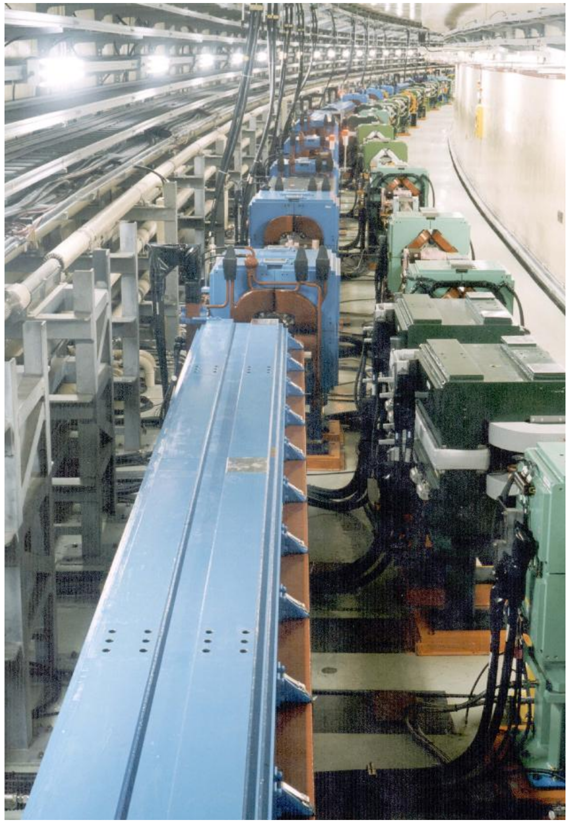
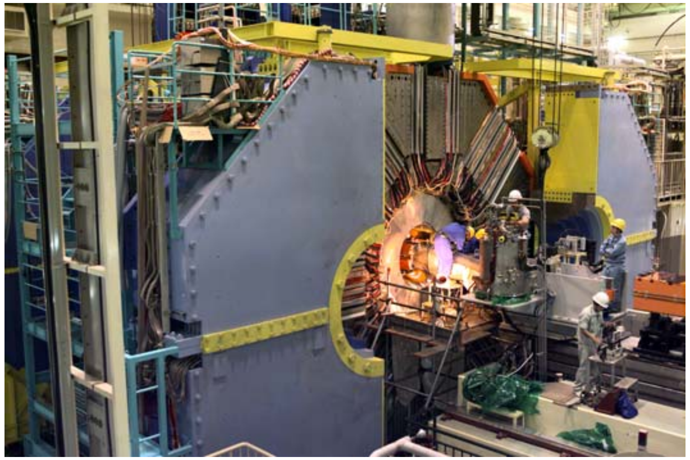
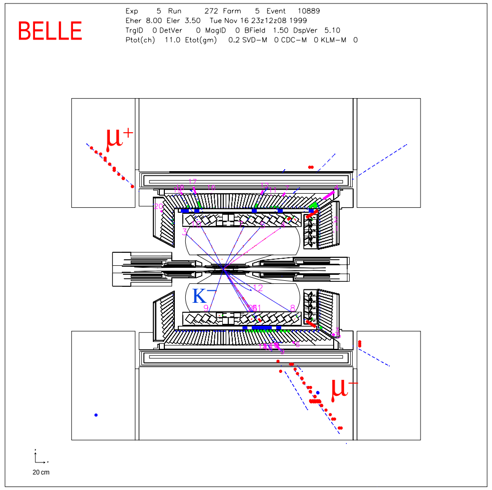
Time-dependent CP Violation (tCPV) at Belle
-- New results at ICHEP2006 --







Masashi Hazumi
(KEK)

October. 10, 2006

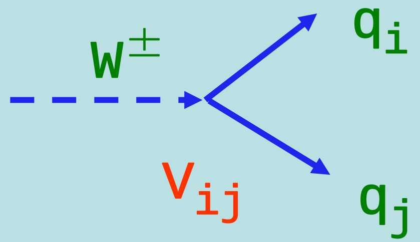
The Belle (B Factory) Physics Program

I. CP Violation in B Decays

II. Fundamental SM Parameters (Complex Quark Couplings)

III. Beyond the SM (BSM)

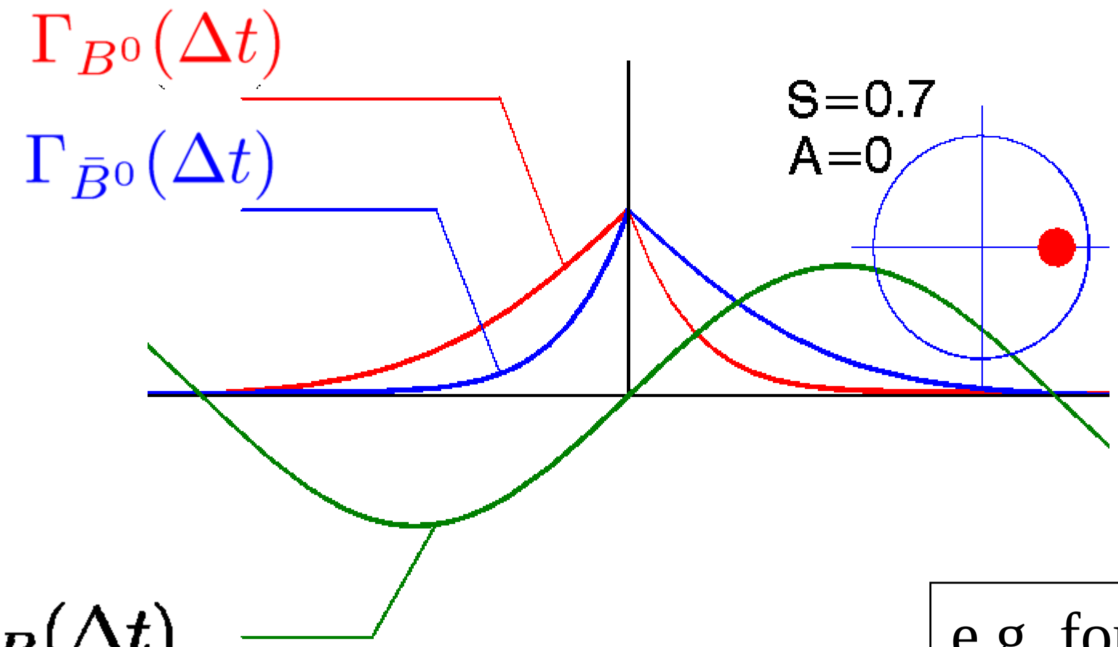
IV. Unanticipated New Particles



Cabibbo-Kobayashi-Maskawa (CKM) matrix

tCPV measurements at the heart of I, II and III !!

t*CP*V in B^0 decays



$$A_{CP}(\Delta t) \equiv \frac{\Gamma_{\bar{B}^0}(\Delta t) - \Gamma_{B^0}(\Delta t)}{\Gamma_{\bar{B}^0}(\Delta t) + \Gamma_{B^0}(\Delta t)} = \mathcal{S}\sin\Delta m\Delta t + \mathcal{A}\cos\Delta m\Delta t$$

Mixing-induced CPV

Direct CPV

e.g. for $J/\psi K_S$

$\mathcal{S} = -\xi_{CP}\sin 2\phi_1 = +\sin 2\phi_1$

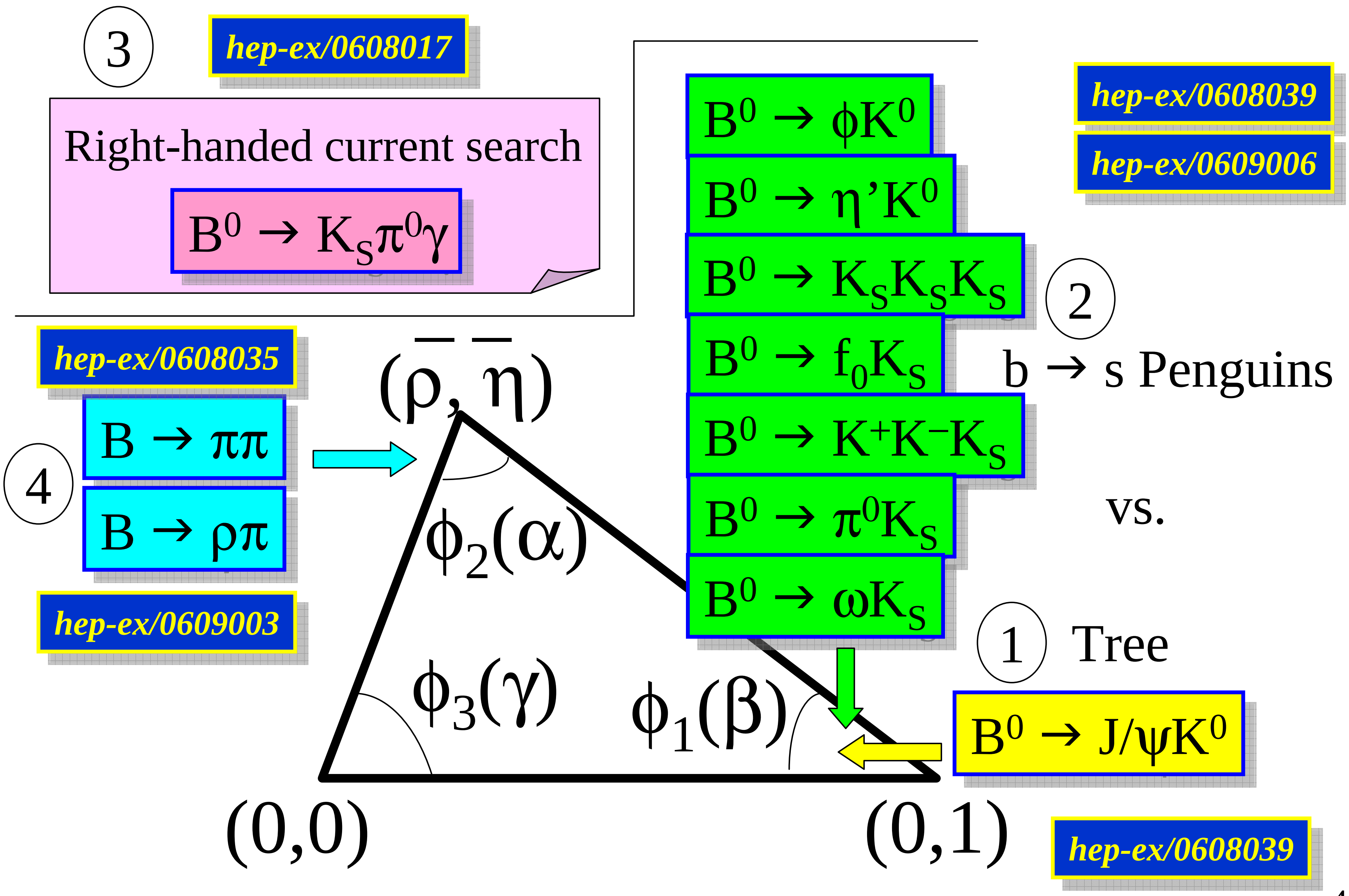
$\mathcal{A} = 0$

to a good approximation

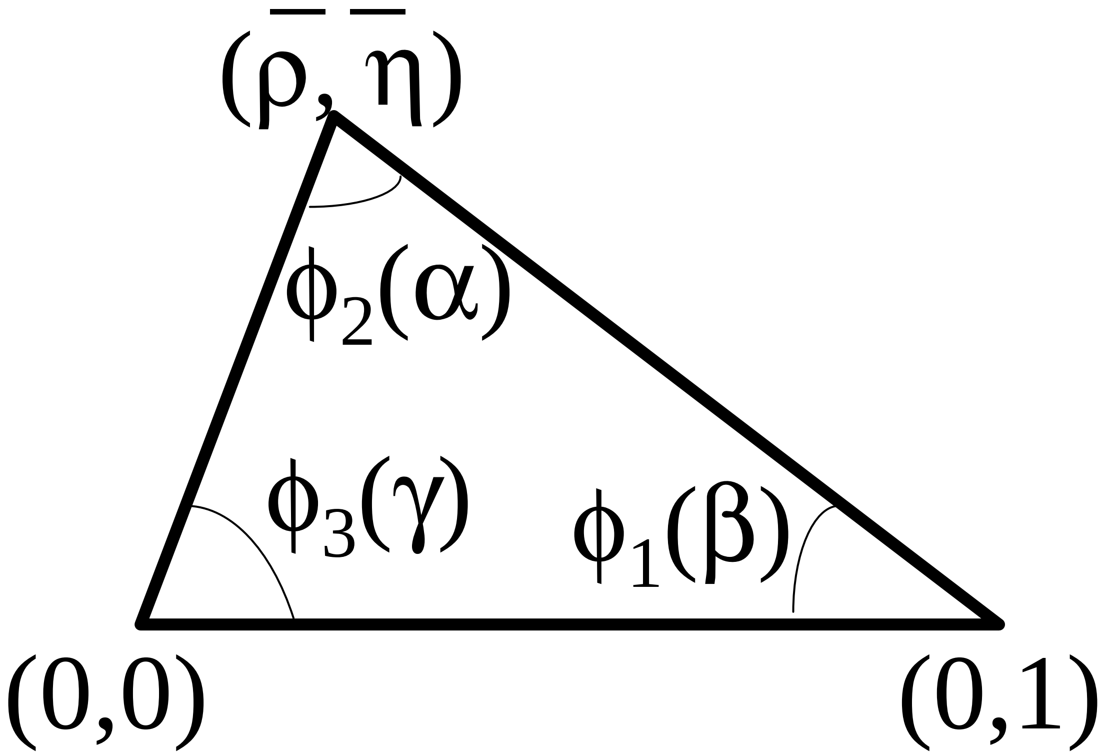
(ξ_{CP} : CP eigenvalue)

($\mathcal{A} = -C$ a la BaBar)

New results shown at ICHEP2006



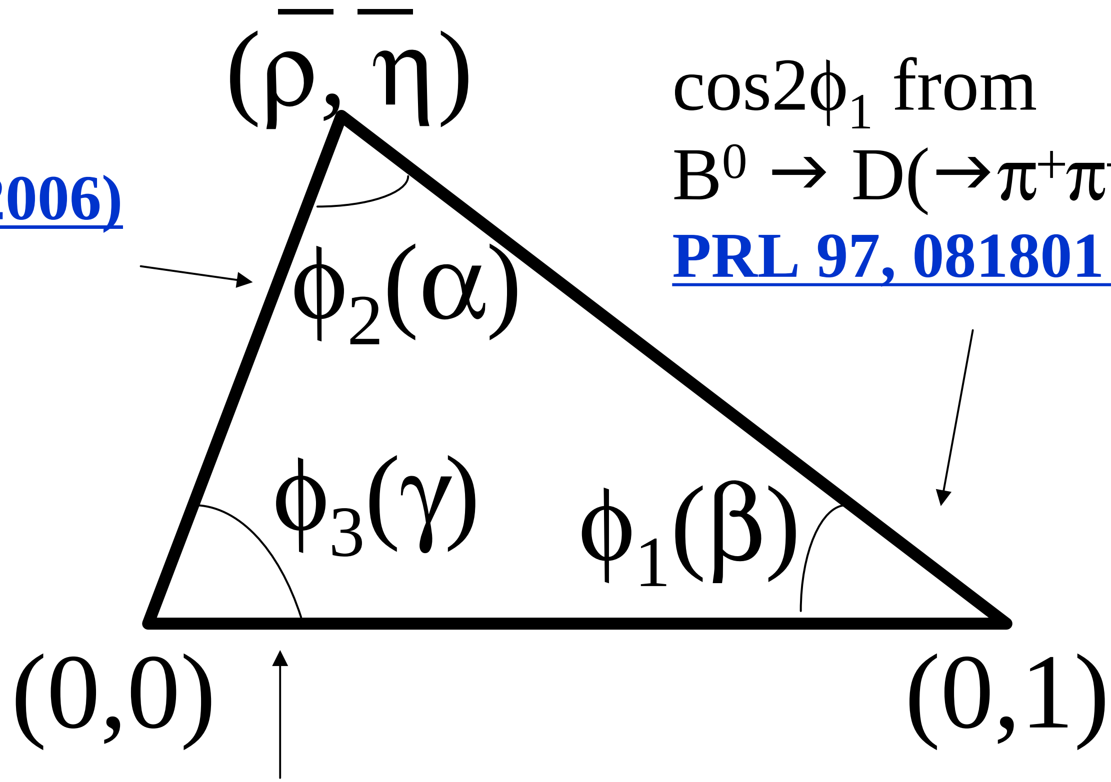
Still new results but not covered in this talk



Still new results but not covered in this talk

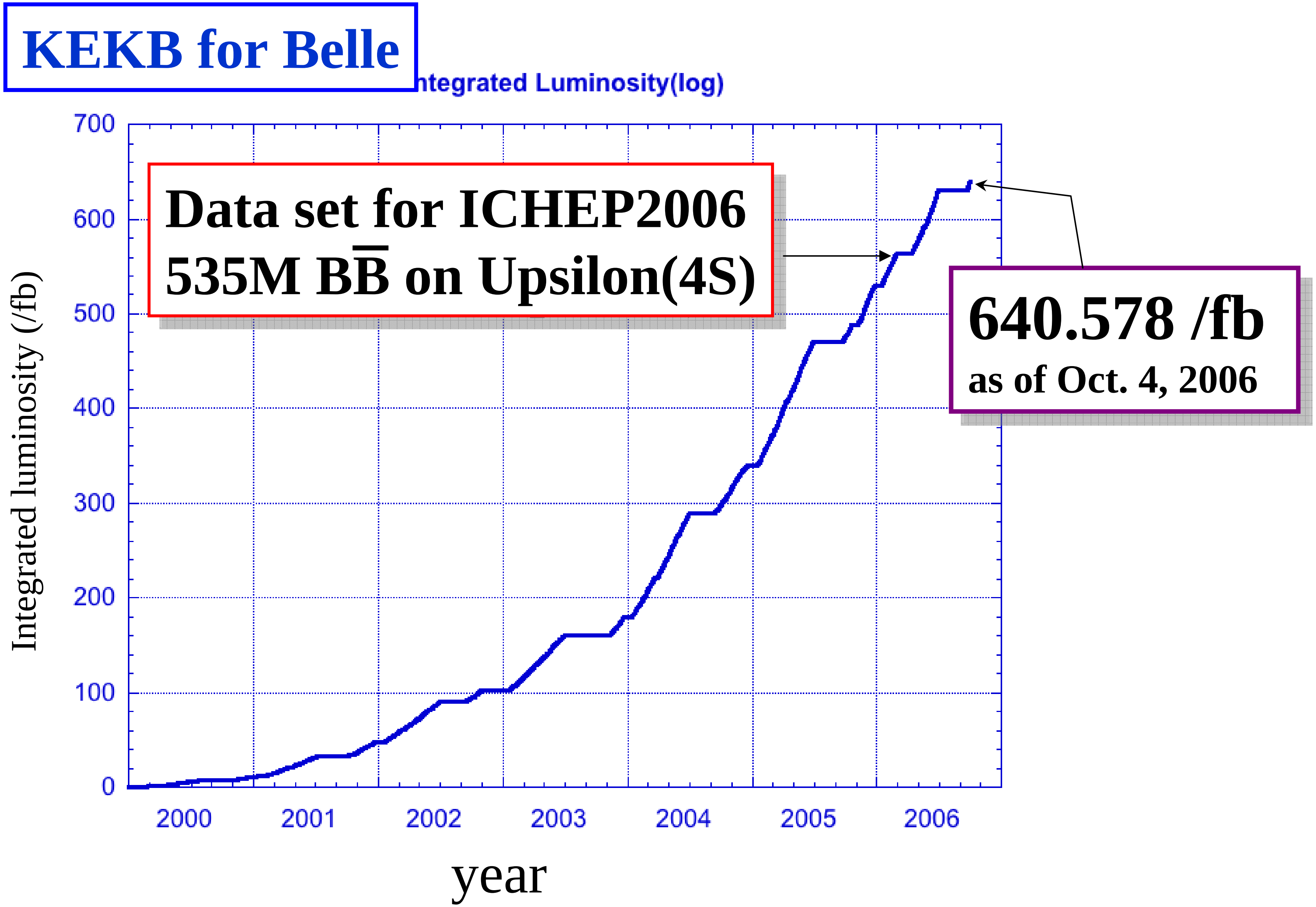
ϕ_2 from $B \rightarrow \rho\rho$
PRL 96, 171801 (2006)

$\cos 2\phi_1$ from
$B^0 \rightarrow D(\rightarrow \pi^+\pi^- K_S)h^0$
PRL 97, 081801 (2006).



