CP Violation results from Belle

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On behalf of the Belle collaboration

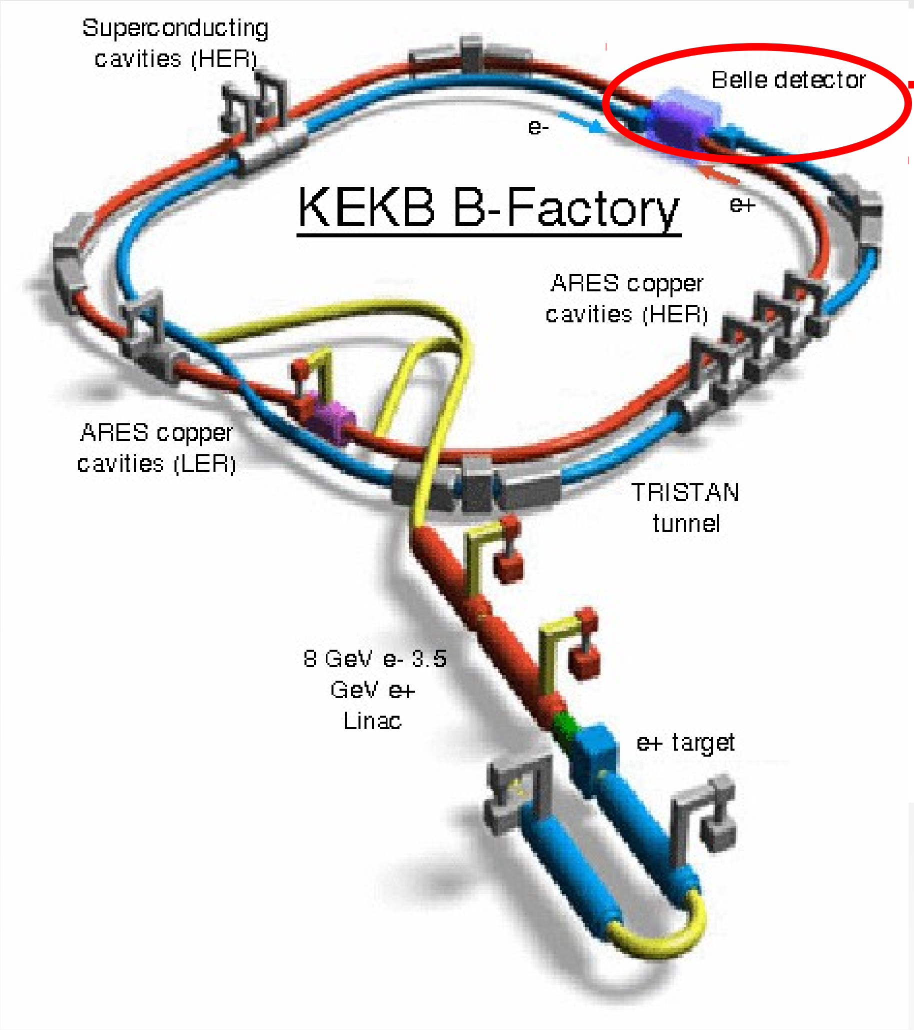
15 August 2013

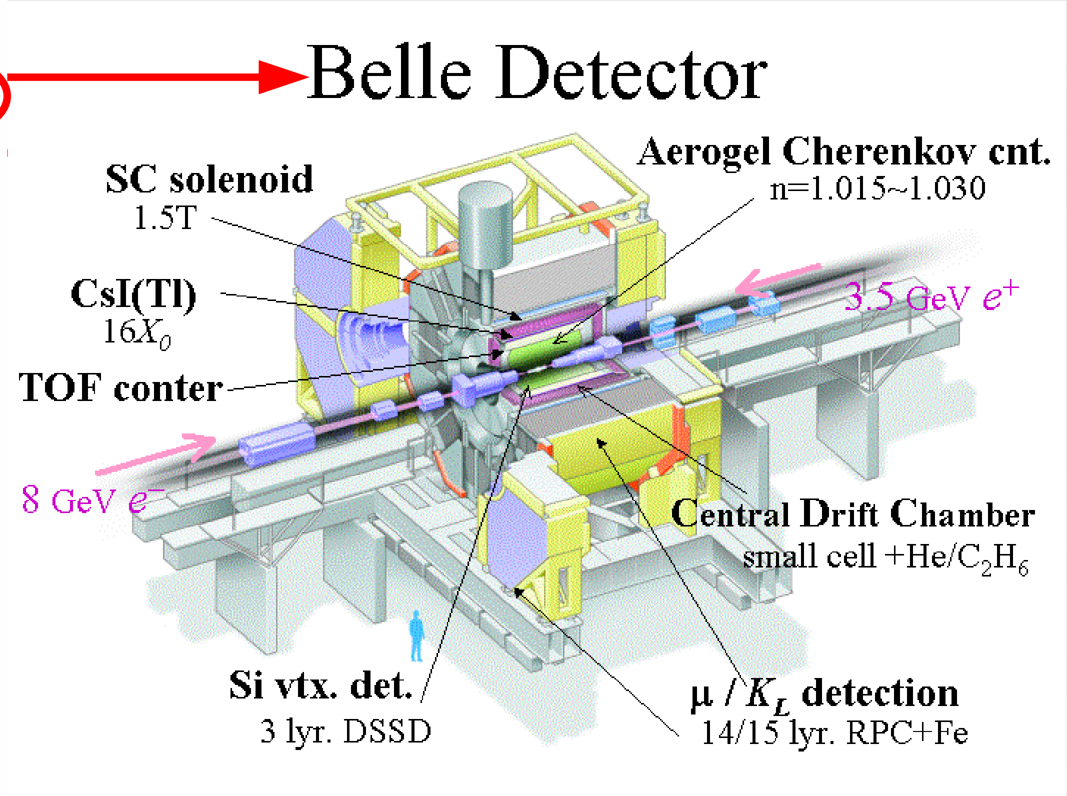
Outline

- CP Violation in:
- $b \to u$ decays:
  - $B^0 \to \pi^+\pi^-$
  - $B^0 \to \rho^0\rho^0$
- $b \to s$ decays:
  - $B^0 \to \omega K_S$
  - $B^0 \to \eta' K_S$

