

# Measurements of CP Violation in B decays at Belle



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**Division of Particles and Fields  
of the American Physical Society**  
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# Quark Mixing in SM

Standard Model quark mixing :

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & \textcircled{V_{ub}} \\ V_{cd} & V_{cs} & V_{cb} \\ \textcircled{V_{td}} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa  
(CKM) matrix ( $V_{\text{CKM}}$ )

$$\begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & \underline{\frac{A\lambda^3(\rho - i\eta)}{A\lambda^2}} \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ \underline{A\lambda^3(1 - \rho - i\eta)} & -A\lambda^2 & 1 \end{pmatrix}$$

$$\lambda=0.22$$

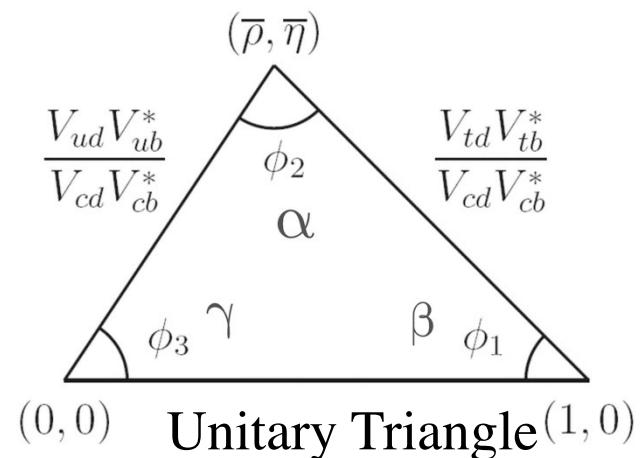
*CP violation enters the SM through the complex phase in the CKM matrix*

Unitarity relation ( $V_{\text{CKM}} V_{\text{CKM}}^+ = 1$ )

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



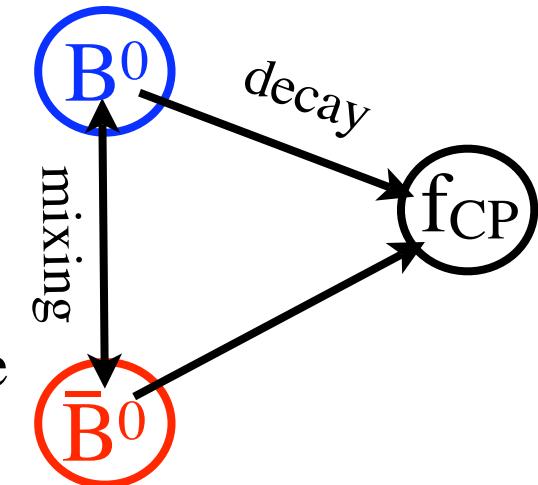
Determination of angles/sides is closely related to measurements of CP asymmetries



# Time-dependent CP Asymmetry

Interference between  $B^0 \rightarrow f_{CP}$  and  $B^0 \rightarrow \bar{B}^0 \rightarrow f_{CP}$

- $B^0$ - $\bar{B}^0$  mixing : A neutral B meson can transform into its own anti-particle
- Both the  $B^0$  and its anti-particle  $\bar{B}^0$  can decay to the same state final state.
- CP violation arises from interference between mixing and decay amplitudes.



Time dependent CP asymmetry

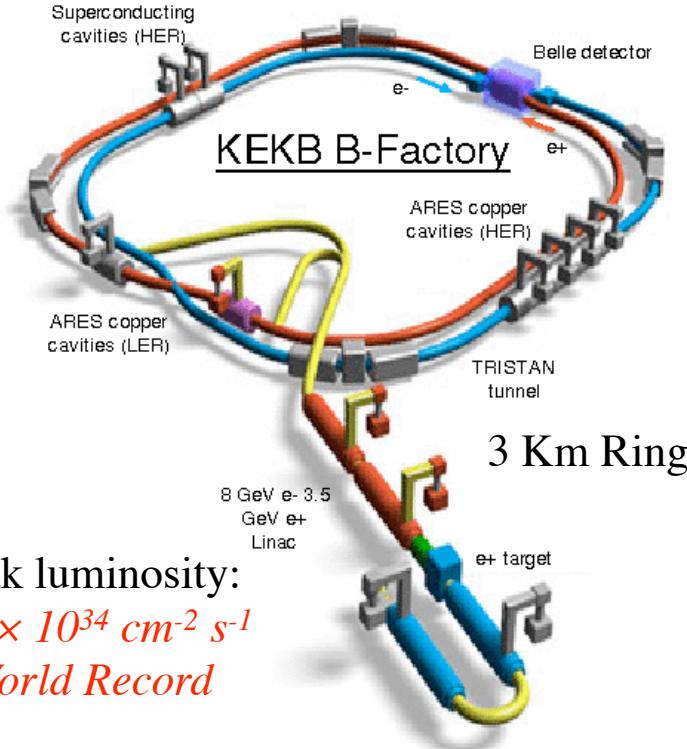
$$\mathcal{A}(\Delta t) = \frac{\Gamma(\bar{B}^0(\Delta t) \rightarrow f_{cp}) - \Gamma(B^0(\Delta t) \rightarrow f_{cp})}{\Gamma(\bar{B}^0(\Delta t) \rightarrow f_{cp}) + \Gamma(B^0(\Delta t) \rightarrow f_{cp})}$$
$$= \underbrace{\frac{2 Im \lambda}{1+|\lambda|^2} \sin(\Delta m \cdot \Delta t)}_{\mathcal{S}} - \underbrace{\frac{1-|\lambda|^2}{1+|\lambda|^2} \cos(\Delta m \cdot \Delta t)}_{\mathcal{A}}$$

$$\lambda = \frac{q}{p} \frac{A(\bar{B}^0 \rightarrow f)}{A(B^0 \rightarrow f)}$$

Mixing-induced CPV

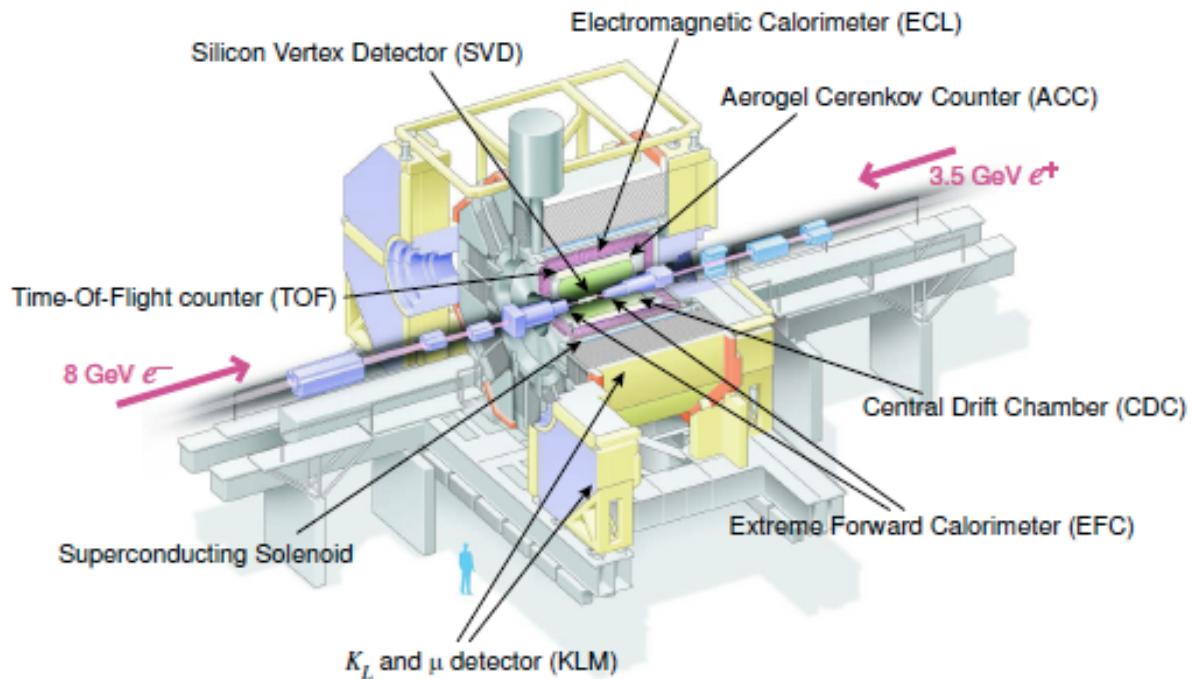
Direct CPV

# Belle Experiment



8 GeV e- on 3.5 GeV e+  
boost  $\beta\gamma=0.43$

## Belle Detector



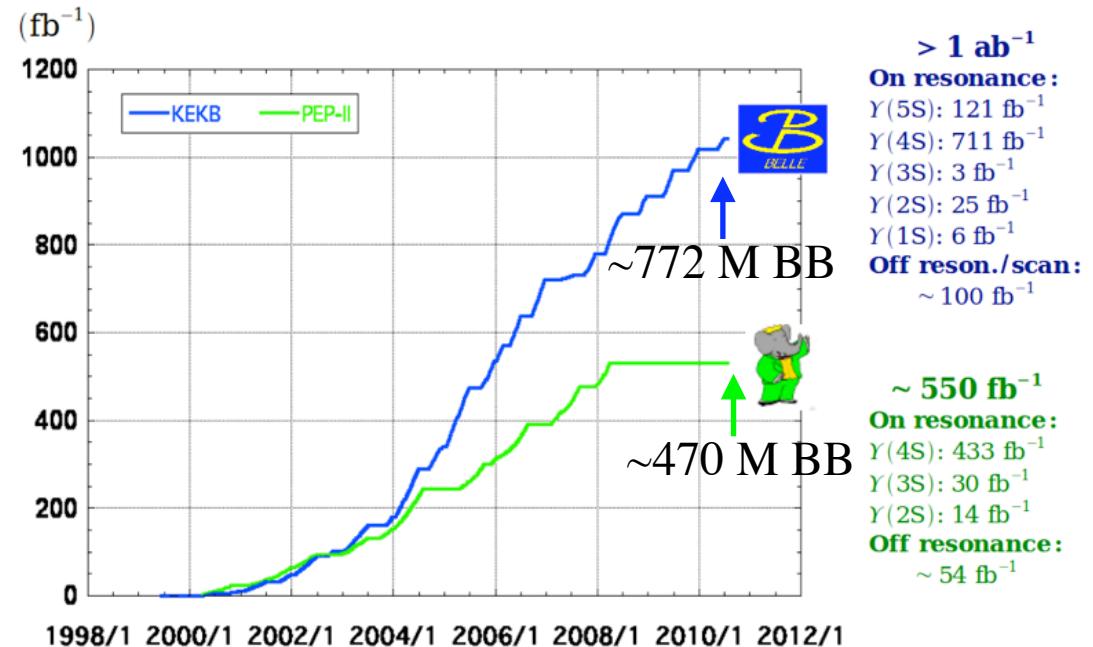
SVD : measures B meson decay vertex position

Asymmetric B factory: Belle at KEK-B

# Luminosity

Full data sample at Y(4S) resonance :  $\sim 772 \text{ M } B\bar{B}$  pairs

## Integrated luminosity of B factories



KEKB and Belle stopped operation on June 30, 2010



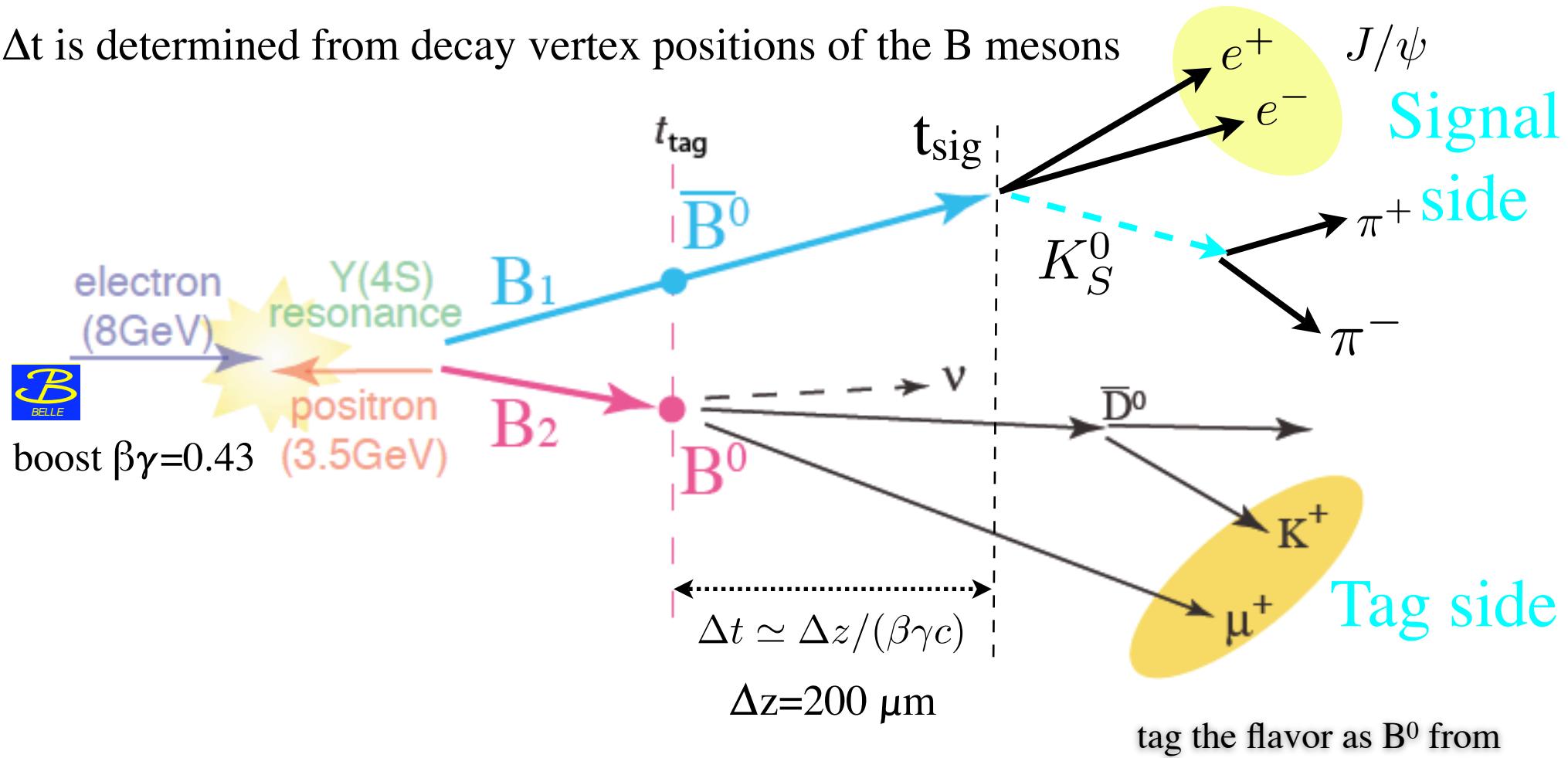
KEKB Control room

Upgrades to Belle II and superKEKB have already started.

