Time-dependent CP violation in B decays at Belle

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Introduction

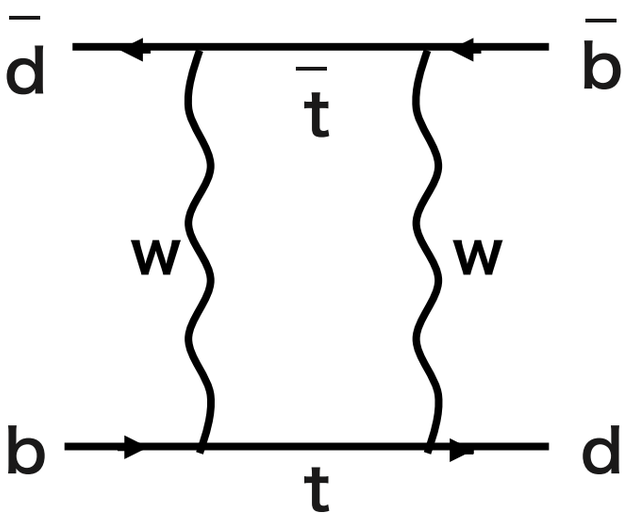
Time-dependent *CP* violation is induced by quantum interference between B^0-$\bar{B}^0$ mixing and B^0 decay to *CP* eigenstate (f_{CP}).

$$\mathcal{A}_{CP} = \frac{\mathcal{P}(\overline{B^0}(\Delta t) \to f_{CP}) - \mathcal{P}(B^0(\Delta t) \to f_{CP})}{\mathcal{P}(\overline{B^0}(\Delta t) \to f_{CP}) + \mathcal{P}(B^0(\Delta t) \to f_{CP})} = \underline{S \sin\Delta m\Delta t + A \cos\Delta m\Delta t}$$

$S = \frac{-2\mathrm{Im}\,\lambda}{|\lambda|^2+1}$: Time-dependent *CPV* parameter, $A(=-C) = \frac{1-|\lambda|^2}{1+|\lambda|^2}$: Direct *CPV* parameter

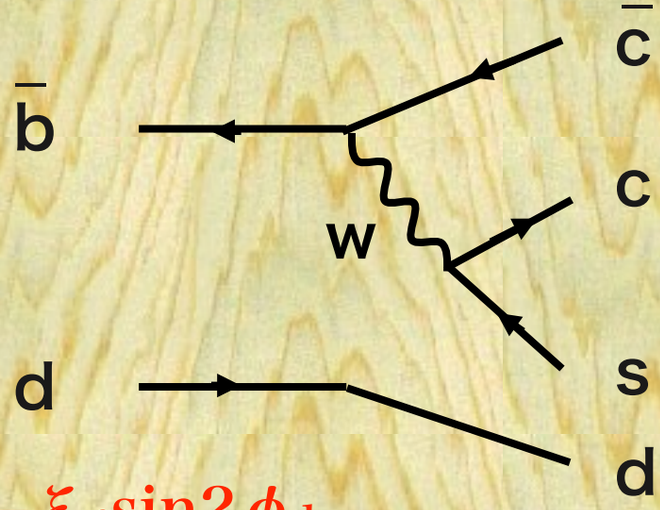
Δm: B-$\bar{B}$ mass difference, Δt: B-$\bar{B}$ decay time difference

$\bar{B}$-B^0 mixing box diagram



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

$B^0 \to (c\bar{c})\, K^0$ "Golden mode"



$S = -\xi_f \sin 2\phi_1$

$= 0.699 \pm 0.017$ (WA)

$A \sim 0$

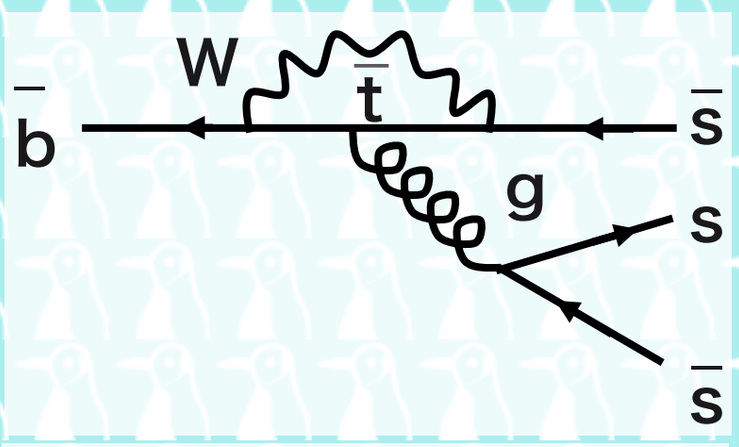
ξ_f: *CP* eigenvalue

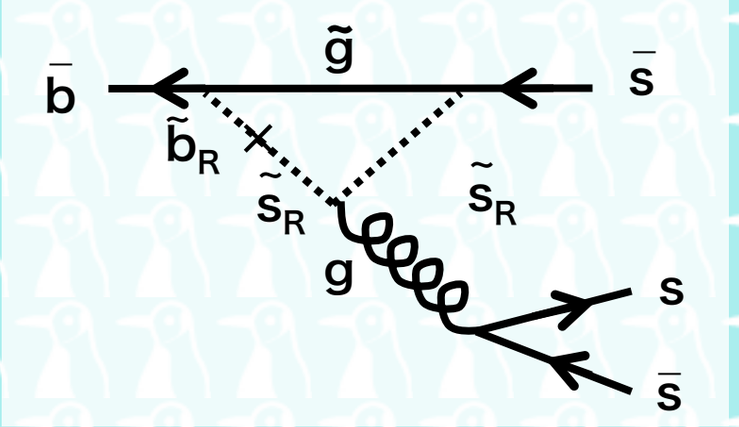
$= -1$ for $J/\psi\,(\eta')\, K^0_S$

$+1$ for $J/\psi\,(\eta')\, K^0_L$

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

$B^0 \to \eta'\, K^0$ "Probe for new physics"

