RESULTS FROM BaBar

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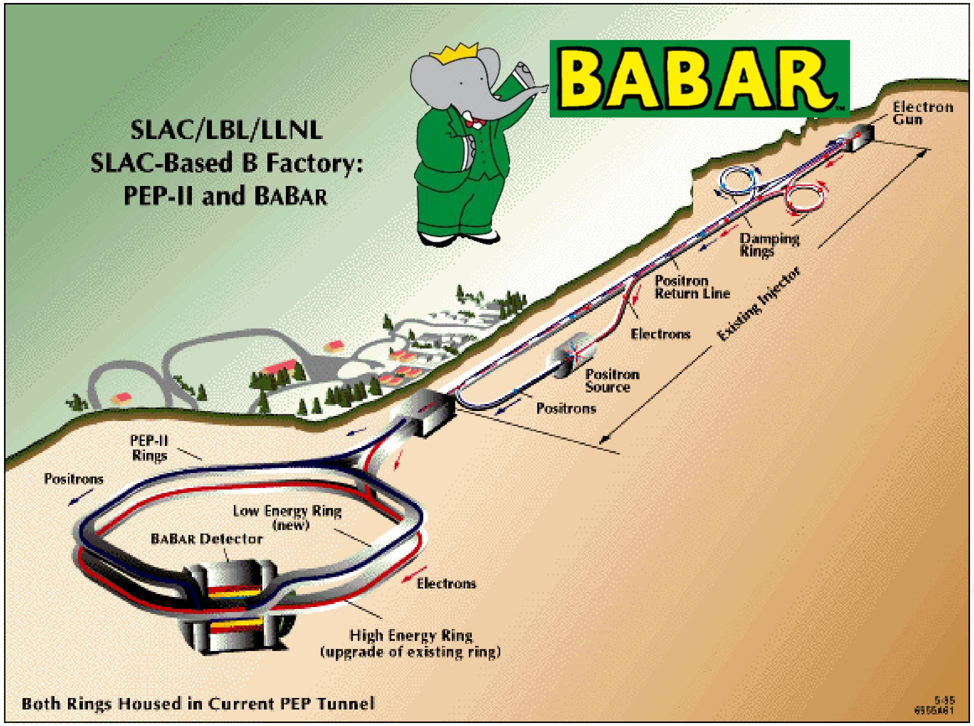
IV Jornadas del CPAN

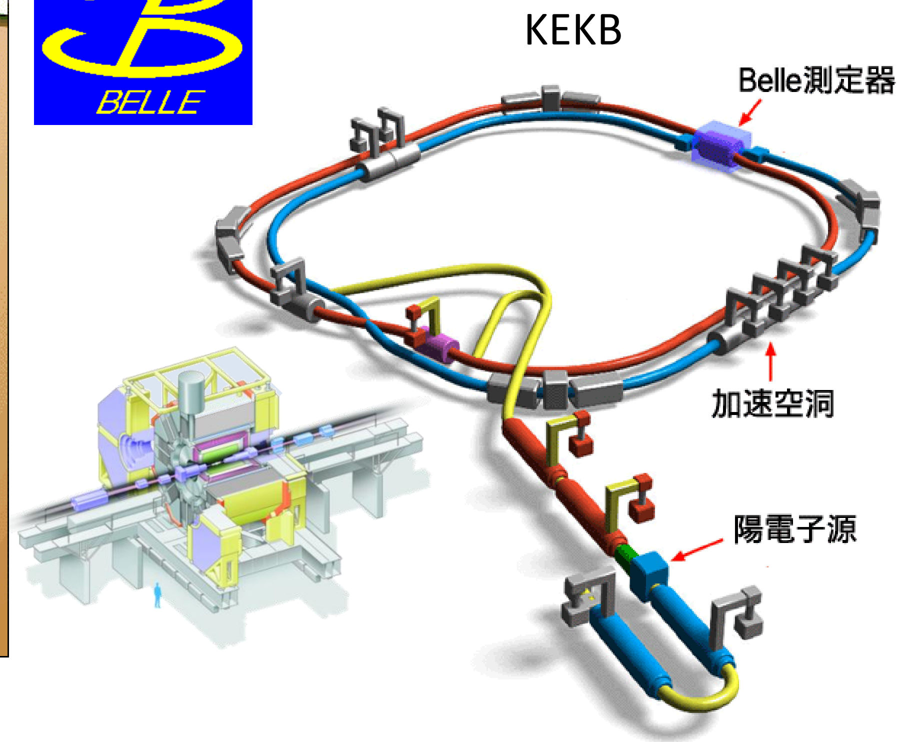
B FACTORIES

AND

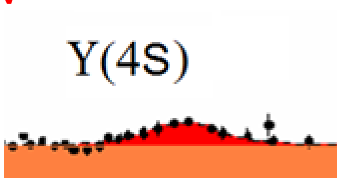
BaBar EXPERIMENT

B Factories

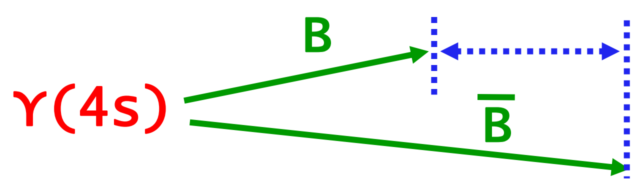




$\sqrt{s}$=10.58 GeV

e^+ → 

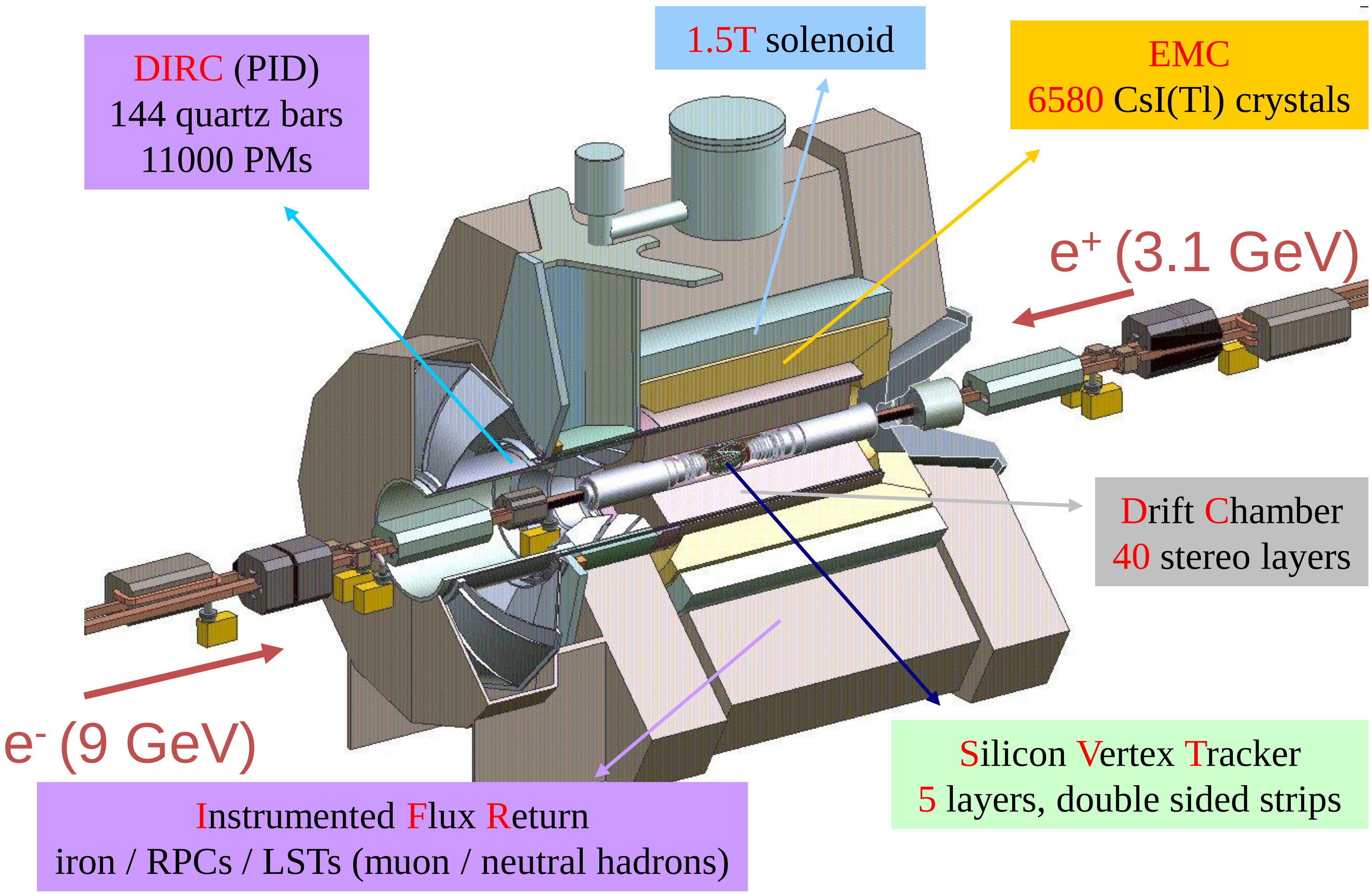
← e^-



$\Delta z \sim c\,\beta\gamma\,\tau_B$
$\sim 200\mu m$

BaBar	$p(e^-)$=9 GeV $p(e^+)$=3.1 GeV	$\beta\gamma$=0.56
Belle	$p(e^-)$=8 GeV $p(e^+)$=3.5 GeV	$\beta\gamma$ =0.42

