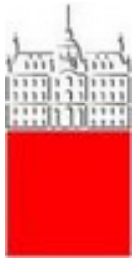
Beauty and charm results from B factories

Boštjan Golob
University of Ljubljana, Jožef Stefan Institute & Belle Collaboration

Helmholz International Summer School “Heavy Quark Physics”
Bogoliubov Laboratory of Theoretical Physics,
Dubna, Russia, August 11-21, 2008

JINR



University
of Ljubljana

“Jožef Stefan”
Institute

Outline

Lecture 1

Beauty

1. Introduction
2. B Oscillations
3. (Mostly) rare B decays
   - leptonic
   - semileptonic
   - $b \to s\gamma$
   - $b \to s\ell\ell$

Lecture 2

Charm and others

4. D^0 mixing and CPV
   - decays to CP states
   - WS decays
   - t-dependent Dalitz
5. D_s leptonic decays
6. Spectroscopy
   - exotic states

Part of B-factories lectures with A.J. Bevan;
division by topics, not by experiments

Introduction

Dual role of charm physics

- experimental tests of theor. predictions (most notably of (L)QCD); improve precision of CKM measurements (B physics);

example: leptonic decays of D mesons → decay constants, tests of LQCD; Dr. Jeckyll

- standalone field of SM tests and search for new phenomena (SM and/or NP);

example: mixing and CPV in D^0 system Mr. Hyde

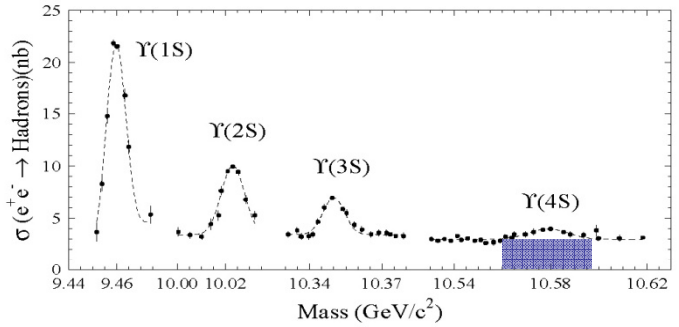
Introduction

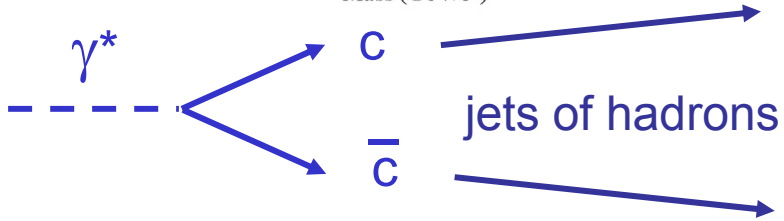
B-factory=charm factory

$\sigma(c\bar{c}) \approx 1.3$ nb (~10^9 $X_c Y_c$ pairs)
+ light qq production;

perfect experimental environment for charm physics;

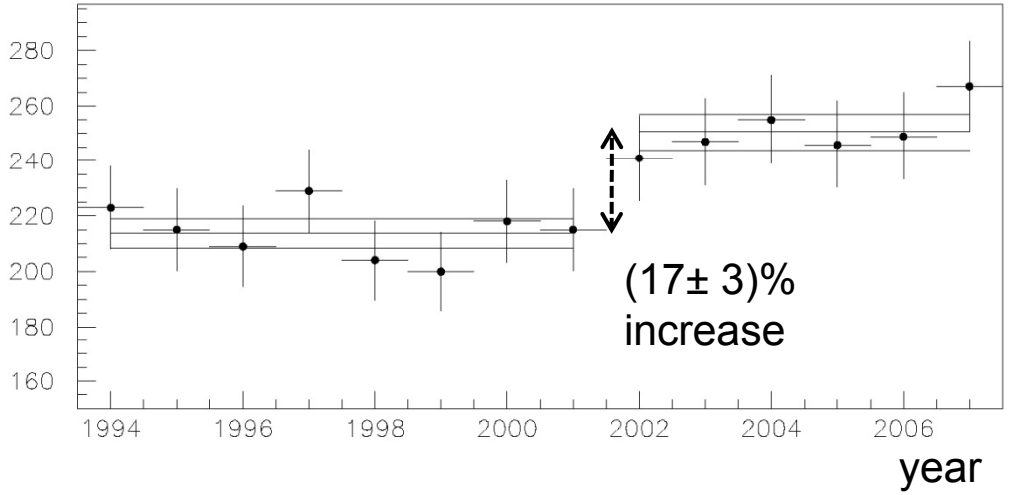
increased interest in charm physics in recent years;





Charm is... a way of getting the answer yes without having asked any clear question. A. Camus (1913 - 1960)

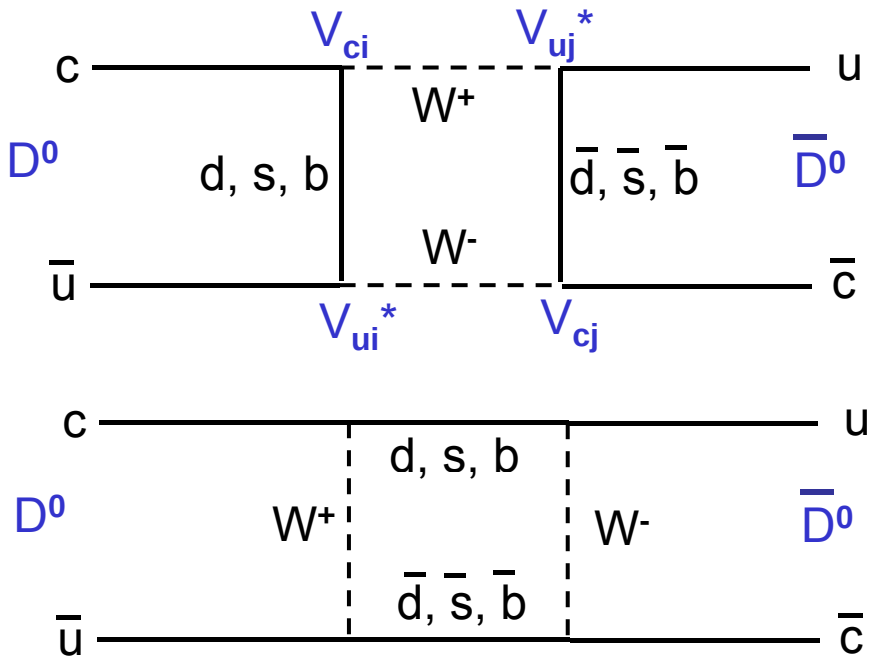
papers in Spires with title "charm*"



D^0 mixing

D^0 case

only M^0 system with down-quarks in loop



$$\left\langle \bar{D}^0 \left| H_{wk} \right| D^0 \right\rangle \propto \sum_{i,j=d,s,b} V_{ui}^* V_{ci} V_{cj} V_{uj}^* m_i m_j$$

(adopting eq. from lecture 1, B oscillations)

History

observation of K^0: 1950 (Caletch)

mixing in K^0: 1956 (Columbia) — 6 years

c quark mass

observation of B_d^0: 1983 (CESR)

mixing in B_d^0: 1987 (Desy) — 4 years

t quark mass

observation of B_s^0: 1992 (LEP)

mixing in B_s^0: 2006 (Fermilab) — 14 years

????

observation of D^0: 1976 (SLAC)

mixing in D^0: 2007 (KEK, SLAC) — 31 years

????

(evidence of)

D^0 mixing

Phenomenology

$|V_{cb}V_{ub}^*| << |V_{cs}V_{us}^*|, |V_{cd}V_{ud}^*|$
assuming unitarity in 2 generations $\Rightarrow$

$$\left\langle \overline{D}^0 \left| H_{wk} \right| D^0 \right\rangle \propto V_{us}^* V_{cs} V_{cd} V_{ud}^* (m_s^2 - m_d^2)^2$$

more precisely:

$$\left\langle \overline{D}^0 \left| H_w^{\Delta C=-2} \right| D^0 \right\rangle = \frac{G_F^2}{4\pi^2} \underbrace{V_{cs}^* V_{cd}^* V_{ud} V_{us}}_{\text{DCS}} \underbrace{\frac{(m_s^2 - m_d^2)^2}{m_c^2}}_{\text{SU(3) breaking}} \left\langle \overline{D}^0 \left| \bar{u}\gamma^\mu(1-\gamma_5)c\bar{u}\gamma_\mu(1-\gamma_5)c \right| D^0 \right\rangle$$

G. Burdman, I. Shipsey,
Ann.Rev.Nucl.Sci. 53, 431 (2003)

mixing parameters:

$$x = \frac{m_1 - m_2}{\overline{\Gamma}} = \frac{2}{\overline{\Gamma}} \Re\left[\frac{q}{p} (M_{12} - i\frac{\Gamma_{12}}{2}) \right]; \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\overline{\Gamma}} = \frac{1}{\overline{\Gamma}} \Im\left[\frac{q}{p} (M_{12} - i\frac{\Gamma_{12}}{2}) \right];$$

D^0 mixing

Phenomenology

2nd order in pert. th.::

$$(M - i\frac{\Gamma}{2})_{ij} = \frac{\langle D_i | H_{eff} | D_j \rangle}{2M_D} =$$

$$= M_D \delta_{ij} + \frac{1}{2M_D}\langle \bar{D}^0 | H_w^{\Delta C=-2} | D^0 \rangle +$$

$$+ \frac{1}{2M_D}\sum_n \frac{\langle \bar{D}^0 | H_w^{\Delta C=-1} | n \rangle \langle n | H_w^{\Delta C=-1} | D^0 \rangle}{M_D - E_n + i\varepsilon}$$

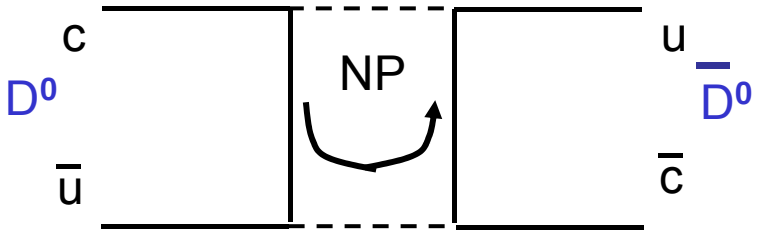
short distance: $|x| \sim \mathcal{O}(10^{-5})$

contributes to x;
common statement: mixing
with large x sign of NP;

long distance:

contributes to y and x;
y is affected by sum over
real intermediate states;
x also affected by
sum over off-shell states;

$|x|, |y| \sim \mathcal{O}(10^{-2})$



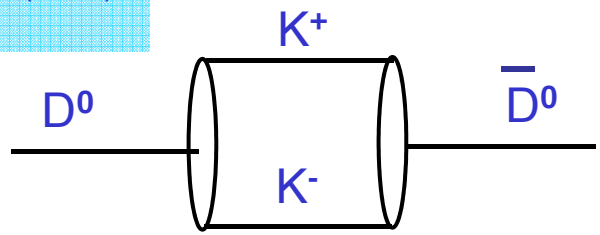
$$\frac{1}{M_D - E_n + i\varepsilon} = PV\left(\frac{1}{M_D - E_n}\right) + i\pi\delta(E_n - M_D)$$

I.I. Bigi, N. Uraltsev, Nucl. Phys. B592, 92 (2001);
A.F. Falk et al., PRD69, 114021 (2004)

D^0 mixing is a rare process

The duration of passion is proportionate
with the original resistance of the woman.

H. de Balzac (1799 -1850)



D^0 mixing

Time evolution

simplified due to |x|, |y| << 1;

various decay modes with specific decay t dependence;

$$\frac{1}{e^{-t}}\frac{d\Gamma(P^0 \to f)}{dt} = \left[\left|A_f\right|^2 + \left|\frac{q}{p}\bar{A}_f\right|^2\right]\cosh(yt) +$$
$$+\left[\left|A_f\right|^2 - \left|\frac{q}{p}\bar{A}_f\right|^2\right]\cos(xt) +$$
$$+2\Re\left[\frac{q}{p}A_f^*\bar{A}_f\right]\sinh(yt) - 2\Im\left[\frac{q}{p}A_f^*\bar{A}_f\right]\sin(xt)$$

⇩

$$\frac{1}{e^{-t}}\frac{d\Gamma(D^0 \to f)}{dt} = \left|A_f + \frac{q}{p}\frac{ix+y}{2}A_{\bar{f}}\right|^2$$

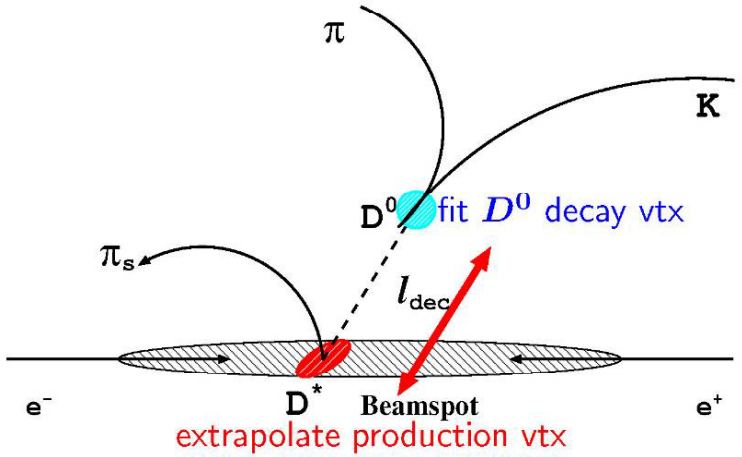
Common features

$D^{*+} \to D^0\pi_s^+$

charge of $\pi_s \Rightarrow$ flavor of D^0;

$\delta M = M(D^0\pi_s) - M(D^0) \Rightarrow$ background reduction

$p^*(D^*) > 2.5$ GeV/c eliminates D^0 from b → c



D^0 mixing

Decays to CP eigenstates

S. Bergman et al., PLB486, 418 (2000)

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

CP even final state;

if no CPV:

$CP|D_1\rangle = |D_1\rangle \Rightarrow \tau = 1/\Gamma_1$;

$K^-\pi^+$: mixture of CP states $\Rightarrow$ $\tau = f(1/\Gamma_1, 1/\Gamma_2)$

$$y_{CP} \equiv \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 \approx y\cos\varphi - \frac{A_M}{2} x \sin\varphi \underset{no\ CPV}{=} y$$

more

A_M, φ: CPV in mixing and interference (addressed later)

Reconstruction

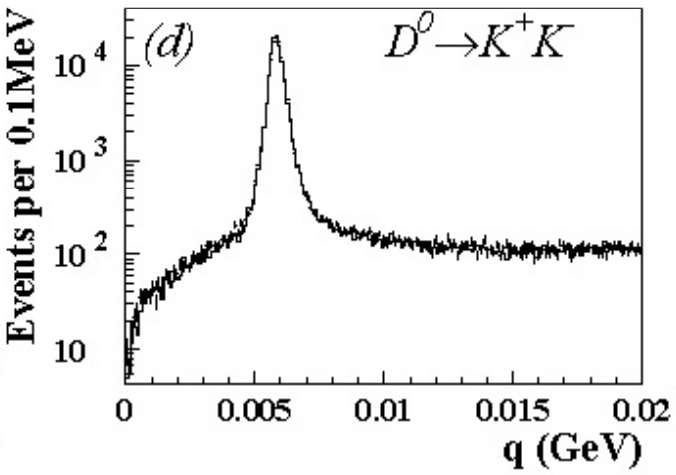
$M(K^+K^-)$,

$Q = M(K^+K^-\pi_s) - M(K^+K^-) - M(\pi)$,

σ_t, selection optimized on MC

	K^+K^-	$K^-\pi^+$	$\pi^+\pi^-$
N_{sig}	111×10^3	1.22×10^6	49×10^3
P	98%	99%	92%

Belle, PRL 98, 211803 (2007), 540fb^{-1}



D^0 mixing

Belle, PRL 98, 211803 (2007), 540fb^{-1}

Decays to CP eigenstates

Fit

simultaneous binned likelihood fit to K^+K^- /$K^-\pi^+$/$\pi^+\pi^-$ decay-t, common free y_{CP}