→ See talk by James Fast

# CPV Analysis Technique

$\Delta t$  is determined from decay vertex positions of the B mesons



Decay rate

$$\mathcal{P}(q=\pm 1, \Delta t) = \frac{1}{4\tau_B} e^{-\frac{|\Delta t|}{\tau_B}} [1 \pm (\mathcal{S} \sin \Delta m \Delta t + \mathcal{A} \cos \Delta m \Delta t)] \otimes \mathcal{R}$$

$$q = \begin{cases} +1 : B^0 \text{ tagged} \\ -1 : \bar{B}^0 \text{ tagged} \end{cases}$$

$\mathcal{R}$  : detector resolution

$w$  : wrong tag fraction  
(mis identification of flavor)

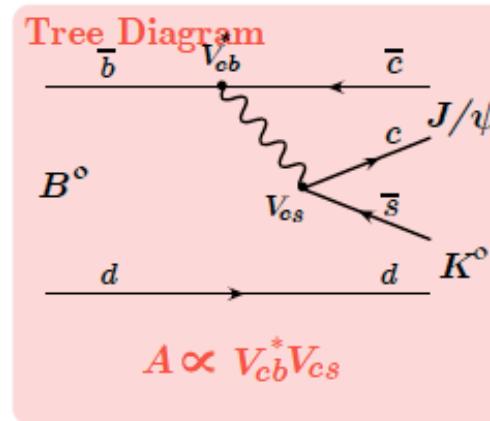
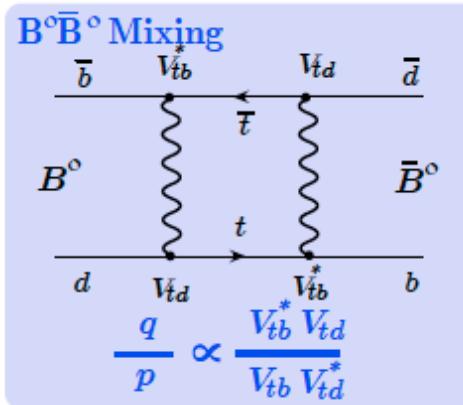
tag the flavor as  $B^0$  from decay product(s)

# B $\rightarrow$ (c $\bar{c}$ )K $^0$ decay modes

## B $\rightarrow$ Charmonium K $^0$ : Golden modes for CP Violation measurements

- Clean Experimental Signature
  - Many accessible modes with (relatively) Large BFs
  - Low Background Levels, high efficiency
- Clean Extraction of CKM angle
  - Dominated by tree diagram
  - Leading penguin diagram has the same weak phase as tree

$$\begin{aligned} B^0 \rightarrow J/\psi K^0 &\sim 8.7 \times 10^{-4} \\ B^0 \rightarrow \psi' K^0 &\sim 6.2 \times 10^{-4} \\ B^0 \rightarrow \chi_{c1} K^0 &\sim 3.9 \times 10^{-4} \\ B^0 \rightarrow \eta_c K^0 &\sim 8.9 \times 10^{-4} \end{aligned}$$



SM expectation

$$\lambda = \frac{q}{p} \frac{\bar{A}}{A} = \eta_{ep} e^{-i z \phi_1} \rightarrow \boxed{\begin{aligned} \mathcal{S} &= -\eta_{ep} \sin 2\phi_1 \\ \mathcal{A}(-C) &= 0 \end{aligned}}$$

$$\mathcal{A}(\Delta t) = -\eta_{ep} \sin 2\phi_1 \sin(\Delta m \cdot \Delta t)$$

# B $\rightarrow$ (c $\bar{c}$ )K $^0$ signals

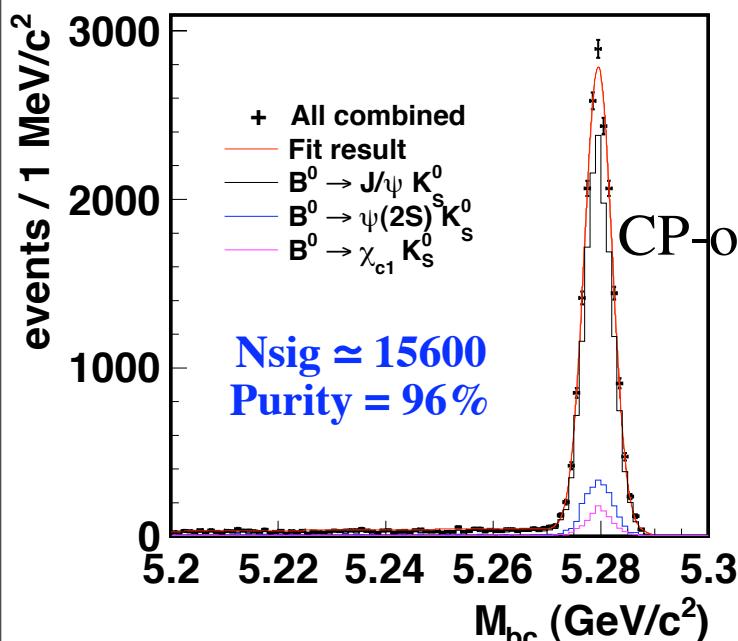
Preliminary!

- Belle's new result with full data sample (772 M BB).
- More data and improved tracking  $\Rightarrow$  nearly 50% more signal than previous analysis.

B candidates selection using  $\Delta E$  and  $M_{bc}$ :

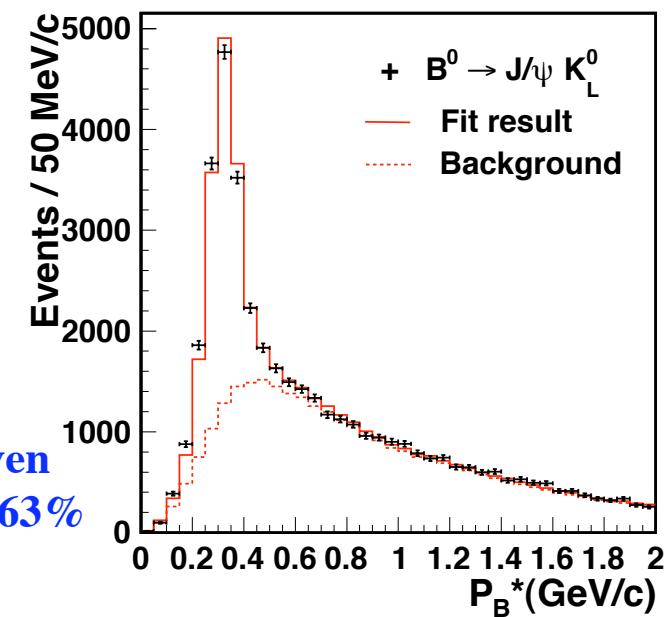
$$\Delta E \equiv E_B^* - E_{\text{beam}}^* \quad M_{bc} \equiv \sqrt{(E_{\text{beam}}^*)^2 - (p_B^*)^2}$$

$P_{B^*}$  for  $K_L$ : only  $K_L$  direction is measured; missing momentum is calculated using known B energy and  $K_L$  direction.



decay modes	signal Yield
$B^0 \rightarrow J/\psi K_S$	$12681 \pm 114$
$B^0 \rightarrow \psi' K_S$	$1981 \pm 46$
$B^0 \rightarrow \chi_{c1} K_S$	$943 \pm 33$
$B^0 \rightarrow J/\psi K_L$	$10041 \pm 154$

CP-even  
purity=63%



$B^0 \rightarrow J/\psi K^0$   
 $J/\psi \rightarrow ee, \mu^+\mu^-$   
 $K_S \rightarrow \pi^+\pi^-$   
 $K_L$  : cluster  
 $B^0 \rightarrow \psi' K_S$   
 $\psi' \rightarrow ee, \mu^+\mu^-, J/\psi\pi^+\pi^-$   
 $B^0 \rightarrow \chi_{c1} K_S$   
 $\chi_{c1} \rightarrow J/\psi\gamma$



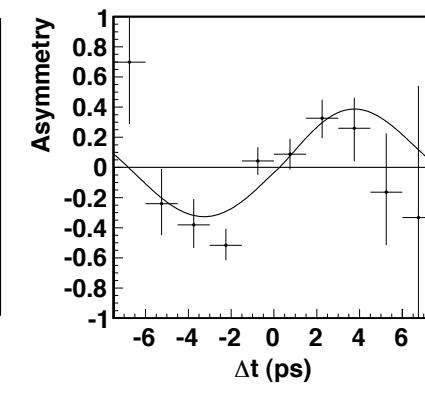
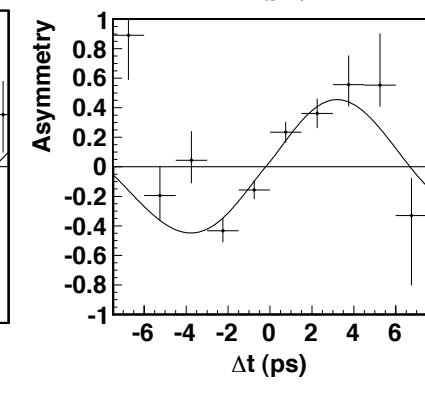
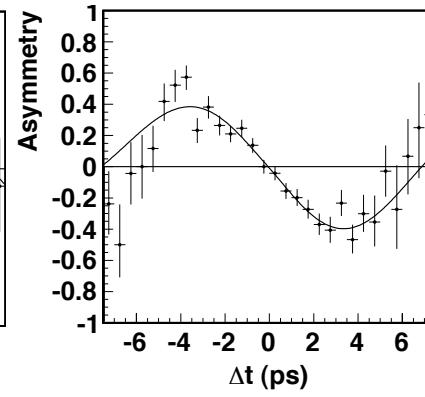
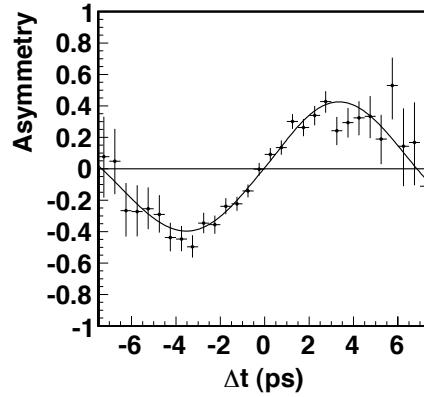
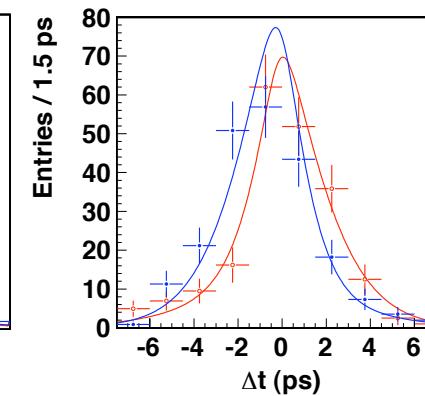
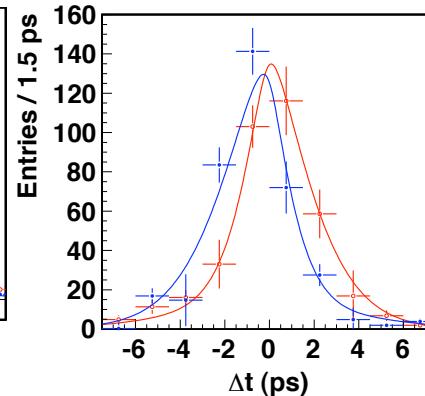
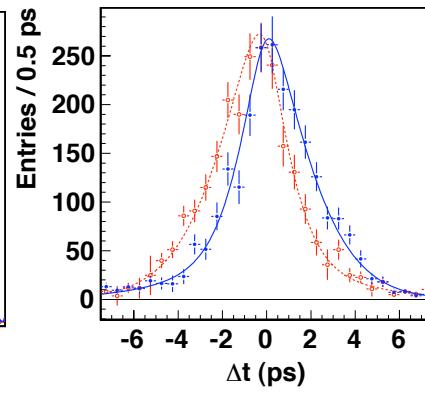
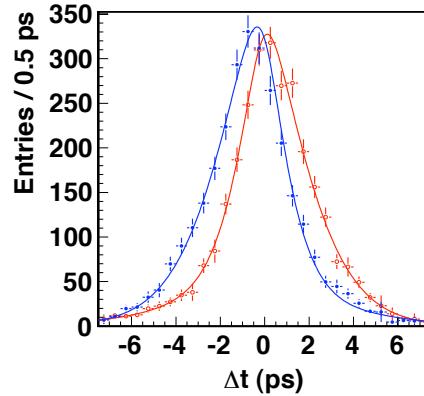
# $\sin 2\phi_1$ in $B \rightarrow (c\bar{c})K^0$ decays

Preliminary!



