Measurements of ϕ_1/β

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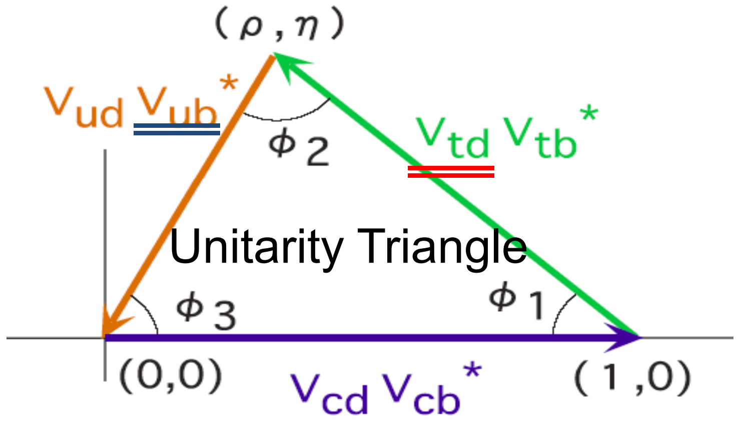
Flavor Physics and CP Violation 2010,
May 25, 2010, Torino, Italy,

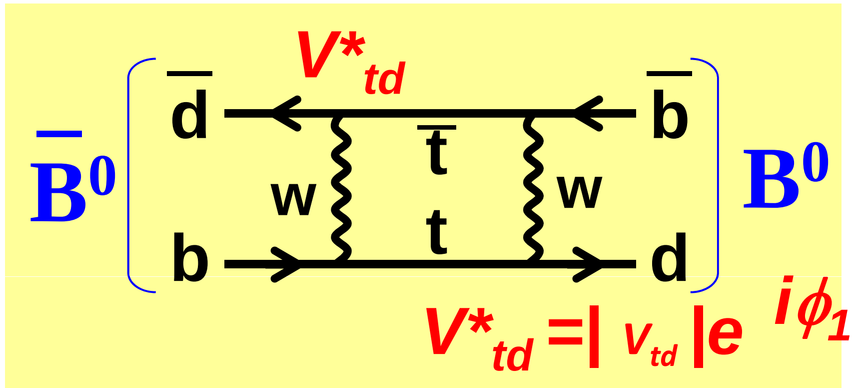
Time-dependent CP Violation in B^0 decays

KM ansatz: CPV is due to a complex phase in the quark mixing matrix

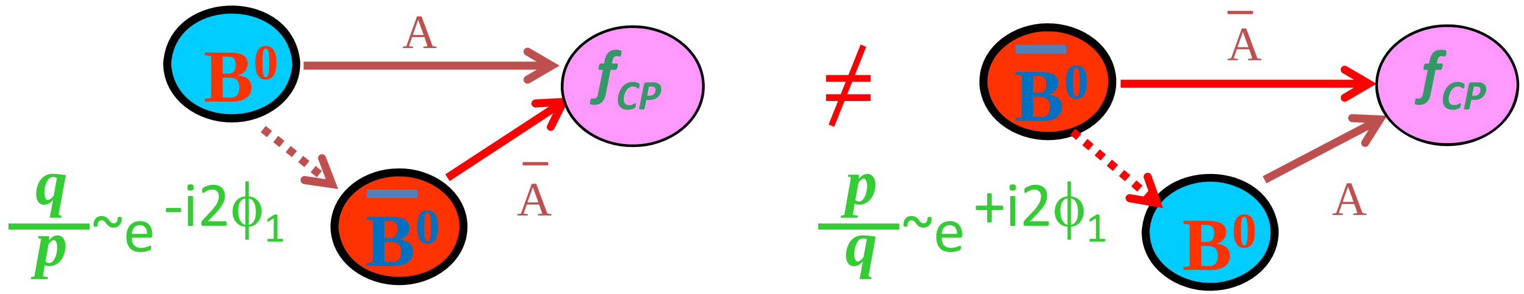
$$V_{n=3} = \begin{pmatrix} V_{ud} & V_{us} & \underline{\underline{V_{ub}}} \\ V_{cd} & V_{cs} & V_{cb} \\ \underline{\underline{V_{td}}} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & \underline{\underline{A\lambda^3(\rho - i\eta)}} \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ \underline{\underline{A\lambda^3(1-\rho-i\eta)}} & -A\lambda^2 & 1 \end{pmatrix}$$



B-$\bar{B}$ mixing



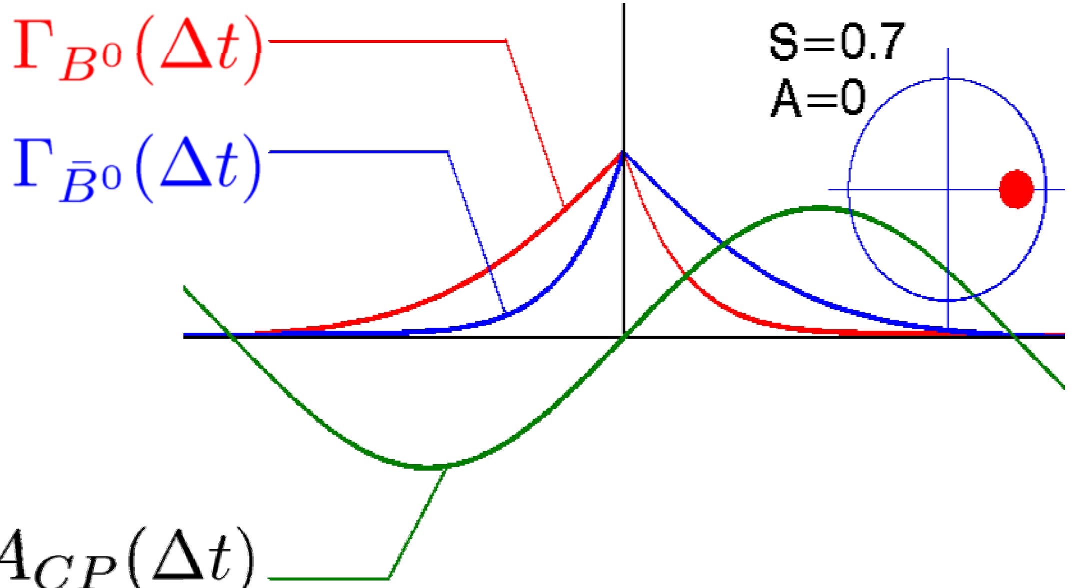
mixing induced CP violation

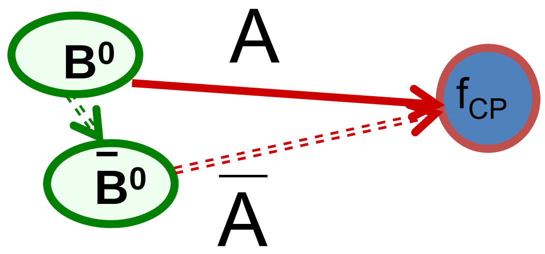


$\beta=\phi_1$
$\alpha=\phi_2$
$\gamma=\phi_3$

Time-dependent CP Violation in B^0 decays

We can measure CPV (asym.) as a function of proper time diff (Δt).





Δt

Decay time difference between B meson pairs

$$A_{CP}(\Delta t) \equiv \frac{\Gamma_{\bar{B}^0}(\Delta t) - \Gamma_{B^0}(\Delta t)}{\Gamma_{\bar{B}^0}(\Delta t) + \Gamma_{B^0}(\Delta t)} = \mathcal{S} \sin \Delta m \Delta t + \mathcal{A} \cos \Delta m \Delta t$$

Mixing-induced CPV

Direct CPV

e.g. for $B^0 \rightarrow J/\psi$ Ks

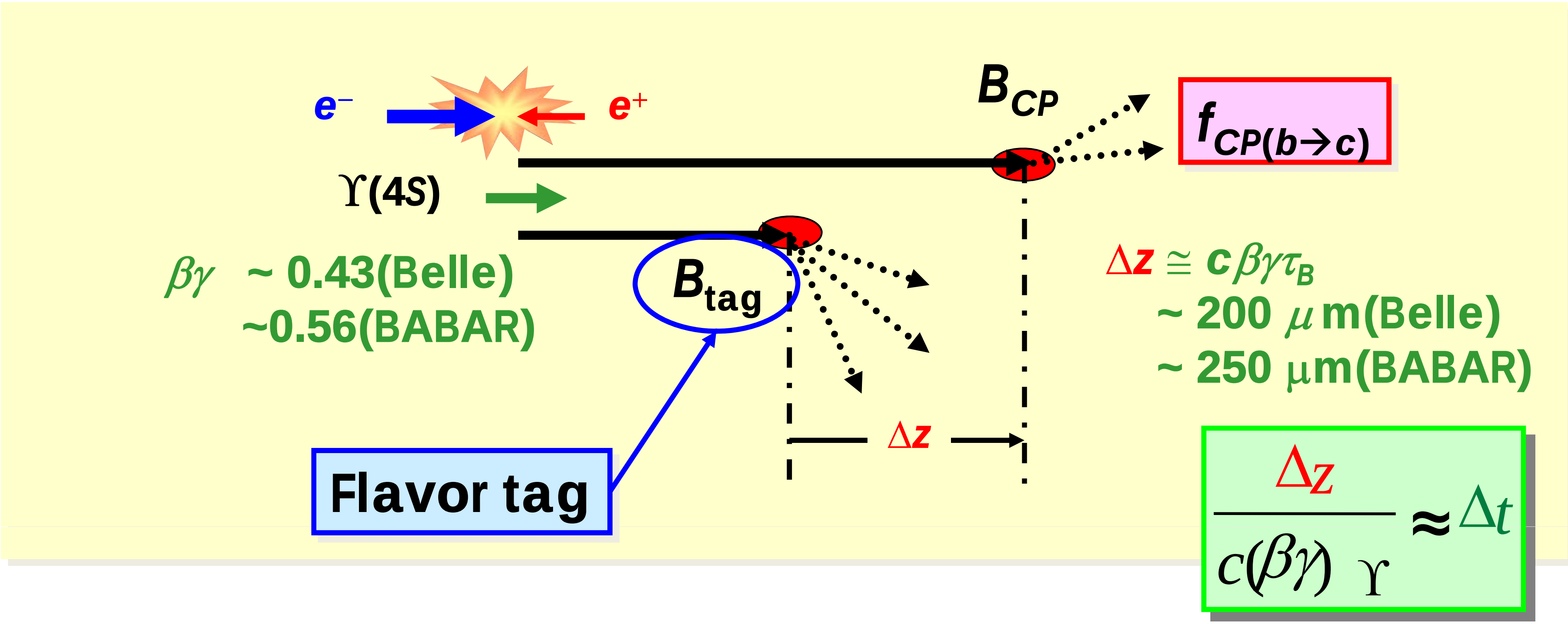
$S = -\xi_{CP} \sin 2\phi_1 = +\sin 2\phi_1$

$A \sim 0$ (A= -C)

(ξ_{CP} : CP eigenvalue ± 1)

$$S = \frac{2\,\mathrm{Im}\left(q/p\,\bar{A}A^*\right)}{|\bar{A}|^2 + |A|^2}, \quad A = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2}$$

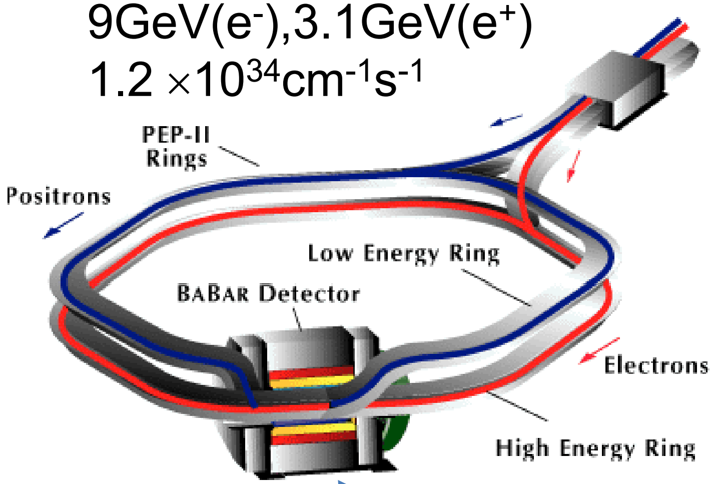
Principle of Measurement in B-factories



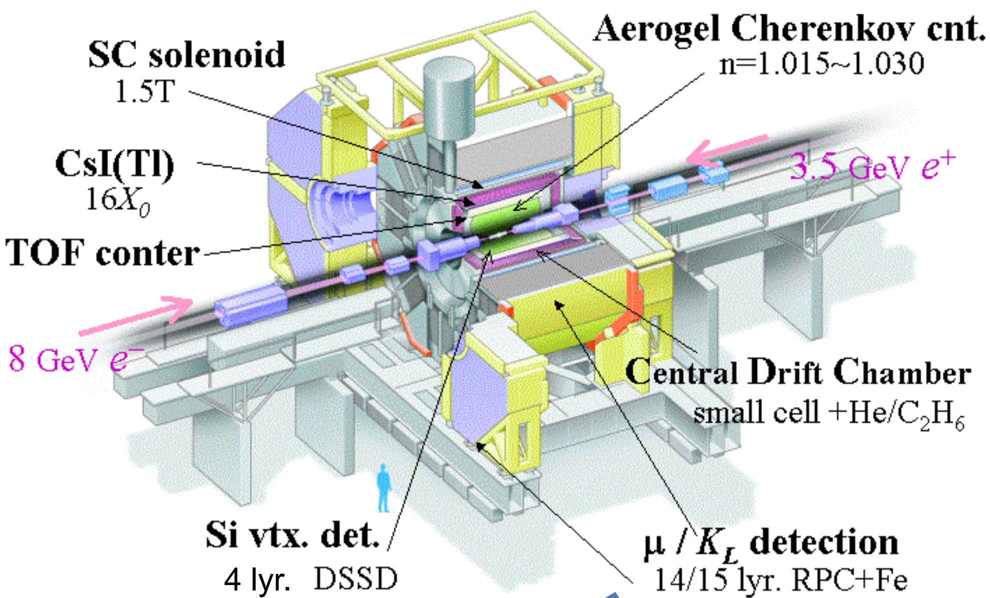
- Reconstruct $B \to f_{CP(b\to c)}$ decays
- Measure proper-time difference: Δt
- Determine flavor of B_{tag}
- Evaluate *CP* asymmetry from Δt and flavor of B_{tag}

