Precision measurements of the CKM parameters (Mainly γ/ϕ_3 measurements)

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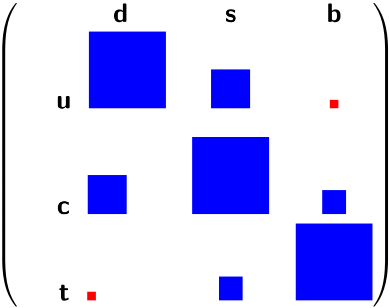
Outline of the talk

See Malcom John's plenary talk

- Status of CKM parameters
- CKM angle γ/ϕ_3
  - Methods
  - Constraints
- Belle II experiment
- ϕ_3 from Belle II
- Summary



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

Current experimental limit on CKM parameters

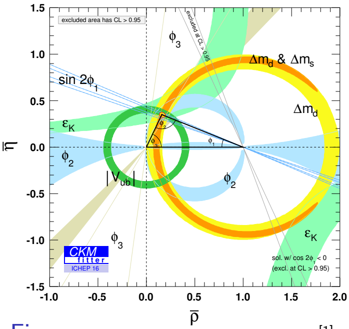
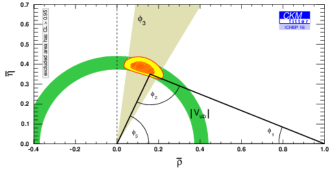
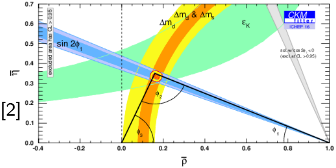


Figure: Current status of the CKM parameters[1].

Tree level only



Loop level only



- $\boldsymbol{\phi_3 = (73.5^{+4.2}_{-5.1})^\circ}$ $[\phi_1 = (21.9 \pm \mathbf{0.7})^\circ]$ [2]
- $\boldsymbol{\delta(\phi_3)/\phi_3 = \mathcal{O}(10^{-7})}$ [3]

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[1] ckmfitter.in2p3.fr/www/html/ckm_results.html

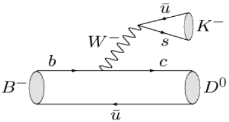
[2] www.slac.stanford.edu/xorg/hflav/triangle/moriond2018/index.shtml

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

Extraction of CKM angle ϕ_3

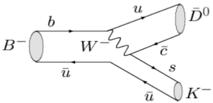
- Via the interference between $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$

A



color allowed
$B^- \to D^0 K^- \sim V_{cb} V^*_{us}$
$\sim A\lambda^3$

$\mathbf{A r_B e^{i(\delta_B - \phi_3)}}$



color suppressed
$B^- \to \bar{D}^0 K^- \sim V_{ub} V^*_{cs}$
$\sim A\lambda^3(\rho + i\eta)$

$$r_B = \frac{|A_{suppressed}|}{|A_{favored}|} \sim 0.1$$ for $B^\pm \to DK^\pm$ decays

- Generally three types of D final states used:
  - CP eigenstates (**GLW**[4]): K^+K^-, $\pi^+\pi^-$, $K^0_S\pi^0$
  - K^+X^- (**ADS**[5]) DCS: $(X^- = \pi^-, \pi^-\pi^0, \pi^-\pi^-\pi^+)$
  - Self-conjugate multi-body states (**GGSZ**[6]): $K^0_S h^+ h^-$, $K^0_S\pi^+\pi^-\pi^0$

[4] PLB **253**, 483 (1991), PLB **265**, 172 (1991)
[5] PRD **63**, 036005 (2001)
[6] PRD **68**, 054018 (2003)

Methods to extract ϕ_3: GLW and ADS

GLW method:

- Both D^0 and $\bar{D}^0$ are decaying to same *CP* eigenstate
- Four observables are

$$R^{\pm}_{CP} = 2\frac{\Gamma(B^- \to D^{\pm}_{CP}K^-) + \Gamma(B^+ \to D^{\pm}_{CP}K^+)}{\Gamma(B^- \to D^{\pm}_{fav}K^-) + \Gamma(B^+ \to D^{\pm}_{fav}K^+)}$$

$$A^{\pm}_{CP} = 2\frac{\Gamma(B^- \to D^{\pm}_{CP}) - \Gamma(B^+ \to D^{\pm}_{CP}K^+)}{\Gamma(B^- \to D^{\pm}_{CP}) + \Gamma(B^+ \to D^{\pm}_{CP}K^+)}$$

