2021 Update on ε_K with lattice QCD inputs

(LANL-SWME Collaboration)
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Input Parameters

- Here we present input parameters in Tables 1, 2, and 3

Table 1: Input parameters

Input	Value	Ref.
$\lvert\varepsilon_K\rvert_{\rm exp}$	$2.228(11) \times 10^{-3}$	PDG 2019
η_{cc}	1.72(27)	Bailey PRD92
η_{tt}	0.5765(65)	Buras PRD78
η_{ct}	0.496(47)	Brod PRD82
G_F	$1.1663787(6) \times 10^{-5}$ GeV^{-2}	PDG 2019
M_W	80.379(12) GeV	PDG 2019
$m_c(m_c)$	1.275(5) GeV	FLAG 19
$m_t(m_t)$	163.08(38)(17) GeV	PDG 2019 + SWME
θ	43.52(5)°	PDG 2019
m_{K^0}	497.611(13) MeV	PDG 2019
ΔM_K	$3.484(6) \times 10^{-12}$ MeV	PDG 2019
F_K	155.7(3) MeV	FLAG 2019
λ	0.2243(5)	PDG 2019
$\bar\rho$	0.146(22)	UTFIT 2017
$\bar\eta$	0.333(16)	UTFIT 2017

Table 2: Input parameter ξ_0

Input	Value	Ref.
ξ_0(indirect)	$-1.738(177) \times 10^{-4}$	SWME + RBC-UK 2020
ξ_0(direct)	$-2.102(472) \times 10^{-4}$	SWME + RBC-UK 2020

Table 3: Input parameters $\lvert V_{cb}\rvert$

channel	method	value	Ref.
Exclusive	CLN $(+\alpha)$	39.25(56)	HFLAV 2021
Exclusive	BGL	38.57(78)	FNAL/MILC 2021
Inclusive	1S scheme	41.98(45)	HFLAV 2021