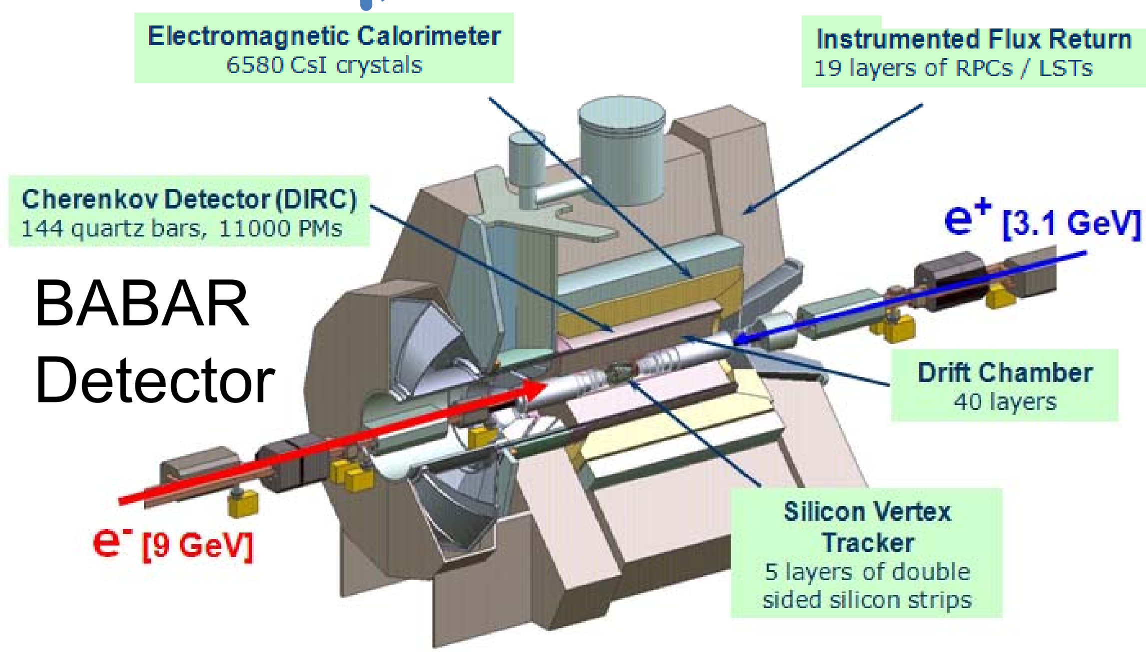
2 B-factories

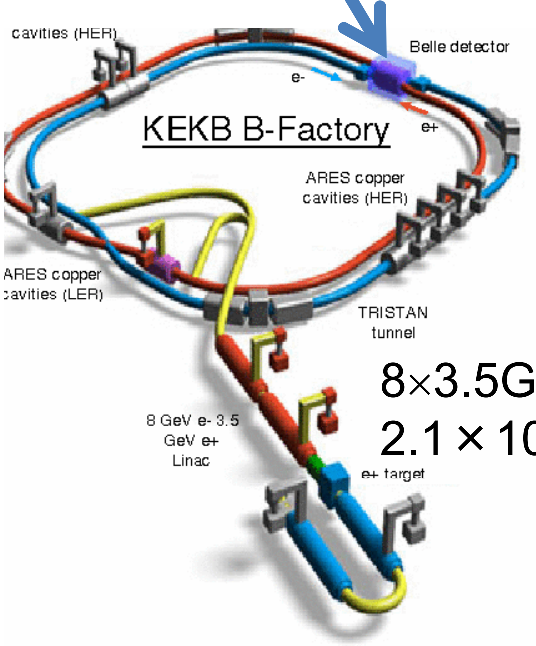
PEP-II
9GeV(e^-),3.1GeV(e^+)
$1.2 \times 10^{34} cm^{-1}s^{-1}$



Belle Detector

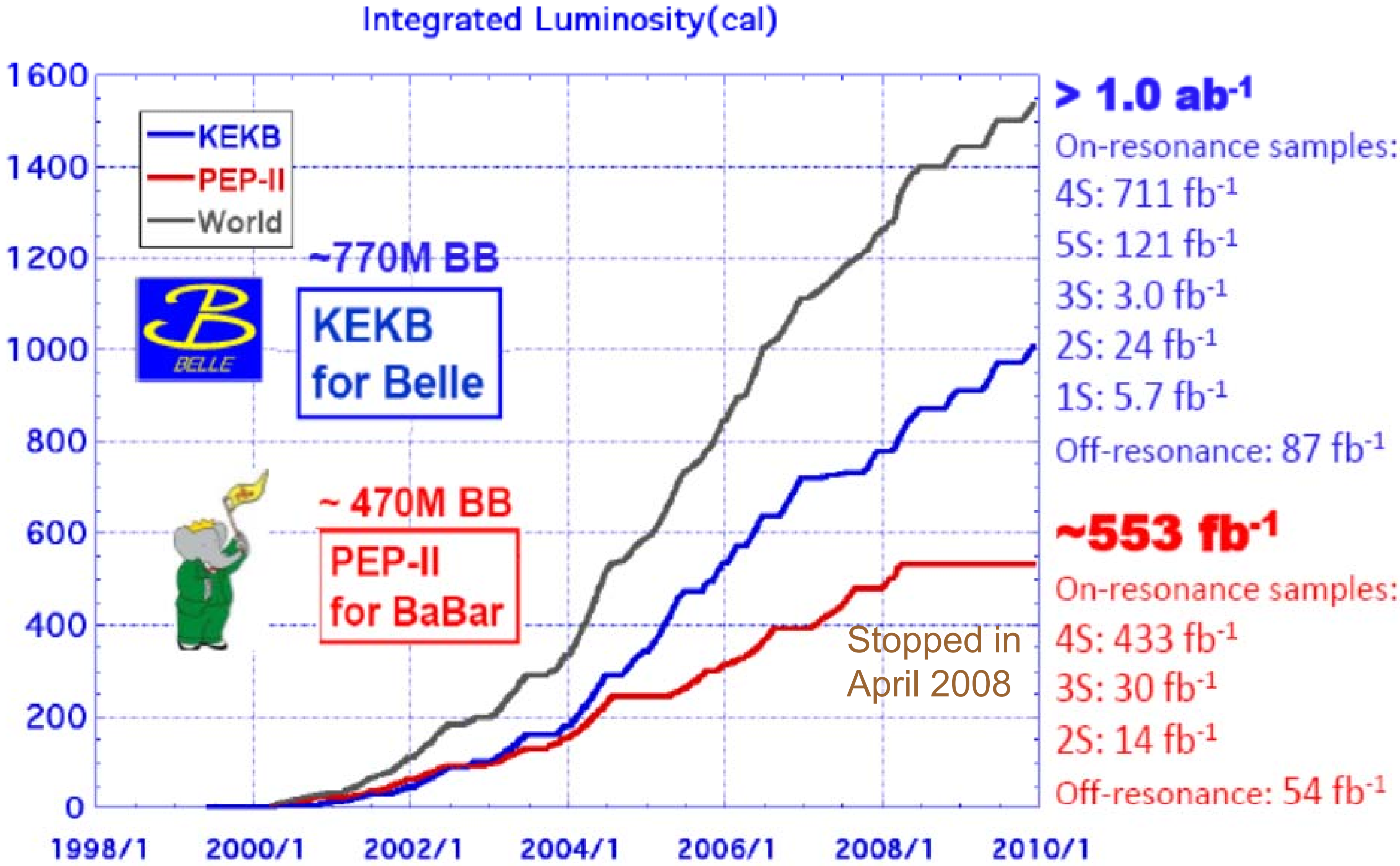






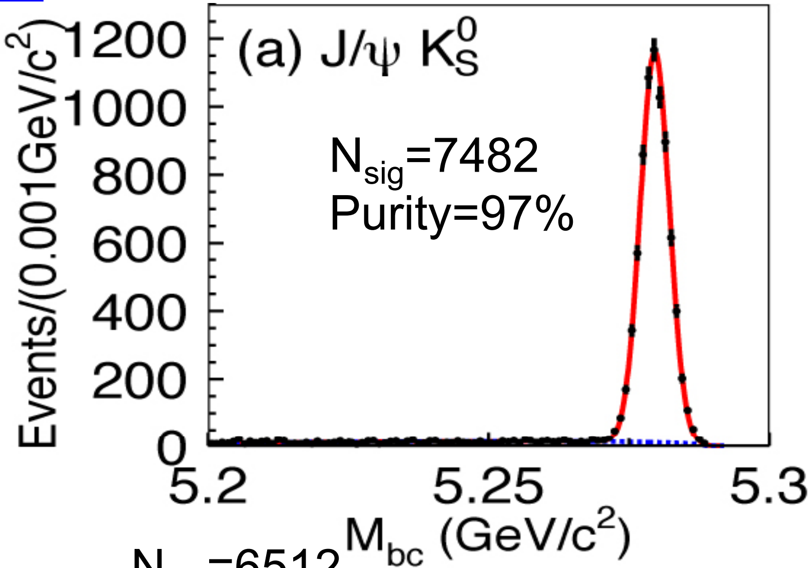
8×3.5GeV
$2.1 \times 10^{34} cm^{-2}s^{-1}$

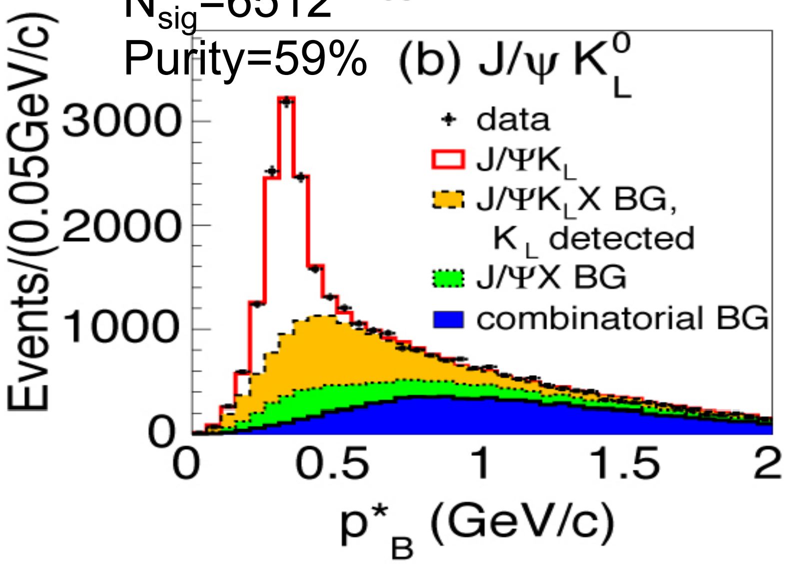
Success of the B-factories



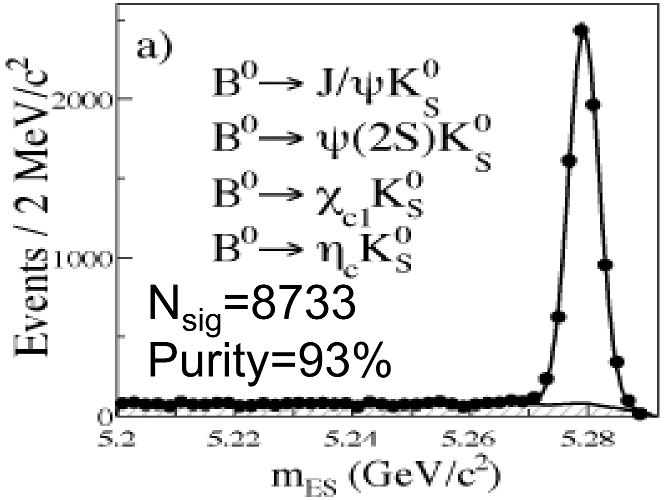
$\sin 2\phi_1$ with charmonium K^0 modes