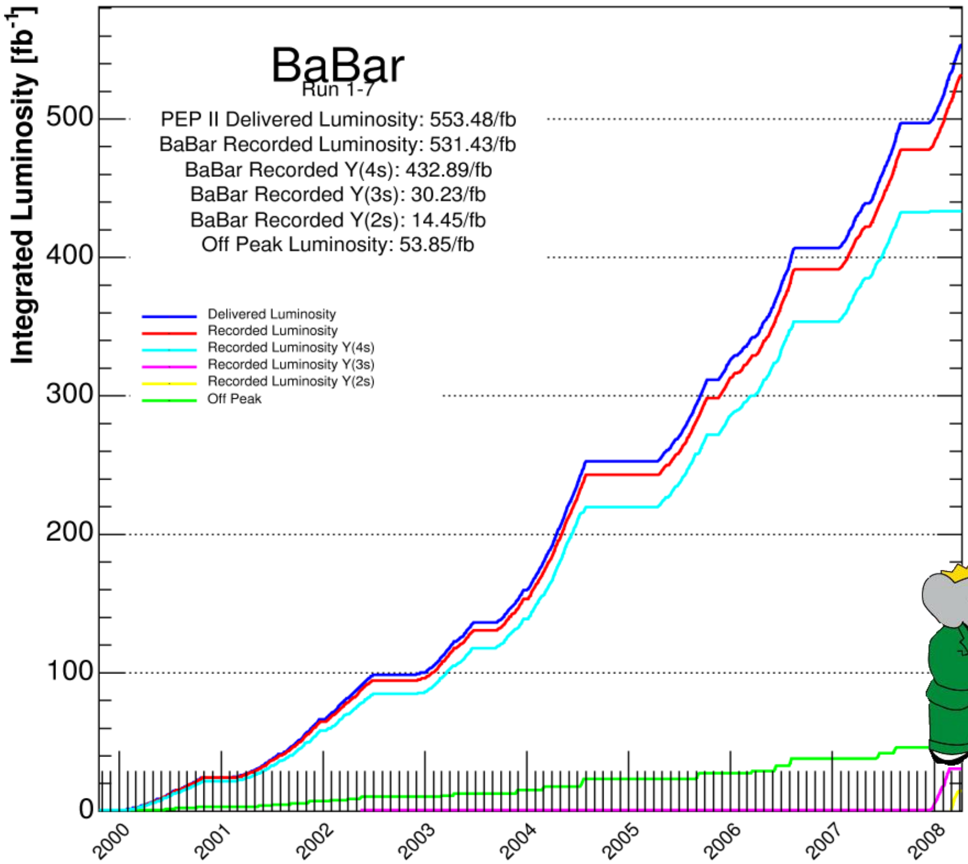
BaBar detector

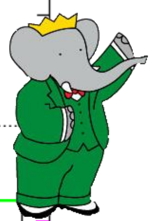


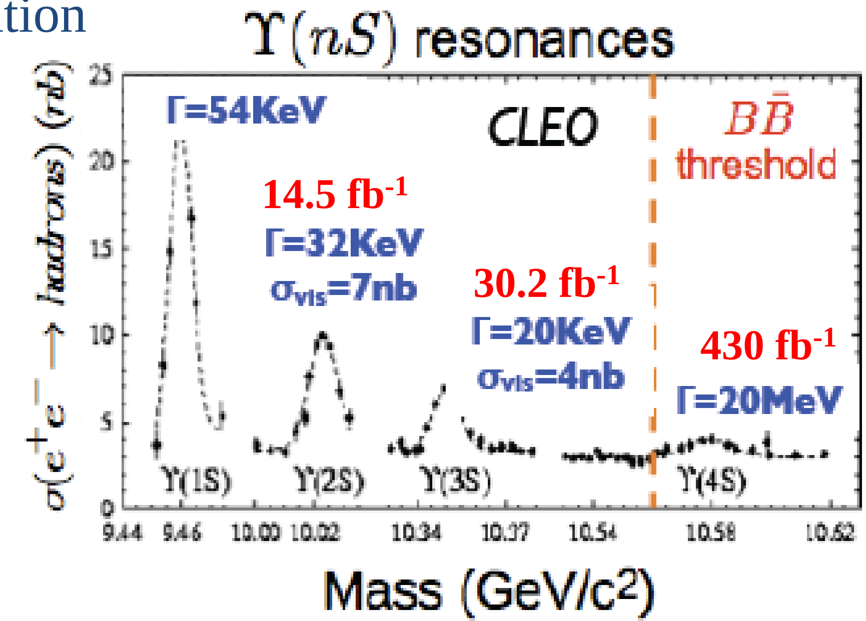
- Asymmetric B-factory: E_{cms} = 10.58 GeV $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
- Performed a wide range of flavor physics results in B, Charm and τ sectors
- General purpose detector in e^+e^- environment: precision tracking, photon/electron detection, particle ID, muon/K_L identification. Very stable over the 9 years of operation

BaBar data

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







54 fb^{-1} **Off-ϒ(nS)**

4 fb^{-1} **above ϒ(4S)**

- ≈ 470×10^6 BB (0.5×Belle)
- ≈ 690×10^6 cc
- ≈ 500×10^6 $\tau^+\tau^-$
- ≈ 1.2×10^8 Y(3S) (7×Belle+Cleo)
- ≈ 1.0×10^8 Y(2S) (0.5×Belle+Cleo)

Outline

- Time Reversal Violation
  - Theoretical motivation
  - Analysis Procedure
  - Results and interpretation

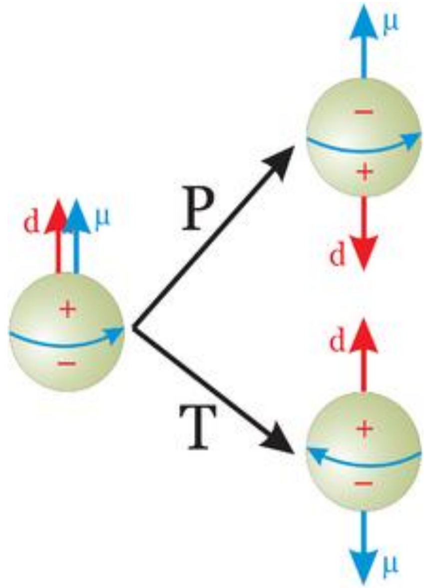
- $B \to D^{(*)}\tau\nu$
  - Motivation
  - Analysis Procedure
  - Results
  - 2HDM discussion

TIME REVERSAL VIOLATION

J. P. Lees et al. Phys. Rev. Lett. 109, 211801 (2012)

Motivation

- Time Reversal in stable systems
  - A non-zero value of a T-odd observable in a stationary state, e.g, electric dipole moment of an elementary particle or an atom.
  - In an oscillation a difference in the probability of a⟶b from b⟶a at a given time, e.g., $\nu_e \rightarrow \nu_\mu$ vs. $\nu_\mu \rightarrow \nu_e$ experiment proposed for the neutrino factories with muon storage ring.



- Time Reversal in unstable systems
  1. Reversal of motion (t⟶-t).
  2. |in>↔|out> exchange.

discard ⟶ ~~Odd effects t⟶-t~~

⟶ Experimentally tricky!

CP violation mechanisms		T violation mechanisms
• Decay • Mixing • Mixing×Decay	⟷ CPT	• Decay • Mixing • Mixing×Decay

TRV in unstable systems

- **Decay TRV searches**

CP: $B^0 \to K^+\pi^-$, R$_1$; $\bar{B}^0 \to K^-\pi^+$, R$_2$

CPT ⟷

$K^-\pi^+ \to \bar{B}^0$, R$_1$; $K^+\pi^- \to B^0$, 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**

$K^0 \to \bar{K}^0$
$B^0 \to \bar{B}^0$

CPT →

$K^0 \to \bar{K}^0$
$B^0 \to \bar{B}^0$

CP ↓

$\bar{K}^0 \to K^0$
$\bar{B}^0 \to B^0$

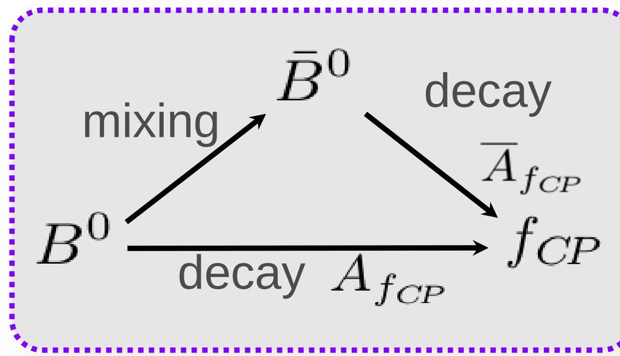
T ↘

$\bar{K}^0 \to K^0$
$\bar{B}^0 \to B^0$

CPLEAR

We cannot distinguish CP and T.
Not a DIRECT observation of TRV

- **Interference TRV searches**



CPV time dependent (TD) studies:

- There are no exchanges $t \leftrightarrow -t$ and $|in> \leftrightarrow |out>$.
- Assumes CPT invariance and $\Delta\Gamma = 0$.

Foundations of the analysis

- Ingredients: M. C. Bañuls and J. Bernabeu, Phys. Lett. B 464, 117 (1999); Nucl. Phys. B 590, 19 (2000).
  - EPR entanglement produced by the decay of the $\Upsilon(4S)$.

$$|i>= 1/\sqrt{2}[B^0(t_1)\bar{B}^0(t_2) - \bar{B}^0(t_1)B^0(t_2)]$$
$$= 1/\sqrt{2}[B_+(t_1)B_-(t_2) - B_-(t_1)B_+(t_2)]$$

B_+, B_- projected by $\rightarrow$ $J/\psi K_L$, $J/\psi K_S$

  - Quantum Mechanics.