Then,

$$R^{\pm}_{CP} = 1 + r_B^2 \pm 2r_B \cos\delta_B \mathbf{\cos\phi_3}$$
$$A^{\pm}_{CP} = \pm 2r_B \sin\delta_B \mathbf{\sin\phi_3} / R^{\pm}_{CP}$$

- No need of external inputs

ADS method:

- *D* from a favored amplitude decays to a DCS state
- Two observables are

$$R_{ADS} = \frac{\Gamma(B^- to[K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- to[K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)}$$

$$A_{ADS} = \frac{\Gamma(B^- to[K^+\pi^-]_D K^-) - \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- to[K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)}$$

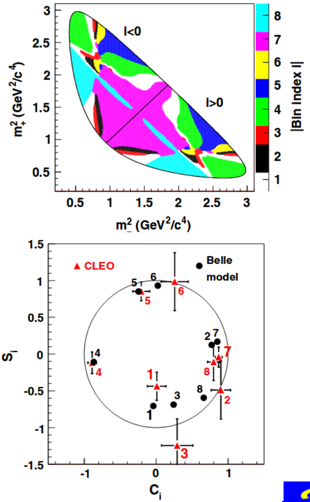
Then,

$$R_{ADS} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D)\mathbf{\cos\phi_3}$$
$$A_{ADS} = 2r_B r_D(\sin\delta_B + \mathbf{\phi_3})/R_{ADS}$$

- r_D and δ_D from charm factories

Methods to extract ϕ_3: GGSZ

- For self-conjugate multi-body D final states such as $K_S^0\pi^+\pi^-$ [7]
- Bin the Dalitz plot symmetrically about $m_-^2 = m_+^2$
- Fraction of D events for K_i & $\bar{K}_i$ from $D^{*\pm} \to D\pi^{\pm}_{\mathrm{slow}}$
- External charm factory inputs needed- **avg. cosine (c_i) and sine (s_i)** of the strong phase difference between D^0 and $\bar{D}^0$ decay amplitude i^{th} bin
- $\mathbf{e^+e^- \to \psi(3770) \to D^0\bar{D}^0}$
- Advantage: $\mathbf{r_B}$ and $\boldsymbol{\delta_B}$ from single mode



[7] PRD **85** (2012) 112014

Constraints on γ/ϕ_3

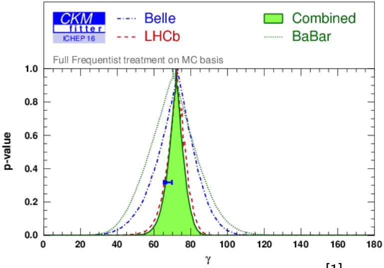


Figure: Current status of ϕ_3 [1].

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

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

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

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

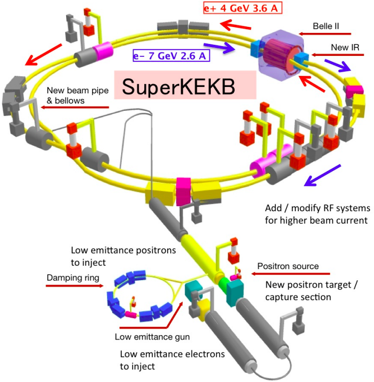
- From all measurements of $B \to D(^*)K(^*)$ from GLW, ADS, and GGSZ
- All data from B factories: Belle & BaBar
- $+$ LHCb run I

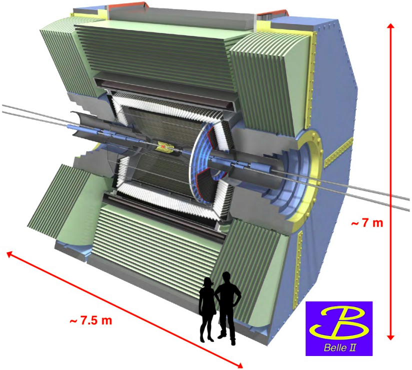
$\rightarrow$ **Dominated by GGSZ**

$\rightarrow$ PRD **87** (2013) 052015

$\rightarrow$ LHCb-CONF-2018-002

SuperKEKB and Belle II experiment

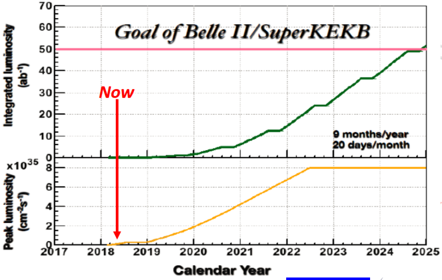




- Improved K_S^0 reconstruction efficiency
- Better K/π separation

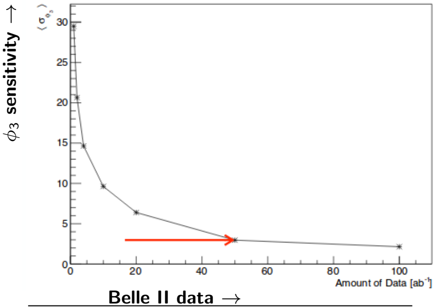
Status of phase 2 of Belle II experiment

