Measurement of CKM angle ϕ_3 at Belle II

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Conference on Flavor Physics and CP Violation

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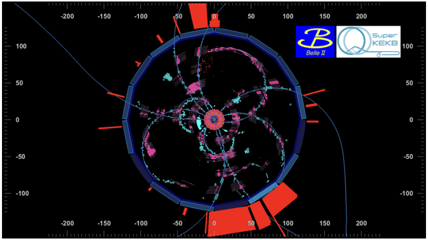
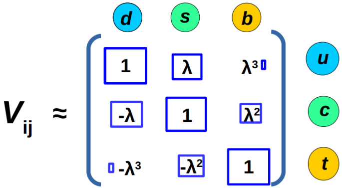


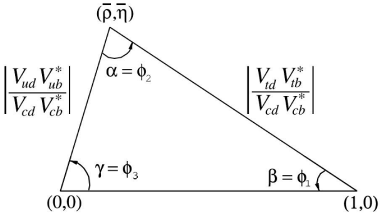
Outline

1. Introduction
2. Current status of CKM parameters
3. Extraction of ϕ_3 from $B^{\pm} \to D^{(*)}K^{(*)\pm}$
4. Belle II outlook
5. Future prospects
6. Summary



λ ≈ 0.22 : Cabbibo angle

Unitarity condition $\Longrightarrow$ ($1^{\rm st} \leftrightarrows 3^{\rm rd}$)



Measuring SM *CP* violation $\Rightarrow$ Measure complex phase of CKM elements.

$$\phi_1/\beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\phi_2/\alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

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

- Definition of ϕ_3 does not depend on coupling to top quark.
  - Thus measurable via **tree level decays** $\Rightarrow$ **theoretically cleaner** [$\mathcal{O}(10^{-7})$] [1].
- Precise measurement provides SM benchmark.

[1] J. Brod, J. Zupan, arxiv:1308.5663

Current status of CKM parameters

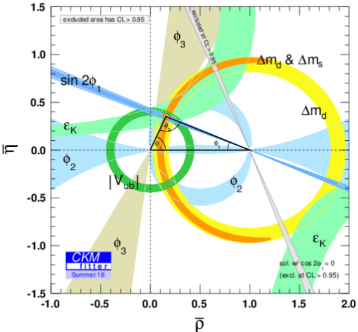


Figure : Constraints on CKM parameters [2]

Direct measurements

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

Indirect extrapolation

$$(\phi_3)^{\text{combined}} = (65.3^{+1.0}_{-2.5})^\circ$$

- **ϕ_3 is an excellent probe to NP.**
  - Testing of direct vs indirect disagreement.
  - Need to improve precision on direct measurement.

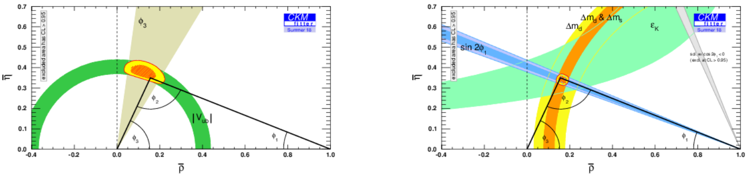
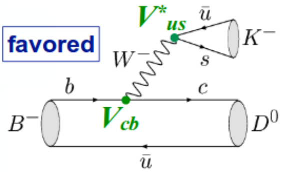


Figure : Constraints on "tree-level" processes (left) and "loop-level" processes (right)

[2]Image source: http://ckmfitter.in2p3.fr/

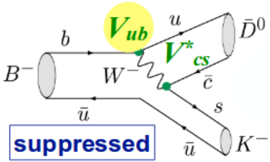
- ϕ_3: Only CKM angle accessible at tree level.
- Sensitivity to ϕ_3 arises from the interference of $b \to u$ and $b \to c$ quark transitions.
- Classic mode: $B^{\pm} \to DK^{\pm}$.
- Interference occurs when D^0 and $\overline{D}^0$ decay to the same final state f.

