Mixing Induced CP Violation at BaBar

R. de Sangro
INFN - Frascati

Representing the BaBar Collaboration

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Outline

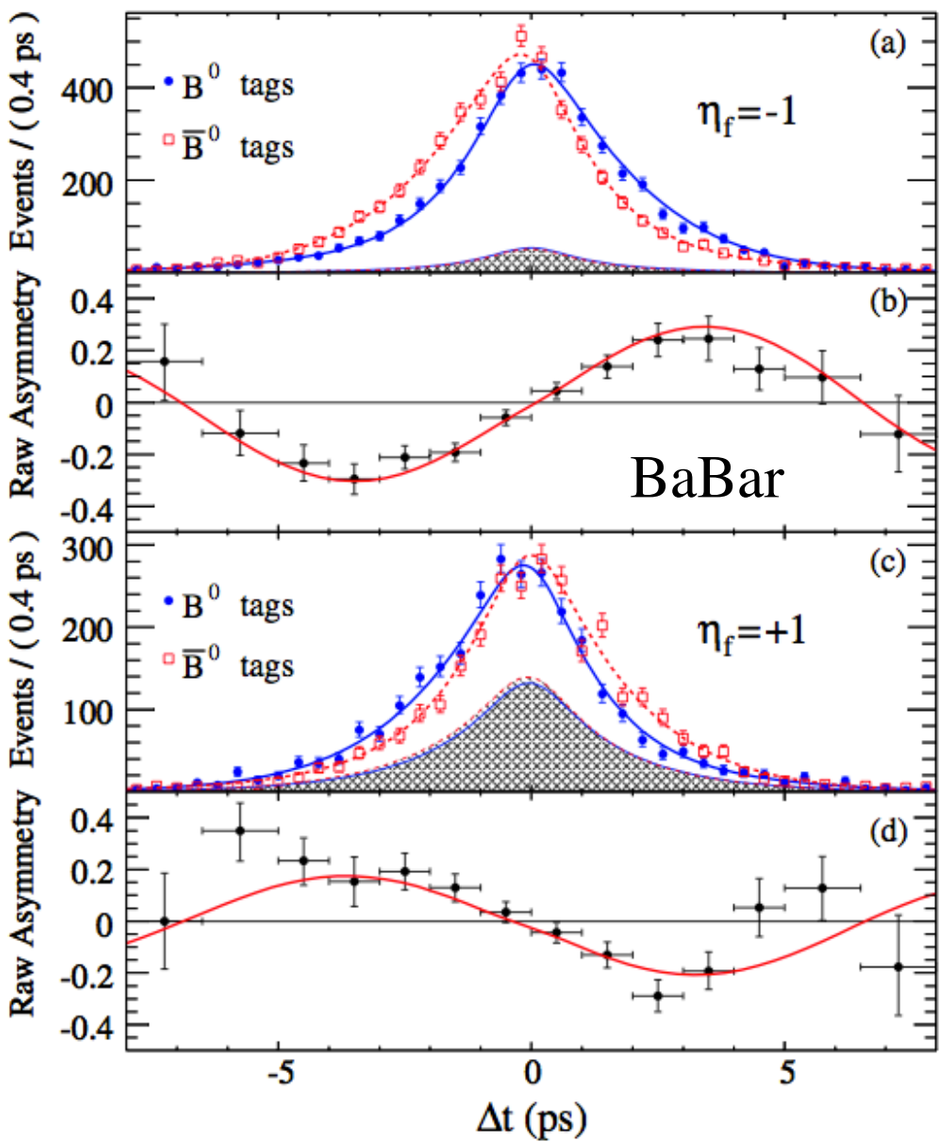
- First direct measurement of time reversal violation
- New measurement of the time dependent CP violation parameters in $B^0 \to D^{*+} D^{*-}$ decays

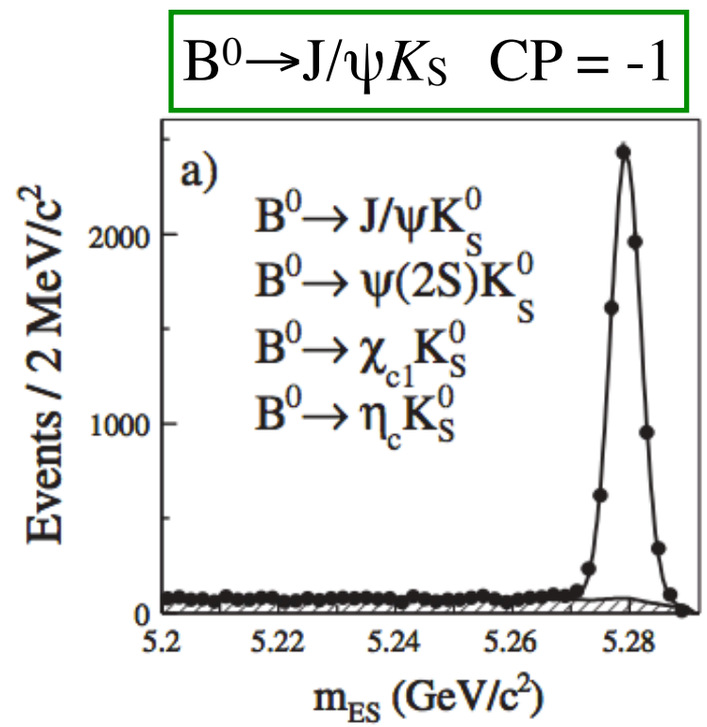
T Reversal Violation

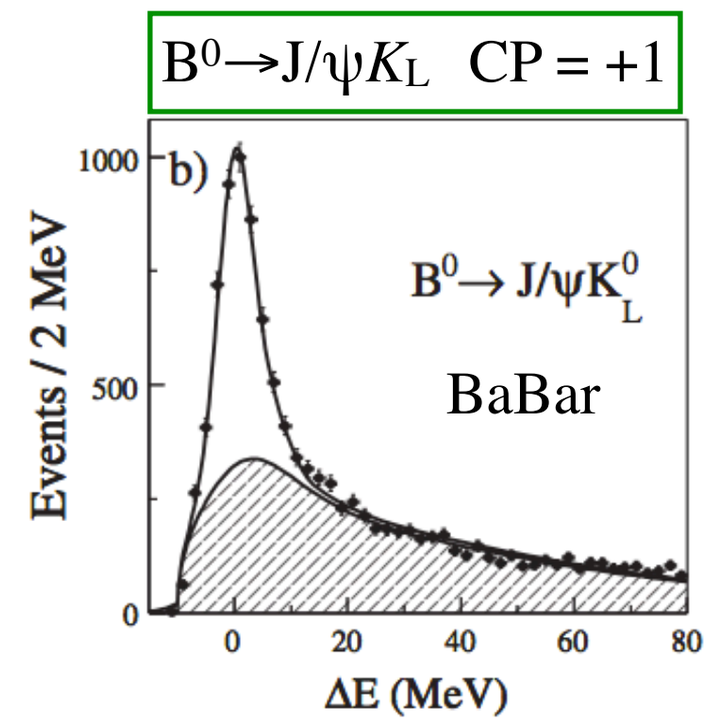
- *CPT* symmetry is a fundamental requirement of quantum field theories (like the SM)
  - No violation observed experimentally
- The Standard Model with three generations allows for *CP* violation to occur in mesons' weak decays.
  - To conserve *CPT*, *CP* violation *requires T* violation
- The measurement of *CP*V in K and B decays therefore provides *indirect evidence* of *T*-violation
- Can *direct* evidence of *T* violation be obtained in *B* meson decays, where *CP*V is large?

CP Violation

- Large *CP*V in B decays was measured precisely with golden channels ($b \to c\bar{c}s$ transitions)

