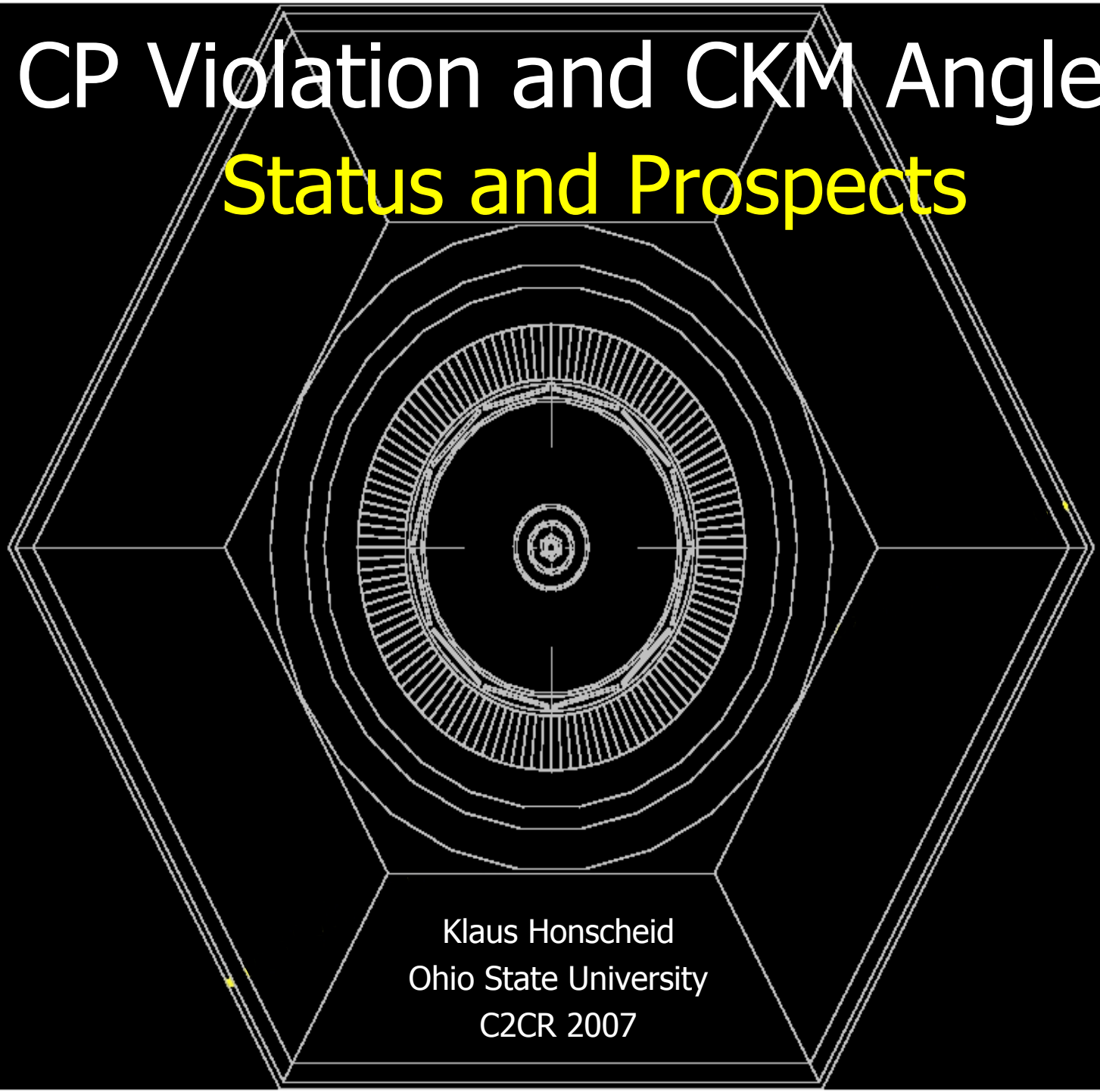
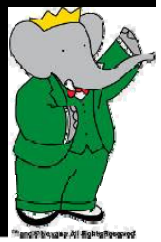
CP Violation and CKM Angles

Status and Prospects



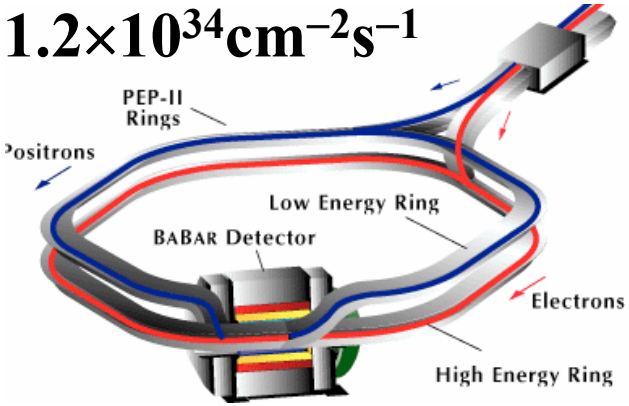
Klaus Honscheid
Ohio State University
C2CR 2007



