Status and progress of lattice QCD

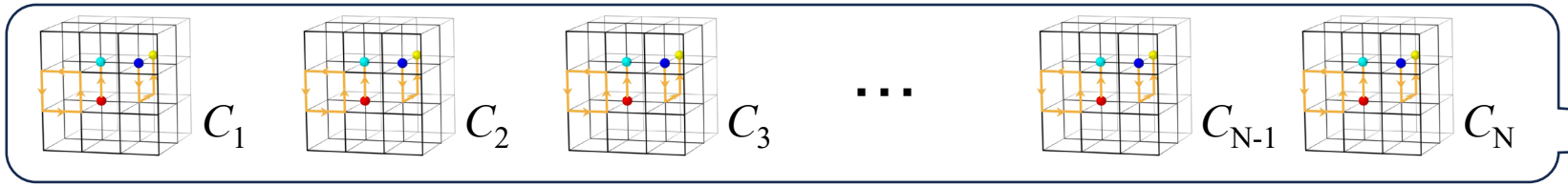
KEK, Sokendai, Nagoya Univ. KMI

Takashi Kaneko

The 12th International Workshop on CKM Unitarity Triangle,
Santiago de Compostela, Sep 18, 2023

lattice QCD simulation

on finite-volume



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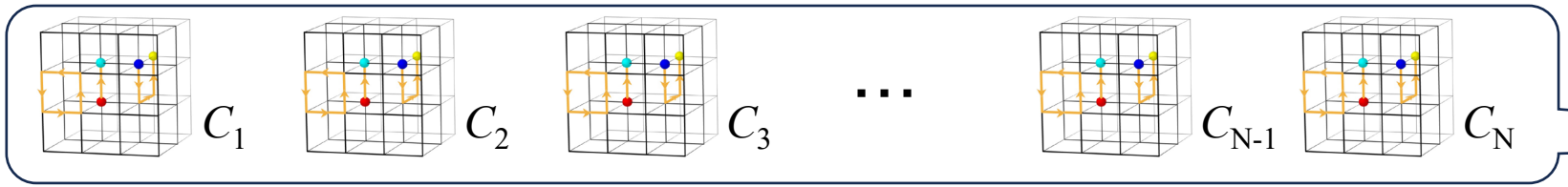

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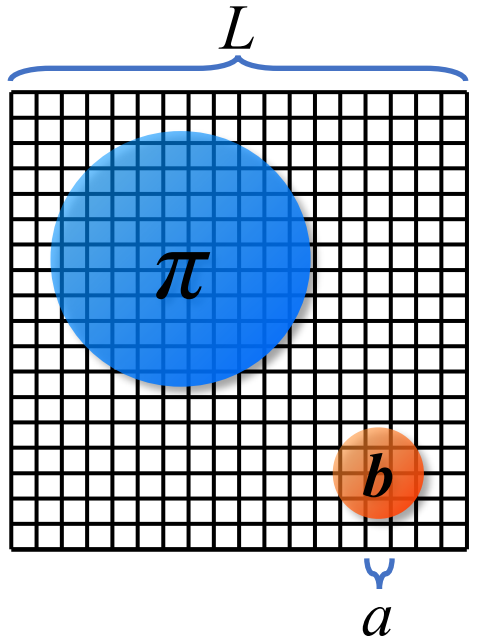
w/ bottom quarks

- multi-scale problem : $a \ll m_b^{-1} \ll M_\pi^{-1} \ll L \Rightarrow\ L/a \geq \mathrm{O}(100)\ \Leftrightarrow\ \text{cost} \propto (L/a)^7$
- relativistic action w/ unphysically small m_b, or effective field theory action for b



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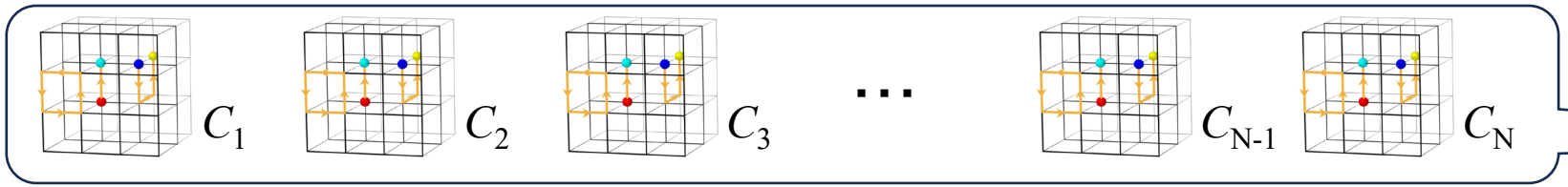

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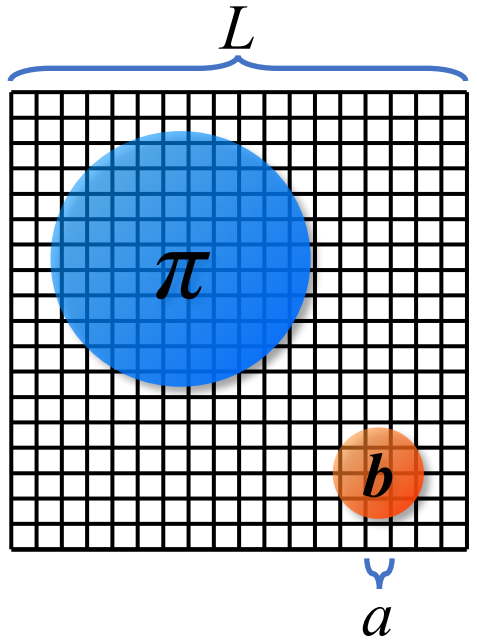

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- need a method to connect finite L Euclidean MEs to infinite L Minkowski ones

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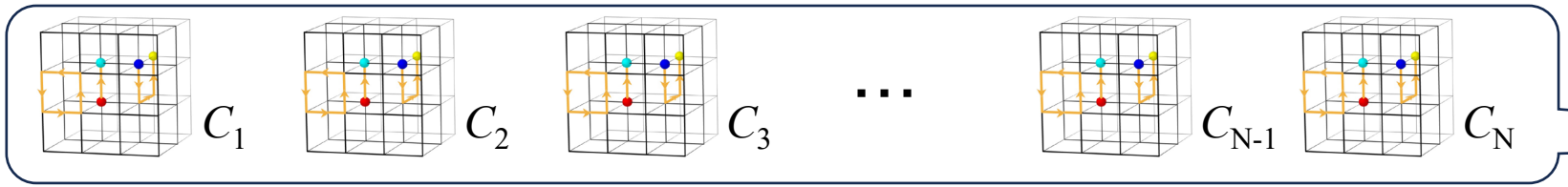

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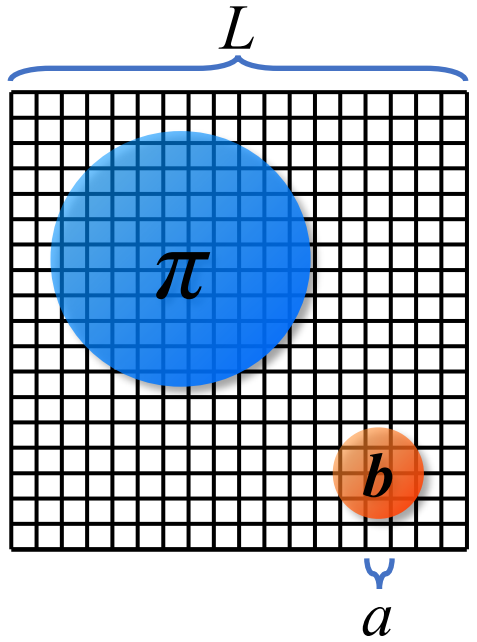

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status and progress w/ powerful computers and newly-developed methods

