Highlights from the BABAR experiment

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On behalf of the BABAR collaboration

ICFP 2012

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Outline

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

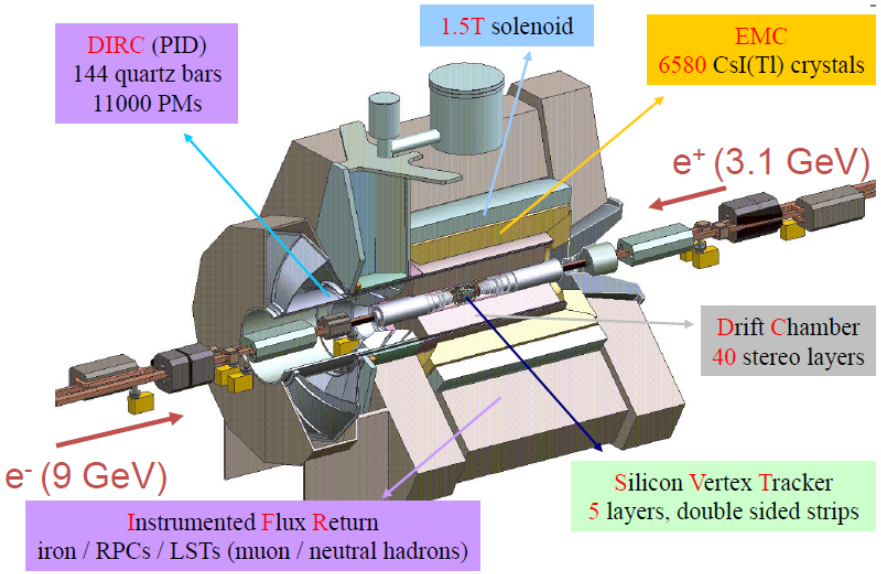
- Quick report – not exhaustive ! – of some recent results based on full dataset
  - B_s semileptonic branching fraction – already published
  - $B \to \nu\bar{\nu}(\gamma)$ – aka $B \to$ 'invisible' – submitted this Wednesday!
    arXiv:1206.2543 [hep-ex]

- 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)

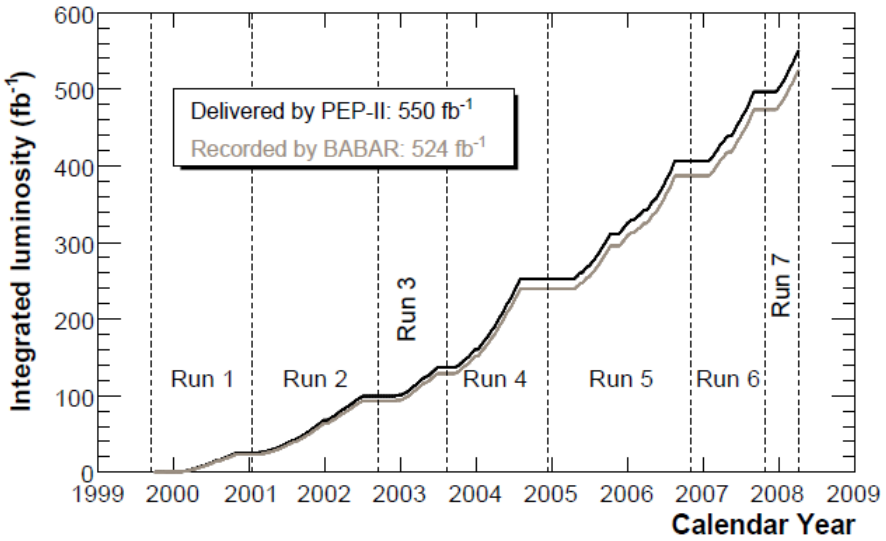
- All analysis reported in this talk use the full dataset available – see next slide

BaBar in a nutshell

- The BaBar detector



- The BaBar dataset



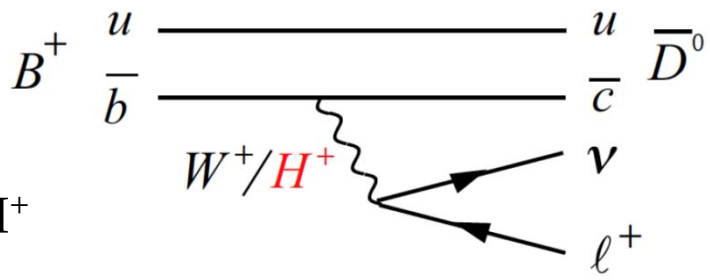
- Data taking ended more than 4 years ago (April 7th 2008)
  → But analysis are still going on – and will continue to do so for a few years
- 424 fb^{-1} @ $\Upsilon(4S)$ $\Leftrightarrow$ $(471.0 \pm 2.8) \times 10^6$ $B\bar{B}$ pairs – 'onpeak'
  - 44 fb^{-1} recorded 40 MeV below the peak – 'offpeak' – to study background
- 30.6 fb^{-1} @ $\Upsilon(3S)$ and 15.0 fb^{-1} @ $\Upsilon(2S)$ – onpeak + offpeak
  → $\eta_b(1S)$ discovery + searches for low-mass Higgs and dark gauge bosons
- ~3.9 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 $m_{ES} = \sqrt{\left(E^*_{beam}\right)^2 - \left(p^*_{tag}\right)^2}$
    → 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
  - $B\bar{B}$ 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 $m^2_{miss} = (P_{ee} - P_{Btag} - P_{D(*)} - P_\ell)^2$
    → Peaks at 0 for normalization events; broad distribution up to ~9 GeV^2 for signal
  - Lepton momentum in B_{sig} rest frame p^*_ℓ
    → 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 $B\bar{B}$, continuum [3]

- 4 $D^{(*)}\pi^0 l\nu$ control samples
  → 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

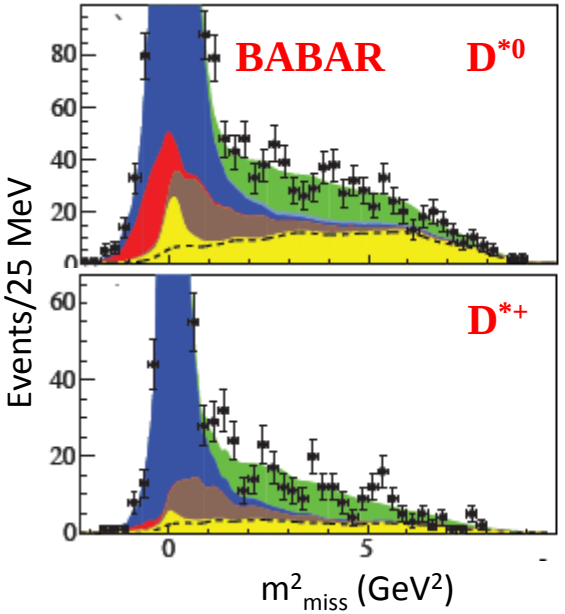
- Main systematics uncertainties
  - $D^{**}l\nu$ background – dominant ⇒ conservative estimation
  - Limited Monte-Carlo signal samples
  - Continuum and $B\bar{B}$ background

