First look at the time-dependent CP violation using early Belle II data

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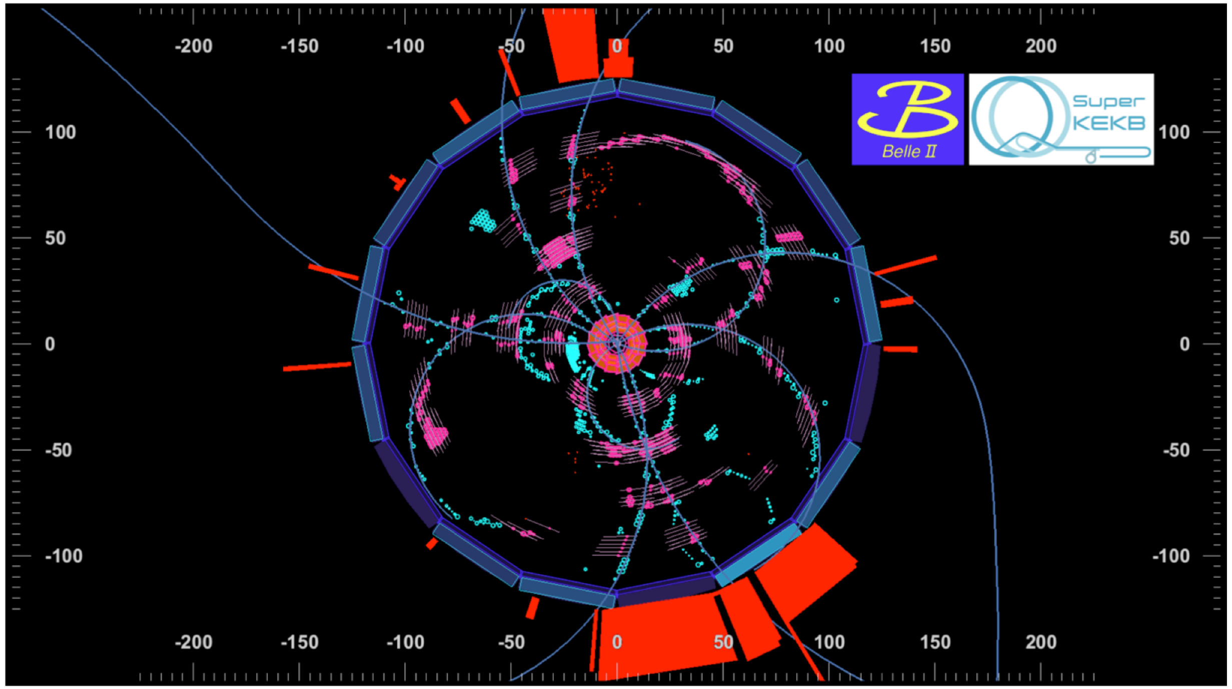
- *measurement of the time-dependent CP violation in Bd → J/ψ K_S^0 was the principal motivation for building the asymmetric B-factories PEP II at SLAC and KEKB*
  → The Nobel Prize 2008 in Physics (CKM)

- *improvement of time-dependent CP violation measurements is one of the major goal for Belle II physics program at the B-factory SuperKEKB aiming for collection of 50 ab^{-1}.*

- *SuperKEKB started operation: from 25 March to 30 June in this early phase of operation Belle II collected ~6.5 fb^{-1}*

2019: First SuperKEKB collisions in the physics run

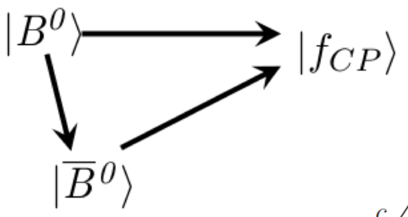


Time-dependent CP violation and the CKM unitarity matrix

- *B^0 system has the largest CP violation effects in the SM described by the CKM unitarity matrix V_{CKM}*

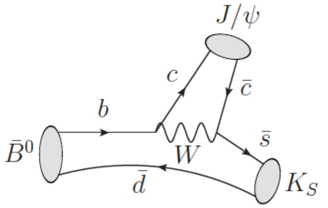
$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

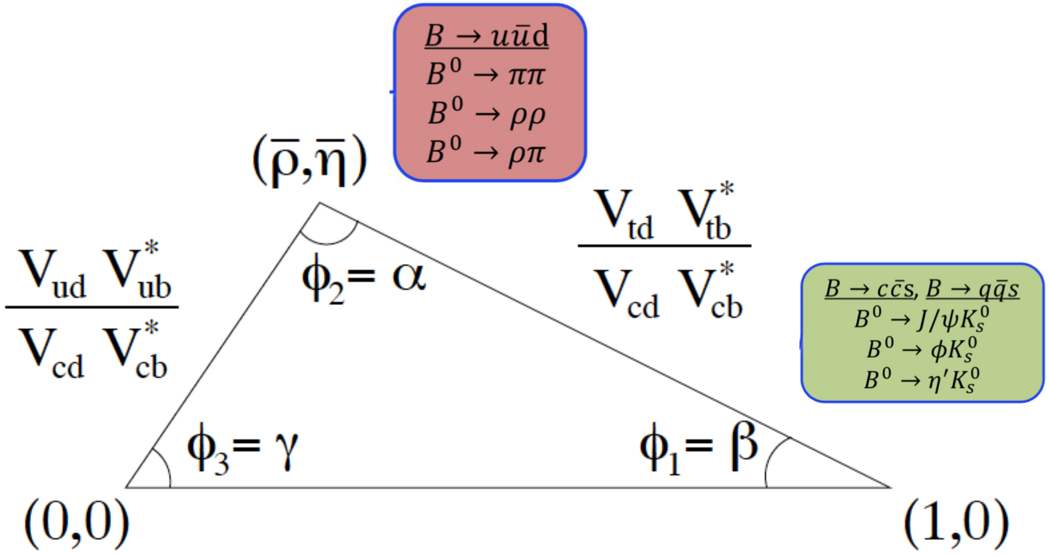
- *time-dependent CPV effects are related to interference between mixing and decay amplitudes (mixing-induced CPV)*



$$A(t) = \frac{\Gamma(\bar{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\bar{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})} = -\xi_f \sin(2\varphi_1)\sin(\Delta m\, t), \qquad S_{CP} = \sin(2\varphi_1)$$

- *φ_1 and φ_2 can be measured in TD CPV analyses of for $B^0 \to c\bar{c}s$, $q\bar{q}s$ and $B^0 \to u\bar{u}d$, e.g. for $B^0 \to J/\psi\, K_S^0$*

