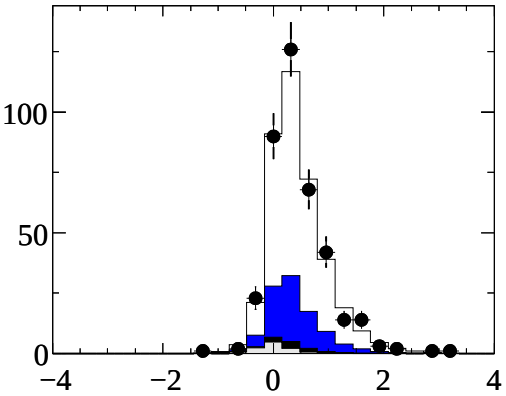
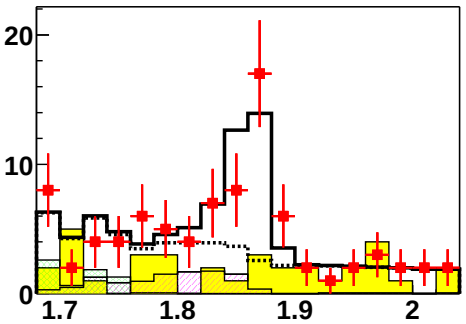
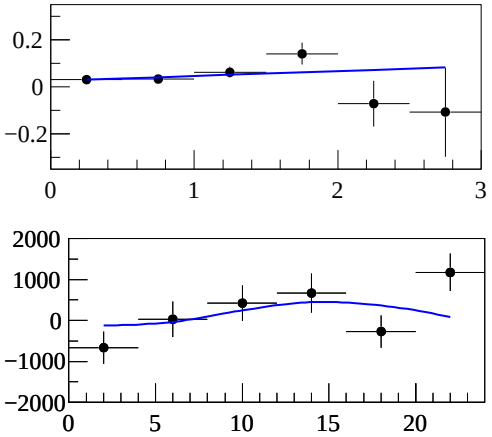
Experimental limits on New Physics from charm decay







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http://belle.kek.jp/~yabsley/

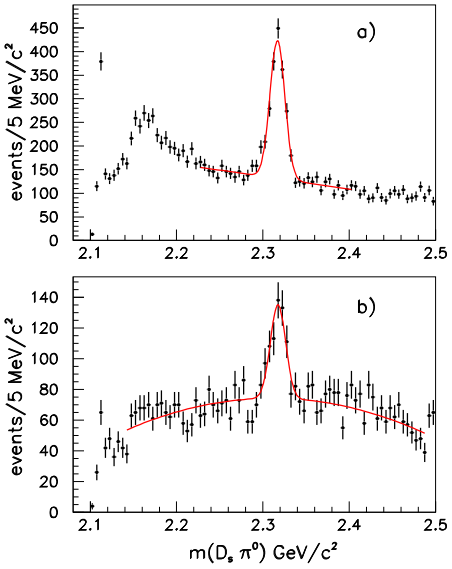
Lepton Photon 2003, Fermilab, 12th August 2003

What I'm *not* talking about ... (1)

BaBar

$D_{sJ}(2317) \to D_s\pi^0$:

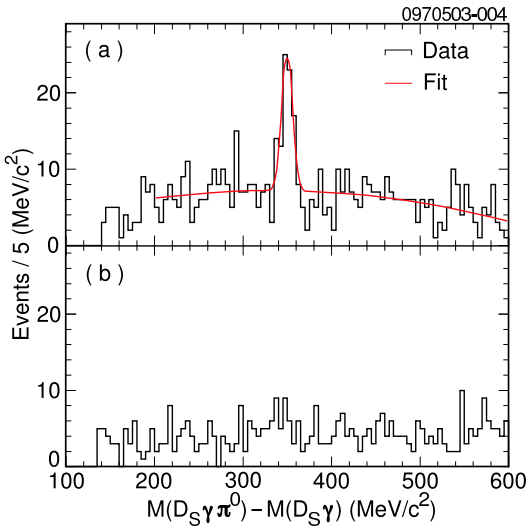
PRL **90**, 242001



CLEO

$D_{sJ}(2457) \to D_s^*\pi^0$:

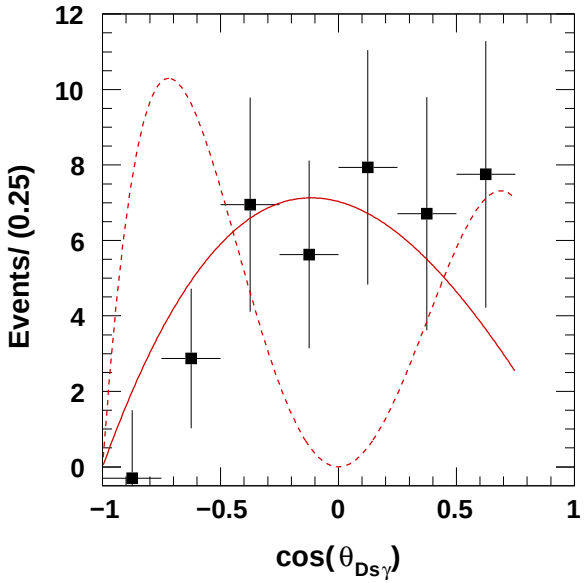
hep-ex/0305100 $\longrightarrow$ *PRD*



Belle

$B \to \overline{D}D_{sJ}$: hep-ex/0308019 $\longrightarrow$ *PRL*

$c \to D_{sJ}$: hep-ex/0307041 $\longrightarrow$ update

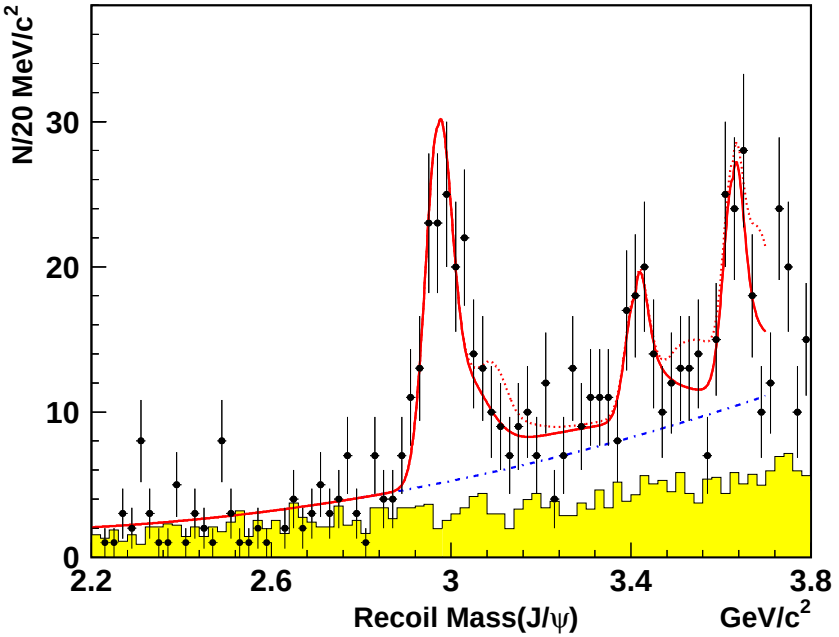


- *decays* consistent with 0^+ (2317) & 1^+ (2457) of $c\bar{s}$ $(L = 1,\ j_q = \frac{1}{2})$
- *masses* are a mystery: we thought we understood $c\bar{q}$; we don't
- $\longrightarrow$ Jussara de Miranda's *Charm (SM)* talk

What I'm *not* talking about ... (2)

PRL **89**, 142001 (2002); updated LP–274 (BELLE–CONF–0331)

- $\sigma(e^+e^- \to \psi\,\eta_c) \times \mathcal{B}(\eta_c \to \geq 4\,\mathrm{pr})$
  $= \left(46 \pm 6^{+7}_{-9}\right)$ fb
  $=$ 10$\times$ NRQCD prediction
- $e^+e^- \to \gamma^*\gamma^* \to \psi\psi$ contribution to the $\psi\eta_c$ peak is negligible (*cf. PRD* **67**, 054023 (2003))
- ψ + open charm remains large:



$$\left.\frac{\sigma(e^+e^- \to \psi\, c\bar{c})}{\sigma(e^+e^- \to \psi\, X)}\right|_{p_\psi > 2.0\ \mathrm{GeV}/c} = 0.82 \pm 0.15 \pm 0.14 \simeq 10\times \text{ NRQCD prediction}$$

- we thought we understood $c\bar{c}$ production at this energy; we don't
- $\longrightarrow$ Tomasz Skwarnicki's *quarkonium* talk

What I *am* talking about

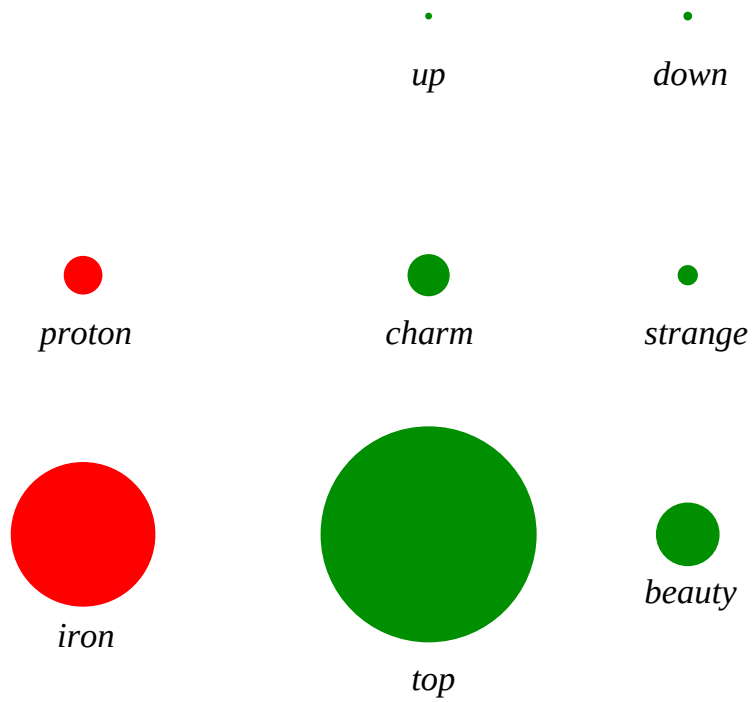
- *clear* signatures of New Physics?
- D^0-$\overline{D}^0$ mixing:
  - phenomenology
  - lifetime difference (y_{CP})
  - $D^0 \to K^+\pi^-$ time-dependent
  - issues and future measurements
- CP, CPT and Lorentz invariance violation
- rare and forbidden decays: FCNC, LFV, LNV . . .
  - phenomenology
  - $D^0 \to \gamma\gamma$, $D^0 \to \ell^+\ell^-$ . . .
  - $D \to h\ell\ell$
  - $D^0 \to V\gamma$
- summary and prospect

clear signatures of New Physics?

It can be hard to know what the SM prediction is:

the charm mass is awkward

- $m_u < m_d \ll \lambda_{QCD}$
  $\longrightarrow$ usefulness of isospin
- beauty quark has $m_b > \lambda_{QCD}$:
  - $\approx$ a HEP "particle"
  - a "billiard ball with quantum numbers attached"
- charm is in-between, $m_c \gtrsim \lambda_{QCD}$
- should think i.t.o *hadrons*



"Long-distance" hadronic contributions are important:

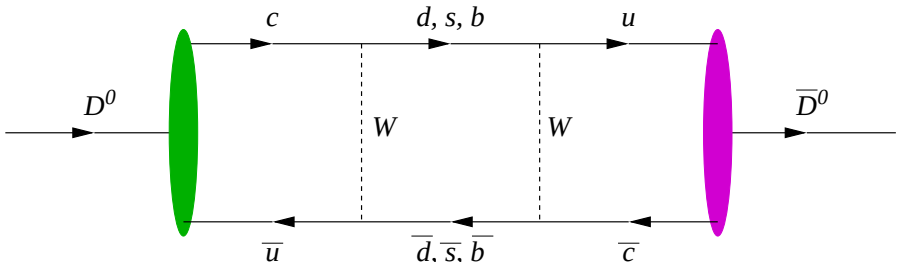
- suppression of quark loops $\longrightarrow$ LD terms lead
- difficult to calculate; note $m_c \sim$ resonance region
- care is needed when interpeting discrepancies as "New Physics"

D^0-$\overline{D}^0$: mixing in the SM & beyond (1)

SM box diagrams

Cabibbo suppressed

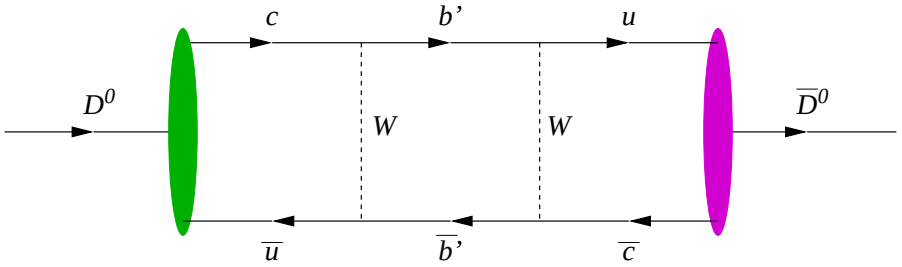
GIM suppressed



New Physics, new loops

raises $x \equiv \Delta M/\Gamma$ (not y?)

