Recent results on CP-Violation Measurements from Belle

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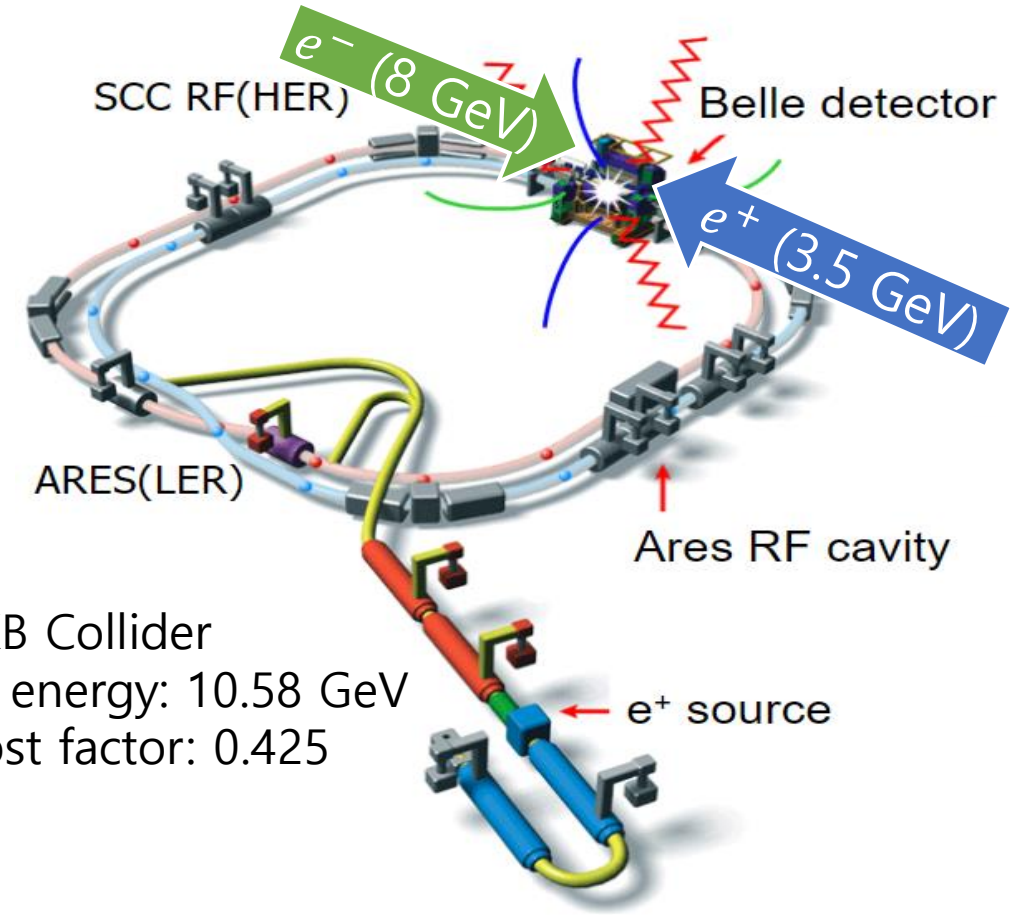
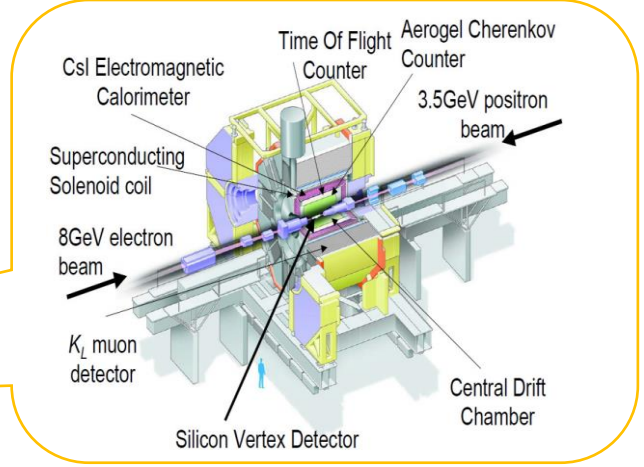
Outline

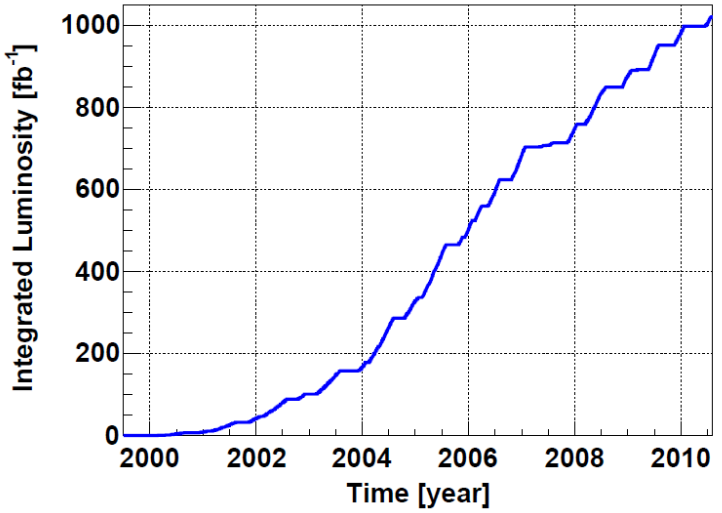
- Introduction
  - Measurements of $\sin 2\phi_1^{eff}$
- Preliminary result - $\boldsymbol{B^0 \to K_S^0 K_S^0 K_S^0}$
- Published result - $\boldsymbol{B^0 \to \pi^0 \pi^0 K_S^0}$, $\boldsymbol{B^0 \to J/\psi \pi^0}$
- Summary

Introduction - Belle experiment



KEKB Collider
CM energy: 10.58 GeV
Boost factor: 0.425





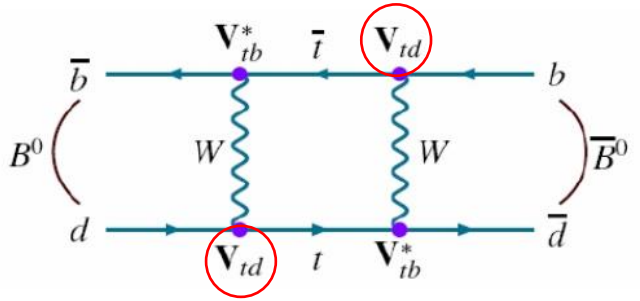
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off resonance /scan: 155 fb^{-1}

A number of 772×10^6 $B\bar{B}$ was obtained from 1999 to 2010.

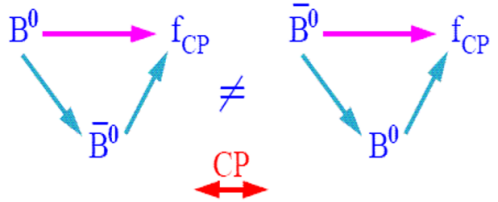
Establishing CP violation in B meson decay

Introduction – time-dependent CP violation

- The time-dependent CP violation ($TCPV$) can be caused by the interference between B^0 decay to CP eigenstate (f_{cp}) and $B^0 - \bar{B}^0$ mixing.



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



- mixing-induced CP violation (S)

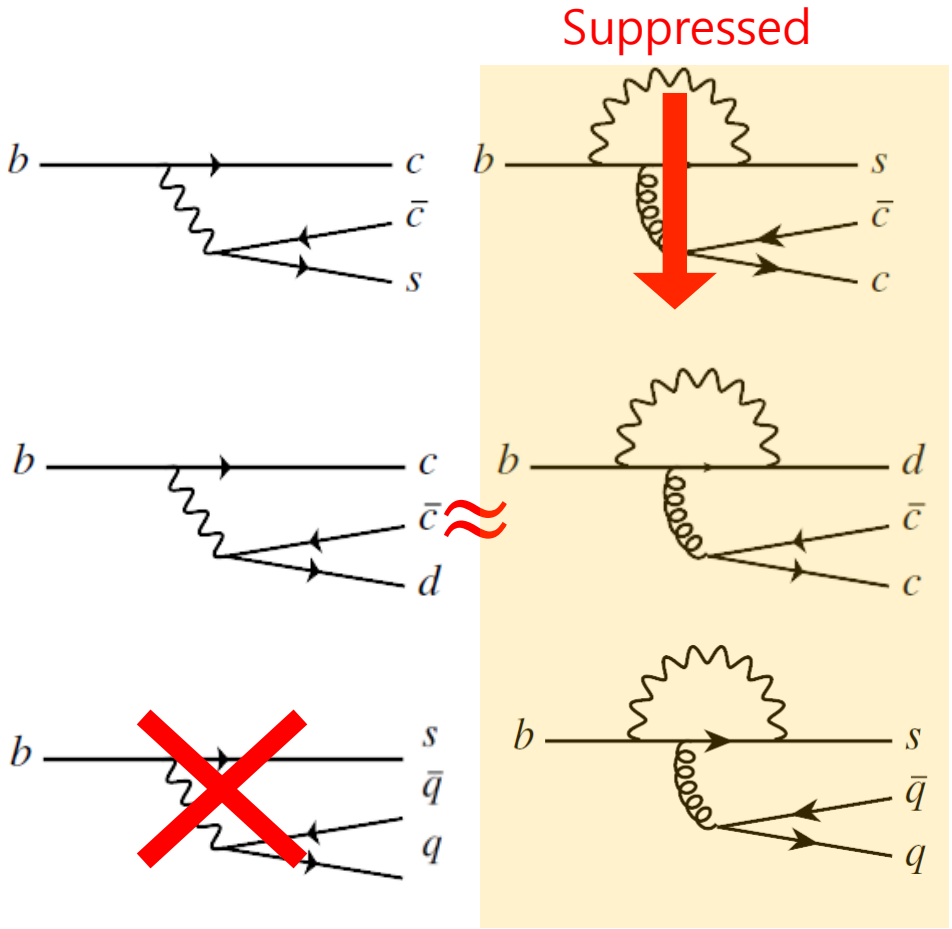
- Time-dependent CP asymmetry

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

S = mixing-induced CP violation
A = direct CP violation

Measurement of S: some typical mode (ex:$B^0 \to J/\psi K^0_S$) → unitarity angle $\phi_1 = \beta$
where $\phi_1 \equiv \arg[-(V_{cd}V^*_{cb})/(V_{td}V^*_{tb})]$

Measurements of $\sin 2\phi_1$



Forbidden in SM

"penguin" diagram
→sensitive to new physics (NP)

$b \to c\bar{c}s$ transition (ex: $B^0 \to J/\psi K_S^0$)
$\sin 2\phi_1 = 0.699 \pm 0.017$ (W.A.)

$b \to c\bar{c}d$ transition (ex: $\boldsymbol{B^0 \to J/\psi\pi^0}$, $J/\psi\rho^0$)
$\sin 2\phi_1^{eff} =$???

$b \to s\bar{q}q$ penguin transition (ex: $\boldsymbol{B^0 \to \pi^0\pi^0 K_S^0}$, $\boldsymbol{K_S^0 K_S^0 K_S^0}$)
$\sin 2\phi_1^{eff} =$???

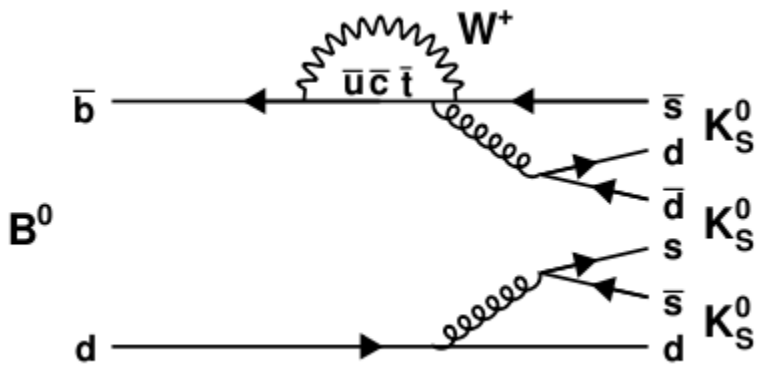
Significant deviation of $\sin 2\phi_1^{eff}$ from $\sin 2\phi_1$ indicates evidence of NP.

