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Heidelberg, 10 April 2013

BLV2013: From the Cosmos to the LHC

CP, T and CPT symmetry studies with the BABAR experiment

Three types of CP violation: in decays, in transitions, and in the interplay of both

All three have been observed in the $K^0\overline{K}^0$, two in the $B^0\overline{B}^0$ system

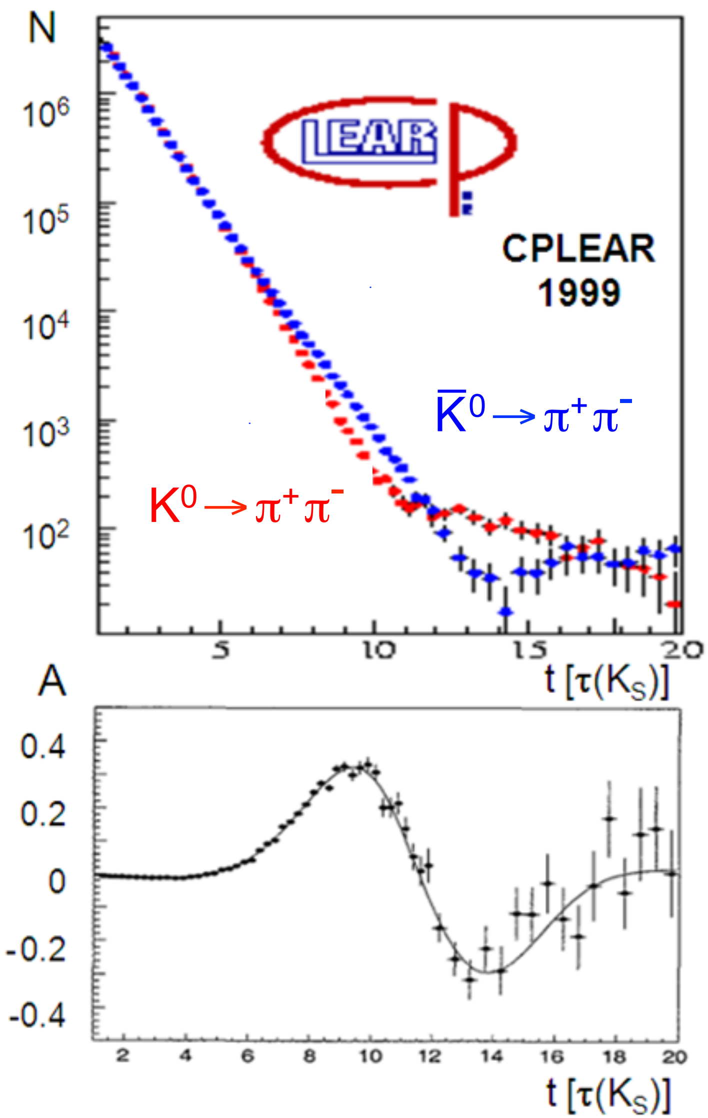
BABAR collected 940 M B mesons from 1999 to 2008, continued analysis

Two examples for („direct") CP violation

Search for CP, T and CPT violation in $B^0\overline{B}^0$ transitions

CP and T violation in the interplay of transitions and decays

CP Symmetry Breaking in the $K^0\bar{K}^0$ System



Discovered 1964, PRL 13,138 (1964),

🡐 easier to see in this result, PLB 458,545 (1999)

Nonexponential decay law due to $K^0\bar{K}^0$ transitions,

Two different decay laws due to CP violation.

Only two states decay exponentially:

$$K_S^0(0) = \left[\left(1+\varepsilon+\delta\right)\cdot K^0 + \left(1-\varepsilon-\delta\right)\cdot \bar{K}^0\right]/\sqrt{2}$$
$$K_L^0(0) = \left[\left(1+\varepsilon-\delta\right)\cdot K^0 - \left(1-\varepsilon+\delta\right)\cdot \bar{K}^0\right]/\sqrt{2}$$

CP: $\varepsilon = \delta = 0$, CPT: $\delta = 0$, T: $\varepsilon = 0$.

Since 1970, PL 31B, 662 (1970): $\mathrm{Re}\,\varepsilon = 1.6\cdot 10^{-3}$, $\delta \approx 0$.

Today, PDG (2012), $\mathrm{Re}\,\varepsilon = (161 \pm 0.5)\,10^{-5}$,
$\mathrm{Im}\,\delta = (-0.7 \pm 1.4)\,10^{-5}$,
$\mathrm{Re}\,\delta = (\,24 \pm 23)\,10^{-5}$.

Three types of CP Violation

CP symmetry is broken in three different types of observations:

- Asymmetry in decay amplitudes, „direct CP violation“
- Asymmetry in transitions, e. g. $K^0 \leftrightarrow \bar{K}^0$
- Asymmetry in the interplay of transition and decay

Direct CP violation: First observed in K^0 decays around 1999, WA today:

$$\frac{\left|\left\langle\pi^+\pi^-\left|T\right|K^0\right\rangle\right|^2-\left|\left\langle\pi^+\pi^-\left|T\right|\bar{K}^0\right\rangle\right|^2}{\left|\left\langle\pi^+\pi^-\left|T\right|K^0\right\rangle\right|^2+\left|\left\langle\pi^+\pi^-\left|T\right|\bar{K}^0\right\rangle\right|^2}\approx 2\,\mathrm{Re}\,\varepsilon'=(5.4\pm 0.6)\cdot 10^{-6}.$$

NA48 PLB 544,97 (2002)

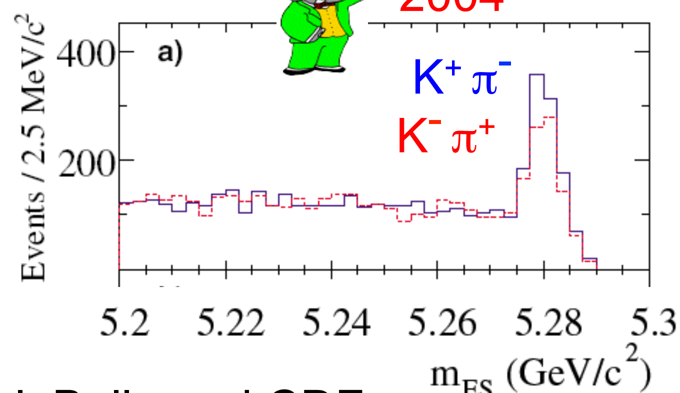
KTeV PRD 83,092001 (2011)

First observation in B-meson decays:

