Recent BaBar Results on rare B decays, CP- and T-violation

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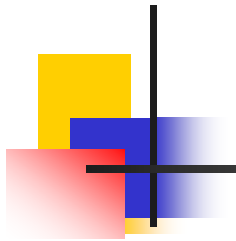
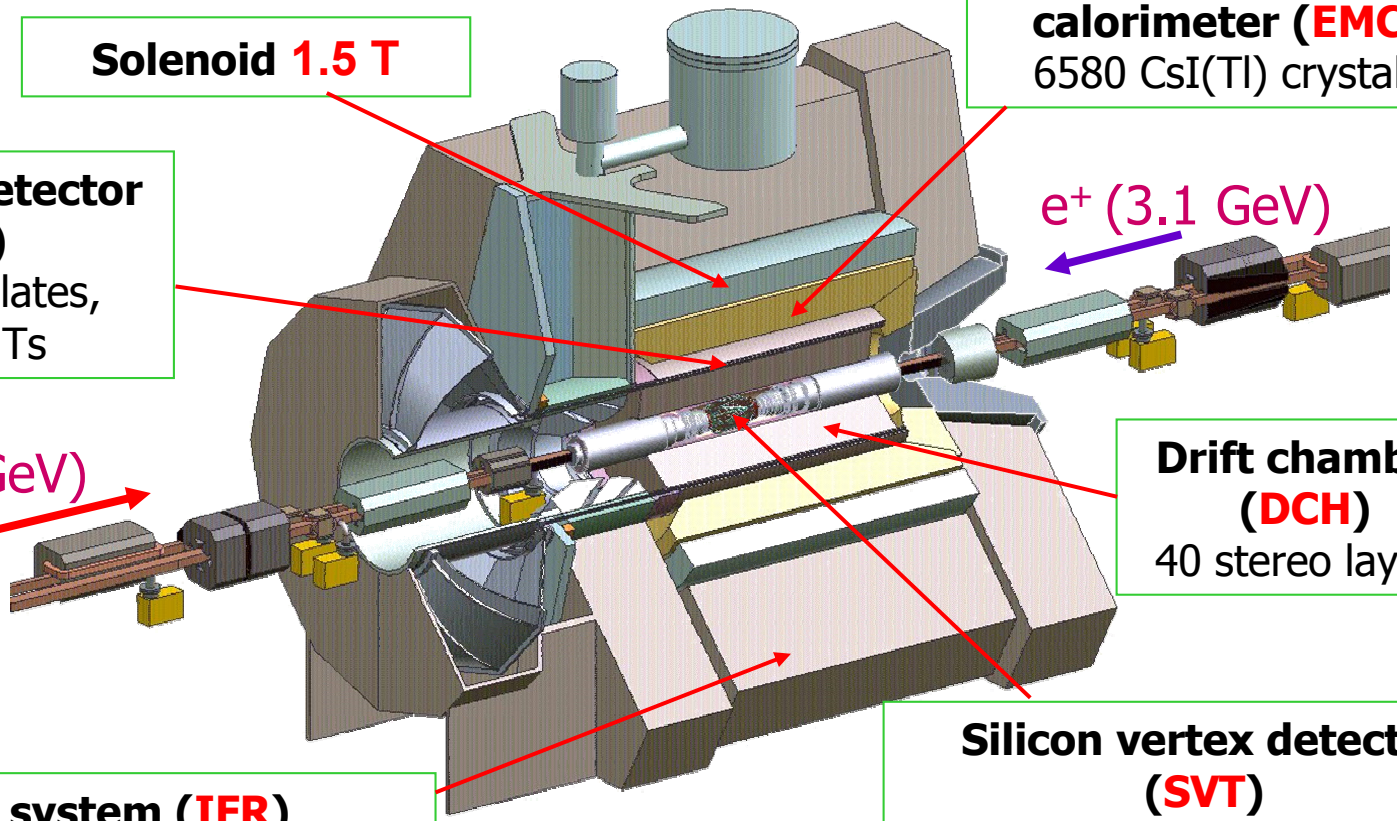


Outline

- CP violation in $B^0\bar{B}^0$ mixing
- CP violation in $B^0 \to (\rho\pi)^0$, Dalitz plot analysis
- Observation of T-violation
- $B \to \pi \ell^+\ell^-$ and $B^0 \to \eta \ell^+\ell^-$ decays
- $B \to D^{(*)}\tau\nu$ decay

BaBar Detector



Solenoid 1.5 T

Electromagnetic calorimeter (EMC)
6580 CsI(Tl) crystals

Cherenkov detector (DIRC)
144 quartz plates,
11000 PMTs

e^+ (3.1 GeV)