$\sin(2\phi_1+\phi_3)$ from $B^0 \rightarrow D^{(*)-}\pi^+$
PRD 73, 092003 (2006).

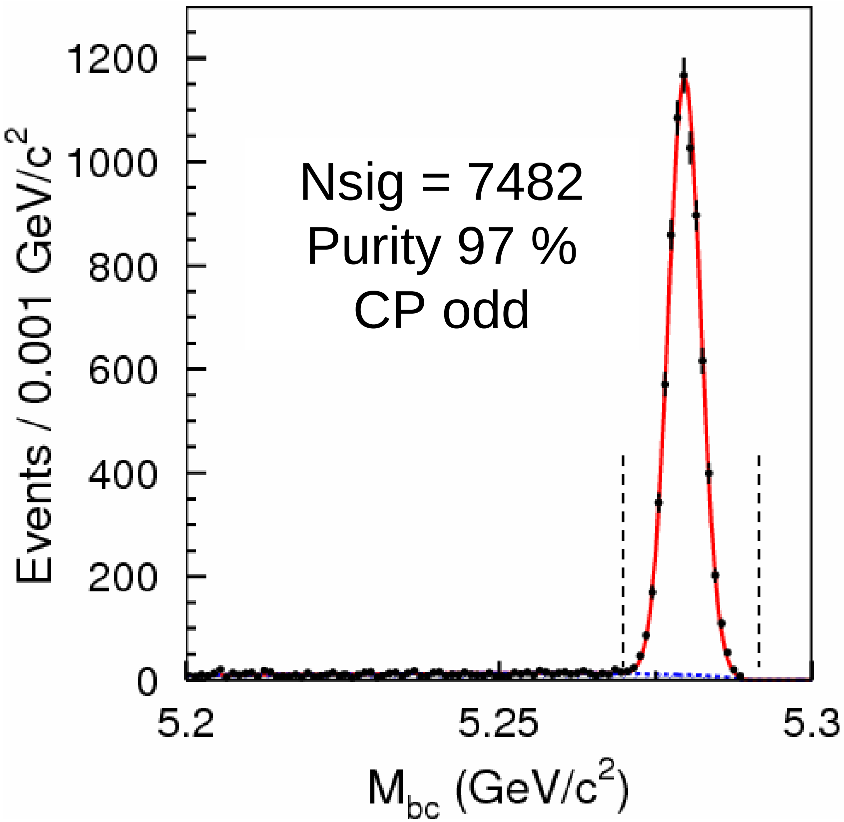
Integrated Luminosity



β/ϕ_1 with trees
- Results -

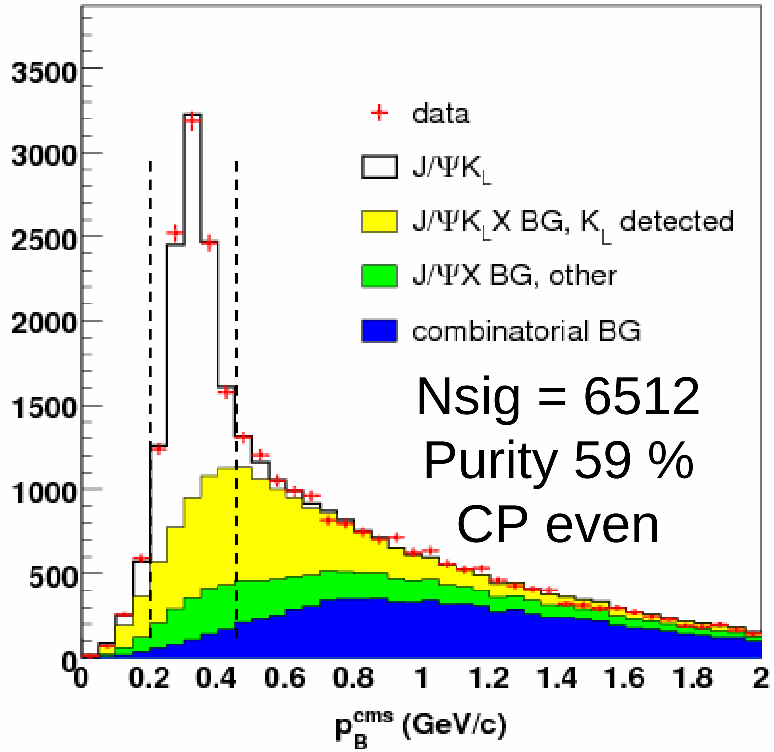
$B^0 \rightarrow J/\psi K^0$: 535 M $B\bar{B}$ pairs

$B^0 \rightarrow J/\psi K_S^0$



$$M_{bc} = \sqrt{E_{beam}^{*2} - P_{J/\psi Ks}^{*2}}$$

$B^0 \rightarrow J/\psi K_L^0$

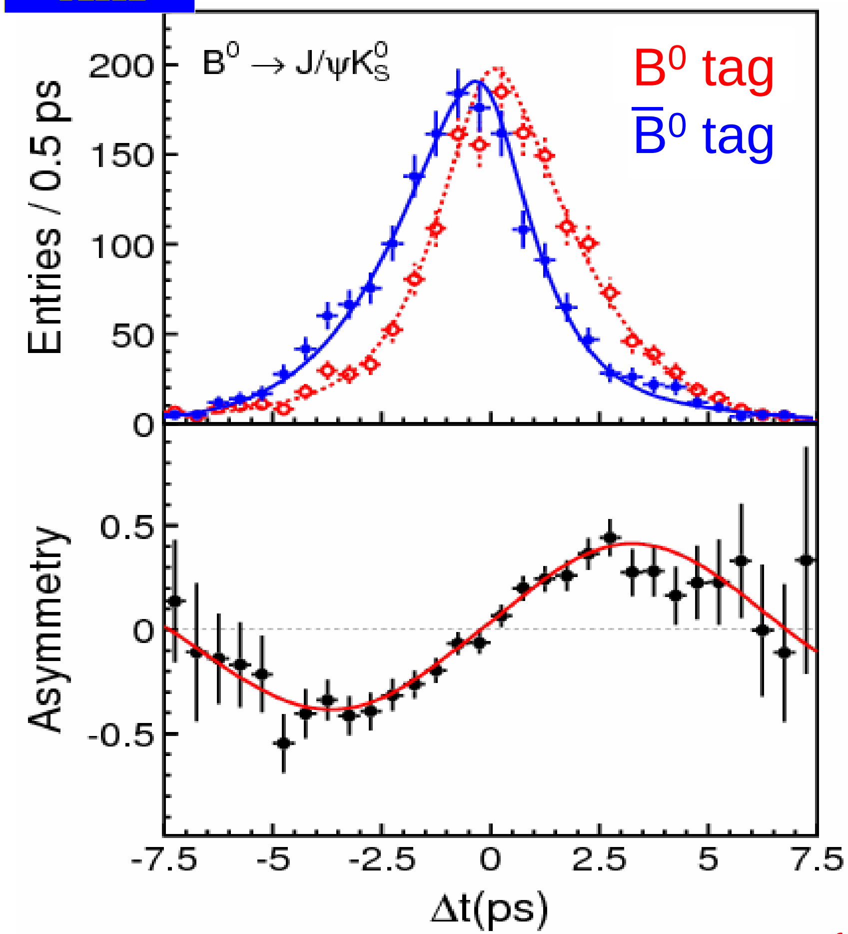


p_{KL} information is poor
→ lower purity

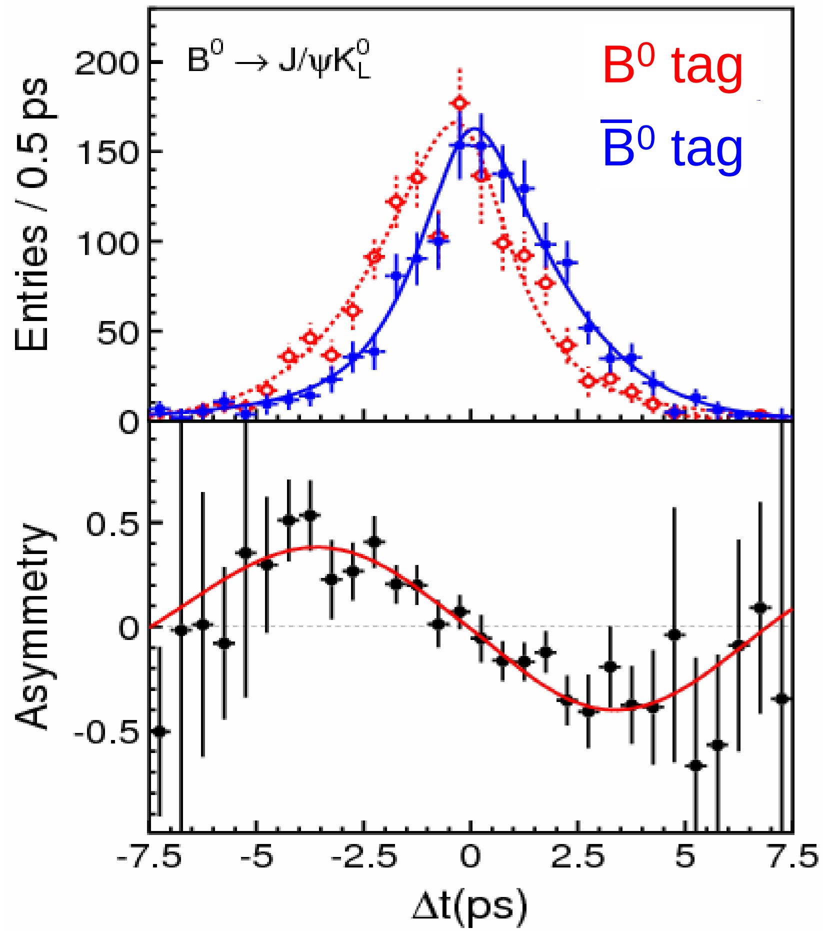
hep-ex/0608039

background subtracted

$B^0 \to J/\psi K^0_S$



$B^0 \to J/\psi K^0_L$



Asym. = $-\xi_{CP} \sin 2\phi_1 \sin \Delta m \Delta t$

hep-ex/0608039

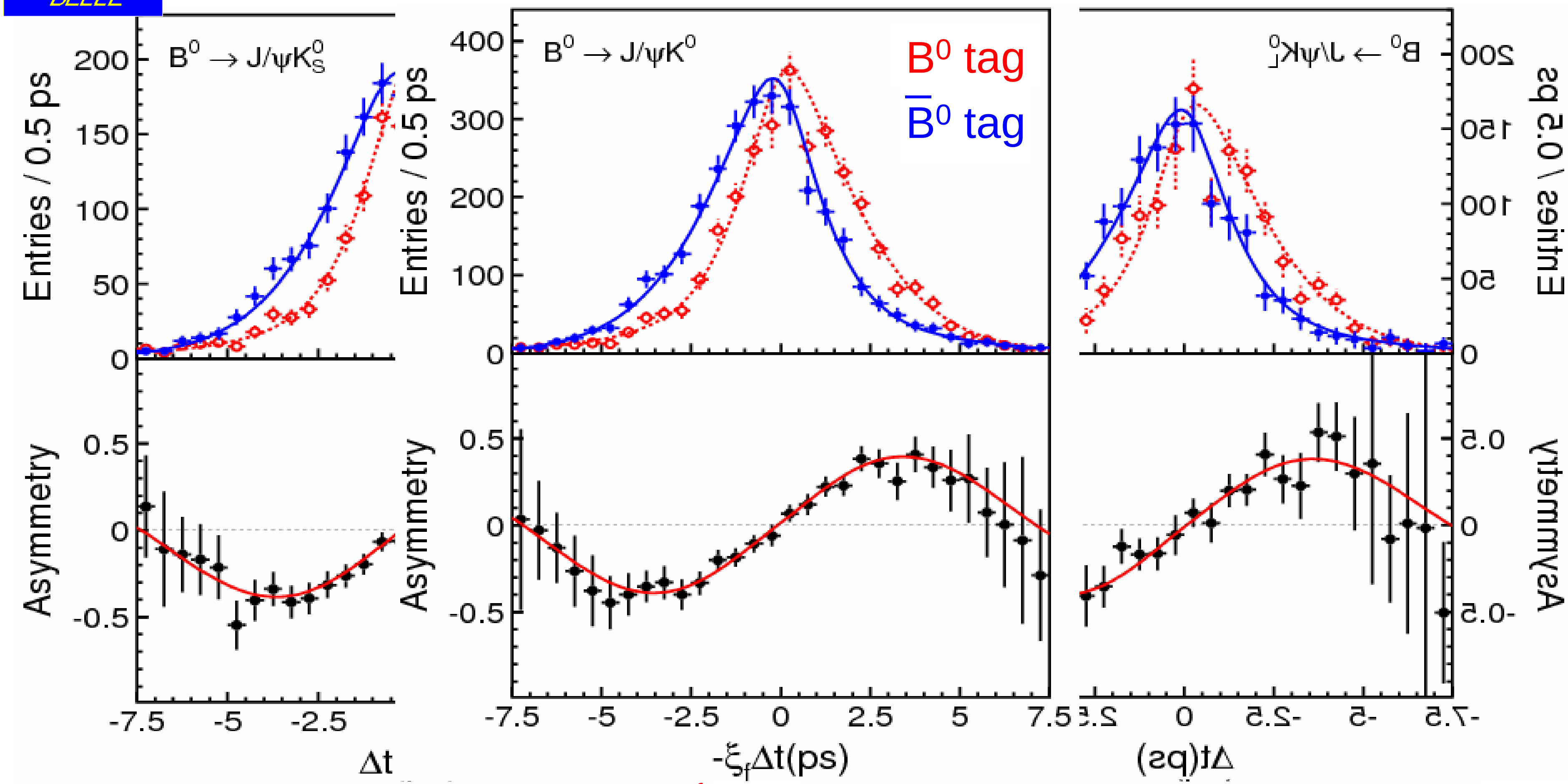
$\sin 2\phi_1 = +0.643 \pm 0.038$
$A = -0.001 \pm 0.028$

stat error

$\sin 2\phi_1 = +0.641 \pm 0.057$
$A = +0.045 \pm 0.033$

stat error

$B^0 \to J/\psi K^0$: combined result



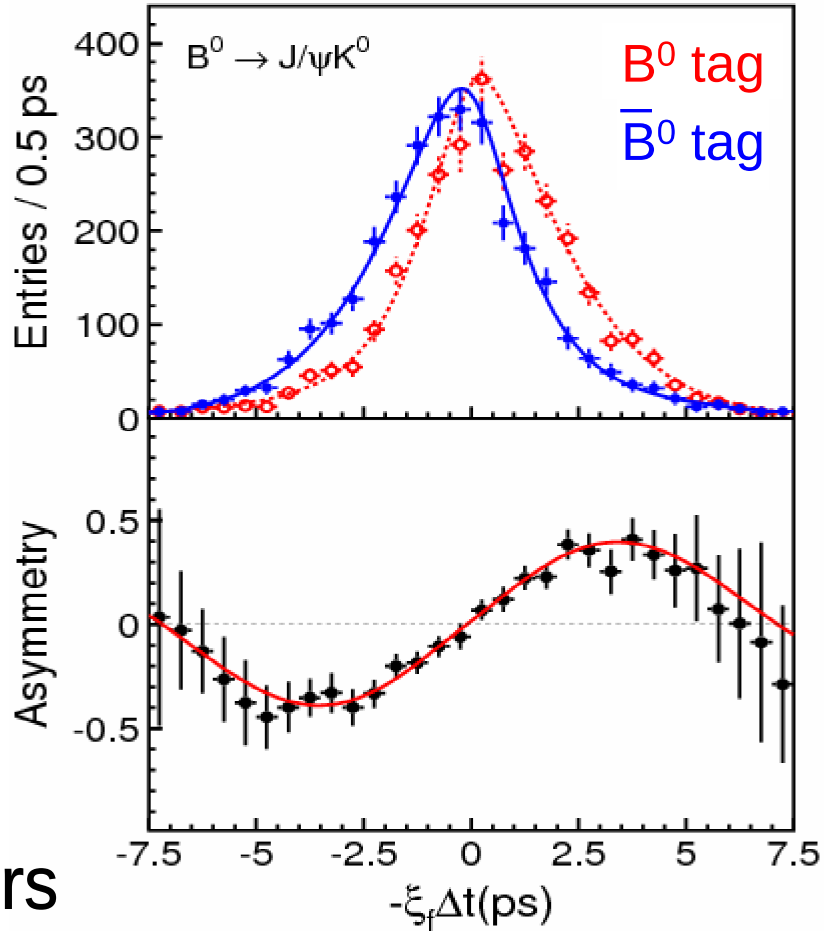
Asym. = $-\xi_{CP}\sin 2\phi_1 \sin\Delta m \Delta t$

hep-ex/0608039

$\sin 2\phi_1 = +0.643 \pm 0.038$	$\sin 2\phi_1 = +0.641 \pm 0.057$
$A = -0.001 \pm 0.028$	$A = +0.045 \pm 0.033$
stat error	*stat error*

$B^0 \rightarrow J/\psi K^0$: combined result

New !



