



# $D^0$-$\bar{D}^0$ Mixing and other Charm Decays at Belle

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On behalf of the Belle Collaboration

**International Workshop on e+e- collisions from Phi to Psi**

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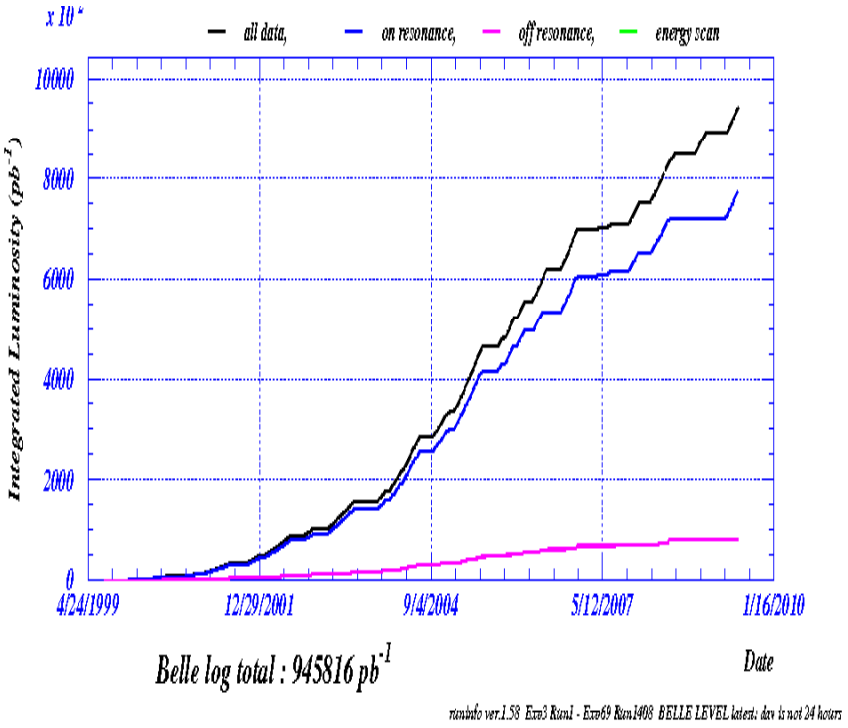
# Outline

- D0 mixing and CPV
  - ✓ Introduction
  - ✓ D0->K+PI-
  - ✓ D0->K+K-/PI+PI-
  - ✓ D0->Phi(1020)Ks ( in D0->KsK+K-)
  - ✓ D0->Ks pi+pi-
- Other charm decays
  - ✓ D0->l+l-
  - ✓ D(s)->Ksh+
  - ✓ Ds->K+K+PI-
- Conclusions

# KEKB and Belle

**the largest integrated luminosity in the world**



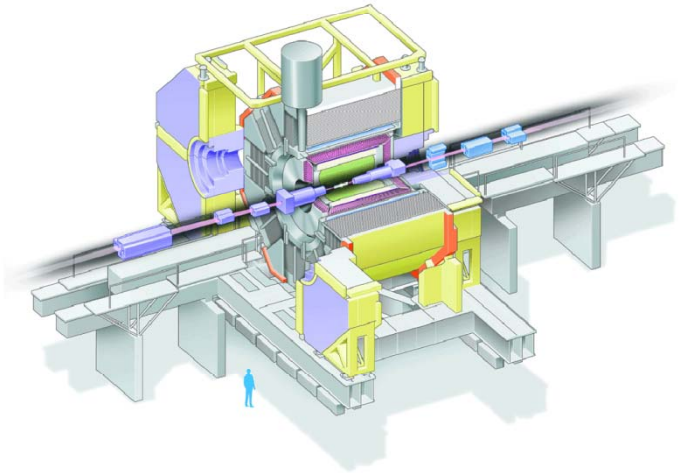

*Physics:* $e^+e^- \rightarrow \Upsilon(4S) \rightarrow b\bar{b}$

*Reaction cross section:*

$\sigma(b\bar{b})$ = 1.1 nb,

$\sigma(c\bar{c})$ = 1.3 nb

**Beside B mesons also largest sample of charm hadrons**



# D0 mixing-Introduction

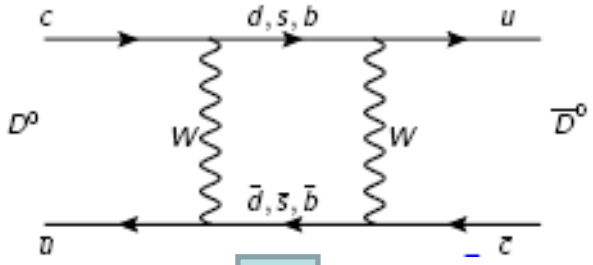
**Standard Model predictions for x and y**

Long distance


$x,\ y \sim \sin^2\theta_C \times [SU(3)\ \text{breaking}]^2 \sim 1\%$

PRD 65, 054034(2002) (Falk, Grossman, Ligeti &Petrov)
PRD 69, 114021(2004) (Falk, Grossman, Ligeti &Petrov)

Short distance



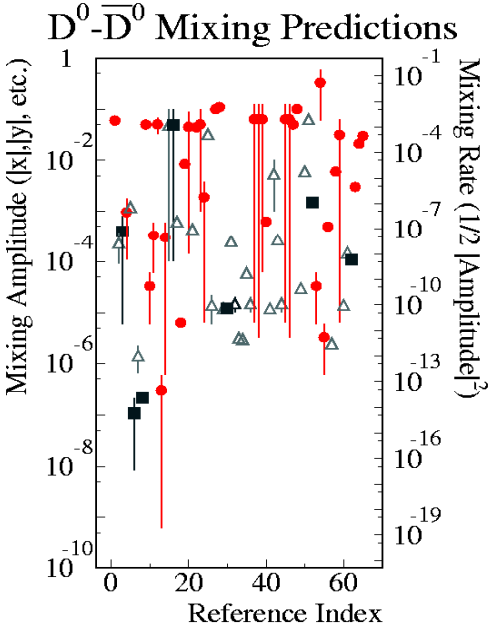

**GIM &CKM suppression**

$x \sim 10^{-5},\ y \sim 10^{-7}$

Burdman, Shipsey, Ann.Rev.Nucl.Part.Sci.53,431

**SU(3) flavor-symmetry breaking and long distance effects may raise both parameters x and y, Difficult to calculate it.**

