Charmed-Meson Physics at Belle II

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on behalf of the Belle II collaboration

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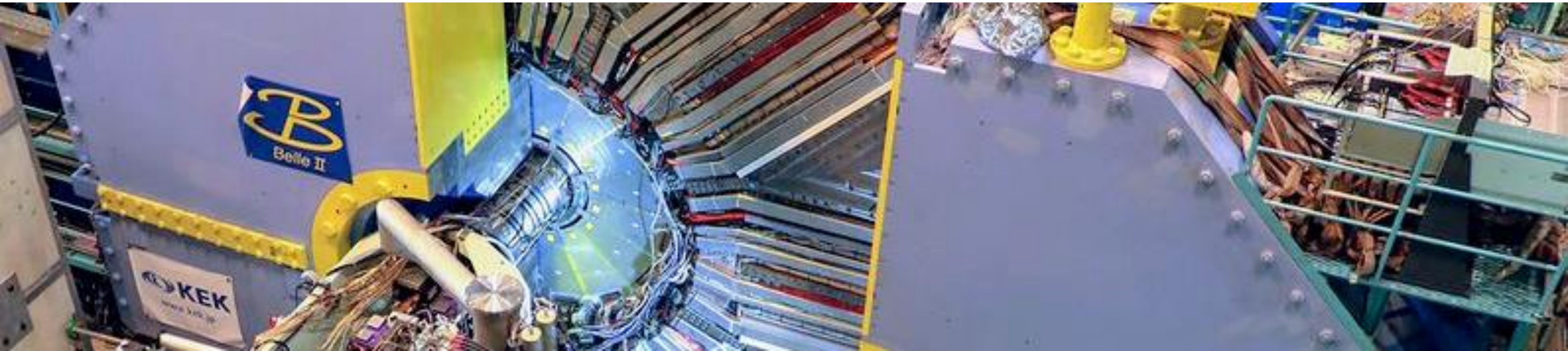
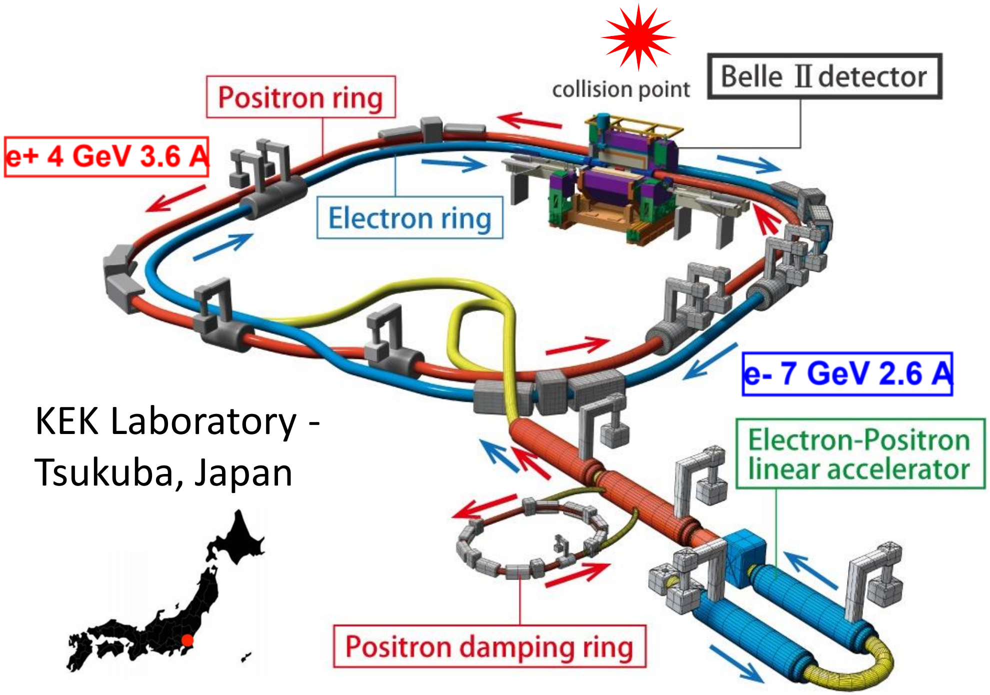


Outline

- **SuperKEKB and Belle II Detector**
- **Status and Prospects of Charmed-Meson Physics**
  - Time-Integrated Measurements
    - Time-integrated *CP* violation
  - Time-Dependent Measurements
    - D^0 lifetime measurement
    - D^0-$\overline{D}^0$mixing
  - Full Charm Event Reconstruction
    - Leptonic, rare decays
- **Conclusions**

SuperKEKB and Belle II Detector

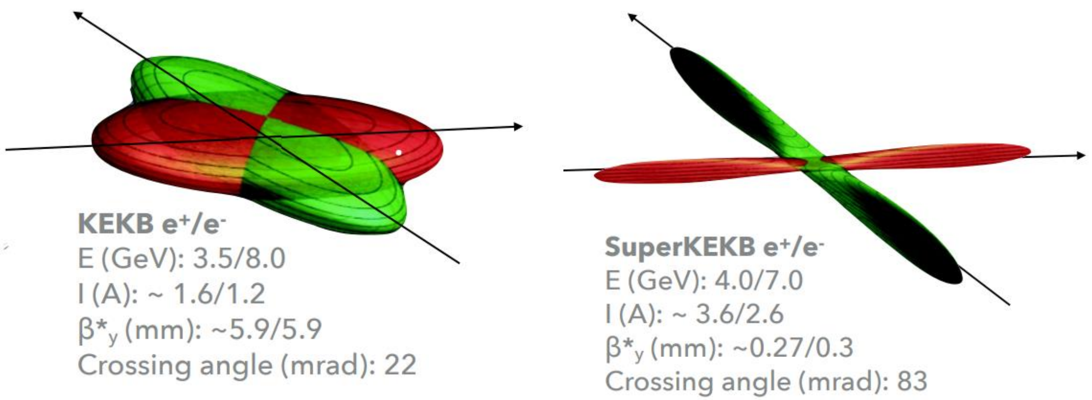
— SuperKEKB



KEK Laboratory - Tsukuba, Japan

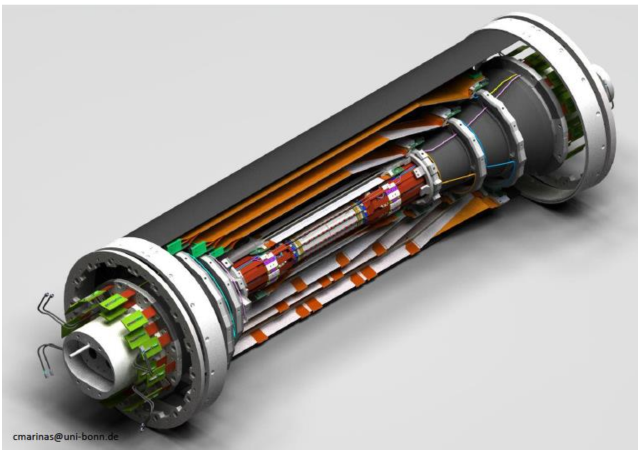
- $E_{CM} = 10.58\ \text{GeV}\ (\Upsilon(4S))$
- Designed peak luminosity
  $= 6.5 \times 10^{35}\ \text{cm}^{-2} s^{-1}$
  $= 6.5 \times 10^{2}\quad \text{nb}^{-1} s^{-1}$
- $ee \to c\bar{c}$ cross section
  $\approx 1.3\ \text{nb}\ @10.58\ \text{GeV}$