[Ed. A.J. Bevan, B. Golob, Th. Mannel, S. Prell, and B.D. Yabsley, Eur. Phys. J. C74 (2014) 3026]

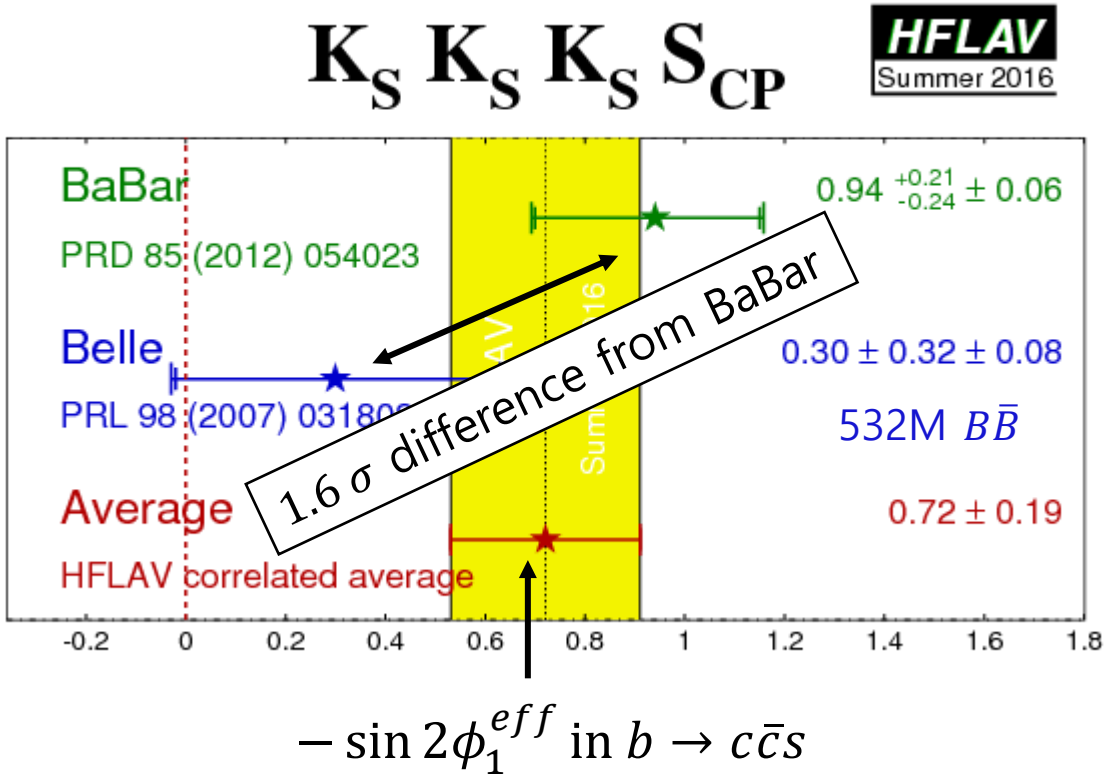
Preliminary result

$$B^0 \rightarrow K_S^0 K_S^0 K_S^0$$

Introduction - motivation



- Pure $b \to s$ penguin transition by loop diagram
  - Sensitive to new physics
- CP-even eigenstate
  - $S = -\sin 2\phi_1^{eff}$
- We aim to accurately measure $TCPV$ value in $B^0 \to K_S^0 K_S^0 K_S^0$ with final data sample (772M $B\bar{B}$).

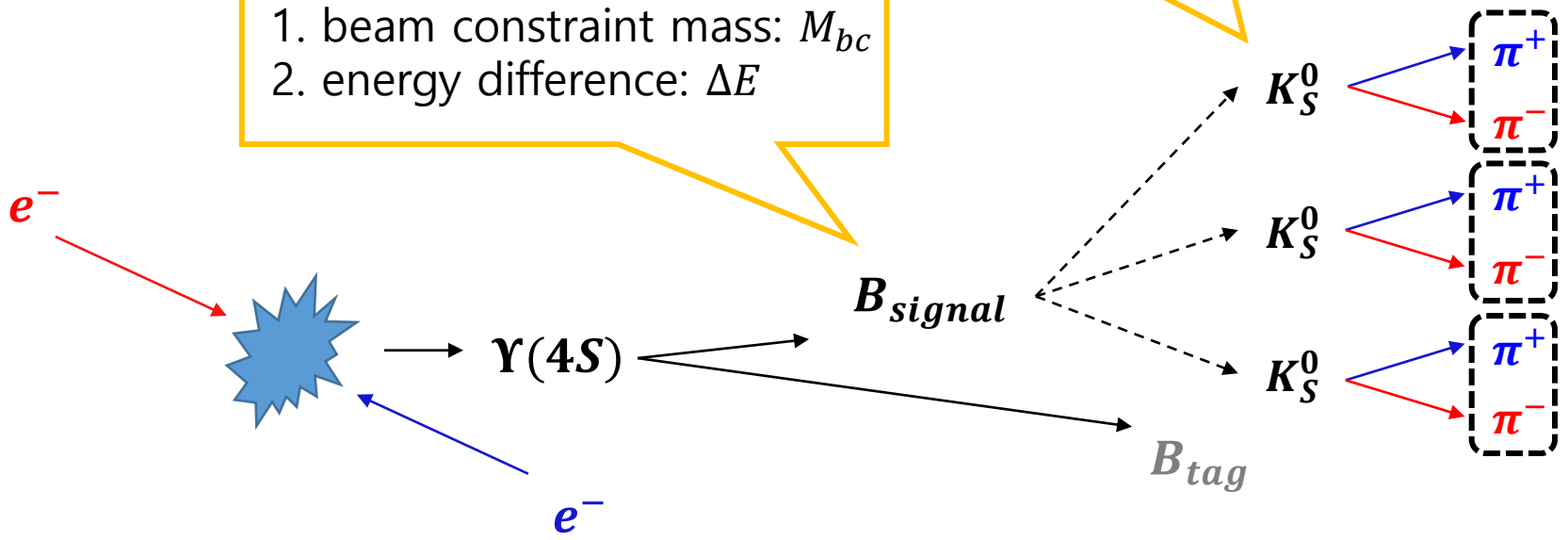


$-\sin 2\phi_1^{eff}$ in $b \to c\bar{c}s$

Signal reconstruction

Only charged pions
- Neural network (NN) with 13 parameters
- $|\Delta M_{\pi\pi}| < 10\,\sigma$

Two kinematic variables:
1. beam constraint mass: M_{bc}
2. energy difference: ΔE



- $\Delta E = E_B - E_{beam}$
  - E_B = energy of B in CM frame
  - E_{beam} = half of beam energy
- $M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$
  - p_B = momentum of B in CM frame

Signal reconstruction

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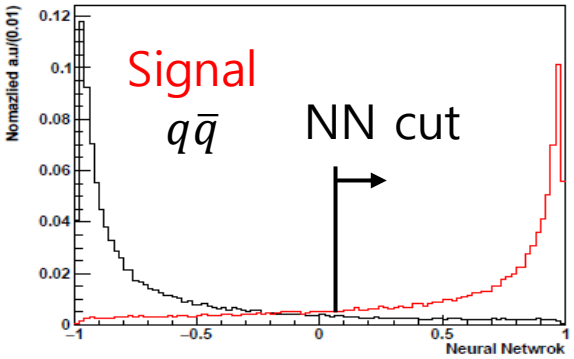
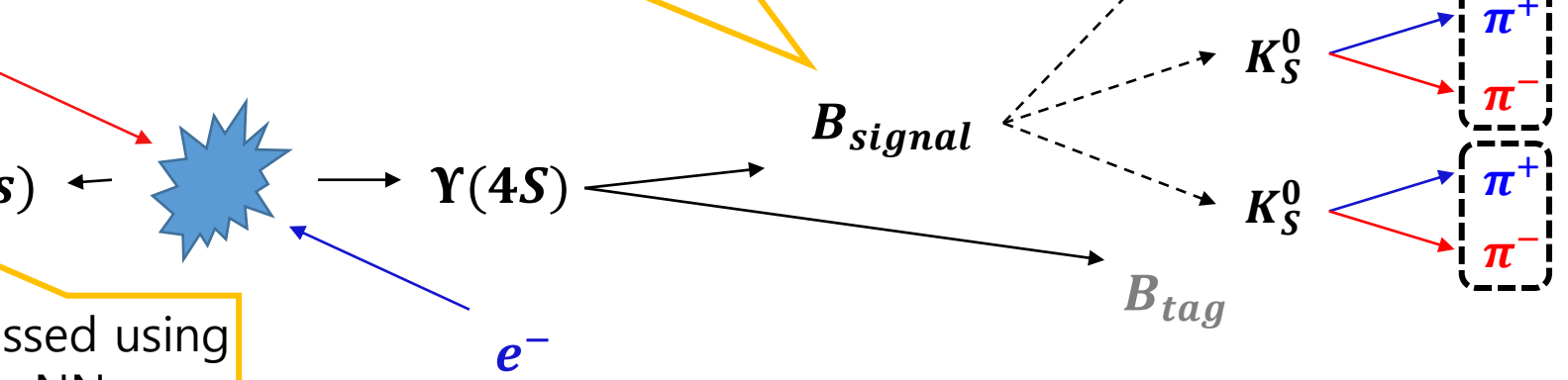
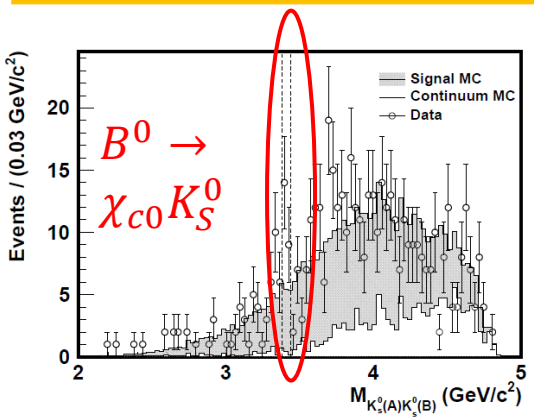


NN output



Continuum backgrounds are suppressed using topology information along with the NN



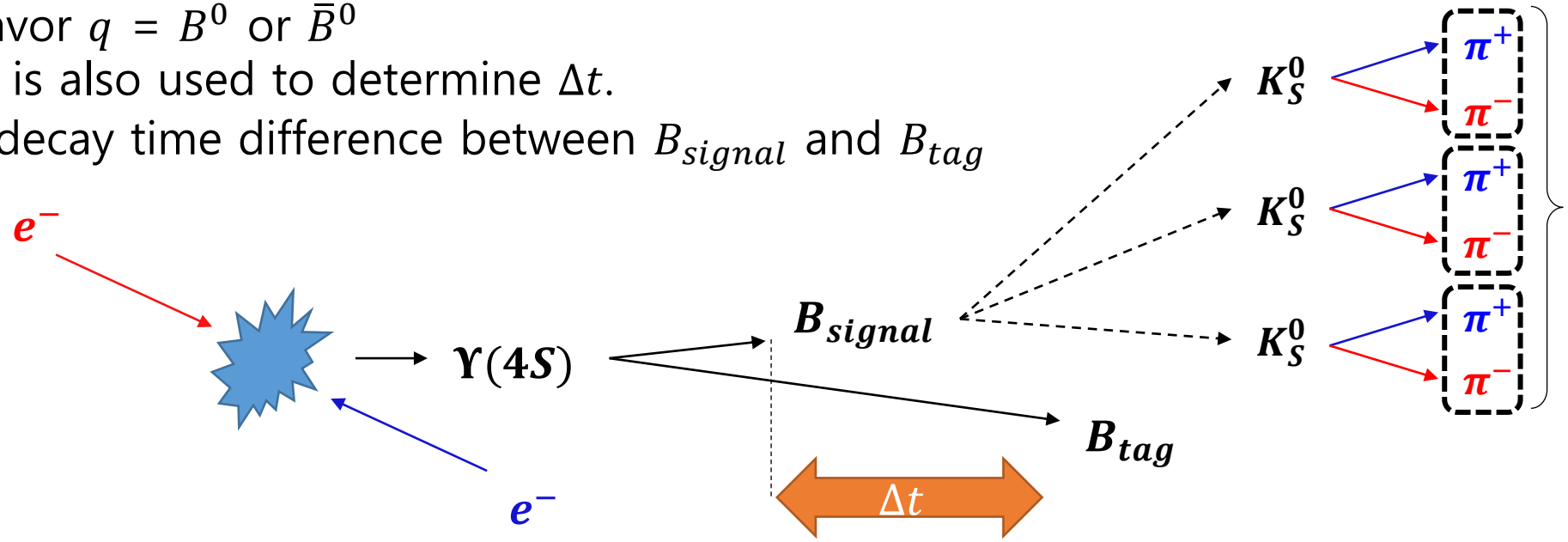
Veto $b \rightarrow c$ quark transition
- $B^0 \rightarrow \chi_{c0} K_S^0$ ($\chi_{c0} \rightarrow K_S^0 K_S^0$)
for $3.388 < M_{K_S^0 K_S^0} < 3.444\ GeV/c^2$

- $\Delta E = E_B - E_{beam}$
  - E_B = energy of B in CM frame
  - E_{beam} = half of beam energy
- $M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$
  - p_B = momentum of B in CM frame

Vertex reconstruction & flavor tagging

- Flavor tagging is performed by using inclusive properties of particles not associated with the B_{signal}.
  - B_{signal} decay to CP eigenstate
  - flavor $q = B^0$ or $\bar{B}^0$
- B_{tag} is also used to determine Δt.

