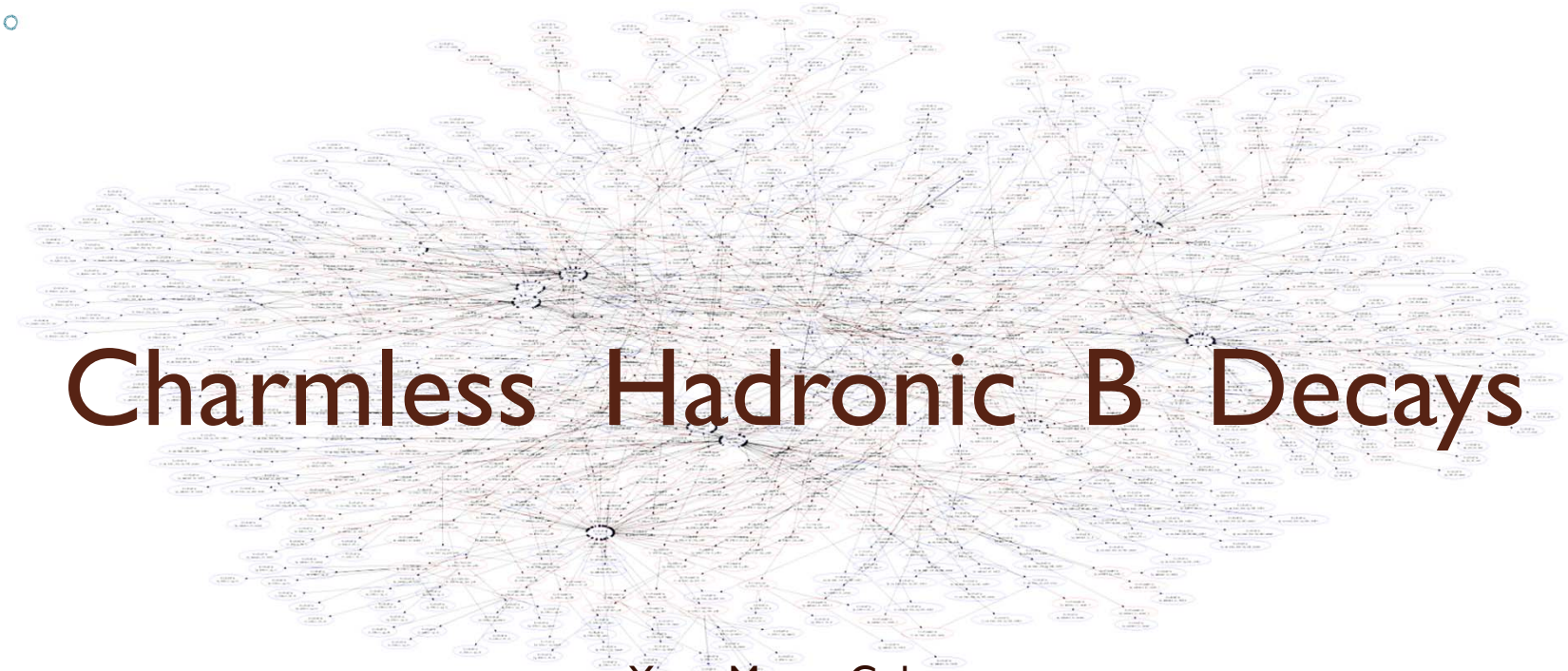


Charmless Hadronic B Decays

YoungMoon Goh

(Hanyang University, Seoul, Korea)

May 26, 2015

Flavor Physics & CP Violation 2015

Outline

- Experimental overview
- B→VV (two vector mesons)
  - BF & f_L in $B^+ \to \overline{K}^{*0} K^{*+}$ by Belle
  - BF in $B^0 \to \omega\omega/\omega\phi$ by BaBar
- $\phi_2(\alpha)$ constraints
  - BF in $B^0 \to \pi^0\pi^0$ by Belle
  - BF in $B^0 \to \eta\pi^0$ by Belle
  - BF & f_L in $B^0 \to \rho^0\rho^0$ by LHCb
- $\phi_3(\gamma)$ constraint and ΔA_{CP} puzzle
  - BF and direct CPV in $B^+ \to K_S\pi^+\pi^0$ by BaBar
- Summary

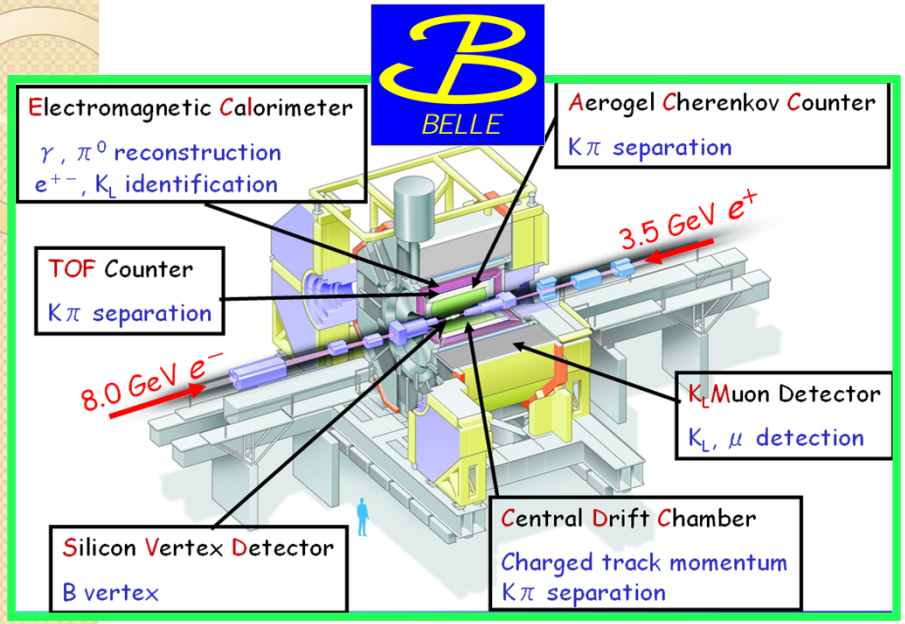
Charmless B decays

- b→c decays take $O(99\%)$ of all B decays.
  The others (b→u,d,s, or b→NP) are charmless and rare.

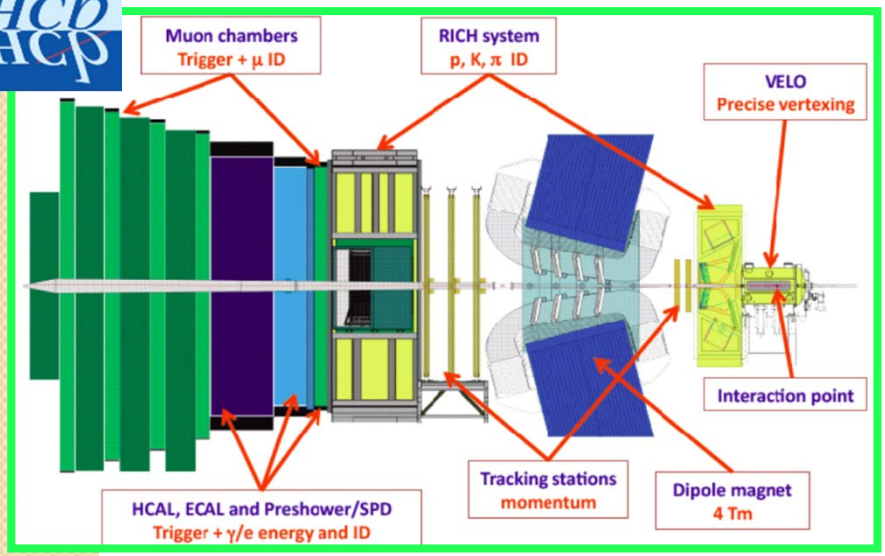
- Charmless B decays probe dynamics of weak and strong interactions
  - Interference between penguin and tree diagrams can lead to direct CP violation
  - Relative weak phase of tree and penguin gives Unitarity Triangle angles

