Recent results on CP and T Violation in B-meson decays at BaBar

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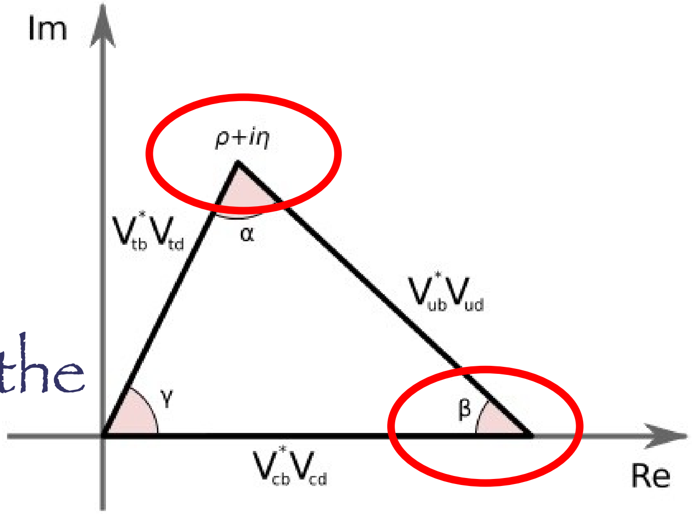
- Introduction
- CKM Angles: β, α, γ
- CP Violation in B^0 Mixing
- T Violation
- Conclusions

Introduction

Questions on CP Violation

- CPV in the quark sector described by a single weak phase $i\eta$ in the CKM mixing matrix



- CPV measurements provide precise values for the CKM parameter β from $b \longrightarrow (c\bar{c})s$ transitions

  (1.a) What about measurements using different channels ?

  (1.b) What can we say for the other CKM angles ?

- CPV in mixing has not yet been observed

  (2) Can we improve wrt existing measurements ?

- CPT + CPV $\longrightarrow$ T Violation

  (3.a) Can we observe T Violation independently of CPT assumption ?

  (3.b) Can we test CPT in the B system ?

Some Answers from BaBar

- CKM Angles:
  - β: "Measurement of the Time-Dependent CP Asymmetry of Partially Reconstructed $B^0 \rightarrow D^{*+}D^{*-}$ Decays" (429.0 fb^{-1}), Phys. Rev. D 86, 112006 (2012)
  - α: "Measurement of CP-violating asymmetries in $B^0 \rightarrow (\rho\pi)^0$ decays using a time-dependent Dalitz plot analysis" (431.0 fb^{-1}) , Phys. Rev. D 88, 012003 (2013)
  - γ: "Observation of direct CP violation in the measurement of the Cabibbo-Kobayashi-Maskawa angle γ with $B^{\pm} \rightarrow D^{(*)}K^{(*)\pm}$ decays" , Phys. Rev. D 87, 052015 (2013)

- CPV in Mixing:
  - "Search for CP Violation in $B^0\bar{B}^0$ Mixing using Partial Reconstruction of $B^0 \rightarrow D^*Xl\nu$ and a Kaon Tag" (425.7 fb^{-1}), ArXiv: 1305.1575 (2013), Accepted by Phys. Rev. Lett.

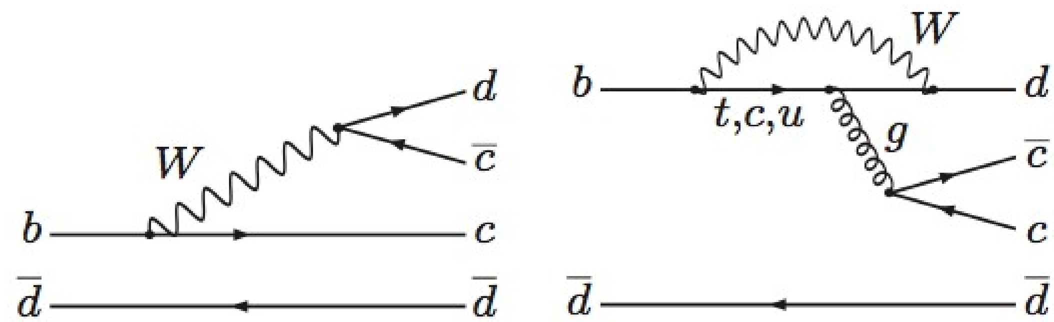
- T-Violation:
  - "Observation of Time Reversal Violation in the B^0 Meson System " (425.7 fb^{-1}), Phys. Rev. Lett. 109, 211801 (2012)

Measurement of β with $B^0 \rightarrow D^{*+}D^{*-}$ Partial Reconstruction

sin(2β) with $B^0 \rightarrow D^{*+}D^{*-}$

Phys. Rev. D 86, 112006 (2012)

- Interference between mixing and decay allows the measurement of sin 2β
- Cabibbo-suppressed $b \rightarrow (c\bar{c})d$ transition: small contribution from penguin diagram



(a) Tree (b) Penguin

- Amplitude dominated by a single weak-phase term as in $b \rightarrow (c\bar{c})s$:
  - Time-dependent decay rate:

$$P_{\eta}^{S_{\rm tag}}(\Delta t) = \frac{e^{-|\Delta t|/\tau_b}}{4\tau_b} \cdot [1 + S_{\rm tag}\, S_\eta \sin(\Delta m_d \Delta t) + S_{\rm tag}\, C \cos(\Delta m_d \Delta t)]\,,$$

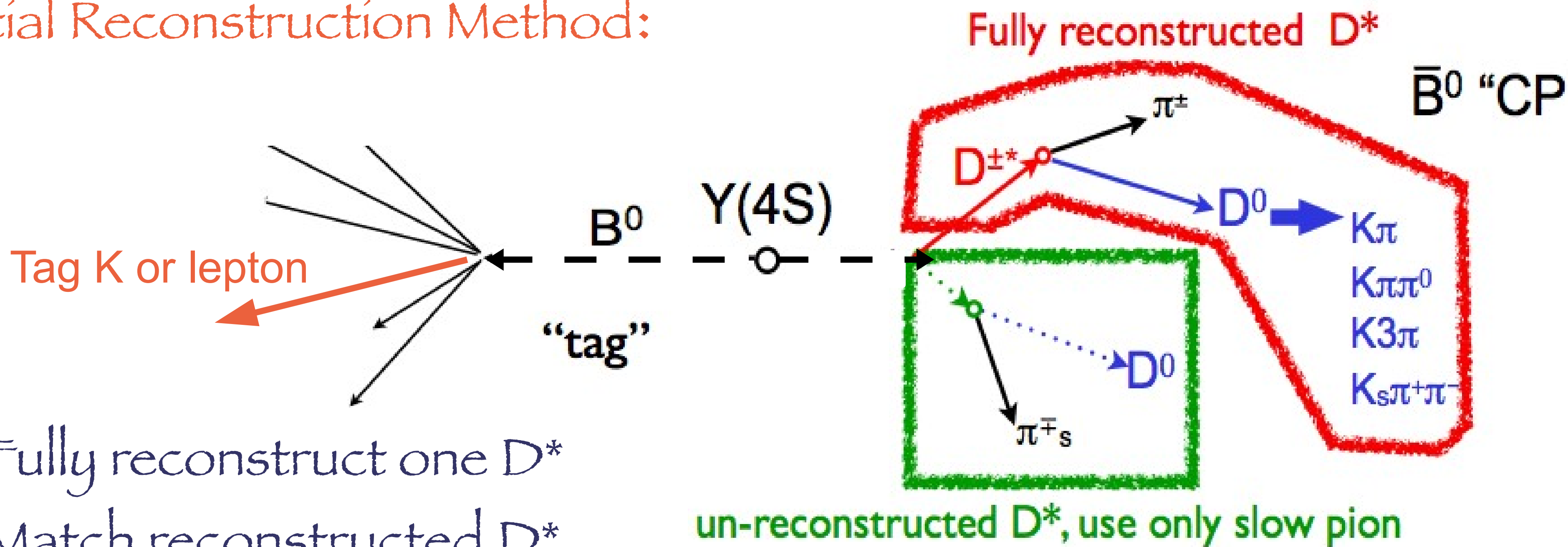
Δt=time interval between the two B^0 decays
S_{tag}=+1(-1) for $B_{tag}=B^0(\bar{B}^0)$
η=+1(-1) for CP even (odd) states

- S_η=η sin(2β_{eff}), C=0 ~ as for "golden" $B^0 \rightarrow J/\psi K^0$
- Large deviation could indicate physics beyond Standard Model

sin(2β) with $B^0 \rightarrow D^{*+}D^{*-}$

Phys. Rev. D 86, 112006 (2012)

- Partial Reconstruction Method:



- Fully reconstruct one D*
- Match reconstructed D* with a slow pion of opposite sign
- Select candidate exploiting event kinematics
- Compute recoiling D^0 mass

- Tag flavor of the other B^0 from lepton or kaon charge

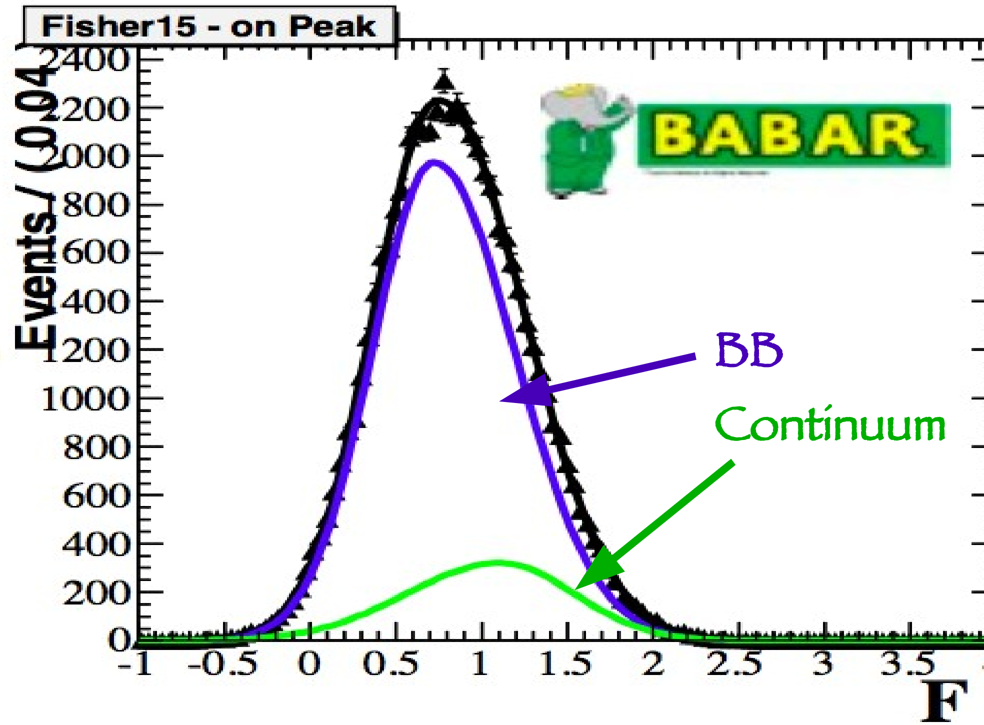
- wrt Full Reconstruction:
  Higher Statistics (x5)
  Higher Background

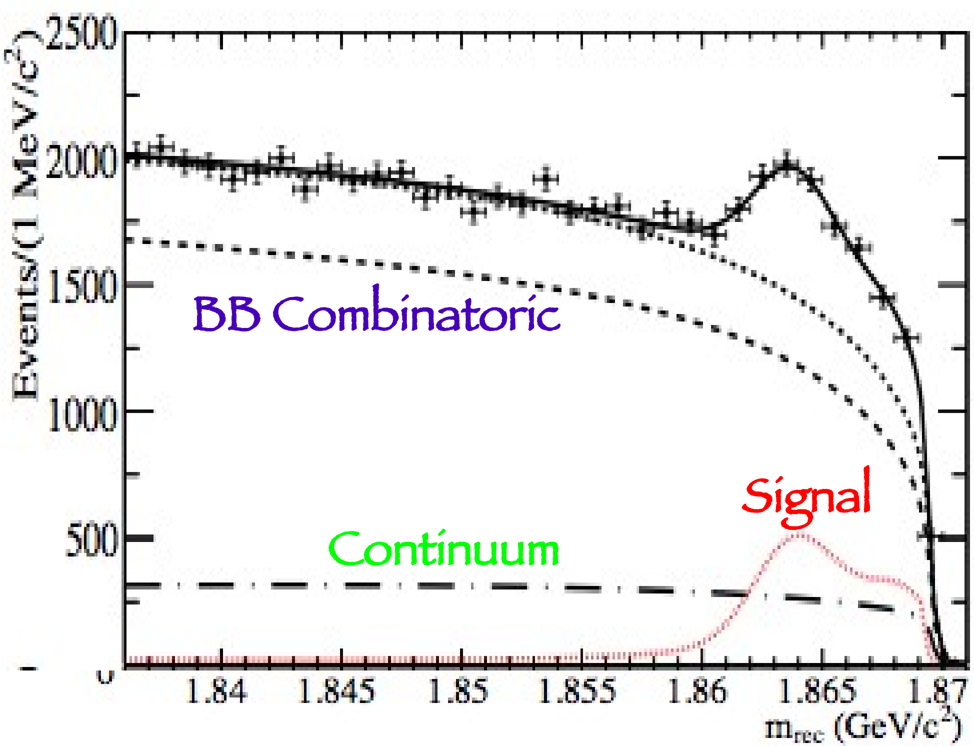
$\sin(2\beta)$ with $B^0 \rightarrow D^{*+}D^{*-}$

Phys. Rev. D 86, 112006 (2012)

- Continuum BKG suppressed using a Fisher discriminant exploiting topological variables

$$P_{\rm on} = f_{B\bar{B}}\underbrace{[\overbrace{f_{\rm sig}P_{\rm sig}}^{\text{signal}} + \overbrace{(1-f_{\rm sig})P_{\rm comb}}^{B\bar{B}\text{ combinatoric}}]}_{B\bar{B}} + \underbrace{(1-f_{B\bar{B}})P_{q\bar{q}}}_{\text{continuum}}$$





- Fisher discriminant included in the fit to sin 2β

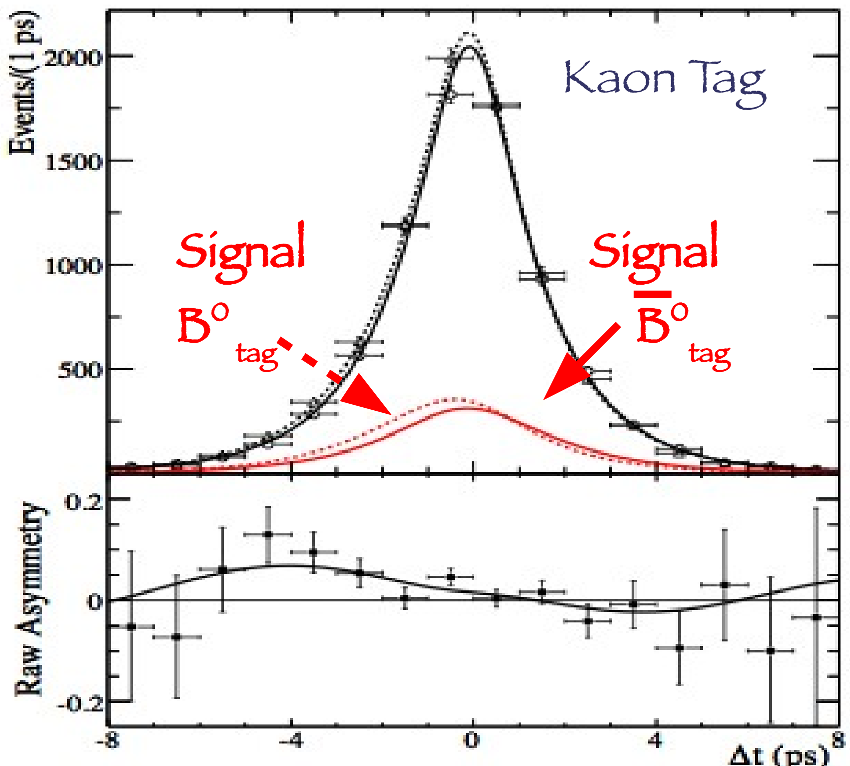
- Signal events selected by means of recoiling D^0 mass m_{rec}

$\sin(2\beta)$ with $B^0 \to D^{*+}D^{*-}$

Phys. Rev. D 86, 112006 (2012)