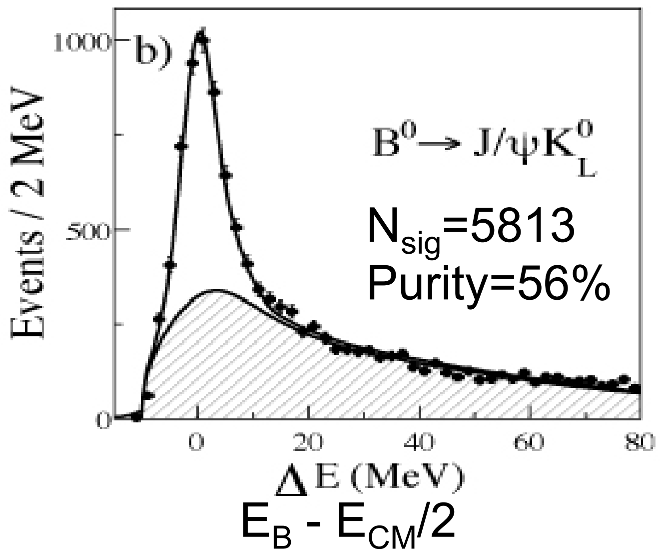
535MB$\bar{B}$



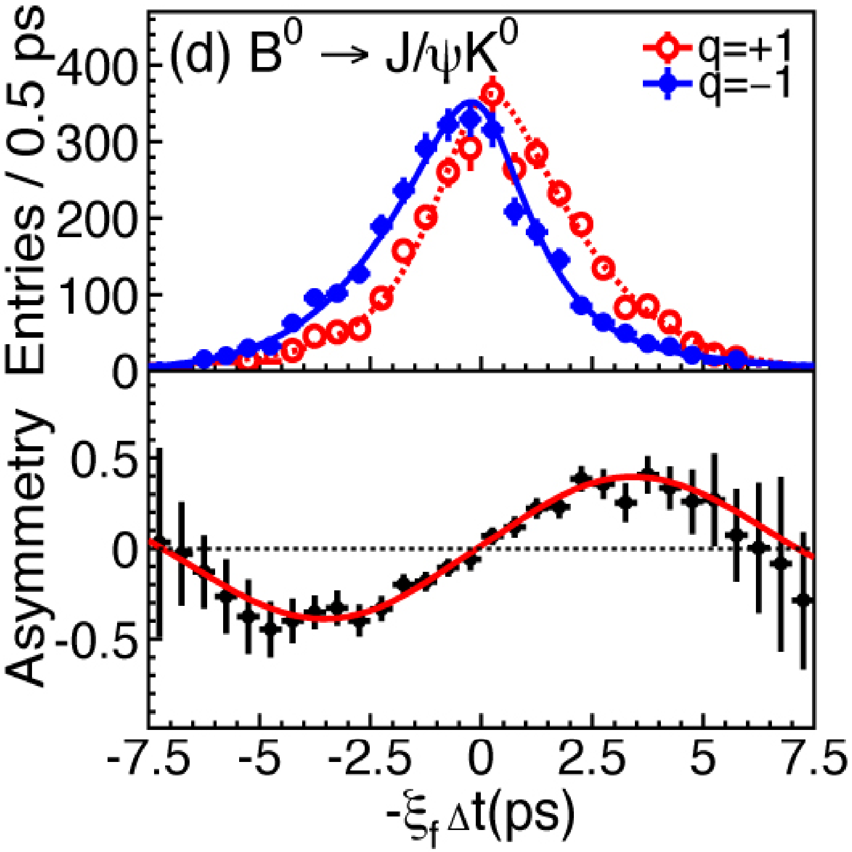


465MB$\bar{B}$





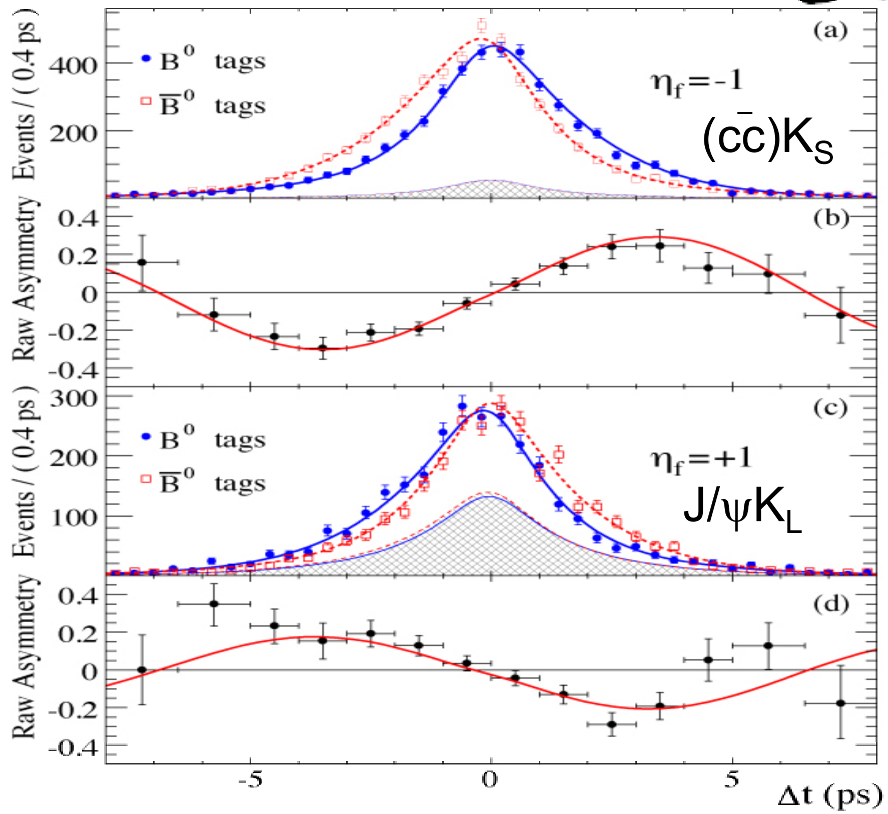
$\sin 2\phi_1$ with charmonium K^0 modes



$\sin 2\phi_1 = 0.642 \pm 0.031 \pm 0.017$

$A_f = 0.018 \pm 0.021 \pm 0.014$

PRL98,031802(2007)

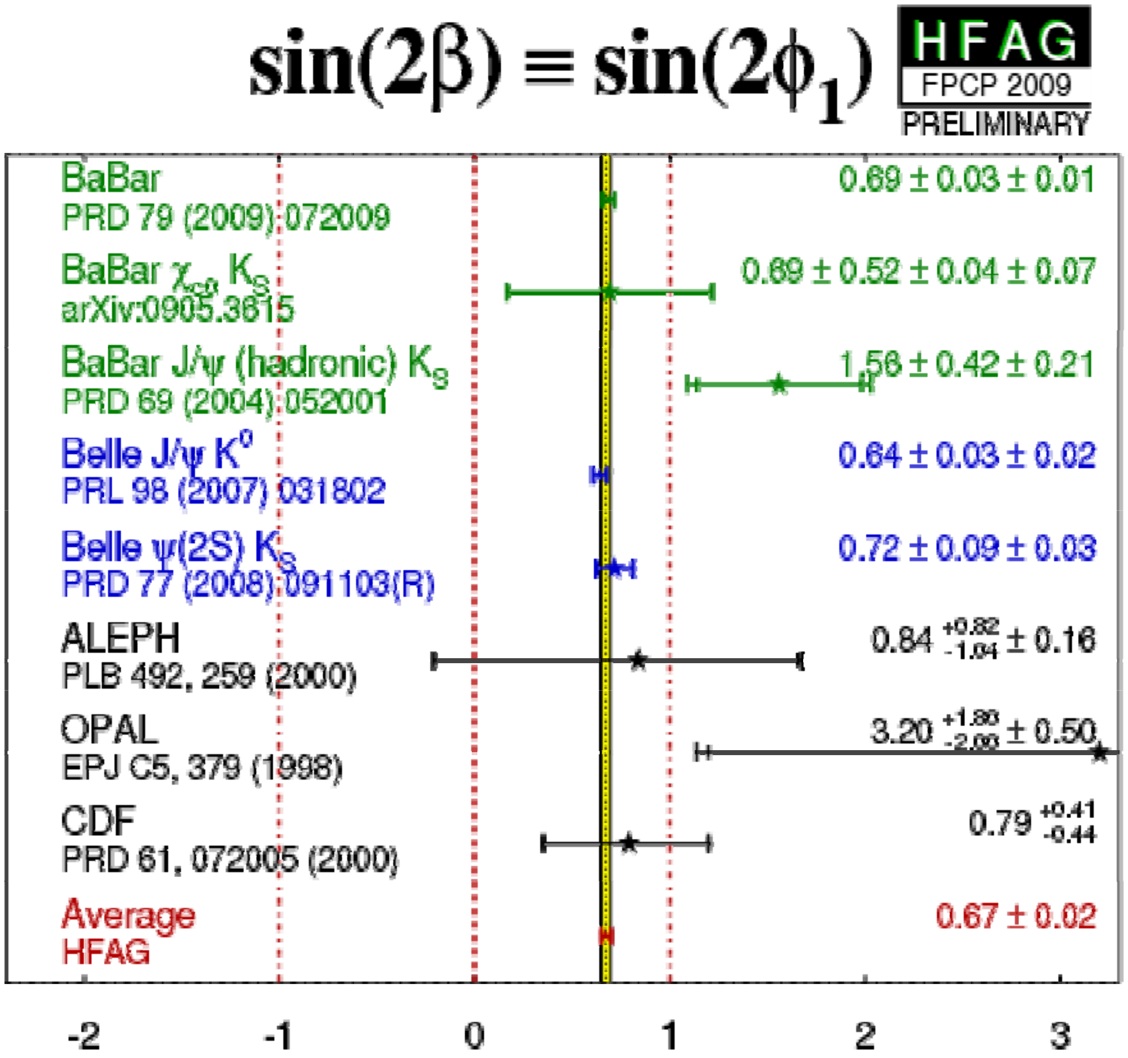


$\sin 2\phi_1 = 0.687 \pm 0.028 \pm 0.012$

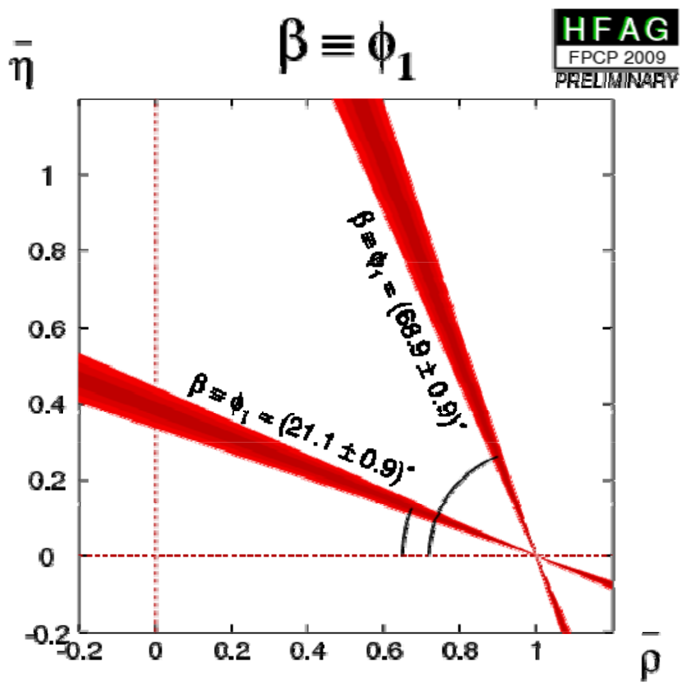
$A_f = -0.024 \pm 0.020 \pm 0.016$

PRD79,072009(2009)

$\sin 2\phi_1 \rightarrow \phi_1$



agreement between two experiments



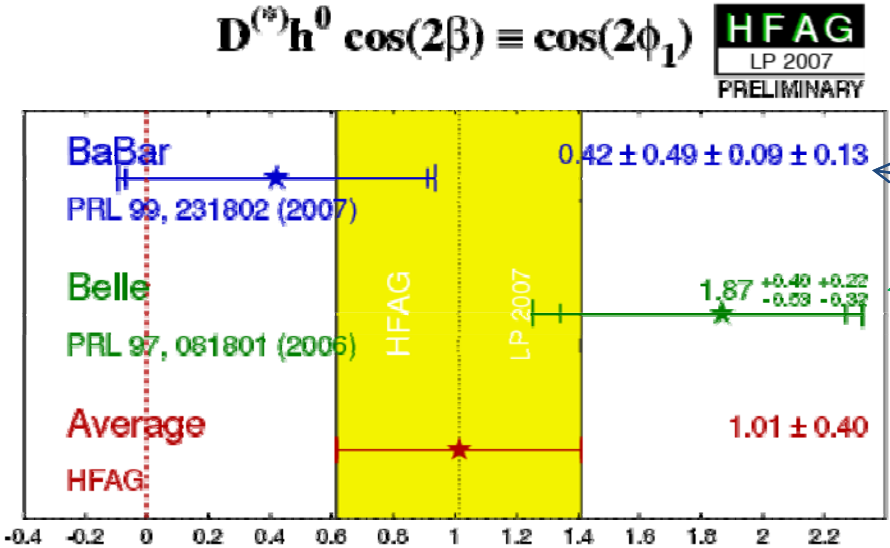
error in ϕ_1 < 1°
but ambiguities exist.

$\bar{B}^0 \rightarrow D[K_S\pi^+\pi^-]h^0$ ($h^0=\pi^0,\omega,\eta$)

Time dependent Dalitz analysis gives $\sin 2\phi_1$ and $\cos 2\phi_1$

$$S \propto \mathrm{Im}\left(\exp(-2i\phi_1)\bar{A}A^*\right) = \mathrm{Re}(\bar{A}A^*)\sin(2\phi_1) - \mathrm{Im}(\bar{A}A^*)\cos(2\phi_1)$$

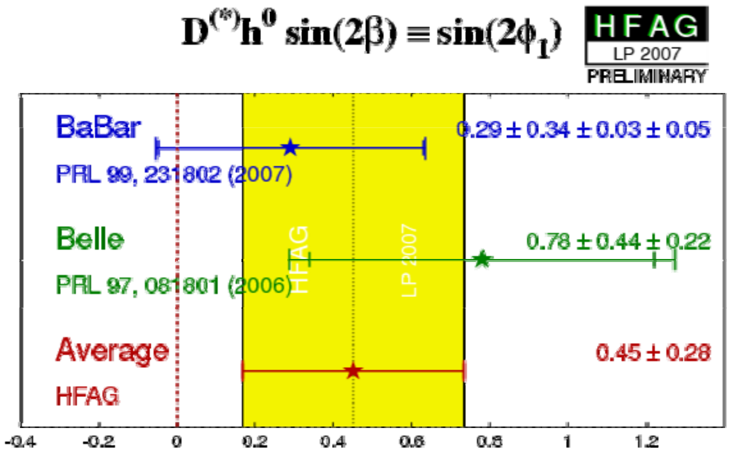
describe Dalitz variables.



$\cos 2\phi_1 > 0$ at 86% C.L

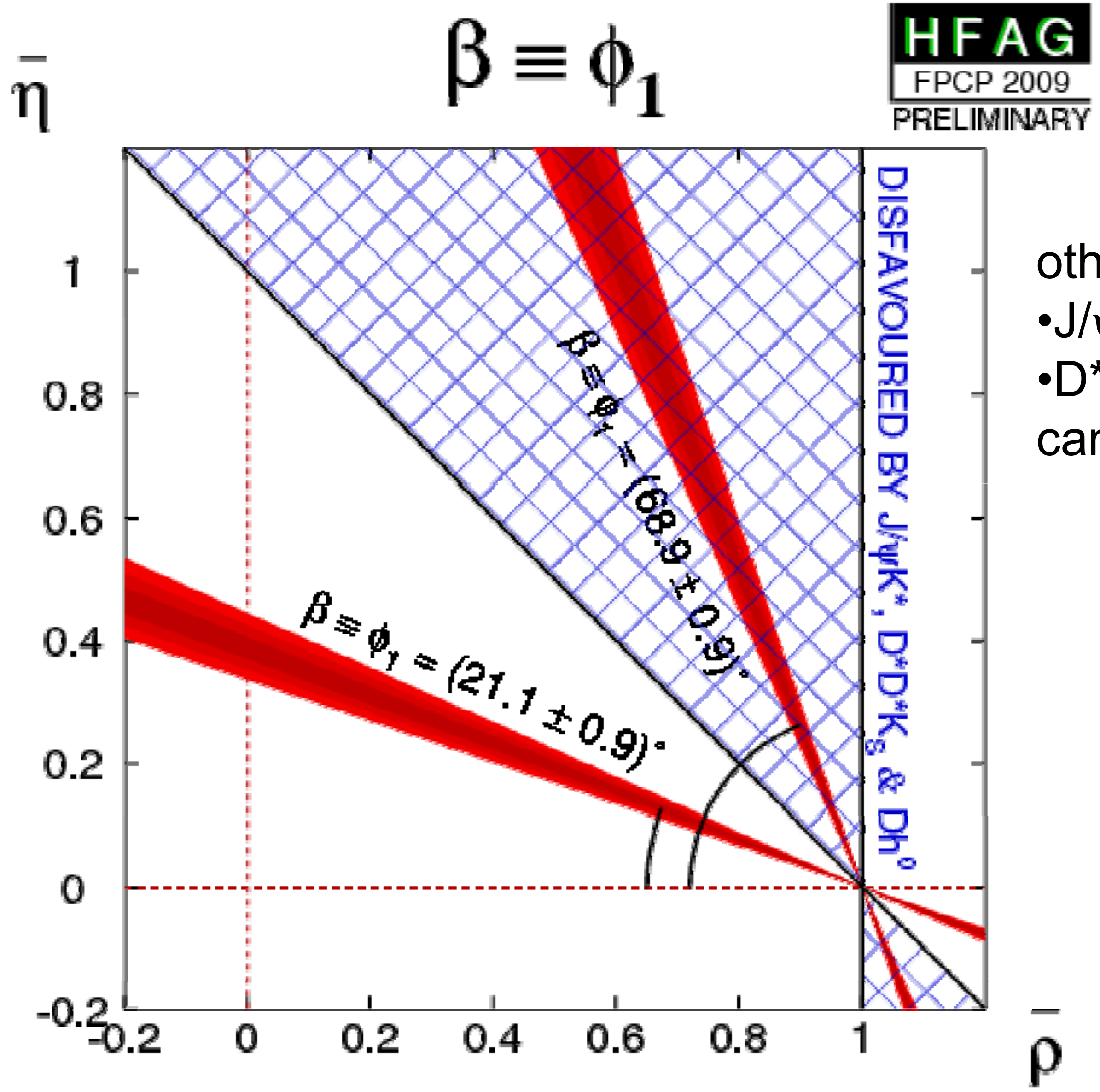
$\cos 2\phi_1 > 0$ at 98.3% C.L.

smaller ϕ_1 (<45°) solution is favored.



consistent with $b \rightarrow c\bar{c}s$ $\sin 2\phi_1$

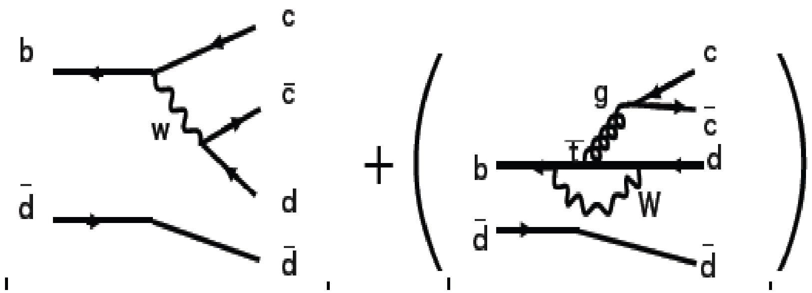
constraint for ϕ_1/β



other measurement using
- $J/\psi K^{*0}$ ($K^{*0} \rightarrow K_S \pi^0$)
- $D^{*+}D^{*-}K_S$

can also contribute.

