BABAR latest results, focusing on CP violation and on rare processes probing the SM and BSM

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On behalf of the BaBar Collaboration

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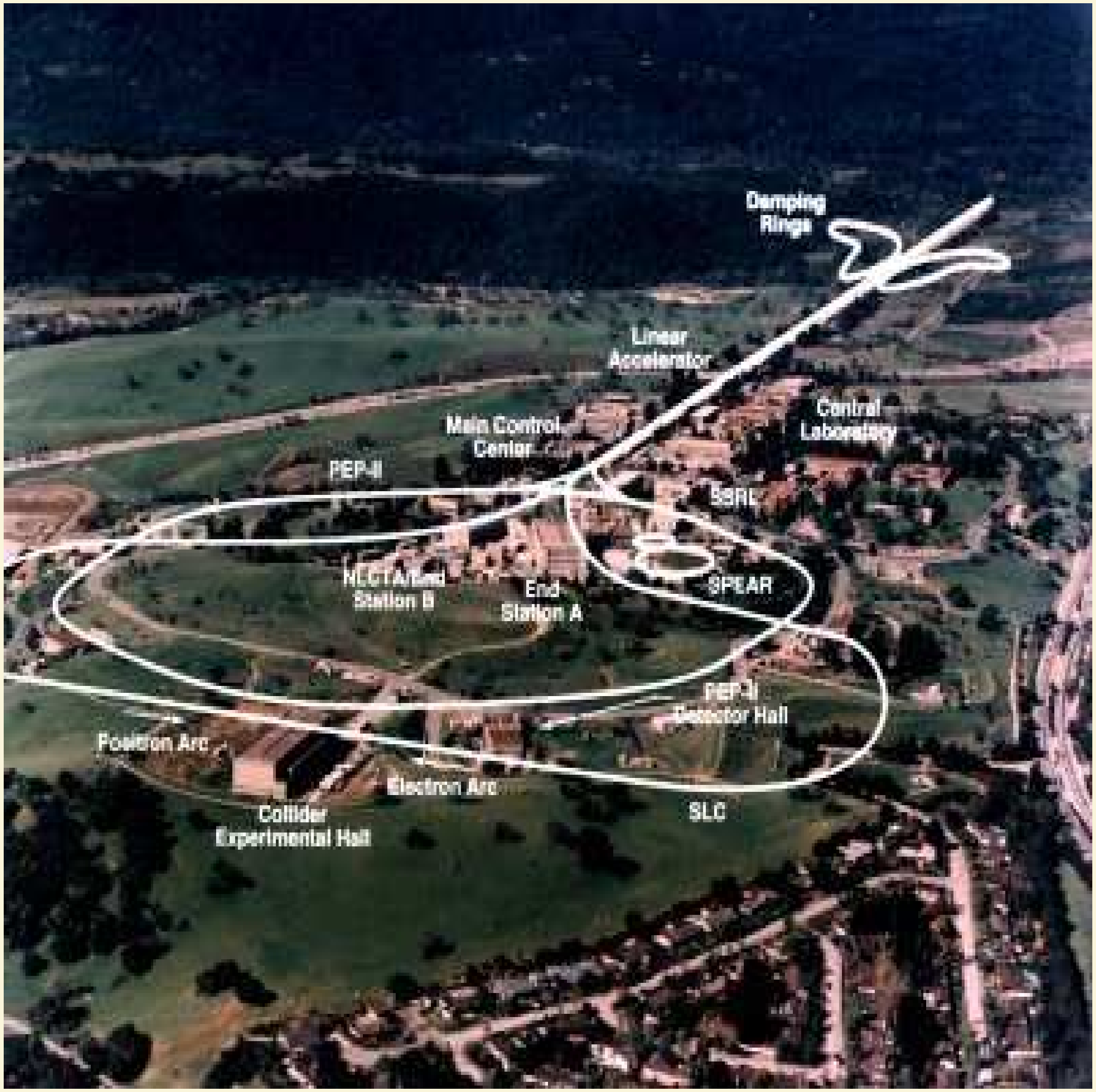
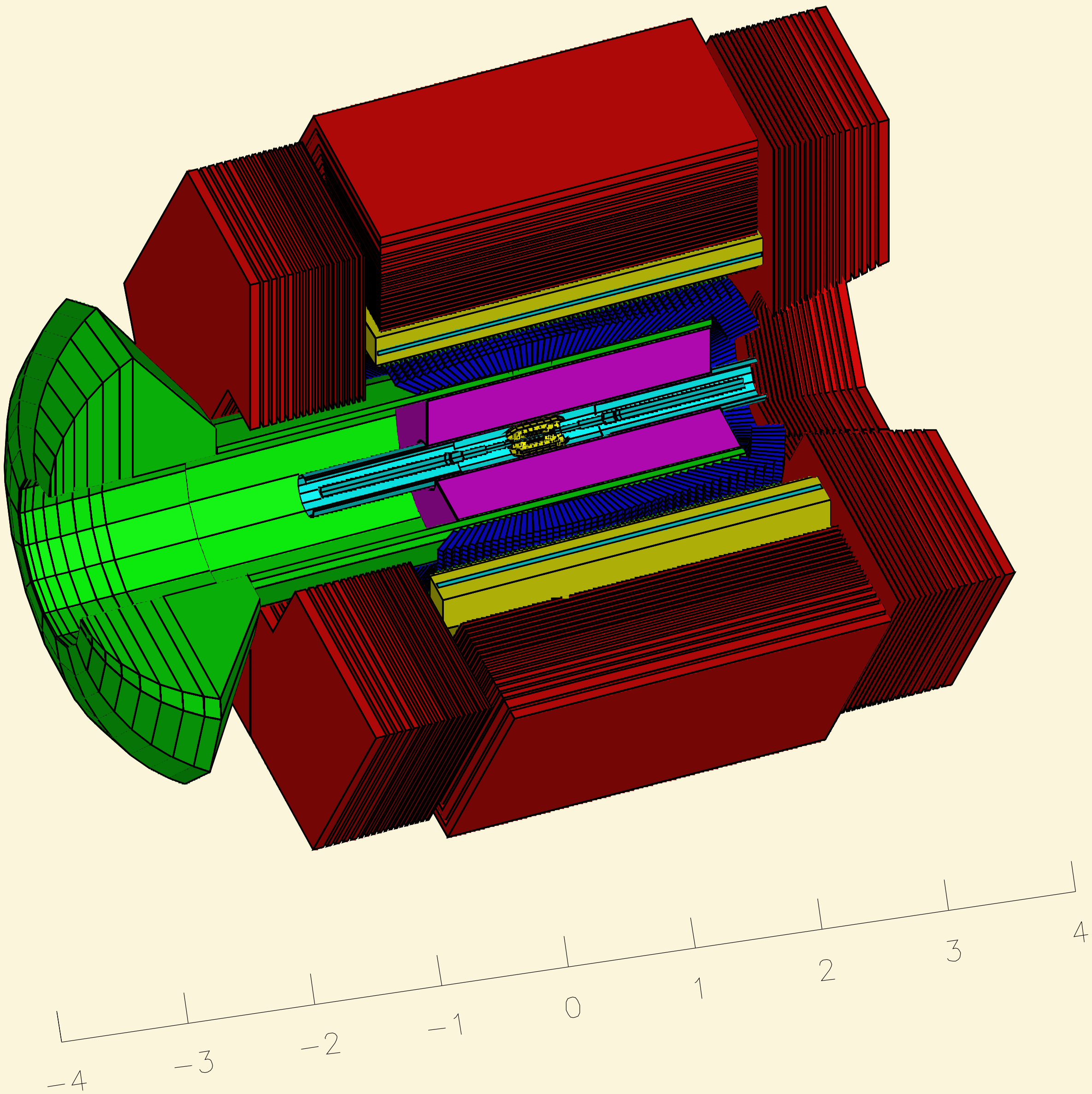


PEP II

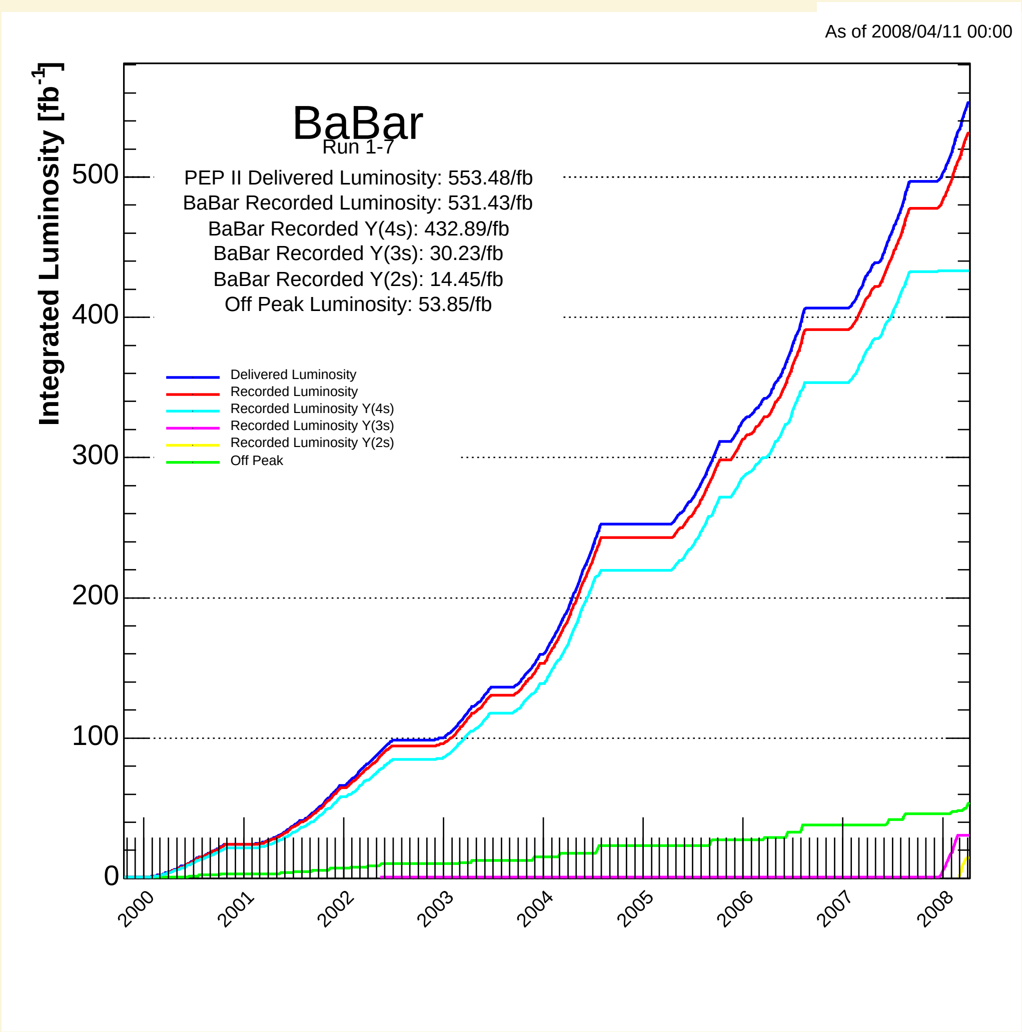
$e^+(3.1\text{ GeV})$
$e^-(9.0\text{ GeV})$
$\beta\gamma = 0.56$