- Nano beams technique
  beam size ↓ 20 times
  currents ↑ 2 times



SuperKEKB and Belle II Detector

— Belle II Detector

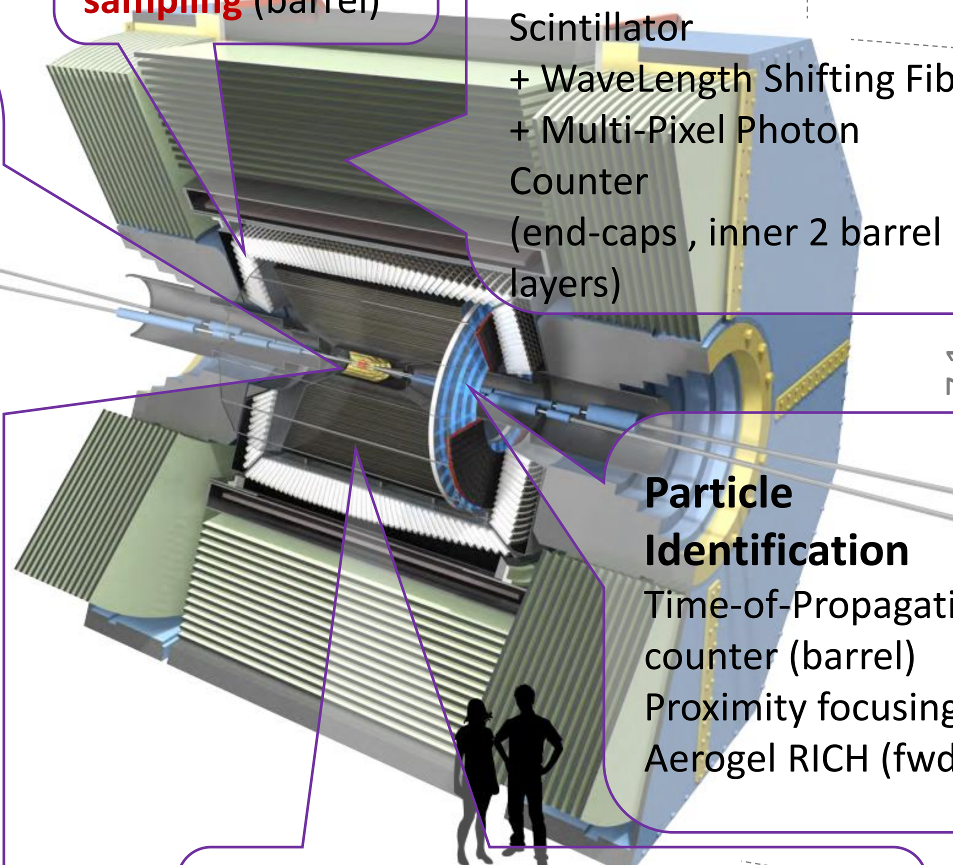


Vertex Detector

PXD: **2** layers **DEPFET** pixels detector

- Beampipe r= 10 mm
- Layer 1 r=14 mm
- Layer 2 r= 22 mm

SVD: **4** layers double side Si strips detector (DSSD)



EM Calorimeter

CsI(Tl), **waveform sampling** (barrel)

K_L & μ detector

Resistive Plate Chambers (barrel outer layers)

Scintillator + WaveLength Shifting Fibers + Multi-Pixel Photon Counter (end-caps , inner 2 barrel layers)

Particle Identification

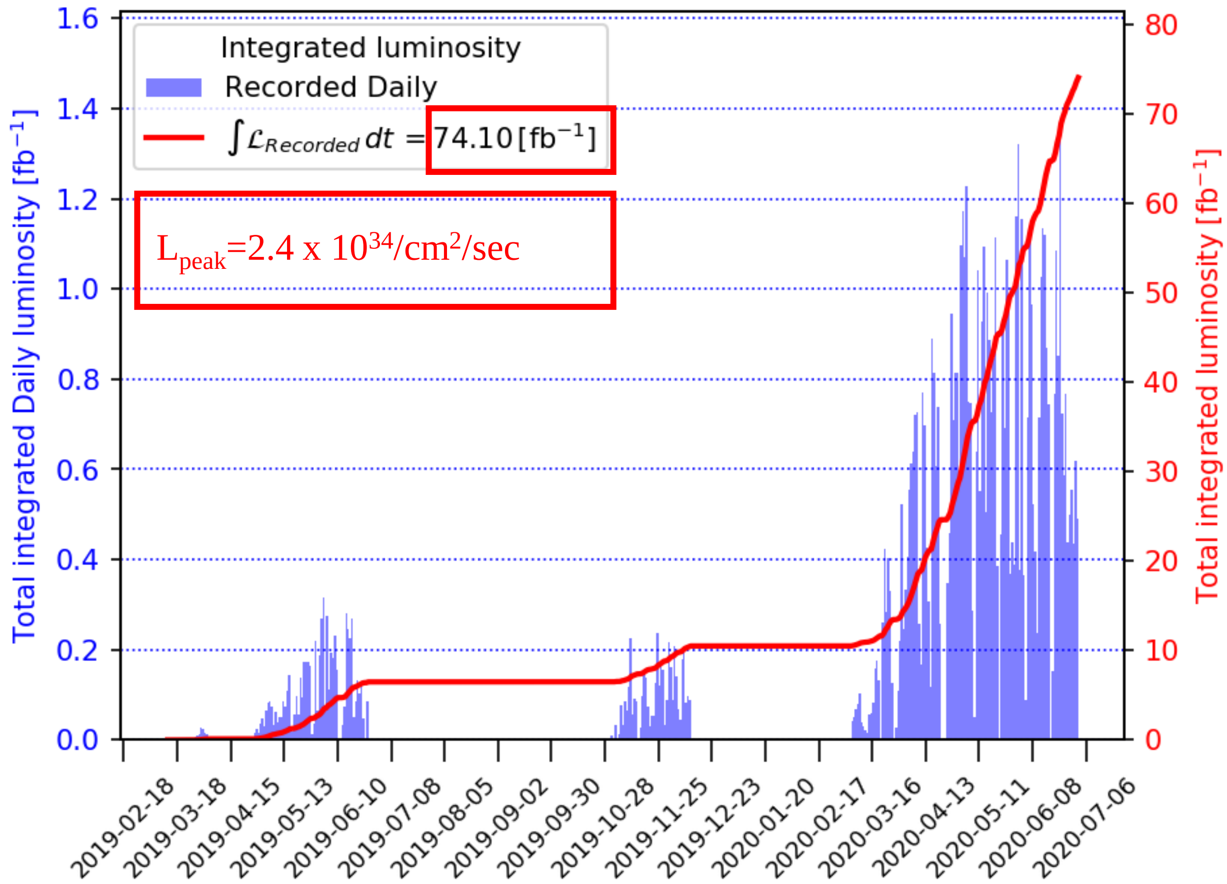
Time-of-Propagation counter (barrel)

