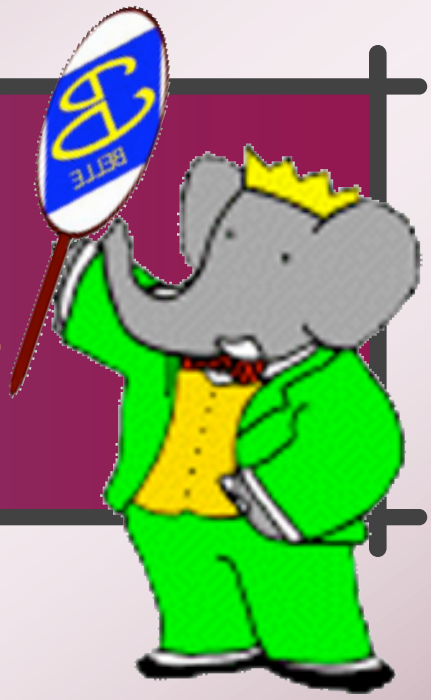
Pheno 2005 Symposium, May 2, 2005

CKM Reflections: Results from Belle and Babar



- CP asymmetry in CKM
- B factories & experiments
- Measurements of sin $2\phi_1$
- Progress on sin $2\phi_2$
- Progress on sin $2\phi_3$
- Other CKM
- Summary

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University of Cincinnati
Belle Collaboration

CKM and CP Asymmetry

Complex coupling constant is CP-violating

$CP\{f \xrightarrow{g} f'\} = \bar{f}' \xrightarrow{g} \bar{f} \neq \bar{f}' \xrightarrow{g^*} \bar{f}$ (hermitian conjugate)

BUT to observe CP asym, need 2+ interfering amplitudes {T,P}:

$T=gA, P=g'A' \rightarrow |gA+g'A'| \xrightarrow{CP} |gA^*+g'A'^*|$

Equal only if relative phase of $g,g'=0$

Cabibbo-Kobayashi-Maskawa (CKM) matrix

{weak<->mass} eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \mathcal{M} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

so that W-couplings are generation-conserving

$$g_F \times \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d' & s' & b' \end{array} \\ \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \end{array}$$

$$\begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \end{array}$$

complex
preserves metric
" orthogonality
} ≡ unitary + in 3-d, irreducibly complex

3-generation CKM

Unitarity conditions -> 4 free parameters

$V_{ji}^* V_{jk} = \delta_{ik}$ $\{i=1,k=3\}$: $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$

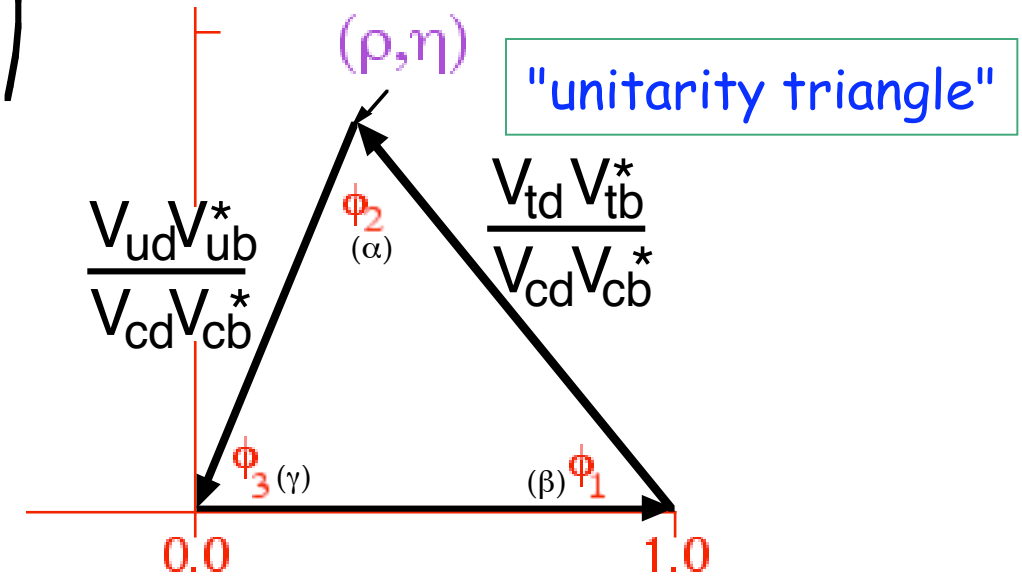
$$\Rightarrow \frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} + 1 + \frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}} = 0$$

$\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} \rightarrow -(\rho+i\eta)$ $\quad$ $\frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}} \rightarrow -(1-\rho-i\eta)$

explicit parametrization(Wolfenstein):

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3 A(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix}$$

irreducibly complex!



from decay rates,

$\lambda = 0.220 \pm 0.002$

$A = 0.81 \pm 0.08$

$|\rho-i\eta| = 0.36 \pm 0.09$

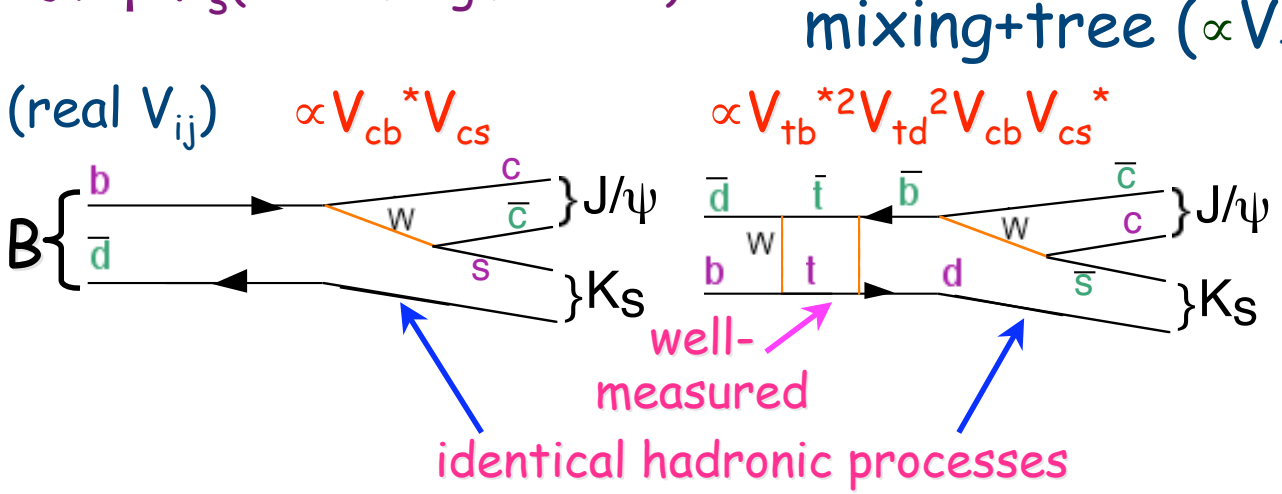
$|1-\rho-i\eta| = 0.79 \pm 0.19$

B-factories: measure angles, test self-consistency of CKM

Observable CP asymmetries

-> to observe, need process w. all 3 generations (<- B decays), interference between ≥2 processes

e.g., B -> J/ψ K_s(Sanda/Bigi/Carter)



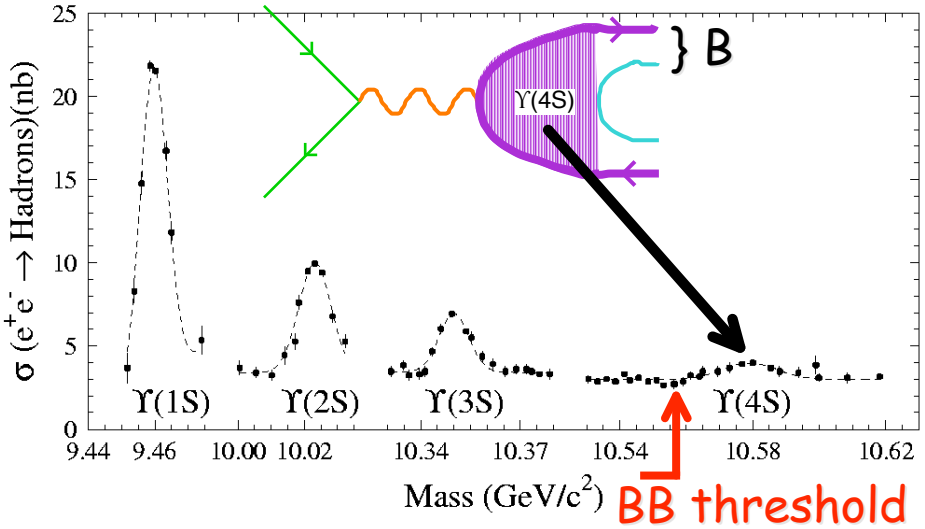
CP asymmetry from x-term(s) - no theoretical uncertainty: $\propto \arg(V_{td}^2) = 2\phi_1$

Bottom line: CP-dependent oscillation in time:

$$\frac{dN}{dt}(B \to f_{CP}) = \frac{1}{2}\Gamma e^{-\Gamma\Delta t}(1 + \eta_b \eta_{CP} \sin 2\phi_1 \sin(\Delta m \Delta t));$$

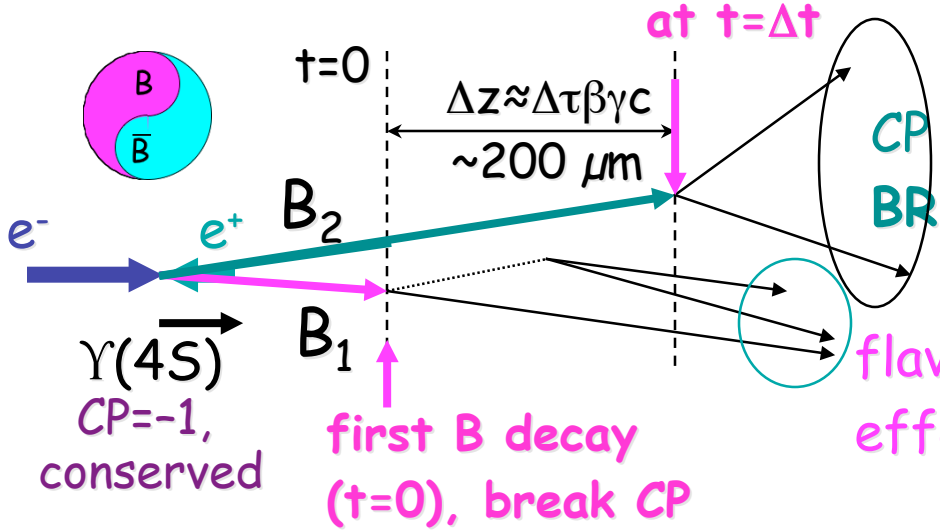
$$\eta_b = \begin{pmatrix} +1 \text{ if } B_{t=0} = B^0 \\ -1 \text{ if } B_{t=0} = \bar{B}^0 \end{pmatrix} \quad \eta_{CP} = \begin{pmatrix} -1 \text{ if } CP \text{ odd} \\ +1 \text{ if } CP \text{ even} \end{pmatrix}$$