BaBar

collecting data
from 1999
to 2008

BaBar

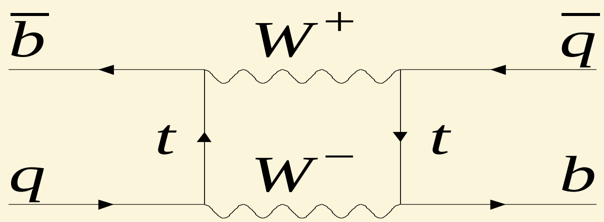


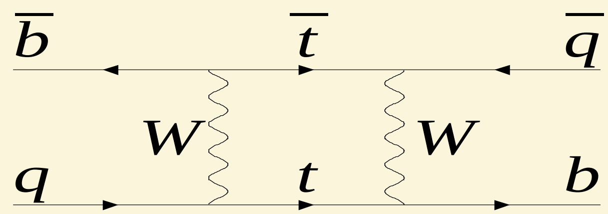
- $\int L \sim 430\ fb^{-1}\ \Upsilon(4S)$ and $\sim 45\ fb^{-1}$ $40\ MeV$ below $\Upsilon(4S)$
- $\sim 470\ M\ B\bar{B}$
- total $\int L \sim 550\ fb^{-1}$
- > 500 publications
- $\sim 30/y$ in present time

Outline

- CP violation in $B^0\bar{B}^0$ mixing
- CP violation in $B^0 \to (\rho\pi)^0$, Dalitz plot analysis
- Direct CP violation with $B^\pm \to D^{(*)}K^{(*)\pm}$
- Observation of T-violation
- $B \to \pi\ell^+\ell^-$ and $B^0 \to \eta\ell^+\ell^-$ decays
- $B \to K^{(*)}\nu\bar{\nu}$ and invisible $J/\psi \to \nu\bar{\nu}$, $\psi(2S) \to \nu\bar{\nu}$ decays
- Direct asymmetry in $B \to X_s\gamma$ decays
- $B \to D^{(*)}\tau\nu$ decay

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





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

  $< \bar{B}^0|H|B^0 >= M_{12}^* - i\Gamma_{12}^*/2$
  $< B^0|H|\bar{B}^0 >= M_{12} - i\Gamma_{12}/2$

- $| < B^0|H|\bar{B}^0 > |^2 - | < \bar{B}^0|H|B^0 > |^2$

  $= 2Im(M_{12}\Gamma_{12})$

- $|B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$
  $|B_H\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$

- CPV in mixing
  $P(B^0 \to \bar{B}^0) \neq P(\bar{B}^0 \to B^0)$

- CP asymmetry $A_{CP} =$

  $$\frac{N(B^0B^0) - N(\bar{B}^0\bar{B}^0)}{N(B^0B^0) + N(\bar{B}^0\bar{B}^0)} =$$

  $$\frac{1 - |q/p|^4}{1 + |q/p|^4}$$

- $\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - (i/2)\Gamma_{12}^*}{M_{12} - (i/2)\Gamma_{12}}$

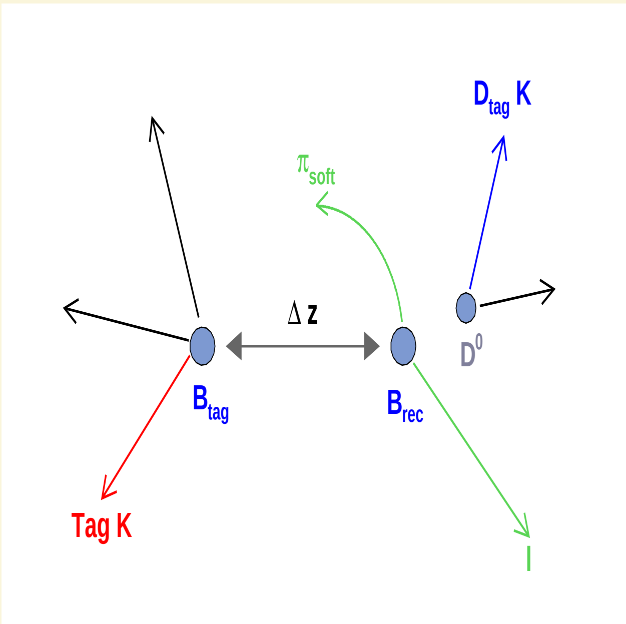
CP violation in $B^0\bar{B}^0$ mixing

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
  $A^d_{SL} = (-0.05 \pm 0.56)\%$
  SM $A^d_{SL} = (-4.1 \pm 0.6) \cdot 10^{-4}$
- 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
  $A^b_{SL} = (-0.787 \pm 0.172 \pm 0.093)\%$
  SM $A^b_{SL} = (-2.8^{+0.5}_{-0.6}) \cdot 10^{-4}$
- $A^s_{SL} = (-0.24 \pm 0.54 \pm 0.33\%$ (LHCb)
  $A^s_{SL} = (-1.12 \pm 0.74 \pm 0.17\%$ (D0)
  SM $A^s_{SL} = (1.9 \pm 0.3) \cdot 10^{-5}$

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



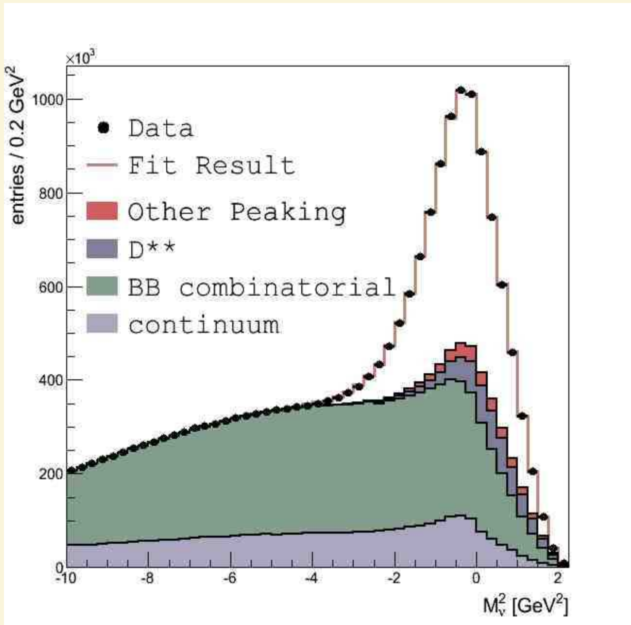
New approach is used in BaBar analysis

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

- partial reconstruction using only the lepton from $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$ 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

- $0.06 < p_{\pi_{soft}} < 0.19\ GeV/c$, $1.40 < p_l < 2.30\ GeV/c$
- K selection by means of energy loss and Cherenkov detector information $p_K > 0.2\ GeV/c$
- continuum and combinatorial background suppressed by Fox-Wolfram moments and vertex probability



- sample composition is derived from a fit to M_ν^2 by floating D^*, D^{**} $M_\nu^2 = (E_{beam} - E_{D^*} - E_l)^2 - (\vec{p}_{D^*} + \vec{p}_l)^2$
- combinatorial background using MC shapes and continuum shapes from off-peak events
- residual peaking fixed from simulation

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

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

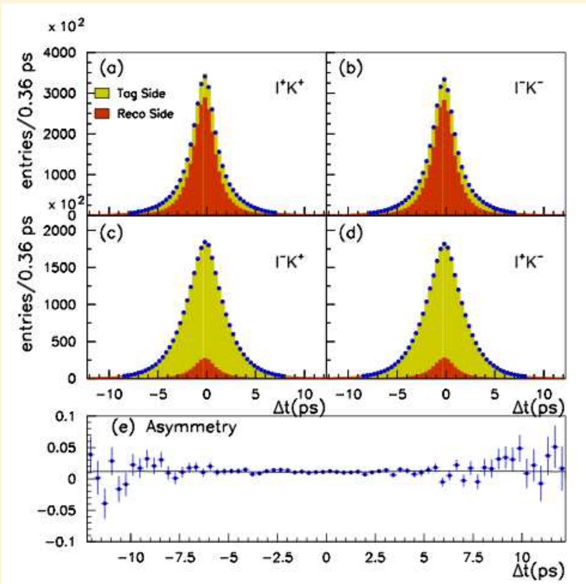
$$A_R = \frac{N(l^+K_R^+) - N(l^-K_R^-)}{N(l^+K_R^+) - N(l^+K_R^-)} \simeq A_{rl} + A_K + A_{CP}\chi_d$$

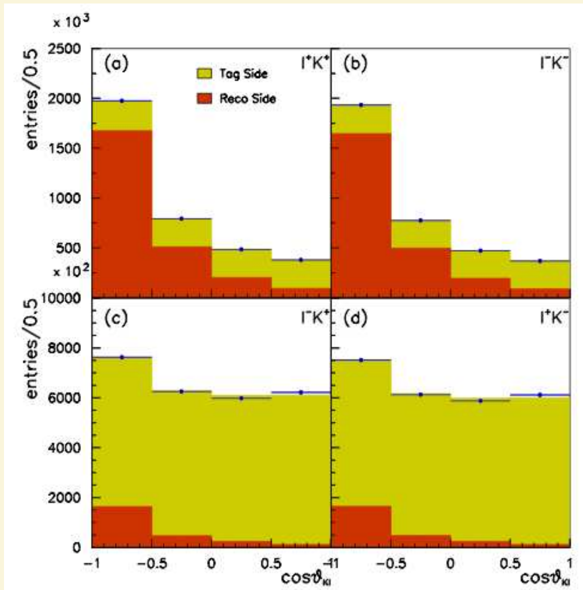
$\chi_d = 0.1862 \pm 0.0023$

- 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_{rl} 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

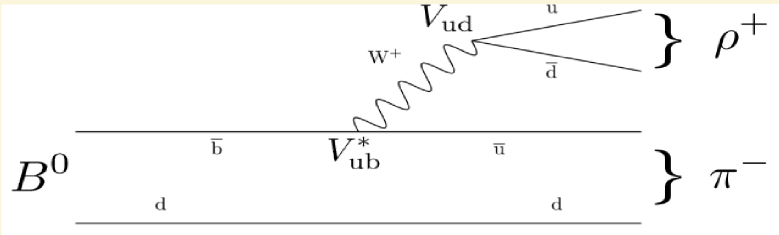


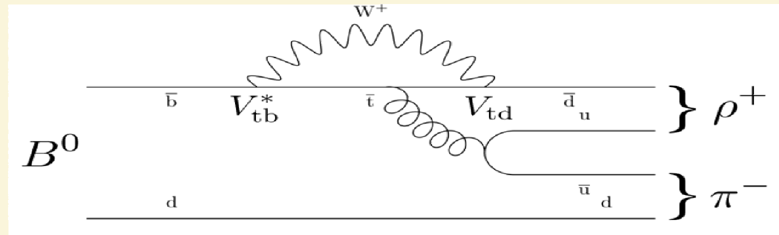


A_{CP} from binned four dimensional fit to $cos\theta_{lK}$, Δz, $\sigma(\Delta t)$, p_K on 4 samples: unmixed $l^{\pm}K^{\mp}$ and mixed $l^{\pm}K^{\pm}$