772 M  $B\bar{B}$

Background subtracted, good tagged only



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

$B^0 \rightarrow J/\psi K_S$

$\mathcal{S} = 0.671 \pm 0.029$

$\mathcal{A} = -0.014 \pm 0.021$

$B^0 \rightarrow J/\psi K_L$

$\mathcal{S} = -0.641 \pm 0.047$

$\mathcal{A} = 0.019 \pm 0.026$

$B^0 \rightarrow \psi' K_S$

$\mathcal{S} = 0.739 \pm 0.079$

$\mathcal{A} = 0.103 \pm 0.055$

$B^0 \rightarrow \chi_{c1} K_S$

$\mathcal{S} = 0.636 \pm 0.117$

$\mathcal{A} = -0.023 \pm 0.083$

(stat errors only)

CP Violation is observed in all modes

# 2011 measurement of $\sin 2\phi_1$ at Belle

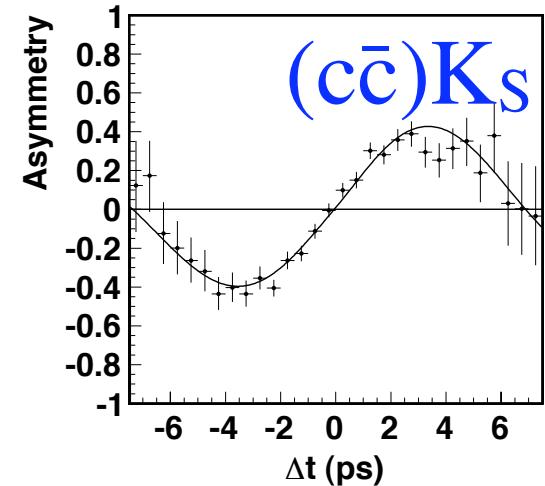
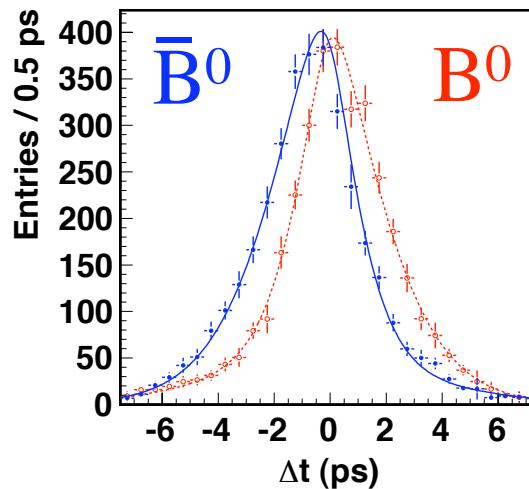


772 M  $B\bar{B}$

Preliminary!

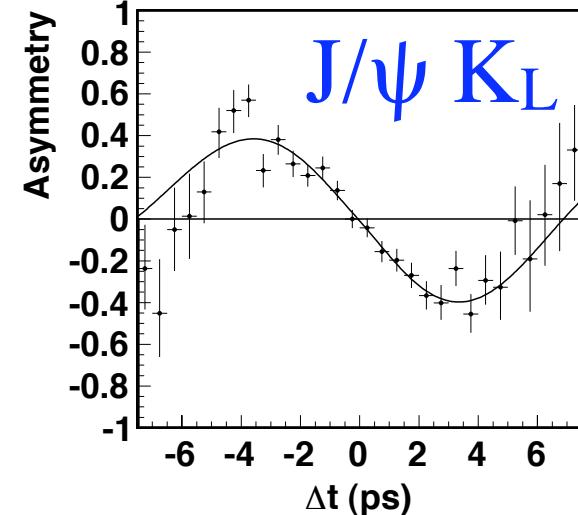
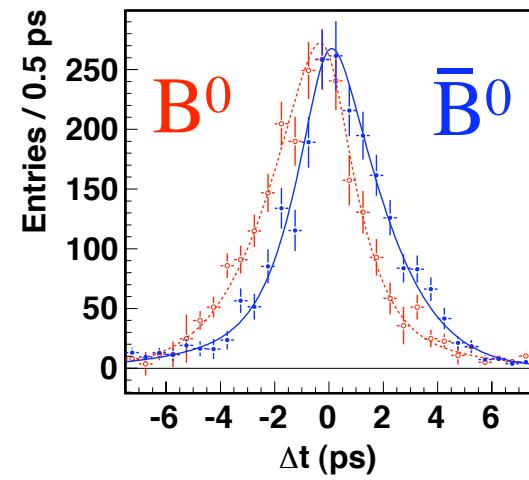
CP-odd

$B^0 \rightarrow J/\psi K_S$   
 $B^0 \rightarrow \psi' K_S$   
 $B^0 \rightarrow \chi_{c1} K_S$



CP-even

$B^0 \rightarrow J/\psi K_L$



Combined result to all charmonium modes

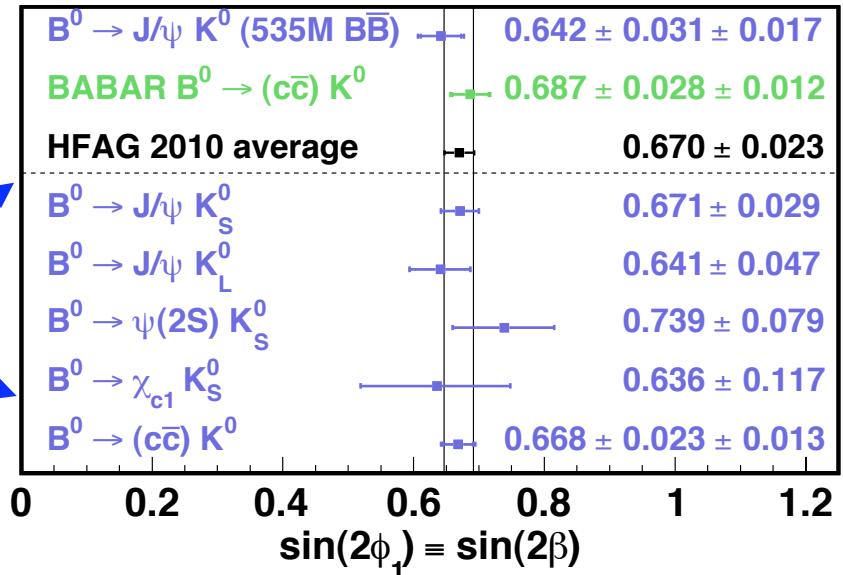
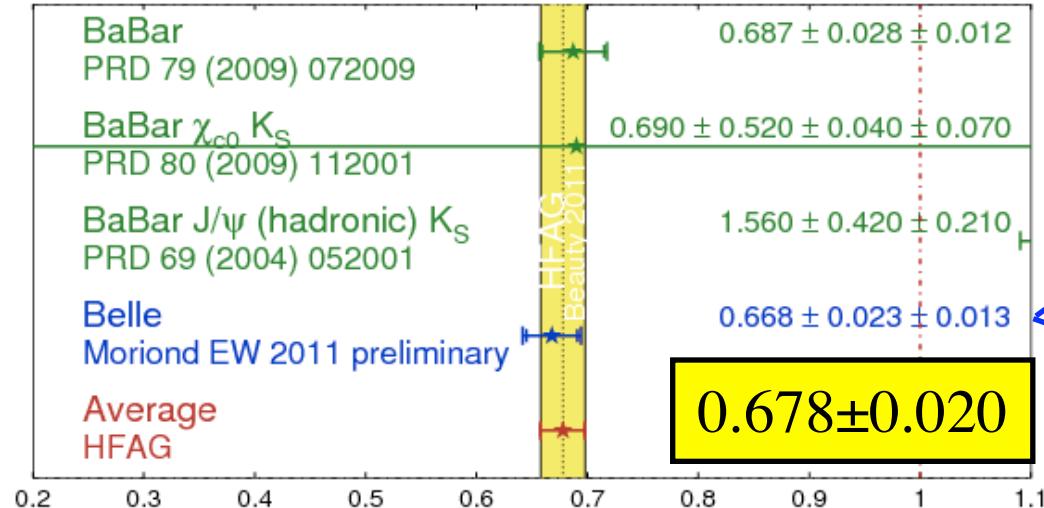
$$\begin{aligned}\sin 2\phi_1 &= 0.668 \pm 0.023(\text{stat}) \pm 0.013(\text{syst}) \\ \mathcal{A} &= 0.007 \pm 0.016(\text{stat}) \pm 0.013(\text{syst})\end{aligned}$$

World's most precise  
measurements

# $\sin 2\phi_1$ : 2011 World Average

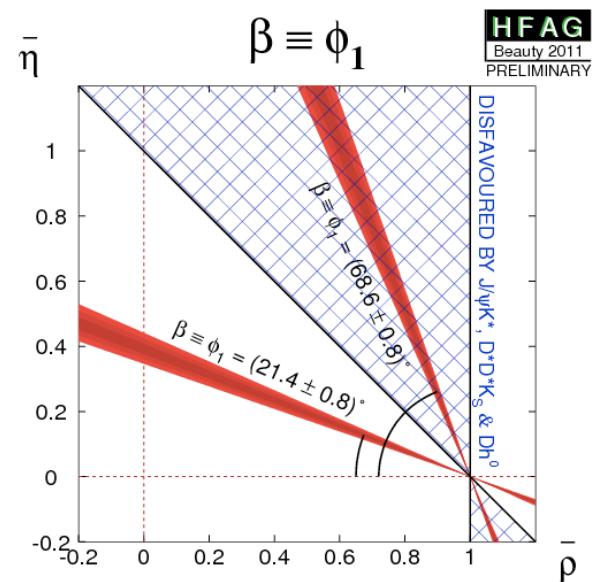
$$\sin(2\beta) \equiv \sin(2\phi_1)$$

HFAG  
Beauty 2011  
PRELIMINARY

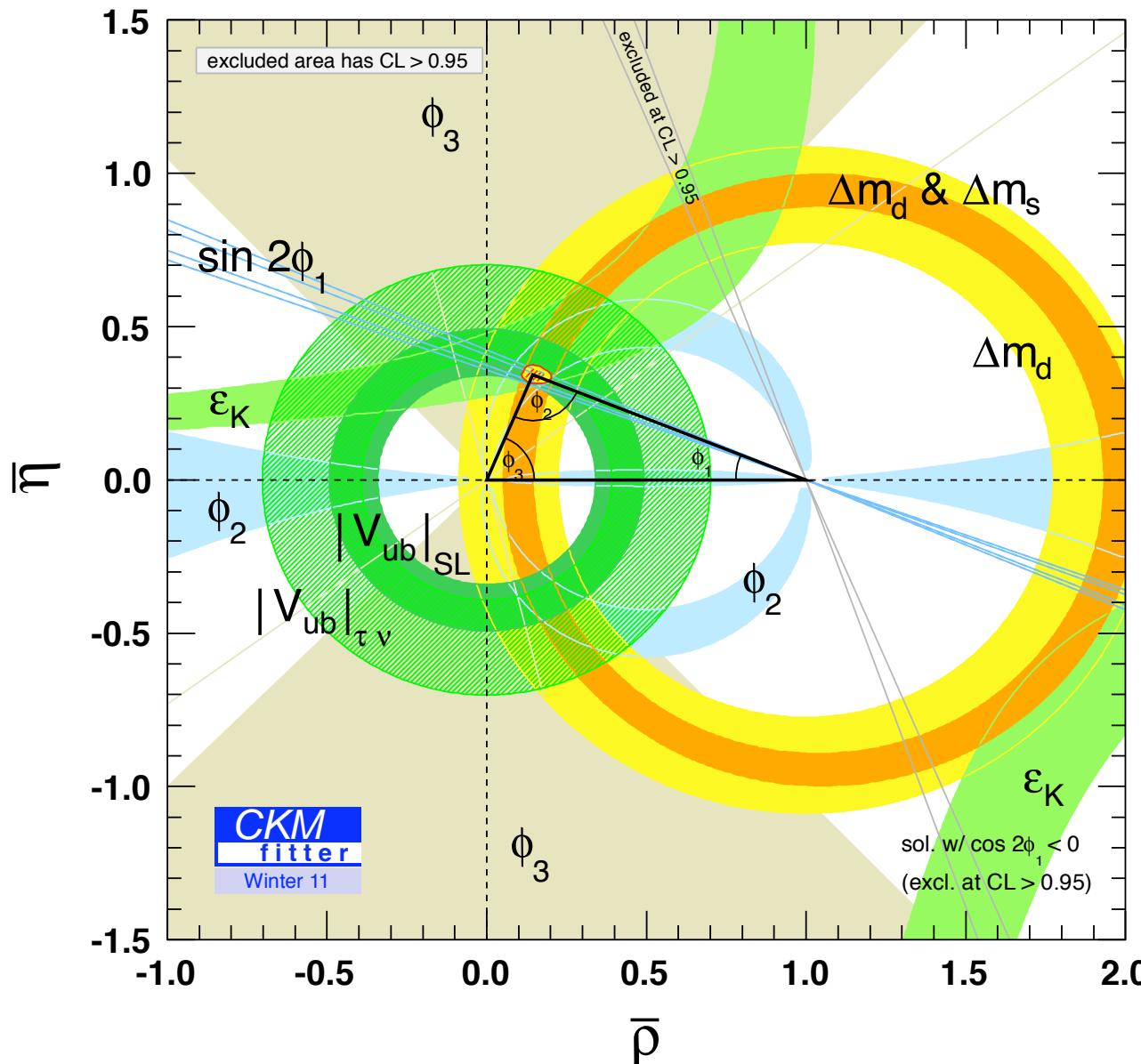


- Experimental uncertainty on  $\sin 2\phi_1 \sim 3\%$  (Reference point for NP search).
- $\mathcal{A}$  value is consistent with zero ( $\mathcal{A} = -0.013 \pm 0.017$ ).
- CKM angle  $\phi_1(\beta)$  is measured with  $< 1^\circ$  precision.

$$\phi_1(\beta) = (21.4 \pm 0.8)^\circ$$



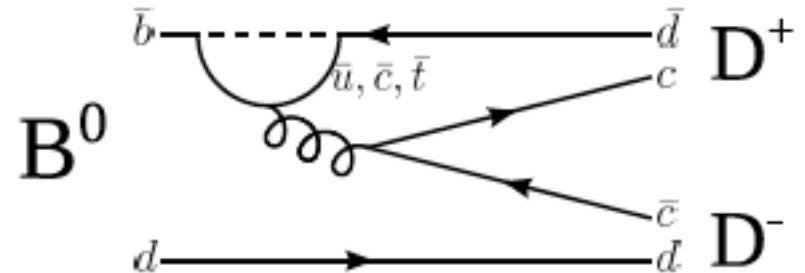
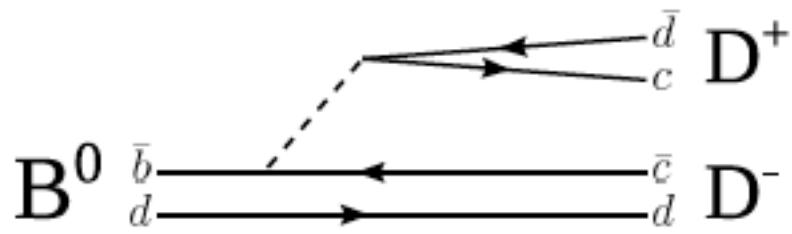
# 2011 picture of SM



Global fit result by CKM fitter

$\sin 2\phi_1$  is the most precise measurement of the Unitary Triangle.

