Silicon Vertex Detector and Time-dependent CP violation analysis at Belle

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2021. 01. 08

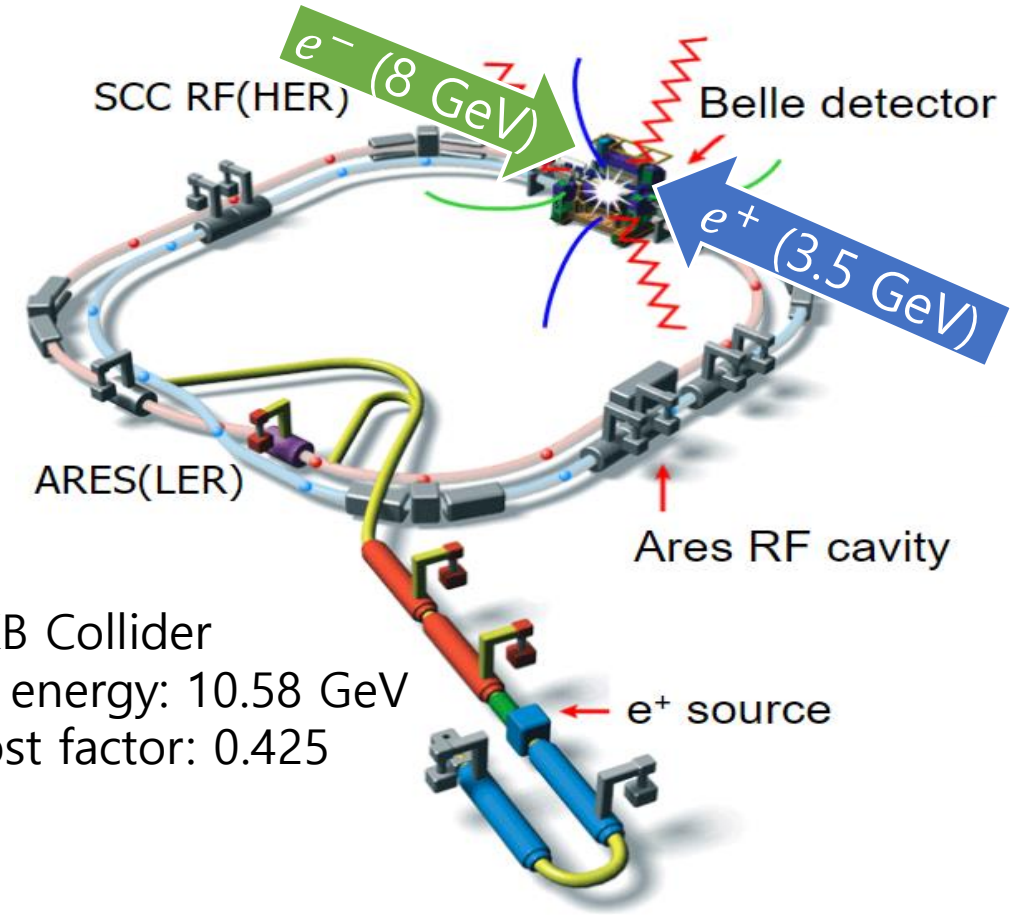
Saga-Yonsei partnership program on High-Energy Physics

KNU

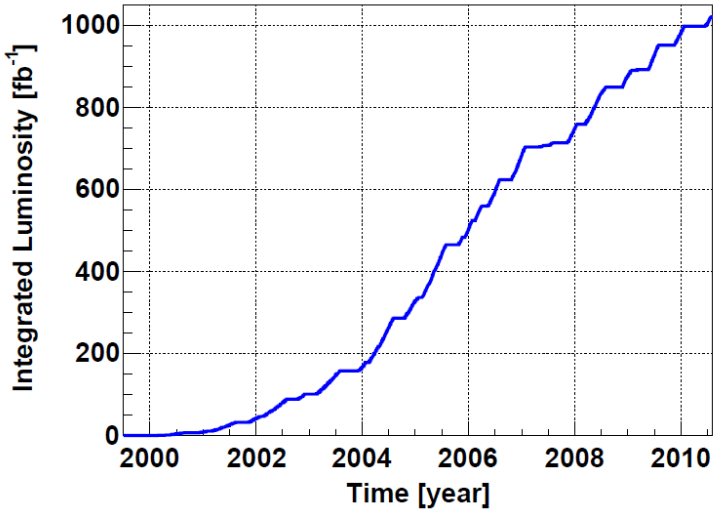
Outline

- Introduction
  - Belle experiment
  - Time dependent CP violation
- Silicon vertex detector for Belle II experiment
- Measurement of Time-dependent CP violation parameters using $\boldsymbol{B^0 \to K_S^0 K_S^0 K_S^0}$ decay at Belle
- Summary

Introduction - Belle experiment



KEKB Collider
CM energy: 10.58 GeV
Boost factor: 0.425



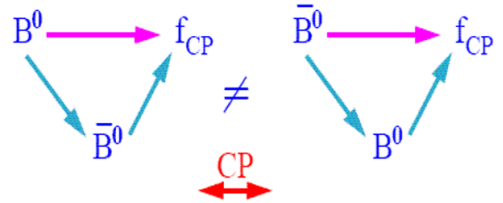
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off resonance /scan: 155 fb^{-1}

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

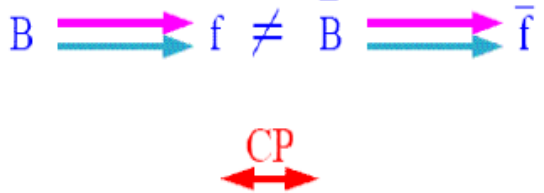
Establishing CP violation in B meson decay

Introduction – time-dependent CP violation (1)

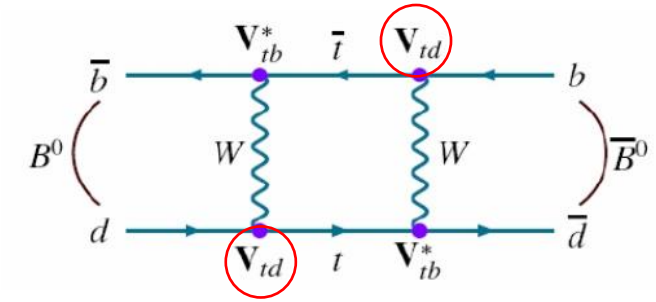
- The time-dependent CP violation ($TCPV$) can be caused by the interference between B^0 decay to CP eigenstate (f_{cp}) and $B^0 - \bar{B}^0$ mixing.



- Mixing-induced CP violation (S)



- Direct CP violation



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

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

complex phase

- CKM matrix

Introduction – time-dependent CP violation (2)

- Time-dependent CP asymmetry

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

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

here the time dependent decay rate (P) is given by

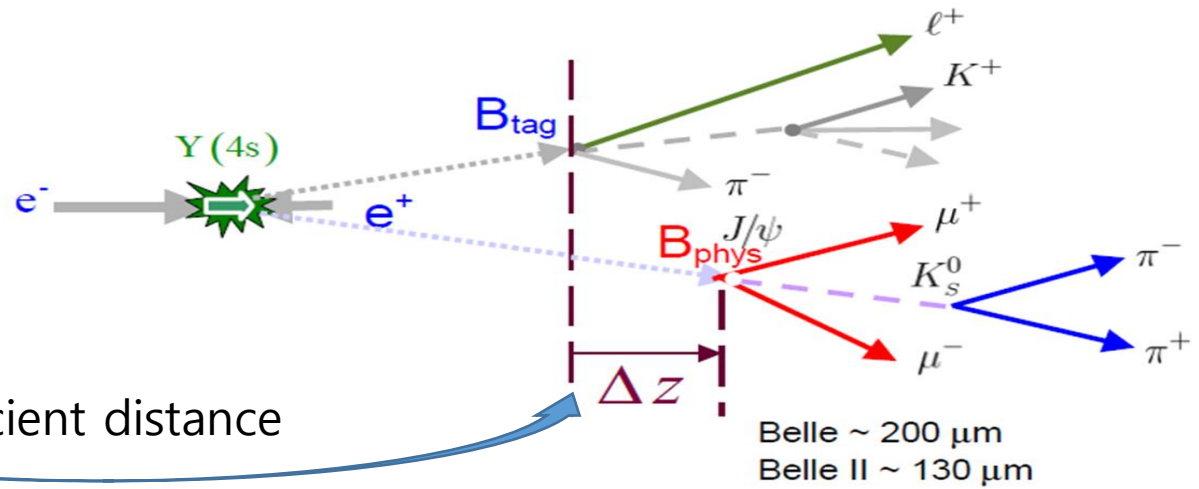
$$P = \frac{e^{-\frac{|\Delta t|}{\tau_{B^0}}}}{4\tau_{B^0}} \times (1 + q[S sin(\Delta m_d \Delta t) + A \cos(\Delta m_d \Delta t))$$

