CP Violation in Charm Decays at Belle

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for the Belle Collaboration

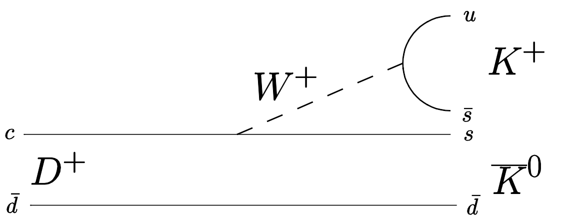
- Introduction
- Method
- A_{CP} in $D^+_{(s)} \to K^0_S \pi^+$ and $D^+_{(s)} \to K^0_S K^+$
- A_{CP} in $D^0 \to K^0_S \pi^0$, $D^0 \to K^0_S \eta$, and $D^0 \to K^0_S \eta'$
- ΔA_{CP} between $D^+ \to \phi \pi^+$ and $D^+_s \to \phi \pi^+$
- Summary

Introduction

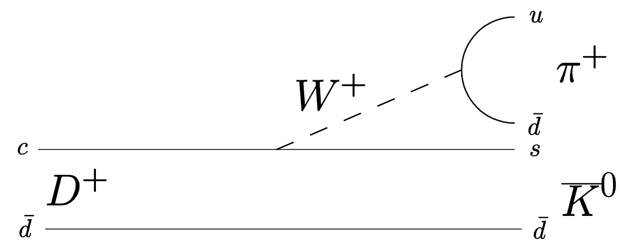
• CP Violation (CPV)

•Direct CPV : CPV in decay rate

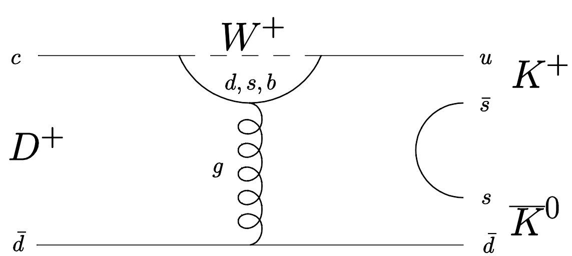
•SM : $O(0.1\%)$ of CPV in Singly Cabibbo Suppresed (SCS) decays, but No direct CPV in Cabibbo Favored (CF) and Doubly Cabibbo Suppressed (DCS) decays



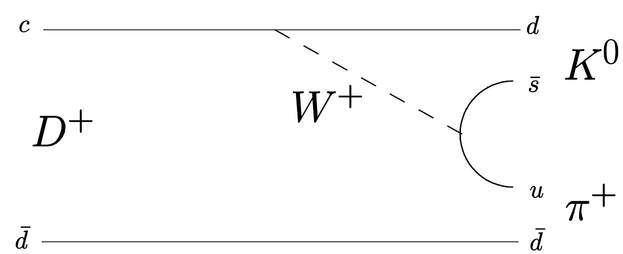
Singly Cabibbo Suppressed (SCS) diagram (tree)



Cabibbo Favored (CF) diagram



SCS diagram (penguin)



Doubly Cabibbo Suppressed (DCS) diagram

•A_{CP} in $D^+_{(s)} \to K^0_S h^+$, $h^+ \in \{\pi^+, K^+\} \to (0.332 \pm 0.006)\%$ CPV due to ε in K^0 mixing

•ΔA_{CP} between $D^+ \to \phi\pi^+$(SCS) and $D^+_s \to \phi\pi^+$(CF)

∘A_{CP} and ΔA_{CP} deviations from expectations at $O(0.1\%)$ would require more precise theory prediction to distinguish BSM from SM

Introduction-cont.

• Indirect CPV : CPV induced by D^0 mixing

• $D^0 \to K_S^0 P^0, \quad P^0 \in \{\pi^0, \eta, \eta'\}$

$\to CPV$ in interference between decays with and without D^0 mixing (type III by PDG convention)

$\to 0.332\%$ CPV due to K^0 mixing

◦ Technical problems in measuring production and decay vertices

: Would be difficult to perform a time dependent analysis

$\to$ Can't extract CPV parameters

◦ Measure time integrated A_{CP}

◦ $A_{CP} \neq 0.332\%$ would indicate the existence of BSM

Method

- $A_{CP}^{D\to X^0 h^+} = \dfrac{\Gamma(D\to X^0 h^+) - \Gamma(\bar{D}\to X^0 h^-)}{\Gamma(D\to X^0 h^+) + \Gamma(\bar{D}\to X^0 h^-)}$, Γ : partial decay width
- $A_{rec}^{D\to X^0 h^+} = A_{CP}^{D\to X^0 h^+} + A_{other}$, $A_{other} \in \{A_{FB}^{D}, A_{\varepsilon}^{h^+}\}$
- A_{other} should be corrected to measure $A_{CP}^{D\to X^0 h^+}$
- $A_{FB}^{D}(\cos\theta_{D}^{CMS})$: Production asymmetry

  $\to$ Independent of decay
- $A_{\varepsilon}^{h^+}(p_{h^+}^{lab}, \cos\theta_{h^+}^{lab})$: Asymmetry in h^+ detection

  $\to$ Depends on decay

- To correct A_{other}, we assume :

  the same A_{FB} for all charmed mesons and no CPV in CF decay
- A_{other} $\leftarrow$ Determined using the data

Method-cont.1

- $A_{rec}^{D\to K_S^0\pi^+} = A_{CP}^{D\to K_S^0\pi^+} + A_{FB}^{D} + A_{\varepsilon}^{\pi^+} \Rightarrow$ Eq.(1)
- $A_{rec}^{D\to K_S^0 K^+} = A_{CP}^{D\to K_S^0 K^+} + A_{FB}^{D} + A_{\varepsilon}^{K^+} \Rightarrow$ Eq.(2)
- $A_{rec}^{D^{*+}\to D^0\pi_s^+} = A_{CP}^{D^0\to K_S^0 P^0} + A_{FB}^{D^{*+}} + A_{\varepsilon}^{\pi_s^+} \Rightarrow$ Eq.(3)
- $A_{rec}^{D_s^+\to\phi\pi^+} = A_{FB}^{D_s^+} + A_{\varepsilon}^{\pi^+} \Rightarrow$ Eq.(4)
- $A_{rec}^{untagged\ D^0\to K^-\pi^+} = A_{FB}^{D^0} + A_{\varepsilon}^{K^-} + A_{\varepsilon}^{\pi^+} \Rightarrow$ Eq.(5)
- $A_{rec}^{tagged\ D^0\to K^-\pi^+} = A_{FB}^{D^{*+}} + A_{\varepsilon}^{K^-} + A_{\varepsilon}^{\pi^+} + A_{\varepsilon}^{\pi_s^+} \Rightarrow$ Eq.(6)