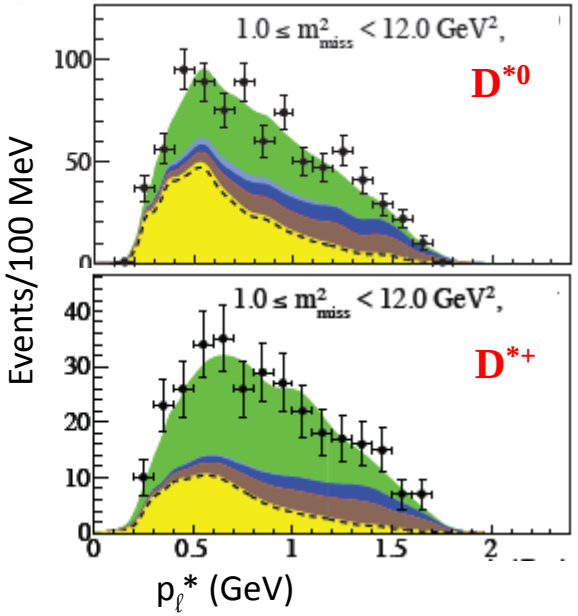
Fit results: $B \to D^{*}\tau\nu$

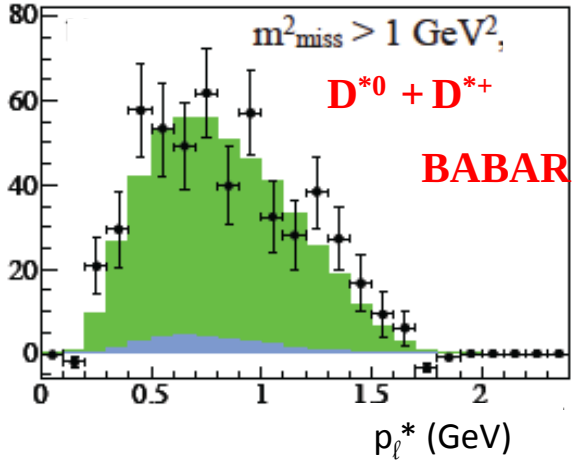
	$D^{*0}\tau\nu$	$D^{*+}\tau\nu$	$D^{*}\tau\nu$
$N_{\rm sig}$	639 ± 62	245 ± 27	888 ± 63
Significance (σ)	11.3	11.6	16.4
$R(D^{*})$	0.322 ± 0.032	0.355 ± 0.039	0.332 ± 0.024

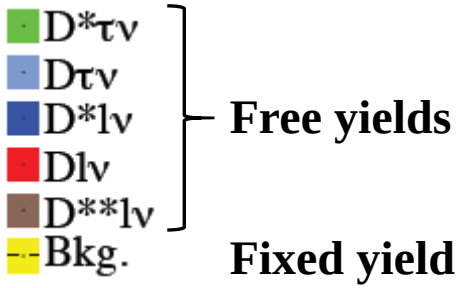
Isospin constrained

Statistical errors only







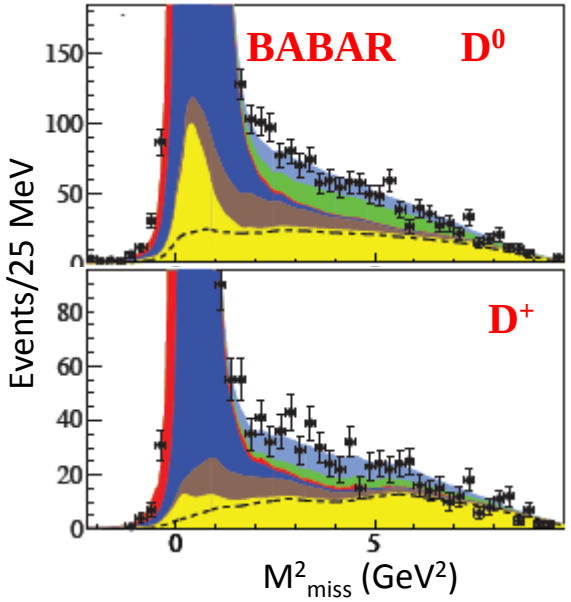


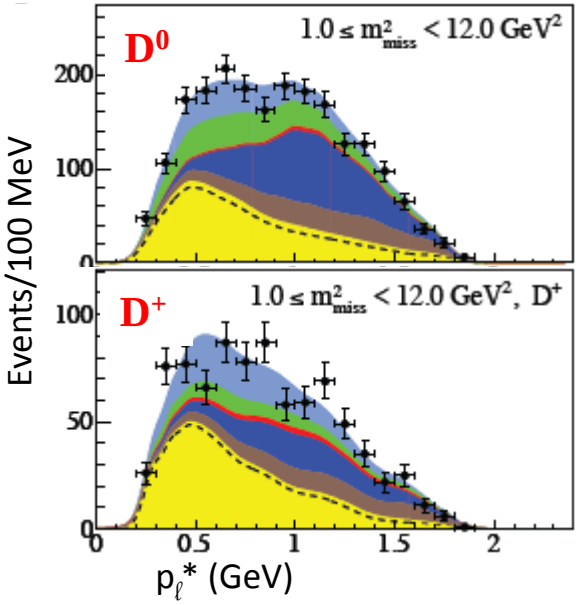
Fit results: B → Dτν

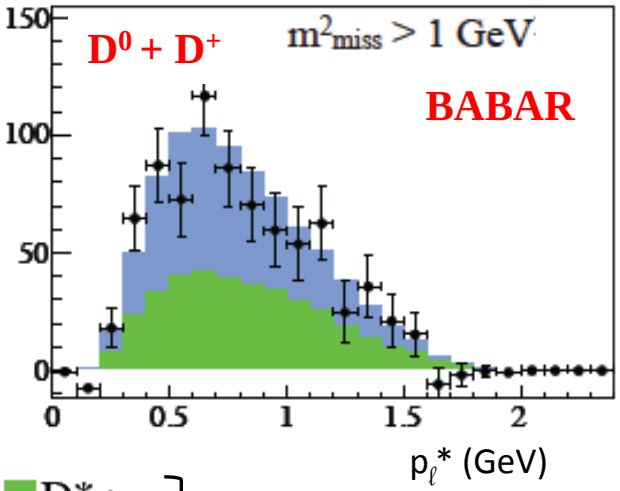
	$D^0\tau\nu$	$D^+\tau\nu$	$D\tau\nu$
$N_{\rm sig}$	314 ± 60	177 ± 31	489 ± 63
Significance (σ)	5.5	6.1	8.4
$R(D)$	0.429 ± 0.082	0.469 ± 0.084	0.440 ± 0.058

