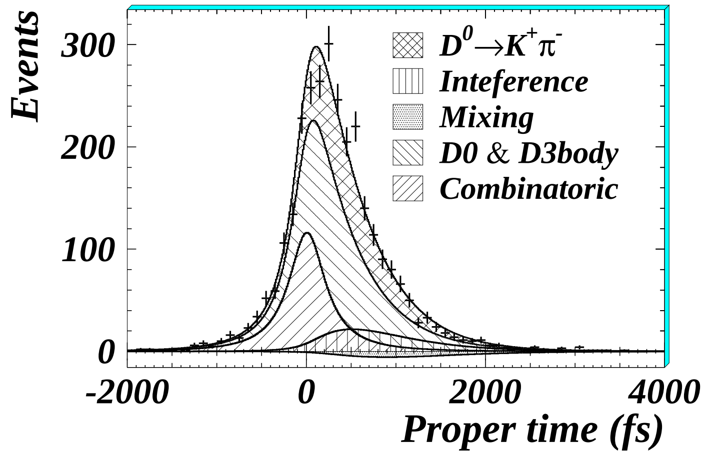
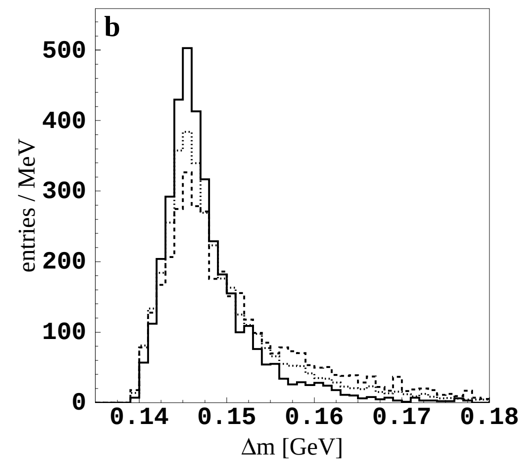
D^0-$\overline{D}^0$ mixing at Belle





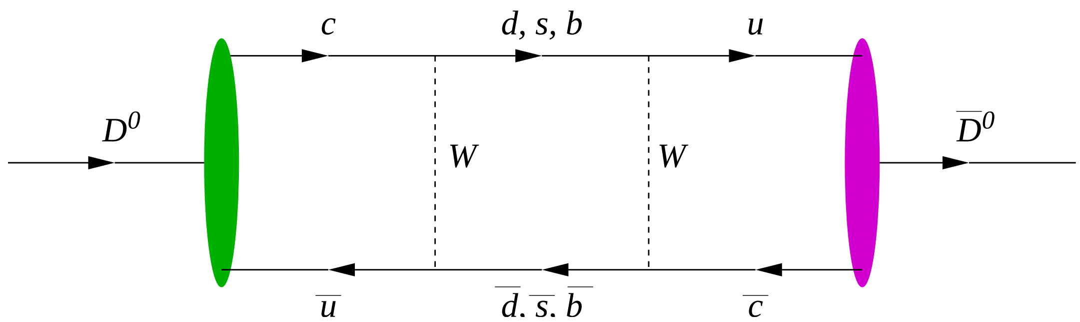
$D^0 \to K^+\pi^-$: 90 fb^{-1}
hep-ex/0408125 final

$D^0 \to K^+e^-\overline{\nu}_e$: 140 fb^{-1}
hep-ex/0408112 prelim.

Bruce Yabsley (Virginia Tech)

DPF 2004 / UC Riverside, 30th August 2004

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



- GIM suppression $\left((m_s^2 - m_d^2)/m_c^2\right)^2$ $\rightarrow$ SM box diagram *tiny*
- higher order diagrams also suppressed (at least $\sin^2\theta_C$)
- OPE estimates: $\left\{ \begin{array}{lcl} x & = & \Delta M/\Gamma \\ y & = & \Delta\Gamma/2\Gamma \end{array} \right\} \lesssim 10^{-3} \longrightarrow R_{mix} \lesssim 10^{-6}$
- Kπ, resonances may raise $x, y \rightarrow O(10^{-2})$???
- New Physics generally adds new box diagrams
  $\Rightarrow$ enhanced x, $\approx$ unchanged y
- mixing-with-CPV would be a NP smoking gun

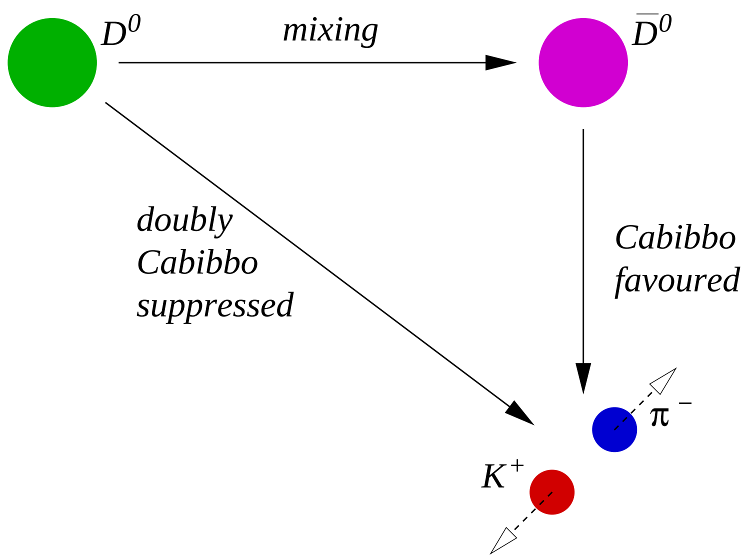
$D^0 \to K^+\pi^-$ analysis à la CLEO

$$\frac{\mathrm{d}N}{\mathrm{d}t} \propto e^{-\overline{\Gamma}t}\left[R_D + \sqrt{R_D}y'(\overline{\Gamma}t) + \frac{x'^2+y'^2}{4}(\overline{\Gamma}t)^2\right]$$

- $\tan^2\theta_C \gg R_{\text{mix}}^{\text{expected}}$: R_D dominates
- time dependence disentangles

e^{-t}	DCSD
$t \cdot e^{-t}$	interference term
$t^2 \cdot e^{-t}$	mixing

- strong phase difference $\delta_{K\pi} \longrightarrow$
  we measure x and y *rotated* by $\delta_{K\pi}$



interference term $f(t) \longrightarrow$ sensitivity to mixing

- categorize backgrounds by $f(t)$
- fix in the timing fit $\longrightarrow$ recover interference

$D^0 \to K^+\pi^-$ analysis outline

- decay chain $D^{*+} \to D^0\pi^+$, $D^0 \to K^+\pi^-$ ("wrong-sign")
- selection cuts
  - *tracks:* good quality, SVD hits, K/π ID cuts
  - D^{*+}: $p(D^{*+}) > 2.5\,\mathrm{GeV}/c$ in CM (*vs* $B\overline{B}$, combinatorics)
- vertexing to get
  - D^0 decay point — from K^+, π^-
  - D^0 origin — from extrapolation to IP
  - better D^{*+} quality — from π^+ refit to D origin)
- vertexing quality cuts
- (M, Q) fit to determine backgrounds ($S/B \sim 1$ after cuts)
- *decay-time fit* to (M, Q) signal box $\longrightarrow (R_D,\, y',\, x'^2)$
  - background levels: set from the larger (M, Q) fit
  - background "decay-time" dist^n: $f_i(t') \otimes \mathcal{R}_{i,\,\mathrm{data}}(t - t')$
  - signal decay-time dist^n: $f(t';\, R_D,\, y',\, x'^2) \otimes \mathcal{R}_{\mathrm{data}}(t - t')$

