Recent Results on CP-Violation at the BaBar and Belle B-Factories

by Homer Neal (SLAC)

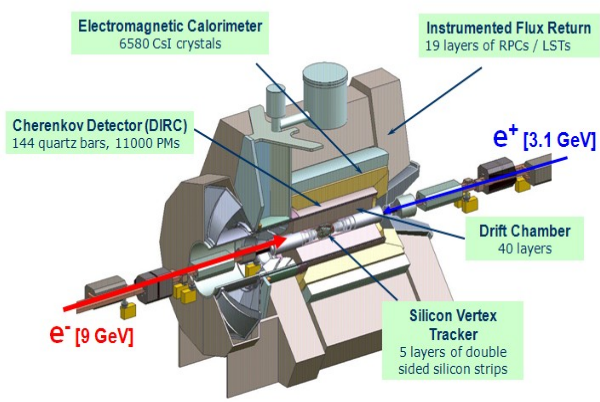
on

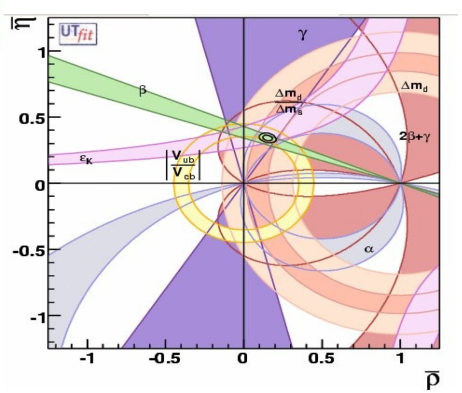
14 June 2010

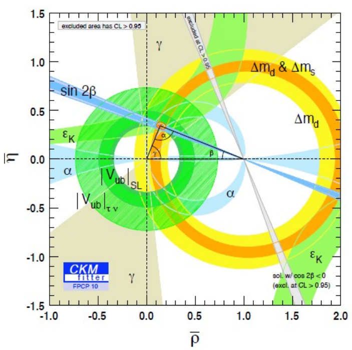
@

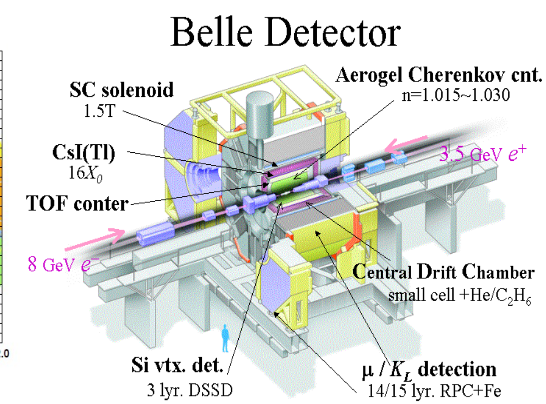
MESON 2010

in KRAKÓW, Poland



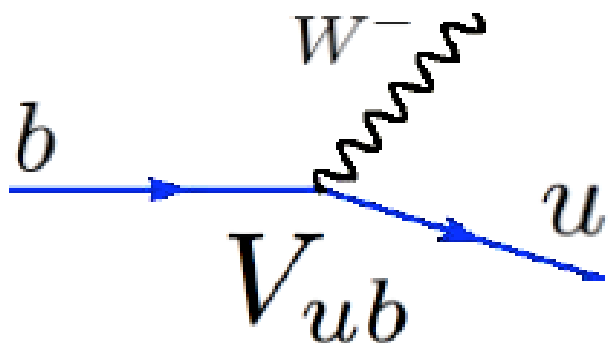






CP violation and the CKM matrix

quark decay

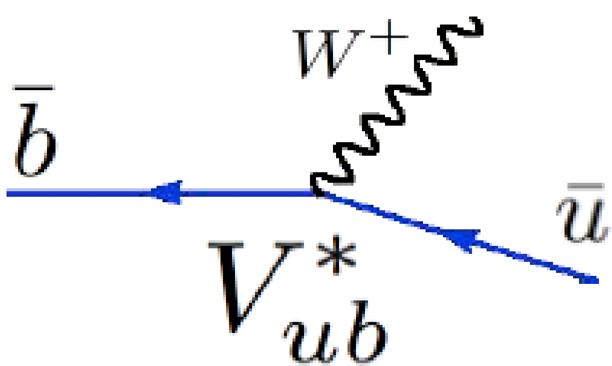


Cabibbo Kobayashi Maskawa matrix

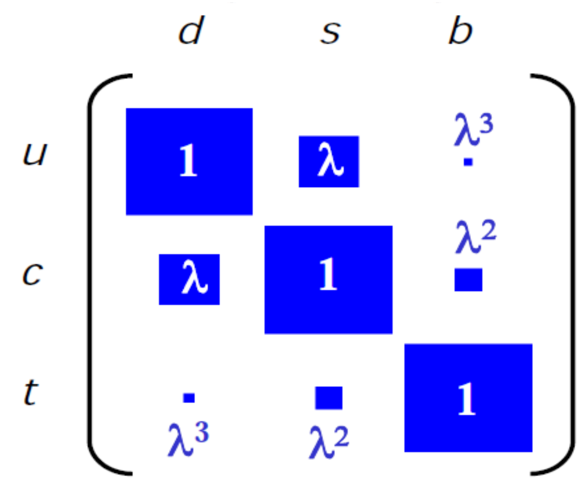
(Wolfenstein parametrization)

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

anti-quark decay



Relative magnitudes

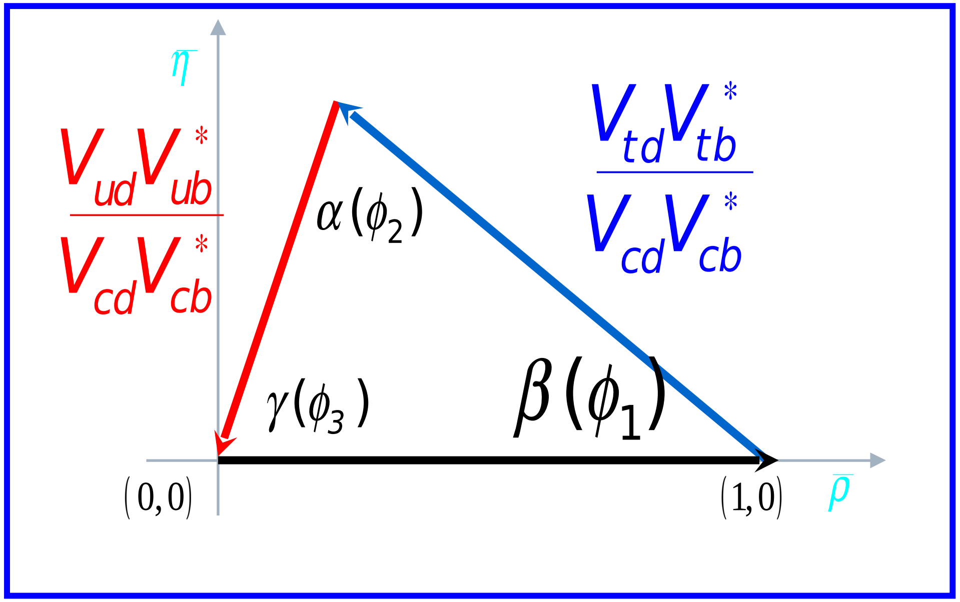


The CP-violating phases

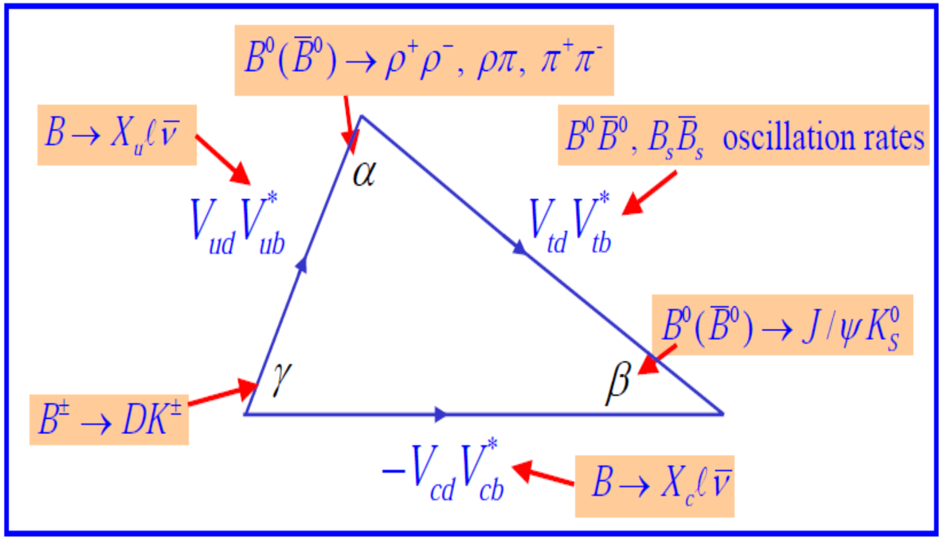
$$\begin{array}{c|ccc} & d & s & b \\ u & 1 & 1 & e^{-i\gamma} \\ c & 1 & 1 & 1 \\ t & e^{-i\beta} & 1 & 1 \end{array}$$

Non-trivial CP violating phases. Amplitude interference different for quark vs anti-quark decay. Observable rate differences.

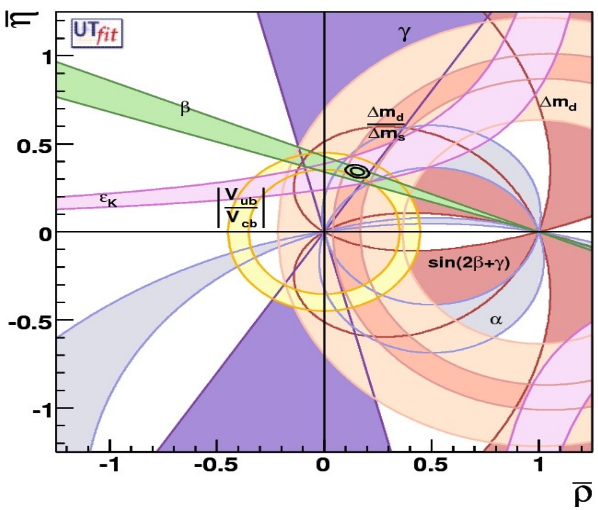
The Unitarity Triangle

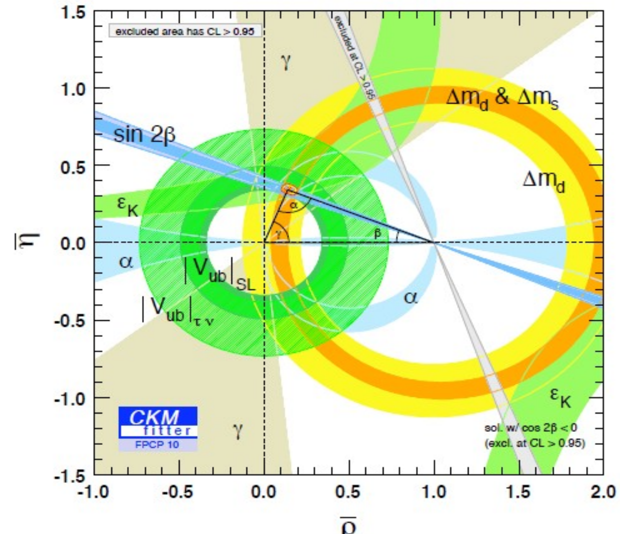


SM prediction: ALL measurements of *W*-mediated quark processes must be consistent with the CKM framework.



