BELLE

Study of Rare Decays of B Mesons at B Factories

Fabrizio Bianchi
University of Torino and INFN-Torino

Rencontres du Vietnam
Windows on the Universe
Qui Nhon, Vietnam August 11-17, 2013

INFN
Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

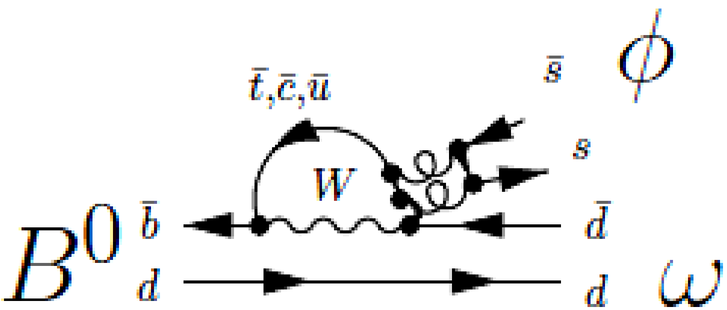
Why Study B Meson Decays ?

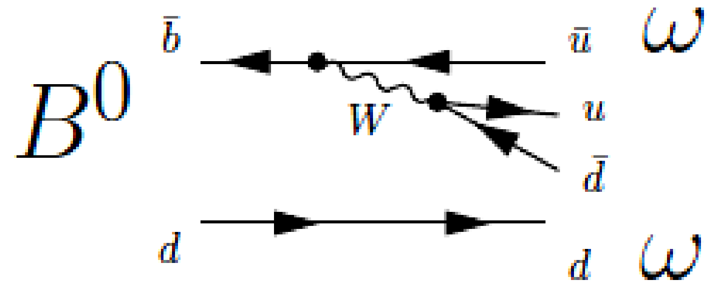
- Constrain the CKM sector of the SM.
  - Observation of CP violation
  - Angles and sides of the UT
- Search for evidence of New Physics beyond the SM
- Two paths in the quest for NP:
  - The relativistic path:
    - Increase the energy and look for direct production of new particles.
  - The quantum path:
    - Increase the luminosity and look for effects of physics beyond the standard model in loop diagrams.
- Recent results on B meson decays already exclude significant phase space of New Physics models.

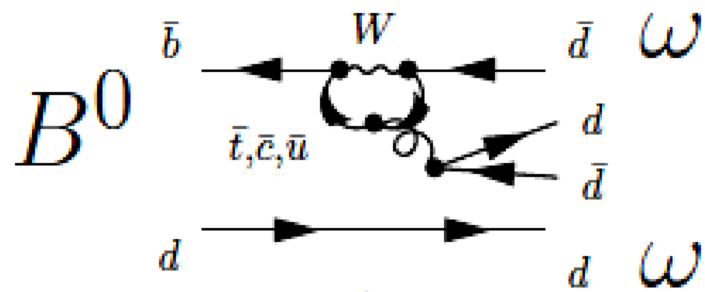
Overview

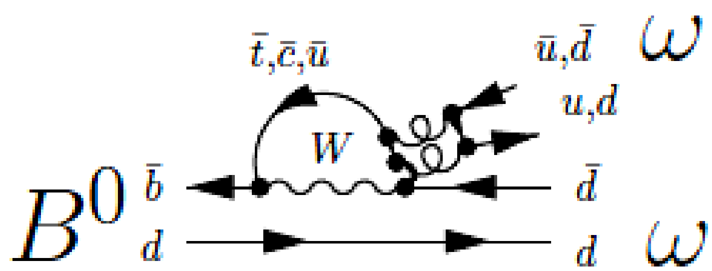
- B^0 -> $\omega\omega$, $\omega\phi$
- Direct A_{CP} in B -> $X_s\gamma$
- Search for Lepton Number Violation in B -> $X^- l^+ l'^+$
- B -> $D^{(*)}\tau\nu$
- Comments:
  - My selection of recent Babar results
  - Related Belle results are also discussed
  - All BaBar results are on full dataset of 471 x 10^6 $B\bar{B}$ decays
  - Charge conjugate processes are always implied

$B^0 \to \omega\omega$ and $B^0 \to \phi\omega$









- At leading order, $\phi\omega$ is pure penguin and $\omega\omega$ is a penguin-tree combination.

Anomalies in Charmless Decays with Loops

- Value of $\sin(2\beta^{eff})$ somewhat lower than in $b \to c\bar{c}s$ decays
- Quite low value of longitudinally-polarized fraction in $B^0 \to \phi K^*$ measured by BaBar and Belle.
  - Dominant longitudinal polarization fraction expected from QCD factorization

$B^0 \to \phi K^*$:

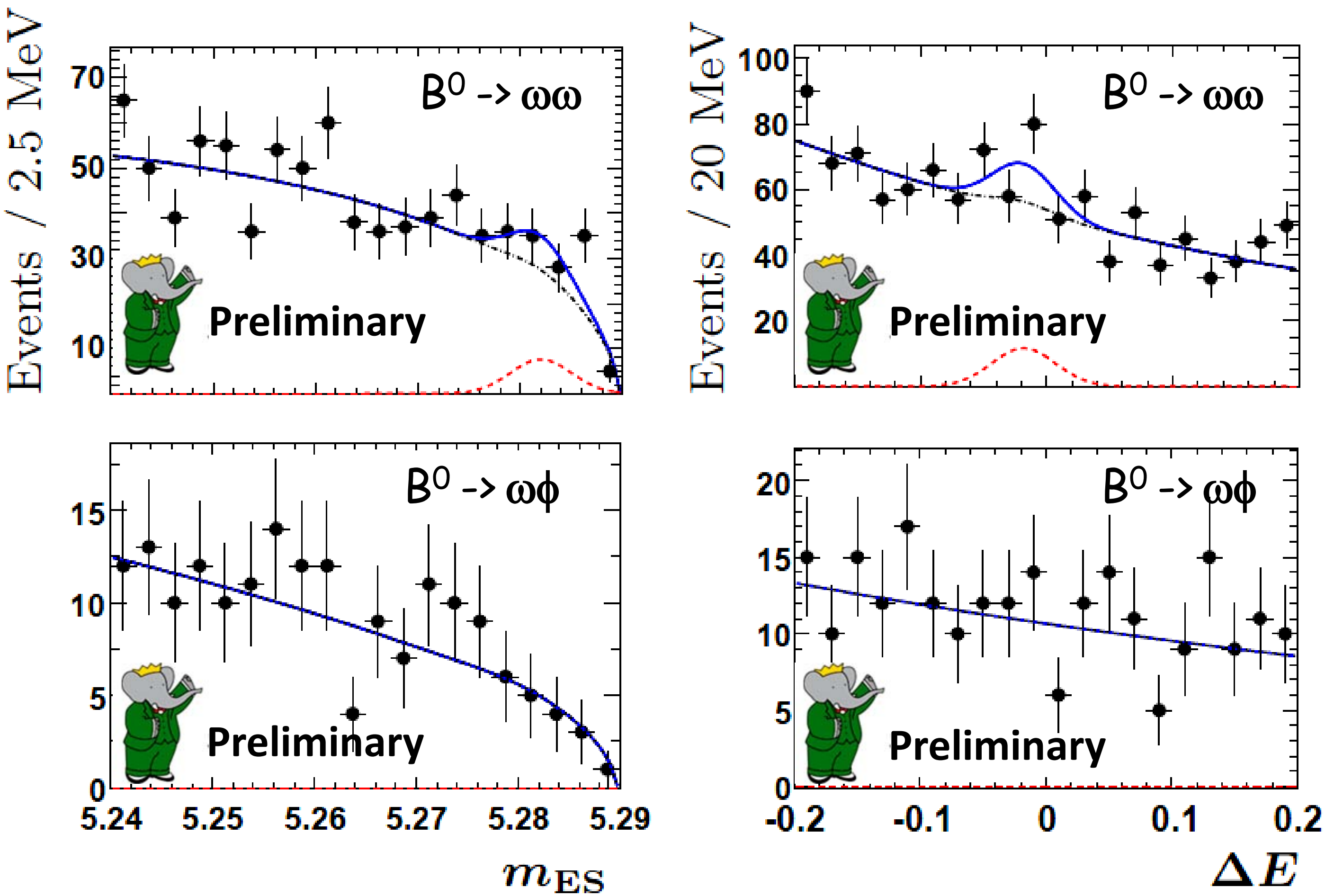
$f_L = 0.45 \pm 0.05 \pm 0.02$	Belle PRL 94, 221804(2005)
$f_L = 0.494 \pm 0.034 \pm 0.013$	BaBar PRD 78, 092008(2008)
$f_L = 0.499 \pm 0.030 \pm 0.010$	Belle (presented at EPS2013)

- Limits on $B^0 \to \omega\omega$ and $B^0 \to \phi\omega$ BFs can provide a constraint on amplitudes of $B^0 \to \phi K^*$. Neither helicity amplitude measurements, nor even significant signal peaks, are required

S. Oh, Phys. Rev. D 60, 034006 (1999)

New Results

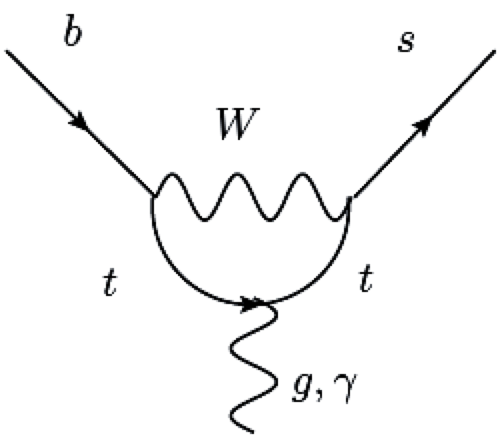
$B^0 \rightarrow \omega\omega$ and $B^0 \rightarrow \phi\omega$: Results

