Prospects of CKM parameter measurements at SuperKEKB and LHC

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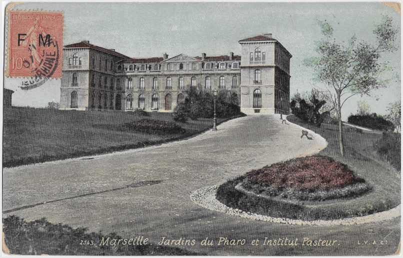
XIII Meeting on B physics [Marseille]



Parametrization of the CKM matrix

With the mixing angles $\cos, \sin(\theta_{ij}) \equiv c_{ij}, s_{ij}$ the CKM matrix is the product of three 2x2 rotation matrices with one phase

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{23} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

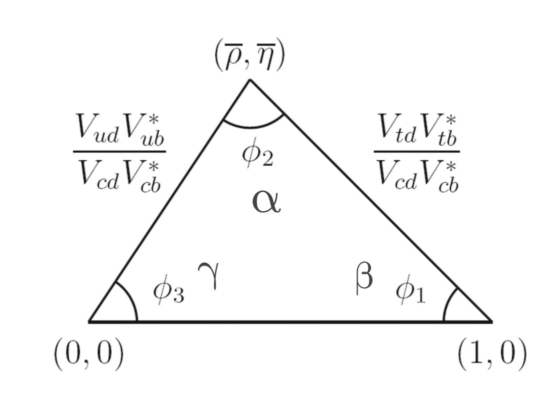
Exact version of the Wolfenstein parametrization

$$\lambda^2 \equiv \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad A^2 \lambda^4 \equiv \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2}$$

$$\bar{\rho} + i\,\bar{\eta} \equiv -\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*}$$

3×3 unitarity implies six triangle relations in the complex plane; because of the λ suppression, four of these triangles are quasi-flat, and the remaining two are almost degenerate. One defines "the" (B_d) Unitarity Triangle by

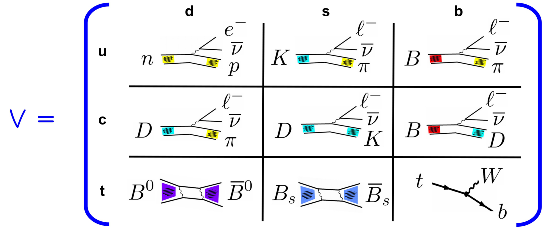
$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

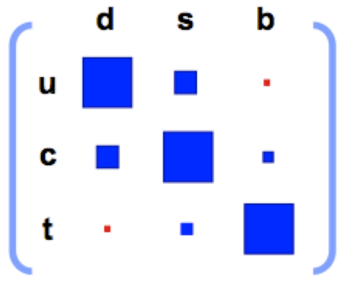


NB: $\beta, \alpha, \gamma = \phi_1, \phi_2, \phi_3$ in the Japanese notation

Extracting the CKM couplings

$$V_{\rm CKM} \equiv V_U^\dagger V_D = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$





The main physical ingredients are the following

- $|V_{ud}|$, $|V_{us}|$, $|V_{cb}|$ and $|V_{ub}|$ from the relevant charged current, tree level weak decays; the needed strong interaction parameters are taken from Lattice QCD or other methods where necessary.

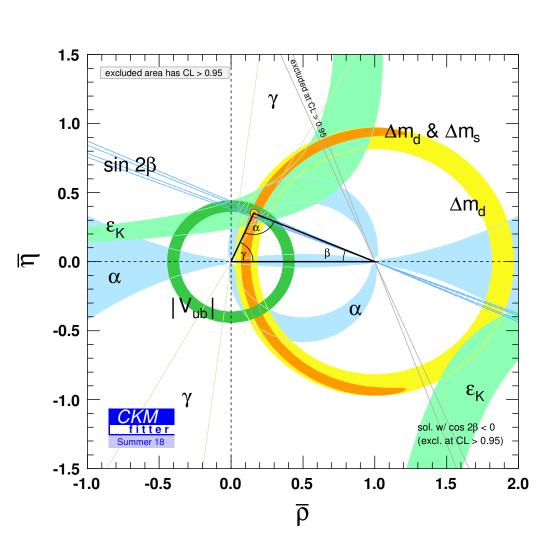
- Δm_{ds} from $B_{d,s} - \bar{B}_{d,s}$ oscillation measurements and Lattice QCD.