$B^- \to D^0 K^-$



A_1

$B^- \to \overline{D}^0 K^-$



$A_1 r_B e^{i(\delta_B - \gamma)}$

- $r_B = |\frac{A_{\rm sup}}{A_{\rm fav}}| \sim |\frac{V_{\rm ub} V^*_{\rm cs}}{V_{\rm cb} V^*_{\rm us}}| \times C_{\rm colorSupp} \sim 0.1$ for $B^{\pm} \to DK^{\pm}$ decays [3].
- δ_B is the strong phase difference between favoured and suppressed modes; ϕ_3 is the weak phase.

[3] HFLAV16, Y. Amhis *et al.* (Heavy Flavor Averaging Group), Eur. Phys. J. C **77** (2017)895 [arXiv:1612.07233 [hep-ex]]

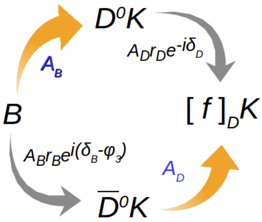
Common final states: primary methods

GLW [Phys. Lett. B **253**, 483]

- Both D^0 and $\overline{D^0}$ decays to same CP eigenstates such as $K^+K^-, \pi^-\pi^+$ (CP-even), $K_S^0\pi^0$ (CP-odd).
- 4 observables ($R_{CP\pm}, A_{CP\pm}$)
- No need of external inputs.

ADS [Phys. Rev. Lett. **78**, 3257]

- D from a favoured amplitude decays to a doubly-Cabibbo-suppressed state.
- 2 Observables (R_{ADS}, A_{ADS})
- External charm factory inputs (r_D and δ_D).



parameters to extract: ϕ_3 , r_B and δ_B

GGSZ [Phys. Rev. D **68**, 054018]

- Uses multi-body $D(K_S^0h^-h^+)$ final states.
- Sensitivity to ϕ_3 by comparing D Dalitz distributions for B^+ and B^-
- Fit D Dalitz plot with full amplitude model.

  $$A_B = \overline{A}(m_-^2, m_+^2) + r_B e^{i(\delta_B+\phi_3)} A(m_+^2, m_-^2)$$

- $m_\pm^2$ = squared invariant masses of $K_S^0h^\pm$: D Dalitz plot variables.

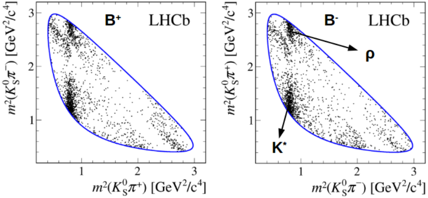


Figure : Dalitz plots of $B^+ \to DK^+$ (left) and $B^- \to DK^-$ (right) arXiv:1806.01202v1 [hep-ex]

GGSZ: Binned model-independent approach

- Optimal binning of the D Dalitz plot which gives the maximum sensitivity to ϕ_3.
- Number of events in i^{th} bin is a function of $x_\pm/y_\pm$:

$$N_i^\pm = h_B[K_{\pm i} + r_B^2 K_{\mp i} + \sqrt{K_i K_{-i}}(x_\pm c_i \pm y_\pm s_i)].$$

  - h_B: Normalization constant. K_i: Number of events in the i^{th} bin of a flavour tagged D decay (obtained using a sample of $D^{*\pm} \to D\pi^\pm$ decays).
  - Fit simultaneously in each bin,

$$\boxed{(x_\pm, y_\pm) = r_B(\cos(\pm\phi_3 + \delta_B), \sin(\pm\phi_3 + \delta_B))}$$

  - c_i and s_i: 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*.

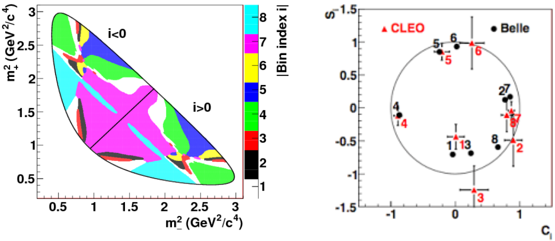
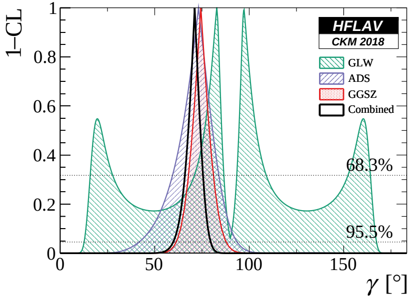