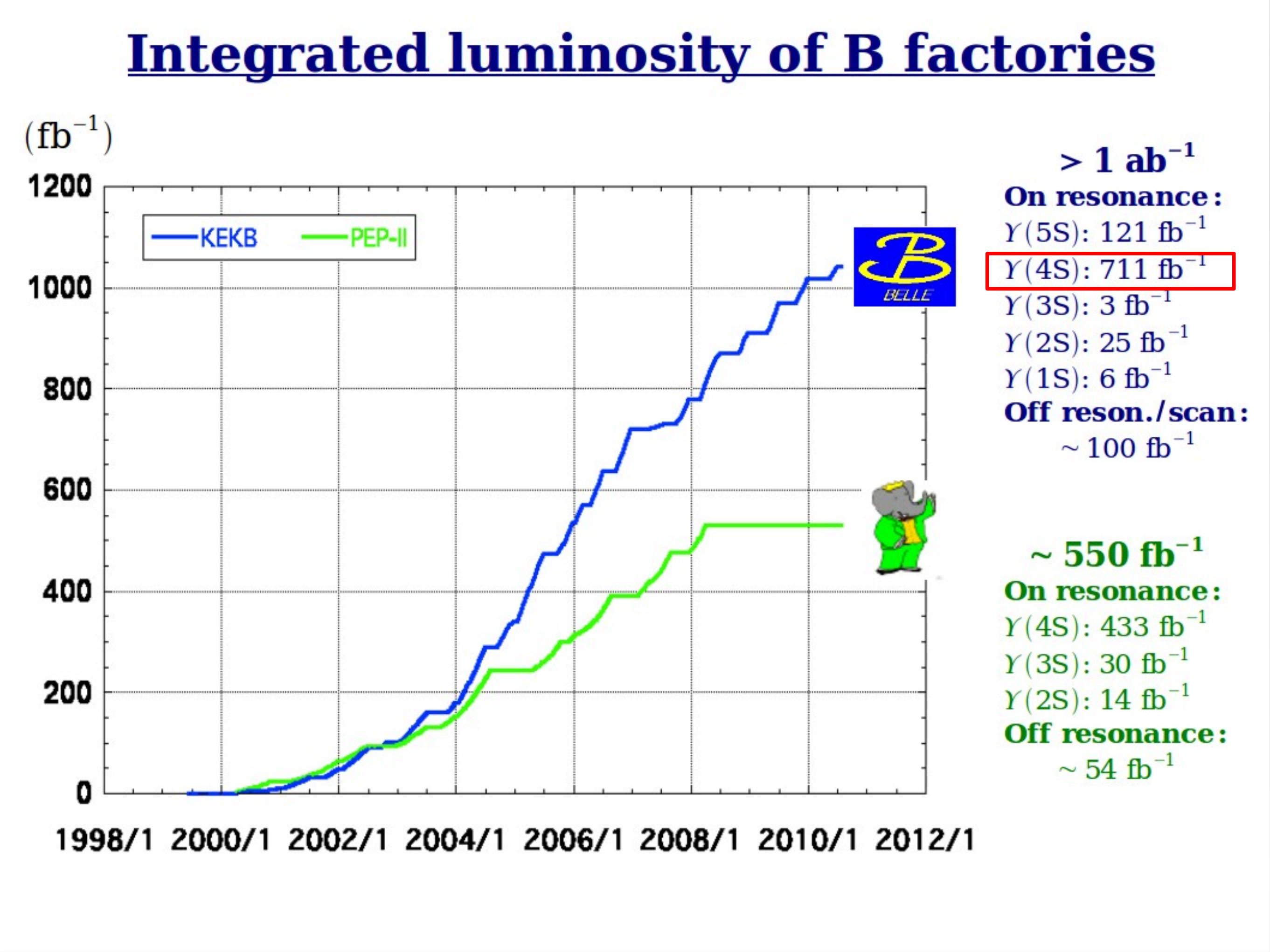
CP Violation in Charm decays was covered in ”Charm mixing and CP Violation at Belle” - A. Schwartz at 14:50 15 August.

The Belle Detector at KEK





The Belle dataset

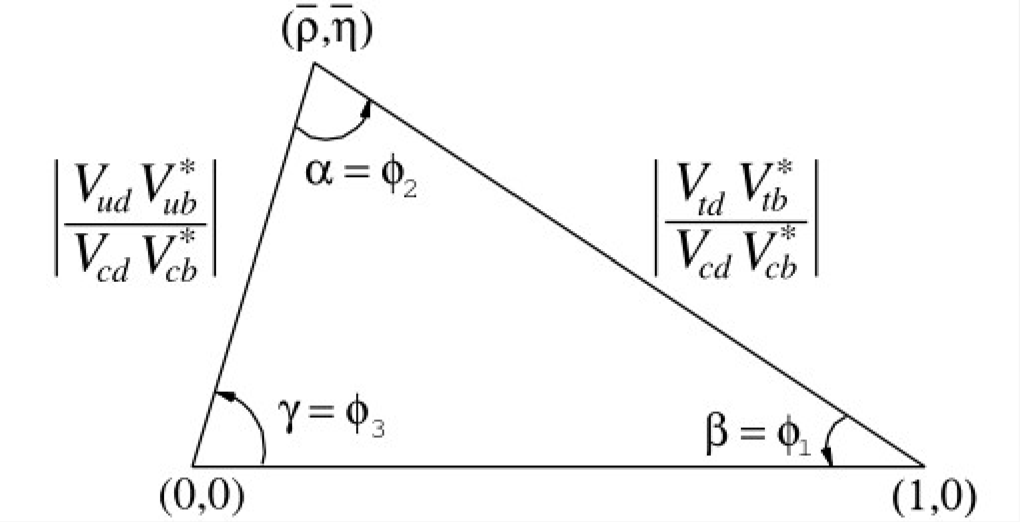


- 772 Million $B\bar{B}$ pairs created from Υ(4S) decays.
- The presented analyses use the full Belle Υ(4S) data set, unless otherwise indicated.

CP Violation

$$V_{\mathrm{CKM}} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- CP violation in the Standard Model Arises due to an irreducible phase in the CKM matrix.
- The CKM matrix has a unitarity condition – this can be represented as the Unitarity triangle.