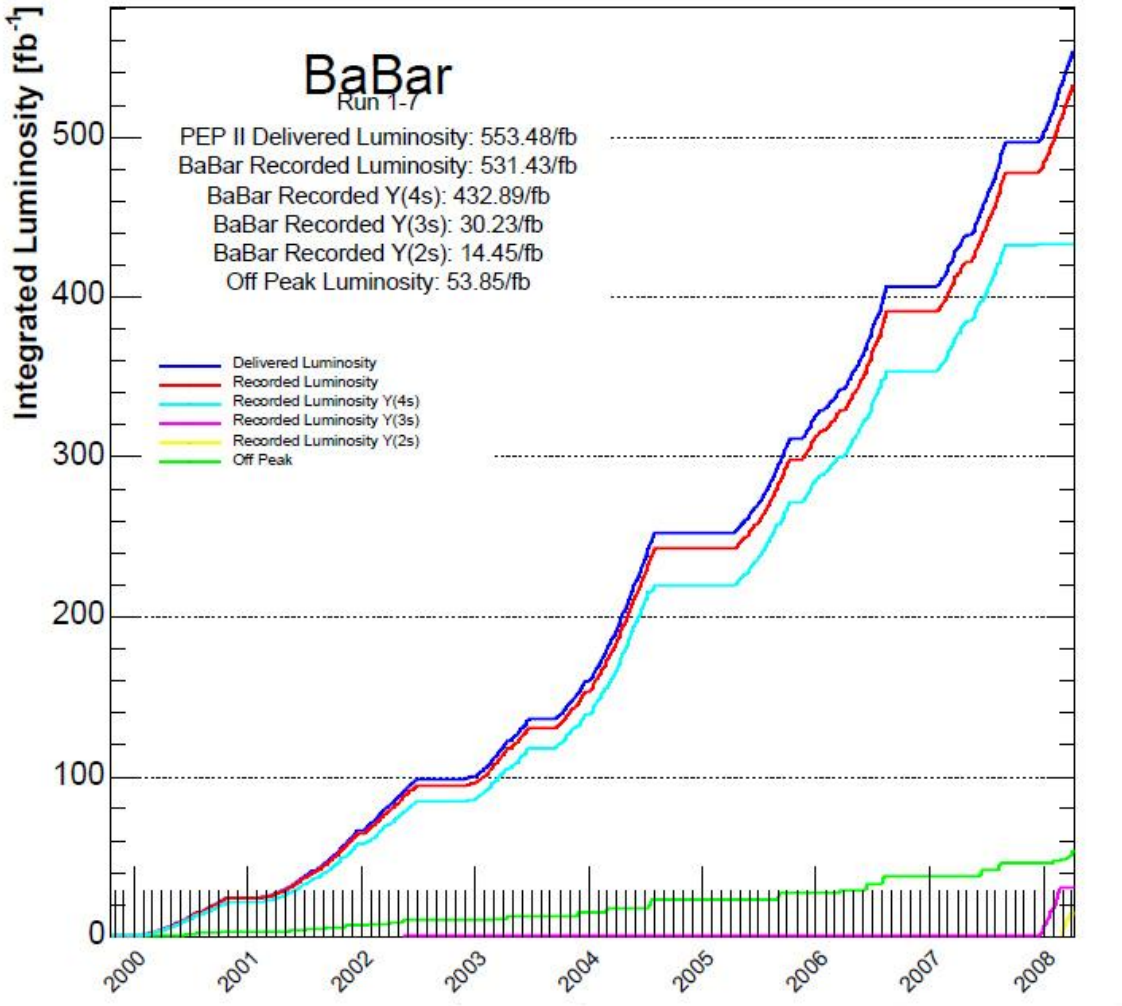
e^- (9 GeV)

Drift chamber (DCH)
40 stereo layers

Silicon vertex detector (SVT)
5 2D layers

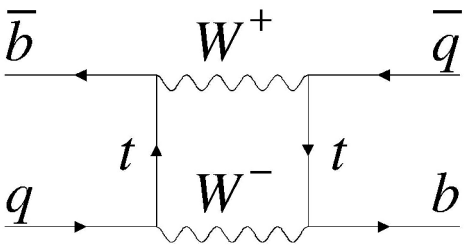
Muon system (IFR)

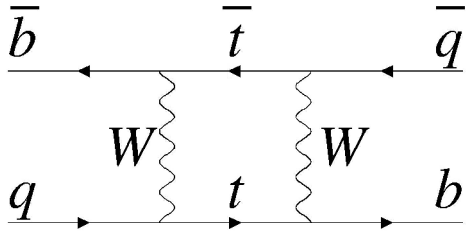
BaBar



- IL ≈ 430 fb^{-1} Y(4S) and ≈ 45 fb^{-1} 40MeV below Y(4S)
- ≈ 470 M $B\bar{B}$
- total IL ≈ 550 fb^{-1}

CP violation in $B^0\bar{B}^0$ mixing





- $(H)=(M)-i/2(\Gamma)$

  $<\bar{B}^0|H|B^0>=M^*_{12}-i\Gamma^*_{12}/2$

  $<B^0|H|\bar{B}^0>=M_{12}-i\Gamma_{12}/2$
- $|<B^0|H|\bar{B}^0>|^2-|<\bar{B}^0|H|B^0>|^2=2Im(M_{12}\Gamma_{12})$
- $|B_L>=p|B^0>+q|\bar{B}^0>$

  $|B_H>=p|B^0>-q|\bar{B}^0>$

- CPV in mixing

  $P(B^0\to\bar{B}^0)\neq P(\bar{B}^0\to B^0)$
- CP asymmetry $A_{CP}=$

  $$\frac{N(B^0B^0)-N(\bar{B}^0\bar{B}^0)}{N(B^0B^0)+N(\bar{B}^0\bar{B}^0)}=\frac{1-|q/p|^4}{1+|q/p|^4}$$
- $$\left(\frac{q}{p}\right)^2=\frac{M^*_{12}-(i/2)\Gamma^*_{12}}{M_{12}-(i/2)\Gamma_{12}}$$

CP violation in $B^0\bar{B}^0$ mixing

Usually measured asymmetry using semileptonic B decays

$$A_{SL} = \frac{N(l^+l^+) - N(l^-l^-)}{N(l^+l^+) + N(l^-l^-)} \sim O(m_c^2 / m_t^2)$$

- A^d_{SL} is measured with $\Upsilon(4S) \to B^0\bar{B}^0$

  HFAG average of CLEO, BaBar, Belle

  $A^d_{SL}=(-5\pm5.6)\cdot 10^{-4}$

  SM $A^d_{SL}=(-4.1\pm0.6)\cdot 10^{-4}$
- Hadronic colliders measure A^b_{SL} which is combination of A^d_{SL} and A^s_{SL}

  D0 result (Phys. Rev. D84, 052007 (2011))

  on charge dimuon asymmetry differs by 3.9σ

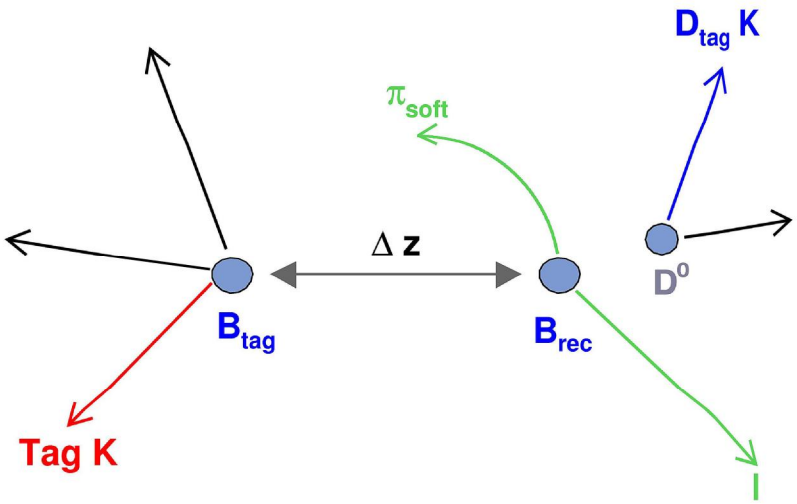
  $A^b_{SL}=(-0.787\pm0.172\pm0.093)\%$

  SM $A^b_{SL}=(-2.8\ ^{+0.5}_{-0.6})\cdot 10^{-4}$
- $A^s_{SL}=(-0.24\pm0.54\pm0.33)\%$ (LHCb)