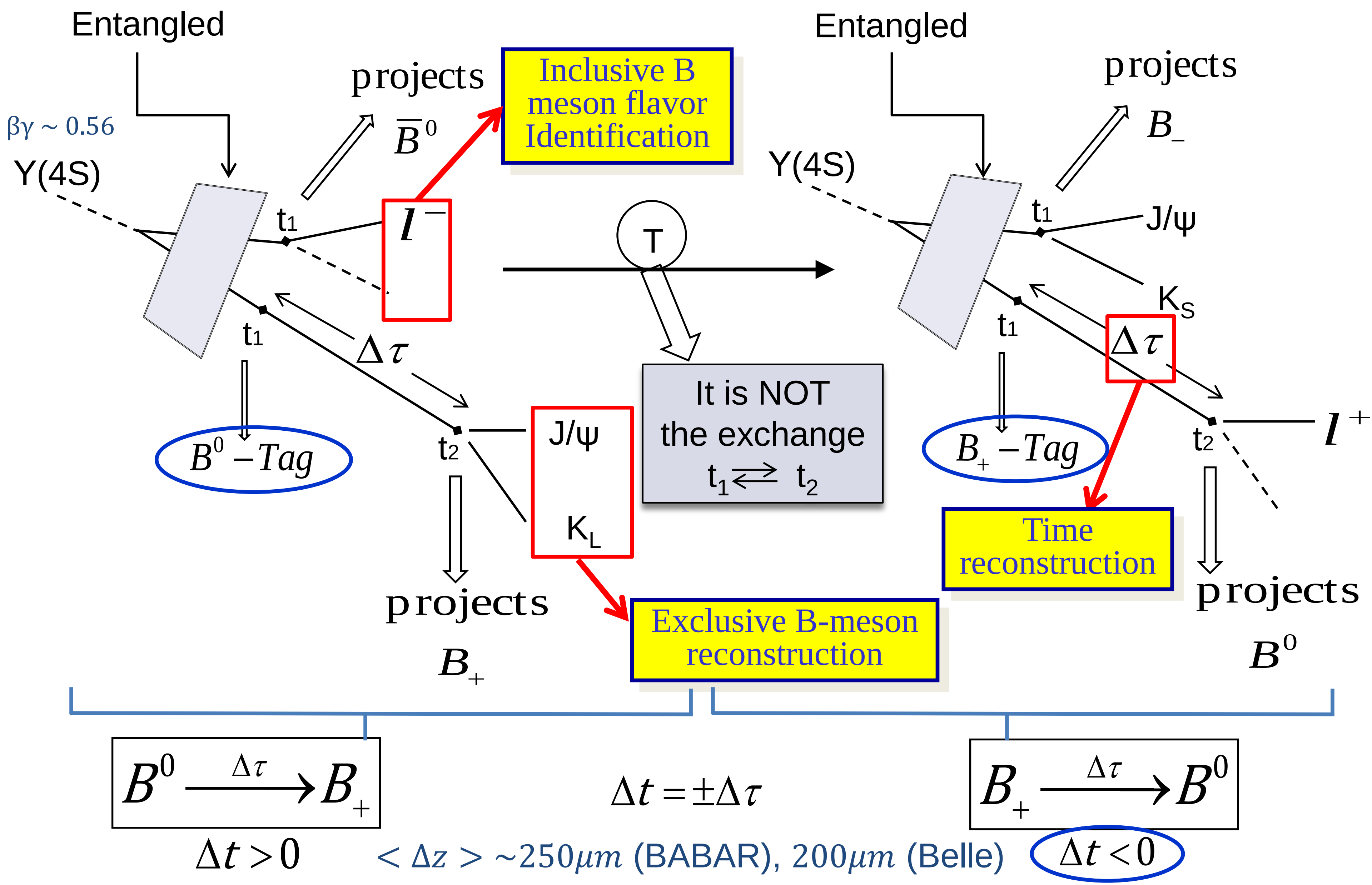
$$\Delta\tau = t_Y - t_X > 0$$

Reference: Physical Process
(X,Y): Reconstructed Final States

Reference (X, Y)		***T-Transformed (X, Y)***	
$B^0 \rightarrow B_+$	(l^- , J/ψ K_L)	$B_+ \rightarrow B^0$	(J/ψ K_S, l^+)
$B^0 \rightarrow B_-$	(l^- , J/ψ K_S)	$B_- \rightarrow B^0$	(J/ψ K_L, l^+)
$\bar{B}^0 \rightarrow B_+$	(l^+ , J/ψ K_L)	$B_+ \rightarrow \bar{B}^0$	(J/ψ K_S, l^-)
$\bar{B}^0 \rightarrow B_-$	(l^+ , J/ψ K_S)	$B_- \rightarrow \bar{B}^0$	(J/ψ K_L, l^-)

l^+ and l^- project over the B flavor, i.e., B^0 and $\bar{B}^0$ respectively

Foundations of the analysis



T-transformed processes

JHEP08 (2012) 064

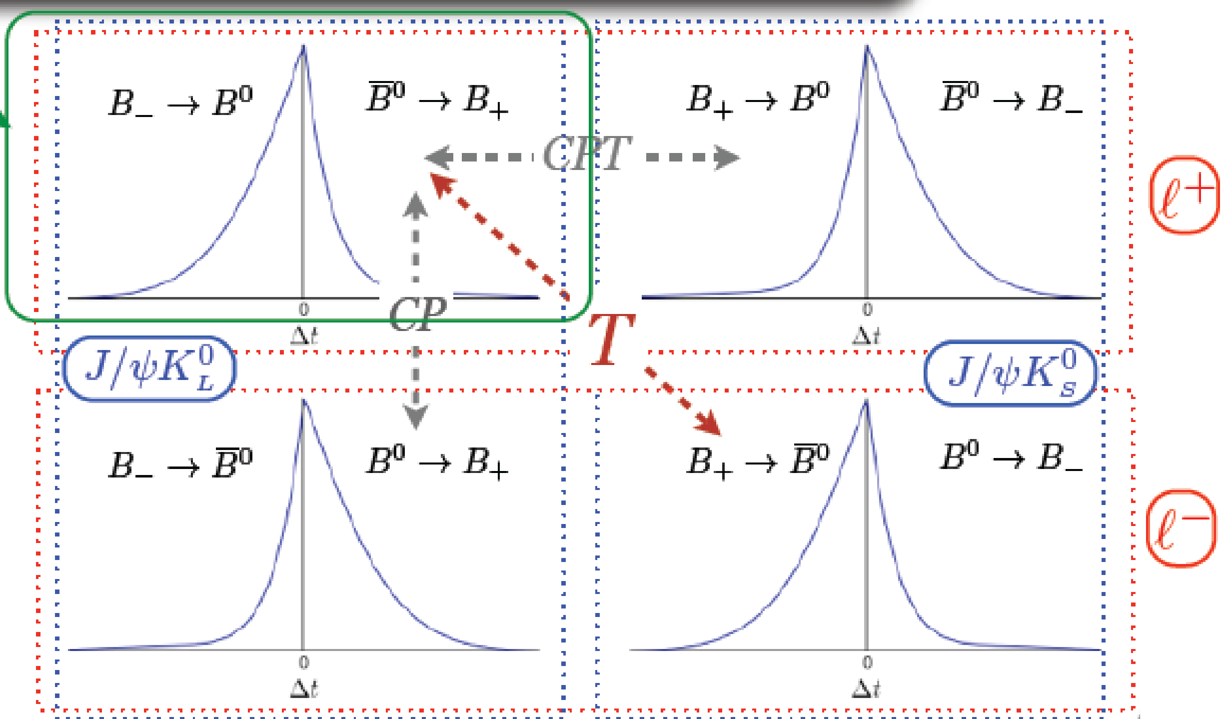
Reference (X,Y)		T-Transformed	
$B^0 \to B_+$	$(\ell^-, J/\psi K^0_L)$	$B_+ \to B^0$	$(J/\psi K^0_S, \ell^+)$
$B^0 \to B_-$	$(\ell^-, J/\psi K^0_S)$	$B_- \to B^0$	$(J/\psi K^0_L, \ell^+)$
$\overline{B}^0 \to B_+$	$(\ell^+, J/\psi K^0_L)$	$B_+ \to \overline{B}^0$	$(J/\psi K^0_S, \ell^-)$
$\overline{B}^0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

(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. $\overline{B}^0$)

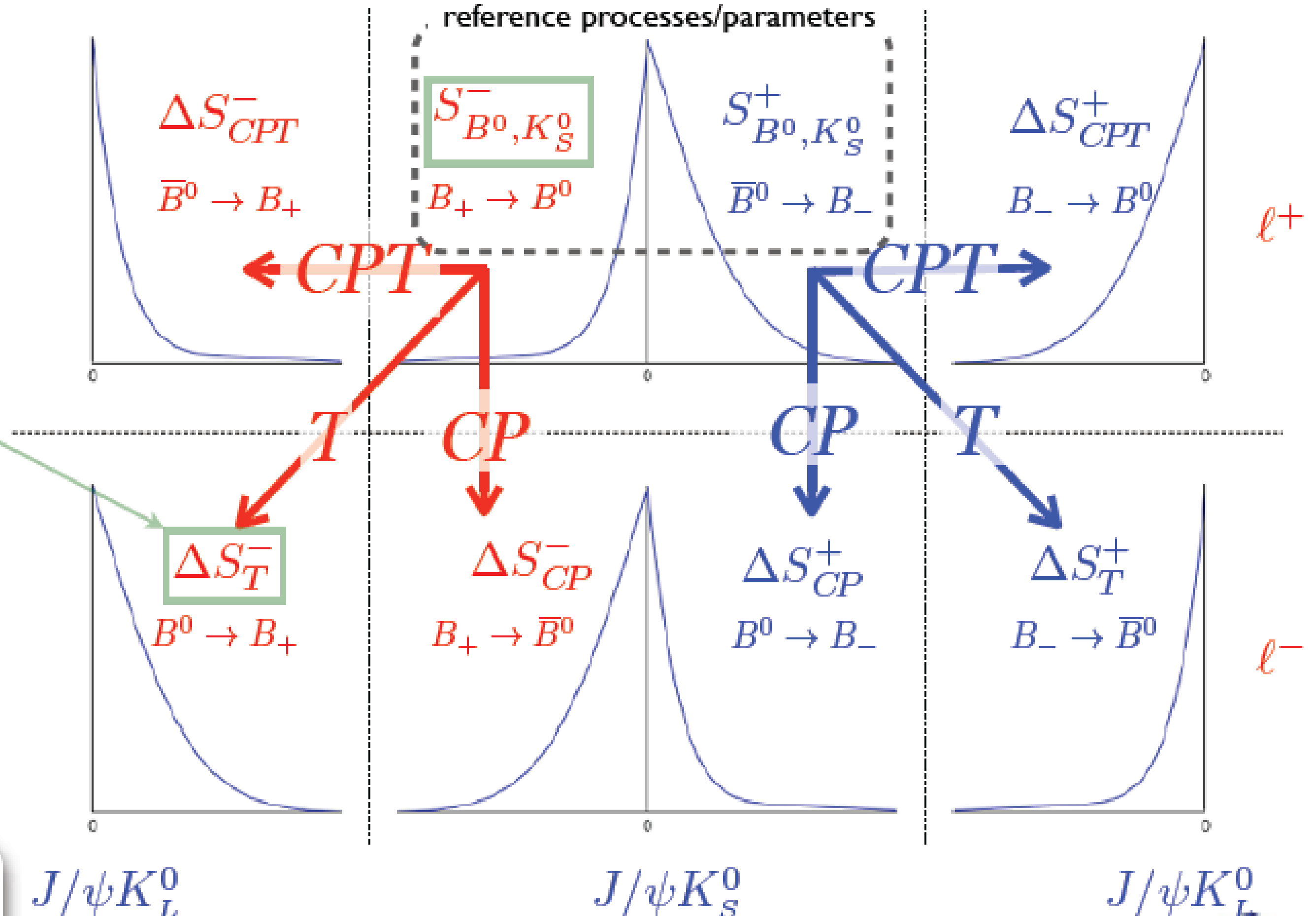
Signal parameters

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

$$\Delta t = t_{CP} - t_{flav} = \begin{cases} +\Delta\tau \text{ for "flavor tag"} \\ -\Delta\tau \text{ for "CP tag"} \end{cases} \qquad \alpha \in \{B^0,\ \overline{B}^0\};\quad \beta \in \{K^0_S,\ K^0_L\}$$

