IPMU Postdoc Colloquium

Measurement of time-dependent CP violation in $B^0 \to K_S^0 K_S^0 K_S^0$ decays at Belle

Kookhyun Kang

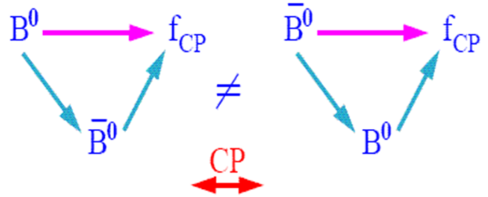
Kavli IPMU

2021.11.05

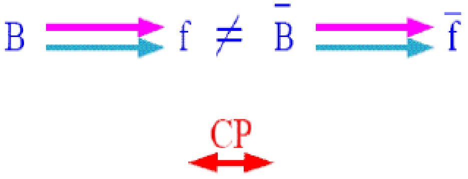
Outline

- Introduction
- Study with Monte Carlo (MC)
  - Signal selection
  - Background suppression
- Results
- Summary

Introduction – motivation (1)

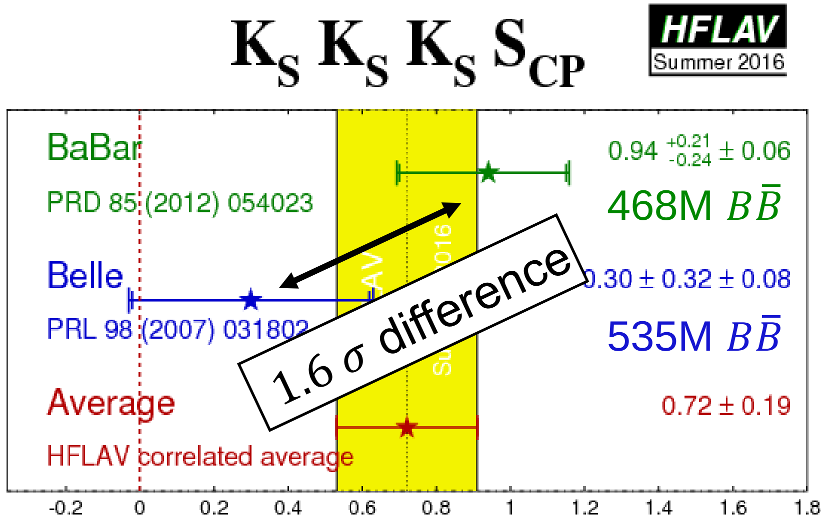


- Mixing-induced CPV



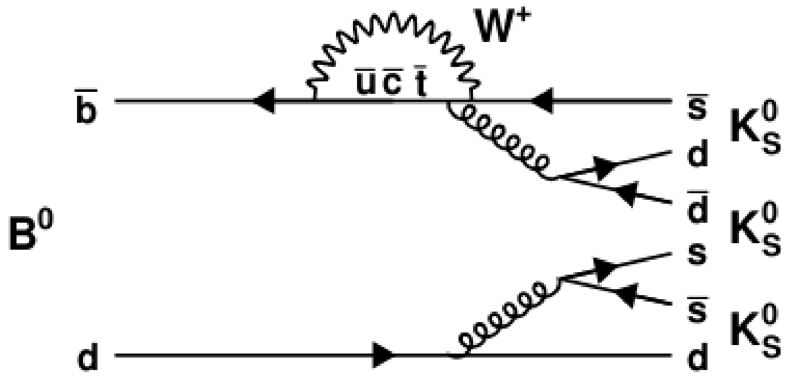
- Direct CPV

- Time-dependent CP violation (TDCPV) parameters are S and A
  - S = mixing induced CP violation
  - A = direct CP violation
- Standard Model expectation in $B^0 \to K_S^0 K_S^0 K_S^0$ decays,
  - $S = \sin(2\phi_1) = 0.688$, $A = 0$, $\phi_1 \equiv \arg(\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*})$
- From the results
  - Deviations from the SM expectation provide sensitivity to new physics.
  - Difference of S at previous Belle and BaBar

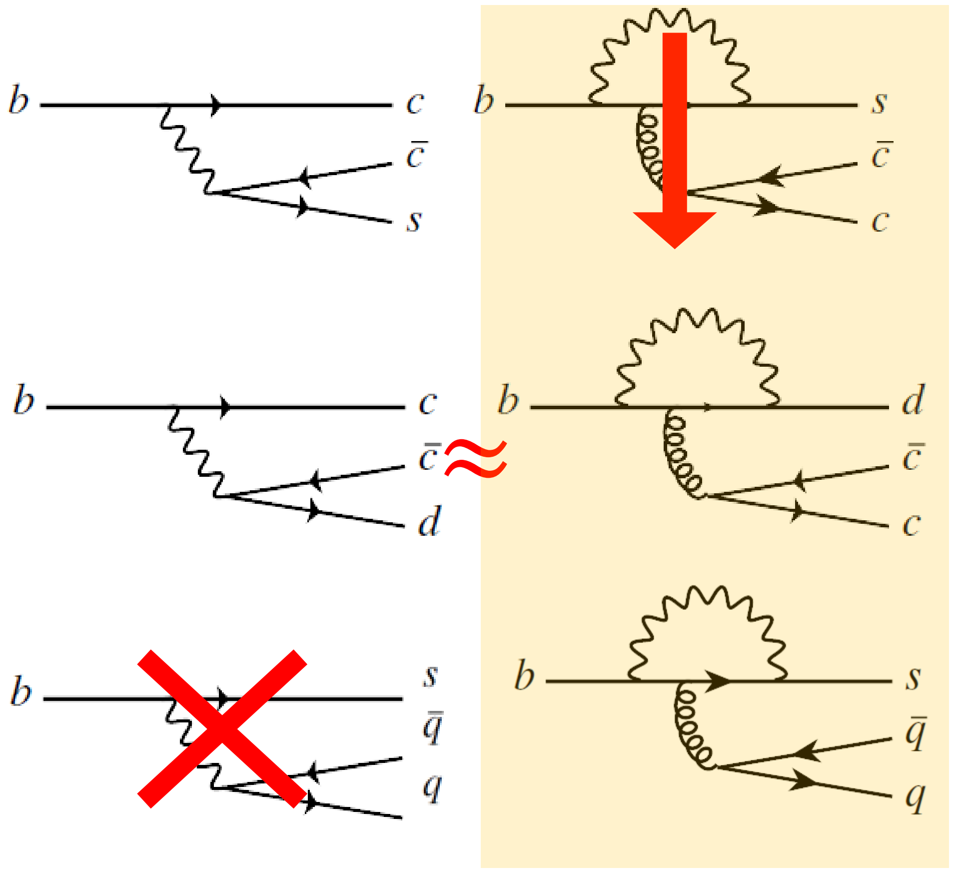


✔ **We measure S and A in the $B^0 \to K_S^0 K_S^0 K_S^0$ decays with the final Belle data set of $772 \times 10^6 B\bar{B}$**

Introduction – motivation (2)



- Pure $b \to s$ penguin transition by loop diagram



$\sin 2\phi_1$

$b \to c\bar{c}s$
ex: $B^0 \to J/\psi K_S^0$

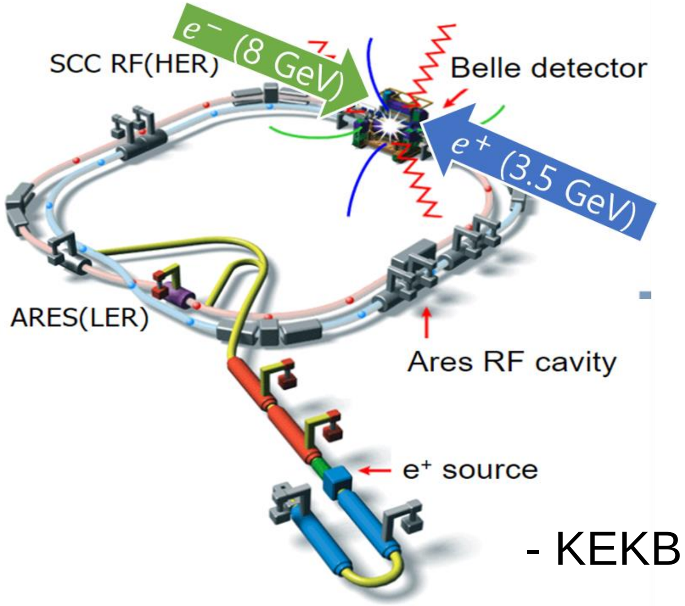
$b \to c\bar{c}d$
ex: $B^0 \to J/\psi \pi^0$