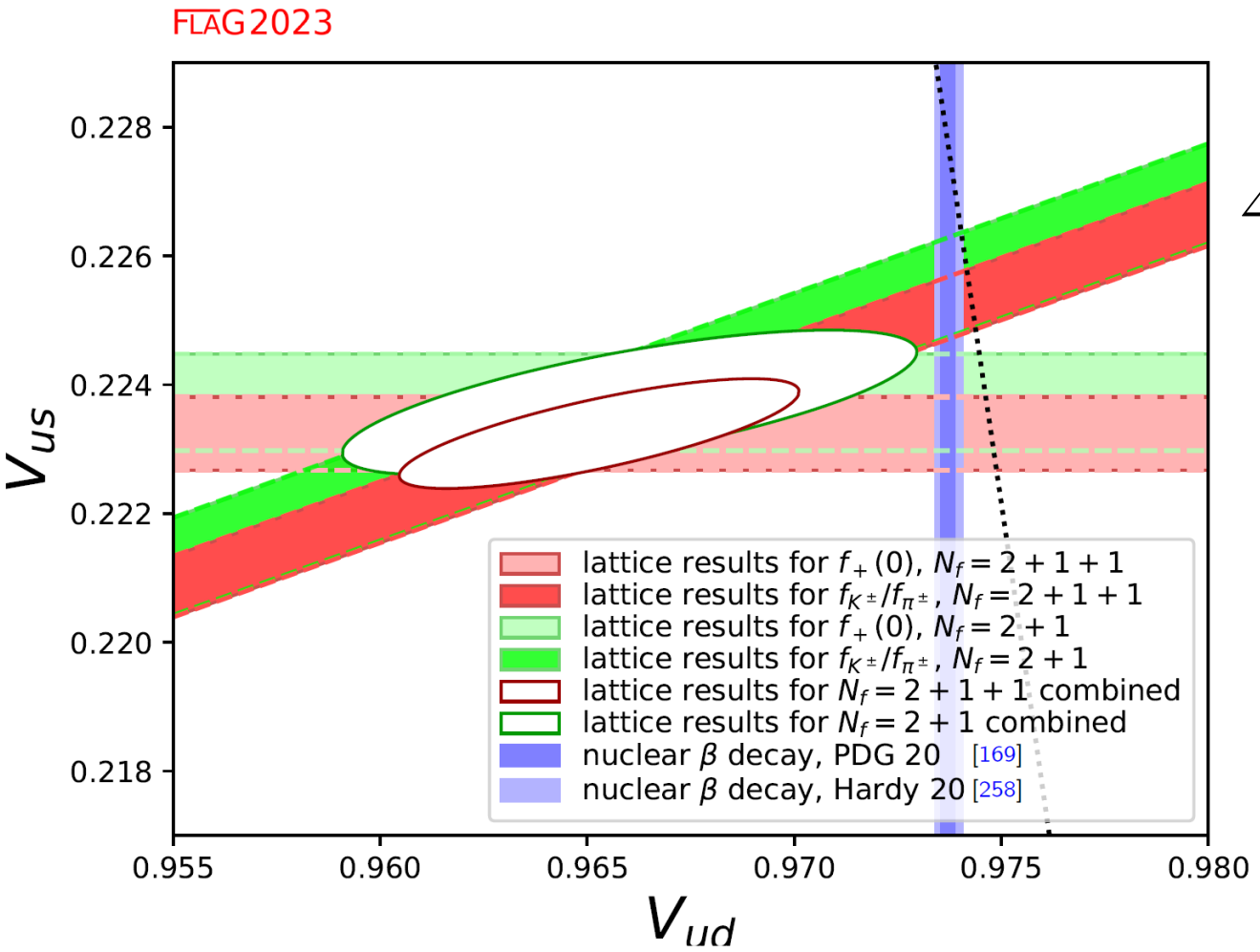
at this workshop

- Elvira Gamiz, "Overview of D form factors and decay constants (lattice)", WG1 Tue 10:00-
- Felix Erben, "Input to V_{us} from lattice QCD including the progress on hyperon decays", WG1 Wed 10:00-
- Mikhail Gorchtein, "Improved radiative corrections for $K_{\ell 3}$ decays and superallowed β decays", WG1 Thu 11:30-
- Ryan Kellermann, "Updates on inclusive charmed and bottomed meson decays from lattice", WG1&2 Tue 12:00-
- Alejandro Vaquero, "$B_{(s)} \to D^{(*)}_{(s)}$ from FNAL/MILC", WG2 Tue 18:03-
- Ludovico Vittorio, "Unitarity constraints and the dispersive matrix", WG2 Wed 9:00-
- Carolina Bolognani, "Combining lattice and sum rules to determine $|V_{ub}|/|V_{cb}|$", WG2 Wed 9:24-
- Luka Leskovec, "Lattice outlook on B->rho and B->K*", WG2&3 Thu 17:50-
- Chris Bouchard, "Rare $B \to \pi$ and $B \to K$ decays on the lattice", WG2&3 Thu 18:20-
- Brian Colquhoun, "$B \to \pi$, $B \to D^{(*)}$ from JLQCD", WG2&3 Thu 18:50-
- En-Hung Chao, "$K \to \mu\mu$ on the lattice", WG3 Mon 14:45-
- Ryan Hill, "Rare kaons on the lattice", WG3 Tue 14:45-
- Felix Erben, "Update on SU(3)-breaking ratios and bag parameters for $B_{(s)}$ mesons", WG4

Erben [WG1] Wed 10:00

Cabibbo angle anomaly

Flavour Lattice Averaging Group (FLAG) Web Update '23



new entry : ETM '21 $f_K / f_\pi (N_f{=}4)$ ~ FLAG'21 ave

$$f_{K^\pm}/f_{\pi^\pm} = 1.1932(21) \Rightarrow 1.1934(19) \quad \text{[0.16\% err]}$$

$$\Delta_{\text{CKM}} = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.00113(67) \quad [1.7\sigma]$$

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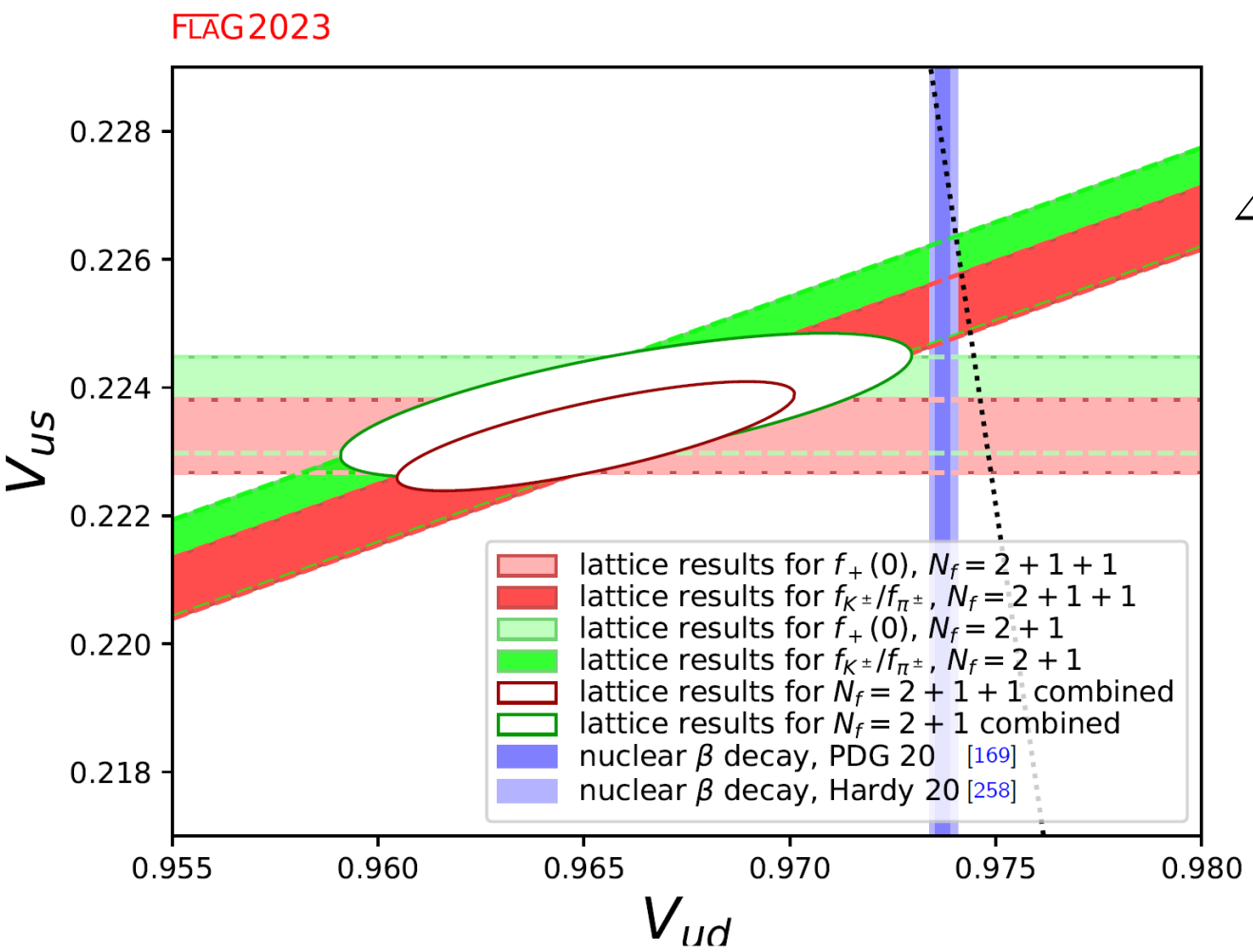

