D^0 mixing and CP violation in D^0 decays from Belle

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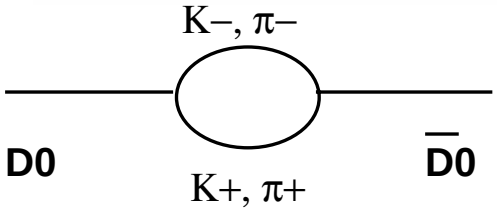
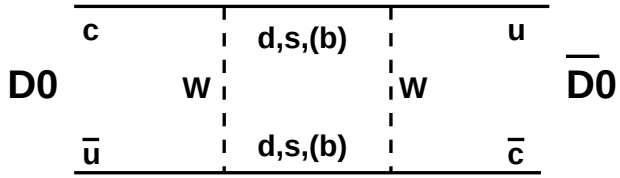
Topic

- $D^0(t) \to K^+\pi^-$, 400 fb^{-1}
- $D^0(t) \to K^{(*)+}e^-\nu$, 253 fb^{-1}
- $D^0 \to K^+(n\pi)^-$, 281 fb^{-1}

D^0-$\bar{D}^0$ mixing formalism:



- **Only mixing via light quark intermediate states**
- **doubly-Cabibbo-suppressed with respect to Γ_D**
- **long-distance contributions**



Flavor eigenstates are not mass eigenstates:

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle \qquad |D_{1,2}(t)\rangle = e^{-(\Gamma_{1,2}/2+im_{1,2})t}|D_{1,2}\rangle$$

$$\overline{m} \equiv \frac{1}{2}(m_1+m_2) \quad \overline{\Gamma} \equiv \frac{1}{2}(\Gamma_1+\Gamma_2) \quad \Delta m \equiv m_2 - m_1 \quad \Delta\gamma \equiv \Gamma_2 - \Gamma_1$$

$$\mathcal{A}_f \equiv \langle f|H|D^0\rangle \quad \bar{\mathcal{A}}_f \equiv \langle f|H|\overline{D}^0\rangle \quad \mathcal{A}_{\bar{f}} \equiv \langle \bar{f}|H|D^0\rangle \quad \bar{\mathcal{A}}_{\bar{f}} \equiv \langle \bar{f}|H|\overline{D}^0\rangle$$

For $\Delta mt \ll 1$ and $\Delta\gamma t \ll 1$:

$$R(D^0(t)\to \bar{f}) \approx |\bar{\mathcal{A}}_{\bar{f}}|^2 \left|\frac{q}{p}\right|^2 e^{-\overline{\Gamma}t}\left\{|\bar{\lambda}|^2 + [yRe(\bar{\lambda}) + xIm(\bar{\lambda})](\overline{\Gamma}t) + \frac{1}{4}(x^2+y^2)(\overline{\Gamma}t)^2\right\}$$

$$R(\overline{D}^0(t)\to f) \approx |\mathcal{A}_f|^2 \left|\frac{p}{q}\right|^2 e^{-\overline{\Gamma}t}\left\{|\lambda|^2 + [yRe(\lambda) + xIm(\lambda)](\overline{\Gamma}t) + \frac{1}{4}(x^2+y^2)(\overline{\Gamma}t)^2\right\}$$

Direct **Interference** **Mixing**

$$x \equiv \frac{m_2-m_1}{\overline{\Gamma}} \qquad y \equiv \frac{\Gamma_2-\Gamma_1}{2\overline{\Gamma}} \qquad \lambda \equiv \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f} \qquad \bar{\lambda} \equiv \frac{p}{q}\frac{\mathcal{A}_{\bar{f}}}{\bar{\mathcal{A}}_{\bar{f}}}$$

MIXING PARAM. ***CPV* enters here**

Expect in SM: $|x| \lesssim |y| \sim$ $10^{-6} - 10^{-3}$ (short distance) Nelson, hep-ex/9908021

$10^{-3} - 10^{-2}$ (long distance) Burdman & Shipsey, Annu.Rev. Nucl.Part.Sci.**53** 431(2003)

- If obtain $|x|>>|y|$ or *CPV* $\Rightarrow$ New Physics

Common features of analyses

- Initial flavor of D^0 is determined from $D^{*+} \to D^0\pi^+$ or $D^{*-} \to D^0\pi^-$

  Background largely reduced: $Q = m_{K\pi\pi} - m_{K\pi} - m_{\pi}$ only 6 MeV (very near threshold)

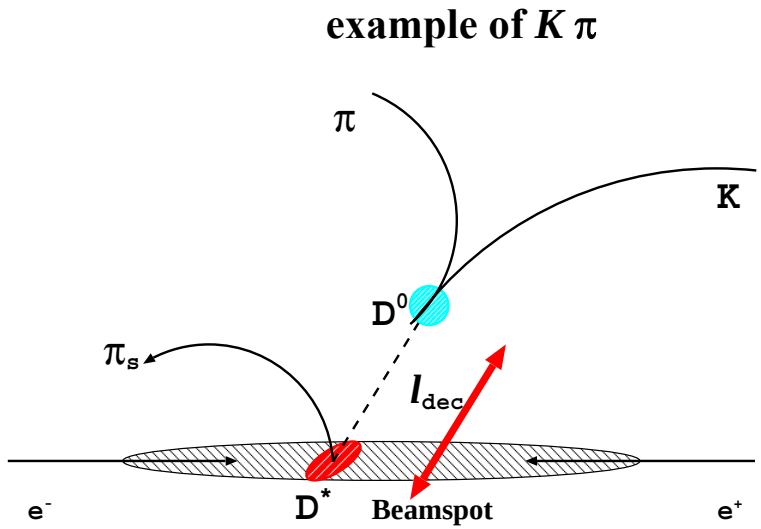
- Common backgrounds:
  - Random π combined with real (Cabibbo-favored) $\overline{D}^0$ decays
  - Combinatorial (random combinations of tracks)

- p_{D^*} cut to eliminate D^*'s from B decays

- Signal/background yields obtained from m-Q fit

- Signal shapes/resolution functions taken from Cabibbo-favored modes

- (Unbinned) ML fit to $t = (l_{dec}/p)(m/c)$



Wrong-sign $D^0(t) \to K^+\pi^-$ decays

$$\lambda = \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f} \equiv \left|\frac{q}{p}\right|\sqrt{R_D^-}e^{i(-\delta+\phi)} \qquad \bar{\lambda} = \frac{p}{q}\frac{\mathcal{A}_{\bar{f}}}{\bar{\mathcal{A}}_{\bar{f}}} \equiv \left|\frac{p}{q}\right|\sqrt{R_D^+}e^{i(-\delta-\phi)}$$

