Charm and CKM, now and in the future

CKMfitter contribution to BESIII book

Sébastien Descotes-Genon

Laboratoire de Physique Théorique
CNRS & Université Paris-Sud 11, 91405 Orsay, France

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Introduction

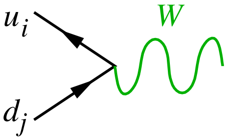
Among many questions related to BESIII (and charm factories) :
what can we learn from the weak interactions of charm ?

- Strong interaction : hard to compute analytically, but good prospects of improved accuracy from lattice
- Standard Model : interesting complementarity of K and D sector ($V_{ud} \simeq V_{cs}, V_{us} \simeq V_{cd}$)
- New Physics : investigating the u-type sector, as b-factories did for d-type quarks (and find a different answer ?)

Triggered a contribution of CKMfitter group to the BESIII Handbook
Charm Physics, Impact on CKM Measurements

Weak interaction and CKM-matrix

In the quark sector of the SM, weak eigenstates $\neq$ Mass eigenstates



$$\frac{g}{\sqrt{2}} \bar{u}_{Li} V_{ij} \gamma^\mu d_{Lj} W^+_\mu + \mathrm{h.c.}$$

with the unitary Cabibbo-Kobayashi-Maskawa matrix:

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

3 generations $\Longrightarrow$ complex phase, source of CP-violation in SM

Standard and Wolfenstein parametrisations

Standard: 1 phase δ, 3 Euler angles ($c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$)

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

Wolfenstein

- exploit the hierarchy experimentally observed
- define λ, A, ρ, η by $s_{12} \equiv \lambda \qquad s_{23} \equiv A\lambda^2 \qquad s_{13}e^{-i\delta} \equiv A\lambda^3(\rho - i\eta)$
- Expand V_{CKM} in powers of λ

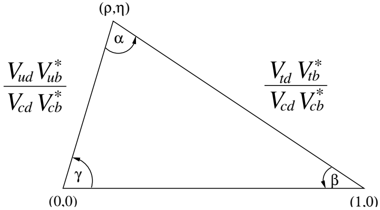
$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \simeq \begin{bmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

(can be extended up to an arbitrary order in λ)

CKM unitarity

Unitarity of the CKM matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



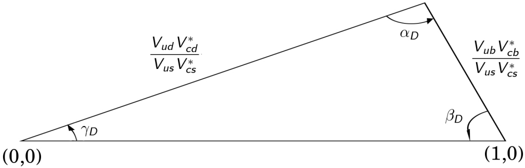
B_d triangle

Many unitarity relations, related to four hadrons (top excluded)

- B_d meson : $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad (\lambda^3, \lambda^3, \lambda^3)$
- B_s meson : $V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \quad (\lambda^4, \lambda^2, \lambda^2)$
- K meson : $V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0 \quad (\lambda, \lambda, \lambda^5)$
- D meson : $V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0 \quad (\lambda, \lambda, \lambda^5)$

The D-meson UT

$$\frac{V_{ud}V_{cd}^*}{V_{us}V_{cs}^*}+1+\frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*}=0$$



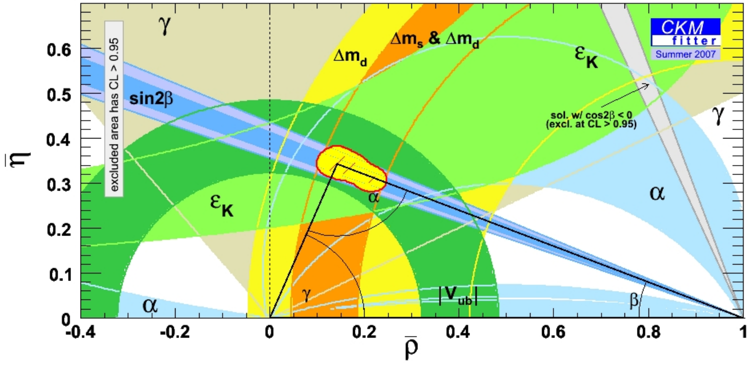
can be used to define a (squashed) D-meson unitarity triangle

- $\bar\rho_D + i\bar\eta_D = -\frac{V_{ud}V_{cd}^*}{V_{us}V_{cs}^*}$
- $\alpha_D = \arg\left(-\frac{V_{ub}V_{cb}^*}{V_{ud}V_{cd}^*}\right) = \arg\left(-\frac{V_{ub}V_{ud}^*}{V_{cb}V_{cd}^*}\right) = -\gamma$
- $\gamma_D = \arg\left(-\frac{V_{ud}V_{cd}^*}{V_{us}V_{cs}^*}\right) = O(\lambda^4)$
- $\beta_D = \arg\left(-\frac{V_{us}V_{cs}^*}{V_{ub}V_{cb}^*}\right) = \pi - \alpha_D - \gamma_D = \pi + \gamma + O(\lambda^4)$

Current indirect constraints on D-UT

In the SM, kaon or B-processes constrain strongly D-UT through CKM

- $|V_{us}|$ constrains (in a first approximation) λ
- $B \to DK$ constrains γ and thus β_D ...



