Improved Constraints on D^0 - $\overline{D}^0$ Mixing in $D^0 \to K^+ \pi^-$ Decays at Belle

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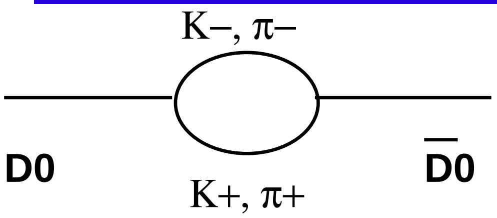
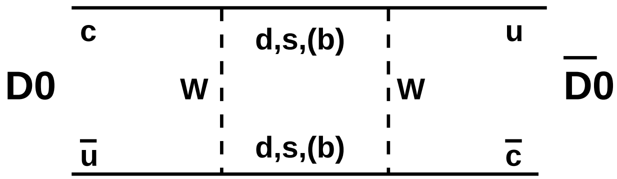
On behalf of the Belle Collaboration

D^0-$\overline{D}^0$ 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:

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

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

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

For $\Delta m t \ll 1$ 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)

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

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

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

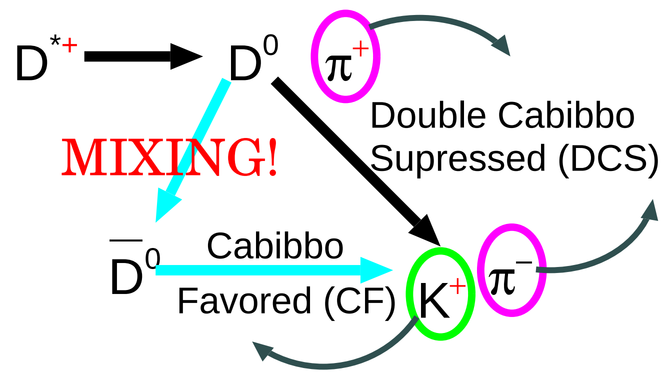
Mixing: $x' \equiv x\cos\delta + y\sin\delta \qquad y' \equiv y\cos\delta - x\sin\delta$

***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 $\phi = 0$):

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



Previous measurements

- Wrong-sign semileptonic $D^0(t) \to Kl\nu$ decays

  measures x^2+y^2, no DCS contamination

  (E791, CLEO, Babar, Belle)
- Wrong-sign hadronic $D^0(t) \to K^-\pi^+$ decays

  measure x' , y'

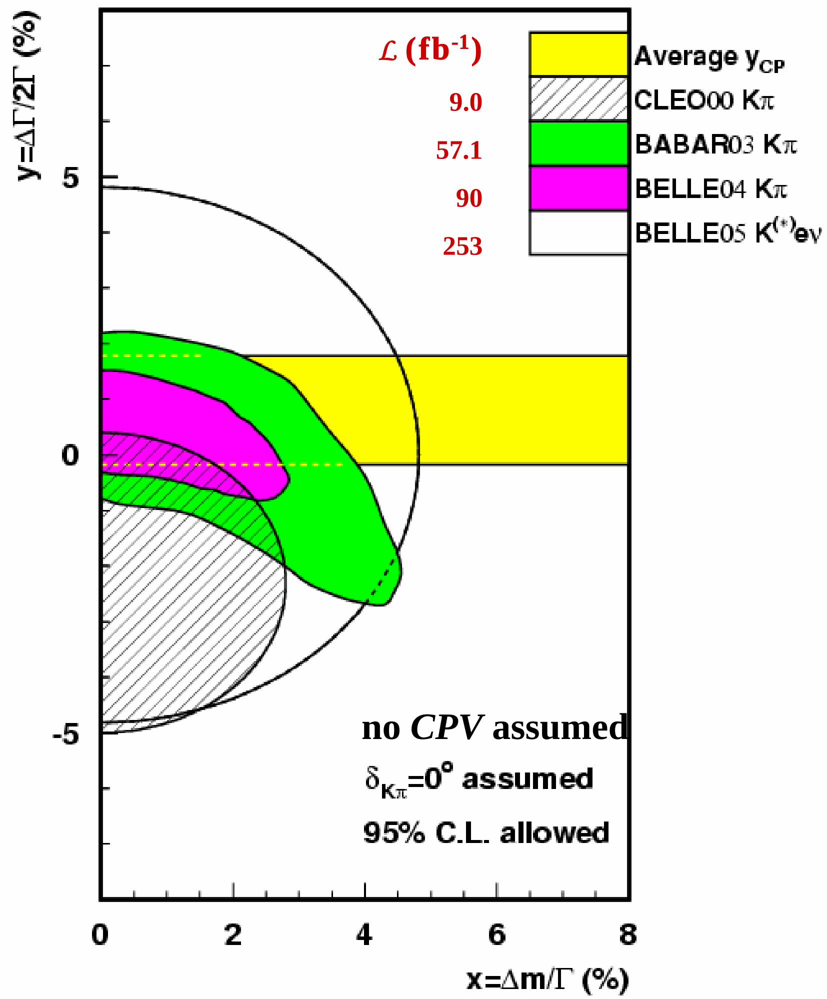
  (FOCUS, CLEO, Babar, Belle)
- Decays to *CP* eigenstates: $D^0(t) \to KK, \pi\pi$

  measure $y_{cp} = y$ (no *CPV*)