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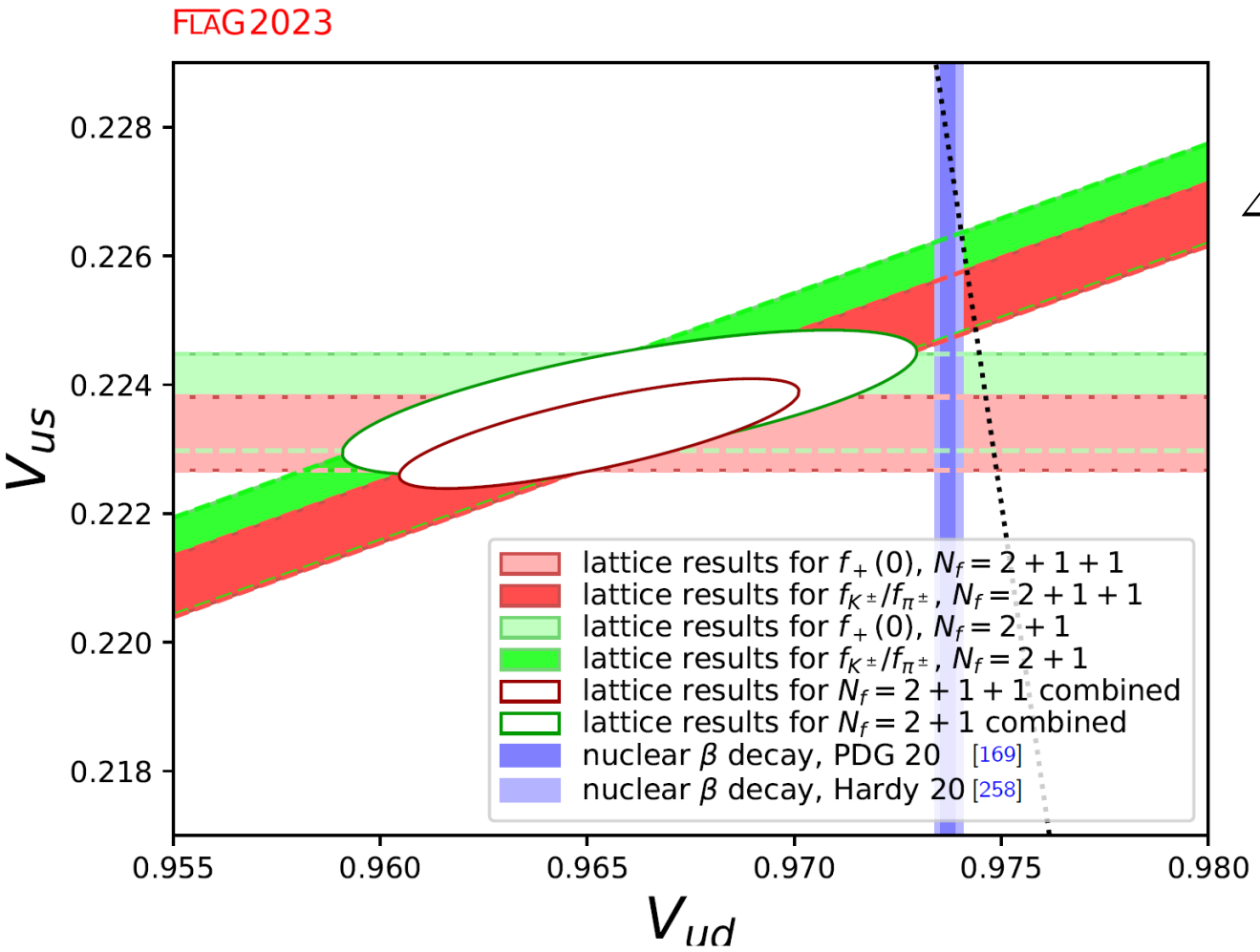

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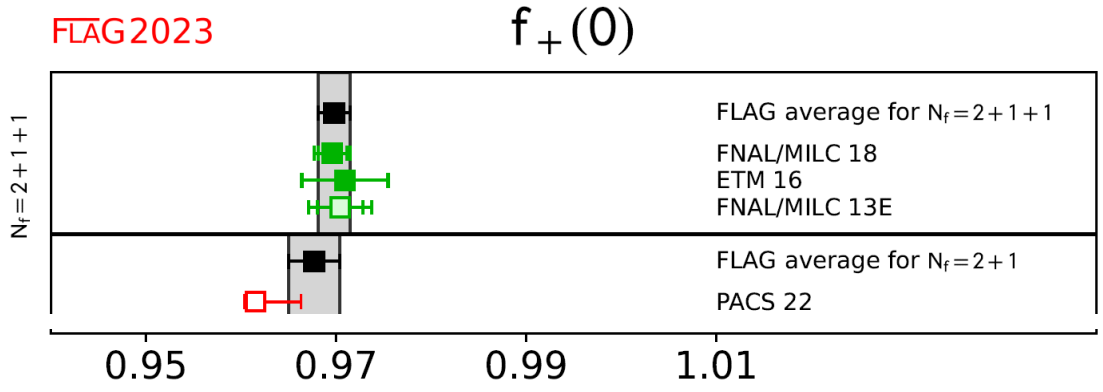

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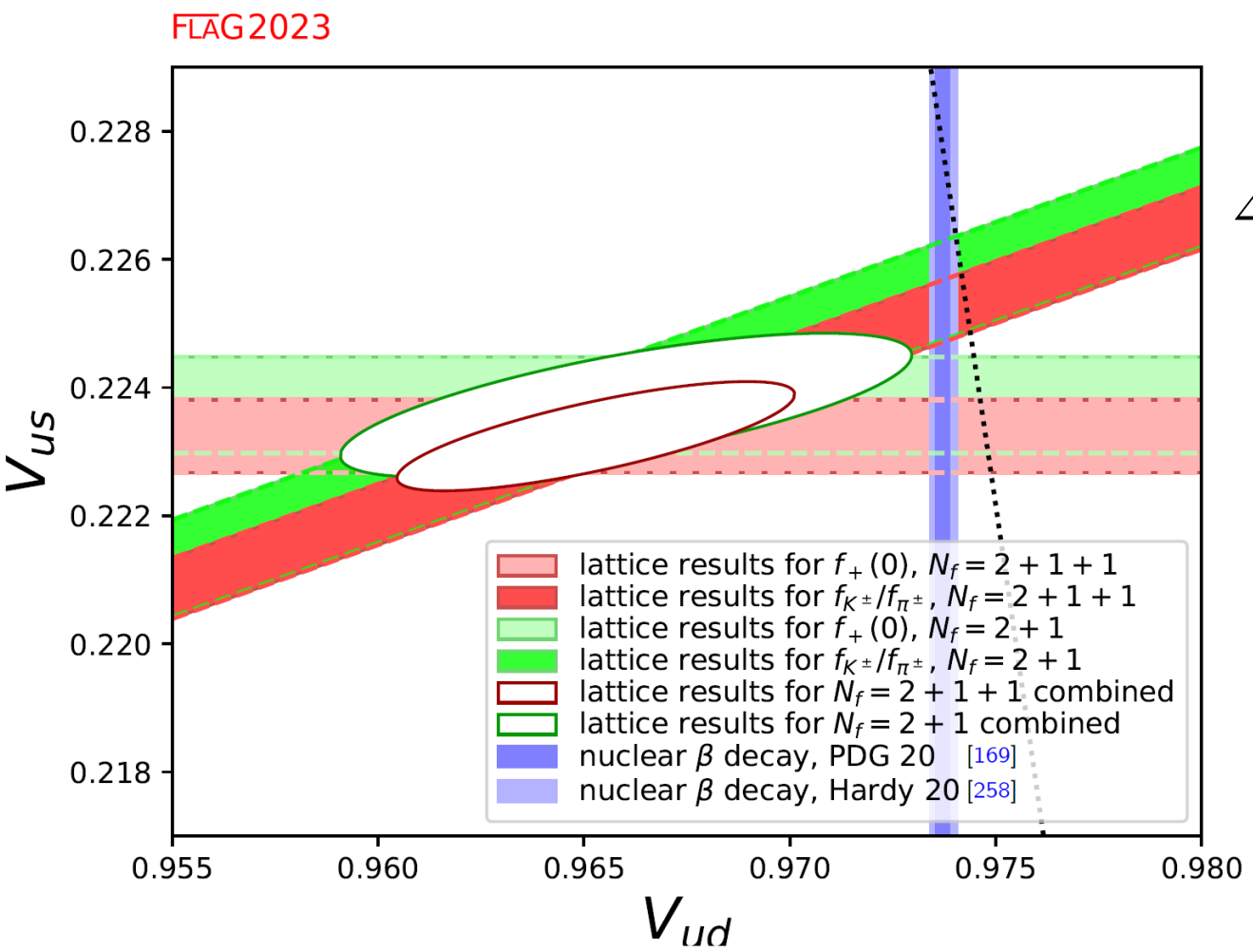

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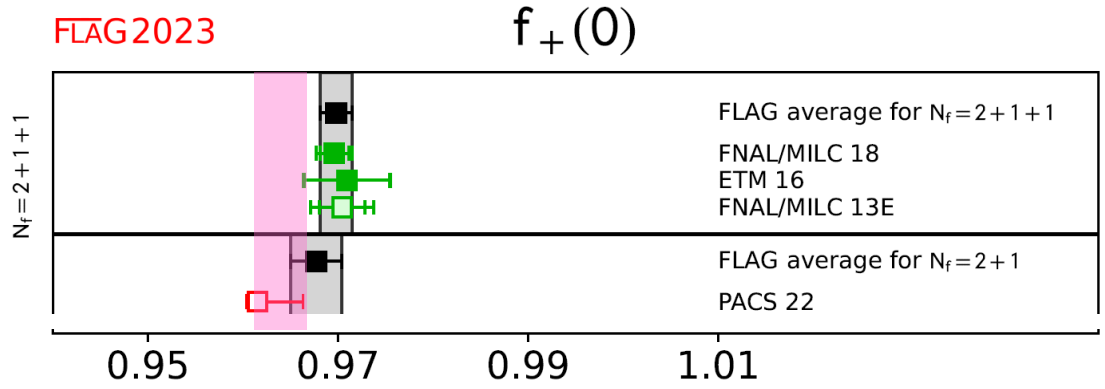