- **First collision on 25 April 2018 & completes on 17 July**
- **Accumulated > 0.5 fb^{-1} data**
- **Phase 3 kick-off from early 2019**
- $\mathcal{L}_{\text{int}} = 50\ \text{ab}^{-1}$ **(50 $\times$ Belle)**
- $\mathcal{L}_{\text{peak}} = 8 \times 10^{35}\ \text{cm}^{-1}\text{s}^{-1}$ **(40 $\times$ KEKB)**



ϕ_3 sensitivity with $B^{\pm} \to D(K_S\pi^+\pi^-)K$ decays in Belle II

- Goal to go for precision $\approx$ **1°** [8]
- Dominated by $B^{\pm} \to D(K^0_S\pi\pi)K^{\pm}$ mode
  - improvements, even modest, will have large impact on ϕ_3 sensitivity
- **GLW like states:** Interference of $B^- \to DK^-$, $D \to K^0_S\rho$
- **ADS like states:** Interference of $B^- \to DK^-$, $D \to K^*\pi$
- Golden mode to determine ϕ_3!



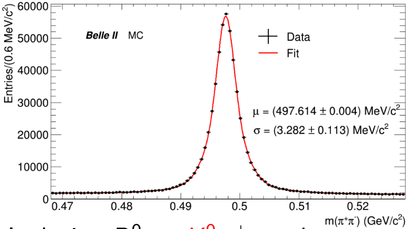
- $\delta(\phi_3)^{50\ \mathrm{ab}^{-1}}$ = **3.0°** by GGSZ (with 10 fb^{-1} BES III data)
- $\delta(\phi_3)^{50\ \mathrm{ab}^{-1}}$ = **1.6°** when Belle GLW + ADS + GGSZ extrapolated

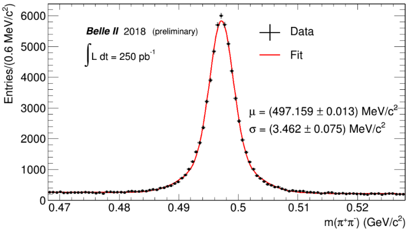
  Further improvements:
  - Additional modes
  - Improved K^0_S reconstruction
  - $q\bar{q}$ background suppression ($q = u, d, s, c$)

[8] J. Brod *et. al*, `arXiv:1412.1446`; BELLE2-PUB-DRAFT-2016-009

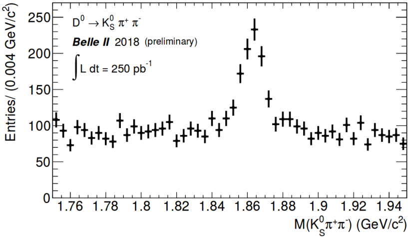
Results from phase 2 data-K_S^0 reconstruction

- Already resolutions in MC (left) & data (right) are in good agreement



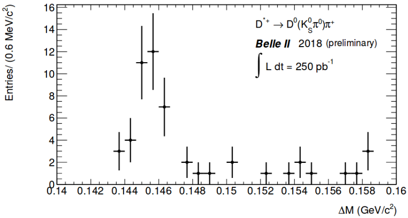


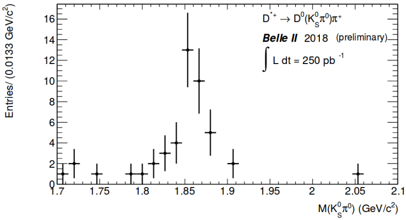
- Inclusive $D^0 \to K_S^0 \pi^+ \pi^-$ decays



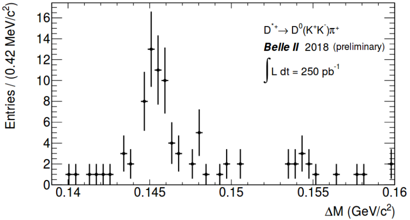
Rediscovering the **CP modes** from phase 2