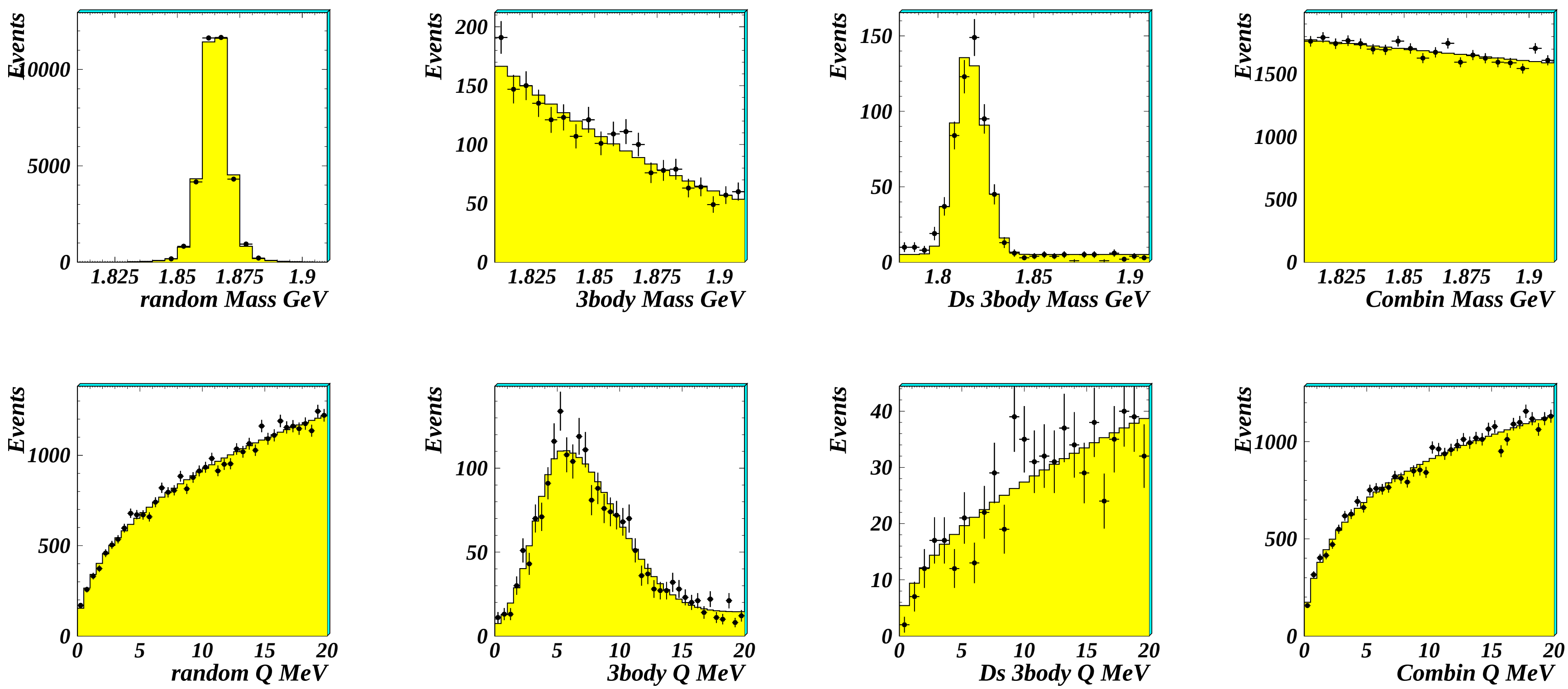
$D^0 \to K^+\pi^-$: backgrounds [with differing $f(t)$]

MC wrong-sign backgrounds (∃ similar breakdown for right-sign)

“random π_{slow}” | D^0 3-body | D^+, D_s^+ | combinatorial

M

Q



relative normalization of D^+, D_s^+ / D^0 3-body fixed in fit . . .

$D^0 \to K^+\pi^-$: background fit in (M, Q)

RIGHT-SIGN:

$N_{RS} = 227\,721 \pm 497$

wrong-sign rate

$R_{WS} \equiv \frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)}$

$= (0.371 \pm 0.018)\%$

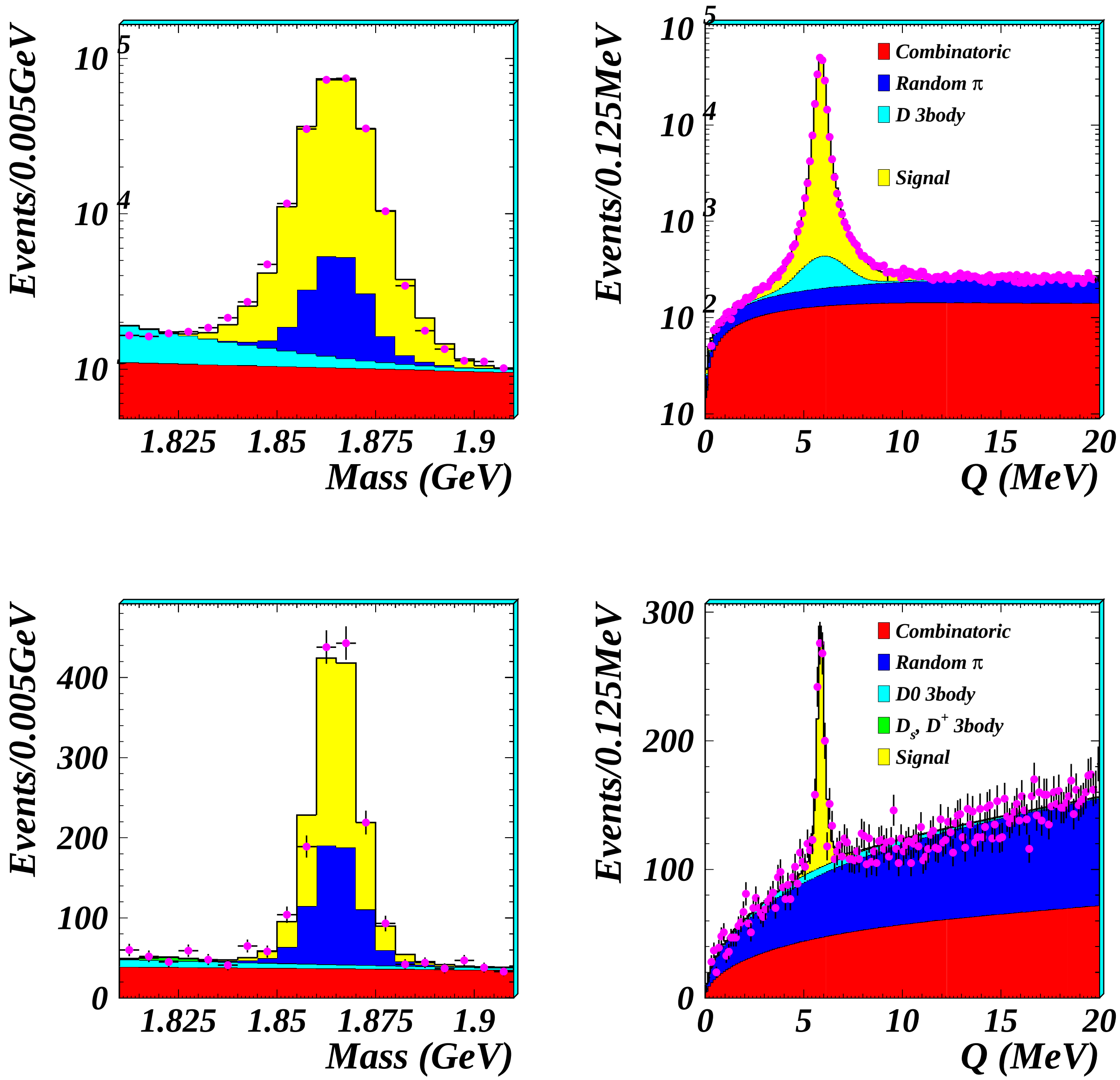
statistical only

[supersedes earlier arXiv:hep-ex/0208051]

WRONG-SIGN:

$N_{WS} = 845 \pm 40$

- ***Combinatoric***
- ***Random π***
- ***D0 3body***
- ***D_s, D^+ 3body***
- ***Signal***