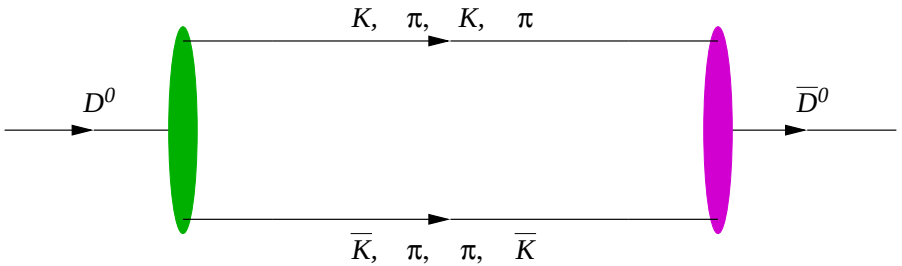
less (or no) cancellation



SM long distance

e.g. hh ($SU(3)_F$ breaking)

raises $y \equiv \Delta\Gamma/\Gamma$



"D^0-$\overline{D}^0$ mixing with measurable x is a signal of New Physics"

D^0-$\overline{D}^0$: mixing in the SM & beyond (2)

SM via the OPE

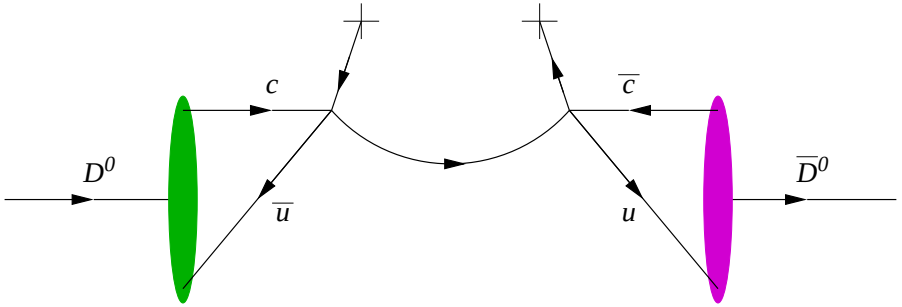
higher order diagrams . . .

still Cabibbo suppressed

other suppressions lifted

$\rightarrow x \sim y \sim O(10^{-3})$

OK within QHD . . .



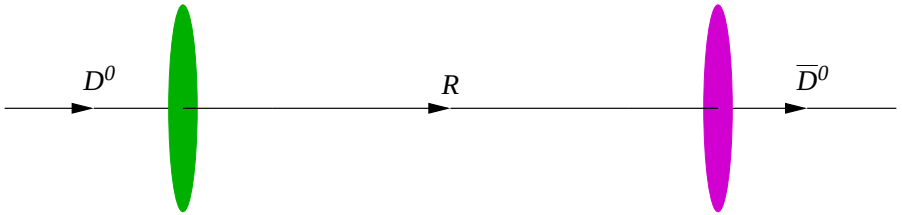
resonance contributions

one of the harder things

to estimate

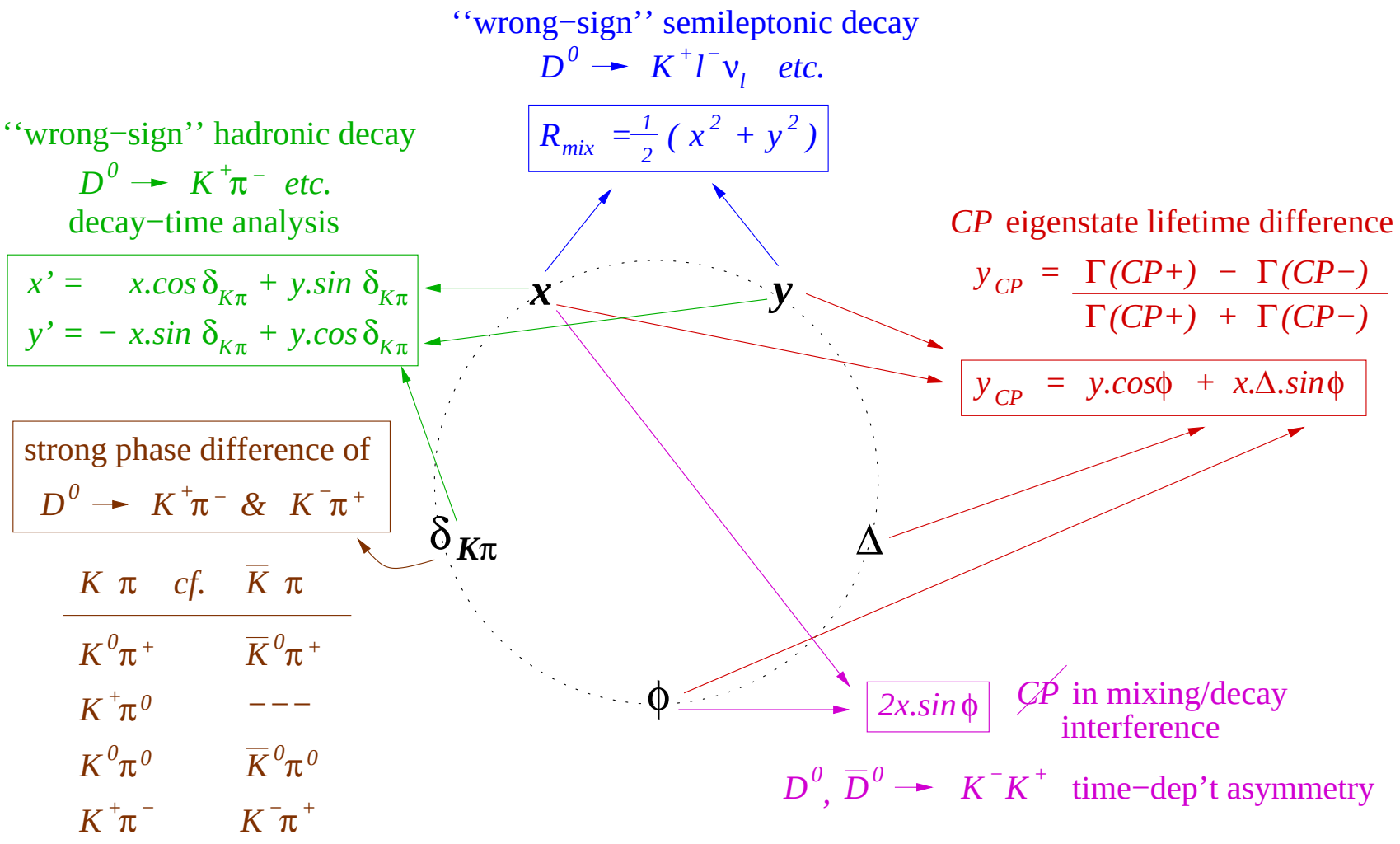
affects y ($< 10^{-2}$?);

effect on x unclear



Hope for large x, small y . . .

D^0-$\overline{D}^0$: mixing parameters & measurements



y_{CP} (1): the FOCUS measurement

$$y_{CP} \equiv \frac{\Gamma(CP+) - \Gamma(CP-)}{\Gamma(CP+) + \Gamma(CP-)} = \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to K^-K^+)} - 1$$

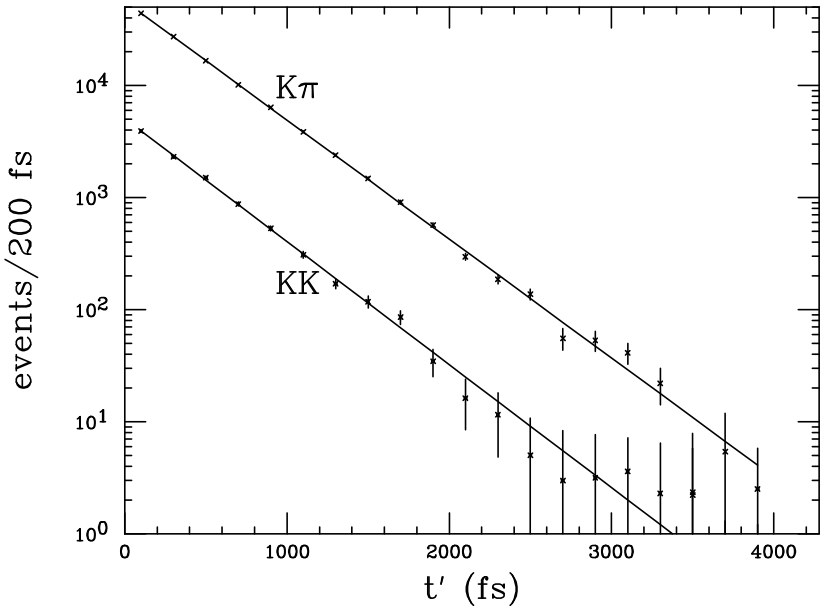
$\longrightarrow y$ in the CP-conserving limit

FOCUS $D^0 \to K^-\pi^-$, K^-K^+:

Phys. Lett. **B 485**, 62–70 (2000)

- inclusive & D^*-tagged
- $D^0 \to K^- h^+$ & PID cuts
- detached vertex cuts
- fit $t' \equiv \frac{l - N.\sigma_l}{\beta\gamma c}$

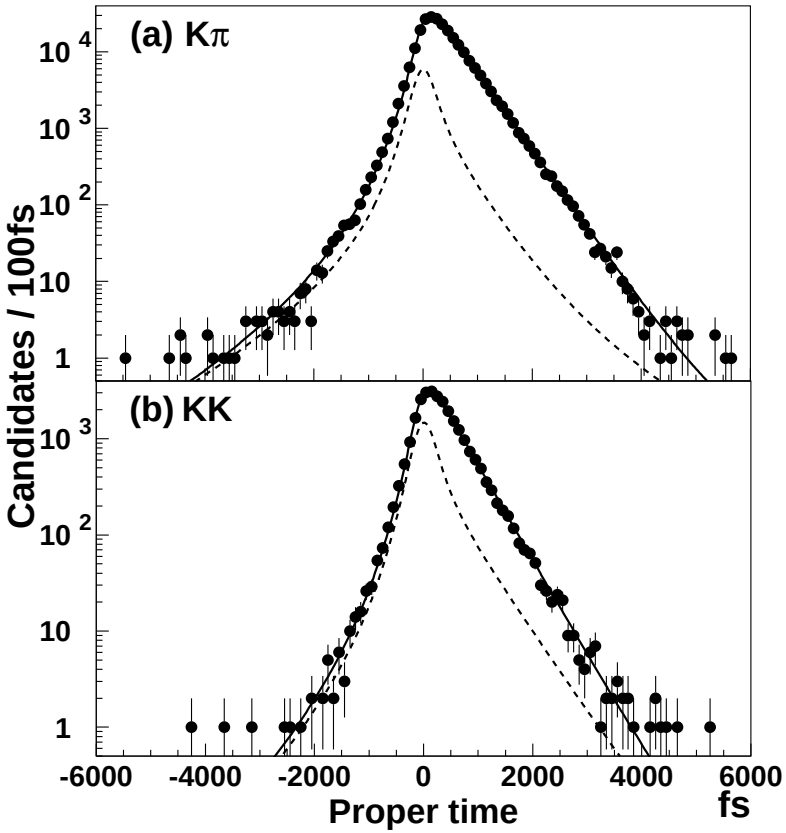
$y_{CP} = (3.42 \pm 1.39 \pm 0.74)\%$



y_{CP} (2): Belle 2001 / CLEO 2002

Belle $D^0 \to K^+K^-$ *vs.* $K^-\pi^-$

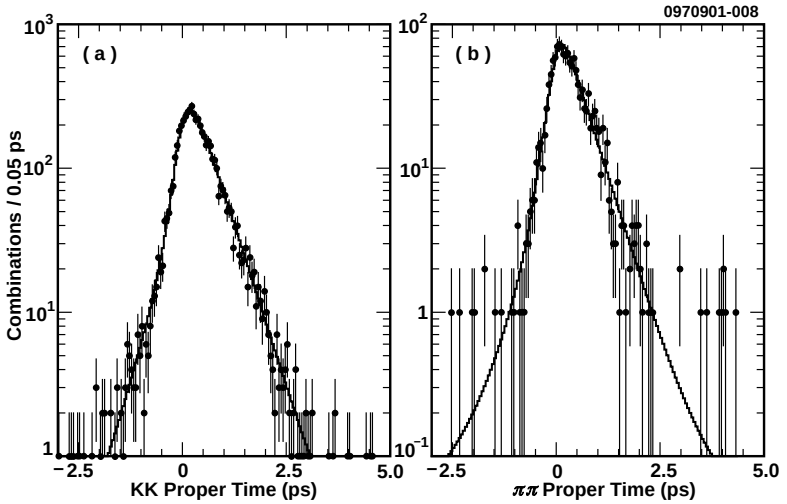
PRL **88**, 162001 (2002)



$$y_{CP} = \left(-0.5 \pm 1.0^{+0.7}_{-0.8}\right)\%$$

CLEO $D^0 \to K^+K^-, \pi^+\pi^-$ *vs.* $K^-\pi^-$

PRD **65**, 092001 (2002)

