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representing the BABAR collaboration

Discrete Symmetry Workshop, Kings College, London, Dec. 2-6, 2014

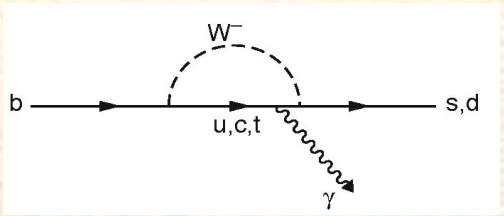
Outline

- Introduction
- *CP* violation in $B \to X_s \gamma$ Decays
- Study of $B \to X_s \ell^+ \ell^-$ Decays
- Search for $B \to \pi/\eta \, \ell^+ \ell^-$
- Search for Lepton Flavor Violation in $B^+ \to X^- \ell^+ \ell'^+$ Modes
- Study of $B^0 \to \omega\omega$ & $B^0 \to \omega\phi$
- Conclusion and outlook

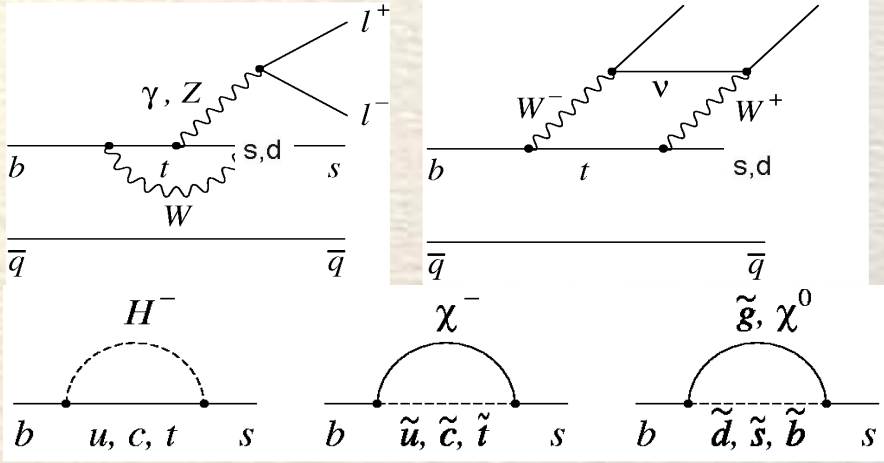
Introduction

- $B \to X\gamma$ & $B \to X\ell^+\ell^-$ are flavor-changing neutral current (FCNC) decays, in the SM forbidden at tree level

C_7^{eff} (EM penguin)



C_9^{eff} & C_{10}^{eff} (V & A parts of weak penguin and box)



- They proceed via penguin loops and box diagrams ➔4 effective Wilson coefficients: C_7^{eff}, C_8^{eff}, C_9^{eff}, C_{10}^{eff}
- New physics adds new loops with new particles ➔ modifies SM values of C_i^{eff} & may introduce new terms, *e.g.* C_S & C_P ➔ probes new physics at a scale~few TeV
- Lepton Flavor violating modes $B^+ \to X^- \ell^+\ell^+$ probe the SM (highly suppressed)
- Charmless $B \to VV$ modes are important for the determination of *CP* violation ➔ measure unitary triangle angle α; measure amplitudes A_0, A_T, $A_{||}$

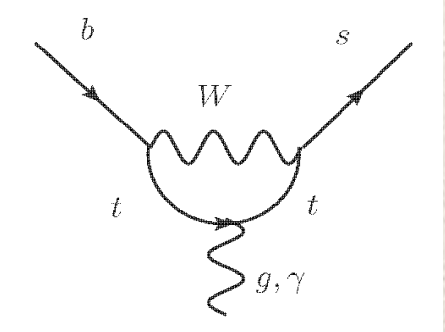
CP Violation in $B \to X_s \gamma$

$B \to X_s\gamma$ Analysis Strategies

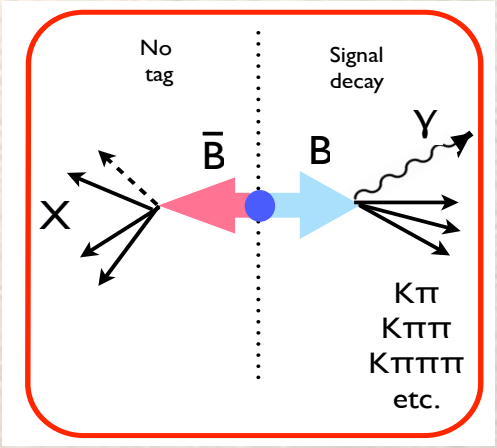
- In the SM, $\mathcal{B}(B \to X_s\gamma)$ is calculated at NNLO (4 loops)

$$\mathcal{B}(B \to X_s\gamma) = \left(3.15 \pm 0.23\right) \times 10^{-4} \quad (E_\gamma > 1.6\ GeV)$$

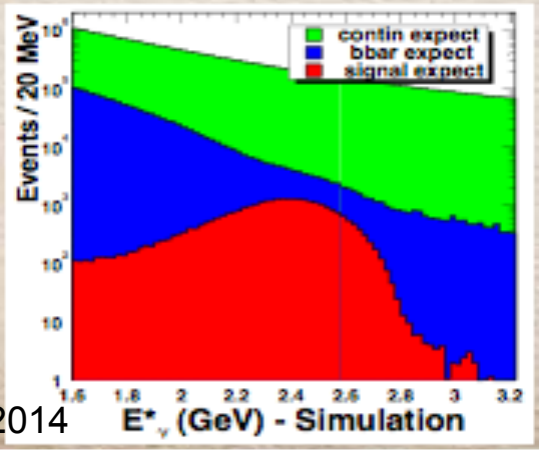
Misiak *et al.*, PRL98, 022002 (2007)

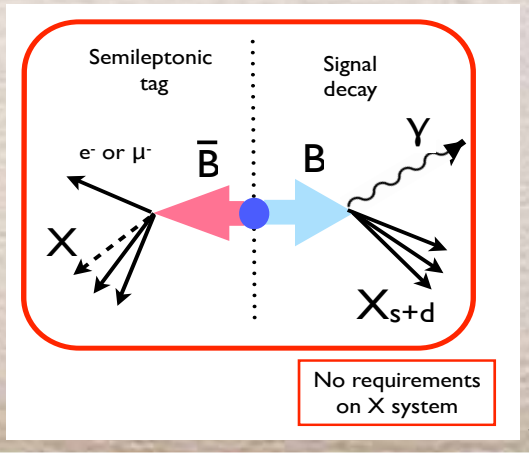


- I. experimental strategy: sum of exclusive modes
  - Use full BABAR sample of 471x10^6 BB events
  - Reconstruct 38 exclusive B $\to X_s\gamma$ modes, with 1(3)K ($\leq$1K^0_s), $\leq$4π ($\leq$2π^0), $\leq$1η
  - Use no tag for $\overline{B}$, select E_γ> 1.9 GeV
  - Need to model missing modes



- II. experimental strategy: fully inclusive decay
  - Use BABAR sample of 383x10^6 $B\overline{B}$ events
  - Veto π^0 and η decays
  - Use semileptonic tag for $\overline{B}$
  - Select E_γ> 1.8 GeV
  - No requirement on X_{s+d}





Direct *CP* Violation in $B \to X_s\gamma$

- For the sum of exclusive decays, the *CP* asymmetry is defined by

$$\mathcal{A}_{CP}(X_s\gamma) \equiv \frac{\Gamma(\bar{B} \to \bar{X}_s\gamma) - \Gamma(B \to X_s\gamma)}{\Gamma(\bar{B} \to \bar{X}_s\gamma) + \Gamma(B \to X_s\gamma)}$$

- The SM predictions yield $-0.6\% < \mathcal{A}_{CP}(X_s\gamma) < 2.8\%$
- With 16 exclusive modes using 471×10^6 $B\bar{B}$ events measure

$$\mathcal{A}_{CP}(X_s\gamma) = \left(1.7 \pm 1.9_{\,stat} \pm 1.0_{\,sys}\right)\%$$

➔ most precise A_{CP} result
PRD 90, 9, 092001

- The difference for charged and neutral B decays is

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

- $\Delta\mathcal{A}_{CP}(B \to X_s\gamma)$ depends on $C_{7\gamma}$ and C_{8g}:

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

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

Benzke *et al.*, PRL106, 141801 (2011)

- In the SM, C_7^{eff} and C_8^{eff} are real ➔ $\Delta\mathcal{A}_{CP}(X_s\gamma)=0$
  - This may be modified by new physics contributions

Implications on $\mathrm{Im}(C_{8g}/C_{7\gamma})$

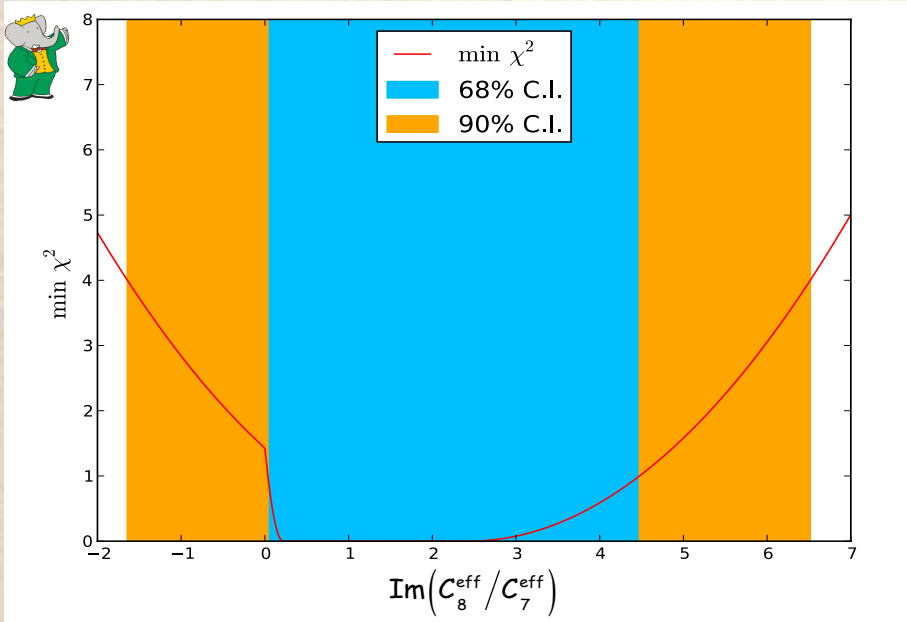
- From the simultaneous fits to charged and neutral B samples measure

