RECENT RESULTS
FROM *BABAR*

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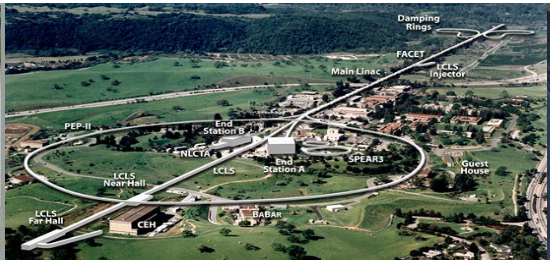
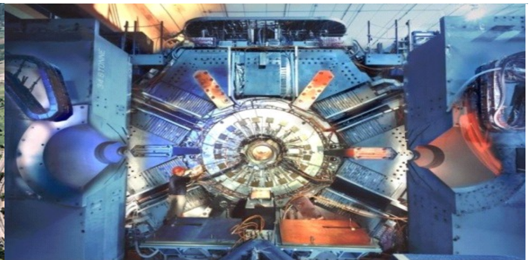
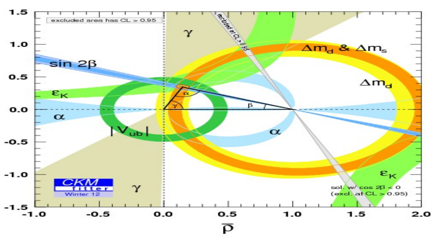
California Institute of Technology

on behalf of the *BABAR* Collaboration

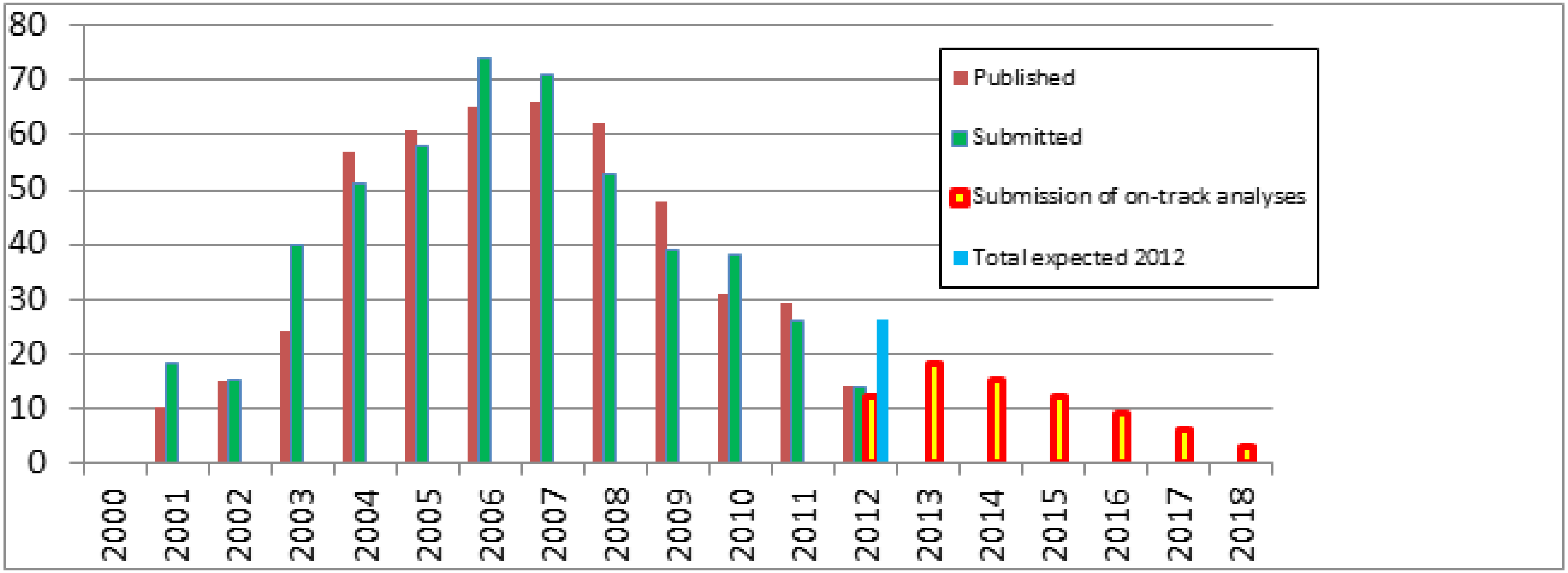
40th SLAC Summer Institute
SLAC – July 2012







Four years after the end of data taking, *BABAR* is still very productive !!!



So far, we have published 482 papers, and we expect to publish another ~80 analyses these next years.

We have already submitted 14 papers in 2012, and expect 12 more by end of this year

I'll discuss some recent results

Selected highlights from BABAR

Searches for T violation and new sources of CP violation

Observation of Time Reversal Violation in the B^0 meson system, to be submitted soon

Search for CP Violation in the Decay $\tau^- \rightarrow \pi^- K_s$ ($\geq 0\pi^0$) ν, submitted to PRD-RC, arXiv:1109.1527

Search for CP violation in the decays $D^\pm \rightarrow K_s K^\pm$, $D^\pm_s \rightarrow K_s K^\pm$ and $D^\pm_s \rightarrow K_s \pi^\pm$, preliminary

Study of CP violation in Dalitz-plot analyses of $B^0 \rightarrow K^+K^-K_s$, $B^+ \rightarrow K^+K^-K^+$, and $B^+ \rightarrow K_sK_sK^+$, submitted to PRD, arXiv:1201.5897

Searches for B decays with unique B factory signatures

Evidence for an excess of $B \rightarrow D^{(*)} \tau\nu$ decays, submitted to PRL, arXiv:1205.5442

Evidence of $B \rightarrow \tau\nu$ decays with hadronic tags, submitted to PRD-RC, arXiv:1207.0698

B^0 Decays to Invisible Final States and to $\nu\bar{\nu}\gamma$, submitted to PRD-RC, arXiv:1206.2543

Branching fraction measurement of $B \rightarrow \omega l \nu$ decays, submitted to PRD, arXiv:1205.6245

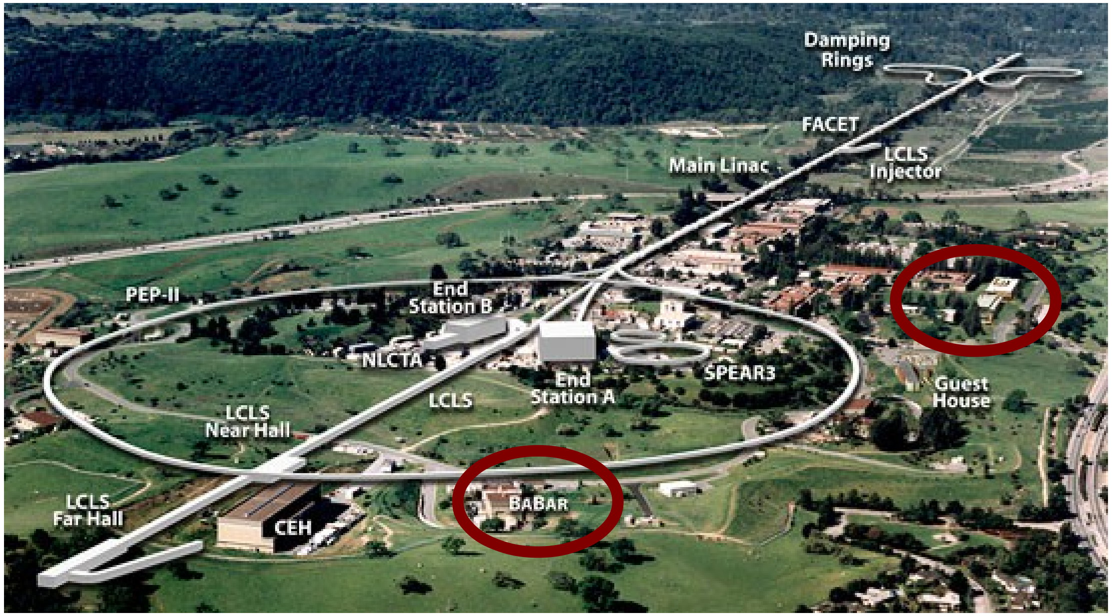
Branching fraction and form-factor shape measurements of exclusive charmless semileptonic B decays, and determination of |Vub|, to be submitted soon

Searches for New physics

Search for Dark Higgs boson, PRL 108, 211801 (2012)

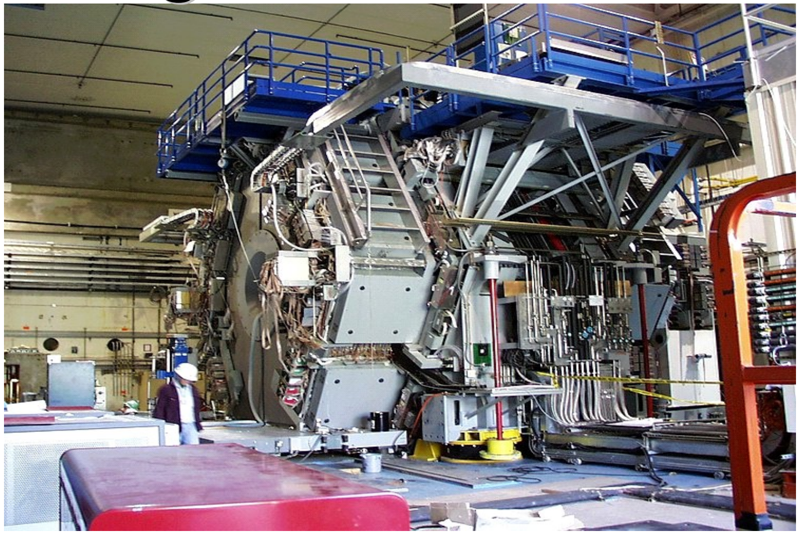
Search for Light Scalar Higgs Boson Decaying to Tau Pairs and Muon Pairs in Single-Photon decays of Y(1S), preliminary