Prediction from CPV

Parameter	Value
$S^{+}_{B^0,K^0_S}$	0.7
$\Delta S^{+}_{T} = S^{-}_{\bar{B}^0,K^0_L} - S^{+}_{B^0,K^0_S}$	−1.4
$\Delta S^{+}_{CP} = S^{+}_{\bar{B}^0,K^0_S} - S^{+}_{B^0,K^0_S}$	−1.4
$\Delta S^{+}_{CPT} = S^{-}_{\bar{B}^0,K^0_L} - S^{+}_{B^0,K^0_S}$	0.0
$S^{-}_{B^0,K^0_S}$	−0.7
$\Delta S^{-}_{T} = S^{+}_{\bar{B}^0,K^0_L} - S^{-}_{B^0,K^0_S}$	1.4
$\Delta S^{-}_{CP} = S^{-}_{\bar{B}^0,K^0_S} - S^{-}_{B^0,K^0_S}$	1.4
$\Delta S^{-}_{CPT} = S^{+}_{B^0,K^0_L} - S^{-}_{B^0,K^0_S}$	0.0
$C^{+}_{B^0,K^0_S}$	0.0
$\Delta C^{+}_{T} = C^{-}_{\bar{B}^0,K^0_L} - C^{+}_{B^0,K^0_S}$	0.0
$\Delta C^{+}_{CP} = C^{+}_{\bar{B}^0,K^0_S} - C^{+}_{B^0,K^0_S}$	0.0
$\Delta C^{+}_{CPT} = C^{-}_{\bar{B}^0,K^0_L} - C^{+}_{B^0,K^0_S}$	0.0
$C^{-}_{B^0,K^0_S}$	0.0
$\Delta C^{-}_{T} = C^{+}_{\bar{B}^0,K^0_L} - C^{-}_{B^0,K^0_S}$	0.0
$\Delta C^{-}_{CP} = C^{-}_{\bar{B}^0,K^0_S} - C^{-}_{B^0,K^0_S}$	0.0
$\Delta C^{-}_{CPT} = C^{+}_{B^0,K^0_L} - C^{-}_{B^0,K^0_S}$	0.0



For T Violation

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

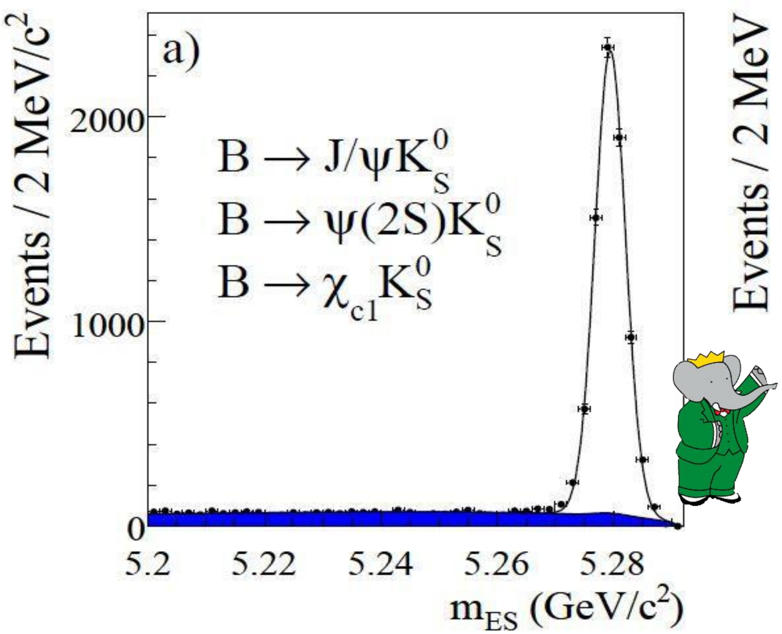
in the decay $\Delta C^{+}_{T} \neq 0$, $\Delta C^{-}_{T} \neq 0$

Dataset

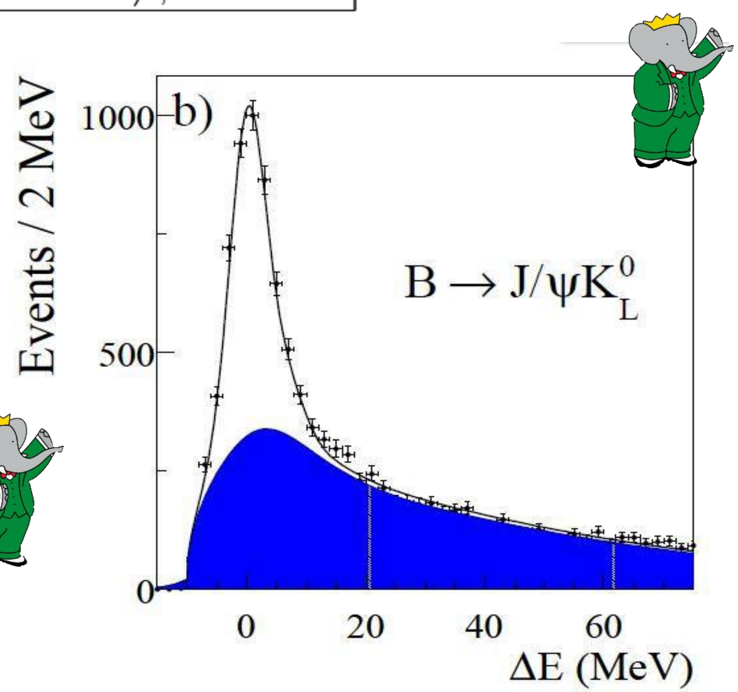
signal sample

Category	Decay(s)
$c\bar{c}K^0_S$	$B^0 \to J/\psi\, K^0_S$ $B^0 \to \psi(2S) K^0_S$ $B^0 \to \chi_{c1} K^0_S$
$c\bar{c}K^0_L$	$B^0 \to J/\psi\, K^0_L$
B_{flav} (high statistics)	$B^0 \to D^*\pi(\rho, a_1)$ $B^0 \to J/\psi\, K^{*0}$
Control sample $c\bar{c}K^{\pm}$, $J/\psi\, K^{*\pm}$	$B^+ \to J/\psi\, K^+$ $B^+ \to \psi(2S) K^+$ $B^+ \to J/\psi\, K^{*+}$