  $A^s_{SL}=(-1.12\pm0.74\pm0.17)\%$ (D0)

  SM $A^s_{SL}=(1.9\pm0.3)\cdot 10^{-5}$

CP violation in $B^0\bar{B}^0$ mixing



New approach is used in BaBar analysis

$$A_{CP} = \frac{N(l^+K^+) - N(l^-K^-)}{N(l^+K^+) + N(l^-K^-)}$$

- partial reconstruction using only the lepton from $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$
  and the soft π from $D^{*+} \to \bar{D}^0\,\pi^+$
  D^* 4-momentum estimated from π_{soft} kinematics
- K-tagging determines the flavor of the other B

CP violation in $B^0\bar{B}^0$ mixing

$$A_T = \frac{N(l^+K_T^+) - N(l^-K_T^-)}{N(l^+K_T^+) - N(l^+K_T^-)} \cong A_{rl} + A_K + A_{CP}$$

$$A_R = \frac{N(l^+K_R^+) - N(l^-K_R^-)}{N(l^+K_R^+) - N(l^+K_R^-)} \cong A_{rl} + A_K + A_{CP}\chi_d$$

$$\chi_d = 0.1862 \pm 0.0023$$

K_R and K_T are charged K mesons from decays of B mesons Reconstructed and Tag, respectively

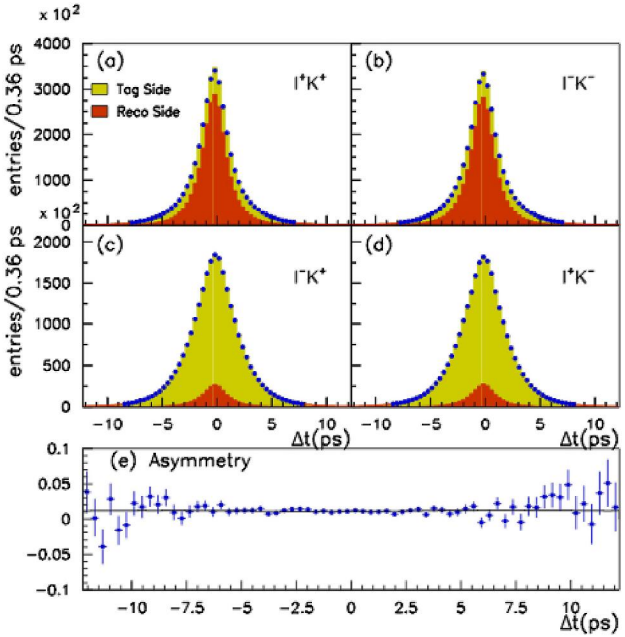
- K_R can come from the Cabibbo-Favored decays of D^0 produced with the lepton from the partially reconstructed side

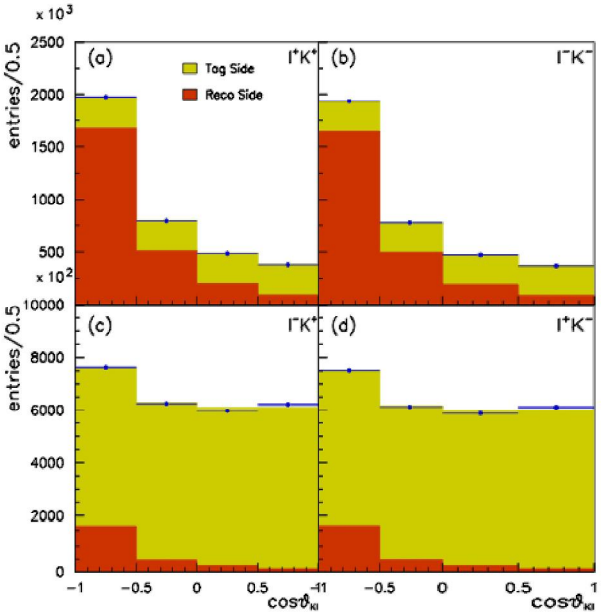
  K_R is usually emitted in hemisphere opposite to ℓ

  K_T is produced randomly
- $A_{r\ell}$ and A_K are detector-induced asymmetries

CP violation in $B^0\bar{B}^0$ mixing

preliminary results arXiv:1305.1575[hep-ex], submitted to PRL





A_{CP} from binned four-dimensional fit to $\cos\theta_{\ell K}$, Δz, $\sigma(\Delta t)$, p_K on 4 samples: unmixed $\ell^{\pm}K^{\mp}$ and mixed $\ell^{\pm}K^{\pm}$

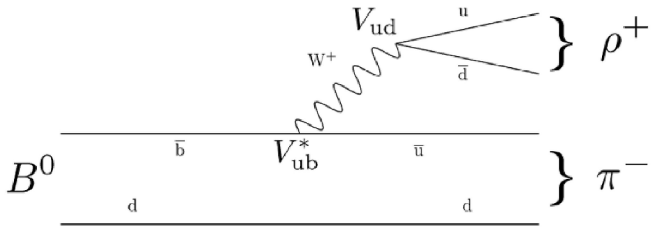
- BaBar

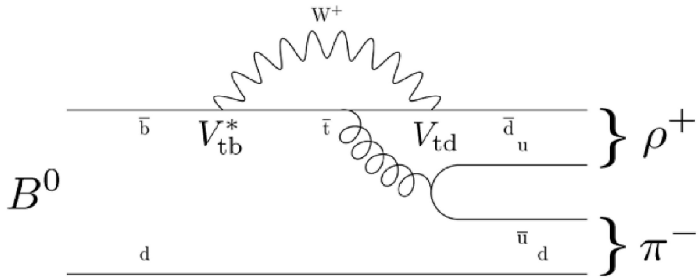
$$A_{SL}^{d} = (0.06 \pm 0.17^{+0.36}_{-0.32})\ \%$$

$$1 - |q/p| = (0.29 \pm 0.84^{+1.78}_{-1.61}) \cdot 10^{-3}$$

- consistent with previous measurements
- consistent with SM
- most precise measurement