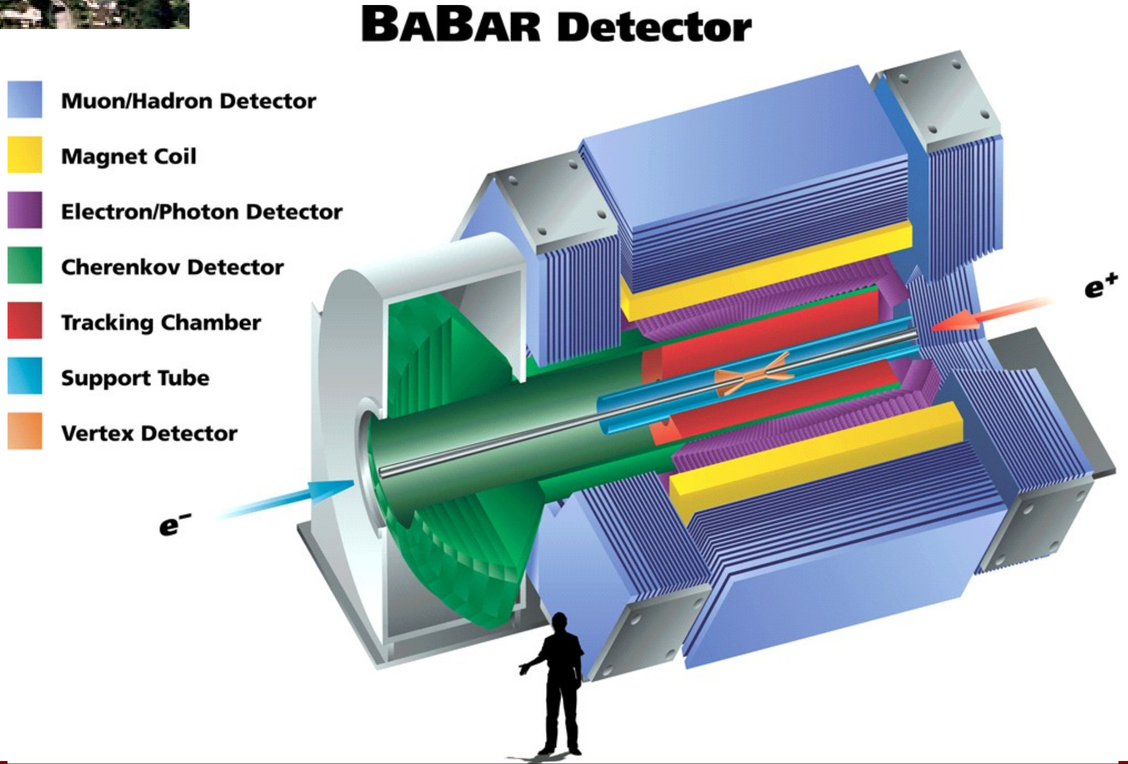
The BABAR experiment at SLAC



BABAR @ PEP-II

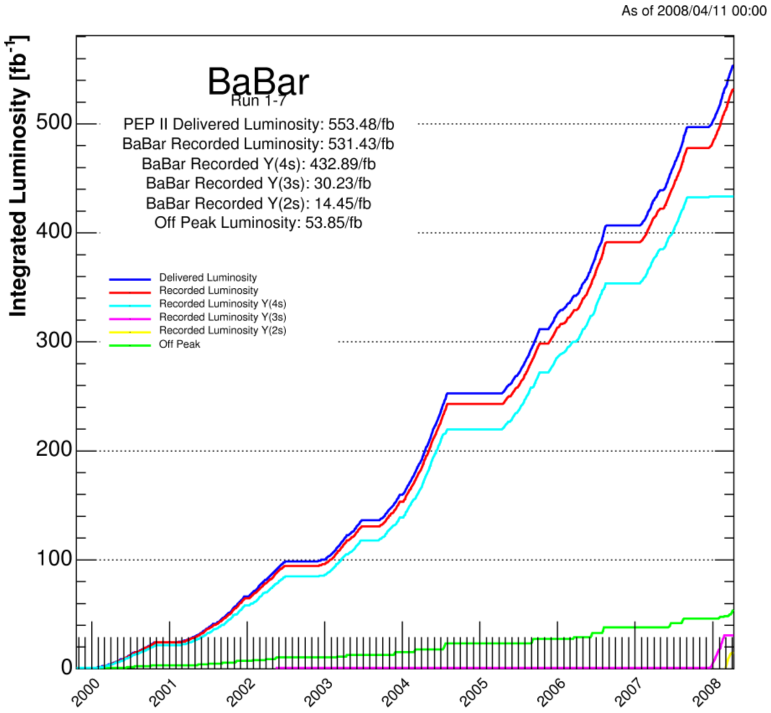
BABAR @ IR2

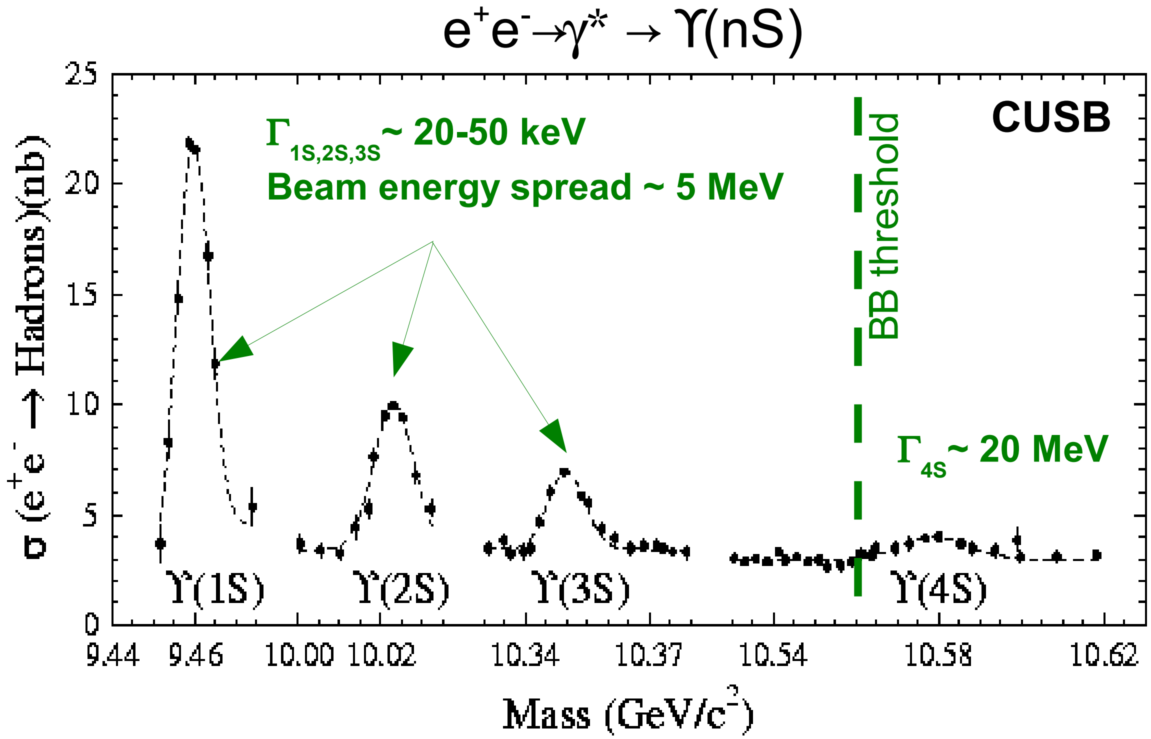




The BABAR experiment at SLAC

BA*BAR* collected around 533 fb^{-1} of e^+e^- collisions around the ϒ(4S)



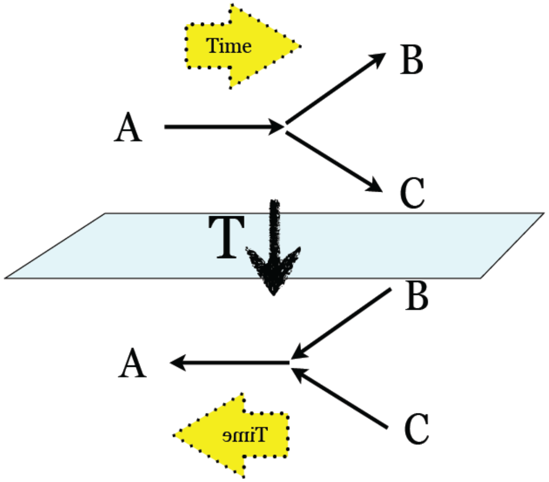


BA*BAR* data sample contains

~470 x 10^6 ϒ(4S)
~120 x 10^6 ϒ(3S) (10x Belle, 25x CLEO)
~100 x 10^6 ϒ(2S) (10x CLEO)
~ 18 x 10^6 ϒ(1S) from ϒ(2S) → $\pi^+\pi^-$ ϒ(1S)

Time reversal violation in B^0 meson decays

Time reversal violation



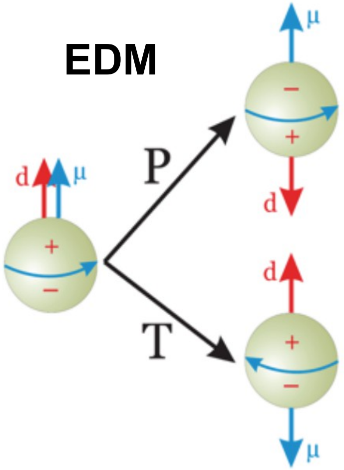
Time reversal is a discrete symmetry

- Exchanges |in> and |out> states, t → -t.

Time reversal violating processes

- A non-zero value of a T-odd observable in a stationary state, (e.g EDM) or a difference in the probability of a→b from b→a in an oscillation process at a given time t (e.g., $\nu_e \rightarrow \nu_\mu$ vs. $\nu_\mu \rightarrow \nu_e$).
  - Not observed yet.

- Exchange |in> and |out> states in unstable systems.
  - Tricky to prepare the initial state.



The CP and T symmetries are connected via the CPT theorem

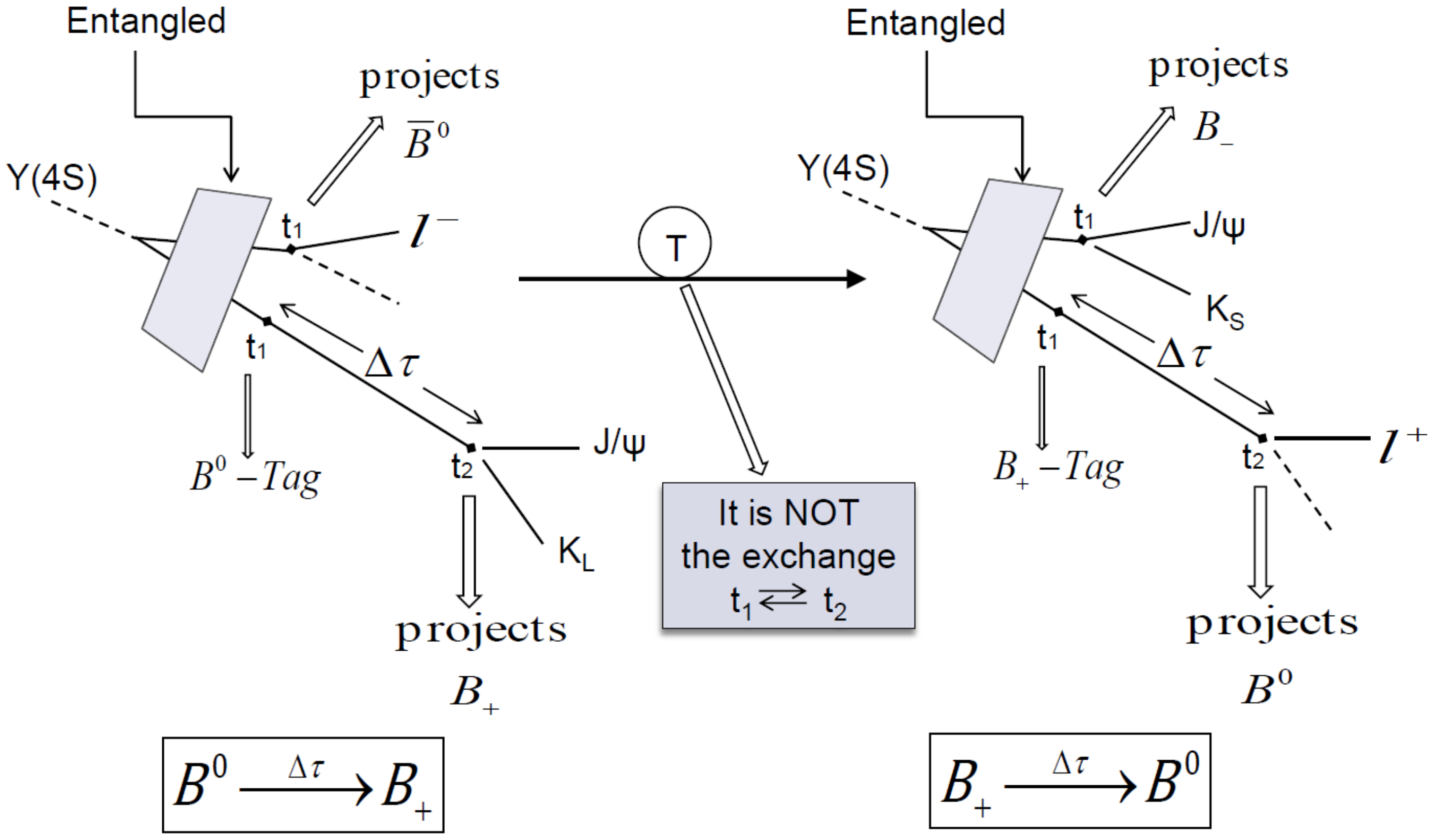
- Observe CP violation → T violation (assuming CPT)

Can we observe direct T violation?

Time reversal violation in $B^0\overline{B}^0$ decays

Exploit quantum entanglement of the $B^0\overline{B}^0$ pair produced at the Y(4S) to overcome the problem of irreversibility

Method described in J. Bernabeu *et al.* arXiv:1203.0171



It is NOT the exchange $t_1 \rightleftarrows t_2$

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

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

Flavor eigenstates
B^0 / $\overline{B}^0$

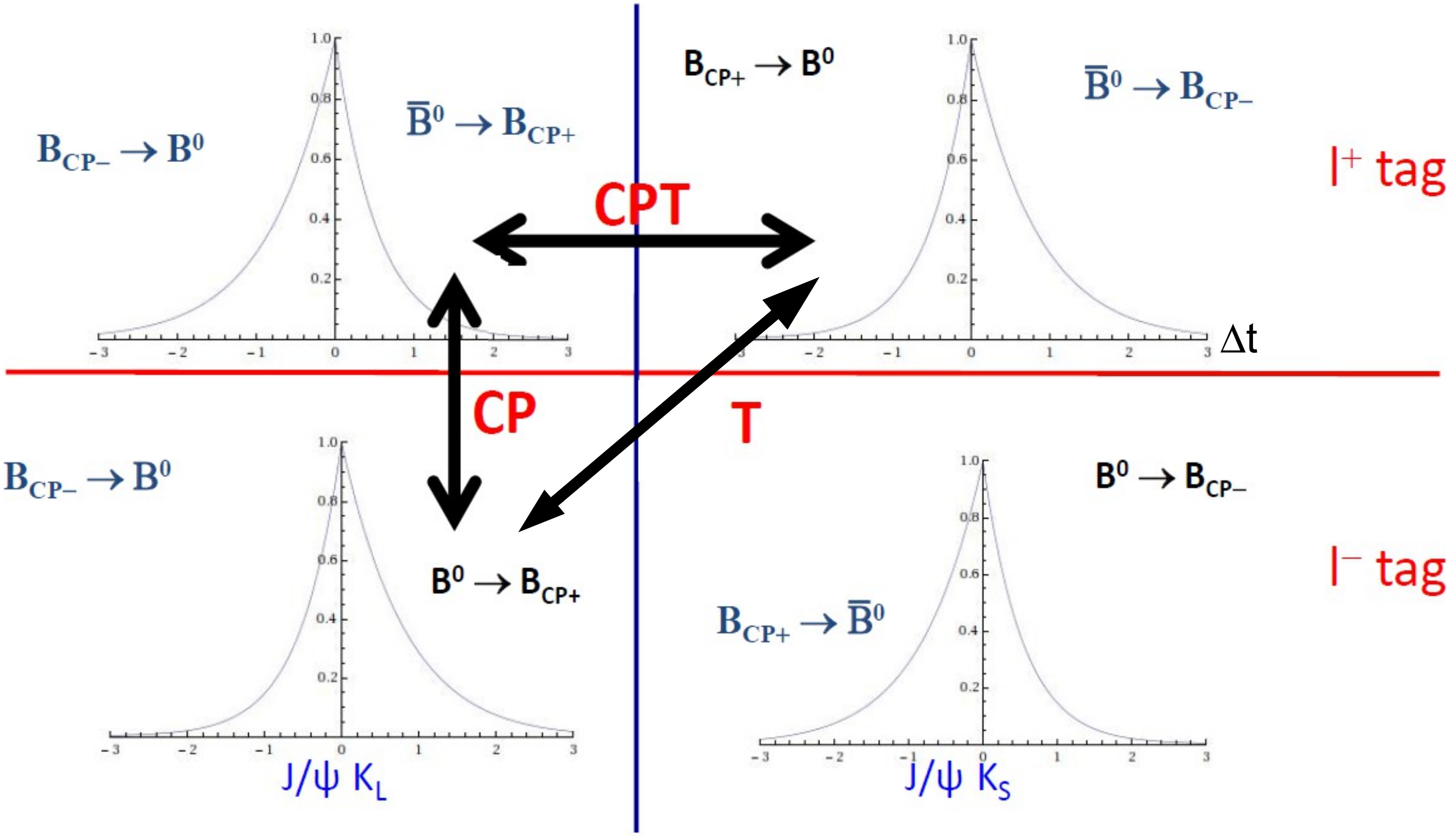
CP eigenstates
B_{CP+} / B_{CP-}

Tagging:

- flavor eigenstate, e.g. the sign of a prompt lepton in $B^0 \rightarrow l^+X$; $\overline{B}^0 \rightarrow l^-X$ decays
- CP eigenstate, reconstructing the final state $J/\psi\ K_L$ (CP+) or $J/\psi\ K_S$ (CP-)

Time reversal processes

We can build 4 independent T comparisons (and 4 CP and 4 CPT)



TRV test imply comparison of

- Opposite Δt sign
- Opposite CP states
- Opposite tag states

$B^0 \rightarrow B_{CP+}$ $(l^-, J/\psi\ K_L)$	**T**	$B_{CP+} \rightarrow B^0$ $(J/\psi\ K_S, l^+)$
$B^0 \rightarrow B_{CP-}$ $(l^-, J/\psi\ K_S)$	$\longrightarrow$	$B_{CP-} \rightarrow B^0$ $(J/\psi\ K_L, l^+)$
$\overline{B}^0 \rightarrow B_{CP+}$ $(l^+, J/\psi\ K_L)$		$B_{CP+} \rightarrow \overline{B}^0$ $(J/\psi\ K_S, l^-)$
$\overline{B}^0 \rightarrow B_{CP-}$ $(l^+, J/\psi\ K_S)$		$B_{CP-} \rightarrow \overline{B}^0$ $(J/\psi\ K_L, l^-)$

Time reversal violating parameters

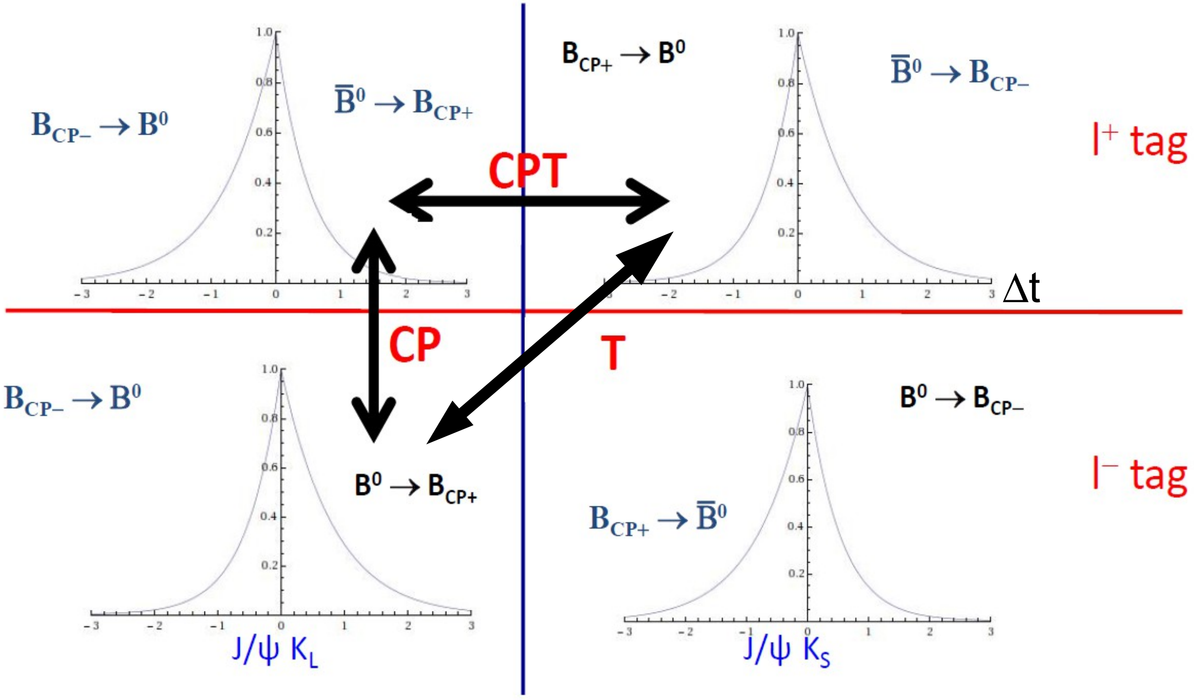
Measure time dependent decay rates

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

$\alpha = B^0 , \overline{B}^0$
$\beta = J/\psi K_s , J/\psi K_L$
$\tau = \pm \Delta t > 0$

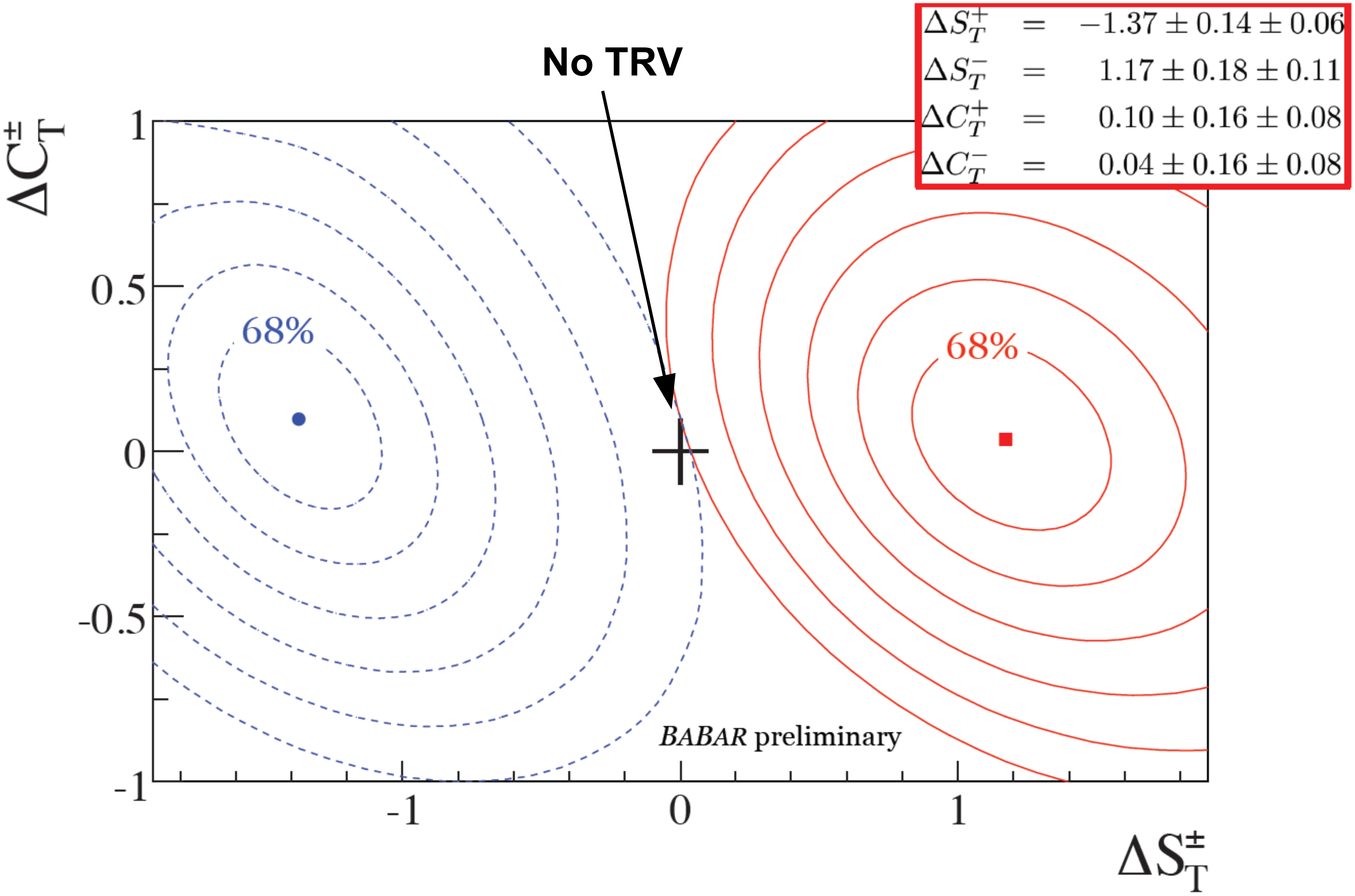
Unbinned maximum likelihood fit to extract the 8 ($S^{\pm}$,$C^{\pm}$) values, including resolution, imperfect tagging and background.

Combine these 8 ($S^{\pm}$,$C^{\pm}$) values to form a set of independent ($\Delta S^{\pm}_{T,CP,CPT}$, $\Delta C^{\pm}_{T,CP,CPT}$) differences sensitive to T, CP and CPT violations



Any non-zero ΔS/ΔC value corresponds to a symmetry violation

Results

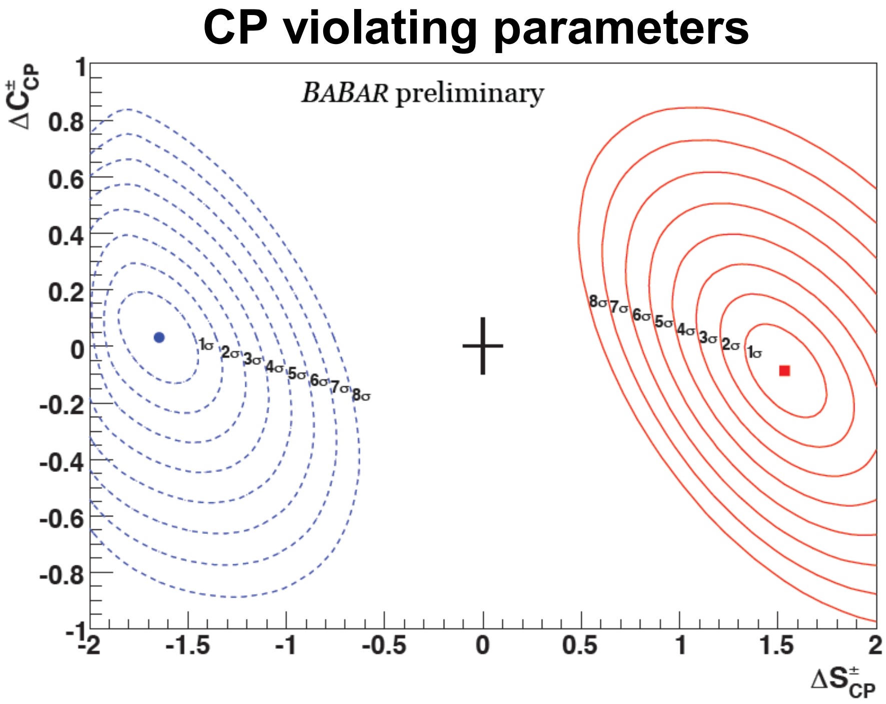


No TRV

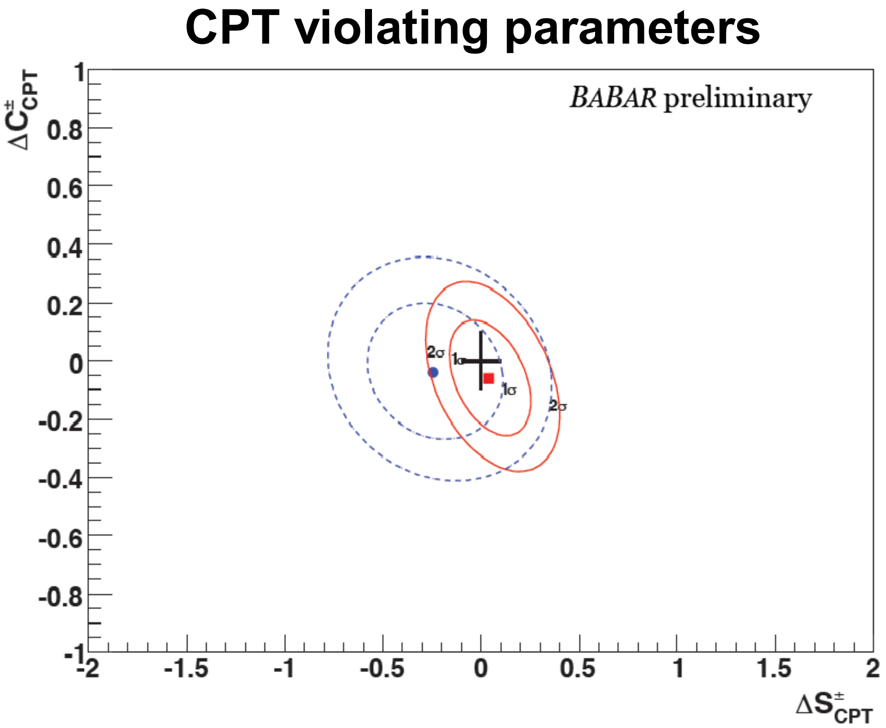
$$\Delta S_T^{+} = -1.37 \pm 0.14 \pm 0.06$$
$$\Delta S_T^{-} = 1.17 \pm 0.18 \pm 0.11$$
$$\Delta C_T^{+} = 0.10 \pm 0.16 \pm 0.08$$
$$\Delta C_T^{-} = 0.04 \pm 0.16 \pm 0.08$$