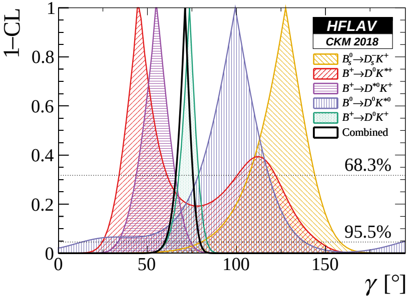
Figure : Optimal binning of D Dalitz plot and comparison of phase terms c_i, s_i measured by CLEO and Belle [4]

[4] Phys. Rev. D **85**, 112014 (2012)

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

(Belle + BaBar + LHCb)





$$(\phi_3)^{\text{combined}} = (73.5^{+4.2}_{-5.1})^\circ$$ [8]

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

$$(\phi_3)^{\text{BaBar}} = (69^{+17}_{-16})^\circ$$ [6]

$$(\phi_3)^{\text{LHCb}} = (74^{+5.0}_{-5.8})^\circ$$ [7]

6 [PRD 87 052015 (2013)]

7 [LHCb-CONF-2017-004]

8 http://www.slac.stanford.edu/xorg/hflav/triangle/moriond2018/index.shtml

Belle II @SuperKEKB

- **Super KEKB**: 4 GeV e^+ and 7 GeV e^- asymmetric collider at KEK, Japan.
- **Belle II detector** is at the interaction point.
- The center-of-mass energy is close to the mass of $\Upsilon(4S)$, which decays to $B\overline{B}$ pair.

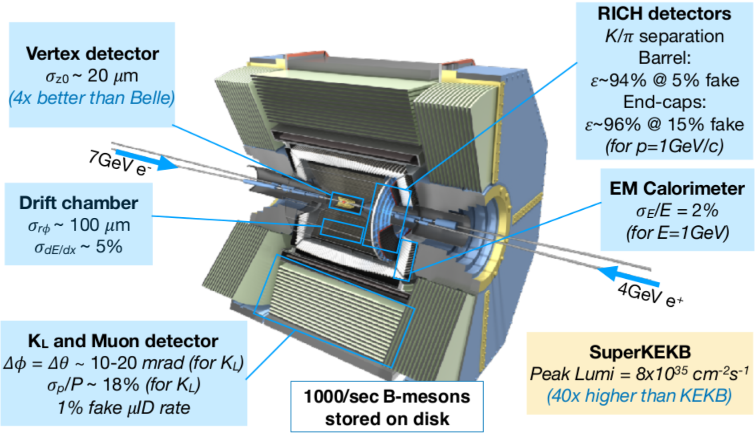


Figure : Belle II detector [9]

[9] Image source: PoS EPS-HEP2017 (2017) 223

- **Phase I** (complete)
  - Accelerator commissioning with single beam.
- **Phase II** (complete)
  - Taken data with partial detector (with small part of vertex detector).
  - Accumulated $\sim$ **0.5** $\mathbf{fb^{-1}}$ data.
  - Physics studies are going on.
- **Phase III** ("Run I" started)
  - SuperKEKB became operational on March 11$^{\text{th}}$ for phase III data taking.
  - First collision was on March 25$^{\text{th}}$.
- **Ultimate goal: 50** $\mathbf{ab^{-1}}$

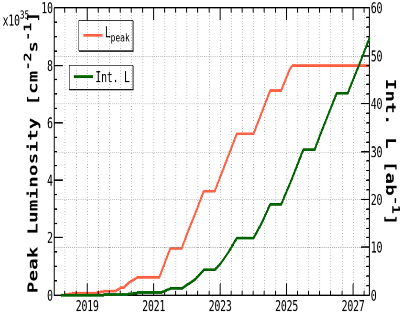
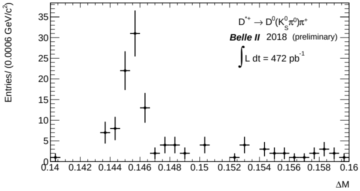
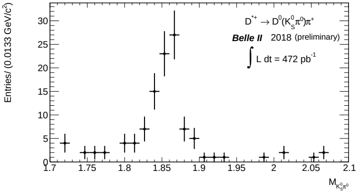