- The CP-violating angles α, β, γ from the corresponding experimental analyses; very little theoretical input is needed here.

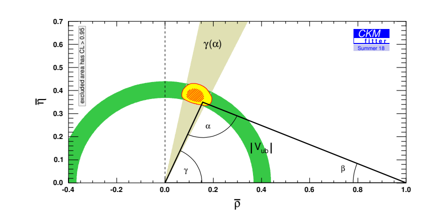
- The CP-violating asymmetry ε_K, the interpretation of which depends on the $K - \bar{K}$ mixing parameter B_K computed on the lattice.

The global CKM analysis in the B_d UT plane

all constraints together [Summer 2018]



Consistency of the KM paradigm



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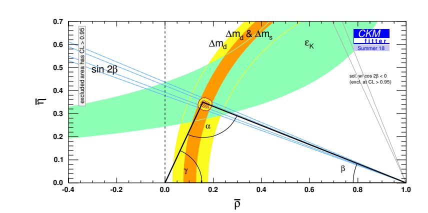

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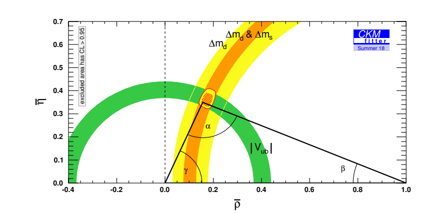
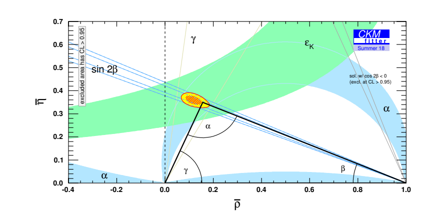


CP conserving only



CP violating only

The global CKM analysis

Wolfenstein parameters from the fit

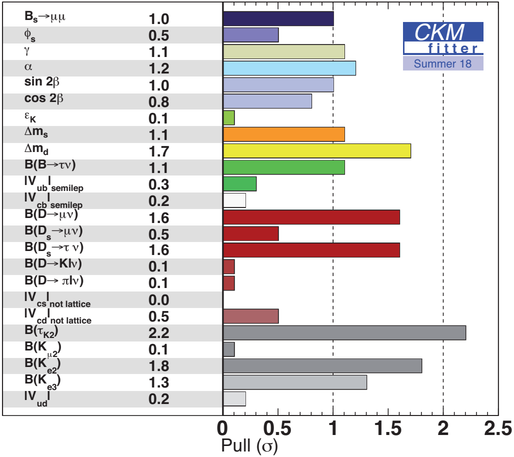
$$A = 0.8403^{+0.0056}_{-0.0201}(2\%) \qquad \lambda = 0.224747^{+0.000254}_{-0.000059}(0.07\%)$$

$$\bar{\rho} = 0.1577^{+0.0096}_{-0.0074}(5\%) \qquad \bar{\eta} = 0.3493^{+0.0095}_{-0.0051}(2\%)$$

Clearly the big picture is that the CKM couplings are the dominant contribution to the physical flavor transitions, whereas the KM phase is the dominant contribution to *CP*-asymmetries.
More accurate tests can be done by comparing the indirect fit prediction for a given quantity, with its direct determination (experimental measurement or theoretical calculation).

Pull values for the CKM observables

no hint of a deviation here



Why the need to improve the CKM metrology ?

New Physics contributions are most likely ‘small’ at the scales that are accessible to our experiments. Hence it could be that significant deviations from SM predictions, if any, will be small and would only show up in precision tests of the CKM sector.

If a deviation is found, we would like to constraint NP scenarios or models. Hence we need to know the SM contributions as precisely as possible, in order to substract it from the measurements.

NP generically involves new hadronic matrix elements that do not contribute to SM predictions. CKM metrology is a way to validate the consistency of the calculations of these matrix elements.

Prospective scenarios

Main references: The Belle II Physics Book (arXiv:1808.10567); The HL/HE-LHC Yellow Book (work in progress). See talks in this workshop.

Phase I: LHCb 23 fb^{-1} and Belle II 50 ab^{-1}.

Phase II: LHCb 300 fb^{-1}.

Central values of inputs are set to their best fit values as of Summer 2018.

Warning: do not take the plots/numbers too seriously ! The aim is to emphasize quantities for which significant progress will be seen or needed.