Proximity focusing Aerogel RICH (fwd)

Central Drift Chamber

He(50%): C_2H_6(50%), small cell size, long lever arm, fast electronics

SuperKEKB and Belle II Detector



- Target dataset : 50 ab^{-1} (50×Belle)
- Current integrated luminosity (2019-2020) $\approx$ 74 fb^{-1}
- New world record luminosity (June 2020) $\approx 2.4 \times 10^{34}\mathrm{cm}^{-2}s^{-1}$

> $2.11 \times 10^{34}\mathrm{cm}^{-2}s^{-1}$ (Belle, June 2009)

Time-Integrated Measurements

— Time-integrated *CP* violation : Prospect@50 ab^{-1}

- *CP* violation is a sensitive probe to physics beyond SM
- **Time-integrated *CP*** violation could be measured by:
  - $A_{CP} = \frac{N_{D^0\to f} - N_{\bar{D}^0\to \bar{f}}}{N_{D^0\to f} + N_{\bar{D}^0\to \bar{f}}}$
- **Belle II** would produce important measurement especially for channels containing **neutral** final states
- Measured A_{CP} will reach a precision of $o(10^{-4})$, also in channels with neutrals in the final state

Mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II 50 ab^{-1}
$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	± 0.03
$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	± 0.05
$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	± 0.09
$D^0 \to K^0_S\pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	± 0.02
$D^0 \to K^0_S K^0_S$	921	$-0.02 \pm 1.53 \pm 0.02 \pm 0.17$	± 0.23
$D^0 \to K^0_S\eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07
$D^0 \to K^0_S\eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.09
$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 1.30$	± 0.13
$D^0 \to K^+\pi^-\pi^0$	281	-0.60 ± 5.30	± 0.40
$D^0 \to K^+\pi^-\pi^+\pi^-$	281	-1.80 ± 4.40	± 0.33
$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.04
$D^+ \to \pi^+\pi^0$	921	$+2.31 \pm 1.24 \pm 0.23$	± 0.17
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.14
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.14
$D^+ \to K^0_S\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.02
$D^+ \to K^0_S K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.04
$D^+_s \to K^0_S\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
$D^+_s \to K^0_S K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05
$D^+_s \to K^+\pi^0$			

Belle II Physics Book; PETP 2019, 123C01 (2019)

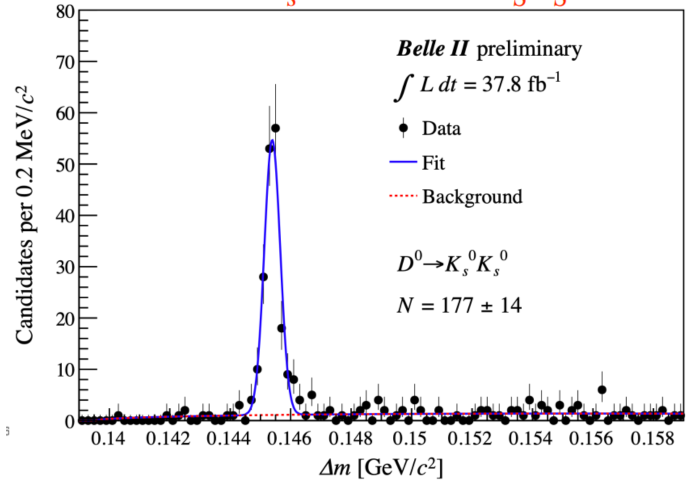
$$\sigma_{\text{Belle II}} = \sqrt{(\sigma^2_{\text{stat}} + \sigma^2_{\text{syst}}) \cdot (\mathcal{L}_{\text{Belle}}/50\,\text{ab}^{-1}) + \sigma^2_{\text{irred}}}.$$

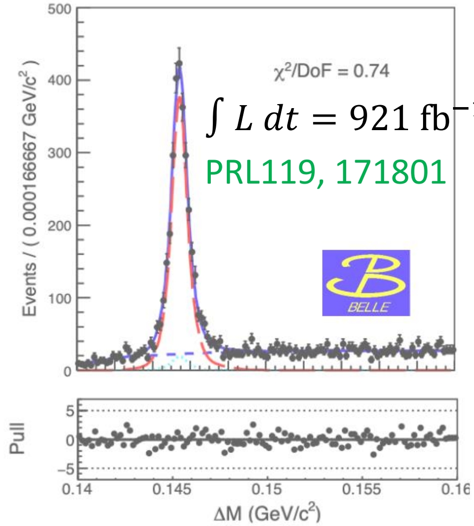
Time-Integrated Measurements

— Time-integrated *CP* Violation : Current Status

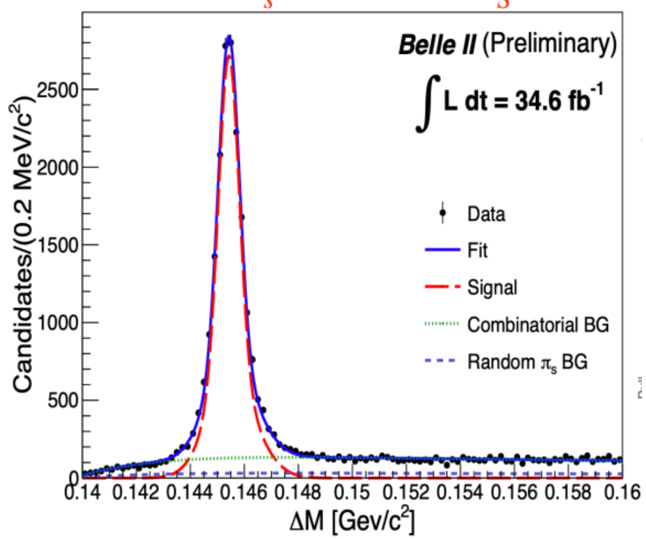
- The following D^0 channels are rediscovered:
  - $D^{*+} \to D^0\pi_S^+,\ D^0 \to K_S K_S$
    SCS decay, sensitive for CPV
  - $D^{*+} \to D^0\pi_S^+,\ D^0 \to K_S\pi^0$
    CF decay, used to be normalization model for $D^0 \to K_S K_S/\pi^0\pi^0/\gamma\gamma$
- The resolution and background level is comparable with Belle, with only 1.5 years of data taking