$\sin 2\phi_1^{eff}$

$b \to s\bar{q}q$
ex: $K_S^0 K_S^0 K_S^0$

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

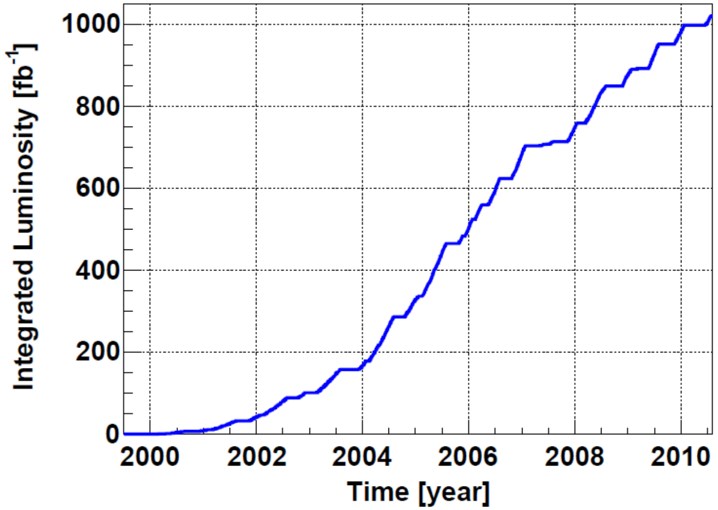
Introduction - Belle experiment



- KEKB collider

- KEKB is B-meson factory in Tsukuba at Japan.
  - Asymmetric e^+e^- collider
  - LER(e^+) = 3.5 GeV
  - HER(e^-) = 8 GeV
  - Center of Mass energy = 10.58 GeV

- $\mathrm{e^+e^-} \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$



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}

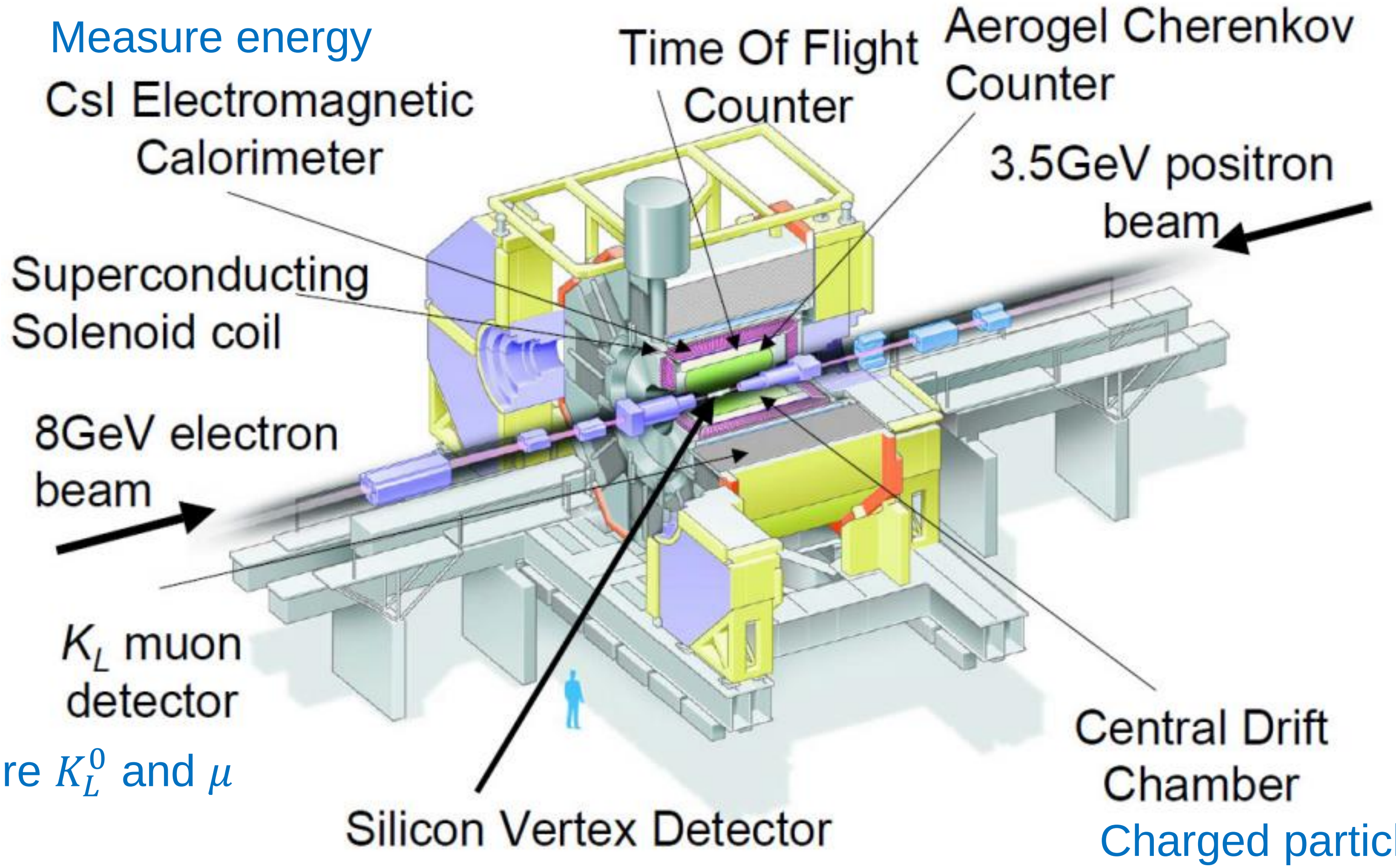
✔ **Verification of the Kobayashi-Maskawa theory of CP-violation in B-meson decay**

Introduction - Belle detector

Particle Identification (PID)

Measure energy

Improve tracking



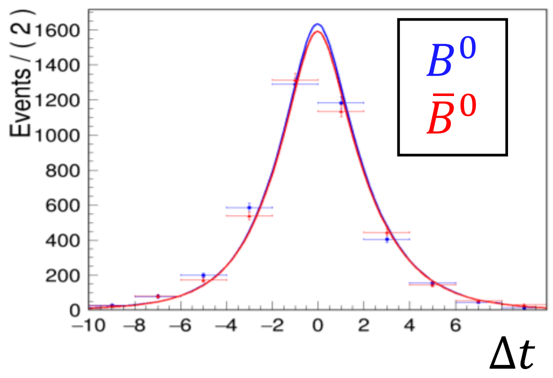
Measure K_L^0 and μ

Charged particle tracking

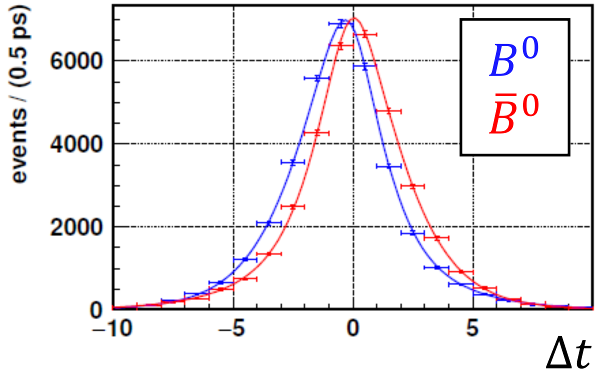
Charged particle tracking & vertexing

Introduction – time-dependent CP violation

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



- non TDCPV



- TDCPV

- $\Upsilon(4S) \to B^0\bar{B}^0$ in to CP eigenstate, the decay rate is given by

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

$$P = \frac{e^{-\frac{|\Delta t|}{\tau_{B^0}}}}{4\tau_{B^0}} \times (1 + q[S sin(\Delta m_d \Delta t) + A\cos(\Delta m_d \Delta t))$$

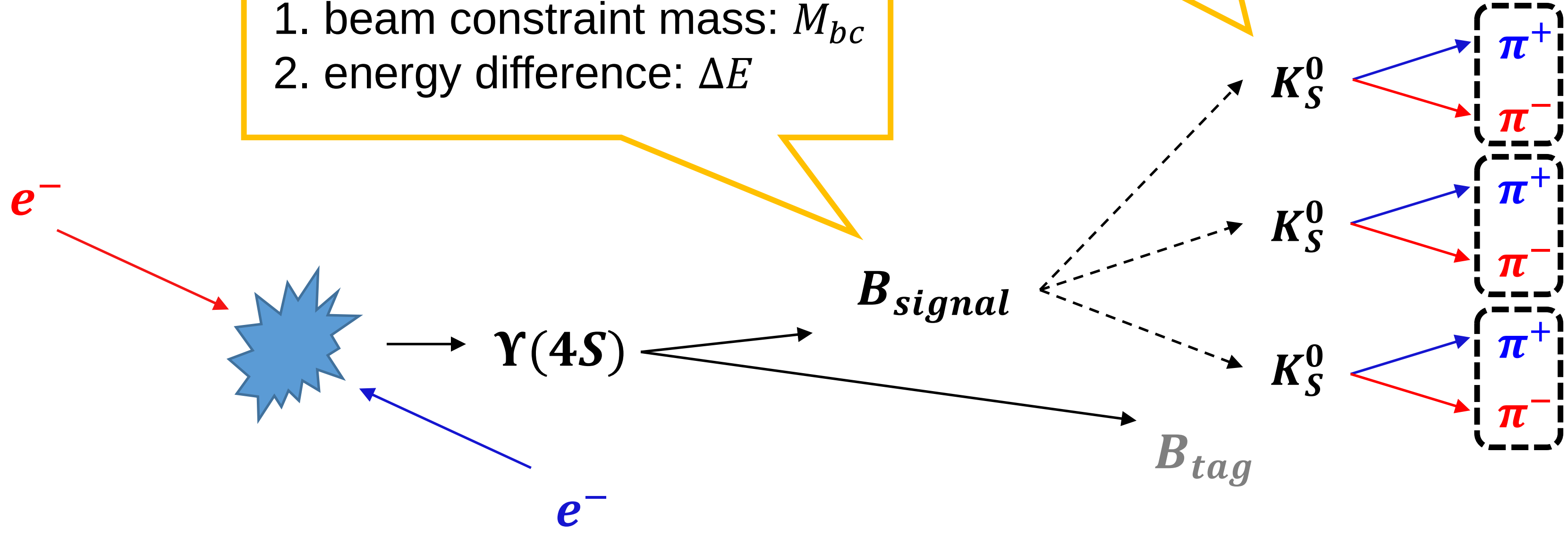
Δm_d = mass difference between
q = flavor information of tag side
Δt = distance between B-meson pairs