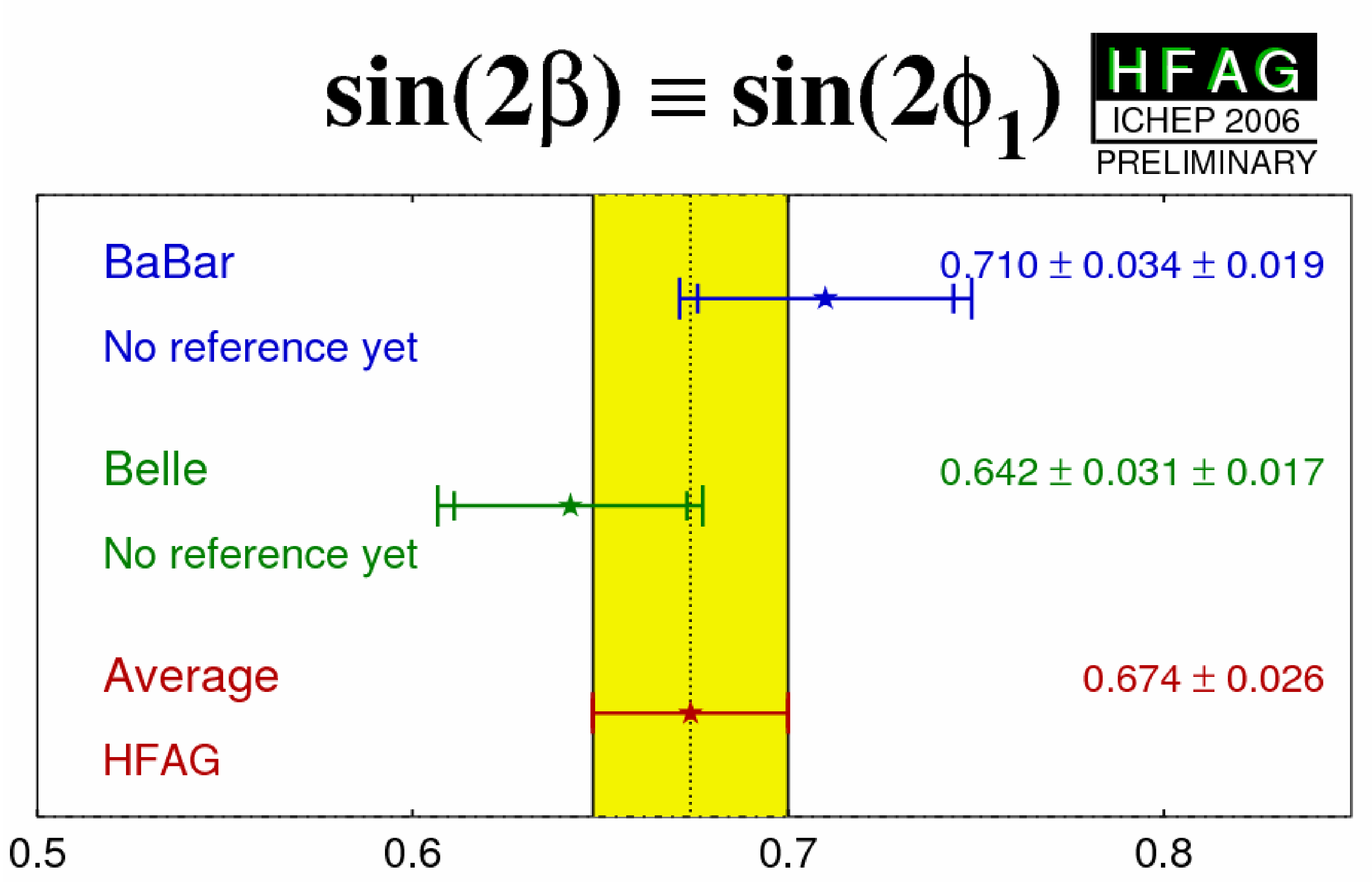
535 M $B\overline{B}$ pairs

previous measurement
$\sin 2\phi_1 = 0.652 \pm 0.044$
(388 M $B\overline{B}$ pairs)

$\sin 2\phi_1 = 0.642 \pm 0.031$ (stat) ± 0.017 (syst)
$A = 0.018 \pm 0.021$ (stat) ± 0.014 (syst)

hep-ex/0608039

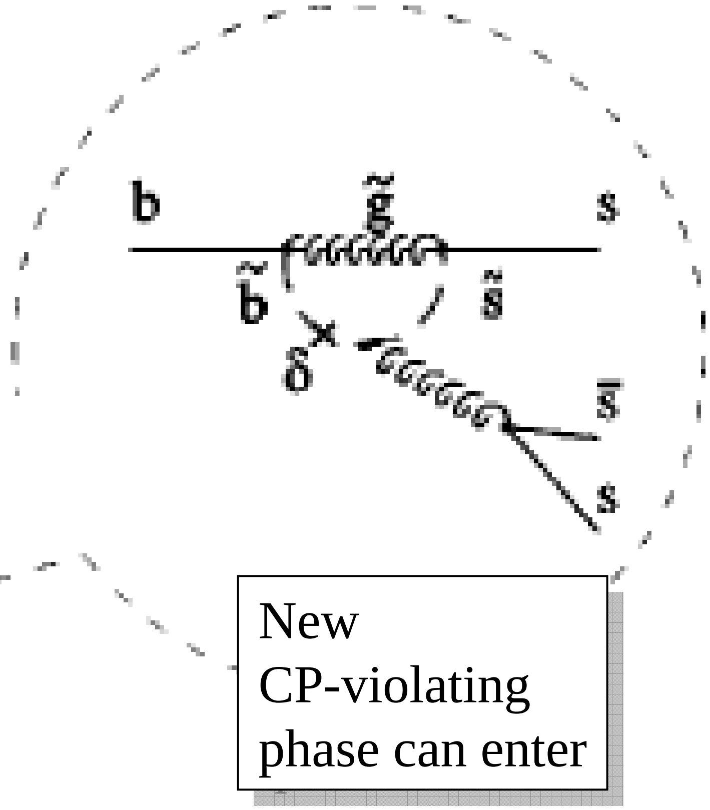
2006: BaBar + Belle

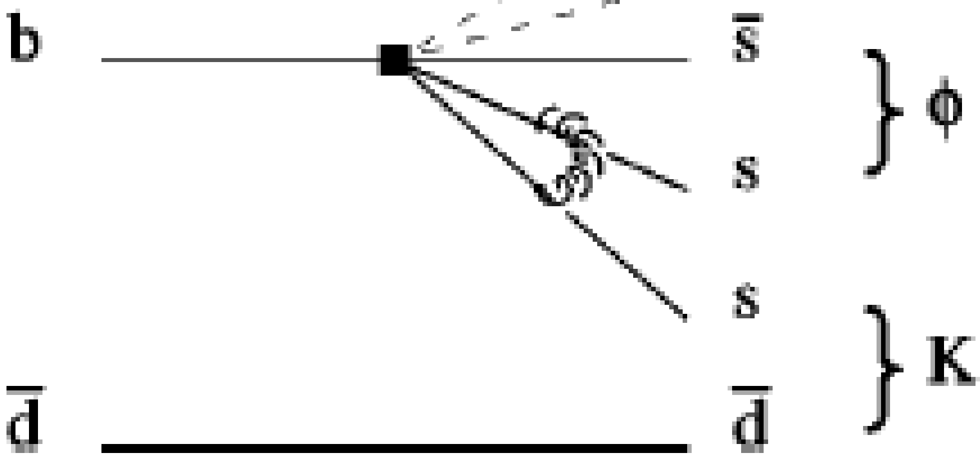


β/ϕ_1 with penguins

b → s tCPV: One of the best probes

SUSY as an example

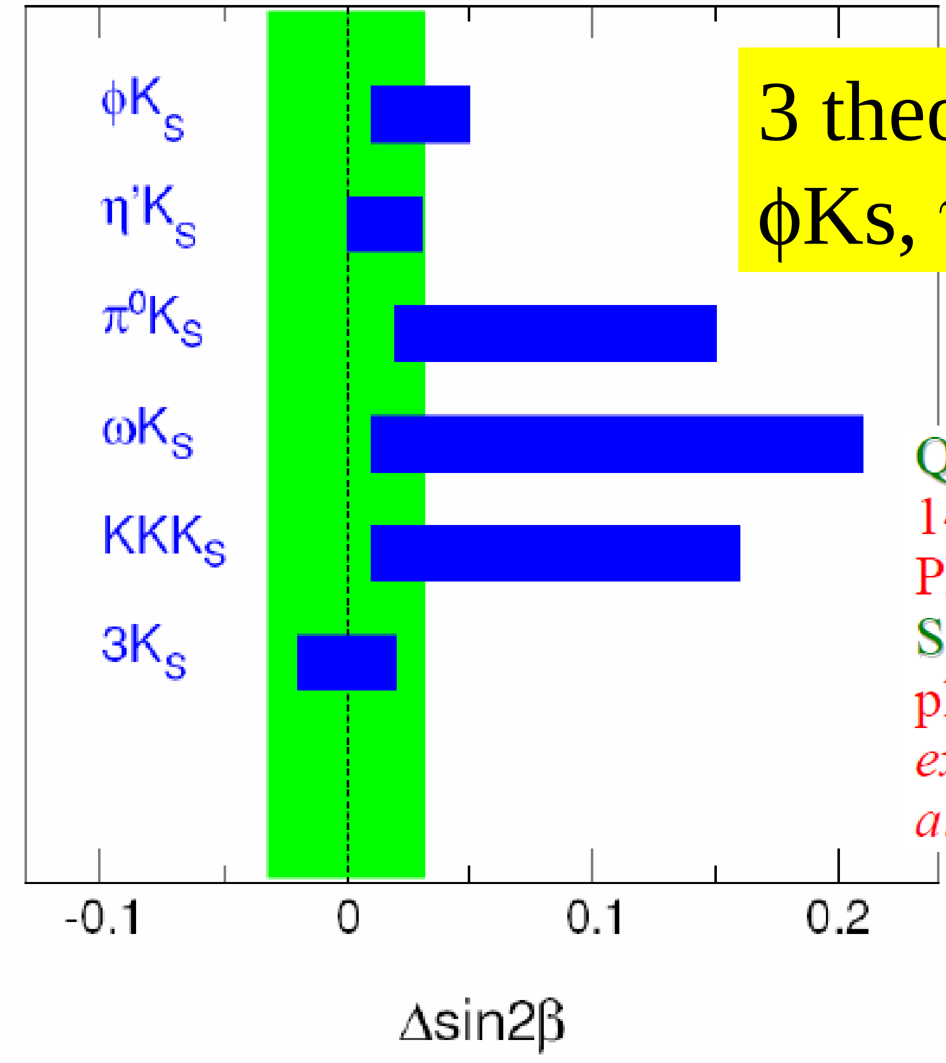




O(1) effect allowed
even if SUSY scale
is above 2TeV.

some of recent QCDF estimates

$\sin 2\beta^f_{eff} - \sin 2\beta$



3 theoretically-clean modes
ϕK_s, $\eta' K_s$, 3Ks

QCDF (Beneke, PLB620 (2005) 143-150; Cheng, Chua, Soni, PRD72 (2005) 094003; …) and SCET (Williamson, Zupan, hep-ph/0601214) allows to estimate ΔS: *expect positive deviation for almost all modes*

Results for 3 theoretically-clean modes ϕK^0, $\eta' K^0$, KsKsKs

Belle 2006: $B^0 \to \phi K^0$ signal

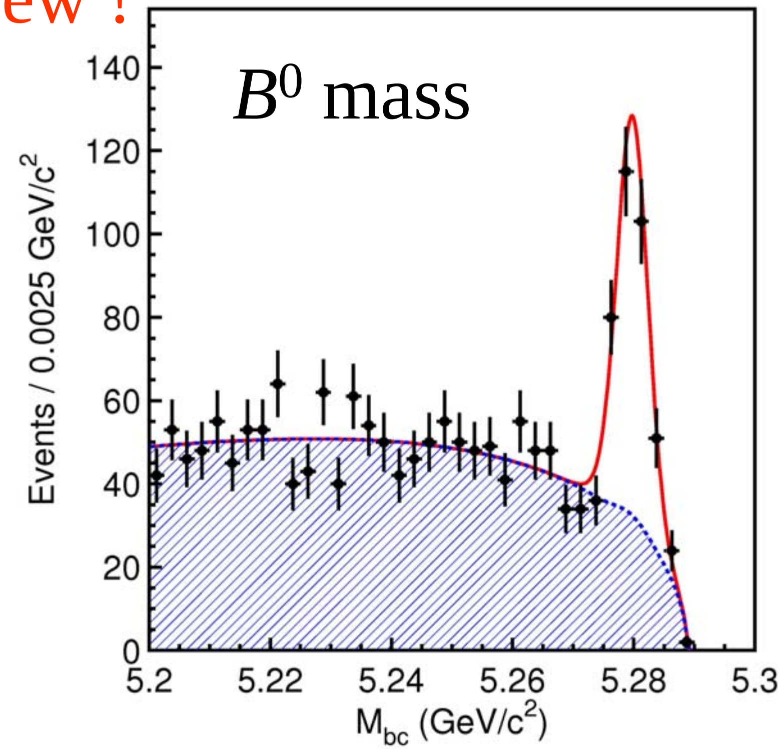
535M $B\bar{B}$

Three modes

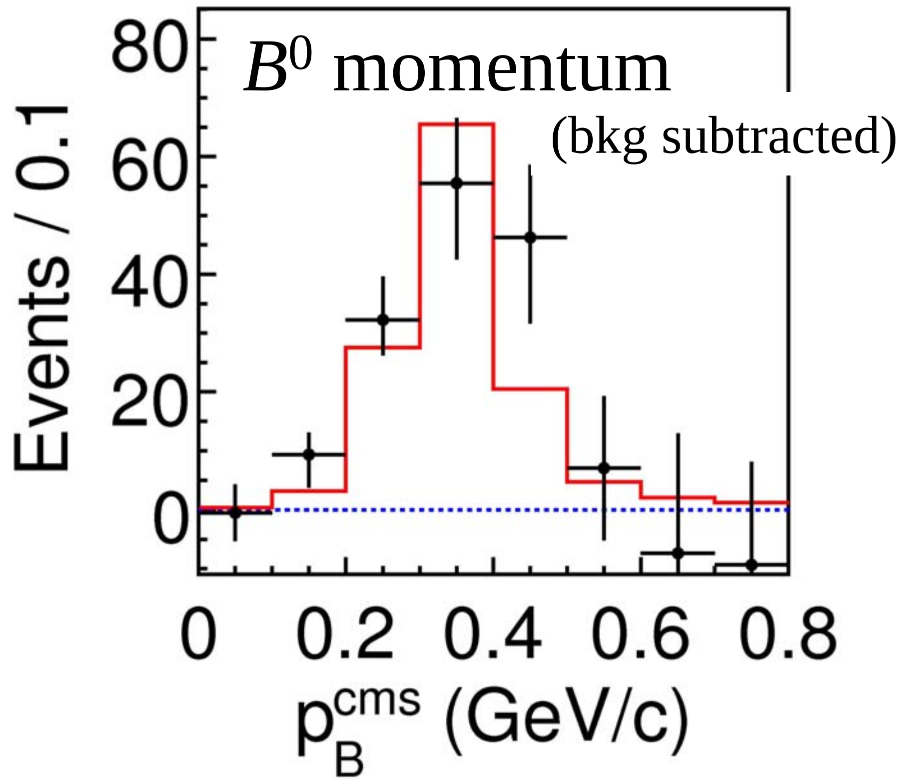
$\phi \to K^+K^-$, $K_S \to \pi^+\pi^-$
$\phi \to K^+K^-$, $K_S \to \pi^0\pi^0$
$\phi \to K_S K_L$, $K_S \to \pi^+\pi^-$

New !