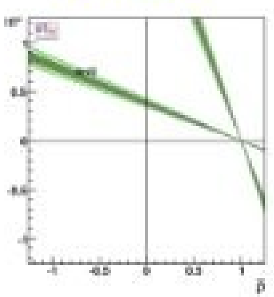
Overall Status of the triangle



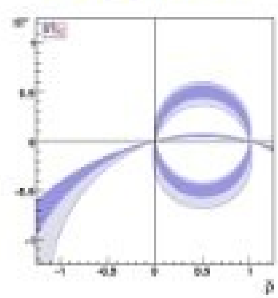


- Apex of the triangle over constrained
- More work needed on γ/ϕ_3
- γ constrained from $B^{\pm}\to D^{(*)} K^{(*)\pm}$

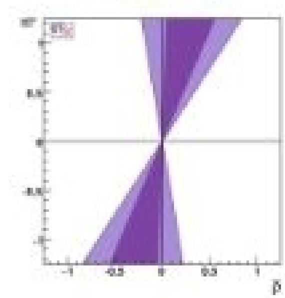
sin2β



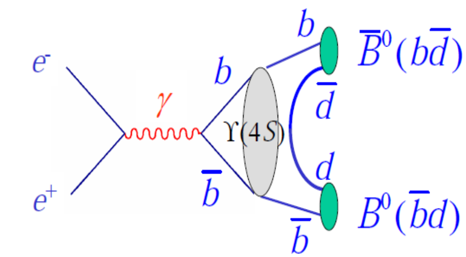
angle α



angle γ

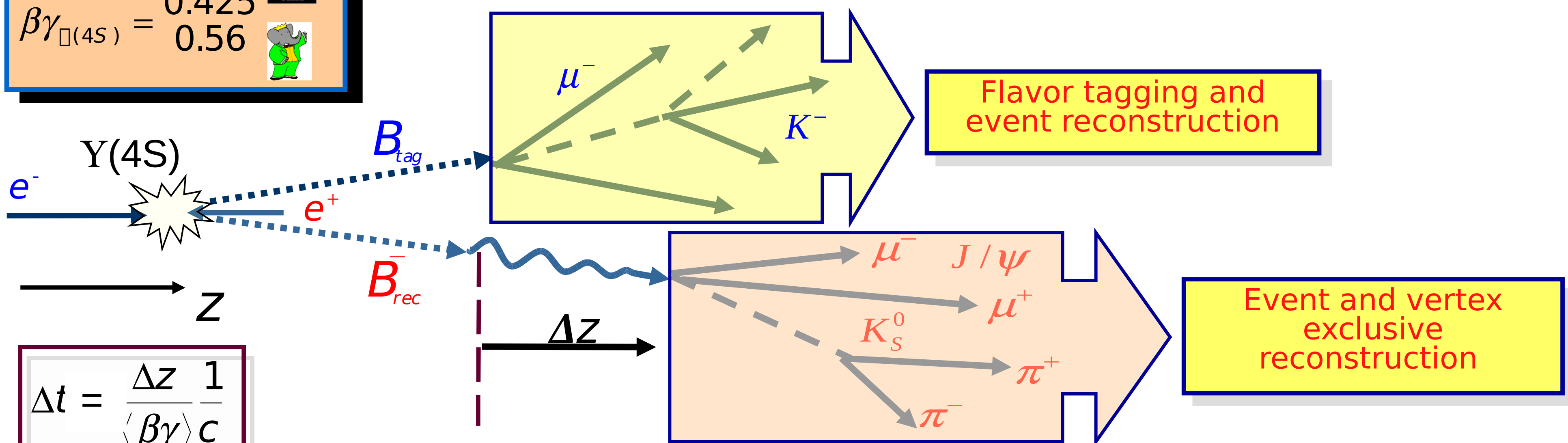


The experimental method



$\beta\gamma_{\Upsilon(4S)} =$ 0.425 (Belle) / 0.56 (BaBar)

Tagging performance: Q ~30%



$$\Delta t = \frac{\Delta z}{\langle \beta\gamma \rangle} \frac{1}{c}$$

- **fighting main background** $(e^+e^- \to q\bar{q})$
  - most important discriminating quantities:

$$m_{es} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$$

$$\Delta E = E_B^* - E_{beam}^*$$

  - topological cuts (Fisher discr. or neural net)

All B decays are CKM suppressed, with $b \to c$ decays dominant

$$\Gamma \propto G_F^2 |V_{cb}|^2 m_b^5 \qquad |V_{cb}| \simeq 0.04 \qquad |V_{cb}|^2 \simeq 1.6\times10^{-3}$$

$$c\tau_B = (3\times10^8\ \mathrm{ms}^{-1})(1.6\times10^{-12}\ \mathrm{s}) = 0.48\ \mathrm{mm}$$

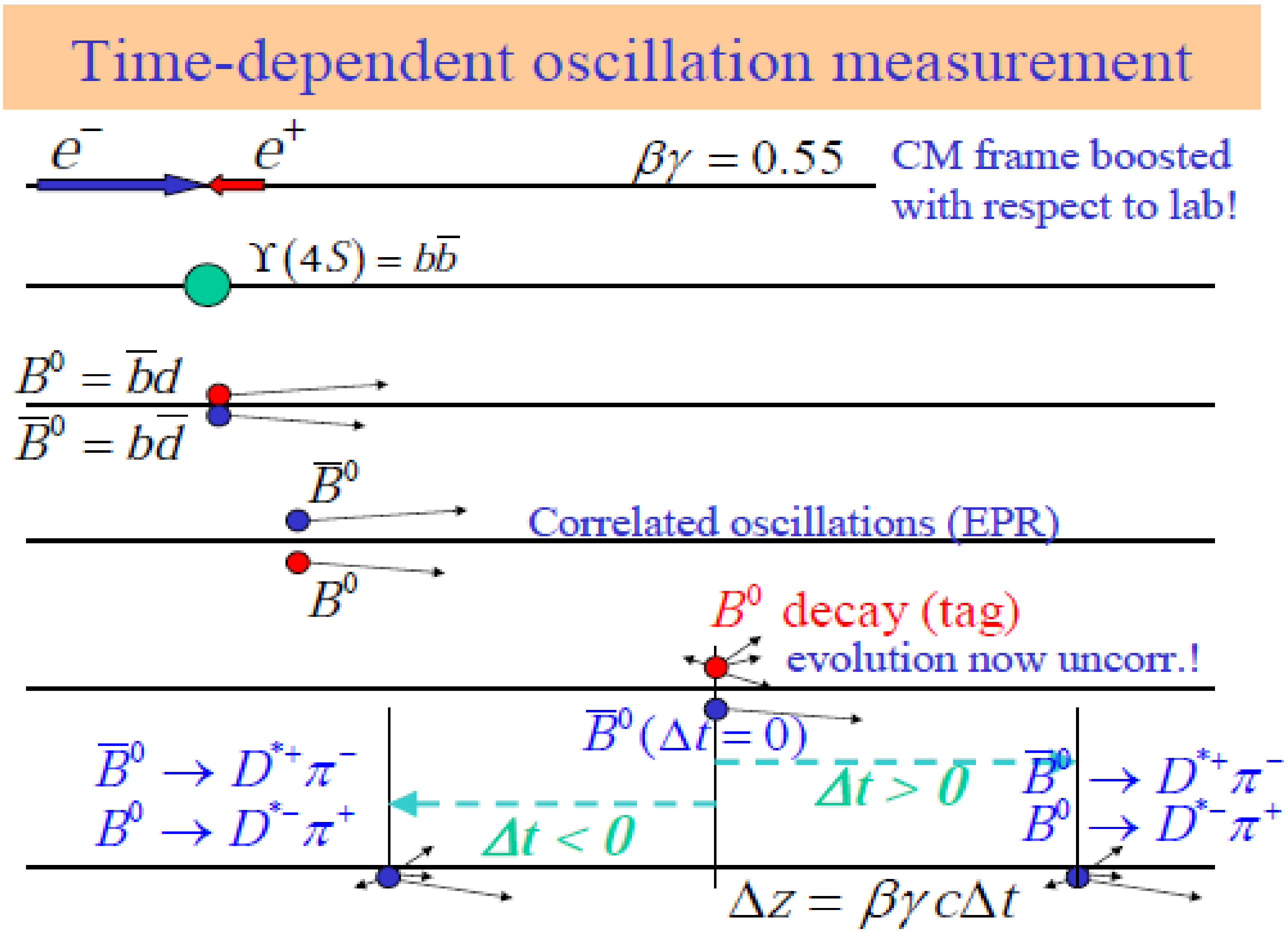
How far will B mesons travel before decaying?

$$\Delta\ell_{\mathrm{lab}} = v\cdot\Delta t_{\mathrm{lab}} = \beta c\cdot\Delta t_{\mathrm{lab}}$$
$$\Delta t_{\mathrm{lab}} = \gamma\cdot\Delta t_{\mathrm{B\,rest}}$$
$$\Rightarrow \Delta\ell_{\mathrm{lab}} = \beta\gamma\cdot c\Delta t_{\mathrm{B\,rest}}$$

average over decays

$$\langle\Delta\ell_{\mathrm{lab}}\rangle = \beta\gamma\cdot c\langle\Delta t_{\mathrm{B\,rest}}\rangle = \beta\gamma\cdot c\tau_B$$

$B^0\overline{B}^0$ correlated until one decays



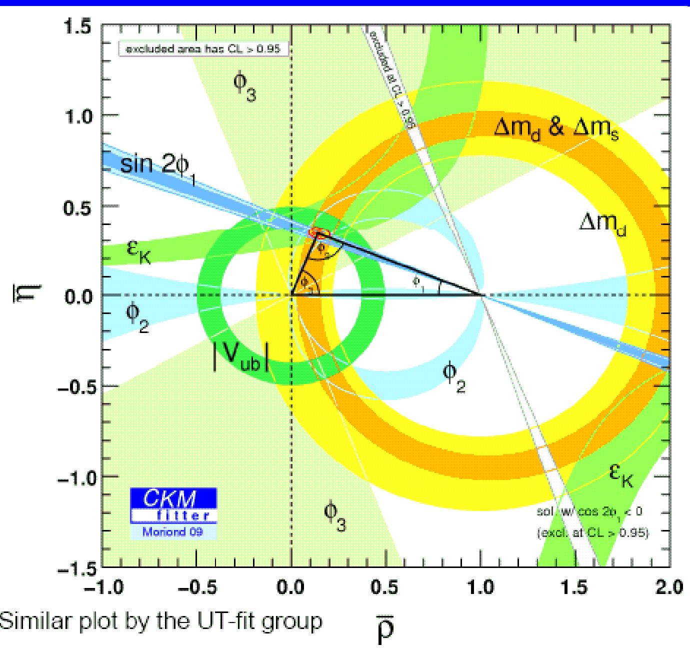
From Jeff Richman's Mexico Physics School Lectures (2008)

http://hep.ucsb.edu/people/richman/richman.html

The reward

Makoto Kobayashi and Toshihide Maskawa awarded 2008 Nobel Prize in Physics for their theory which simultaneously *explained the source of matter/antimatter asymmetries in particle interactions and predicted the existence of the third generation of fundamental particles*.