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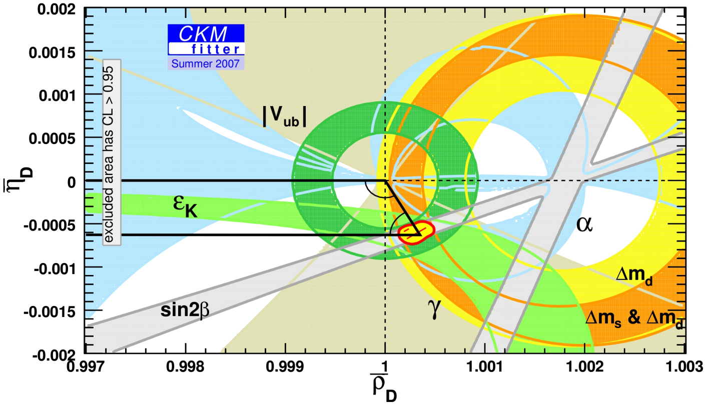


What can we learn from a charm-factory ?

CP-violating observables

- CP-violation very difficult to observe in D meson
- and hard to control theoretically
- Hard to extract information from D_0-$\bar{D}_0$ mixing

$\Longrightarrow$ Unlikely to get angles of the D-meson UT from D processes

CP-conserving observables

- provide $|V_{cd}|$ and $|V_{cs}|$
- accessible through leptonic and semileptonic D-decays
- hadronic part controlled through lattice simulations

$\Longrightarrow$ Focus on $|V_{cd}|$ and $|V_{cs}|$

Current direct constraints on $|V_{cd}|$ and $|V_{cs}|$

Best direct determination

- $|V_{cd}|$: deep-inelastic scattering of ν, $\bar{\nu}$ on nucleons (hard to improve)
- $|V_{cs}|$: charm-tagged W decays

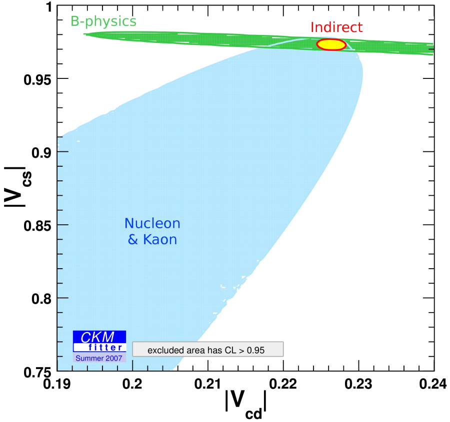
$$|V_{cd}| = 0.230 \pm 0.011 \qquad \sigma(|V_{cd}|)/|V_{cd}| = 5\%$$
$$|V_{cs}| = 0.97 \pm 0.09 \pm 0.07 \qquad \sigma(|V_{cs}|)/|V_{cs}| = 12\%$$

New kid on the block

- lattice inputs for form factors with CLEO-c semileptonic data
- $|V_{cd}| \leftrightarrow D \to \pi\ell\nu$ and $|V_{cs}| \leftrightarrow D \to K\ell\nu$

$$\begin{aligned} |V_{cd}| &= 0.213 \pm 0.008 \pm 0.021 \qquad \sigma(|V_{cd}|)/|V_{cd}| = 11\% \\ |V_{cs}| &= 0.957 \pm 0.017 \pm 0.093 \qquad \sigma(|V_{cs}|)/|V_{cs}| = 10\% \end{aligned}$$

Comparison between direct and indirect measurements



- K and nucleon: $V_{ud} \simeq V_{cs}$ and $V_{cd} \simeq V_{us}$ only at first non trivial order in λ (need b-sector to fix the higher orders)
- B alone: rather constraining
- Indirect (combination of the two above): already quite well determined

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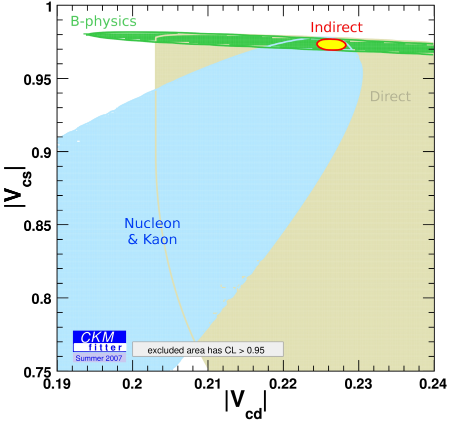