  Δt: decay time difference between B_{signal} and B_{tag}



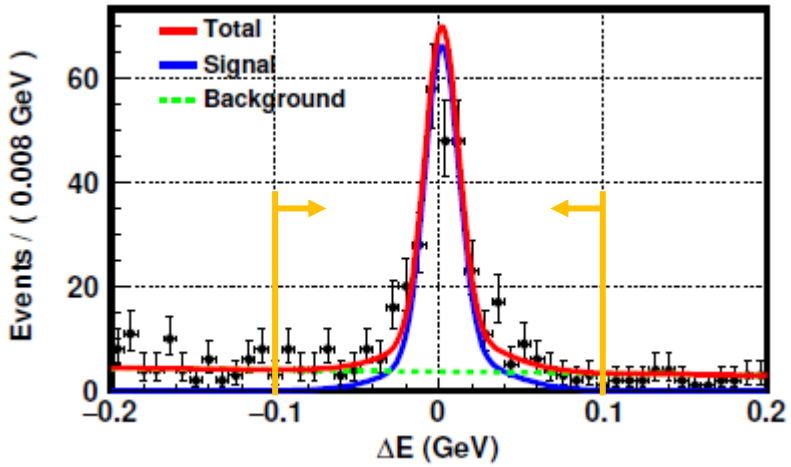
$\Delta t = \Delta z/\beta\gamma c$, $\Delta z \approx 200\ \mu m$

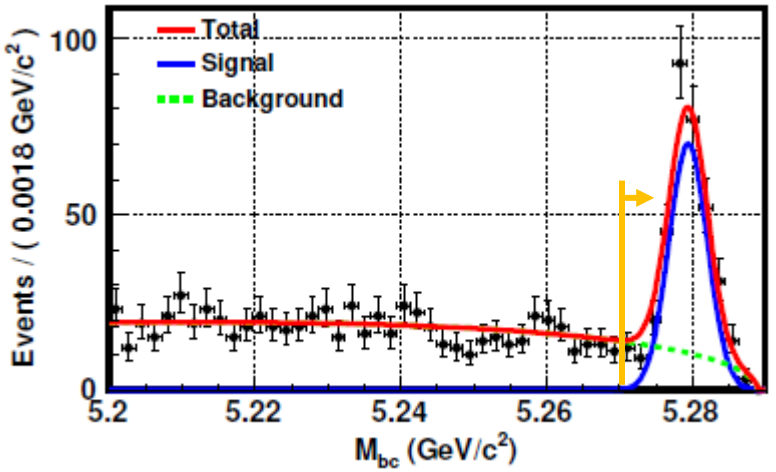
$\beta\gamma$= boost factor 0.425

The flavor and Δt are needed for $TCPV$ extraction

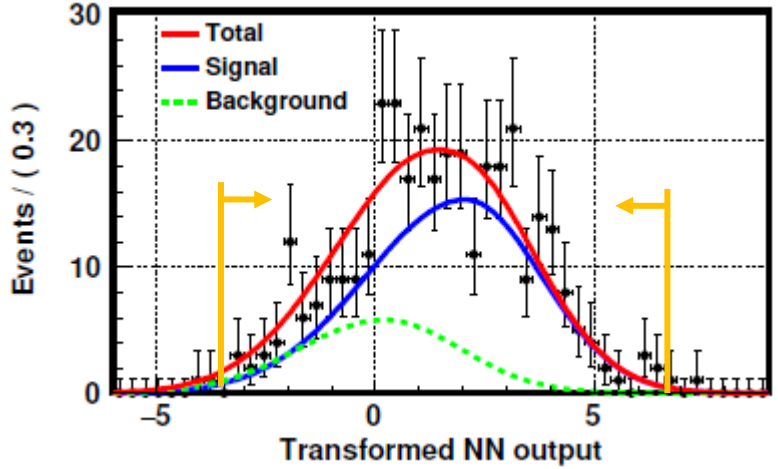
Signal extraction

Preliminary





Transformed NN output:
used for continuum suppression



- An unbinned maximum likelihood (ML) fit with 3D PDF (ΔE, M_{bc}, Transformed NN).
- Signal B^0 & $\bar{B}^0$ is obtained to be 258 ± 17 and the purity in the signal region is 74%.

PDF	ΔE	M_{bc}	Transformed NN
Signal	Double Gaussian	Gaussian	Asymmetry Gaussian
Background	1st Polynomial	ARGUS	Asymmetry Gaussian

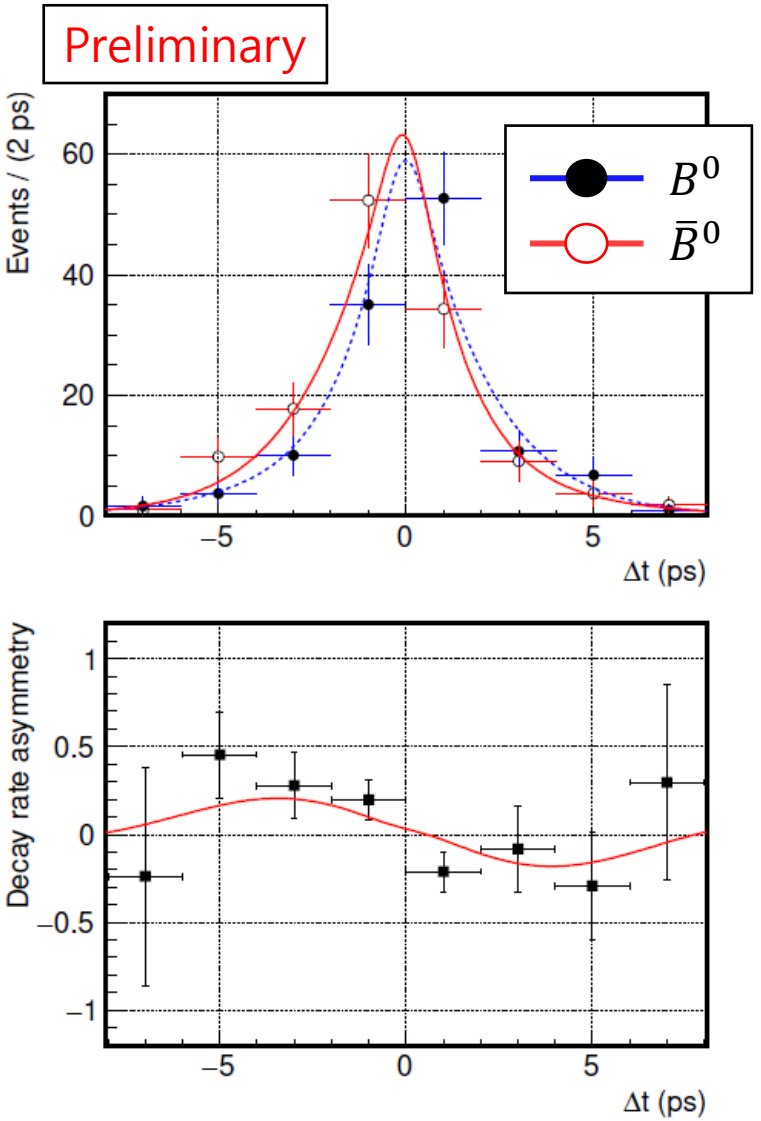
Measurement of CPV parameters

- PDF to extract CPV parameters

$$\mathcal{P}_j(\Delta t_j, q_j) = (1 - f_{\rm ol}) \times [f_j^{\rm sig}\mathcal{P}_{\rm sig}(\Delta t_j, q_j) + (1 - f_j^{\rm sig})\mathcal{P}_{\rm bkg}(\Delta t_j)] + f_{\rm ol}\mathcal{P}_{\rm ol}(\Delta t_j)$$

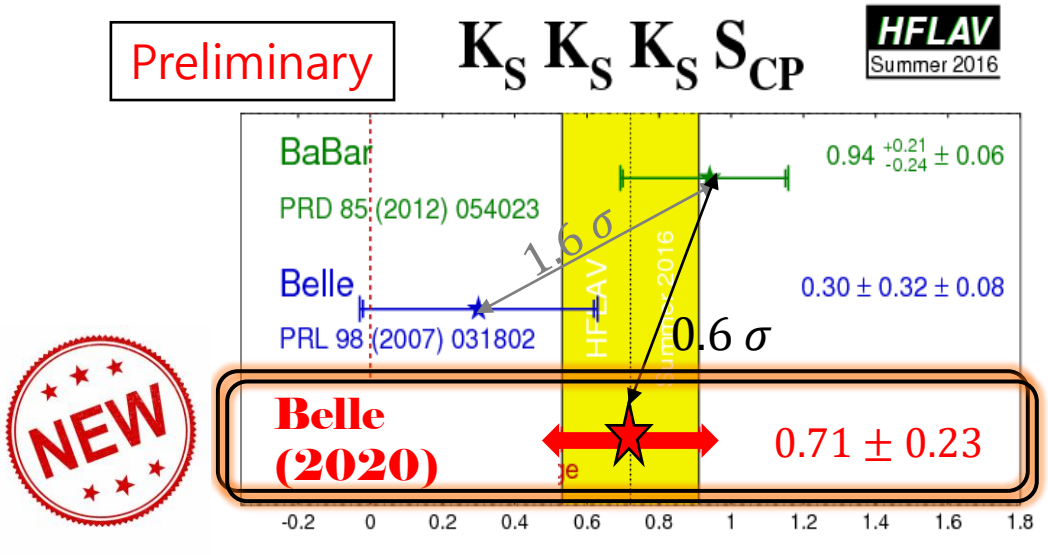
  - P_{sig} : signal PDF
  - P_{bkg}: continuum background PDF
  - P_{ol} : outlier components PDF

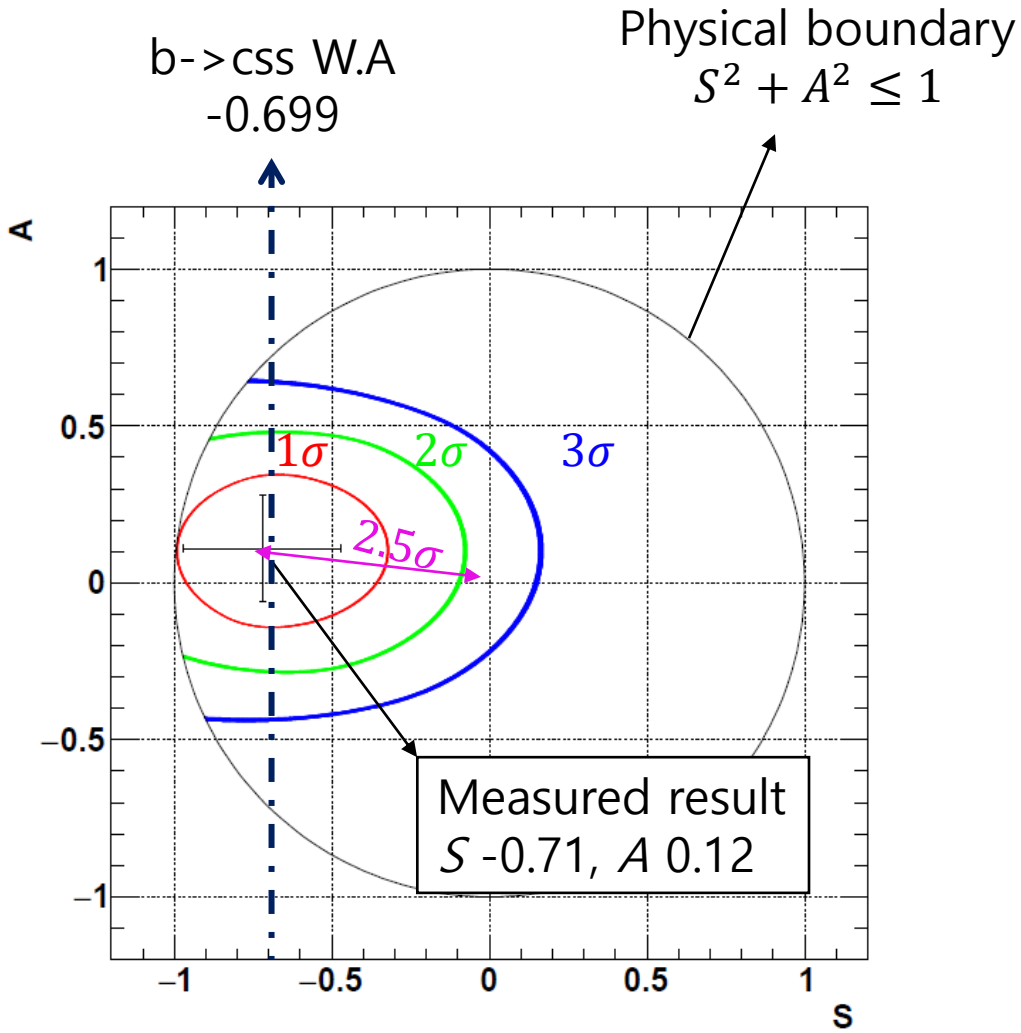
- Fitting results
  - $\boldsymbol{S = -0.71 \pm 0.23\ (stat) \pm 0.05\ (syst)}$
    - $-sin\ 2\phi_1$ in $b \to c\bar{c}s = -0.699$
  - $A = \ \ 0.12 \pm 0.16\ (\text{stat}) \pm 0.05\ (\text{syst})$



Significance of CP violation

- The significance is calculated using the Feldman-Cousins approach.
- The significance of CP violation is determined to be 2.5σ away from (0,0)