$c\bar{c}K_S$ sample



7796 events, purity 87–96%

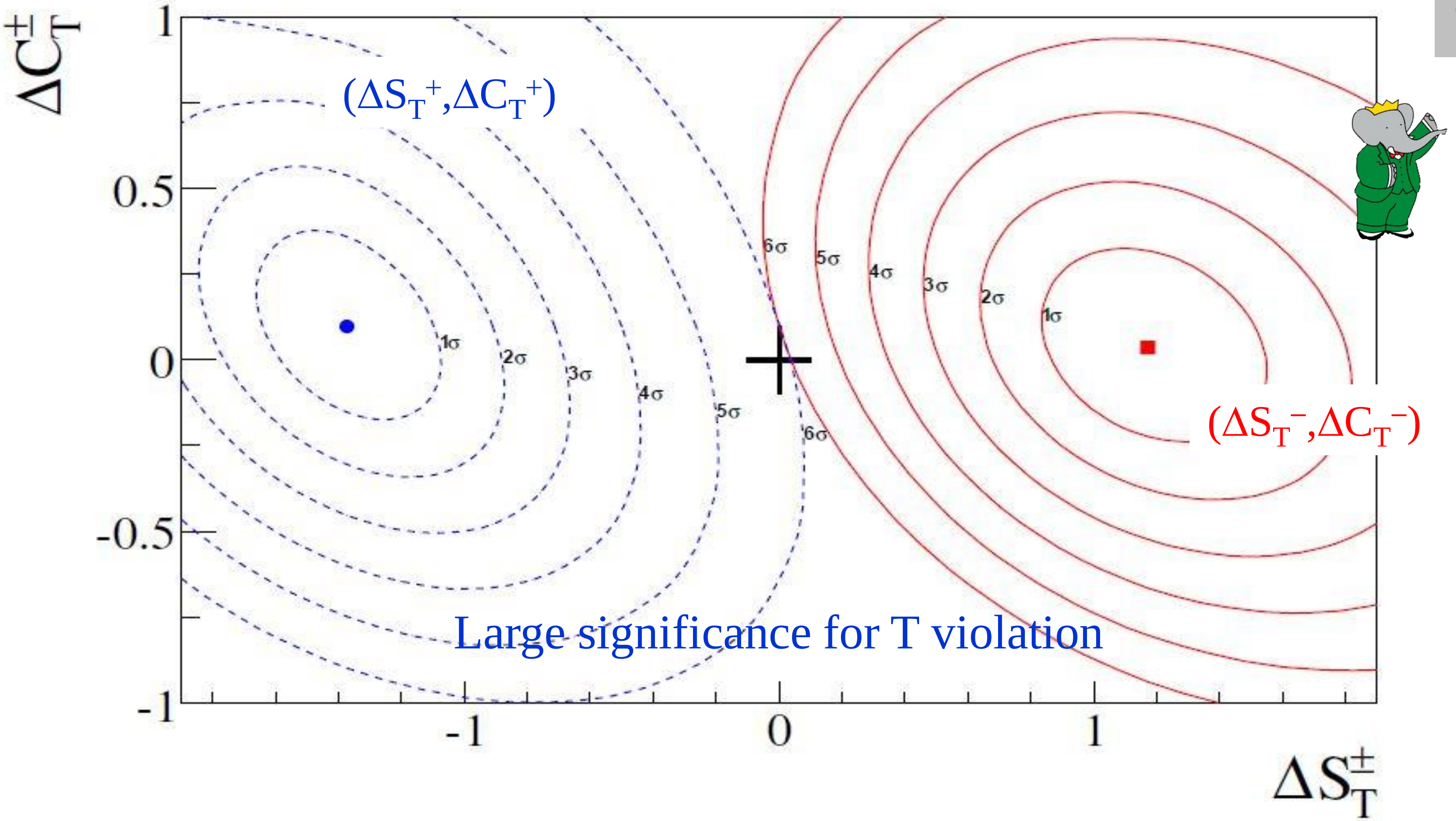


5813 events, purity ≈ 56%

$J/\psi K_S$ sample

Results

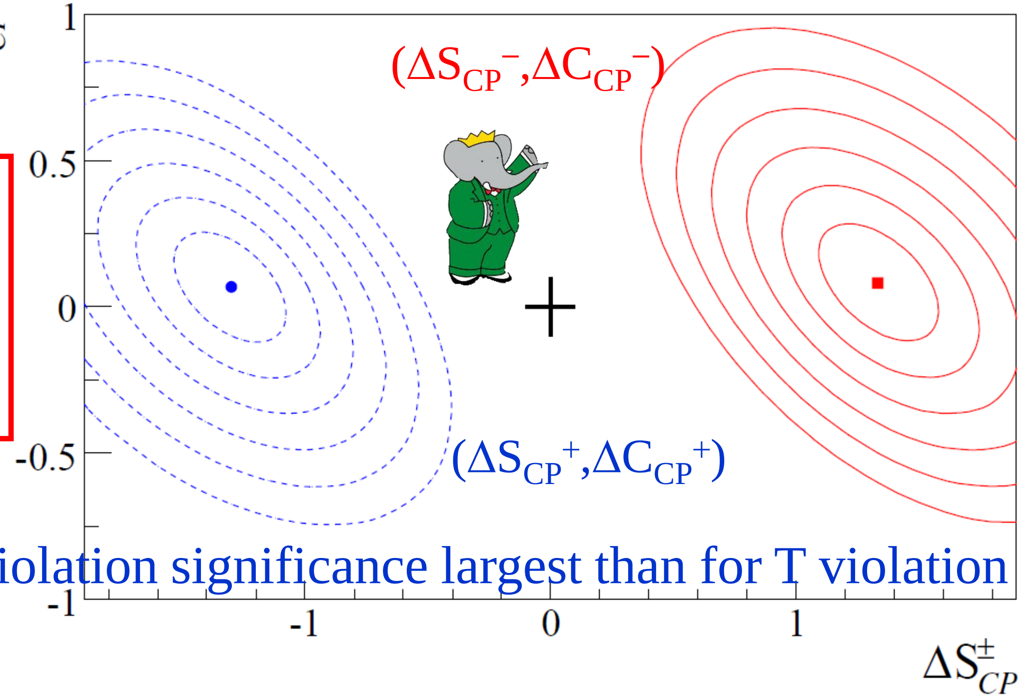
$\Delta S_T^+ = S^-_{\ell^-,K^0_L} - S^+_{\ell^+,K^0_S}$	$-1.37 \pm 0.14 \pm 0.06$	$-2\sin2\beta$
$\Delta S_T^- = S^+_{\ell^-,K^0_L} - S^-_{\ell^+,K^0_S}$	$1.17 \pm 0.18 \pm 0.11$	$+2\sin2\beta$
$\Delta C_T^+ = C^-_{\ell^-,K^0_L} - C^+_{\ell^+,K^0_S}$	$0.10 \pm 0.14 \pm 0.08$	0
$\Delta C_T^- = C^+_{\ell^-,K^0_L} - C^-_{\ell^+,K^0_S}$	$0.04 \pm 0.14 \pm 0.08$	0
		expectation from canonical *CP*



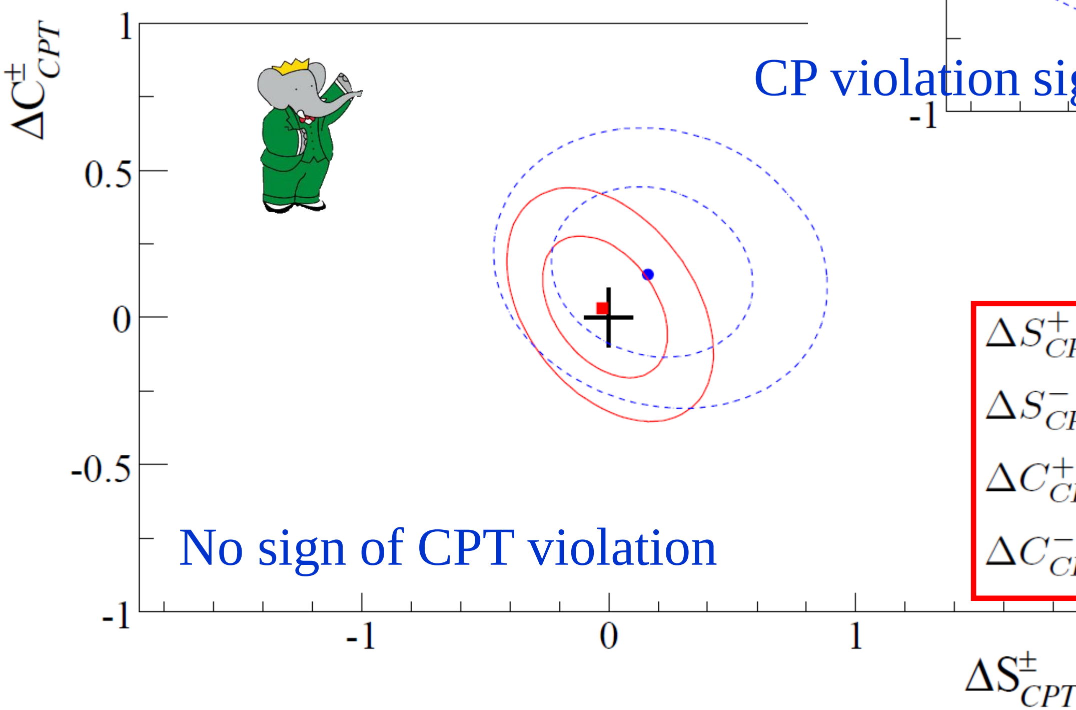
Results

CP-violating parameters

ΔS^{+}_{CP}	$= S^{+}_{\ell-,K^0_S} - S^{+}_{\ell+,K^0_S}$	$-1.30 \pm 0.11 \pm 0.07$
ΔS^{-}_{CP}	$= S^{-}_{\ell-,K^0_S} - S^{-}_{\ell+,K^0_S}$	$1.33 \pm 0.12 \pm 0.06$
ΔC^{+}_{CP}	$= C^{+}_{\ell-,K^0_S} - C^{+}_{\ell+,K^0_S}$	$0.07 \pm 0.09 \pm 0.03$
ΔC^{-}_{CP}	$= C^{-}_{\ell-,K^0_S} - C^{-}_{\ell+,K^0_S}$	$0.08 \pm 0.10 \pm 0.04$



CP violation significance largest than for T violation



No sign of CPT violation

CPT-violating parameters

ΔS^{+}_{CPT}	$= S^{-}_{\ell+,K^0_L} - S^{+}_{\ell+,K^0_S}$	$0.16 \pm 0.21 \pm 0.09$
ΔS^{-}_{CPT}	$= S^{+}_{\ell+,K^0_L} - S^{-}_{\ell+,K^0_S}$	$-0.03 \pm 0.13 \pm 0.06$
ΔC^{+}_{CPT}	$= C^{-}_{\ell+,K^0_L} - C^{+}_{\ell+,K^0_S}$	$0.14 \pm 0.15 \pm 0.07$
ΔC^{-}_{CPT}	$= C^{+}_{\ell+,K^0_L} - C^{-}_{\ell+,K^0_S}$	$0.03 \pm 0.12 \pm 0.08$

Observed T violation as due to compensate CP violation

Significance of T violation

T invariance
$\Delta S_T^+ = 0$
$\Delta S_T^- = 0$
$\Delta S_{CP}^+ = \Delta S_{CPT}^+$
$\Delta S_{CP}^- = \Delta S_{CPT}^-$
$\Delta C_T^+ = 0$
$\Delta C_T^- = 0$
$\Delta C_{CP}^+ = \Delta C_{CPT}^+$
$\Delta C_{CP}^- = \Delta C_{CPT}^-$

1. We obtain the likelihood value of the fit to S, C for the 8 independent samples (Standard Fit).
2. We repeat the fit, reassembling the parameters for T-conjugated processes, to forbid T violation.
3. Significance of T violation evaluated from the difference of the likelihood values.
4. Raw asymmetries and fit projections can be now plotted in the standard way.

$$\Delta\chi^2 = -2(\ln L_{No\_T\_Violation} - \ln L)$$

$$\Delta\nu = 8$$

5. CP, and CPT significance is evaluated similarly.
6. Using Gaussian approximation, we evaluate the change of likelihood in 1σ systematic variation.

$$m_j^2 = -2[\ln L(q_j, o_j) - \ln L(p_0)] / s_{stat,j}^2$$

7. We take the max{m_j^2} and we devide our significace (s^2) by (1+ max{m_j^2})

Asymmetries

- We build an asymmetry for these four reference transitions:

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

- For the first reference:

$$A_T(\Delta t) \equiv \frac{H^-_{l^-,K_L}(\Delta t) - H^+_{K_S,l^+}(\Delta t)}{H^-_{l^-,K_L}(\Delta t) + H^+_{K_S,l^+}(\Delta t)} \approx \boxed{\frac{\Delta C_T^+}{2}\cos\Delta m\Delta t + \frac{\Delta S_T^+}{2}\sin\Delta m\Delta t}$$

Assuming no experimental effects

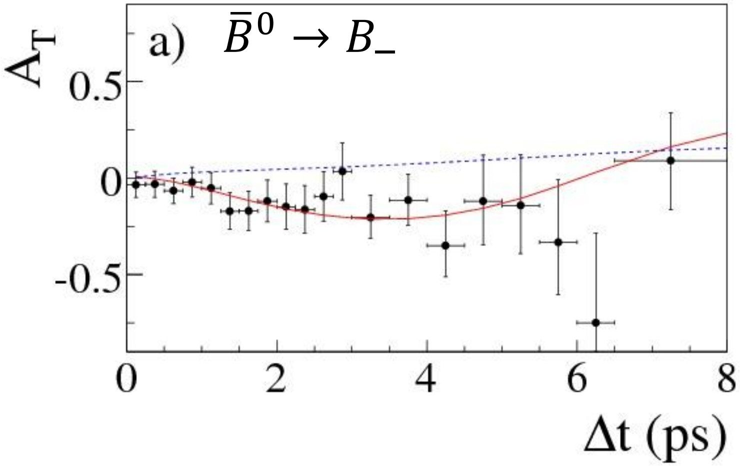
$H^{\pm}_{\alpha,\beta}(\Delta t)$ is the intensity for each sample with $\Delta t>0$ and all experimental effects.