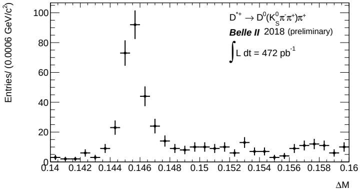
Figure : **SuperKEKB luminosity projection**

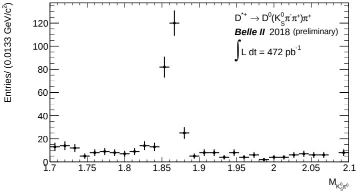
- $\mathbf{D^{*\pm} \to D^0(K^0_S\pi^0)\pi^\pm}$





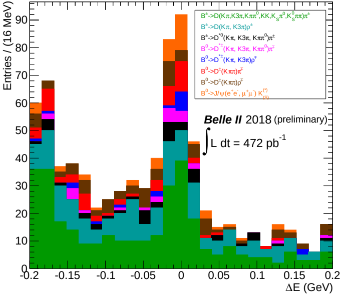
- $\mathbf{D^{*\pm} \to D^0(K^0_S\pi^+\pi^-)\pi^\pm}$

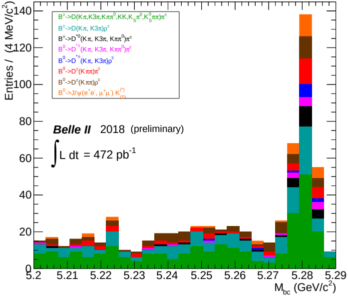




- Better reconstruction, selection and tagging algorithm.
- Improved PID performance.
- Good neutral (K^0_S, π^0) reconstruction efficiency.

- $M_{\mathrm{bc}} = \sqrt{E_{\mathrm{beam}}^2 - (\Sigma \vec{p_i})^2}$, $M_{\mathrm{bc}} > 5.27\ \mathrm{GeV/c^2}$, $\Delta E = \Sigma E_i - E_{\mathrm{beam}}$, $|\Delta E| < 0.05\ \mathrm{GeV}$.





More than 200 B candidates from hadronic modes!!

ARGUS Results on B Decays via b -» C Transitions

Henning Schroder
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/^ mesons (1.4< pj^ < 2.0 GeV/c) in B decays have helicity 0. An indication of non-jBB decays of the T(45) into J/t/> mesons is shown.

- ADS, GLW and GGSZ can all be reproduced at Belle II.
- Ongoing analyses (D final states)
  - $KK, \pi\pi$: CP-even.
  - $K_S^0\pi^0$: CP-odd.
  - $K_S^0\pi\pi$: GGSZ
- Need to focus on:
  - PID improvements.
  - Continuum suppression.
  - Tracking, K_S^0 selection.

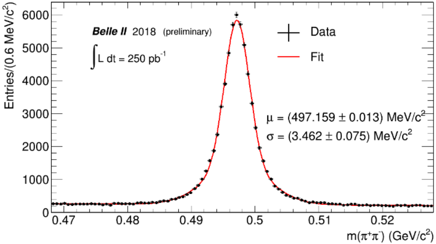
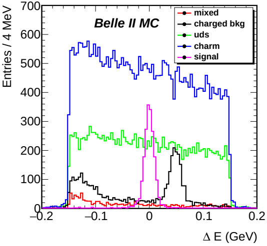
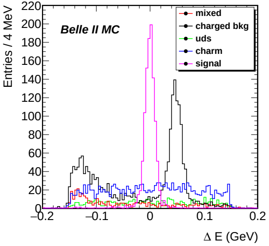


Figure : K_S^0 **reconstruction at Belle II**



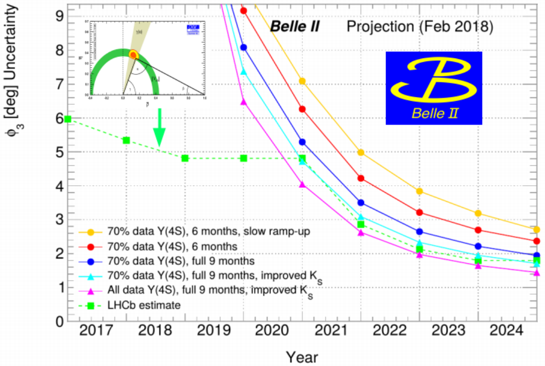
Continuum suppression $\Longrightarrow$

95% bkg rej
30% sig loss



Future prospects

- Expect Belle II and LHCb upgrade to match each other's performance!
- $\delta(\phi_3) < 2^\circ$ by 2027.