- BaBar
  $A^d_{SL} = (0.06 \pm 0.17^{+0.36}_{-0.32})\%$
  $1 - |q/p| = (0.29 \pm 0.84^{+1.78}_{-1.61}) \cdot 10^{-3}$
- consistent with previous measurement
- 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 $\alpha = arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*]$

Updated by 2007 BaBar analysis

- increased dataset, $431 fb^{-1}$ vs. $346 fb^{-1}$
- 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 B momentum or the B thrust axis

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

Time-dependent amplitudes for B^0 and $\bar{B}^0$ decays

$A_{3\pi} = f_+ A^+ + f_- A^- + f_0 A^0$
$\overline{A}_{3\pi} = f_+ \overline{A}^+ + f_- \overline{A}^- + f_0 \overline{A}^0$
$A^{\pm,0}$ corresponds $\rho^{\pm,0}$

$$|\mathcal{A}^{\pm}_{3\pi}(\Delta t)|^2 = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \Big(|A_{3\pi}|^2 + |\overline{A}_{3\pi}|^2$$
$$\mp \left(|A_{3\pi}|^2 - |\overline{A}_{3\pi}|^2 \right) \cos(\Delta m_d \Delta t)$$
$$\pm 2 \ \mathrm{Im} \left[\frac{q}{p} \overline{A}_{3\pi} A^*_{3\pi} \right] \sin(\Delta m_d \Delta t) \Big)$$

Fitting

- m_{ES}, ΔE, NN output
- time dependent DP
- 26 free parameters

$B^0(\mathcal{A}^-_{3\pi})$ or $\bar{B}^0(\mathcal{A}^+_{3\pi})$

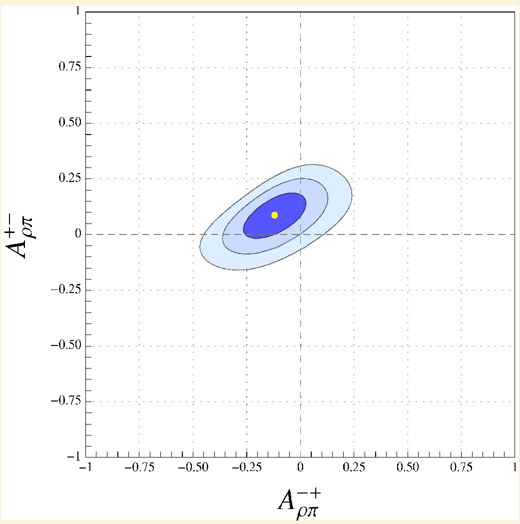
$$f^{\rho^\pm \pi^\mp}_{Q_{\mathrm{tag}}}(\Delta t) = (1 \pm \mathcal{A}_{\rho\pi}) \frac{e^{-|\Delta t|/\tau}}{4\tau} \times \Big[1 + Q_{\mathrm{tag}}(\mathcal{S} \pm \Delta\mathcal{S}) \sin(\Delta m_d \Delta t) - Q_{\mathrm{tag}}(\mathcal{C} \pm \Delta\mathcal{C}) \cos(\Delta m_d \Delta t) \Big],$$

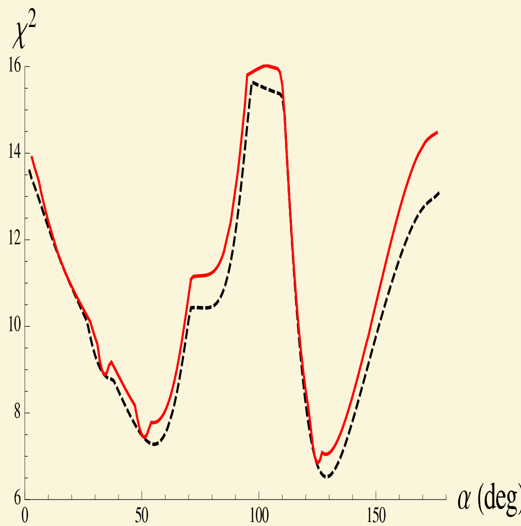
$Q_{\mathrm{tag}} = +1(-1)$ for $B_{\mathrm{tag}} = B^0(\bar{B}^0)$

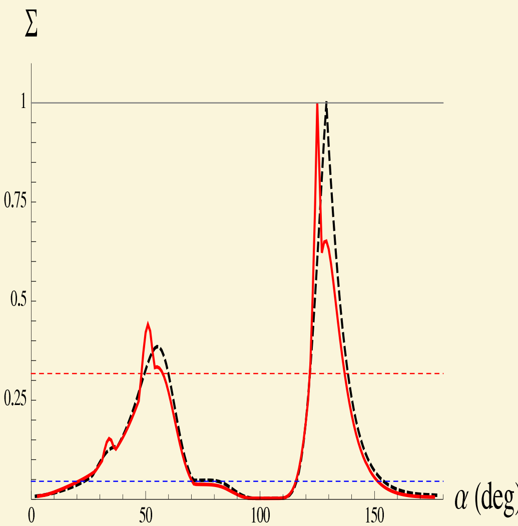
- $\mathcal{A}_{\rho\pi}$ quantifies direct CP violation
- $\mathcal{S}$ parameterize mixing-induced CP violation related to α
- $\mathcal{C}$ parameterize flavor-dependent direct CP violation
- $\Delta\mathcal{C}$ asymmetry between rates $\Gamma(B^0 \to \rho^+\pi^-) + \Gamma(\overline{B}^0 \to \rho^-\pi^+)$ and $\Gamma(B^0 \to \rho^-\pi^+) + \Gamma(\overline{B}^0 \to \rho^+\pi^-)$
- $\Delta\mathcal{S}$ relates to the strong-phase difference between the different amplitudes

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

preliminary results   arXiv:1304.3503[hep-ex], submitted to Physical Review D



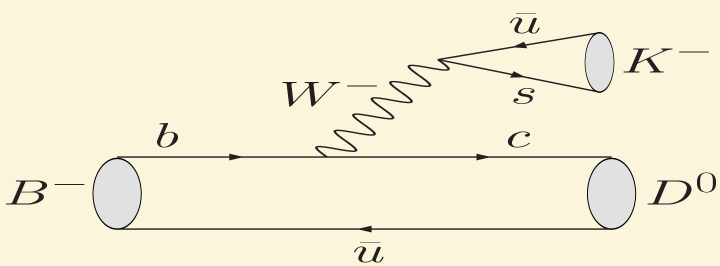




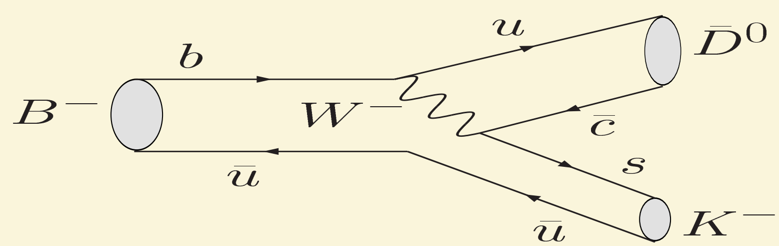
isospin-constrained
unconstrained

$\mathcal{A}^{+-}_{\rho\pi} = 0.09^{+0.05}_{-0.06} \pm 0.04$
$\mathcal{A}^{-+}_{\rho\pi} = -0.12 \pm 0.08^{+0.04}_{-0.05}$
$\mathcal{C} = 0.016 \pm 0.059 \pm 0.036,\ \Delta\mathcal{C} = 0.234 \pm 0.061 \pm 0.048$
$\mathcal{S} = 0.053 \pm 0.081 \pm 0.034,\ \Delta\mathcal{S} = 0.054 \pm 0.082 \pm 0.039$

Direct CP violation with $B^{\pm} \to D^{(*)} K^{(*)\pm}$



$b \to c\bar{u}s$



$b \to u\bar{c}s$

interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$ depends on

- weak phase $\gamma = arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$
- relative strong phase δ_B
- $r_B = |\mathcal{A}(b \to u\bar{c}s)/\mathcal{A}(b \to c\bar{u}s)|$

- the three approaches employed by the B factory experiments
- the combination of these approaches were used in this analysis

Direct CP violation with $B^{\pm} \to D^{(*)} K^{(*)\pm}$

- Dalitz plot or Giri-Grossman-Soffer-Zupan (GGSZ) method, based on three-body, self-conjugate final states, such as $K_S \pi^+ \pi^-$

$$\Gamma_{\pm}^{(*)}(m_-^2, m_+^2) \propto |\mathcal{A}_{\pm}|^2 + {r_{B\pm}^{(*)}}^2 |\mathcal{A}_{\mp}|^2 + 2\lambda \,\mathrm{Re}[\mathsf{z}_{\pm}^{(*)} \mathcal{A}_{\pm}^{\dagger} \mathcal{A}_{\mp}] \text{ for } B^{\pm} \to D^{(*)} K^{\pm}$$

$$\Gamma_{\pm}^{s}(m_-^2, m_+^2) \propto |\mathcal{A}_{\pm}|^2 + \kappa^2 r_{s\pm}^2 |\mathcal{A}_{\mp}|^2 + 2 \,\mathrm{Re}[\mathsf{z}_{s\pm} \mathcal{A}_{\pm}^{\dagger} \mathcal{A}_{\mp}] \text{ for } B^{\pm} \to D K^{*\pm}$$

$$m_-^2 = m^2(K_S^0 h^-),\ m_+^2 = m^2(K_S^0 h^+),\ \mathcal{A}_{\pm} \equiv \mathcal{A}(m_{\pm}^2, m_{\mp}^2)$$

- Gronau-London-Wyler (GLW) method, based on decays to CP-eigenstate final states, such as K^+K^- and $K_S\pi^0$

$$A_{CP\pm}^{(*)} \equiv \frac{\Gamma(B^- \to D_{CP\pm}^{(*)} K^-) - \Gamma(B^+ \to D_{CP\pm}^{(*)} K^+)}{\Gamma(B^- \to D_{CP\pm}^{(*)} K^-) + \Gamma(B^+ \to D_{CP\pm}^{(*)} K^+)} = \pm \frac{x_-^{(*)} - x_+^{(*)}}{1 + |\mathsf{z}^{(*)}|^2 \pm (x_-^{(*)} + x_+^{(*)})}$$