**New physics can enhance D0 mixing x and y.**



# CPV of charm decays

**CPV of charm decays in the SM is strongly suppressed by CKM, negligible.**

SM predictions for direct *CPV* in *SCS* decays are at most of the order of $10^{-3}$

**Observation of large O(1%) CPV in charm-decays would be a sign of new physics, similar as other FCNC(Flavor Changing Neutral Current) processes.**

**Classification of CP-violating effects:**

$$A_{CP} = \frac{\Gamma(D\to f)-\Gamma(\bar{D}\to\bar{f})}{\Gamma(D\to f)+\Gamma(\bar{D}\to\bar{f})} = a_f^d + a_f^m + a_f^i$$

$a_f^d$: *CP* violation in decay

$\hookrightarrow \left|\frac{A_f}{\bar{A}_{\bar{f}}}\right| \equiv 1 + \frac{A_D}{2}\ (A_D \neq 0)$

$a_f^m$: *CP* violation in mixing

$\hookrightarrow \left|\frac{q}{p}\right| \equiv 1 + \frac{A_M}{2} \quad (A_M \neq 0)$

$a_f^i$: *CP* violation in interference $(f = \bar{f}) \rightarrow \phi = arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right)\ (\phi \neq 0)$

# D0 mixing Formulae

The time evolution of the System is described: $D^0 - \overline{D^0}$

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

as ***mass eigenstates*** $D_1$, $D_2$

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned}$$

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

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

***Eigenstates*** $D_1$, $D_2$ **have masses** $M_1$, $M_2$ **and widths** $\Gamma_1, \Gamma_2$.

**Mixing occurs when there is a**

***non-zero* mass difference**

$$\Delta M = M_1 - M_2$$

**or lifetime difference**

$$\Delta\Gamma = \Gamma_1 - \Gamma_2$$

**For convenience define quantities**

***x* and *y*:** $x = \frac{\Delta M}{\Gamma}$, $y = \frac{\Delta\Gamma}{2\Gamma}$

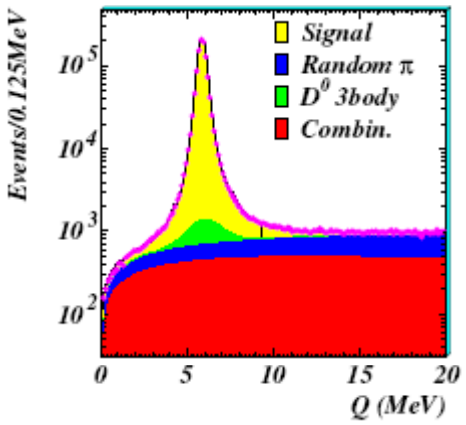
**where** $\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$

time evolution of flavor eigenstate

$$|D^0(t)\rangle = \left[|D^0\rangle \cosh\left(\frac{ix+y}{2}t\right) + \frac{q}{p}|\bar{D}^0\rangle \sinh\left(\frac{ix+y}{2}t\right)\right] \times e^{-\frac{1}{2}(1+\frac{im}{\Gamma})t}$$

# D0 mixing in D0 WS hadronic decays: D0->K+PI-

**RS events**

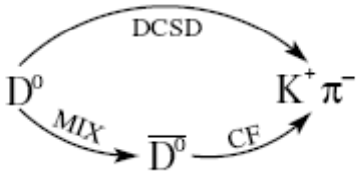



$$D^{*+} \to D^0(K^-\pi^+)\pi^+$$

$$\Gamma_{RS} \propto e^{-t/\tau_{D^0}}$$

$$D^{*+} \to D^0(K^+\pi^-)\pi^+$$

↪ DCS or mixing




**Flavor tagging**

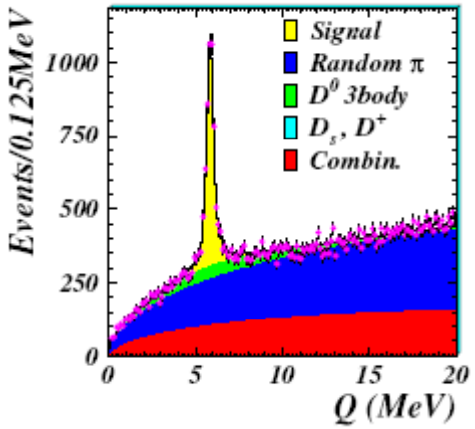
require $D^{*+} \to D^0\pi^+$

↪ flavor tagging with $\pi$'s charge

↪ background suppression with

$Q = M_{D^*} - M_{D^0} - M_{\pi^+}$

**WS events**




$$\Gamma_{WS} \propto [R_D + y'\sqrt{R_D}(\Gamma t) + \tfrac{x'^2+y'^2}{4}(\Gamma t)^2]e^{-\Gamma t}$$

● DCS ● interference ● mixing

↪ $R_D$: DCS/CF rate

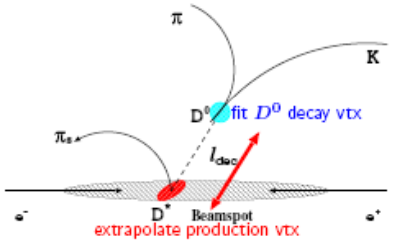
↪ $x' = x\cos\delta + y\sin\delta$

↪ $y' = y\cos\delta - x\sin\delta$

↪ $\delta$ strong phase between DCS and CF

**Proper decay time**

Vertexing with beam point constraint



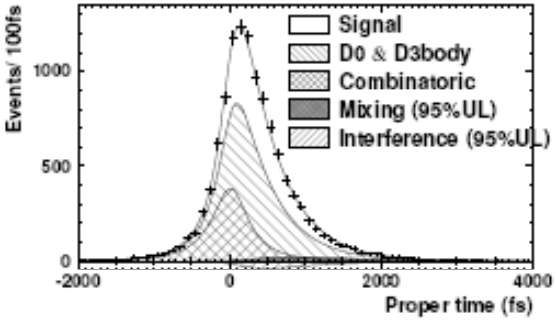

$$t = \frac{l_{dec}}{c\beta\gamma}, \quad \beta\gamma = \frac{p_{D^0}}{M_{D^0}}$$

$\sigma_t$ uncertainty of the measurement

# D0 mixing in D0 WS hadronic decays: D0->K+PI-

Belle [400 fb$^{-1}$]

PRL96, 151801 (2006).