$\delta =$ strong phase $\qquad \phi =$ weak phase

$$\frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\overline{D}^0 \to K^+\pi^-)} = e^{-\overline{\Gamma}t}\left\{R_D^+ + \left|\frac{q}{p}\right|\sqrt{R_D^+}(y'\cos\phi - x'\sin\phi)(\overline{\Gamma}t) + \left|\frac{q}{p}\right|^2\frac{x'^2+y'^2}{4}(\overline{\Gamma}t)^2\right\}$$

$$\frac{\Gamma(\overline{D}^0(t) \to K^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+)} = e^{-\overline{\Gamma}t}\left\{R_D^- + \left|\frac{p}{q}\right|\sqrt{R_D^-}(y'\cos\phi + x'\sin\phi)(\overline{\Gamma}t) + \left|\frac{p}{q}\right|^2\frac{x'^2+y'^2}{4}(\overline{\Gamma}t)^2\right\}$$

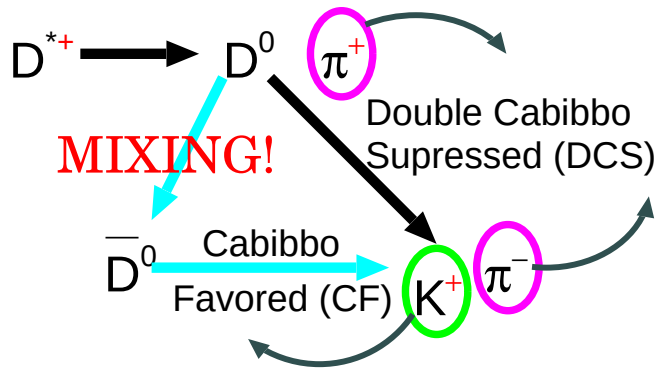
Mixing: $x' \equiv x\cos\delta + y\sin\delta \qquad y' \equiv y\cos\delta - x\sin\delta$

***CPV*:**

$A_M \equiv (1-\lvert q/p\rvert^4)/(1+\lvert q/p\rvert^4)$	CPV in mixing
$A_D \equiv (R_D^+ - R_D^-)/(R_D^+ + R_D^-)$	CPV in the decay amplitude (direct CPV)
ϕ	CPV in mixed/direct interferecne

No CPV ($R_D^+ = R_D^-$, $|q/p| = 1$, and $\phi = 0$):

$$r_{\rm WS}(t) = e^{-\overline{\Gamma}t}\left\{R_D + \sqrt{R_D}y'(\overline{\Gamma}t) + \frac{x'^2+y'^2}{4}(\overline{\Gamma}t)^2\right\}$$



$D^0(t) \to K^+\pi^-$, Data distribution

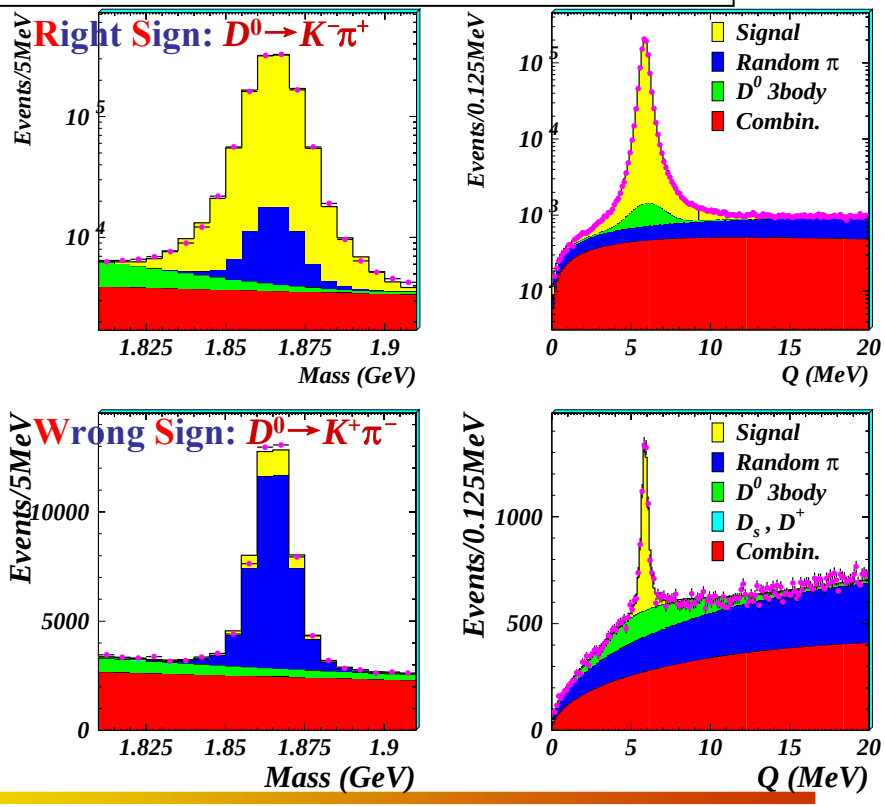
E. M. Aitala *et al.* (E791), PRD 57, 13 (1998):	36 WS events
R. Godang *et al.* (CLEO), PRL 84, 5038 (2000):	45 WS events
J. M. Link *et al.* (FOCUS), PRL 86, 2955 (2001), PLB 618, 23 (2005):	234 WS events
B. Aubert *et al.* (Babar), PRL 91, 171801 (2004):	430 WS events
J. Li *et al.* (Belle), PRL 94, 071801 (2005):	845 WS events
L. M. Zhang *et al.* (Belle), PRL 96, 151801 (2006):	4024 WS events