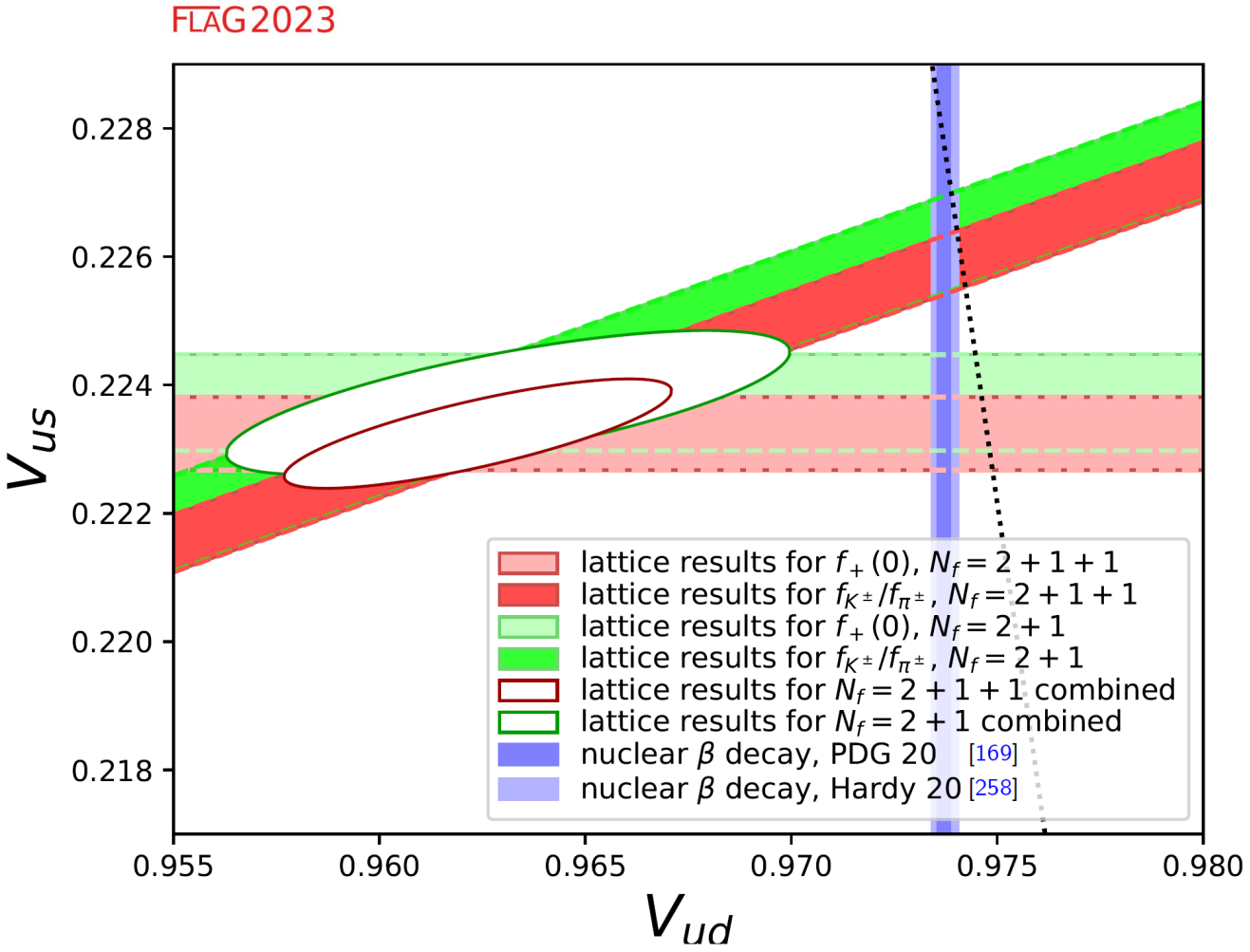
PACS @ Lattice 2023; N_f=3, 3 a's, L~10fm

$f_+(0) = 0.9634(24)_{\text{stat}} \Leftrightarrow 0.9696(19)$ (FNAL/MILC)

Gorchtein [WG1] Thu 11:30

Cabibbo angle anomaly

radiative corrections



isospin correction to $\Gamma(K\to\ell\nu)/\Gamma(\pi\to\ell\nu)$

- ChPT $\Rightarrow$ $\delta_{\mathrm{EM+SU(2)}}/2 = -0.56(11)\%$ [LEC, higher orders]
- RM123+SOTON '19 : $\delta_{\mathrm{EM+SU(2)}}/2 = -0.63(7)\%$
  - + smaller $|\Delta_{\mathrm{CKM}}|$ [1.2σ] with $P_{\ell 2}$ + β decay
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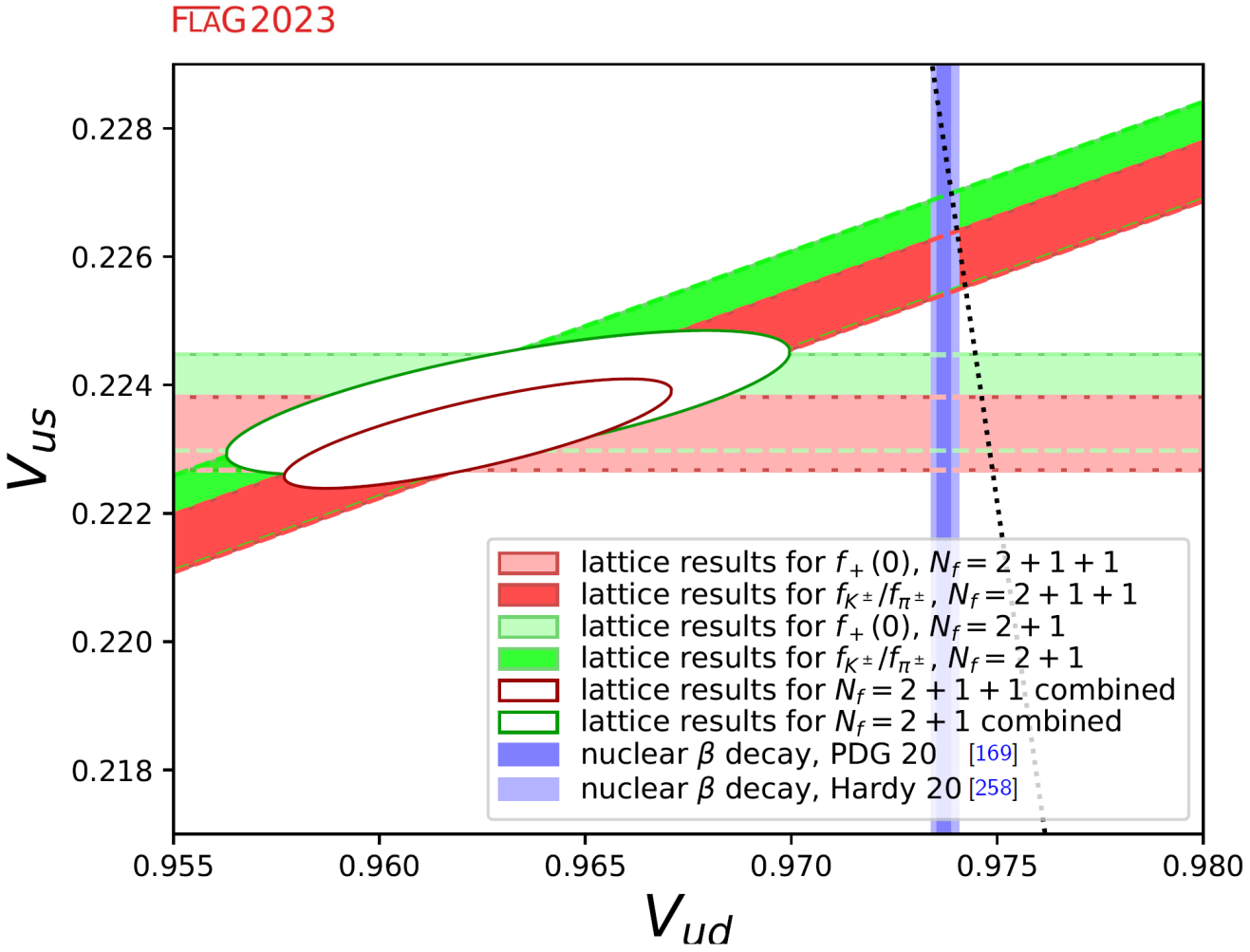