- For $K_S^0\pi^+$: Eq.(1) − Eq.(4) $= A_{CP}^{D\to K_S^0\pi^+}$
- For $K_S^0 K^+$: Eq.(5) − Eq.(4) $= A_{\varepsilon}^{K^-}$
- Eq.(2) $- A_{\varepsilon}^{K^+} = A_{CP}^{D\to K_S^0 K^+} + A_{FB}^{D} \equiv A_{rec}^{D\to K_S^0 K_{corr}^+}$
- Using the antisymmetry of $A_{FB}(\cos\theta_D^{CMS})$

$$A_{CP}^{D\to K_S^0 K^+} = \frac{A_{rec}^{D\to K_S^0 K_{corr}^+}(\cos\theta_D^{CMS}) + A_{rec}^{D\to K_S^0 K_{corr}^+}(-\cos\theta_D^{CMS})}{2}$$

$$A_{FB}^{D} = \frac{A_{rec}^{D\to K_S^0 K_{corr}^+}(\cos\theta_D^{CMS}) - A_{rec}^{D\to K_S^0 K_{corr}^+}(-\cos\theta_D^{CMS})}{2}$$

- For $K_S^0 P^0$: Eq.(6) − Eq.(5) $= A_{\varepsilon}^{\pi_s^+}$, then the same as the $K_S^0 K^+$

Method-cont.2

- ΔA_{CP} between $D^+ \to \phi\pi^+$ and $D_s^+ \to \phi\pi^+$
- $A_{rec}^{D\to\phi\pi^+} = A_{CP}^{D\to\phi\pi^+} + A_{FB}^{D} + A_{\varepsilon}^{\pi^+} + A_{\varepsilon}^{K^+K^-}$
- $A_{\varepsilon}^{K^+K^-} = 0$ for ϕ, but K^* contribution exists under ϕ

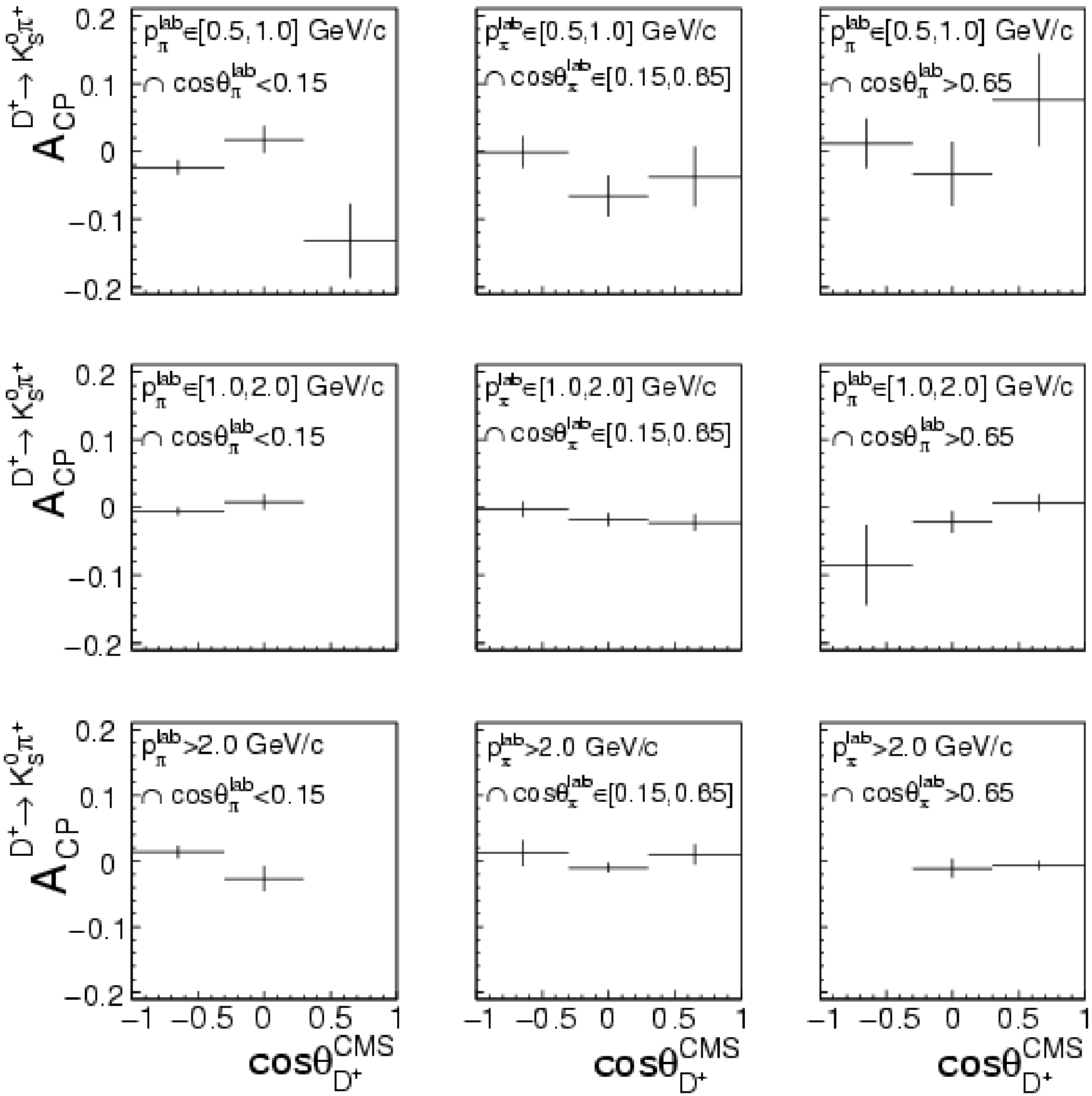
  This effect was negligible in measurment of A_{CP} in $K_S^0 h^+$
- $\Delta A_{rec} = A_{rec}^{D^+\to\phi\pi^+} - A_{rec}^{D_s^+\to\phi\pi^+} = \Delta A_{CP} + \Delta A_{FB}$
- Then, the same as the $K_S^0 K^+$