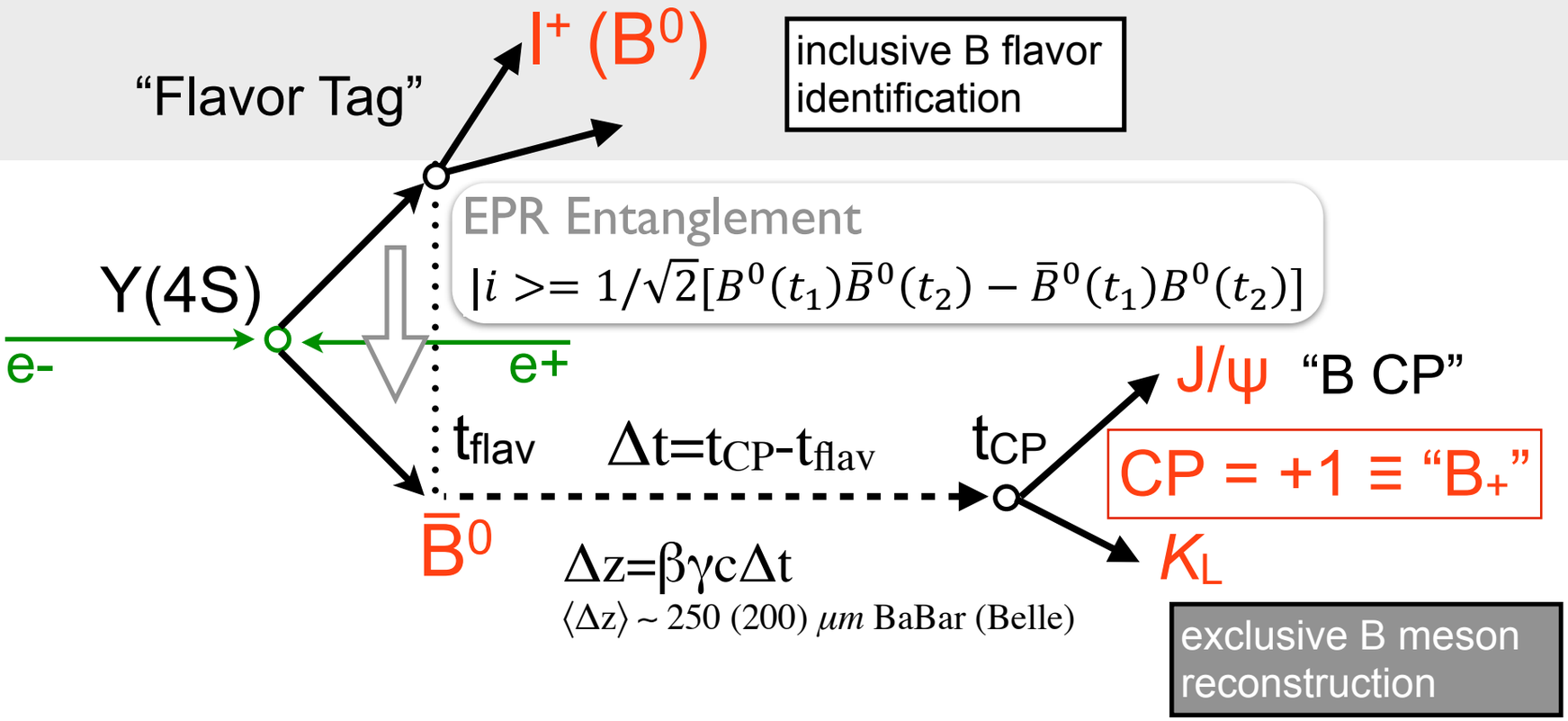


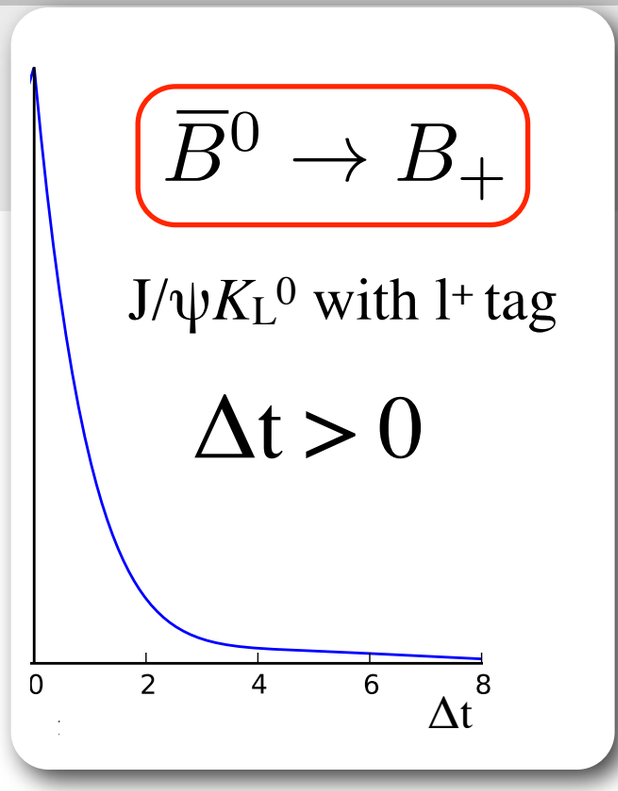


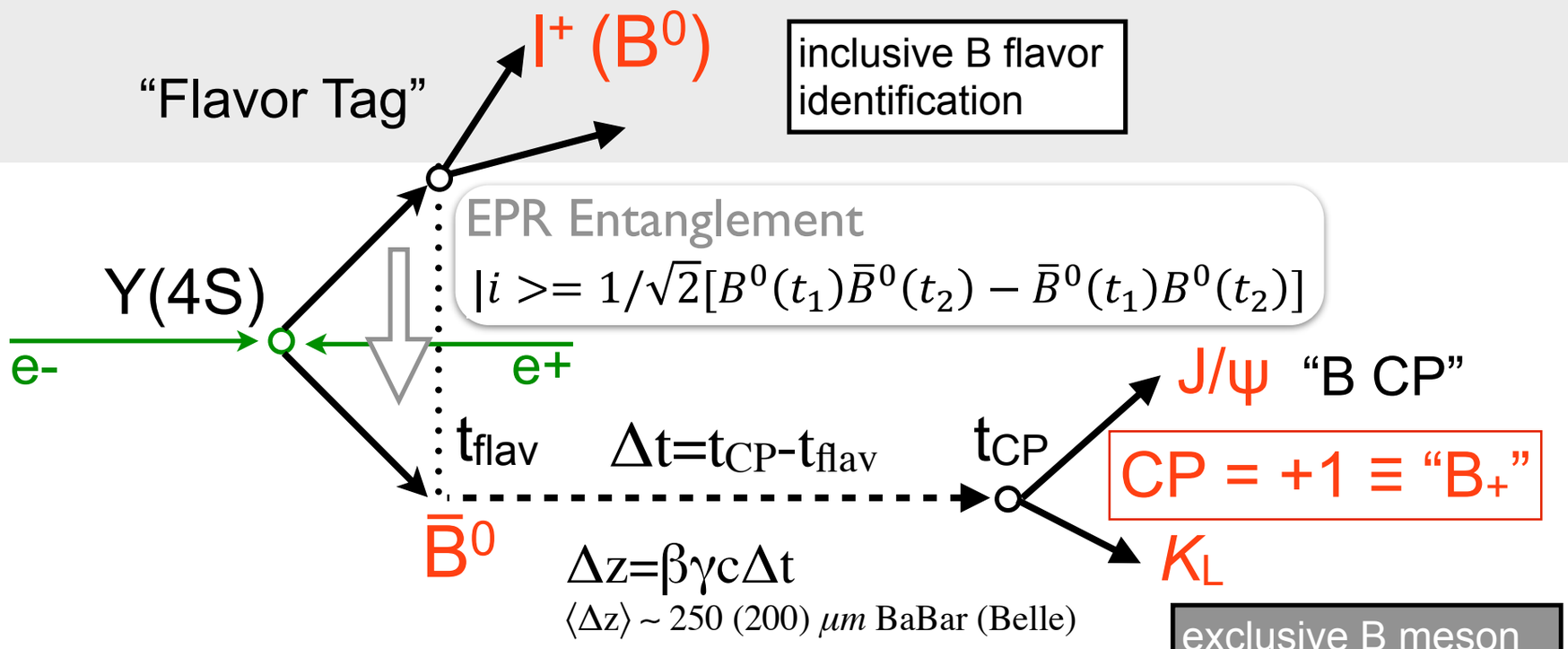


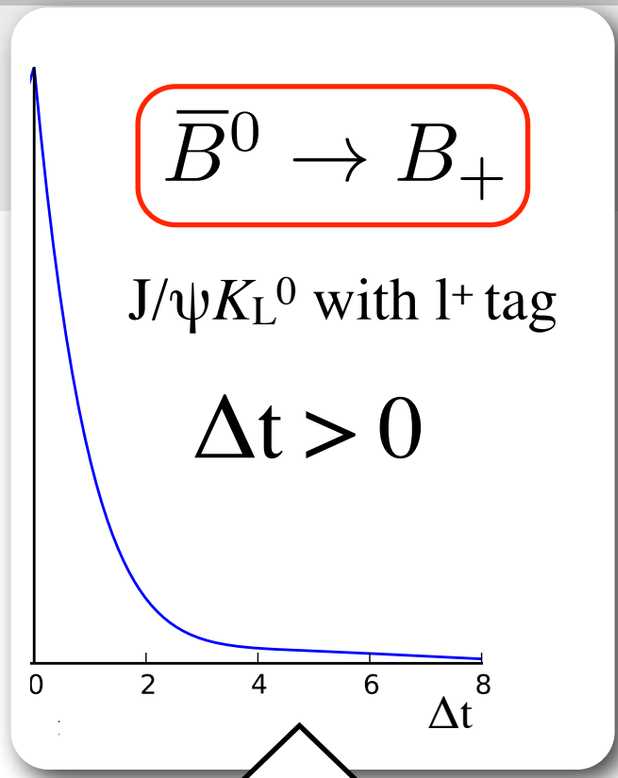
$$g_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{(1 \mp \Delta w) \pm (1 - 2w) \times [S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)]\}$$

The same *CP*V sample can be used to look for *TR*V
HOW?


"Flavor Tag"
l^+ (B^0)
inclusive B flavor identification
EPR Entanglement
$|i>= 1/\sqrt{2}[B^0(t_1)\bar{B}^0(t_2) - \bar{B}^0(t_1)B^0(t_2)]$
Y(4S)
e-
e+
t_{flav}
$\Delta t = t_{CP} - t_{flav}$
t_{CP}
J/ψ "B CP"
CP = +1 ≡ "B_+"
K_L
$\bar{B}^0$
$\Delta z = \beta\gamma c\Delta t$
$\langle\Delta z\rangle \sim 250\ (200)\ \mu m$ BaBar (Belle)
exclusive B meson reconstruction


$\bar{B}^0 \to B_+$
$J/\psi K_L^0$ with l^+ tag
$\Delta t > 0$
0
2
4
6
8
Δt

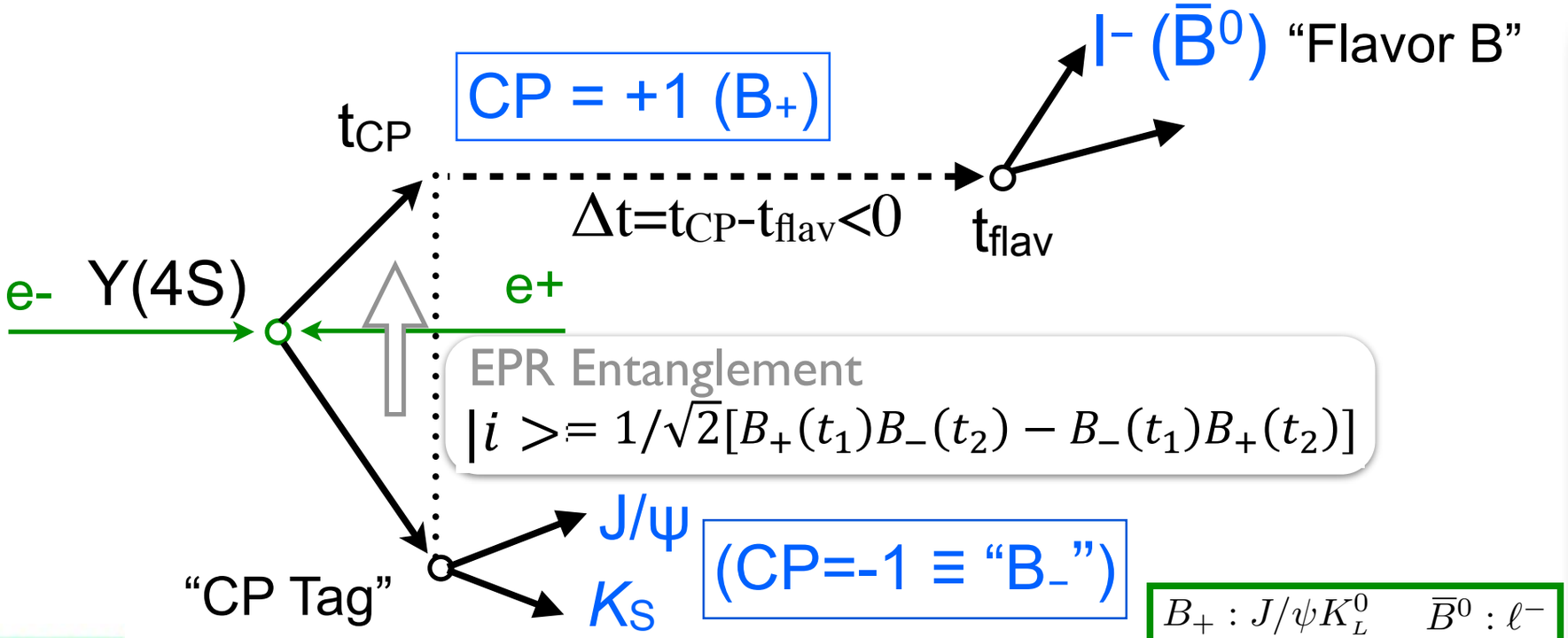


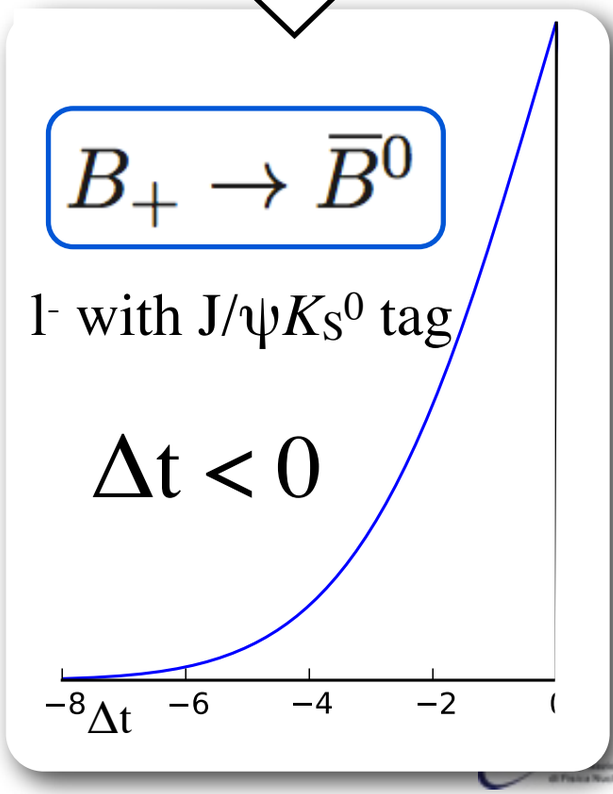


M.C.Bañuls, J. Bernabéu, Phys. Lett. B 464, 117 (1999)

If $\Delta t < 0$, we can exchange the roles of the two *B*'s in above picture: use reconstructed CP final state as "CP-tag" and look for flavor final state

T-conjugate transitions!





$B_+ : J/\psi K_L^0 \quad \bar{B}^0 : \ell^-$
$B_- : J/\psi K_S^0 \quad B^0 : \ell^+$

T-Reversal Processes

Define processes of interest and their T-transformed counterparts:

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.)

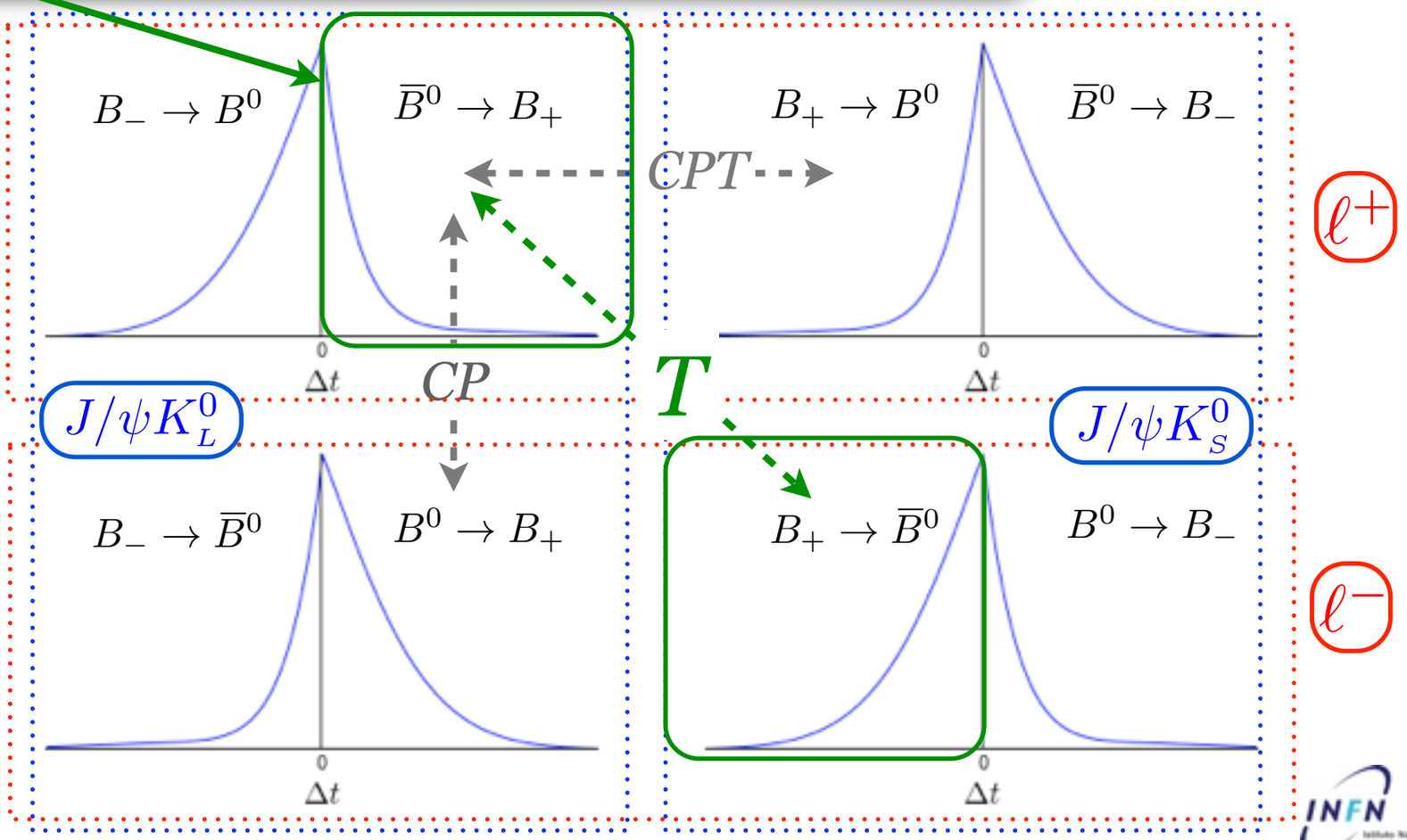
...and similar for CP, CPT

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. $\overline{B}^0$)



Fit parameters $\Delta S^{\pm}$ and $\Delta C^{\pm}$

8 Signal PDFs (assuming $\Delta\Gamma=0$):

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

Mistag dilutes the S, C parameters by a factor of (1-2w)

$\alpha \in \{B^0,\ \overline{B}^0\}$;