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

Asymmetric energy

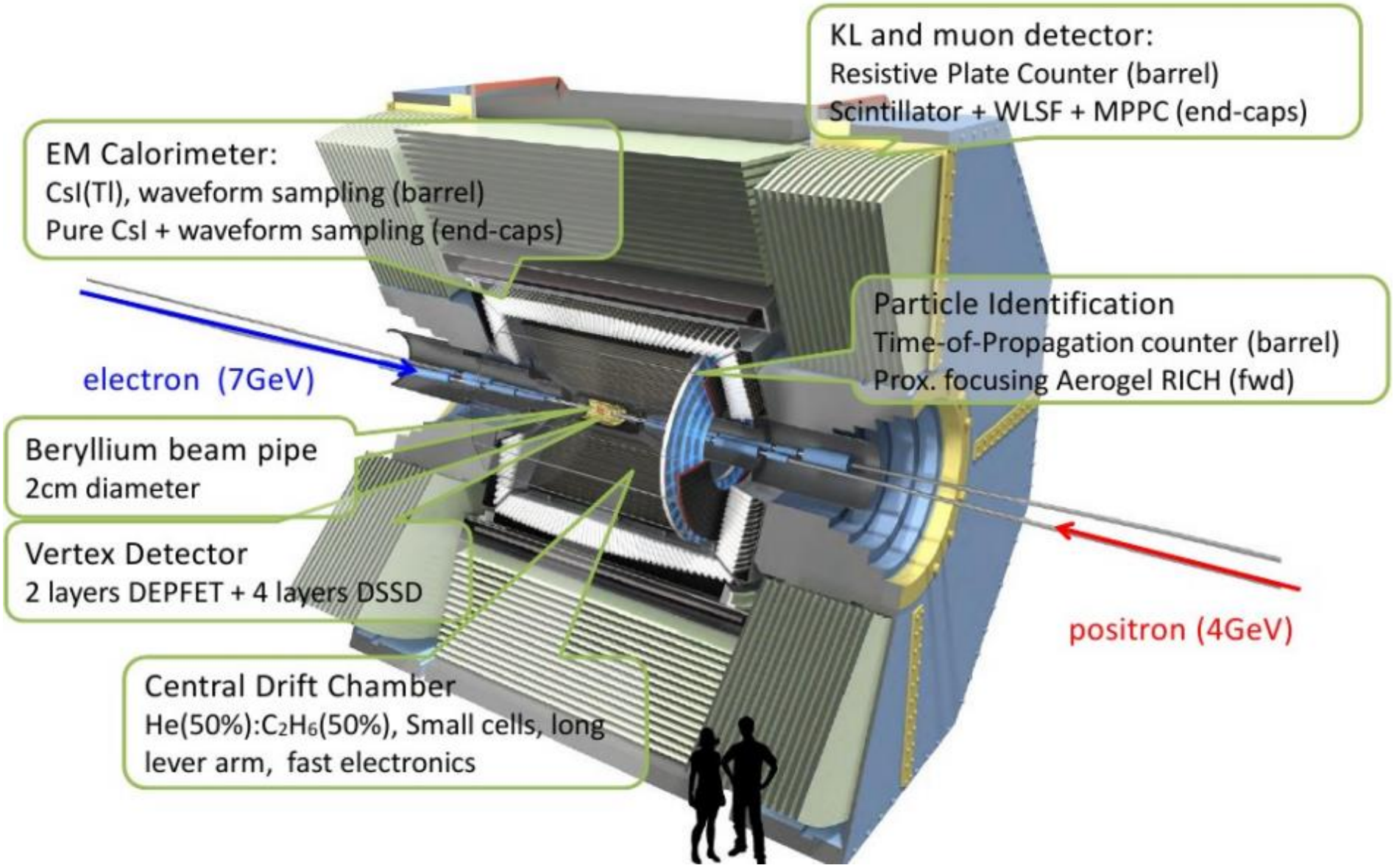
Lorentz boost = 0.425

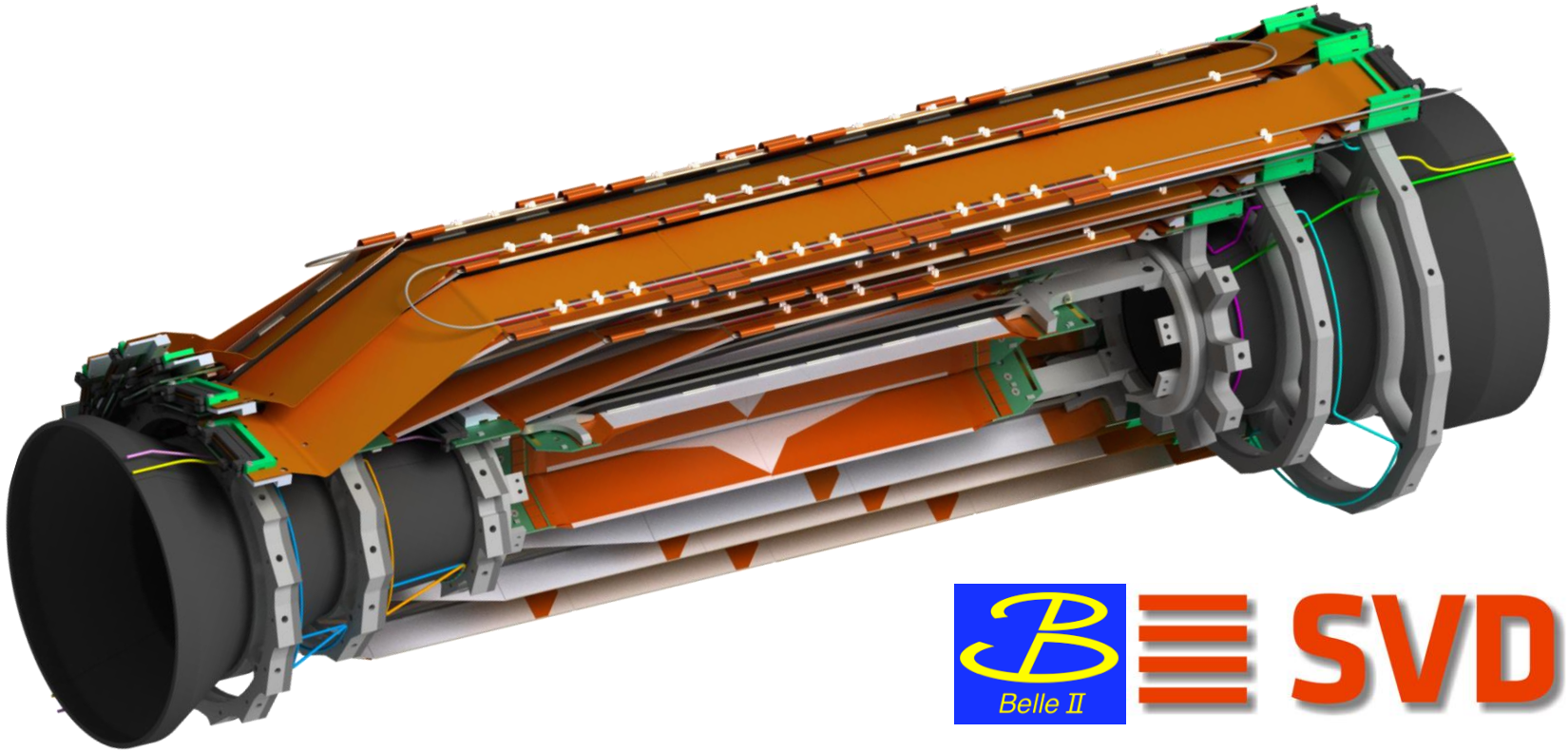
Sufficient distance



$\Delta t = \Delta z / \beta\gamma c$, $\Delta z \approx 200\ \mu m$
$\beta\gamma$ = boost factor 0.425