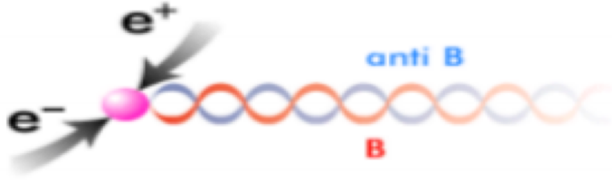




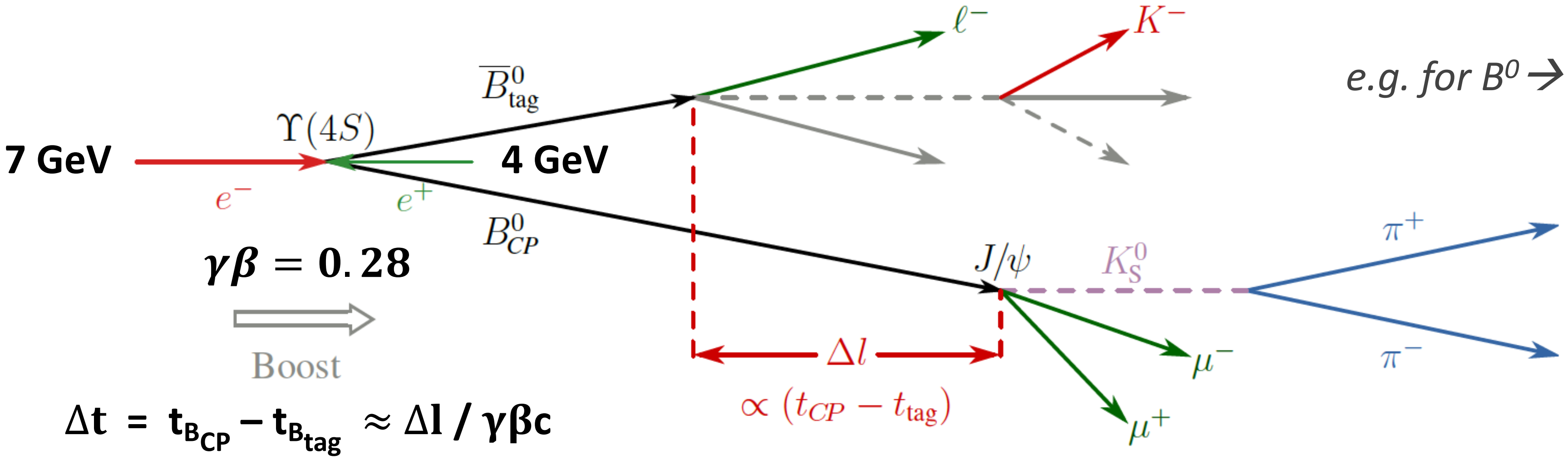
→ *room for improvement of the CPV measurements at Belle II projections to 5 ab^{-1} and 50 ab^{-1} (arXiv:1808.10567)*

	WA (2017)		5 ab^{-1}		50 ab^{-1}	
Channel	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$
$J/\psi K^0$	0.022	0.021	0.012	0.011	0.0052	0.0090
ϕK^0	0.12	0.14	0.048	0.035	0.020	0.011
$\eta' K^0$	0.06	0.04	0.032	0.020	0.015	0.008
ωK_S^0	0.21	0.14	0.08	0.06	0.024	0.020
$K_S^0\pi^0\gamma$	0.20	0.12	0.10	0.07	0.031	0.021
$K_S^0\pi^0$	0.17	0.10	0.09	0.06	0.028	0.018

Time-dependent CP violation analyses at the asymmetric B-factories



The $B^0\overline{B^0}$ pairs from $\Upsilon(4S)$ are produced in a ***coherent, entangled quantum mechanical state.***
When $B^0(\overline{B^0})$ decays, the flavor wavefunction of other $\overline{B^0}(B^0)$ collapses and it propagates alone.
One needs to measure decay times of both B^0s to observe CP violation.



e.g. for $B^0 \to J/\psi\ K_S^0$ (ξ_{CP} =-1)

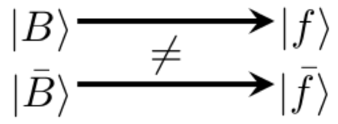
$\Delta t = t_{B_{CP}} - t_{B_{tag}} \approx \Delta l / \gamma\beta c$

B^0: CP violation, mixing and lifetime are coming together and can be found in the fit to Δt distribution in data

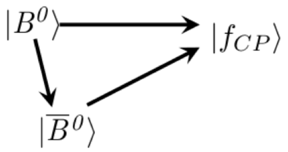
$$P_{sig}(\Delta t) = \frac{exp\left(-\frac{|\Delta t|}{\tau}\right)}{4\tau}\left(1 + q_{tag}\left(A_{CP}\cos(\Delta m\,\Delta t) + S_{CP}\sin(\Delta m\,\Delta t)\right)\right)$$

q_{tag} = $-\xi_{CP}$ for B^0_{tag}
q_{tag} = ξ_{CP} for $\bar{B}^0_{tag}$

A_{CP}: direct CPV

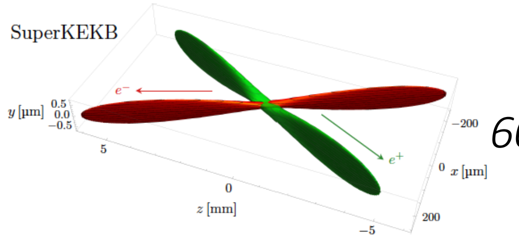


$S_{CP} = \sin(2\varphi_1)$ mixing-induced CPV



SuperKEKB & Belle II

SuperKEKB

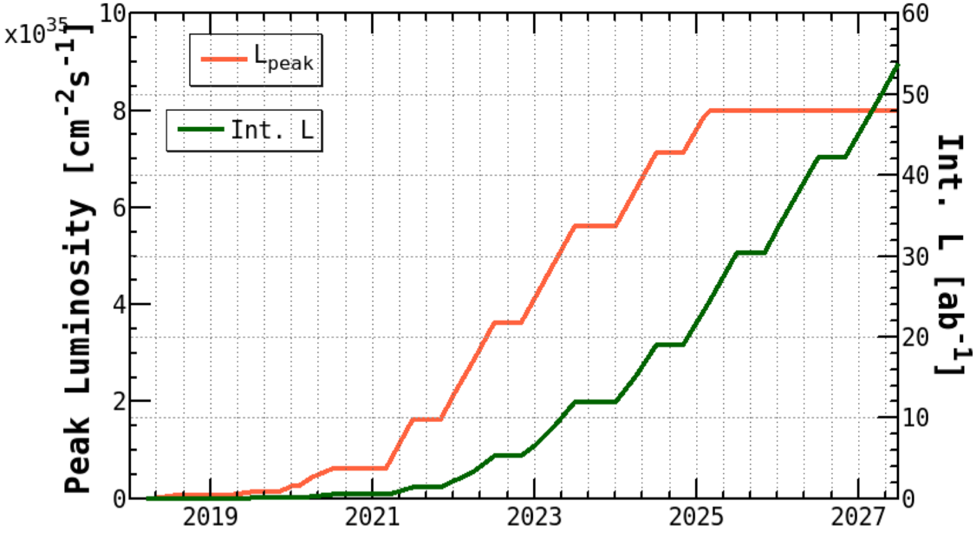


40 times larger luminosity than at KEKB using nano-beam scheme with a tiny beam spot: 60 nm x 10 μm x few 100 μm in y, x, z

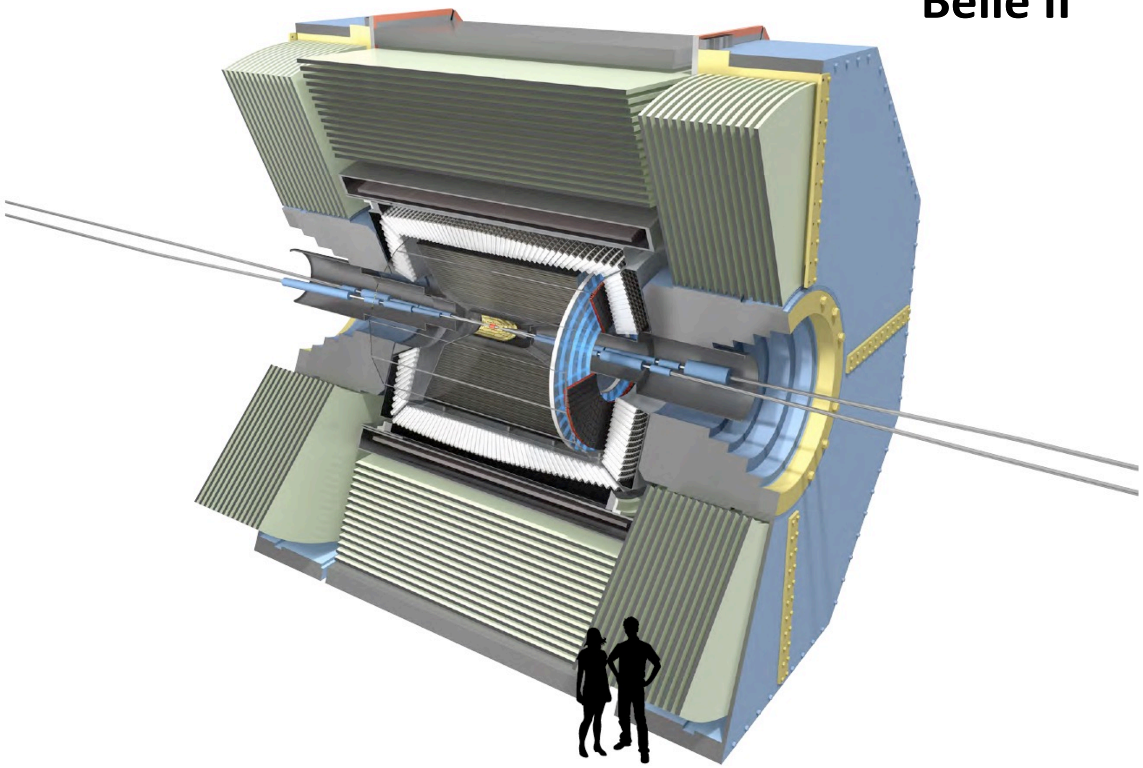
The first physics run 25 March – 30 June 2019