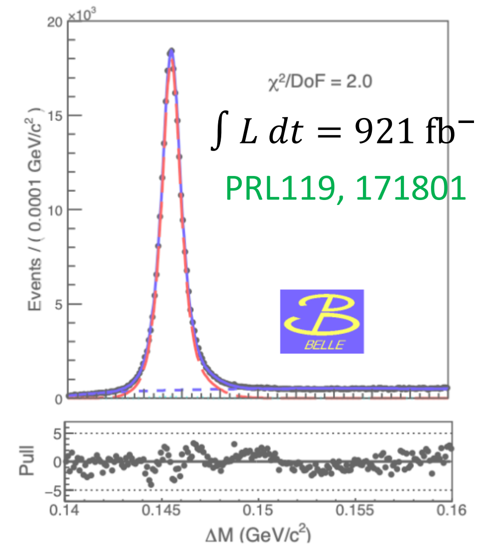
$D^{*+} \to D^0\pi_s^+ \qquad D^0 \to K_S K_S$





$D^{*+} \to D^0\pi_s^+ \qquad D^0 \to K_S\pi^0$



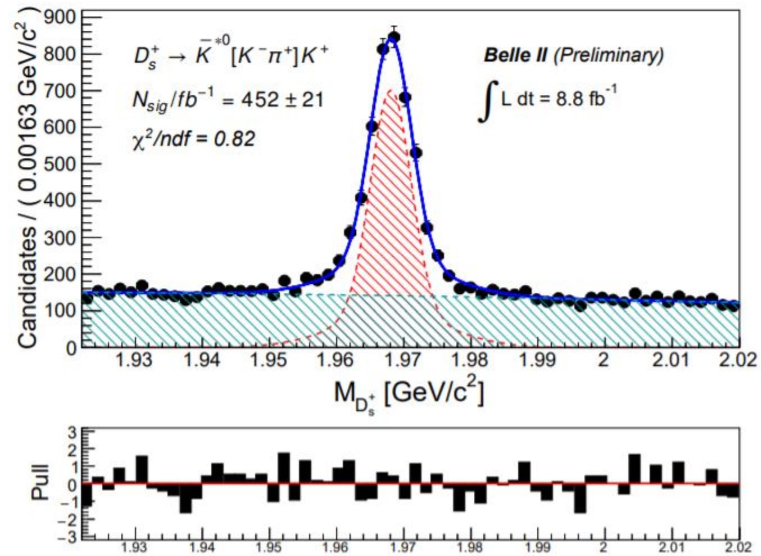


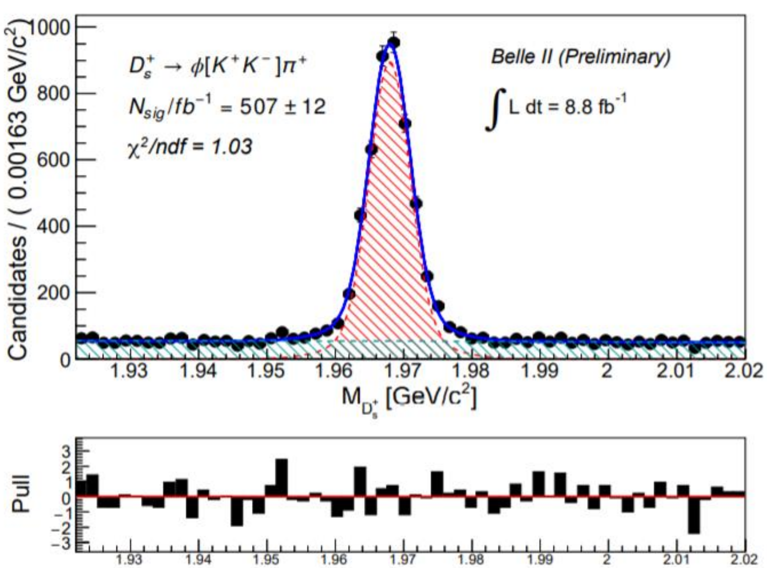
The selection criteria are different in the left plots (Belle II) and right plots (Belle)

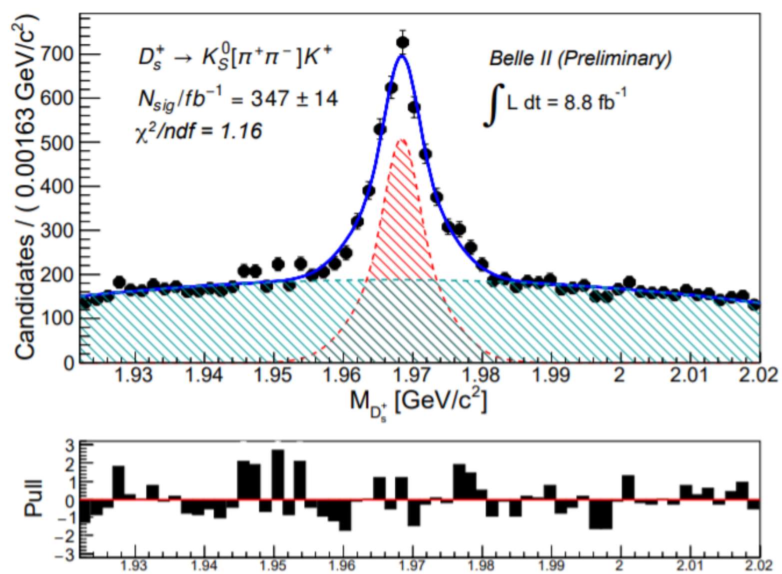
Time-Integrated Measurements

— Time-integrated *CP* Violation : Current Status

- Three D_S^+ channels are also rediscovered in the data:
  - $D_S^+ \to \phi\pi^+$
  - $D_S^+ \to \overline{K}^{*0}\pi^+$
  - $D_S^+ \to K_S^0\pi^+$
- Rediscoveries of other channels are in progress