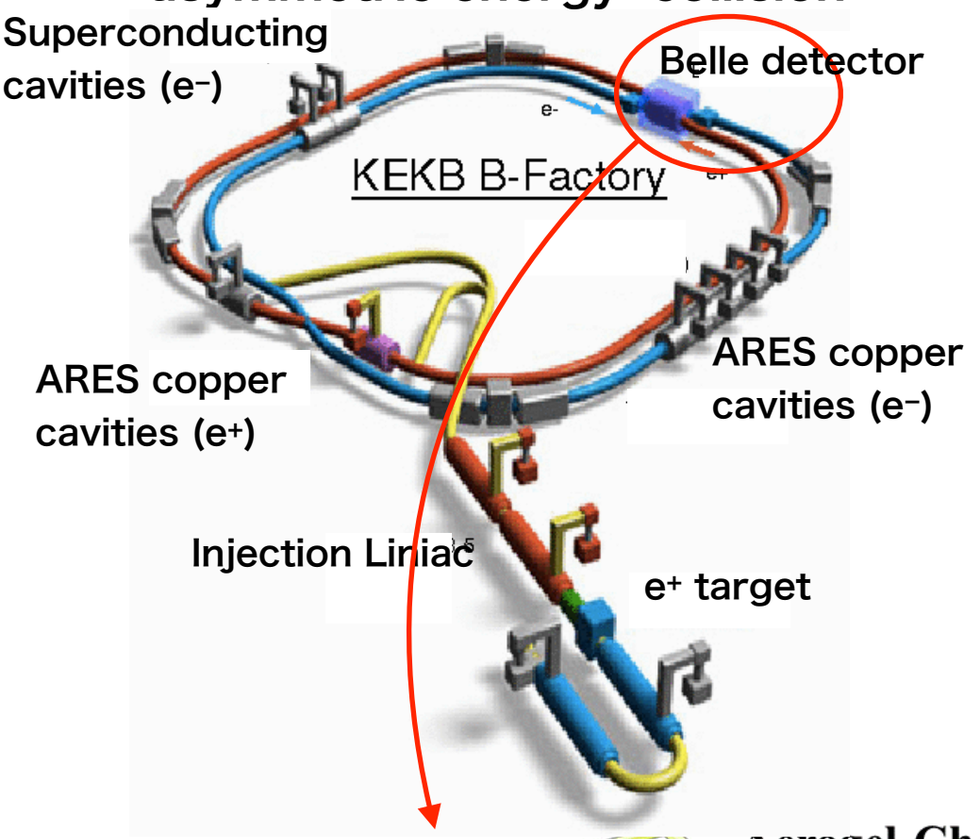


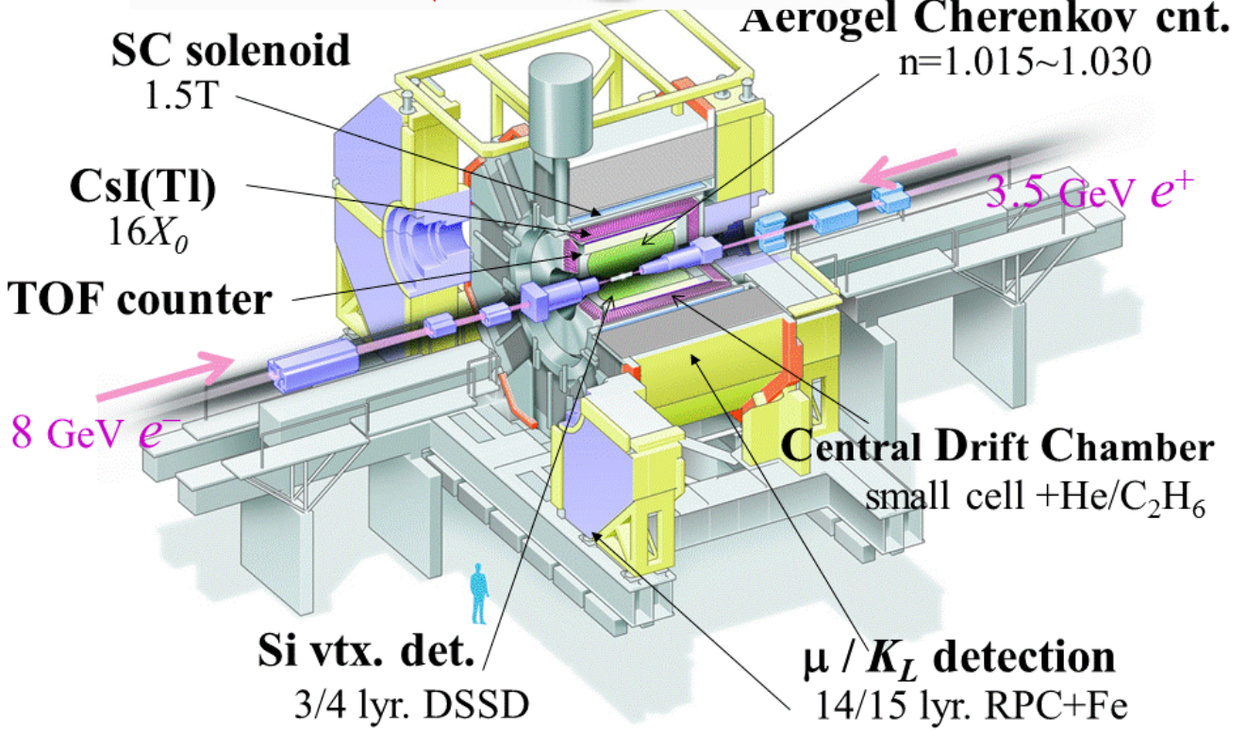


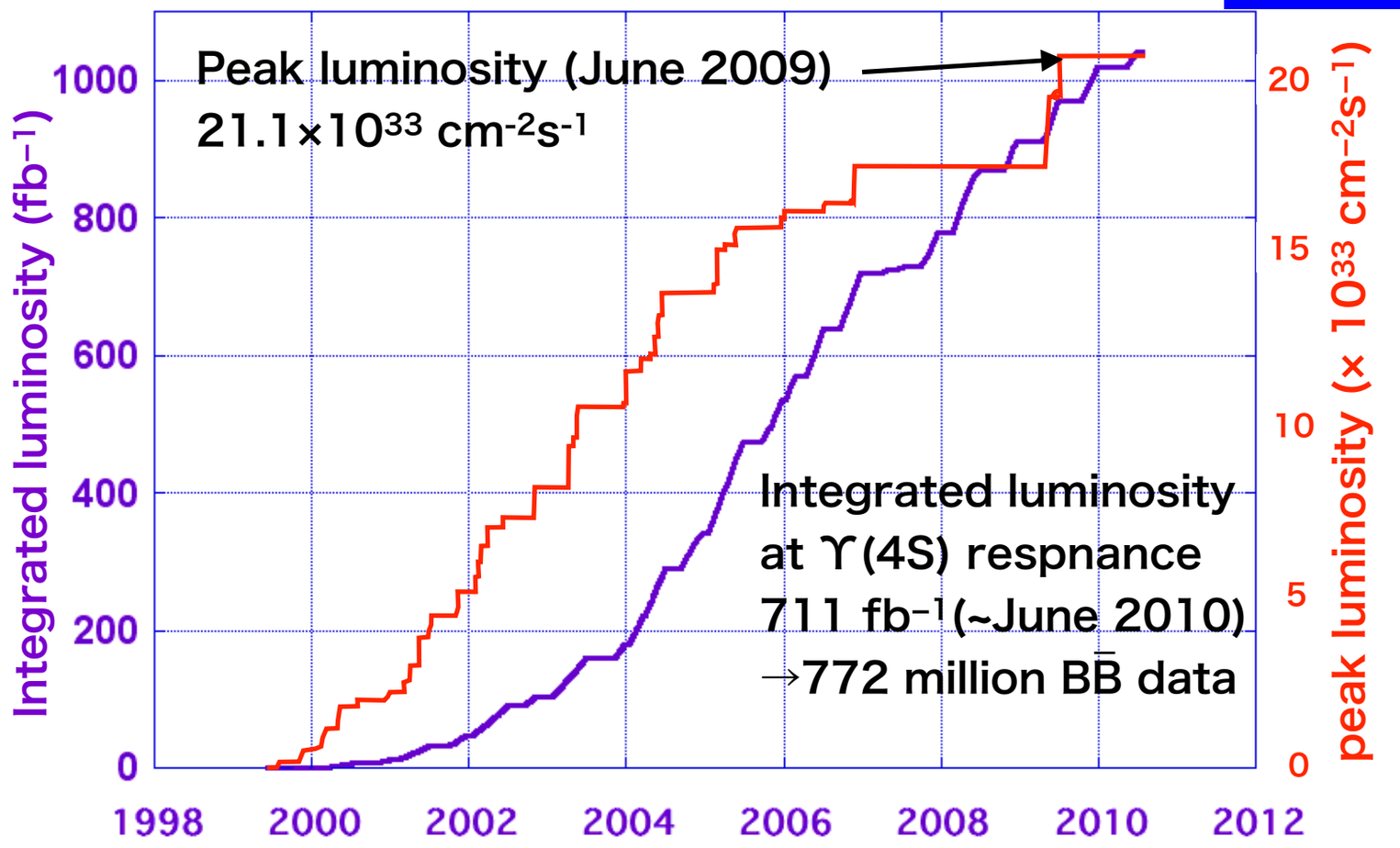
KEKB accelerator and Belle detector

e^-(8.0 GeV) × e^+(3.5 GeV)

asymmetric energy collision







Vertex reconstruction

Silicon vertex detector: 3/4 layers double-sided sillicon strips

Charged particle tracking

Central Drift Chamber: small cell +He/C_2H_6

Superconducting solenoid: 1.5T magnetic field

Particle identification

Aerogel Cherenkov counter: Aerogel radiator + PMT

Time-of-Flight counter

γ/electron detection

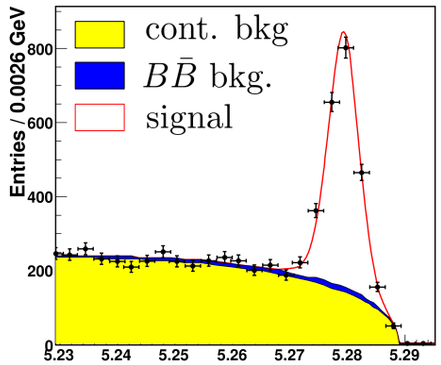
CsI(Tl) Electromagnetic calorimeter

μ ID /K_L detection

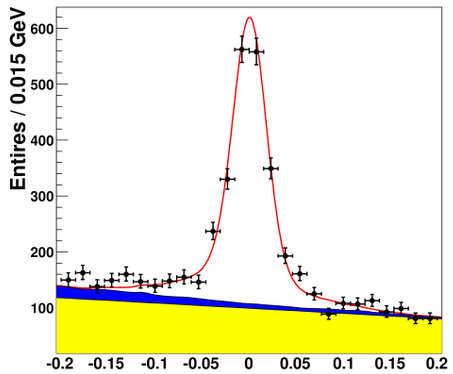
14/15 layers Resistive Plate Counter+Iron yoke

Overview of time-dependent CP violation analysis

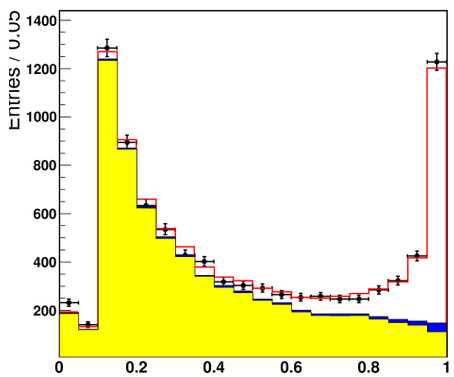
- Signal B is reconstructed and selected using kinematic variables (mass, energy)
- Continuum background is rejected using event shape variables from all observables.