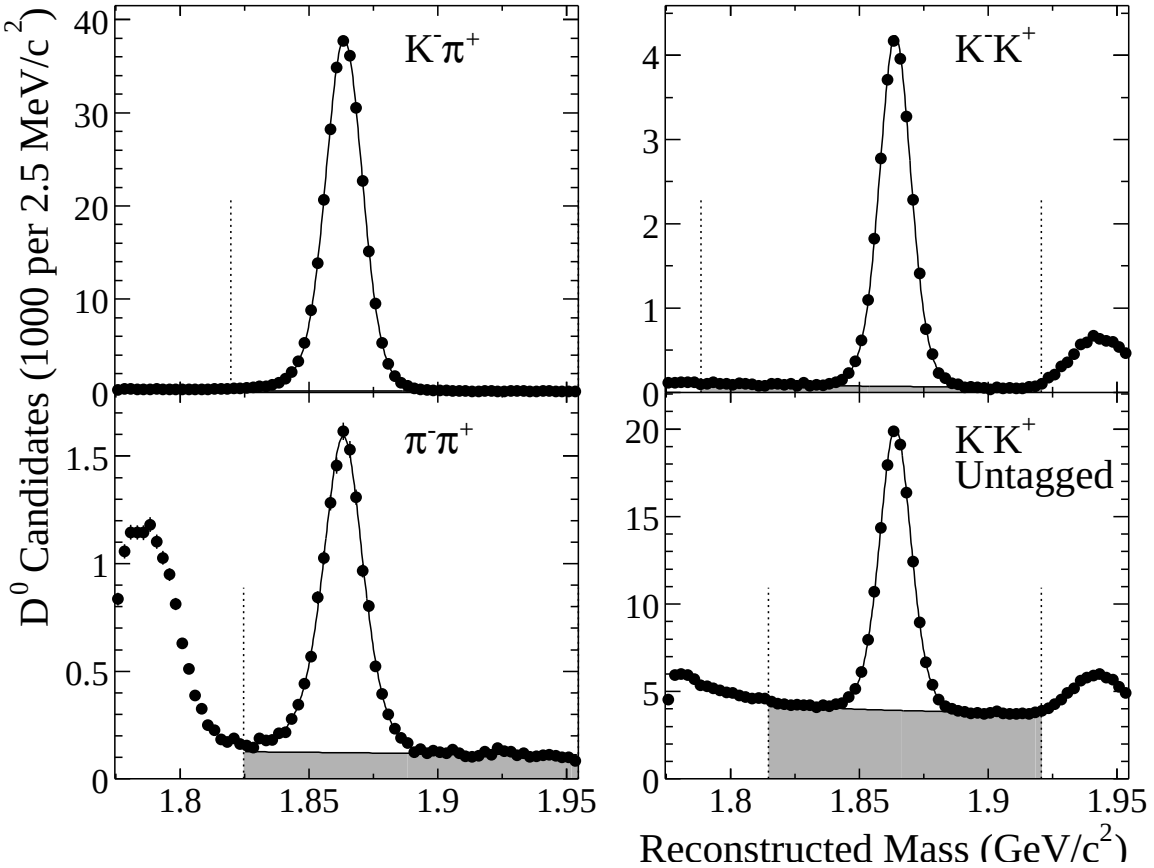


$$y_{CP} = (-1.2 \pm 2.5 \pm 1.4)\,\%$$

y_{CP} (3): BaBar selection / background

- 91 fb^{-1} sample
- $p^*_D > 2.4\,\mathrm{GeV}/c$
- vtx $p(\chi^2) > 1\%$
- PID on daughters
- project $p_D \rightarrow$ IP; require $\sigma_t < 500$ fs
- D^{*+}-tagged:
  - π_s IP refit, $p(\chi^2) > 1\%$
  - m_D cut
- untagged K^+K^-
- M fit $\rightarrow P_{sig}$

hep-ex/0306003 $\longrightarrow$ *PRL*

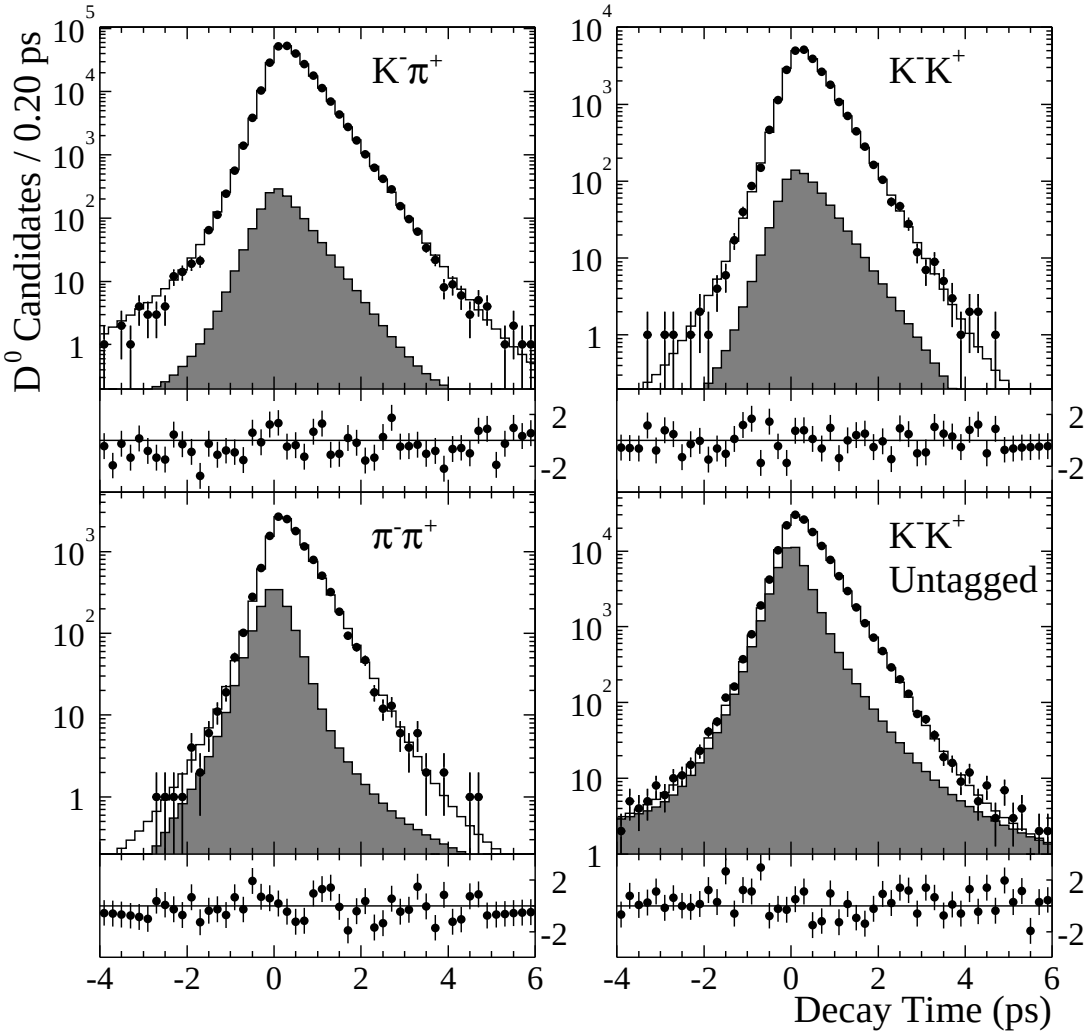


y_{CP} (3): BaBar timing fit

- UML fit each sample
- blind analysis
- $\mathcal{L} =$
  $P_{sig} f_{sig}(t) \otimes \mathcal{R}_{sig} +$
  $(1 - P_{sig}) f_{bkgd}(t) \otimes \mathcal{R}_{bkgd}$
- $\mathcal{R}_{sig}(t, \sigma_t) =$
  $c_1.G(0, S_1\sigma_t) +$
  $c_2.G(0, S_2\sigma_t) +$
  $c_3.G(0, \sigma_3)$
- $\mathcal{R}_{bkgd}$ similar + 4th G

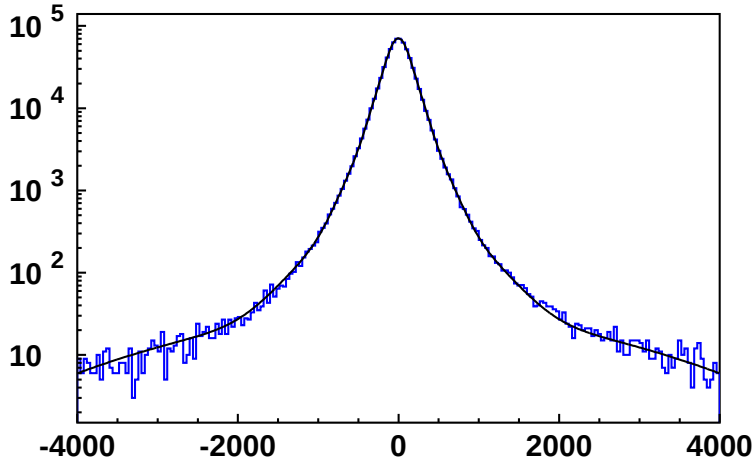
$$y_{CP} = \left(0.8 \pm 0.4^{+0.5}_{-0.4}\right) \%$$

hep-ex/0306003 $\longrightarrow$ *PRL*

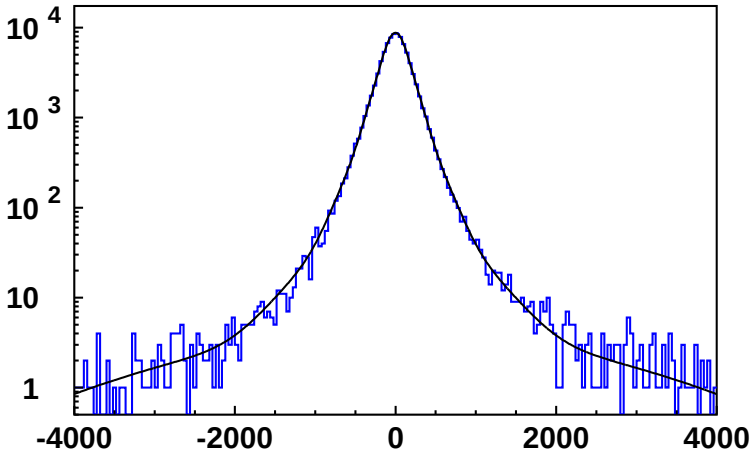


y_{CP} (4): BELLE–CONF–0347 res^n function

$K^-\pi^+$: C.L. = 22.2%



K^-K^+: C.L. = 71.3%

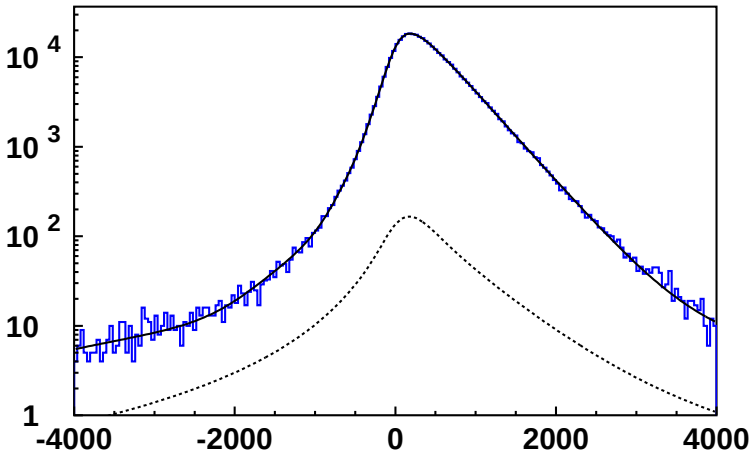


param.	fraction (%)	resolution f^n (fs)	lifetime fit (fs)
σ_1	26.1	95.1 ± 1.3	94.4 ± 1.7
σ_2	50.4	177.0 ± 2.2	179.0 ± 1.2
σ_3	19.8	328.7 ± 7.4	328.2 ± 2.2
σ_4	3.1	675.7 ± 24.9	664.4 ± 8.5
σ_5	0.6	2199 ± 95	2225 ± 70
X_0	[common shift]	-1.51 ± 0.22	-0.95 ± 0.54
α	[K$\pi \to$ KK scale]	1.043 ± 0.004	1.042 ± 0.007

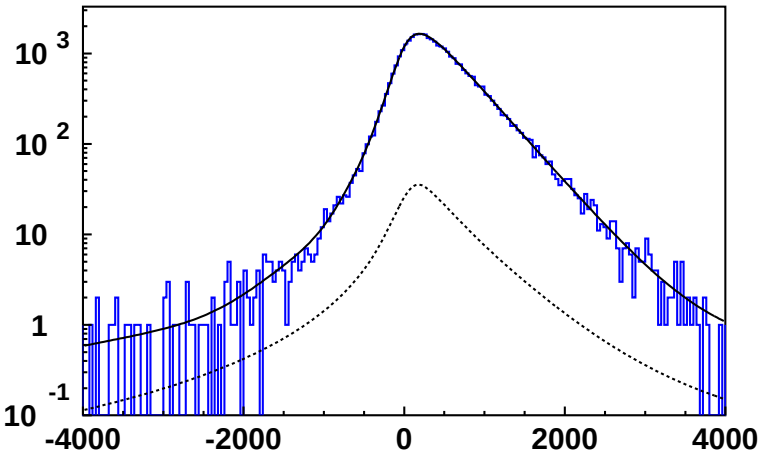
y_{CP} (4): BELLE–CONF–0347 timing fit

- decay distance, time in 2D; $\sigma_{x,y} < 150\,\mu$m
- *binned* ML fit using $\mathcal{R} = \sum_{i=1}^{5} c_i.G(X_0, \sigma_i)$; bkgd: sideband exp $\otimes G + BW$