- A_{other} corrections are done w.r.t.

  the corresponding phase spaces for all channels

A_{CP} in $D^+_{(s)} \to K^0_S h^+$: PRL 104, 181602 (2010) (with 673 fb^{-1})

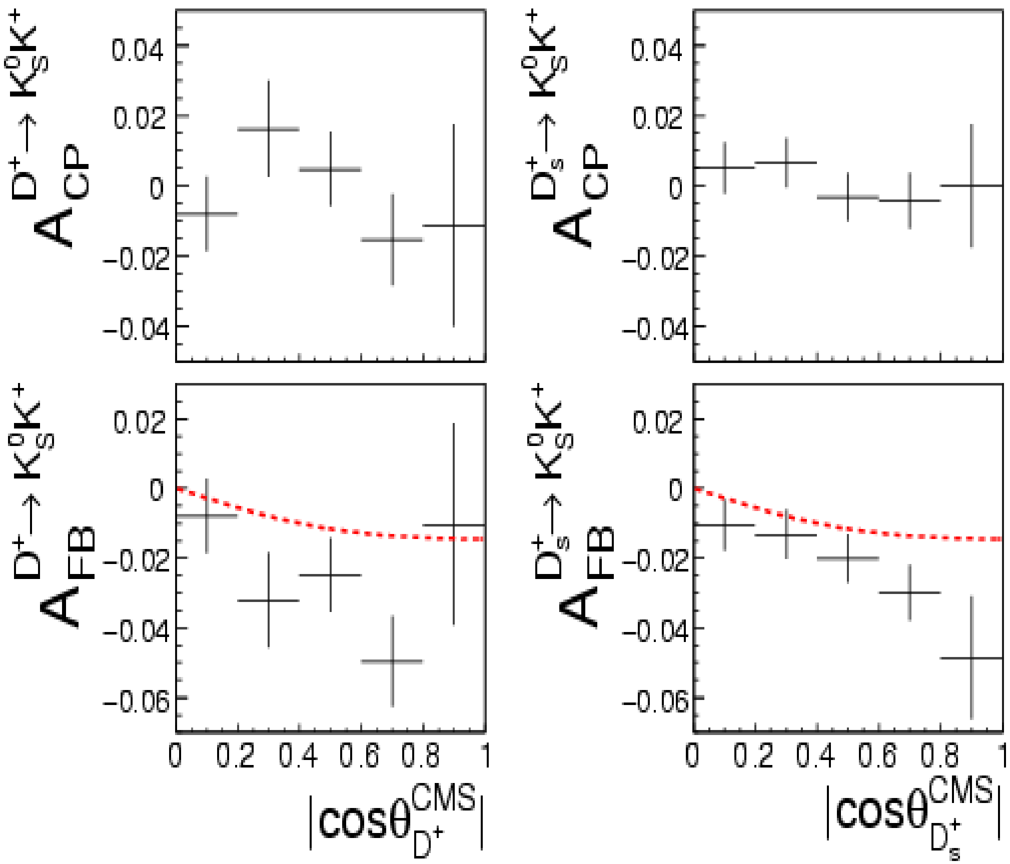
- Measured $A_{CP}^{D^+\to K^0_S\pi^+}$ in bins of $(p_\pi^{lab}, \cos\theta_\pi^{lab}, \cos\theta_D^{CMS})$



- $A_{CP}^{D^+\to K^0_S\pi^+} = (-0.71 \pm 0.19 \pm 0.20)\%$

$\to$ 2.6 σ away from 0, consistent with -0.33% expected due to K^0_S

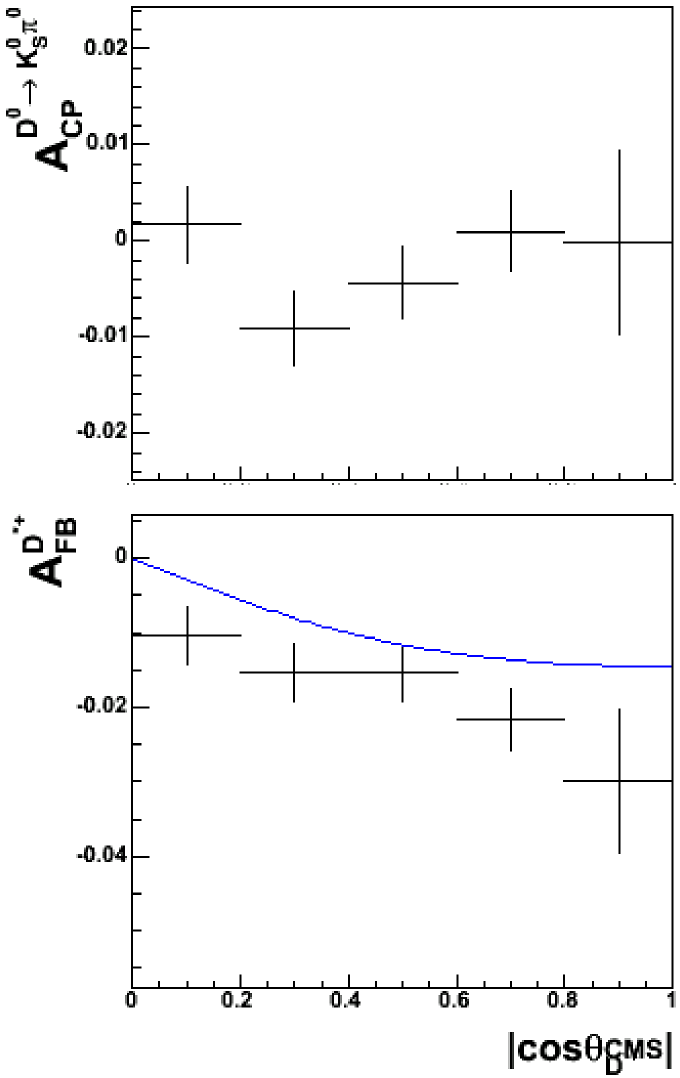
•Measured $A_{CP}^{D_{(s)}^{+}\to K_S^0 K^+}$ and A_{FB}^{D} in $\cos\theta_D^{CMS}$ bins