- Vector-Vector final state is a superposition of CP+ and CP- states:
  - Fraction of CP- from angular analysis of fully reconstructed events

$R_- = 0.158 \pm 0.028 \pm 0.006$ (BaBar Phys. Rev. D 79 032002)



- By fitting Δt distribution, assuming negligible penguin contributions:

$C_+ = +0.15 \pm 0.09 \pm 0.04$

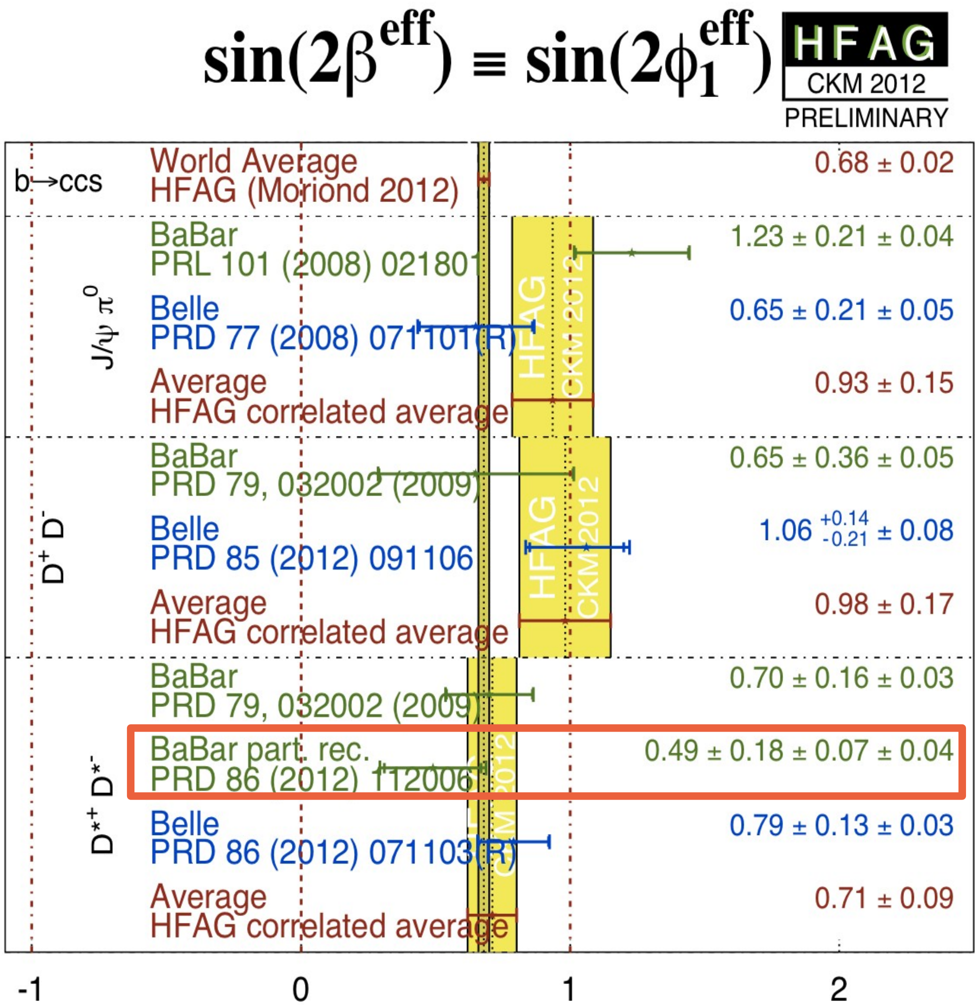
$S_+ = -0.49 \pm 0.18 \pm 0.07 \pm 0.04 (R_-)$

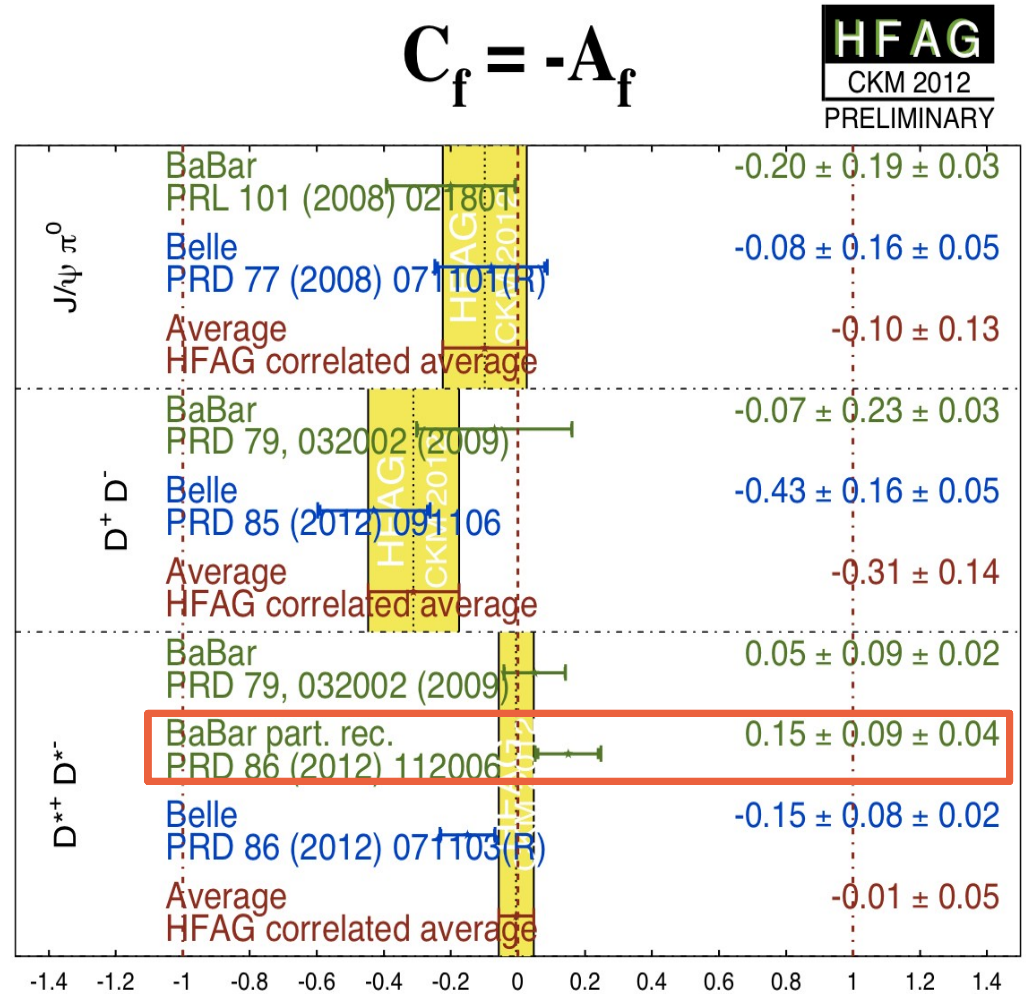
In agreement with SM

- Systematics dominated by uncertainty on mistag (from MC), BKG shape modelling & signal fraction

$\sin(2\beta)$ with $B^0 \to D^{*+}D^{*-}$

- Results in good agreement with $b \to (c\bar{c})s$ World Average:





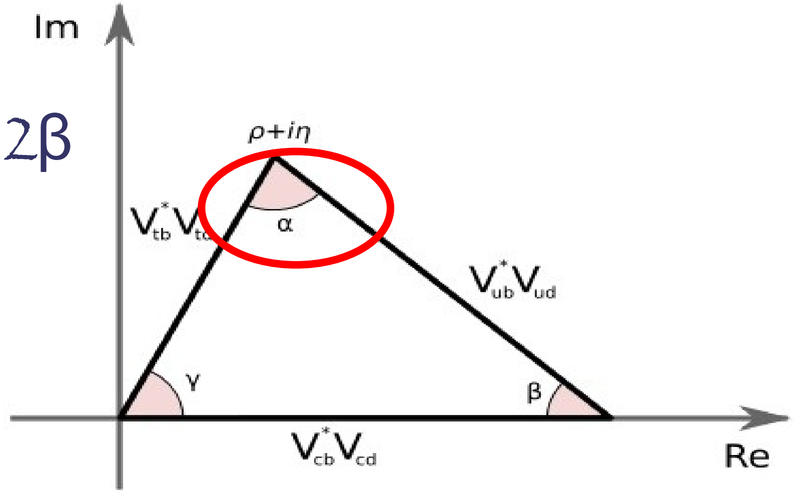
Measurement of α

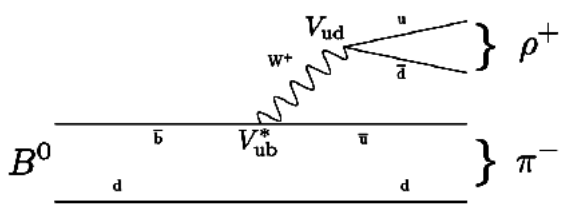
with $B^0 \to \rho\pi \to \pi^+\pi^-\pi^0$

Measurement of α

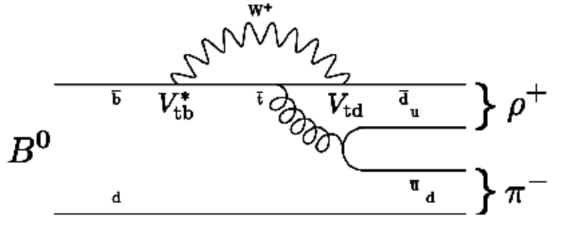
Phys. Rev. D 88, 012003 (2013)

- Interference between mixing and decay allows the measurement of sin 2α a-la sin 2β
- $B^0 \rightarrow \rho\pi$: Tree & penguin diagrams have comparable size. Their interference:
  - introduces a strong phase difficult to compute
  - may induce a sizeable amount of direct CP violation
- Time-dependent analysis across the ρπ Dalitz plot permits in principle unambiguous measurement of α





Tree Diagram



Penguin Diagram

Measurement of α

Phys. Rev. D 88, 012003 (2013)

- Time-dependent Probability to decay to $\pi^+\pi^-\pi^0$ for a meson that is a B^0 ($A^-_{3\pi}$) or $\overline{B}^0$ ($A^+_{3\pi}$) at the decay time of the other meson:

$$|\mathcal{A}^{\pm}_{3\pi}(\Delta t)|^2 = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[|A_{3\pi}|^2 + |\overline{A}_{3\pi}|^2 \mp \left(|A_{3\pi}|^2 - |\overline{A}_{3\pi}|^2\right)\cos(\Delta m_d \Delta t) \pm 2\mathrm{Im}\left[\frac{q}{p}\overline{A}_{3\pi}A^{*}_{3\pi}\right]\sin(\Delta m_d \Delta t)\right]$$

Δt=time interval between the two B^0 decays

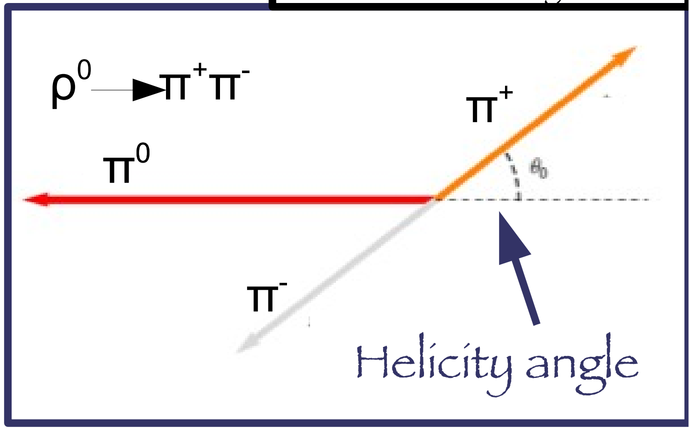
- Time-independent Amplitudes:

$$A_{3\pi} = f_+A^+ + f_-A^- + f_0A^0$$
$$\overline{A}_{3\pi} = f_+\overline{A}^+ + f_-\overline{A}^- + f_0\overline{A}^0$$

(f_+: ρ^+, f_-: ρ^-, f_0: ρ^0)

For $B^0 \to \pi^+\pi^-\pi^0$

For $\overline{B}^0 \to \pi^+\pi^-\pi^0$



$$f_\kappa(m,\theta_\kappa) \propto F_{\rho(770)}(m,\theta_\kappa) + a_{\rho'}e^{i\phi_{\rho'}}F_{\rho(1450)}(m,\theta_\kappa)$$

Mass, helicity angle

Modified relativistic Breit-Wigner resonances
ρ(1700) is neglected

Measurement of α

Phys. Rev. D 88, 012003 (2013)

- Time-dependent Probability to decay to $\pi^+\pi^-\pi^0$ for a meson that is a B^0 ($A^-_{3\pi}$) or $\overline{B^0}$ ($A^+_{3\pi}$) at the decay time of the other meson:

$$|\mathcal{A}^{\pm}_{3\pi}(\Delta t)|^2 = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\Big[|A_{3\pi}|^2 + |\overline{A}_{3\pi}|^2 \mp \left(|A_{3\pi}|^2 - |\overline{A}_{3\pi}|^2\right)\cos(\Delta m_d \Delta t) \pm 2\mathrm{Im}\left[\frac{q}{p}\overline{A}_{3\pi}A^*_{3\pi}\right]\sin(\Delta m_d \Delta t)\Big]$$

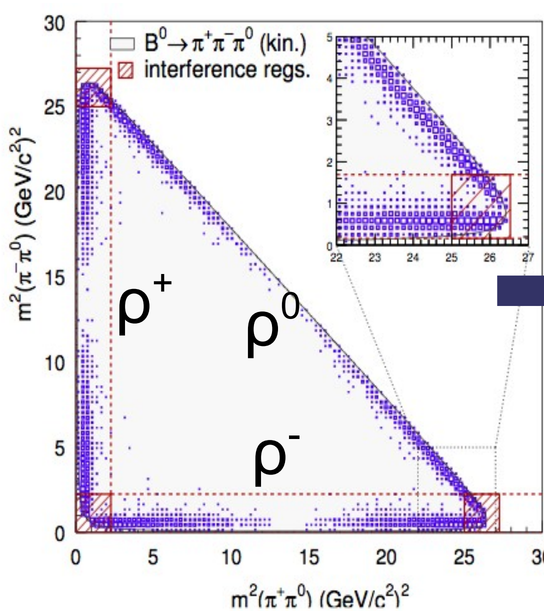
Δt=time interval between the two B^0 decays

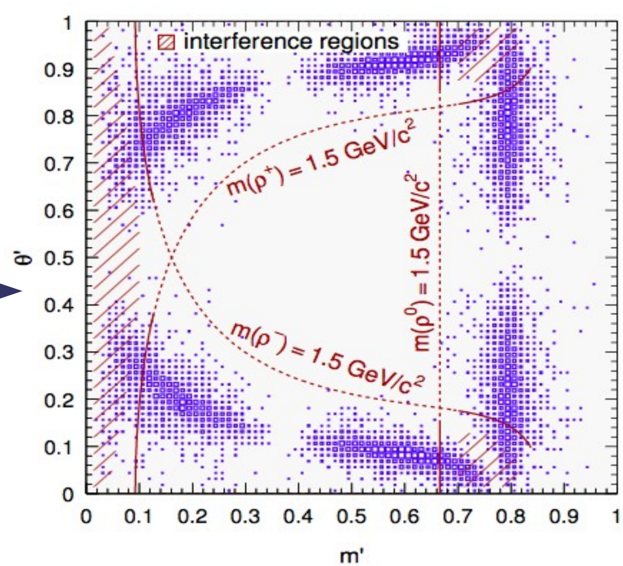
- Interference regions between ρ^+, ρ^-, ρ^0 expanded by mapping the Dalitz Plot in a square domain