$6.5\ fb^{-1}$ in total: at Y(4S) and off-resonance ($0.83\ fb^{-1}$)

→ *The final goal in an integrated luminosity of $50\ ab^{-1}$ at Y(4S)*



Belle II



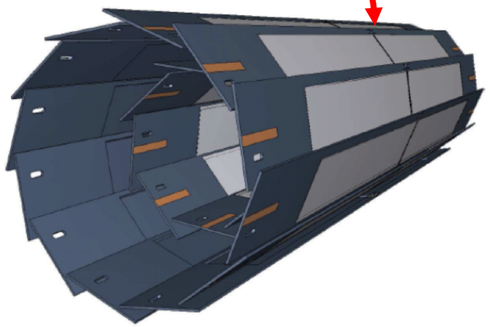
- *use frame of the Belle detector and ECL*
- *new vertex detector VXD (PXD + SVD)*
- *new particle identification for K/p/π separation*
- *new CDC tracking - smaller cells and larger coverage*
- *improved KLM for μ and K_L detection*
- *new electronics for ECL*

The pixel detector PXD and the silicon vertex detector SVD

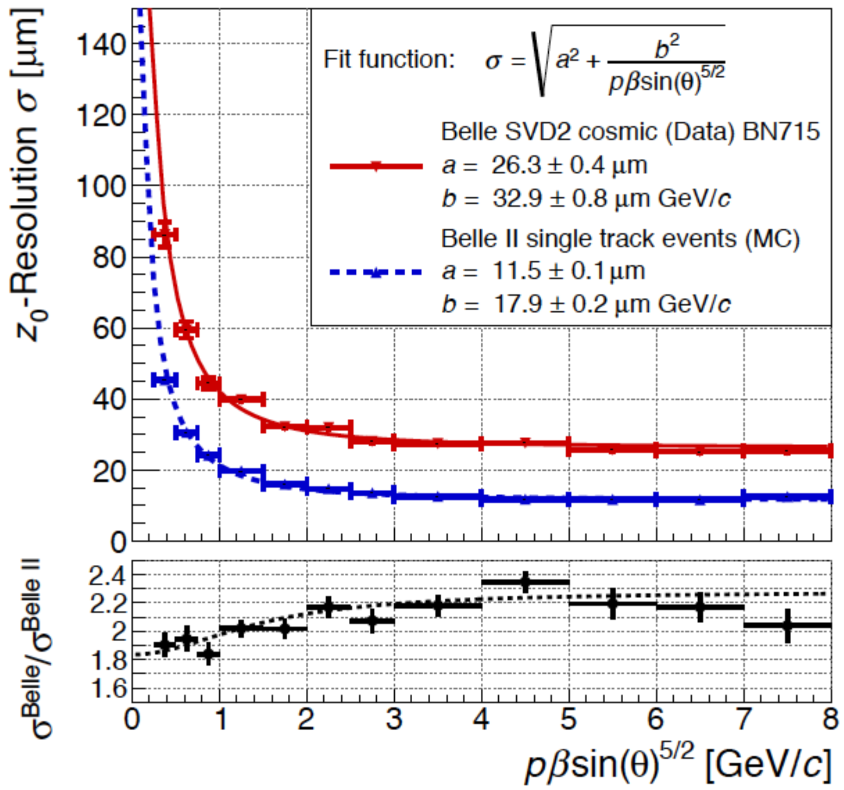
PXD *DEPFET technology with the pixel size 50 x 55(85) x 75 μm^3*
1st layer is at 14 mm from the beam, 2^{nd} layer will be installed in 2021
SVD *4 double sided strip layers at radii from 39 mm to 135 mm*

Improvement of precision of the vertex position measurements by almost a factor of two w.r.t. Belle