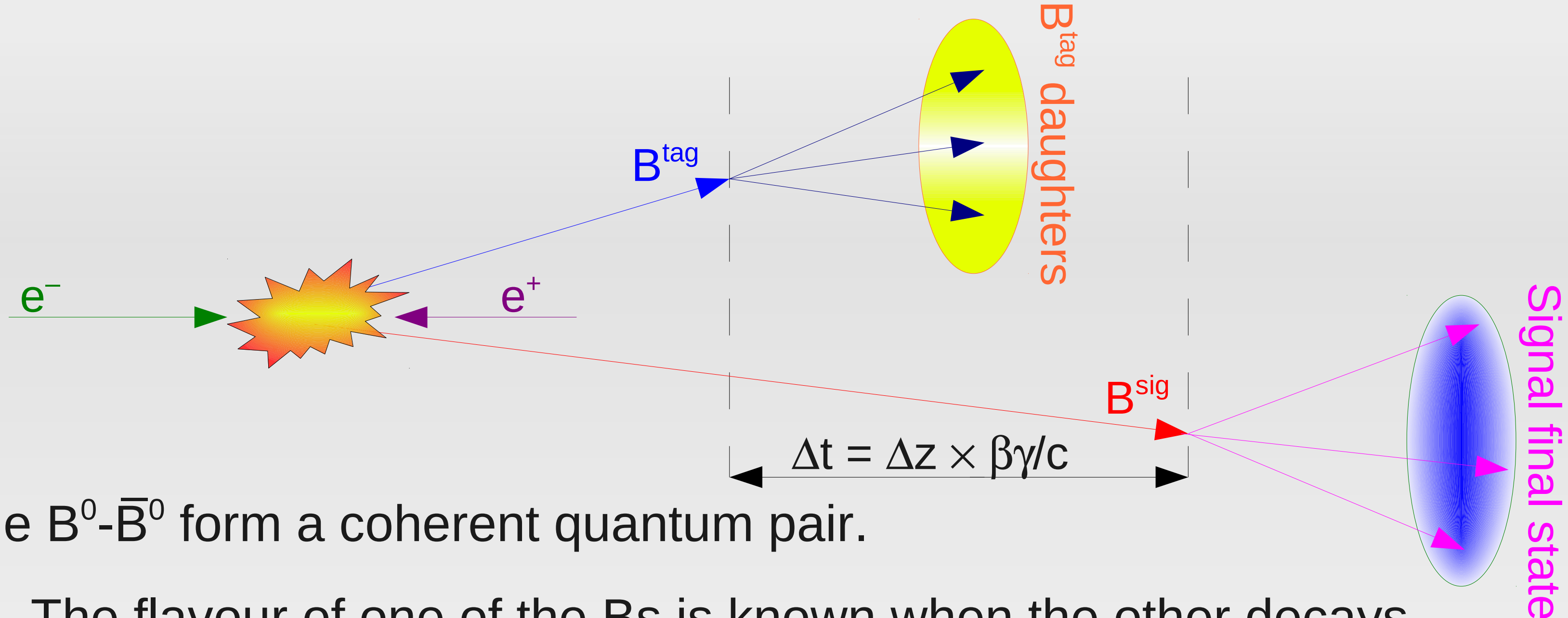


- b → u decays can be sensitive to

$$\phi_2 \text{ (or } \alpha) \equiv \arg[(-V_{td}V_{tb}^*)/(V_{ud}V_{ub}^*)]$$

- Whereas b → s decays can be sensitive to ϕ_1 only when mixing is present.
- CP violation can occur directly in a decay, or due to mixing (or in interference between processes). Direct CPV can be expressed as a parameter A_{CP}, and mixing induced CPV as a parameter S_{CP}.

Common Analysis Techniques



- The B^0-$\bar{B}^0$ form a coherent quantum pair.
  - The flavour of one of the Bs is known when the other decays.
  - Tag one of the Bs as a state of known flavour.
  - Reconstruct signal B, where flavour of signal B will vary as a function of Δt.
- Time dependent CP violation often expressed in terms of parameters A_{CP} and S_{CP}:

$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left\{1 + q\left[\mathcal{A}_{CP}\cos\Delta m_d \Delta t + \mathcal{S}_{CP}\sin\Delta m_d \Delta t\right]\right\}$$

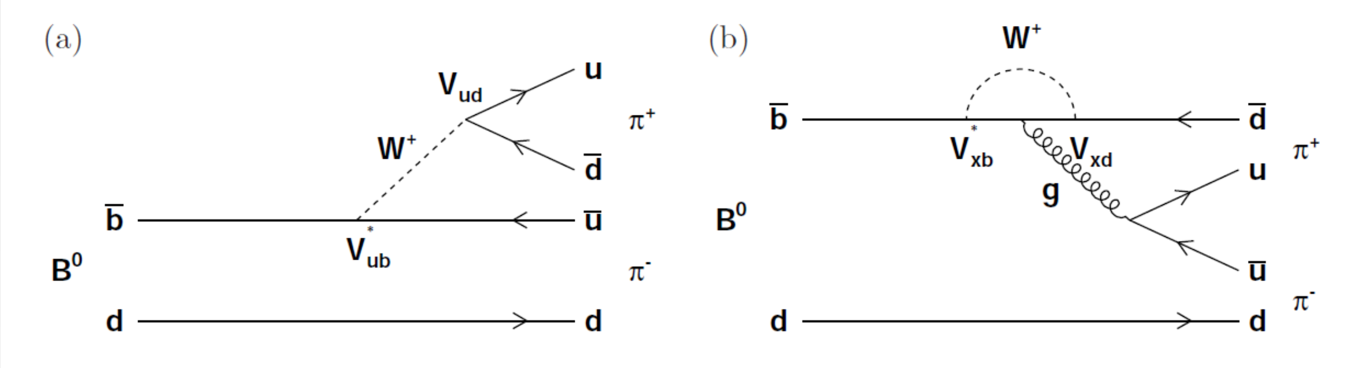
Common Analysis techniques II

- Analyses in the presentation use many common variables for event selection and/or fitting, these include:
  - Beam constrained mass: $M_{bc} \equiv \sqrt{(E_{beam}^{cms})^2 - (p_B^{cms})^2}$;
  - Delta E: $\Delta E = E_B^{cms} - E_{beam}^{cms}$;
  - where E^{cms}_{beam} is the beam energy in centre of mass frame. E^{cms}_{B} (p^{cms}_{B}) is the Energy (momentum) of the B candidate in the cms frame.
  - Fisher discriminants and Likelihood ratios are used. These collect together a number of weakly discriminating event shape variables, such as Fox-Wolfram moments, cos θ_B (angle between Beam axis and B direction), helicity angles, etc...
- The exact variables used for each analysis vary.

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

arXiv:1302.0551

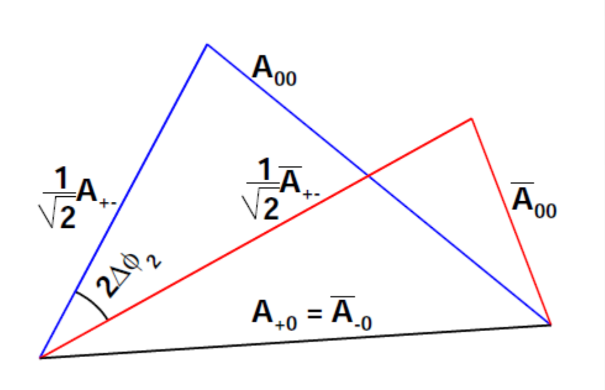
- $B^0 \to \pi^+\pi^-$ has both tree and penguin contributions:



- Interference between tree and penguins means that ϕ_2 is not directly observable, instead $\mathcal{S}_{CP} = \sqrt{1 - \mathcal{A}_{CP}^2}\sin(2\phi_2 + 2\Delta\phi_2)$

