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

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Representing the BaBar Collaboration at

EPSHEP 2013

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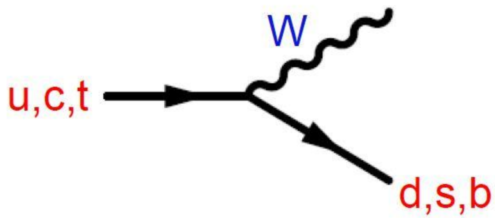
18th-24th May

CKM mechanism

- Flavor quark changing in the Standard Model proceed via charged weak currents



$$-\frac{g}{\sqrt{2}}\left(\bar{u}_L, \bar{c}_L, \bar{t}_L\right)\gamma^\mu W_\mu^+ \mathbf{V}_{\mathrm{CKM}} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \textbf{h.c.}$$

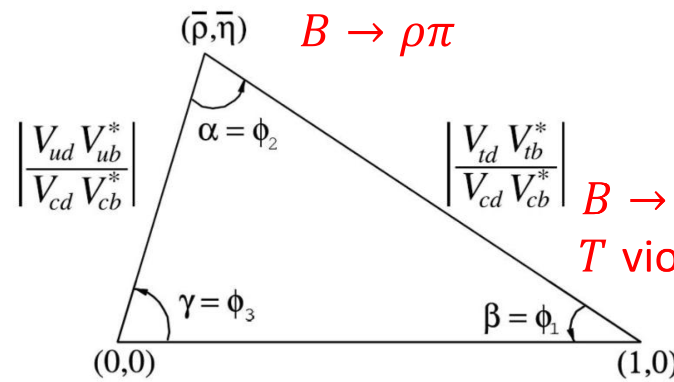
V_{CKM} matrix relates mass and weak eigenstates $(d', s', b') = V_{CKM}(d, s, b)$

- Only 4 independent parameters: Only 4 independent parameters: A, λ, ρ, η (Wolfenstein parametrization). These elements need to be measured and are not predicted.
- Unitarity of the V_{CKM} implies 6 conditions, 6 triangles, in particular

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

$$\alpha = (89.0^{+4.4}_{-4.2})^o$$
$$\beta = (21.4 \pm 0.6)^o$$
$$\gamma = (68^{+10}_{-11})^o$$
$$\alpha + \beta + \gamma = 178 \pm 10^0$$

$B \to \rho\pi$



$B \to J/\psi K_S$
T violation

$B \to DK$ $B \to D^* D^*$

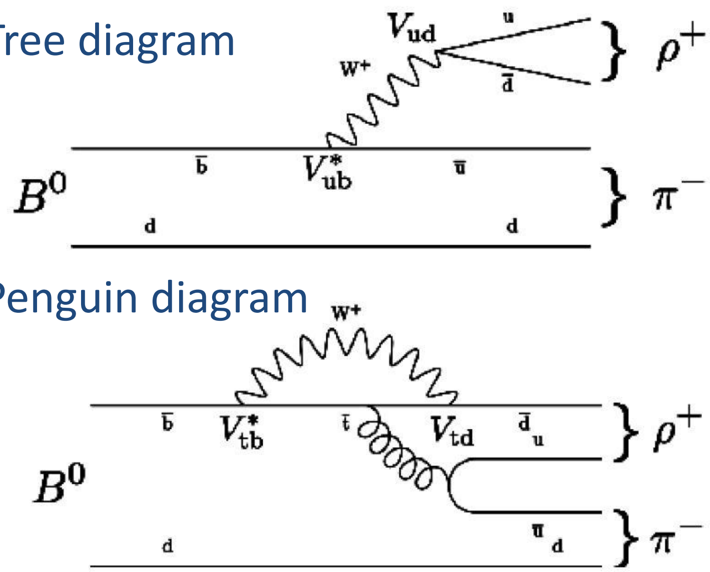
CP: TD Dalitz plot $B \to (\rho\pi)^0$ (1)

- $B \to \pi^+\pi^-\pi^0$ is a *CPV* measurement.
- Dominant channel is $B^0 \to \rho\pi$
- Complicated isospin relations
  - $B^0 \to \rho^+\pi^-/\rho^-\pi^+/\ \rho^0\pi^0$ and $B^+ \to \rho^+\pi^0/\ \rho^0\pi^+$ amplitudes
- Time-dependent amplitude analysis assuming isospin symmetry
  - Permits, in principle, an unambiguous measurement of α

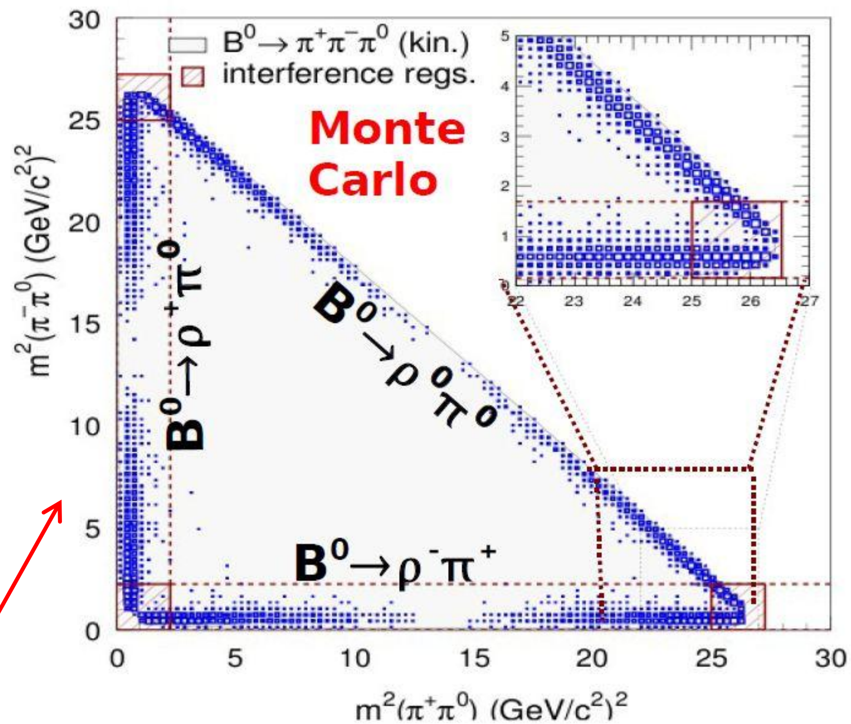
Snyder-Quinn Phys.Rev. D 48,2139 (1993)

Tree diagram

Penguin diagram



Comparable size of both diagrams
Introduces strong phases difficult to compute



CP: TD Dalitz plot $B \to (\rho\pi)^0$ (2)