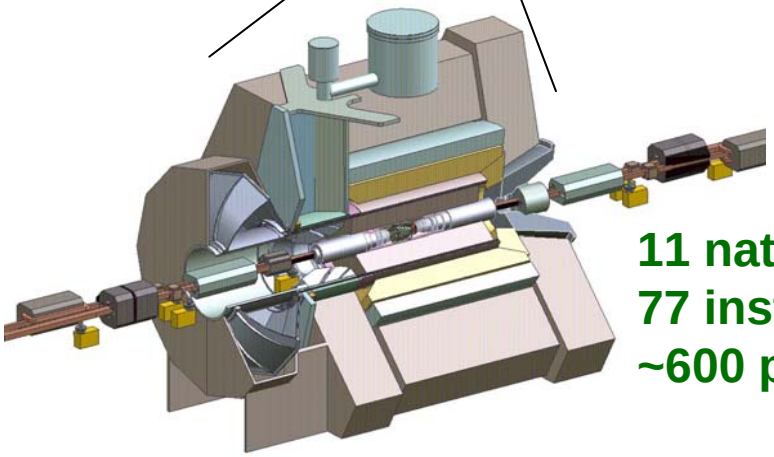
The Two Asymmetric Energy B Factories

PEP-II at SLAC

9 GeV (e^-) × 3.1 GeV (e^+)
peak luminosity:
$1.2\times10^{34}cm^{-2}s^{-1}$

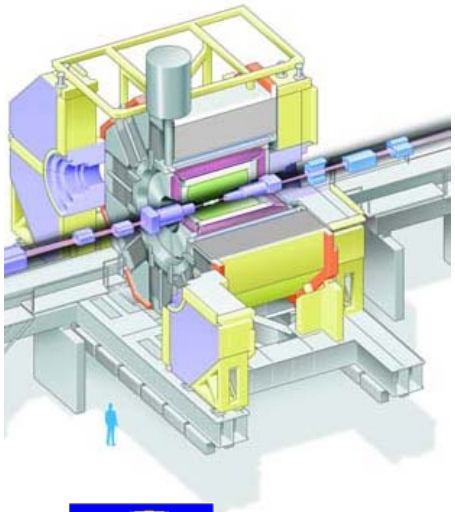


BaBar

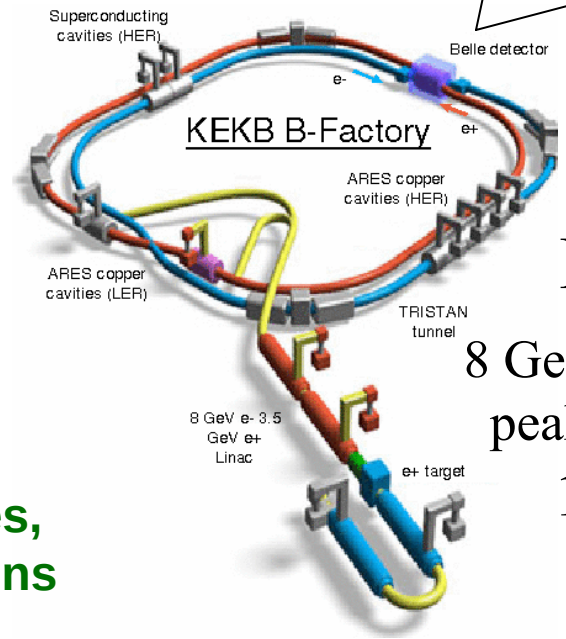


11 nations,
77 institutes,
~600 persons

13 countries,
57 institutes,
~400 collaborators



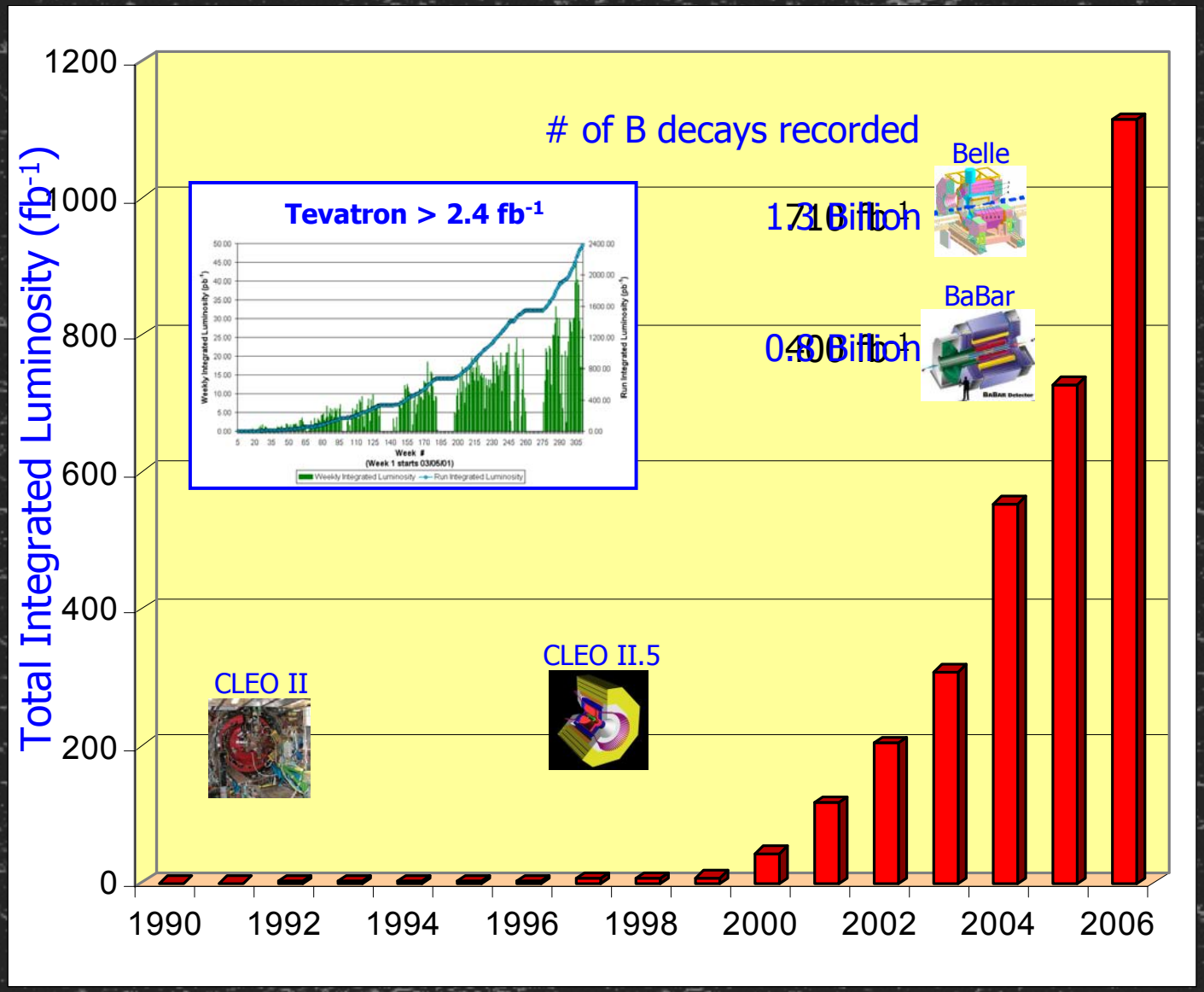
Belle



KEKB at KEK

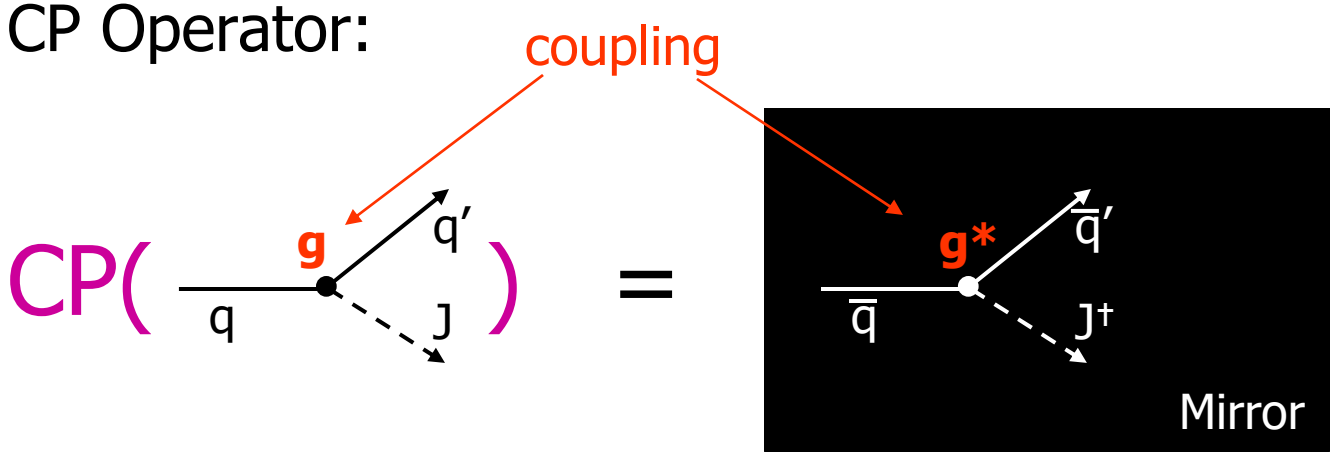
8 GeV (e^-) × 3.5 GeV (e^+)
peak luminosity:
$1.7\times10^{34}cm^{-2}s^{-1}$

Experimental Landscape (early 2007)



CP Violation in the Standard Model

CP Operator:



To incorporate CP violation

$g \neq g^*$

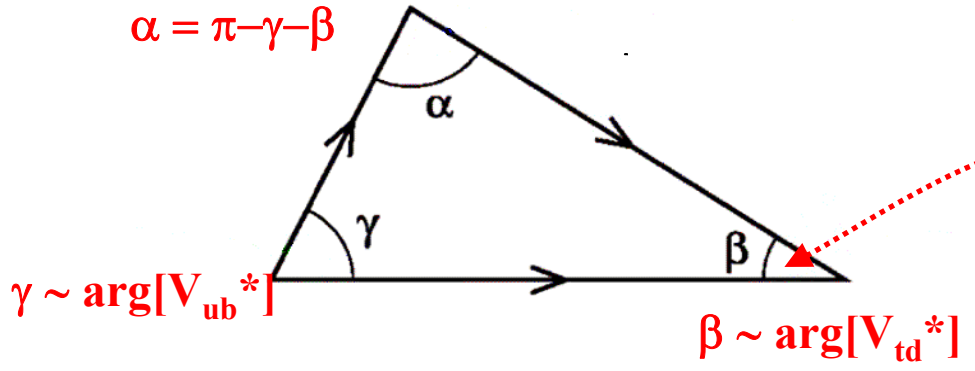
(coupling has to be complex)

CP Violation in the SM: The CKM Matrix

- The CKM matrix V_{ij} is unitary with 4 independent fundamental parameters
- Unitarity constraint from 1st and 3rd columns: $\Sigma_i V^*_{i3} V_{i1} = 0$

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

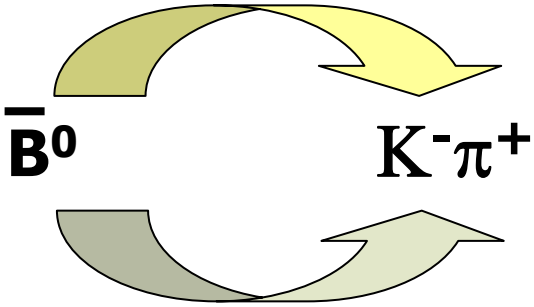
$$\begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \end{array}$$



CKM phases
(in Wolfenstein convention)

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

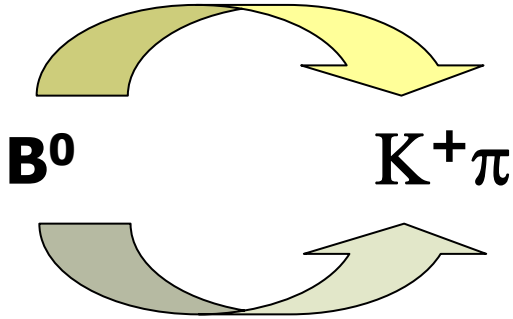
Interfering Amplitudes in $B^0 \to K\pi$ Decays



$$A_1 = a_1\, e^{i\phi_1}\, e^{i\delta_1}$$

$$+$$

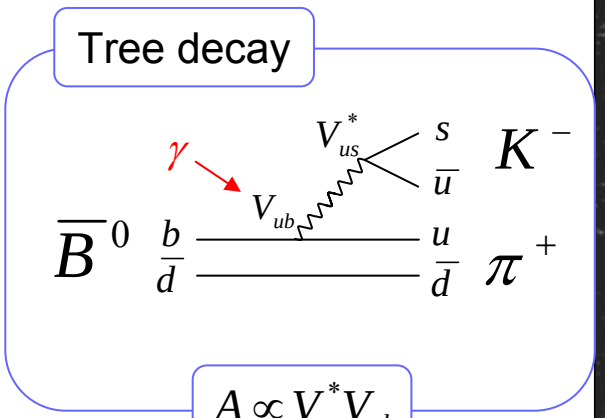
$$A_2 = a_2\, e^{i\phi_2}\, e^{i\delta_2}$$

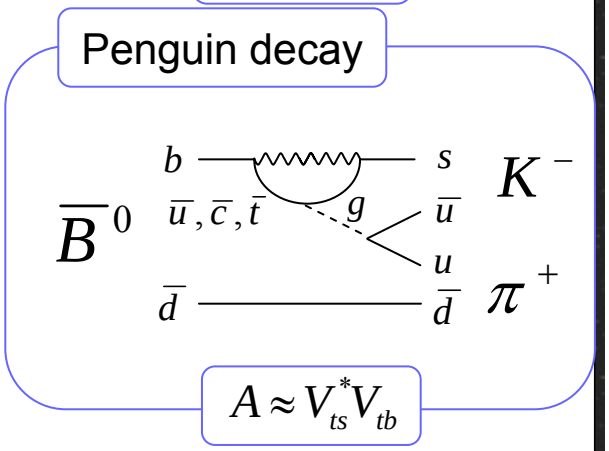


$$\bar{A}_1 = a_1\, e^{-i\phi_1}\, e^{i\delta_1}$$

$$+$$

$$\bar{A}_2 = a_2\, e^{-i\phi_2}\, e^{i\delta_2}$$





Interference $\rightarrow (A_1 + A_2)^2 \neq (\bar{A}_1 + \bar{A}_2)^2$

$$\text{Asymmetry} = \frac{\Gamma(B) - \Gamma(\bar{B})}{\Gamma(B) + \Gamma(\bar{B})} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} \neq 0 \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)$$

CP Violation in $B^0 \to K\pi$ Decays

227 x 10^6 B^0 Mesons

↓

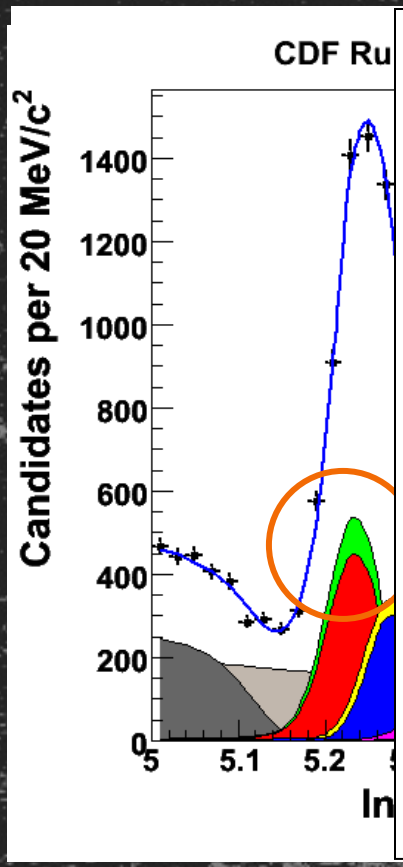
Count $B^0 \to K^+\pi^-$ Decays

227 x 10^6 $\bar{B}^0$ Mesons

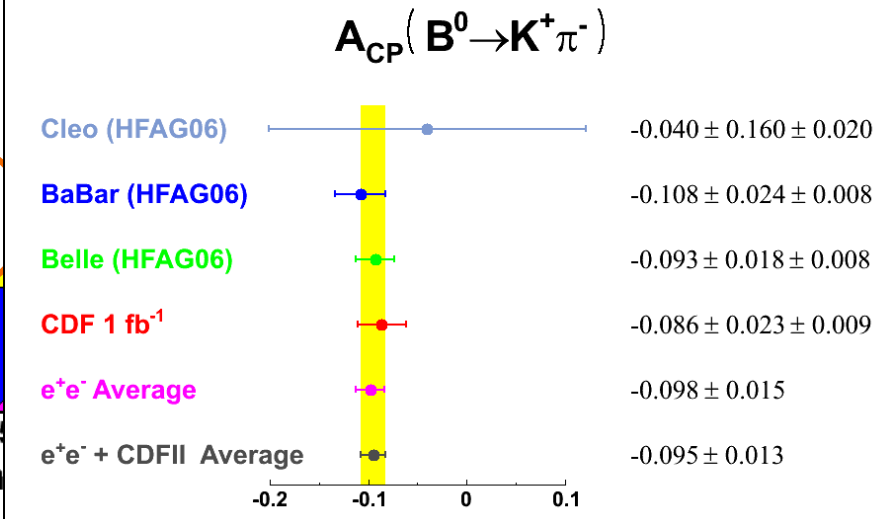
↓

Count $\bar{B}^0 \to K^-\pi^+$ Decays

Is N($B^0 \to K^+\pi^-$) equal to N($\bar{B}^0 \to K^-\pi^+$)?

