

# Measurement of the CKM angle $\phi_3$ at Belle II

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*Krakow, Poland*

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# Outline of the talk

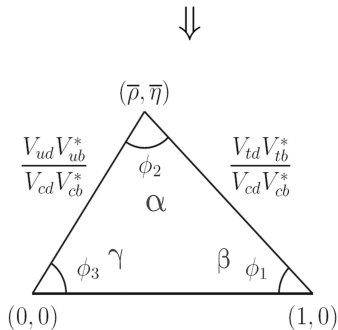
- Introduction
  - CKM matrix
  - Current experimental status of parameters
- CKM angle  $\phi_3/\gamma$ 
  - Estimation
  - Different methods
  - World average values
- Status of Belle II experiment
- $\phi_3$  sensitivity at Belle II
- Summary

# Introduction

- The CKM matrix is of the form

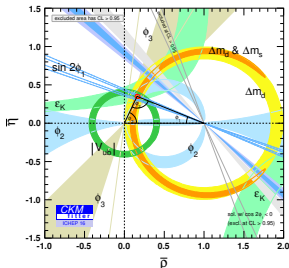
$$\begin{pmatrix} & \mathbf{d} & \mathbf{s} & \mathbf{b} \\ \mathbf{u} & \blacksquare & \blacksquare & \blacksquare \\ \mathbf{c} & \blacksquare & \blacksquare & \blacksquare \\ \mathbf{t} & \blacksquare & \blacksquare & \blacksquare \end{pmatrix}$$

- Unitarity conditions between 1<sup>st</sup> and 3<sup>rd</sup> columns

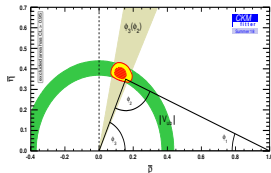


- $CP$  violation is measured as the complex phase coming in CKM elements  $V_{ub}$  and  $V_{td}$ .
- A precise measurement required to establish SM description of  $CP$  violation.

# CKM parameters - current status



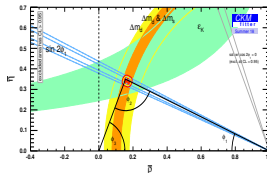
Constraints on CKM parameters [1].



Constraints from tree quantities.

## Current best results for CKM angles [1,2]

- $\phi_1^{\text{measured}} = (21.9^{+0.7}_{-0.7})^\circ$
- $\phi_3^{\text{measured}} = (73.5^{+4.2}_{-5.1})^\circ$
- $\phi_3^{\text{predicted}} = (65.3^{+1.0}_{-1.7})^\circ$



Constraints from loop quantities.

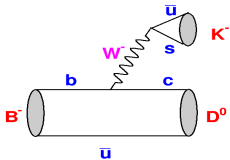
<sup>1</sup> <http://ckmfitter.in2p3.fr>

<sup>2</sup> <http://www.slac.stanford.edu/xorg/hflav/triangle/moriond2018/index.shtml>



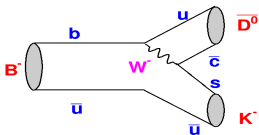
# $\phi_3$ measurements from $B \rightarrow DK$ decays

- Determine  $\phi_3$  via interference between  $B^- \rightarrow D^0 K^-$  and  $B^- \rightarrow \bar{D}^0 K^-$ , tree-level diagrams  $\Rightarrow 10^{-7}$  theoretical uncertainty [3].



colour allowed

$$B^- \rightarrow D^0 K^- \approx V_{cb} V_{us}^* A_1$$



colour suppressed

$$B^- \rightarrow \bar{D}^0 K^- \approx V_{ub} V_{cs}^* A_1 r_B e^{i(\delta_B - \phi_3)}$$

- Statistically limited due to small branching fractions of decays involved.
- The statistical uncertainty on  $\phi_3 \propto r_B$ .
- $r_B^{DK} \approx 0.1$  and  $r_B^{D\pi} \approx 0.005$ ; So  $B \rightarrow D\pi$  decays are not sensitive!
- But they serve as excellent calibration modes due to similar topology as of  $B \rightarrow DK$ . Larger sample ( $\frac{B(B \rightarrow D\pi)}{B(B \rightarrow DK)} \approx 10$ ) due to Cabibbo-favoured nature.

<sup>3</sup>J. Brod, J. Zupan, JHEP 01, 051 (2014)

# Primary methods

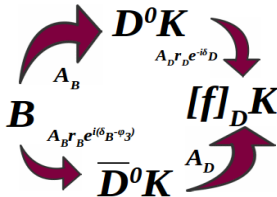
- The methods differ according to the  $D$  final state considered.

