Charm status and prospects at Belle II

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On behalf of Belle II collaboration

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Belle II

Outline

- Belle II detector
  - overview, special feature and timeline
- Charm intro, activities and future prospects
  - life-time, mixing, CPV
- Summary

Why Charm

- CP violation in charm sector is special !
  - Only up-type quark family, where mixing and CPV can occur
  - Complementary information to K and $B_{(s)}$ decays

- In SM, D-mixing is heavily suppressed (both CKM, and GIM suppressed)
  - Very small splitting in both mass and width (small x, y parameters)
  - Non-SM particles contributing to the box diagram could significantly affect the measured values

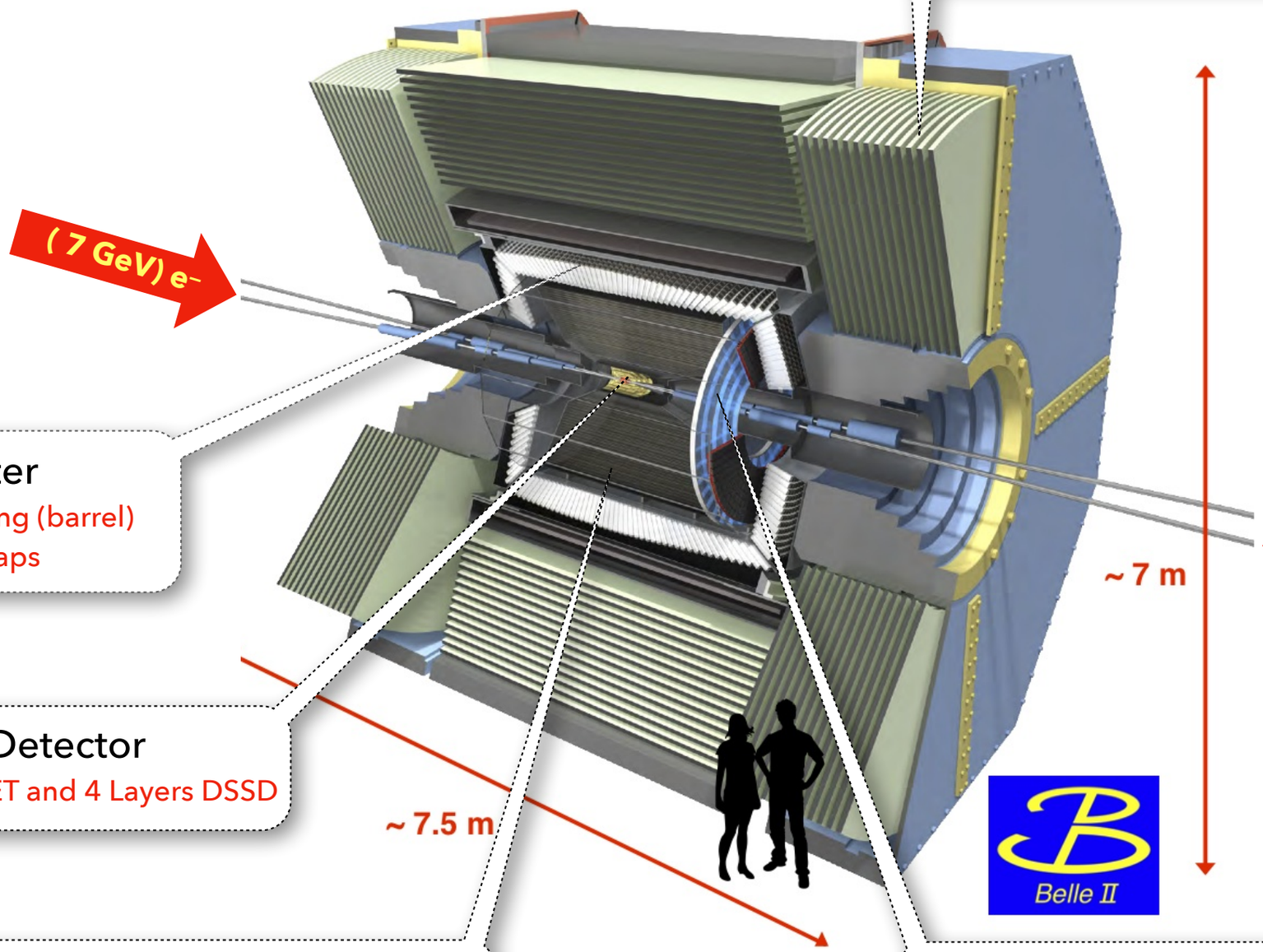
  ⇝ **Potential room for New Physics**

  ⇝ **But challenging**

  - Predictions are difficult, not a precision probe

Charm CPV by LHCb: Phys. Rev. Lett. 122, 211803 (2019)

Belle II overview



KL and muon Detector
Resistive Plate Chamber
Scintillator + WLSF + MPPC

EM calorimeter
CsI(Ti), waveform Sampling (barrel)
Pure CsI for end caps

Vertex Detector
2 Layers PXD DEPFET and 4 Layers DSSD

Central Drift Chamber
Smaller cells, long lever arm, fast electronics

Particle Identification
Time of Propagation in barrel region
and ARICH in forward region

Belle2 TDR: arXiv: 1011.0352

Charm opportunities in Belle II

↝ w/ superKEKB and Belle II advancement

Powerful SuperKEKB

- 50 ab^{-1} = 50x Belle
  - Provide clean environment for B Physics: low background with respect to hadron colliders (e.g. LHC)
    - Excellent Dalitz plot analysis with low background
    - Better reconstruction of neutrals/neutrinos ↝ unique access to final states with invisible particles.
  - Large samples of B and D decays (5×10^{10} pairs of b and c over planned operation of 50 ab^{-1})
  - Lorentz boost (asymmetric energy) allows precision measurement mixing parameters, and CP violations.
  - .. more in Physics Book

highlights of Belle II

- New VXD provides better vertex resolution
  - IP resolution is improved by PXD being at radius of 1.4 cm (x2 better D^0 proper time resolution)
- Good PID even with higher beam background environment (w/ upgraded SVD, CDC, TOP and ARICH)
- Better reconstruction efficiency with improved tracking efficiency
- More tracking volume from upgraded CDC and SVD provides higher K_s efficiency ~ 30%
- .. more in TDR and Physics Book

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- **Overall performance is expected to improve w.r.t. to Belle, if**
  - **resolution is better/comparable (in particular VXD is better)**
  - **systematic uncertainties are reduced**

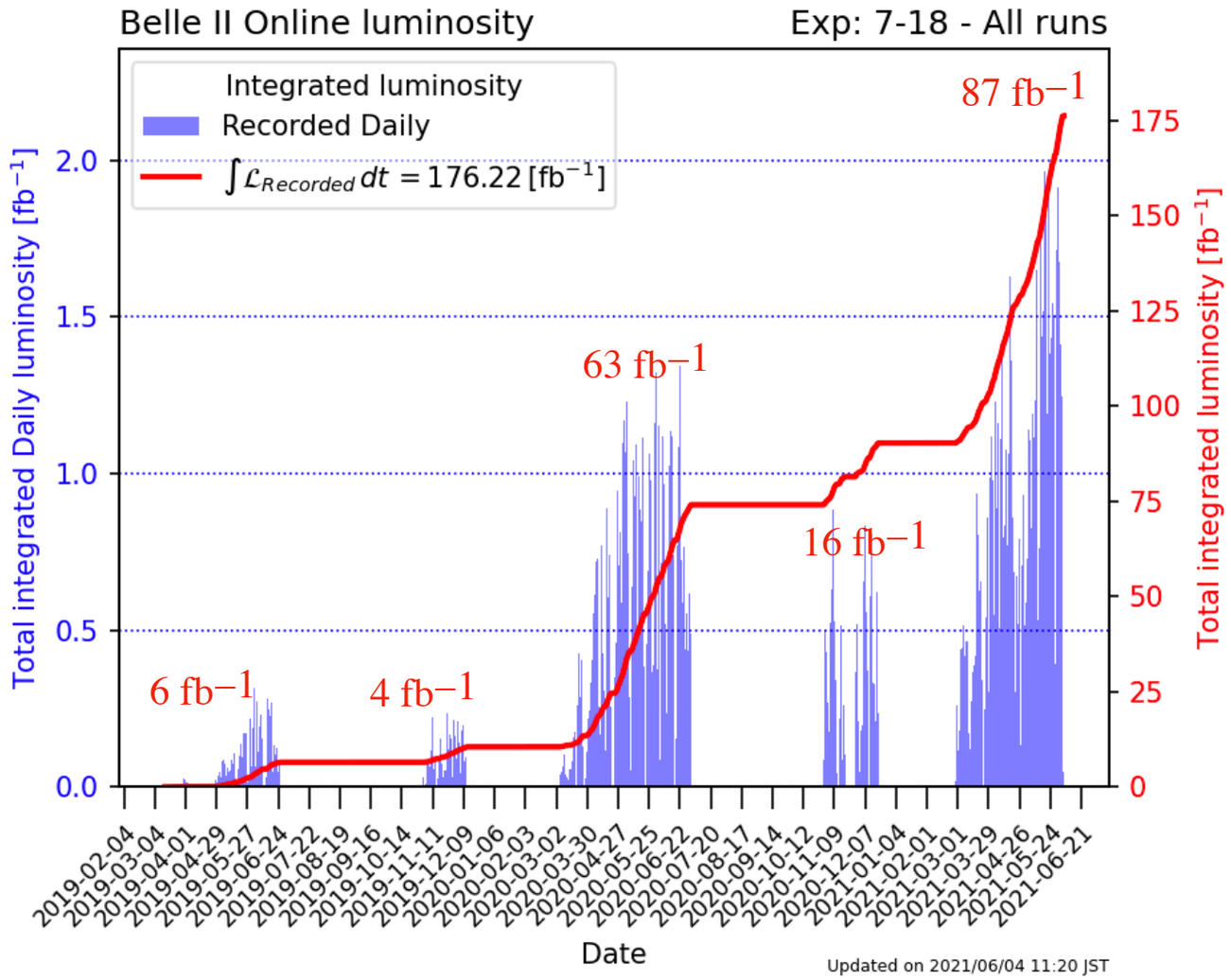
Belle2 Physics Book arxiv1808.10567

Belle II data status

as of **now**

- Integrated luminosity L_{int} ~176 fb^{-1} (June 4, 2021)
- Highest instantaneous luminosity ~2.9 × 10^{34} cm^{-2}s^{-1}
  - SuperKEKB design luminosity: 6.5 × 10^{35} cm^{-2}s^{-1}
  - New world record archived in June 2020 🥇 **(Belle** highest (June'09) : 2.1 × 10^{34} cm^{-2}s^{-1})
- Continued data-taking through Covid-19 pandemic

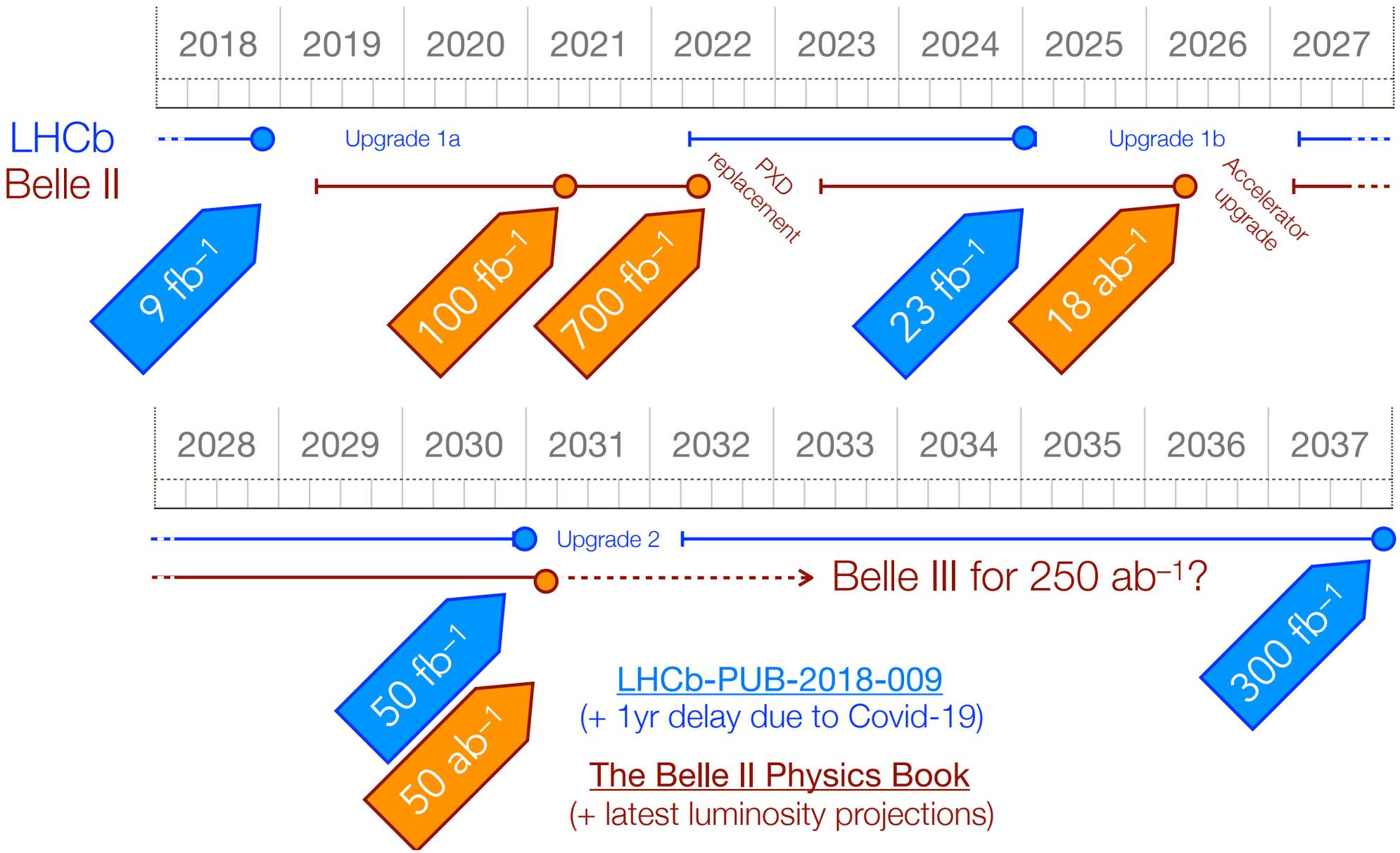
- so far..
  BelleII charm studies focused on re-discoveries, detector/reconstruction performance, resolutions, and systematic effects..



https://confluence.desy.de/display/BI/Belle+II+Luminosity

Belle II data status

future **timeline**..