$\pi^+\pi^-$ invariant mass

$$m' \equiv \frac{1}{\pi}\arccos\left(2\frac{m_0 - m_0^{\min}}{m_0^{\max} - m_0^{\min}} - 1\right)$$

$$\theta' \equiv \frac{1}{\pi}\theta_0,$$

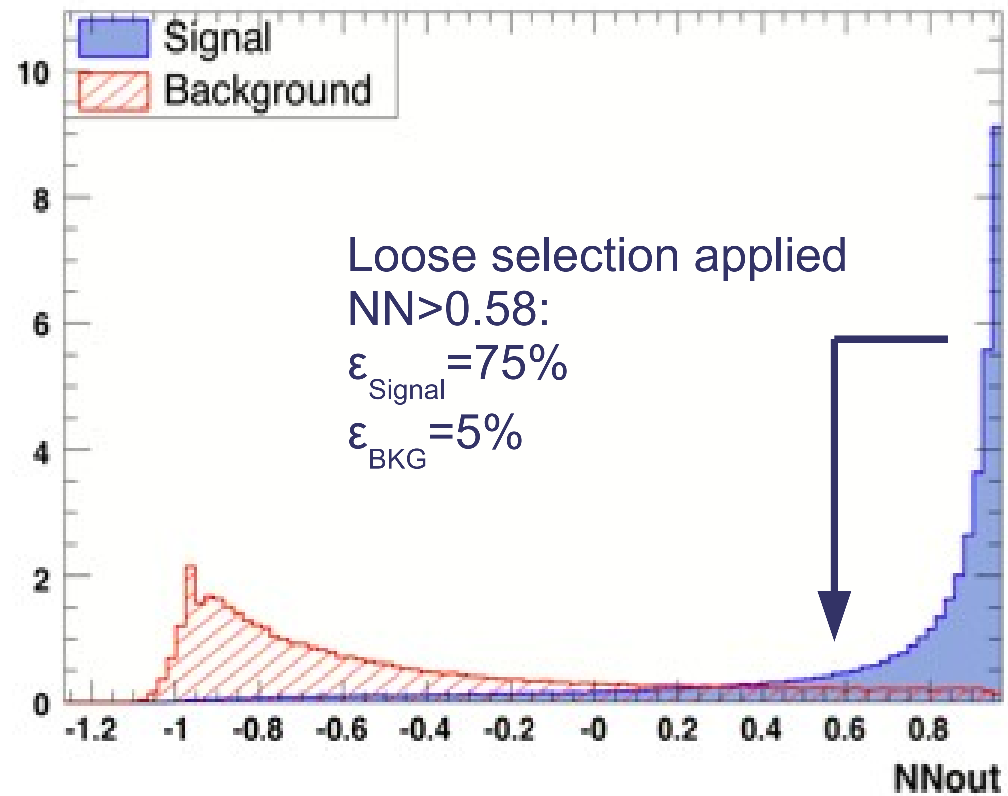




Measurement of α

Phys. Rev. D 88, 012003 (2013)

- Events selected by means of $\Delta E = E_B - E_{beam}$; $m_{ES} = \sqrt{E_{beam}^2 - p_B^2}$ in the Υ(4S) reference frame from 431.0 fb^{-1}
- Continuum jet-like BKG suppressed by means of a Neural Network exploiting event shape variables
- NN output included in the fit



- Still large amount of residual background
- Fit estimates :

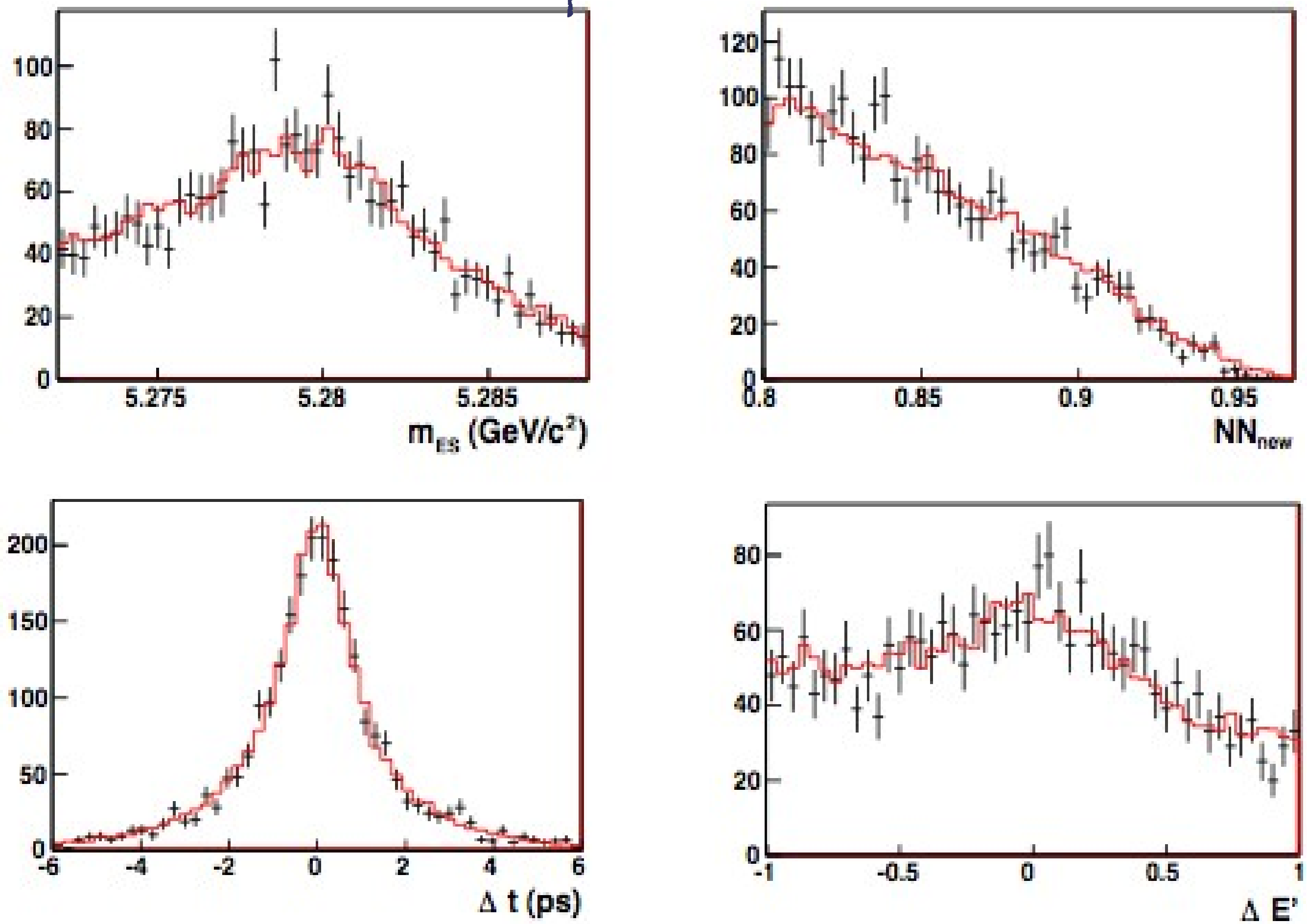
2940±100 signal events

46750±220 continuum events

Measurement of α

Phys. Rev. D 88, 012003 (2013)

- Unbinned extended maximum likelihood fit to m_{ES}, ΔE, NN, Δt & DP parameters
- Likelihood function includes signal, continuum (parameterized on off-peak events), B^0 and B^+ BKG (parameterized on MC)



Measurement of α

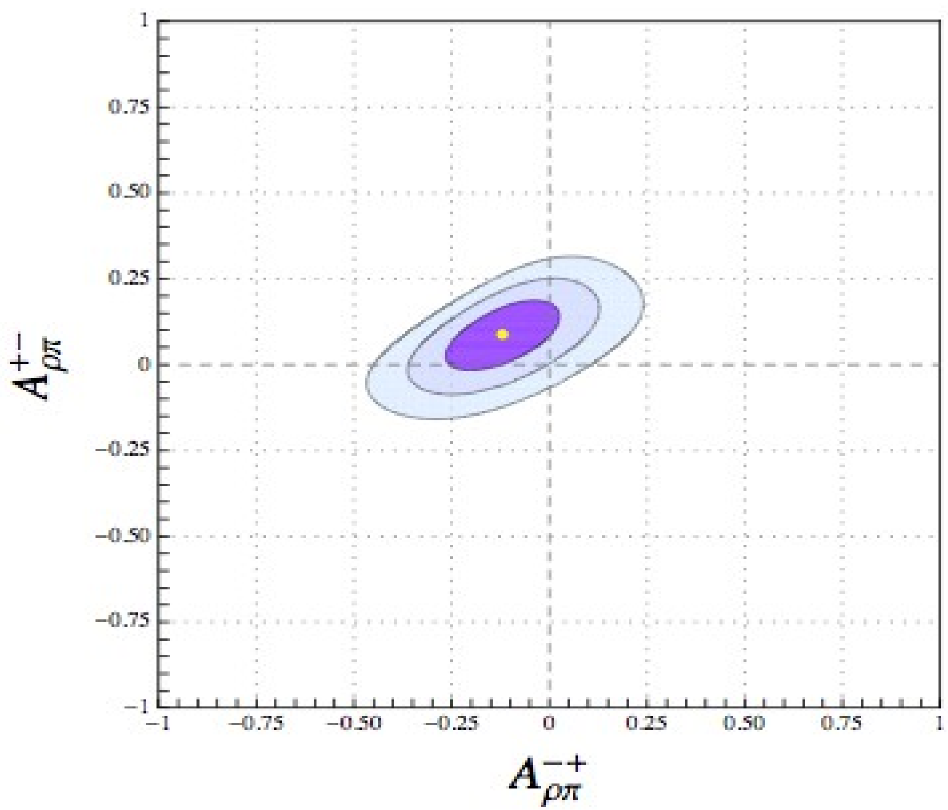
Phys. Rev. D 88, 012003 (2013)

- Measure direct CP violation from the asymmetries:

$$\mathcal{A}_{\rho\pi}^{+-} \equiv \frac{\Gamma(\overline{B}^0 \to \rho^-\pi^+) - \Gamma(B^0 \to \rho^+\pi^-)}{\Gamma(\overline{B}^0 \to \rho^-\pi^+) + \Gamma(B^0 \to \rho^+\pi^-)} = 0.09^{+0.05}_{-0.06} \pm 0.04$$

$$\mathcal{A}_{\rho\pi}^{-+} \equiv \frac{\Gamma(\overline{B}^0 \to \rho^+\pi^-) - \Gamma(B^0 \to \rho^-\pi^+)}{\Gamma(\overline{B}^0 \to \rho^+\pi^-) + \Gamma(B^0 \to \rho^-\pi^+)} = -0.12 \pm 0.08^{+0.04}_{-0.05}$$

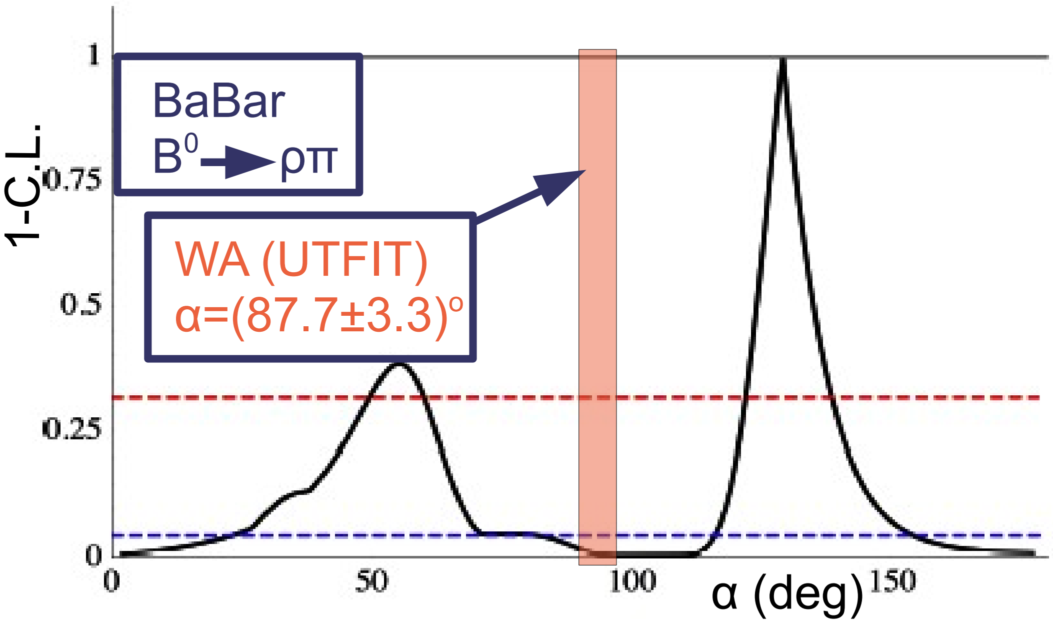
- The origin, corresponding to no direct CP violation, lies on the 96.0% CL contour

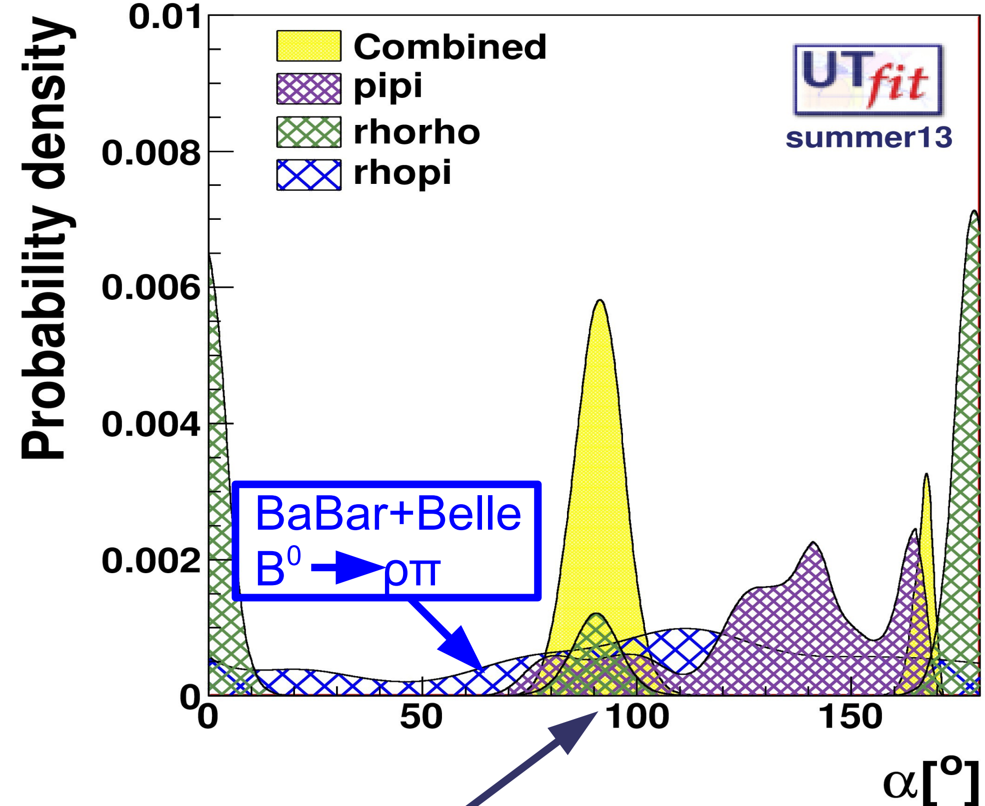


Measurement of α

Phys. Rev. D 88, 012003 (2013)

- α scan to get $\Delta\chi^2$ profile and 1-CL plot





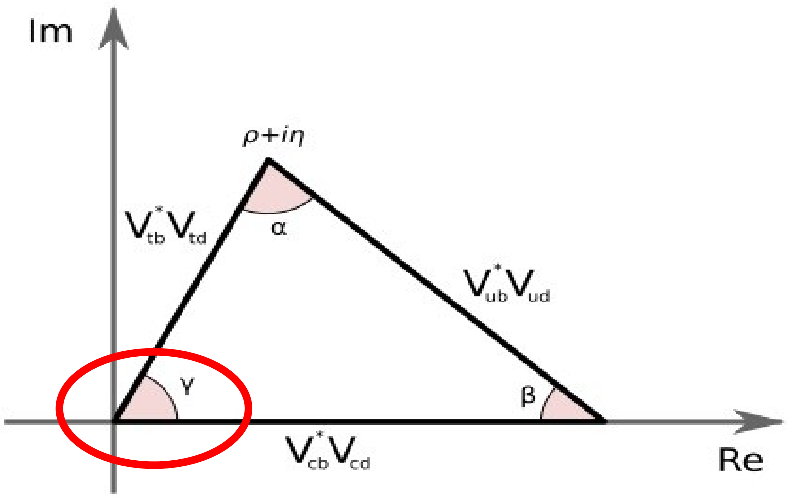
- Result disagrees with World Average
- Extraction of α is difficult due to limited statistics. Due to small S/N ratio, secondary minima are often favored