Observe time reversal violation with a significance > 10σ

CP and CPT violation



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

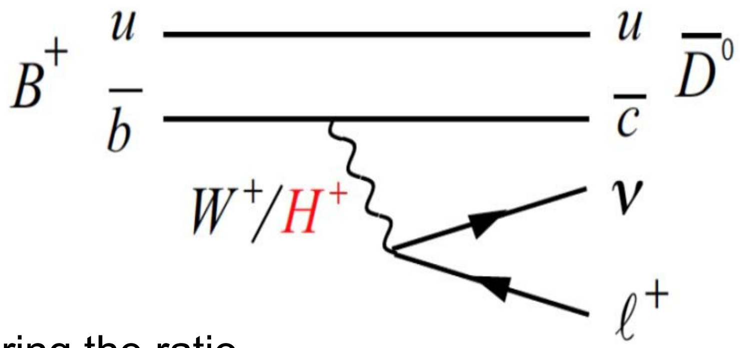


$$\begin{aligned}\Delta S^{+}_{CPT} &= 0.16 \pm 0.20 \pm 0.09\\ \Delta S^{-}_{CPT} &= -0.03 \pm 0.13 \pm 0.06\\ \Delta C^{+}_{CPT} &= 0.15 \pm 0.17 \pm 0.07\\ \Delta C^{-}_{CPT} &= 0.03 \pm 0.14 \pm 0.08\end{aligned}$$

Clear evidence of CP violation and no evidence of CPT violation

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

Motivation



Tree-level semi-leptonic decay mediated by a W±

- τ mode sensitive to New Physics contributions, e.g. charged Higgs boson H± in type-II Two Higgs Doublet Model (2HDM)
- Reduce sensitivity to hadronic form factor and V_{cb} by measuring the ratio

$$R\left(D^{(*)}\right)=\frac{BF\left(B\rightarrow D^{(*)}\tau\nu\right)}{BF\left(B\rightarrow D^{(*)}l\nu\right)}\ l=e,\mu$$

← "signal"

← "normalization"

Previous measurements from B-factories

- Above Standard Model predictions, but limited significance

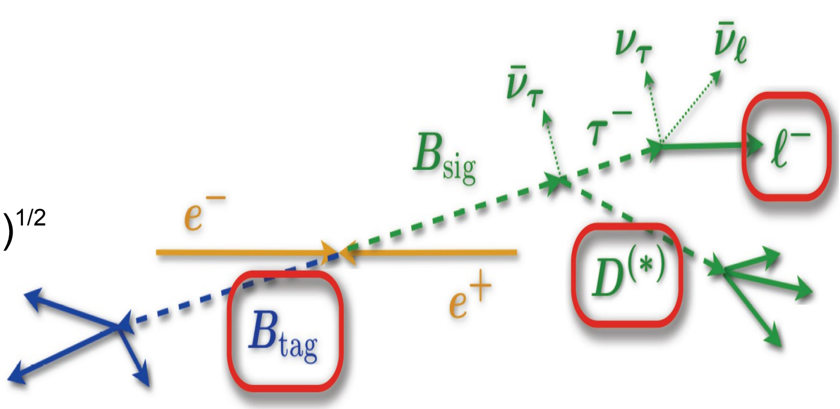
New result from *BABAR*

- Based on full dataset (2x more statistics than previous result1))
- Improved B reconstruction
- Signal yield increased by more than a factor 3

Main challenge: many neutrinos in the final state!!!

1) Z. Phys. C46, 93 (1990), PRD 78, 0156006 (2008), PRD 85, 094025 (2012)

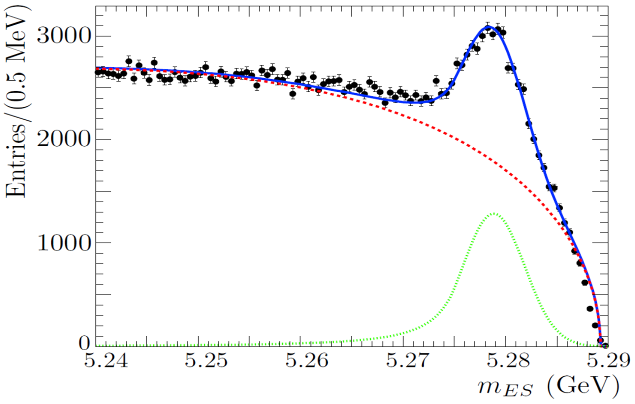
Event selection



Tagged analysis

- exclusive reconstruction of one B meson, the "B_{tag}"
- The beam-energy substituted mass $m_{ES} = ((E^*_{beam})^2 - (p^*_{tag})^2)^{1/2}$
  - peaks at the B mass for signal with a resolution ~ 2.5 MeV
- The energy difference $\Delta E = E^*_{tag} - E^*_{beam}$
  - peaks at zero for signal with a resolution of ~ 18 MeV

Example of m_{ES} distribution



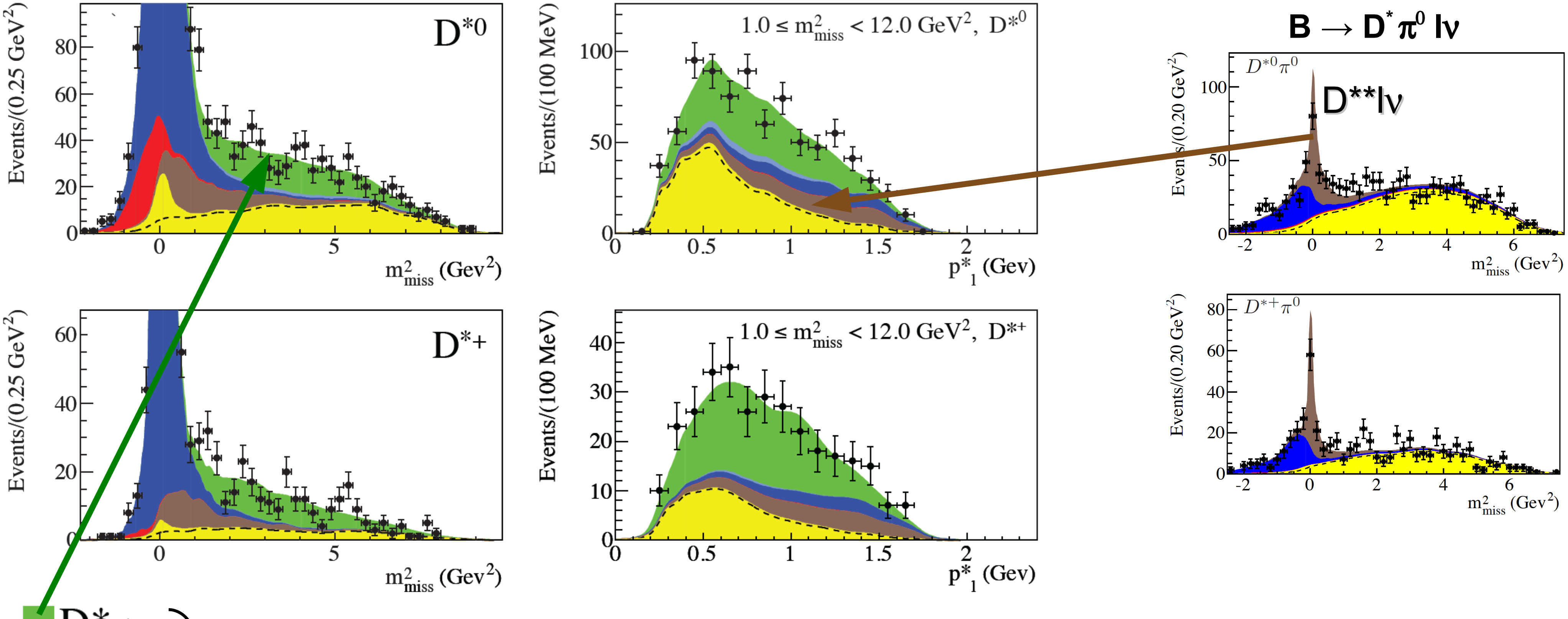
The rest of the event is assigned to the signal B

- Must be compatible with $B \to D^{(*)} \tau \nu_\tau$ / $B \to D^{(*)} l \nu_l$ hypothesis
- Reconstruct D/D* candidate
- Identify leptonic decays of τ lepton (final states have identical content except neutrinos)
- No additional charged particles and no significant extra neutral energy

Extract signal by a 2D unbinned maximum likelihood fit to

- Invariant mass of undetected particles and lepton momentum in B_{sig} rest frame
- Simultaneous fit with $B \to D^{(*)} \pi^0 l\nu$ to constrain the contribution of $B \to D^{**} \tau\nu + B \to D^{**} l\nu$

Results for $B \to D^* \tau \nu$



🟩 $D^*\tau\nu$
🟦 $D\tau\nu$
🟦 $D^*l\nu$
🟥 $Dl\nu$
🟫 $D^{**}l\nu$
🟨 Bkg.

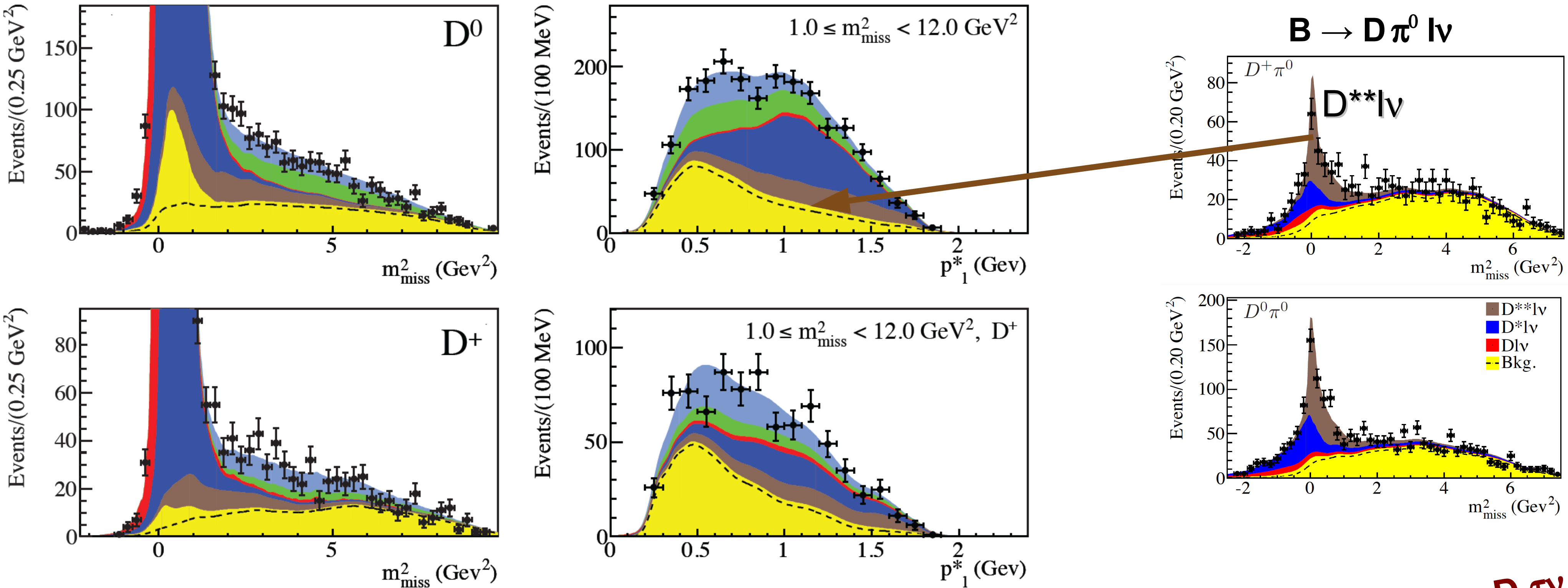
Free in fit

Fixed

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

Only statistical uncertainties

Results for $B \rightarrow D \tau \nu$



🟩 $D^*\tau\nu$
🟦 $D\tau\nu$
🟦 $D^*l\nu$
🟥 $Dl\nu$
🟫 $D^{**}l\nu$
🟨 Bkg.