Exclusive $\lvert V_{cb}\rvert$ between CLN and BGL

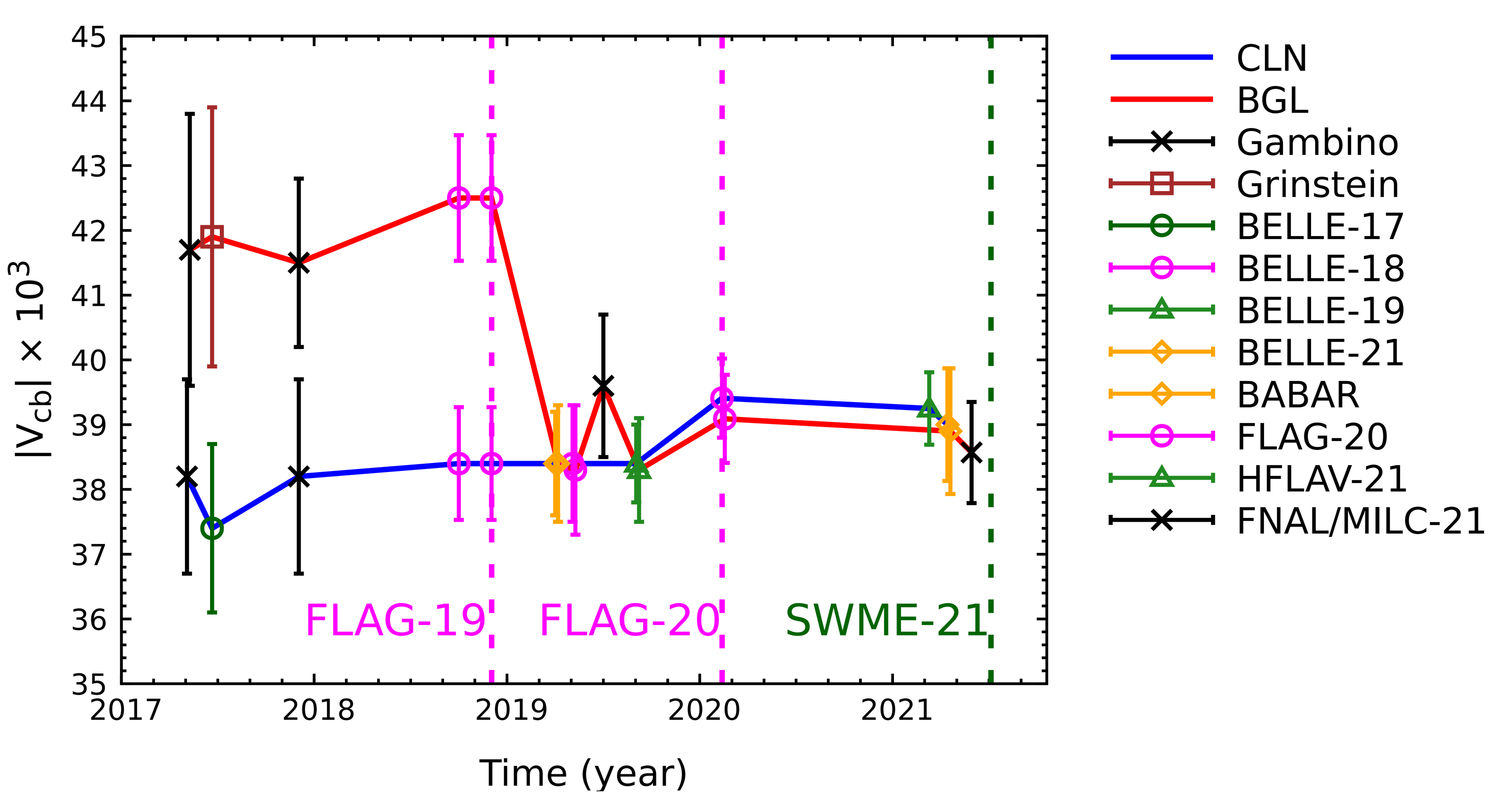

Figure 1: Exclusive $\lvert V_{cb}\rvert$ between CLN and BGL

- In Fig. 1, we present time evolution of exclusive $\lvert V_{cb}\rvert$ obtained using both CLN and BGL parametrization methods.
- It turns out that results for CNL and BGL are consistent with each other.

Master formula for ε_K

- The master formula for ε_K is given in SWME 2016, 2018 (PRD98).

$$\varepsilon_K = \exp(i\theta)\,\sqrt{2}\,\sin(\theta)\left(C_\varepsilon\, X_{\rm SD}\, \hat B_K + \frac{\xi_0}{\sqrt{2}} + \xi_{\rm LD}\right) + \mathcal{O}(\omega\varepsilon') + \mathcal{O}(\xi_0\Gamma_2/\Gamma_1)$$

$$X_{\rm SD} = {\rm Im}\,\lambda_t\Big[{\rm Re}\,\lambda_c\,\eta_{cc}\,S_0(x_c) - {\rm Re}\,\lambda_t\,\eta_{tt}\,S_0(x_t) - ({\rm Re}\,\lambda_c - {\rm Re}\,\lambda_t)\,\eta_{ct}\,S_0(x_c,x_t)\Big]$$

$$\lambda_i = V_{is}^* V_{id}, \qquad x_i = m_i^2/M_W^2, \qquad C_\varepsilon = \frac{G_F^2 F_K^2 m_K M_W^2}{6\sqrt{2}\,\pi^2 \Delta M_K}$$

$$\frac{\xi_0}{\sqrt{2}} = \frac{1}{\sqrt{2}}\frac{{\rm Im}A_0}{{\rm Re}A_0} = \text{Absorptive LD Effect} \approx -7\%$$

$$\xi_{\rm LD} = \text{Dispersive LD Effect} \approx \pm 2\% \quad \longrightarrow \text{systematic error}$$

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Results for ε_K from the Standard Model

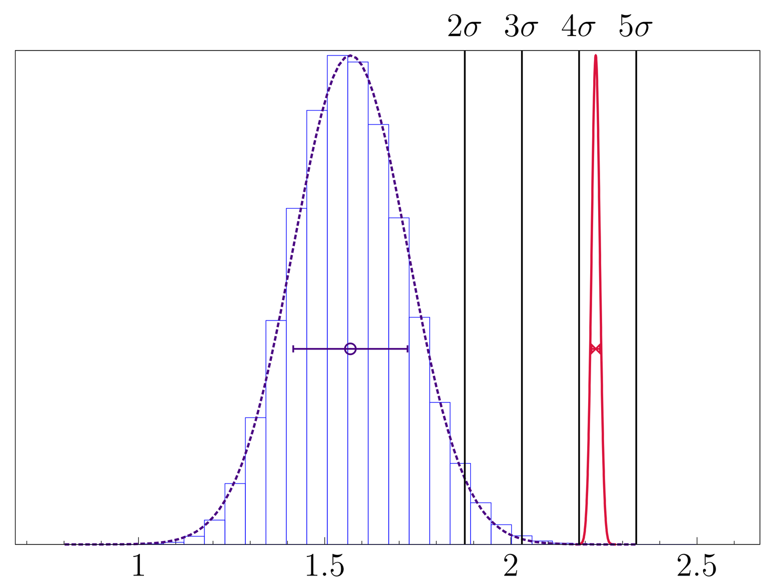

Figure 2: $\lvert\varepsilon_K\rvert$ with ex. $\lvert V_{cb}\rvert$ (CLN)