Statistical errors only

Isospin constrained







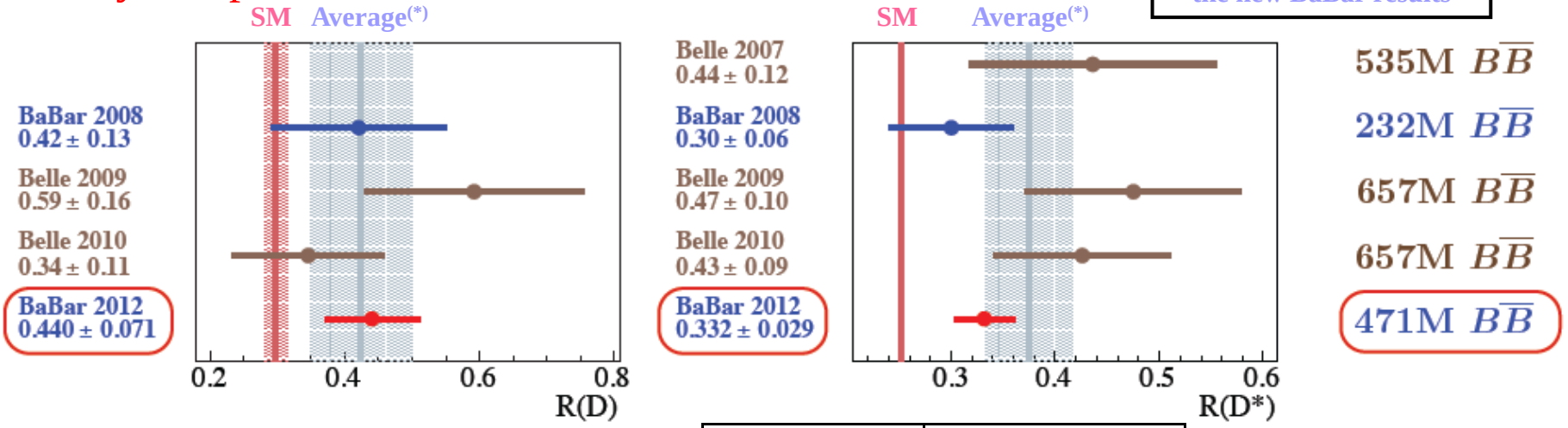
Free yields

Fixed yield

Comparison with the Standard Model prediction

- Fully compatible with earlier measurements …

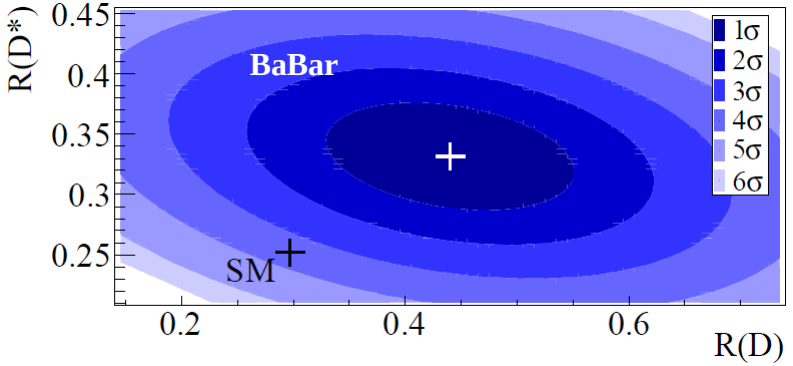
(*)Averages do not include the new BaBar results



- … 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 σ	2.7 σ

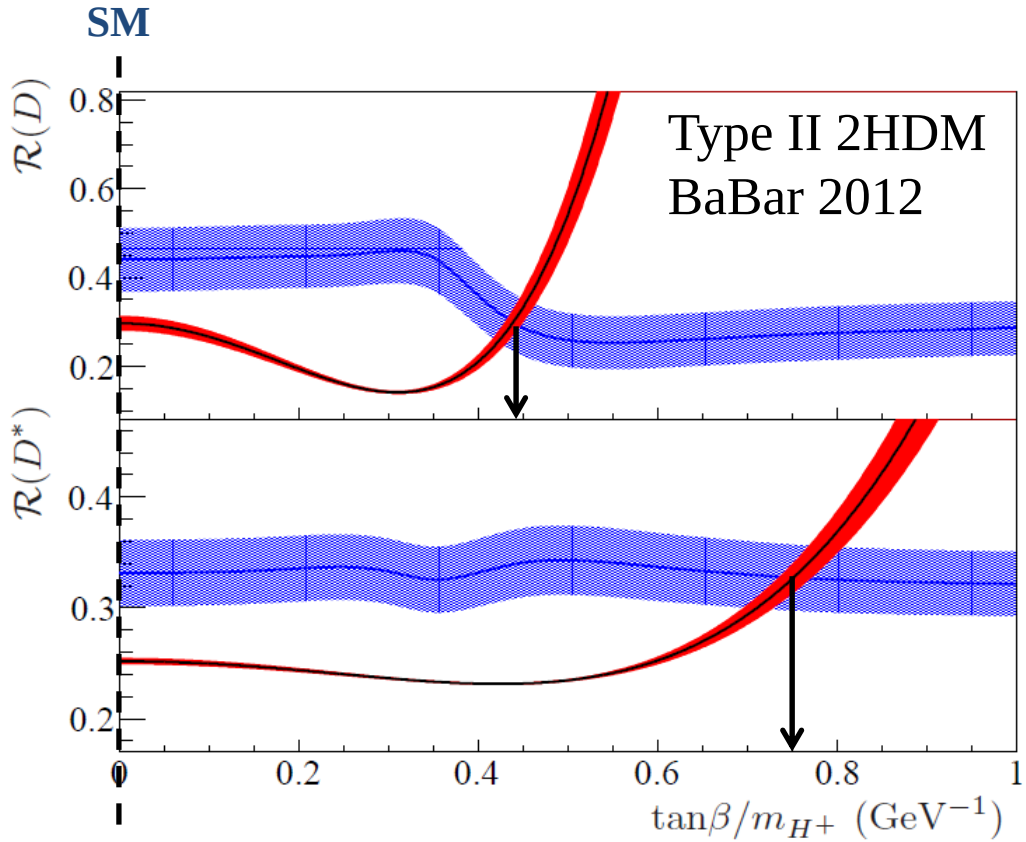
- Combination of the two measurements
  - Correlation of –0.27
    → Feed down from D* in D sample
  → χ^2/NDF = 14.6/2,
    p value = 6.9×10^{-4} [3.4σ away]



Interpretation for type II two-Higgs-doublet model

- Simulated events reweighted at the matrix element level for 20 values of $\tan\beta / m_{H^+}$
  → 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
  → Model excluded at 99.8% CL on the whole range for H^+ mass > ~10 GeV
  - Low-mass range already excluded by $B \to X_s \gamma$ data

Time-reversal violation

Preliminary result

To be submitted soon

Time reversal violation: challenging!

