Highlights from the BABAR experiment

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On behalf of the BABAR collaboration

ICFP 2012

Kolymbari, Greece – June 10-16

Outline

- Emphasis on two analysis
  - New $B \rightarrow D^{(*)}\tau\nu$ result – submitted to PRL: arXiv:1205.5442 [hep-ex]
  - Direct measurement of time-reversal violation – to be submitted soon

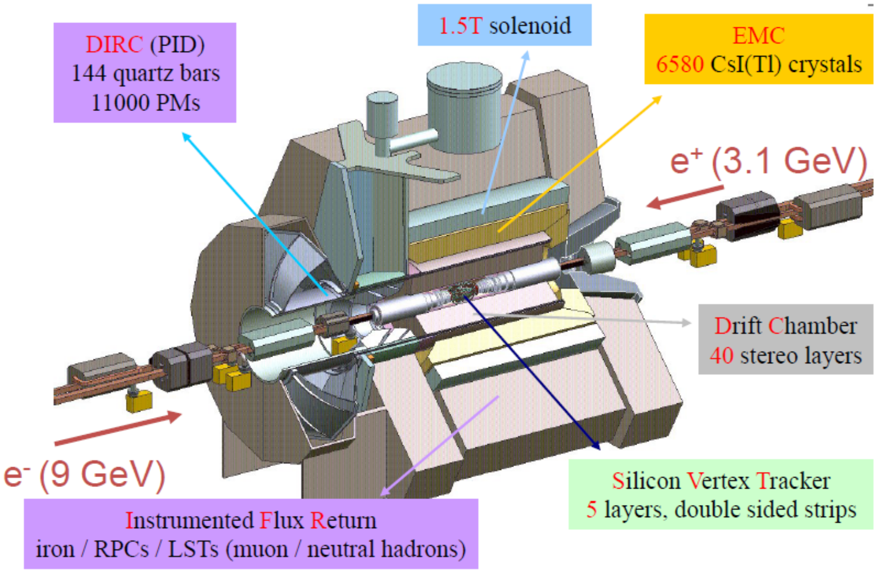
- Quick report – not exhaustive ! – of some recent results based on full dataset
  - B_s semileptonic branching fraction – already published
  - $B \rightarrow \nu\bar{\nu}(\gamma)$ – aka $B \rightarrow$ 'invisible' – submitted this Wednesday! arXiv:1206.2543 [hep-ex]

- See parallel session talks for latest BaBar results on
  - Searches for low-mass Higgs and dark gauge bosons (G. Lafferty, last Monday)
  - Searches for new sources of CP violation (G. Simi, this evening at 18:20)

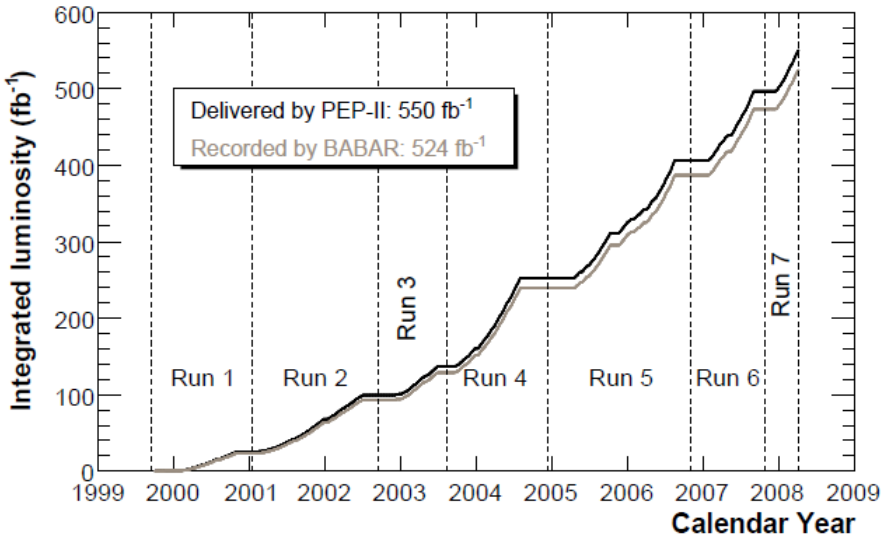
- All analysis reported in this talk use the full dataset available – see next slide

BaBar in a nutshell

- The BaBar detector



- The BaBar dataset



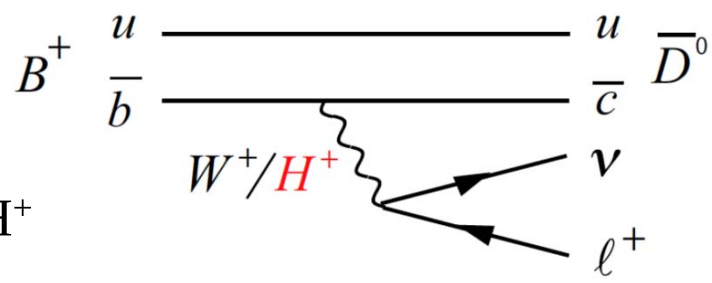
- Data taking ended more than 4 years ago (April 7th 2008)
  → But analysis are still going on – and will continue to do so for a few years
- $424\ \text{fb}^{-1}$ @ $\Upsilon(4S)$ ⇔ $(471.0 \pm 2.8) \times 10^6$ $B\bar{B}$ pairs – ‘onpeak’
  - $44\ \text{fb}^{-1}$ recorded 40 MeV below the peak – ‘offpeak’ – to study background
- $30.6\ \text{fb}^{-1}$ @ $\Upsilon(3S)$ and $15.0\ \text{fb}^{-1}$ @ $\Upsilon(2S)$ – onpeak + offpeak
  → $\eta_b(1S)$ discovery + searches for low-mass Higgs and dark gauge bosons
- ~$3.9\ \text{fb}^{-1}$ from the final energy scan up to 11.2 GeV

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

arXiv:1205.5442

Submitted to PRL

Motivation



- Tree-level semileptonic decays mediated by a W^+
  → τ mode: sensitivity to additional contributions,
  e.g. from an intermediate charged Higgs Boson H^+
- Decays sensitive to V_{cb} and hadronic form factors
  → Most of these dependences cancelled in the ratio (τ mode) / (e, μ modes)

$$R\left(D^{(*)}\right) = \frac{BF\left(B \to D^{(*)}\tau\nu\right)}{BF\left(B \to D^{(*)}l\nu\right)}$$

← 'Signal' decays
← 'Normalization' decays

- Previous measurements from B-factories exceed Standard Model (SM) predictions
  → Low significance – statistically limited

Z. Phys. C46, 93 (1990)
PRD 78, 0156006 (2008)
PRD 85, 094025 (2012)
+ updates for this analysis

- New BaBar result based on the full data sample
  → Twice the statistics of the previous analysis
- Improved reconstruction
  - Better B selection – see next slide
  - $D^{(*)}$ and l reconstruction extended to lower momenta

  → Signal yield increased by more than a factor 3!
- Main experimental challenge: separate final states based on the number of ν's

Event selection

- Limited kinematical information due to neutrino(s) in the final states
  → Exclusive hadronic reconstruction of one of the B mesons – the 'B_{tag}'
- B_{tag} candidates selected using two kinematical variables
  - The beam energy-substituted mass $m_{ES} = \sqrt{(E^*_{beam})^2 - (p^*_{tag})^2}$
    → Peaks at the B mass for signal with a 2.5 MeV/c^2 resolution
  - The energy difference $\Delta E = E^*_{tag} - E_{beam}$
    → Centered at 0 for signal with a 18 MeV resolution
- Signal B corresponds to the rest of the event (tracks + energy deposits)
  → Improved knowledge of kinematics and missing energy
- B_{tag} candidate combined with a $D^{(*)}$ meson candidate and a charged lepton l
  - No additional charged particle
  - $B\overline{B}$ pair with the lowest extra energy selected
  → Full reconstruction of the event – except neutrinos
- Only purely leptonic decays of the τ ($\rightarrow l^- \bar{\nu}_l \nu_\tau$)
  → Same particles in the final states for all decay modes
  - Signal (normalization) events have 3 (1) neutrinos in the final state

Fit

- 2D unbinned maximum likelihood fit – all PDFs extracted from high stat. MC
  - Invariant mass of the undetected particles $m^2_{miss} = (P_{ee} - P_{Btag} - P_{D(*)} - P_\ell)^2$
    $\rightarrow$ Peaks at 0 for normalization events; broad distribution up to ~9 GeV^2 for signal
  - Lepton momentum in B_{sig} rest frame p^*_ℓ
    $\rightarrow$ Signal spectrum softer for signal events (secondary particle from τ decay)

- 4 $D^{(*)}l\nu$ samples = Σ(8 contributions)
  - $D^{(*)}\tau\nu$ and $D^{(*)}(e,\mu)\nu$ [4]
  - $D^{**}(l,\tau)\nu$ [1]
  - Backgrounds: charge cross-feed, other $B\overline{B}$, continuum [3]

- 4 $D^{(*)}\pi^0 l\nu$ control samples
  $\rightarrow$ Constrain background with charm resonances heavier than D^*

- Simultaneous fit on the 8 samples
  - Yields for the last 3 background categories are fixed to the expected value

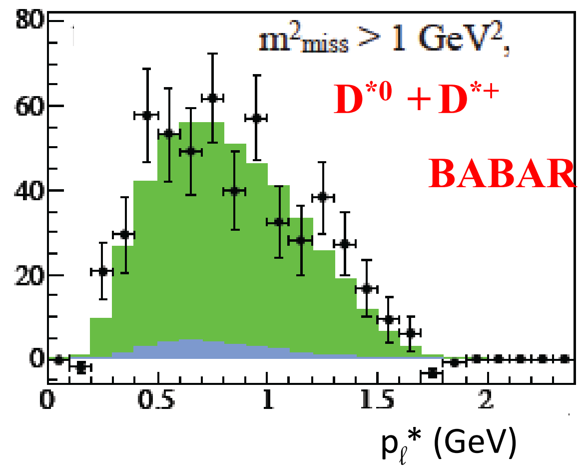
- Main systematics uncertainties
  - $D^{**}l\nu$ background – dominant $\Rightarrow$ conservative estimation
  - Limited Monte-Carlo signal samples
  - Continuum and $B\overline{B}$ background