**CPV is not observed**

$D^0$ **Fit separately** $\overline{D}^0$

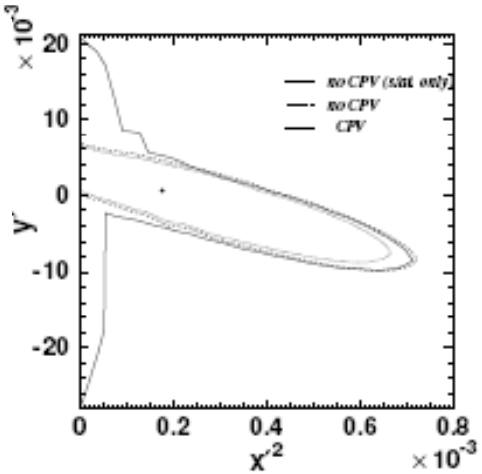
| Fit case | Parameter | Fit result | 95% C.L. interval |
|---|---|---|---|
| No $CPV$ | $R_D(\times 10^{-3})$ | $3.64 \pm 0.17$ | (3.3,4.0) |
| | $x'^2(\times 10^{-3})$ | $0.18^{+0.21}_{-0.23}$ | $< 0.72$ |
| | $y'(\times 10^{-2})$ | $0.06^{+0.40}_{-0.39}$ | $(-0.99,0.68)$ |
| | $R_M(\times 10^{-3})$ | - | $(0.63 \times 10^{-5},0.40)$ |
| $CPV$ | $x'^2(\times 10^{-3})$ | - | $< 0.72$ |
| | $y'(\times 10^{-2})$ | - | $(-2.8,2.1)$ |
| | $R_M(\times 10^{-3})$ | - | $< 0.40$ |
| | $A_D$ | $0.023 \pm 0.047$ | $(-0.076,0.107)$ |
| | $A_M$ | $0.67 \pm 1.20$ | $(-0.995,1.0)$ |
| | $\lvert\phi\rvert(^\circ)$ | $9.4(84.5) \pm 25.3$ | No limits |
| No mixing | $R_D$ | $3.77 \pm 0.08(\text{stat.}) \pm 0.05(\text{syst.})$ | |

Belle [400 fb$^{-1}$]

PRL96, 151801 (2006).

$A_D = (23 \pm 47) \times 10^{-3}$

$A_M = 0.67 \pm 1.2$




$(R_D^+,\ x'^{+2},\ y'^{+})_{D^0} \iff (R_D^-,\ x'^{-2},\ y'^{-})_{\overline{D}^0}$

$CPV$ in decay $\Rightarrow$ $A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$; $R_D$ (DCS/CF rate)

$CPV$ in mixing $\Rightarrow$ $A_M = \frac{R_M^+ - R_M^-}{R_M^+ + R_M^-}$; $R_M = \frac{x^2+y^2}{2}$ (mixing rate)

**No-mixing point (0,0) is 3.9%, significance: 2**

# D0 mixing in D0->K+K-, PI+PI- Decays

Measurement of lifetime difference between $D^0 \to K^-\pi^+$ (*CP*-mixed) and $D^0 \to K^+K^-,\ \pi^+\pi^-$ (*CP*-even) decays

$\hookrightarrow \Gamma(D^0, \overline{D}^0 \to K^{-,+}\pi^{+,-}) \propto e^{-t/\tau_{D^0}}$

$\hookrightarrow \Gamma(D^0, \overline{D}^0 \to K^+K^-,\ \pi^+\pi^-) \propto e^{-(1+y_{CP})t/\tau_{D^0}}$

$$y_{CP} \equiv \frac{\tau_{K\mp,\pi\pm}}{\tau_{K^+K^-,\pi^+\pi^-}} - 1 = \frac{1}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) y \cos\phi - \frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) x \sin\phi$$

In limit of no *CPV* $y_{CP} = y$

**They all have the high signal purity (>90%)**

*CP* Violation

$$A_\Gamma = \frac{\tau(\overline{D}^0 \to f_{CP}) - \tau(D^0 \to f_{CP})}{\tau(\overline{D}^0 \to f_{CP}) + \tau(D^0 \to f_{CP})} = \frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y \cos\phi - \frac{1}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x \sin\phi$$

# D0 mixing in D0->K+K-, PI+PI- Decays

Fit to the proper decay time distribution

$$\frac{dN}{dt} \propto \int e^{-t'/\tau} \cdot R(t-t')dt' + B(t)$$

$$\Downarrow$$

$$R(t-t') = \sum_i^N f_i \sum_{k=1}^3 w_k G(t-t', \sigma_{ik}, t_0)$$

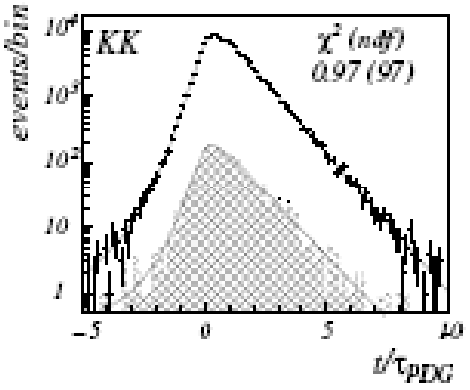
**significance: $3.2\sigma$, *the first evidence***

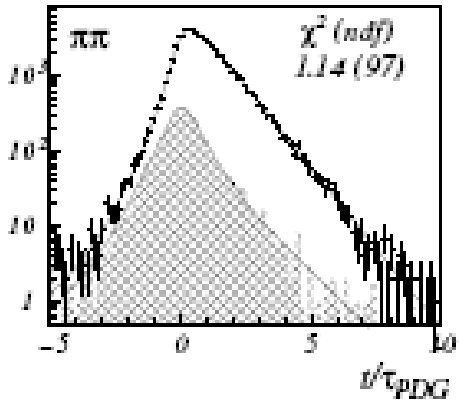
$$y_{CP} = (1.31 \pm 0.32 \pm 0.25)\%$$

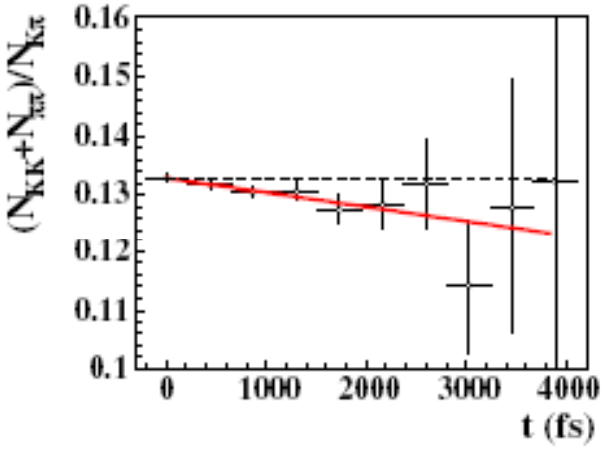
PRL98, 211803 (2007)