- $A_{CP}^{D^+\to K_S^0K^+}$ = $(-0.16\pm0.58\pm0.25)\%$
- $A_{CP}^{D_s^+\to K_S^0K^+}$ = $(+0.12\pm0.36\pm0.22)\%$
- Dashed line : LO prediction for $A_{FB}^{c\bar{c}}$

A_{CP} in $D^0 \to K_S^0 P^0$

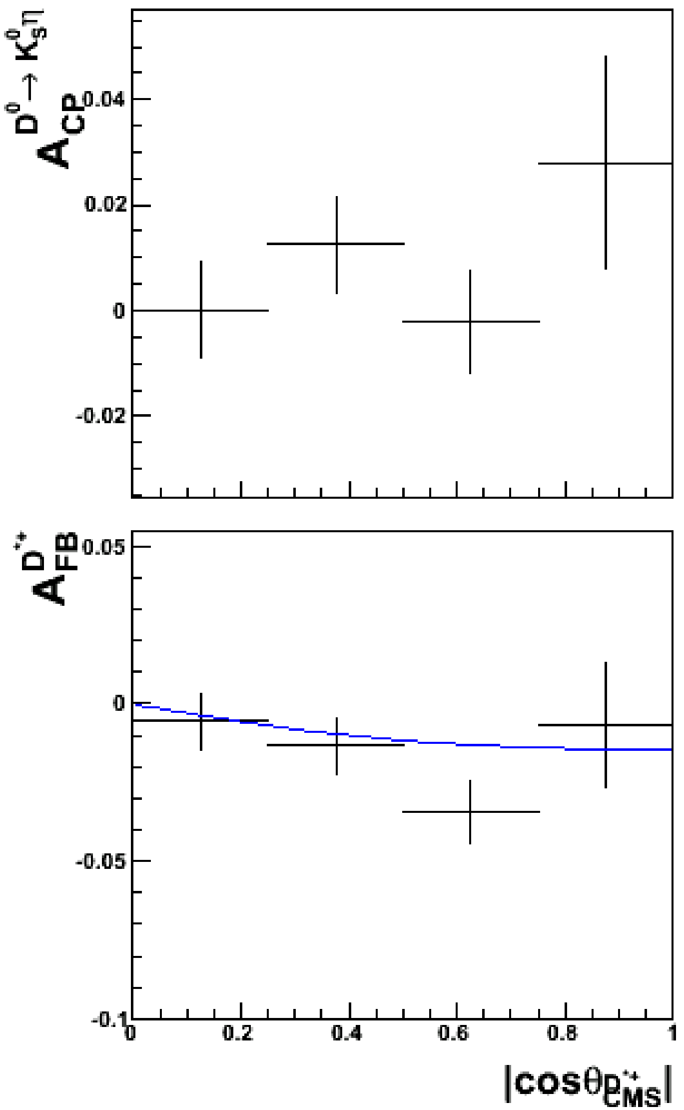
- Measured $A_{CP}^{D^0 \to K_S^0 \pi^0}$ and A_{FB}^{D} in $\cos\theta_D^{CMS}$ bins



Preliminary result with 791 fb^{-1}

- $A_{CP}^{D^0 \to K_S^0 \pi^0} =$ $(-0.28 \pm 0.19 \pm 0.10)\%$
- Line : LO prediction for $A_{FB}^{c\bar{c}}$

•Measured $A_{CP}^{D^0\to K_S^0\eta}$ and A_{FB}^{D} in $\cos\theta_D^{CMS}$ bins



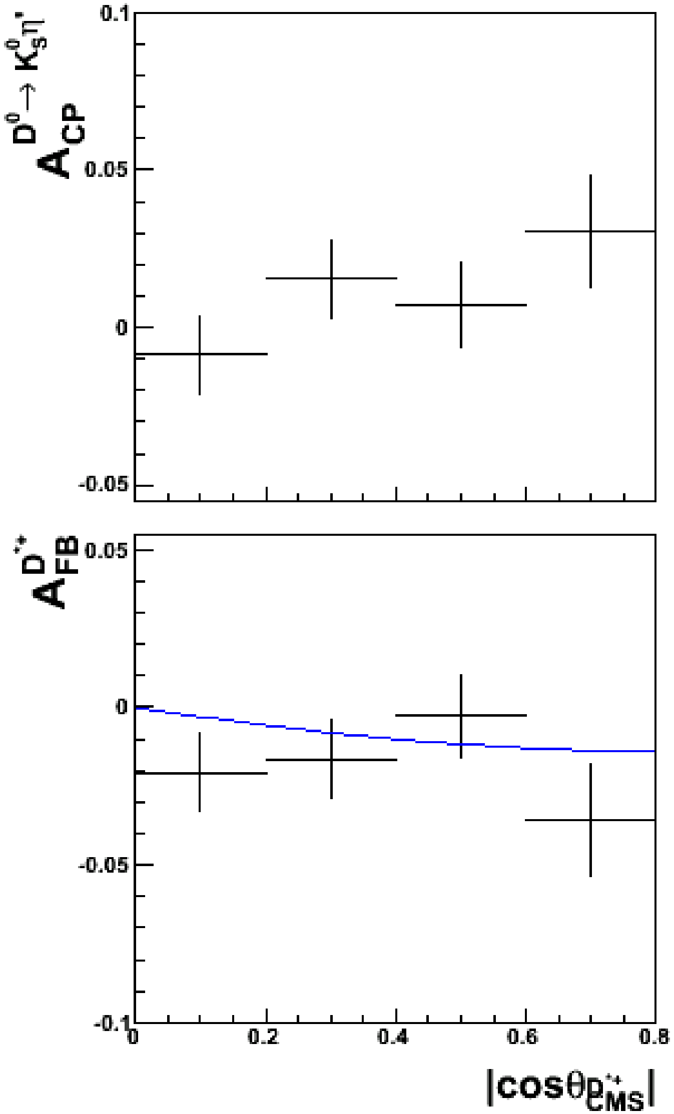
Preliminary result with 791 fb^{-1}

- Use $\eta \to \gamma\gamma$
- $A_{CP}^{D^0\to K_S^0\eta} =$ $(+0.54\pm0.51\pm0.13)\%$