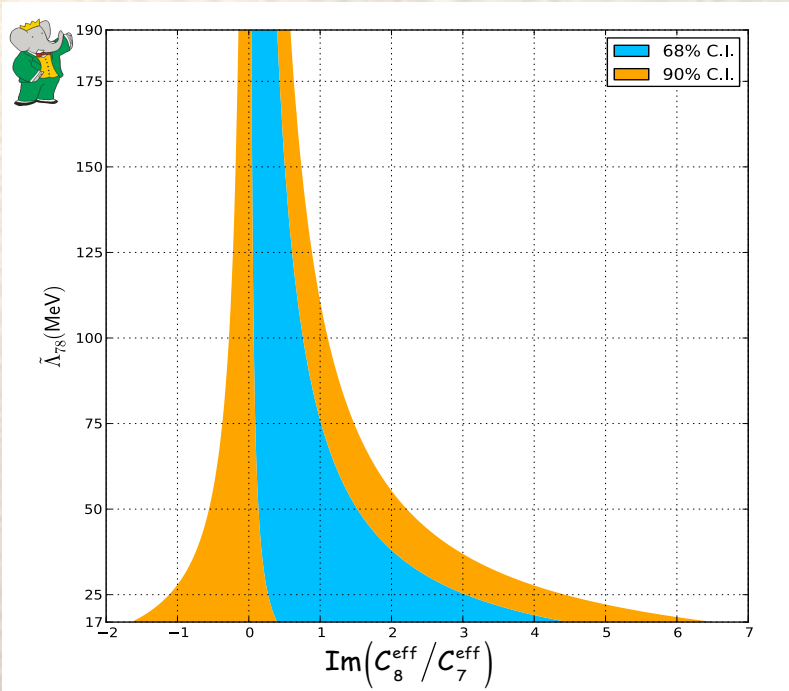
$$\Delta\mathcal{A}_{CP}(X_s\gamma) = \left(5.0 \pm 3.9_{\,stat} \pm 1.5_{\,sys}\right)\%$$

- Set 90% CL constraints on $\mathcal{I}m\,(C_8^{eff}/C_7^{eff})$

$$-1.64 < \mathrm{Im}\left(C_8^{eff}/C_7^{eff}\right) < 6.52 \;@90\%\;CL$$

PRD 90, 9, 092001





- This is the first $\Delta\mathcal{A}_{CP}(X_s\gamma)$ measurement and the first constraint on the ratio of Wilson coefficients C_8^{eff}/C_7^{eff} for new physics in this process

$B \to X_s\gamma$ CP Asymmetries

- In the fully inclusive analysis, $\mathcal{A}_{CP}$ has $b \to s\gamma$ & $b \to d\gamma$ contributions

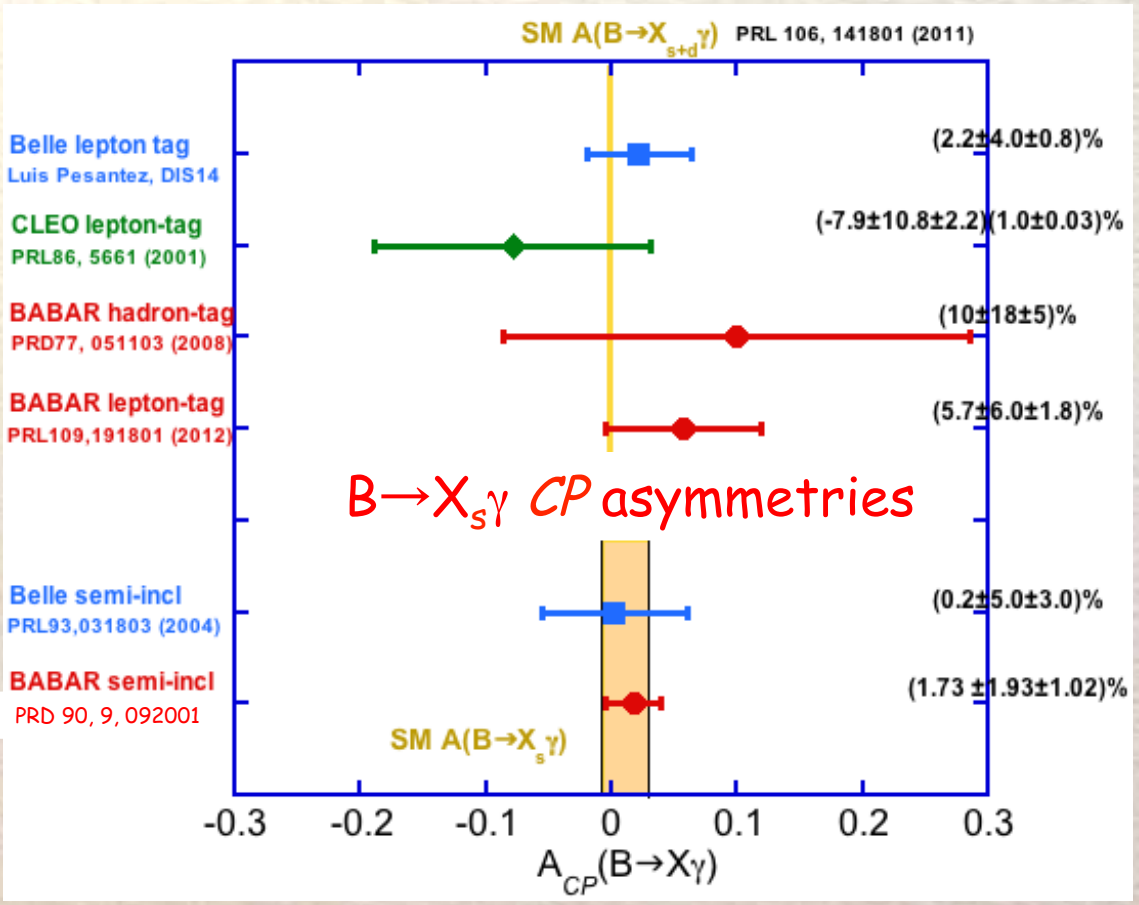
$$\mathcal{A}_{CP}(X_{s+d}\gamma) \equiv \frac{\mathcal{B}(\bar{B} \to X_{s+d}\gamma) - \mathcal{B}(B \to X_{s+d}\gamma)}{\mathcal{B}(\bar{B} \to X_{s+d}\gamma) + \mathcal{B}(B \to X_{s+d}\gamma)}$$

- In the SM, $\mathcal{A}_{CP}(B \to X_{s+d}) = 0$
- Determine $B/\bar{B}$ from the tag charge
- After correcting for charge bias and mistagging yield (383×10^6 $B\bar{B}$ events)

$$\mathcal{A}_{CP}(X_{s+d}\gamma) = 0.057 \pm 0.060_{stat} \pm 0.018_{sys}$$

PRL109, 191801 (2012)

$B \to X_{s+d}\gamma$ CP asymmetries

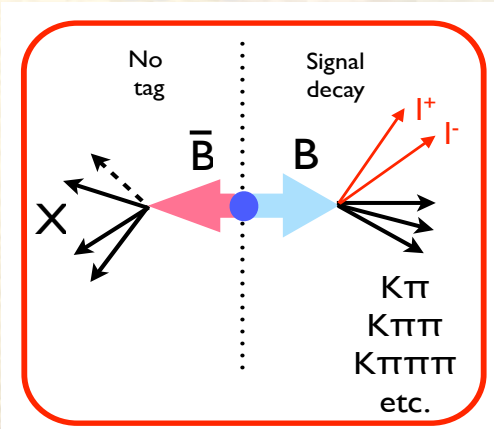


Study of $B \to X_s \ell^+ \ell^-$ Decays

Analysis Strategy for $B \to X_s \ell^+ \ell^-$ Modes

- Reconstruct 20 exclusive final states with K ($K^0_S \to \pi^+\pi^-$), $\leq 2\pi^\pm$ & $\leq 1\pi^0(\to\gamma\gamma)$ for branching fraction and 14 self-tagging modes (red) for CP asymmetry measurements