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- Direct: still poorly known (ellipse deformed by $|V_{cd}|^2 + |V_{cs}|^2 \leq 1$)

Prospective exercise

Take your favourite crystal ball, and imagine in 2012

- The final analyses of B-factories (2 ab^{-1})
- The outcome from LHCb (8 ab^{-1})
- The latest results from super-B-factories (3 ab^{-1})
- The improvement of lattice on D decay constants and form factors

and compare with BES projected accuracy on various relevant observables

Indirect constraints in 2012

In 2012, we expect from B-machines (super-B factories and LHCb)

$$\sigma[\sin(2\beta)] \to 0.011 \qquad \sigma(\alpha) \to 5^\circ \qquad \sigma(\gamma) \to 3^\circ$$

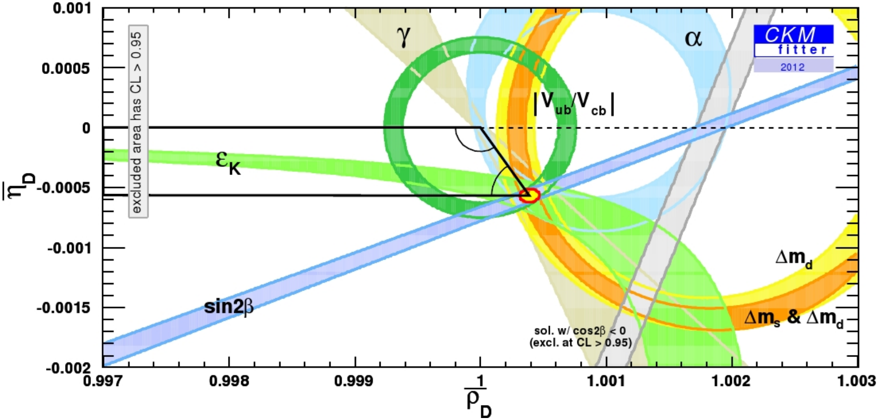
$$\sigma(|V_{ub}|) \to 4\% \qquad \sigma(|V_{cb}|) \to 1.5\%$$

Improved B and K other observables both from theory and experiment

Observable	CKM	Had. param	Lattice error	Exp. error
$Br(B \to \tau\nu)$	$\lvert V_{ub}\rvert$	f_B	4%	10%
Δm_s	$\lvert V_{ts}V_{tb}\rvert$	$f_{Bs}\sqrt{B_{Bs}}$	3%	0.7%
$\frac{\Delta m_s}{\Delta m_d}$	$\left\lvert\frac{V_{ts}}{V_{td}}\right\rvert$	ξ	1.5%	For Δm_d : 0.8%
ε_K	$V_{qs}V_{qd}^*$	B_K	2%	0.4%

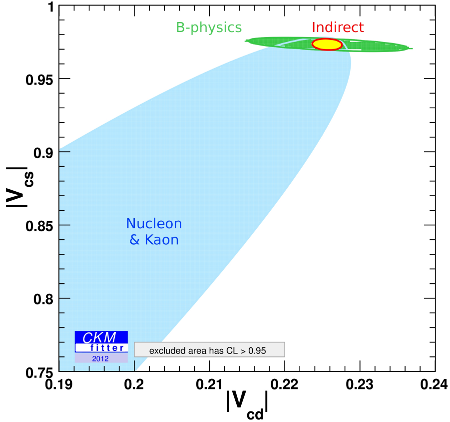
(accuracy on $|V_{ud}|$ and $|V_{us}|$ essentially unchanged)

2012 indirect constraints : D-UT



$$\frac{V_{ud}V_{cd}^*}{V_{us}V_{cs}^*} + 1 + \frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*} = 0 \qquad \bar{\rho}_D + i\bar{\eta}_D = -\frac{V_{ud}V_{cd}^*}{V_{us}V_{cs}^*}$$

2012 indirect constraints : $|V_{cd}|$ and $|V_{cs}|$



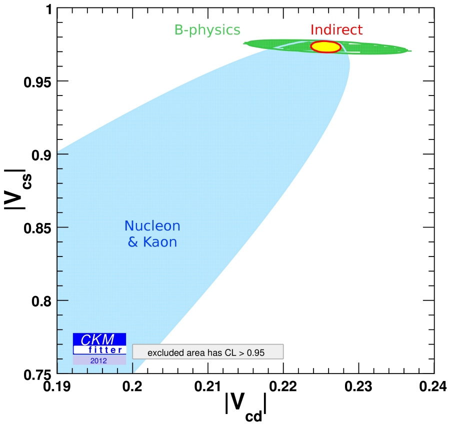
$$\sigma(|V_{cd}|)/|V_{cd}| = 0.4\% \quad \sigma(|V_{cs}|)/|V_{cs}| = 0.4\% \quad \frac{\sigma(|V_{cd}|/|V_{cs}|)}{|V_{cd}|/|V_{cs}|} = 0.02\%$$