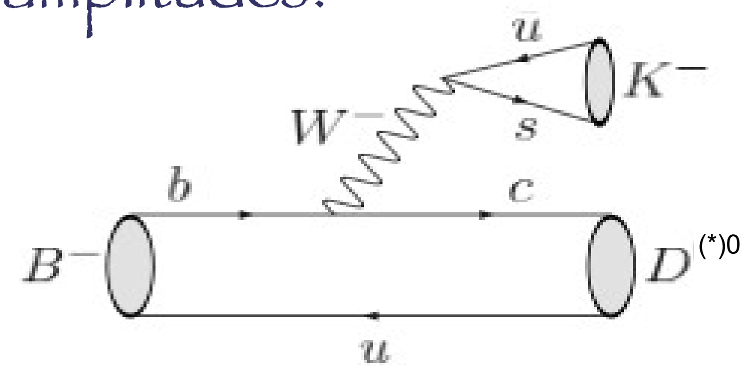
- Using only direct α measurements: α=(90.9±8.0)°

Observation of Direct CPV from γ measurements with $B^{\pm} \rightarrow D^{(*)} K^{(*)\pm}$

γ Measurement

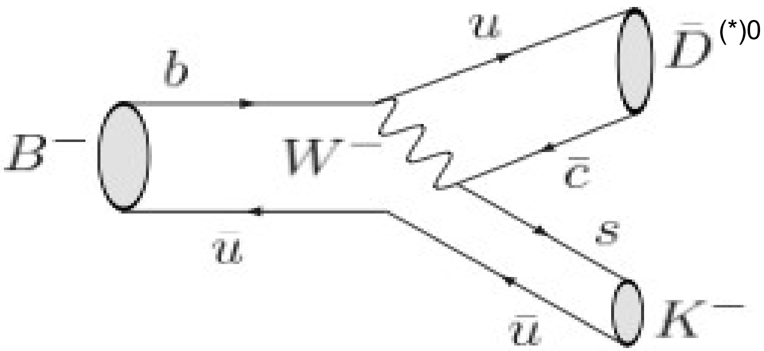
- Angle γ is the phase of V_{ub}
- Accessible through interference of $b \rightarrow c\bar{u}s$ and $b \rightarrow u\bar{c}s$ tree amplitudes:





CKM and Color allowed

$A_1 \propto V_{cb} V_{us}^*$



CKM and Color suppressed

$A_2 \propto V_{ub} V_{cs}^*$

- Final states common to $D^{(*)0}$ and $\overline{D}^{(*)0}$ considered
- Theoretically clean since no penguin contributions

Combination of BaBar γ Measurements

- γ obtained from the interference of the two amplitudes:

$$|A_{tot}|^2 = |A_1 + A_2|^2 = |A_1|^2 + |A_2|^2 + 2|A_1|^2 r_B \cos(\delta_B + \delta_D - \gamma)$$

$r_B = \left|\frac{A_2}{A_1}\right| \sim 0.1,\ \delta_B,\ \delta_D =$ Relative strong phases from B and D decays

- If $\gamma \neq 0,\ \delta_B + \delta_D \neq 0 \Rightarrow \Gamma(B^+) \neq \Gamma(B^-) \Rightarrow$ direct CP Violation

- BaBar performed several independent γ measurements using up to 474 million $B\bar{B}$ pairs with three different methods:
  - GLW: Use two-body CP eigenstates as $D^0 \to K^+K^-$
  - ADS: Use Doubly Cabibbo-Suppressed states as $D^0 \to K^+\pi^-$
  - GGSZ (Dalitz): Use 3-body self-conjugate modes as $D^0 \to K_s\pi^+\pi^-$

- Combine them using information on parameter correlations not previously published

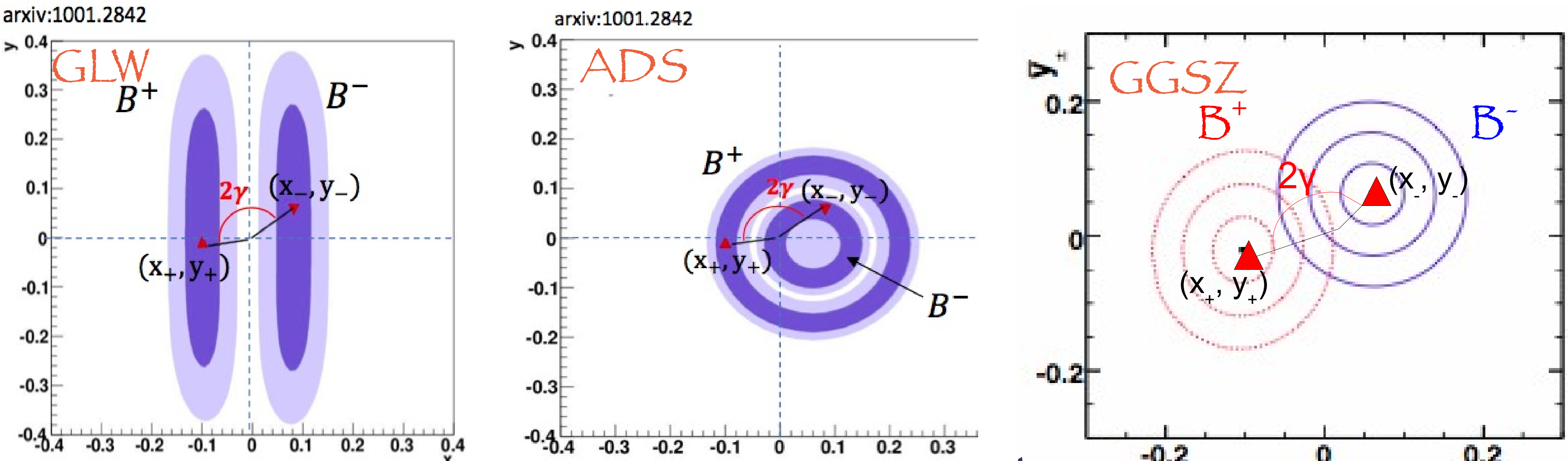
Combination of BaBar γ Measurements

Phys. Rev. D 87, 052015 (2013)

- Results of the three methods can be expressed in terms of "cartesian coordinates":

$$x_{\pm} = r_B \cos(\delta_B \pm \gamma)$$
$$y_{\pm} = r_B \sin(\delta_B \pm \gamma)$$

➡ They have Gaussian behaviour and provide an unbiased estimator also for $r_B \sim 0$

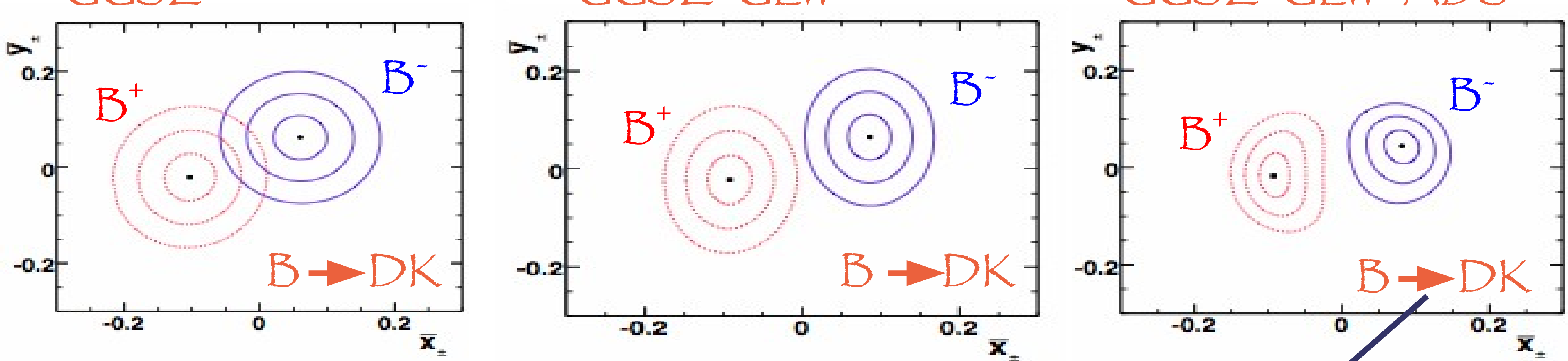


- Good constraint on $x_{\pm}$ Loose constraint on $y_{\pm}$
- $x_{\pm}$, $y_{\pm}$ over two circles GLW+ADS constrain γ
- Most precise measurement

Combination of BaBar γ Measurements

Phys. Rev. D 87, 052015 (2013)

- Combination of GGSZ+GLW+ADS in two steps:
  1) Combine the GGSZ, GLW and ADS $B \to D^{(*)}K^{(*)\pm}$ observables (34 in total) to extract the combined $x_\pm$, $y_\pm$ (4 for each B mode)



Results:

$\bar{z}_\pm = x_\pm + i y_\pm$

		Real part (%)	Imaginary part (%)
DK	$\bar{z}_-$	$8.1 \pm 2.3 \pm 0.7$	$4.4 \pm 3.4 \pm 0.5$
	$\bar{z}_+$	$-9.3 \pm 2.2 \pm 0.3$	$-1.7 \pm 4.6 \pm 0.4$
D*K	$\bar{z}^*_-$	$-7.0 \pm 3.6 \pm 1.1$	$-10.6 \pm 5.4 \pm 2.0$
	$\bar{z}^*_+$	$10.3 \pm 2.9 \pm 0.8$	$-1.4 \pm 8.3 \pm 2.5$
DK*	$\bar{z}_{s-}$	$13.3 \pm 8.1 \pm 2.6$	$13.9 \pm 8.8 \pm 3.6$
	$\bar{z}_{s+}$	$-9.8 \pm 6.9 \pm 1.2$	$11.0 \pm 11.0 \pm 6.1$

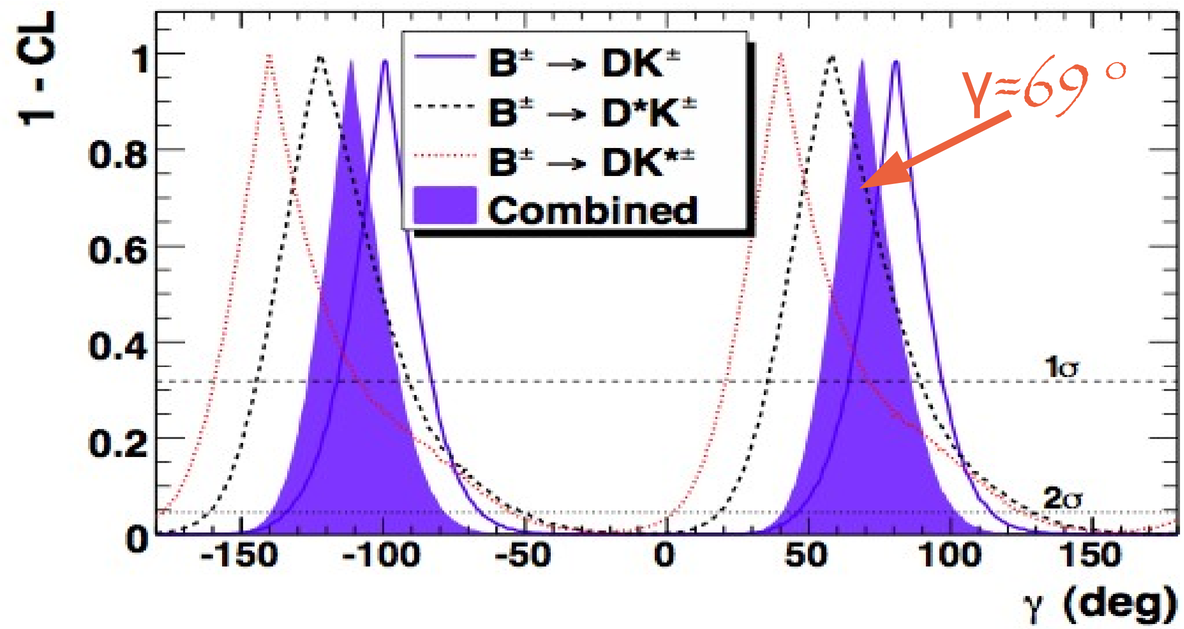
Combination of BaBar γ Measurements

Phys. Rev. D 87, 052015 (2013)

2) Transform the combined $x_{\pm}$, $y_{\pm}$ into γ, r_B, δ_B with frequentist approach

$\gamma = (69^{+17}_{-16})°$ (modulo 180°)

Systematic error =±4° (experimental+Dalitz-Plot model)



- CPV Significance: 5.9 σ

GGSZ alone: 4.0 σ

GGSZ+GLW: 5.4 σ

	Parameter	68.3% C.L. Combination	GGSZ	95.5% C.L. Combination	GGSZ
	γ (°)	69^{+17}_{-16}	68^{+15}_{-14}	[41, 102]	[39, 98]
DK	r_B (%)	$9.2^{+1.3}_{-1.2}$	9.6 ± 2.9	[6.0, 12.6]	[3.7, 15.5]
D*K	r^*_B (%)	$10.6^{+1.9}_{-3.6}$	$13.3^{+4.2}_{-3.9}$	[3.0, 14.7]	[4.9, 21.5]
DK*	κr_s (%)	$14.3^{+4.8}_{-4.9}$	$14.9^{+6.6}_{-6.2}$	[3.3, 25.1]	< 28.0
DK	δ_B (°)	105^{+16}_{-17}	119^{+19}_{-20}	[72, 139]	[75, 157]
D*K	δ^*_B (°)	-66^{+21}_{-31}	-82 ± 21	[−132, −26]	[−124, −38]
DK*	δ_s (°)	101 ± 43	111 ± 32	[32, 166]	[42, 178]

A^{d}_{SL} with $B^0 \rightarrow D^* l \nu$

Partial Reconstruction

CPV in B⁰ mixing

- CP Asymmetry in $B^0_{(s)}$ mixing (time-independent):

$$A^q_{CP} = \frac{Prob(\bar{B}^0_q \to B^0_q, t) - Prob(B^0_q \to \bar{B}^0_q, t)}{Prob(\bar{B}^0_q \to B^0_q, t) + Prob(B^0_q \to \bar{B}^0_q, t)} = \frac{1-|q/p|^4_q}{1+|q/p|^4_q} = \frac{|\Gamma^q_{12}|}{|M^q_{12}|}\sin\phi_q$$

- Experimentally: measure charge asymmetry in mixed semileptonic B^0_q decays:

$$A^q_{CP} = A^q_{SL} = \frac{\Gamma(\bar{B}^0_q \to B^0_q \to l^+\nu X) - \Gamma(B^0_q \to \bar{B}^0_q \to l^-\nu X)}{\Gamma(\bar{B}^0_q \to B^0_q \to l^+\nu X) + \Gamma(B^0_q \to \bar{B}^0_q \to l^-\nu X)}$$

- CPV in mixing if:

$A^q_{SL} \neq 0 \leftrightarrow |q/p|_q \neq 1 \leftrightarrow \phi_q \neq 0$

Standard Model predicts

(Nierste, arXiv:1212.5805 (2012)):

- B^0_d: $A^d_{SL} = (-4.0 \pm 0.6)10^{-4}$

  $\Phi_d = -4.9° \pm 1.4°$

- B^0_s: $A^s_{SL} = (1.8 \pm 0.3)10^{-5}$

  $\Phi_s = 0.24° \pm 0.06°$

Beyond Standard Model

(Lenz, Nierste, JHEP 0706, 072 (2007))

- New Physics could modify M^q_{12} and A^q_{SL} leaving Γ^q_{12} unchanged:

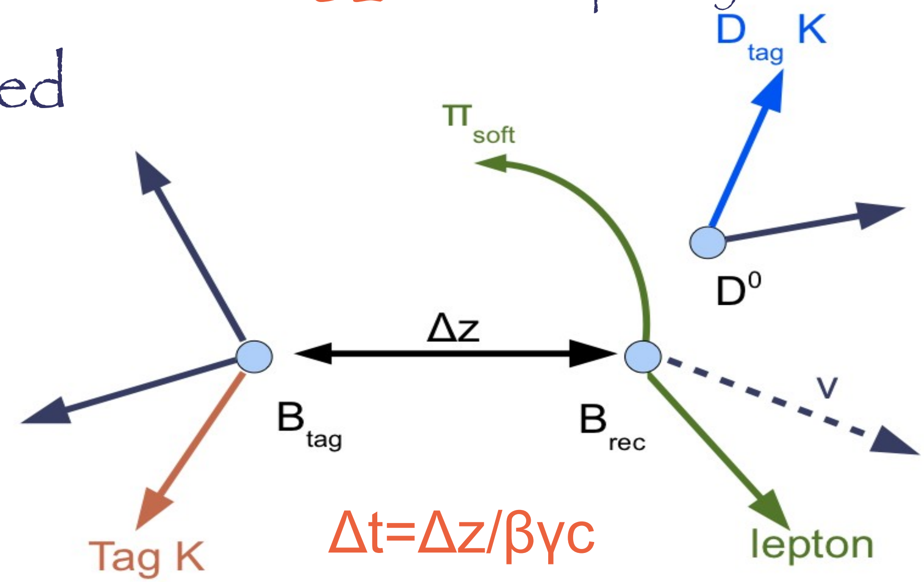
$$M^{NP,q}_{12} = M^{SM,q}_{12}\,\Delta_q\,;\ \Delta_q = |\Delta_q| e^{i\phi^\Delta_q}$$

$$A^{NP}_{SL} = \frac{|\Gamma^q_{12}|}{|M^{SM,q}_{12}|}\frac{\sin(\phi^{SM}_q + \phi^\Delta_q)}{|\Delta_q|}$$