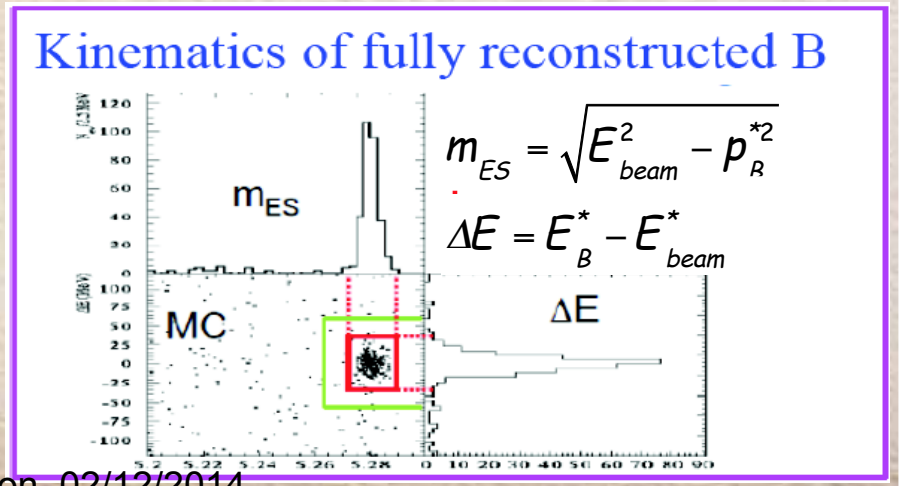
- The 20 exclusive modes represents 70% of the inclusive rate with $m_{Xs} < 1.8$ GeV accounting for K^0_L modes, $K^0_S \to \pi^0\pi^0$ and π^0 Dalitz decays



- Extrapolate for the missing modes and those with $m_{Xs} > 1.8$ GeV using JETSET fragmentation and theory predictions

- Kinematic constraints
  - $m_{ES} > 5.225$ GeV
  - $-0.1 < \Delta E < 0.05$ for X_s ee
  - $-0.05 < \Delta E < 0.05$ for X_s μμ

- Use no tag for $\bar{B}$

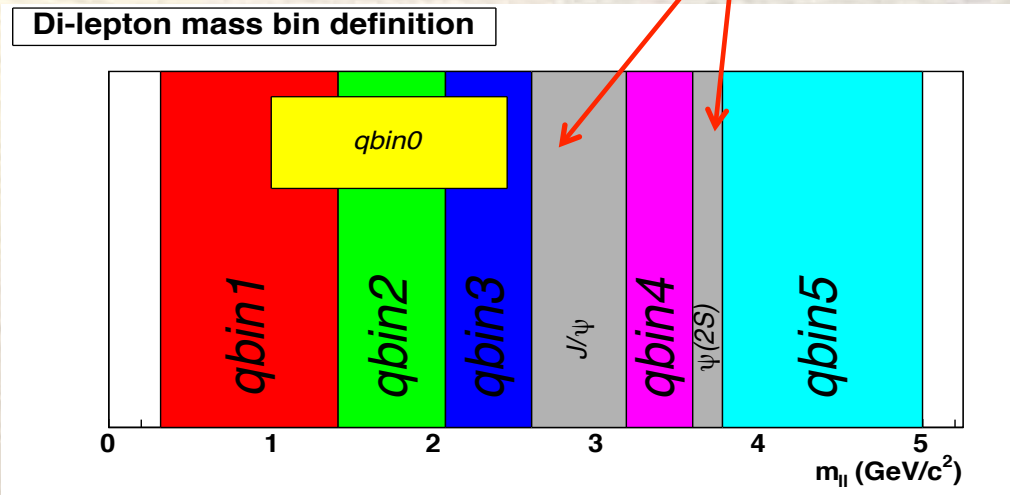


$B^0 \to K^0_S \mu^+\mu^-$
$B^+ \to K^+ \mu^+\mu^-$
$B^0 \to K^0_S e^+e^-$
$B^+ \to K^+ e^+e^-$
$B^0 \to K^{*0}(K^0_S\pi^0)\mu^+\mu^-$
$B^+ \to K^{*+}(K^+\pi^0)\mu^+\mu^-$
$B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$
$B^+ \to K^{*+}(K^0_S\pi^+)\mu^+\mu^-$
$B^0 \to K^{*0}(K^0_S\pi^0)e^+e^-$
$B^+ \to K^{*+}(K^+\pi^0)e^+e^-$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

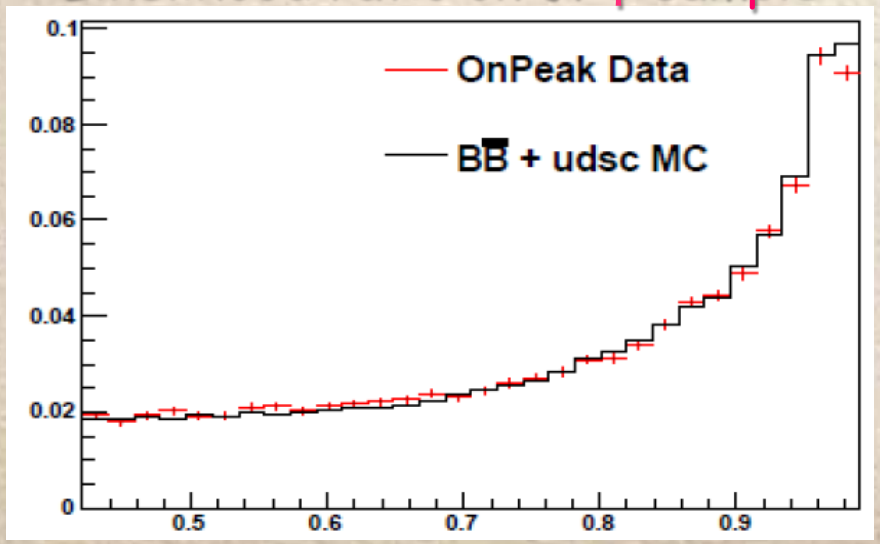
Analysis Strategy for $B \to X_s \ell^+ \ell^-$

- Use likelihood ratio defined from BDT outputs to separate signal from backgrounds
- Veto J/ψ and ψ(2S) mass regions and use them as control samples
- Measure $d\mathcal{B}(B \to X_s \ell^+ \ell^-)/dq^2$ in 6 $q^2 = m_{ll}^2$ bins and 4 m_{Xs} bins
- Measure $A_{CP}(B \to X_s \ell^+ \ell^-)$ in 5 q^2 bins
- 471×10^6 $B\bar{B}$ events

Charmonium veto regions



Likelihood ratio on J/ψ sample



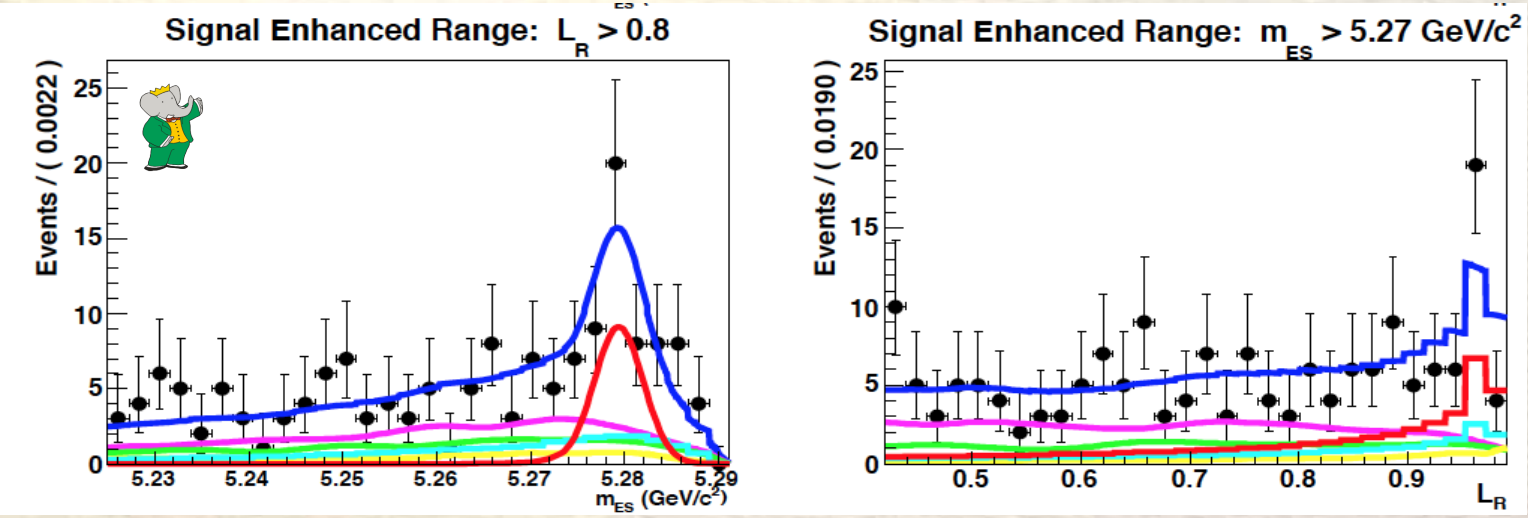
q^2 bin	$m_{\ell\ell}^2$ (GeV$^2/c^4$)	$m_{\ell\ell}$ (GeV/c^2)
0	1.0 – 6.0	1.00 – 2.45
1	0.1 – 2.0	0.32 – 1.41
2	2.0 – 4.3	1.41 – 2.07
3	4.3 – 8.1	2.07 – 2.60
4	10.1 – 12.9	3.18 – 3.59
5	14.2 – $(M_B - M_K^*)^2$	3.77 – $(M_B - M_K^*)$

$B \to X_s \ell^+ \ell^-$ m_{ES} and L_R Distributions

- Extract signal from a 2D maximum likelihood fit to m_{ES} and L_R

q_5 bin for $X_s ee$

q_1 bin for $X_s \mu\mu$



Total PDF
Signal
Signal Crossfeed
$B\bar{B}$ Bkgd.
udsc Bkgd.
Charmonium Bkgd.

