Time-dependent studies with early Belle II data

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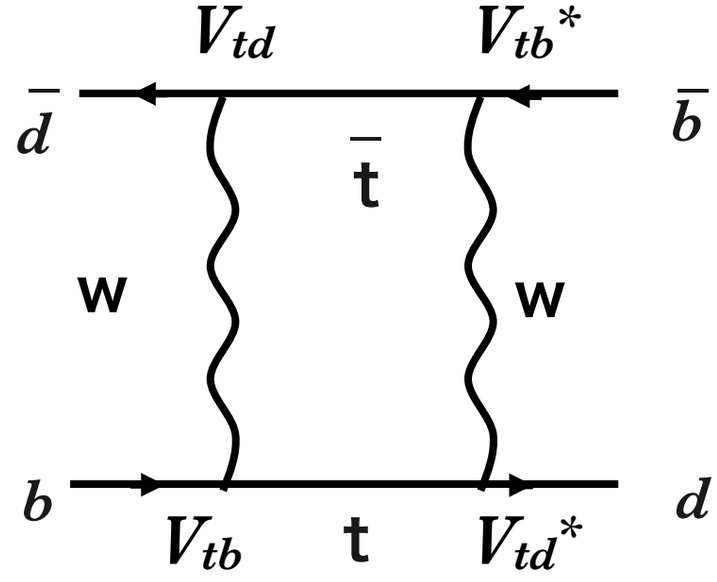
Introduction

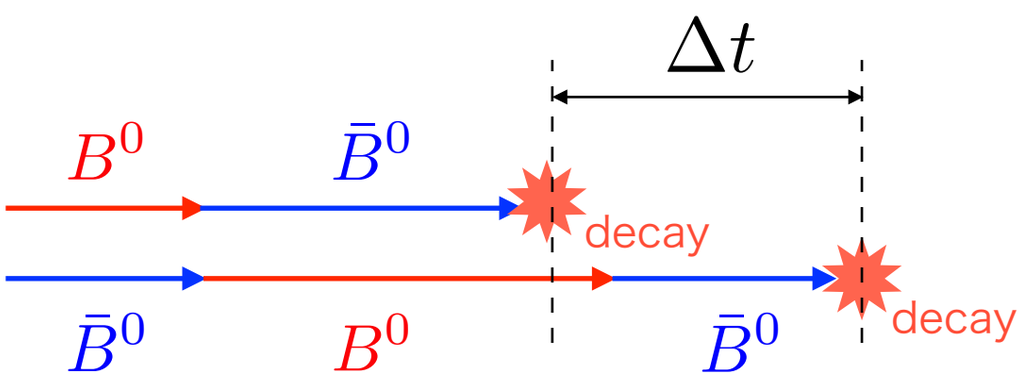
B^0-$\bar{B}^0$ mixing

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:

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

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

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

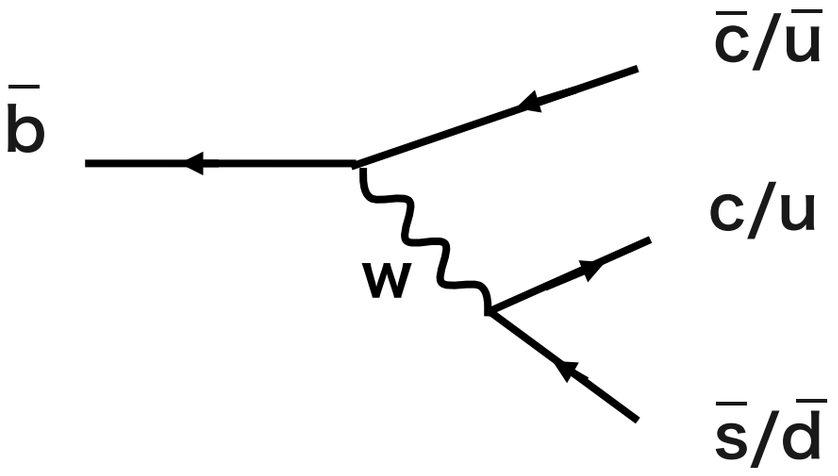
A(=−C): Direct CPV parameter

Δm: B-B mass difference

Δt: B-B decay time difference

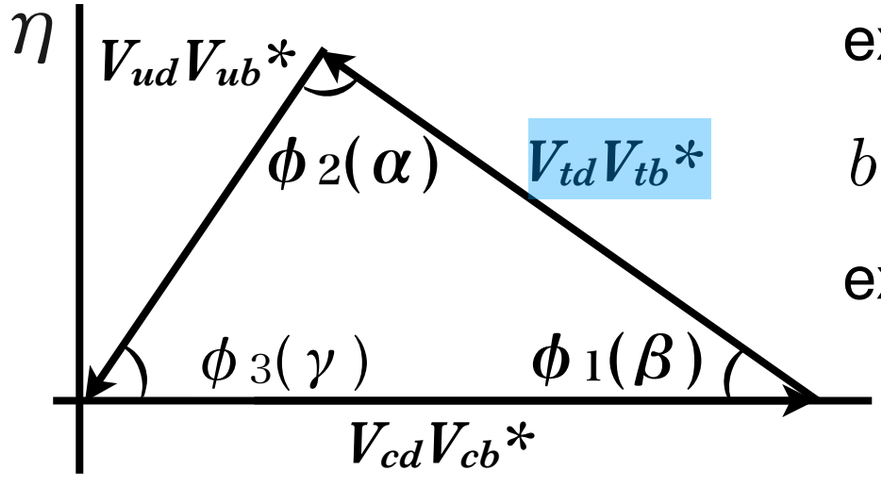
Tree with box diagrram

→ 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. $B^0 \to J/\psi K^0$

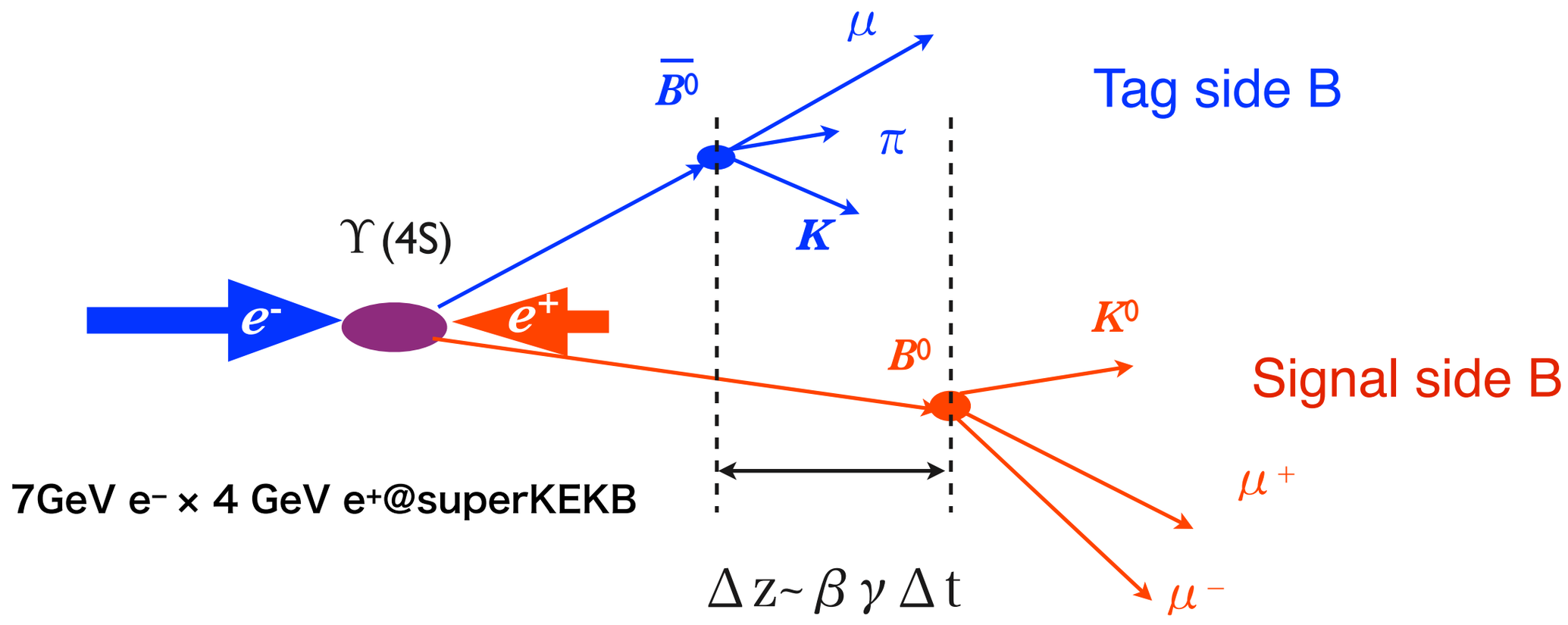
$b \to u\bar{u}d$: ϕ_2

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.

