Determination of CKM Angle ϕ_3 at Belle and Belle II

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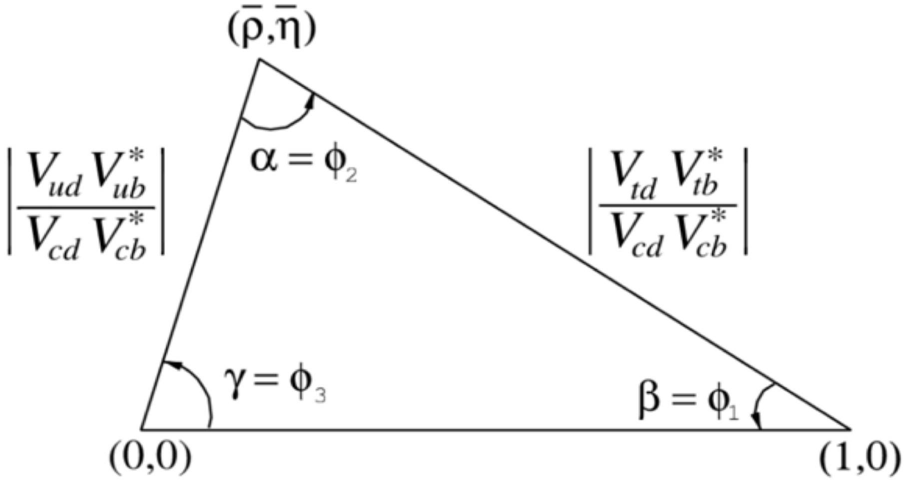
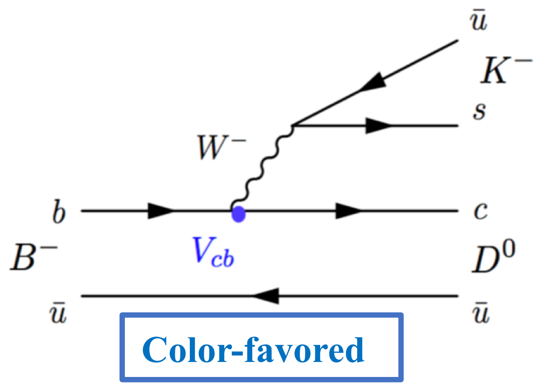
27^{th} October 2021

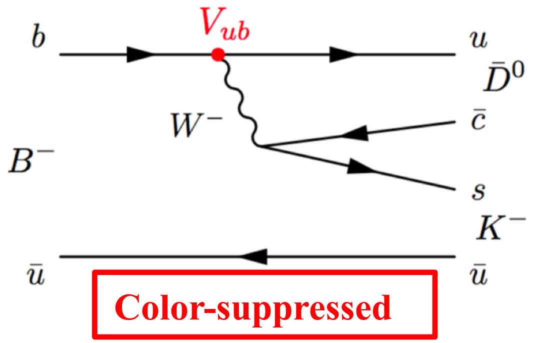
The CKM angle ϕ_3



$$\phi_3/\gamma \equiv arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

- Very precise theoretical prediction $\frac{\delta\phi_3}{\phi_3} \sim 10^{-7}$ arxiv:1308.5663
- Test physics beyond SM





- The interference between color-favored and color-suppressed processes can be related :

$$\frac{A^{suppr.}[B^-\to\overline{D^0}K^-]}{A^{favor.}[B^-\to D^0K^-]} = r_B e^{i(\delta_B-\phi_3)}$$

r_B -the magnitude of the ratio of amplitudes ~0.1 ; δ_B -strong-phase difference

- 3 main methods to extract ϕ_3:
  - GLW method: CP eigenstates: K^-K^+, $\pi^-\pi^+$, $K_S^0\pi^0$
  - ADS method: DCS modes: $K^+\pi^-$, $K^+\pi^-\pi^0$
  - BPGGSZ method: self-conjugate multibody final states: $K_S^0\pi^+\pi^-$, $K_S^0K^+K^-$, $K_S^0\pi^+\pi^-\pi^0$

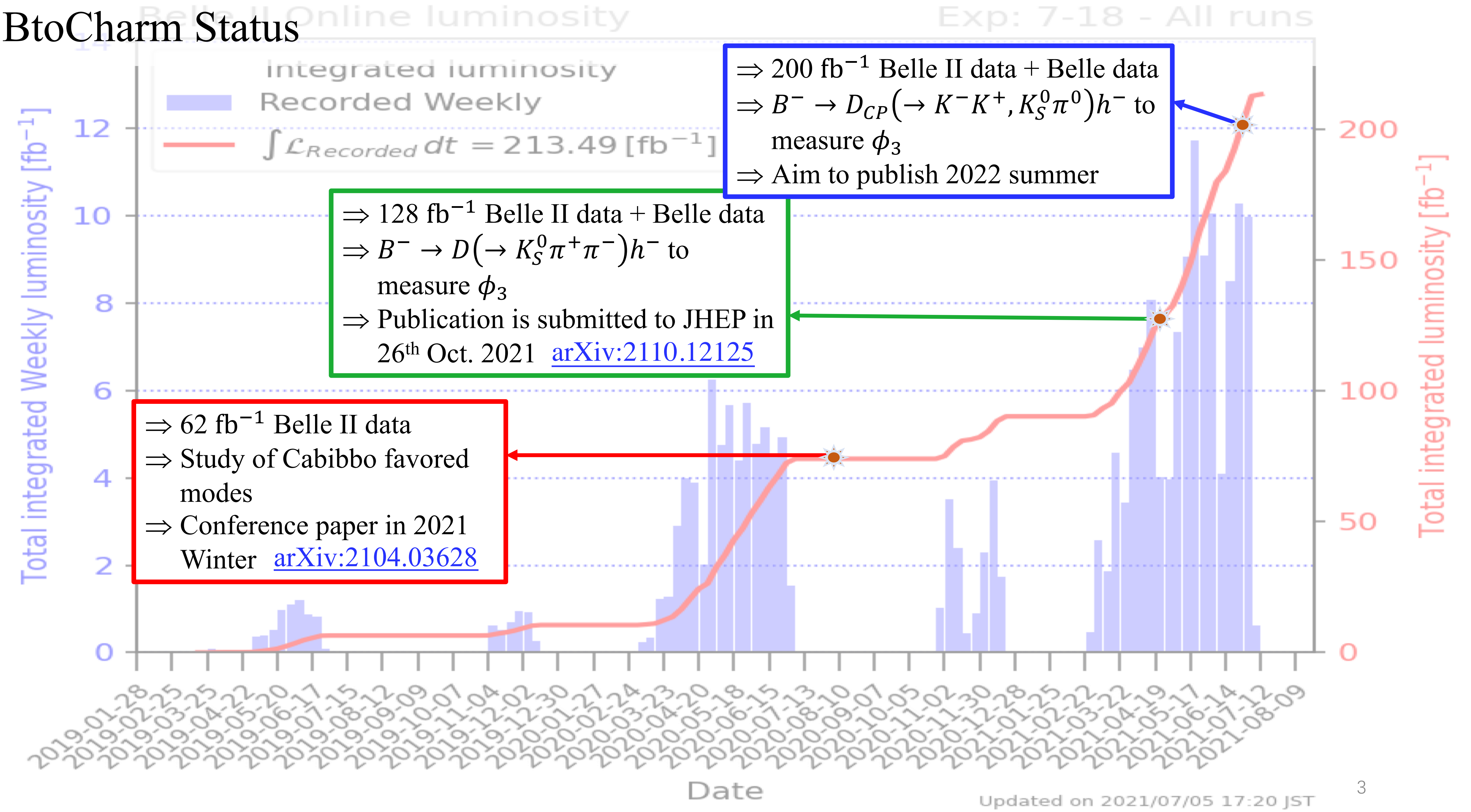
- Foreseen precision of ϕ_3 is expected to be $\mathcal{O}(1°)$ (current world-average $\delta\phi\sim4°$) with the full Belle II dataset of 50 ab^{-1}