$B \to X_s \ell^+ \ell^-$ Branching Fractions

- For $1 < q^2 < 6$ GeV^2 BABAR measures

$$\mathcal{B}(B \to X_s \mu^+ \mu^-) = (0.66^{+0.82+0.30}_{-0.76-0.24} \pm 0.07) \times 10^{-6}$$
$$\mathcal{B}(B \to X_s e^+ e^-) = (1.93^{+0.47+0.21}_{-0.45-0.16} \pm 0.18) \times 10^{-6}$$
$$\mathcal{B}(B \to X_s \ell^+ \ell^-) = (1.60^{+0.41+0.17}_{-0.39-0.13} \pm 0.18) \times 10^{-6}$$

Phys.Rev.Lett. 112, 211802 (2014)

- Agrees well with the SM prediction

$$\mathcal{B}(B \to X_s \mu^+ \mu^-) = (1.59 \pm 0.11) \times 10^{-6}$$
$$\mathcal{B}(B \to X_s e^+ e^-) = (1.64 \pm 0.11) \times 10^{-6}$$

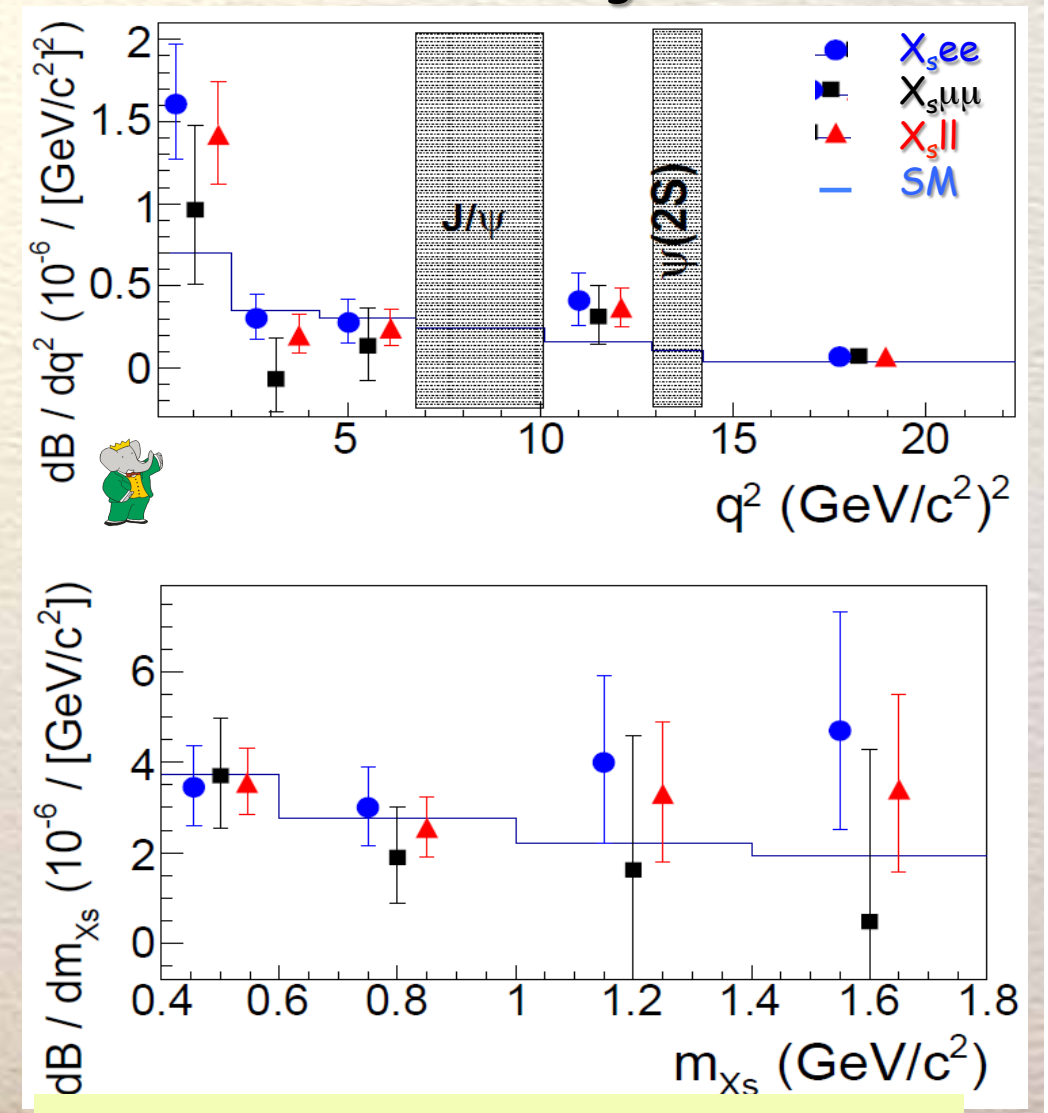
- For $q^2 > 14.2$ GeV^2 BABAR measures

$$\mathcal{B}(B \to X_s \mu^+ \mu^-) = (0.60^{+0.31+0.05}_{-0.29-0.04} \pm 0.00) \times 10^{-6}$$
$$\mathcal{B}(B \to X_s e^+ e^-) = (0.56^{+0.19+0.03}_{-0.18-0.03} \pm 0.00) \times 10^{-6}$$
$$\mathcal{B}(B \to X_s \ell^+ \ell^-) = (0.57^{+0.16+0.03}_{-0.15-0.02} \pm 0.00) \times 10^{-6}$$

- Consistent with SM prediction at ~1σ

$$\mathcal{B}(B \to X_s \mu^+ \mu^-) = (0.25^{+0.07}_{-0.06}) \times 10^{-6}$$

Partial branching fraction



Errors: statistical + systematic + model

$B \to X_s \ell^+ \ell^-$ Direct *CP* Violation

- Over the full q^2 range BABAR measures a direct *CP* asymmetry of

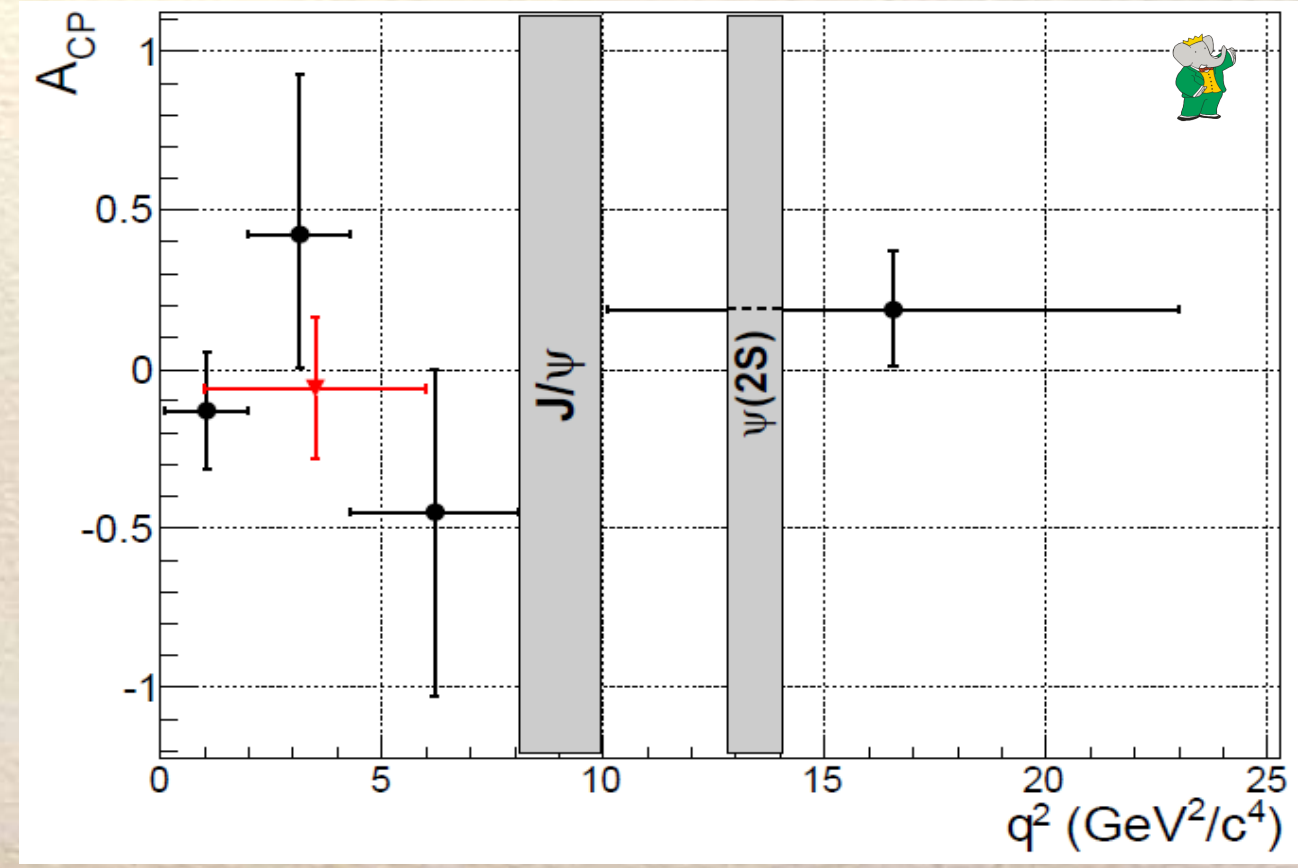
$$\mathcal{A}_{CP}(B \to X_s \ell^+ \ell^-) = 0.04 \pm 0.11 \pm 0.01$$

Phys.Rev.Lett. 112, 211802 (2014)

$$\mathcal{A}_{CP} = \frac{\mathcal{B}(\bar{B} \to \bar{X}_s \ell^+ \ell^-) - \mathcal{B}(B \to X_s \ell^+ \ell^-)}{\mathcal{B}(\bar{B} \to \bar{X}_s \ell^+ \ell^-) + \mathcal{B}(B \to X_s \ell^+ \ell^-)}$$