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

constructed using event-by-event σ_t

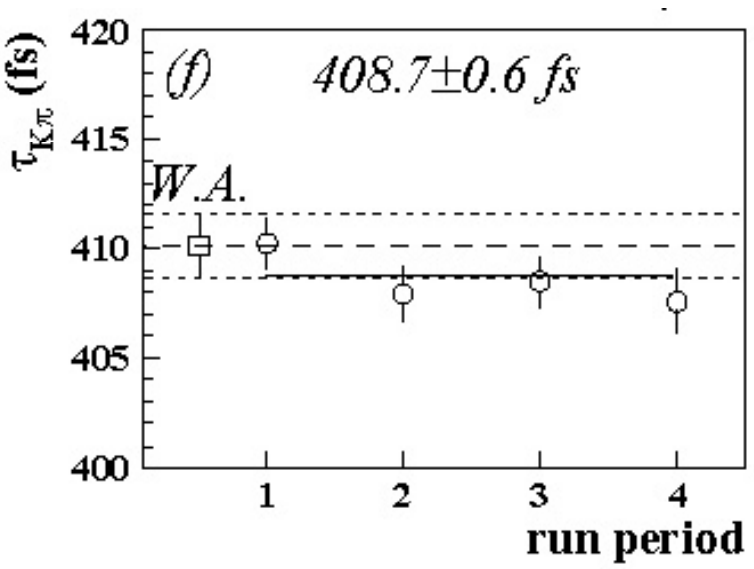
M sideband

more

parameters of $\mathcal{R}$ depend slightly on data taking conditions

τ = 408.7±0.6 fs

τ_{PDG}=410.1±1.5 fs

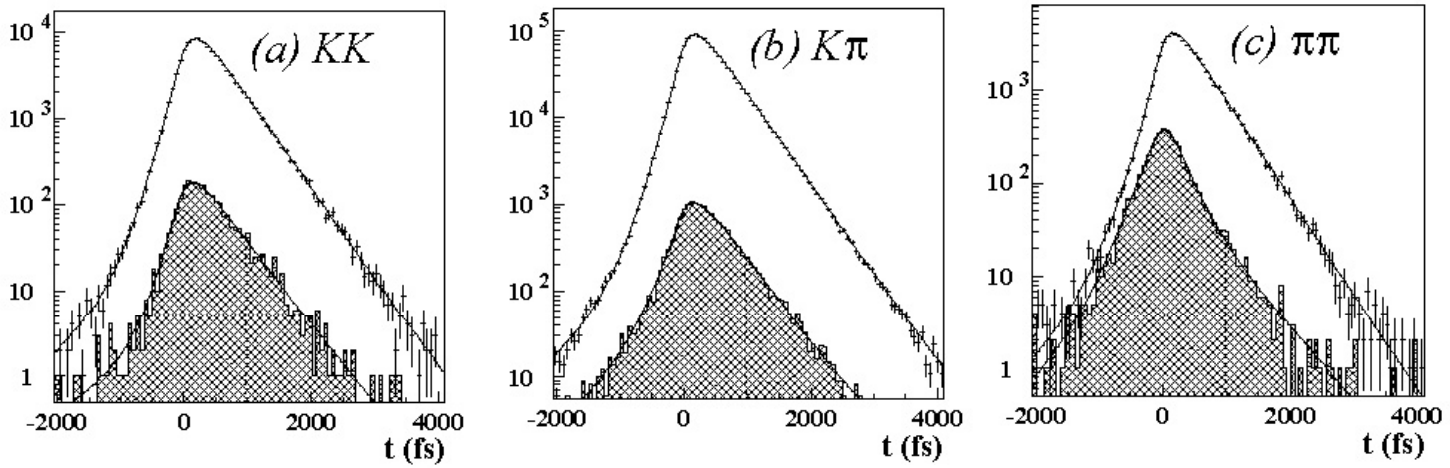


D^0 mixing

Decays to CP eigenstates

Belle, PRL 98, 211803 (2007), 540fb^{-1}

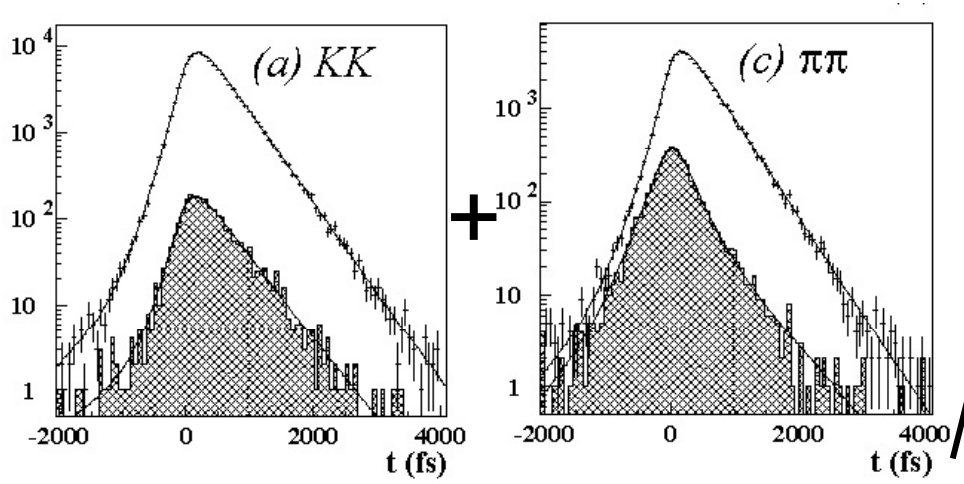
χ^2/ndf=1.084 (ndf=289)



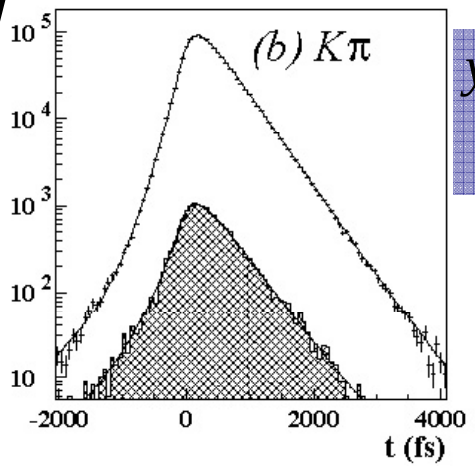
D^0 mixing

Decays to CP eigenstates

Belle, PRL 98, 211803 (2007), 540fb^{-1}

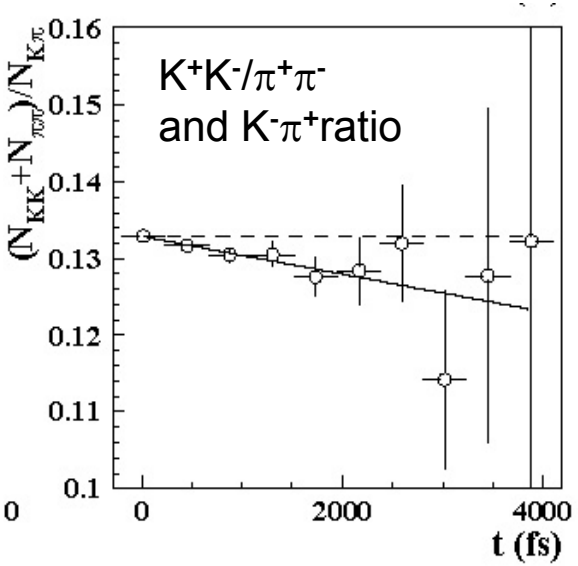


χ^2/ndf=1.084 (ndf=289)



y_{CP} =(1.31± 0.32±0.25)%

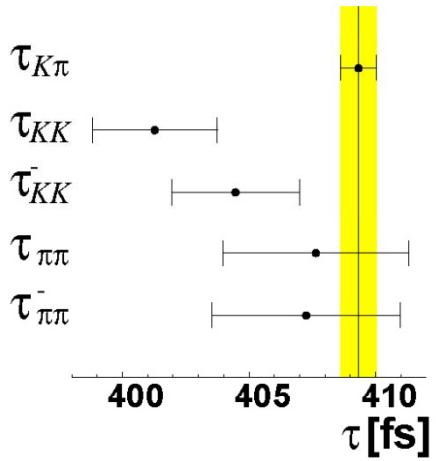
3.2 σ
(4.1 σ
stat. only)



evidence
for D^0 mixing
(regardless of
possible CPV)

confirmation:

BaBar, arXiv:0712.2249, 384fb^{-1}



y_{CP}=(1.24± 0.39±0.13)%

y_{CP} currently most precisely measured param.

D^0 mixing

WS decays (non-CP)

$D^{*+} \to D^0 \ \pi_{slow}^+ \qquad D^0 \to \bar{D}^0 \to K^+\pi^-$

DCS decays $\Rightarrow$ interference;

t-dependence to separate DCS/mixed

$$\left|\left\langle K^+\pi^- \middle| D^0(t)\right\rangle\right|^2 \propto \left[\underbrace{R_D}_{DCS} + \underbrace{\sqrt{R_D}\,y't}_{interf.} + \underbrace{\frac{x'^2+y'^2}{4}t^2}_{mix}\right]e^{-t}$$

$$x' = x\cos\delta + y\sin\delta$$

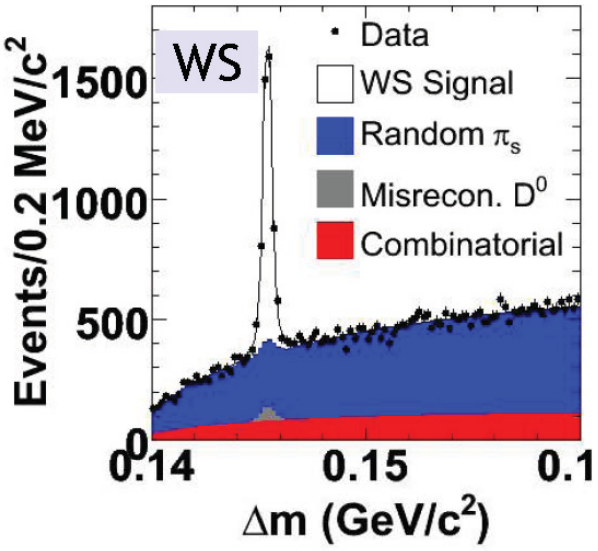
$$y' = y\cos\delta - x\sin\delta$$

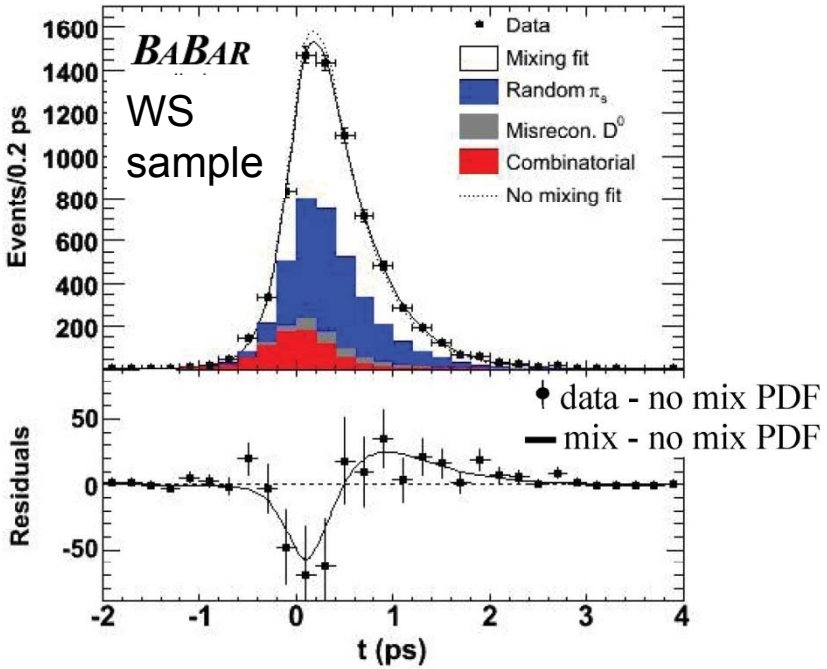
δ: unknown strong phase DCS/CF

reconstruction

N_{WS}=4030±90;

BaBar, PRL 98, 211802 (2007), 384fb^{-1}





fit

$\mathcal{R}$: sum of 3 Gaussians;

RS sample: τ=(410.3±0.6) fs

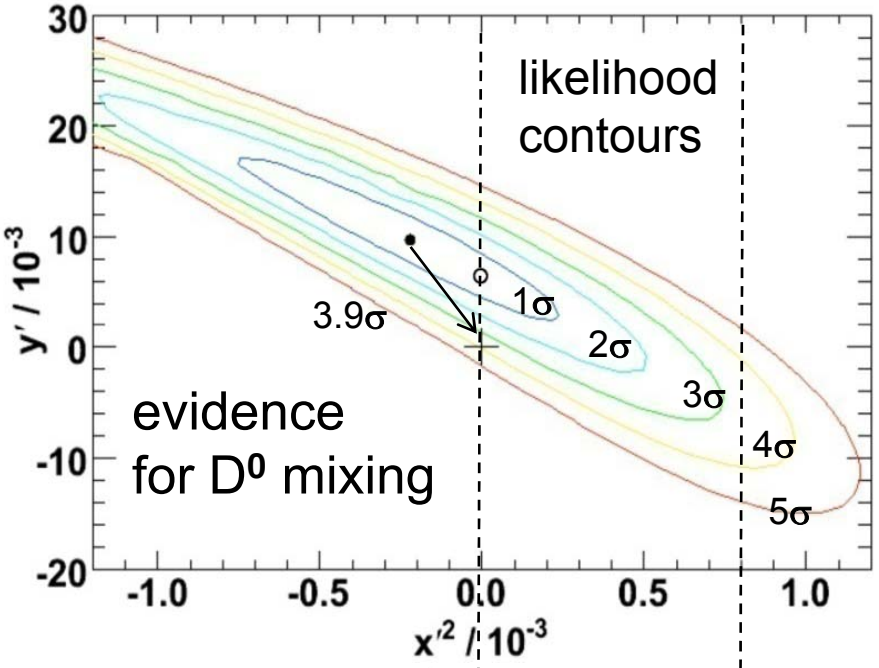
D^0 mixing

WS decays (non-CP)

Result
x'^2, y' region

BaBar, PRL 98, 211802 (2007), 384fb^{-1}

$$R_D = (3.03 \pm 0.16 \pm 0.10) \cdot 10^{-3}$$
$$x'^2 = (-0.22 \pm 0.33 \pm 0.21) \cdot 10^{-3}$$
$$y' = (9.7 \pm 4.4 \pm 3.1) \cdot 10^{-3}$$