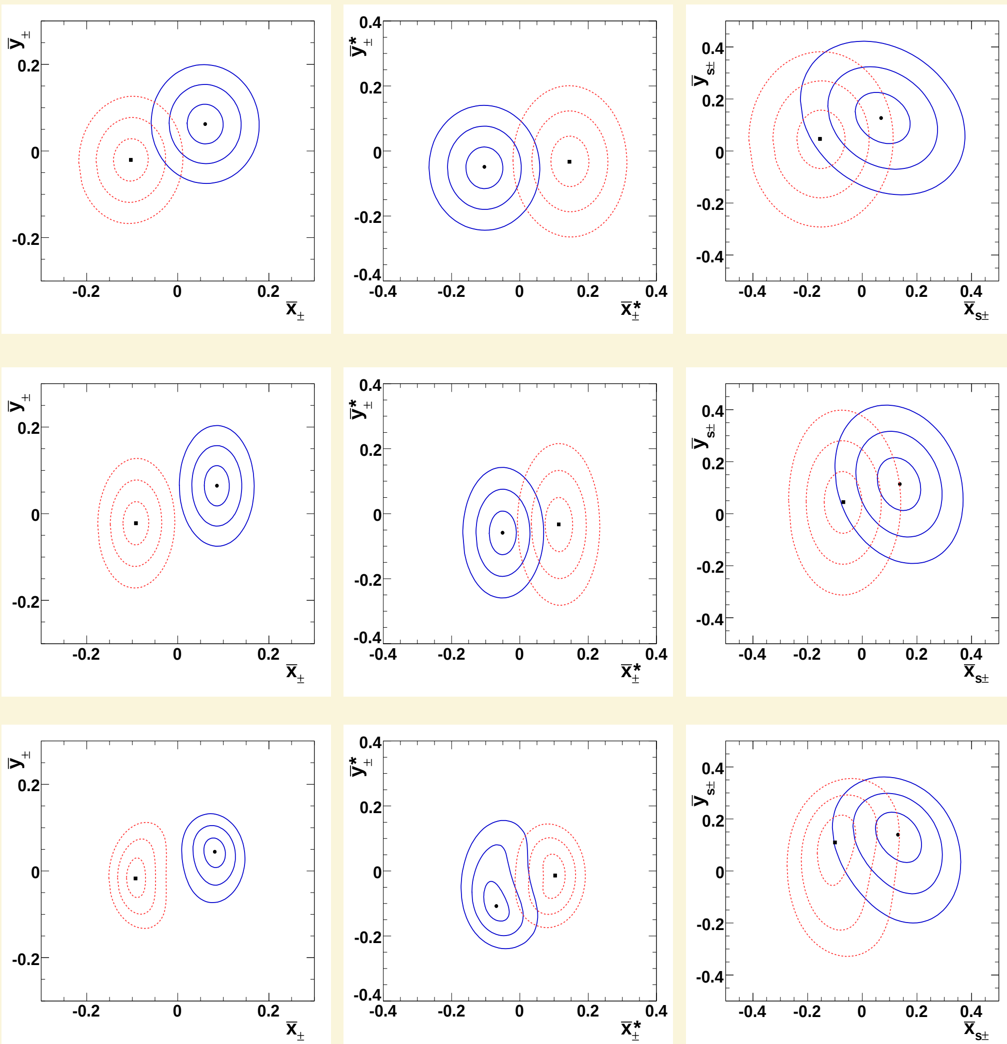
$$R_{CP\pm}^{(*)} \equiv 2 \frac{\Gamma(B^- \to D_{CP\pm}^{(*)} K^-) + \Gamma(B^+ \to D_{CP\pm}^{(*)} K^+)}{\Gamma(B^- \to D^{(*)0} K^-) + \Gamma(B^+ \to \overline{D}^{(*)0} K^+)} = 1 + |\mathsf{z}^{(*)}|^2 \pm (x_-^{(*)} + x_+^{(*)})$$

- Atwood-Dunietz-Soni (ADS) method, based on D decays to doubly-Cabibbo-suppressed final states, such as $D^0 \to K^+\pi^-$

$$R_{\pm}^{(*)} \equiv \frac{\Gamma(B^{\pm} \to [K^{\mp}\pi^{\pm}]_D^{(*)} K^{\pm})}{\Gamma(B^{\pm} \to [K^{\pm}\pi^{\mp}]_D^{(*)} K^{\pm})} = {r_{B\pm}^{(*)}}^2 + r_D^2 + 2\lambda r_D \left[x_{\pm}^{(*)} \cos\delta_D - y_{\pm}^{(*)} \sin\delta_D\right]$$

$$R_{\pm}^{K\pi\pi^0} = {r_{B\pm}}^2 + r_{K\pi\pi^0}^2 + 2\kappa_{K\pi\pi^0} r_{K\pi\pi^0} \times \left[x_{\pm} \cos\delta_{K\pi\pi^0} - y_{\pm} \sin\delta_{K\pi\pi^0}\right]$$

Direct CP violation with $B^{\pm} \to D^{(*)}K^{(*)\pm}$



GGSZ

Two-dimensional contours up to three standard deviations. The blue and red contours correspond to B^{-} and B^{+} decays.

GGSZ and GLW

GGSZ, GLW, and ADS combination

Direct CP violation with $B^{\pm} \to D^{(*)} K^{(*)\pm}$

Combined GGSZ, GLW, ADS

- $\gamma = (69^{+17}_{-16})^{\circ}$
  $\gamma = (68^{+15}_{-14})^{\circ}$ (Belle) and $\gamma = (71.1^{+16.6}_{-15.7})^{\circ}$ (LHCb)
- uncertainty is dominated by the statistical component
- experimental and amplitude-model systematic uncertainties amounting to $\pm 4^{\circ}$
- two-standard-deviation region is $41^{\circ} < \gamma < 102^{\circ}$
- result is inconsistent with $\gamma = 0$ with a significance of 5.9 standard deviations

Phys. Rev. D 87, 052015 (2013)

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)

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

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

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

  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

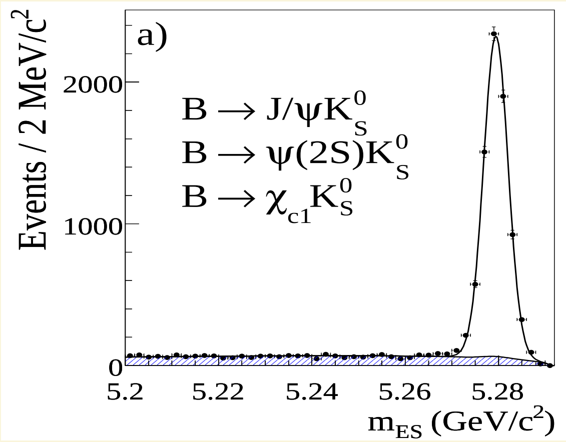
4 independent CPT comparisons

Observation of T-violation

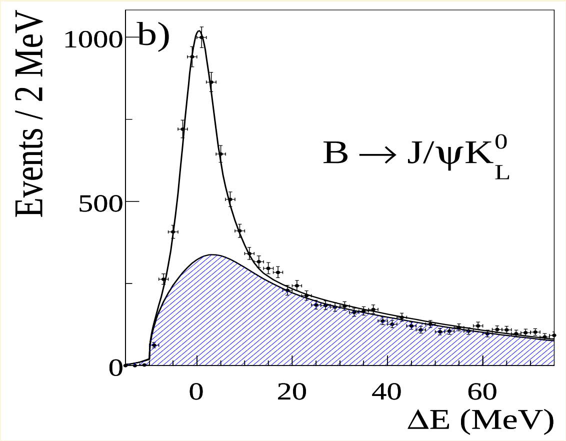
Signal sample

- select B candidates using beam-energy substituted mass and energy difference
  $m_{ES} = \sqrt{E_{beam}^2 - p_B^2}$
  $\Delta E = E_B - E_{beam}$
- background rejection: vetoes to B background and suppress continuum using event shape variables

reconstructed modes	
$c\bar{c}K_S$	$B^0 \to J/\psi K_S$
	$B^0 \to \psi(2S) K_S$
	$B^0 \to \chi_{c1} K_S$
$c\bar{c}K_L$	$B^0 \to J/\psi K_L$
B_{flavor}	$B^0 \to D^* \pi(\rho, a_1)$
	$B^0 \to J/\psi K^{*0}$



7796 events
purity 87-96%



5813 events
purity 56%

Observation of T-violation

Fit to signal parameters

8 time-dependent decay rates

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

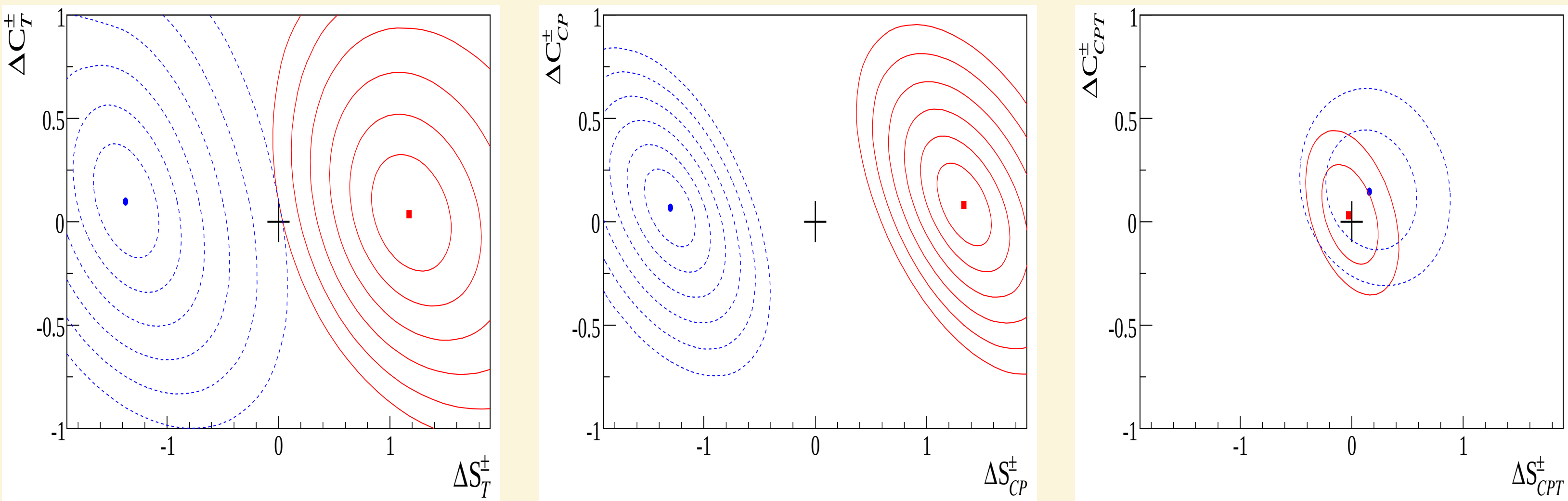
$\pm$ - $\Delta t > 0, < 0$

α, β - flavor, CP reco

- for example $\bar{B}^0 \rightarrow B_-$ (l^+, K_S) is characterized by $S^+_{l^+,K_S}$
- T reversed transition $B_- \rightarrow \bar{B}^0$ (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^-

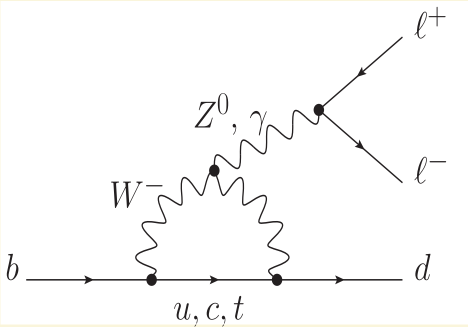
$1 - CL = 0.317,\ 4.55 \times 10^{-2},\ 2.70 \times 10^{-3},\ 6.33 \times 10^{-5},\ 5.73 \times 10^{-7},\ 1.97 \times 10^{-9}$