- This is consistent with zero as expected in the SM

- The direct CP asymmetry measured in 5 bins of q^2 (q_0, q_1, q_2, q_3, q_4+q_5) is also consistent with zero

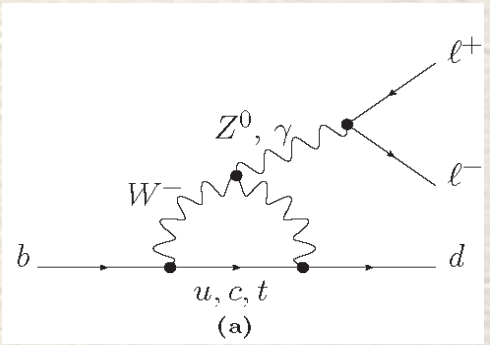


Search for

$B \to \pi/\eta \ell^+ \ell^-$

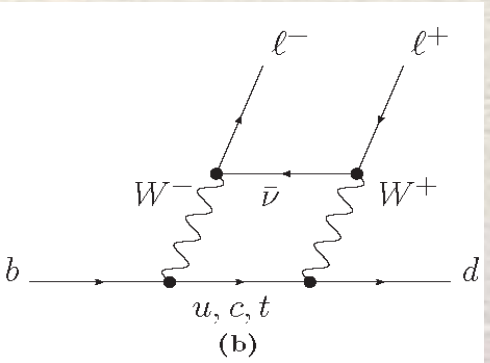
Search for $B \to \pi/\eta\, \ell^+\ell^-$ Decays

- In the SM, $B \to X_d\, \ell^+\ell^-$ modes are also mediated in in lowest order by the photon penguin, Z-penguin and WW box diagrams



- Decays are suppressed by $|V_{td}/V_{ts}|^2 \sim 0.04$ wrt related $b \to s\, \ell^+\ell^-$ modes

- In extensions of the SM, rates may increase significantly

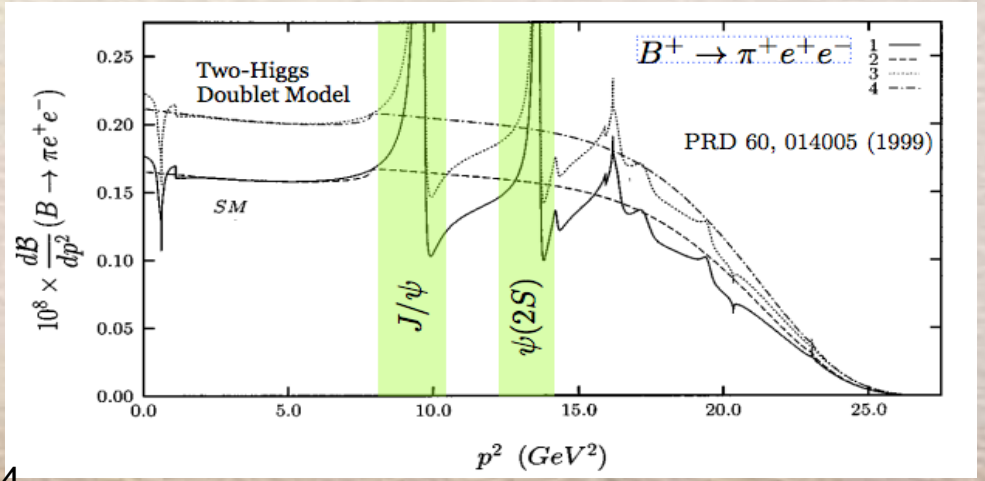


- BABAR has updated the search for $B \to \pi\, \ell^+\ell^-$ modes and performed the first search for $B \to \eta\, \ell^+\ell^-$ modes using 471×10^6 $B\bar{B}$ events

- SM predictions:

$$\mathcal{B}\left(B^{\pm} \to \pi^{\pm}\ell^+\ell^-\right) = \left(1.96 - 3.30\right) \times 10^{-8}$$

$$\mathcal{B}\left(B^{0} \to \eta\ell^+\ell^-\right) = \left(2.5 - 3.7\right) \times 10^{-8}$$



$B \to \pi/\eta\, \ell^+\ell^-$: Branching Fraction Upper Limits

- Perform simultaneous unbinned maximum likelihood fit to the m_{ES} & ΔE distributions of $B \to \pi^\pm \ell^+\ell^-$ & $B \to \pi^0 \ell^+\ell^-$, ($B \to \eta \ell^+\ell^-$) separately for e^+e^- & $\mu^+\mu^-$ modes
- Veto J/ψ and ψ(2S) regions
- See no signal in any mode ➔ set 90% CL $\mathcal{B}$ upper limits
- LHCb observed $B^\pm \to \pi^\pm \mu^+\mu^-$

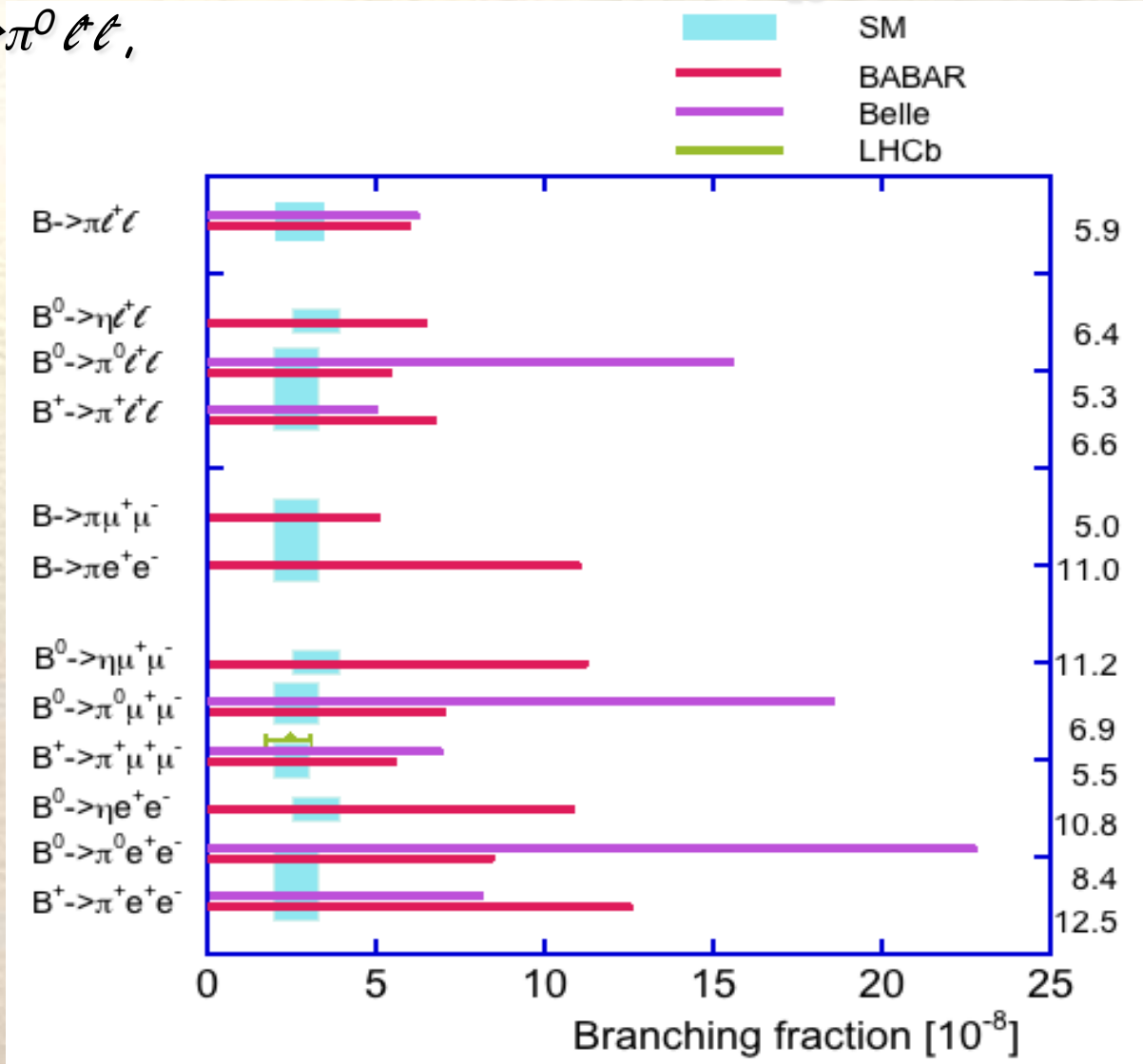
$$\mathcal{B}\left(B^+ \to \pi^+\mu^+\mu^-\right) = \left(2.4 \pm 0.6 \pm 0.1\right) \times 10^{-8}$$

LHCb, JHEP 12, 125 (2012)

- Best limit for $B^0 \to \pi^0 \ell^+\ell^-$

$$\mathcal{B}\left(B^+ \to \pi^0 \ell^+\ell^-\right) < 5.3 \times 10^{-8} \ \ (90\%CL)$$

- First results for $B \to \eta \ell^+\ell^-$
- Limits are within factor ~2-3 of the SM predictions