arXiv:1808.10567

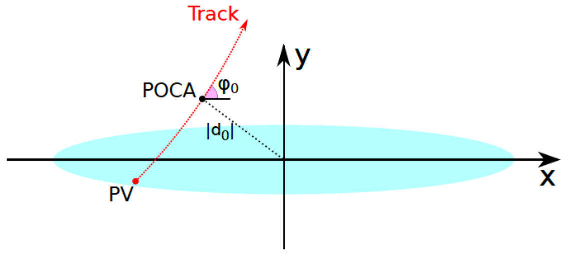


PXD

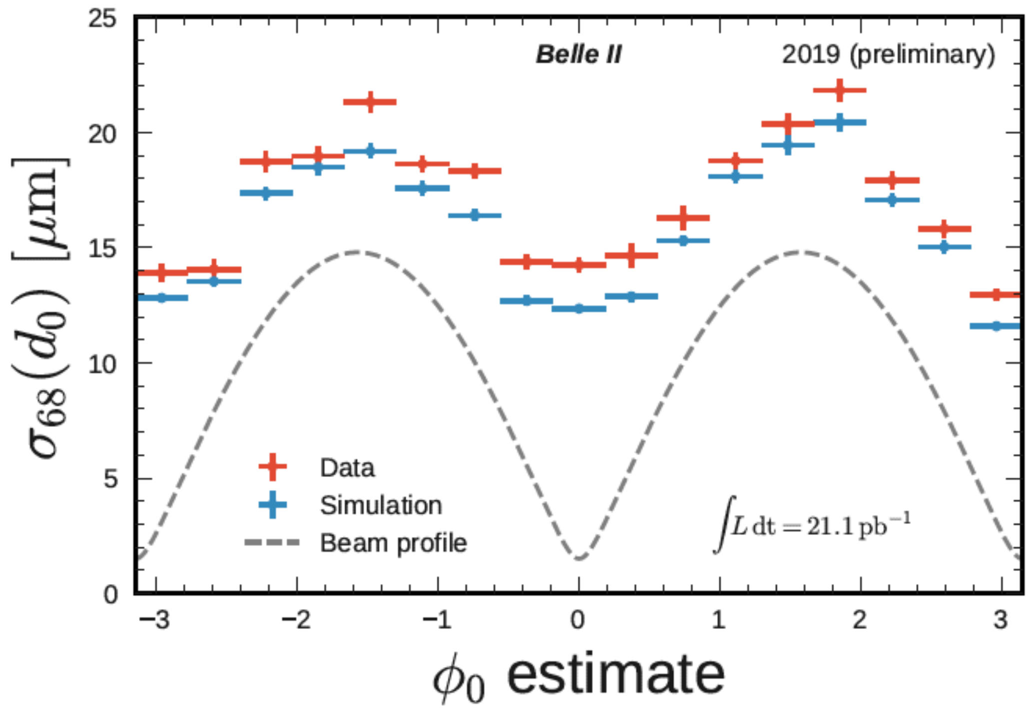


VXD and space & time measurements in the early Belle II data

Distance d_0 of track point of closest approach to x=y=0



as a function of φ_0 for two-track events

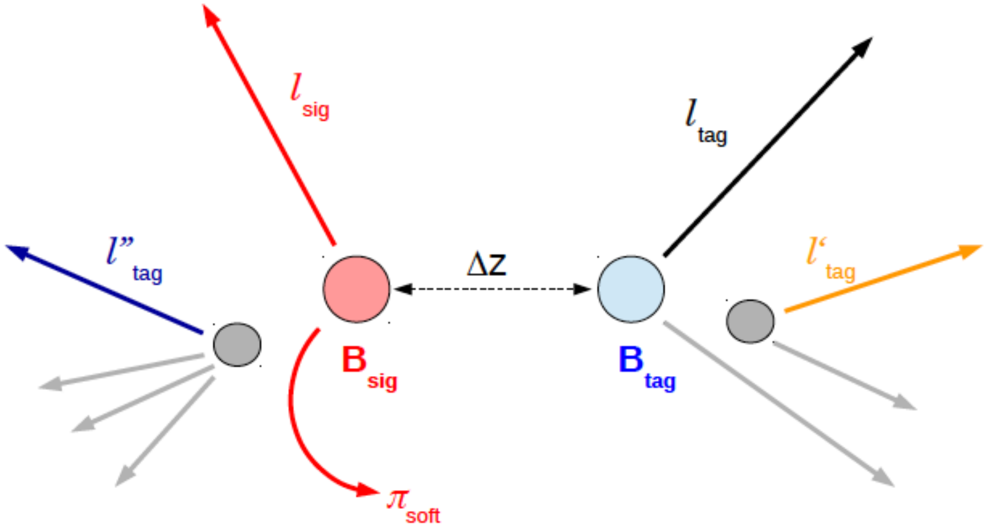


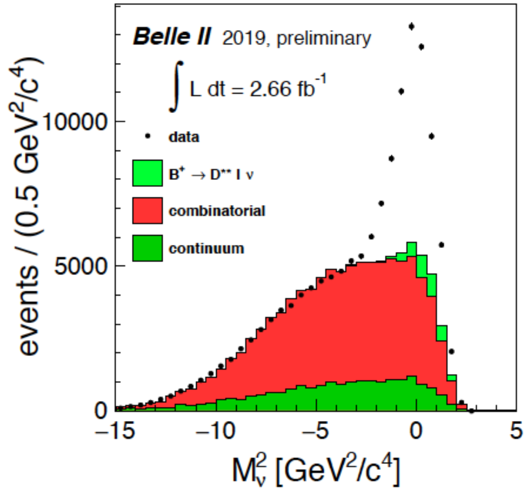
→ *Belle II data are close to expectations for*

- ***beam spot profile** convoluted with*
- ***vertex position resolution** (at φ_0 = 0): 14.2±0.1 μm compared to 12.5±0.1 μm in MC*

B^0 - $\overline{B}^0$ mixing in the early Belle II data

→ *start with a B^0, wait a while and after few pico-seconds get a $\bar{B}^0$*





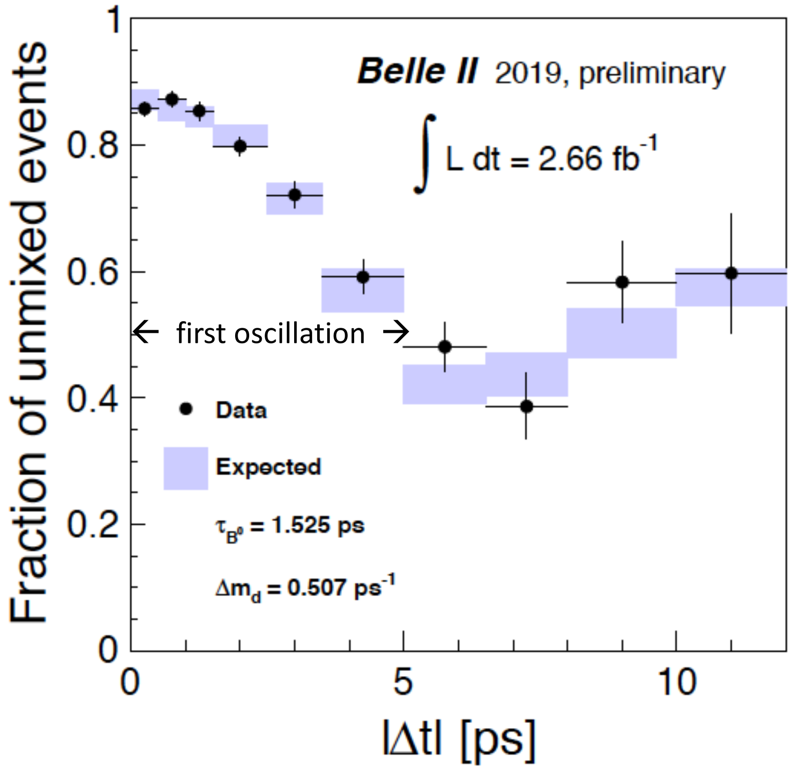
Semileptonic B^0s decays on both sides:

- B^0_{sig} → $D^*\ l_{sig}\ \nu$ $(D^{*-} \rightarrow D^0\ \pi_{soft})$
- B^0_{tag} → l_{tag}

← *peak at $M_\nu^2 = 0$ for B^0_{sig}*

Vertex positions are calculated by intersecting lepton tracks with the beam spot

The ratio of the opposite charged leptons to the sum of the same and opposite charged leptons



→ ***B^0 mixing causes an appearence of the same charged leptons with the time***

Observation of the golden decay mode $B^0 \to J/\psi\, K_S^0$

- about half of available data: 2.62 fb^{-1}

- both channels $J/\psi \to \mu\mu, ee$ are considered

- 2D unbinned ML fit on two variables

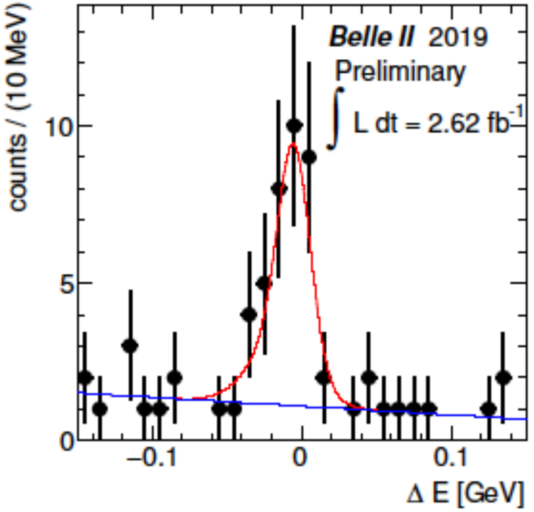
$$\Delta E = E^*_B - E^*_{beam}$$
$$M_{bc} = \sqrt{E*_{beam}{}^2 - p*2}$$

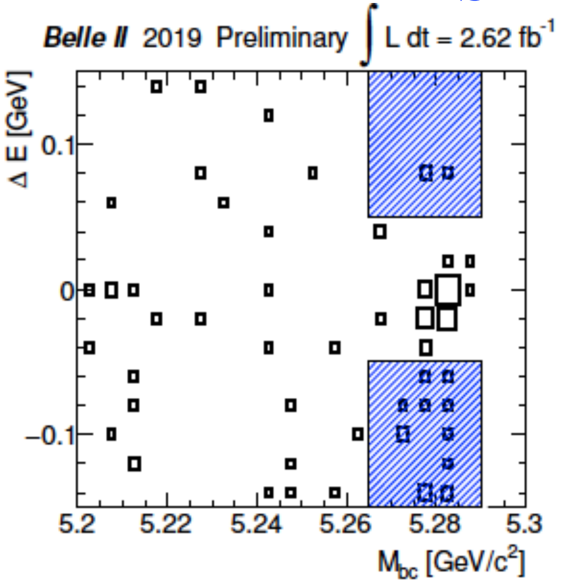
- shades areas are excluded from the fit
  to suppress contribution from $B^0 \to J/\psi\, K^{*0}$