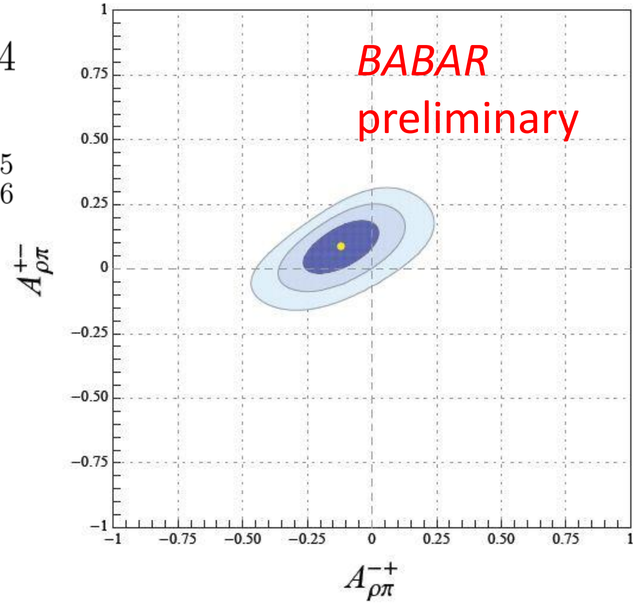
- Updated measurement with full BaBar data set
- Direct CPV asymmetries

ArXiv: 1304.3503 *BABAR* preliminary

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

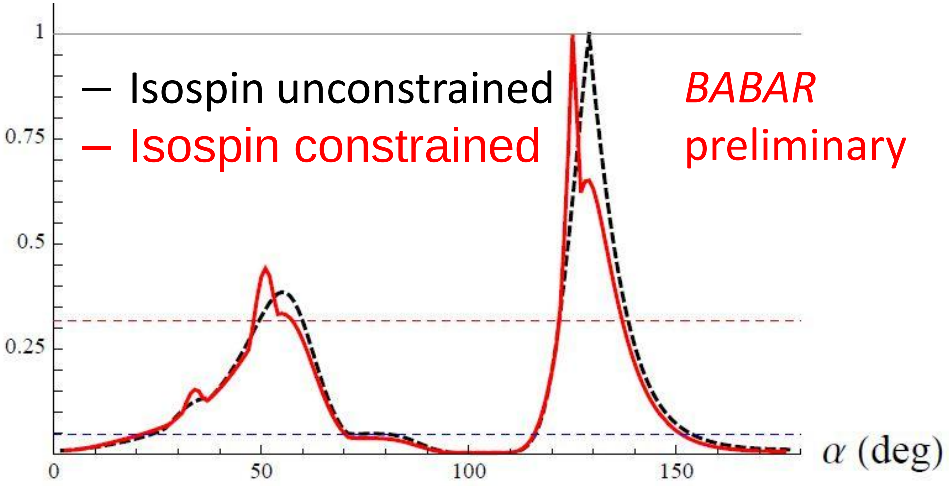
$$\mathcal{A}_{\rho\pi}^{-+} \equiv \frac{\Gamma(\bar{B}^0 \to \rho^+\pi^-) - \Gamma(B^0 \to \rho^-\pi^+)}{\Gamma(\bar{B}^0 \to \rho^+\pi^-) - \Gamma(B^0 \to \rho^-\pi^+)} = -0.12 \pm 0.08^{+0.05}_{-0.06}$$

no direct-CPV is $\Delta\chi^2 = 6.42$ units from minimum



- α-Scan

$\Sigma \neq 1 - CL$

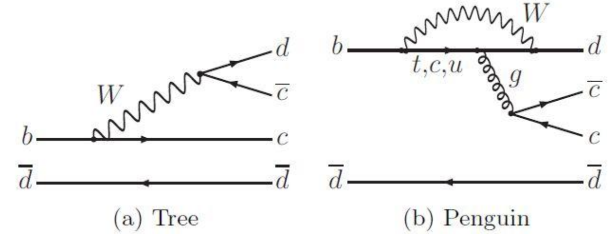


Importantly, studies find that α-scan is not robust with current statistics

- Secondary solutions may be favoured due to statistical fluctuations
- Problem disappears for higher S/B
- Analysis would benefit from increased dataset from high-luminosity exp.

CP: $B \rightarrow D^{*+}D^{*-}$

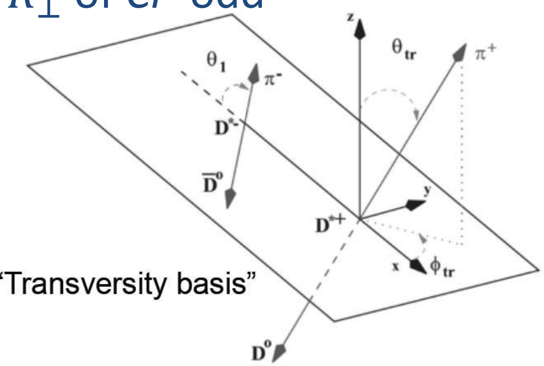
- Measurement of $\sin(2\beta)$ in $b \rightarrow c\bar{c}d$
  - Time Dependent asymmetry sensitive to $S_\eta \sim \eta\sin(2\beta)$
    - If penguin contribution can be neglected
    - In the SM, penguin contributions lead to corrections of ~few % to the determination of sin2β from the TD *CPV* asymmetry
  - Large deviation of S_η from value measured in $b \rightarrow c\bar{c}s$ transitions could indicate physics beyond the SM



- VV final state: mixture of *CP*=+1 and *CP*=−1 depending on final state polarization
  - Angular analysis with fully reconstructed events needed to separate *CP* eigenstates
  - BaBar and Belle full reconstruction analyses measured the *CP* even component, *CPV* parameters S_+ and C_+, and the fraction $R_\perp$ of *CP*-odd amplitude, $R_\perp$=0.158±0.028±0.006

$$R_\perp = \frac{|A^0_\perp|^2}{|A^0_0|^2 + |A^0_\parallel|^2 + |A^0_\perp|^2}$$

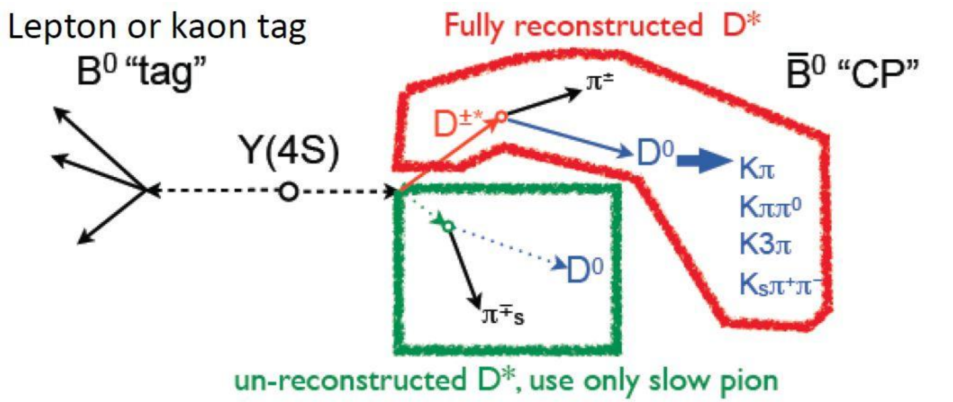
CP=+1 for $A_{\parallel}$,A_0
CP=−1 for $A_\perp$