Belle II detector

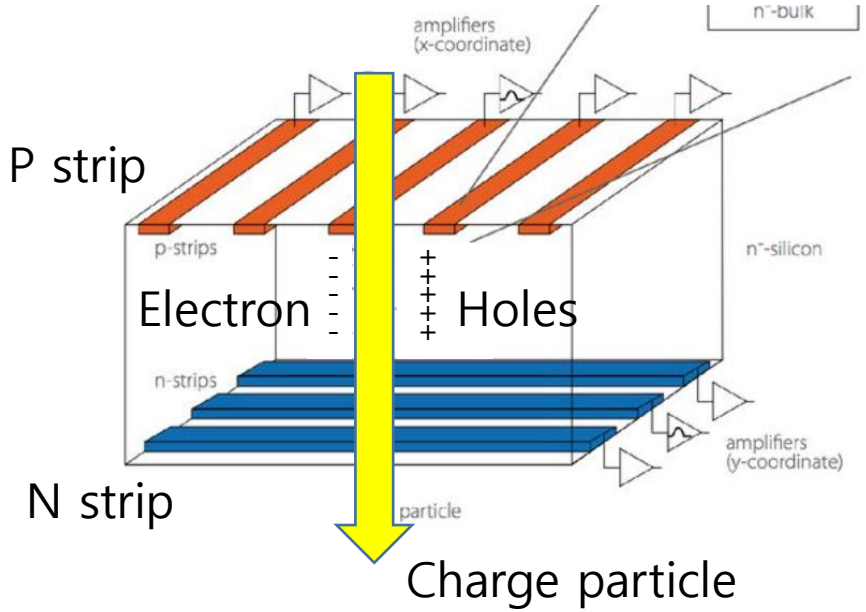




Silicon Vertex Detector @ Belle II

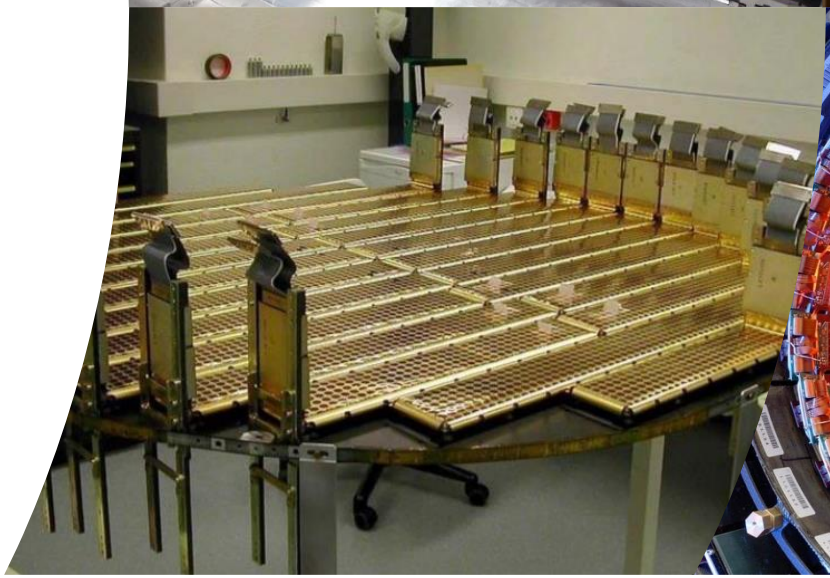
Silicon detector

- High resolution for
  - Position
  - Energy
  - Time

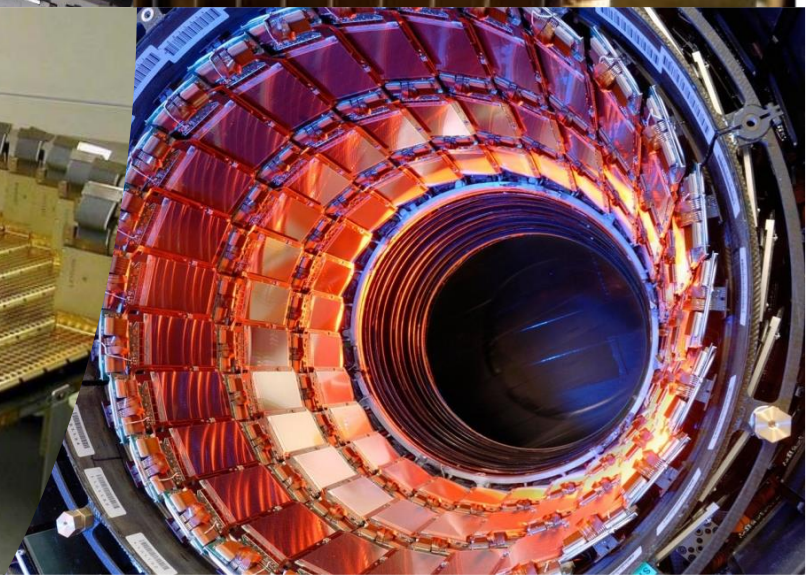


Belle II

LHCB



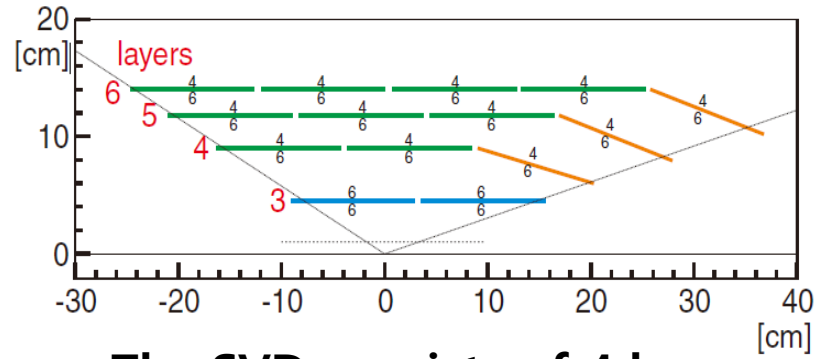
AMS



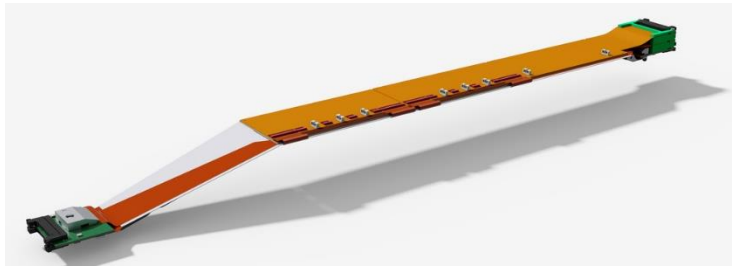
CMS

Belle II SVD overview

Readout connector



The SVD consists of 4 layers



The layer is consisted of several ladders

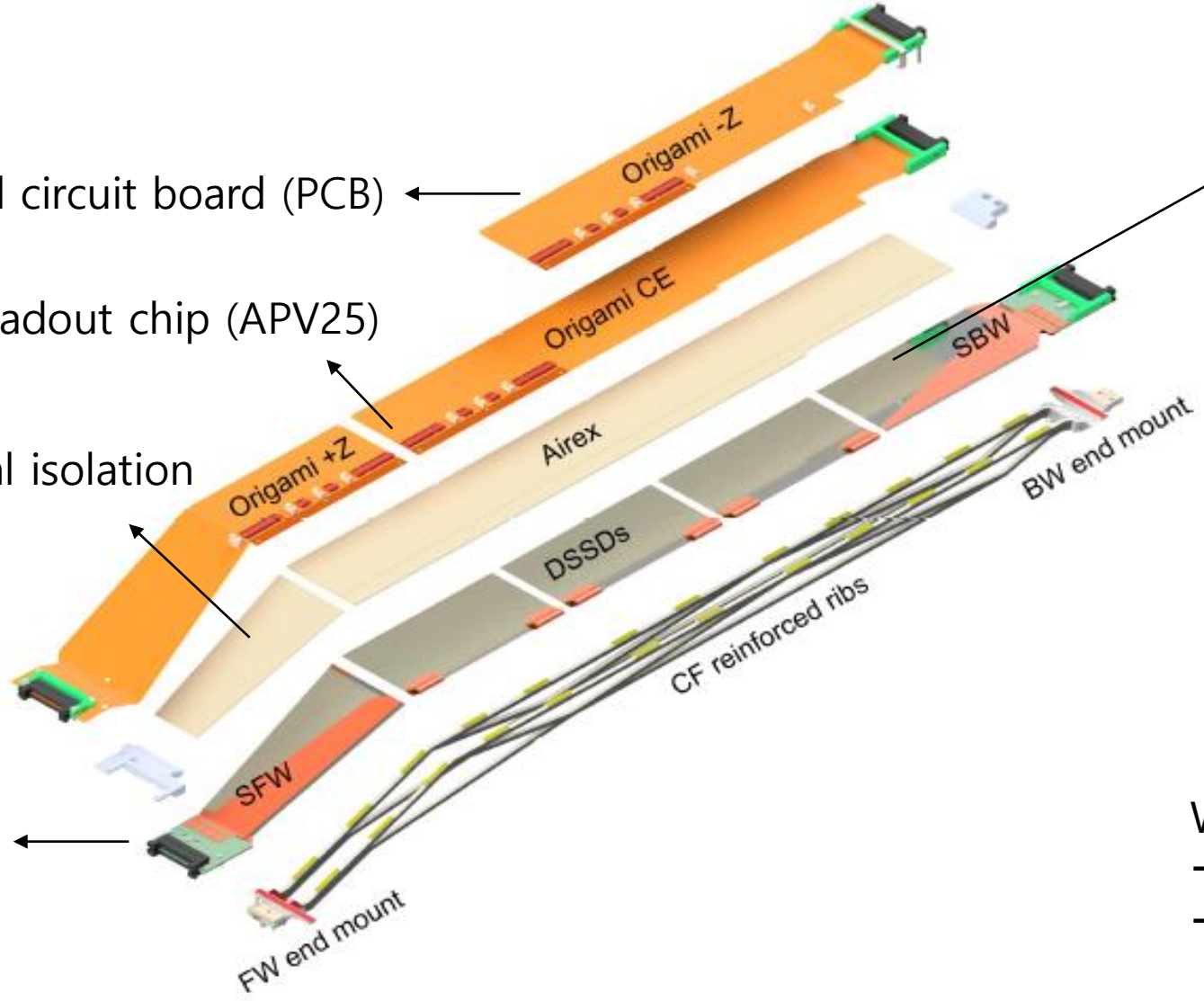
Exploded view of outmost SVD

Flexible printed circuit board (PCB)

Readout chip (APV25)

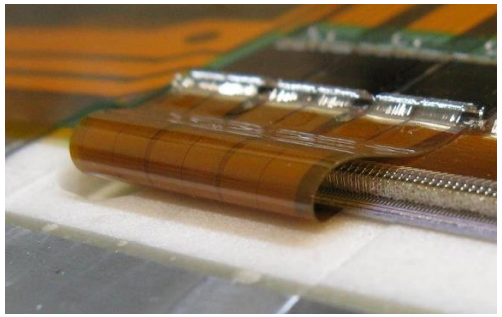
Airex sheet
- thermal & electrical isolation

