Characterization of the Particle Identification of the Belle II Detector and Measurement of $\sin(2\phi_1)$ and Δm_d

Justin Skorupa

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MAX-PLANCK-INSTITUT FÜR PHYSIK

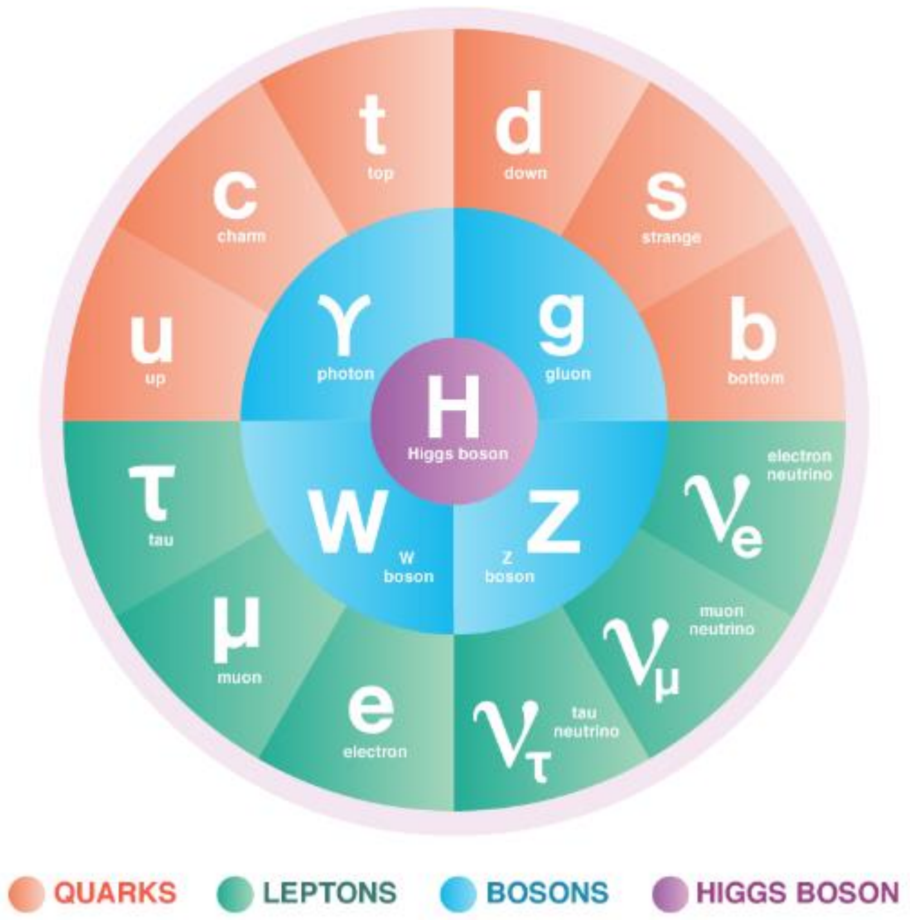
Belle II

Outline

- Introduction
- Two Topics of Flavour Physics
- SuperKEKB and Belle II Detector
- Particle Identification Algorithm
- Particle Identification Analysis
- Measurement of $\sin(2\phi_1)$ and $\Delta \mathrm{m_d}$
- Conclusion and Outlook

Introduction

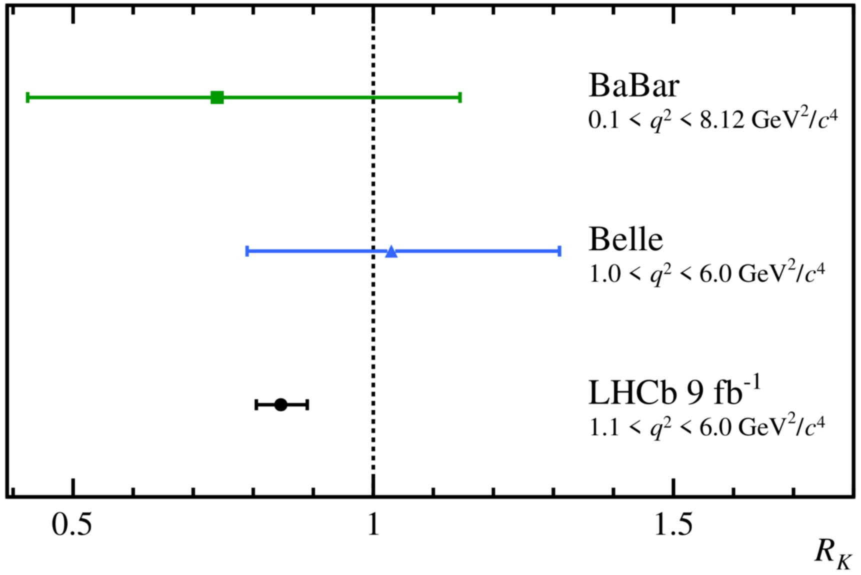
- The Standard Model of Particle Physics (SM) describes the observed universe with a reasonable set of particles
- But: It is incomplete
  - Dark matter
  - Matter-Antimatter asymmetry



Two Flavour Physics Topics

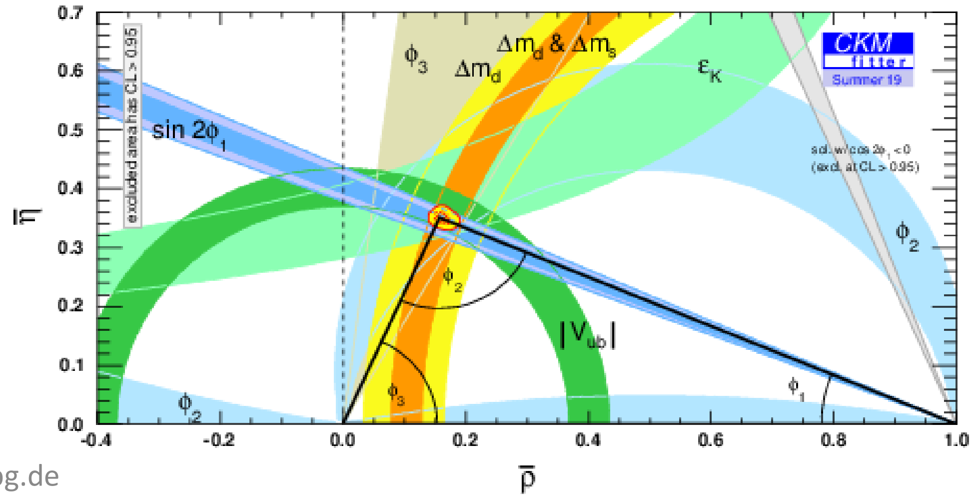
Lepton flavour universality:

- The coupling of gauge bosons independent of the lepton flavour
- $R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} = 1$



CP violation:

- In the SM, CP violation arises via a complex phase in the CKM matrix

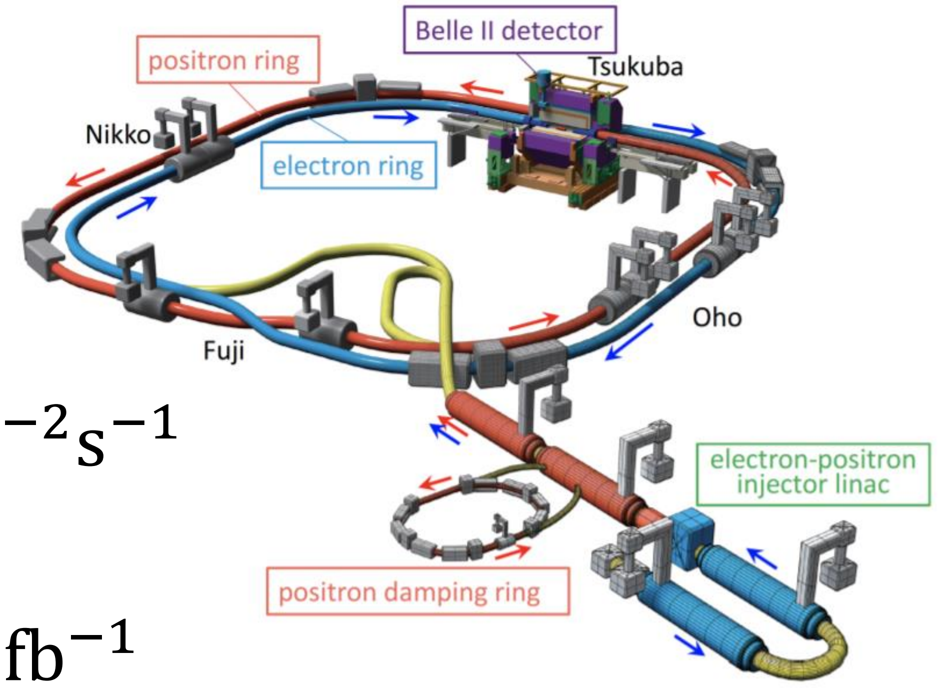


jskorupa@mpp.mpg.de

SuperKEKB

- Asymmetric electron-positron collider
- Centre of mass energy: 10.58 GeV

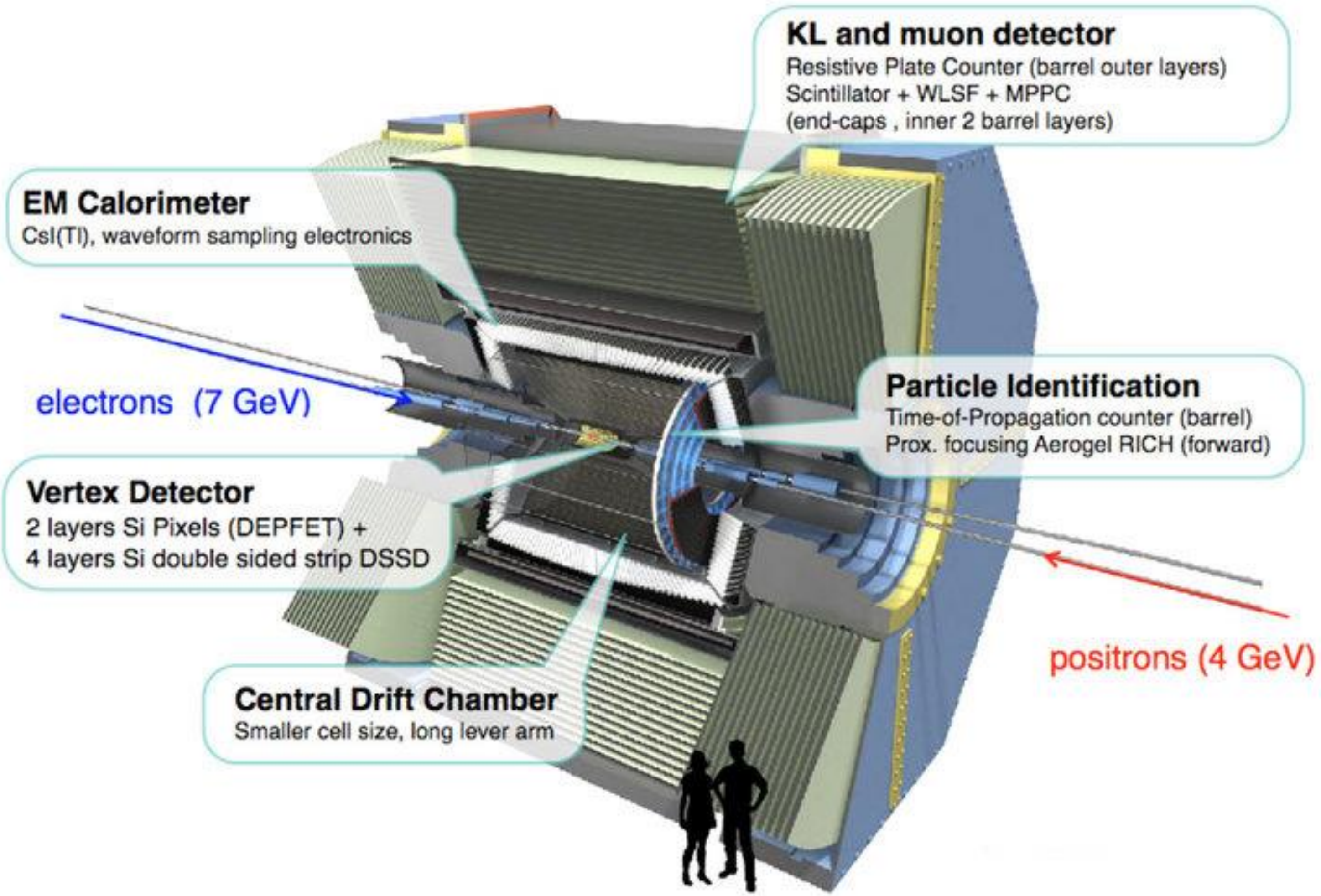
→Υ(4S) resonance



Aim:

- Instantaneous luminosity: $6 \cdot 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Integrated luminosity: $50\ \mathrm{ab}^{-1}$
- Biggest dataset used in analysis: $34.6\ \mathrm{fb}^{-1}$