BABAR, PRL 93,131801 (2004) 230 M $B\bar{B}$

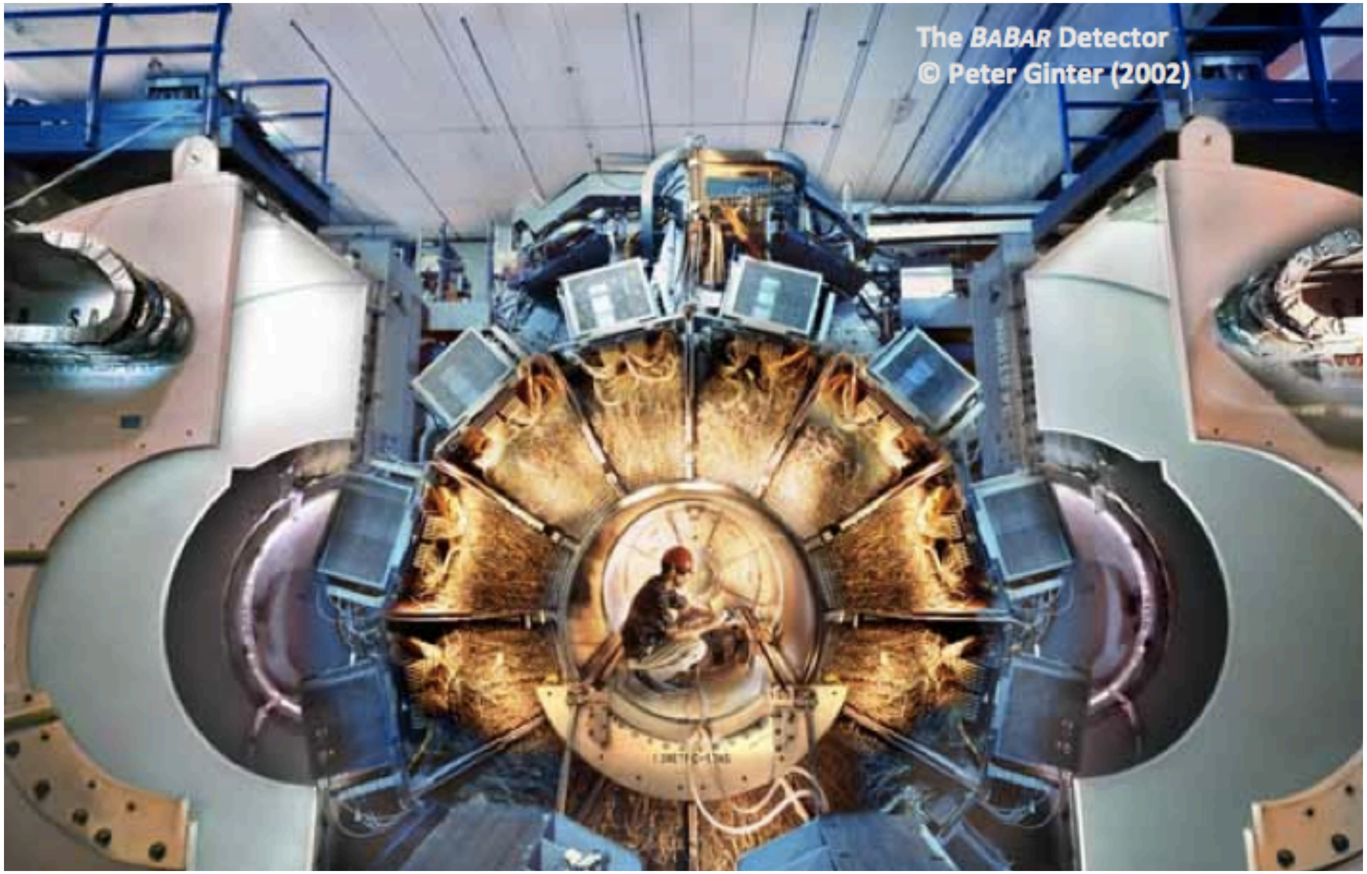
$$\frac{\left|\left\langle K^+\pi^-\left|T\right|B^0\right\rangle\right|^2-\left|\left\langle K^-\pi^+\left|T\right|\bar{B}^0\right\rangle\right|^2}{\left|\left\langle K^+\pi^-\left|T\right|B^0\right\rangle\right|^2+\left|\left\langle K^-\pi^+\left|T\right|\bar{B}^0\right\rangle\right|^2}=0.133\pm 0.031.$$

2004



S = 4.2 σ; 5.5 σ in 2007. WA today: 0.097 ± 0.012 incl. Belle and CDF.

BABAR @ PEP-II, SLAC



The BABAR experiment recorded 470 M events $\Upsilon(4S) \rightarrow B\,\bar{B}$ from 1999 to 2008, produced by PEP-II in e^+ (3.1 GeV) + e^- (9 GeV) collisions.

Now ~ 510 publications, continued with ~ 40/y.

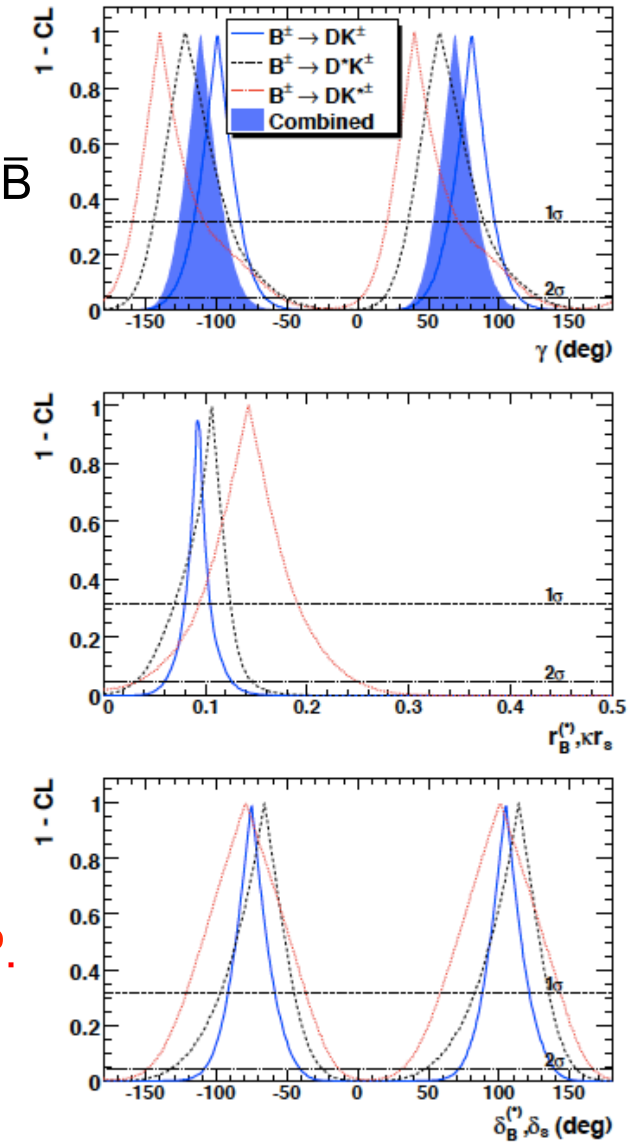
A 2nd significant example for direct CP violation