**CPV is not observed**

$$A_\Gamma = (0.01 \pm 0.30 \pm 0.15)\%$$



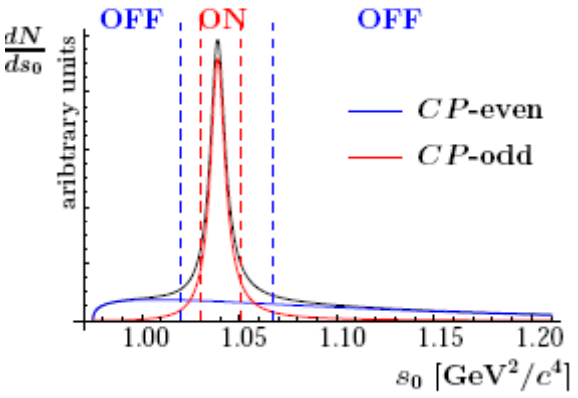



# D0 mixing in D0->KsPhi decays

arXiv:0905.4185 (PRD accepted) [673 fb$^{-1}$]

Measurement of lifetime difference between *CP*-even and *CP*-odd eigenstates




$\sqrt{s_0} = m_{K^+K^-}$ dependent CP mixture

$\hookrightarrow$ ON region: mainly *CP*-odd ($\phi(1020)$)

$\hookrightarrow$ OFF region: mainly *CP*-even ($a_0(980)^0$)

$$\frac{d^2N(s_0,t)}{ds_0 dt} \propto a_1(s_0)e^{-(1+y_{CP})t/\tau_{D^0}} + a_2(s_0)e^{-(1-y_{CP})t/\tau_{D^0}}$$

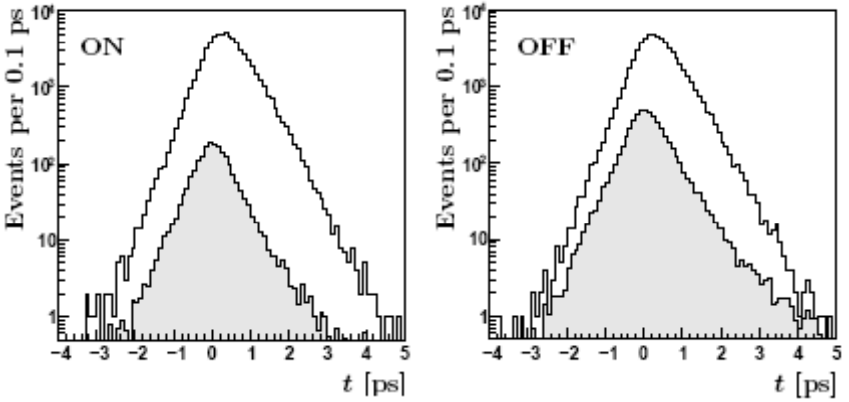
Effective lifetimes in ON and OFF regions

$$\tau_{\mathrm{ON,OFF}} = [1 + (1 - 2f_{\mathrm{ON,OFF}})y_{CP}]\tau_{D^0} \Rightarrow y_{CP} = \frac{1}{f_{\mathrm{ON}} - f_{\mathrm{OFF}}}\left(\frac{\tau_{\mathrm{OFF}} - \tau_{\mathrm{ON}}}{\tau_{\mathrm{OFF}} + \tau_{\mathrm{ON}}}\right)$$

$f_{\mathrm{ON}}, f_{\mathrm{OFF}}$ are *CP*-even fractions in ON and OFF regions

Topologically equal events in ON and OFF regions $\rightarrow$ reduced effects of resolution function.

# D0 mixing in D0->KsPhi decays




Untagged sample used to increase the statistics

| Region | ON | OFF |
|---|---|---|
| Signal [$\times 10^3$] | 72 | 62 |
| Purit | 97% | 91% |

Background estimated from sidebands in $(m_{K^0_S K^+ K^-}, m_{K^0_S})$ plane

$f_{\rm ON}$, $f_{\rm OFF}$ from fit to $m_{K^+K^-}$ using 8-resonance Dalitz model

$\tau_{\rm ON}$, $\tau_{\rm OFF}$ determined from mean proper decay times of all events and background events

$$\hookrightarrow \tau_{\rm ON,OFF} + t_0 = \frac{\langle t\rangle_{\rm ON,OFF} - (1-p_{\rm ON,OFF})\langle t\rangle_b^{\rm ON,OFF}}{p_{\rm ON,OFF}}$$

$$y_{CP} = +(0.11 \pm 0.61(\text{stat.}) \pm 0.52(\text{syst.}))\%$$

**it is consistent with above results($y_{CP}$)**

# D0 mixing in D0->KsPI+PI- decays

**BY measuring the time evolution of Dalitz plot , x, y can be determined separately,**
**D0 decays to final states:**

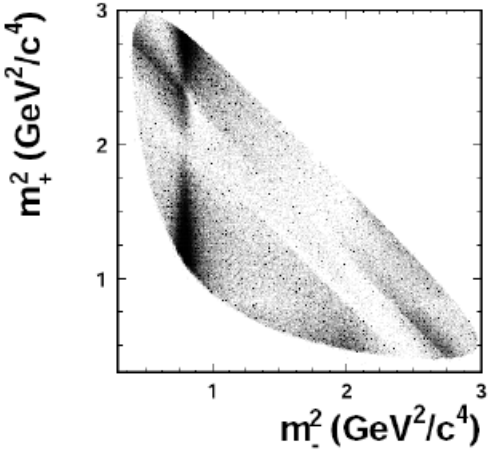
$$\langle s|H|D^0(t)\rangle = e_1(t)A_1 + e_2(t)A_2 = M$$

$$\langle \bar{s}|H|\overline{D^0(t)}\rangle = e_1(t)\overline{A_1} + e_2(t)\overline{A_2} = \overline{M}$$

$$D^0: \ \mathcal{A}(m_-^2, m_+^2) = \sum_r a_r e^{i\phi_r}\mathcal{A}_r(m_-^2, m_+^2) + a_{nr}e^{\phi_{nr}}$$

$$\overline{D^0}: \ \bar{\mathcal{A}}(m_-^2, m_+^2) = \sum_r \bar{a}_r e^{i\bar{\phi}_r}\bar{\mathcal{A}}_r(m_-^2, m_+^2) + a_{nr}e^{\phi_{nr}}$$