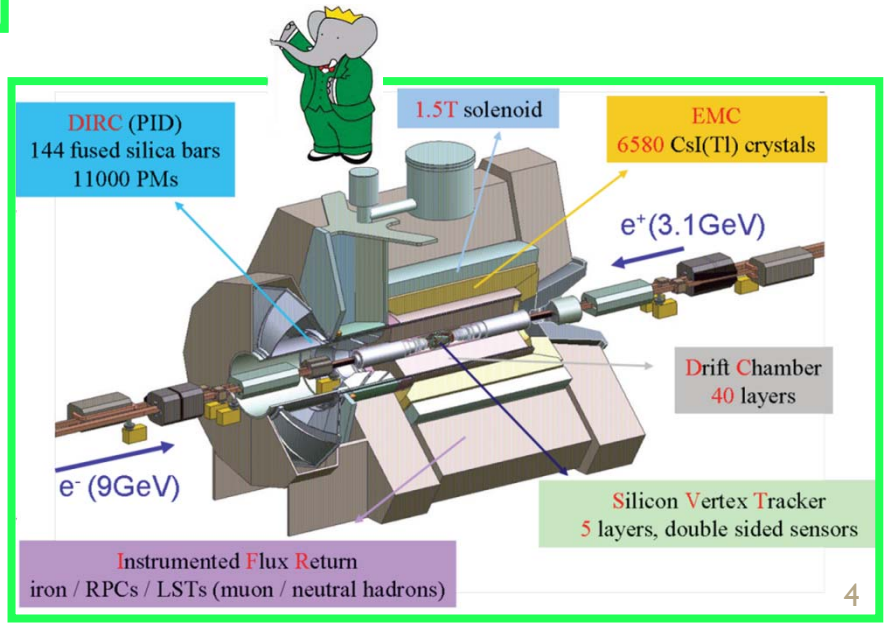
- Allows searches for New Physics from new particles by looking for enhanced BF, A_{CP}, …

Detectors of Belle/Babar/LHCb



- Dataset
  - ~770M BB (Belle)
  - ~470M BB (BaBar)
  - Used dataset for LHCb ~ 3 fb^{-1} (2011+2012)



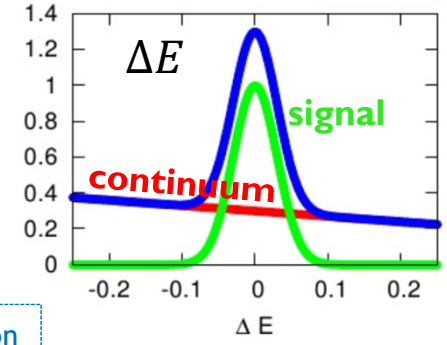


Analysis techniques

- Use precise kinematical information (M_{bc} (m_{ES}) and ΔE) from beam and two B-vertices. (Belle/BaBar)
- Use loose selections (flight distance/direction) of B and NeuroBayes Multivariate discriminator for the identification of secondary vertices consistent with b hadron decays. (LHCb)
- Combined event topology variables in a Neural Network or Fisher Discriminant for continuum ($e^+e^- \to q\bar{q}$) suppression.
- Use vetos to reduce large BB backgrounds contributions.

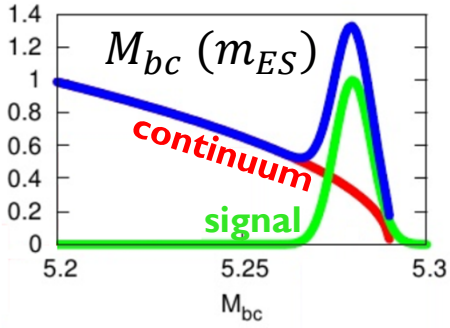
energy difference

$\Delta E = E_B - E_{beam}$

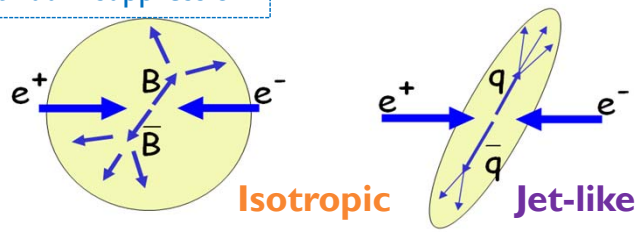


beam-constrained mass

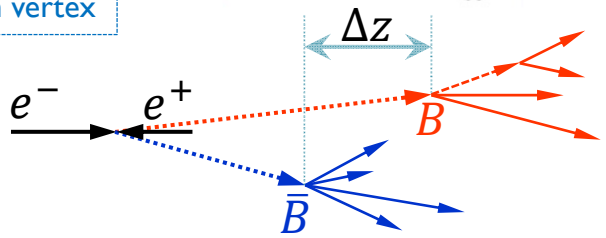
$M_{bc}(m_{ES}) = \sqrt{E_{beam}^2 - p_B^2}$



continuum suppression

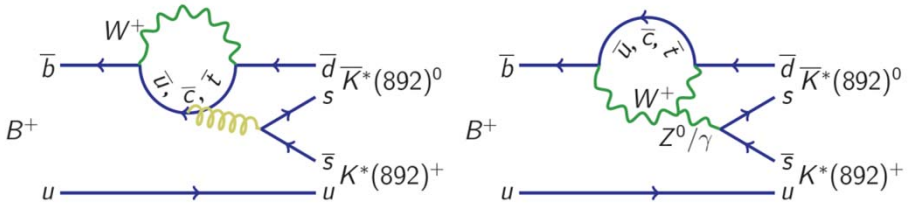


B meson vertex

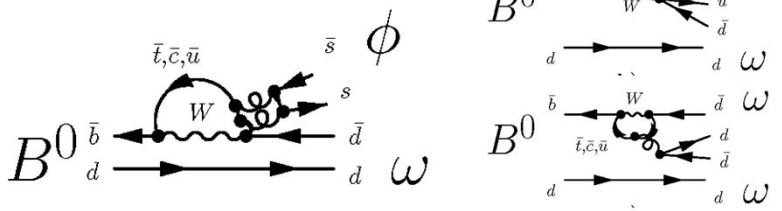


B→VV

$B^+ \to \overline{K}^{*0} K^{*+}$



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

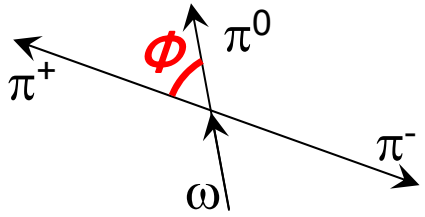


- Proceeds via the b→u tree and b→d penguin transitions
- Sensitive to possible new particle contributions in the loop
- Most f_L of b→d decays not measured.
- A baffling pattern in the longitudinal polarizations of B→VV
  - QCD factorization → expected f_L~1
  - *Belle:* $B^0 \to \phi K^{*0}$ $f_L = 0.499 \pm 0.030 \pm 0.018$ PRD 88, 072004 (2013)

B→VV - analysis

- Cut based selection with continuum $e^+e^- \to q\bar{q}$ background suppression (neural network / Fisher discriminant / Boosted decision tree).
- Use Multi-dimensional fit with S/B separation and polarization variables.