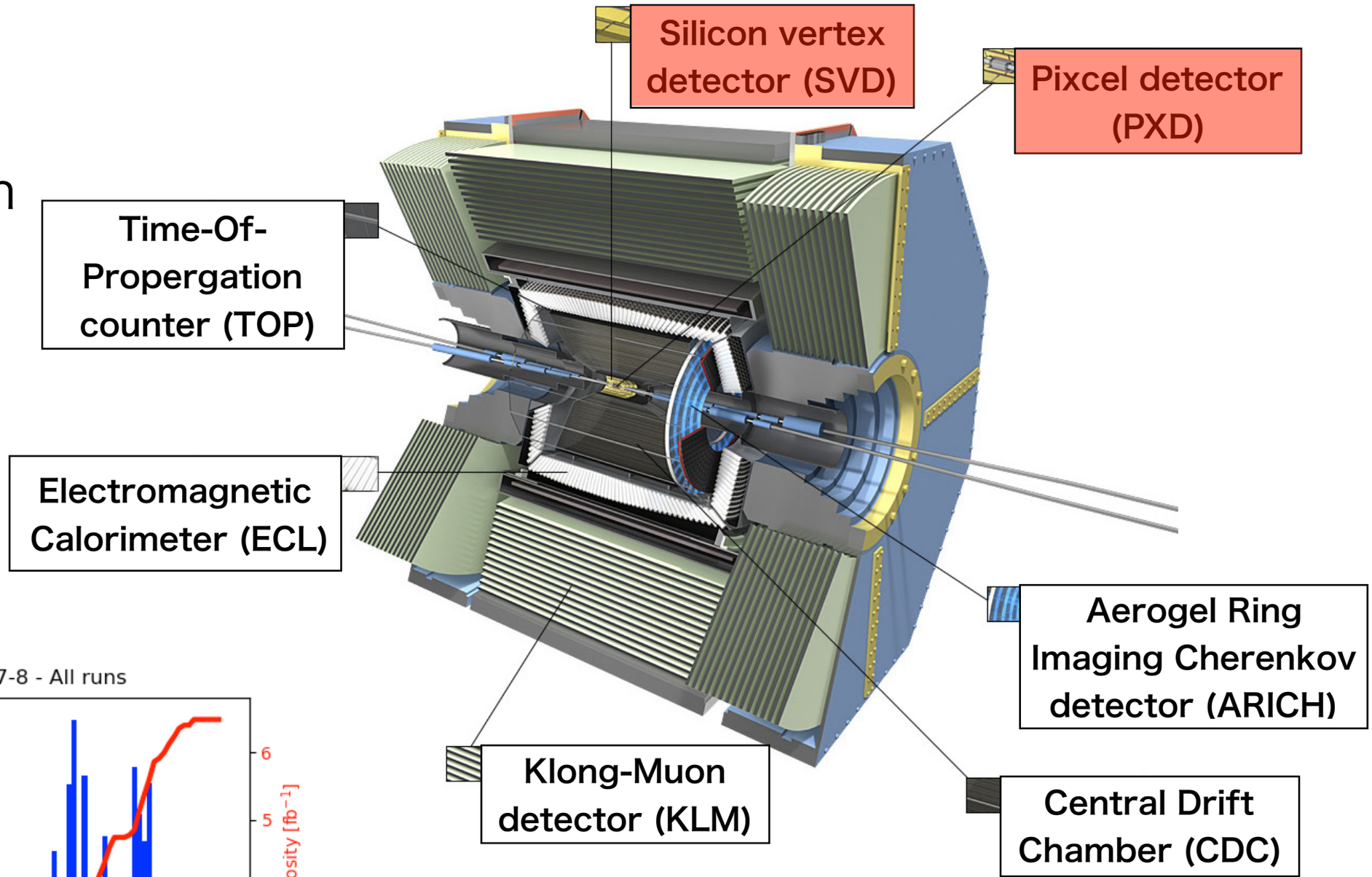


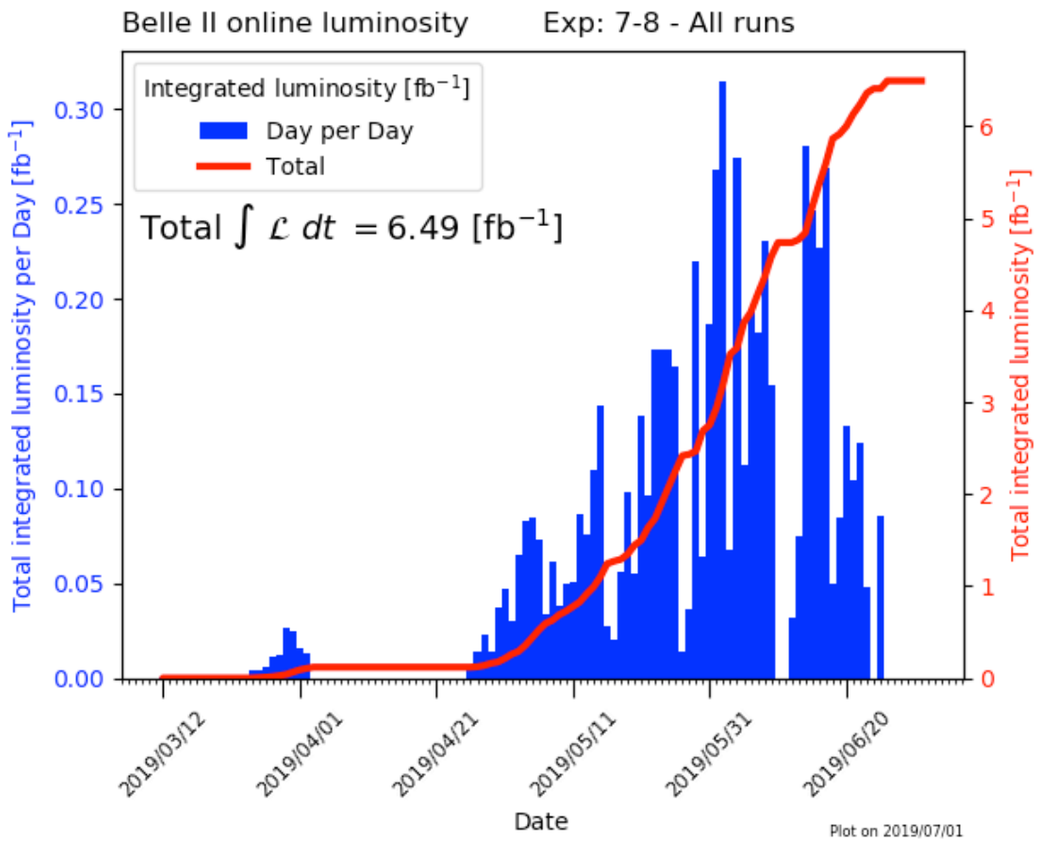
Reconstruction of decay vertex of B meson with good accuracy is a key item for time-dependent analysis in B-factory.