B production: $e^+e^- \to \Upsilon(4S) \to B\bar{B}$

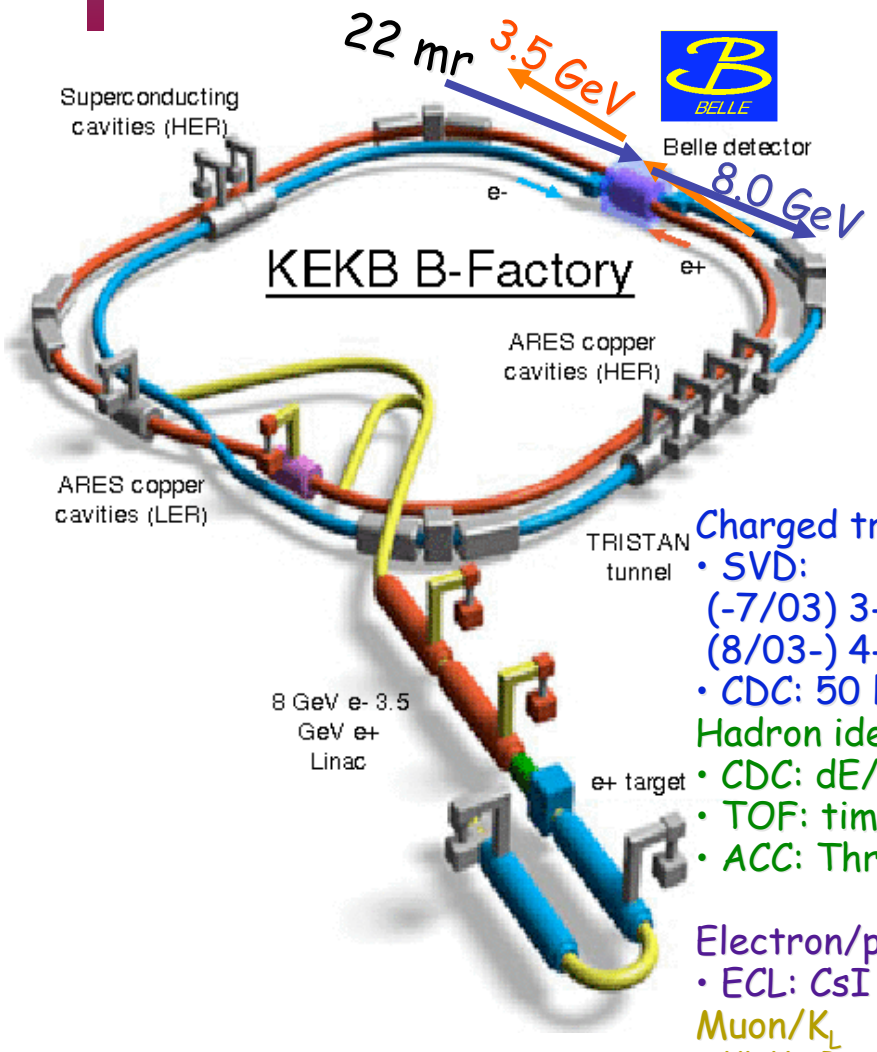


Δt by asymmetric energy e^+e^- -> Υ(4S)
(symmetric Υ(4S): CLEO 1979-2001)

Experimental design:
hadron (K/π), lepton ID
<<200μm vertexing
statistics >>10^7 events



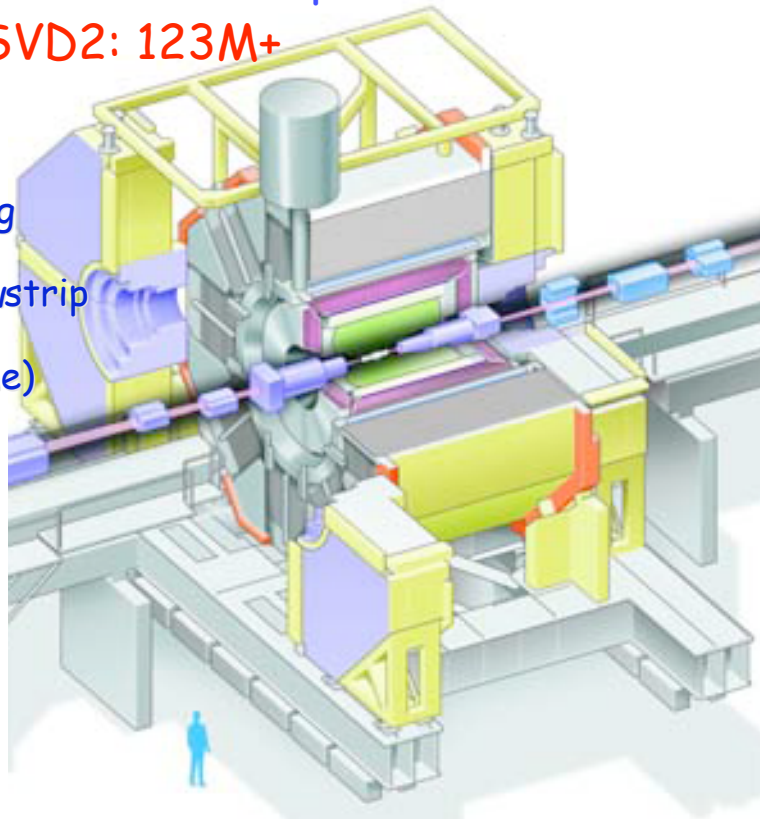
KEKB & Belle



- L_{max} = 1.53 X 10^{34} $cm^{-2}s^{-1}$ (world record)
- Data (6/1999-4/2005)
- $\int Ldt$ = 420 fb^{-1}@{Υ(4S)+off(~10%)}
- (>4.2x10^8 B events)

SVD1: 152M B pairs

SVD2: 123M+



Charged tracking/vertexing
- SVD:
  (-7/03) 3-layer DSSD Si μstrip
  (8/03-) 4-layer
- CDC: 50 layers (He-ethane)

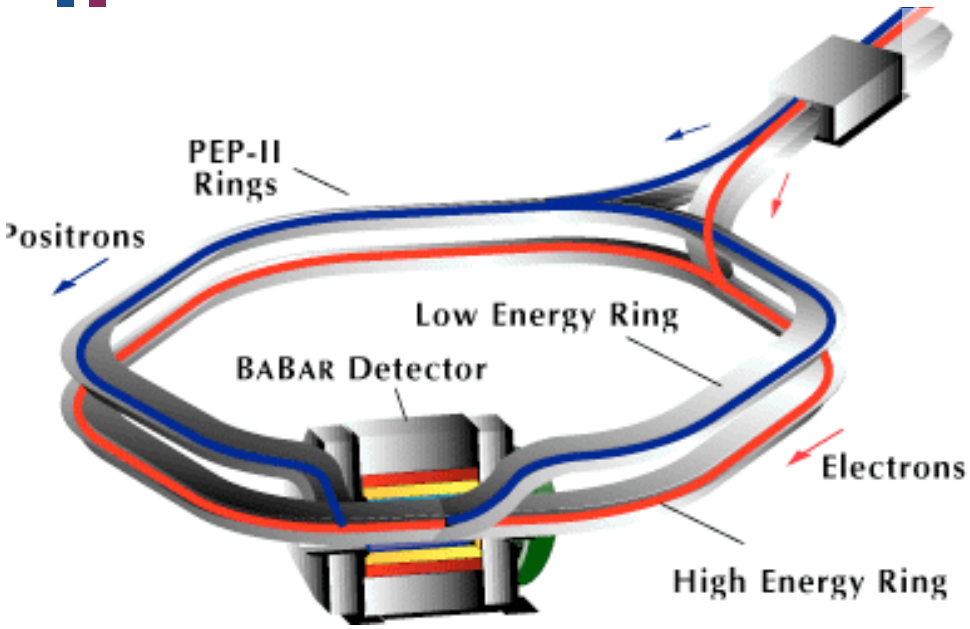
Hadron identification
- CDC: dE/dx
- TOF: time-of-flight
- ACC: Threshold Cerenkov (aerogel)

Electron/photon
- ECL: CsI calorimeter

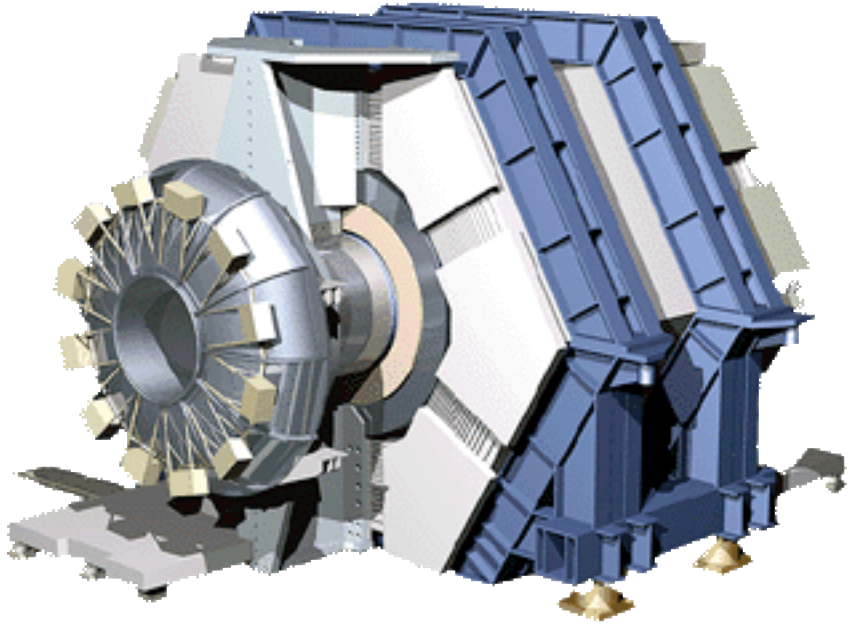
Muon/K_L
- KLM: Resistive plate counter/iron

~13 nations, 57 institutes, ~400 persons

PEP-II & Babar



- L_{max} = 9.2 X 10^{33} $cm^{-2}s^{-1}$
- Data (1999-4/2005)
- $\int L dt$ = 250 fb^{-1}@{Υ(4S)+off(~10%)}
- (>2.5x10^8 B events)



Charged tracking/vertexing
- 5-layer DSSD Si μstrip
- 40 layers (He-isobutane)

Hadron identification
- tracker: dE/dx
- DIRC imaging Cerenkov

Electron/photon
- CsI calorimeter

Muon/K_L
- Instrumented flux return

~11 nations, 80 institutes, ~650 persons

time-dependent CP analysis: overview

(Belle)

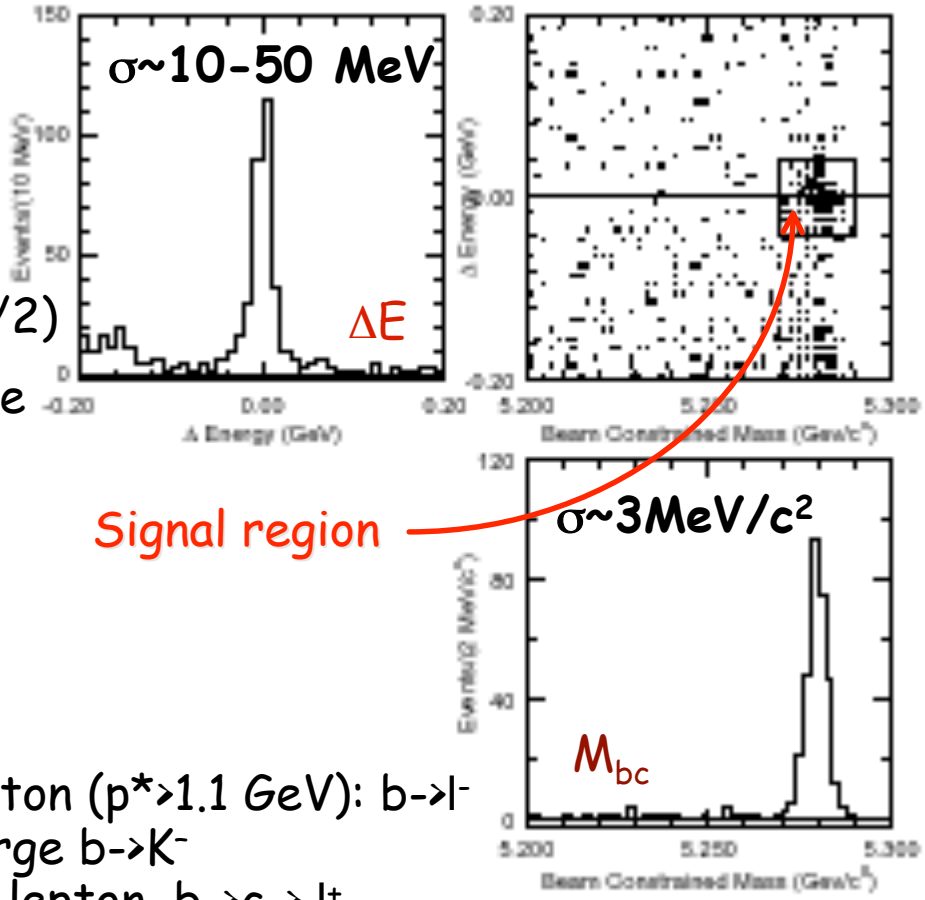
1) CP final state reconstruction exploit
   - exclusive pair production of B
   - narrow resolution of collision energy