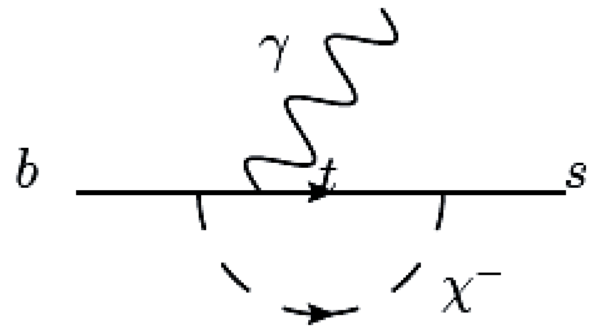


$$\mathrm{BF}(\omega\omega) = (1.2 \pm 0.3^{+0.3}_{-0.2}) \times 10^{-6} \quad (4.4\sigma \text{ significance})$$

$$\mathrm{BF}(\omega\phi) < 0.7 \times 10^{-6} \,(90\% CL)$$

Direct CP Asymmetries in $B \to X_s \gamma$





FCNC process which is forbidden at tree level in SM.
New Physics can enter in loops.
HFAG branching fraction average:

$$BF(B \to X_s\gamma) = (343 \pm 21 \pm 7) \times 10^{-6} (E_\gamma > 1.6 GeV)$$

Introduction to $B \to X_s \gamma$

- Effective Hamiltonian can be factorized in terms of short-distance (C_i, Wilson Coefficients) and long-distance (O_i) terms:

$$H_{eff} = \frac{4G_F}{\sqrt{2}} \sum_i C_i(\mu) O_i$$

- The CP asymmetry A_{CP} is defined as:

$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{X}_s\gamma) - \Gamma(B \to X_s\gamma)}{\Gamma(\bar{B} \to \bar{X}_s\gamma) + \Gamma(B \to X_s\gamma)}$$

- Difference between charged and neutral B decays:

$$\Delta A_{CP} = A_{CP}(B^+ \to X_s^+\gamma) - A_{CP}(B^0 \to X_s^0\gamma)$$

- ΔA_{CP} is proportional to $\mathrm{Im}(C_8^{eff}/C_7^{eff})$:

$$\Delta A_{CP}(X_s\gamma) = 4\pi^2\alpha_s \frac{\bar{\Lambda}_{78}}{m_b} \Im\left(\frac{C_8^{eff}}{C_7^{eff}}\right) \approx 0.12 \frac{\bar{\Lambda}_{78}}{100MeV} \Im\left(\frac{C_8^{eff}}{C_7^{eff}}\right)$$

$$17\ \mathrm{MeV} < \bar{\Lambda}_{78} < 190\ \mathrm{MeV}$$

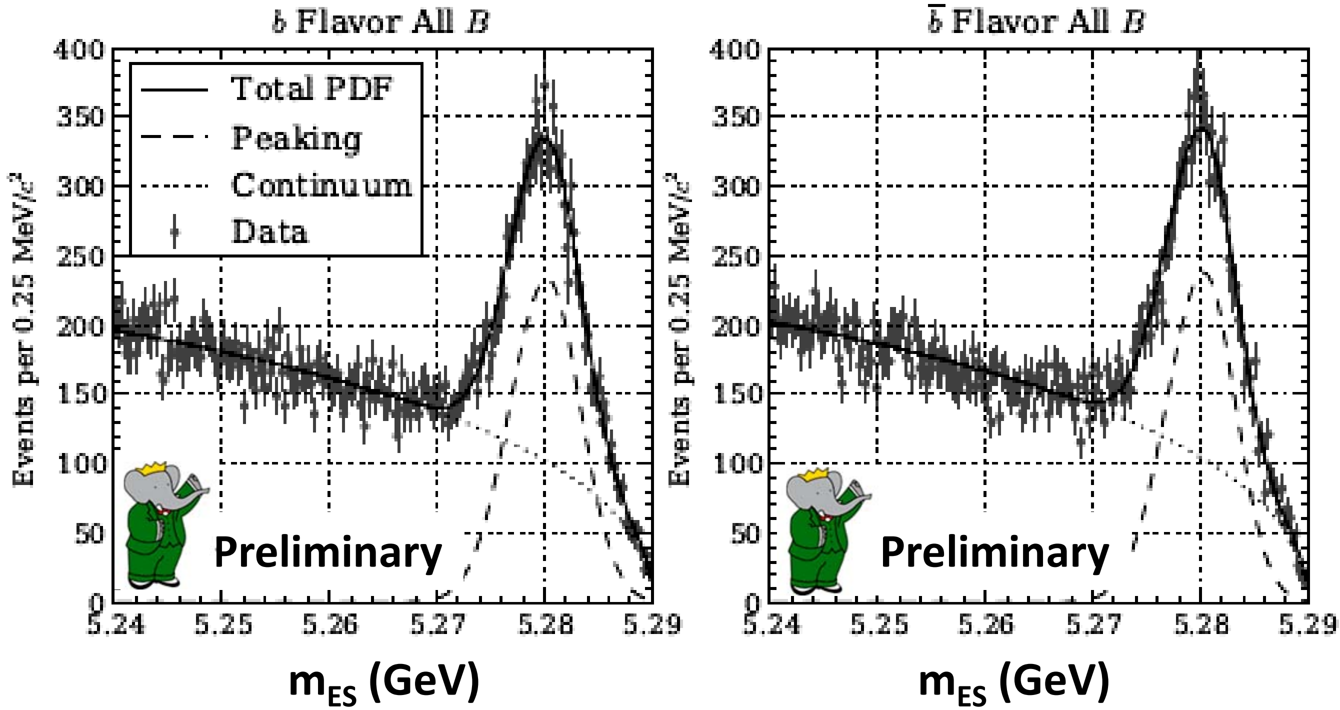
Benzke et al PRL 106, 141801 (2011)

- In SM, C_7^{eff} and C_8^{eff} are real $\to$ $\Delta A_{CP} \neq 0$ is evidence of NP

New Results

B -> $X_s\gamma$: Direct A_{CP} results

- $1.6 < E^*_\gamma < 3.0$ GeV; $0.6 < m_{X_s} < 3.2$ GeV/c^2; $|\Delta E| < 0.15$ GeV
- B^+ tagged by overall charge, B^0 by Kaon charge.
- Fit m_{ES} for b and $\overline{b}$ tagged samples simultaneously to extract A_{CP}



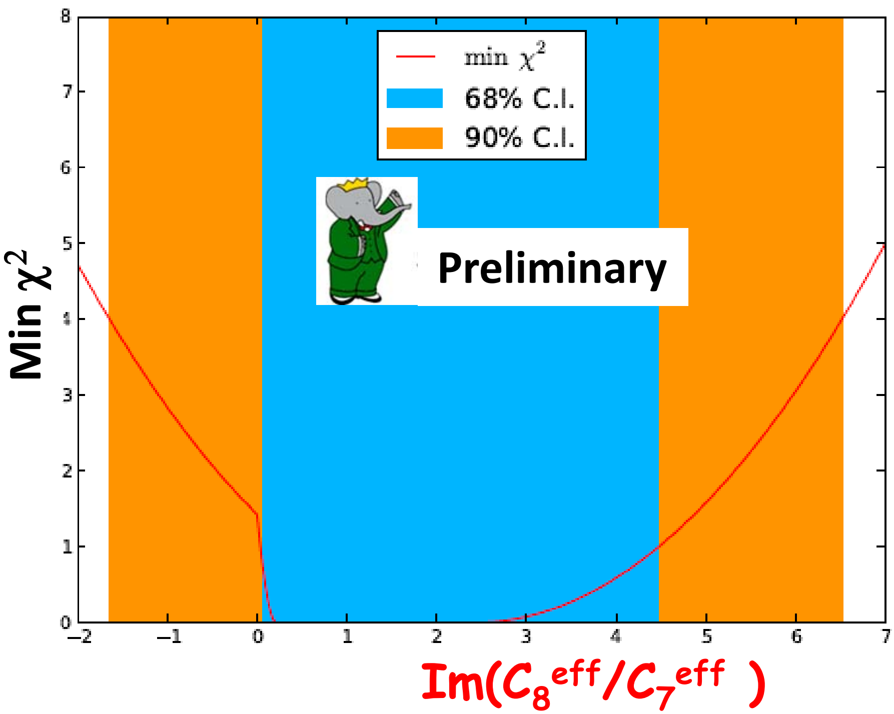
- After corrections for backgrounds and detector K^+/K^- response: A_{CP} =1.7±1.9±1.0%
- Agrees with SM predictions: $-0.6\% < A_{CP} < 2.8\%$