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

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

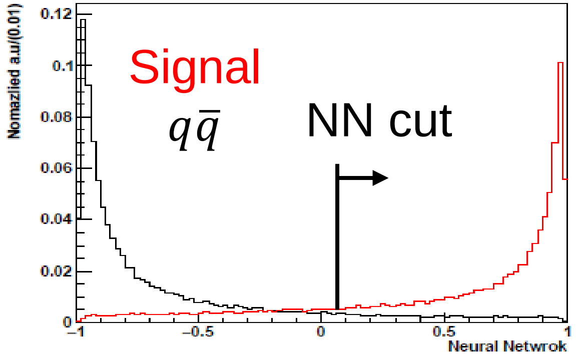


- $\Delta E = E_B - E_{beam}$
  - E_B= energy of B in CM frame
  - E_{beam}= half of beam energy
- $M_{bc}=\sqrt{E_{beam}^2 - p_B^2}$
  - p_B = momentum of B in CM frame

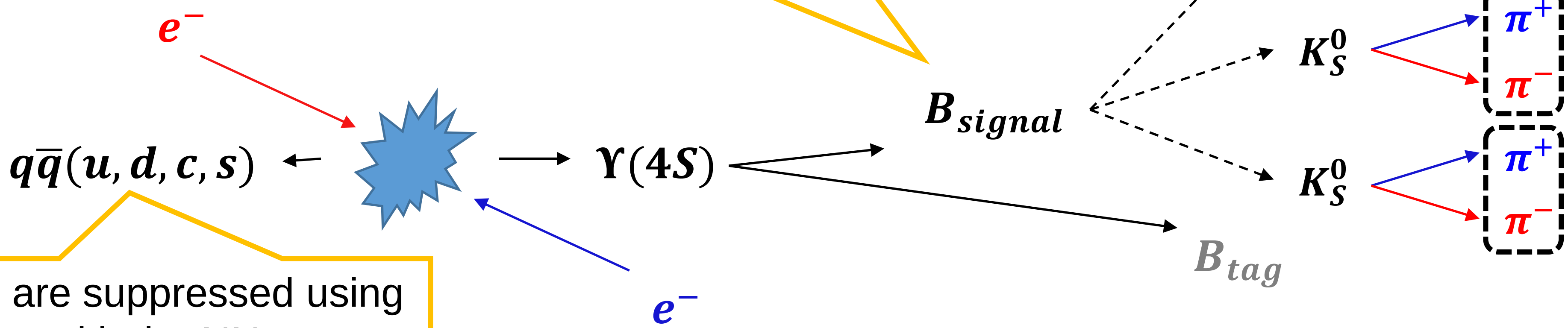
Signal reconstruction

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



NN output



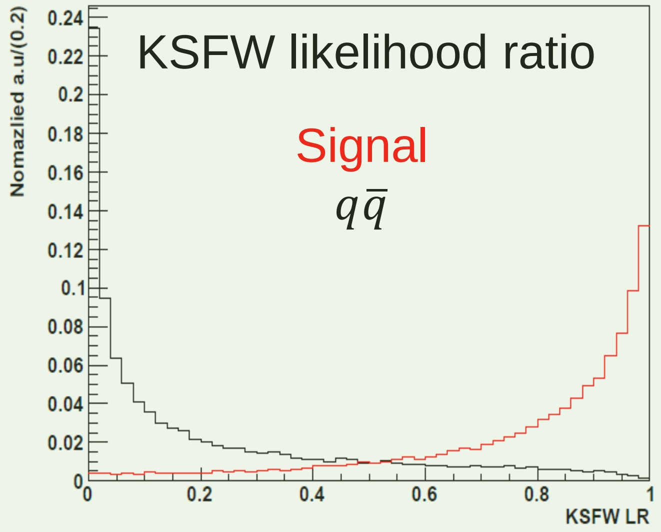
Continuum backgrounds are suppressed using topology information along with the NN

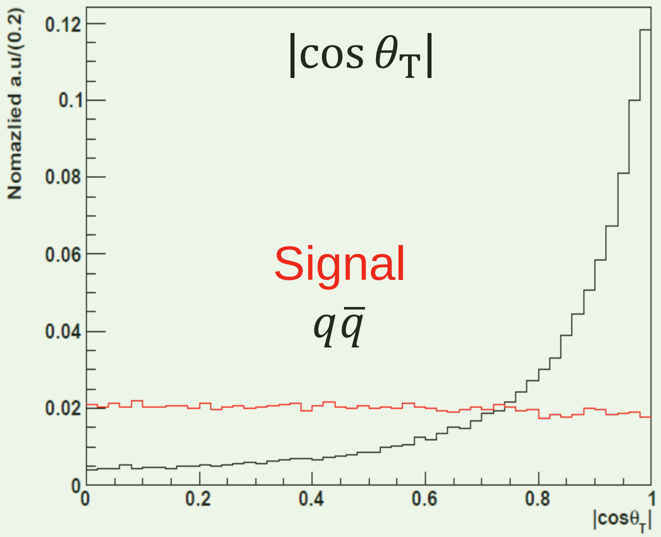
B mesons are produced all most at rest in the $\Upsilon(4S)$ frame
→ In contrast for $q\bar{q}$ events, it has a large initial momentum

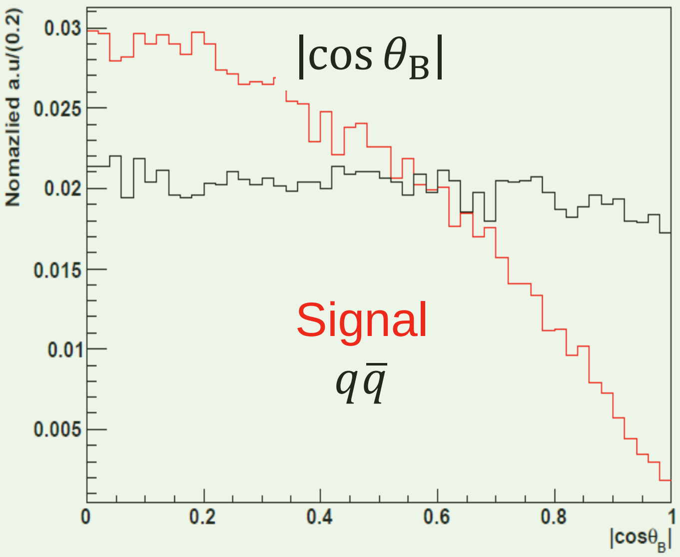
- $\Delta E = E_B - E_{beam}$
  - E_B= energy of B in CM frame
  - E_{beam}= half of beam energy
- $M_{bc}=\sqrt{E_{beam}^2 - p_B^2}$
  - p_B = momentum of B in CM frame

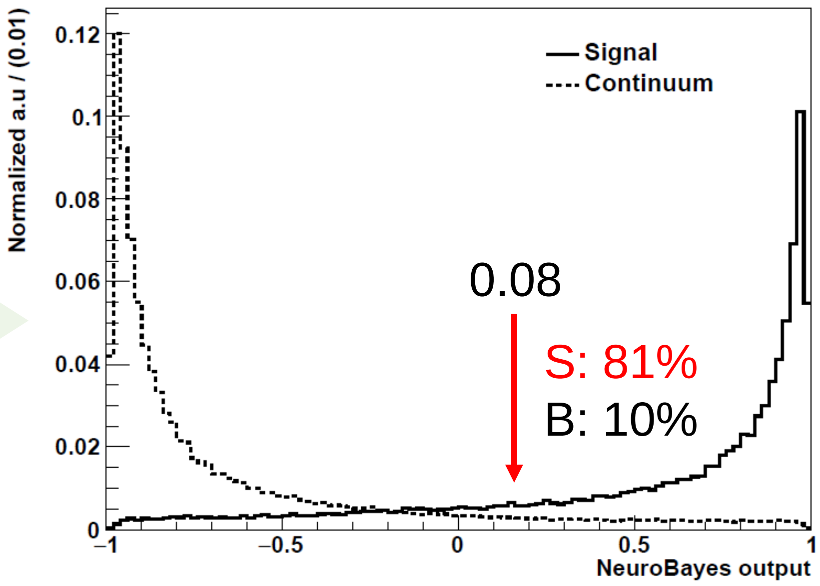
Continuum background

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)