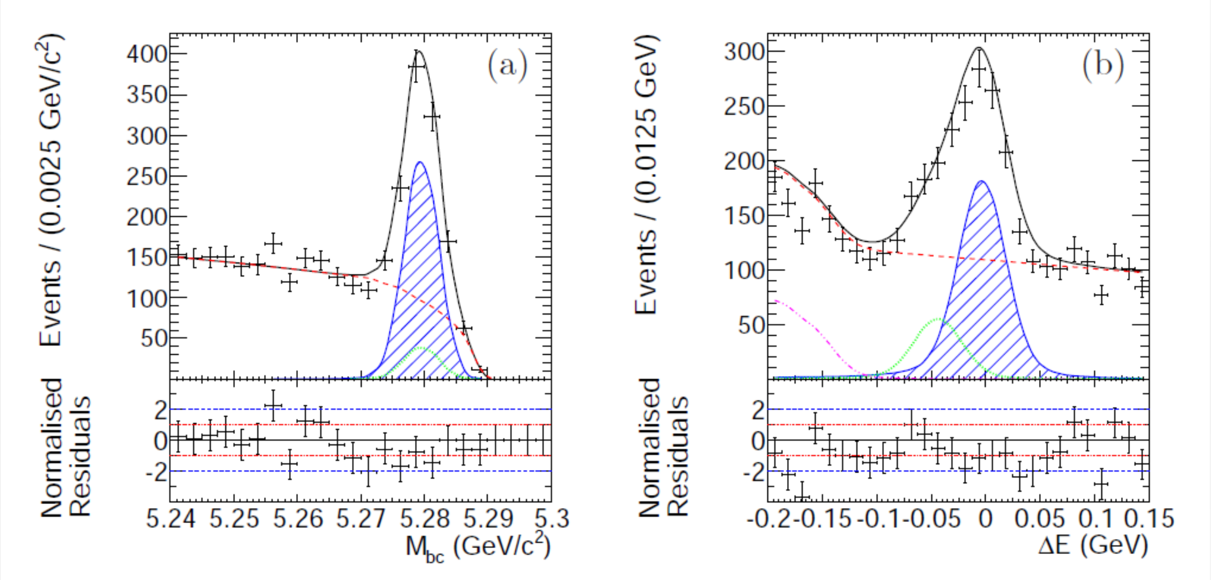
- ϕ_2 can still be calculated using an isospin analysis
  - The full set of $B \to \pi\pi$ decays for different pion charge combinations needs to be considered.

$$A_{+0} = \frac{1}{\sqrt{2}}A_{+-} + A_{00}, \quad \bar{A}_{-0} = \frac{1}{\sqrt{2}}\bar{A}_{+-} + \bar{A}_{00},$$

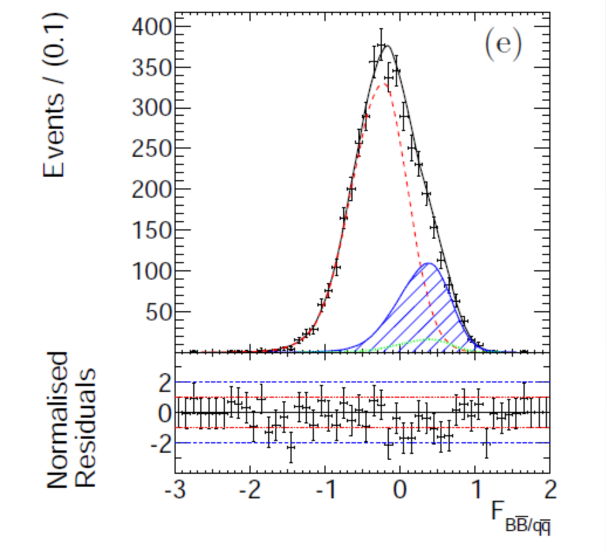


$B^0 \to \pi^+\pi^-$ arXiv:1302.0551

- $B^0 \to \pi^+\pi^-$ is fitted using 7 variables: M_{bc}, ΔE, Fisher discriminant, $\mathcal{L}^+_{K\pi}$, $\mathcal{L}^-_{K\pi}$, Δt and q.
- $\mathcal{L}^\pm_{K\pi}$ are likelikihood ratios for K/π identification:
  - Important background is from misidentified kaons.



$B^0 \to \pi^+\pi^-$ signal;
$B^0 \to K^+\pi^-$ background;
Total background.

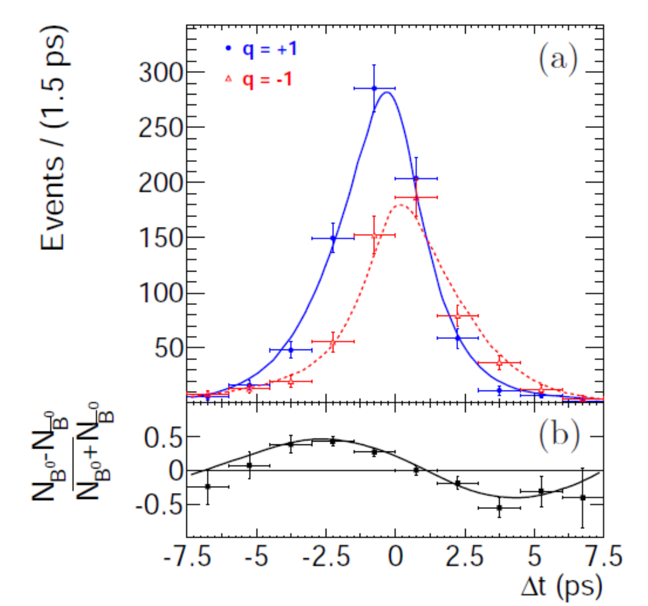


$B^0 \to \pi^+\pi^-$

arXiv:1302.0551

- Fitted A_{CP}, S_{CP} results:

$$\mathcal{A}_{CP}(B^0 \to \pi^+\pi^-) = +0.33 \pm 0.06\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst}),$$
$$\mathcal{S}_{CP}(B^0 \to \pi^+\pi^-) = -0.64 \pm 0.08\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst}),$$