Belle II Detector



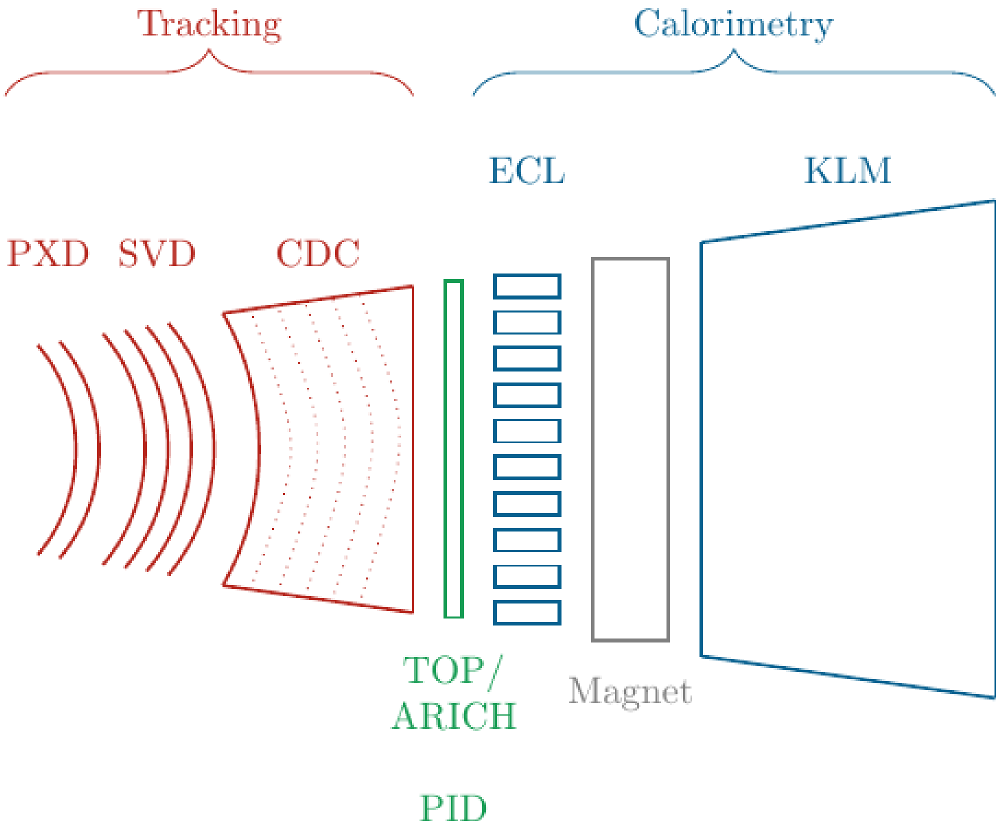
Particle Identification

- Likelihood calculated independently for each subdetector and hypotheses

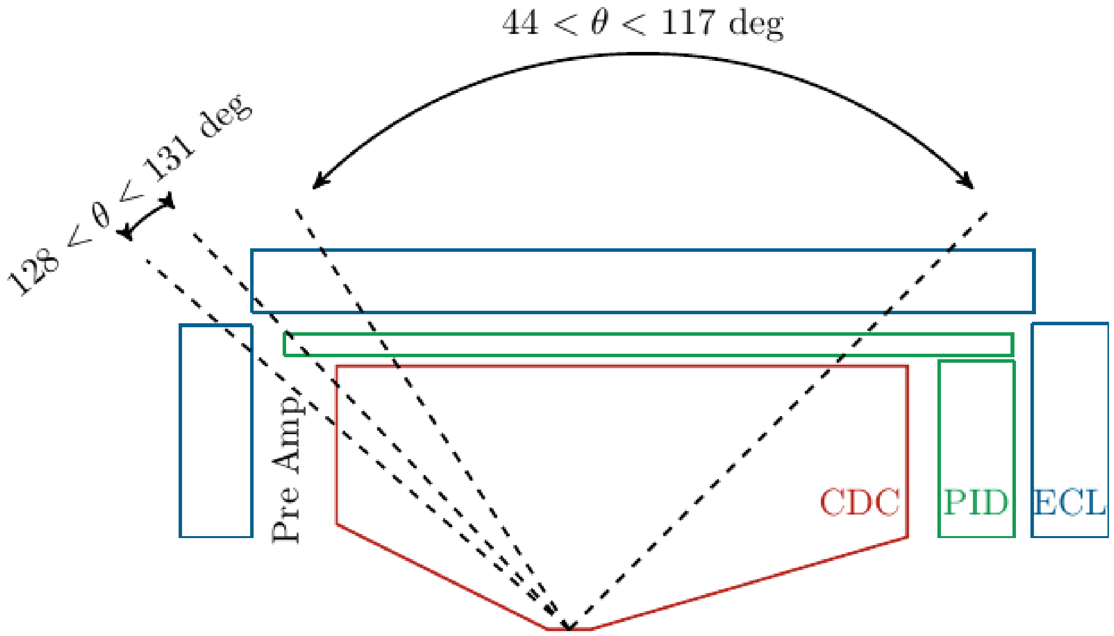
$$\mathcal{L}_i = \prod_{\text{det}} \mathcal{L}_i^{\text{det}}$$

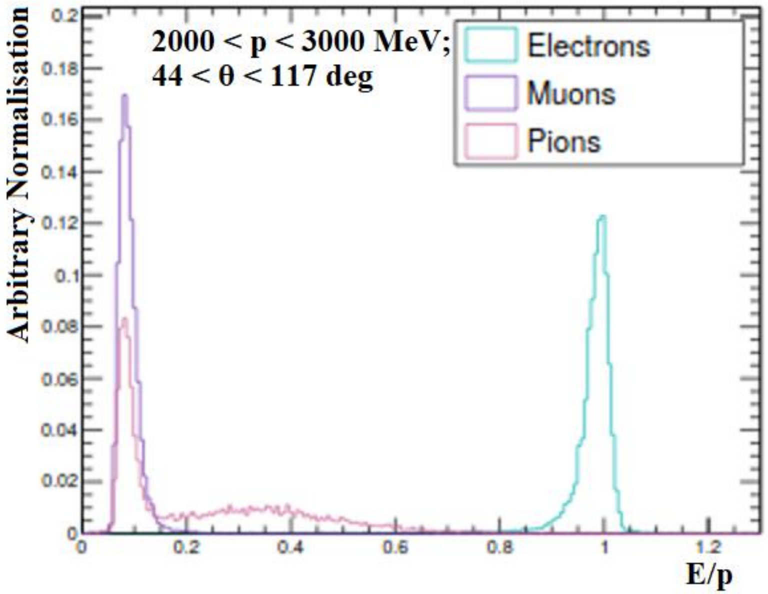
- Particle Identification probability:

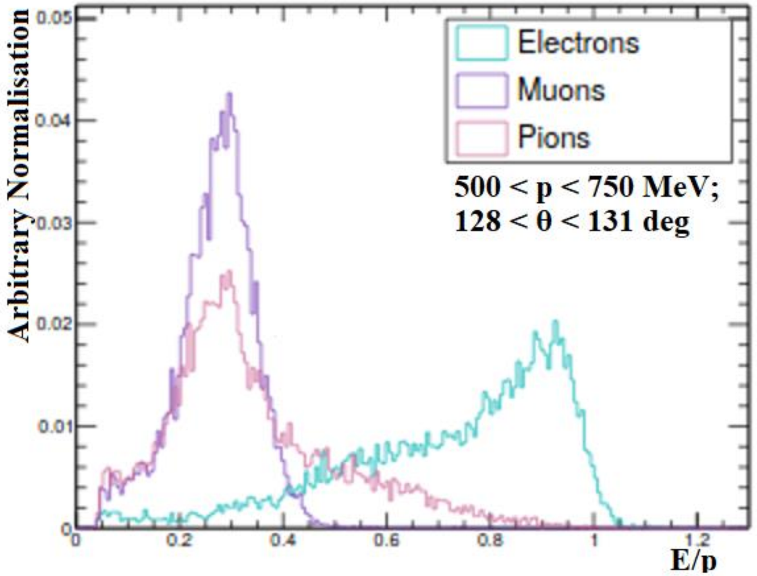
$$P_i = \frac{\mathcal{L}_i}{\sum_j \mathcal{L}_j}$$



Particle Identification

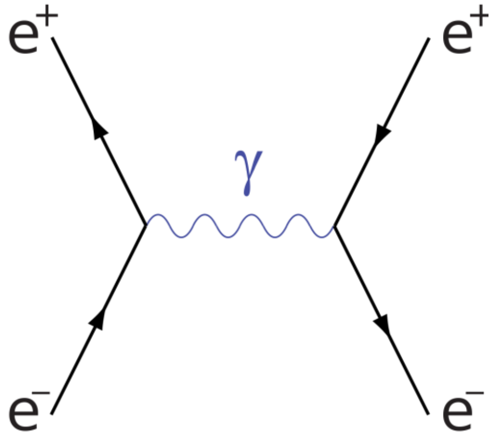


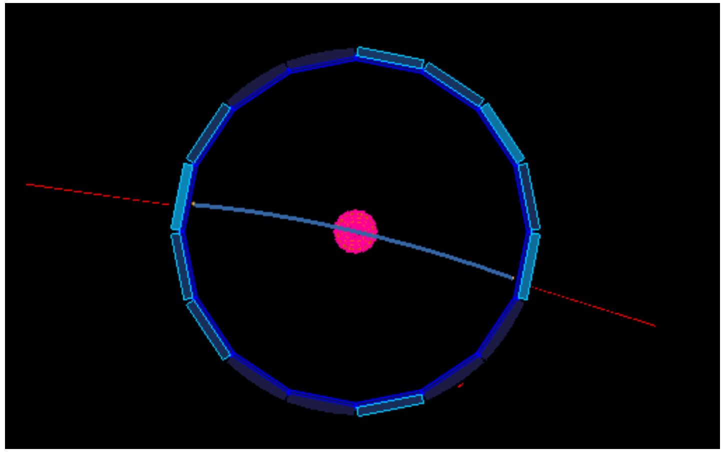




Analysis Particle Identification Efficiency

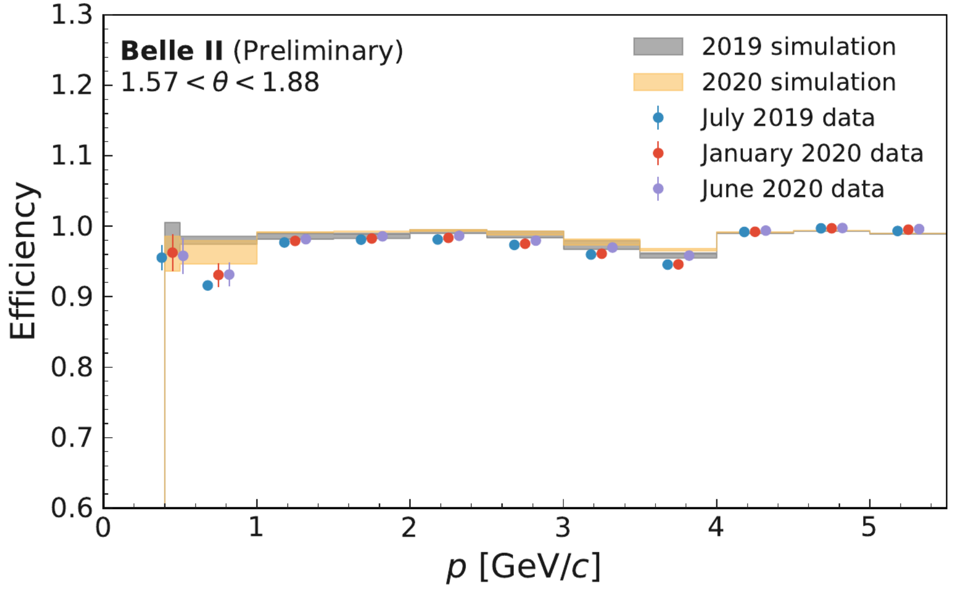
- Use Bhabha events in a tag and probe approach to measure efficiency of electron identification (eID)
- Advantages of Bhabha events:
  - High cross section
  - Cover wide momentum range
  - Clear event signature

