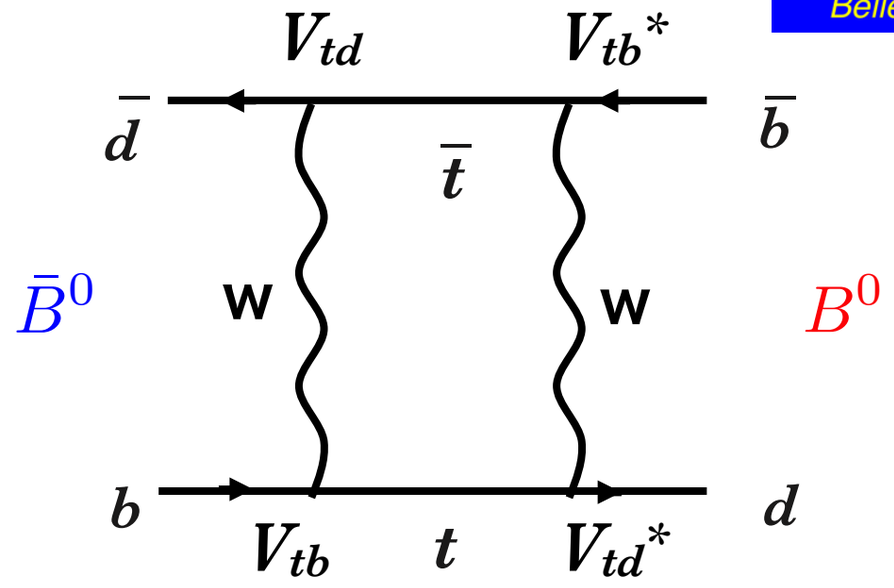
Time-dependent studies with early Belle II data

Yosuke Yusa
Niigata University

Introduction

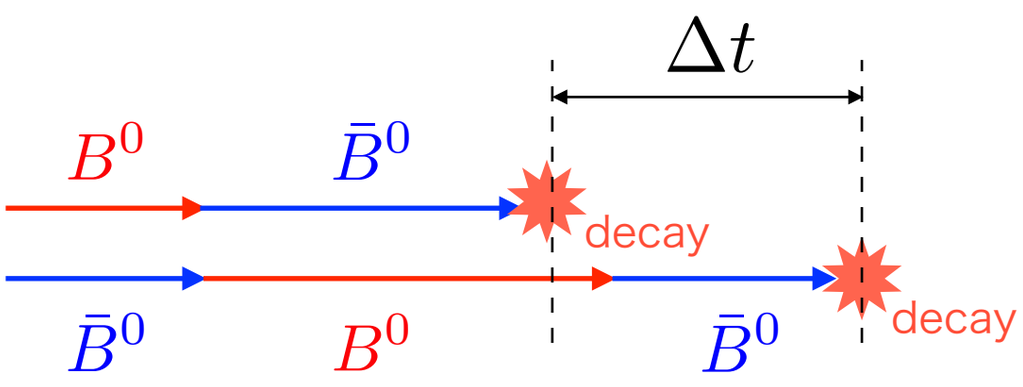
B^0-$\bar{B}^0$ mixing

B meson flavor changes via a box diagram and flavor oscillates with time evolution.



In Belle II, B meson pairs are produced from $\Upsilon(4S)$ decay and mixing occurs simlutaneously in two B mesons due to quntum entanglement.

→ Time-dependent analyses are performed by measuring a decay time difference of B mesons Δt.



Numbers of Mixed (B^0-B^0 or $\bar{B}^0$-$\bar{B}^0$) and Un-mixed (B^0-$\bar{B}^0$) events:

$$N_M \propto e^{-|\Delta t|/\tau_{B^0}} [1 - \cos(\Delta m \Delta t)]$$

$$N_U \propto e^{-|\Delta t|/\tau_{B^0}} [1 + \cos(\Delta m \Delta t)]$$

Introduction

Time-dependent CP violation (TDCPV)

Induced by quntum interference with decay to the CP-eigenstates.

Asymmery of TDCPV

$$A_{CP}(\Delta t) = \frac{\mathcal{P}(\overline{B^0}(\Delta t) \to f_{CP}) - \mathcal{P}(B^0(\Delta t) \to f_{CP})}{\mathcal{P}(\overline{B^0}(\Delta t) \to f_{CP}) + \mathcal{P}(B^0(\Delta t) \to f_{CP})}$$

$$= S \sin\Delta m\Delta t + A \cos\Delta m\Delta t$$

S: Time-dependent CPV parameter

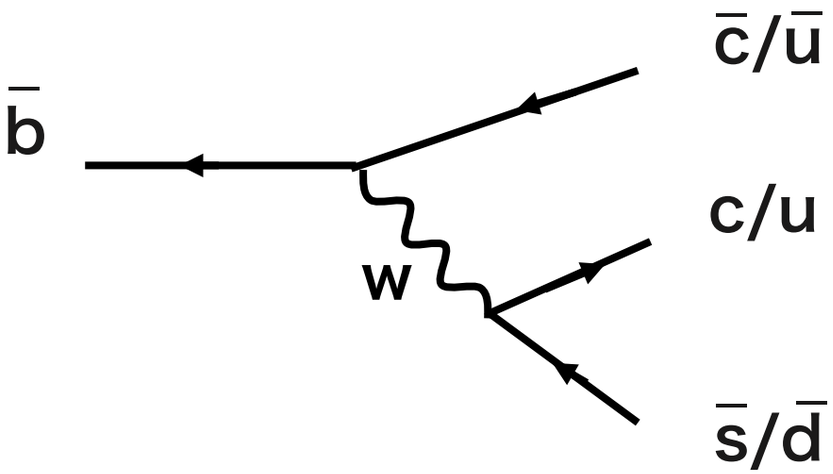
A(=−C): Direct CPV parameter

Δm: B-B mass difference

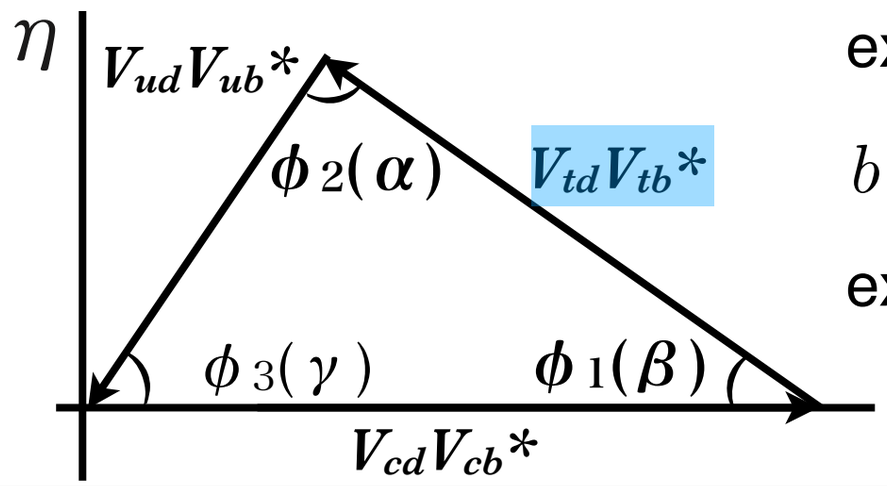
Δt: B-B decay time difference

Tree with box diagrram

→ S term contains CKM angles



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



$b \to c\bar{c}s$: ϕ_1

ex. $B^0 \to J/\psi K^0$

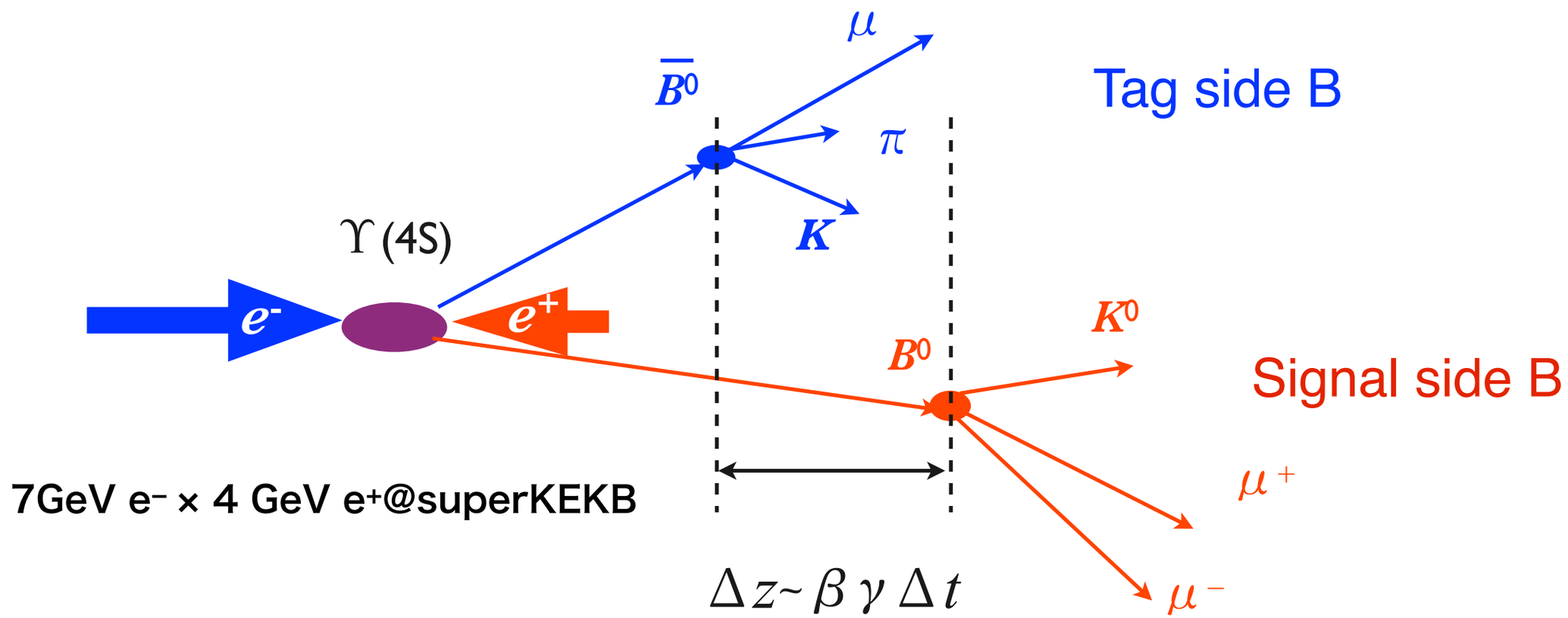
$b \to u\bar{u}d$: ϕ_2

ex. $B^0 \to \pi^+\pi^-$

Time-dependent analysis

To measure very small Δt, B mesons are produced through asymmeric energy collision of e^+e^- and displaccement of decay vertecies is measured.

→ convert to decay time using boost factor.