$\Delta E = E^*_{cand} - E^*_{beam} = 0$ ($E^*_{beam} = s^{1/2}/2$)

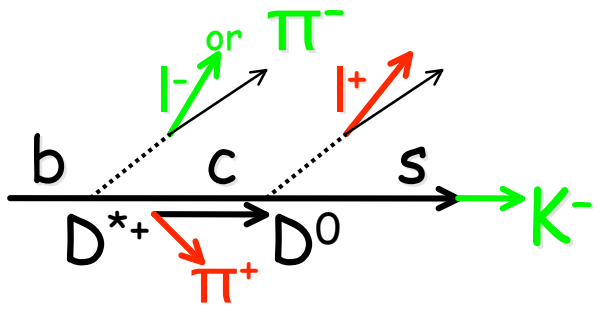
σ~10-50 MeV, depending on mode

M_{bc} (Beam-constrained mass)

$M_{bc} = (E^{*2}_{beam} - p^{*2}_{cand})^{1/2}$



2) Flavor tagging: sign of other b
all remaining particles in the event



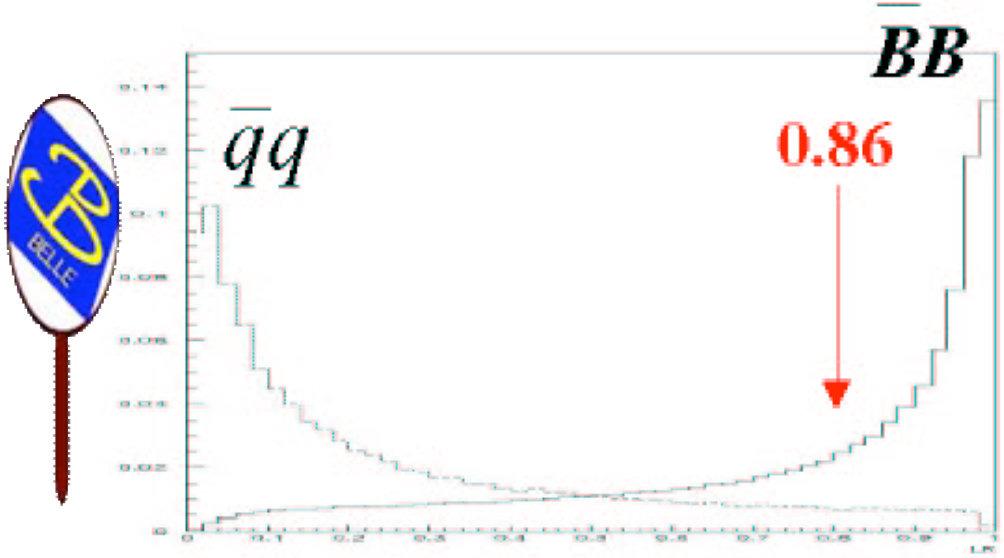
- high-p lepton (p*>1.1 GeV): b->l⁻
- net K charge b->K⁻
- medium-p lepton, b->c-> l⁺
- soft π b->c{D*⁺->D⁰π⁺}
- hard π b->{c}π⁻X

multidimensional likelihood, ε>99%

incorrect tag reduces ε, net (28.7±0.5)%

time-dependent CP analysis: overview

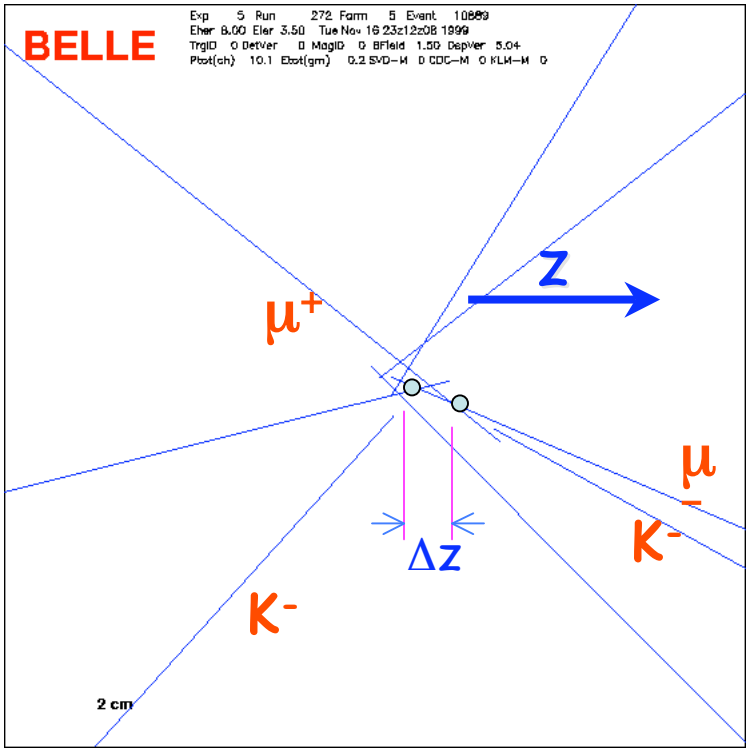
3) Continuum suppression:
event parameters ("shape")



$$R \equiv \frac{\mathcal{L}_{sig}}{\mathcal{L}_{sig} + \mathcal{L}_{bg}}$$

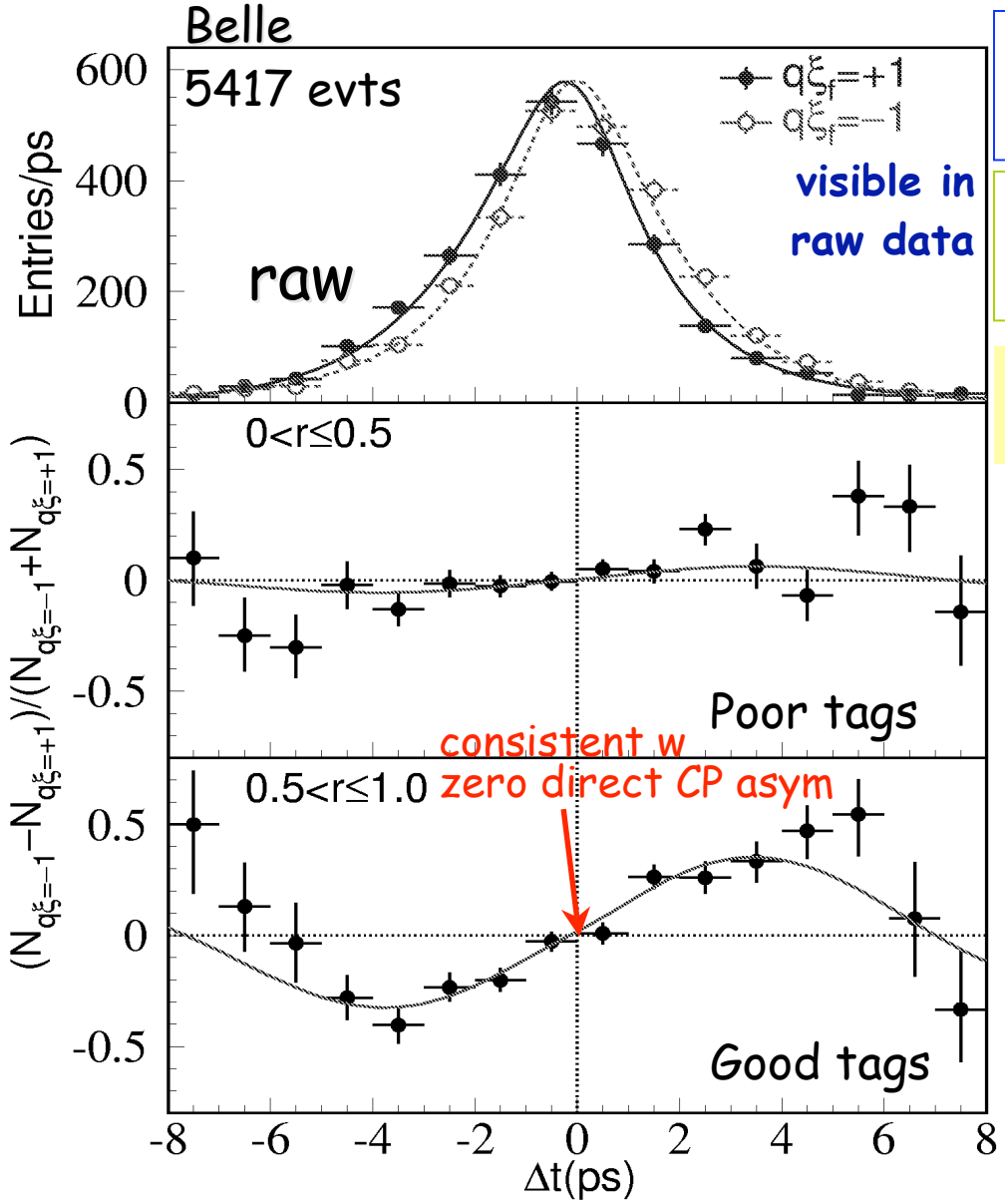
4) Vertex reconstruction

$\Delta t \sim \Delta z / \beta\gamma c$



5) Fit to Δt distribution:
unbinned maximum likelihood

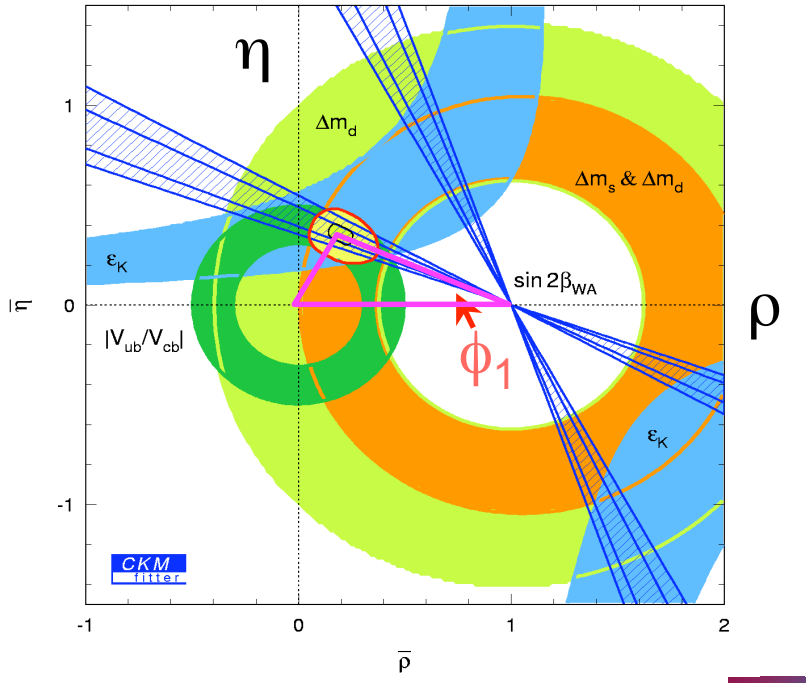
B->{Charmonium}+K$^{(*)0}$ -> sin2ϕ_1



Belle 140 fb^{-1} PRD71, 072003 (2005)
sin2ϕ_1= 0.728±0.056±0.023

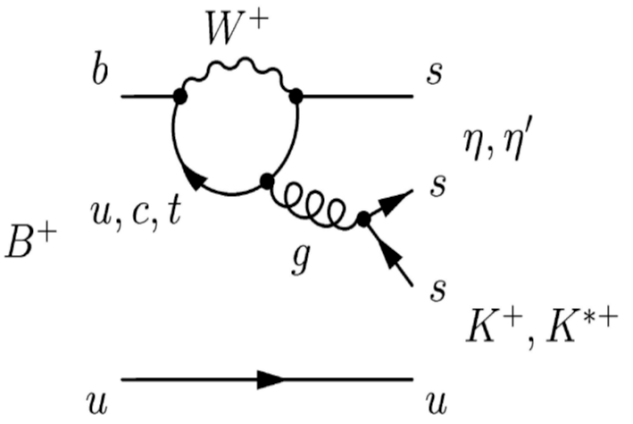
Babar 227 M evts hep-ex/0408127
sin2ϕ_1= 0.722±0.040±0.023