PCB



Double sided strip detector
- thickness = 320 μm
- 768 & 512 strips

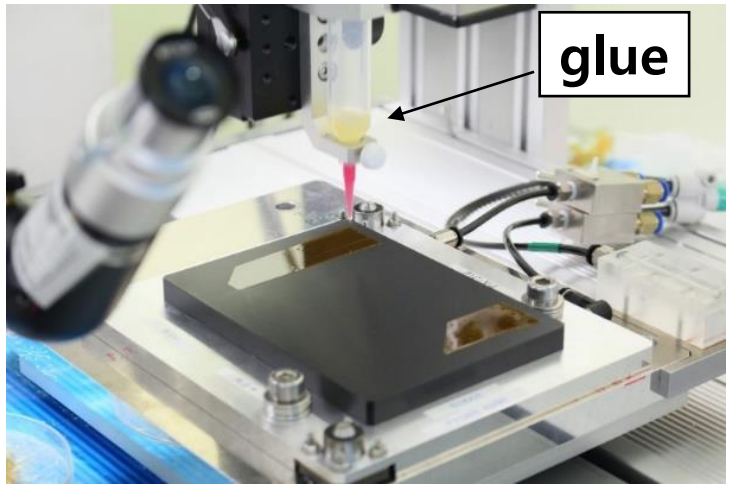
"Origami" structure

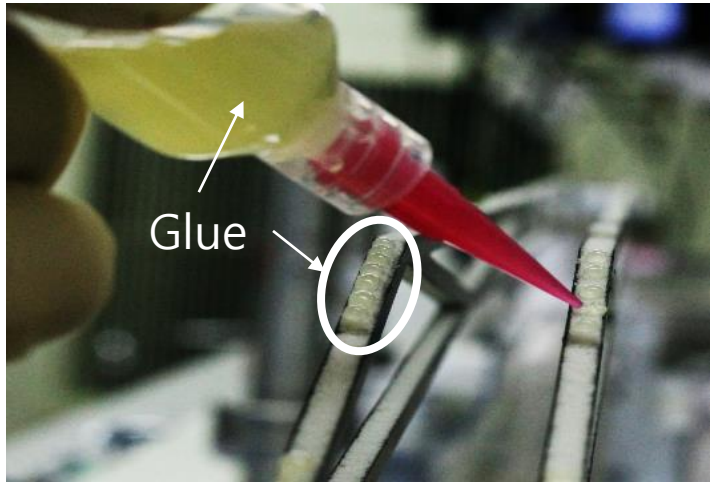


Wrapped signal for backside
→ Reduce one FPCB layer
→ low material budget

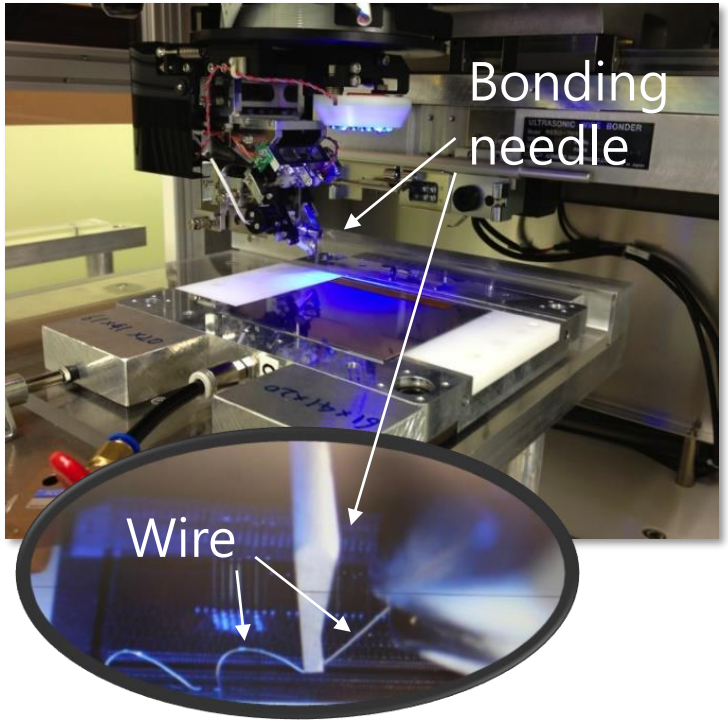
Gluing and wire bonding

- Gluing → for mechanical assemble

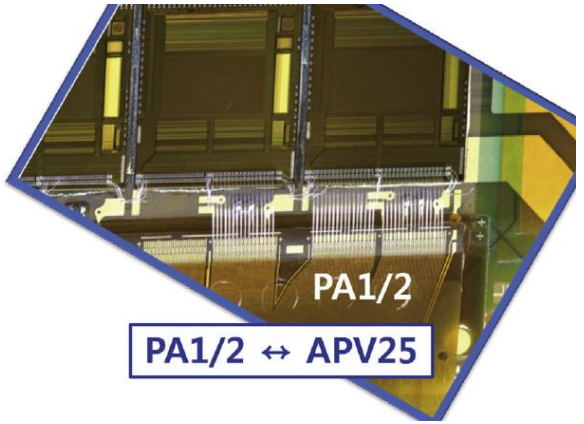




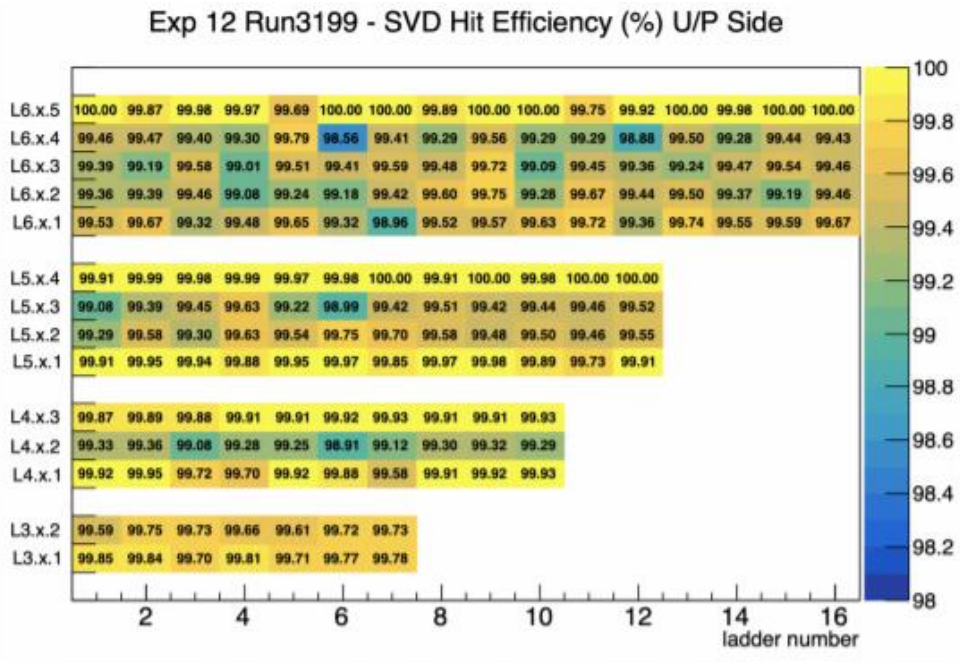
- Wire bonding → for electrical connection

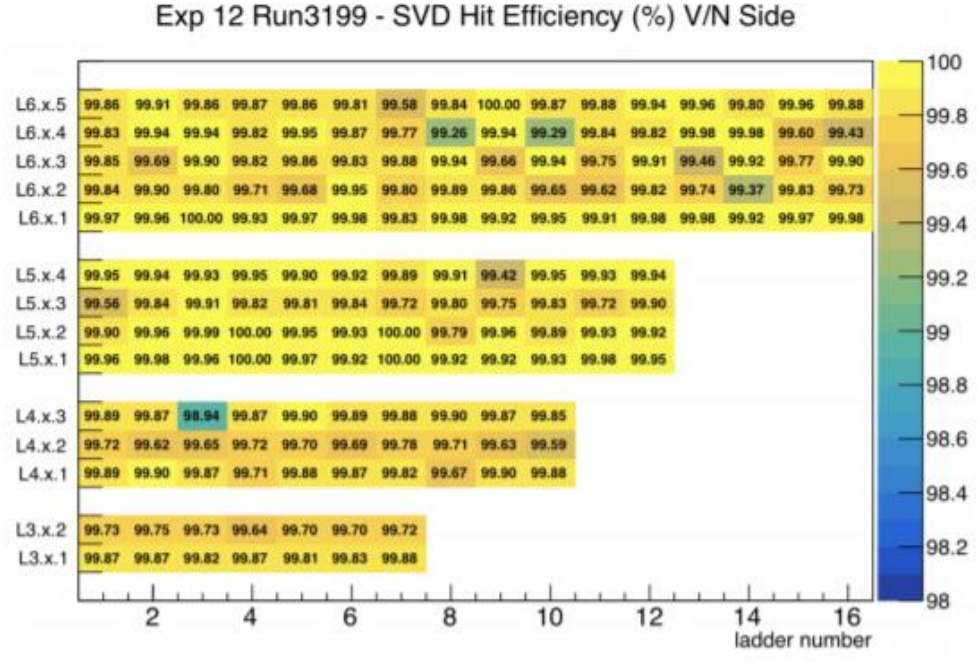


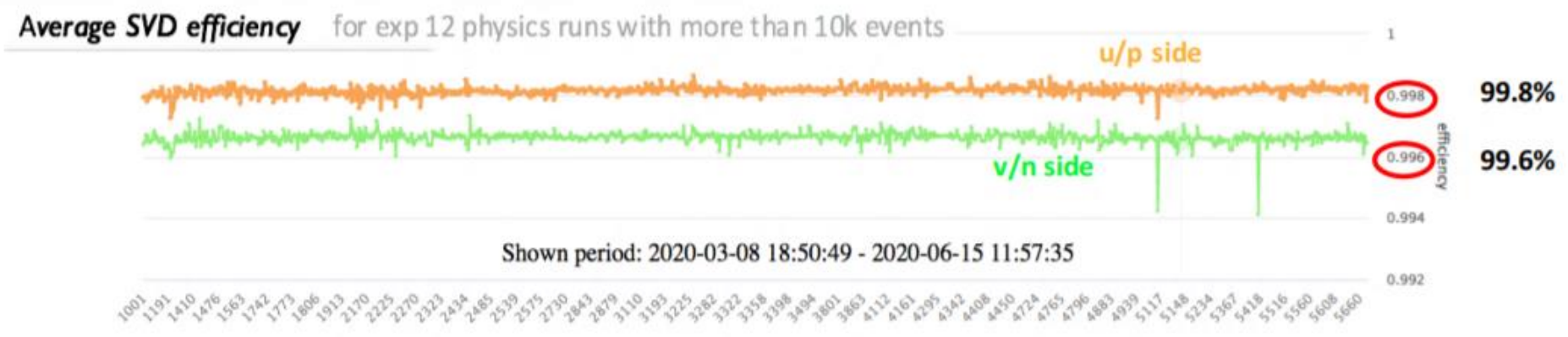
Wire diameter : 25 μm



Performance of SVD





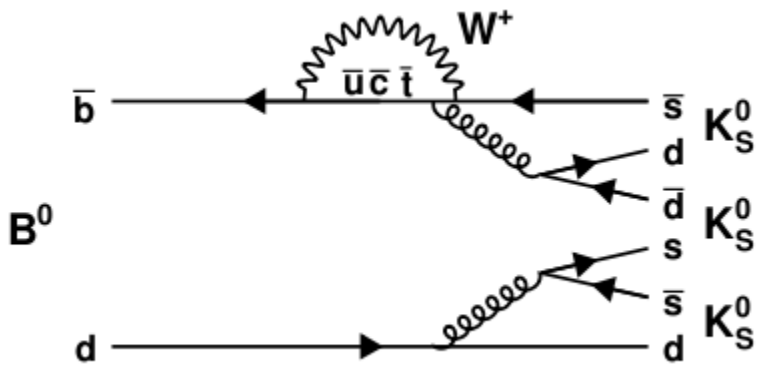


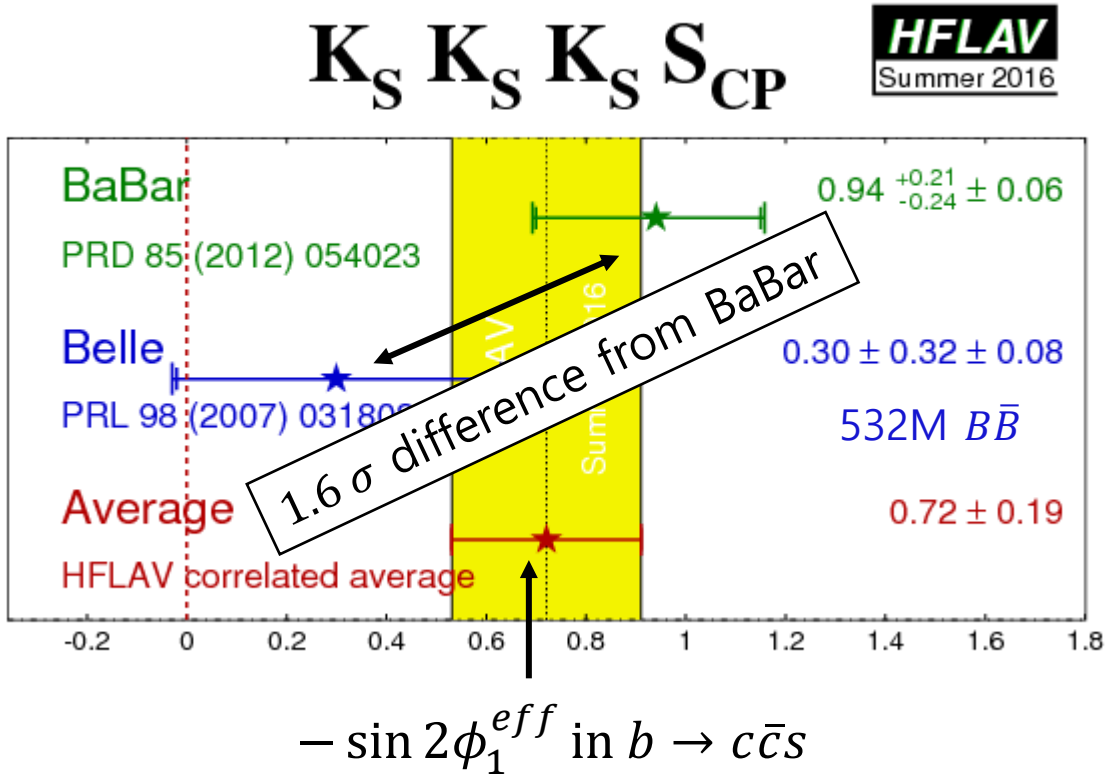
SVD assembly at IPMU

Measurement of TCPV violation parameters using $B^0 \to K_S^0 K_S^0 K_S^0$ decays at Belle

arXiv (2011.00793)