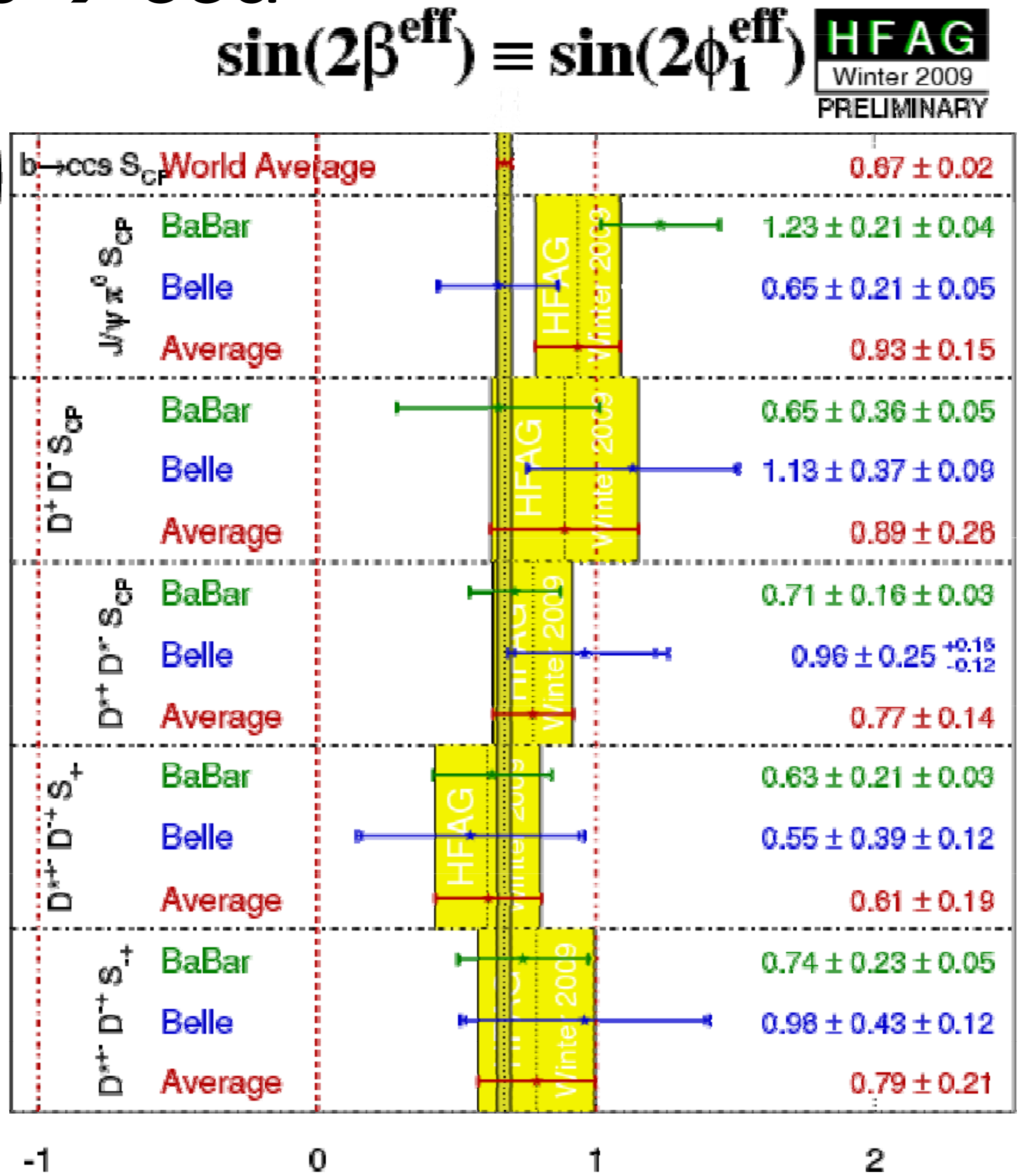
b→ccd



tree + (penguin)

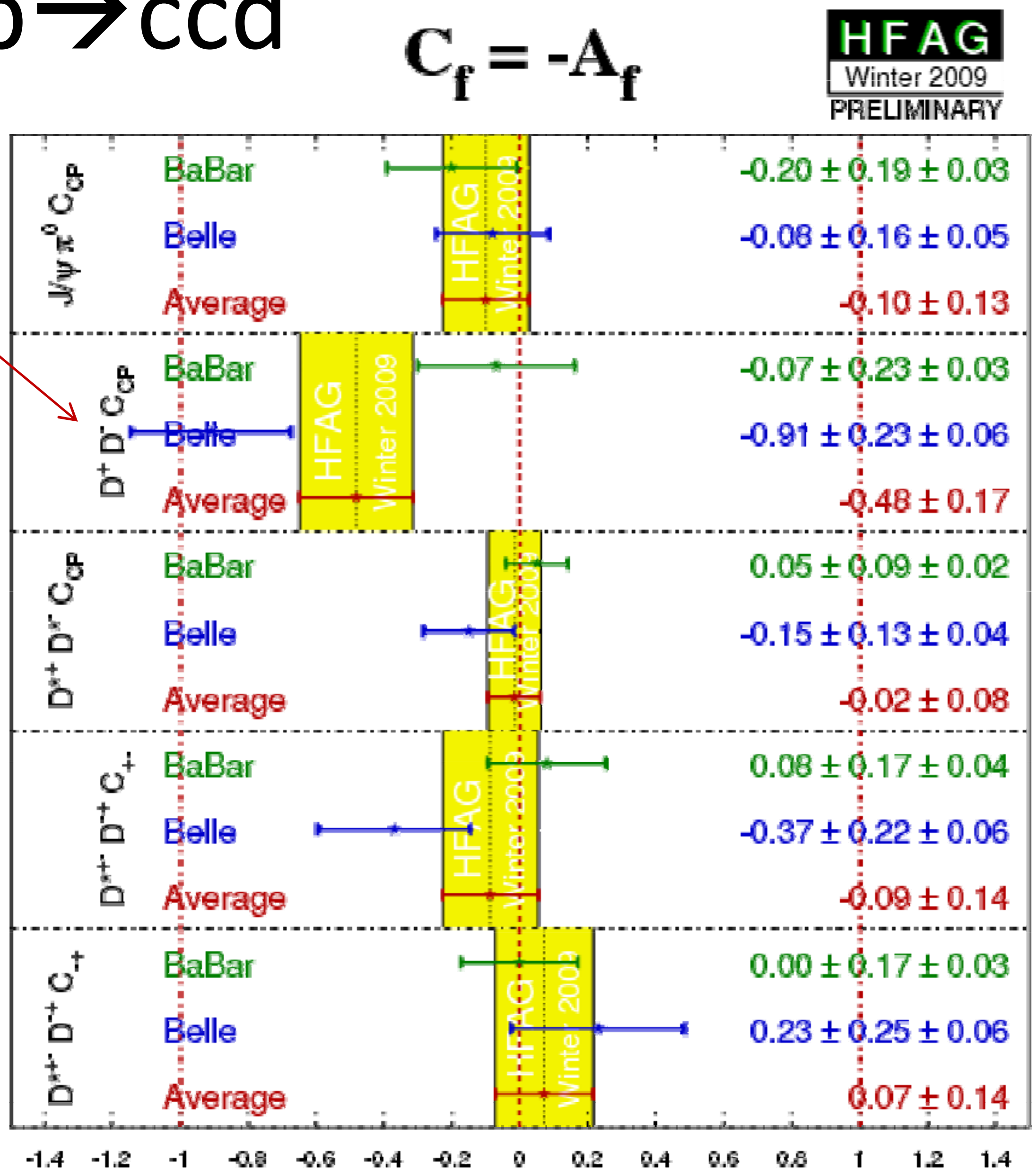
$J/\psi\ \pi^0$:
 constrain penguin contribution in Golden mode($J/\psi K^0$) without model dependence.

$D^{(*)+}\ D^{(*)-}$:
penguin contribution is expected to be small.



b→ccd

Belle
A=-C=0.91±0.23 ± 0.06
(3.2σ significance A≠0)



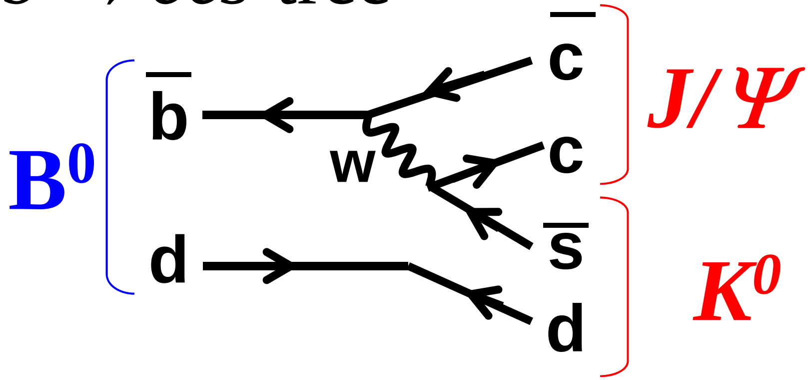
$J/\psi\ \pi^0$:
constrain penguin contribution in Golden mode($J/\psi K^0$) without model dependence.

$D^{(*)+} D^{(*)-}$:
penguin contribution is expected to be small.

b→sqq TCPV

Time-Dependent *CP* asymmetry in B^0 decays

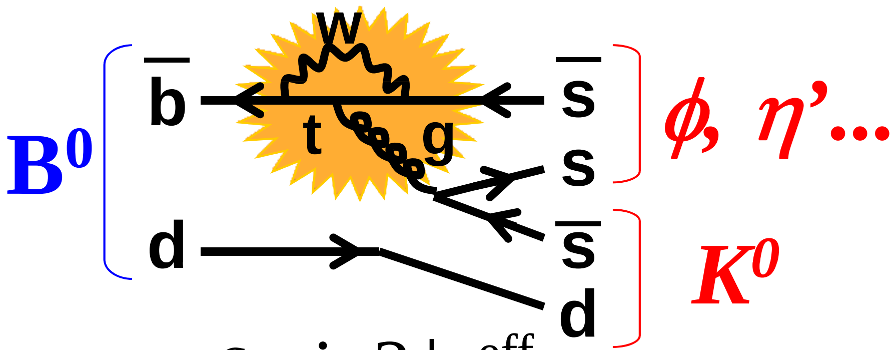
$b \to c\bar{c}s$ tree



$\mathcal{S}$=sin2ϕ_1

$\mathcal{A} \sim 0$

$b \to sq\bar{q}$ penguin



$\mathcal{S}$=sin2ϕ_1^{eff}

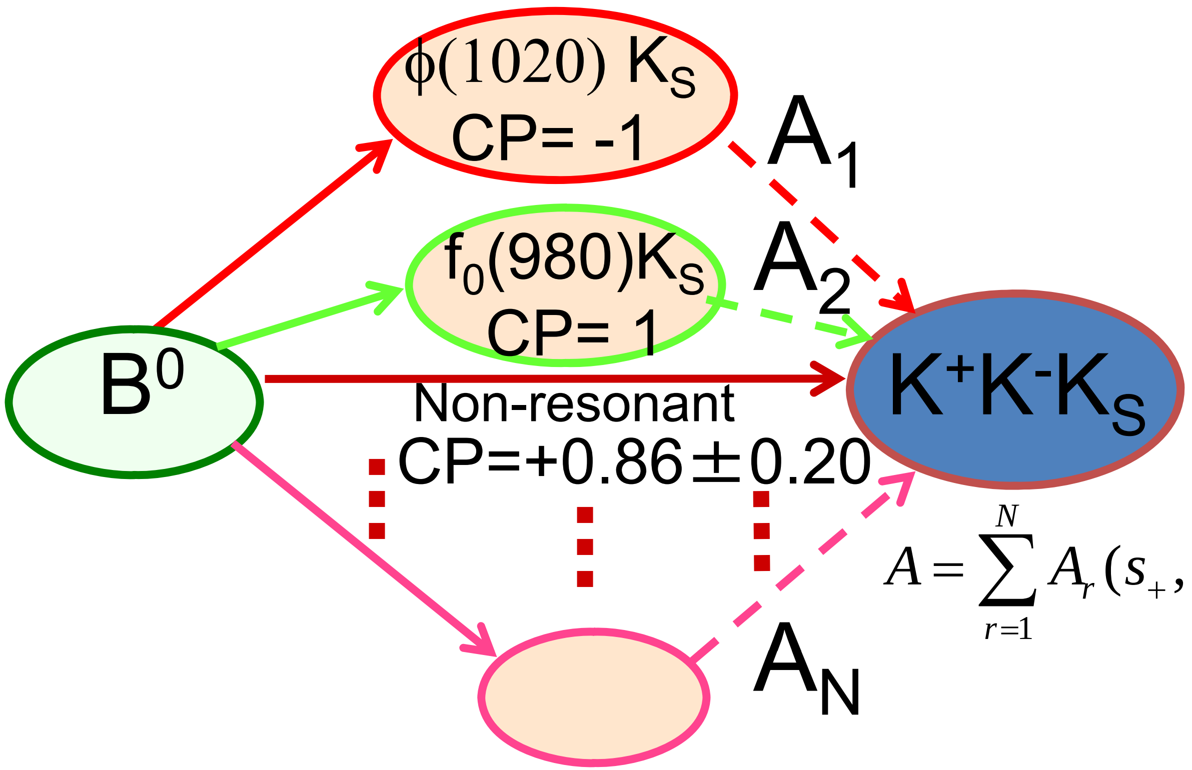
$\mathcal{A} \sim 0$

Extra CPV phase from New Physics → $\Delta \sin 2\phi_1 = \sin 2\phi_1^{eff} - \sin 2\phi_1 \neq 0$

Many two-body and quasi-two body analyses have been done. Since $\phi \to K^+K^-$, $f_0 \to K^+K^-$ and non-resonant contributions overlap invariant mass(as do $\rho^0 \to \pi^+\pi^-$ and $f_0 \to \pi^+\pi^-$), recently time-dependent Dalitz analyses have been performed in three-body decays such as $B^0 \to (K^+K^-)K_S$ and $B^0 \to (\pi^+\pi^-)K_S$.