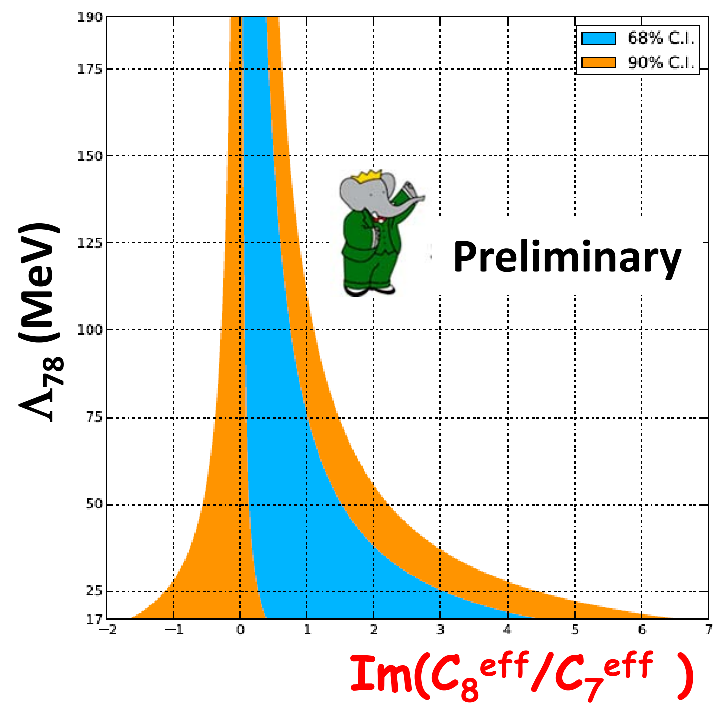
M. Benzke et al., PRL 106, 141801 (2011)

New Results

ΔA_{CP} and Wilson Coefficients

- From simultaneous fit to charged and neutral B samples:
  - $\Delta A_{CP} = 5.0 \pm 3.9 \pm 1.5$ %
- Set 90% CL constraints on $Im(C_8^{eff}/C_7^{eff})$:
  - $1.64 < Im(C_8^{eff}/C_7^{eff}) < 6.52$



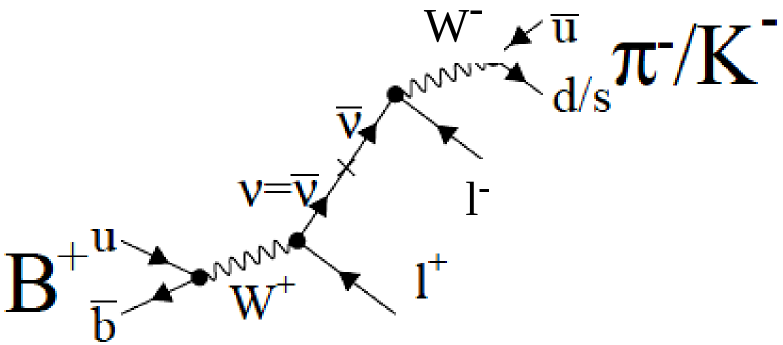


- First $\Delta A_{CP}(X_s\gamma)$ measurement and first constraint on $Im(C_8^{eff}/C_7^{eff})$

$B^+ \to X^- l^+ l'^+$

- Lepton Number Violation is highly suppressed in the SM.

- Many New Physics scenarios introduce LNV
  - Majorana neutrino exchange

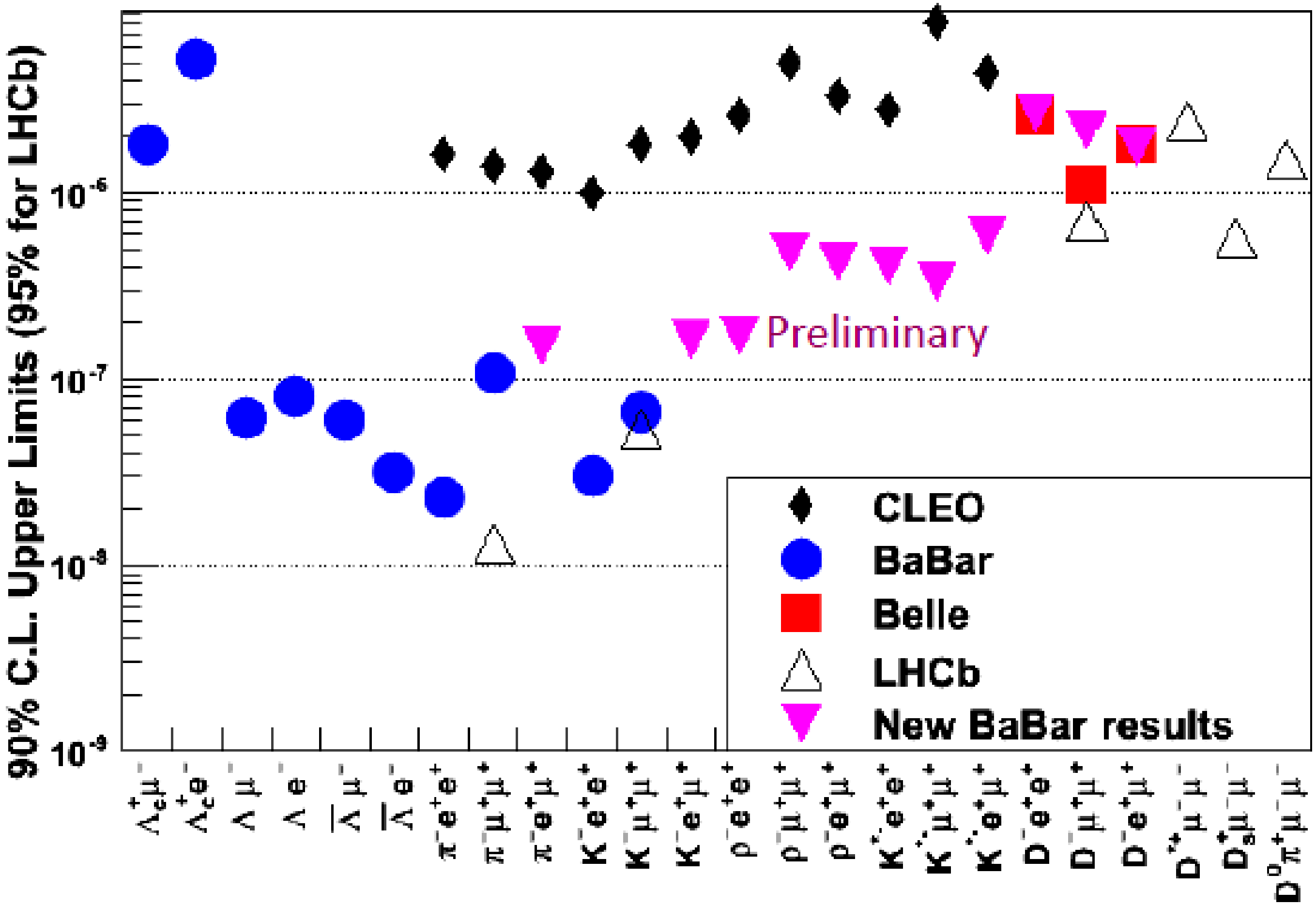


- Searched for the modes:
  - $B^+ \to \rho^-(\to \pi^-\pi^0)\ l^+l'^+$
  - $B^+ \to K^{*-}(\to K_S^0\pi^-$ and $\to K^-\pi^0)\ l^+l'^+$
  - $B^+ \to D^-(\to K^-\pi^-\pi^+)\ l^+l'^+$
  - $B^+ \to K^-/\pi^-\ e^+\mu^+$

Related results:
CLEO: PRD 65, 111102 (2002)
Belle: PRD 84, 071106 (2011)
BaBar: PRD 85, 071102 (2012)
LHCb: PRL 108, 106601 (2012);
PRD 85, 112004 (2012)

New Results

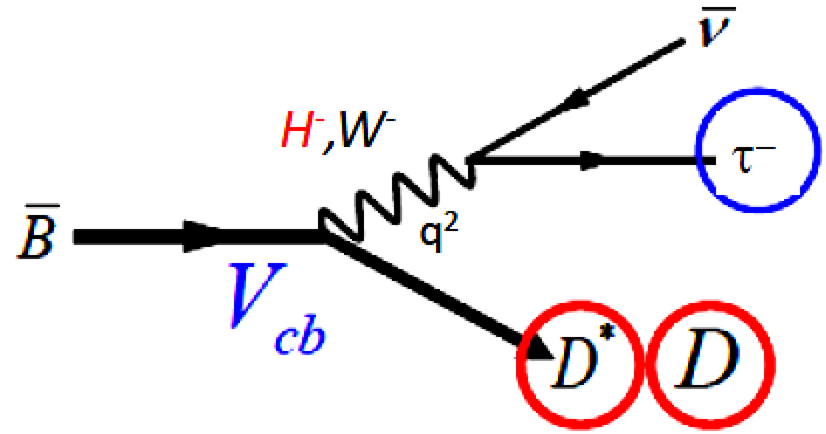
B⁺ -> X⁻l⁺l′⁺: Preliminary Results



- 11 updated measurements; 90% CL UL in range (1.5 – 26.4) x 10^{-7}
- Order of magnitude improvement over CLEO results.
- Similar precision to Belle for $B^+ \rightarrow D^- l^+ l'^+$

Ratio of $B \to D^{(*)}\tau\nu$ vs $B \to D^{(*)} l \nu$ Decays

- Semileptonic decays sensitive to charged Higgs.