“Transversity basis”

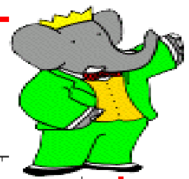
CP: $B \to D^{*+}D^{*-}$

PRD **86**, 112006 (2012)



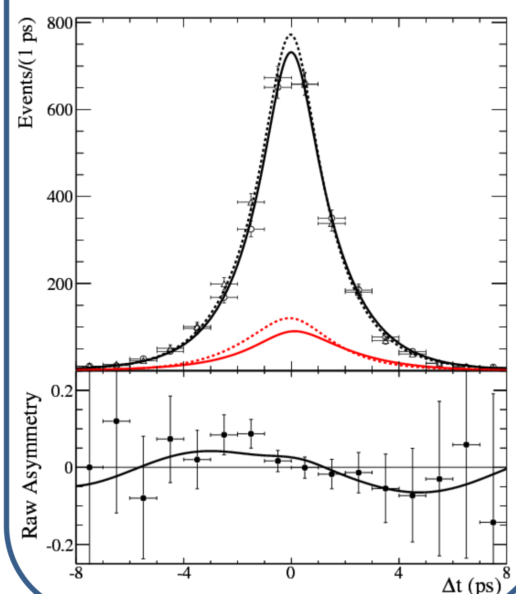
Partial Reconstruction Method

- Fully reconstruct $D^* \to D^0\pi$
- Match reconstructed D^* with a slow pion of opposite sign in the event
- Select candidate if the kinematics is consistent with a $B^0 \to D^* D^0 \pi$
- Compute recoiling D^0 mass

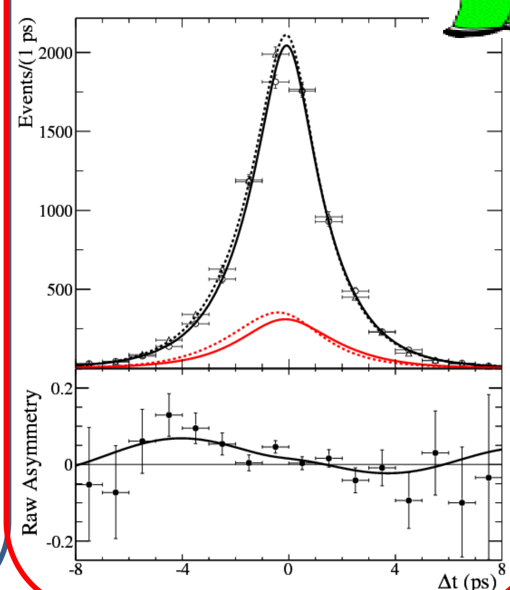


Pros: gain in statistics
Cons: Higher background, larger systematic uncertainty

Lepton tag



Kaon tag

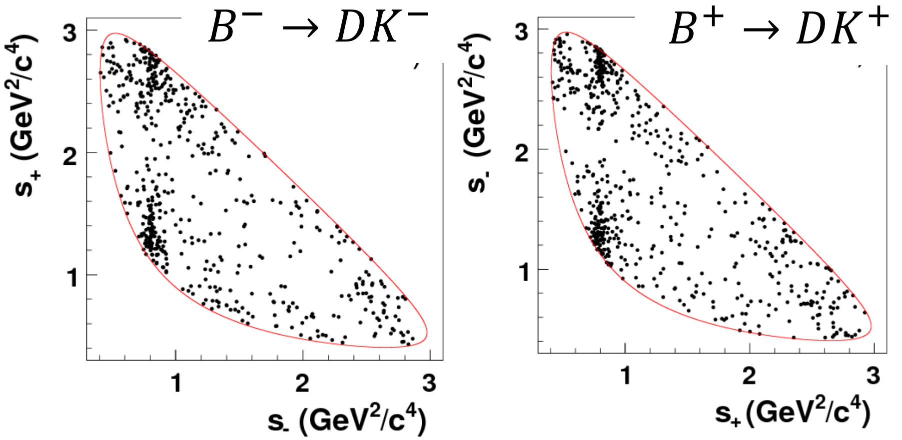


- Assuming negligible penguin contributions
  $S_+ = -S_-;\ C_- = -C_+$
  $S = S_+(1-2R_\perp);\ C = C_+$
- Using(1) $R_\perp = 0.158 \pm 0.029$
  $C_+ = +0.15 \pm 0.09 \pm 0.04$
  $S_+ = -0.49 \pm 0.18 \pm 0.07 \pm 0.04$
  stat. syst. $R_\perp$

(1)B. Aubert et al. (BABAR collaboration), Phys. Rev. D79, 032002 (2009)

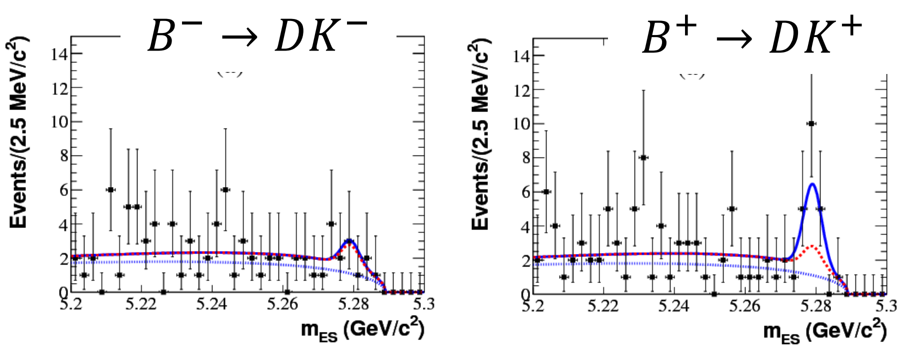
CP: γ methods

- Dalitz plot method (GGSZ) Method
  - A. Giri, Yu. Grossman, A. Soffer, J. Zupan, PRD **68**, 054018(2003)
  - Three-body decays
    PRL **105** (2010) 121801