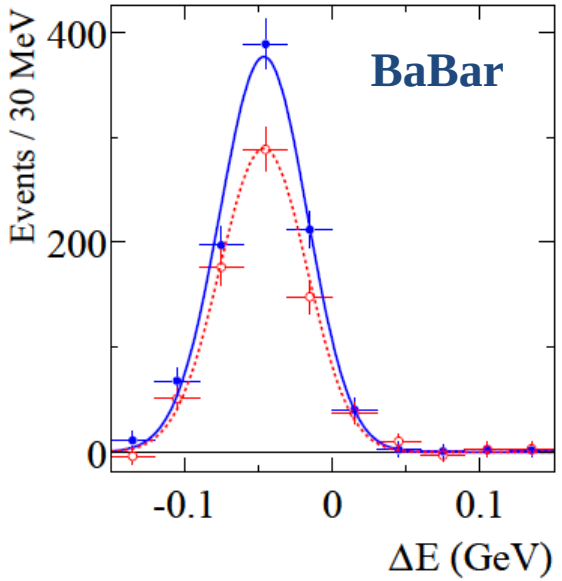
- The CP and T symmetries are theoretically connected through the CPT theorem
  - CP violation (CPV) established in K, B and D systems
  - But no proof yet of T non-invariance (TRV), not assuming CPV nor CPT

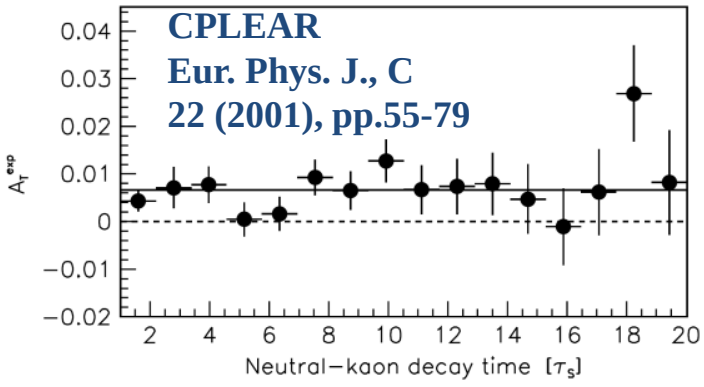
- TRV in a decay process requires
  - Reversal of motion ($t \rightarrow -t$)
  - And exchange of |in> and |out> states
    $\rightarrow$ Experimentally challenging

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

- Searching TRV in mixing
  - CPLEAR: Prob($K^0 \rightarrow \bar{K}^0$) $\neq$ 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 $\overline{B}^0$
  - CP eigenstates B_{CP+} and B_{CP-}

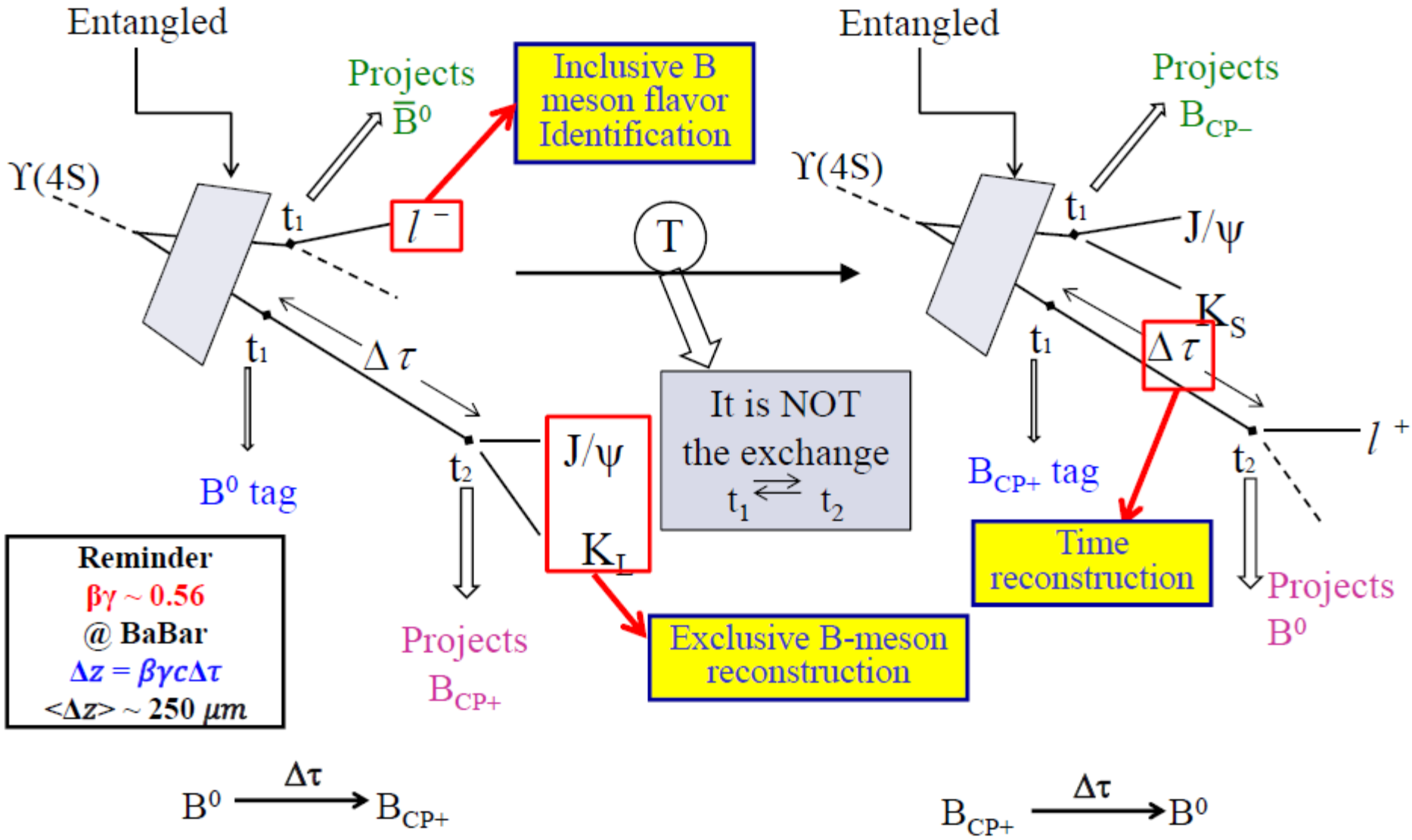
$$< in >= \frac{1}{\sqrt{2}}\left[B^0(t_1)\overline{B}^0(t_2) - \overline{B}^0(t_1)B^0(t_2)\right] = \frac{1}{\sqrt{2}}\left[B_{CP+}(t_1)B_{CP-}(t_2) - B_{CP-}(t_1)B_{CP+}(t_2)\right]$$