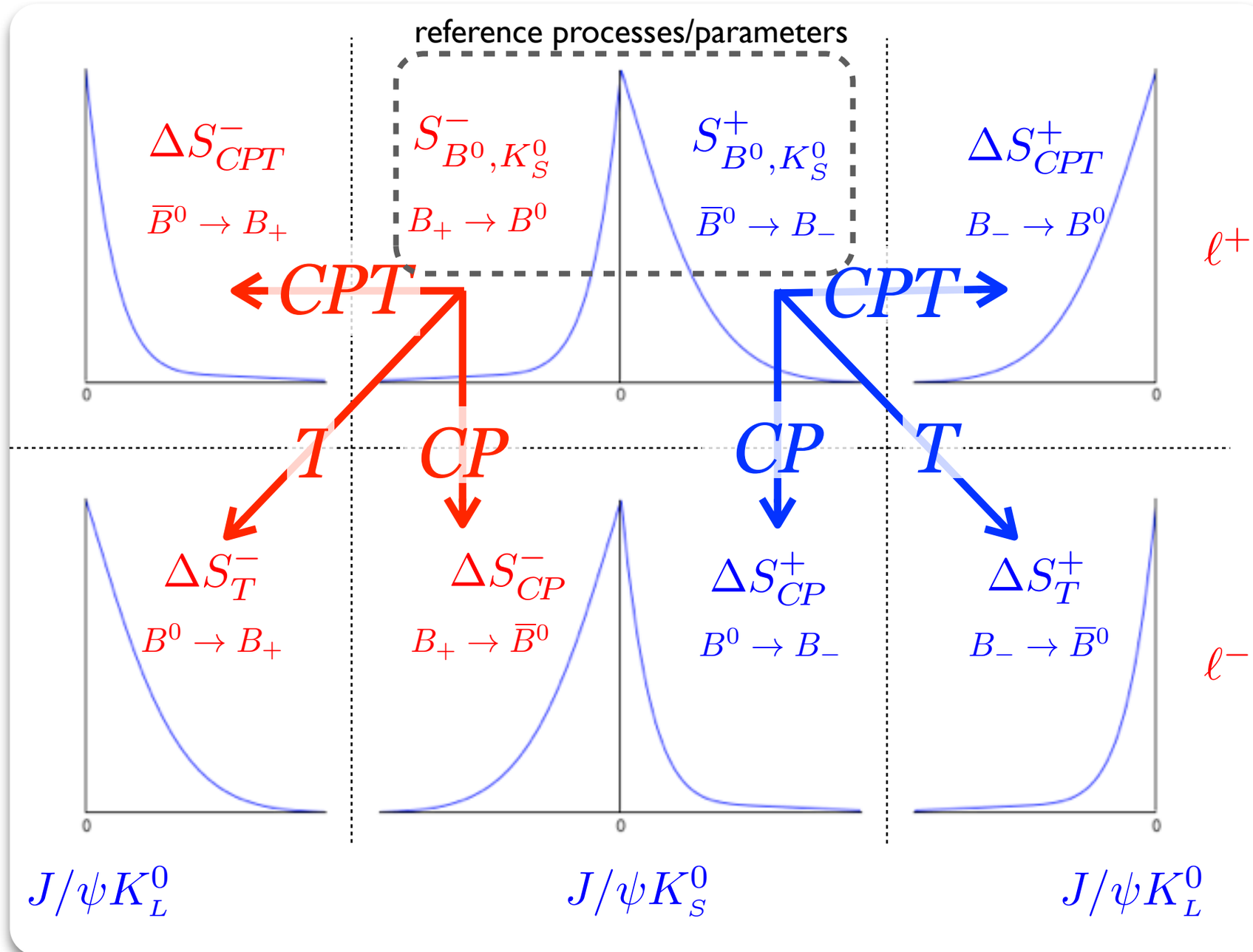
$\beta \in \{K^0_S,\ K^0_L\}$

$\tau = \pm\Delta t > 0$

For T Violation

in the interference $\Delta S^{+}_{T} \neq 0$, $\Delta S^{-}_{T} \neq 0$

in the decay $\Delta C^{+}_{T} \neq 0$, $\Delta C^{-}_{T} \neq 0$



TRV Results

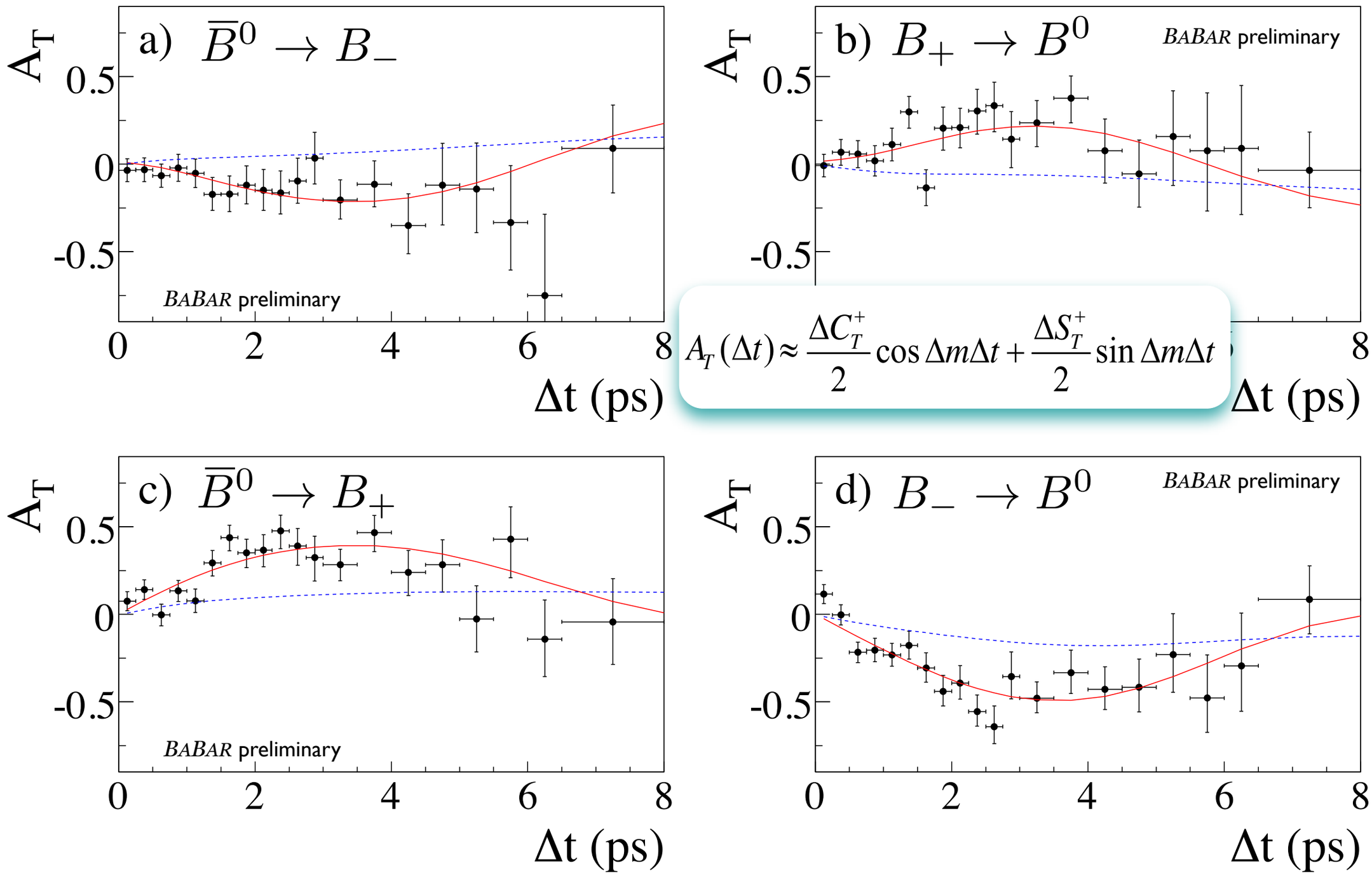
BABAR Preliminary

Reference parameters

	Parameter	Result	expectation from canonical *CP*
	$S^{+}_{\ell^+X,c\bar{c}K^0_S}$	$0.55 \pm 0.08 \pm 0.06$	+sin2β
	$S^{-}_{\ell^+X,c\bar{c}K^0_S}$	$-0.66 \pm 0.06 \pm 0.04$	–sin2β
	$C^{+}_{\ell^+X,c\bar{c}K^0_S}$	$0.11 \pm 0.06 \pm 0.05$	0
	$C^{-}_{\ell^+X,c\bar{c}K^0_S}$	$-0.05 \pm 0.06 \pm 0.03$	0
T	$\Delta S^{+}_{\mathrm{T}} = S^{-}_{\ell^-X,J/\psi K^0_L} - S^{+}_{\ell^+X,c\bar{c}K^0_S}$	$-1.37 \pm 0.14 \pm 0.06$	–2sin2β
	$\Delta S^{-}_{\mathrm{T}} = S^{+}_{\ell^-X,J/\psi K^0_L} - S^{-}_{\ell^+X,c\bar{c}K^0_S}$	$1.17 \pm 0.18 \pm 0.11$	+2sin2β
	$\Delta C^{+}_{\mathrm{T}} = C^{-}_{\ell^-X,J/\psi K^0_L} - C^{+}_{\ell^+X,c\bar{c}K^0_S}$	$0.10 \pm 0.16 \pm 0.08$	0
	$\Delta C^{-}_{\mathrm{T}} = C^{+}_{\ell^-X,J/\psi K^0_L} - C^{-}_{\ell^+X,c\bar{c}K^0_S}$	$0.04 \pm 0.16 \pm 0.08$	0
CP	$\Delta S^{+}_{\mathrm{CP}} = S^{+}_{\ell^-X,c\bar{c}K^0_S} - S^{+}_{\ell^+X,c\bar{c}K^0_S}$	$-1.30 \pm 0.10 \pm 0.07$	–2sin2β
	$\Delta S^{-}_{\mathrm{CP}} = S^{-}_{\ell^-X,c\bar{c}K^0_S} - S^{-}_{\ell^+X,c\bar{c}K^0_S}$	$1.33 \pm 0.12 \pm 0.06$	+2sin2β
	$\Delta C^{+}_{\mathrm{CP}} = C^{+}_{\ell^-X,c\bar{c}K^0_S} - C^{+}_{\ell^+X,c\bar{c}K^0_S}$	$0.07 \pm 0.09 \pm 0.03$	0
	$\Delta C^{-}_{\mathrm{CP}} = C^{-}_{\ell^-X,c\bar{c}K^0_S} - C^{-}_{\ell^+X,c\bar{c}K^0_S}$	$0.08 \pm 0.10 \pm 0.04$	0
CPT	$\Delta S^{+}_{\mathrm{CPT}} = S^{-}_{\ell^+X,J/\psi K^0_L} - S^{+}_{\ell^+X,c\bar{c}K^0_S}$	$0.16 \pm 0.20 \pm 0.09$	0
	$\Delta S^{-}_{\mathrm{CPT}} = S^{+}_{\ell^+X,J/\psi K^0_L} - S^{-}_{\ell^+X,c\bar{c}K^0_S}$	$-0.03 \pm 0.13 \pm 0.06$	0
	$\Delta C^{+}_{\mathrm{CPT}} = C^{-}_{\ell^+X,J/\psi K^0_L} - C^{+}_{\ell^+X,c\bar{c}K^0_S}$	$0.15 \pm 0.17 \pm 0.07$	0
	$\Delta C^{-}_{\mathrm{CPT}} = C^{+}_{\ell^+X,J/\psi K^0_L} - C^{-}_{\ell^+X,c\bar{c}K^0_S}$	$0.03 \pm 0.14 \pm 0.08$	0

sin2β= 0.679±0.020 (HFAG winter'12)