- We measure:

$$R(D) = \frac{\Gamma(\bar{B} \to D\tau\nu)}{\Gamma(\bar{B} \to D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(\bar{B} \to D^*\tau\nu)}{\Gamma(\bar{B} \to D^*\ell\nu)} \qquad \ell = e,\mu$$

  - Several experimental and theoretical uncertainties cancel in the ratio
  - non-SM contribution from $H^\pm$ expected to change rates for $B \to D^{(*)}\tau\nu$

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

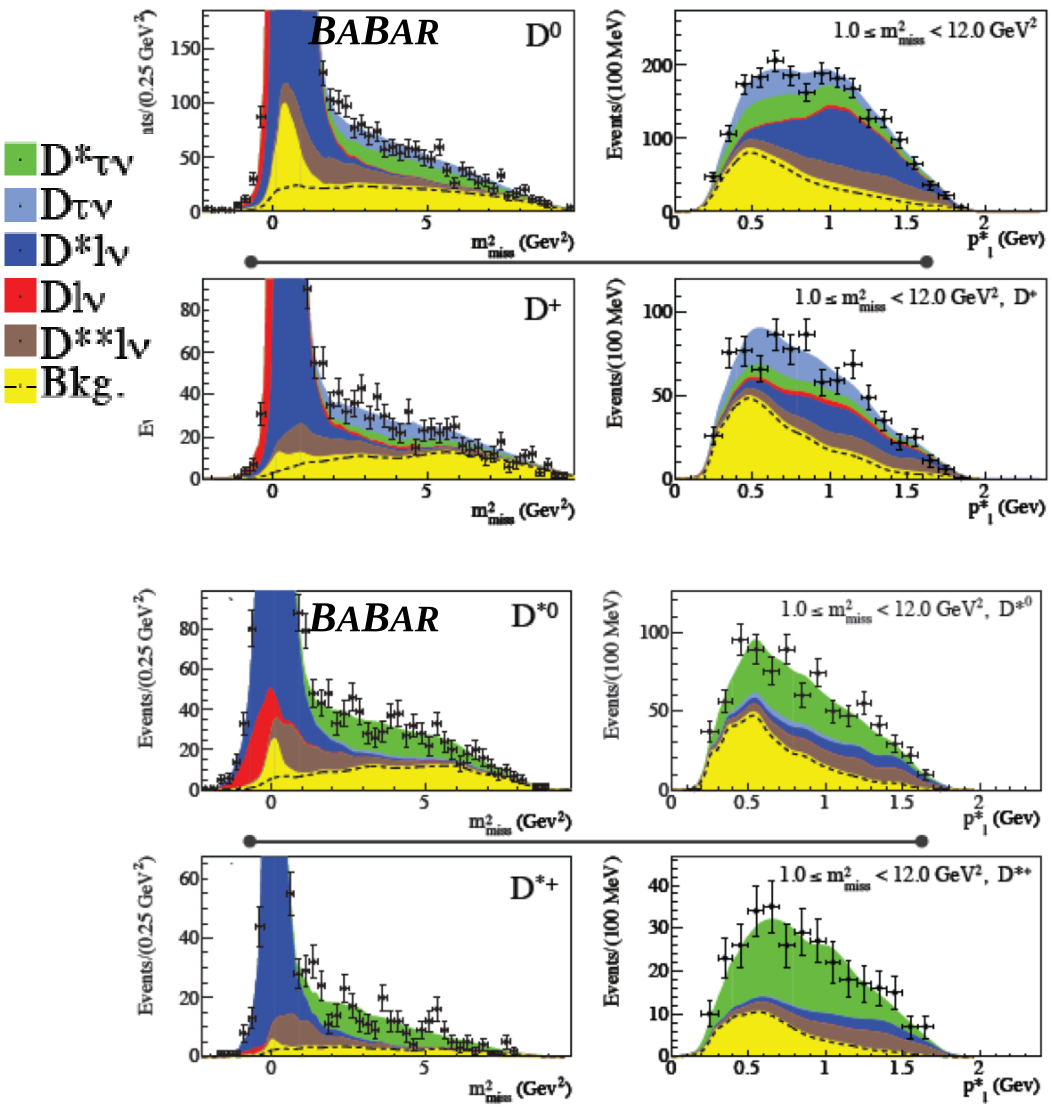
$-$ for $B \to D\tau\upsilon$

$+$ for $B \to D^*\tau\upsilon$

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

Event selection:

- Reconstruct $D^{(*)}$ candidate
- Exactly one extra lepton candidate ($\tau \to e\nu\nu, \mu\nu\nu$)
- Multivariate analysis to suppress backgrounds (uses control sample and off-peak data)
- m_{miss} higher and lepton momentum p^*_l smaller for signal than normalization
- 2D Extended Maximum LH fit to m^2_{miss} and p^*_l to extract yields
- Simultaneous fit with $B \to D^{(*)} \pi^0 l n$ to account for D** contribution



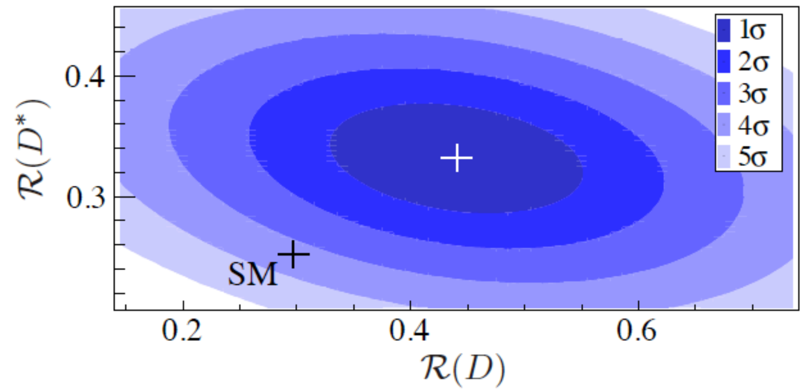
$B \to D^{(*)} \tau \nu$: Results

$\mathcal{R}(D)_{\rm exp} = 0.440 \pm 0.072$ $\mathcal{R}(D^*)_{\rm exp} = 0.332 \pm 0.030$

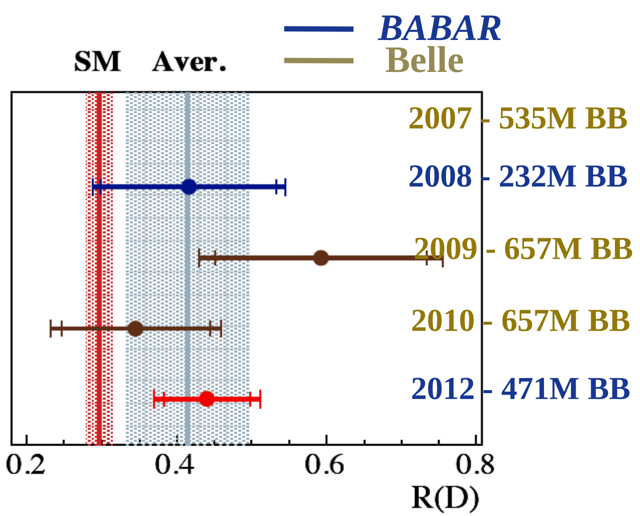
$\updownarrow$ 2.0σ $\updownarrow$ 2.7σ

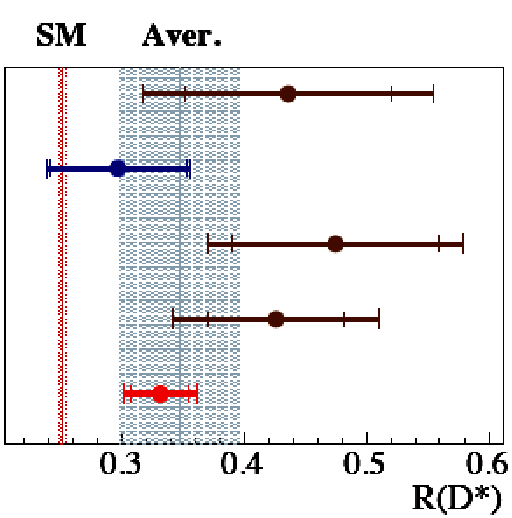
$\mathcal{R}(D)_{\rm SM} = 0.297 \pm 0.017$ $\mathcal{R}(D^*)_{\rm SM} = 0.252 \pm 0.003$

SM expectations in S. Fajfer, J. Kamenik, I. Nisandzic, PRD 85, 094025 (2012).



- -27% correlation between R(D) and R(D*)
- combined BABAR results 3.4σ higher than SM





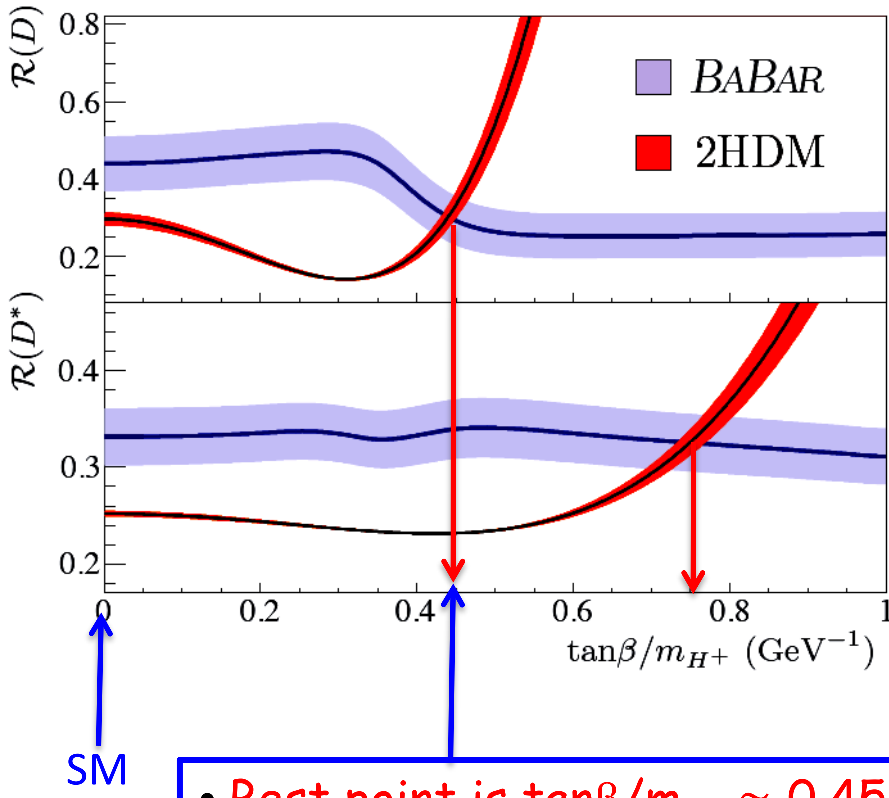
- Unpublished deviations from SM of Belle results presented at FPCP 2013 (A. Bozek)
  - R(D*): 3.0σ ; R(D): 1.4σ
  - Combined Belle+BABAR: $R(D^{(*)})$: 4.6 σ

Need more results for confirmations!