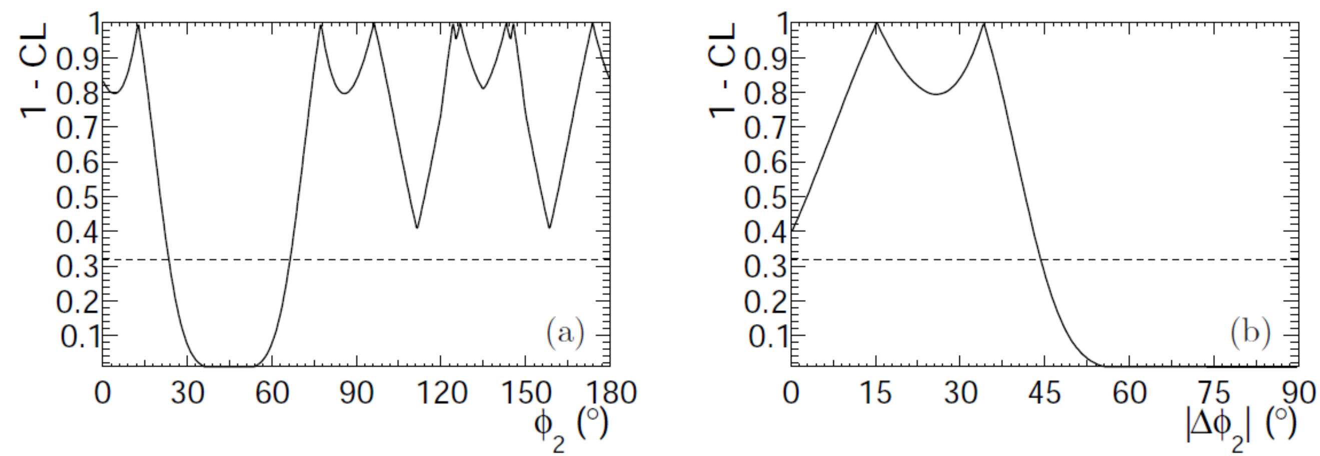
- Isospin analysis to this mode and other B → ππ measurements from Belle [1,2] yields constraints on ϕ2 and Δϕ2:

$$23.8^\circ < \phi_2 < 66.8^\circ$$

is disfavoured.

$$|\Delta\phi_2| < 44.8^\circ$$

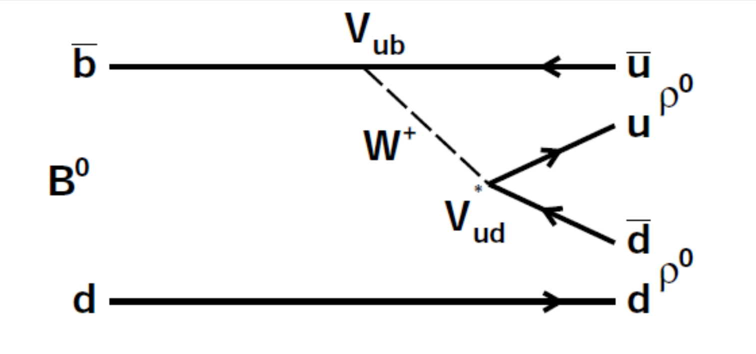
for 1 σ bound.



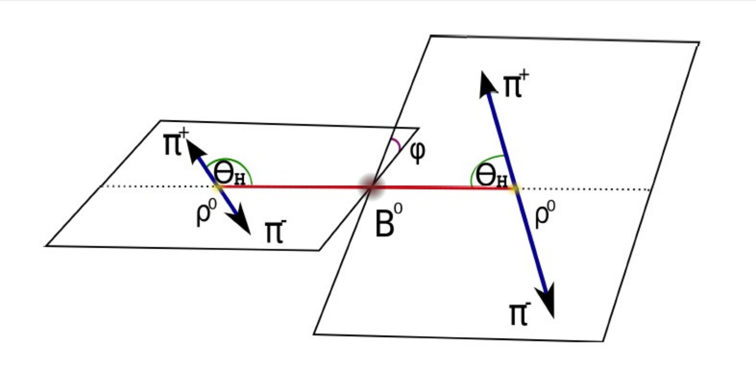
[1] Y.-T. Duh et al. (Belle Collaboration), Phys. Rev. D 87, 031103(R) (2012).
[2] Y. Chao et al. (Belle Collaboration), Phys. Rev. Lett. 94, 181803 (2005).

$B^0 \rightarrow \rho^0\rho^0$ arXiv:1212.4015

- $B^0 \rightarrow \rho^0\rho^0$ is dominated by a $b \rightarrow u\bar{u}d$ tree decay
  - The decay is not a CP eigenstate.
  - Helicity analysis is required.



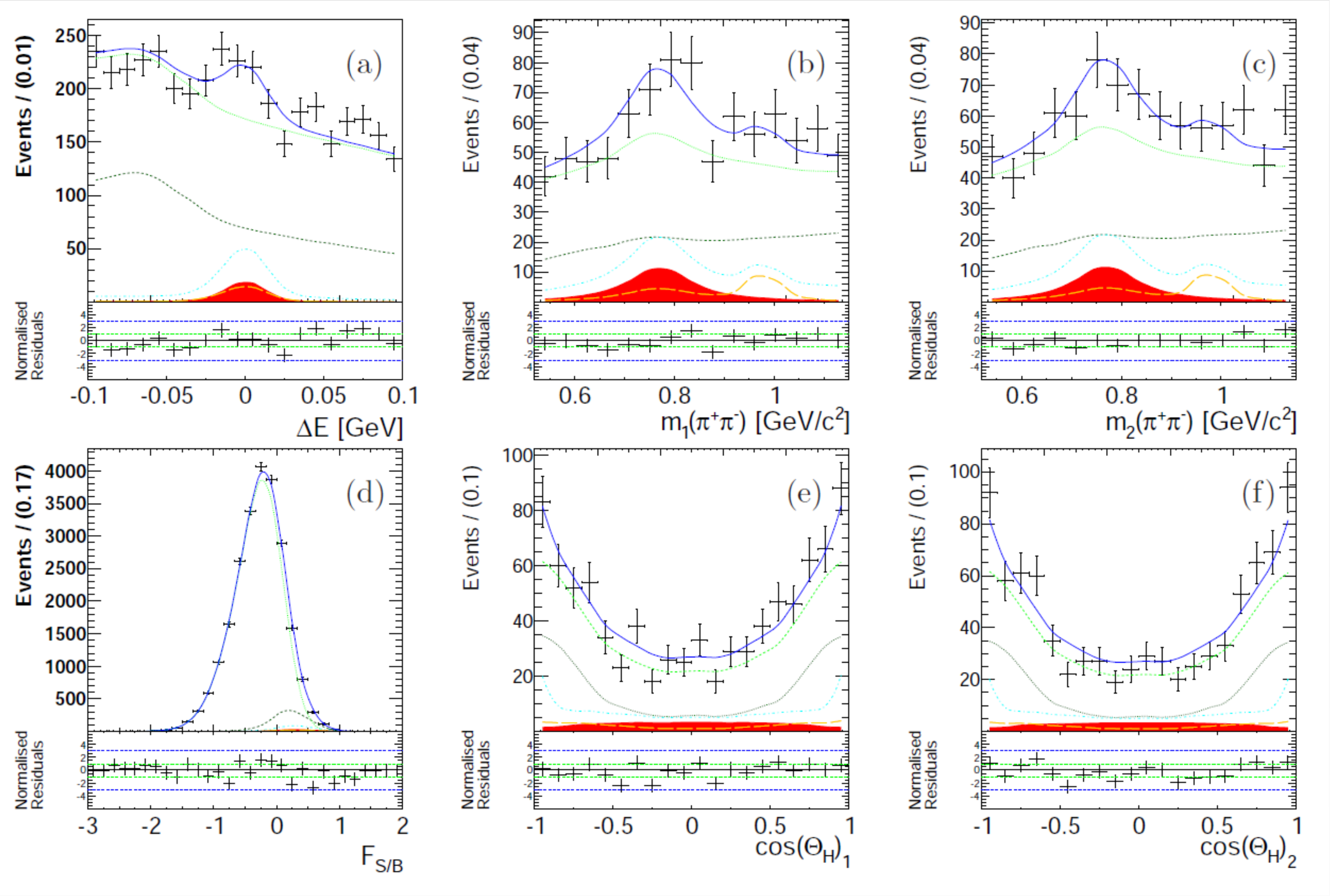
- Major background from $B \rightarrow 4\pi$ decays, including resonant modes:
- Several $B \rightarrow 4\pi$ modes are studied: $B^0 \rightarrow \rho^0\rho^0$, $B^0 \rightarrow f_0f_0$, $B^0 \rightarrow f_0\rho^0$, $B^0 \rightarrow f_0\pi^+\pi^-$, $B^0 \rightarrow \rho^0\pi^+\pi^-$, $B^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$;
- Events with two charged pion pairs are selected.
  - Invariant mass and helicity angle are calculated for both pairs.