Introduction - motivation

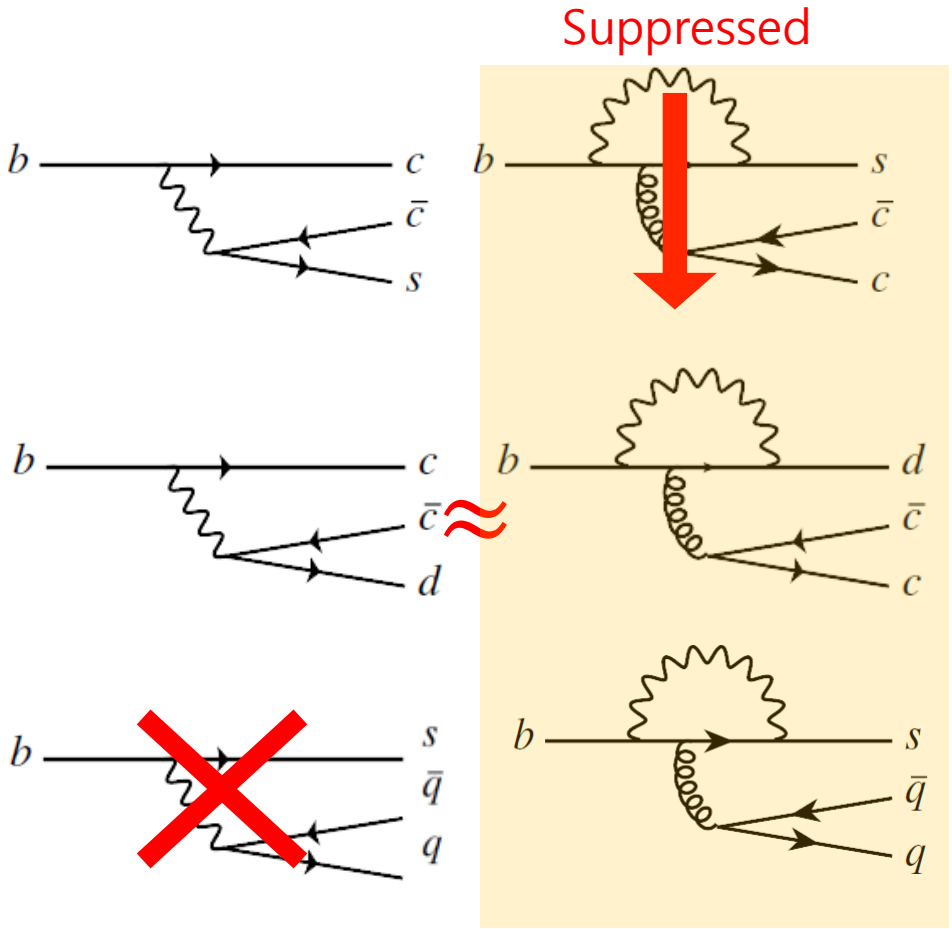




$-\sin 2\phi_1^{eff}$ in $b \to c\bar{c}s$

- 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 $B\bar{B}$).

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: $B^0 \to J/\psi\pi^0, J/\psi\rho^0$)
$\sin 2\phi_1^{eff} =$???

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

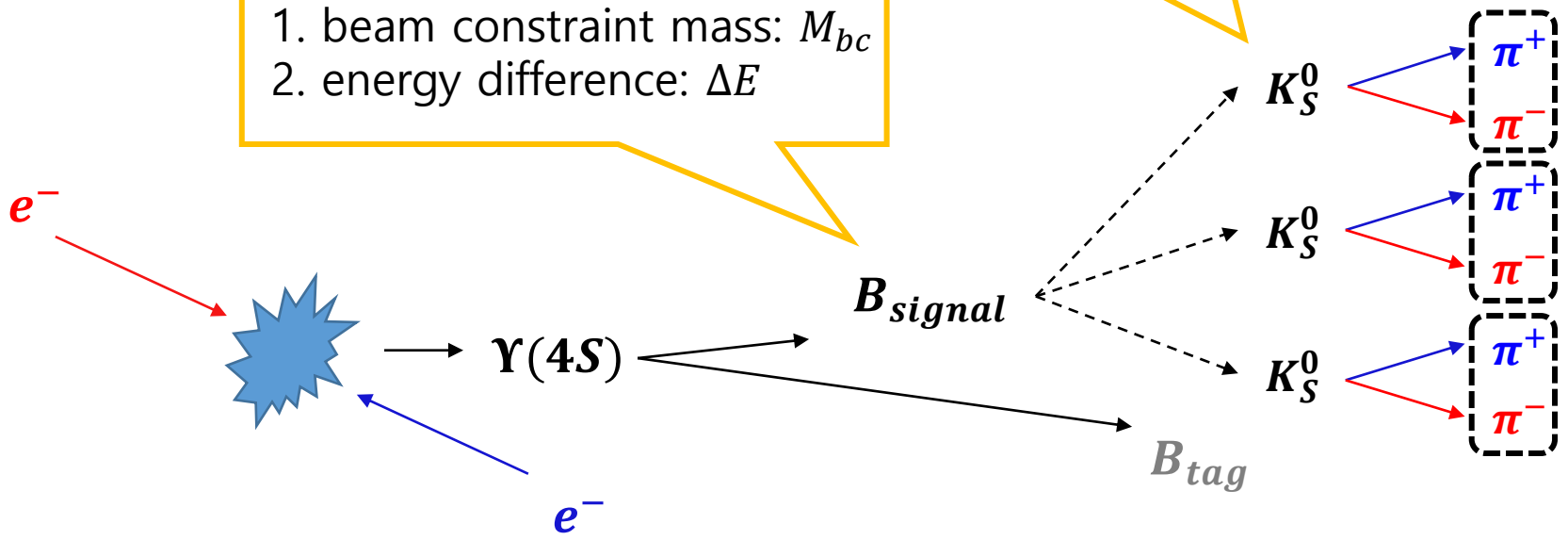
Significant deviation of $\sin 2\phi_1^{eff}$ from $\sin 2\phi_1$ indicates evidence of NP.

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

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
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Two kinematic variables:
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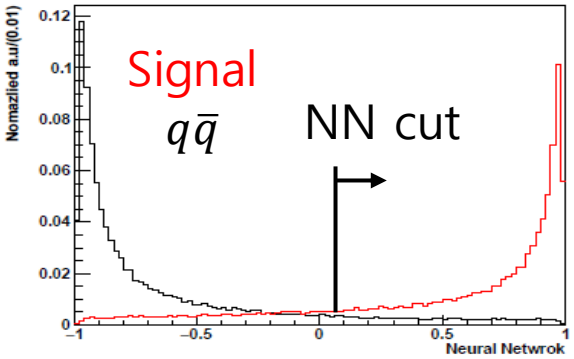
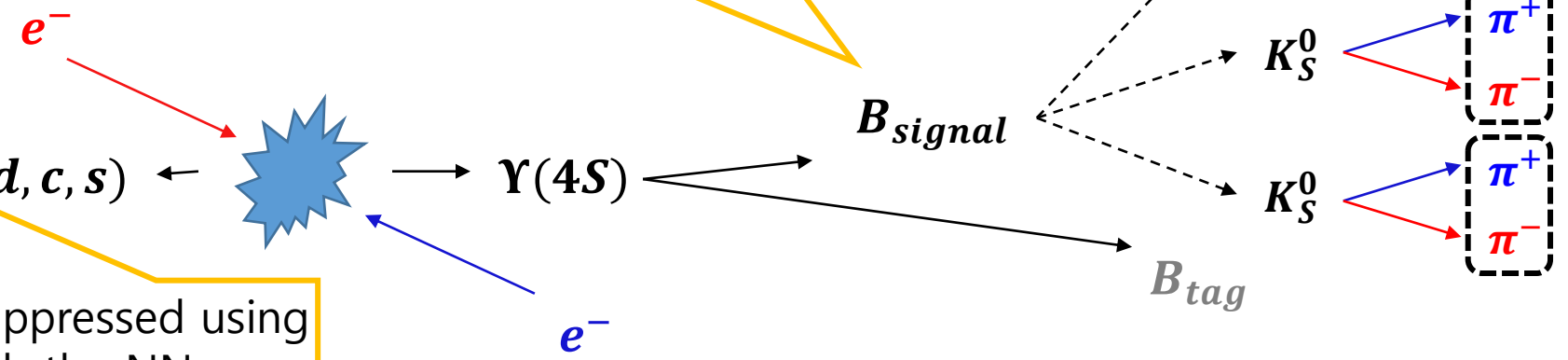
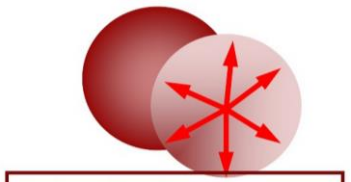


NN output



Continuum backgrounds are suppressed using topology information along with the NN

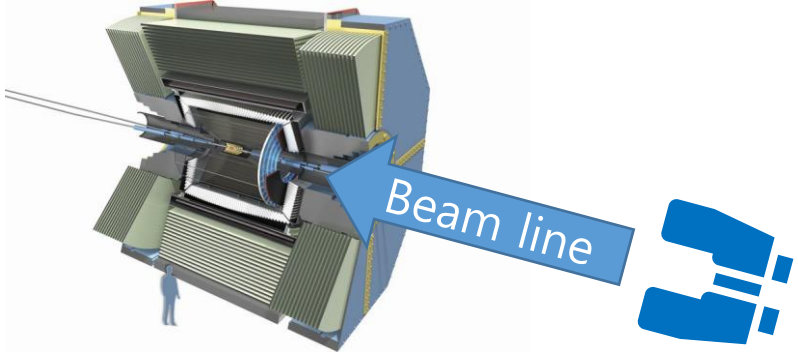

Spherical BB events


Jet-like qq events

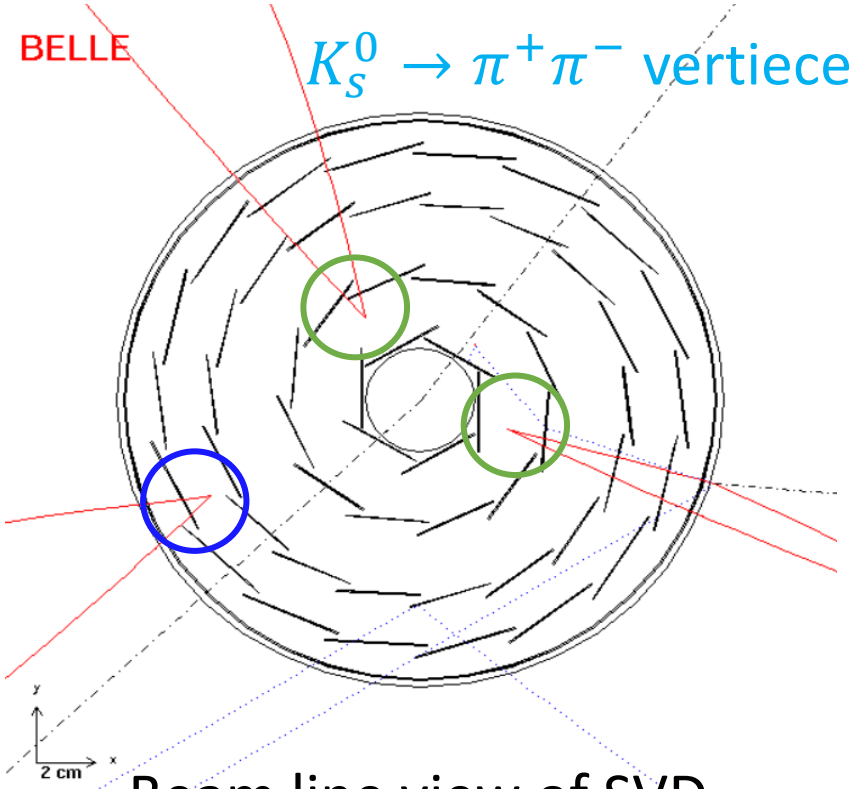
B mesons are produced all most at rest in the $\Upsilon(4S)$ frame
→ In contrast for $q\bar{q}$ events, it has a large initial momentum