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

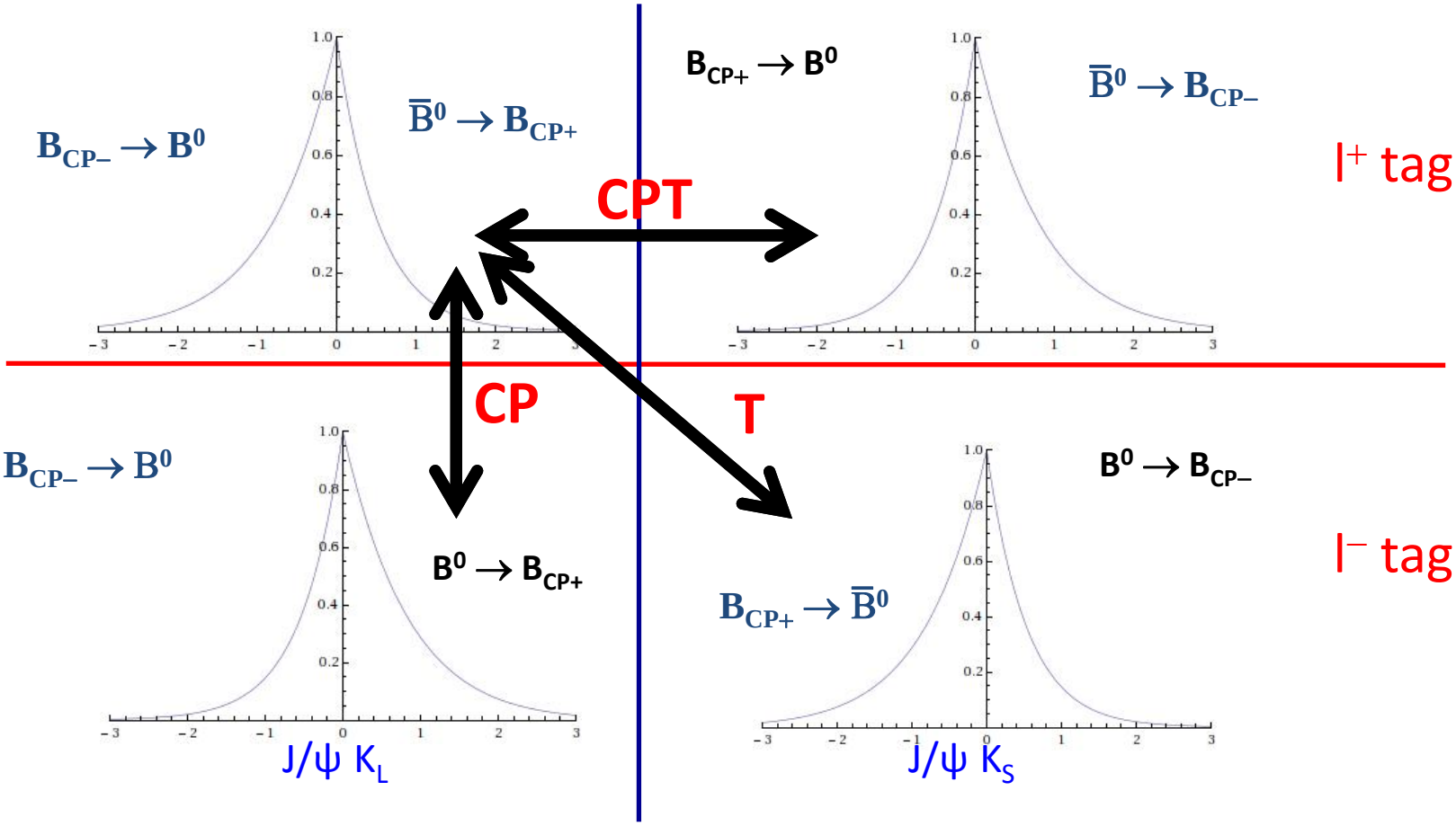
- $\Delta\tau = t_{2nd\ decay} - t_{first\ decay}$
  - Time ordering matters!

- Tag B^0 flavor – using e.g. the sign of a prompt charged lepton ($B^0 \to l^+X$; $\overline{B}^0 \to l^-X$)
- 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



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 ($\tau>0$):

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

  - $\alpha = B^0$ or $\bar{B}^0$
  - $\beta = J/\psi K_S$ 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 $\Rightarrow$ TRV
- Signal model: $H_{\alpha,\beta}(\Delta t) \propto$

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

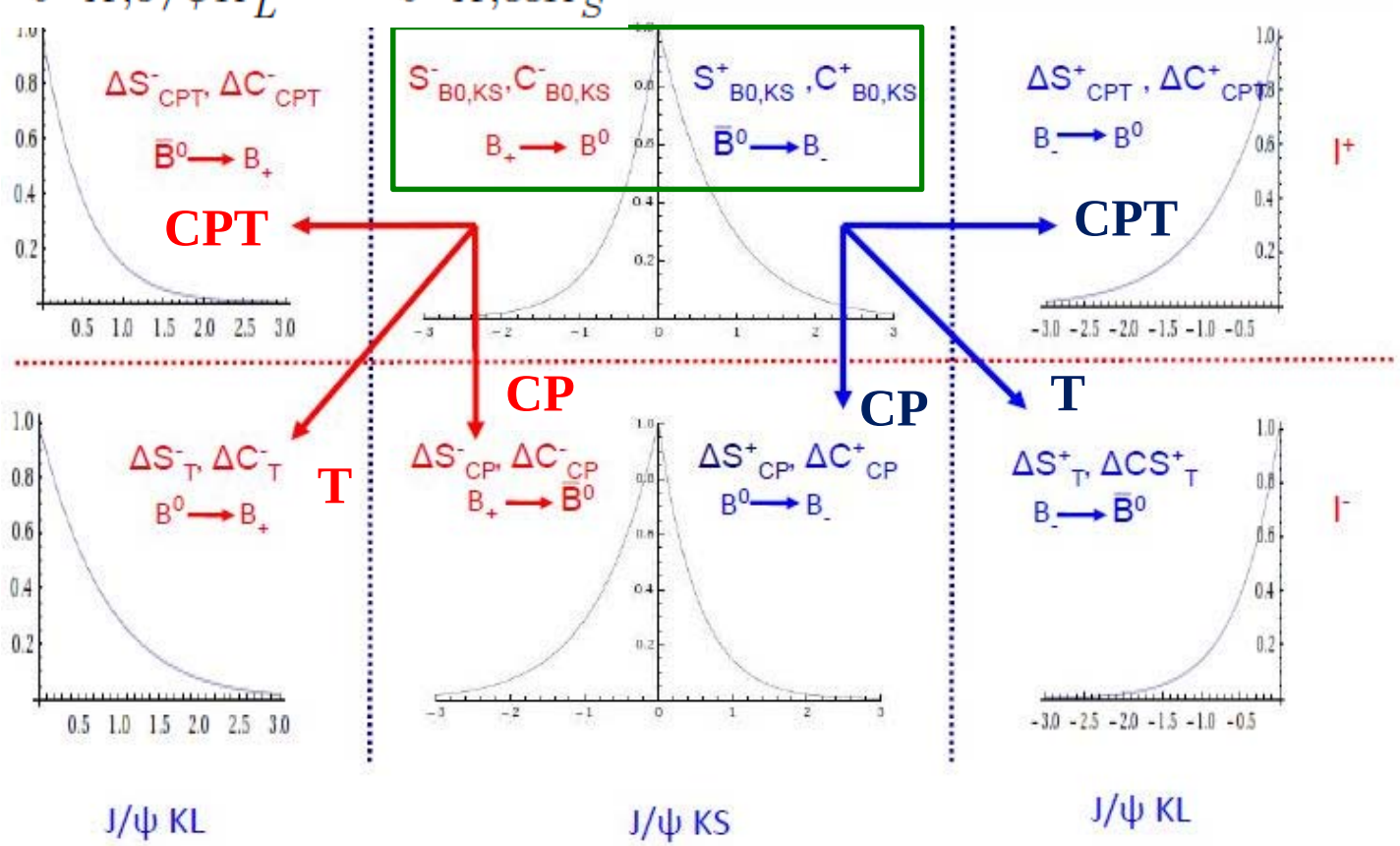
  - H: Heaviside step function; R: resolution function; $\delta t = \Delta t - \Delta t_{\text{true}}$