S/B separation	$M_{bc}(m_{ES})$	(beam-constrained) *B* mass
	ΔE	energy difference btw *B* and beam
	m_{V_1}, m_{V_1}	vector meson candidate invariant mass
	$\cos\Phi_{\omega_1}, \cos\Phi_{\omega_2}$	π^0 polar angle (w.r.t ω flight direction) in $\pi^+\pi^-$ rest frame
	C	continuum suppression
polar.	$\cos\theta_{V_1}$	vector meson helicity angles
	$\cos\theta_{V_2}$	



- Fit usually includes polarized signals, continuum, charm/charmless, and peaking background components.

$B^+ \to \overline{K}^{*0} K^{*+}$ - $\mathcal{B}$ & f_L

- Previous measurement:

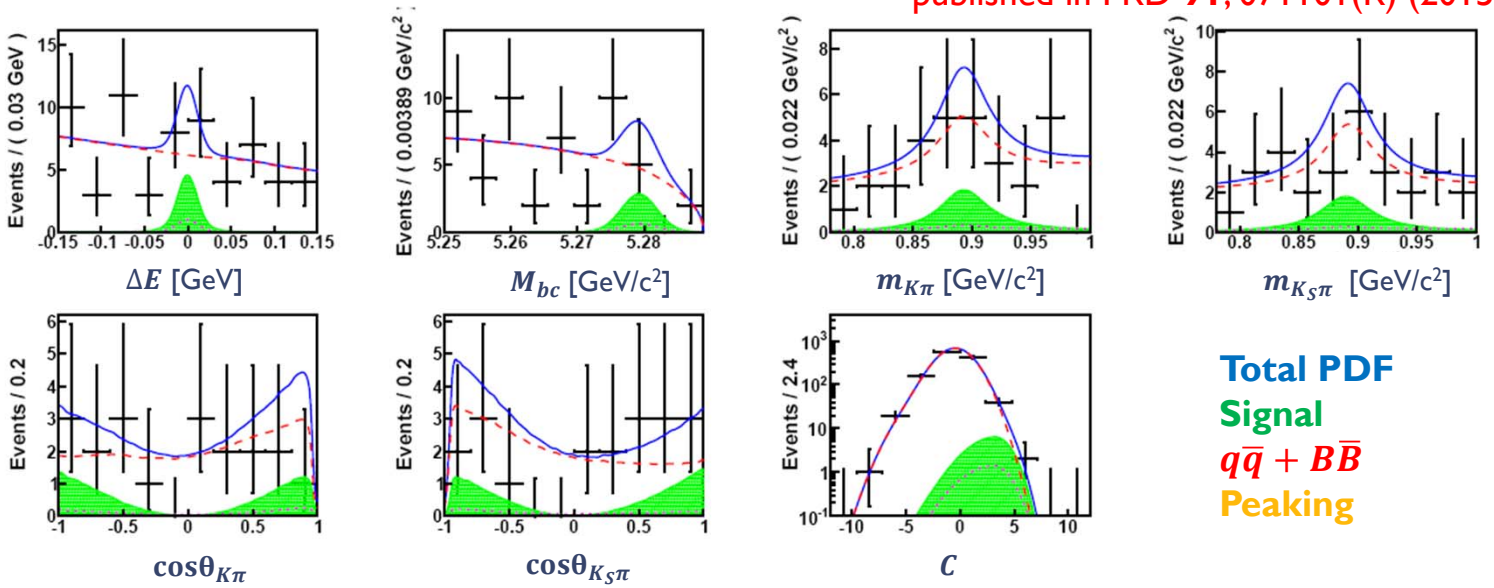
  BABAR: $B^+ \to \overline{K}^{*0} K^{*+}$ $B = (1.2 \pm 0.5 \pm 0.1) \times 10^{-6}$ PRD 79, 051102(R) (2009)

  $f_L = 0.75^{+0.16}_{-0.26} \pm 0.03$

- Result:

published in PRD **91**, 071101(R) (2015)

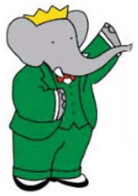
Signal enhanced projections for $K_S\pi$ channel



$\mathcal{B}\,(B^+ \to \overline{K}^{*0} K^{*+}) = \left(0.77^{+0.35}_{-0.30} \pm 0.12\right) \times 10^{-6}$ **(2.7σ)**

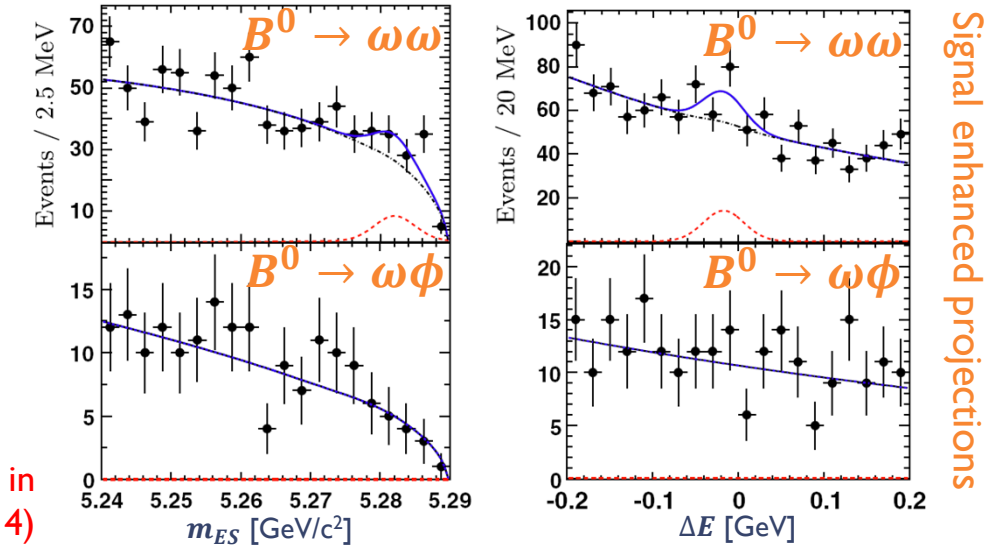
$< \mathbf{1.31 \times 10^{-6}}$ at 90% C.L.

$f_L(B^+ \to \overline{K}^{*0} K^{*+}) = \mathbf{1.06 \pm 0.30 \pm 0.14}$



$B^0 \to \omega\omega/\omega\phi$ - $\mathcal{B}$

- Previous measurements:
  - CLEO $\mathcal{B}(B^0 \to \omega\omega) < 1.9 \times 10^{-5}$ PRL **81**, 272 (1998)
  - Babar $\mathcal{B}(B^0 \to \omega\omega) < 4.0 \times 10^{-6}$,
    $\mathcal{B}(B^0 \to \omega\phi) < 1.2 \times 10^{-6}$ PRD **74**, 051102 (2006)
  - SM expectations : $\mathcal{B}(B^0 \to \omega\omega/\omega\phi) = [0.5 - 3] \times 10^{-6}$ / $[0.01 - 2] \times 10^{-6}$
- Results:



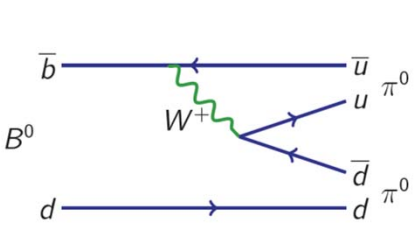
For both modes, f_L fixed with 0.88, and $\mathcal{B}$ systematics from f_L variations

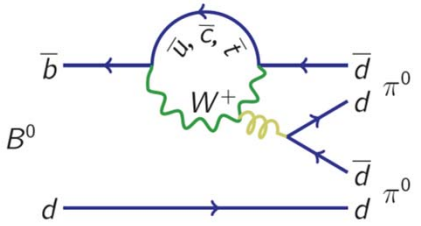
published in
PRD **89**, 051101(R) (2014)

$\mathcal{B}(B^0 \to \omega\omega) = (1.2 \pm 0.3^{+0.3}_{-0.2}) \times 10^{-6}$ (4.4σ) : first evidence
$\mathcal{B}(B^0 \to \omega\phi) < 0.7 \times 10^{-6}$ at 90% C.L.