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



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



fit	σ_1	σ_2	σ_3	σ_4	σ_5	X_0	α
MC	95.1 ± 1.3	177.0 ± 2.2	328.7 ± 7.4	675.7 ± 24.9	2199 ± 95	-1.51 ± 0.22	1.043 ± 0.004
data	112.3 ± 2.6	198.2 ± 1.8	378.0 ± 3.2	864.2 ± 16.4	3197 ± 309	8.6 ± 0.8	1.056 ± 0.012

preliminary $y_{CP} = (1.15 \pm 0.69)\%$: $\begin{cases} \tau(D^0 \to K^-\pi^+) & 412.6 \pm 1.1\,\text{fs} \\ \Delta\tau & 4.76 \pm 2.85\,\text{fs} \end{cases}$

"y_{CP} + +": D^0-$\overline{D}^0$ mixing and CP violation

mixing-with-CPV *is* a reliable New Physics signal
(both mixing and CPV are suppressed in the SM)

$$A_\Gamma \equiv \frac{\hat{\Gamma}(D\to KK)-\hat{\Gamma}(\overline{D}\to KK)}{\hat{\Gamma}(D\to KK)+\hat{\Gamma}(\overline{D}\to KK)} \approx \left(\frac{R_m - R_m^{-1}}{R_m + R_m^{-1}}\right) y\cos\phi - x\sin\phi$$

- $R_m = |q/p|$, CPV in mixing
- $\phi = \arg(q\bar{A}/pA)$, CPV in interference decay & mixing
- note cancellation of systematics
- comes $\approx$ "for free" with the D^*-tagged KK
- (BaBar uses "ΔY"; differs by a factor $(1 + y_{CP})$)

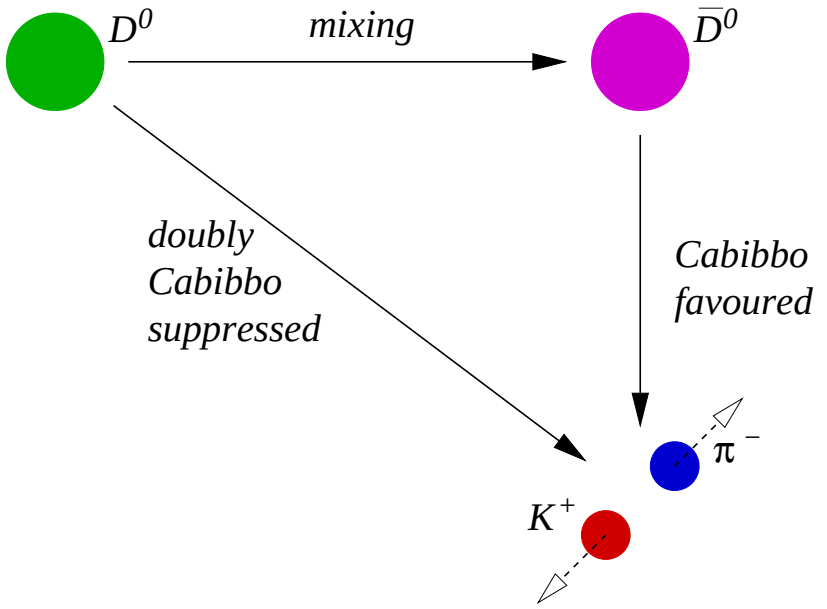
BaBar	$\Delta Y =$	$(-0.8 \pm 0.6 \pm 0.2)\%$
Belle prelim.:	$A_\Gamma =$	$(-0.2 \pm 0.6 \pm 0.3)\%$

D^0-$\overline{D}^0$: $D^0 \to K^+\pi^-$ method

- $\tan^2\theta_C \gg$ expected mixing rate
- must measure time dependence of decay to disentangle components:

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

- strong phase difference $\delta_{K\pi}$ between the decay paths; we measure x and y *rotated* by $\delta_{K\pi}$

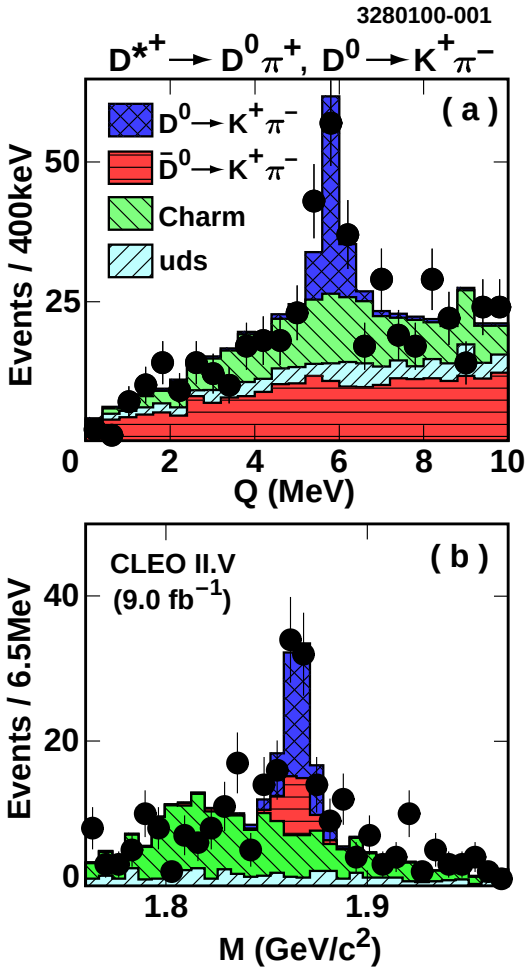


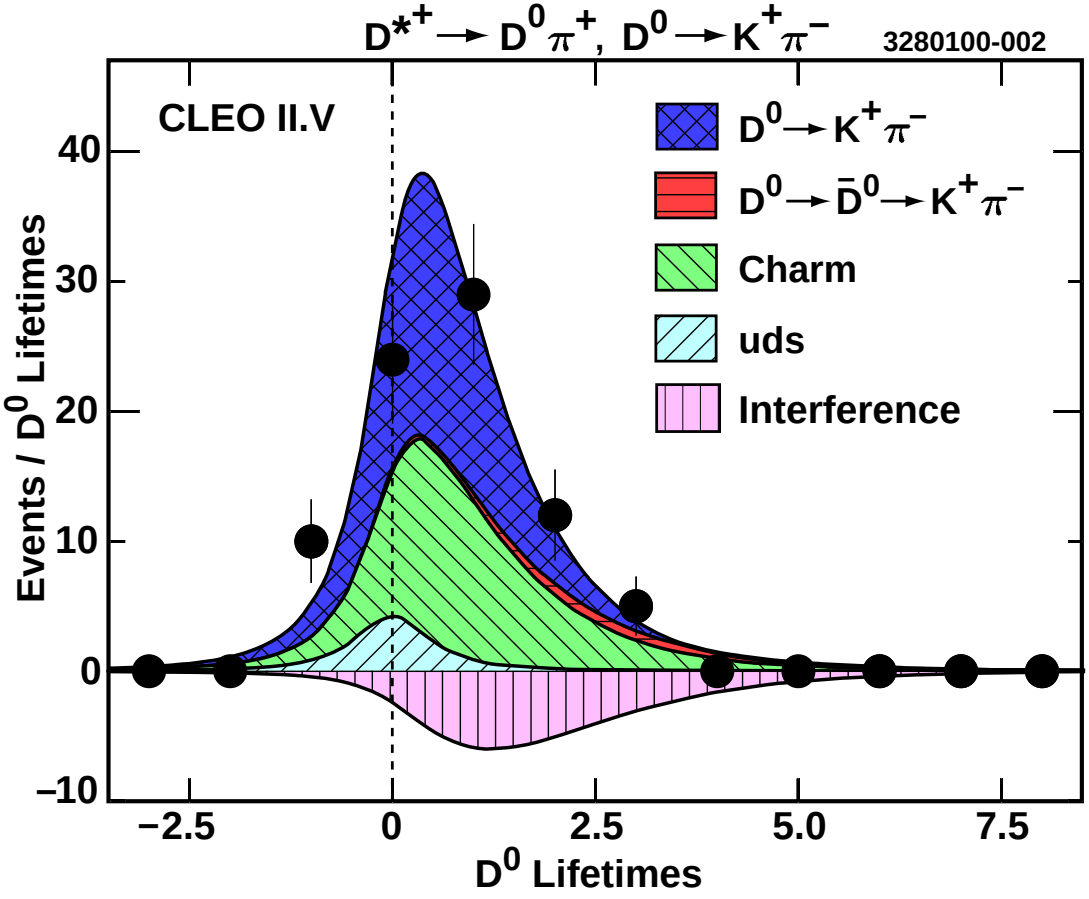
interference term $f(t) \longrightarrow$ sensitivity to mixing

- categorize backgrounds by $f(t)$;
- distinguish backgrounds using distributions in $M = M(K\pi)$, $Q = M(K\pi\pi) - M(K\pi) - m_\pi$
- fix in the timing fit $\longrightarrow$ recover interference

D^0-$\overline{D}^0$: $D^0 \to K^+\pi^-$ method

CLEO implementation: *Phys. Rev. Lett.* **84**, 5038–5042 (2000)



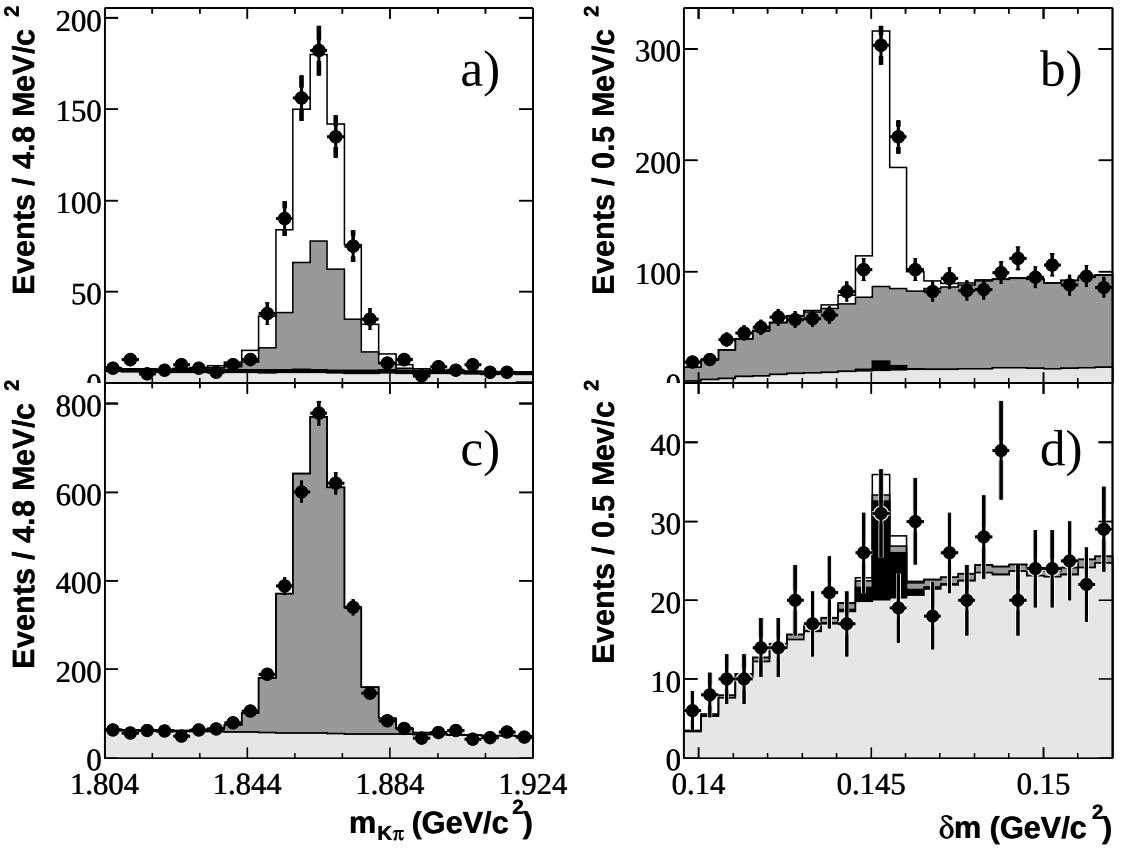


$\frac{1}{2}x'^2 < 0.041\% \quad -5.8\% < y' < 1.0\%$ at 95% C.L.