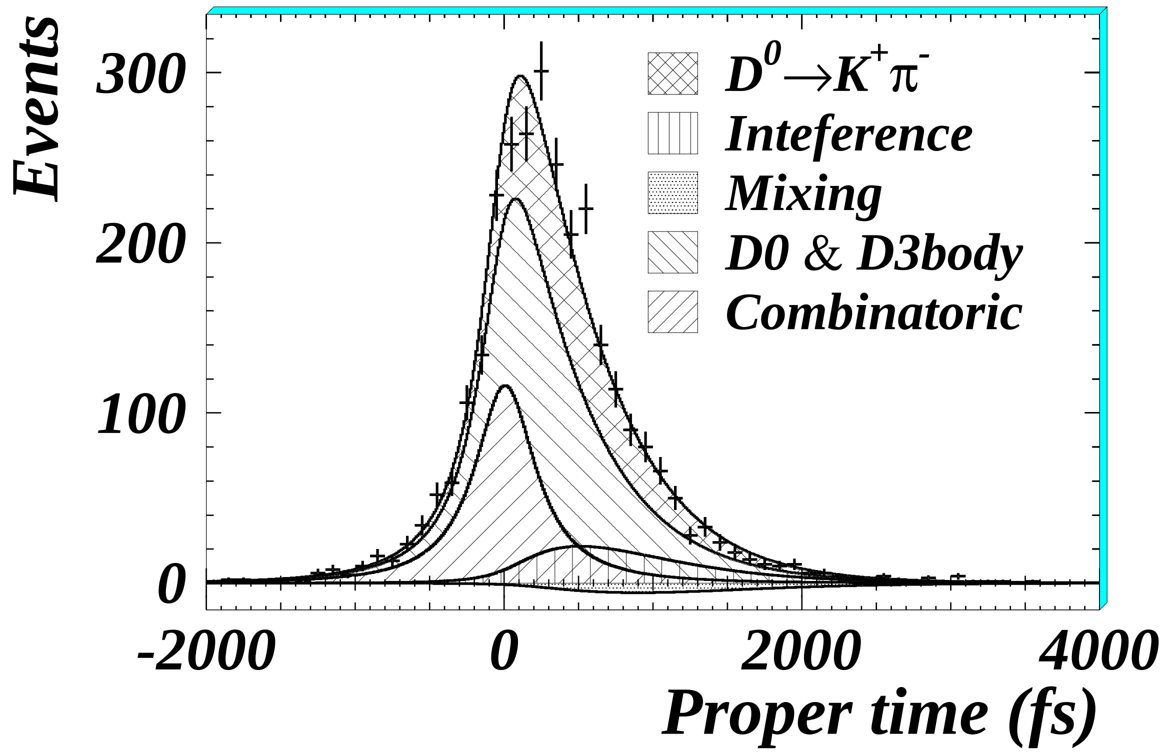


$D^0 \to K^+\pi^-$: timing fit results ($/10^{-3}$)

	R_D	y'	x'^2
mixing fit, x' free:	2.87 ± 0.37	$+25.4^{+11.1}_{-10.2}$	$-1.53^{+0.80}_{-1.00}$
mixing fit, x' fixed:	3.43 ± 0.26	$+6.0 \pm 3.3$	0

project^n of full (M, Q) region:

- $\chi^2/n_{\text{bins}} = 71.9/60$
- $x' = 0$ fixed $\mapsto$ $\chi^2/n_{\text{bins}} = 73.2/60$
- toy MC at $x' = 0$: $P(x'^2 < x'^2_{\text{fit}}) = 8\%$
- CPV fits also done (D^0, $\overline{D}^0$ separately) . . .



$D^0 \to K^+\pi^-$: timing fit results ($/10^{-3}$)

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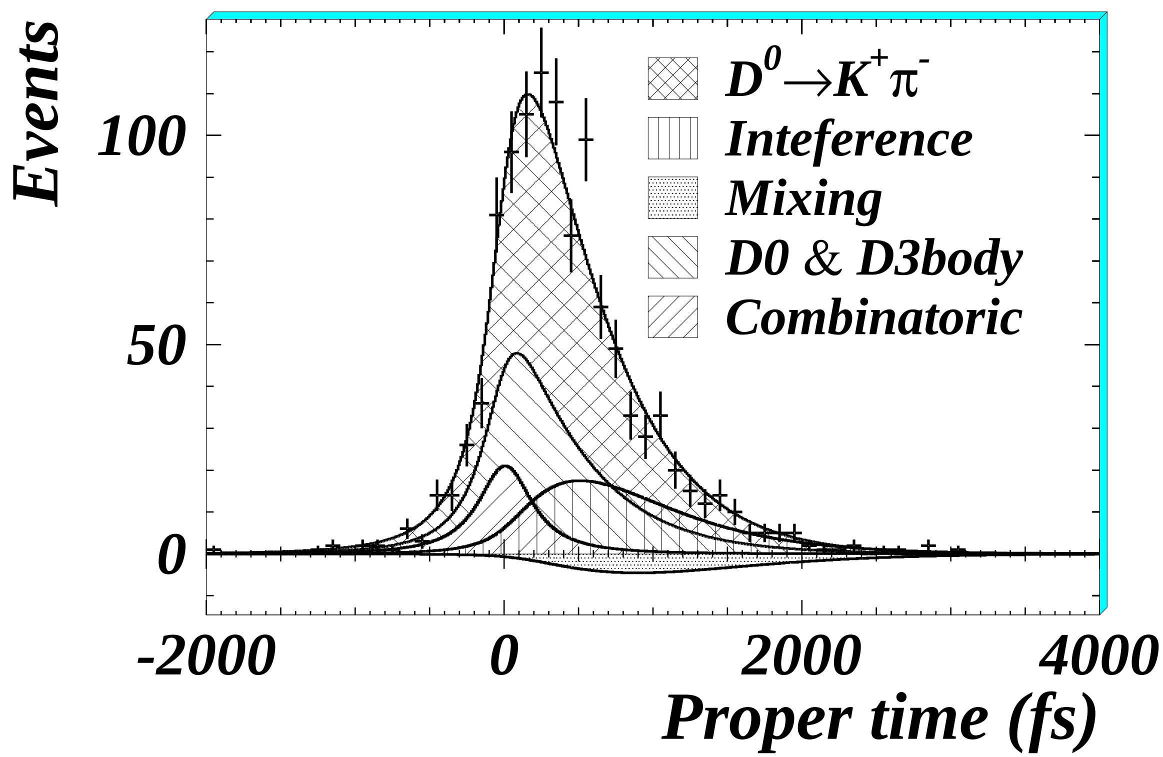
mixing fit, x' fixed:	3.43 ± 0.26	$+6.0 \pm 3.3$	0

project^n of tighter (M, Q) region:

- $\chi^2/n_{\text{bins}} = 71.9/60$
- $x' = 0$ fixed $\mapsto$ $\chi^2/n_{\text{bins}} = 73.2/60$
- toy MC at $x' = 0$: $P(x'^2 < x'^2_{\text{fit}}) = 8\%$
- CPV fits also done (D^0, $\overline{D}^0$separately)

. . .



$D^0 \to K^+\pi^-$: cross-checks / interval-setting

A number of checks were performed before unblinding the result:

- consistent time distributions/resolutions/fit procedure
- MC background parameters: sideband $\sim$ describes signal region
- MC *vs.* data: resolution functions similar
- right signal region fit: $\tau_{D^0} = 415.1 \pm 1.4\,\mathrm{ps}$; good fit
- full MC simulation: fit consistent with input (x'^2, y')
- toy MC simulation: negligible bias
  smeared per full MC

95% confidence contours are based on toy MC datasets

generated at (candidate) contour points $\vec{\alpha} = (x'^2, y')$:

the procedure implements likelihood-ratio ordering

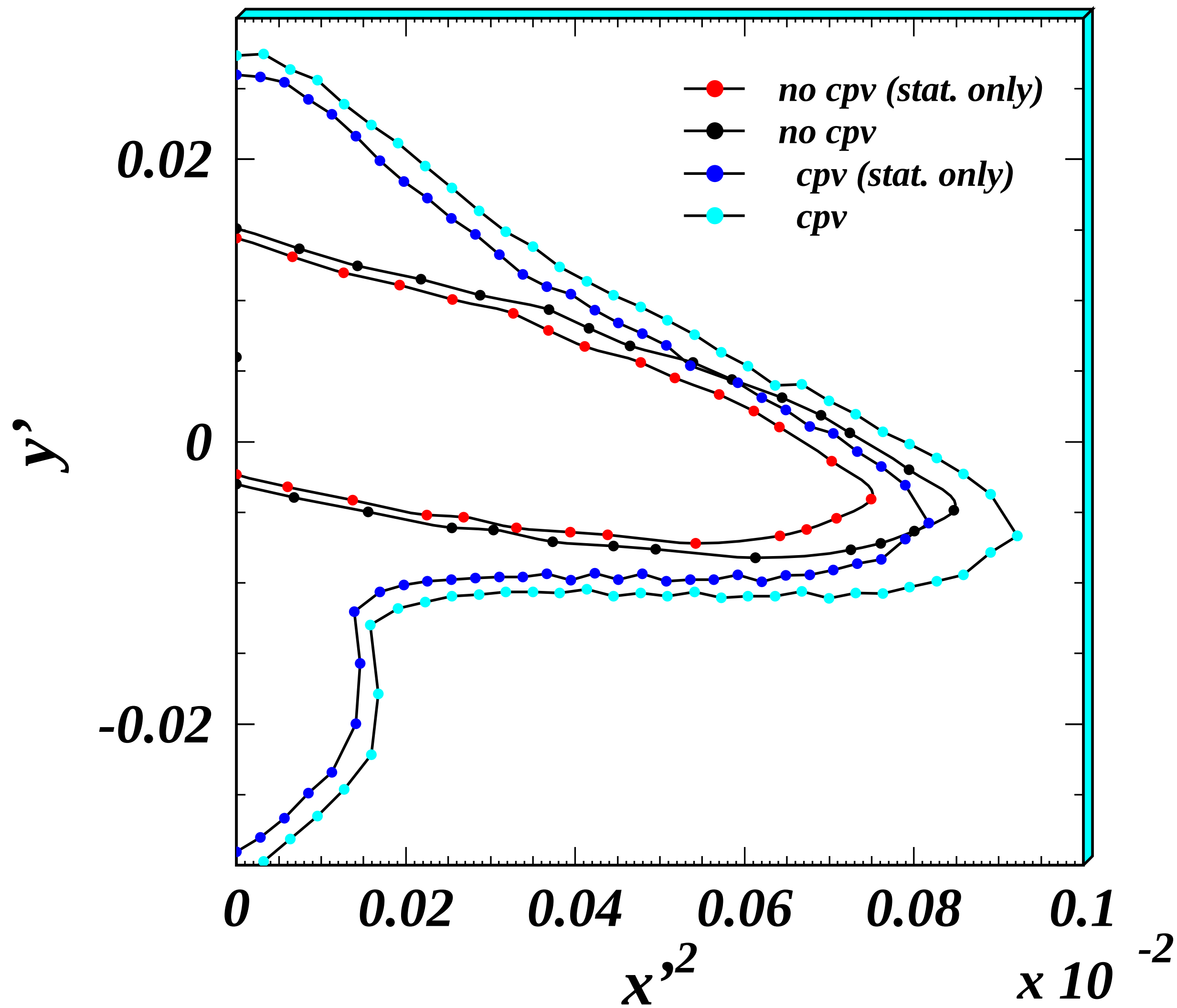
i.e. Feldman-Cousins

$D^0 \to K^+\pi^-$: 95% confidence intervals

- improves BaBar ~ 2
- intervals $\ni (0, 0)$
- systematics: scale contour points by Δ(significance)

CPV case:

- D^0: (R_D^+, x'^{+2}, y'^+)
- $\overline{D}^0$: (R_D^-, x'^{-2}, y'^-)
- combine the $D^0, \overline{D}^0$ $1 - \sqrt{0.05} = 77.6\%$ CL contours
- 2 sol^{ns}: take both
- form envelope



$D^0 \to K^+ e^- \overline{\nu}_e$: analysis method

$$\frac{dN}{dt} \propto e^{-\overline{\Gamma} t} \left[\qquad\qquad\qquad\qquad + \frac{x'^2 + y'^2}{4} (\overline{\Gamma} t)^2 \right]$$

- no DCS amplitude: decay rate proportional to R_{mix}
- we can still use the time dependence:

e^{-t}	mistagged D^0-decay background
$t \cdot e^{-t}$	NO INTERFERENCE TERM
$t^2 \cdot e^{-t}$	mixing signal

- simpler analysis, with no irreducible background

  but no $\sqrt{R_D} y'$ term to increase rate

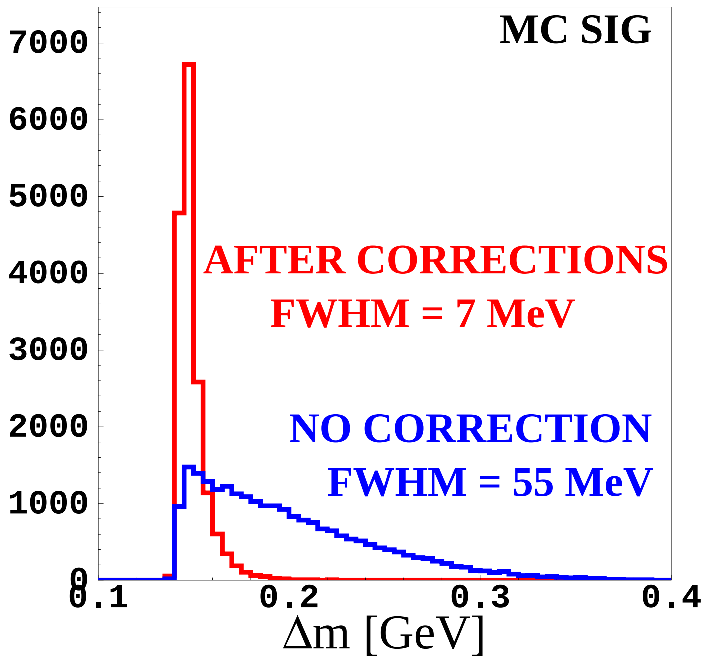
  and $\nu \longrightarrow$ lost information: background $N_B \propto \frac{dN_B}{dQ} \cdot \sigma_Q$

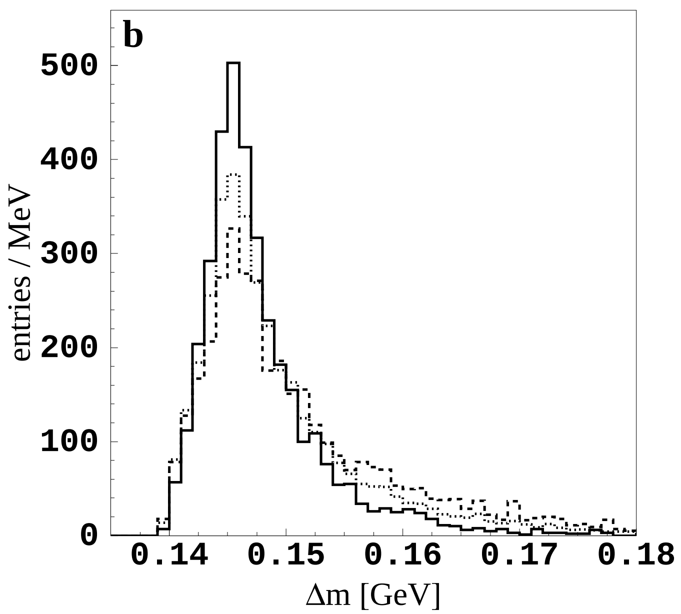
⊙ use simple t cut to suppress background [traditional]

⊙ use constraints to improve $\vec{\sigma}$ ($\vec{p}$), hence σ_Q [$\sim$ new]

$D^0 \to K^+ e^- \overline{\nu}_e$: constraints

1. take naïve $P_\nu = P_{\text{cms}} - P_{\pi\text{Ke}} - P_{\text{rest}}$
2. require $-4\,\text{GeV}^2/c^4 < M(\pi\text{Ke}\nu)^2 < 36\,\text{GeV}^2/c^4$
3. rescale P_{rest}: $M(\pi\text{Ke}\nu)^2 = (P_{\text{cms}} - x \cdot P_{\text{rest}})^2 \equiv m_{\text{D}^*}$
4. require $-2\,\text{GeV}^2/c^4 < P_\nu^2 < 0.5\,\text{GeV}^2/c^4$
5. rotate $\vec{p}_{\text{rest}}$: $m_\nu^2 = (E_{\text{cms}} - E_{\pi\text{Ke}} - E_{\text{rest}})^2 - p_{\pi\text{Ke}}^2 - p_{\text{rest}}^2 - 2p_{\pi\text{Ke}}p_{\text{rest}}\cos\alpha \equiv 0$