$B^\pm \to D^0 K^\pm$ interfering with $B^\pm \to \bar{D}^0 K^\pm$ where D^0 and $\bar{D}^0$ decay into the same final state f = $K^0_S \pi^+ \pi^-$, $K^+ K^-$... PRD 87,052015 (2013) 470 M $B\bar{B}$

The CP-violating asymmetry *A* between the rates for f K^+ and f K^- depends on the CKM angle γ, on the decay ratio r_B of the two interfering contributions, and on the difference δ_B of the two final-state strong-interaction phases. All three parameters are determined model-independently →

A is non-zero with 5.1 σ. The same analyses with $D^*K^\pm$ and $D K^{*\pm}$ give asymmetries with 3.0 and 2.1 σ. Combined 5.9 σ, $\gamma = \arg(V_{ub} V_{ud}^* V_{cd} V_{cb}^*) = (69^{+17}_{-16})^o$.

Agrees with Belle, $(68^{+15}_{-14})^o$, CKM-2012 and LHCb, $(71^{+17}_{-16})^o$, LHCb-CONF-2012-032, Average ≈ ±10°.



Search for CP and T Violation in Transitions $B^0 \leftrightarrow \bar{B}^0$

$$R_1(B\to B) = e^{-\Gamma t}\left[\cosh(\Delta\Gamma t/2) + 4\,\mathrm{Re}\,\delta\cdot\sinh(\Delta\Gamma t/2) + \cos\Delta m t - 4\,\mathrm{Im}\,\delta\cdot\sin\Delta m t\right]/2$$

$$R_2(\bar{B}\to \bar{B}) = e^{-\Gamma t}\left[\cosh(\Delta\Gamma t/2) - 4\,\mathrm{Re}\,\delta\cdot\sinh(\Delta\Gamma t/2) + \cos\Delta m t + 4\,\mathrm{Im}\,\delta\cdot\sin\Delta m t\right]/2$$

$$R_3(B\to \bar{B}) = e^{-\Gamma t}(1-4\,\mathrm{Re}\,\varepsilon)\left[\cosh(\Delta\Gamma t/2) - \cos\Delta m t\right]/2$$

$$R_4(\bar{B}\to B) = e^{-\Gamma t}(1+4\,\mathrm{Re}\,\varepsilon)\left[\cosh(\Delta\Gamma t/2) - \cos\Delta m t\right]/2$$

$R_1 \neq R_2$ violates CP & CPT, and
$R_3 \neq R_4$ violates CP & T, as for K^0

Well known: $\tau = 1/\Gamma = 1.5 \cdot 10^{-12}$ s, $\Delta m/\Gamma = 0.770$,

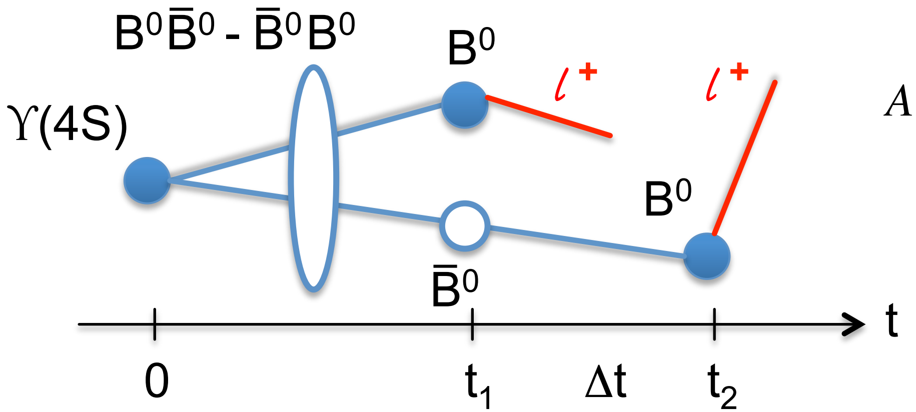
Not so well: $\Delta\Gamma/\Gamma = 0.015 \pm 0.018$, Re $\varepsilon = (0.0 \pm 0.9)\cdot 10^{-3}$, PDG 2012

St.Model: $\Delta\Gamma/\Gamma = (4.2 \pm 0.8)\cdot 10^{-3}$, Re $\varepsilon = (-1.0 \pm 0.15)\cdot 10^{-4}$, arXiv:1102.4274

BABAR contr.: PRL 96,251802 (2006) 230 M $B\bar{B}$ Re $\varepsilon = (+0.4 \pm 1.3 \pm 0.9)\cdot 10^{-3}$

Method:

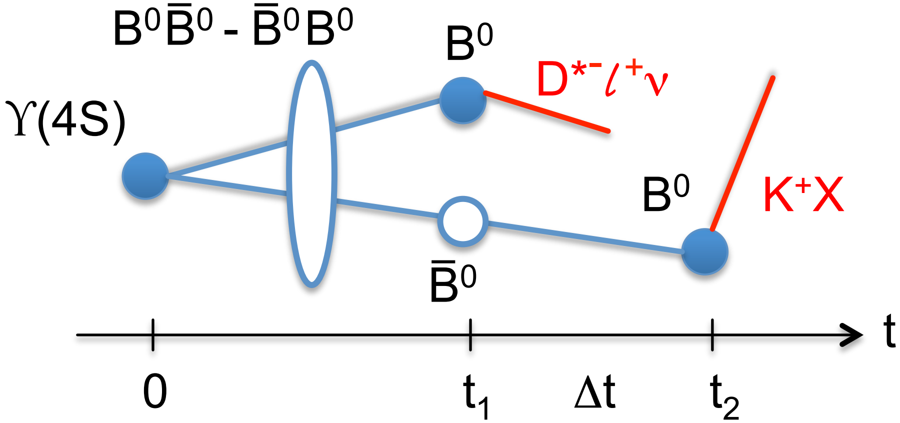
e + μ used



$$A = \frac{N(\ell^+\ell^+) - N(\ell^-\ell^-)}{N(\ell^+\ell^+) + N(\ell^-\ell^-)} = 4\,\mathrm{Re}\,\varepsilon$$