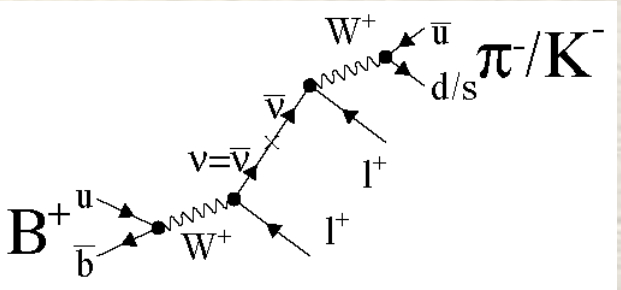


Lees, PRD 88, 032012 (2013)
Belle, PRD 78, 011101 (2008)

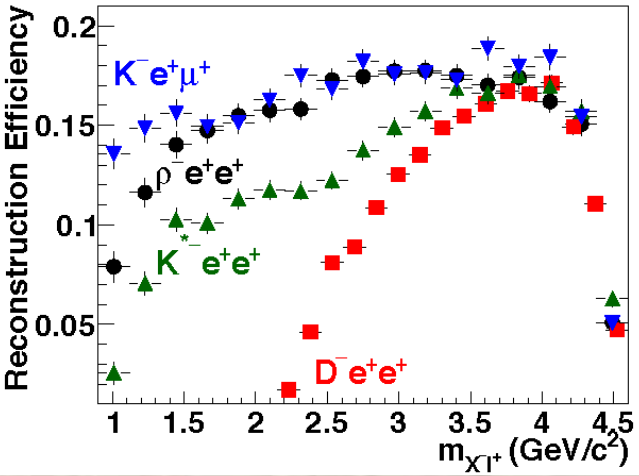
Search for Lepton Flavor/Number Violation in $B^+ \to X^- \ell^+ \ell'^+$ Modes

$B^+ \to X^- \ell^+ \ell'^+$: Motivation

- Lepton flavor/number violation (LFV) is highly suppressed in the SM
- However, LFV is expected at high energy or high density
- The observation of neutrino oscillations implies that ν's have mass ➔ for Majorana ν' s, we expect LFV



- We search for LFV in 11 B decay modes:
  - $B^+ \to \rho^-(\pi^+\pi^-)\ell^+\ell'^+$
  - $B^+ \to K^{*-}(K^0_S\,\pi^-$ and $K^-\,\pi^0)\ell^+\ell'^+$
  - $B^+ \to D^-(K^-\pi^+\pi^-)\ell^+\ell'^+$
  - $B^+ \to \pi^- e^+\mu^+$
  - $B^+ \to K^- e^+\mu^+$



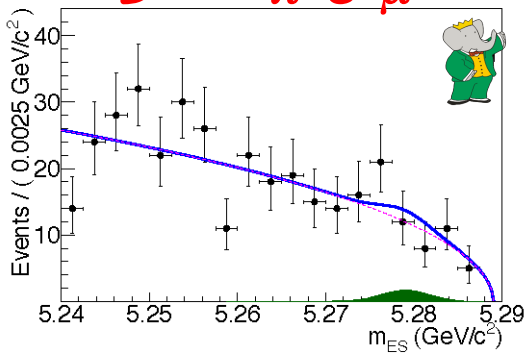
- We use the full BABAR data set: 471×10^6 $B\bar{B}$ events
- We construct BDTs based on event shape parameters to discriminate signal from $B\bar{B}$ and $q\bar{q}$ continuum backgrounds (q=u,d,s,c)

$B^+ \to X^- \ell^+ \ell'^+$: ML Fit Projections

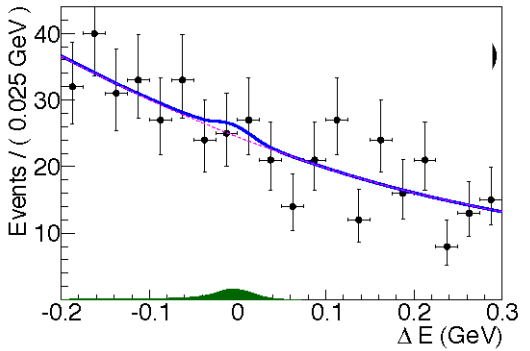
- Perform maximum likelihood fit to 3 (4) observables: m_{ES}, ΔE, BDT, ($m_{K^*}/m_\rho/m_D$)

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

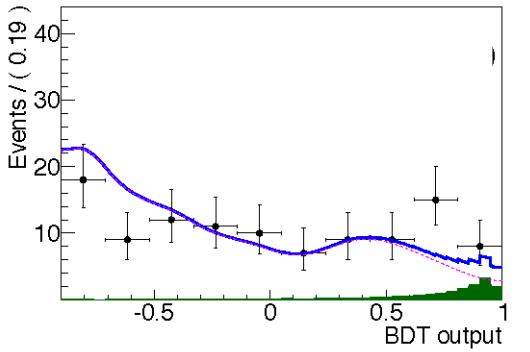
m_{ES}



ΔE

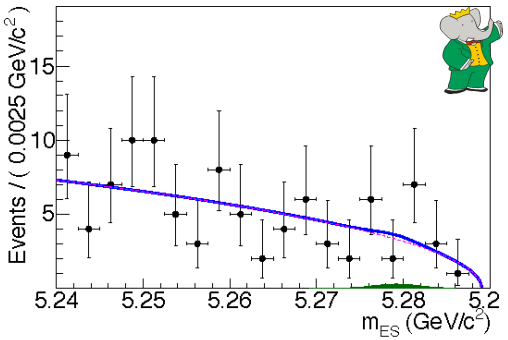


BDT

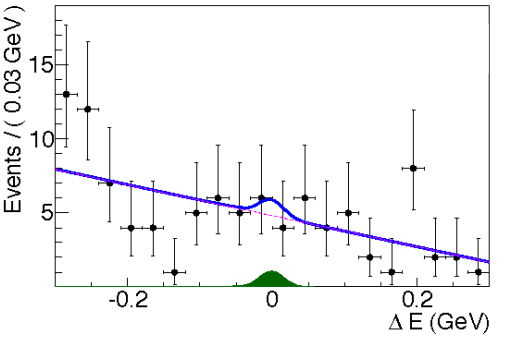


$B^+ \to K^{*-}(\to K^0_S \pi^-)\mu^+\mu^+$

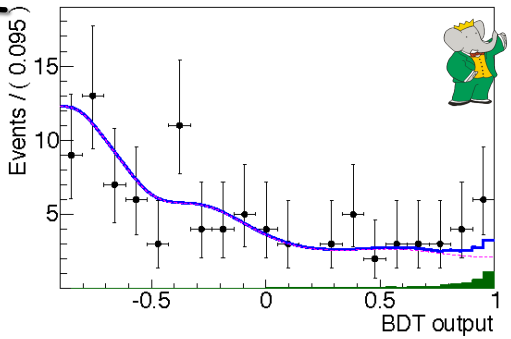
m_{ES}



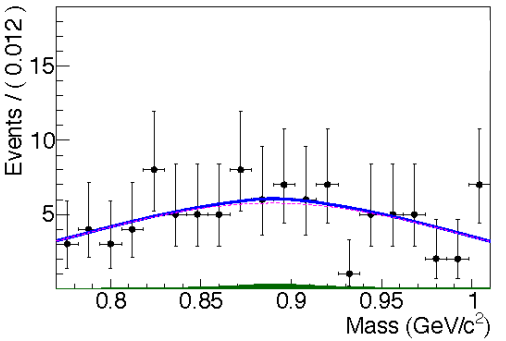
ΔE



BDT



m_{K^*}



- In all 11 modes, data is consistent with combinatorial background

PRD-89, 1, 011102 (2014)

$B^+ \to X^- \ell^+ \ell'^+$: Results

- Observe no significant signal ➔ set $\mathcal{B}$ upper limits @90% CL using Bayesian approach