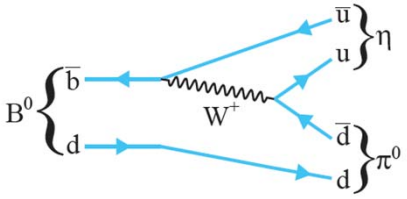
$\phi_2(\alpha)$ constraints

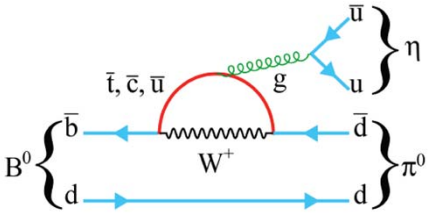
$B^0 \to \pi^0\pi^0$



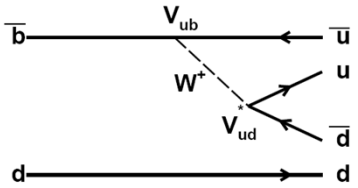


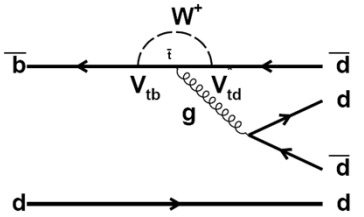
$B^0 \to \eta\pi^0$





$B^0 \to \rho^0\rho^0$





- Proceeds via the b→u tree and penguin diagrams
- B→ππ/ηπ/ρ⁰ρ⁰ sensitive to $\phi_2(\alpha)$.
  - $\phi_2(\alpha)$ can be extracted from an isospin analysis of π-π(ρ-ρ) system by using the branching fraction and A_{CP}.
  - B→ηπ can be used to constrain isospin-breaking effects on $\sin\phi_2$ $(\sin\alpha)$.

$B^0 \to \pi^0\pi^0$ - analysis

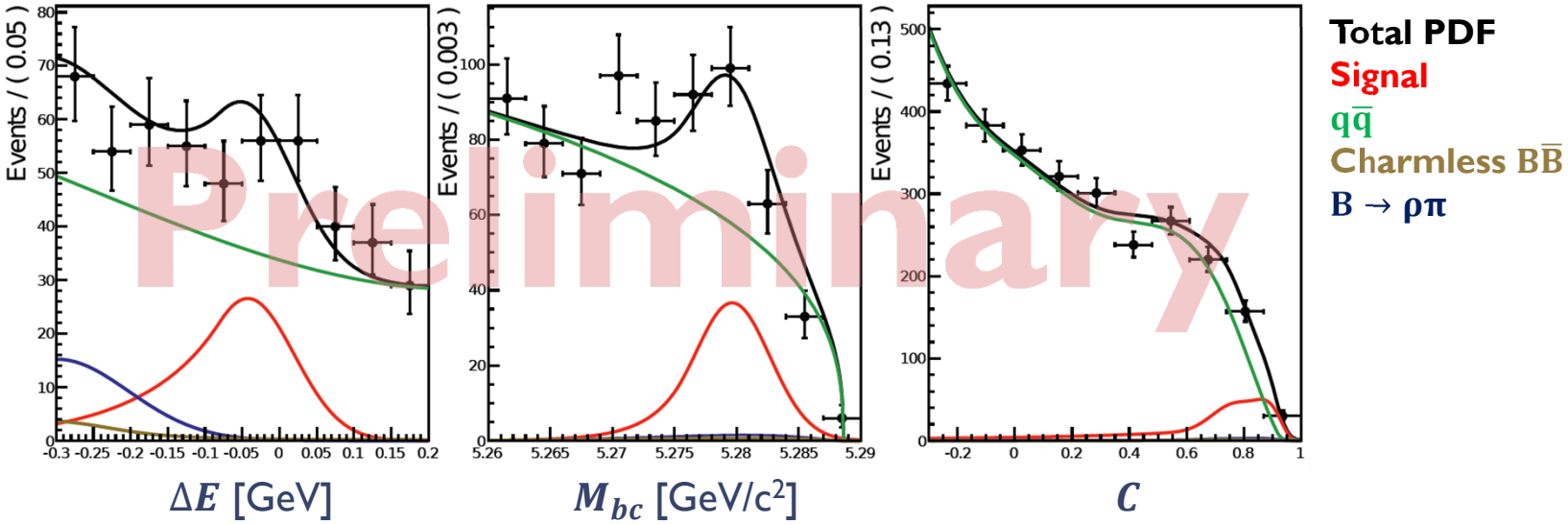
- Previous measurements:
  - Belle $\mathcal{B} = (2.3 \pm 0.4 \pm 0.5) \times 10^{-6}$ PRL **94**, 181803 (2005) ($275M\ B\bar{B}$)
  - Belle $\mathcal{B} = (1.1 \pm 0.3 \pm 0.1) \times 10^{-6}$ ICHEP 2006 ($535M\ B\bar{B}$)
  - Babar $\mathcal{B} = (1.83 \pm 0.21 \pm 0.13) \times 10^{-6}$ PRD **87**, 052009 (2013) ($467M\ B\bar{B}$)
  - Theory (QCDF) $\mathcal{B} \leq 1 \times 10^{-6}$ Nucl.Phys. **B675** 333 (2003)

- Analysis ($752M\ B\bar{B}$)
  - Fit variables :

M_{bc}	beam-constrained mass	S/B separation
ΔE	energy difference	
C	continuum suppression (Fisher Discriminant)	

  - ECL hit timing removes 99% of the background and keeps 99% of the signal
  - Fit includes 4 components of signal, continuum, $\rho^+\pi^0$, and other rare charmless B decays.

$B^0 \to \pi^0\pi^0$ - fit result $\mathcal{B}$



Projections into signal region

- Simultaneous fit to B^0 and $\bar{B}^0 \to$ signal yield 224 ± 29

Preliminary

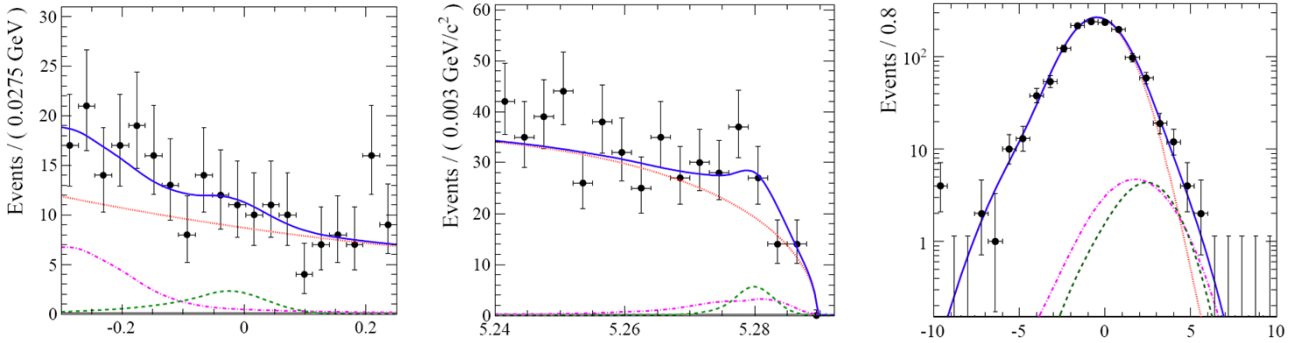
$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (\mathbf{0.90 \pm 0.12 \pm 0.10}) \times \mathbf{10^{-6}} \quad \mathbf{(6.7\sigma)}$$