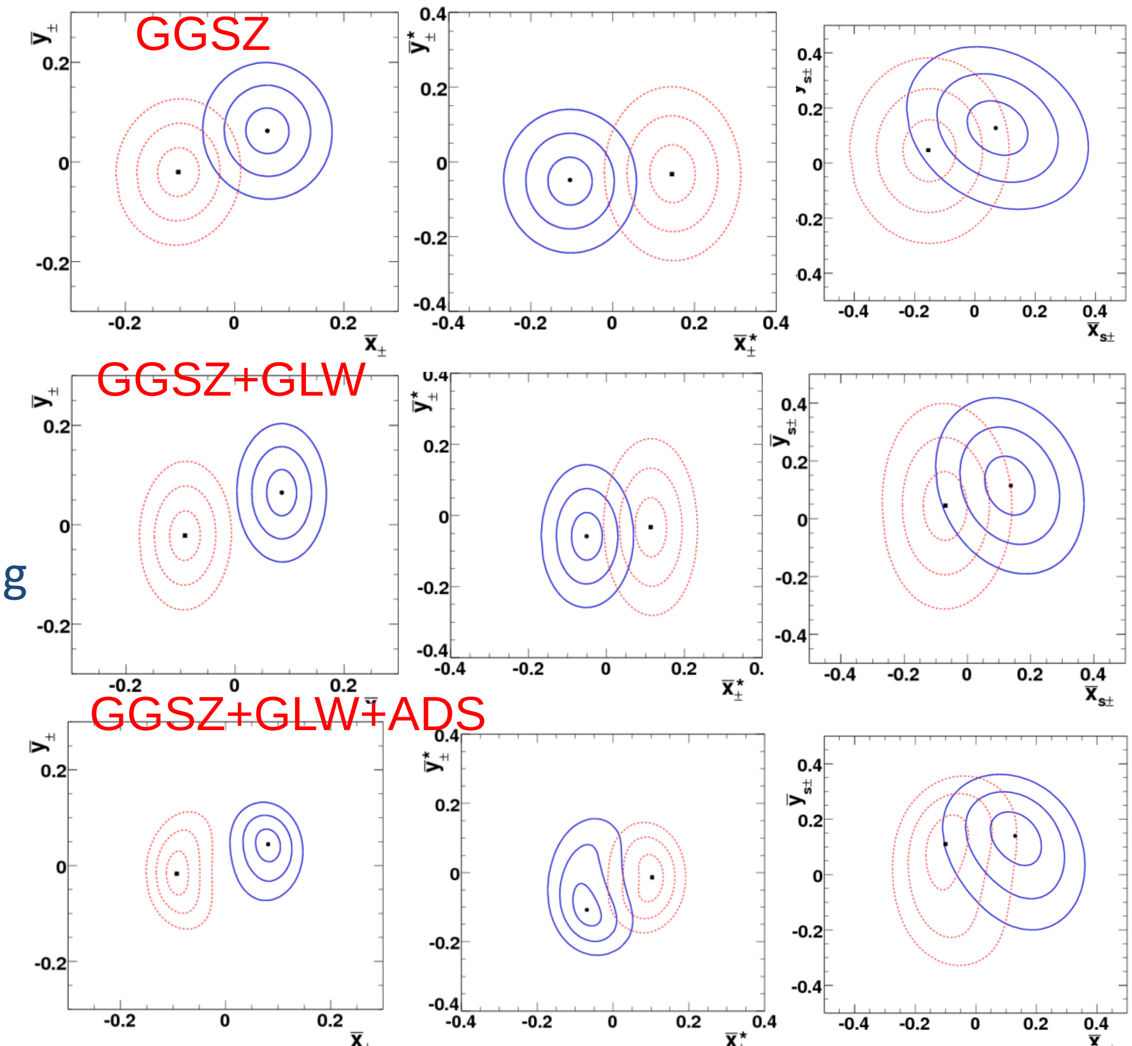
- Gronau-London-Wyler (GLW) Method
  - M. Gronau, D. London, D. Wyler, PLB **253**, 483 (1991); PLB **265**, 172 (1991)
  - CP eigenstates $(D^0 \to K_S\pi^0,\ D^0 \to K^+K^-)$
    PRD **82** (2010) 072004

- Atwood-Dunietz-Soni(ADS) Method
  - D. Atwood, I. Dunietz, A. Soni, PRL 78, 3357 (1997)
  - Doubly –Cabbibo suppressed decays $(D^0 \to K^+\pi^-)$
    PRD **82** (2010) 072006



CP: γ combination

- Parameterize the experimental likelihood convoluted with systematic errors.
- Express the GLW and ADS parameters through Cartesian coordinates.
- Build global likelihood as a product of partial PDFs inserting also the external constraints from charm sector
- Maximize the Likelihood and extract the best values of coordinates and D hadronic decays parameters.
  - 18 fit parameters+39 input observables
- Compute γ



PRD **87**, 052015 (2013)

CP: γ extraction

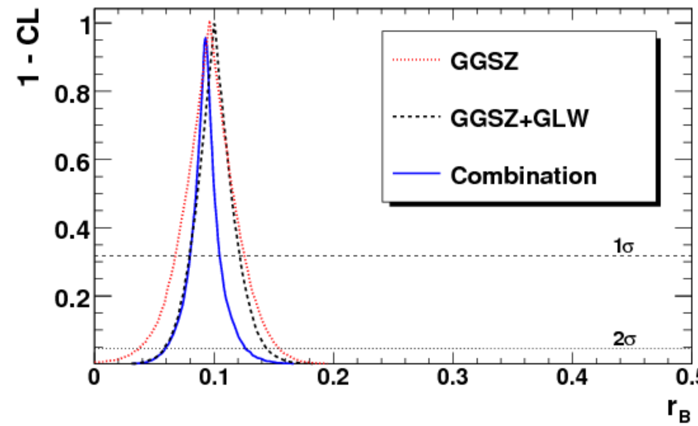
- Transform the combined Cartesian coordinates into polar coordinates γ and $\{r_B, \delta_B\}$ for each decay type

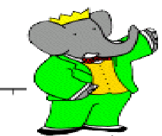
$$x_\pm = Re\left(r_B e^{i(\delta\pm\gamma)}\right) = r_B\cos(\delta\pm\gamma)$$
$$y_\pm = Im\left(r_B e^{i(\delta\pm\gamma)}\right) = r_B\sin(\delta\pm\gamma)$$
$$z_\pm = x_\pm + i\, y_\pm$$

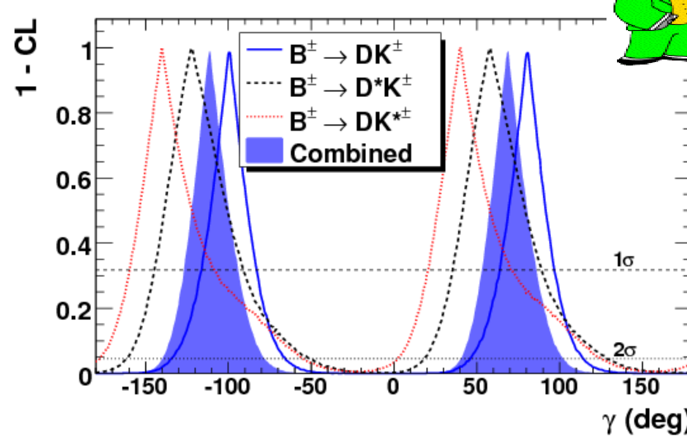
- Use the frequentist (Neyman) approach
- The scan relies on the pseudo-experiments
- The significance of the CP violation is 5.9σ (to be compared to 3.9σ for the GGSZ method)
- The uncertainty on γ increases since the preferred value of r_B lower for the combination