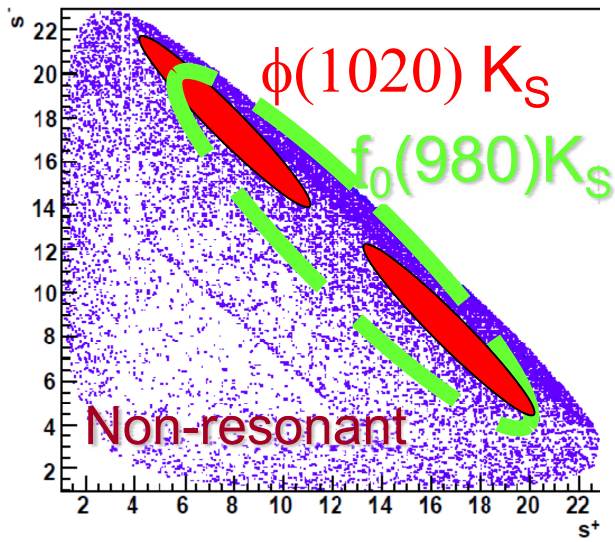
Interferences in *B* decays with K^+K^-Ks final state

- Dalitz-plot
  ⇒ distinguish the intermediate states considering interferences
- Opposite CP eigenvalue from ϕKs
  ⇒State-by-state CP measurement



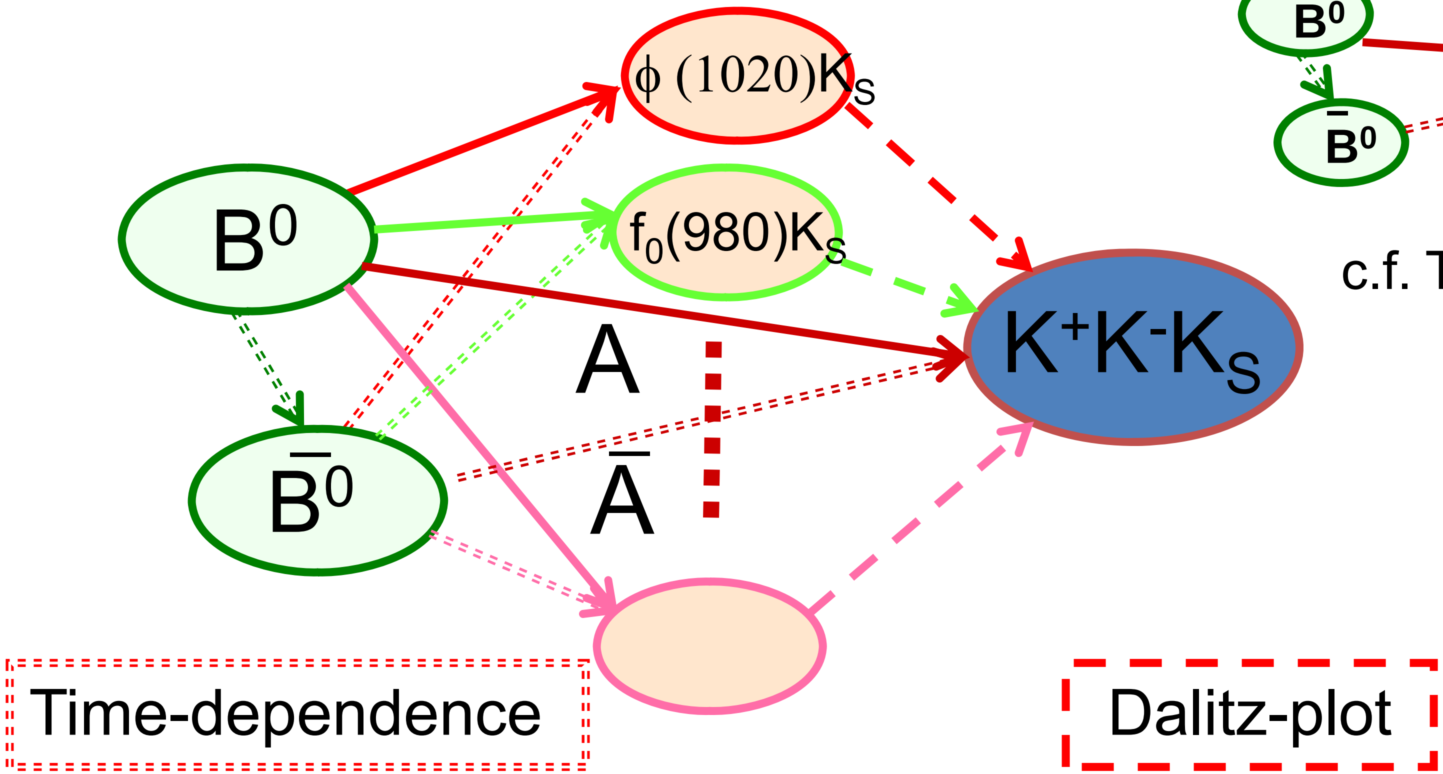
$$A = \sum_{r=1}^{N} A_r(s_+, s_-)$$

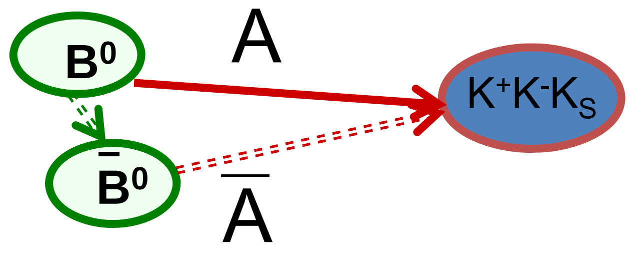
Dalitz-plot



$$s_+ = M^2(K^+K_S)$$
$$s_- = M^2(K^-K_S)$$

Time-dependence of Dalitz plot in $B^0 \to K^+ K^- Ks$





c.f. Time-dependence

Interference in $B^0 \bar{B}^0$ ($\phi_{1,eff}$)+ intermediate states (Dalitz phase)

CP asymmetry ($\phi_{1,eff}$, A_{CP}) of $B \to \phi(1020)\ K_S$
using Time-dependent Dalitz plot analysis in $B \to K^+K^-Ks$

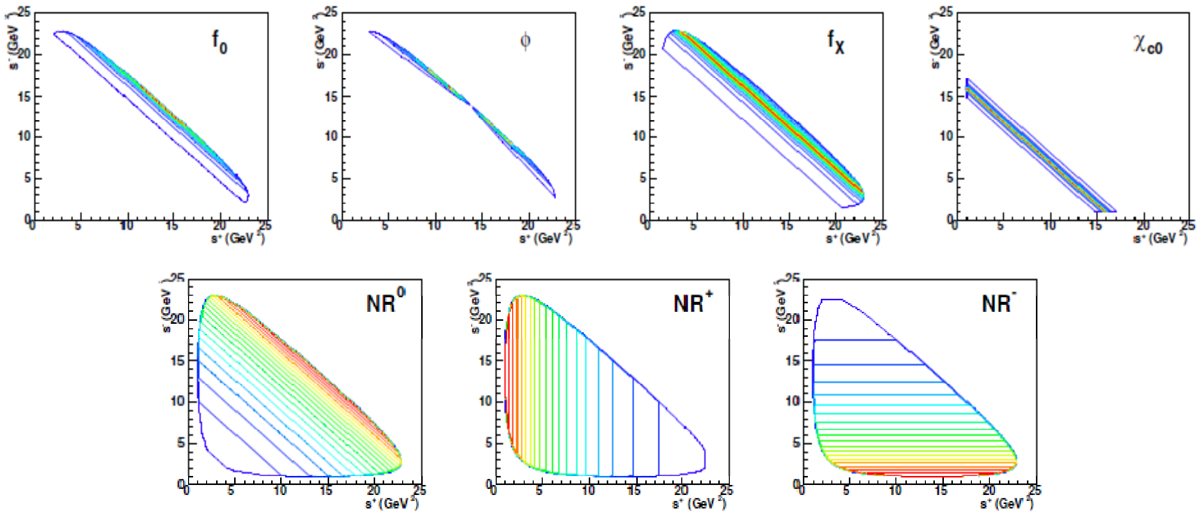
updated Belle result ($B^0 \rightarrow K^+K^-Ks$)

Decay amplitude

Belle 657MBB to be submitted to PRD.

resonance	Form factor	Spin	CP eigenvalue
$f_0(980)$	Flatté	0	1
$\phi(1020)$	RBW	1	-1
$f_x(1500)$	RBW	0	1
χ_{c0}	RBW	0	1
$(KsK^-)K^+$	$\exp(-\alpha s_-)$	0	1
$(KsK^+)K^-$	$\exp(-\alpha s_+)$	0	1
$(K^+K^-)Ks$	$\exp(-\alpha s_0)$	0	1

RBW:
Relativistic
Breit Wigner



19 free parameters
- 12: isobar model
- 6: CPV parameters.
- 1: α for NR

Multiple solution

4 preferable solutions

Decay mode fractions

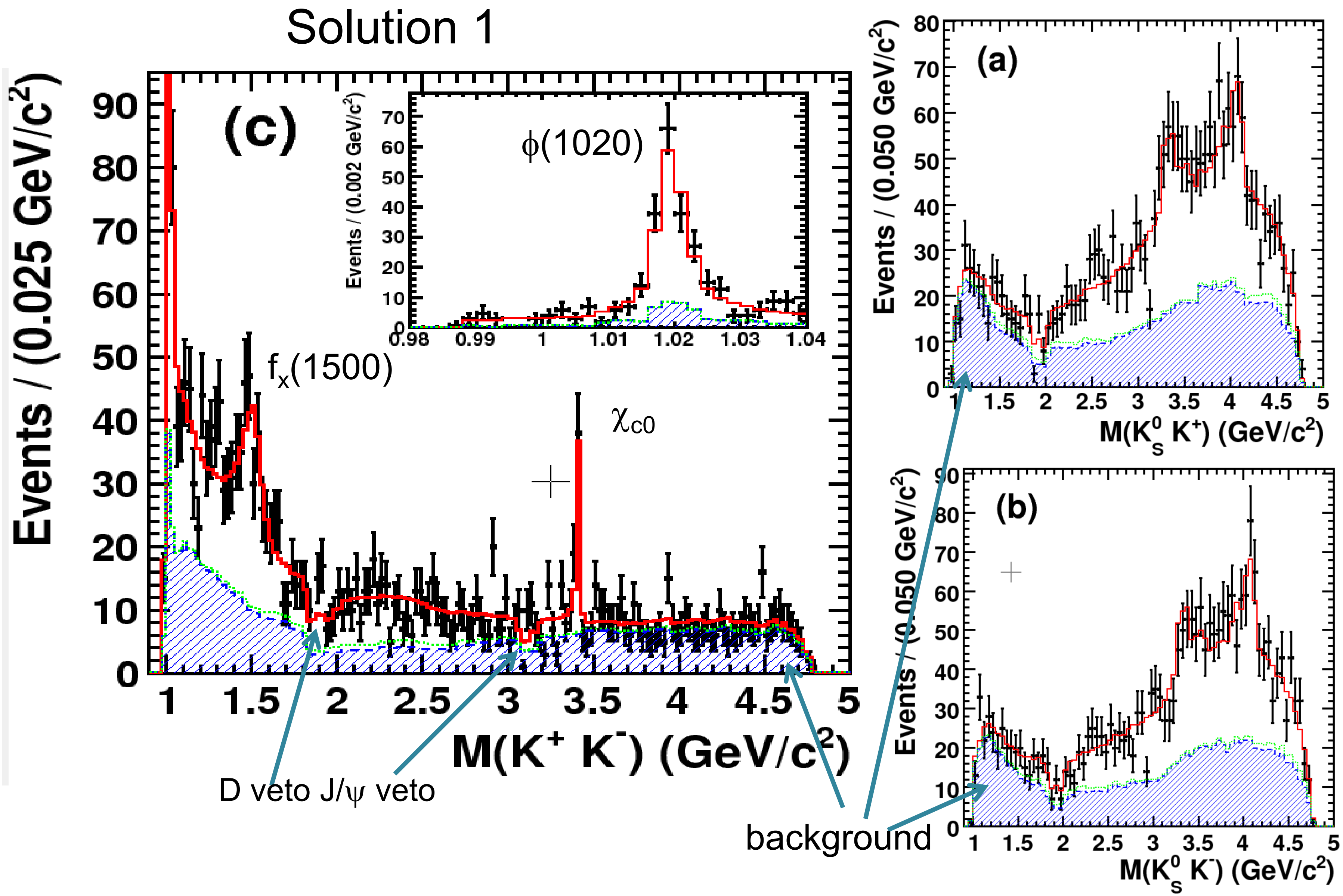
Parameter	Solution 1	Solution 2	Solution 3	Solution 4
$f_{f_0 K_S^0}$	26.0 ± 7.4	54.0 ± 9.6	26.4 ± 7.8	68.1 ± 12.3
$f_{\phi K_S^0}$	14.2 ± 1.2	14.5 ± 1.2	14.2 ± 1.2	14.4 ± 1.2
$f_{f_X K_S^0}$	5.10 ± 1.39	5.89 ± 1.86	39.6 ± 2.6	59.0 ± 3.0
$f_{\chi_{c0} K_S^0}$	3.73 ± 0.74	3.71 ± 0.73	3.68 ± 0.73	4.15 ± 0.79
$f_{(K^+K^-)_{\rm NR} K_S^0}$	138.4 ± 44.8	175.0 ± 52.6	157.4 ± 29.5	48.1 ± 11.7
$f_{(K_S^0 K^+)_{\rm NR} K^-}$	1.65 ± 4.17	21.0 ± 17.3	4.63 ± 6.76	7.87 ± 4.78
$f_{(K_S^0 K^-)_{\rm NR} K^+}$	26.0 ± 12.9	78.0 ± 36.2	38.6 ± 18.1	6.27 ± 3.81
$F_{\rm tot}$	215.2 ± 47.5	352.0 ± 66.8	284.5 ± 36.3	207.9 ± 18.4

External information from $B^0 \to \pi^+\pi^- Ks$

- f_0(980)
  - B.F.($f_0(980) \to \pi^+\pi^-$)/B.F.($f_0(980) \to K^+K^-$) and compare with PDG
  - solutions with low f_0(980)Ks fraction preferred
- f_x(1500)
  - If $f_x(1500)=f_0(1500)$ for both decays
  - B.F.($f_0(1500) \to \pi^+\pi^-$)/B.F.($f_0(1500) \to K^+K^-$) and compare with PDG
  - solutions with low f_x(1500)Ks fraction preferred

