Rencontres de Physique de la Vallée d'Aoste

La Thuile, Aosta Valley, Italy

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Recent Highlights from BABAR

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On behalf of the BABAR collaboration

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Outline

Introduction

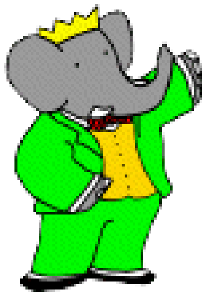
Time dependent studies:

- First direct observation of Time Reversal Violation - **PRL 109, 211801 (2012)**
- CP Violation in $B^0 \to D^{*+}D^{*-}$ decays - **PRD 86, 112006 (2012)**
- Search for CP Violation in $B^0\bar{B}^0$ mixing - **Preliminary.**

Time-independent studies:

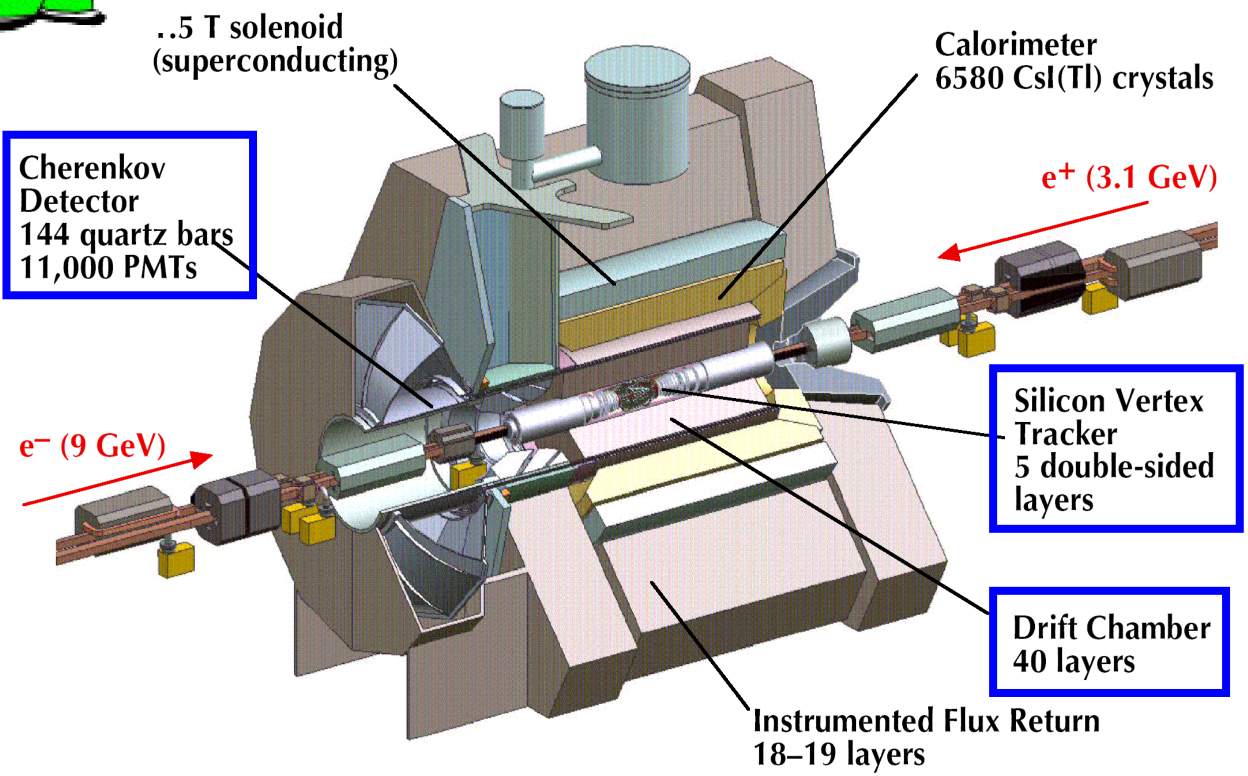
- Search for $B \to K^{(*)} \nu \bar{\nu}$ decay - **New, preliminary.**
- Search for $B \to \pi/\eta\, \ell^+ \ell^-$ decay - **New, preliminary.**
- Study of $B \to D^{(*)} \tau \nu$ decay - **PRL 109, 101802 (2012)** & **New preliminary extra studies.**

BABAR Experiment



$e^+e^- \rightarrow \Upsilon(4s) \rightarrow B\bar{B}$ $B^0\bar{B}^0$ (coherent state) , or B^+B^- with $\beta\gamma$~0.5

BABAR at PEPII, SLAC, USA From 1999 to 2008



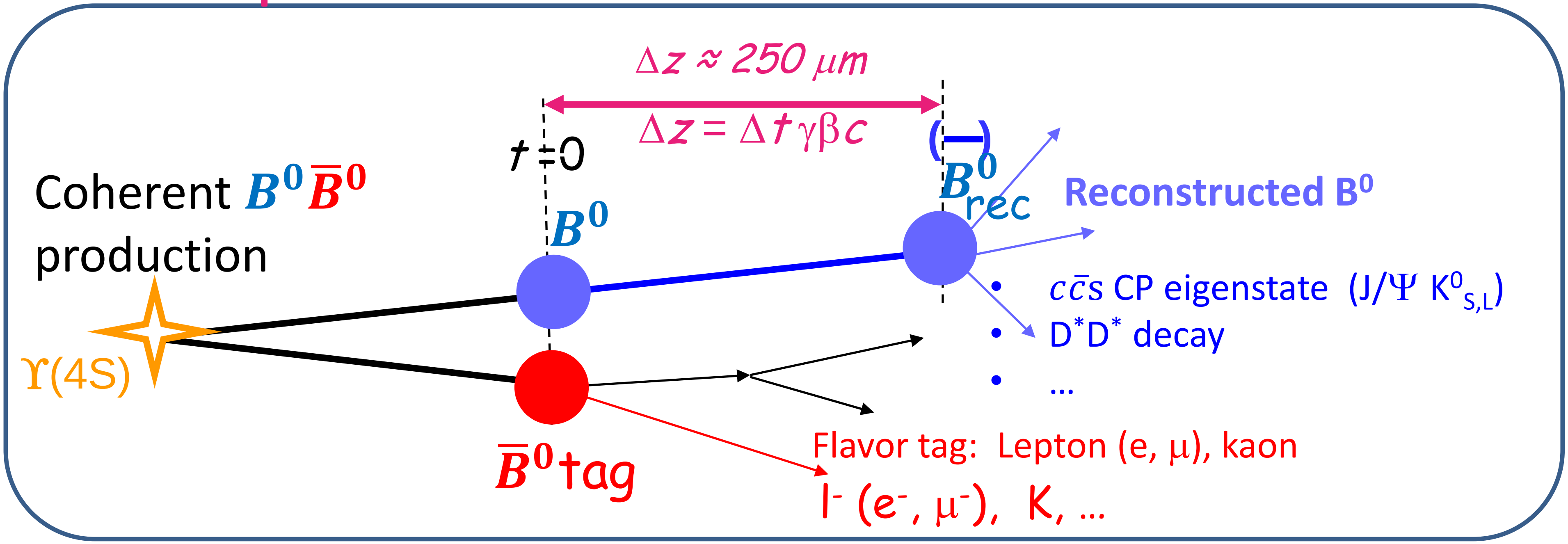
$\int$ Ldt ~ 433 fb^{-1}@Υ(4S)

$\int$ Ldt ~ 550 fb^{-1} total
(Off resonance,Υ(ns))

~ 470 *millions* $B\bar{B}$, full dataset used in analyses shown here

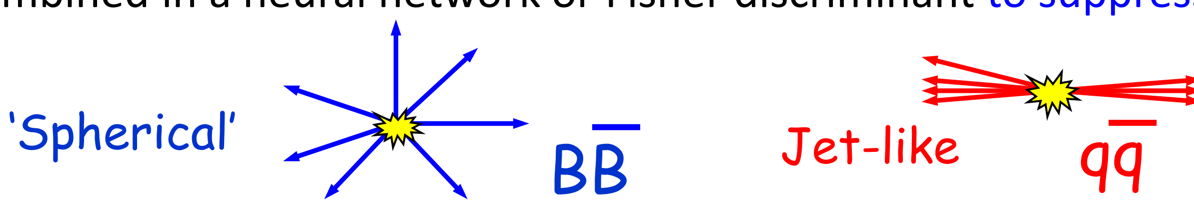
Analyses methods

Time dependent measurement



- Kinematical identification with
  - $m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$ (Beam energy substituted mass)
  - $\Delta E = E^*_B - E^*_{beam}$ (Energy difference)

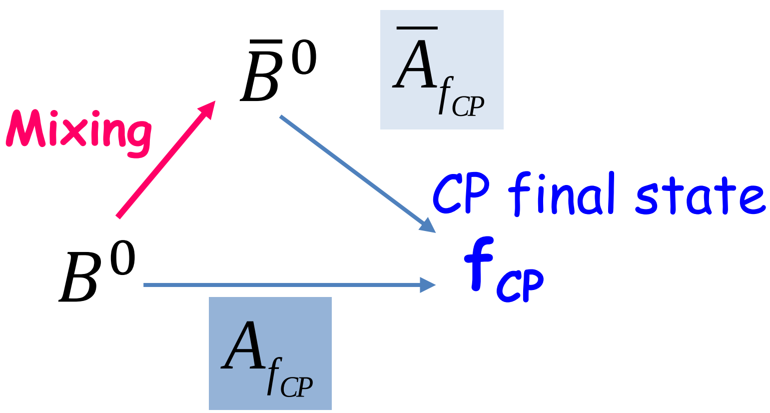
- Event-shape variables combined in a neural network or Fisher discriminant to suppress jet-like continuum events

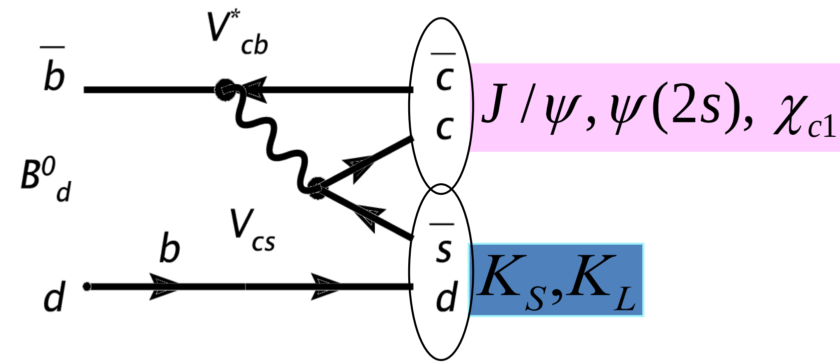


Direct observation of time reversal violation (1)

PRL 109, 211801 (2012)

First direct observation of Time Reversal Violation, in any system.



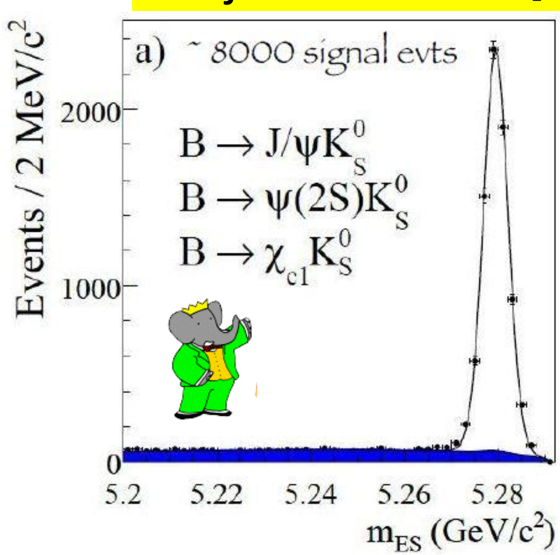


If CPT holds : T violation since CP violation observed in the interference between decay with/without B^0 mixing.

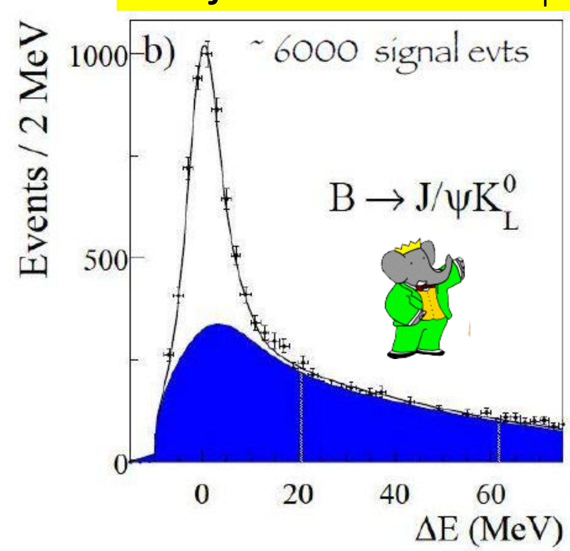
Never measured before.