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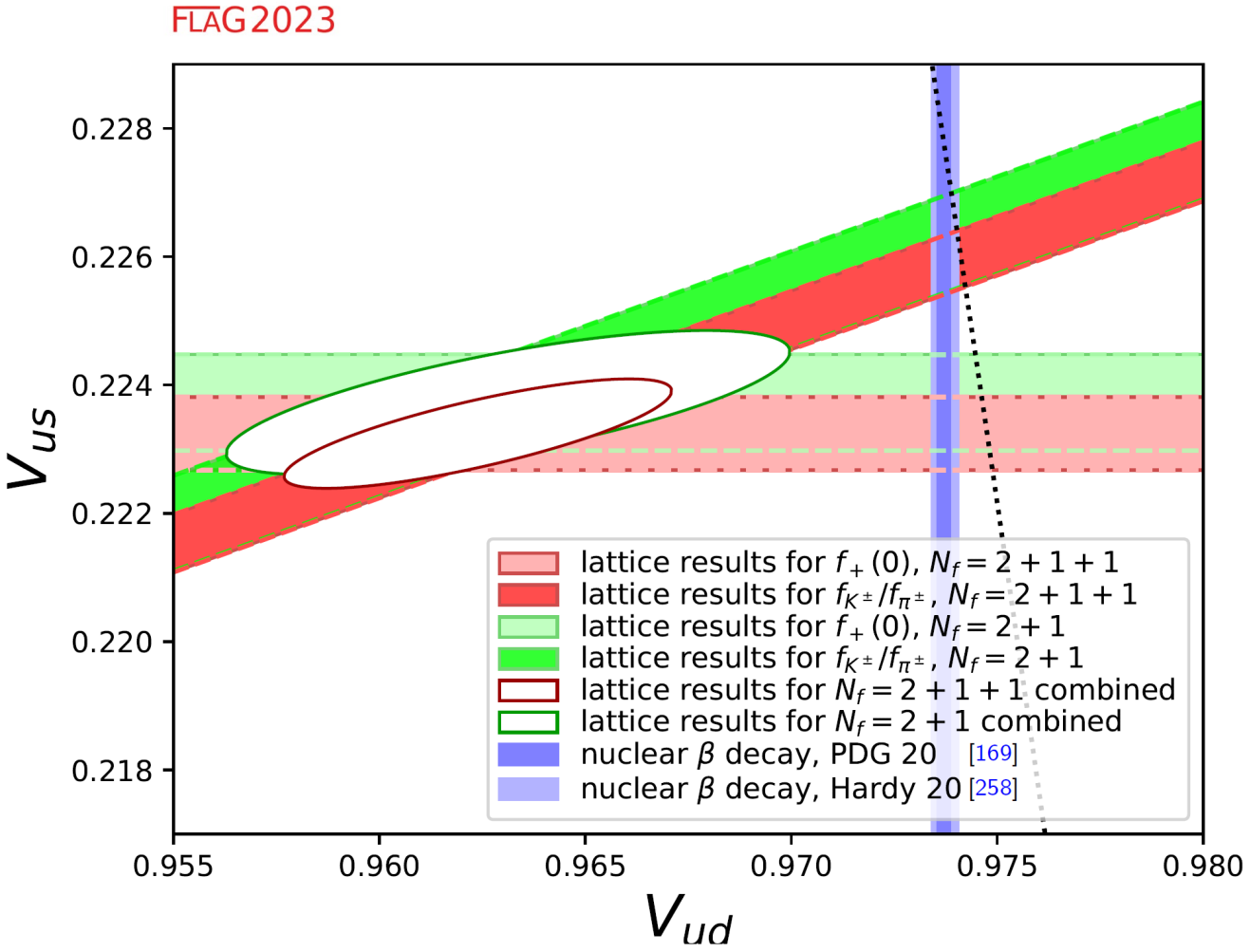

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γW box diagram to β decay

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Cabibbo angle anomaly

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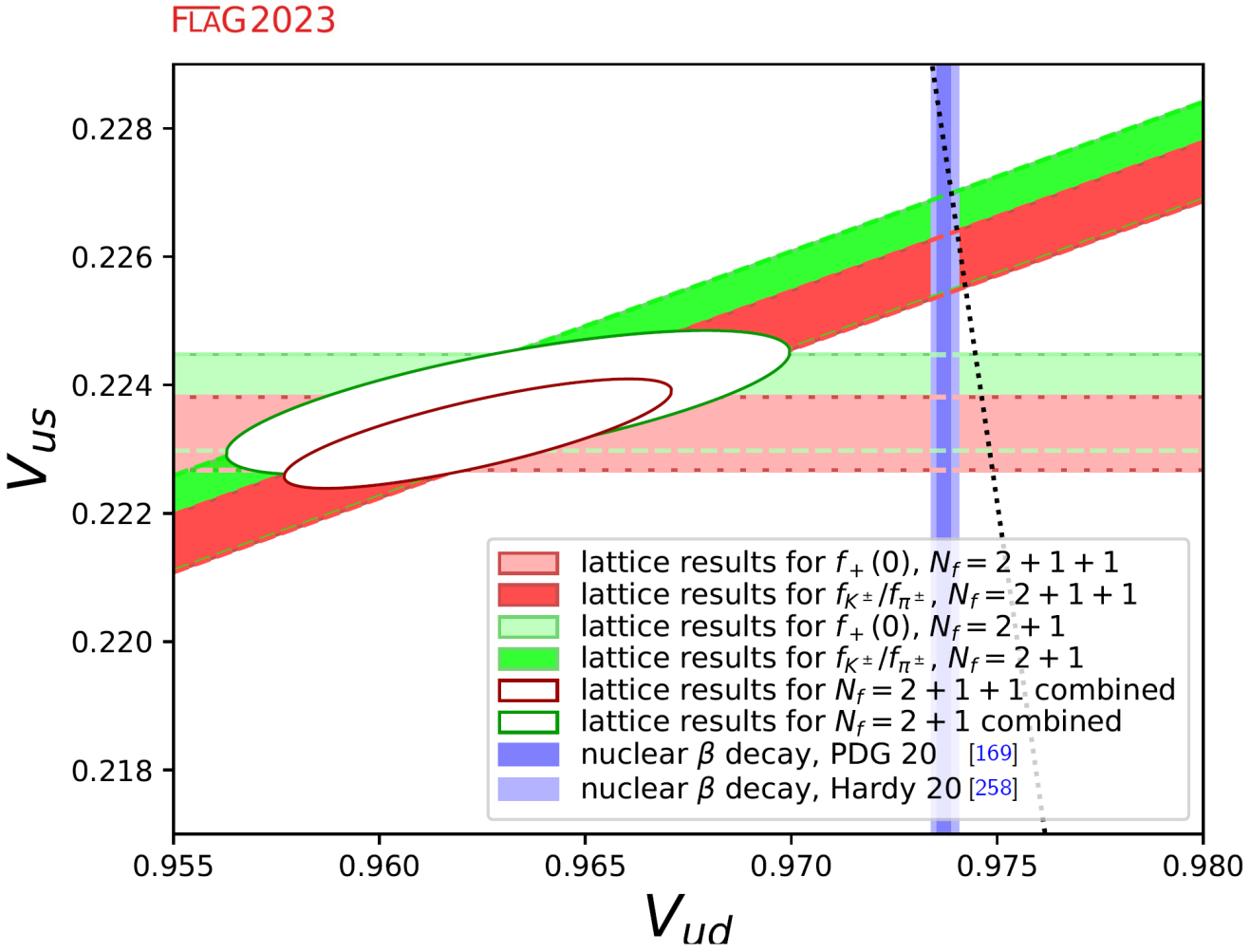

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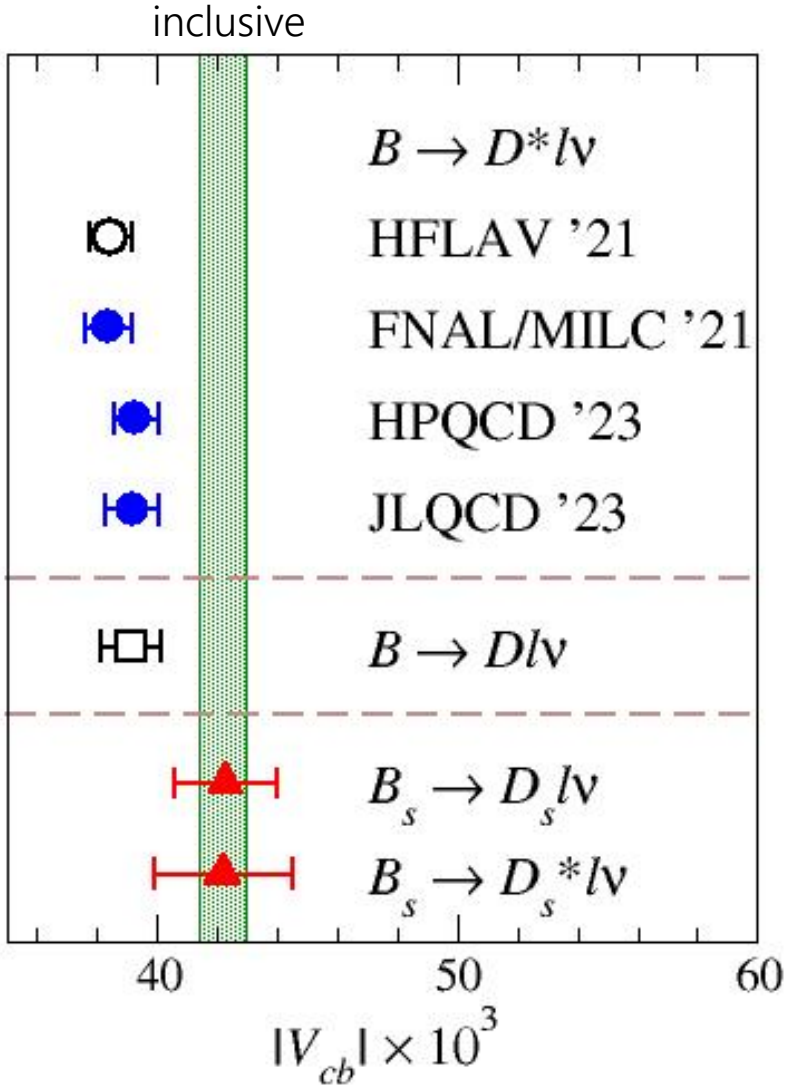
- Ma+ 2308.16755 : $\langle p|T[J_{\mathrm{EM}}J_{\mathrm{W},A}]|n\rangle$ on the lattice
  - $\Box_{\gamma W}(\le 2\mathrm{GeV}) \times 10_3$ = 1.62(10) → 1.49(8)
  - $|V_{ud}|$ = 0.97386(31), Δ_{CKM} = 2.1σ → 1.8σ
  - independent calc : Yoo+ @ Lattice 2023