$\to$ World's first measurement

- Line : LO prediction for $A_{FB}^{c\bar{c}}$

•Measured $A_{CP}^{D^0 \to K_S^0 \eta'}$ and A_{FB}^{D} in $\cos\theta_D^{CMS}$ bins



Preliminary result
with 791 fb^{-1}

•Use $\eta' \to \pi^+\pi^-\eta\ [\eta \to \gamma\gamma]$

•$A_{CP}^{D^0 \to K_S^0 \eta'} =$
$(+0.90 \pm 0.67 \pm 0.15)\%$

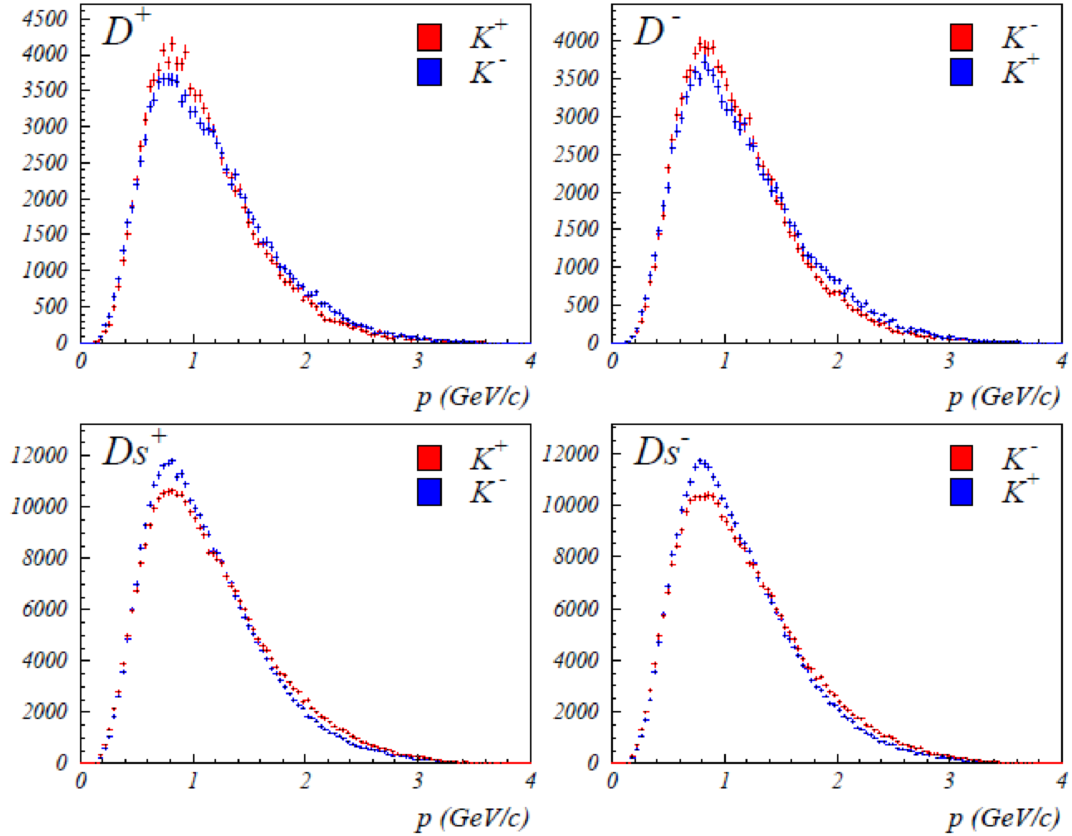
$\to$ World's first measurement

•Line :

LO prediction for $A_{FB}^{c\bar{c}}$

ΔA_{CP} between $D^+ \to \phi\pi^+$ and $D_s^+ \to \phi\pi^+$

- $\phi \to K^+K^-$ and $m(K^+K^-)$ within $m_{PDG}^{\phi} \pm 16\ \mathrm{MeV}/c^2$
- $A_\varepsilon^{K^+K^-}$ would be negligible, but different sign of $A_\varepsilon^{K^+K^-}$ in D^+ and D_s^+ decays might produce a non-negligible $\Delta A_\varepsilon^{K^+K^-}$