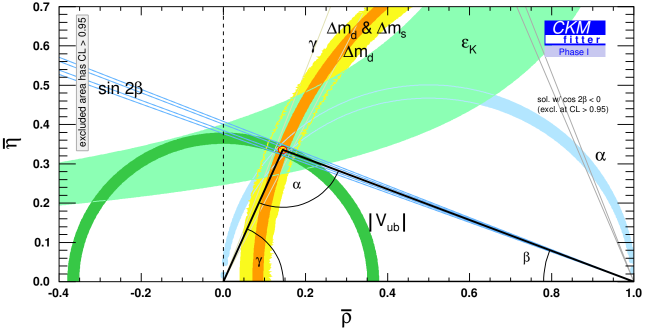
Matrix elements from Lattice QCD

Prospective for LQCD simulations is challenging because the progress depends on various things, hardware, algorithms, new ideas ...

For this reason the YB presents a prospective for LQCD Phase I but then we freeze the matrix elements for Phase II.

	Quantity	2018	2025
Examples	f_{Bs}	1.6%	0.6%
	B_{B_s}	4%	0.8%
	$B \to \pi$	2.9%	1%
	$B \to D$	1.4%	0.3%

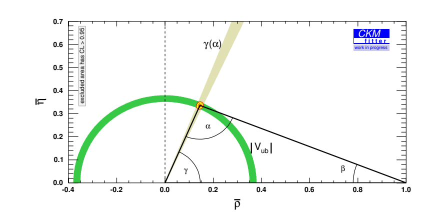
Phase I prospective [preliminary]



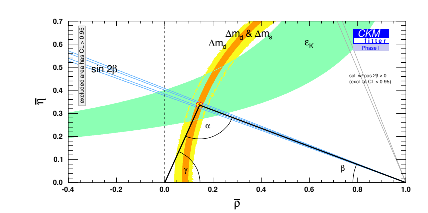
$$A = 0.8351^{+0.0095}_{-0.0079} (1\%) \qquad \lambda = 0.22494^{+0.00047}_{-0.00048} (0.4\%)$$

$$\bar{\rho} = 0.1445^{+0.0040}_{-0.0041} (3\%) \qquad \bar{\eta} = 0.3354^{+0.0036}_{-0.0037} (1\%)$$

Phase I prospective [preliminary]



tree only



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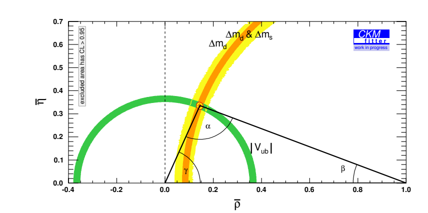
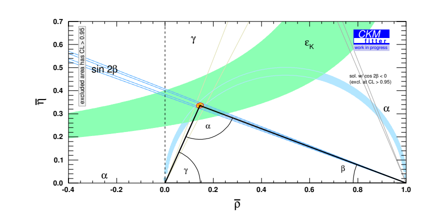
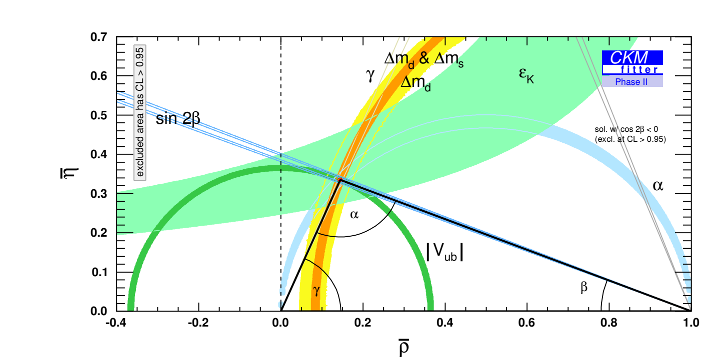


CP conserving only



CP violating only

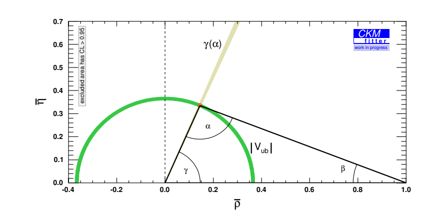
Phase II prospective [preliminary]