CP violation in $B^0 \to (\rho\pi)^0$, Dalitz-plot analysis





Motivation

- CP violation in $B^0 \to \pi^+\pi^-\pi^0$ dominated by $B^0 \to \rho^\pm \pi^\mp$
- precision measurement $\alpha = arg[-V_{td}V^*_{tb} / V_{ud}V^*_{ub}]$

The update of earlier 2007 BaBar analysis was done due to:

- increased dataset, 431fb^{-1} vs. 346fb^{-1}
- improved tracking and particle identification
- reoptimized cuts
- more rigorous study of the ρ line-shape systematic uncertainties

Selection

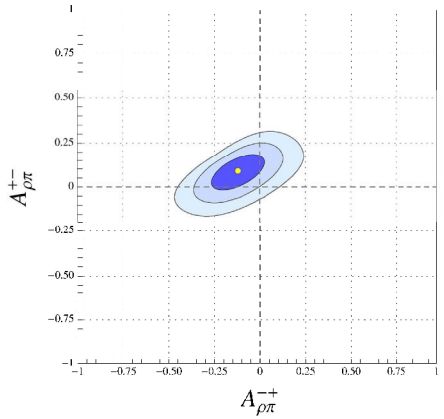
- measured energy of the B candidate between 4.99 and 5.59 GeV
- m_{ES} between 5.200 and 5.288 GeV/c^2

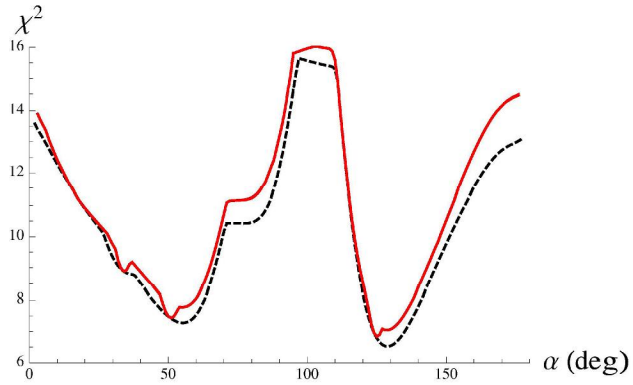
NN selection

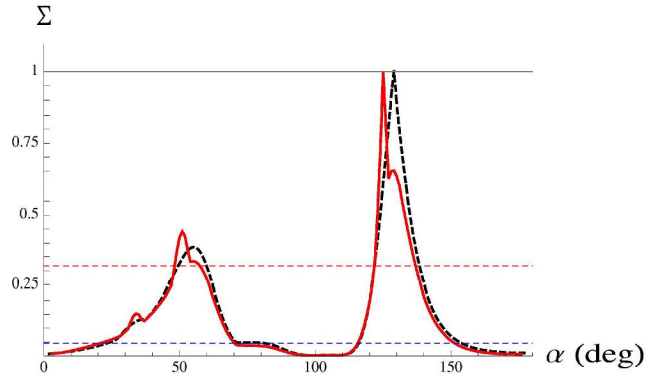
- Legendre moment L0, L2
- angle between the beam axis and the momentum or the B thrust axis

CP violation in $B^0 \to (\rho\pi)^0$, Dalitz-plot analysis

preliminary results arXiv:1304.3503[hep-ex], submitted to Phys. Rev. D







isospin-constrained
unconstrained

Extruction of α is not robust

$$A^{+-}_{\rho\pi} = 0.09^{+0.05}_{-0.06} \pm 0.04$$

$$A^{-+}_{\rho\pi} = -0.12 \pm 0.08^{+0.04}_{-0.05}$$

$C = 0.016 \pm 0.059 \pm 0.036, \quad \Delta C = 0.234 \pm 0.061 \pm 0.048$

$S = 0.053 \pm 0.081 \pm 0.034, \quad \Delta S = 0.054 \pm 0.082 \pm 0.039$

Observation of T-violation

T transformation is antiunitary

$\vec{v} \to -\vec{v}$ *and exchange of in and out states*

- P violation in nuclear β decay (T.D.Lee, C.N.Yan, C.S.Wu et. al., 1957)
- CP violation in K^0 mesons (J.W.Cronin et. al., 1964)
- CP violation in B^0 mesons (BaBar and Belle, 2001)

$Y(4S)$ decay yields an entangled state of B mesons

- $|i>=\frac{1}{\sqrt{2}}(B^0(t_1)\overline{B}^0(t_2)-\overline{B}^0(t_1)B^0(t_2))$

  Flavor tag: semileptonic decay to $\ell^- X(\ell^+ X)$ projects $\overline{B}^0(B^0) \to B^0(\overline{B}^0)$ tag
- $|i>=\frac{1}{\sqrt{2}}(B_+(t_1)B_-(t_2)-B_-(t_1)B_+(t_2))$

  CP tag: B decay to $J/\psi\ K_L$ projects $B_+ \to B_-$ tag and

  B decay to $J/\psi\ K_S$ projects $B_- \to B_+$ tag

Observation of T-violation

T-transformed processes

4 independent T comparisons

$B^0 \to B_+$	$(l^-, J/\psi K_L^0)$	$B_+ \to B^0$	$(J/\psi K_S^0, l^+)$
$B^0 \to B_-$	$(l^-, J/\psi K_S^0)$	$B_- \to B^0$	$(J/\psi K_L^0, l^+)$
$\bar{B}^0 \to B_+$	$(l^+, J/\psi K_L^0)$	$B_+ \to \bar{B}^0$	$(J/\psi K_S^0, l^-)$
$\bar{B}^0 \to B_-$	$(l^+, J/\psi K_S^0)$	$B_- \to \bar{B}^0$	$(J/\psi K_L^0, l^-)$