- Inperfect tagging taken into account
  $\rightarrow$ 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} → {ΔS, ΔC}

- 8 {S,C} sets ⇒ 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

    → e.g. $\Delta S_T^- = S^+_{\ell^- X, J/\psi K_L^0} - S^-_{\ell^+ X, c\bar{c} K_S^0}$
- Similar definitions for ΔC



- Any non-zero ΔS/ΔC 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

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

  - 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

- 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

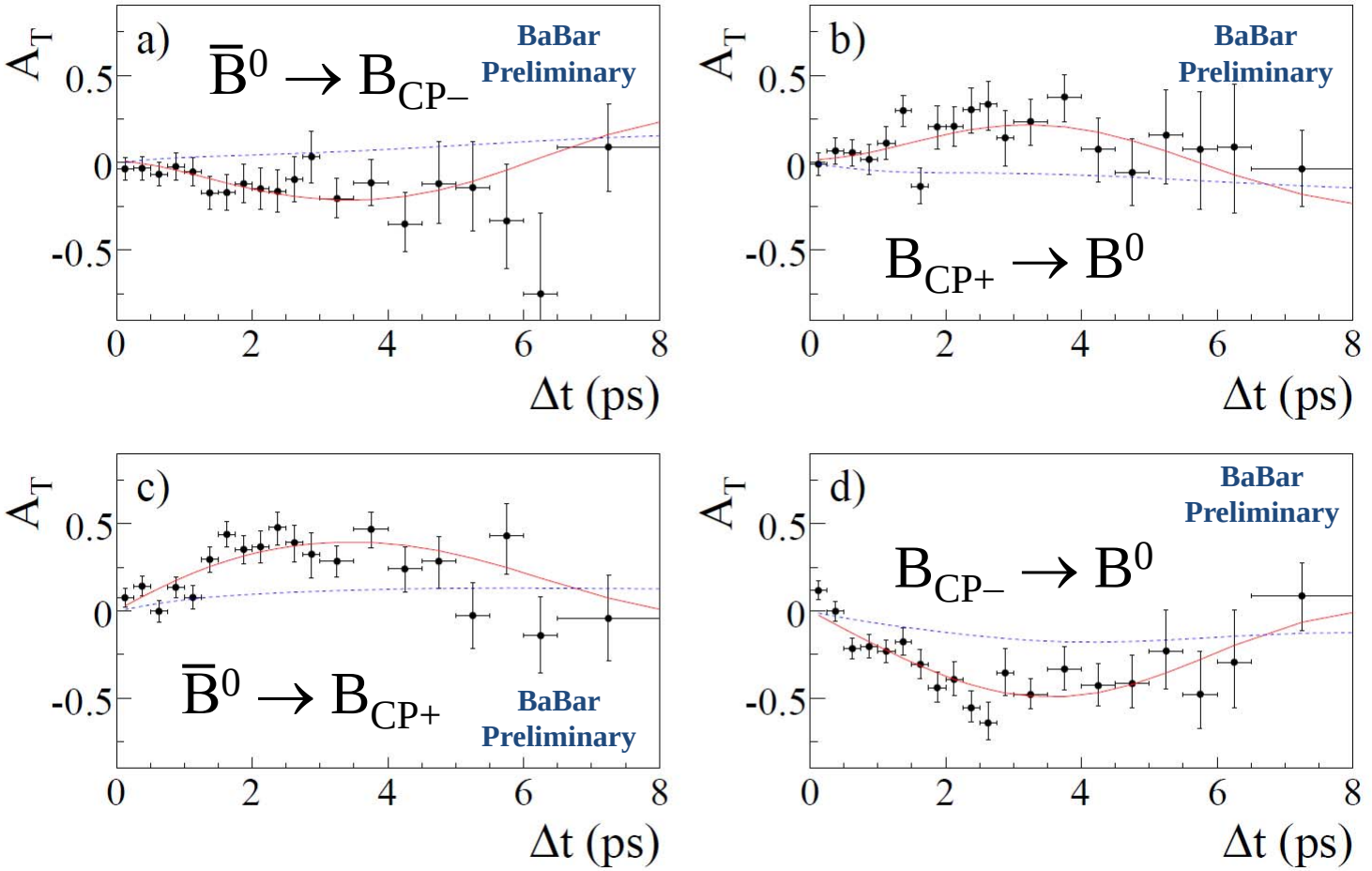
- Asymmetries for the 4 transitions studied (assuming perfect reconstruction):

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

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

- Nominal fit
  $\to$ 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 $\Upsilon(5S)$ 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)

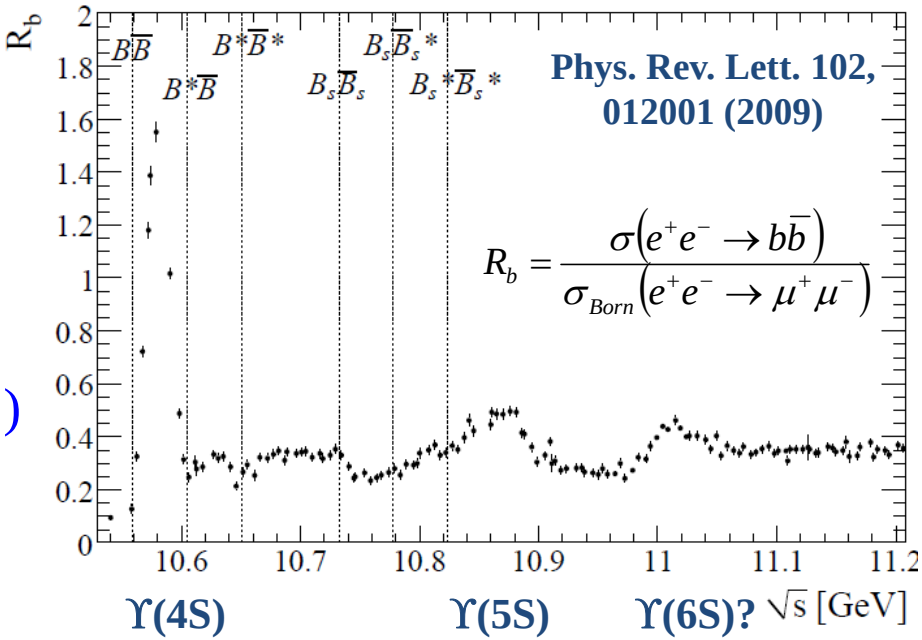
$$f_s = \frac{N_{B_s}}{N_{B_s} + N_{B^0} + N_{B^+}}$$