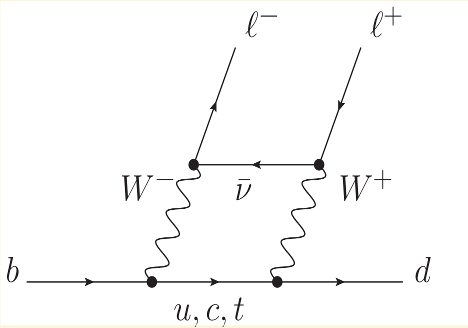
Significance of T violation 14σ, CP violation 17σ, CPT violation 0.3σ

FIRST DIRECT OBSERVATION OF T VIOLATION

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

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





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

Event selection

- $p_l > 0.3\ GeV/c$
- $0.03 < m_{ll} < 5\ GeV/c^2$
- $115 < m_{\gamma\gamma} < 150\ MeV/c^2$ for π^0
- η reconstruction $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$
- $500 < m_{\gamma\gamma} < 575\ MeV/c^2$ $535 < m_{3\pi} < 565\ MeV/c^2$ for η
- lepton pair and hadron are fit to common vertex
- $m_{ES} > 5.1\ GeV/c^2$
- $-300 < \Delta E < 250\ MeV$
- $B \to J/\psi X$ and $B \to \psi(2S)X$ reject events with m_{ll} near J/ψ and $\psi(2S)$ masses

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

Event selection: NN to reject combinatorial background

Variables for continuum NN

- Fox-Wolfram moments
- polar angle of thrust axis of event
- polar angle of thrust axis of rest of event (ROE)
- $L_i^j = \sum_k p_k^j cos^i\theta$
- polar angle of B candidate
- probability of vertex fit

Variables for $B\bar{B}$ NN

- m_{ES} and ΔE
- total P_t
- missing energy
- momentum ROE transverse to beam direction
- momentum ROE transverse to thrust axis
- polar angle of B candidate
- probability of vertex fit

Also some set of tune cuts for angles and momenta of particles

To select the best candidate the follwing ratio is used

$$\mathcal{L}_R(x,y) = \frac{\mathcal{P}^{\rm sig}_{B\overline{B}}(x) + \mathcal{P}^{\rm sig}_{\rm cont}(y)}{(\mathcal{P}^{\rm sig}_{B\overline{B}}(x) + \mathcal{P}^{\rm sig}_{\rm cont}(y)) + (\mathcal{P}^{\rm bkg}_{B\overline{B}}(x) + \mathcal{P}^{\rm bkg}_{\rm cont}(y))}$$

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

preliminary

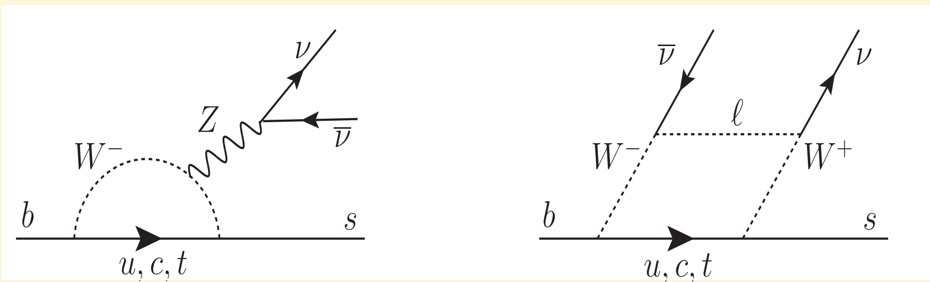
Mode	ε	Yield	$\mathcal{B}\,(10^{-8})$	Upper Limit (10^{-8})
$B^+ \to \pi^+ e^+ e^-$	0.207	$4.2^{+5.7}_{-4.6}$	$4.3^{+5.9}_{-4.3} \pm 2.0$	12.5
$B^0 \to \pi^0 e^+ e^-$	0.166	$1.0^{+4.2}_{-3.2}$	$1.3^{+5.4}_{-4.1} \pm 0.2$	8.4
$B^0 \to \eta e^+ e^-$			$-4.0^{+10.0}_{-8.0} \pm 0.6$	10.8
$B^0 \to \eta_{\gamma\gamma} e^+ e^-$	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

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

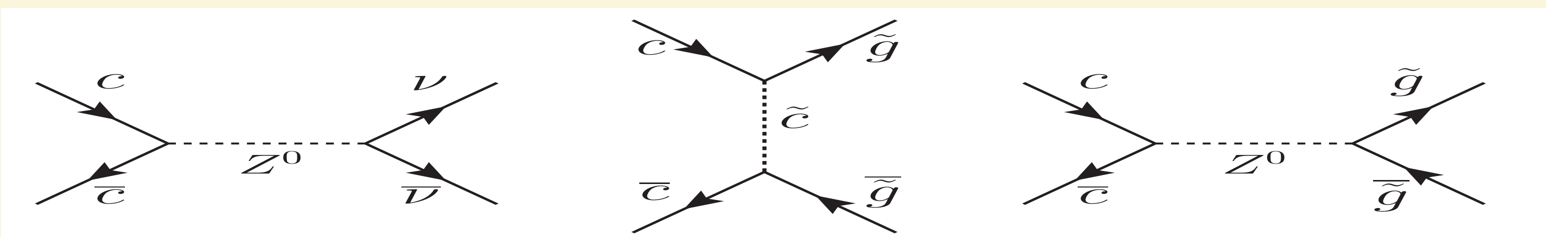
- observe no statistically significant signal
- lepton-flavor and isospin averaged upper limit at the 90% CL
  $\mathcal{B}(B \to \pi\ell^+\ell^-) < 5.9 \times 10^{-8}$
  factor of three of the SM expectation.
- upper limits have also been calculated for different $\pi\ell^+\ell^-$modes
- $\mathcal{B}(B^0 \to \eta\ell^+\ell^-) < 6.4 \times 10^{-8}$
- upper limits have also been calculated for different $\eta\ell^+\ell^-$ modes
- lowest upper limits to date for $B \to \pi^0\ell^+\ell^-$
- first search for the decays $B^0 \to \eta\ell^+\ell^-$

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

$B \to K^{(*)}\nu\bar{\nu}$ and invisible $J/\psi \to \nu\bar{\nu}$, $\psi(2S) \to \nu\bar{\nu}$ decays



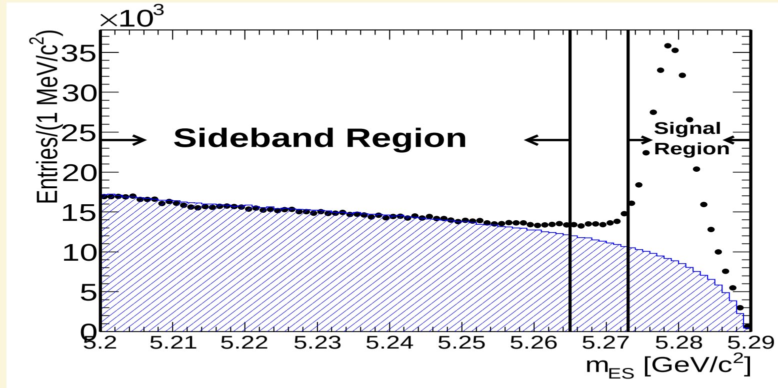
- flavour-changing neutral current $b \to s$
- forbidden at tree level in SM



- lowest-order diagrams of SM decay $c\bar{c}$ into $\nu\bar{\nu}$ and SUSY decay into pair of goldstinos
- SM predicts
  $Br(B^+ \to K^+\nu\bar{\nu} = Br(B^0 \to K^0\nu\bar{\nu} = (4.5 \pm 0.7) \cdot 10^{-6}$
  $Br(B^+ \to K^{*+}\nu\bar{\nu} = Br(B^0 \to K^{*0}\nu\bar{\nu} = (6.8^{+1.0}_{-1.1}) \cdot 10^{-6}$
  $Br(J/\psi \to \nu\bar{\nu}) = (4.54 \cdot 10^{-7}) \cdot Br(J/\psi \to l^+l^-)$

$B \to K^{(*)}\nu\bar{\nu}$ and invisible $J/\psi \to \nu\bar{\nu}$, $\psi(2S) \to \nu\bar{\nu}$ decays

- B_{tag} reconstructed in one of many hadronic final states
- require purity greater than 68%
  448 final states
- $-0.12 < \Delta E < 0.12\ GeV$
- $5.273 < m_{ES} < 5.290\ GeV$



Continuum background is suppressed by using multivariate likelihood selector
input is six event-shape variables

- angle between B_{tag} momentum and beam axis
- B_{tag} thrust
- B_{tag} thrust along beam axis
- angle between missing momentum and beam axis
- second-to-zeroth Fox-Wolfram moment

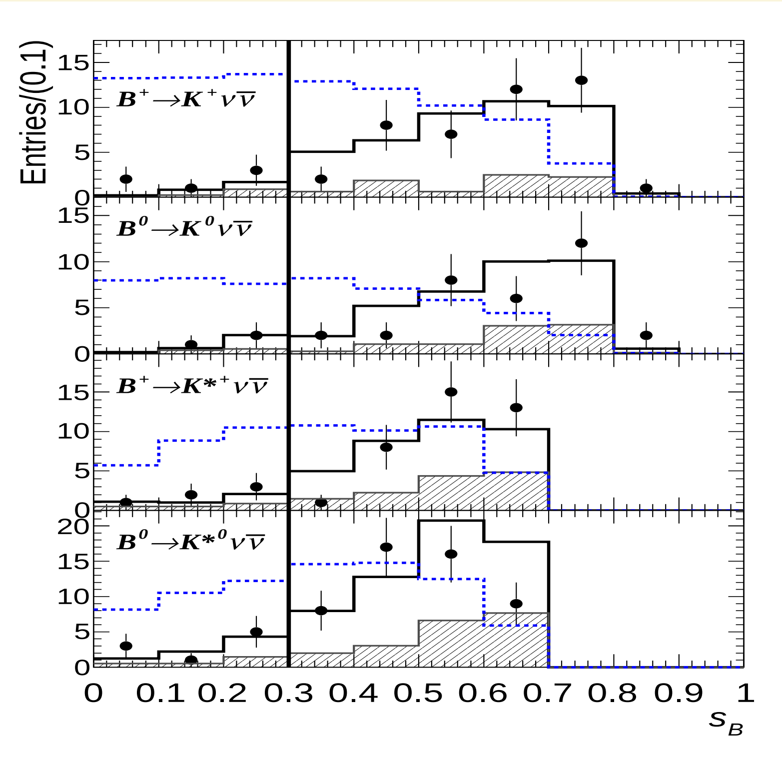
Six channels $B \to K^{(*)}\nu\bar{\nu}$

- $B^+ \to K^+\nu\bar{\nu}$
- $B^0 \to K_S\nu\bar{\nu}$
- $B^+ \to K^{*+}\nu\bar{\nu}$
  $K^{*+} \to K^+\pi^0$ and $K^{*+} \to K_S\pi^+$
- $B^0 \to K^{*0}\nu\bar{\nu}$
  $K^{*0} \to K^+\pi^-$ and $K^{*0} \to K_S\pi^0$