First direct observation of T violation ! with also CP and CPT measurements.

Projects CP odd B_-



Projects CP even B_+

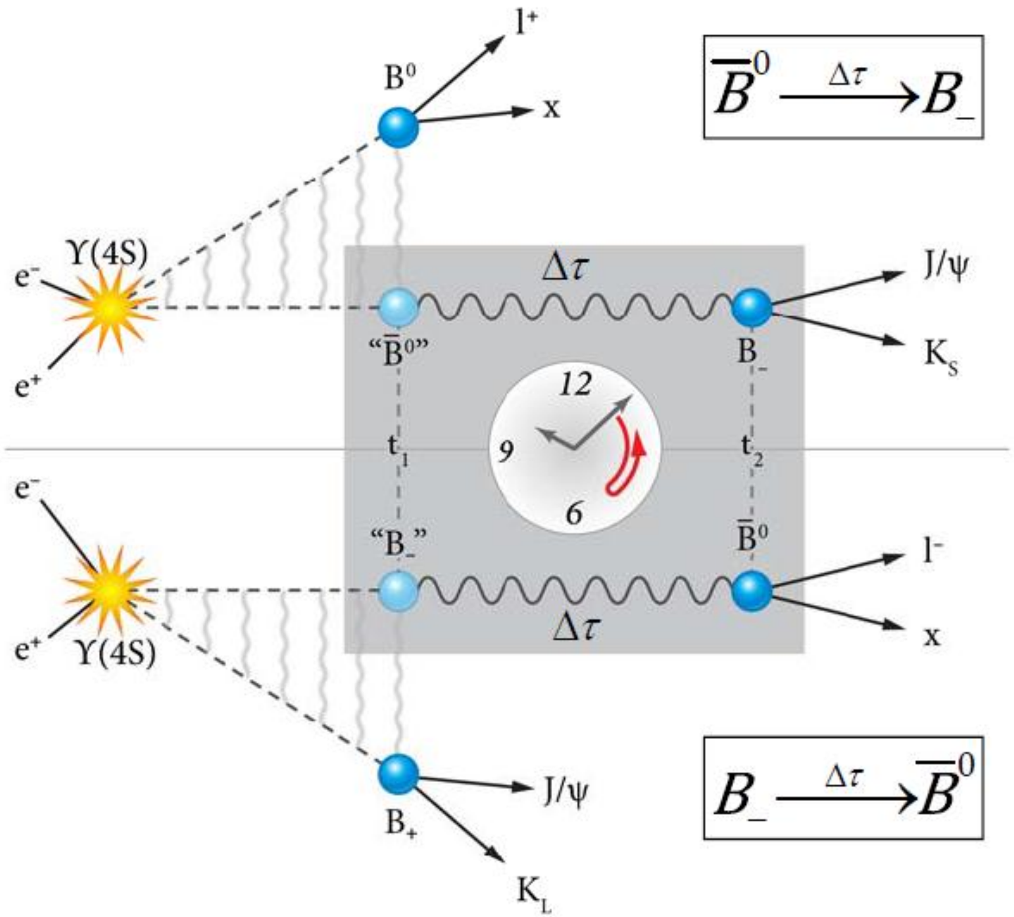


Direct observation of time reversal violation (2)

EPR entanglement from Υ(4*S*)

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

Semileptonic decay projects:
B^0 *to* l^+, $\bar{B}^0$ *to* l^-
$J/\Psi K_L$ *projects CP even* B_+
$J/\Psi K_S$ *projects CP odd* B_-



4 independent T comparisons (as 4 CP and 4 CPT comparisons)

T implies comparison of :

1. Opposite Δτ sign
   $\Delta\tau = t_{CP} - t_{flav}$
2. Different CP reco states ($J/\Psi K_S$ vs. $J/\Psi K_L$).
3. Opposite flavor tag states (B^0 vs $\bar{B}^0$).

Direct observation of time reversal violation (3)

Signal model **Assumes $\Delta\Gamma_d$=0 but does NOT assume CPT**

(for perfect time reconstruction: corrections needed to include time resolution)

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

$\mathcal{H}$ → Heavyside step function

8 sets of S, C parameters : 2 $\Delta\tau$ ($\Delta\tau>0$, $\Delta\tau<0$) × 2 flavor ($B^0, \bar{B}^0$) × 2 CP (K_S, K_L)

$\pm$ — α — β

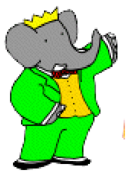
Extracted from simultaneous ML fit to

B^0, $\bar{B}^0$, $c\bar{c}K_S$, and $J/\psi K_L$ for $\Delta\tau>0$ and $\Delta\tau<0$ events.

In usual CPV studies, one single set S, C **Assumes $\Delta\Gamma_d$ =0 and CPT**

SM and CKM formalism: S ~ sin 2β and C ~ 0

Direct observation of time reversal violation (4)



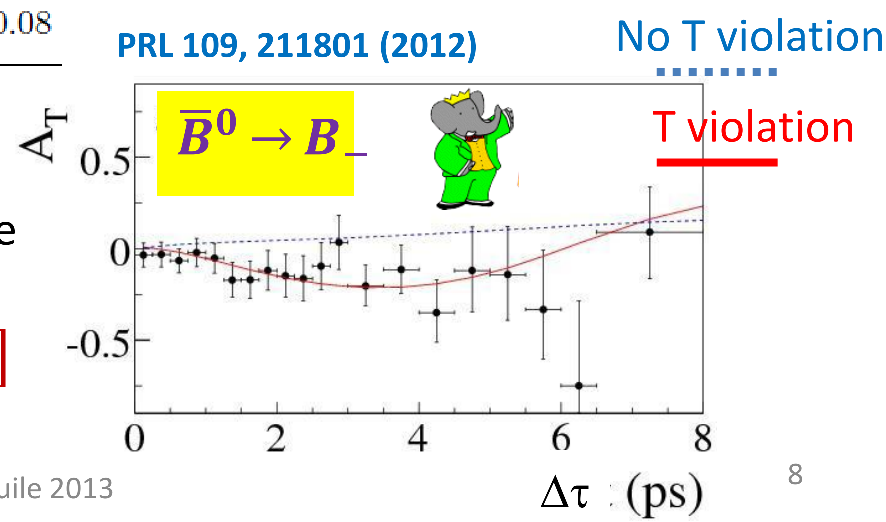
PRL 109, 211801 (2012)

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

T and CP violation parameters compensate each other to result in no CPT violation

CPT violation parameters consistent with 0

PRL 109, 211801 (2012)



Illustrative :

One of the 4 independent T violating asymmetrie

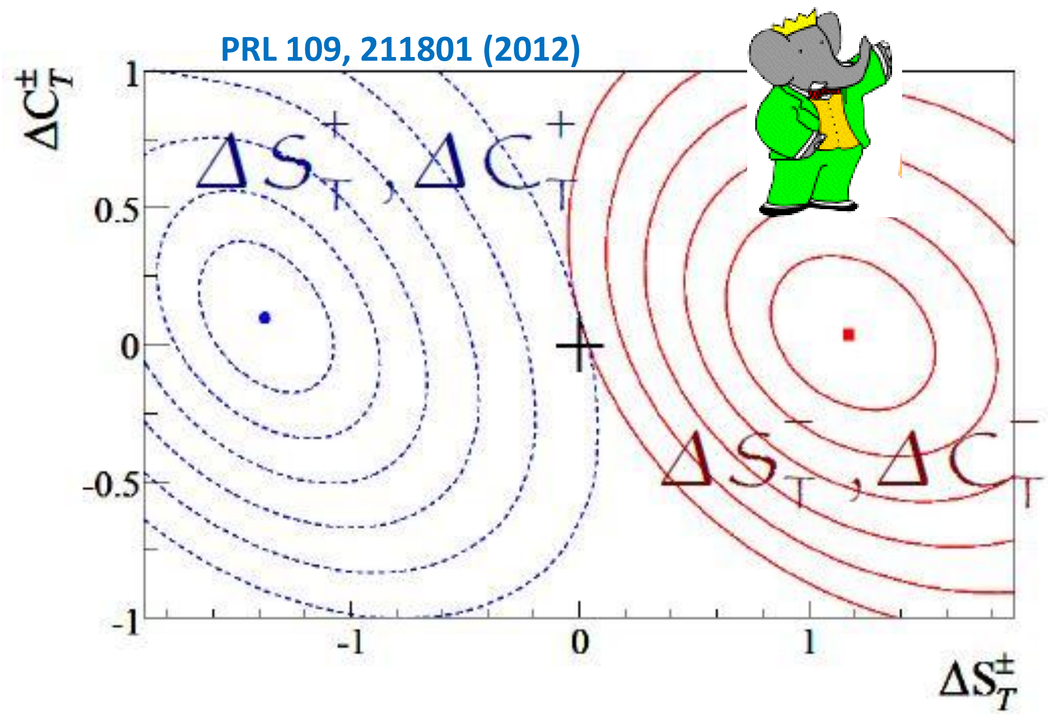
if there was no reco. effects :

$A_T \approx \frac{1}{2}\left[\Delta S_T^{\pm}\sin(\Delta m\,|\Delta\tau|) + \Delta C_T^{\pm}\cos(\Delta m\,|\Delta\tau|)\right]$

Direct observation of time reversal violation (5)

-2 ln ΔL scan with systematics included

PRL 109, 211801 (2012)



First direct observation of T violation in any system! (with 14 σ significance)

due to CP violation in the interference between the decay with/wo B mixing (ΔS ≠0), but not directly in the decay (ΔC consistent with 0).

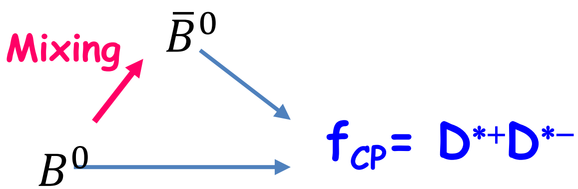
CP violation seen with 16.6 σ significance

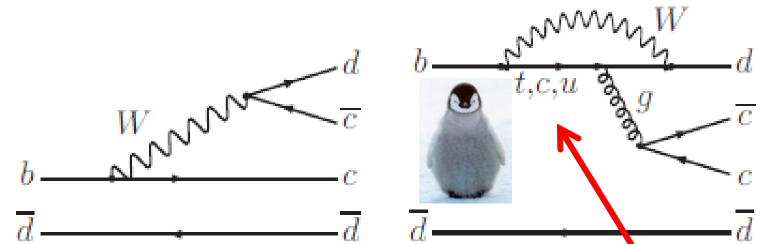
No CPT violation seen: 0.33 σ significance

Time dependent CP asymmetry of partially reconstructed $B^0 \to D^{*+}D^{*-}$ decays (1)

PRD 86, 112006 (2012)

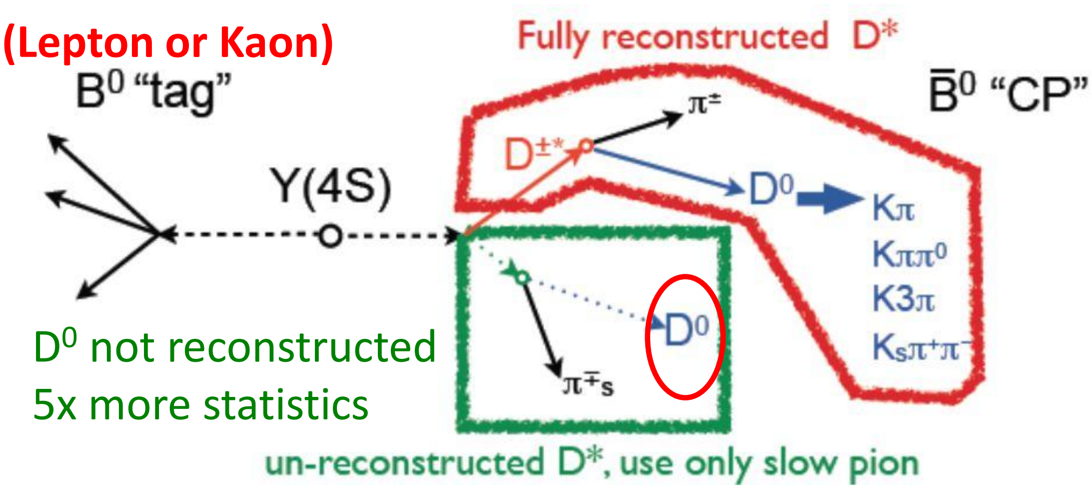
$b \to c\bar{c}d$ transition: neglecting penguins TD asymmetry is a measurement of sin(2β).