  (E791, FOCUS, CLEO, Babar, Belle)
- Dalitz plot analysis of $D^0(t) \to K^0\pi^+\pi^-$ decays

  measure x, y

  (CLEO)



Overview of this study

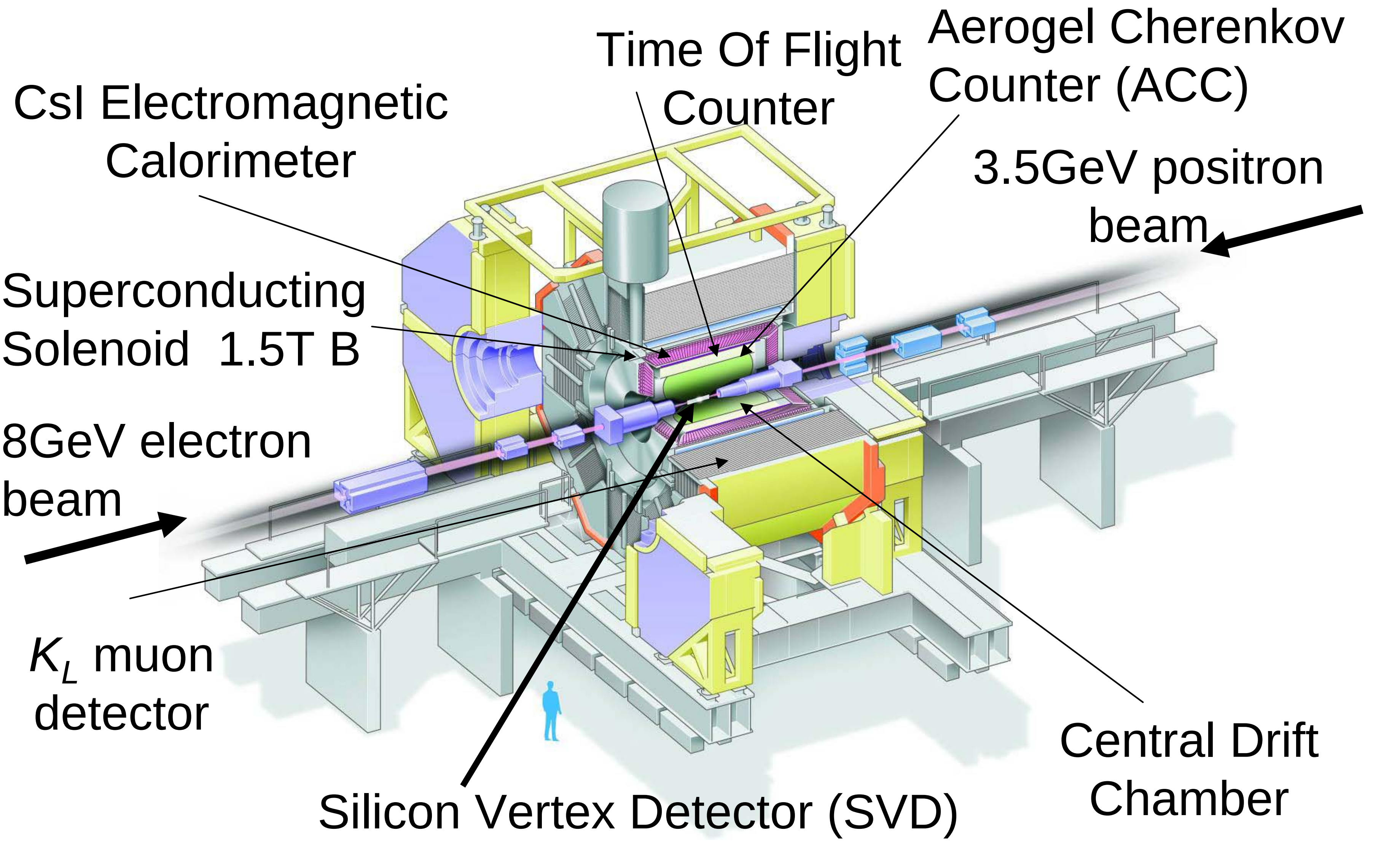
- 90 fb^{-1} measurement of Belle [J.Li *et al.* PRL 94, 071801 (2005)]
  - 95% C.L. contour obtained by me

- 400 fb^{-1} is done, sensitivity improved by 2
  - Data Sample (two SVD configurations):