Experimental appartus 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}

Caribrated on-resonance sample

2.62 fb^{-1}

Vertex detectors

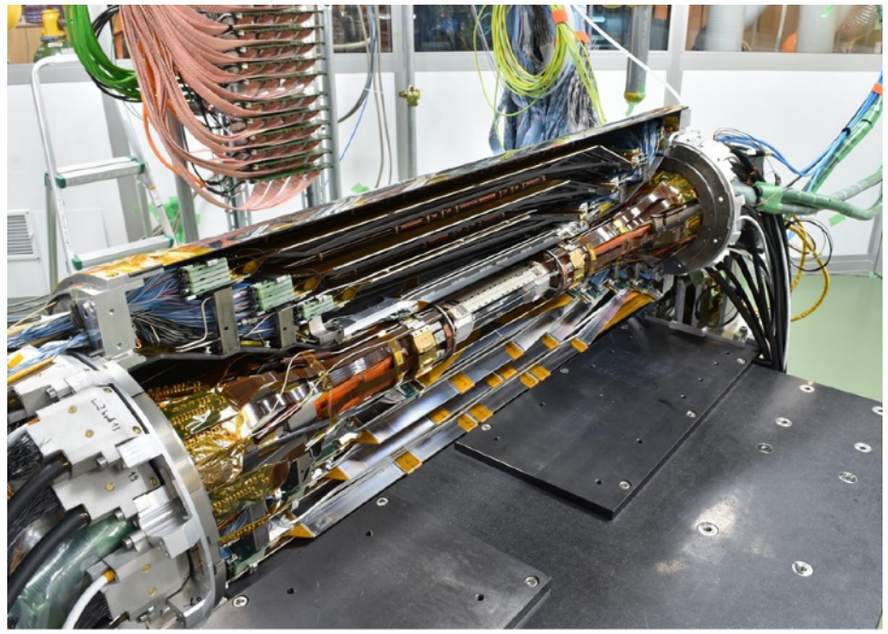
2-layers pixcel（PXD）＋ 4-layers Double sided silicon detector（SVD）

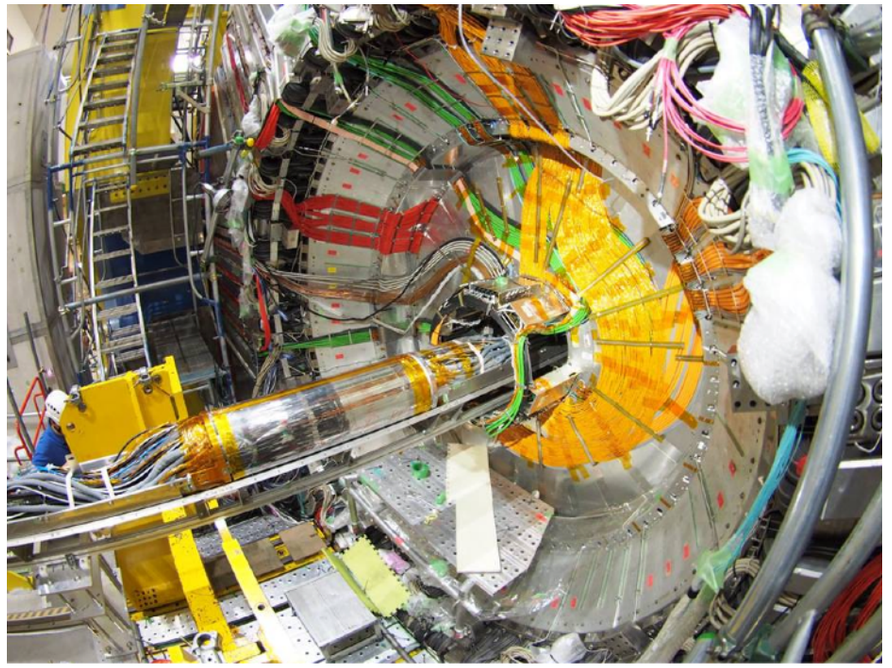
Due to problem in module production, we ran without a part of 2nd PXD layer.

・Closer inner layer contributes to improve vertex resolution.（~40%）

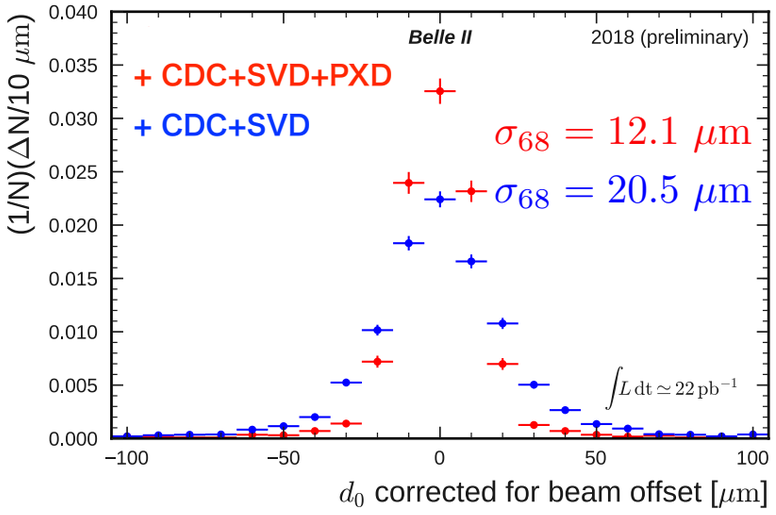
・More K_S^0 decays in SVD due to larger volume.

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

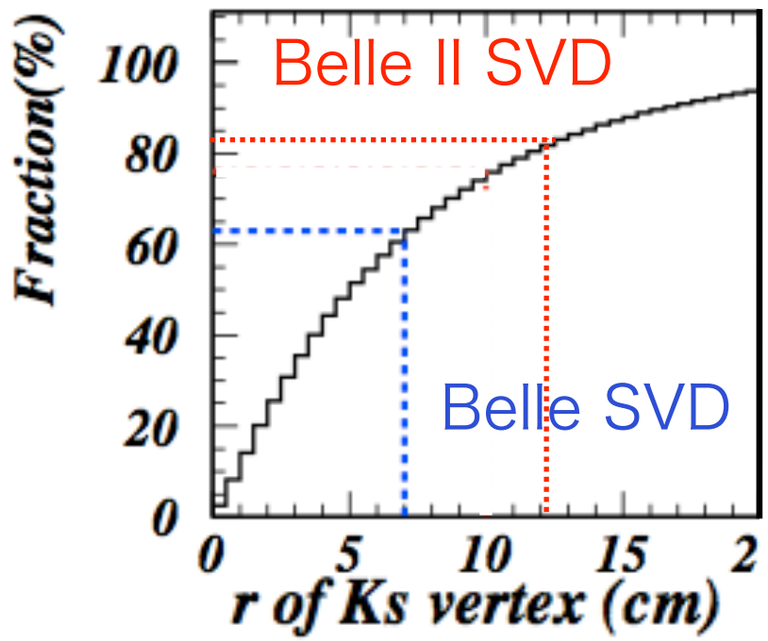




Installed in Belle II Nov. 2018



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:

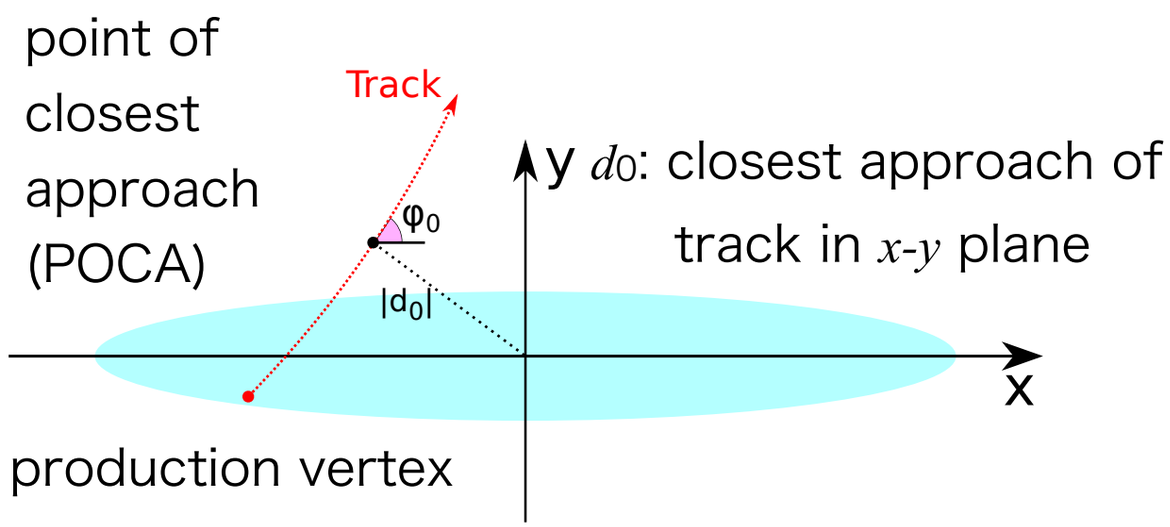
$[\ d_0(t_-) + d_0(t_+)\ ]/\sqrt{2}$

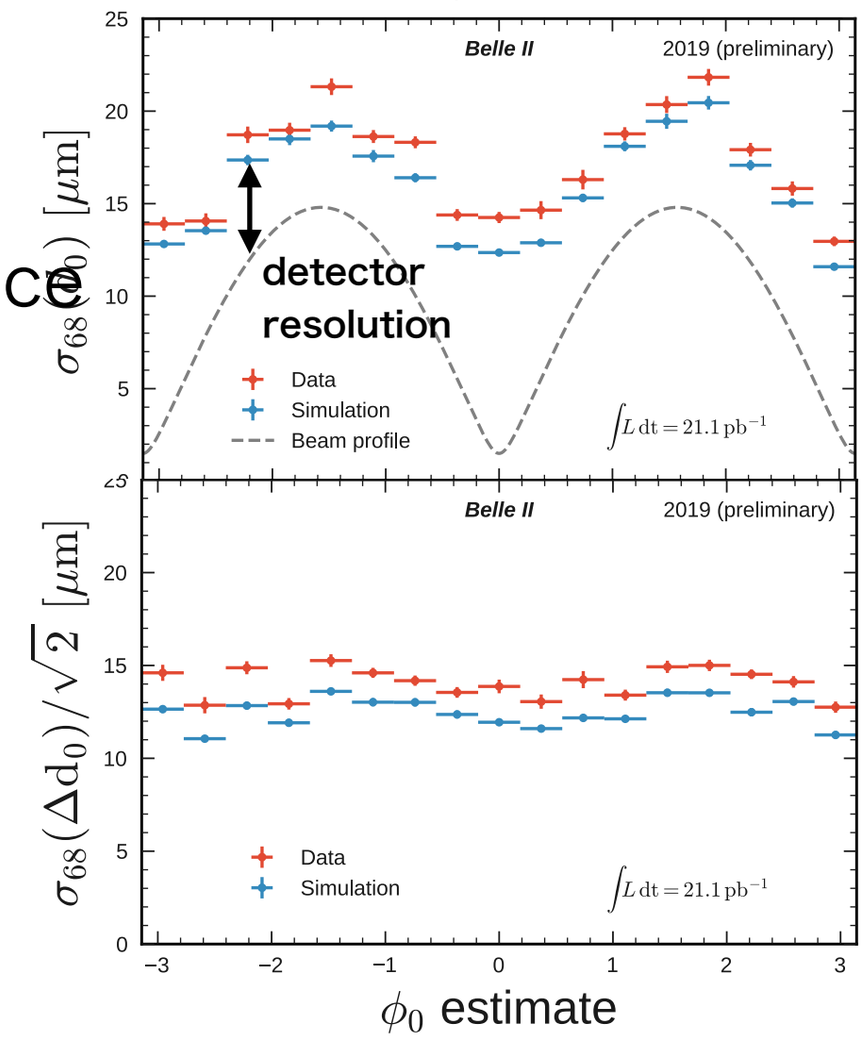
Average:

14.2±0.1 μm (Data)

12.5±0.1 μm (Simulation)

To improve data/MC matching, alignment study is ongoing.





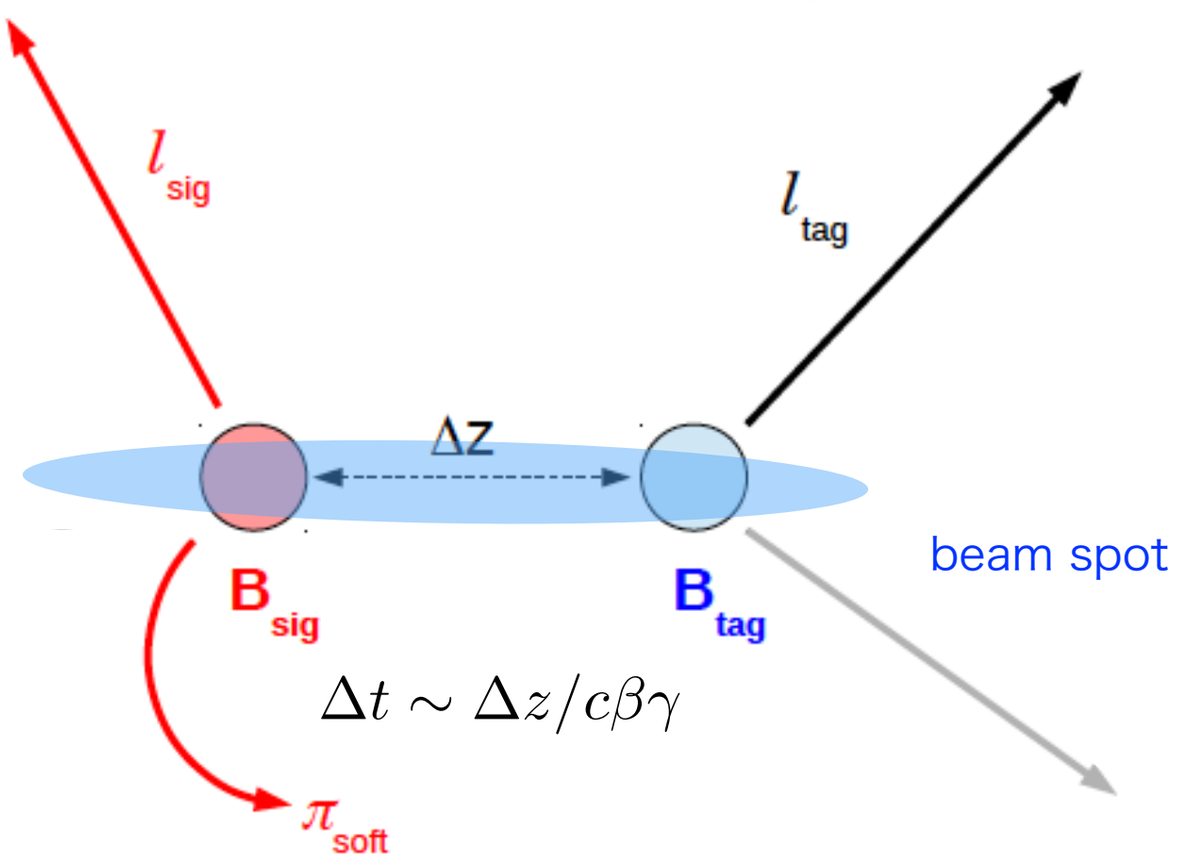
Measurement of mixing

Mixing rate is measured using flavor information of B mesons.

Branching fractions of semi-leptonic B decays are relatively large.
$B^0 \to D^{*-}\ell^+\nu_\ell$ (5.05±0.14)%

To keep signal efficiency, B meson is partially reconstructed.

Signal is reconstructed using high momentum lepton and
low momentum pion from $D^{*0} \to D^0\pi^+$ decay.