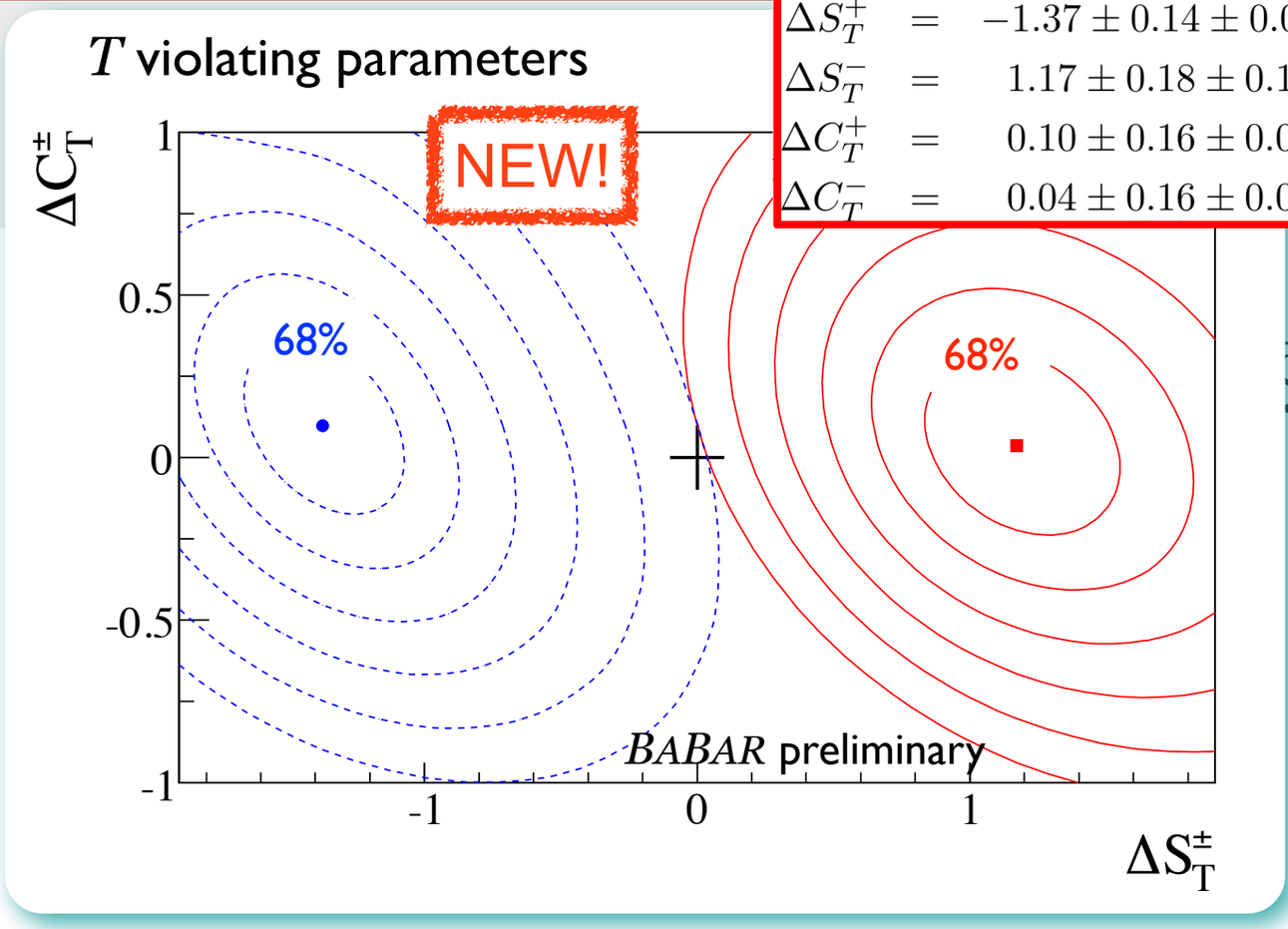
Independent T Asymmetries



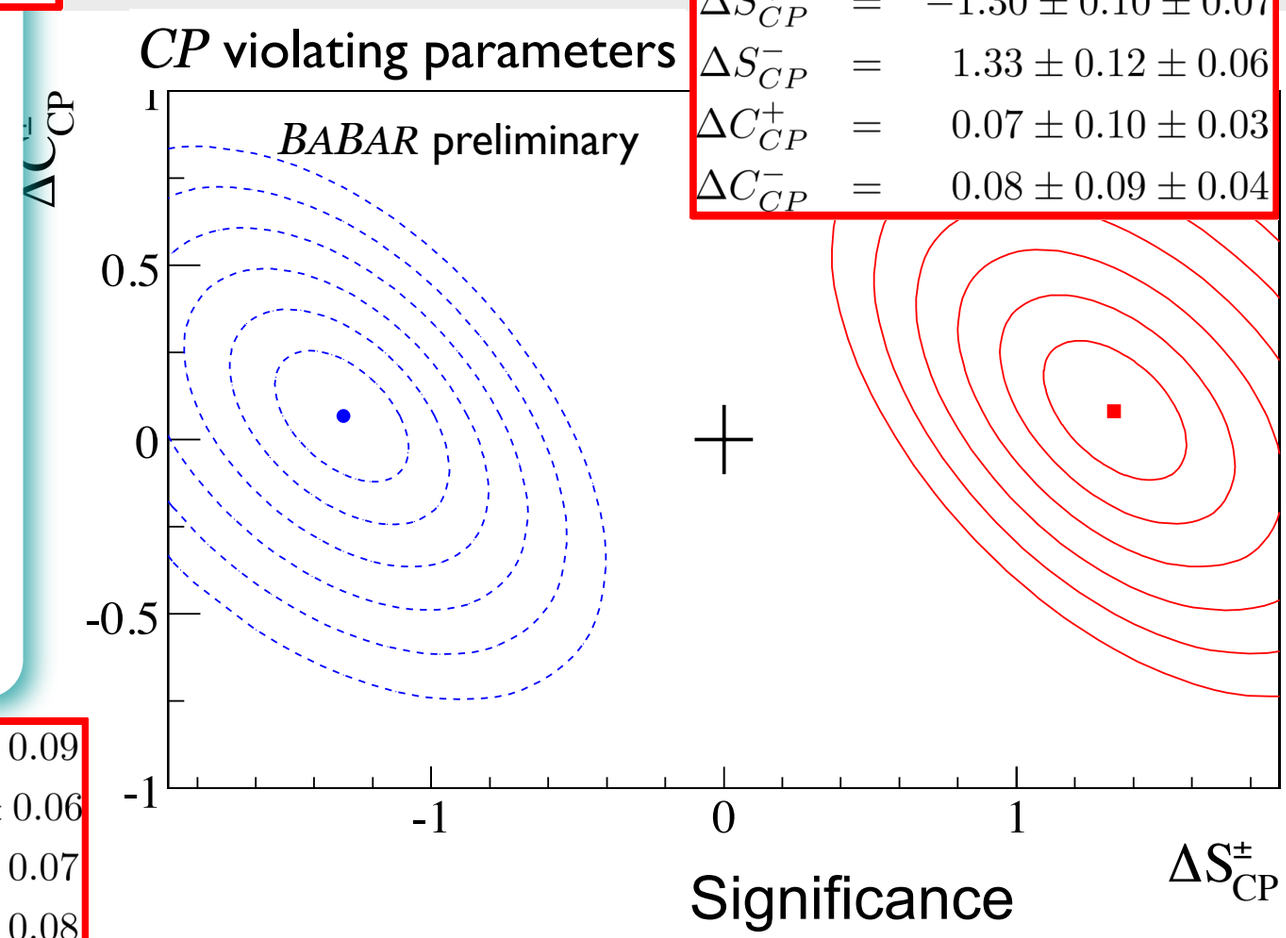
$$A_T(\Delta t) \approx \frac{\Delta C_T^+}{2}\cos\Delta m\Delta t + \frac{\Delta S_T^+}{2}\sin\Delta m\Delta t$$

Points: data; red (blue) curves: projections of fits with (without) T violation

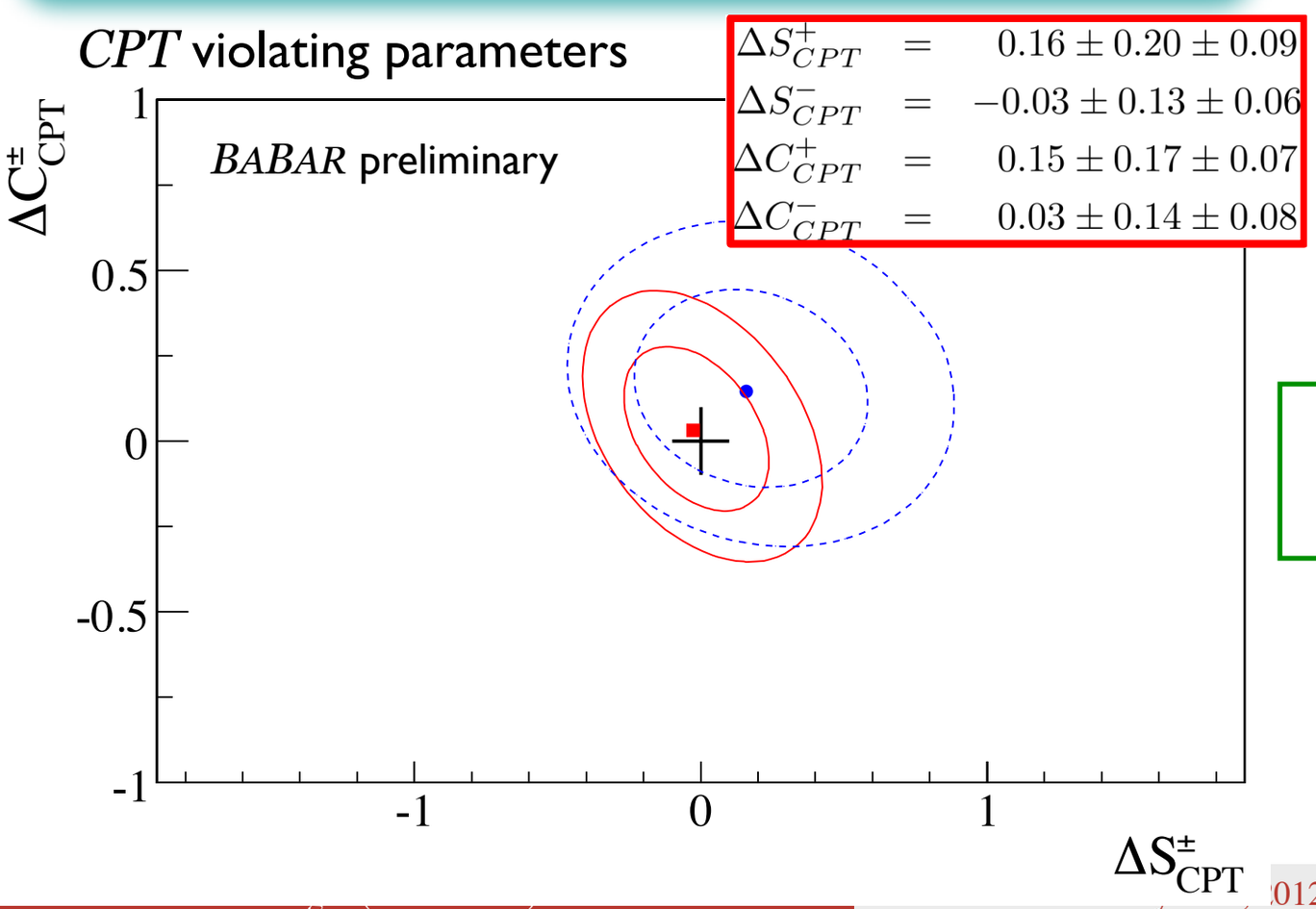
T, *CP* and *CPT*



$$\Delta S_T^+ = -1.37 \pm 0.14 \pm 0.06$$
$$\Delta S_T^- = 1.17 \pm 0.18 \pm 0.11$$
$$\Delta C_T^+ = 0.10 \pm 0.16 \pm 0.08$$
$$\Delta C_T^- = 0.04 \pm 0.16 \pm 0.08$$



$$\Delta S_{CP}^+ = -1.30 \pm 0.10 \pm 0.07$$
$$\Delta S_{CP}^- = 1.33 \pm 0.12 \pm 0.06$$
$$\Delta C_{CP}^+ = 0.07 \pm 0.10 \pm 0.03$$
$$\Delta C_{CP}^- = 0.08 \pm 0.09 \pm 0.04$$



$$\Delta S_{CPT}^+ = 0.16 \pm 0.20 \pm 0.09$$
$$\Delta S_{CPT}^- = -0.03 \pm 0.13 \pm 0.06$$
$$\Delta C_{CPT}^+ = 0.15 \pm 0.17 \pm 0.07$$
$$\Delta C_{CPT}^- = 0.03 \pm 0.14 \pm 0.08$$

(0,0) = no violation

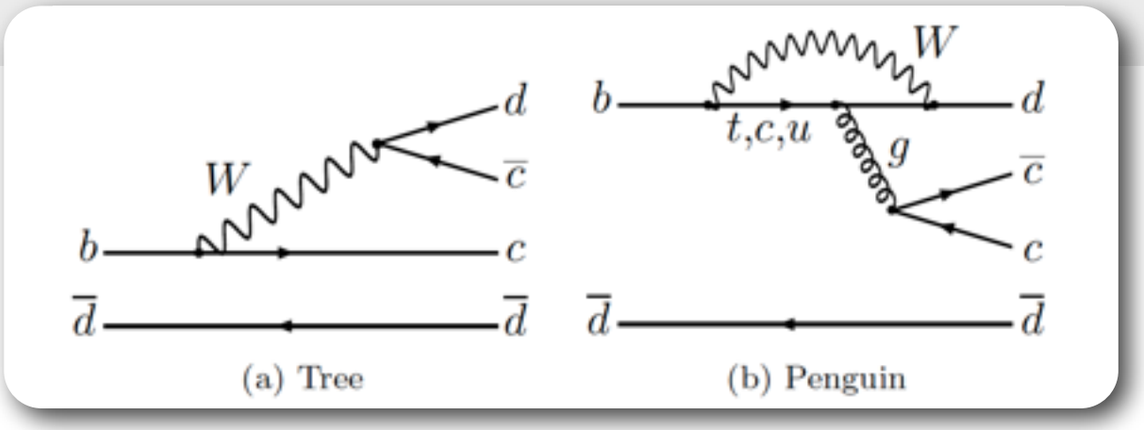
Significance

	$-2\Delta \ln L$	Signif.
T	226	> 10 σ
CP	307	> 10 σ
CPT	5	0.33 σ

(Includes systematics)

*CP*V in $B^0 \to D^{*+} D^{*-}$

*CP*V in $B^0 \to D^{*+}D^{*-}$



(a) Tree (b) Penguin

$$P_\eta^{S_{\rm tag}}(\Delta t) = \frac{e^{-|\Delta t|/\tau_b}}{4\tau_b} \cdot [1 + S_{\rm tag}\, S_\eta \sin(\Delta m_d \Delta t) + S_{\rm tag}\, C \cos(\Delta m_d \Delta t)], \quad S_{\rm tag} = +1\ (-1)\ B^0\ (\bar{B}^0)$$

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2}; \quad S_\eta = -\eta \frac{2\Im m(\lambda)}{1+|\lambda|^2}; \quad \lambda = \frac{q}{p}\frac{\bar{A}}{A}$$

- In $b \to c\bar{c}d$ transition like $B \to D^{*+}D^{*-}$, the TD CPV asymmetry is a measure of $S_\eta \cong \eta \sin(2\beta)$, provided that the contribution from penguin diagrams to the tree amplitude can be neglected
- Theoretical calculations, based on factorization and heavy quark symmetry, have shown that the penguin contributions lead to ~few % corrections to the determination of $\sin 2\beta$ from the TD CPV asymmetry

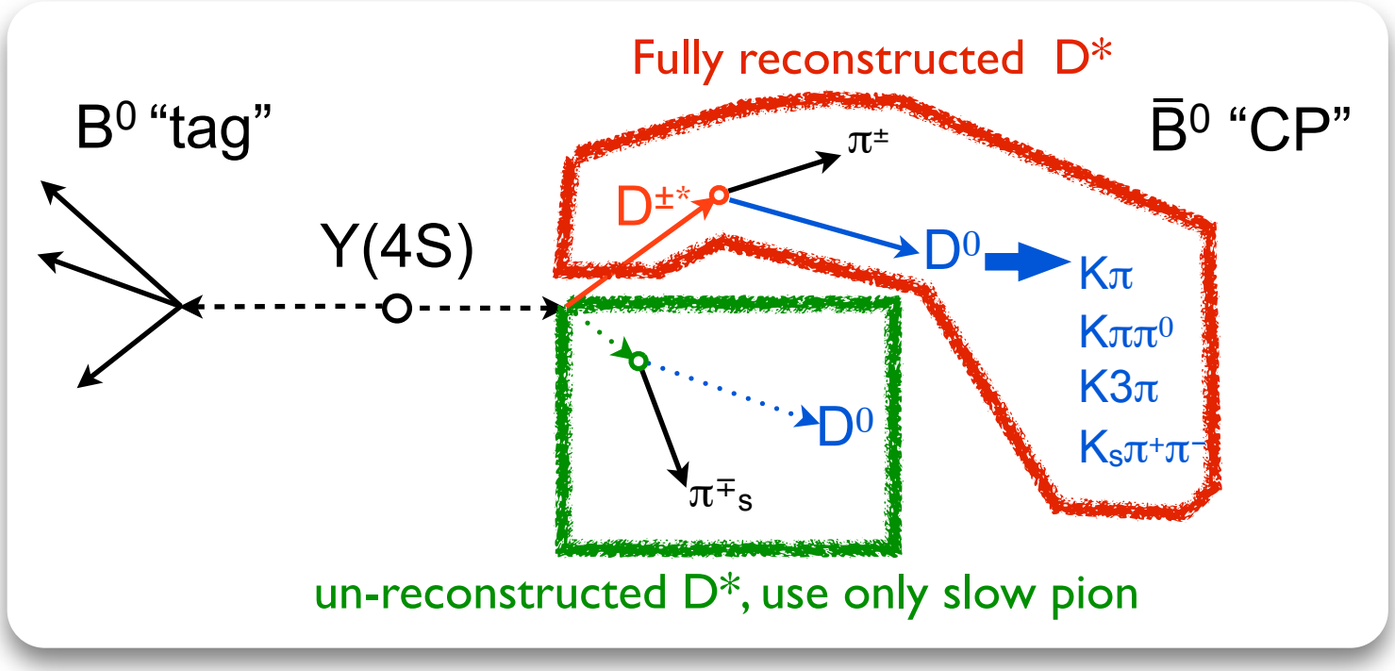
Z. Z. Xing, Phys. Lett. **B443**, 365 (1998).
Z. Z. Xing, Phys. Rev. **D61**, 014010 (1999).