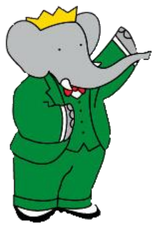
T raw asymmetries + significance

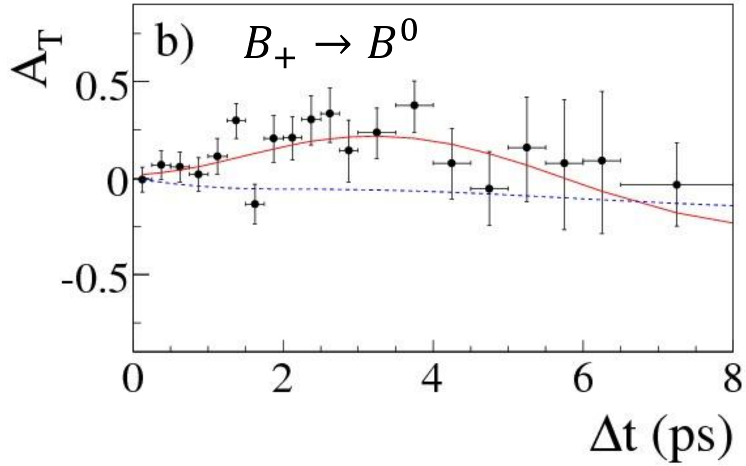
Significance test

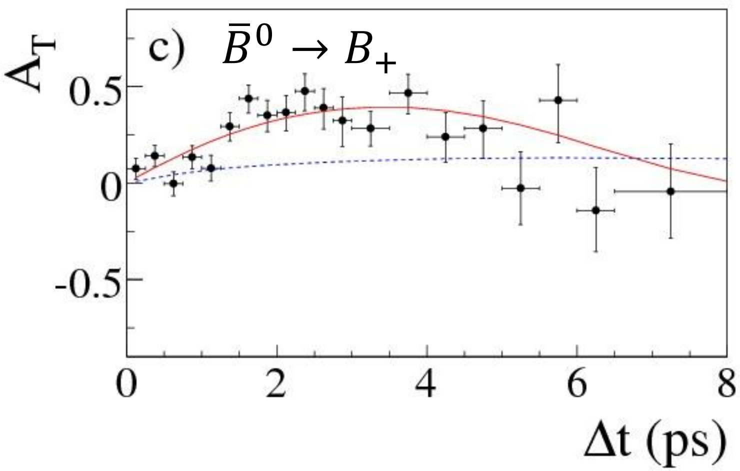
$$s^2_{NoT} = 226 \quad \Rightarrow \quad 14\sigma$$
$$s^2_{NoCP} = 307 \quad \Rightarrow \quad 16.6\sigma$$
$$s^2_{NoCPT} = 5 \quad \Rightarrow \quad 0.33\sigma$$

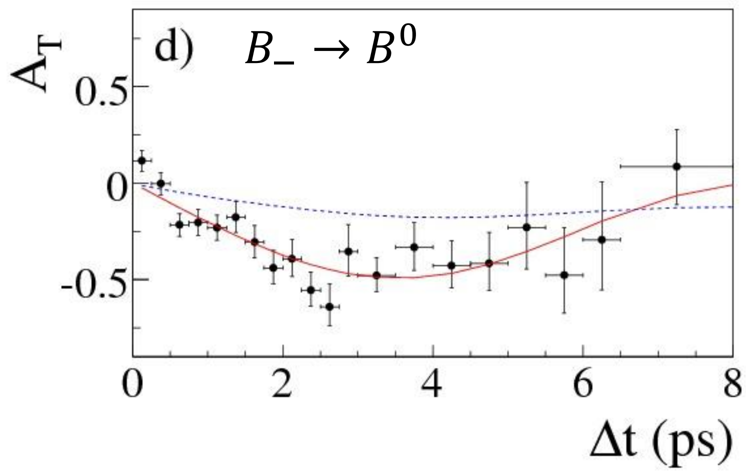
Stat. and Syst. $\Delta\nu$=8











Conclusions

- We have measured T-violating parameters in the time evolution of neutral-B mesons.
- These parameters have been measured:
  - Directly: without exp. connection to CP and CPT.
  - Genuinely: exchanging *in-states* and *out-states*.
- We observe a large deviation of T invariance at 14σ level.
- Our result is consistent with CP-violating measurements assuming CPT invariance.
- This constitutes the first direct observation of Time Reversal Violation in the evolution of the B mesons.

$B \rightarrow D^{(*)} \tau \nu$

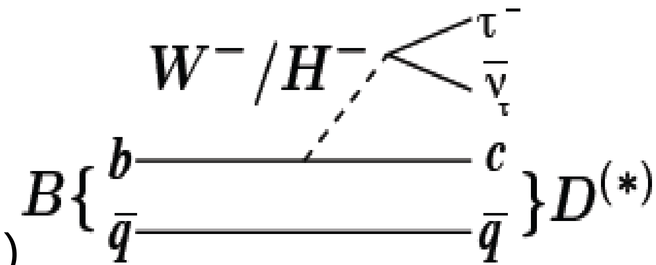
J. P. Lees et al. Phys. Rev. Lett. 109, 101802 (2012)

Motivation

- Observables: R(D) and R(D*) ratios

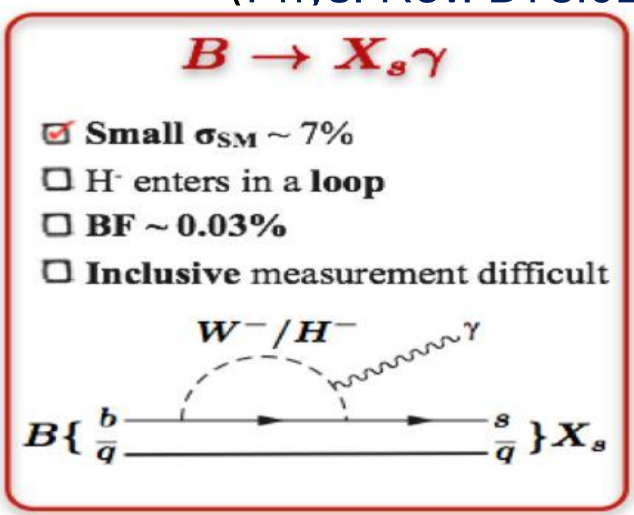
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\tau)}$$

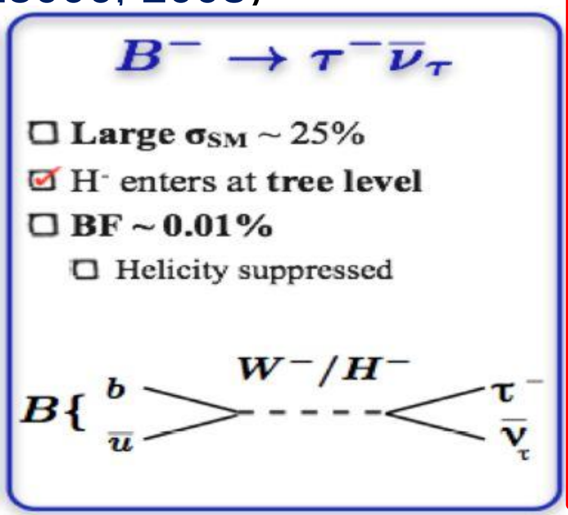
  - can be enhanced by the charged-Higgs (tanβ/m_H)
  - several syst. and theo. uncertainties cancel out