# TCPV in $b \rightarrow c\bar{c}d$ decays



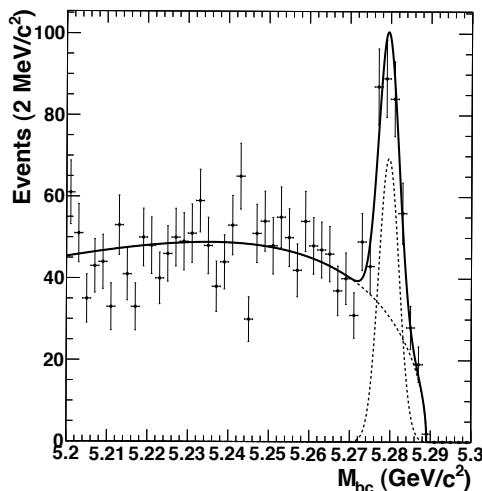
Similar diagrams for  $B^0 \rightarrow D^{*+} D^{*-}$

- Dominant contribution is from the tree-diagram.
- SM prediction :  $S = -\sin 2\phi_1$  and  $A = 0$  (Z.-Z Xing, PRD 61, 014010 (1999))
- Penguins can also contribute : changes the values of  $S$  and  $A$  by a few percent.
- Large deviation from  $\sin 2\phi_1$  will be clear hint of NP.

# Branching Fraction in $B^0 \rightarrow D^+D^-$



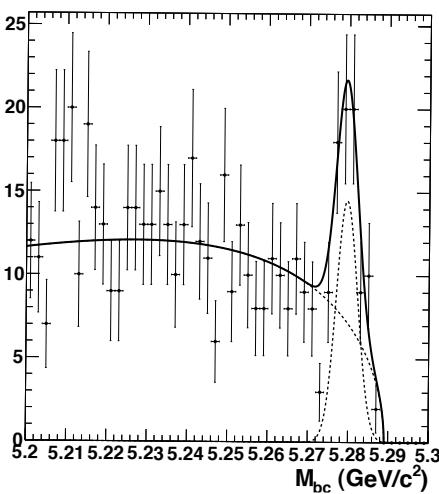
Preliminary!



$(K^-\pi^+\pi^+) (K^+\pi^-\pi^-)$

$N_{\text{sig}} = 221.4 \pm 18.6$

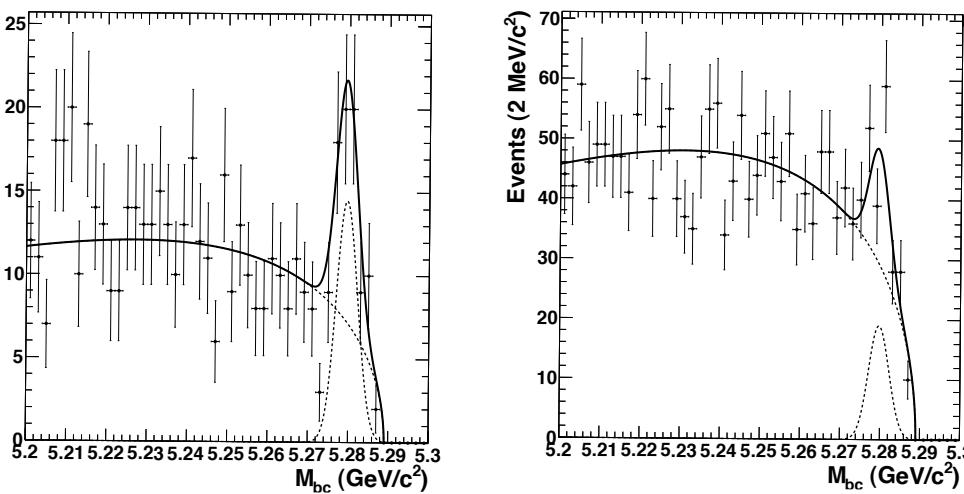
$\mathcal{B} = (2.16 \pm 0.18) \times 10^{-4}$



$(K^-\pi^+\pi^+) (K_S^0\pi^-)$

$N_{\text{sig}} = 48.0 \pm 8.9$

$\mathcal{B} = (1.96 \pm 0.36) \times 10^{-4}$



$(K^-\pi^+\pi^+) (K_S^0\pi^-\pi^0)$

$N_{\text{sig}} = 54.1 \pm 14.6$

$\mathcal{B} = (1.83 \pm 0.49) \times 10^{-4}$

$$\begin{aligned} B^0 \rightarrow D^+D^- &\rightarrow (K^-\pi^+\pi^+) (K^+\pi^-\pi^-) \\ &\rightarrow (K^-\pi^+\pi^+) (K_S^0\pi^-) \\ &\rightarrow (K^-\pi^+\pi^+) (K_S^0\pi^-\pi^0) \end{aligned}$$

Signal Extraction :  
from  $\Delta E$ - $M_{bc}$  2D fit

(systematic errors)

Category	$\delta(BF)$
Tracking efficiency	2.0 %
$K_S^0$ recon. efficiency	1.0 %
$\pi^0$ recon. efficiency	0.5 %
$K/\pi$ selection efficiency	5.4 %
$D$ and $K_S^0$ BF	4.3 %
Number of $B\bar{B}$	1.4 %
Fit model	1.1 %
Event recon. efficiency	1.0 %
$q\bar{q}$ continuum suppression	4.1 %
Total	8.6 %



NEW! Combined result to the three sub-decay modes

$\mathcal{B}(B^0 \rightarrow D^+D^-) = (2.09 \pm 0.15 \pm 0.18) \times 10^{-4}$

Previous Belle result with 535 M BB pairs

$\mathcal{B}(B \rightarrow D^+D^-) = (1.97 \pm 0.20 \pm 0.20) \times 10^{-4}$

Phys. Rev. Lett. 98, 221802 (2007)

# TCPV in $B^0 \rightarrow D^+D^-$

Preliminary!

$K\pi\pi$  and  $K_S\pi$  modes are used in TCPV



NEW!

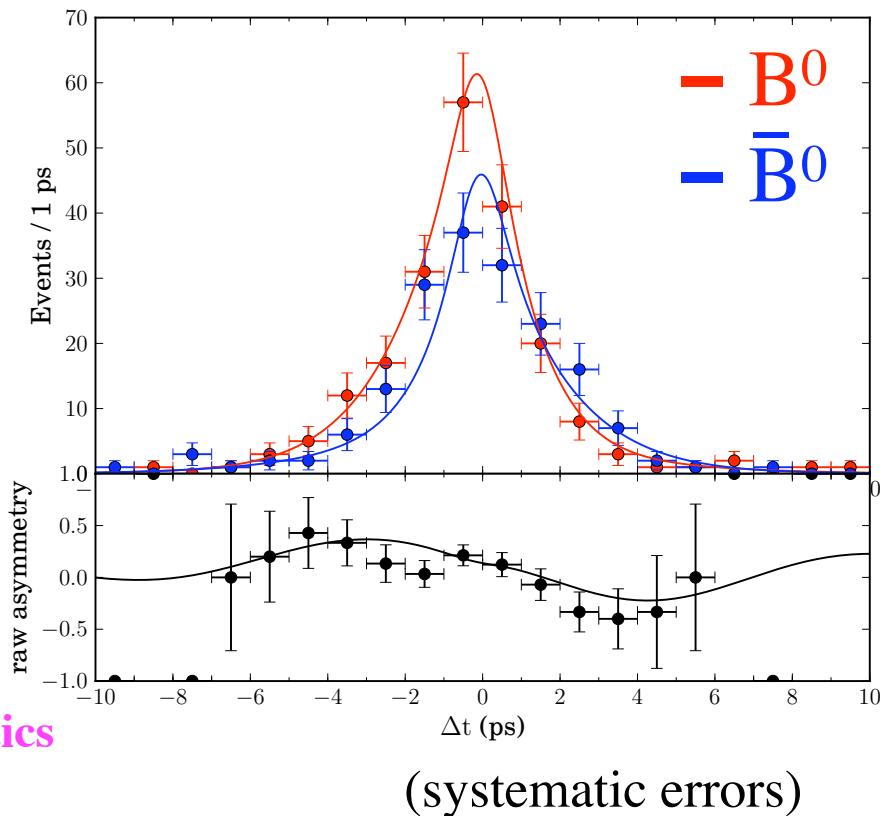
$$\begin{aligned} S &= -1.06 \pm 0.21(\text{stat}) \pm 0.07(\text{syst}) \\ A &= +0.43 \pm 0.17(\text{stat}) \pm 0.04(\text{syst}) \end{aligned}$$

→ The  $A$  value comes closer to zero with larger statistics

Previous Belle result with 535 M BB pairs

$$\begin{aligned} S &= -1.13 \pm 0.37 \pm 0.09 \\ A &= +0.91 \pm 0.23 \pm 0.06 \end{aligned}$$

Phys. Rev. Lett. 98, 221802 (2007)



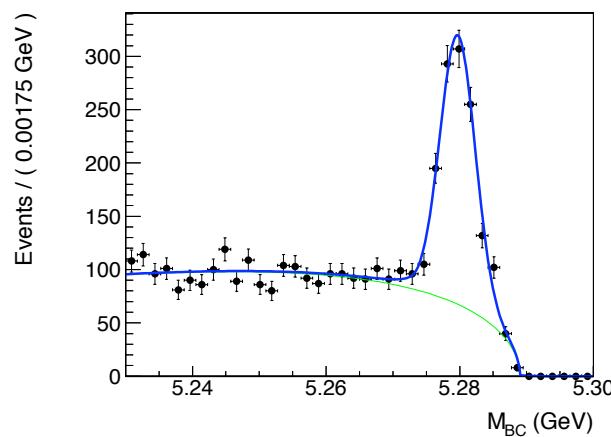
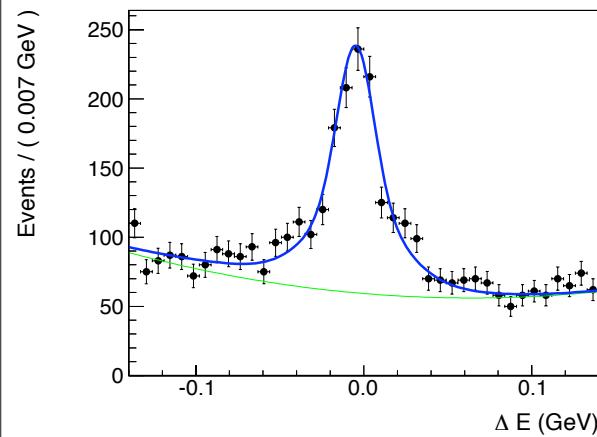
(systematic errors)

Category	$\delta S$	$\delta A$
Vertexing	$\pm 0.011$	$\pm 0.006$
Flavor tagging	$\pm 0.011$	$\pm 0.017$
Vertex resolution	$\pm 0.063$	$\pm 0.022$
Physics parameters	$\pm 0.007$	$\pm 0.004$
Signal fraction	$\pm 0.012$	$\pm 0.019$
Background $\Delta t$	$\pm 0.027$	$\pm 0.006$
Tag-side interference	$\pm 0.001$	$\pm 0.008$
Total	$\pm 0.072$	$\pm 0.036$

# Branching Fraction in $B^0 \rightarrow D^{*+}D^{*-}$



772 M  $B\bar{B}$



Signal Extraction : from  $\Delta E$ - $M_{bc}$  2D fit

**N<sub>sig</sub>=1225±59 events**

Previous Belle result with 657 M  $B\bar{B}$  pairs

**N<sub>sig</sub>=553±30 events**      Phys. Rev. D 80, 111104 (2009)

→ Large improvement is due to more track multiplicity.

**NEW!**

**$\mathcal{B}(B \rightarrow D^{*+}D^{*-}) = (7.82 \pm 0.38 \pm 0.60) \times 10^{-4}$**

**Preliminary!**

$$B^0 \rightarrow D^{*+}(\rightarrow D^+\pi^0) D^{*-}(\rightarrow \bar{D}^0\pi^-)$$

$$B^0 \rightarrow D^{*+}(\rightarrow D^0\pi^+) D^{*-}(\rightarrow D^-\pi^0)$$

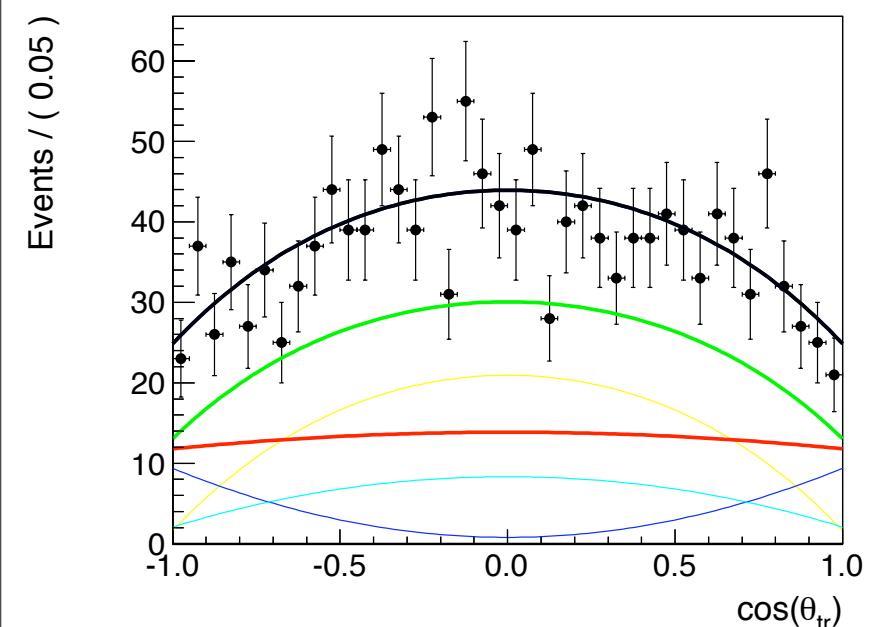
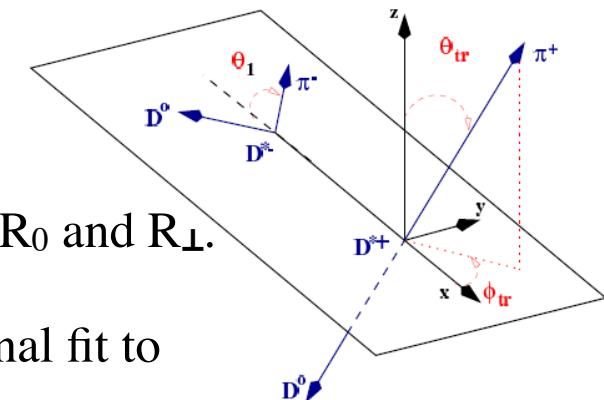
$$B^0 \rightarrow D^{*+}(\rightarrow D^0\pi^+) D^{*-}(\rightarrow \bar{D}^0\pi^-)$$