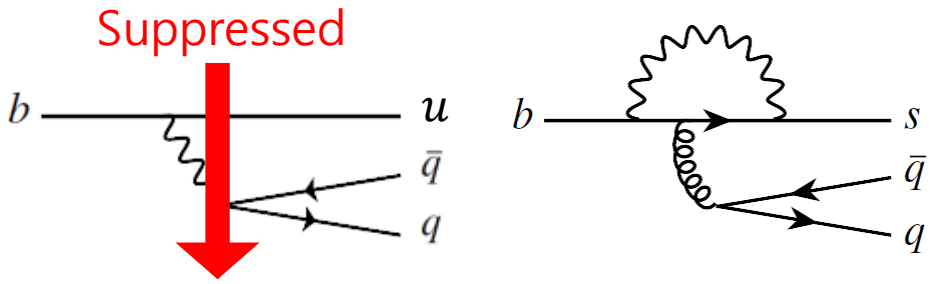
Confidence region for S and A

Consistent with previous measurements and $b \to c\bar{c}s$

Published result

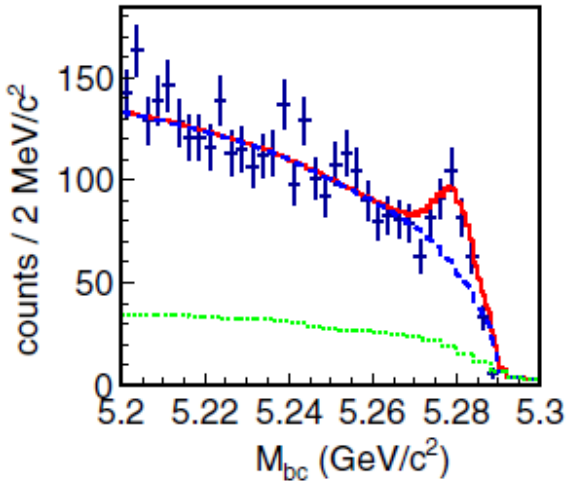
$B^0 \to \pi^0\pi^0 K_S^0$ - PRD **99** 011102 (2019)
$B^0 \to J/\psi\pi^0$ - PRD **98** 112008 (2018)

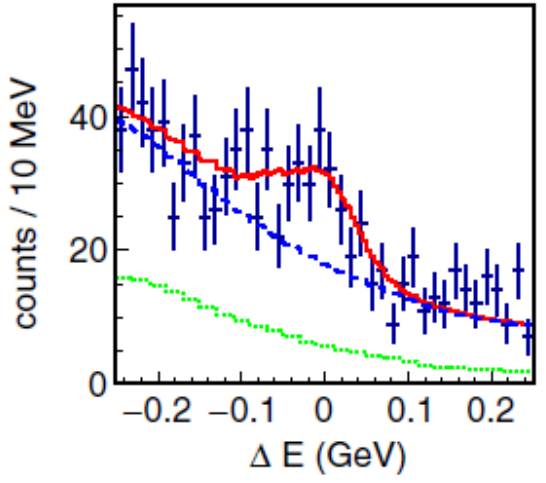
$B^0 \to \pi^0\pi^0 K_S^0$

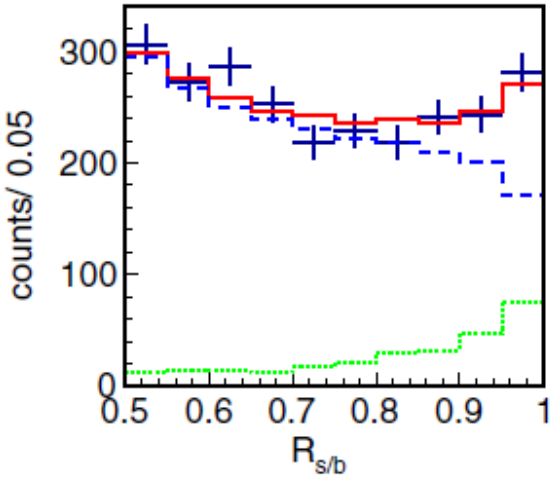


- $b \to s\bar{q}q$ three body decays
  - Tree diagram $b \to s\bar{u}u$ → doubly Cabibbo suppressed
  - Penguin diagram $b \to s\bar{d}d$ → main decay

- Any NP will shift $S = -\sin 2\phi_1^{eff}$ by penguin diagram
- First measurement using the final Belle data ($772 \times 10^6\ B\bar{B}$)







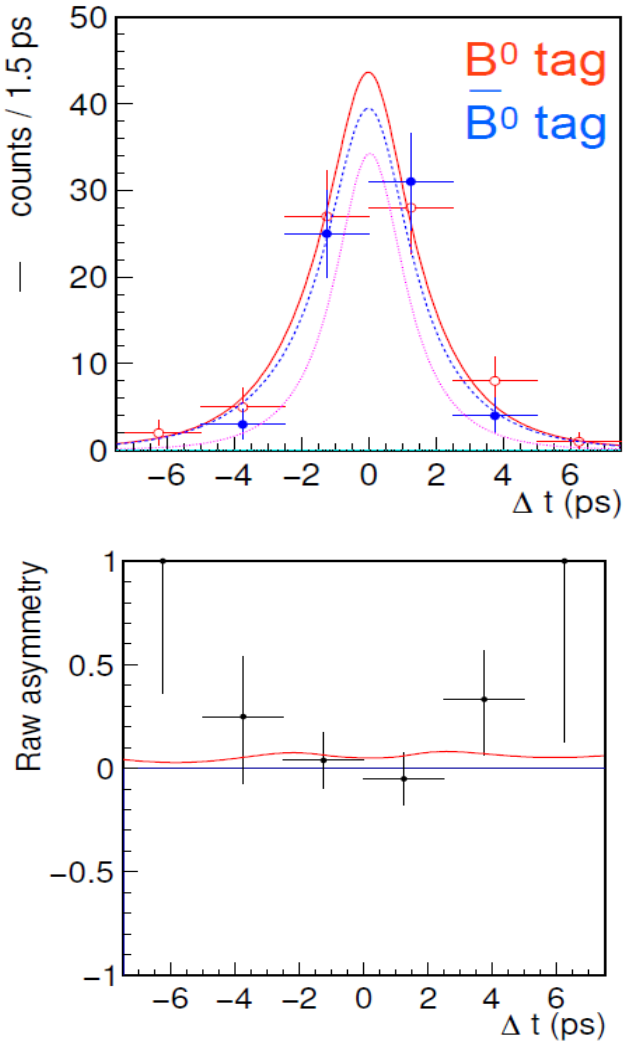
Fit result

Total background

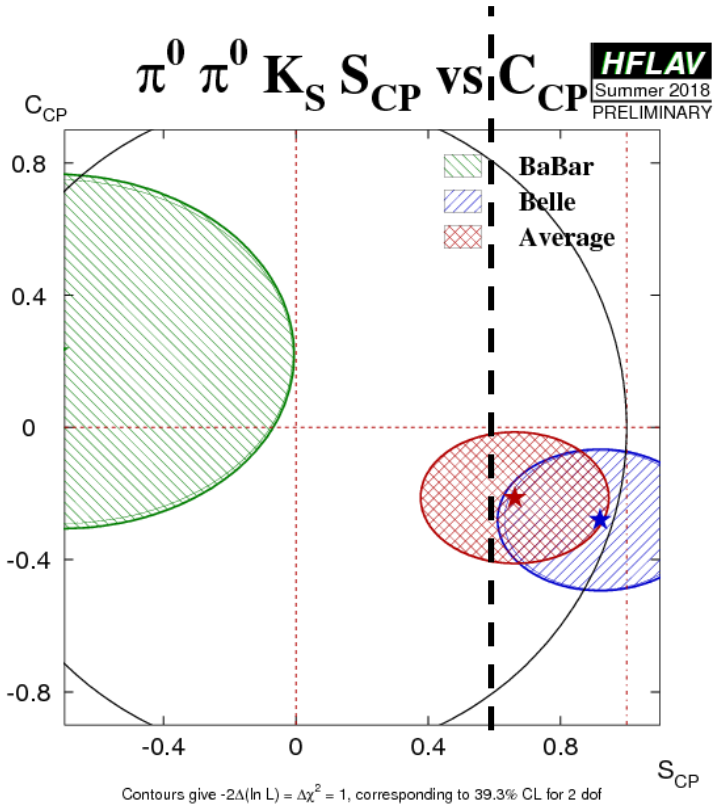
$B\bar{B}$ backgrounds

$R_{s/b}$ = likelihood ratio for continuum suppression

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



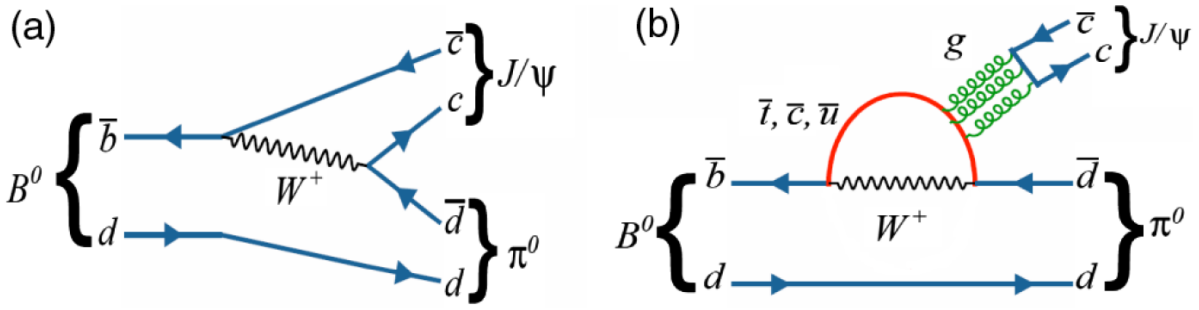
$\sin 2\phi_1$ in $b \to c\bar{c}s$



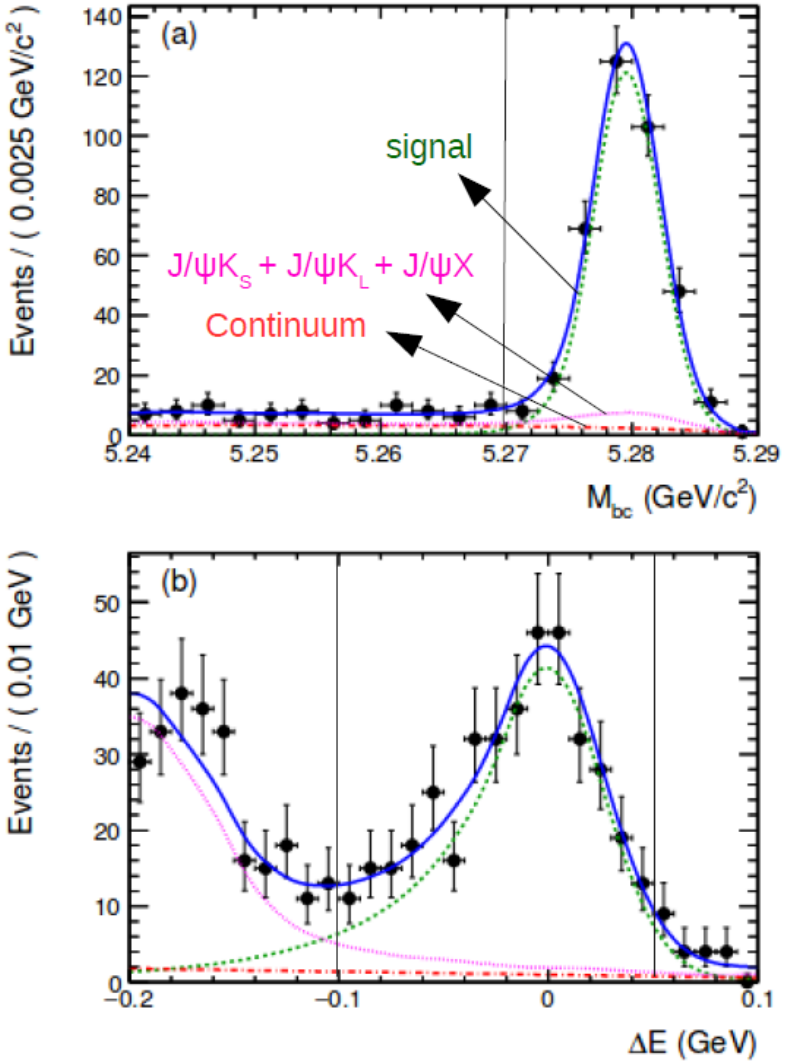
$$S = -0.92 \pm 0.31\ (\text{stat}) \pm 0.11\ (\text{syst})$$
$$A = \quad 0.28 \pm 0.21\ (\text{stat}) \pm 0.04(\text{syst})$$

The measurement results
- S is consisted with the value of $\sin 2\phi_1$ in $b \to c\bar{c}s$.
- A is consisted with the zero → no direct CP violation in the SM expectation.