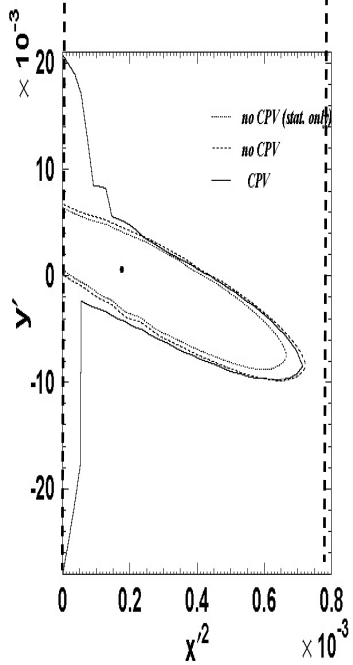


$$R_D = (3.64 \pm 0.17) \cdot 10^{-3}$$
$$x'^2 = (0.18 \pm {}^{0.21}_{0.23}) \cdot 10^{-3}$$
$$y' = (0.6 \pm {}^{4.0}_{3.9}) \cdot 10^{-3}$$

uncertainty includes syst. error

95% C.L. (x'^2, y') contour
frequentist, FC ordering

Belle, PRL 96, 151801 (2006), 400fb^{-1}



D^0 mixing

t-dependent Dalitz analyses

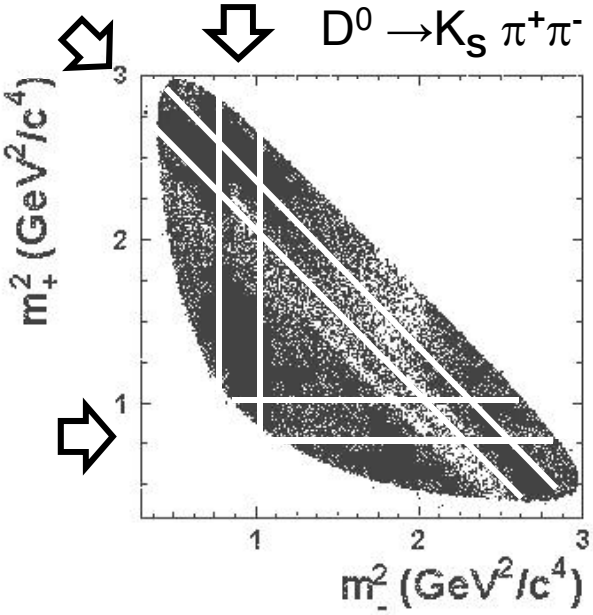
different types of interm. states;

CF: $D^0 \to K^{*-}\pi^+$

DCS: $D^0 \to K^{*+}\pi^-$

CP: $D^0 \to \rho^0 K_S$

if $f = \overline{f} \Rightarrow$ populate same Dalitz plot;
relative phases determined
(unlike $D^0 \to K^+\pi^-$);



D^0 mixing

t-dependent Dalitz analyses

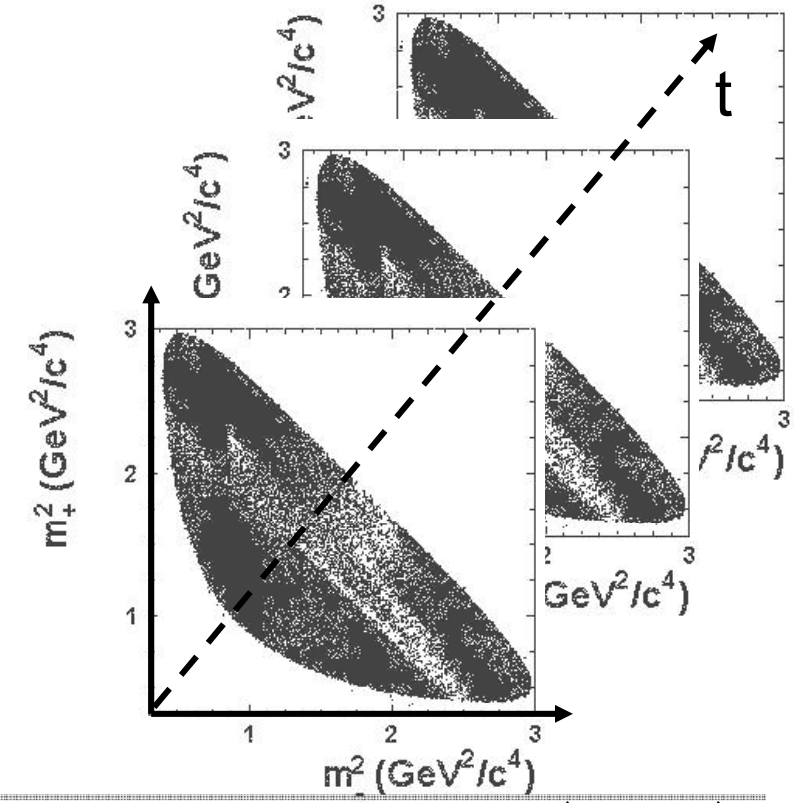
different types of interm. states;

CF: $D^0 \to K^{*-}\pi^+$

DCS: $D^0 \to K^{*+}\pi^-$

CP: $D^0 \to \rho^0 K_S$

if $f = \overline{f} \Rightarrow$ populate same Dalitz plot;
relative phases determined
(unlike $D^0 \to K^+\pi^-$);



t-dependence:

regions of Dalitz plane $\to$
specific t dependence f(x, y);
$m_\pm^2 = m^2(K_S\pi^\pm)$, $\lambda_{1,2} = f(x,y)$;
n.b.: $K^+\pi^-$:x'^2, y'

access directly x, y

$$\mathcal{M}(m_-^2, m_+^2, t) \equiv \left\langle K_S\pi^+\pi^- \middle| D^0(t) \right\rangle =$$

$$= \frac{1}{2}\mathcal{A}(m_-^2, m_+^2)\left[e^{-i\lambda_1 t} + e^{-i\lambda_2 t}\right] + \quad (D^0 \to f)$$

$$+ \frac{1}{2}\frac{q}{p}\overline{\mathcal{A}}(m_-^2, m_+^2)\left[e^{-i\lambda_1 t} - e^{-i\lambda_2 t}\right] \quad (\overline{D}^0 \to f)$$

sum of intermediate states: $\mathcal{A}(m_-^2, m_+^2) = \sum a_r\, e^{i\Phi_r} B(m_-^2, m_+^2) + a_{NR}\, e^{i\Phi_{NR}}$

D^0 mixing

t-dependent Dalitz analyses

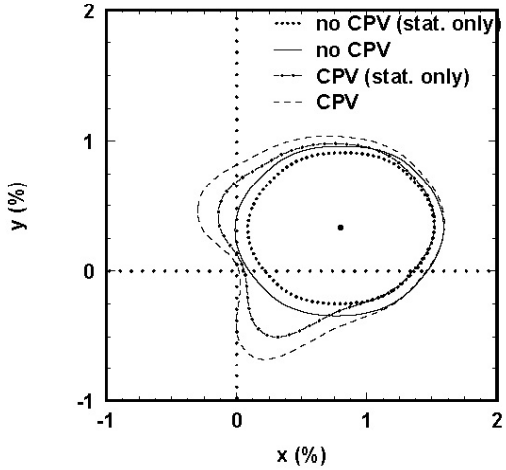
Belle, PRL 99, 131803 (2007), 540fb^{-1}

N_{sig}= (534.4±0.8)x10³
P ≈ 95%

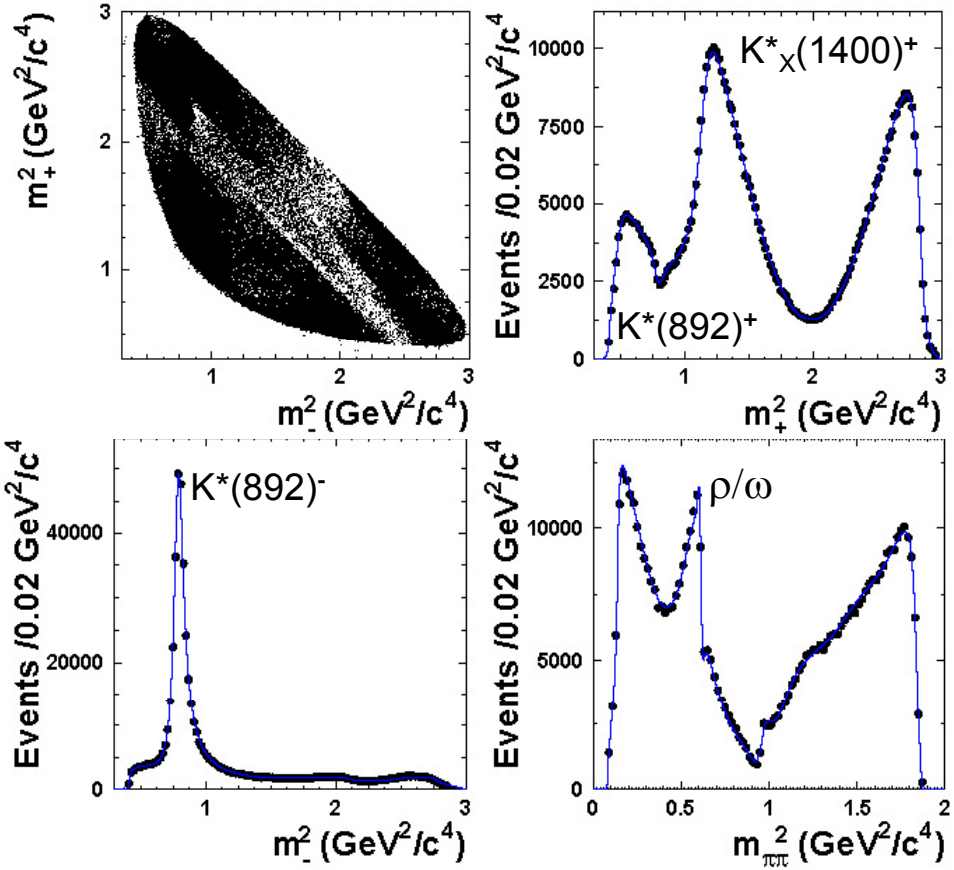
Dalitz fit projections;
decay-t fit projection;

$$x = (0.80 \pm 0.29 \pm {}^{0.13}_{0.16})\%$$

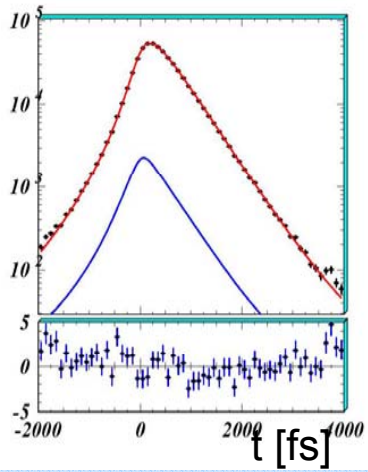
$$y = (0.33 \pm 0.24 \pm {}^{0.10}_{0.14})\%$$



most sensitive meas. of x



τ = (409.9±0.9) fs

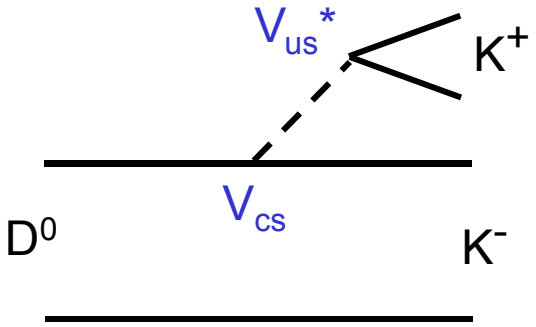


more

D^0 mixing

CP violation

D^0: first two quark generations;
CKM elements ≈ real;



using CKM unitarity:

$$\arg\left(\frac{\langle \bar{f}|\overline{D}^0\rangle}{\langle f|D^0\rangle}\right) \approx \Im\frac{V_{cb}^* V_{ub}}{V_{cs}V_{us}^*} \sim \mathcal{O}(10^{-3})$$

bellow current exp. sensitivity;
signals New Physics

parameterization:

$R_D \neq 1$: Cabbibo suppression

$A_D \neq 0$: CPV in decay
$A_M \neq 0$: CPV in mixing
$\phi \neq 0$: CPV in interference

$$\left|\frac{\langle \bar{f}|D^0\rangle}{\langle f|D^0\rangle}\right| \equiv \sqrt{R_D},$$

more

$$\left|\frac{\langle f|D^0\rangle}{\langle \bar{f}|\overline{D}^0\rangle}\right| \equiv 1+\frac{A_D}{2}, \quad \left|\frac{q}{p}\right| \equiv (1+\frac{A_M}{2}),$$

$$\frac{q}{p}\frac{\langle f|\overline{D}^0\rangle}{\langle f|D^0\rangle} \equiv -\frac{(1+A_M/2)\sqrt{R_D}}{1+A_D/2}e^{-i(\delta_f-\varphi)}$$

D^0 mixing

CP violation

Decays to CP states

$$A_{CP}^f = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} = a_{dec}^f + a_{mix} + a_{int}$$

with $a_{dec} \ll 1$:

$$A_\Gamma = \frac{\tau(\bar{D}^0 \to K^+K^-) - \tau(D^0 \to K^+K^-)}{\tau(\bar{D}^0 \to K^+K^-) + \tau(D^0 \to K^+K^-)} \approx \approx \frac{A_M}{2} y\cos\varphi - x\sin\varphi \underset{no\ CPV}{=} 0$$

more

t-dependent

Belle, PRL 98, 211803 (2007), 540fb^{-1}

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

BaBar, arXiv:0712.2249, 384fb^{-1}

$$A_\Gamma = (0.26 \pm 0.36 \pm 0.08)\%$$

t-integrated

$A_{CP}^{meas} = A_\varepsilon^\pi + A_{FB} + A_{CP}^f$

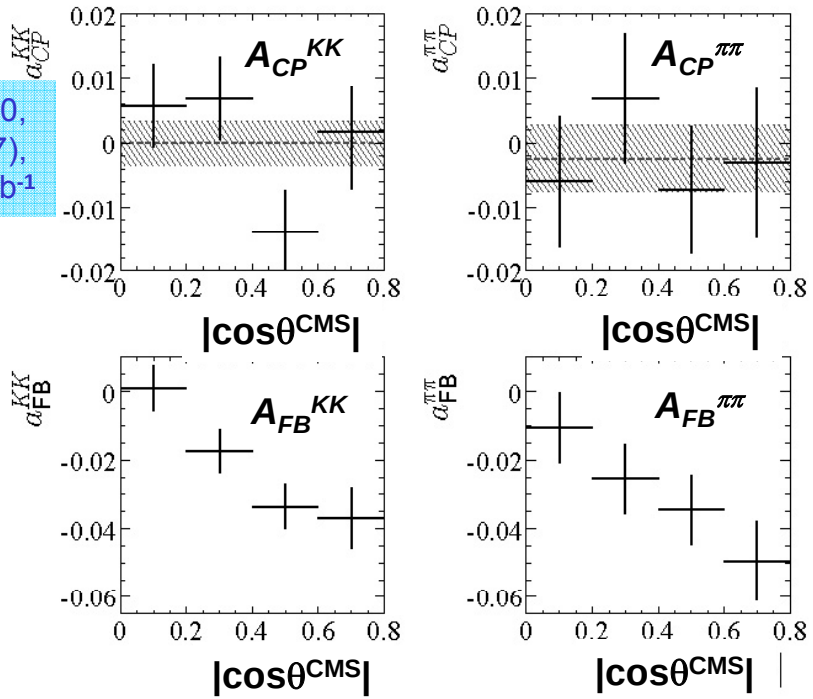
A_ε^π : comparison of tagged/untagged $(D^{*+} \to D^0\pi^+), D^0 \to K^-\pi^+$

A_{FB}: asymmetric f($\cos\theta^{CMS}$)

more

$$A_{CP}^{KK} = (0.00 \pm 0.34 \pm 0.13)\%$$

BaBar, PRL 100, 061803 (2007), 386fb^{-1}



Belle, arXiv:0807.0148, 540fb^{-1}

$$A_{CP}^{KK} = (-0.43 \pm 0.30 \pm 0.11)\%$$

D^0 mixing

CP violation

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

WS decays (non-CP)

separate D^0 and $\overline{D}^0$ tags;

fit $(x'^2, y', R_D) \rightarrow (x'^{\pm 2}, y'^{\pm}, R_D^{\pm})$; consistent with 0

BaBar, PRL 98, 211802 (2007), 384fb^{-1}

R_D	3.03	± 0.16	± 0.10	
A_D	-21	± 52	± 15	
x'^{2+}	-0.24	± 0.43	± 0.30	x10^{-3}
y'^{+}	9.8	± 6.4	± 4.5	
x'^{2-}	-0.20	± 0.41	± 0.29	
y'^{-}	9.6	± 6.1	± 4.3	

consistent

consistent

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

Belle, PRL 96, 151801 (2006), 400fb^{-1}

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

$A_M = (670 \pm 1200) \cdot 10^{-3}$

t-dependent Dalitz analyses

additional free param, $|q/p|$, ϕ;

Belle, PRL 99, 131803 (2007), 540fb^{-1}

$$|q/p| = 0.86 \pm {}^{0.30}_{0.29} \pm {}^{0.10}_{0.09}$$

$$\varphi = (-0.24 \pm {}^{0.28}_{0.30} \pm 0.09)\ rad$$

D^0 mixing

Don't keep mixing in these other things. It only confuses.