LHCb-PUB-2018-009
(+ 1yr delay due to Covid-19)

The Belle II Physics Book
(+ latest luminosity projections)

BELLE2-TALK-CONF-2021-021

CPV: Time integrated

- Extrapolations from Belle
- Belle II status
  - .. D^0 decays re-discoveries
  - .. D_s decays re-discoveries

- CP asymmetries

$$A_{CP} = \frac{N_{D^0 \to f} - N_{\overline{D}^0 \to \bar{f}}}{N_{D^0 \to f} + N_{\overline{D}^0 \to \bar{f}}}$$

Belle2 Physics Book
arxiv1808.10567

Time integrated CPV

↝ Belle II projections w/ 50 ab^{-1}

Extrapolations from **Belle Measurements**

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

σ_{stat}: *Scaling the Belle statistical error w/ luminosities,*
σ_{syst}: *Only those who scale with luminosity such as background shapes measured with control samples*
σ_{irred}: *Those who do not scale with luminosity such as decay time resolution due to detector misalignment*

1. Time integrated CPV

- Belle II will specially contributes to decays with neutrals in the final state
- The precision on A_{CP} will be improved by $\mathcal{O}(10^{-4})$
  - Also valid for decay with naturals in final states

LHCb[1]: ΔA_{CP}
5.3σ deviation from zero

Table 122: Time-integrated CP asymmetries measured by Belle, and the precision expected for Belle II in 50 ab^{-1} of data.

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
$D_s{}^+ \to K^+\pi^0$			

Belle2 Physics Book arxiv1808.10567

1: Phys. Rev. Lett. 122, 211803 (2019)

Ongoing time-integrated measurement at Belle II (1)

↝ rediscoveries of D* tagged D^0 decays

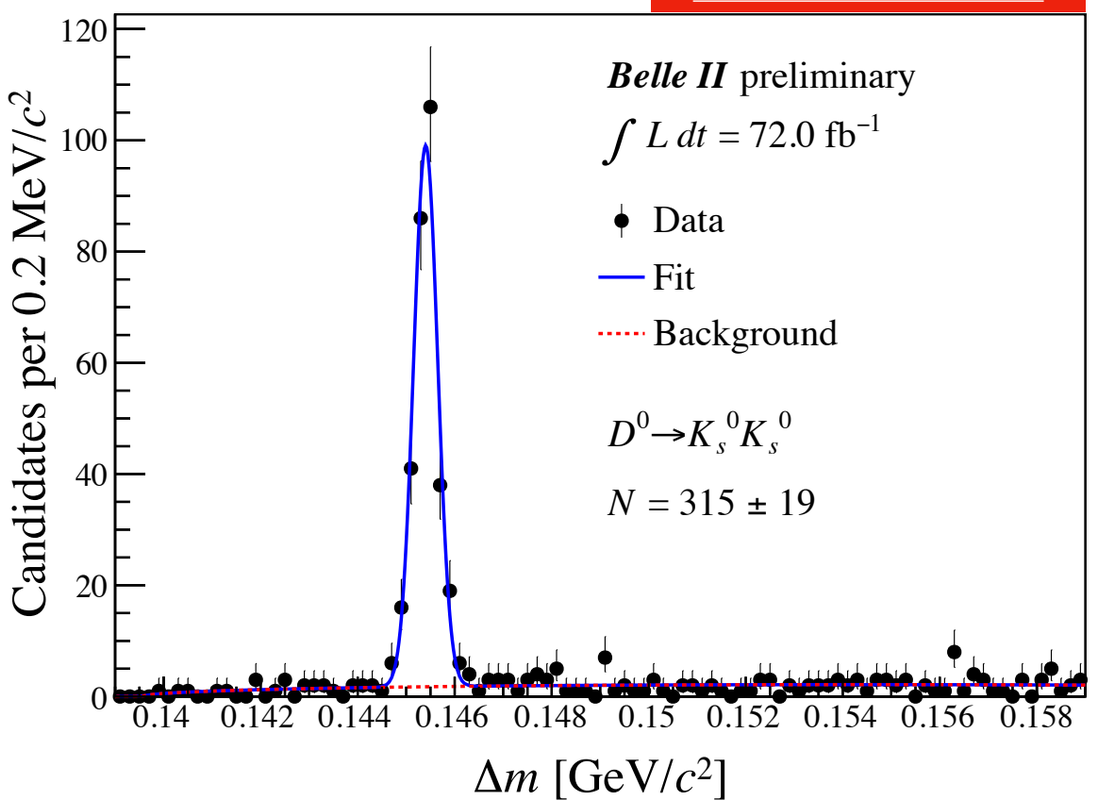
1 $D^0 \to K_S^0 K_S^0$

- SCS decay, most promising channels, and can probe for CPV origin
- Current A_{CP} measurement are limited with statistics
  - Best so far is from Belle $(-0.02 \pm 1.53 \pm 0.02 \pm 0.17)\%$

- Belle II so far..
  - Re-discovery with very good reconstruction performance
  - Resolution, background, yield/luminosity are comparable with Belle*

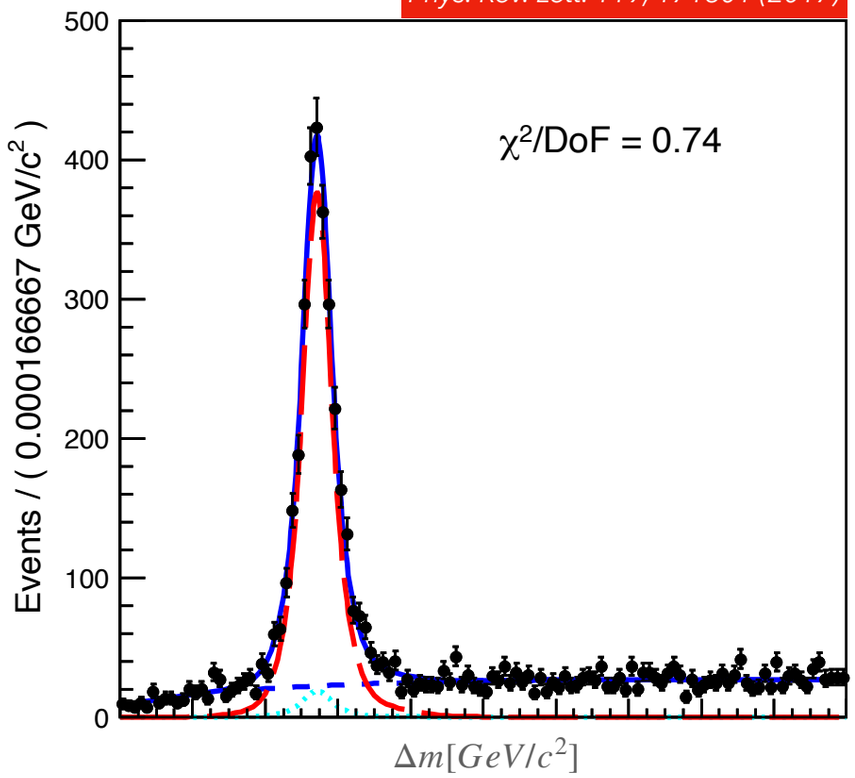
Belle II w/ 72.0 fb^{-1}

BELLE2-NOTE-PH-2020-054



Belle w/ 921 fb^{-1}

Phys. Rev. Lett. 119, 171801 (2017)



only qualitative comparison due to different selections

Ongoing time-integrated measurement at Belle II (1)

↝ rediscoveries of D* tagged D^0 decays

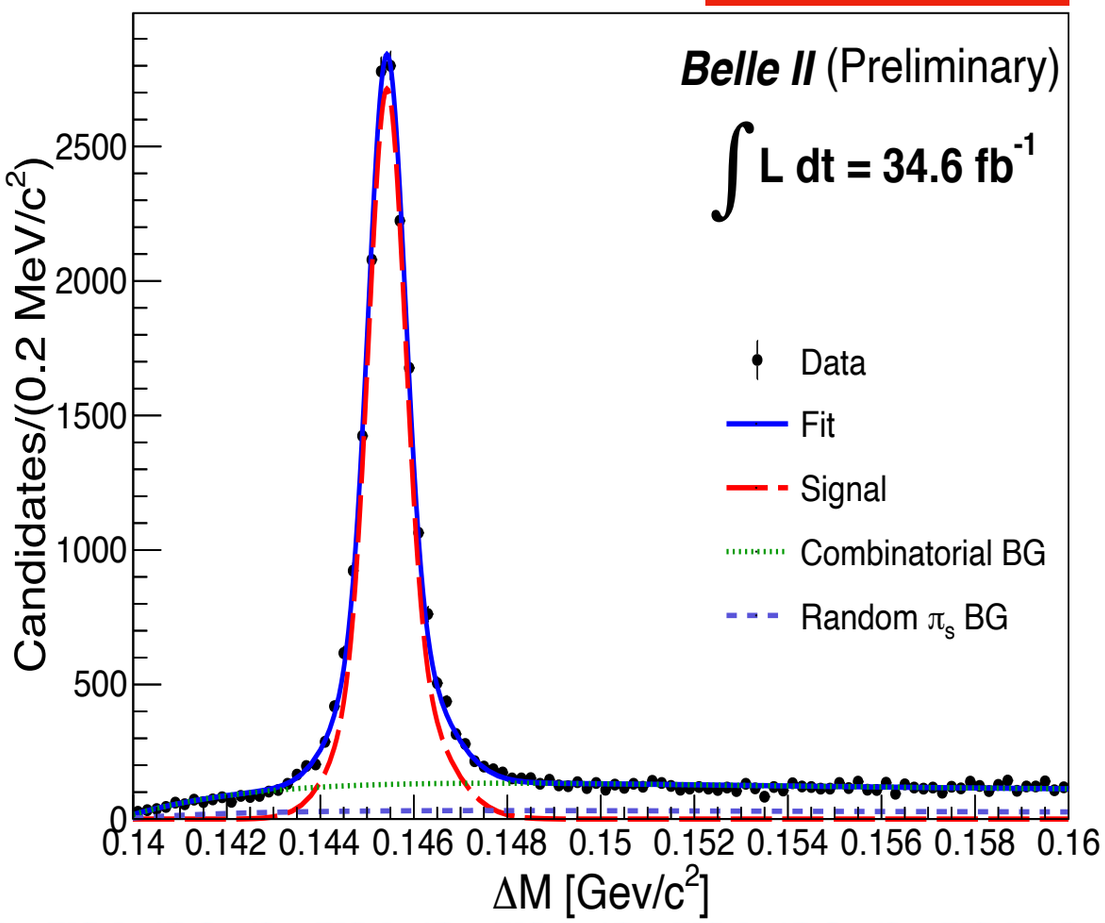
$2\ D^0 \to K^0_s\pi^0$

- CF decay (+ DCSD inference)
- Important for normalization model in $D^0 \to K^0_s K^0_s$, $D^0 \to \pi^0\pi^0$, $D^0 \to \gamma\gamma$

- Belle II so far..
  - Re-discovery with very good reconstruction performance
  - Resolution, background, yield/luminosity are comparable with Belle*

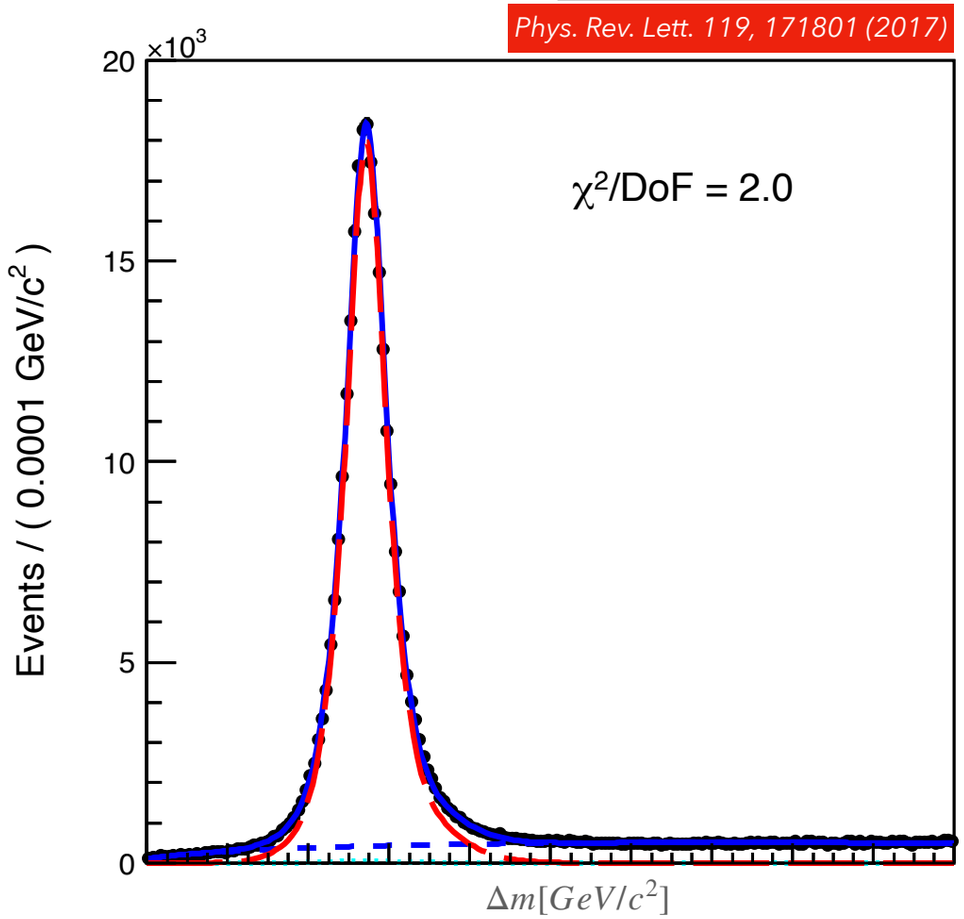
Belle II w/ 34.6 fb^{-1}

BELLE2-NOTE-PH-2020-037



Belle w/ 921 fb^{-1}

Phys. Rev. Lett. 119, 171801 (2017)



only qualitative comparison due to different selections

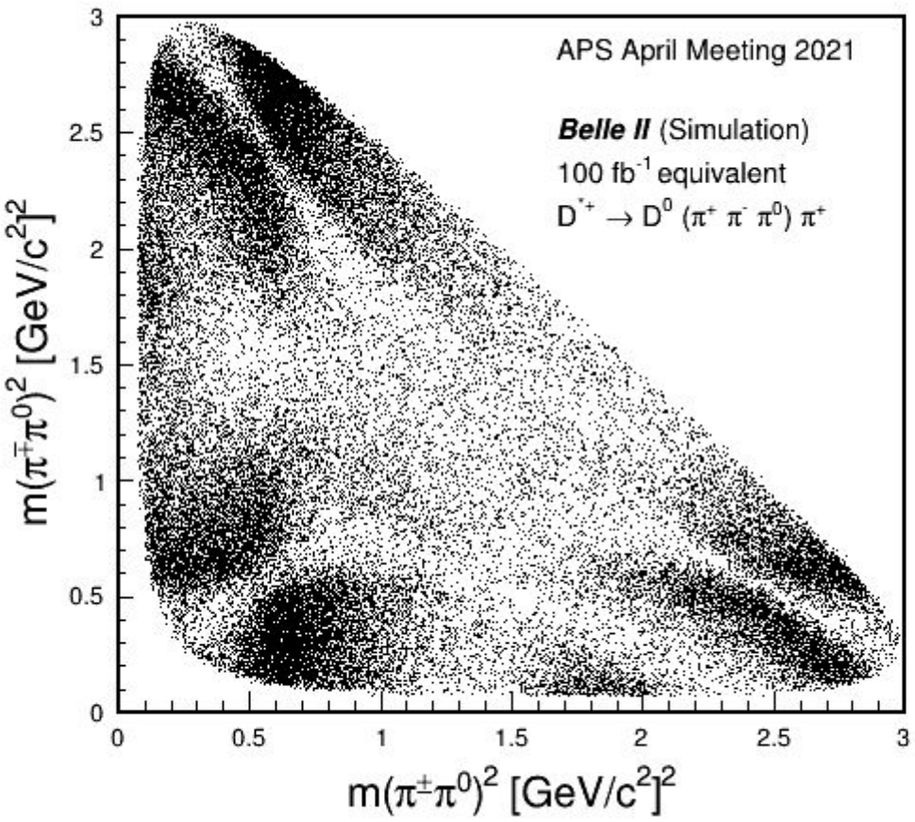
Ongoing time-integrated measurement at Belle II (1)