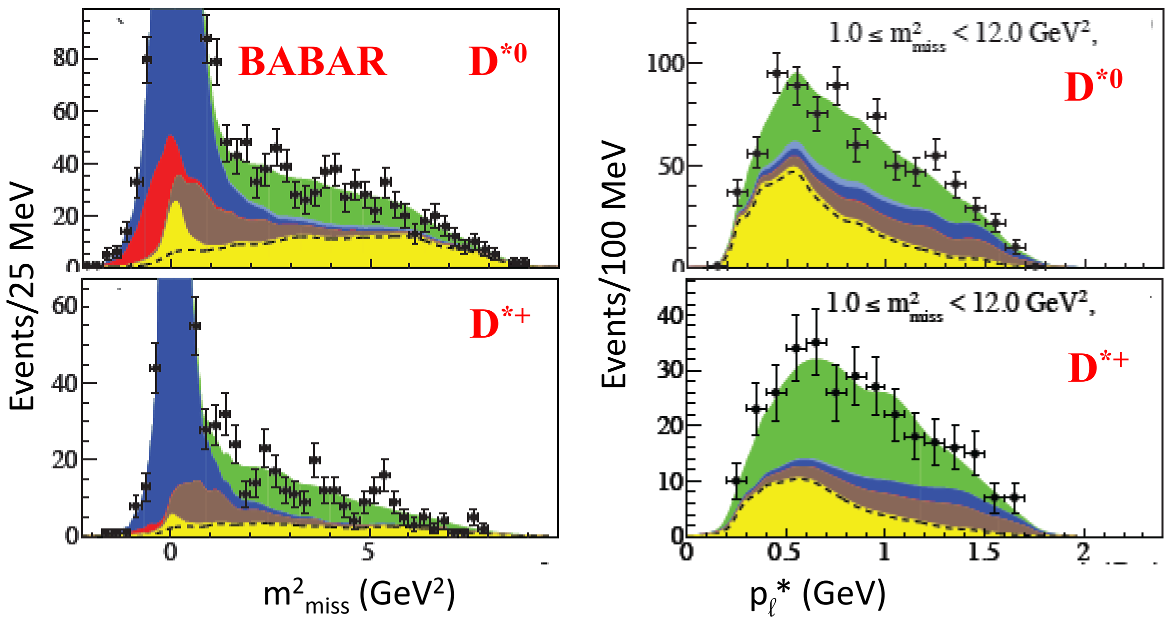
Fit results: $B \to D^{*}\tau\nu$

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

Isospin constrained

Statistical errors only





$D^*\tau\nu$
$D\tau\nu$
$D^*l\nu$
$Dl\nu$
$D^{**}l\nu$
Bkg.

Free yields

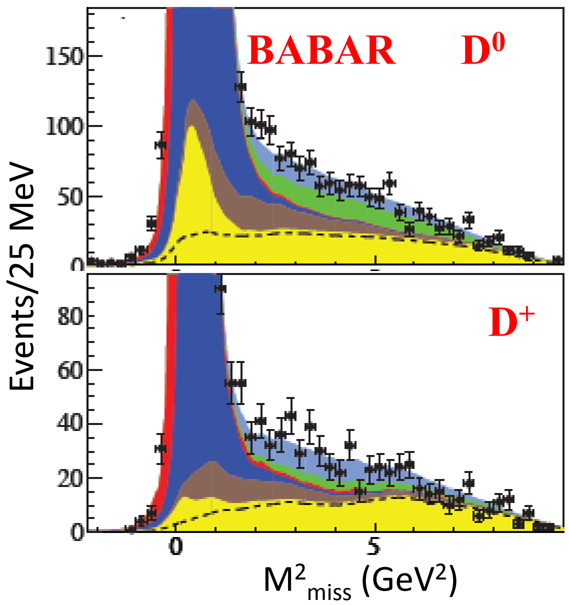
Fixed yield

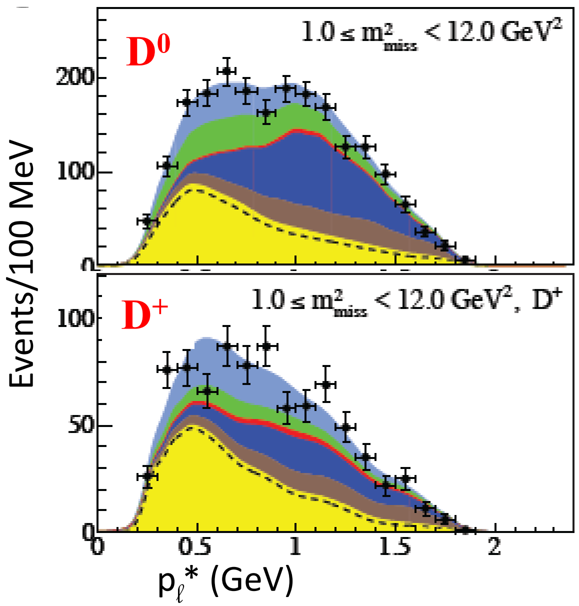
Fit results: $B \to D\tau\nu$

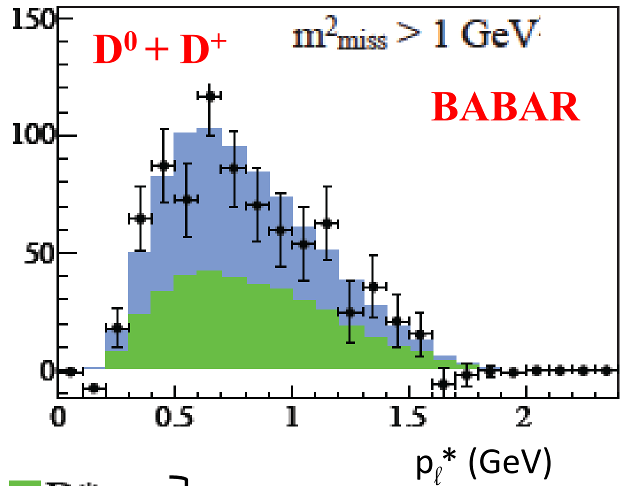
	$D^0\tau\nu$	$D^+\tau\nu$	$D\tau\nu$
N_{sig}	314 ± 60	177 ± 31	489 ± 63
Significance (σ)	5.5	6.1	8.4
$R(D)$	0.429 ± 0.082	0.469 ± 0.084	0.440 ± 0.058

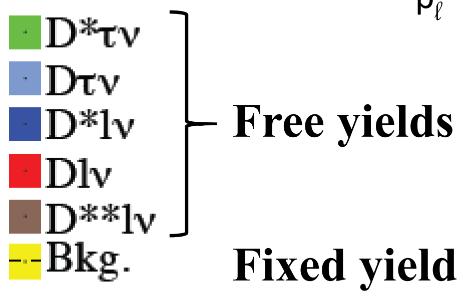
Statistical errors only

Isospin constrained









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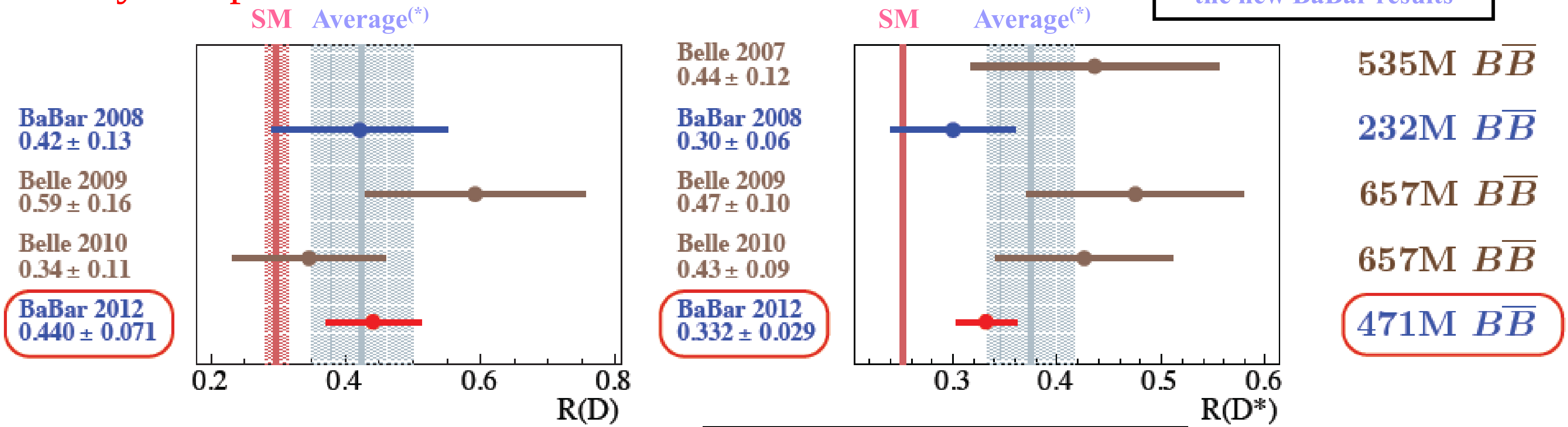
Comparison with the Standard Model prediction

(*)Averages do not include the new BaBar results

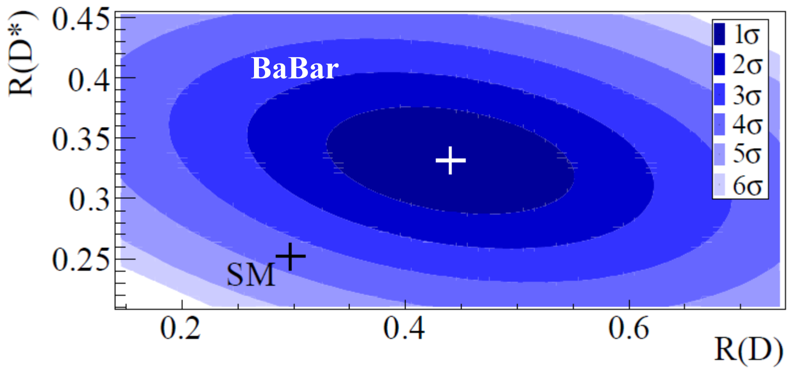
- Fully compatible with earlier measurements …



- … and above the SM predictions!

	R(D)	R(D*)
BaBar 2012	0.440 ± 0.071	0.332 ± 0.029
Standard Model	0.293 ± 0.017	0.252 ± 0.003
Difference	$2.0\,\sigma$	$2.7\,\sigma$

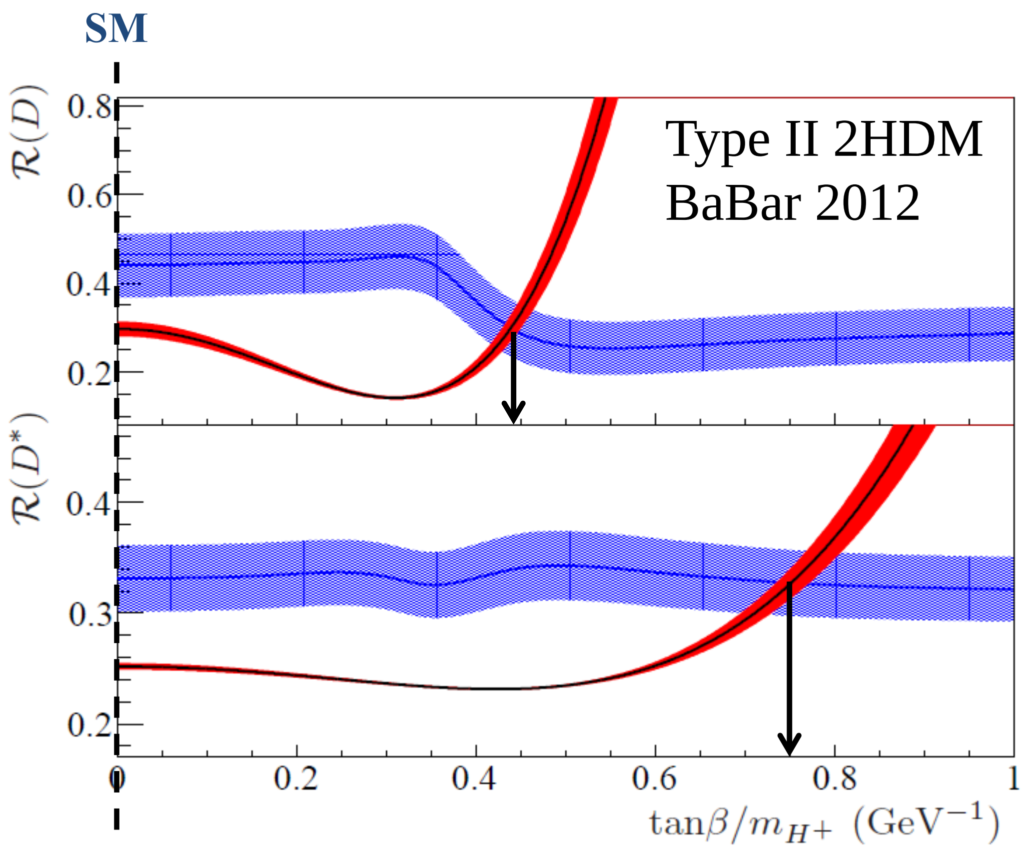
- Combination of the two measurements
  - Correlation of –0.27
    → Feed down from D* in D sample
  - → χ^2/NDF = 14.6/2,
    p value = 6.9×10^{-4} [3.4σ away]