- RS signal shape: double-Gaussian ($m_{K\pi}$) + sum of bifurcated Student and Gaussian (Q)
- background shape fixed to MC
- WS signal shape fixed to RS signal's

$$N_{RS} = 1073993 \pm 1108$$

$$N_{WS} = 4024 \pm 88$$

$$R_{WS} = N_{WS}/N_{RS} = (0.375 \pm 0.008)\%$$



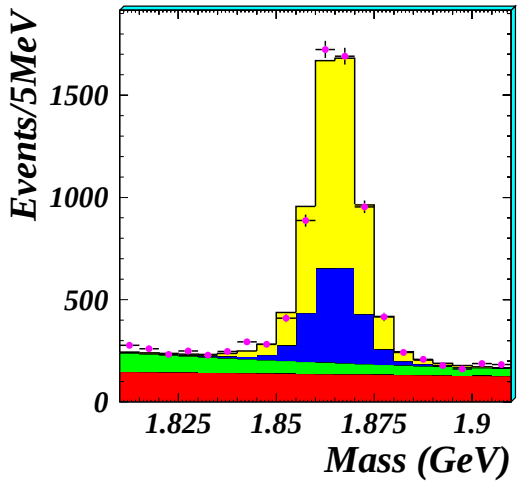
$D^0(t) \to K^+\pi^-$, WS signal

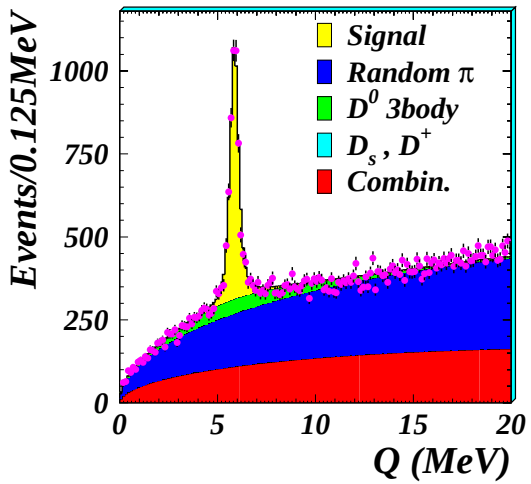
- No. of events in $m_{K\pi}$, Q 3σ region

Signal	3509 ± 77
Random π	1595 ± 13
D^0 3 body	443 ± 17
$D^+_{(s)}$	1.66 ± 0.99
Combin.	1103.1 ± 9.4

Signal/Background = 1.1

Data@400/fb





$D^0(t) \to K^+\pi^-$, Proper-time fit

Probability density function

$$P_i = \int_0^\infty dt' \left\{ f^i_{\rm sig} P_{\rm sig}(t'; R_D, x'^2, y') R_{\rm sig}(t_i - t') + \sum_{\rm bkg} f^i_{\rm bkg} P_{\rm bkg}(t') R_{\rm bkg}(t_i - t') \right\}$$

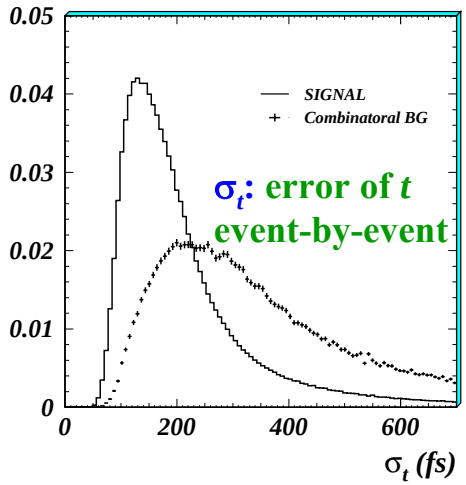
- **Signal resolution function and lifetime fixed to RS fit**
  - **Check: τ_{D^0}(RS) = 409.9 ± 0.7 fs**
    (PDG: 410.3 ± 1.5 fs)
- **BG param.'s fixed from sideband fit or MC**
- **Fit 4σ signal region**
- **(R_D, x'^2, y') the only free parameters**
- **Event fractions include σ_t dependent**

$$f^i(M,Q) \Rightarrow f^i(M,Q,\sigma_t)$$

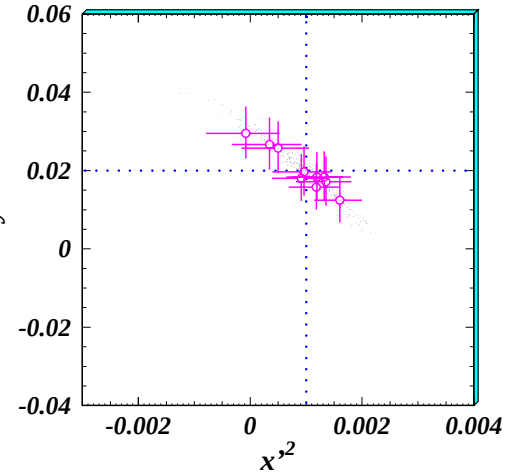
(old fit method in previous analysis) (new fit method)

- **Checked with 450 full MCs**

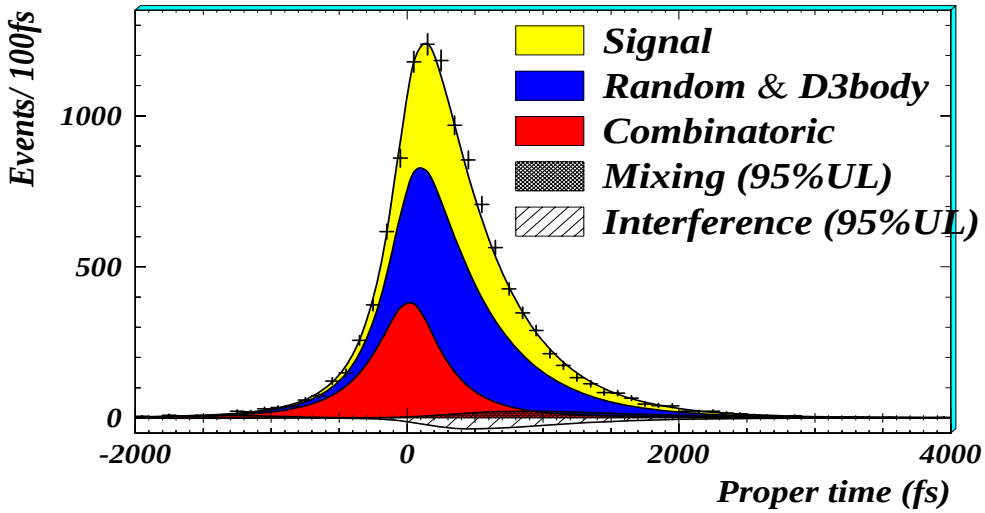
Large difference in σ_t between signal and BG



One example
10 full MCs
400 "Toy"



$D^0(t) \to K^+\pi^-$, Fit result



Fit Case	Parameter	Fit Result ($\times 10^{-3}$)
No CPV	x'^2	$0.18\,^{+0.21}_{-0.23}$
	y'	$0.6\,^{+4.0}_{-3.9}$
	R_D	3.64 ± 0.17
CPV allowed	A_D	23 ± 47
	A_M	670 ± 1200
No mixing or CPV	R_D	$3.77 \pm 0.08\,(\text{stat.}) \pm 0.05\,(\text{syst.})$

CP test

Fit D^0 and $\overline{D}^0$ separately:

$\Rightarrow \{R_D^{\pm}, x'^{\pm 2}, y'^{\pm}\}$

CP Asymmetry

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$$

$$A_M = \frac{R_M^+ - R_M^-}{R_M^+ + R_M^-}$$

$\phi = [9.4\ (\text{or } 84.5) \pm 25.3]^\circ$

where

$$R_M^+ = \frac{x'^{+2} + y'^{+2}}{2}$$

$$R_M^- = \frac{x'^{-2} + y'^{-2}}{2}$$

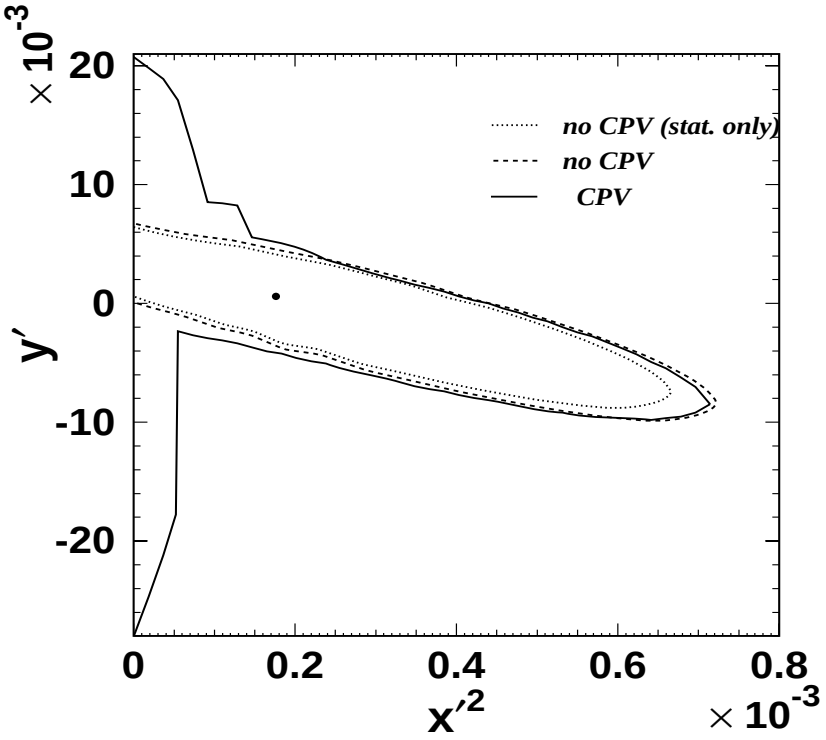
$D^0(t) \to K^+\pi^-$, 95% C.L. contour

Use toy MC to obtain frequentist (Feldman-Cousins) confidence region (95% C.L.):

two solutions of (x'^2, y') in *CPV* allowed case

$$x'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (x'\cos\phi \pm y'\sin\phi)$$

$$y'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (y'\cos\phi \mp x'\sin\phi)$$



Fit Case	Parameter	95% CL interval ($\times 10^{-3}$)
No *CPV*	x'^2	$x'^2 < 0.72$
	y'	$-9.9 < y' < 6.8$
	R_D	$3.3 < R_D < 4.0$
	R_M	$0.63 \times 10^{-5} < R_M < 0.40$
CPV allowed	A_D	$-76 < A_D < 107$
	A_M	$-995 < A_M < 1000$
	x'^2	$x'^2 < 0.72$
	y'	$-28 < y' < 21$
	R_M	$R_M < 0.40$

no *CPV*: (x'^2, y')=(0,0) has 1−C.L. of 3.9% (out of 95% C.L. contour)

Wrong-sign $D^0(t) \to K^{(*)+} e^- \nu$ decays

E. M. Aitala *et al.* (E791), PRL 77, 2384 (1996):	**2504 RS events**
B. Aubert *et al.* (Babar), PRD 70, 091102 (2004):	**49620 RS events**
U. Bitenc *et al.* (Belle), PRD 72, 071101 (2005):	**229452 RS events**

Method: flavor at production tagged via $D^{*+} \to D^0\pi^+$ (pion charge)

flavor at decay tagged via $D^0 \to K^{(*)+} e^- \nu$ (lepton charge)

$\Rightarrow$ mixing signal is $\pi^+ e^-$ or $\pi^- e^+$ (Wrong Sign)

normalize sens. to $\pi^+ e^+$ or $\pi^- e^-$ (Right Sign)

- Only mixing term, no DCS contaminant in WS
- To measure mixing rate $R_M \approx \dfrac{(x^2+y^2)}{2} = \dfrac{N_{\rm WS}}{N_{\rm RS}}$

Neutrino Reconstruction: ν momentum: $P_\nu = P_{\rm cms} - P_{\pi Ke} - P_{\rm rest}$

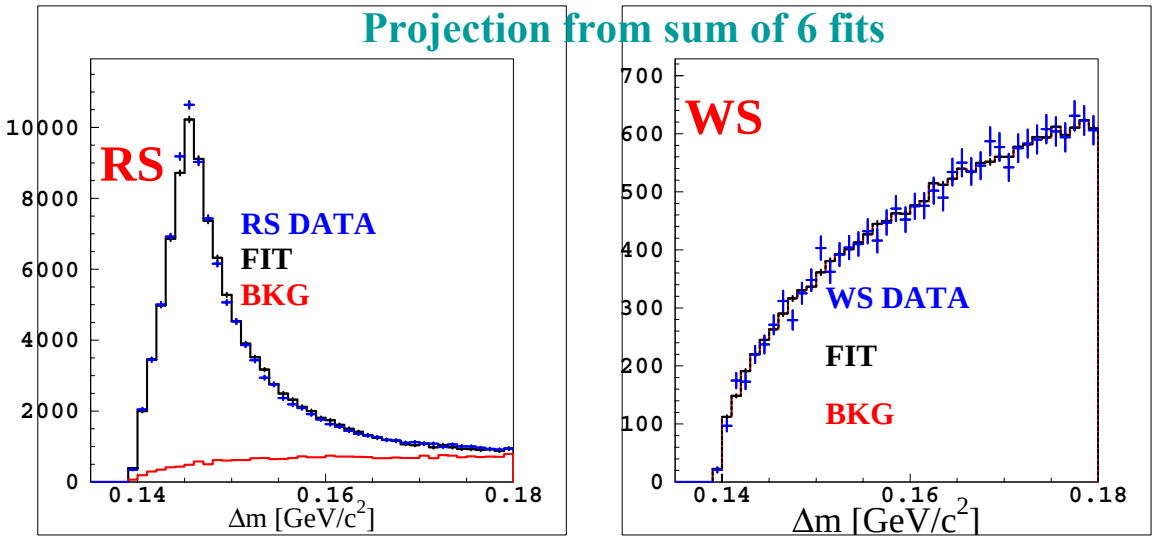
- $|P_{\rm rest}|$ adjusted to give $(P_{\rm cms} - P_{\rm rest})^2 = m_{D^*}{}^2$
- $\vec{p}_{\rm rest}$ direction adjusted to satisfy $m_\nu{}^2 = 0$