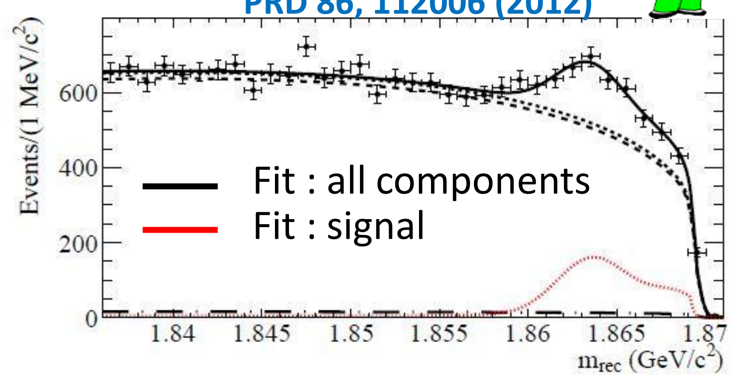


A few % in SM but possible new physics

Need angular analysis to separate CP eigenstates (with fully reco events).
BABAR and Belle full reco. analyses measured CP even component CP parameters S_+ and C_+, and the fraction $R_\perp$ of CP-odd amplitude.
Here with Partial reco. **measure average S and C** related to C_+ and S_+ : **C**=C_+ ; **S**=$S_+(1-2R_\perp)$



Ex : lepton to tag B flavor
PRD 86, 112006 (2012)

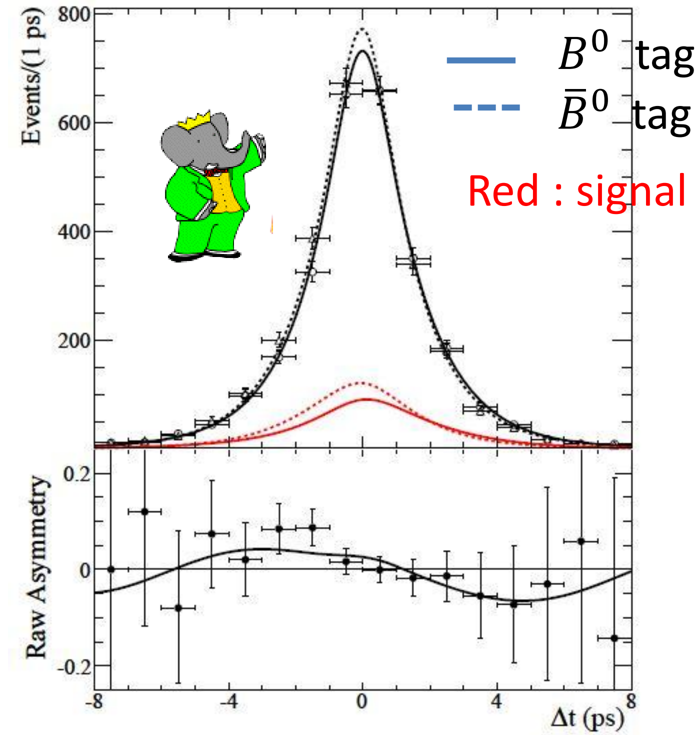


Reco. recoiling D⁰ mass

$B^0 \to D^{*+}D^{*-}$ decays (2)

Ex: kaon to tag B flavor

PRD 86, 112006 (2012)



Fit uses reco. recoiling D^0 mass, Fisher discriminant (event shape), and time. **PRD 86, 112006 (2012)**

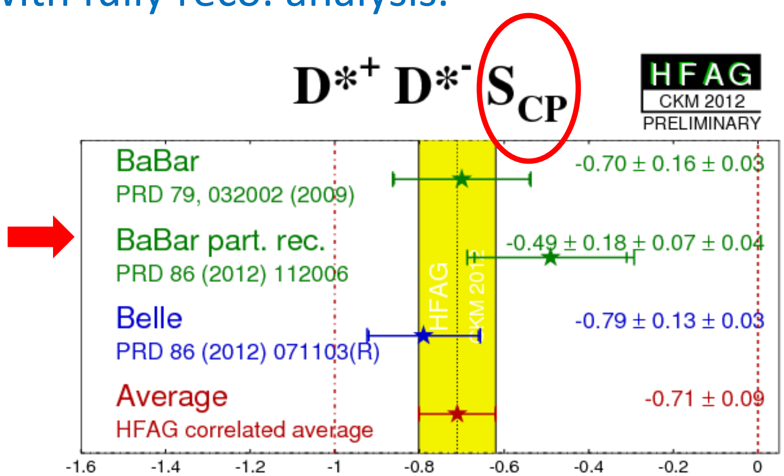
$C = +0.15 \pm 0.09$ (stat) ± 0.04 (syst)
$S = -0.34 \pm 0.12$ (stat) ± 0.05 (syst)

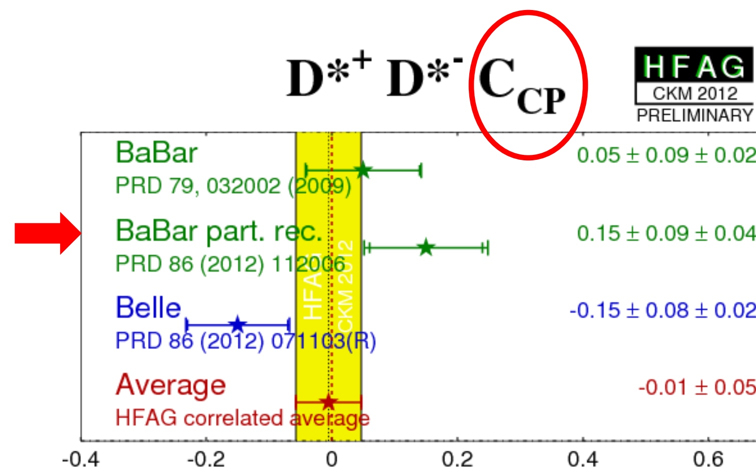
Neglect penguin : $S_+ = -S_-$; $C = C_+$; $S = S_+ (1 - 2R_\perp)$
Use $R_\perp = 0.158 \pm 0.029$ - **BABAR PRD 79, 032002 (2009)**

$C_+ = +0.15 \pm 0.09$ (stat) ± 0.04 (syst)
$S_+ = -0.49 \pm 0.18$ (stat) ± 0.07 (syst) ± 0.04 (from $R_\perp$)

Result consistent with the latest (fully reco) BaBar and Belle results, and with SM predictions.

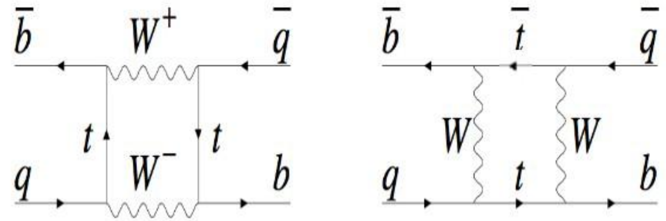
Decreases BABAR uncertainties by ~20% by combining with fully reco. analysis.





Search for CP Violation in $B^0\bar{B}^0$ Mixing using $B^0 \rightarrow D^* \ell \nu$ Partial Reconstruction (1) – New, preliminary.

Assume CPT



q=d for BABAR

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

CP violation in mixing : $P(B^0 \rightarrow \bar{B}^0) \neq P(\bar{B}^0 \rightarrow B^0)$

Or $A_{CP} = \frac{N(B^0B^0)-N(\bar{B}^0\bar{B}^0)}{N(B^0B^0)+N(\bar{B}^0\bar{B}^0)} \neq 0$

$$A_{CP} = \frac{1-\left|\frac{q}{p}\right|^4}{1+\left|\frac{q}{p}\right|^4}$$

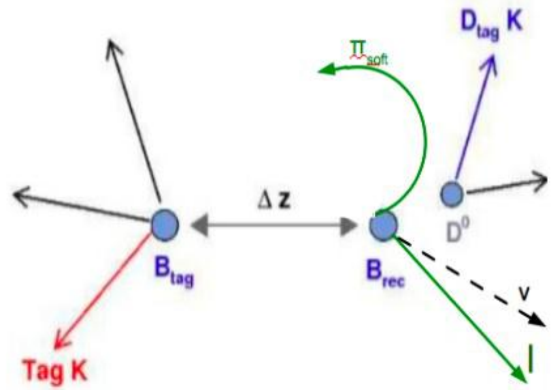
Time independent
$O(10^{-4})$ in SM
Large value indicates new physics

$$A_{CP} \neq 0 \Leftrightarrow \Delta_{CP} = 1 - \left|\frac{q}{p}\right| \neq 0$$

A_{CP} was previously measured with dilepton

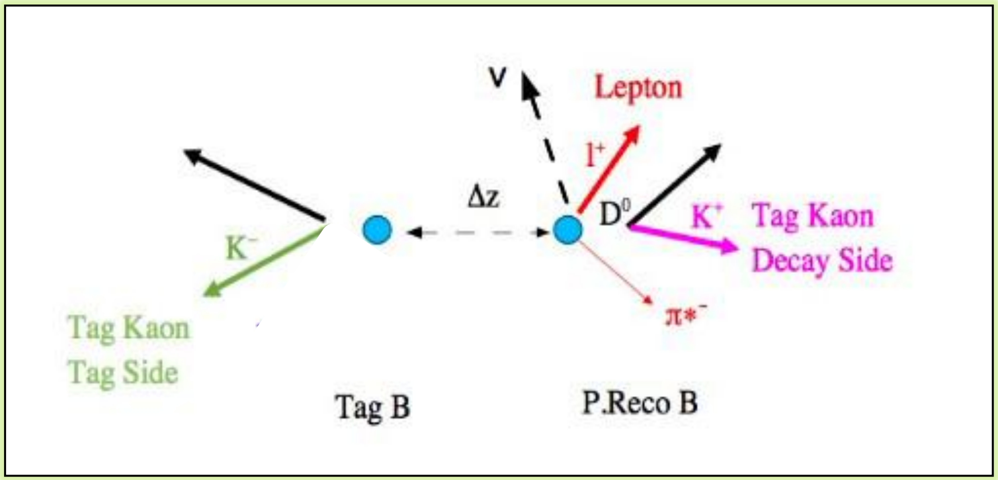
New approach : partial D* reco (lepton, soft pion) and kaon tag

$$A_{CP} = \frac{N(B^0B^0)-N(\overline{B^0}\,\overline{B^0})}{N(B^0B^0)+N(\overline{B^0}\,\overline{B^0})} = \frac{N(\ell^+K^+)-N(\ell^-K^-)}{N(\ell^+K^+)+N(\ell^-K^-)}$$



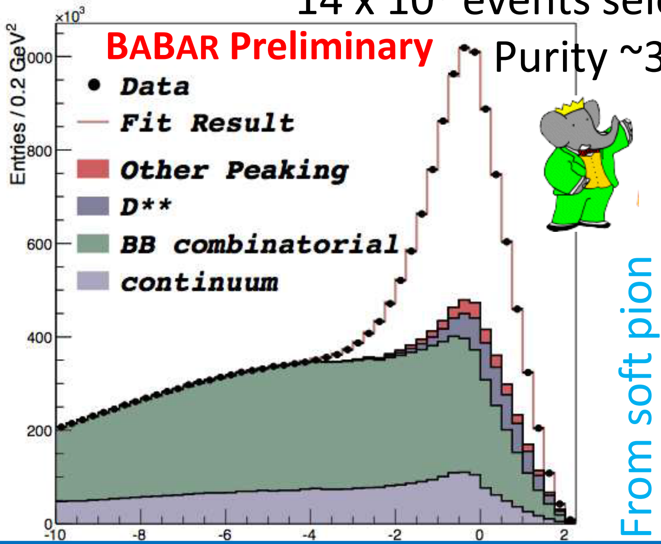
Search for CP Violation in $B^0\bar{B}^0$ Mixing (2)