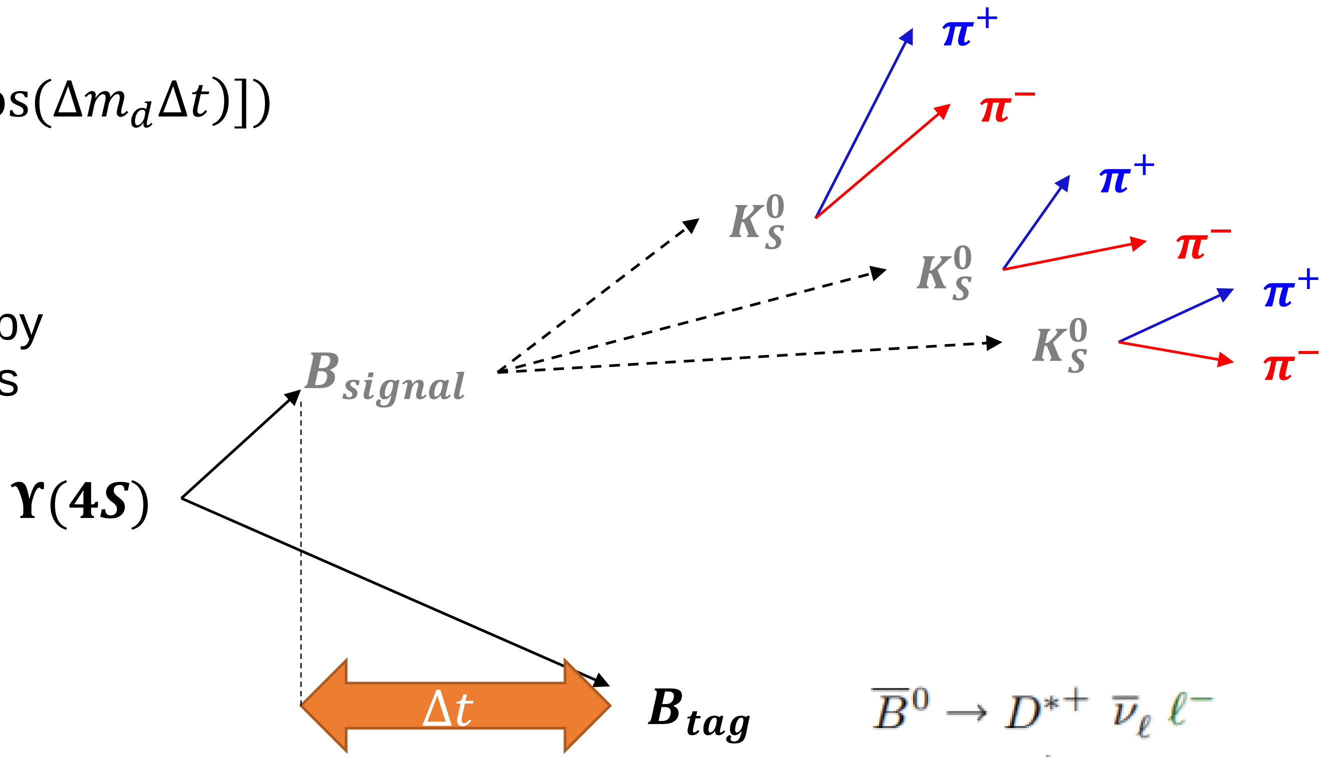
$$\mathrm{FOM} = \frac{N_{sig}}{\sqrt{N_{sig}+N_{bkg}}}$$

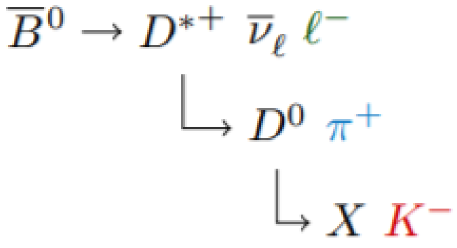
Vertex reconstruction & flavor tagging

$$P = \frac{e^{-\frac{|\Delta t|}{\tau_{B^0}}}}{4\tau_{B^0}} \times (1 + q[S sin(\Delta m_d \Delta t) + A\cos(\Delta m_d \Delta t)])$$

- To identify B meson flavor,
  - flavor tagging for B_{tag} is performed by using inclusive properties of particles not associated with the signal B^0
  - B_{signal} is CP eigenstate

- Flavor-specific decay modes
  - r = tagging quality value (0-1)
  - r = 0 for no tagging
  - r = 1 for perfectly tagging

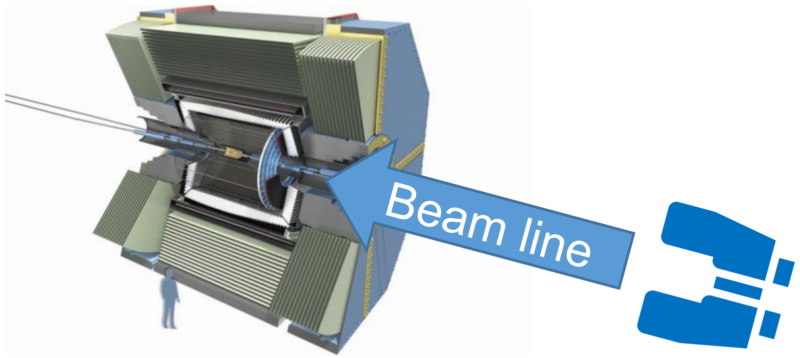




$\Delta t = \Delta z/\beta\gamma c$, $\Delta z \approx 200\ \mu m$

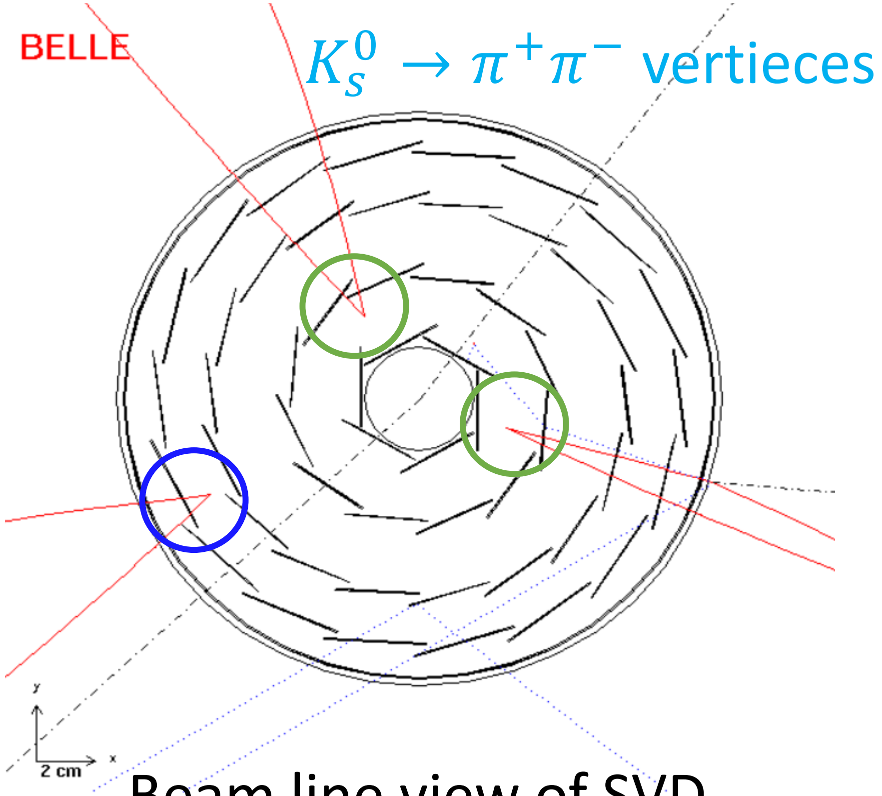
$\beta\gamma$= boost factor 0.425

Vertex reconstruction



- In $B^0 \to K_S^0 K_S^0 K_S^0$, there is no primary charged track
  - to find vertex position we make Ks trajectory using pion hit

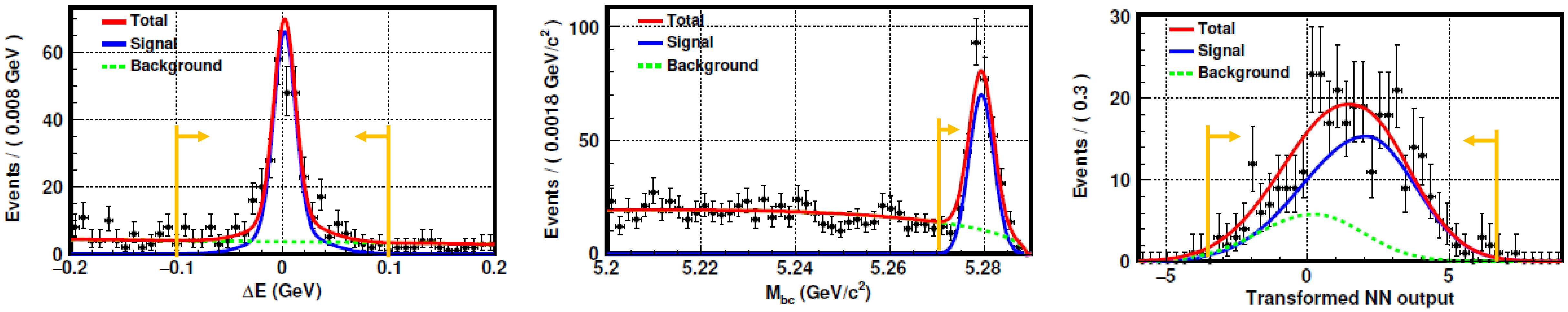
- Resolution function of Δt
  - Detector resolution
  - Non-primary track effect for B_{tag}
  - Kinematical approximation due to the difference in the p_{lab} of $B^0\bar{B}^0$