Solution 1 preferred.

fit result (Dalitz plot)



fit result (Δt plot)

Solution 1

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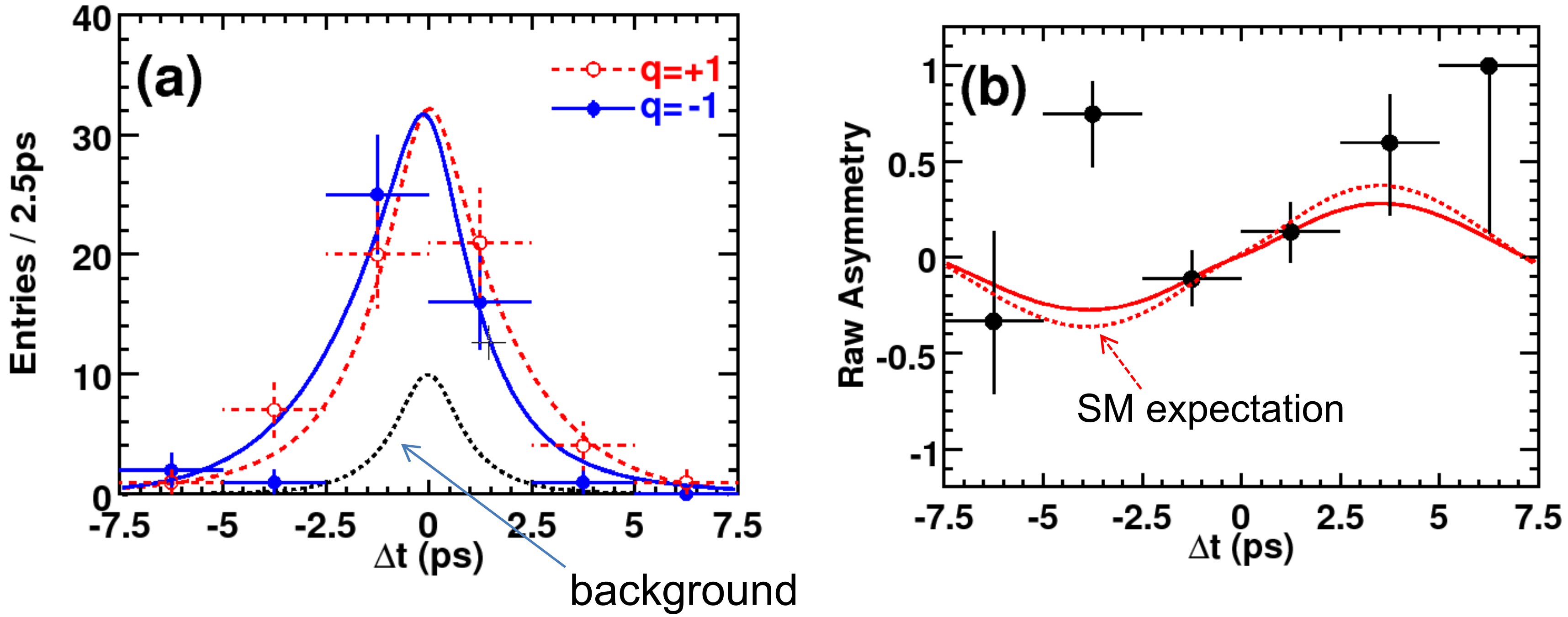
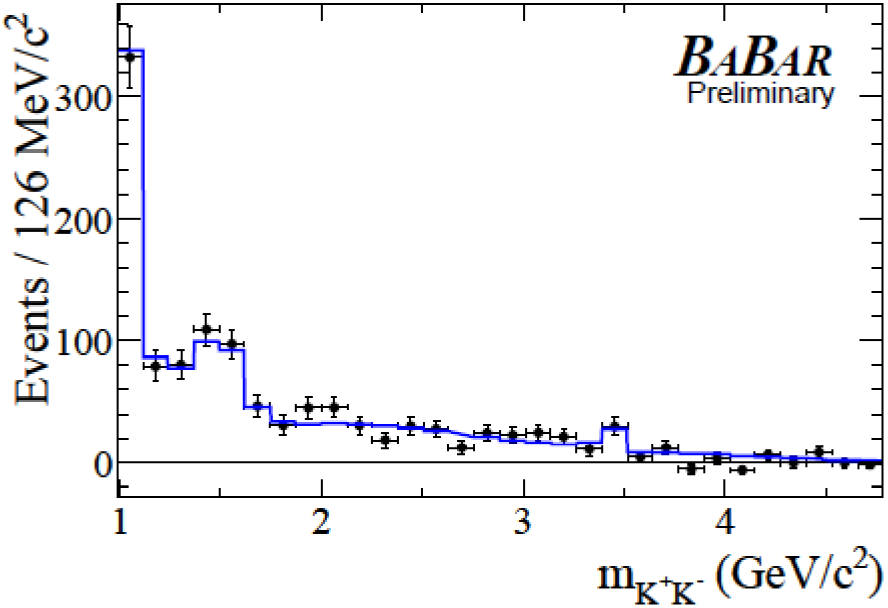
proper time distribution and raw asymmetry plot in ϕ mass region



	Solution 1	Solution 2	Solution 3	Solution 4
$\mathcal{A}_{CP}(f_0 K_S^0)$	$-0.30 \pm 0.29 \pm 0.11 \pm 0.09$	$-0.20 \pm 0.15 \pm 0.08 \pm 0.05$	$+0.02 \pm 0.21 \pm 0.09 \pm 0.09$	$-0.18 \pm 0.14 \pm 0.08 \pm 0.06$
$\phi_1^{\rm eff}(f_0 K_S^0)$	$(31.3 \pm 9.0 \pm 3.4 \pm 4.0)^\circ$	$(26.1 \pm 7.0 \pm 2.4 \pm 2.5)^\circ$	$(25.6 \pm 7.6 \pm 2.9 \pm 0.8)^\circ$	$(26.3 \pm 5.7 \pm 2.4 \pm 5.8)^\circ$
$\mathcal{A}_{CP}(\phi K_S^0)$	$+0.04 \pm 0.20 \pm 0.10 \pm 0.02$	$+0.08 \pm 0.18 \pm 0.10 \pm 0.03$	$-0.01 \pm 0.20 \pm 0.11 \pm 0.02$	$+0.21 \pm 0.18 \pm 0.11 \pm 0.05$
$\phi_1^{\rm eff}(\phi K_S^0)$	$(32.2 \pm 9.0 \pm 2.6 \pm 1.4)^\circ$	$(26.2 \pm 8.8 \pm 2.7 \pm 1.2)^\circ$	$(27.3 \pm 8.6 \pm 2.8 \pm 1.3)^\circ$	$(24.3 \pm 8.0 \pm 2.9 \pm 5.2)^\circ$

the third error: Dalitz plot model uncertainty

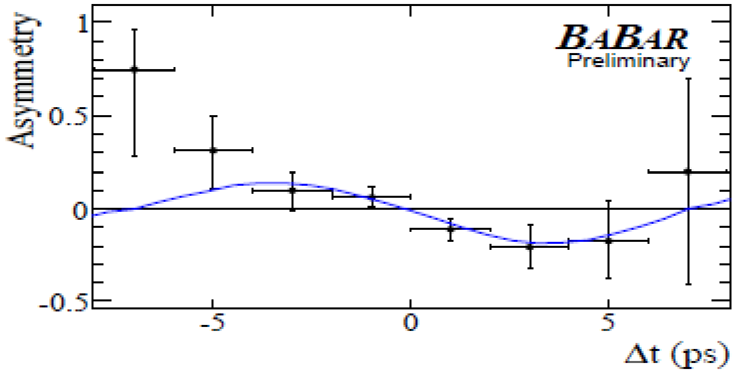
BABAR K^+K^-Ks result



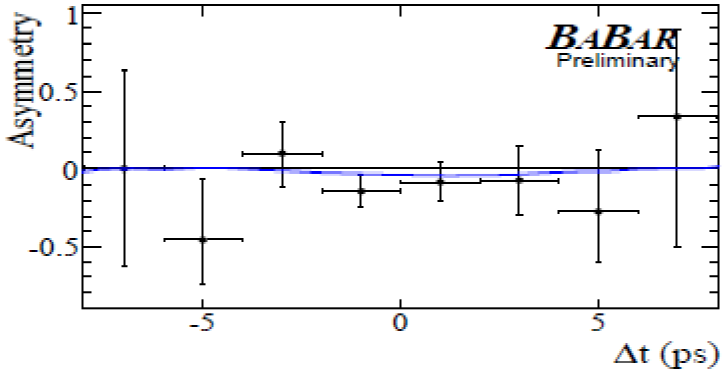
BABAR 465MBB arXiv:0808.0700

Name	Solution (1)
1 $A_{CP}(\phi K^0_S)$	$0.14 \pm 0.19 \pm 0.02$
2 $\beta_{eff}(\phi K^0_S)$	(7.7±7.7 ±0.9)°
3 $A_{CP}(f_0 K^0_S)$	$0.01 \pm 0.26 \pm 0.07$
4 $\beta_{eff}(f_0 K^0_S)$	(8.5±7.5 ±1.8)°

whole region



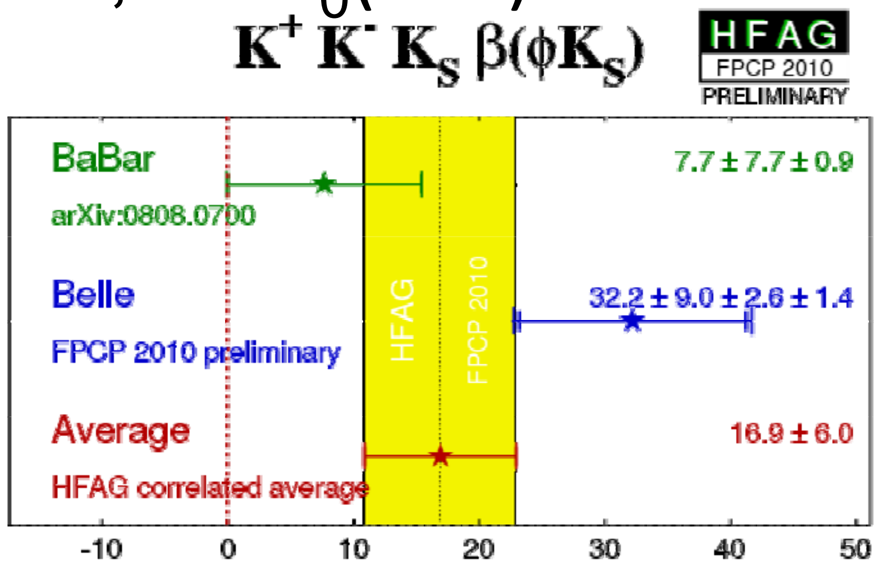
low mass region

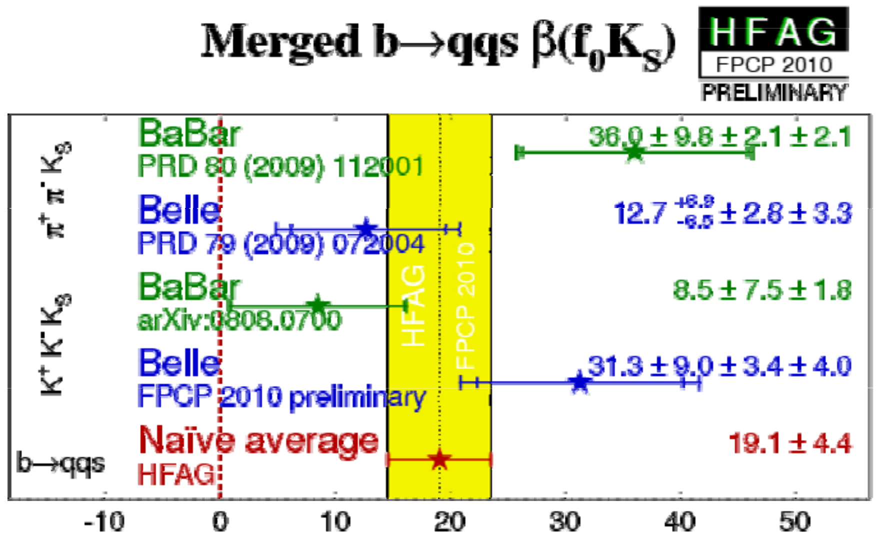


average in B→ϕKs, B→f_0(980)Ks

	Solution 1
$\mathcal{A}_{CP}(f_0 K_S^0)$	$-0.30 \pm 0.29 \pm 0.11 \pm 0.09$
$\phi_1^{\rm eff}(f_0 K_S^0)$	$(31.3 \pm 9.0 \pm 3.4 \pm 4.0)^\circ$
$\mathcal{A}_{CP}(\phi K_S^0)$	$+0.04 \pm 0.20 \pm 0.10 \pm 0.02$
$\phi_1^{\rm eff}(\phi K_S^0)$	$(32.2 \pm 9.0 \pm 2.6 \pm 1.4)^\circ$

Name	Solution (1)
1 $A_{CP}(\phi K_S^0)$	$0.14 \pm 0.19 \pm 0.02$
2 $\beta_{\it eff}(\phi K_S^0)$	(7.7±7.7 ±0.9)°
3 $A_{CP}(f_0 K_S^0)$	$0.01 \pm 0.26 \pm 0.07$
4 $\beta_{\it eff}(f_0 K_S^0)$	(8.5±7.5 ±1.8)°