K. Kinski (1926 - 1991)

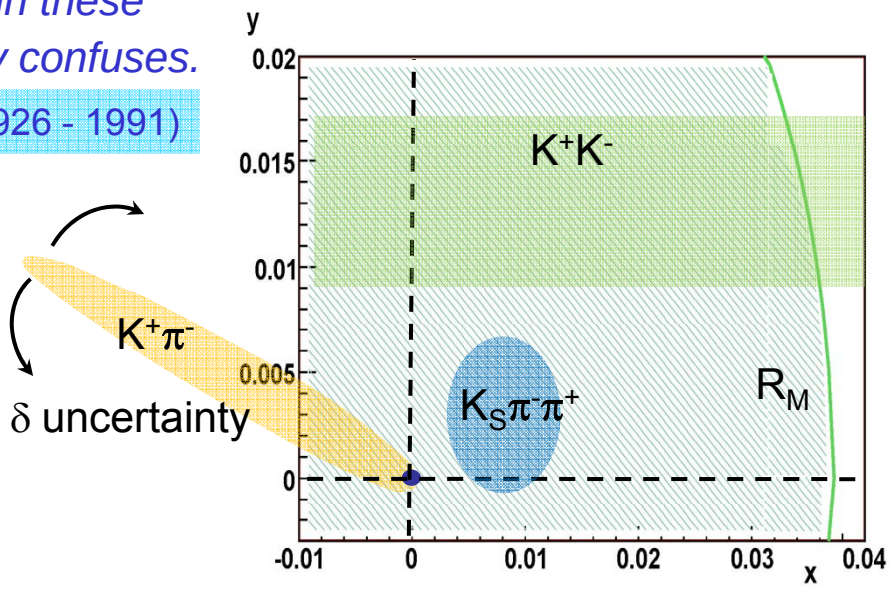
Average of results

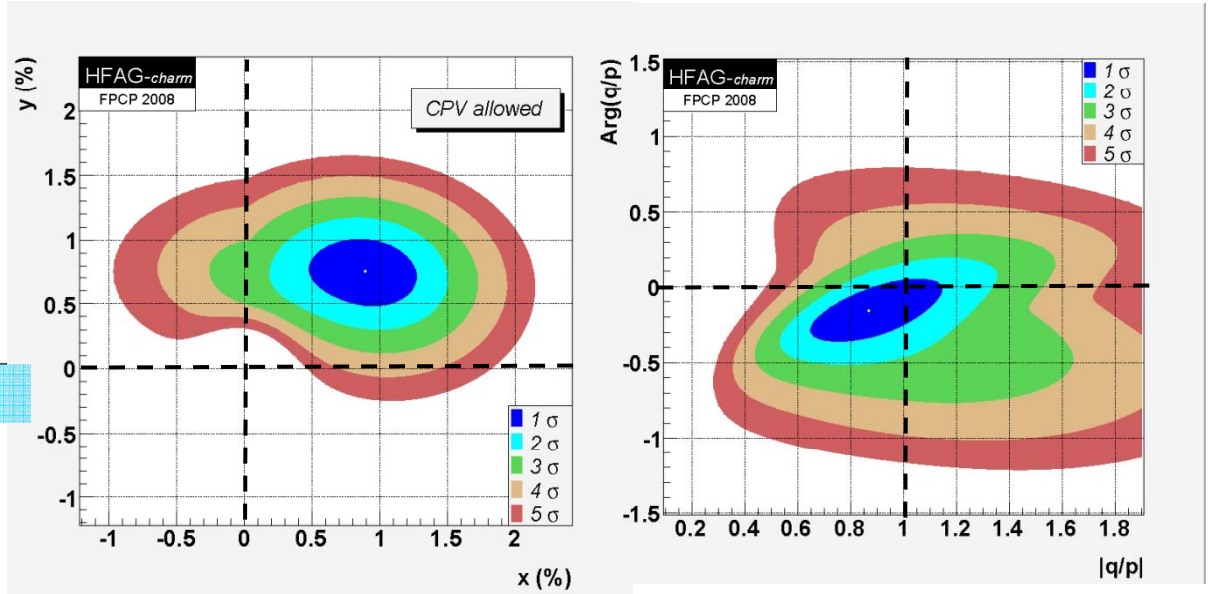
χ^2 fit including correlations among measured quantities

	Parameter	*CPV*-allowed
	x (%)	$0.89\ ^{+0.26}_{-0.27}$
	y (%)	$0.75\ ^{+0.17}_{-0.18}$
	δ (°)	$21.9\ ^{+11.3}_{-12.4}$
	R_D (%)	0.3348 ± 0.0086
CPV	A_D (%)	-2.0 ± 2.4
CPV	$\|q/p\|$	$0.87\ ^{+0.18}_{-0.15}$
CPV	ϕ (°)	$-9.1\ ^{+8.1}_{-7.8}$
	$\delta_{K\pi\pi}$ (°)	$33.0\ ^{+25.9}_{-26.6}$

http://www.slac.stanford.edu/xorg/hfag/charm/

χ^2/n.d.f.= 23.5/18





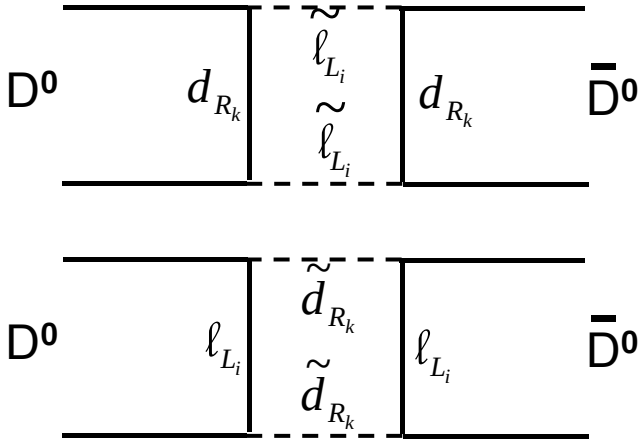
(x,y)≠(0,0): 6.7σ;
CP even state heavier and shorter lived;
no CPV within 1σ

D^0 mixing

Constraints on NP

uncertain SM predictions for x, y;
measured values can impose constraints on NP models parameter space;
e.g. R-parity violating SUSY;
existing constraints largely improved for many NP models

E. Golowich et al., PRD76, 095009 (2007)



Approximate sensitivity

SuperB, $\mathcal{L}$ = 5 ab^{-1}

σ(x)	σ(y)	σ(|q/p|)	σ(ϕ)
0.1%	0.1%	0.1	0.1

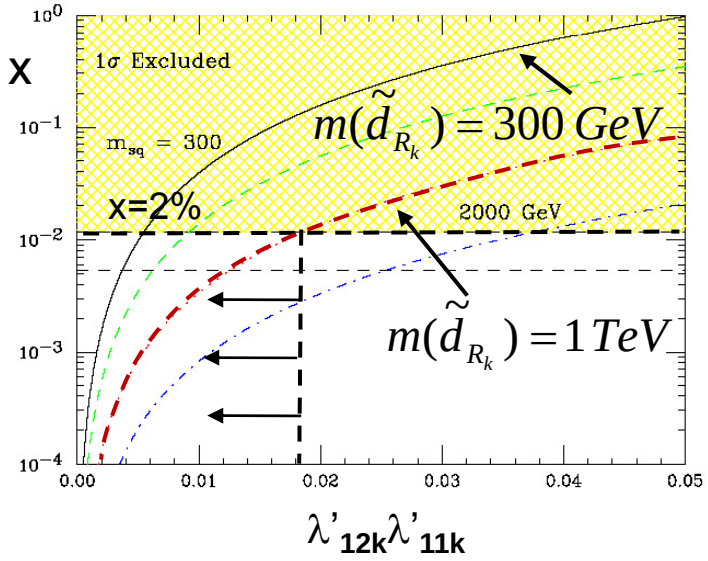
LHCb, $\mathcal{L}$ = 10 fb^{-1}

σ(x'^{2})	σ(y')
6x10^{-5}	0.1%

Prediction is very difficult, especially of the future.

N. Bohr (1885 - 1962)

x, y accuracy ~3x better than current WA; sensitivity to CPV would cover range of SM predictions



R-parity violating coupling const.

D_s leptonic decays

$D_s \to \mu\nu$

analogy of B leptonic decays, see Lecture 1;

check of LQCD (f_P) ?

Method: Belle, PRL 100, 241801 (2008), 548fb^{-1}

inverse (recoil) reconstruction

$D \to Kn\pi$, n=1,3

relative charge (K_{prim}, D)/D_s*

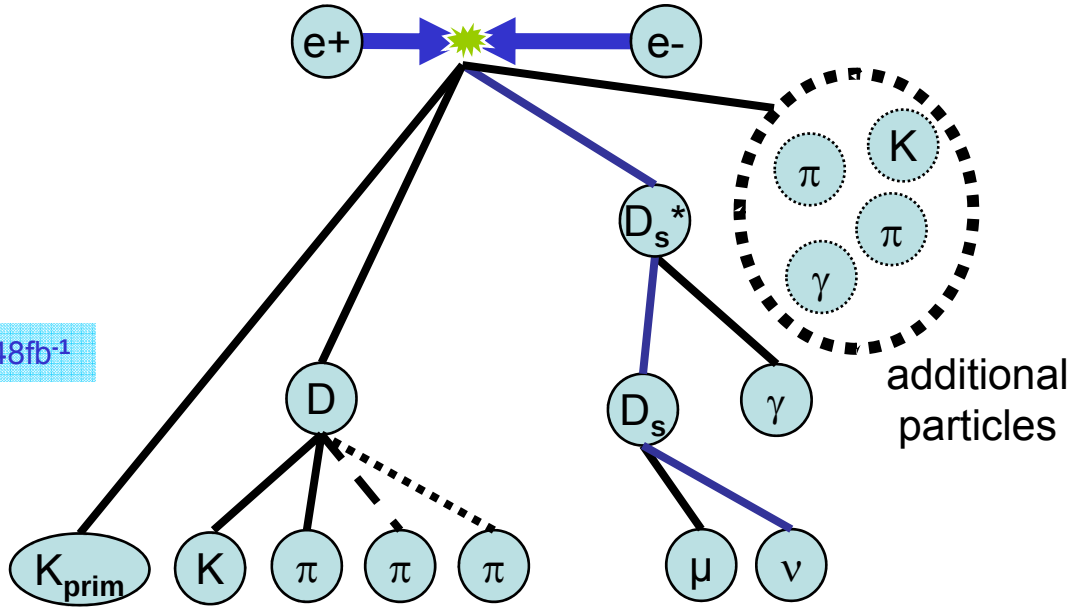
right-, wrong-sign

$M(D_s)=M_{rec}(DK_{prim}X\gamma)$

inclusive D_s signal (no μ requirement)

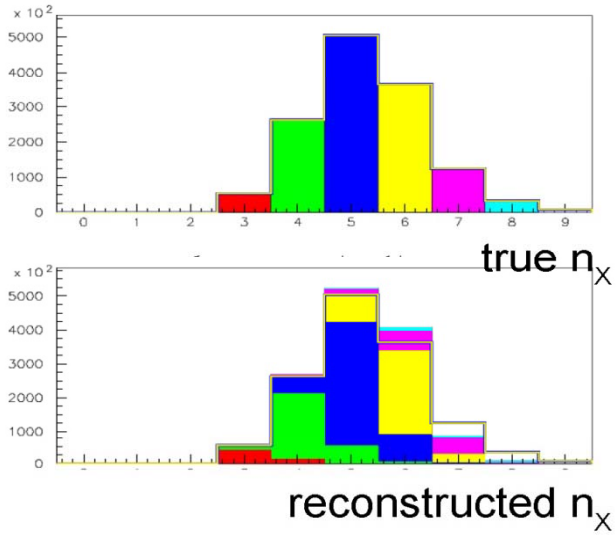
$M^2(\nu)=M^2_{rec}(DK_{prim}X\gamma\mu)$

$D_s \to \mu\nu$ signal



tag — full recon.

signal — recon. in recoil



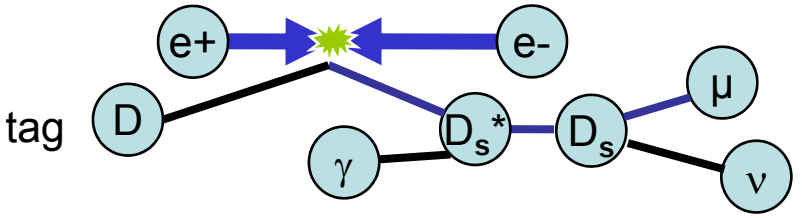
efficiency depends on # primary particles:

n_x = 3 (DD_s*K_{prim}) + N

differences data/MC

D_s leptonic decays

$D_s \to \mu\nu$

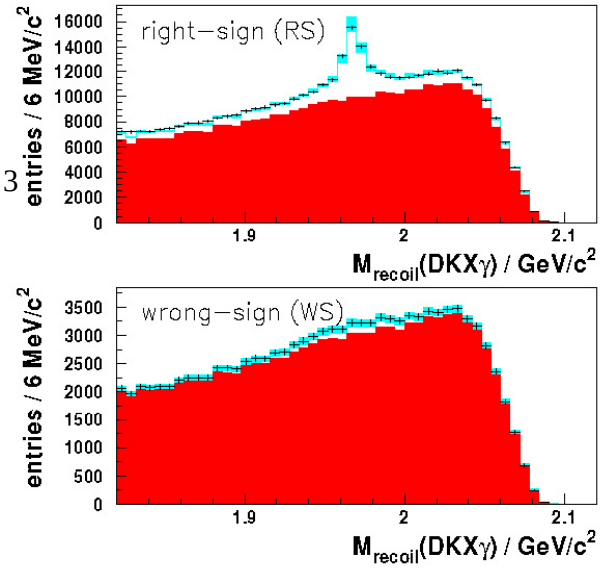


Method Belle, PRL100, 241801 (2008), 548fb^{-1}

fit data M(D_s) distr. with MC signal in bins of n_X^{rec}; bkg. from WS

inclusive $D_s \Rightarrow$ normalization;

$$N_{Ds}^{rec} = \sum_{i=3}^{8} w_i^{Ds} N_{Ds}^{MC,i} = (32.10 \pm 0.87) \cdot 10^3$$