(A_{CP} result will come soon)

$B^0 \to \eta\pi^0$ - fit result $\mathcal{B}$

- Previous measurements:
  - Belle $\mathcal{B} < 2.5 \times 10^{-6}$ PRD **71**, 091106 (2005)
  - Babar $\mathcal{B} < 1.5 \times 10^{-6}$ PRD **78**, 011107 (2008)
  - Theory (QCDF, Soft Collinear Effective, flavor SU(3)) : $\mathcal{B} = (2 - 12) \times 10^{-7}$
    Nucl.Phys. **B609** 469 (2001), PRD **74**, 014003 (2006), PRD **68**, 074012 (2003)
- Result

(Projections into signal region)



ΔE [GeV] M_{bc} [GeV/c²] C

arXiv:1504.00957, Submitted to PRD(RC)

- $\mathcal{B}(B^0 \to \eta\pi^0) = (4.1^{+1.7+0.5}_{-1.5-0.7}) \times 10^{-7}$ **(3.0σ)**
- The first evidence and Good agreement with theoretical expectations
- Isospin-breaking correction to $\phi_2(\alpha)$ in B→ππ due to $\pi^0 - \eta - \eta'$ mixing is less than 0.97° at 90% CL based on PRD **71** 074017 (2005)

$B^0 \to \rho^0\rho^0$ - $\mathcal{B}$ & f_L

- Previous measurements:

  BABAR: $B = (0.92 \pm 0.32 \pm 0.14) \times 10^{-6}$ PRD 78, 071104(R) (2008)

  $f_L = 0.75^{+0.11}_{-0.14} \pm 0.05$

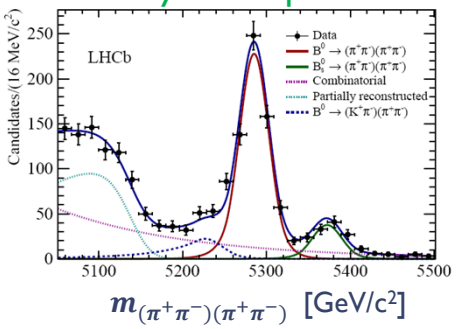
  BELLE: $B = (1.02 \pm 0.30 \pm 0.15) \times 10^{-6}$ PRD 89, 072008 (2014)

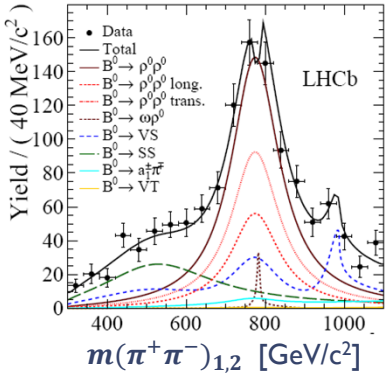
  $f_L = 0.21^{+0.18}_{-0.22} \pm 0.15$

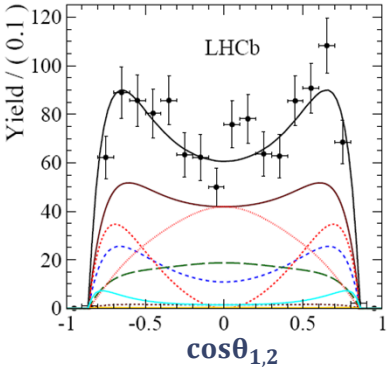
- Result:

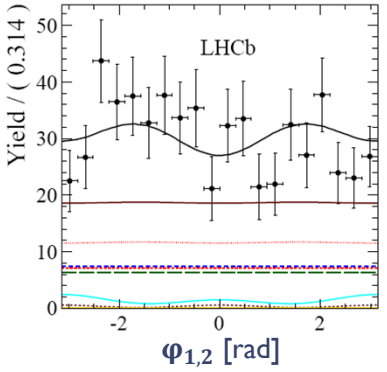
sPlot technique

4-body mass spectrum









$$\mathcal{B}\,(B^0 \to \rho^0\rho^0) = (0.94 \pm 0.17 \pm 0.09 \pm 0.06^{*}) \times 10^{-6}\ \ (7.1\sigma)$$

$$f_L(B^0 \to \rho^0\rho^0) = 0.745^{+0.048}_{-0.058} \pm 0.034$$

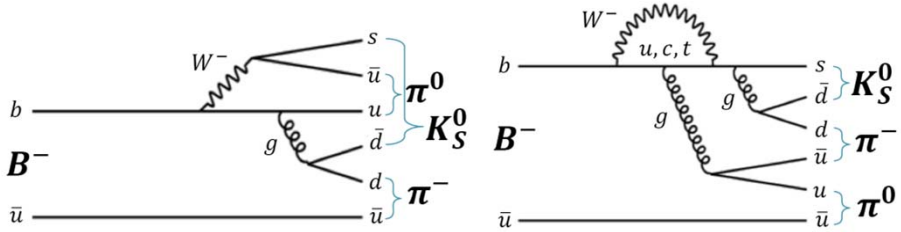
(First observation)

(*) last uncertainty is due to the $B^0 \to \phi K^{*0}$ reference mode.

arXiv:1503.07770, Submitted to PLB

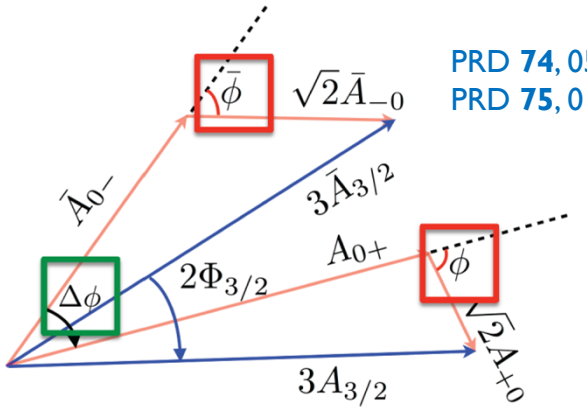
$\phi_3(\gamma)$ constraint

$B^+ \rightarrow K_S \pi^+ \pi^0$



- Proceeds via the b→u tree and penguin diagrams
- B→K*π tree amplitude sensitive to $\phi_3(\gamma)$.
  - $\phi_3(\gamma)$ can be extracted from interferences btw intermediate states in Kππ Dalitz plane.
- Relative phases between two $K^*\pi$ intermediate states
  - $K^{*0}\pi^+$ & $K^{*+}\pi^0$
  - In $K_S\pi^+\pi^0$, Dalitz plot can be used to measure CKM angle $\phi_3(\gamma)$
- $K^{*0}\pi^+$ is a pure penguin decay
  - $\Delta\phi$ is approximately zero
- In absence of EW penguins,
  - $\Phi_{3/2} = \phi_3(\gamma)$

Isospin relations



PRD **74**, 051301 (2006)
PRD **75**, 014002 (2007)