Beam constraint mass:
$M_{bc} = \sqrt{(E_{beam}/2)^2 - p_{rec}^2}$



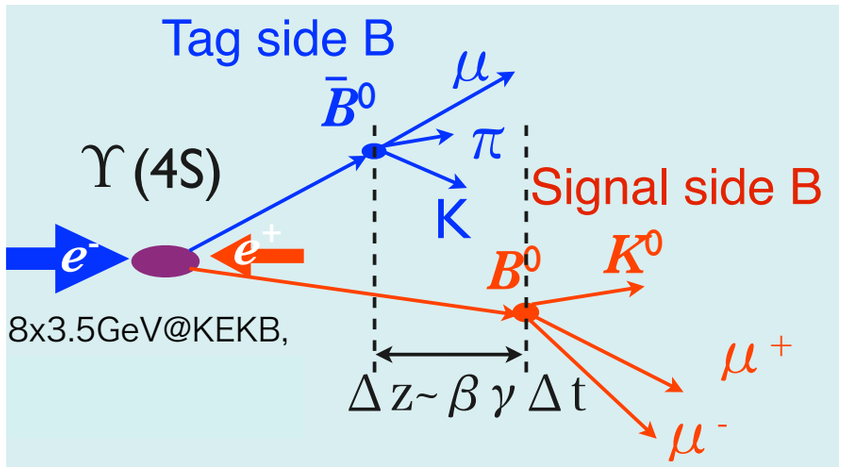
Eenergy difference:
$\Delta E = E_{rec}^{CM} - E_{beam}/2$

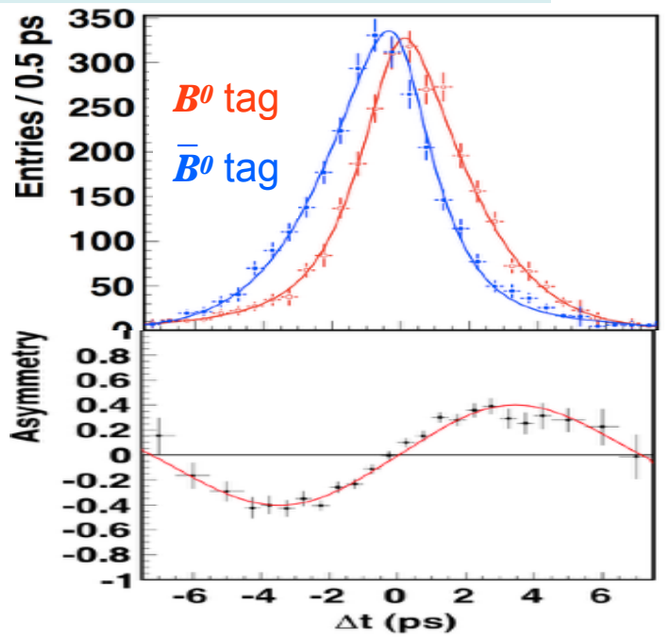


qq suppression (Likelihood, Neural-net)

- Tag side
  Remaining observables in an event is used for flavor determination
  $\bar{B}^0 \to D^{*+} l^- \nu$, $B^0 \to D^{*\pm} \to D^0 \pi^+$, $D^0 \to K^- l^+ \nu$

- Δt is measured by vertex positions of B and $\bar{B}$.

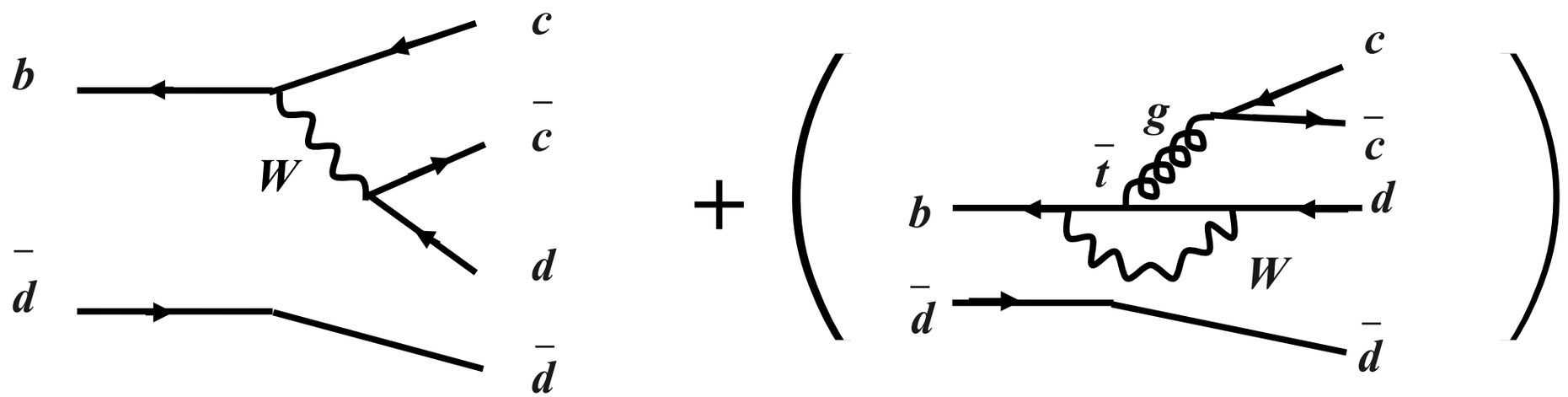




CP violation parameters are obtained by the fit to Δt.

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} q(A\cos\Delta m\Delta t + S\sin\Delta m\Delta t)$$

ϕ_1 measurement in $B^0 \to J/\psi\ \pi^0$



Cabbibo-suppressed tree

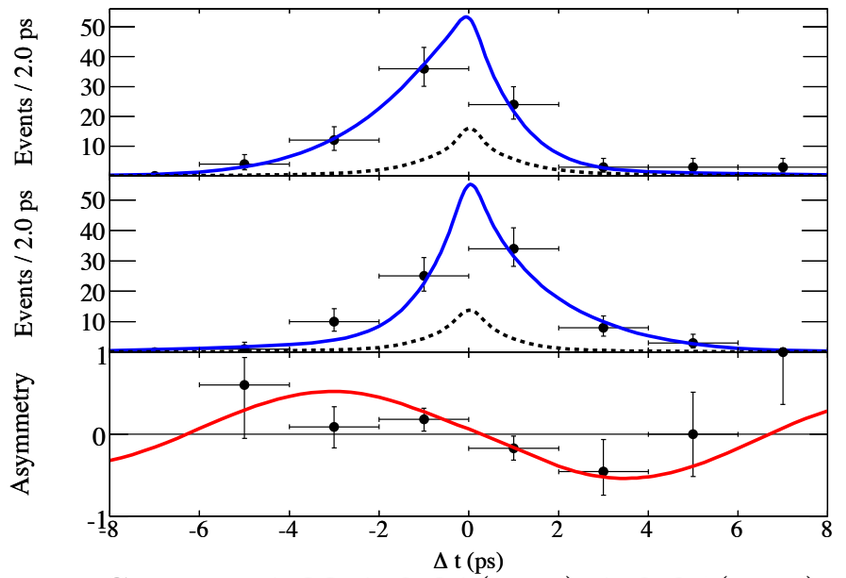
penguin contribution?

$S = -\sin 2\phi_1,\ A = 0 \longrightarrow S \neq -\sin 2\phi_1,\ A \neq 0$

(Z. Z Xing, PRD 61 014010 (1999))

If new physics contributes to the penguin loop, S and A shift due to different weak phase.