    150 fb^{-1} SVD1 (3 ladder), 250 fb^{-1} SVD2(4 ladder)

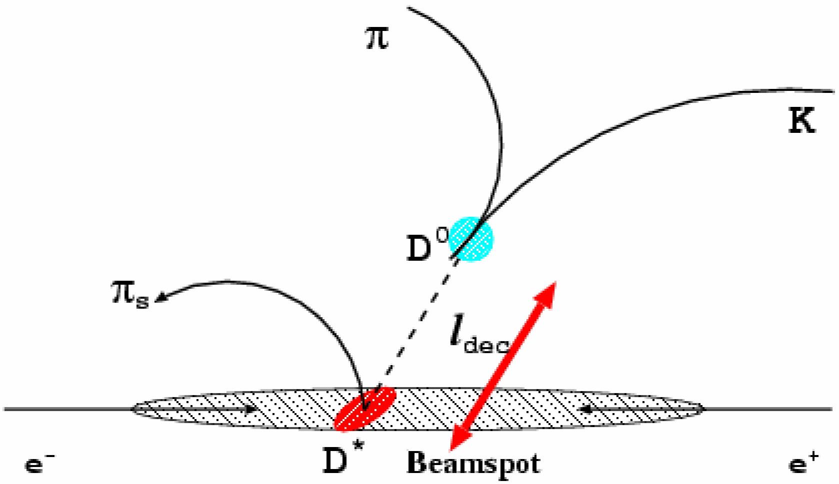
- Improvement from the previous study
  - Selection criteria reoptimized, S/N=1.1 from 0.9, with same efficiency
  - Include σ_t in event probability to avoid bias
  - Some minor changes to improve fitting quality

The Belle detector



Event Reconstruction

Decay chain: $D^{*+} \to D^0 \pi_s^+$, $D^0 \to K^+ \pi^-$



Vertexing techniques:

- D^0 decay point: K^+ π^- vertex fit (3D)
- D^* decay point: D^0 trajectory extrapolated with Beam spot constraint
- Soft pion from D^* refitted to D^* point

- D^0 proper decay time: $t = l_{dec} \frac{m_{D^0}}{c p_{D^0}}$
- Decay length: $l_{dec} = (\vec{r}_{dec} - \vec{r}_{IP}) \cdot \frac{\vec{p}}{p}$
- time error σ_t computed event-by-event

- **Energy released:**

$Q = m_{K\pi\pi} - m_{K\pi} - m_{\pi}$

Near threshold (5.85 MeV)

Candidate selection

- At least 2 hits for both SVD r,ϕ and z

  => improve moment resolution
- PID for D^0 daughters: Prob(K)>0.5(0.6) and Prob(π)<0.9(0.6)
- $p^*(D^*) > 2.7(2.5)$ GeV/c

  => eliminate $B\bar{B}$ BG and suppress combin. BG
- Good vertexing fit required
- $\sigma_t < 700(820)$ fs
- Rejected doubly-misIDed events
- Multi-Candidates Selection (5%)
  - Reject events have opposite signs

    Remove 30% Random π BG, 1% signal lost
  - Otherwise, choose the one with the best vertexing

(cut in previous study)

Data distribution

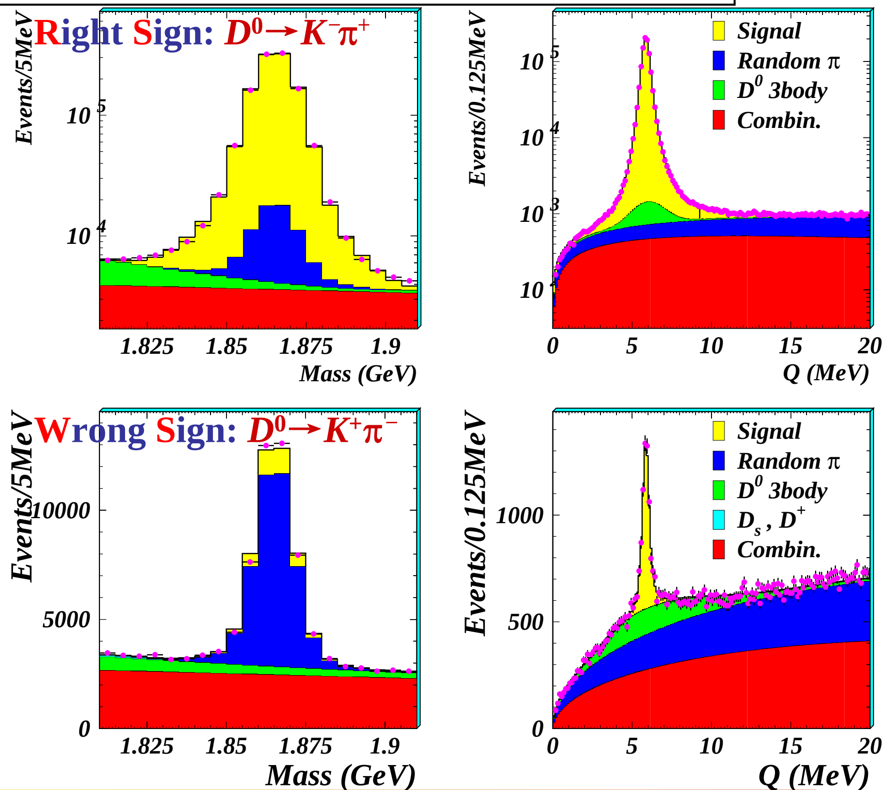
E. M. Aitala *et al.* (E791), PRD 57, 13 (1998):	36 WS events
R. Godang *et al.* (CLEO), PRL 84, 5038 (2000):	45 WS events
J. M. Link *et al.* (FOCUS), PRL 86, 2955 (2001), PLB 618, 23 (2005):	234 WS events
B. Aubert *et al.* (Babar), PRL 91, 171801 (2004):	430 WS events
J. Li *et al.* (Belle), PRL 94,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