$D^0 \to K^+\pi^-$: BaBar selection / background

- 57.1 fb^{-1} sample
- blind analysis
- $p^*_{D^*} > 2.6\,GeV/c$
- vtx $p(\chi^2) > 1\%$
- first fit $(m_{K\pi}, \delta m)$, #bkgd$_i$, $i = 1-3$:
  1. random π^+_{slow}
  2. combinatorial
  3. double mis-ID $K^-\pi^+ \to \pi^-K^+$
- signal (upper) and background (lower) regions shown

hep-ex/0304007 ⟶ *PRL*

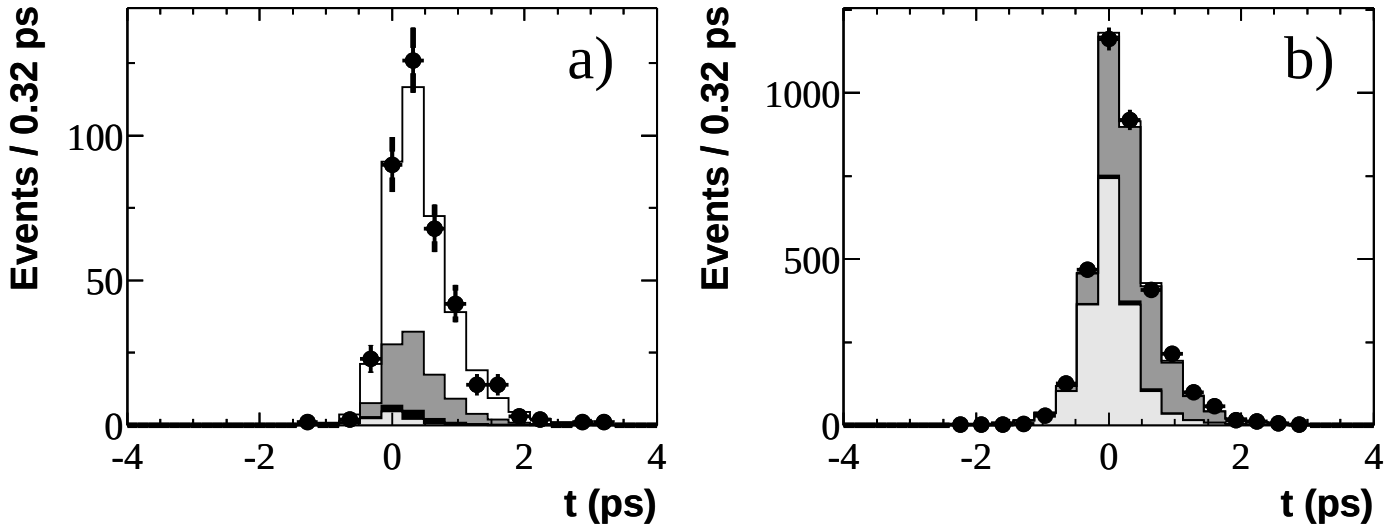


light: combinatorial
dark: random π^+_{slow}
black: double mis-ID

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

hep-ex/0304007 $\longrightarrow$ *PRL*

light: combinatorial
dark: random π^+_{slow}
black: double mis-ID

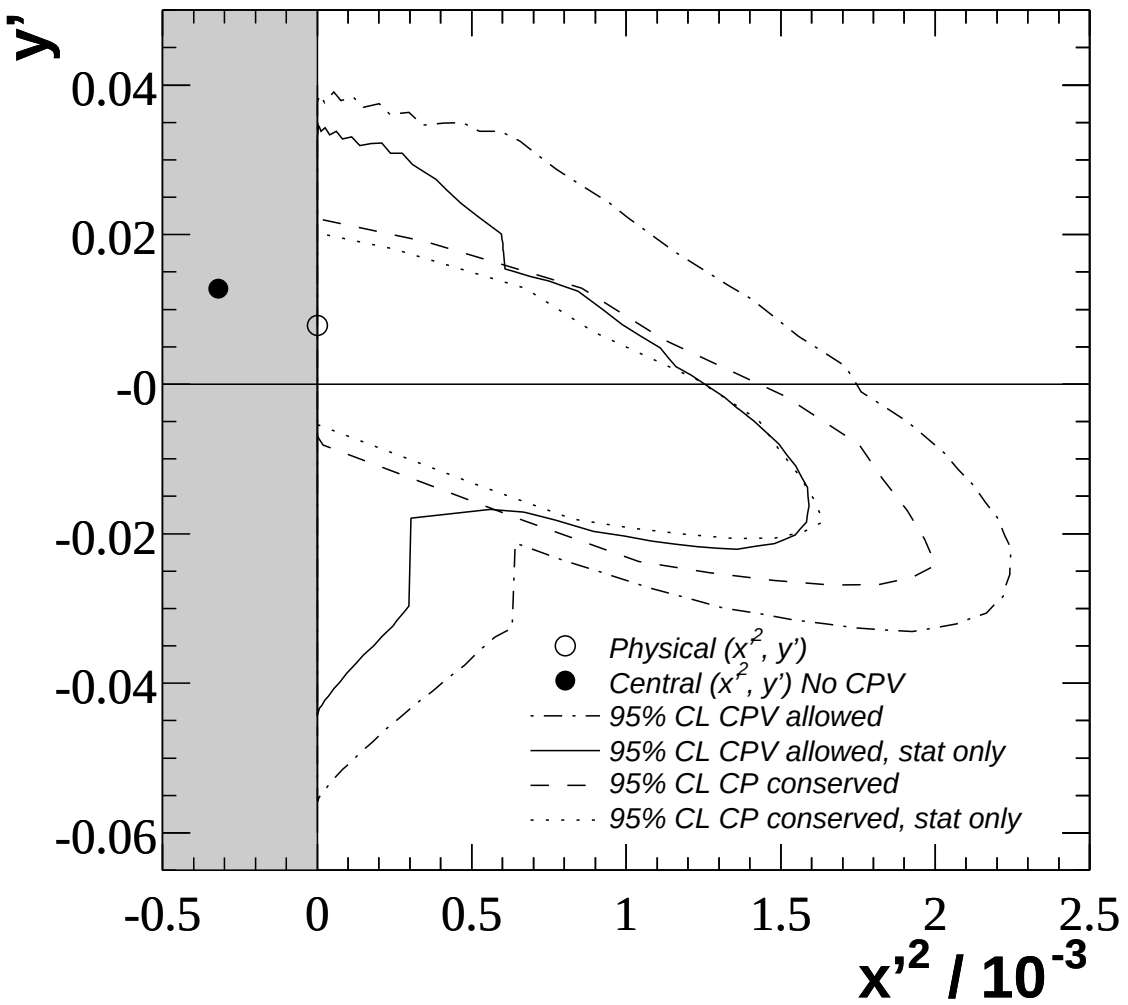


Fit case	Parameter	D^0	$\overline{D}^0$	$D^0 + \overline{D}^0$
Mixing allowed	$R_{WS}^{(\pm)}$	3.9	3.2	3.6
	$x'^{(\pm)^2}$	-0.79	-0.17	-0.32
	$y'^{(\pm)}$	17	12	13
No mixing	$R_{WS}^{(\pm)}$	3.9	3.2	3.6

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

- $(x')^2 < 0$ allowed
- four fits: R_D, CPV, mixing, general
- intervals:
  - toy MC
  - D^0,$\overline{D}{}^0$ contours combined $\longrightarrow$ CPV contours
  - syst.: scaling
- *cf.* CLEO interval: *similar size!!*
- $\sigma(x'), \sigma(y') = f(y')$
- difficult problem

hep-ex/0304007 $\longrightarrow$ *PRL*



D^0-$\overline{D}^0$: issues and future measurements

- (x', y') confidence intervals are strong functions of y':
  - combined results require combined analysis
  - joint working group for CLEO-c era?
- still don't know how to relate y' and y_{CP}
  - $\cos\delta_{K\pi}$ unmeasured; wait for CLEO-c?? ($\sigma = 0.08$?)
  - $D \to K\pi$ (DCSD): $K^+\pi^-$; $K^0_L\pi^0$ (**hep-ex/0107078**)
  - evidence for significant FSI (incl. *inelastic*) in $D \to hh$:
    FOCUS *PLB* **555**, 167–173 (2003) & CLEO hep-ex/0306019
    $\longrightarrow$ assumption of small $\delta_{K\pi}$ unsafe?
- (back to) the future
  - don't forget $D^0 \to K^{(*)+}\ell^-\bar{\nu}_\ell$: CLEO study
  - $D^0 \to K^0_S\pi^+\pi^-$: note x; good scaling properties
  - CPV fit routine $\mapsto$ main measurement
  - CLEO-c: high stats, opposite-side tags, geometric S/B ...
    and a coherent initial state $\to$ new observables

CPT & Lorentz inv^{ce} violation: FOCUS

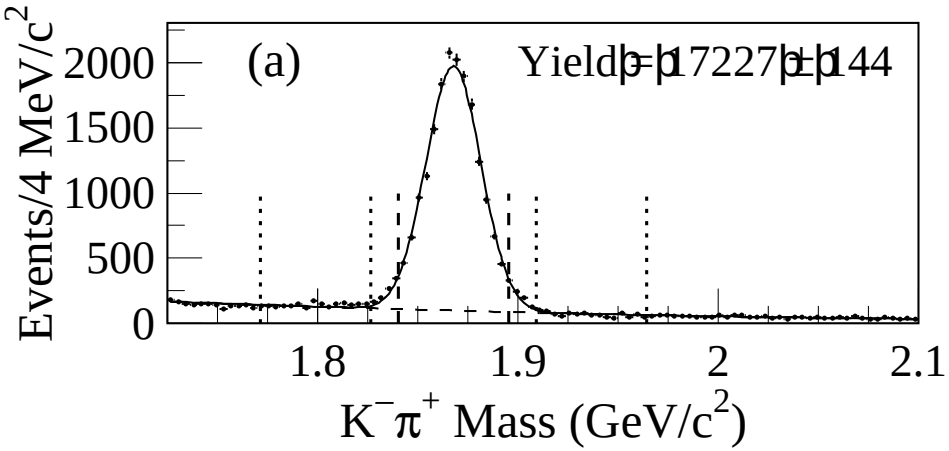
- parameterize CPTV using $\xi \equiv (\Lambda_{11} - \Lambda_{22})/(\lambda_1 - \lambda_2)$
- $D^0 \to K^-\pi^+$ decay probability $P_f(t)$
- $\overline{D}{}^0 \to K^+\pi^-$ decay probability $\bar{P}_{\bar{f}}(t)$
- measure asymmetry

$$A_{CPT}(t) \equiv \frac{\overline{P}_{\bar{f}}(t) - P_f(t)}{\overline{P}_{\bar{f}}(t) + P_f(t)} = \frac{2\,\mathrm{Re}(\xi)\sinh(y\Gamma t) - 2\,\mathrm{Im}(\xi)\sin(x\Gamma t)}{(1+|\xi|^2)\cosh(y\Gamma t) + (1-|\xi|^2)\cos(x\Gamma t)}$$

$$\longrightarrow (\mathrm{Re}(\xi)y - \mathrm{Im}(\xi)x)\,\Gamma t \quad \text{for } xt, yt \ll \frac{1}{\Gamma}$$

PLB **566**, 7–13 (2003)

- $D^{*+} \to D^0\pi^+$; cuts
- $D^0 \to K^+\pi^-$ & PID cuts
- detached vertex cuts
- *cf.* D^0 (shown) & $\overline{D}{}^0$



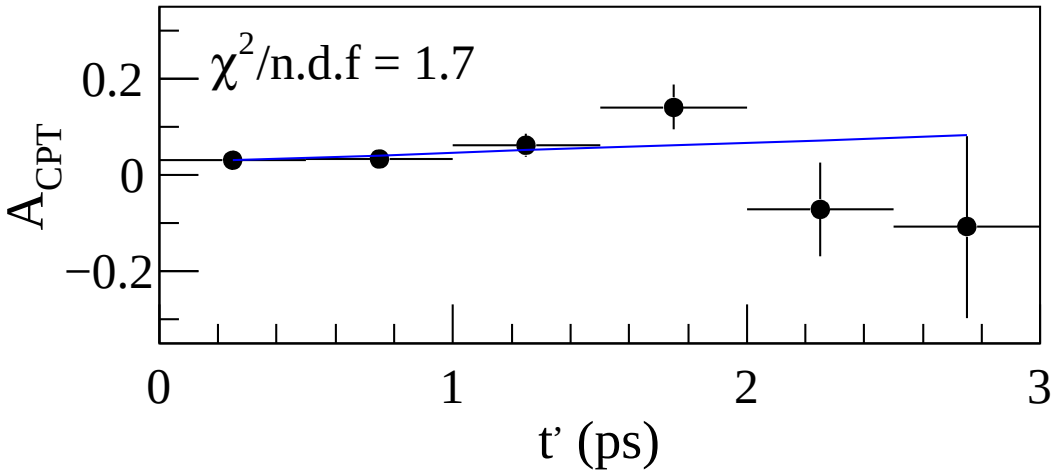
CPT & Lorentz inv^{ce} violation: FOCUS

fit A_{CPT} *vs.* t':

Phys. Lett. **B 566**, 7–13 (2003)