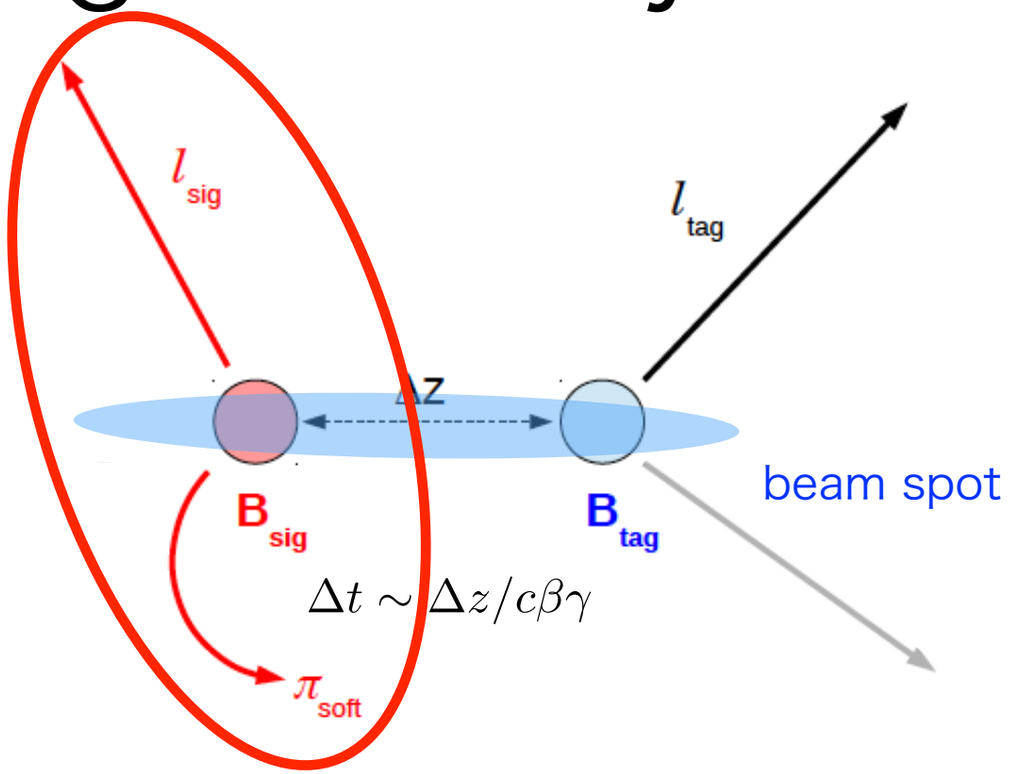


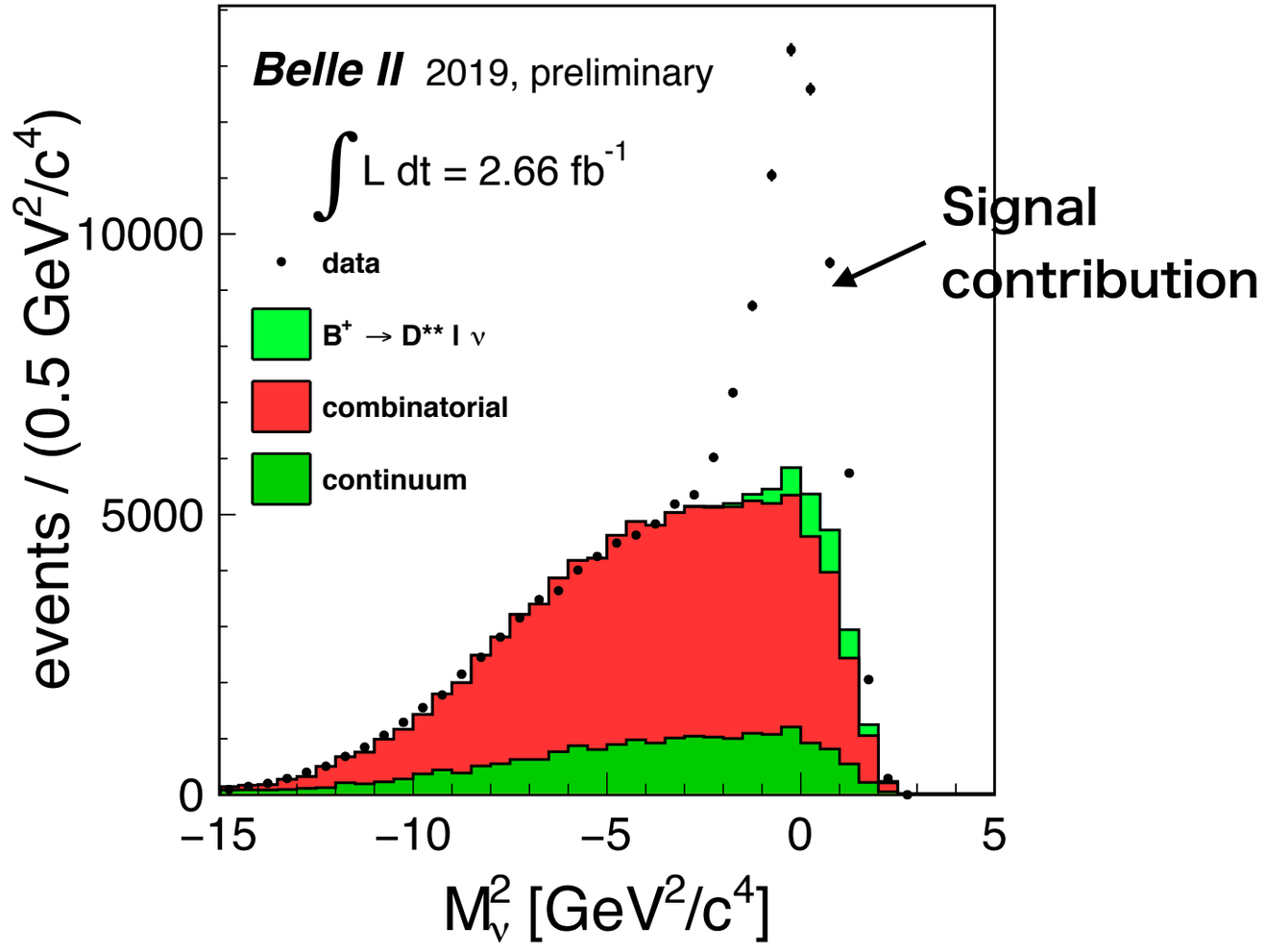
Reconstruction of signal decay

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

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

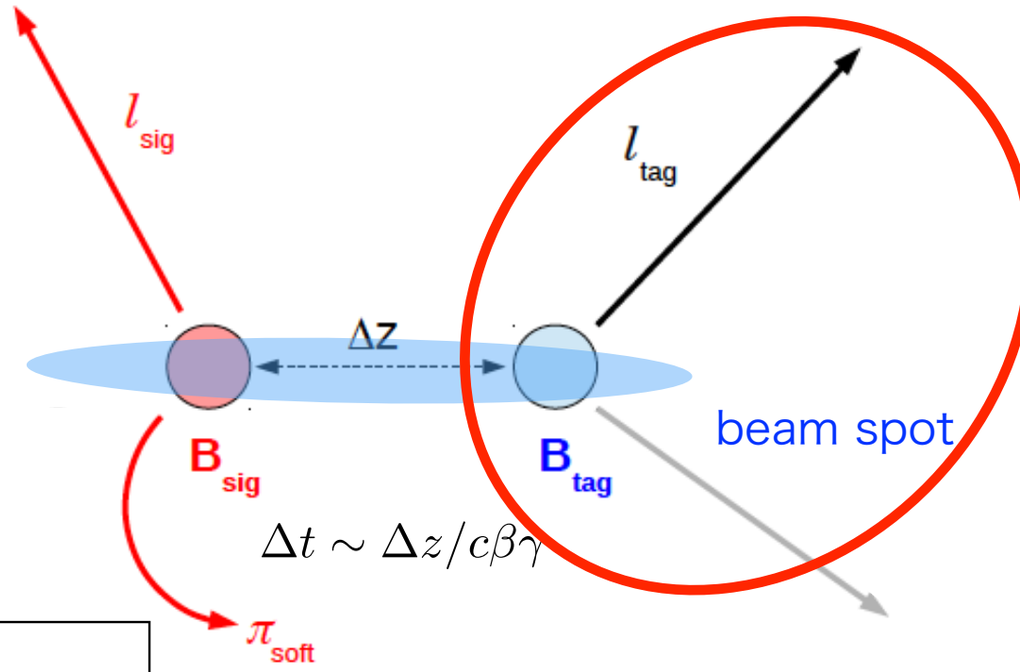
Reconstructed signals:
35492±2209

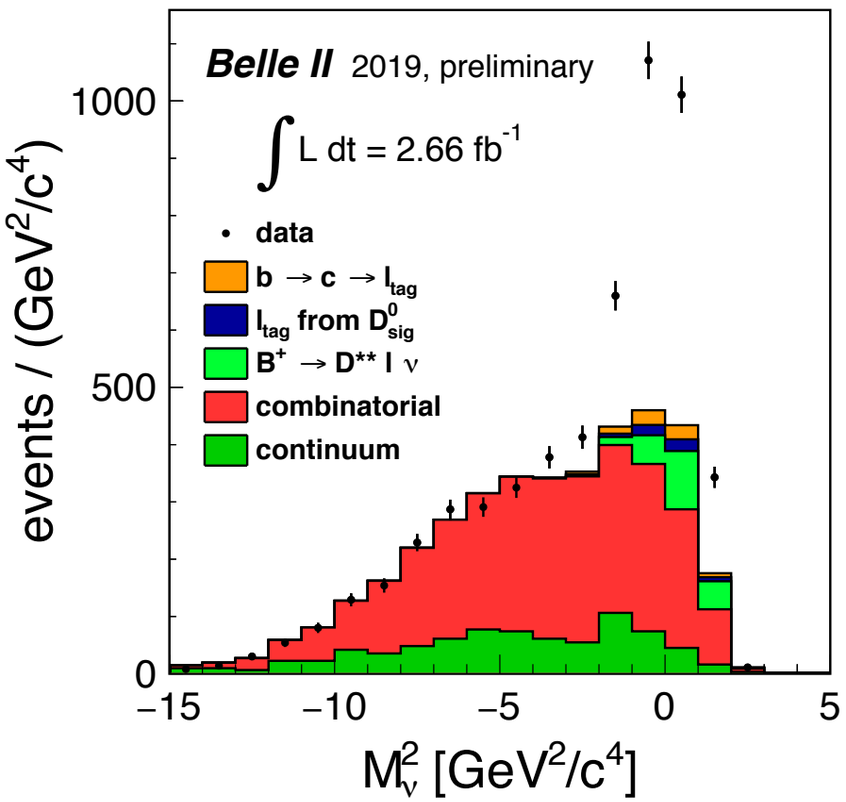




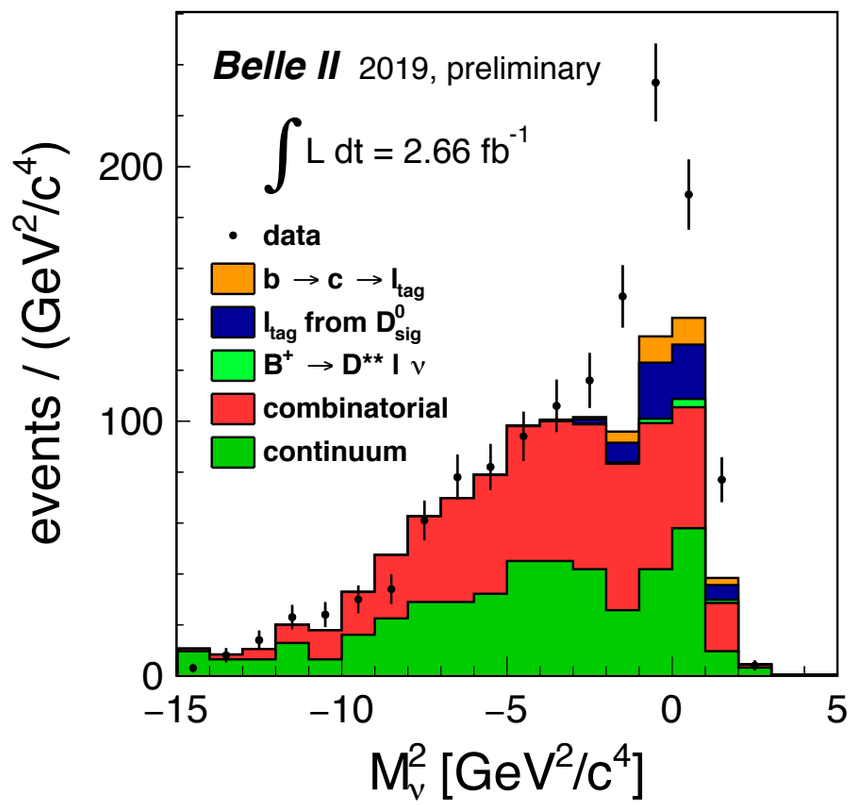