$N_{RS} = 1073993 \pm 1108$

$N_{WS} = 4024 \pm 88$

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



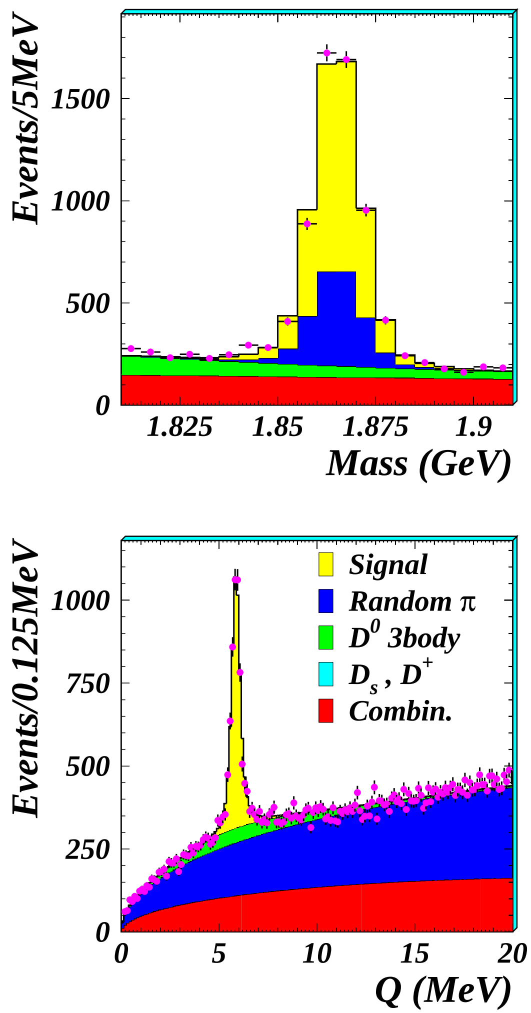
WS signal

- 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



RS proper-time fitting

Unbinned fit to RS (complete BG model):

$$L = \prod_i [\mathcal{P}(t_i; \tau_{D^0}) \bigotimes R_{\rm sig}(t) + \mathcal{P}_{\rm BG}(t_i)]$$

The RS signal is $\bigotimes$ed with $R_{\rm sig}(t)$.

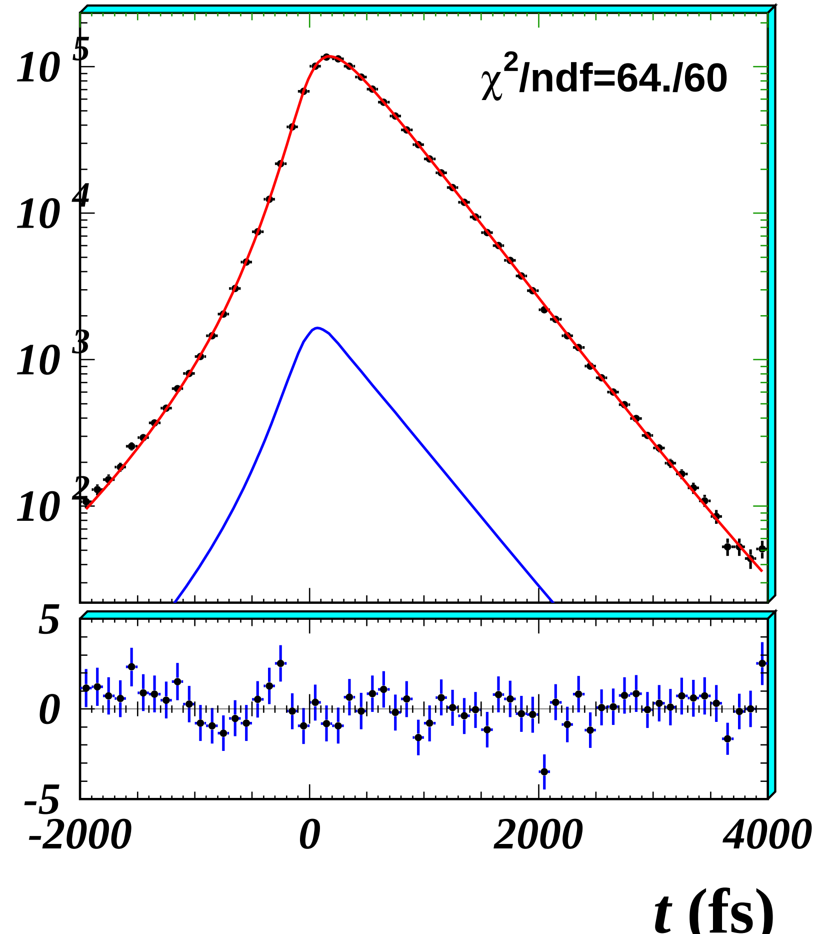
Fit RS => resolution function of signal $R_{\rm sig}(t)$