- Due to Belle II unbiased trigger it will be better in Dalitz plot analysis and sensitivity to the neutrals will allow to include more D modes.
- LHCb will clearly have more precise results in fully-charged final states.

- Precision measurement of ϕ_3 is very crucial.
- **Current uncertainty on** $\phi_3 \sim 5^\circ$
- Combined sensitivity of 1.6° is expected:
  - Including more $D^{(*)}$ modes!
  - Integrated luminosity $= 50$ ab^{-1}
  - Input from *Charm* factory

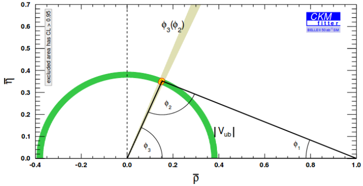


Figure : fit extrapolated to the 50 ab^{-1} for an SM-like scenario [*B2TIP report*]

- Assuming BESIII will collect 10 fb^{-1}, D^0 hadronic parameters measured at BESIII will play vital role.
- Uncertainty on indirect prediction of ϕ_3 already $\sim 1^\circ$
- Many modes can be added to improve the uncertainity.

Thank you!

Backup

ϕ_3 sensitivity studies with Belle II

- Goal is to go up-to precision $\approx 1^\circ$.
- $B^\pm \to D^0(K_S^0\pi^-\pi^+)K^\pm$: **Golden mode to determine ϕ_3!**
  - Large branching fraction involved.
  - Significant overlap between D^0 and $\overline{D^0}$ amplitudes which gives a large interference term sensitive to ϕ_3.
  - Rich resonant structure which provides large variations of the strong phase in D decay: sesnsitive to ϕ_3.
    - * GLW like states: Interference of $B^- \to DK^-$, $D \to K_S^0\rho$
    - * ADS like states: Interference of $B^- \to DK^-$, $D \to K^*\pi$

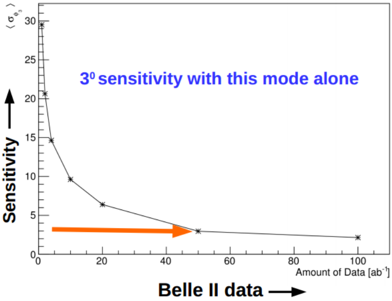


Figure : Expected uncertainty on ϕ_3 (based on toy Monte Carlo studies) versus luminosity

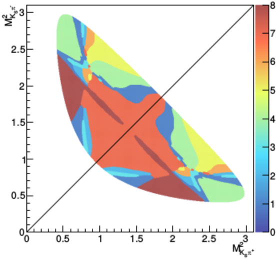
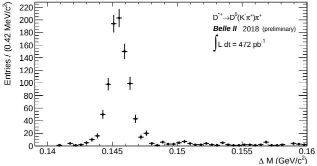
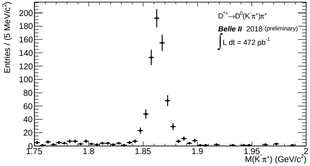


Figure : Dalitz binning used for $D \to K_S^0\pi\pi$ analysis

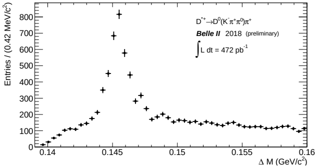
$\delta(\phi_3)^{50\mathrm{ab}^{-1}} = 1.6^\circ$ when Belle GLW + ADS + GGSZ extrapolated.

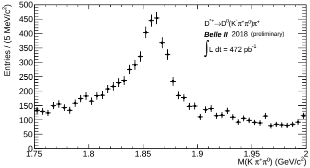
- $D^{*\pm} \to D^0(K^-\pi^+)\pi^\pm$





- $D^{*\pm} \to D^0(K^-\pi^+\pi^0)\pi^\pm$





- $D^{*\pm} \to D^0(K^-\pi^+\pi^-\pi^+)\pi^\pm$