$(\mathrm{Re}(\xi)y - \mathrm{Im}(\xi)x) =$
$0.0083 \pm 0.0065 \pm 0.0041$

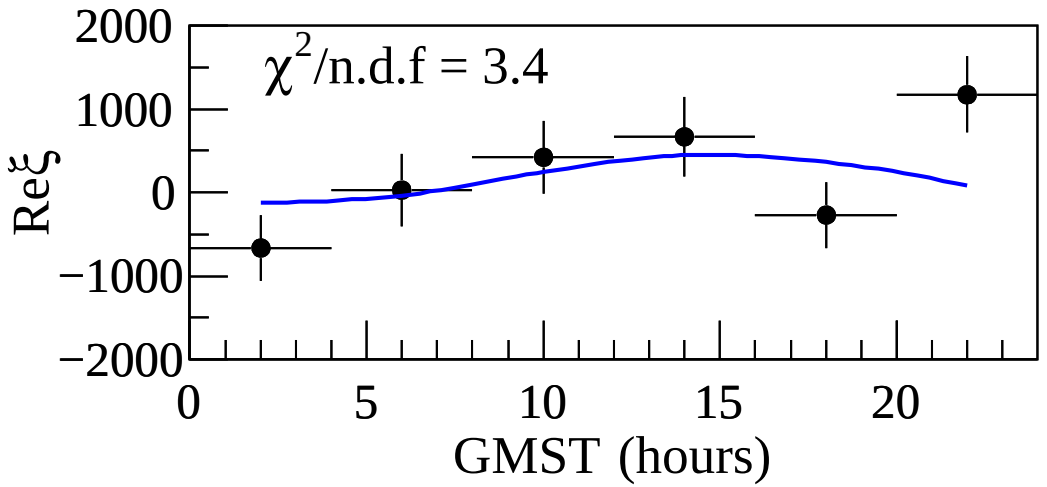
$\equiv \mathrm{Re}\,\xi = 0.83 \pm 0.65$
for $(x, y) = (0.0, 0.01)$



CPTV $\Longrightarrow$ ~~Lorentz~~

fit *vs.* *siderial* *time:*

null result $\equiv$
$|\Delta a_\mu| < O\left(10^{-12}\right)$ GeV
at 95% C.L. for
$(x, y, \delta) = (0.01, 0.01, 15^\circ)$



cf. $O(10^{-21})$ for K^0-$\overline{K}^0$

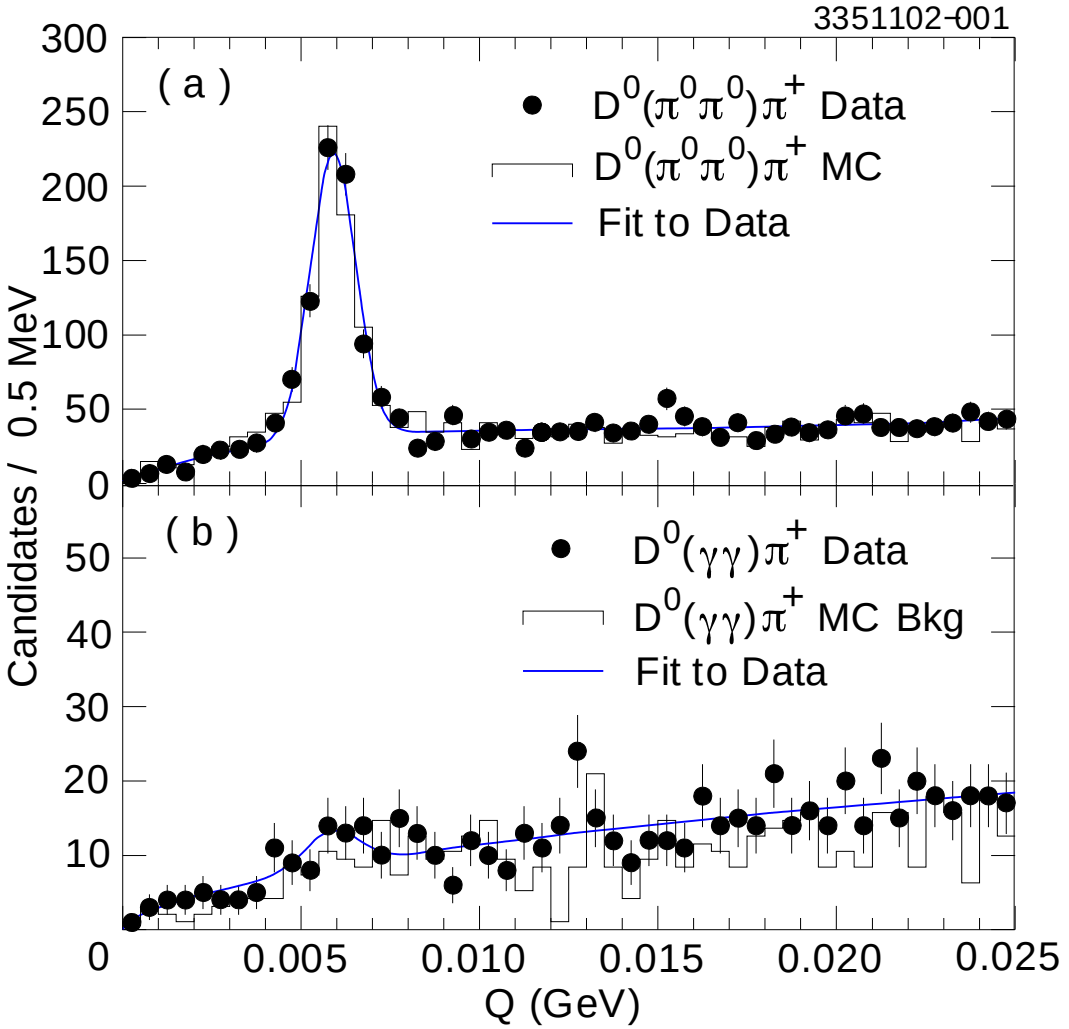
- FCNC not yet seen in the charm sector
  - SM parton level: loops, powerful cancellations
  - long distance contributions (*e.g.* $D^0 \to VV \to V\gamma$) dominant
  - difficult to calculate the SM expectation
- best NP signals are those with special features:
  - $D^0 \to \mu^+\mu^-$ is $O(10^{-13})$ in the SM;
    cf. $D^0 \to \gamma\gamma$, $O(10^{-8})$ in the SM (VMD)
  - $M(\ell^+\ell^-)$ in $D \to h\ell^+\ell^-$ ...
- *forbidden* decays (LFV, LNV ...)
  - experimentally similar $\Longrightarrow$ come for free
  - SM prediction easy (!); NP predictions exist
  - even if not: IIB's "King Kong scenario"

rare decays: $D^0 \to \gamma\gamma$ at CLEO

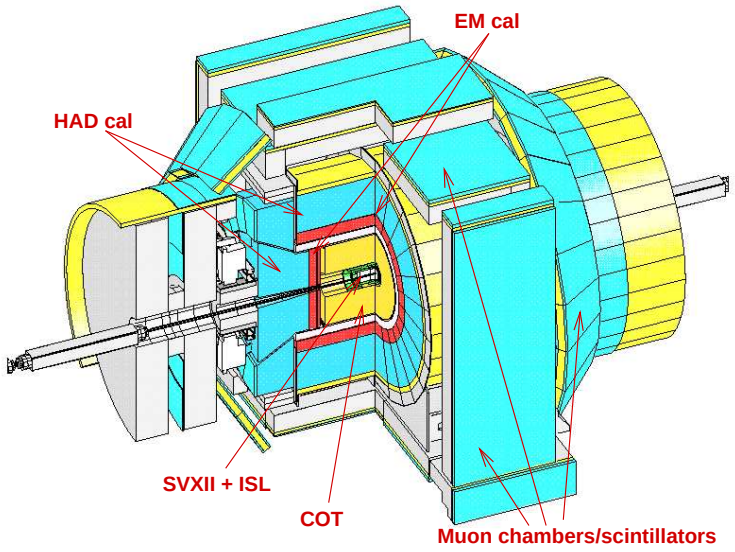
- 13.8 fb^{-1} CLEO II, II.V
- exploit good u'standing of detector:
  - $D^0 \to \pi^0\pi^0$ normaliz^n
  - $D^{*+} \to D^0\pi^+$ tag
  - fit yields to Q: similar resolution
- $p_{D^*} > 2.2\,\mathrm{GeV}/c$
- $p_{\pi^0}, p_\gamma > 0.55\,\mathrm{GeV}/c$
- veto $M(\gamma\gamma) \sim m_{\pi^0}$ in $D^0 \to \gamma\gamma$ recon.

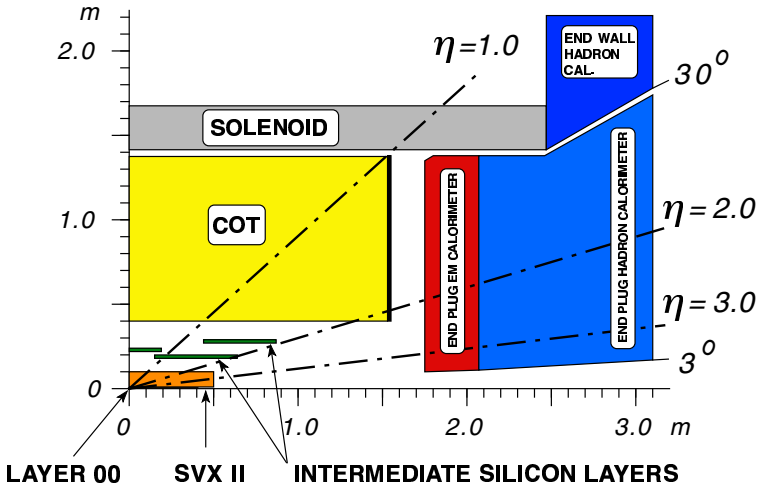
$\mathcal{B}(D^0 \to \gamma\gamma) < 2.9 \times 10^{-5}$ at 90% C.L.; first meas^t

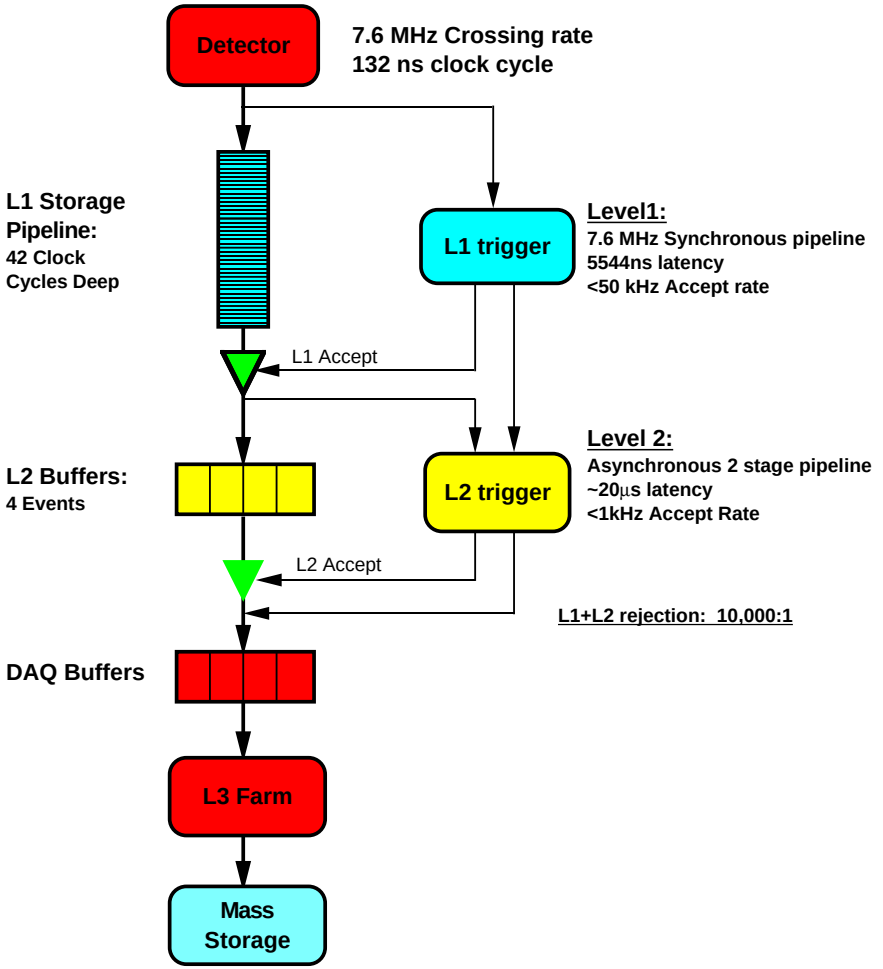
Phys. Rev. Lett. **90**, 101801 (2003)



