Study of time-dependent and direct CP violation at Belle

K. Sumisawa(KEK)

40th International Conference on High Energy Physics

30 July, 2020

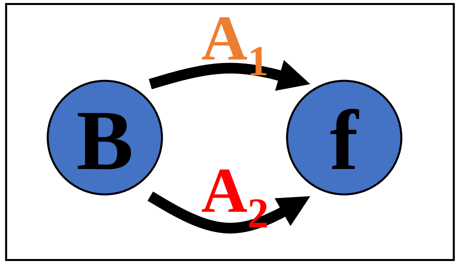
- time-dependent CP violation in $B^0 \to K_S^0 K_S^0 K_S^0$ Preliminary
- direct CP violation in $B \to \overline{D^0}\ \pi$ Preliminary

CP violation

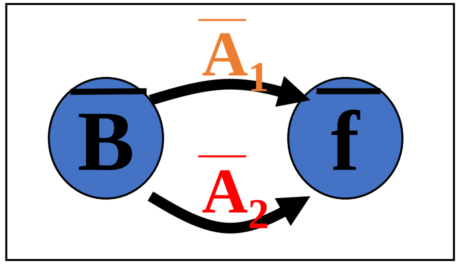
CP violation(CPV): the difference of partial decay width between B and anti-B.

$$\Gamma(B \to f) \neq \Gamma(\overline{B} \to \overline{f})$$

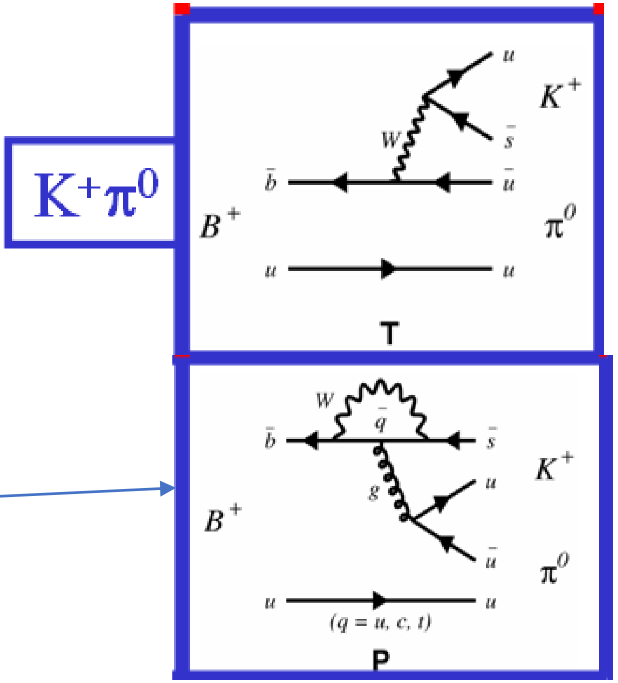
interference between 2 amplitude with different complex phase make CPV



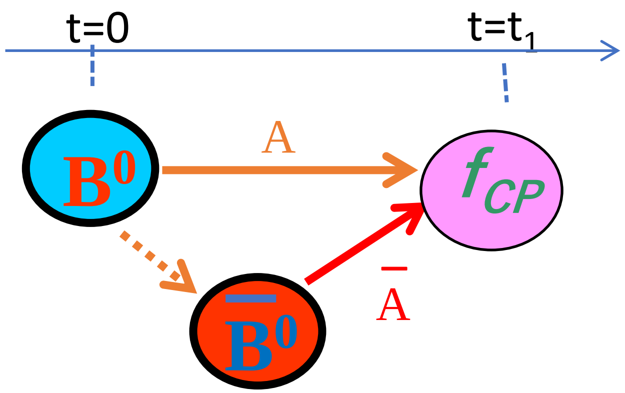
$\neq$



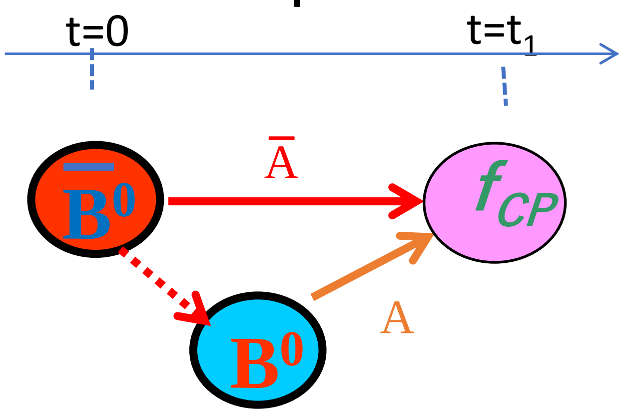
$$A_{CP} = \frac{\Gamma_{\bar{B}} - \Gamma_B}{\Gamma_{\bar{B}} + \Gamma_B}$$



- direct CP violation: 2 decay diagram
- mixing induced CP violation: time-dependent CPV



$\neq$



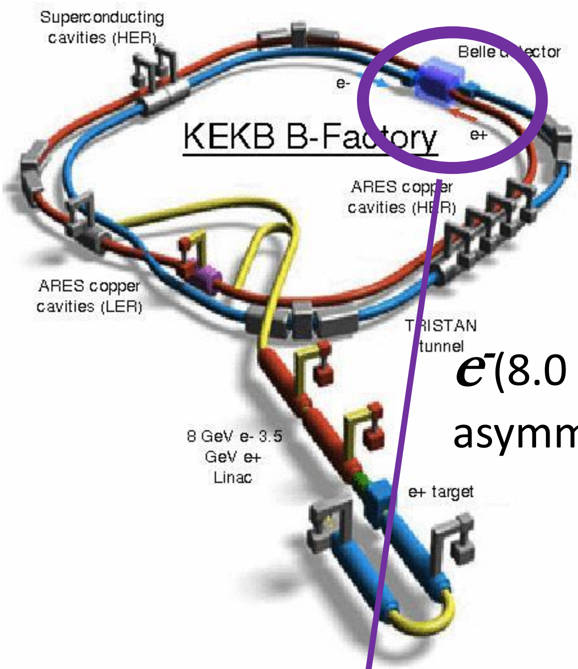
$$A_{CP}(\Delta t) \equiv \frac{\Gamma_{\bar{B}^0}(\Delta t) - \Gamma_{B^0}(\Delta t)}{\Gamma_{\bar{B}^0}(\Delta t) + \Gamma_{B^0}(\Delta t)} = \mathcal{S}\sin\Delta m\Delta t + \mathcal{A}\cos\Delta m\Delta t$$

Mixing-induced CPV

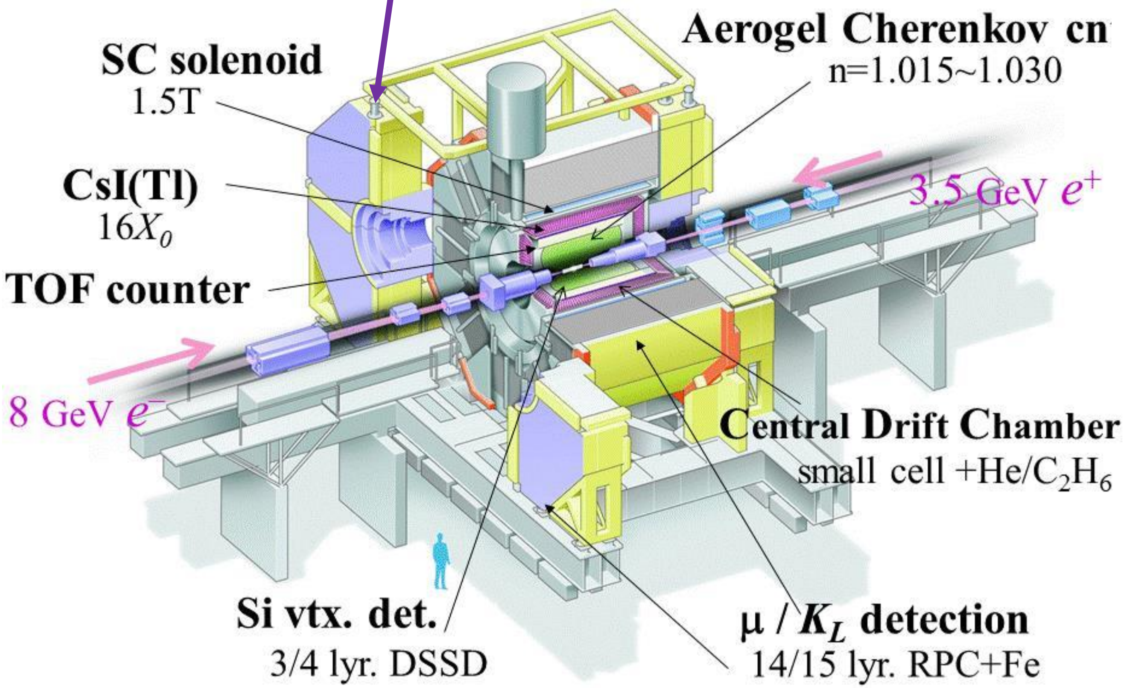
Direct CPV

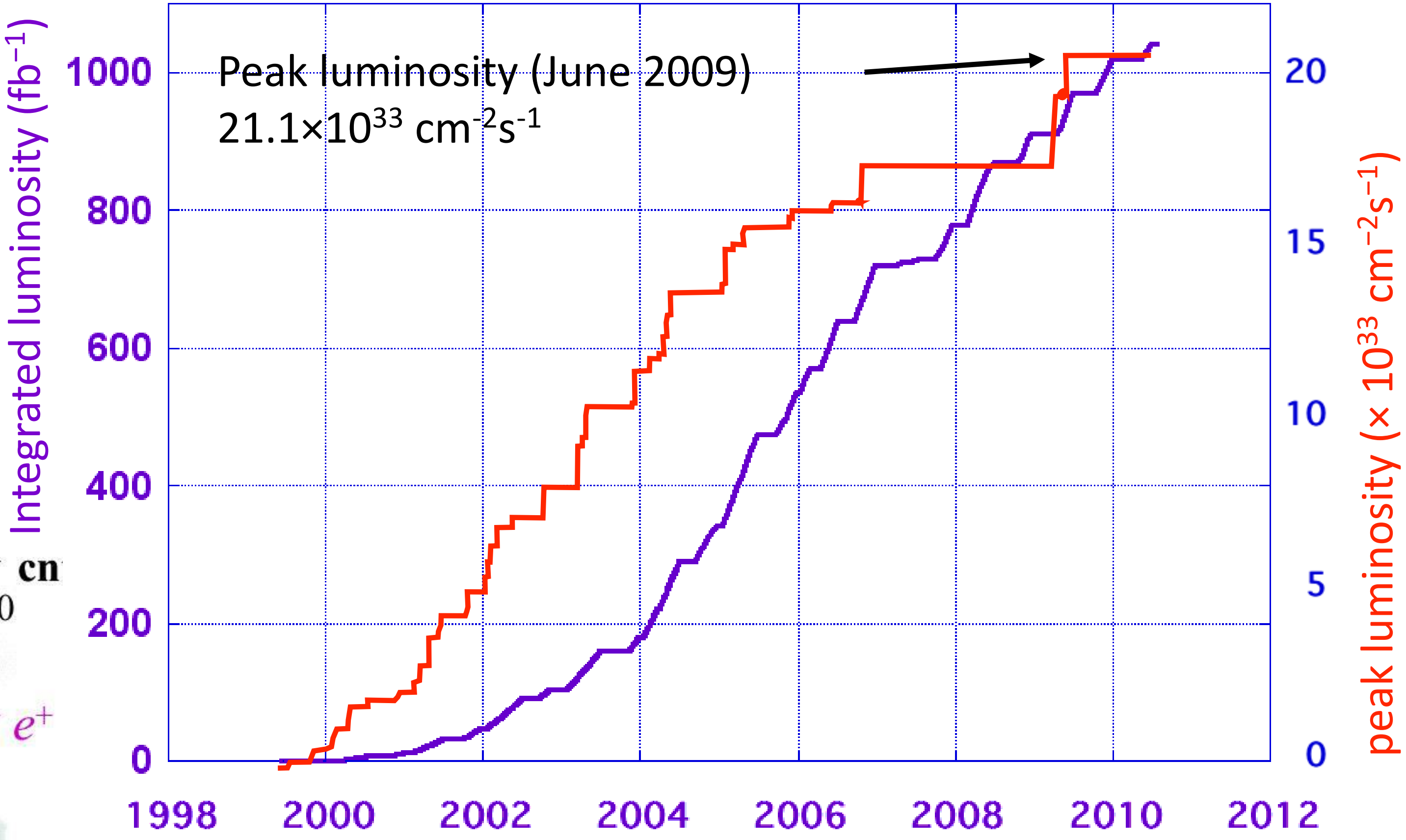
good probes of new physics (ex. $b \to sq\bar{q}$ TCPV, $\Delta A_{K\pi}$ puzzle)