π^0: $100 < m_{\gamma\gamma} < 160\ MeV/c^2$
K_S: $\pm 7\ MeV/c^2$ of nominal
K^*: $\pm 70\ MeV/c^2$ of nominal

$B \to K^{(*)}\nu\bar{\nu}$ and invisible $J/\psi \to \nu\bar{\nu}$, $\psi(2S) \to \nu\bar{\nu}$ decays

Phys. Rev. D87, 112005 (2013)



- $s_B = m^2_{\nu\bar{\nu}}/m^2_B$
- combinatorial (shaded)
  m_{ES} peaking (solid)
- signal MC (dashed)
  $Br(B^+ \to K^+\nu\bar{\nu}) = 20 \cdot 10^{-5}$
  other modes $50 \cdot 10^{-5}$
- events to the left of the vertical line are selected to obtain limits

Results

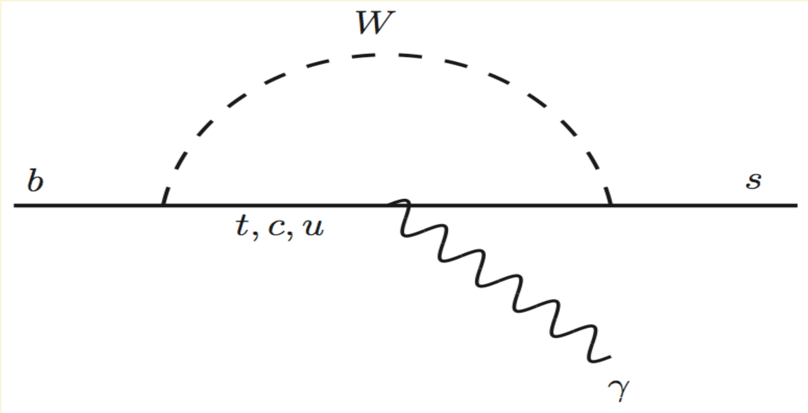
- $0 < s_B < 0.3$ signal region to calculate upper limits
- $Br(B \to K\nu\bar{\nu}) < 3.2 \cdot 10^{-5}$
- $Br(B \to K^*\nu\bar{\nu}) < 7.9 \cdot 10^{-5}$

$Br(J/\psi \to \nu\bar{\nu}) < 3.9 \cdot 10^{-3}$ and $Br(\psi(2S) \to \nu\bar{\nu}) < 15.5 \cdot 10^{-3}$

BES: $Br(J/\psi \to \nu\bar{\nu}) < (1.2 \cdot 10^{-2}) \cdot Br(J/\psi \to \mu^+\mu^-)$ 90% CL

Direct asymmetry in $B \to X_s\gamma$ decays

- $A_{CP} = \frac{\Gamma_{b\to s\gamma} - \Gamma_{\bar{b}\to\bar{s}\gamma}}{\Gamma_{b\to s\gamma} + \Gamma_{\bar{b}\to\bar{s}\gamma}}$
- $\propto Im\,[(V_{ub}V_{us}^*)/(V_{tb}V_{ts}^*]$
- $-0.6\% < A_{CP}^{SM} < 2.8\%$ long distance dominated
- $A_{CP}(average) = -(1.2 \pm 2.8)\%$ BaBar, Belle, CLEO



- $\Delta A_{X_s\gamma} = A_{X_s^-\gamma} - A_{X_s^0\gamma}$
- $\Delta A_{X_s\gamma} \propto Im(C_{8g}/C_{7\gamma})$
- electro-magnetic $C_{7\gamma}$ and chromo-magnetic C_{8g} dipole operators are real in SM
- $\Delta A_{X_s\gamma} = 0$ in SM

38 of exclusive decays were reconstructed

Direct asymmetry in $B \to X_s\gamma$ decays

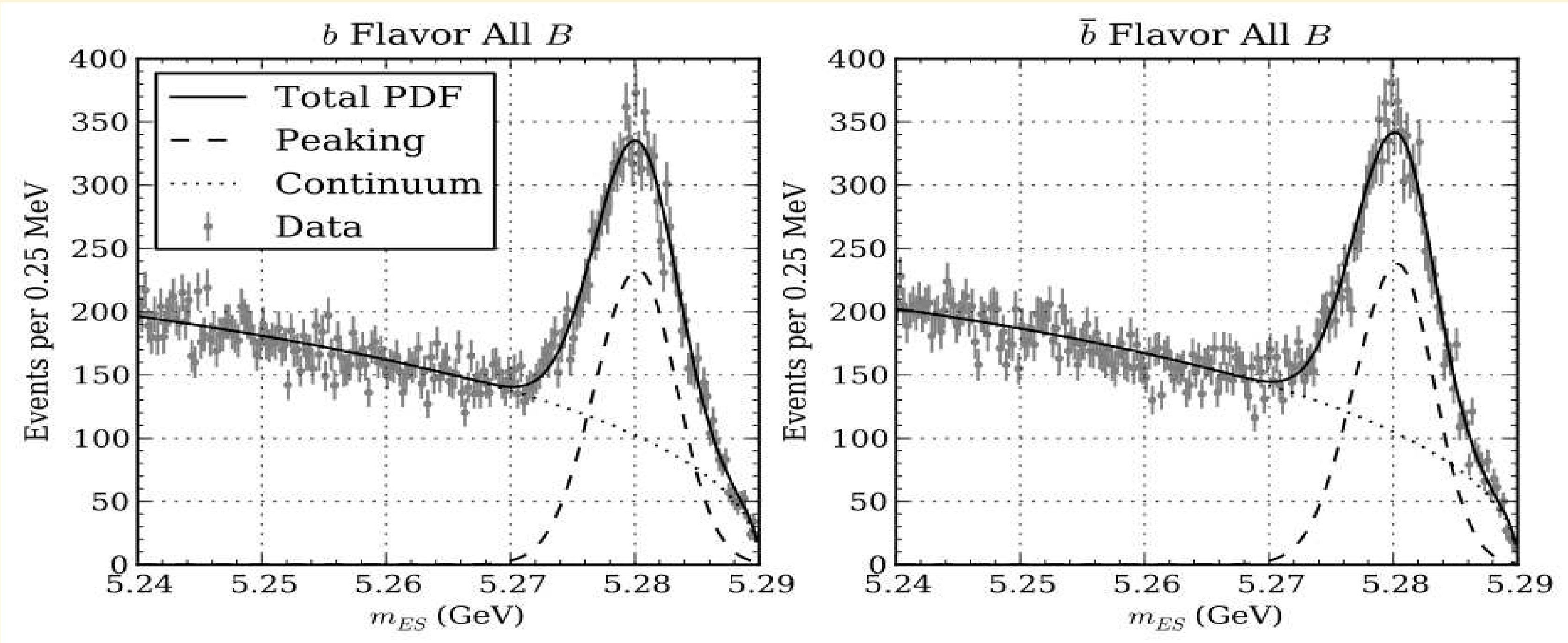
#	Final State	#	Final State
1*	$B^+ \to K_S\pi^+\gamma$	20	$B^0 \to K_S\pi^+\pi^-\pi^+\pi^-\gamma$
2*	$B^+ \to K^+\pi^0\gamma$	21	$B^0 \to K^+\pi^+\pi^-\pi^-\pi^0\gamma$
3*	$B^0 \to K^+\pi^-\gamma$	22	$B^0 \to K_S\pi^+\pi^-\pi^0\pi^0\gamma$
4	$B^0 \to K_S\pi^0\gamma$	23*	$B^+ \to K^+\eta\gamma$
5*	$B^+ \to K^+\pi^+\pi^-\gamma$	24	$B^0 \to K_S\eta\gamma$
6*	$B^+ \to K_S\pi^+\pi^0\gamma$	25	$B^+ \to K_S\eta\pi^+\gamma$
7*	$B^+ \to K^+\pi^0\pi^0\gamma$	26	$B^+ \to K^+\eta\pi^0\gamma$
8	$B^0 \to K_S\pi^+\pi^-\gamma$	27*	$B^0 \to K^+\eta\pi^-\gamma$
9*	$B^0 \to K^+\pi^-\pi^0\gamma$	28	$B^0 \to K_S\eta\pi^0\gamma$
10	$B^0 \to K_S\pi^0\pi^0\gamma$	29	$B^+ \to K^+\eta\pi^+\pi^-\gamma$
11*	$B^+ \to K_S\pi^+\pi^-\pi^+\gamma$	30	$B^+ \to K_S\eta\pi^+\pi^0\gamma$
12*	$B^+ \to K^+\pi^+\pi^-\pi^0\gamma$	31	$B^0 \to K_S\eta\pi^+\pi^-\gamma$
13*	$B^+ \to K_S\pi^+\pi^0\pi^0\gamma$	32	$B^0 \to K^+\eta\pi^-\pi^0\gamma$
14*	$B^0 \to K^+\pi^+\pi^-\pi^-\gamma$	33*	$B^+ \to K^+K^-K^+\gamma$
15	$B^0 \to K_S\pi^0\pi^+\pi^-\gamma$	34	$B^0 \to K^+K^-K_S\gamma$
16*	$B^0 \to K^+\pi^-\pi^0\pi^0\gamma$	35	$B^+ \to K^+K^-K_S\pi^+\gamma$
17	$B^+ \to K^+\pi^+\pi^-\pi^+\pi^-\gamma$	36	$B^+ \to K^+K^-K^+\pi^0\gamma$
18	$B^+ \to K_S\pi^+\pi^-\pi^+\pi^0\gamma$	37*	$B^0 \to K^+K^-K^+\pi^-\gamma$
19	$B^+ \to K^+\pi^+\pi^-\pi^0\pi^0\gamma$	38	$B^0 \to K^+K^-K_S\pi^0\gamma$

- 38 final states
- (*) in CP measurement
  10 charged and 6 neutral
- π^0 and η decays to 2γ
  $E_\gamma > 30\ MeV$ for π^0
  $E_\gamma > 50\ MeV$ for η
- $1.6 < E^*_\gamma < 3.0\ GeV$
  $-0.74 < cos\theta < 0.93$
- $0.6 < m_{X_s} < 3.2\ GeV/c^2$
- $m_{ES} > 5.24\ GeV/c^2$
- $|\Delta E| < 0.15\ GeV$
- $|cos\theta^*_{Troe-\gamma}| < 0.85$

Direct asymmetry in $B \to X_s \gamma$ decays

Continuum background (random forest classifier)

- all photons to reject high energy photon from π^0
- momentum flow in 10° increments about reconstructed B
- up to second Legendre monomials along photon axis of ROE
- angle between B and beam axis
- angle between trust axis of B and ROE
- angle between photon and thrust axis of ROE

