Prospects for Penguin-free measurement of Φ_d (and Φ_s) at FCC-ee

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Prospects for knowledge of Φ_d (and Φ_s) in 2030s and beyond

Measurement of, Φ_d (=2β in SM*), phase between B^0-B^0bar mixing and decay, was first great success of B-factories and confirmed CKM paradigm. Despite this validation of the SM, it remains important to improve knowledge as far as is experimentally possible, to probe for sub-dominant New Physics contributions.

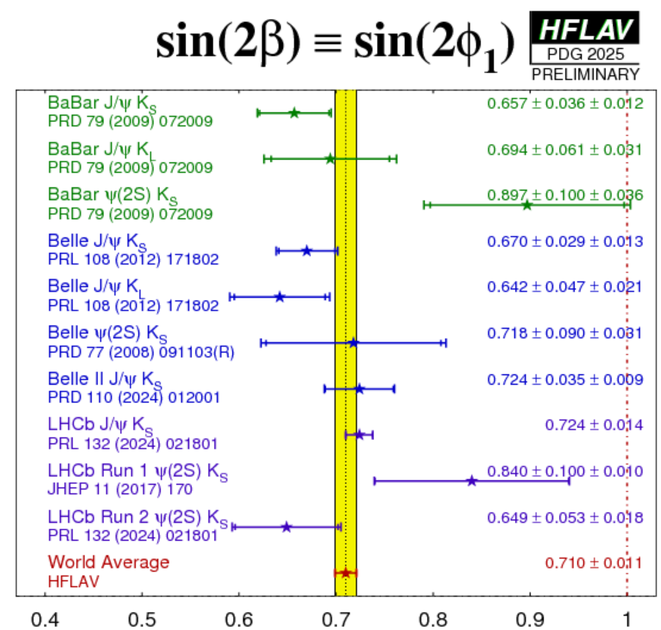
Same story applies for Φ_s – but this is not the subject of today's presentations.

Current knowledge from charmonium modes

$$\sin 2\beta = 0.710 \pm 0.011 \; (0.010_{\text{stat-only}})$$

which corresponds to a β uncertainty of 0.45°.

Currently dominated by Run 2 LHCb result, but we can presumably hope for precise measurements from Belle II, ATLAS and CMS.



* Respecting familiarity we will refer to β throughout this talk, but the true interest of the measurement is that possibly Φ_d != 2β.

Projections for sin2β with charmonium modes

Official projections prepared for EPPSU [ATLAS, Belle II, CMS, LHCb arXiv:2503.24346]:

Experiment Assumed data sample	ATLAS $3000\,\text{fb}^{-1}$	CMS $3000\,\text{fb}^{-1}$	LHCb $300\,\text{fb}^{-1}$	Belle II $50\,\text{ab}^{-1}$
CKM angles				
β	—	—	0.08°	0.3°

LHCb projection is a simple scaling of current result, dominated by $B^0 \to J/\psi(\mu\mu)K_S$.

NB a naïve scaling of Belle 'all charmonium' result (sin2β uncertainty of 0.026 for 772M BBbar pairs, for $J/\psi K_S$, $J/\psi K_L$, $\psi(2S)K_S$…) suggests ultimate sensitivity of 0.15^o for Belle II (and this assumes no improvement in flavour tagging w.r.t. Belle…)

Scaling Belle 'all charmonium' to Tera-Z (equivalent to 7.4×10^{11} `BBbar') → 0.04^o.
(This is not an official FCC-ee estimate – work underway at Cambridge.)

We will be deep in regime where Penguin pollution is expected to be significant !

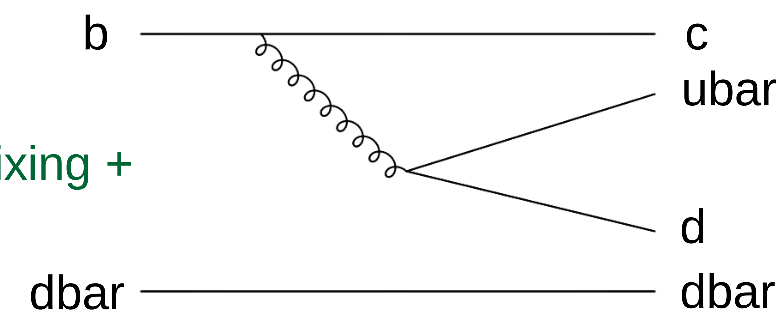
Φ_d (and Φ_s) without Penguins

In charmonium modes we are already approaching the regime where we must worry about Penguin pollution. Issue will become more acute in HL-LHC era & FCC-ee. Desirable to have another approach that is fully clean in this respect.