Interpretation for type II two-Higgs-doublet model

- Simulated events reweighted at the matrix element level for 20 values of $\tan\beta / m_{H^+}$
  $\rightarrow$ PDFs and efficiencies updated; fits repeated then

- Results



$\tan\beta / m_{H^+} = 0.44 \pm 0.02$

$\tan\beta / m_{H^+} = 0.75 \pm 0.04$

- Each ratio matches the prediction at values of $\tan\beta / m_{H^+}$ which are not compatible
  $\rightarrow$ Model excluded at 99.8% CL on the whole range for H^+ mass > ~10 GeV
  - Low-mass range already excluded by $B \rightarrow X_s \gamma$ data

Time-reversal violation

Preliminary result

To be submitted soon

Time reversal violation: challenging!

- The CP and T symmetries are theoretically connected through the CPT theorem
  - CP violation (CPV) established in K, B and D systems
  - But no proof yet of T non-invariance (TRV), not assuming CPV nor CPT

- TRV in a decay process requires
  - Reversal of motion ($t \rightarrow -t$)
  - And exchange of |in> and |out> states

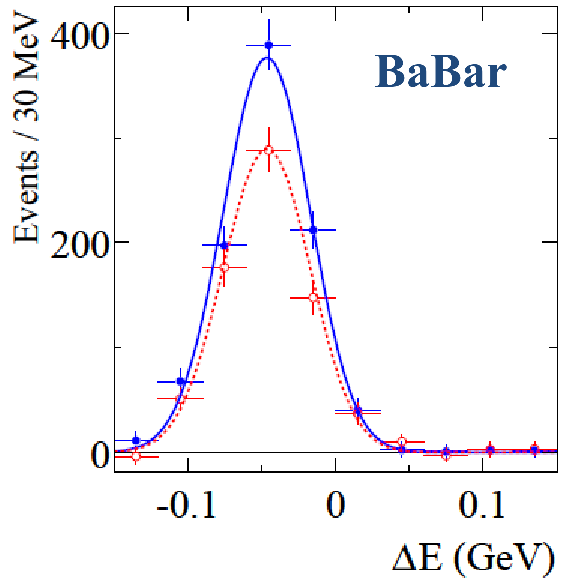
  $\rightarrow$ Experimentally challenging

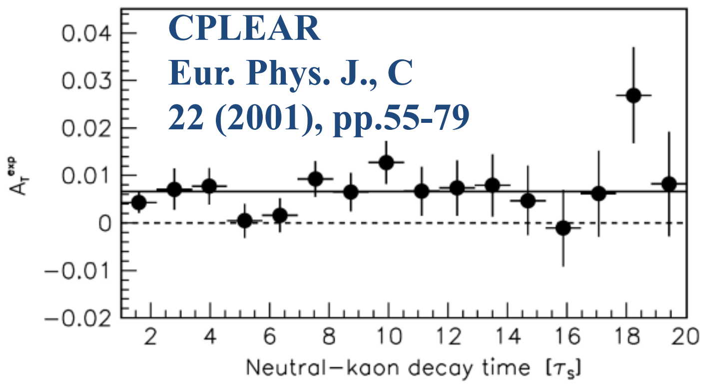
- Searching TRV in decays
  - $\Gamma(K^-\pi^+ \rightarrow \bar{B}^0) \neq \Gamma(K^+\pi^- \rightarrow B^0)$???

- Searching TRV in mixing
  - CPLEAR: $\mathrm{Prob}(K^0 \rightarrow \bar{K}^0) \neq \mathrm{Prob}(\bar{K}^0 \rightarrow K^0)$

  $\rightarrow$ CPV and TRV cannot be distinguished
  - Nothing similar in the B^0 system ($\Delta\Gamma \sim 0$)

- Searching TRV in interferences
  - Neither motion reversal nor exchange of initial and final states!





Innovative analysis methodology

- Use Einstein-Podolsky-Rosen entanglement @ $\Upsilon(4S)$ to overcome the problem of irreversibility

Method described in J. Bernabeu *et al.* arXiv:1203.0171 [hep-ph]

- $\Upsilon(4S)$ decay: use two sets of orthogonal states
  - Flavor eigenstates B^0 and $\bar{B}^0$
  - CP eigenstates B_{CP+} and B_{CP-}

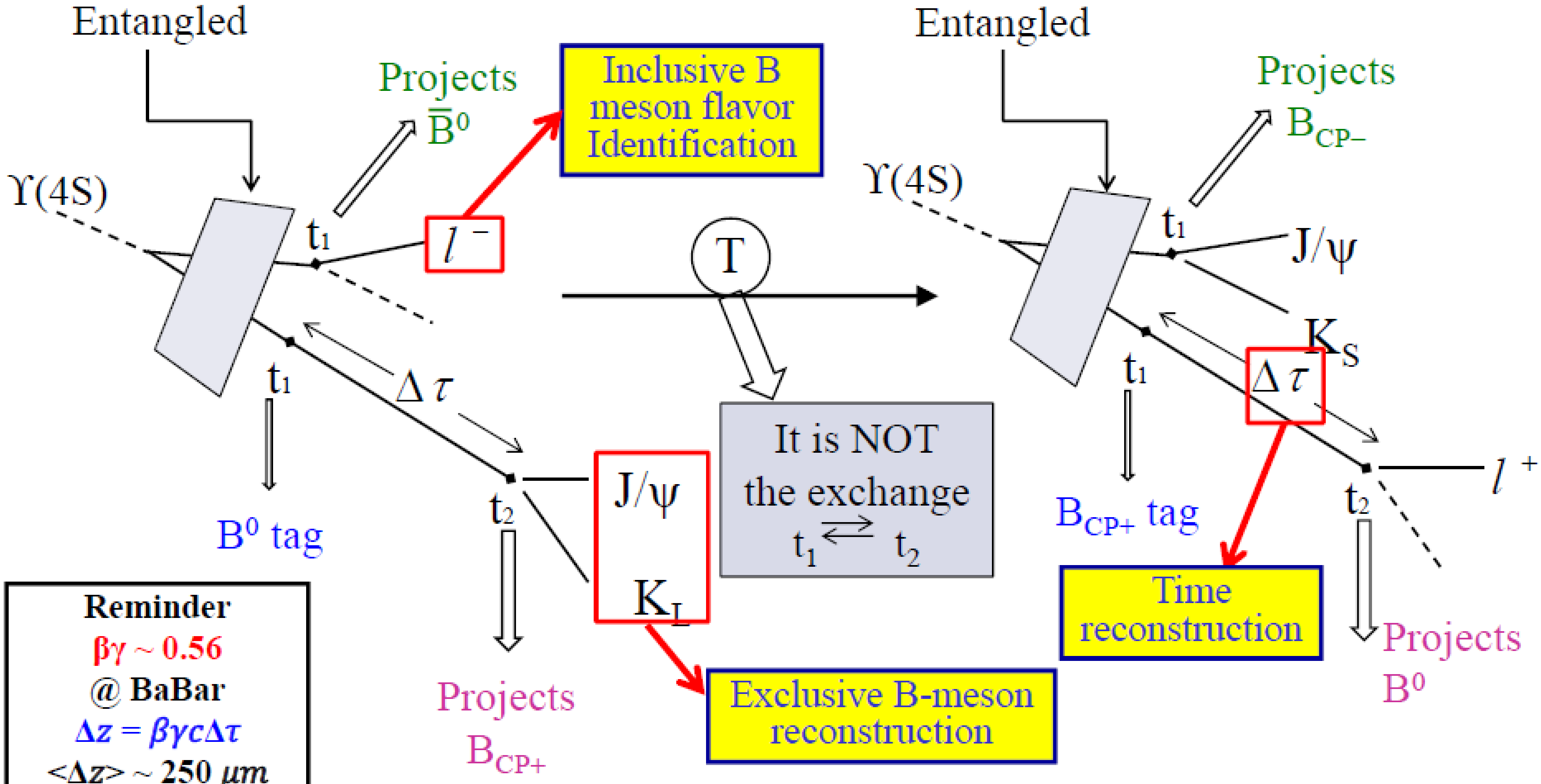
$$< in >= \frac{1}{\sqrt{2}}\left[B^0(t_1)\bar{B}^0(t_2) - \bar{B}^0(t_1)B^0(t_2)\right] = \frac{1}{\sqrt{2}}\left[B_{CP+}(t_1)B_{CP-}(t_2) - B_{CP-}(t_1)B_{CP+}(t_2)\right]$$

- Look for the following transitions
  - $B^0 \to B_{CP+}$
  - $B^0 \to B_{CP-}$
  - $\bar{B}^0 \to B_{CP+}$
  - $\bar{B}^0 \to B_{CP-}$
- and for their T-conjugates
  - $B_{CP+} \to B^0$
  - $B_{CP-} \to B^0$
  - $B_{CP+} \to \bar{B}^0$
  - $B_{CP-} \to \bar{B}^0$

- $\Delta\tau = t_{2nd\ decay} - t_{first\ decay}$
  - Time ordering matters!