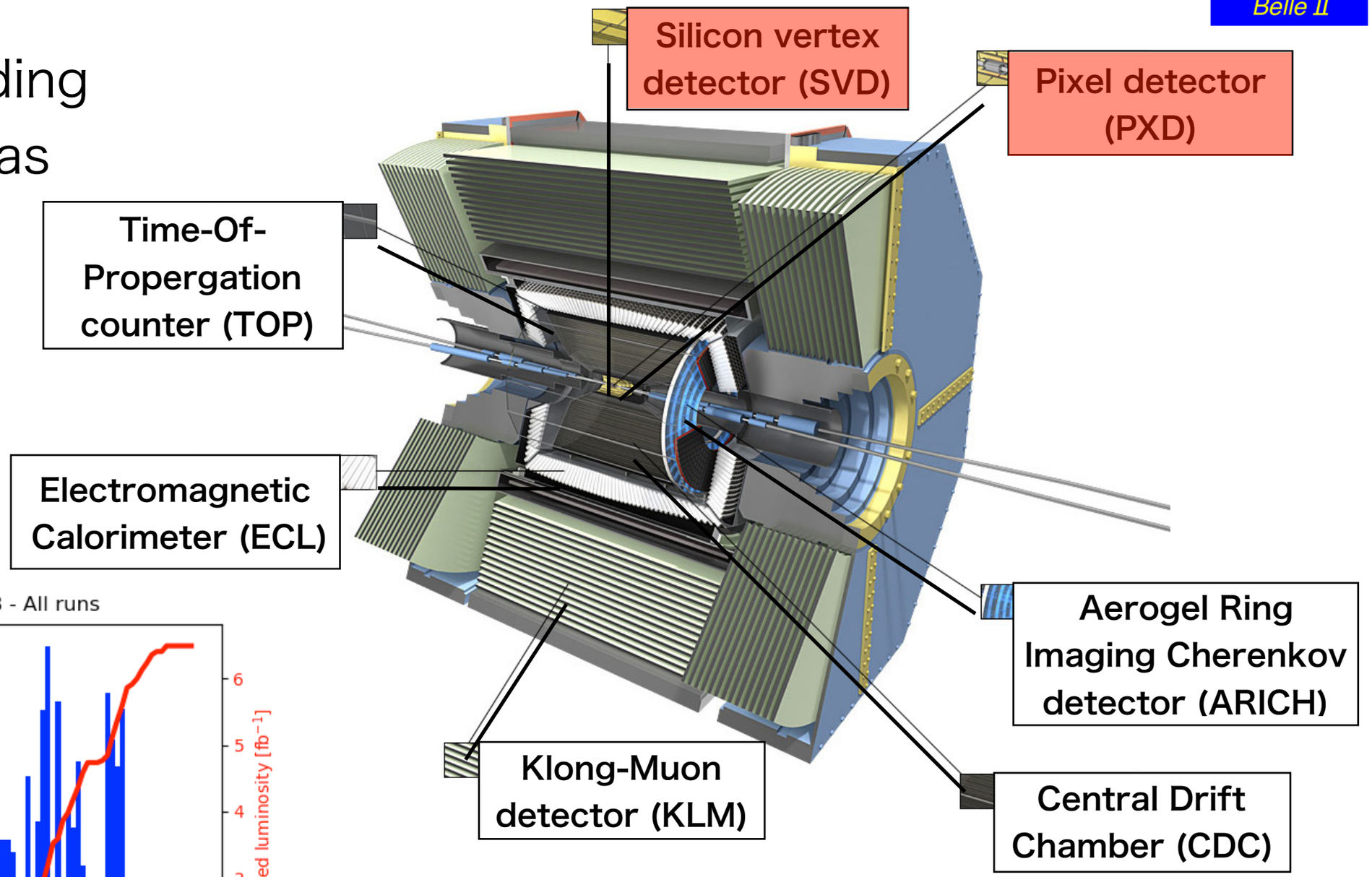


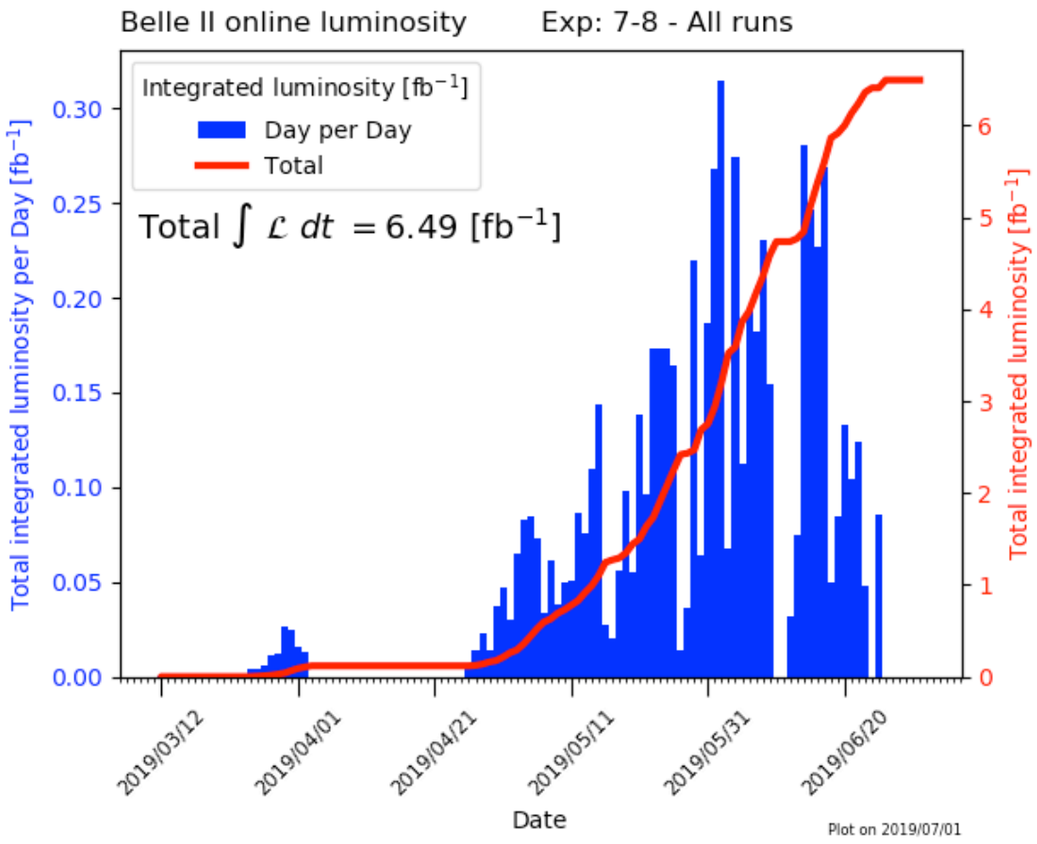
Reconstruction of decay vertex of B meson with good accuracy is a key item for time-dependent analysis in B-factory.

Experimental apparatus and data set

Full detector including vertex detectors has been in operation from 2019.

→Time-dependent analyses are in our reach.





Integrated luminosity (2019 runs)

On-resonance ~5.7 fb^{-1}

Off-resonance ~0.8 fb^{-1}

Calibrated on-resonance sample 2.62 fb^{-1}

Vertex detectors

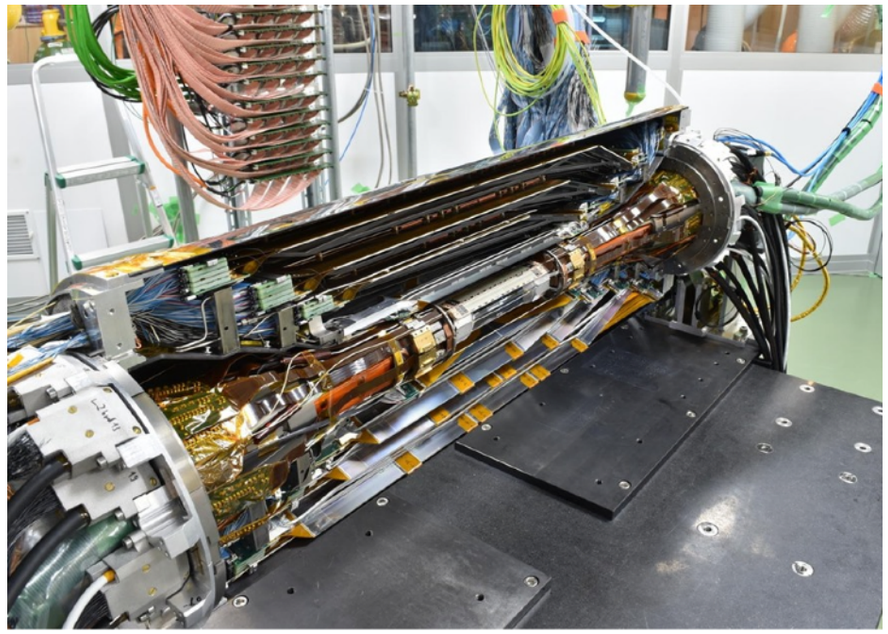
2-layers pixel（PXD）＋ 4-layers Double sided silicon detector（SVD）

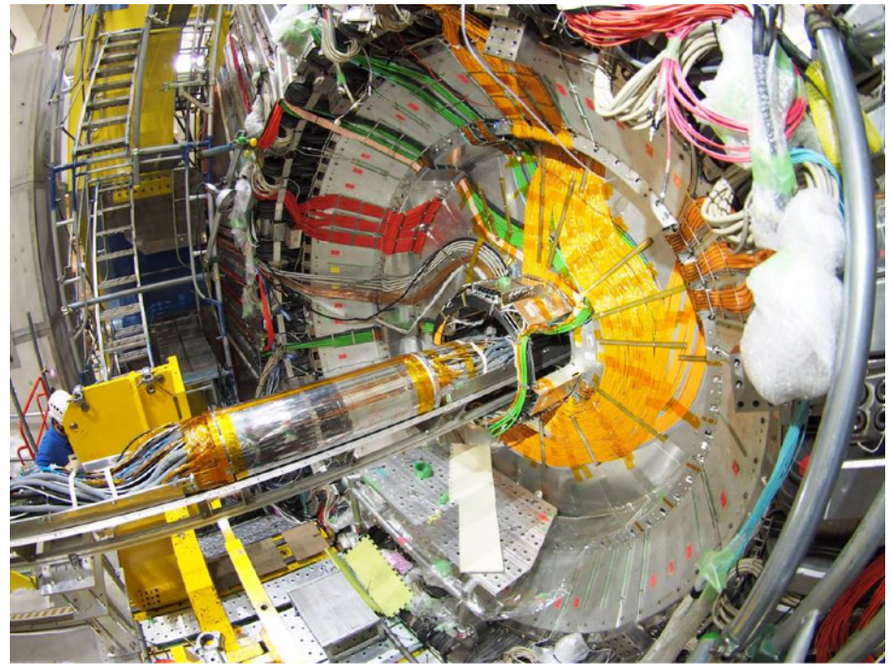
Due to problem in module production, we ran without a part of 2nd PXD layer.