BtoCharm Status

⇒ 200 fb^{-1} Belle II data + Belle data
⇒ $B^- \to D_{CP}(\to K^-K^+, K_S^0\pi^0)h^-$ to measure ϕ_3
⇒ Aim to publish 2022 summer

⇒ 128 fb^{-1} Belle II data + Belle data
⇒ $B^- \to D(\to K_S^0\pi^+\pi^-)h^-$ to measure ϕ_3
⇒ Publication is submitted to JHEP in 26th Oct. 2021 arXiv:2110.12125

⇒ 62 fb^{-1} Belle II data
⇒ Study of Cabibbo favored modes
⇒ Conference paper in 2021 Winter arXiv:2104.03628



Study of $B \to D^{(*)}_{fav} h$ with 62.8 fb^{-1} Belle II data

$h = \pi, K$ arXiv:2104.03628

- The improved measurement of the color-favored hadronic two body decay of B meson helps to a better understanding of QCD effects
- Decay ratio to be extracted:

$$R^{D(*)} = \frac{\Gamma[B \to D^{(*)}K]}{\Gamma[[B \to D^{(*)}\pi]} \simeq \tan^2\theta_C \left(\frac{f_K}{f_\pi}\right)^2$$

which will eliminate some systematic uncertainties

⇨ R2<0.3 is sufficient to suppress the background

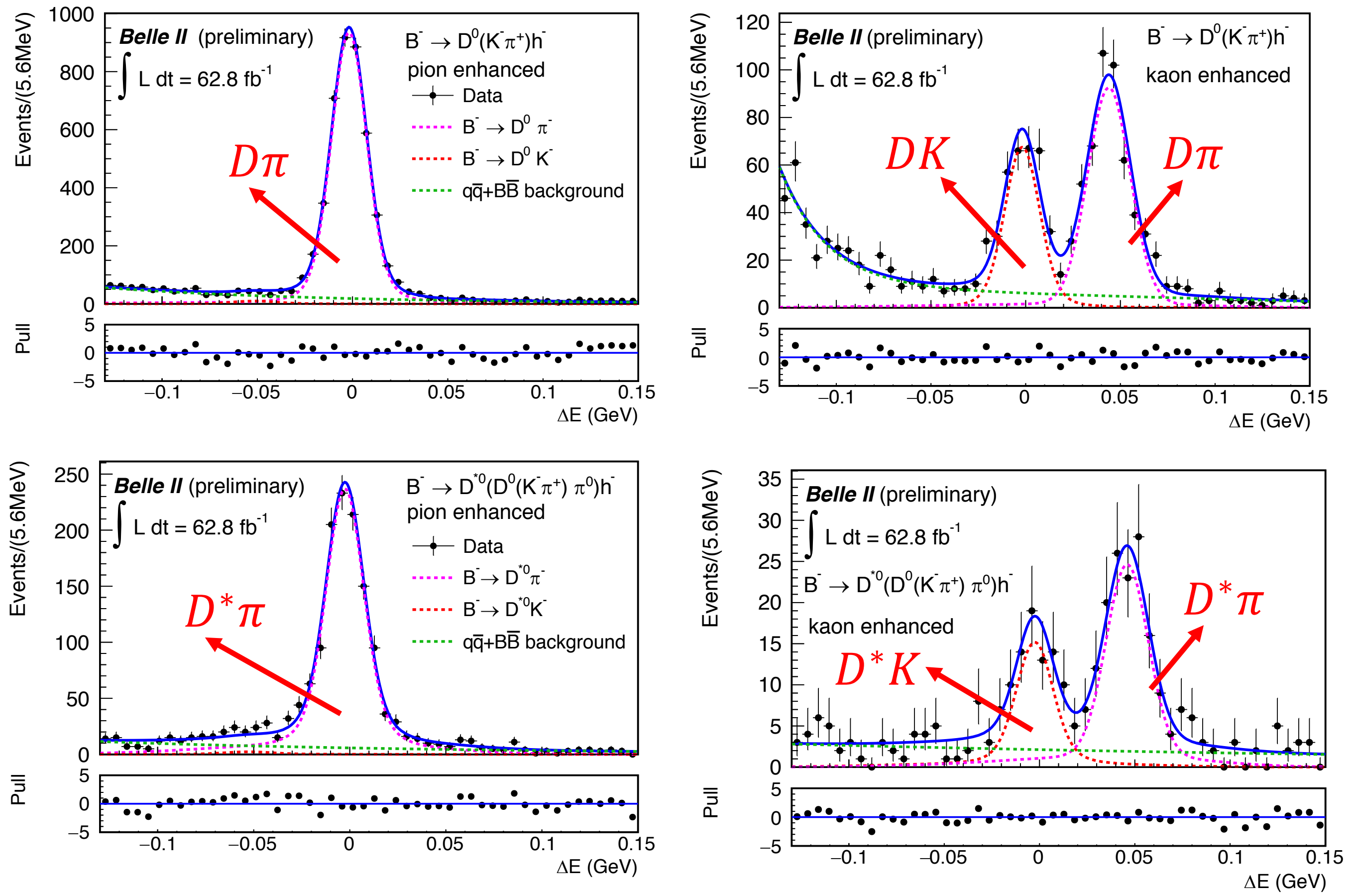
- Unbinned 1D simultaneous fit of ΔE

$$N^{D^{(*)}\pi}_{KID<0.6} = (1 - \kappa_{KID>0.6})\, N^{D^{(*)}\pi}_{Total}$$
$$N^{D^{(*)}K}_{KID<0.6} = (1 - \epsilon_{KID>0.6}) R^{(*)}\, N^{D^{(*)}\pi}_{Total}$$

$$N^{D^{(*)}K}_{KID>0.6} = \epsilon_{KID>0.6} R^{(*)}\, N^{D^{(*)}\pi}_{Total}$$
$$N^{D^{(*)}\pi}_{KID>0.6} = \kappa_{KID<0.6} N^{D^{(*)}\pi}_{Total}$$

pion enhanced $\mathcal{L}(K/\pi) < 0.6$

kaon enhanced $\mathcal{L}(K/\pi) > 0.6$



κ- pion fake rate(free) ; ϵ-kaon efficiency(fixed from official PID table);

KID –short for binary PID likelihood $\mathcal{L}(K/\pi) = \frac{\mathcal{L}(K)}{\mathcal{L}(K)+\mathcal{L}(\pi)}$