Selecting Kaon from reco B can mimic B mixing



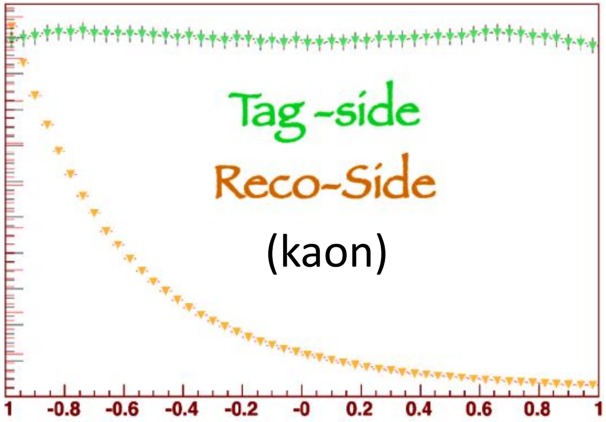
14 x 10^6 events selected

Purity ~30%



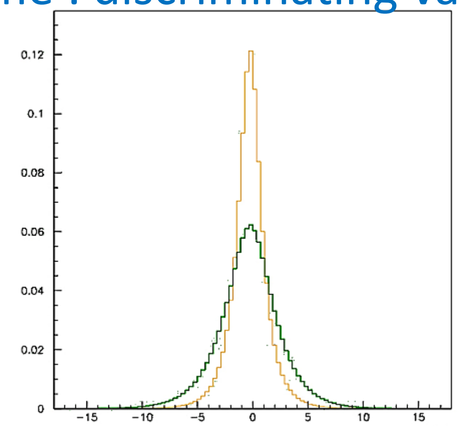
$$\mathcal{M}_\nu{}^2 \equiv (E_{\text{beam}} - E_{D^*} - E_\ell)^2 - (\vec{p}_{D^*} + \vec{p}_\ell)^2$$

4D binned fit to : M_ν^2, $\cos\theta_{lK}$, Δz, p_K



$\cos\theta_{lK}$

Time : discriminating variable



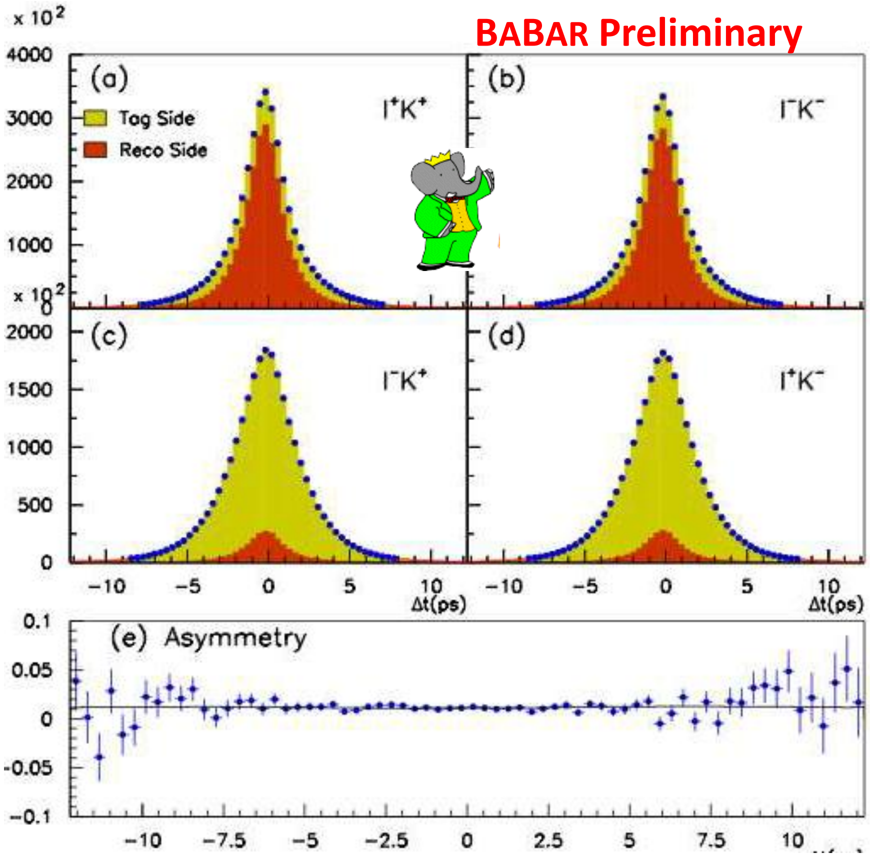
Δt (ps) $\propto \Delta z$

CP violation in mixing : time independent.

Time analysis constrains nuisance parameters : backgrounds & detector charge asymmetries…

Search for CP Violation in $B^0\bar{B}^0$ Mixing (3)

Continuum subtracted data



Δt (ps) $\propto$ Δz

4D binned fit to : Δz, $\cos\theta_{lK}$, M_ν^2, p_K

ℓK opposite signs also used to gain sensitivity

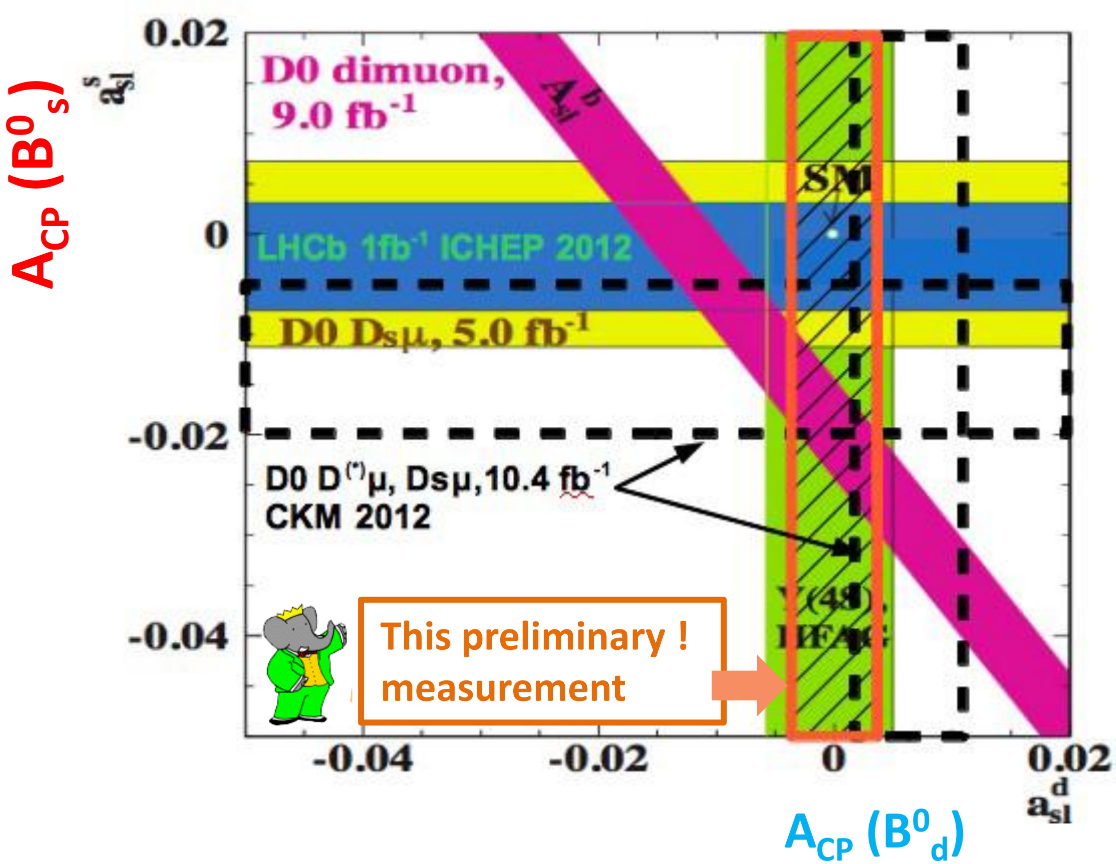
BABAR Preliminary

$$\Delta_{CP} = 1- \left|\frac{q}{p}\right| = [0.29 \pm 0.84\ (\text{stat})^{+1.78}_{-1.61}\ (\text{syst})]\times 10^{-3}$$

$$A_{CP} = [0.06 \pm 0.17\ (\text{stat})^{+0.36}_{-0.32}\ (\text{syst})]\%.$$

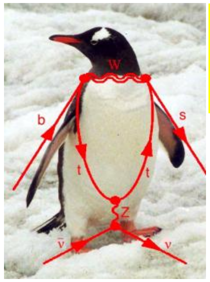
Main systematics on Δ_{CP} : uncertainty in composition of M_ν^2 peaking sample: $\delta\Delta_{CP} = {}^{+1.50}_{-1.17}$ x 10^{-3}

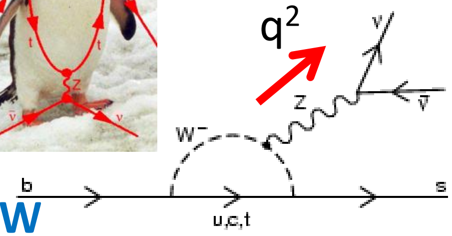
Search for CP Violation in $B^0\bar{B}^0$ Mixing (4)



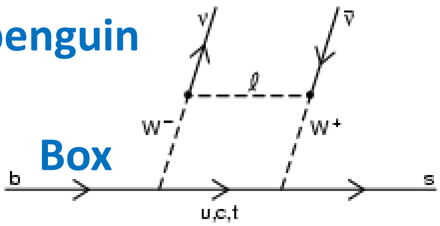
- Consistent and more accurate than previous Υ(4s) HFAG average.
- Consistent with SM and other results.
- (tension between D0 dimuons & SM)

Search for B→ $K^{(*)}\nu\bar{\nu}$ and invisible charmonium decays



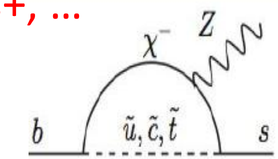


EW penguin



Box

New physics : Non standard Z couplings, MSSM chargino or Higgs+, …



SM : BR(B→Kνν) = (3.6 to 5.2) ×10^{-6}

BR(B→K*νν)= (6.8 to 13) ×10^{-6}

Theoretical prediction more accurate than for B→ $K^{(*)}\ell^+\ell^-$

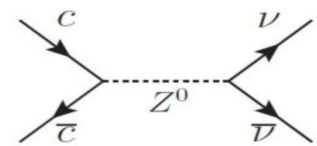
Invisible charmonium decay

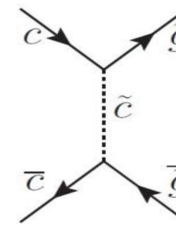
Same final state with:

B→ $K^{(*)}$ $(c\bar{c})$, $c\bar{c} \rightarrow \nu\bar{\nu}$

Search also for rare decay:

$c\bar{c} \rightarrow \nu\bar{\nu}$, $c\bar{c}$=J/Ψ or Ψ(2s)





Standard Model **New physics**

Several previous upper limits on B→$K^{(*)}\nu\bar{\nu}$:

- BaBar (2005): Hadronic & Semileptonic B→K$^+$ $\nu\bar{\nu}$ [PRL 94, 101801]
- BELLE (2007): Hadronic B→K$^{(*)}$ $\nu\bar{\nu}$ [PRL 99, 221802]
- BaBar (2008): Hadronic & SL B→K* $\nu\bar{\nu}$ [PRD 78, 072007]
- BaBar (2010): Semileptonic B→K $\nu\bar{\nu}$ [PRD 82, 112002]

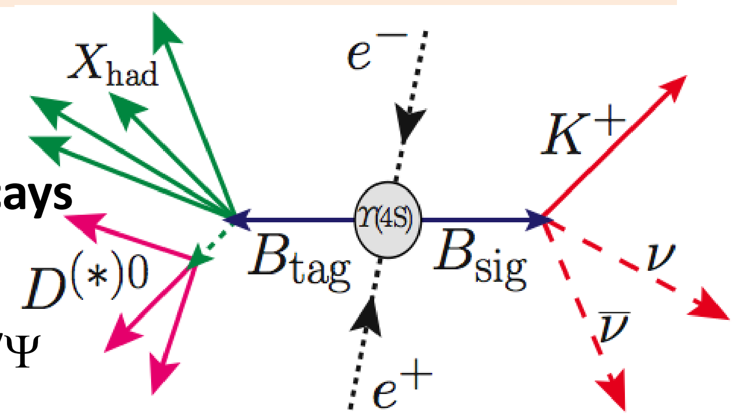
New BABAR measurement with exclusively reco hadronic B_{tag}.