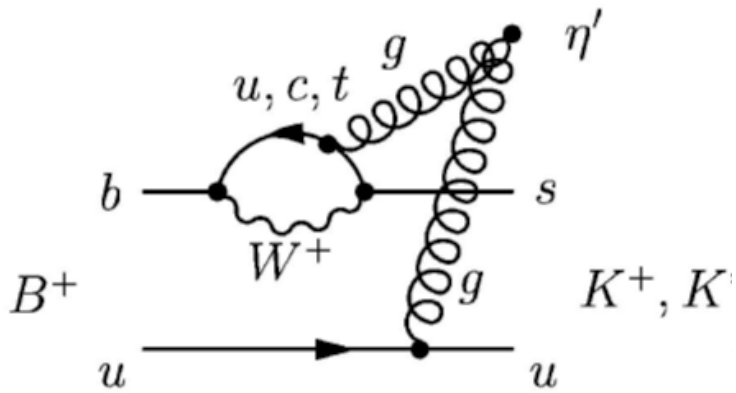
average:
sin2ϕ_1= 0.726±0.037



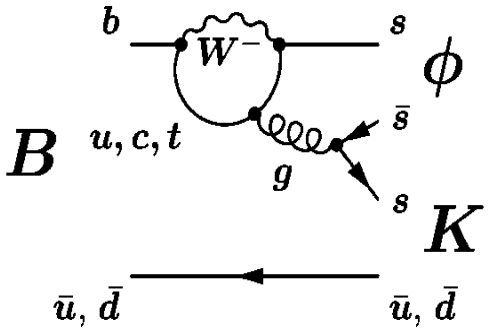
sin2ϕ_1 in time-dependent b->s – or new physics?

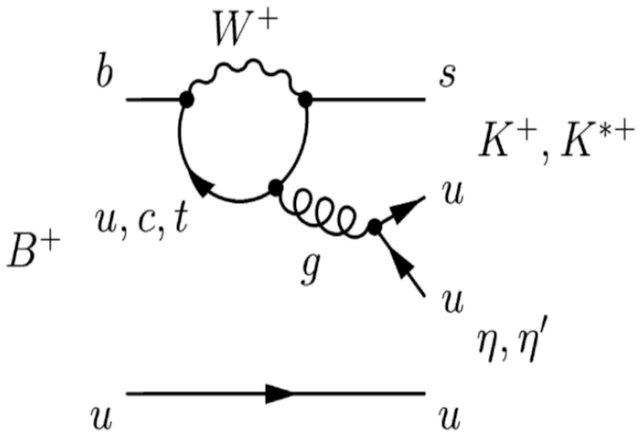
modes dominated by b->sq$\bar{q}$ penguins

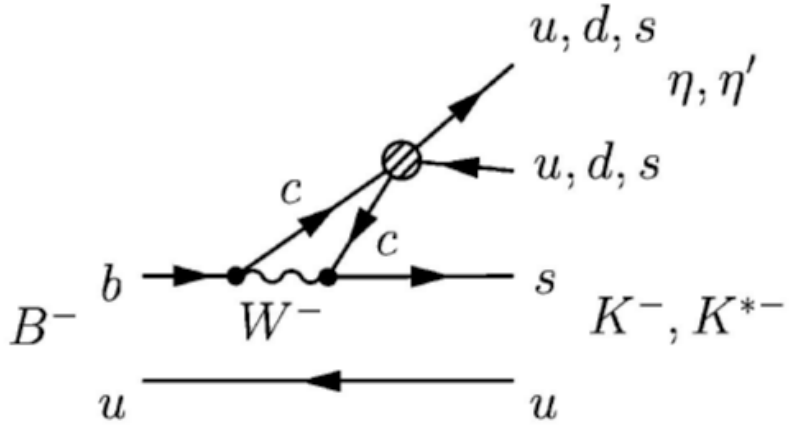




Theoretically cleanest

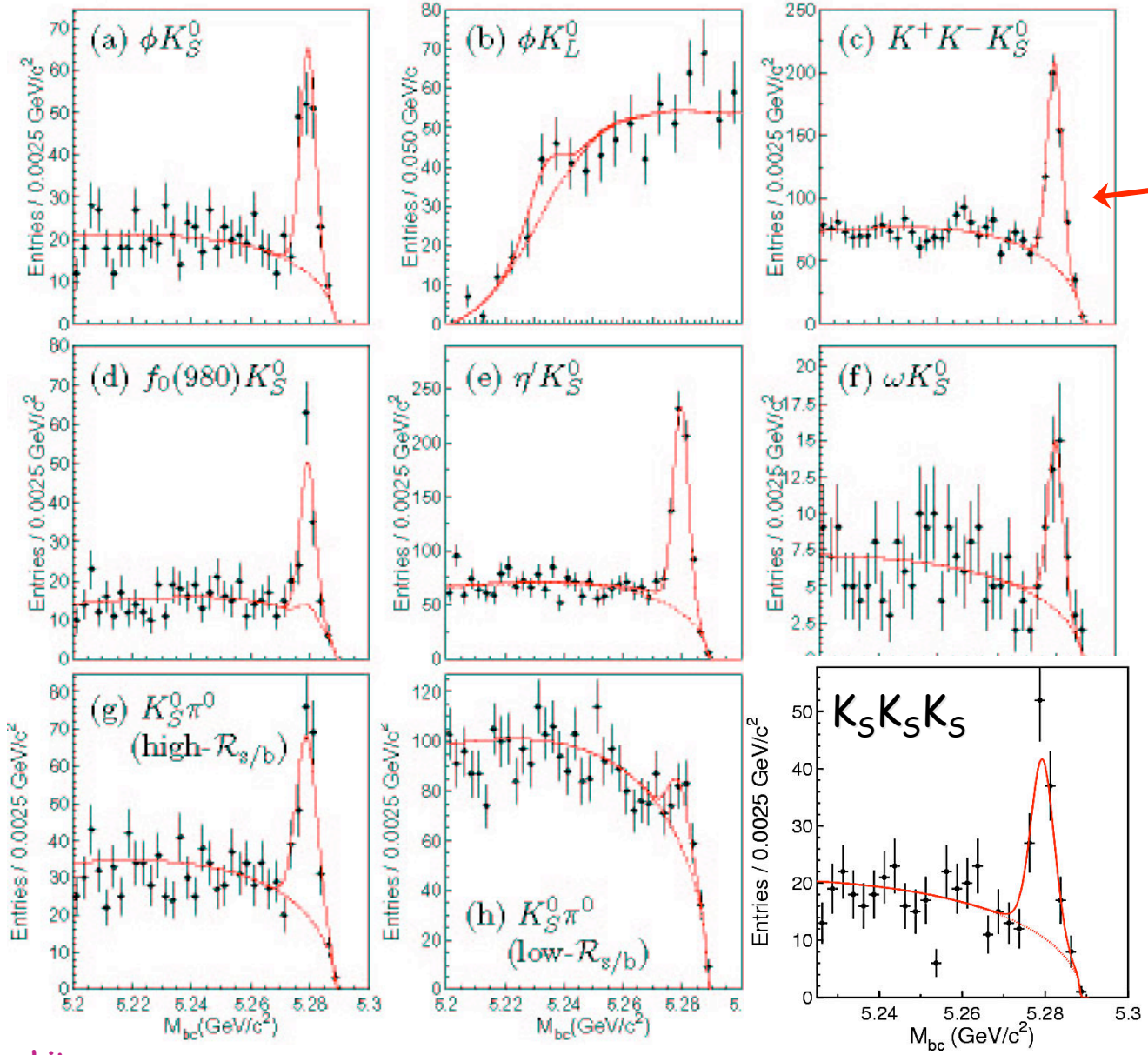






in the absence of New Physics, S = sin2ϕ_1

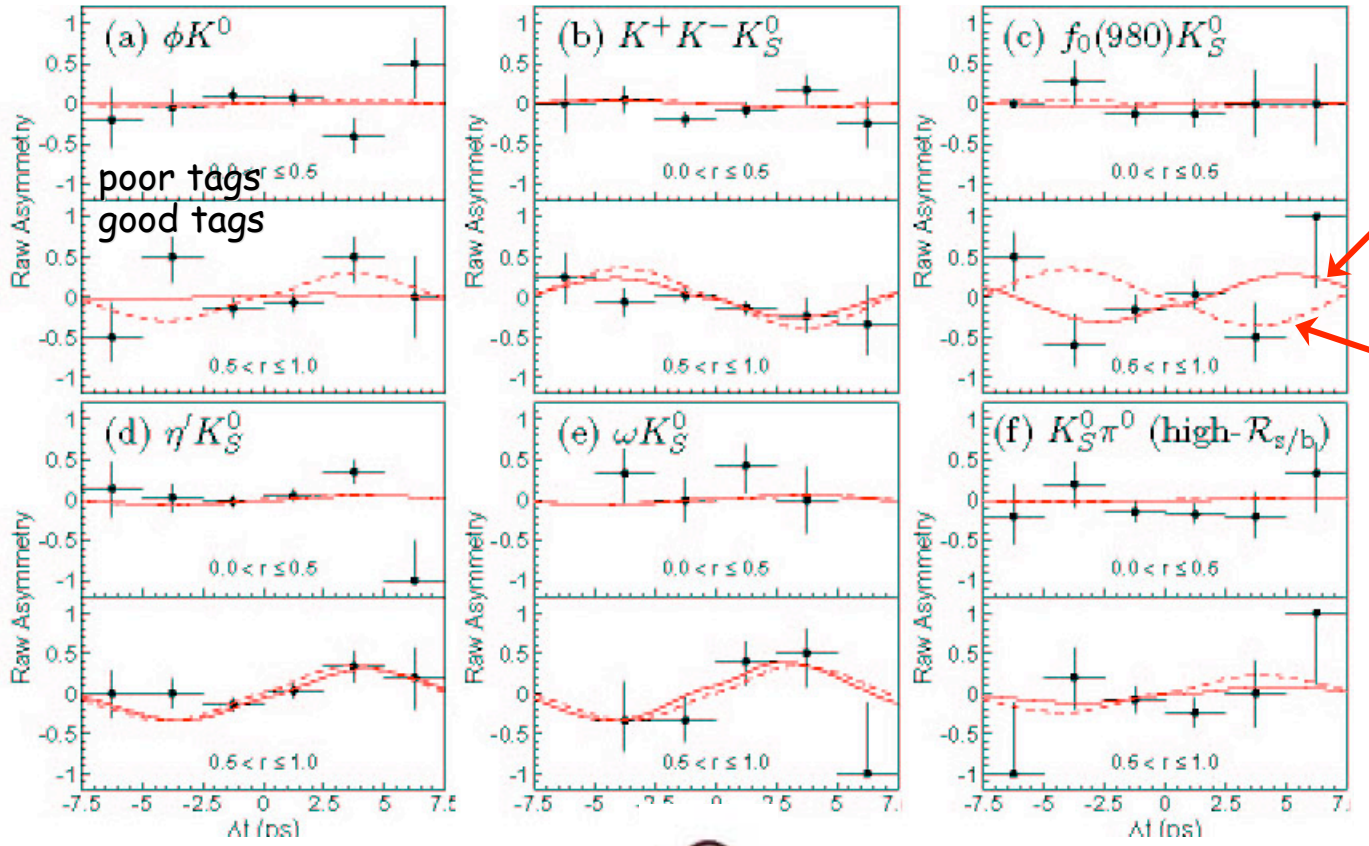
Reconstruction of b->sqq



253 fb^{-1}

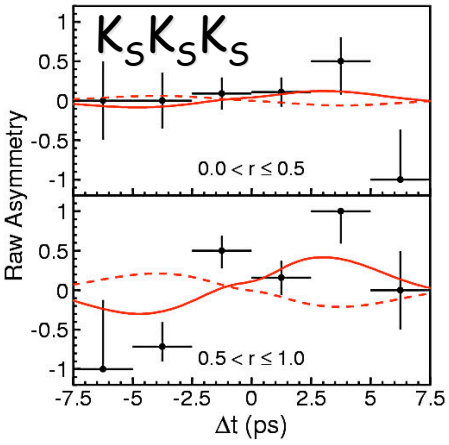
CP = +1 (angular analysis)