Study of $B \to D_{fav}^{(*)} h$ done with 62.8 fb^{-1} Belle II data

$h = \pi, K$ arXiv:2104.03628

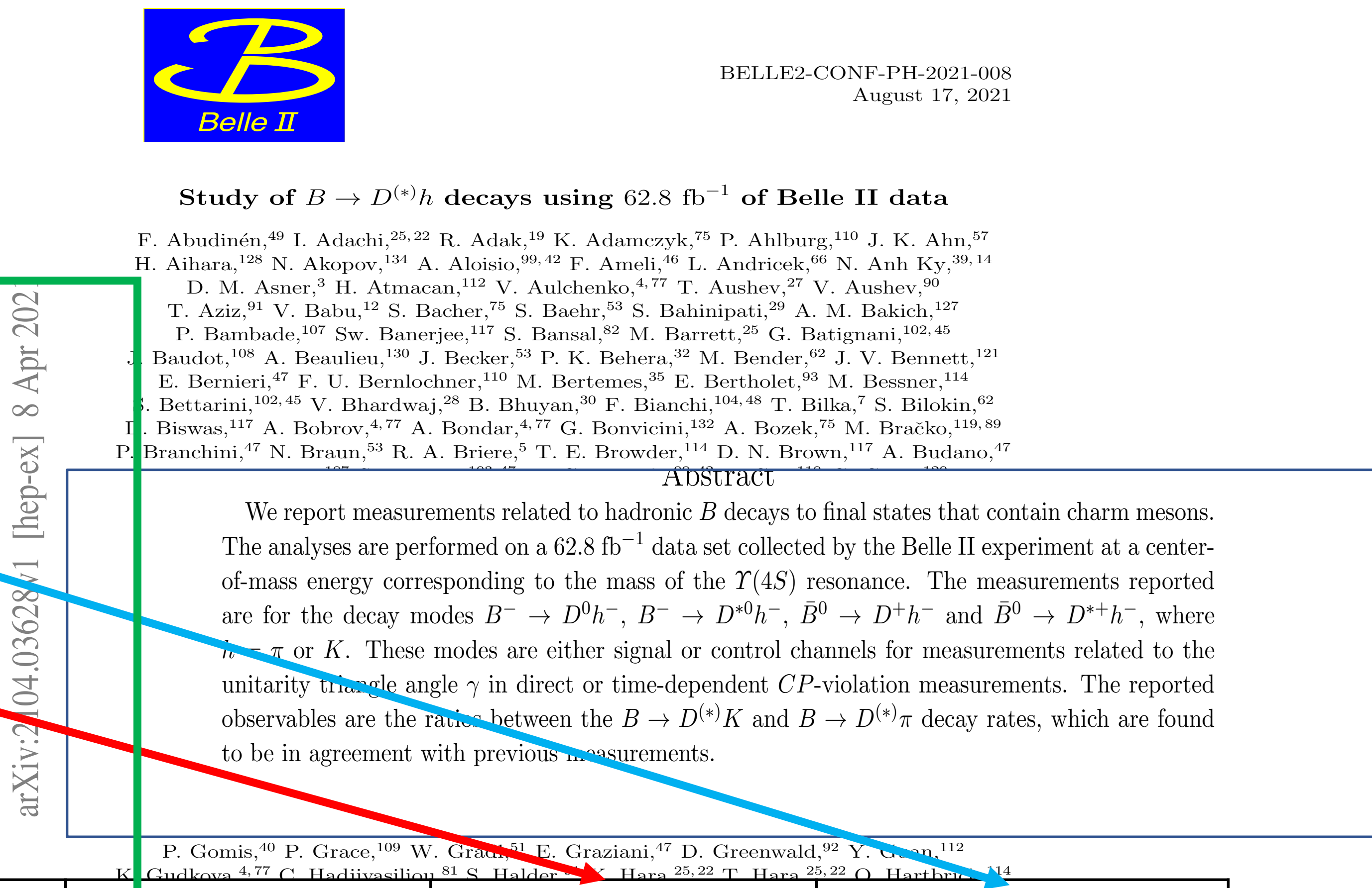
- A conference paper in winter 2021

Colleague A

Colleague B

Colleague C

Yi Zhang


Belle II

BELLE2-CONF-PH-2021-008
August 17, 2021

Study of $B \to D^{(*)}h$ decays using 62.8 fb^{-1} of Belle II data

F. Abudinén,[49] I. Adachi,[25,22] R. Adak,[19] K. Adamczyk,[75] P. Ahlburg,[110] J. K. Ahn,[57]
H. Aihara,[128] N. Akopov,[134] A. Aloisio,[99,42] F. Ameli,[46] L. Andricek,[66] N. Anh Ky,[39,14]
D. M. Asner,[3] H. Atmacan,[112] V. Aulchenko,[4,77] T. Aushev,[27] V. Aushev,[90]
T. Aziz,[91] V. Babu,[12] S. Bacher,[75] S. Baehr,[53] S. Bahinipati,[29] A. M. Bakich,[127]
P. Bambade,[107] Sw. Banerjee,[117] S. Bansal,[82] M. Barrett,[25] G. Batignani,[102,45]
J. Baudot,[108] A. Beaulieu,[130] J. Becker,[53] P. K. Behera,[32] M. Bender,[62] J. V. Bennett,[121]
E. Bernieri,[47] F. U. Bernlochner,[110] M. Bertemes,[35] E. Bertholet,[93] M. Bessner,[114]
S. Bettarini,[102,45] V. Bhardwaj,[28] B. Bhuyan,[30] F. Bianchi,[104,48] T. Bilka,[7] S. Bilokin,[62]
D. Biswas,[117] A. Bobrov,[4,77] A. Bondar,[4,77] G. Bonvicini,[132] A. Bozek,[75] M. Bračko,[119,89]
P. Branchini,[47] N. Braun,[53] R. A. Briere,[5] T. E. Browder,[114] D. N. Brown,[117] A. Budano,[47]

Abstract