2012 direct constraints

- projected experimental accuracy from BES
- (admittedly handwaving) estimates concerning lattice QCD

Observable	CKM	QCD	Lattice	Exp meas	Exp err
$Br(D \to \ell\nu)$	$\lvert V_{cd}\rvert$	f_D	2%	$f_D \lvert V_{cd}\rvert$	1.1%
$Br(D_s \to \ell\nu)$	$\lvert V_{cs}\rvert$	f_{Ds}	1.5%	$f_{Ds} \lvert V_{cs}\rvert$	0.7%
$\frac{Br(D_s\to\ell\nu)}{Br(D\to\ell\nu)}$	$\left\lvert\frac{V_{cs}}{V_{cd}}\right\rvert$	$\frac{f_{Ds}}{f_D}$	1%	$\left\lvert\frac{V_{cs} f_{Ds}}{V_{cd} f_D}\right\rvert$	0.8%
$d\Gamma(D^0 \to \pi^-)$	$\lvert V_{cd}\rvert$	$F_{D\to\pi}(0)$	4%	$\lvert V_{cd}\rvert F_{D\to\pi}(0)$	0.6%
$d\Gamma(D^0 \to K^-)$	$\lvert V_{cs}\rvert$	$F_{D\to K}(0)$	3%	$\lvert V_{cs}\rvert F_{D\to K}(0)$	0.5%
$d\Gamma(D_s \to K)$	$\lvert V_{cd}\rvert$	$F_{D_s\to K}(0)$	2%	$\lvert V_{cd}\rvert F_{D_s\to K}(0)$	1.2%
$d\Gamma(D_s \to \phi)$	$\lvert V_{cs}\rvert$	$F_{D_s\to\phi}(0)$	1%	$\lvert V_{cs}\rvert F_{D_s\to\phi}(0)$	0.8%

2012 constraints : $|V_{cd}|$ and $|V_{cs}|$



BES accuracy

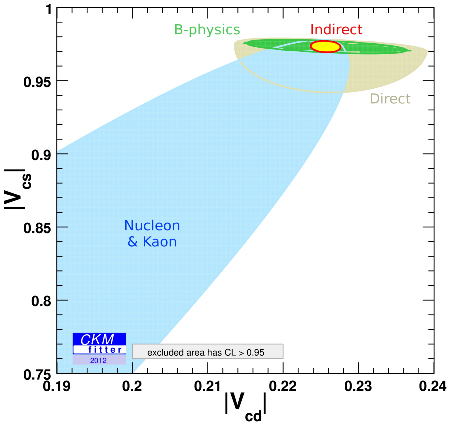
- For leptonic D decays

$$\begin{aligned}\sigma(|V_{cd}|)/(|V_{cd}|) &= 2.3\% \\ \sigma(|V_{cs}|)/|V_{cs}| &= 1.7\% \\ \frac{\sigma(|V_{cd}|/|V_{cs}|)}{|V_{cd}|/|V_{cs}|} &= 1.3\%\end{aligned}$$

- For semileptonic D decays ($D_s \to K$ and $D_s \to \phi$):

$$\begin{aligned}\sigma(|V_{cd}|)/(|V_{cd}|) &= 2.4\% \\ \sigma(|V_{cs}|)/|V_{cs}| &= 1.3\%\end{aligned}$$

2012 constraints : $|V_{cd}|$ and $|V_{cs}|$



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Interesting competition between indirect and direct constraints

What if... there was a disagreement ?

CKMfitter provides

- a metrology tool : what are the CKM parameters assuming the SM ?
- but also a test of hypothesis : how well are the measurements compatible with the SM ?

Build a test for $|V_{cd}|$ and $|V_{cs}|$

- Determine $|V_{cd}|$ and $|V_{cs}|$ directly (D decays)
- Determine $|V_{cd}|$ and $|V_{cs}|$ indirectly (K and B decays + SM)
- Determine compatibility between the two determinations (p-value)

$\Longrightarrow$ Needed in case of "tension" between direct and indirect determinations

Outlook

CKM mechanism unifying scheme for flavour physics

- Weak part of charm decays constrained by B and $K\ldots$
- As long as one knows strong interaction part (lattice can help)

Two different ways of seeing the problem

- CP-violation : D-unitarity triangle
- Semileptonic and leptonic decays : $[V_{cd}, V_{cs}]$ plot

Outlook

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Very rough summary of

- 2007 : $[V_{cd}, V_{cs}]$ poorly known directly
- 2012 : similar accuracy for indirect (SM) and direct determination

More work to be done : limited to leptonic and semileptonic D decays

- CP-violation in D-decays
- Combining B- and D-decays (related by heavy-quark expansion)