The BaBar experiment at the SLAC National Accelerator Laboratory in the U.S., together with the Belle experiment at KEK in Japan, recently provided experimental confirmation of the theory, some thirty years after it was published, *through precision measurements of matter/antimatter asymmetries.*

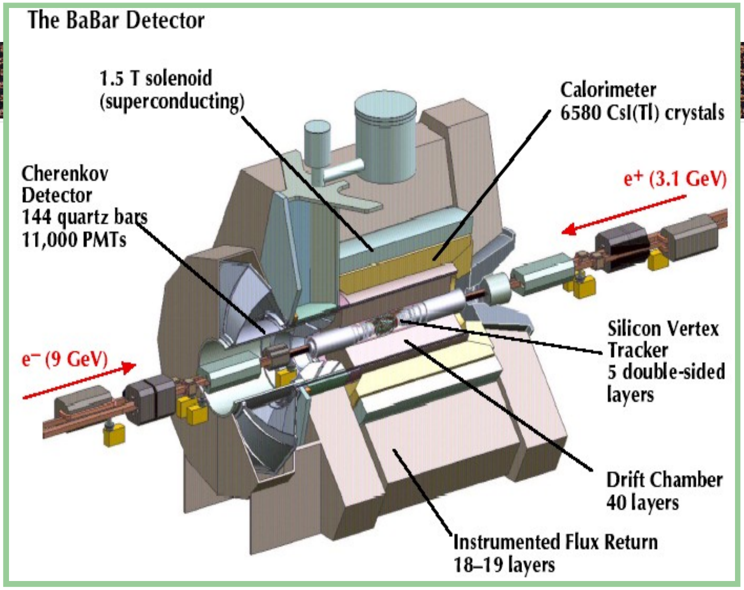


Similar plot by the UT-fit group

See: http://www-public.slac.stanford.edu/babar/Nobel2008.htm

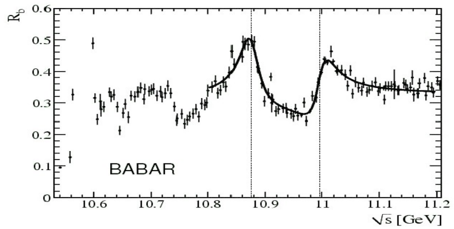
The BaBar experiment

Multipurpose particle detector at SLAC used to observe collisions of e^+e^- PEPII beams of asymmetric energies primarily at the Υ (4S) mass peak (10.58 GeV)



Recorded Data Samples:

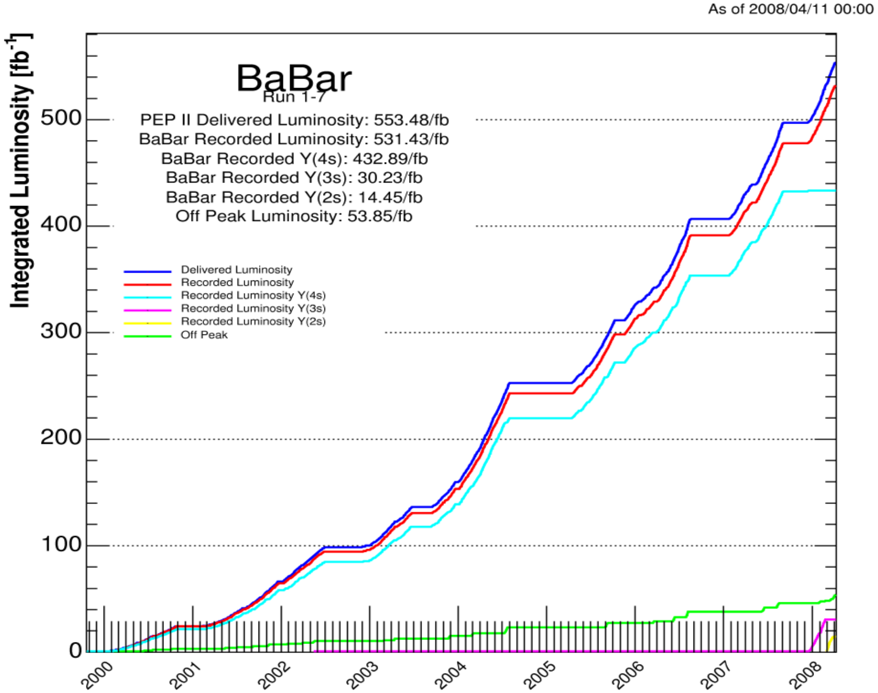
Y(4S): 432 fb^{-1}
(+ 10% off-peak data)



Y(3S): 30 fb^{-1}
Y(2S): 15 fb^{-1}

22 billion events (~9 billion after filters applied)

~470 million $B\bar{B}$ events

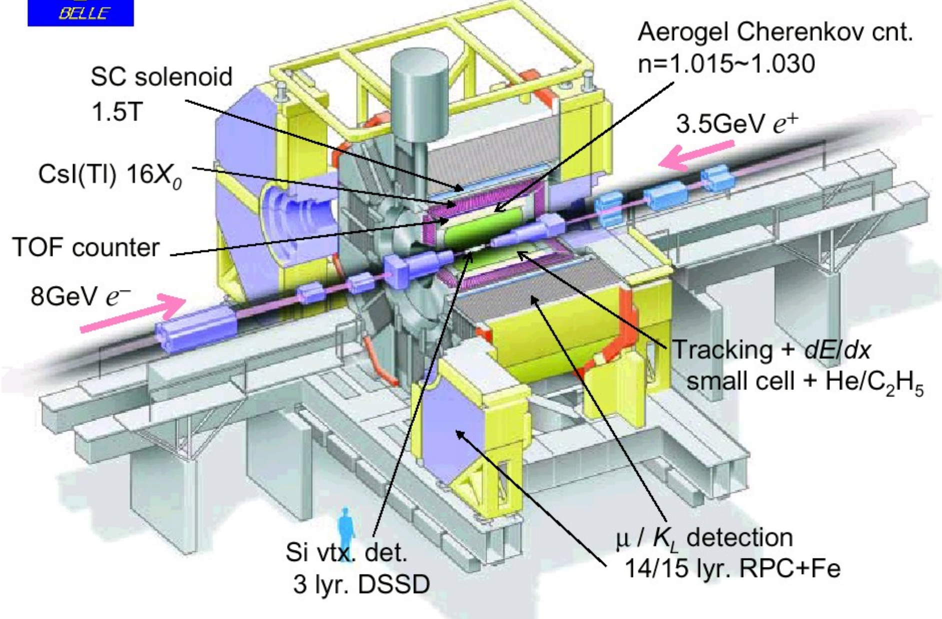


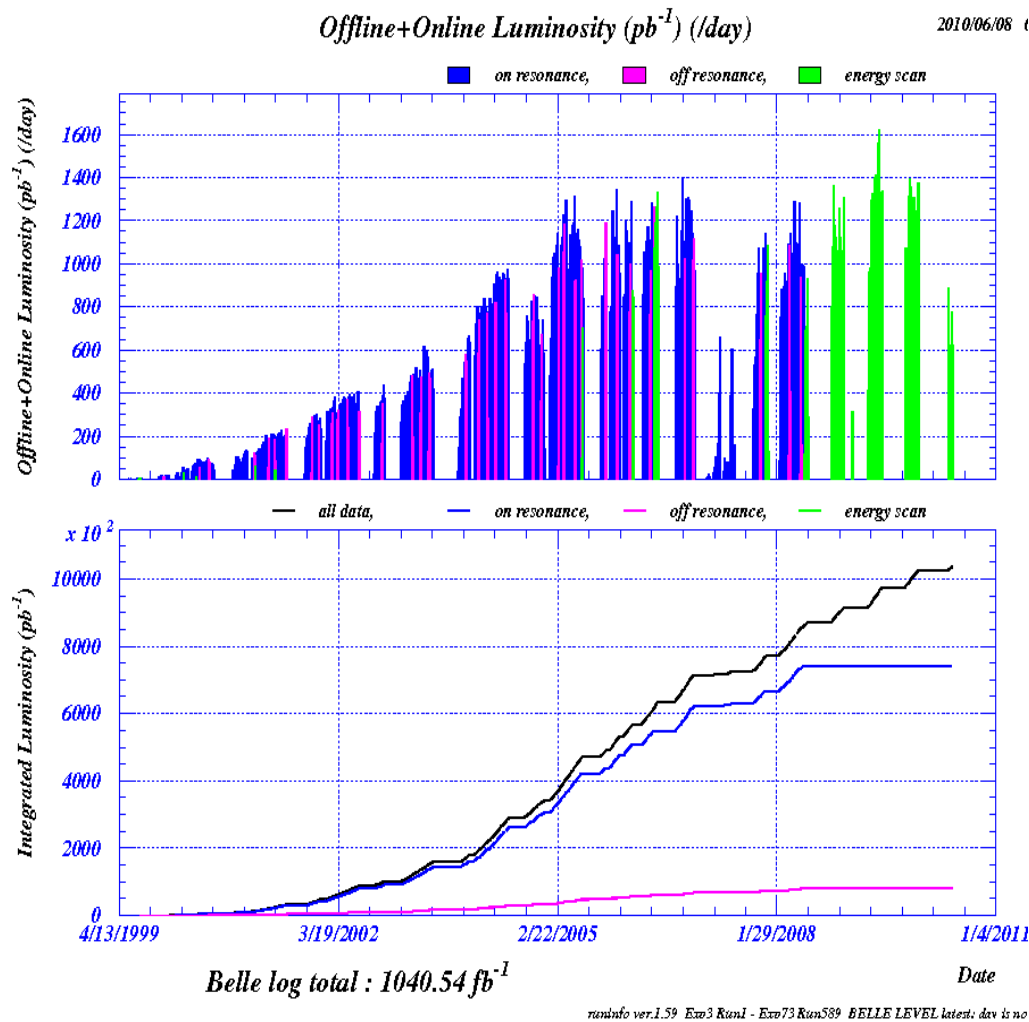
Belle detector records data delivered by KEKB asymmetric B-factory ($\beta\gamma$ =0.425) running at the Υ (4S) mass peak (10.58 GeV) at KEK.

Recorded Data Samples:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 24 fb^{-1}
$\Upsilon(1S)$: 5.7 fb^{-1}