BaBar Flavor Specific A^d_{SL}

arXiv:1305.1575 (2013)
Accepted by PRL

- B^0 Semileptonic Asymmetry measured from Partially Reconstructed $B^0 \rightarrow D^* l\nu$, $D^* \rightarrow \pi_{soft} D^0$ and K Tag



- P.R. B^0 flavor from lepton charge
- Tag B^0 flavor from K charge
- Tag B vertex from K track estrapolation to the e^+e^- Interaction Region

$$A^d_{SL} \approx \frac{N(\ell^+ K_T^+) - N(\ell^- K_T^-)}{N(\ell^+ K_T^+) + N(\ell^- K_T^-)}$$

- A^d_{SL} from an Extended Maximum Likelihood binned fit to the Δt & cos($\theta_{K\text{-}Lepton}$) distributions of the 4 subsamples:

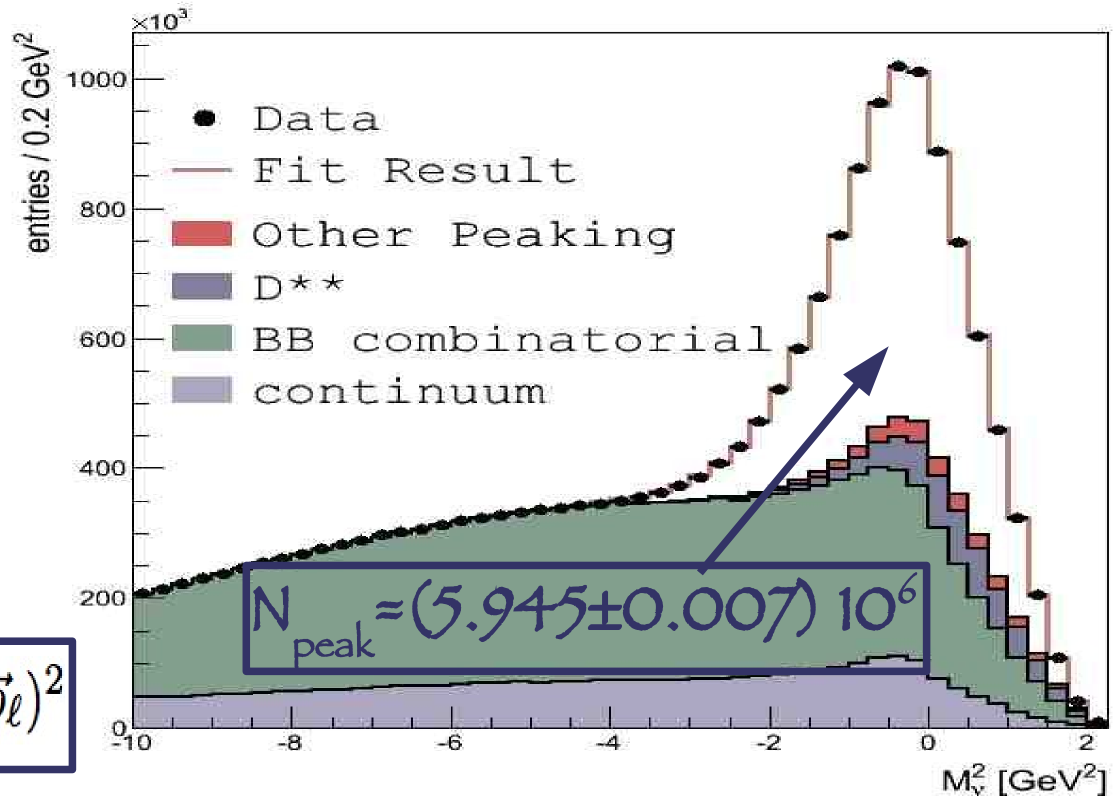
Unmixed (l^-K^+, l^+K^-); Mixed (l^+K^+, l^-K^-)

BaBar Flavor Specific A^d_{SL}

arXiv:1305.1575 (2013)
Accepted by PRL

- Reconstruct only lepton & π_{soft} with opposite charge
- D^* 4-momentum estimated from π_{soft} kinematics
- Signal selection using missing mass squared:

$$\mathcal{M}_\nu{}^2 \equiv (E_{\rm beam} - E_{D^*} - E_\ell)^2 - (\vec{p}_{D^*} + \vec{p}_\ell)^2$$



which should correspond to the neutrino squared mass

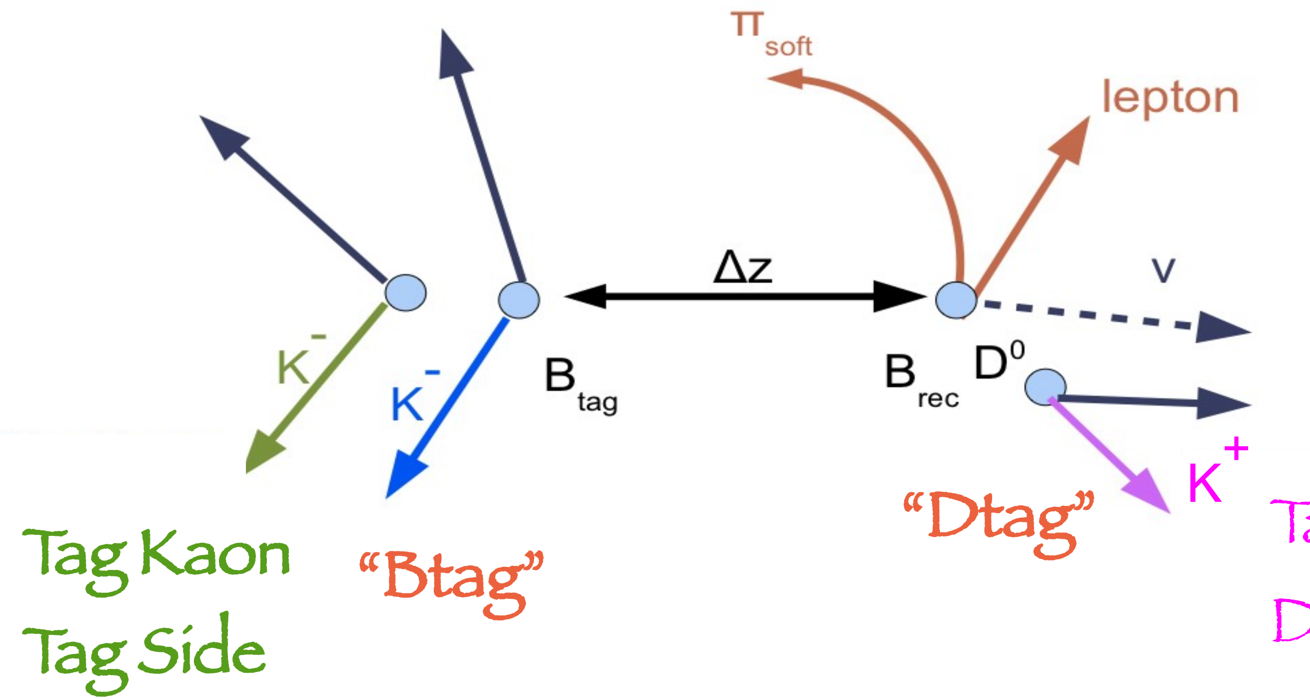
- Sample composition from a fit to M^2_ν by floating D^*, D^{**} and Combinatorial using MC shapes and Continuum shape from Off-Peak events

BaBar Flavor Specific A^d_{SL}

arXiv:1305.1575 (2013)
Accepted by PRL

- Tagging Kaon Sample: $\{ b \to K + b \to c \to K$; $D^0 \to K$

From Tag B	"Btag"
From Reco B	"Dtag"



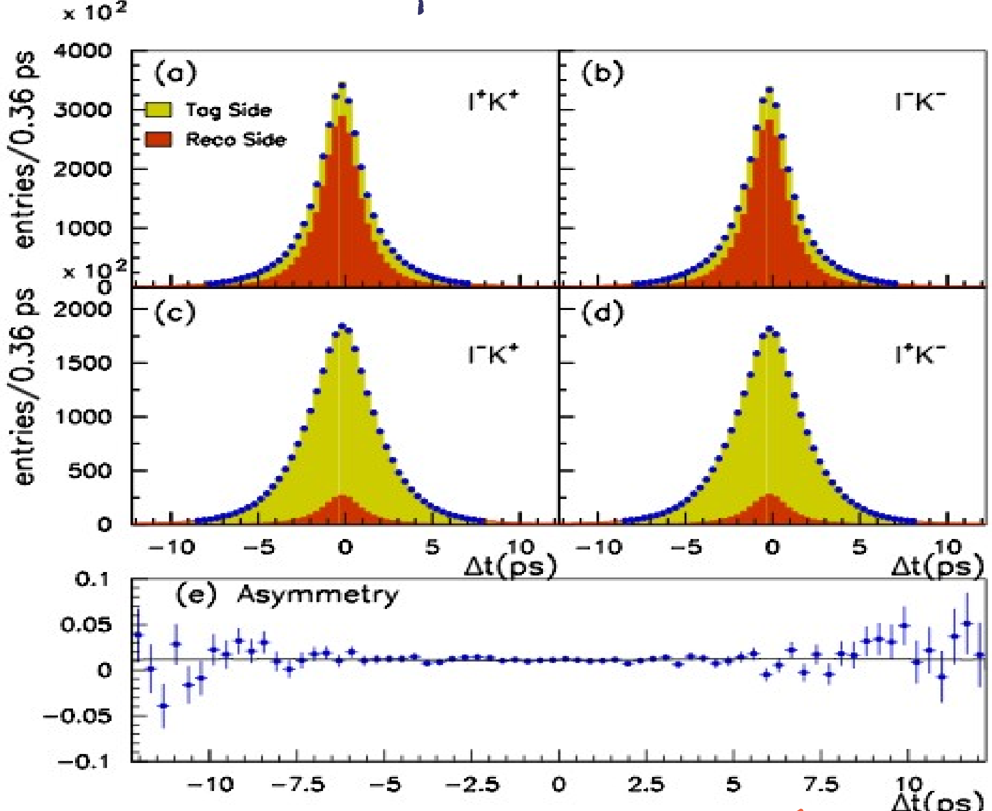
Different subsamples share Physical & Detector Asymmetries in different combinations

- Physical and Detector asymmetries disentangled by exploiting all the available information from different sub-samples (no control samples)

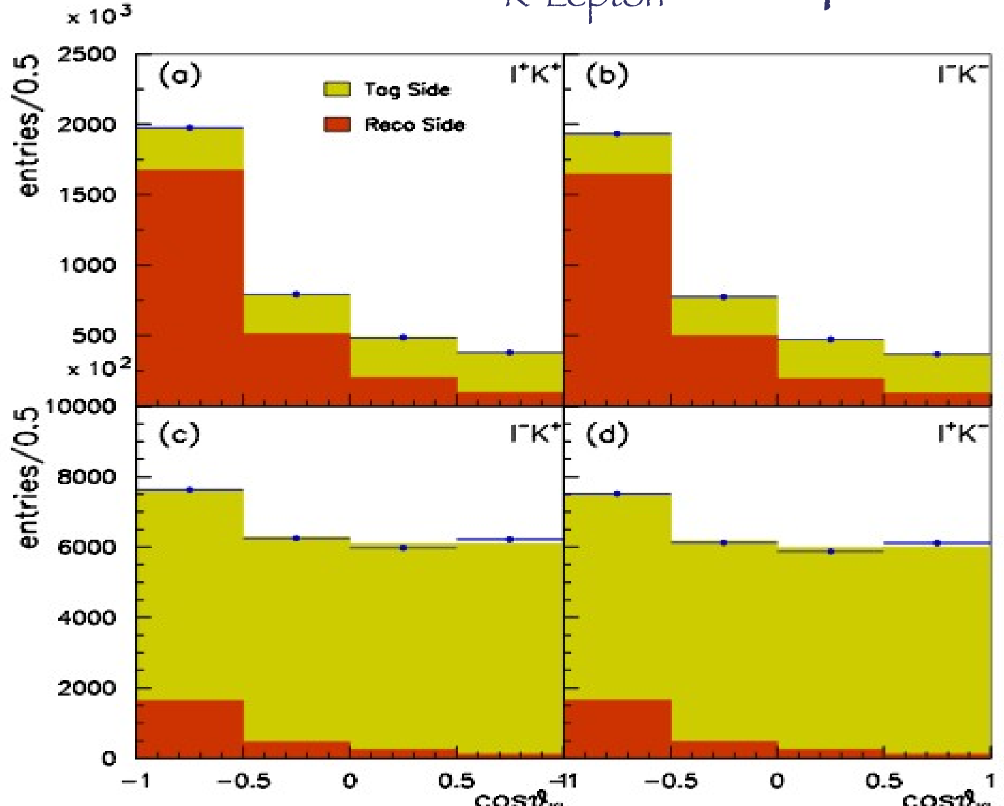
BaBar Flavor Specific A^d_{SL}

arXiv:1305.1575 (2013)
Accepted by PRL

Fitted Δt Shapes



Fitted cos($\theta_{K\text{-Lepton}}$) Shapes



$$|q/p|-1=(-0.29\pm0.84^{+1.61}_{-1.78})\times10^{-3} \rightarrow A^d_{SL}=(0.06\pm0.17^{+0.38}_{-0.32})\%$$

- Systematics dominated by uncertainty on sample composition

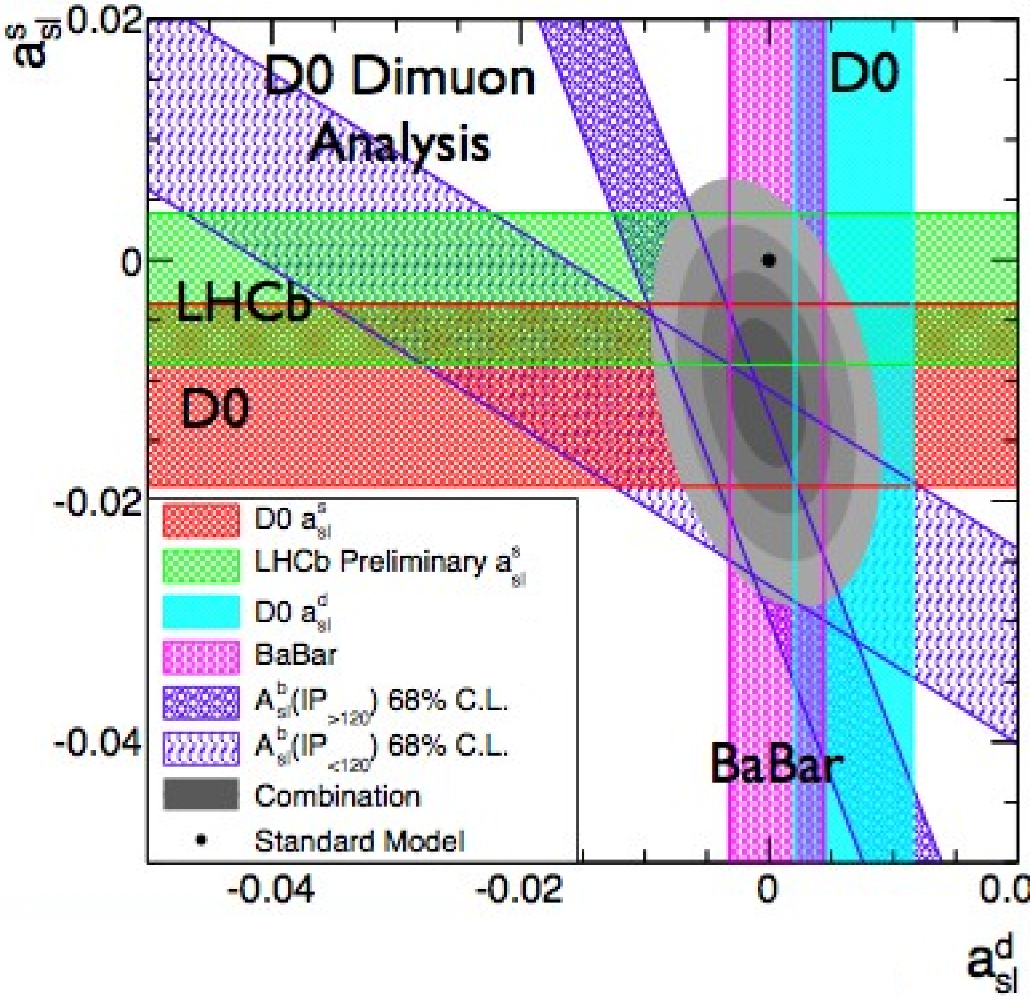
Best single Measurement, in agreement with SM