・Closer inner layer contributes to improve vertex resolution.

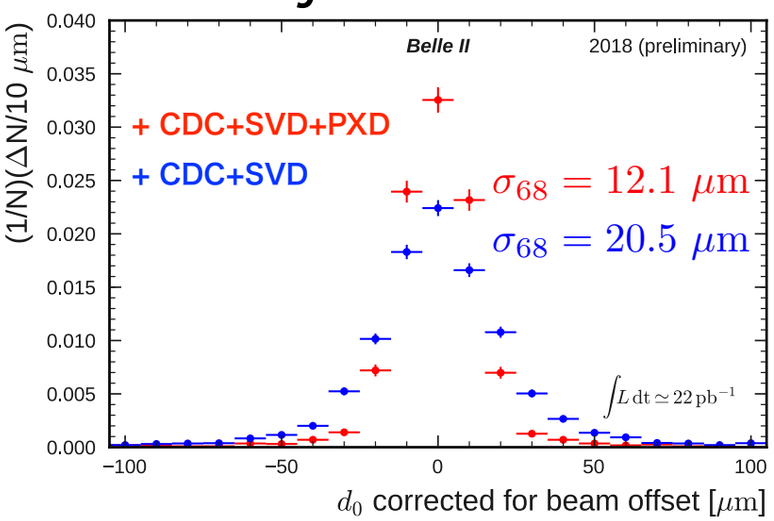
・More K_S^0 decays in SVD due to larger volume.

→ Increase efficiency of K_S^0 detection and vertex reconstruction using K_S^0 direction in the decays without primary track from decay vertex: $B^0 \to K_S^0\pi^0, B^0 \to K^*(\to K_S^0\pi^0)\gamma$

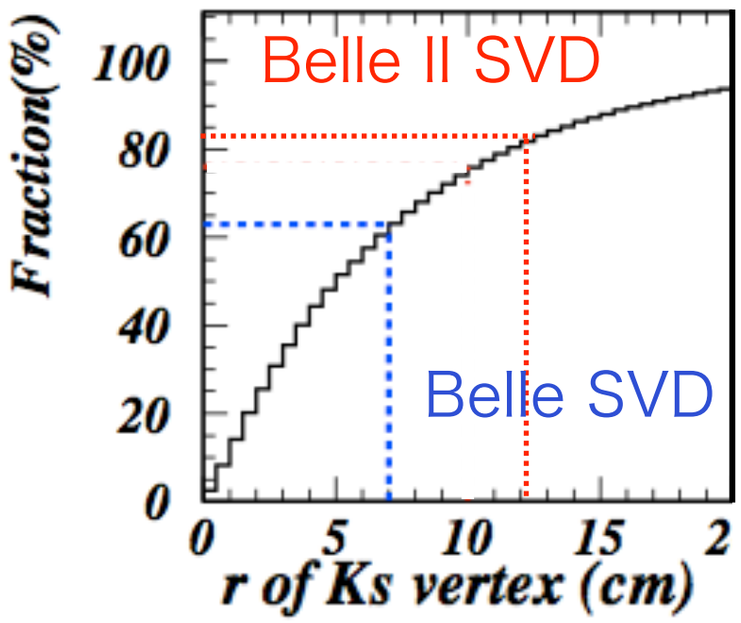




Installed in Belle II Nov. 2018



d_0: closest approach of track in x-y plane



Performance study of vertex detctors

Measurement of tracking impact parameter using Bhabha events.

Difference between width of the d_0 distribution and beam profile (σ_x= 14.8 μm, σ_y = 1.5 μm) corresponds to the detector resolution.

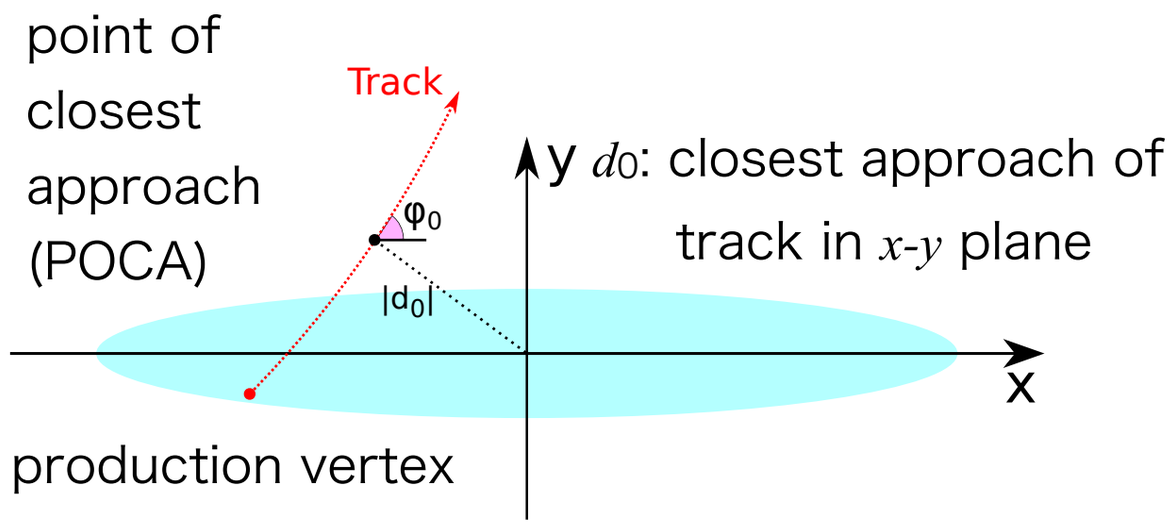
d_0 resolution is calculated as difference between electron and positron:

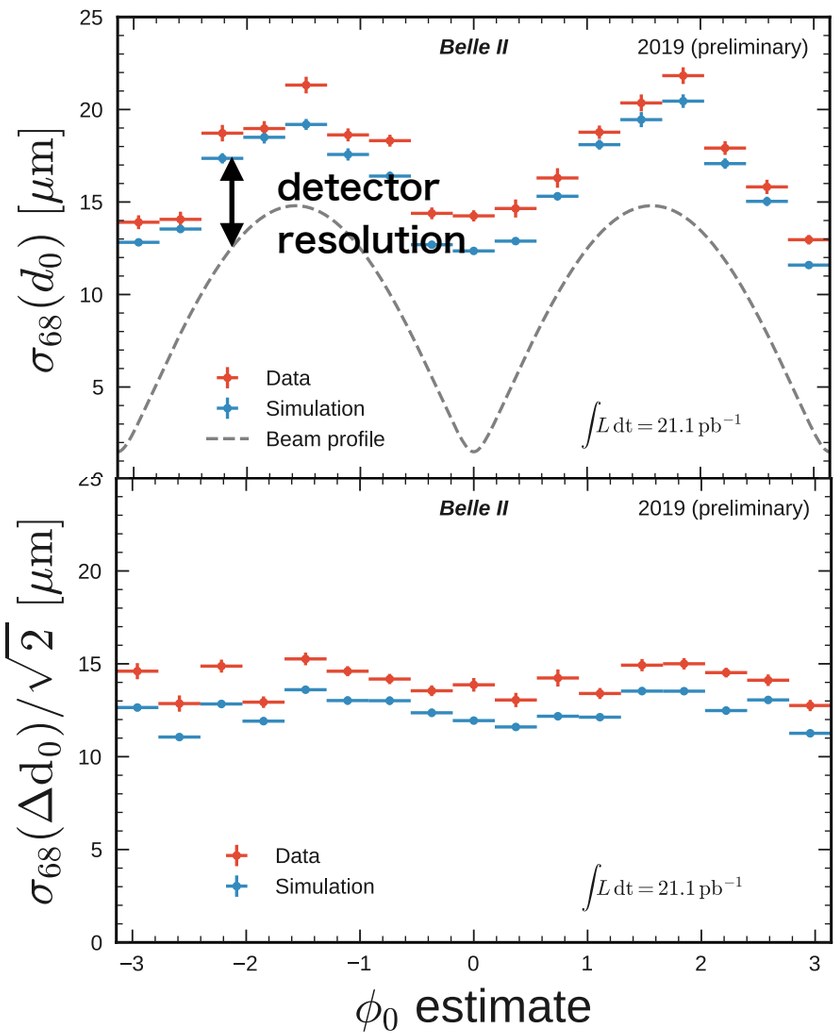
[$d_0(t_-) + d_0(t_+)$]/$\sqrt{2}$

Average: 14.2±0.1 μm (Data)

12.5±0.1 μm (Simulation)

→ Detector resolution is confirmed for small beam spot in x-y plane, we can move on to Δz (~O(100) μm) measurements.





Measurement of mixing

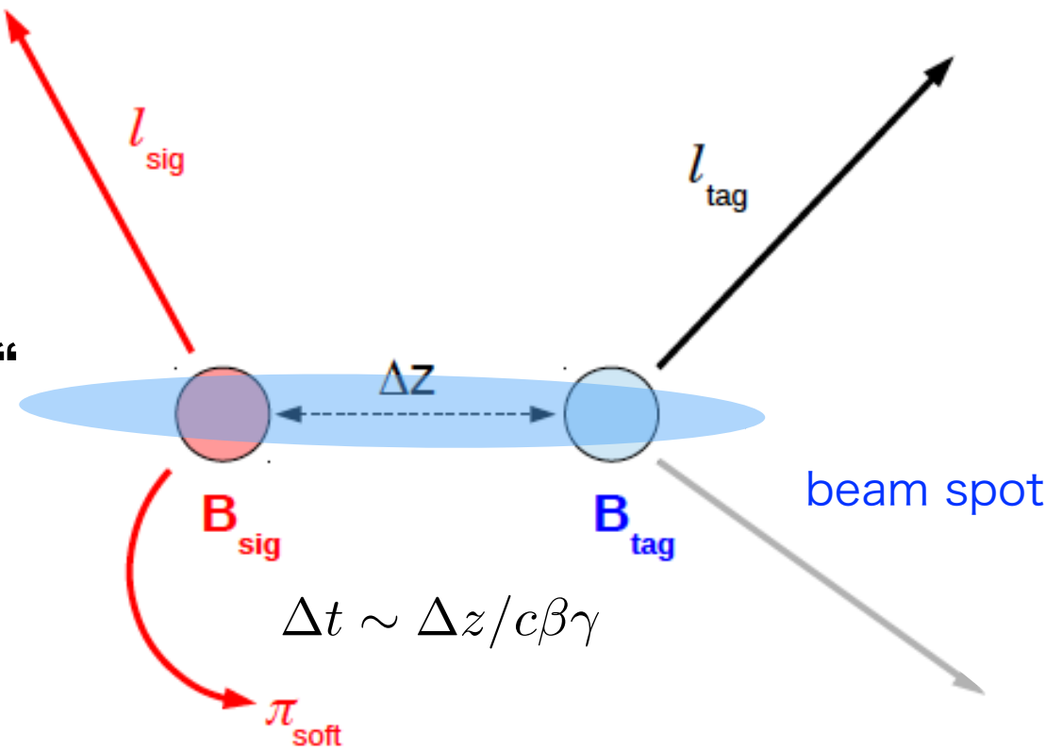
Mixing rate is measured using flavor information of B mesons.