$B^0 \rightarrow \rho^0\rho^0$

arXiv:1212.4015

- Fit to 6 variables:
- ΔE, $m_{1,2}(\pi^+\pi^-)$, $\cos(\Theta_H)_{1,2}$, $\mathcal{F}$ (fisher discriminant).
- $B^0 \rightarrow \rho^0\rho^0$;
- $B^0 \rightarrow f_0\rho^0$;
- $B^0 \rightarrow 4\pi$;
- Non-peaking BB;
- All Non-peaking.

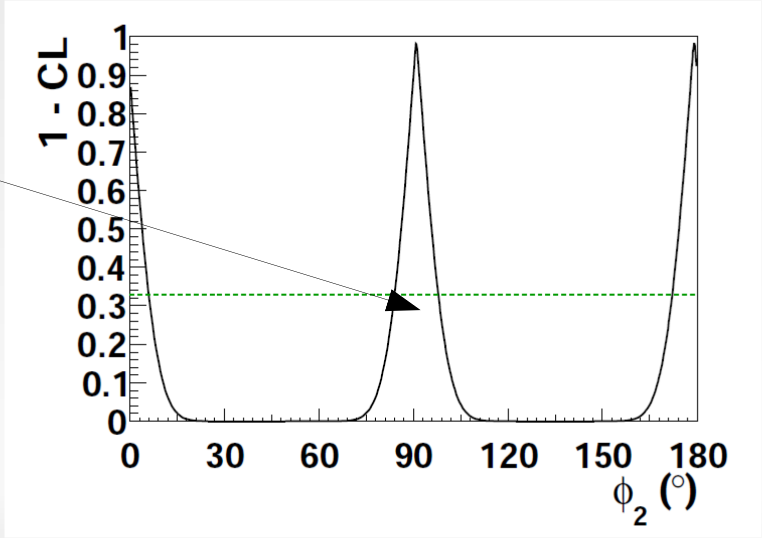


$B^0 \to \rho^0\rho^0$

arXiv:1212.4015

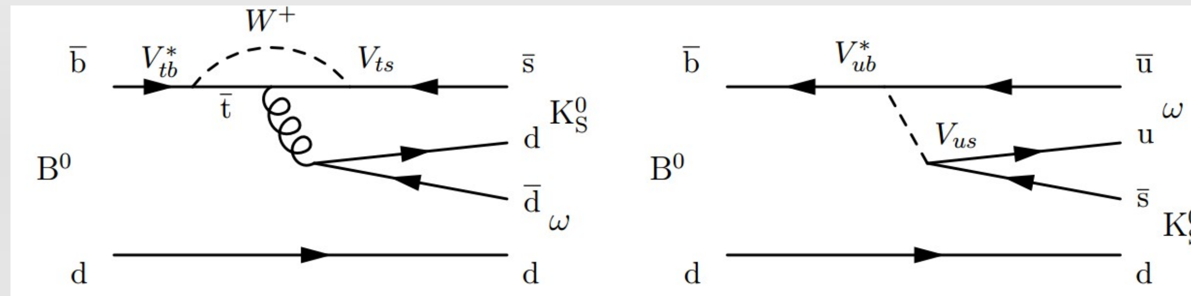
Branching fraction ($\times 10^{-6}$)	Events	UL ($\times 10^{-6}$)	$\mathcal{S}$ (σ)
$\mathcal{B}(B^0 \to \rho^0\rho^0) = 1.02 \pm 0.30 \pm 0.22$	166	< 1.5	2.9
$f_L = 0.21^{+0.18}_{-0.22} \pm 0.11$	-	-	
$\mathcal{B}(B^0 \to \pi^+\pi^-\pi^+\pi^-) = -3.58^{+7.75}_{-7.19} \pm 2.99$	-25	< 11.7	-
$\mathcal{B}(B^0 \to \rho^0\pi^+\pi^-) = 1.70^{+4.21}_{-4.12} \pm 5.30$	33	< 12.2	< 1
$\mathcal{B}(B^0 \to f_0\pi^+\pi^-) \times \mathcal{B}(f_0 \to \pi^+\pi^-) = -1.34^{+2.12}_{-1.97} \pm 0.98$	-27	< 3.1	-
$\mathcal{B}(B^0 \to f_0\rho^0) \times \mathcal{B}(f_0 \to \pi^+\pi^-) = 0.86 \pm 0.27 \pm 0.15$	149	-	3.0
$\mathcal{B}(B^0 \to f_0 f_0) \times \mathcal{B}(f_0 \to \pi^+\pi^-)^2 = 0.03^{+0.10}_{-0.09} \pm 0.04$	-5	< 0.2	-