- Large deviation in S_η from $B^0 \to D^{*+}D^{*-}$ with respect to that measured in $b \to c\bar{c}s$ ($J/\psi K$) transitions could be an indication of physics beyond the SM

M. Gronau, J. L. Rosner and D. Pirjol, Phys. Rev. D **78** 033011 (2008).
Y. Grossman and M. P. Worah, Phys. Lett. **B395**, 241 (1997).
R. Zwicky, Phys. Rev. D **77**, 036004 (2008).

Partial Reconstruction

- VV final state not CP eigenstate: admixture of *CP*=+1 and *CP*=-1 amplitudes. Angular analysis needed to disentangle components, possible with fully reconstructed events.
- BaBar and Belle full reconstruction analyses measured the *CP* even component *CP*V parameters S_+ and C_+, and the fraction $R_\perp$ of CP-odd amplitude: $R_\perp=0.158\pm0.028\pm0.006$
- In a partial reconstruction analysis, we measure average S and C parameters which are related to C_+ and S_+ by the relations $C=C_+$ and $S=S_+(1-2R_\perp)$



Partial Reconstruction Method

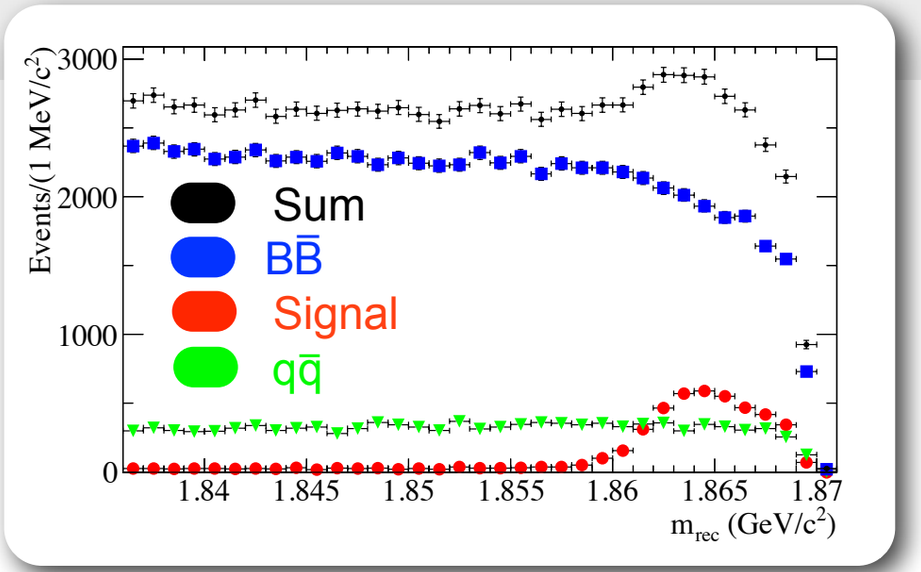
- Fully reconstruct one D* decaying to $D^0\pi$, with the D^0 decaying to one of 4 modes
- Match reconstructed D* with a slow pion of opposite sign in the event
- Select candidate if the kinematics is consistent with a B^0 decaying to a D^*-$D^0\pi$ combination with a missing D^0
- Compute recoiling D^0 mass m_{rec}

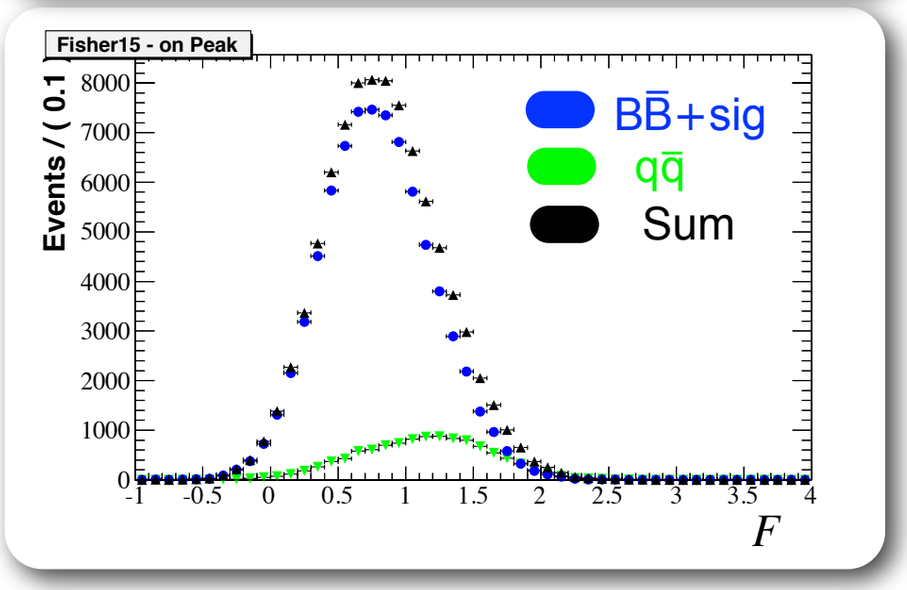
- Advantages:
  - Gain is statistics
  - Almost independent sample
- Disadvantages:
  - Higher background
  - Larger systematic errors

Analysis Variables

- Recoil mass, m_{rec}
  - Signal peaks at D^0 mass
  - Backgrounds from $B\bar{B}$ combinatorial and continuum $q\bar{q}$ doesn't
  - Separate PDFs for different sample components: Signal, $B\bar{B}$ combinatorial, $q\bar{q}$ continuum
  - Require $m_{rec} \geqq 1.835$ GeV/c^2
- Fisher Discriminant based on event shape variables
  - Help discriminate between spherical $B\bar{B}$ and jet-like continuum $q\bar{q}$ events
    - No cut: PDF used in fit
  - Separate PDFs for $B\bar{B}$ and continuum
- Time difference Δt
  - Separate PDFs for all sample components
- Tagging based on single track (K or Lepton)
  - Additional dilution in partial reconstruction analysis due to tagging tracks from missing D^0
    - $(1-\alpha)$, where α is the fraction of tags from the unreconstructed D^0