Constrain penguin contribution in B decays induced by $b \to ccs$ diagram without model dependence.



$$S = -1.23 \pm 0.21(\text{stat}) \pm 0.04(\text{syst})$$
$$C = -0.20 \pm 0.19(\text{stat}) \pm 0.03(\text{syst})$$

Large asymmetry was seen in BABAR (non-zero with 4.0 σ significance)
PRL 101 021801 (2008)

ϕ_1 measurement in $B^0 \to J/\psi\ \pi^0$

N_{signal} = 332±22

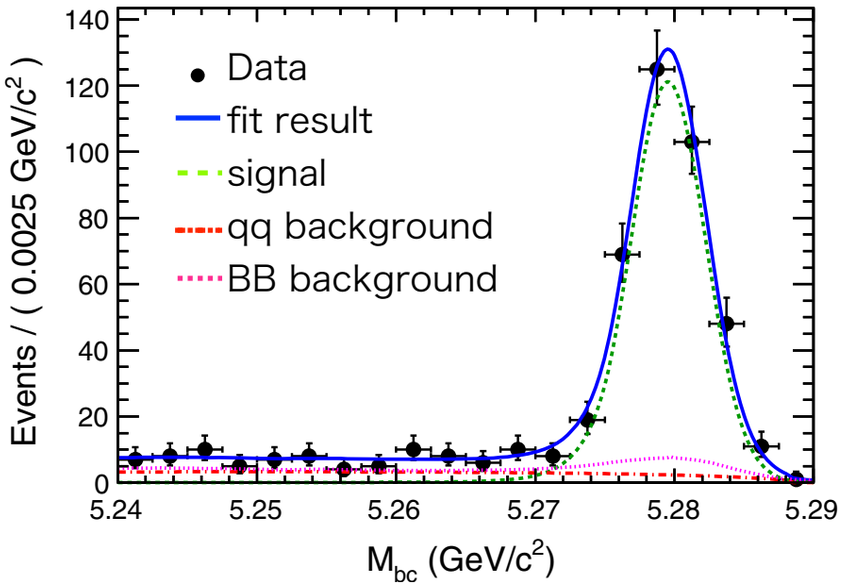
$$\mathcal{B}(B^0 \to J/\psi\pi^0) = (1.62 \pm 0.11 \pm 0.06) \times 10^{-5}$$

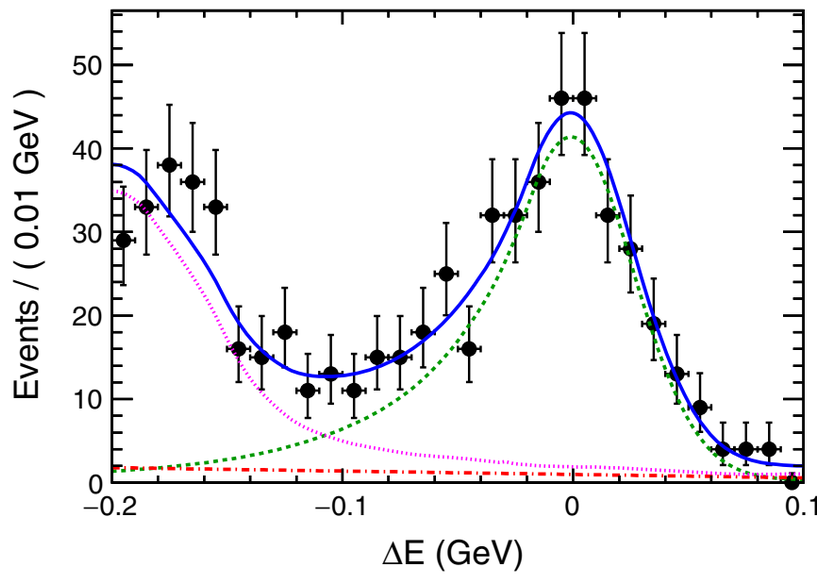
$$\mathcal{S} = -0.59 \pm 0.19 \pm 0.03$$

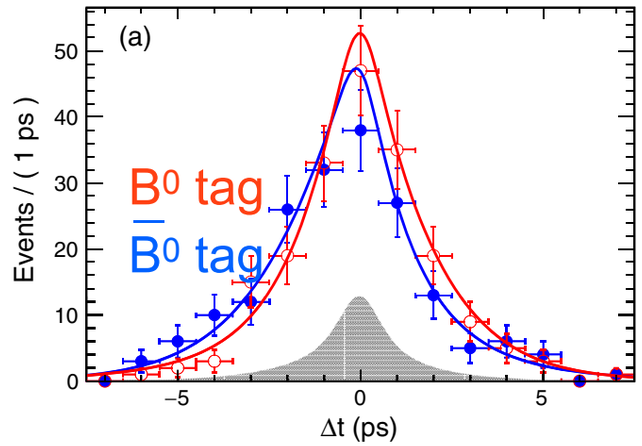
$$\mathcal{A} = -0.15 \pm 0.14^{+0.04}_{-0.03},$$

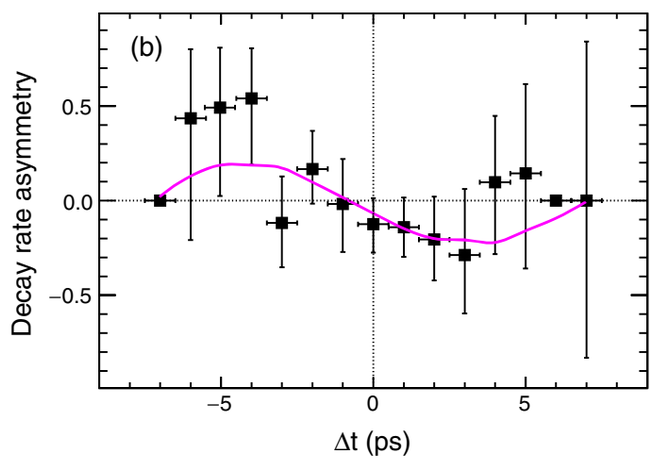
$S \neq 0$ by 3.0 σ confidence level. Consistent with Standard model (SM) expectation.

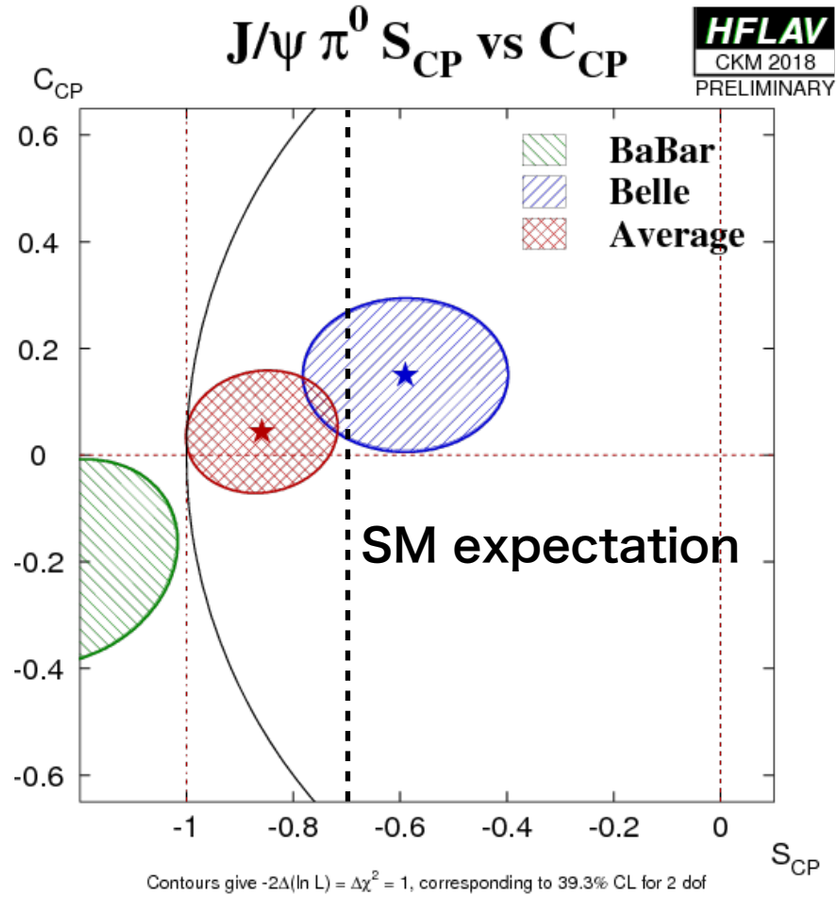
Published:
PRD98 112008 (2018)











Time-dependent CPV in 3-body B decays

$B^0 \to \pi^0 \pi^0 K^0_S$, $B^0 \to K^0_S K^0_S K^0_S$

CP-even eigenstates with K^0_S.

↔ Two-body B^0 decays with K^0_S are *CP*-odd eigenstates ($J/\psi\, K^0_S$, $\phi\, K^0_S$, $\eta' K^0_S \cdots$).

→ Validation using both eigenstates is important.

$\sin(2\beta^{\rm eff}) \equiv \sin(2\phi_1^{\rm eff})$ HFLAV Summer 2016

Induced by $b \to s q \bar{q}$ penguin diagram.