Semi-leptonic signal characterized with high momentum lepton and low momentum pion from $D^{*+} \to D^0 \pi^+$ decay is reconstructed partially. $\mathcal{B}(B^0 \to D^{*-} \ell^+ \nu_\ell)$ = (5.05±0.14)%

Other B meson is tagged by high momentum lepton.
$\mathcal{B}(B^0 \to \ell^+ \nu_\ell X)$ = (10.33±0.28)%

B meson flavor is determined by charge of lepton.

"di-lepton events"

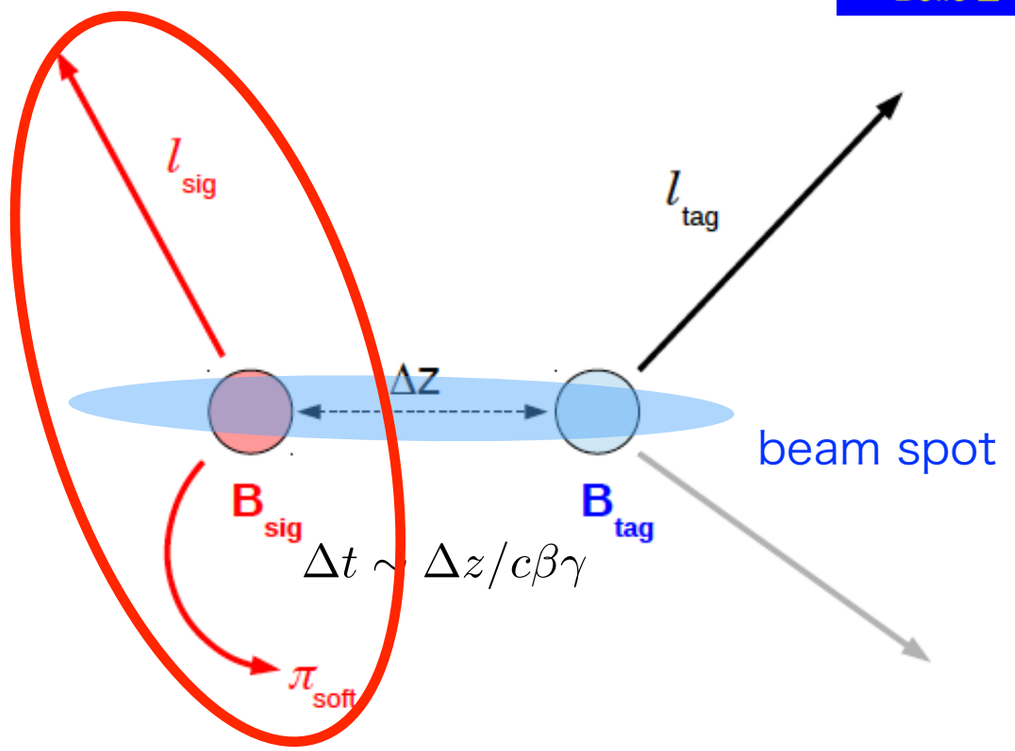


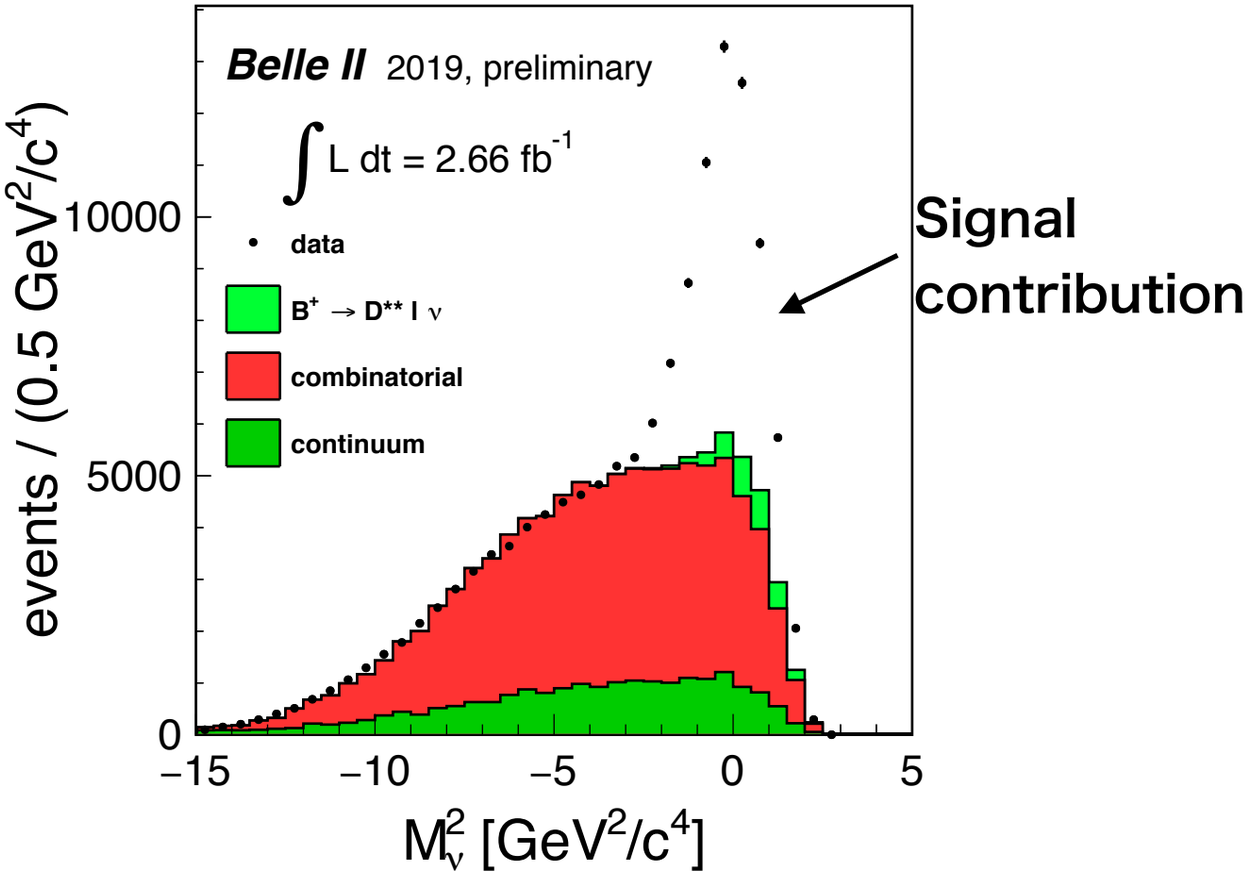
Reconstruction of signal decay

$B^0 \to D^{*-}\ell^+\nu_\ell$ signal is reconstructed using high momentum lepton and low momentum pion from $D^{*+} \to D^0\pi^+$ decay.

Kinematic variables of neutrino is calculated from lepton and pion momentum with assumption of B at rest.