↝ rediscoveries of D* tagged D^0 decays

$3\,D^0 \to \pi^+\pi^-\pi^0$

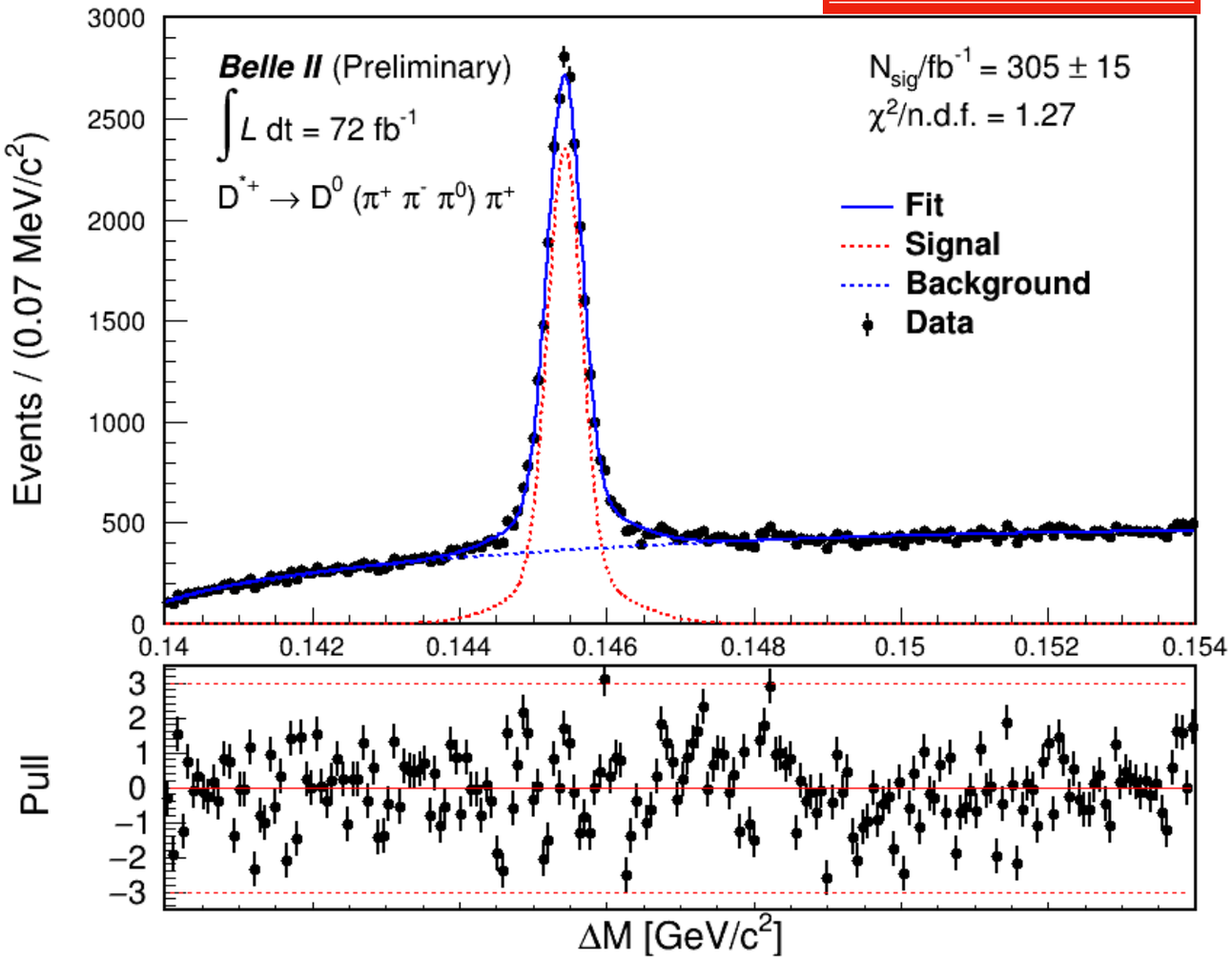
- SCS decay with a possible admixture from a penguin amplitude
  - The interference of these amplitudes ↝ CP violation
- Aim to perform a time-averaged Dalitz analysis with full data
  - CPV hints ↝ asymmetry in events distribution over the Dalitz plot

- Belle II so far..
  - Re-discovery w/ very good reconstruction performance



Belle II w/ 72 fb^{-1}

BELLE2-NOTE-PH-2020-047



Ongoing time-integrated measurement at Belle II (2)

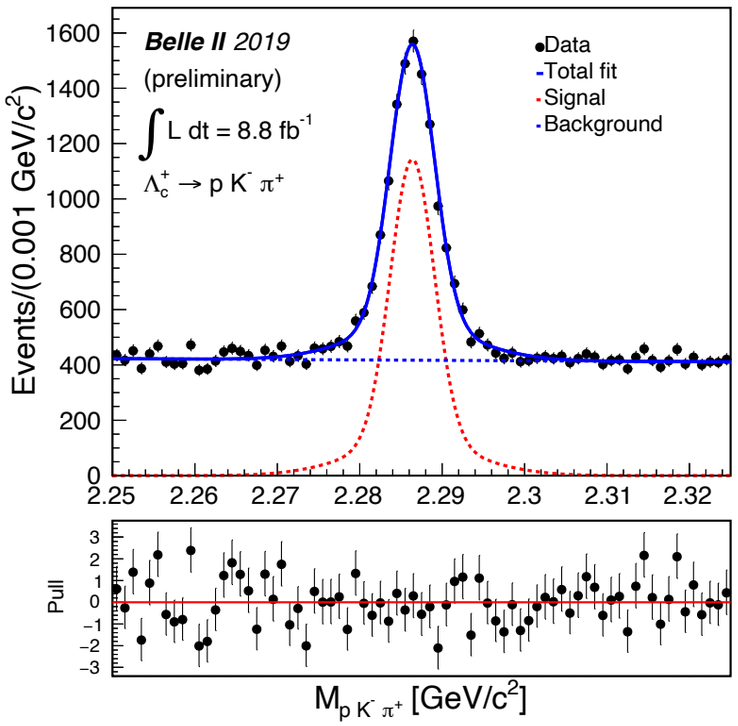
↝ rediscoveries of D* tagged D_s decays

- Ds decays ($\phi\pi^+, K_sK^+, \overline{K}^{*0}K^+$)
  - ..are re-discovered
  - Used for normalization in most analysis studying Ds
- Other Ds channels are also under study

Also charm baryons

$\Lambda_c^+ \to pK^-\pi^+$

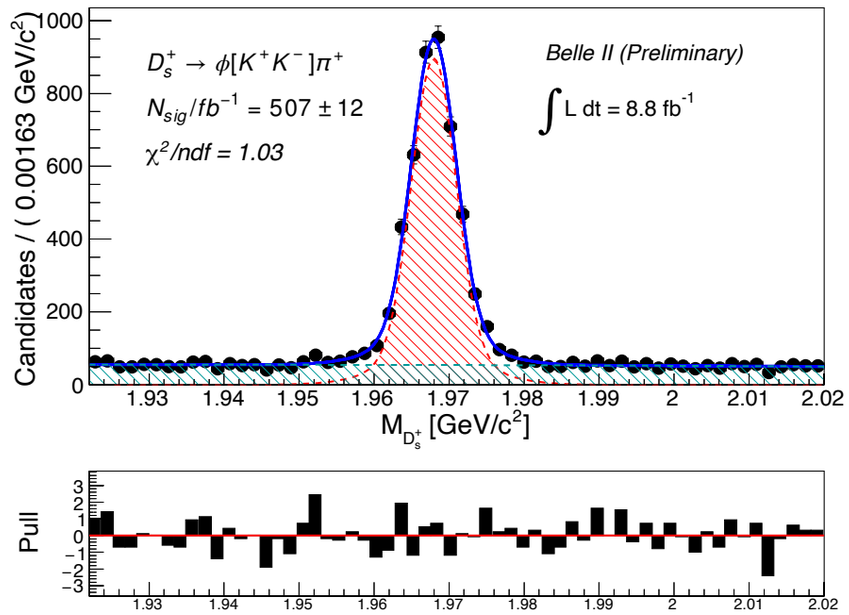
BELLE2-NOTE-PH-2020-020



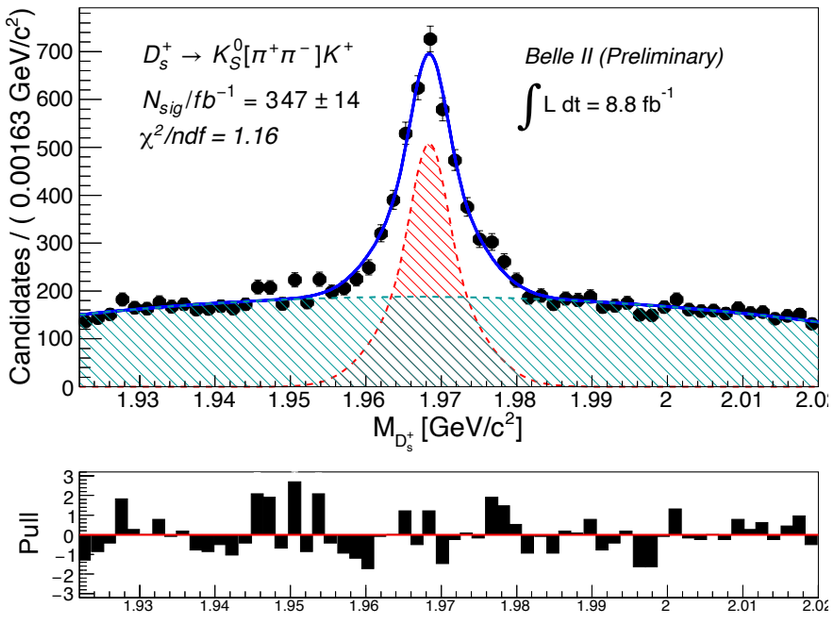
Belle II w/ 8.8 fb^{-1}

BELLE2-NOTE-PH-2020-049

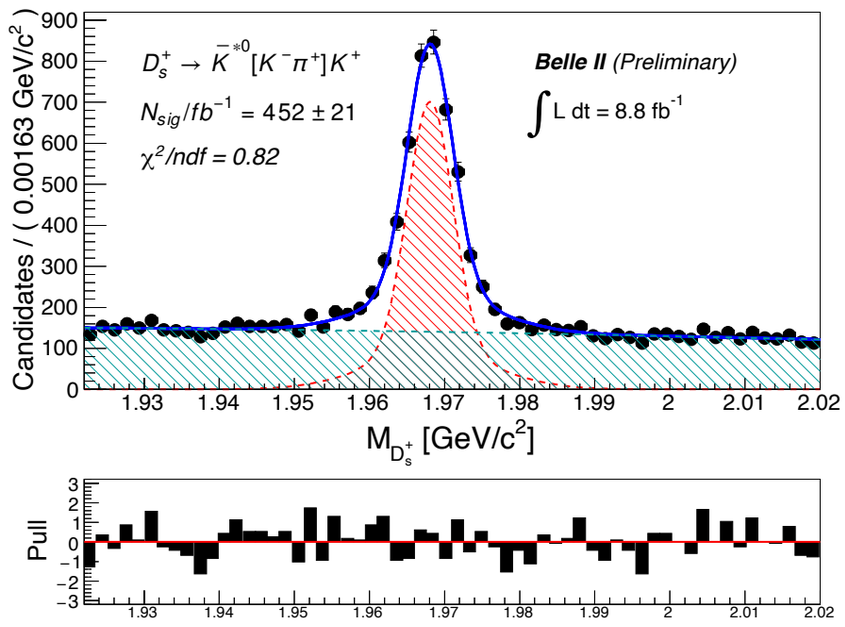
1 $D_s \to \phi\pi^+$



2 $D_s \to \overline{K}^{*0}K^+$



3 $D_s \to K_sK^+$



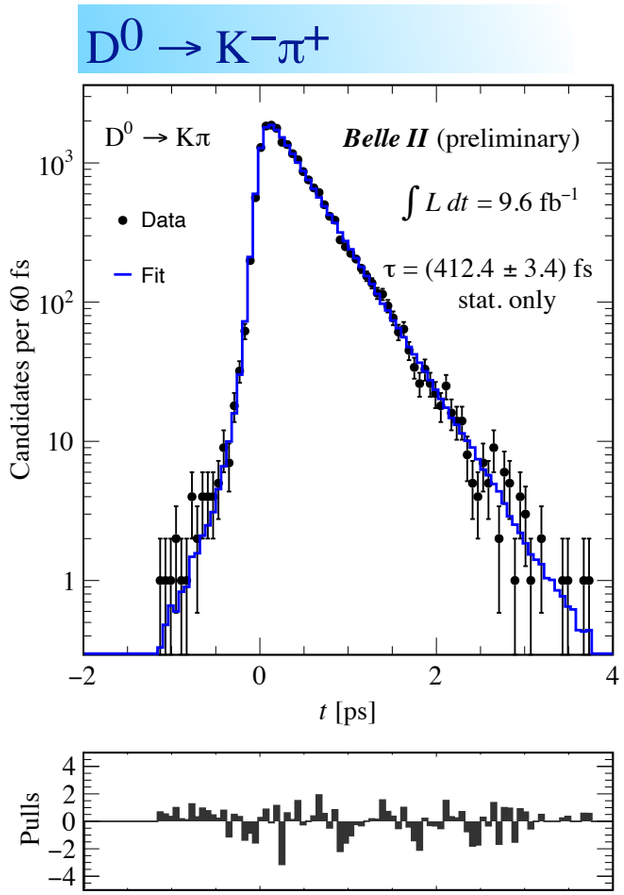
Decay time resolution study with Belle II data