Colour-suppressed $b \rightarrow c$ ubar d transitions:

Φ_d (*i.e.* 2β)

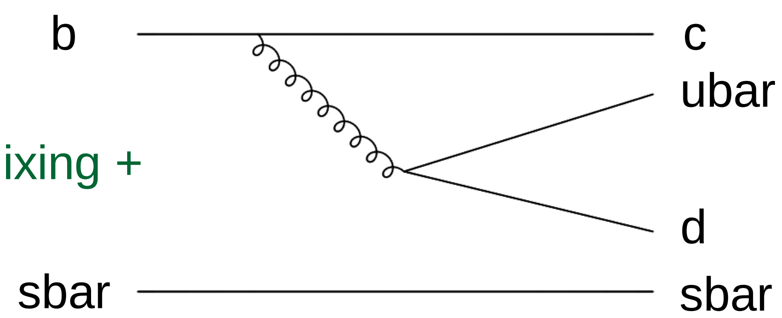
mixing +



B^0bar $\rightarrow$ Dh^0 ($h^0=\pi^0,\omega,\eta,\eta'$…)

Φ_s

mixing +



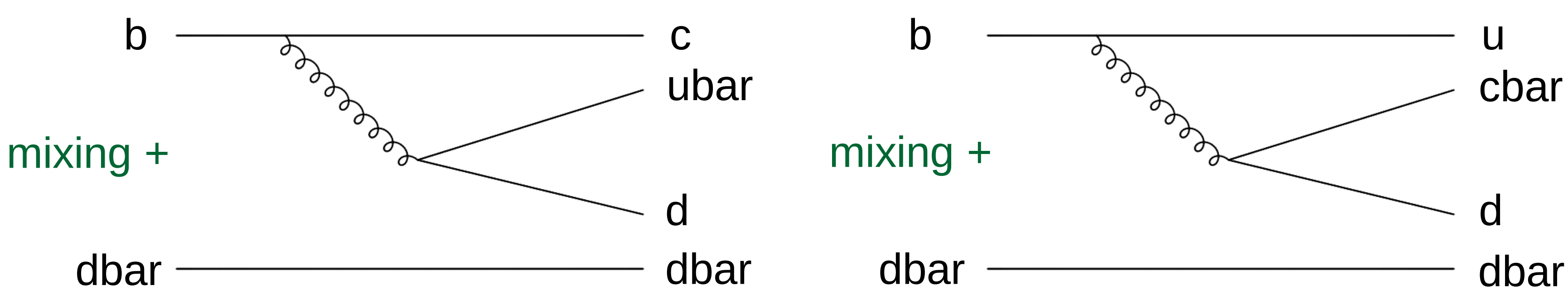
B^0_sbar $\rightarrow$ DK_S^0

D reconstructed in mode common to D^0 & D^0bar, *e.g.* CP eigenstate or multibody self-conjugate (*e.g.* $K_S\pi\pi$). Reminiscent of γ measurement with $B \rightarrow DK$ decays.

Today will focus on the B^0 case (*i.e.* Φ_d), but B^0_s (*i.e.* Φ_s) will be studied later.

A detail…

Even though there is no Penguin pollution, there is a b→u cbar d contribution.



This introduces some direct CPV and brings γ into game – indeed, makes these modes potentially interesting for the γ measurement *e.g.* [Fleischer, NPB 659 (2003) 321].

However, relative amplitude of the second diagram to the first is ~0.02,

- So, if regarded as pollution it is a very small effect, and one which can probably be fully controlled from observables themselves plus excellent knowledge of γ.
- FCC data will allow this contribution to be used as a γ measurement, but it is unlikely to be competitive with established methods.

Both these assertions will be checked as part of ongoing studies.

Expectations based on b-factory experience

First Observation of CP Violation in $\overline{B}^0 \to D_{CP}^{(*)} h^0$ Decays by a Combined Time-Dependent Analysis of *BABAR* and Belle Data