$D^0(t) \to K^{(*)+} e^- \nu$ fit

- Proper decay time used to reduce background and increase sensitivity:

$$\frac{dN_{sig}}{dt} \propto \frac{x^2+y^2}{4} t^2 e^{-t} \qquad \frac{dN_{bkg}}{dt} \propto \delta(t) + e^{-t}$$

- Select $1 < t < 10$ $[\tau_{D^0}]$ to fit $\Delta m = m_{K\pi ev} - m_{Kev}$ in 6 bins of t



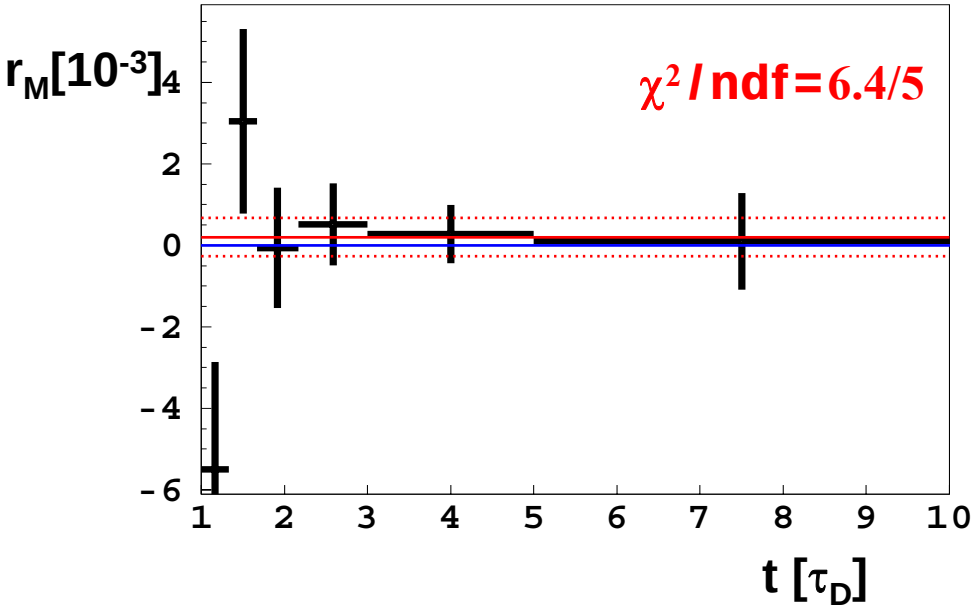
- main RS/WS BKG is combin./random
- Their shape obtained from combination of uncorrelated tracks/event in data

$$R_M = \frac{N_{WS}}{N_{RS}} \frac{\varepsilon^t_{RS}}{\varepsilon^t_{WS}}$$

RS and WS signals differ in proper decay time distribution

$D^0(t) \to K^{(*)+} e^- \nu$ result

- **Result: Fit RS and WS in 6 *t* bins**



$$R_M = (x^2 + y^2)/2 = [0.20 \pm 0.47\ (\text{stat.}) \pm 0.14\ (\text{syst.})] \times 10^{-3}$$

95% C.L. upper limit: $\boxed{R_M < 1.2 \times 10^{-3}}$

(Currently best limit in semileptonic decays)

Wrong-sign $D^0 \to K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$ decays

E. M. Aitala *et al.* (E791), PRD 57, 13 (1998): 7 WS $K^+\pi\pi\pi$

G. Brandenburg *et al.* (CLEO), PRL 87, 071802 (2001): 38 WS $K^+\pi\pi^0$

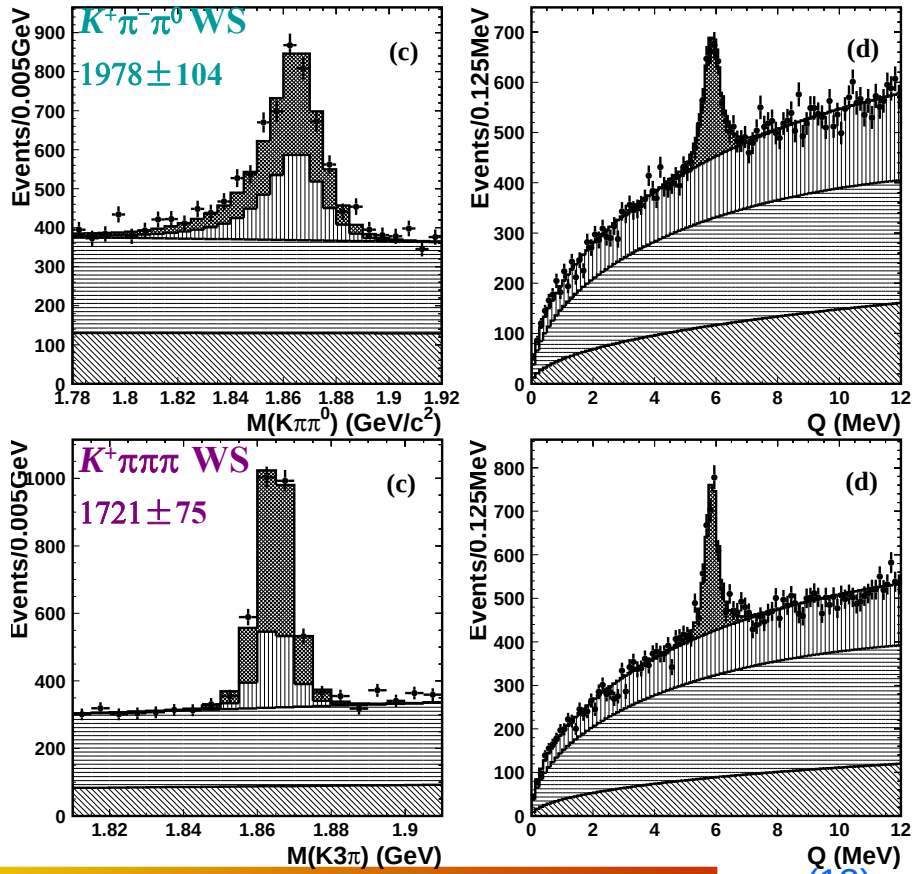
S. A. Dytman *et al.* (CLEO), PRD 64, 111101 (2001): 54 WS $K^+\pi\pi\pi$