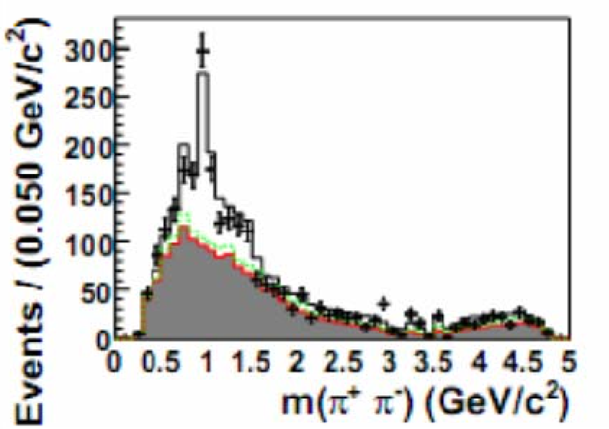


Consistent with the Standard Model prediction at current sensitivity

$\phi_{1(b\to c\bar{c}\bar{s})} = (21.0 \pm 0.9)^\circ$

result using $\pi^+\pi^-$Ks

Belle 657MBB PRD79(2009) 072004



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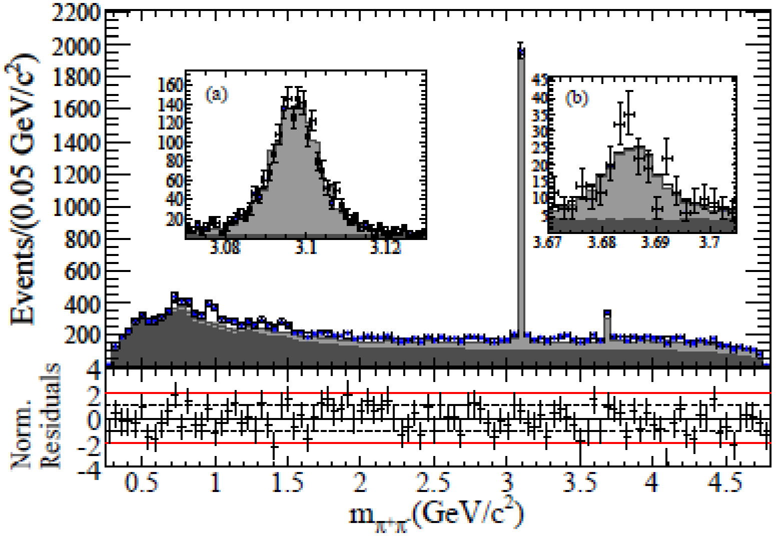
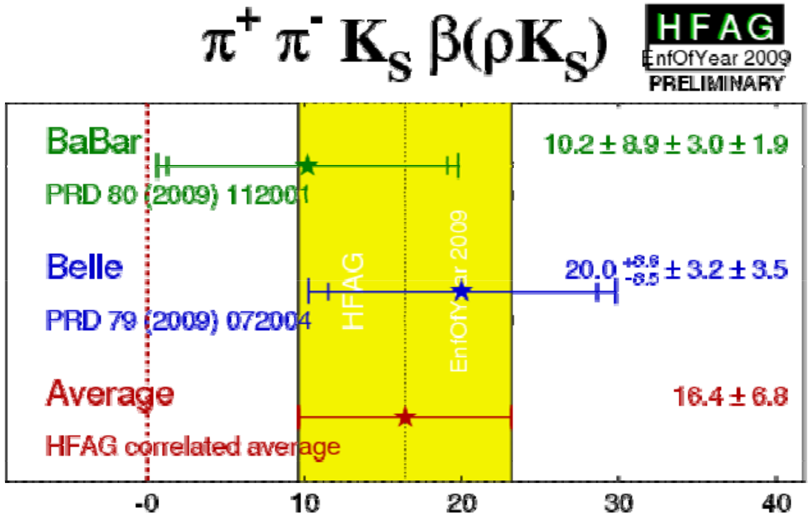
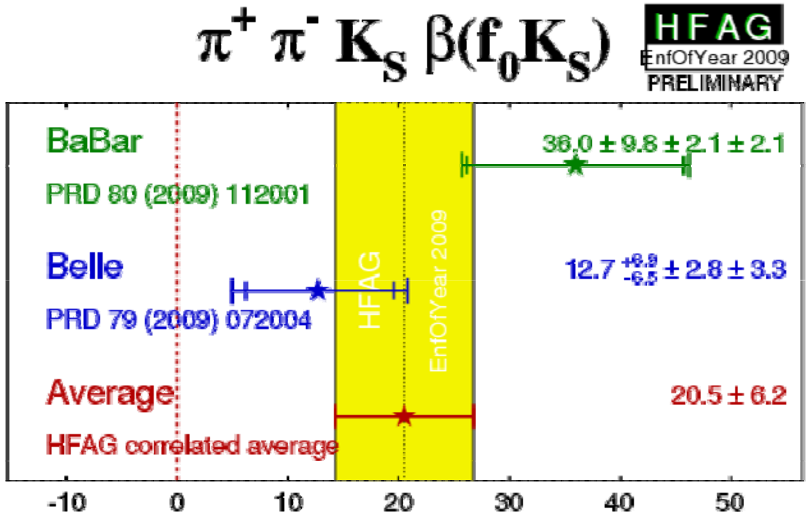
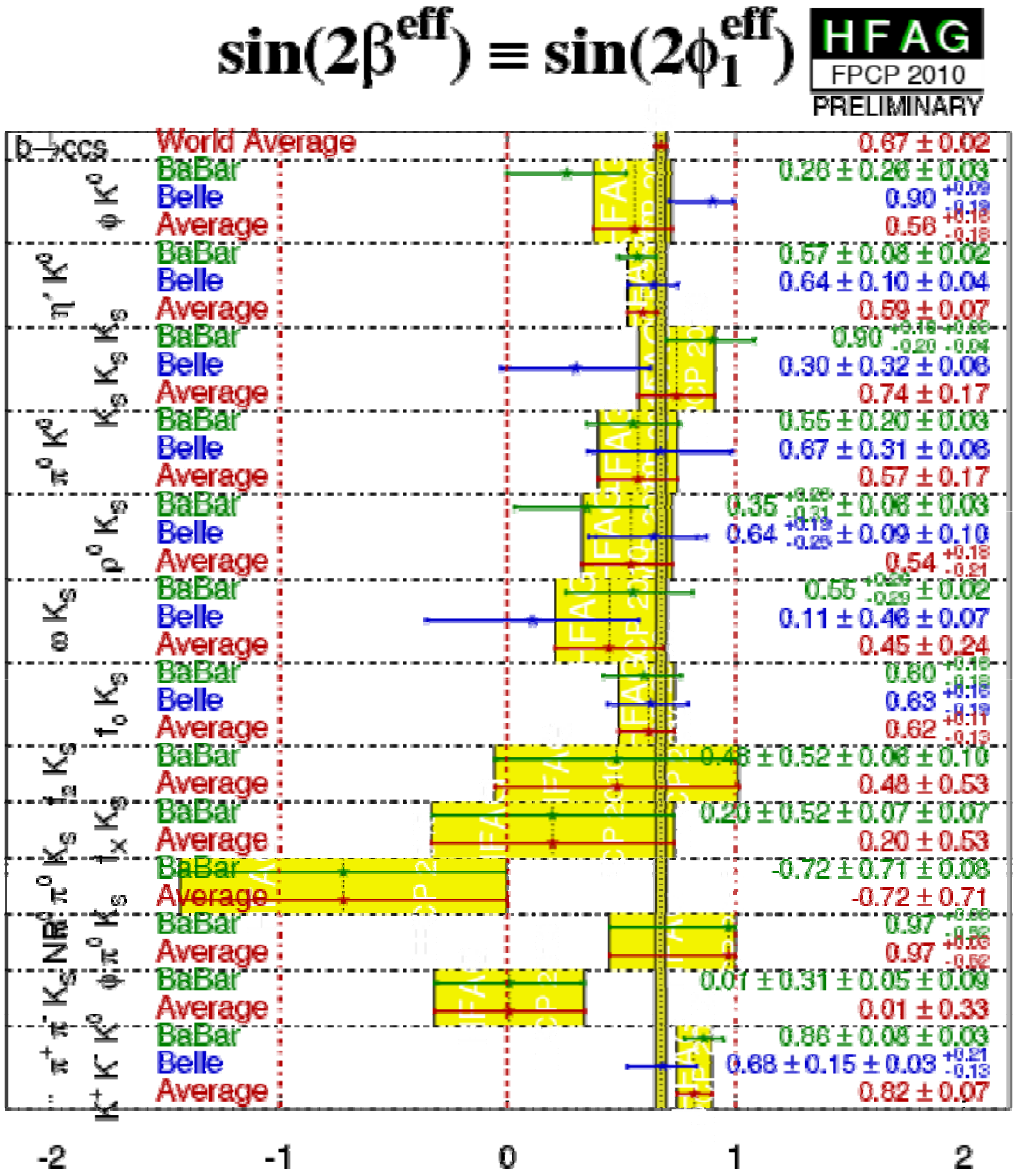






Compilation of effective $\sin 2\phi_1$



Still precision is statistically dominated.

↓

To obtain sensitivity in effective $\sin 2\phi_1$ of $O(10^{-2})$, we need $O(10ab^{-1})$ of integrated luminosity.

Summary

- ϕ_1/β = $(21.1 \pm 0.9)^\circ$ in B-factories
  - $\sin 2\phi_1$ from $b \rightarrow c\bar{c}s$ modes.
  - resolve the quadratic ambiguity by measuring $\cos 2\phi_1$ with Dalitz analysis, etc.
- penguin modes are good probes of new physics.
  We need more data.
- Belle is now updating its result with the full data sample.
  - $J/\psi K^0$
    - full data: 535M→771MBB (factor 1.44)
    - improved tracking software: 20% gain for $J/\psi Ks$
    - yield : factor 1.61
  - $\psi(2S)Ks$, $\chi_{c1}Ks$, $\eta_c Ks$, and combined analysis
    last update with150$MB\bar{B}$ (657$MB\bar{B}$ for $\psi(2S)Ks$)
  - (statistical error for $\sin 2\phi_1$)~0.02
  - etc..

backup

$b \to c\bar{c}s$

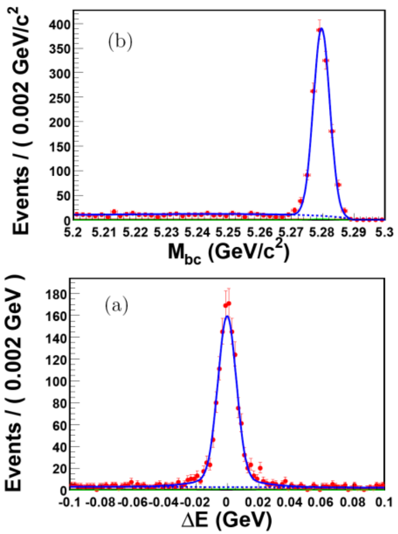
$B^0 \to \psi(2S)K_S$

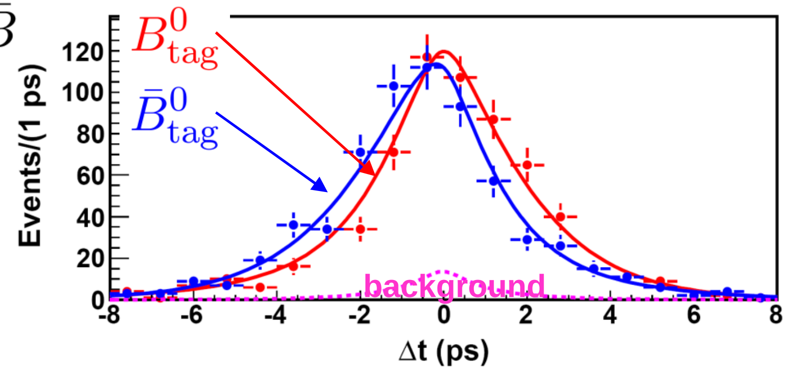
arXiv:0708.2604v2[hep-ex] 4 Feb 2008

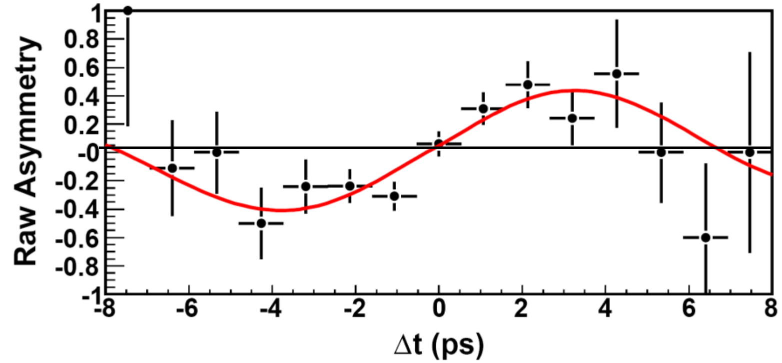
$657 \times 10^6 B\bar{B}$

1284 ± 37 signal events

$92 \pm 1\%$ purity







$$\mathcal{S}_{\psi(2S)K^0_S} = 0.72 \pm 0.09(\mathrm{stat}) \pm 0.03(\mathrm{syst})$$

$$\mathcal{A}_{\psi(2S)K^0_S} = 0.04 \pm 0.07(\mathrm{stat}) \pm 0.05(\mathrm{syst})$$

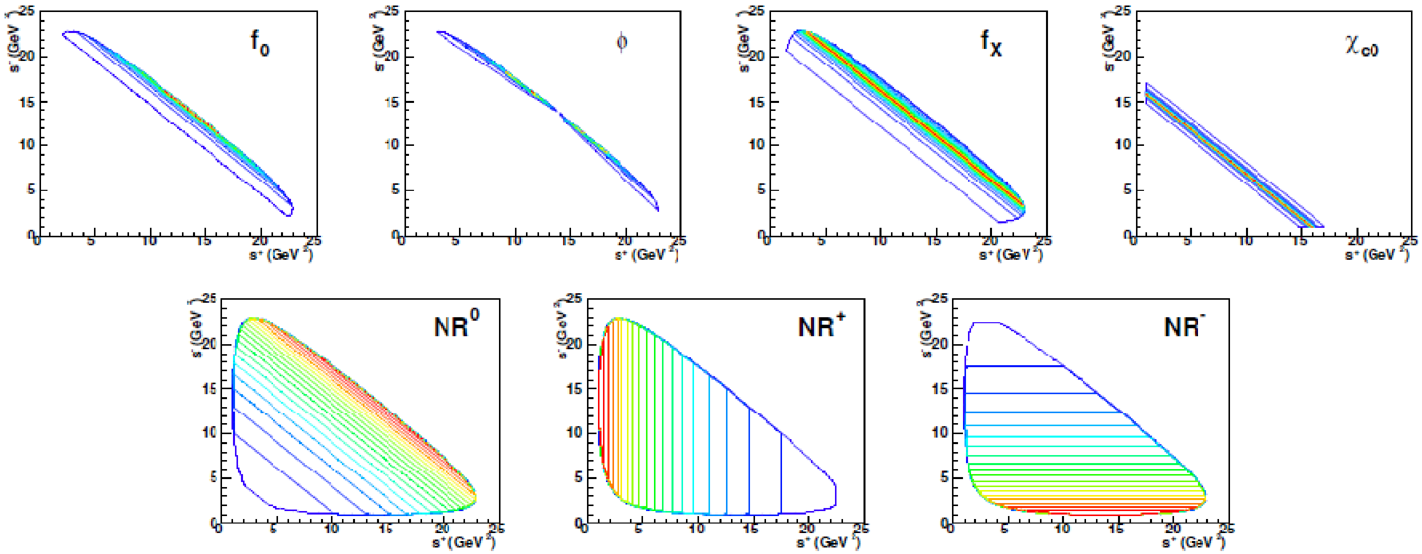
Combined $b \to c\bar{c}s$ result:

$$\sin 2\phi_1 = 0.650 \pm 0.029(\mathrm{stat}) \pm 0.018(\mathrm{syst})$$ (Belle)

$$\sin 2\phi_1 = 0.714 \pm 0.032(\mathrm{stat}) \pm 0.018(\mathrm{syst})$$ (BaBar)