- 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

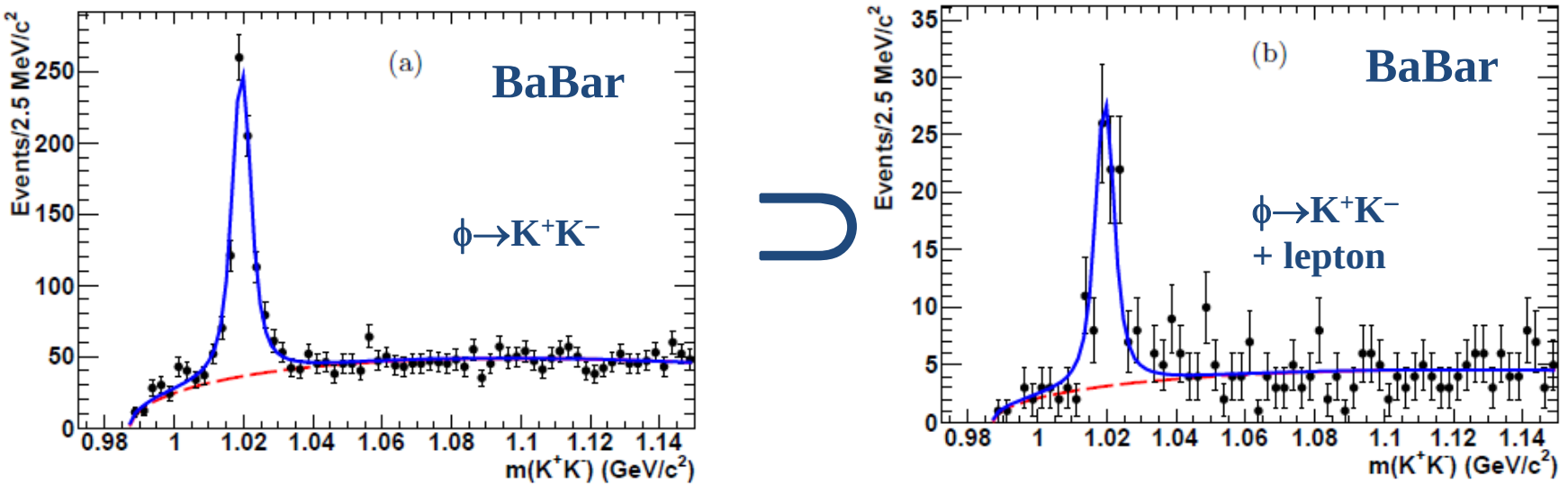
- Compute 3 quantities at each energy:
  - B hadron event rate = $f_1(R_b, f_s, \ldots)$
  - Inclusive ϕ rate = $f_2(R_b, f_s, \ldots)$
  - Inclusive ϕ+lepton rate = $f_3(R_b, f_s, Br, \ldots)$

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



Analysis key points

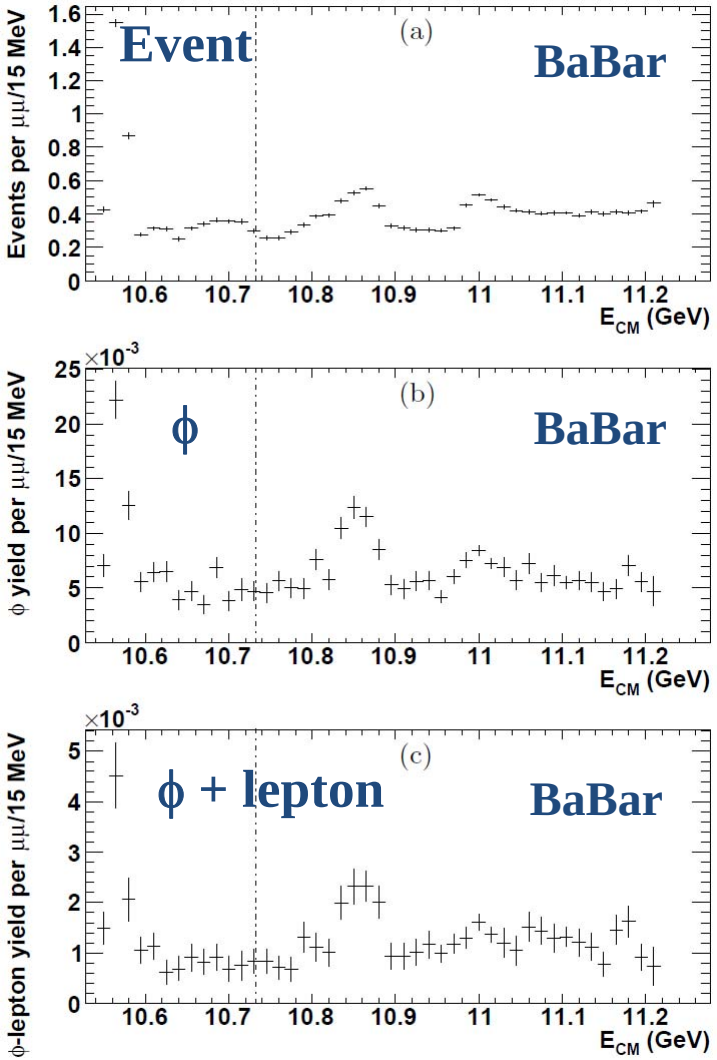
- Continuum contribution subtracted using data below the $B\bar{B}$ threshold
- $B_{u/d}$ contributions measured in $\Upsilon(4S)$ data
- f_s extracted at each energy point
- χ^2 fit performed to the measured yields to extract the semileptonic branching ratio
- Dominant systematics: inclusive D_s yield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



For a given representative energy scan point

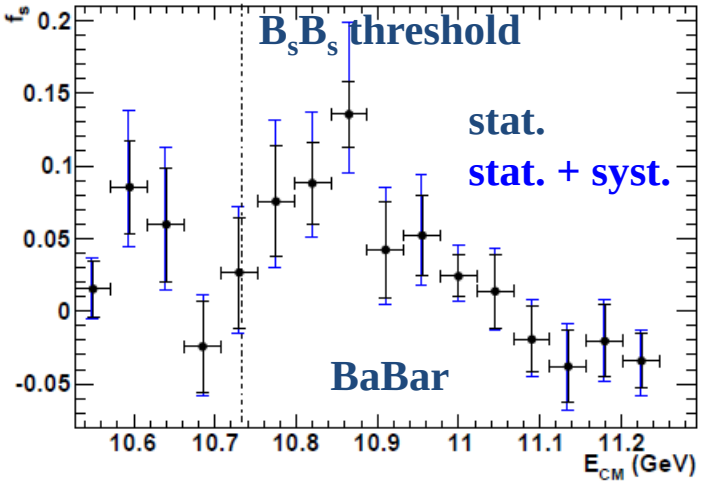
Results and interpretation

- Relative yields



→ Consistent with theoretical predictions

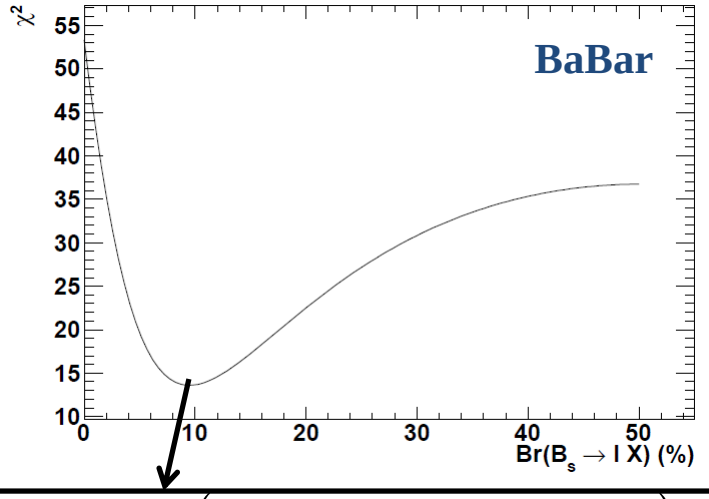
- f_s



→ Consistent with theory predictions

- B_s production peaks near $\Upsilon(5S)$
- Off-resonance production small

- Scan



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

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

arXiv:1206.2543 [hep-ex]