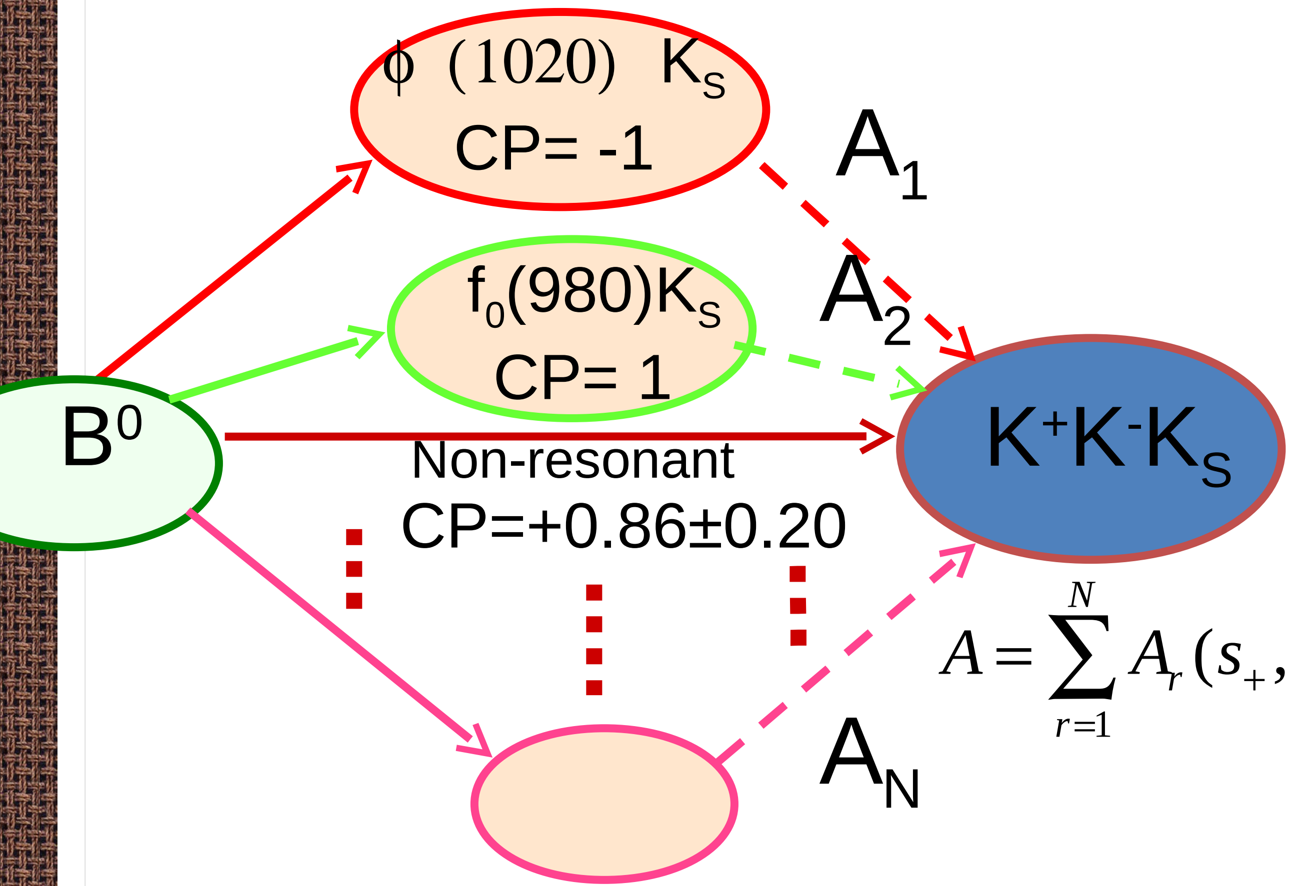
~770 million $B\bar{B}$ events

Belle Detector

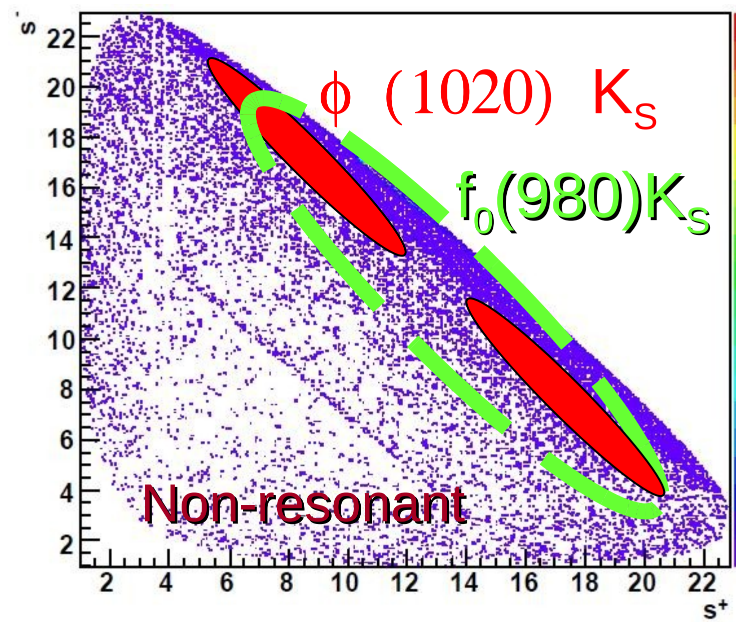




CPV Measurements in the $B \to K^- K^+ K^o_s$ Dalitz Plot



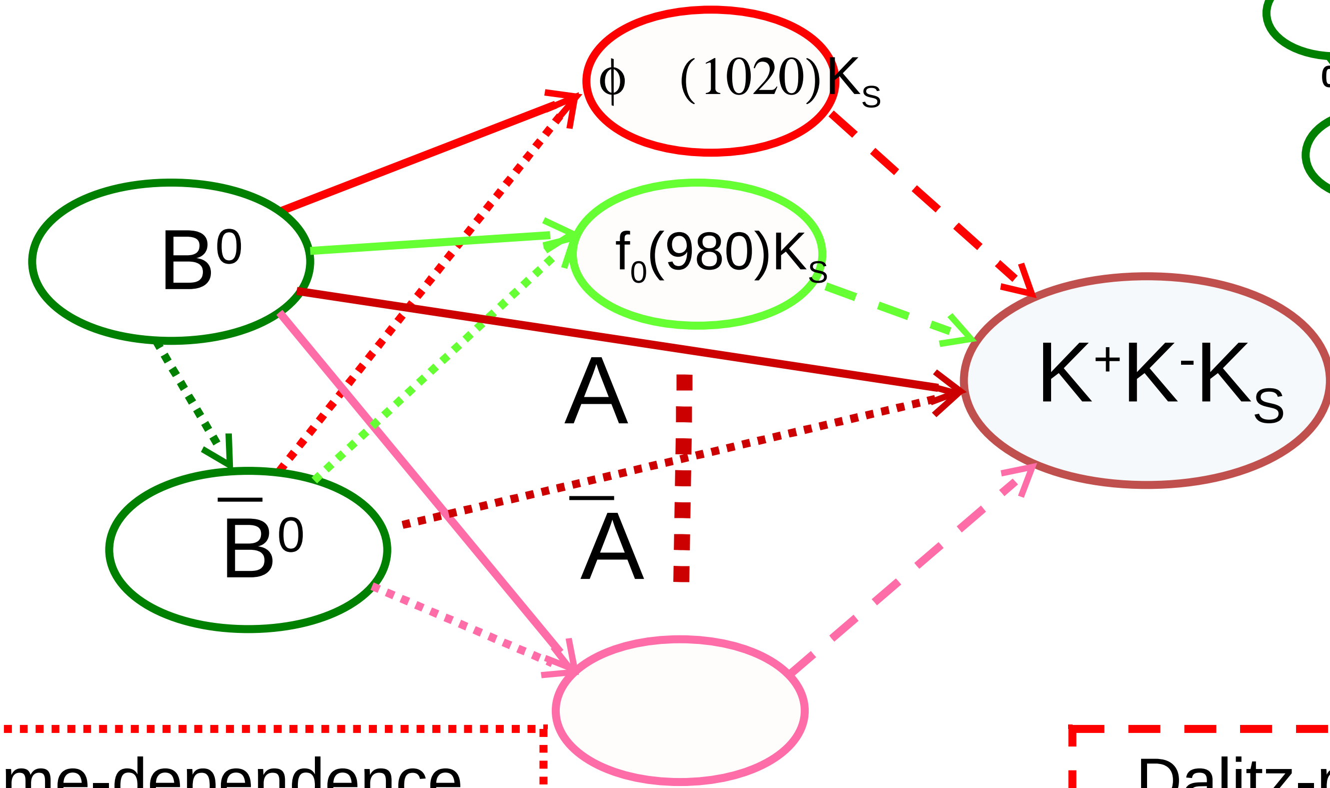
$$A = \sum_{r=1}^{N} A_r(s_+, s_-)$$

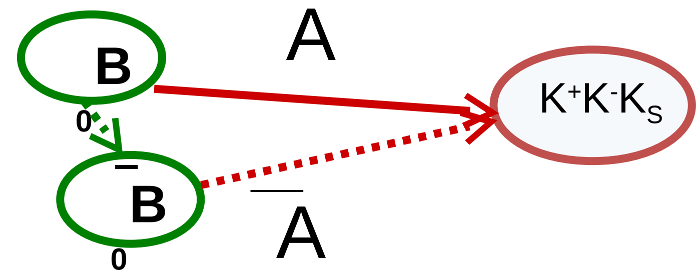


$$s_+ = M^2(K^+K_S)$$
$$s_- = M^2(K^-K_S)$$

Diagrams thanks to K. Sumisawa (KEK)
(FPCP 2010 talk)

Time-dependence of Dalitz plot in $B^0 \to K^+ K^- Ks$





c.f. Time-dependence

Time-dependence

Dalitz-plot

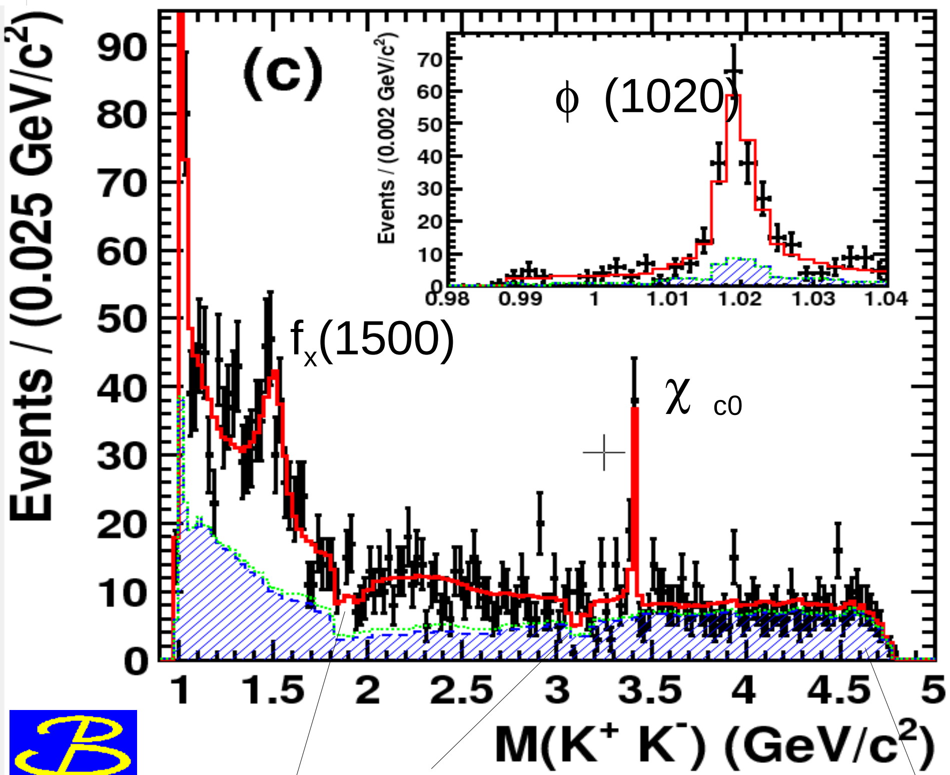
Interference in $B^0 \bar{B}^0$ ($\phi_{1,eff}$)+ intermediate states (Dalitz phase)

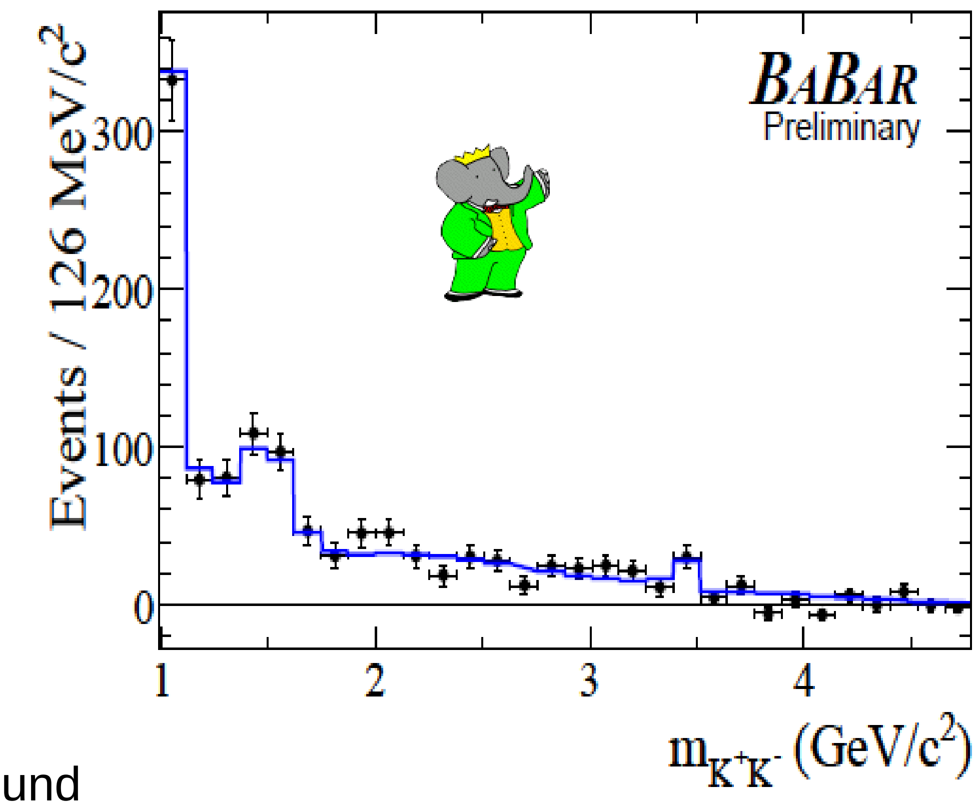
CP asymmetry ($\phi_{1,eff}$, A_{CP}) of B→ϕ (1020) K_S
using Time-dependent Dalitz plot analysis in B→K^+K^-Ks