4 independent CP comparisons

4 independent CPT comparisons

Observation of T-violation

Fit to signal parameters
8 time-dependent decay rates

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

$\pm$ – $\Delta t > 0, < 0$

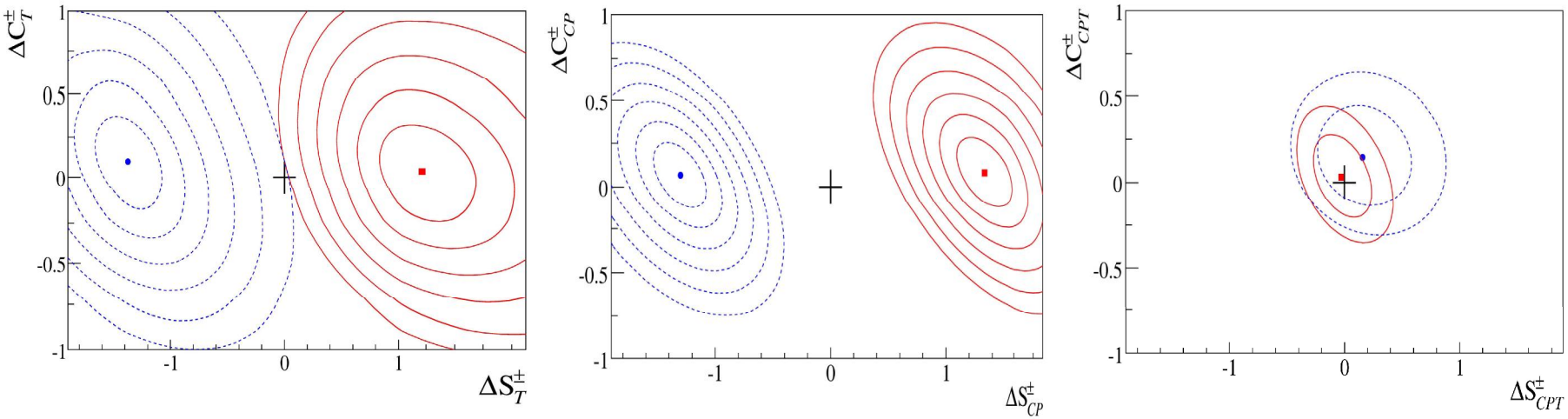
α, β – flavor, CP reco

- for example $\overline{B}^0 \to B_-(l^+ K_S)$ is characterized by $S^+_{l^+,K_S}$
- T-reversed transition $B_- \to \overline{B}^0(K_L, l^-)$ is characterized by $S^-_{l^-,K_L}$
- parameter of T violation: $\Delta S^+_T = S^-_{l^-,K_L} - S^+_{l^+,K_S}$

  $(\Delta S^-_T = S^+_{l^-,K_L} - S^-_{l^+,K_S})$

Observation of T-violation

Results



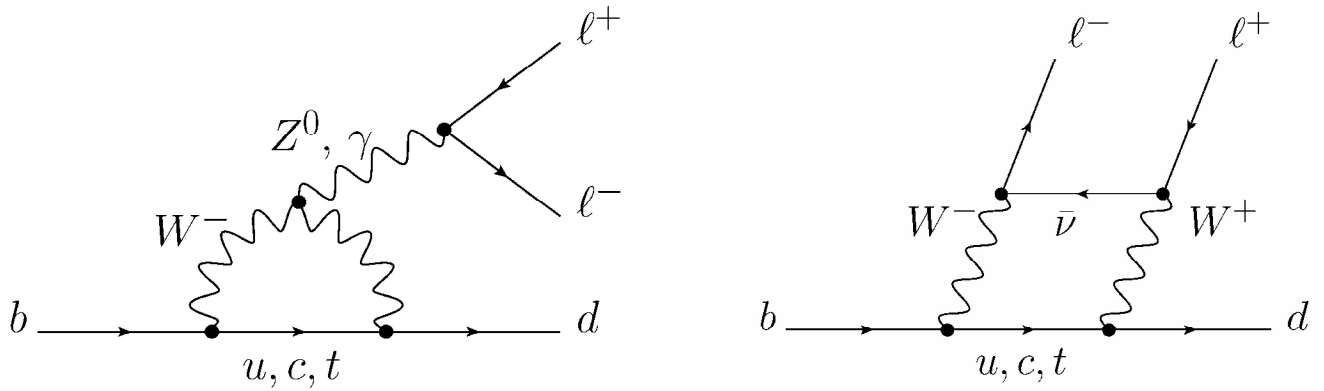
ΔC^+ vs. ΔS^+ and ΔC^- vs. ΔS^- ; Central values (blue points and red squares) and countors of (1−C.L.) at 1σ intervals for the T(left), CP(middle), and CPT(right) results. The + sign shows no-violation point on each plot.

Significance of T violation 14σ, CP violation 17σ, CPT violation 0.3 σ

FIRST DIRECT OBSERVATION OF T VIOLATION

Phys. Rev. Lett. 109, 211801, (2012)

$B \to \pi\, l^+ l^-$ and $B^0 \to \eta\, l^+ l^-$ decays



- flavour-changing neutral current $b \to d$
- forbidden at tree level in SM
- predicted fraction ~ 10^{-8}
- LHCb $B^+ \to \pi^+ \mu^+ \mu^-$
  $Br = (2.3 \pm 0.6 \pm 0.1) \times 10^{-8}$