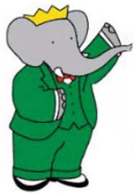
$B^+ \to K_S \pi^+ \pi^0$ – analysis

- Cut based selection with Boosted Decision Tree based continuum suppression
- Dalitz plot (DP) based analysis gives relative phase, BF, and A_{CP}
  - DP fit model contains $K^*(892)$, $K\pi$ S-wave and $\rho(770)$ contributions
- 5D simultaneous fit to $B^\pm$

S/B separation

m_{ES}	beam-constrained *B* mass
ΔE	energy difference btw *B* and beam
$m^2_{K_S\pi^+}, m^2_{\pi^+\pi^0}$	Dalitz plot parameters
BDT_{out}	continuum suppression

- Fit components
  - Signal ($K^0\pi^+\pi^0, K^{*0}\pi^+, K^{*+}\pi^0, K^{*0}(1430)\pi^+, K^{*+}(1430)\pi^0, \rho^+K^0$)
  - Continuum and $B\bar{B}$ backgrounds
- Previous measurements:
  - *Belle&Babar* $A_{CP}(B^0 \to K^{*+}\pi^-) = -0.23 \pm 0.06$ HFAG Average
  - *Babar* $A_{CP}(B^+ \to K^{*+}\pi^0) = -0.06 \pm 0.24$ (using $K^+\pi^0\pi^0$) PRD **84**, 092007 (2011)
  - *CLEO* $\mathcal{B}(B^+ \to K^0\pi^+\pi^0) < 66 \times 10^{-6}$ PRL **89**, 251801 (2002)



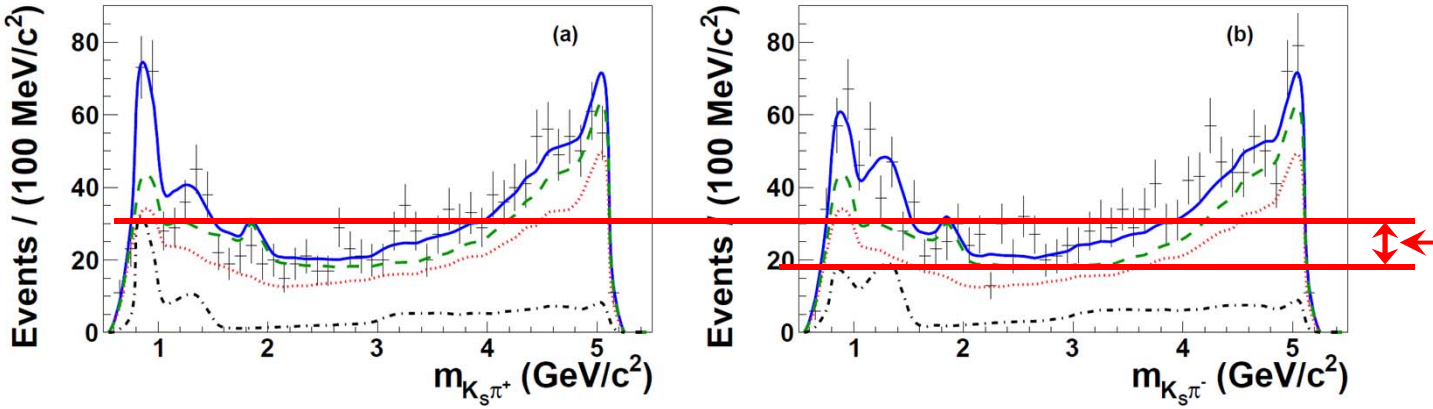
$B^+ \to K_S\pi^+\pi^0$ – result

- First measurement of inclusive $K^0\pi^+\pi^0$ and $K^{*+}(1430)\pi^0$ BFs
- First evidence of direct CP violation in $B^+ \to K^{*+}\pi^0$
- A_{CP} for $B^+ \to K^{*0}(892)\pi^+$ consistent with zero (as expected)
- Relative phase $(K^*\pi)$ uncertainty is too large to measure $\phi_3(\gamma)$