KEKB accelerator and Belle detector



e^-(8.0 GeV) × e^+(3.5 GeV)
asymmetric energy collision



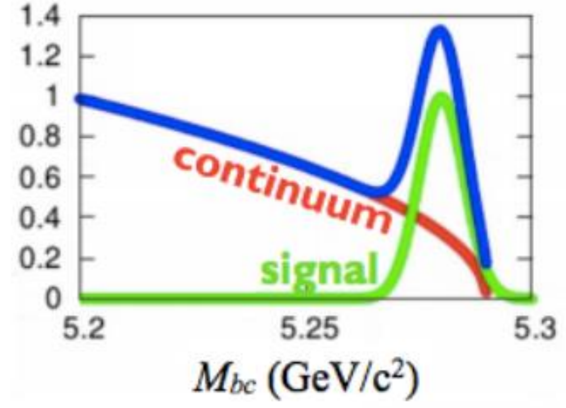


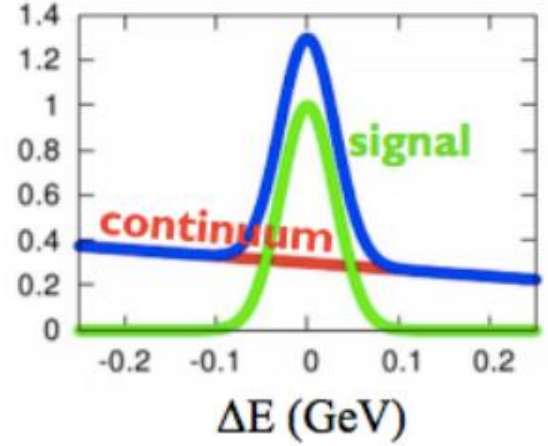
Integrated luminosity
at Υ(4S) resonance
711 fb^{-1}(~June 2010)
→772 million BB data

parameter for signal extraction

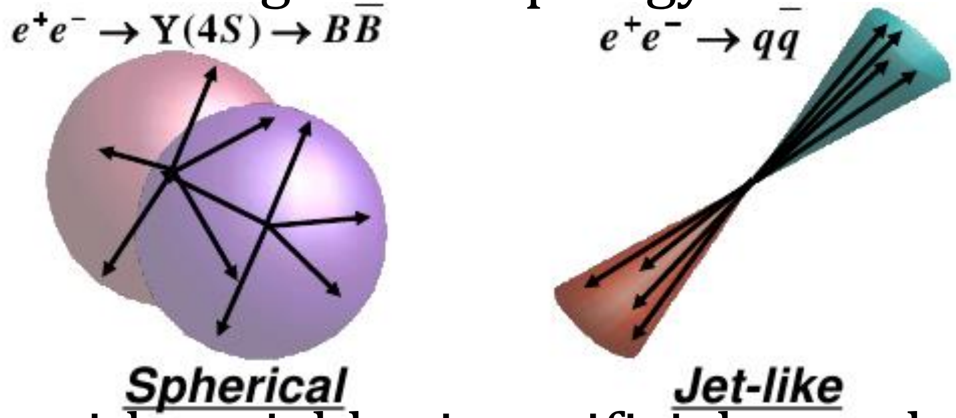
- Kinematic variables:

$$M_{bc} = \sqrt{E_{Beam}^2 - p_B^2}, \qquad \Delta E = E_B - E_{Beam}$$

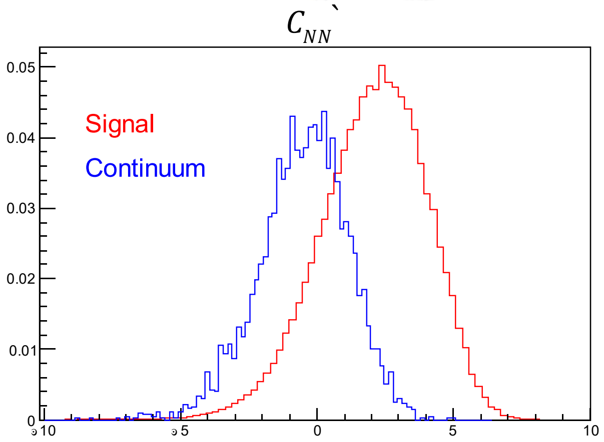




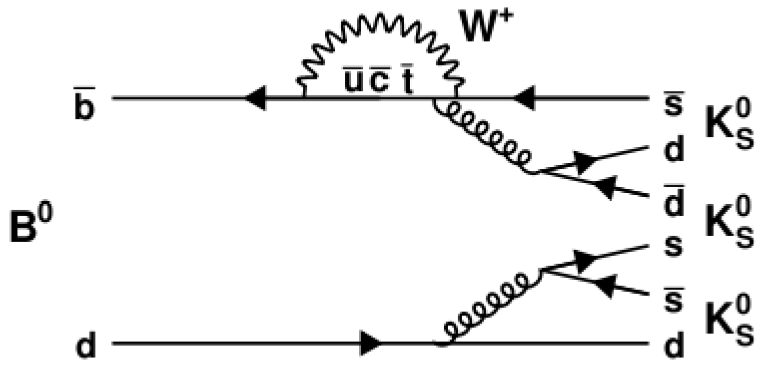
- $e^+e^- \to q\bar{q}$ ($q \in u, d, s, c$) dominant background. $\sim$3 times $e^+e^- \to \Upsilon(4S)$ cross-section.
- Discriminate using event topology.

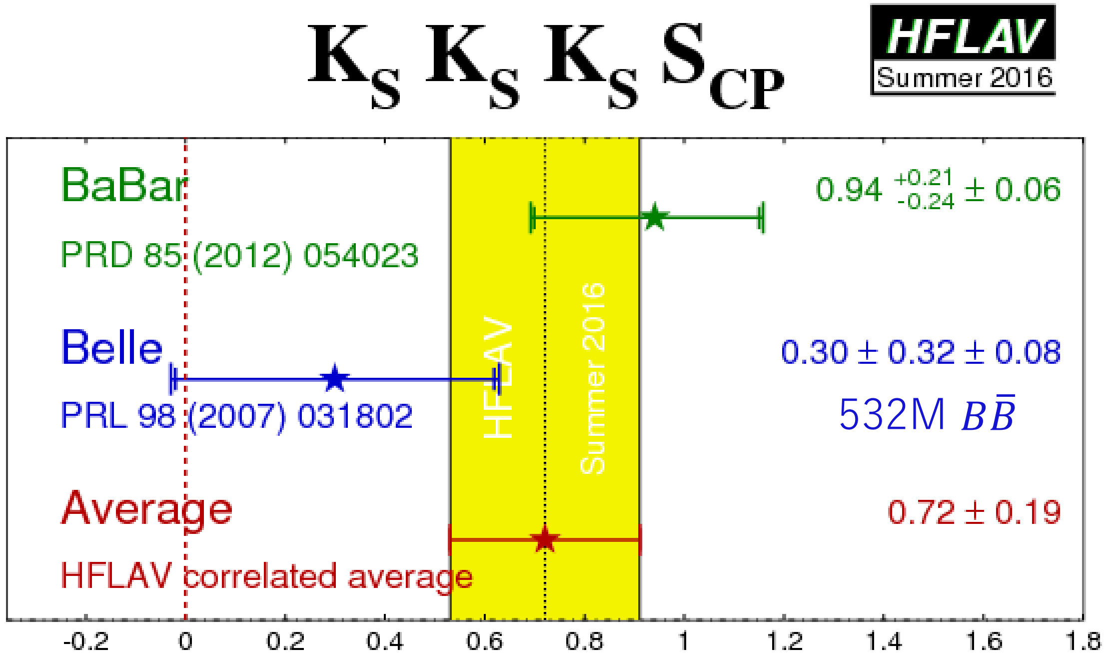


- Combine with variables in artificial neural network.
  modified NN, $C_{NN}^{`}$



Introduction – motivation for $B^0 \to K_S^0 K_S^0 K_S^0$





532M $B\bar{B}$

1.55 σ difference from BaBar

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

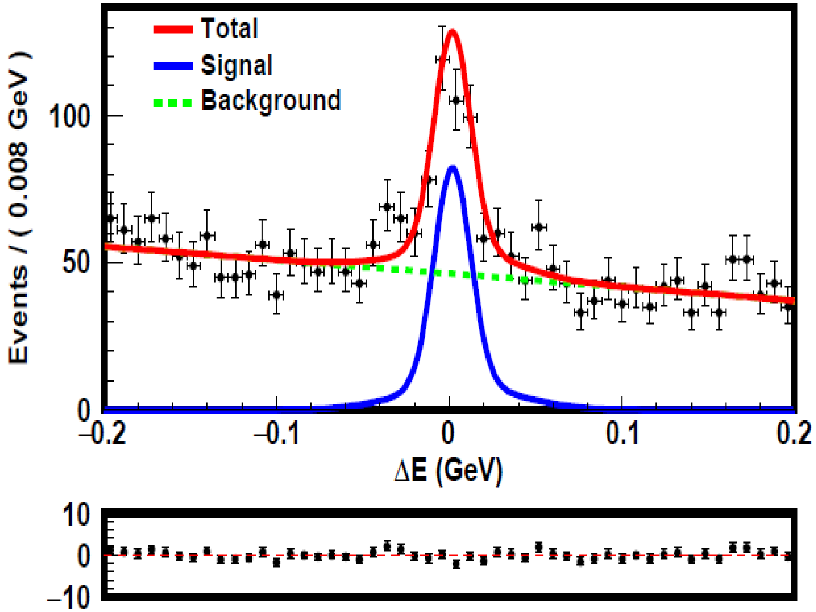
- Pure $b \to s$ penguin transition by loop diagram
- CP-even eigenstate
- $TCPV$ measurement in the SM
  - Direct CPV $(A) = 0$
  - mixing induced CPV (S) $\sim -\sin 2\phi_1$
- The deviations from SM expectations for S and A may indicate of new physics.