- Tag B^0 flavor – using e.g. the sign of a prompt charged lepton ($B^0 \to l^+X$; $\bar{B}^0 \to l^-X$)
- Tag CP eigenstates by the final states $J/\psi K_L$ (CP+) and $J/\psi K_S$ (CP–)

Example of an event and of its T-conjugate

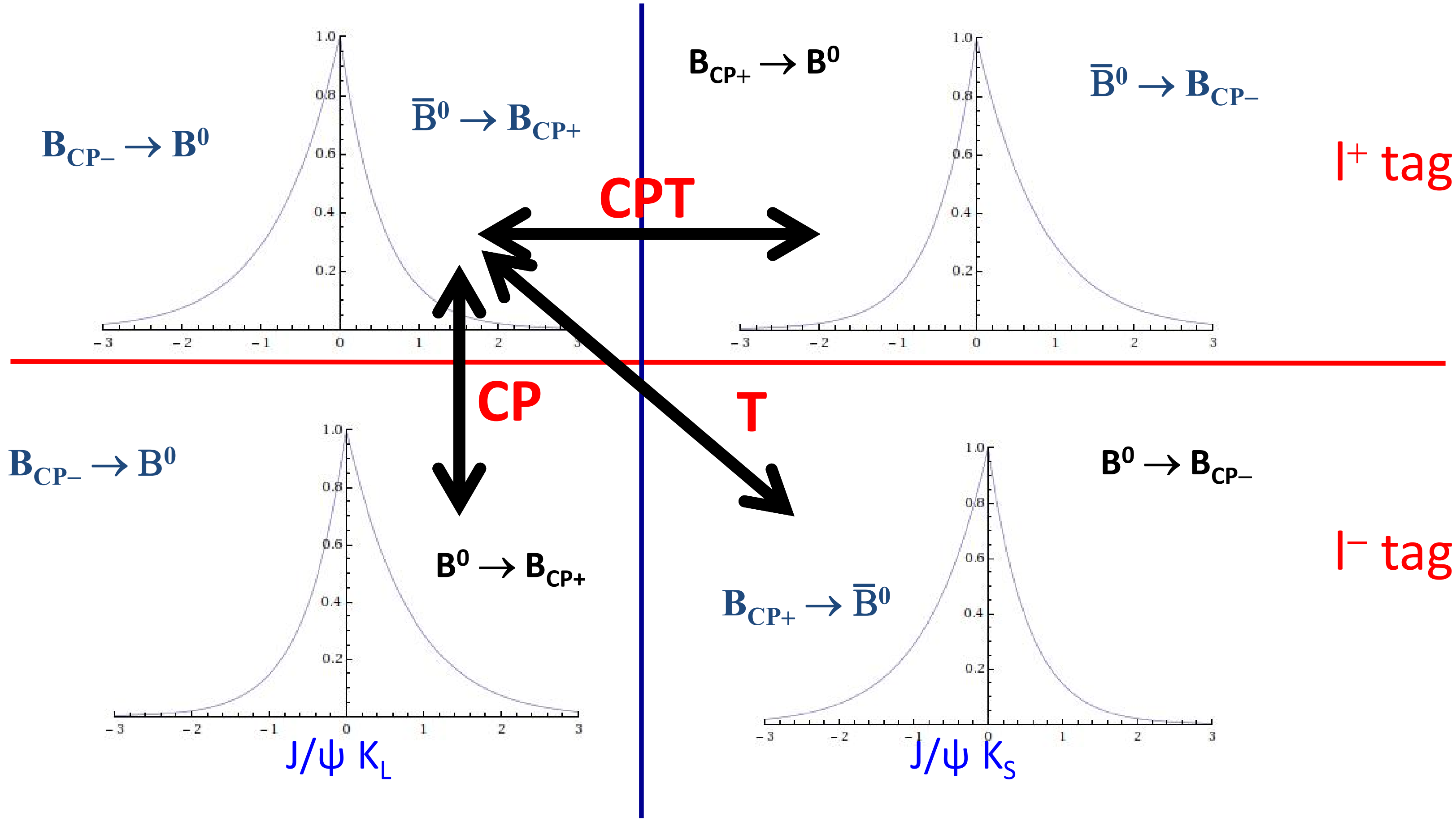


Reminder
$\beta\gamma \sim 0.56$
@ BaBar
$\Delta z = \beta\gamma c\Delta\tau$
$\langle\Delta z\rangle \sim 250\ \mu m$

$B^0 \xrightarrow{\Delta\tau} B_{CP+}$

$B_{CP+} \xrightarrow{\Delta\tau} B^0$

Connecting transitions through T, CP and CPT



- In total we can build
  - 4 independent T comparisons
  - 4 independent CP comparisons
  - 4 independent CPT comparisons
- T implies comparison of
  - Opposite $\Delta\tau$ sign
  - Different reco states ($J/\psi K_s$ vs $J/\psi K_L$)
  - Opposite tag states (B^0 vs $\bar{B}^0$)

Fit

Δm_d: B^0 mass difference

- Time dependent decay rates (τ>0):

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

  - α = B^0 or $\overline{B}^0$
  - β = $J/\psi K_S$ or $J/\psi K_L$
  - $\pm$ corresponds to the sign of $t_{\text{CP tagged decay}} - t_{\text{flavor tagged decay}}$

  8 decay rates total

- Different C and S for processes connected by T symmetry ⇒ TRV
- Signal model: $H_{\alpha,\beta}(\Delta t) \propto$

$$g^{+}_{\alpha,\beta}(\Delta t_{\text{true}}) \times \mathrm{H}(\Delta t_{\text{true}}) \otimes \mathcal{R}(\delta t, \sigma_{\Delta t})$$
$$+ g^{-}_{\alpha,\beta}(\Delta t_{\text{true}}) \times \mathrm{H}(-\Delta t_{\text{true}}) \otimes \mathcal{R}(\delta t, \sigma_{\Delta t})$$

  - H: Heaviside step function; R: resolution function; $\delta t = \Delta t - \Delta t_{\text{true}}$

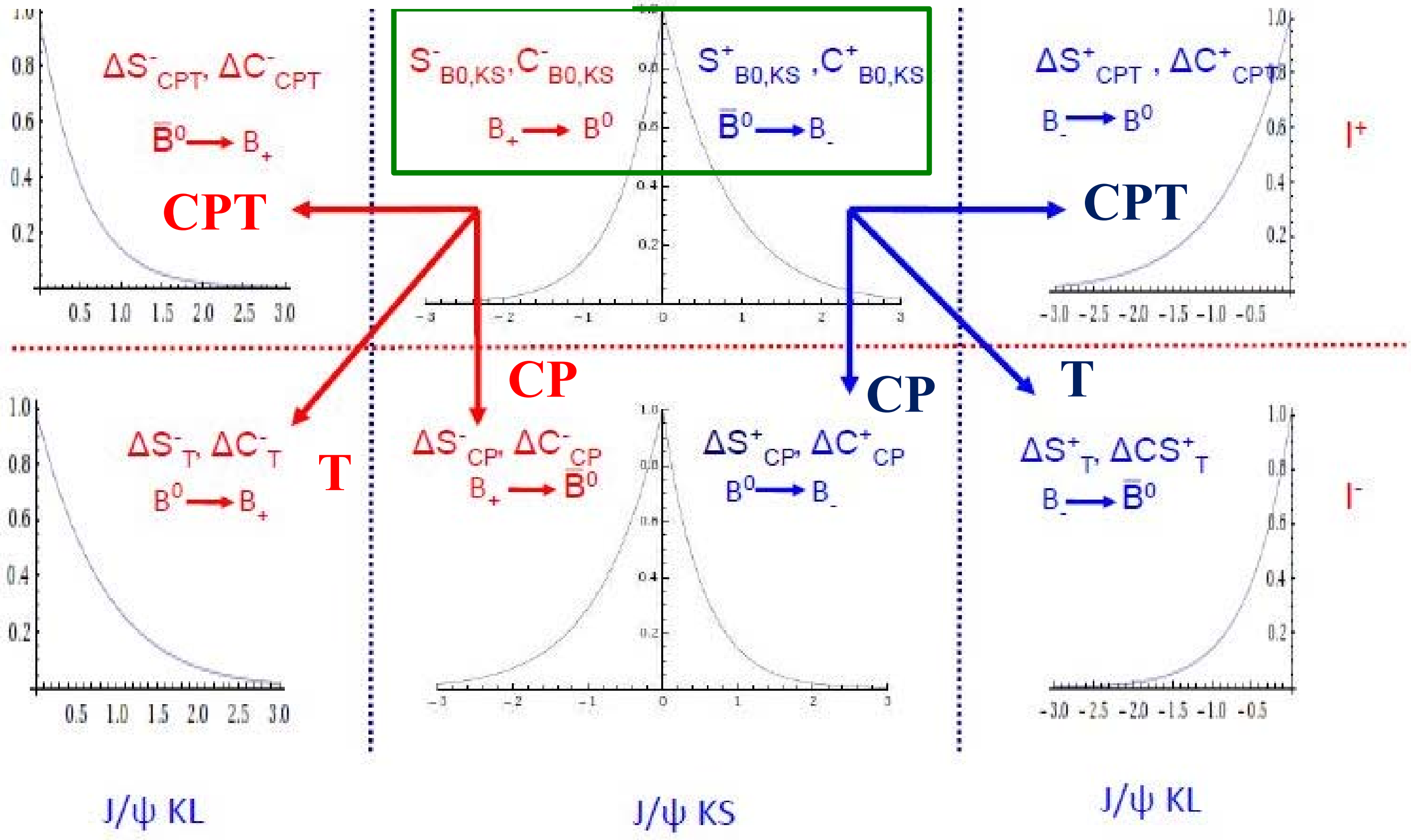
- Inperfect tagging taken into account
  → Mix correct and uncorrect flavor assignments; dilution of asymetries
- Unbinned maximum likelihood fit to the $c\bar{c}K_S$ and $c\bar{c}K_L$ events, split by flavor
- Background accounted for by adding terms to the likelihoods

Alternative parameterization: $\{S,C\} \rightarrow \{\Delta S, \Delta C\}$

- 8 {S,C} sets $\Rightarrow$ T, CP and CPT violating parameters $\{\Delta S_{T,CP,CPT}, \Delta C_{T,CP,CPT}\}$
- Definition of the $\Delta S_{\{T,CP,CPT\}}$ parameters
  - Decays with a B^0 and $J/\psi K_S$ taken as references

    $\rightarrow$ e.g. $\Delta S_{\mathrm{T}}^{-} = S^{+}_{\ell^- X, J/\psi K^0_L} - S^{-}_{\ell^+ X, c\bar{c}K^0_S}$

- Similar definitions for ΔC



- Any non-zero $\Delta S/\Delta C$ parameter corresponds to a symmetry violation

Fit results

Parameter	Final result	Expected values given $\sin(2\beta) \approx 0.7$
$\Delta S_{\mathrm{T}}^{+}$	$-1.37 \pm 0.14 \pm 0.06$	–1.4
$\Delta S_{\mathrm{T}}^{-}$	$1.17 \pm 0.18 \pm 0.11$	1.4
$\Delta C_{\mathrm{T}}^{+}$	$0.10 \pm 0.16 \pm 0.08$	0.0
$\Delta C_{\mathrm{T}}^{-}$	$0.04 \pm 0.16 \pm 0.08$	0.0
$\Delta S_{\mathrm{CP}}^{+}$	$-1.30 \pm 0.10 \pm 0.07$	–1.4
$\Delta S_{\mathrm{CP}}^{-}$	$1.33 \pm 0.12 \pm 0.06$	1.4
$\Delta C_{\mathrm{CP}}^{+}$	$0.07 \pm 0.09 \pm 0.03$	0.0
$\Delta C_{\mathrm{CP}}^{-}$	$0.08 \pm 0.10 \pm 0.04$	0.0
$\Delta S_{\mathrm{CPT}}^{+}$	$0.16 \pm 0.20 \pm 0.09$	0.0
$\Delta S_{\mathrm{CPT}}^{-}$	$-0.03 \pm 0.13 \pm 0.06$	0.0
$\Delta C_{\mathrm{CPT}}^{+}$	$0.15 \pm 0.17 \pm 0.07$	0.0
$\Delta C_{\mathrm{CPT}}^{-}$	$0.03 \pm 0.14 \pm 0.08$	0.0
$S_{\mathrm{B^0,K_S^0}}^{+}$	$0.545 \pm 0.084 \pm 0.06$	0.7
$S_{\mathrm{B^0,K_S^0}}^{-}$	$-0.660 \pm 0.059 \pm 0.04$	–0.7
$C_{\mathrm{B^0,K_S^0}}^{+}$	$0.011 \pm 0.064 \pm 0.05$	0.0
$C_{\mathrm{B^0,K_S^0}}^{-}$	$-0.049 \pm 0.056 \pm 0.03$	0.0

Interpretation of the results

- Nominal fit on the 8 independent samples provides S's and C's + a likelihood value
  → How significant is the observed T violation?