$B \to \pi\, l^+ l^-$ and $B^0 \to \eta\, l^+ l^-$ decays

preliminary

Mode	ε	Yield	$B(10^{-8})$	Upper limit (10^{-8})
$B^+ \to \pi^+ e^+ e^-$	0.207	$4.2^{+5.7}_{-4.6}$	$4.3^{+5.9}_{-4.3} \pm 2.0$	12.5
$B^0 \to \pi^0 e^+ e^-$	0.166	$1.0^{+4.2}_{-3.2}$	$1.3^{+5.4}_{-4.1} \pm 0.2$	8.4
$B^0 \to \eta\, e^+ e^-$			$-4.0^{+10.0}_{-8.0} \pm 0.6$	10.8
$B^0 \to \eta_{\gamma\gamma} e^+ e^-$	0.166	$-1.2^{+3.1}_{-2.4}$		
$B^0 \to \eta_{3\pi} e^+ e^-$	0.111	$-0.5^{+1.2}_{-0.9}$		
$B^+ \to \pi^+ \mu^+ \mu^-$	0.149	$-0.5^{+3.1}_{-2.3}$	$-0.7^{+4.4}_{-3.2} \pm 0.9$	5.5
$B^0 \to \pi^0 \mu^+ \mu^-$	0.121	$-0.2^{+3.0}_{-2.0}$	$-0.3^{+5.3}_{-3.6} \pm 0.6$	6.9
$B^0 \to \eta \mu^+ \mu^-$			$-2.0^{+10.0}_{-6.6} \pm 0.4$	11.2
$B^0 \to \eta_{\gamma\gamma} \mu^+ \mu^-$	0.104	$-0.4^{+1.9}_{-1.3}$		
$B^0 \to \eta_{3\pi} \mu^+ \mu^-$	0.063	$-0.1^{+0.6}_{-0.4}$		
$B \to \pi\, e^+ e^-$			$4.0^{+5.1}_{-4.3} \pm 1.6$	11.0
$B \to \pi\, \mu^+ \mu^-$			$-0.7^{+4.1}_{-3.1} \pm 1.2$	5.0
$B^+ \to \pi^+ \ell^+ \ell^-$			$1.6^{+3.6}_{-3.0} \pm 1.2$	6.6
$B^0 \to \pi^0 \ell^+ \ell^-$			$0.5^{+3.7}_{-2.9} \pm 0.3$	5.3
$B^0 \to \eta\, \ell^+ \ell^-$			$-2.8^{+6.6}_{-5.2} \pm 0.3$	6.4
$B \to \pi\, \ell^+ \ell^-$			$1.6^{+3.2}_{-2.7} \pm 1.0$	5.9

$B \to \pi\, l^+ l^-$ and $B^0 \to \eta\, l^+ l^-$ decays

- no statistically significant signal observed
- lepton-flavor and isospin averaged upper limit at the 90% CL

  $\mathcal{B}(B \to \pi \ell^+ \ell^-) < 5.9 \times 10^{-8}$

  factor of three of the SM expectation
- upper limits have also been calculated for different $\pi \ell^+ \ell^-$ modes
- $\mathcal{B}(B^0 \to \eta \ell^+ \ell^-) < 6.4 \times 10^{-8}$
- upper limits have also been calculated for different $\eta \ell^+ \ell^-$ modes
- lowest upper limits to date for $B^0 \to \pi^0 \ell^+ \ell^-$
- first search for the decays $B^0 \to \eta \ell^+ \ell^-$

arXiv:1303.6010[hep-ex], submitted to Phys. Rev. D

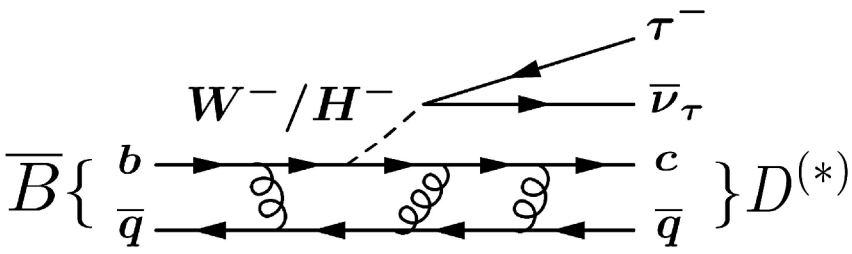
$B \to D^{(*)}\tau\nu$ decay

- SM rate well predicted, ~ 2%
- many common factors in decay rate to e, μ, τ
- $$R(D^{(*)}) = \frac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}l\nu)}$$

  independent of $|V_{cb}|$ and to large extent of parametrization of hadronic matrix elements
- SM uncertainty for $R(D)$ 6% and for $R(D^*)$ 2%
- charged Higgs contributions at tree level
- sensitive to vector vs. scalar current

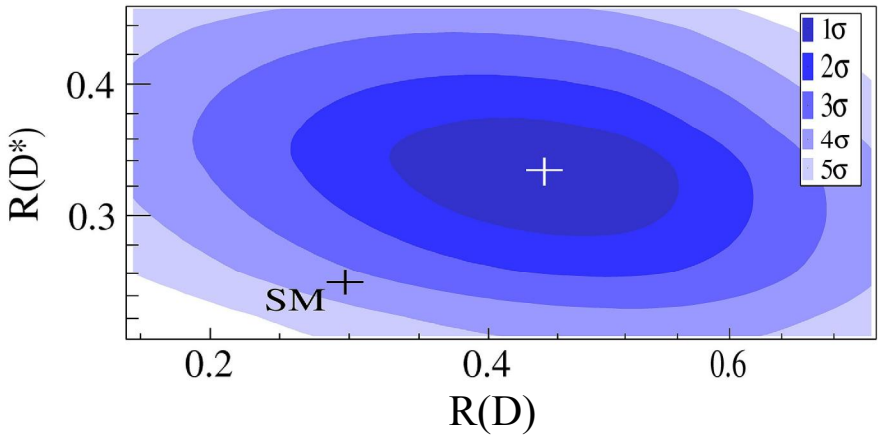
- reconstruct only
  $\tau^- \to e^- \bar{\nu}_e \nu_\tau$ and
  $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$
- fully reconstructing
  B_{tag}
  $m_{ES} > 5.27$ GeV/c^2
  $|\Delta E| < 0.072$ GeV
- B_{sig}: $D^{(*)}$, lepton and ν (missing energy)