- 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 $B\bar{B}$).

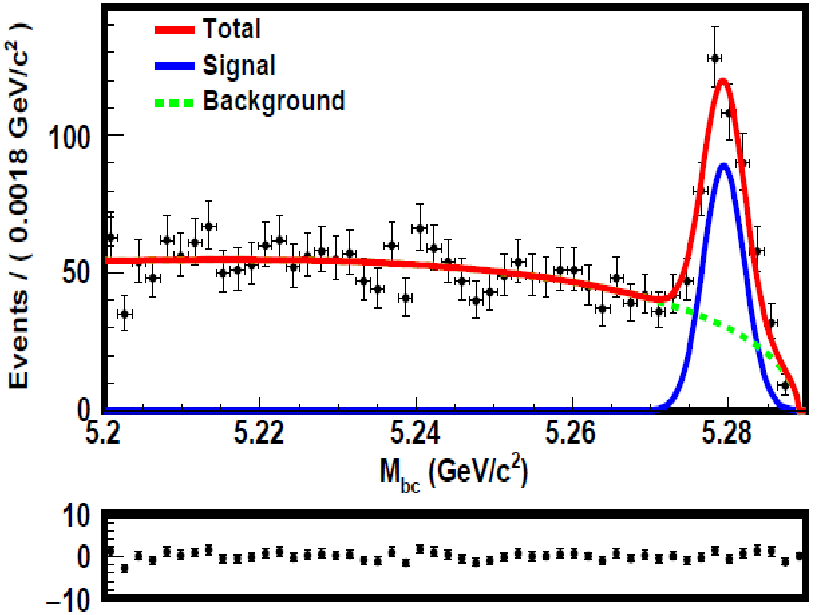
Signal extraction

Preliminary

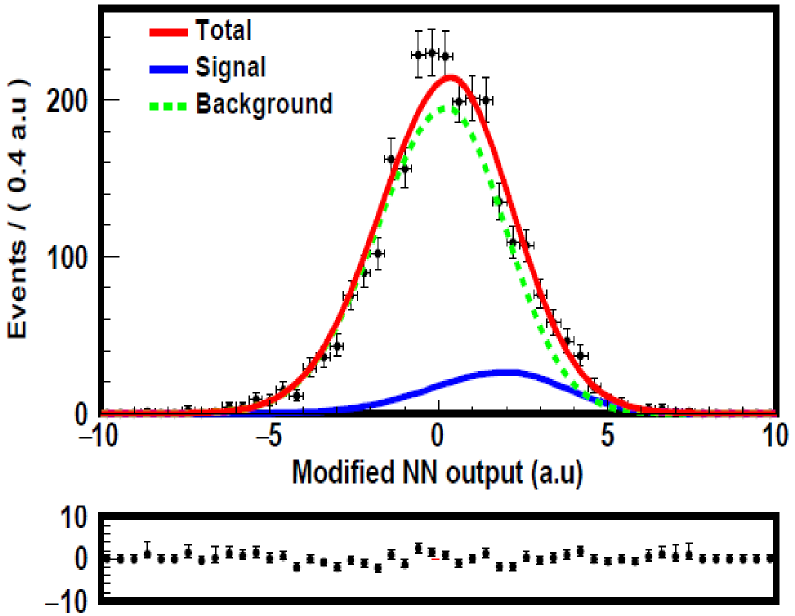
ΔE



M_{bc}



Modified NN



- An unbinned maximum likelihood (ML) fit with 3D PDF (ΔE, M_{bc}, Modified NN).
- Signal is obtained to be 329 ± 20 and the purity in the signal region is 72%.
  - Signal region is defined as $\pm 3\sigma$ based on the fit value for ΔE, M_{bc}.

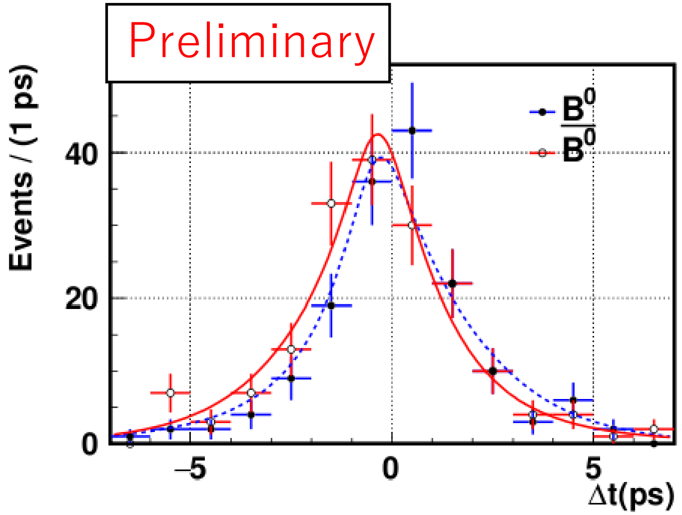
Measurement of CPV parameters

- PDF to extract CPV parameters

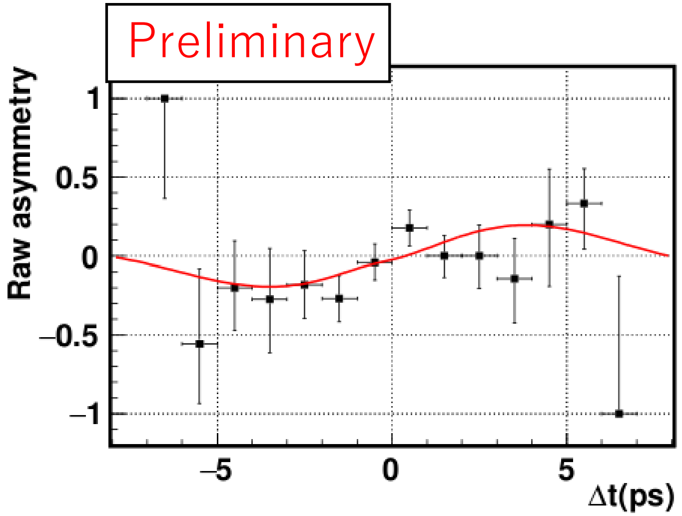
$$\mathcal{P}_j(\Delta t_j, q_j) = (1 - f_{\rm ol}) \times [f_j^{\rm sig}\mathcal{P}_{\rm sig}(\Delta t_j, q_j) + (1 - f_j^{\rm sig})\mathcal{P}_{\rm bkg}(\Delta t_j)] + f_{\rm ol}\mathcal{P}_{\rm ol}(\Delta t_j)$$

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

- Fitting results
  - $\boldsymbol{S = -0.72 \pm 0.23\ (\mathrm{stat}) \pm 0.05\ (\mathrm{syst})}$
  - $A = \quad 0.11 \pm 0.16\ (\mathrm{stat}) \pm 0.05\ (\mathrm{syst})$



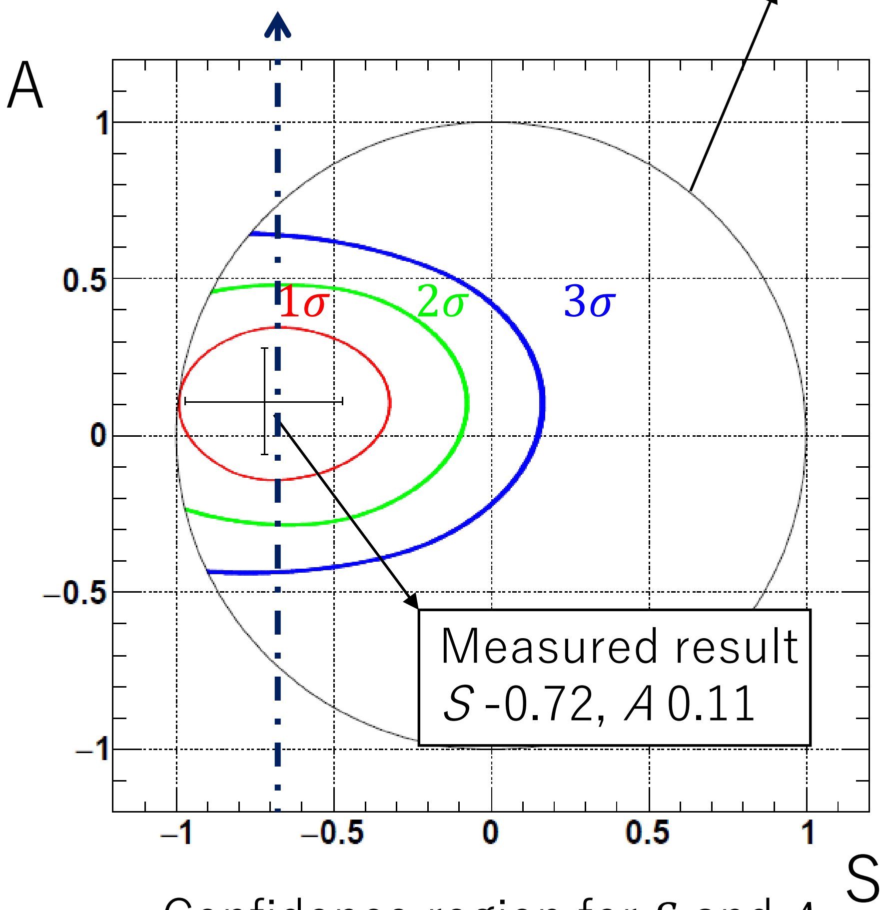
Include background



Significance of CP violation

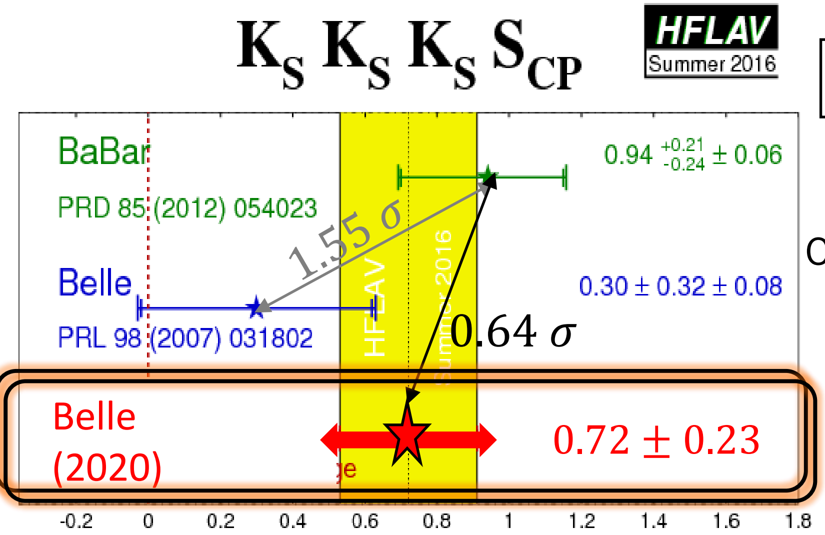
Preliminary

- The significance is calculated using the Feldman-Cousins approach.
- The significance of CP violation: our result is 2.4σ away from $(S,A)=(0,0)$



Confidence region for S and A

Result



Preliminary

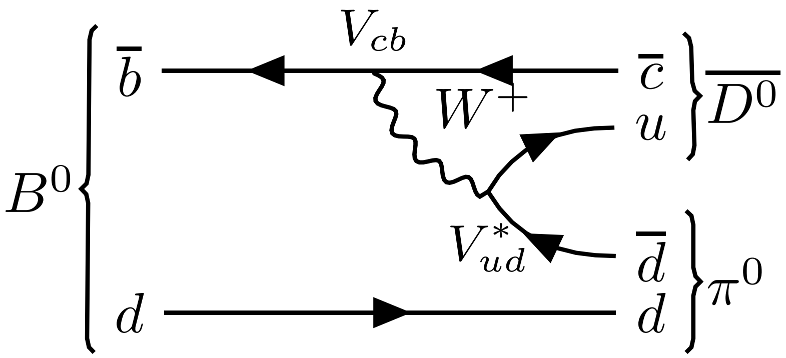
consistent with:

- SM expectation: $S\ (\sin 2\phi_1) = -0.688$
- Previous Belle result within 1σ

$B^0 \to \overline{D^0}\pi^0$ and $B^+ \to \overline{D^0}\pi^+$

Preliminary

- $b \to c\bar{u}d$ decay.