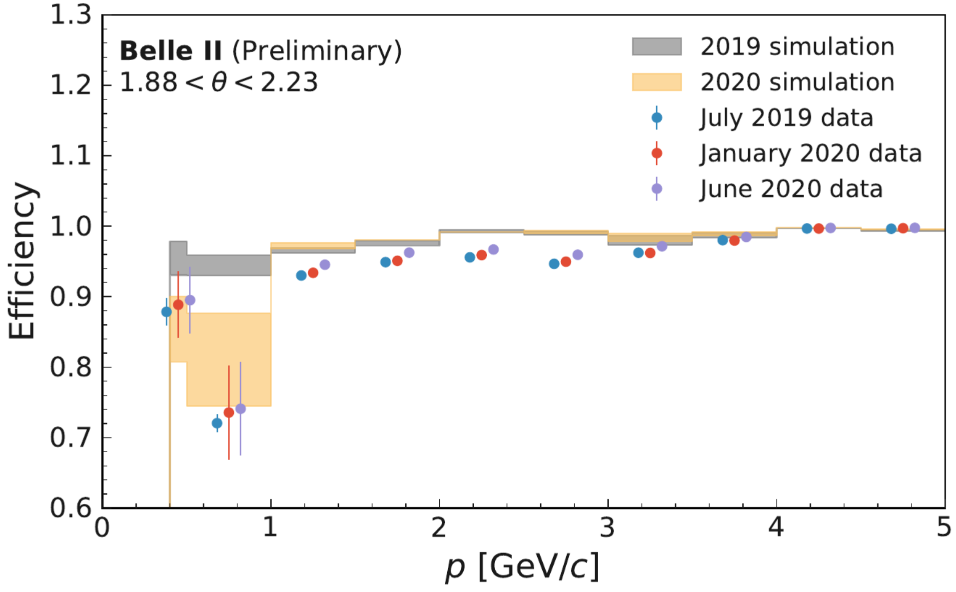




Result

- Simple selection
- Corrections for background
- Calculate systematic uncertainties