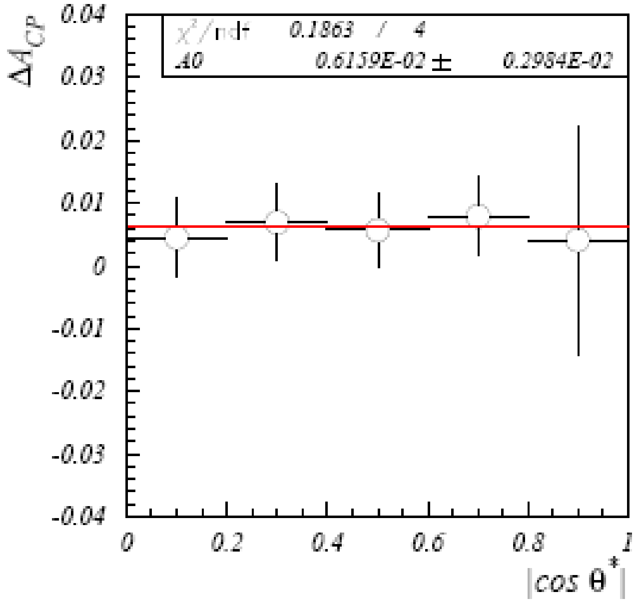


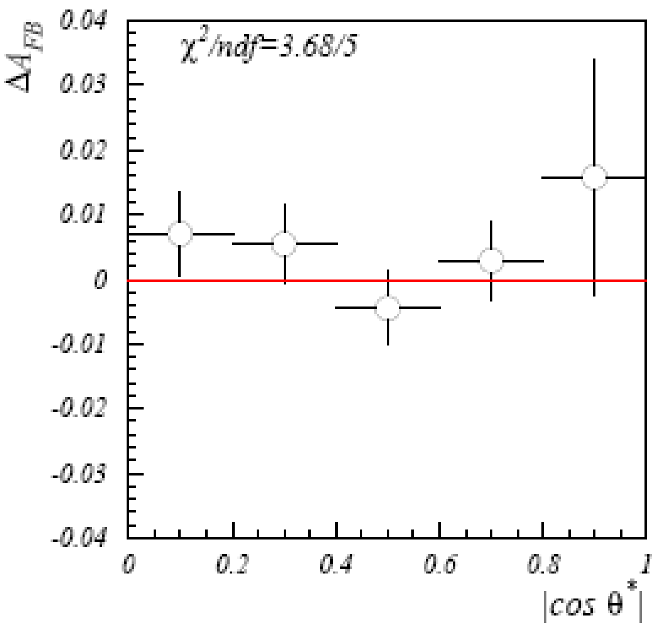
Preliminary result with 850 fb^{-1}

- $A_\varepsilon^{K^+K^-} = (+0.067 \pm 0.015)\%$ for D^+, $(-0.053 \pm 0.014)\%$ for D_s^+
- $\Delta A_\varepsilon^{K^+K^-} = (+0.120 \pm 0.028)\%$

  $\to$ Non-neglgible and dominant systematics

•Measured ΔA_{CP} and ΔA_{FB} in $\cos\theta_D^{CMS}$ bins





Preliminary result with 850 fb^{-1}

- $\Delta A_{CP} = (+0.62 \pm 0.30 \pm 0.15)\%$
- χ^2/dof w.r.t. $\Delta A_{FB} = 0$ is 3.68/5

→ No significant difference in production asymmetry of D^+ and D_s^+

Summary

- A wide program of CPV searches in charm decays from Belle are shown
- So far no evidence for CPV at sensitivities $\geq 0.2\%$ depending on decay mode
- Report the most sensitive measurements to date
- First A_{CP} measurements in $D^0 \to K_S^0\eta$ and $D^0 \to K_S^0\eta'$

Summary-cont.

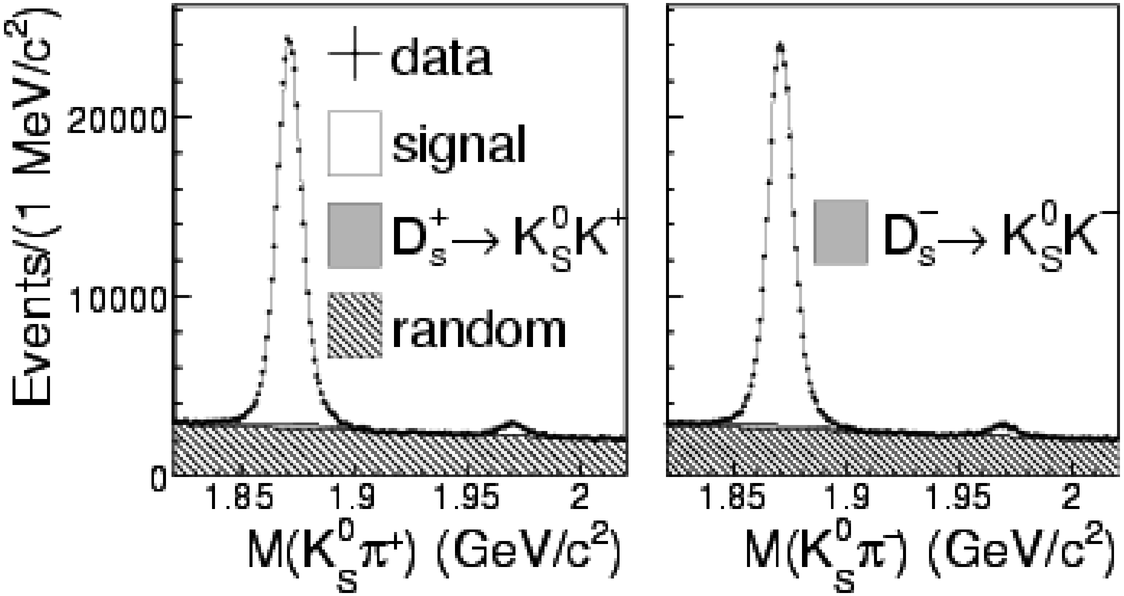
PRL 104,181602 (2010)

Decay Mode	A_{CP} (%) (Belle)	A_{CP} (%)(other)	A_{CP} (%) (SM from K_S^0)
$D^+ \to K_S^0 \pi^+$	$-0.71 \pm 0.19 \pm 0.20$	$-1.3 \pm 0.7 \pm 0.3$	-0.332
$D^+ \to K_S^0 K^+$	$-0.16 \pm 0.58 \pm 0.25$	$-0.2 \pm 1.5 \pm 0.9$	-0.332
$D_s^+ \to K_S^0 \pi^+$	$+5.45 \pm 2.50 \pm 0.33$	$+16.3 \pm 7.3 \pm 0.3$	$+0.332$
$D_s^+ \to K_S^0 K^+$	$+0.12 \pm 0.36 \pm 0.22$	$+4.7 \pm 1.8 \pm 0.9$	-0.332
$D^0 \to K_S^0 \pi^0$	$-0.28 \pm 0.19 \pm 0.10$	$+0.1 \pm 1.3$	-0.332
$D^0 \to K_S^0 \eta$	$+0.54 \pm 0.51 \pm 0.13$	N.A.	-0.332
$D^0 \to K_S^0 \eta'$	$+0.90 \pm 0.67 \pm 0.15$	N.A.	-0.332