World Average

- HFAG averages (after CKM2012)

(http://www.slac.stanford.edu/xorg/hfag/osc/fall_2012/#CPV)

Iain Bertram – DIS 2013



- From a 2-D fit to $A^{d,s}_{SL}$:
  - A^d_{SL} (world) = (-0.03±0.21) %
  - A^s_{SL} (world) = (-1.09±0.40) %

- World average of experimental results deviates 2.4 σ from SM prediction

Discovering T-Violation & testing CPT

Time Reversal Violation

Phys. Rev. Lett. 109, 211801 (2012)

- Exploit entanglement of the two B meson system from $\Upsilon(4S)$ decay to measure T-violation and test CPT

$$e^+ e^- \to \Upsilon(4S) \to b\bar{b} \qquad J^{PC} = 1^{--}$$

$$\to \frac{1}{\sqrt{2}}\left(|B^0(t_1)\overline{B^0}(t_2)> - |B^0(t_2)\overline{B^0}(t_1)>\right)$$

flavor eigenstates: $B^0 = (\bar{b}\, d),\ \bar{B}^0 = (b\, \bar{d})$

$$\to \frac{1}{\sqrt{2}}\left(|B_+(t_1)B_-(t_2)> - |B_+(t_2)B_-(t_1)>\right)$$

CP eigenstates: $CP|B_\pm> = \pm|B_\pm>$

- Flavor eigenstates

$$\overline{B^0} \to \ell^- X$$
$$\overline{B^0} \to K^- X$$
$$\overline{B^0} \to \pi^+_{soft} X, \ldots$$

CP eigenstates

$$B_+ \to J/\psi K_L$$
$$B_- \to (c\bar{c}) K_S$$

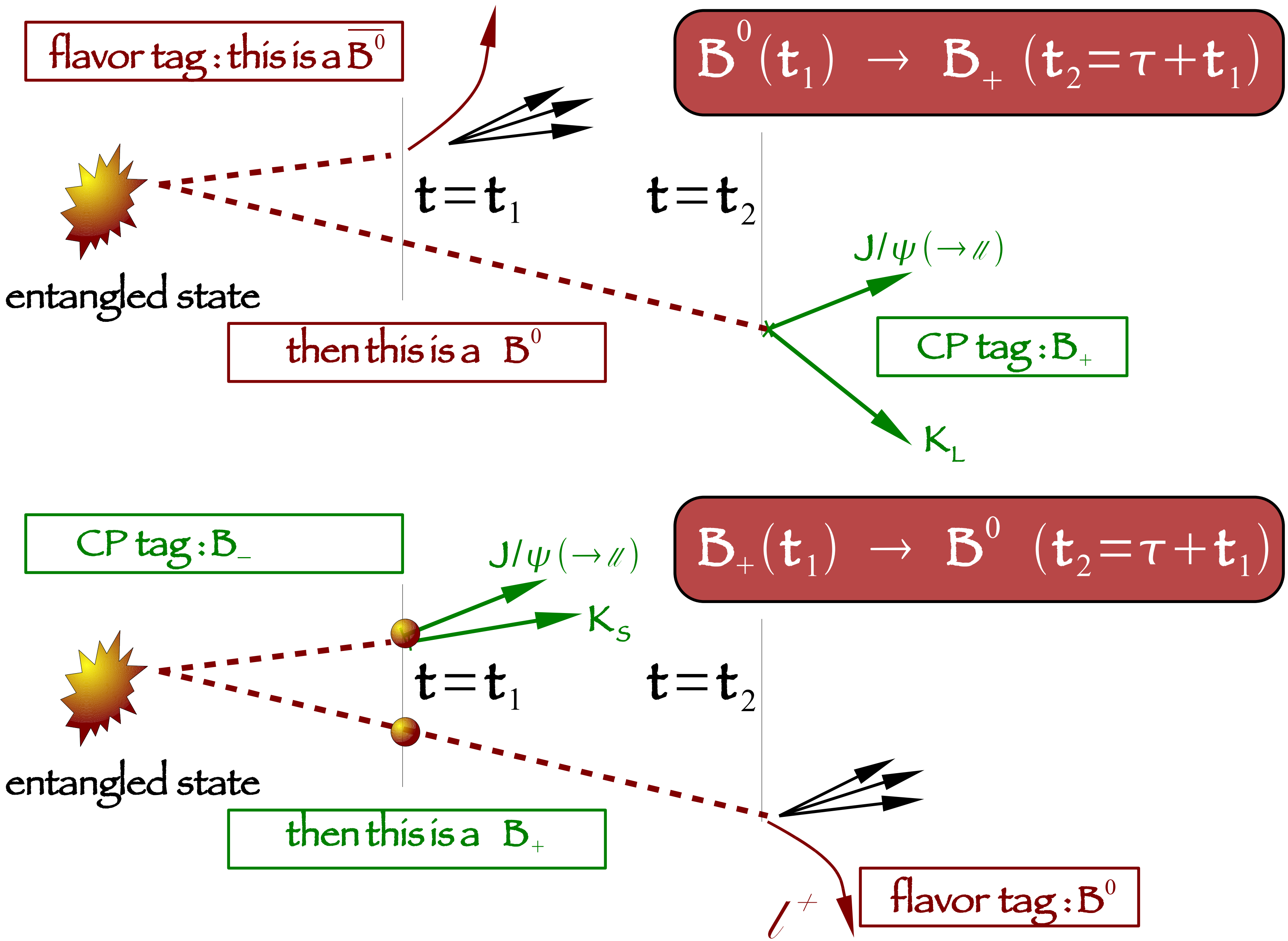
- Perform 4 complementary tests:

$B_+ \to B^0$ vs $B^0 \to B_+$ $\qquad$ $B_- \to B^0$ vs $B^0 \to B_-$

$B_- \to \overline{B^0}$ vs $\overline{B^0} \to B_-$ $\qquad$ $B_+ \to \overline{B^0}$ vs $\overline{B^0} \to B_+$

Time Reversal Violation

Phys. Rev. Lett. 109, 211801 (2012)



Time Reversal Violation

Phys. Rev. Lett. 109, 211801 (2012)

- Define $\Delta t = t(CP) - t(Flavor)$
- Consider eight combinations (flavor x CP x sign of Δt)
- Fit each with Einstein-Podolsky-Rosen-motivated function

$$g^{\pm}_{\alpha,\beta}(\Delta\tau) \propto e^{-\Gamma|\Delta\tau|}\ \mathcal{H}(\pm\Delta\tau)\ [1+S^{\pm}_{\alpha,\beta}\sin(\Delta m_d\Delta\tau)+C^{\pm}_{\alpha,\beta}\cos(\Delta m_d\Delta\tau)]\times\mathcal{R}(\delta t,\sigma\Delta t)$$

Heavyside step function

Resolution function

- $S^{+-}_{\alpha\beta}$, $C^{+-}_{\alpha\beta}$: fit parameters
  - +-: Sign of Δt
  - α: Flavor Tag ($B^0/\bar{B}^0$)
  - β: CP eigenstate (K_S/K_L)

Time Reversal Violation

Phys. Rev. Lett. 109, 211801 (2012)

- Simmetry violation tested by comparing the fitted parameters for conjugate processes:
  - T-Violation :

    $\Delta S_T^{\pm} = S^{\mp}_{\overline{B}^0, K_L} - S^{\pm}_{B^0, K_S} \neq 0$ Compare $B_- \rightarrow \overline{B}^0$ vs $\overline{B}^0 \rightarrow B_-$, $B^0 \rightarrow B_+$ vs $B_+ \rightarrow B^0$
  - CP-Violation :

    $\Delta S_{CP}^{\pm} = S^{\pm}_{\overline{B}^0, K_S} - S^{\pm}_{B^0, K_S} \neq 0$ Compare $B^0 \rightarrow B_-$ vs $\overline{B}^0 \rightarrow B_-$, $B_+ \rightarrow \overline{B}^0$ vs $B_+ \rightarrow B^0$
  - CPT-Violation :

    $\Delta S_{CPT}^{\pm} = S^{\mp}_{B^0, K_L} - S^{\pm}_{B^0, K_S} \neq 0$ Compare $B_- \rightarrow B^0$ vs $\overline{B}^0 \rightarrow B_-$, $\overline{B}^0 \rightarrow B_+$ vs $B_+ \rightarrow B^0$

$\Delta C^{\pm}$ defined accordingly

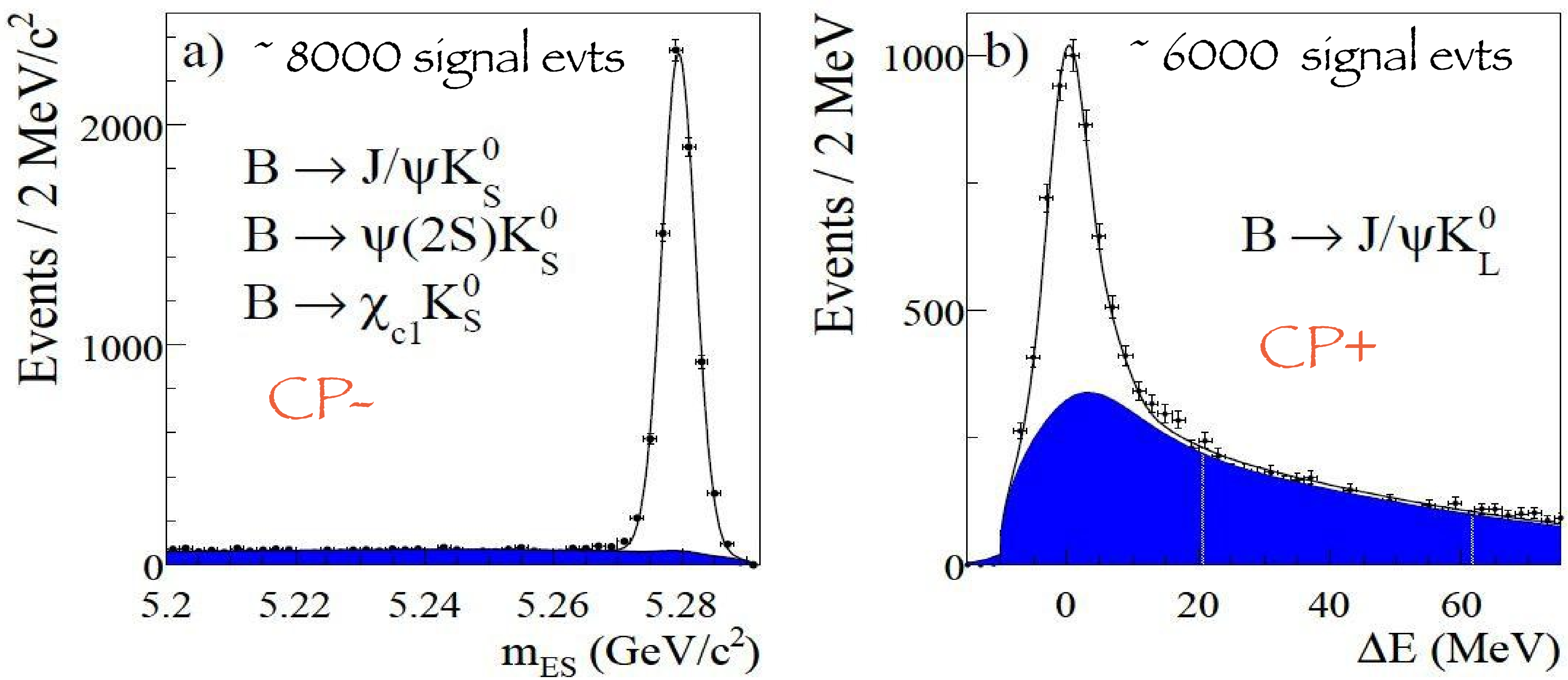
- Assuming CPT & CP violation, expect :

$$\Delta S_T^{\pm} = \mp 2 \sin(2\beta)$$
$$\Delta C_T^{\pm} = 0$$

Time Reversal Violation

Phys. Rev. Lett. 109, 211801 (2012)

- Events selected by means of $\Delta E = E_B - E_{beam}$; $m_{ES} = \sqrt{E_{beam}^2 - p_B^2}$ in the $\Upsilon(4S)$ rest frame from 425.7 fb^{-1}

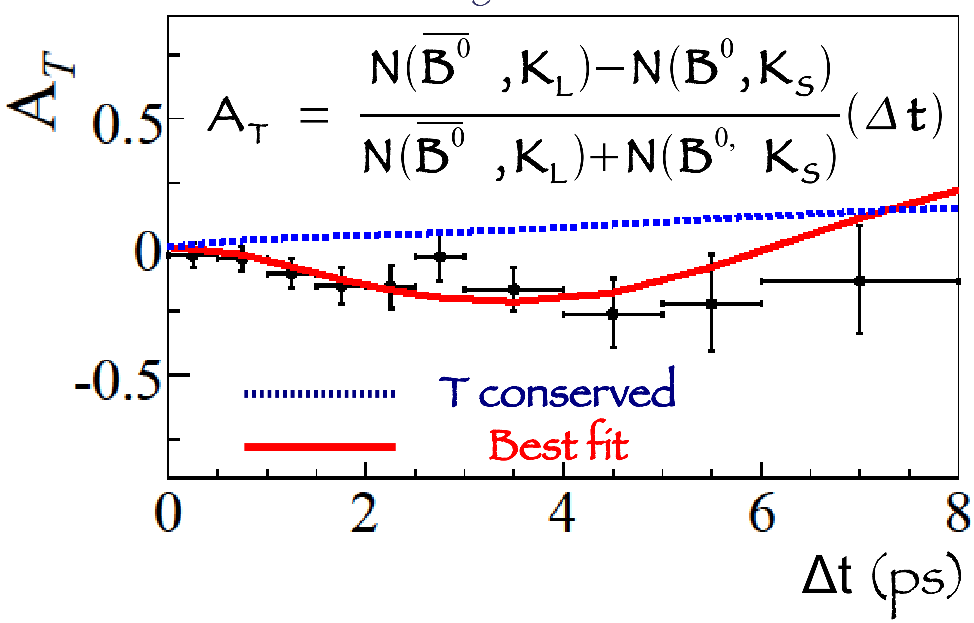


- Flavor of the other B^0 meson from a NN exploiting charge of e/μ, K, π
- Mistag determined on $D^{(*)}\pi$, $D^{(*)}K$, $J/\psi\ K^{*0}$ flavor eigenstates control samples

Time Reversal Violation

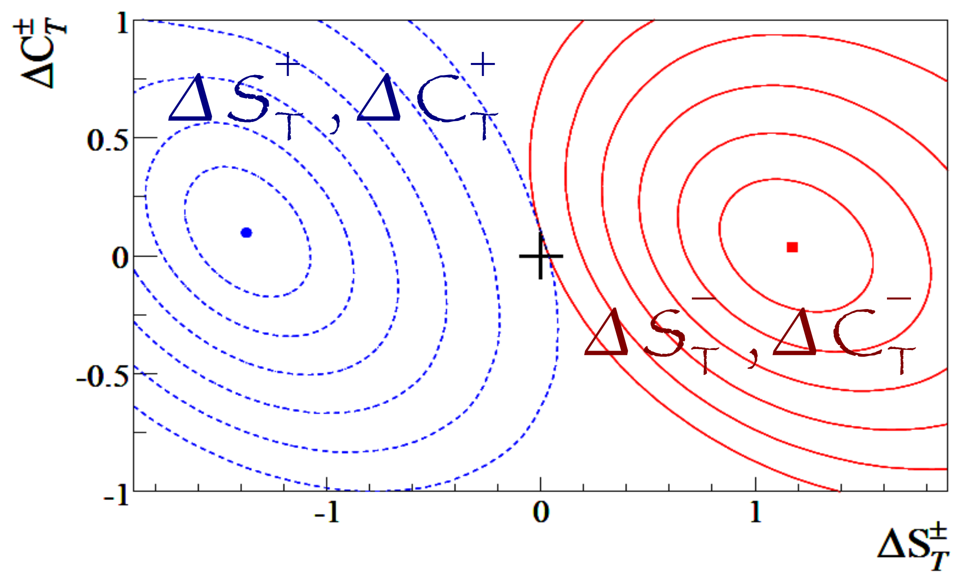
Phys. Rev. Lett. 109, 211801 (2012)