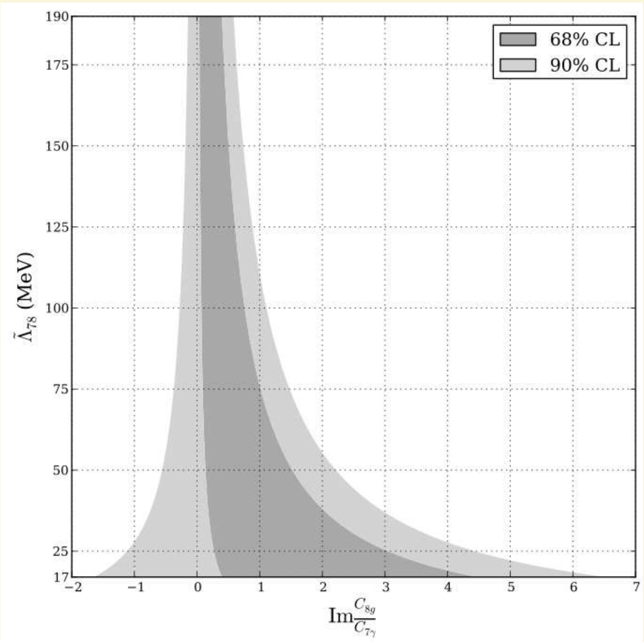


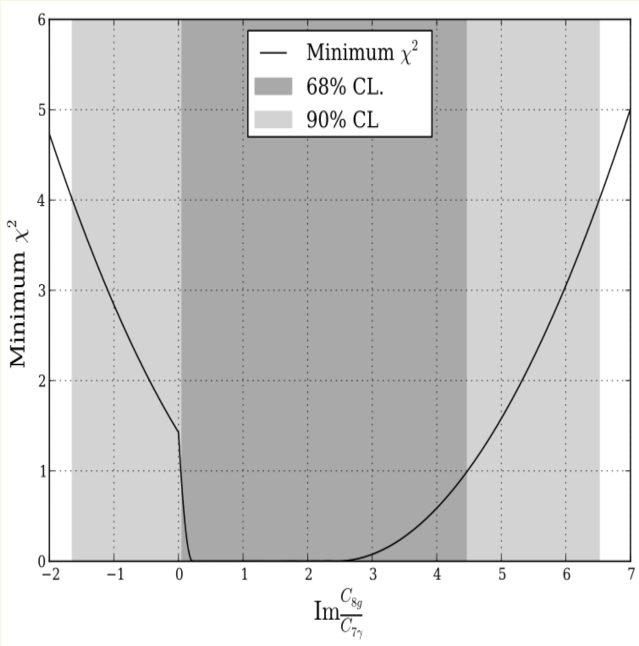
Direct asymmetry in $B \to X_s\gamma$ decays

- $A_{CP} = (1.7 \pm 1.9 \pm 1.0)\%$
  uncertainty smaller than current world average
- $\Delta A_{X_s\gamma} = (5.0 \pm 3.9 \pm 1.5)\%$
  the first measurement

$0.07 \leq Im(C_{8g}/C_{7\gamma}) \leq 4.74$ 68% CL
$-1.64 \leq Im(C_{8g}/C_{7\gamma}) \leq 6.52$ 90% CL

preliminary results





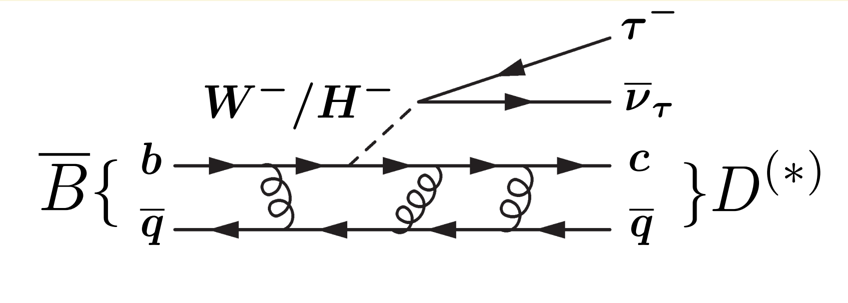
all possible values of $\tilde{\Lambda}_{78}$

$B \to D^{(*)}\tau\nu$ 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 obseved by Belle in 2007
  Phys.Rev.Lett. 99 (2007) 191807



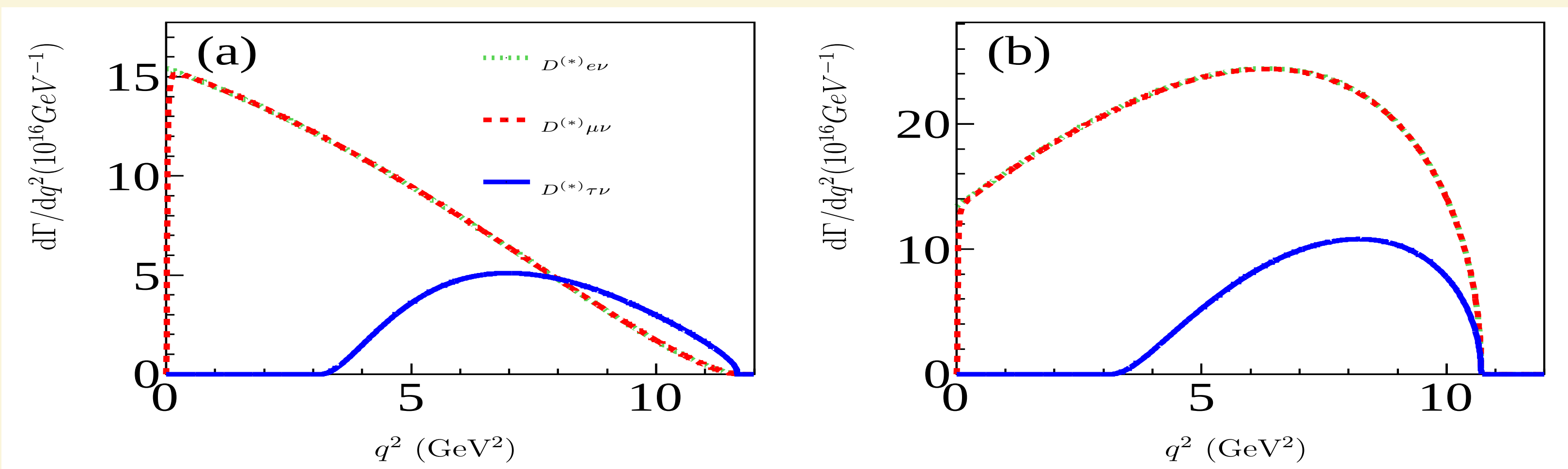
$B \to D^{(*)}\tau\nu$ decay

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

- $H_\pm, H_0$ - Helicity amplitudes common to e, μ, τ
- only H_0 affects $D(e, \mu, \tau)\nu$ decays
- H_s only relevant for τ

$$R(D^{(*)})_{SM} = \begin{cases} 0.297 \pm 0.017(D) \\ 0.252 \pm 0.003(D^*) \end{cases}$$

$Dl\nu$ $D^*l\nu$



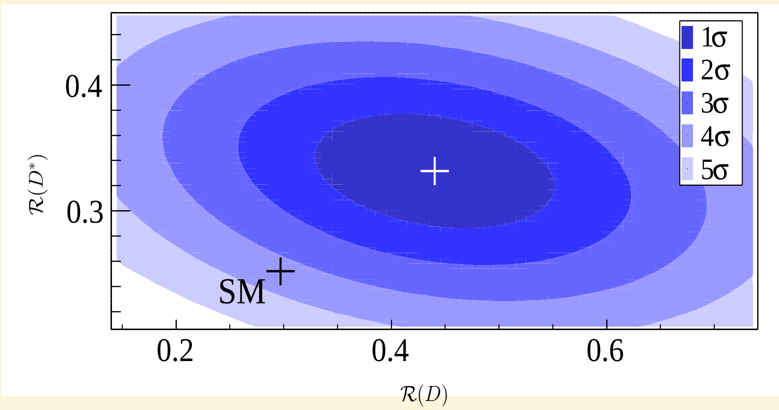
$B \to D^{(*)}\tau\nu$ decay

- $p_e > 0.3\ GeV/c$ and $p_\mu > 0.2\ GeV/c$
- $D^0 \to K^-\pi^+$, K^-K^+, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, $K_S\pi^+\pi^-$
- $D^+ \to K^-\pi^+\pi^+$, $K^-\pi^+\pi^+\pi^0$, $K_S\pi^+$, $K_S\pi^+\pi^+\pi^-$, $K_S\pi^+\pi^0$, $K^+\pi^+$
- $D^{*+} \to D^0\pi^+$, $D^+\pi^0$
- $D^{*0} \to D^0\pi^0$, $D^0\gamma$
- $|cos\Delta\theta_{th}| < 0.8$, $\Delta\theta_{th}$ angle between thrust axes B_{tag} and B_{sig}
- $q^2 > 4\ GeV^2$
- $p_{miss} > 0.2\ GeV$
- boosted decision tree multivariate method with variables: E_{extra}, ΔE, $m_{D^{(*)}}$, $m_{D^*} - m_D$, mass of B_{tag}, $m_{D^*_{tag}} - m_{D_{tag}}$, charge multiplicity of B_{tag}, $cos\Delta\theta_{th}$

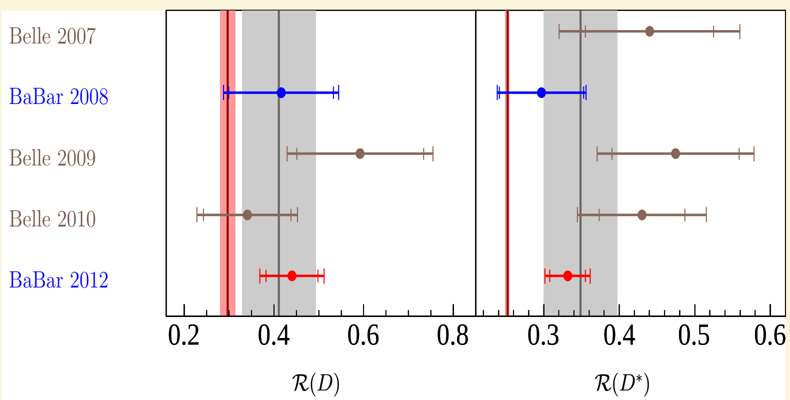
To extract signal from a fit to two dimensional distribution m^2_{miss} vs. p_l

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

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



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



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

average of the previous measurements (shading)

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

Two-Higgs-Doublet Model (2HDM)