- $A_{CP}^{D^+ \to \phi\pi^+} - A_{CP}^{D_s^+ \to \phi\pi^+} = (+0.62 \pm 0.30 \pm 0.15)\%$ {PDG: $A_{CP}^{D^+ \to \phi\pi^+} = (-0.1 \pm 1.5)\%$}

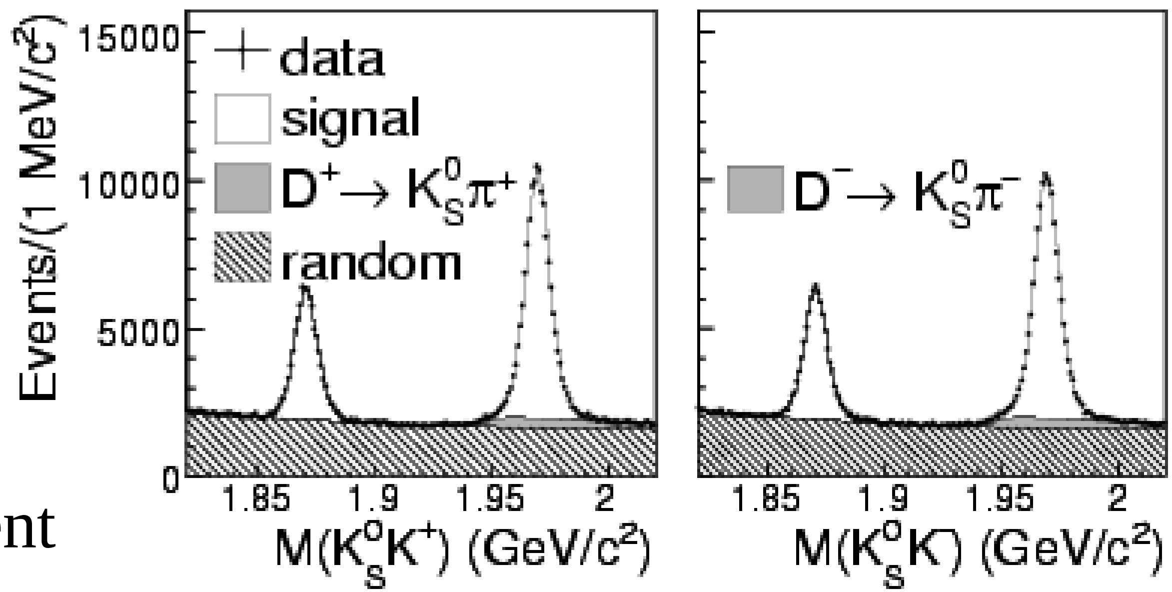
Preliminary results

Backup

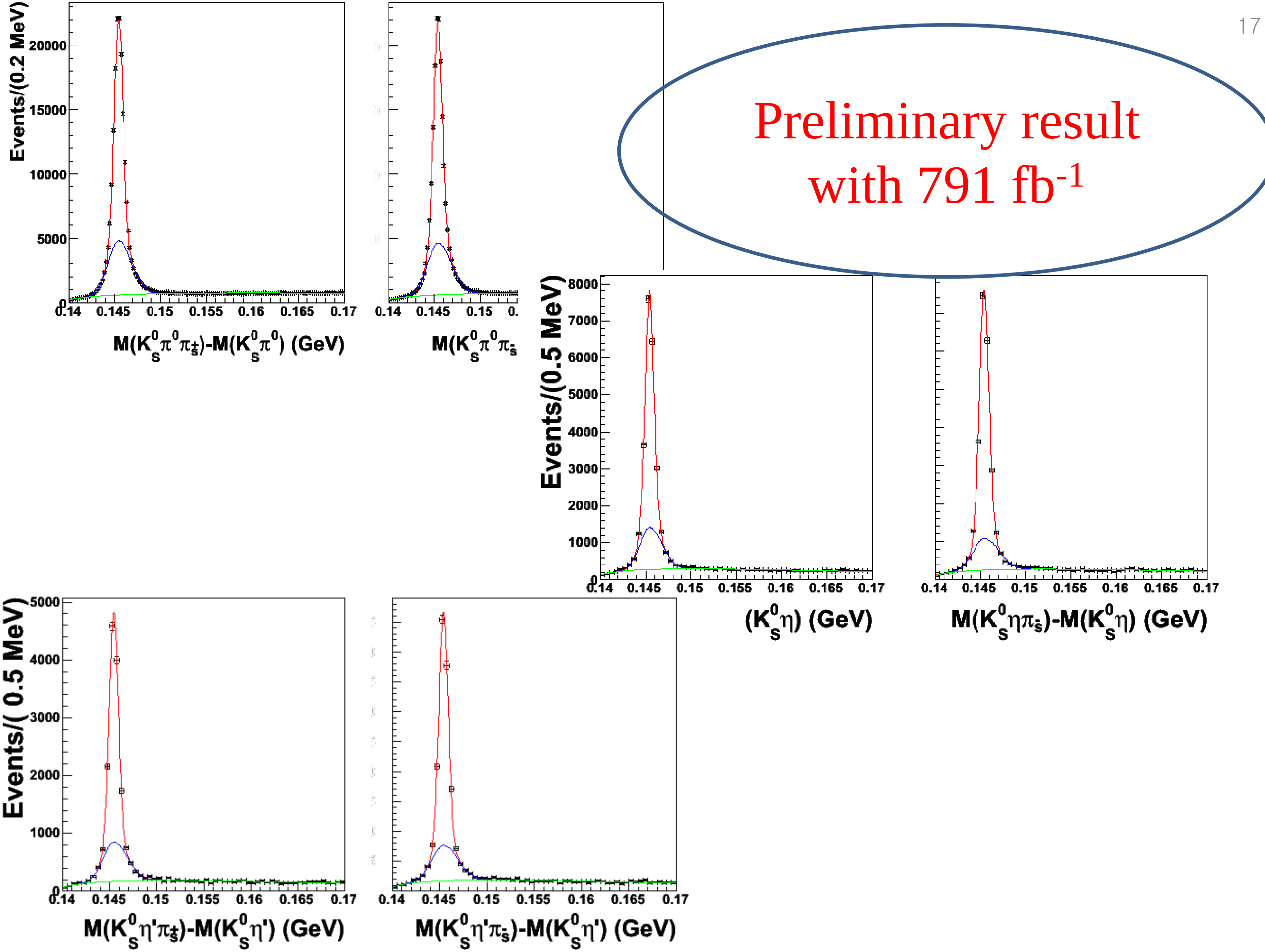


PRL 104, 181602 (2010) with 673 fb^{-1}

- $A_{CP}^{D_s^+ \to K_S^0 \pi^+} =$ $(+5.45 \pm 2.50 \pm 0.33)\%$:Corrections are done with an inclusive correction obtained from $A_{CP}^{D^+ \to K_S^0 \pi^+}$ measurement $(A_{rec}^{D^+ \to K_S^0 \pi^+} - A_{CP}^{D^+ \to K_S^0 \pi^+})$

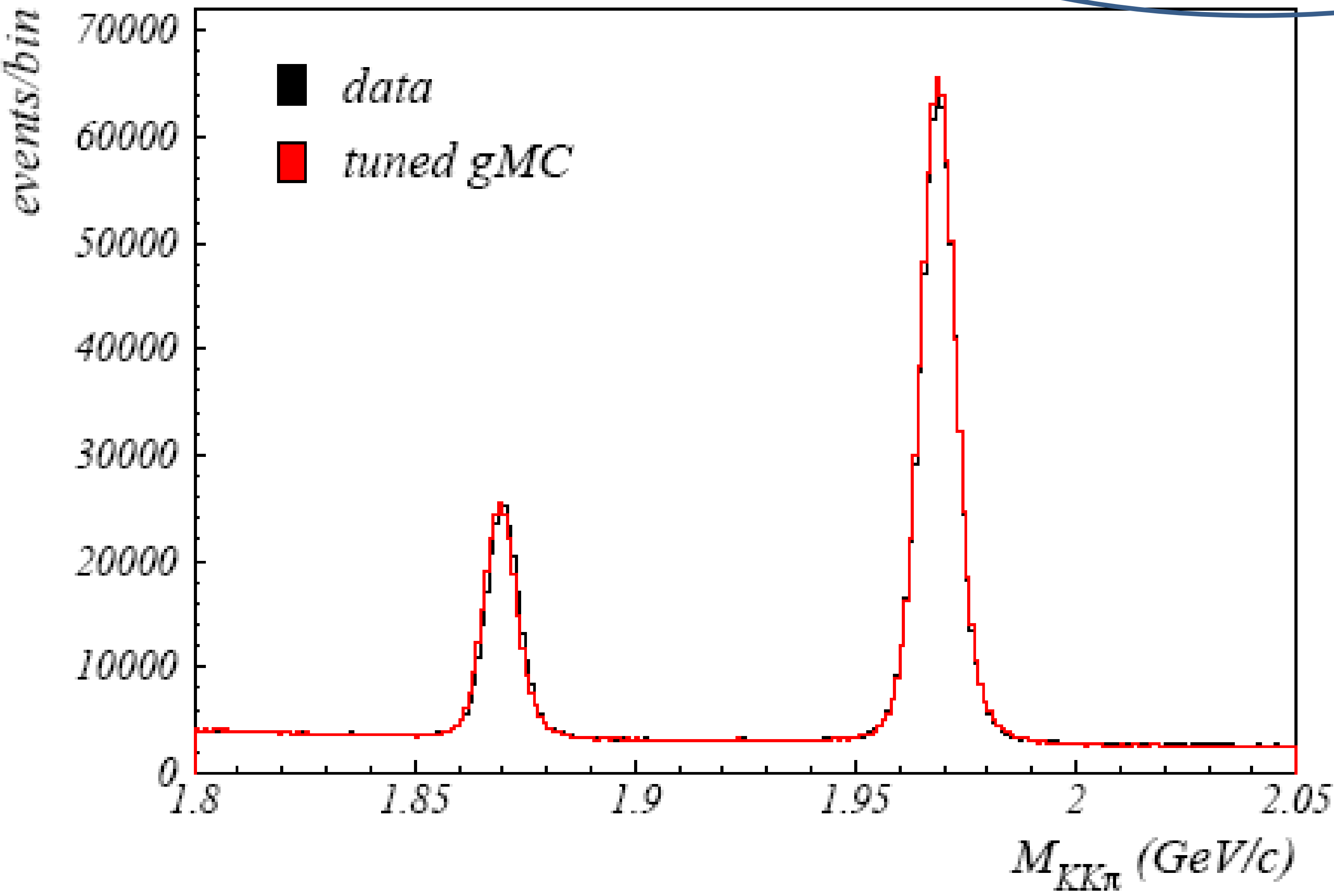


Preliminary result with 791 fb^{-1}



Preliminary result with 850 fb^{-1}

$M_{KK\pi}$ distribution



Signal yields (850 fb^{-1})

D^+ 210k

D_s^+ 640k

$$A_{\varepsilon}^{K^+K^-} = \int (P_1(x) - P_2(x)) A_{\varepsilon}^{K}(x) dx$$

$P_1(x)\ (P_2(x))$: detected same (opposite) sign

single kaon phase space distribution

$$P_1(x_1) = \frac{\varepsilon(x_1)\int dx_2 P(x_1, x_2)\varepsilon(x_2)}{\iint dx_1 dx_2 P(x_1, x_2)\varepsilon(x_1)\varepsilon(x_2)}$$

$$P_2(x_2) = \frac{\varepsilon(x_2)\int dx_1 P(x_1, x_2)\varepsilon(x_1)}{\iint dx_1 dx_2 P(x_1, x_2)\varepsilon(x_1)\varepsilon(x_2)}$$

$P(x_1, x_2)$: Normalized phase space distribution of K^+K^-

$x_1 \equiv (p_1, \cos\theta_1)$: phase space of the same-sign kaon

$x_2 \equiv (p_2, \cos\theta_2)$: phase space of the opposite-sign kaon