Method BaBar, PRL98, 141801 (2007), 230fb^{-1}

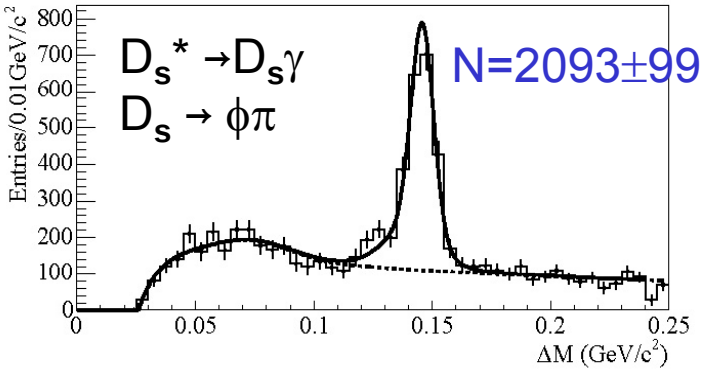
fully reconstruct tag side D_s,D^+,D^0,D^{*+}; μ,γ;

p_ν from p_{miss} with $m(\nu,\mu) \equiv m_{Ds}$;

signal in $\Delta M = M(\mu\nu\gamma) - M(\mu\nu)$ (~ $m_{Ds^*} - m_{Ds}$);

exact D_s production in $c\bar{c}$ not known

normalization: $D_s \to \phi\pi$



D_s leptonic decays

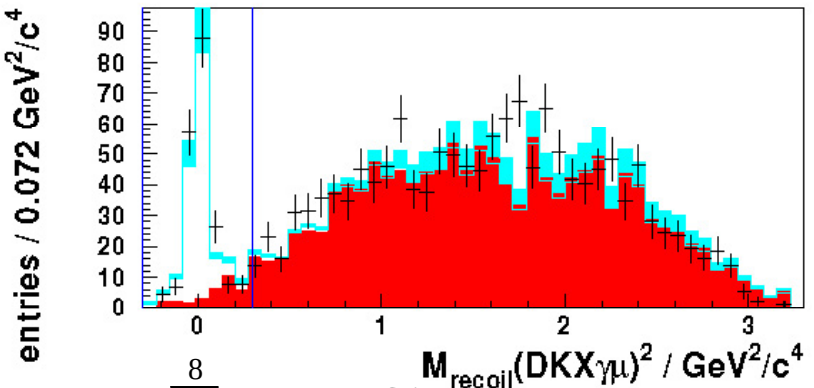
$D_s \to \mu\nu$

Signal — Belle, PRL100, 241801 (2008), 548fb^{-1}

fit data M(ν) distribution with MC signal in bins of n_X^{rec}; bkg. from $D_s \to e\nu$

$$Br(D_s \to \mu\nu) = \frac{N_{\mu\nu}^{rec}}{\bar{\varepsilon}_{\mu\nu} N_{Ds}^{rec}}$$

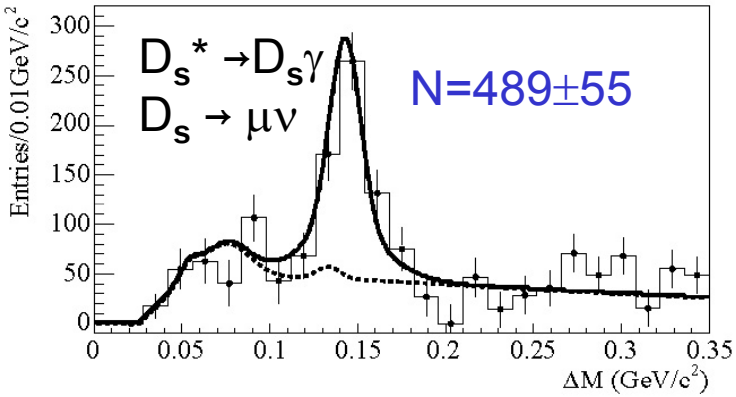
ε dependence reduced (single track (μ) recon.)



$$N_{\mu\nu}^{rec} = \sum_{i=3}^{8} w_i^{\mu\nu} N_{\mu\nu}^{MC,i} = 169 \pm 16 \pm 8$$

$Br(D_s \to \mu\nu) = (6.44 \pm 0.76 \pm 0.56) \times 10^{-3}$

BaBar, PRL98, 141801 (2007), 230fb^{-1}



$Br(D_s \to \mu\nu) = (6.74 \pm 0.83 \pm 0.26 \pm 0.66) \times 10^{-3}$

last uncertainty Br($D_s \to \phi\pi$)

using $|V_{cs}| = 0.9730 \pm 0.0002$ from overall fit including unitarity (PDG)

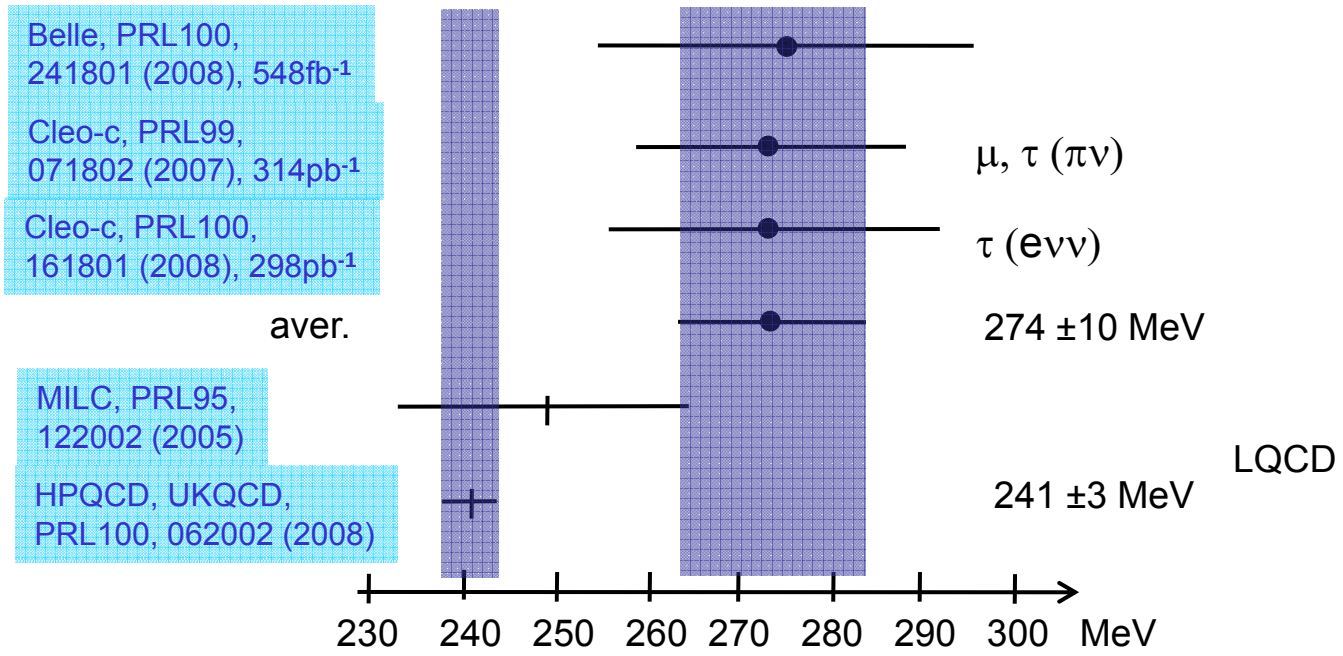
$f_{Ds} = (275 \pm 16 \pm 12)$ MeV — Belle, PRL100, 241801 (2008), 548fb^{-1}

$f_{Ds} = (283 \pm 17 \pm 7 \pm 14)$ MeV — BaBar, PRL98, 141801 (2007), 230fb^{-1}

D_s leptonic decays

$D_s \to \mu\nu$

Average of absolute meas.;



huge improvement in LQCD accuracy;

agreement for f_{D+}:
LQCD: 208 ± 4 MeV
exp.: 223 ±17 MeV
(but exp. error larger than for f_{Ds})

to do list:
confirm LQCD uncertainty;
reduce exp. uncertainty;

more

Spectroscopy

Production @ B-factories

open and hidden charm;

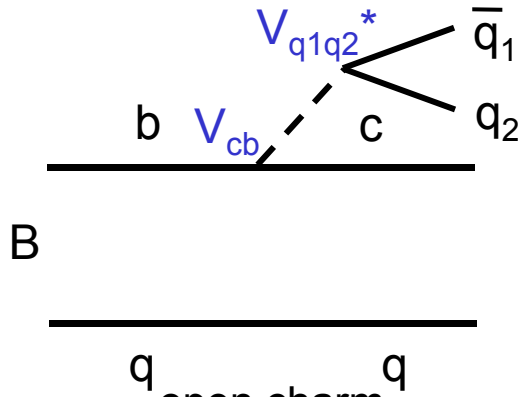
clean exp. environment;

various methods related to different prod. mechanisms;

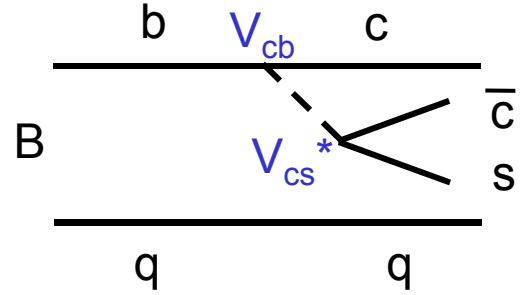
rich harvest of previously unknown states at B-factories;

only few (“exotic”) examples discussed;

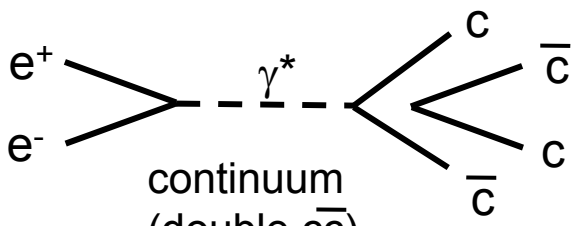
spectroscopy: tests of QCD, bounding q’s and g’s in hadrons



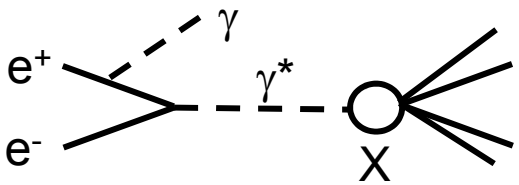
open charm
(D_s**, D**,...)



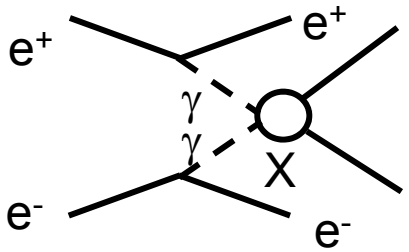
colour suppressed;
hidden charm
($c\bar{c}$, charmonium-like...)



continuum
(double $c\bar{c}$)



initial state radiation
(1^{--} states)



two photon processes

Spectroscopy

Exotic states

states other than $q_1\bar{q}_2$, $q_1q_2q_3$
not forbidden in SM;
exotic J^{PC} (e.g. 0^{+-}, 1^{-+}, 2^{+-},...
forbidden for $q\bar{q}$);
exotic decay modes (not possible from $q\bar{q}$);
strange properties (widths,...);

pentaquarks:
  $q_1q_2q_3q_4q_5$;
hybrids:
  $c\bar{c}$ + g's;
tetraquarks:
  diquark-antidiquark, $[cq][\bar{c}\bar{q}]$
molecules:
  $M(c\bar{q})\bar{M}(\bar{c}q)$, loosely bound mesons

...Life is like a box of chocolates, you never know...:
Forrest Gump (1994)

Spectroscopy

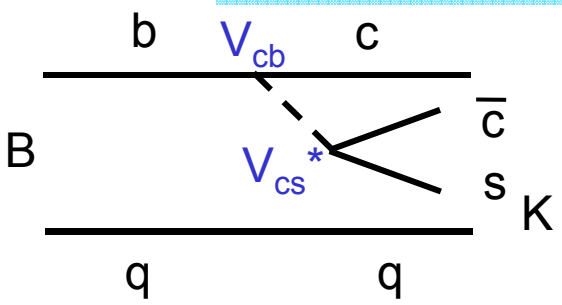
X(3872)

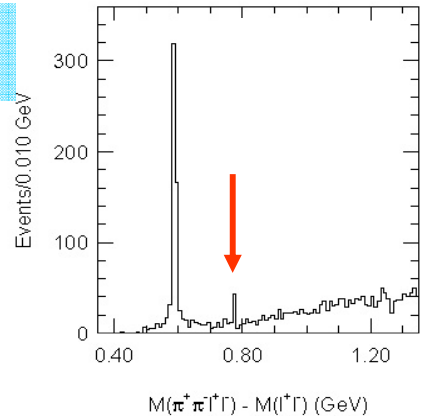
observed in B decays,
$B \to (J/\psi\pi\pi)K$;
charmonium-like;

well established state;

$$M_{X(3872)} = 3871.2 \pm 0.5\ MeV$$
$$M_{X(3872)} - M_{D^{*0}} - M_{D^0} = -0.6 \pm 0.6\ MeV$$
$$\Gamma < 2.3\ MeV$$

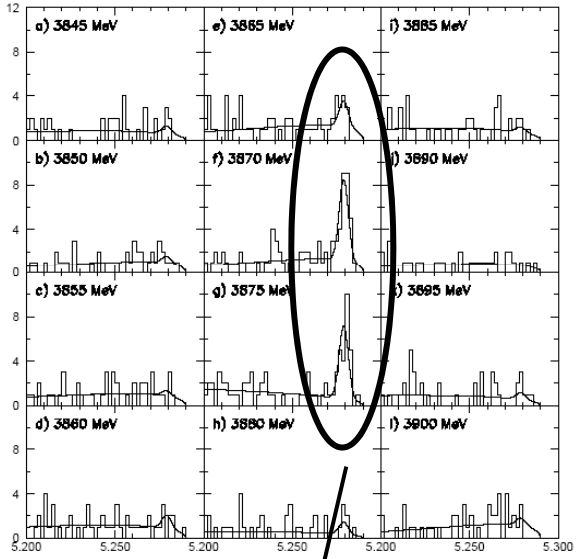
Belle, PRL 91, 262001 (2003), 140fb^{-1}

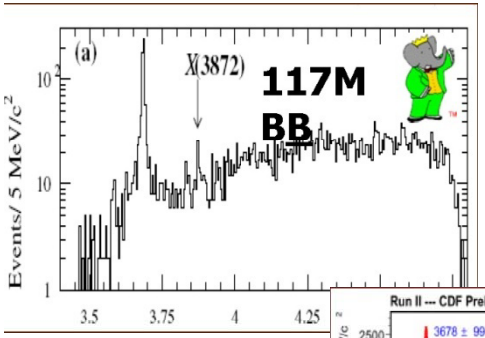


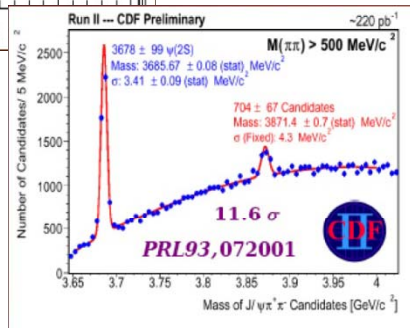


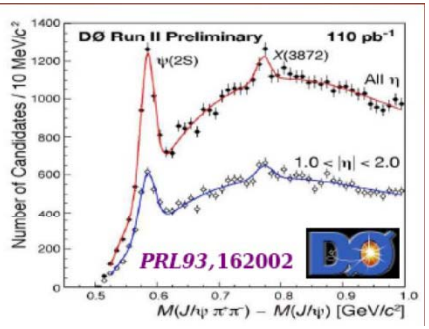
M_{bc} in 5 MeV bins of $M(\pi^+\pi^- J/\psi)$