- First observed by Belle in 2007
  Phys. Rev. Lett. 99 (2007) 191807

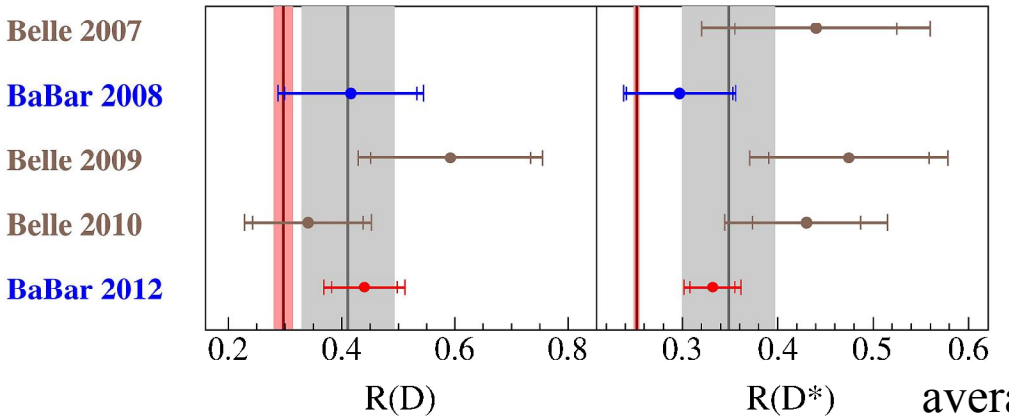


$B \to D^{(*)}\tau\nu$ decay

Phys. Rev. Lett. 109, 101802, (2012)



- excesses over the SM predictions for $R(D)$ and $R(D^*)$ of 2.0σ and 2.7σ
- $R(D^{(*)})_{th} = R(D^{(*)})_{SM}$ probability of 6.9×10^{-4} SM predictions is excluded at the 3.4σ

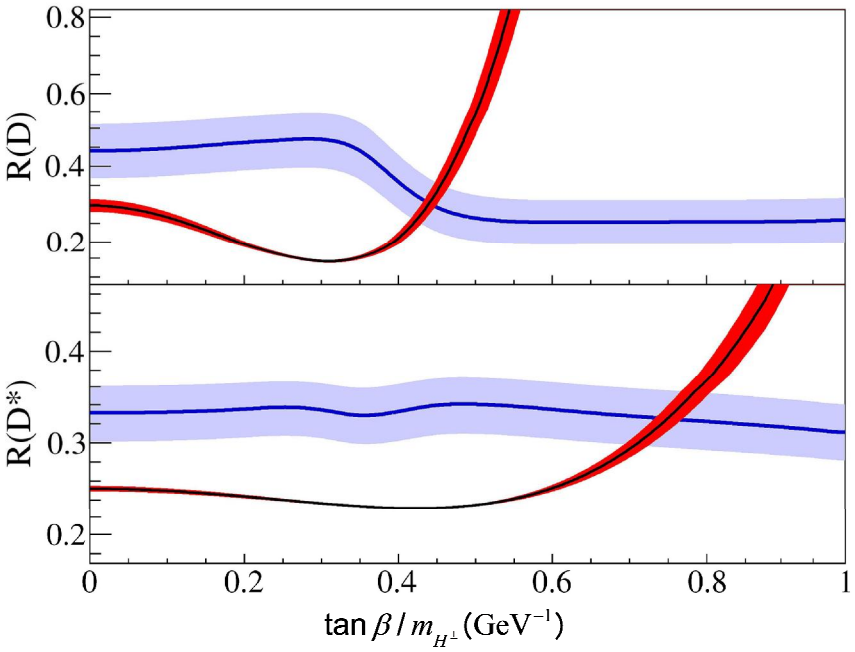


- $R(D) = 0.440 \pm 0.058 \pm 0.042$
  $R(D)_{SM} = 0.297 \pm 0.017$
- $R(D^*) = 0.332 \pm 0.024 \pm 0.018$
  $R(D^*)_{SM} = 0.252 \pm 0.003$

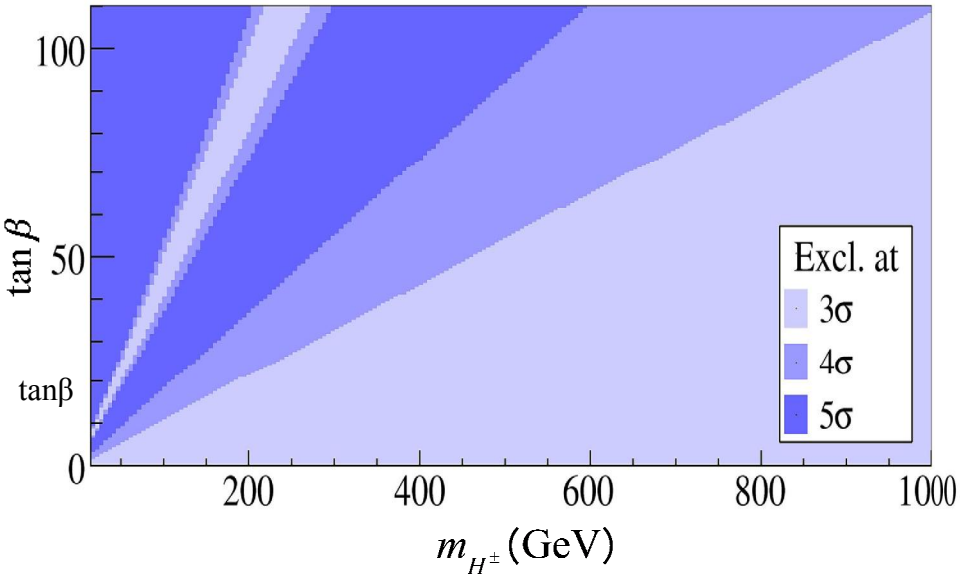
average of the previous measurements (shading)