Reconstructed signals:
35492±2209

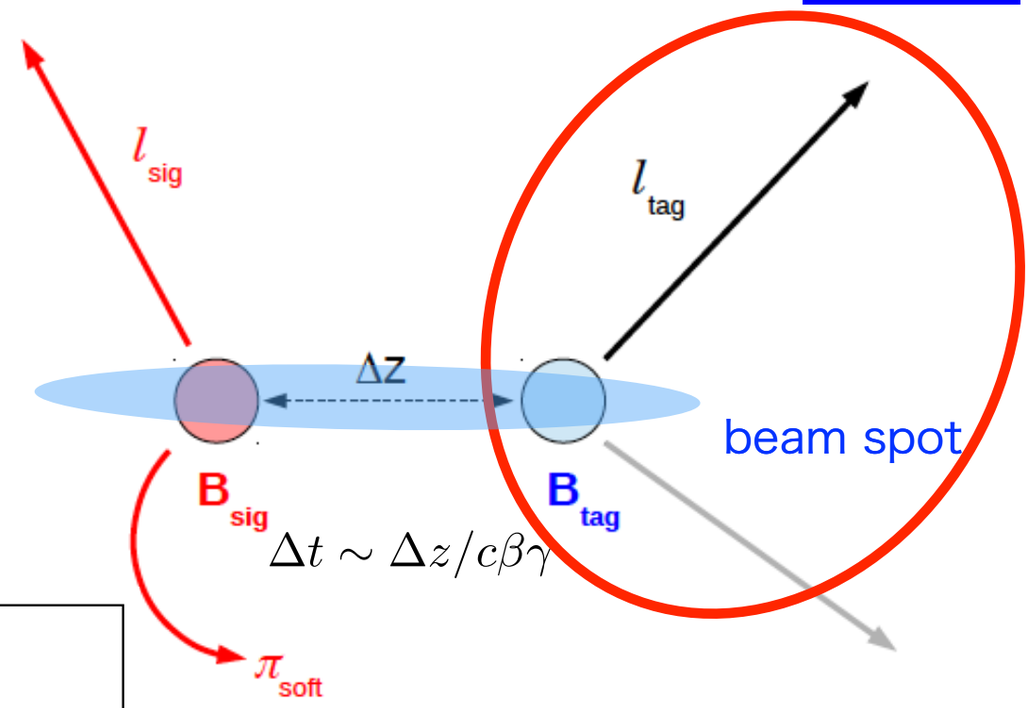


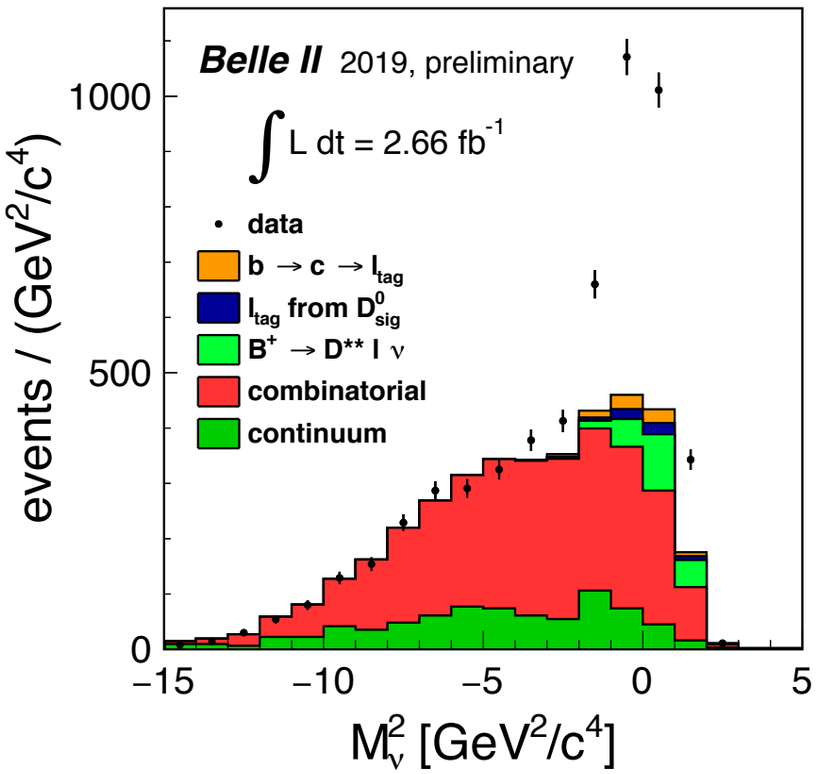


Tagged analysis

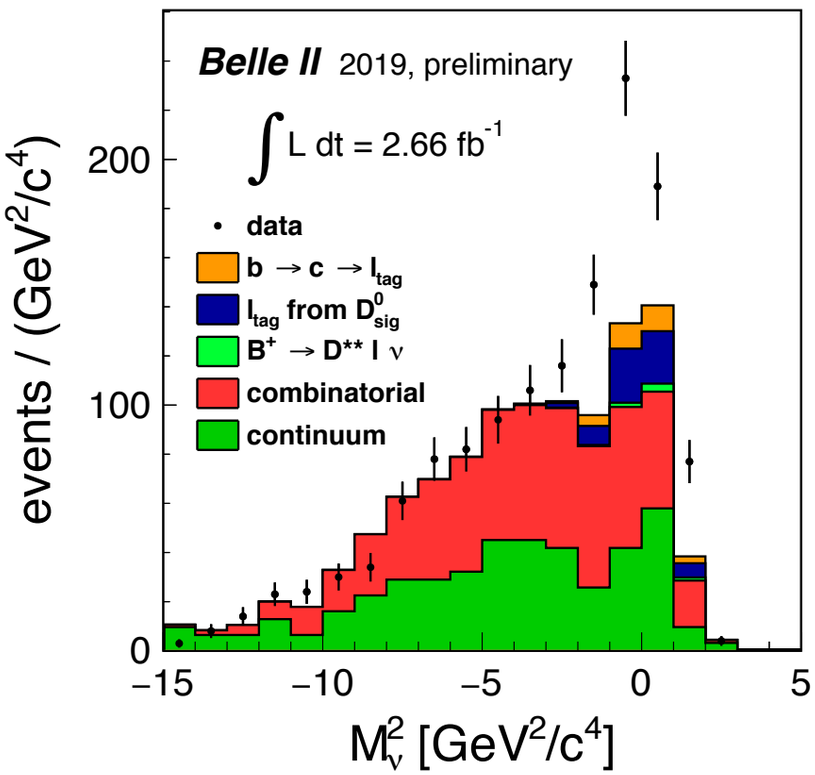
Flavor of B meson is tagged by high momentum lepton track and other B meson

Vertex is reconstructed with beam spot information for time-dependent analysis.





Unmixed signal (opposite sign) 1642±113



Mixed signal (same sign) 253±45

Fraction of mixed events with reconstruction efficiency ε

$$\chi_d = \frac{N_M/\varepsilon_M}{N_U/\varepsilon_U + N_M/\varepsilon_M}$$

= **(17.2±3.6)%**

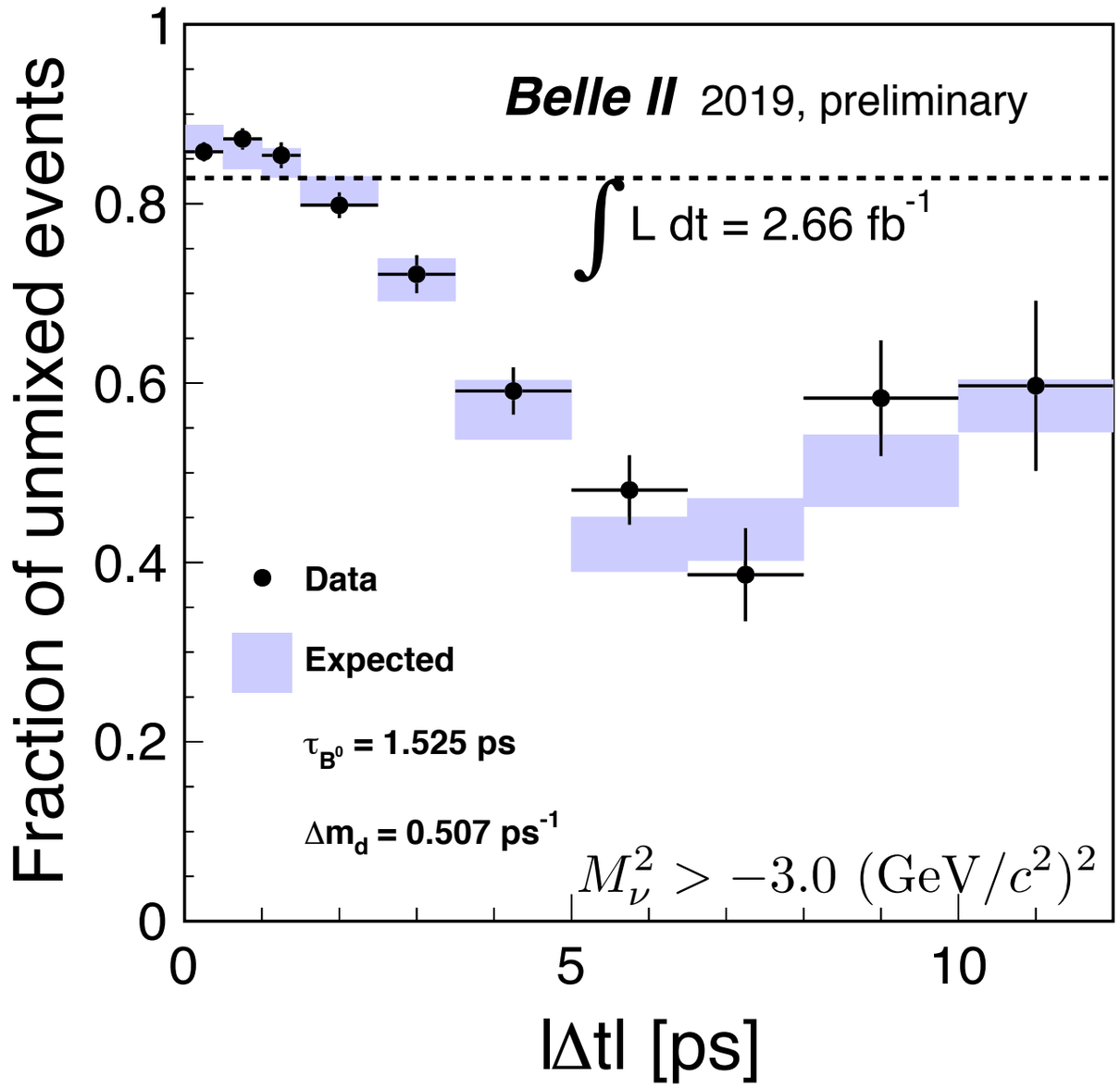
(WA= 18.6%)

Time-dependent analysis

Subdivide sample in each $|\Delta t|$ region and calculate fraction of unmixed events.

Oscillation pattern is observed as $|\Delta t|$ evolution.

→ consistent with MC expectation with τ_{B^0} and Δm_d world average.

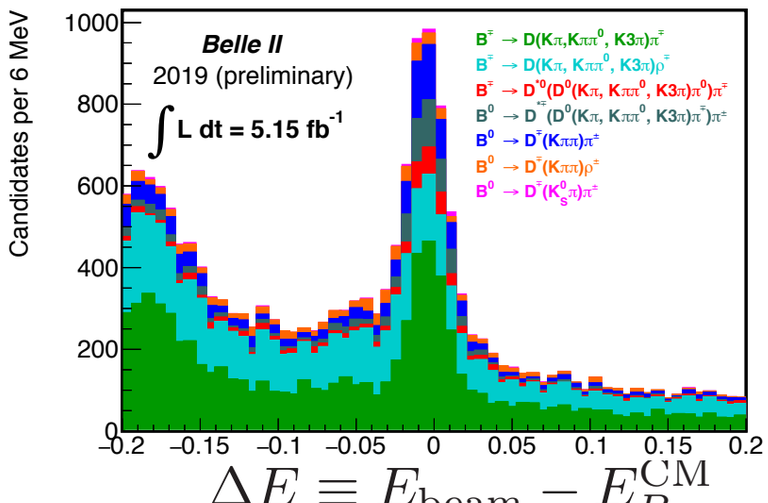


$\chi_d = (17.2 \pm 3.6)\%$

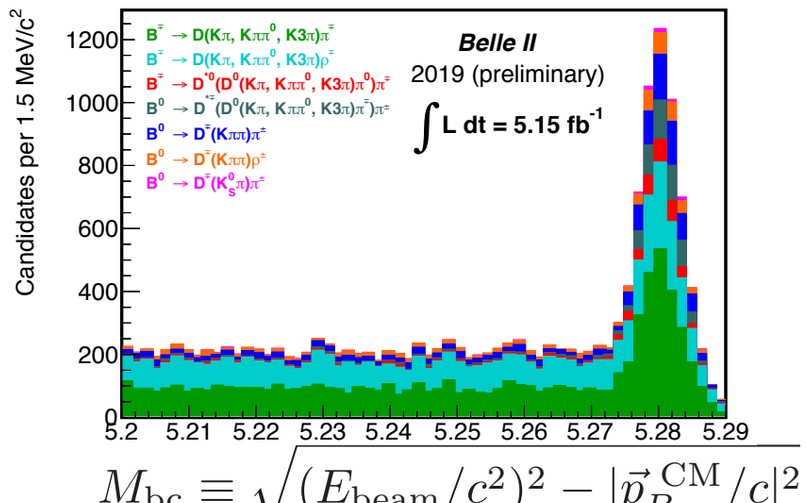
Samples for τ_{B^0} / Δm_d measurements

τ_{B^0} and Δm_d will be measured using large numbers of flavor-specific samples of $B \to Dh(h = \pi, \rho)$ and $B^0 \to D^{*-}\ell^+\nu_\ell(\ell = e, \mu)$.

They have been found in experimental data.