arXiv:1501.00705, Submitted to PRD

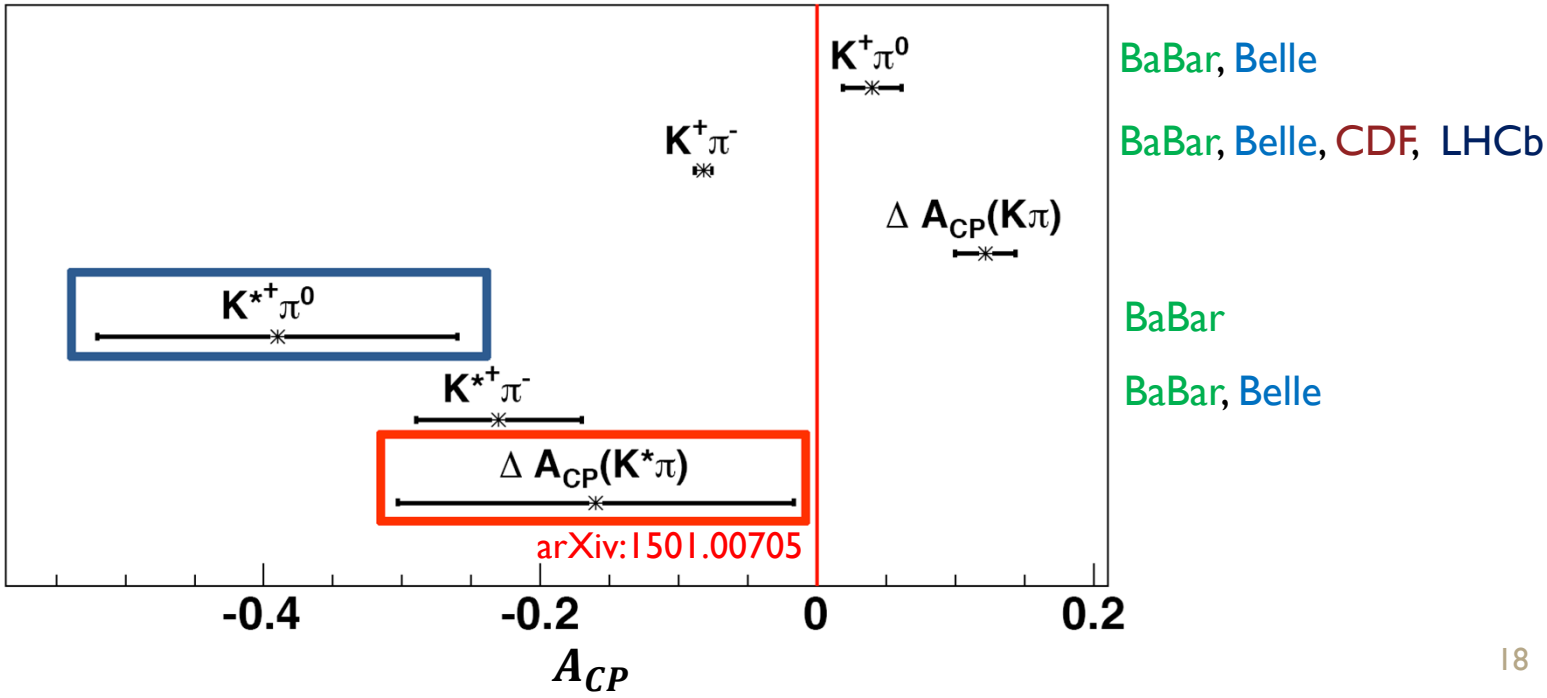
Last error due to the signal model

Decay channel	$\mathcal{B}$	A_{CP}
$B^0 \to K^0\pi^+\pi^0$	$(45.9 \pm 2.6 \pm 3.0^{+8.6}_{-0.0}) \times 10^{-6}$	$0.07 \pm 0.05 \pm 0.03^{+0.02}_{-0.03}$
$K^{*0}(892)\pi^+$	$(14.6 \pm 2.4 \pm 1.4^{+0.3}_{-0.4}) \times 10^{-6}$	$-0.12 \pm 0.21 \pm 0.08^{+0.0}_{-0.11}$
$K^{*+}(892)\pi^0$	$(9.2 \pm 1.3 \pm 0.6^{+0.3}_{-0.5}) \times 10^{-6}$	$\mathbf{-0.52 \pm 0.14 \pm 0.04^{+0.04}_{-0.02}}$ **(3.4σ)**
$K^{*0}(1430)\pi^+$	$(50.0 \pm 4.8 \pm 6.1^{+2.7}_{-2.6}) \times 10^{-6}$	$0.14 \pm 0.10 \pm 0.04^{+0.13}_{-0.05}$
$K^{*+}(1430)\pi^0$	$(17.2 \pm 2.4 \pm 1.5^{+0.0}_{-1.8}) \times 10^{-6}$ (5.4σ)	$0.26 \pm 0.12 \pm 0.08^{+0.12}_{-0.0}$
$\rho^0(770)K^0$	$(9.4 \pm 1.6 \pm 1.1^{+0.0}_{-2.6}) \times 10^{-6}$	$0.21 \pm 0.19 \pm 0.07^{+0.23}_{-0.19}$



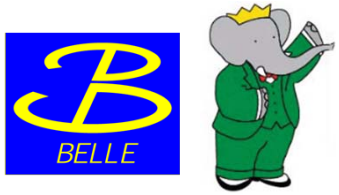
$B^+ \to K_S \pi^+ \pi^0$ – effect on Kπ puzzle

- Plot uses world average values for $K\pi$ and $K^{*+}\pi^-$ asymmetries and average of two BaBar results for $K^{*+}\pi^0$
- Gives $\Delta A_{CP}(K^*\pi) \equiv A_{CP}(K^{*+}\pi^0) - A_{CP}(K^{*+}\pi^-) = -0.16 \pm 0.13$
  - Consistent with zero
- Uncertainty much improved but still too large to be conclusive



Summary

- Belle and BaBar presented the angular analysis in $B^+ \to \overline{K}^{*0} K^{*+}$ and $B^0 \to \omega\omega/\omega\phi$, and $B^0 \to \omega\omega$ result is the first evidence.
- Belle presented the precise measurement of $\mathcal{B}$ in $B^0 \to \pi^0\pi^0$ and the first evidence of $\mathcal{B}$ in $B^0 \to \eta\pi^0$.
- LHCb presented the first observation in $B^0 \to \rho^0\rho^0$ and the precise f_L.
- BaBar presented the first evidence of DCPV in $B^+ \to K^{*+}\pi^0$.
- More data is required to increase sensitivity to potential signs of New Physics and improved results will come from Belle II and LHCb.



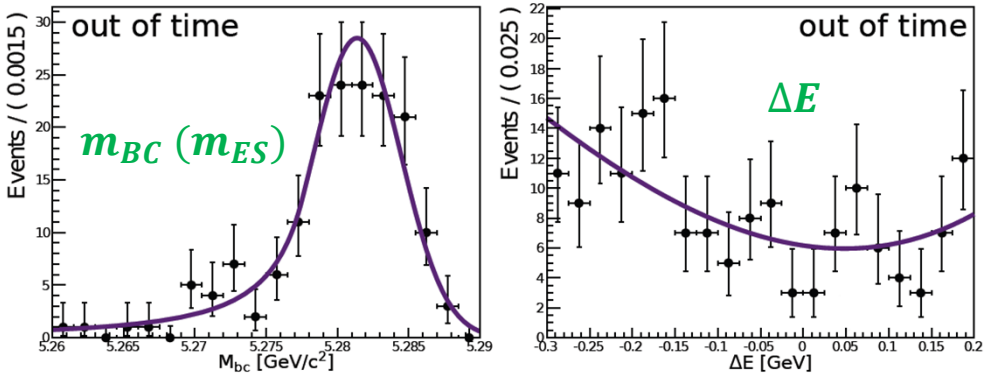
Result summary

Decay channel		Keyword	Result
	$B^0 \to \pi^0\pi^0$ Preliminary	Precise BF measurement, 6.7σ	$\mathcal{B} = (0.90 \pm 0.12 \pm 0.10) \times 10^{-6}$
	$B^0 \to \eta\pi^0$ arXiv:1504.00957	First BF evidence, 3.0σ	$\mathcal{B} = \left(4.1^{+1.7+0.5}_{-1.5-0.7}\right) \times 10^{-7}$
	$B^0 \to K^0_S\pi^+\pi^0$ arXiv:1501.00705	Evidence (3.4σ) for DCPV in $B^+ \to K^{*+}\pi^0$ from Dalitz plot analysis of $B^0 \to K^0_S\pi^+\pi^0$	$A_{CP}(B^+ \to K^{*+}\pi^0) = -0.52 \pm 0.14 \pm 0.04^{+0.04}_{-0.02}$ $\Delta A_{CP}(K^*\pi) = -0.16 \pm 0.13$
	$B^+ \to \bar{K}^{*0}K^{*+}$ PRD 91, 071101 (2015)	Angular analysis	$\mathcal{B} < 1.31 \times 10^{-6}$ at 90% CL $f_L = 1.06 \pm 0.30 \pm 0.14$
	$B^0 \to \omega\omega/\omega\phi$ PRD 89, 051101 (2015)	Angular analysis, first evidence (4.4σ) for $B^0 \to \omega\omega$	$\mathcal{B}(B^0 \to \omega\omega) = (1.2 \pm 0.3^{+0.3}_{-0.2}) \times 10^{-6}$ $\mathcal{B}(B^0 \to \omega\phi) < 0.7 \times 10^{-6}$ at 90% CL
	$B^0 \to \rho^0\rho^0$ arXiv:1503.07770	First observation, 7.1σ	$\mathcal{B} = (0.94 \pm 0.17 \pm 0.09 \pm 0.06) \times 10^{-6}$ $f_L = 0.745^{+0.048}_{-0.058} \pm 0.034$

BACKUPS

$B^0 \to \pi^0\pi^0$ - analysis

- $B\bar{B}$ background is dominant:
  - background from out of time ECL showers
  - out of time ECL hit + $B\bar{B}$ event → peaking background



  - Use ECL timing information to remove out-of-time events
- Fit variables:

m_{BC} (m_{ES})	beam-constrained mass	S/B separation
ΔE	energy difference	
C	continuum suppression	