MC distributions



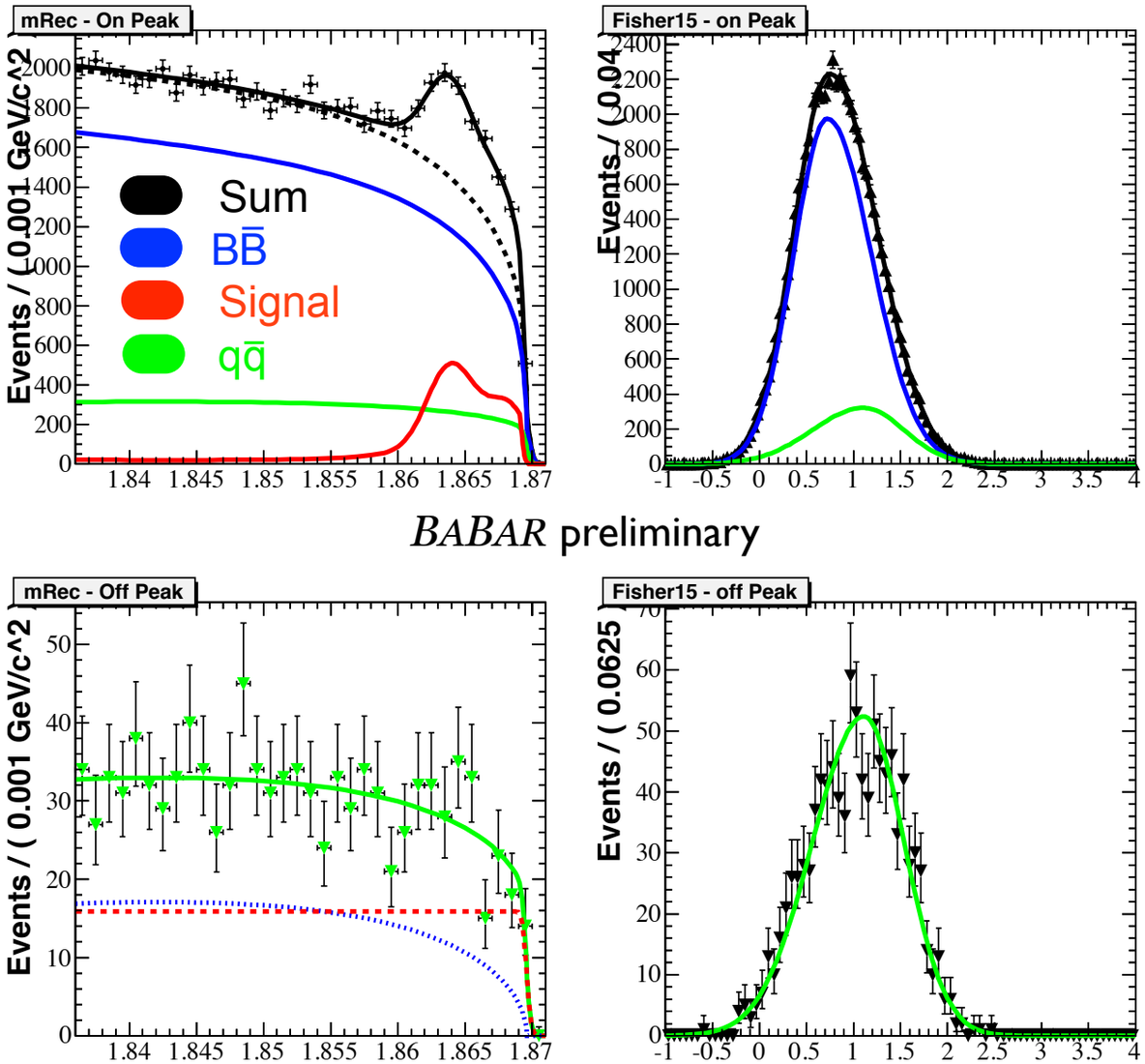


$$\Delta t = \Delta z / \gamma \beta c$$

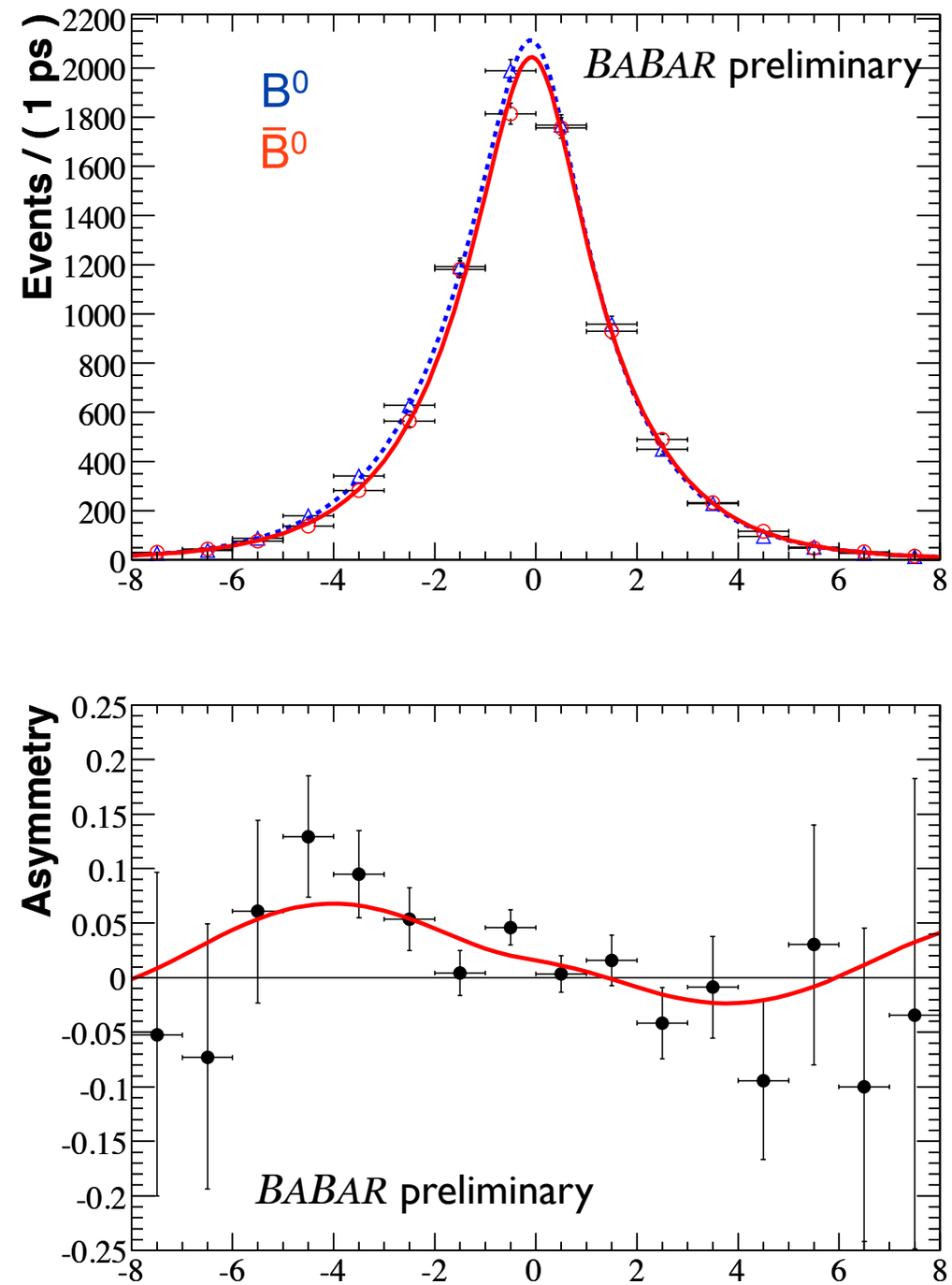
$$\Delta z = z_{rec} - z_{tag}$$

CPV in $B^0 \to D^{*+} D^{*-}$

Kin Fit Result - DATA



Δt Fit Result and Raw Asymmetry

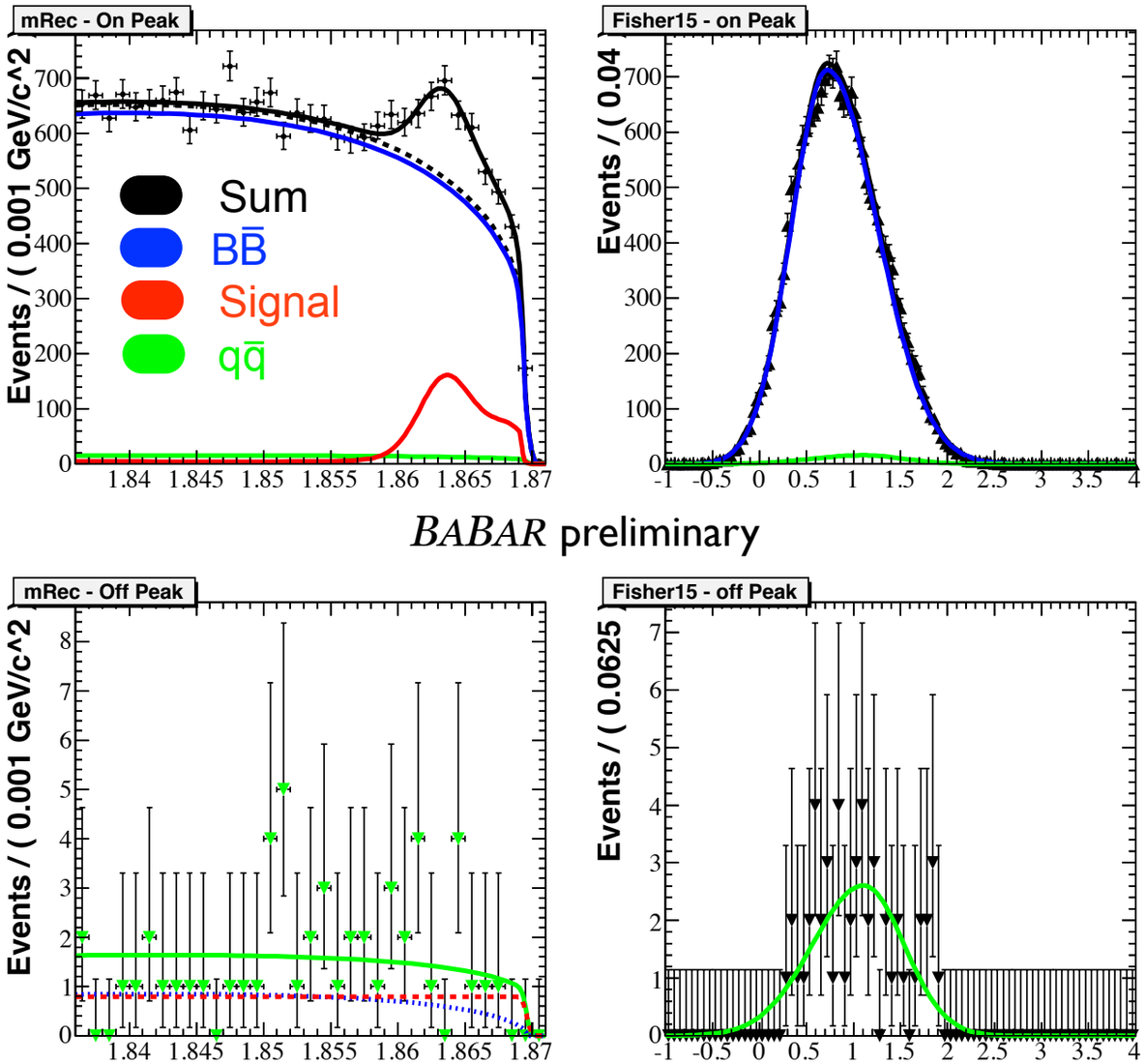


Kaon Tags

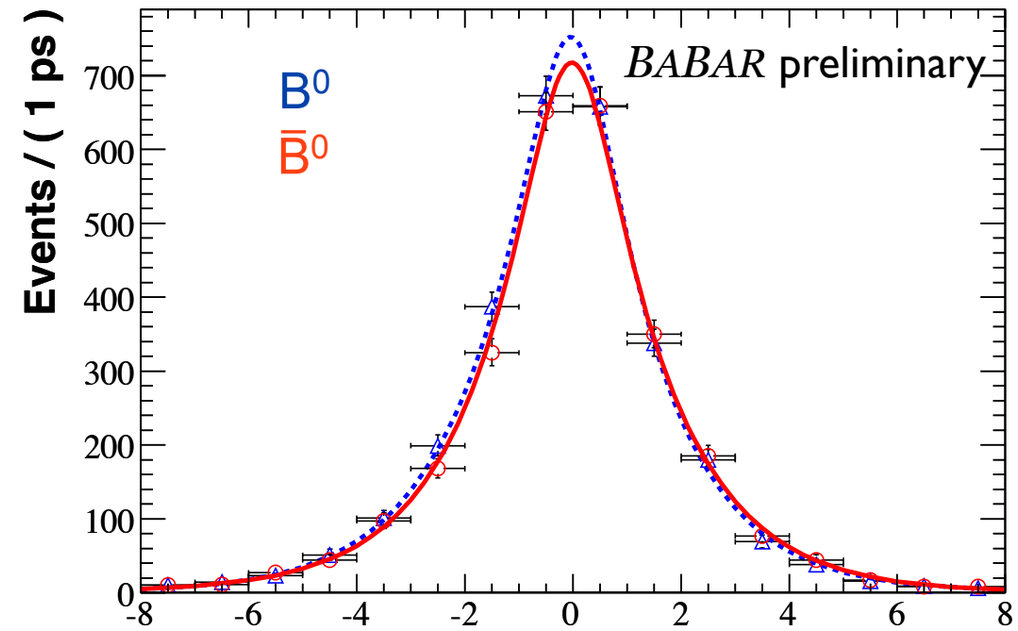
$$C = +0.12 \pm 0.11$$
$$S = -0.42 \pm 0.16$$

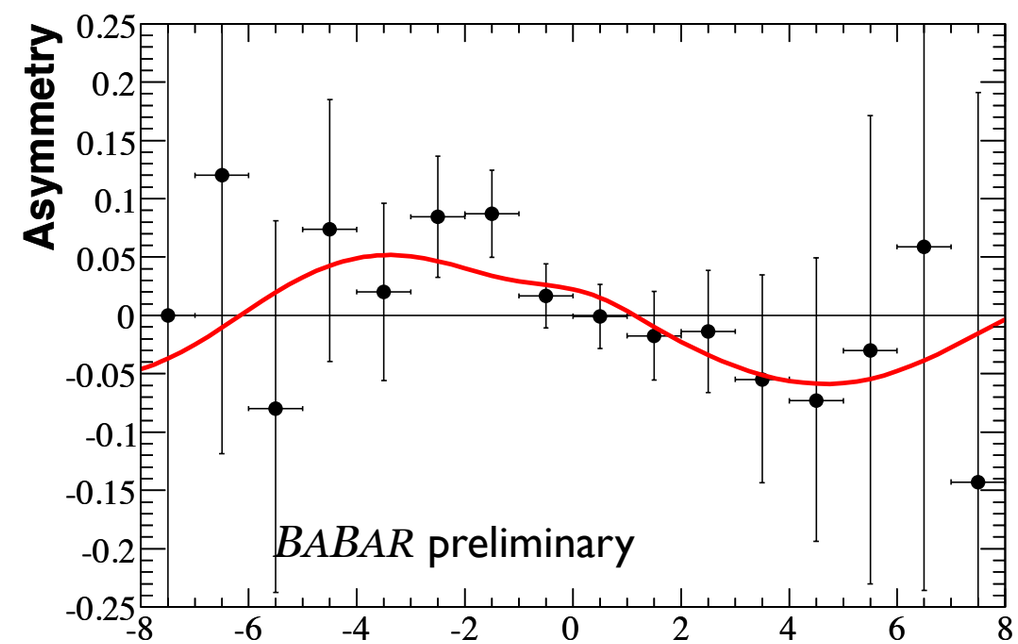
CPV in $B^0 \to D^{*+} D^{*-}$

Kin Fit Result - DATA



Δt Fit Result and Raw Asymmetry





Lepton Tags

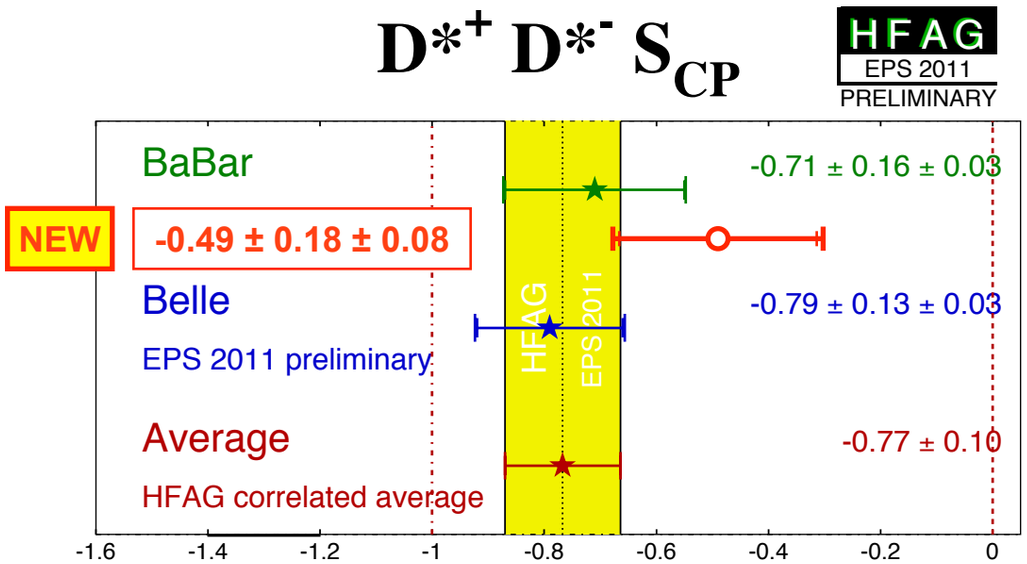
$$C = +0.20 \pm 0.15$$
$$S = -0.21 \pm 0.20$$

Combined Kaon-Lepton Results

Combined $B^0 \to D^{*+} D^{*-}$ Inclusive

$$C = +0.15 \pm 0.09 \pm 0.04$$
$$S = -0.34 \pm 0.12 \pm 0.05$$

BABAR preliminary



Assuming negligible penguin contributions, then $S_+ = -S_-$, and:

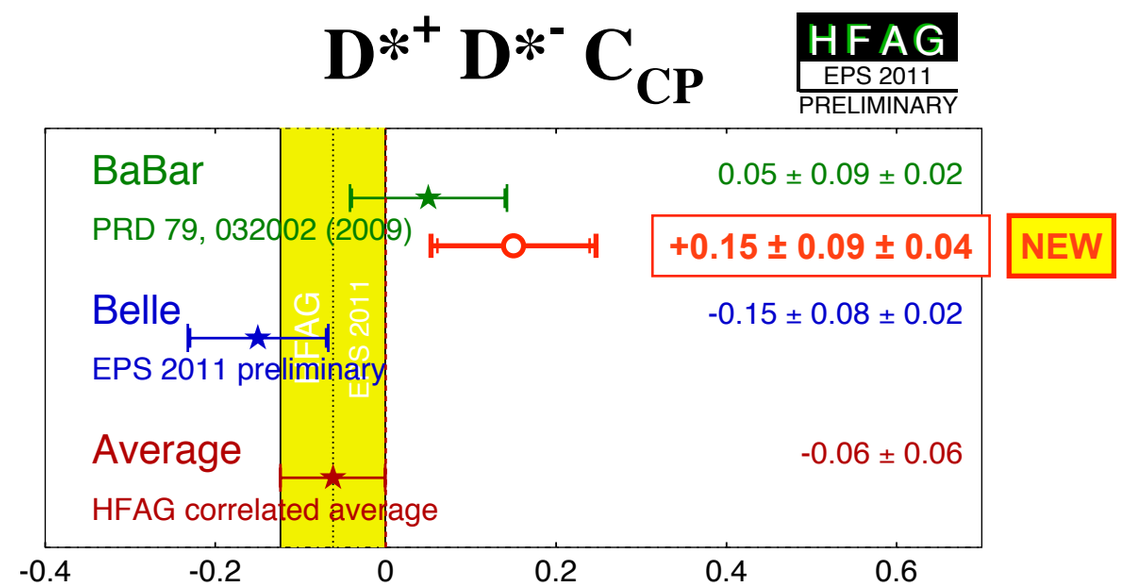
$$C = C_+$$
$$S = S_+ (1 - 2R_\perp)$$

and using[1]: $R_\perp = 0.158 \pm 0.02$

$$C_+ = +0.15 \pm 0.09 \pm 0.04$$
$$S_+ = -0.49 \pm 0.18 \pm 0.07 \pm 0.04$$

from $R_\perp$

All errors are statistical + systematic



This result is compatible with previous BaBar[1] and Belle[2] measurements and in agreement with SM predictions