$B^0 \to \overline{D^0}\pi^0$

Colour suppressed

Previous results:

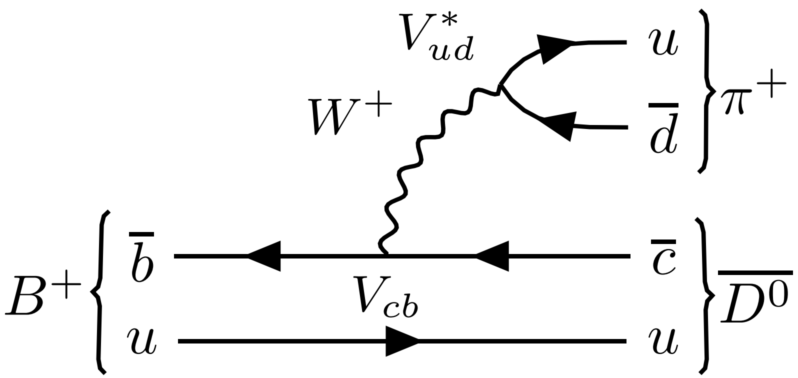
Belle: $\mathfrak{B} = (2.25 \pm 0.14 \pm 0.35) \times 10^{-4}$

PRD 74, 092002 (2006)

Babar: $\mathfrak{B} = (2.69 \pm 0.09 \pm 0.13) \times 10^{-4}$

PRD 84(3), 112007 (2011)

A_{CP} is unmeasured.



$B^+ \to \overline{D^0}\pi^+$

Colour favour, $\mathfrak{B}$ is $\mathcal{O}(10)$ higher.

Previous results:

Belle: $\mathfrak{B} = (4.34 \pm 0.10 \pm 0.23) \times 10^{-3}$

PRD 97(1), 012005 (2018)

Babar: $\mathfrak{B} = (4.90 \pm 0.07 \pm 0.22) \times 10^{-3}$

PRD 75, 031101 (2007)

Belle: $A_{CP} = (-0.8 \pm 0.8)\%$

PRD 73, 051106 (2006)

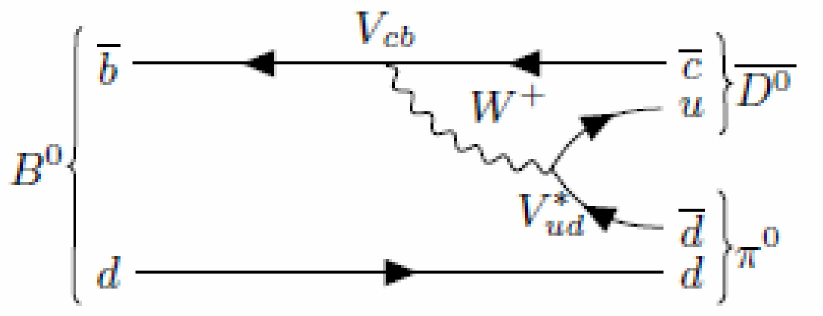
LHCb: $A_{CP} = (-0.6 \pm 0.5 \pm 1.0)\%$

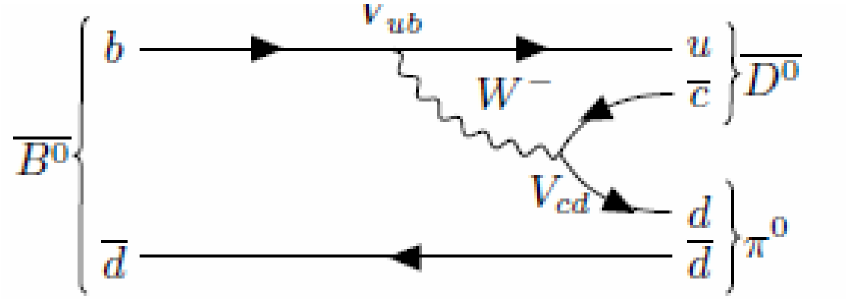
PLB 723, 4453 (2013)

$B \to \overline{D^0}\pi$ Motivations

Preliminary

- Both commonly used control mode in other analysis(ex. $B^0 \to \pi^0\pi^0$, $B \to K\pi^0$), allow for high-precision validations of techniques.
  - Important for Belle II precision frontier.



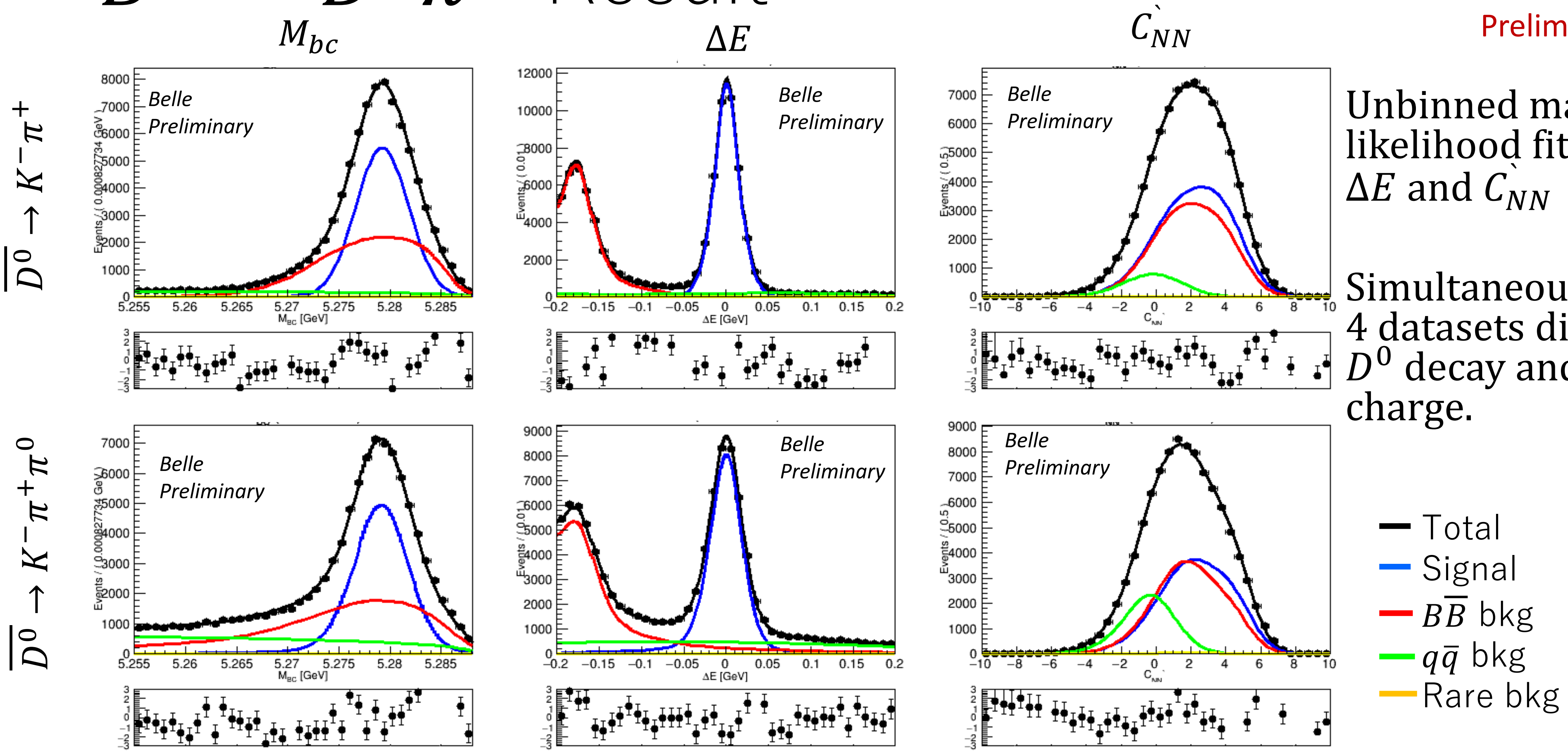


Cabibbo-suppressed decay

- secondary diagram: significantly lower amplitude than main diagram $\Rightarrow$ expect no A_{CP}.
- $\mathrm{B}^0 \to \overline{\mathrm{D}^0}\pi^0$ notably large non-factorisable components.
  - $\mathfrak{B} \gg$ ‘naïve’ factorisation predictions.
  - Constraints for models of final state interactions