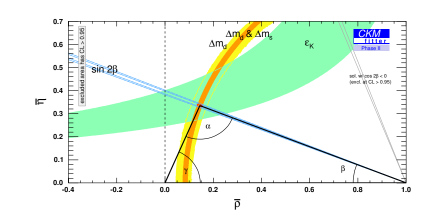


$A = 0.8351^{+0.0082}_{-0.0061}(0.9\%)$ $\lambda = 0.22494 \pm 0.00044(0.2\%)$

$\bar{\rho} = 0.1444 \pm 0.0019(1\%)$ $\bar{\eta} = 0.3353 \pm 0.0016(0.5\%)$

Phase II prospective [preliminary]





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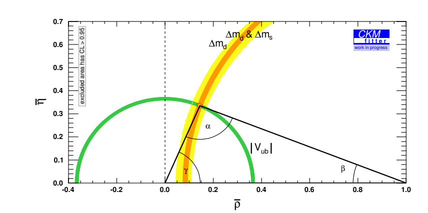
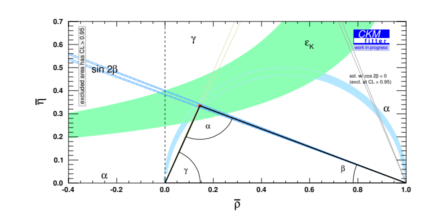




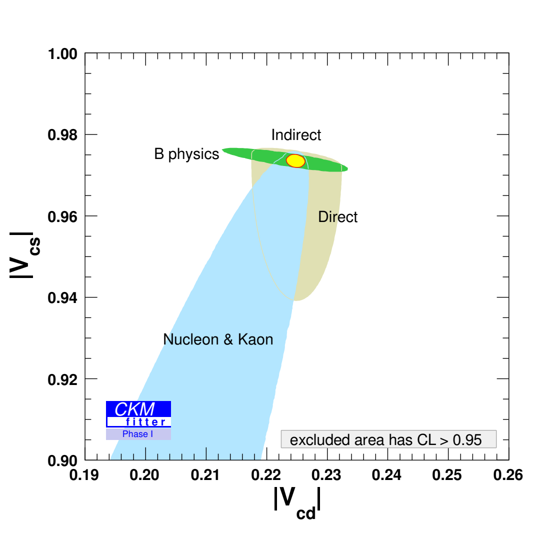
CP conserving only

CP violating only

Impact of BES III measurements [preliminary]

The BES III experiment measures the weak couplings of D mesons to light ones, that can be interpreted in terms of $|V_{cd}|$ and $|V_{cs}|$ with the knowledge of form factors from Lattice QCD. [BESIII white paper]

An important validation step for LQCD, and a cross check for the B physics sector.



QED radiative corrections

At this level of precision we have to make sure that all corrections are under control.

In particular the status of QED corrections in exclusive B decays is not at the level of, *e.g*, K decays.

Naively QED corrections are suppressed by $\alpha/\pi \sim 0.3\%$. However infrared (soft and collinear) divergences generate enhancement factors

$$\log^k \left[\frac{(\textit{large scale})}{(\textit{small scale})} \right]$$

In B decays we may encounter m_e, m_μ, m_π, m_D, m_B. . . . Note that $\log(m_B/m_e) \sim 9$, $\log(m_B/m_\mu) \sim 4$, so that QED corrections can easily reach a few %.

QED radiative corrections

The soft photon approximation has been used to identify the leading QED corrections $\sim \log(E_\gamma)$. [Becirevic *et al.*, Isidori *et al.*] The actual evaluation depends on the details of the experimental settings (namely the threshold under which soft photons are not detected), and is usually implemented in PHOTOS MC tool. Explicit calculations show agreement with PHOTOS.

However even in the soft photon approximation not all terms are taken into account by PHOTOS. A more detailed interplay between theorists and experimentalists will be needed to check that the potentially neglected contributions remain under control.

QED radiative corrections

In addition there exists enhanced QED corrections that are not captured by the $\log(E_\gamma)$ terms. An explicit example has been found for $B \to \mu^+\mu^-$, that is both power and logarithmically enhanced [Beneke *et al.*]:

$$m_B \int_0^\infty \frac{d\omega}{\omega} \phi_{B+}(\omega) \log^k(\omega) \sim \frac{m_B}{\lambda_B} \sigma_k \sim 30$$

These 'new' enhanced contributions depend on poorly known non local matrix elements (B meson distribution amplitudes) and induce a non trivial light mass dependence to the decay amplitudes.