- Signific. $S = \sqrt{2\Delta \ln \mathcal{L}}$

- Largest yield in $B^+ \to K^- e^+ \mu^+$

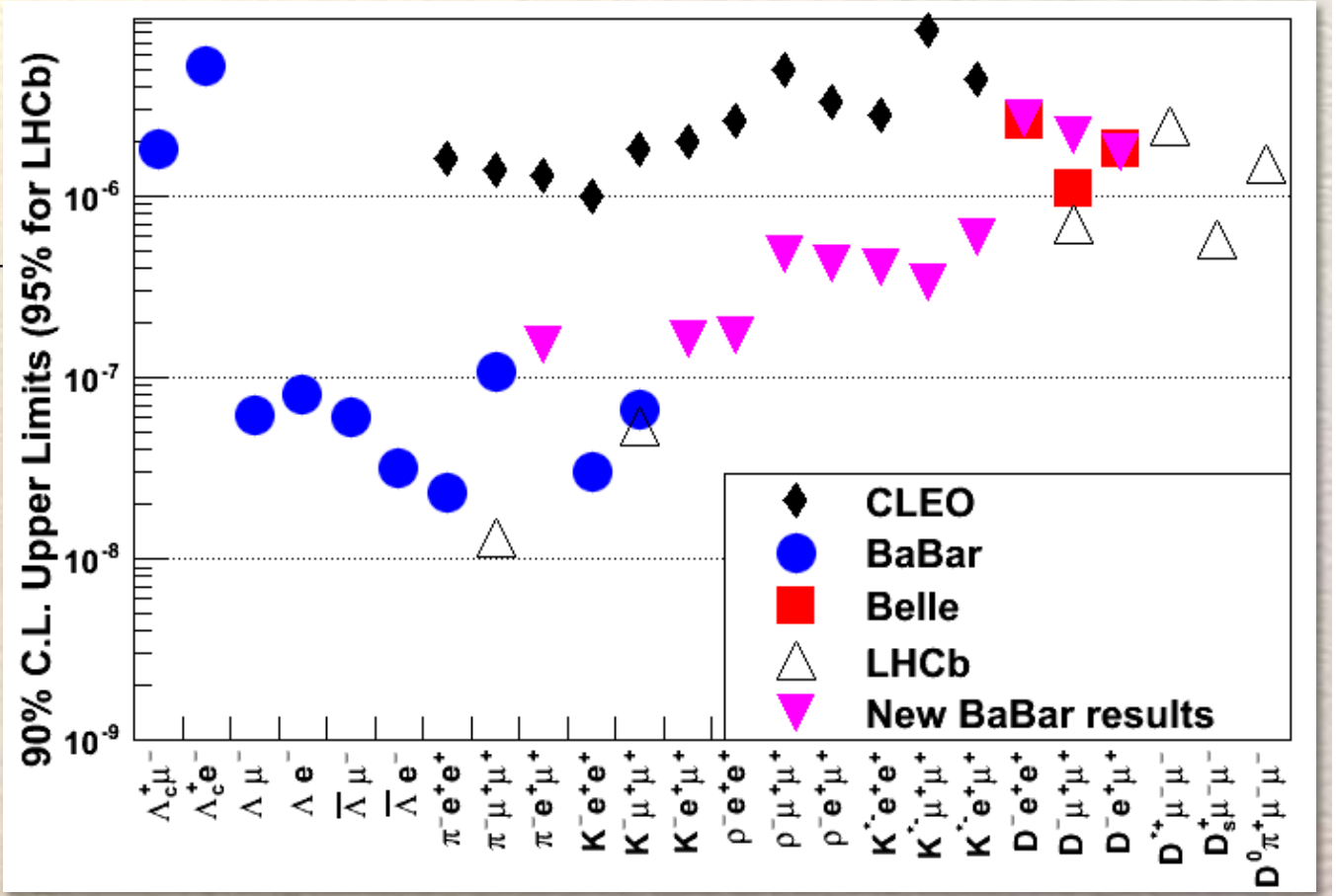
- Lowest BF upper limit in $B^+ \to \pi^- e^+ \mu^+$

Mode	Events	Yield	$\eta(\%)$	$\Pi\mathcal{B}_i(\%)$	S(σ)	$\mathcal{B}$ ($\times 10^{-7}$)	$\mathcal{B}_{UL}$ ($\times 10^{-7}$)
$B^+ \to K^{*-}\, e^+\, e^+$					1.2	$1.7 \pm 1.4 \pm 0.1$	4.0
$K^{*-} \to K^- \pi^0$	63	3.8 ± 3.3	11.5 ± 0.1	33.3	1.2	$2.1 \pm 1.8 \pm 0.2$	5.1
$K^{*-} \to K^0_S \pi^-$	91	0.8 ± 3.9	12.3 ± 0.1	22.8	0.3	$0.6 \pm 2.9 \pm 0.2$	6.0
$B^+ \to K^{*-}\, e^+\, \mu^+$					0.0	$-4.5 \pm 2.6 \pm 0.4$	3.0
$K^{*-} \to K^- \pi^0$	117	-1.9 ± 4.7	7.9 ± 0.1	33.3	0.0	$-1.5 \pm 3.8 \pm 0.4$	6.5
$K^{*-} \to K^0_S \pi^-$	172	-5.1 ± 2.6	8.5 ± 0.1	22.8	0.0	$-6.0 \pm 2.8 \pm 0.7$	4.2
$B^+ \to K^{*-}\, \mu^+\, \mu^+$					1.3	$2.4 \pm 1.8 \pm 0.4$	5.9
$K^{*-} \to K^- \pi^0$	85	2.3 ± 1.8	6.1 ± 0.1	33.3	1.3	$2.0 \pm 1.8 \pm 0.2$	7.0
$K^{*-} \to K^0_S \pi^-$	98	2.0 ± 1.8	5.8 ± 0.1	22.8	1.0	$3.1 \pm 2.9 \pm 0.9$	9.8
$B^+ \to \rho^-\, e^+ e^+$	411	-2.1 ± 5.7	12.1 ± 0.1	100.0	0.0	$-0.4 \pm 1.0 \pm 0.1$	1.7
$B^+ \to \rho^-\, e^+ \mu^+$	1651	4.6 ± 11.4	10.3 ± 0.1	100.0	0.4	$1.0 \pm 2.4 \pm 0.2$	4.7
$B^+ \to \rho^-\, \mu^+ \mu^+$	936	2.9 ± 6.8	7.3 ± 0.1	100.0	0.5	$0.9 \pm 2.0 \pm 0.3$	4.2
$B^+ \to D^-\, e^+ e^+$	401	3.9 ± 4.8	10.2 ± 0.1	9.13	1.0	$8.8 \pm 8.6 \pm 1.5$	26
$B^+ \to D^-\, e^+ \mu^+$	549	1.1 ± 3.2	7.7 ± 0.1	9.13	0.5	$3.4 \pm 9.4 \pm 1.1$	21
$B^+ \to D^-\, \mu^+ \mu^+$	229	-1.7 ± 2.5	5.7 ± 0.1	9.13	0.0	$-6.5 \pm 9.9 \pm 0.9$	17
$B^+ \to K^-\, e^+ \mu^+$	117	5.5 ± 3.5	15.2 ± 0.1	100.0	1.8	$0.6 \pm 0.5 \pm 0.1$	1.6
$B^+ \to \pi^-\, e^+ \mu^+$	464	3.8 ± 3.5	16.4 ± 0.2	100.0	1.2	$0.5 \pm 0.5 \pm 0.1$	1.5

PRD-89, 1, 011102 (2014)

$B^+ \to X^- \ell^+ \ell'^+$: Comparison of LFV Results

- BABAR has improved CLEO $\mathcal{B}$ upper limits at 90% CL by an order of magnitude
- Except for $D^-\mu^+\mu^+$, BABAR has set the lowest limits ($\mathcal{B} < 1.5 - 26\times10^{-7}$) in this study
- The BABAR limits set in a previous study are also the lowest except for LHCb results in $K^-/\pi^-\mu^+\mu^-$
- Note that LHCb $\mathcal{B}$ upper limits are @ 95% CL

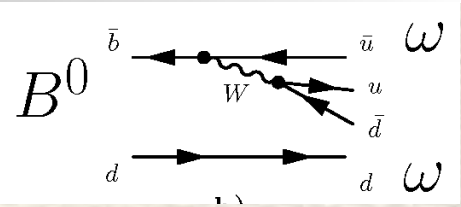


CLEO Coll., PRD65, 111102 (2002)
Belle Coll., PRD84, 071106 (2011)
BaBar Coll., PRD85, 071103 (2012)
LHCb Coll., PRL108, 101601 (2012)
LHCb Coll., PRD85, 112004 (2012)

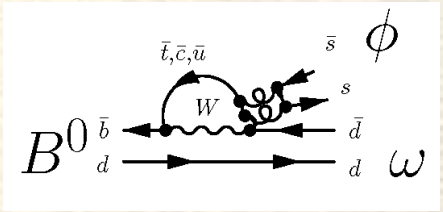
Study of $B^0 \to \omega\omega$ & $B^0 \to \omega\phi$

$B^0 \to \omega\omega/\omega\phi$: Motivation

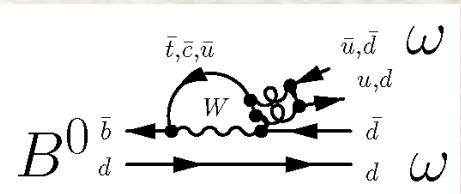
- $B^0 \to \omega\omega$ has large gluonic penguin contributions in addition to tree diagram while $B^0 \to \omega\phi$ is a pure gluonic penguin decay



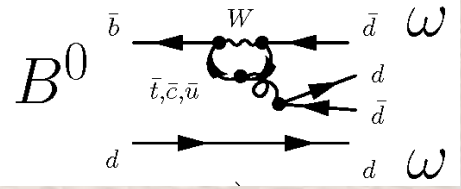
- Both VV modes have not been seen yet
  $\mathcal{B}(B^0 \to \omega\omega) < 0.4\times10^{-6}$ @90%CL
  $\mathcal{B}(B^0 \to \omega\phi) < 1.2\times10^{-6}$ @90%CL



PRD-RC **74**, 051102 (2006)



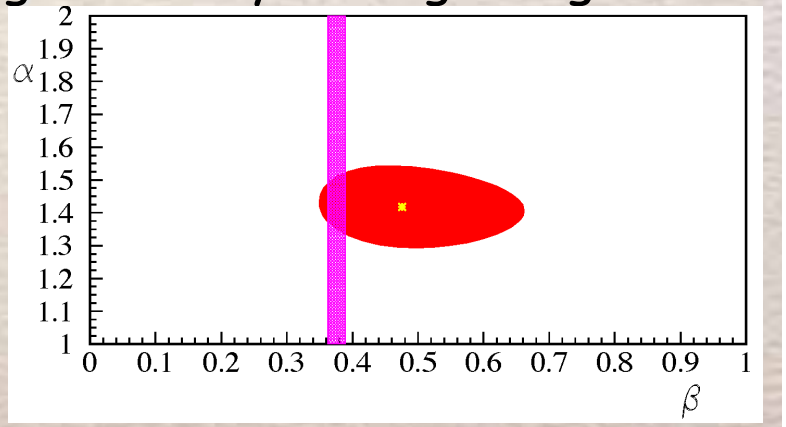
- While in $B^0 \to \rho\rho$ the longitudinal polarization is high ($f_L(\rho^0\rho^0)=0.75^{+0.12}_{-0.15}$), it is low in $B^0 \to K^{*0}\phi$ ($f_L=0.48\pm0.03$) predicted $f_L > 0.8$ for both modes