Nine hadronic D decays are used

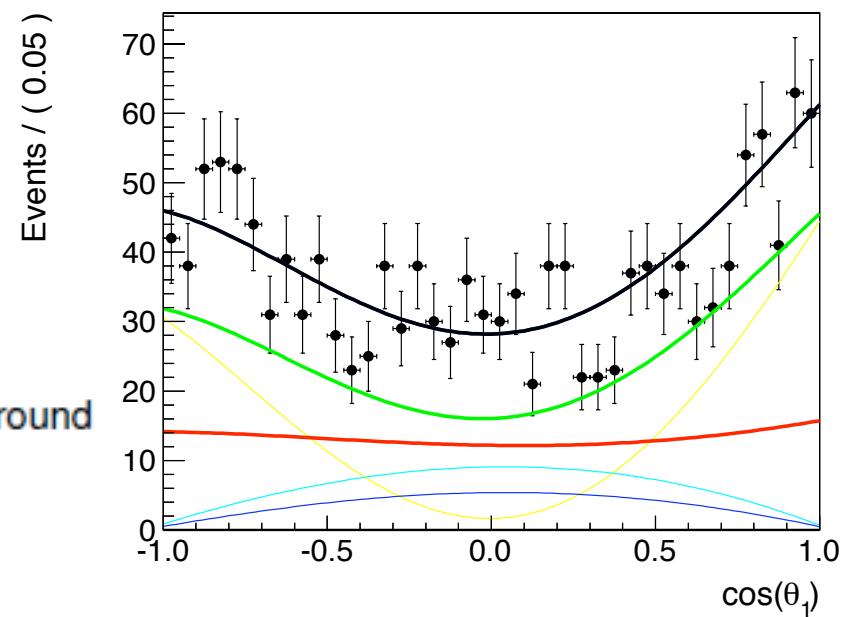
Category	$\delta(BF)$	Category	$\delta(BF)$
Tracking efficiency	1.73 %	Number of $B\bar{B}$	1.40 %
$K_S^0$ recon. efficiency	0.79 %	Fit model	0.24 %
$\pi^0$ recon. efficiency	2.99 %	Event recon. efficiency	0.82 %
$K/\pi$ selection efficiency	5.02 %	Slow $\pi^\pm$ recon. efficiency	3.19 %
$D^-$ and $D^*$ BF	3.13 %		
Total			7.77 %

# Polarization in $B^0 \rightarrow D^{*+} D^{*-}$

- $B^0 \rightarrow D^{*+} D^{*-}$  : mixture of CP-even and CP-odd ( $P \rightarrow VV$  decay)
- Angular analysis is performed to extract CP violation parameters.
- Distributions of angles  $\theta_{tr}$  and  $\theta_1$  give polarization amplitude ratios  $R_0$  and  $R_\perp$ .
- We determine  $S$ ,  $A$ ,  $R_0$  and  $R_\perp$  simultaneously from a five-dimensional fit to the  $\Delta E$ ,  $M_{bc}$ ,  $\cos\theta_{tr}$ ,  $\cos\theta_1$  and  $\Delta t$  distributions.



green: signal  
 red: background  
 orange:  $A_0$   
 blue:  $A_\perp$   
 cyan:  $A_{||}$



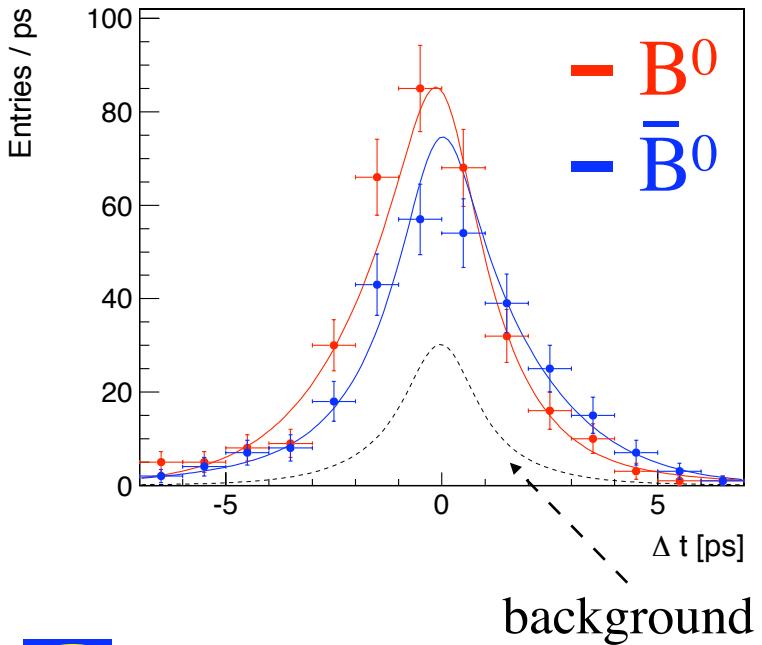
Projections of the angular distributions in the signal region of  $\Delta E$  and  $M_{bc}$

# TCPV in $B^0 \rightarrow D^*+D^*$

 772 M  $B\bar{B}$

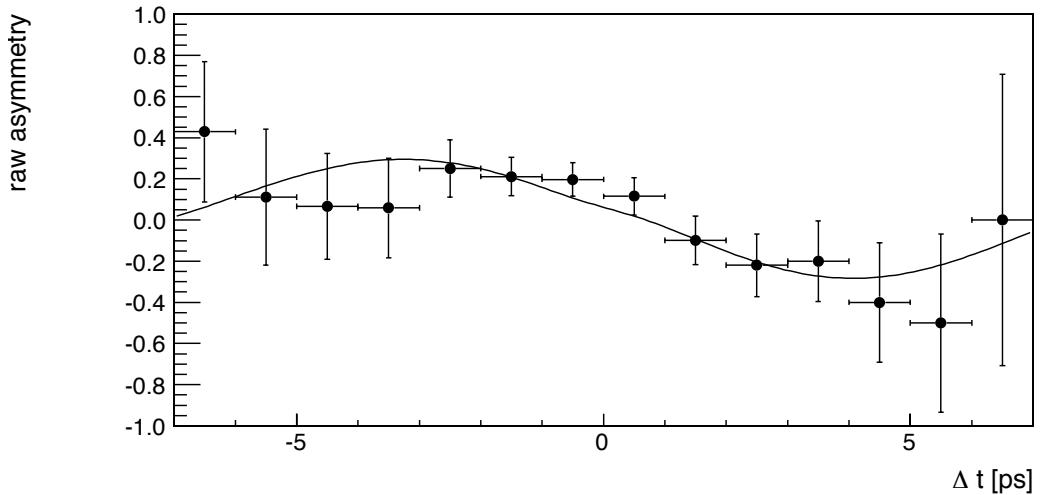
Preliminary!

$\Delta t$  and raw asymmetry plots for good tagged events only



 NEW!

$$\begin{aligned} S &= -0.79 \pm 0.13(\text{stat}) \pm 0.03(\text{syst}) \\ A &= +0.15 \pm 0.08(\text{stat}) \pm 0.02(\text{syst}) \\ R_0 &= 0.62 \pm 0.03(\text{stat}) \pm 0.01(\text{syst}) \\ R_\perp &= 0.14 \pm 0.02(\text{stat}) \pm 0.01(\text{syst}) \end{aligned}$$

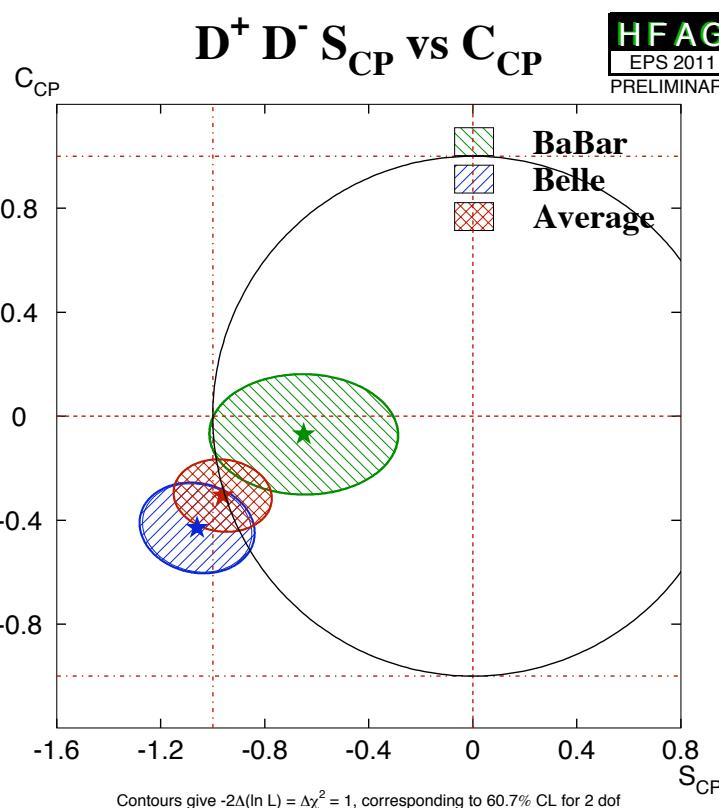


(systematic errors)

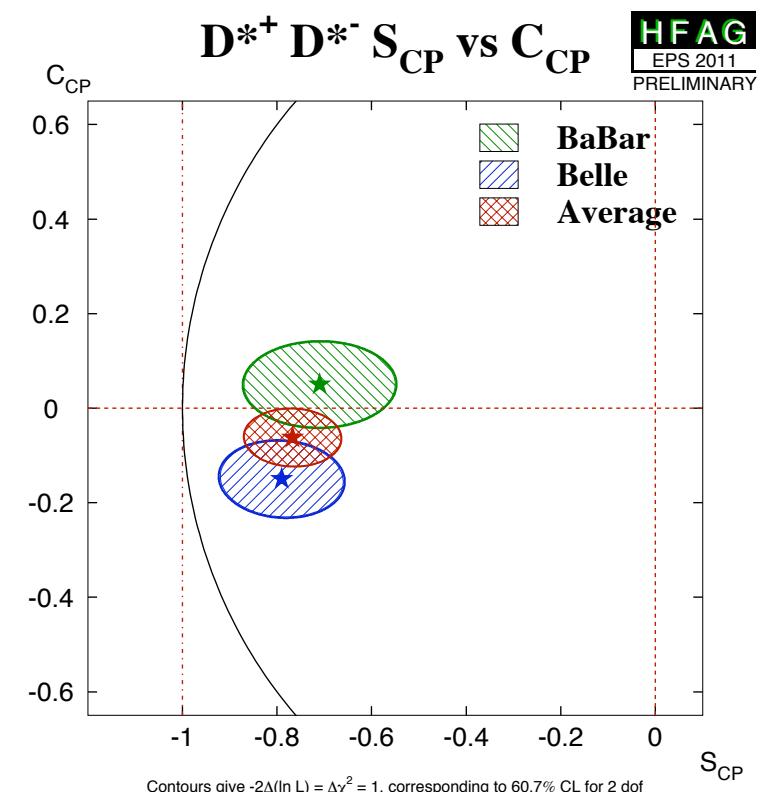
Category	$\delta S$	$\delta A$	$\delta(R_0)$	$\delta(R_\perp)$
Vertexing	$\pm 0.019$	$\pm 0.021$	$\pm 0.004$	$\pm 0.004$
Flavor tagging	$\pm 0.004$	$\pm 0.003$	$< 0.001$	$< 0.001$
Vertex resolution	$\pm 0.020$	$\pm 0.004$	$\pm 0.001$	$\pm 0.001$
Physics parameters	$\pm 0.004$	$\pm 0.001$	$\pm 0.001$	$< 0.001$
Fit model	$\pm 0.002$	$< 0.001$	$\pm 0.005$	$\pm 0.002$
Tag-side interference	$\pm 0.001$	$\pm 0.008$	$< 0.001$	$< 0.001$
Polarization recon. eff.	$< 0.001$	$< 0.001$	$\pm 0.002$	$\pm 0.001$
Total	$\pm 0.028$	$\pm 0.023$	$\pm 0.007$	$\pm 0.005$

# HFAG Summary

$B^0 \rightarrow D^+ D^-$



$B^0 \rightarrow D^{*+} D^{*-}$



HFAG summary of comparison of results from Belle and BaBar

# CPT Violation $B^0$ decays

CPT violation in  $B^0 \leftrightarrow \bar{B}^0$  mixing :

$$|B_L\rangle = p\sqrt{1-z}|B^0\rangle + q\sqrt{1+z}|\bar{B}^0\rangle$$

$$|B_H\rangle = p\sqrt{1+z}|B^0\rangle - q\sqrt{1-z}|\bar{B}^0\rangle$$



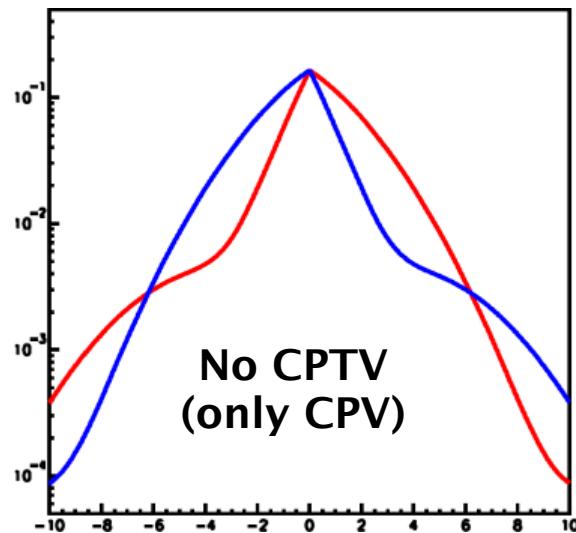
535 M  $B\bar{B}$

→ z is the CPT violating complex parameter

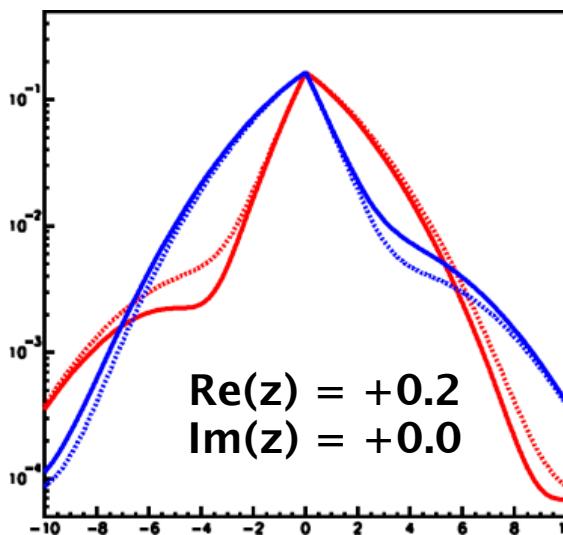
→ Non-zero value of z indicates the CPT violation in mixing.