- $\Delta E = E_B - E_{beam}$
  - 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

Vertex reconstruction

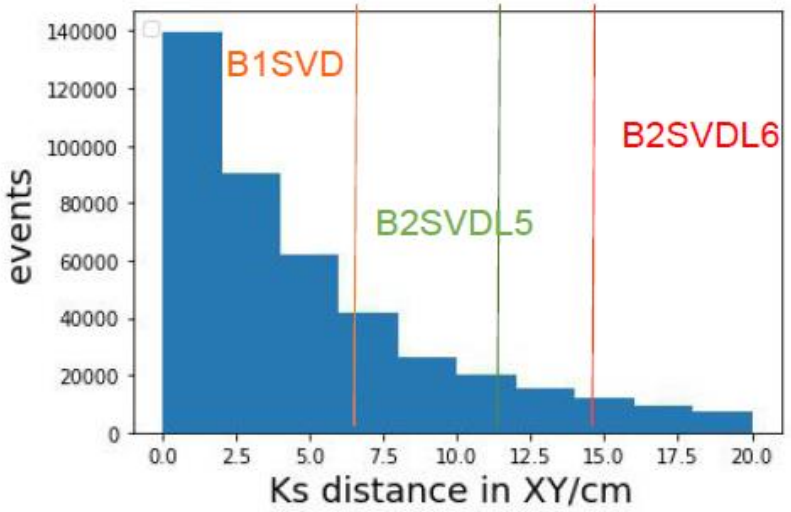


In this decay mode there is no primary charged track
→ to find vertex position we make Ks trajectory using pion hit



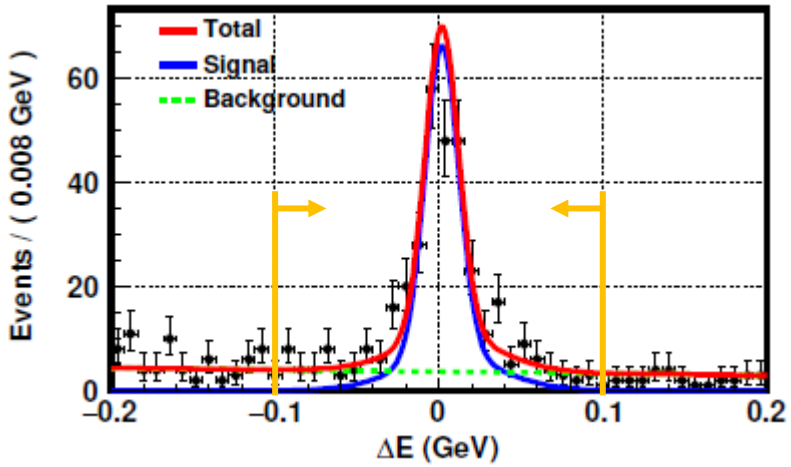
Beam line view of SVD

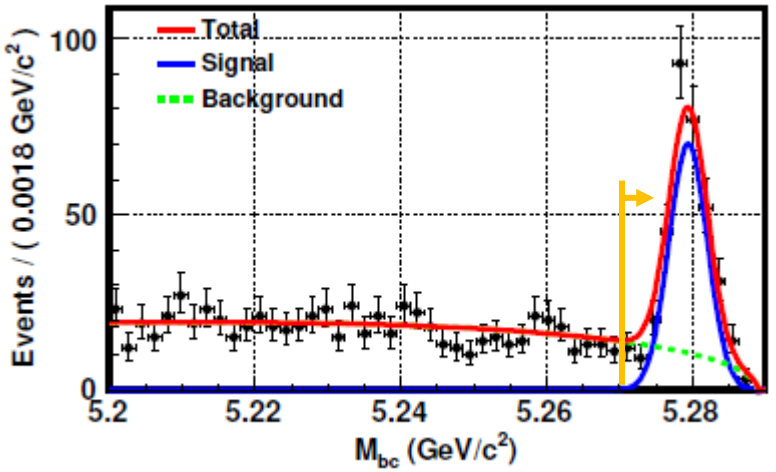
In the Belle experiment
about 40% Ks does not have any pion hit
→ improved at Belle II



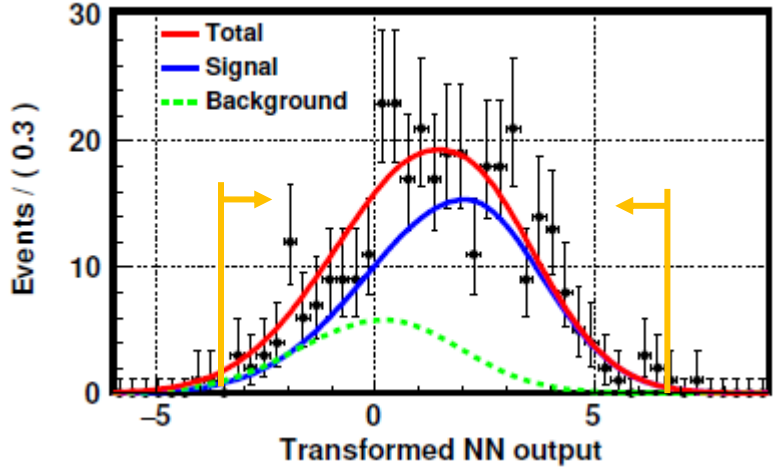
Signal extraction

Preliminary





Transformed NN output:
used for continuum suppression

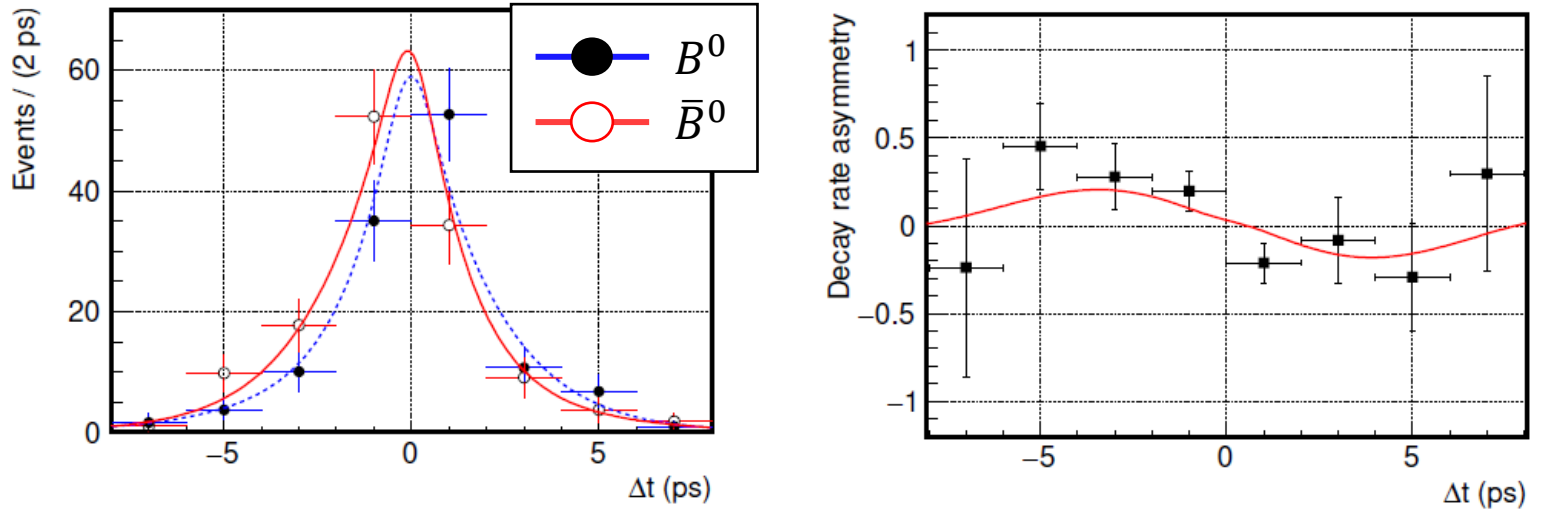


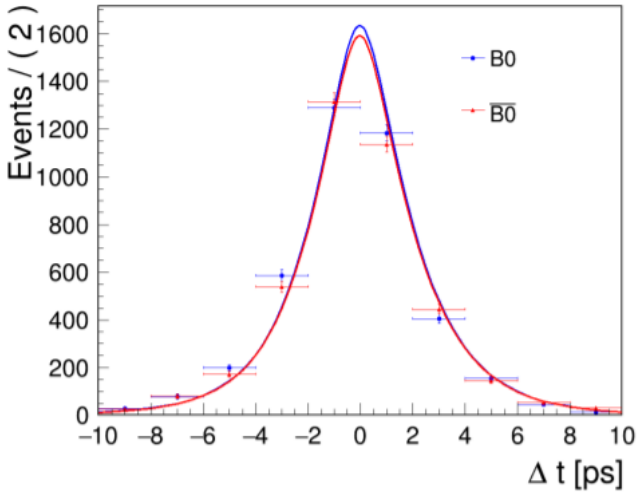
- An unbinned maximum likelihood (ML) fit with 3D PDF (ΔE, M_{bc}, Transformed NN).
- Signal B^0 & $\bar{B}^0$ is obtained to be 258 ± 17 and the purity in the signal region is 74%.