Reconstruct 6 Kaon modes for B_{sig}:

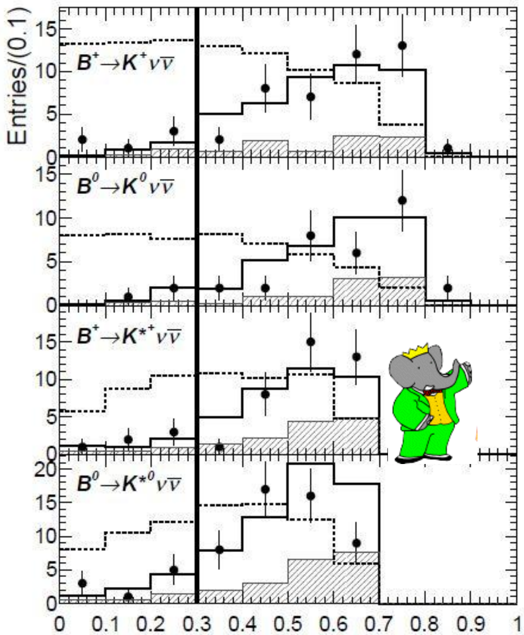
- B^+→K^+ $\nu\bar{\nu}$
- B^0 →K_s^0 $\nu\bar{\nu}$
- B^+ →[K^{*+}→$K^+\pi^0$] $\nu\bar{\nu}$
- B^+ →[K^{*+}→$K_s^0\pi^+$] $\nu\bar{\nu}$
- B^0→[K^{*0}→$K^+\pi^-$] $\nu\bar{\nu}$
- B^0 →[K^{*0}→$K_s^0\pi^0$] $\nu\bar{\nu}$

Various Hadronic decays

or $D^{(*)+}$,$D_s^{(*)+}$,J/Ψ



B→ $K^{(*)}\nu\bar{\nu}$ decays (2)

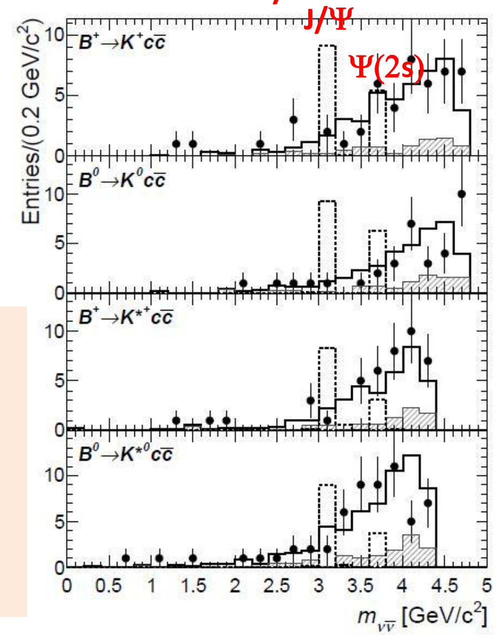


Expected combinatoric : grey shades
mES peaking background : solid lines

No significant signal

Consistent with SM

- First lower limit for $B^+ \to K^+ \nu\bar{\nu}$
- Most stringent upper limits using the hadronic-tag reco for: $B^0 \to K^0 \nu\bar{\nu}$, $B^+ \to K^{*+}\nu\bar{\nu}$ and $B^0 \to K^{*0} \nu\bar{\nu}$ decays
- First upper limit for $\Psi(2S) \to \nu\bar{\nu}$.



Normalized invariant $\nu\bar{\nu}$ mass

$s_B = q^2/m_B^2 = (pB_{sig} - pK^{(*)})/mB^2$

Invariant $\nu\bar{\nu}$ mass

Channel **BABAR Preliminary**	BF x 10^{-5}	90% CL Limit this meas. x 10^{-5}	Combined with S.Lept. X 10^{-5}
$B^+ \to K^+ \nu\bar{\nu}$	$1.5^{+1.7+0.4}_{-0.8-0.2}$	> 0.4 < 3.7	< 1.6
$B^0 \to K^0 \nu\bar{\nu}$	$0.14^{+6.0+1.7}_{-1.9-0.9}$	< 8.1	< 4.9
$B^+ \to K^{*+} \nu\bar{\nu}$	$3.3^{+6.2+1.7}_{-3.6-1.3}$	< 11.6	< 6.4
$B^0 \to K^{*0} \nu\bar{\nu}$	$2.0^{+5.2+2.0}_{-4.3-1.7}$	< 9.3	< 12
$B \to K \nu\bar{\nu}$	$1.4^{+1.4+0.3}_{-0.9-0.2}$	> 0.2 < 3.2	< 1.7
$B \to K^* \nu\bar{\nu}$	$2.7^{+3.8+1.2}_{-2.9-1.0}$	< 7.9	< 7.6

BABAR Preliminary

Search for invisible charmonium

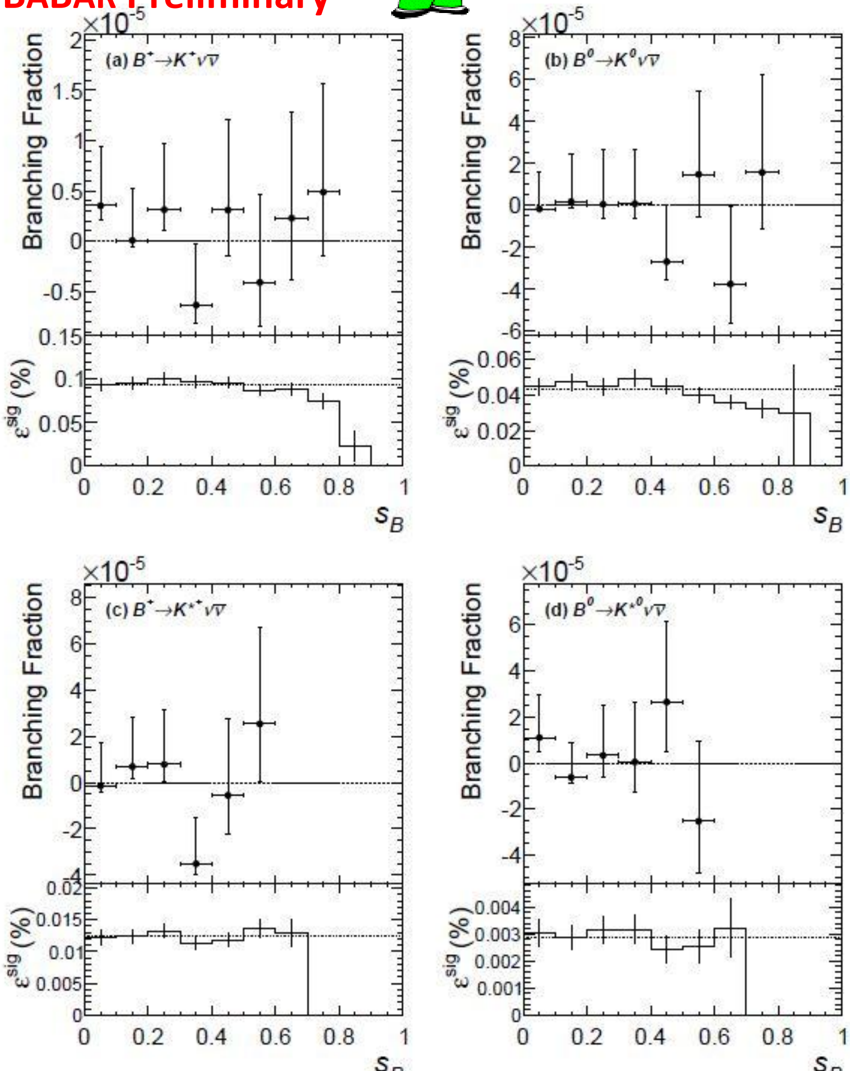
Channel	BF x 10^{-3}	Limit : this meas. x 10^{-3}	$B(c\bar{c} \to \nu\bar{\nu}) / B(c\bar{c} \to e^+ e^-)$
$J/\Psi \to \nu\bar{\nu}$	0.2 +2.7 + 0.5 -0.9 – 0.4	< 3.9	< 6.6 x 10^{-2}
$\Psi(2S) \to \nu\bar{\nu}$	5.6 +7.4 + 1.6 -4.6 - 1.4	< 15.5	< 2.0

Search for B→ $K^{(*)}\nu\bar{\nu}$ decay (3)

Normalized invariant $\nu\bar{\nu}$ mass

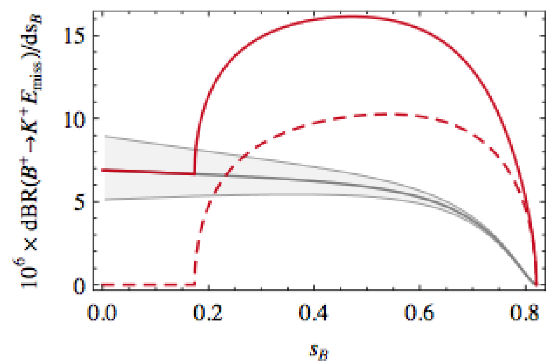
s_B = q^2/m_B^2

BABAR Preliminary



New physics can change not only global BF but also the dependence of BF vs s_B.

Altmannshofer, et al., JHEP 0904:022 (2009)

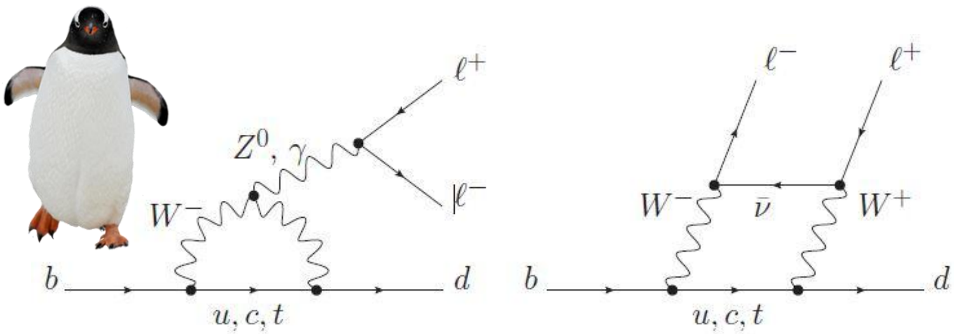


Red: Enhancement in **q^2 ($\nu\bar{\nu}$ invariant mass)** from invisible scalars.

No BF enhancement seen at high s_B.

Search for B→ $\pi/\eta\ \ell^+\ell^-$ decay (1)

New, preliminary



Electroweak penguin

Box

Search for new physics :

b→d $\ell^+\ell^-$ similar to b→s $\ell^+\ell^-$ but

Rate suppressed by $|V_{td}/V_{ts}|^2 \approx$ 0.04

SM prediction for BF ≈ 10^{-8}

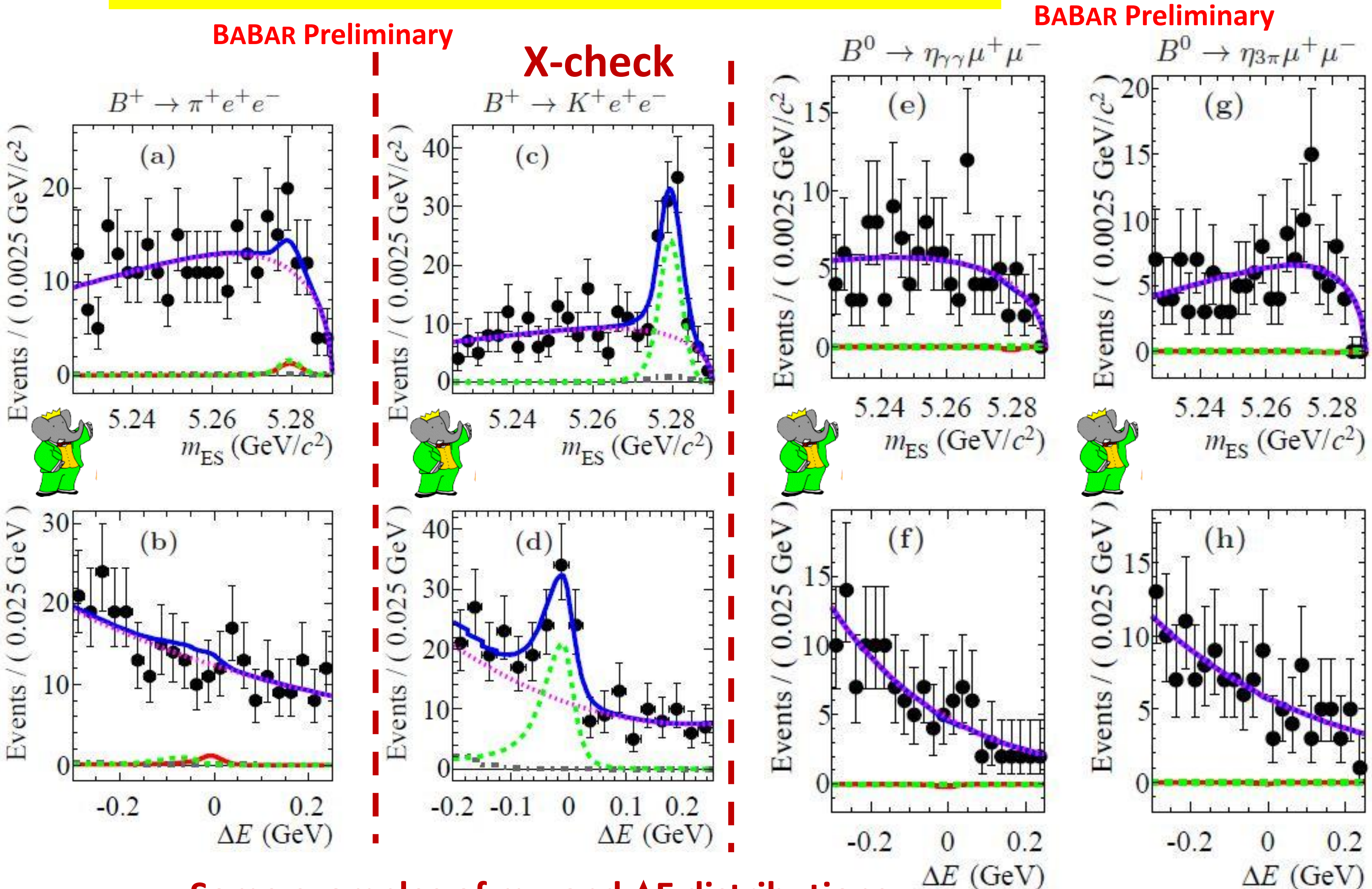
- Only $B^+ \to \pi^+\mu^+\mu^-$ observed with LHCb
- Smallest upper limits from the B factories within an order of magnitude of the SM predictions.