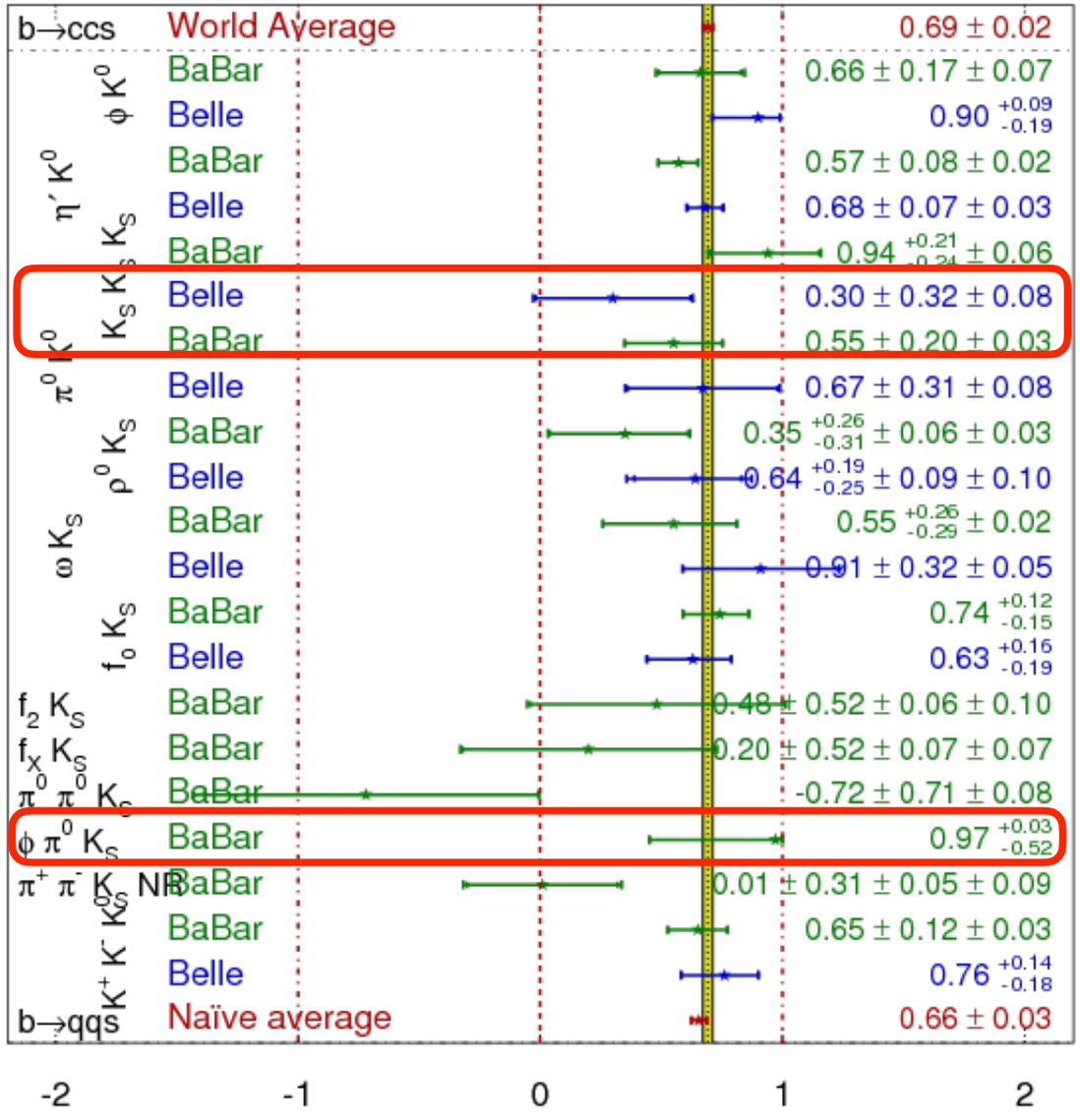
→ Sensitive to new physics: $S \equiv -\xi_f \sin 2\phi_1^{\rm eff}$.

Shift in ϕ_1 from $b \to c\bar{c}s$ diagram (mainly from $b \to u$ tree contribution) is expected to be small.

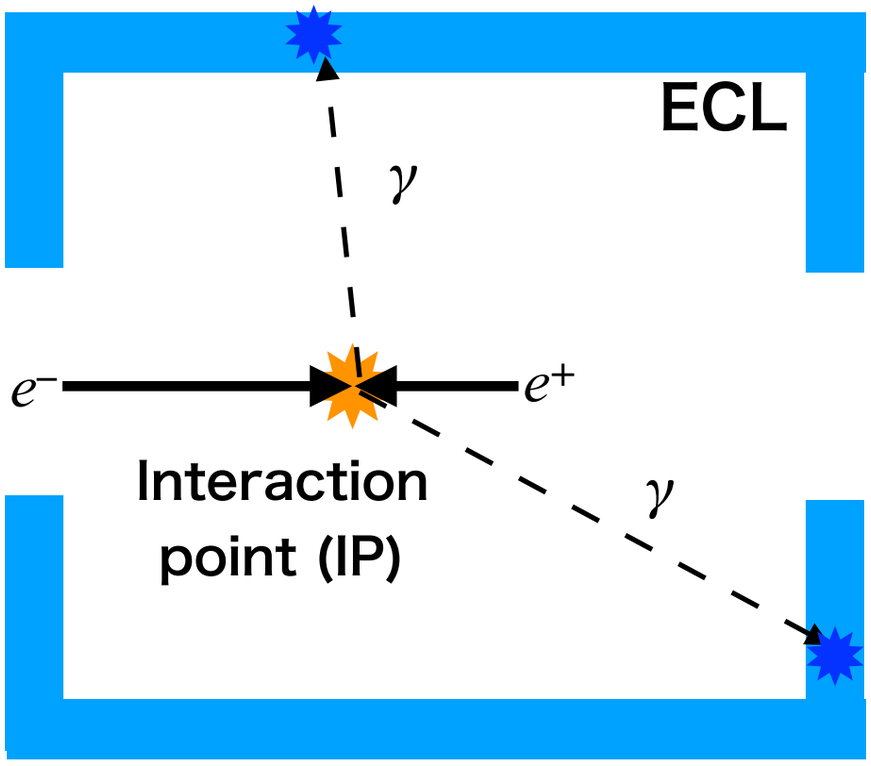
$K^0_S K^0_S K^0_S$: $\Delta S = 0.02^{+0.02}_{-0.03}$ (hep-ph/0702252)

$\pi^0 \pi^0 K^0_S$: $\Delta S = 0.034\ ^{+0.020}_{-0.025}$ (PLB596 163)

Center values of current results are apart from SM expectation.



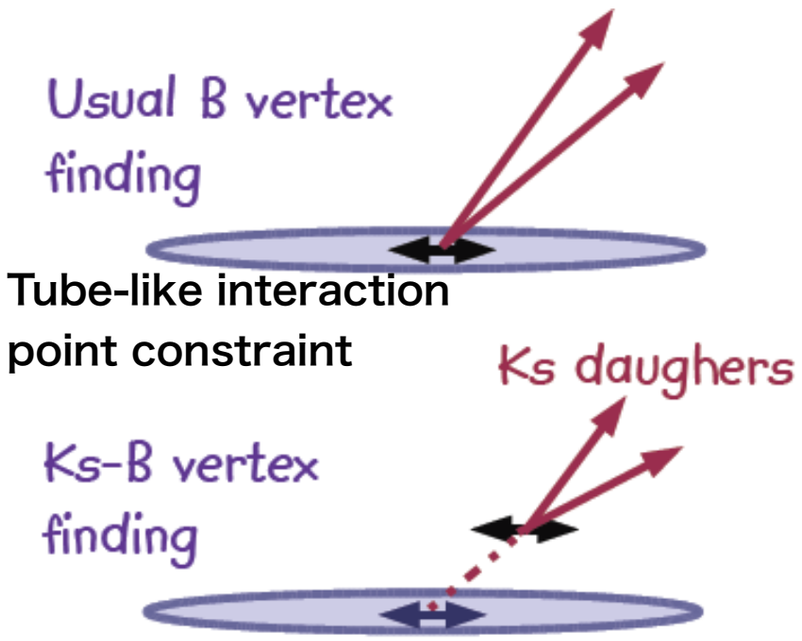
Vertex reconstruction of neutral final states



B^0 decay vertex is reconstructed using charged track path obtained by the vertex detector (SVD).

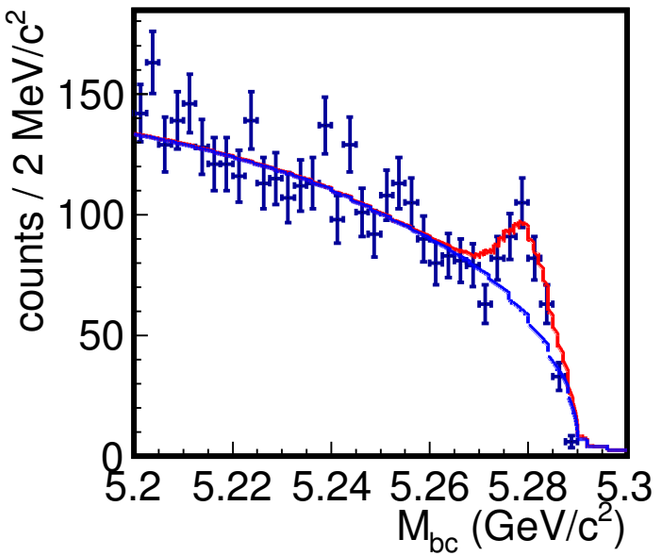
Electromagnetic calorimeter (ECL) detects photon hit postion and no path information is obtained.
→ We can not reconstruct B^0 decay vertex using information of photons from π^0 decay.