## GLW PLB 253, 483 (1991), PLB 265, 172 (1991)

- $CP$  eigenstates like  $K^+K^-$ ,  $\pi^+\pi^-$ ,  $K_S^0\pi^0$  etc.
- $CP$ -content as external input for multibody decays like  $\pi^+\pi^-\pi^0$ .

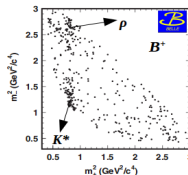
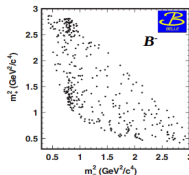
## ADS PRL 78, 3357 (1997)

- DCS modes  
 $K^+\pi^-$ ,  $K^+\pi^-\pi^0$ ,  $K^+\pi^-\pi^+\pi^-$
- $\delta_D$ ,  $r_D$  - charm inputs.



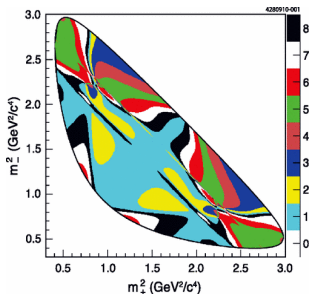
## GGSZ PRD 68, 054018 (2003)

- Multibody self-conjugate states
- Model-dependent and independent approaches



# Model-independent method

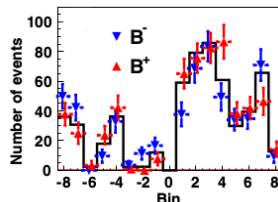
- Model-independent method by binning the Dalitz plot of multibody  $D$  final states like  $K_S^0 \pi^+ \pi^-$ ,  $K_S^0 K^+ K^-$ ,  $K_S^0 \pi^+ \pi^- \pi^0$ .



Dalitz plot binning for  $K_S^0 \pi^+ \pi^-$ .

PRD82, 112006(2010)

- For the decay  $B^- \rightarrow D(K_S^0 h^+ h^-) K^-$ ,  $\Gamma_i^- = K_i + r_B^2 \bar{K}_i + 2\sqrt{K_i \bar{K}_i}(c_i x_- + s_i y_-)$ , and similarly for the  $B^+$  decay.



$B^+$  and  $B^-$  yields for  $D$  final state  $K_S^0 \pi^+ \pi^-$  at Belle.

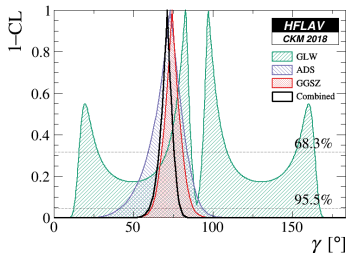
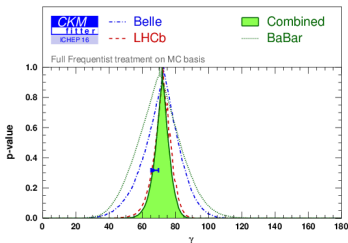
PRD85, 112014(2012)

- $x_{\pm} = r_B \cos(\delta_B \pm \phi_3)$ ;  $y_{\pm} = r_B \sin(\delta_B \pm \phi_3)$ .
- $c_i, s_i$  - cos and sin of the strong phase difference between  $D^0$  and  $\bar{D}^0$  averaged over the region of phase space  $\Rightarrow$  input from CLEO-c or BESIII.
- $K_i, \bar{K}_i$  - fraction of flavour-tagged  $D^0$  and  $\bar{D}^0$  events from  $D^{*\pm} \rightarrow D\pi^{\pm}$  decays.

# $\phi_3$ : Average values

- From all measurements of  $B \rightarrow D^{(*)}K^{(*)}$  from GLW, ADS, and GGSZ.

## Belle + BaBar + LHCb run I



$$(\phi_3)_{\text{Belle}} = (73_{-15}^{+13})^\circ [4]$$

$$(\phi_3)_{\text{BaBar}} = (69_{-16}^{+17})^\circ [5]$$

$$(\phi_3)_{\text{LHCb}} = (74.0_{-5.8}^{+5.0})^\circ [6]$$

- Dominated by LHCb result and GGSZ method.