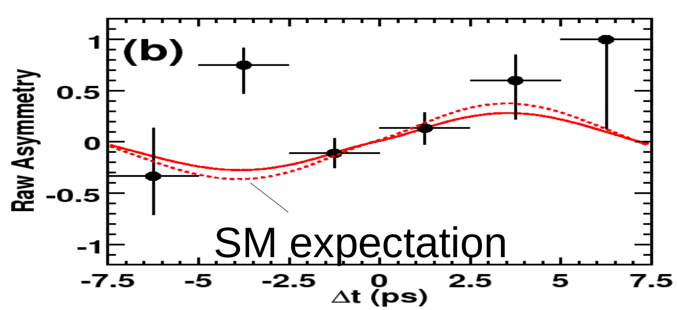
Dalitz plot fit results

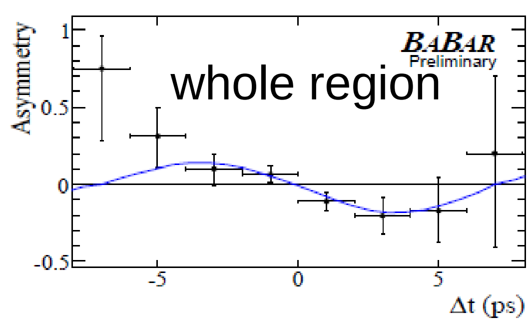
Belle 657MBB to be submitted to PRD.

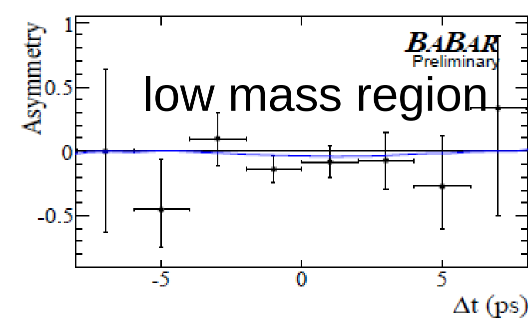
BABAR 465MBB arXiv:0808.0700







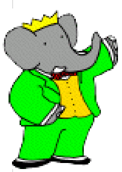


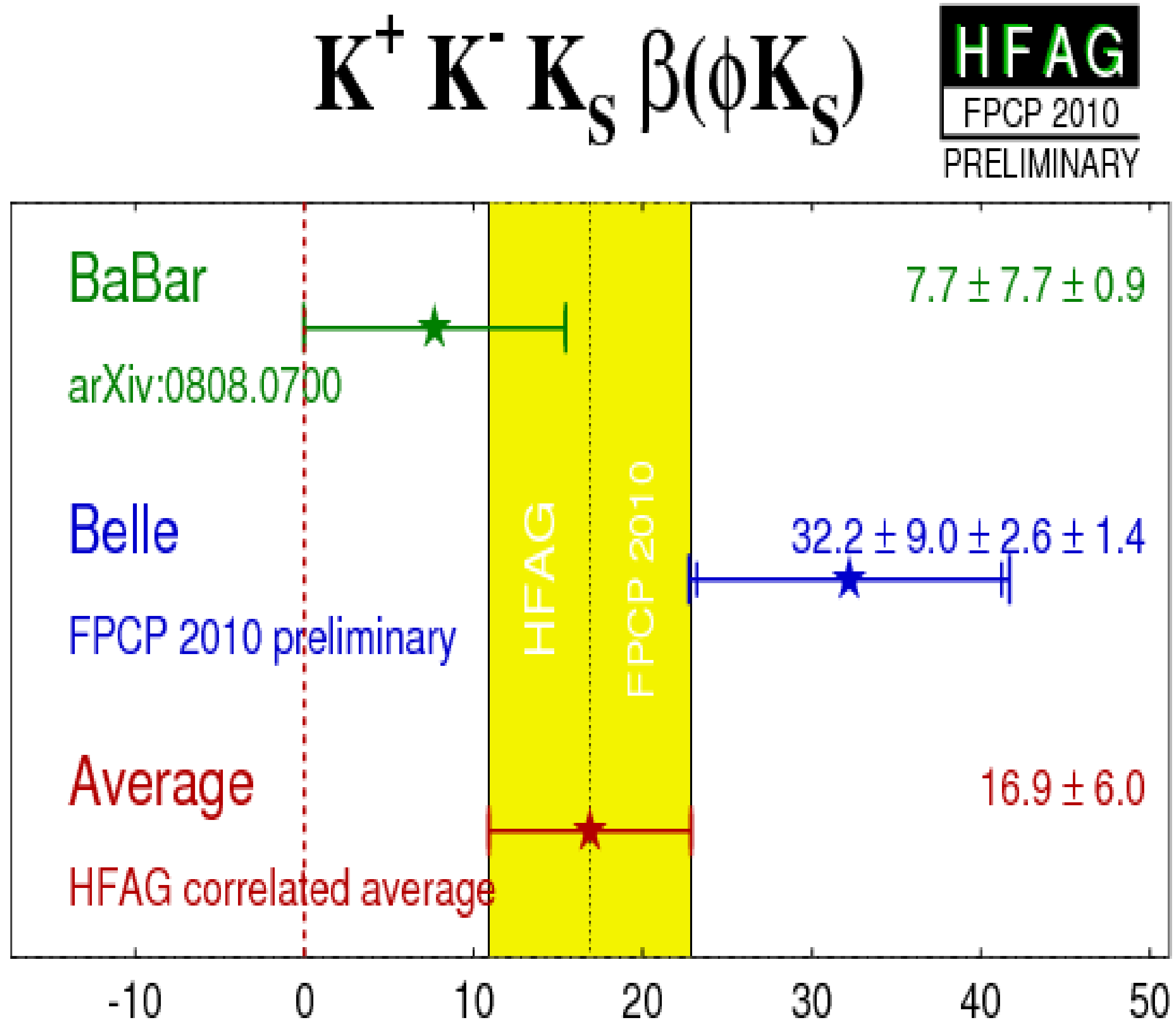


NOTE: Only the 1st of the four solutions is shown above.

Results from BaBar and Belle on Direct CPV using Dalitz plot analyses

	Solution 1
$\mathcal{A}_{CP}(f_0 K_S^0)$	$-0.30 \pm 0.29 \pm 0.11 \pm 0.09$
$\phi_1^{\rm eff}(f_0 K_S^0)$	$(31.3 \pm 9.0 \pm 3.4 \pm 4.0)^\circ$
$\mathcal{A}_{CP}(\phi K_S^0)$	$+0.04 \pm 0.20 \pm 0.10 \pm 0.02$
$\phi_1^{\rm eff}(\phi K_S^0)$	$(32.2 \pm 9.0 \pm 2.6 \pm 1.4)^\circ$



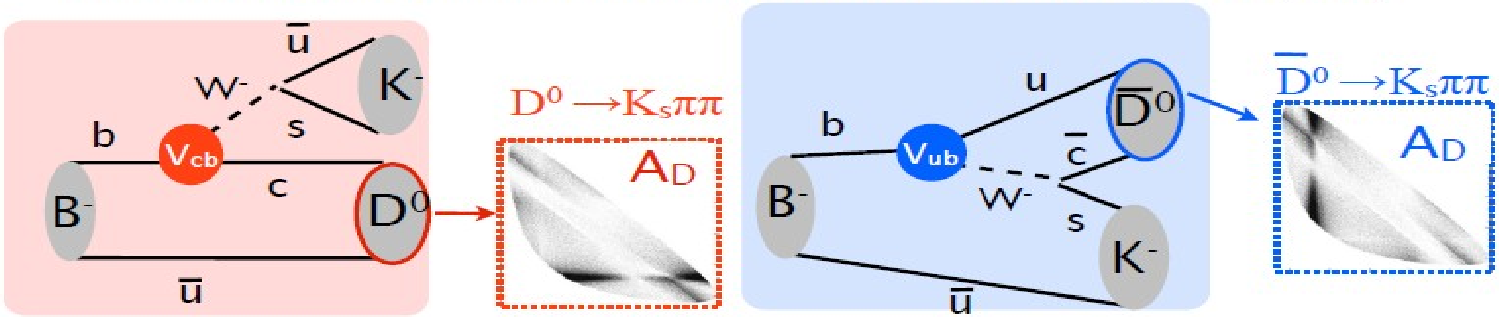


Name	Solution (1)
1 $A_{CP}(\phi K_S^0)$	$0.14 \pm 0.19 \pm 0.02$
2 $\beta_{\rm eff}(\phi K_S^0)$	$(7.7 \pm 7.7 \pm 0.9)^\circ$
3 $A_{CP}(f_0 K_S^0)$	$0.01 \pm 0.26 \pm 0.07$
4 $\beta_{\rm eff}(f_0 K_S^0)$	$(8.5 \pm 7.5 \pm 1.8)^\circ$

Measuring γ

- From interference of the decay amplitudes

γ in the interference term between transitions $b \to c\bar{u}s$ and $b \to u\bar{c}s$
when we reconstruct a final state accessible to both: $K_s\pi\pi$, K_sKK (GGSZ)



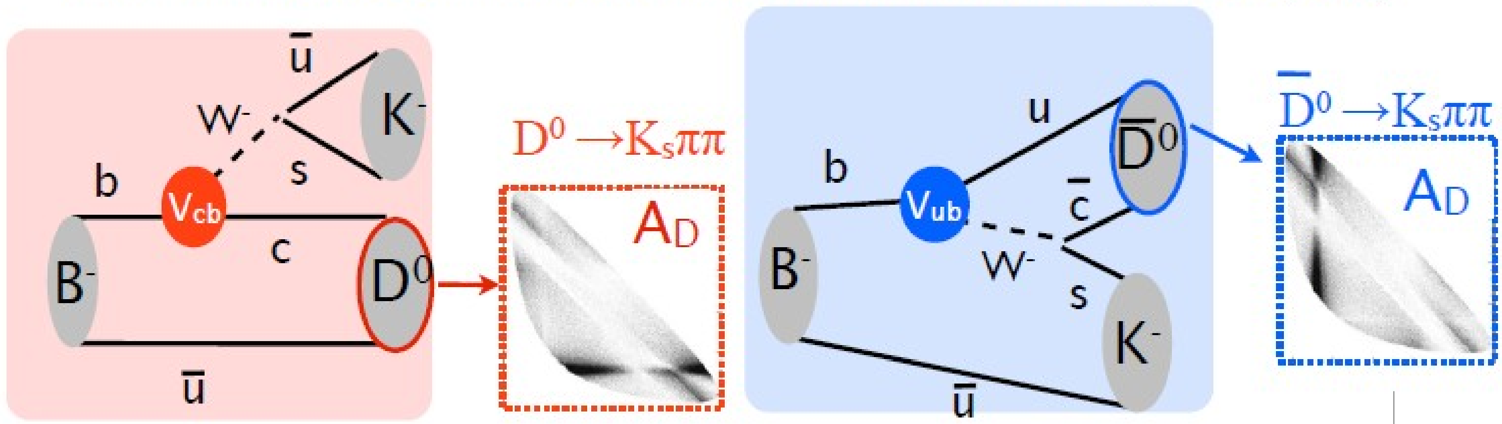
- Use final state accessible from both D^o and $\overline{D}^o$
  - Methods:
    * Gronau,London,Wyler Method,
    * Atwood, Dunietz, Soni Method (incl. DCS decays of the D meson)
    * Dalitz plot
- Common hadronic parameters

$$r_b = \left| \frac{A(b \to u)}{A(b \to c)} \right|$$

Strong (CP conserving) phase difference δ between $A(b \to u)$ and $A(b \to c)$

CP violation in the measurement of the CKM angle γ with $B^{\pm} \rightarrow D^{*} K^{*\pm}$ decays