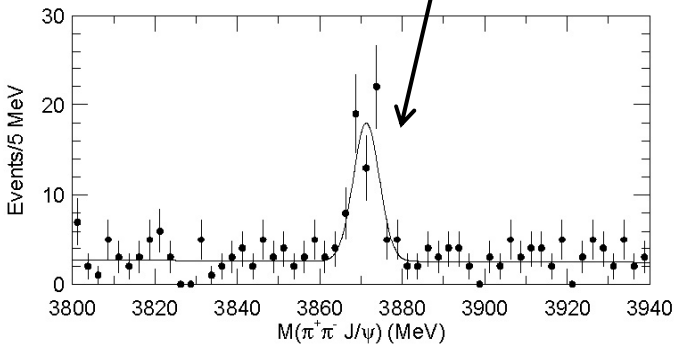
Belle, hep-ex/0505038, 250fb^{-1}











Spectroscopy

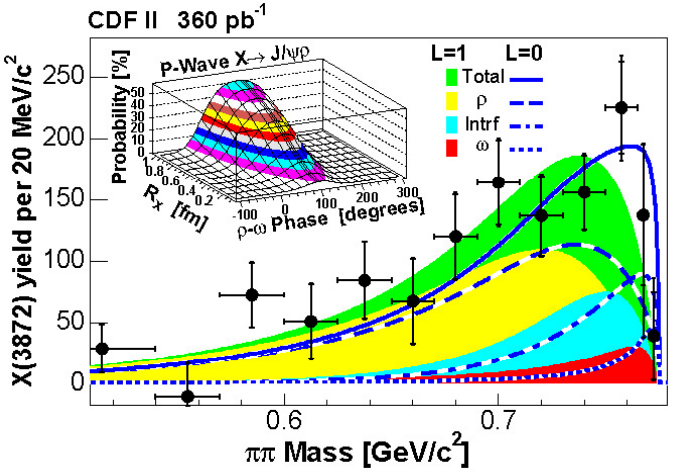
CDF, PRL96, 1 02002 (2006), 360pb^{-1}

X(3872)

properties

$$\frac{Br(X \to \gamma J/\psi)}{Br(X \to \pi^+\pi^- J/\psi)} = 0.14 \pm 0.05$$

more



C=+1;

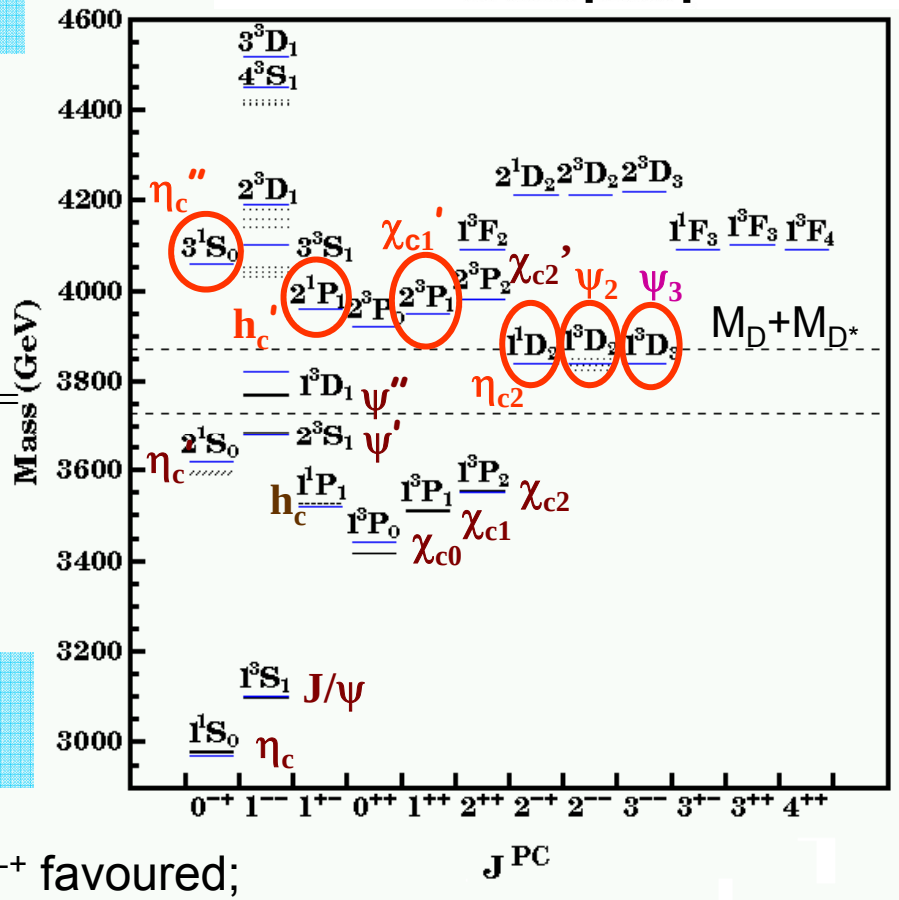
Belle, hep-ex/0505037, 250fb^{-1}

M(ππ) distrib., ρ-like;
($c\bar{c}$) →J/ψρ isospin breaking;
4-quark states:

$$|c\bar{c}u\bar{u}\rangle = \frac{1}{\sqrt{2}}|c\bar{c}\rangle\left[\frac{1}{\sqrt{2}}(|u\bar{u}\rangle + |d\bar{d}\rangle) + \frac{1}{\sqrt{2}}(|u\bar{u}\rangle - |d\bar{d}\rangle)\right] = \frac{1}{\sqrt{2}}\left[|I=0\rangle + |I=1\rangle\right]$$

η_c'': ang. distr., M, Γ;
χ_{c0}': ang. distr., D$\bar{D}$;
χ_{c1}': γJ/ψ
η_{c2}: ππη_c dominant, DD*;
χ_{c2}': DD*;
no obvious $c\bar{c}$ candidate;

ang. distrib.:
Belle, hep-ex/0505038, 250fb^{-1}



J^{PC}= 1^{++}, 2^{-+} favoured;

Spectroscopy

X(3872)

other possibilities

DD* molecule:
isospin breaking;
$J^{PC}=1^{++}$;
$J/\psi\pi\pi$ favoured over $DD\pi$;
R~0.1

E. Braten, M. Lu, PRD77, 014029 (2008);
see also E.S. Swanson, Phys. Rept. 429, 243 (2006) for review

more

Belle, PRL97, 162002 (2006), 414 fb^{-1}

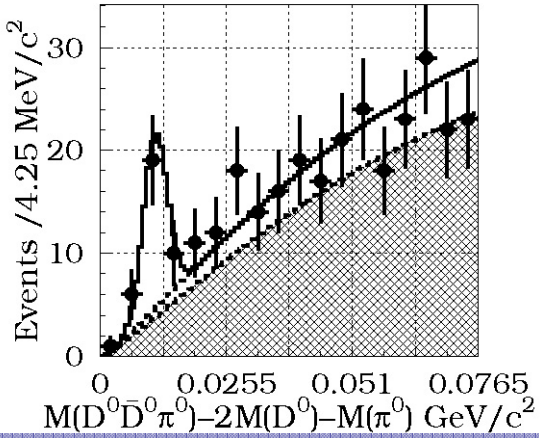
Belle, hep-ex/0505037, 250fb^{-1}

$$R=\frac{Br(X\to D^0D^0\pi^0)}{Br(X\to J/\psi\pi\pi)}=10\pm4$$

J=2 decays to DD*
suppressed by $(p^*)^{2L+1}$
with L=1,2;
1^{++} state favoured

Belle, PRL97, 162002 (2006), 414 fb^{-1}

$B^+\to X(\bar{D}^0D^0\pi^0)K^+$

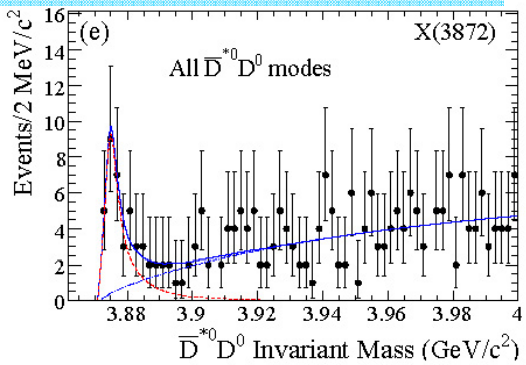


$$M_{X(3872)}=(3875.4\pm0.7\pm^{0.4}_{1.7}\pm0.9)\ MeV$$

last uncertainty: m_{D0};
main syst.: π^0 calibration and signal shape

BaBar, PRD77, 111102 (2008), 347 fb^{-1}

$B^+\to X(\bar{D}^{*0}D^0)K^+$

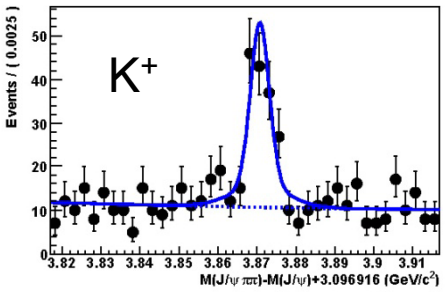


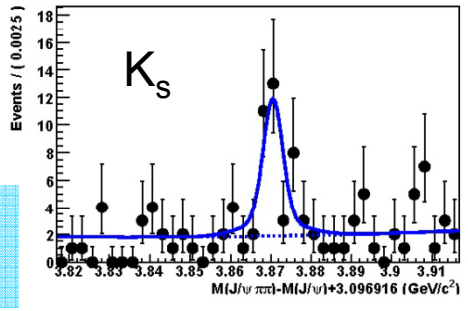
$$M_{X(3872)}=(3875.1\pm^{0.7}_{0.5}\pm0.5)\ MeV$$

Spectroscopy

X(3872)

M(J/ψππ) for B →XK





other possibilities

DD* molecule:

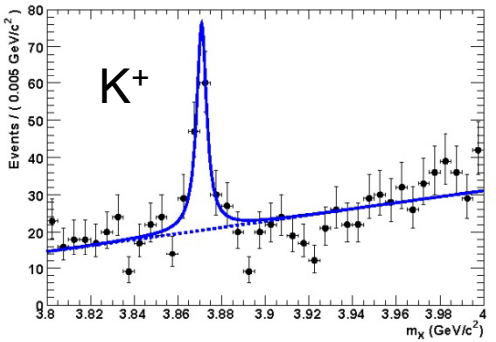
prod. from B^0 suppressed compared to B^+ (depending on model parameters);

It is characteristic of wisdom not to do desperate things.

H.D. Thoreau (1817 - 1862)

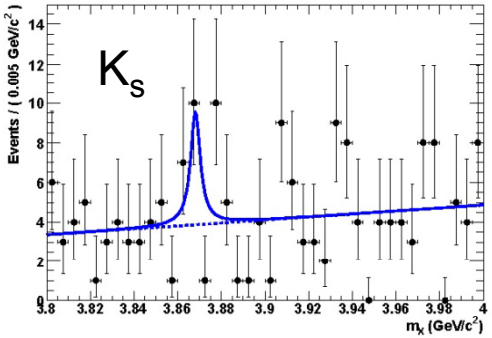
$$\frac{Br(B^0 \to XK^0)}{Br(B^+ \to XK^+)} = 0.94 \pm 0.24 \pm 0.10$$
$$M(B^+ \to X) - M(B^0 \to X) = (0.22 \pm 0.90 \pm 0.27)\ MeV$$

Belle, BELLE-CONF-0711, 605 fb^{-1}



$$\frac{Br(B^0 \to XK^0)}{Br(B^+ \to XK^+)} = 0.41 \pm 0.24 \pm 0.05$$
$$M(B^+ \to X) - M(B^0 \to X) = (2.7 \pm 1.6 \pm 0.4)\ MeV$$

BaBar, PRD77, 111101 (2008), 413 fb^{-1}



tetraquarks:

two mixed states, [cu][$\overline{cu}$], [cd][$\overline{cd}$];
one produced mainly in B^0, other in B^+ decays ⇒ mass difference;
also charged X^+ [cu][$\overline{cd}$], no evidence so far;

L. Maiani et al., PRD71, 014028 (2005)

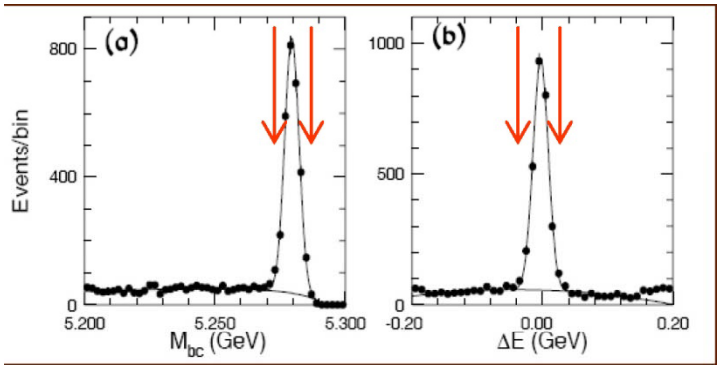
more

Spectroscopy

$Z^+(4430)$

Belle, PRL100, 142001 (2008), 605 fb^{-1}

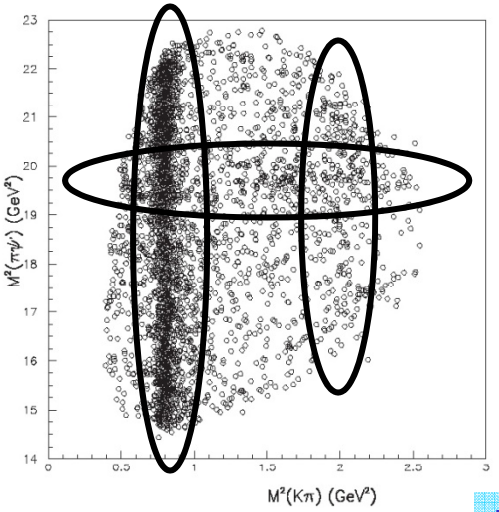
$B \rightarrow (\psi'\pi^+)K$;
$\psi' \rightarrow \ell\ell$, $J/\psi\pi\pi$;

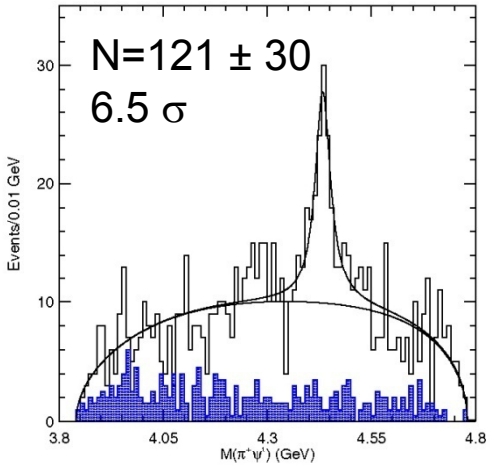


Dalitz plot;
K* veto;

$\Rightarrow$ $M(\psi'\pi^+)$;
fit: BW + phase space;

$$M(Z) = (4433 \pm 4 \pm 2)\ MeV$$
$$\Gamma(Z) = (45 \pm {}^{18}_{13} \pm {}^{30}_{13})\ MeV$$





L.Maiani et al., arxiv:0708.3997
J. Rosner, PRD74, 114002 (2007)
C. Meng et al., arxiv:0708.4222

signal stable in subsamples, w.r.t. K* veto, etc.;

known S-, P- and D-wave $K\pi$ resonances tried, cannot reproduce the peak;
first charged charmonium-like resonance;

more

possibilities:
tetraquark, radial excitation of $X^+(3872)$
($J^P=1^+$; neutral partner?);
$D^*D_1(2420)$ threshold effect;
$D^*D_1(2420)$ molecule
($J^P=0^-,1^-,2^-$;decays to $D^*D^*\pi$?)