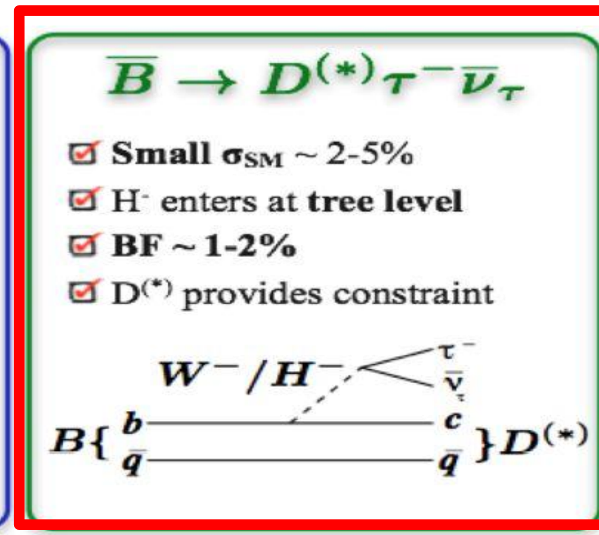


- Involve form factors which can be measured in $B \to D^{(*)} e/\mu\nu$ decays

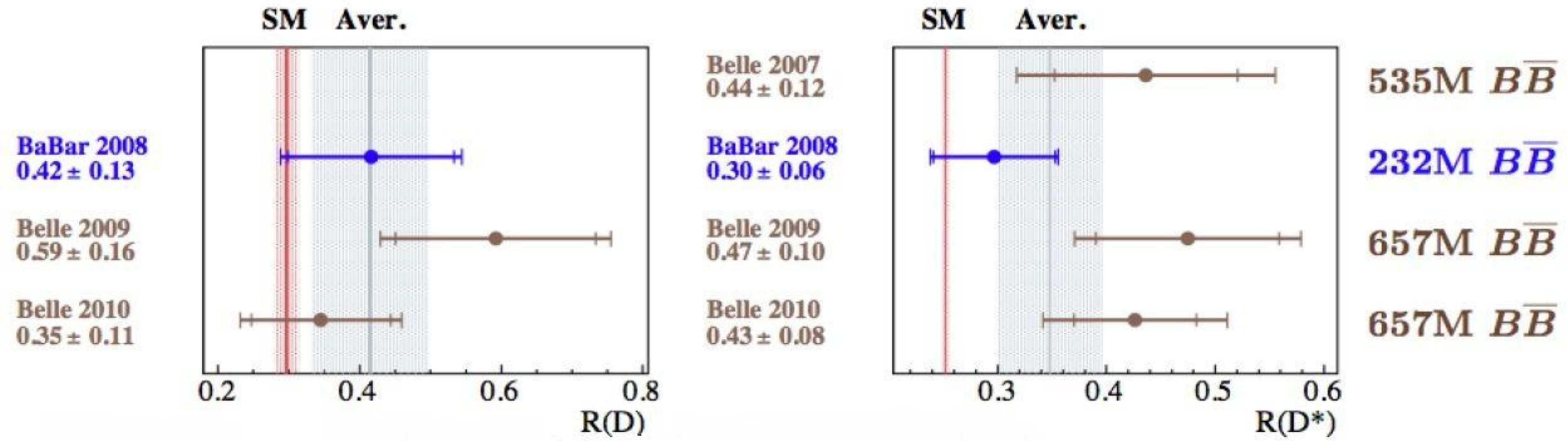
- Sensitive to charged-Higgs effects. τ hadronic decays can give interesting information on charged Higgs couplings (Phys. Rev. D78:015006, 2008)







Previous situation



- Consistent slightly excess over the SM prediction.
- Large uncertainties.
- Update the BaBar 2008 measurement to the full dataset

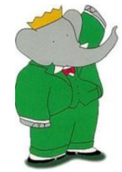
SM predictions:

$R(D)_{SM} = 0.297 \pm 0.017$
$R(D^*)_{SM} = 0.252 \pm 0.003$

[S. Fajfer, J. F. Kamenik, and I. Nisandzic, arXiv:1203.2654; J. F. Kamenik and F. Mescia, Phys. Rev. D 78, 014003, (2008)]

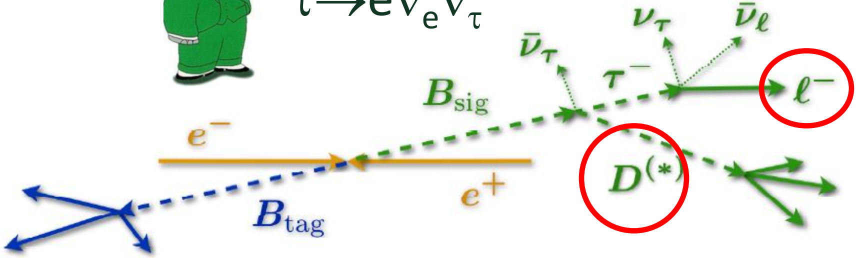
Experimental method

- BaBar: Btag fully reconstructed into hadrons (Improved efficiencies (lepton and Btag))
  Effciency: 0.21%→0.40% **2xhigher**
- Bsig: $D^{(*)}$ and lepton (μ, e)
  - 4 signal samples: $(D^0, D^+, D^{*0}, D^{*+})\ell\nu$ (to extract $B \to D^{(*)}\tau\nu$)
  - 4 control samples: $(D^0, D^+, D^{*0}, D^{*+})\pi^0\ell\nu$ (to derive $D^{**}\ell\nu$ bkg)



$\tau \to \mu \nu_\mu \nu_\tau$

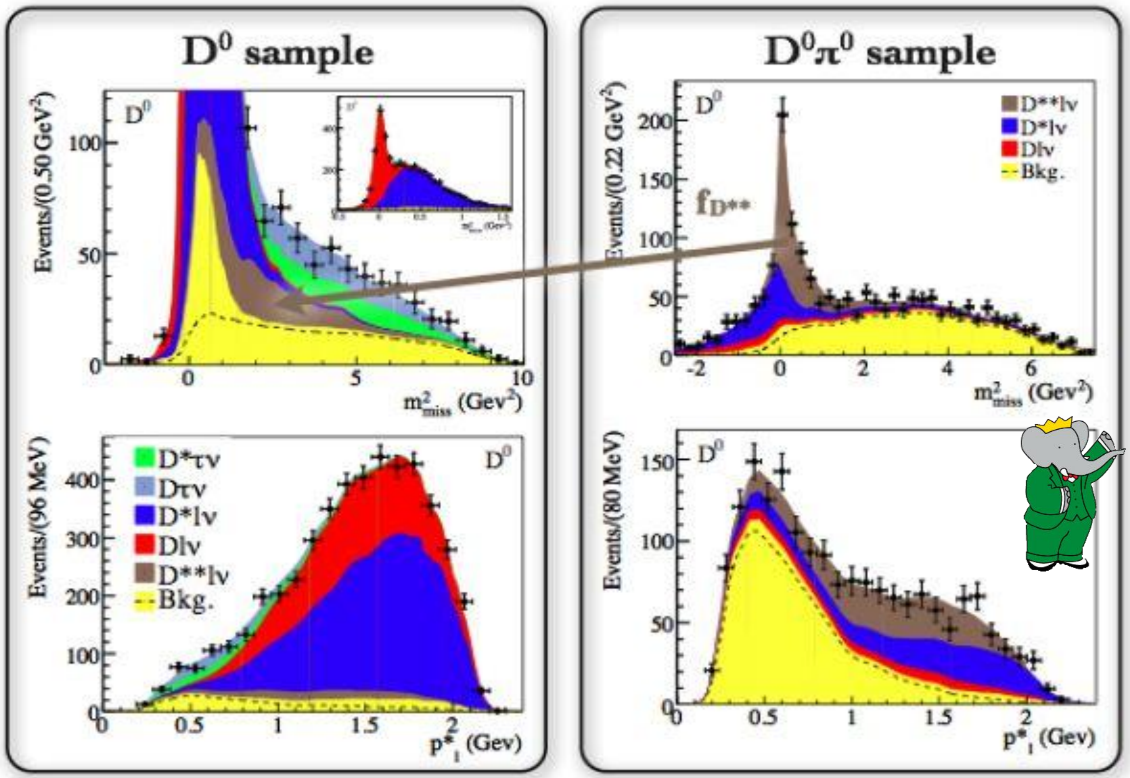
$\tau \to e \nu_e \nu_\tau$



- 2D unbinned ML fit m_{miss}^2-p^*_ℓ
  Yields for:
  $B \to (D^0, D^+, D^{*0}, D^{*+})\tau\nu$
  $B \to (D^0, D^+, D^{*0}, D^{*+})\ell\nu$
  $B \to (D^0, D^+, D^{*0}, D^{*+})\pi^0\ell\nu$

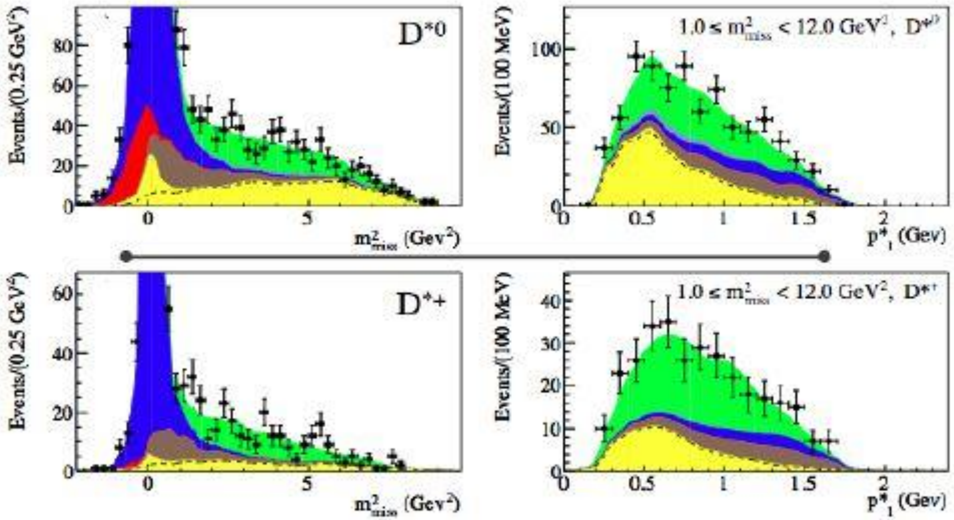
$$m_{miss}^2 = (p_{e+e-} - p_{Btag} - p_{D(*)} - p_\ell)^2$$

MC sample



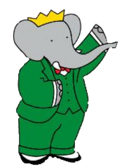
Fit results

D^*

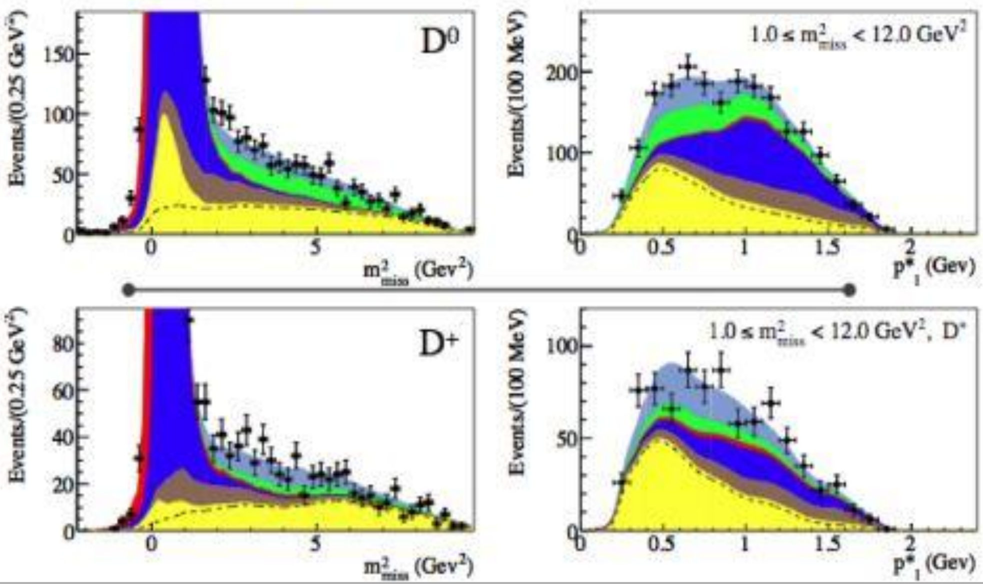


Statistical only

	$D^{*0}\tau\nu$	$D^{*+}\tau\nu$	$D^*\tau\nu$
N_{sig}	639±62	245±27	888±63
Sig.	11.3 σ	11.6 σ	16.4 σ
R(D*)	0.322±0.032	0.355±0.039	0.332±0.024