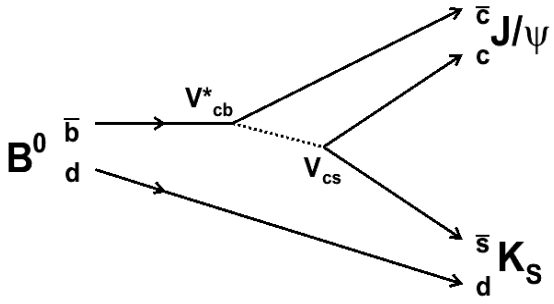


$$A_{CP} = \frac{Br\left(\bar{B} \to \bar{f}\right) - Br\left(B \to f\right)}{Br\left(\bar{B} \to \bar{f}\right) + Br\left(B \to f\right)}$$

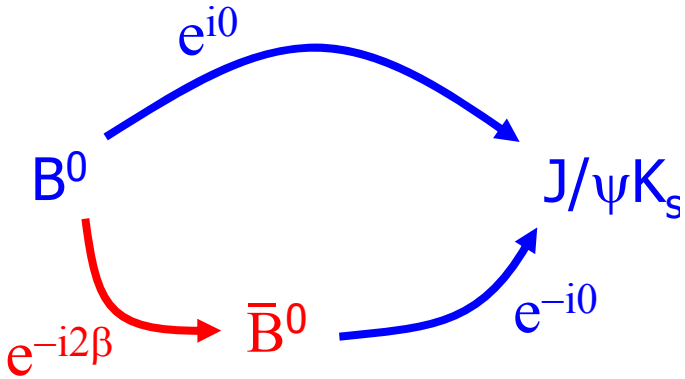


Mixing Induced CP violation

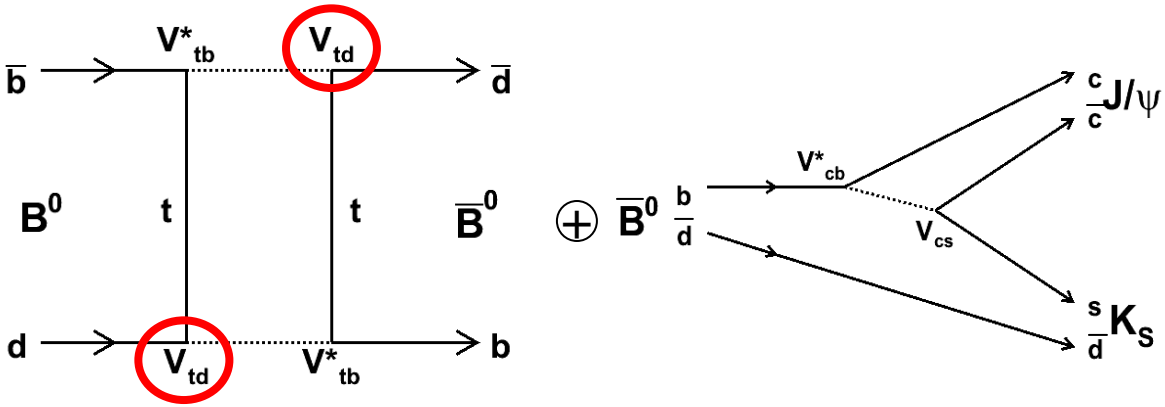
Golden mode $B^0 \to J/\psi K_s$: CP eigenstate, high rate, theoretically clean



No weak phase



Two V_{td} vertices $e^{-i2\beta}$

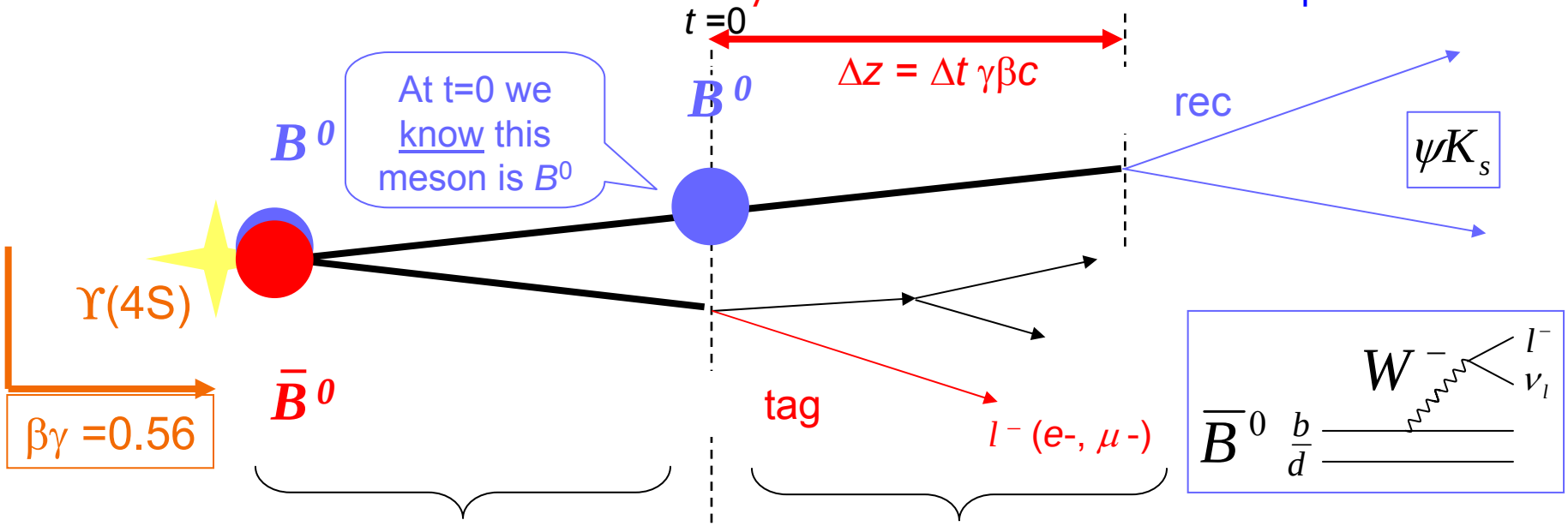


Two Amplitudes ➡ Interference ➡ $A_{CP} \sim \sin 2\beta$

A Complication: Quantum Coherence

We need to know the flavor of the *B* at a reference t=0
and measure the difference in decay time Δt

Flavor Tagging
Time Dependence



The two mesons oscillate coherently : at any given time, if one is a B^0 the other is necessarily a $\bar{B}^0$

In this example, the tag-side meson decays first. It decays semi-leptonically and the charge of the lepton gives the flavour of the tag-side meson : $l^- = \bar{B}^0$ $l^+ = B^0$.

Δt picoseconds later, the B^0 (or perhaps its now a $\bar{B}^0$) decays.

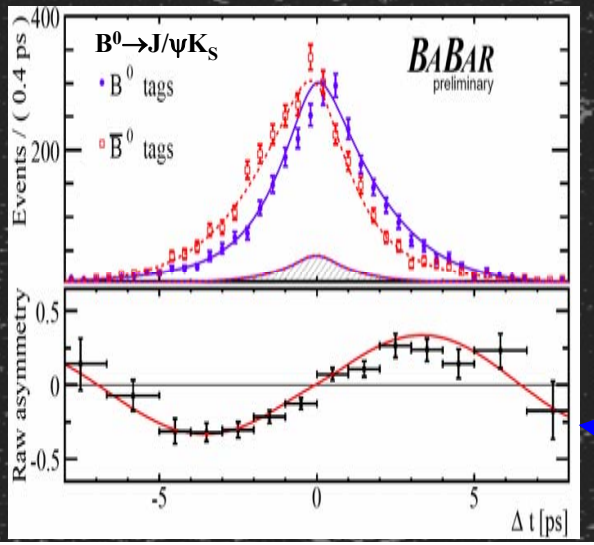
Time dependent asymmetry $A_{CP} = S_{CP}\sin(\Delta m \Delta t) - C_{CP}\cos(\Delta m \Delta t)$

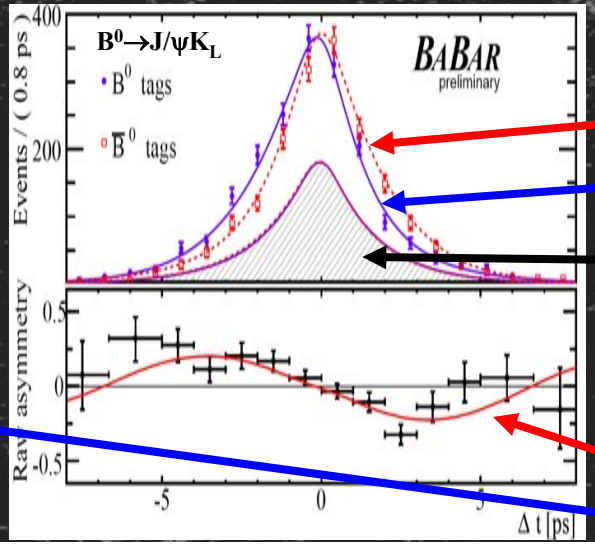
$S_{CP} = -f_{CP} \sin 2\beta$ ($f_{CP} = \pm 1$), C_{CP} "direct" CP violation = 0 for $J/\psi K$

CP Violation in $B^0 \to J/\psi K_s$

PRL 98, 031802 (2007)

BaBar preliminary, hep-ex/0607107
Belle preliminary, hep-ex/0608039





Δt for $\bar{B}^0$ tag ≈ $B^0 \to J/\psi K$

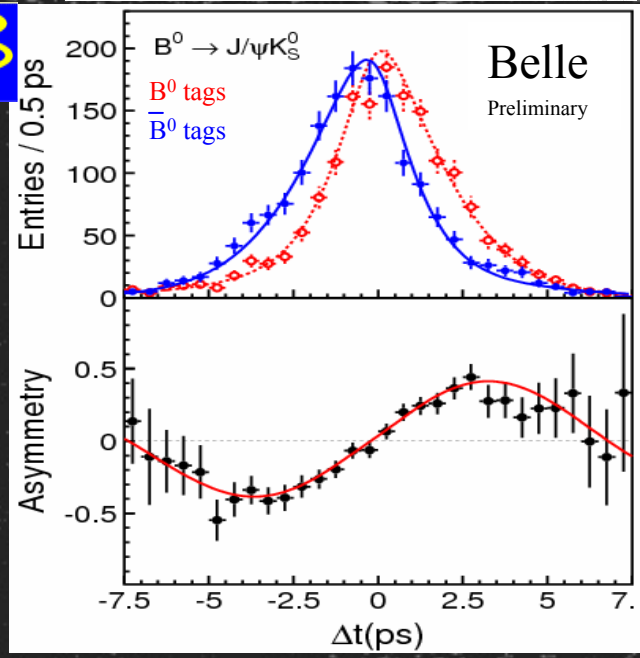
Δt for B^0 tag ≈ $\bar{B}^0 \to J/\psi K$