307 ± 21
ϕK_S signal



114 ± 17
ϕK_L signal



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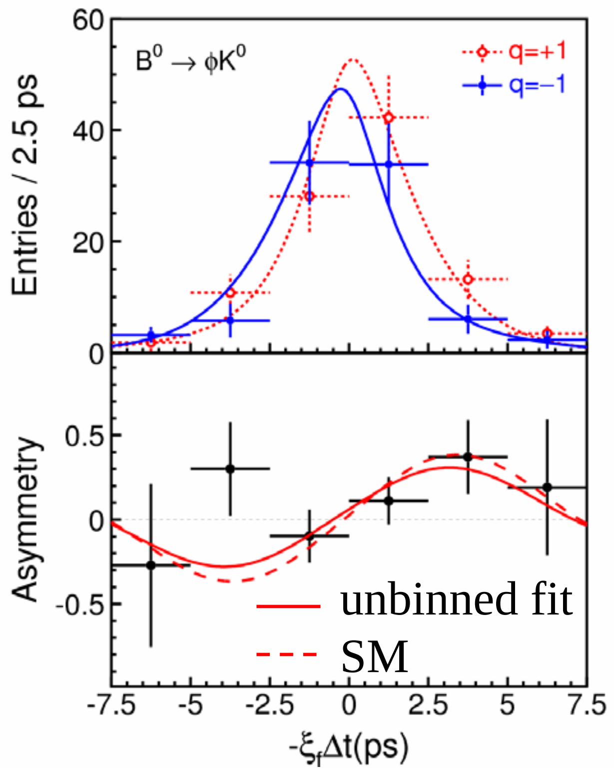
Belle 2006: t*CPV* in $B^0 \to \phi K^0$

535M $B\bar{B}$

New !

$$\text{“}\sin 2\phi_1\text{”} = +0.50 \pm 0.21(\text{stat}) \pm 0.06(\text{syst})$$
$$\mathcal{A} = +0.07 \pm 0.15(\text{stat}) \pm 0.05(\text{syst})$$

Δt distribution and asymmetry



- Consistent with the SM (~1σ lower)
- Consistent with Belle 2005

  (Belle2005: “$\sin 2\phi_1$” = +0.44±0.27±0.05)
- The most precise measurement now

- ϕK_S and ϕK_L combined
- background subtracted
- good tags
- $\Delta t \to -\Delta t$ for ϕK_L

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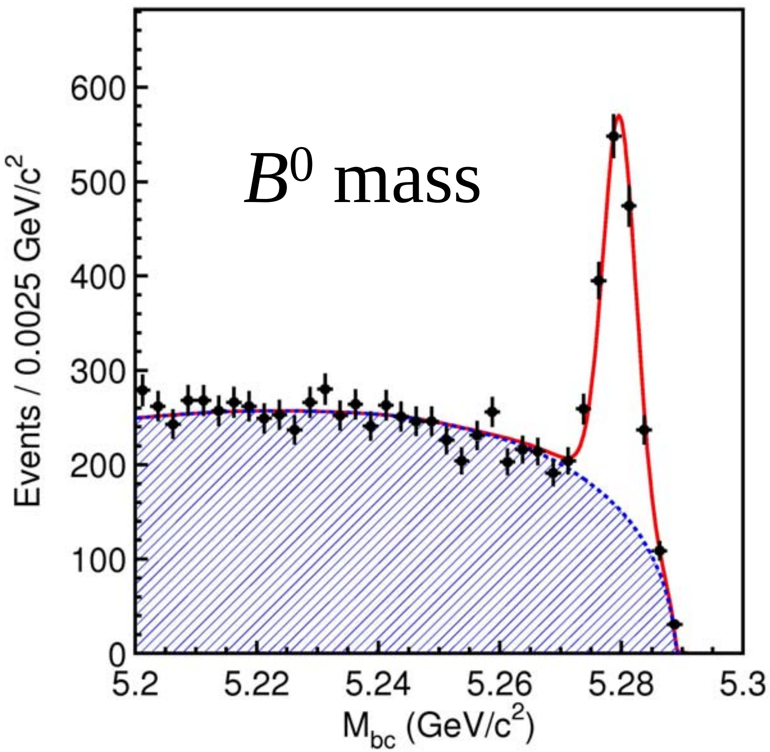
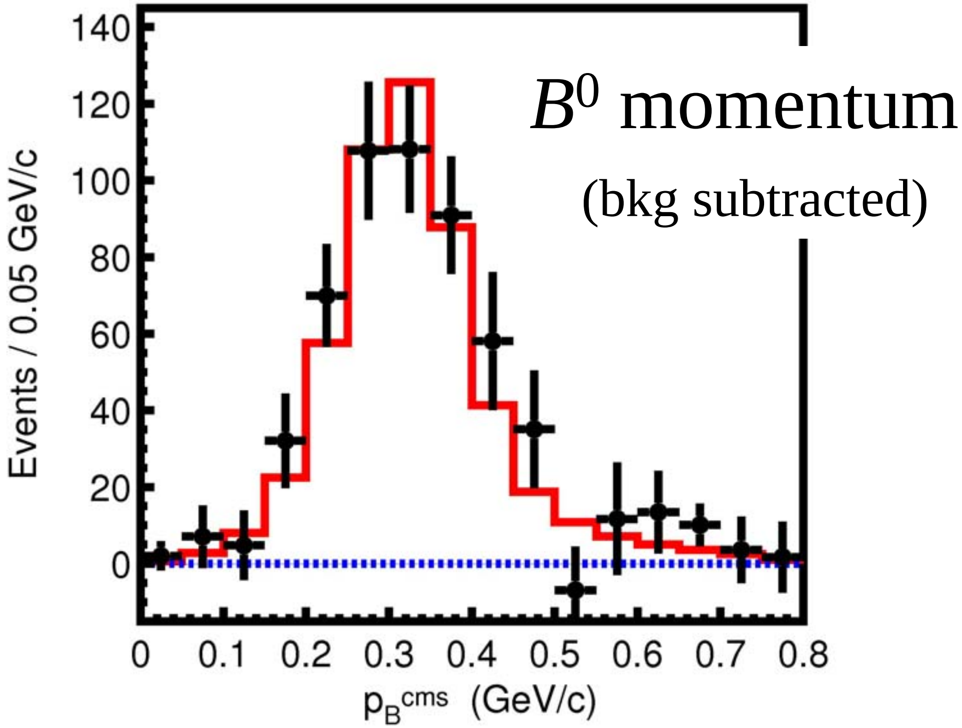
Belle 2006: $B^0 \to \eta' K^0$ signal

535M $B\bar{B}$

1421 ± 46
$\eta' K_S$ signal

454 ± 39
$\eta' K_L$ signal





hep-ex/0608039

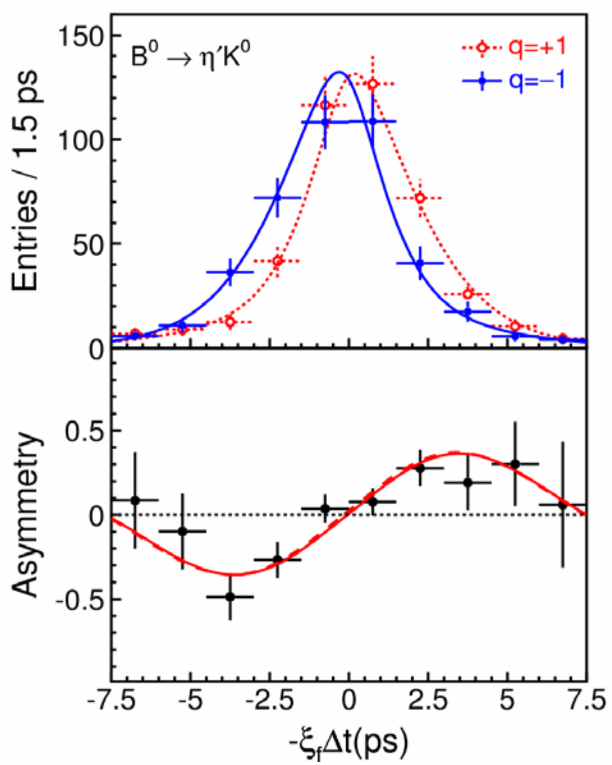
Belle 2006: tCPV in $B^0 \rightarrow \eta' K^0$

535M $B\bar{B}$

New !

$$\text{“}\sin 2\phi_1\text{”} = +0.64 \pm 0.10(\text{stat}) \pm 0.04(\text{syst})$$
$$\mathcal{A} = -0.01 \pm 0.07(\text{stat}) \pm 0.05(\text{syst})$$

Δt distribution and asymmetry



- **First observation** of tCPV (5.6σ) in a single $b \rightarrow s$ mode
- Consistent with the SM
- Consistent with Belle 2005

(Belle 2005: “$\sin 2\phi_1$” = +0.62±0.12±0.04)

- $\eta' K_S$ and $\eta' K_L$ combined
- background subtracted
- good tags
- $\Delta t \rightarrow -\Delta t$ for $\eta' K_L$

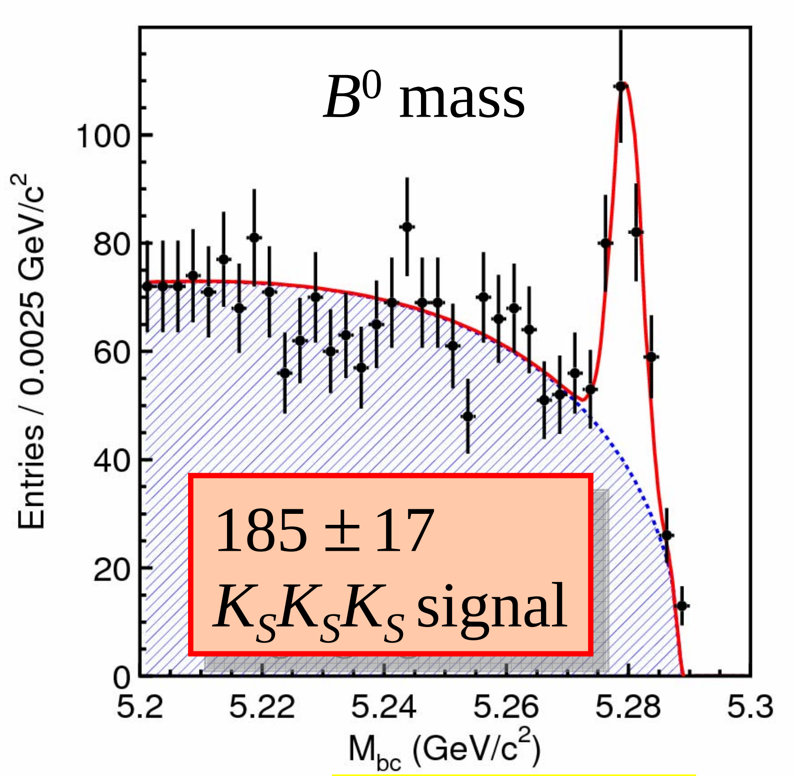
hep-ex/0608039

Belle 2006: t*CPV* in $B^0 \to K_S K_S K_S$

535M $B\bar{B}$

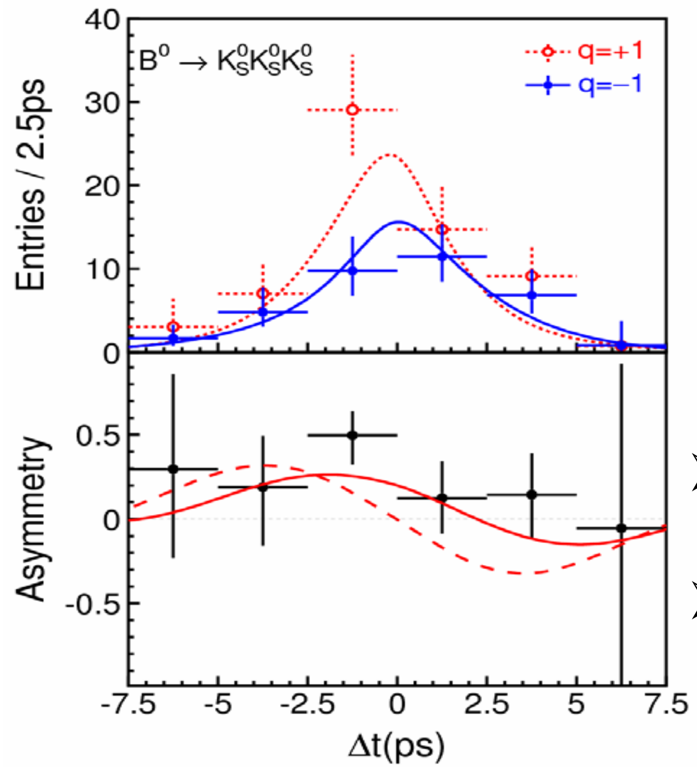
New !

$$\text{"}\sin 2\phi_1\text{"} = +0.30 \pm 0.32(\text{stat}) \pm 0.08(\text{syst})$$
$$\mathcal{A} = +0.31 \pm 0.20(\text{stat}) \pm 0.07(\text{syst})$$



hep-ex/0608039

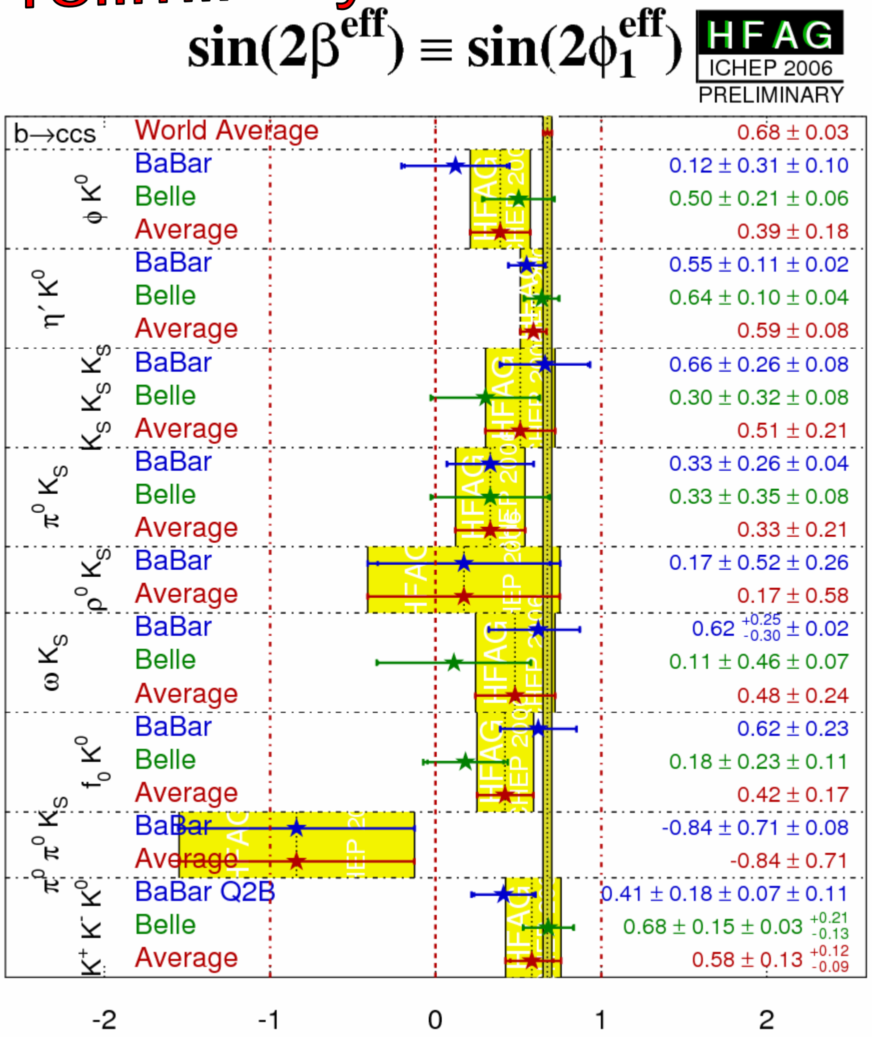
Δt distribution and asymmetry



- background subtracted
- good tags

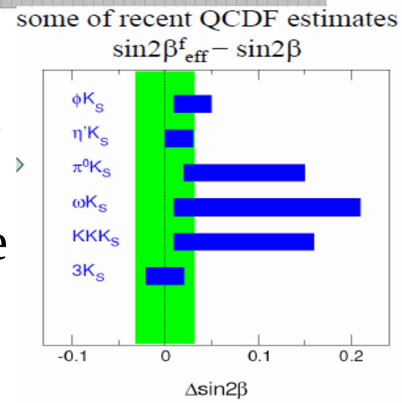
2006: ϕ_1 with $b \rightarrow s$ Penguins

Preliminary



Smaller than $b \rightarrow c\bar{c}s$ in all of 9 modes

Theory tends to predict positive shifts (originating from phase in Vts)



Naïve average of all $b \rightarrow s$ modes

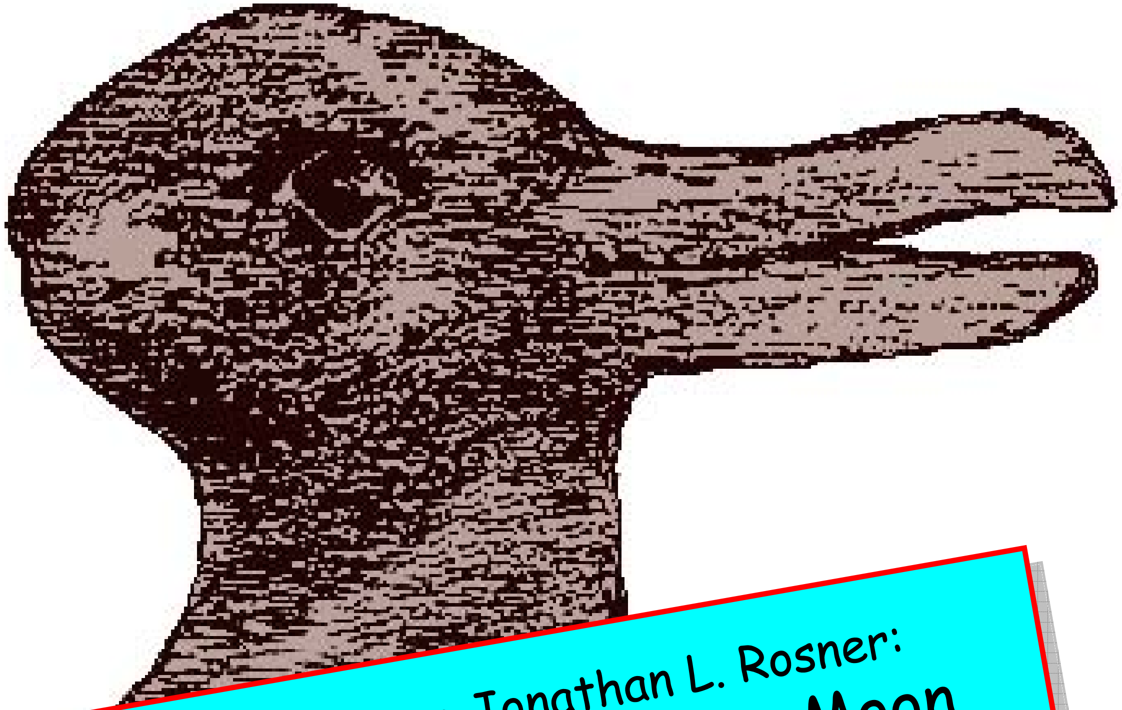
$\sin 2\beta^{eff} = 0.52 \pm 0.05$

2.6 σ deviation between penguin and tree

$(b \rightarrow s)$ $(b \rightarrow c)$

More statistics crucial for mode-by-mode studies

Standard penguin (bird), or something else (rabbit may be) ?



A comment (e-mail) from Jonathan L. Rosner:
If one can see a rabbit in the Moon,
why not in a penguin diagram?