D



First observation

	$D^0\tau\nu$	$D^+\tau\nu$	$D\tau\nu$
N_{sig}	314±60	177±31	489±63
Sig.	5.5 σ	6.1 σ	8.4 σ
R(D)	0.429±0.082	0.469±0.084	0.440±0.058

Fit results

Decay	$N_{\rm sig}$	$N_{\rm norm}$	$\mathcal{R}(D^{(*)})$	$\mathcal{B}(B \to D^{(*)}\tau\nu)$ (%)	$\Sigma_{\rm tot}$
$B^- \to D^0\tau^-\overline{\nu}_\tau$	314 ± 60	1995 ± 55	$0.429 \pm 0.082 \pm 0.052$	$0.99 \pm 0.19 \pm 0.13$	4.7
$B^- \to D^{*0}\tau^-\overline{\nu}_\tau$	639 ± 62	8766 ± 104	$0.322 \pm 0.032 \pm 0.021$	$1.71 \pm 0.17 \pm 0.13$	9.6
$\overline{B}^0 \to D^+\tau^-\overline{\nu}_\tau$	177 ± 31	986 ± 35	$0.469 \pm 0.084 \pm 0.052$	$1.01 \pm 0.18 \pm 0.12$	5.3
$\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$	245 ± 27	3186 ± 61	$0.355 \pm 0.039 \pm 0.020$	$1.74 \pm 0.19 \pm 0.12$	10.5
$\overline{B} \to D\tau^-\overline{\nu}_\tau$	489 ± 63	2981 ± 65	$0.440 \pm 0.058 \pm 0.042$	$1.02 \pm 0.13 \pm 0.10$	6.8
$\overline{B} \to D^*\tau^-\overline{\nu}_\tau$	888 ± 63	11953 ± 122	$0.332 \pm 0.024 \pm 0.017$	$1.76 \pm 0.13 \pm 0.11$	13.4

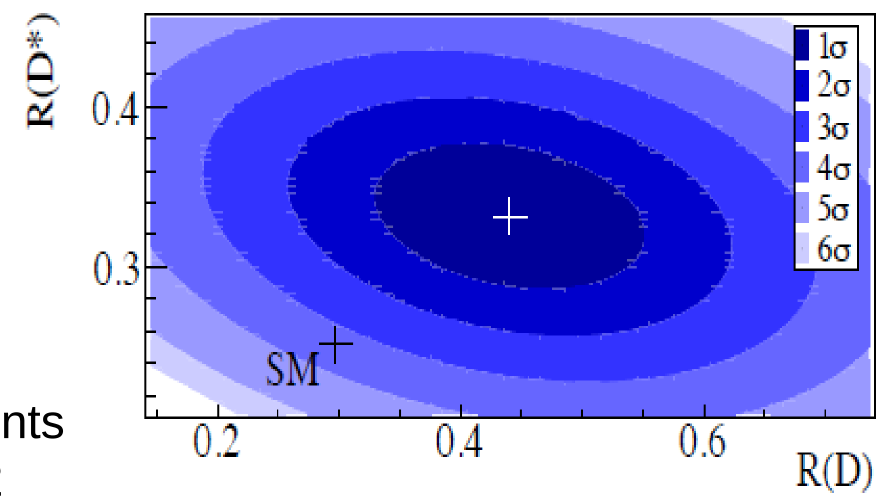
- **Comparison with the SM:**

R(D) = 0.440 ± 0.071
SM = 0.297(17)

2.0σ

R(D*) = 0.332 ± 0. 029
SM = 0.252(3)

2.7σ



The combination of the two measurements (-0.27 correlation) yields χ^2/NDF=14.6/2 (i.e. Prob. = 6.9 x10^{-4})→ The SM prediction is excluded at 3.4 σ

2HDM Scan

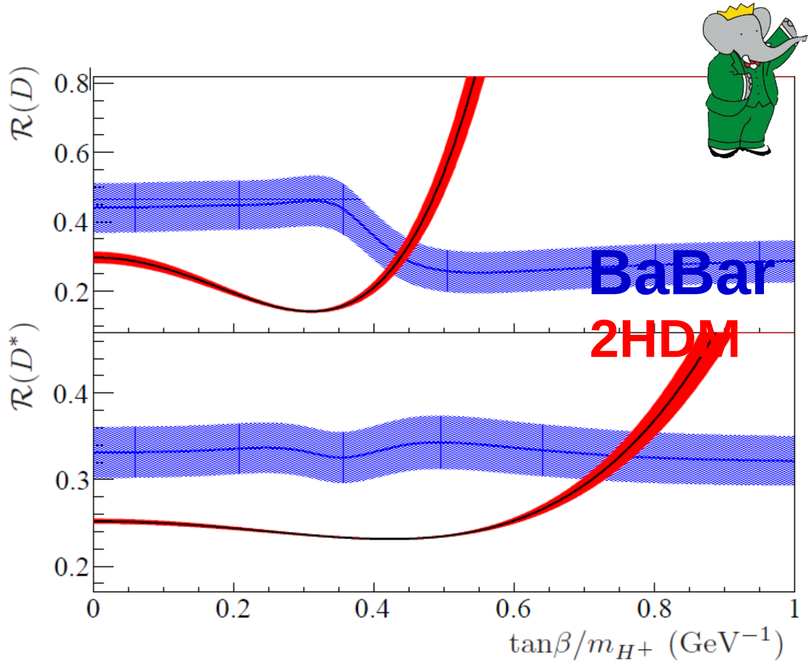
- Interpretation Beyond the Standard Model:

  A charged Higgs (2HDM type II) could enhance or decrease the R(D) and R(D*) ratios depending on tanβ/mH

$$R(D^{(*)}) = R(D^{(*)})_{\mathrm{SM}} + A^{(*)}\frac{\tan^2\beta}{m_{H+}^2} + B^{(*)}\frac{\tan^4\beta}{m_{H+}^4}$$

Effect of 2DHM (accounting for difference in efficiency):

$\tan\beta/m_H = 0.44 \pm 0.02$ for R(D)
$\tan\beta/m_H = 0.75 \pm 0.04$ for R(D*)



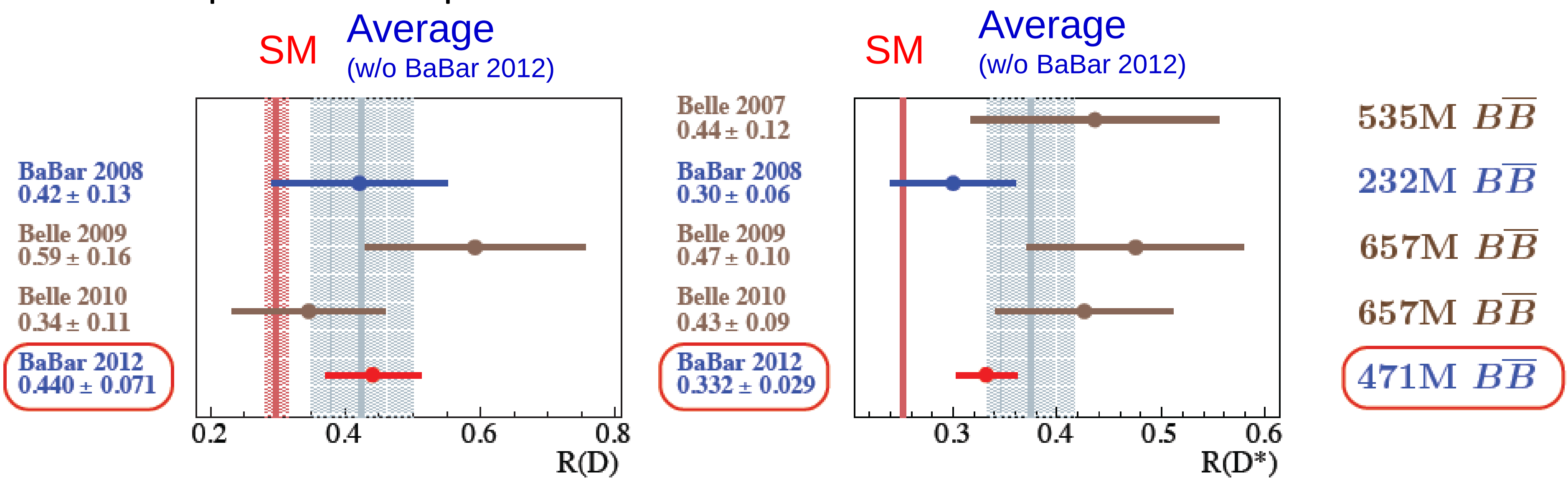
The combination of R(D) and R(D*) excludes the Type II 2HDM in the full tanβ-m_H parameter space with a probability of >99.8% (M_H>10GeV)

Conclusions

This is the first measurement of $D^{(*)} \to \tau\nu$ with the full BaBar data set

- ➢ **Larger improvement than $\sqrt{L}$**

- Comparison with previous measurements:



Scorecard:

- First observation of $D \to \tau\nu$ with 6.8 σ
- 3.4 σ excess over the SM prediction
- Not compatible with Type II 2HDM model

General conclusions

- Despite BaBar stopped taking data at 2008, it is producing publications.
- Not only because of repeating the old analysis with the whole data sample.
- Great improvement in the analysis tools and the machine performance.
- New ideas are coming to analize the data.
- Collaboration with theorist
- · M. C. Bañuls and J. Bernabeu, Phys. Lett. B 464, 117 (1999); Nucl. Phys. B 590, 19 (2000).