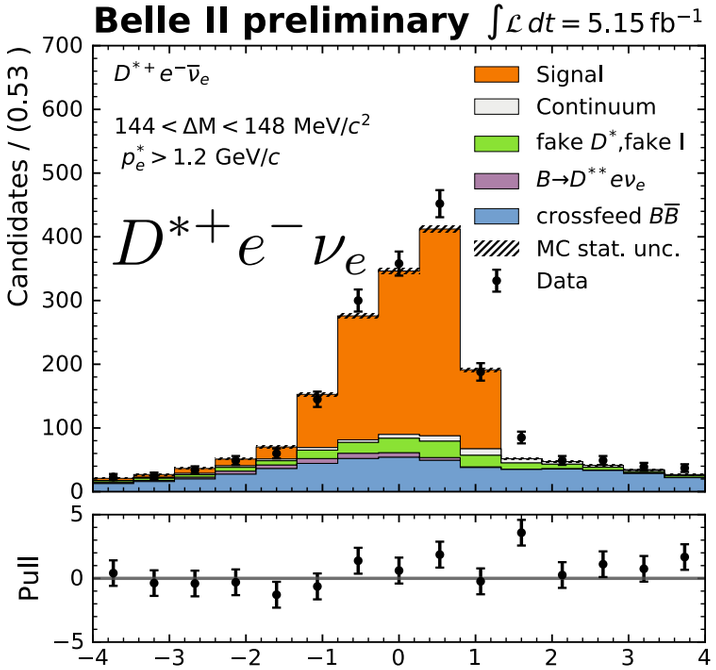


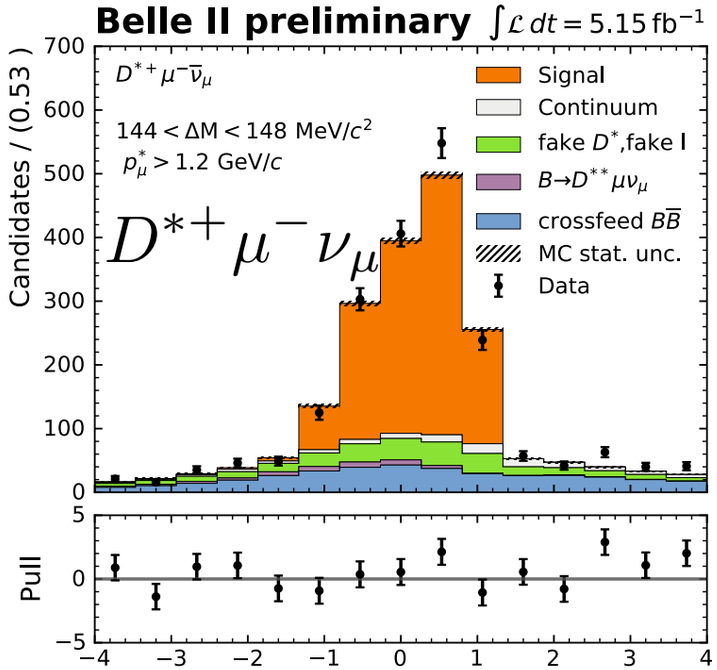
$$\Delta E \equiv E_{\rm beam} - E_B^{\rm CM}$$



$$M_{\rm bc} \equiv \sqrt{(E_{\rm beam}/c^2)^2 - |\vec{p}_B^{\,\rm CM}/c|^2}$$

~4500 signals



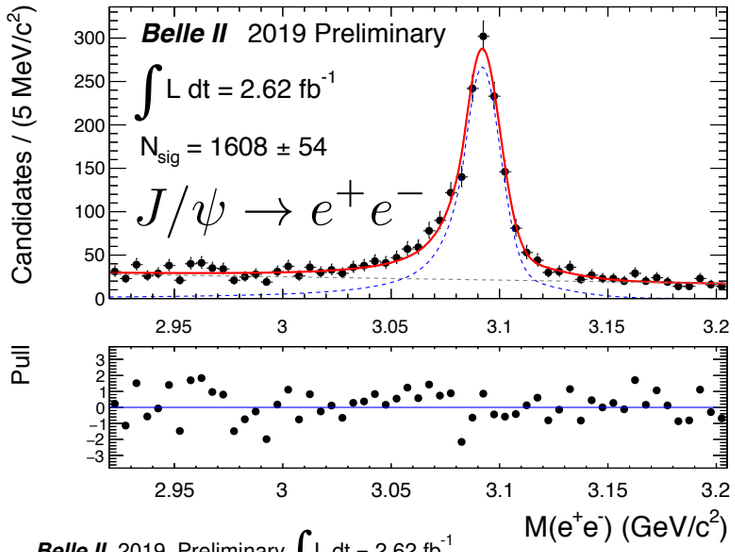


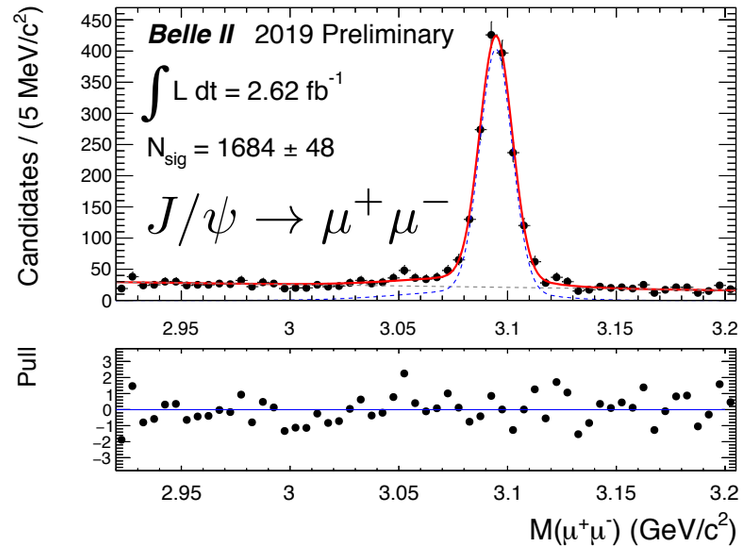
~2300 signals

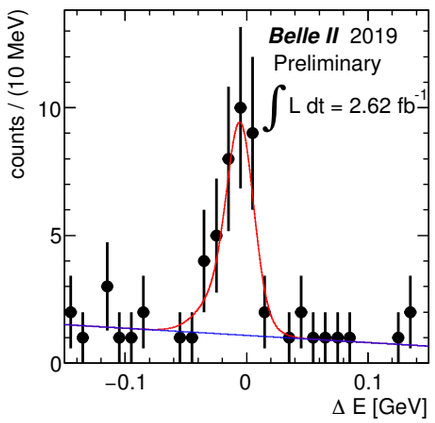
$$\cos\theta_{BY} = \frac{2E_B^* E_Y^* - M_B^2 - m_Y^2}{2p_B^* p_Y^*} \qquad Y : D^*\ell \ \text{ system}$$

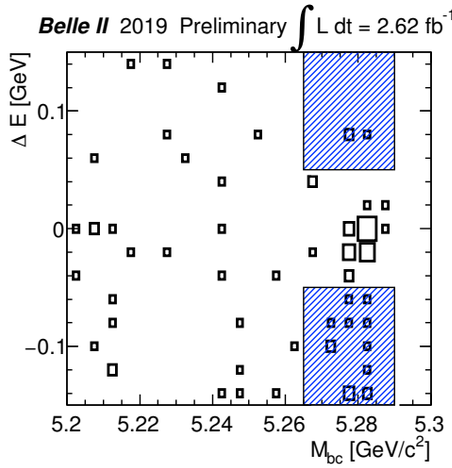
Samples for TDCPV study

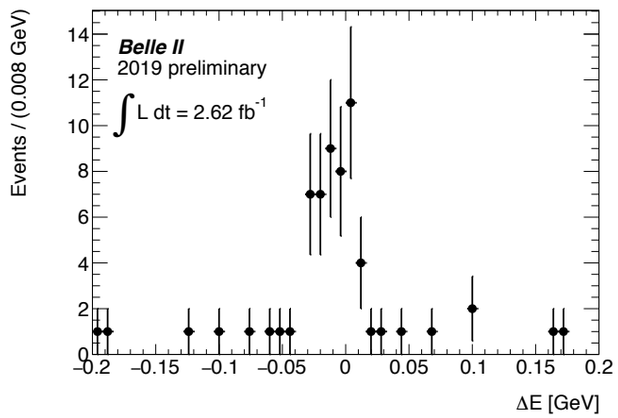
$B \to J/\psi X$

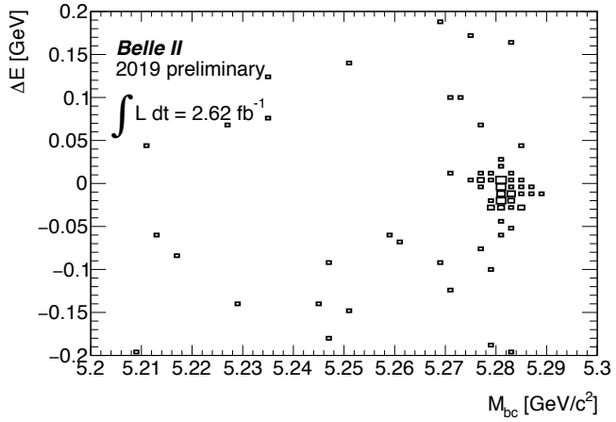






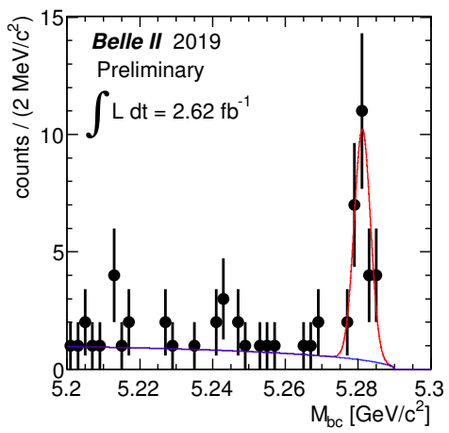






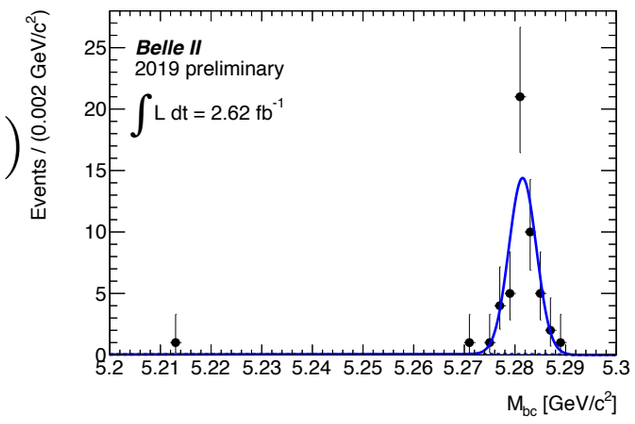
$B^0 \to J/\psi K^0_S$

yield = 26.9±5.2



$B^0 \to J/\psi\ K^{*0}(\to K^+\pi^-)$

yield = 48.6±7.0



CP-eigenstate for $\sin 2\phi_1$ measurement and its control sample mode are observed using early data.

Summary

- Time-dependent analysis using B decay vertex information is available in Belle II owing to vertex detectors installed in last year.