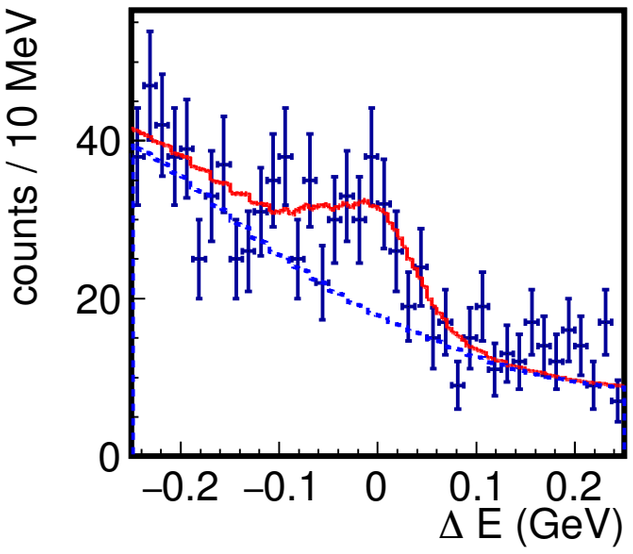
K^0_S decays a point apart from B^0 decay vertex.
→ Reconstruct signal side vertex using flight direction of K^0_S with constraint of e^+e^- interaction point.
Comparing to the 2-body decays, decay point is close to the B^0 decay vertex in $B^0 \to \pi^0\pi^0 K^0_S$ and $B^0 \to K^0_S K^0_S K^0_S$, K^0_S modes since momentum is lower than.
→ Vertex reconstruction efficiency is better by 20-30%.

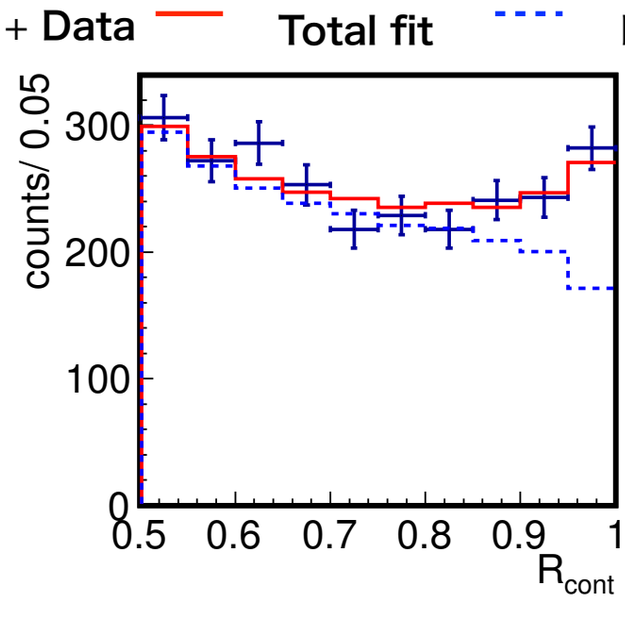


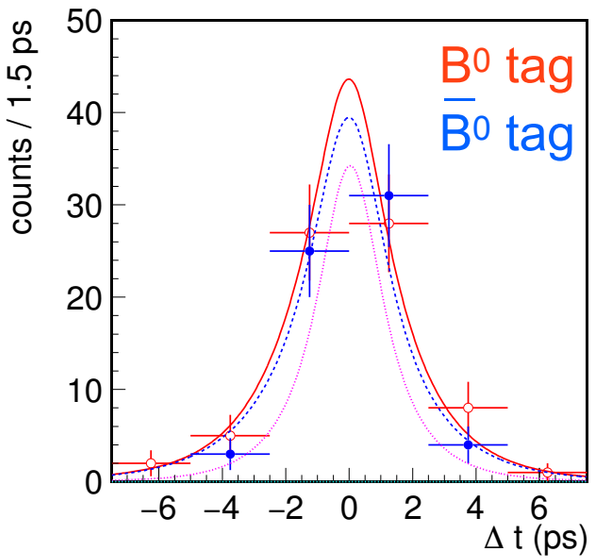
ϕ_1^{eff} measurement in $B^0 \to \pi^0\pi^0 K^0_S$

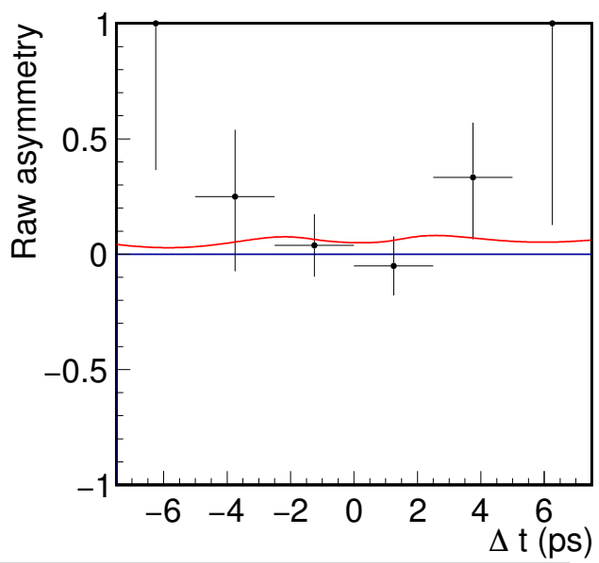
Signal yield with vertex information = 146.7±23.6 events



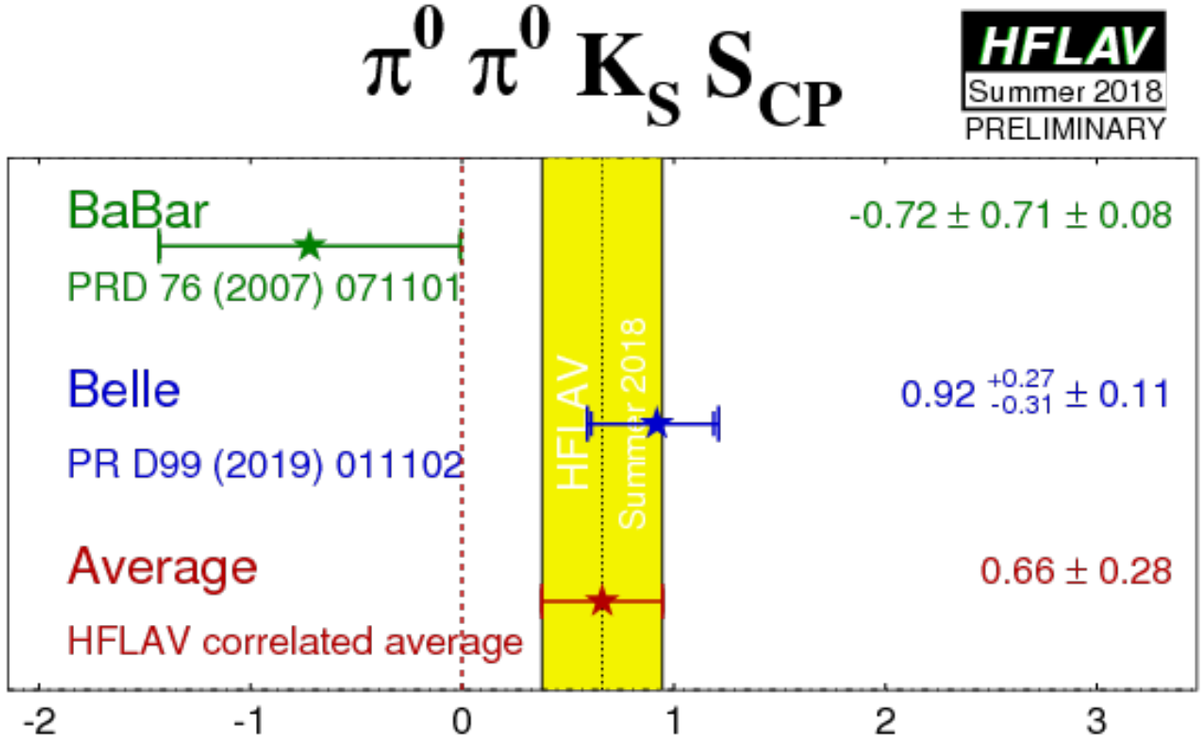








$$\sin 2\phi_1^{\text{eff}} = 0.92^{+0.27}_{-0.31}\ (\text{stat.})\ ^{+0.10}_{-0.11}\ (\text{syst.})$$
$$\mathcal{A} = 0.28 \pm 0.21\ (\text{stat.})\ \pm 0.04\ (\text{syst.})$$



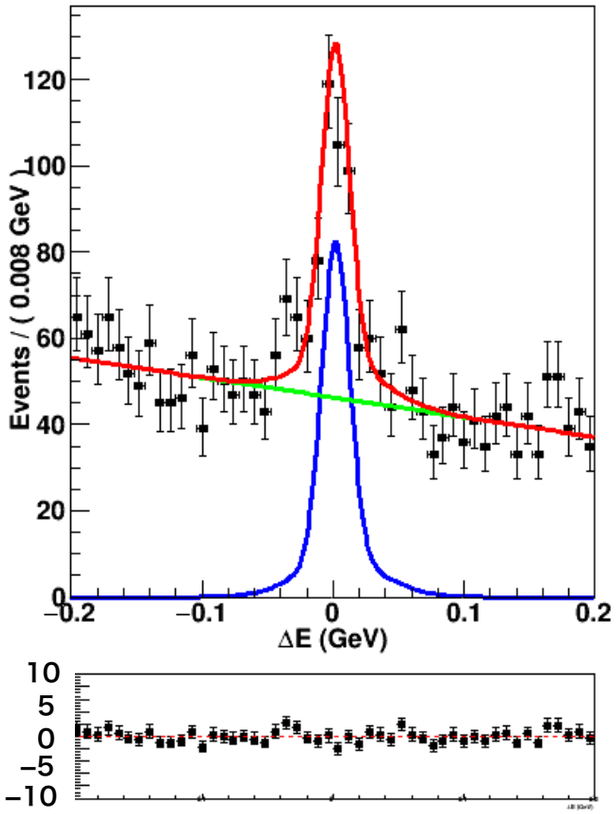
Deviation from non-CP violation is 1.8 σ.