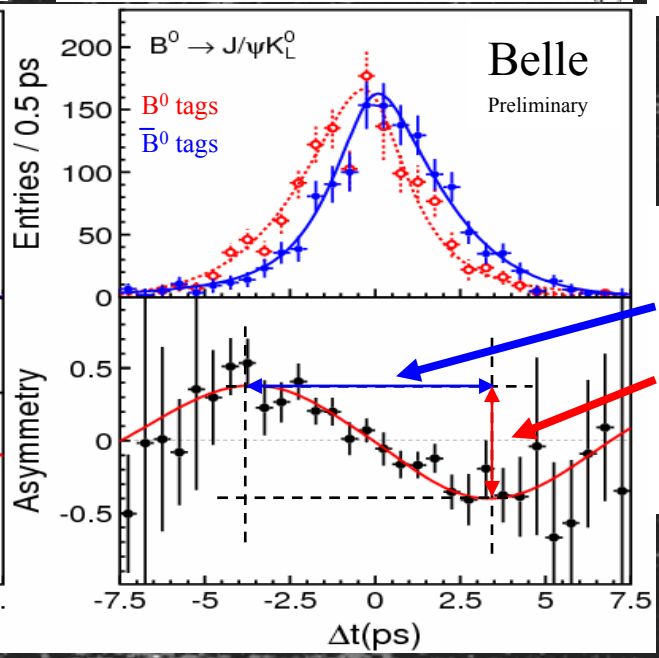
Background

Δt asymmetry

$J/\psi K_L$ is $f_{CP} = +1$

$J/\psi K_S$ is $f_{CP} = -1$





Δt oscillation

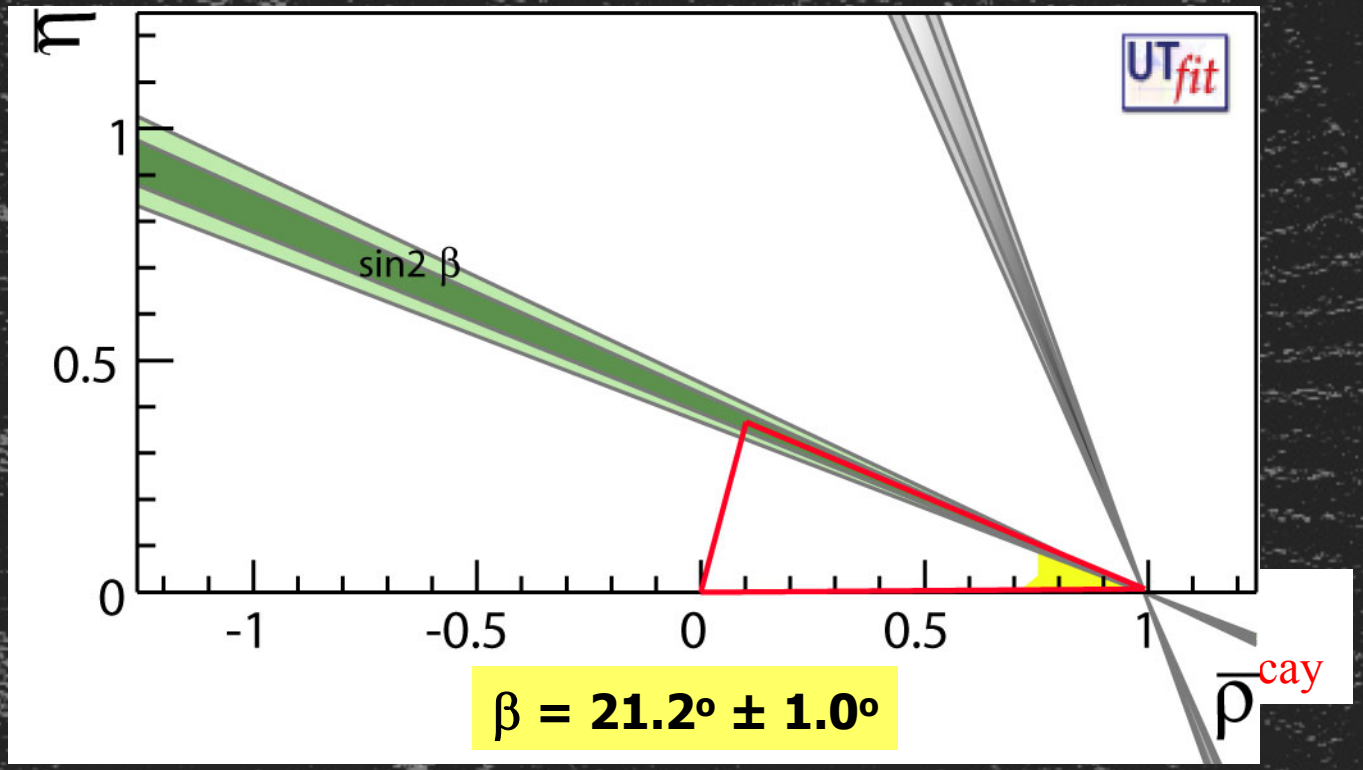
Period = B mixing Δm

Amplitude = D sin2β

(Dilution D due to mistags; measured experimentally)

Sin(2β) World Average

Heavy Flavors Averaging Group
E.Barberio et al., hep-ex/0603003

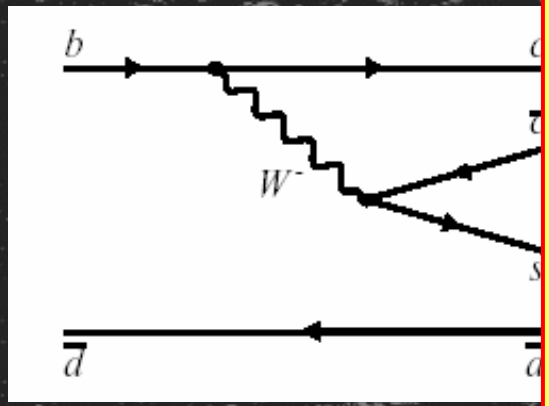


Extracting β from sin2β has ambiguities;
removed by $J/\psi K^*$, $D^*D^*K_S$ and $D\pi^0/\eta/\eta'/\omega$ analyses

Is "β" Universal?

Can use 3 differ

a) $b \to c\bar{c}s$ (charmonium)



$J/\psi K_S^0$ golden mod

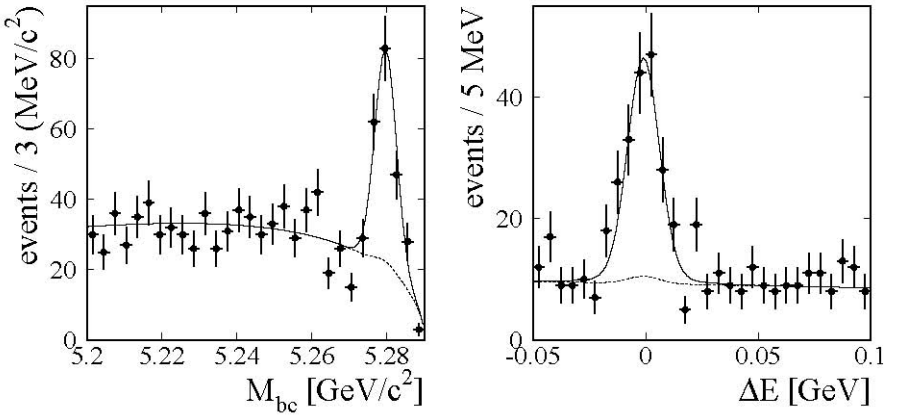
$\psi(2S)K_S^0, \chi_{c1}K_S^0, \eta_c K$

$J/\psi K_L^0$

$J/\psi K^{*0}(K^{*0} \to K_S^0 \pi^0$

News Flash

hep/ex 0702031



B→D⁺D⁻

S = -1.12 ± 0.37 ± 0.09

A = 0.91 ± 0.23 ± 0.06 (= -C)

(expected to be close to 0)

nated

$\bar{s}$ η' s $\bar{s}$ K^0 d

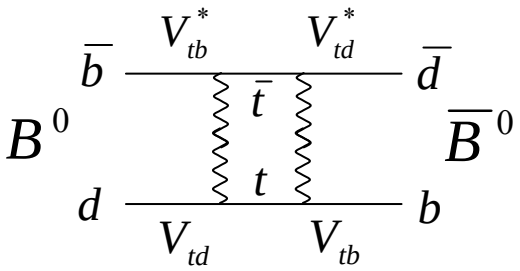
ion from
P): new
the loop

g talk
der

Let's try this for the next angle: α

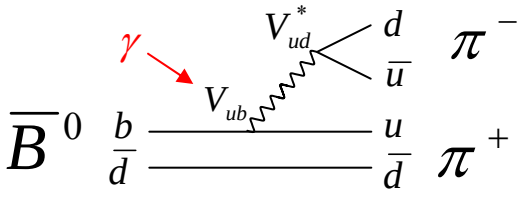
- Access to α from the interference of a $b \to u$ decay (γ) with $B^0\bar{B}^0$ mixing (β)

$B^0\bar{B}^0$ mixing



$q/p \propto V_{tb}^* V_{td} / V_{tb} V_{td}^*$

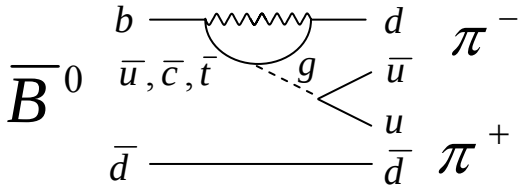
Tree decay



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

⊕

Penguin decay



$A \approx V_{td}^* V_{tb}$

$$\lambda = \frac{q}{p}\frac{\bar{A}}{A} = e^{-i2\beta} e^{-i2\gamma} = e^{i2\alpha}$$

$$S = \sin(2\alpha)$$

$$C = 0$$

$$\lambda = e^{i2\alpha} \frac{T + P e^{+i\gamma} e^{i\delta}}{T + P e^{-i\gamma} e^{i\delta}}$$

$$S = \sqrt{1 - C^2}\, \sin(2\alpha_{eff})$$

$$C \propto \sin\delta$$

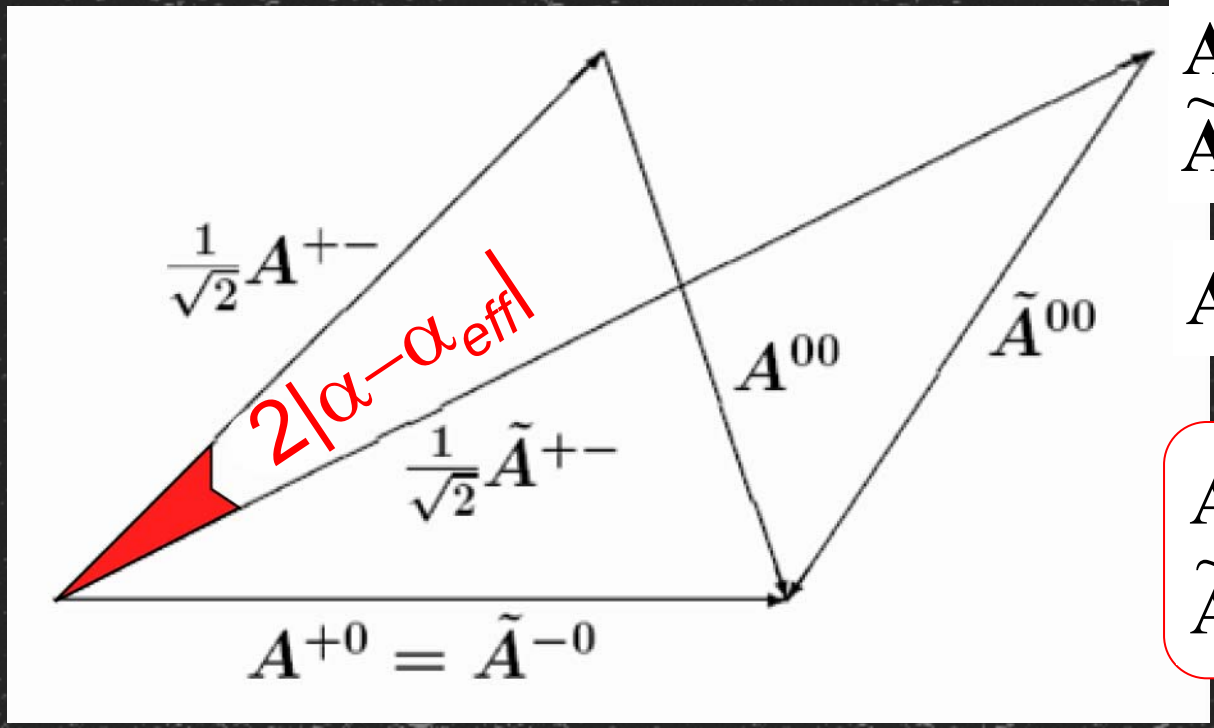
How can we obtain α from α_{eff} ?

Time-dep. asymmetry : $A_{\pi\pi}(\Delta t) = S_{\pi\pi} \sin(\Delta m_d \Delta t) - C_{\pi\pi} \cos(\Delta m_d \Delta t)$

NB : T = "tree" amplitude P = "penguin" amplitude

How to estimate $|\alpha - \alpha_{eff}|$: Isospin analysis

- Use SU(2) to relate decay rates of different *hh* final states ($h \in \{\pi,\rho\}$)
- Need to measure several related B.F.s



$$\mathbf{A}^{+-} = A(B^0 \to \pi^+\pi^-)$$
$$\tilde{\mathbf{A}}^{+-} = A(\overline{B}^0 \to \pi^+\pi^-)$$

$$\mathbf{A}^{+0} = A(B^+ \to \pi^+\pi^0)$$

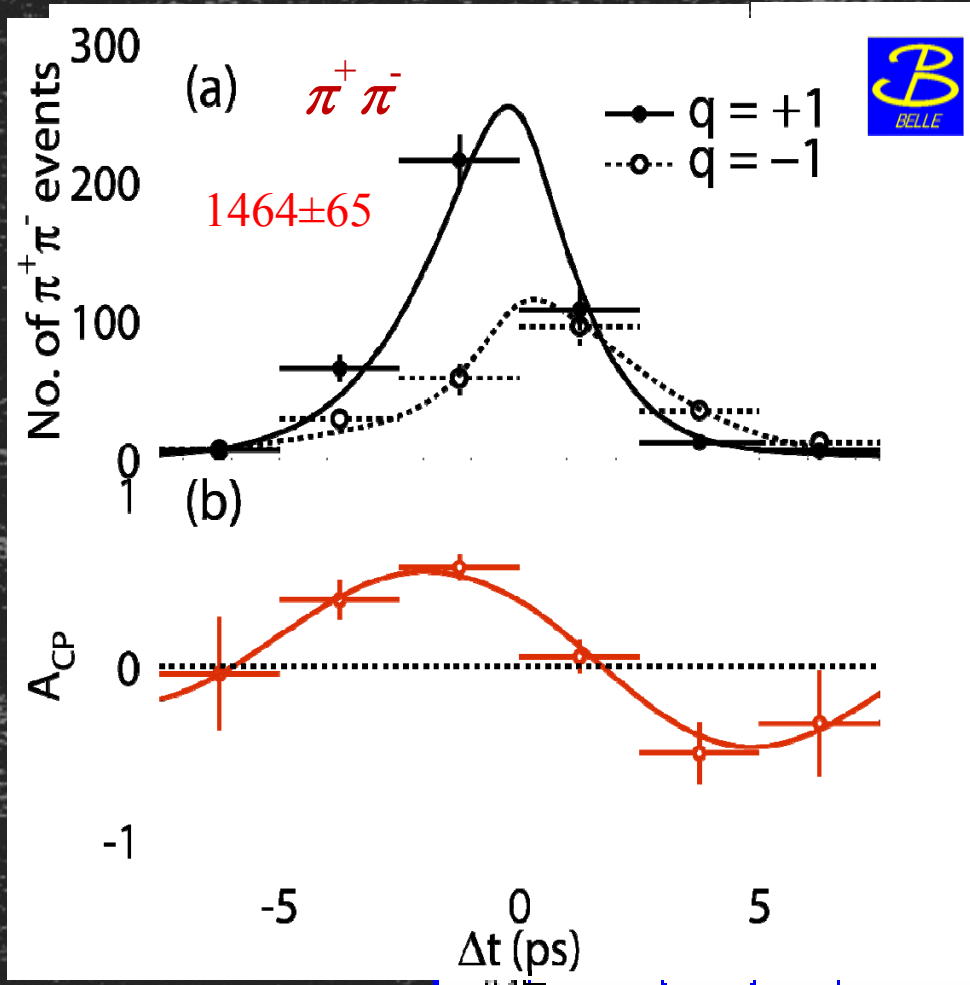
$$\mathbf{A}^{00} = A(B^0 \to \pi^0\pi^0)$$
$$\tilde{\mathbf{A}}^{00} = A(\overline{B}^0 \to \pi^0\pi^0)$$