Beam line view of SVD

Results - signal extraction

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	$\Delta\mathrm{E}$	M_{bc}	Transformed NN
Signal	Double Gaussian	Gaussian	Asymmetry Gaussian
Background	1st Polynomial	ARGUS	Asymmetry Gaussian

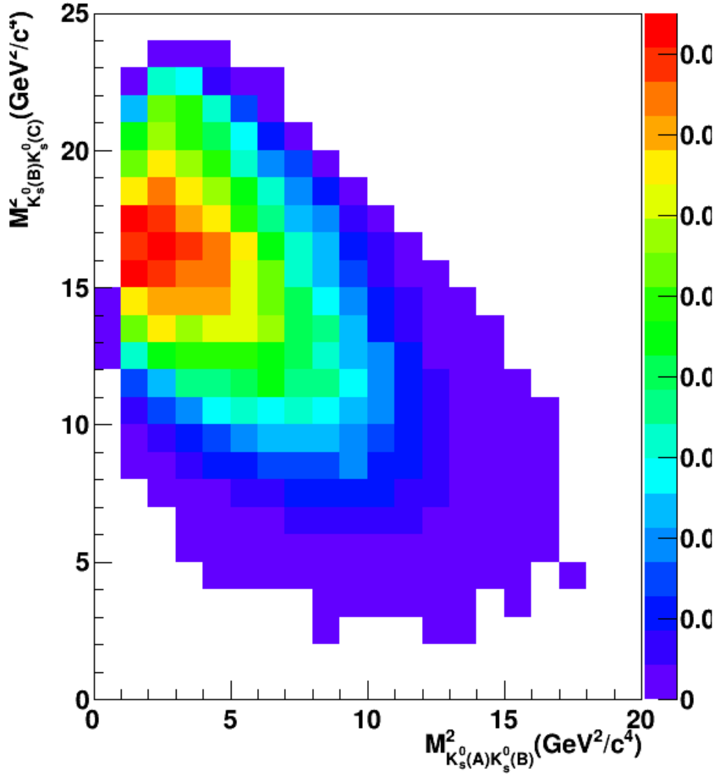
List of resonance modes

Several resonance mode can be included to signal event because we require three K_S^0 from B^0

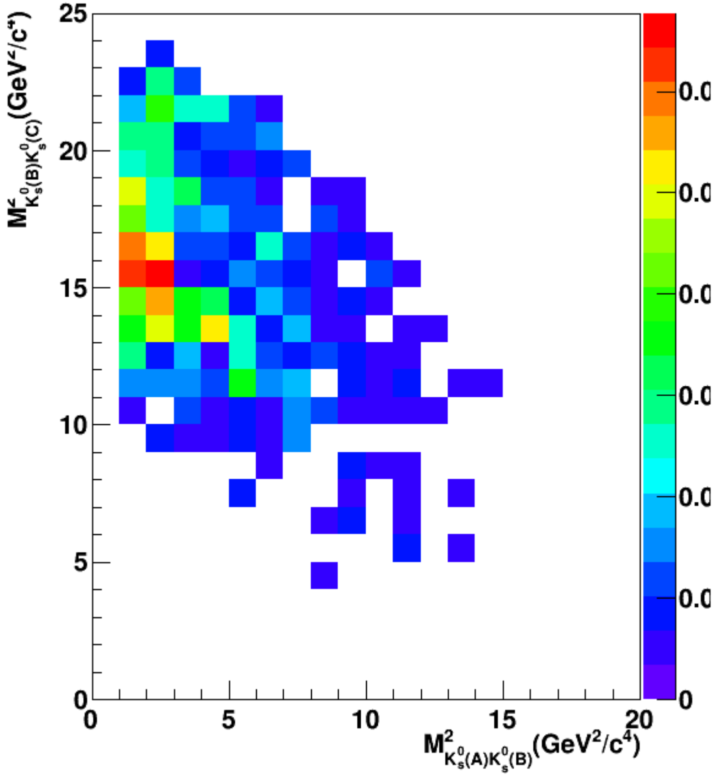
	Decay mode	$B(B^0 \to XK_S^0)$	$B(X \to K_S^0 K_S^0)$	Expected events
Background $b \to c$ CP odd	$B^0 \to D^0 K_S^0$	$(2.6 \pm 0.35) \times 10^{-5}$	$(1.7 \pm 0.12) \times 10^{-4}$	0.3±0.0
	$B^0 \to \eta_c K_S^0$	$(3.45 \pm 0.6) \times 10^{-4}$	$< 3.1 \times 10^{-4}$ 90%	<7.6±1.2
	$B^0 \to J/\psi K_S^0$	$(4.35 \pm 0.16) \times 10^{-4}$	$< 1.4 \times 10^{-8}$	<0.0±0.0
	$B^0 \to \psi(2S) K_S^0$	$(2.9 \pm 0.25) \times 10^{-4}$	$< 4.6 \times 10^{-6}$	<0.1±0.0
	$B^0 \to \chi_{c0} K_S^0$	$(0.73 \pm 0.13) \times 10^{-4}$	$(3.16 \pm 0.17) \times 10^{-3}$	16.3±3.1
	$B^0 \to \chi_{c1} K_S^0$	$(1.96 \pm 0.13) \times 10^{-4}$	$< 6 \times 10^{-5}$ CL=90%	<0.8±0.1
	$B^0 \to \chi_{c2} K_S^0$	$(0.75) \times 10^{-5} CL = 90\%$	$(2.6 \pm 0.2) \times 10^{-4}$	0.3±0.0
Signal $b \to s$	$B^0 \to f_2(1270) K_S^0$	$(1.35^{+0.65}_{-0.6}) \times 10^{-6}$	$(1.15^{+0.12}_{-0.1}) \times 10^{-2}$	$1.1^{+0.5}_{-0.5}$
	$B^0 \to f_0(1500) K_S^0$	$(0.65^{+0.35}_{-0.25}) \times 10^{-5}$	$(2.15 \pm 0.25) \times 10^{-2}$	$9.9^{+5.5}_{-4.0}$
	$B^0 \to f_2'(1525) K_S^0$	$(1.5^{+2.5}_{-2.0}) \times 10^{-7}$	$(22.17 \pm 0.55) \times 10^{-2}$	$2.4^{+3.9}_{-3.1}$
	$B^0 \to f_0(980)(K_S^0 K_S^0) K_S^0$	$(2.7 \pm 1.8) \times 10^{-6}$		191.3±127.6
	$B^0 \to f_0(1710)(K_S^0 K_S^0) K_S^0$	$(5.0^{+5.0}_{-2.6}) \times 10^{-7}$		$35.4^{+35.4}_{-18.4}$
	$B^0 \to f_2(2010)(K_S^0 K_S^0) K_S^0$	$(5 \pm 6) \times 10^{-7}$		35.4±42.5