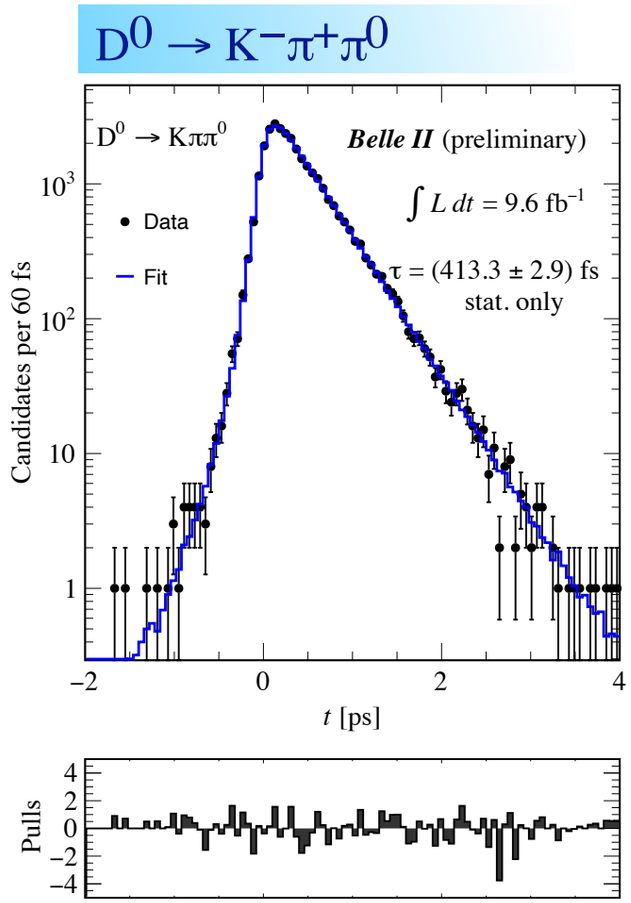
- D0 decays proper time

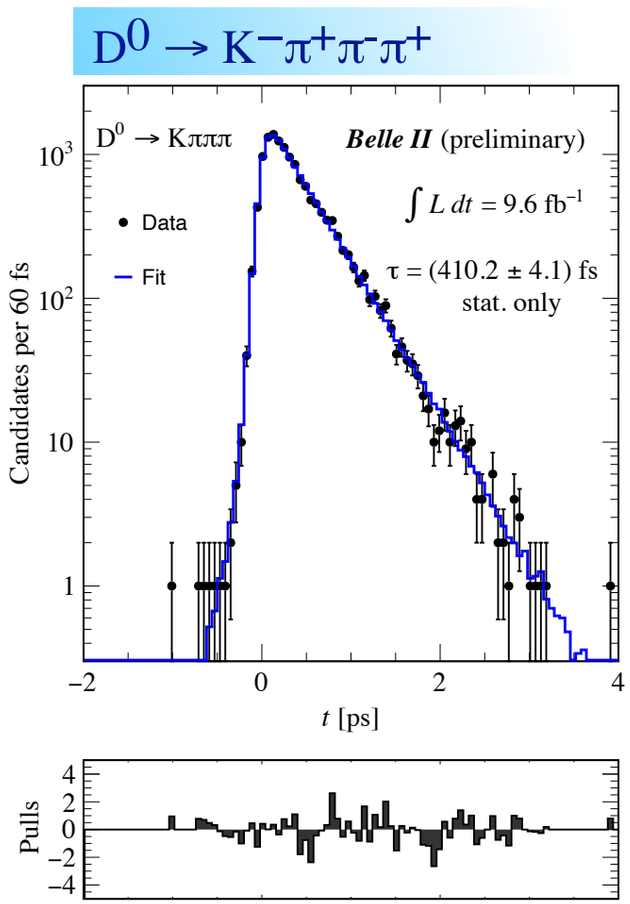
D^0 lifetime Study

- 2019 Belle II data : $L_{int} \sim 9.6\ fb^{-1}$
- D* tagged D^0 decay channels;
- Proper time distribution fit
  - w/ unbinned maximum likelihood 2D fit
  - using per-candidate proper time errors

- The average lifetime is $\tau_{D^0} = (412.3 \pm 2.0)$ fs is compatible with the world-average = (410.1 ± 1.5) fs.





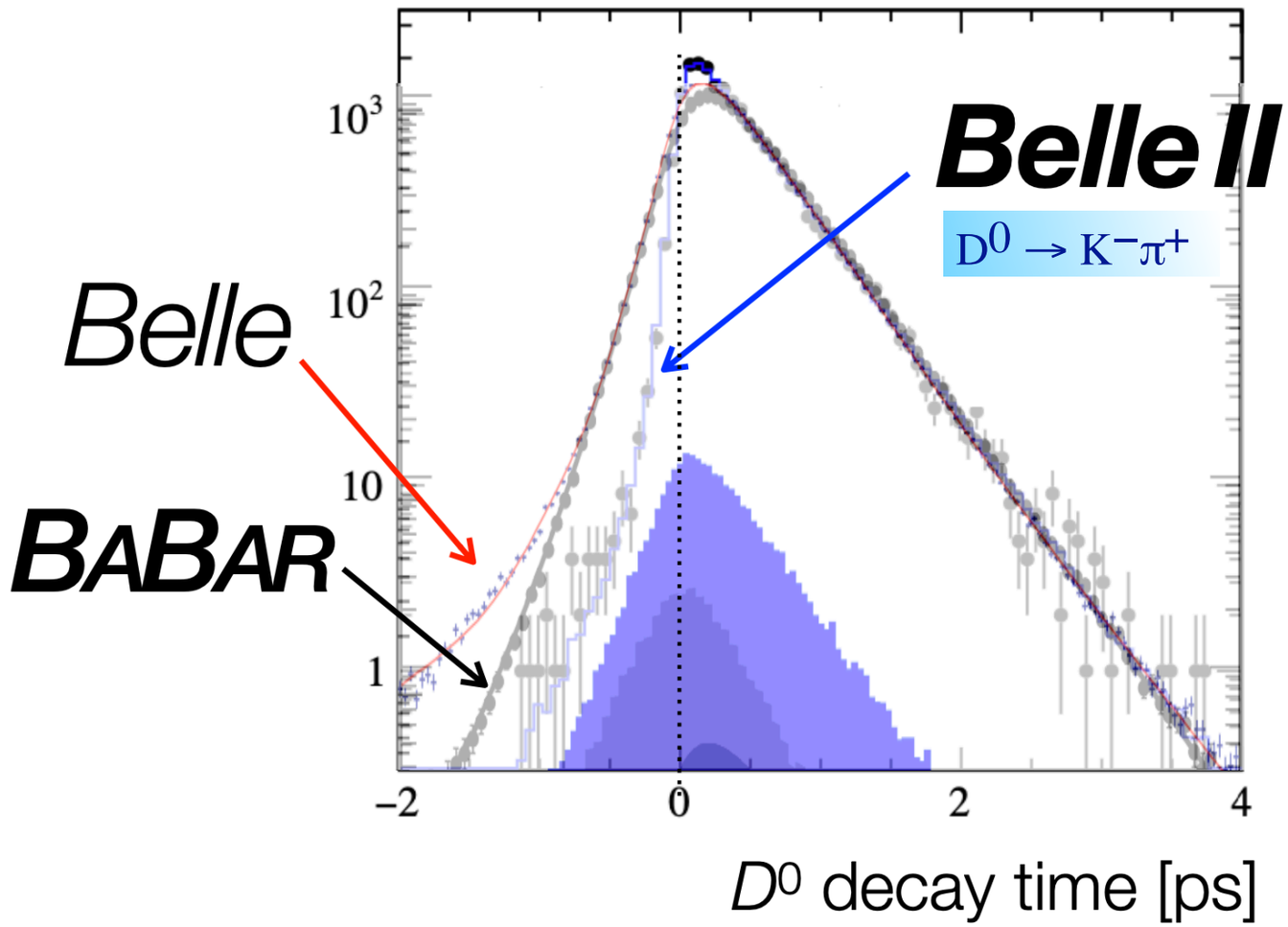


BELLE2-NOTE-PH-2020-033

D^0 lifetime Study

1. Decay time resolution
   ⇝Belle II vs others

- x2 better than Belle and BABAR
  - resolution improvement visible at t < 0
  - thanks to a better- performing vertex detector (Click here for details ▶)



Reference talk by Giulia

2. Impact on
   ⇝ time-dependent measurements

- improved precision on mixing and CPV observables
  - Toy MC to estimate the impact on (WS) $D^0 \to K^-\pi^+$ analysis (almost systematically free):

Parameter	Current HFLAV	Belle Scaled 50/ab	Belle II Toy MC 50ab^{-1}
$\delta x'^2$	-	0.009	-
$\delta x'$ (%)	-	0.45▸	0.13
$\delta y'$ (%)	-	0.16	0.097
$\delta\lvert q/p\rvert$	0.09	-	0.043
$\delta\varphi$ (°)	9	-	5.4

▸measurement NOT sensitive to x',
the error is computed from the error on x'^2

CPV: Time Dependent

- BelleII status
  - .. re-discoveries of WS D^0 decays
  - .. Dalitz analysis of $D^0 \to K_S\pi^+\pi^-$

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

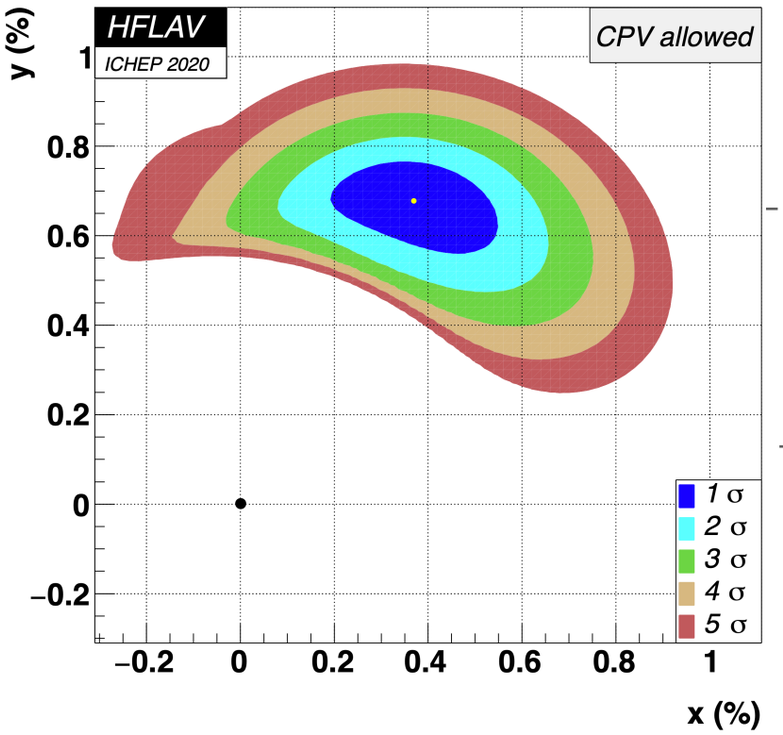
Indirect CPV (Mixing)

$$\left|\frac{q}{p}\right| \neq 1$$

Interference of Mixing and Decay

$$\left(\frac{q}{p}\frac{\bar{A}}{A}\right) \neq 0$$

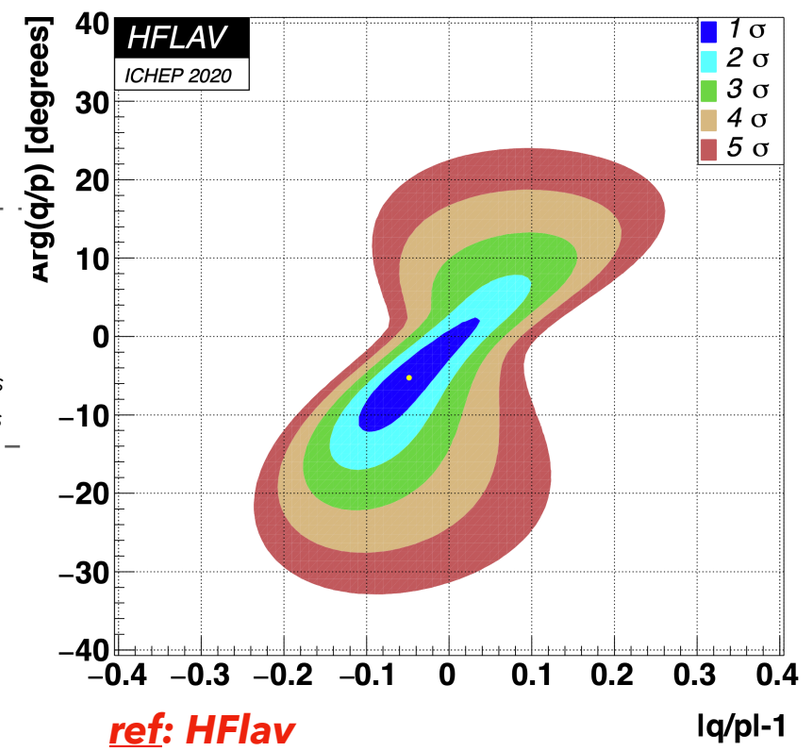
$$-\eta_{CP}\left|\frac{q}{p}\right|\left|\frac{\bar{A}_f}{A_f}\right|e^{i\phi}$$