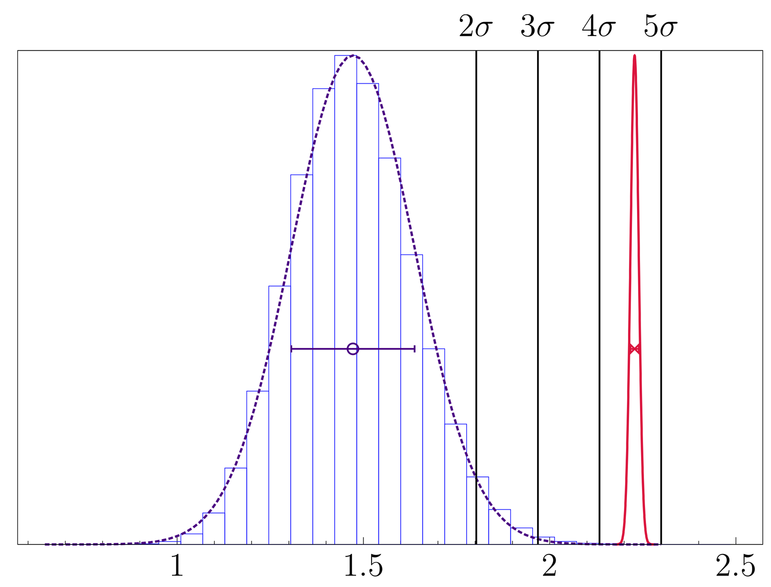

Figure 3: $\lvert\varepsilon_K\rvert$ with ex. $\lvert V_{cb}\rvert$ (BGL)

- In Fig. 2, we present results for $\lvert\varepsilon_K\rvert$ obtained using lattice QCD inputs with exclusive $\lvert V_{cb}\rvert$ of HFLAV 2021 (CLN).
- In Fig. 3, we present results for $\lvert\varepsilon_K\rvert$ obtained using lattice QCD inputs with exclusive $\lvert V_{cb}\rvert$ of FNAL-MILC 2021 (BGL).
- $\Delta\varepsilon_K = \lvert\varepsilon_K^{\rm SM}\rvert - \lvert\varepsilon_K^{\rm Exp}\rvert$
- $\Delta\varepsilon_K$ represents a gap in ε_K between the SM theory and the experiment.

Table 4: $\lvert\varepsilon_K\rvert$ and $\Delta\varepsilon_K$

Method	$\lvert\varepsilon_K\rvert$ (in unit of 10^{-3})	$\Delta\varepsilon_K$
Exclusive $\lvert V_{cb}\rvert$(CLN)	1.569 ± 0.153	4.3σ
Exclusive $\lvert V_{cb}\rvert$(BGL)	1.472 ± 0.165	4.6σ
Inclusive $\lvert V_{cb}\rvert$(1S)	2.012 ± 0.176	1.2σ
Experiment	2.228 ± 0.011	0