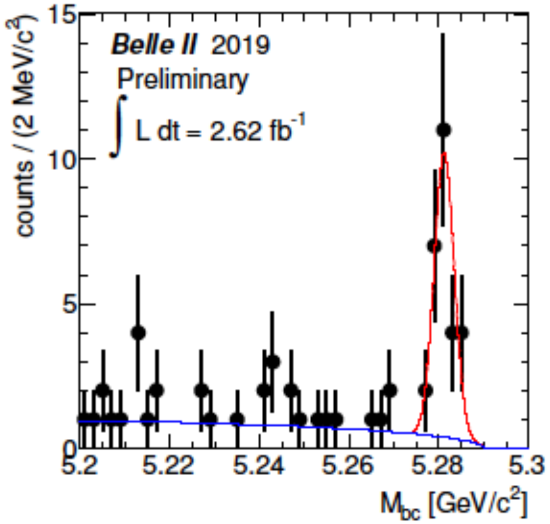
\

Yield of $B^0 \to J/\psi\, K_S^0$ 26.9 ± 5.2 events
background ***1.6 ± 0.3 events***

→ *not enough data yet for the time-dependent CP violation fit,*
the collection of data will continue in October

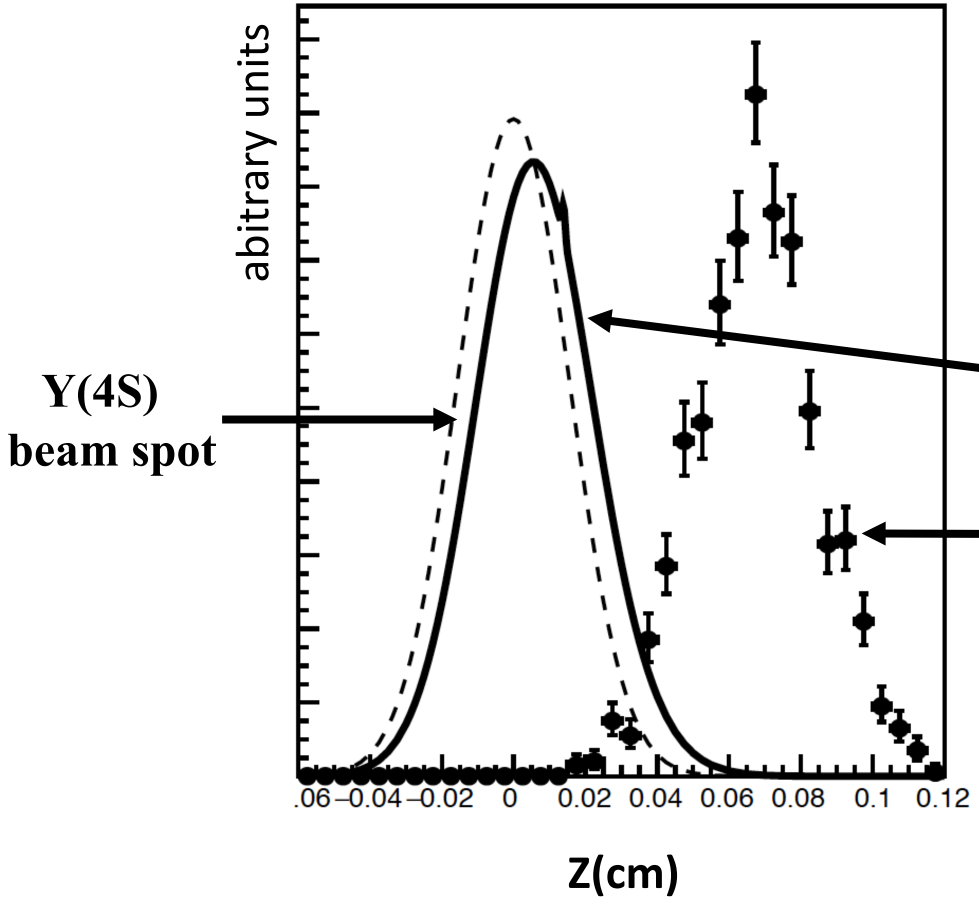


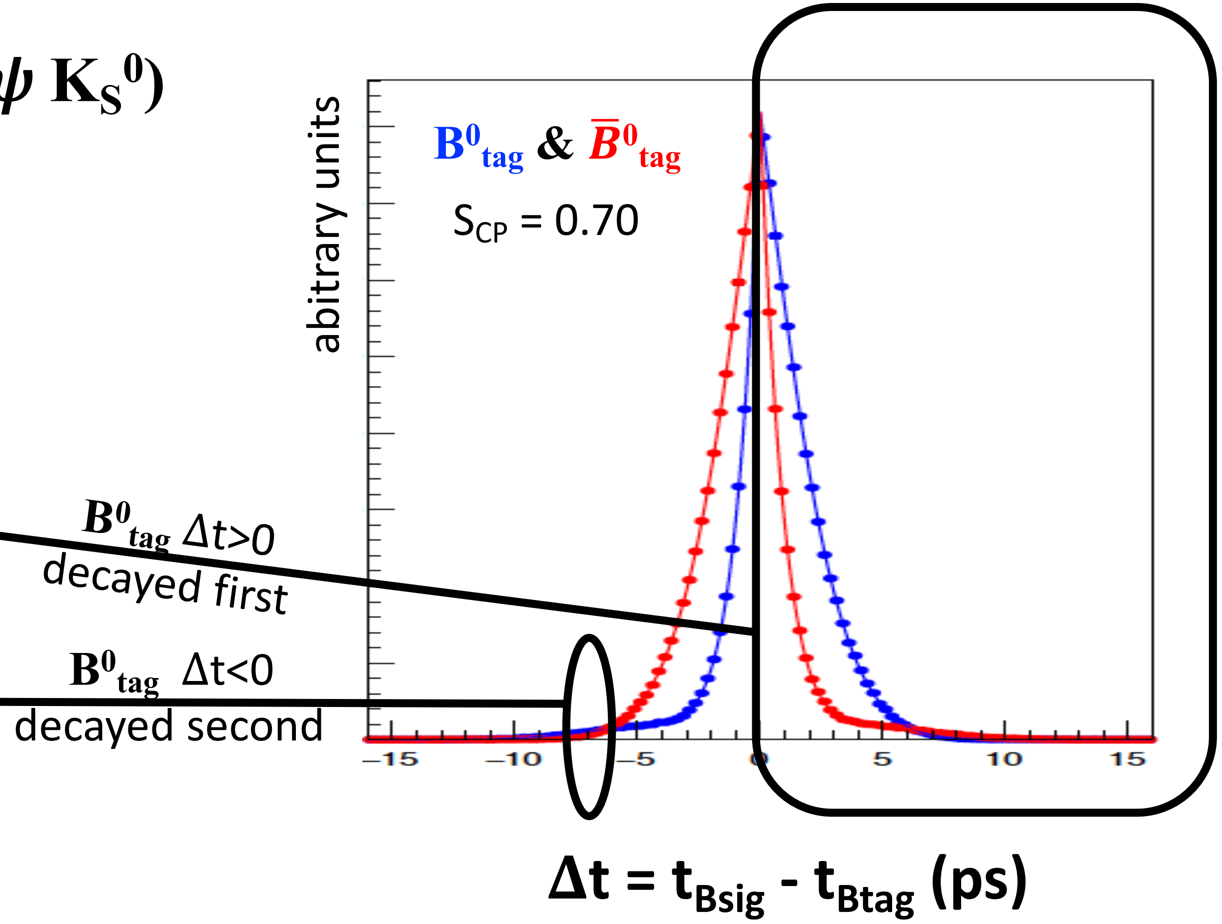




A new feature at Belle II – the tiny size of the beam spot

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0_{tag} + B^0_{sig}(J/\psi\, K_S^0)$