- Repeat the fit including T-invariance constraints
  - Variation of $-2\Delta\ln L$ gives the T violation significance: $\Delta\chi^2 = -2(\ln L_{NoTRV} - \ln L)$ for 8 degrees of freedom

$$\begin{cases} \Delta S_T^{\pm} = \Delta C_T^{\pm} = 0 \\ \Delta S_{CP}^{\pm} = \Delta S_{CPT}^{\pm} \\ \Delta C_{CP}^{\pm} = \Delta C_{CPT}^{\pm} \end{cases}$$

- Compute T-violation significance
  - CP and CPT significances estimated the same way

	Significance (syst. included)
Time reversal violation	14σ
CP violation	16.6σ
CPT violation	0.33σ

- Results
  - TRV observed at the 14σ level
    → First direct observation (no experimental connection with CP or CPT)
  - Consistent with CP violation measurement assuming CPT invariance

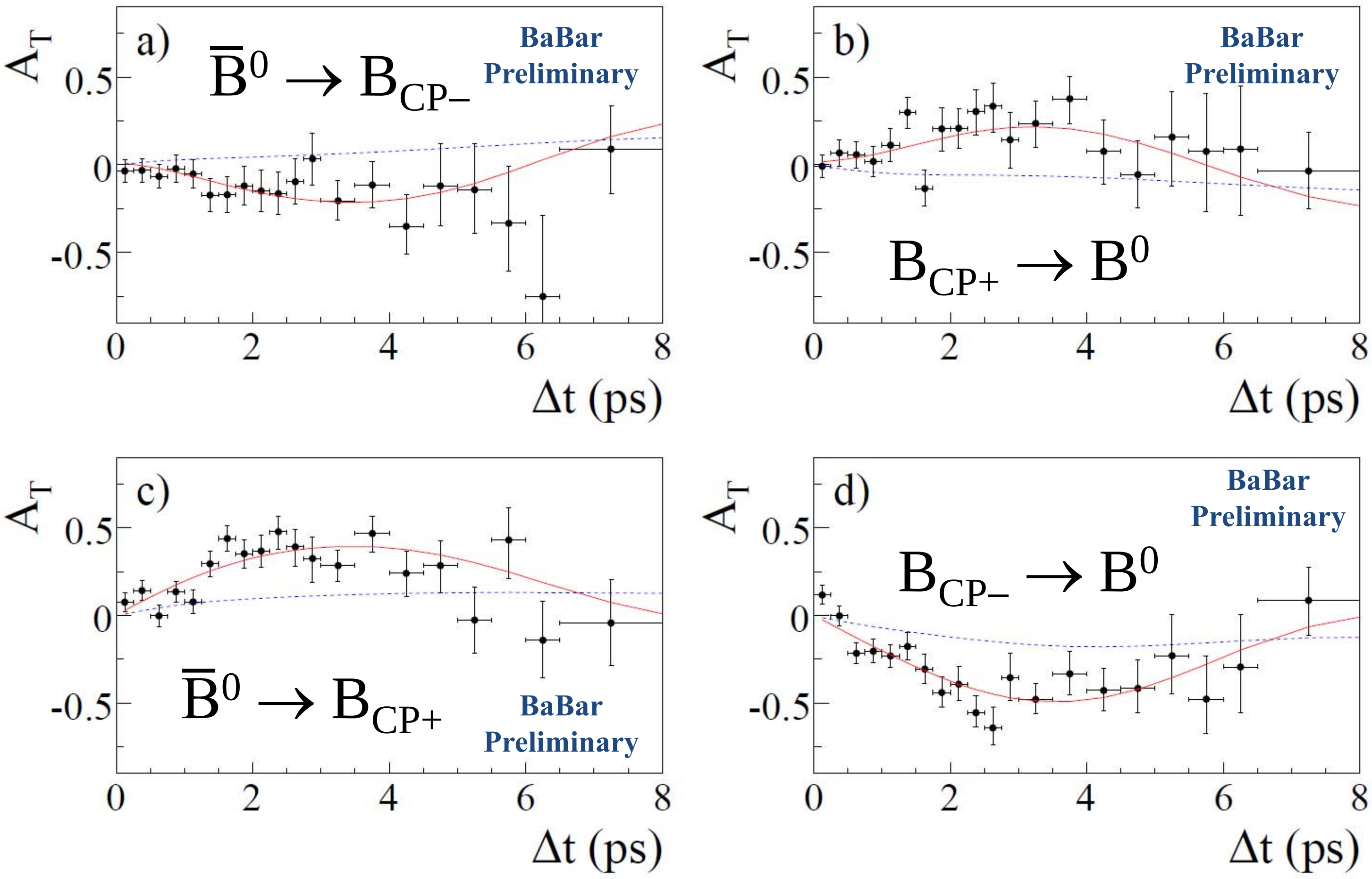
T Asymmetries

- Asymmetries for the 4 transitions studied (assuming perfect reconstruction):
  $\overline{B}^0 \rightarrow B_{CP+}$
  $\overline{B}^0 \rightarrow B_{CP-}$
  $B_{CP+} \rightarrow B^0$
  $B_{CP-} \rightarrow B^0$

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

- Nominal fit
  $\rightarrow$ TRV

- Fit w/o TRV



B_s semileptonic branching fraction

Phys. Rev. D 85, 011101(R) (2012)

Motivation & method

- Use inclusive ϕ rate and ϕ rate in correlation with high momentum lepton to measure
  - B_s production rate vs. energy in scan region: f_s
    → Only known at the ϒ(5S) peak (CLEO, 2007)
    or in the onpeak region (Belle, 2007)
  - B_s semileptonic branching ratio: $Br(B_s \to Xl\nu)$
    → Preliminary result from Belle (2010)

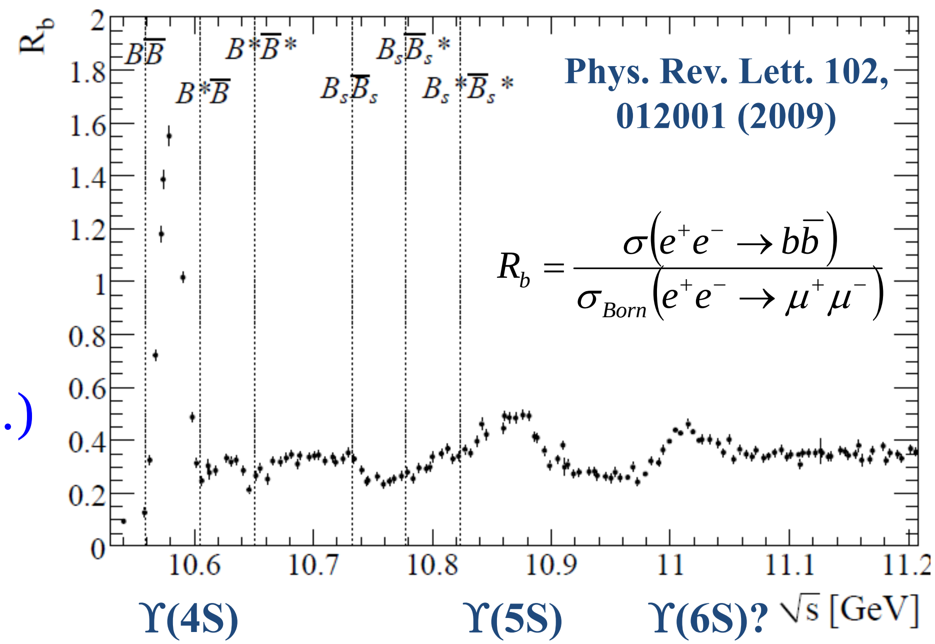
$$f_s = \frac{N_{B_s}}{N_{B_s} + N_{B^0} + N_{B^+}}$$

- ϕ (+ lepton) yields from B_s large compared to $B_{u/d}$ decays (dominant production)
  - CKM-favored $B_s \to D_s$ transition

- Use BaBar data from the final energy scan

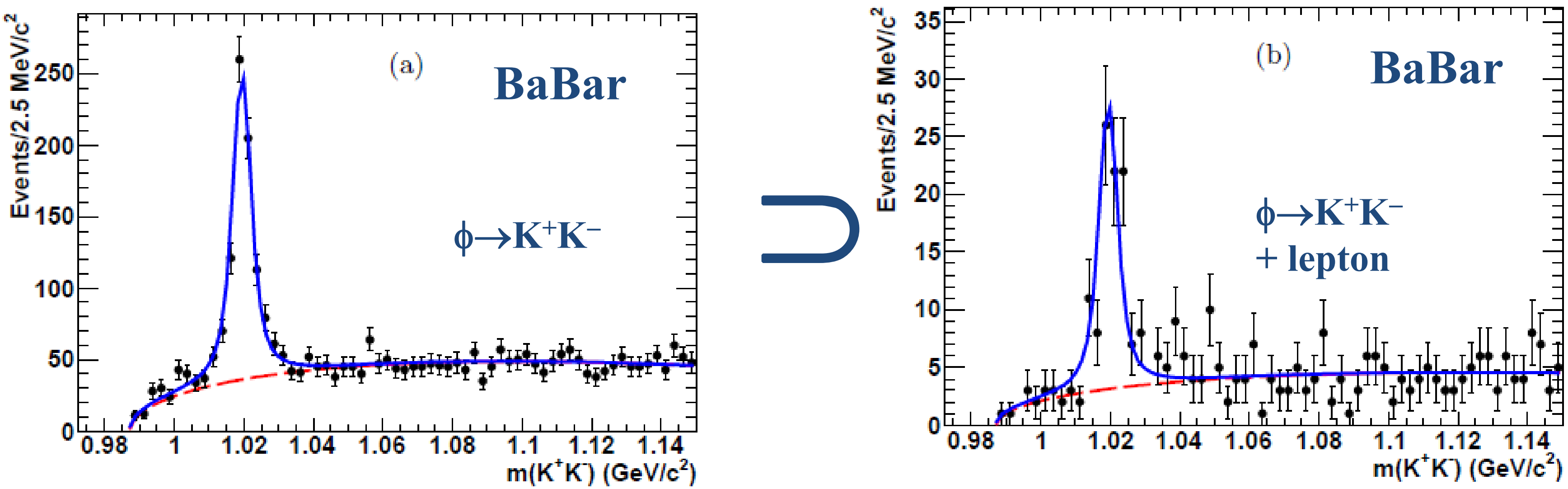
- Compute 3 quantities at each energy:
  - B hadron event rate = $f_1(R_b, f_s, \ldots)$
  - Inclusive ϕ rate = $f_2(R_b, f_s, \ldots)$
  - Inclusive ϕ+lepton rate = $f_3(R_b, f_s, Br, \ldots)$