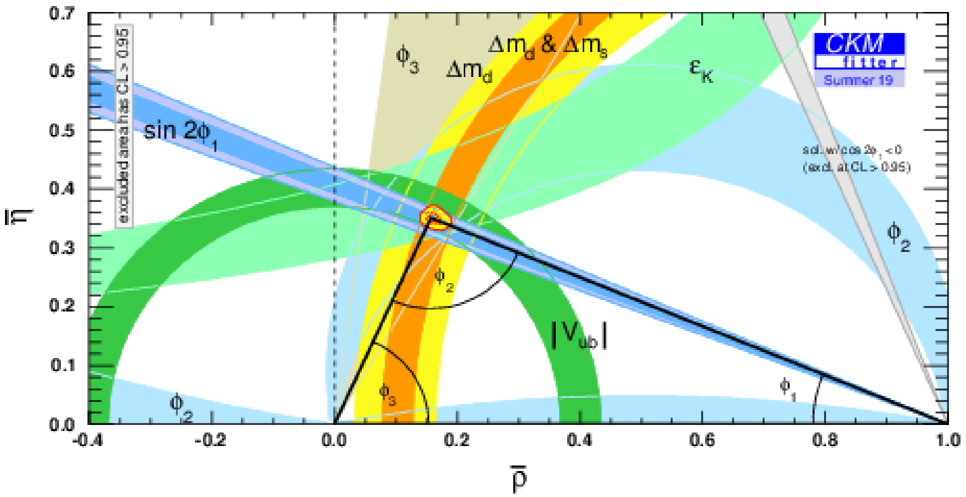


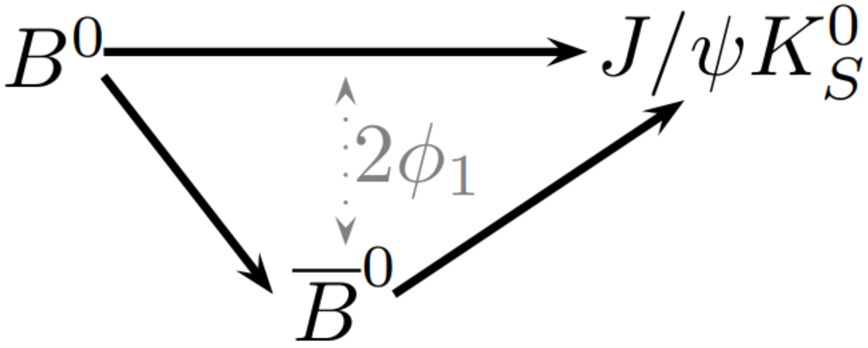


Measurement of $\sin(2\phi_1)$ and Δm_D

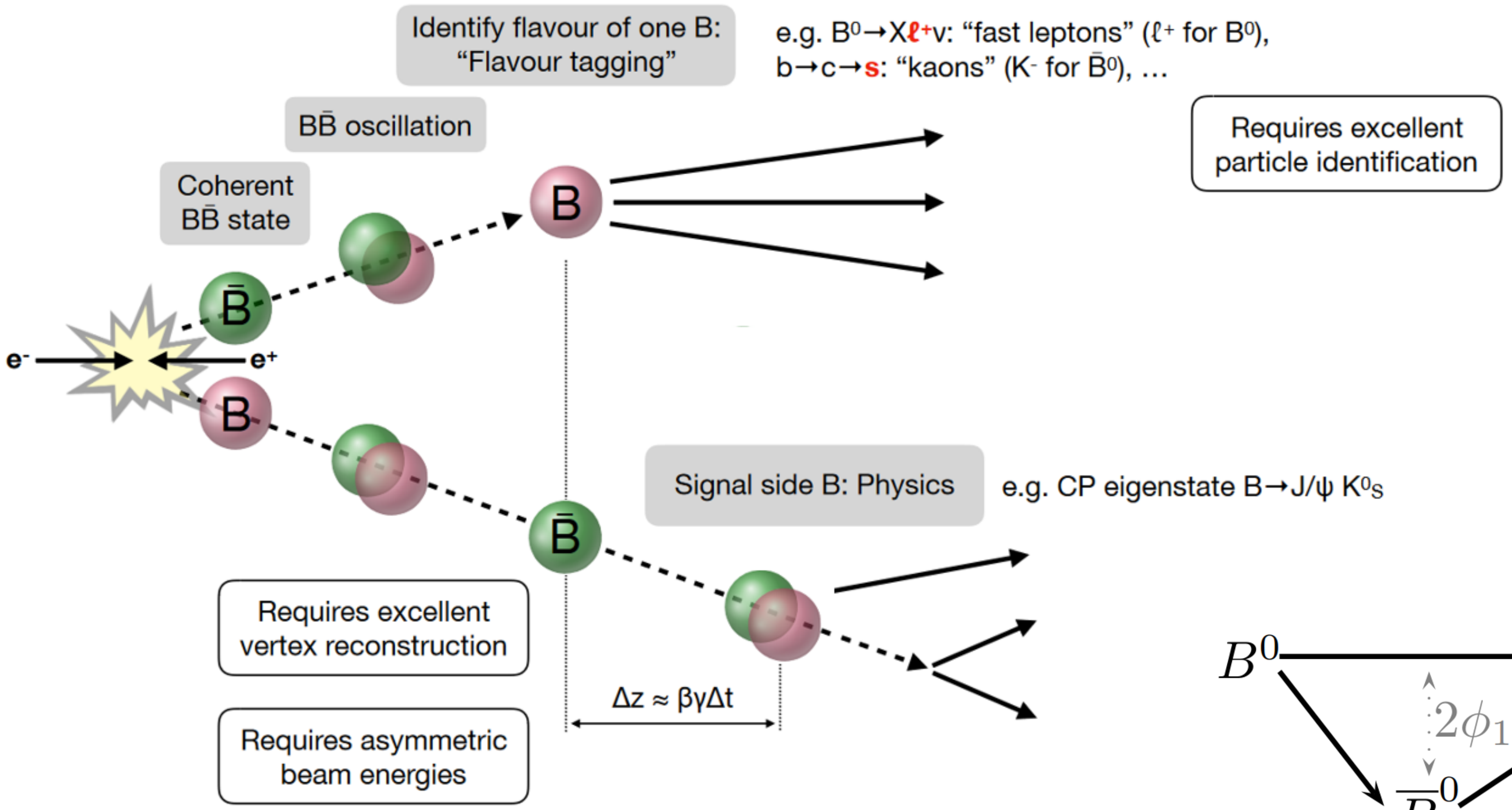
TDCPV Measurement

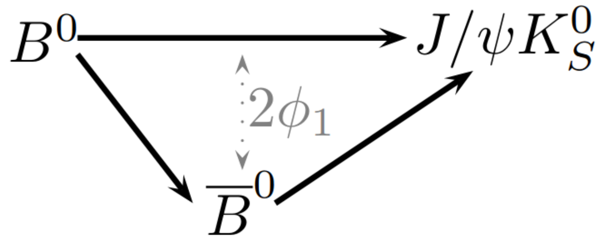
- Determine $\sin(2\phi_1)$ via measurement of the asymmetry between the number of $B^0$and $\bar{B}^0$ decays into the CP-eigenstate $J/\psi K_S^0$ as a function of the decay time
- World average (PDG):
  $$\sin(2\phi_1) = 0.699 \pm 0.017$$
- Aim of Belle II: Increase precision to $\approx 0.5\%$





Time Dependent CP Violation at Belle II





General Principle of the Analysis

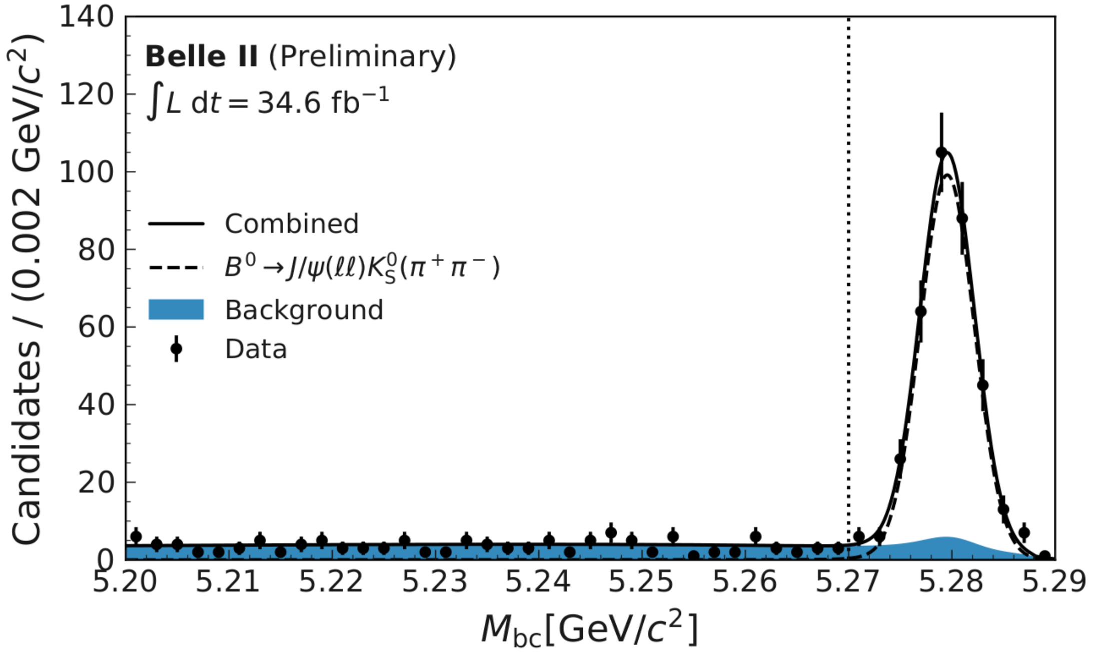
- The distribution for positive (negative) flavour events as a function of Δt follows:

$$N_{\pm}(\Delta t) = N \cdot \frac{\exp(-\Delta t/\tau)}{4\tau} \left[1 \pm (1 - 2w) S_f \sin(\Delta m_D \Delta t)\right]$$

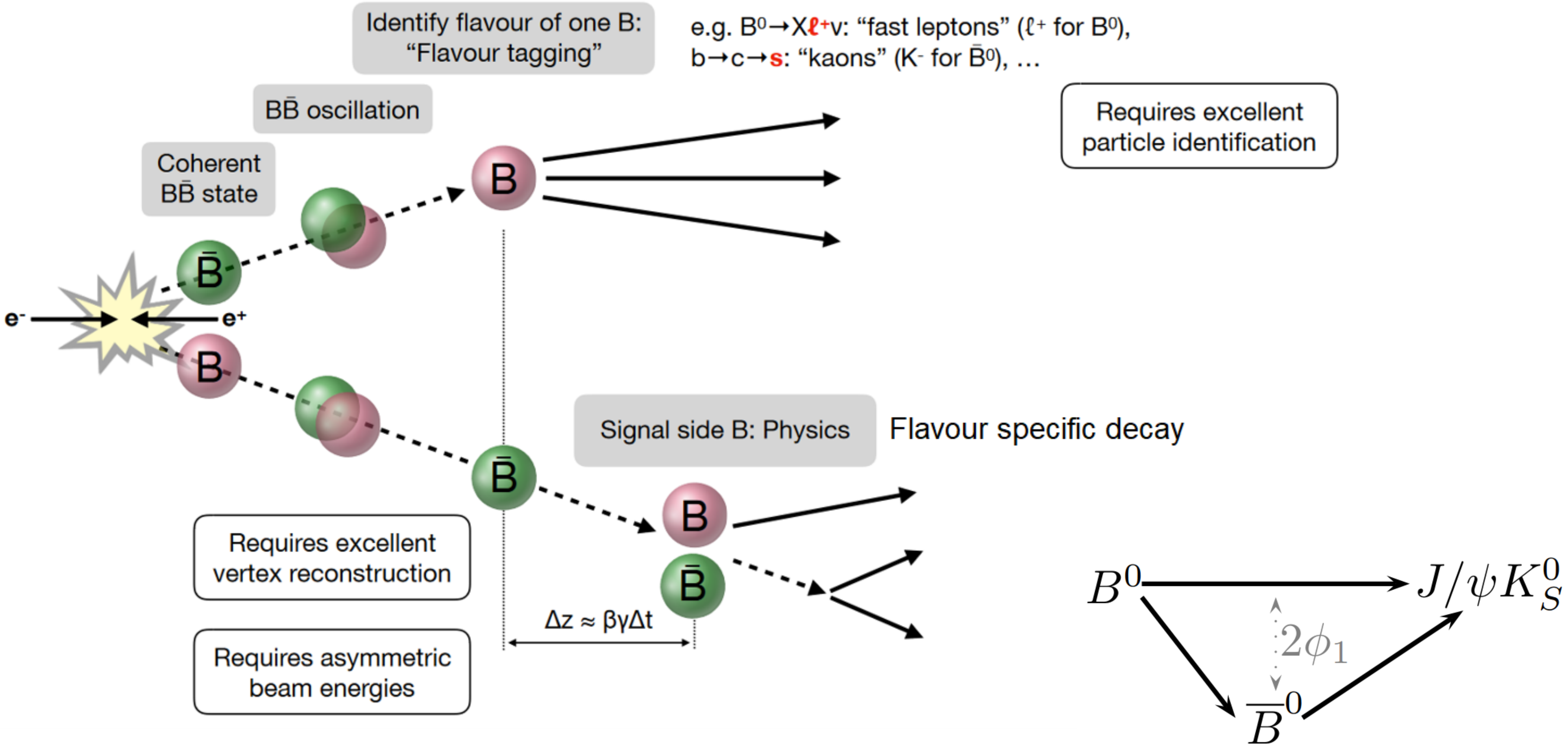
- Goal: Extract $S_f \approx \sin(2\phi_1)$
- Lifetime τ and mixing frequency Δm_D are set to PDG values
- Wrong tag fraction w needs to be determined
- Estimate background