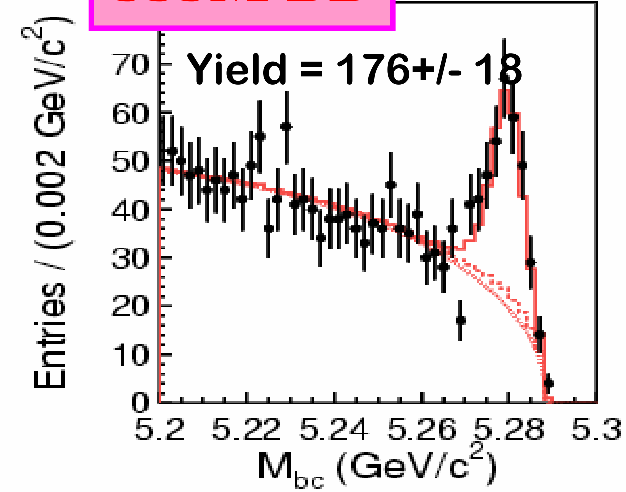
More statistics crucial for mode-by-mode studies

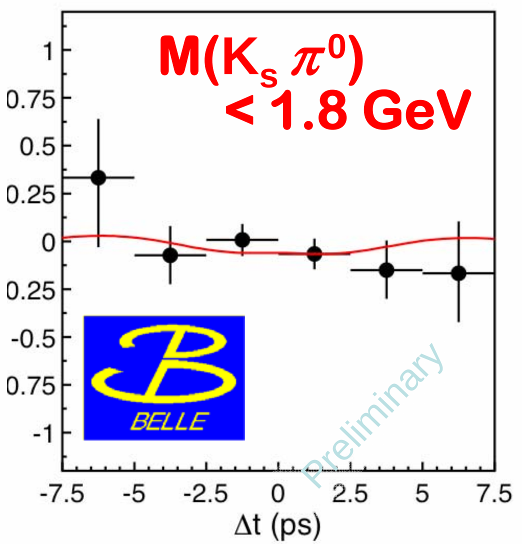
$b \to s$ Penguin : *Radiative*

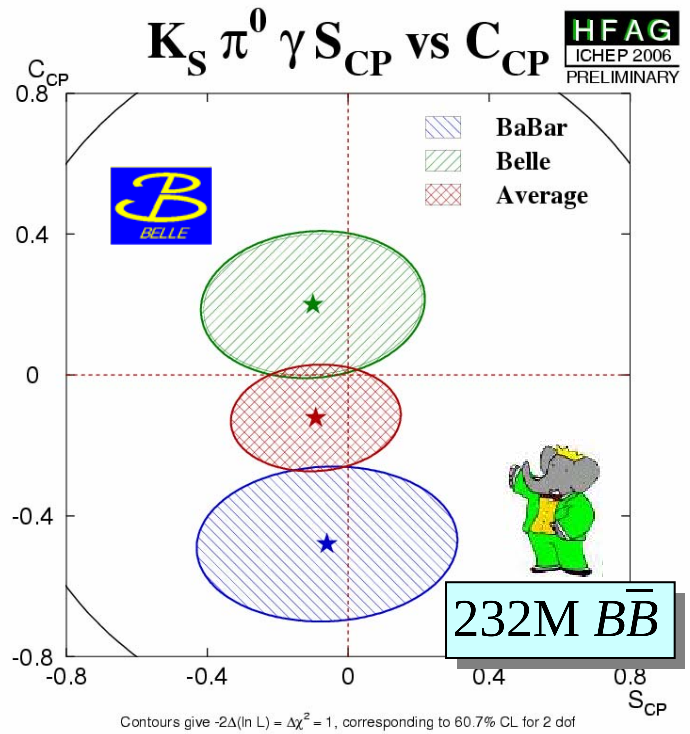
Signals: well established (BF~SM) ⟹ ***New approach for NP***

$B \to K_S \pi^0 \gamma$ tCPV

535M $B\bar{B}$







$$\mathcal{S} = -0.10 \pm 0.31 \pm 0.07$$

$$\mathcal{A} = -0.20 \pm 0.20 \pm 0.06$$

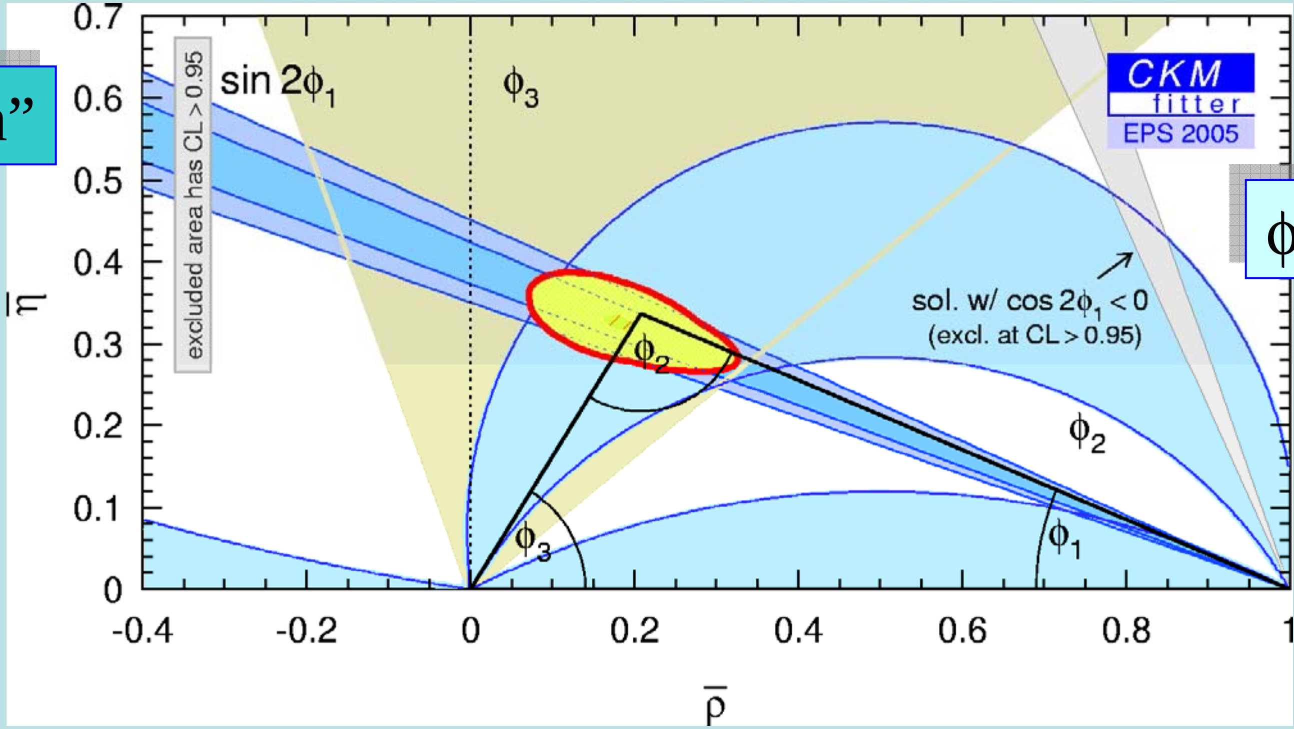
(–C)

New !

hep-ex/0608017

α/ϕ_2

ϕ_1 "beam"



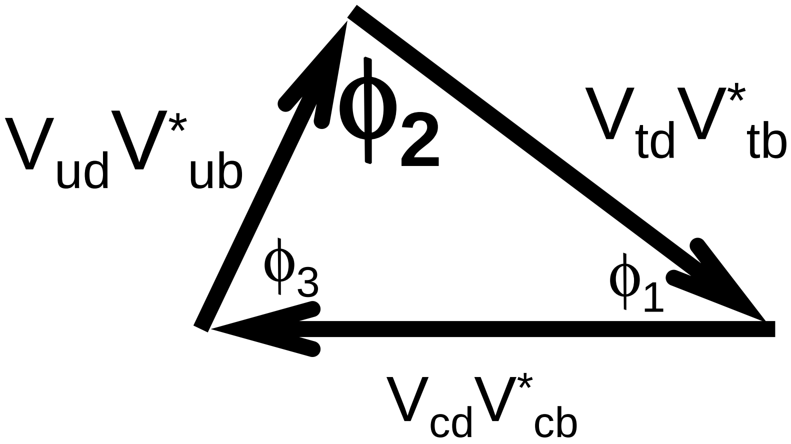
ϕ_2 "banana"

$$B \to \pi^+\pi^-,\ \pi^\pm\pi^0,\ \pi^0\pi^0$$

$$B \to \rho^0\rho^0,\ \rho^\pm\rho^0,\ \rho^+\rho^-$$

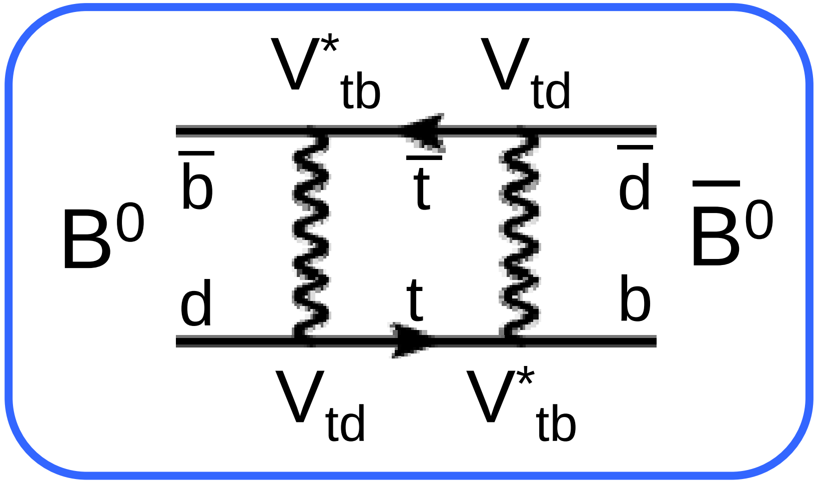
$$B^0 \to (\rho\pi)^0$$

t*CP*V and ϕ_2 (α)

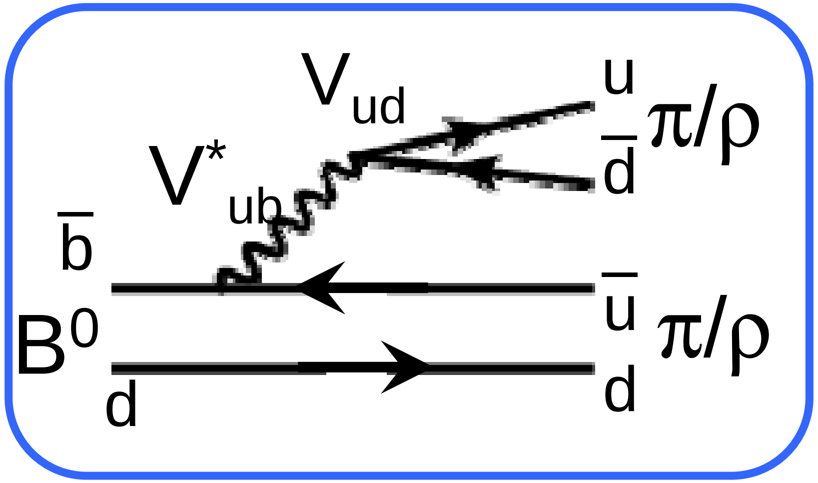


With the tree diagram only

$$\mathcal{S}\pi^+\pi^- = +\sin 2\phi_2$$
$$\mathcal{A}\pi^+\pi^- = 0$$



Mixing diagram



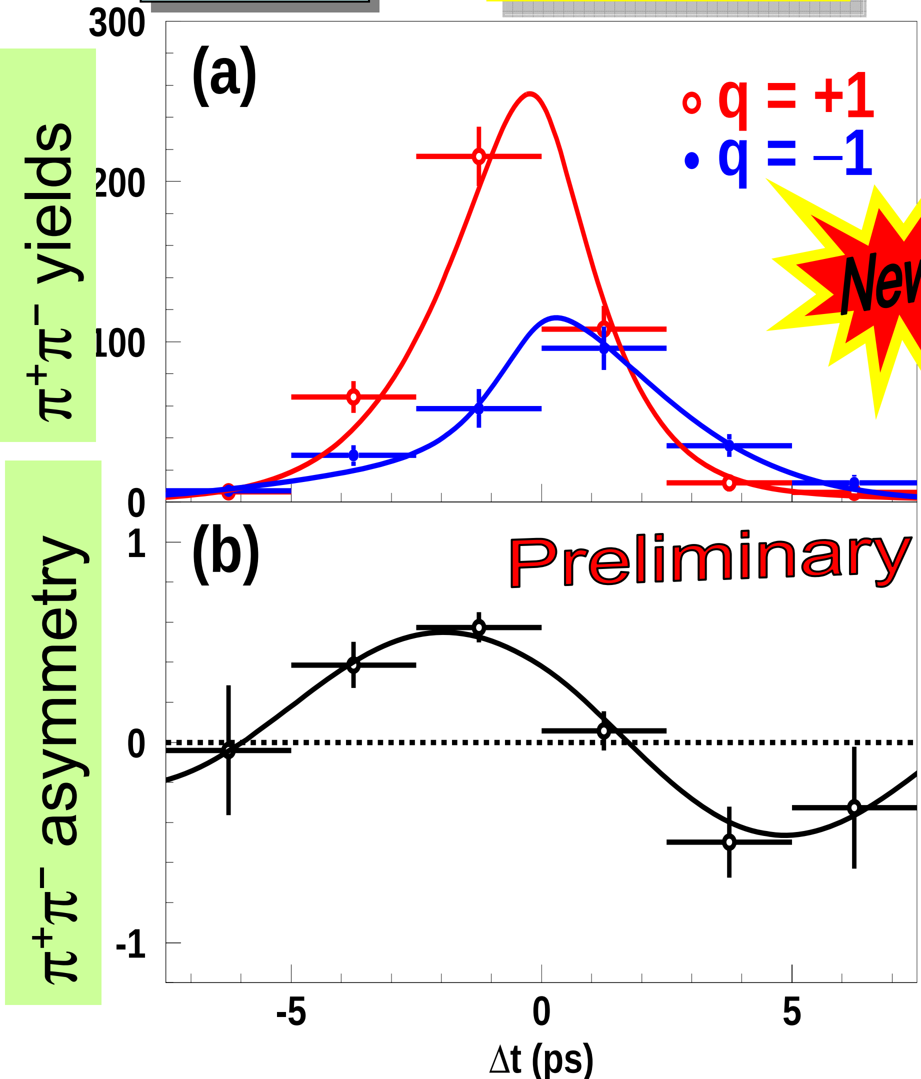
Decay diagram (tree)

3 possibilities: $\pi\pi$, $\rho\rho$, $\rho\pi$

Belle 2006: $B^0 \to \pi^+\pi^-$ decay (CP asymmetry)

535M $B\bar{B}$

hep-ex/0608035



background subtracted

1464±65 signal events

$$A_{\pi\pi} = +0.55 \pm 0.08 \pm 0.05$$

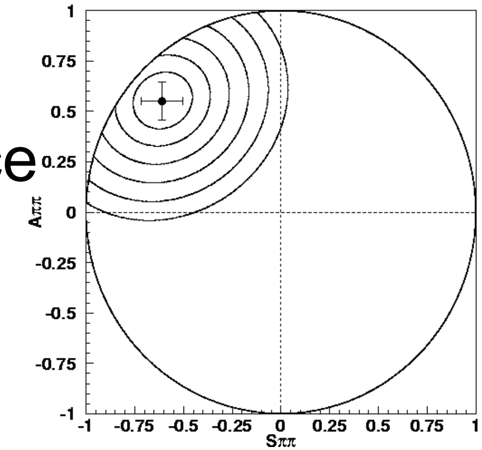
$$S_{\pi\pi} = -0.61 \pm 0.10 \pm 0.04$$

first error: stat., second: syst.

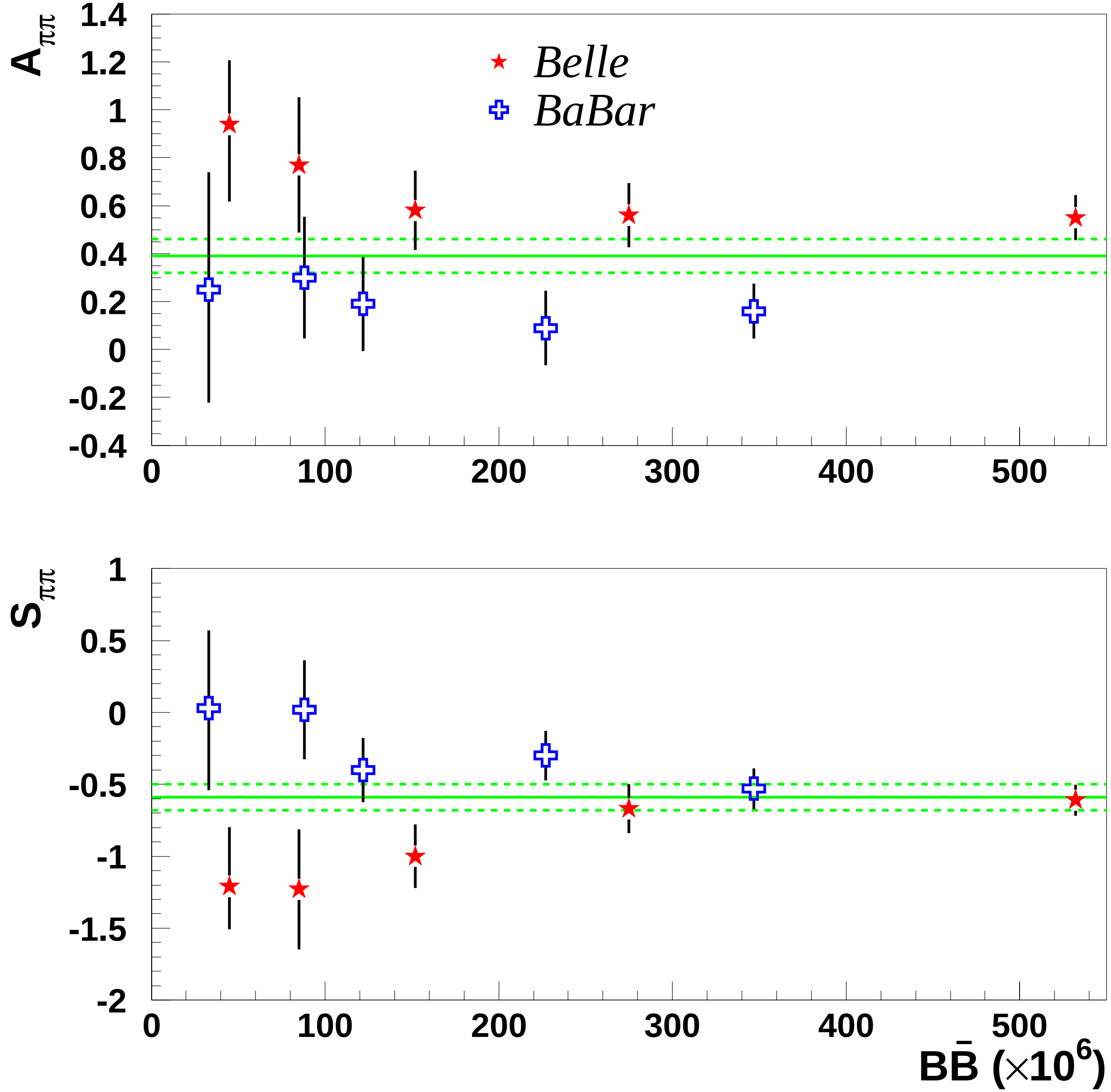
Large Direct CP violation (5.5σ)

Large mixing-induced CP violation (5.6σ)