LHCb recent results

Decay channel	Keyword	Result
$\mathbf{B^0 \to \rho^0 \rho^0}$ arXiv:1503.07770	First observation, 7.1σ	$\mathcal{B} = (0.94 \pm 0.17 \pm 0.09 \pm 0.06) \times 10^{-6}$ $f_L = 0.745^{+0.048}_{-0.058} \pm 0.034$
$\mathbf{B^0 \to K^+ \pi^-}$ arXiv:1406.7204	Effective lifetime measurement	$\tau = 1.524 \pm 0.011 \pm 0.004$ ps
$\mathbf{B^0 \to \phi K^{*0}}$ JHEP 05, 069 (2014)	Angular analysis with $\Delta A_{CP} = A_{CP}(\phi K^{*0}) - A_{CP}(J/\psi K^{*0})$	$\Delta A_{CP} = (+1.5 \pm 3.2 \pm 0.5)\%$
$\mathbf{B_s^0 \to \bar{K}^{*0} K^{*0}}$ arXiv:1503.05362	Measurement of BF and f_L	$\mathcal{B} = (10.6 \pm 1.8 \pm 1.0 \pm 0.6) \times 10^{-6}$ $f_L = 0.201 \pm 0.057 \pm 0.040$
$\mathbf{B^\pm \to \pi^+ \pi^- K^\pm}$, $\mathbf{B^\pm \to K^+ K^- K^\pm}$, $\mathbf{B^\pm \to K^+ K^- \pi^\pm}$, $\mathbf{B^\pm \to \pi^+ \pi^- \pi^\pm}$ PRD 90, 112004 (2014)	Inclusive CP asymmetries using Dalitz plot	$A_{CP}(B^\pm \to \pi^+\pi^- K^\pm) = +0.025 \pm 0.004 \pm 0.004 \pm 0.007$ $A_{CP}(B^\pm \to K^+ K^- K^\pm) = -0.036 \pm 0.004 \pm 0.002 \pm 0.007$ $A_{CP}(B^\pm \to K^+ K^- \pi^\pm) = -0.123 \pm 0.017 \pm 0.012 \pm 0.007$ $A_{CP}(B^\pm \to \pi^+\pi^- \pi^\pm) = +0.058 \pm 0.008 \pm 0.009 \pm 0.007$

$\phi_2(\alpha)$ constraints of ρρ

- $S_{\rho\rho} = \sqrt{1 - A_{\rho\rho}^2}\sin(2\phi_2^{\text{eff}})$ $\qquad \phi_2^{\text{eff}} = \phi_2 + \delta$
- **Determine penguin pollution δ with isospin analysis:**
  - $\rho^+\rho^-$: Br, A_{CP}, f_L
  - $\rho^+\rho^0$: Br, f_L
  - $\rho^0\rho^0$: Br, A_{CP}, f_L

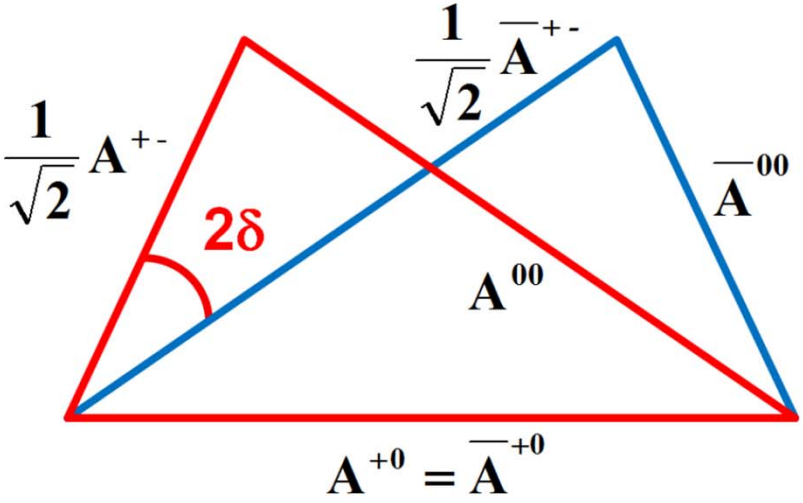
[M.Gronau and D.London,PRL65,3381(1990)]

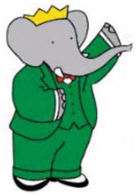
$$A^{+-} + \sqrt{2}A^{00} = \sqrt{2}A^{+0}$$

$$\bar{A}^{+-} + \sqrt{2}\bar{A}^{00} = \sqrt{2}\bar{A}^{+0}$$

$$|\bar{A}^{+0}| = |\bar{A}^{+0}|$$

Assuming no EWP





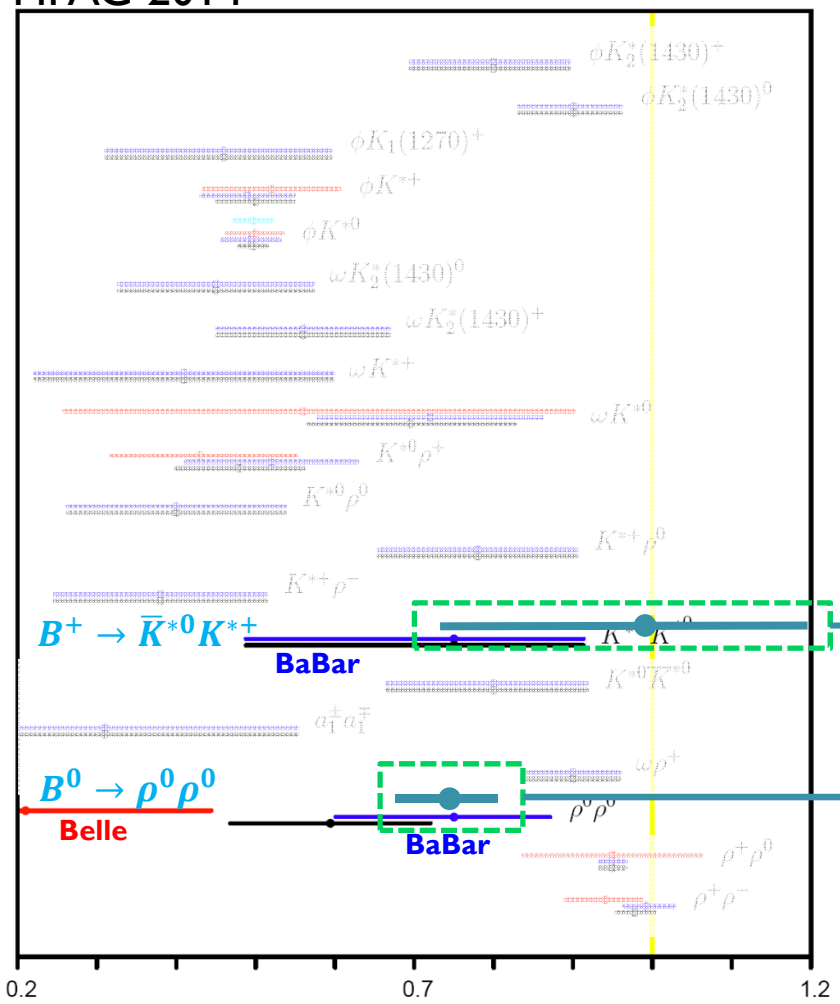
$B^+ \to K_S \pi^+ \pi^0$ – result

Reference amplitude \ Resonant contribution	Relative phase (degrees)				
	$K^*(892)^0\pi^+$	$K^*(892)^+\pi^0$	$(K\pi)_0^{*0}\pi^+$	$(K\pi)_0^{*+}\pi^0$	$\rho(770)^+K_S^0$
$B^+ \to K^*(892)^0\pi^+$	0	-95 ± 43	174 ± 11	-89 ± 43	-122 ± 43
$B^+ \to K^*(892)^+\pi^0$	–	0	-90 ± 42	6 ± 10	-27 ± 26
$B^+ \to (K\pi)_0^{*0}\pi^+$	–	–	0	96 ± 42	63 ± 37
$B^+ \to (K\pi)_0^{*+}\pi^0$	–	–	–	0	-32 ± 25
$B^+ \to \rho(770)^+K_S^0$	–	–	–	–	0

Large uncertainty indicates measuring CKM angle γ will be difficult

f_L for B→VV

HFAG 2014



$f_L(B^+ \to \bar{K}^{*0}K^{*+}) = 1.06 \pm 0.30 \pm 0.14$

$f_L(B^0 \to \rho^0\rho^0) = 0.745^{+0.048}_{-0.058} \pm 0.034$