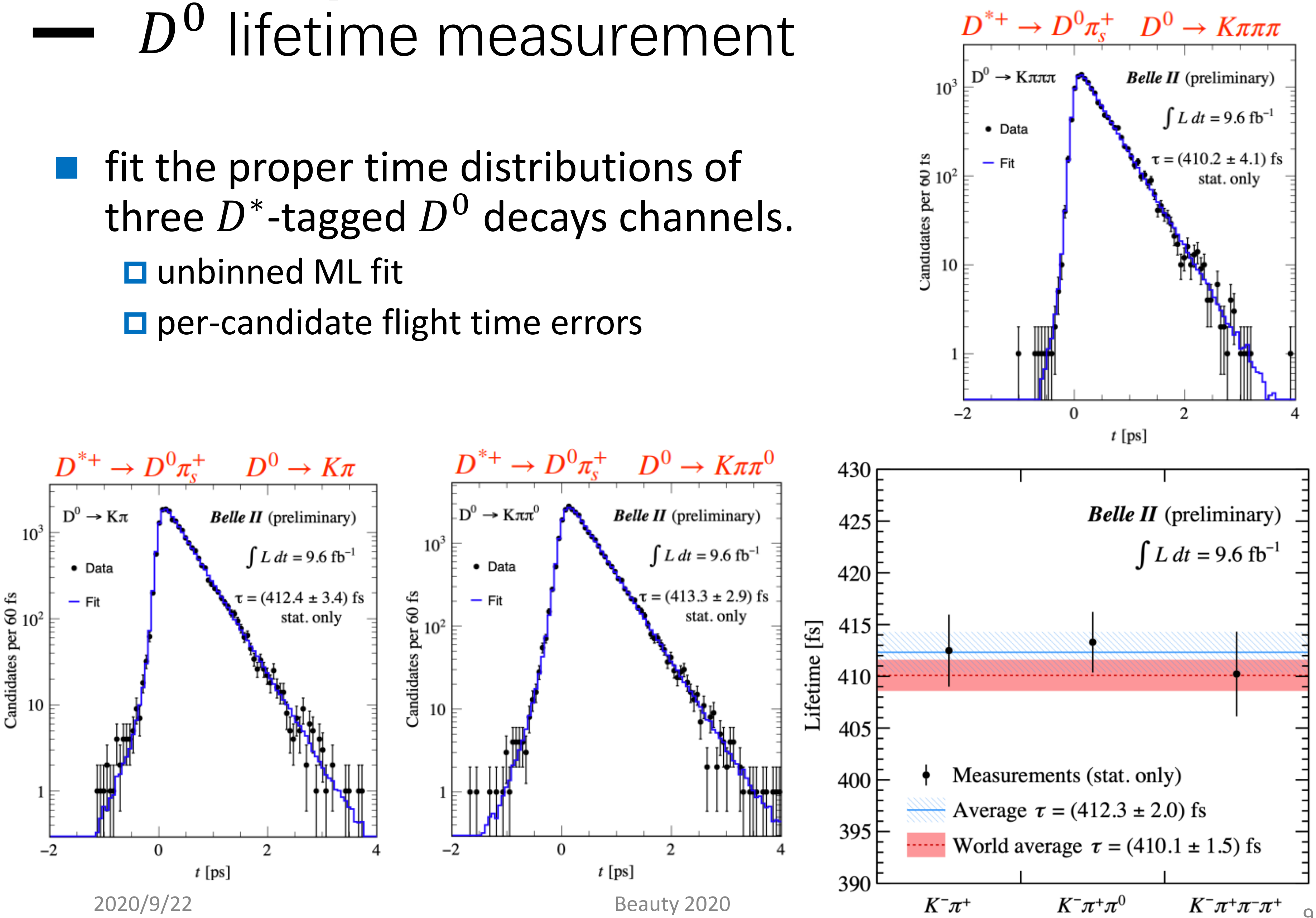




Time-Dependent Measurements

— D^0 lifetime measurement

- fit the proper time distributions of three D^*-tagged D^0 decays channels.
  - unbinned ML fit
  - per-candidate flight time errors

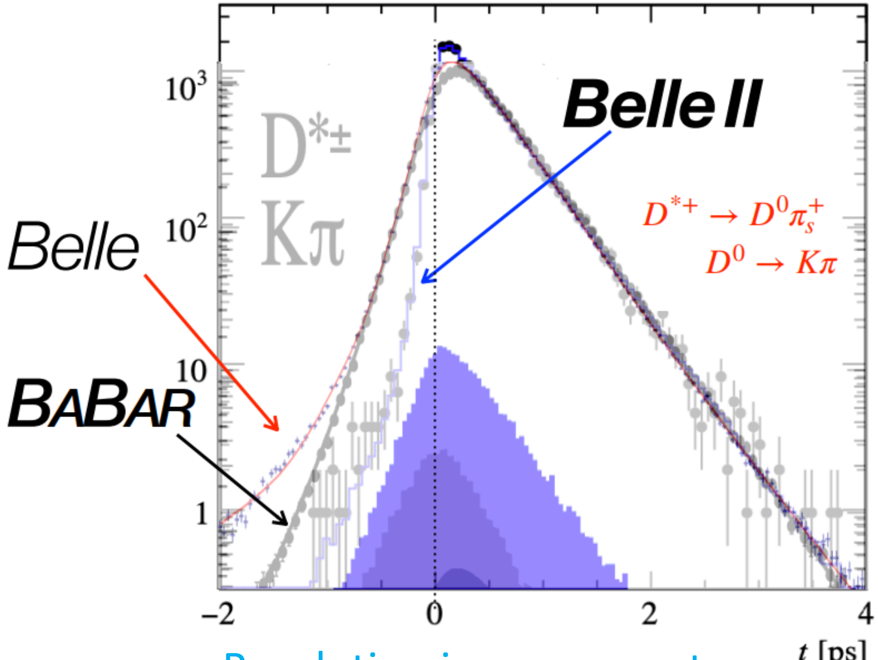


Time-Dependent Measurements — D^0 lifetime measurement

- Proper time resolution at **Belle II** is a factor of 2 better than Belle & BaBar, thanks to the improved vertex detector and the "nano-beams" technique
  - Belle SVD2 = 4 layers DSSD → Distance from first layer to beam: 30 mm
  - BaBar SVT = 5 layers DSSD → Distance from first layer to beam: 32 mm
  - Belle II VXD = 2 layers DEPFET **pixels** + 4 layers DSSD → Distance from first layer to beam: **14 mm**