$B^+ \to \overline{D^0}\pi^+$ Result

Preliminary



Unbinned maximum likelihood fit in M_{BC}, ΔE and C'_{NN}

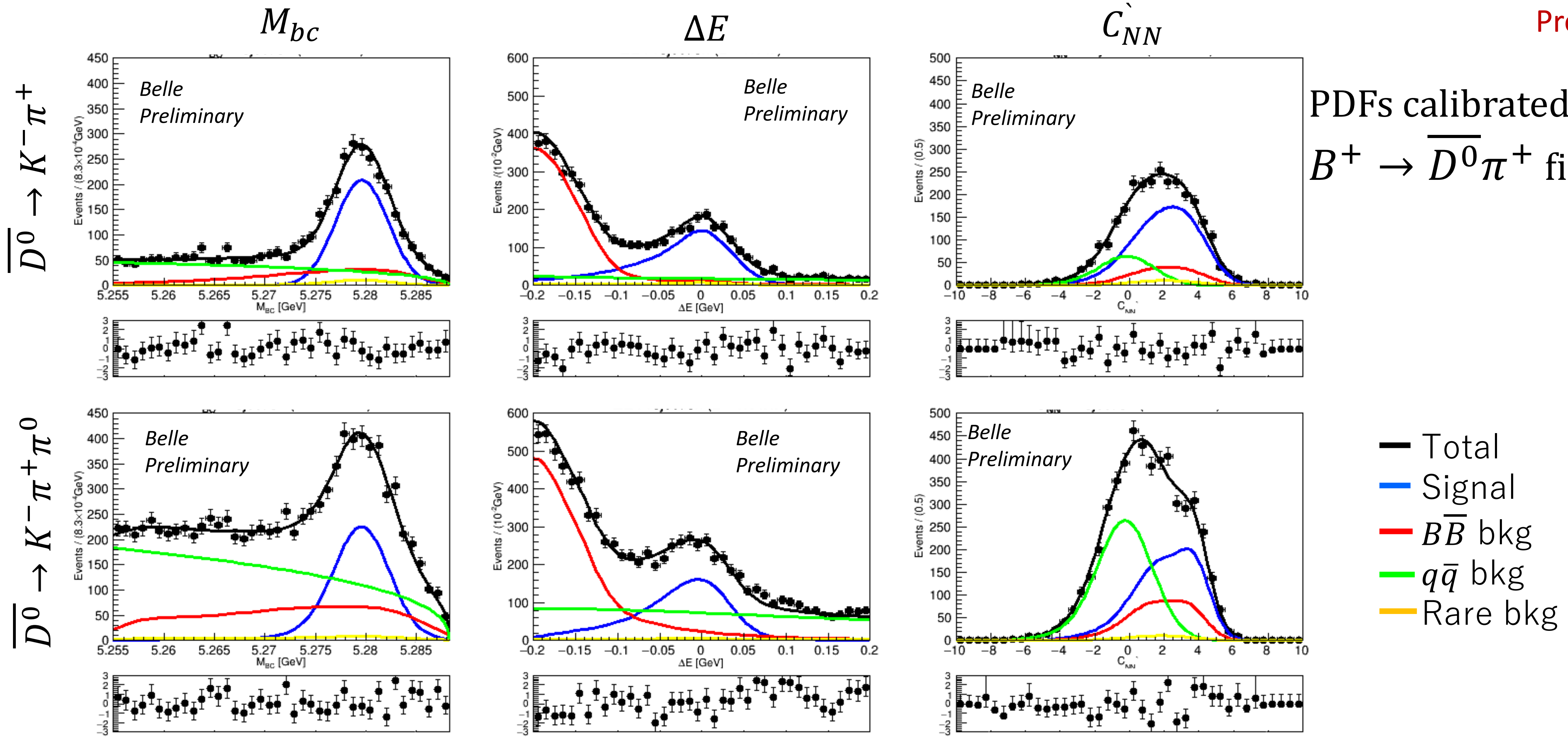
Simultaneous fit over 4 datasets divided by D^0 decay and Kaon charge.

$$\mathfrak{B} = (4.53 \pm 0.02 \pm 0.14) \times 10^{-3}$$
$$A_{CP} = (0.19 \pm 0.36 \pm 0.57)\%$$

~1.7x improvement in precision

$B^0 \to \overline{D^0}\pi^0$ Result

Preliminary



PDFs calibrated with $B^+ \to \overline{D^0}\pi^+$ fit.

$$\mathfrak{B} = (2.69 \pm 0.06 \pm 0.09) \times 10^{-4}$$

Most precise measurement in this channel

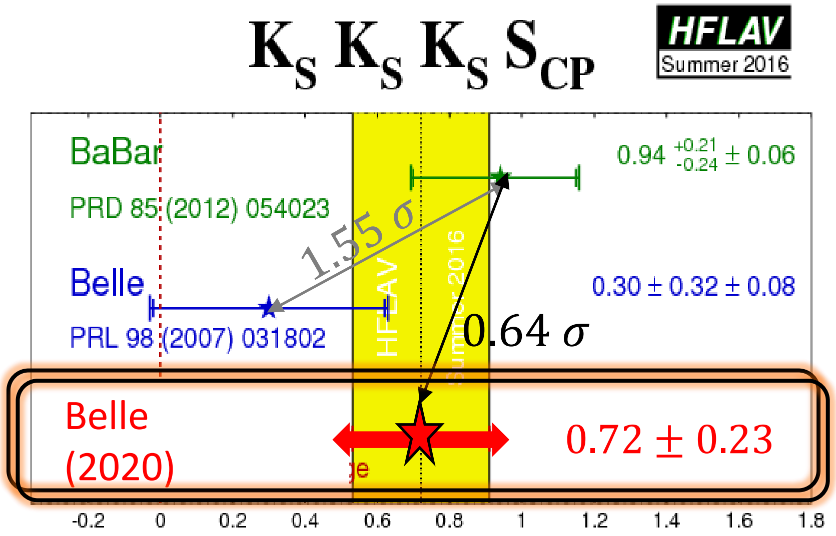
$$A_{CP} = (0.10 \pm 2.05 \pm 1.22)\%$$

First measurement in this channel

Summary

Preliminary

- time-dependent CP violation in $B^0 \to K_S^0 K_S^0 K_S^0$
  - $S = -0.72 \pm 0.23\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst})$
  - $A = \quad 0.11 \pm 0.16\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst})$
  - The significance of CP violation is found to be 2.4σ



- The results are consistent with:
  - SM expectation: $S\,(\sin 2\phi_1) = -0.688$
  - Previous Belle result within 1σ

$B^0 \to \overline{D}{}^0\pi^0$: Preliminary

$$\mathfrak{B} = (2.69 \pm 0.06 \pm 0.09) \times 10^{-4}$$
$$A_{CP} = (0.10 \pm 2.05 \pm 1.22)\%$$

First measurement of A_{CP}
Highest precision $\mathfrak{B}$.

$B^+ \to \overline{D}{}^0\pi^+$: Preliminary

$$\mathfrak{B} = (4.53 \pm 0.02 \pm 0.14) \times 10^{-3}$$
$$A_{CP} = (0.19 \pm 0.36 \pm 0.57)\%$$

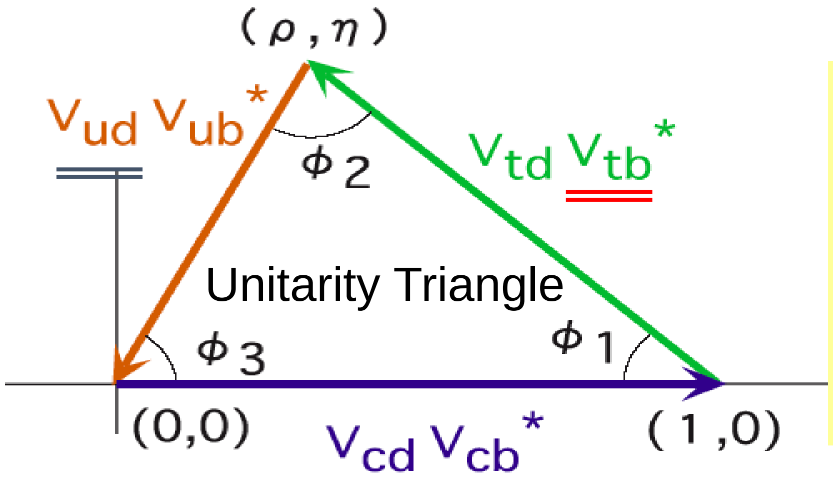
Most precise measurement
by almost 2x.

backup

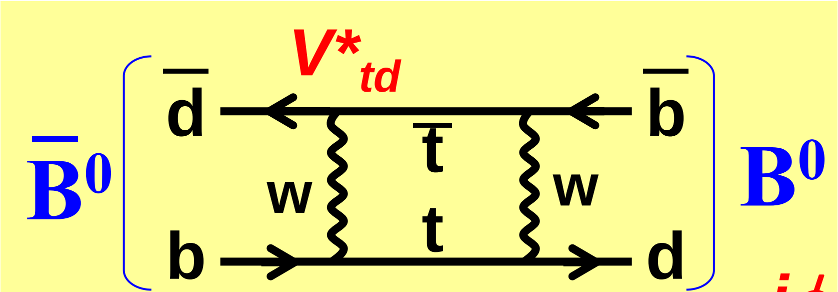
CP Violation in B^0 decays

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

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



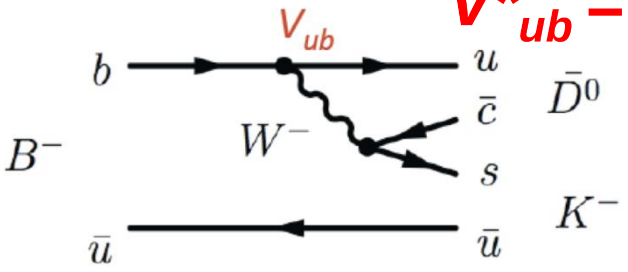
B-$\bar{B}$ mixing



$$V^*_{td} = |V_{td}| e^{i\phi_1}$$

$$B^- \to \bar{D}^0 K^-$$

$$V^*_{ub} = |V_{ub}| e^{i\phi_3}$$



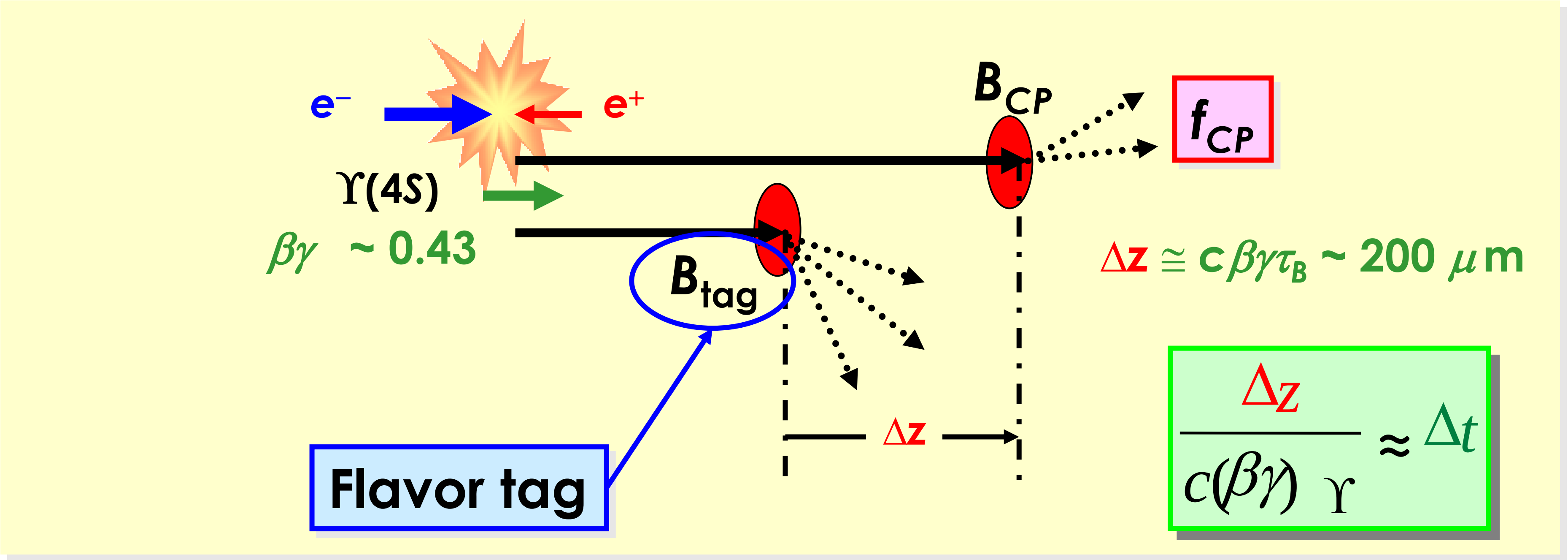
$$\phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