Decay modes (event counts)	Sensitivity
$J/\psi K_S^0(7,713), J/\psi K_L^0(10,966)$	Mainly to $\text{Re}(z)$ and $\Delta\Gamma_d/\Gamma_d$
$D^-\pi^+(39,366), D^{*-}\pi^+(46,292), D^{*-}\rho^+(45,913)$	Mainly to $\text{Im}(z)$
$D^{*-}\ell^+\nu_\ell(383,818)$	
$D^0\pi^+(216,605), J/\psi K^+(32,150)$	Only to $\Delta t$ resolution

A total of 534,068  $B^0$  and 248,775  $B^+$  events



If CPT is  
violated



—  $B^0$   
—  $\bar{B}^0$

# CPT Violation $B^0$ decays

Preliminary!

Unbinned maximum likelihood fit to 72 free parameters



NEW!

$$\begin{aligned} \text{Re}(z) &= (+1.9 \pm 3.7 \pm 3.2) \times 10^{-2} \\ \text{Im}(z) &= (-5.7 \pm 3.3 \pm 6.0) \times 10^{-3} \\ \Delta\Gamma_d/\Gamma_d &= (-1.7 \pm 1.8 \pm 1.1) \times 10^{-2} \end{aligned}$$

## Other parameters

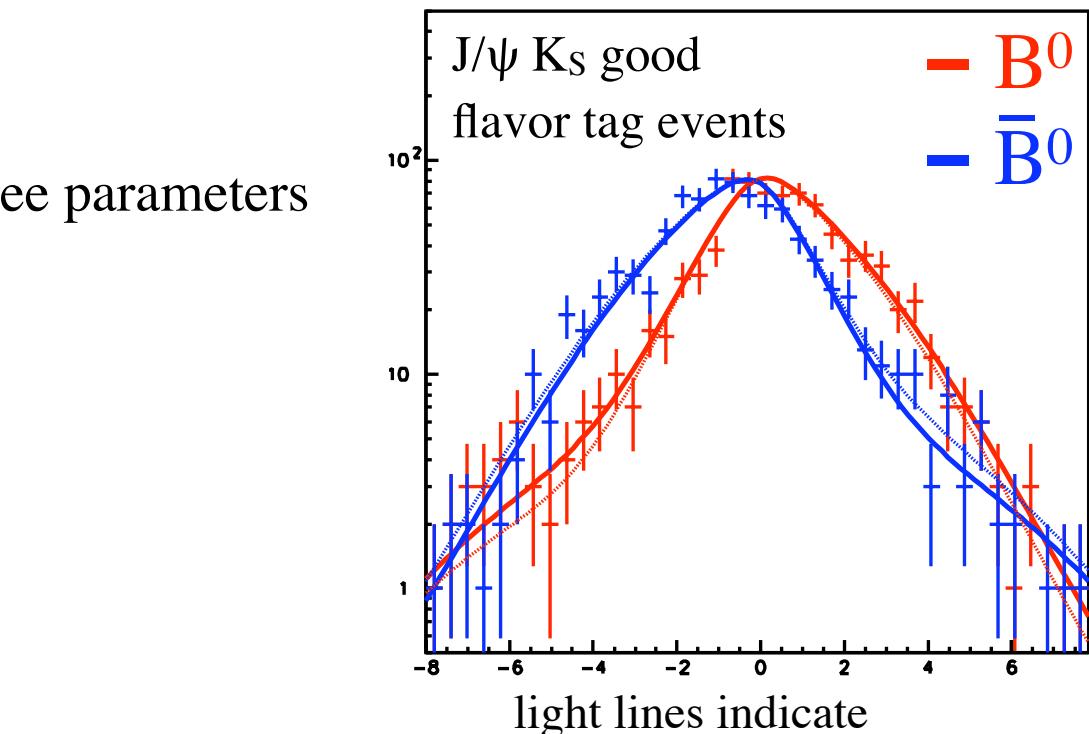
$$\tau_{B^0} = 1.531 \pm 0.004 \text{ (ps)}$$

$$\tau_{B^+} = 1.639 \pm 0.006 \text{ (ps)}$$

$$\Delta m_d = 0.506 \pm 0.003 \text{ (ps}^{-1}\text{)}$$

$$|\lambda_{CP}| = 0.999 \pm 0.004$$

$$\arg(\eta_{CP}\lambda_{CP}) = -0.70 \pm 0.04$$

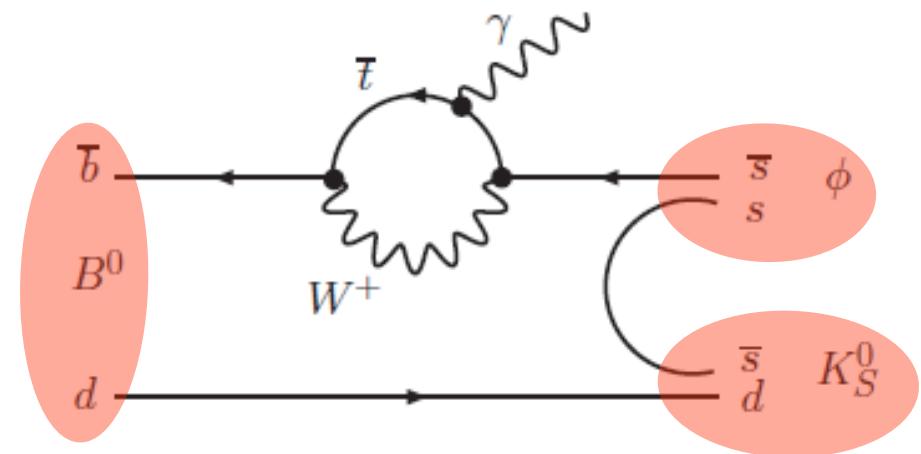


(systematic errors)

Category	$\delta(\text{Re}(z))$	$\delta(\text{Im}(z))$	$\delta(\Delta\Gamma_d/\Gamma_d)$
Vertexing	+0.005 -0.009	$\pm 0.006$	+0.006 -0.009
Vertex resolution	+0.001 -0.003	< 0.001	+0.002 -0.001
Fit bias	$\pm 0.012$	$\pm 0.001$	$\pm 0.005$
Signal fraction	$\pm 0.004$	< 0.001	$\pm 0.001$
Background $\Delta t$	+0.003 -0.005	< 0.001	$\pm 0.002$
Tag-side interference	+0.000 -0.027	+0.000 -0.001	+0.001 -0.000
DCS decay	+0.004 -0.002	$\pm 0.001$	+0.003 -0.002
Others	+0.000 -0.001	< 0.001	+0.000 -0.002
Total	+0.015 -0.032	$\pm 0.006$	+0.009 -0.011

# Radiative Penguin

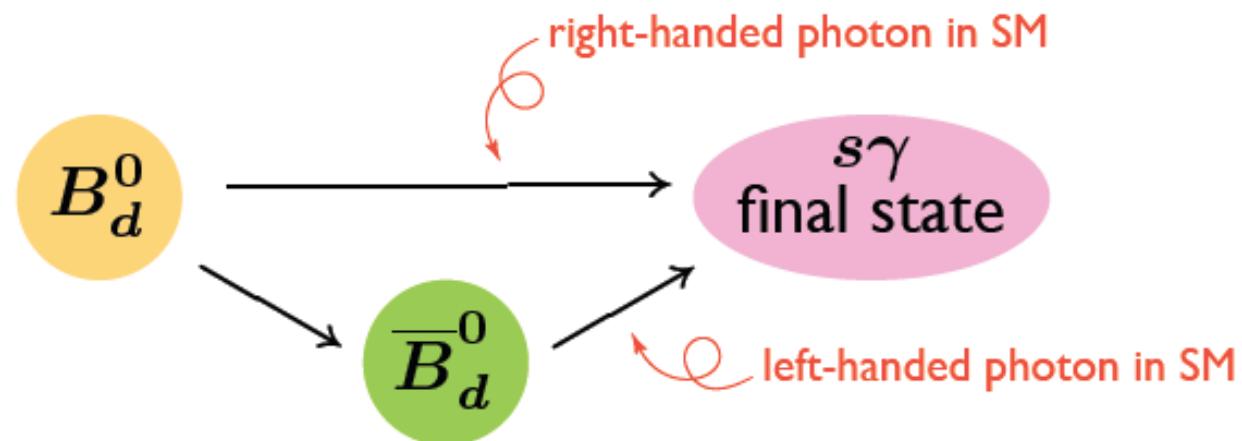
- Radiative  $b \rightarrow s\gamma$  decays : excellent probe for physics beyond the SM.



- Flavor Changing Neutral Current processes.
- Forbidden at tree-level in the SM, but allowed through loop (penguin) diagrams.
- Non-SM particles can contribute to the loop.

# Search for Right-handed currents

D. Atwood, M.Gronau, A.Soni,  
PRL 79, 185 (1997)



- In SM, radiative photon from  $b \rightarrow s\gamma$  transition is flavor-specific.
- $B^0 \leftrightarrow \bar{B}^0$  interference can occur only through a helicity flip.
- The CP asymmetry in SM is suppressed by the quark mass ratio.

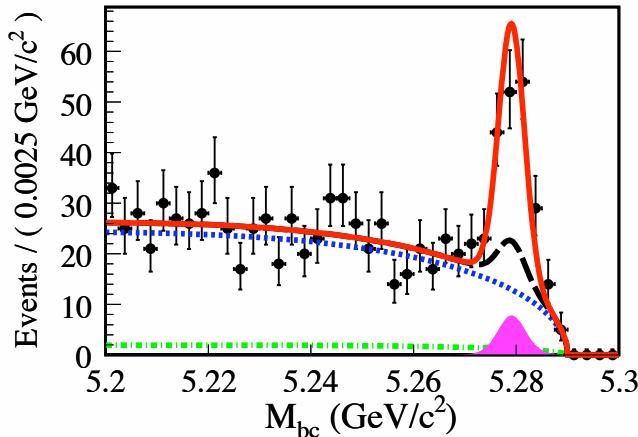
$$S \approx -2(m_s/m_b) \sin(2\phi_1) \sim 0.03$$

- A large CP asymmetry will be a clear hint of new physics (e.g. LRSM model) : Sensitive to right handed currents rather than a new phase.
- Applicable to any  $B^0 \rightarrow P^0 Q^0 \gamma$  decays with C eigenstate mesons (e.g.  $B^0 \rightarrow \varphi K_s \gamma$ )

D. Atwood, T. Gershon, M. Hazumi, A. Soni,  
PRD 71, 076003 (2005)

# Branching Fraction

$B^+ \rightarrow \phi K^+ \gamma$

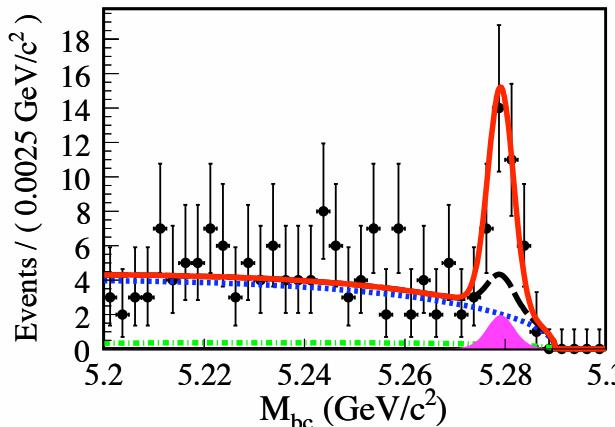


$N_{\text{sig}} = 144 \pm 17$  events  
 $\text{eff} = (15.3 \pm 0.1)\%$

$$\mathcal{B}(B^+ \rightarrow \phi K^+ \gamma) = (2.48 \pm 0.30 \pm 0.24) \times 10^{-6} \quad (9.6\sigma)$$

$$\mathcal{B}(B^0 \rightarrow \phi K^0 \gamma) = (2.74 \pm 0.60 \pm 0.32) \times 10^{-6} \quad (5.4\sigma)$$

$B^0 \rightarrow \phi K_S \gamma$



$N_{\text{sig}} = 37 \pm 8$  events  
 $\text{eff} = (10.0 \pm 0.1)\%$

- Data
- Signal
- Total BG
- qq BG
- $b \rightarrow c$  BG
- Nonres+Charmless

Signal Extraction :  $\Delta E - M_{bc}$  2D fit  
 Non-resonant  $K^+ K^- K\gamma$  is obtained from  $\phi$  mass sideband in data (13% of signal)