Tagged analysis

Flavor of B meson is tagged by high momentum lepton track and other B meson vertex is reconstructed with beam spot information.





Unmixed signal
(opposite sign)
1642±113



Mixed signal
(same sign)
253±45

Fraction of mixed events with reconstruction efficiency ε

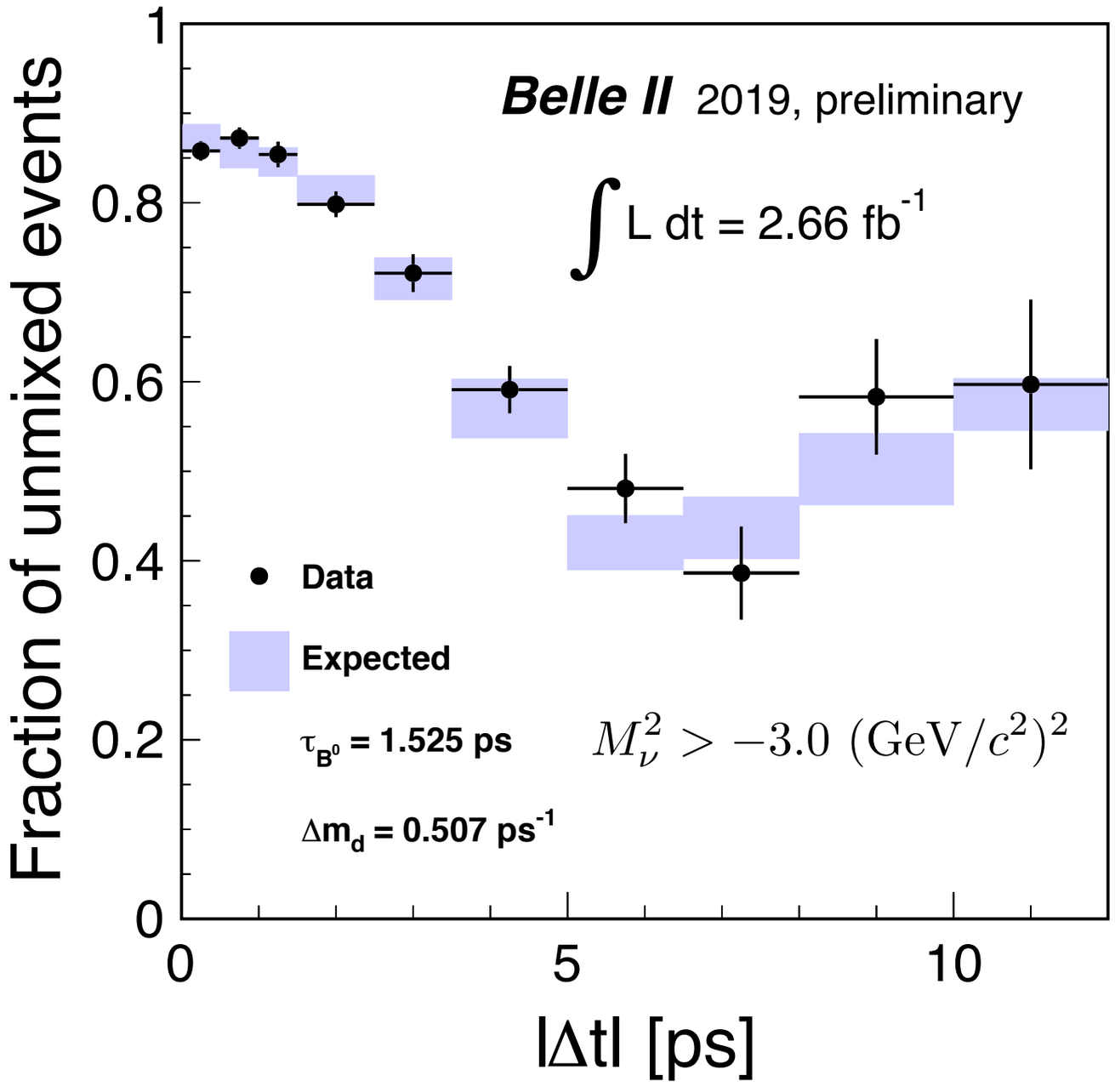
$$\chi_d = \frac{N_M/\varepsilon_M}{N_U/\varepsilon_U + N_M/\varepsilon_M}$$