In this analysis:

- Search for $B^+ \to \pi^+ \ell^+\ell^-$, $B^0 \to \pi^0 \ell^+\ell^-$ and $B^0 \to \eta\ \ell^+\ell^-$ (first search) with $\ell^+\ell^- = e^+e^-$ or $\mu^+\mu^-$
- η reconstructed into 3π or 2γ
- Lepton-flavor averages assume equal BF for e^+e^- and $\mu^+\mu^-$
- Isospin average assumes BF($B^+ \to \pi^+\ell^+\ell^-$) = 2× BF($B^0 \to \pi^0\ell^+\ell^-$)

Unbinned maximum likelihood fit to kinematic variables mES and ΔE to extract branching fractions.

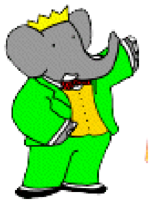
Search for B→ π/η ℓ⁺ℓ⁻ decay (2)



Some examples of m_{ES} and ΔE distributions

Search for B→ π/η $\ell^+\ell^-$ decay (3)

BABAR Preliminary **No significant signal found**



Mode	ε	Yield	$\mathcal{B}\,(10^{-8})$	Upper Limit (10^{-8})
$B^+ \to \pi^+ e^+ e^-$	0.199	$4.2^{+5.7}_{-4.6}$	$4.3^{+5.9}_{-4.7} \pm 2.0$	12.5
$B^0 \to \pi^0 e^+ e^-$	0.163	$1.0^{+3.2}_{-1.1}$	$1.2^{+5.4}_{-4.0} \pm 0.2$	8.4
$B^0 \to \eta e^+ e^-$			$-4.0^{+10.0}_{-8.0} \pm 0.6$	10.8
$B^0 \to \eta_{\gamma\gamma} e^+ e^-$	0.164	$-1.2^{+3.1}_{-2.4}$		
$B^0 \to \eta_{3\pi} e^+ e^-$	0.115	$-0.5^{+1.2}_{-1.0}$		
$B^+ \to \pi^+ \mu^+ \mu^-$	0.140	$-0.5^{+3.1}_{-2.3}$	$-0.6^{+4.4}_{-3.2} \pm 0.9$	5.5
$B^0 \to \pi^0 \mu^+ \mu^-$	0.115	$-0.2^{+2.0}_{-0.7}$	$-1.0^{+5.0}_{-3.4} \pm 0.6$	6.9
$B^0 \to \eta \mu^+ \mu^-$			$-2.0^{+9.7}_{-6.6} \pm 0.4$	11.2
$B^0 \to \eta_{\gamma\gamma} \mu^+ \mu^-$	0.102	$-0.4^{+1.7}_{-1.3}$		
$B^0 \to \eta_{3\pi} \mu^+ \mu^-$	0.063	$-0.1^{+0.7}_{-0.4}$		
$B \to \pi e^+ e^-$			$4.0^{+5.1}_{-4.2} \pm 1.6$	11.0
$B \to \pi \mu^+ \mu^-$			$-0.9^{+3.9}_{-3.0} \pm 1.2$	5.0
$B^+ \to \pi^+ \ell^+ \ell^-$			$2.5^{+3.9}_{-3.3} \pm 1.2$	6.6
$B^0 \to \pi^0 \ell^+ \ell^-$			$1.2^{+3.9}_{-3.3} \pm 0.2$	5.3
$B^0 \to \eta \ell^+ \ell^-$			$-2.8^{+6.6}_{-5.2} \pm 0.3$	6.4
$B \to \pi \ell^+ \ell^-$			$2.5^{+3.3}_{-3.0} \pm 1.0$	5.9

hep-ex/1210.2645

LHCb : B($B^+ \to \pi^+\mu^+\mu^-$) = $(2.4 \pm 0.6 \pm 0.2) \times 10^{-8}$

But most of other modes hard to study at LHC

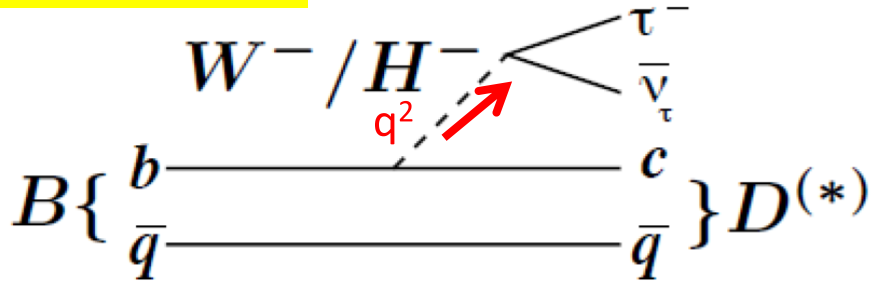
Lepton flavor and/or isospin Combined results

X-check : measure BF($B^+ \to K^+\ell^+\ell^-$) found consistent with current world averages.

Lowest upper limits to date on the $B^0 \to \pi^0 e^+e^-$, $B^0 \to \pi^0 \mu^+\mu^-$, and $B^0 \to \pi^0 \ell^+\ell^-$ branching fractions.

Study of B→ $D^{(*)}$ τ ν decay (1)

PRL 109, 101802 (2012)



- Semileptonic decays with a τ.

ℓ = e, μ, τ

Hadronic amplitudes

$$\frac{d\Gamma_\ell}{dq^2} = \frac{G_F^2 |V_{cb}|^2 |\boldsymbol{p}_{D^{(*)}}| q^2}{96\pi^3 m_B^2} \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \left[\left(|H_+|^2 + |H_-|^2 + |H_0|^2\right) \left(1 + \frac{m_\ell^2}{2q^2}\right) + \frac{3m_\ell^2}{2q^2} |H_s|^2 \right]$$

only for B → D* τ ν

H^- enters here (scalar).
Small term for l=e,μ

- Test the SM by measuring the ratios:

$$R(D) = \frac{B(\bar{B}\to D\tau\nu)}{B(\bar{B}\to Dl\nu)} \text{ and } R(D^*) = \frac{B(\bar{B}\to D^*\tau\nu)}{B(\bar{B}\to D^*l\nu)}.$$

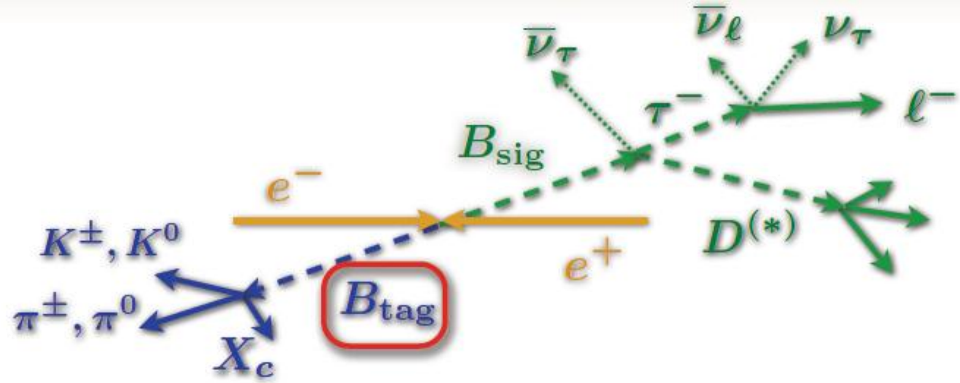
  – Several theoretical and experimental uncertainties cancel in the ratio.

- Sensitive to additional amplitudes.
  – Charged Higgs (entering through the scalar amplitude).

Study of $B \rightarrow D^{(*)} \tau \nu$ decay (2)

PRL 109, 101802 (2012)

- **Fully reconstructed tag B**
  - Efficiency 2x previous analysis

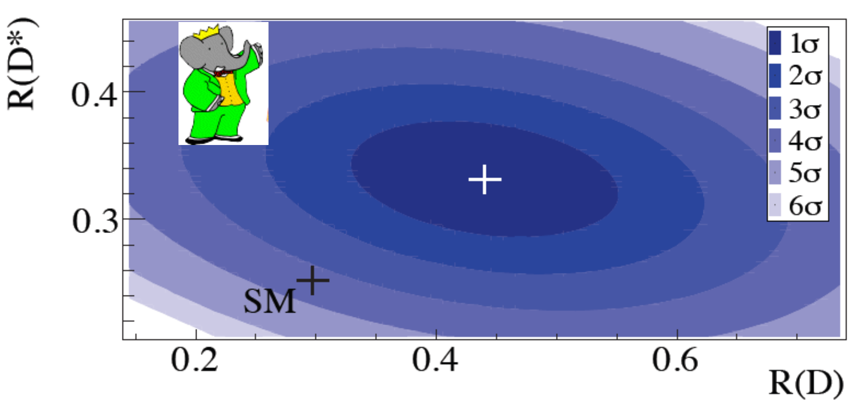


Old $B_{tag}: X_c = D, D^*$ New $B_{tag}: X_c = D, D^*, D_s^+, D_s^{*+}, J/\Psi$

Unbinned maximum likelihood fit over p_l^* and $m^2_{miss} = (P_{e+e-} - P_{Btag} - P_D^{(*)-} P_l)^2$

Decay	N_{sig}	N_{norm}	$R(D^{(*)})$	$\mathcal{B}(B \rightarrow D^{(*)}\tau\nu)$ (%)	$\Sigma_{tot}(\sigma)$
$D\tau^-\overline{\nu}_\tau$	489 ± 63	2981 ± 65	$0.440 \pm 0.058 \pm 0.042$	$1.02 \pm 0.13 \pm 0.11$	6.8
$D^*\tau^-\overline{\nu}_\tau$	888 ± 63	11953 ± 122	$0.332 \pm 0.024 \pm 0.018$	$1.76 \pm 0.13 \pm 0.12$	13.2

PRL 109, 101802 (2012)

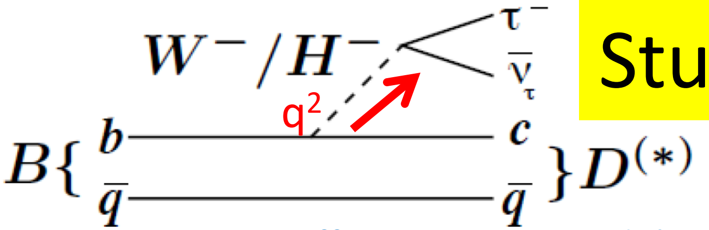


R(D) and R(D*) not independent

-27% correlation

3.4 σ deviation from SM

Study of B→ $D^{(*)} \tau \nu$ decay (3)