mixing parameters

$$x = \frac{\Delta m}{\Gamma}, \quad y = \frac{\Delta\Gamma}{2\Gamma},$$

where Δm = mass differences
and ΔΓ = lifetimes differences



ref: HFlav

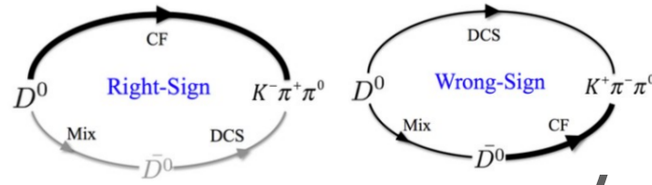
WS: D^0 Decay

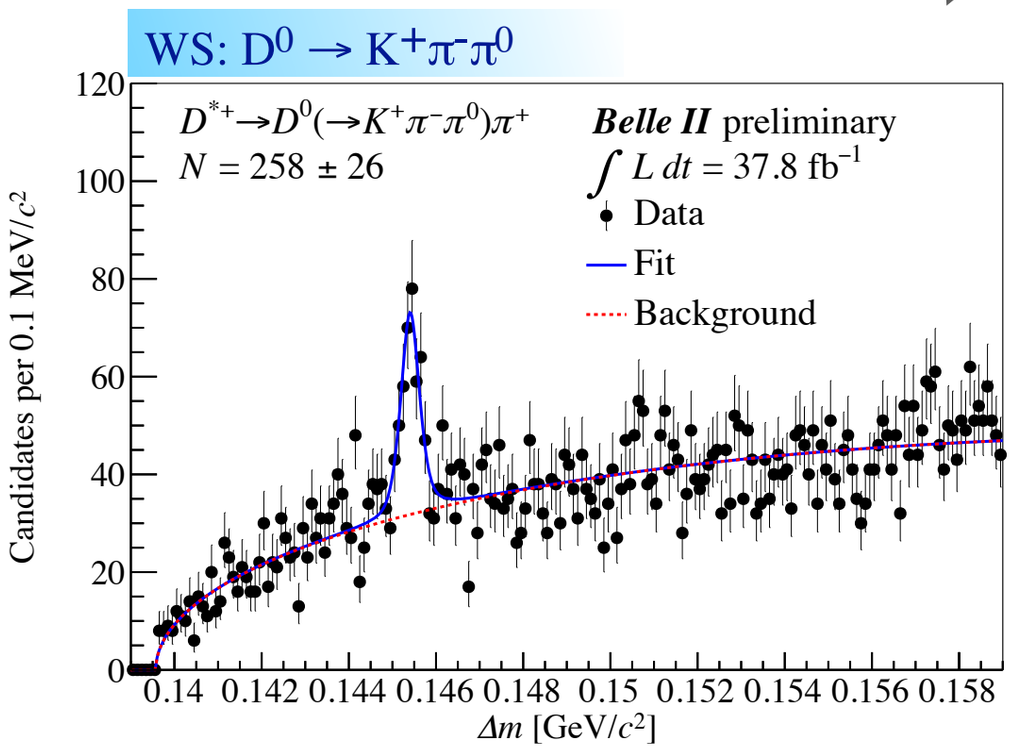
- WS decay directly via a DCS decay, and indirectly via mixing followed by a CF decay
- Measurement of R_D, x'^2 and y'
- Small phase (ϕ) gives direct access to |q/p|

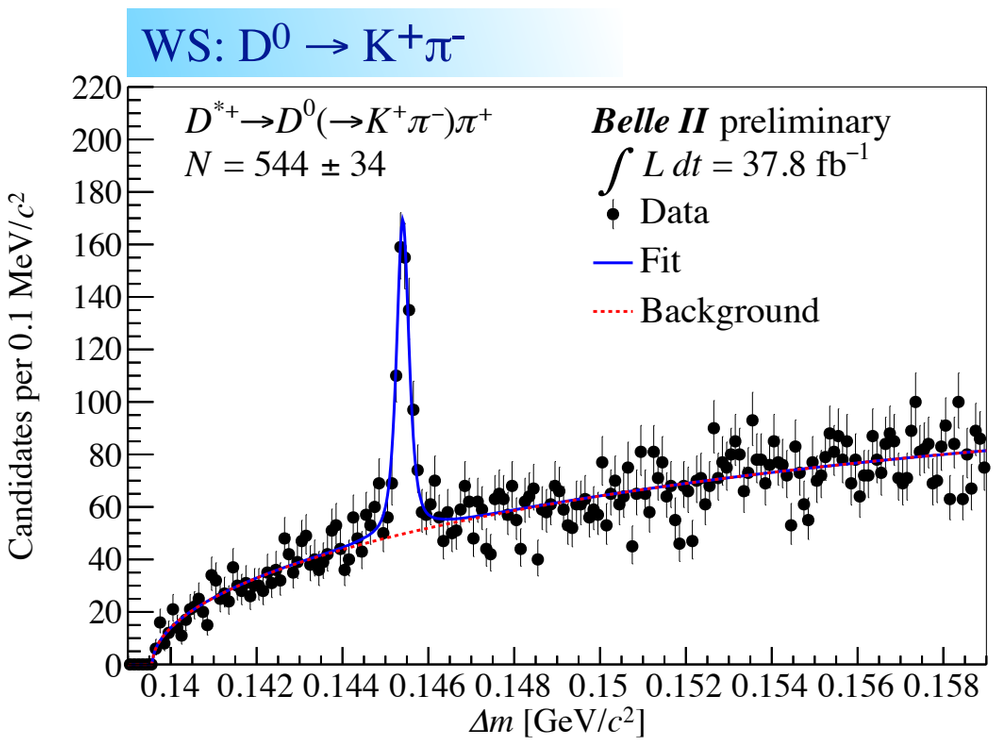
Belle II status w/ 37.8 fb^{-1}

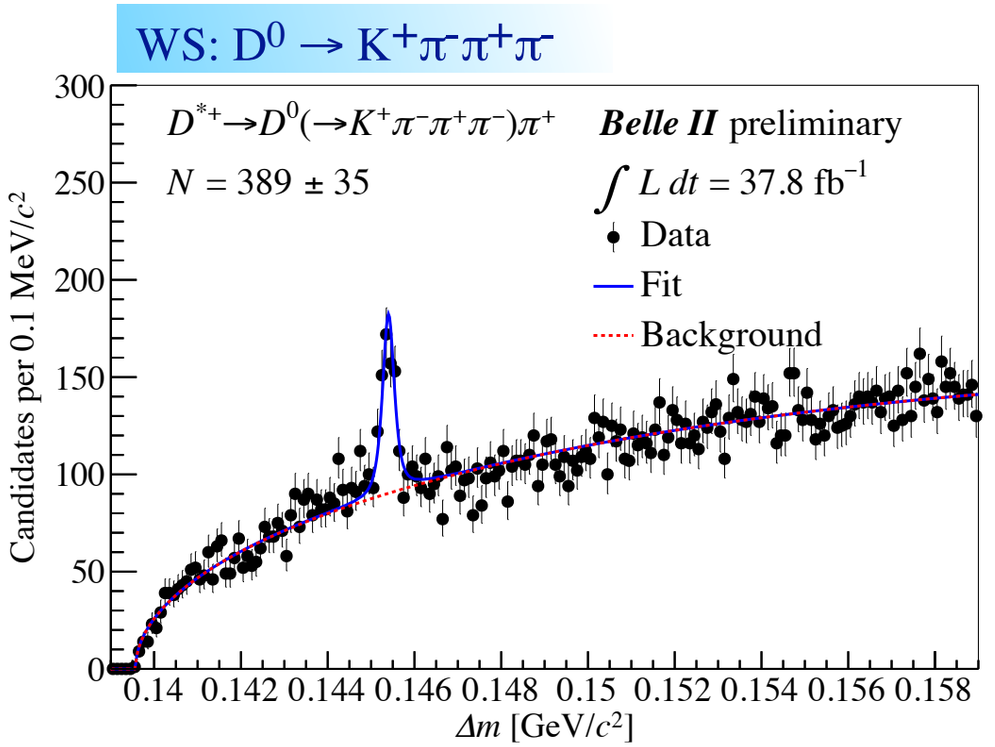
- re-discoveries of D* tagged WS D^0 decay channels

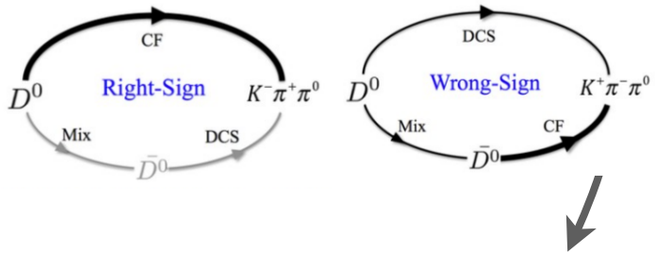
BELLE2-NOTE-PH-2020-032











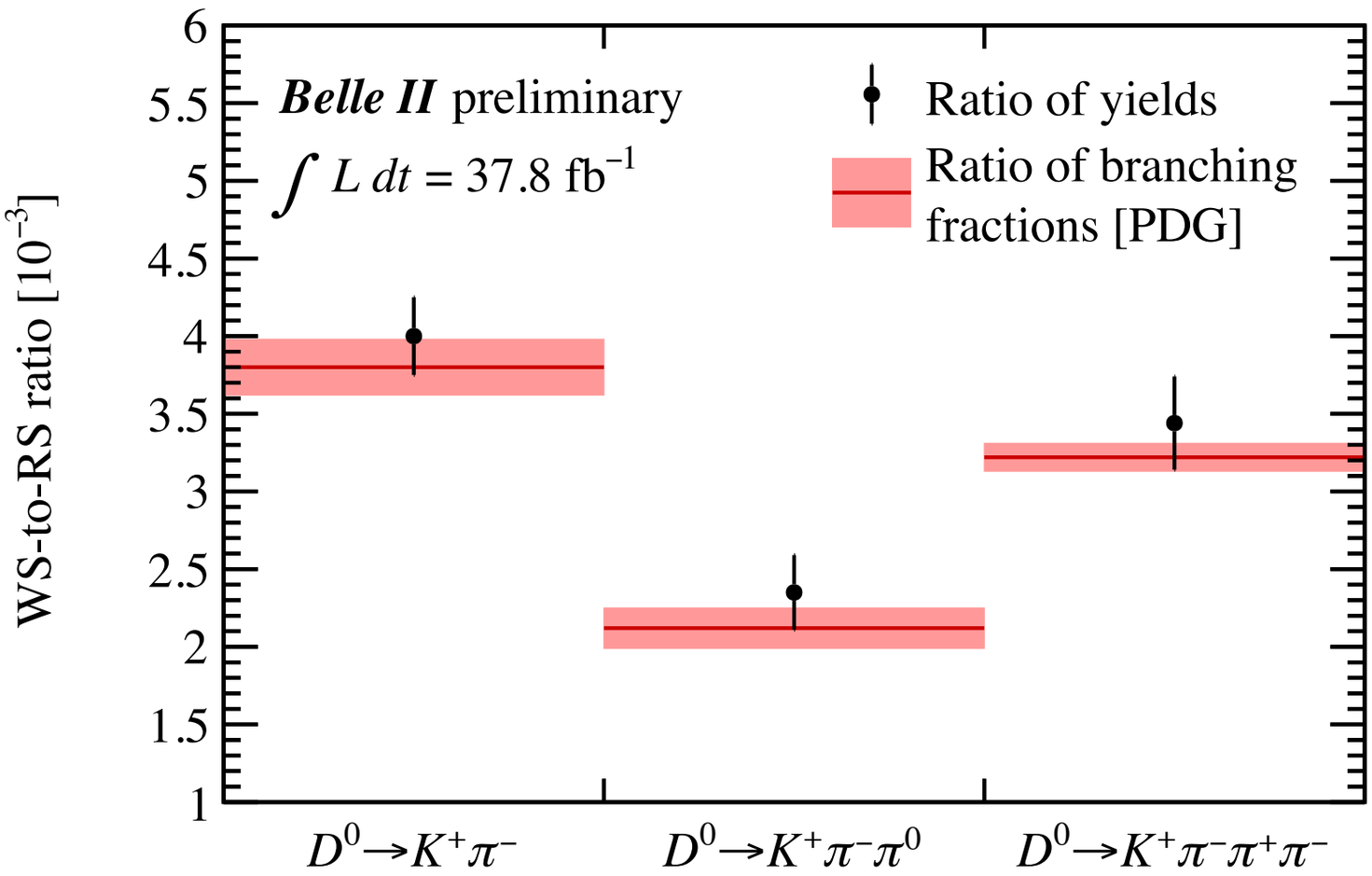
WS: D^0 Decay

WS/RS ratio

- PDF from RS is use it to fit the WS distributions. Then ratio of yields is extracted

Belle II status
w/ 37.8 fb^{-1}

BELLE2-NOTE-PH-2020-032



Other experiments

Belle: Phys.Rev.Lett. 96 151801,2006
BaBar: Phys. Rev. Lett. 98 (2007) 211802
LHCb: Phys. Rev. Lett. 110 (2013) 101802

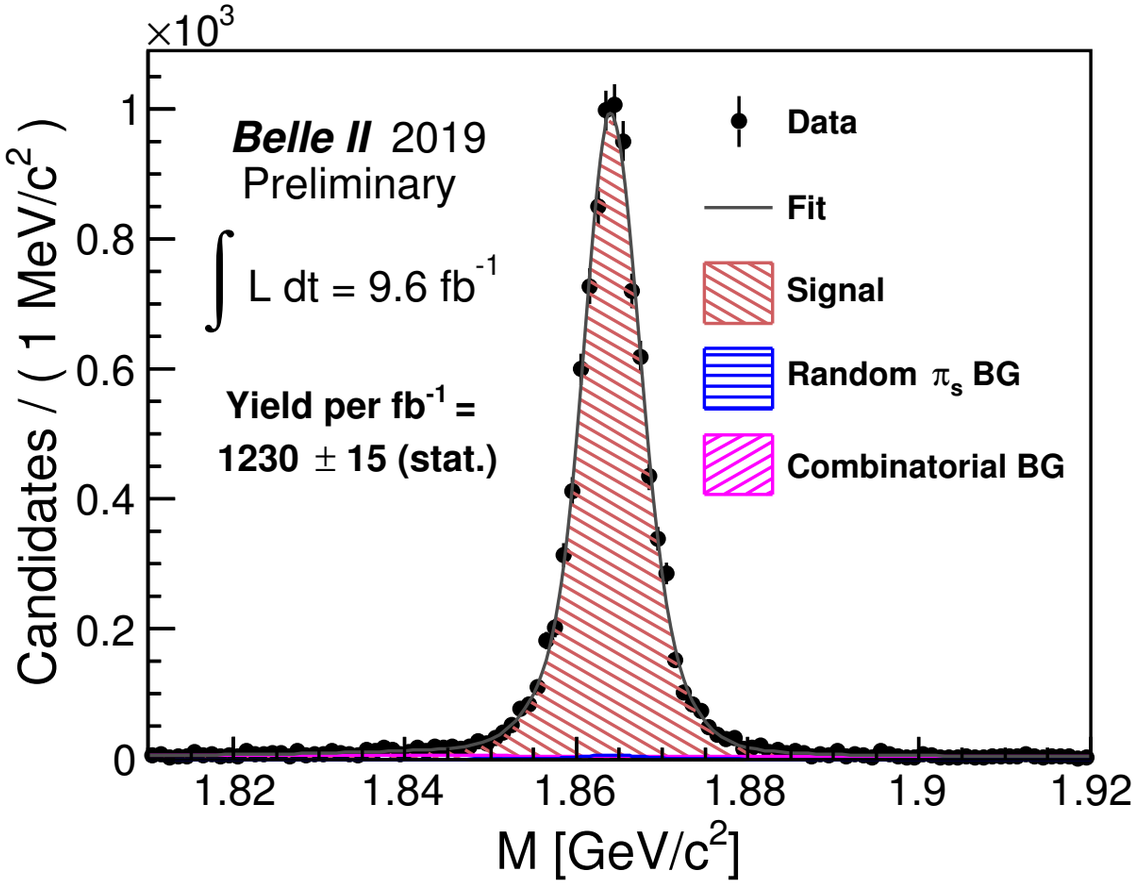
Dalitz analysis $D^0 \to K_S\pi^+\pi^-$

- One of the golden channel $D^0 \to K_S\pi^+\pi^-$
- Provide most precise mixing parameter
- To avoid systematic limitation:
  - either reduce model limitation OR strong phase measurement (at BESIII)