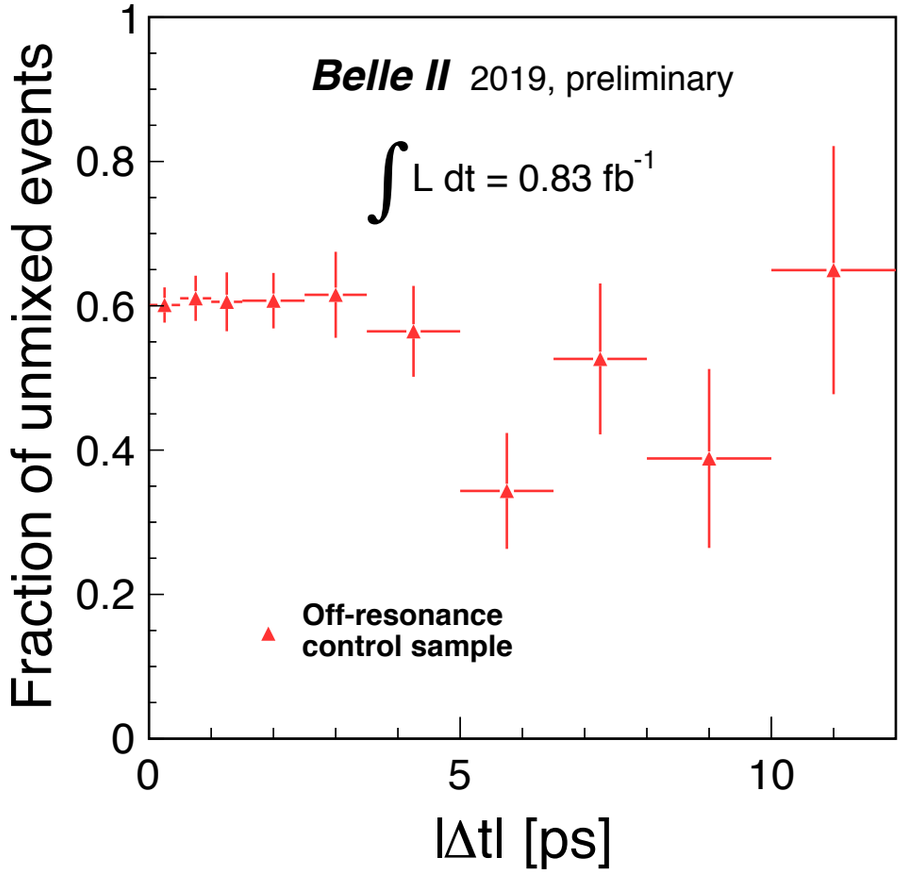
= **(17.2±3.6)%**
(WA= 18.6%)

Time-dependent analysis

Oscillation is observed in fraction in each $|\Delta t|$ region.

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

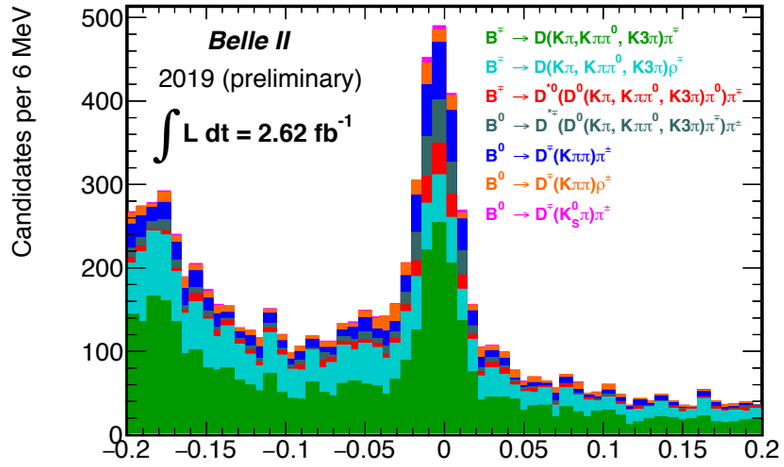


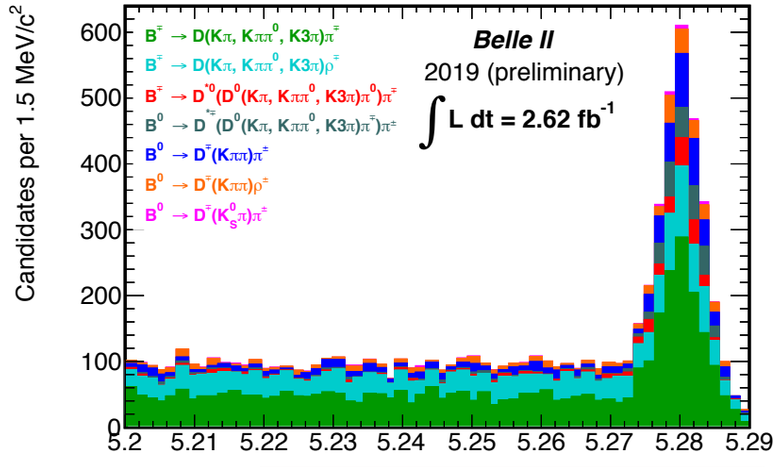


No oscillation pattern is seen in sample without $B\bar{B}$.
(compatible with flat with $\chi^2/\mathrm{ndf} = 1.541$)

Samples for τ_{B^0} and Δm_d measurements

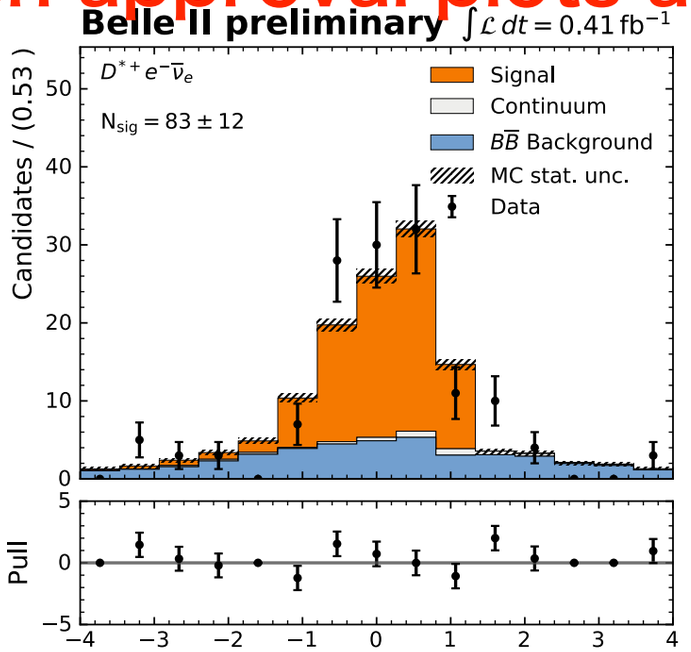
τ_{B^0} and Δm_d will be measured using large numbers of control samples $B \to Dh(h = \pi, \rho)$ and $B^0 \to D^{*-}\ell^+\nu_\ell(\ell = e, \mu)$. and they have been found in experimental data.