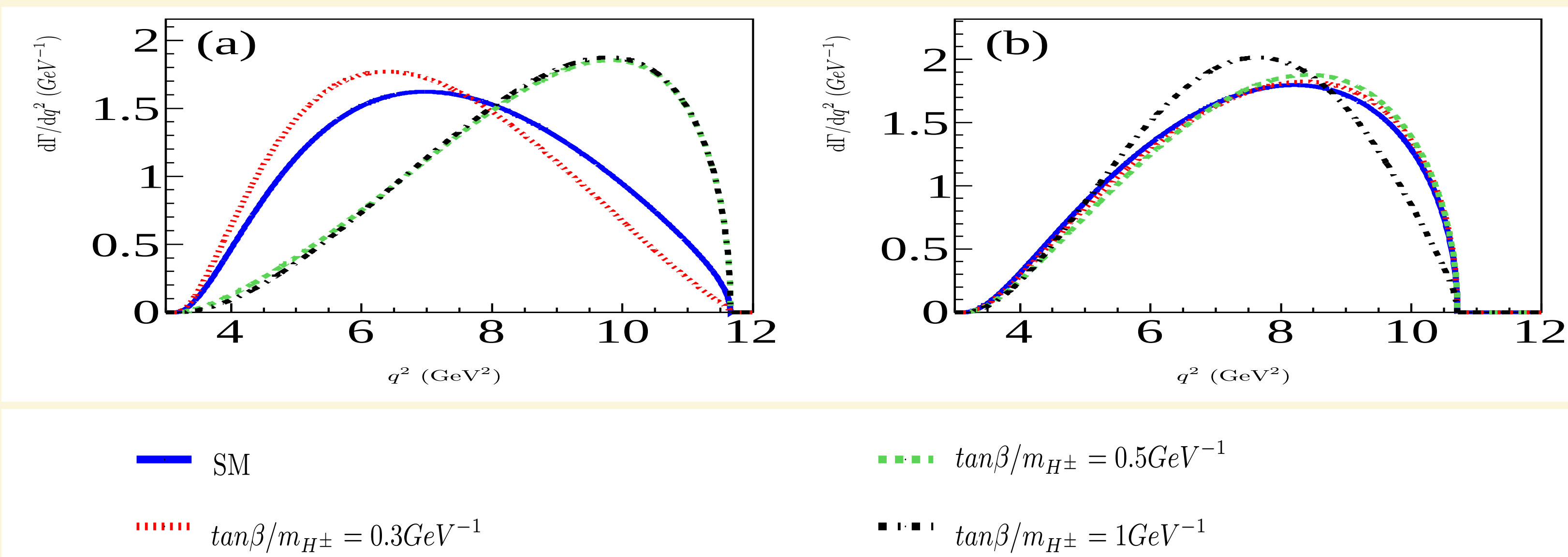
$$H_{eff} = \frac{4G_F V_{cb}}{\sqrt{2}} \left[(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\tau) + S_L(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\tau) + S_R(\bar{c}\gamma_\mu P_R b)(\bar{\tau}\gamma_\mu P_L \nu_\tau) \right]$$

$$H_s^{2HDM} \simeq H_s^{SM} \cdot \left(1 + (S_R \pm S_L) \frac{q^2}{m_\tau(m_b \mp m_c)} \right)$$

type III : S_R and S_L independent complex parameters

type II : $S_R = -m_b m_\tau tan\beta/m_{H^\pm}$ and $S_L = 0$

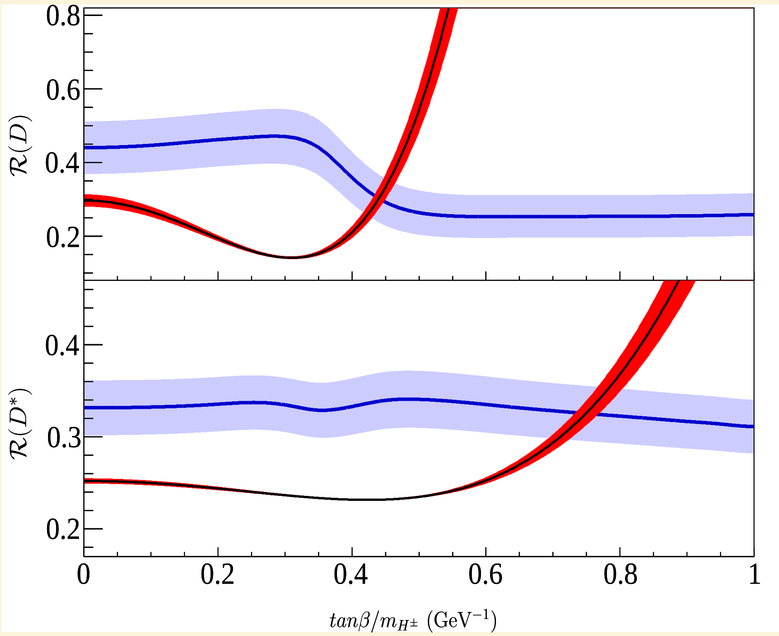
$Dl\nu$ $D^*l\nu$

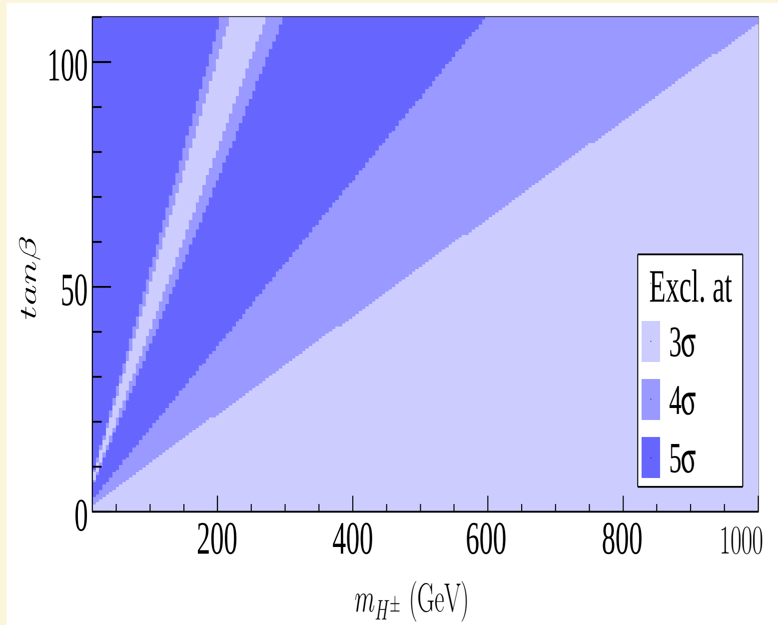


$B \to D^{(*)}\tau\nu$ decay

experimental result
theoretical prediction

2HDM type II



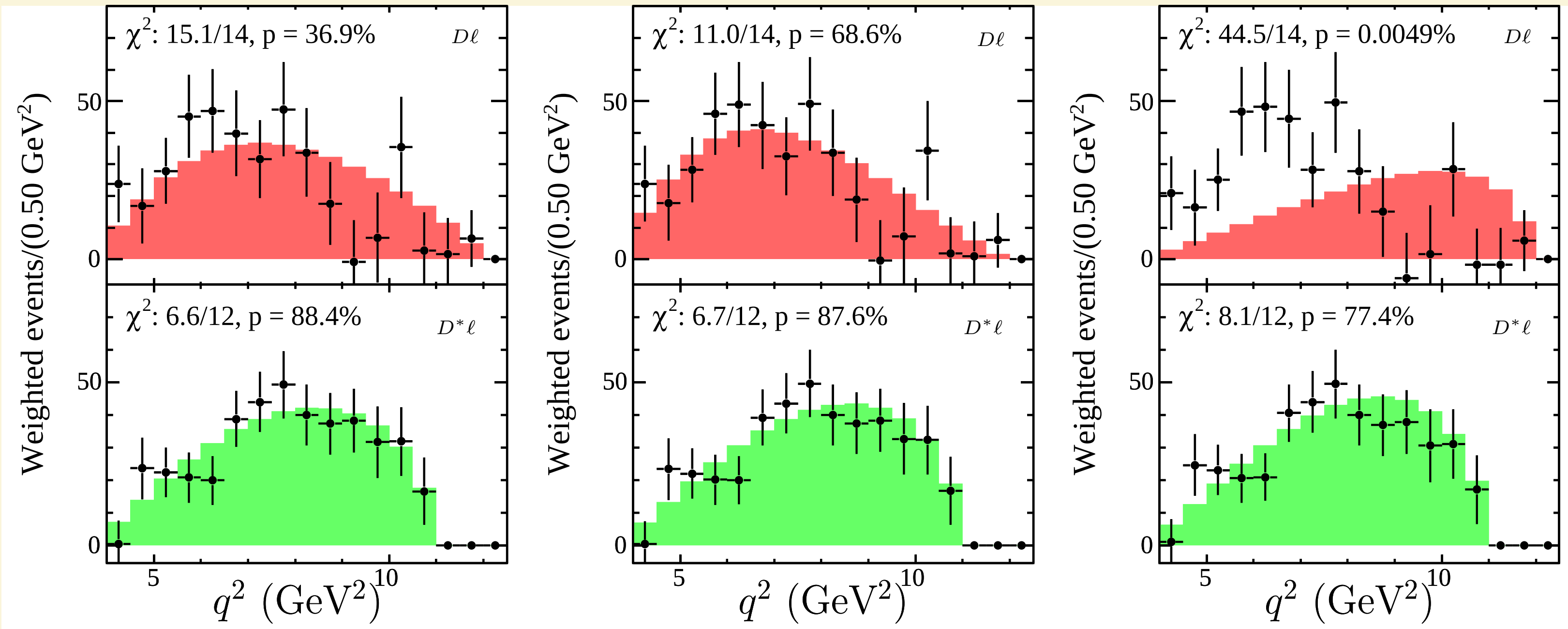


- $tan\beta/m_{H^\pm} = 0.44 \pm 0.02\,\text{GeV}^{-1}$
  $\mathcal{R}(D)$
- $tan\beta/m_{H^\pm} = 0.75 \pm 0.04\,\text{GeV}^{-1}$
  $\mathcal{R}(D^*)$

Level of disagreement

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

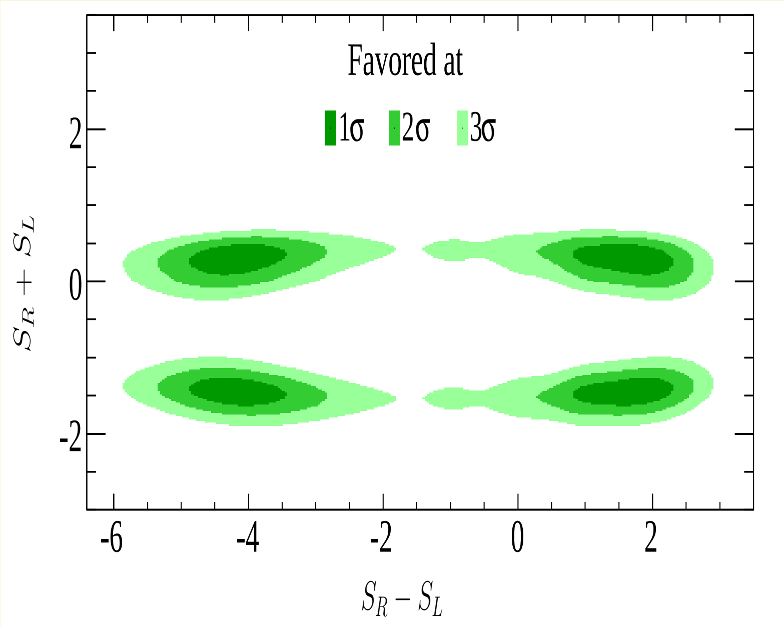
2HDM type II arXiv:1303.0571[hep-ex], submitted to PRD preliminary



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 S_R and S_L
- bottom two solutions are excluded by the measured q^2 spectra with significance of at least 2.9σ

Summary

- *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 analysis in progress*