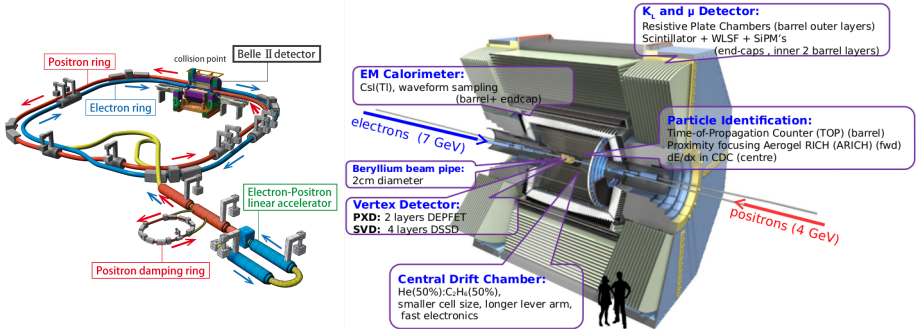
$$(\phi_3)_{\text{Combined}} = (73.5_{-5.1}^{+4.2})^\circ$$

<sup>4</sup> PRD **85**, 112014 (2012)

<sup>5</sup> PRD **87**, 052015 (2013)

<sup>6</sup> LHCb-CONF-2018-002

# SuperKEKB and Belle II experiment



- Center-of-mass energy at  $\Upsilon(4S)$  resonance which decays to  $B\bar{B}$  pair.

## Important improvements for $\phi_3$

- Improved  $K_S^0$  reconstruction efficiency
- Better  $K/\pi$  separation

# Status of Belle II

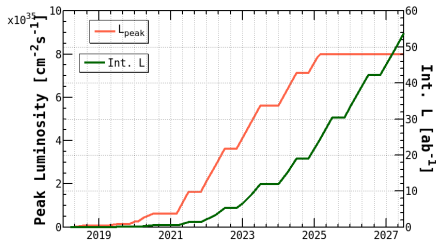
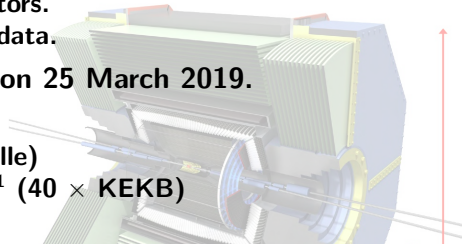
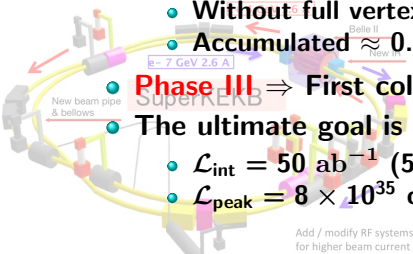
- **Phase II**  $\Rightarrow$  25 April to 17 July 2018.

- Without full vertex detectors.
- Accumulated  $\approx 0.5 \text{ fb}^{-1}$  data.

- **Phase III**  $\Rightarrow$  First collisions on 25 March 2019.

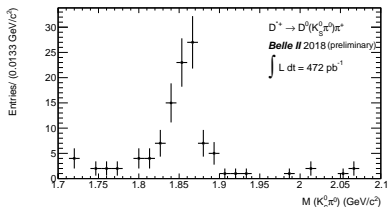
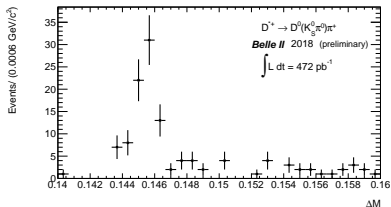
- The ultimate goal is

- $\mathcal{L}_{\text{int}} = 50 \text{ ab}^{-1}$  ( $50 \times \text{Belle}$ )
- $\mathcal{L}_{\text{peak}} = 8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$  ( $40 \times \text{KEKB}$ )

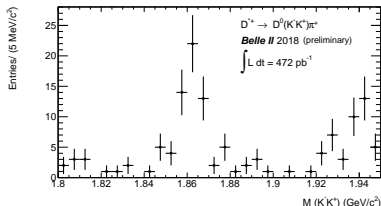
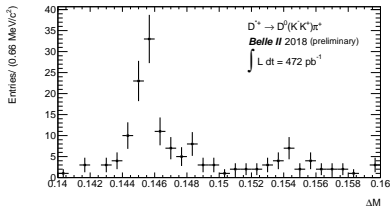


# Results from phase II

- $D^{*\pm} \rightarrow D(K_S^0 \pi^0) \pi_{\text{slow}}^{\pm}$  decays :  $CP$ -odd eigenstate



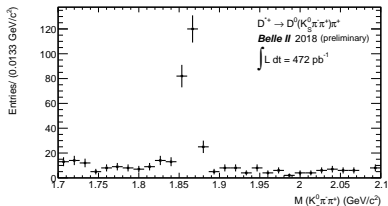
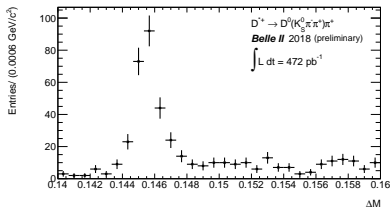
- $D^{*\pm} \rightarrow D(K^+ K^-) \pi_{\text{slow}}^{\pm}$  decays :  $CP$ -even eigenstate



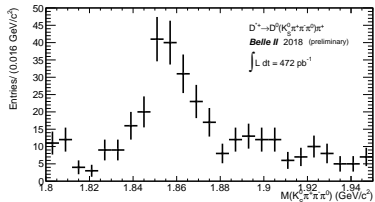
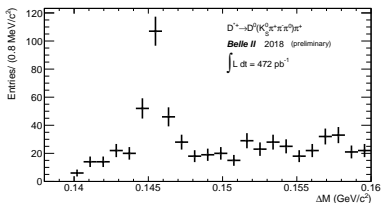
- Belle II is capable of reconstructing a variety of final states including neutrals.