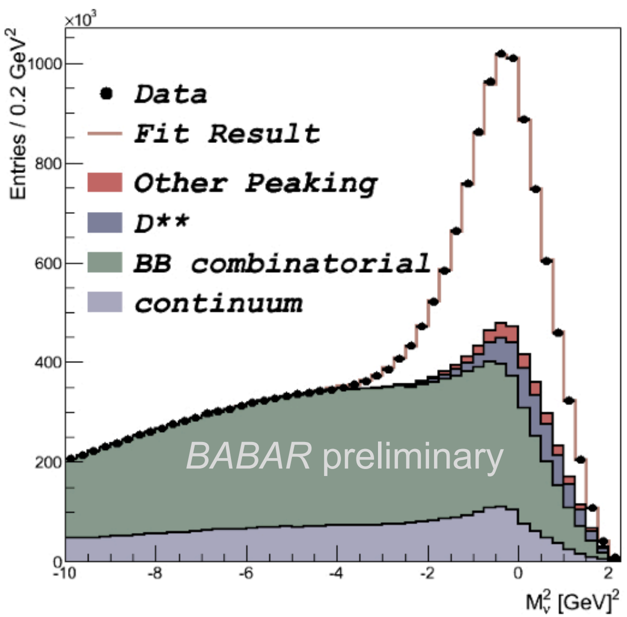
other significant results:
Belle 2006, D0 2011

New preliminary BABAR result

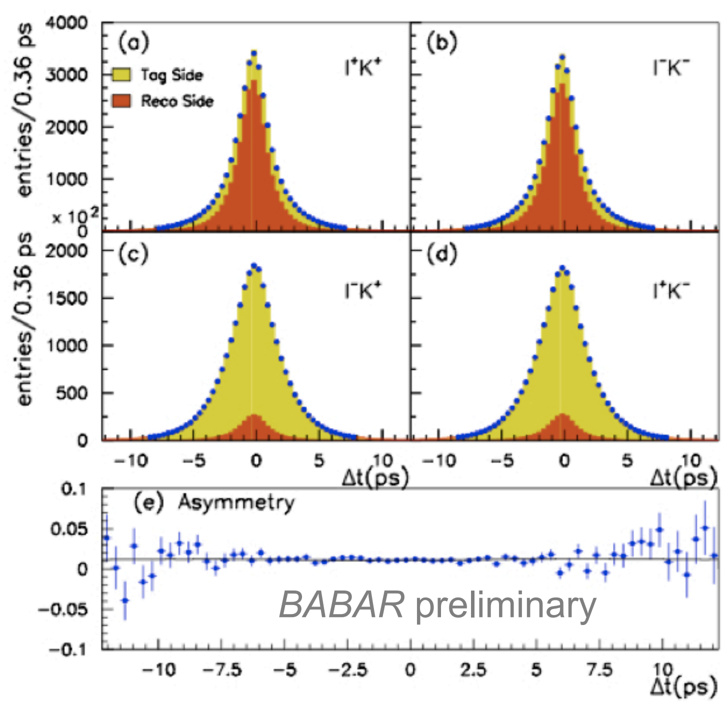


$$A_{CP} = \frac{N\left(D^{*-}\ell^+\nu, K^+\right) - N\left(D^{*+}\ell^-\bar{\nu}, K^-\right)}{N\left(D^{*-}\ell^+\nu, K^+\right) + N\left(D^{*+}\ell^-\bar{\nu}, K^-\right)} = 4\,\mathrm{Re}\,\varepsilon$$

Using the full dataset of 470 M $B\bar{B}$ with e and μ. D* only „reconstructed" by the slow π from $D^* \rightarrow D\,\pi$.



$$M_\nu^2 = \left(\sqrt{s}/2 - E_{D^*} - E_\ell\right)^2 - \left(\vec{p}_{D^*} + \vec{p}_\ell\right)^2$$



Result: Re ε = $(+0.2 \pm 0.4 \pm 0.9) \cdot 10^{-3}$

PDG 2012:

Re ε = $(0.0 \pm 0.9) \cdot 10^{-3}$

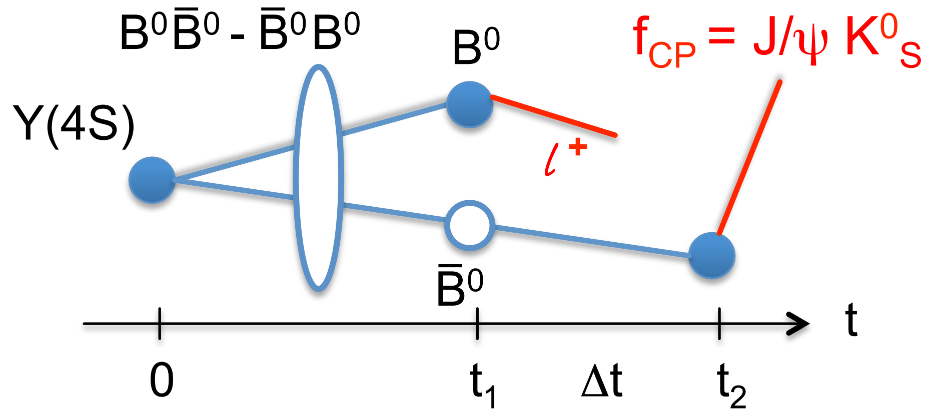
New prelim. average:

Re $\varepsilon \approx (0.1 \pm 0.6) \cdot 10^{-3}$

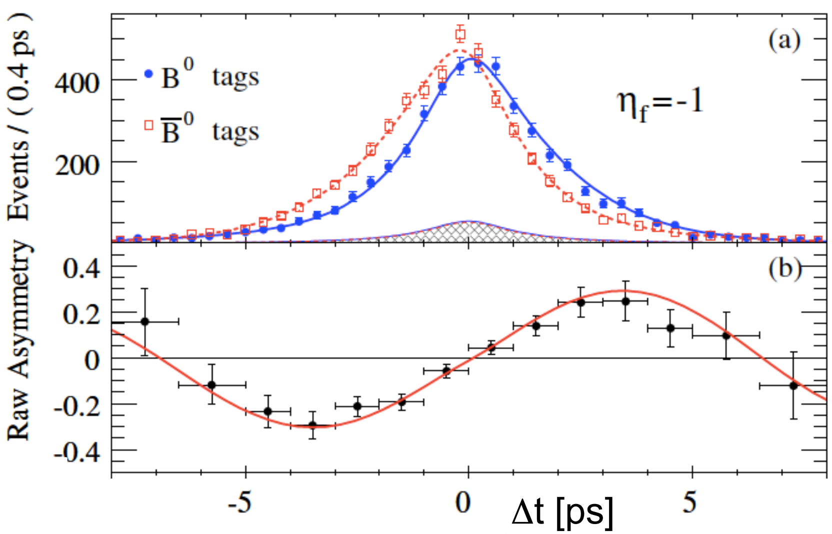
Belle?