Background

- Loose and simple selection to supress background (backup)
- Fit to M_{bc} distribution to determine remaining background fraction
  - $M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$
  - Signal Events peak at the B mass
- Shapes extracted from 500 fb^{-1} simulation sample



Determining wrong tag fraction *w*



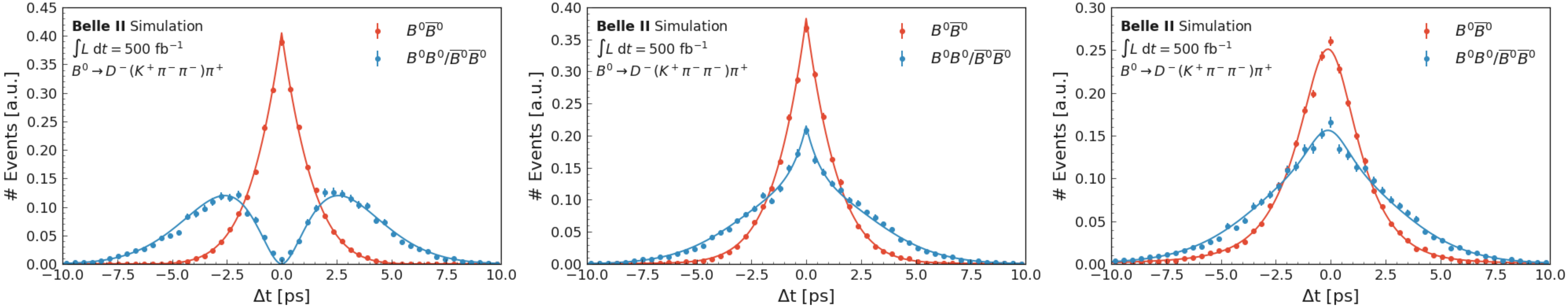
Mixing Fit

- Fit to events with a flavour specific decay
- Classify events into two categories where the B^0_{sig} and B^0_{tag} have the same flavour (SF) or the opposite flavour (OF)

$$N_{\mathrm{SF/OF}}(\Delta t) = N_{\mathrm{SF/OF}} \cdot \frac{\exp(-\Delta t/\tau)}{4\tau} \left[1 \pm (1-2w)\cos(\Delta m_D \Delta t)\right]$$

→Fit to $B^0 \to D^-(K^+\pi^-\pi^-)\pi^+$ (most abundant)

Detector and Reconstruction Effects



- Left: $w = 0$ and Δt from simulation
- Middle: $w \neq 0$ and Δt from simulation
- Right: $w \neq 0$ and Δt is measured quantity

→ $\mathrm{N_{SF/OF}}(\Delta\mathrm{t}) \rightarrow (\mathrm{N_{SF/OF}} * \mathcal{R})(\Delta\mathrm{t})$

Mixing Fit

- Wrong tag fraction:

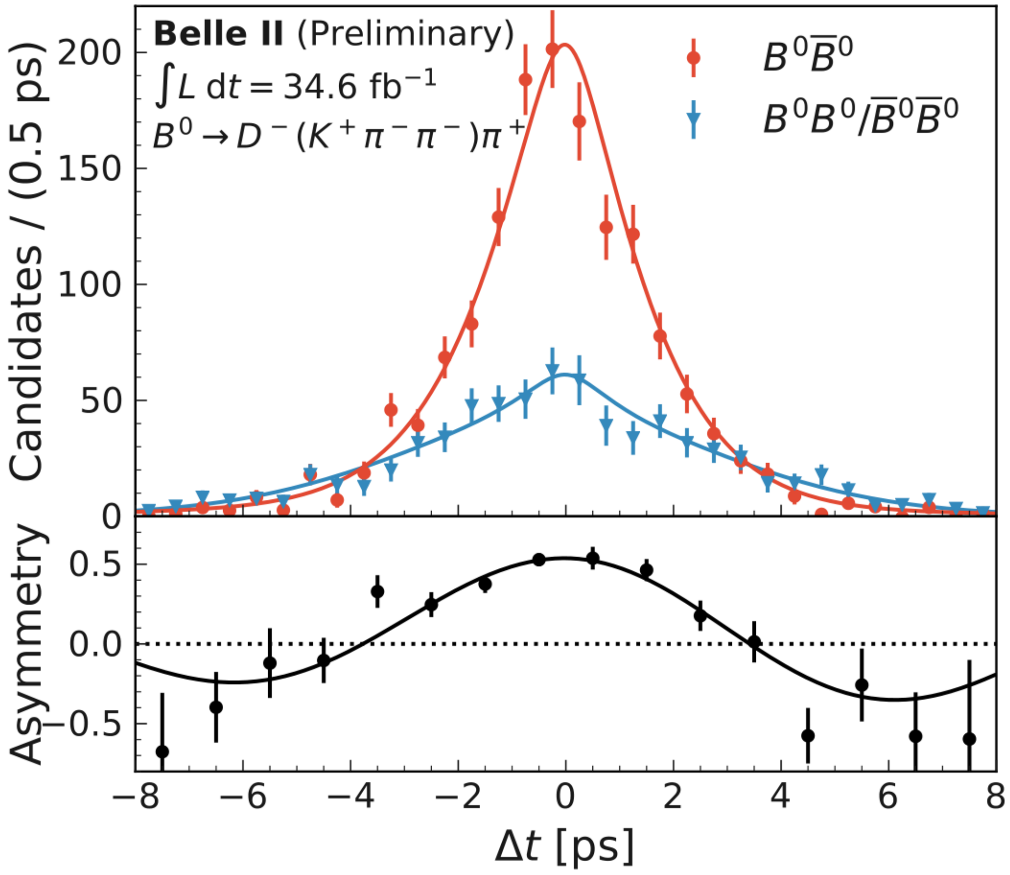
$$w = (20.9 \pm 2.1)\%$$

- Simulation: 20.0 %

- $\Delta m_d =$

$(0.531 \pm 0.046\ (\text{stat.}) \pm 0.013\ (\text{syst.}))\ \mathrm{ps}^{-1}$

- PDG: $(0.5065 \pm 0.0019)\ \mathrm{ps}^{-1}$



Combined Fit Strategy

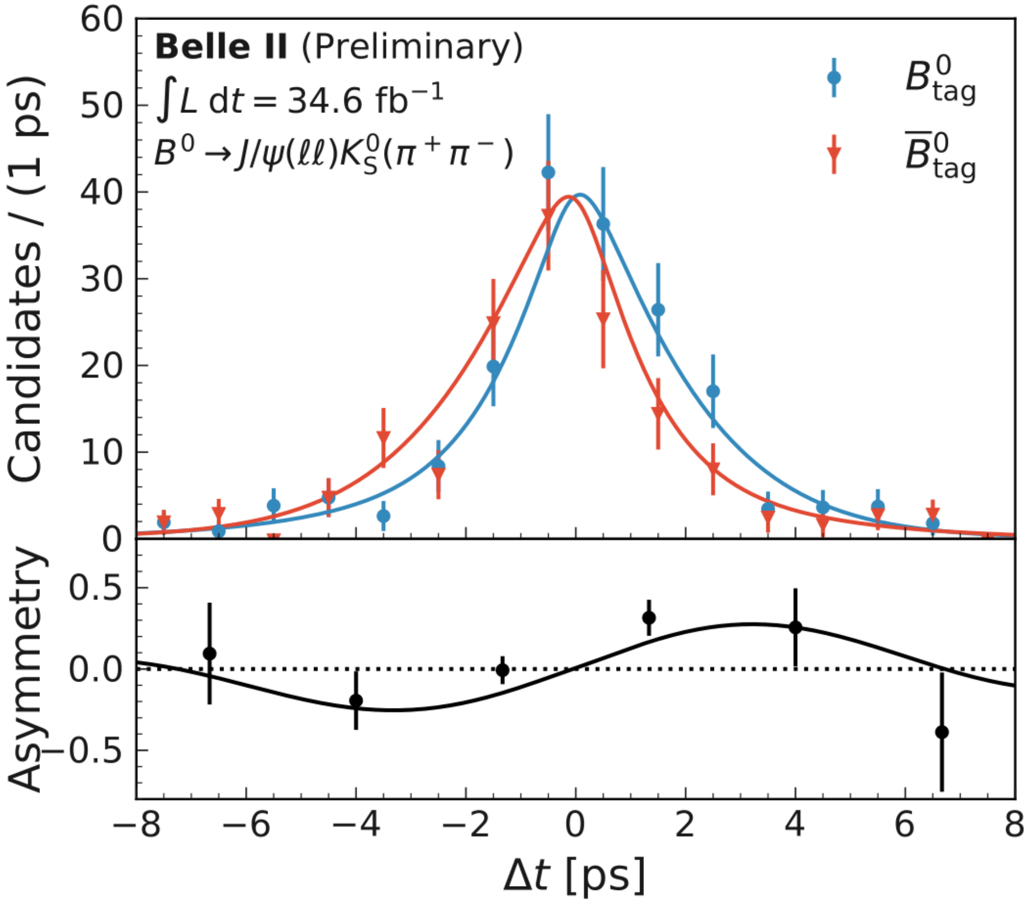
- The parameter S_f is extracted using an extended unbinned maximum likelihood fit simultaneous to six datasets:
- 1,2 $B^0 \rightarrow D^-\pi^+$ same flavour and opposite flavour
- 3,4 $B^0 \rightarrow J/\psi(\mu\mu)K_S$ with a B^0 and $\bar{B}^0$ tag
- 5,6 $B^0 \rightarrow J/\psi(ee)K_S$ with a B^0 and $\bar{B}^0$ tag
- Free shape parameters for TDCPV fit:

$$S_f \ , w, \sigma_{\mathrm{smear}}, \mu_{\mathrm{shift}}, M_{bc;\mathrm{shift}}$$

- With this method, stat errors on w and bkg fraction are propagated automatically to the physics parameters by the fit.

Result: Time Dependent CP Violation

- S_f = 0.55 $\pm$0.21 (stat.) $\pm$0.04 (syst.)
- PDG: 0.699 $\pm$ 0.017



Summary and Outlook

- Obtained values agree well with PDG
- Belle II sees hint of Time Dependent CP Violation with 2.71σ
- w = (20.9 $\pm$ 2.1)% (Simulation: 20.0 %)
- Next step: Improve background treatment, resolution function , fitting…

→ Transform measurement into precision measurement

- Electron ID efficiency is generally above 90%
- Distribution is well understood
- Next steps: More sophisticated treatment of uncertainties, modify study if data acquisition/trigger (HLT) setup changes

jskorupa@mpp.mpg.de

Backup

LID: Analysis Procedure

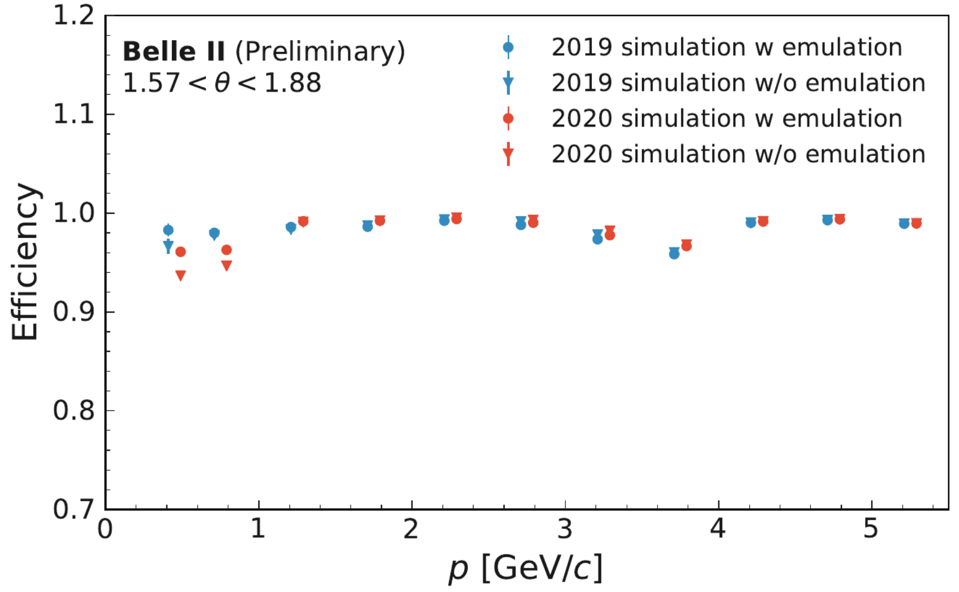
- Simple event selection, tight tag requirement
- Compute efficiency in bins of θ and p
- Efficiency: $\epsilon = \frac{p_{\text{probe}} \cdot N_{\text{probe}}}{p_{\text{tag}} \cdot N_{\text{tag}}}$
- Three different data samples corresponding to different data taking periods and two different simulation samples to evaluate performance of eID over time

Event selection
|dz| < 5 cm & |dr| < 2 cm
Number of tracks = 2
m2Recoil < 10 GeV
Low multiplicity trigger + emulation
Tag selection: eID > 0.95
Probe selection: eID > 0.90

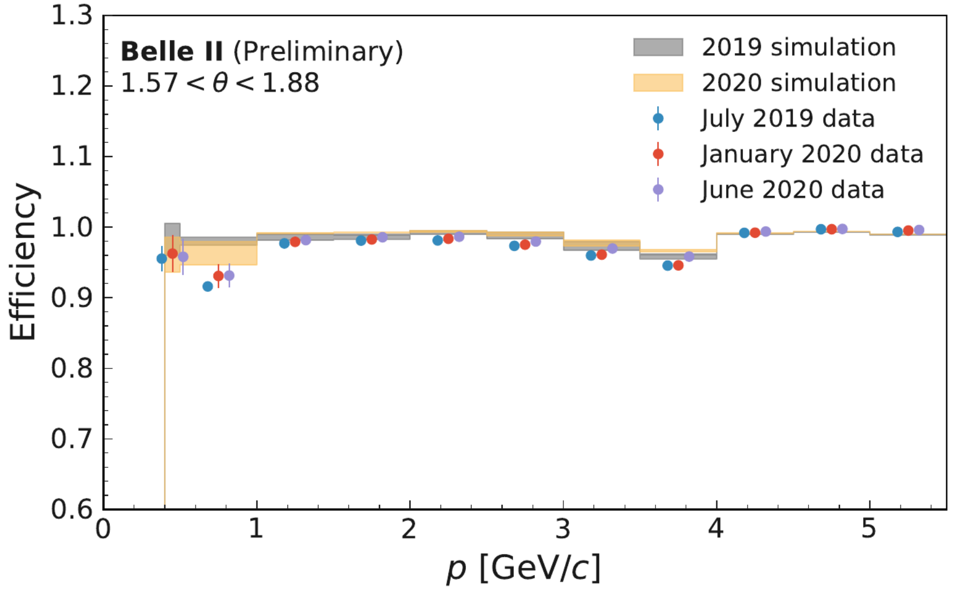
LID: Systematics

- Calculate efficiency with and without purity factors
- Calculate efficiency with and without trigger emulation using simulation samples