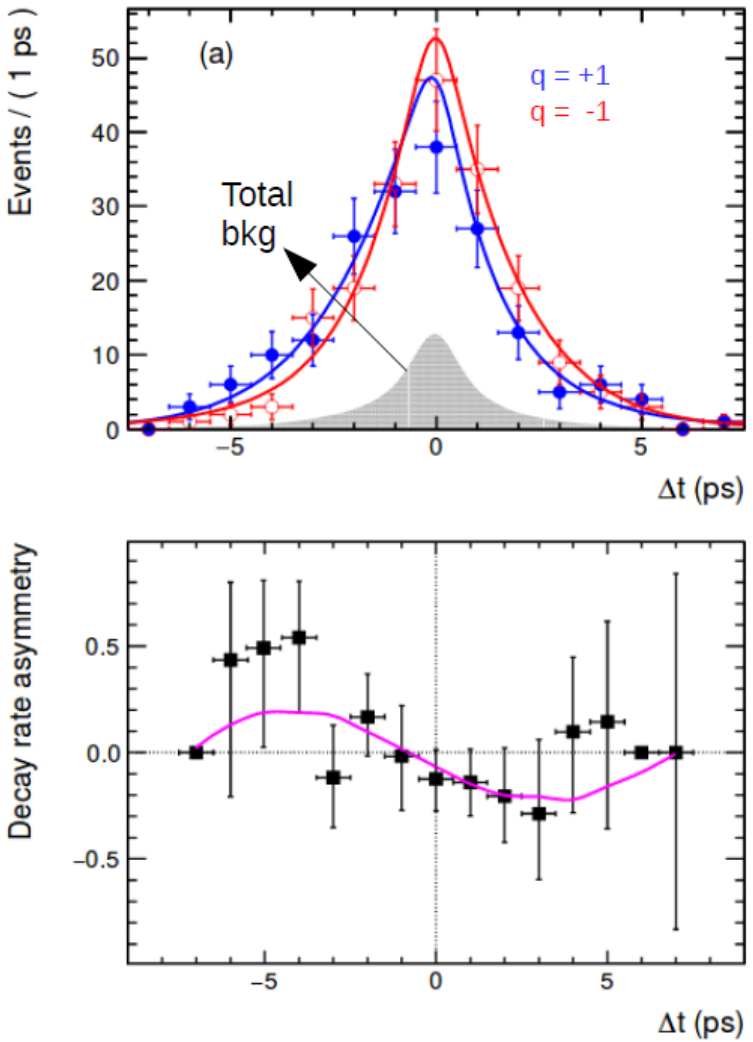
$B^0 \to J/\psi\pi^0$



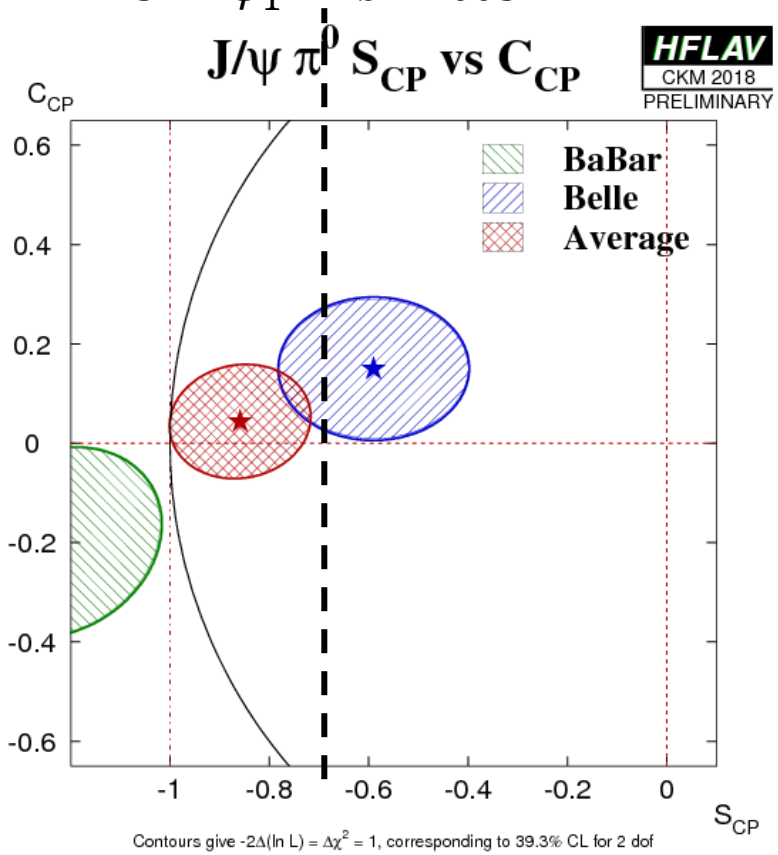
- $b \to c\bar{c}d$ two body decays
  - Penguin diagram is not suppressed ↔ $b \to c\bar{c}s$
- Penguin and any NP will shift $S = -\sin 2\phi_1^{eff}$
- Constrain the small penguin contribution in $B^0 \to J/\psi K_S^0$ by introducing a plausible flavor SU(3) asymmetry.



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



$-\sin 2\phi_1$ in $b \to c\bar{c}s$



$$\boldsymbol{S = -0.59 \pm 0.19\ (stat) \pm 0.03\ (syst)}$$

$$A = \ -0.15 \pm 0.14\ (\text{stat}) \pm 0.04(\text{syst})$$

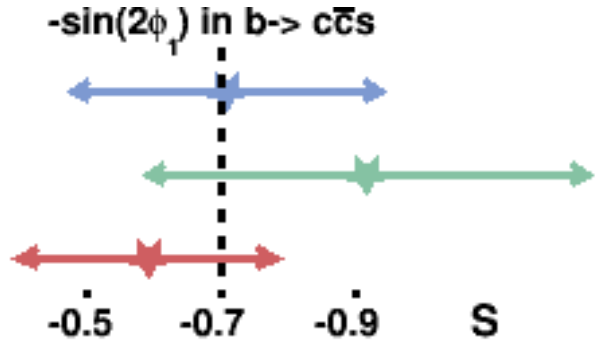
The measured CP results

- are consistent with, and supersede previous Belle results.
- S is consistent with the value of $\sin 2\phi_1$ in $b \to c\bar{c}s$.
- show penguin and any NP to $B^0 \to J/\psi K_S^0$ are small.

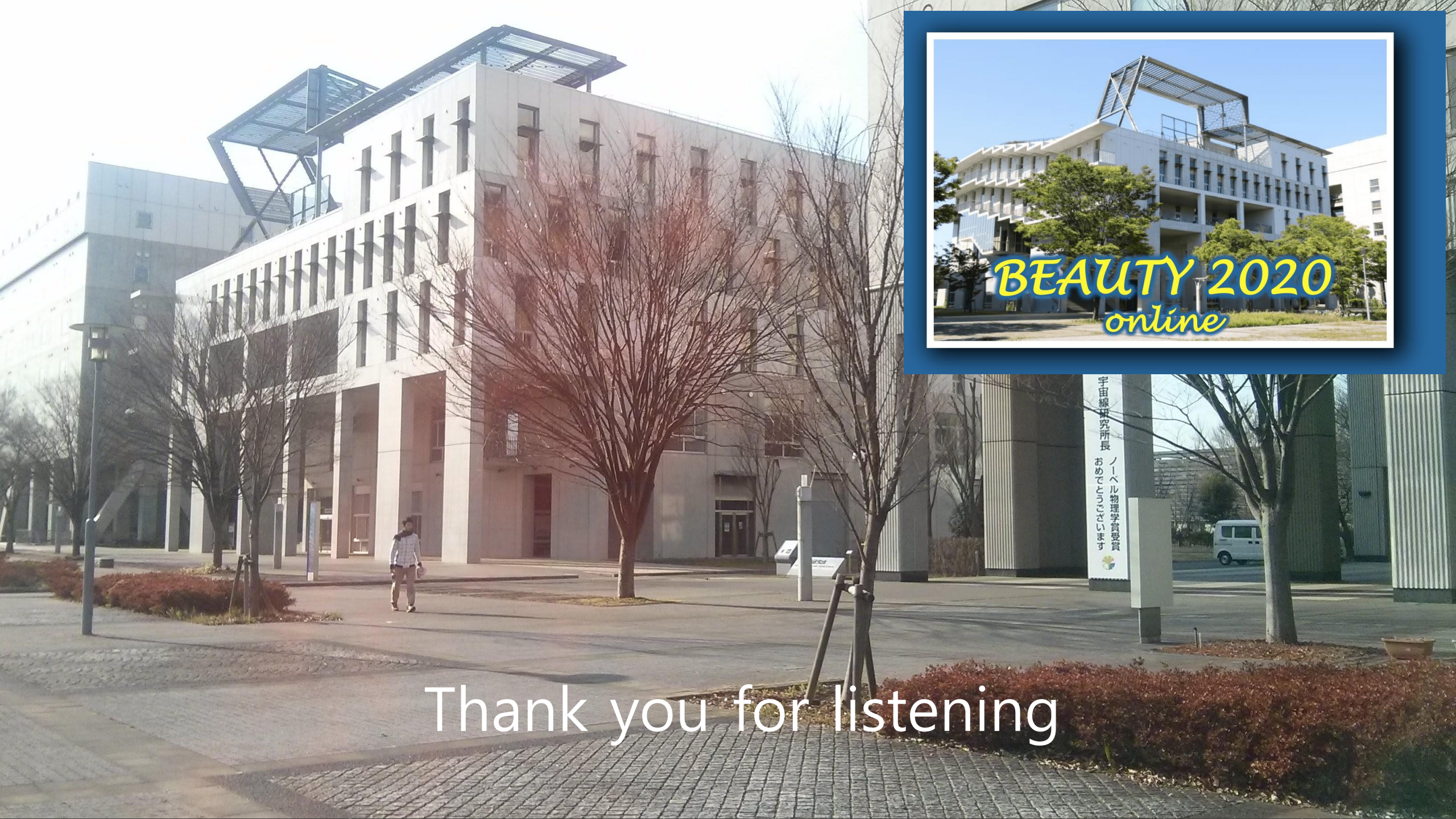
Summary

- The measurements of $\sin 2\phi_1^{eff}$ provide sensitivity to new physics.

- Using the final data sample ($772 \times 10^6\ B\bar{B}$)
  - $B^0 \to K_S^0 K_S^0 K_S^0$ → $S = -0.71 \pm 0.23\ (stat) \pm 0.05\ (syst)$
  - $B^0 \to \pi^0 \pi^0 K_S^0$ → $S = -0.92 \pm 0.31\ (stat) \pm 0.11\ (syst)$
  - $B^0 \to J/\psi \pi^0$ → $S = -0.59 \pm 0.19\ (stat) \pm 0.03\ (syst)$
  - These results are consisted with the value of $\sin 2\phi_1$ in $b \to c\bar{c}s$.



- The result of $B^0 \to K_S^0 K_S^0 K_S^0$ will be submitted to PRD.



Thank you for listening

Backup

Systematic error

Source	S	A
Vertex reconstruction	0.031	0.038
Flavor tagging	0.002	0.004
Resolution function	0.016	0.014
Physics parameters	0.004	0.001
Fit bias	0.012	0.009
Signal fraction	0.024	0.021
Background Δt shape	0.016	0.001
SVD misalignment	0.004	0.005
Δz bias	0.002	0.004
Tag-side interference	0.001	0.008
Total	0.05	0.05

Main source of systematic error comes from non-primary charged track.

But statistical error is much larger than systematic.

- statistics: $S(0.23), A(0.16)$

Signal reconstruction
– selection criteria and best candidate selection

- We use K_S^0 only from charged decay to avoid background.