  → Other quantities known or computed
  → Extract f_s from the first two equations
  → Estimate Br from a likelihood scan



Analysis key points

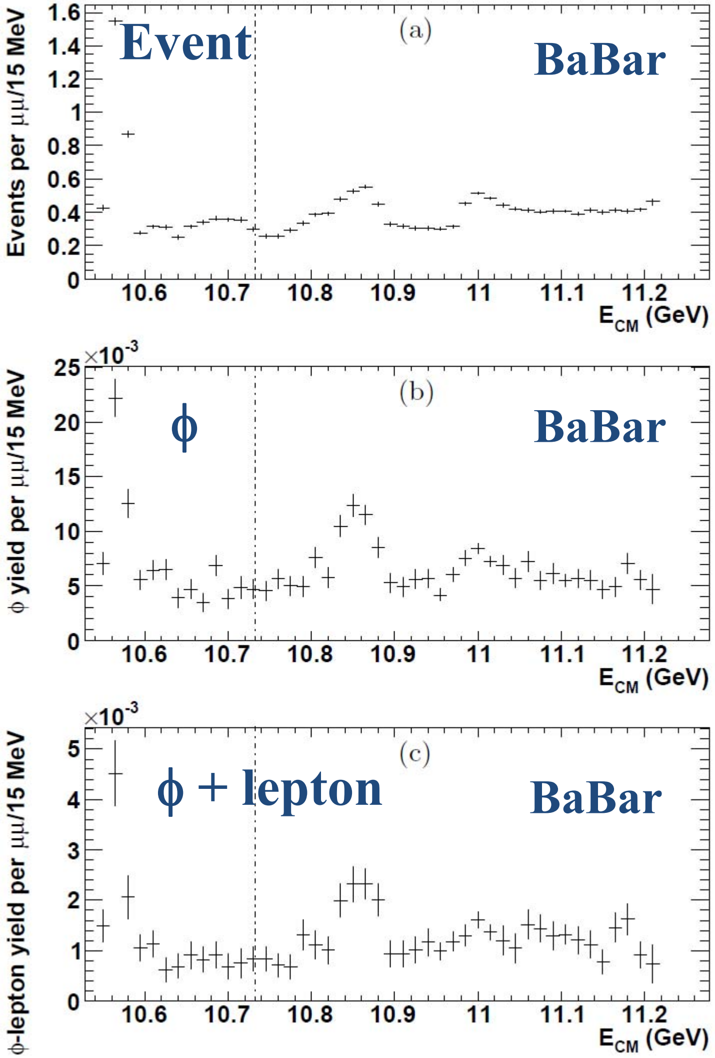
- Continuum contribution subtracted using data below the $B\bar{B}$ threshold
- $B_{u/d}$ contributions measured in $\Upsilon(4S)$ data
- f_s extracted at each energy point
- χ^2 fit performed to the measured yields to extract the semileptonic branching ratio
- Dominant systematics: inclusive D_s yield per B_s



For a given representative energy scan point

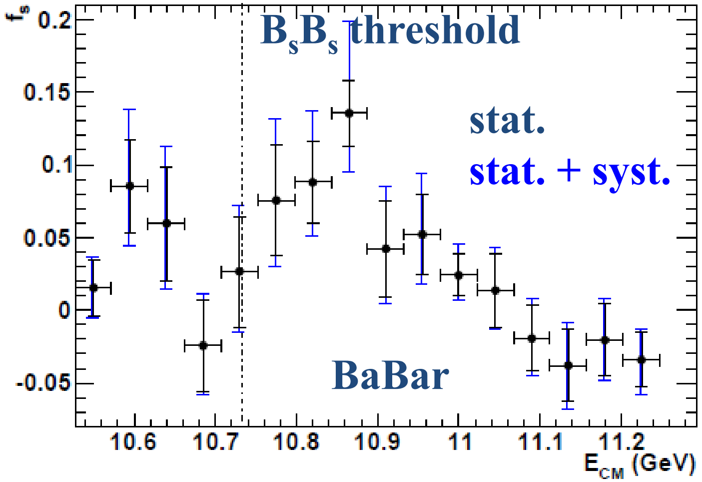
Results and interpretation

- Relative yields



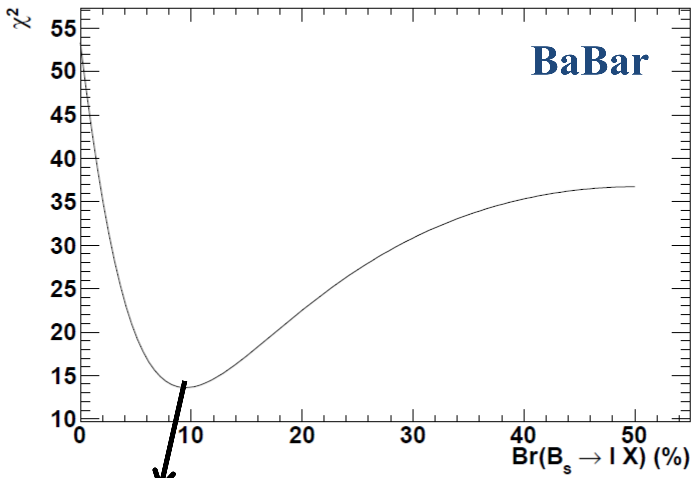
→ Consistent with theoretical predictions

- f_s



→ Consistent with theory predictions
  - B_s production peaks near $\Upsilon(5S)$
  - Off-resonance production small

- Scan



$$B\left(B_s \rightarrow X l \nu\right) = \left(9.9^{+2.6}_{-2.1}(\text{stat})^{+1.3}_{-2.0}(\text{syst})\right)\%$$

$B \to \nu\bar{\nu}(\gamma)$
‘invisible’

arXiv:1206.2543 [hep-ex]

Submitted to PRD-RC

Motivation & analysis key points

- Look for B decays producing neutrinos and potentially some exotic particles

- SM: $B^0 \rightarrow \nu\bar{\nu}$ suppressed by $(m_\nu/m_B)^2$
  $BF(B^0 \rightarrow \nu\bar{\nu}\gamma) \sim 10^{-9}$

  << experimental reach

- In some SUSY models, BRs can be as high as 10^{-7}–10^{-6}
  - Neutrino + neutralino production in the final state

  $\rightarrow$ Any signal would be a clear sign of new physics

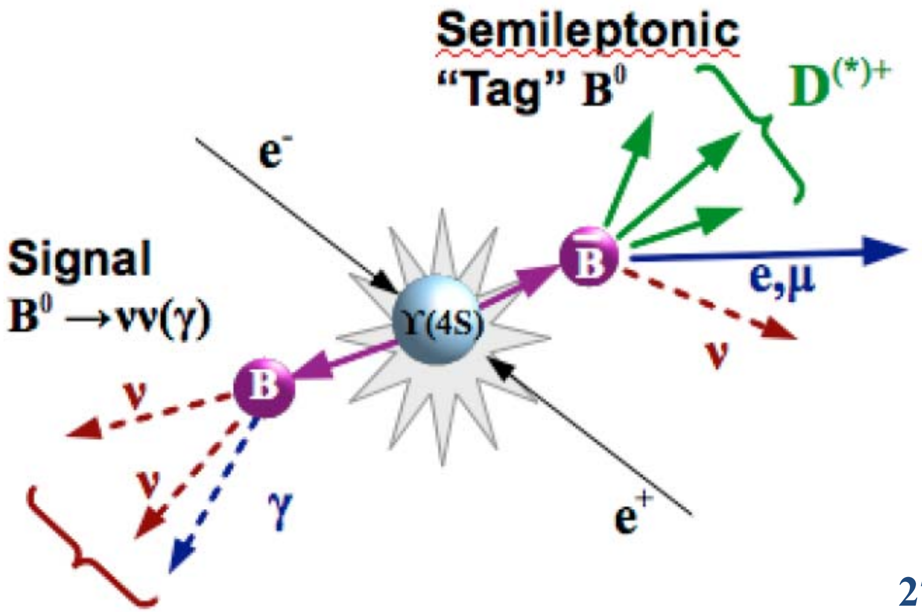
- Semileptonic reconstruction of the B_{tag}

- Require no additional charged tracks on the B_{sig} side

- Select events with limited energy in the calorimeter on the signal side
  $\rightarrow$ Low 'extra energy': E_{extra}

$B^0 \rightarrow D^- l \nu$
$D^- \rightarrow K^+\pi^-\pi^-$
$D^- \rightarrow K_S\pi^-$

$B^0 \rightarrow D^{*-} l \nu$
$D^{*-} \rightarrow D^0\pi^-, D^-\pi^0$
$D^0 \rightarrow K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$