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

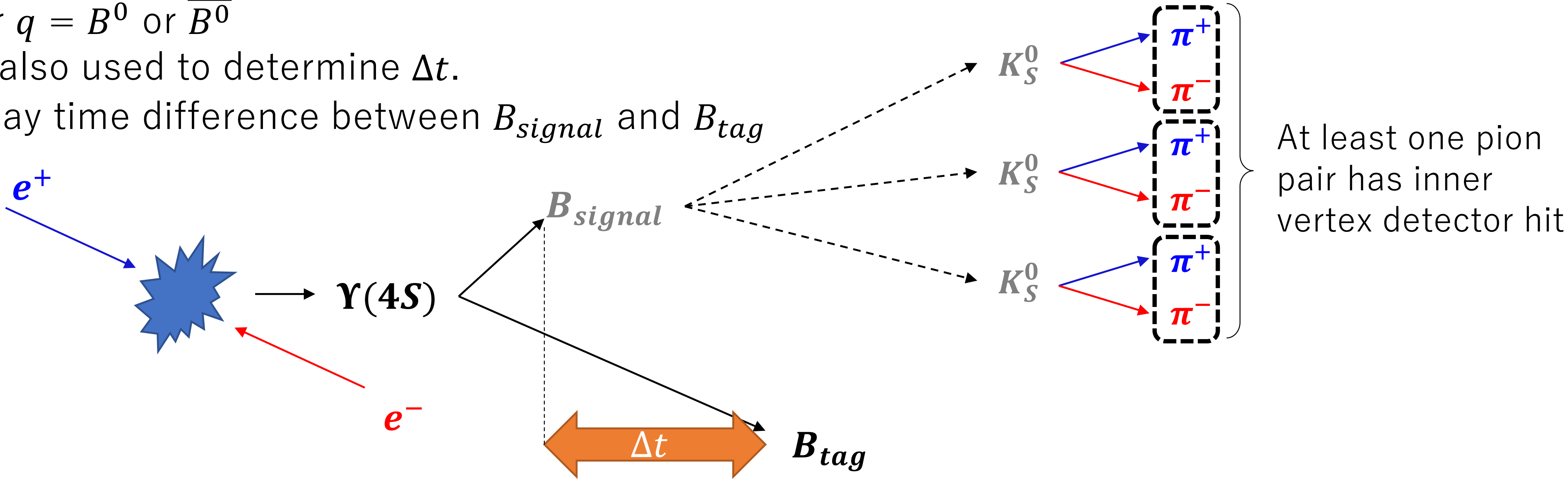
Principle of Measurement in B-factories



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

Vertex reconstruction & flavor tagging

- Flavor tagging for B_{tag} is performed by using inclusive properties of particles not associated with the signal B^0.
  - B_{signal} decay to CP eigen state
  - flavor $q = B^0$ or $\overline{B^0}$
- 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

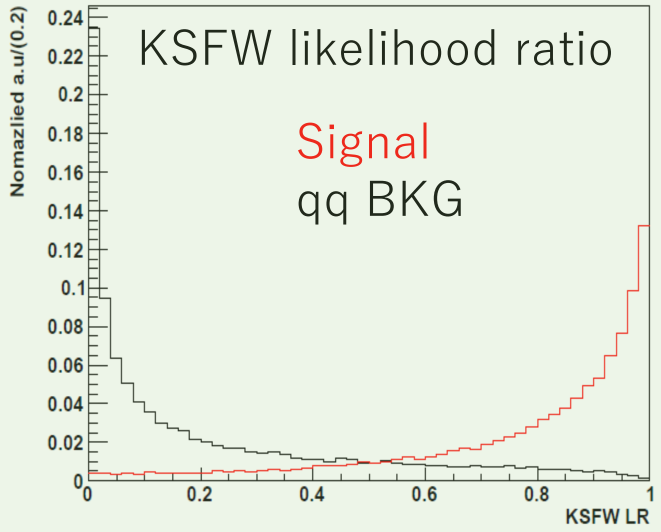
The flavor and Δt are needed for $TCPV$ extraction

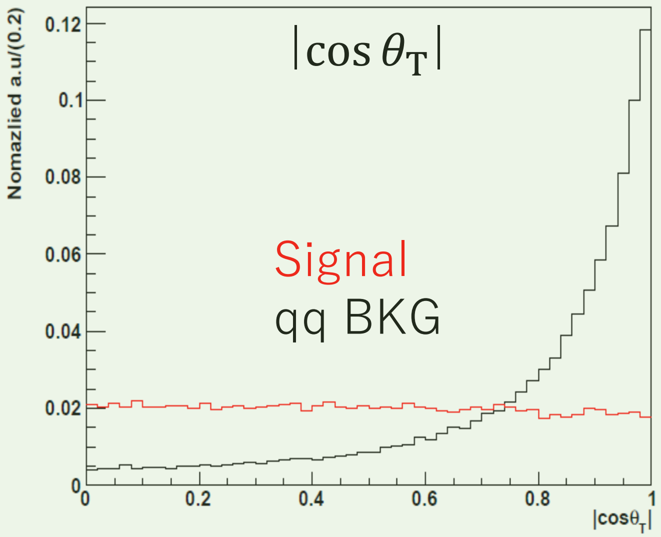
Continuum background

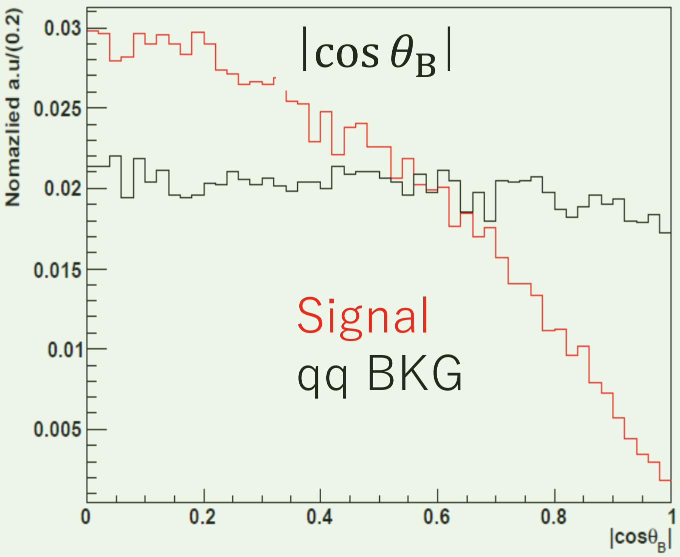
KSFW LR – Kakuno Super Fox-Wolfram moment

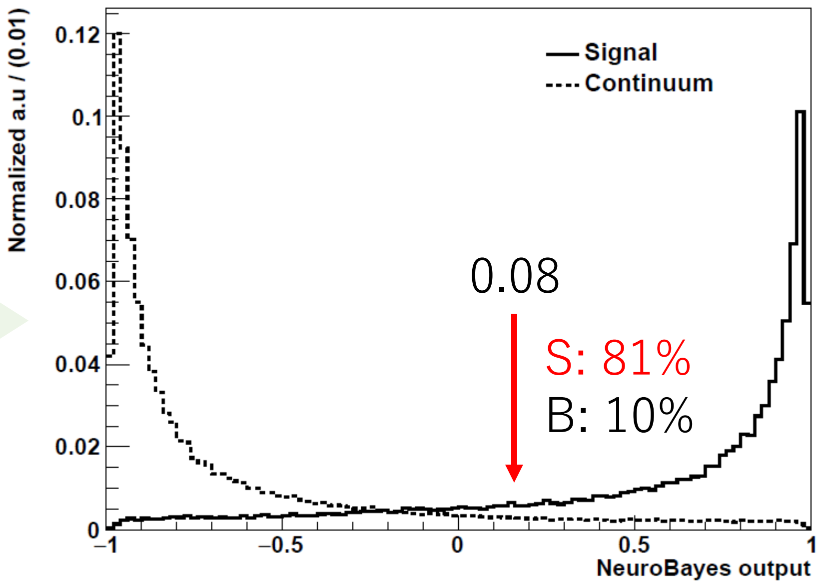
$cos\theta_{\mathrm{B}}$= cosine of the angle between beam pipe and B_{CP}

$cos\theta_{\mathrm{T}}$= cosine of the angle between thrust axis of B_{cp} and B_{tag}





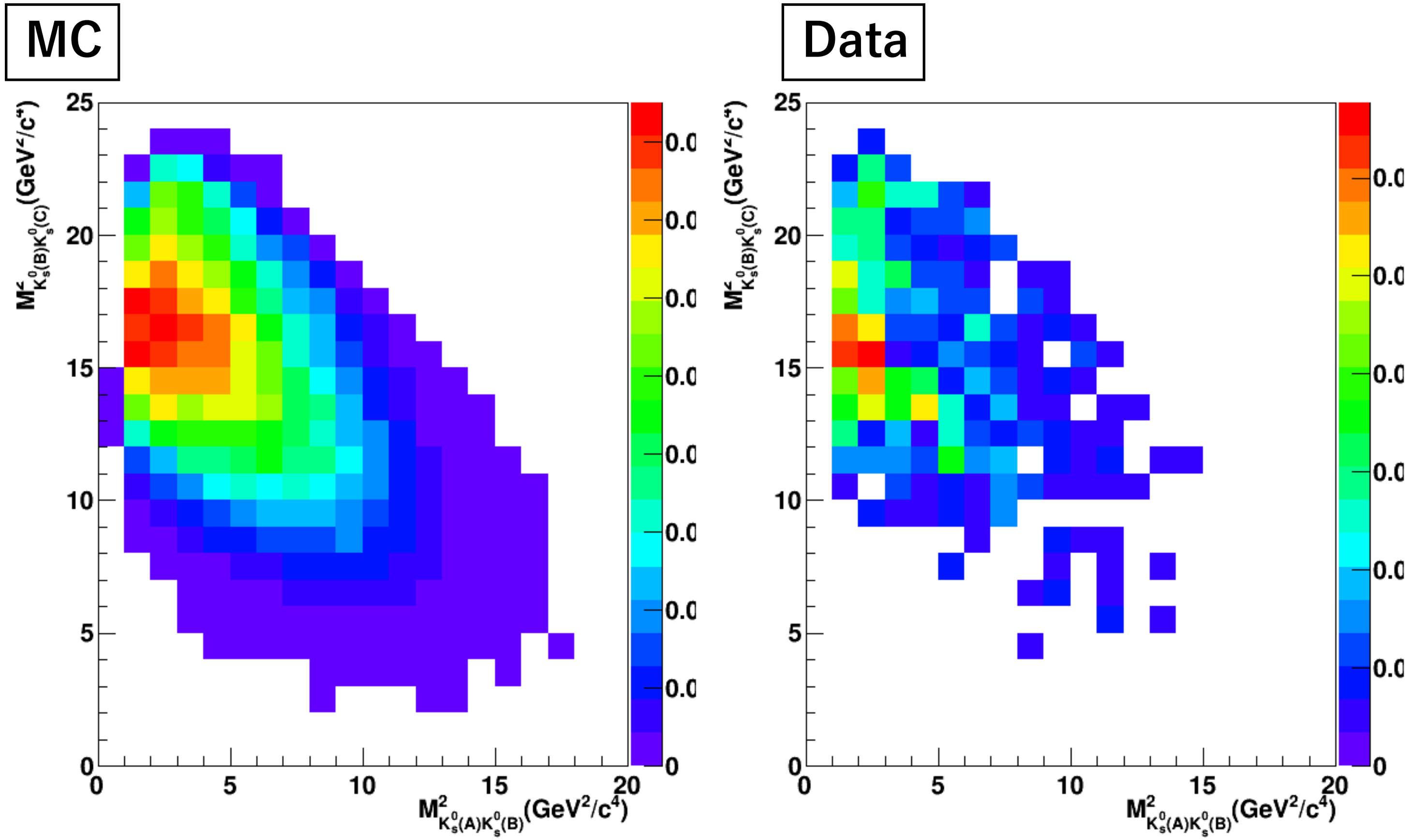




The NB cut is selected with highest figure of merit (FOM)