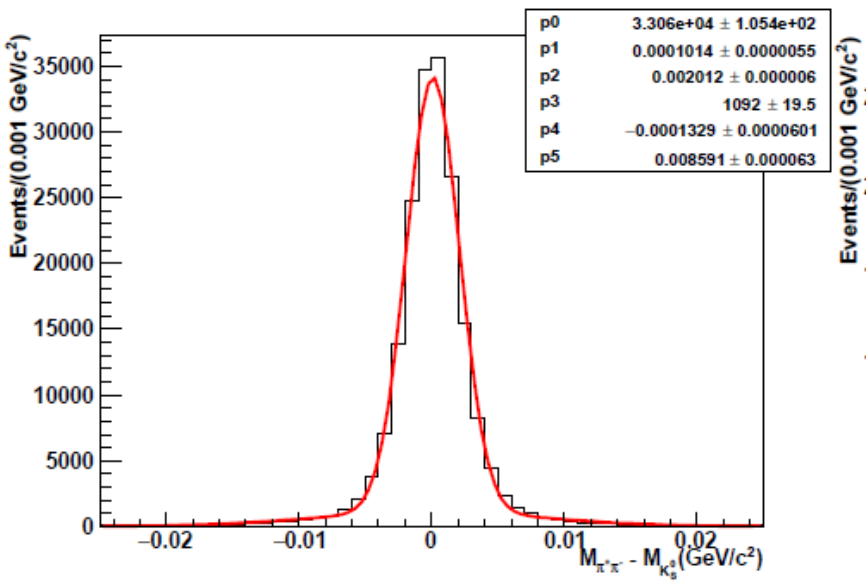
	$B^0 \to K_S^0 K_S^0 K_S^0$
$K_S^0(\pi^+\pi^-)$ selection in mdst_vee2	$\lvert\Delta M_{\pi\pi}\rvert < 10\,\sigma$, nisKsfinder cut (nb_vlike>0.2)
ΔE [GeV]	-0.2 $< \Delta E <$ 0.2
M_{bc} [GeV/c^2]	5.2 $< M_{bc}$
Best candidate selection	smallest of $\chi^2 = \sum_{i=1}^{3} \left(\frac{M_{\pi\pi}^i - M_{K_S^0}}{\sigma_{\pi\pi}} \right)^2$
Continuum BKG suppression	KSFW LR, $cos\theta_{\mathrm{B}}$, $cos\theta_{\mathrm{T}}$ $NeuroBayes\ output$>0.08

Parameters for K_S^0 selection

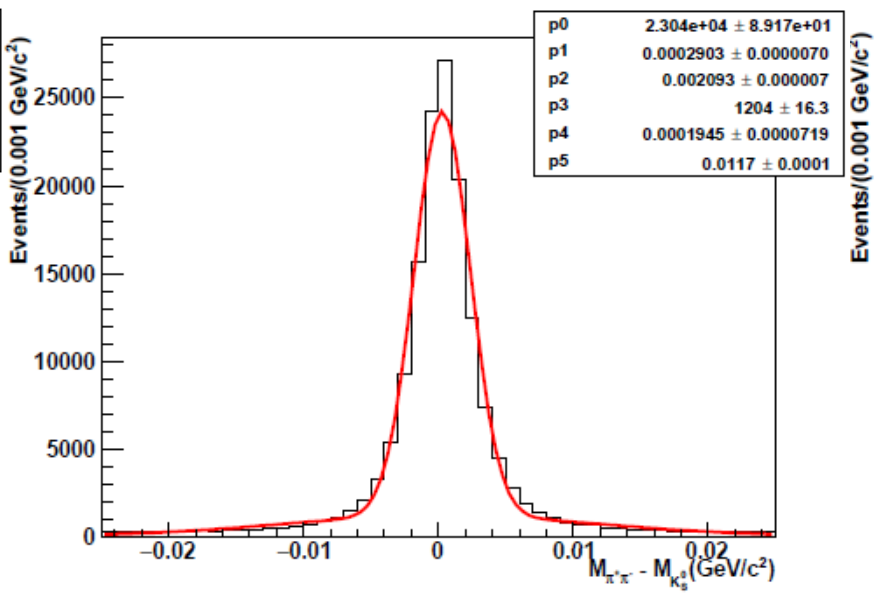
Variable name	Meaning
p_ks_lab	K_S^0 momentum in lab frame
zdist	distance between two helices in z direction
fl	flight length in x-y plane
dphi	angle between K_S^0 momentum and K_S^0 direction
dr_low	shorter distance between IP and child helix
dr_high	longer distance between IP and child helix
decang	angle between K_S^0 momentum (lab frame) and pion momentum (K_S^0 frame)
svdhit1	whether positive child hit SVD or not
svdhit2	whether negative child hit SVD or not
cdc_r1	axial wire hit number of positive child
cdc_z1	stereo wire hit number of positive child
cdc_r2	axial wire hit number of negative child
cdc_z2	stereo wire hit number of negative child

$M_{\pi^+\pi^-}$ distribution by SVD hit

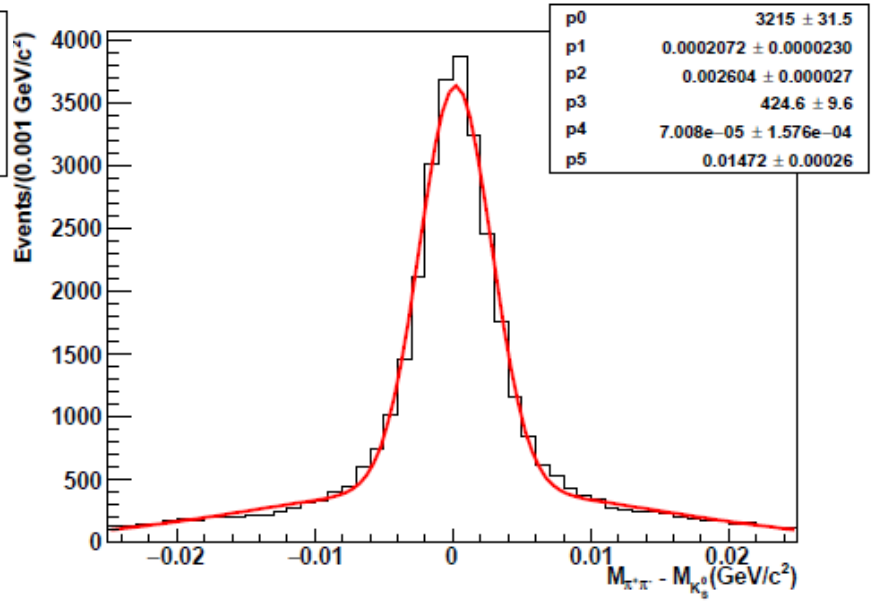
- The mass range for
  - both or non pions hit the SVD: $0.478 < M_{\pi^+\pi^-} < 0.517 < GeV/c^2$
  - Only one pion hits the SVD: $0.474 < M_{\pi^+\pi^-} < 0.522 < GeV/c^2$



(a) Both pions have SVD hit.



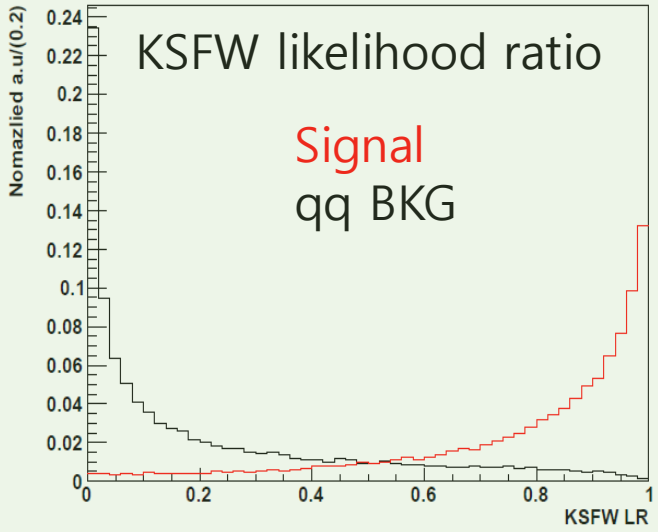
(b) None of pions have SVD hit.

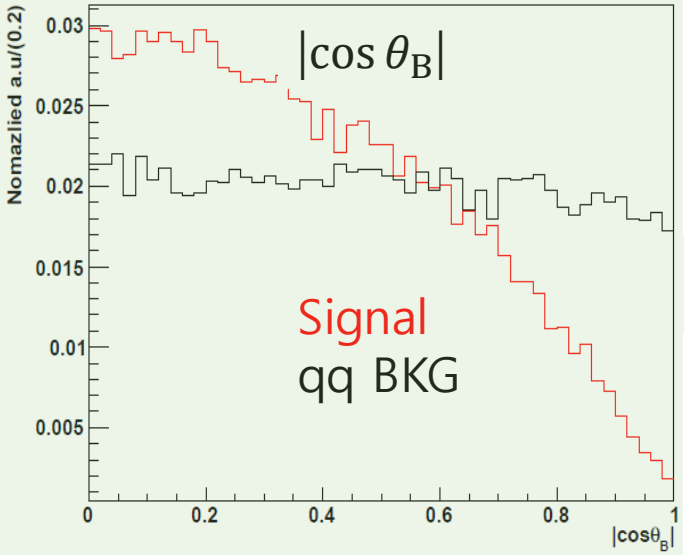


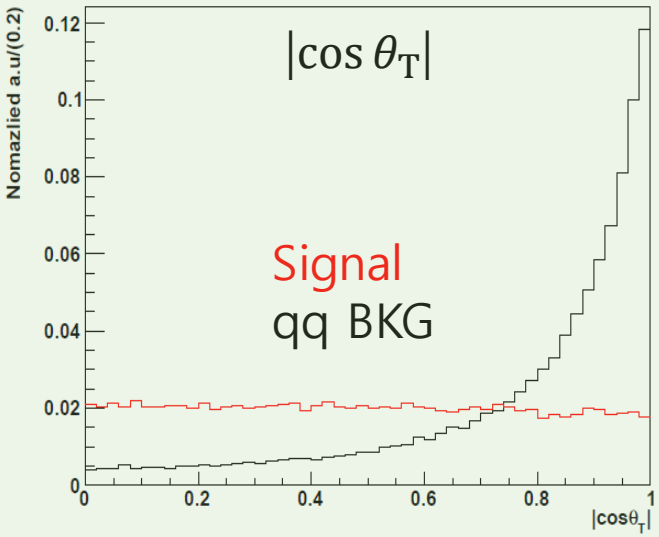
(c) Only one of two pions has SVD hit.

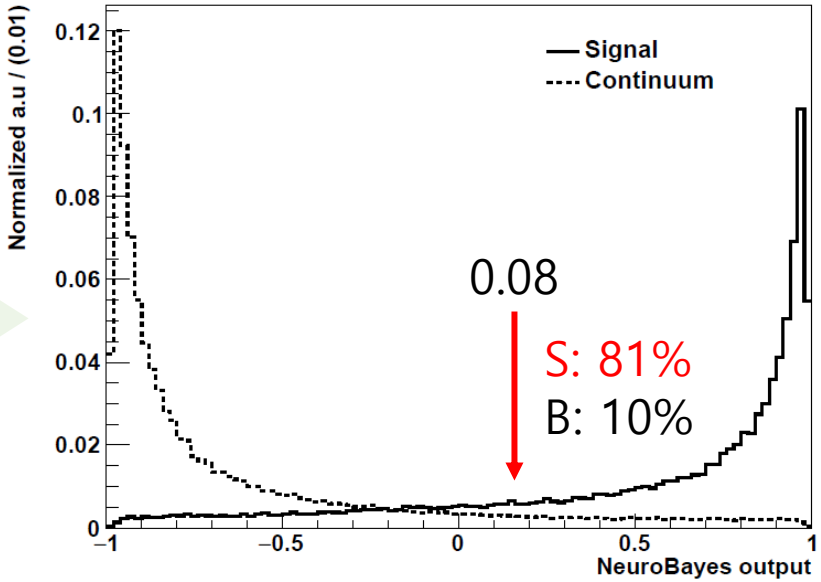
Continuum background

KSFW LR – Kakuno Super Fox-Wolfram moment
$cos\theta_{\mathrm{B}}$= cosine of the angle between beam pipe and B_{CP}
$cos\theta_{\mathrm{T}}$= cosine of the angle between thrust axis of B_{cp} and B_{tag}





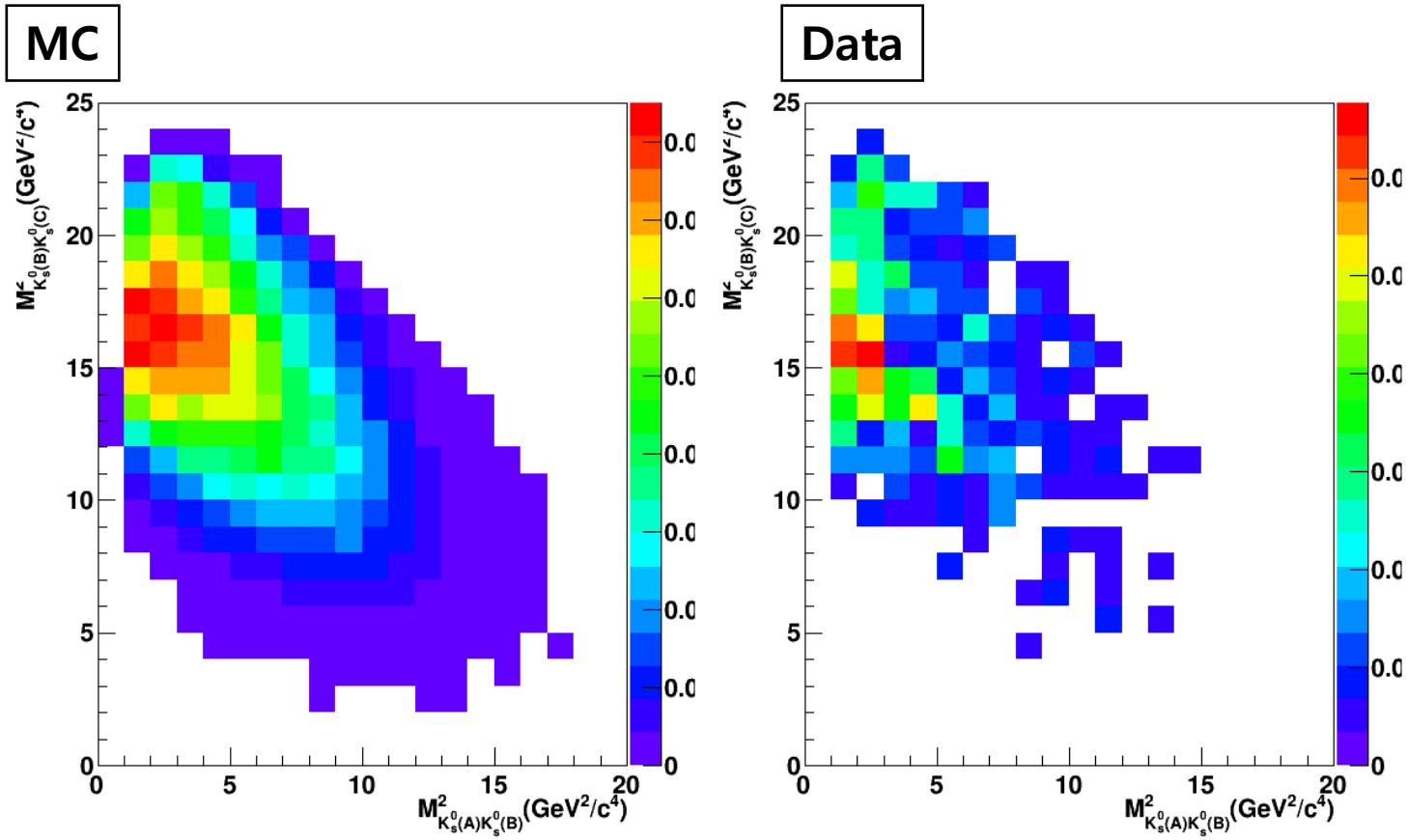




The NB cut is selected with highest figure of merit (FOM)