ε_K history

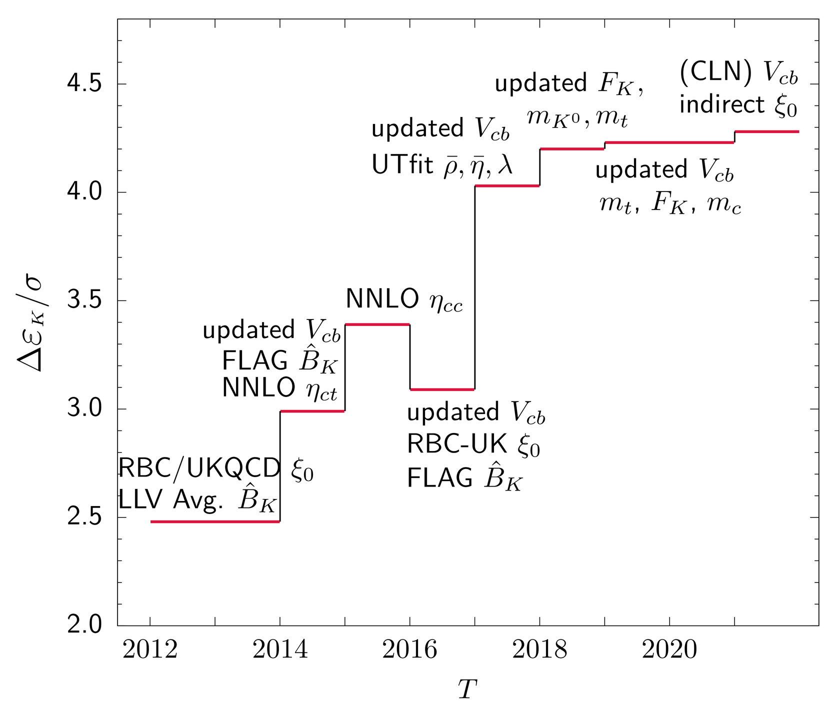

Figure 4: History of $\Delta\varepsilon_K$ with CLN

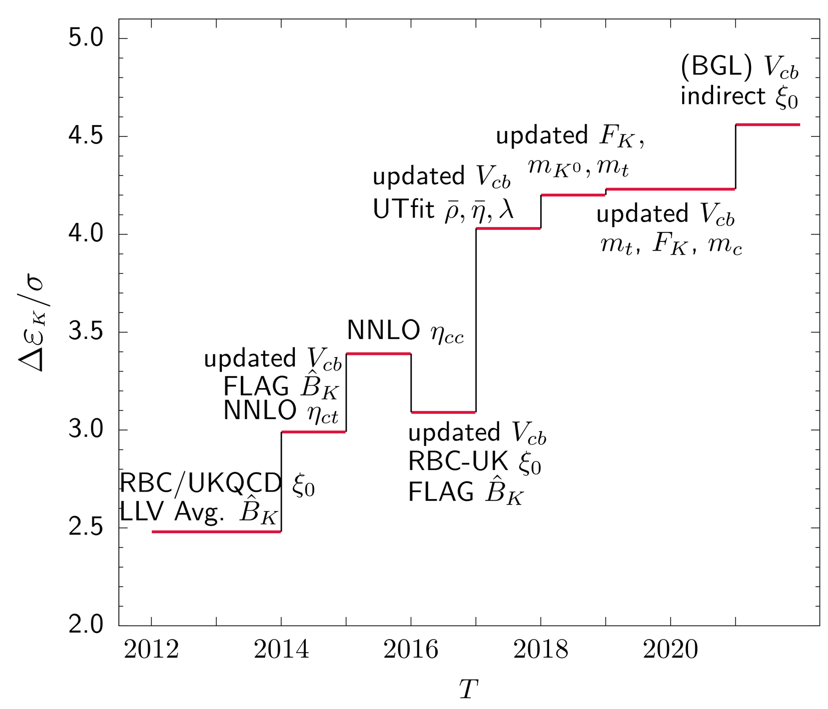

Figure 5: History of $\Delta\varepsilon_K$ with BGL

- In Fig. 4, we present $\Delta\varepsilon_K$ as a function of time, which are obtained using lattice QCD inputs with exclusive $\lvert V_{cb}\rvert$ (HFLAV 2021, CLN).
- In Fig. 5, we present $\Delta\varepsilon_K$ as a function of time, which are obtained using lattice QCD inputs with exclusive $\lvert V_{cb}\rvert$ (FNAL-MILC 2021, BGL).

Summary & Outlook

1. We find that

$$\Delta\varepsilon_K^{\rm excl} = 4.6\sigma \sim 3.9\sigma \qquad \text{(Lattice QCD)} \qquad (1)$$

$$\Delta\varepsilon_K^{\rm incl} = 1.2\sigma \qquad \text{(HQE, QCD Sum Rules)} \qquad (2)$$

2. It is too early to conclude that there might be something wrong with the SM.
3. Let us wait for the next round reanalysis of the BELLE2 group on the entire data sets of the $\bar B \to D^*\ell\bar\nu$ decays, using both CLN and BGL.
4. Meanwhile, it would be very helpful to reduce the errors for $h_{A_1}(w=1)$, $\bar\eta$, ξ_0, ξ_2, and $\xi_{\rm LD}$ in lattice QCD.
5. Please stay tuned for the update.

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