We report measurements related to hadronic B decays to final states that contain charm mesons. The analyses are performed on a 62.8 fb^{-1} data set collected by the Belle II experiment at a center-of-mass energy corresponding to the mass of the $\Upsilon(4S)$ resonance. The measurements reported are for the decay modes $B^- \to D^0 h^-$, $B^- \to D^{*0} h^-$, $\bar{B}^0 \to D^+ h^-$ and $\bar{B}^0 \to D^{*+} h^-$, where $h = \pi$ or K. These modes are either signal or control channels for measurements related to the unitarity triangle angle γ in direct or time-dependent CP-violation measurements. The reported observables are the ratios between the $B \to D^{(*)}K$ and $B \to D^{(*)}\pi$ decay rates, which are found to be in agreement with previous measurements.

P. Gomis,[40] P. Grace,[109] W. Gradl,[51] E. Graziani,[47] D. Greenwald,[92] Y. Guan,[112]

arXiv:2104.03628v1 [hep-ex] 8 Apr 2021

- Measurement results:

Experiment	$B^- \to D^0(K^-\pi^+)h^-$	$B^- \to D^0(K_S^0\pi^+\pi^-)h^-$	$B^0 \to D^- h^+$	$B^- \to D^{*0}h^-$	$B^0 \to D^{*-}h^+$
Belle II $R^{(*)+/0}$(%)	$7.66 \pm 0.55^{+0.11}_{-0.08}$	$6.32 \pm 0.81^{+0.09}_{-0.11}$	$9.22 \pm 0.58 \pm 0.09$	$6.80 \pm 1.01 \pm 0.07$	$5.99 \pm 0.82^{+0.17}_{-0.08}$
LHCb$R^{(*)+/0}$(%)	$7.77 \pm 0.04 \pm 0.07$ Phys. Lett. B 777, 16 (2018).	$7.77 \pm 0.04 \pm 0.07$ Phys. Lett. B 777, 16 (2018).	$8.22 \pm 0.11 \pm 0.25$ JHEP 1304, 001 (2013).	$7.93 \pm 0.11 \pm 0.56$ Phys. Lett. B 777, 16 (2018).	$7.76 \pm 0.34 \pm 0.26$ Phys. Rev. D 87, 092001 (2013).

BPGGSZ Method Study of $B^- \to D(\to K_S^0 h^+ h^-)h^-$

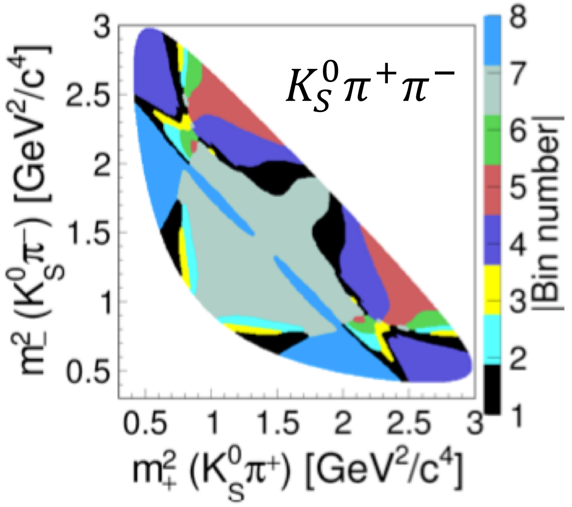
https://arxiv.org/abs/2110.12125
$h = \pi, K$

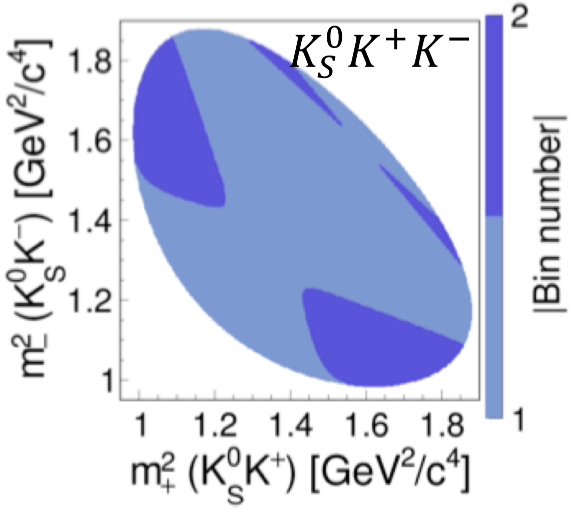
First Belle + Belle II analysis Done By Niharika Rout, Jim Libby, Karim Trabelsi