- **Resolution function is triple-Gaussian**
- **Event fractions from *M*-*Q* fit**
- **BG parameters get from sideband fit**
- **Fit 4σ signal region with BG par.'s fixed**

$\tau_{D^0} = 409.9 \pm 0.7$ fs

PDG'04 410.3±1.5 fs

Data@400/fb



WS Proper-time fit

Probability density function

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

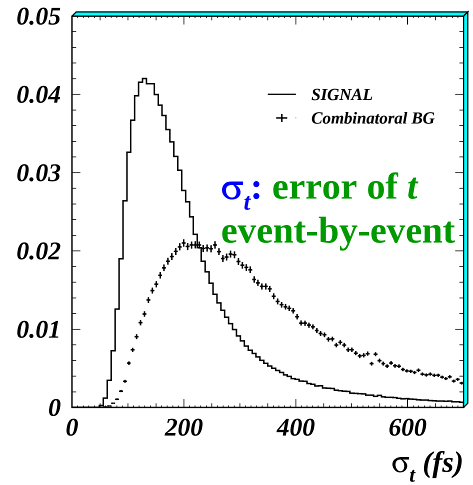
- **Signal resolution function and lifetime fixed to RS fit**
- **BG param.'s fixed from sideband fit or MC**
- **Fit 4σ signal region**
- **(R_D, x'^2, y') the only free parameters**
- **Event fractions include σ_t dependent**

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

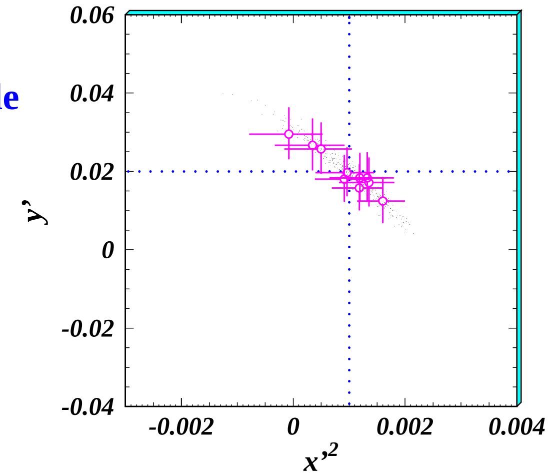
(old fit method in previous analysis) **(new fit method)**