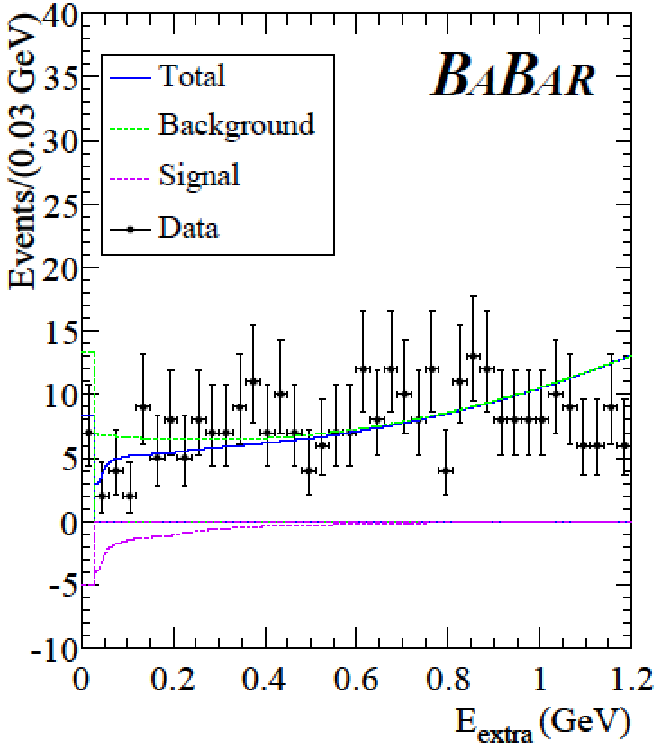


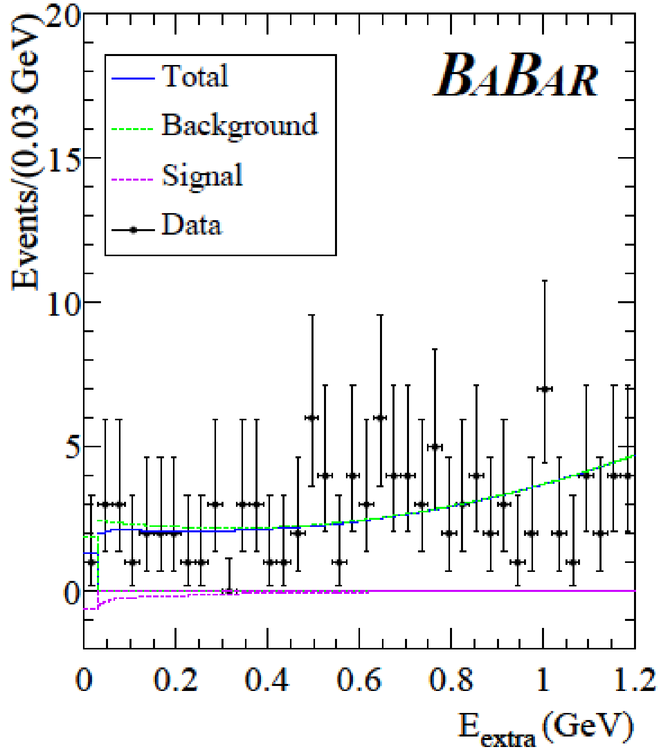
Results

- No signal found
  - Upper limits

	$B^0 \to$ invisible	$B^0 \to$ invisible + γ
Fitted yield	$-22 \pm 9 \pm 16$	$-3.1 \pm 5.2 \pm 7.0$
Signal efficiency	0.018%	0.016%
Br upper limit (90% C.L.)	2.4×10^{-5}	1.7×10^{-5}
Previous BaBar upper limit (based on ~20% of the full dataset)	22×10^{-5}	4.7×10^{-5}

- Fit results





Summary

- Significant excess of events in $B \to D^{(*)}\tau\nu$ decays
  $\to$ 3.4σ above the Standard Model
  - Cannot be explained by a 2DHM Higgs of Type II
    $\to$ Completely ruled out
  - Waiting for a confirmation by Belle – larger dataset + improved tagger

- First direct observation (14σ) of Time-reversal violation

- First measurement of the B_s semileptonic branching fraction

$$B(B_s \to Xl\nu) = \left(9.9^{+2.6}_{-2.1}(\text{stat})^{+1.3}_{-2.0}(\text{syst})\right)\%$$

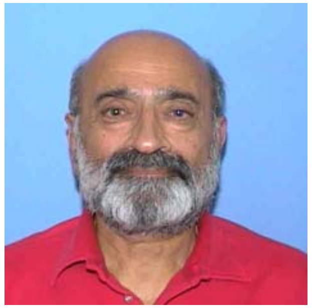
  - plus the B_s production fraction

- Significantly improved limits on $B \to$ invisible $(+\gamma)$

$Br(B \to \text{invisible}) < 2.4 \times 10^{-5}$
$Br(B \to \text{invisible} + \gamma) < 1.7 \times 10^{-5}$
@ 90% C.L.

- Only a fraction of recent BaBar results
  - Analysis ongoing for a variety of processes
  $\to$ To be continued…

Dedicated to the memory of **Popat Patel** (McGill)



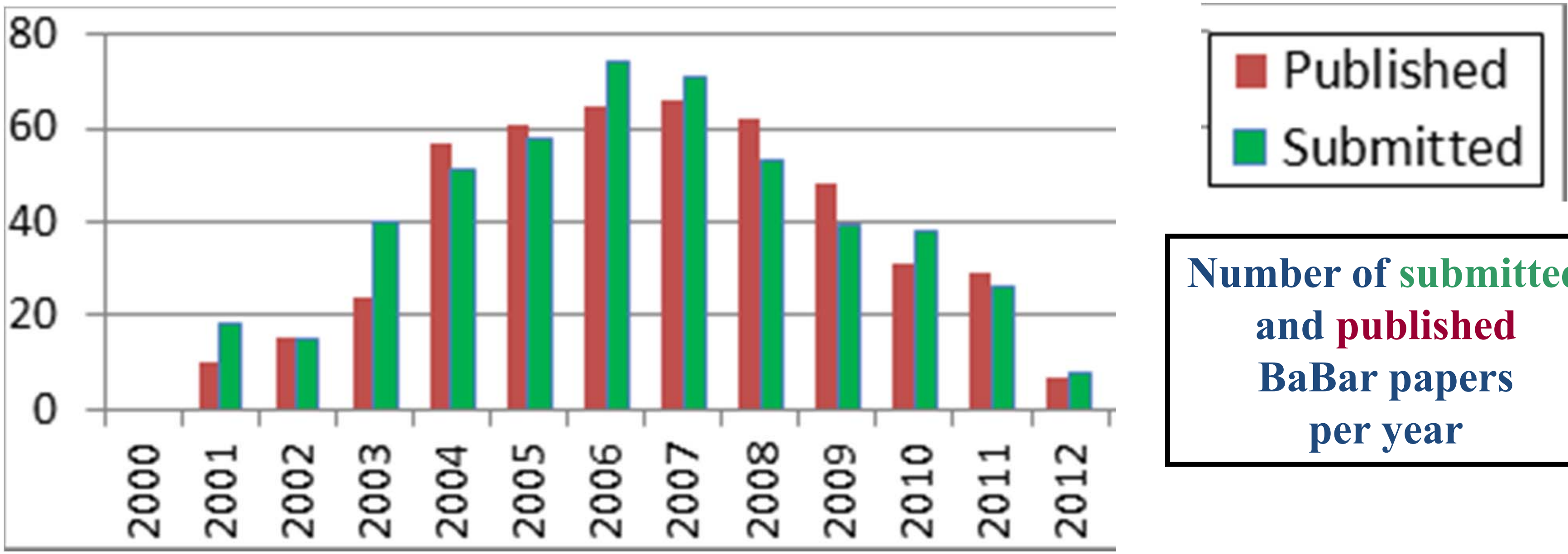
who passed away last Saturday

BACKUP

BaBar is still an active collaboration

- Data taking ended more than four years ago
  - April 7th 2008 @ 12:43 SLAC time
- But the analysis of the BaBar data is still going on
  - Updates of analysis with the full dataset and improved methods; new ideas

  → Analysis switching to the Long Term Data Analysis system



Number of submitted and published BaBar papers per year

- Completion of the 'Physics of the B-Factories' book – BaBar + Belle
- Publication of the final BaBar detector paper later this year
  - Covering the high luminosity period 2002-2008

Analysis method: B decay reconstruction

- Limited kinematical information due to neutrino(s) in the final states
  $\rightarrow$ Reconstruction of one of the B mesons in 1680 exclusive hadronic modes:
  $B_{tag} \rightarrow SX^{\pm}$, S being a seed meson($D_{(s)}^{(*)}$ or J/ψ)
  and $X^{\pm}$ a charged state decaying to up to 5 hadrons (π, K, π^0 and K_S)

- Btag candidates selected using two kinematical variables
  - The beam energy-substituted mass $m_{ES} = \sqrt{(E^*_{beam})^2 - (p^*_{tag})^2}$
    $\rightarrow$ Peaks at the B mass for signal with a 2.5 MeV/c^2 resolution
  - The energy difference $\Delta E = E^*_{tag} - E_{beam}$
    $\rightarrow$ Centered at 0 for signal with a 18 MeV resolution

- Signal B corresponds to the rest of the event (tracks + energy deposits)
  $\rightarrow$ Improved knowledge of kinematics and missing energy

- Hadronic tag method helps fighting combinatorial background
  $\rightarrow$ Light quark pairs: $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, $c\bar{c}$ – the 'continuum'

- B_{tag} candidate combined with a $D^{(*)}$ meson candidate and a charged lepton l
  - No additional charged particle
  - $B\bar{B}$ pair with the lowest extra energy selected

Backup for the $D^{(*)}\tau\nu$ analysis

- Background fighting
  - Cut on the leptonic mass squared: $q^2 > 4$ GeV^2
  - Missing momentum in c.m. frame > 200 MeV/c
  - Use of boosted decision trees for each of the 4 $D^{(*)}l\nu$ samples

- Semileptonic decay involving a τ lepton:

$$\frac{d\Gamma_\tau}{dq^2} = \frac{G_F^2|V_{cb}|^2|\mathrm{p}|q^2}{96\pi^3 m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2\left[\left(|H_{++}|^2+|H_{--}|^2+|H_{00}|^2\right)\left(1+\frac{m_\tau^2}{2q^2}\right)+\frac{3}{2}\frac{m_\tau^2}{q^2}|H_{t}|^2\right]$$

  - Only H_{00} and H_t contribute to $D\tau\nu$

- A charged Higgs (2HDM type II) of spin 0 coupling to the τ will only affect H_t

$$H_t^{2\mathrm{HDM}} = H_t^{\mathrm{SM}} \times \left(1 - \frac{\tan^2\beta}{m_{H\pm}^2}\frac{q^2}{1 \mp m_c/m_b}\right)$$

– for $D\tau\nu$
+ for $D^*\tau\nu$

- This could enhance or decrease the ratios R(D*) depending on $\tan\beta/m_H$

TRV: dataset and event selection

- Use full BaBar dataset

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 $c\bar{c}K^\pm$, $J/\psi K^{*\pm}$	$B^+ \to J/\psi K^+$ $B^+ \to \psi(2S)K^+$ $B^+ \to J/\psi K^{*+}$

BCP-

BCP+

Flavor tagging **and Δt resolutions**

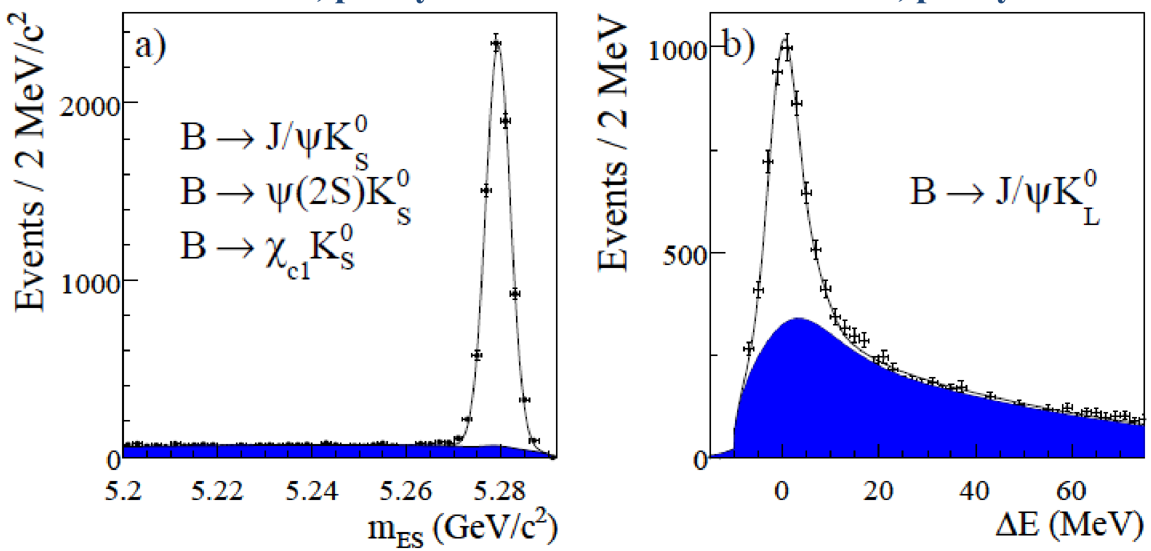
Fit

- 6 mutually exclusive categories
  - Efficiencies ε (9-17%)
  - MisID fractions ω (3-42%)