Time-dependent CP asymmetry:



Projected fit

SM expectation



(Belle)
hep-ex/0409049
hep-ex/0503023

(Babar)
hep-ex/0408090
hep-ex/0408095
hep-ex/0502013

hep-ex/0502017
hep-ex/0502019
hep-ex/0503011
hep-ex/0503018

Average "sin2ϕ_1" from *b->s* penguins

$\sin 2\phi_1(b \to sq\bar{q}) =$

- 0.39 ± 0.11 (Belle)
- 0.45 ± 0.09 (*BABAR*)

World Average

$\sin 2\phi_1(b \to sq\bar{q}) = 0.43 \pm 0.07$

(excluding $K_SK_SK_S$, f_0K_S)

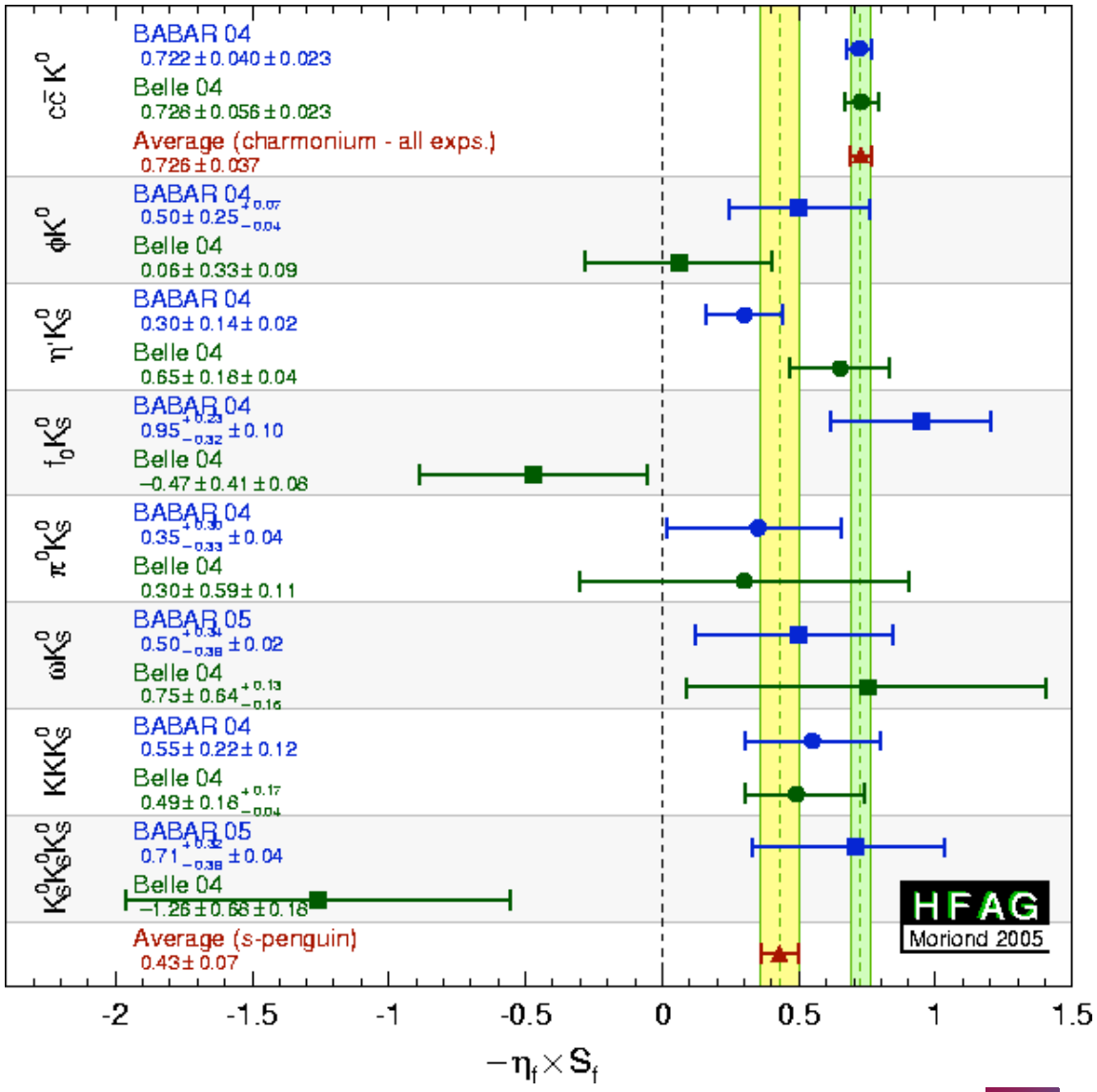
0.44 ± 0.08

Compare with $c\bar{c}s$:

$\sin 2\phi_1(b \to c\bar{c}s) = 0.726 \pm 0.037$

CL = 2.1×10^{-4} (3.7σ)

- statistics?
- experimental systematics?
- theory corrections?
- new physics?



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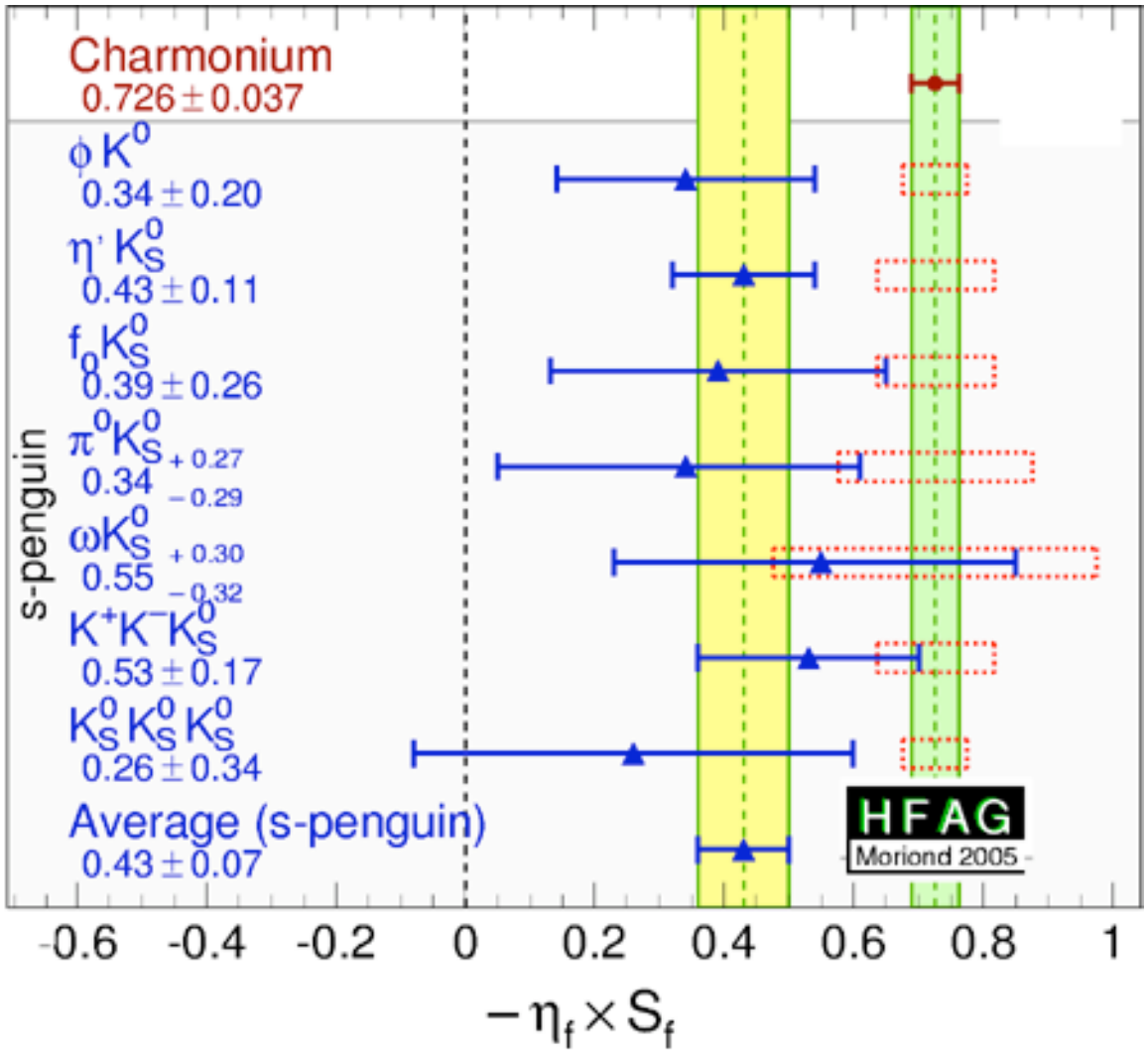
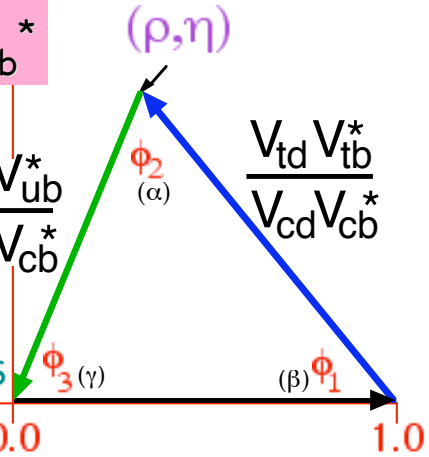


- statistics?
- experimental systematics?
- theory corrections?
- new physics?