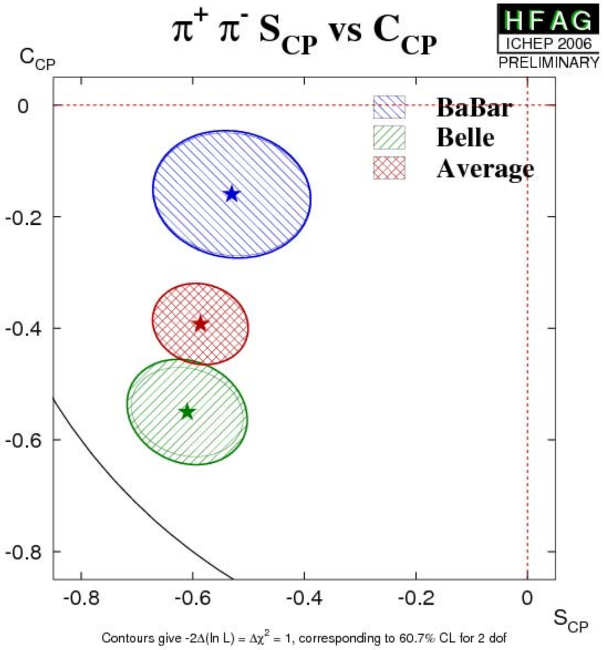
confidence level contour



History of $B^0 \to \pi^+\pi^-$ decay



$(\mathcal{C} = -\mathcal{A})$



2.3σ diff.
btw. Belle
and BaBar

Interpretation: Direct CP violation+SU(3)

The results support the expectation from SU(3) symmetry that

$$A_{CP}(\pi^+\pi^-) \sim -3A_{CP}(K^+\pi^-)$$

N.G. Deshpande and X.-G. He, PRL 75, 1703 (1995)

M. Gronau and J.L. Rosner, PLB 595, 339 (2004)

$$A_{CP}(K^+\pi^-) = -0.093 \pm 0.018 \pm 0.008$$ (Belle 2006: 4.7σ)

⇓

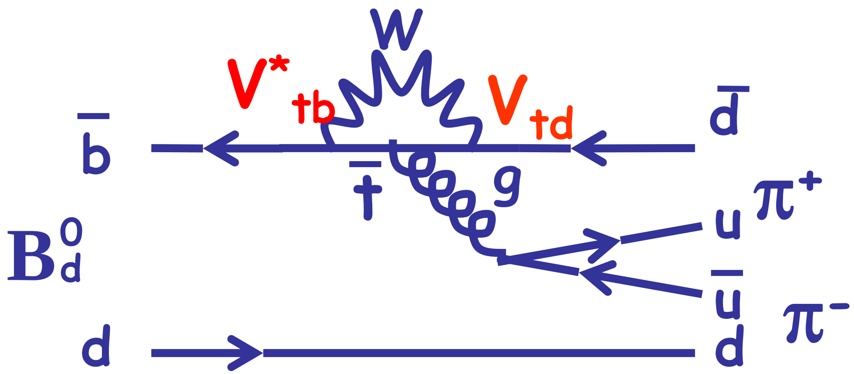
$$A_{CP}(\pi^+\pi^-) \sim +0.3$$

ICHEP2006 World Average

$$A_{CP}(\pi^+\pi^-) = +0.39 \pm 0.07$$

ππ :tough bananas

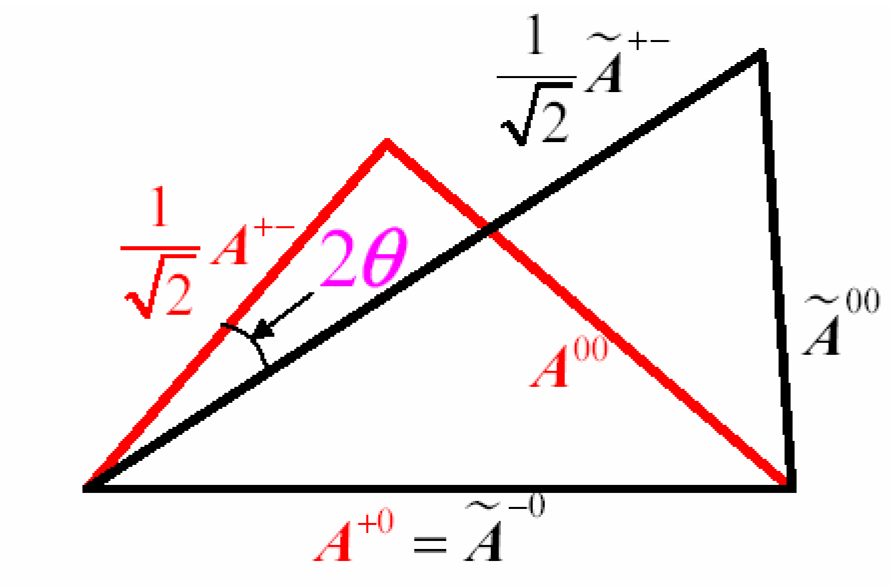
- $\mathcal{A}$ππ world average → observation of large direct *CP*V
- Large penguin diagram (P) ~ Tree diagram (T)
- Large strong phase difference between P and T



$$S_{\pi\pi} = \sqrt{1 - A_{\pi\pi}^2}\,\sin(2\phi_2^{eff}) \qquad \phi_2^{eff} = \phi_2 + \theta$$

Isospin analysis: flavor SU(2) symmetry

[Gronau-London 1990]



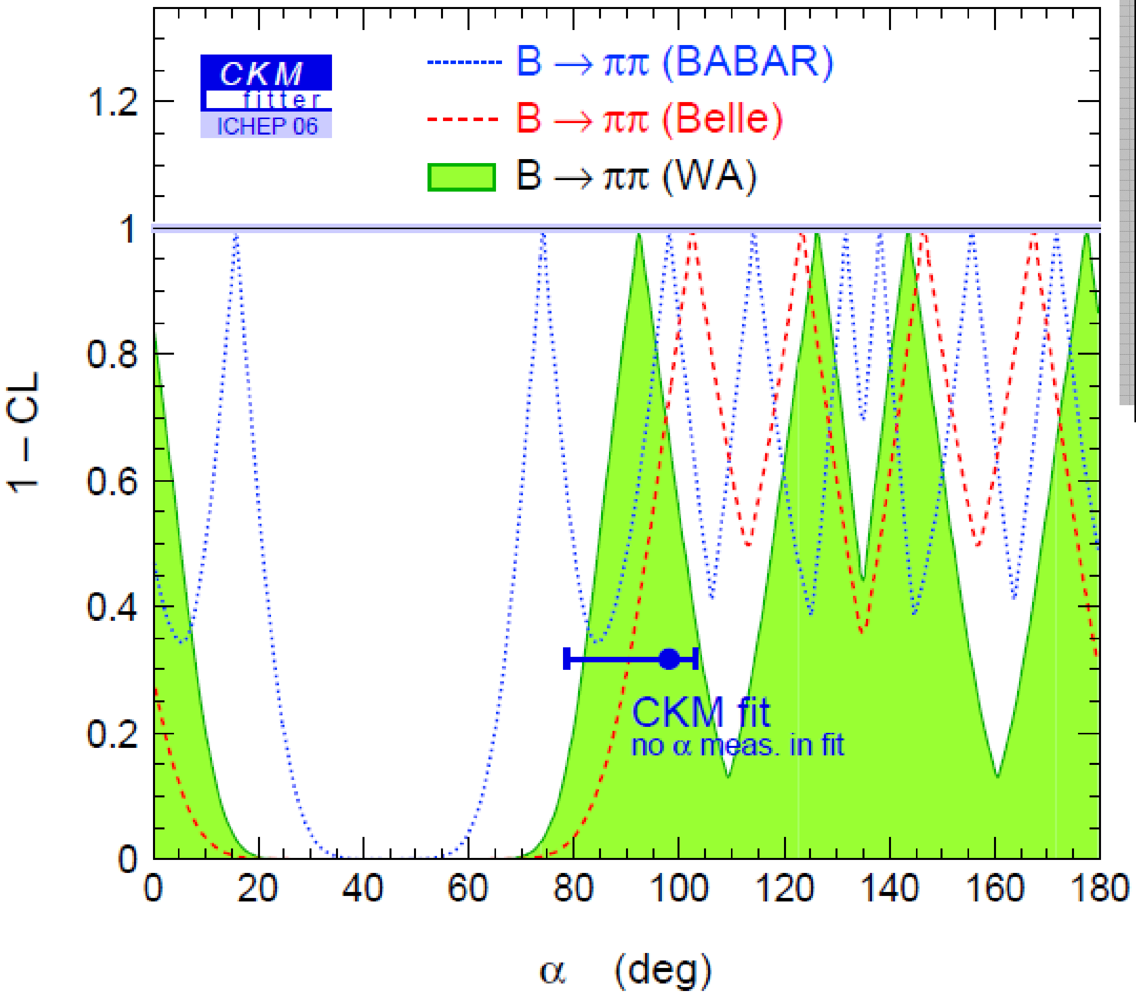
	Amplitude for
$A^{+-}(\overline{A}^{+-})$	$B^0(\overline{B}^0) \to \pi^+\pi^-$
$A^{00}(\overline{A}^{00})$	$B^0(\overline{B}^0) \to \pi^0\pi^0$
$A^{+0}(\overline{A}^{-0})$	$B^+(B^-) \to \pi^+\pi^0(\pi^-\pi^0)$

$$\tilde{A}^{ij} = e^{2\phi_3}\overline{A}^{ij}$$

- Model-independent (symmetry-dependent) method
- SU(2) breaking effect well below present statistical errors

"Penguin pollution" can be removed by isospin analysis

ϕ_2 constraints from $B^0 \to \pi^+\pi^-$ decay



<u>inputs</u>

$\mathcal{B}(\pi^+\pi^0) = (5.75 \pm 0.42)$
$\mathcal{B}(\pi^+\pi^-) = (5.20 \pm 0.25)$ $\times 10^{-6}$
$\mathcal{B}(\pi^0\pi^0) = (1.30 \pm 0.21)$
$\mathcal{A}(\pi^0\pi^0) = +0.35 \pm 0.33$
$\mathcal{S}(\pi^+\pi^-) = -0.59 \pm 0.09$
$\mathcal{A}(\pi^+\pi^-) = +0.39 \pm 0.07$

No stringent constraint obtained
with ππ system alone
→ need ρρ and ρπ

Belle 2006: ϕ_2 from $B \to \rho\pi$

449M $B\bar{B}$

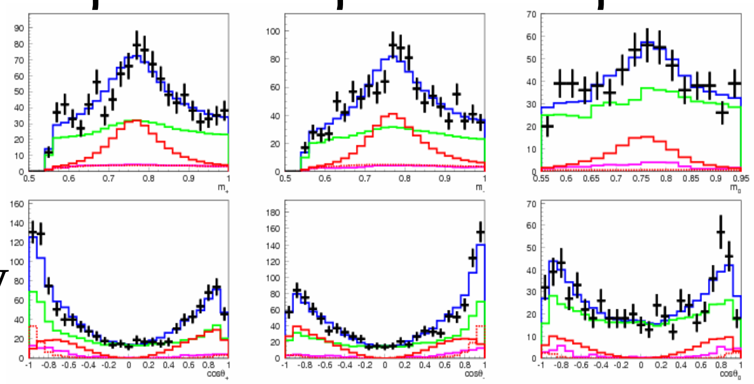
Dalitz analysis + isospin (pentagon) analysis

- 26(Dalitz) + 5(Br($\rho^{\pm}\pi^{\pm}$), Br($\rho^{+}\pi^{0}$), Br($\rho^{0}\pi^{+}$), $\mathcal{A}(\rho^{+}\pi^{0})$, and $\mathcal{A}(\rho^{0}\pi^{+})$)

$\rho^{+}\pi^{-}$ $\rho^{-}\pi^{+}$ $\rho^{0}\pi^{0}$

mass

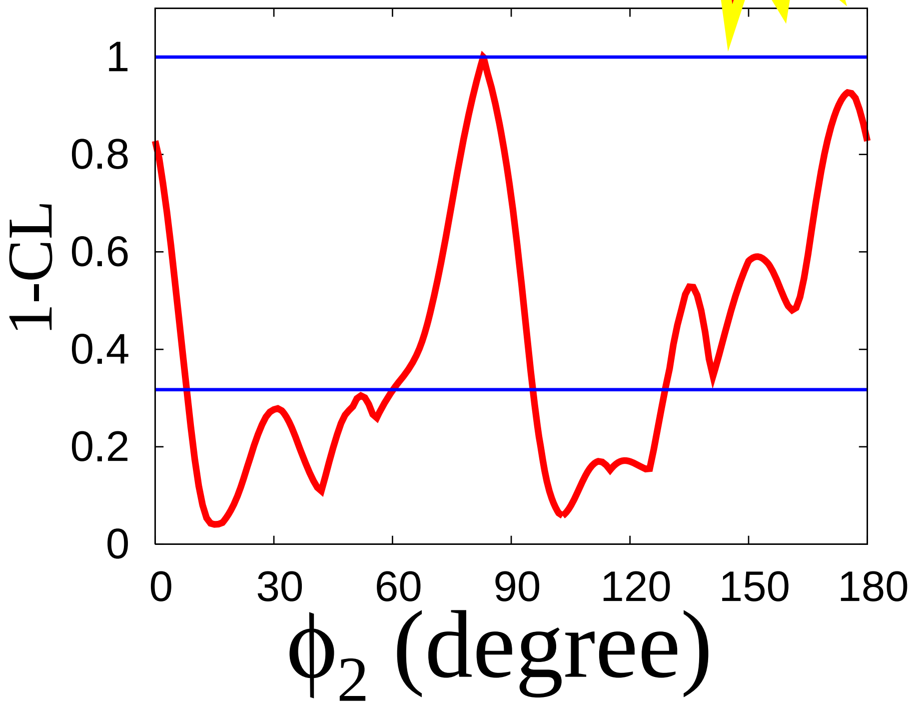
helicity



Preliminary

Results

New !



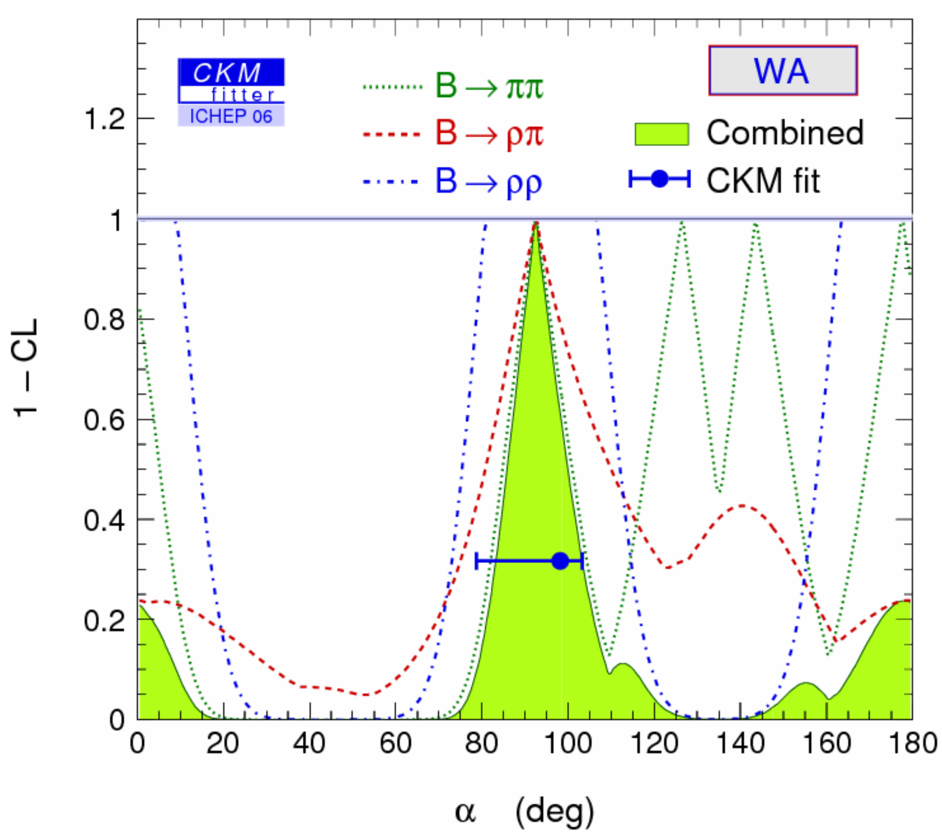
$$\alpha/\phi_2 = [83^{+12}_{-23}]^{\circ}$$ (1σ)

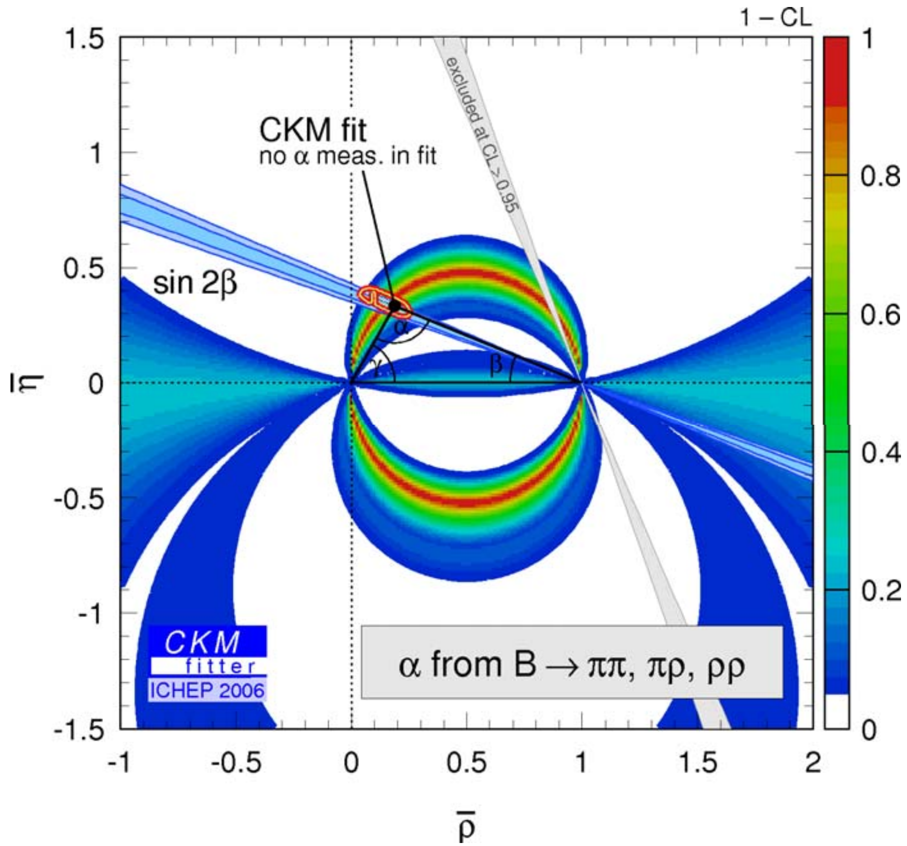
(no constraint at 2σ)

will be included in the world average

hep-ex/0609003

ICHEP2006: BaBar(ππ/ρπ/ρρ) + Belle(ππ/ρρ)