$$\mathrm{FOM} = \frac{N_{sig}}{\sqrt{N_{sig}+N_{bkg}}}$$

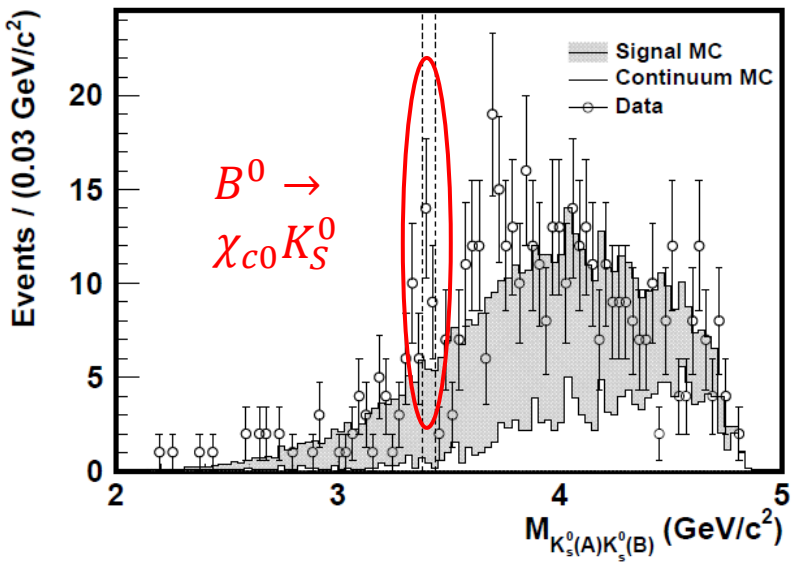
Dalitz plot

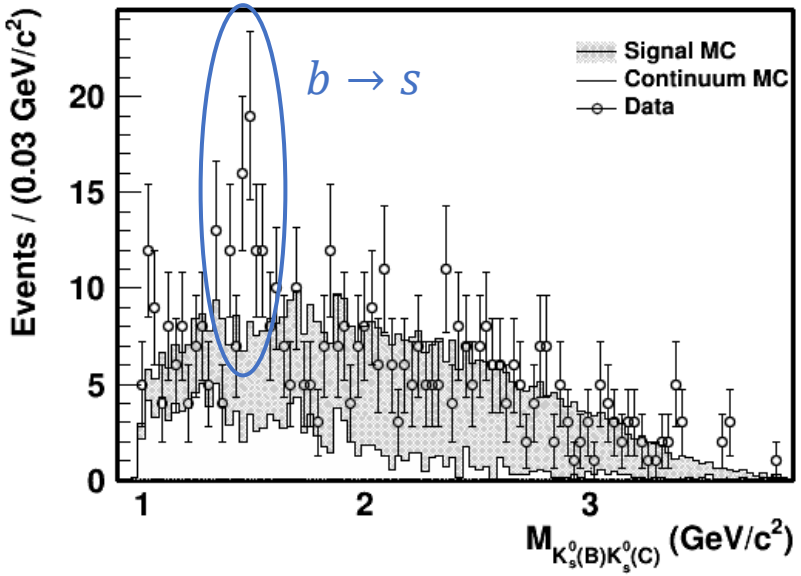


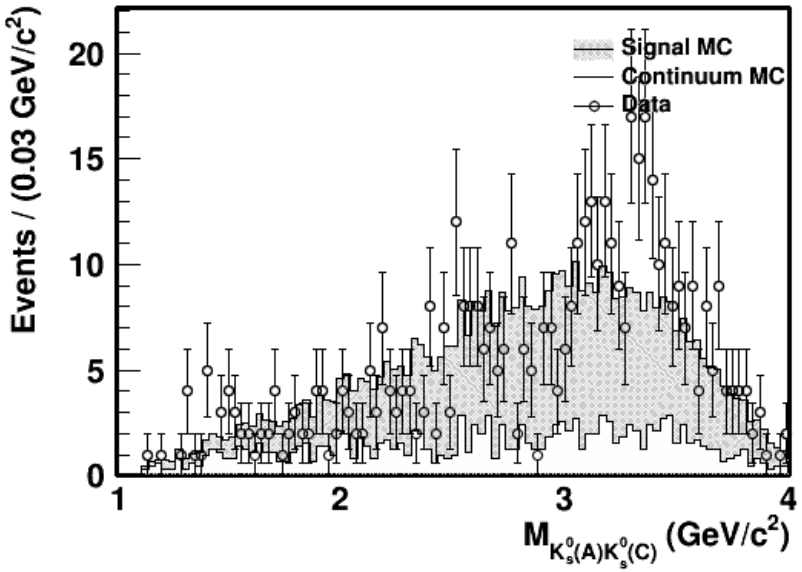
- Compare the dalitz plot for MC and data, our evtgen model for MC generation, PHSP_CP, well describes data.

B-mesons background

$K^0_S{}_{A,B,C}$: momentum order



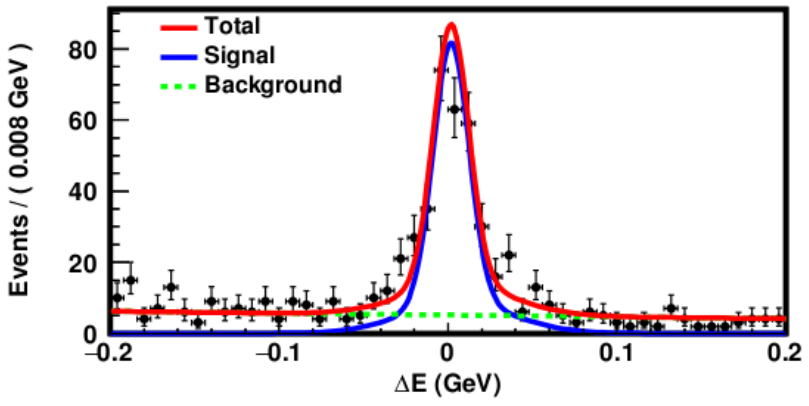


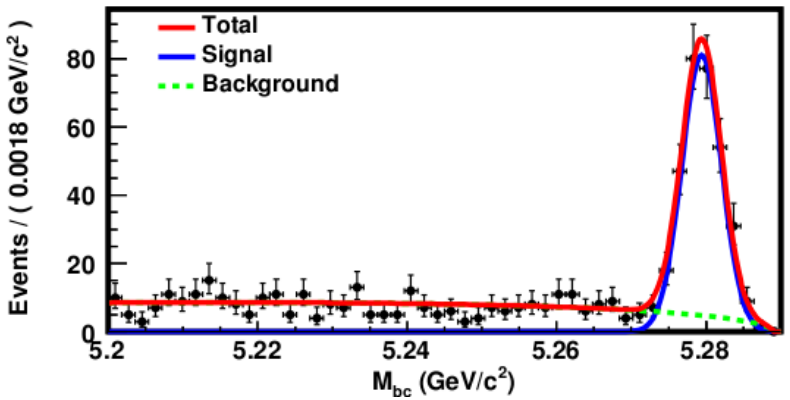


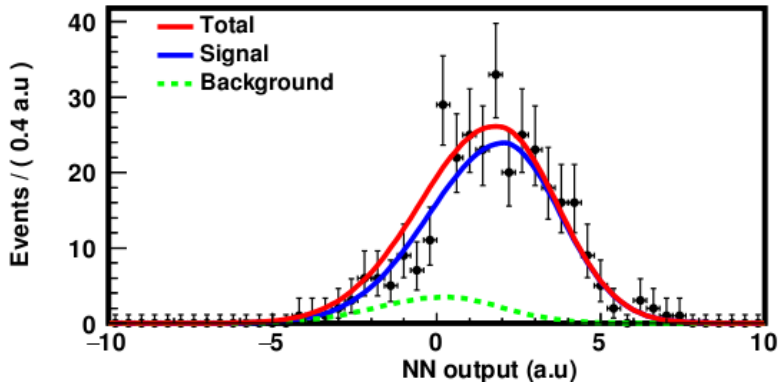
- Using invariant mass $M_{K^0_S K^0_S}$, quasi-two-body decay are considered:
  - $b \rightarrow c$ quark transition by the tree diagram → considered as a background
    - Veto: $B^0 \rightarrow \chi_{c0}(K^0_S K^0_S) K^0_S$ → $3.388\ GeV/c^2 < M_{K^0_S K^0_S} < 3.444\ GeV/c^2$
  - $b \rightarrow s$ quark transition by the penguin diagram → considered as a signal

Signal extraction with projection

With projection



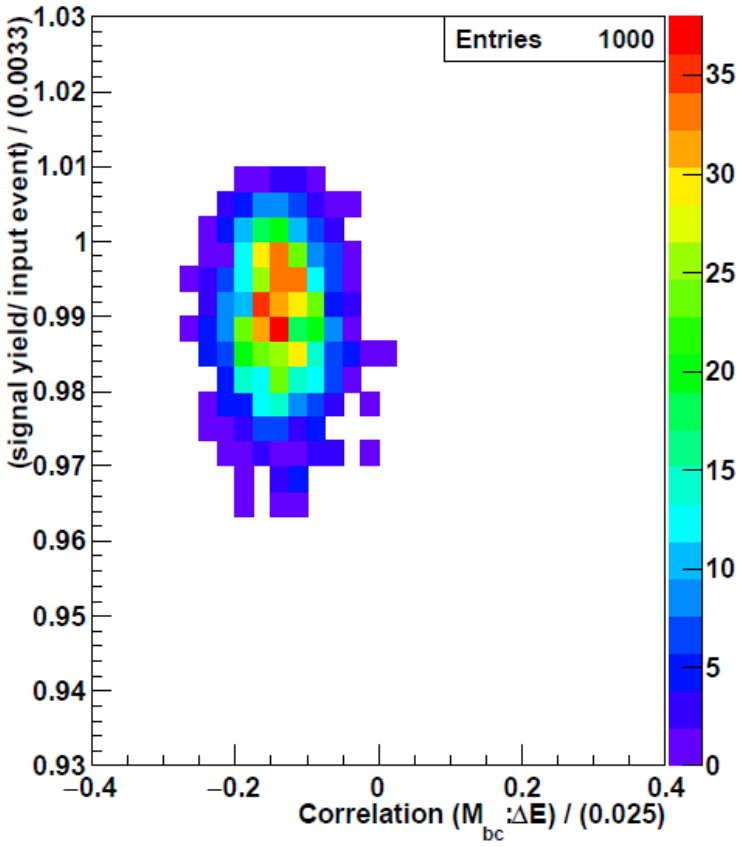




Signal extraction – validiation check by correlation

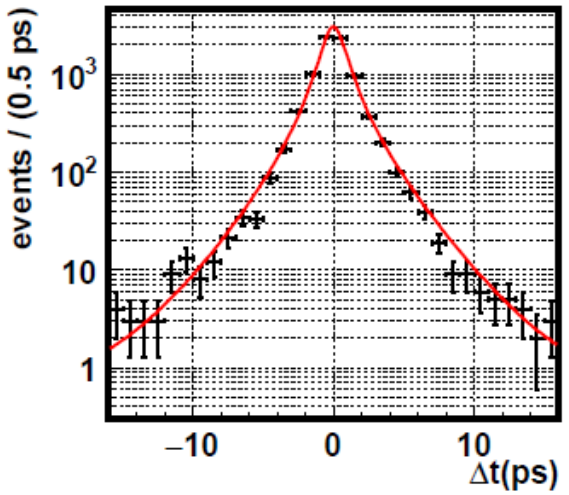
- To check any bias in signal extraction due to 14% correlation between M_{bc} and ΔE parameters.
- The 1000 signal MC samples are generated via evtgen and gsim.