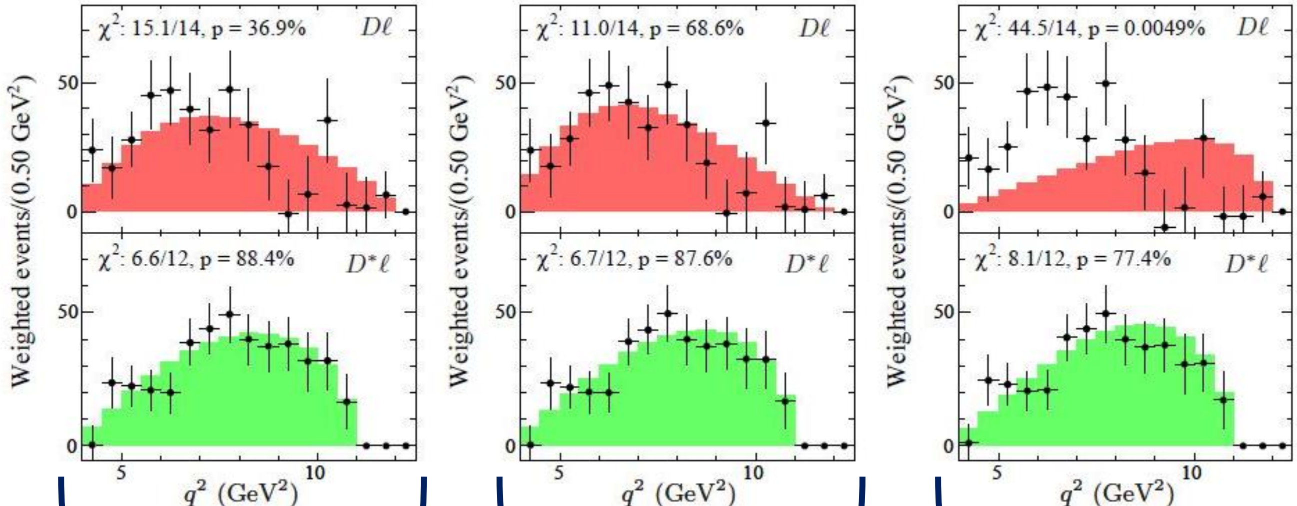


$q = p_B - p_D^{(*)}$: four-momentum of the virtual W

Efficiency corrected, backg. subtracted q^2

Normalized to nb of observed events. B^0 and B^+ samples combined

BABAR Preliminary

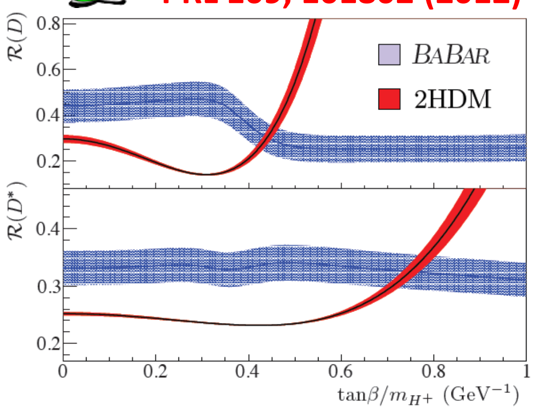


$\bar{B} \to D\tau^-\bar{\nu}_\tau$

$\bar{B} \to D^*\tau^-\bar{\nu}_\tau$

Standard Model | $\tan\beta/m_{H^+}$ = 0.30 GeV^{-1} | $\tan\beta/m_{H^+}$ = 0.45 GeV^{-1}

PRL 109, 101802 (2012)



HDM = « Higgs Doublet Model »

PRL: Combination of $R(D^{(*)})$ excludes 2HDM type II (@>99.8%)

New, preliminary : 2HDM type III model is constrained (but not excluded) using both $R(D^{(*)})$ and q^2 distributions.

Other more general charged Higgs models of New Physics contributions with nonzero spin also compatible with measurements ...

Conclusion

Time and CP violation measurements

First direct observation of Time Reversal Violation - **PRL 109, 211801 (2012)**
In any system! Expected from SM but observed for the first time.

CP Violation in $B^0 \rightarrow D^{*+}D^{*-}$ decays - **PRD 86, 112006 (2012)**
Results consistent with SM. BABAR global accuracy on S_{CP} and C_{CP} improved by ~20%

Search for CP Violation in $B^0\bar{B}^0$ mixing - **Preliminary**.
Improvement of the average Υ(4s) result on |q/p| for the B^0_d mixing.

Search for new physics in rare decays

Search for $B \rightarrow K^{(*)} \nu\bar{\nu}$ decay **New, Preliminary.**
Search for $B \rightarrow \pi/\eta\, \ell^+\ell^-$ decay **New, Preliminary.**
No significant signal found – New upper limits and improvement of existing limits on BF.
Study of $B \rightarrow D^{(*)} \tau \nu$ decay **PRL 109, 101802 (2012)**
New, Preliminary studies of q^2 distributions to test new physics models.

BACK-UP

Direct observation of time reversal violation

EPR entanglement from $\Upsilon(4S)$

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

Semileptonic decay projects:

B^0 *with* l^+, $\bar{B}^0$ *with* l^-

$J/\Psi K_L$ *projects CP even* $B_+ = \frac{1}{\sqrt{2}}[B^0 + \bar{B}^0]$

$J/\Psi K_S$ *projects CP odd* $B_- = \frac{1}{\sqrt{2}}[B^0 - \bar{B}^0]$

Final state (X, Y), one B^0 or $\bar{B}^0$, and one CP state B_+ or B_-, with decay time $t_X < t_Y$

Physical process / Reco Final state Reference (X,Y)		Physical process / Reco Final state T transformed (X,Y)	
$B^0 \rightarrow B_+$	l^-, $J/\Psi K_L$	$B_+ \rightarrow B^0$	$J/\Psi K_S$, l^+
$B^0 \rightarrow B_-$	l^-, $J/\Psi K_S$	$B_- \rightarrow B^0$	$J/\Psi K_L$, l^+
$\bar{B}^0 \rightarrow B_+$	l^+, $J/\Psi K_L$	$B_+ \rightarrow \bar{B}^0$	$J/\Psi K_S$, l^-
$\bar{B}^0 \rightarrow B_-$	l^+, $J/\Psi K_S$	$B_- \rightarrow \bar{B}^0$	$J/\Psi K_L$, l^-

4 independent T comparisons (as 4 CP and 4 CPT comparisons)

T implies comparison of :

1. Opposite Δt sign.
2. Different reco states ($J/\Psi K_S$ vs. $J/\Psi K_L$).
3. Opposite tag states (B^0 vs $\bar{B}^0$).

Time reversal violation

Assumes $\Delta\Gamma_d = 0$

- Define $\Delta\tau = t(\text{flavor}) - t(CP)$
- Consider eight combinations (flavor x CP x sign of $\Delta\tau$)
- Fit each with EPR-motivated function

$\alpha = B^0/\overline{B^0}$

$\beta = K_L/K_S$

Does NOT assume CPT

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

Heavyside step function

- $S^{+-}_{\alpha\beta}$, $C^{+-}_{\alpha\beta}$: fit parameters
  - T-Violation : $\Delta S^{\pm}_{T} = S^{\pm}_{\overline{B^0},K_L} - S^{\mp}_{B^0,K_S} \neq 0$
  - CP-Violation : $\Delta S^{-}_{CP} = S^{\pm}_{B^0,K_L} - S^{\mp}_{B^0,K_S} \neq 0$
  - CPT-Violation : $\Delta S^{-}_{CPT} = S^{\pm}_{B^0,K_S} - S^{\mp}_{\overline{B^0},K_S} \neq 0$
- Assuming CPT & CP fit results, expect :

$$S^{\pm}_{T,\alpha,\beta} = \pm\sin(2\beta)$$
$$\Delta S^{\pm}_{T} = 2\sin(2\beta)$$

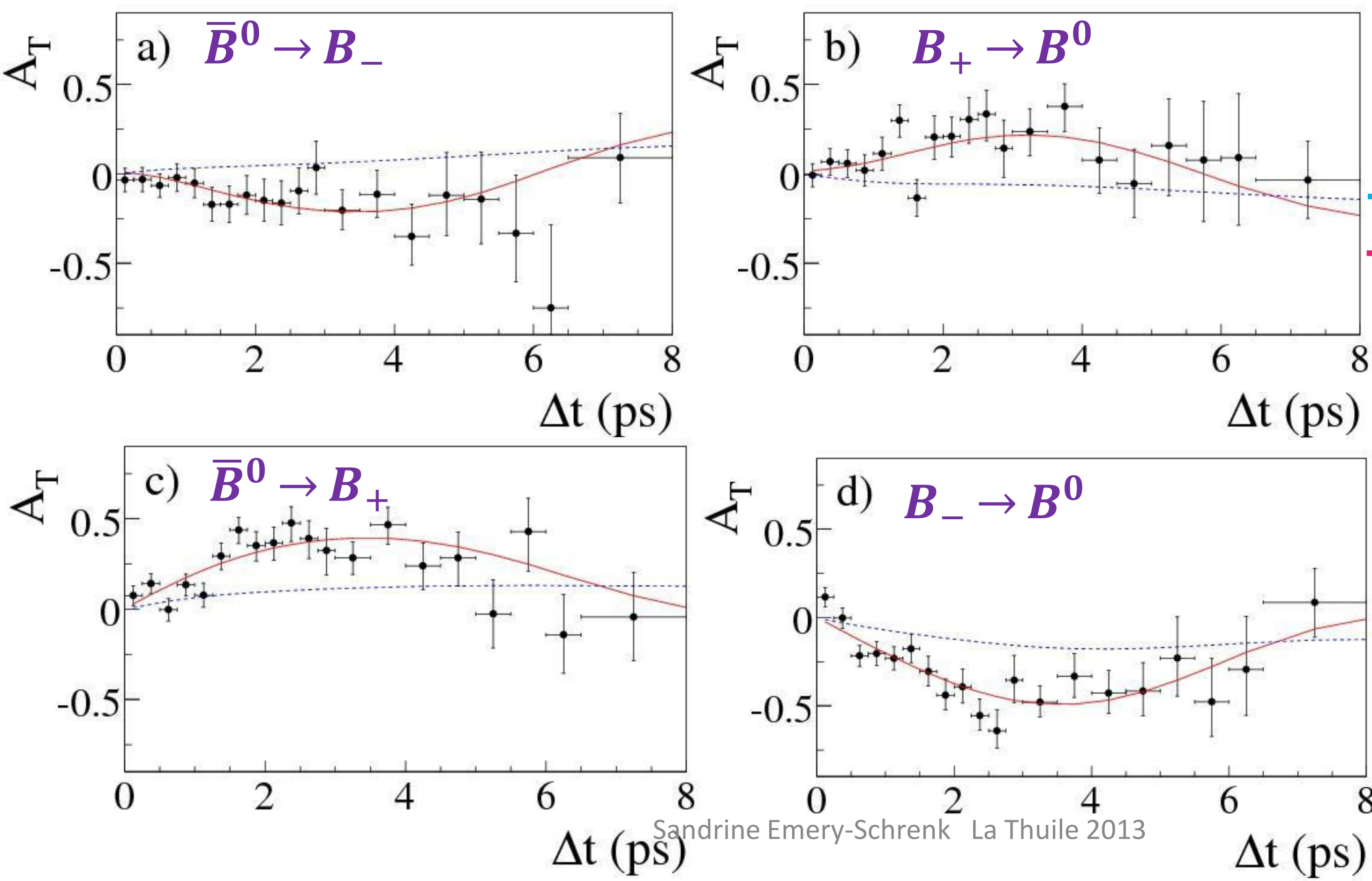
Direct observation of time reversal violation

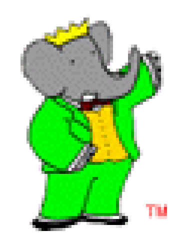
Illustrative : 4 independent T violating asymmetries

Include experimental reconstruction effects.