Free in fit ($D^*\tau\nu$, $D\tau\nu$, $D^*l\nu$, $Dl\nu$, $D^{**}l\nu$)

Fixed (Bkg.)

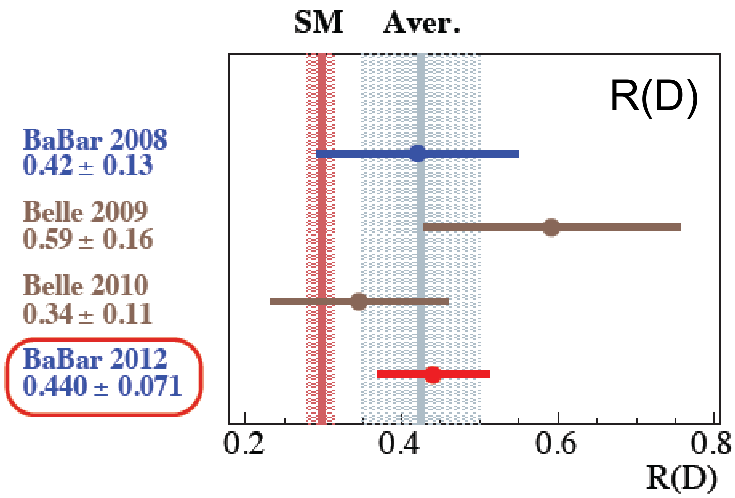
First 5σ observation of $B \rightarrow D \tau\nu$

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

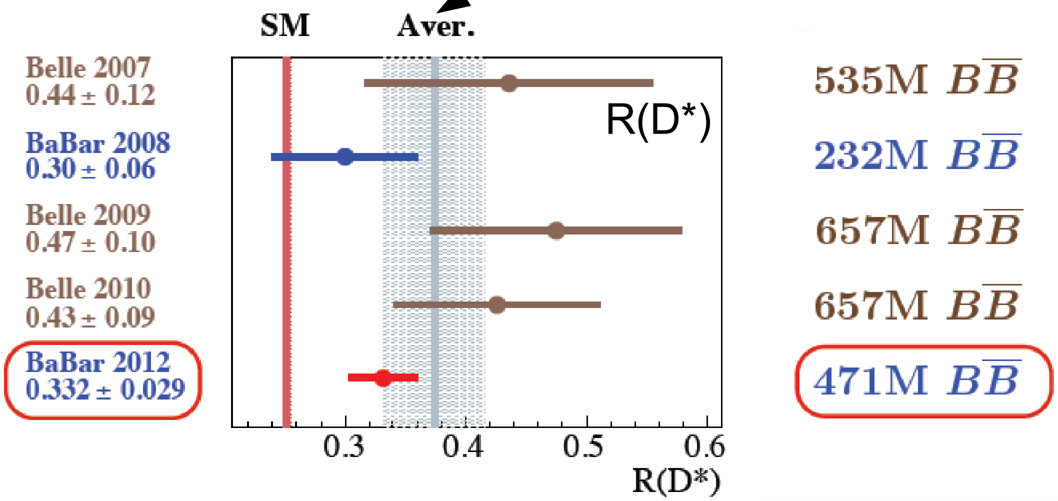
Only statistical uncertainties

Comparison with previous measurements and SM predictions

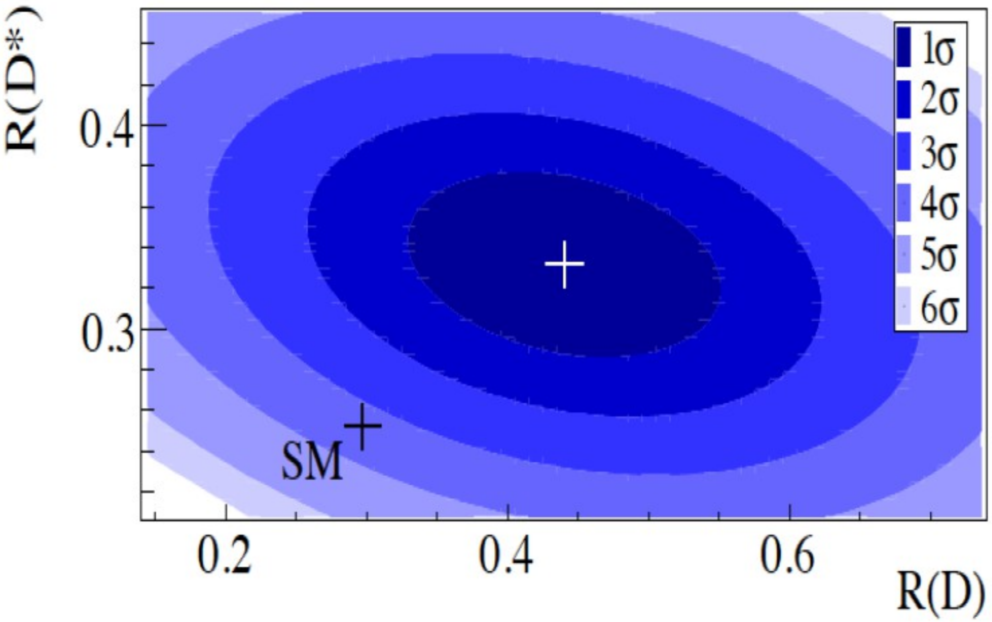
Consistent with previous measurements



Average does not include this result



	R(D)	R(D*)
BaBar	0.440 ± 0.071	0.332 ± 0.029
SM [*]	0.293 ± 0.017	0.252 ± 0.003
Δ	2.0σ	2.7σ



The SM prediction is excluded at 3.4σ

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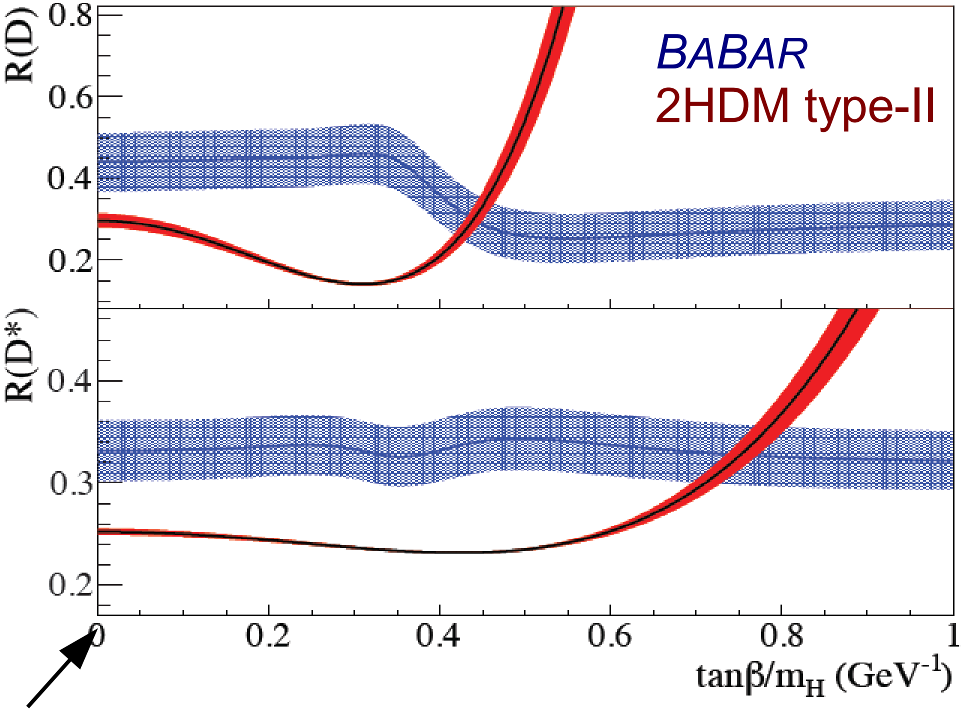
[*] J.F. Kaminik and F. Mescia, Phys. Rev. D 78, 014003 (2008)
S. Fajfer *et al.*, PRD 85, 094025 (2012).

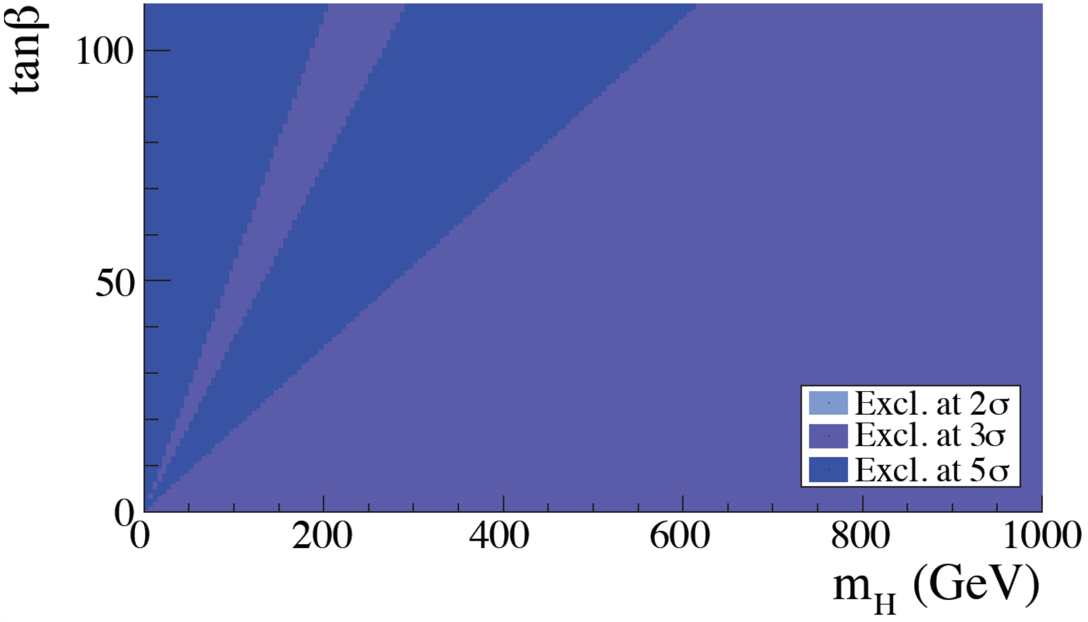
Implication for 2HDM type-II

Simulated events reweighted at the matrix element level for 20 values of tanβ / m_H to reevaluate PDF, efficiencies and repeating fits.



SM

Constraints on tanβ / m_H plane



2HDM type-II excluded at 99.8% CL on the whole range for H^+ mass > ~10 GeV, and excluded below 10 GeV by $B \to X_s \gamma$ measurements

Search for light CP-odd Higgs

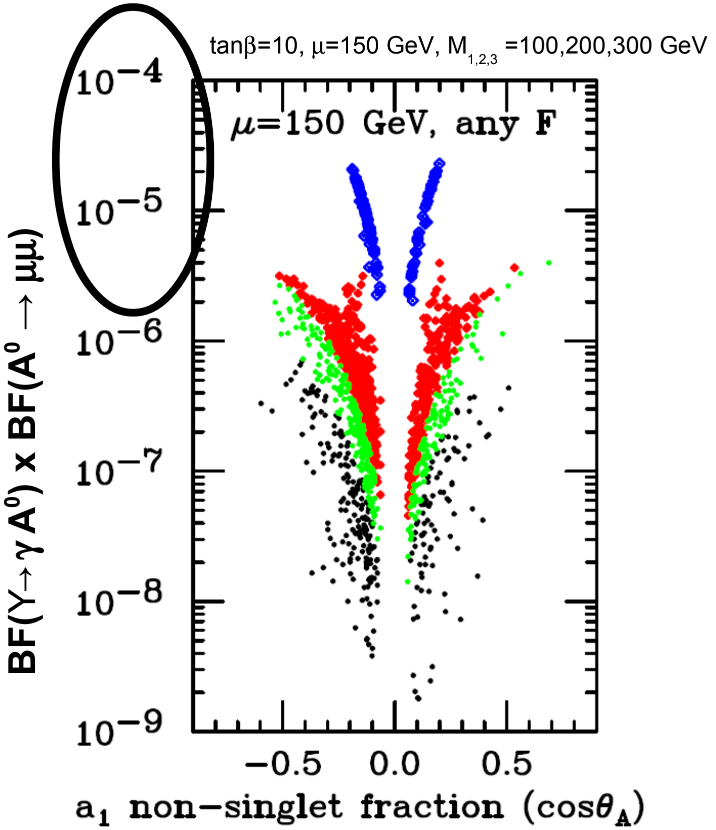
Search for light CP-odd Higgs boson

Dermisek et al., PRD 81, 075003 (2010)