rare decays: $D^0 \to \mu^+\mu^-$ at CDF; upgrade





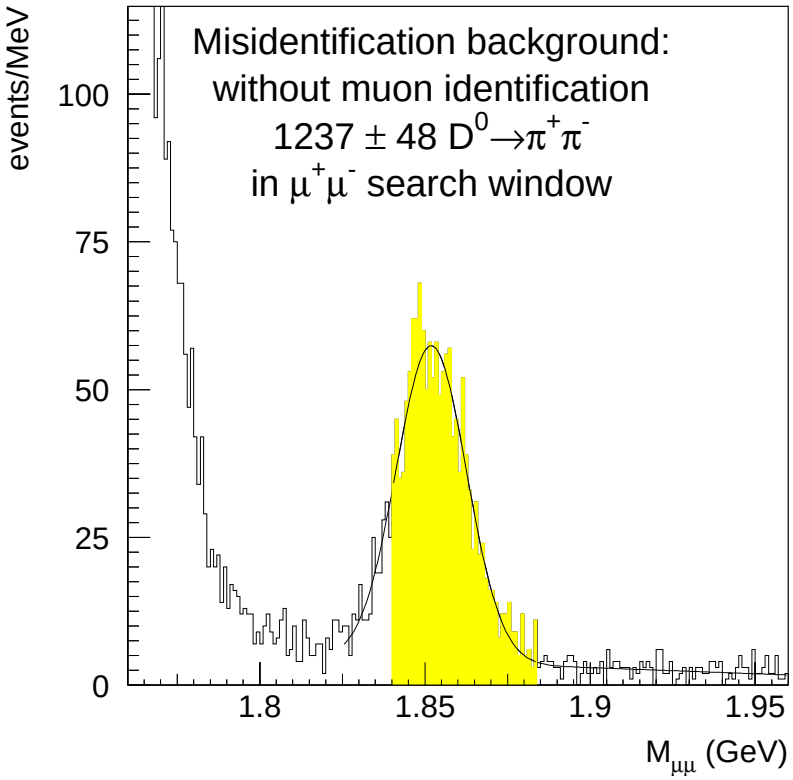


rare decays: $D^0 \to \mu^+\mu^-$ at CDF; results

normalisation mode

$D^{*+} \to D^0\pi^+,\ D^0 \to \pi^+\pi^-$

CDF Run II Preliminary



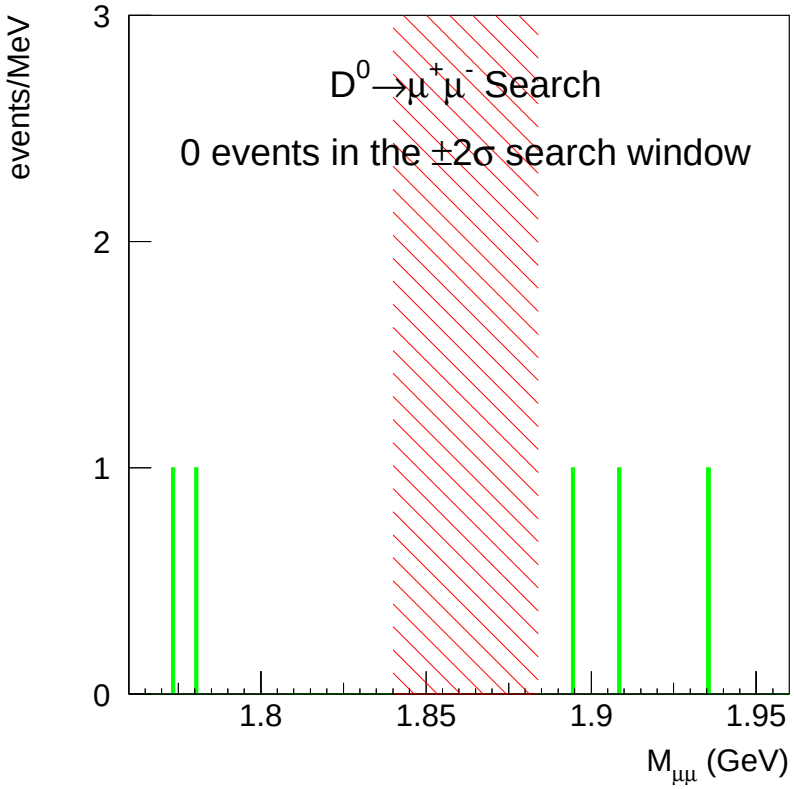
$2 \times \pi \to \mu$ mis-ID

$\longrightarrow 0.22 \pm 0.02$ events

signal mode

$D^{*+} \to D^0\pi^+,\ D^0 \to \mu^+\mu^-$

CDF Run II Preliminary



(non-misID background dominates)

$\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.4 \times 10^{-6}$ at 90% C.L.

rare decays: D $\to h\ell\ell$ at FOCUS (1)

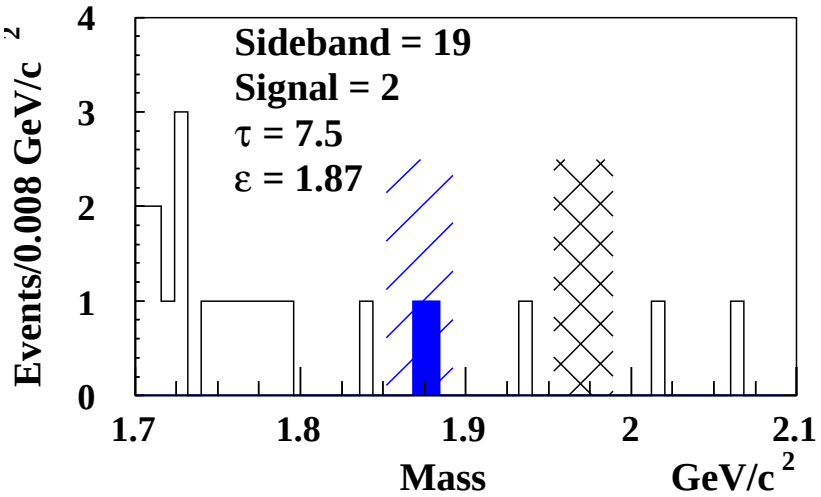
hep-ex/0306049 $\longrightarrow$ *Phys. Lett.* **B**

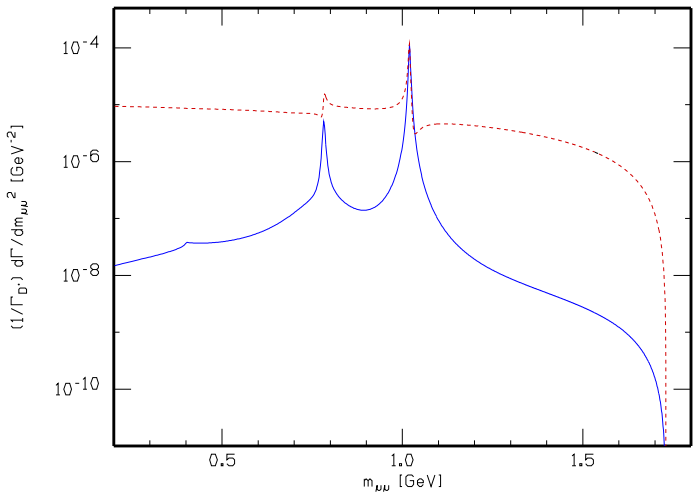
- detached vertex
- PID & μ ID
- large MC
- double bootstrap
- limits: syst. + MC stat.

theory

- SM quark level: tiny
- use $M(\ell^+\ell^-)$
- SM $\simeq$ SM LD
  note the resonances
- RPV SUSY at limit
- need more stats!!

$\pi^+\mu^+\mu^-$

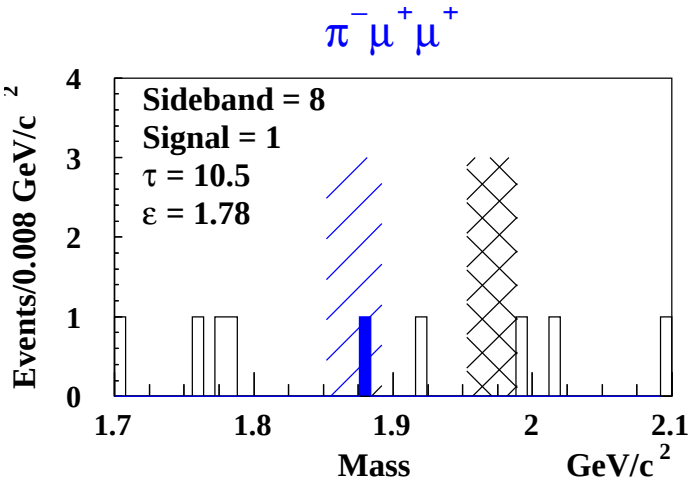




rare decays: $D \to h\ell\ell$ at FOCUS (2)

hep-ex/0306049 $\longrightarrow$ *Phys. Lett.* **B**

The corresponding LNV mode:

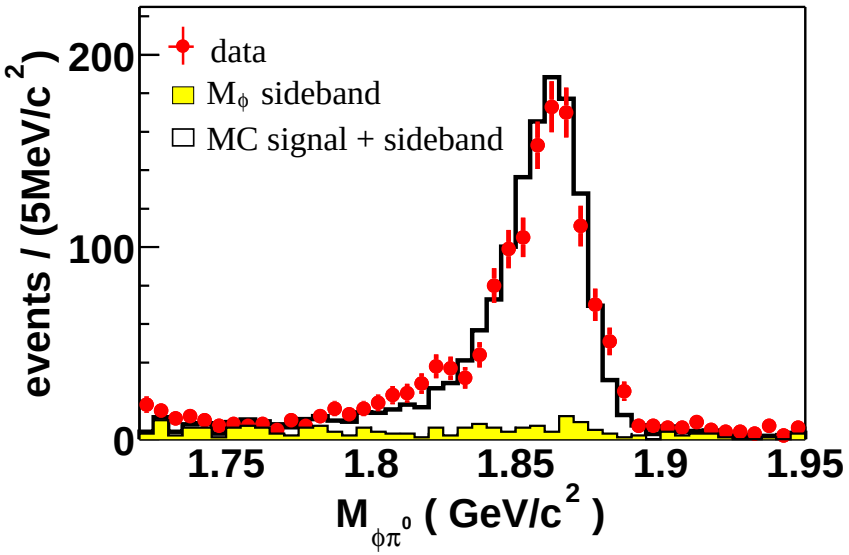


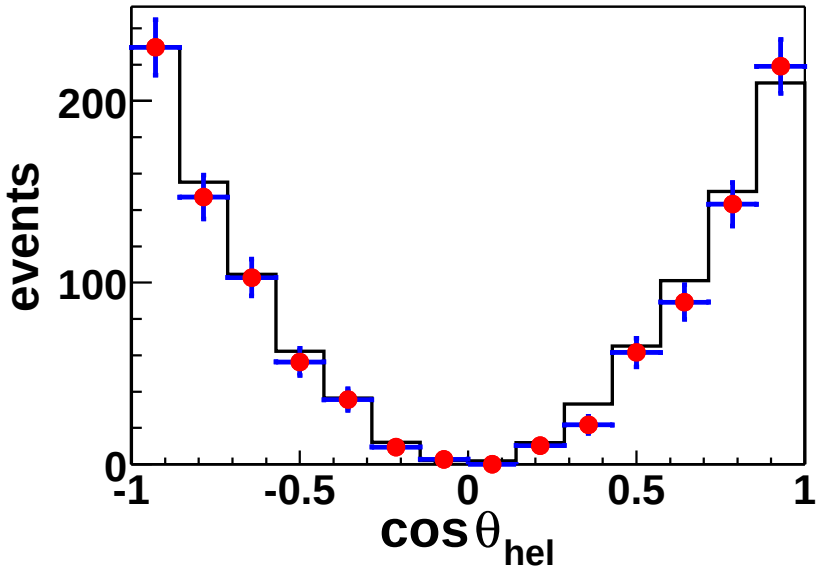
mode	FOCUS	SM	RPV	Previous	CLEO-c
$D^+ \to K^+\mu^-\mu^+$	9.2	0.007	-	44	1.5
$D^+ \to K^-\mu^+\mu^+$	13	-	-	120	1.5
$D^+ \to \pi^+\mu^-\mu^+$	8.8	1.0	15	15	1.5
$D^+ \to \pi^-\mu^+\mu^+$	4.8	-	-	17	1.5
$D_s^+ \to K^+\mu^-\mu^+$	36	0.043	-	140	15
$D_s^+ \to K^-\mu^+\mu^+$	13	-	-	180	15
$D_s^+ \to \pi^+\mu^-\mu^+$	26	6.1	-	140	15
$D_s^+ \to \pi^-\mu^+\mu^+$	29	-	-	82	15

rare decays: $D^0 \to V\pi^0$, $V\eta$, $V\gamma$ at Belle

LP–xxx (BELLE–CONF–0346)

- $\phi \to K^+K^-$: exploit 2× PID
- $\mathcal{B}(D^0 \to \phi\gamma)_{th} = (0.04 \sim 3.4) \times 10^{-5}$
- Cabibbo- & color-suppressed backgrounds: $D^0 \to \phi\pi^0$, $\phi\eta$
- selection:
  - D^* tag; $p^*_{D^*} > 2.9\,\mathrm{GeV}/c$
  - $p_{\pi^0,\eta,\gamma} > xxx$ acc. to $S/\sqrt{B}$
  - θ_{hel} as a cross-check
  - $D^0 \to K^+K^-$ as reference
- $\mathcal{B}(D^0 \to \phi\pi^0)$ $= (8.01 \pm 0.26 \pm 0.46) \times 10^{-4}$
- fit in $\cos\theta_{hel}$ bins → expected dist^n