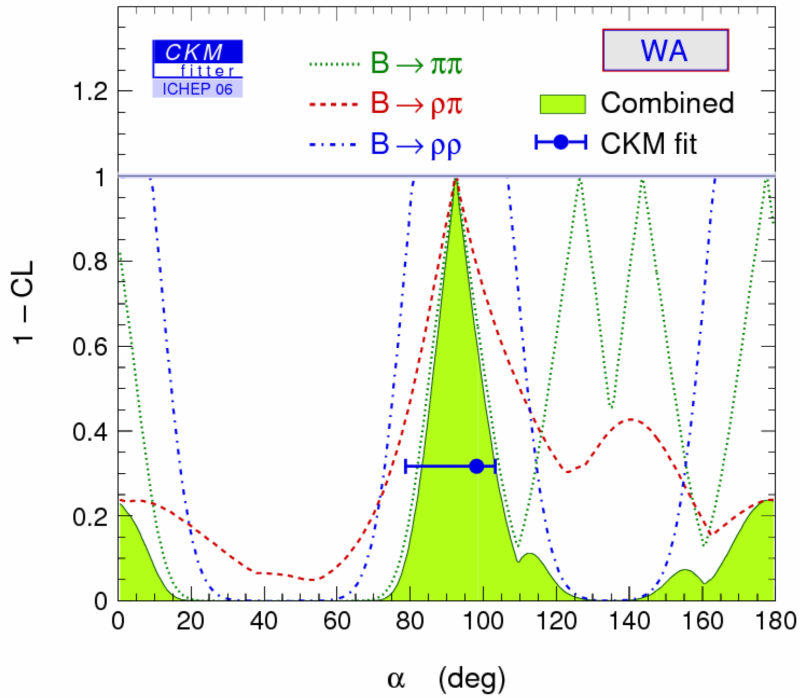


$\alpha/\phi_2 = [93^{+11}_{-9}]^\circ$ consistent with a global fit w/o α/ϕ_2

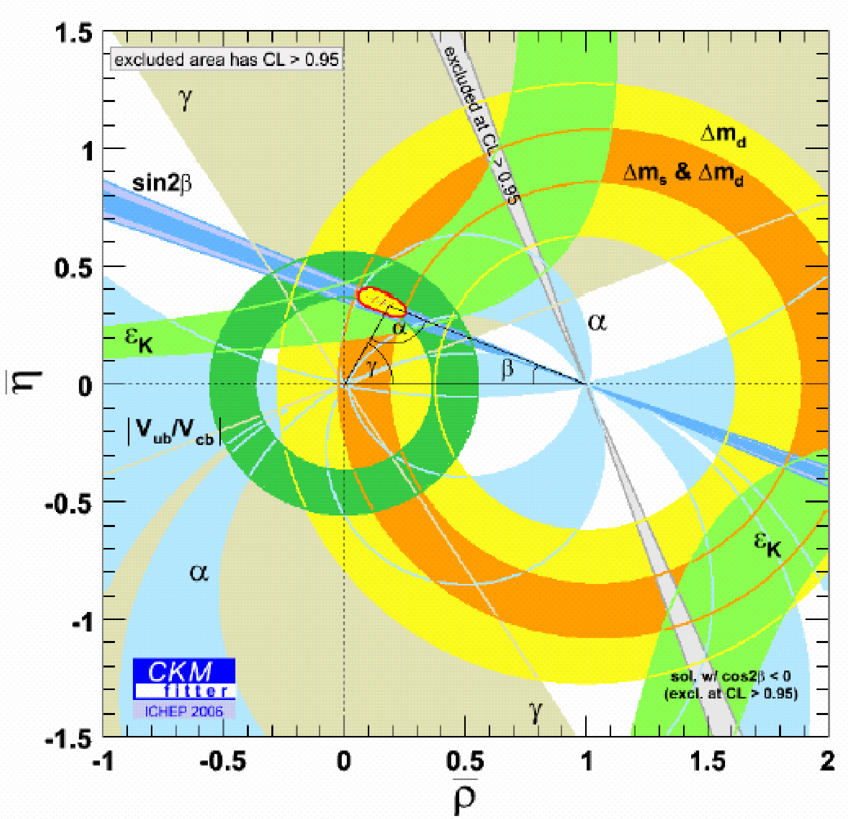
$\alpha_{\text{Global Fit}} = [\,98\,^{+5}_{-19}]\,^{o}$

α/ϕ_2: Discussions

- $\rho\rho$ sets a "window" around 90°
- $\pi\pi$ chooses the correct position inside the window: revival of $\pi\pi$!
- $\rho\pi$ essential to suppress ϕ_2~ 0° or 180°
- Good agreement b/w the CKM fit (α determined by others) and the direct measurements
- Still a lot to do
  - solution around 0 or 180°, which requires |P/T|~1, can/should be much more suppressed
  - subtleties in statistical analyses with small statistics
  - uncertainty in background modeling, unknown phases etc.



CKM Global Fit



Very good overall agreement. O(1) new physics unlikely.
Need to be able to detect O(0.1) effects.

Roughly speaking; O(0.1) $\sim(M_{top}/M_{NP})^2$ or $\sim(M_{top}/M_{NP})$, therefore a reasonable target if TeV new physics exists.

What have we learned ?

- Large CP violation observed → large CPV phase established
  - approximate CP symmetry, which can be consistent with small CPV (e.g. seen in Kaons), is ruled out.

- Only with B factories, we have succeeded to overconstrain the quark flavor sector for the first time in the history.

- The Kobayashi-Maskawa model of CP violation is now a tested theory.

This is a great historic achievement !

What's next ?

Deeper, more fundamental questions !

General Effective Lagrangian and Flavor Symmetries for Quark Flavor Physics

G. Isidori – NP benchmarks in flavour physics *Flavour in the era of the LHC*

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_i, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi_i, A_i, \psi_i; Y) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{\,d}(\phi_i, A_i, \psi_i)$$

- 3 identical fermion families ⇒ huge flavour-degeneracy:
- partial breaking of the flavour group:

$$\mathscr{L}_{\rm Yukawa} = \bar{Q}_L Y_D D_R \phi + \bar{Q}_L Y_U U_R \phi_c + \bar{L}_L Y_L e_R \phi + \text{h.c.}$$

$(\bar{3},1,1)$ $(3,1,\bar{3})$ $(1,1,3)$

convenient to treat the Y
[& any additional source of flavour sym.breaking]
as spurions of

$$U(3)^5 = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R} \times \ldots$$

- MFV with 1 Higgs [or low tanβ] ⇒ no additional spurions
- MFV with multi Higgs ⇒ additional U(1) spurions
- NMFV ⇒ additional SU(3)-breaking spurions
- ⋮ ⋮

General Effective Lagrangian and Flavor Symmetries for Quark Flavor Physics

G. Isidori – NP benchmarks in flavour physics

TeV New physics for EWSB, DM etc.

$$\mathscr{L}_{eff} = \mathscr{L}_{gauge}(A_i, \psi_i) + \mathscr{L}_{Higgs}(\phi_i, A_i, \psi_i; Y) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{\,d}(\phi_i, A_i, \psi_i)$$

→ 3 identical fermion families ⇒ huge flavour-degeneracy:

Big question 2)
Is there flavor symmetry yet to be discovered ?

Big question 1)
What does the flavor structure of TeV new physics look like ? (How does it taste ?)

Subquestions

1-1) Are there new CP-violating phases ?
1-2) Are there new right-handed currents ?
1-3) Are there effects from new Higgs fields ?
1-4) Are there new flavor violation ?

<u>Big question 2)</u>
Is there flavor symmetry yet to be discovered ?

<u>Big question 1)</u>
What does the flavor structure of TeV new physics look like ? (How does it taste ?)

<u>Subquestions</u>
- **1-1) Are there new CP-violating phases ?**
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Big question 1)

What does the flavor structure of TeV new physics look like ? (How does it taste ?)

Subquestions

1-1) Are there new CP-violating phases ?

1-2) Are there new right-handed currents ?

1-3) Are there effects from new Higgs fields ?

1-4) Are there new flavor violation ?

1-1) tCPV in $B^0 \to \phi K^0$, $\eta' K^0$, KsKsKs

1-2) (t)CPV in $b \to s\gamma$

1-3) $B \to \tau\nu$, $\mu\nu$, $\mu\mu$, ee, $D\tau\nu$

1-4) $\tau \to \mu\gamma$

Big question 2)

Is there flavor symmetry yet to be discovered ?

Unitarity triangle with 1% precision

Near Future (till ~2008)

- Room for some surprise if new physics energy scale is still close to the present limit !
  - e.g. 4σ deviation from SM in b → s tCPV
  - At least 1 ab^{-1} from each B factory experiment is a MUST.
- In the LHC era (i.e. 2010's), however, obviously needed is a major upgrade for much higher statistics !

At least one Super *B* factory needed !

Conclusion

- **Time-dependent CP violation measurements were, are, and will be,**

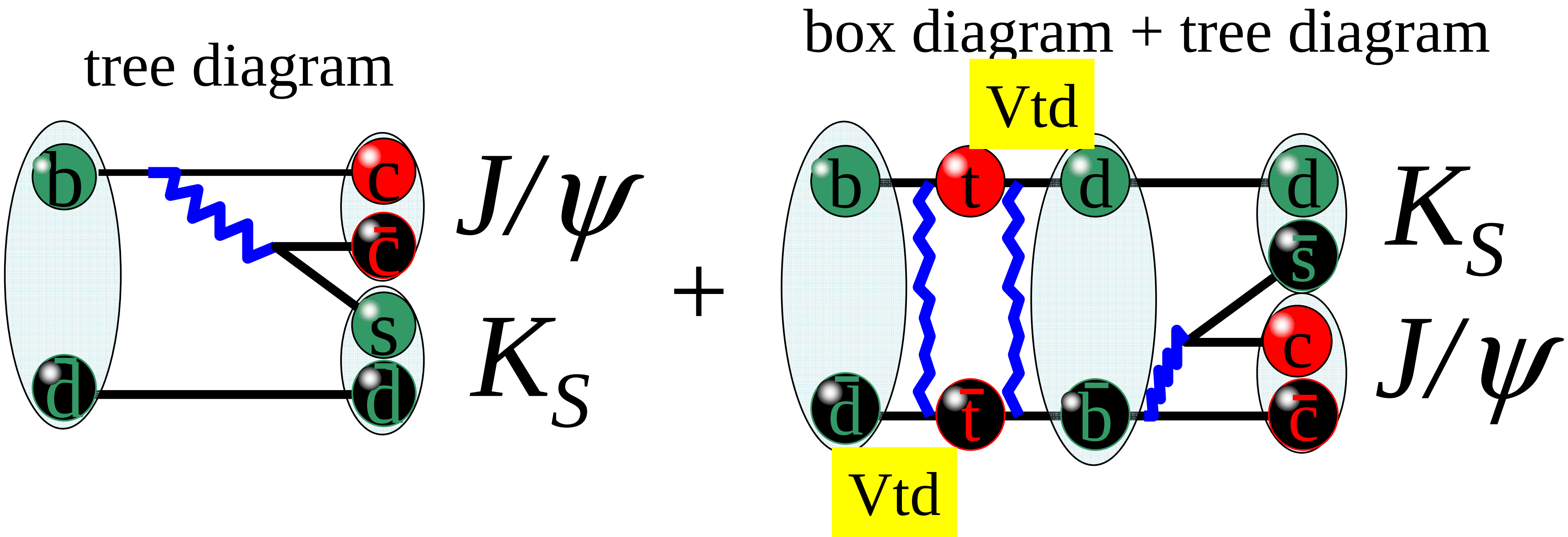
exciting !

Backup Slides

Time-dependent *CP* violation (t*CPV*)

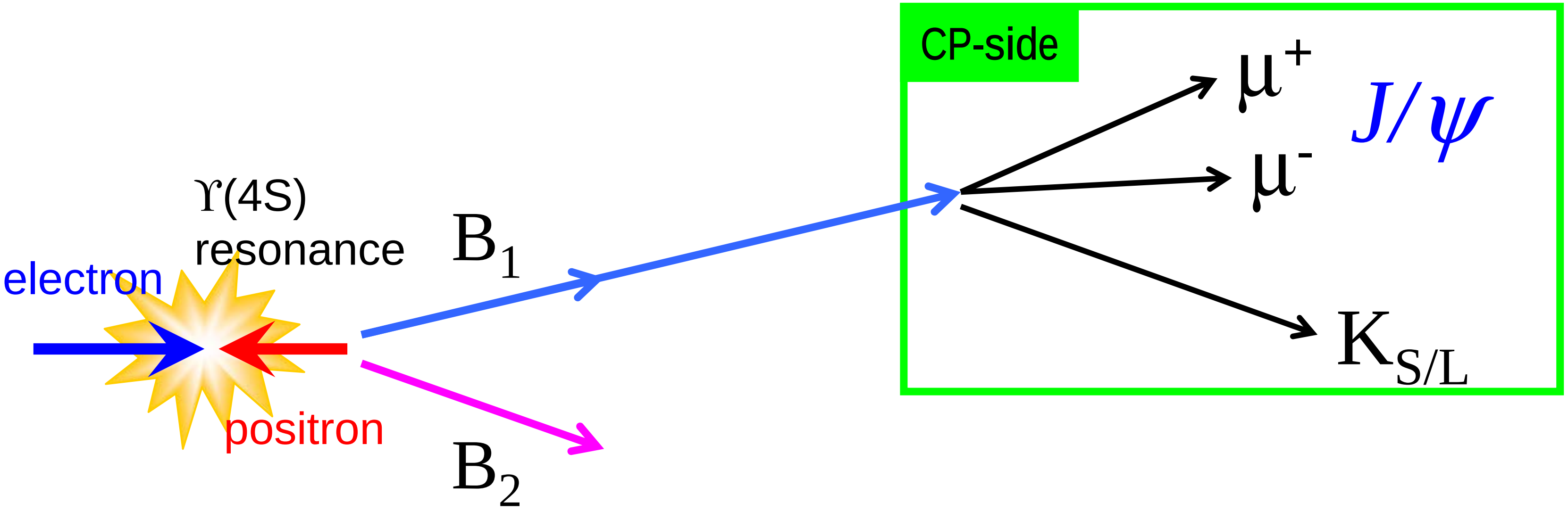
"double-slit experiment" with particles and antiparticles

Quantum interference between two diagrams



You need to "wait" (i.e. Δt≠0) to have the box diagram contribution.

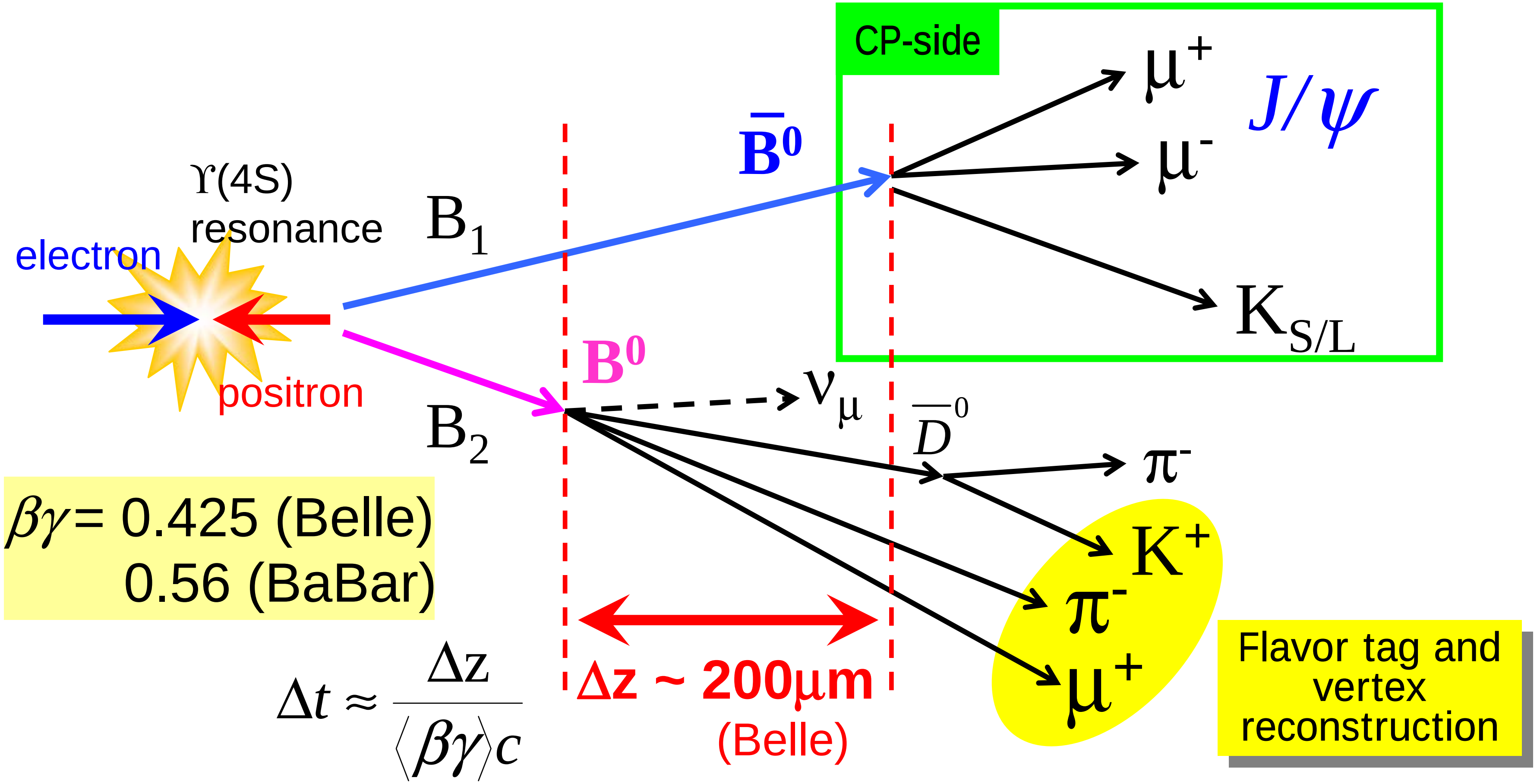
Principle of t*CP*V measurement



$\beta\gamma$= 0.425 (Belle)
0.56 (BaBar)