Neglecting reconstruction effects : $A_T \approx \frac{1}{2}\left[\Delta S_T{}^{\pm}\sin(\Delta m\,|\Delta t|) + \Delta C_T{}^{\pm}\cos(\Delta m\,|\Delta t|)\right]$

BABAR **PRL 109, 211801 (2012)**





Direct observation of time reversal violation

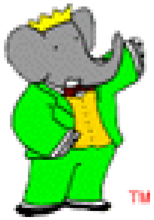
The T –invariance point is obtained applying these eight restrictions :

$\Delta S^{\pm}_{T} = 0$

$\Delta C^{\pm}_{T} = 0$

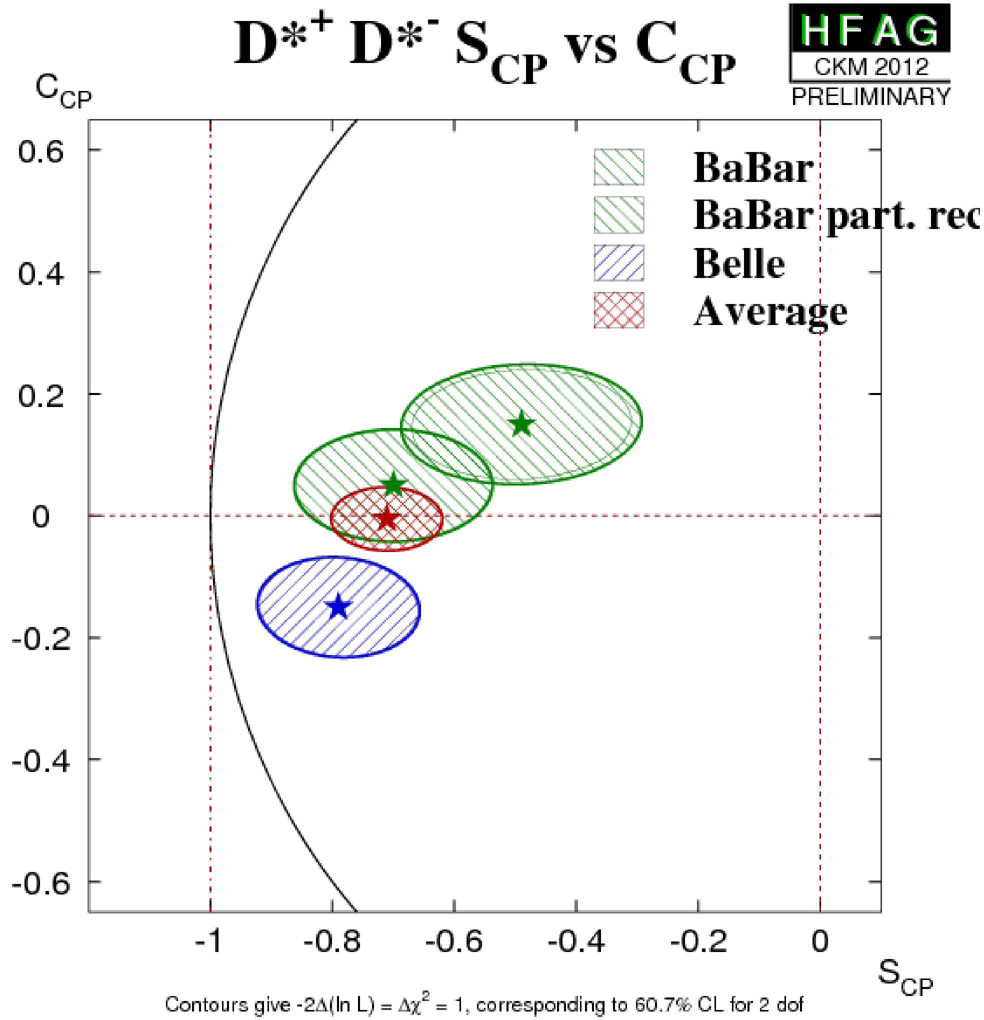
$\Delta S^{\pm}_{CP} = \Delta S^{\pm}_{CPT}$

$\Delta C^{\pm}_{CP} = \Delta C^{\pm}_{CPT}$

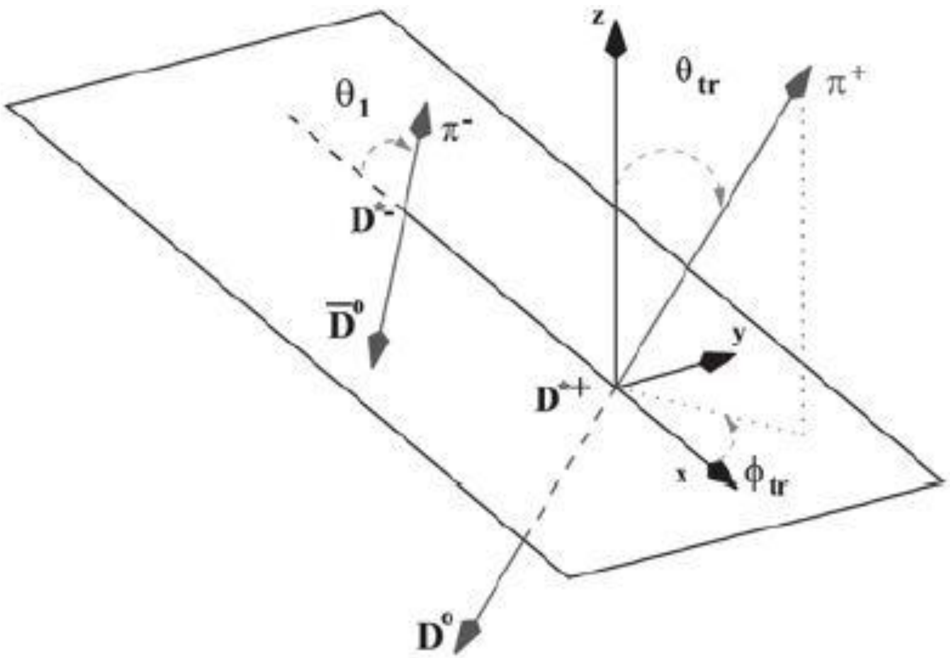


PRL 109, 211801 (2012)

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



D*+ D*- S_CP vs C_CP
HFAG
CKM 2012
PRELIMINARY
C_CP
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
BaBar
BaBar part. rec
Belle
Average
-1
-0.8
-0.6
-0.4
-0.2
0
S_CP
Contours give -2Δ(ln L) = Δχ2 = 1, corresponding to 60.7% CL for 2 dof


z
θ_{tr}
π^+
θ_1
π^-
D^{*-}
$\overline{D}^0$
y
D^{*+}
x
ϕ_{tr}
D^0

Search for CP Violation in $B^0\bar{B}^0$ Mixing using $B^0 \to D^* l\nu$ Partial Reconstruction

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

$$\left. - \left(1 - \left|\frac{q}{p}\right|^2 r'^2\right) \cos(\Delta m_d \Delta t) + \left|\frac{q}{p}\right| (b+c) \sin(\Delta m_d \Delta t) \right]$$

$$r' = \left|\overline{\mathcal{A}}_{DCS}/\mathcal{A}_{CF}\right|$$
$$b = 2r' \sin(2\beta+\gamma)\cos\delta'$$
$$c = -2r' \cos(2\beta+\gamma)\sin\delta'$$
$\delta' =$ Strong phase

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

Assumptions:

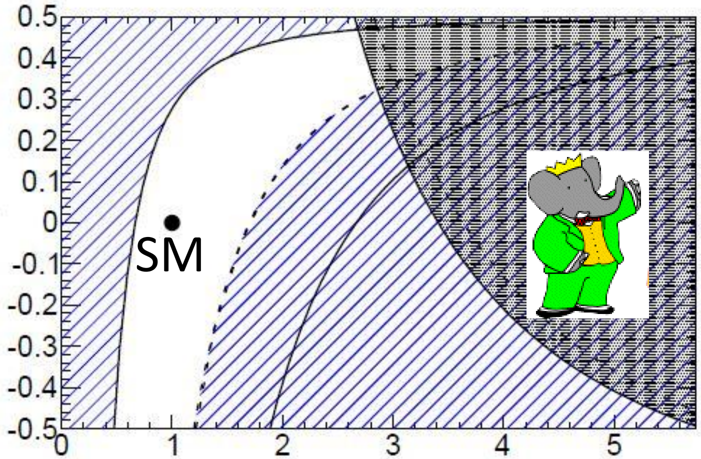
- ΔΓ=0
- b, c are treated as effective parameters due to strong correlation with resolution function

➔ Only |q/p| is measured

Search for B→ $K^{(*)}\nu\bar{\nu}$ decay (backup)

BABAR Preliminary

$$\eta \equiv \frac{-\mathrm{Re}(C_L^{\nu} C_R^{\nu *})}{|C_L^{\nu}|^2 + |C_R^{\nu}|^2}.$$



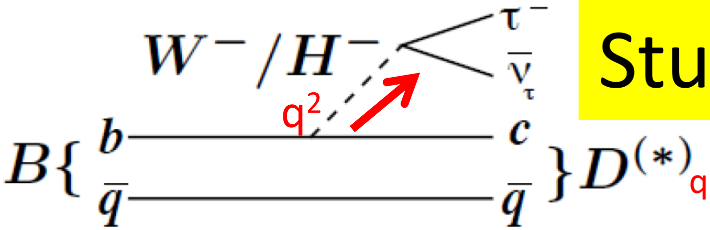
$$\epsilon \equiv \frac{\sqrt{|C_L^{\nu}|^2 + |C_R^{\nu}|^2}}{|C_{L,\mathrm{SM}}^{\nu}|}$$

B→ $K^{(*)}\nu\bar{\nu}$ sensitive to short distance Wilson coefficients $|C^{\nu}_{L,R}|$ for weak current ($|C^{\nu}_{R}|$=0 in SM).

Constraints from B→ K $\nu\bar{\nu}$ (striped) & B→ $K^{*}\nu\bar{\nu}$ (grey shaded), from this analysis (solid line) and semileptonic-tag analyses (dashed).

Consistent with SM

Study of $B \to D^{(*)} \tau \nu$ decay

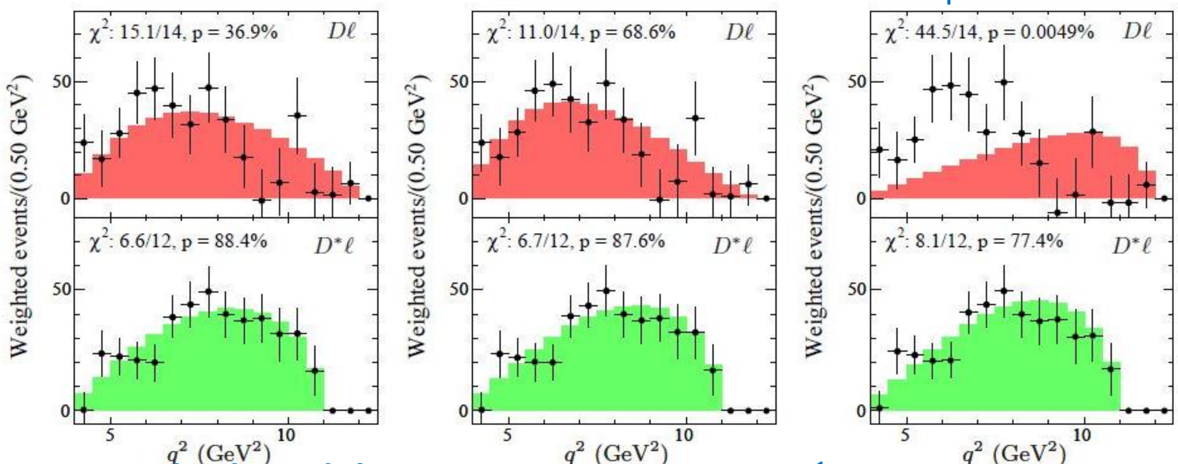


BABAR Preliminary

q = pB−pD$^{(*)}$: four-momentum of the virtual W

Efficiency corrected, background subtracted q^2 distributions,
Normalized to numbers of observed events. B^0 and B^+ samples combined

BABAR Preliminary



$\bar{B} \to D\tau^-\bar{\vartheta}_\tau$

$\bar{B} \to D^*\tau^-\bar{\vartheta}_\tau$

Standard Model $\quad$ $\tan\beta/m_{H^+} = 0.30\ GeV^{-1}$ $\quad$ $\tan\beta/m_{H^+} = 0.45\ GeV^{-1}$

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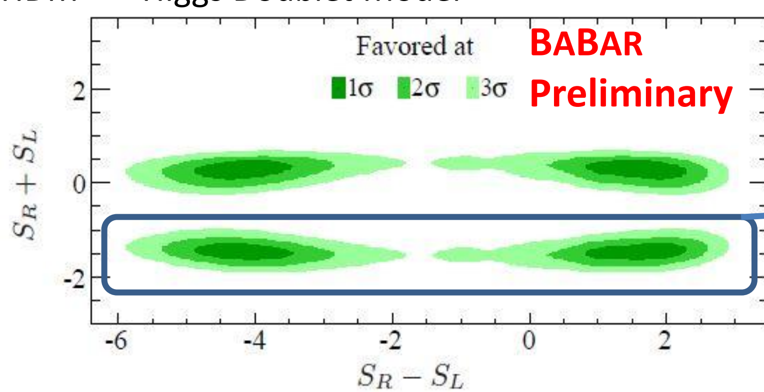
HDM = « Higgs Doublet Model »

Combination of R(D$^{(*)}$) excludes 2HDM type II



Excluded by measured q^2 distributions

Favored regions in independent scalar part of complex parameters SR,L for 2HDM type III from R(D$^{(*)}$)