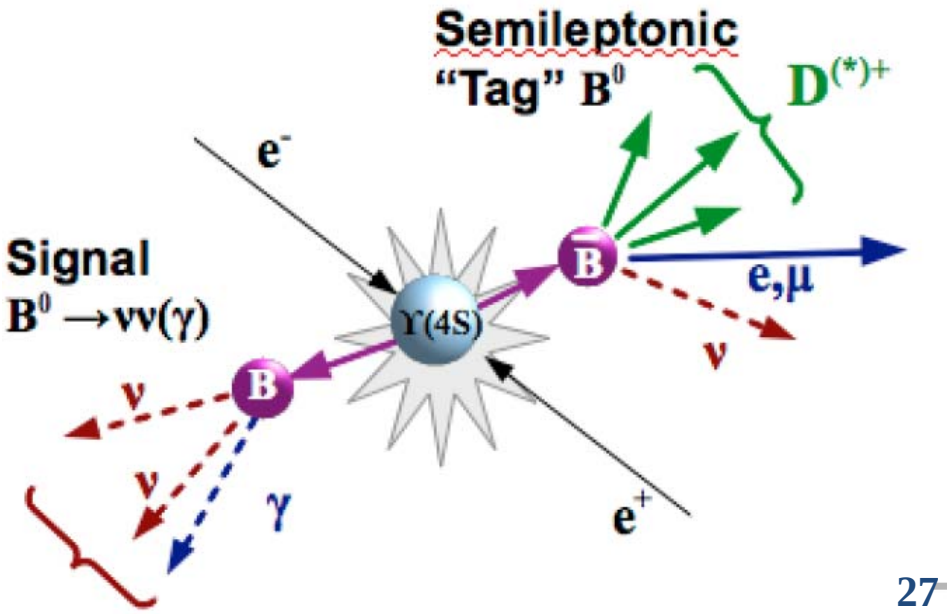
Submitted to PRD-RC

Motivation & analysis key points

- Look for B decays producing neutrinos and potentially some exotic particles
- SM: $B^0 \to \nu\bar{\nu}$ suppressed by $(m_\nu/m_B)^2$
  $BF(B^0 \to \nu\bar{\nu}\gamma) \sim 10^{-9}$] << experimental reach
- In some SUSY models, BRs can be as high as 10^{-7}–10^{-6}
  - Neutrino + neutralino production in the final state
  → 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
  → Low 'extra energy': E_{extra}

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

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

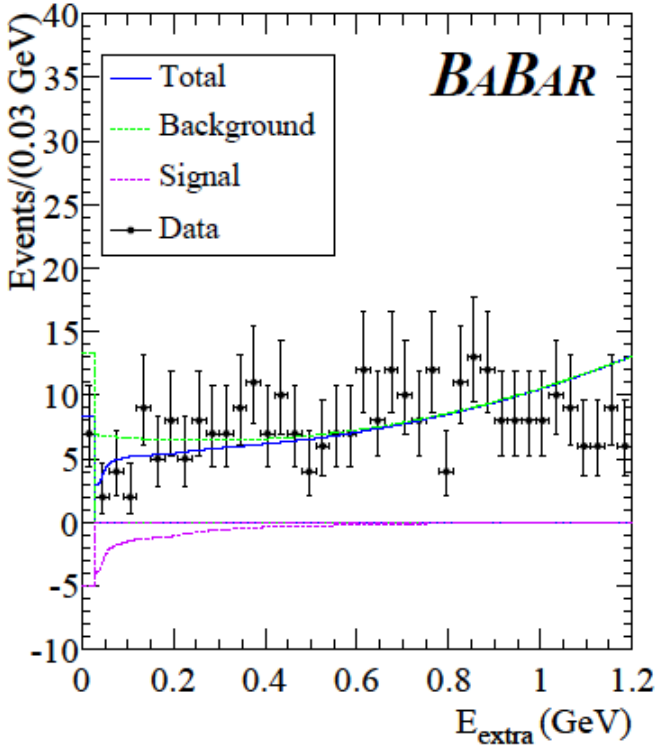


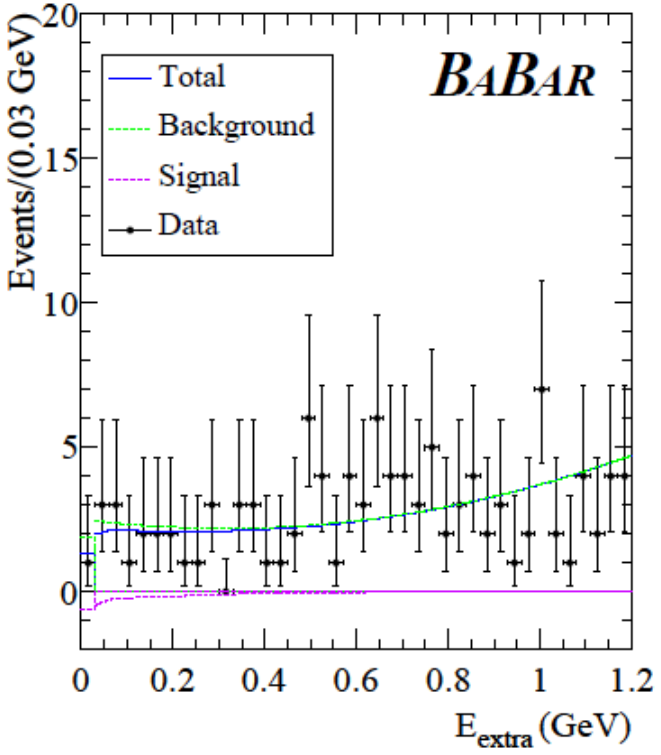
Results

- 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

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

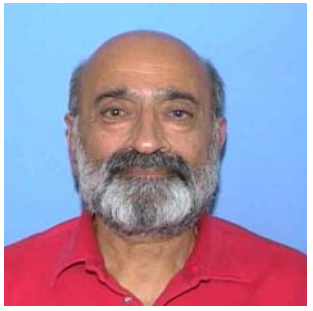
  - plus the B_s production fraction

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

$$\left.\begin{array}{l} \text{Br}(B \to \text{invisible}) \quad < 2.4 \times 10^{-5} \\ \text{Br}(B \to \text{invisible} + \gamma) < 1.7 \times 10^{-5} \end{array}\right] \text{@ 90\% C.L.}$$

- 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