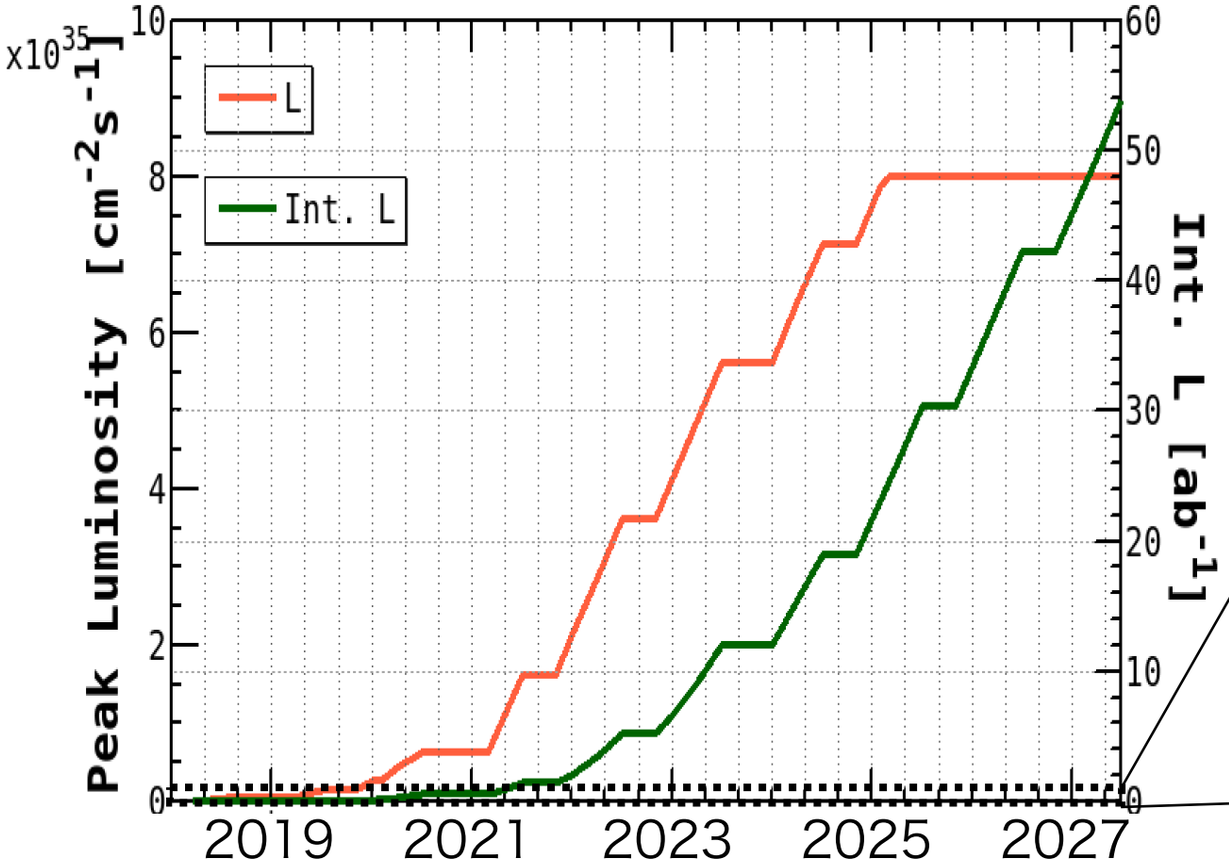
- Calibration and Performance check of the vertex detectors are confirmed using experimental data.

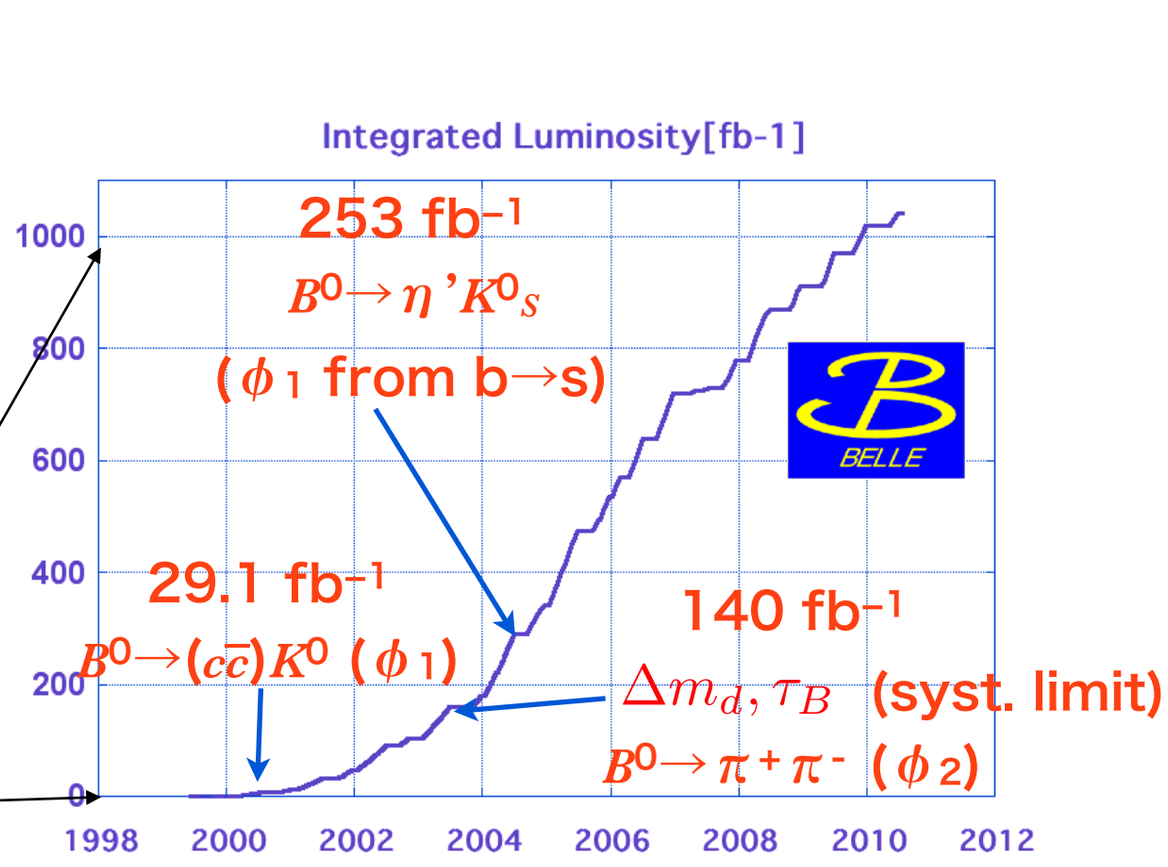
- B^0-$\bar{B}^0$ mixing is observed as an oscillation of time-dependent mixing rate distribution.

- Many decays for time-dependent studies are reconstructed found in early data sample.

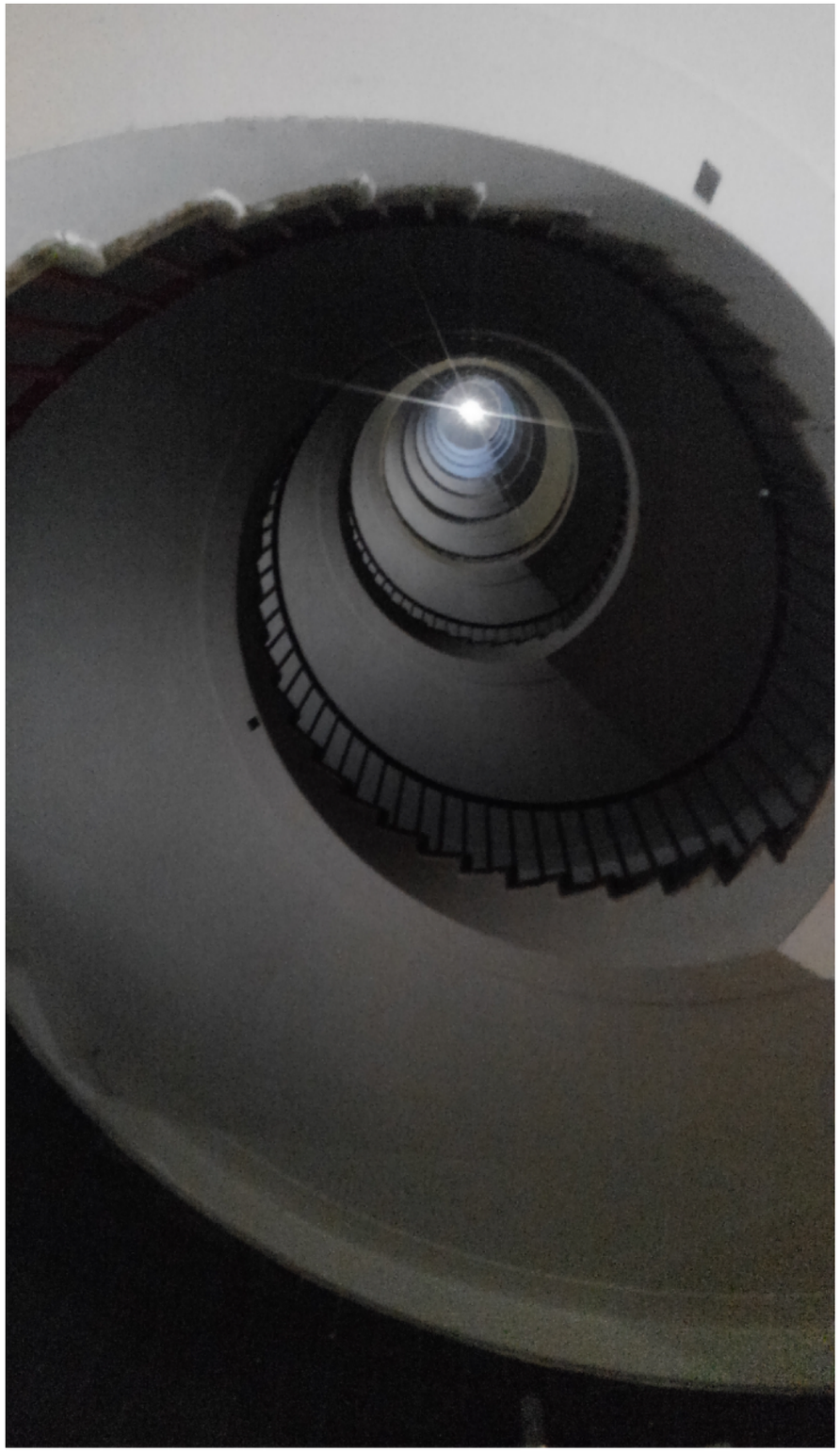
Future prospects

We plan to accumulate a few hundred fb^{-1} data until next summer.
Re-observations of time-dependent CP violation in several CP-eigenstates are expected.
Mixing and lifetime measurement will reach to systematic limit soon.
We have to consider strategy to reduce systematic uncertainty.





We have just started to go up stairs toward 50 ab^{-1}.