γ in the interference term between transitions $b \rightarrow c\bar{u}s$ and $b \rightarrow u\bar{c}s$ when we reconstruct a final state accessible to both: $K_s\pi\pi$, K_sKK (GGSZ)

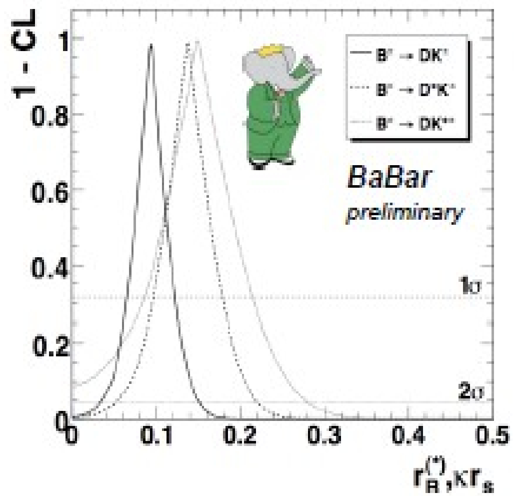


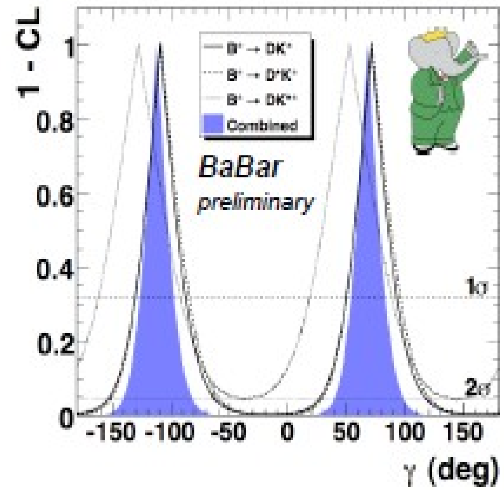
$$A(B^-) = \underline{\qquad\qquad} + r_b\, e^{-i\gamma + i\delta b} \underline{\qquad\qquad}$$

Determined from data

«... the full sub-resonance structure of the three-body decay is considered, involving also Cabibbo allowed decays. » - utfit.org

CP violation in the measurement of the CKM angle γ with $B^{\pm} \rightarrow D^{*} K^{*\pm}$ decays





BaBar *preliminary*

$\gamma = (68 \pm 14 \pm 4 \pm 3)^{o}$

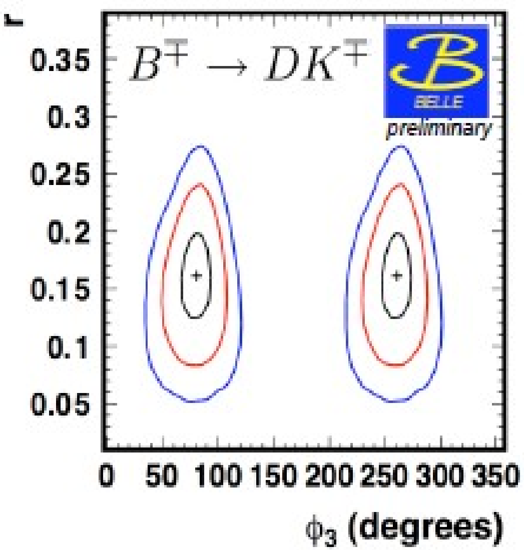
(value ± stat. ± sys. ± model)^{o}

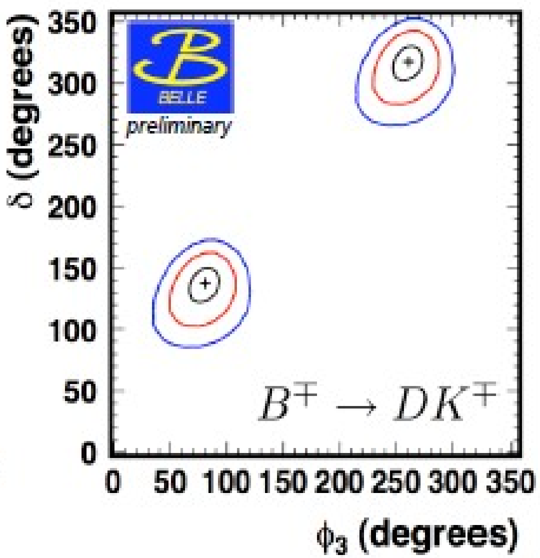
Excludes γ =0 at 3.5 std.dev.

$r_B(DK) = (9.4\ ^{+2.8}_{-2.9})\%$

(value ± total error)%

Error breakdown (±0.5 *expt.*, ±0.4 *model*)%





BELLE *preliminary*

$\gamma = (78.4\ ^{+10.8}_{-11.6} \pm 3.6 \pm 8.9)^{o}$

(value ± stat. ± sys. ± model)^{o}

*B→DK and B→D*K only, 657 MB$\bar{B}$*

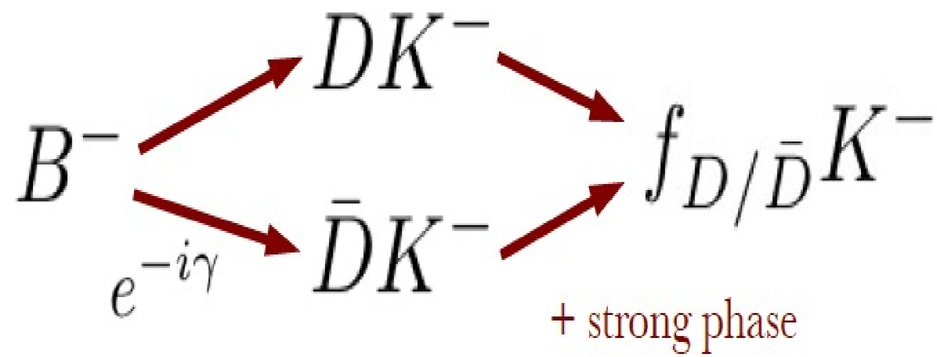
Excludes γ =0 at 3.5 std.dev.

$r_B(DK) = (16.0\ ^{+4.0}_{-3.8} \pm 0.011\ ^{+5.0}_{-1.0})\%$

(value ± stat. ± sys. ± model)%

Measurement of the CKM angle γ using a GLW analysis of $B^{\pm} \rightarrow D(CP)\, K^{\pm}$ decays at BaBar

- The Gronau, London, Wyler (GLW) method:
  Gronau & London, PLB 253, 483 (1991)
  Gronau & Wyler, PLB 265, 172 (1991)



$$R_{CP\pm} = 1 + r^2 \pm 2r\cos\delta\cos\gamma$$
$$A_{CP\pm} = \pm 2r\sin\delta\sin\gamma / R_{CP\pm}$$

–

Make use of a larger control sample:

$$R_{CP\pm} \approx \frac{R^{\pm}_{K/\pi}}{R^{\text{flv}}_{K/\pi}}$$

Many systematics cancel in the double ratio.

$$R^{\pm}_{K/\pi} \equiv \frac{\mathcal{B}(B^- \rightarrow D^0_{CP\pm}K^-) + \mathcal{B}(B^+ \rightarrow D^0_{CP\pm}K^+)}{\mathcal{B}(B^- \rightarrow D^0_{CP\pm}\pi^-) + \mathcal{B}(B^+ \rightarrow D^0_{CP\pm}\pi^+)}$$

$$B^+ \rightarrow \overline{D^0}K^+$$
$$B^+ \rightarrow \overline{D^0}\pi^+$$

Measurement of the CKM angle γ using a GLW analysis of $B^{\pm}\to D(CP)\,K^{\pm}$ decays at BaBar

- Reconstruct $B^{\pm}\to D\,K^{\pm}$
  - D meson is reconstructed in CP-eigenstates and
  - Non-CP final states

$\overline{D^0}\to$	CP+	CP-	non-CP
	$\pi^+\pi^-$	$K_S\pi^0$	$K^+\pi^-$
	K^+K^-	$K_S\omega$	
		$K_S\Phi$	

Preliminary Results:

(submitted to PRD)

$$A_{CP+} = 0.25 \pm 0.06(\mathrm{stat}) \pm 0.03(\mathrm{syst})$$
$$A_{CP-} = -0.09 \pm 0.07(\mathrm{stat}) \pm 0.02(\mathrm{syst})$$
$$R_{CP+} = 1.18 \pm 0.09(\mathrm{stat}) \pm 0.06(\mathrm{syst})$$
$$R_{CP-} = 1.07 \pm 0.08(\mathrm{stat}) \pm 0.05(\mathrm{syst})$$

Improves over old result with:

- 20% more data; 467 million $B\overline{B}$ decays
- Improved fit strategy
- Now constrains γ

Measurement of the CKM angle γ using a GLW analysis of $B^{\pm} \to D(CP) K^{\pm}$ decays at BaBar

Preliminary Results:

(submitted to PRD)

At the 68% CL :

γ belongs to one of the three intervals
$[11.3^{\circ}, 22.7^{\circ}]$,
$[80.9^{\circ}, 99.1^{\circ}]$
or
$[157.3^{\circ}, 168.7^{\circ}]$

and

$0.24 < r_B < 0.45$

BaBar ADS analysis: b→u transitions in $B^-\to D^0K^-$ and $B^-\to D^{*0}K^-$ decays

In the ADS technique the amplitudes are equalized

- **A**twood, **D**unietz, **S**oni (ADS), PRL 78, 3257 (1997) & PRD 63, 036005 (2001)

$$\overset{\text{favored}}{B^- \to D^0 K^-} \quad \overset{\text{suppressed}}{D^0 \to K^+\pi^-}$$

$$\overset{\text{suppressed}}{B^- \to \overline{D}^0 K^-} \quad \overset{\text{favored}}{\overline{D}^0 \to K^+\pi^-}$$

$$\to [K^+\pi^-]_D K^-$$

Small BF(~10-7), but *A2 = O(A1)*: expect large CPV

Very sensitive to r_b

$$R_{ADS} = \frac{BF([K^+\pi^-]K^-) + BF([K^-\pi^+]K^+)}{BF([K^-\pi^+]K^-) + BF([K^+\pi^-]K^+)} = r_D^2 + r_B^2 + 2r_B r_D \cos(\delta_D + \delta_B)\cos\gamma$$

- Amount of interference depends on CKM angle γ/ϕ_3

$$A_{ADS} = \frac{BF([K^+\pi^-]K^-) - BF([K^-\pi^+]K^+)}{BF([K^+\pi^-]K^-) + BF([K^-\pi^+]K^+)} = 2r_B r_D \sin(\delta_D + \delta_B)\sin\gamma / R_{ADS}$$

CP asymmetry can be very large

BaBar ADS analysis: $b \to u$ transitions in $B^- \to D^0 K^-$ and $B^- \to D^{*0} K^-$ decays