X. C. Tian *et al.* (Belle), PRL 95, 231801 (2005): 3699 WS $K^+\pi\pi^0+K^+\pi\pi\pi$

- p_{D^*}>2.5 GeV/c to reject D^*'s from B decays
- veto Cabibbo-suppressed $D^0 \to K^+K_S\pi^-$
- $m_{K(n\pi)}$-Q fit to obtain wrong-sign and right-sign yield $N_{K(n\pi)}$, similar to $D^0 \to K^+\pi^-$ mode
- acceptance for RS and WS events do not cancel: resonant substructure is different and acceptance varies over the Dalitz plot

=> bin events in $m_{K\pi}$ $m_{\pi\pi}$ etc., calculate acceptance for each bin, then average acceptance for RS and WS

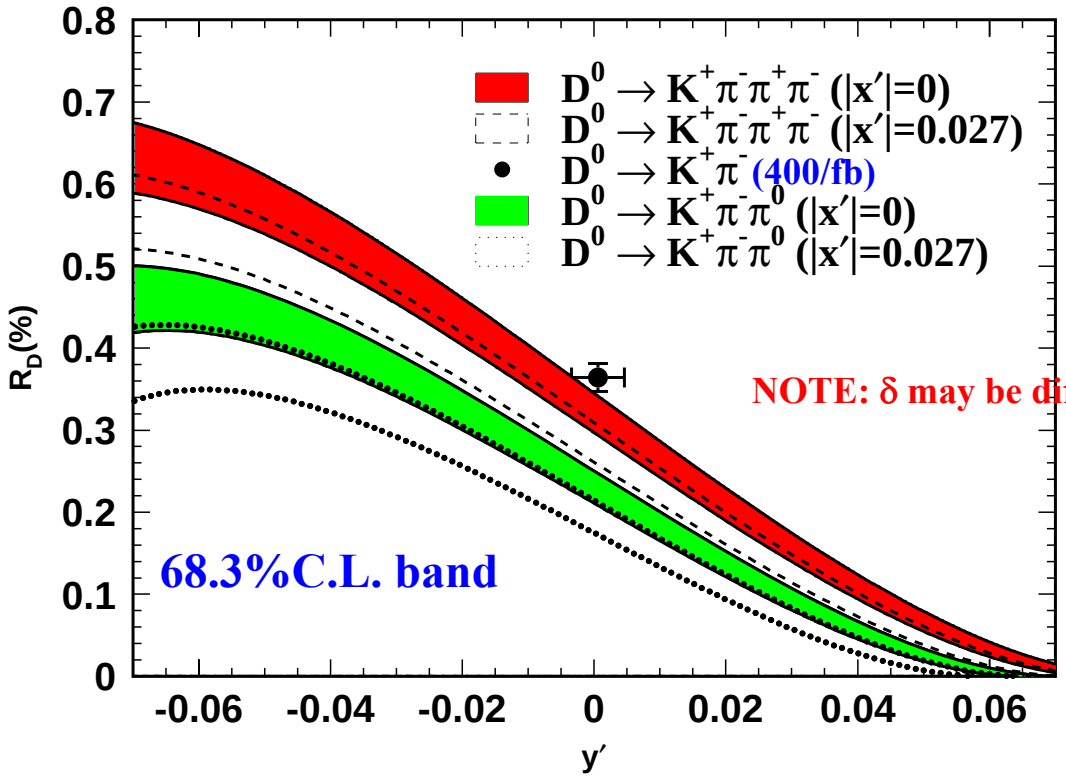
$\langle\varepsilon_{RS}\rangle/\langle\varepsilon_{WS}\rangle$ =1.01±0.05, 0.98±0.04



Results of WS $D^0 \to K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$

$$R_{WS} \equiv \frac{\int \mathcal{P}[D^0 \to K^+\pi^-(n\pi)]\,dt}{\int \mathcal{P}[D^0 \to K^-\pi^-(n\pi)]\,dt} \approx R_D + \sqrt{R_D}\,y' + \frac{x^2+y^2}{2}$$

$$= \begin{cases} \left[2.29 \pm 0.15\,(\text{stat.})\,^{+0.13}_{-0.09}\,(\text{syst.})\right] \times 10^{-3} & \boxed{K^+\pi^-\pi^0} \\ \left[3.20 \pm 0.18\,(\text{stat.})\,^{+0.18}_{-0.13}\,(\text{syst.})\right] \times 10^{-3} & \boxed{K^+\pi^-\pi^+\pi^-} \end{cases}$$