Parameter	Final result
ΔS_T^+	$-1.37 \pm 0.14 \pm 0.06$
ΔS_T^-	$1.17 \pm 0.18 \pm 0.11$
ΔC_T^+	$0.10 \pm 0.16 \pm 0.08$
ΔC_T^-	$0.04 \pm 0.16 \pm 0.08$



First observation of T-violation, with 14 σ significance

- Systematics dominated by mistag determination and Δt resolution



Test CP and CPT

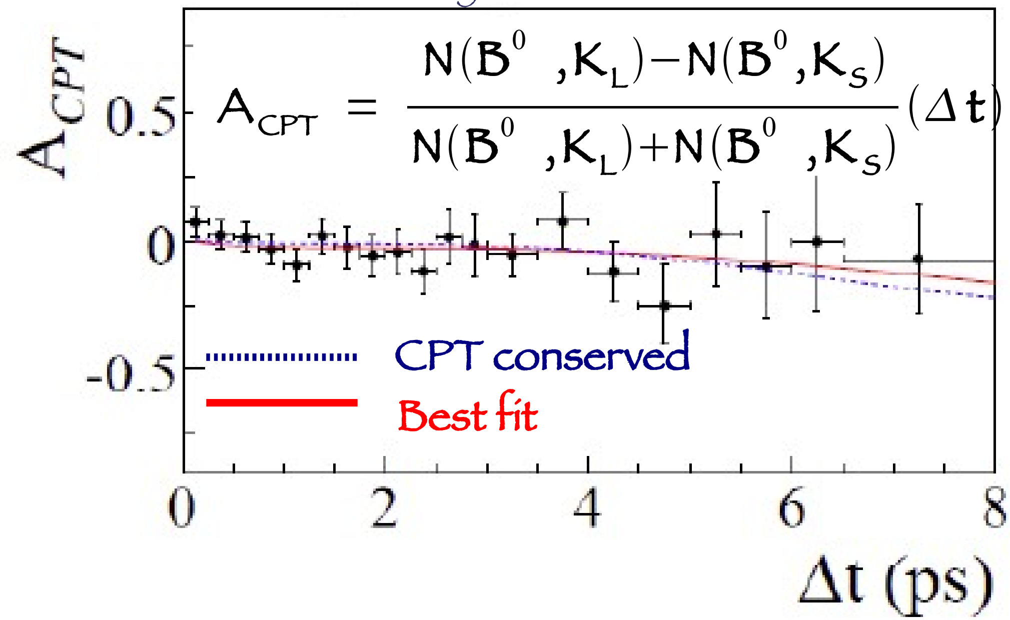
Phys. Rev. Lett. 109, 211801 (2012)

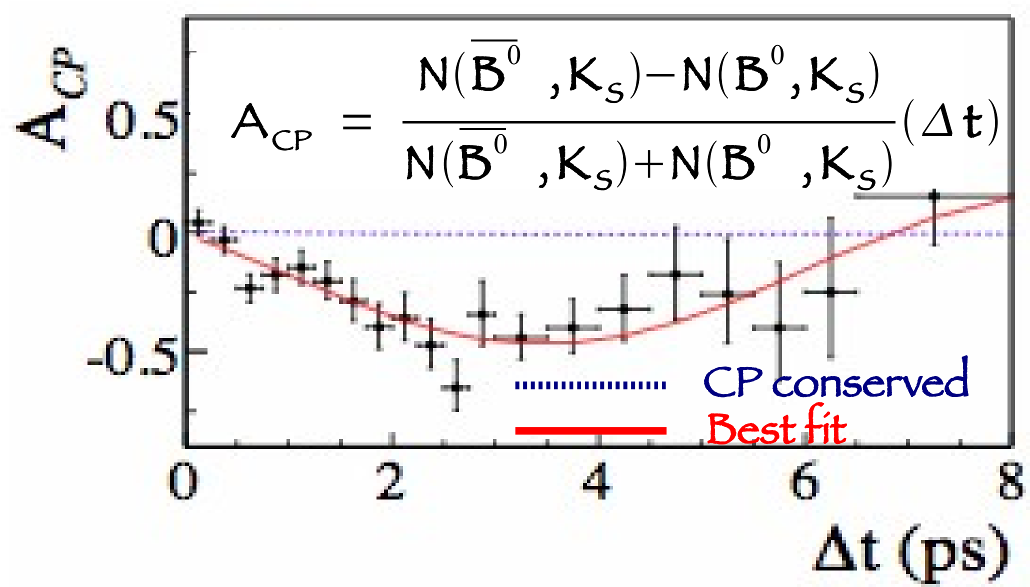
CPT is Conserved

ΔS^{+}_{CPT}	$0.16 \pm 0.21 \pm 0.09$
ΔS^{-}_{CPT}	$-0.03 \pm 0.13 \pm 0.06$
ΔC^{+}_{CPT}	$0.14 \pm 0.15 \pm 0.07$
ΔC^{-}_{CPT}	$0.03 \pm 0.12 \pm 0.08$

CP is Violated

ΔS^{+}_{CP} :	$-1.30 \pm 0.11 \pm 0.07$
ΔS^{-}_{CP} :	$1.33 \pm 0.12 \pm 0.06$
ΔC^{+}_{CP}	$0.07 \pm 0.09 \pm 0.03$
ΔC^{-}_{CP}	$0.08 \pm 0.10 \pm 0.04$





Conclusions

Conclusions

- The search for CP violation is an excellent laboratory for the investigation for physics beyond the Standard Model
- Five new measurements from BaBar using the full statistics have been discussed:
  - Almost all the results are in agreement with expectations

- In the Near Future, LHC experiments & Belle II will offer the Opportunity to:
  - Provide very stringent SM tests
  - Hopefully discover/understand New Physics

Backup

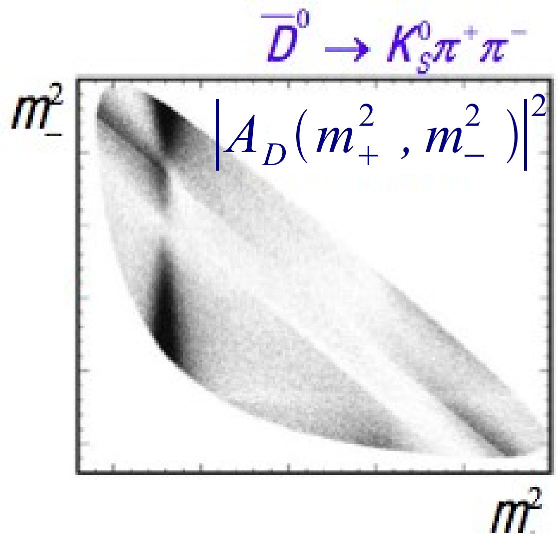
Combination of BaBar γ Measurements

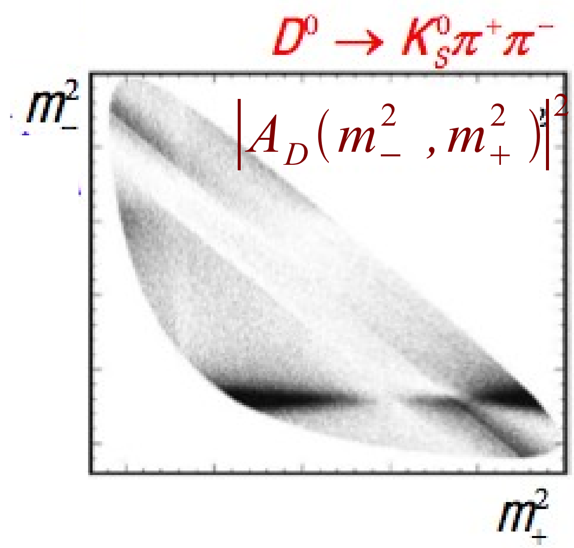
Phys. Rev. D 87, 052015 (2013)

- GGSZ Method (Dalitz):
  - Rates vary as function of the position in the D⁰ Dalitz plot

$$\Gamma(B^{+}) \propto |f_{+}|^2 + (x_{+}^2 + y_{+}^2)|f_{-}|^2 + 2x_{+}\,\Re(f_{+} f_{-}^{*}) + 2y_{+}\,\Im(f_{+} f_{-}^{*})$$
$$\Gamma(B^{-}) \propto |f_{-}|^2 + (x_{-}^2 + y_{-}^2)|f_{+}|^2 + 2x_{-}\,\Re(f_{+} f_{-}^{*}) + 2y_{-}\,\Im(f_{+} f_{-}^{*})$$
$$f_{\mp} = A_D(m_{\mp}^2, m_{\pm}^2), \quad m_{\pm}^2 = m^2(K_S\pi^{\pm})$$

  - $A_D(m_{\mp}^2, m_{\pm}^2)$ From Dalitz plot analysis of high statistics samples of flavor-tagged D^0 and $\overline{D^0}$:





Native observables vs cartesian coordinates

Phys. Rev. D 87, 052015 (2013)

- GLW Method:

$$R_{CP\pm}=\frac{\Gamma(B^-\to D^0_{CP\pm}K^-)+\Gamma(B^+\to D^0_{CP\pm}K^+)}{2\,\Gamma(B^-\to D^0K^-)}=1+r_B^2\pm(x_-+x_+)$$

$$A_{CP\pm}=\frac{\Gamma(B^-\to D^0_{CP\pm}K^-)-\Gamma(B^+\to D^0_{CP\pm}K^+)}{\Gamma(B^-\to D^0_{CP\pm}K^-)+\Gamma(B^+\to D^0_{CP\pm}K^+)}=\frac{\pm(x_--x_+)}{R_{CP\pm}}$$

- ADS Method:

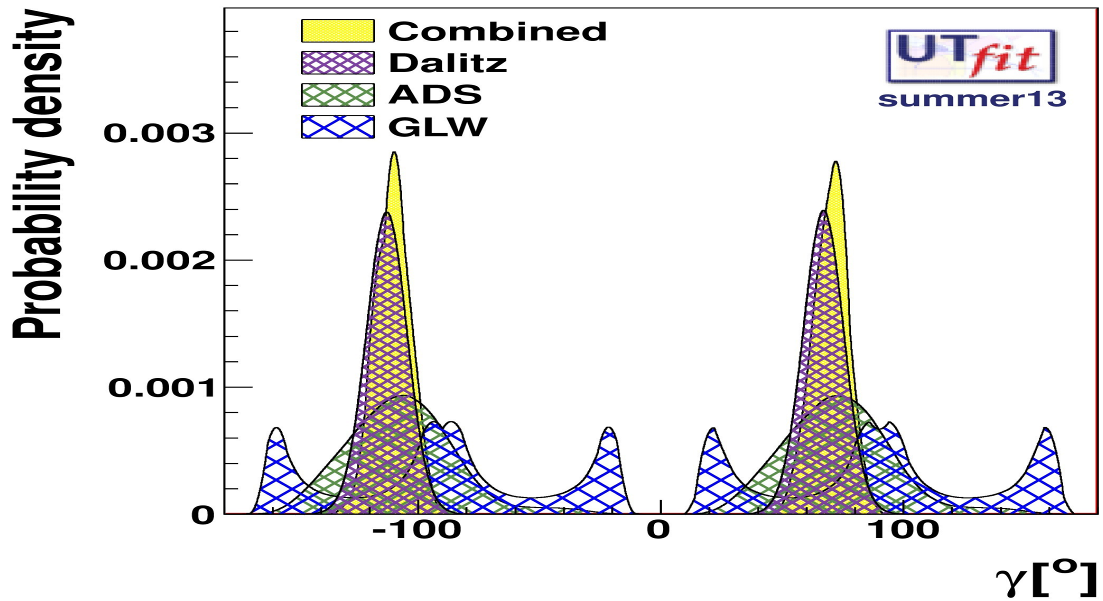
$$R_\pm=\frac{\Gamma(B^\pm\to[K^\mp\pi^\pm]_DK^\pm)}{\Gamma(B^\pm\to[K^\pm\pi^\mp]_DK^\pm)}=r_B^2+r_{D^0}^2+2\mathrm{r}_{D^0}(x_\pm\cos\delta_{D^0}-y_\pm\sin\delta_{D^0})$$

$$r_{D^0}=\frac{A(D^0\to K^+\pi^-)}{A(D^0\to K^-\pi^+)}$$

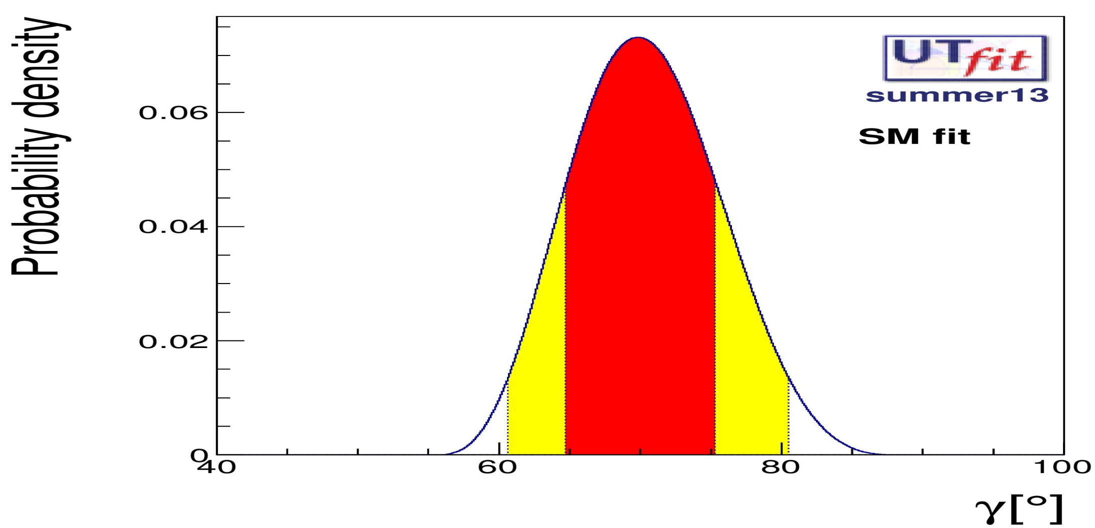
$\delta_{D^0}=$ Relative strong phase

World Average

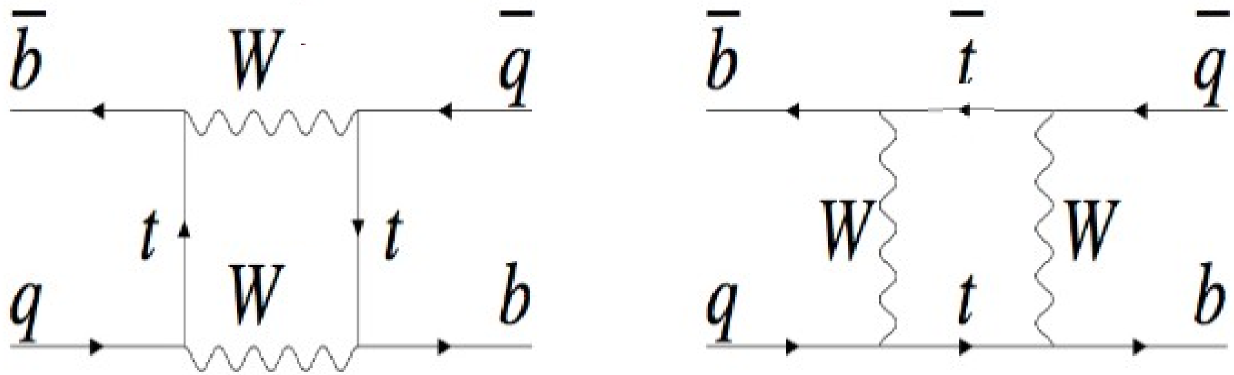
- Using only direct γ measurements:
  γ=(70.1±7.1)°