Results - Dalitz plot

MC



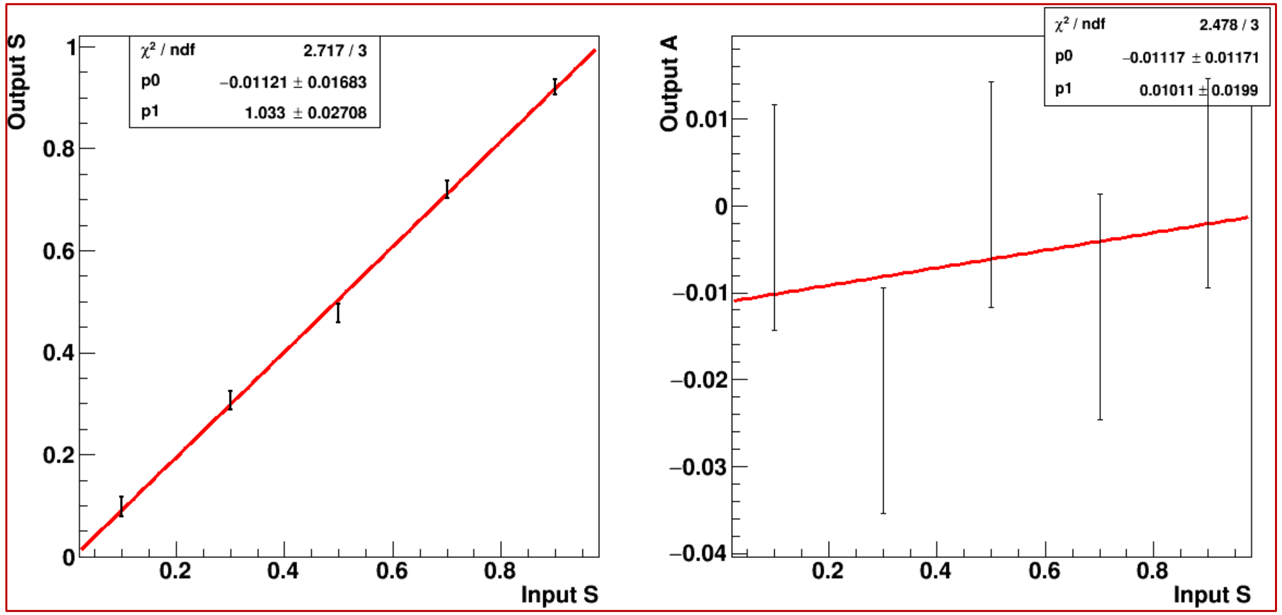
Data



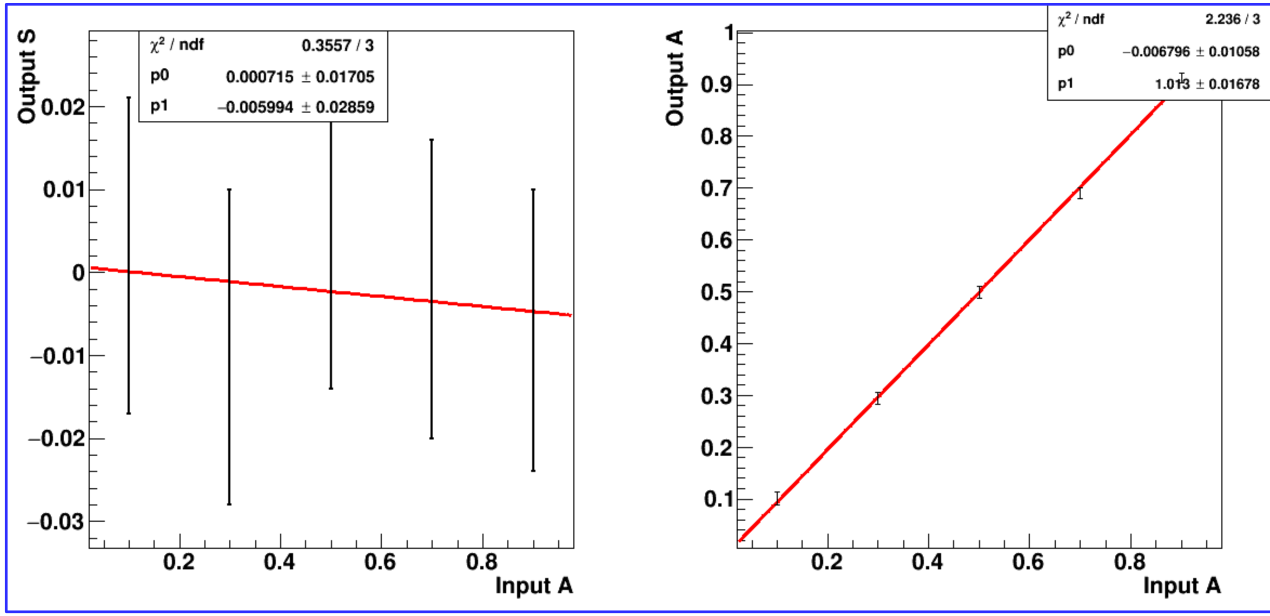
✔ **Compare the dalitz plot for MC and data, our evtgen model for MC generation by PHSP well describes data.**