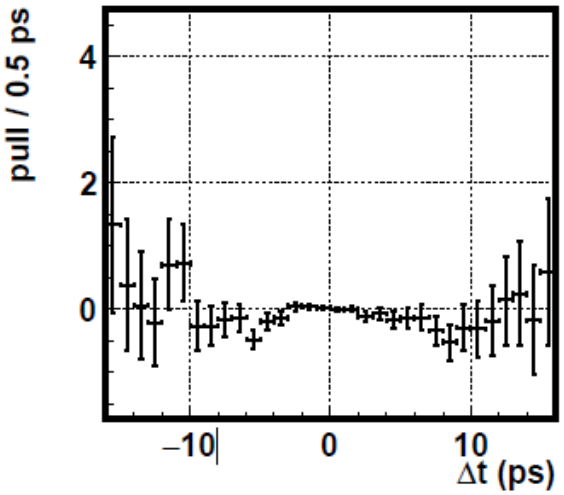
- There is no bias between correlation and (signal yield/ input event)
  - The signal yield is divdied by input event to remove gsim effect.



CP fitting - background δt distribution

- Data sample: $M_{bc} < 5.26\ or\ 0.15 < |\Delta E| < 0.2$
  - Continuum suppression cut is not applied to increase events

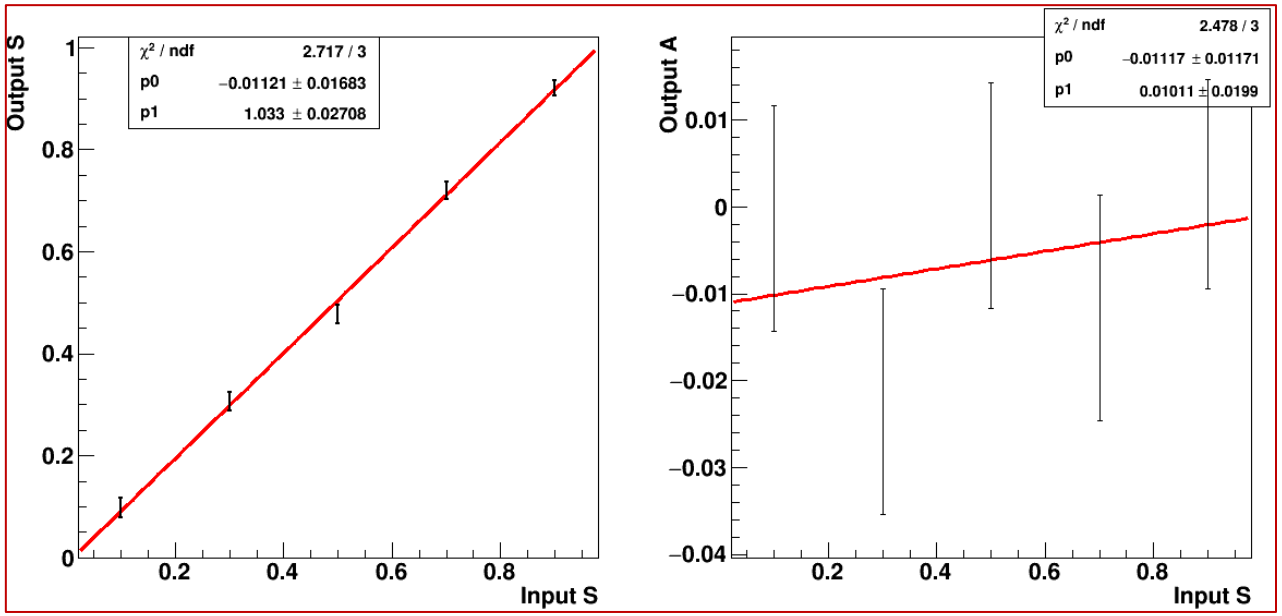




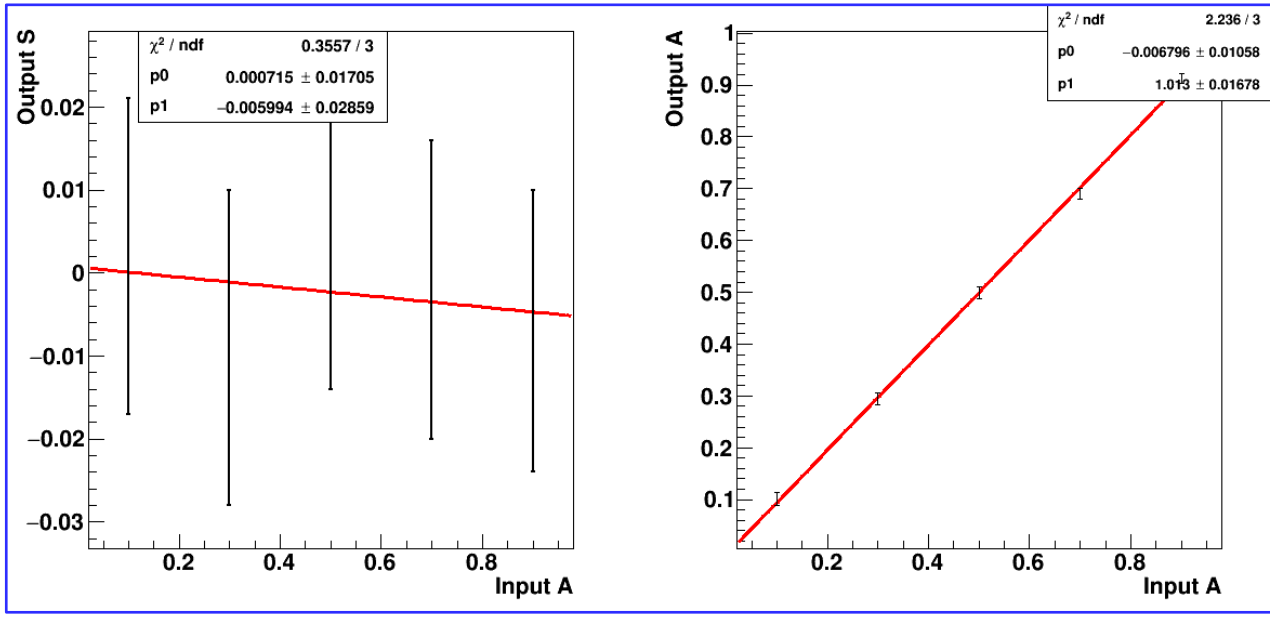
Shape	Mean
τ	2.5018
μ_l	0.39759
μ_d	-0.37944E-0
s^{mul}_{main}	1.1232
s^{mul}_{tail}	2.3082
f^{mul}_{tail}	0.32354
f^{mul}_{δ}	0.89373
s^{sgl}_{main}	1.2456
s^{sgl}_{tail}	29.217
f^{sgl}_{tail}	0.36542E-0
f^{sgl}_{δ}	0.76419

CP fitting – linearity check using signal MC

- Input S : 0.1, 0.3, 0.5, 0.7, 0.9 with A = 0
- Input A : 0.1, 0.3, 0.5, 0.7, 0.9 with S = 0



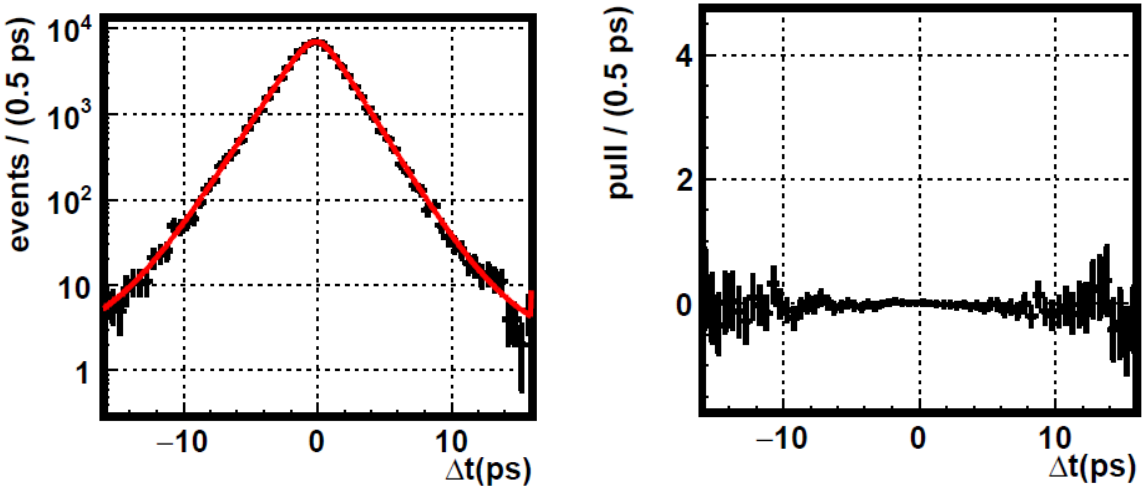
For S variation



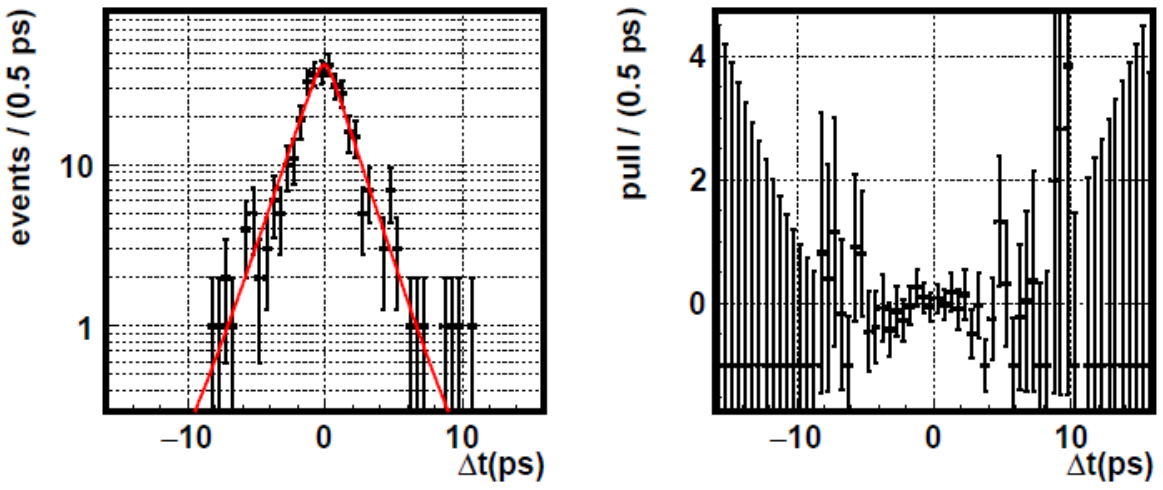
For A variation

CP fitting – lifetime measurement

MC



Data



- Using 1M signal MC with input τ_B is 1.5367
  - Fitting result: 1.5461 ± 0.0072 ps
  - Difference (fitting result - input) : 0.0106 ps

- Data result
  - Fitting result: 1.4271 ± 0.1129 ps
  - PDG value (1.520 ± 0.004 ps)

The result of lifetime fitting is consistent with PDG value

Compare with the previous Belle result

- Previous Belle result
  - Using $532 \times 10^6 B\bar{B}$ $(492\ \text{fb}^{-1})$
  - Include $B \to K_S^0 K_S^0 K_S^0 \to \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$
  - Measured result
    - $S = -0.30 \pm 0.32 \pm 0.08$
    - $\mathrm{A} = 0.31 \pm 0.20 \pm 0.07$

- In this analysis
  - exp 7~47 data set: $504\ \text{fb}^{-1}$
  - Reprocessed data (improved tracking) + improved K_S^0 efficiency (77% → 87%)
  - Measured result
    - $S = -0.73 \pm 0.31$
    - $A = 0.16 \pm 0.20$

Compare with BaBar result

- In this analysis = $S = -0.72 \pm 0.23\ (\text{stat}) \pm 0.05\ (\text{syst})$
  - Purity from signal extraction : 72%
  - Number of fitted event after discard poor vertex events : 345
  - Used signal events at CP fitting: 345*0.72 = 248 events

- BaBar (486 M $B\bar{B}$) $S = -0.94^{+0.21}_{-0.24}\ (\text{stat}) \pm 0.06\ (\text{syst})$

TABLE VII. Event yields for the different event species, resulting from the maximum-likelihood fit for the time-dependent analysis. "B^+B^- ($B^0\bar{B}^0$) background" represents background from charged (neutral) B decays. Quoted uncertainties are statistical only.

Species	$3K^0_S(\pi^+\pi^-)$	$2K^0_S(\pi^+\pi^-)K^0_S(\pi^0\pi^0)$
Signal	201^{+16}_{-15}	62^{+13}_{-12}
Continuum	3086^{+56}_{-54}	7086^{+85}_{-83}
B^+B^- background	-54^{+29}_{-24}	45^{+34}_{-30}
$B^0\bar{B}^0$ background	9^{+31}_{-30}	4^{+38}_{-29}

~267 events