$D^0 \to K_s{}^0\pi^+\pi^-$



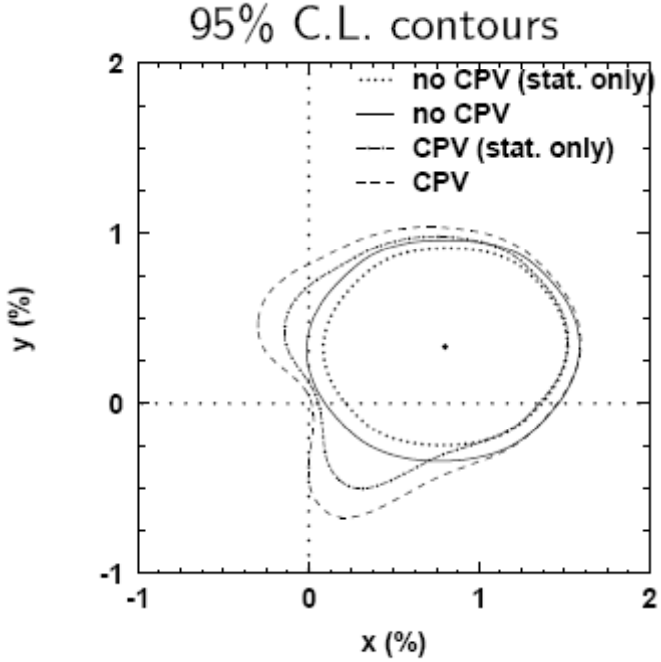

PRL99, 131803 (2007). [540 fb$^{-1}$]

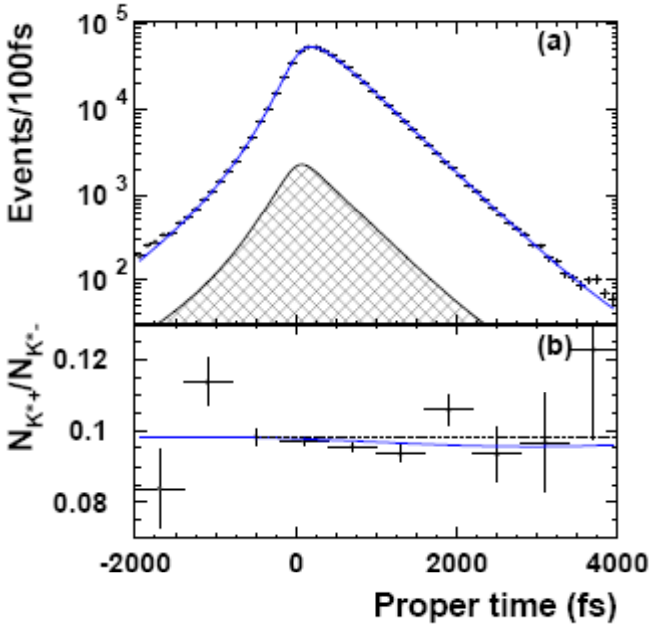
**Therefore, the decay rate of D0 is a function of time, it includes x and y, where t is in unit of D0 lifetime.**

$$|M|^2 = \left\{|A_1|^2 e^{-yt} + |A_2|^2 e^{yt} + 2R\left[A_1A_2^*\right]\cos(xt) + 2I\left[A_1A_2^*\right]\sin(xt)\right\}e^{-t},$$

$$|\overline{M}|^2 = \left\{|\overline{A_1}|^2 e^{-yt} + |\overline{A_2}|^2 e^{yt} + 2R\left[\overline{A_1}\,\overline{A_2^*}\right]\cos(xt) + 2I\left[\overline{A_1}\,\overline{A_2^*}\right]\sin(xt)\right\}e^{-t}$$

# D0 mixing in D0->KsPI+PI- decays




**Significance: 2.2$\sigma$ for x, current best x value**

**CPV is not observed**

Conserved *CP* symmetry ($|q/p| = 1$ & $\phi = 0$)

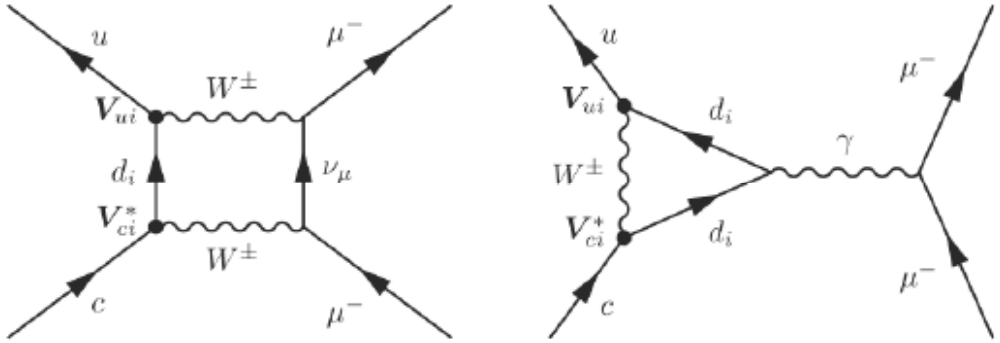
$$x = (0.80 \pm 0.29^{+0.13}_{-0.16})\%$$
$$y = (0.33 \pm 0.24^{+0.10}_{-0.14})\%$$

CPV allowed ($|q/p|$ & $\phi$ free parameters of the fit)

$$|q/p| = 0.86 \pm 0.30 \pm 0.09$$
$$\phi = -0.24 \pm 0.30 \pm 0.09$$

# Search for D0->L+L-

**Motivation:** FCNC does not appear in SM on tree level (higher order below allowed)




PRD79 114030 (2009)

**Certain new physics scenarios allows this process: new particle replacing W boson**

| Model | $\mathcal{B}_{D^0\to\mu^+\mu^-}$ |
|---|---|
| Experiment | $\leq 4.3 \times 10^{-7}$ (CDF preliminary) |
| Standard Model (SD) | $\sim 10^{-18}$ |
| Standard Model (LD) | $\sim$ several $\times 10^{-13}$ |
| $Q = +2/3$ Vector-like Singlet | $4.3 \times 10^{-11}$ |
| $Q = -1/3$ Vector-like Singlet | $1 \times 10^{-11}\ (m_S/500\ \text{GeV})^2$ |
| $Q = -1/3$ Fourth Family | $1 \times 10^{-11}\ (m_S/500\ \text{GeV})^2$ |
| $Z'$ Standard Model (LD) | $2.4 \times 10^{-12}/(M_{Z'}(\text{TeV}))^2$ |
| Family Symmetry | $0.7 \times 10^{-18}$ |
| RPV-SUSY | $4.8 \times 10^{-9}\ (300\ \text{GeV}/m_{\tilde{d}_i})^2$ |