$|V_{cb}|$

Vaquero [WG1+2] Tue 18:03

Colquhoun [WG2+3] Thu 18:50

$|V_{cb}|$ from $B_{(s)}$ decays



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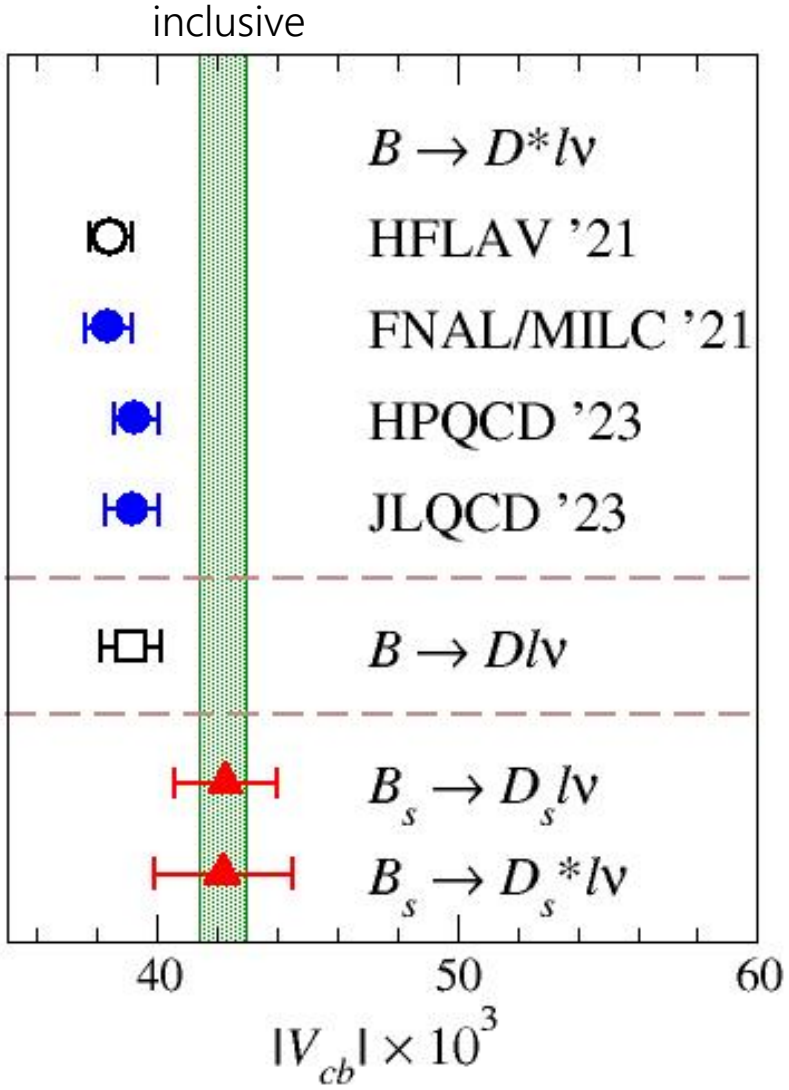

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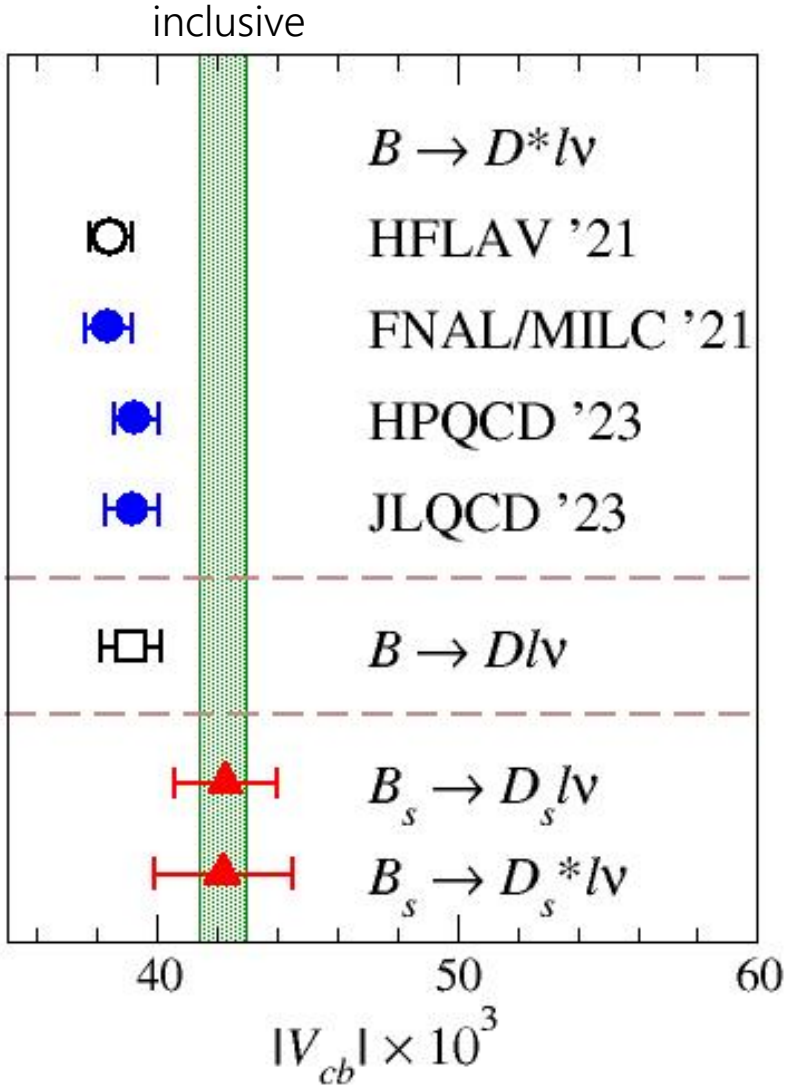

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D'Agostini bias Nucl. Inst. Meth.Phys. Res. A 346 (1994) 306

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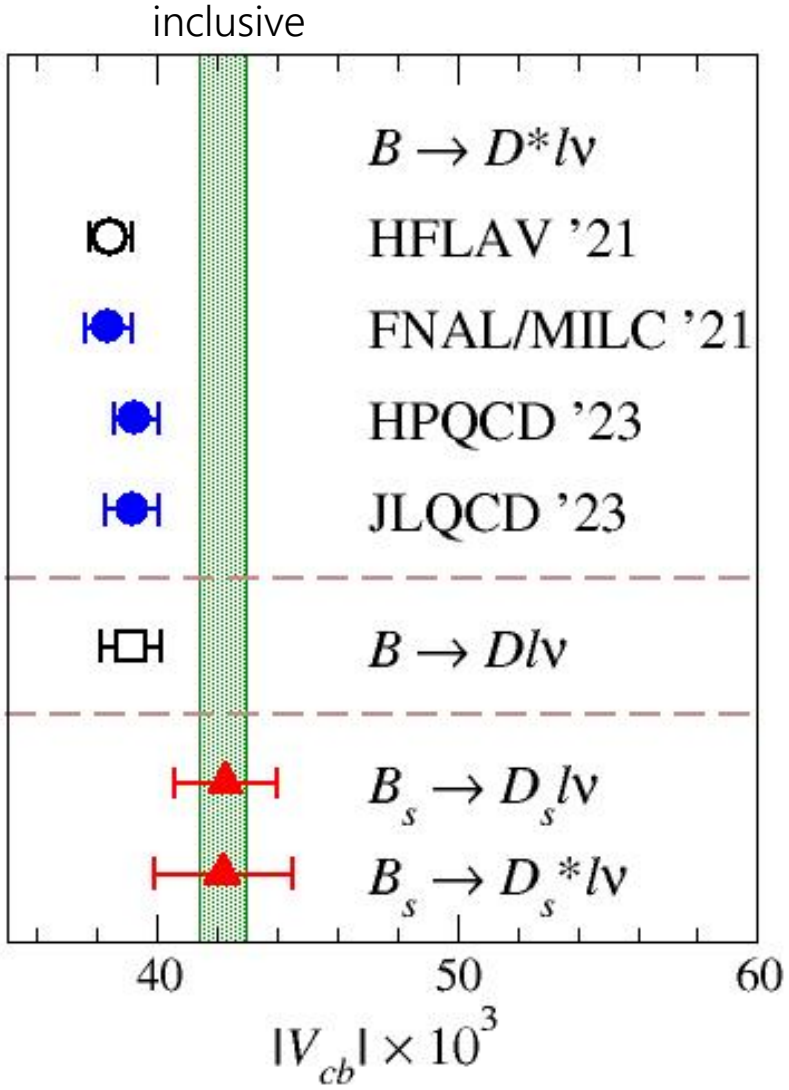

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HPQCD $B_s \to D_s^{(*)} \ell\nu$ FFs [1906.00701, 2105.11433] + LHCb data ⇒ 5% err