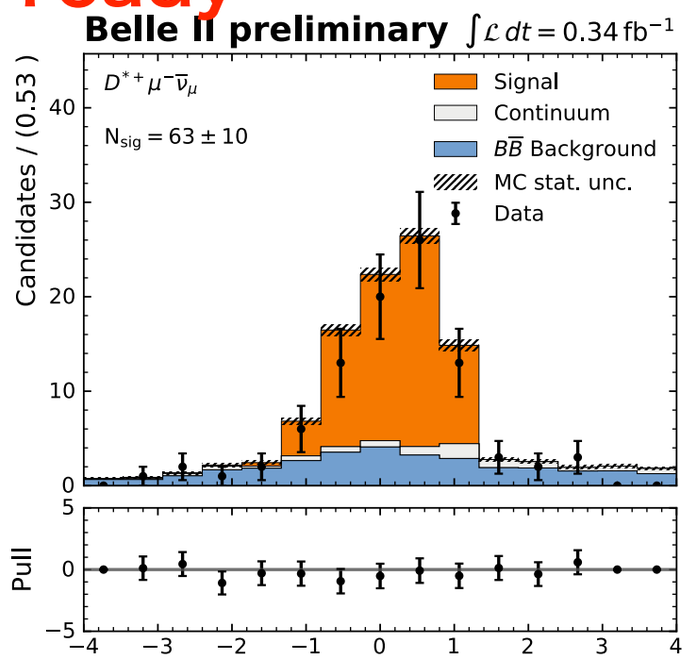




$$\Delta E \equiv E_{\rm beam} - E_B^{\rm CM} \qquad M_{\rm bc} \equiv \sqrt{(E_{\rm beam}/c^2)^2 - |\vec{p}_B^{\,\rm CM}/c|^2}$$

Revised when approval plots are ready

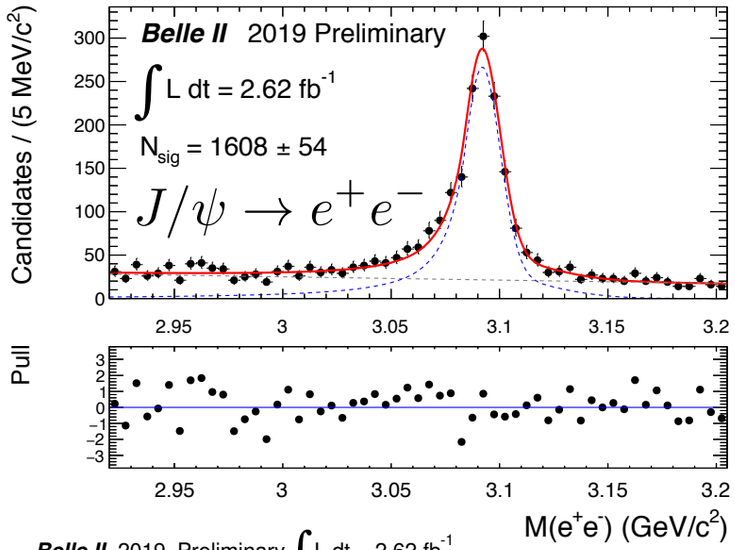


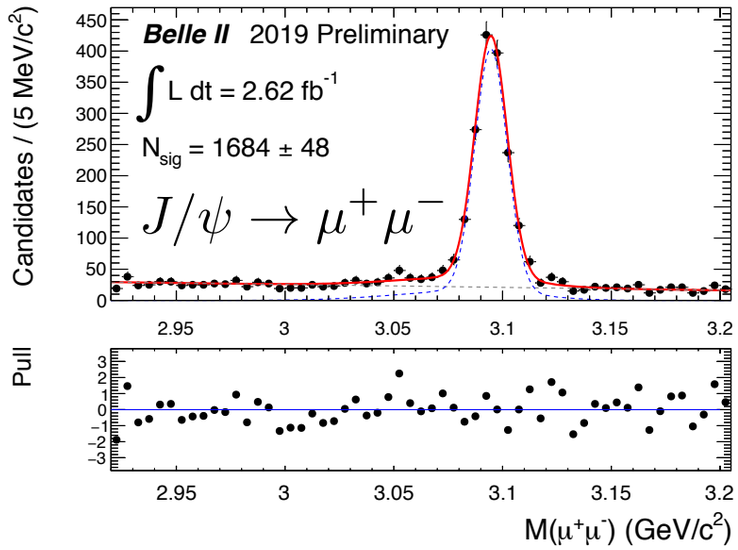


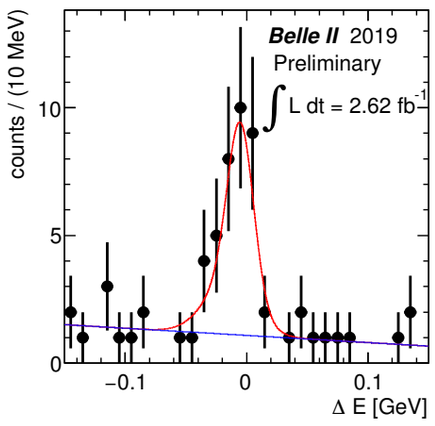
$$\cos\theta_{BY} = \frac{2E_B^* E_Y^* - M_B^2 - m_Y^2}{2p_B^* p_Y^*} \qquad Y : D^*\ell \ \text{system}$$

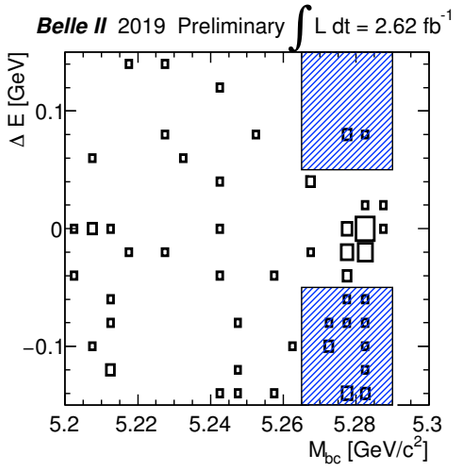
Samples for TDCPV study

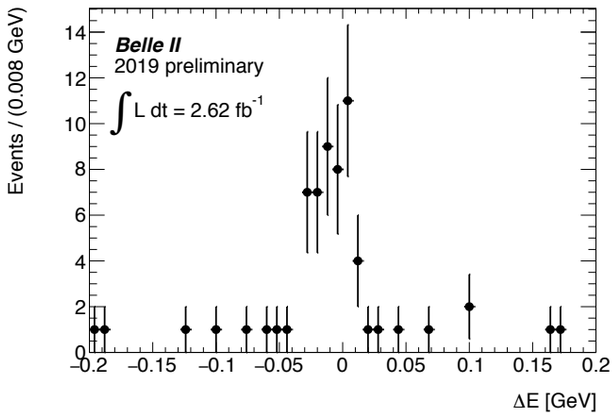
$B \to J/\psi X$

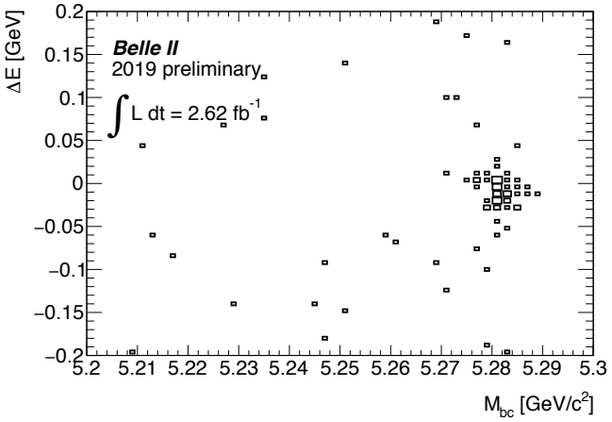






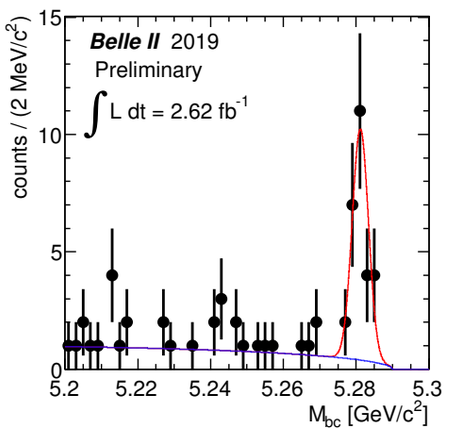






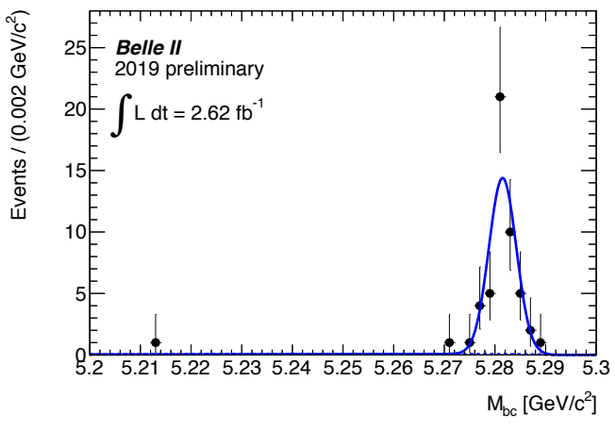
$B^0 \to J/\psi K^0_S$

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.