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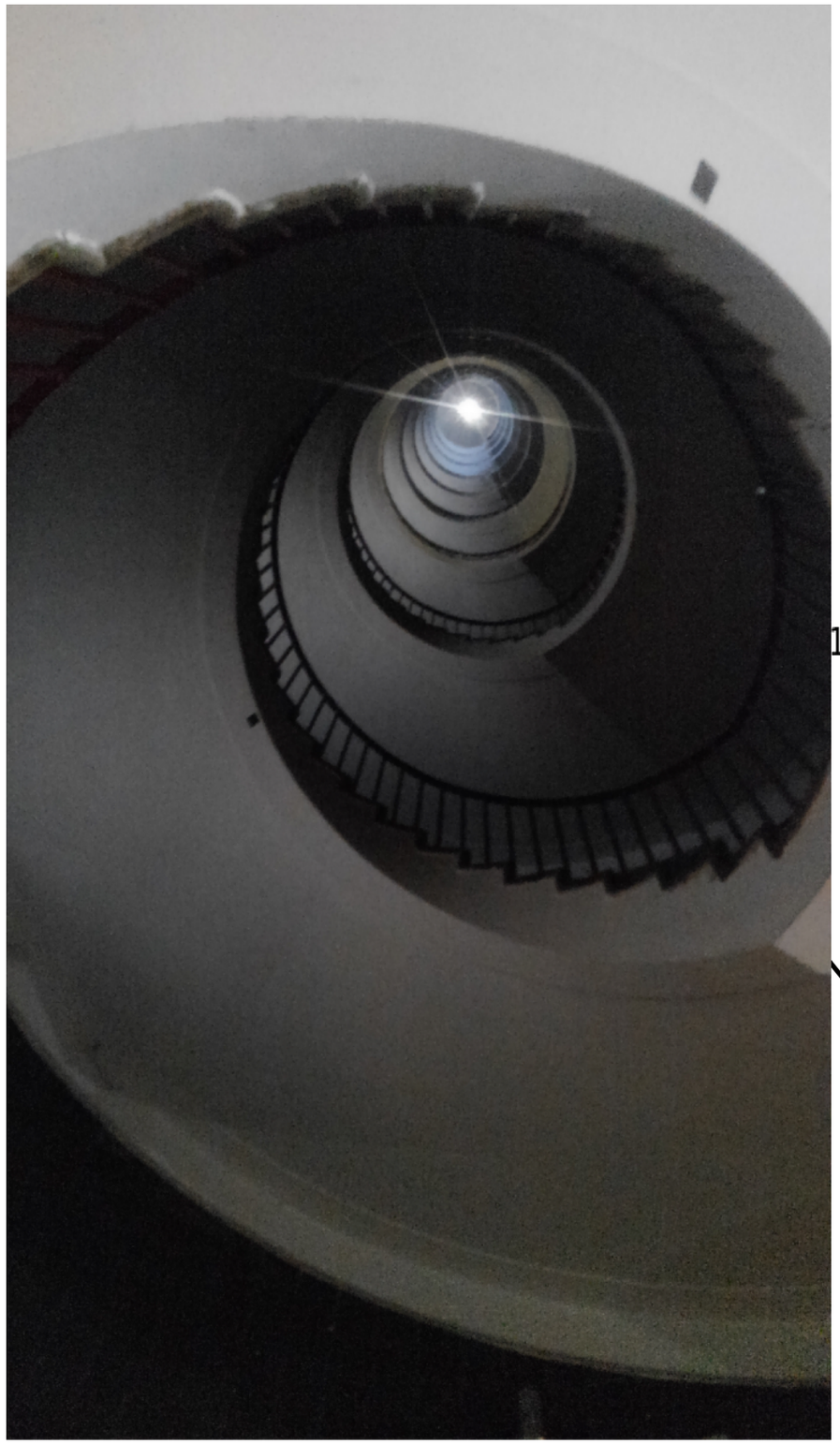
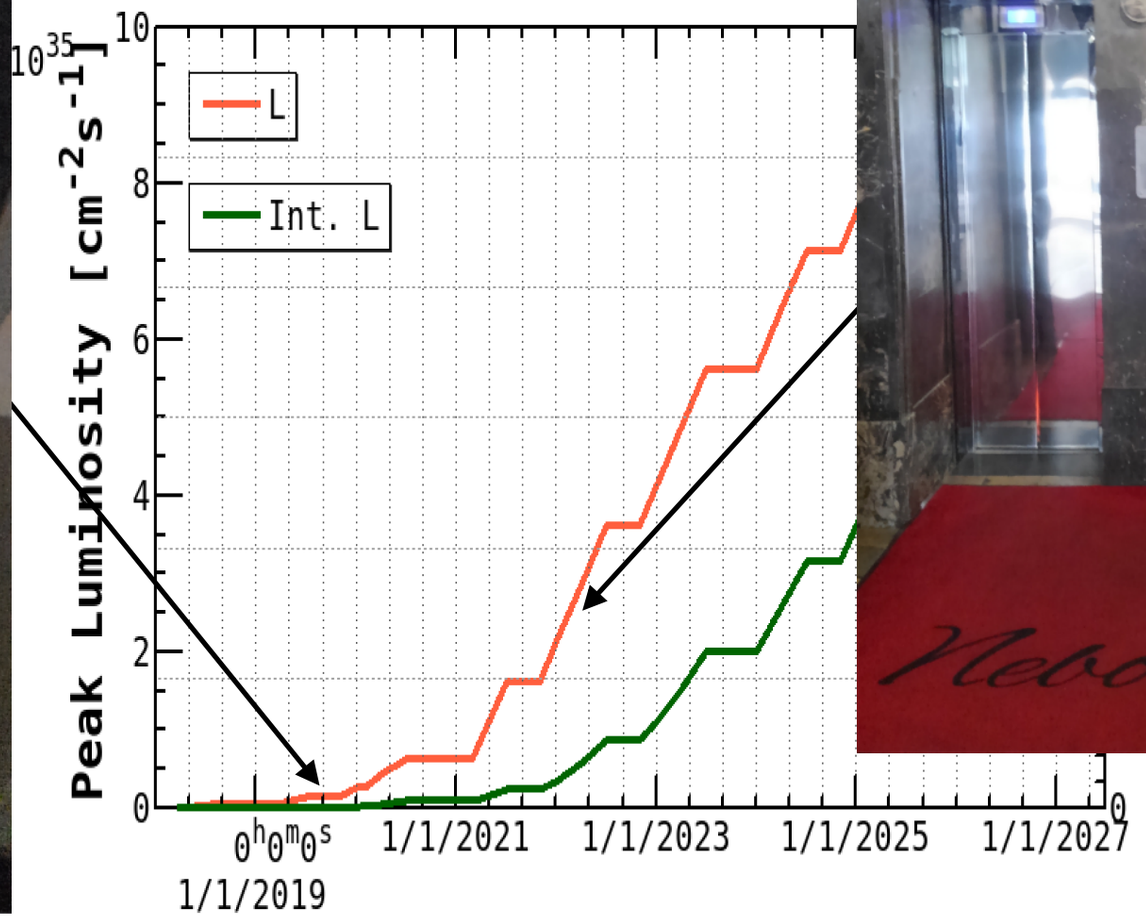


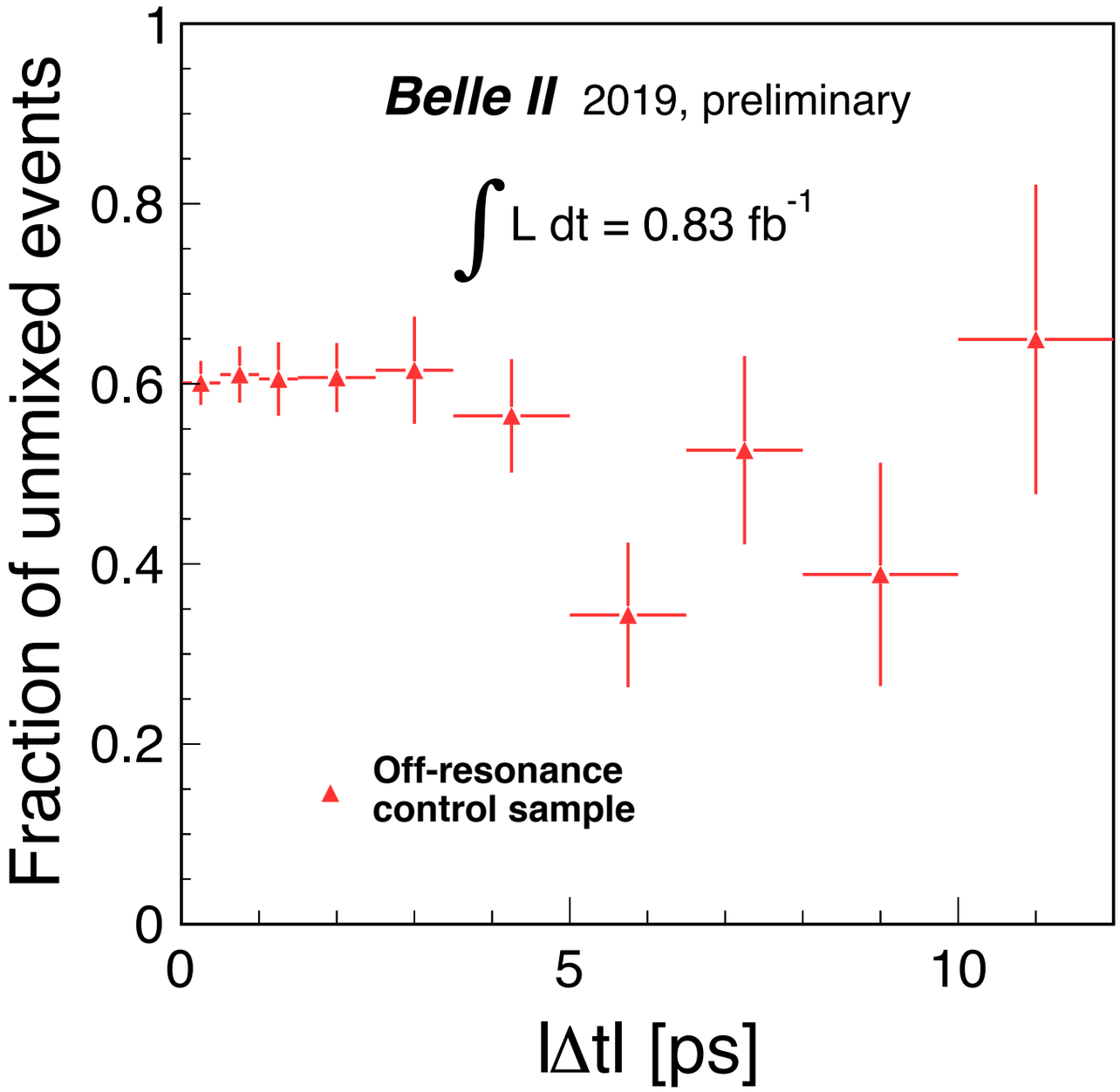
and get elevator at some floor…



At top floor, we expect to view around flavor physics world to find out new physics! (I hope it will be sunny at that time.)

backup

Time-dependent analysis



No oscillation pattern is seen in sample without $B\bar{B}$.
(compatible with flat with $\chi^2/\mathrm{ndf} = 1.541$)