PRL 109, 101802 (2012)

$B \to D^{(*)} \tau \nu$: Type II 2HDM scan

2HDM affects fit variables distributions and hence the efficiency.
PDF recalculated for different values of $\tan\beta/m_H$



$\tan\beta/m_{H+} =$
0.44 ± 0.02 GeV^{-1}

$\tan\beta/m_{H+} =$
0.75 ± 0.04 GeV^{-1}

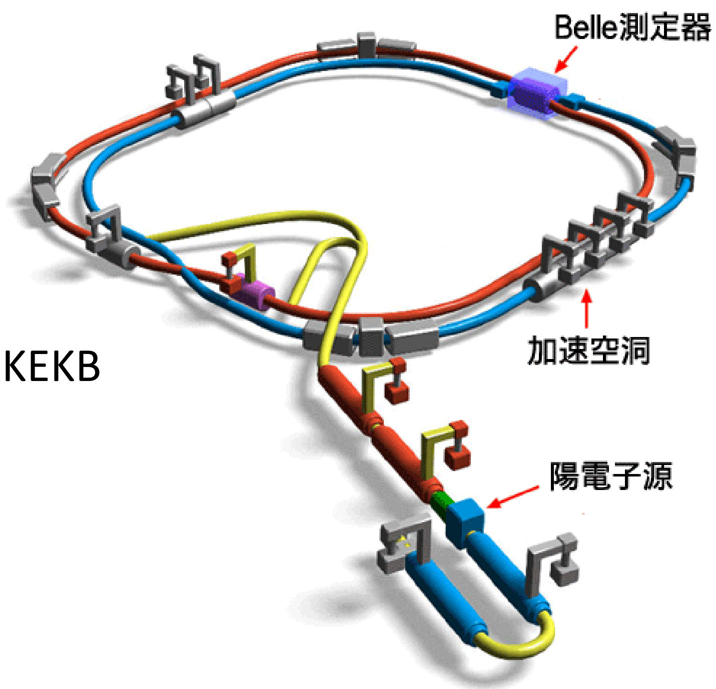
- Best point is $\tan\beta/m_{H+} \simeq 0.45$ GeV^{-1}, and it is excluded at 99.8% C.L. (3.1σ)
- All other points (with m_{H+}>15 GeV/c^2) are worse

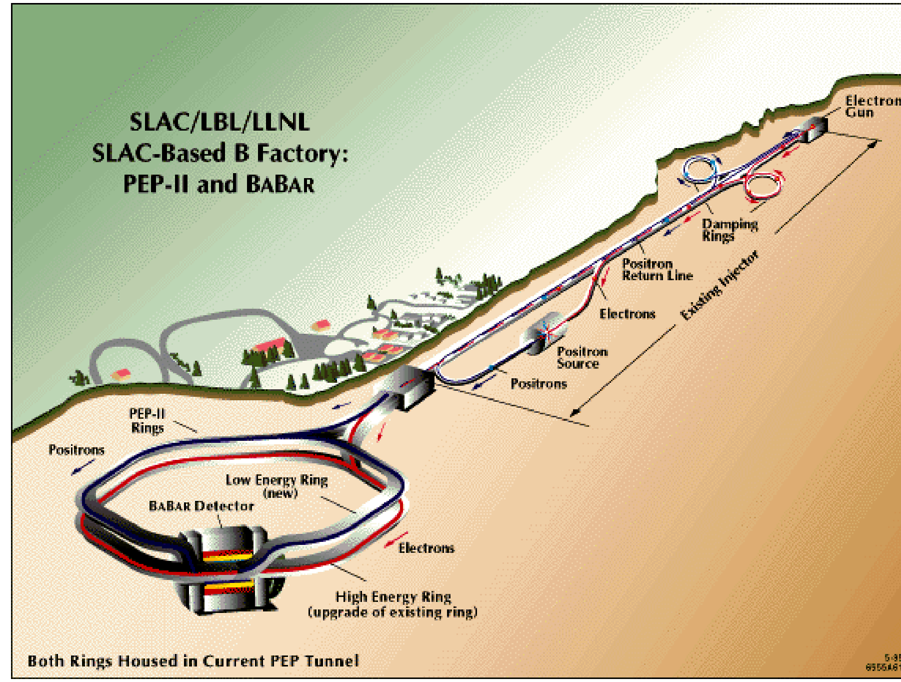
Summary and Outlook

- New BaBar measurements of:
  - Branching Fractions of $B^0 \to \omega\omega$, $\omega\phi$,
  - Direct A_{CP} in $B \to X_s\gamma$
  - Search for Lepton Number Violation in $B \to X^- l^+ l'^+$
- Average of published BaBar and Belle measurements of $B \to D^{(*)}\tau\nu$ shows a 4.6σ deviation from SM prediction.
  - Eagerly waiting for Belle result on full dataset.
- Looking forward to future data coming from LHCb and Belle II
  - Start of Belle II data taking expected in 2016

Backup

The colliders





$\sqrt{s}=10.58$ GeV

$e^+ \rightarrow \Upsilon(4s) \leftarrow e^-$

$\Upsilon(4s) \rightarrow B\,\bar{B}$

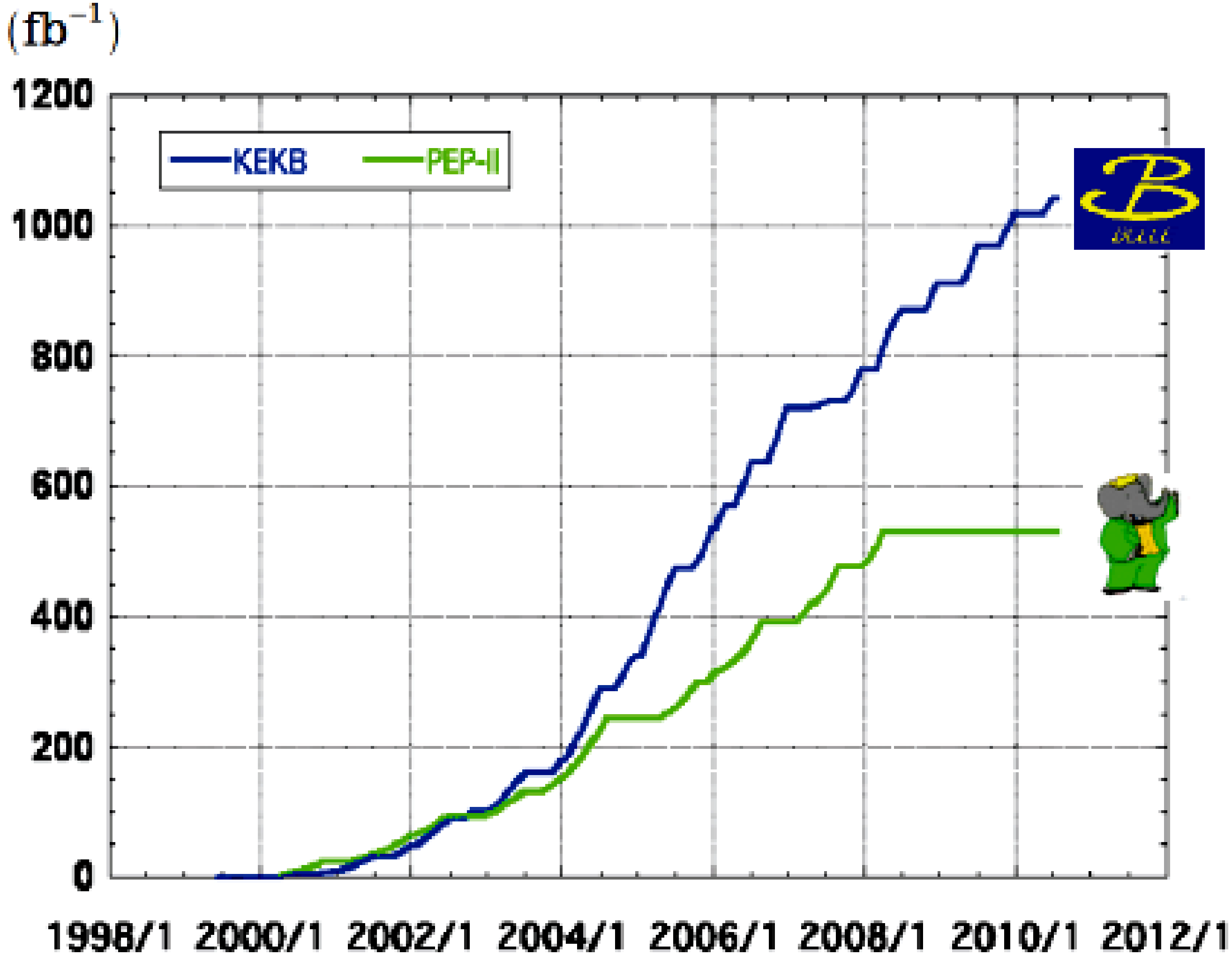
$\Delta_z \sim c\beta\gamma t_B$

$\sim 200\mu m$

BaBar	$p(e^-)=9$ GeV	$p(e^+)=3.1$ GeV	$\beta\gamma=0.56$
Belle	$p(e^-)=8$ GeV	$p(e^+)=3.5$ GeV	$\beta\gamma=0.42$