LHCb ?

Type 3: Interplay of Transition and Decay



PRD 79,072009 (2009), 470 $MB\bar{B}$



$A = \sin 2\beta \sin \Delta m \Delta t$, $\beta = \arg (V_{cb} V_{cd}^* V_{td} V_{tb}^*)$

BABAR result including other $c\bar{c}$ states: $\sin 2\beta = 0.687 \pm 0.028 \pm 0.012$

World Average HFAG-2012: $\sin 2\beta = 0.682 \pm 0.019$. $\beta = (21.5 \pm 0.8)^o$

Similar measurements with the final state $f_{CP} = \pi^+ \pi^-$ give

$\alpha = \arg (V_{ub} V_{ud}^* V_{td} V_{tb}^*)$. Average CKMfitter-2012 incl. $\pi\pi, \pi\rho, \rho\rho$: $\alpha = (88.5 \pm 4.7)^o$

From direct CPV in $B^+ \to D^0 K^+$ (page 5) we had: $\gamma = (69 \pm 10)^o$

The St.Model condition $\alpha + \beta + \gamma = 180^o$ is well fullfilled. All observed CPV is part of the St.Model which is CPT-symmetric. Are there tests of CPT in the B system?

Searches for CP & CPT Violation in Transitions

$$R_1\left(B\to B\right)=e^{-\Gamma t}\left[\cosh\left(\Delta\Gamma\, t/2\right)+4\,\mathrm{Re}\,\delta\cdot\sinh\left(\Delta\Gamma\, t/2\right)+\cos\Delta m t-4\,\mathrm{Im}\,\delta\cdot\sin\Delta m t\right]/2$$

$$R_2\left(\bar{B}\to \bar{B}\right)=e^{-\Gamma t}\left[\cosh\left(\Delta\Gamma\, t/2\right)-4\,\mathrm{Re}\,\delta\cdot\sinh\left(\Delta\Gamma\, t/2\right)+\cos\Delta m t+4\,\mathrm{Im}\,\delta\cdot\sin\Delta m t\right]/2$$

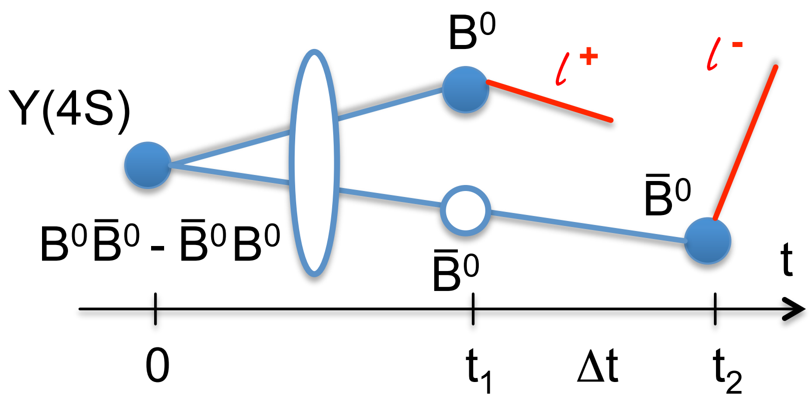
$$R_3\left(B\to \bar{B}\right)=e^{-\Gamma t}\left(1-4\,\mathrm{Re}\,\varepsilon\right)\left[\cosh\left(\Delta\Gamma\, t/2\right)-\cos\Delta m t\right]/2$$

$$R_4\left(\bar{B}\to B\right)=e^{-\Gamma t}\left(1+4\,\mathrm{Re}\,\varepsilon\right)\left[\cosh\left(\Delta\Gamma\, t/2\right)-\cos\Delta m t\right]/2$$

Recall p. 6, 7: $R_3 = R_4 \pm o(10^{-3})$,

No CP & T violation observed.

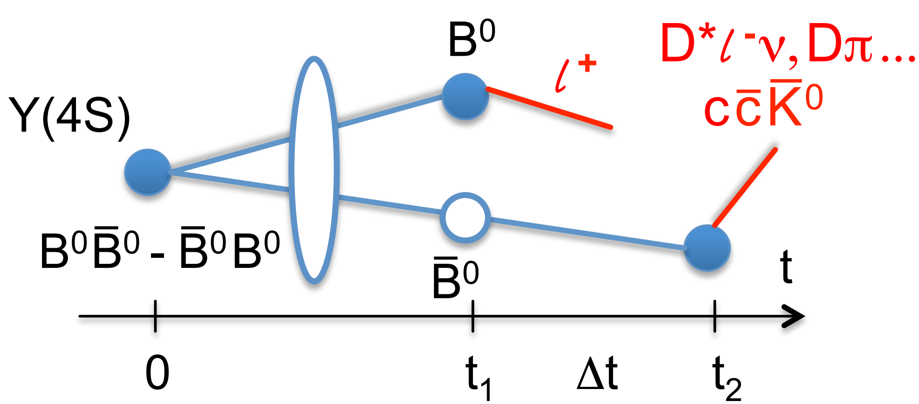
Here searches for $R_1 \neq R_2$:



PRL 96,251802 (2006), 232 M $B\bar{B}$

Asymmetry between $\ell^+\ell^-$ pairs with $\Delta\tau > 0$ and $\Delta t < 0$: $\mathrm{Im}\,\delta = (7.0 \pm 3.7 \pm 1.6)\,10^{-3}$

No info on Re δ because of $\Delta\Gamma \approx 0$.