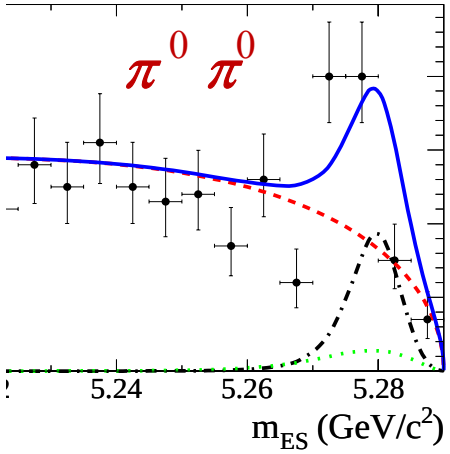
Limiting factor in analysis

Gronau, London : PRL**65**, 3381 (1990)

Measuring α in $B \to \pi\pi$

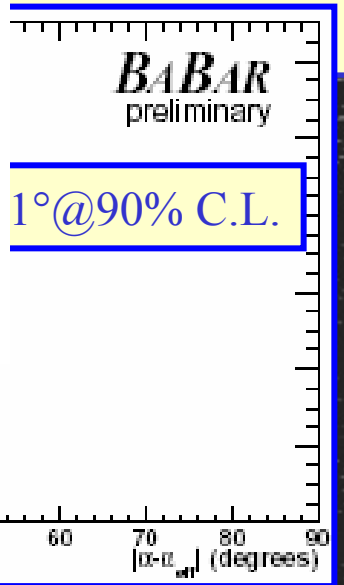
hep-ex/0608035 hep-ex/0607106



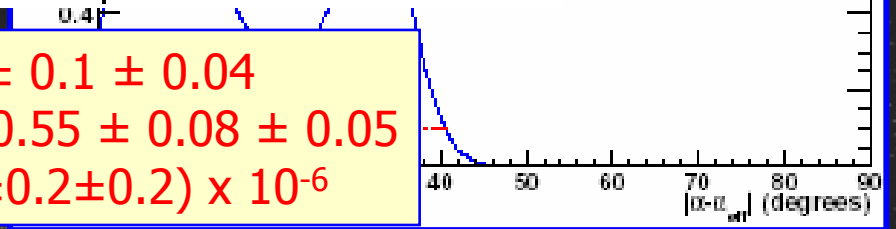


0 ± 25

(1.48 ± 0.26 ± 0.12)×10^{-6}



1°@90% C.L.



$S_{\pi+\pi-}$ = -0.61 ± 0.1 ± 0.04

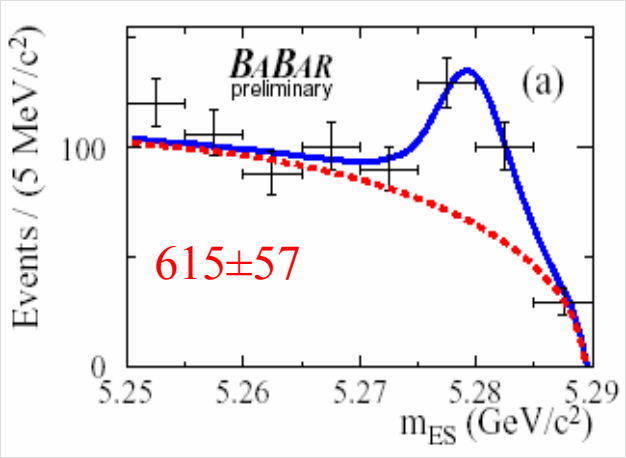
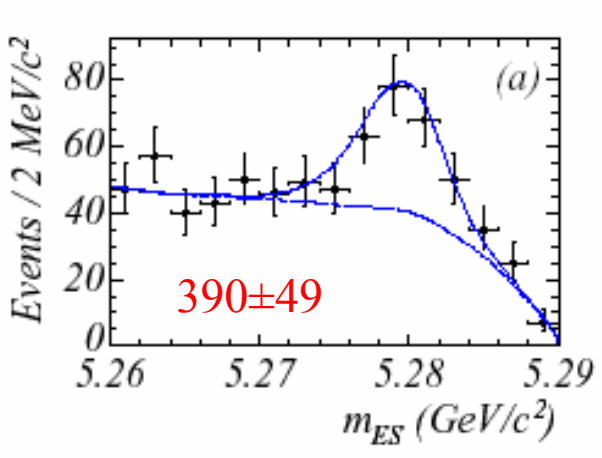
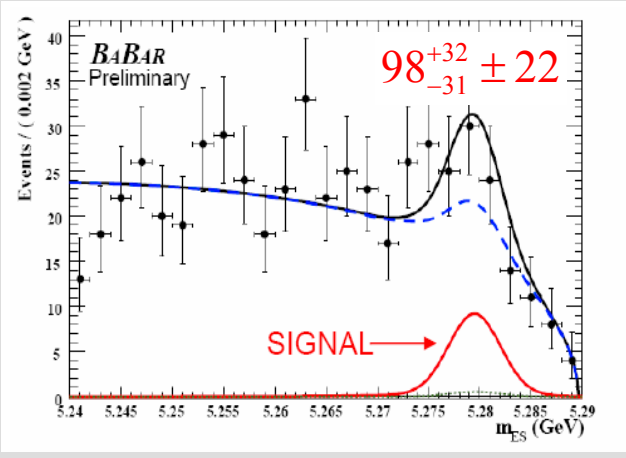
$A_{\pi+\pi-}$ (=-C) = 0.55 ± 0.08 ± 0.05

$BR_{\pi+\pi-}$ = (5.1±0.2±0.2) x 10^{-6}

Sometimes you have to be lucky

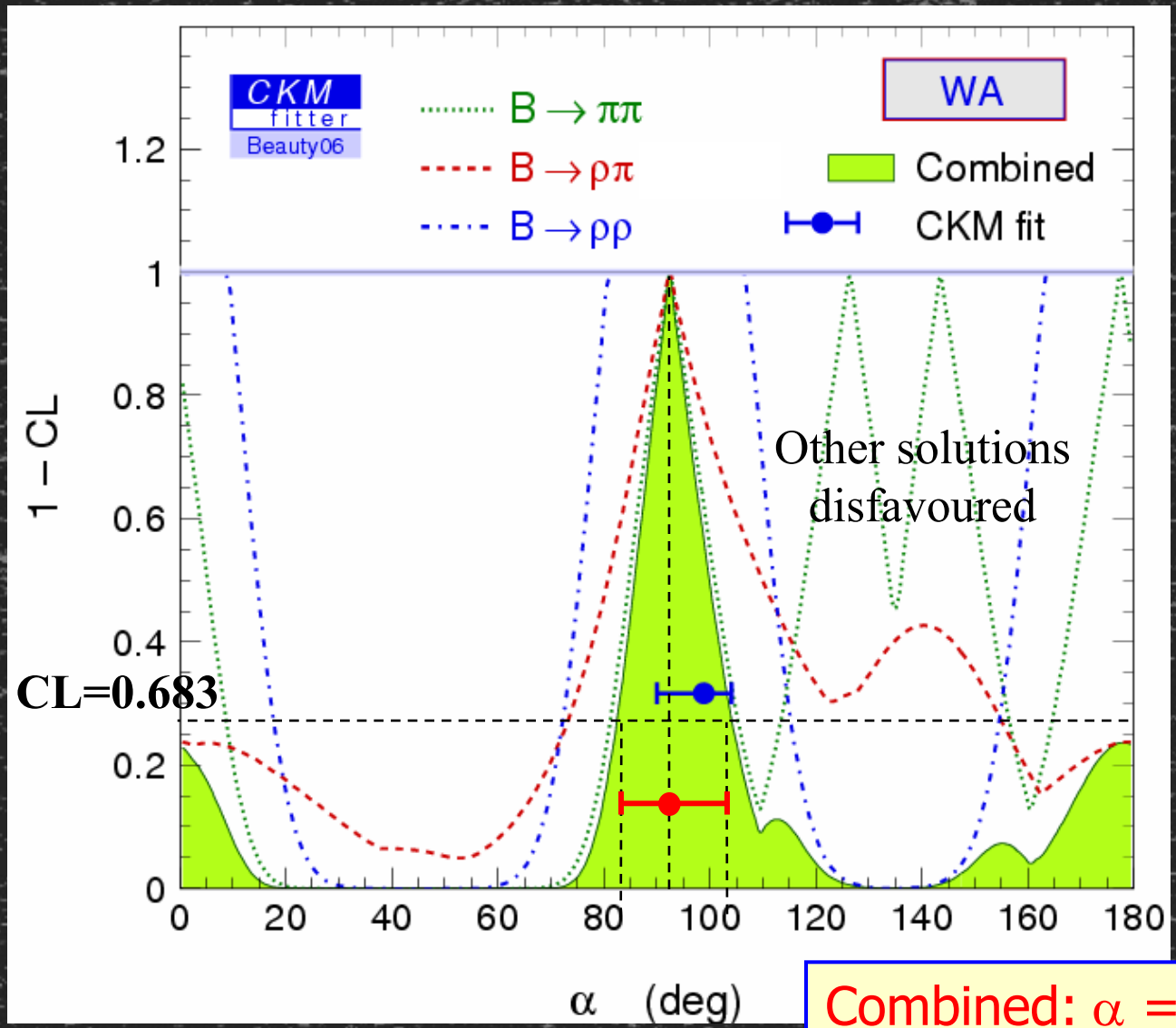
hep-ex/0607092
hep-ex/0607097
hep-ex/0607098

- $B \to \rho\rho$ is almost completely polarized

$B^0 \to \rho^+\rho^-$	$B^+ \to \rho^+\rho^0$	$B^0 \to \rho^0\rho^0$
		
$f_{L,\rho^+\rho^-} = 0.977 \pm 0.024^{+0.015}_{-0.013}$	$BR_{\rho^\pm\rho^0} = (16.8 \pm 2.2 \pm 2.3) \times 10^{-6}$	$BR_{\rho^0\rho^0} = (1.16^{+0.37}_{-0.36} \pm 2.7) \times 10^{-6}$
$S_{\rho^+\rho^-} = -0.19 \pm 0.21^{+0.05}_{-0.07}$	$f_{L,\rho^\pm\rho^0} = 0.905 \pm 0.042^{+0.023}_{-0.027}$	$f_{L,\rho^0\rho^0} = 0.86^{+0.11}_{-0.13} \pm 0.05$
$C_{\rho^+\rho^-} = -0.07 \pm 0.15 \pm 0.06$	$A_{\rho^\pm\rho^0} = -0.12 \pm 0.13 \pm 0.10$	