Consistent with sin2ϕ_1 from $b \to c\bar{c}s$ diagram.

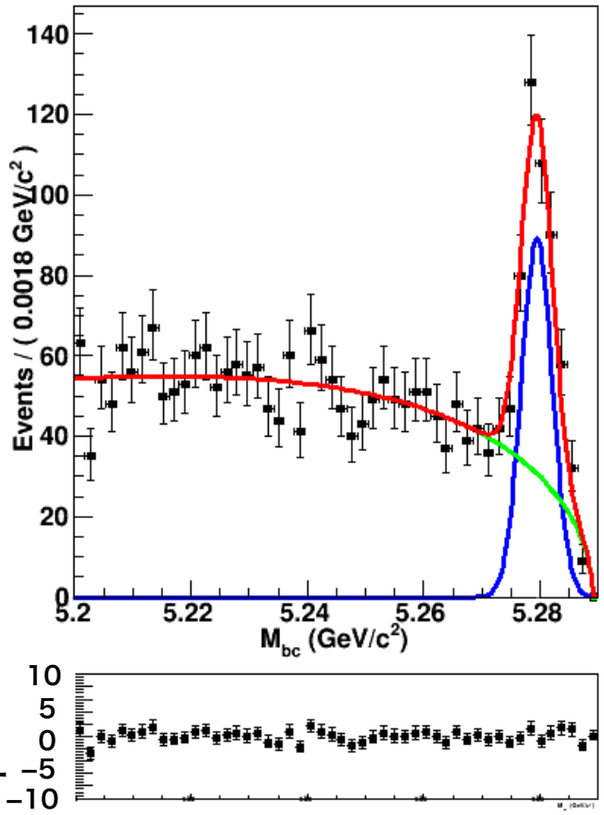
ϕ_1^{eff} measurement in $B^0 \to K^0_S K^0_S K^0_S$

Signals candidates for *CP* violation measurement are reconstructed well (N_{signal} = 329±20). After validation of analysis procedure and systematic error estimation, *CP* violation parameters are measured.

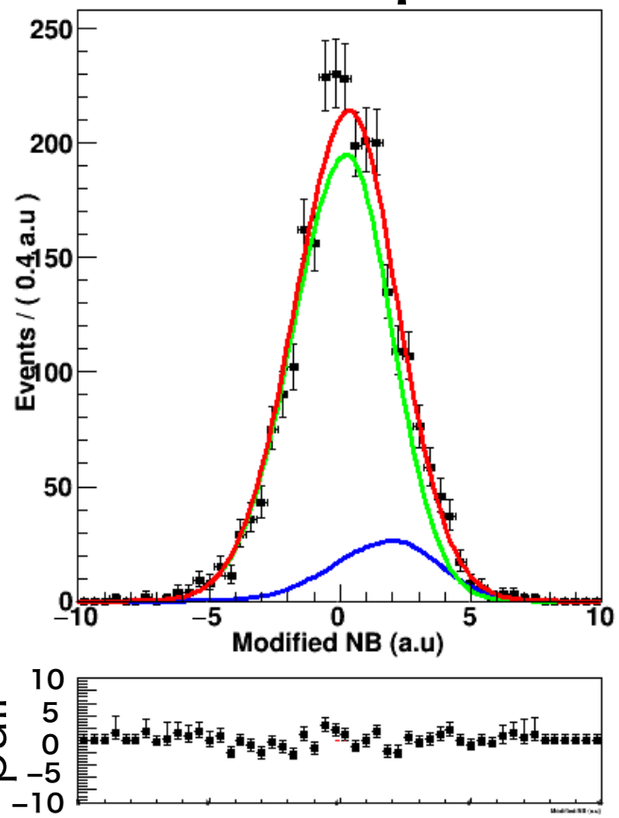
ΔE



M_{bc}

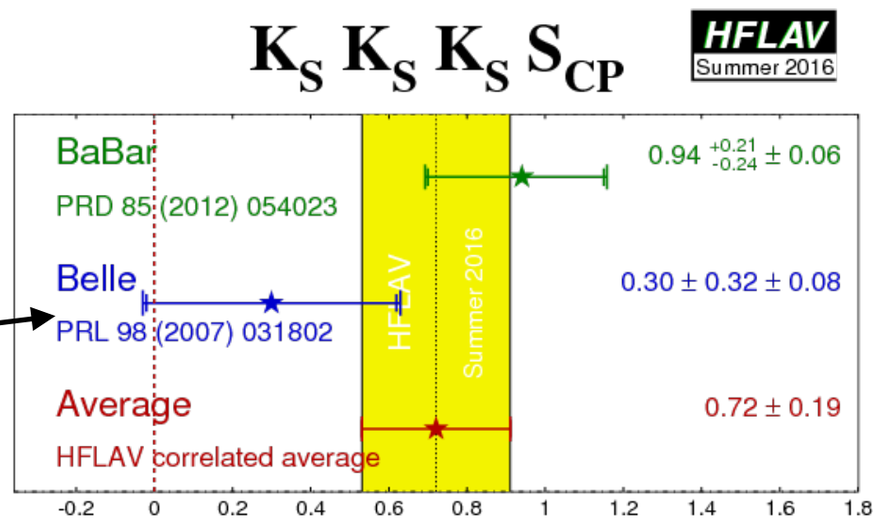


NN output



+ Data
— Fit result
— Signal
— Background

will be updated soon



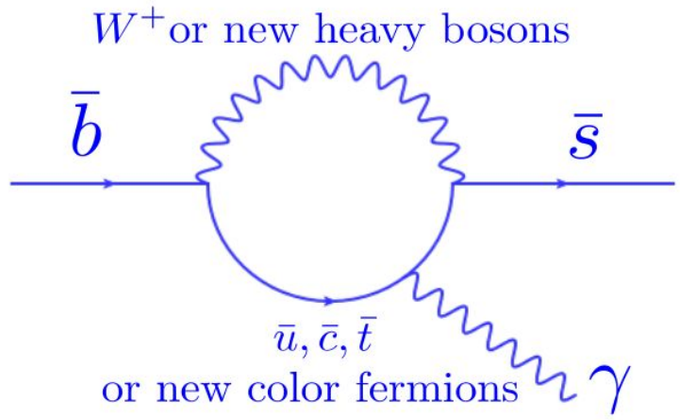
Belle preliminary

Time-dependent CPV in $B^0 \to K^0_S \pi^+ \pi^- \gamma$

Induced by $b \to s\gamma$ diagram

In SM, S~0 since contamination by right-handed photon is supressed by facor m_s/m_b.