- $B^- \to D(\to K_S^0\pi^+\pi^-)K$ is golden mode at Belle II
- Sensitivity to ϕ_3 by comparing D Dalitz (fit with full amplitude model)distribution of B^- and B^+ : $$A_B = \overline{A}(m_-^2, m_+^2) + r_B e^{i(\delta_B+\phi_3)} A(m_+^2, m_-^2)$$
- Model-dependent analysis have model uncertainty up to 3° -9°
- Using binned model-independent approach
  - Optimal binning of the D Dalitz plot which gives the maximum sensitivity to ϕ_3
  - Observed yields in each bin can be related to physics parameters of interest and D^0 decay information

$$N_i^{\pm} = h_{B^\pm}\left[F_i + r_B^2 \overline{F}_i + 2\sqrt{F_i \overline{F}_i}(c_i x_\pm + s_i y_\pm)\right].$$

- $h_{B^\pm}$:Normalization constant
- Physics parameters of interest: $(x_\pm,\ y_\pm) = r_B(\cos(\phi_3 + \delta_B),\ \sin(\phi_3 \pm \delta_B))$
- Amplitude-averaged strong phase difference between $\overline{D^0}$ and D^0 over i^{th} bin and are obtained from external charm factories like CLEO and BESIII
- Fraction of pure D^0 decay to bin i taking into account the reconstruction and selection efficiency





BPGGSZ Method Study of $B^- \to D(\to K_S^0 h^+ h^-)h^-$

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$h = \pi, K$

First Belle + Belle II analysis Done By Niharika Rout, Jim Libby, Karim Trabelsi

- Analysis with $711 fb^{-1}$ Belle data and $128 fb^{-1}$ Belle II data

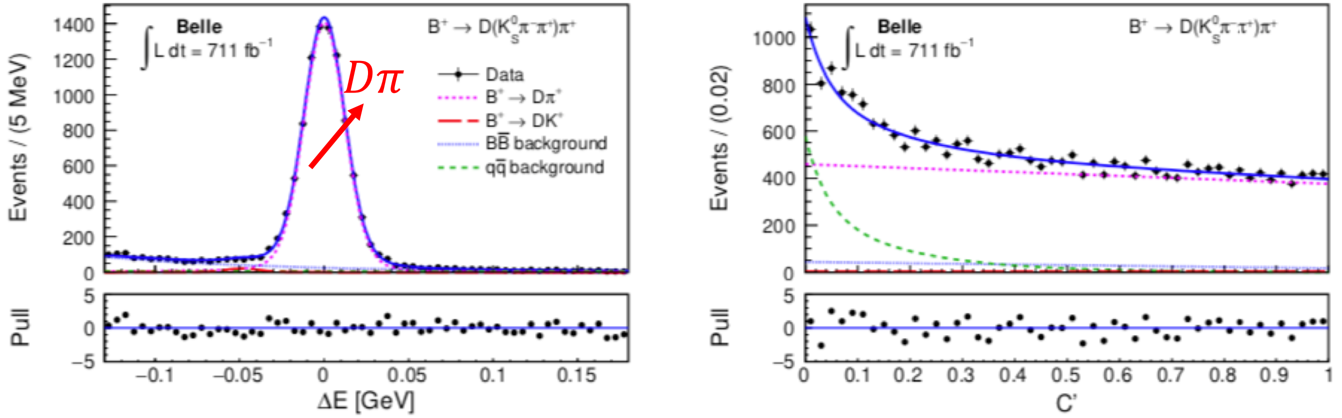
- Unbinned 2D simultaneous fit of ΔE versus C' (right plot) for $B^- \to D^0(K_S^0\pi^+\pi^-)K^-$.

Component	PDF (ΔE)	PDF ($\mathrm{FBDT_{trans}}$)
Signal	DG + Bifur-Gaus	poly (1st)
$B\bar{B}$ bkg	expo +(poly)	Chebychev poly-1st(2nd)
$q\bar{q}$ bkg	Chebychev poly (1st)	2 expo
DK ($D\pi$) component	DG + Bifur-Gaus	Chebychev poly (1st)

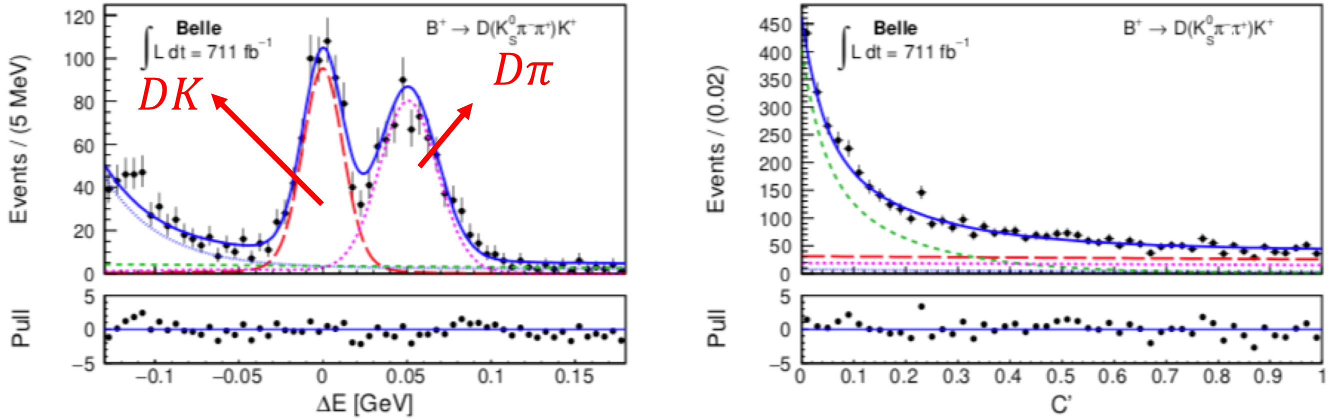
- Performed simultaneous fit in 160 categories; 80(16×4 + 4×4) of Belle and 80 of Belle II
- Signal region :
  - $|\Delta E| < 0.05\ GeV$
  - $0.65 < C' < 1.0$