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

$$\gamma = (69^{+17}_{-16})^o$$



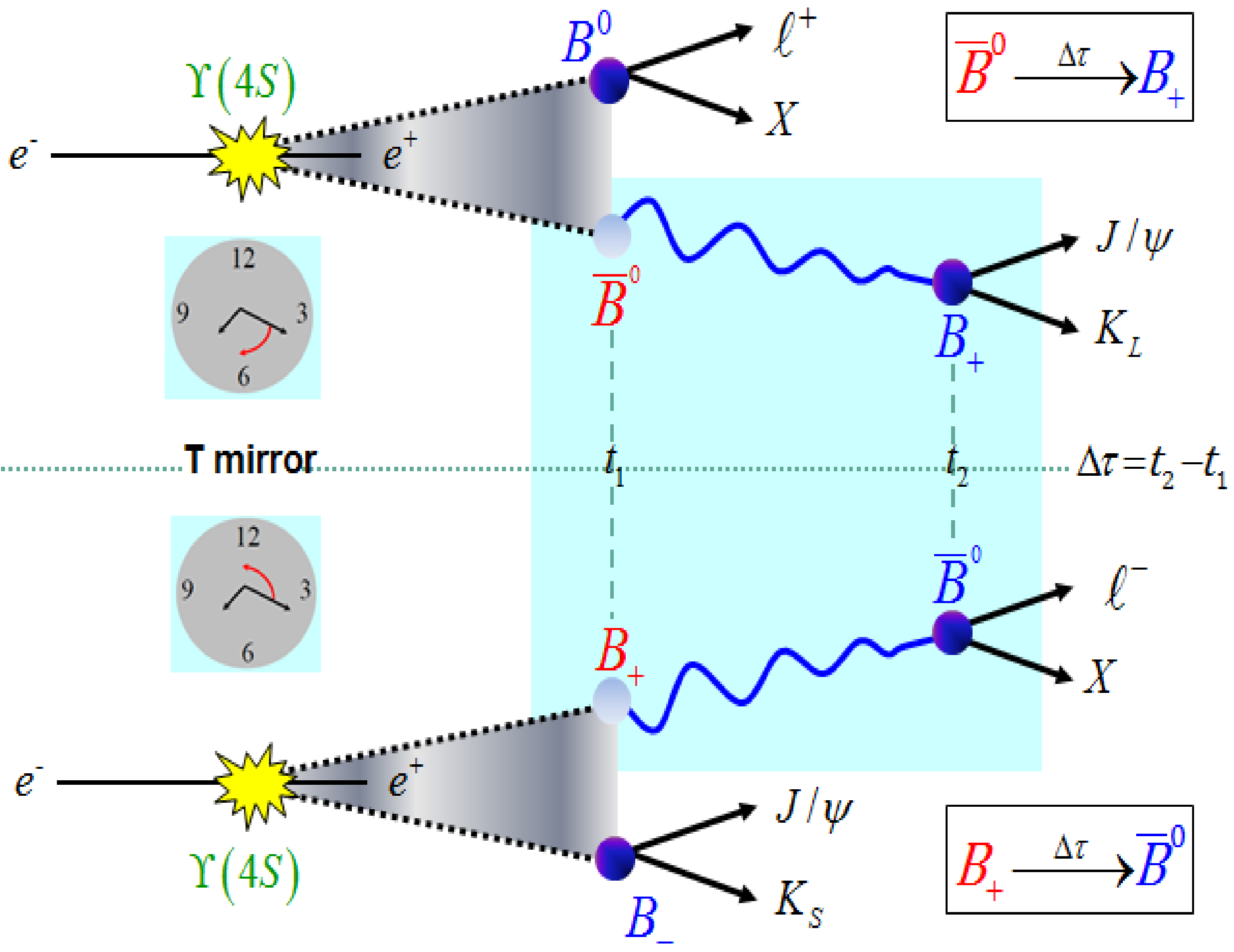




TV: The idea

- Exploit $B^0\bar{B}^0$ entanglement in $\Upsilon(4S) \rightarrow B^0\bar{B}^0$ decays to define time dependent processes related by *T*, . i.e., define a ratio

$$A_T = \frac{P(a \rightarrow b) - P(b \rightarrow a)}{P(a \rightarrow b) + P(b \rightarrow a)}$$



a: Flavor eigenstate B^0 or $\bar{B}^0$ identified by semileptonic decay ℓ^+ or ℓ^-

b: *CP* eigenstate B_+ or B_- identified by $J/\psi K_L$ or $J/\psi K_S$

We measure the time difference between the decays of the two B's

$\Delta t \equiv t_{CP} - t_{flav} > 0$ e.g. $\bar{B}^0 \rightarrow B_+$

< 0 e.g. $B_+ \rightarrow \bar{B}^0$

TV: The measurement

$$g^{\pm}_{\alpha,\beta}(\Delta\tau) \propto e^{-\Gamma\Delta\tau}\{1 + S^{\pm}_{\alpha,\beta}\sin(\Delta m_d \Delta\tau) + C^{\pm}_{\alpha,\beta}\cos(\Delta m_d \Delta\tau)\}$$

$$\alpha \in \{\ell^+,\ \ell^-\} \quad , \quad \beta \in \{K_S,\ K_L\}$$

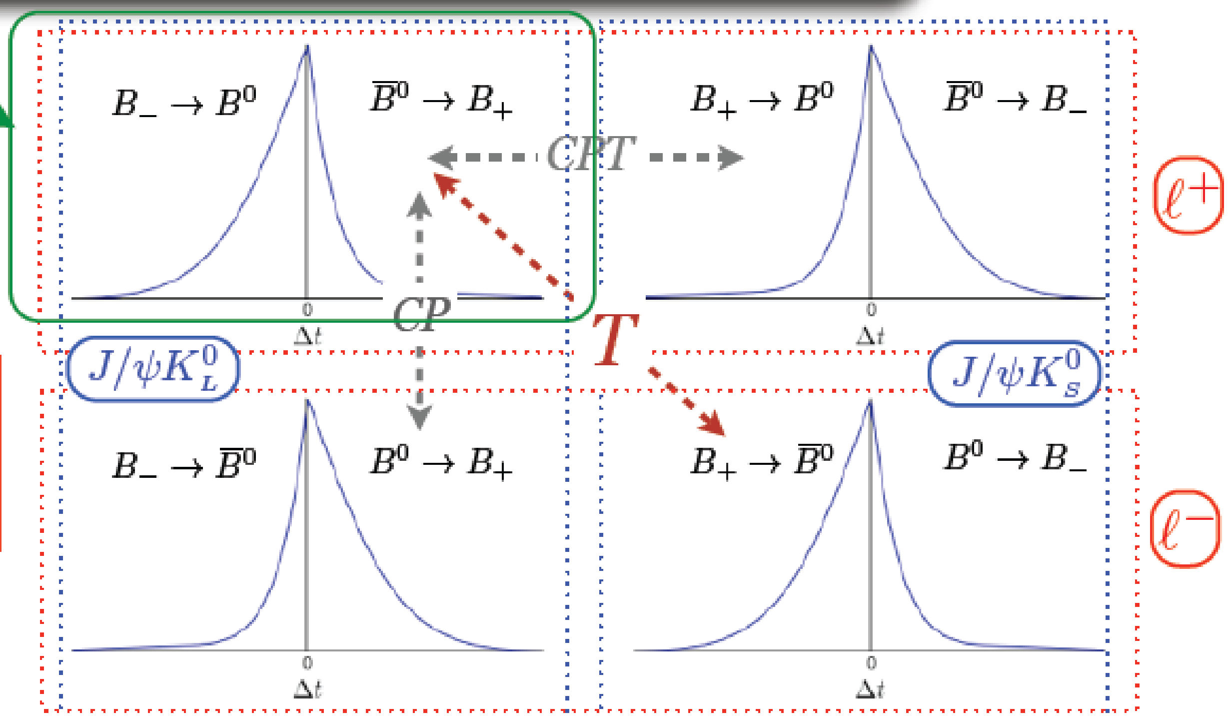
Reference (X,Y)		T-Transformed	
$B^0 \to B_+$	$(\ell^-, J/\psi K^0_L)$	$B_+ \to B^0$	$(J/\psi K^0_S, \ell^+)$
$B^0 \to B_-$	$(\ell^-, J/\psi K^0_S)$	$B_- \to B^0$	$(J/\psi K^0_L, \ell^+)$
$\overline{B}^0 \to B_+$	$(\ell^+, J/\psi K^0_L)$	$B_+ \to \overline{B}^0$	$(J/\psi K^0_S, \ell^-)$
$\overline{B}^0 \to B_-$	$(\ell^+, J/\psi K^0_S)$	$B_- \to \overline{B}^0$	$(J/\psi K^0_L, \ell^-)$