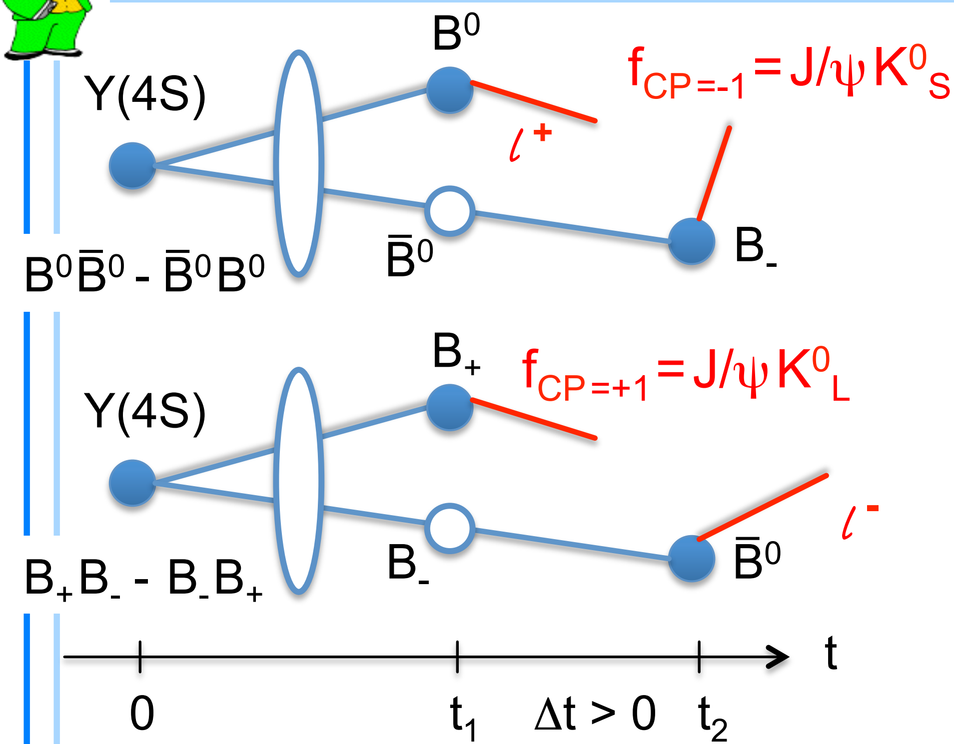


PRD 85,071105 (2012), 535 M $B\bar{B}$

$\mathrm{Im}\,\delta = (2.9 \pm 1.7 \pm 1.7)\,10^{-3}$

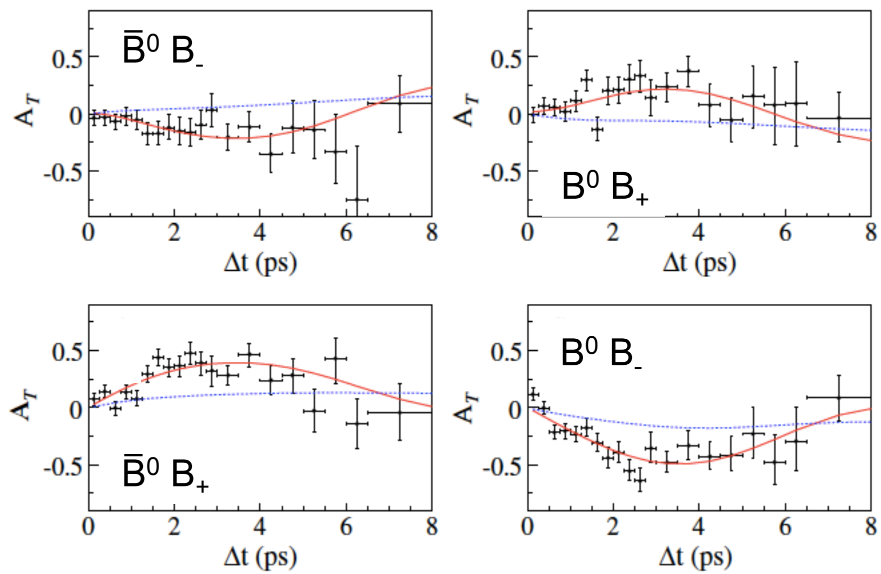
$\mathrm{Re}\,\delta = (-10 \pm 18 \pm 16)\,10^{-3}$

T Violation in the Interplay of Transition and Decay



PRL 109,211801 (2012), 470 $MB\bar{B}$

The 4 rate differences $(\bar{B}^0 \rightarrow B_-) - (B_- \rightarrow \bar{B}^0)$, $(B^0 \rightarrow B_-) - (B_- \rightarrow B^0)$, $(\bar{B}^0 \rightarrow B_+) - (B_+ \rightarrow \bar{B}^0)$, $(B^0 \rightarrow B_+) - (B_+ \rightarrow B^0)$ violate T symmetry:



$(K^0 \rightarrow \bar{K}^0) - (\bar{K}^0 \rightarrow K^0) \neq 0$ violates CP and T.

Here, $(\bar{B}^0 \rightarrow B_-) - (B_- \rightarrow \bar{B}^0) \neq 0$ violates T,

$(B^0 \rightarrow B_-) - (\bar{B}^0 \rightarrow B_-) \neq 0$ violates CP (p- 8).

The significance of the observed T violation corresponds to 14 σ.

The 4 CPT-testing rate differences $(\bar{B}^0 \rightarrow B_-) - (B_- \rightarrow B^0)$ ... are zero within 0.3 σ.

CP, T and CPT Summary

In transitions, the K^0 system shows

CP & T violation: $\text{Re}\,\varepsilon = (161 \pm 0.5)\,10^{-5}$

no CPT violation: $\text{Im}\,\delta = (-0.7 \pm 1.4)\,10^{-5}$

$\text{Re}\,\delta = (\,24 \pm 23)\,10^{-5}$

In decays, the K^0 shows CP violation:

$$\frac{\left|\langle \pi^+\pi^- | T | K^0 \rangle\right|^2 - \left|\langle \pi^+\pi^- | T | \bar{K}^0 \rangle\right|^2}{\left|\langle \pi^+\pi^- | T | K^0 \rangle\right|^2 + \left|\langle \pi^+\pi^- | T | \bar{K}^0 \rangle\right|^2} = (5.4 \pm 0.6)10^{-6}.$$

In the interplay of transition and decay

CP violation: $\text{Im}\,\eta_{+-} = (152 \pm 3)\,10^{-5}$

(all numbers are world averages 2012)

In transitions, the B^0 system does not

violate CP & T: $\text{Re}\,\varepsilon = (0.1 \pm 0.6)\,10^{-3}$

violate CP & CPT: $\text{Im}\,\delta = (4 \pm 2)\,10^{-3}$

$\text{Re}\,\delta = (-10 \pm 26)\,10^{-3}$

in agreement with the St.M.: $\delta = 0$ and

$\text{Re}\,\varepsilon = (-1.0 \pm 0.15)\,10^{-4}$

In decays, the B^0 shows CP violation:

$$\frac{\left|\langle K^+\pi^- | T | B^0 \rangle\right|^2 - \left|\langle K^-\pi^+ | T | \bar{B}^0 \rangle\right|^2}{\left|\langle K^+\pi^- | T | B^0 \rangle\right|^2 + \left|\langle K^-\pi^+ | T | \bar{B}^0 \rangle\right|^2} = 0.097 \pm 0.012.$$

2004

and $\gamma = \arg(V_{ub}V_{ud}^{*}V_{cd}V_{cb}^{*}) = (69 \pm 10)^{\circ}$

In the interplay of transition and decay:

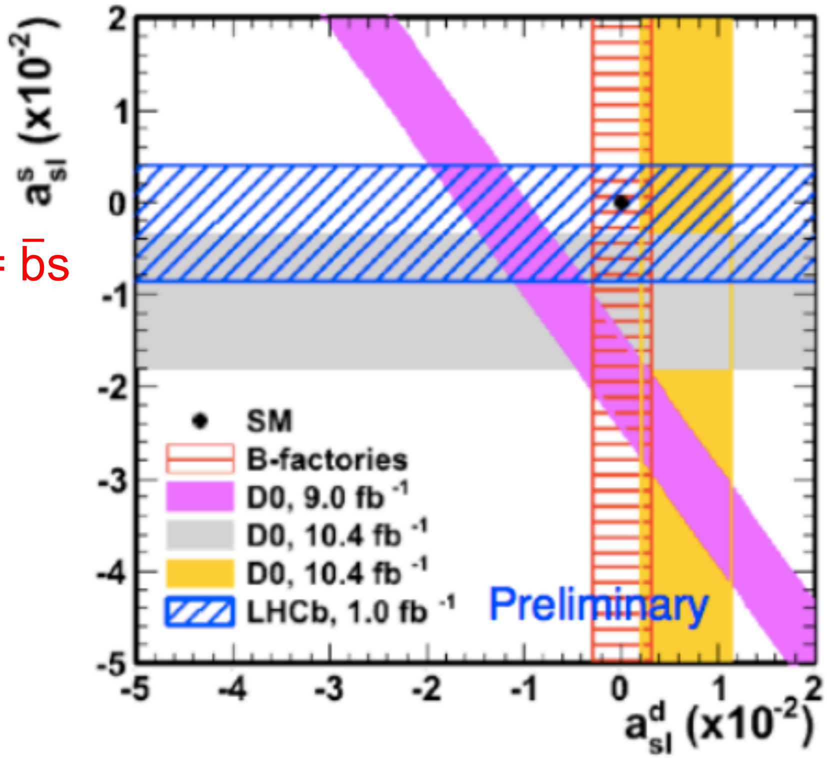
CP violation: $\sin 2\beta = 0.682 \pm 0.019$

T violation: $N(\bar{B}^0 \to B_-) \neq N(B_- \to \bar{B}^0)$ ... $14\,\sigma$

2012

Backup 1: a_{SL} (March 2013)

$B_s = \bar{b}s$



$B^0 = \bar{b}d$

from U. Uwer

La Thuile 2013

LHCb preliminary: $a^s_{sl} = (-0.24 \pm 0.54 \pm 0.33)\%$ = 4 Re ε (B_s)

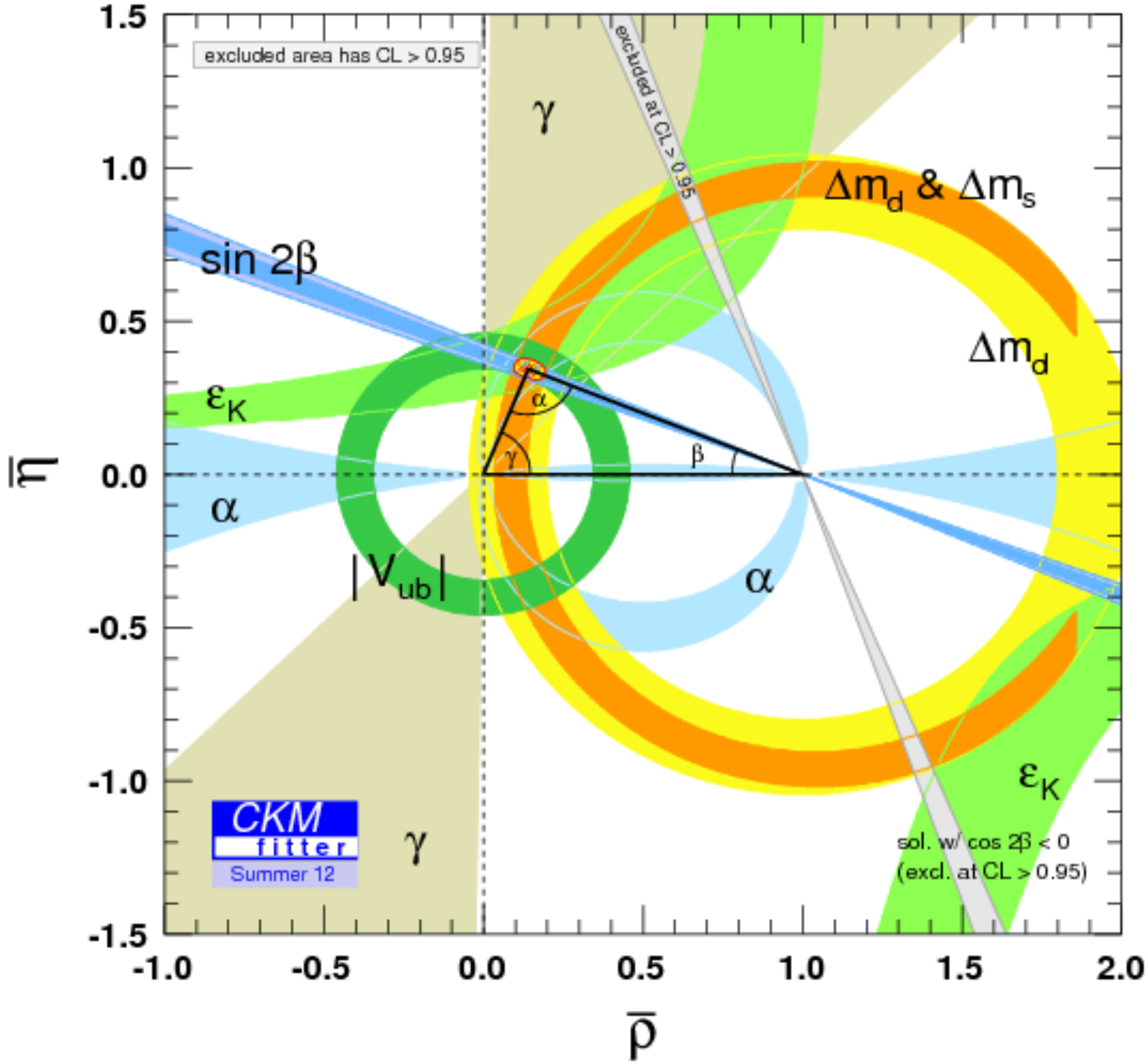
LHCB-CONF-2012-032

Main syst.: L0 μ-trigger efficiency

Consistent with Standard Model

$a^s_{sl} = (1.9 \pm 0.3) \times 10^{-5}$ *(A.Lenz)*[11]

Backup 2: CKM fitter Summer 2012



The „unitarity triangle“
with the 1st
and 3rd column
of the CKM matrix

$$\bar{\rho} + i\bar{\eta} = \frac{-V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