First observation in neutral mode

## Charged Asymmetry

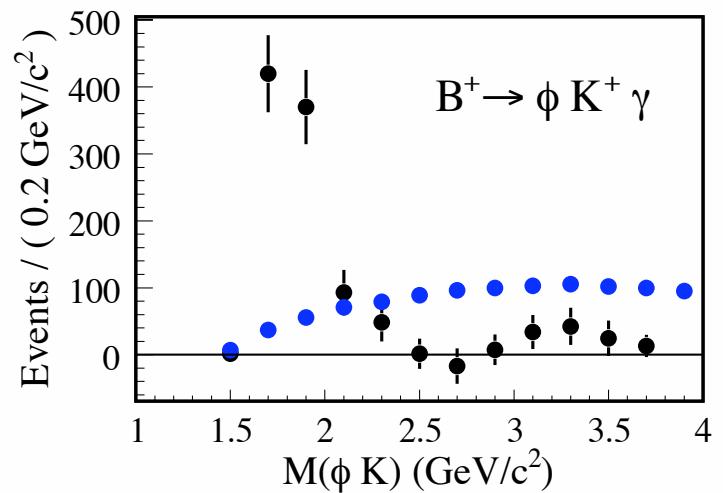
$$A_{CP} = \frac{N(B^- \rightarrow \phi K^- \gamma) - N(B^+ \rightarrow \phi K^+ \gamma)}{N(B^- \rightarrow \phi K^- \gamma) + N(B^+ \rightarrow \phi K^+ \gamma)} = (-0.03 \pm 0.11 \pm 0.08)$$

(consistent with no CP asymmetry)

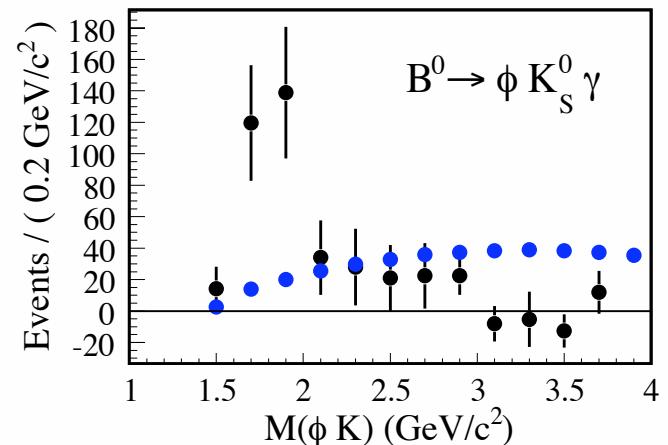
# M( $\phi$ K) mass distribution

- Background-subtracted and efficiency-corrected M( $\phi$ K) mass distributions
- Yield in each bin of M( $\phi$ K) mass is from  $\Delta E$ - $M_{bc}$  2D-fit
- Nearly 72% events are concentrated in the low mass region (1.5-2.0 GeV/c<sup>2</sup>)
- No clear evidence is found for the existence of a kaonic resonance decaying to  $\phi$ K.
- The spectra are in qualitative agreement with expectation from pQCD model for non-resonant decays (the peak at threshold can be explained by form factor effects).

C.H.Chen and H.-n.Li, PRD 70, 054006 (2004)  
[hep-ph/0404097]



- Data
- Phase-space from MC

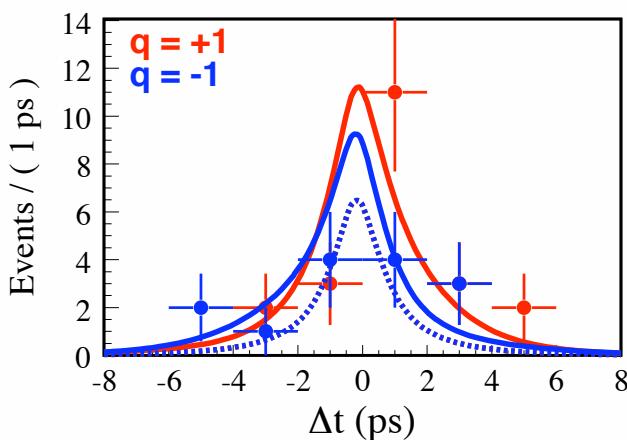


# TCPV in $B^0 \rightarrow \phi K_S \gamma$

First TCPV measurement in neutral mode with 35 signal events.

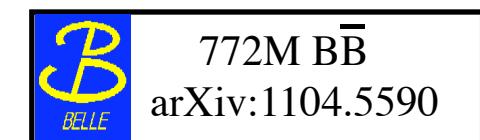
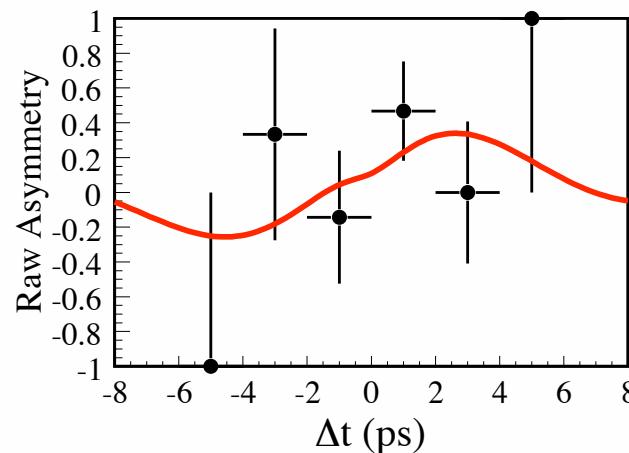
(vertexing from  $\phi \rightarrow K^+ K^-$  tracks,  $K_S$  vertexing is not required)

Nonresonant  $K^+ K^- K\gamma$  is included in the signal for TCPV study

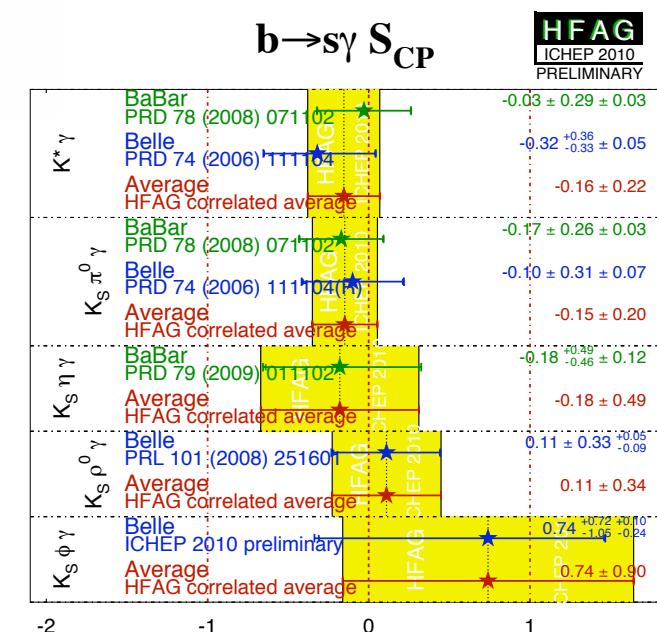


$$S = 0.74^{+0.72}_{-1.05} \text{ (stat)} ^{+0.10}_{-0.24} \text{ (syst)}$$

$$A = 0.35 \pm 0.58 \text{ (stat)} ^{+0.23}_{-0.10} \text{ (syst)}$$



submitted to PRL



→ We have established a new mode for future high-luminosity  $e^+e^-$  and hadronic facilities

# Summary

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- Many new results from Belle on CP violation with full data sample.
- Most precise measurement of  $\sin 2\phi_1$  in  $B \rightarrow (cc)K^0$  decays  
 $\sin 2\phi_1 = 0.668 \pm 0.023 \pm 0.013, \mathcal{A} = 0.007 \pm 0.016 \pm 0.013$
- TCPV in  $B \rightarrow D^+D^-$  decays (NEW!)  
 $\mathcal{S} = -1.06 \pm 0.21 \pm 0.07, \mathcal{A} = +0.43 \pm 0.17 \pm 0.04$
- TCPV in  $B \rightarrow D^{*+}D^{*-}$  decays (NEW!)  
 $\mathcal{S} = -0.79 \pm 0.13 \pm 0.03, \mathcal{A} = +0.15 \pm 0.08 \pm 0.02$
- CPT Violation (NEW!)  
 $\text{Re}(z) = (+1.9 \pm 3.7 \pm 3.2) \times 10^{-2}, \text{Im}(z) = (-5.7 \pm 3.3 \pm 6.0) \times 10^{-3}, \Delta\Gamma_d/\Gamma_d = (-1.7 \pm 1.8 \pm 1.1) \times 10^{-2}$
- First TCPV in radiative  $B^0 \rightarrow \phi K_S \gamma$  decays  
 $\mathcal{S} = 0.74_{-1.05}^{+0.72}{}_{-0.24}^{+0.10}, \mathcal{A} = 0.35 \pm 0.58_{-0.10}^{+0.23}$   
(submitted to PRL)

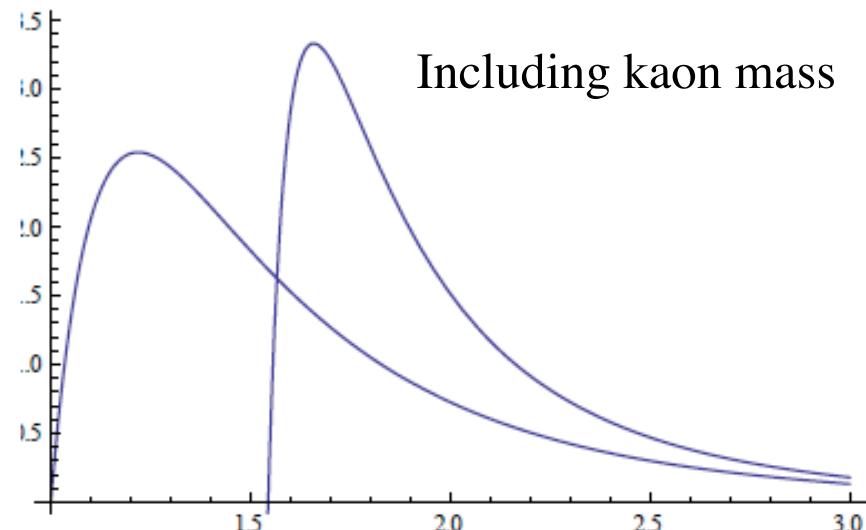
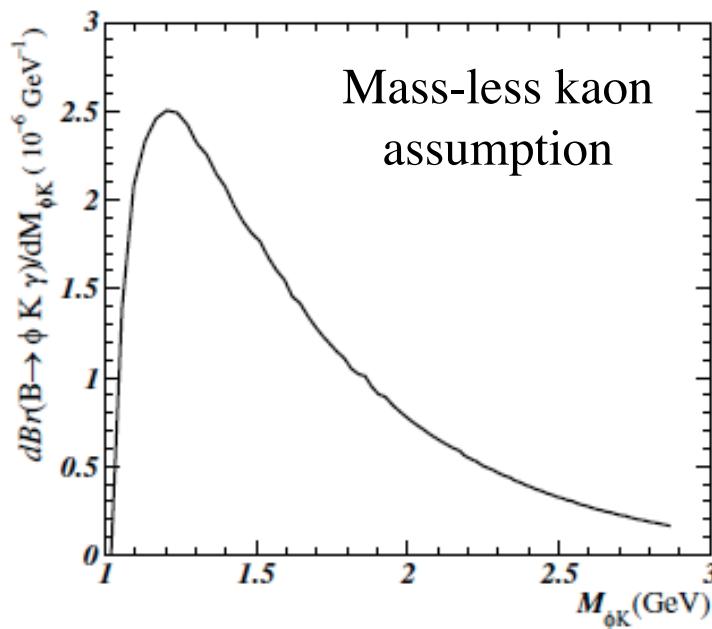
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# BACK UP

# Theoretical Prediction

- Two-meson distribution amplitude in a three-body decay (neglecting the resonant contribution).
- Predicted  $B \rightarrow \phi K \gamma$  decay spectrum exhibits maximum at  $\phi K$  invariant mass around 1.3 GeV.

Hsiang-nan Li  
PRD 70, 054006 (2004) [hep-ph/0404097]



$B \rightarrow \phi K \gamma$  decay spectrum in the  $\phi K$  invariant mass

# Charmonium K<sup>0</sup> Systematics

Preliminary!