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

Measurement of $TCPV$ parameters

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

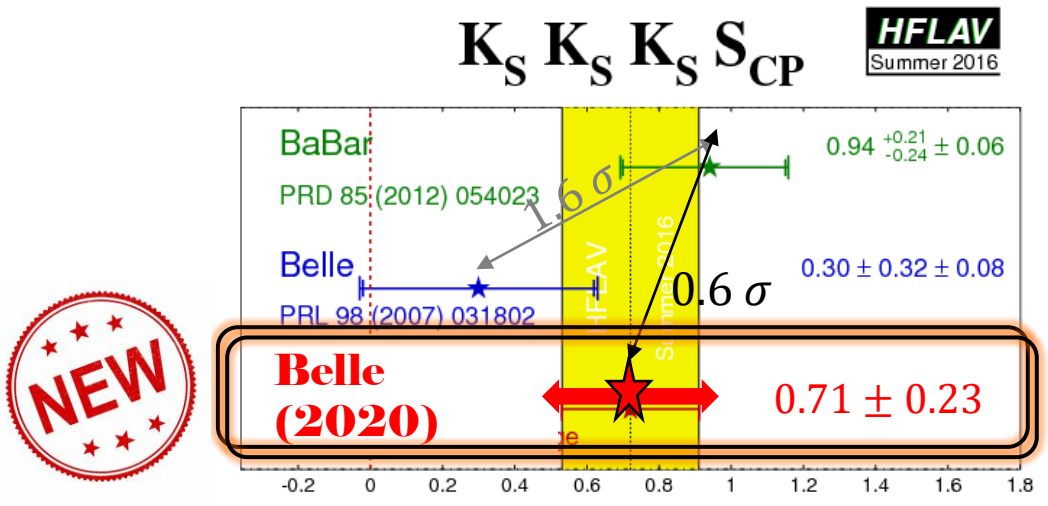


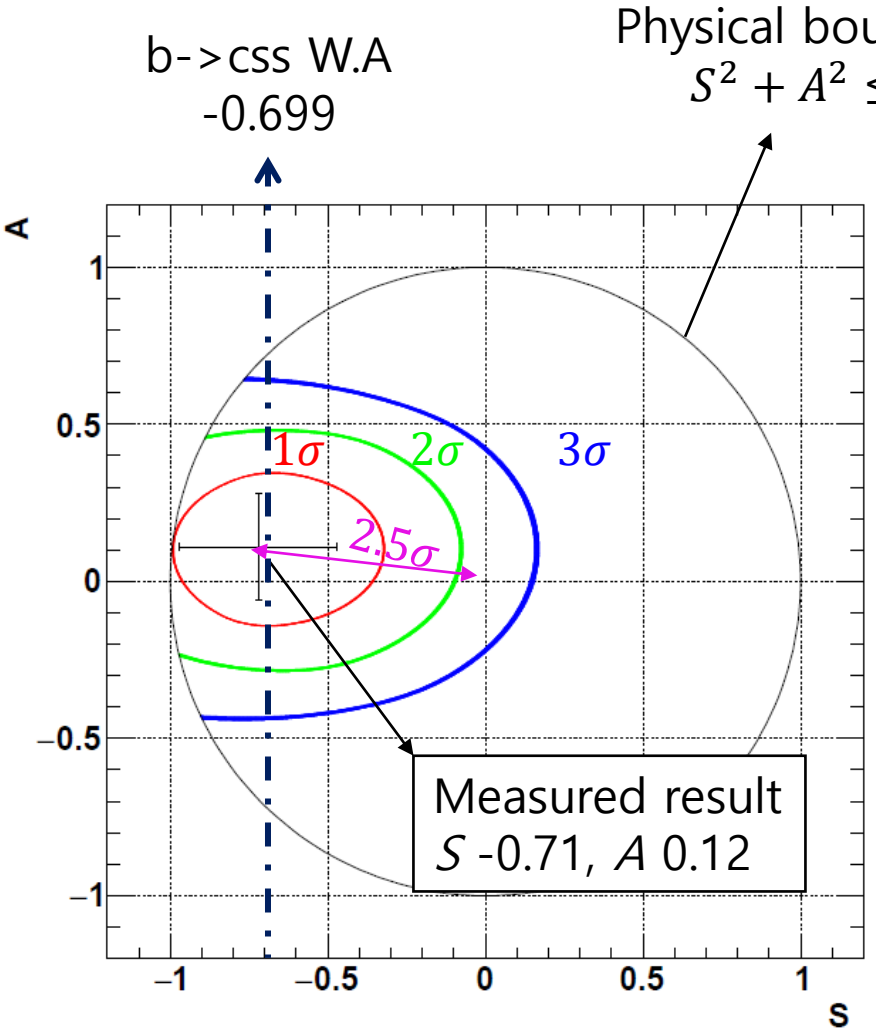


Without TCPV

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

- Main purpose of Belle experiment is measurement of CP violation
  - Measurement distance between B-mesons is important
  - Silicon vertex detector provides good vertex resolution for TCPV analysis

- Belle II SVD
  - SVD was installed in the Belle II detector in Nov. 2018
  - During physics run, SVD has been operated smoothly

- 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 consistent with SM expectation and previous Belle result

Backup

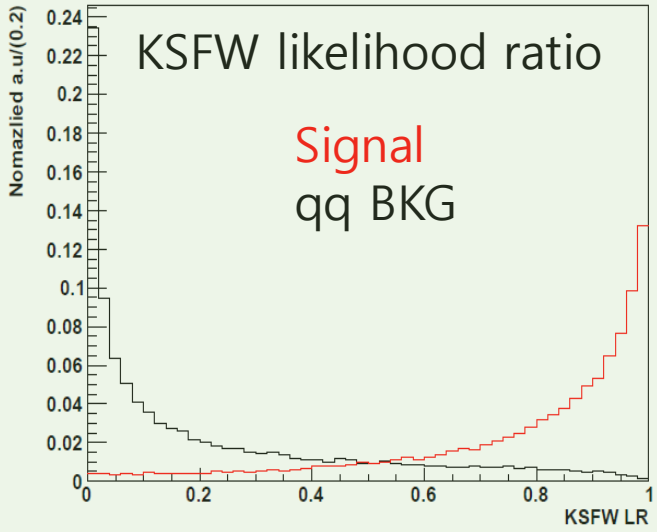
Signal reconstruction
– selection criteria and best candidate selection

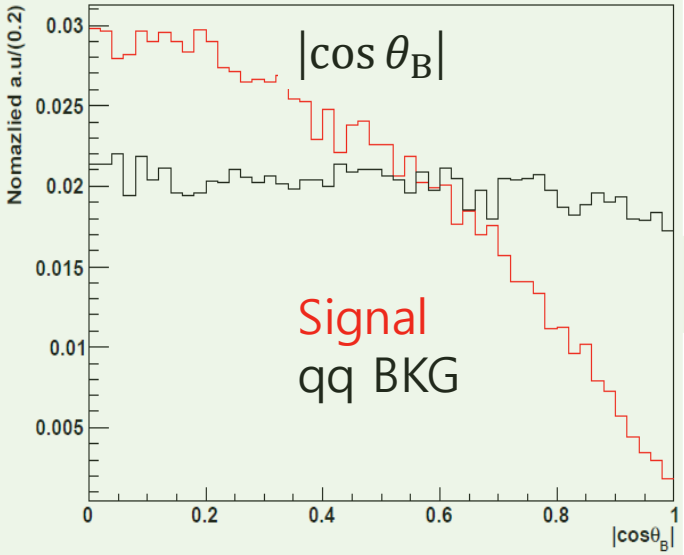
- We use K_S^0 only from charged decay to avoid background.

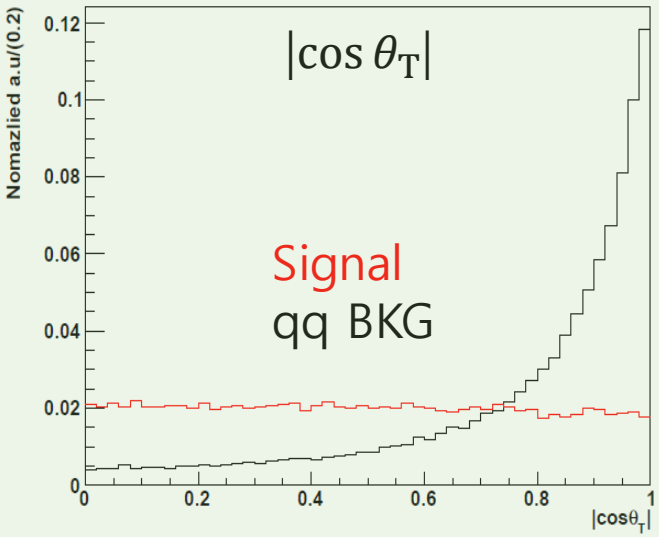
	$B^0 \to K_S^0 K_S^0 K_S^0$
$K_S^0(\pi^+\pi^-)$ selection in mdst_vee2	$\lvert\Delta M_{\pi\pi}\rvert < 10\,\sigma$, nisKsfinder cut (nb_vlike>0.2)
ΔE [GeV]	-0.2 $< \Delta E <$ 0.2
M_{bc} [GeV/c^2]	5.2 $< M_{bc}$
Best candidate selection	smallest of $\chi^2 = \sum_{i=1}^{3} \left(\frac{M_{\pi\pi}^i -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