Summary

B-factories succesfully perform the precission measurements in determination of SM processes
as a complement to direct NP searches (starting on Sep. 10)

SM stands, although hints (~3 σ) of discrepancies are seen

B-factories have outreached the program as foreseen at the start

B oscillations
in conjunction with breakthrough in B_s confirms SM to a high accuracy

leptonic and radative B decays
constrain NP but large room for improvement from SuperB

Important results in charm

D^0 mixing and CPV
another milestone achieved, need more precise measurements and predictions

D_s leptonic decays
testing LQCD

Spectroscopy
may need revision

D^0 mixing more

CPV parameterization

three types of CPV

$$\left|\frac{A_{\bar f}}{A_f}\right| \equiv \sqrt{R_D}; \quad \left|\frac{\overline{A}_f}{\overline{A}_{\bar f}}\right| \equiv \sqrt{R_D}$$

$R_D \neq 1 \Rightarrow$ Cabbibo supp.

$$\left|\frac{A_f}{\overline{A}_{\bar f}}\right| \equiv 1 + \frac{A_D}{2}$$

$A_D \neq 0 \Rightarrow$ direct CPV

- sign due to relative sign of V_{us} and V_{cd};

$$\frac{\overline{A}_f}{A_f} \equiv -\frac{\sqrt{R_D}}{1+\frac{A_D}{2}} e^{-i\delta}; \quad \frac{A_{\bar f}}{\overline{A}_{\bar f}} \equiv -\sqrt{R_D}\left(1+\frac{A_D}{2}\right)e^{-i\delta}$$

$$\frac{\overline{A}_f}{A_f} \propto \frac{V_{cd}^* V_{us}}{V_{ud}^* V_{cs}} = \frac{-\lambda\,\lambda}{(1-\lambda^2)(1-\lambda^2)} = -\frac{\lambda^2}{(1-\lambda^2)^2}$$

$$\frac{A_{\bar f}^*}{\overline{A}_{\bar f}^*} \equiv -\sqrt{R_D}\left(1+\frac{A_D}{2}\right)e^{i\delta}; \quad \frac{\overline{A}_f^*}{A_f^*} \equiv -\frac{\sqrt{R_D}}{1+\frac{A_D}{2}} e^{i\delta}$$

$$\frac{q}{p} \equiv \left(1+\frac{A_M}{2}\right)e^{i\varphi}$$

$A_M \neq 0 \Rightarrow$ CPV in mixing

$\phi \neq 0 \Rightarrow$ CPV in interf.

back

back

D^0 mixing more

Decays to CP eigenstates

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

$$f = \bar{f};\quad A_f = A_{\bar{f}};\quad \overline{A}_f = \overline{A}_{\bar{f}};\quad \left|\frac{A_f}{\overline{A}_{\bar{f}}}\right| \equiv 1 + A_D$$

$$\frac{\left|\left\langle f \left| P^0(t)\right\rangle\right|^2}{e^{-t}} = \left|A_f\right|^2\left[1 + \frac{1+A_M}{1+A_D}\left(x\sin\varphi - y\cos\varphi\right)t + \frac{(1+A_M)^2}{(1+A_D)^2}\frac{x^2+y^2}{4}t^2\right]$$

$$\frac{\left|\left\langle f \left| \overline{P}^0(t)\right\rangle\right|^2}{e^{-t}} = \left|A_f\right|^2\left[\frac{1}{(1+A_D)^2} - \frac{1}{(1+A_D)(1+A_M)}\left(x\sin\varphi + y\cos\varphi\right)t + \frac{1}{(1+A_M)^2}\frac{x^2+y^2}{4}t^2\right]$$

to linear order:

$$\frac{\left|\left\langle f \left| P^0(t)\right\rangle\right|^2}{e^{-t}} = \left|A_f\right|^2\left[1 + (1 + A_M - A_D)(x\sin\varphi - y\cos\varphi)\,t\right]$$

$$\frac{\left|\left\langle f \left| \overline{P}^0(t)\right\rangle\right|^2}{e^{-t}} = \left|A_f\right|^2\left[1 - 2A_D - (1 - A_D - A_M)\left(x\sin\varphi + y\cos\varphi\right)t\right]$$

back

D^0 mixing more

Decays to CP eigenstates

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

$$\frac{\left|\langle f|P^0(t)\rangle\right|^2}{e^{-t}} + \frac{\left|\langle f|\overline{P}^0(t)\rangle\right|^2}{e^{-t}} = |A_f|^2\left[1 - A_D - \left((1-A_D)\,y\cos\varphi - A_M\,x\sin\varphi\right)t\right]$$

since $A_D << 1$

$$\frac{\left|\langle f|P^0(t)\rangle\right|^2}{e^{-t}} + \frac{\left|\langle f|\overline{P}^0(t)\rangle\right|^2}{e^{-t}} = |A_f|^2\left[1 - (y\cos\varphi - A_M\,x\sin\varphi)\,t\right] \equiv |A_f|^2\left[1 - y_{CP}t\right]$$

$$\left|\langle f|P^0(t)\rangle\right|^2 + \left|\langle f|\overline{P}^0(t)\rangle\right|^2 \propto e^{-t}(1 - y_{CP}t) \approx e^{-t}e^{-y_{CP}t} = e^{-(1+y_{CP})t}$$

$1/\bar{\Gamma} = \tau_f = \tau/(1+y_{CP})$; $y_{CP} = (\tau/\tau_f) - 1 = y\cos\phi - A_m x \sin\phi$

if same procedure applied separately to D^0 and $\overline{D}^0$ lifetime:

$$\tau_f = \tau\left[1 + (1 + A_M - A_D)(x\sin\varphi - y\cos\varphi)\right],\quad \bar{\tau}_f = \tau\left[1 - (1 - A_M - A_D)(x\sin\varphi + y\cos\varphi)\right]$$

$$A_\Gamma \equiv \frac{\bar{\tau}_f - \tau_f}{\bar{\tau}_f + \tau_f} = A_M\,y\cos\varphi - (1 - A_D)\,x\sin\varphi \approx A_M\,y\cos\varphi - x\sin\varphi$$

back

back

D^0 mixing more

Decays to CP eigenstates

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

Fit

simultaneous binned likelihood fit to K^+K^- /$K^-\pi^+$/$\pi^+\pi^-$ decay-t, common free y_{CP}

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

$\mathcal{R}$: ideally each σ_i Gaussian resol. term with fraction f_i;

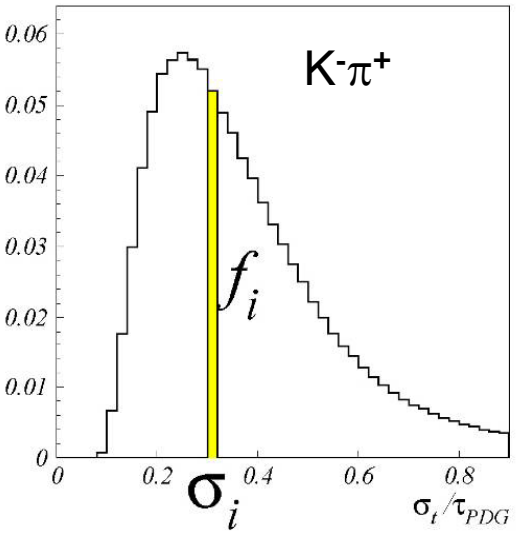
t_{rec}-t_{gen}/σ_t : described by 3 Gaussians $\Rightarrow$

$$\mathcal{R}(t-t') = \sum_{i=1}^{N} f_i \sum_{k=1}^{3} w_k G(t-t', s_k\sigma_i, t_0)$$

parameters of $\mathcal{R}$ depend slightly on data taking conditions

τ = 408.7±0.6 fs

σ_t distribution



event-by-event σ_t

back

D^0 mixing more

Decays to CP eigenstates

t-integrated CPV in $D^0 \to K^+K^-$ / $\pi^+\pi^-$

method of

BaBar, PRL 100, 061803 (2007), 386fb^{-1}

$$A_{CP} = \frac{\mathcal{B}(X \to f) - \mathcal{B}(\overline{X} \to \overline{f})}{\mathcal{B}(X \to f) + \mathcal{B}(\overline{X} \to \overline{f})}$$

$$A^{reco} = A_{FB}^{D^{*+}} + A_{CP}^{D^0\pi} + A_{CP}^{KK} + A_{\epsilon}^{KK} + A_{\epsilon}^{\pi}$$

$A_{CP}^{D^0\pi}$ = 0 (strong int.)

A_{ϵ}^{KK} = 0 (same for D^0, $\overline{D^0}$)

$$A^{reco} = A_{FB}^{D^{*+}}(\cos\theta^*) + A_{CP}^{KK} + A_{\epsilon}^{\pi}$$

$$A_{FB}(\cos\theta^*) = -A_{FB}(-\cos\theta^*)$$

$$A_{corr}^{reco} = A^{reco} - A_{\epsilon}^{\pi}$$

$$A_{CP} = \frac{A_{corr}^{reco}(\cos\theta^*) + A_{corr}^{reco}(-\cos\theta^*)}{2}$$

$$A_{FB} = \frac{A_{corr}^{reco}(\cos\theta^*) - A_{corr}^{reco}(-\cos\theta^*)}{2}$$

A_{ε}^{π} from comparison A_{untag}/A_{tag}

$$A^{untag} = A_{FB}^{D^0} + A_{CP}^{K\pi} + A_{\epsilon}^{K\pi}$$

$$A^{tag} = A_{FB}^{D^{*+}} + A_{CP}^{K\pi} + A_{\epsilon}^{K\pi} + A_{\epsilon}^{\pi_{slow}}$$

back

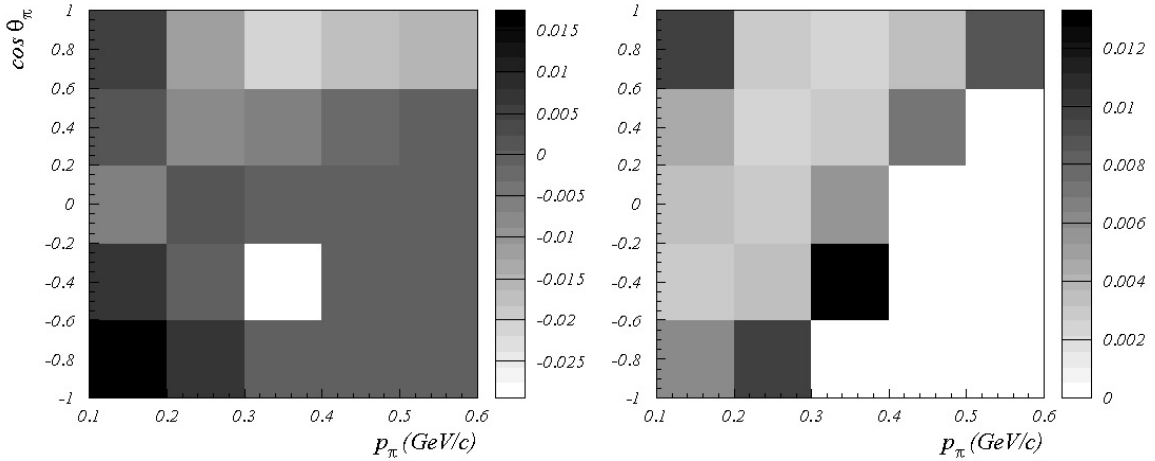
D^0 mixing more

Decays to CP eigenstates

t-integrated CPV in $D^0 \to K^+K^-$ / $\pi^+\pi^-$

Belle, arXiv:0807.0148, 540fb^{-1}

$A_\varepsilon^{\pi}(p_\pi, \cos\theta_\pi)$



back

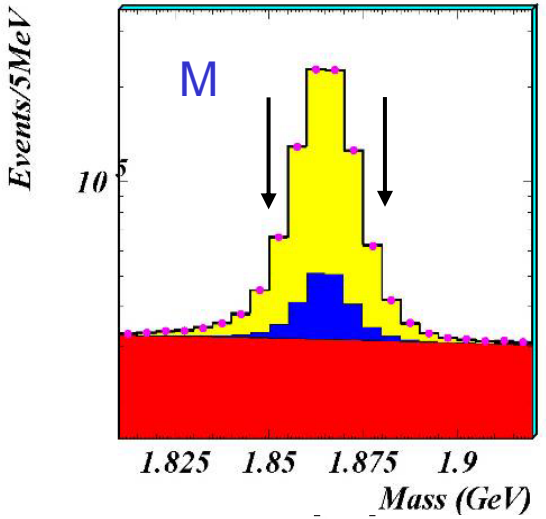
D^0 mixing more

Belle, PRL 99, 131803 (2007), 540fb^{-1}

t-dependent Dalitz analyses

selection;

signal
rnd slow π
combin.



Dalitz model;

$$\mathcal{A}(m_-^2, m_+^2) = \sum a_r \, e^{i\Phi_r} B(m_-^2, m_+^2) + a_{NR} \, e^{i\Phi_{NR}}$$

13 BW resonances, non-resonant contr.;
comb. bkg.: from M sideband

test of S-wave $\pi\pi$ contr. (f_0, $\sigma_{1,2}$):
K-matrix formalism

Results (fit fractions, phases) in agreement with Belle, PRD73, 112009 (2006) (measurement of ϕ_3)

Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.629 ± 0.006	134.3 ± 0.3	0.6227
$K_0^*(1430)^-$	2.12 ± 0.02	-0.9 ± 0.8	0.0724
$K_2^*(1430)^-$	0.87 ± 0.02	-47.3 ± 1.2	0.0133
$K^*(1410)^-$	0.65 ± 0.03	111 ± 4	0.0048
$K^*(1680)^-$	0.60 ± 0.25	147 ± 29	0.0002
$K^*(892)^+$	0.152 ± 0.003	-37.5 ± 1.3	0.0054
$K_0^*(1430)^+$	0.541 ± 0.019	91.8 ± 2.1	0.0047
$K_2^*(1430)^+$	0.276 ± 0.013	-106 ± 3	0.0013
$K^*(1410)^+$	0.33 ± 0.02	-102 ± 4	0.0013
$K^*(1680)^+$	0.73 ± 0.16	103 ± 11	0.0004
$\rho(770)$	1 (fixed)	0 (fixed)	0.2111
$\omega(782)$	0.0380 ± 0.0007	115.1 ± 1.1	0.0063
$f_0(980)$	0.380 ± 0.004	-147.1 ± 1.1	0.0452
$f_0(1370)$	1.46 ± 0.05	98.6 ± 1.8	0.0162
$f_2(1270)$	1.43 ± 0.02	-13.6 ± 1.2	0.0180
$\rho(1450)$	0.72 ± 0.04	41 ± 7	0.0024
σ_1	1.39 ± 0.02	-147 ± 1	0.0914
σ_2	0.267 ± 0.013	-157 ± 3	0.0088
NR	2.36 ± 0.07	155 ± 2	0.0615

back

D^0 mixing more

t-dependent Dalitz analyses

Belle, PRL 99, 131803 (2007), 540fb^{-1}

Largest systematics

model dependence [10^{-4}]:

Δx	Δy	
-10.3	+0.1	$K^*_0(1430)$ DCS/CF -15%
+ 6.9	-2.5	$K^*_2(1430)$ DCS/CF -30%
-1.6	-0.9	$K^*(1410)$ DCS & CF -20%
-5.1	-4.1	$\Gamma(q^2)$ const.
+10	+6	Total model dep.
-14	-8	

observed discrepancy from input in MC

statistical uncertainty:

$\sigma(x)=29\times10^{-4}$
$\sigma(y)=24\times10^{-4}$

experimental:

Δx	Δy	
+7.6	-7.8	p* variation
-5.6	-5.7	Dalitz pdf for bkg. from different t bins
+9	+8	Total experimental
-7	-12	

back

D^0 mixing more

t-dependent Dalitz analyses

Belle, PRL 99, 131803 (2007), 540fb^{-1}

efficiency and resol. in M($\pi\pi$)

$$p(m_+^2, m_-^2) = \varepsilon(m_+^2, m_-^2) \int_{-\infty}^{\infty} |M(m_+^2 + \mu^2, m_-^2 + \mu^2)|^2 \exp\left(-\frac{\mu^2}{2\sigma_m^2(m_{\pi\pi}^2)}\right) d\mu^2 + B(m_+^2, m_-^2),$$

rnd π_s bkg.:

$P_{rnd} \propto [(1\text{-}f_w)\, \mathcal{M}(m_-^2, m_+^2, t) + f_w\, \mathcal{M}(m_+^2, m_-^2, t)] \otimes \mathcal{R}(t)$

f_w from fit to Q side band: $f_w = 0.452 \pm 0.005$
diff. w.r.t. f_w=0.5 in systematic error

comb. bkg.:

$P_{cmb} \propto B(m_-^2, m_+^2) * ([\, \delta(t) + \mathrm{Exp}(t)\,] \otimes \mathcal{R}'(t)$

parameters from fit to Dalitz and t distrib. of M($K_S\, \pi^+\pi^-$) sideband
(systematics: Dalitz distrib. in different t intervals)

back

D_s leptonic decays more

$D_s \to \mu\nu$

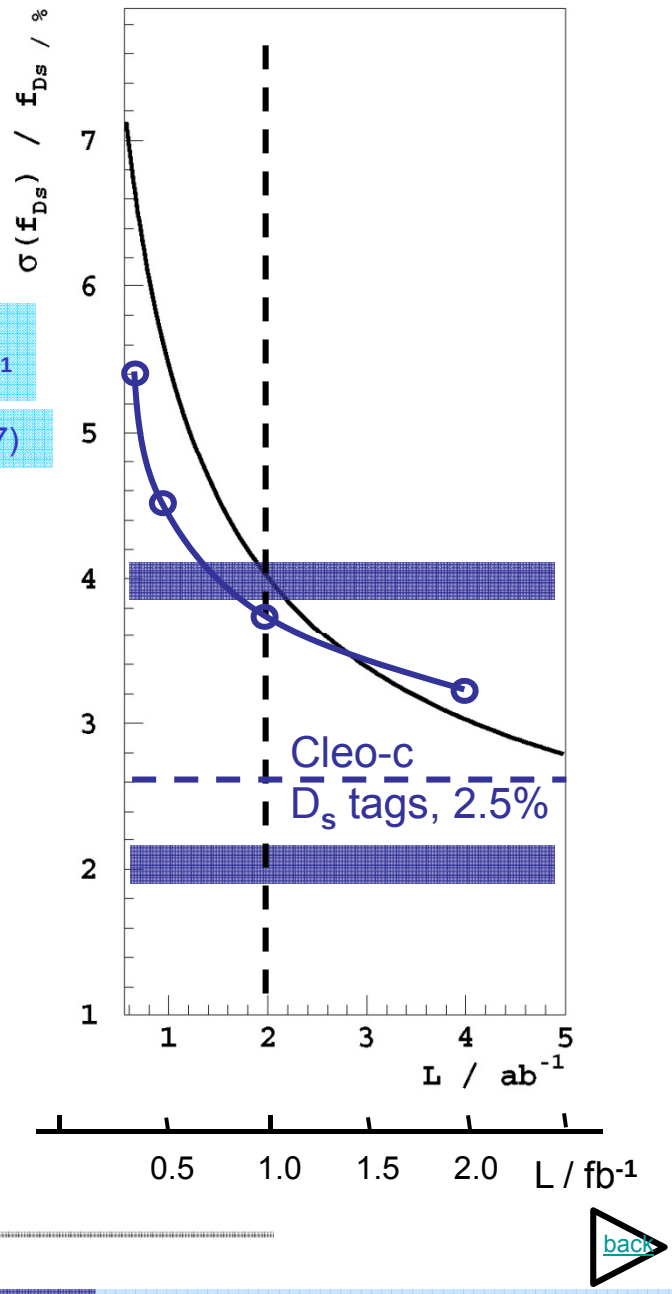
projection

$$\frac{\sigma(f_{Ds})}{f_{Ds}} \approx \frac{7.1\%}{\sqrt{L/L_0}} \oplus 1.5\%$$

B factories with 2 ab^{-1}
~4% uncertainty on f_{Ds};
Charm-factory: syst. on D_s tags?
test of LQCD to ~2-3%;

Belle, PRL100, 241801 (2008), 548fb^{-1}

Cleo-c, PRD 76, 072002 (2007)



possible NP effects:

B.A. Dobrescu, A.S. Kronfeld,, PRL100, 241802 (2008)

$$B(D_s \to \ell\nu) = \frac{m_{D_s}}{8\pi}\tau_{D_s} f_{D_s}^2 |G_F V_{cs}^* m_\ell|^2 \left(1 - \frac{m_\ell^2}{m_{D_s}^2}\right)^2$$

$$G_F V_{cs}^* m_\ell + \frac{1}{\sqrt{2}M^2}\left(C_A^\ell m_\ell + \frac{C_P^\ell m_{D_s}^2}{m_c + m_s}\right)$$

$$\frac{M}{(\mathrm{Re}\, C_A^\ell)^{1/2}} \gtrsim \begin{cases} 710 \text{ GeV for } \ell = \tau \\ 850 \text{ GeV for } \ell = \mu \end{cases}$$

$$\frac{M}{(\mathrm{Re}\, C_P^\ell)^{1/2}} \gtrsim \begin{cases} 920 \text{ GeV for } \ell = \tau \\ 4500 \text{ GeV for } \ell = \mu \end{cases}$$

M: NP mass

back

Spectroscopy more

X(3872)

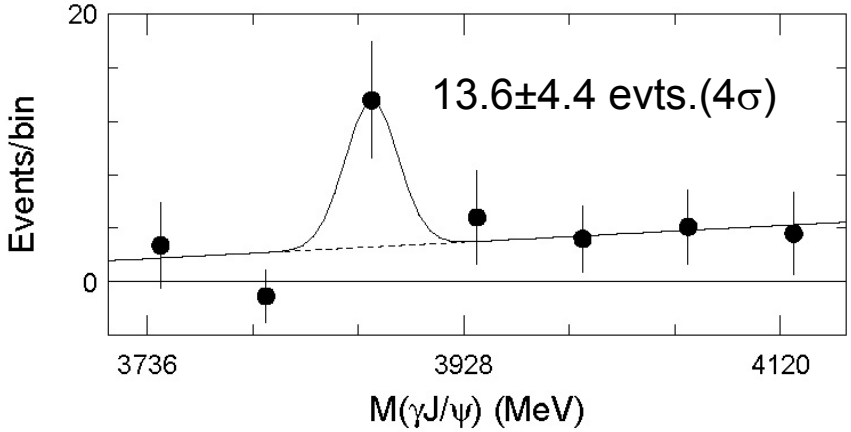
$B \to KX\ (J/\psi\gamma)$:
$B \to K\chi_{c1}(J/\psi\gamma)$ calibration;

$B \to KX\ (J/\psi\pi\pi)$:
$B \to K\psi(2S)$ calibration;

$B \to KX\ (J/\psi\pi\pi\pi^0)$:

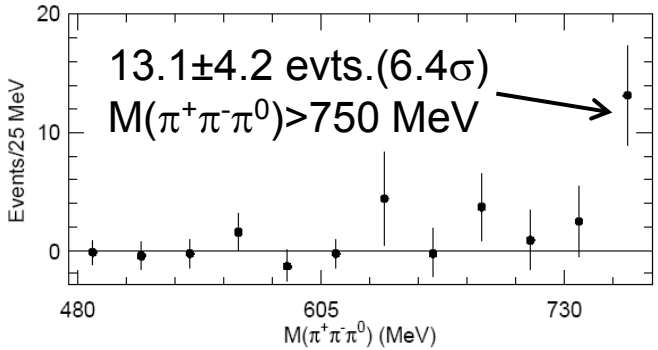
Belle, hep-ex/0505037, 250fb^{-1}

no. of B's in bins of M($\gamma J/\psi$)

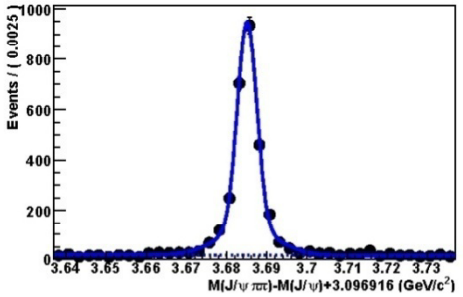


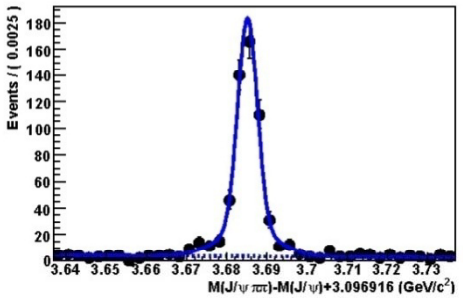
Belle, hep-ex/0505037, 250fb^{-1}

no. of B's in bins of M($\pi\pi\pi^0$)



$$\frac{Br(X \to \pi^+\pi^-\pi^0 J/\psi)}{Br(X \to \pi^+\pi^- J/\psi)} = 1.0 \pm 0.4 \pm 0.3$$





Belle, BELLE-CONF-0711, 605 fb^{-1}

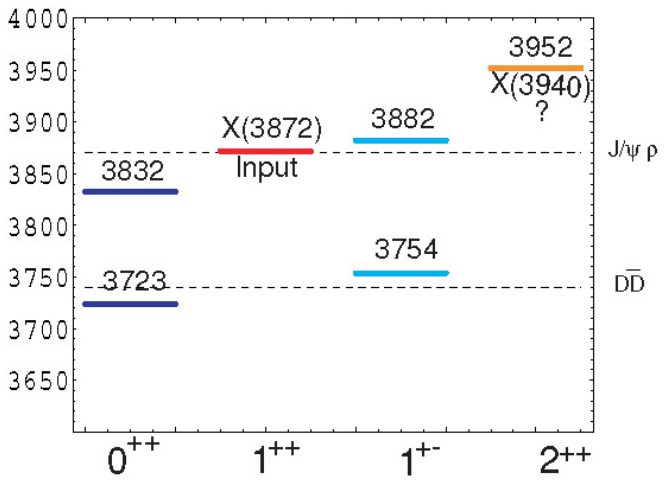
back

Spectroscopy more

X(3872)

tetraquarks: L. Maiani et al., PRD71, 014028 (2005)

predicted spectrum;



mass difference;

$$M(X_h) - M(X_l) = \frac{7 \pm 2}{\cos\vartheta}\, MeV$$

θ: mixing angle

back

DD* molecule:

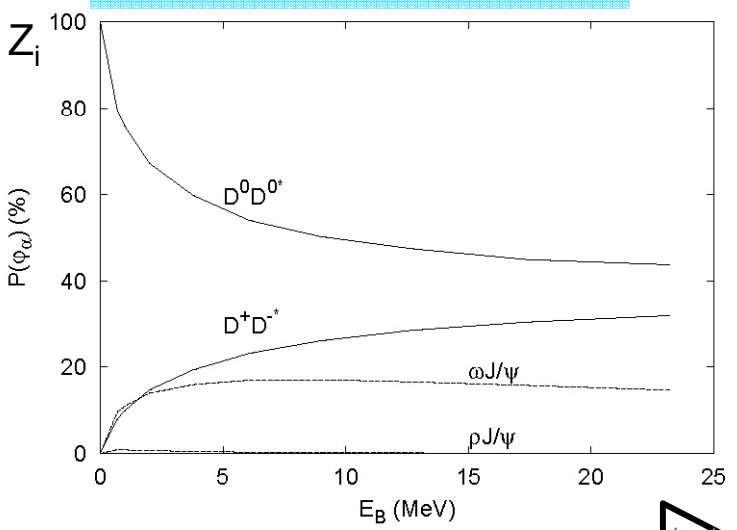
wave function fractions

E.S.Swanson, PLB588, 189 (2004)

$$\frac{Br(B^0 \to K^0 X)}{Br(B^+ \to K^+ X)} = \frac{|4Z_{+-}^{1/2} + Z_{00}^{1/2}|^2}{|4Z_{00}^{1/2} + Z_{+-}^{1/2}|^2}$$

$$R = \frac{2Z_{00}\Gamma(D^{*0})}{Z_{\rho\psi}\Gamma(\rho)}.$$

$$R = \frac{Br(X \to D^0 D^0 \pi^0)}{Br(X \to J/\psi\pi\pi)} = 10 \pm 4$$



binding energy

back

Spectroscopy more

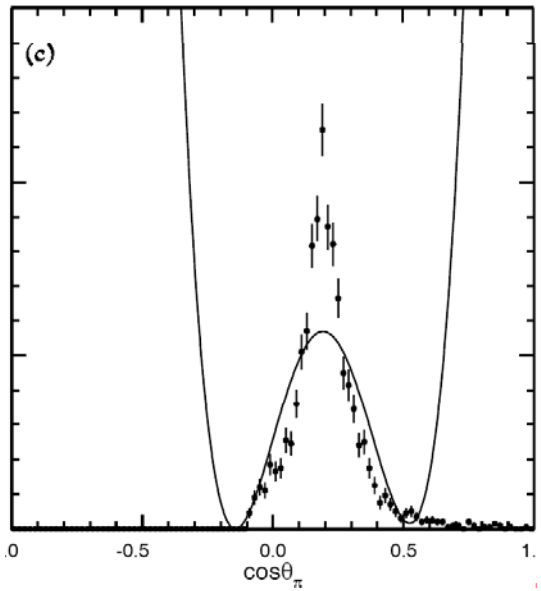
$Z^+(4430)$ Belle, PRL100, 142001 (2008), 605 fb^{-1}

S-, P-, D-wave interference:

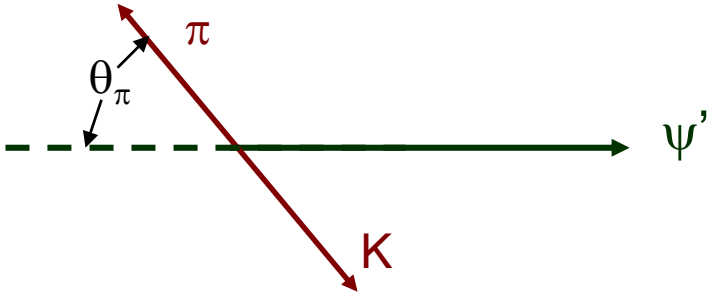
resonance	Longitudinal ψ'	Transverse ψ'
κ	constant	$--$
$K^*(890)$	$\cos\theta_\pi$	$\frac{1}{\sqrt{2}}\sin\theta_\pi$
$K_2^*(1430)$	$\frac{3}{2}\cos\theta_\pi^2 - \frac{1}{2}$	$\sqrt{\frac{3}{2}}\sin\theta_\pi\cos\theta_\pi$

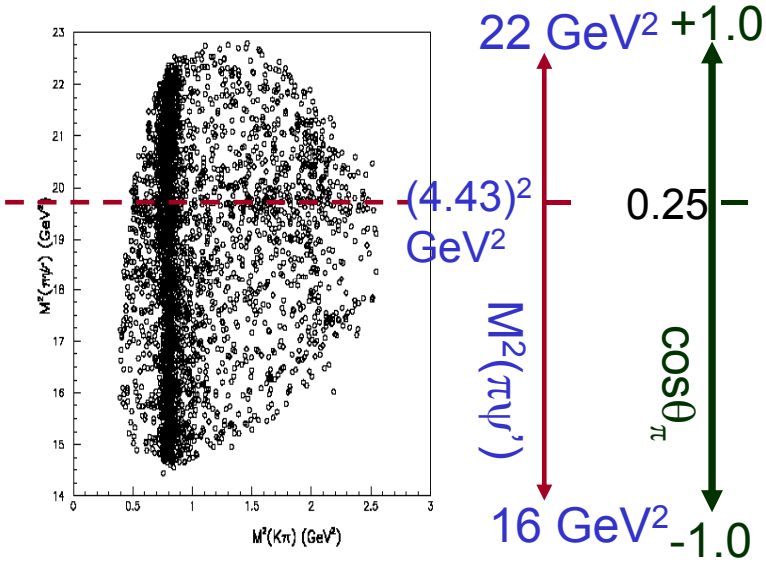
interference

incoherent



cannot produce a single peak at $\cos\theta_\pi \sim 0.25$





back