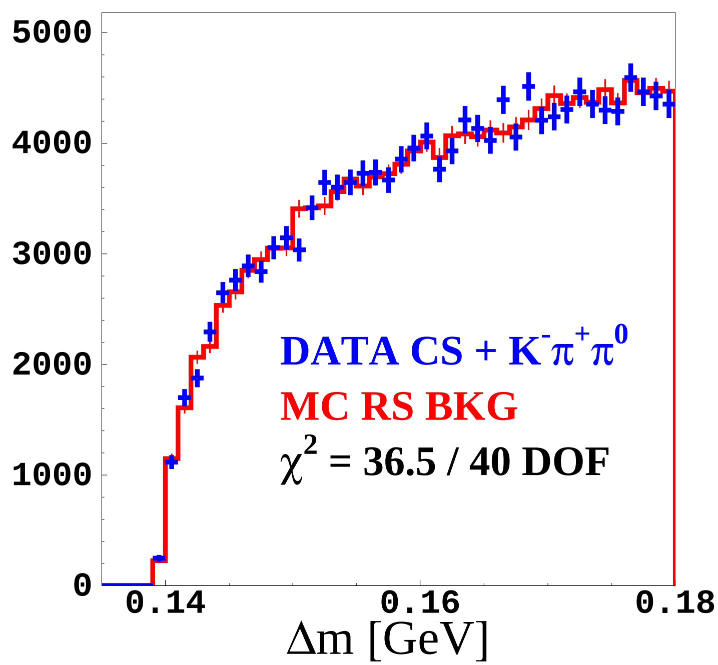




$D^0 \to K^+ e^- \overline{\nu}_e$: background modelling

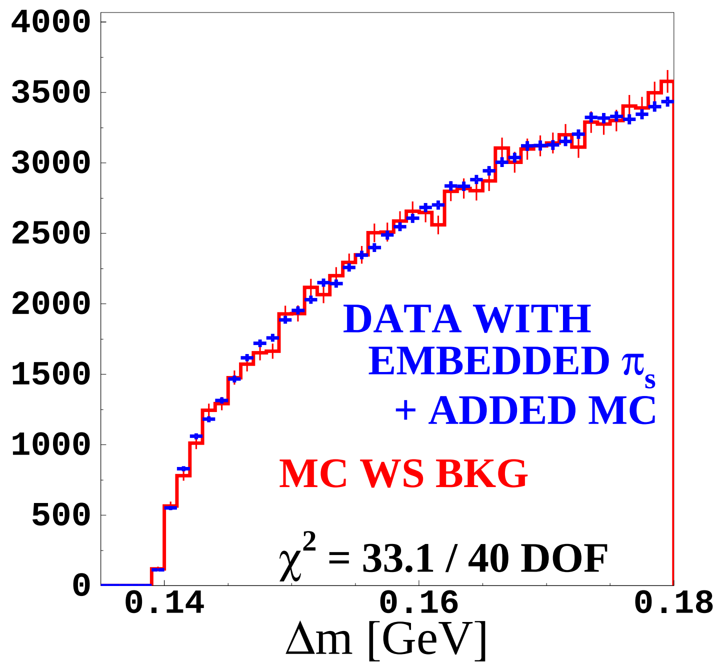
- suppress photon conversions, serious when $e^+e^- \xrightarrow{\text{ID}} \pi^+_{\text{slow}} e^-$: $M(e^+e^-) > 150\,\text{MeV}/c^2$ $\forall$ combinations with π^+_{slow} or e^-
- model backgrounds using data, with MC corrections:

right sign:



“combinatorial sign” $K^\pm e^\pm$
+ MC charge-correlated: $K^-\pi^+\pi^0$

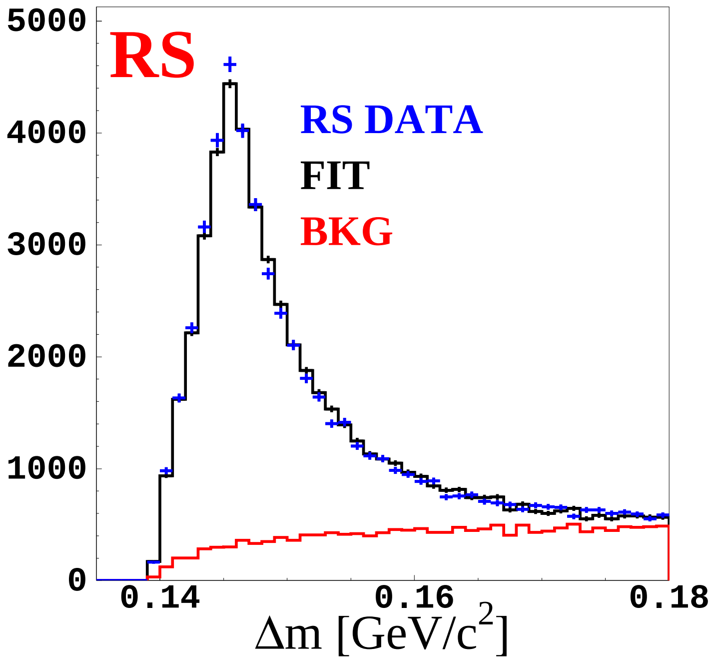
wrong sign:



event mixing for (un)correlated bkgd
+ MC ang-correlated: $K^-\pi^+\pi^0$

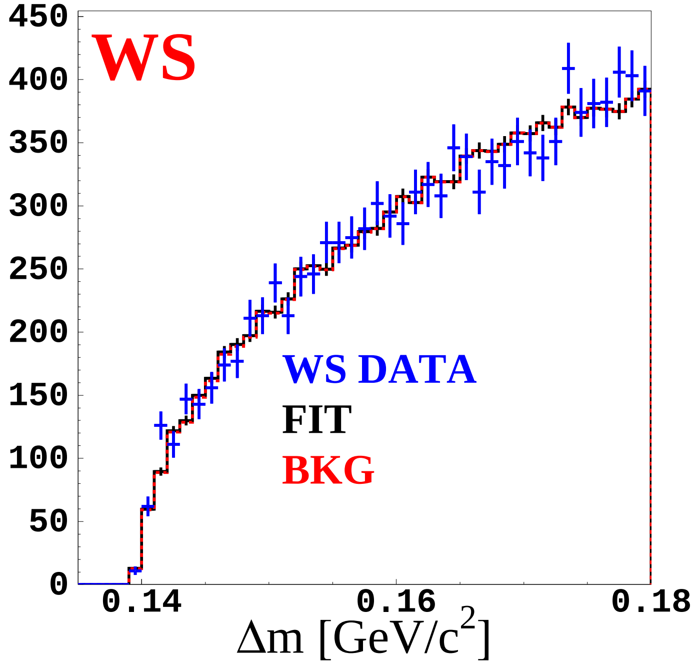
$D^0 \to K^+ e^- \overline{\nu}_e$: Δm fit with $t > \tau_{D^0}$

right sign:



$N_{RS} = 40198 \pm 329$

wrong sign:



$N_{WS} = 19 \pm 67$

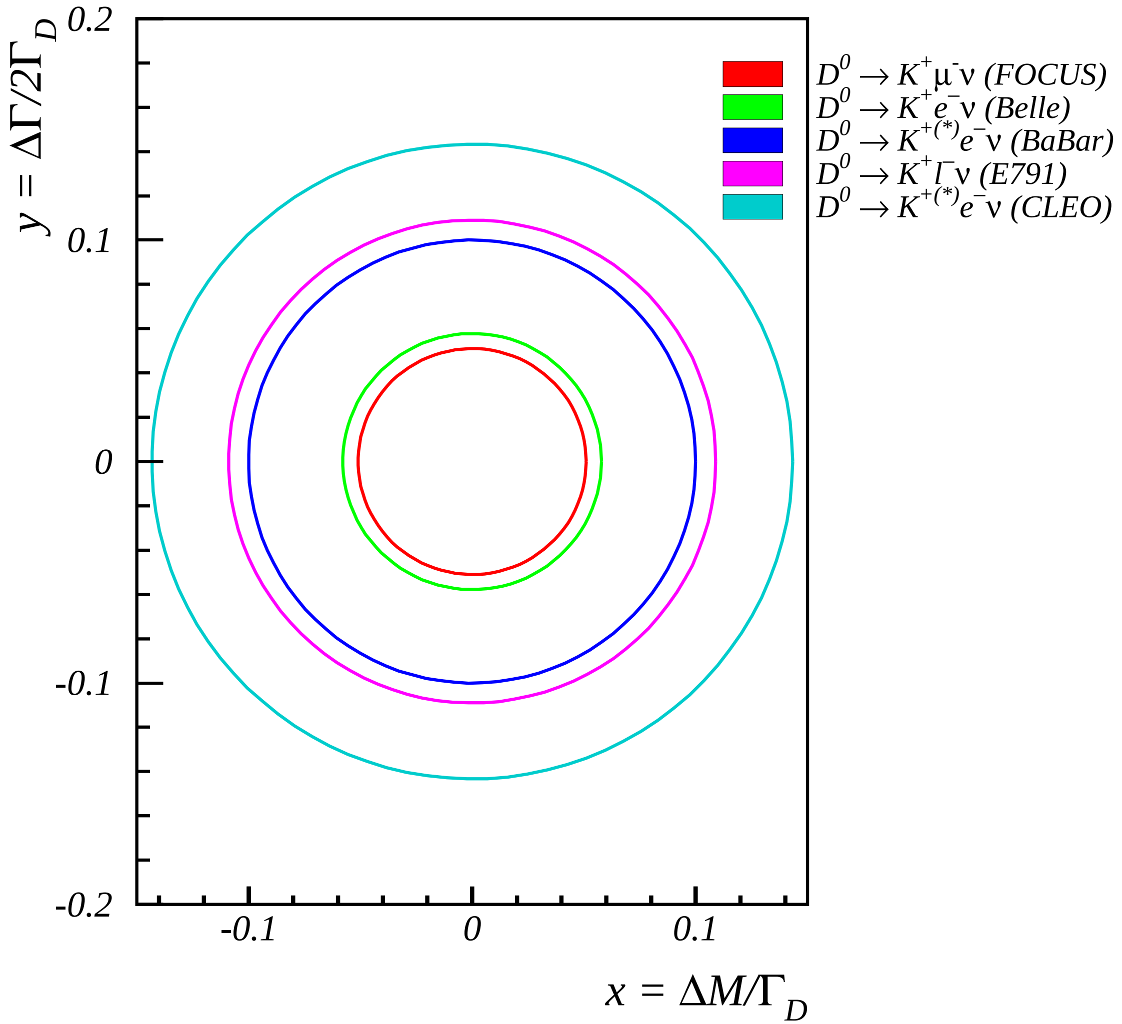
$$r_D = (0.20 \pm 0.70 \pm 0.11) \times 10^{-3}$$
$$< 1.4 \times 10^{-3} \text{ @ } 90\% \text{ CL}$$

D^0-$\overline{D}^0$ mixing summary (semileptonic)

From G. Burdman and I. Shipsey, `arXiv:hep-ph/0310076`, updated 20-Aug-2004:

`arXiv:hep-ex/0408112`

- most restrictive save the FOCUS thesis (unpublished 2002)
- extending: 2× data
- adding $K^+\mu^-\overline{\nu}_\mu$
- → *PRD* this year
- *cf.* the reach of . . .

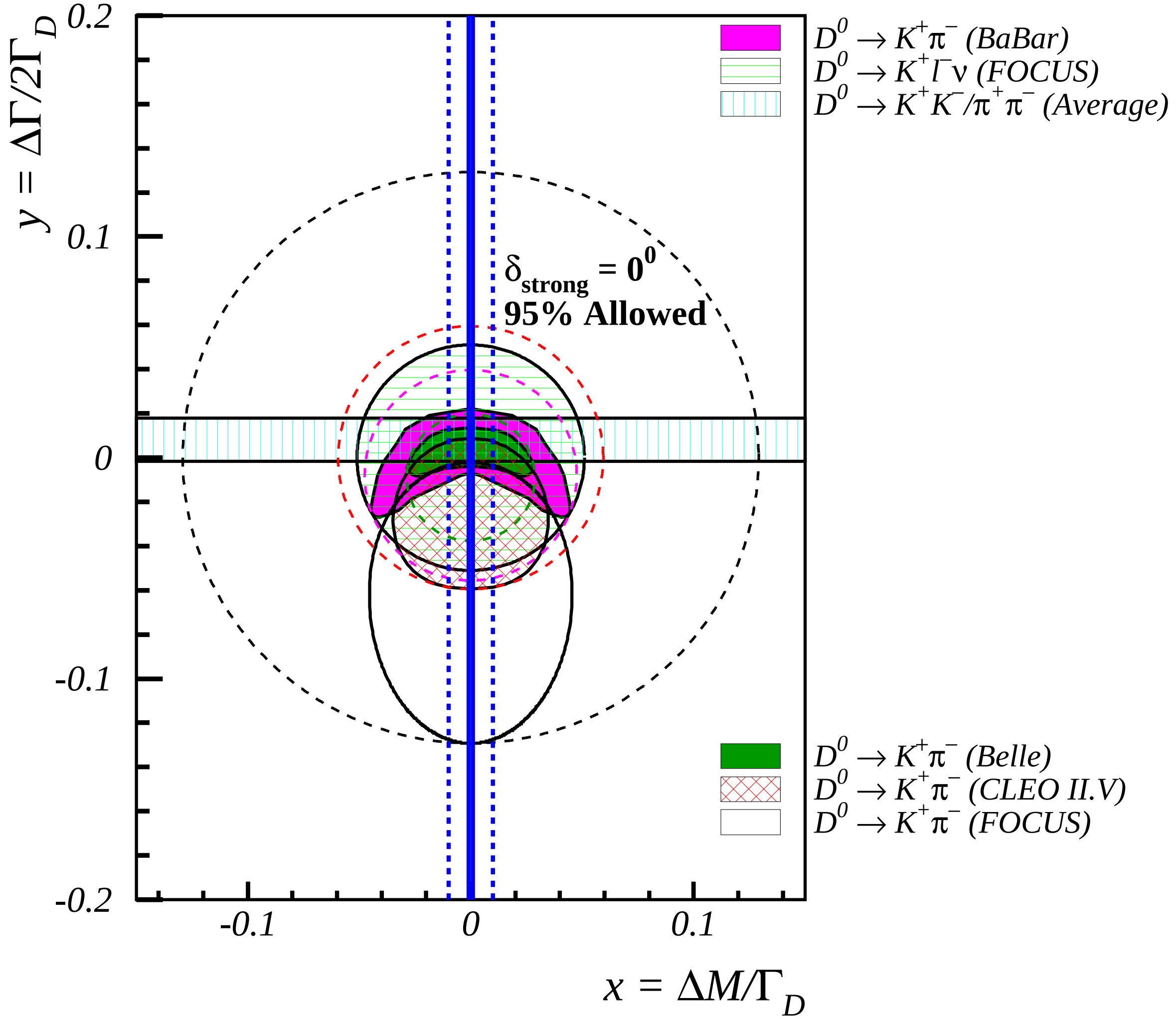


D^0-$\overline{D}^0$ mixing summary (all)

From G. Burdman and I. Shipsey, `arXiv:hep-ph/0310076`, updated 20-Aug-2004:

`arXiv:hep-ex/0408125`

- most restrictive single result
- $\rightarrow$ *PRL* now
- *cf.* y_{CP} . . .
- note $\delta_{K\pi}$ unknown
- reached % level