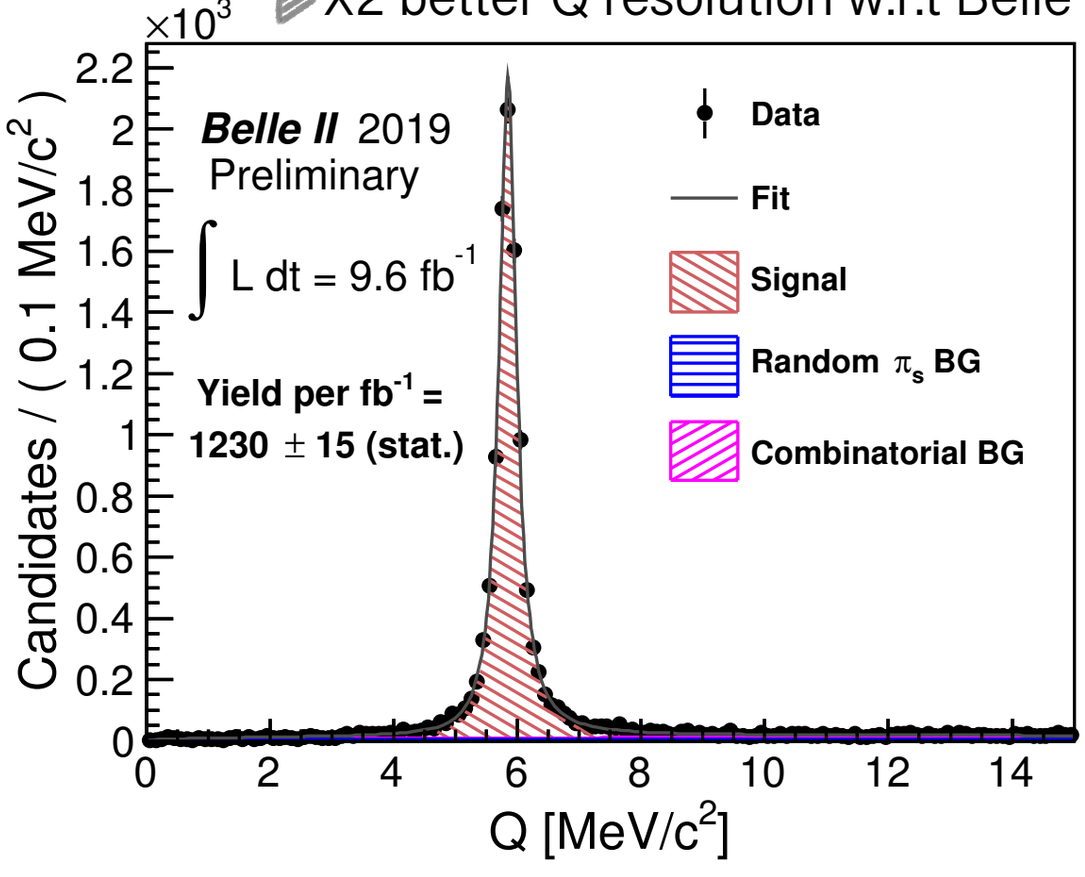
Belle II status w/ 9.6 fb^{-1}

BELLE2-NOTE-PH-2020-031

- Time-dependent fit to the Dalitz amplitudes
  - assuming a Dalitz model, extracting amplitudes and phases from data
    → source of irreducible systematics



- X2 better Q resolution w.r.t Belle

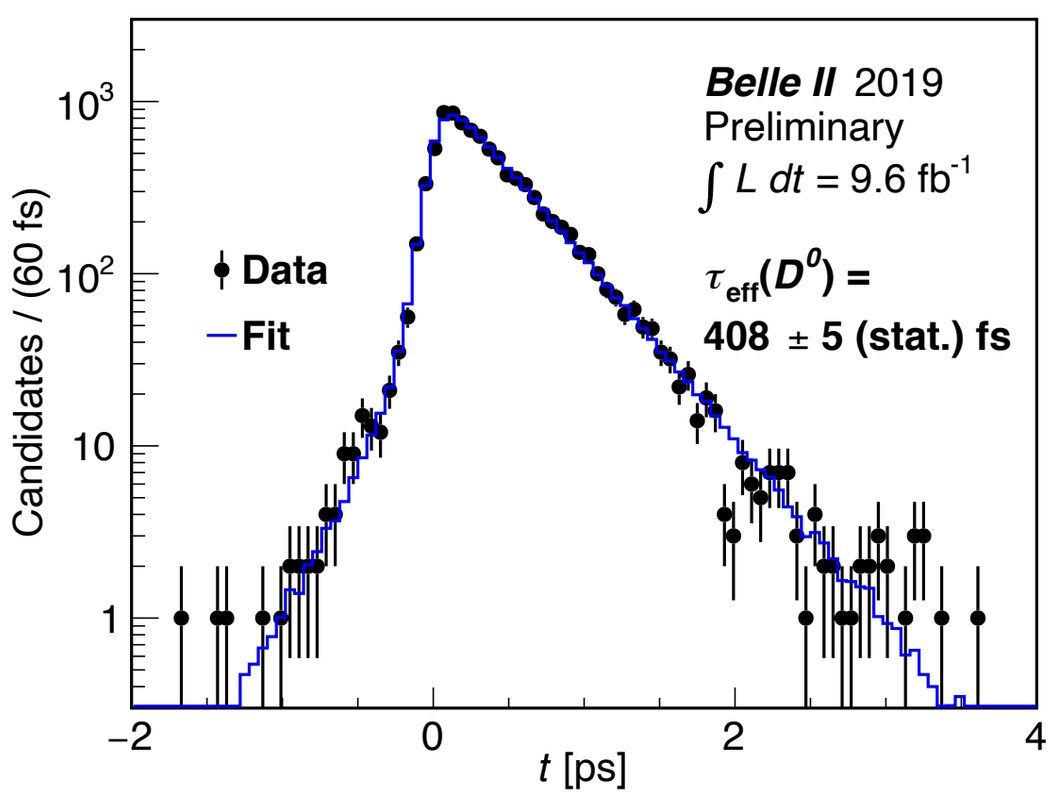


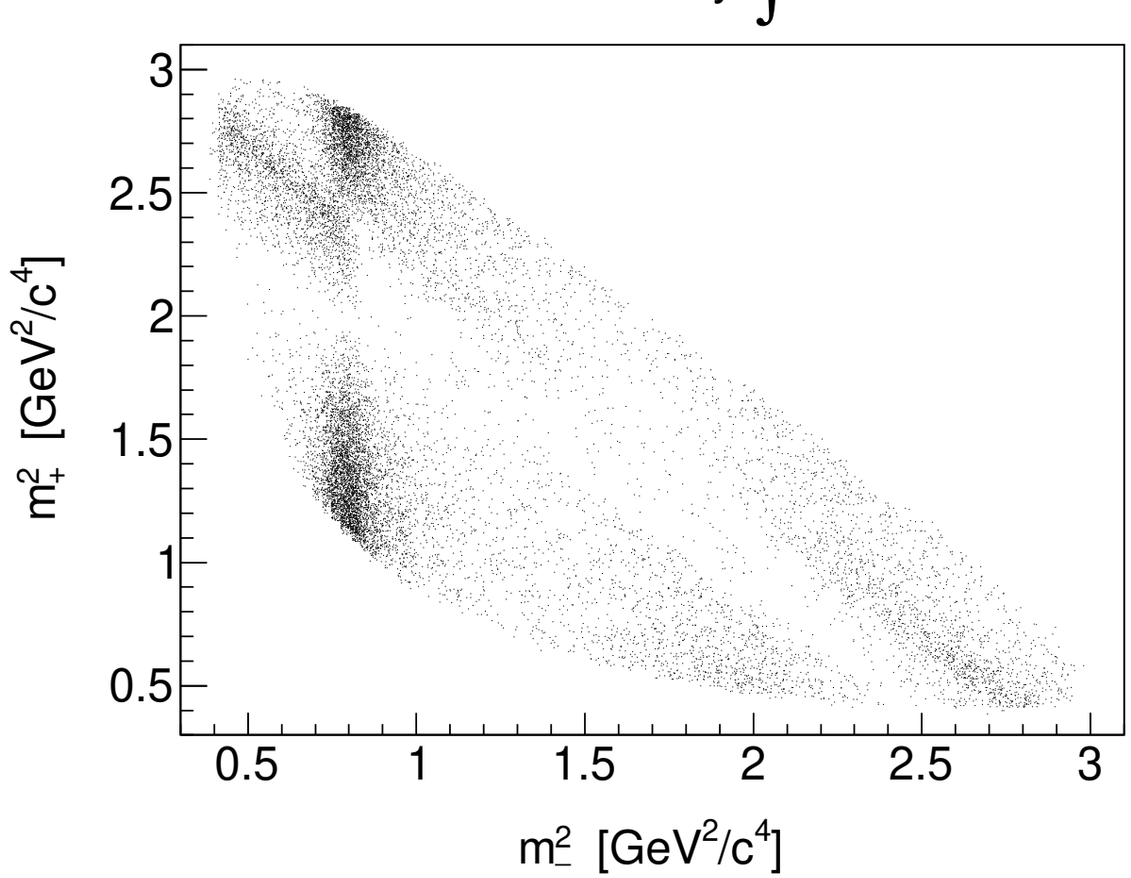
Dalitz analysis $D^0 \to K_S\pi^+\pi^-$

Belle II status w/ 9.6 fb^{-1}

BELLE2-NOTE-PH-2020-031

- Proper time resolution
  - Comparable to the ones observed in lifetime analysis
  - Also compatible with expected WA (410.1 ± 1.5) fs
- Nice Dalitz plots with visible resonances
- Goal: Sensitivity study for mixing and CPV parameters measurements via Dalitz analysis





Summary

- SuperKEKB and Belle II provides an excellent platform for charm measurements
  - Integrated luminosity so far (June 04, 2021) L_{int} ~176 fb^{-1}
  - Highest instantaneous luminosity ~2.9×10^{34} $cm^{-2}s^{-1}$
    - ➡ SuperKEKB design luminosity: 6.5×10^{35} $cm^{-2}s^{-1}$
    - ➡ New world record archived in June 2020 🥇
- D^0 decay time resolution is x2 better than that of Belle/Babar (upgraded VXD)
- A good start with many rediscoveries and more exciting results to come soon with larger luminosity in coming years.
- ..with full $50ab^{-1}$
  - Better precision on CPV observables (x and y variables ≤ 0.1%)

Extras

Full charm event reconstruction

$e^+e^- \to c\bar{c} \to D_{tag} X_{frag} D_{sig}$

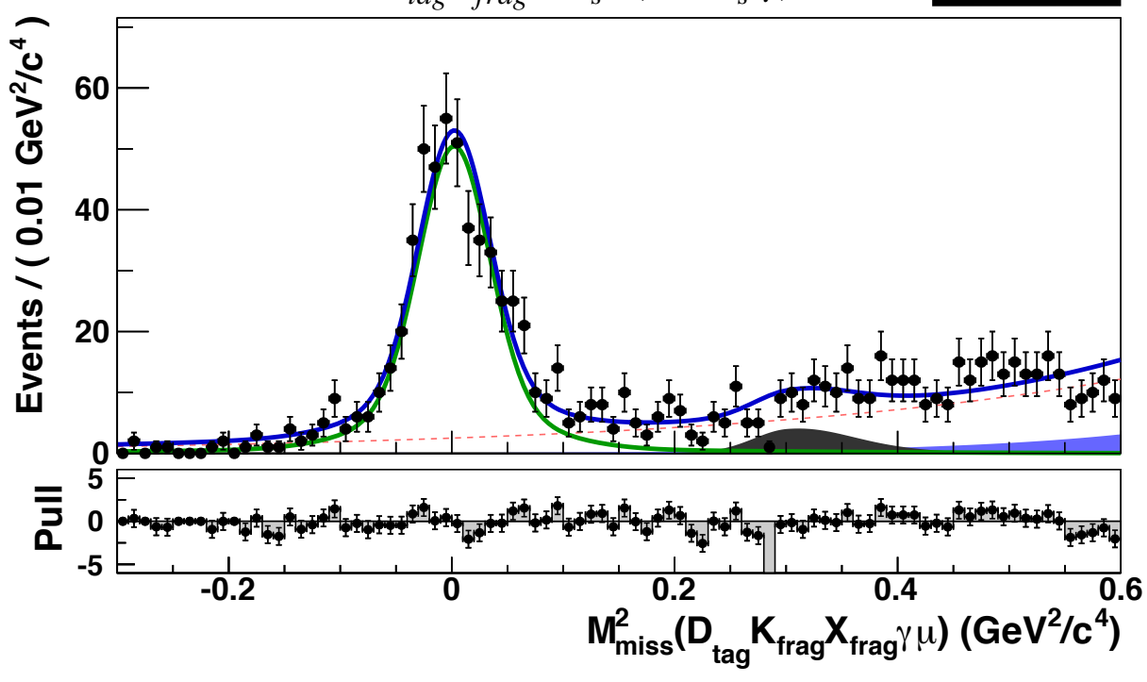
- Provides useful insights in;
  - inclusive branching fraction measurement
  - (semi-)leptonic study
  - rare/forbidden decays search