- Clear evidence for $B \to D^{(*)}\pi$ DCSD

- Indication of a $D^0 K$ ADS signal at the 2.1σ level and $D^{*0}K$ at the 2.2σ level ($D^0\pi^0$)

BaBar Preliminary Results:

$$\mathcal{R}_{DK} = (1.1 \pm 0.5 \pm 0.2) \times 10^{-2}. \quad \mathcal{R}^*_{DK,D^0\pi^0} = (1.8 \pm 0.9 \pm 0.4) \times 10^{-2}.$$

$$= r_B^2 + r_D^2 + 2\, r_B r_D \cos\gamma \cos\delta$$

BaBar Preliminary Results:

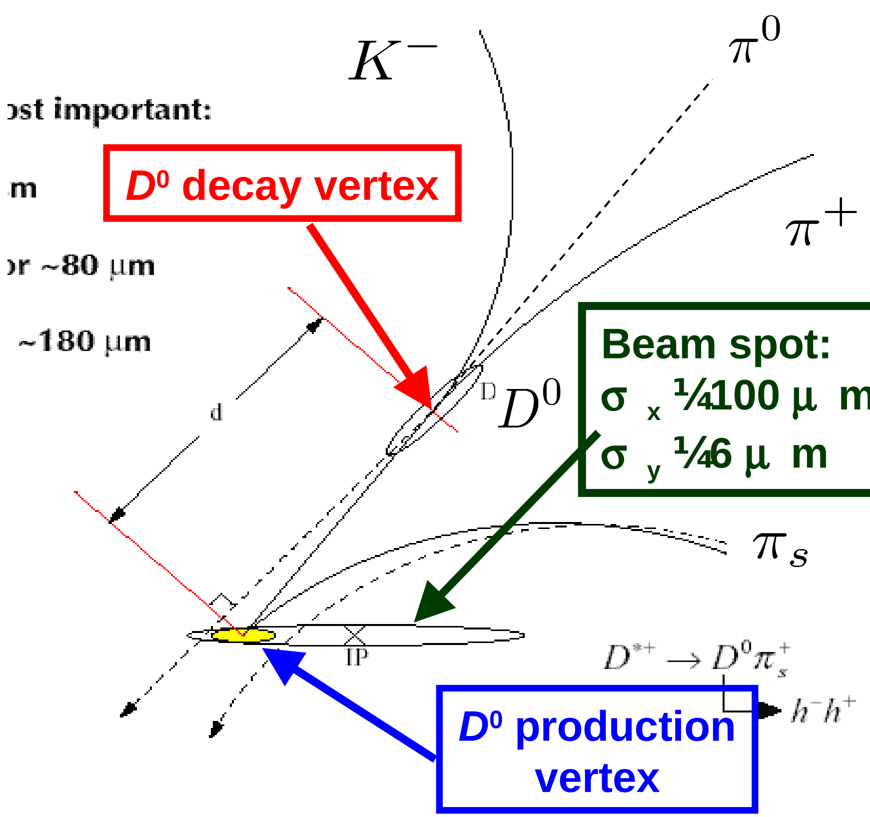
$$\mathcal{A}_{DK} = -0.86 \pm 0.47\ ^{+0.11}_{-0.15}\,. \qquad \mathcal{A}^*_{DK,D^0\pi^0} = +0.77 \pm 0.35 \pm 0.12.$$

$$= 2\, r_B r_D \sin\gamma \sin\delta / \mathcal{R}_{DK}$$

CP Violation in D decays at the B-factories

1.3 million charm events per /fb at Y(4S)

(Y(4S): cc cross section = 1/4 observed total)



Charm meson Tagging and Selection

- **Tagging at production:**
  - Inclusive D* production. Using $D^{*\pm} \rightarrow D^0 \pi_s^{\pm}$ decays.
  - The flavor of the D^0 is determined by the charge of the π_s.
- **Tagging at decay:**
  - The flavor can be determined by the wrong sign (WS) or right sign (RS) D^0 decay products.

$D^0 \rightarrow K^-\pi^+\pi^0$ right-sign (RS)

$D^0 \rightarrow K^+\pi^-\pi^0$ wrong-sign (WS)

- **Selection:**
  - $e^+e^- \rightarrow c\bar{c}$ events have high D^0 momentum in the CM frame.
    - Use momentum to reject BB events ($p_{D0}^{CMF} > 2.5$ GeV/c)
  - Beam spot constraint determines t and σ_{t} and improves m_D and $\Delta m = m(D^0 \pi_s) - m(D^0)$ resolutions.

D^0 mixing: $D^0 \to KK$ vs $K\pi$ and y_{CP}

- Since 2007 evidence, $D^0 \longleftrightarrow \overline{D}^0$ mixing established by combination of many measurements.
- D^0 mixing and CP violation alter decay time distribution of CP eigenstates
- – No single measurement with >5σ significance.

$$|D_1\rangle = p|D^0\rangle + q|\overline{D}^0\rangle$$
$$|D_2\rangle = p|D^0\rangle - q|\overline{D}^0\rangle$$

In the limit of *CP* conservation: $D_1 = CP+$, $D_2 = CP-$

- If CP is conserved (CPV<0.1% in SM) $D0 \to K+K-$ directly measures $\Gamma 1$.

D^0 mixing parameters

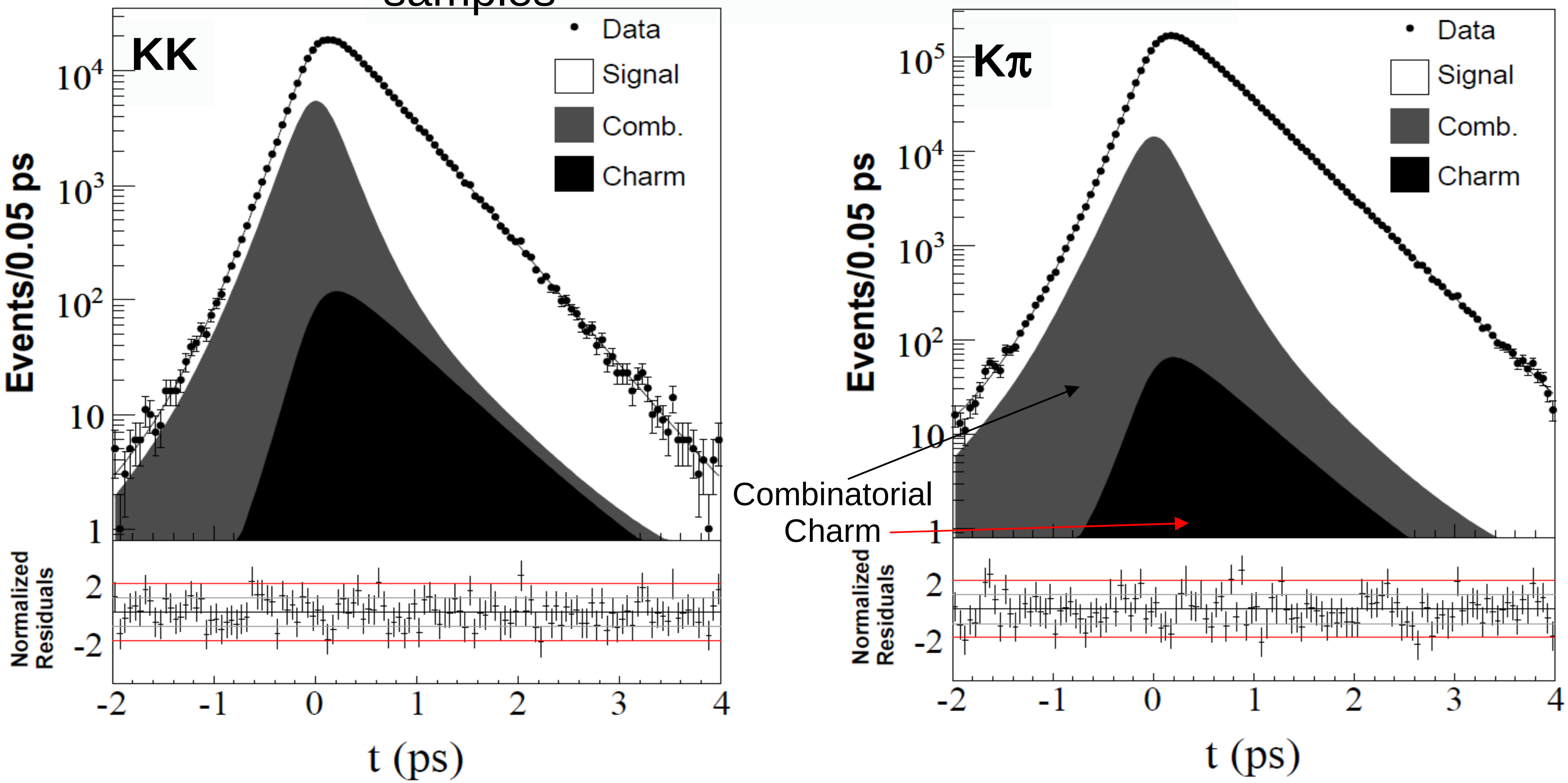
$$x \equiv 2\frac{M_1 - M_2}{\Gamma_1 + \Gamma_2}, \quad y \equiv \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2} = \frac{\Gamma_1}{\Gamma} - 1$$

$$y_{CP} \equiv \frac{\tau_{K\pi}}{\tau_{KK}} - 1 \quad = y$$

If CP conserved (SM)

D^0 mixing: $D^0 \rightarrow KK$ vs $K\pi$ and y_{CP}

Combined fit to KK and K**π** data samples

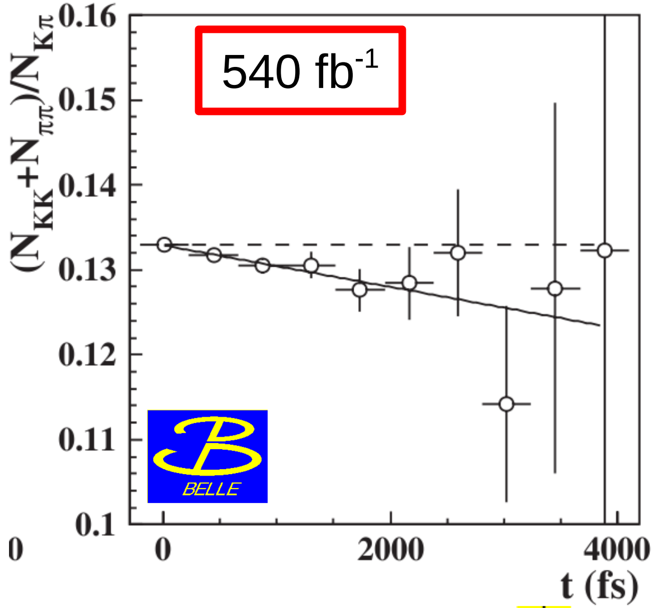


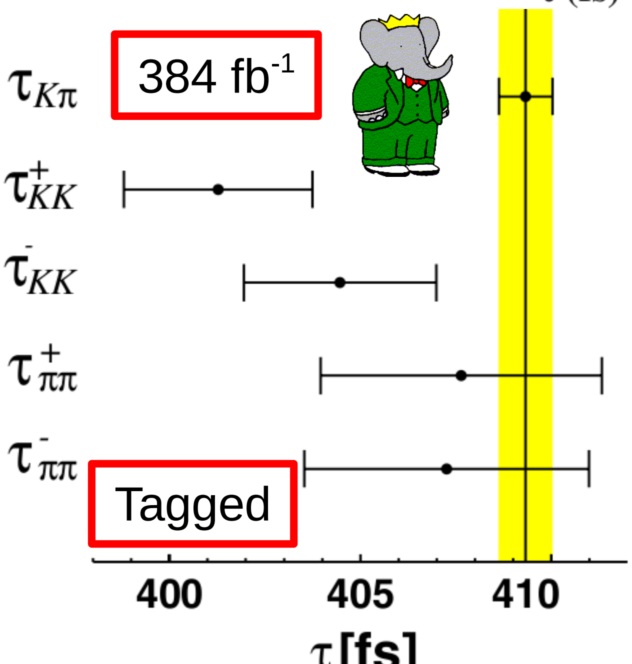
τ_{KK} (fs) ~= 405.85

$\tau_{K\pi}$ (fs) ~= 410.39

Resolution Offset
t_0 = - 5.67 ± 0.28 fs

Lifetime ratio $D^0 \rightarrow h^+ h^- / D^0 \rightarrow K^- \pi^+$





PRL 98, 211803 (2007) – Belle

y_{CP} = (1.31 ± 0.32 (stat) ± 0.25 (syst))·10^{-2}
A_τ = (0.01 ± 0.30 (stat) ± 0.15 (syst))·10^{-2}