BACKUP SLIDES

The Belle Collaboration

~400 physicists from 13 regions, 59 institutions

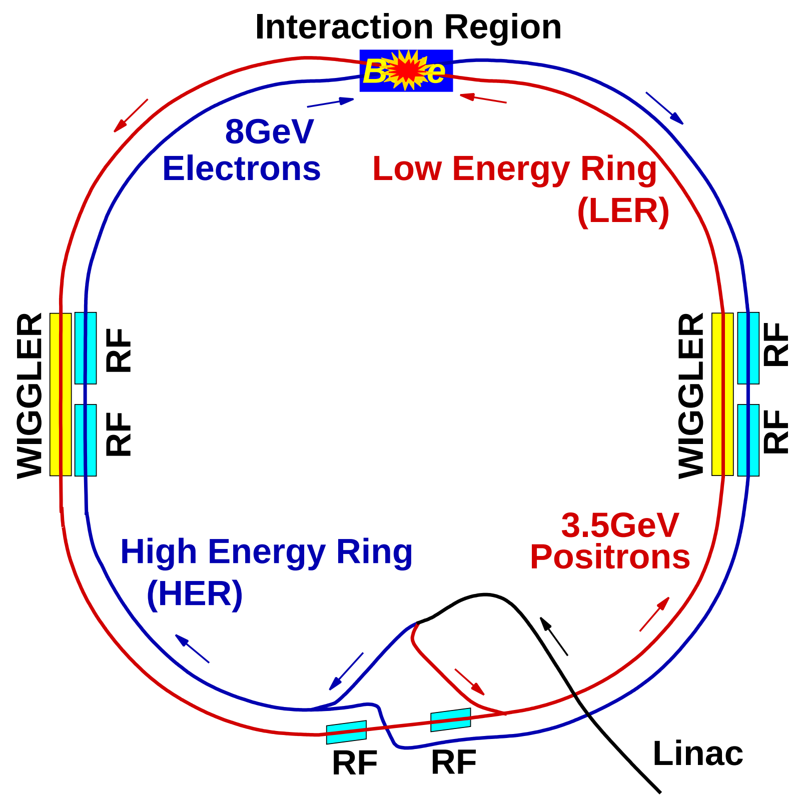
Aomori University
Budker Institute of Nuclear Physics
Chiba University
Chonnan National University
Chuo University
University of Cincinnati
Ehwa Womens University
University of Frankfurt
Gyeongsang National University
University of Hawaii
Hiroshima Institute of Technology
IHEP, Beijing
IHEP, Vienna
ITEP, Moscow
Kanagawa University
KEK
Korea University
Krakow Institute of Nuclear Physics
Kyoto University
Kyungpook National University
Swiss Federal Institute of Technology, Lausanne
Jozef Stephan Institute, University of Ljubliana
University of Maribor
University of Melbourne
Nagoya University
Nara Women's University
National Central University
National Kaoshiung Normal University
National Lien-Ho Institute of Technology
Nihon Dental College
Niigata University
Osaka University
Osaka City University
Panjab University
Peking University
Princeton University
Riken/BNL
Saga University
USTC
Seoul National University
Shinshu University
University of Sydney
Tata Institute
Toho University
Tohoku University
Tohoku Gakuin University
University of Tokyo
Tokyo Institute of Technology
Tokyo Metropolitan University
Tokyo University of Agriculture and Technology
Toyama National College
University of Tsukuba
Utkal University
Virginia Polytechnic Institute
Yonsei University

The Belle experiment: collider

The "KEKB" asymmetric energy e^+e^- collider:

- 3.5 GeV e^+ on 8.0 GeV e^-
- $\sqrt{s} = 10.58\,\text{GeV} \equiv M(\Upsilon(4S))$
- continuous injection
- peak performance:
  - $1.39 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ $= 14\,\text{nb}^{-1}\,\text{s}^{-1}$
  - $944\,\text{pb}^{-1}/\text{day}$

  cf. $\sigma_{\Upsilon(4S)} \approx 1\,\text{nb}$, $\sigma_{c\bar{c}} \approx 1.3\,\text{nb}$
- $\int \text{d}t\,\mathcal{L} > 287\,\text{fb}^{-1}$

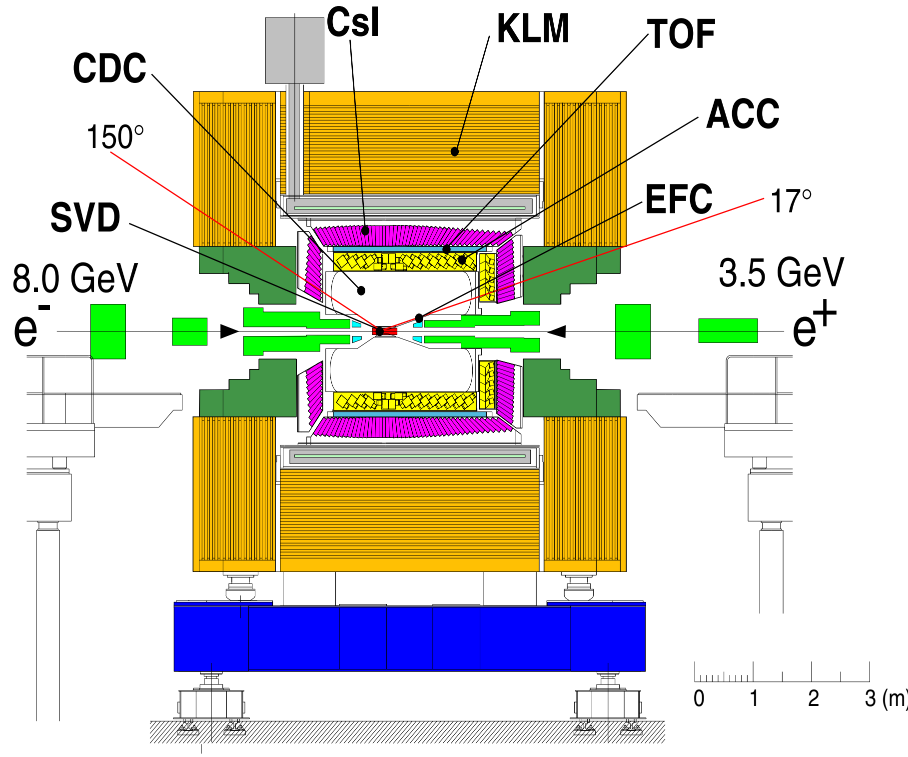


single collision point instrumented with . . .

The Belle experiment: dataset and detector

e^+e^- at $\sqrt{s} = 10.58\,\mathrm{GeV}$: $90\,\mathrm{fb}^{-1}$ $(K^+\pi^-)$, $140\,\mathrm{fb}^{-1}$ $(K^+e^-\overline{\nu}_e)$

- 1.5 T solenoid
- 3-layer SVD, 50-layer CDC
- $\frac{\sigma_{p_T}}{p_T} = (0.19 p_T \oplus 0.3)\%$
- $\sigma_{xy} = \left(19 \oplus \frac{49}{p\beta \sin^{3/2}\theta}\right)\,\mu\mathrm{m}$
- $\sigma_z = \left(28 \oplus \frac{41}{p\beta \sin^{5/2}\theta}\right)\,\mu\mathrm{m}$
- $\frac{\sigma_E}{E} = \left(1.3 \oplus \frac{0.07}{E} \oplus \frac{0.8}{E^{1/4}}\right)\%$
- PID: $\begin{cases} \sigma_{\mathrm{d}E/\mathrm{d}x} = 6.9\% \\ \sigma_{TOF} = 95\,\mathrm{ps} \\ \text{aerogel Čerenkov} \end{cases}$