[1] B. Aubert et al. (BABAR collaboration), Phys. Rev. D79, 032002 (2009) ;
[2] B. Vervink et al. (Belle collaboration), Phys. Rev. D80, 111104 (2009).; Belle Collab. EPS 2011 Preliminary

Summary

- *BABAR* has measured for the first time T-violating parameters in the time development of neutral B mesons by comparing conjugate processes that can only be achieved by T reversal, not CP.
  - This novel approach does not need CPT invariance to link T with CP
  - T violation is observed at >10 σ level.
  - Result is consistent with measurements of CP violation assuming CPT invariance.
- *BABAR* has made a new measurement of the *CP*-V parameters S,C in $b \to c\bar{c}d$ transitions, from which the *CP*-even components S_+,C_+ have been extracted
  - Improves previous BaBar overall (stat+sys) error on S,C by ~20%
  - Results compatible with previous BaBar and Belle measurements using fully reconstructed decays
  - In agreement with SM predictions of small penguin contributions and $S_+ \cong \sin 2\beta$

SPARES

T-Violation in Meson Decays

Decay TRV searches

CP

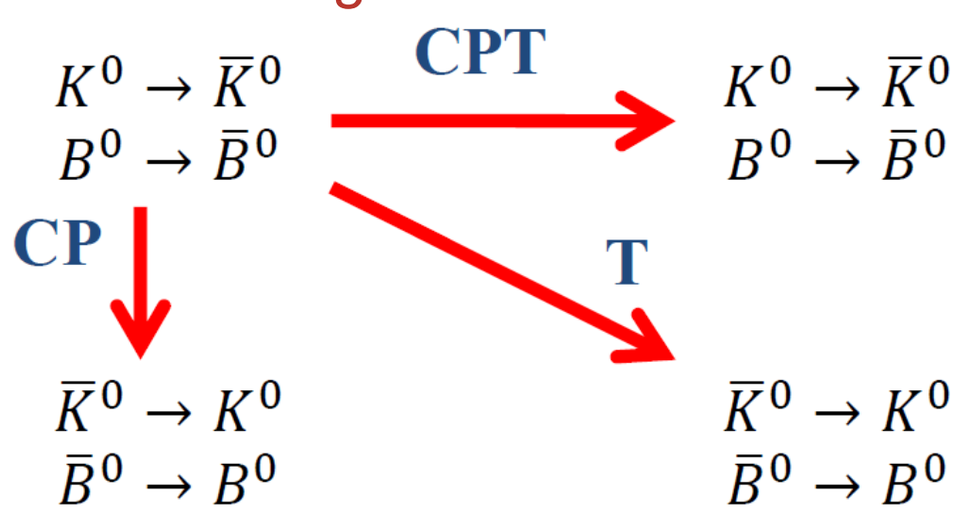
$B^0 \to K^+\pi^-$, R_1 $\xleftrightarrow{\text{CPT}}$ $K^-\pi^+ \to \bar{B}^0$, R_1

$\bar{B}^0 \to K^-\pi^+$, R_2 $\qquad$ $K^+\pi^- \to B^0$, R_2

Unable to perform the T test:

- Preparation of the initial state.
- The strong processes will swamp the feeble weak processes.

Mixing TRV searches

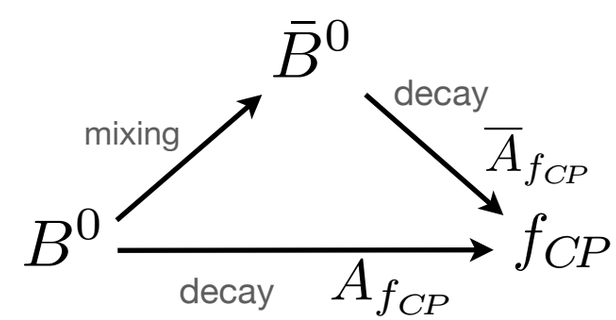


- Measured by CPLEAR in K system. Needs $\Delta\Gamma \neq 0$, too small in B system **[Phys. Lett. B 444, 43 (1998)]**
- Cannot distinguish CP and T.
  - Not a DIRECT observation of TRV

[Phys.Rev.Lett 83, 911 (1999)]

TRV in Interference

- Large CPV observed in B system.
- Expect large T violation as well.



$$\Gamma(B^0 \to f_{CP})(t) \neq \Gamma(\bar{B}^0 \to f_{CP})(t)$$

Significance of T violation

- Standard fit yields a likelihood value of the fit to S, C using the 8 independent samples.
- Repeat the fit, applying constraints to the parameters for T-conjugate processes
- Difference in likelihood values yields the significance of T violation.

T-inv. constraints
$\Delta S^{\pm}_{\mathrm{T}} = \Delta C^{\pm}_{\mathrm{T}} = 0$
$\Delta S^{\pm}_{\mathrm{CP}} = \Delta S^{\pm}_{\mathrm{CPT}}$
$\Delta C^{\pm}_{\mathrm{CP}} = \Delta C^{\pm}_{\mathrm{CPT}}$

$$\begin{aligned} \Delta\chi^2 &= -2\left(\ln L_{\mathrm{NoTRV}} - \ln L\right) \\ \Delta\nu &= 8 \text{ degrees of freedom} \end{aligned}$$

- CP and CPT significance can be determined the same way with proper constraints.
- Systematic uncertainties are included by calculating $2\Delta\ln L$ ($=m^2_j$) varying each parameter by $\pm 1\ \sigma_{syst.}$ and reduce the overall statistical $-2\Delta\ln L$ by $1+\max(m^2_j)$.

	$-2\Delta \ln L$	Signif.
T	226	> 10 σ
CP	307	> 10 σ
CPT	5	0.33 σ

TRV Systematics (for $\Delta S_T^{\pm}$)

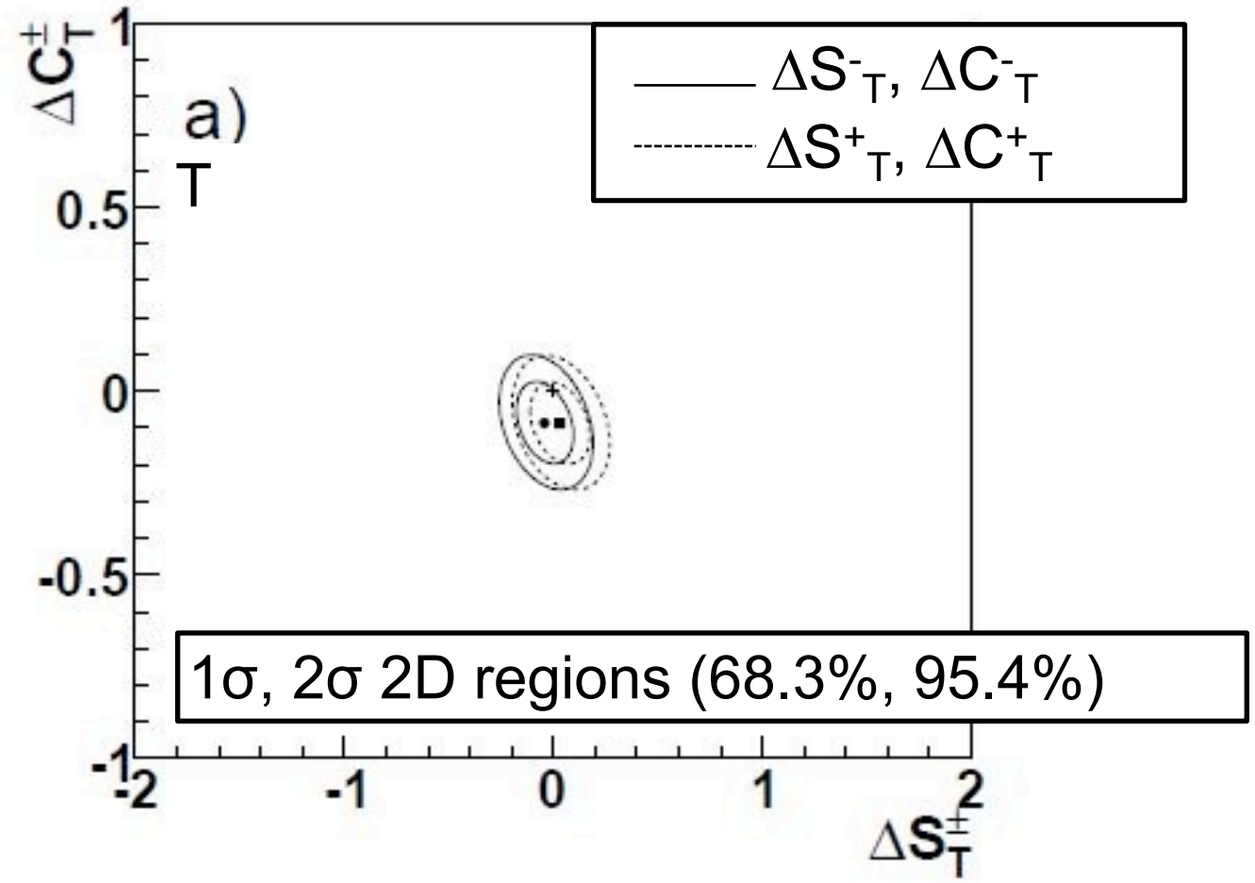
Systematic source	ΔS_T^+	ΔS_T^-
misID flavour	0.019	0.019
Δt resolution function	0.02	0.05
Outlier's scale factor	0.012	-0.013
m_{ES} parameters	0.012	0.0018
ΔE parameters	0.017	0.017
K_L systematics	0.03	0.03
Differences between B_{CP} and B_{flav}	0.02	0.02
Background effects	0.03	0.04
Uncertainty on fit bias from MC	0.010	0.08
Detector and vertexing effects.	0.011	0.04
$\Delta\Gamma \neq 0$ effects	0.004	0.003
External physics parameters	0.005	0.006
Normalization effects	0.012	0.009
Total Systematics	0.06	0.11

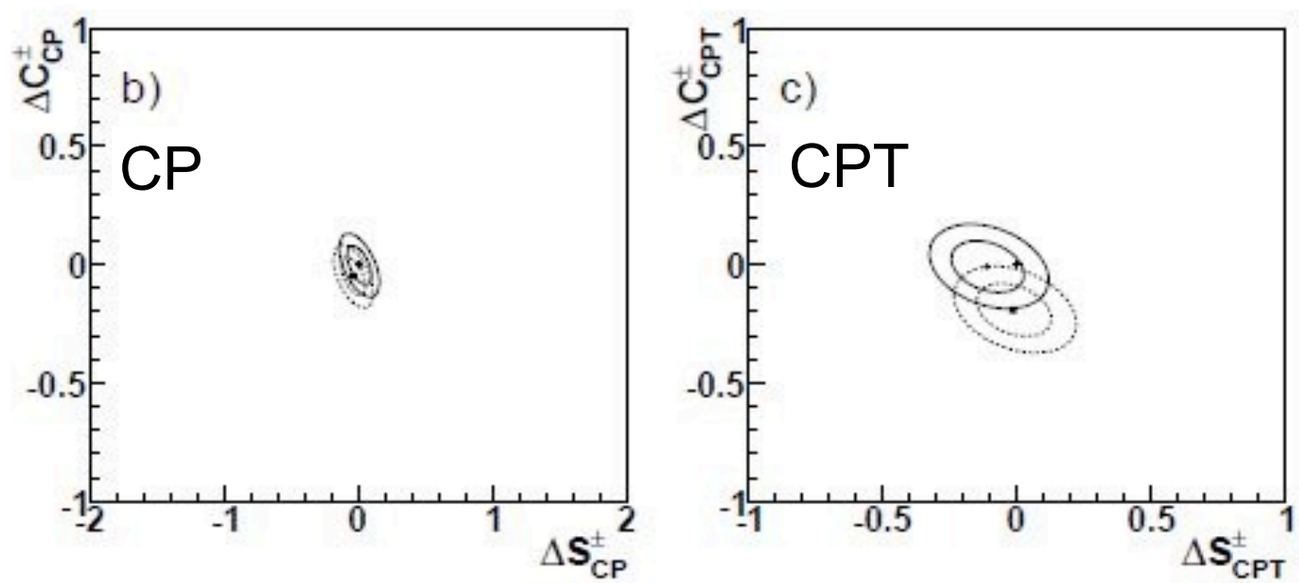
Similar tables for all others

Fitting Fit results (Control Data Sample)

$c\bar{c}K^{\pm}$ as $J/\psi K_S$
$J/\psi K^{*+}$ as $J/\psi K_L$

Parameter	Value
$\Delta C^{-}_{\mathrm{CP}}$	0.036 ± 0.050
$\Delta C^{-}_{\mathrm{CPT}}$	-0.0042 ± 0.068
$\Delta C^{-}_{\mathrm{T}}$	-0.0405 ± 0.073
$\Delta C^{+}_{\mathrm{CP}}$	-0.0044 ± 0.049
$\Delta C^{+}_{\mathrm{CPT}}$	-0.1586 ± 0.070
$\Delta C^{+}_{\mathrm{T}}$	-0.0237 ± 0.073
$\Delta S^{-}_{\mathrm{CP}}$	0.088 ± 0.054
$\Delta S^{-}_{\mathrm{CPT}}$	-0.1035 ± 0.083
$\Delta S^{-}_{\mathrm{T}}$	0.041 ± 0.089
$\Delta S^{+}_{\mathrm{CP}}$	0.041 ± 0.053
$\Delta S^{+}_{\mathrm{CPT}}$	0.030 ± 0.086
$\Delta S^{+}_{\mathrm{T}}$	0.155 ± 0.094
$C^{-}_{\mathrm{B^0,K^0_S}}$	0.025 ± 0.032
$C^{+}_{\mathrm{B^0,K^0_S}}$	0.038 ± 0.031
$S^{-}_{\mathrm{B^0,K^0_S}}$	-0.0072 ± 0.038
$S^{+}_{\mathrm{B^0,K^0_S}}$	-0.0002 ± 0.038