Light Higgs boson

- Many SM extensions, such as the NMSSM, include the possibility of a light Higgs boson
- NMSSM proposed to solve the "μ problem", adding one CP-odd Higgs, one CP-even Higgs and one neutralino to MSSM content
- A light CP-odd Higgs A^0 with mass lower than $2m_b$ is not excluded by LEP constraints
- Radiative decays $\Upsilon(nS) \rightarrow \gamma A^0$ (n=1,2,3) offer an ideal environment to search for light Higgs:
  - Fully reconstructed in $A^0 \rightarrow \mu^+\mu^-$
  - Partially reconstructed in $A^0 \rightarrow \tau^+\tau^-, q\overline{q}$
  - Invisible decay $A^0 \rightarrow \chi_1\chi_1$ if $m_{A0} > 2m_\chi$

Can have a very large branching fraction



$A^0 = \cos\theta_A\, A_{MSSM} + \sin\theta_A\, A_S$

$0 < m_{A0} < 2m_\tau$

$2m_\tau < m_{A0} < 7.5$ GeV

$7.5 < m_{A0} < 8.8$ GeV

$8.8 < m_{A0} < 9.2$ GeV

Search for light CP-odd Higgs boson

Dermisek et al., PRD 81, 075003 (2010)

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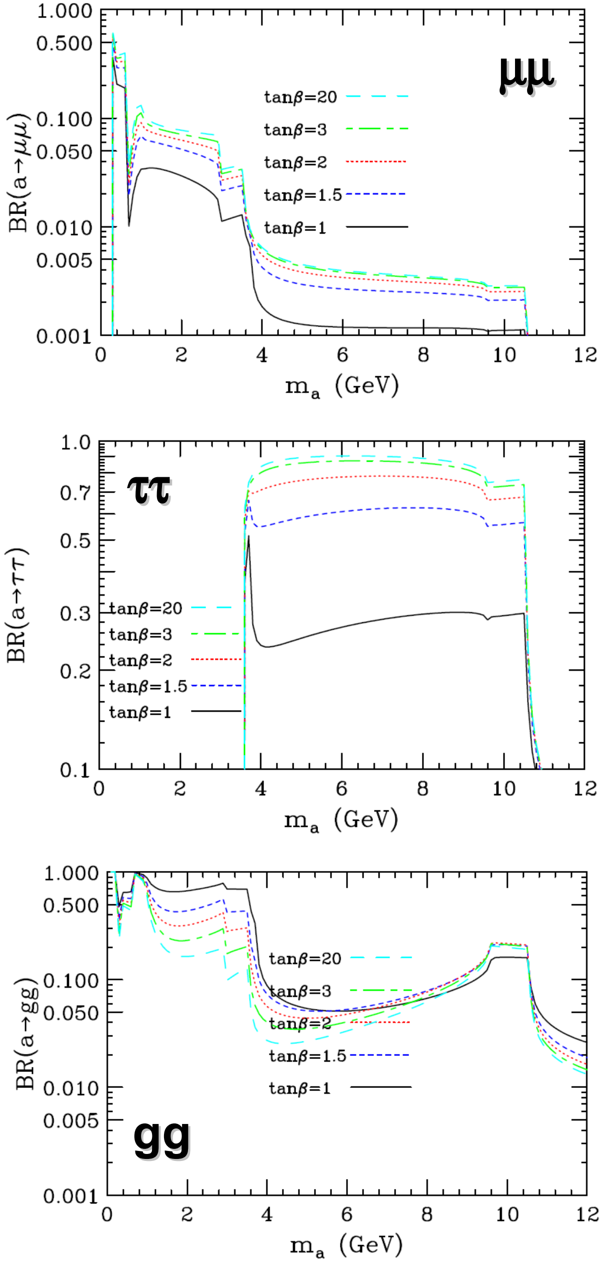
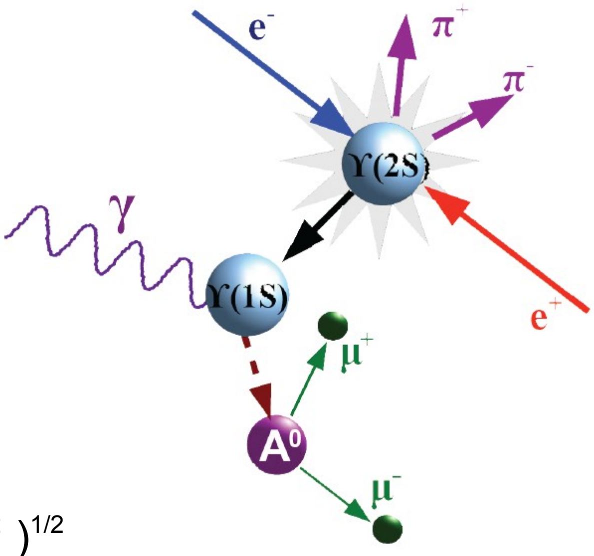
Can have a very large branching fraction

Branching fractions



Search for A^0 in $\Upsilon(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$

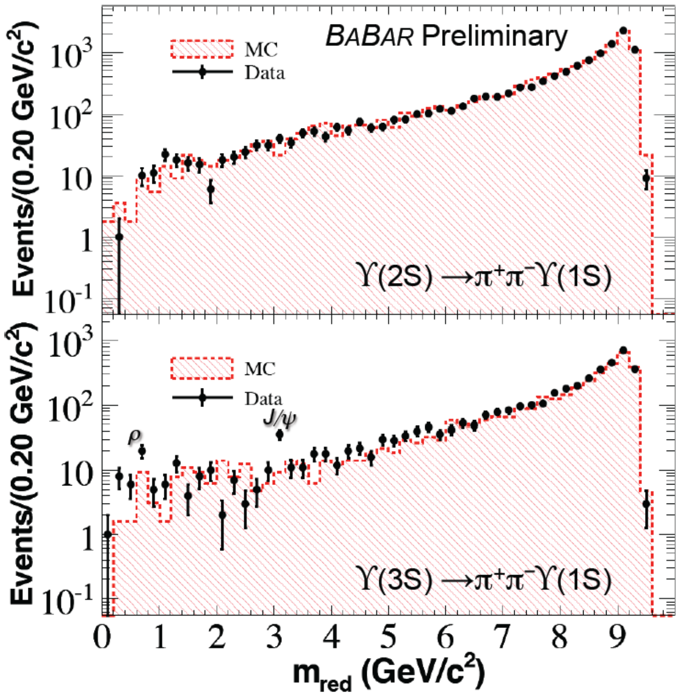


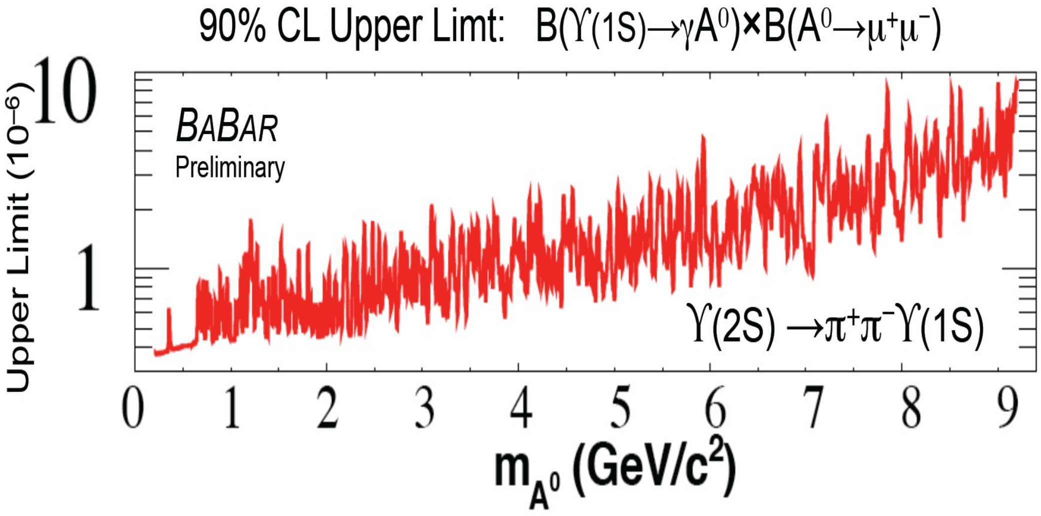
Search for a light CP-odd Higgs in

$$\Upsilon(2S,3S) \rightarrow \pi^+\pi^- \Upsilon(1S),\ \Upsilon(1S) \rightarrow \gamma A^0,\ A^0 \rightarrow \mu^+\mu^-$$

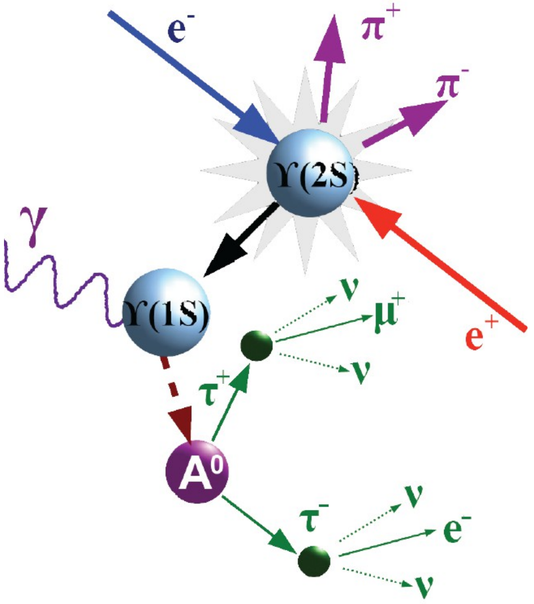
Analysis highlights

- Tag the Y(1S) from the dipion transition
- Require the $\gamma\mu\mu$ system to be compatible with a Y(1S) meson
- Fit for a narrow peak to the reduced dimuon mass $m_R = (m^2_{A0} - 4m^2_\mu)^{1/2}$





Search for A^0 in $\Upsilon(1S) \to \gamma A^0$, $A^0 \to \tau^+\tau^-$

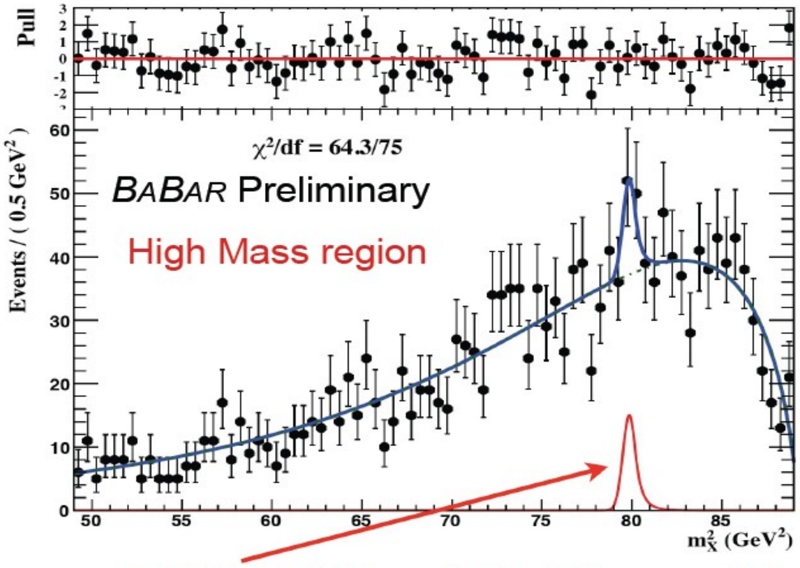


Search for a light CP-odd Higgs in

$$\Upsilon(2S,3S) \to \pi^+\pi^- \Upsilon(1S),\ \Upsilon(1S) \to \gamma A^0,\ A^0 \to \tau^+\tau^-$$