If new physics contributes to enhance right-handed component, $S \neq 0$.



$$\mathcal{S}^+ \equiv \mathcal{S}^I_{\pi^+\pi^- K^0_S\gamma} + \mathcal{S}^{\bar{I}}_{\pi^+\pi^- K^0_S\gamma} = \frac{8}{1+|\xi|^2}\left(\mathrm{Im}\xi\cos 2\beta - \mathrm{Re}\xi \sin 2\beta\right) \mathrm{a}^I,$$

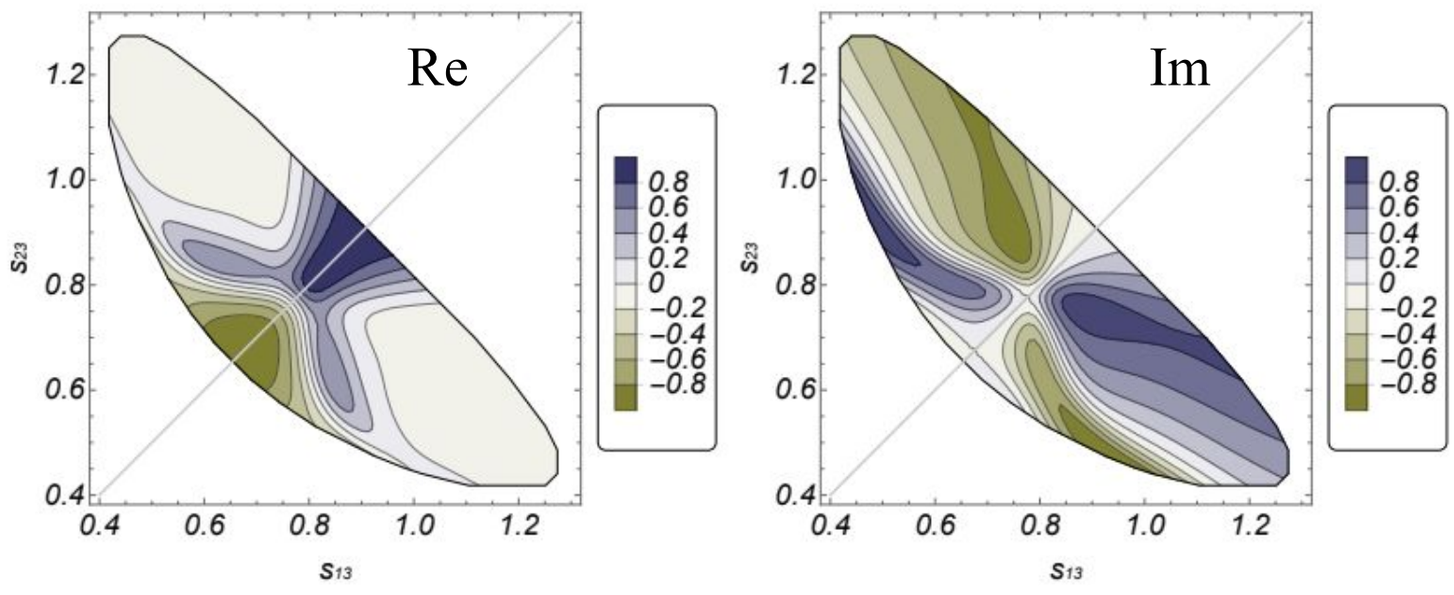
$$\mathcal{S}^- \equiv \mathcal{S}^I_{\pi^+\pi^- K^0_S\gamma} - \mathcal{S}^{\bar{I}}_{\pi^+\pi^- K^0_S\gamma} = \frac{8}{1+|\xi|^2}\left(\mathrm{Re}\xi\cos 2\beta + \mathrm{Im}\xi \sin 2\beta\right) \mathrm{b}^I.$$

$\xi \equiv c'/c$: retio of right- to left-handed amplitudes

$I^{(-)}$ denotes a symmetric region of Dalitz plane above (below) the bisector of m_{13}–m_{23}

(arxiv:1802.09433)

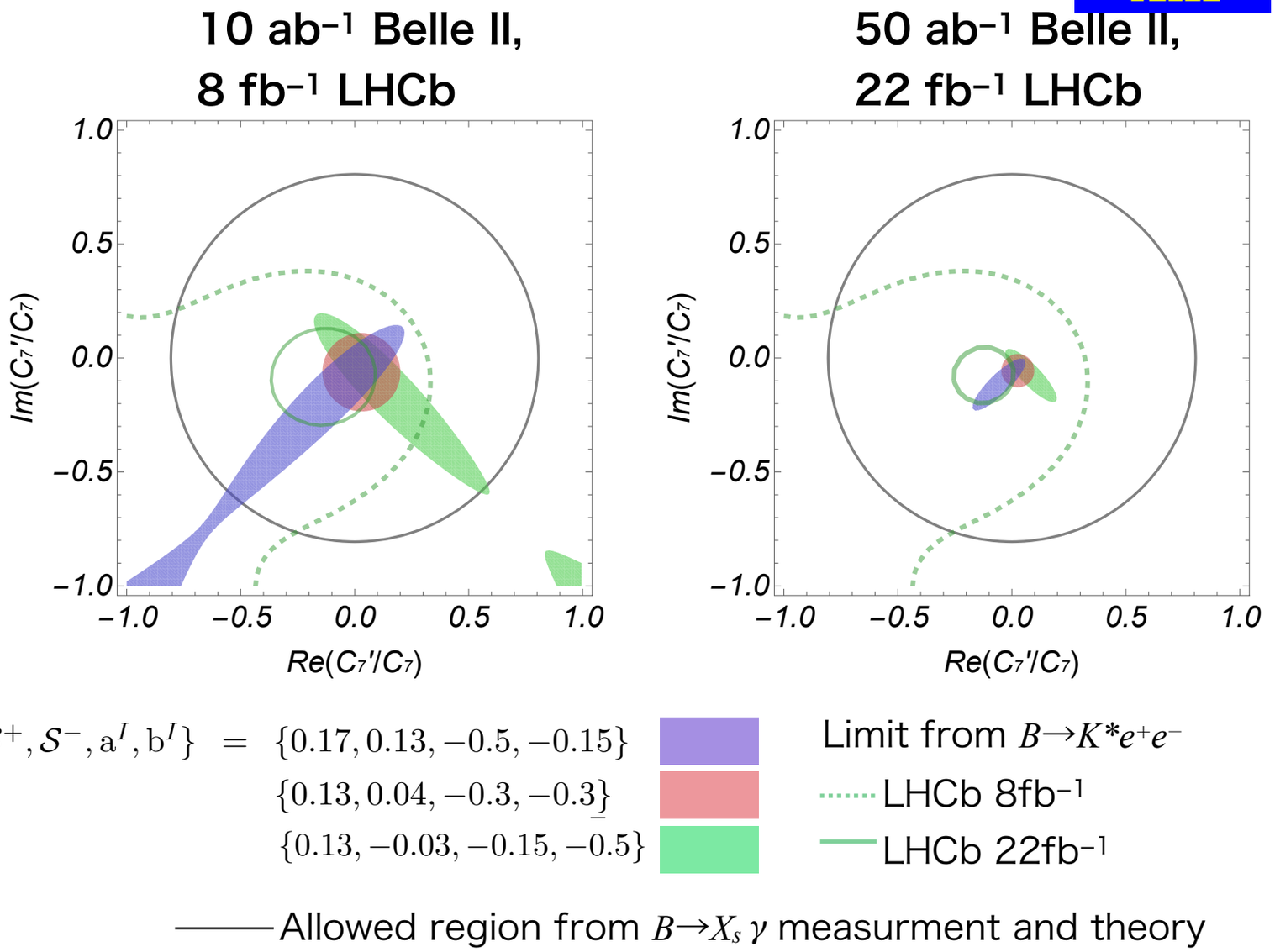
Decay amplitude of $K_1(1270) \to \pi^+\pi^- K^0_S$



Time-dependent CPV in $B^0 \to K^0_S \pi^+ \pi^- \gamma$

$$\frac{\mathrm{Re}\xi}{1+|\xi|^2} = \frac{1}{8}\left(\frac{\mathcal{S}^-}{\mathrm{b}^I}\cos 2\beta - \frac{\mathcal{S}^+}{\mathrm{a}^I}\sin 2\beta\right)$$
$$\frac{\mathrm{Im}\xi}{1+|\xi|^2} = \frac{1}{8}\left(\frac{\mathcal{S}^-}{\mathrm{b}^I}\sin 2\beta + \frac{\mathcal{S}^+}{\mathrm{a}^I}\cos 2\beta\right)$$

(arxiv:1802.09433)



S^+ and S^- from time-dependent analysis on Dalitz space leads to constrain on Willson coefficients $\mathrm{Re}(C_7'/C_7)$ and $\mathrm{Im}(C_7'/C_7)$.

It can be accessible with statistic in Belle II but analysis strategy is demonstrated using Belle full data. → Analysis is on-going.

Summary

Time-dependent CP violation measurements are on the way using full data set of the Belle experiment.

We focus on recently published two decay modes.

$B^0 \to J/\psi\ \pi^0$

$$\mathcal{S} = -0.59 \pm 0.19 \pm 0.03$$
$$\mathcal{A} = -0.15 \pm 0.14^{+0.04}_{-0.03},$$

PRD98 112008 (2018)

$B^0 \to \pi^0 \pi^0 K^0_S$

$$\sin 2\phi_1^{\rm eff} = 0.92^{+0.27}_{-0.31}\ (\text{stat.})\ ^{+0.10}_{-0.11}\ (\text{syst.})$$
$$\mathcal{A} = 0.28 \pm 0.21\ (\text{stat.})\ \pm 0.04\ (\text{syst.})$$

PRD99 011102 (2019)

→ consitent with SM expectation.

Further studies for other CP-eigenstates is still on-going.

$B^0 \to K^0_S K^0_S K^0_S$ will be updated in near future.