Mixing evidence at 3.2σ

PRD 78, 011105(R) (2008) – BaBar

Tagged:
y_{CP} = (1.03 ± 0.33 (stat) ± 0.19 (syst))·10^{-2}
Δy = (-0.26 ± 0.36 (stat) ± 0.08 (syst))·10^{-2}

Mixing evidence at 3σ

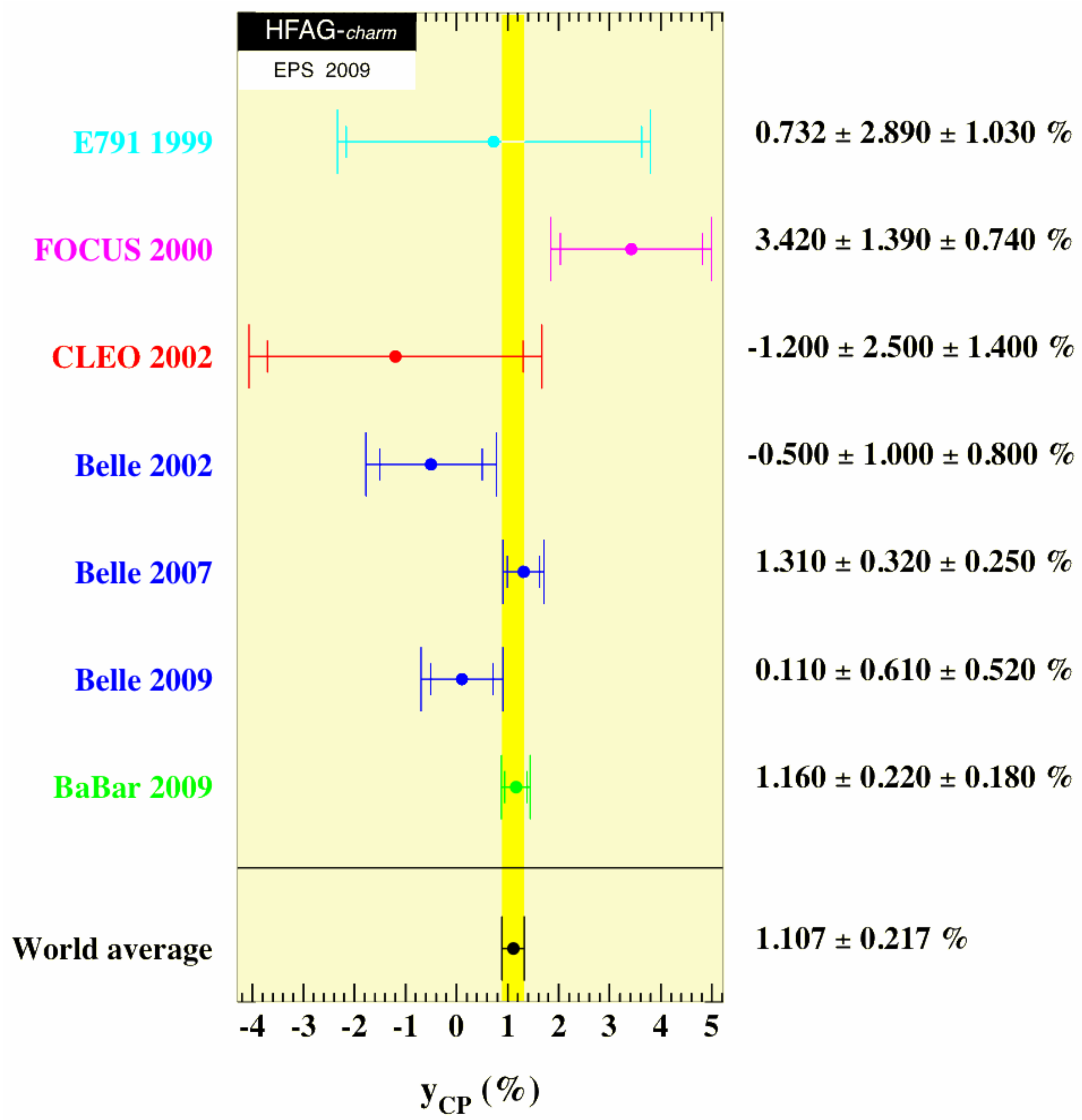
PRD 80, 071103(R) (2009) – BaBar

Combined tagged + untagged:
y_{CP} = (1.13 ± 0.22 (stat) ± 0.18 (syst))·10^{-2}

Mixing evidence at 4.1σ

HFAG averages (measurements of y_{CP})

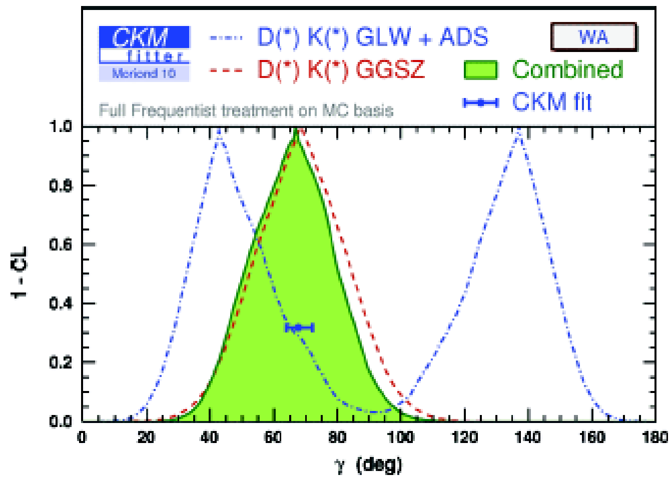
http://www.slac.stanford.edu/xorg/hfag/charm/index.html



Last Full Fit γ/ϕ_3 Results

Frequentist interpretation

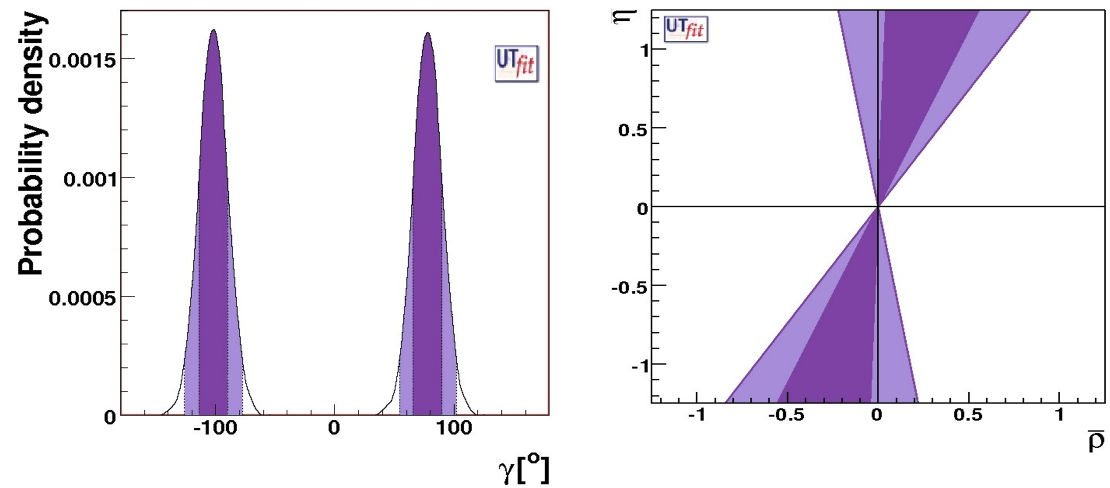
http://ckmfitter.in2p3.fr



$$\gamma = (69\ ^{+19}_{-21})^\circ$$

μ supremum method used to combine HFAG averages of experimental inputs (conservative, but guarantees coverage).
See Karim Trabelsi's talk at CKM 2008 for details.

Bayesian interpretation



bound from
B → DK, D*K andDK* decays with present measurements using all the methods.

γ = 78 ± 12 ([54,102] @ 95% Prob.)

See:

http://www.utfit.org/gamma/ckm-gamma.html

Conclusions

- New results from Belle and BaBar in particular for the CKM angle γ/ϕ_3:
  - Results from BaBar and Belle on Direct CPV using Dalitz plot analyses (new meaurement on β and γ)
  - Measurement of the CKM angle γ using a GLW analysis of $B^{\pm}\rightarrow D(CP)\ K^{\pm}$ decays at BaBar
  - BaBar ADS analysis: $b\rightarrow u$ transitions in $B^{-}\rightarrow D^{0}K^{-}$ and $B^{-}\rightarrow D^{*0}K^{-}$ decays (new result on γ)
  - D^0 mixing: $D^0\rightarrow KK$ vs $K\pi$ and y_{CP}

Conclusions (continued)

- The data collection has ended but expect many more new and improved measurements and for the statistically limited measurements we look forward to the SuperB and BELLEII factories
- Many thanks to the Meson2010 organizers and the funding agencies

The end ...

Results from the Full Fit (utfit.org)

Parameter	Value ± Error
λ	0.2259 ± 0.0016
ρ	0.154 ± 0.022
η	0.342 ± 0.014
$\alpha(^o)$	92.0 ± 3.4
$\beta(^o)$	22.0 ± 0.8
$\gamma(^o)$	65.6 ± 3.3

Dalitz plot fit results

BELLE

	Solution 1	Solution 2	Solution 3	Solution 4
$\mathcal{A}_{CP}(f_0 K_S^0)$	$-0.30 \pm 0.29 \pm 0.11 \pm 0.09$	$-0.20 \pm 0.15 \pm 0.08 \pm 0.05$	$+0.02 \pm 0.21 \pm 0.09 \pm 0.09$	$-0.18 \pm 0.14 \pm 0.08 \pm 0.06$
$\phi_1^{\mathrm{eff}}(f_0 K_S^0)$	$(31.3 \pm 9.0 \pm 3.4 \pm 4.0)^\circ$	$(26.1 \pm 7.0 \pm 2.4 \pm 2.5)^\circ$	$(25.6 \pm 7.6 \pm 2.9 \pm 0.8)^\circ$	$(26.3 \pm 5.7 \pm 2.4 \pm 5.8)^\circ$
$\mathcal{A}_{CP}(\phi K_S^0)$	$+0.04 \pm 0.20 \pm 0.10 \pm 0.02$	$+0.08 \pm 0.18 \pm 0.10 \pm 0.03$	$-0.01 \pm 0.20 \pm 0.11 \pm 0.02$	$+0.21 \pm 0.18 \pm 0.11 \pm 0.05$
$\phi_1^{\mathrm{eff}}(\phi K_S^0)$	$(32.2 \pm 9.0 \pm 2.6 \pm 1.4)^\circ$	$(26.2 \pm 8.8 \pm 2.7 \pm 1.2)^\circ$	$(27.3 \pm 8.6 \pm 2.8 \pm 1.3)^\circ$	$(24.3 \pm 8.0 \pm 2.9 \pm 5.2)^\circ$