## Systematic errors:

	$\Delta S$	$\Delta A$
Vertexing	+0.008 -0.009	$\pm 0.008$
Flavor tagging	+0.004 -0.003	$\pm 0.003$
Resolution function	$\pm 0.007$	$\pm 0.001$
Physics parameters	$\pm 0.001$	< 0.001
Fit bias	$\pm 0.004$	$\pm 0.005$
$J/\psi K_S^0$ signal fraction	$\pm 0.002$	$\pm 0.001$
$J/\psi K_L^0$ signal fraction	$\pm 0.004$	$\pm 0.000$ -0.002
$\psi(2S)K_S^0$ signal fraction	< 0.001	< 0.001
$\chi_{c1}K_S^0$ signal fraction	< 0.001	< 0.001
Background $\Delta t$	$\pm 0.001$	< 0.001
Tag-side interference	$\pm 0.001$	$\pm 0.008$
Total	$\pm 0.013$	$\pm 0.013$

2011

2006

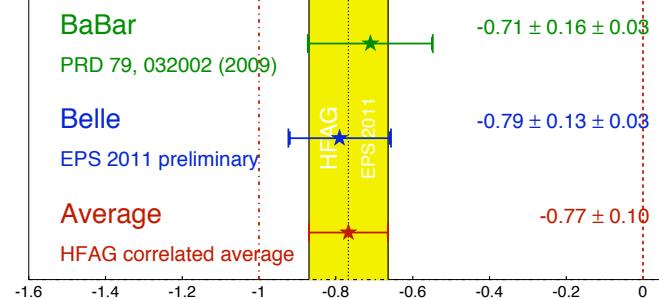
- Significant improvement in systematic error:  
 $0.017 \rightarrow 0.013$
- Better model for resolution function (decay mode independent)

	$dS$	$dA$
Vertexing	0.012	0.009
(Ks: 0.013)	0.021	
Flv tag	0.004	0.003
Res. func.	0.006	0.001
Phys.	0.001	0.001
Fit bias	0.007	0.004
Ks frac.	0.003	0.001
KL frac.	0.005	0.002
BG dt	0.001	0.001
T.S.I.	0.001	0.009
-----		
total	0.017	0.014

# $B^0 \rightarrow D^{*+} D^{*-}$ TCPV Results

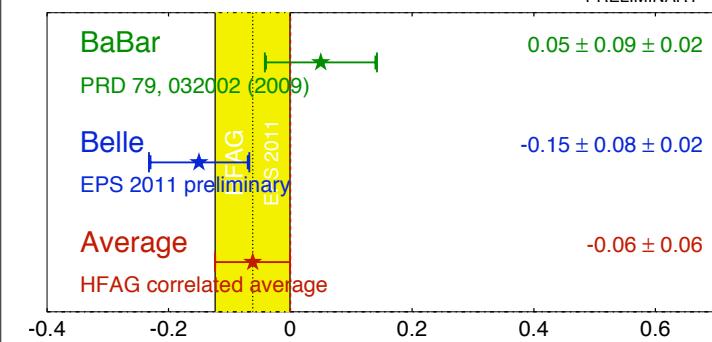
$D^{*+} D^{*-} S_{CP}$

HFAG  
EPS 2011  
PRELIMINARY



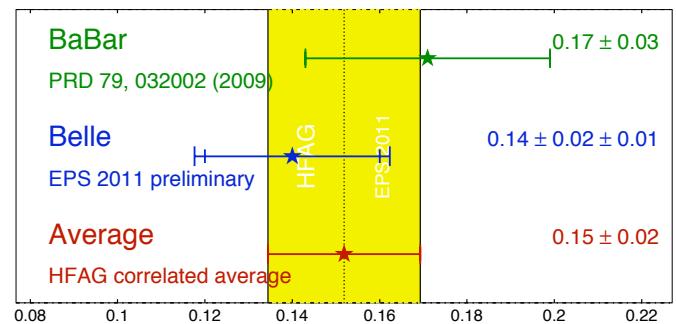
$D^{*+} D^{*-} C_{CP}$

HFAG  
EPS 2011  
PRELIMINARY



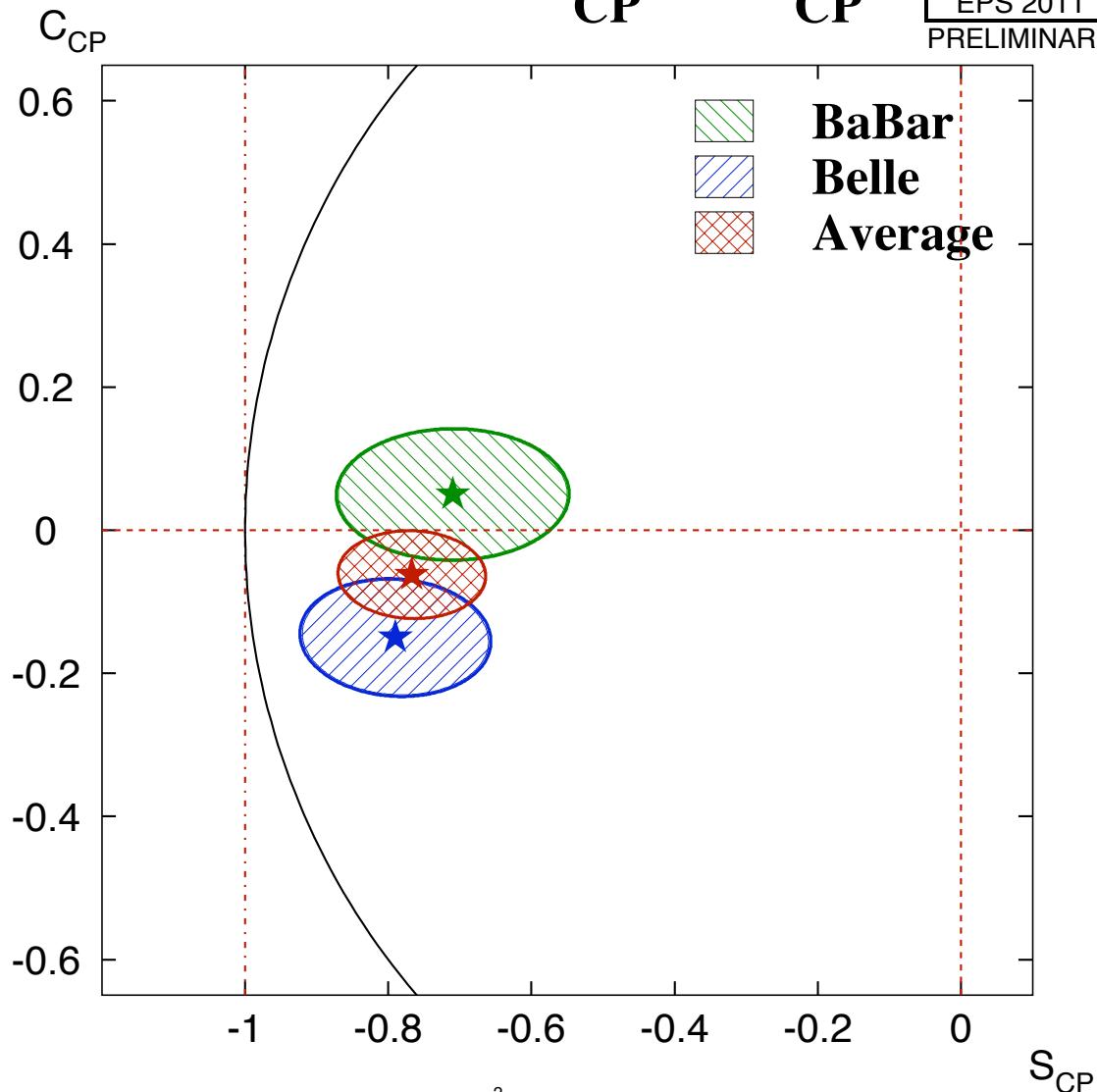
$D^{*+} D^{*-} R_{perp}$

HFAG  
EPS 2011  
PRELIMINARY

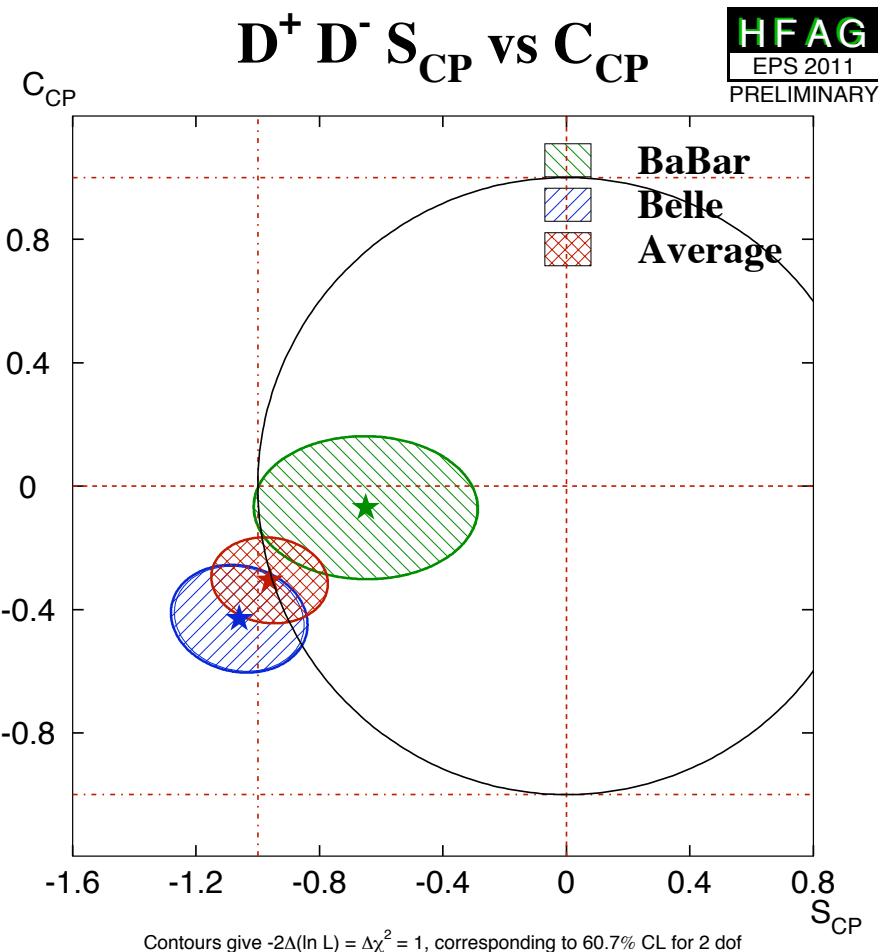
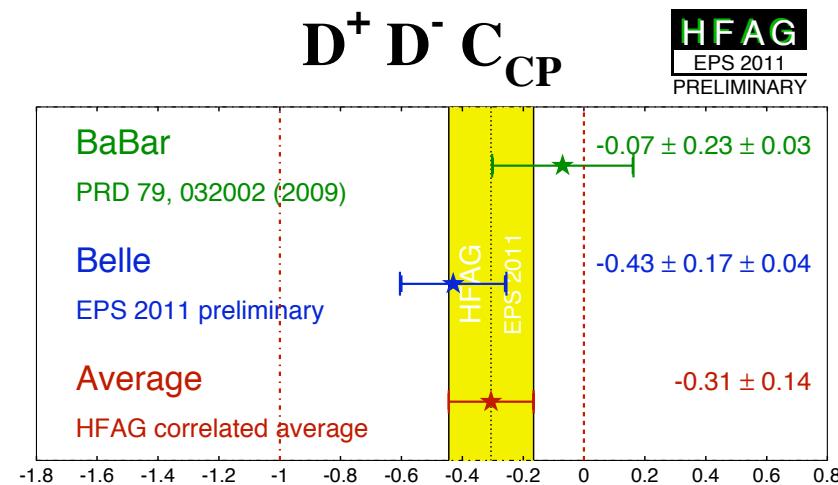
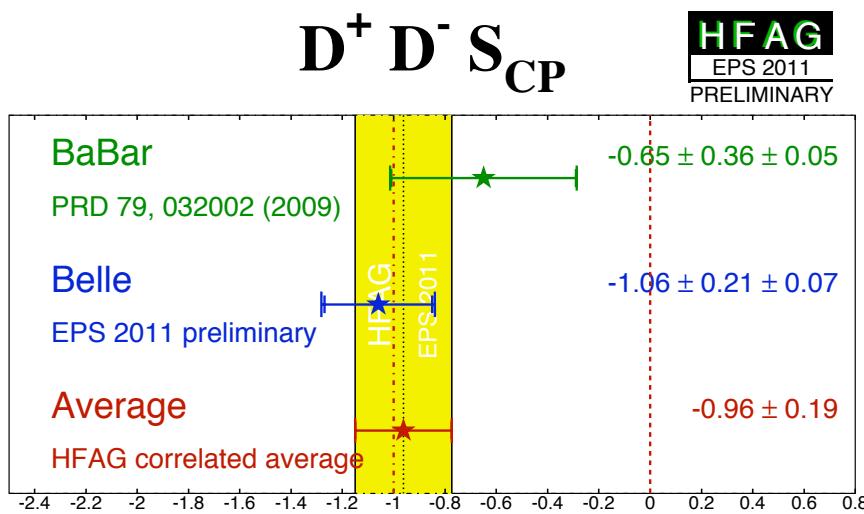


$D^{*+} D^{*-} S_{CP}$  vs  $C_{CP}$

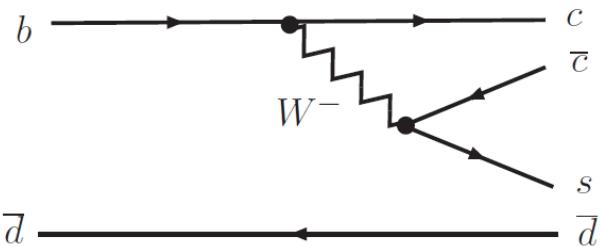
HFAG  
EPS 2011  
PRELIMINARY



# $B^0 \rightarrow D^+ D^-$ TCPV Results

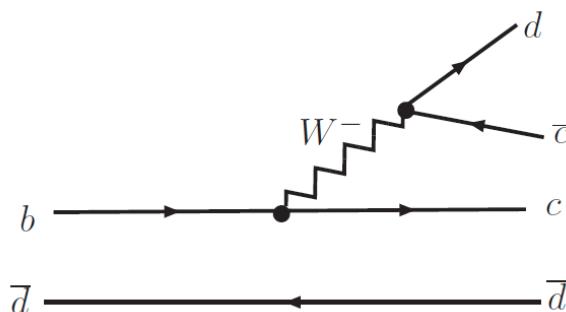


# Other ways to measure $\sin^2\phi_1(\beta)$



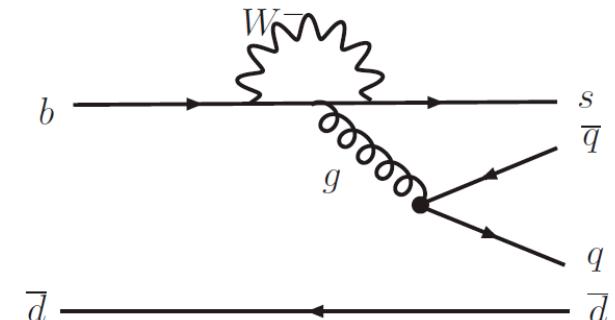
Charmonium  
“Tree-dominated”

$B^0 \rightarrow J/\psi K_S, \psi' K_S$   
 $B^0 \rightarrow \chi_{c1} K_S, \eta_c K_S$   
 $B^0 \rightarrow J/\psi K_L, J/\psi K^*(\rightarrow K_S \pi^0)$



Open charm or Charmonium  
Tree-dominance, Loop may  
contribute

$B^0 \rightarrow J/\psi \pi^0$   
 $B^0 \rightarrow D^{(*)+} D^{*-}, D^+ D^-$



Charmless,  $b \rightarrow s$  loop decays  
“penguin-dominance”

$B^0 \rightarrow \phi K_S, K^+ K^- K_S, K_S K_S K_S$   
 $B^0 \rightarrow K_S \pi^0, \eta' K_S, \omega K_S, f_0 K_S$

**Increase tree diagram contribution**

**Increase sensitivity to new physics**