- *the beam spot at Belle II (~400 μm in z) is comparable with the B^0 lifetime*

→ *the B^0 decay position in z is far away from the beam spot in the tails of the Δt distribution*

New challenge for the time-dependent analysis

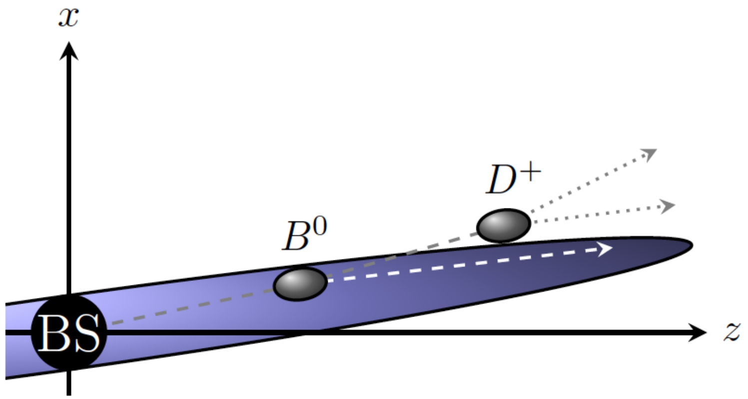
In the traditional approach for time-dependent fits (used at Belle and BaBar) the maximum of the unbinned likelihood is used

$$\max \quad L = \prod_i P^i_{ev}(\Delta t) \quad \text{with} \quad P^i_{ev}(\Delta t) = \int_{-\infty}^{+\infty} d(\Delta t^{true})\ P_{theory}(\Delta t^{true})\ R(\Delta t - \Delta t^{true})$$

assuming that ***theory and detector effects are independent*** *and the Δt resolution function* $\boldsymbol{R}$ *does not depend on true Δt^{true}*

→ ***this is not granted at Belle II*** ***because of the tiny size of the beam spot, excellent precision of PXD and a need to make use the beam spot information for improvement of the B^0_{tag} vertex position on the tag side:***

the beam information helps to select tracks directly from B^0_{tag} decay and remove displaced tracks from decays of charmed particles (Ds) or K_S^0



Several developments at Belle II to deal with the new challenge

1. *Optimisation of the B^0_{tag} vertexing on the tag side: to get precision and to mitigate problems related to the beam spot*
2. *Further development of the traditional approach*
3. ***A new paradigm of time-dependent fits which is robust and could deal with correlations between theory and detector effects,*** ***see below →***

An alternative paradigm of time-dependent fits at Belle II

see also V. Chekelian "The MPI Concept of Time-Dependent Fits at Belle II", xFitter Workshop, Minsk, March 2019
https://indico.desy.de/indico/event/22011/session/7/contribution/24/material/slides/0.pdf

- $\boldsymbol{P^i}_{\boldsymbol{ev}}(\Delta \boldsymbol{t})$ → *calculated numerically using weighted MC events (i.e. use convolution of theory and detector from simulation)*

- ***variation of input physics parameters (τ, Δm, S_{CP} and A_{CP})*** → *by weighting of an auxiliary, "assistive" MC sample*

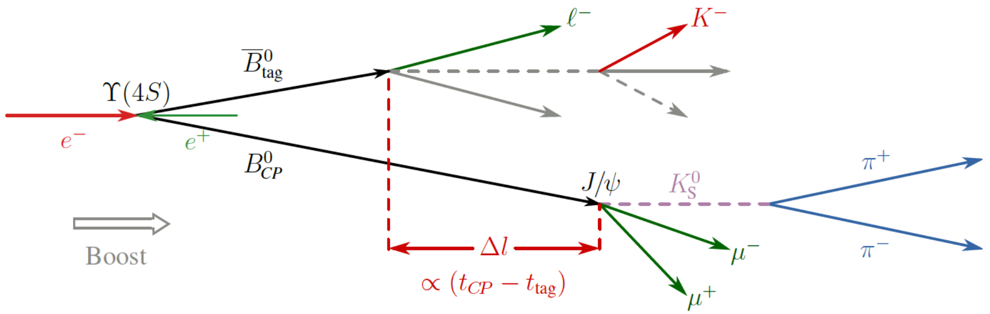
- ***differences in the detector response between data and simulation*** → *by downgrading (smearing) of the detector response in an auxiliary, "assistive" MC sample, using weighting of the simulated event*

- ***physics parameters and the detector smearing*** → *determined simultaneously in the TD CPV fit of the signal and control channels*

New input physics parameters – analytic expression for weighting of MC

Input from generator to simulation:

$$P_{theory}\left(t^{\,B^0 first}, \Delta t\right) = \frac{exp\left(-\frac{\left|t^{\,B^0 first}\right|}{\tau}\right)}{4\tau}\,\frac{exp\left(-\frac{|\Delta t|}{\tau}\right)}{4\tau}\left[1 + q\left(A\cos(\delta m\,\Delta t) + S\sin(\delta m\,\Delta t)\right)\right]$$



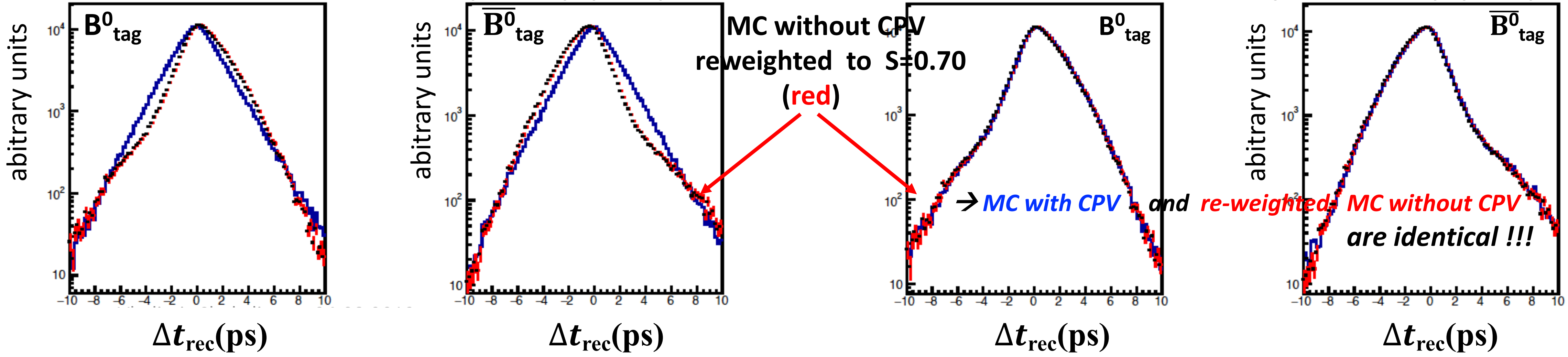
If values of $t^{B^0 first}$ and Δt are defined (and frozen):

→ *simulation of the detector effects does not depend on* $\boldsymbol{\tau, \delta m, A, S}$

→ *only probability of event with given* $\boldsymbol{t^{B^0 first}}$ *and* $\Delta \boldsymbol{t}$ *depends on* $\boldsymbol{\tau, \delta m, A, S}$