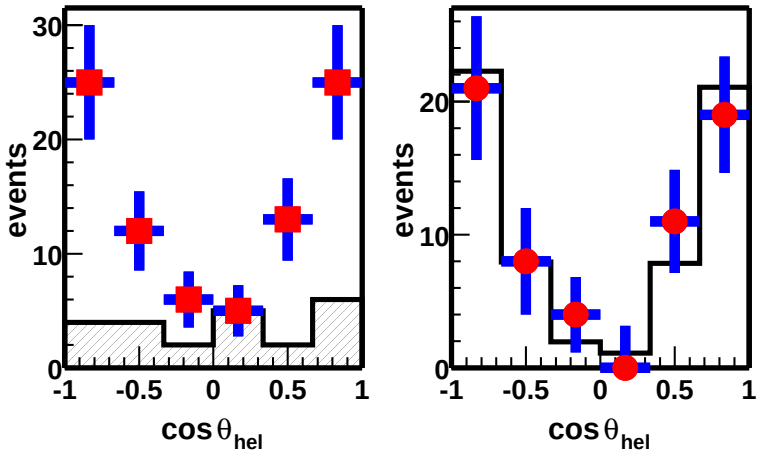


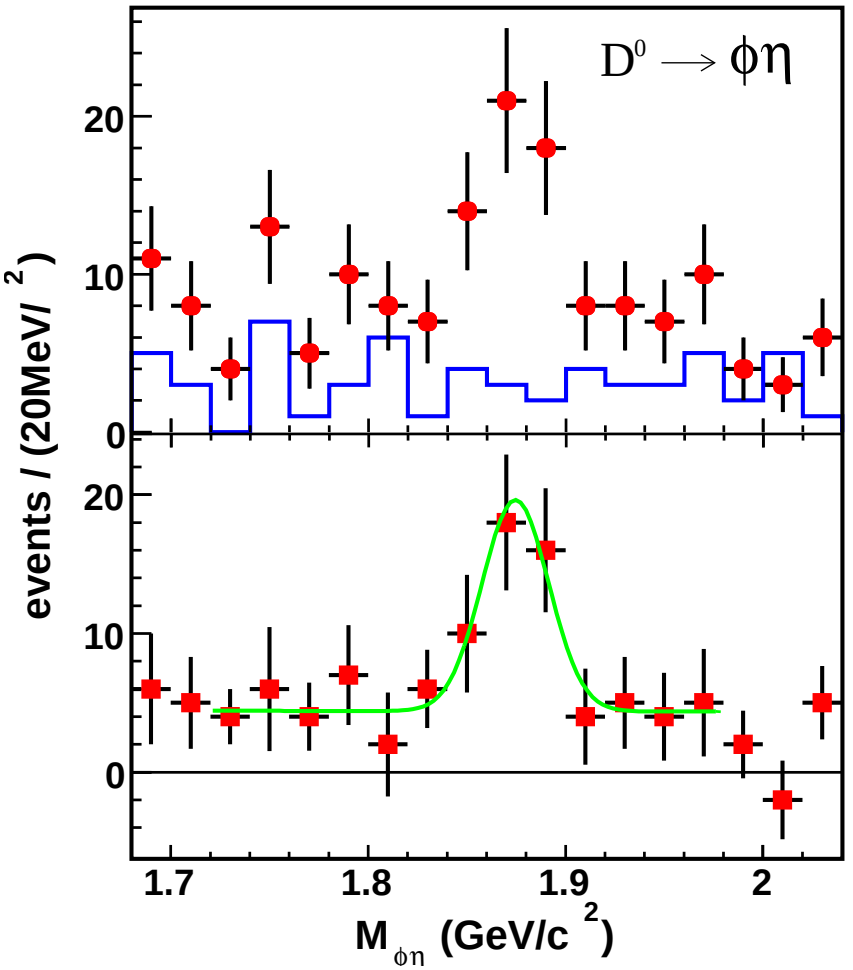


rare decays: $D^0 \to \phi\eta$

LP–xxx (BELLE–CONF–0346)

- $\eta \to \gamma\gamma$; π^0 veto
- 31 ± 9.8 events
- helicity: $\cos^2\theta_{\rm hel}$
- $\mathcal{B} = (1.48 \pm 0.47 \pm 0.09) \times 10^{-4}$

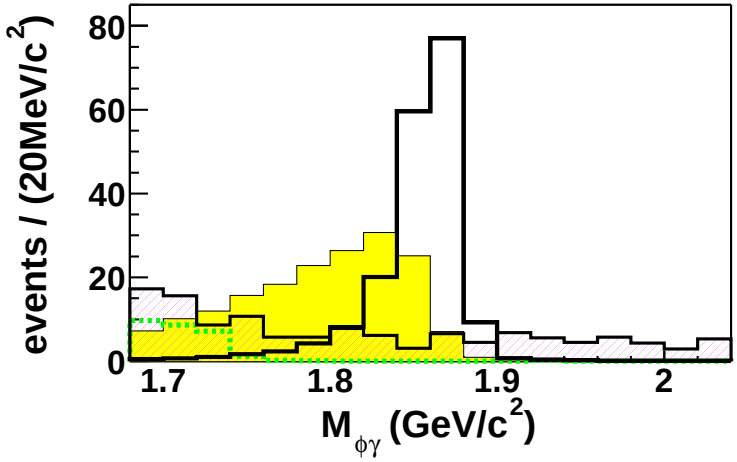


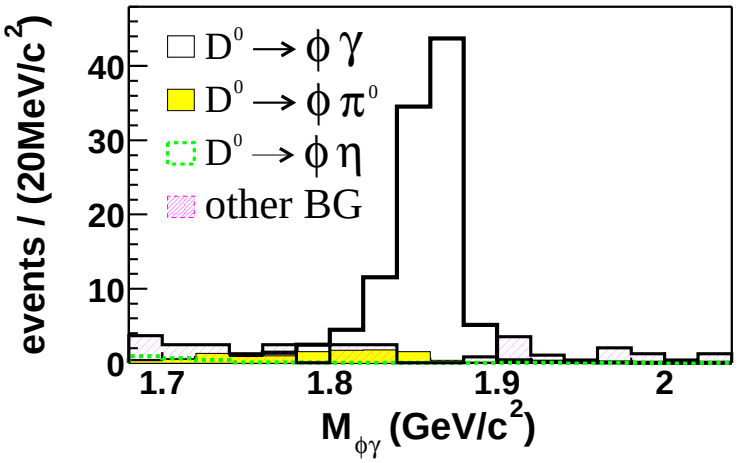


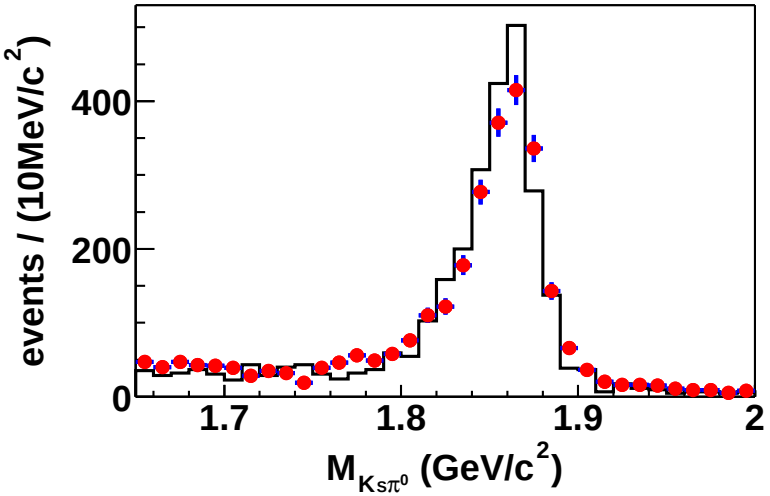
rare decays: $D^0 \to \phi\gamma$ (1)

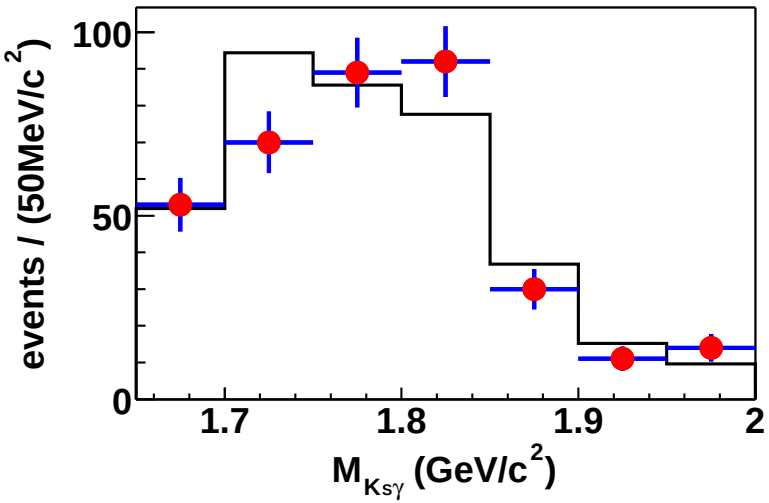
MC: $|\cos\theta_{\rm hel}| < 0.4$ (optimised)

data: $D^0 \to$ "$K^0_S\gamma$" check of π^0 merger



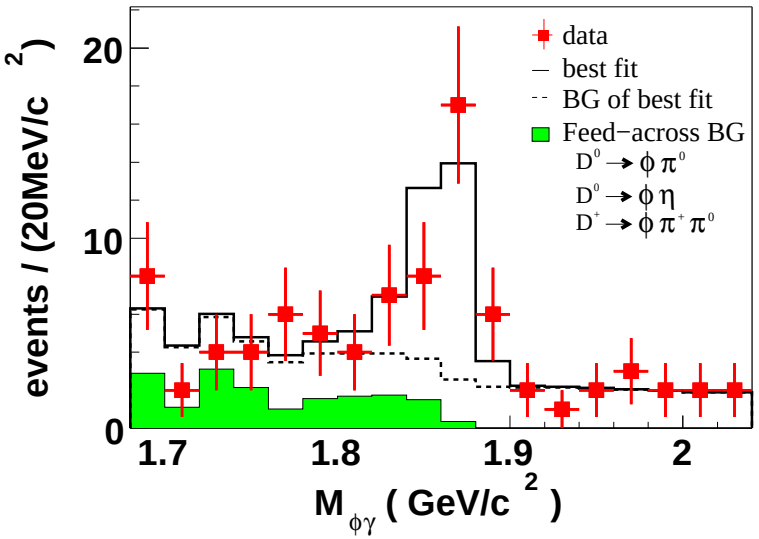




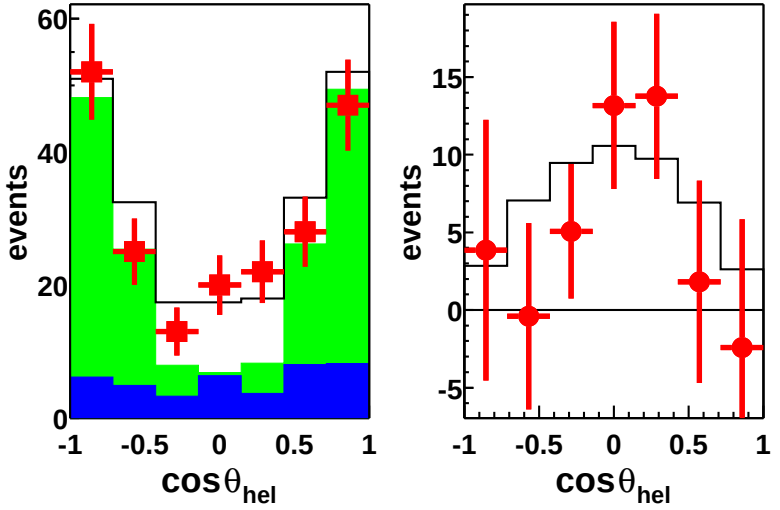


rare decays: $D^0 \to \phi\gamma$ (2)

mass fit: $27.6^{+7.4+0.5}_{-6.5-1.0}$ events



helicity distribution cross-check



$$\mathcal{B}(D^0 \to \phi\pi^0) = (8.01 \pm 0.26 \pm 0.46) \times 10^{-4}$$

$$\mathcal{B}(D^0 \to \phi\eta) = (1.48 \pm 0.47 \pm 0.09) \times 10^{-4}$$

$$\mathcal{B}(D^0 \to \phi\gamma) = \left(2.60^{+0.70+0.15}_{-0.61-0.17}\right) \times 10^{-5}$$

first observation of a FCNC decay in the D system

LP–xxx (BELLE–CONF–0346)

summary and prospect

- progress on D^0-$\overline{D}^0$ mixing is foreseen
  - mature $D^0 \to K^+\pi^-$ WS, BaBar 57.1 fb (*cf.* CLEO): B-factories will exhaust this (difficult) technique
  - y_{CP} sensitivity continues to improve: 1% meas^t in reach
  - $D^0 \to K^0_S\pi^+\pi^-$ . . . other new methods?
  - soon, CLEO-c: new methods; new variables; $\delta_{K\pi}$
  - as a New Physics search, mixing-with-CPV is the future
- the first FCNC charm decay has been seen: $D^0 \to \phi\gamma$
  - consistent with SM expectations (VMD)
  - calibration point for Standard Model $D^0 \to V\ell^+\ell^-$?
- incremental improvements in rare / exotic decay searches
  - range: *e.g.* $D^0 \to \gamma\gamma$, CLEO $\mathcal{B} < 2.9 \times 10^{-5}$
  - reach: *e.g.* $D^0 \to h\ell\ell$ at FOCUS
- we all (? incl. FOCUS/BaBar/Belle/CDF?) look forward to CLEO-c