(X,Y) is the reconstructed final states (tag, reco.)

… and similar for *CP, CPT*

In total we can build:

- 4 independent T comparisons
- 4 independent CP comparisons
- 4 independent CPT comparisons



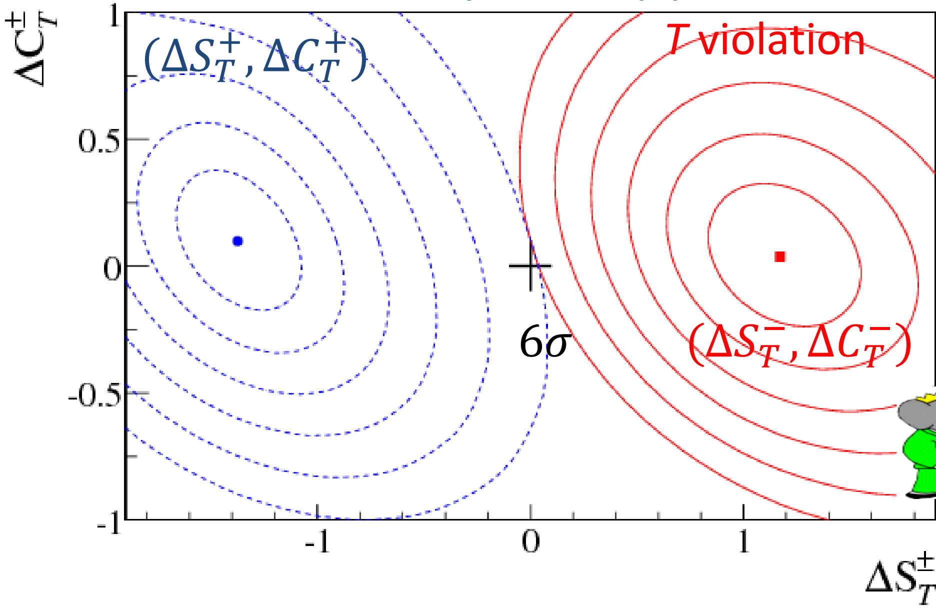
T implies comparison of:

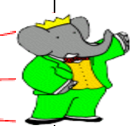
1) Opposite Δt sign
2) Different reco states (ψK_S v. ψK_L)
3) Opposite flavor states (B^0 v. $\overline{B}^0$)

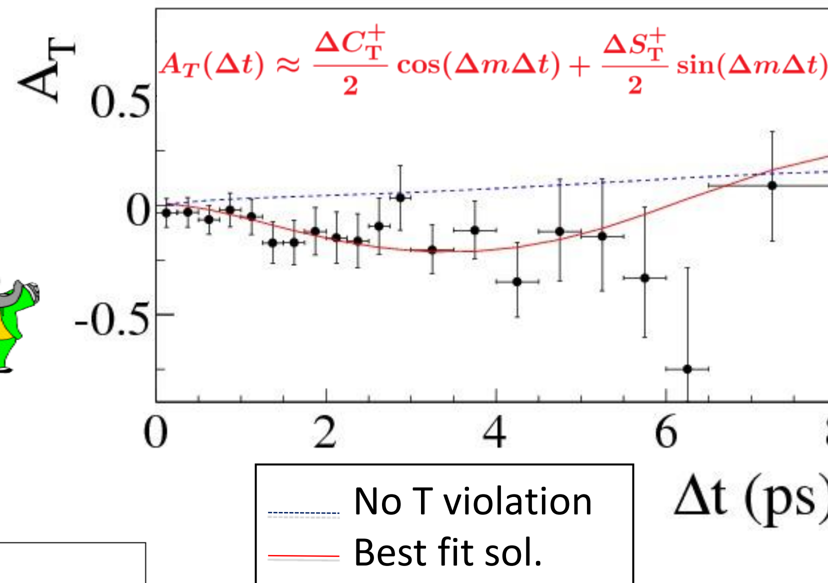
TV: The result

We perform a ML fit to extract 8 set of S and C parameters. With them, we define ΔS and ΔC asymmetry parameters

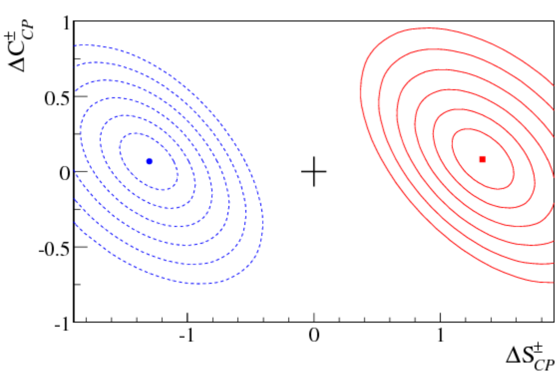
ΔS_T^+	$= S^-_{\ell^-,K_L^0} - S^+_{\ell^+,K_S^0}$	$-1.37 \pm 0.14 \pm 0.06$
ΔS_T^-	$= S^+_{\ell^-,K_L^0} - S^-_{\ell^+,K_S^0}$	$1.17 \pm 0.18 \pm 0.11$
ΔC_T^+	$= C^-_{\ell^-,K_L^0} - C^+_{\ell^+,K_S^0}$	$0.10 \pm 0.14 \pm 0.08$
ΔC_T^-	$= C^+_{\ell^-,K_L^0} - C^-_{\ell^+,K_S^0}$	$0.04 \pm 0.14 \pm 0.08$