→ *Thus, MC sample generated with* $\boldsymbol{\tau_0, \delta m_0, A_0, S_0}$ *can be used to get MC sample equivalent to simulation with* $\boldsymbol{\tau, \delta m, A, S}$ *by the weighting of MC events* $\boldsymbol{w = P_{theory}\left(t^{\,B^0 first}, \Delta t; \tau, \delta m, A, S\right) / P_{theory}\left(t^{\,B^0 first}, \Delta t; \tau_0, \delta m_0, A_0, S_0\right)}$

simulation without CPV (S=A=0) (blue) **simulation with CPV (S=0.70,A=0) (blue)**



Treatment of discrepancies between data and MC in the detector response

prior the TD fit (once) → *smearing of reconstructed quantities (Δ**t**) in the MC sample*

- *very flexible and can have any level of complexity if there is a model for downgrading of the detector resolution*
- *the simplest and also very efficient smearing model:* $\Delta t' = \Delta t + G(\alpha_{smear} \cdot \delta(\Delta t))$ *($\delta(\Delta t)$ – uncertainty of Δt)*

during the TD fit (many times) → *approximation of the "simplest smearing model" by the weighting of the MC sample*

- *could be directly included in the TD fit with the smearing factor and the physics parameters determined simultaneously*

First, determine a simplified Δt resolution function in a two gaussian fit of the simulated MC sample:

$$P_{res.func}(\Delta t - \Delta t_{true}) = f\, G_1(\mu_1, \sigma_1) + (1-f)\, G_2(\mu_2, \sigma_2)$$

where $\mu_i = \mu_i^{pull} \cdot \delta(\Delta t)$ *and* $\sigma_i = \sigma_i^{pull} \cdot \delta(\Delta t)$

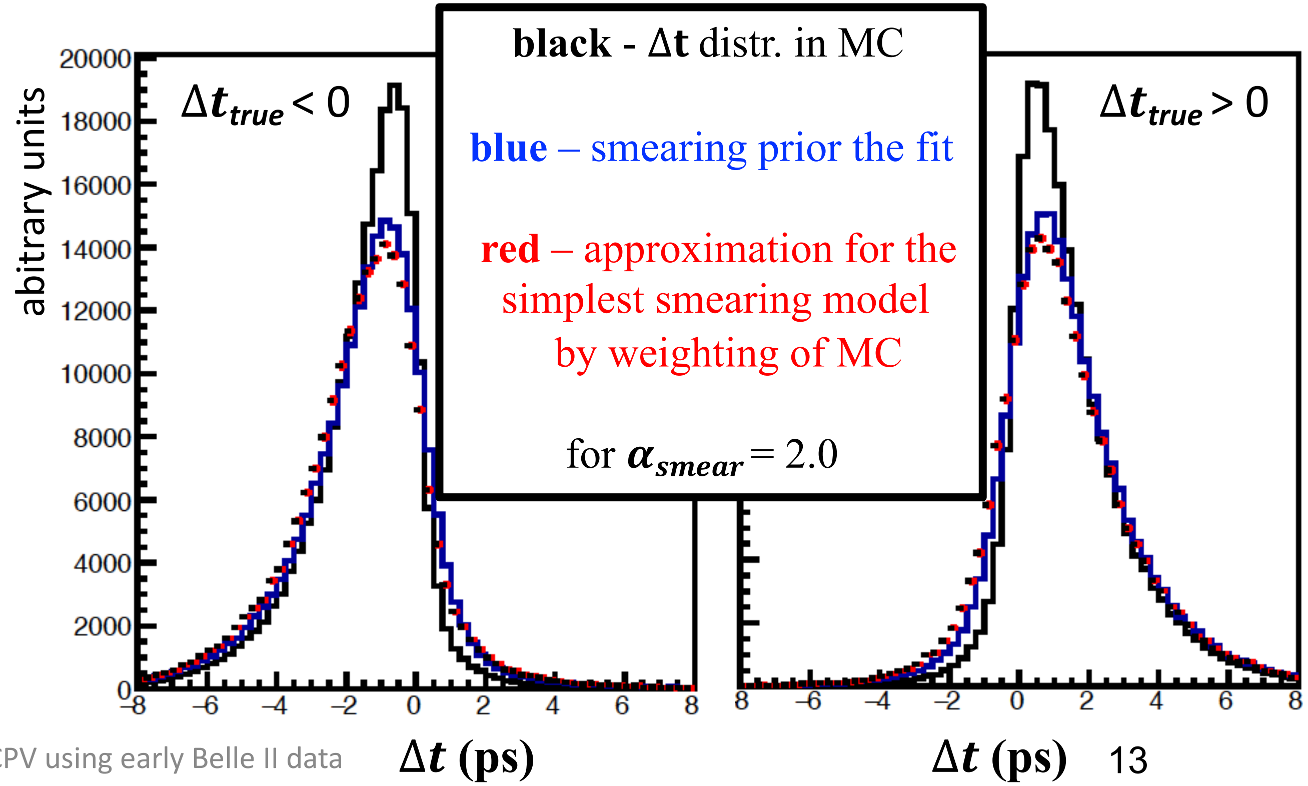
determined separately for positive and negative Δt_{true}

Then, analytic expression for weighting of MC events

$$w = P_{res.func}^{new} / P_{res.func}, \quad \text{where}$$

$$P_{res.func}^{new} = f\, G_1(\mu_1, \sigma_1^{new}) + (1-f)\, G_2(\mu_2, \sigma_2^{new})$$

with $\sigma_i^{new} = \sqrt{\sigma_i^2 + (\alpha_{smear}\, \delta(\Delta t))^2}$



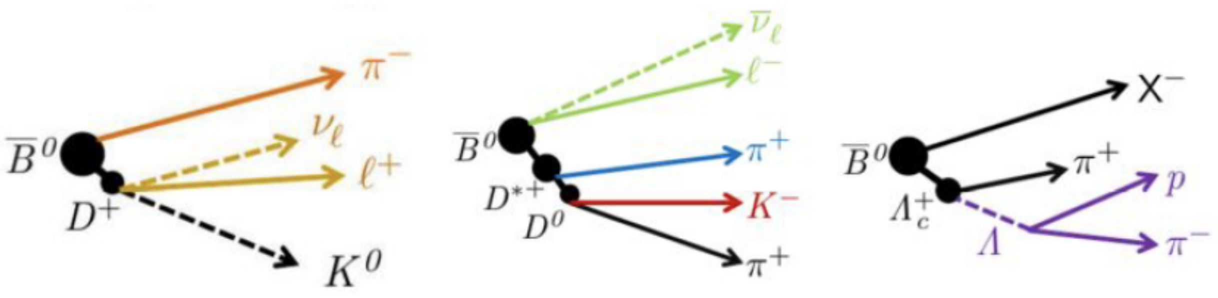
Summary

- *The first Belle II physics run at the B Factory SuperKEKB just finished with collected luminosity of ~6.5 fb^{-1}*
- *The Belle II physics run will resume in October and continue until summer 2020*
- *Rediscovery of known phenomena with early data (~6.5 fb^{-1})*
  - B^0 - $\overline{B^0}$ mixing, …
- *Demonstration of time-dependent capabilities with early data*
  - beam spot profile,
  - performance of VXD (PXD+SVD) and space & time measurements
  - observation of the signal channel $B^0 \rightarrow J/\psi\ K_S^0$
- *Large room for improvements of precision for the TD CPV measurements by far not limited by systematics*
  - long term project aiming for 50 ab^{-1}
- *New challenges and new developments related to TD CPV analyses at Belle II*
  - correlation of physics parameters with detector resolution function due to the tiny size of the beam spot
  - optimization of vertexing on tag side and traditional & alternative approaches for TD fits

Flavor tagging: B^0 or $\bar{B}^0$ on the tag side ?