- $B \to \rho^0\rho^0$ is small ⟶ better constraint on $\Delta\alpha$

Combining all methods: α



Combined: $\alpha = [93^{+11}_{-9}]^\circ$

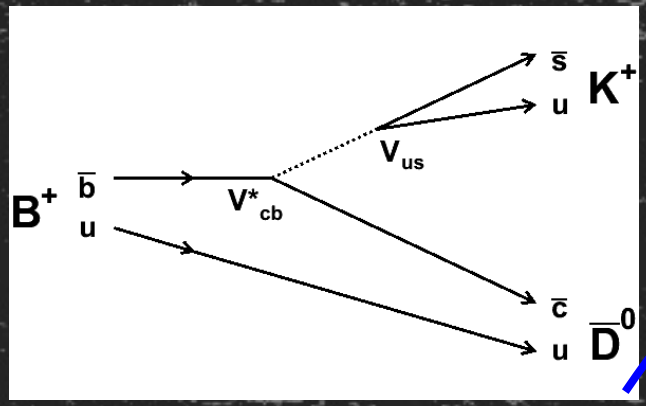
Global fit without α:

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

$\gamma = \arg[V_{ub}^*]$: CP violation in DK modes

GLW: Gronau, London, Wyler (2001)
ADS: Atwood, Dunietz, Soni (1997)
GGSZ: Giri, Grossman, Soffer, Zupan (2003)

E.g. $B^+ \to D^0/\bar{D}^0 K^+$



e^{i0}

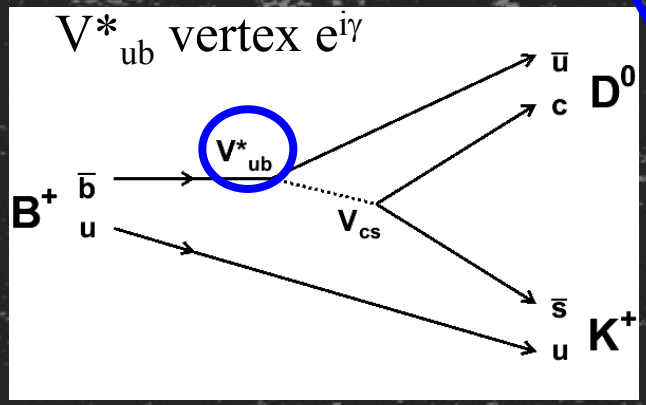
$\bar{D}^0 K^+$

e^{i0}

D decays do not involve V_{ub} or V_{td}: no contribution to phase

$\bar{D}^0/D^0 \to$ CP state (GLW)
$\bar{D}^0/D^0 \to K^-\pi^+/K^+\pi^-$, CA/DCS (ADS)
$\bar{D}^0/D^0 \to K_S\pi^+\pi^-$, Dalitz (GGSZ)

B^+



$e^{i\gamma}$

$D^0 K^+$

e^{i0}

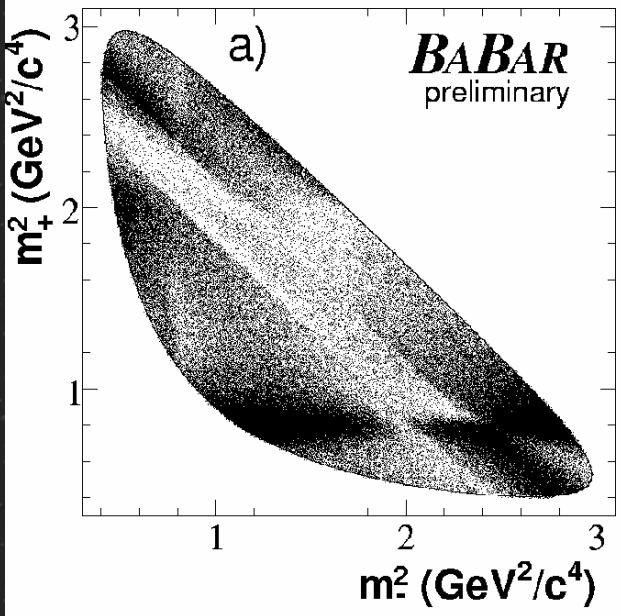
Relative phase = $e^{-i\gamma}$

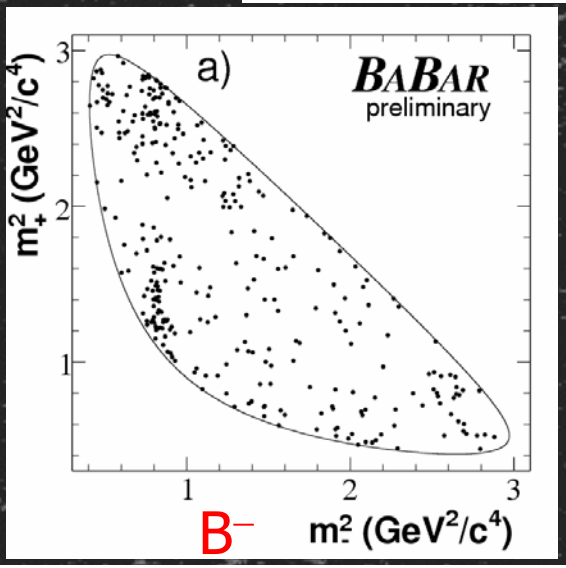
$B^\pm \to DK$: no time dependence; extract γ from rates and CP asymmetries
but $b \to u$ amplitude is small (for example r_B (DK^-) = 0.16 ± 0.05 ± 0.01 ± 0.05 Belle)

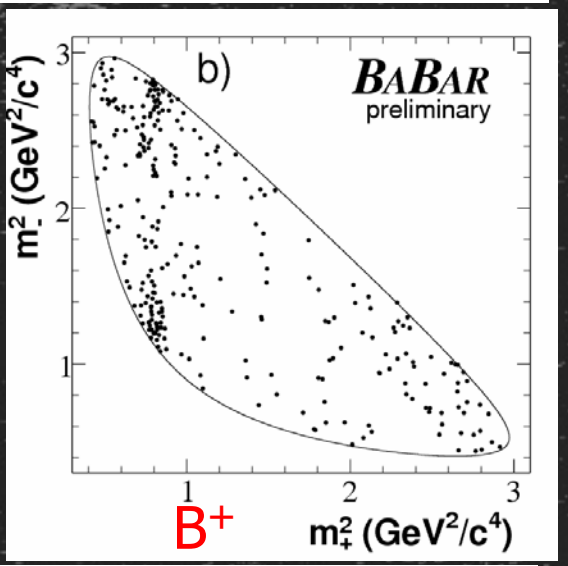
The GGSZ method – an example

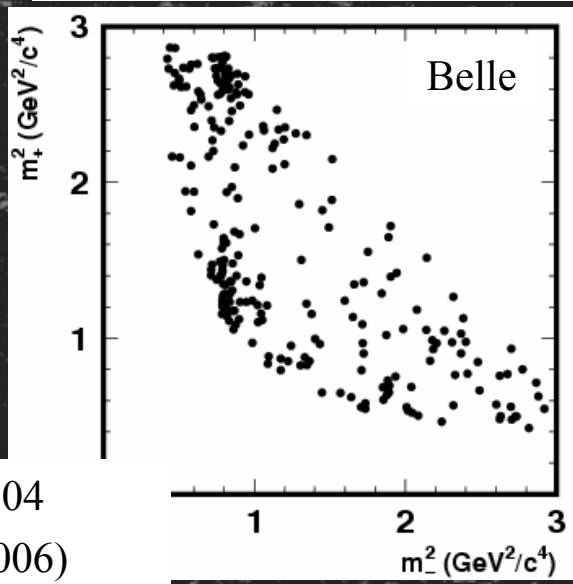
Look for deviations in $B^{\pm} \to D^0 K^{\pm}$ plots

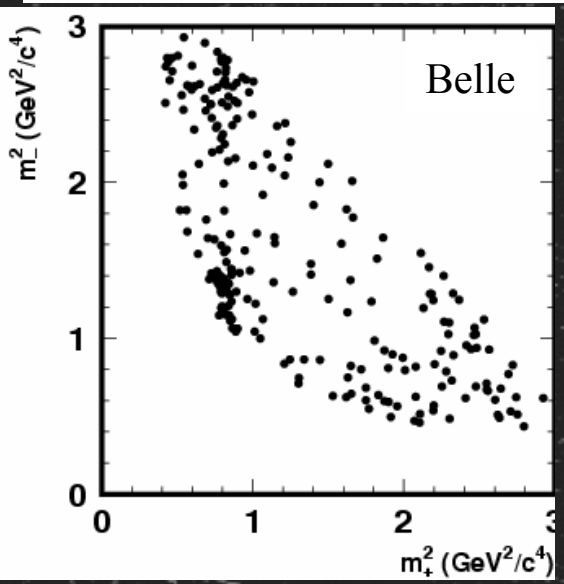
Map out Dalitz plot from all $D^0 \to K_s \pi^+ \pi^-$ decays







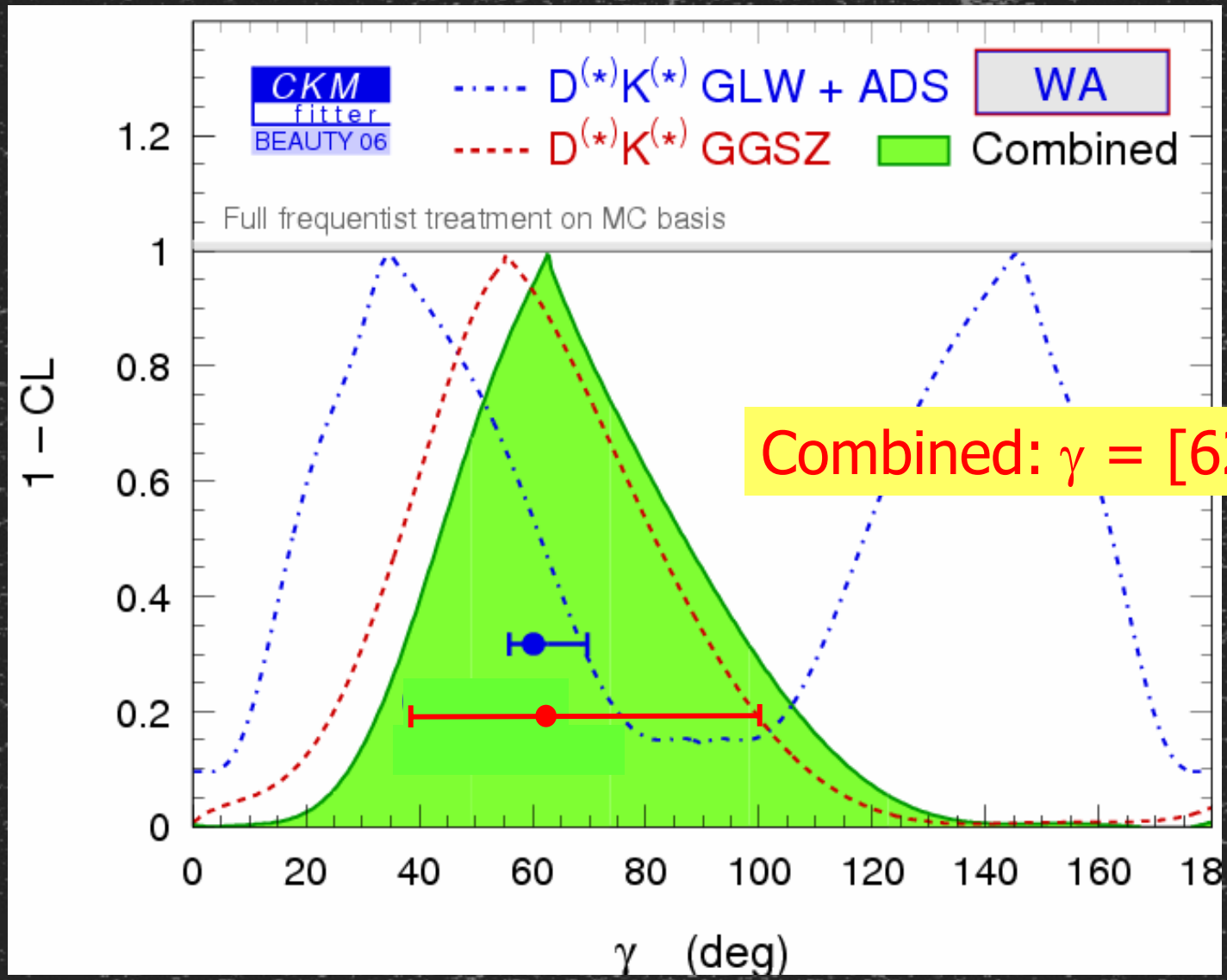




BaBar preliminary; hep-ex/0607104

Belle; Phys.Rev.D 73, 172009 (2006)