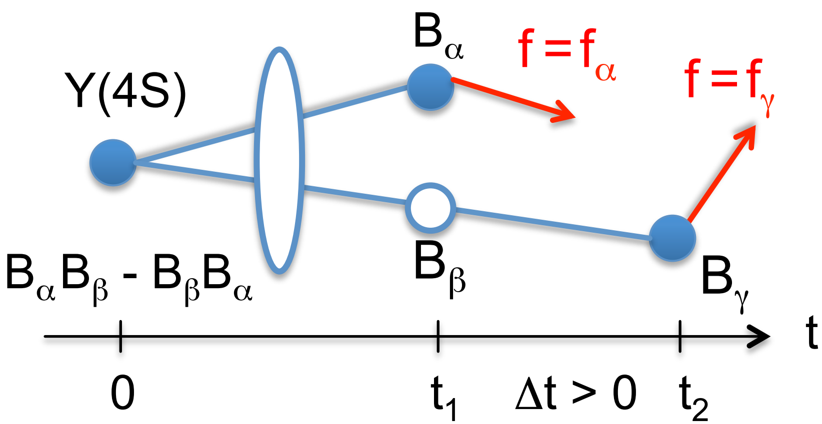
March 1013:

$$\gamma = \arg(V_{ub}V_{ud}^*V_{cd}V_{cb}^*)$$
$$= (69 \pm 12)^o$$
$$\rightarrow (69 \pm 10)^o$$

Backup 3: The beauty of entanglement

The $\Upsilon(4S)$ resonance decays with 50% probability into an entangled pair of two neutral B mesons: $\Upsilon(4S) \to \Psi_2 = [B^0(p)\,\bar{B}^0(-p) - \bar{B}^0(p)\,B^0(-p)]\,/\sqrt{2}$, $\langle B^0|\bar{B}^0\rangle = 0$.

Any superposition $B_\alpha = \alpha\,B^0 + \alpha'\,\bar{B}^0$ has an orthogonal state $B_\beta = \beta\,B^0 + \beta'\,\bar{B}^0$ with $\alpha\beta^* + \alpha'\beta'^* = 0$, $\langle B_\alpha|B_\beta\rangle = 0$, and $\Upsilon(4S) \to \Psi_2 = [B_\alpha(p)\,B_\beta(-p) - B_\beta(p)\,B_\alpha(-p)]\,/\sqrt{2}$.



When the meson in direction p decays at t_1 into a mode f_α, entanglement disappears and the meson in direction -p becomes a single-particle state Ψ_1, fixed by quantum mechanics („EPR paradoxon") depending on the mode f_α: $\Psi_1 = B_\beta \perp B_\alpha$. Examples:

1) $f_\alpha = \ell^+ \nu X$, $B_\alpha = B^0$, $B_\beta = \bar{B}^0$.

2) $f_\alpha = J/\psi\, K^0_S$, $B_\alpha = B_-$, $B_\beta = B_+$. The states B_- and B_+ are given by decay amplitudes:

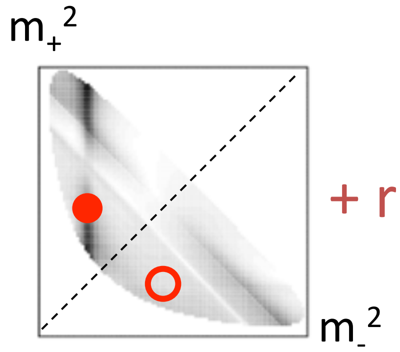
$$A = \langle c\bar{c}\,K^0|T|B^0\rangle,\ \bar{A} = \langle c\bar{c}\,\bar{K}^0|T|\bar{B}^0\rangle.\ B_+ = \left(B^0 + A/\bar{A}\cdot\bar{B}^0\right)/\sqrt{2},\ B_- = \left(B^0 - A/\bar{A}\cdot\bar{B}^0\right)/\sqrt{2}.$$

With the observations $|A/\bar{A}| = 1$ and $\langle c\bar{c}\,K^0|T|\bar{B}^0\rangle = \langle c\bar{c}\,\bar{K}^0|T|B^0\rangle = 0$, B_- and B_+ are orthogonal, and B_+ decays only into K_L, not into K_S, B_- only into K_S, not into K_L.

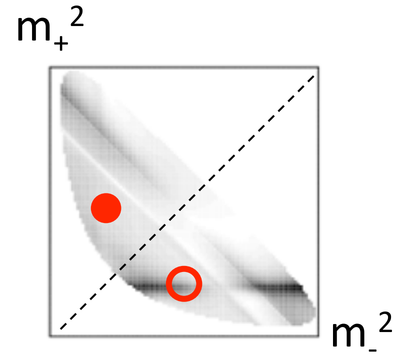
Backup 4: The Dalitz Method for Determining γ

One of three methods for γ: The „Dalitz“-Method of A. Bondar (BELLE) 2002 and Giri Grossmann Soffer Zupan, PRD 68(2003)054018

$\Gamma[B^- \rightarrow K^-(\pi^+\pi^- K_S)] = A^2 \cdot \Big|$



$+\ r_B e^{-i\gamma} e^{i\delta}$



$\Big|^2$

$m_+ = m(K_S\pi^+)$, $m_- = m(K_S\pi^-)$ $\quad D(m_-, m_+) = D$, $\bar{D}(m_-, m_+) = D(m_+, m_-) = D\, r_D\, e^{i\Phi}$

$$A^-_{-+} = AD\left(1 + r_B e^{-i\gamma} e^{i\delta} r_D e^{i\Phi}\right) \qquad \Gamma^-_{-+} = A^2 D^2 \left(1 + r_B{}^2 r_D{}^2 + 2 r_B r_D \cos(\delta + \Phi - \gamma)\right)$$

$$A^-_{+-} = AD\left(r_D e^{i\Phi} + r_B e^{-i\gamma} e^{i\delta}\right) \qquad \Gamma^-_{+-} = A^2 D^2 \left(r_D{}^2 + r_B{}^2 + 2 r_B r_D \cos(\delta - \Phi - \gamma)\right)$$

$$A^+_{-+} = AD\left(r_D e^{i\Phi} + r_B e^{+i\gamma} e^{i\delta}\right) \qquad \Gamma^+_{-+} = A^2 D^2 \left(r_D{}^2 + r_B{}^2 + 2 r_B r_D \cos(\delta - \Phi + \gamma)\right)$$

$$A^+_{+-} = AD\left(1 + r_B e^{+i\gamma} e^{i\delta} r_D e^{i\Phi}\right) \qquad \Gamma^+_{+-} = A^2 D^2 \left(1 + r_B{}^2 r_D{}^2 + 2 r_B r_D \cos(\delta + \Phi + \gamma)\right)$$

The phases Φ are determined from Dalitzplot fits with interfering resonances.