$(x_\pm, y_\pm) = r_B(\cos(\phi_3 + \delta_B), \sin(\phi_3 \pm \delta_B))$ are common to all the bins and are extracted from the fit

pion enhanced $\mathcal{L}(K/\pi) < 0.6$



kaon enhanced $\mathcal{L}(K/\pi) > 0.6$



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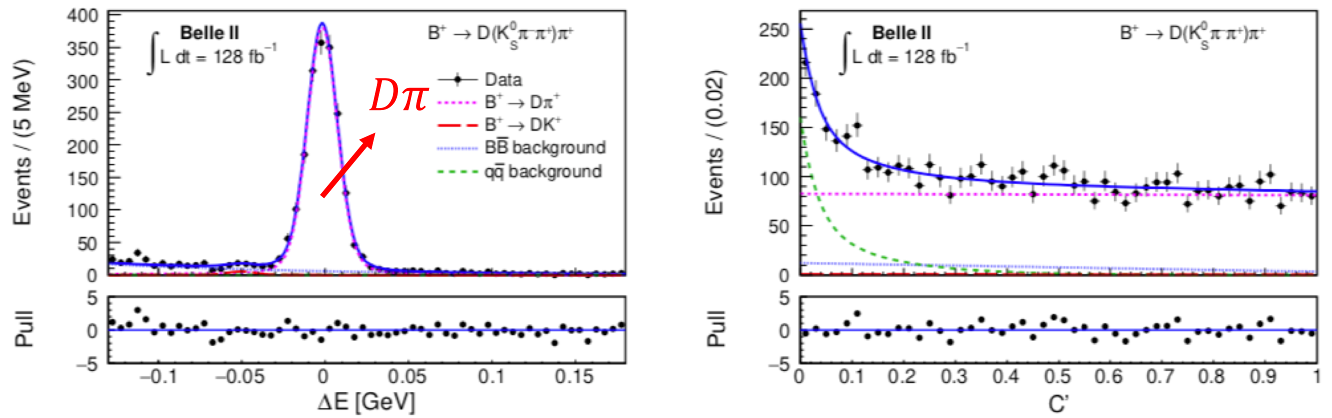
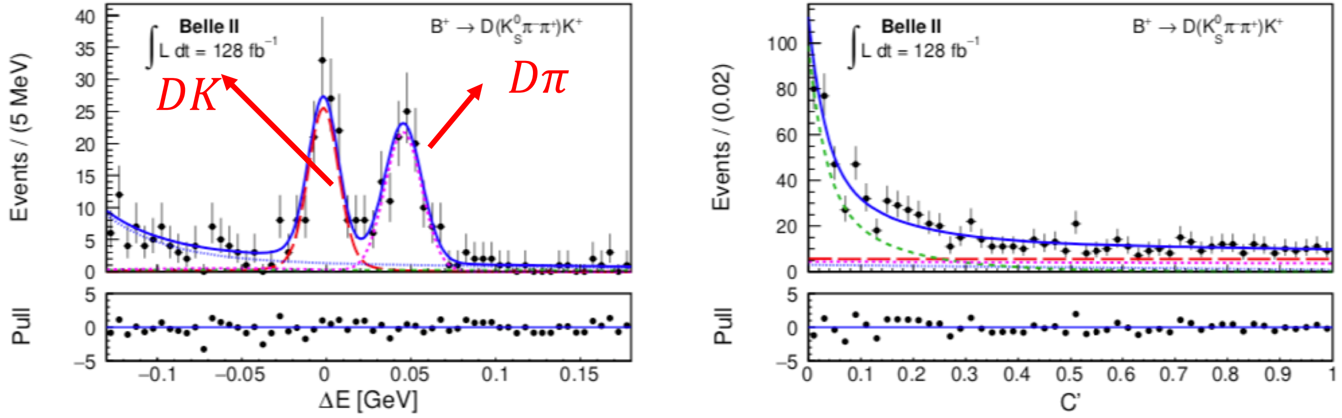


kaon enhanced $\mathcal{L}(K/\pi)$>0.6



BPGGSZ Method Study of $B^- \to D(\to K_S^0 h^+ h^-) h^-$

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$h = \pi, K$

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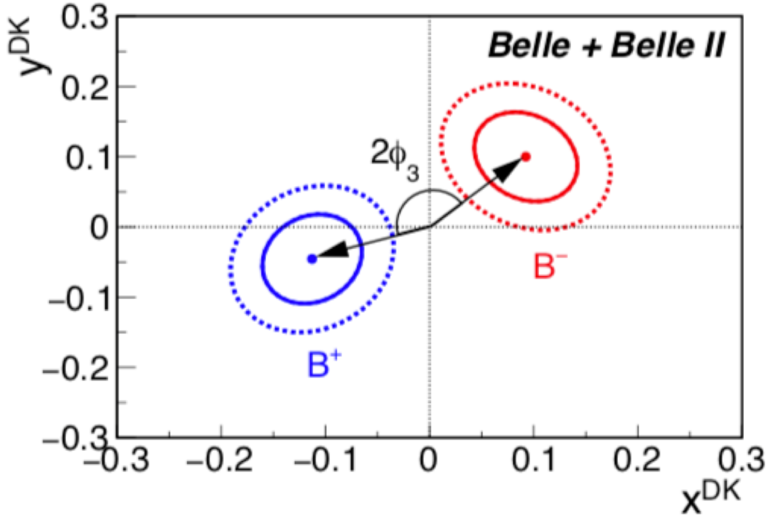
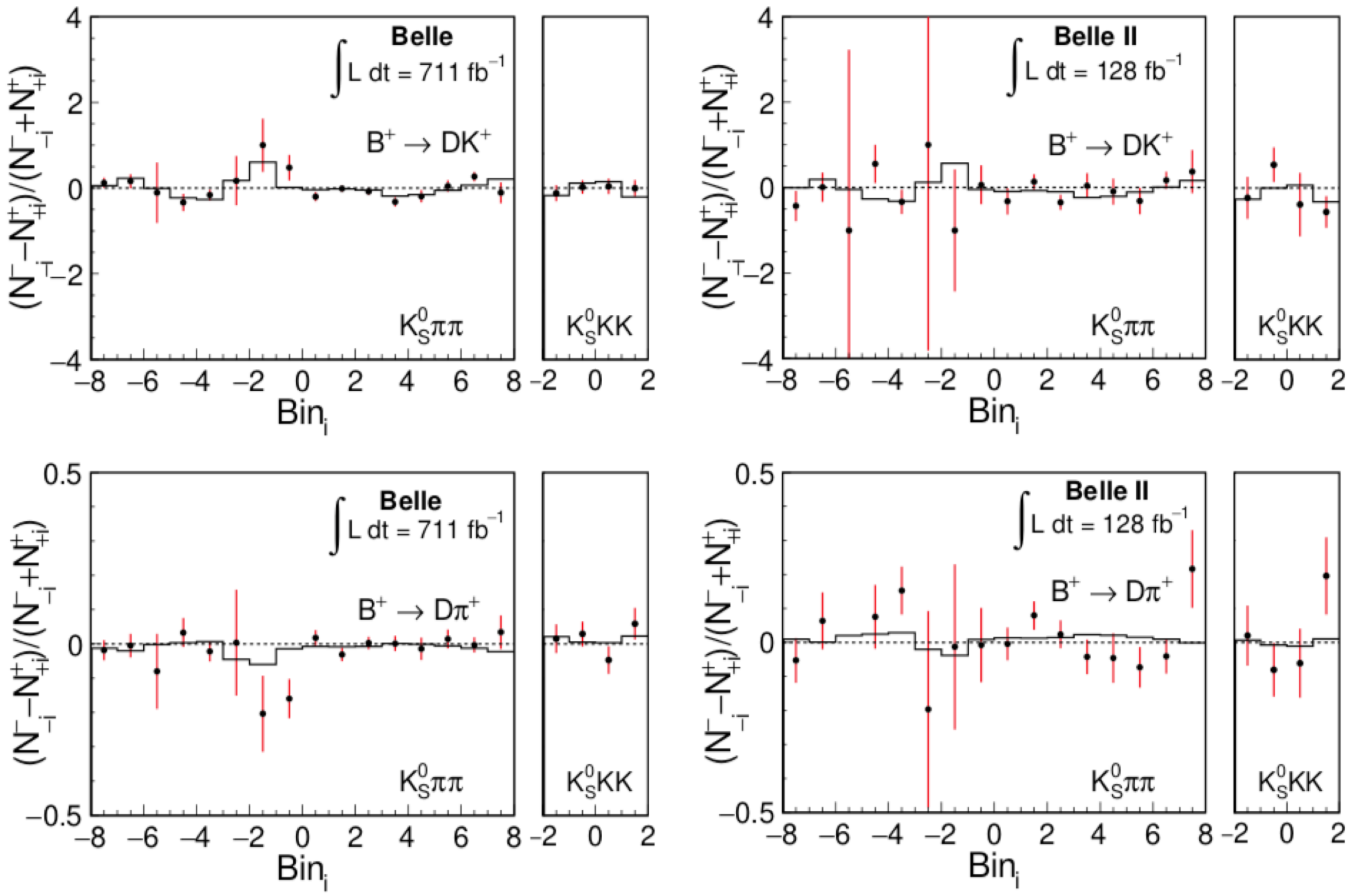