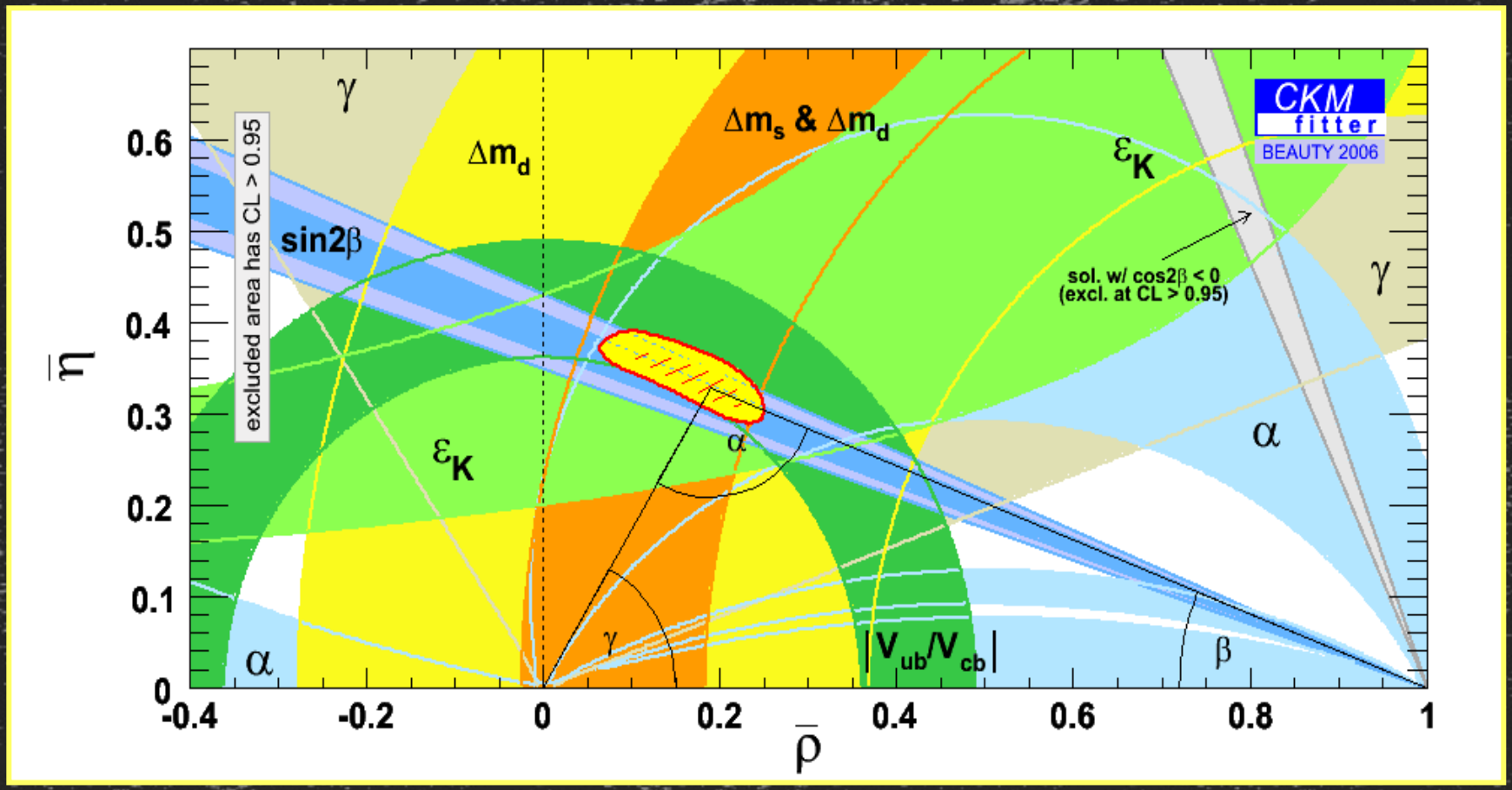
Combined Result for γ



Combined: $\gamma = [62^{+38}_{-24}]^\circ$

Indirect (CKM) $\gamma = [59^{+9}_{-4}]^\circ$

The CKM Model has passed the experimental test

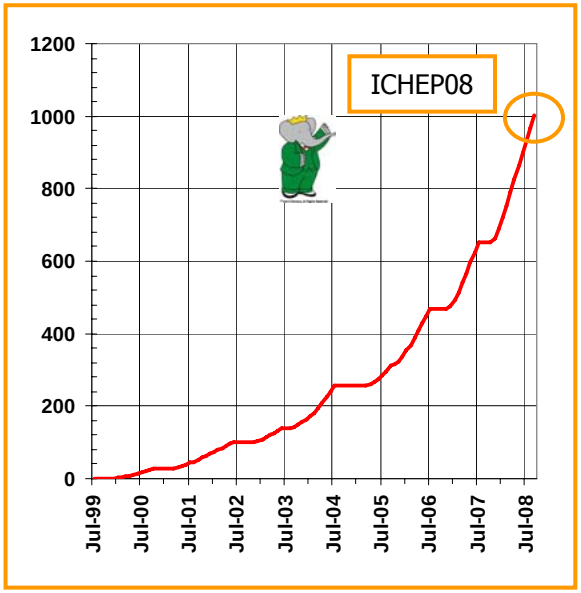


New Targets

- Effects of TeV new physics → deviations from SM
- LFV and new source of CPV
- Hidden flavor symmetry and its breaking

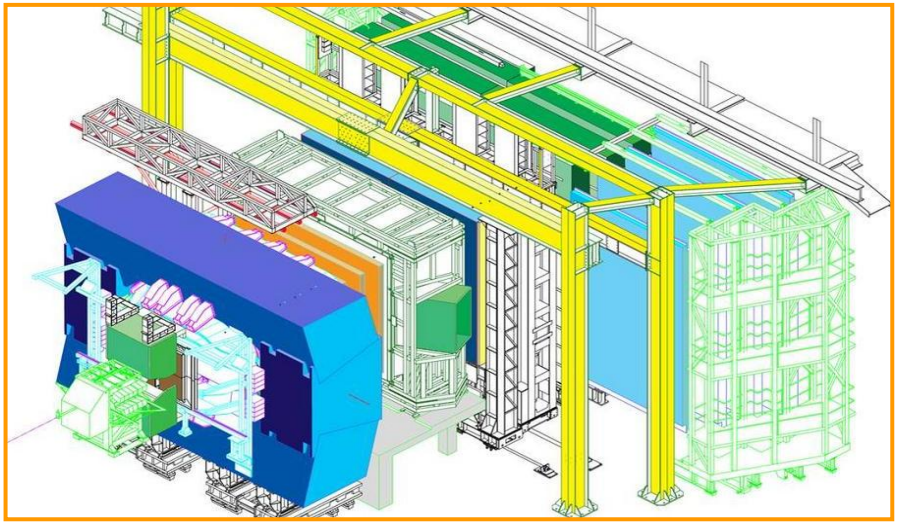
The next few years (2007 – 2010)

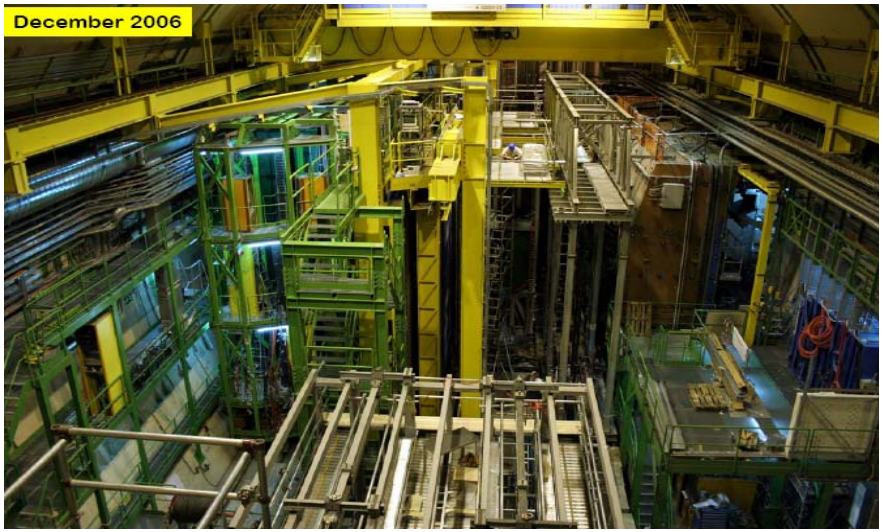
- Belle and BaBar
  - 1 ab^{-1} (2006)
  - 2 ab^{-1} (2008)



- Tevatron
  - 2 fb^{-1} (2006)
  - 8 fb^{-1} (2009)

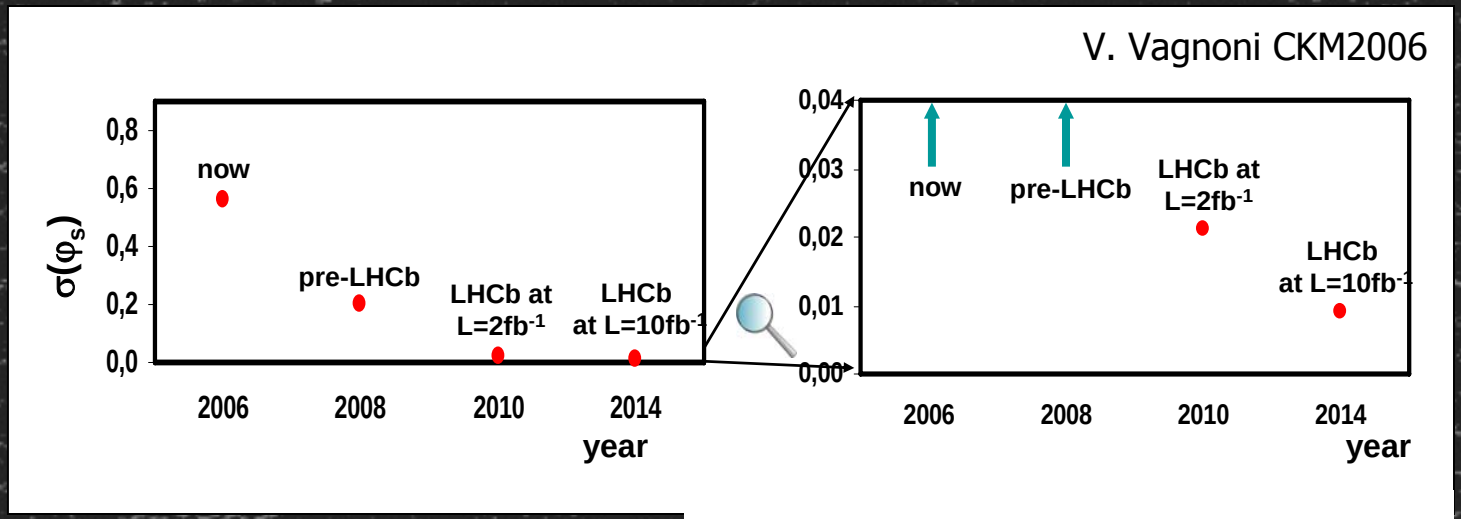
- LHCb is nearing completion



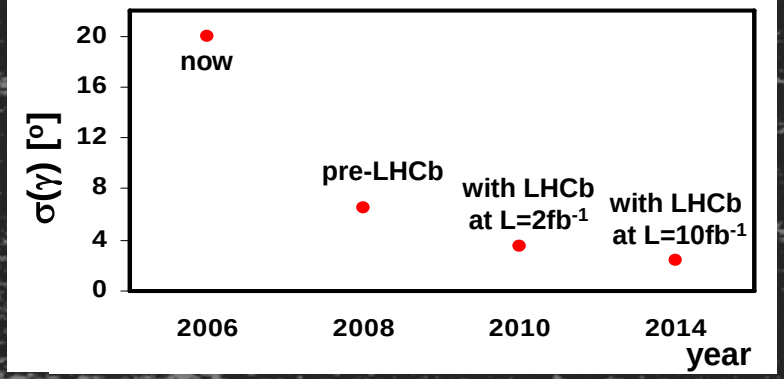


LHCb Prospects (Some of the things they can do)