Asymmetric-energy B factories => Flavor Physics at the intensity frontier

Integrated luminosity of B factories



$> 1\ ab^{-1}$

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan

$\sim$ 100 fb^{-1}

$\sim 550\ fb^{-1}$

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

$\sim$ 54 fb^{-1}

$B^0 \to \phi K^*$ - Preliminary Results (Numbers)

EPS 2013

Parameter	$\phi(K\pi)^*_0$ $J=0$	$\phi K^*(892)^0$ $J=1$	$\phi K^*_2(1430)^0$ $J=2$
$\mathcal{B}_J$ (10^{-6})	$4.3 \pm 0.4 \pm 0.3$	$10.4 \pm 0.5 \pm 0.5$	$5.5^{+0.9}_{-0.7} \pm 0.7$
f_{LJ}		$0.499 \pm 0.030 \pm 0.010$	$0.918^{+0.029}_{-0.060} \pm 0.008$
$f_{\perp J}$		$0.238 \pm 0.026 \pm 0.005$	$0.056^{+0.050}_{-0.035} \pm 0.006$
$\phi_{\parallel J}$ (rad)		$2.23 \pm 0.10 \pm 0.02$	$3.76 \pm 2.88 \pm 1.32$
$\phi_{\perp J}$ (rad)		$2.37 \pm 0.10 \pm 0.04$	$4.45^{+0.43}_{-0.38} \pm 0.07$
δ_{0J} (rad)		$2.91 \pm 0.10 \pm 0.04$	$3.53 \pm 0.11 \pm 0.12$
$\mathcal{A}_{CPJ}$	$0.093 \pm 0.094 \pm 0.015$	$-0.007 \pm 0.048 \pm 0.020$	$-0.155^{+0.152}_{-0.133} \pm 0.024$
$\mathcal{A}^0_{CPJ}$		$-0.030 \pm 0.061 \pm 0.006$	$-0.016^{+0.066}_{-0.051} \pm 0.004$
$\mathcal{A}^{\perp}_{CPJ}$		$-0.14 \pm 0.11 \pm 0.01$	$-0.01^{+0.85}_{-0.67} \pm 0.04$
$\Delta\phi_{\parallel J}$ (rad)		$-0.02 \pm 0.10 \pm 0.01$	$-0.02 \pm 1.08 \pm 0.99$
$\Delta\phi_{\perp J}$ (rad)		$0.05 \pm 0.10 \pm 0.02$	$-0.19 \pm 0.42 \pm 0.06$
$\Delta\delta_{0J}$ (rad)		$0.08 \pm 0.10 \pm 0.01$	$0.06 \pm 0.11 \pm 0.01$

- BR and polarization parameters consistent with existing results
- All parameters related to direct *CP* violation consistent with zero

$B^0 \to \omega\omega$; $\phi\omega$: Analysis Strategy

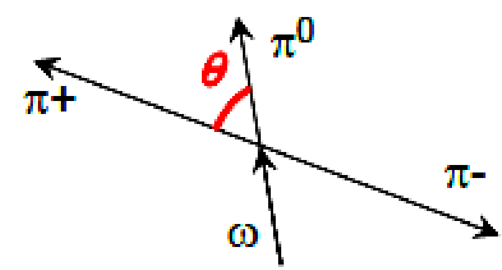
- Full reconstruction of B^0 candidates, with $\omega \to \pi^+\pi^-\pi^0$ and $\phi \to K^+K^-$.
- Resulting B^0 signal candidates are characterized by the standard variables:

$$\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$$

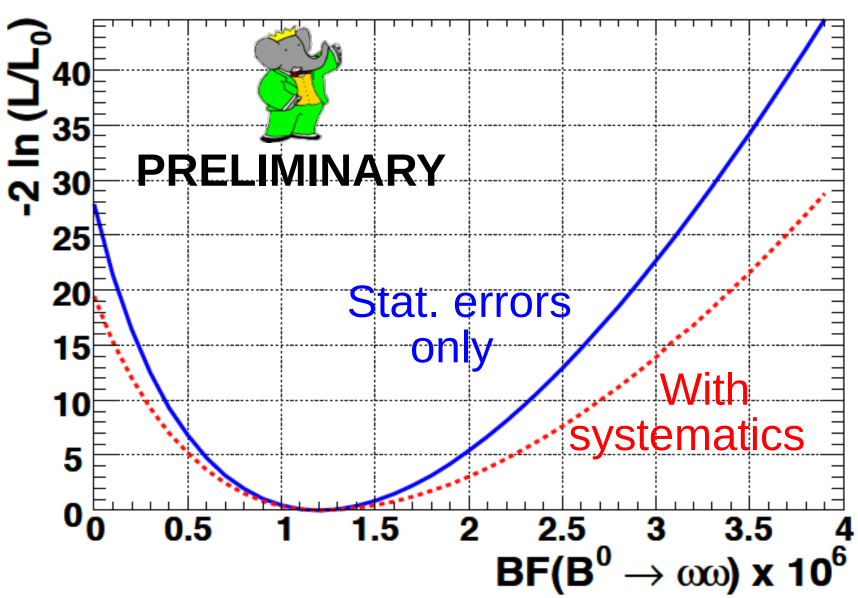
$$m_{ES} = \sqrt{(\tfrac{1}{2}s + \mathbf{p}_0 \cdot \mathbf{p}_B)^2 / E_0^{*2} - \mathbf{p}_B^2}$$

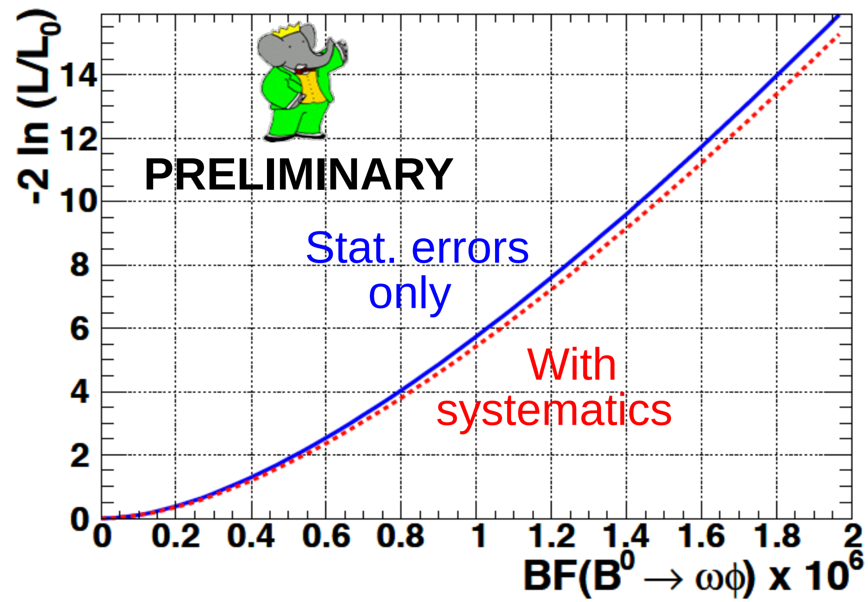
- Signal, combinatory background, and peaking background yields are extracted from an UML fit to m_{ES}, ΔE, resonance masses and helicities, event shape Fisher discriminant, ω internal helicity angle(s) θ

Di-pion (π+π-) rest frame:



$B^0 \to \omega\omega$ and $B^0 \to \omega\phi$: Fit Result





- **B**($\omega\omega$) = $\mathbf{(1.2 \pm 0.3^{+0.3}_{-0.2}) \times 10^{-6}}$ (**4.4σ** significance)
- **B**($\phi\omega$) **< 0.7 x 10^{-6}** (90% CL)