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

experimental results
theoretical predictions



2HDM type II

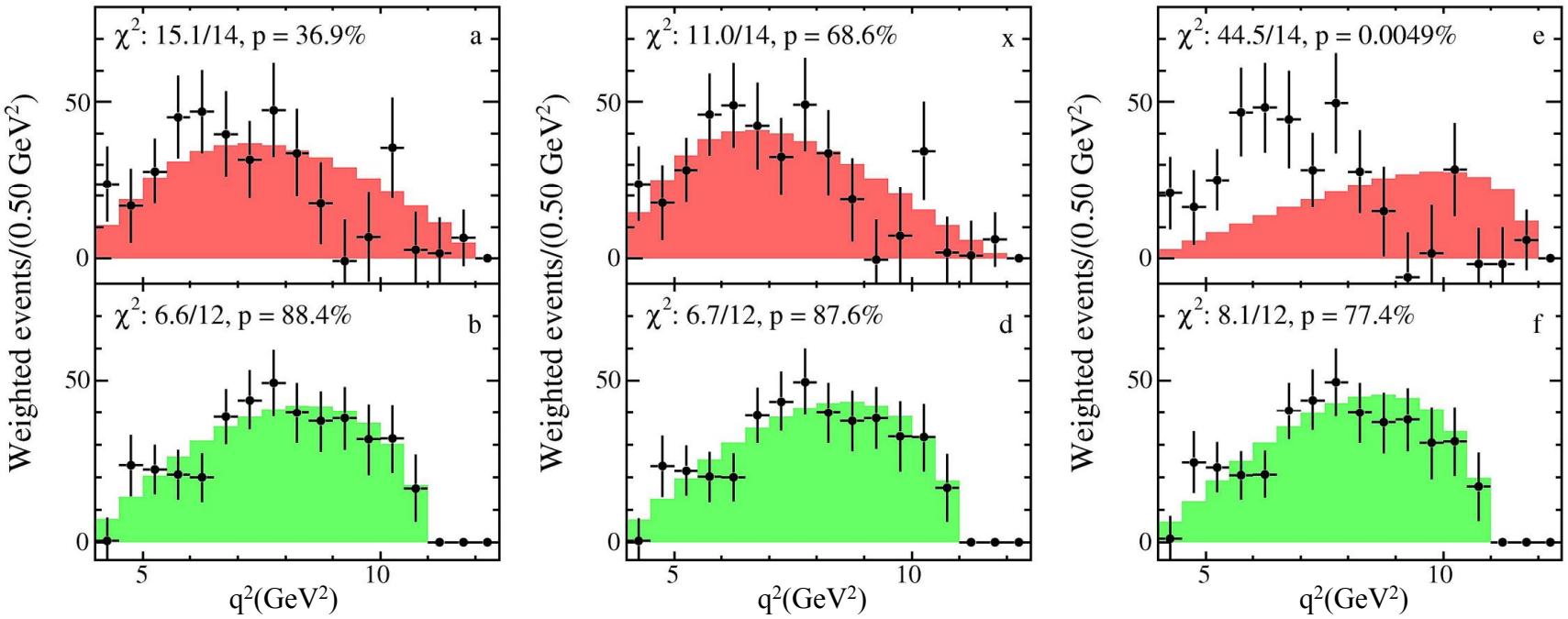


Level of disagreement

- $\tan\beta/m_{H^\pm} = 0.44 \pm 0.02 \mathrm{GeV}^{-1}$
  $R(D)$
- $\tan\beta/m_{H^\pm} = 0.75 \pm 0.04 \mathrm{GeV}^{-1}$
  $R(D^*)$

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

2HDM type II arXiv:1303.0571[hep-ex], submitted to PRD preliminary



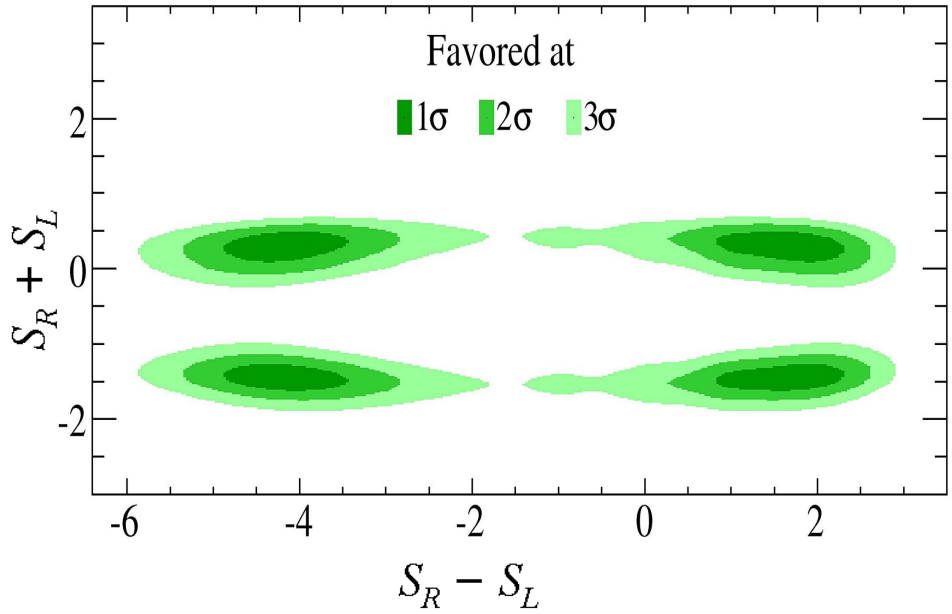
efficiency corrected q^2 distributions for $D\tau\nu$ (top) and $D^*\tau\nu$ (bottom) events with $m^2_{miss} > 1.5$ GeV^2 scaled to the results of the isospin-constrained fit.

Left: SM, Center: $\tan\beta/M_{H^\pm}=0.30$ GeV^{-1}. Right: $\tan\beta/M_{H^\pm}=0.45$ GeV^{-1}.

The uncertainty on the data points includes the statistical uncertainties of data and simulation

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

2HDM type III preliminary



- favored regions for real values of the type III 2HDM parameters S_R and S_L given by measured values of R(D$^{(*)}$)
- bottom two solutions are excluded by the measured q^2 spectra with significance of at least 2.9σ

Summary

- Search for CP violation in $B^0\bar{B}^0$ mixing (New)
  Improvement of the average $Y(4S)$ result on $|q/p|$ for the B^0_d mixing
- Search for CP violation in $B^0 \to (\rho\pi)^0$
  Results are consistent with SM
- First direct observation of Time-Reversal Violation
  Expected from CP violation, but was not directly observed before
- Search for $B \to \pi\ell^+\ell^-$ and $B^0 \to \eta\ell^+\ell^-$ decays (New)
  Lowest upper limits to date for $B^0 \to \pi^0\ell^+\ell^-$ and first search for the decays $B^0 \to \eta\ell^+\ell^-$
- Study of the $B \to D^{(*)}\tau\nu$ decay
  Hints of tension with SM
- BaBar finished collecting data five years ago
  but the collaboration continues to publish new results
- the current publication rate is about 30 journal publications per year
- many analyses in progress