- Charmless $B \to VV$ modes are useful for measuring Unitarity Triangle angle α

- SM expectations: $\mathcal{B}(B^0 \to \omega\omega) = \mathcal{O}(1\times10^{-6})$
  $\mathcal{B}(B^0 \to \omega\phi) = \mathcal{O}(1\times10^{-7})$

- Use 471×10^6 BB decays and do full B reconstruction with $\omega \to \pi^+\pi^-\pi^0$ and $\phi \to K^+K^-$

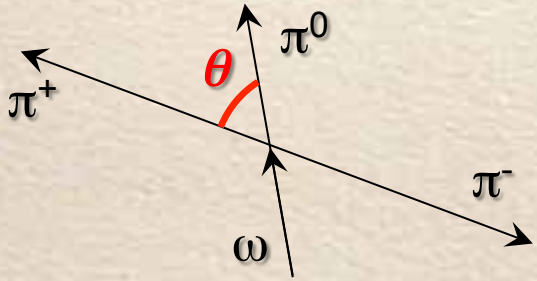


Eigen et al, PRD 89, 033004 (2014)

$B^0 \to \omega\omega/\omega\phi$: Signal Extraction

- We use an unbinned extended ML fit in 8 $\omega\phi$ and 9 $\omega\omega$ variables
  - $m_{ES} = \sqrt{E^2_{beam} - p^{*2}_B}$
  - Energy difference $\Delta E = E^*_B - E_{beam}$
  - 2 resonance masses
  - 2 resonance helicity angles θ_1, θ_2
  - Fisher discriminant
  - Helicity angle θ for ω decay

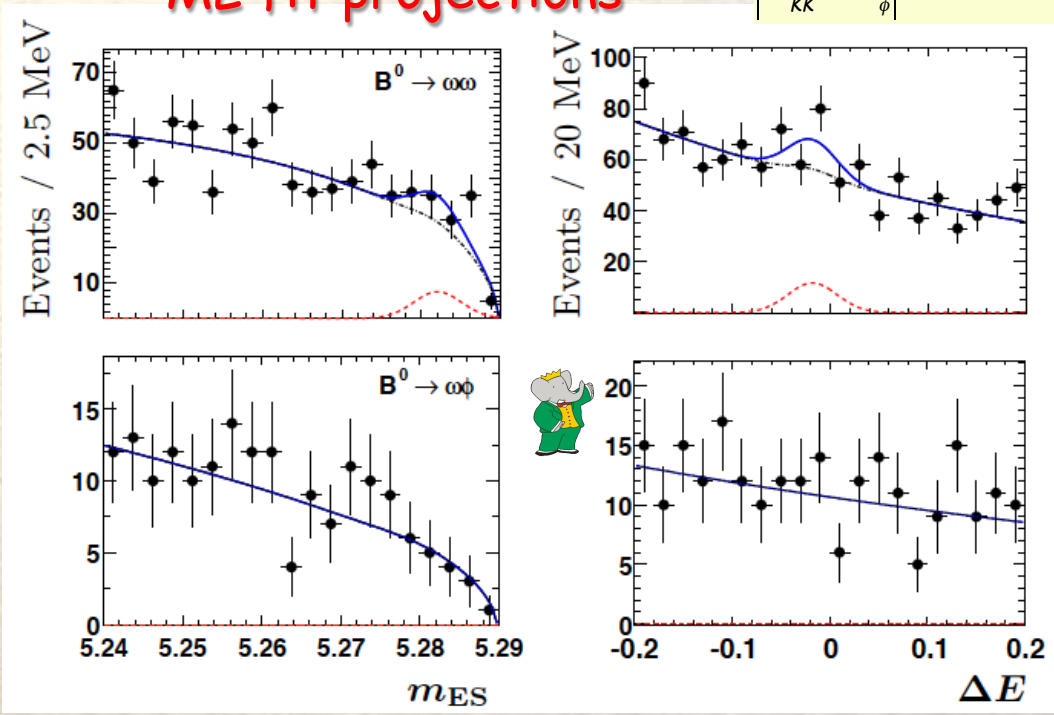
  Di-pion ($\pi^+\pi^-$) rest frame:



$|m_{3\pi} - m_\omega| < 15$ MeV

$|m_{KK} - m_\phi| < 8$ MeV

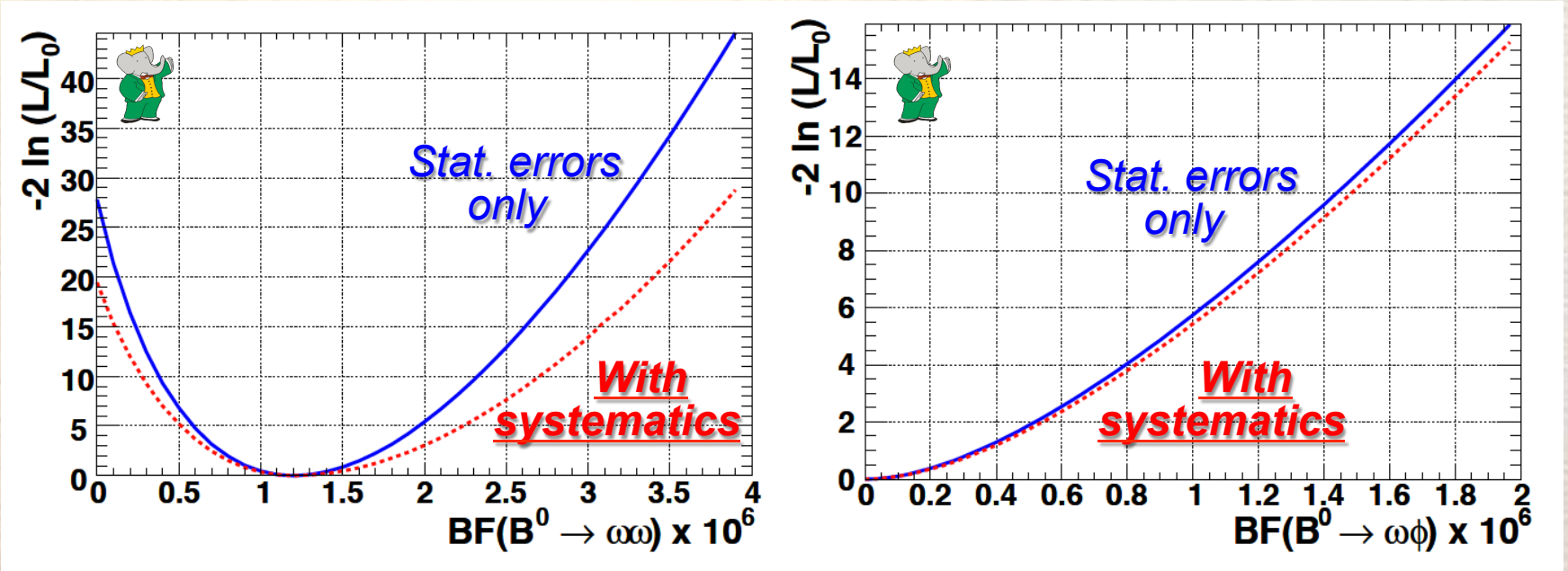
ML fit projections



- Signal PDF: 2 relativistic BWs for masses × angular distribution $f(\theta_1, \theta_2)$
- Combinatorial backgrounds from $e^+e^- \to q\bar{q}$ and $B\bar{B}$ (➔cos θ_T < 0.8 (0.9) for $\omega\omega$ ($\omega\phi$))
  ➔ use Argus function for m_{ES} and 3rd-order polynomial for ΔE
- Peaking background from $B^0 \to \omega\omega\pi^0$, $\omega\phi\pi^0$, $\omega\rho^0\pi^0$, ωa_1, … ➔ include in fit

$B^0 \to \omega\omega/\omega\phi$: Results

- Observe $69^{+16.4}_{-15.2}$ $B^0 \to \omega\omega$ signal events and $-2.8^{+5.7}_{-4.0}$ $B^0 \to \omega\phi$ signal events



- Measure branching fraction: $\mathcal{B}\left(B^0 \to \omega\omega\right) = \left(1.2 \pm 0.3^{+0.3}_{-0.2}\right) \times 10^{-6} \quad \left(4.4\sigma\right)$
- Set branching fraction upper limit: $\mathcal{B}\left(B \to \omega\phi\right) < 0.7 \times 10^{-6}$ @ 90% CL
- Results are consistent with SM predictions PRD 89, 5, 051101 (2014)
- Largest systematic error comes from fit yield bias estimation ($\mathcal{O}(5)$ events ≤10% for $\omega\omega$) and uncertainty on f_L (0.88 is used as nominal central value)

Conclusions and Outlook

- In semi-inclusive $B \to X_s \ell^+ \ell^-$ analysis perform most precise $\mathcal{A}_{CP}$ measurement
  ➔ $\Delta\mathcal{A}_{CP}(B \to X_s \gamma)$ yields first constraint on $\mathrm{Im}(C_{8g}/C_{7\gamma})$
- $\mathcal{B}(B \to X_s \ell^+ \ell^-)$ & $\mathcal{A}_{CP}(B \to X_s \ell^+ \ell^-)$ measurements agree well with the SM predictions
- No hint for $B \to \pi/\eta \, \ell^+ \ell^-$ decays
- No hint for lepton flavor violating $B^+ \to X^- \ell^+ \ell^+$ decays
- Find evidence for $B^0 \to \omega\omega$ decays and set improved limits on $B^0 \to \omega\phi$ decays
- Improved results will come from Belle II and from LHCb for some modes

Backup Slides