- **Checked with 450 full MCs**

Large difference in σ_t between signal and BG

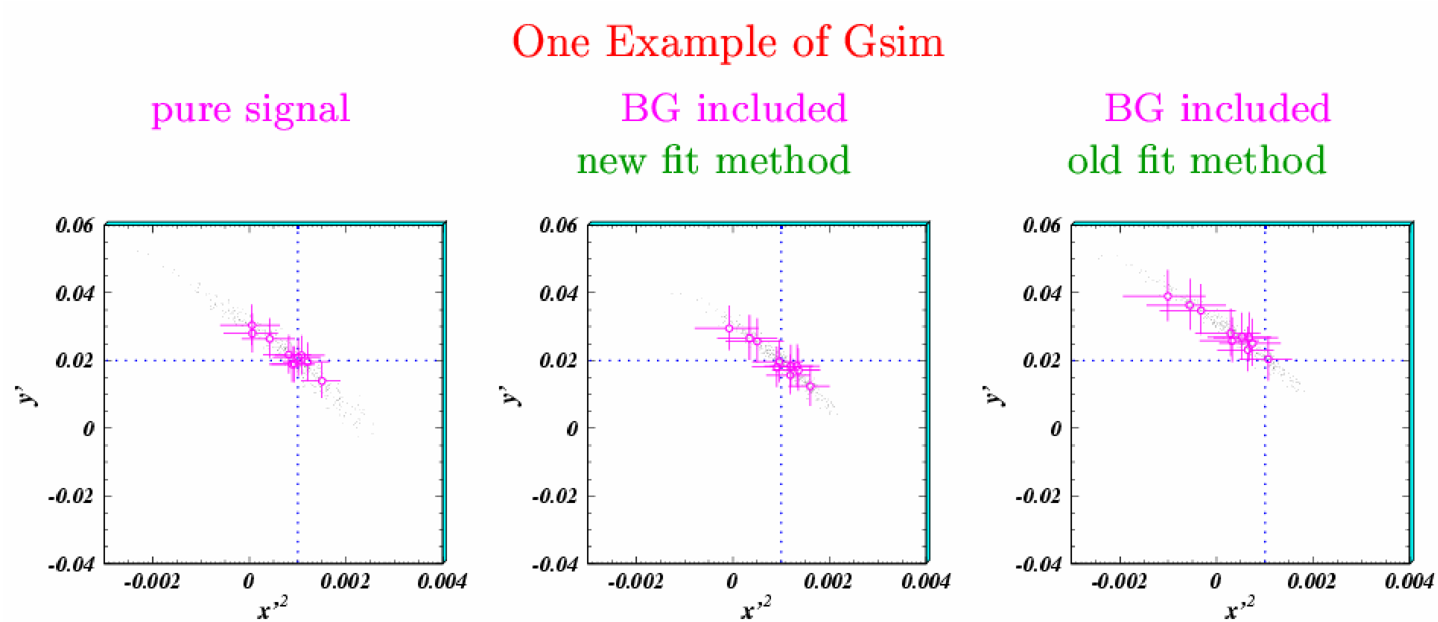


One example
10 full MCs
400 “Toy”

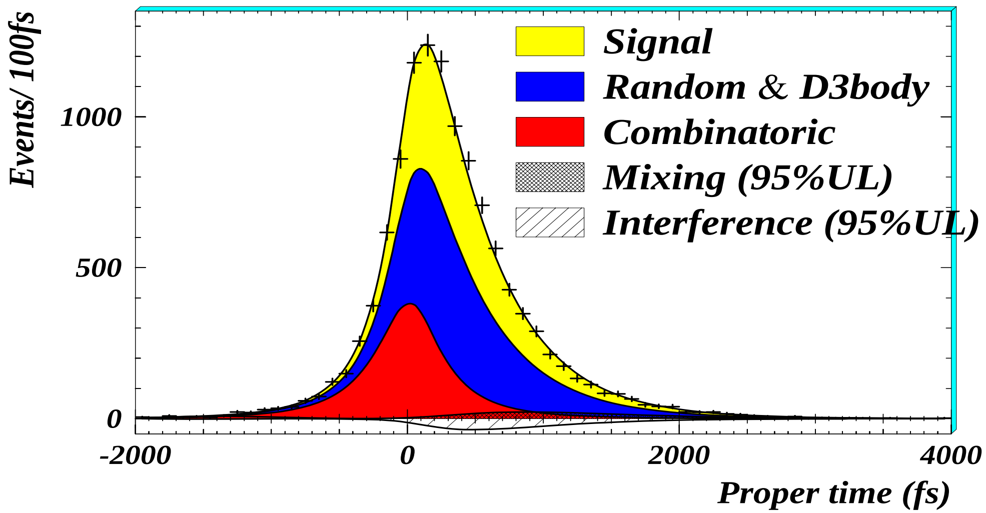


Full and Toy MC tests

- Gsim (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 Gsim MC.



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:

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

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

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

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

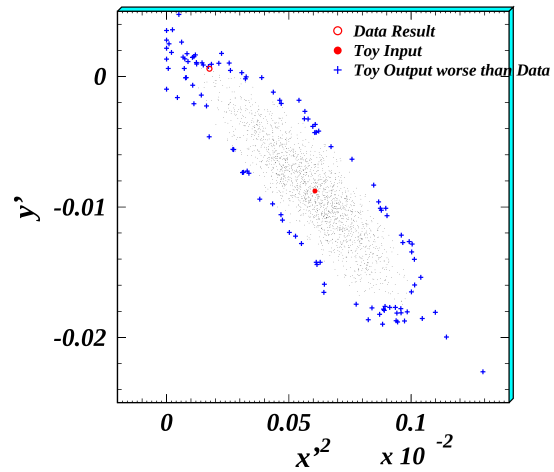
Method to set C.L. contour

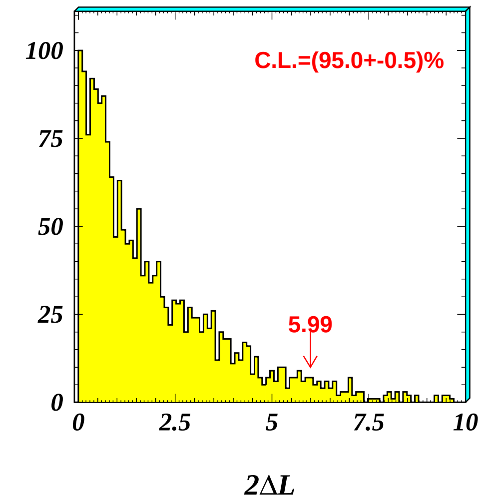
Using Toy MC to obtain frequentist (Feldman-Cousins) confidence region.