1 $D_s^+ \to \mu^+\nu$

10.1007/JHEP09(2013)139

Belle

$e^+e^- \to c\bar{c} \to D_{tag} X_{frag} K D_s^{*+} (\to D_s^+ \gamma)$



stat. error ~1/3 of the theory error (unc for 50ab-) ⇐

competitive with CLEOc and BESIII (Belle sim for 50ab-) ⇐

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

Extrapolations from Belle Measurements

Mode	Belle $(0.91, 0.92\ \text{ab}^{-1})$	Belle II $(50\ \text{ab}^{-1})$
$D_s^- \to \mu^- \bar{\nu}$	492 ± 26	27000
$D^- \to \mu^- \bar{\nu}$	–	1250
inclusive $D^0 \to$ anything	$(695 \pm 2) \times 10^3$	38×10^6

2 $D^0 \to \nu\bar{\nu}$

Belle

10.1103/PhysRevD.95.011102

38x10⁶ inclusive D^0 with 50 ab^{-1}

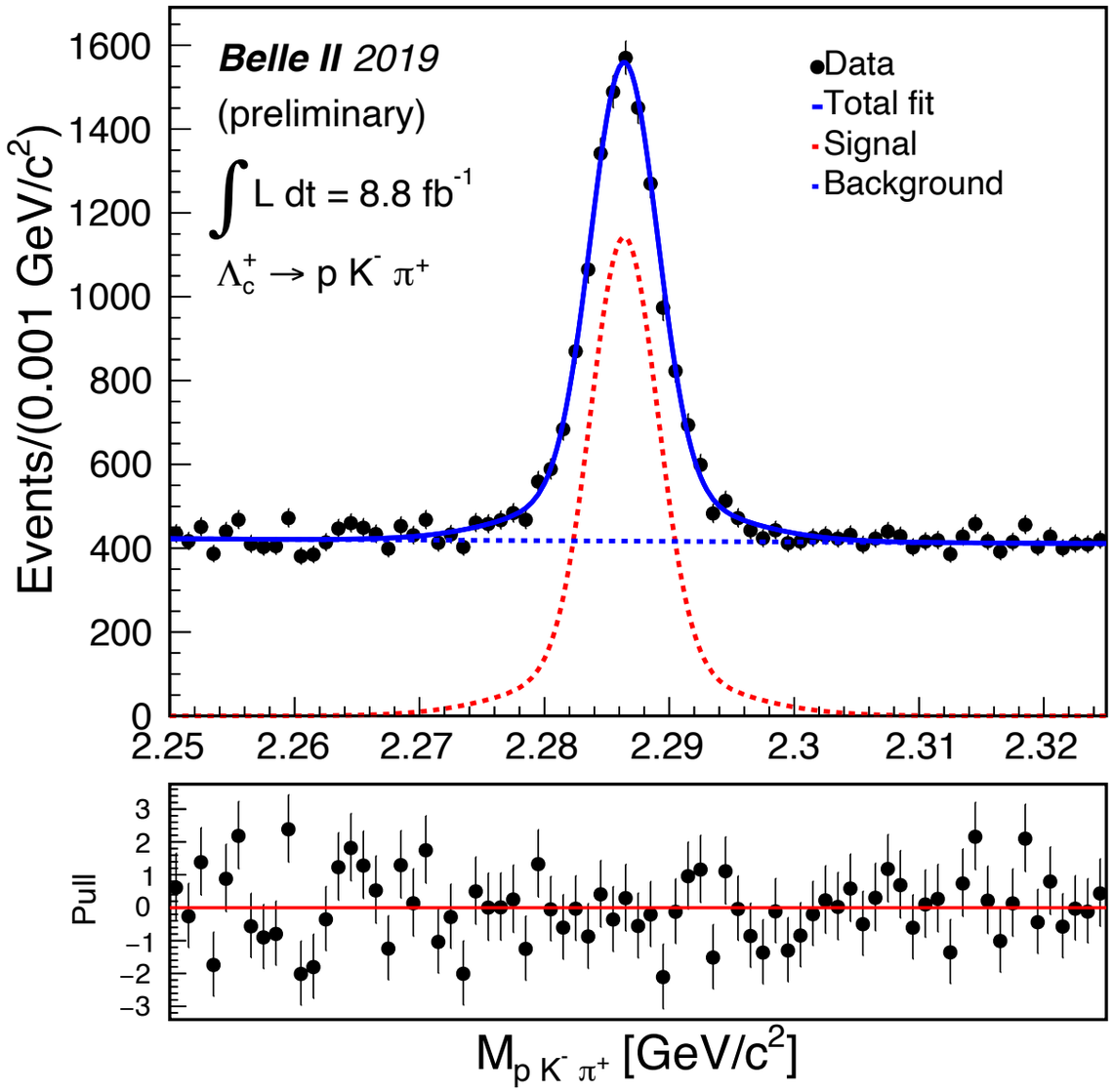
Ongoing time-integrated measurement at Belle II (3)

↝ rediscoveries of charm baryons

$\Lambda_c^+ \to pK^-\pi^+$

Belle II w/ 8.8 fb^{-1}

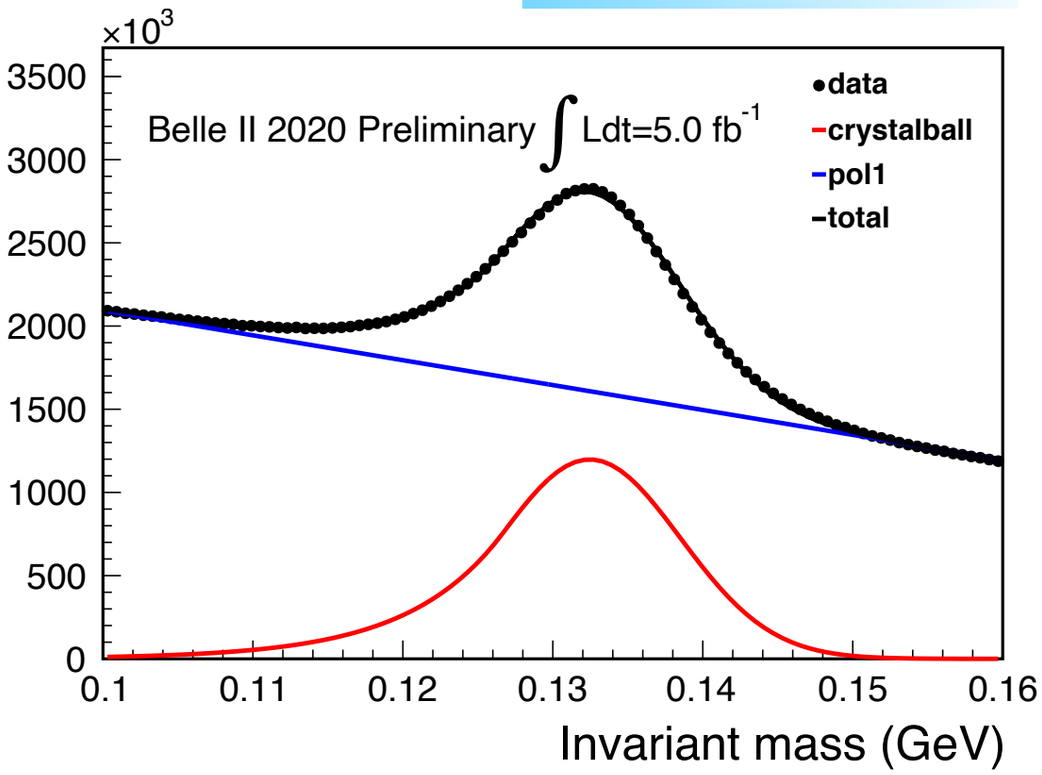
BELLE2-NOTE-PH-2020-020



	data (Proc11)
Peak position [MeV/c^2]	2286.4 ± 0.1
$< \sigma >$ [MeV/c^2]	4.287 ± 0.759
χ^2/ndf	1.09
Signal yields per 1/fb	984 ± 6
Purity	0.508 ± 0.002