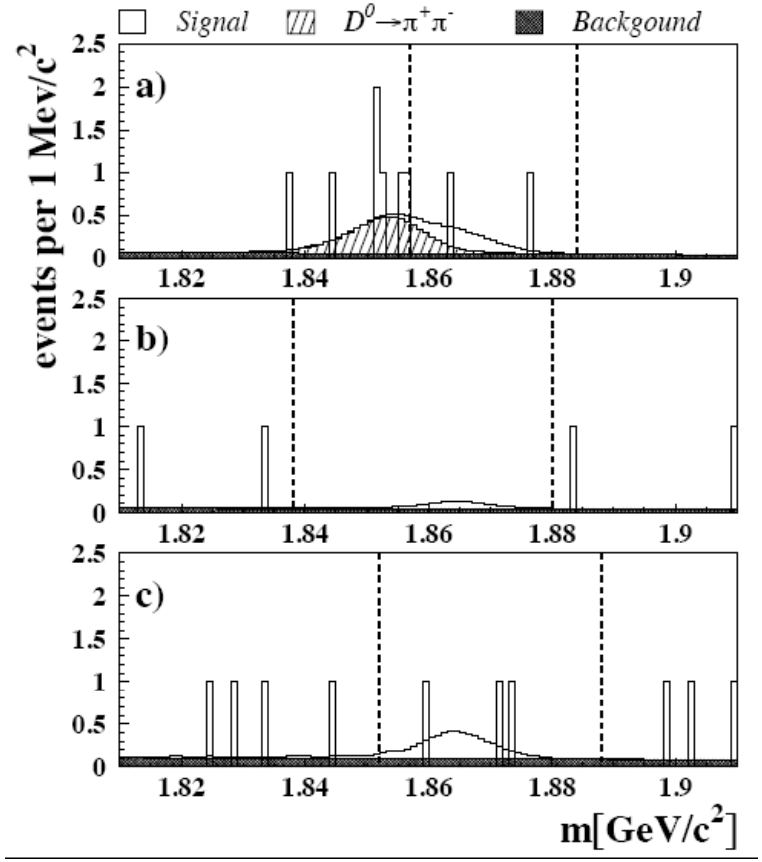
**Except Family Symmetry All NP exceed the SM prediction**

**Largest data:** 659 fb-1

**Belle is most sensitive to RPV-SUSY scenario**

# Search for D0->L+L-

## Estimation of background




## Combinatorial background

2 D estimation with $a(1-bm)/\sqrt{q}$

The ratio of combinatorial background in the signal to the number in the side band

| channel | p[%] |
|---|---|
| $\mu^+\mu^-$ | 1.08 |
| $e^+e^-$ | 1.49 |
| $e^\pm\mu^\mp$ | 1.43 |

## Reflection background from

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

peak shifted in $m$ but on peak in $q$

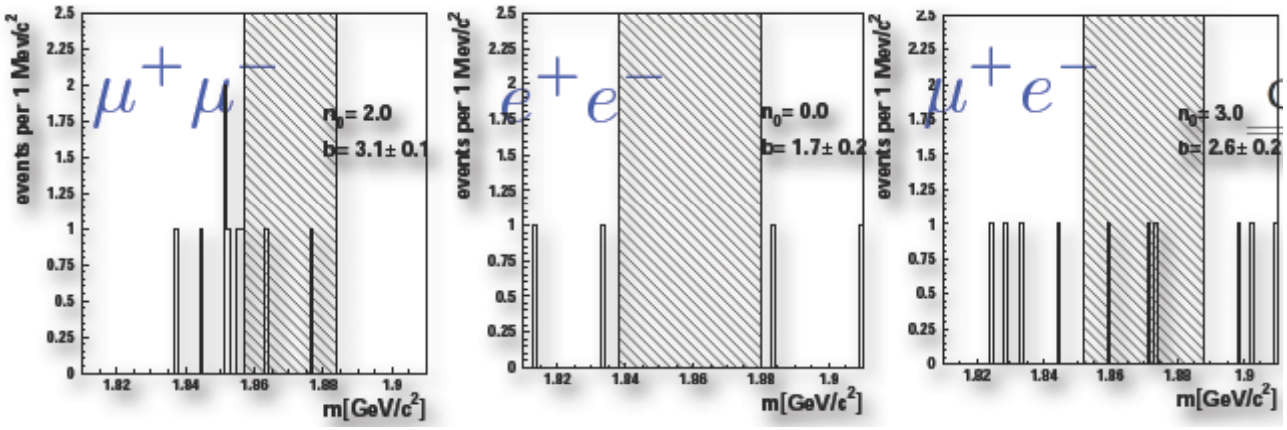
$\pi^+ \to \ell^+$ mis-id measured with $D^0 \to K^-\pi^+$

(Number of reflection in the signal window)

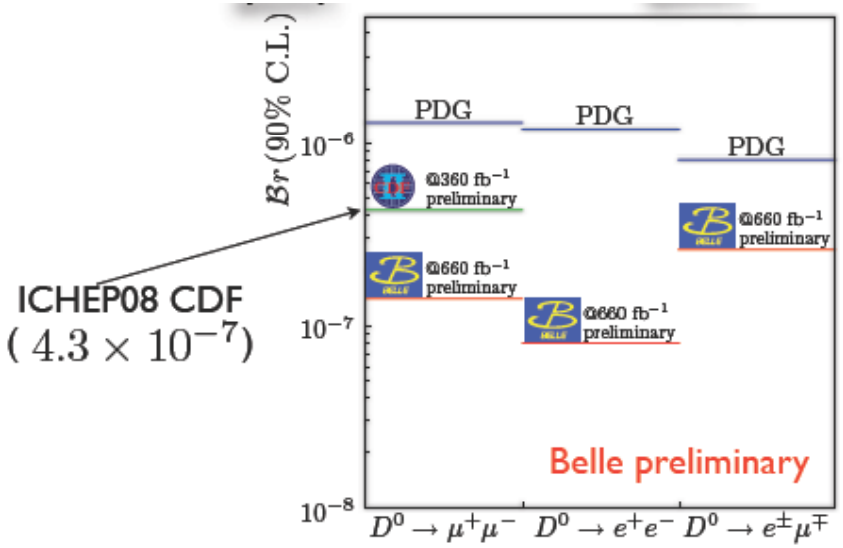
| channel | $N_{refl}^{DATA}$ |
|---|---|
| $\mu^+\mu^-$ | $1.81 \pm 0.002$ |
| $e^+e^-$ | $0.0372 \pm 0.0002$ |
| $e^\pm\mu^\mp$ | $0.1935 \pm 0.0006$ |