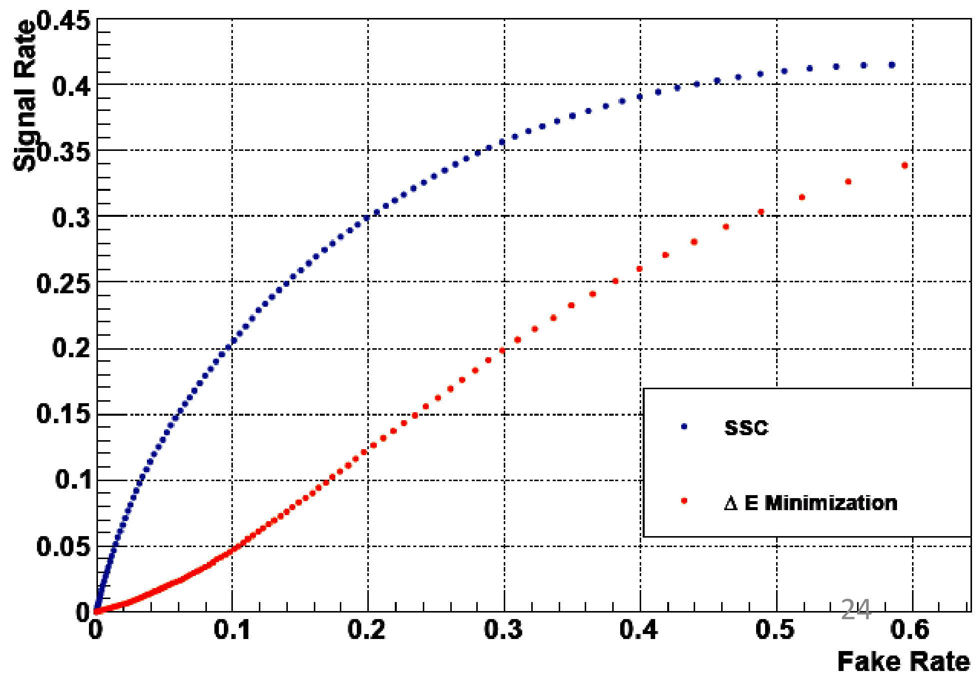
Brand new! To be submitted to PRL

- Largest systematic contributions from fit yield bias estimation (O(5 events) ≲ 10% for $\omega\omega$) and marginalizing over longitudinal vs transverse fraction (f_L = 0.88 is used as the nominal central value).

B -> X_s γ: Event Selection

- Reconstruct 16 exclusive modes to measure A_{CP}; further 22 modes reconstructed to eliminate peaking background
- Two multivariate classifiers used:
  - Signal Selecting Classifier (SSC): based on signal properties. Factor 2 improvement compared to using ΔE alone.
  - Background Rejection Classifier (BRC): Based on event shapes.
  - Trained in four X_s mass regions, selection criteria based on optimizing sqrt($S/S+B$).

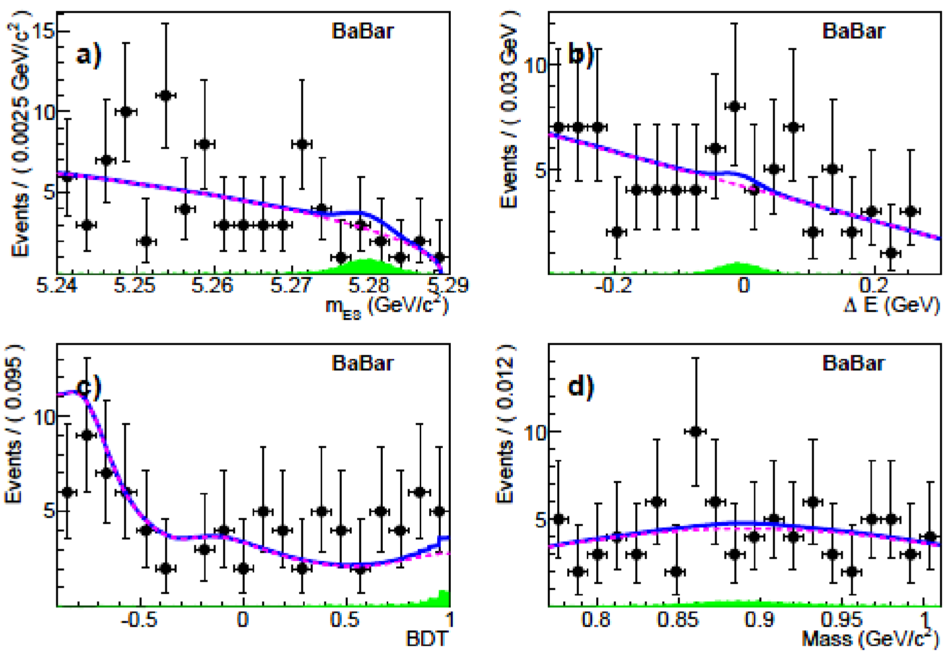
	Decay Mode		Decay Mode
1	$B^+ \to K^0_S \pi^+ \gamma$	9	$B^+ \to K^+ \pi^+ \pi^- \pi^0 \gamma$
2	$B^+ \to K^+ \pi^0 \gamma$	10	$B^+ \to K^0_S \pi^+ \pi^0 \pi^0 \gamma$
3	$B^0 \to K^+ \pi^- \gamma$	11	$B^0 \to K^+ \pi^+ \pi^- \pi^- \gamma$
4	$B^+ \to K^+ \pi^+ \pi^- \gamma$	12	$B^0 \to K^+ \pi^- \pi^0 \pi^0 \gamma$
5	$B^+ \to K^0_S \pi^+ \pi^0 \gamma$	13	$B^+ \to K^+ \eta \gamma$
6	$B^+ \to K^+ \pi^0 \pi^0 \gamma$	14	$B^0 \to K^+ \eta \pi^- \gamma$
7	$B^0 \to K^+ \pi^- \pi^0 \gamma$	15	$B^+ \to K^+ K^- K^+ \gamma$
8	$B^+ \to K^0_S \pi^+ \pi^- \pi^+ \gamma$	16	$B^0 \to K^+ K^- K^+ \pi^- \gamma$



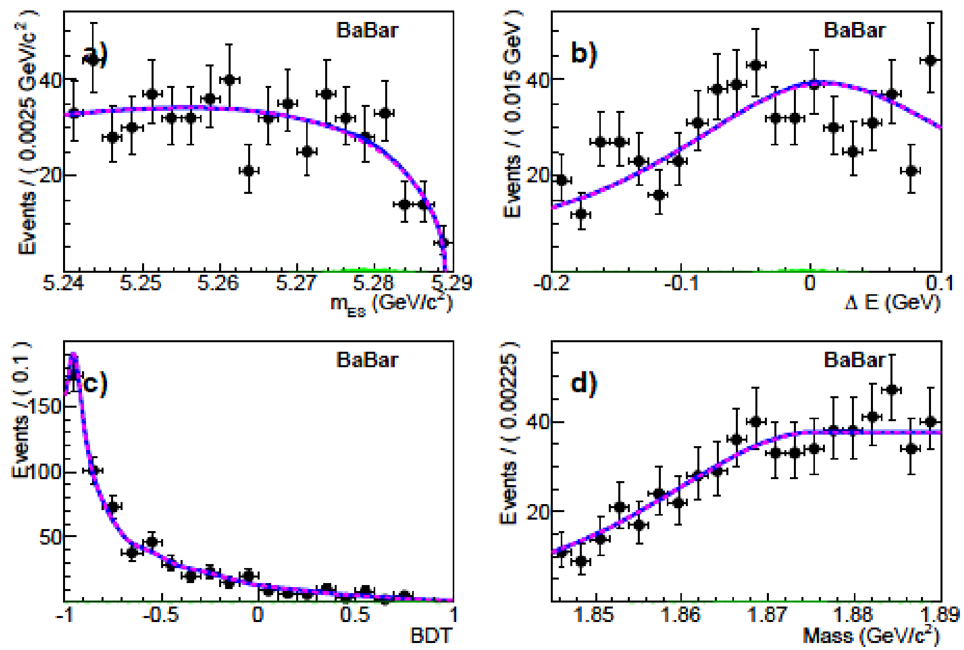
$B^+ \to X^- l^+ l'^+$: Event Selection

- A multivariate discriminant (BDT) has been constructed to reject backgrounds.
- Event yields from ML fit to m_{ES}, ΔE, BDT, [$K^*/\rho/D$ mass]