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

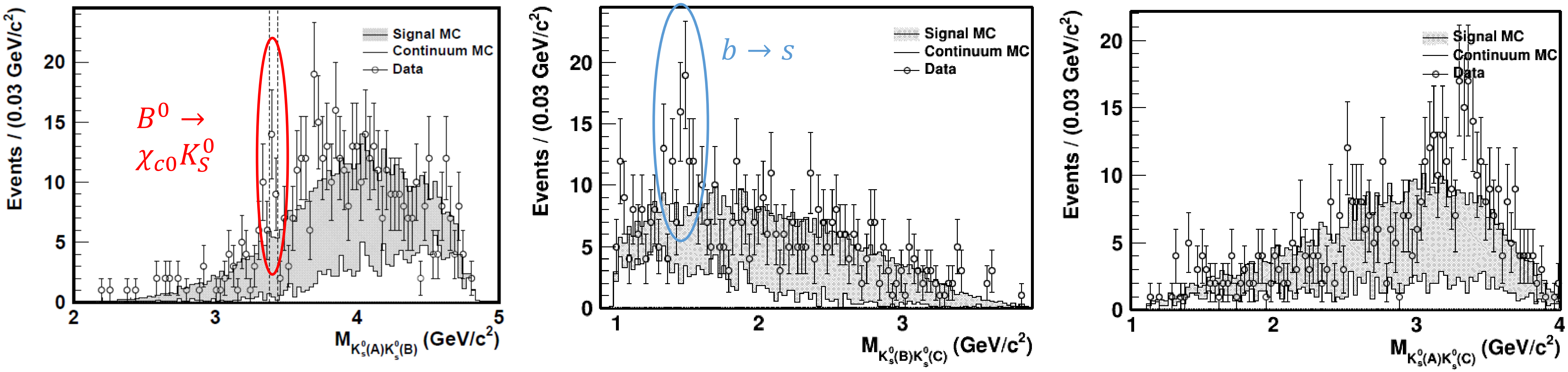
Dalitz plot



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

B-mesons background

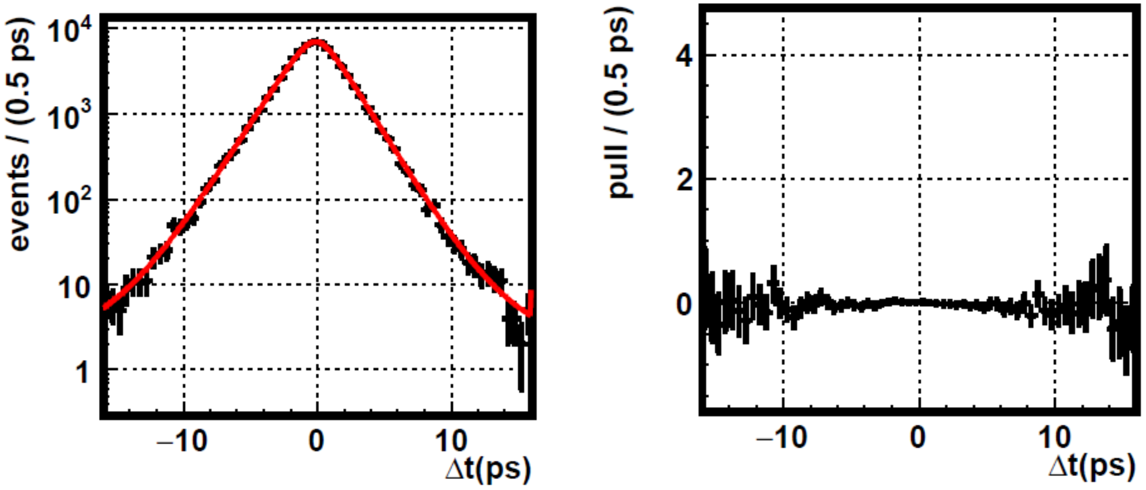
$K^0_S{}_{A,B,C}$: momentum order



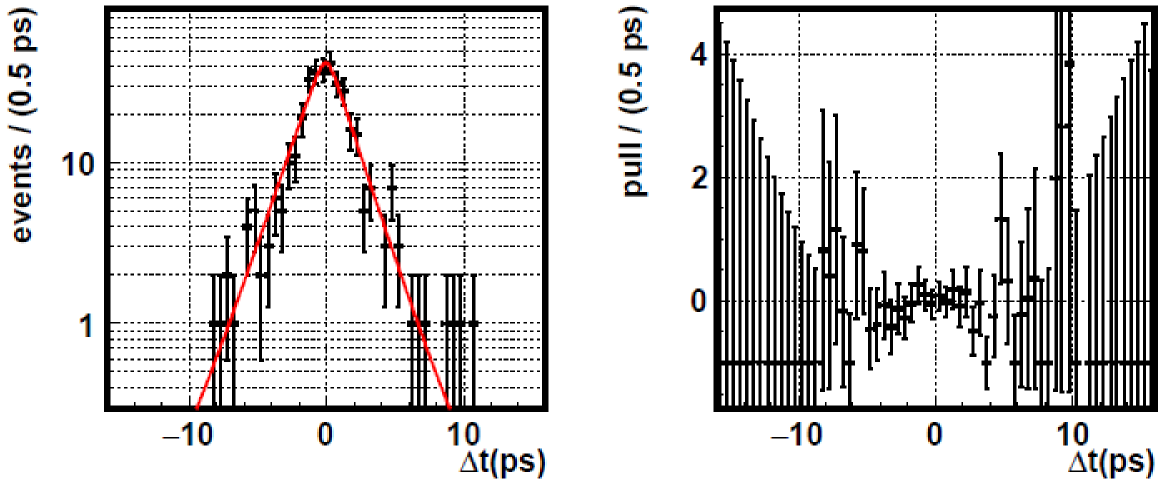
- Using invariant mass $M_{K^0_S K^0_S}$, quasi-two-body decay are considered:
  - $b \to c$ quark transition by the tree diagram → considered as a background
    - Veto: $B^0 \to \chi_{c0}(K^0_S K^0_S)K^0_S$ → $3.388\ GeV/c^2 < M_{K^0_S K^0_S} < 3.444\ GeV/c^2$
  - $b \to s$ quark transition by the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

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

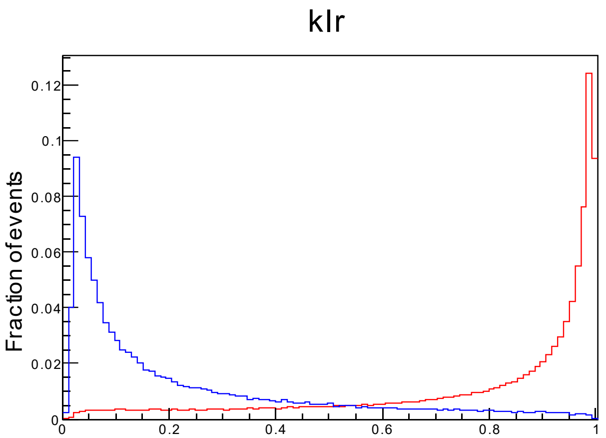
- Previous Belle result
  - Using $532 \times 10^6 B\bar{B}$ $(492\ \mathrm{fb}^{-1})$
  - Include $B \to K_S^0 K_S^0 K_S^0 \to \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$
  - Measured result
    - $S = -0.30 \pm 0.32 \pm 0.08$
    - $\mathrm{A} = 0.31 \pm 0.20 \pm 0.07$

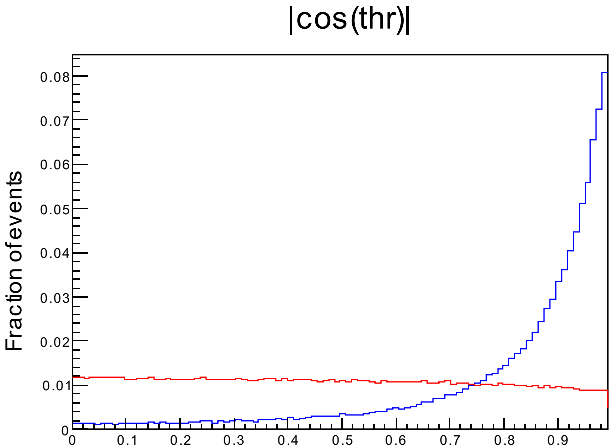
- In this analysis
  - exp 7~47 data set: $504\ \mathrm{fb}^{-1}$
  - Reprocessed data (improved tracking) + improved K_S^0 efficiency (77% → 87%)
  - Measured result
    - $S = -0.73 \pm 0.31$
    - $A = 0.16 \pm 0.20$