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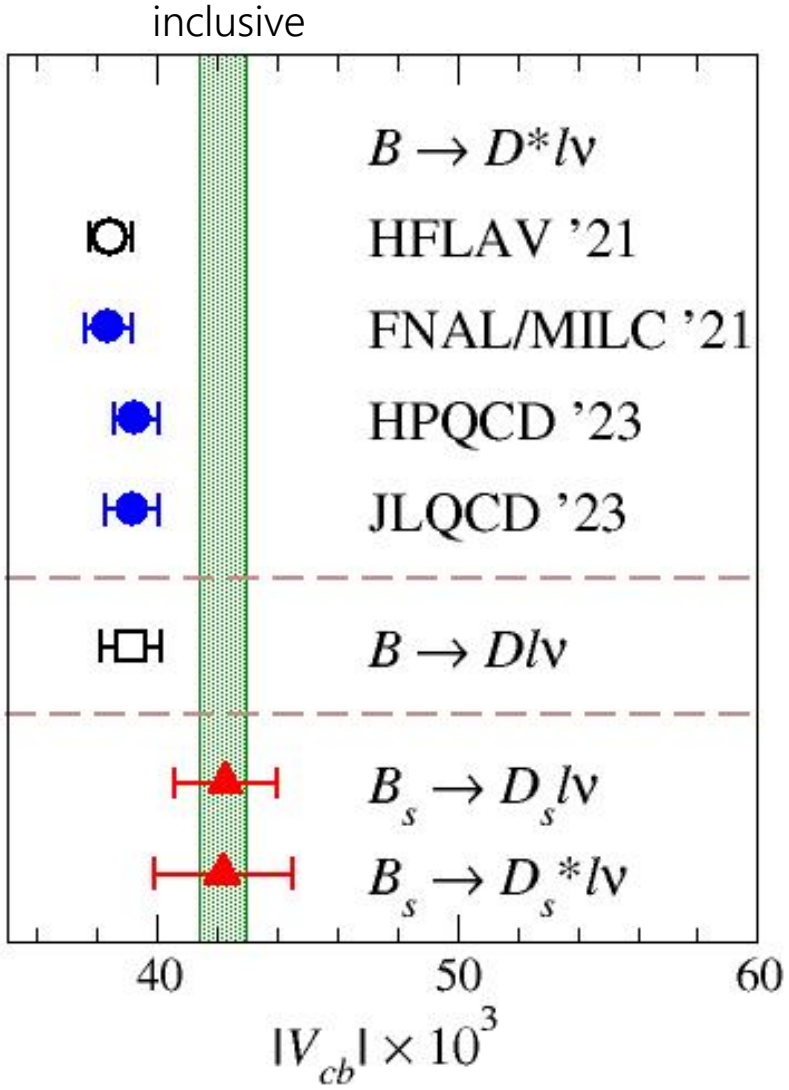

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quoted error ≈ comparable to exp: stat., $a \neq 0$, [$m_b < m_{b,\text{phys}}$]

@ Lattice '23: ($B \to D^*$) LANL-SWME ($B_s \to D_s$) Fermilab/MILC, …

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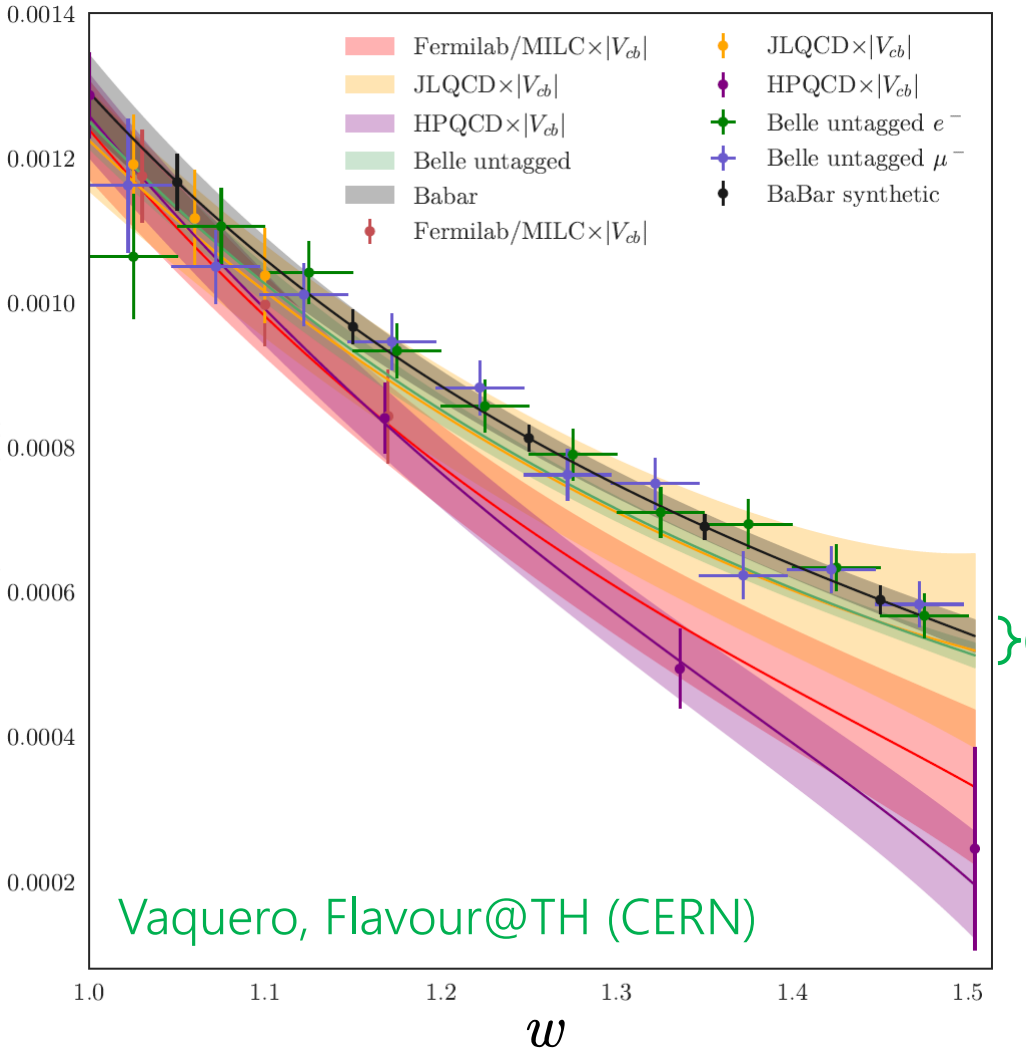

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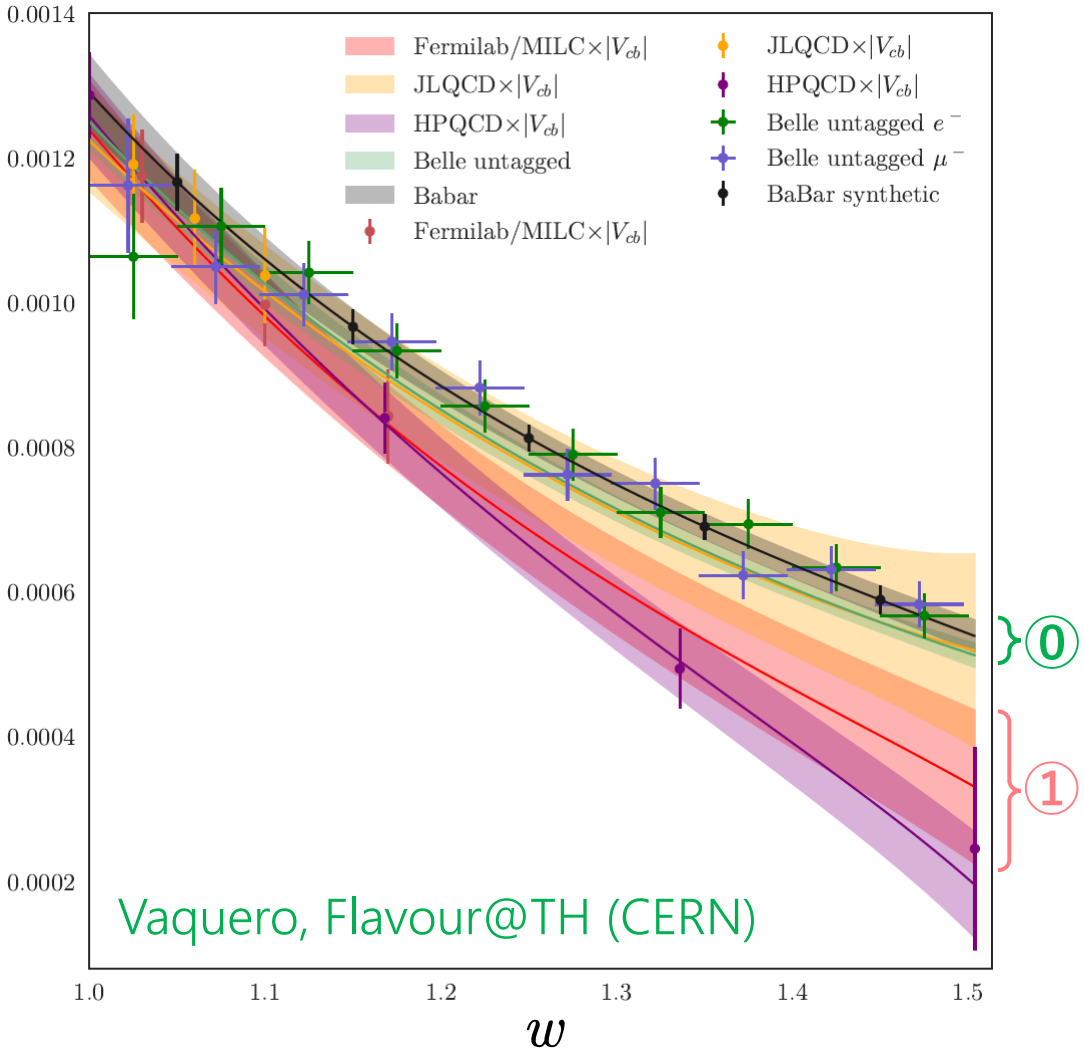