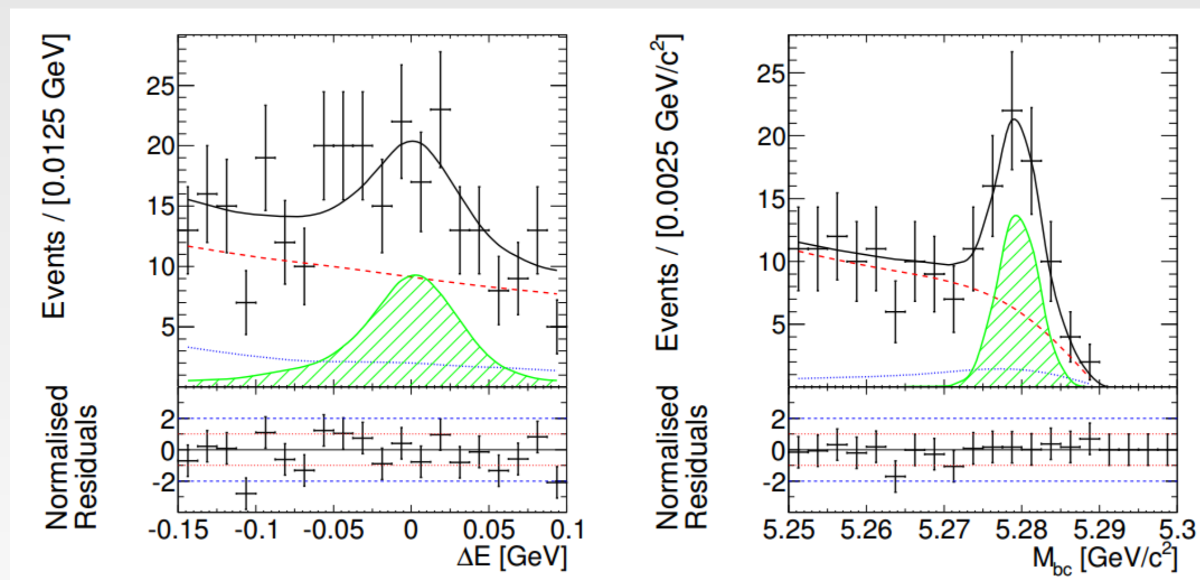
- First evidence for $B^0 \to f_0\rho^0$.
- Constraint put on ϕ_2: $\phi_2 = (91.0 \pm 7.2)^\circ$
  - Via Isospin analysis using $B^0 \to \rho^0\rho^0$ (only the longitudinal fraction), and current HFAG values and BaBar PRD **76**, 051007 (2007).



$B^0 \rightarrow \omega K_S$

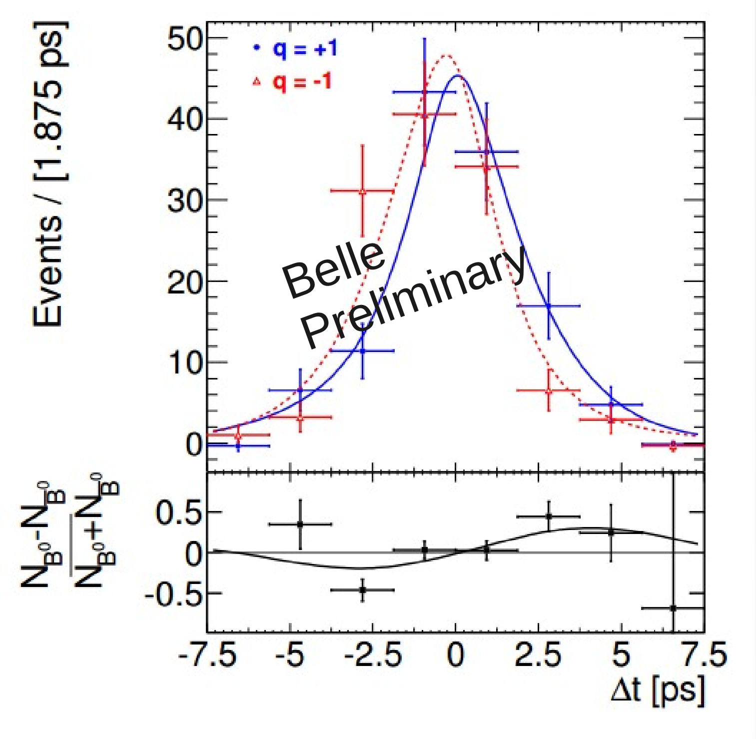
- Both tree and penguin diagrams can contribute.
- ω is constructed as $\omega \rightarrow \pi^+\pi^0\pi^-$, and K_S in the decay $K_S \rightarrow \pi^+\pi^-$.
- Branching fractions and CP parameters extracted via a seven dimensional fit to:
- M_{bc}, ΔE, likelihood ratio, $m_{3\pi}$, cos $(\Theta H)_{3\pi}$, Δt, and q.
- Mbc and DE distributions show signal, BB background and qq background.