- Sensitivity for mixing parameters would benefit from such resolution improvement. An example of Toy MC study for $D^0 \to K\pi$:

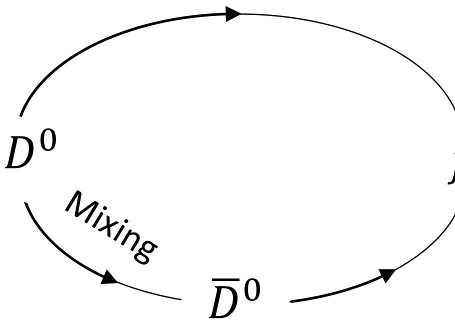
estimated **error** on	current HFLAV	Belle scaled to 50/ab	Toy MC 50/ab, CPV
x' (%)	–	(*) 0.45 →	0.15
x'^2 (%)	–	0.009	–
y' (%)	–	0.16 →	0.10
$\|q/p\|$	~ 0.09	–	0.051
ϕ (°)	~ 9	–	5.7



Resolution improvement visible at $t < 0$

Time-Dependent Measurements

— D^0-$\bar{D}^0$ mixing: brief introduction



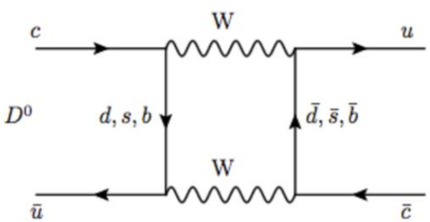
- Mass eigenstates and flavor eigenstates

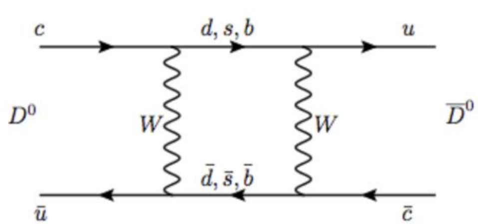
  $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$

- Definition of mixing parameters

$$x = \frac{m_1 - m_2}{\Gamma} \quad \text{and} \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \quad , \qquad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

- SM prediction mixing via short and long distance interaction





- *CP* violation in mixing
  - Direct *CP* violation

    $$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1$$

  - *CP* violation in pure mixing

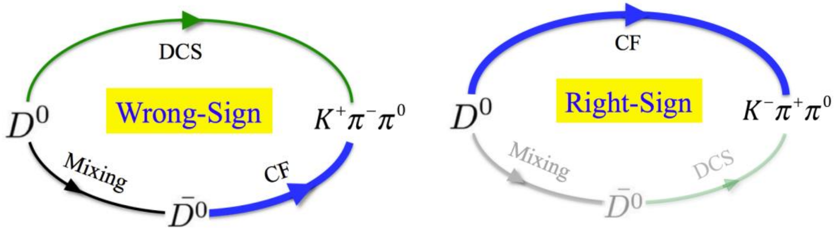
    $$\left|\frac{q}{p}\right|^2 \neq 1\,, \quad \phi = \mathrm{Arg}\left(\frac{q}{p}\right) \neq 0$$

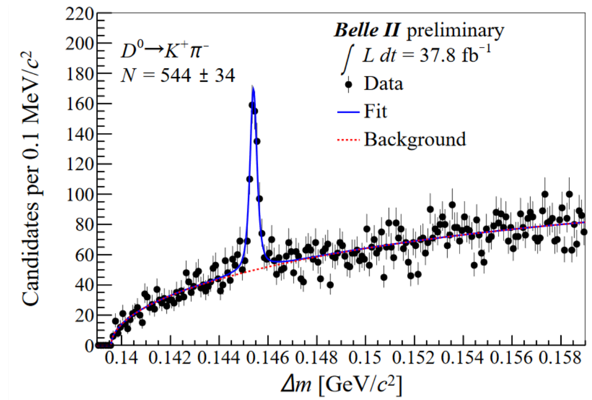
  - *CP* violation in interference of decay amplitudes with and without mixing

    $$\frac{q}{p}\frac{\bar{A}_f}{A_f} \neq 1$$

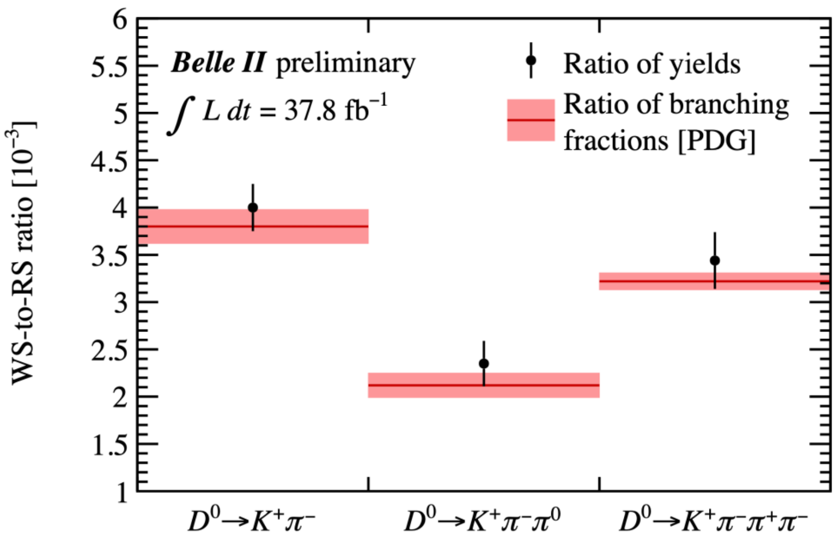
Time-Dependent Measurements
— D^0-$\bar{D}^0$ mixing: D^0 wrong sign decays

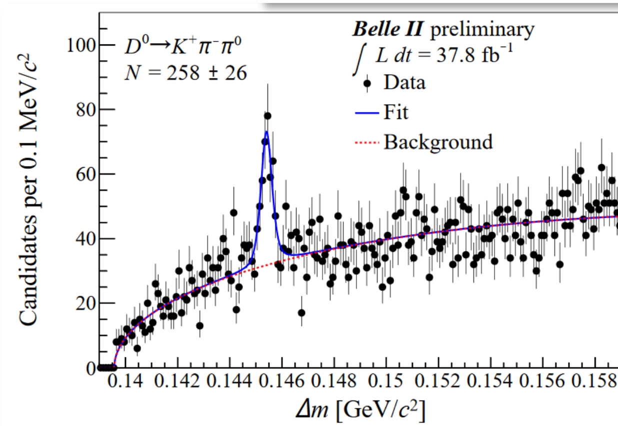
- $R_{WS}(t) = N_{WS}(t)/N_{RS}(t)$, could be used to measure mixing parameters and CPV