Analysis highlights

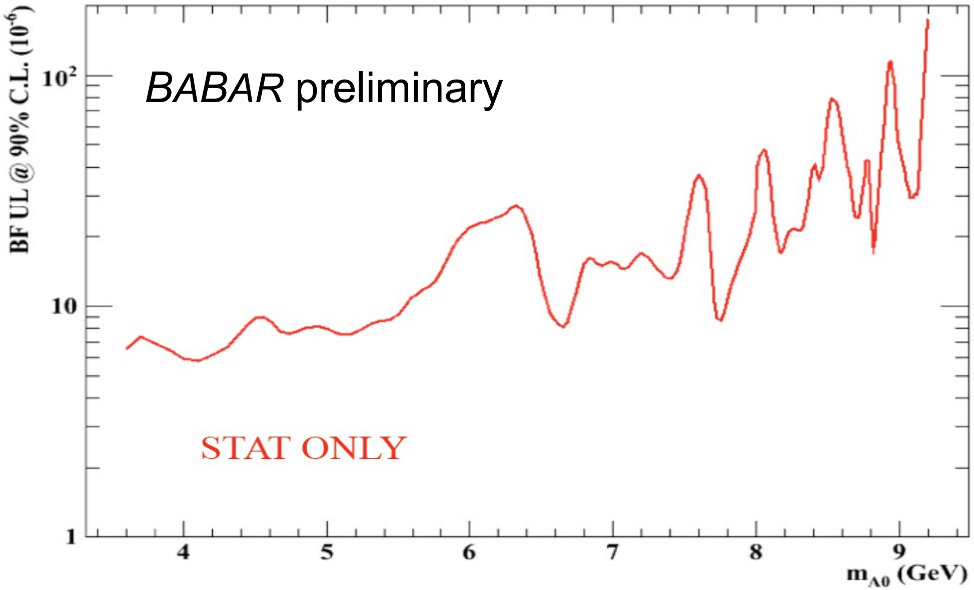
- Tag the Y(1S) from the dipion transition
- Use 1-prong decay of tau ($\tau \to \mu\nu\nu$, $\tau \to e\nu\nu$, $\tau \to \pi\nu\nu$)
- Fit for a narrow peak to the photon recoil mass in the Y(1S) system



m_{A^0}=8.93 GeV, Local significance=3.0σ

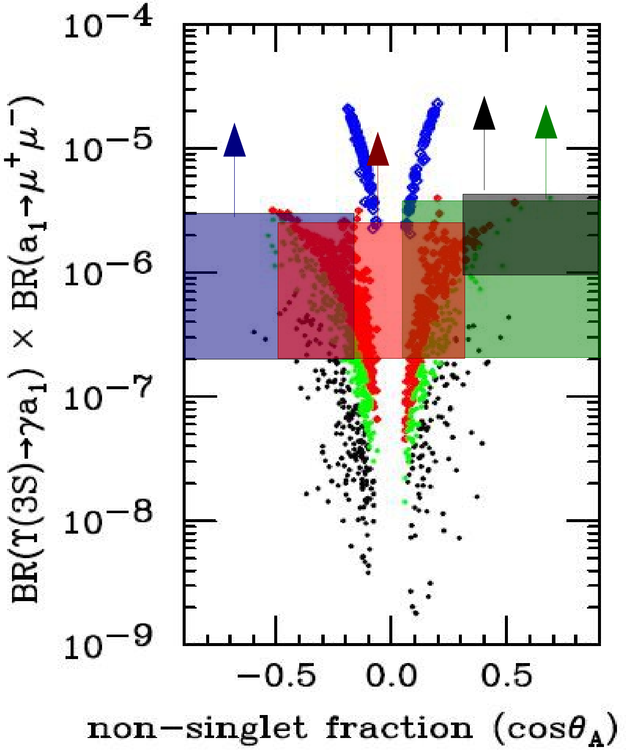
Global significance = 1.4σ

Branching fraction upper limit



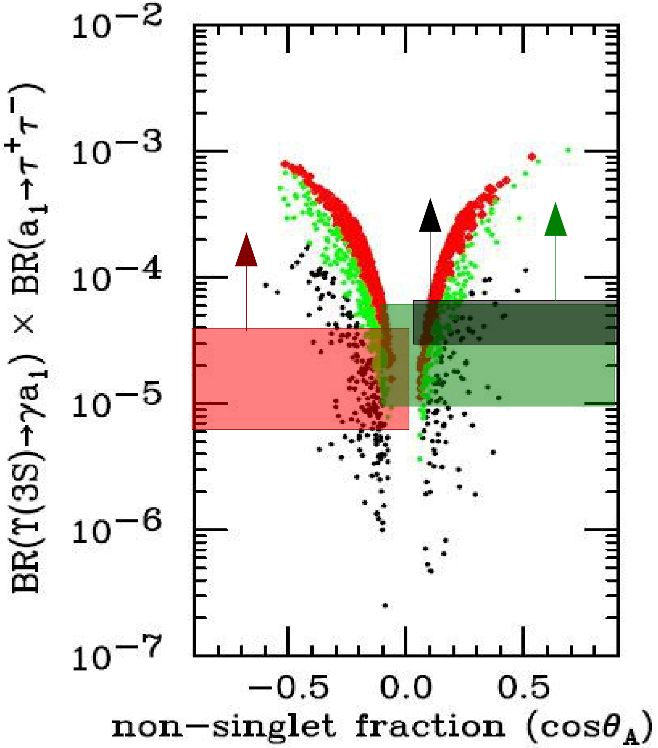
Search for light CP-odd Higgs - results

$A^0 \rightarrow \mu^+\mu^-$

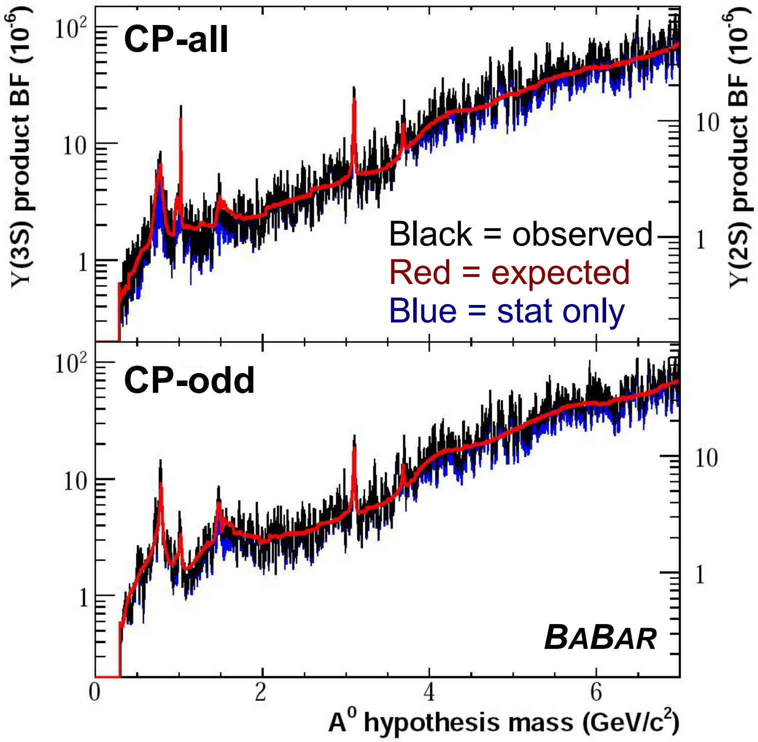


$\tan\beta$=10, μ=150 GeV, $M_{1,2,3}$ =100,200,300 GeV

$A^0 \rightarrow \tau^+\tau^-$



$A^0 \rightarrow$ hadrons



🟦 $0 < m_{A0} < 2m_\tau$
🟥 $2m_\tau < m_{A0} < 7.5$ GeV
🟩 $7.5 < m_{A0} < 8.8$ GeV
⬛ $8.8 < m_{A0} < 9.2$ GeV

Upper limits (90% CL)

$\Upsilon(2,3S) \rightarrow \gamma A^0$; $A^0 \rightarrow \mu^+\mu^-$
PRL 103, 081803 (2009)

$\Upsilon(3S) \rightarrow \gamma A^0$; $A^0 \rightarrow \tau^+\tau^-$
PRL 103, 181801 (2009)

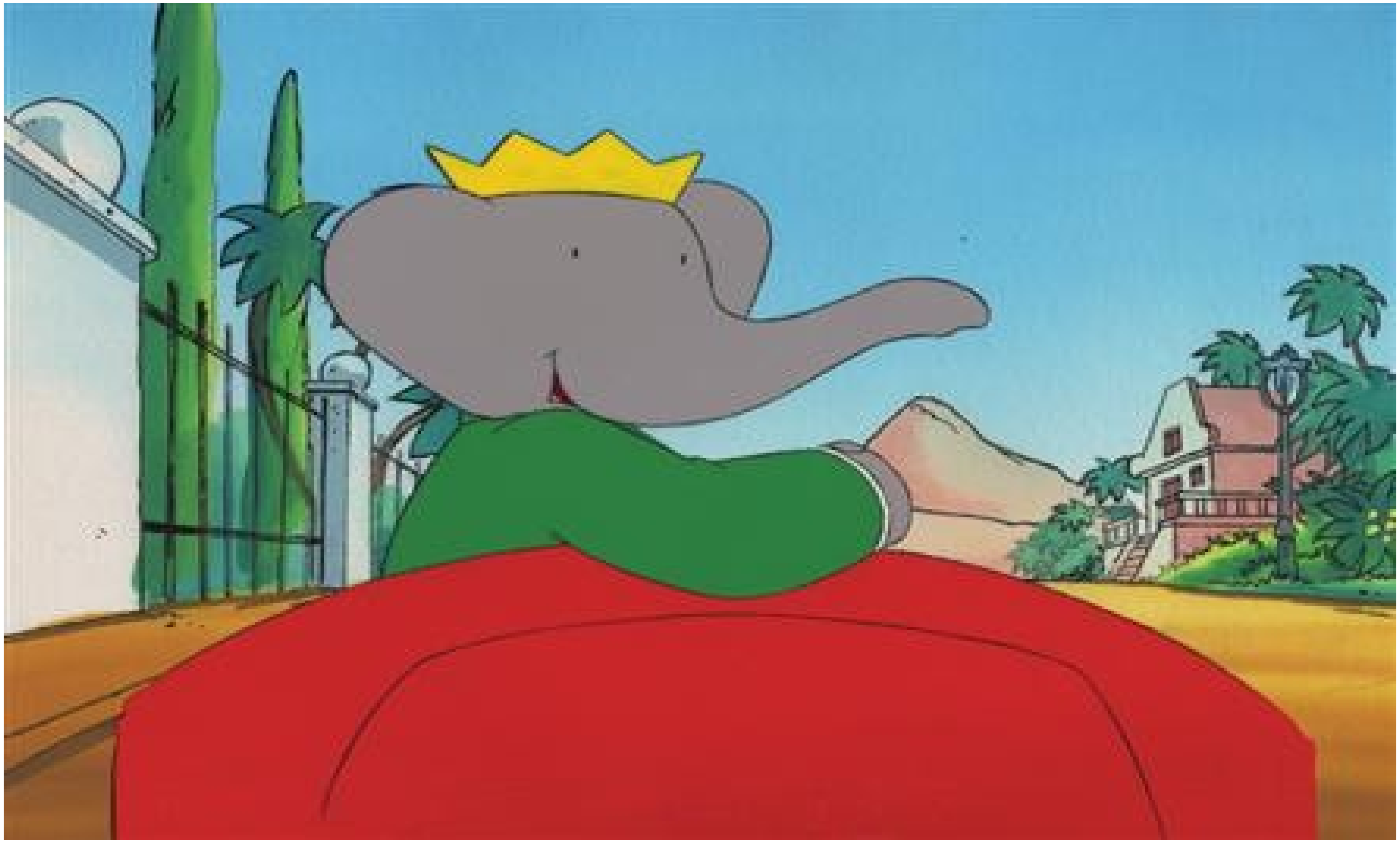
$\Upsilon(1S) \rightarrow \gamma A^0$; $A^0 \rightarrow$ invisible
PRL 107, 021804 (2011)

$\Upsilon(2,3S) \rightarrow \gamma A^0$; $A^0 \rightarrow$ hadrons
PRL 107, 221803 (2011)

Substantial fraction of the parameter space excluded

Conclusion

BABAR **is still producing many interesting results, and more are to come.**
See you soon...