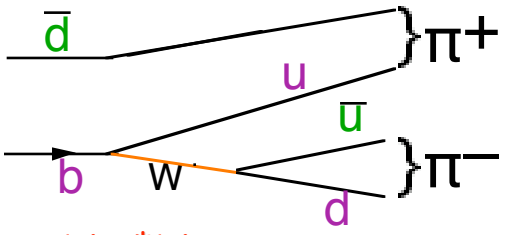
$\sin 2\phi_2$: $B^0 \to \pi^+\pi^-$

2 paths, each w/wo mixing:

$$\phi_2 = \arg \frac{V_{td}V_{tb}^*}{-V_{ud}V_{ub}^*}$$



1) Tree (T)



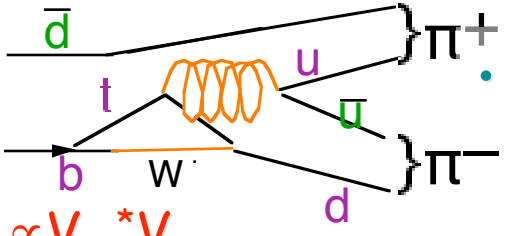
$\propto V_{ub}^* V_{ud}$

+ with mixing

$\propto V_{ub}V_{ud}^* \times V_{tb}^{*2} V_{td}^2$

• if T dominates, -> $\sin 2\phi_2$, as w J/ψ K_S

2) Penguin (P)



$\propto V_{tb}^* V_{td}$

• if P, T comparable, A_{CP} may include direct CP violation

$$q = \begin{pmatrix} +1 \text{if } B_{t=0} = B^0 \\ -1 \text{if } B_{t=0} = \bar{B}^0 \end{pmatrix}$$

$$\frac{dN}{dt}(B \to f_{CP}) = \frac{1}{2}\Gamma e^{-\Gamma\Delta t}(1 + q \cdot [\mathcal{A}_{\pi\pi}\cos(\Delta m \Delta t) + \mathcal{S}_{\pi\pi}\sin(\Delta m \Delta t)])$$

$A_{\pi\pi} \neq 0$, $S_{\pi\pi} \sim \sin(2\phi_2 + 2\theta) \cdot 2/(|\lambda|^2+1)$

difference of strong phase

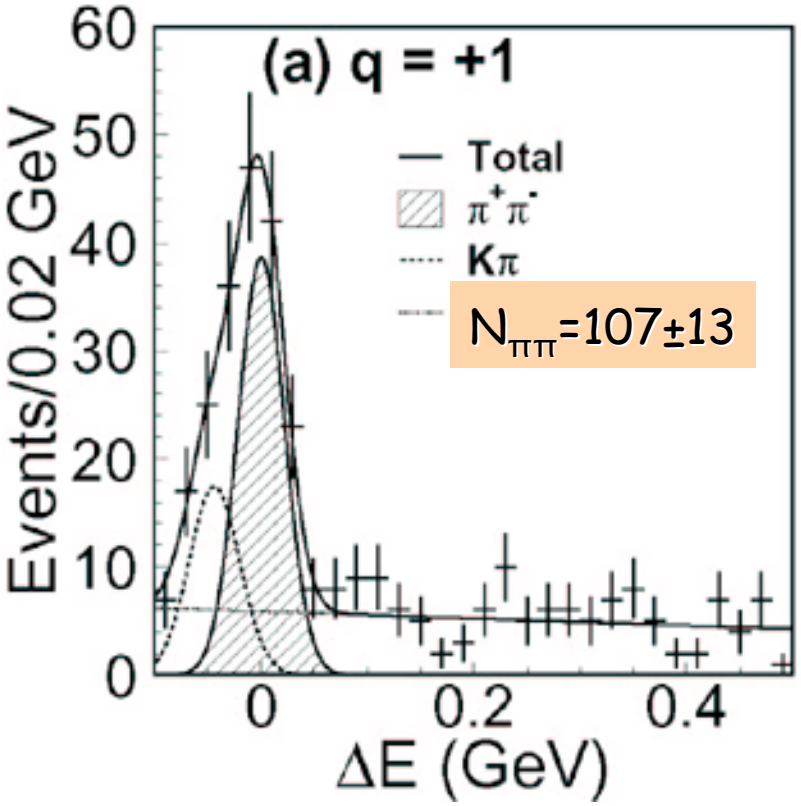
≠1 if direct CP violation

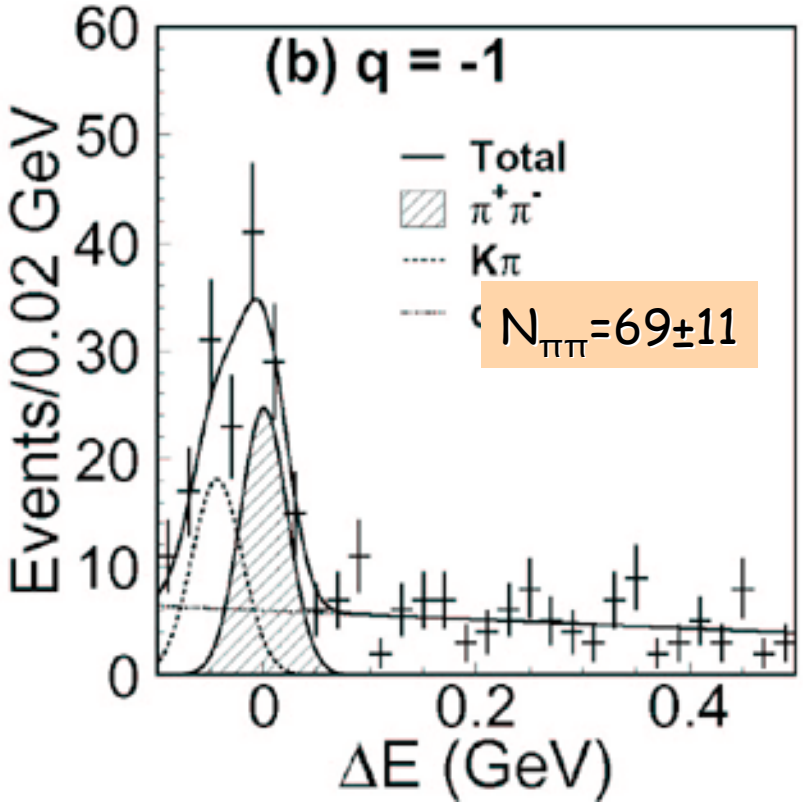
$\sin 2\phi_2$: $B^0 \to \pi^+\pi^-$

An observable time-integrated asymmetry

hep-ex/0502035

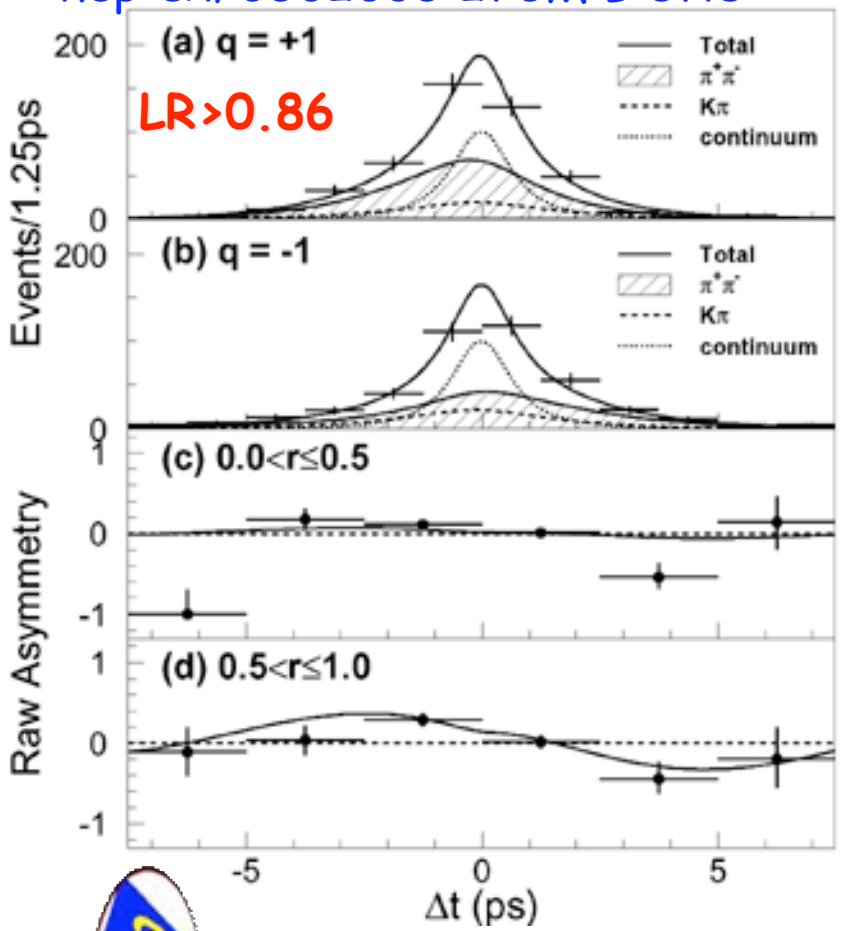
High quality tags (LR>0.86. 0.5<r<1.0)