- B_s Mixing phase (φ_s) using $B_s \rightarrow J/\psi\phi$
  - Signal yield: 130k events per L=2fb^{-1} with a B/S≈0.1, Sensitivity φ_s ~ 0.021
  - Sensitive probe of New Physics effects in the B_s mixing
    - $\varphi_s = \varphi_s(SM) + \varphi_s(NP)$ with $\varphi_s(SM) = -2\lambda^2\eta$ ~ -0.037±0.002

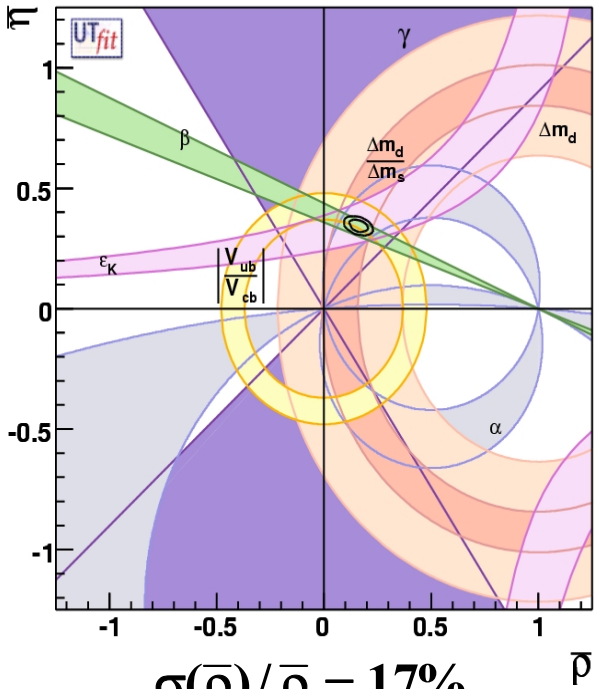


- Sensitivity to γ
  - Standard methods
  - Golden Mode $B_s \rightarrow D_s K$
  - Sensitivity ~ 4.2° with 2 fb^{-1}



From B-Factories to LHCb – without new physics

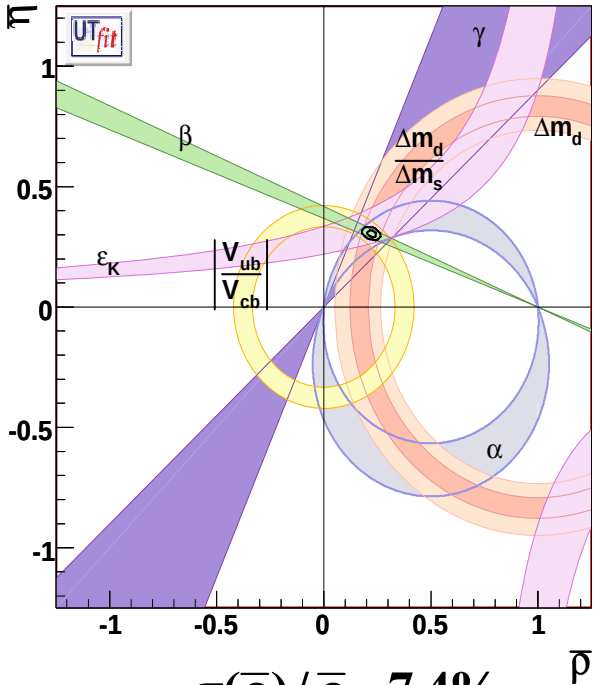
Summer 2006



$\sigma(\bar{\rho})/\bar{\rho} = 17\%$

$\sigma(\bar{\eta})/\bar{\eta} = 4.7\%$

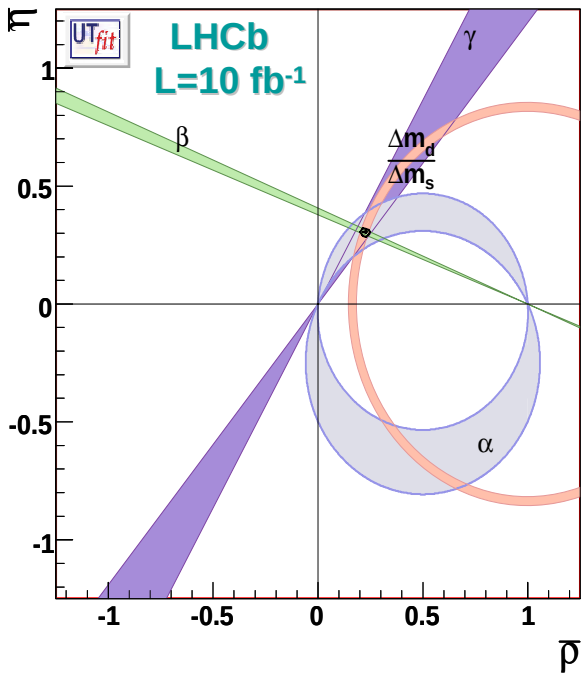
2008*



$\sigma(\bar{\rho})/\bar{\rho} = 7.4\%$

$\sigma(\bar{\eta})/\bar{\eta} = 3.3\%$

2014

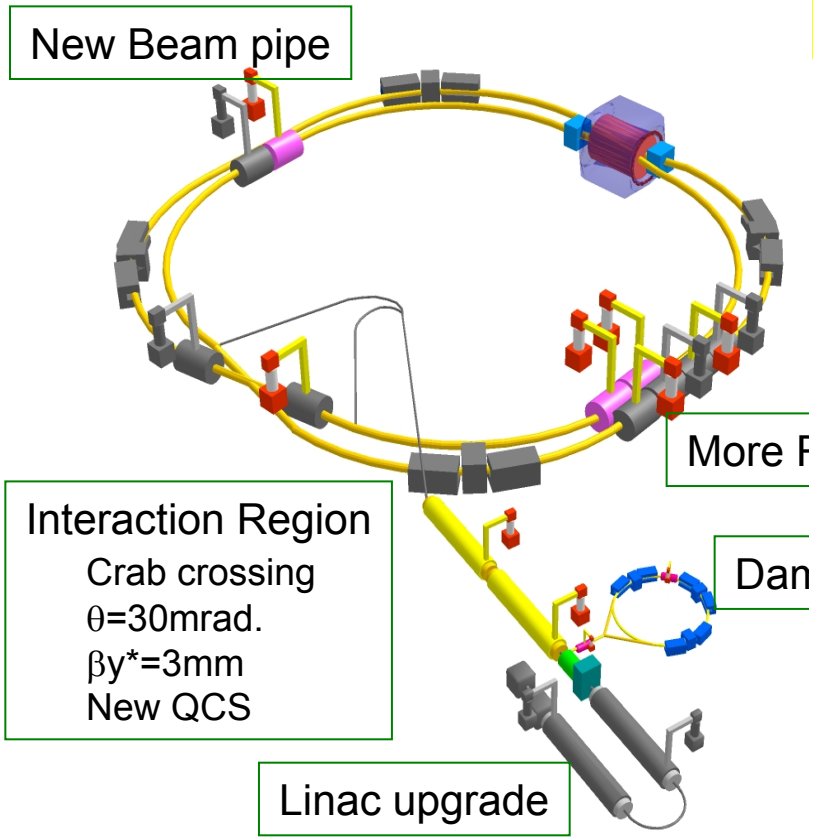


$\sigma(\bar{\rho})/\bar{\rho} = 3.6\%$

$\sigma(\bar{\eta})/\bar{\eta} = 1.8\%$

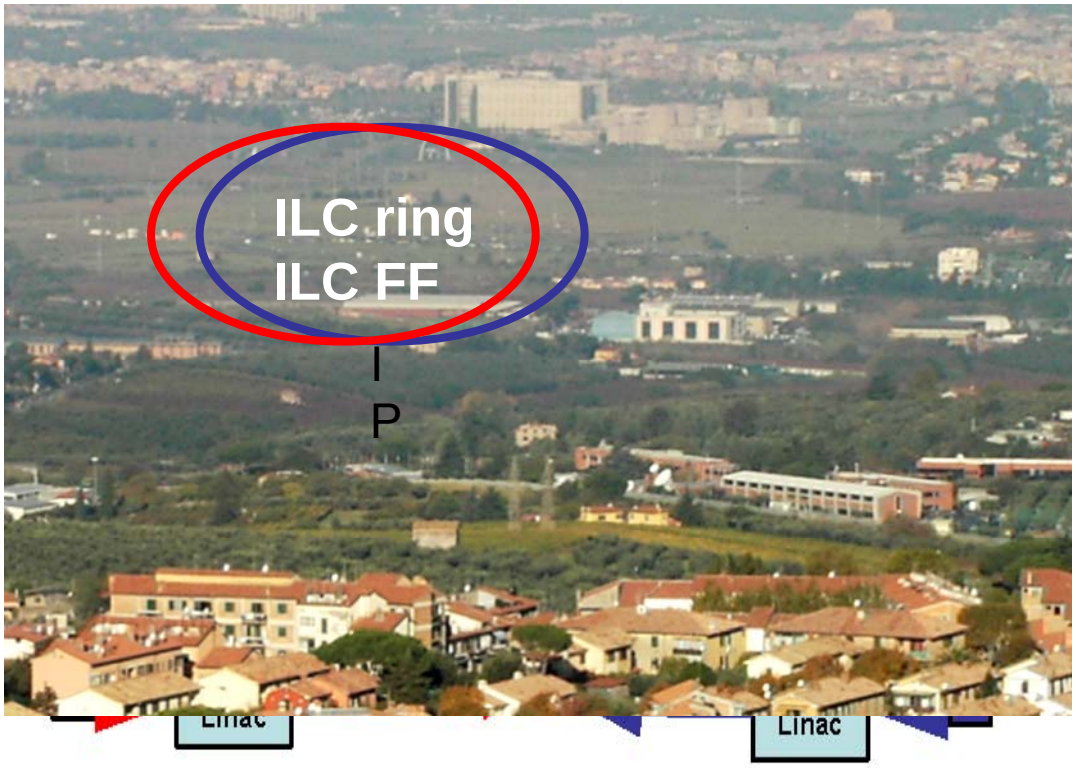
Super B-Factory Plans at KEK and Frascati

Design Luminosity ~ 1 x 10^{36} /cm^2/sec
Synergy with ILC
Recycle components (PEP, BaBar)
Lots of R&D needed



$L = 8 \times 10^{35}/cm^2$ /sec

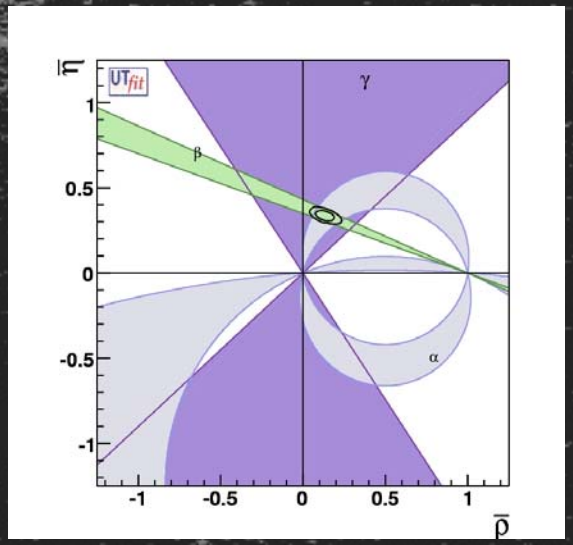
KEK



Frascati

Summary

- CKM Model is now a tested theory
  - Great success for theorist
  - Great success for experimentalist
  - Great success for the Standard Model
    - $\alpha = (93^{+11}_{-9})^{o}$
    - $\beta = (21.2 \pm 1.0)^{o}$
    - $\gamma = (62^{+38}_{-24})^{o}$



- Search for Deviations from SM and New Physics
  - Near Term Future Looks Promising
    - B Factories only half way done
    - Tevatron will triple data sample
    - LHC(b) turn on
  - Long Term Prospects
    - LHC(b) upgrades
    - Super B Factories (KEK, INFN)