Extra material

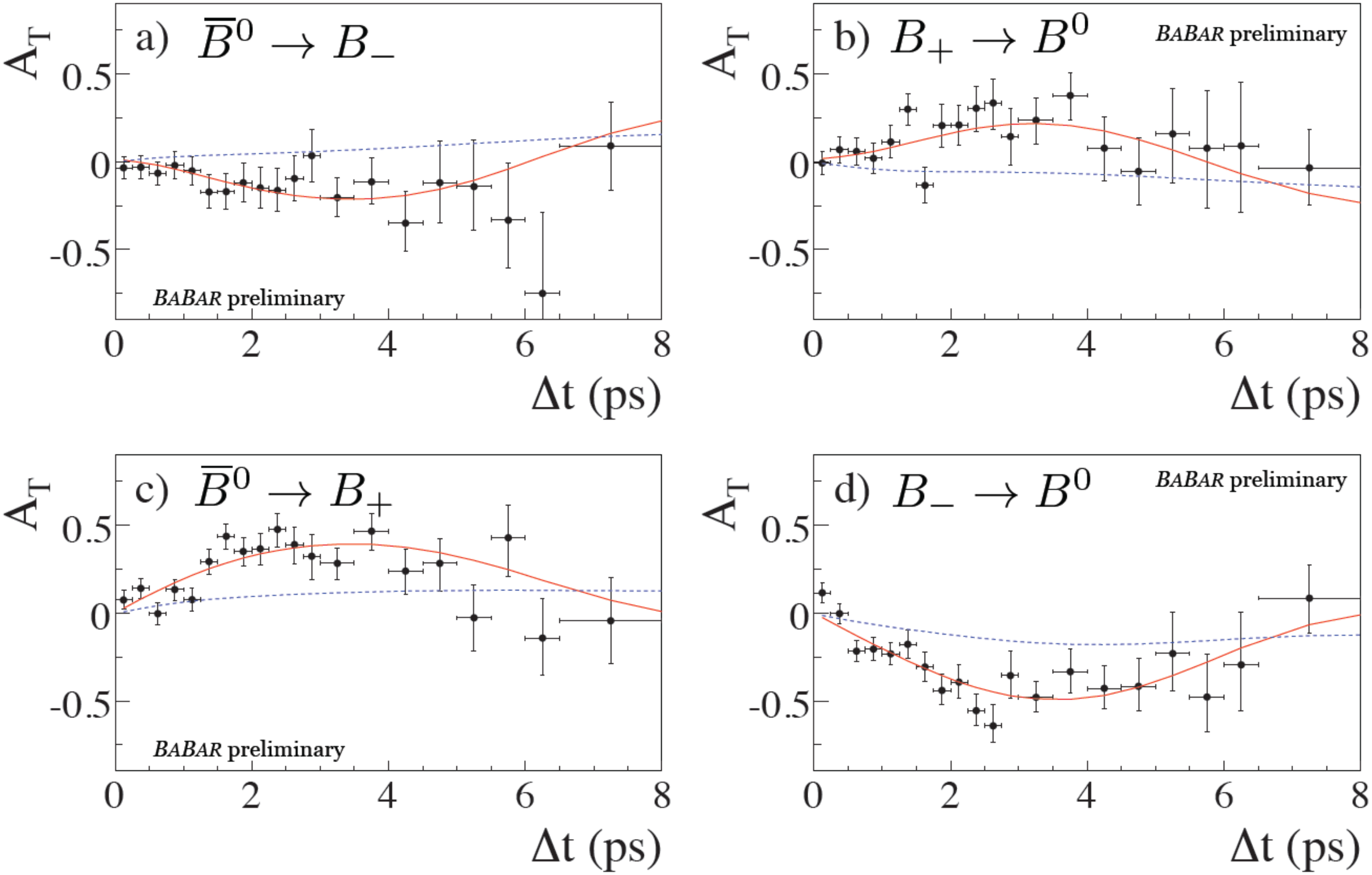
Independent T asymmetries

Asymmetries of the 4 transitions studied

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

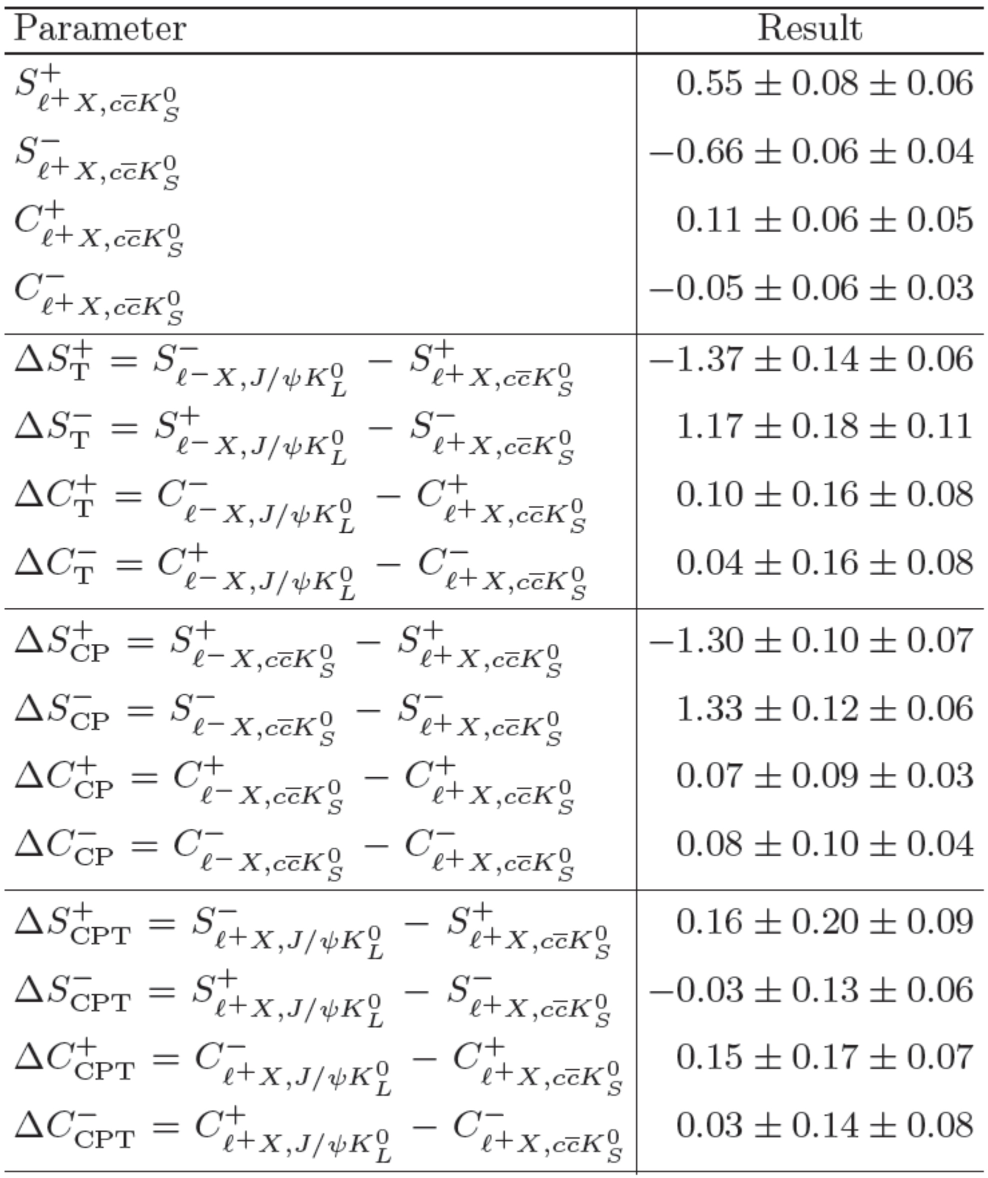
Projection of fit without TRV

Projection of fit with TRV



Time reversal violation

***BABAR* preliminary**

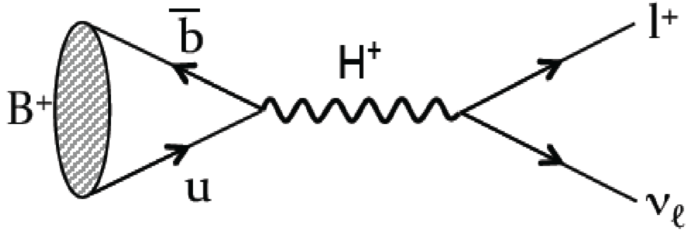


	Parameter	Result	expectation from canonical *CP*
	$S^+_{\ell^+X,c\bar{c}K^0_S}$	$0.55 \pm 0.08 \pm 0.06$	+sin2β
	$S^-_{\ell^+X,c\bar{c}K^0_S}$	$-0.66 \pm 0.06 \pm 0.04$	–sin2β
	$C^+_{\ell^+X,c\bar{c}K^0_S}$	$0.11 \pm 0.06 \pm 0.05$	0
	$C^-_{\ell^+X,c\bar{c}K^0_S}$	$-0.05 \pm 0.06 \pm 0.03$	0
T	$\Delta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

sin(2β) = 0.679 ± 0.020 (HFAG Winter'12)

Connection with $B \to \tau\nu$ decays

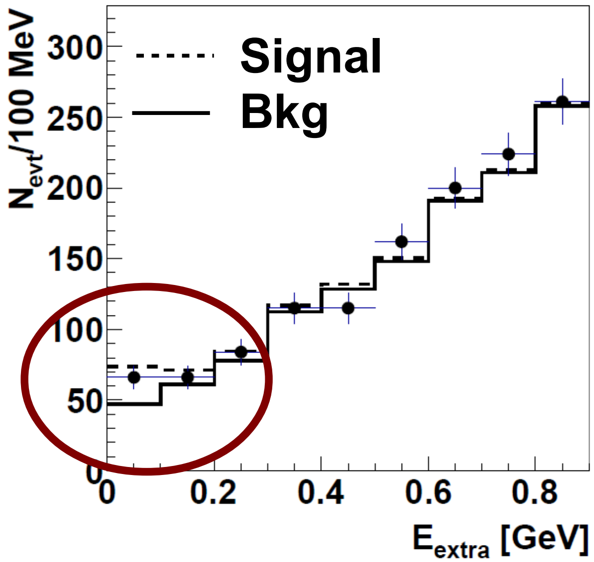
$B \to \tau\nu$ is also a tree level decay mediated by a $W^{\pm}$, sensitive to New Physics contributions such as $H^{\pm}$.



Analysis similar to that of $B \to D\,\tau\,\nu$

- Reconstruct of B_{tag}, assign rest of events to B_{sig}
- Reconstruct leptonic and hadronic tau decays
- Extract signal as UML fit to the extra neutral energy of the event

All channels combined



Combine result with statistically independent measurement in semi-leptonic tagging¹⁾

$$\mathcal{B}\,(B^{+} \to \tau^{+}\nu) = 1.79 \pm 0.48 \text{ (stat+syst)}$$

Recent result from Belle (ICHEP 2012)

$$\mathcal{B}\,(B^{+} \to \tau^{+}\nu) = 0.72^{+0.27}_{-0.25} \pm 0.11$$

Tension between *BABAR* / Belle

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1) *BABAR* Collab., Phys.Rev. D81 (2010) 051101

Connection with B → $\tau\nu$ decays

BABAR result

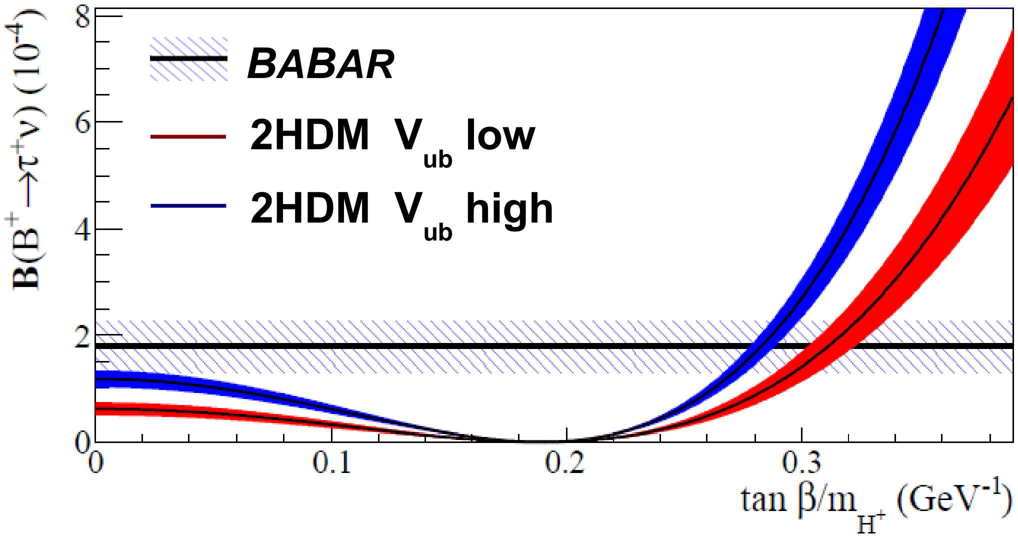
$\mathcal{B}(B^+ \to \tau^+\nu) = 1.79 \pm 0.48$

SM Model predictions (depends on V_{ub})

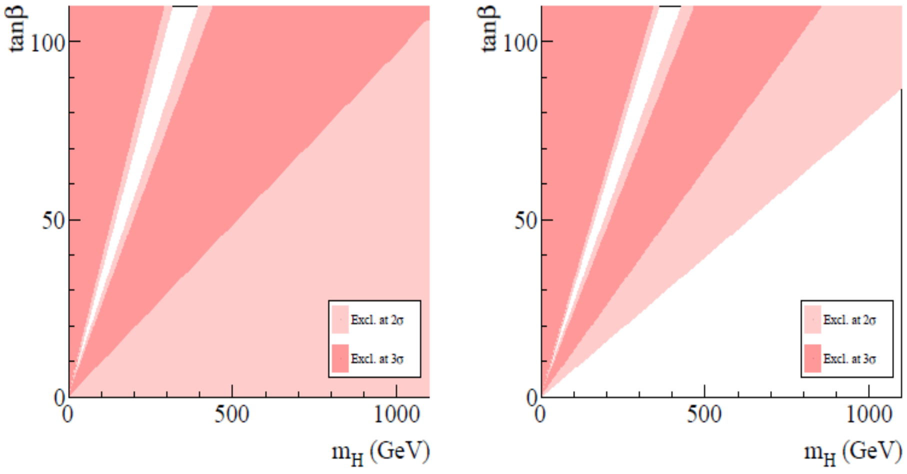
$\mathcal{B}_{SM}(B^+ \to \tau^+\nu) = 0.62 \pm 0.12$ $|V_{ub}| = 3.13 \pm 0.14 \pm 0.27$ (M.F. Sevilla, PoS(EPS-HEP2011)155 (2011))

$\mathcal{B}_{SM}(B^+ \to \tau^+\nu) = 1.18 \pm 0.16$ $|V_{ub}| = 4.33 \pm 0.24 \pm 0.15$ (*BABAR* Collab., arXiv:1112.0702)

2HDM type-II predictions



Constraints on $\tan\beta$ / m_H plane



Tension with the SM (1.6σ / 2.4σ) and constraints on the 2HDM type-II

Preferred values of $\tan\beta / m_H$ different from preferred by $B \to D^{(*)} \tau\nu$