|x'|=0.027 is 95% C.L. upper limit from 400 fb^{-1} $K^+\pi^-$ analysis

NOTE: δ may be different from that of $K^+\pi^-$

Summary I

- $D^0(t) \to K^+\pi^-$, 400 fb^{-1}

  $|x'| < 2.7\%$

  $-0.99\% < y' < 0.68\%$ **@95% C.L., no *CPV***

  $0.01\% < \sqrt{x^2+y^2} < 2.8\%$

  † **No-mixing point (0, 0) corresponds to a 1-C.L.=3.9% (no *CPV*) ⇒ 2.1σ**

  † **No *CPV* observed**

- $D^0(t) \to K^{(*)+}e^-\nu$, 253 fb^{-1}

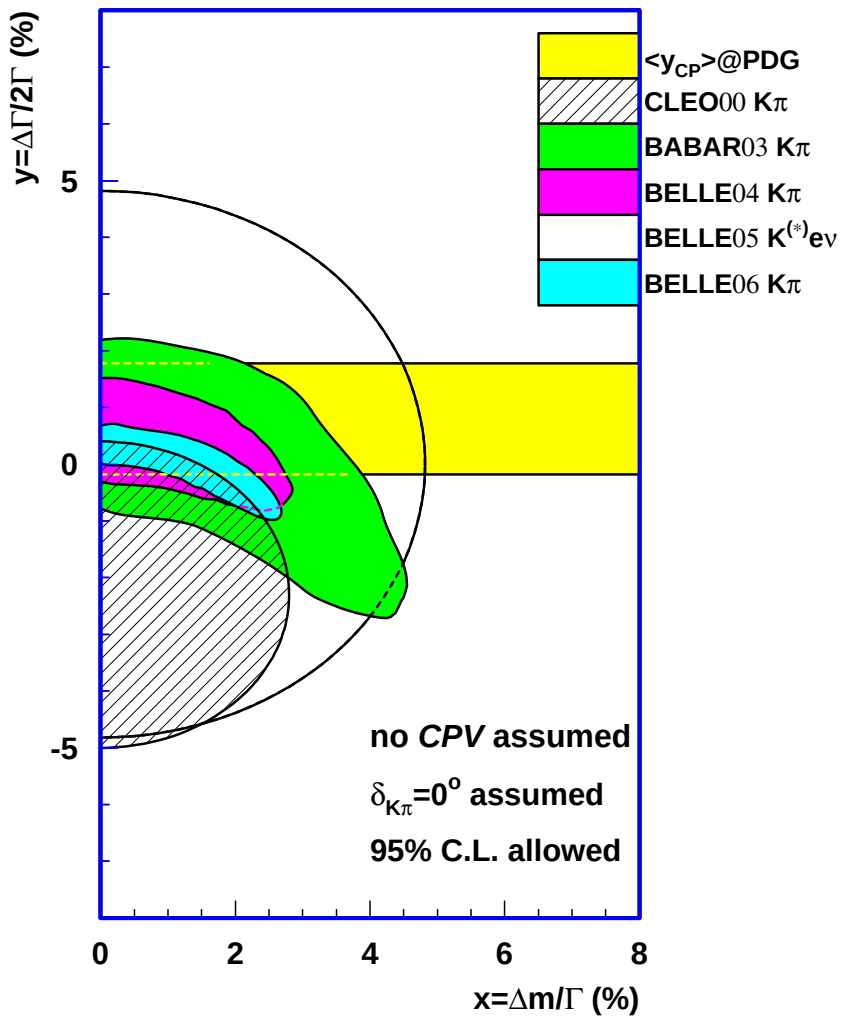
  $\sqrt{x^2+y^2} < 4.9\%$ **@95% C.L.**

- $D^0 \to K^+(n\pi)^-$, 281 fb^{-1}

  $A_{CP}(K\pi\pi^0) = -0.006 \pm 0.053$

  $A_{CP}(K3\pi) = -0.018 \pm 0.044$

$$A_{CP} = \frac{N_{WS}^{D^0\to K^+(n\pi)^-} - N_{WS}^{\bar{D}^0\to K^-(n\pi)^+}}{N_{WS}^{D^0\to K^+(n\pi)^-} + N_{WS}^{\bar{D}^0\to K^-(n\pi)^+}}$$



Summary II

- Current sensitivity by experiments
  - $|x|, |y| \sim 10^{-2}$
  - $R_M \sim 10^{-4}$
- Strong phase difference $\delta_{K\pi}$:

From $K\pi$ result and world average $\langle y_{CP} \rangle = (1.09 \pm 0.46)\%$ [hep-ex/0605032]

$$\begin{cases} x' = x\cos\delta + y\sin\delta \\ y' = y\cos\delta - x\sin\delta \end{cases}$$

Assuming no *CPV*

$$\Rightarrow \boxed{\delta_{K\pi} = (52 \pm 22)^\circ \text{ or } (122 \pm 39)^\circ}$$

Larger SU(3) breaking?

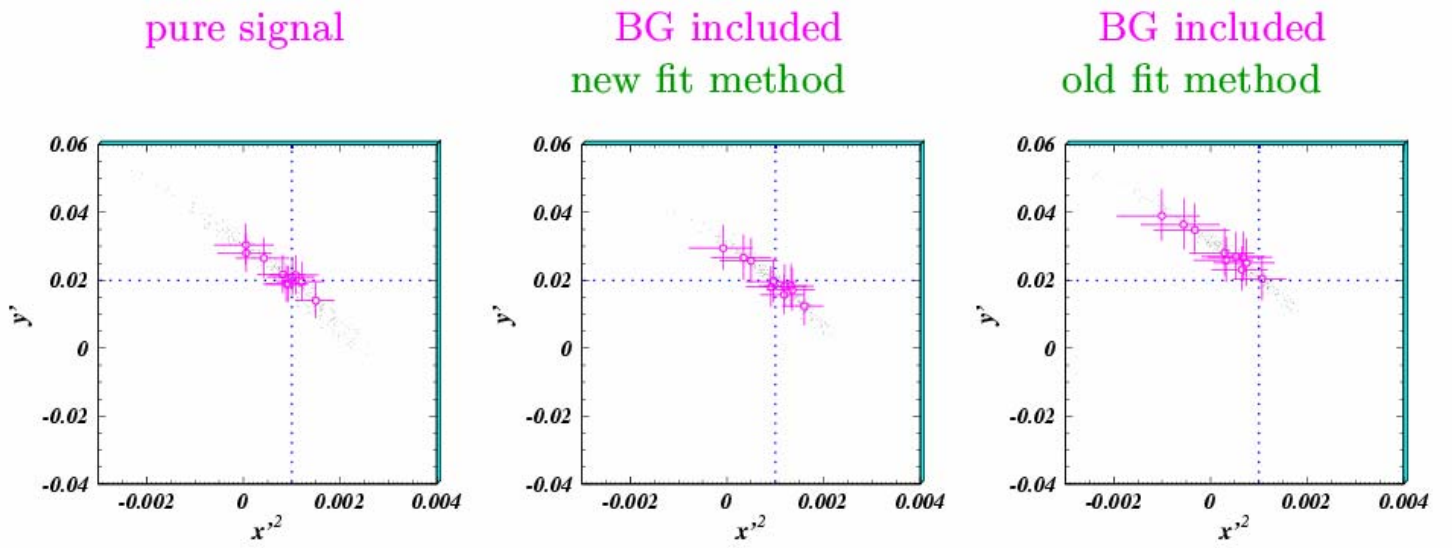
- D^0-mixing may be within our reach with present statistics (hints of positive signals in y_{CP}
- Need much larger samples to precisely pin down the mixing phenomena in D^0 system

Backup

$D^0(t) \to K^+\pi^-$, full and Toy MC tests

- Full (Geant simulation) MC show no bias in large (M,Q) region
- And consistent with Toy (simple generator) MC
- Old fit method give 0.5-1σ bias shift to unphysical region
- We didn't know the bias source in the previous study, because σ_t difference wasn't included in Toy MC, even some bias appeared in the Full MC.