- From Full Standard Model Fit:
  γ=(70.3±3.5)°



CPV in B^0 mixing



- New Particles in the boxes could modify SM expectations

- $B^0_q - \overline{B^0_q}$ oscillations & decay governed by an Effective Hamiltonian:

$$i\frac{d}{dt}\begin{pmatrix} B_q \\ \bar{B}_q \end{pmatrix} = \left[\begin{pmatrix} M^q_{11} & M^{q\,*}_{21} \\ M^q_{21} & M^q_{11} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma^q_{11} & \Gamma^{q\,*}_{21} \\ \Gamma^q_{21} & \Gamma^q_{11} \end{pmatrix}\right]\begin{pmatrix} B_q \\ \bar{B}_q \end{pmatrix}$$

$[M_{ij}]$ = mass matrix

$[\Gamma_{ij}]$ = decay matrix

- Physical Eigenstates with defined masses and widths:

$$|B_q^{L,H}\rangle = \frac{1}{\sqrt{1+|(q/p)_q|^2}}\left(|B_q\rangle \pm (q/p)_q\,|\overline{B}_q\rangle\right)$$

- If $|(q/p)_q|=1$ they would be also CP Eigenstates

- Neglecting $o(m^2_b/M^2_W)$:

$$\Delta m_q = m_H - m_L \simeq 2\left|M^q_{12}\right|;\ \Delta\Gamma_q = \Gamma_L - \Gamma_H \simeq 2\left|\Gamma^q_{12}\right|\cos\phi_q$$

$\phi_q = arg(-M^q_{12}/\Gamma^q_{12})$ CP violating phase

BaBar Flavor Specific A^d_{SL}

arXiv:1305.1575 (2013)

- Signal B⁰ Btag PDF for Positive Mixed (l^+K^+) sample, (similar expressions apply for the other ones):

$$\mathcal{F}_{signal}(\Delta t, s_t, s_m) = \frac{\Gamma}{2(1+r'^2)} e^{-\Gamma|\Delta t|} \left|\frac{p}{q}\right|^2 \left[\left(1 + \left|\frac{q}{p}\right|^2 r'^2\right) \cosh(\Delta\Gamma \Delta t/2) - \right.$$
$$\left. - \left(1 - \left|\frac{q}{p}\right|^2 r'^2\right) \cos(\Delta m_d \Delta t) + \left|\frac{q}{p}\right| (b+c) \sin(\Delta m_d \Delta t) \right]$$

- r', b, c: parameters resulting from interference between Cabibbo-Favoured and Doubly Cabibbo-Suppressed decays on the tag side

$r' = |\overline{A}_{DCS}/A_{CF}|$

$b = 2r' \sin(2\beta+\gamma)\cos\delta'$

$c = -2r' \cos(2\beta+\gamma)\sin\delta'$

$\delta' =$ Strong Phase

- Assumed $\Delta\Gamma = 0$
- b, c are treated as effective parameters due to strong correlation with resolution function
  - Only |q/p| is measured

PDF Description: Dtag

- Dominant BKG in Mixed events: shows single-tag semileptonic asymmetry

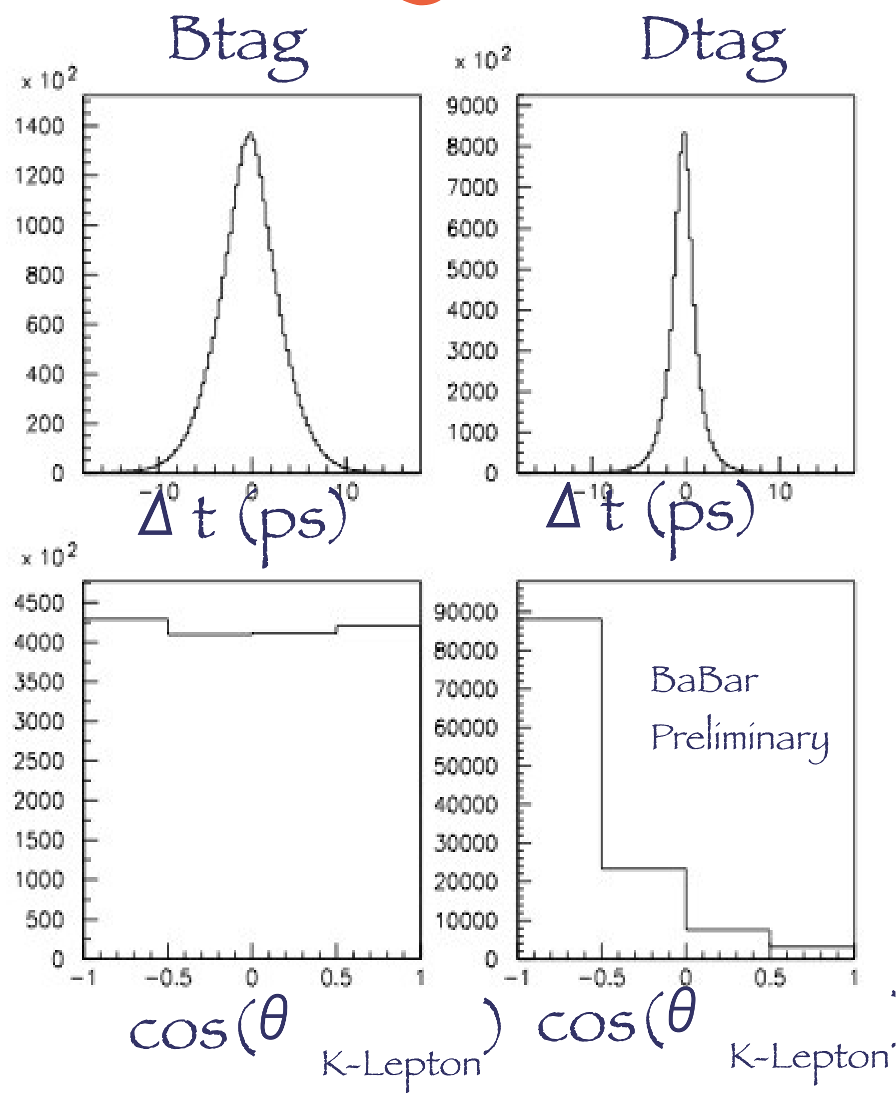
- F_{Dtag} floated by exploiting the different Δt & θ (K-Lepton) distributions wrt Btag events in different P_K bins

- Dtag fraction in B^+ events constrained to B^0 using simulation informations:

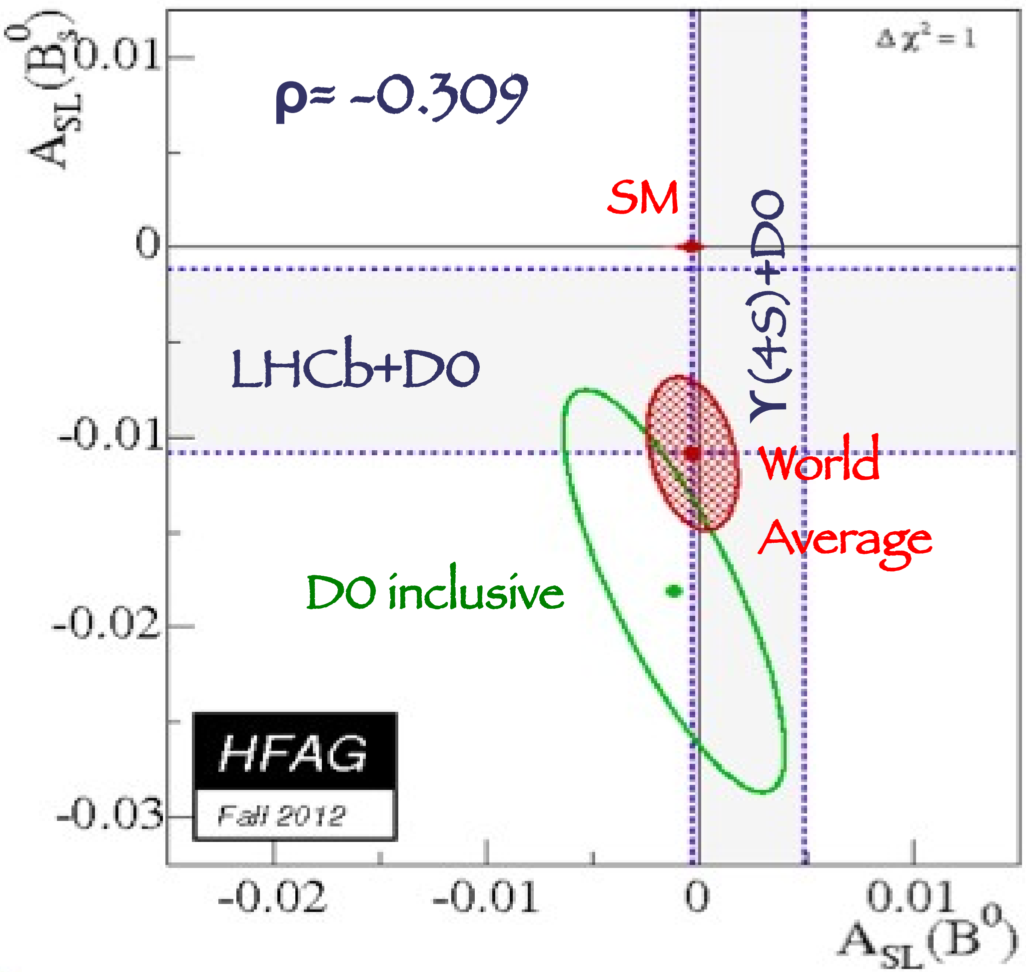
$F^{B+}_{Dtag}=R_{MC}(P_K)*F^{B0}_{Dtag}$

- $\cos(\theta_{K\text{-}Lepton})$ PDF from MC

- Δt PDF from **a High Purity selection on Real Data (Dtag Purity ~95%)**



Combination of Results



- Results from flavor specific measurements:
- A^d_{SL} :
  - $\Upsilon(4S) = (0.02 \pm 0.31)\,\%$
  - $\Upsilon(4S) + D0 = (0.23 \pm 0.26)\,\%$
- A^s_{SL} :
  - $D0 + LHCb = (-0.60 \pm 0.49)\,\%$

- World averages of flavor specific measurements agree with SM

Constraints on New Physics

- New Physics could modify M^q_{12} and A_{SL} leaving Γ^q_{12} unchanged

(Lenz et al., Phys, Rev. D 86, 033008 (2012), Nierste, arXiv:1212.5805 (2012))

$$M_{12}^{NP,q} = M_{12}^{SM,q}\Delta_q\,;\,\Delta_q = |\Delta_q| e^{i\phi_q^\Delta}$$

$$\Delta_q^{SM} = 1$$

$$A_{SL}^{NP} = \frac{|\Gamma_{12}^q|}{|M_{12}^{SM,q}|}\frac{\sin(\phi_q^{SM} + \phi_q^\Delta)}{|\Delta_q|}$$

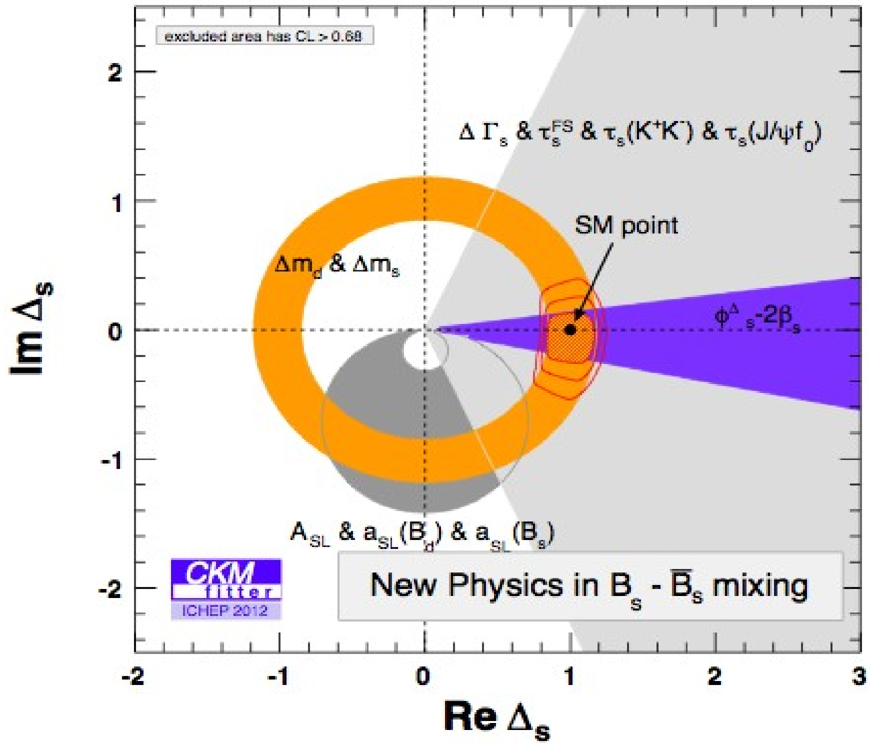
- New phases ϕ_q^Δ would shift also the CP phases from the mixing-induced CP asymmetries:
  - $B^0 \rightarrow J/\psi K_S$: $2\beta \rightarrow 2\beta + \phi_d^\Delta$
  - $B^0_s \rightarrow J/\psi\Phi$: $2\beta_s \rightarrow 2\beta_s - \phi_s^\Delta$
- Strong constraint from recent LHCb $B^0_s \rightarrow J/\psi\Phi$ measurement:
  - $2\beta_s - \phi_s^\Delta = (0.1 \pm 5.8 \pm 1.5)^o$ (LHCb-CONF-2012-002)

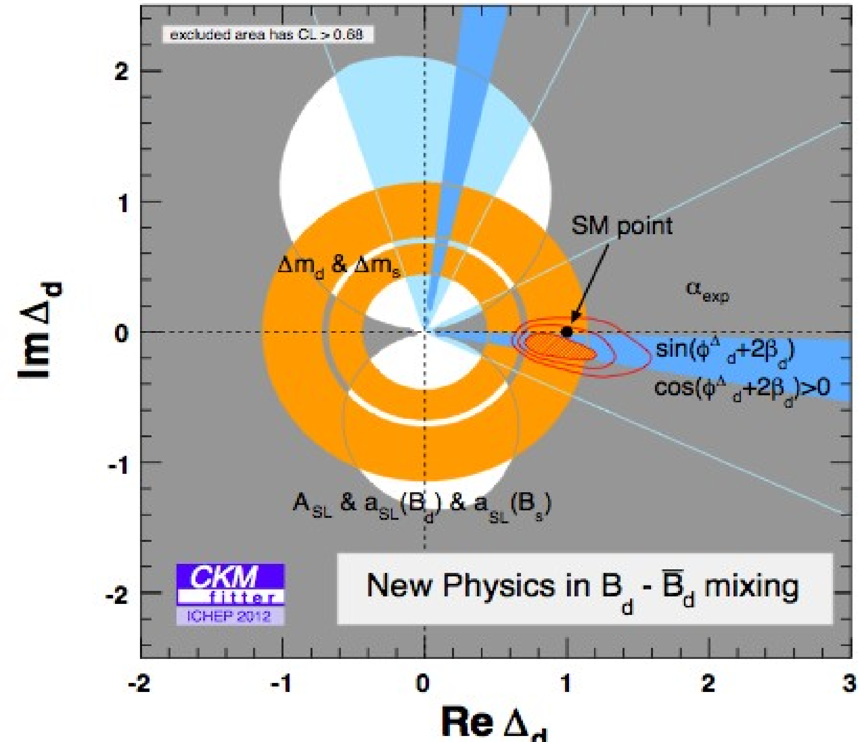
$(2\beta_s = 2\,arg(-V_{ts}V^*_{tb}/V_{cs}V^*_{cb}) \simeq 2.1^o)$

Constraints on New Physics

- Global fit of $\Delta_{d,s}$ and CKM elements performed to all relevant data

(Nierste, arXiv:1212.5805 (2012), CKMfitter Group (J. Charles et al.), http://ckmfitter.in2p3.fr):





- Average still not includes recent D0 & BaBar flavor specific results
- Due to LHCb costraint on ϕ_s^Δ, SM prediction disfavored by only 1 σ
- Difficult to accomodate the D0 inclusive A_{SL} result in this framework