# Search for D0->L+L-

Event counting at the signal window




| channel | events | bg |
|---|---|---|
| $\mu^+\mu^-$ | 2 | 3.1±0.1 |
| $e^+e^-$ | 0 | 1.7±0.2 |
| $e^\pm\mu^\mp$ | 3 | 2.6±0.2 |

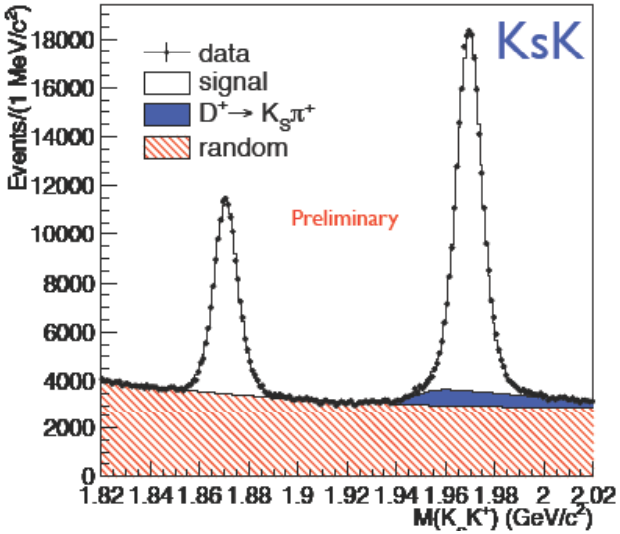


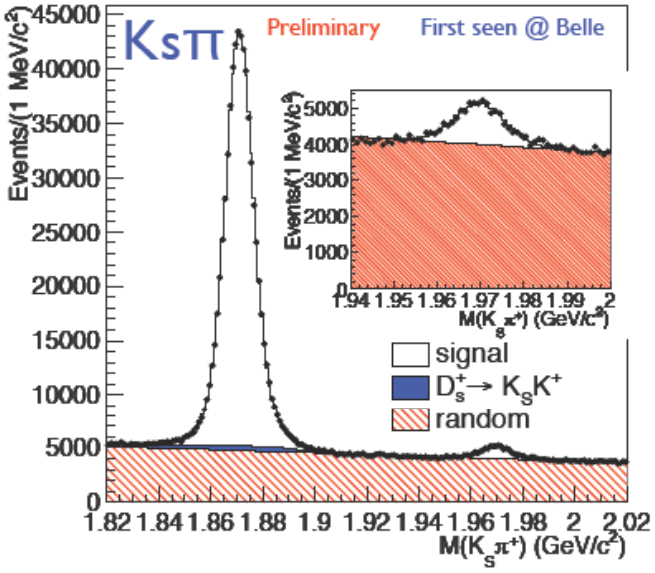

**New, best upper limits for leptonic decays of D0**

90% CL upper limit Belle preliminary

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.4 \times 10^{-7}$$
$$\mathcal{B}(D^0 \to e^+e^-) < 7.9 \times 10^{-8}$$
$$\mathcal{B}(D^0 \to \mu^\pm e^\mp) < 2.6 \times 10^{-7}$$

# Study of $D_{(s)}^{+}$->Ksh+




look for ratios of CS to CF $D^{+}_{(s)}$ decays

Preliminary fit yields

| Decay modes | Yields |
|---|---|
| $D^+ \to K_S K^+$ | $100855 \pm 561$ |
| $D_s^+ \to K_S K^+$ | $204093 \pm 768$ |
| $D^+ \to K_S \pi^+$ | $566105 \pm 1159$ |
| $D_s^+ \to K_S \pi^+$ | $16817 \pm 448$ |

**new best measurements**

$\mathcal{B}(D^+ \to K_S K^+)/\mathcal{B}(D^+ \to K_S \pi^+)$ =0.190±0.001±0.002

$\mathcal{B}(D_s^+ \to K_S \pi^+)/\mathcal{B}(D_s^+ \to K_S K^+)$ =0.077±0.002±0.002

| Mode | PDG2008 | CLEO 2009 (*) |
|---|---|---|
| $\mathcal{B}(D^+ \to K_S K^+)/\mathcal{B}(D^+ \to K_S \pi^+)$ | 0.189±0.016±0.007 | 0.199±0.010 |
| $\mathcal{B}(D_s^+ \to K_S \pi^+)/\mathcal{B}(D_s^+ \to K_S K^+)$ | 0.082±0.009±0.002 | 0.085±0.009 |

# Observation of $Ds^+ -> K+K+PI-$

**Motivation:**

**1) not observed yet;**

**2) one can look at the double ratio to test SU(3) flavor symmetry;** Lipkin, NPB 115 117 (2003)

$$\frac{\mathcal{B}(D_s^+ \to K^+K^+\pi^-)}{\mathcal{B}(D_s^+ \to K^+K^-\pi^+)} \frac{\mathcal{B}(D^+ \to K^+\pi^+\pi^-)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)} = \tan^8\theta_C$$