$\sin 2\phi_2$: $B^0 \to \pi^+\pi^-$

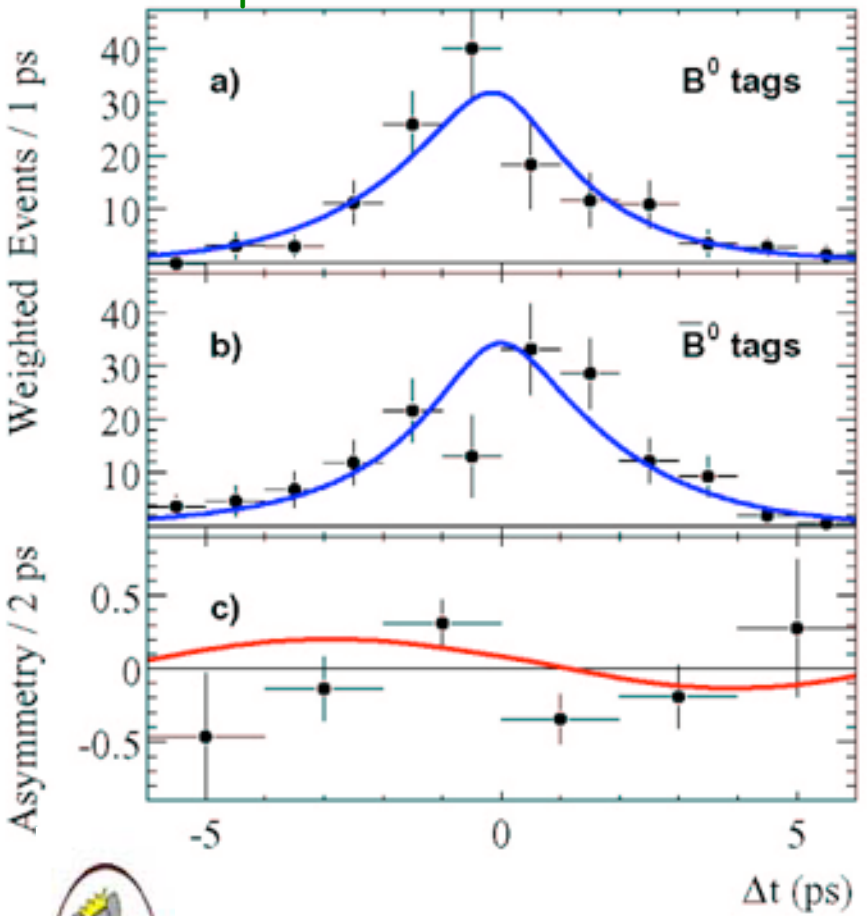
hep-ex/0502035 275M B evts



$A = +0.58 \pm 0.12 \pm 0.06$

$S = -0.67 \pm 0.16 \pm 0.06$

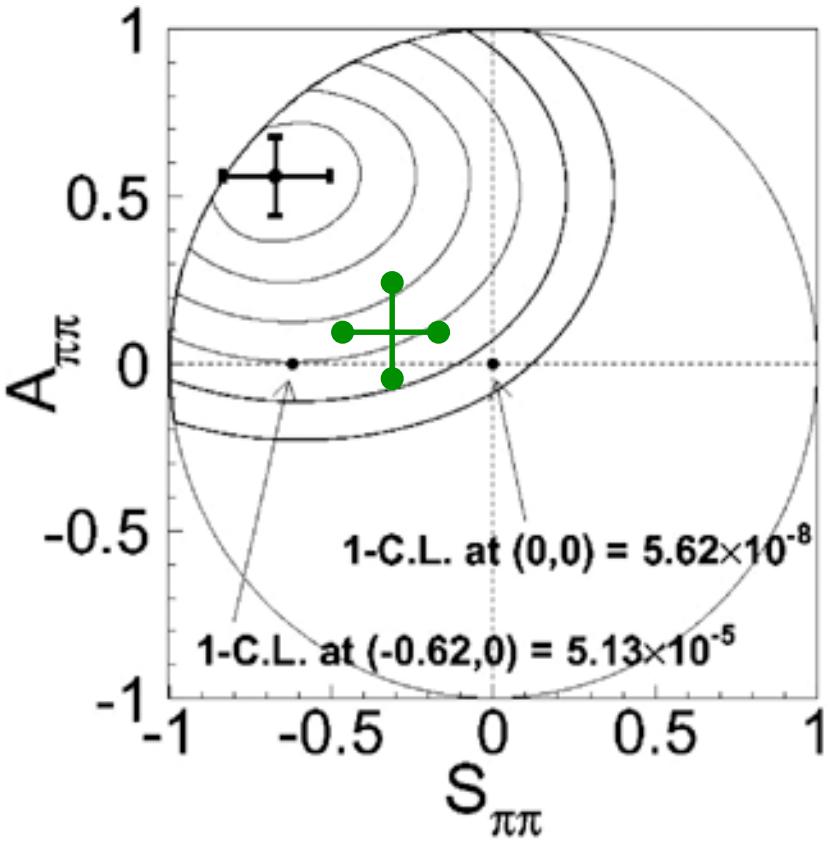
hep-ex/0408090 227M B evts



$-A = C = -0.09 \pm 0.15 \pm 0.04$

$S = -0.30 \pm 0.17 \pm 0.03$

$\sin 2\phi_2$: $B^0 \to \pi^+\pi^-$

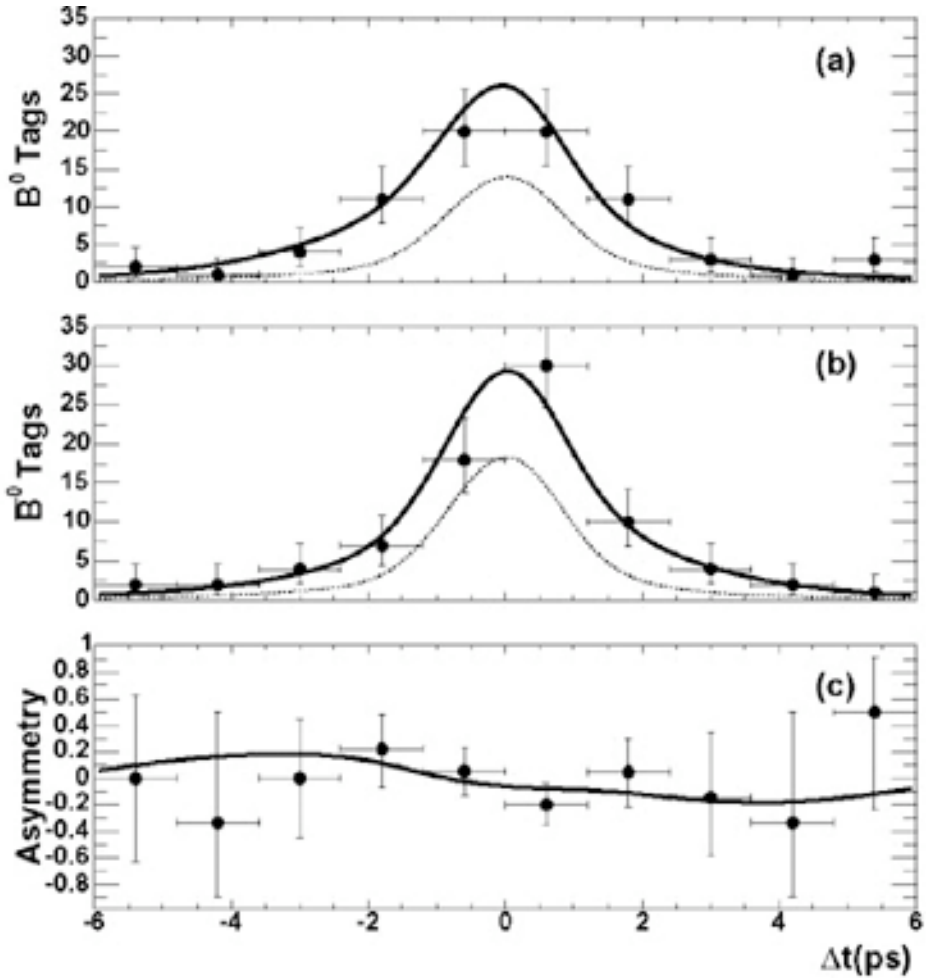


Validation of results

- lifetime
- sidebands
- Kπ lifetime, mixing, CP asymmetry
- many subsamples – consistent results
- time-integrated asymmetry
- statistics – ensemble simulation study

$\sin 2\phi_2$: $B^0 \to \rho^+\rho^-$

hep-ex/0505049 232M B evts



CP depends on polarization

Longitudinal: CP = +1

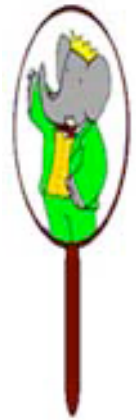
Transverse: CP mixed

CP fit includes helicity:

$$f_L = 0.978 \pm 0.014^{+0.021}_{-0.029}$$

$$S_L = -0.33 \pm 0.24^{+0.08}_{-0.14}$$

$$C_L = -0.03 \pm 0.18 \pm 0.09$$



Constraints on ϕ_2

Gronau & Rosner, PRD 65, 093012 (2002)

$$A(B^0 \to \pi^+\pi^-) = -(|T|e^{i\delta_T}e^{i\phi_2} + |P|e^{i\delta_P})$$

$$A(\bar{B}^0 \to \pi^+\pi^-) = -(|T|e^{i\delta_T}e^{-i\phi_2} + |P|e^{i\delta_P})$$

$$\delta \equiv \delta_P - \delta_T$$

$$\mathcal{A}_{\pi\pi} = \frac{-2|P/T|\sin(\phi_1+\phi_2)\sin\delta}{1-2|P/T|\cos(\phi_1+\phi_2)\cos\delta+|P/T|^2}$$

$$\mathcal{S}_{\pi\pi} = \frac{2|P/T|\sin(\phi_1-\phi_2)\cos\delta+\sin 2\phi_2-|P/T|^2\sin 2\phi_1}{1-2|P/T|\cos(\phi_1+\phi_2)\cos\delta+|P/T|^2}$$

Known: $\sin 2\phi_1 = 0.726 \pm 0.037$

Unknown: $|P/T|$, δ, ϕ_2

New constraints: A, S -> ϕ_2 not fully constrained (CL contours)

ϕ_2: isospin relations

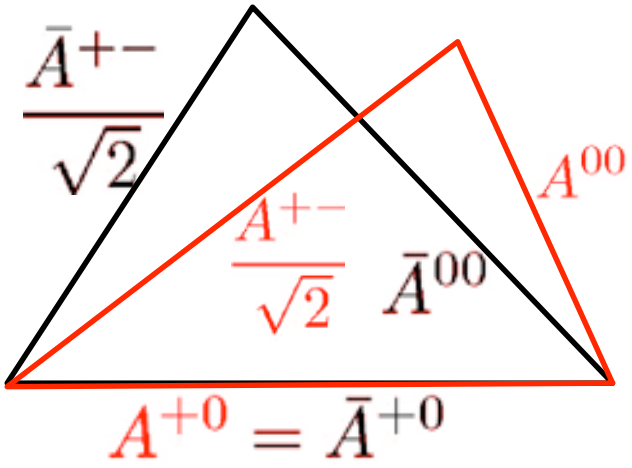
Gronau & London, PRL 65, 3381 (1990)

Isospin-related final states, different T, P content :

$$\frac{A(B^0 \to \pi^+\pi^-)}{\sqrt{2}} + A(B^0 \to \pi^0\pi^0) = A(B^+ \to \pi^+\pi^0)$$

$$\Big\| \text{ (pure T)}$$

$$\frac{A(\bar{B}^0 \to \pi^+\pi^-)}{\sqrt{2}} + A(\bar{B}^0 \to \pi^0\pi^0) = A(\bar{B}^- \to \pi^-\pi^0)$$



-> solve & disentangle:

$\mathcal{B}(B^0 \to \pi^+\pi^-)$

$\mathcal{B}(B^0 \to \pi^0\pi^0)$

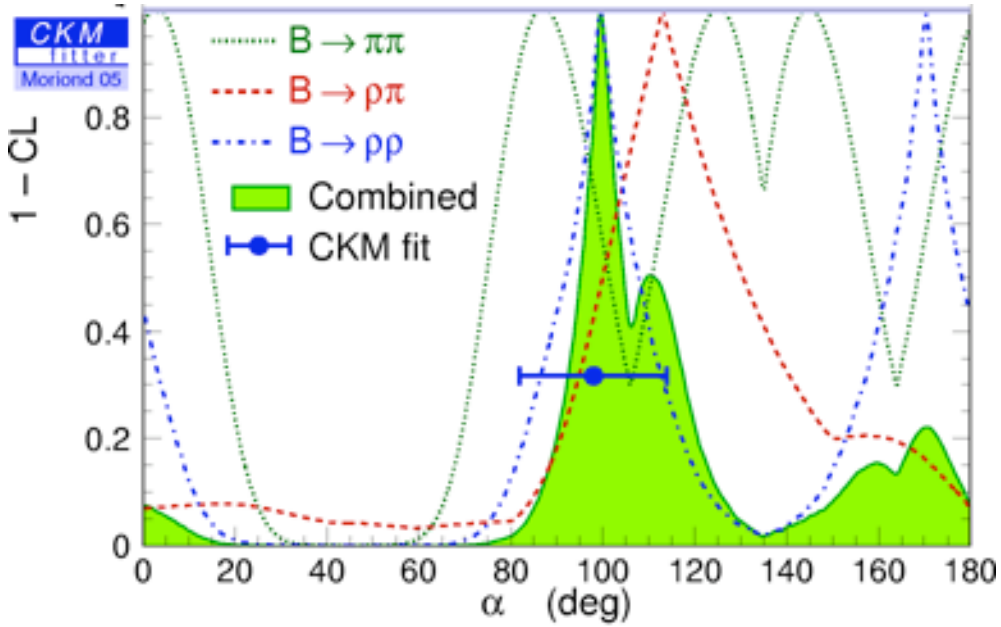
$\mathcal{B}(B^+ \to \pi^+\pi^0)$

+ $\pi^+\pi^-$,$\pi^0\pi^0$ CP asymmetries

Also applies to $\rho\rho$

ϕ_2: isospin relations

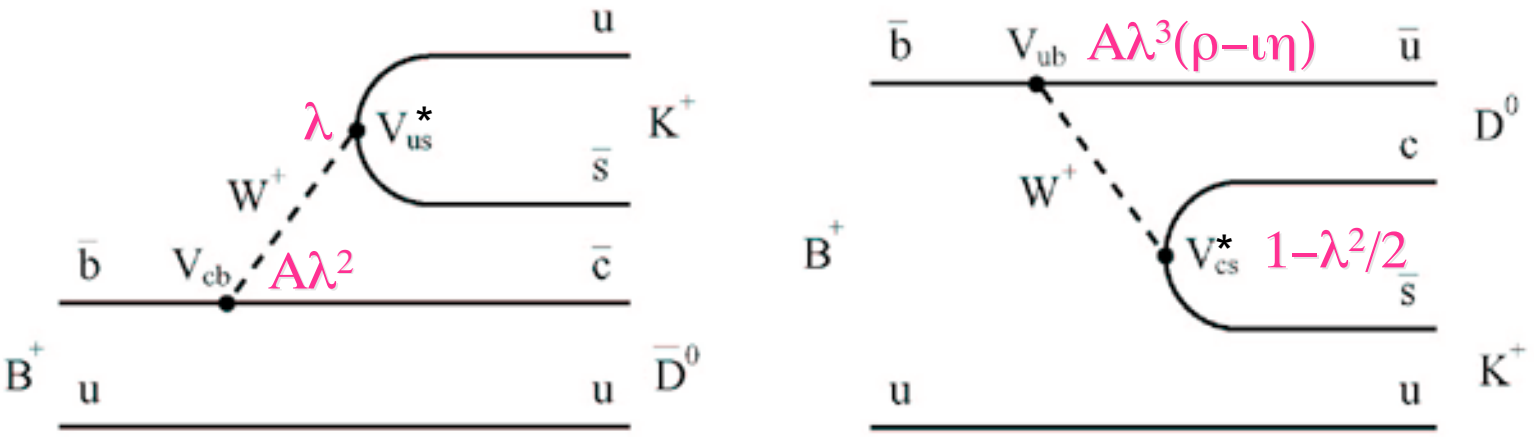
χ^2 analysis to constrain ϕ_2 (hep-ph/0406184)