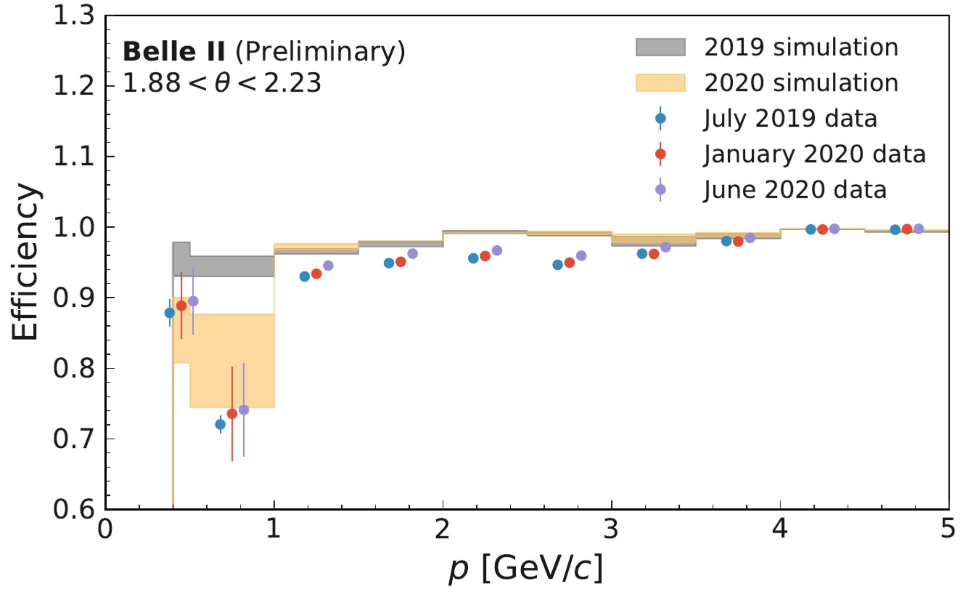
→ Absolute difference as uncertainty



LID: Result



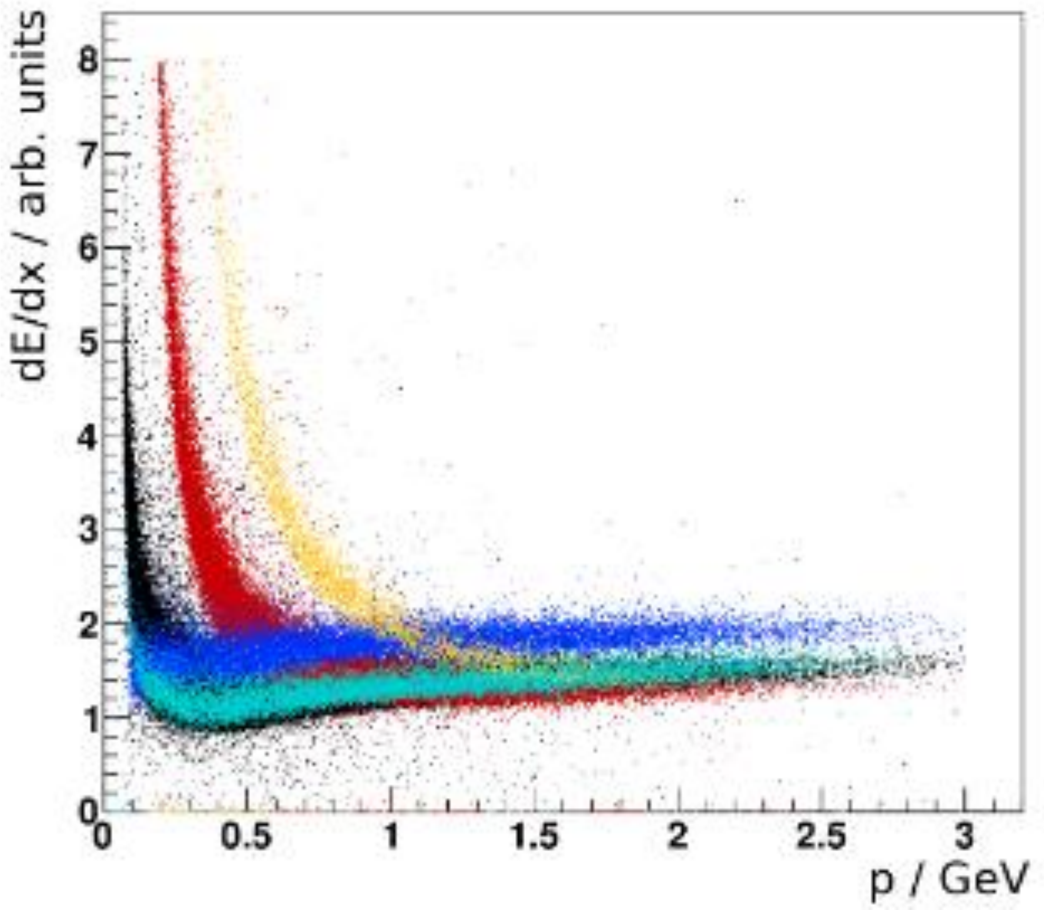
Belle II (Preliminary)
1.57 < θ < 1.88
2019 simulation
2020 simulation
July 2019 data
January 2020 data
June 2020 data
Efficiency
p [GeV/c]



Belle II (Preliminary)
1.88 < θ < 2.23
2019 simulation
2020 simulation
July 2019 data
January 2020 data
June 2020 data
Efficiency
p [GeV/c]

LID: dE/dx

- dE/dx for:
  - Electrons
  - Muons
  - Pions
  - Kaons
  - Protons



TDCPV: Background

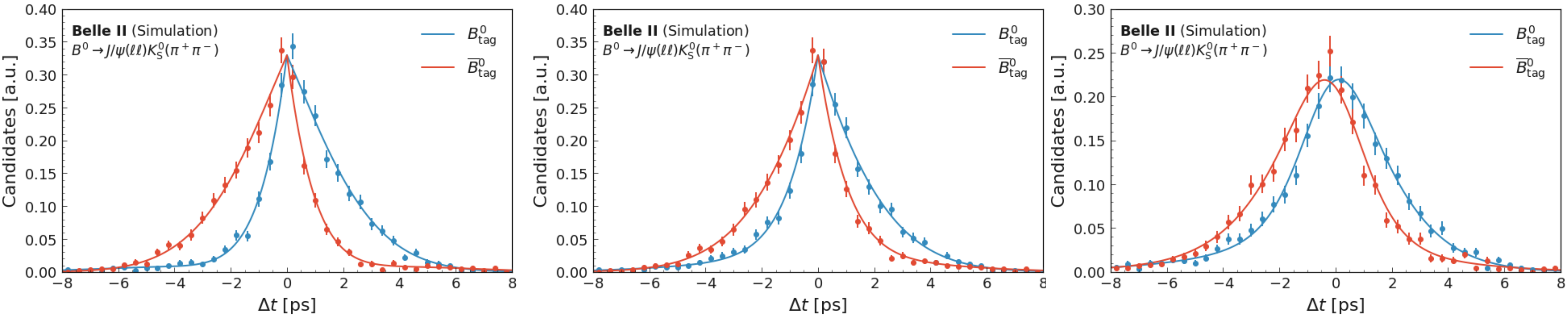
all channels		
$\lvert qr \rvert$	$>$	0.2
R_2	$<$	0.4
Δt_{err}	$>$	0.1 ps
	$<$	6.0 ps
p-val(tag)	$>$	1%
p-val(sig)	$>$	-1
m_{bc}	$\in$	(5.2, 5.3) GeV

$B^0 \to J/\psi(\to \ell\ell)K_S$			$B^0 \to D\pi$		
$m_{\mu\to\pi}(\ell\ell)$	$>$	3.05 GeV	$\lvert\Delta E\rvert$	$<$	0.05 GeV
$m_{\mu^\pm\to\pi^\pm}(K_S\ell^\pm)$	$\notin$	(1.85, 1.89) GeV	$m(D)$	$\in$	(1.844, 1.894) GeV
$m(\pi\pi)$	$\in$	(0.47, 0.53) GeV	$ID_K(\pi_B)$	$<$	0.5
$dr(K_S)$	$>$	0.6 cm	$ID_K(K)$	$>$	0.4
$B^0 \to J/\psi(\to \mu^+\mu^-)K_S$					
$\lvert\Delta E\rvert$	$<$	0.05 GeV			
$m(\mu\mu)$	$\in$	(3.00, 3.15) GeV			
$ID_\mu(\mu^+)$ or $ID_\mu(\mu^-)$	$>$	0.2			
$B^0 \to J/\psi(\to e^+e^-)K_S$					
$\lvert\Delta E_{\mathrm{ctr}}\rvert$	$<$	0.04 GeV			
$m(ee)$	$\in$	(2.90, 3.15) GeV			
$ID_e(e^+)$ or $ID_e(e^-)$	$>$	0.2			

TDCPV: Systematics

Source	Δm_d [%]	S_f [%]
Background scale and shift	-0.2	-0.3
Peaking Background $B^0 \to J/\psi\ K_S \pm 100\%$	-	-2.7
$B\overline{B}$ fraction $\pm 50\%$ in $B^0 \to D\pi$	0.03	-2.1
Δm_{eff} for $B\overline{B}$ free	0.8	0.4
w_{eff} for $B\overline{B}$ free	-0.15	4.9
w difference between $B^0 \to J/\psi\ K_S$ and $B^0 \to D\pi$	-	2.9
Resolution function tail scale	1.2	0.6
Resolution function tail fraction $\pm 50\%$	1.4	0.4
Kinematic approximation w, Δm_d	1.2	0.0
Kinematic approximation S_f	-	-0.9
VXD misalignment	0.4	2.0
total	2.4	7.1

$B^0 \to J/\psi K_s$ Shape



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