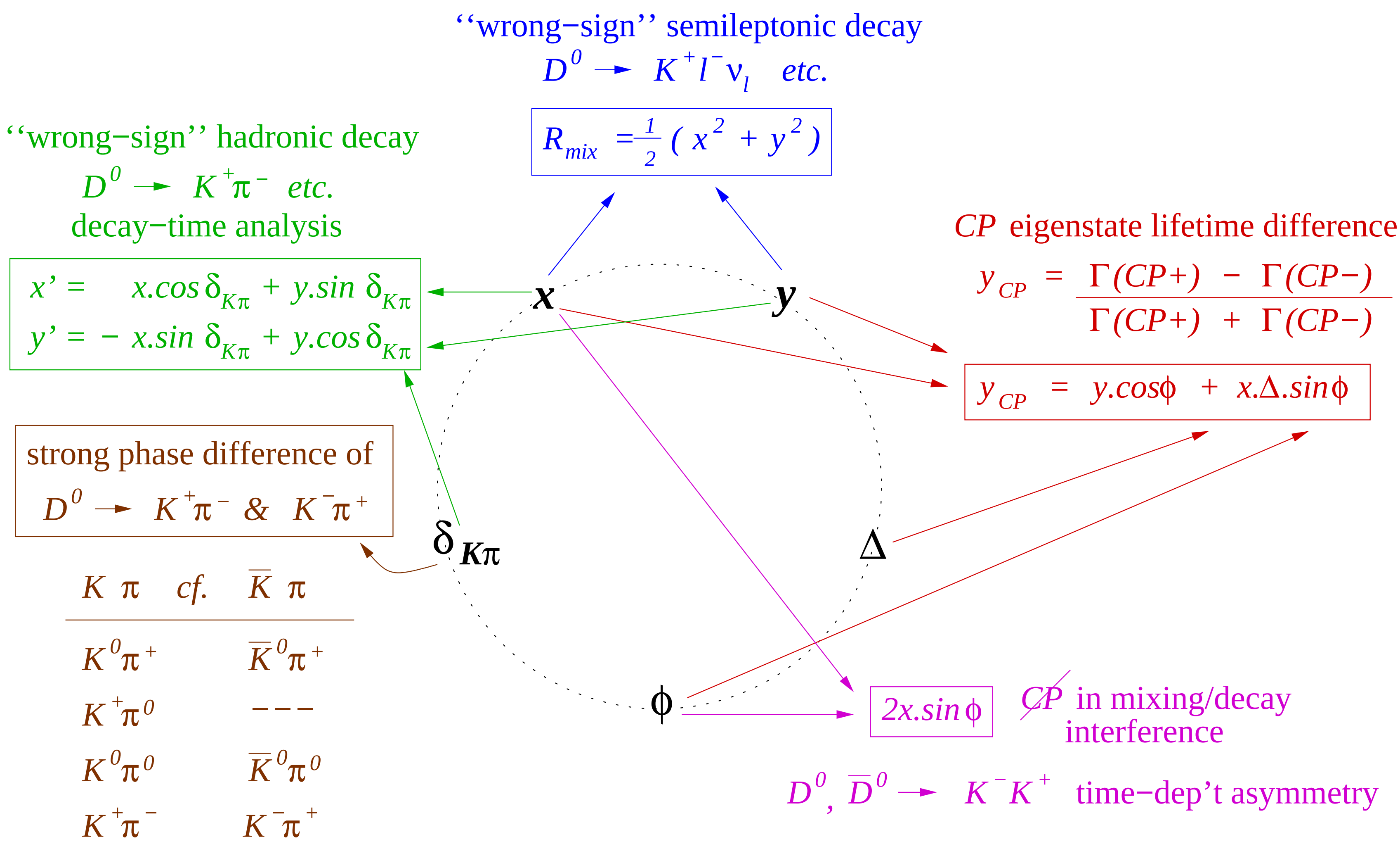


+ ECAL, $\mathrm{d}E/\mathrm{d}x$ *etc.* for $e^\pm$ ID ...

+ the KLM (K_L^0 and μ system) ...

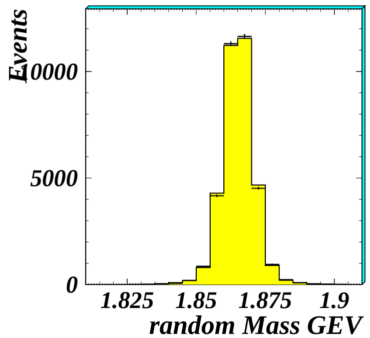
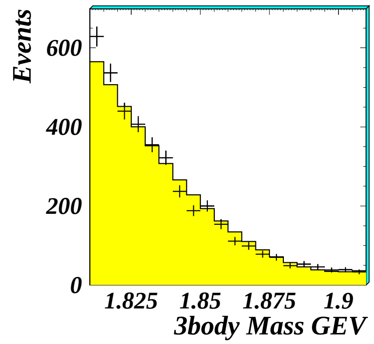
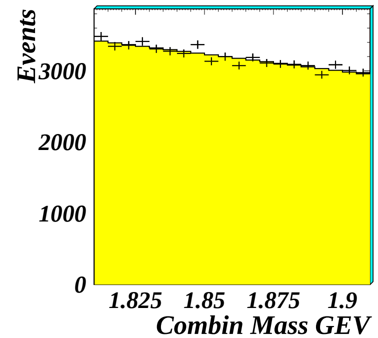
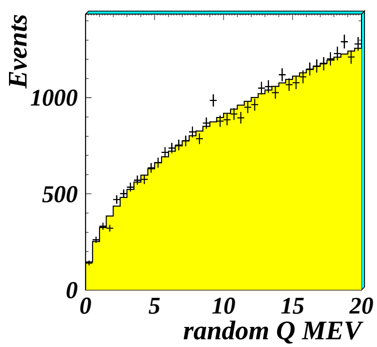
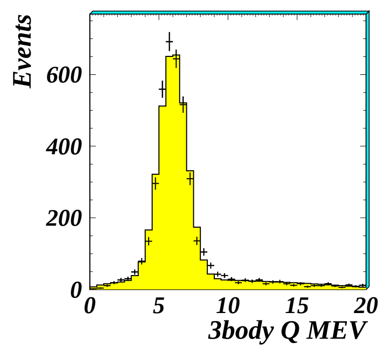
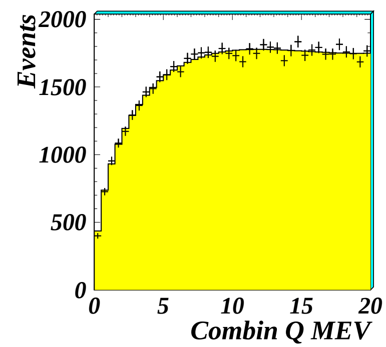
$\epsilon(K^\pm) \approx 85\%$ for $\pi^\pm$ fake-rate $\lessapprox 10\%$ up to $3.5\,\mathrm{GeV}/c$

D^0-$\overline{D}^0$ parameters and measurements



$D^0 \to K^+\pi^-$: backgrounds [with differing $f(t)$]

MC right-sign backgrounds (*cf.* wrong-sign breakdown)

	"random π_{slow}"	D^0 3-body	D^+, D_s^+	combinatorial
M			[negligible]	
Q			[negligible]	

negligible D^+, D_s^+ background in this case

$D^0 \to K^+\pi^-$: timing distributions & resolution

bkgd:	random π_{slow}	D^0 3-body	D^+, D_s^+	comb^l
$f_i(t)$	$\exp(-t/\tau_{D^0})$	$\exp(-t/\tau_{D3b})$	$\exp(-t/\tau_{Dch})$	$\delta(t)$
τ param.	PDG	sideband	MC	—
resolution	$\mathcal{R}_{\mathrm{signal}}$	$\mathcal{R}_{\mathrm{signal}}$	$\mathcal{R}_{\mathrm{signal}}$	$\mathcal{R}_{\mathrm{comb}}$

$$\mathcal{R}(t_i,\, t';\, \sigma_{t,i}) = (1 - f_{\mathrm{tail}})\mathcal{G}(t_i - t';\, \mu,\, S\sigma_{t,i}) + f_{\mathrm{tail}}\mathcal{G}(t_i - t';\, \mu,\, S_{\mathrm{tail}}\sigma_{t,i})$$

Beginning with a simplified background model,

- fit 1: RS signal region $\longrightarrow$ provisional $\mathcal{R}_{\mathrm{signal}}$ parameters
- fit 2: RS sideband region $\longrightarrow$ $\mathcal{R}_{\mathrm{comb}}$ parameters & τ_{D3b} for RS
- fit 3: RS signal region $\longrightarrow$ $\mathcal{R}_{\mathrm{signal}}$ parameters; τ_{D^0} as check
- fit 4: WS sideband region $\longrightarrow$ $\mathcal{R}_{\mathrm{comb}}$ parameters & τ_{D3b} for WS
- fit 5: WS signal region $\longrightarrow$ FINAL RESULT

$D^0 \to K^+\pi^-$: CPV parametrization

- $A_D = (R_D^+ - R_D^-)/(R_D^+ + R_D^-)$: CPV in DCS decay
- $A_M = (R_M^+ - R_M^-)/(R_M^+ + R_M^-)$: CPV in D^0-$\overline{D}^0$ mixing

  where $R_M^{\pm} = 0.5(x'^{\pm 2} + y'^{\pm 2})$
- ϕ (weak phase): CPV in interference of DCS/mixed amplitudes

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

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

convention-independent set ($x' \sin\phi$, $y' \cos\phi$, $(x'^2 + y'^2)$)

also suggested in the literature

$D^0 \to K^+\pi^-$: interval-setting procedure

For points $\vec{\alpha} = (x'^2, y')$

- generate ensemble of toy MC datasets $\{X_i\}_j$
- $\forall j$, fit the dataset $\{X_i\}$ and
  - record $\Delta\ell_j = \ln \mathcal{L}_j^{\max} - \ln \mathcal{L}_j\ (\vec{\alpha})$
  - compare with $\Delta\ell_{\mathrm{data}} = \ln \mathcal{L}_{\mathrm{data}}^{\max} - \ln \mathcal{L}_{\mathrm{data}}(\vec{\alpha})$
- do 95% of the $\{X_i\}_j$ have $\Delta\ell_j\ < \Delta\ell_{\mathrm{data}}$??

  if yes, this α is on the contour

  if no, choose another α [a search strategy is used]

The resulting contour implements likelihood-ratio ordering (Feldman-Cousins) without having to generate ensembles $\forall\alpha$

Taken from B.Aubert *et al.* (BaBar), *Phys. Rev. Lett.* **91**, 171801 (2003).