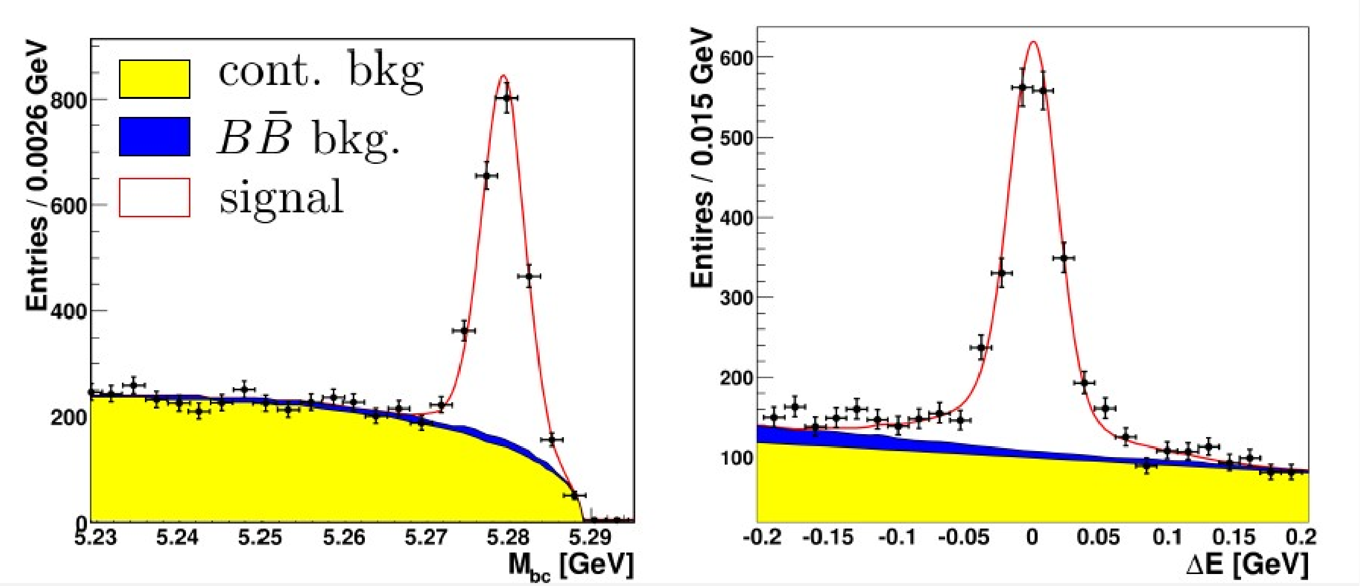
$B^0 \to \omega K_s$

- Preliminary results:
  Both $B^0 \to \omega K_s$ and $B^+ \to \omega K^+$ measured:
- $$\mathcal{B}(B^0 \to \omega K^0) = (4.5 \pm 0.4(stat) \pm 0.3(syst)) \times 10^{-6}$$
  $$\mathcal{B}(B^+ \to \omega K^+) = (6.8 \pm 0.4(stat) \pm 0.4(syst)) \times 10^{-6}$$
- First evidence of CPV in $B^0 \to \omega K_s$:
- $$\mathcal{S}_{\omega K^0_S} = +0.91 \pm 0.32(stat) \pm 0.05(syst)$$
  $$\mathcal{A}_{\omega K^0_S} = -0.36 \pm 0.19(stat) \pm 0.05(syst)$$



$B^0 \to \eta' K_S$

- Dominant diagram is a b → s penguin diagram. A_{CP} expected to be small, but S_{CP} can be sensitive to new loop physics.
- The decay is reconstructed via: $\eta' \to \eta\pi^+\pi^-$ (with $\eta \to \gamma\gamma$, or $\eta \to \pi^+\pi^0\pi^-$), and $\eta' \to \rho^0\gamma$. The K_S is reconstructed via $K_S \to \pi^+\pi^-$ or $K_S \to \pi^0\pi^0$ (except where there is also a π^0 from the η' decay).
- Fit is performed to 3 variables: M_{bc}, ΔE, and a likelihood ratio.

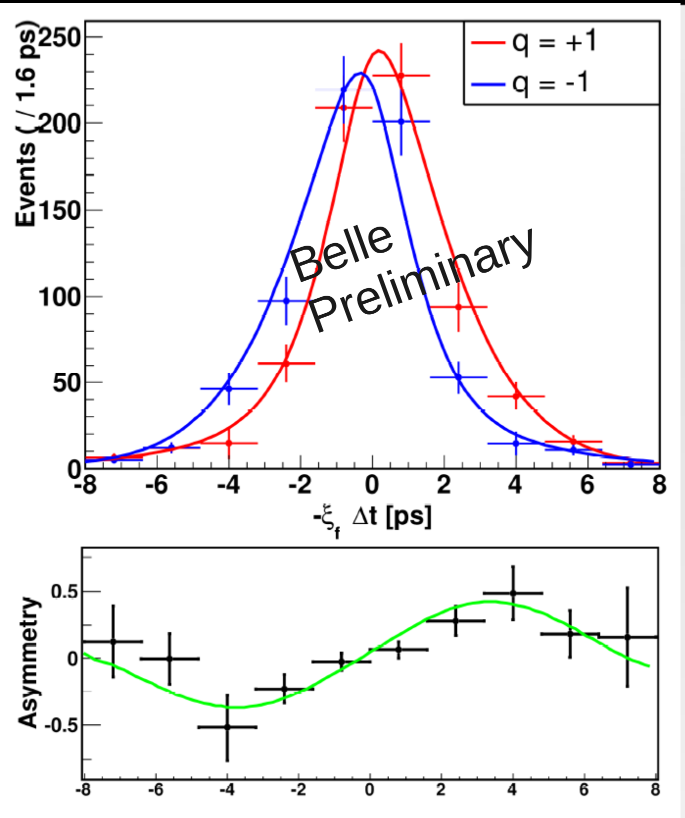


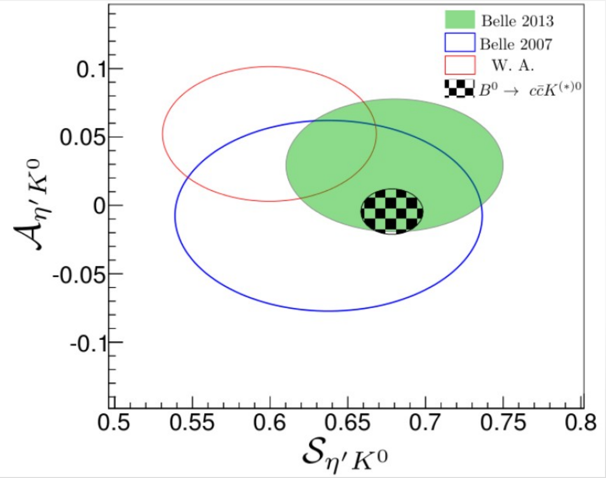
$B^0 \to \eta' K_S$

- Preliminary results.
- CP violation parameters:

$$\mathcal{S}_{\eta' K^0} = 0.68 \pm 0.07(stat) \pm 0.03(syst)$$
$$\mathcal{A}_{\eta' K^0} = +0.03 \pm 0.05(stat) \pm 0.03(syst)$$

- A_{CP} is consistent with zero;
- S_{CP} is consistent with sin $2\phi_1$ measurements from charmed B decays, such as b $J/\psi K_S$.
- Preliminary result would represent most sensitive measurement in this channel.





Summary

- Results of four CP violation analyses have been presented:
- $B^0 \to \pi^+\pi^-$:

$$\mathcal{A}_{CP}(B^0 \to \pi^+\pi^-) = +0.33 \pm 0.06\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst}),$$
$$\mathcal{S}_{CP}(B^0 \to \pi^+\pi^-) = -0.64 \pm 0.08\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst}),$$

- $B^0 \to \rho^0\rho^0$: $\phi_2 = (91.0 \pm 7.2)^\circ$
  - Also first evidence for $B^0 \to f_0\rho^0$:

$$\mathcal{B}(B^0 \to f_0\rho^0) \times \mathcal{B}(f_0 \to \pi^+\pi^-) = (0.86 \pm 0.27\ (\mathrm{stat}) \pm 0.15\ (\mathrm{syst})) \times 10^{-6}$$

- $B^0 \to \omega K_S$:

$$\mathcal{S}_{\omega K^0_S} = +0.91 \pm 0.32(stat) \pm 0.05(syst)$$
$$\mathcal{A}_{\omega K^0_S} = -0.36 \pm 0.19(stat) \pm 0.05(syst)$$

- $B^0 \to \eta' K_S$:

$$\mathcal{S}_{\eta' K^0} = 0.68 \pm 0.07(stat) \pm 0.03(syst)$$
$$\mathcal{A}_{\eta' K^0} = +0.03 \pm 0.05(stat) \pm 0.03(syst)$$