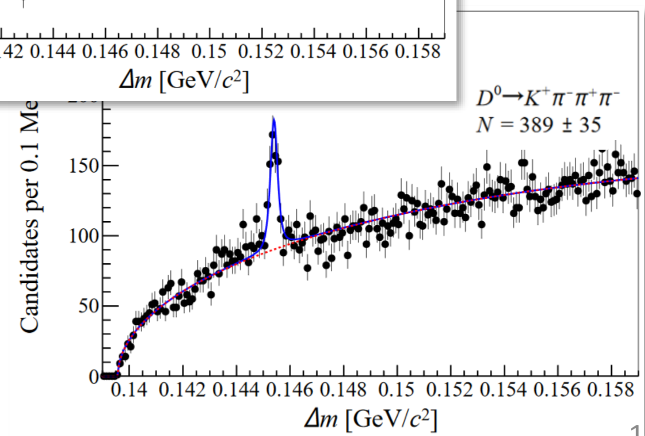




- R_{WS} (time integrated) in the Belle II data
  - Reconstruct RS & WS decays, extract PDF from RS and use it to fit the WS distributions



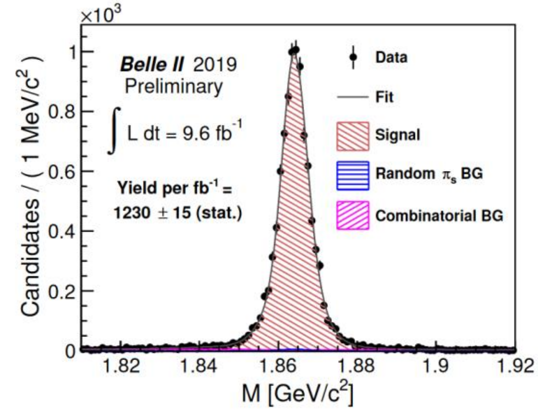




Time-Dependent Measurements

— D^0-$\bar{D}^0$mixing: $D^0 \to K_S\pi^+\pi^-$ time-dependent Dalitz analysis

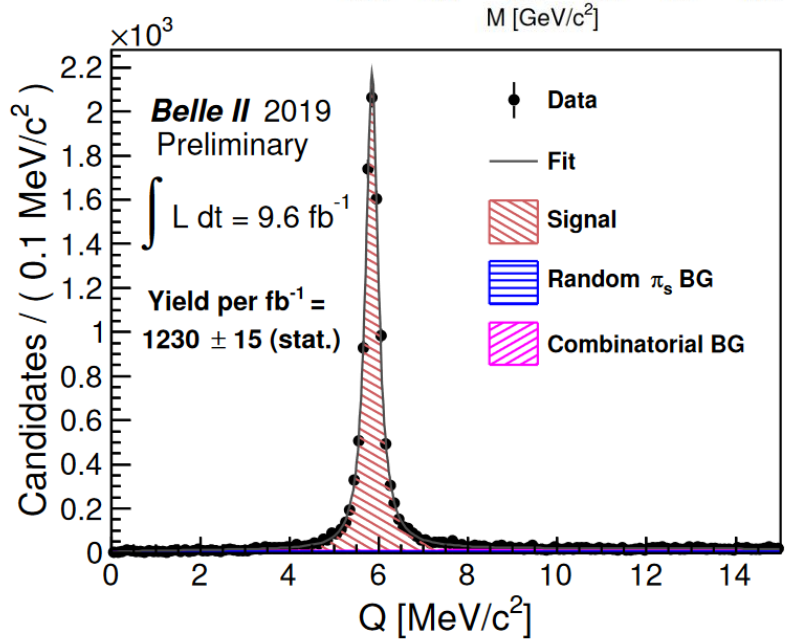
- Time-dependent amplitude fit
  - In self-conjugate channels like $D^0 \to K_S\pi^+\pi^-$, x and y parameters could be easily disentangle from the strong phase.



- Mixing parameters sensitivity @50 ab^{-1}
  - $$\sigma_{\text{Belle II}} = \sqrt{(\sigma_{\text{stat}}^2 + \sigma_{\text{syst}}^2) \cdot (\mathcal{L}_{\text{Belle}}/50\,\mathrm{ab}^{-1}) + \sigma_{\text{irred}}^2}.$$
  - The improved proper time resolution is not considered

Data	stat.	syst. red.	syst. irred.	Total	stat.	syst. red.	syst. irred.	Total
		x (10^{-2})				y (10^{-2})		
976 fb^{-1}	0.19	0.06	0.11	0.20	0.15	0.06	0.04	0.16
5 ab^{-1}	0.08	0.03	0.11	0.14	0.06	0.03	0.04	0.08
50 ab^{-1}	0.03	0.01	0.11	0.11	0.02	0.01	0.04	0.05
		$\lvert q/p\rvert$ (10^{-2})				ϕ (°)		
976 fb^{-1}	15.5	5.2-5.6	7.0-6.7	17.8	10.7	4.4-4.5	3.8-3.7	12.2
5 ab^{-1}	6.9	2.3-2.5	7.0-6.7	9.9-10.1	4.7	1.9-2.0	3.8-3.7	6.3-6.4
50 ab^{-1}	2.2	0.7-0.8	7.0-6.7	7.0-7.4	1.5	0.6	3.8-3.7	4.0-4.2

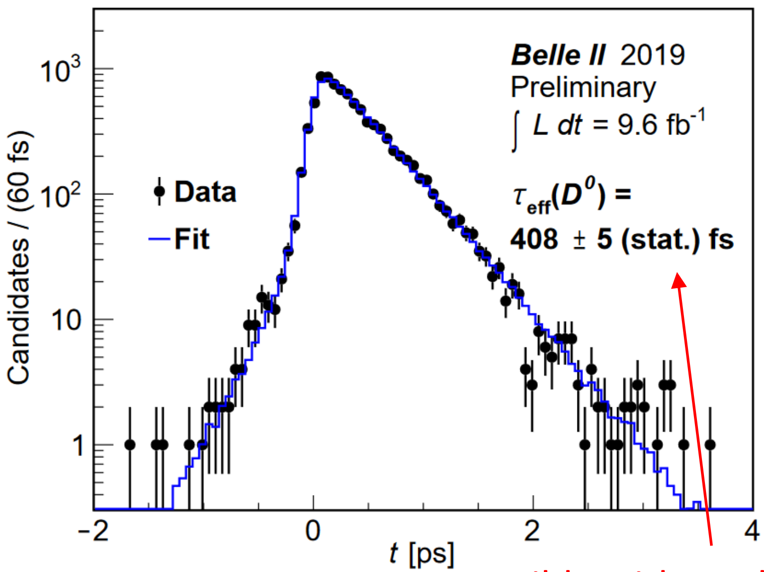
Belle II Physics Book; PETP 2019, 123C01 (2019)