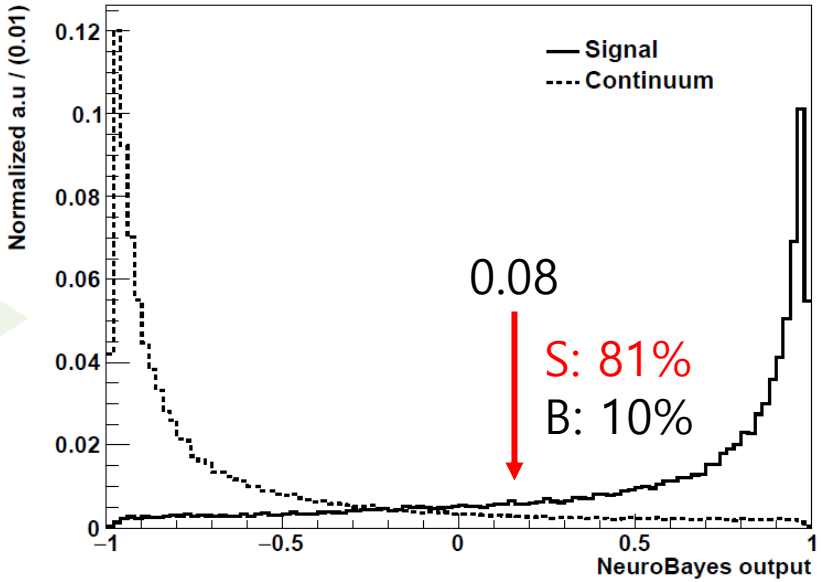
Continuum background

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}





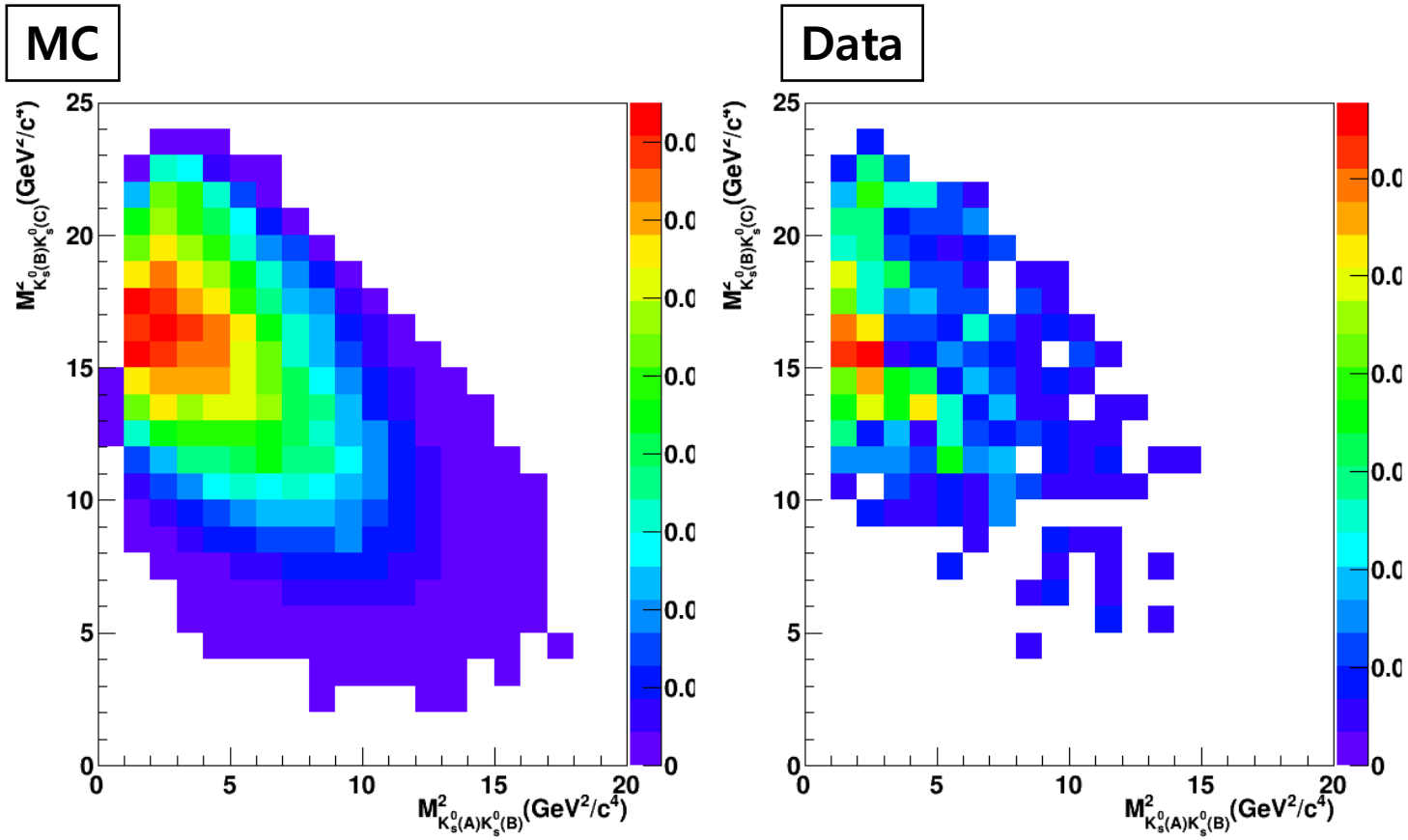




The NB cut is selected with highest figure of merit (FOM)

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

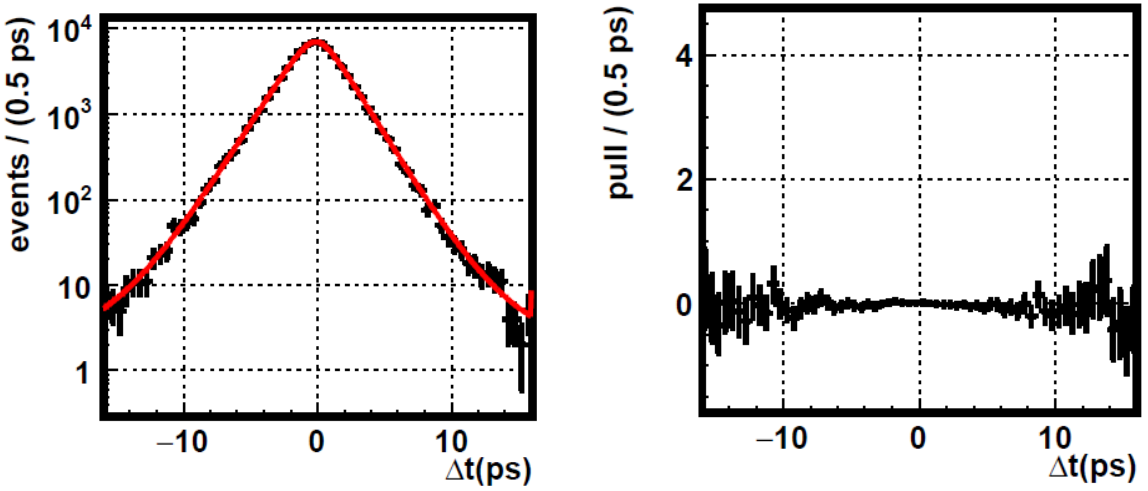
Dalitz plot



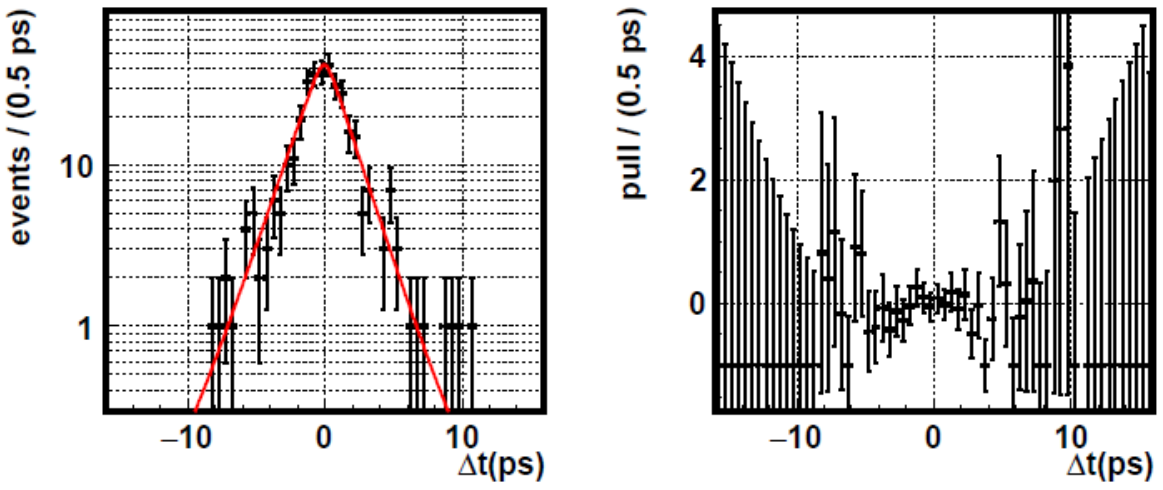
- Compare the dalitz plot for MC and data, our evtgen model for MC generation, PHSP_CP, well describes data.

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

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

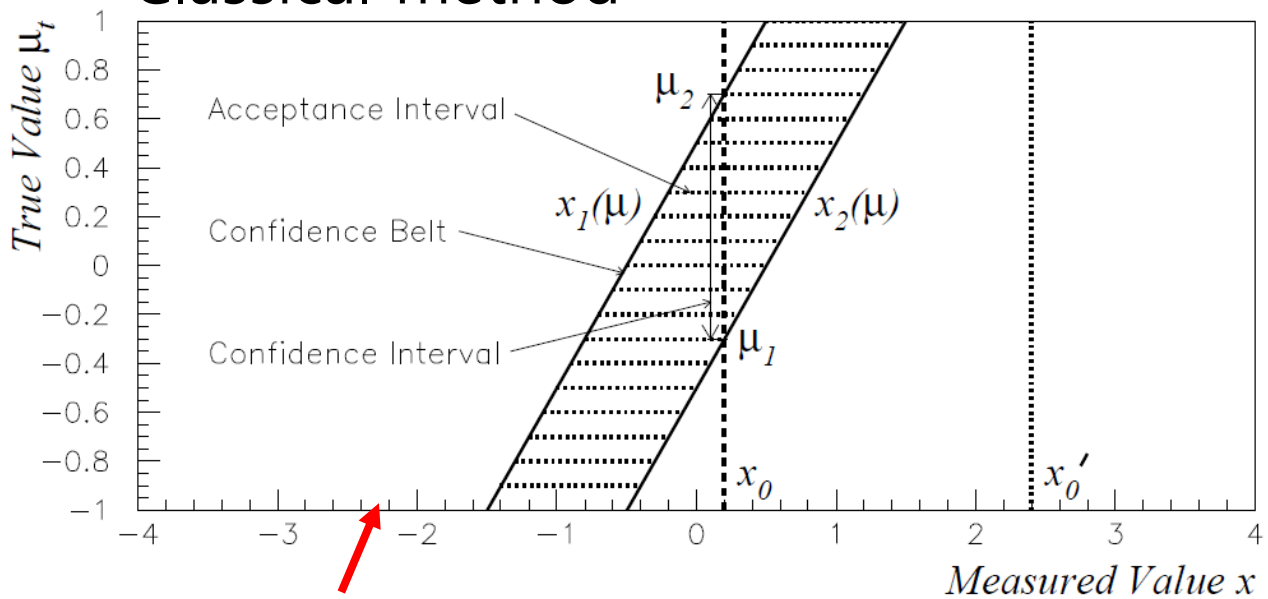
Main source of systematic error comes from non-primary charged track.

But statistical error is much larger than systematic.

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

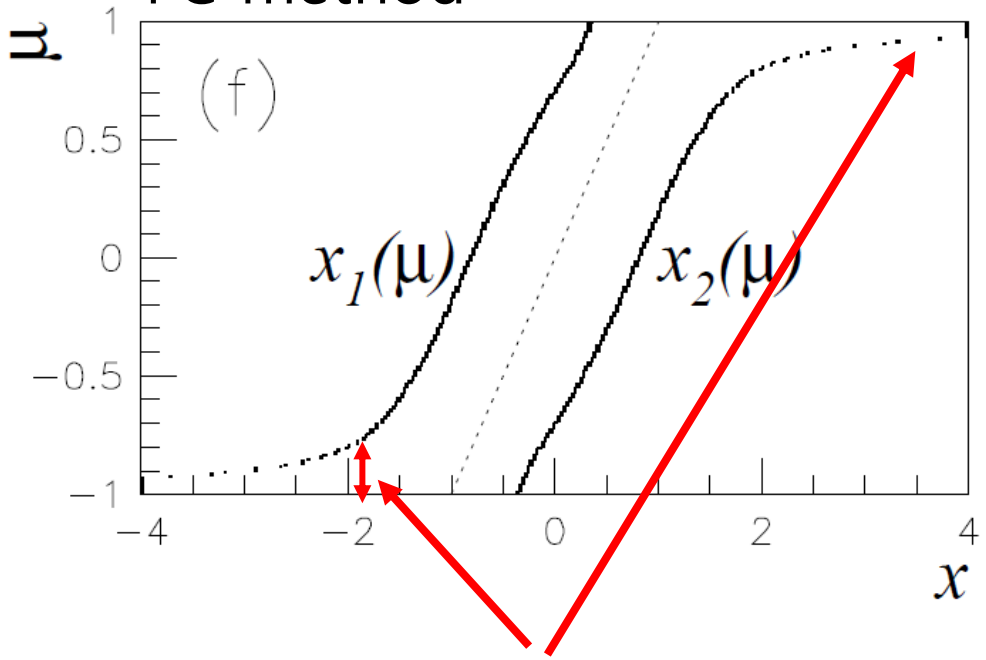
Classical and FC frequentist

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