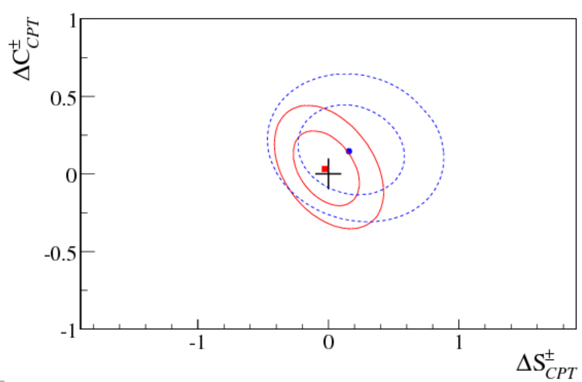




CP violation



CPT violation



T violation has been observed with 14σ

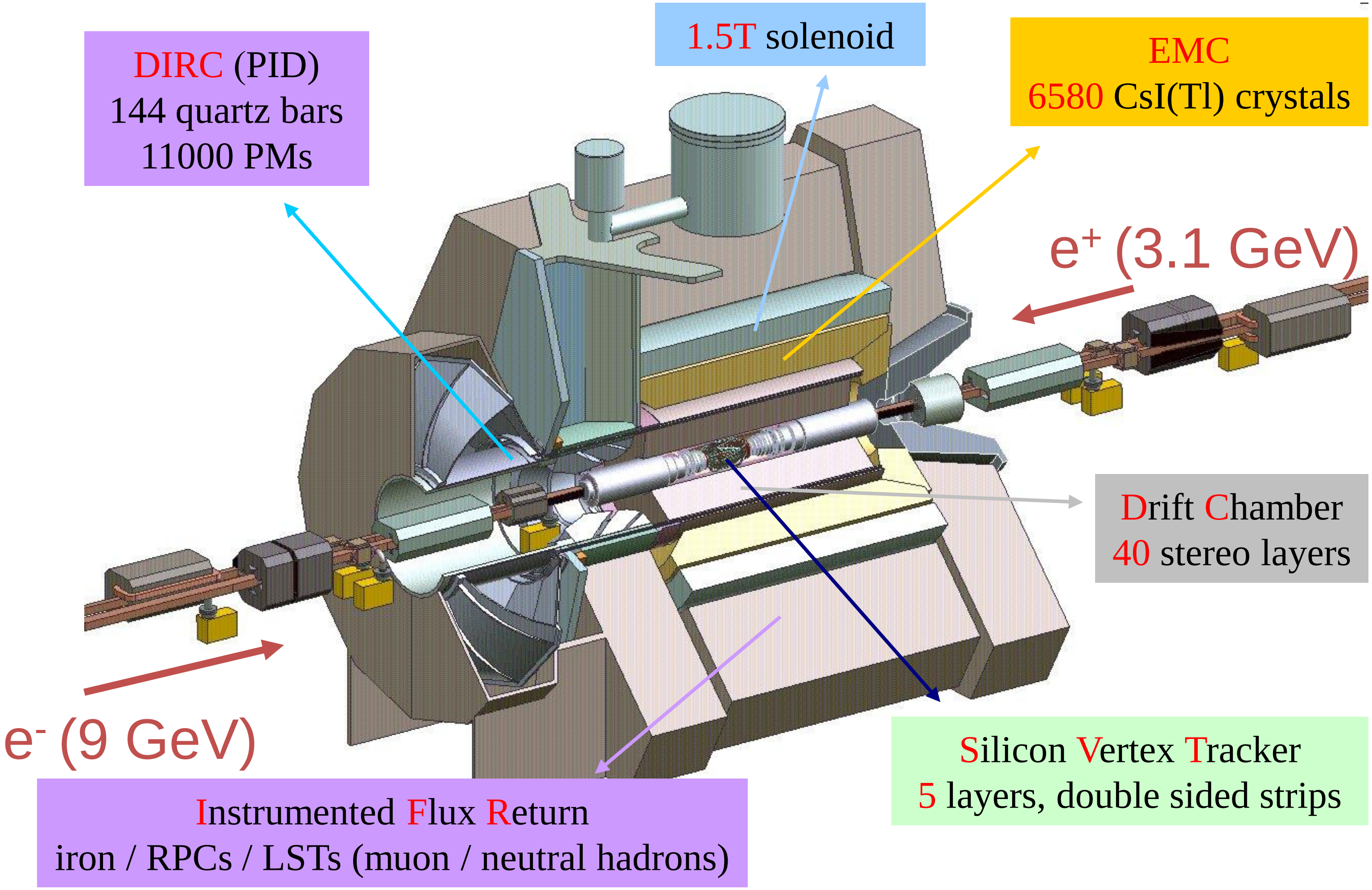
Conclusions

- We have shown the update of the BaBar α measurement through $B^0 \rightarrow (\rho\pi)^0$
  - The α scan is not statistically robust and will benefit of bigger data samples
- $B^0 \rightarrow D^{+*}D^{-*}$ with partial reconstruction in agreement with the SM expectations
- We report the BaBar determination of the γ angle through the combination of $B^{\pm} \rightarrow DK^{\pm}$, $B^{\pm} \rightarrow D^{*}K^{\pm}$, and $B^{\pm} \rightarrow DK^{*\pm}$ obtaining $\gamma = (69^{+17}_{-16})^{o}$ in perfect agreement with the SM prediction
- We have measured *T*-violating parameters in the time evolution of neutral B mesons at BaBar experiment. This result represents the first direct observation of *T* violation through the exchange of *in* and *out* states only connected by *T*

BACK-UP

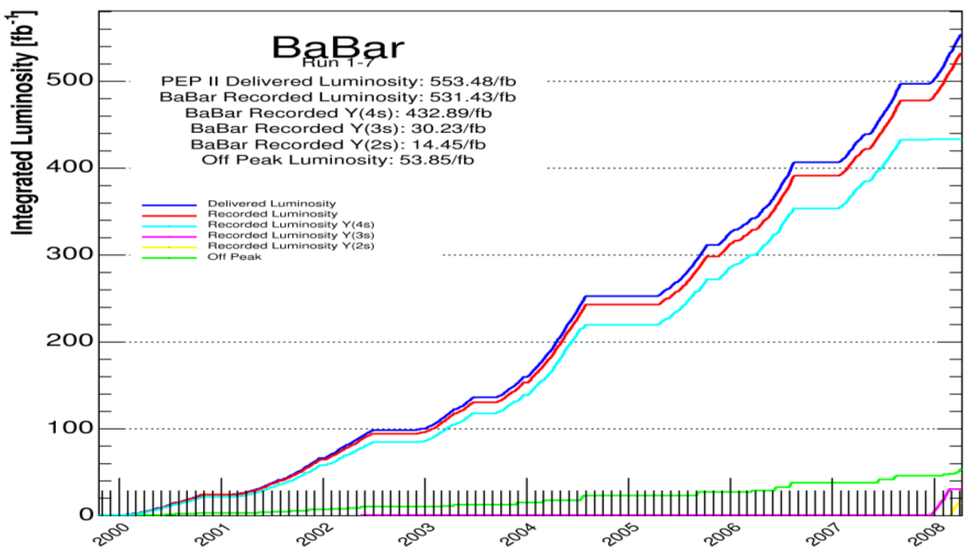
BaBar detector

General purpose detector in e^+e^- environment: precision tracking, photon/electron detection, particle ID, muon/K_L identification