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



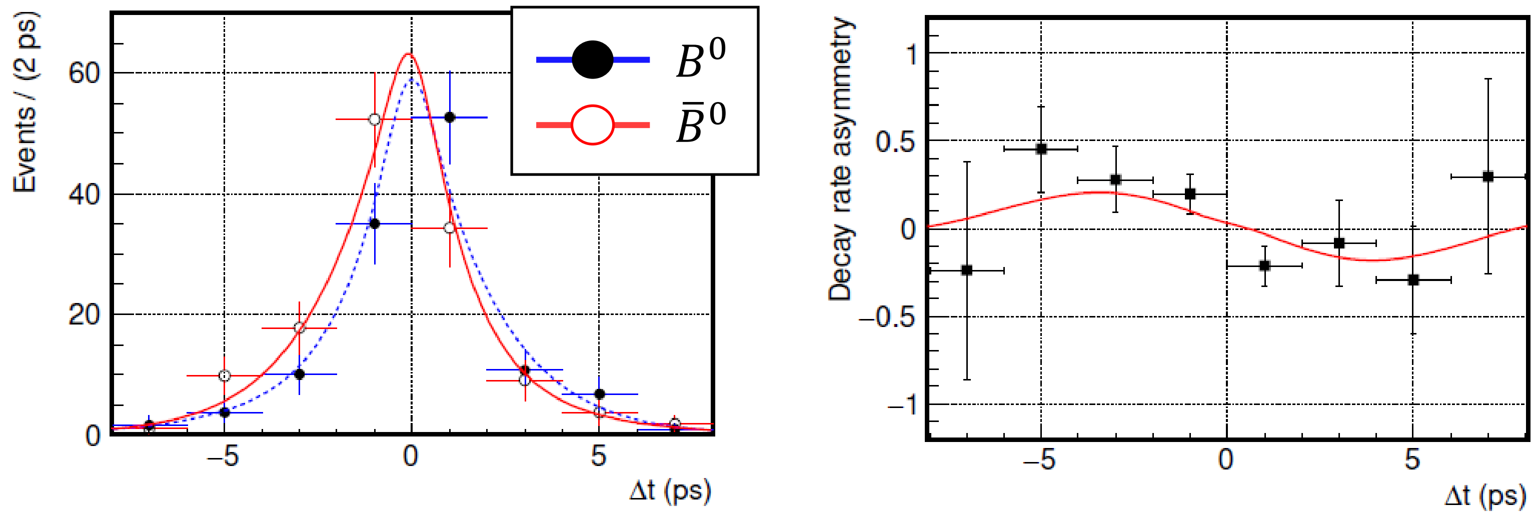
For S variation

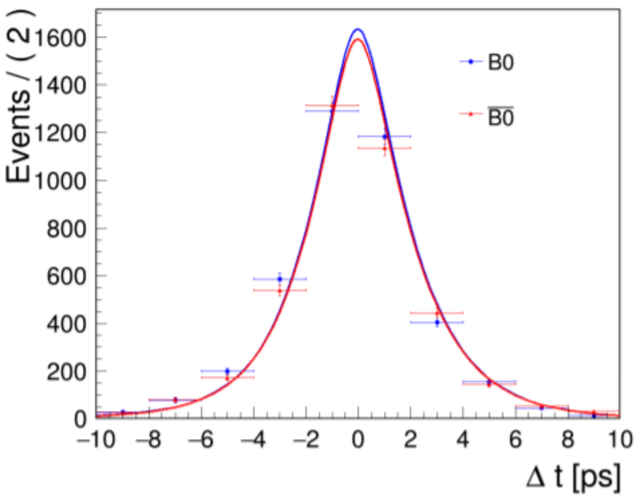


For A variation

Measurement of TDCPV parameters

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





Without TCPV

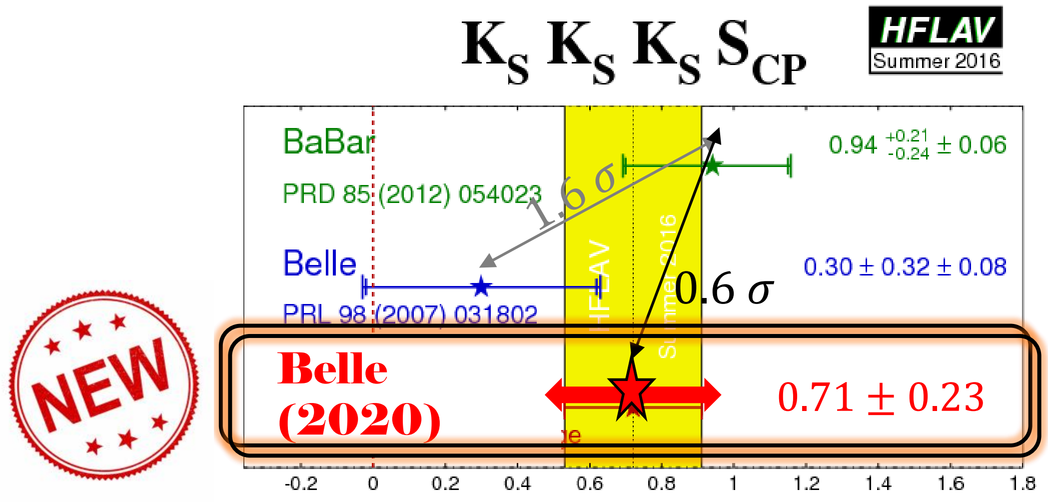
Systematic error

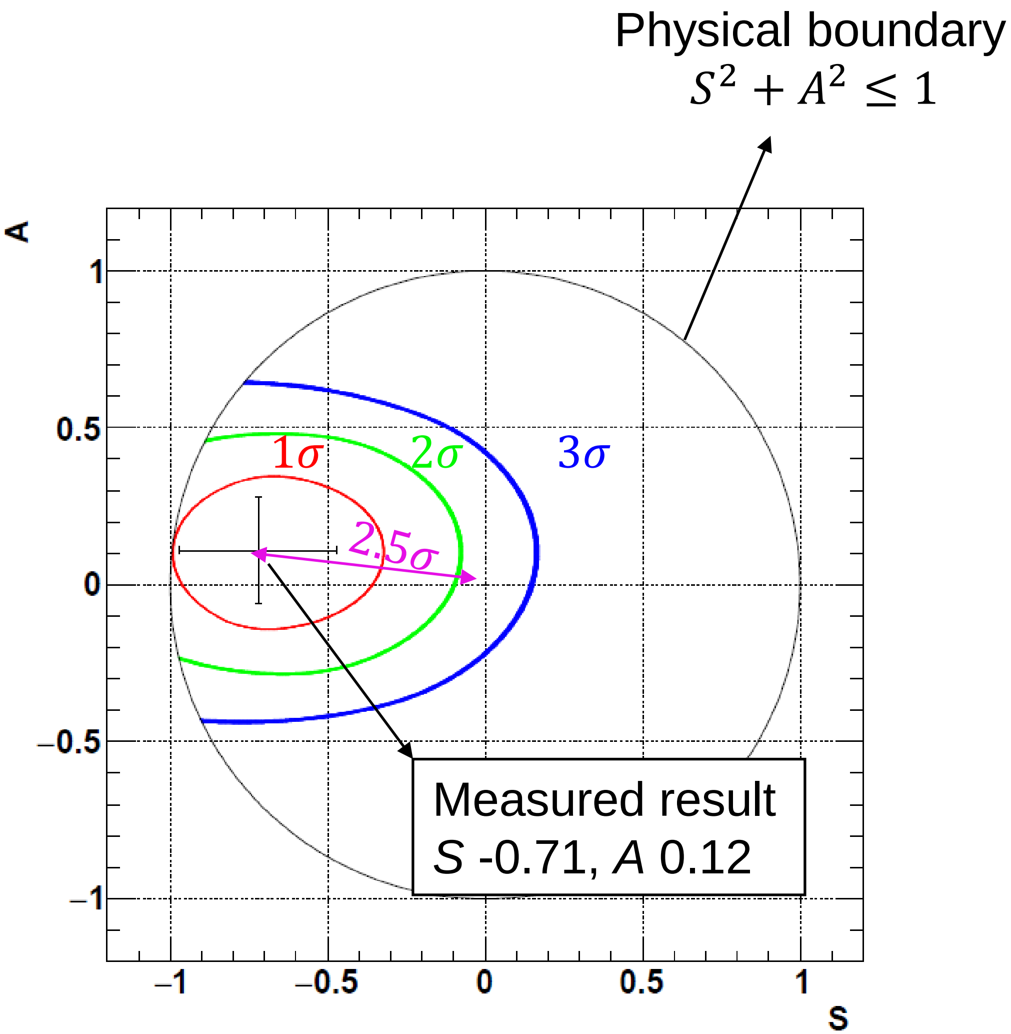
Source	S	A
Vertex reconstruction	0.031	0.038
Flavor tagging	0.002	0.004
Resolution function	0.016	0.014
Physics parameters	0.004	0.001
Fit bias	0.012	0.009
Signal fraction	0.024	0.021
Background Δt shape	0.016	0.001
SVD misalignment	0.004	0.005
Δz bias	0.002	0.004
Tag-side interference	0.001	0.008
Total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

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

Significance of CP violation

- The significance is calculated using the Feldman-Cousins approach.
  - Frequentist approach
    ↔ Bayesian approach (PDF based on hypothesis)
- 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 $b \to c\bar{c}s$

Summary

- The measurements of time-dependent CP violation in $B^0 \to K_S^0 K_S^0 K_S^0$ decays using the final data sample ($772 \times 10^6\ B\bar{B}$):
  - $S = -0.72 \pm 0.23\ (\mathrm{stat}) \pm 0.05\ (\mathrm{syst})$
  - $A = \ \ 0.11 \pm 0.16\ (\mathrm{stat}) \pm 0.05\ (\mathrm{syst})$

- The results are
  - The results are consistent with SM expectation (-0.70)
  - Previous Belle & BaBar result

- PHYSICAL REVIEW D 103, 032003 (2021)
  - https://doi.org/10.1103/PhysRevD.103.032003

Backup

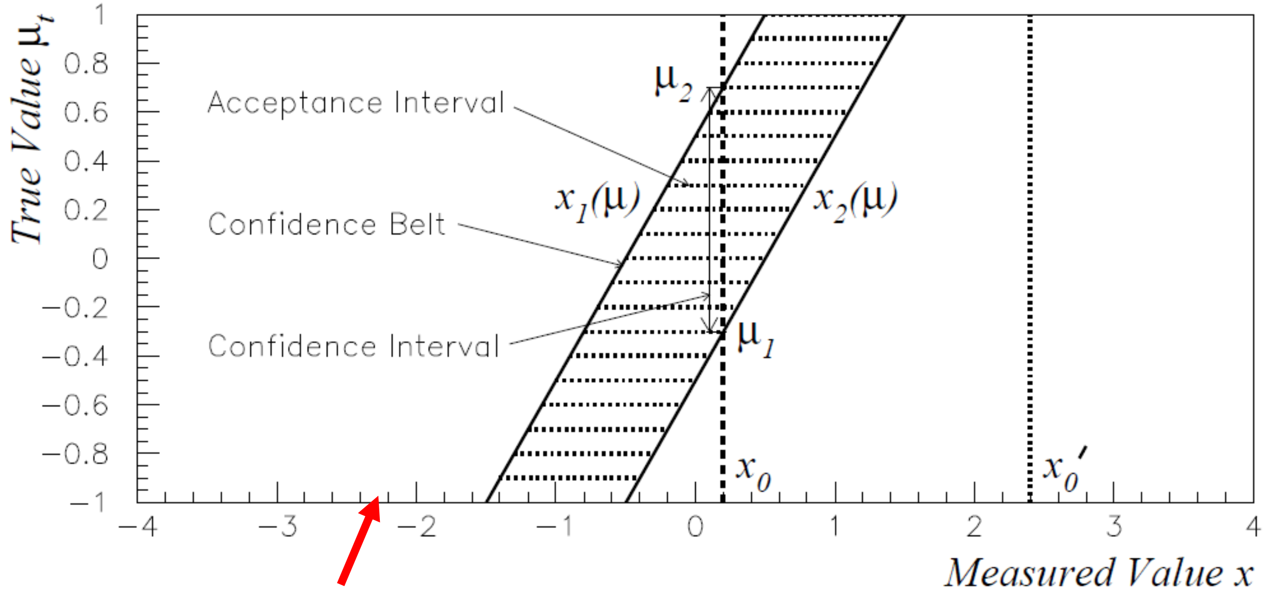
Signal reconstruction
– selection criteria and best candidate selection

- 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 < ΔE < 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

