^{-1}	0.16	0.09	0.01	0.16
5 ab^{-1}	0.29	0.05	0.01	0.29	5 ab^{-1}	0.07	0.04	0.01	0.08
50 ab^{-1}	0.09	0.01	0.01	0.09	50 ab^{-1}	0.02	0.1	0.01	0.03