We report a measurement of the time-dependent CP asymmetry of $\overline{B}^0 \to D_{CP}^{(*)} h^0$ decays, where the light neutral hadron h^0 is a π^0, η or ω meson, and the neutral D meson is reconstructed in the CP eigenstates K^+K^-, $K_S^0\pi^0$ or $K_S^0\omega$. The measurement is performed combining the final data samples collected at the $\Upsilon(4S)$ resonance by the *BABAR* and Belle experiments at the asymmetric-energy B factories PEP-II at SLAC and KEKB at KEK, respectively. The data samples contain $(471\pm3)\times10^6$ $B\overline{B}$ pairs recorded by the *BABAR* detector and $(772\pm11)\times10^6$ $B\overline{B}$ pairs recorded by the Belle detector. We measure the CP asymmetry parameters $-\eta_f\mathcal{S} = +0.66\pm0.10\,(\text{stat.})\pm0.06\,(\text{syst.})$ and $\mathcal{C} = -0.02\pm0.07\,(\text{stat.})\pm0.03\,(\text{syst.})$. These results correspond to the first observation of CP violation in $\overline{B}^0 \to D_{CP}^{(*)} h^0$ decays. The hypothesis of no mixing-induced CP violation is excluded in these decays at the level of 5.4 standard deviations.

[PRL 115 (2015) 121604]

$B^0 \to D_{CP}h^0$ with $h^0 = \pi, \eta$ & ω and CP modes $K_S\pi^0$, $K_S\omega$ & KK.

$B^0 \to D^*h^0$, $D^* \to D_{CP}\pi^0$ with $h^0 = \pi^0$ & ω, & CP modes $K_S\pi^0$ & KK.

BaBar + Belle: 1,243 x 10^6 BBbar pairs $\to \sigma_{\sin 2\beta} = \pm 0.10 \pm 0.06$

Make crude assumption that FCC-ee reconstruction & flavour tagging performance will be identical. With 6 x 10^{12} Z^0, FCC-ee will accumulate a sample 600x larger.

Assuming √N scaling of both stat and syst uncertainties $\to \sigma_{\sin 2\beta}|^{CP}_{FCC} \sim 0.0048$

The BaBar, Belle analysis can be extended to include other CP eigenstates ($\pi\pi$, $K_S\eta'$, $K_S\pi^0\pi^0$) and quasi-CP-eigenstates ($\pi\pi\pi^0$), and $D^* \to D\gamma$ decays

So, an additional factor of ~2 quite plausible $\to \sigma_{\sin 2\beta}|^{CP}_{FCC} \sim 0.0034$, or $\sigma_{\beta}|^{CP}_{FCC} \sim 0.14^{o}$

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[PRL 115 (2015)]

$B^0 \to D_{CP} h^0$ with $h^0 = \pi, \eta$ & ω and CP modes $K_S\pi^0$, $K_S\omega$ & KK.

$B^0 \to D^* h^0$, $D^* \to D$ ... π^0 with h^0 = ...

In ongoing workshop studies we will benchmark performance in $B^0 \to D(KK)\pi^0$.

In BaBar/Belle analysis, $B^0 \to D_{CP}\pi^0$ contributed 568 signal events, over the three CP modes. No breakdown given, but guess around half were D→KK.

Gives an expectation of ~1.8×10^5 at FCC. Keep this in mind for Charlie's talk.

Assuming √N scaling of both stat and syst uncertainties → $\sigma_{\sin 2\beta}|^{CP}_{FCC} \sim 0.0048$

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Adding self-conjugate multibody D decays

Belle extended study to use $D \rightarrow K_S \pi\pi$ decays. These access both sin2β and cos2β.

Using a model-ind. approach

σ_β = +/- 7.8° +/- 2.1°

from 772 x 10^6 BBbar events.

Measurement of the CKM angle φ_1 in $B^0 \rightarrow \overline{D}^{(*)0} h^0$, $\overline{D}^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays with time-dependent binned Dalitz plot analysis

We report a measurement of the *CP* violation parameter φ_1 obtained in a time-dependent analysis of $B^0 \rightarrow \overline{D}^{(*)0} h^0$ decays followed by $\overline{D}^0 \rightarrow K_S^0 \pi^+ \pi^-$ decay. A model-independent measurement is performed using the binned Dalitz plot technique. The measured value is $\varphi_1 = 11.7^\circ \pm 7.8^\circ$ (stat.) $\pm$ 2.1° (syst.). Treating $\sin 2\varphi_1$ and $\cos 2\varphi_1$ as independent parameters, we obtain $\sin 2\varphi_1 = 0.43 \pm 0.27$ (stat.) ± 0.08 (syst.) and $\cos 2\varphi_1 = 1.06 \pm 0.33$ (stat.)$^{+0.21}_{-0.15}$ (syst.). The results are obtained with a full data sample of $772 \times 10^6 B\overline{B}$ pairs collected near the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider.

[PRD 94 (2016) 052004]

Naïve scaling of statistical uncertainty to Tera-Z $\rightarrow \sigma_\beta |^{K_S\pi\pi}_{FCC} = 0.25^\circ$.