One example of Full MC

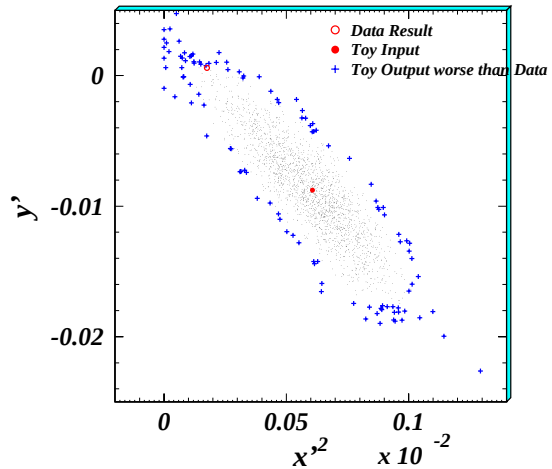


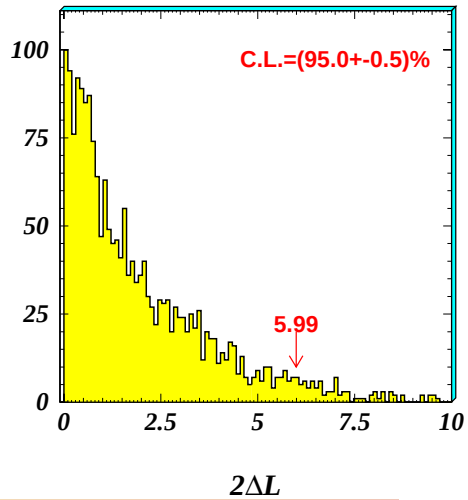
$D^0(t) \to K^+\pi^-$, Method to set C.L. contour

Using Toy MC to obtain frequentist (Feldman-Cousins) confidence region.

- choose $\vec{\alpha} = (x'^2, y')$, generate Toy MC
- fit toy MC sample, calculate $\Delta \ln \mathcal{L}(\vec{\alpha}) = \ln \mathcal{L}_{max} - \ln \mathcal{L}(\vec{\alpha})$ **for each toy experiment**
- find fraction p with values $< \Delta \ln \mathcal{L}_{data}(\vec{\alpha})$
- contour is locus of (x'^2, y') points with $p = 0.95$

All fits require x'^2 in physical region.





Not standard Feldman-Cousins method

$D^0(t) \to K^+\pi^-$, systematics

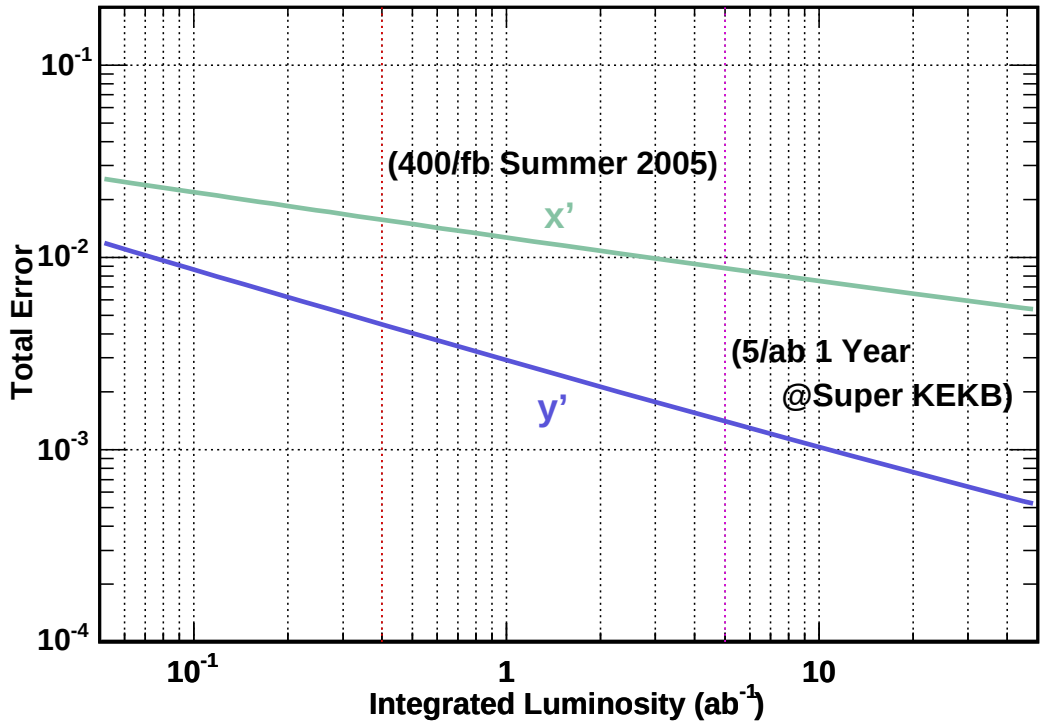
Source	$\Delta y'/\sigma_{y'}$ (%)	$\Delta x'^2/\sigma_{x'^2}$ (%)	$\Delta(-2\ln L)$ (%)
KID cut	25.5	−26.7	7.37
PID cut	−22.9	16.2	6.94
χ^2 cut	23.0	−21.2	5.31
$p^*(D^*)$ cut	34.0	−20.7	19.2
σ_t PDF	24.4	−18.3	7.0
resolution function	9.2	−9.4	0.90
resolution para.'s	-	-	6.90
BG yields	-	-	0.44
M,Q PDFs	-	-	1.06
Lifetime bias	−7.0	7.0	0.78
Total	-	-	55.9

Scaling factor = $\sqrt{1+0.559/2.3} = 1.12$

$D^0(t) \to K^+\pi^-$, Prospect of future

- Log-likelihood $\propto \mathcal{L}_{int}$
  => 3σ (~750 fb^{-1})

- Better precision:
  - Stat. error $\propto (\mathcal{L}_{int})^{-0.5}$
  - Relative syst. error $\propto (\mathcal{L}_{int})^{0.15}$
  - For small enough x' :
    $\sigma_{x'} \approx \sqrt{\sigma_{x'^2}}$



Sensitivity	Total Error on x'			Total Error on y'		
	$1\ ab^{-1}$	$5\ ab^{-1}$	$50\ ab^{-1}$	$1\ ab^{-1}$	$5\ ab^{-1}$	$50\ ab^{-1}$
Value ($\times 10^{-3}$)	12.7	8.8	5.3	2.9	1.4	0.52

$D^0(t) \to K^{(*)+} e^- \nu$

Neutrino reconstruction

Get $P_{\nu_e} = P_{\rm CMS} - P(\pi_s K e) - P_{\rm REST}$ (4-momentum conservation).

Correction for better ν 4-momentum:

1. rescale $P_{\rm REST}$ (M_{D^*} constraint).

$$\mathbf{P_{REST} \to x \cdot P_{REST}}$$
$$|\mathbf{P_{CMS} - x \cdot P_{REST}}|^2 \equiv \mathbf{M^2_{D^{*+}}}$$

2. correct direction ($M_\nu = 0$ constraint).

$$\text{new } \angle(\vec{\mathbf{p}}_{\mathbf{REST}}, \vec{\mathbf{p}}_{\pi_s \mathbf{Ke}})$$

for $\mathbf{M^2_\nu \equiv 0}$.