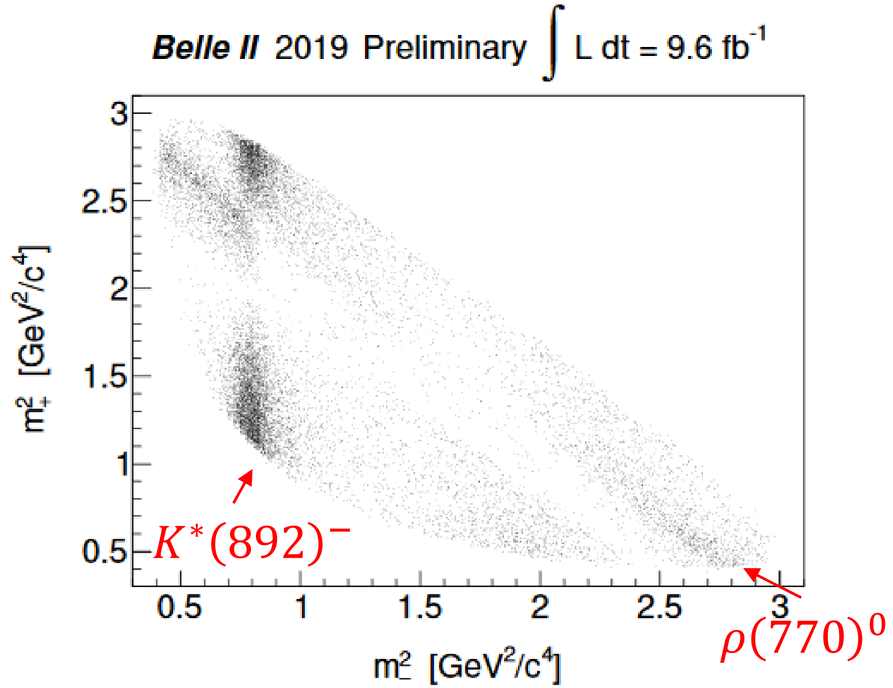
- The resolution of release energy, Q, is a factor of 2 better than Belle

Time-Dependent Measurements

— D^0-$\bar{D}^0$mixing: $D^0 \to K_S\pi^+\pi^-$ time-dependent Dalitz analysis



compatible with world average $(410.1 \pm 1.5\ \text{fs})$



- Proper time resolution comparable to the ones observed in lifetime analysis

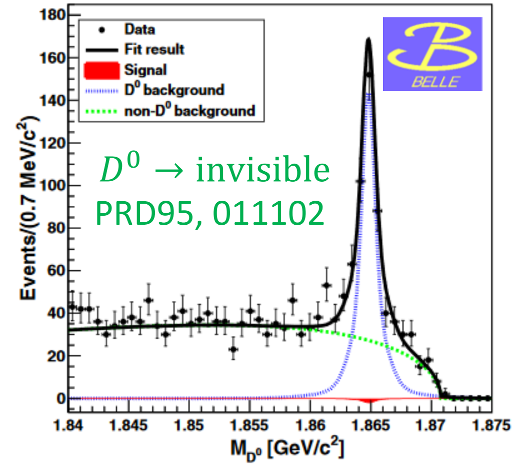
- Sensitivity study for mixing and *CPV* parameters measurements, **with the consideration of resolution of Belle II detector,** is ongoing.

Full Charm Event Reconstruction

- Method: Tag the D meson in the rest of event, deduce the kinematic information of desired final state by information of other particles
  - Light mesons $(K, \pi, \dots\dots)$

    $$e^+e^- \to c\bar{c} \to D_{\mathrm{tag}} X_{\mathrm{frag}} D_{\mathrm{sig}} \longrightarrow \text{signal channel}$$

    Reconstructed in several channels $(D^0, D^*, D_s \dots\dots)$
  - Useful in: inclusive branching fraction measurement, (semi-)leptonic study, rare/forbidden decays search



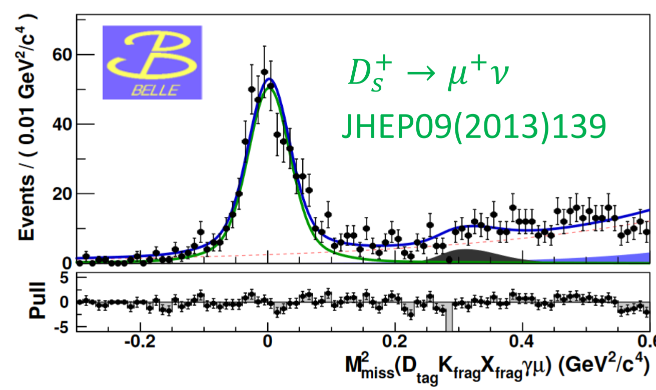
- Example: recoiled method for D_S leptonic decays
  - $$e^+e^- \to c\bar{c} \to D_{\mathrm{tag}} X_{\mathrm{frag}} K D_s^{*+}, \quad D_s^{*+} \to D_s^+ \gamma, \quad D_s^+ \to \mu^+ \nu$$

$$P_{miss} = P_{cms} - P(D_{\mathrm{tag}} X_{\mathrm{frag}} K \gamma \mu)$$

- Expected signal yields @50 ab^{-1}

Mode	Belle (0.91, 0.92 ab^{-1})	Belle II (50 ab^{-1})
$D_s^- \to \mu^-\bar{\nu}$	492 ± 26	27 000
$D^- \to \mu^-\bar{\nu}$	—	1250
Inclusive $D^0 \to$ anything	$(695 \pm 2) \times 10^3$	38×10^6

Belle II Physics Book; PETP 2019, 123C01 (2019)



Conclusions

- **Belle II** is expected to have important contribution for many charm measurements, and we are moving forward with the newly collected data.
  - Designed peak luminosity of **SuperKEKB** : $6.5 \times 10^{35}\ \mathrm{cm}^{-2} s^{-1}$
  - Target dataset: 50×Belle
- The resolution for proper time and release energy Q are better than Belle, owing to the new vertex detector and “nano beams” technique.
  - Proper time resolution improves a factor of ~2
  - In $D^0 \to K_S \pi^+ \pi^-$ channel, the resolution of Q improves a factor of ~2
- Some nice works are ongoing and there will be more exciting results in the coming years.

Thank you!