1. Fully reconstruct one B-meson which decays to CP eigenstate

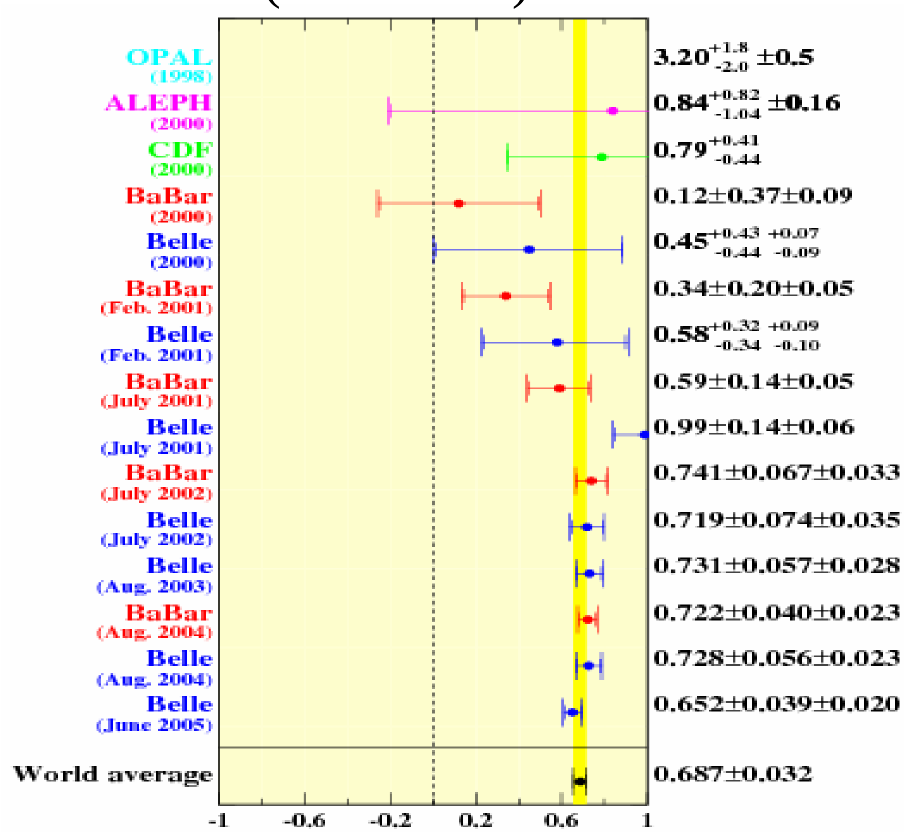
Principle of t*CPV* measurement



1. Fully reconstruct one B-meson which decays to CP eigenstate
2. Tag-side determines its flavor (effective efficiency = 30%)
3. Proper time (Δt) is measured from decay-vertex difference (Δz)

Motivation

sin2β history
(1998-2005)



Q. What is the main source of *CP* violation ?

A. Kobayashi-Maskawa phase IS the dominant source !

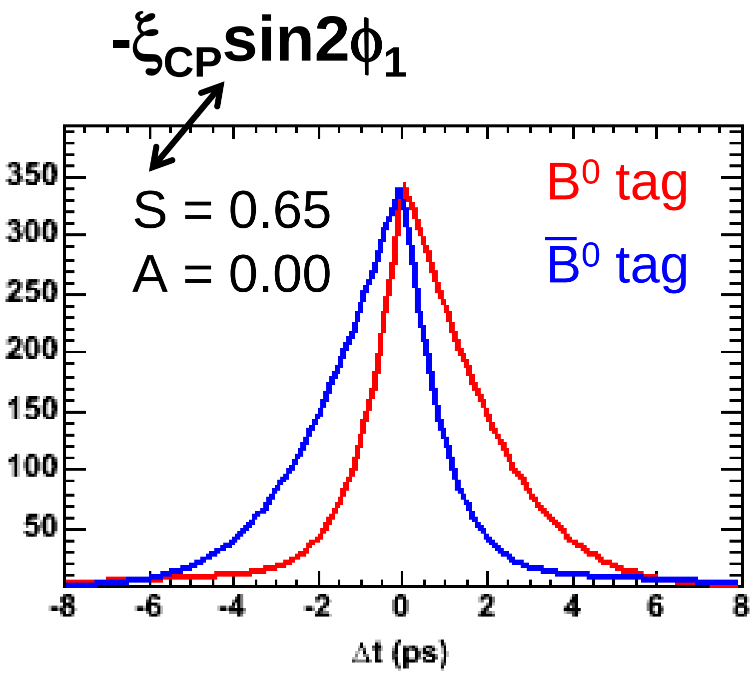
Paradigm shift !

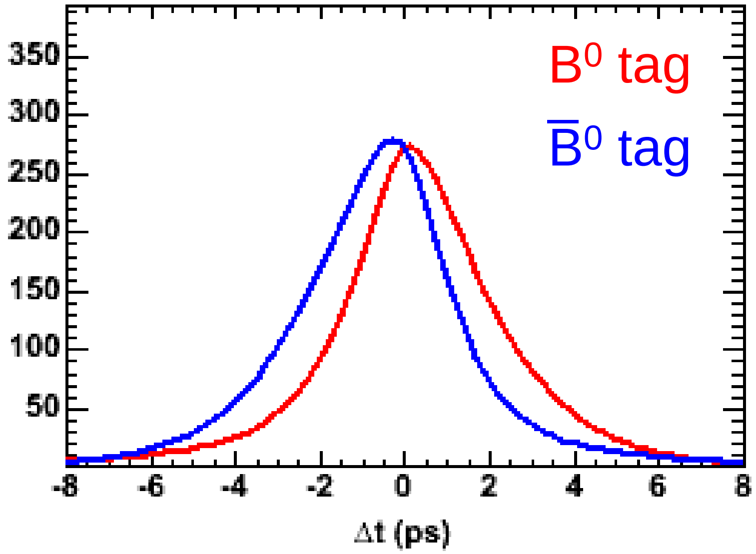
Q. Are there deviations from the CKM picture ? (e.g. new *CP*-violating phases)

<u>Two promising approaches</u>

1) Overconstrain the unitarity triangle: precise measurements of α and β needed

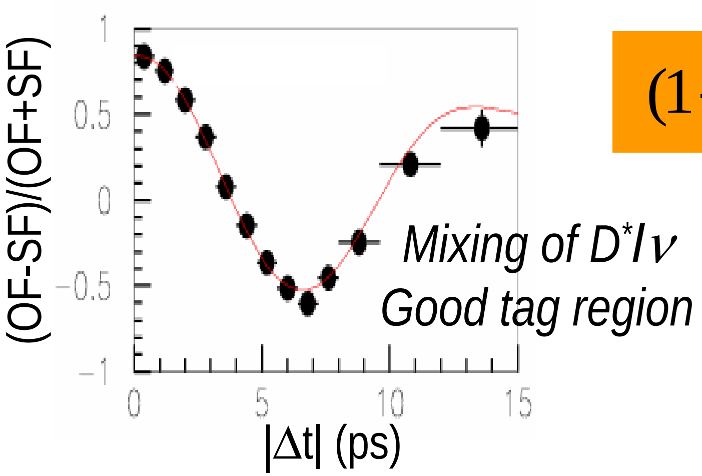
2) Compare sin2β in tree diagram and penguin diagram (e.g. $b \rightarrow s$)





$$P(q=\pm 1,\Delta t)=\frac{1}{4\tau}e^{-\frac{|\Delta t|}{\tau}}\left[1\pm(S\sin\Delta m\Delta t+A\cos\Delta m\Delta t)\right] \otimes R$$

$(1-2w)$



R : detector resolution

w : wrong tag fraction

(misidentification of flavor)

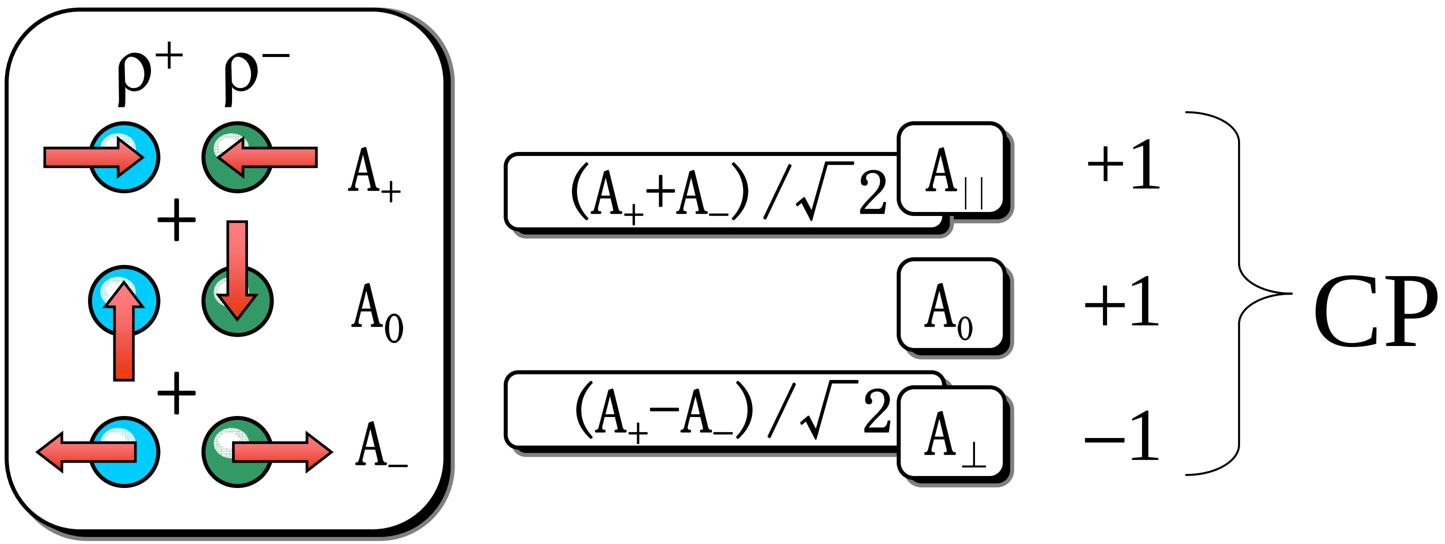
⇔ (1-2w) quality of flavor tagging

They are well determined by using control sample $D^*l\nu$, $D^{(*)}\pi$ etc…

tCPV with $B^0 \to \rho^+\rho^-$?

vector vector

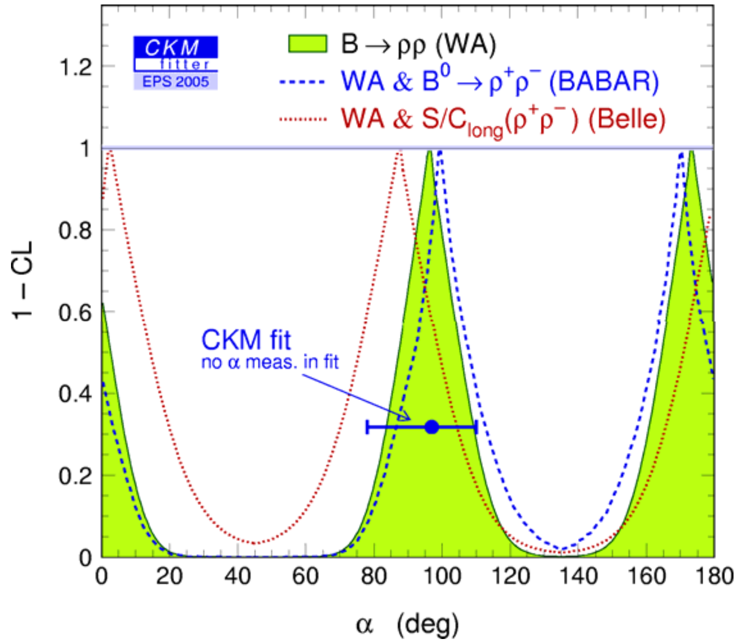
- Even worse on first sight ...
  - Dirty final state: $\rho^+\rho^- \to \pi^+\pi^0\pi^-\pi^0$
  - Mixture of CP = +1 and –1: need to know each fraction



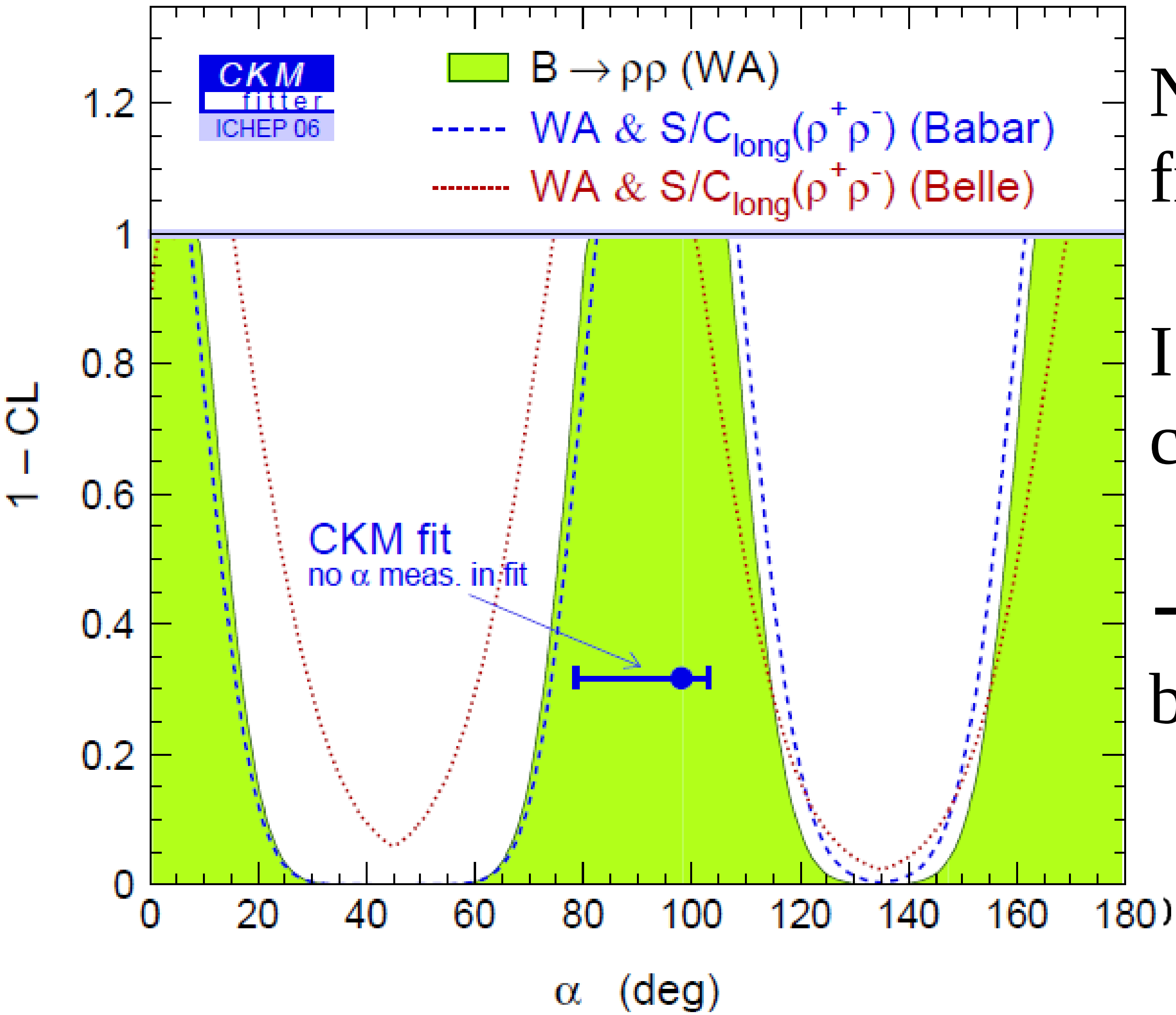
Isospin analysis with $B \to \rho\rho$

- Branching fraction for $B^0 \to \rho^+\rho^-$ is larger than $\pi^+\pi^-$
- Branching fraction for $B^0 \to \rho^0\rho^0$ is small ($<1.1\text{x}10^{-6}$)
  - small penguin pollution
- ~100% longitudinally polarized (~pure *CP*-even state)
  - no need for elaborate angular analysis
- No significant 3-body/4-body contamination
- Dirty final states including π^0
  - OK in the clean e^+e^- environment

the best mode
as of summer 2005



ϕ_2 constraints from $B^0 \to \rho^+\rho^-$ decay



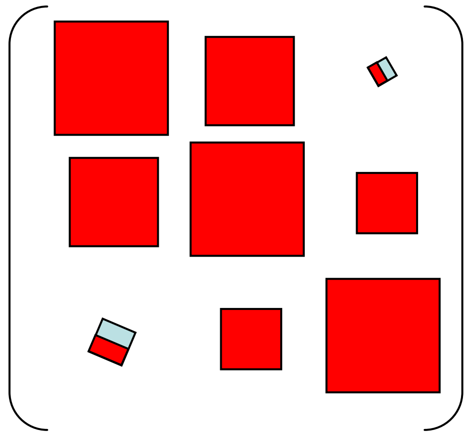
New $\rho^0\rho^0$ branching fraction

Isospin triangle now closed (new $\rho^+\rho^0$)

→ constraint on ϕ_2 becomes less stringent.

CKM Matrix: Enigmatic Hierarchy

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cs} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} =$$



This is correct,
but is very strange !

Flavor symmetry ?

Many proposals, not conclusive at the moment.
(Observed pattern consistent with many models)

- Ex: Q6 (with SUSY)
  - 9 independent parameters to describe 10 observables (6 quark masses + 4 CKM parameters)

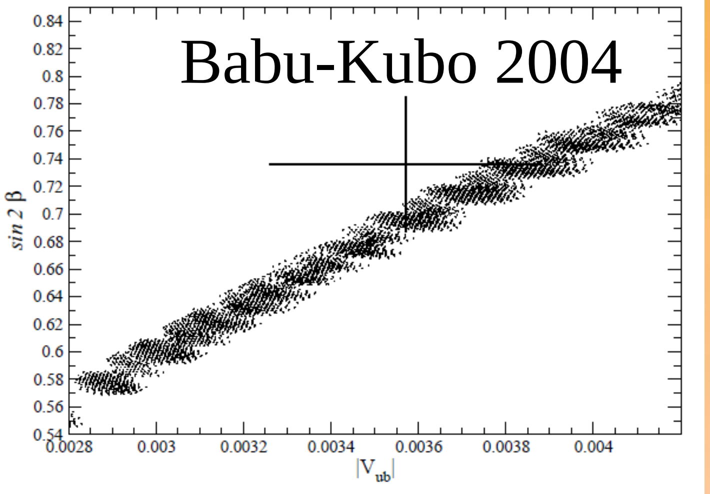


FIG. 2: Predictions in the $|V_{ub}| - \sin 2\beta(\phi_1)$ plane.

1% “spot”

Testable (falsifiable) if sufficient precision obtained !
Precise ϕ_3 measurements may play an essential role to be free from theory uncertainties