- $c\bar{c}K^0_S$ events characterized by m_{ES}
- $c\bar{c}K^0_L$ events characterized by ΔE

- $|\Delta t| < 20$ ps
- $\sigma_{\Delta t} < 2.5$ ps

7796 events, purity 87–96% **5813 events, purity ≈ 56%**



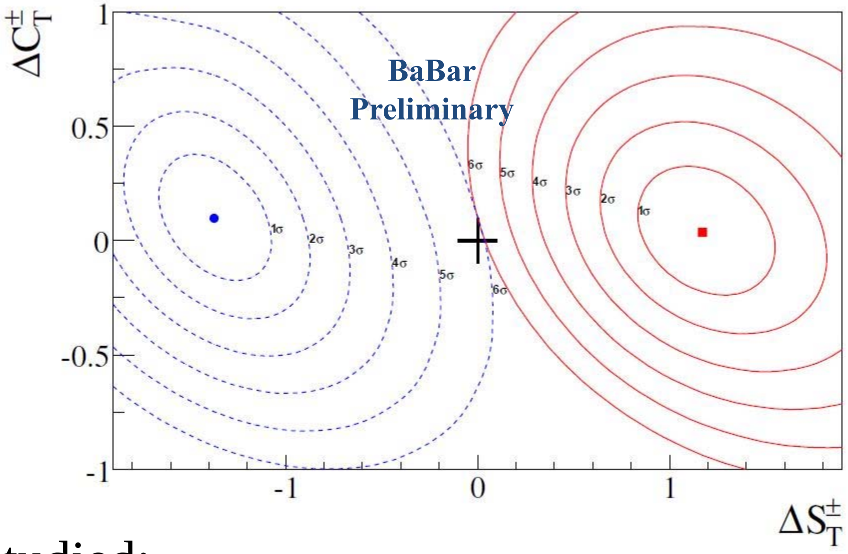
TRV analysis systematics

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

T violation: contours and raw asymmetries

- Contours in the (ΔC, ΔS) plane

$$\begin{aligned} \Delta S_T^+ &= -1.37 \pm 0.14 \pm 0.06 \\ \Delta S_T^- &= 1.17 \pm 0.18 \pm 0.11 \\ \Delta C_T^+ &= 0.10 \pm 0.16 \pm 0.08 \\ \Delta C_T^- &= 0.04 \pm 0.16 \pm 0.08 \end{aligned}$$



- Asymmetries for the 4 transitions studied:
  $\overline{B}^0 \to B_{CP+}$, $\overline{B}^0 \to B_{CP-}$, $B_{CP+} \to B^0$, $B^0 \to B_{CP-}$

  - For instance: $A_T(\Delta t) = \dfrac{\mathcal{H}^-_{\ell^- X, J/\psi K^0_L}(\Delta t) - \mathcal{H}^+_{\ell^+ X, c\bar{c}K^0_S}(\Delta t)}{\mathcal{H}^-_{\ell^- X, J/\psi K^0_L}(\Delta t) + \mathcal{H}^+_{\ell^+ X, c\bar{c}K^0_S}(\Delta t)}$ for Δt>0

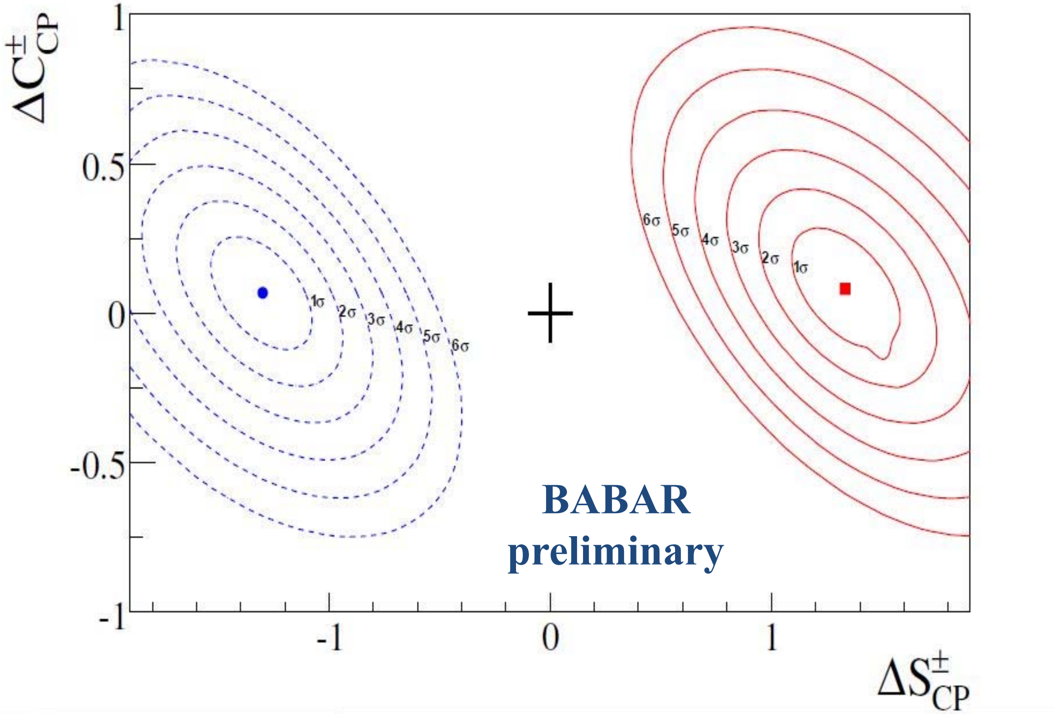
  with $\mathcal{H}^\pm_{\alpha,\beta}(|\Delta t|) \equiv \mathcal{H}^\pm_{\alpha,\beta}(\pm\Delta t) = \mathcal{H}_{\alpha,\beta}(\pm\Delta t) H(\Delta t)$

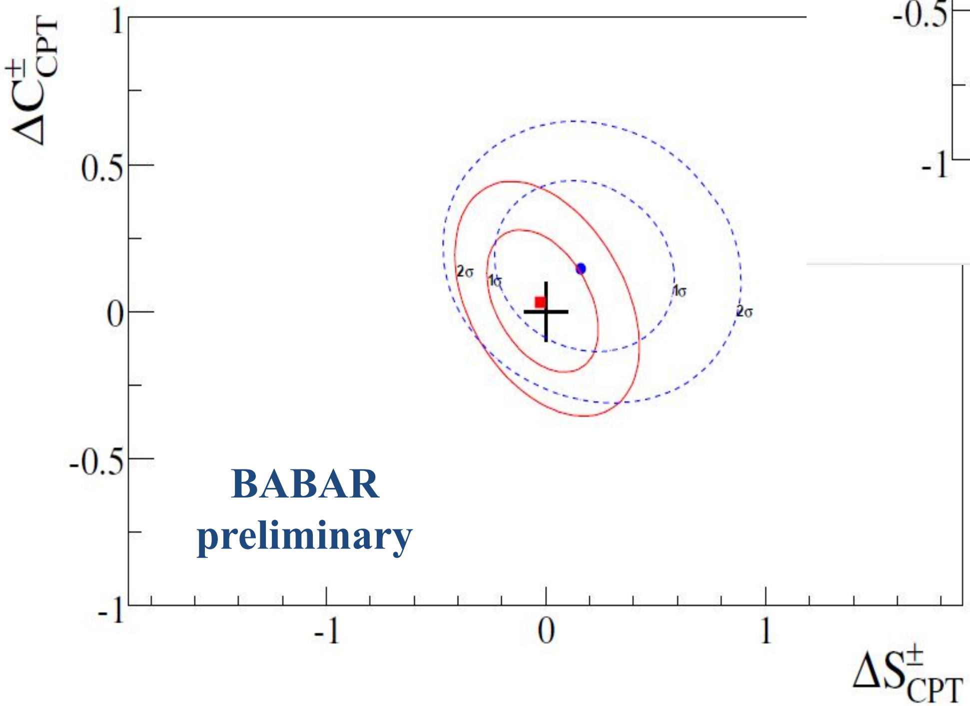
- Assuming perfect reconstruction

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

CP and CPT likelihood scans

$$\begin{aligned}
\Delta S^{+}_{CP} &= -1.30 \pm 0.10 \pm 0.07 \\
\Delta S^{-}_{CP} &= 1.33 \pm 0.12 \pm 0.06 \\
\Delta C^{+}_{CP} &= 0.07 \pm 0.10 \pm 0.03 \\
\Delta C^{-}_{CP} &= 0.08 \pm 0.09 \pm 0.04
\end{aligned}$$





$$\begin{aligned}
\Delta S^{+}_{CPT} &= 0.16 \pm 0.20 \pm 0.09 \\
\Delta S^{-}_{CPT} &= -0.03 \pm 0.13 \pm 0.06 \\
\Delta C^{+}_{CPT} &= 0.15 \pm 0.17 \pm 0.07 \\
\Delta C^{-}_{CPT} &= 0.03 \pm 0.14 \pm 0.08
\end{aligned}$$

Bs fraction and semileptonic branching fraction

- B hadron events: $$R_b\left[f_s\varepsilon_{1s}+(1-f_s)\varepsilon_1\right]$$
- Inclusive ϕ rate: $$R_b\left[f_s P\left(B_s\overline{B}_s\to\phi X\right)\varepsilon_{2s}+(1-f_s)P\left(B\overline{B}\to\phi X\right)\varepsilon_2\right]$$
- Inclusive ϕ+lepton rate: $$R_b\left[f_s P\left(B_s\overline{B}_s\to\phi l\,\nu X\right)\varepsilon_{3s}+(1-f_s)P\left(B\overline{B}\to\phi l\,\nu X\right)\varepsilon_3\right]$$

Contains information on $Br(B_s\to\phi l\nu)$

$B \to$ invisible analysis

- Neural Network to separate signal from background

- Extended maximum likelihood fit in E_{extra}
  - 2 species: signal & background
  - Minimum neutral energy threshold is 30 MeV
    $\to$ E_{extra} distribution not continuous: taken into account in the fit

- Analysis crosscheck with 'modes' $B^+ \to$ invisible ($+\gamma$) violating charge conservation
  - Signal consistent with 0

- $B^0 \to$ invisible + γ UL assumes that the γ momentum distribution follows the one given by the constituent quark model for $B^0 \to \nu\bar{\nu}\gamma$
- $B^0 \to$ invisible limit not decay-model dependent