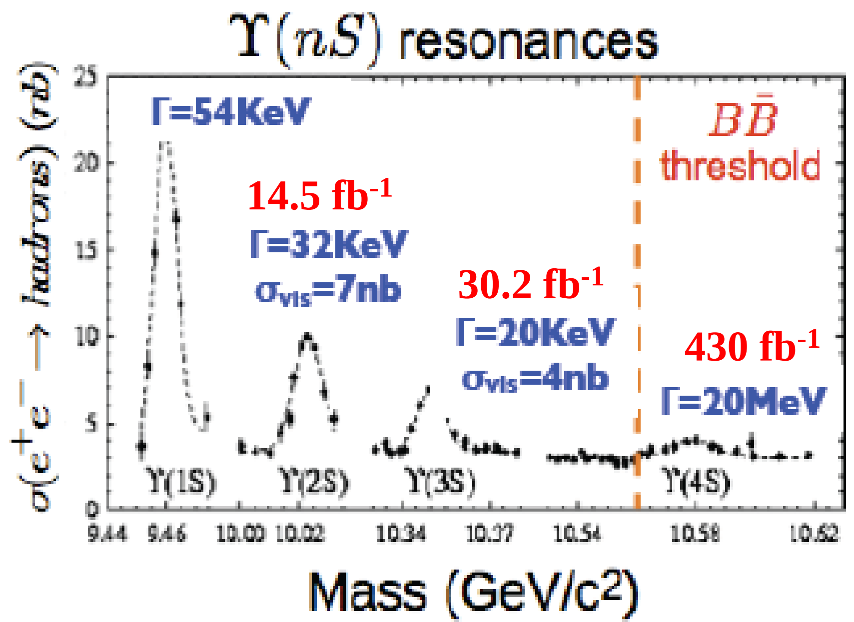


BaBar data set

- 530 fb^{-1} recorded in the 9 years of operation



Reconstructed modes



54 fb^{-1} Off-Υ(nS)
4 fb^{-1} above Υ(4S)

$\approx$ 470×10^{6} $B\bar{B}$
$\approx$ 690×10^{6} $c\bar{c}$
$\approx$ 500×10^{6} $\tau^{+}\tau^{-}$
$\approx$ 1.2×10^{8} Y(3S)
$\approx$ 1.0×10^{8} Y(2S)

CP raw asymmetries(CP Data Sample)

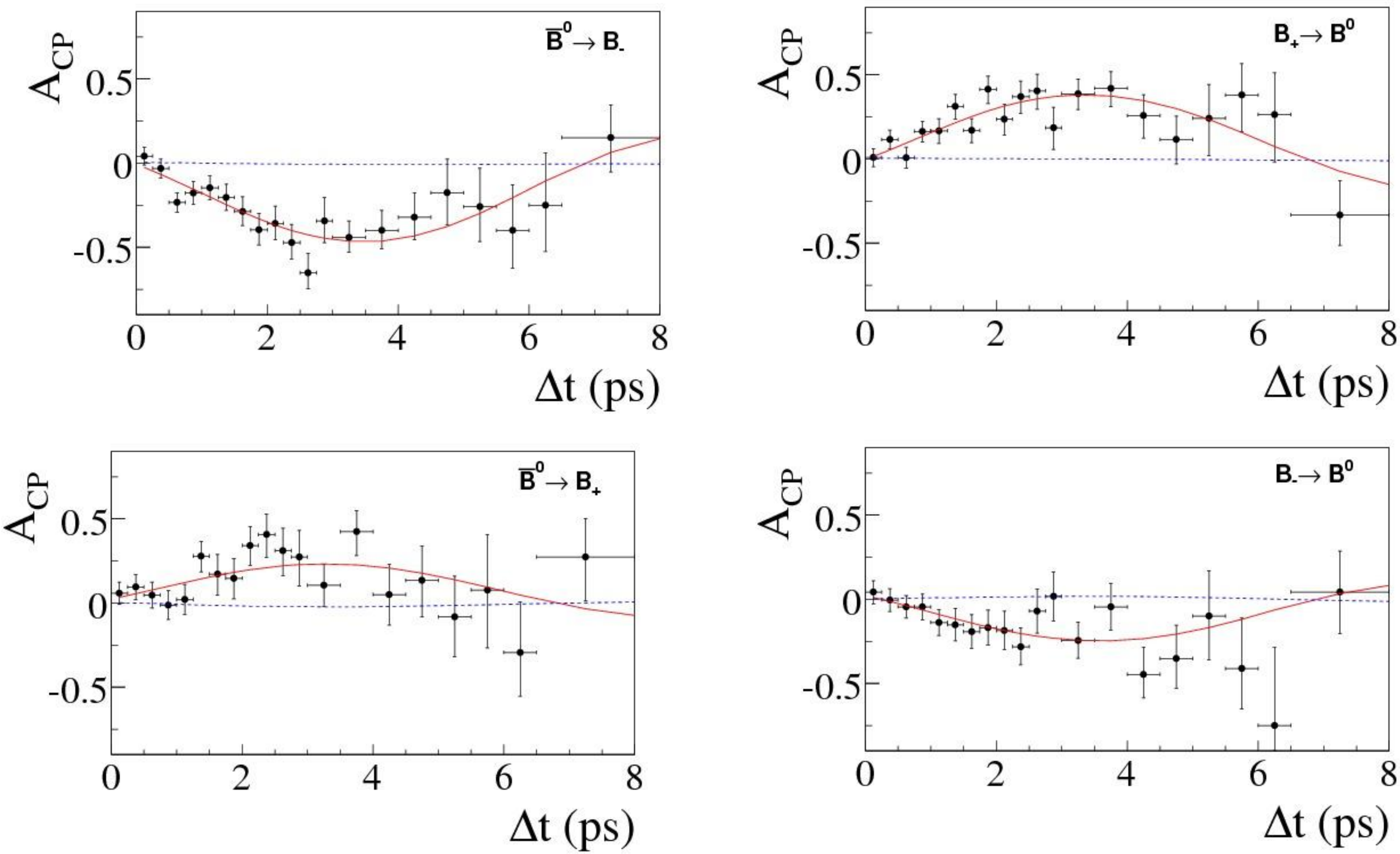
No CP violation

Experimental data

Signal region:

$5.27 < m_{ES} < 5.29\ \mathrm{GeV}/c^2$

$|E| < 0.010$ GeV



CPT raw asymmetries(CP Data Sample)

No CPT violation
Experimental data

Signal region:
$5.27 < m_{ES} < 5.29$ GeV/c^2
$|E| < 0.010$ GeV