Resonances considered in the KsKK signal model

Resonances	Fixed parameters (GeV)	Form Factor, $R_i(s_+,s_-)$	L
f_0	$M = 0.965 \pm 0.010$	Flatté	0
	$g_\pi = 0.165 \pm 0.018$		
	$g_K = (4.21 \pm 0.09) g_\pi$		
ϕ	$M = 1.019455 \pm 0.020$	RBW	1
	$\Gamma = 0.00426 \pm 0.00004$		
f_X	$M = 1.524 \pm 0.014$	RBW	0
	$\Gamma = 0.136 \pm 0.023$		
χ_{c0}	$M = 3.41475 \pm 0.00035$	RBW	0
	$\Gamma = 0.0104 \pm 0.0007$		
$(K^+K^-)_{NR}$		$e^{-\alpha s^0}$	
$(K^0_S K^+)_{NR}$		$e^{-\alpha s^+}$	
$(K^0_S K^-)_{NR}$		$e^{-\alpha s^-}$	



Signal PDF

$P(\Delta t, q; s_+, s_-)$ Dalitz-plot × Time-dependence

$$= \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[(|A|^2 + |\bar{A}|^2) - q\ (|A|^2 - |\bar{A}|^2)\cos\Delta m_d \Delta t + 2\,q\ \mathrm{Im}(\bar{A}A^*)\sin\Delta m_d \Delta t\right]$$

Decay amplitude

ϕ_1^{eff}

B^0: $A = \sum_{r=1}^{7} a_r(1+c_r)e^{i(b_r+d_r)} \cdot f_r(s_+, s_-)$

$\overline{B^0}$: $\bar{A} = \sum_{r=1}^{7} a_r(1-c_r)e^{i(b_r-d_r)} \cdot f_r(s_+, s_-)$

⇒19 fit parameters

1. Dalitz amplitude and phases
2. *CP*-violating amplitude and phases (ϕ Ks, f_0Ks, others)
3. Kinematics (Dalitz plot) $f_r(s_+, s_-)$
   α for NR

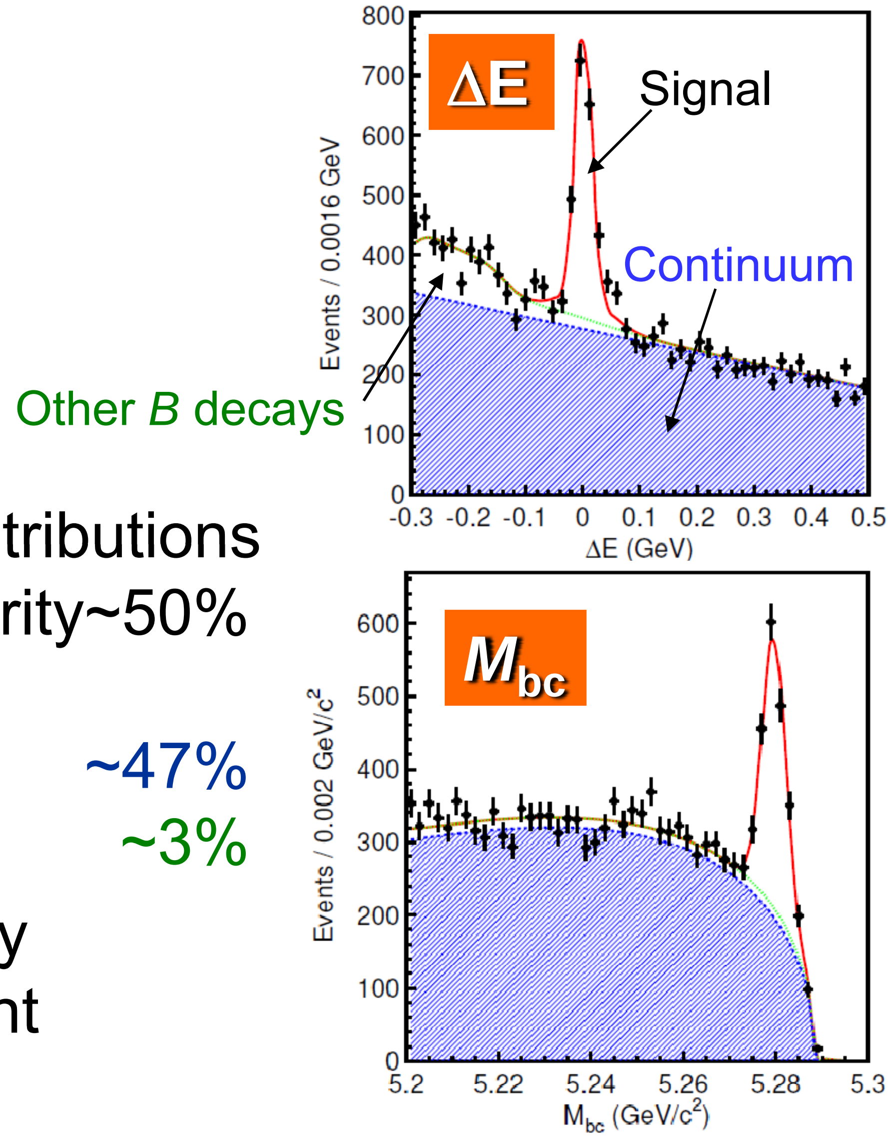
Reconstructed $B^0 \to K_S K^+ K^-$ candidates

- Event selection
  - $B^0 \to K_S K^+ K^-$ reconstruction
    - Ks selection
    - $K^\pm$ selection by PID (K/π)
  - Continuum suppression
  - Efficiency: ~16%

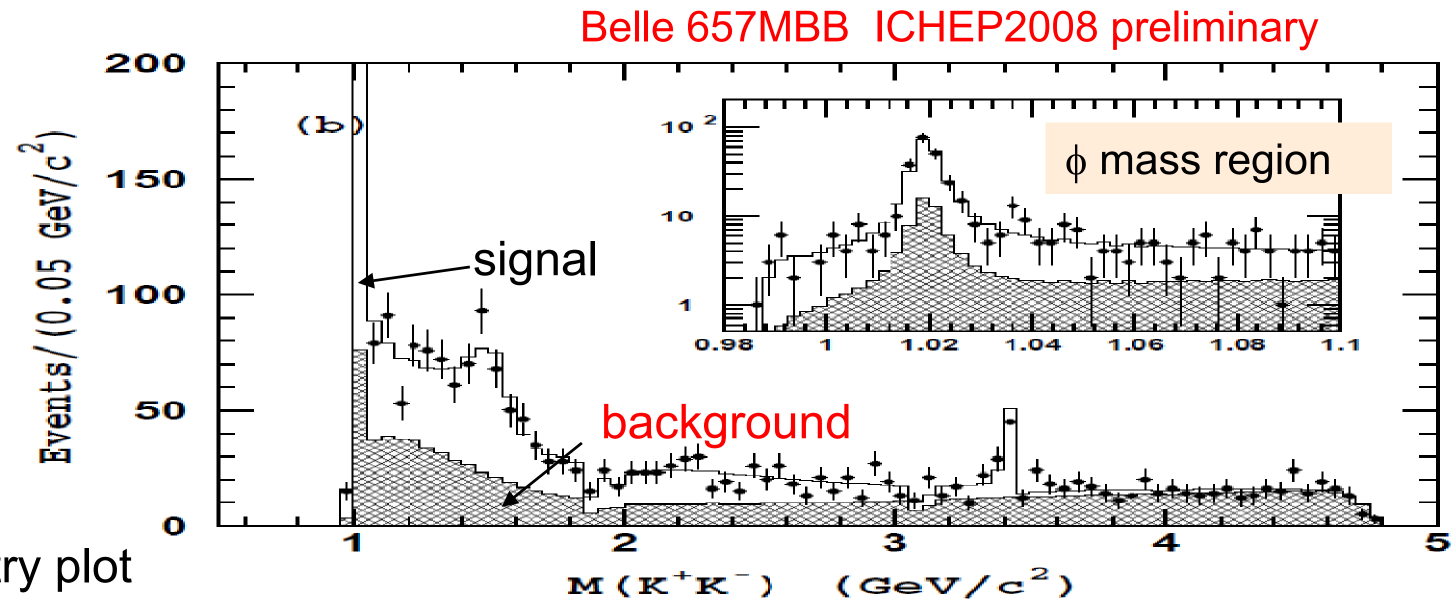
- Unbinned ML fit to ΔE and M_{bc} distributions
  - $B^0 \to K_S K^+ K^-$ 1176±51evts. Purity~50%
  - Background
    - Continuum ~47%
    - Other *B* decays ~3%

➡ Event-by-event signal probability $f_{sig}(\Delta E, M_{bc})$ for CP measurement

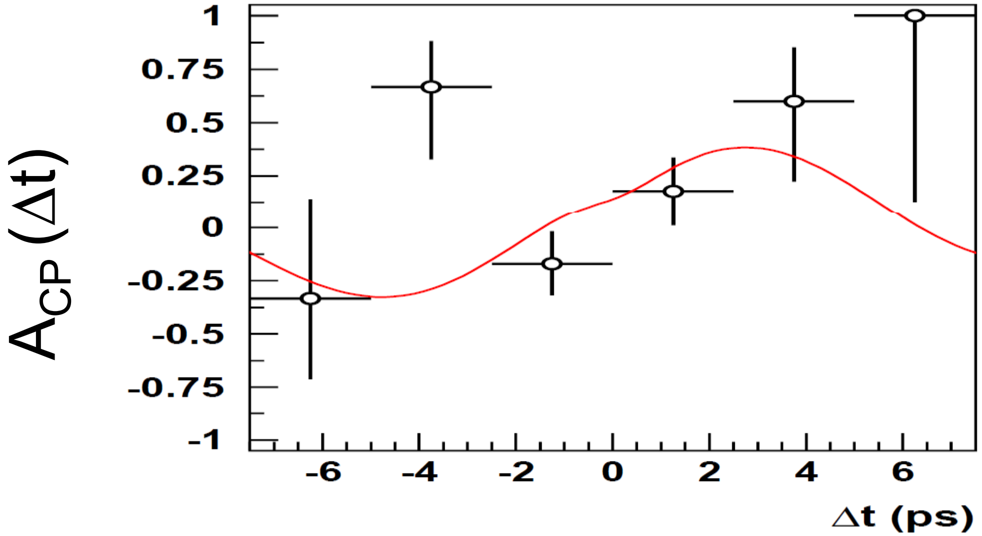
➡ Time-dependent Dalitz plot fit to the selected $B^0 \to K_S K^+ K^-$ candidates.



plots for $K^+K^-K_s$

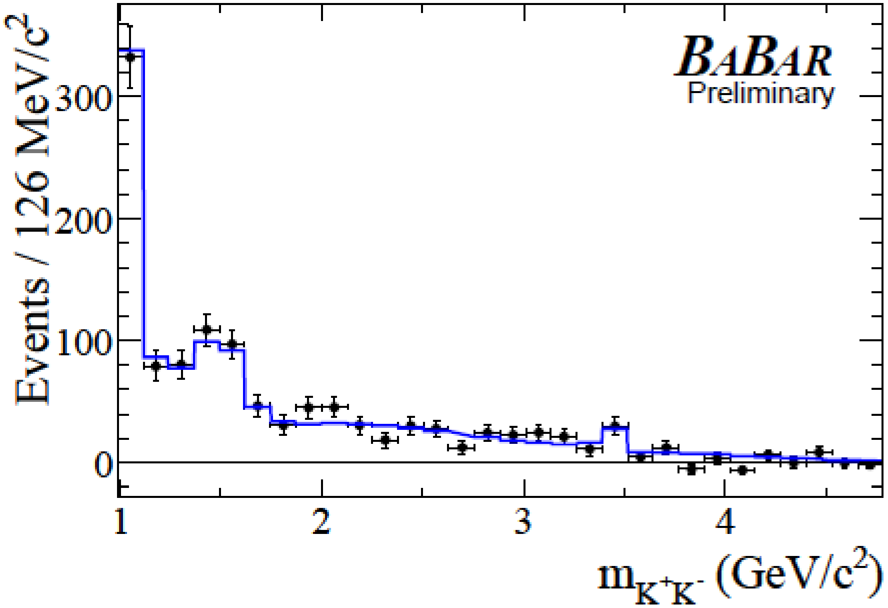


raw asymmetry plot
in ϕ mass region



Solution	CP Parameter	Fit Result
1	$\phi_1^{\rm eff}(f_0(980)K_S^0)$	$(28.2^{+9.8}_{-9.9})^\circ$
	$\phi_1^{\rm eff}(\phi(1020)K_S^0)$	$(21.2^{+9.8}_{-10.4})^\circ$
2	$\phi_1^{\rm eff}(f_0(980)K_S^0)$	$(64.1^{+7.6}_{-8.0})^\circ$
	$\phi_1^{\rm eff}(\phi(1020)K_S^0)$	$(62.1^{+8.3}_{-8.8})^\circ$
3	$\phi_1^{\rm eff}(f_0(980)K_S^0)$	$(61.5^{+6.5}_{-6.5})^\circ$
	$\phi_1^{\rm eff}(\phi(1020)K_S^0)$	$(65.1^{+8.7}_{-8.7})^\circ$
4	$\phi_1^{\rm eff}(f_0(980)K_S^0)$	$(36.9^{+10.9}_{-9.6})^\circ$
	$\phi_1^{\rm eff}(\phi(1020)K_S^0)$	$(44.9^{+13.2}_{-13.6})^\circ$

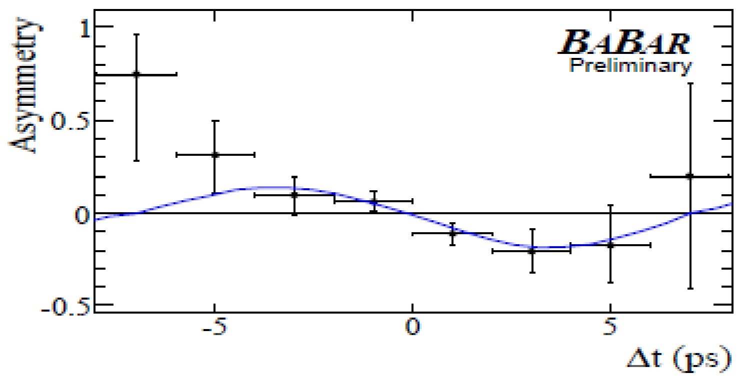
BABAR $K^+K^-K_s$ result



BABAR 465MBB arXiv:0808.0700

Name	Solution (1)	Solution (2)
1 $A_{CP}(\phi K^0_S)$	$0.14 \pm 0.19 \pm 0.02$	0.13 ± 0.18
2 $\beta_{eff}(\phi K^0_S)$	(7.7±7.7 ±0.9)°	(8.?±8.?)°
3 $A_{CP}(f_0 K^0_S)$	$0.01 \pm 0.26 \pm 0.07$	-0.49 ± 0.25
4 $\beta_{eff}(f_0 K^0_S)$	(8.5±7.5 ±1.8)°	(197±11)°

whole region



low mass region