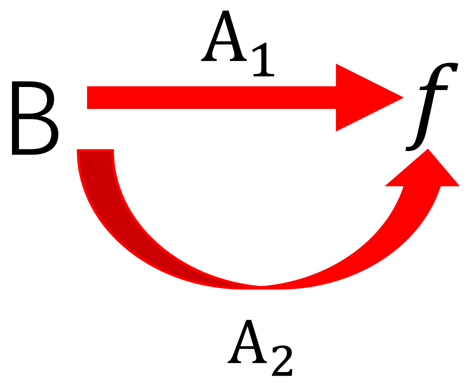


Uncertainty ~14° in earlier Belle measurement
PhysRevD.85.112014

- Preliminary result :

$\delta_B(°)$ = 124.8 ± 12.9 (stat.) ± 0.5 (syst.) ± 1.7 (ext. input)
r_B^{DK} = 0.129 ± 0.024 (stat.) ± 0.001 (syst.) ± 0.002 (ext. input)
$\phi_3(°)$ = 78.4 ± 11.4 (stat.) ± 0.5 (syst.) ± 1.0 (ext. input)

GLW Method of $B^- \to D_{CP} h^-$ $\quad h = \pi, K$



$A(B \to f) = A = A_1 + A_2$
$A(\bar{B} \to \bar{f}) = \bar{A} = \bar{A}_1 + \bar{A}_2$

$A_1 = |A_1|$, $A_2 = |A_2| e^{i\delta} e^{i\phi}$ $\xrightarrow{CP}$ $\bar{A}_1 = |A_1|$, $\bar{A}_2 = |A_2| e^{i\delta} e^{-i\phi}$

- Using CP eigenstates mode of K^+K^-(CP+), $K_s^0\pi^0$(CP-)
- D_{CP} modes interference => relate with ϕ_3

$$A_{CP\pm} = \frac{\Gamma[B^- \to D_{CP}K^-] - \Gamma[B^+ \to D_{CP}K^+]}{\Gamma[B^- \to D_{CP}K^-] + \Gamma[B^+ \to D_{CP}K^+]} = \pm \frac{2r_B sin\delta_B sin\phi_3}{1 + r_B^2 \pm 2r_B cos\delta_B cos\phi_3}$$

$$R_{CP\pm} = \frac{R^{D_{CP\pm}}}{R^{D^0}} = 1 + r_B^2 \pm 2r_B cos\delta_B cos\phi_3$$

- $B^- \to D^0(K^-\pi^+)h^-$ as control modes to obtain R^{D^0}
- Related measurements listed on HFLAV

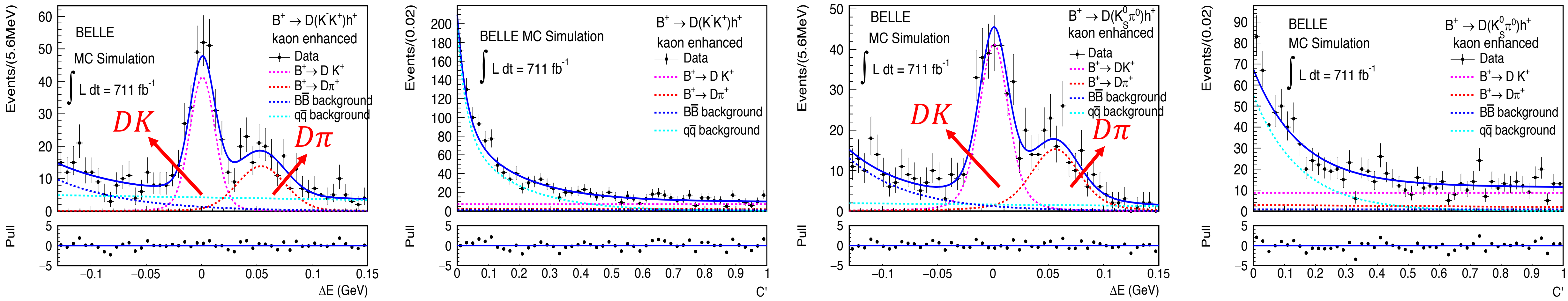
Experiment	A_{CP+}	A_{CP-}	R_{CP+}	R_{CP-}	
BaBar N(BB)=467M	0.25 ± 0.06 ± 0.02	−0.09 ± 0.07 ± 0.02	1.18 ± 0.09 ± 0.05	1.07 ± 0.08 ± 0.04	PRD 82 (2010) 072004
Belle (*) N(BB)=275M	0.06 ± 0.14 ± 0.05	−0.12 ± 0.14 ± 0.05	1.13 ± 0.16 ± 0.08	1.17 ± 0.14 ± 0.14	PRD 73 (2006) 051106
CDF ∫Ldt=1 fb^{-1}	0.39 ± 0.17 ± 0.04	-	1.30 ± 0.24 ± 0.12	-	PRD 81 (2010) 031105(R)
LHCb ∫Ldt=8.7 fb^{-1}	0.136 ± 0.009 ± 0.001	-	0.950 ± 0.009 ± 0.010	-	JHEP 2104 (2021) 081