	$\mathcal{B}_{+-}(10^{-6})$	$\mathcal{B}_{+0}(10^{-6})$	$\mathcal{B}_{00}(10^{-6})$	$\mathcal{A}_{00}$	ϕ_2
$\pi\pi$					
Belle	$4.4 \pm 0.6 \pm 0.3$	$5.0 \pm 1.2 \pm 0.5$	$2.32^{+0.44\ +0.22}_{-0.48\ -0.18}$	$0.43 \pm 0.51^{+0.17}_{-0.16}$	$[71°, 180°]$ (95.4% CL)
Babar	$4.7 \pm 0.6 \pm 0.2$	$5.8 \pm 0.6 \pm 0.4$	$1.17 \pm 0.32 \pm 0.10$	$0.12 \pm 0.56 \pm 0.06$	$[61°, 180°]$ (90% CL)
$\rho\rho$					
Babar	$30 \pm 4 \pm 5$	$22.5^{+5.7}_{-5.4} \pm 5.8$	$< 1.1 (90\% CL)$	–	$[79°, 123°]$ (90% CL)

ϕ_3:

A. Bondar, Belle internal (2003)
Giri et al, PRD 68, 054018 (2003)



$$A(B^+ \to D^0 K^+) = r e^{i(\delta - \phi_3)} A(B^+ \to \bar{D}^0 K^+) \quad (r \sim 0.1 - 0.2)$$

IF $D^0, \bar{D}^0 \to K_S \pi^+ \pi^-$: $\quad m_+ \equiv m_{K_s\pi^+} \quad m_- \equiv m_{K_s\pi^-}$

$$A(\bar{D}^0 \to K_S \pi^+ \pi^-) = f(m_+^2, m_-^2) \to A(D^0 \to K_S \pi^+ \pi^-) = f(m_-^2, m_+^2)$$

$$M_+ = A(B^+ \to \bar{D}^0 K^+)[f(m_+^2, m_-^2) + r e^{i(\delta - \phi_3)} f(m_-^2, m_+^2)]$$

$$M_- = A(B^- \to D^0 K^-)[f(m_-^2, m_+^2) + r e^{i(\delta + \phi_3)} f(m_+^2, m_-^2)]$$

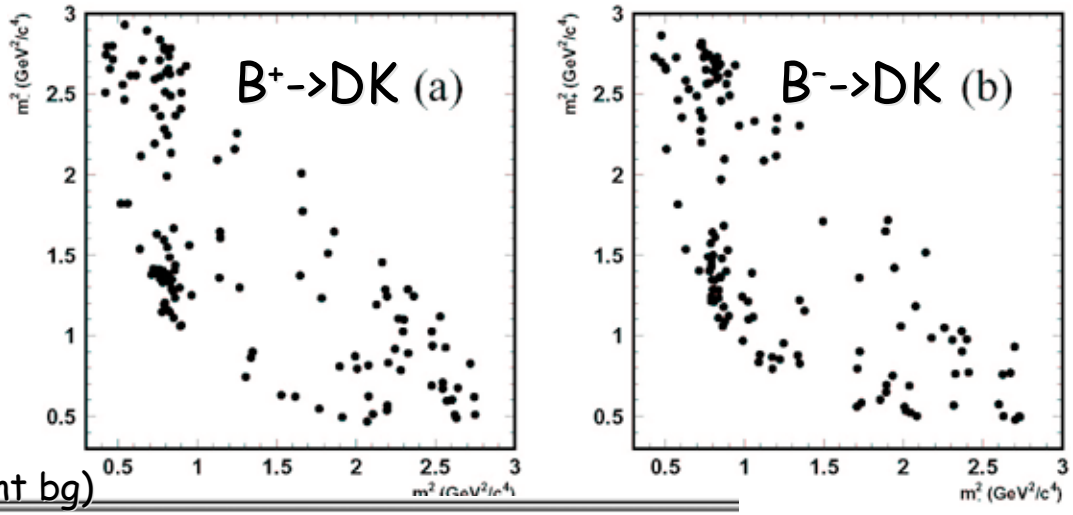
$f(m_+^2, m_-^2)$ from continuum D^0

ϕ_3:

Belle: hep-ex/0411049 253 fb^{-1}
Babar: hep-ex/0504039 227 M B evts

Dalitz plots -
unbinned ML fit for ϕ_3, δ, r

Results for
B->DK
B->D*K
B->DK* (K*->$K_S\pi^+$)



X±(stat)±(sys)±(D model)±(nonresonant bg)

	r	$\phi_3(^\circ)$	$\delta(^\circ)$
DK			
Belle	$0.21 \pm 0.08 \pm 0.03 \pm 0.04$	$64 \pm 19 \pm 13 \pm 11$	$157 \pm 19 \pm 11 \pm 21$
Babar	< 0.19 (90%CL	$70 \pm 44 \pm 10 \pm 10$	$114 \pm 41 \pm 8 \pm 10$
$D^{*0}K$			
Belle	$0.12^{+0.16}_{-0.11} \pm 0.02 \pm 0.04$	$75 \pm 57 \pm 11 \pm 11$	$321 \pm 57 \pm 11 \pm 21$
Babar	$0.155 \pm^{+0.070}_{-0.077} \pm 0.040 \pm 0.020$	$73 \pm 35 \pm 10 \pm 10$	$303 \pm 34 \pm 14 \pm 10$
DK^*			
Belle	$0.25^{+0.17}_{-0.18} \pm 0.09 \pm 0.04 \pm 0.08$	$112 \pm 35 \pm 9 \pm 11 \pm 8$	$353 \pm 35 \pm 8 \pm 21 \pm 49$

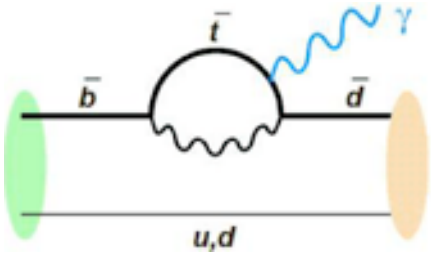
Belle average (excl DK*): (68±15±13±11)°

Babar average: (70±26±10±10)°

$|V_{td}/V_{ts}|$: b->dγ/b->sγ

Belle: hep-ex/0408137
Babar: PRL 94, 011801 (2005)

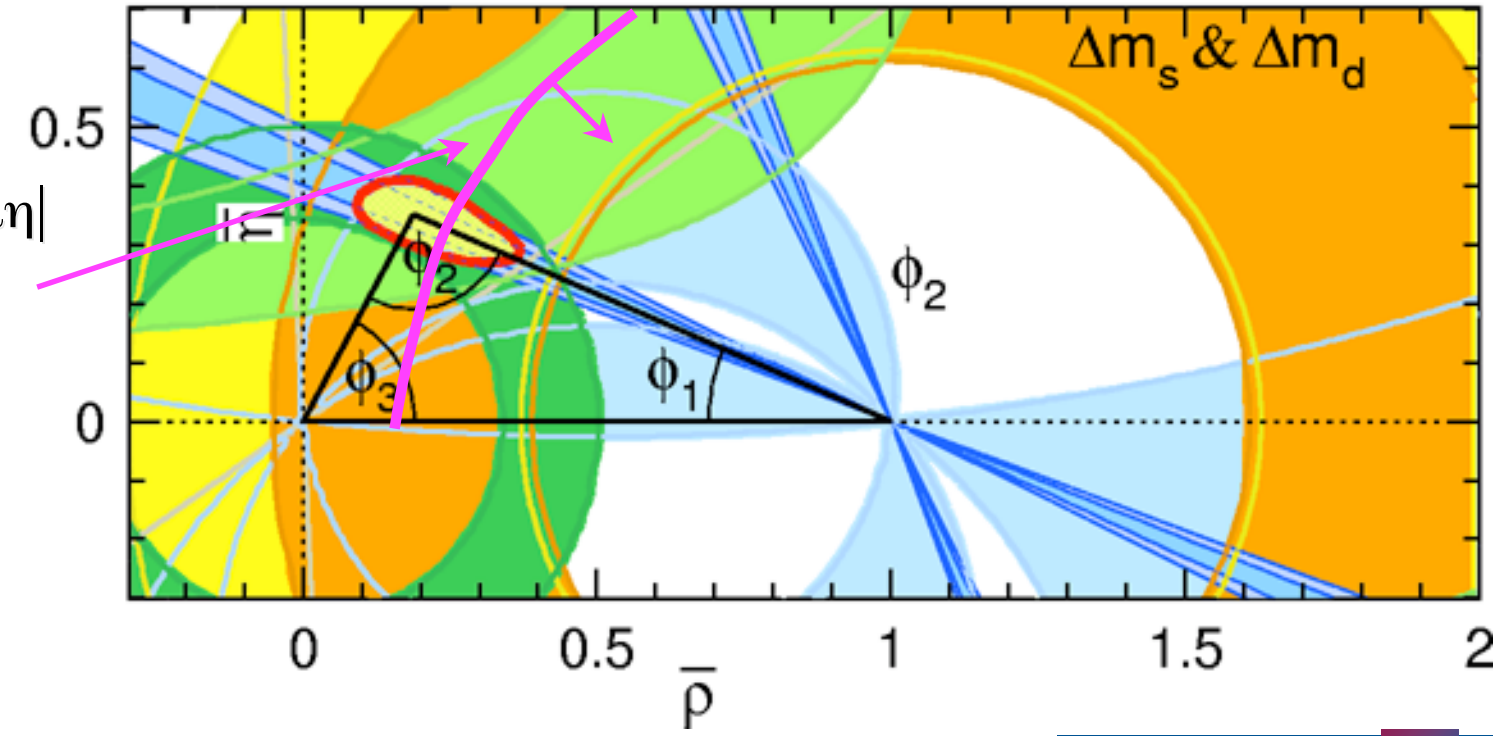
Ratio -> smaller theory error ~10%



274 M B evts (1.9σ)
$|V_{td}/V_{ts}|$<0.21 (90% CL)

221 M B evts (2.1σ)
$|V_{td}/V_{ts}|$<0.19 (90% CL)

$|V_{td}/V_{ts}| = \lambda|1-\rho-i\eta|$
=> $|1-\rho-i\eta| < 0.86$
(90%CL)



Summary

B Factories 1999-2005:

- Total > 6.5 x 10^8 B pairs, results on ~ 5 x 10^8
- $\sin 2\phi_1$ via $\psi K^{(*)0}$ to ±5%
- alternative probes of $\sin 2\phi_1$– sensitive to new physics
  penguin-dominated B -> sqq - suggestive!
- $\sin 2\phi_2$ - direct CP violation, π/ρ modes -> ±20°
- ϕ_3: first constraints -> ±20°
- possible hints of b->dγ (+ other CKM) ->
  higher precision on sides

Next

- summer 2005 >450 fb^{-1} Belle, >300 fb^{-1} Babar
- multiple modes, techniques

-> improving precision on angles and sides;
CKM challenge is heating up - stay tuned!