# Results from phase II

- $D^{*\pm} \rightarrow D(K_S^0 \pi^+ \pi^-) \pi_{\text{slow}}^\pm$  decays



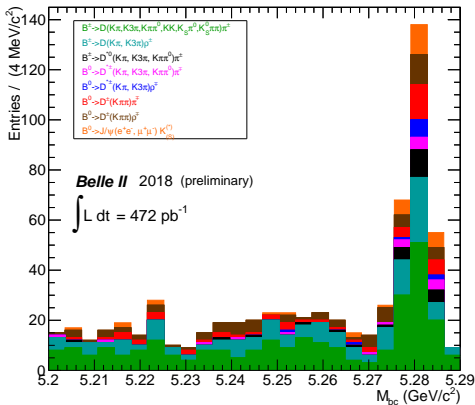
- $D^{*\pm} \rightarrow D(K_S^0 \pi^+ \pi^- \pi^0) \pi_{\text{slow}}^\pm$  decays



- Multibody self-conjugate final states, important for  $\phi_3$  estimation.



# B mesons in phase II data



- About 245  $B$  candidates reconstructed from hadronic final states.

## ARGUS Results on $B$ Decays via $b \rightarrow c$ Transitions

Henning Schröder  
 DESY, Hamburg, Germany

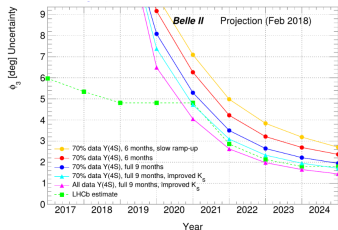
### ABSTRACT

Using the ARGUS detector at the  $e^+e^-$  storage ring DORIS II at DESY new results on beauty physics have been obtained. About 280  $B$  mesons have been reconstructed in 26 hadronic decay modes. The masses and lifetimes of charged and neutral  $B$  mesons are the same within the errors. Fast  $J/\psi$  mesons ( $1.4 < p^* < 2.0 \text{ GeV}/c$ ) in  $B$  decays have helicity 0. An indication of non- $J/\psi$  decays of the  $T(45)$  into  $J/\psi$  mesons is shown.

- $B \rightarrow D\pi$  decays are good calibration modes for  $\phi_3$  estimation from  $B \rightarrow DK$  decays.

# $\phi_3$ sensitivity at Belle II

- $B^\pm \rightarrow D(K_S^0 \pi^+ \pi^-) K^\pm$  : golden mode at Belle II.
- $\delta(\phi_3)^{50 \text{ ab}^{-1}} = 3.0^\circ$  (with  $10 \text{ fb}^{-1}$  BESIII data)
- $B^\pm \rightarrow D(K_S^0 \pi^+ \pi^- \pi^0) K^\pm$  : another promising mode.
- $\delta(\phi_3)^{50 \text{ ab}^{-1}} = 4.4^\circ [7]$  (Assuming  $\epsilon \times BF$  similar to  $K_S^0 \pi^+ \pi^-$ ).

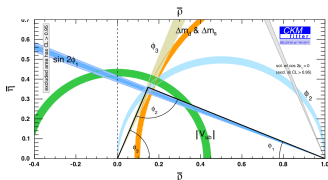


- The GLW modes from  $B \rightarrow D^{(*)} K$  also has significant impact on the projected uncertainty.

- Better PID,  $K_S^0$  selection, continuum suppression would bring further improvements.

<sup>7</sup> JHEP 01, 82 (2018)

- Current precision on average value of  $\phi_3$  is  $\approx 5^\circ$ .
- Precise measurement is crucial for establishing SM picture of  $CP$  violation.
- A combined sensitivity of  $1.6^\circ$  is expected with
  - full  $50 \text{ ab}^{-1}$  data,
  - additional  $D^{(*)}$  modes.
- Measurements of  $D$  hadronic parameters from  $10 \text{ fb}^{-1}$  BESIII data is crucial.



Expected precision on CKM parameters with  $50 \text{ ab}^{-1}$  Belle II data<sup>[8]</sup>.

<sup>8</sup>B2TIP report arXiv:1808.10567 [hep-ex]