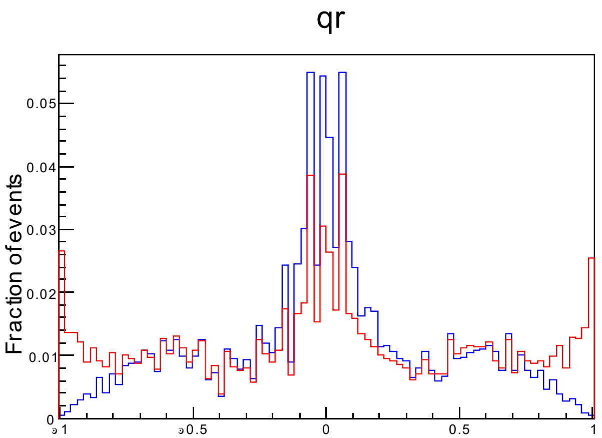
Continuum Suppression Variables

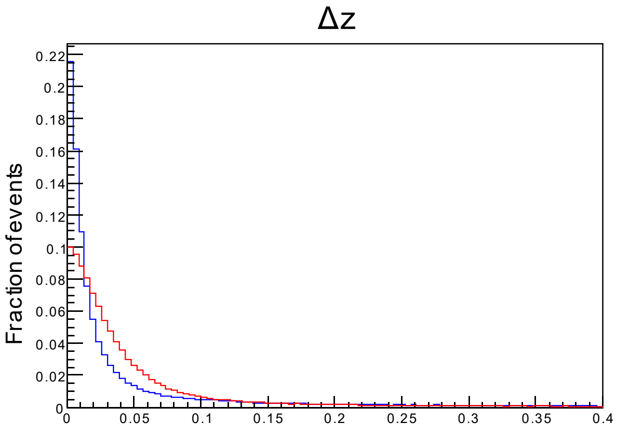
NeuroBayes input
2bd

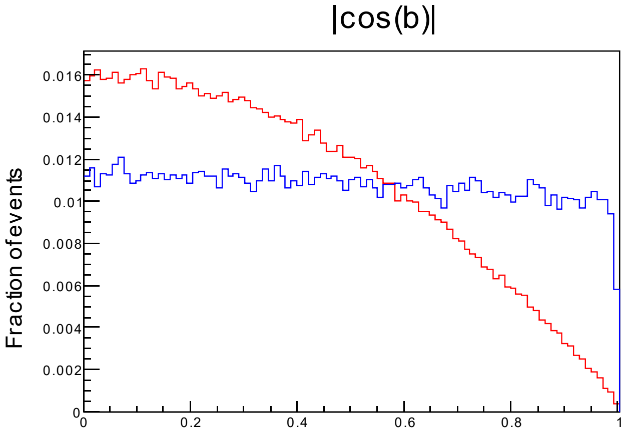
Signal
Continuum











Fitter

- Unbinned maximum likelihood fit in M_{BC}, ΔE and C_{NN} using RooFit for Yield and A_{CP} of each event type (signal, qq, $B\bar{B}$ bkg, Rare).
- 4 datasets divided by D^0 decay and Kaon charge.
- Constrained by $\overline{D^0} \to K^+\pi^-\pi^0$: $\overline{D^0} \to K^+\pi^-$ Yield ratio and A_{CP}.
  - $N_{K^+,2bd} = N \times (1 - A_{CP}) \times 0.5 \times (1 - R_{D^0 mode})$
  - $N_{K^-,2bd} = N \times (1 + A_{CP}) \times 0.5 \times (1 - R_{D^0 mode})$
  - $N_{K^+,3bd} = N \times (1 - A_{CP}) \times 0.5 \times (R_{D^0 mode})$
  - $N_{K^-,3bd} = N \times (1 + A_{CP}) \times 0.5 \times (R_{D^0 mode})$
- Background A_{CP} and signal $R_{D^0 mode}$ are fixed.
- PDF shapes from Monte Carlo.

Systematic Uncertainties ($\mathfrak{B}$)

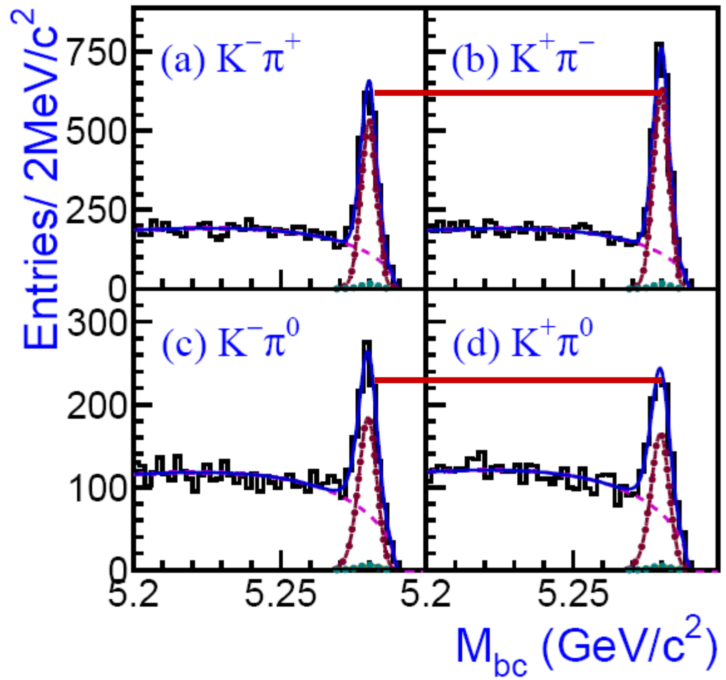
	$\boldsymbol{B^0 \to \overline{D^0}\pi^0}$	$\boldsymbol{B^+ \to \overline{D^0}\pi^+}$
No. $B\overline{B}$	1.37%	1.37%
$\mathfrak{B}(\Upsilon(4S))$	1.23%	1.17%
DCS mode correction	0.01%	0.02%
Fit bias	0.60%	0.20%
Mean efficiency	2.44%	2.54%
$\overline{D^0} \to K^+\pi^-\pi^0 : \overline{D^0} \to K^+\pi^-$ ratio	$+0.31\%$ -0.38%	$+0.19\%$ -0.08%
A_{CP} detector bias (backgrounds)	0.01%	0.05%
Calibration Factors (C'_{NN})	0.34%	0.06%
Modified KEST signal (M_{BC}, ΔE)	0.63%	0.24%
KEST PDFs	0.58%	0.05%
Fixed Charmless $B\overline{B}$ Yields	$+0.26\%$ -0.27%	$< 0.01\%$
Total	$\boldsymbol{\pm 3.28\%}$	$\boldsymbol{\pm 3.13\%}$

Systematic Uncertainties (A_{CP})

	$\boldsymbol{B^0 \to \overline{D^0}\pi^0}$ $(\times \mathbf{10^{-2}})$	$\boldsymbol{B^+ \to \overline{D^0}\pi^+}$ $(\times \mathbf{10^{-2}})$
Fit bias	0.03	0.02
$\overline{D^0}$ decay A_{CP}	0.35	0.35
A_{CP} detector bias (signal)*	0.66	0.42
A_{CP} detector bias (backgrounds)*	$+0.49$ -0.49	$+0.03$ -0.03
$\overline{D^0} \to K^+\pi^-\pi^0 : \overline{D^0} \to K^+\pi^-$ ratio	$+0.03$ -0.02	< 0.01
Calibration Factors (C'_{NN})	0.06	< 0.01
Modified KEST signal (M_{BC}, ΔE)	0.06	< 0.01
KEST PDFs	0.15	< 0.01
Fixed Charmless $B\overline{B}$ Yields	< 0.01	< 0.01
Total	$\pm\mathbf{1.22}$	$\pm\mathbf{0.57}$

$\Delta A_{K\pi}$ Puzzle in 2010

Belle Results: Nature 452, 332 (2008)



$A_{cp}(K^+\pi^-) = \begin{cases} -0.107 \pm 0.016 ^{+0.006}_{-0.004} & \text{BaBar} \\ -0.094 \pm 0.018 \pm 0.008 & \text{Belle} \\ -0.086 \pm 0.023 \pm 0.009 & \text{CDF} \\ -0.04 \pm 0.16 \pm 0.02 & \text{CLEO} \end{cases}$

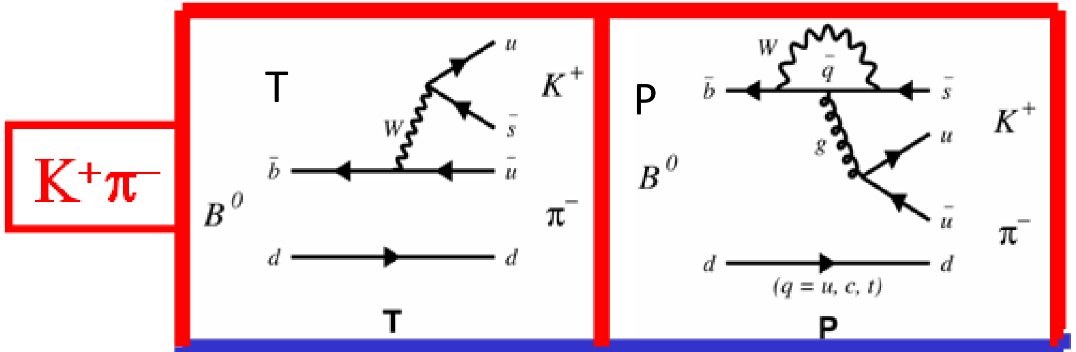
$\Rightarrow -0.098 ^{+0.012}_{-0.011}$ @ 8.1σ AVG

$A_{cp}(K^+\pi^0) = \begin{cases} +0.030 \pm 0.039 \pm 0.010 & \text{BaBar} \\ +0.07 \pm 0.03 \pm 0.01 & \text{Belle} \\ -0.29 \pm 0.23 \pm 0.02 & \text{CLEO} \end{cases}$

$\Rightarrow +0.050 \pm 0.025$ @2.0σ AVG

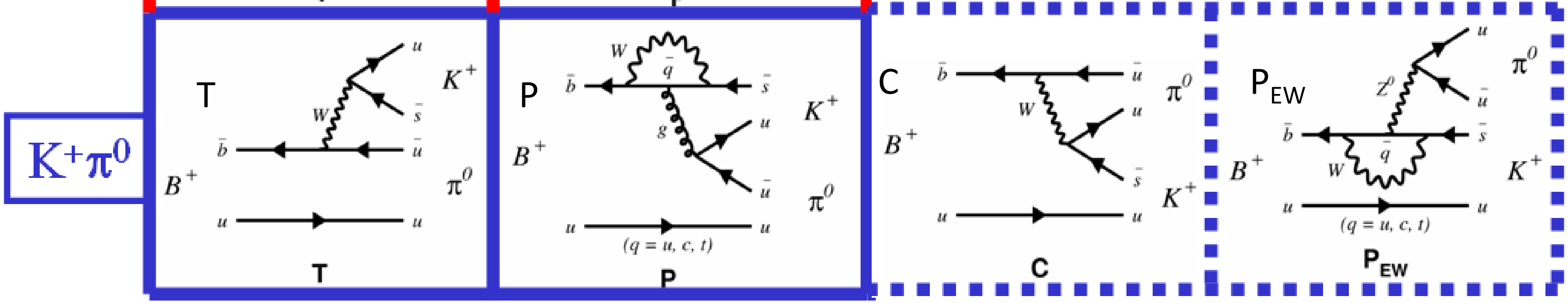
$\Delta A_{K\pi} = A_{cp}(K^+\pi^-) - A_{cp}(K^+\pi^0)$
$= -0.147 \pm 0.028$ @ 5.3σ

Solutions to the $\Delta A_{K\pi}$ Puzzle



Expectation from current theory

T & P are dominant $\Rightarrow \Delta A_{K\pi} \sim 0$



- Enhancement of large C with large strong phase to T
$\Rightarrow$ strong interaction !?

Chiang et. al. 2004
Li, Mishima & Sanda 2005

- Enhancement of large P_{EW}
$\Rightarrow$ New physics

Yoshikawa 2003; Mishima & Yoshikawa 2004;
Buras et. al. 2004, 2006; Baek & London 2007;
Hou et. al. 2007; Feldmann, Jung & Mannel 2008