$$B^+ \to K^{*-}(\to K^- \pi^0)\mu^+\mu^+$$

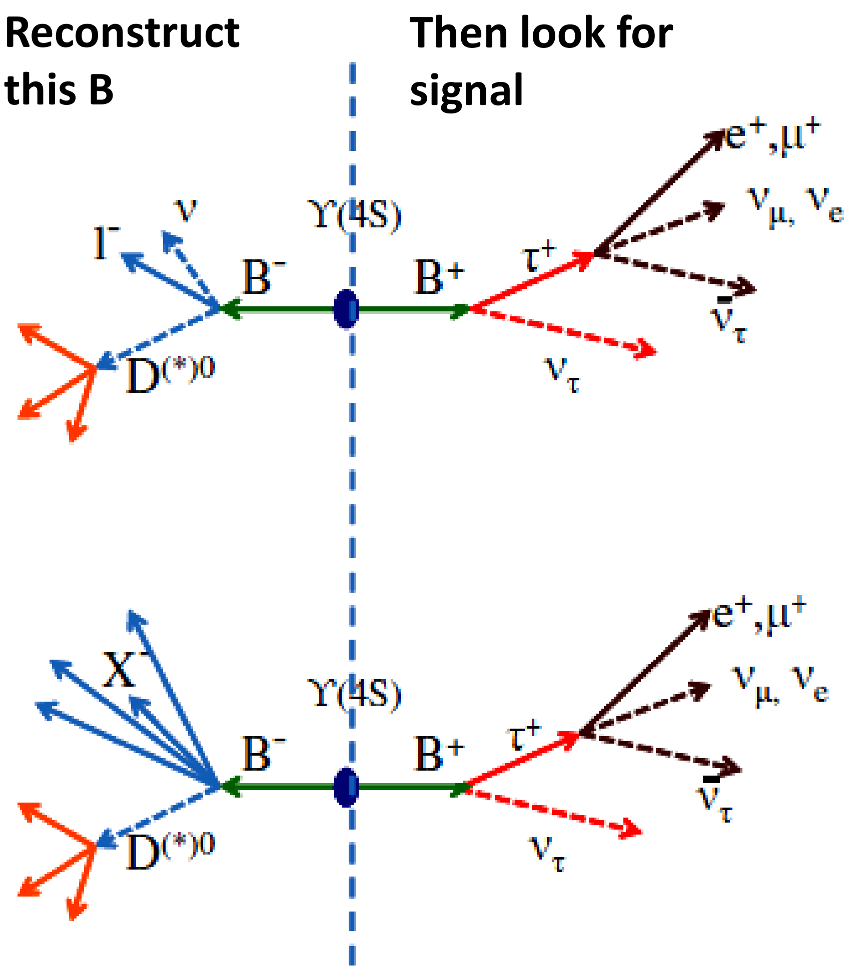


$$B^+ \to D^- e^+ \mu^+$$



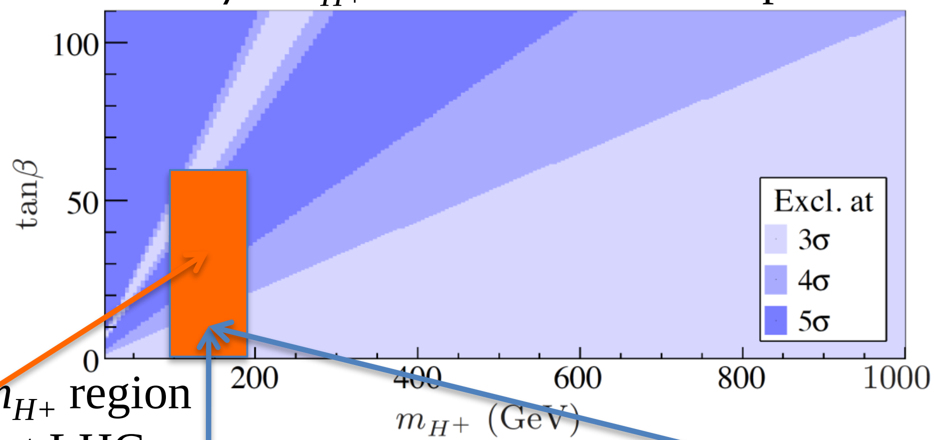
Hadronic and Semileptonic Tags

- Semileptonic B decays
  - $B \rightarrow D^* l \nu$
  - PRO: Higher efficiency $\varepsilon_{tag} \sim 1.5\%$
  - CON: more backgrounds, B momentum unmeasured
- Hadronic B decays with charm
  - $B^+ \rightarrow D^{(*)0} X^+$ or $B^0 \rightarrow D^{(*)+} X^-$
  - X is a charged system of hadrons among (π, K, π^0, K_s) up to 5 charged particles and 2 neutrals
  - PRO: cleaner events, B momentum reconstructed
  - CON: smaller efficiency $\varepsilon_{tag} \sim 0.15\%$



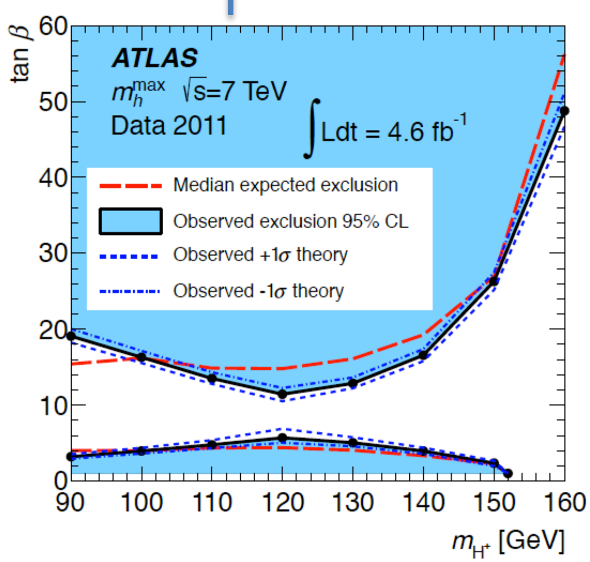
Type-II 2HDM - connection with LHC

$\tan\beta - m_{H+}$ BABAR exclusion plot

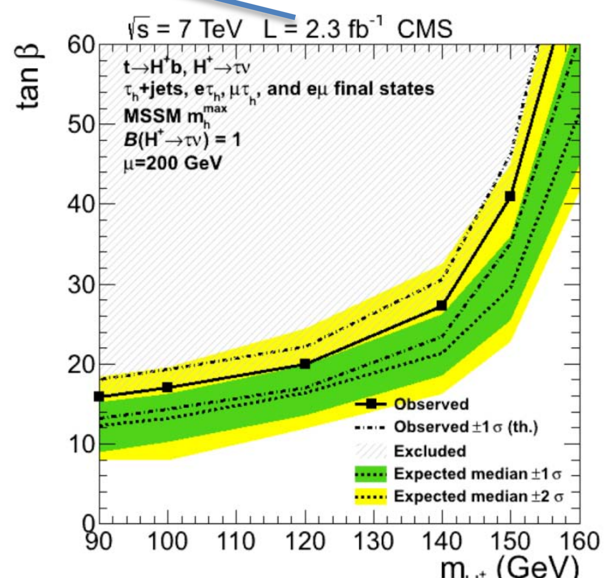


$\tan\beta - m_{H+}$ region probed at LHC

$B \rightarrow D^{(*)} \tau \nu$ and $B \rightarrow \tau \nu$ searches at *B* factories are complementary to direct searches at LHC in $t \rightarrow b H^+$, $H^+ \rightarrow \tau\nu$



ATLAS: JHEP 1206, 039 (2012)



CMS: JHEP 07, 143 (2012)

$B \to D^{(*)} \tau \nu$: limits on Type-III 2HDM

General spin-0 interactions
$$\mathcal{H}_{\rm eff} = \frac{4G_F V_{cb}}{\sqrt{2}} \left[(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu_\tau) + S_R (\bar{c} P_R b)\,(\bar{\tau} P_L \nu_\tau) + S_L (\bar{c} P_L b)\,(\bar{\tau} P_L \nu_\tau) \right]$$

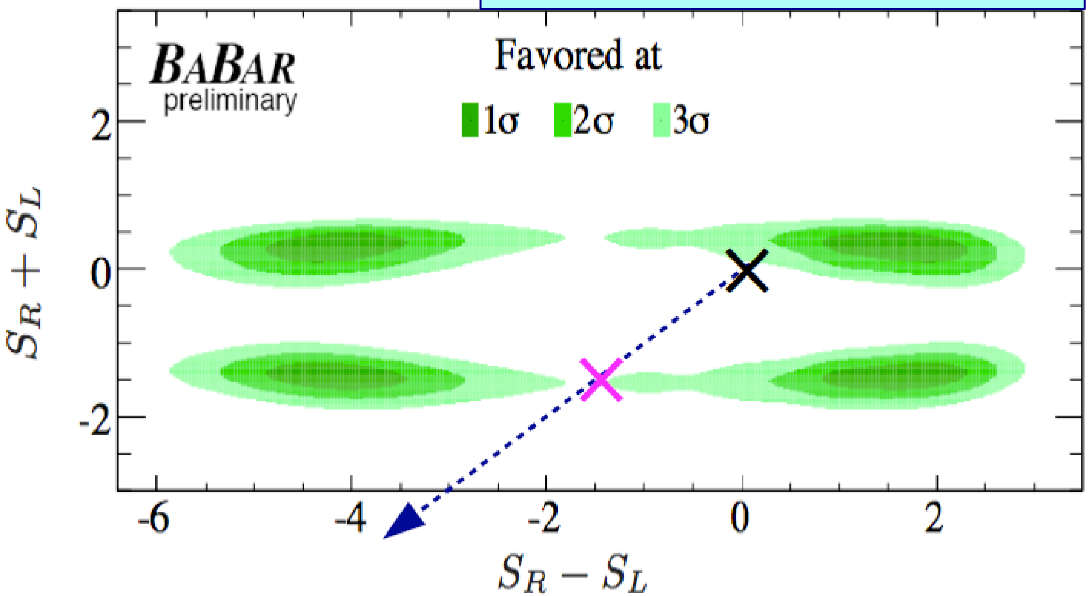
Impact on R(D$^{(*)}$):
$$\mathcal{R}(D) = \mathcal{R}(D)_{\rm SM} + A'_D {\rm Re}(S_R + S_L) + B'_D |S_R + S_L|^2$$
$$\mathcal{R}(D^*) = \mathcal{R}(D^*)_{\rm SM} + A'_{D^*} {\rm Re}(S_R - S_L) + B'_{D^*} |S_R - S_L|^2$$

Corresponds to Type-II 2HDM case for S_L=0

Crivellin, Greub, & Kokulu, arXiv:1206.2634 (2012); Datta et al, PRD 86, 034027 (2012)

BABAR, arXiv:1303.0571 (2013)

Type III
- 4 solutions for real S_R,S_L values.
- Complex values alo allowed
- Type II has no solutions



- - Type-II: $S_R + S_L = S_R - S_L$

× SM value

× Measured value for R(D) in Type-II: $S_R \pm S_L$ = -1.51