Differences in the phase space cancel in the ratios

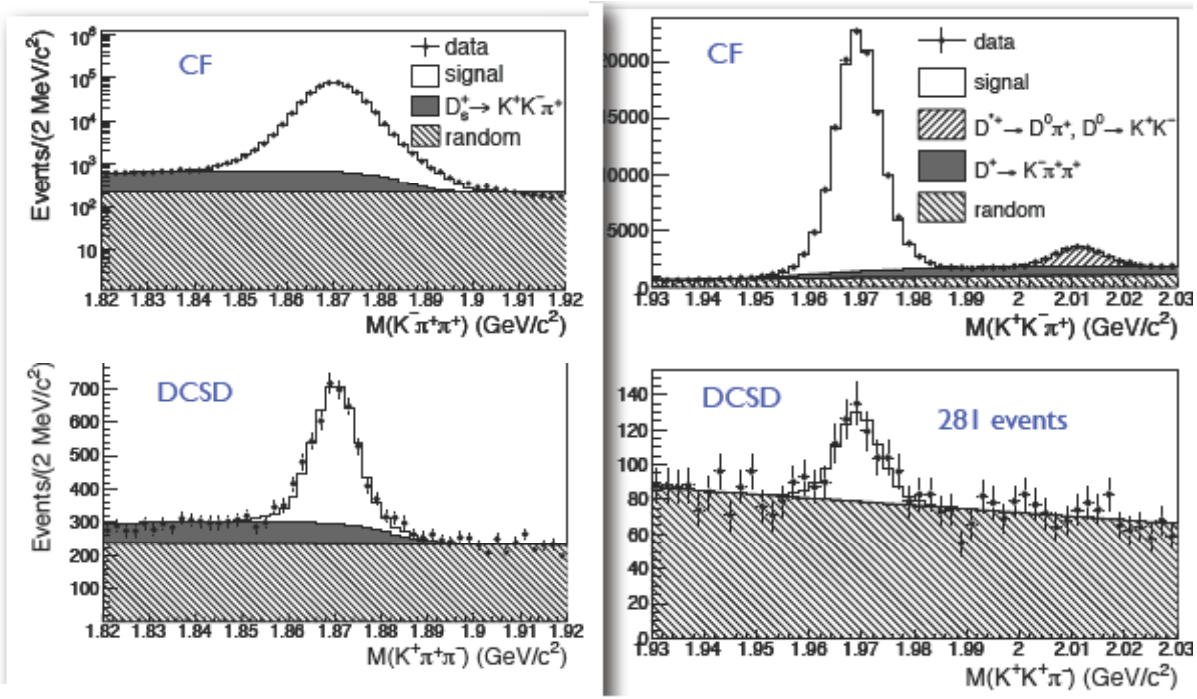
SU(3) breaking effects due to resonant intermediate states in the 3-body violates the equation above

# Observation of Ds+->K+K+PI-

PRL 102 221802 (2009)

$$\frac{\mathcal{B}(D_s^+ \to K^+K^+\pi^-)}{\mathcal{B}(D_s^+ \to K^+K^-\pi^+)} \frac{\mathcal{B}(D^+ \to K^+\pi^+\pi^-)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)} = (1.57 \pm 0.21) \cdot \tan^8 \theta_C$$

**double ratio is OK**




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

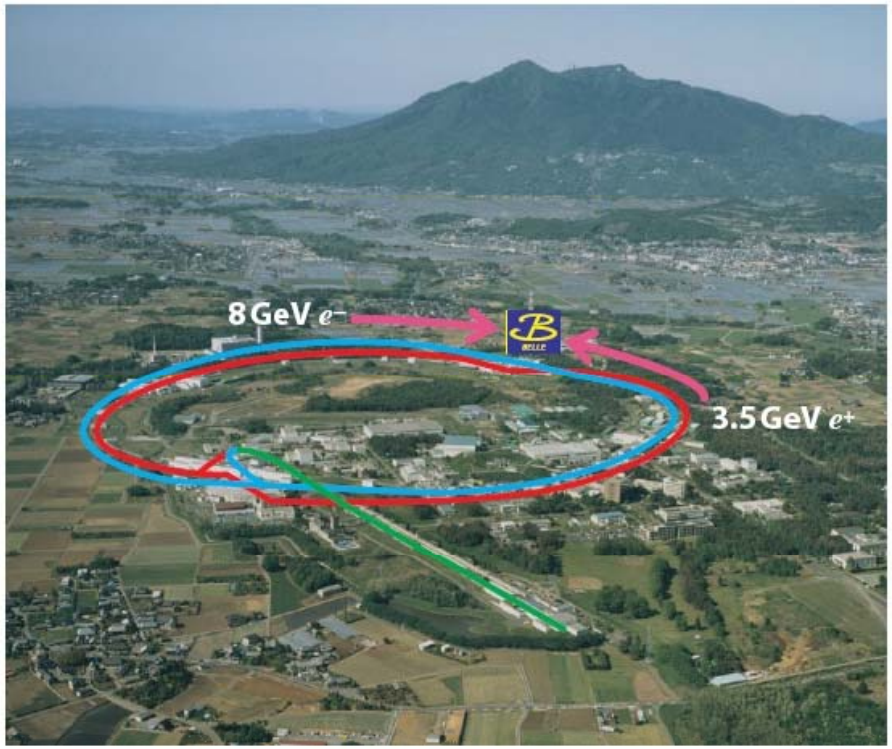
**First observation of this decay**
**9.1 standard deviation**

| Branching fraction | Belle | World average [3] |
|---|---|---|
| $\mathcal{B}(D^+ \to K^+\pi^+\pi^-)$ | $(5.2 \pm 0.2 \pm 0.1) \times 10^{-4}$ | $(6.2 \pm 0.7) \times 10^{-4}$ |
| $\mathcal{B}(D_s^+ \to K^+K^+\pi^-)$ | $(1.3 \pm 0.2 \pm 0.1) \times 10^{-4}$ | $(2.9 \pm 1.1) \times 10^{-4}$ |

# Conclusions

- ✓ It seems that there is a clear evidence for no-zero y (D0 mixing parameter)
- ✓ The measurement of x is still a challenge
- ✓ No evidence of CP violation is observed
- ✓ The best limits are achieved for leptonic decays of D0 (preliminary)
- ✓ The most precise branch ratios of $D_{(s)}^{+}$->Ksh+ are obtained (preliminary)
- ✓ The first Observation of DCSD in $Ds^{+}$->K+K+PI-.

# The end
# thanks a lot




KEKB consists of a linear injector and two 3km-circumference storage rings.

# Backup

# Search for D0->L+L-

**Selection**

Particle identification, soft pion tagging for D meson

vertex fit for D(*) meson, $q \equiv m_{D^{*+}} - m_{D^0} - m_{\pi_s} < 0.02\ \mathrm{GeV}/c^2$

D meson momentum cut: $p_{D^{*+}} > 2.5\ \mathrm{GeV}/c$

**Optimization**

maximizing $\epsilon_{\ell\ell}/N_{UL}$

$\epsilon_{\ell\ell}$ : efficiency $N_{UL}$ : Poisson average of FC 90% CL upper limit

lepton ID, $\Delta m, \Delta q, E_{\mathrm{miss}}, p^*_{D^{*+}}$ are used for the optimization