In the end for $B \to \mu\mu$ the total correction does not exceed the 1% level due to numerical cancellations between terms of different signs. However it is not clear to which extent this order of magnitude is valid for all B decays.

Other theoretical issues

Thanks to single CKM coupling amplitudes, the extraction of the UT angle γ from the golden channels is free of theoretical uncertainties.

This is not the case for β, ϕ_s and α.

The penguin contributions to β has been estimated at the level of 0.3–0.5° from SU(3) and/or factorization arguments (up to 1° for ϕ_s). This is already similar to the Phase I experimental uncertainty but a more precise calculation of these effects is out of reach of present theoretical techniques. [Fleischer *et al.*, Ciuchini *et al.*, Frings *et al.*]

Same issue for α: isospin symmetry is assumed to get rid of penguin pollution, first corrections are expected at the level of 1° and involve a delicate (but interesting) interplay of different effects: QED, quark masses, meson mixing, ... [JC *et al.*]

Conclusion

The KM mechanism so far has been tested and validated at the few % level.

In the next future we will reach the 1% threshold for many observables and parameters of interest.

The metrology of the CKM matrix will still be needed to check for possible small discrepancies among SM predictions, and to validate the calculations of the hadronic matrix elements.

We will have to face a number of challenging theoretical issues: control LQCD uncertainties at the percent level in the B sector, understand QED corrections that are enhanced by large ratios of different scales, and develop quantitative methods for non leptonic matrix elements.

Backup: prospective for LQCD matrix elements

Quantity	Published value	Reference	error (to be published)	2025
f_K	155.7 ± 0.7 MeV	$N_f = 2+1$ [1]	0.4%	
$f_+^{K\to\pi}(0)$	0.9706(27)	$N_f = 2+1+1$ [1]	0.28% (0.19% [2])	0.12%
B_K	0.7625(97)	$N_f = 2+1$ [1]	1.3%	0.7%
f_{B_s}	228.4(3.7)	$N_f = 2+1$ [1]	1.6%(0.56% [3])	
f_{B_s}/f_{B^+}	1.205(7)	$N_f = 2+1+1$ [1]	0.6%(0.4% [3])	
B_{B_s}	1.32(5)/1.35(6)	$N_f = 2/N_f = 2+1$ [1]	$\sim 4\%$	0.8%
B_{B_s}/B_{B_d}	1.007(21)/1.032(28)	$N_f = 2/N_f = 2+1$ [1]	2.1%/2.7%	0.5%
ξ	1.206(17)	$N_f = 2+1$ [1]	1.4%	0.3%
$\overline{m}_c(\overline{m}_c)$	1.275(8) GeV	$N_f = 2+1$ [1]	0.6%	0.4%
$f_{K^\pm}/f_{\pi^\pm}$	1.193(3)	$N_f = 2+1+1$ [1]	0.25%(0.15%, symmet. [3])	
f_{D_s}	248.83(1.27)	$N_f = 2+1+1$ [1]	0.5%(0.16% [3])	
f_{D_s}/f_{D^+}	1.1716(32)	$N_f = 2+1+1$ [1]	0.27%(0.14% [3])	
$B \to \pi$ for $\lvert V_{ub}\rvert_{\text{theor}}$		$N_f = 2+1$ [1]	2.9%	1%(1.4%)
$B \to D$ for $\lvert V_{cb}\rvert_{\text{theor}}$		$N_f = 2+1$ [1]	1.4%	0.3%(1%)
(first param. BCL z-exp.)		$N_f = 2+1$ [1]	1.5%	0.5%(1.1%)
$B \to D^*$ for $\lvert V_{cb}\rvert_{\text{theor}}$	-	$N_f = 2+1$ [1]	1.4%	0.4%(0.7%)
$h_{A_1}^{B\to D^*}(\omega = 1)$			=	=
$P_1^{B\to D^*}(\omega = 1)$		No LQCD available		1-1.5%
$\Lambda_b \to p(\Lambda_c)$ for $\lvert V_{ub}/V_{cb}\rvert_{\text{theor}}$		[4]	4.9%	1.2%(1.6%)
$B \to K$		$N_f = 2+1$ [1]	2%	0.7%(1.2%)
(first param. BCL z-exp.)				
$B_s \to K$		$N_f = 2+1$ [1]	4%	1.3%(1.7%)
(first param. BCL z-exp.)				

[HL/HE-LHC Yellow Book]