- 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





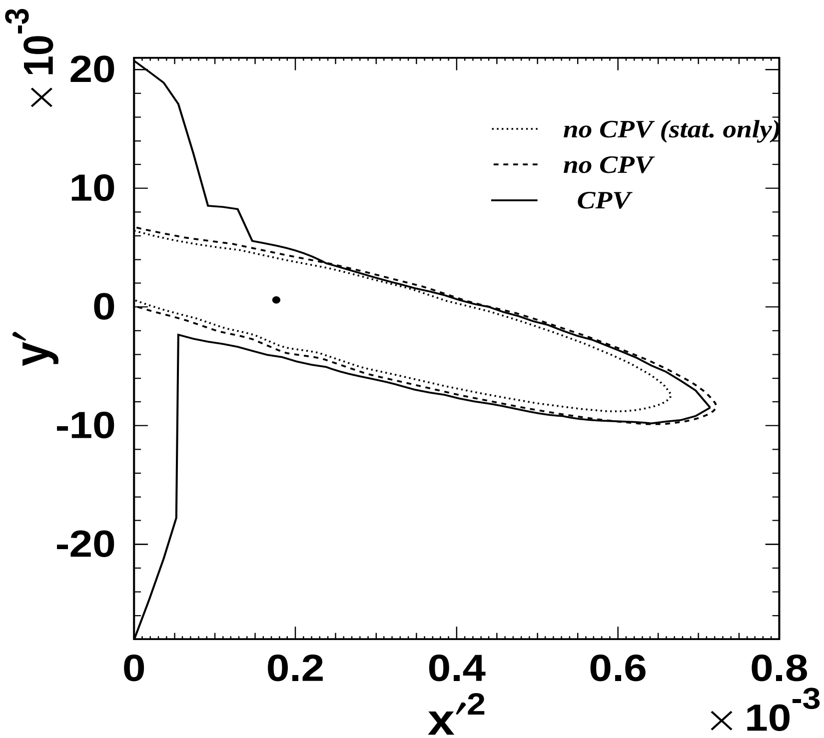
95% C.L. contour

***CPV* allowing:** combining 77.6% C.L. contours of D^0 and $\overline{D}^0$

two solutions of (x'^2, y')

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

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



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)