Hope for significant improvement through inclusion of other self-conjugate modes

$K_S\pi\pi\pi^0$, $K_S KK$, $\pi\pi\pi\pi$, $KK\pi\pi$, $\pi\pi\pi^0\pi^0$ …

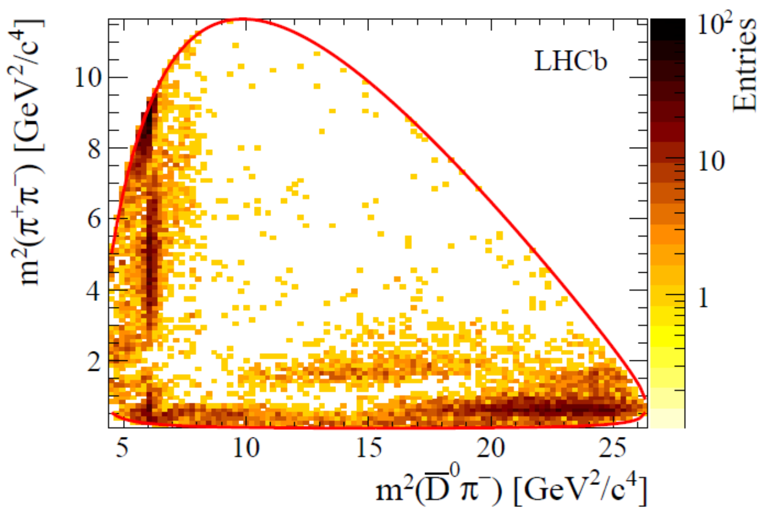
Need to understand requirements on strong-phase inputs from BESIII or STCF. This same information is also required for γ measurement.

Adding $B^0 \to D\pi^+\pi^-$ decays

Another example of $B^0 \to Dh^0$ is $B^0 \to D\rho$, $\rho \to \pi^+\pi^-$, but this can be extended to exploit full Dalitz space of $D\pi\pi$ system, as noted in [Lathan, Gerson, JPG 36 (2009) 025006].

Well suited to LHCb because of charged tracks, and equally good for FCC-ee. Also allows $\cos 2\beta$ to be determined, as well as $\sin 2\beta$, even with $D \to CP$ modes alone.

LHCb have studied contributions to Dalitz plot [PRD 92 (2015) 032002]:



Resonance	Spin	Model	m_r (MeV/c^2)	Γ_0 (MeV)
$\overline{D}^0\pi^-$ P-wave	1	Eq. 14	Floated	
$D_0^*(2400)^-$	0	RBW	Floated	
$D_2^*(2460)^-$	2	RBW	Floated	
$D_J^*(2760)^-$	3	RBW	Floated	
$\rho(770)$	1	GS	775.02 ± 0.35	149.59 ± 0.67
$\omega(782)$	1	Eq. 13	781.91 ± 0.24	8.13 ± 0.45
$\rho(1450)$	1	GS	1493 ± 15	427 ± 31
$\rho(1700)$	1	GS	1861 ± 17	316 ± 26
$f_2(1270)$	2	RBW	1275.1 ± 1.2	$185.1^{+2.9}_{-2.4}$
$\pi\pi$ S-wave	0	K-matrix	See Sec. 4	
$f_0(500)$	0	Eq. 15	See Sec. 4	
$f_0(980)$	0	Eq. 18	See Sec. 4	
$f_0(2020)$	0	RBW	1992 ± 16	442 ± 60
Nonresonant	0	Eq. 20	See Sec. 4	

In principle could attempt a binned phase-space approach, and determine hadronic parameters directly from data, to achieve full model independence.

Tentative conclusions

FCC-ee well suited to measurement of β with b→c ubar d transitions because of very large number of B mesons produced in 6 x 10^{12} Z decays, (presumed) good flavour-tagging performance and neutral reconstruction.

A simple scaling of B-factory numbers has been performed, assuming identical reconstruction and flavour-tagging performance (to be validated!), and foreseeing inclusion of additional channels (reasonable). Results of this scaling also assume that experimental and strong-phase systematics can be controlled.

➡ uncertainty of ~0.1^o on β, *with no Penguin pollution*, could be achievable

Similar to what might be possible with charmonium modes at HL-LHC + Belle II.

Further motivates best possible performance of detectors, in particular for neutrals, and efforts with initial-state flavour tagging.

Next talk – reconstruction studies in a benchmark mode: $B^0 \to D(KK)\pi^0$.