Flavor tagging using 13 different categories and many input variables

arXiv:1808.10567



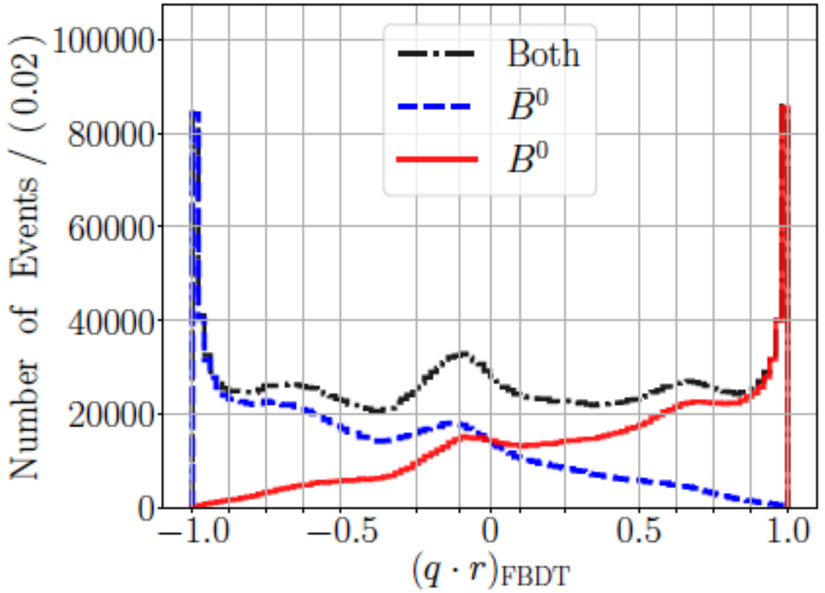
Categories	Targets for $\bar{B}^0$
Electron	e^-
Intermediate Electron	e^+
Muon	μ^-
Intermediate Muon	μ^+
Kinetic Lepton	l^-
Intermediate Kinetic Lepton	l^+
Kaon	K^-
Kaon-Pion	K^-, π^+
Slow Pion	π^+
Maximum P*	l^-, π^-
Fast-Slow-Correlated (FSC)	l^-, π^+
Fast Hadron	π^-, K^-
Lambda	Λ

Underlying decay modes

$\bar{B}^0 \to D^{*+}\ \bar{\nu}_\ell\ \ell^-$
↳ $D^0\ \pi^+$
↳ $X\ K^-$

$\bar{B}^0 \to D^+\ \pi^-\ (K^-)$
↳ $K^0\ \nu_\ell\ \ell^+$

$\bar{B}^0 \to \Lambda_c^+\ X^-$
↳ $\Lambda\ \pi^+$
↳ $p\ \pi^-$



- *"effective efficiency" ($N_{tag}/N * r^2$) is about 37% (Belle II MC)*

→ this very involved procedure with many inputs is now in the commissioning phase for the data

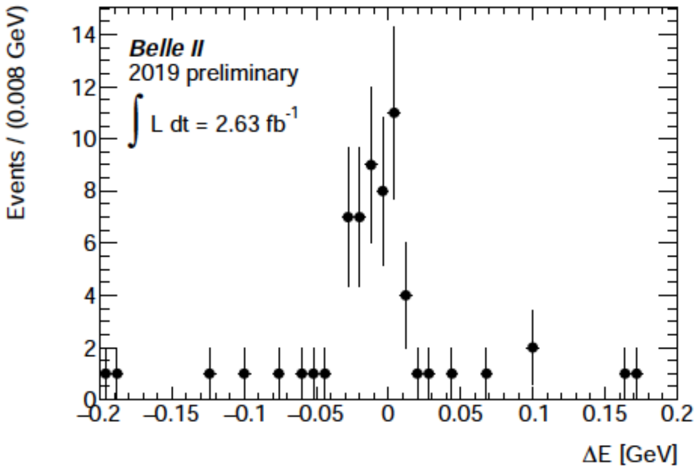
Observation of the control channel $B^0 \rightarrow J/\psi\ K^{*0}\ (K^-\pi^+)$

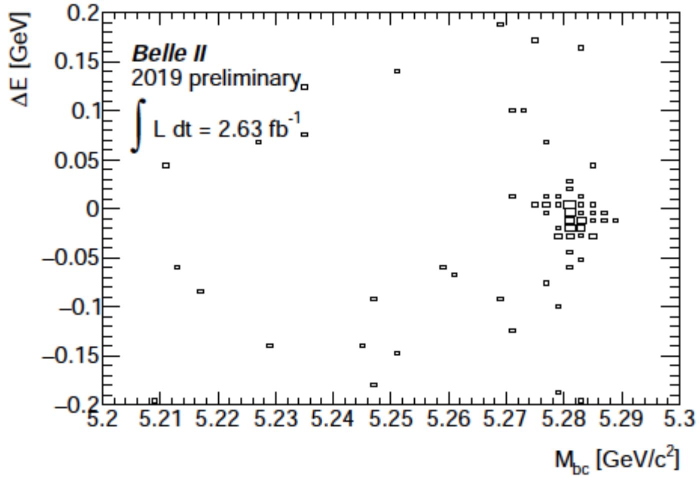
- about half of available data: 2.63 fb^{-1}

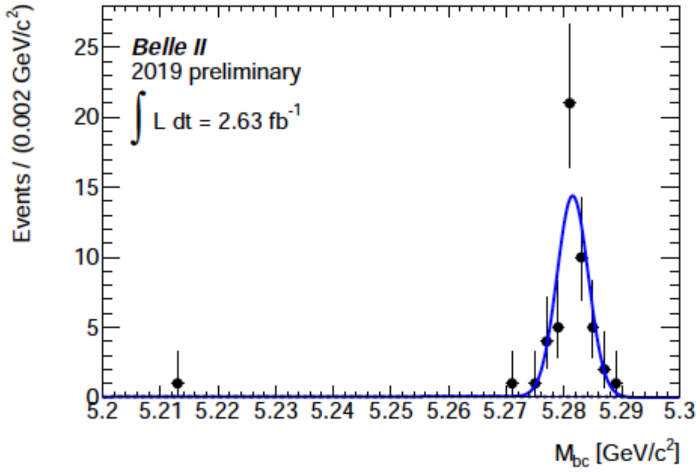
- both channels $J/\psi \rightarrow \mu\mu, ee$ are considered

- two variables

$$\Delta E = E^*_B - E^*_{beam}$$
$$M_{bc} = \sqrt{E^{*2}_{beam} - p^{*2}}$$







Yield of $B^0 \rightarrow J/\psi\ K^{*0}\ (K^-\pi^+)$: 48.6 ± 7.0 events

Note, this channel is not a CP eigenstate
For CP studies one would need $B^0 \rightarrow J/\psi\ K^{*0}\ (K^0_S\ \pi^0)$

An example of alternative time-dependent CP violation fit of signal $B^0 \to J/\psi\ K_S^0$ and control $B^{\pm} \to J/\psi\ K^{\pm}$ channels for Belle II MC (500 fb^{-1})

	$\tau(B^{\pm})\ ps$	$\tau(B^0)\ ps$	S	$\delta m(ps^{-1})$	α_{smear}
$ass.MC(BGx0)\ J/\psi(\mu\mu)K_S^0$		1.525	0	0	
$ass.MC(BGx0)\ J/\psi(ee)K_S^0$		1.525	0	0	
$ass.MC(BGx1)\ J/\psi(\mu\mu)K^{\pm}$	1.637				
$expected$	1.637	1.525	0.695	0.502	
$MC12b(BGx1)\ J/\psi(\mu\mu,ee)K_S^0$		1.554 ± 0.037	0.700 ± 0.059	0.536 ± 0.048	0 ± 0.63
$MC12b(BGx1)\ J/\psi(\mu\mu)K^{\pm}$	1.596 ± 0.036				0 ± 0.44
$MC12b(BGx1)\ combined$	1.596 ± 0.036	1.554 ± 0.037	0.701 ± 0.059	0.536 ± 0.048	0 ± 0.36

→ all results of the alternative TD CPV fits are consistent with the expectations within one sigma