Summary Ⅰ

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

  $|x'| < 2.7\%$ @95% C.L., no *CPV*

  $-0.99\% < y' < 0.68\%$

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

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

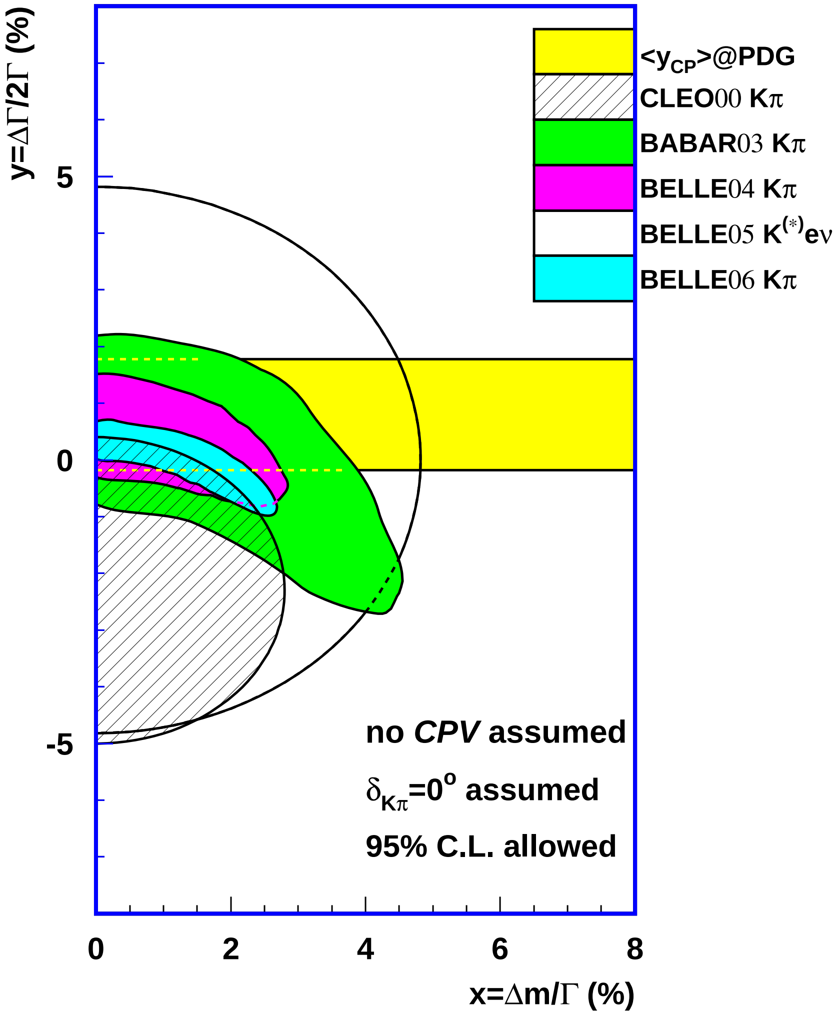
  † No *CPV* observed

- Published in PRL 96, 151801 (2006):

  † Cited by 7 times

  † Totally cited by 31 times including results of 90/fb of Belle

  † Cited by PDG06 for 5 times, average values dominated by this measurement



Summary II

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

From $K\pi$ result and world average $\langle y_{CP}\rangle = (0.7 \pm 0.5)\%$ [PDG06]

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

Assuming no *CPV*

$\Rightarrow$ $\delta_{K\pi} = (29 \pm 33)^\circ$ or $(146 \pm 47)^\circ$

Consistent with zero

- 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

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

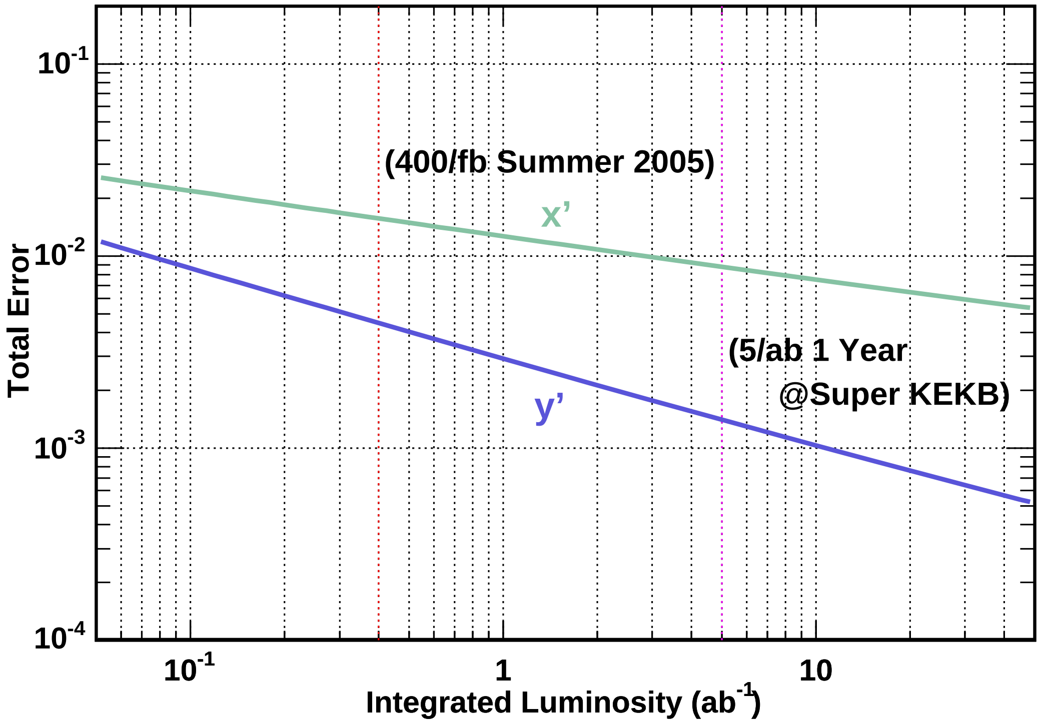
Source	$\Delta y'/\sigma_{y'}$ (%)	$\Delta x'^2/\sigma_{x'^2}$ (%)	$\Delta(-2\ln L)$ (%)
KID cut	25.5	-26.7	7.37
PID cut	-22.9	16.2	6.94
χ^2 cut	23.0	-21.2	5.31
$p^*(D^*)$ cut	34.0	-20.7	19.2
σ_t PDF	24.4	-18.3	7.0
resolution function	9.2	-9.4	0.90
resolution para.'s	-	-	6.90
BG yields	-	-	0.44
M,Q PDFs	-	-	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 $\propto (\mathcal{L}_{int})^{0.15}$
  - x' enough small: $\sigma_{x'} \approx \sqrt{\sigma_{x'^2}}$



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