Neutral performance

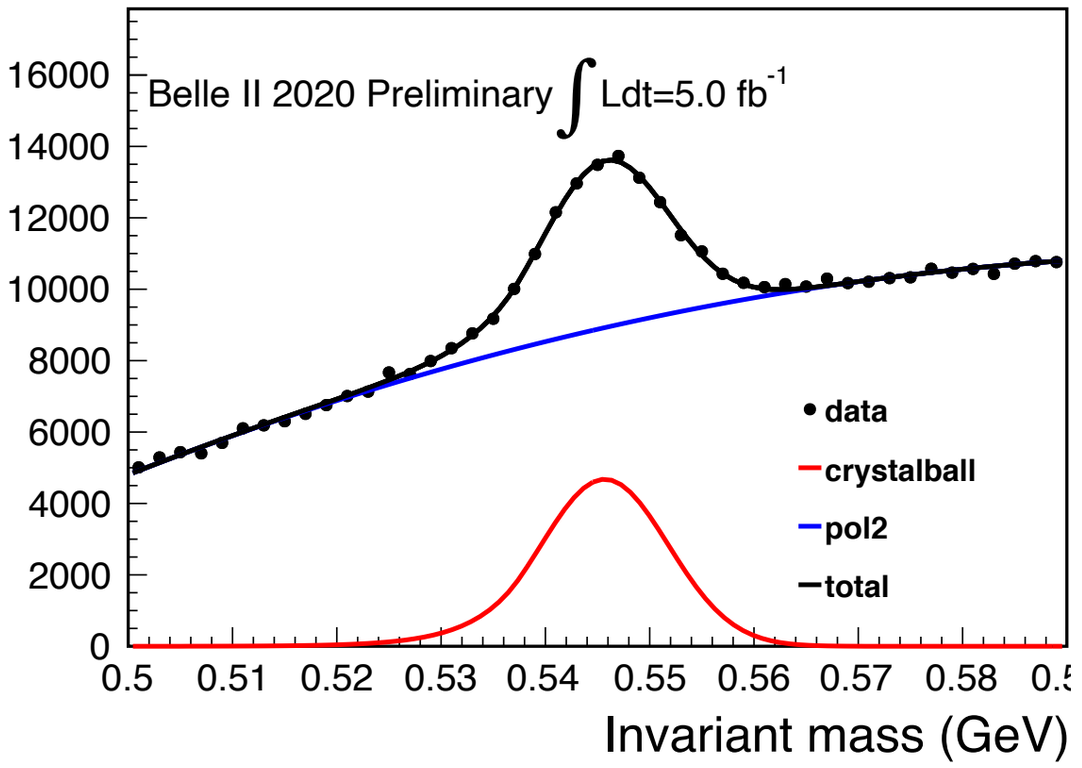
$\pi^0 \to \gamma\gamma$



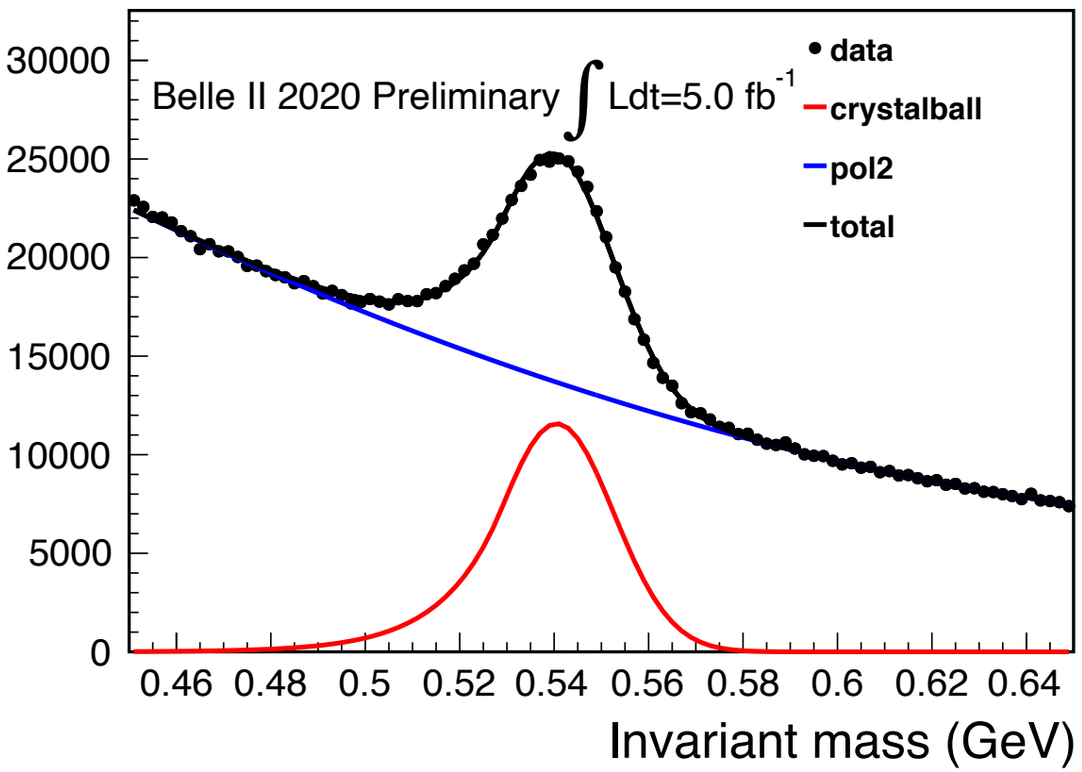
Belle II status w/ 5.0 fb^{-1}

/BELLE2-NOTE-PH-2020-003

$\eta \to 3\pi^0$



$\eta \to \gamma\gamma$



rediscoveries of charm baryons

$\Lambda_c^+ \to pK^-\pi^+$

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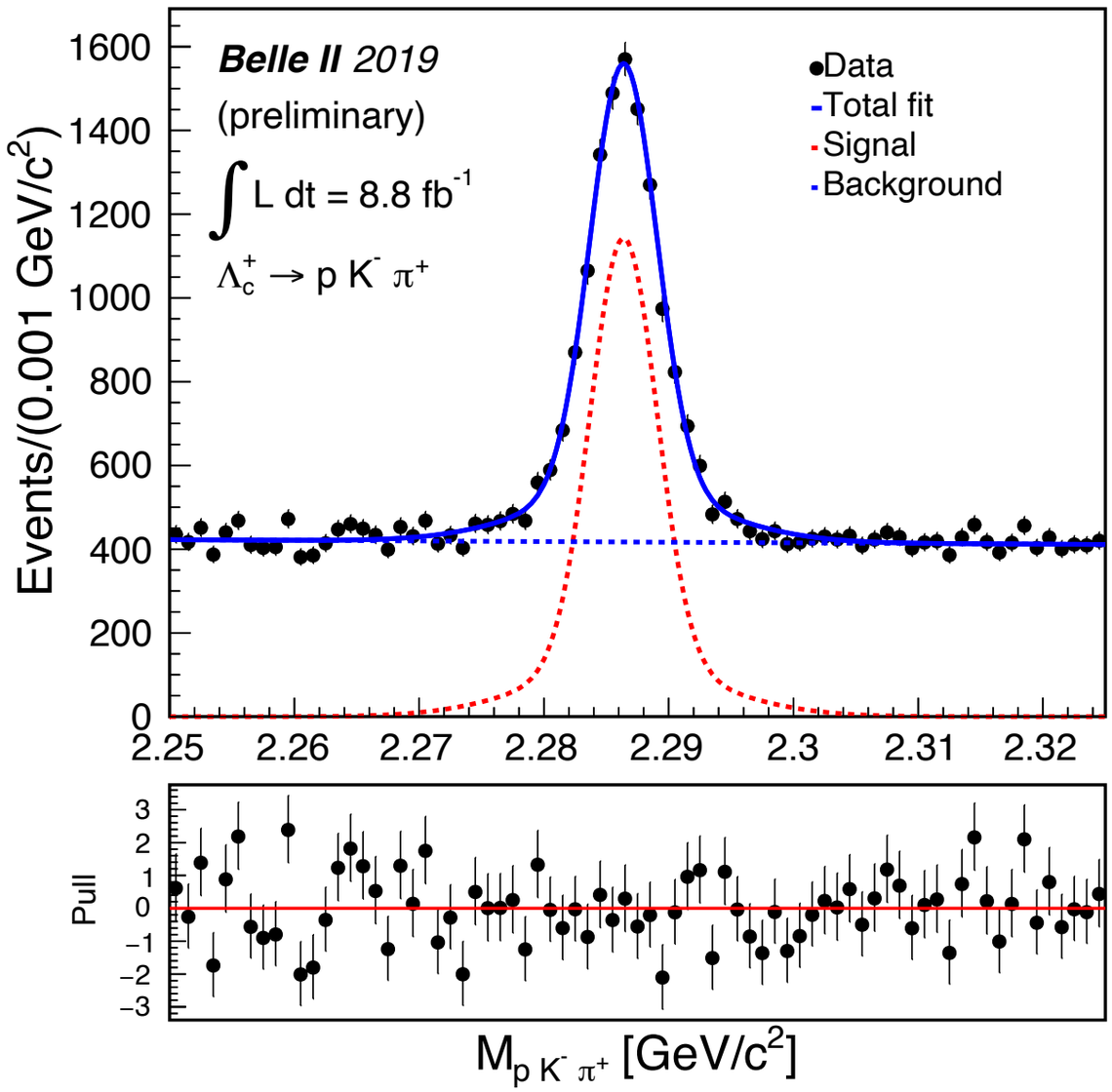
BELLE2-NOTE-PH-2020-020



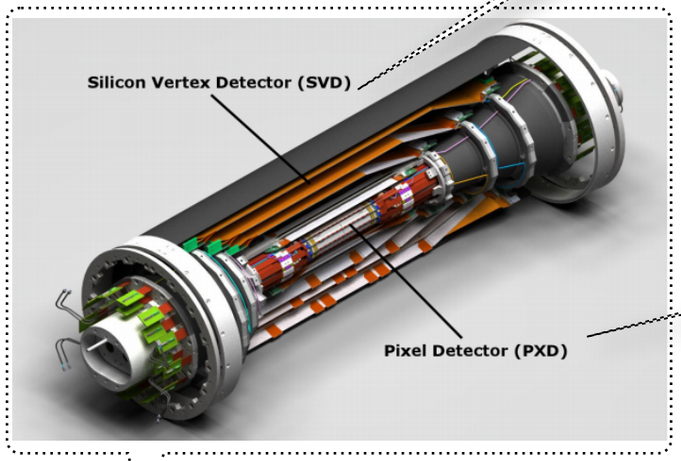
VXD

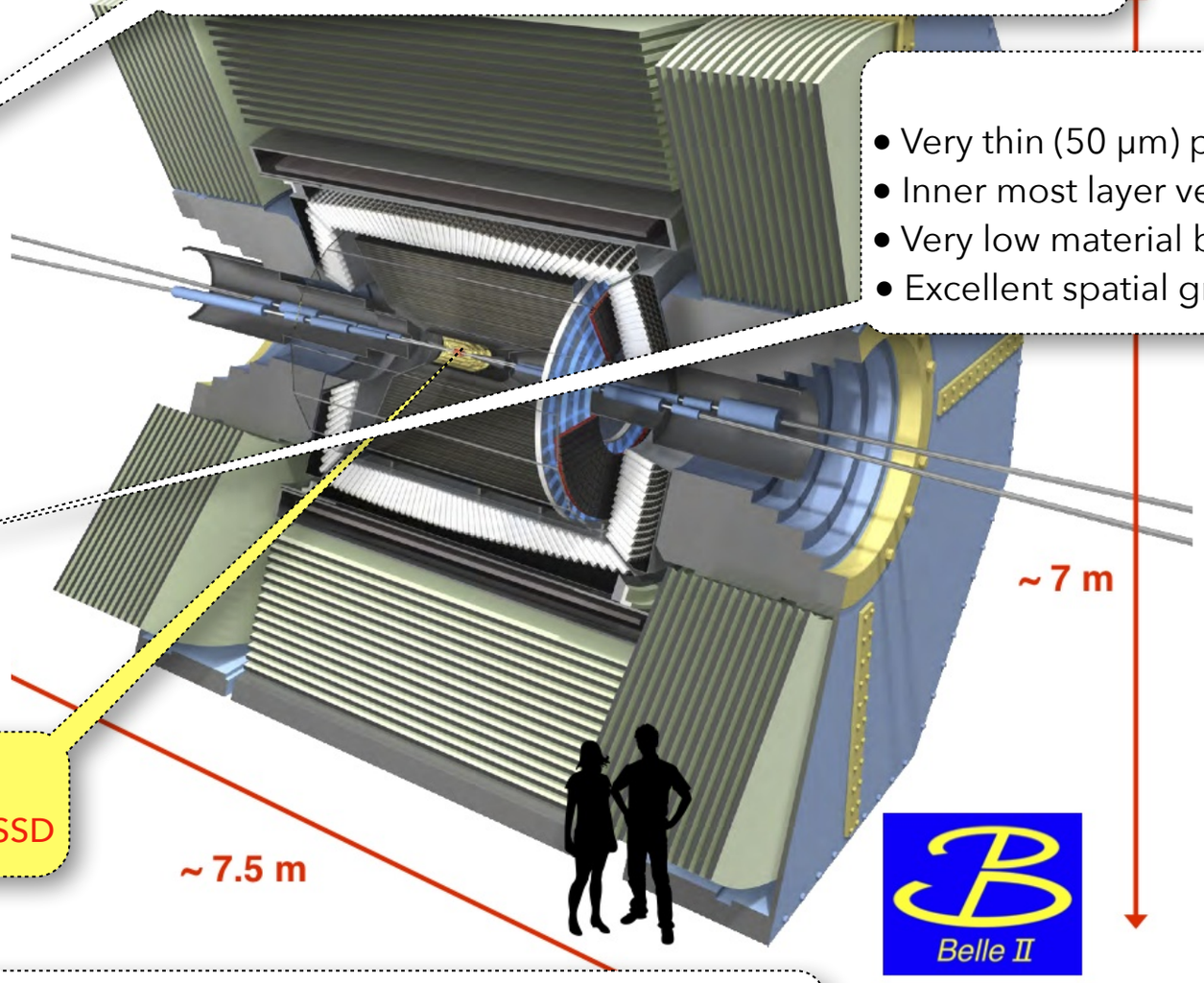
SVD

- Excellent timing resolution (σ ~ 2-3 ns)
- Low material budget
- Larger outer radius (6.05 cm → 14 cm)
- Inner radius: 3.8 cm
- covers the full Belle II angular acceptance of 17-150 degree

PXD

- Very thin (50 μm) pixel sensor
- Inner most layer very close to IP (r = 1.4 cm)
- Very low material budget
- Excellent spatial granularity (σ ≤15 μm)





Vertex Detector

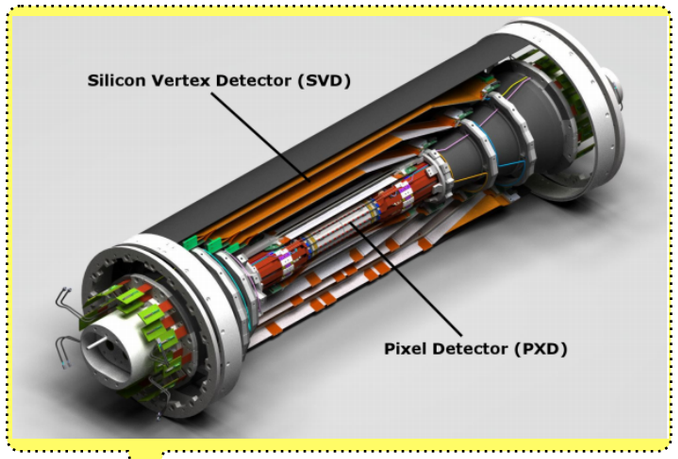
2 Layers PXD DEPFET and 4 Layers DSSD

- Installation is set for phase III stage of belle2 program
- Key player for D-mixing sensitivity measurements !
  - Highly granular pixel sensors provide most accurate 2D position information
  - Reconstruction of primary and secondary vertices of short-lived particles (<100 μm from IP)

Go back

see more at Belle2 TDR: arXiv: 1011.0352

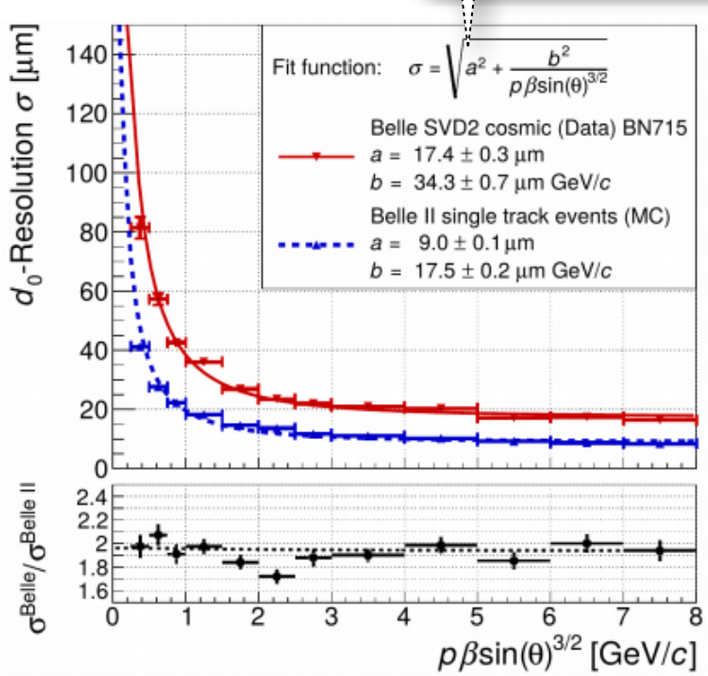
VXD

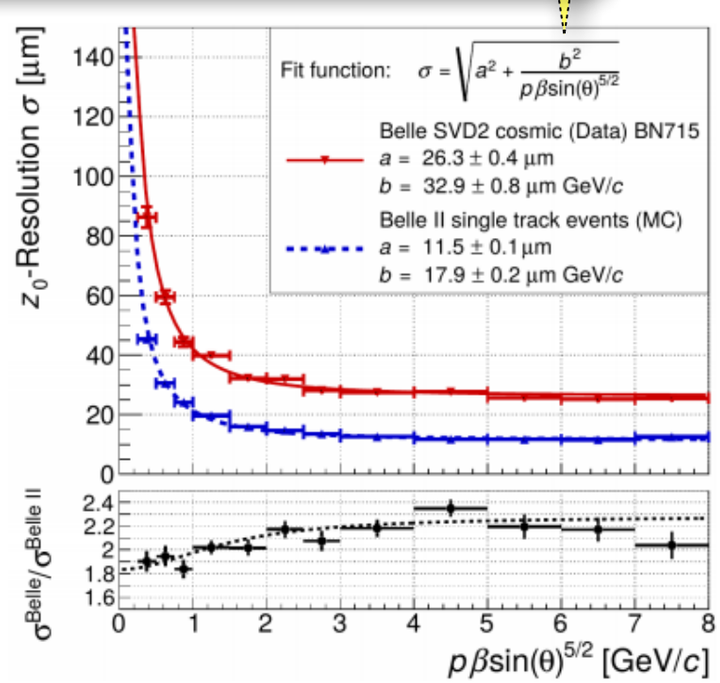


Vertex Detector

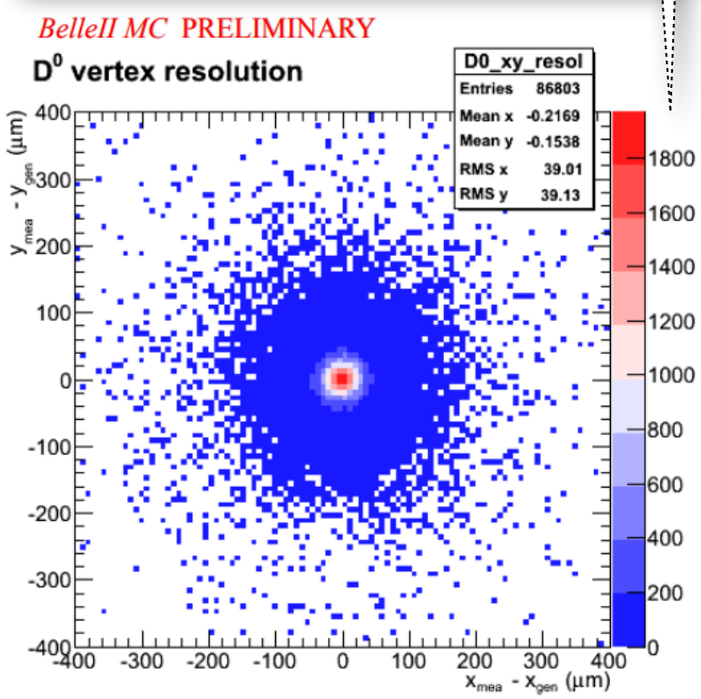
2 Layers PXD DEPFET and 4 Layers DSSD

A factor 2 improvement with respect to Belle





Better vertex resolution ~ 40 μm



see more at Belle2 TDR: arXiv: 1011.0352

Dalitz analysis $D^0 \to K_s\pi^+\pi^-$

Extrapolations from Belle Measurements

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

Data	**stat.**	**syst.**		**Total**	**stat.**	**syst.**		**Total**
		red.	irred.			red.	irred.	
	σ_x (10^{-2})				σ_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 $(^\circ)$			
^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

- Scaling doesn't include x2 improvement in proper time!

^Phys. Rev. D 89, 091103 (2014)