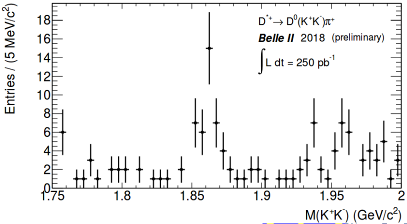
- $D^{*\pm} \to D(K_S^0\pi^0)\pi^{\pm}_{\rm slow}$ decays



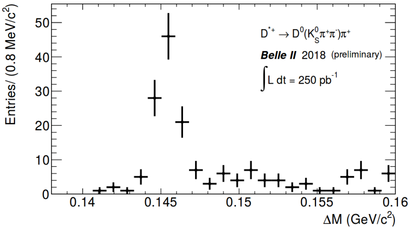


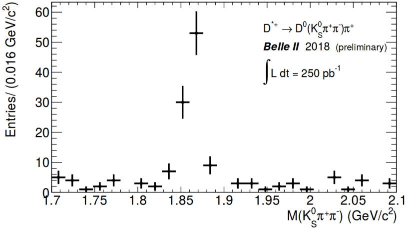
- $D^{*\pm} \to D(K^+K^-)\pi^{\pm}_{\rm slow}$ decays



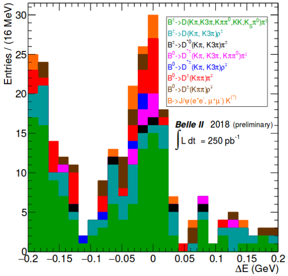


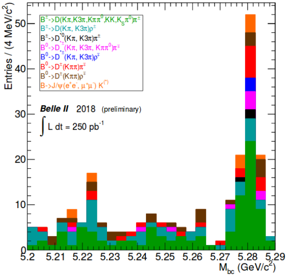
Rediscovery of $D^{*\pm} \to D(K_S^0\pi^+\pi^-)\pi^{\pm}_{\rm slow}$ & B from phase 2





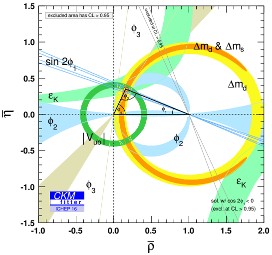
- Found $\approx$ 100 $\mathbf{B \to D\pi}$ candidates, **control modes for $\mathbf{B \to DK}$ for ϕ_3!**





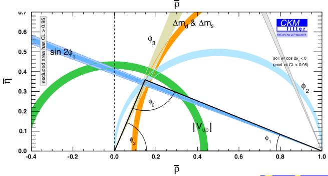
Summary

Now:



- Current precision on ϕ_3 is $\approx 5^\circ$
- With 50 ab^{-1} of Belle II data:
  - $\mathbf{B^\pm \to D(K^0_S\pi^+\pi^-)K^\pm}$:
    ϕ_3 sensitivity will improve to $\mathbf{3.0^\circ}$
  - $\mathbf{B^\pm \to D(K^0_S\pi^+\pi^-\pi^0)K^\pm}$:
    ϕ_3 sensitivity will improve to $\mathbf{4.4^\circ}$ [9]
    (See talk by P.K. Resmi)
- Combined ϕ_3 sensitivity is $\mathbf{1.6^\circ}$

Future (50 ab^{-1} Belle II data):



[9] JHEP **01** (2018) 082

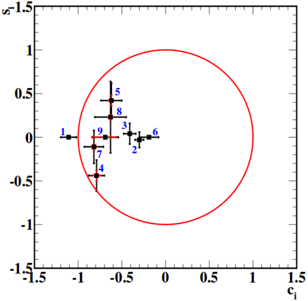
Backup slides

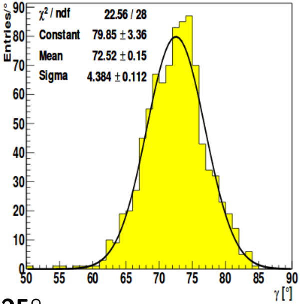
ϕ_3 sensitivity with $B \to D(K^0_S\pi^+\pi^-\pi^0)K$ decays

- Four-body final state[9]

See talk by P.K. Resmi

- $\epsilon \times \mathcal{B}$ similar to $D^0 \to K^0_S\pi^+\pi^-$
- Many interesting resonant substructures such as $K^0_S\omega, K^{*\pm}\rho^{\mp}$





- From 1200 events in Belle, $\boldsymbol{\delta(\phi_3) = 25^\circ}$
- Projection to 50 ab^{-1} Belle II sample $\boldsymbol{\delta(\phi_3) = 4.4^\circ}$

[9] JHEP, **01** (2018) 82