Evaluation of Systematic Errors

Systematic source	kaon tags C	kaon tags S	lepton tags C	lepton tags S
Kinematic fit parameters	0.013	0.034	0.023	0.057
Continuum Δt fit parameters	0.002	0.001	–	–
Signal s_w	0.0002	0.0007	–	–
$B\overline{B}$ Combinatoric s_w	0.017	0.0007	0.001	0.005
Signal tagging dilution: tag side (w)	0.012	0.045	0.002	0.002
Mistag difference (Δw)	0.007	0.0004	0.007	0.0009
Signal tagging dilution: CP side (α_{D^0})	0.006	0.017	0.002	0.002
Peaking background	0.0002	0.0003	0.0002	0.00004
Fit bias (MC statistics)	0.011	0.018	0.012	0.019
Tag interference from DCSD	0.030	0.002	–	–
B^0 lifetime variation	0.0002	0.002	0.0003	0.004
Δm_d variation	0.0003	0.001	0.0004	0.002
SVT misalignment	0.003	0.007	0.002	0.004
Boost uncertainty	0.002	0.006	0.005	0.007
Total	0.042	0.062	0.028	0.061

= top contributions

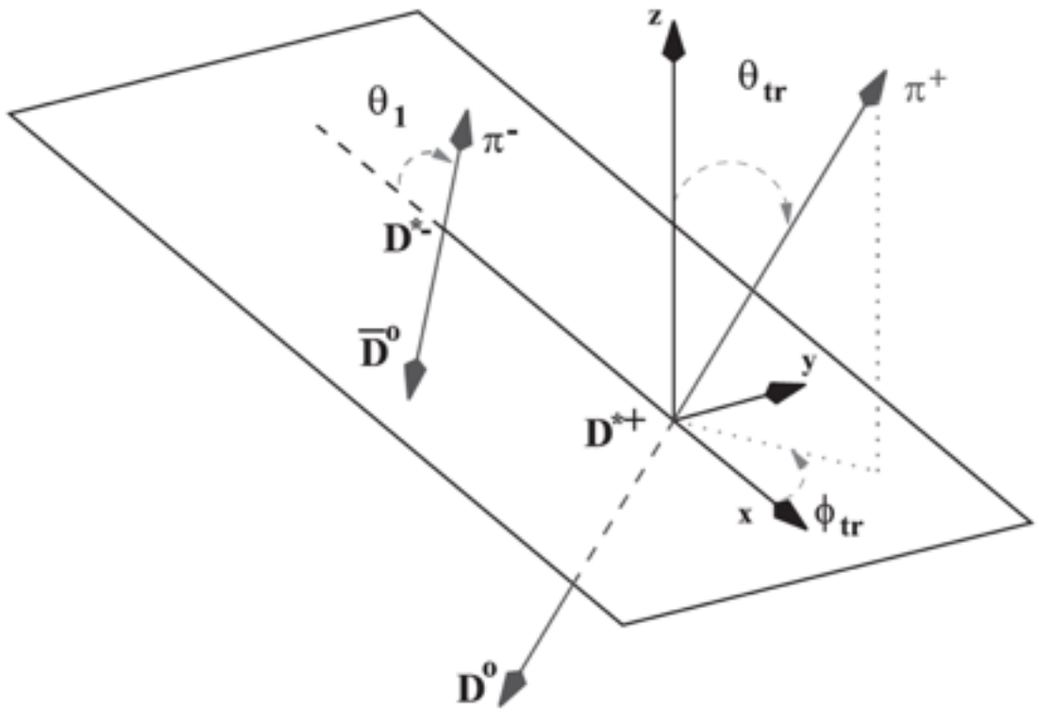
$B^0 \to D^{*+} D^{*-}$

Full TD amplitude

$$\frac{1}{\Gamma}\frac{d^4\Gamma}{d\cos\theta_1 d\cos\theta_{tr} d\phi_{tr} dt} = \frac{9}{16\pi}\frac{1}{|A_0|^2+|A_\parallel|^2+|A_\perp|^2}\times$$
$$\Big\{2\cos^2\theta_1\sin^2\theta_{tr}\cos^2\phi_{tr}|A_0|^2$$
$$+\sin^2\theta_1\sin^2\theta_{tr}\sin^2\phi_{tr}|A_\parallel|^2$$
$$+\sin^2\theta_1\cos^2\theta_{tr}|A_\perp|^2$$
$$-\sin^2\theta_1\sin 2\theta_{tr}\sin\phi_{tr}\,\mathrm{Im}(A_\parallel^* A_\perp)$$
$$+\frac{1}{\sqrt{2}}\sin 2\theta_1\sin^2\theta_{tr}\sin 2\phi_{tr}\,\mathrm{Re}(A_0^* A_\parallel)$$
$$-\frac{1}{\sqrt{2}}\sin 2\theta_1\sin 2\theta_{tr}\cos\phi_{tr}\,\mathrm{Im}(A_0^* A_\perp)\Big\}\,, \qquad (2)$$

where A_k, with $k = \parallel, 0, \perp$, represent time-dependent amplitudes given by

$$A_k(t) = \frac{\sqrt{2}A_k(0)}{1+|\lambda_k|^2}e^{-imt}e^{-t/2\tau_{B^0}}$$
$$\times\left(\cos\frac{\Delta m_d t}{2} + i\eta_{CP}^k\lambda_k\sin\frac{\Delta m_d t}{2}\right). \qquad (3)$$



- The VV final state is a superposition of CP+ and CP- states depending on the angular momentum of the decay products
- Need angular analysis to distinguish the two components
- This has been done by BaBar (and Belle) with fully reconstructed events, measuring the CP-odd fraction $R_\perp$ and the time dependent CP asymmetry

$$R_\perp = \frac{|A_\perp^0|^2}{|A_0^0|^2+|A_\parallel^0|^2+|A_\perp^0|^2}$$

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

Probability Density Functions

- Overall PDF for the on-Peak sample is the sum of three components

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

- Each component is the product of a kinematical and a Δt part

$$P_i(m_{\rm rec}, F, \Delta t, \sigma_{\Delta t}, S_{\rm tag}) = \underbrace{\mathcal{M}_i(m_{\rm rec})\,\mathcal{F}_i(F)}_{\text{“KIN”}}\,\underbrace{T'_i(\Delta t, \sigma_{\Delta t}, S_{\rm tag})}_{\text{“Δt”}}$$

- Δt PDF: $T'_i(\Delta t, \sigma_{\Delta t}, S_{\rm tag}) = \int d\Delta t_{\rm true}\, T_i(\Delta t_{\rm true}, S_{\rm tag})\,\mathcal{R}_i(\Delta t - \Delta t_{\rm true}, \sigma_{\Delta t})$

- Signal Δt:

$$\begin{aligned} T_{\rm sig} \;=\; & \frac{1}{4\tau_b}\, e^{-|\Delta t_{\rm true}|/\tau_b} \cdot \Big\{ (1 - S_{\rm tag}\,\Delta\omega(1-\alpha)) + \\ & + S_{\rm tag}\,(1-2\omega)\,(1-\alpha) \\ & \cdot [C\cos(\Delta m_d \Delta t_{\rm true}) + S\,\sin(\Delta m_d \Delta t_{\rm true})] \Big\} \end{aligned}$$

$$S = -\frac{2\Im m(\lambda)}{1+|\lambda|^2} \qquad C = \frac{1-|\lambda|^2}{1+|\lambda|^2} \qquad \lambda = \frac{q}{p}\frac{\overline{A}}{A}$$

Event Selection

4.7 Event Selection Summary

This is a summary of cuts used in our selection of events.

- Cuts in $\Upsilon(4S)$ center-of-mass on D^* and soft pion momentum, and missing D^0 mass::

$$1.3\ \mathrm{GeV}/c \leq p^*_{D^*} \leq 2.1\,\mathrm{GeV}/c$$

$$p^*_\pi \leq 0.6\,\mathrm{GeV}/c$$

- Continuum rejection cut:

$$R_2 \leq 0.3$$

- "Quality" cuts on reconstructed D^* (see Sec. 4.3):

$$P^{vrt}_{D^*} \text{ and } P^{vrt}_{D^0} > 10^{-2}$$

$$\text{Dch yes}: |Q_{D^*} - Q_{\mathtt{PDG}}| = |M_{D^*} - M_{D^0} - M_\pi - 6\,\mathrm{MeV}/c^2| \leq 1\,\mathrm{MeV}/c^2$$

$$\text{Dch no}: |Q_{D^*} - Q_{\mathtt{PDG}}| = |M_{D^*} - M_{D^0} - M_\pi - 6\,\mathrm{MeV}/c^2| \leq 1.5\,\mathrm{MeV}/c^2$$

$$|M_{D^0} - M_{\mathtt{PDG}}| \leq [1. - 1.5] \cdot \sigma_i\,\mathrm{MeV}/c^2$$

- "PID" and flight-length cuts on Kaons in D^0 mesons (see Sec. 4.3)
- Slow pion $\mathrm{d}E/\mathrm{d}x$ cuts:

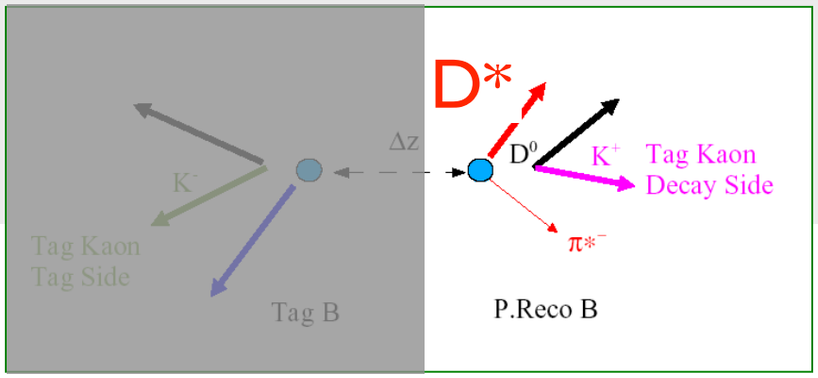
$$p_{\pi_s} \leq 0.150\,\mathrm{GeV}/c^2 \ : \quad \mathrm{d}E/\mathrm{d}x\ (MeV/cm) \ \geq (\frac{0.25}{(p_{\pi_s} - 0.030)} + 1.0);$$

$$0.150\,\mathrm{GeV}/c^2 < p_{\pi_s} \leq 0.500\,\mathrm{GeV}/c^2 \ : \quad \mathrm{d}E/\mathrm{d}x\ (MeV/cm) \ \leq (\frac{1.75}{(p_{\pi_s})} + 2.0);$$

- Missed D^0 cuts:

$$|\cos(\theta_{BD^*})| \leq 1$$

Tagging



- Mis-tag due to unreconstructed D^0 tracks
  - This introduces an additional dilution $D=(1-\alpha)$, where α is the fraction of tags coming from the missing D^0
  - This fraction can be obtained from data with some input from signal MC
  - Can be reduced with a cut on the cosine of the opening angle between the tagging track and the missing D^0 direction θ_{tag}

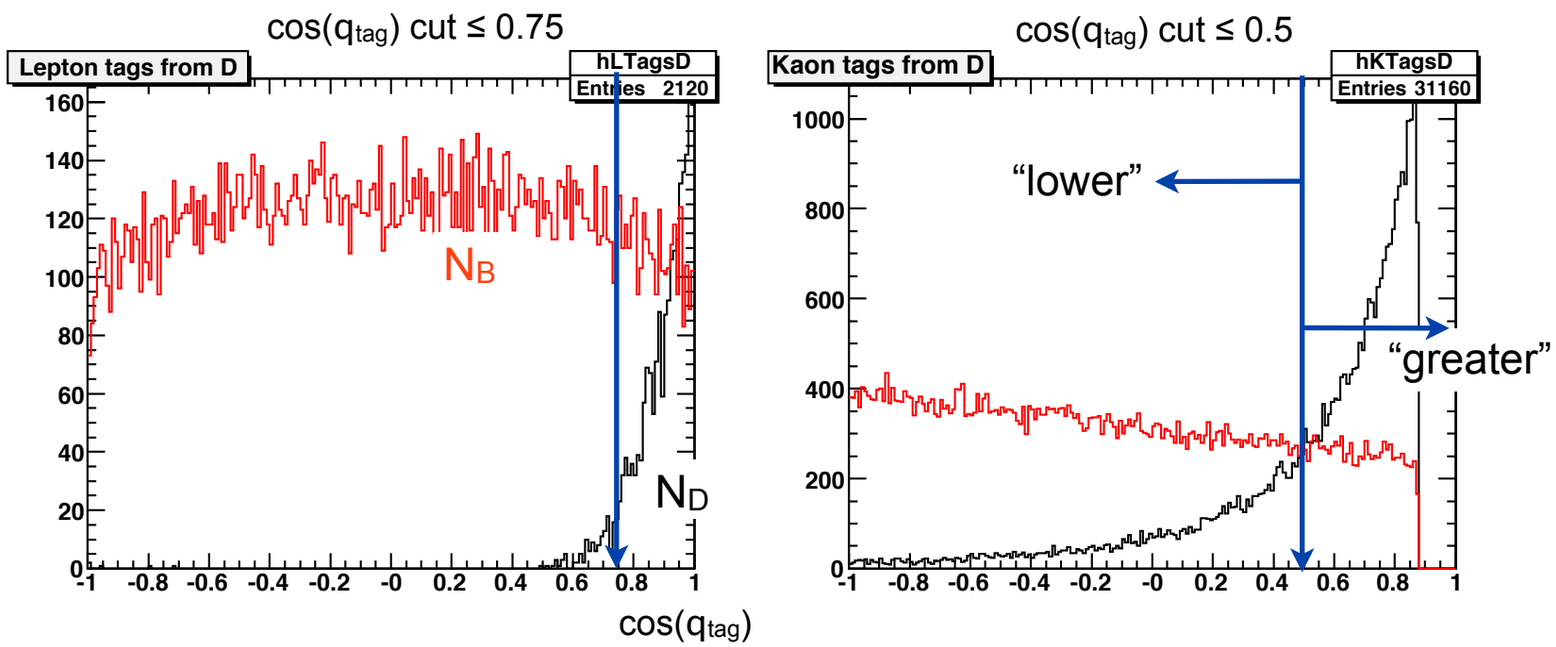


Figure 2.1: Signal Monte Carlo distributions of $\cos(\vartheta_{tag})$ for tracks from the missed D^0 (black) and from the other B^0 (red); lepton tags on the left, kaon tags on the right.