CP only accessible in B Factory

Previous Belle measurement with 200 fb^{-1} (~similar size as Belle II data today)

2D Simultaneous Fit of $B^- \to D_{CP} h^-$

- Signal enhanced fit : -0.05<ΔE <0.05 & C'>0.4



- Concerning fit results (13 observables and 55 free fit parameters)

Parameters(%)	R^{D^0}	$R^{D_{cp+}}$	$R^{D_{cp-}}$	A^K_{D0}	A^π_{D0}	A^K_{Dcp+}	A^π_{Dcp+}	A^K_{Dcp-}	A^π_{Dcp-}
MC Input	8.264	8.264	8.264	0	0	0	0	0	0
Stream 3	8.38±0.15	7.72±0.58	7.96±0.58	-2.40±1.72	-0.38±0.43	9.50±6.80	-0.73±1.55	0.53±6.02	0.17±1.36

→ Uncertainty of $A_{CP\pm}$ ~6%

ϕ_3 Sensitivity

$B^- \to D(K_S^0\pi^+\pi^+)h^-$ Mode

$x_\pm = r_B \cos(\delta_B \pm \phi_3)$

$y_\pm = r_B \sin(\delta_B \pm \phi_3)$

$\Rightarrow$ Measurement

parameter	value
x_+	-0.1194±0.0346
x_-	0.0945±0.0360
y_+	-0.0634±0.0473
y_-	0.1192±0.0467

arXiv:2110.12125

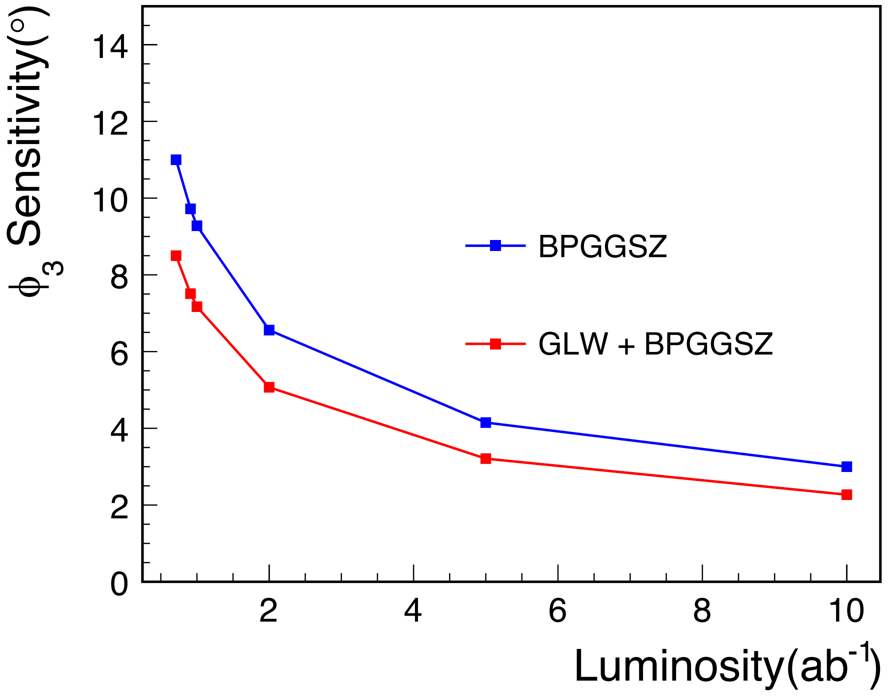
$\Rightarrow$ ϕ_3 Uncertainty ~10.7°
$\Rightarrow$ Result from analysis: ~11.0°
$\Rightarrow$ Estimation method is valid

GLW Method

$$x_\pm = r_B \cos(\delta_B \pm \phi_3) = \frac{R_1(1 \mp A_1) - R_2(1 \mp A_2)}{4}$$

parameter	Uncertainty from one stream MC
R_1	±0.0058
A_1	±0.0690
R_2	±0.0057
A_2	±0.0650

$\Rightarrow$ ϕ_3 Uncertainty ~13°



GLW+ $B^- \to D(K_S^0\pi^+\pi^+)K^-$ one stream Belle MC
$\Rightarrow$ ϕ_3 Uncertainty ~9° (will investigate further)

Summary

- Determination of CKM angle ϕ_3 is important and Belle II provides a good opportunity to extract it with high precision

- Belle II analysis of $B \to D^{(*)}h$ is done with Cabibbo favored modes to valid the performance of 62.8 fb^{-1} Belle II data arXiv:2104.03628
  →Performance of Belle II at this stage is similar to Belle

- Determination of ϕ_3 from the combined result of Belle + Belle II of $B^- \to D^0(K_S^0 h^+ h^-)K^-$ is submitted to JHEP and are available on arXiv.org https://arxiv.org/abs/2110.12125

- GLW method with final states K^-K^+, $K_S^0\pi^0$ modes is being analyzed with Belle and Belle II data samples (summer 2022). Simultaneously fitting with 6 modes to extract the signal and concerning observables.

- We estimated the GLW+BPGGSZ sensitivity of ϕ_3 ~ 9°(0.711 ab^{-1}) , ~ 2°(10 ab^{-1})