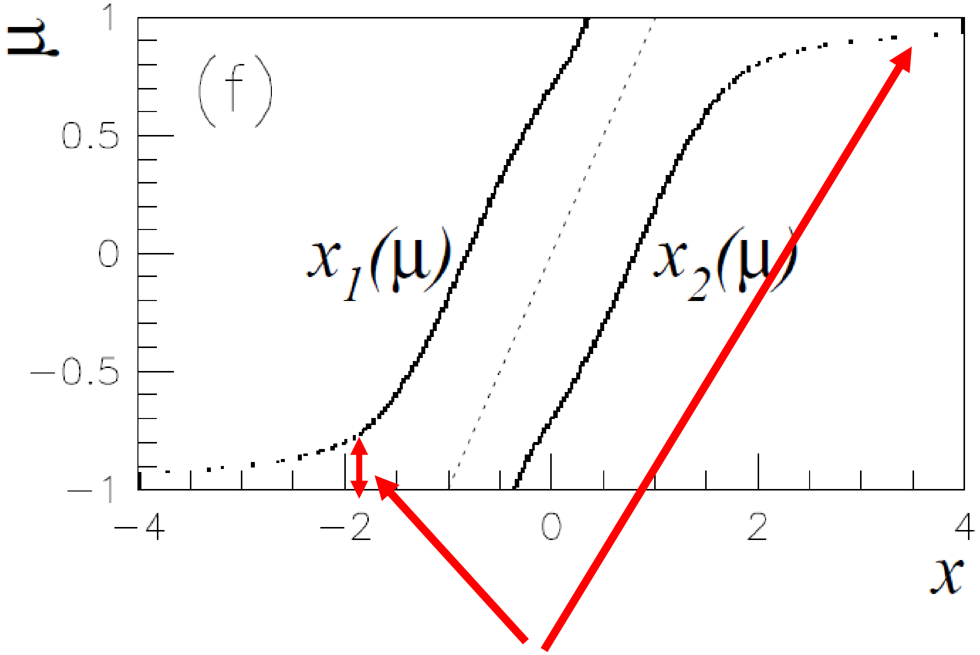
Classical and FC frequentist

Classical method



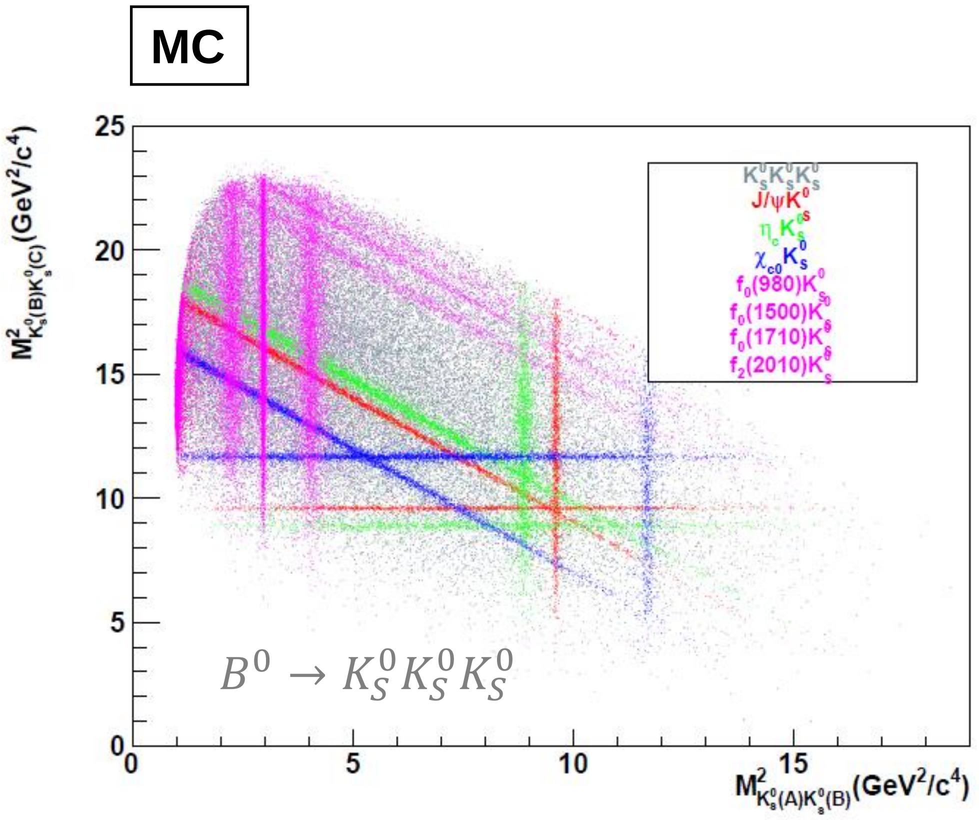
Confidence belt is empty
when measured value x is far from physical region

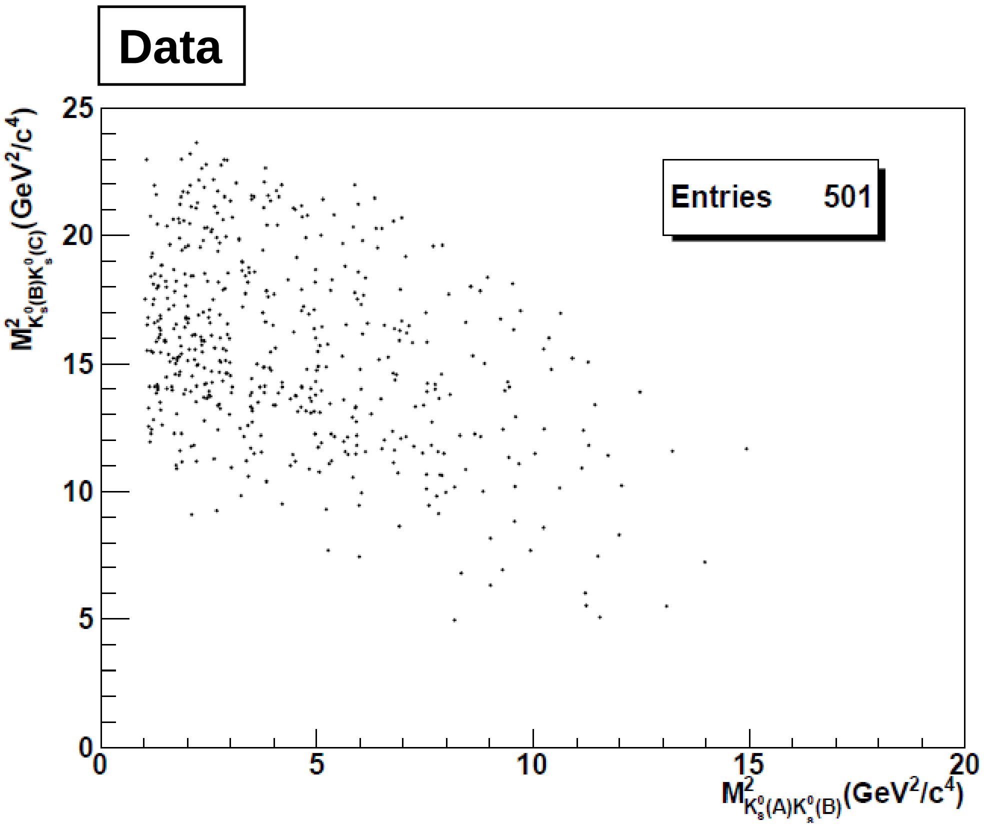
FC method



Confidence belt is never empty!
By ordering principle

Dalitz plot

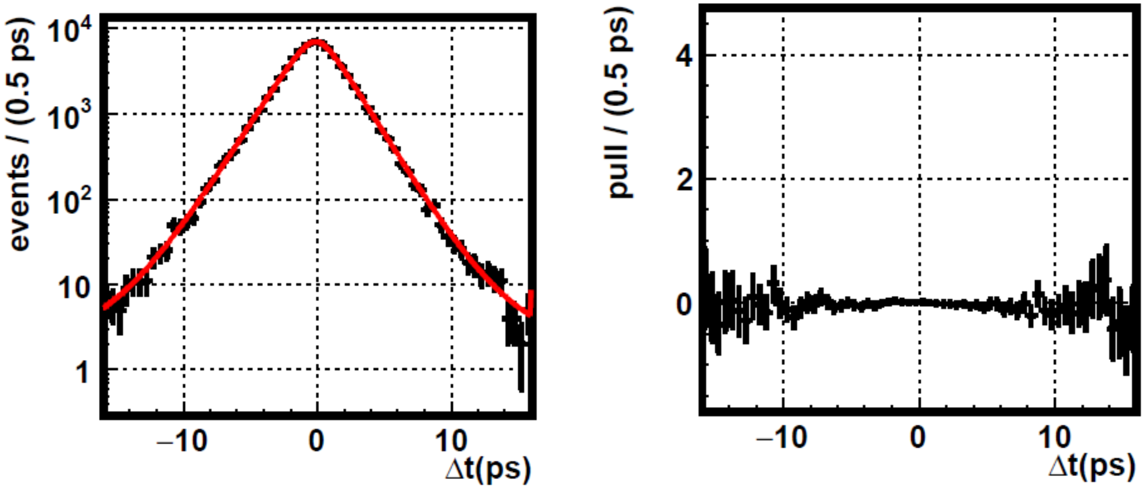




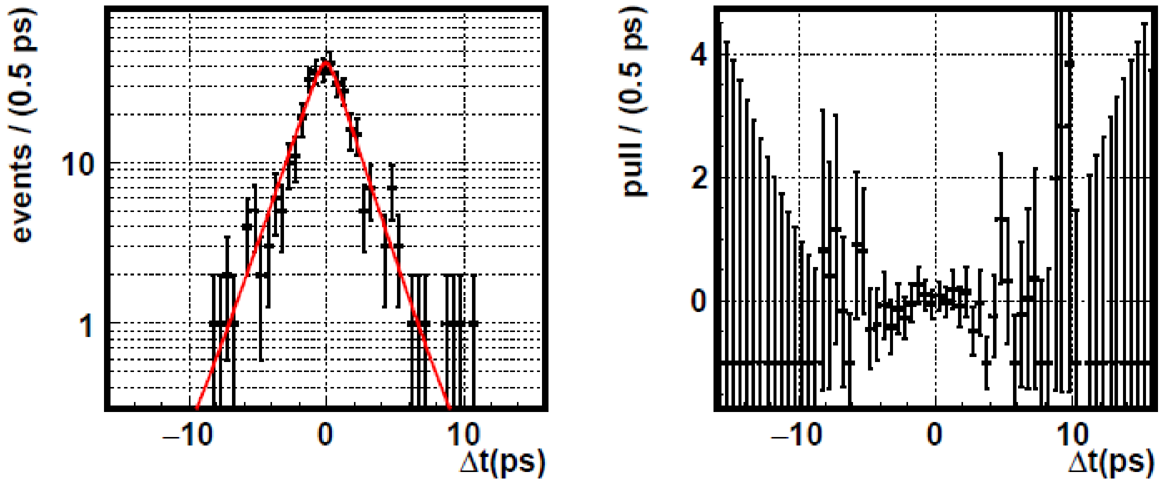
- Compare the dalitz plot for MC and data, our evtgen model for MC generation, PHSP_CP, well describes data.

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**