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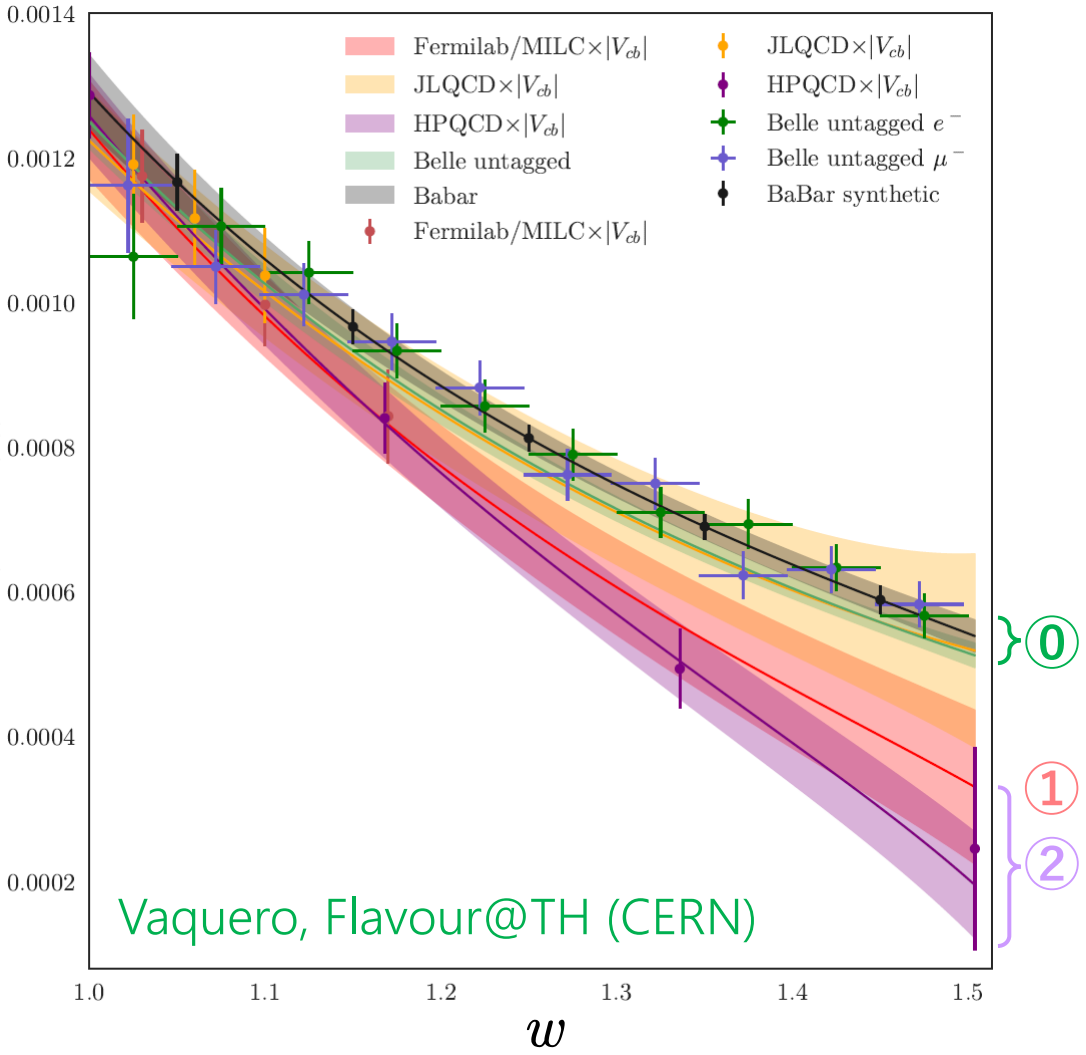

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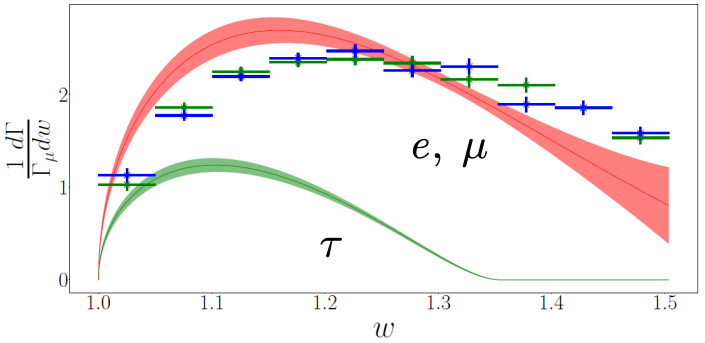
+ $|V_{cb}| = 44.2(1.8) \times 10^{-3}$ from total Γ



$\frac{1}{\Gamma_\mu}\frac{d\Gamma}{dw}$ vs w

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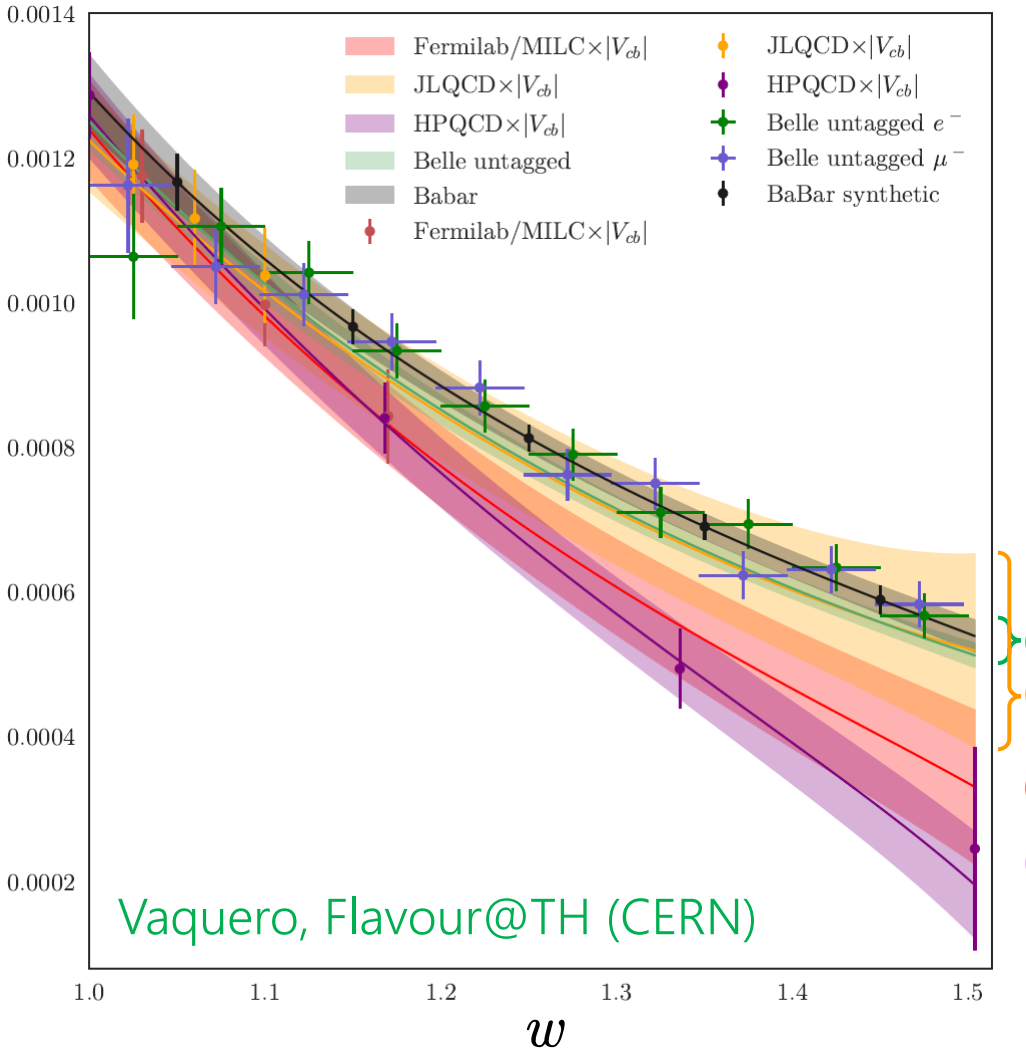

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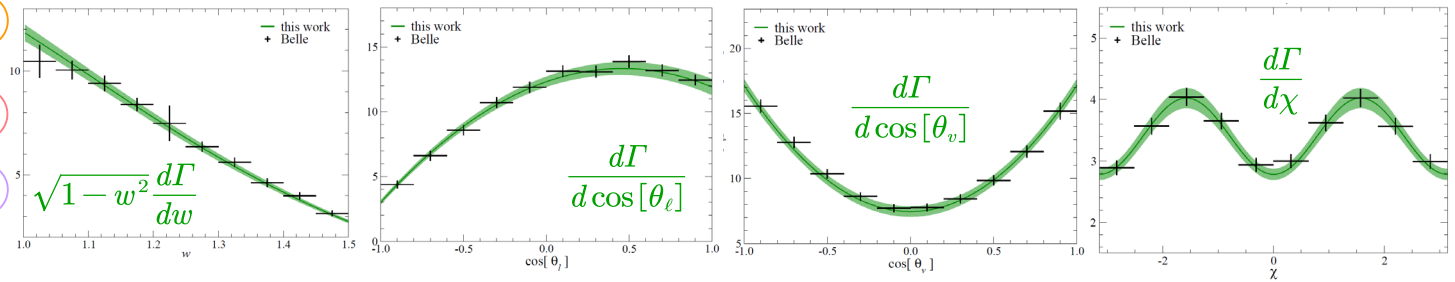

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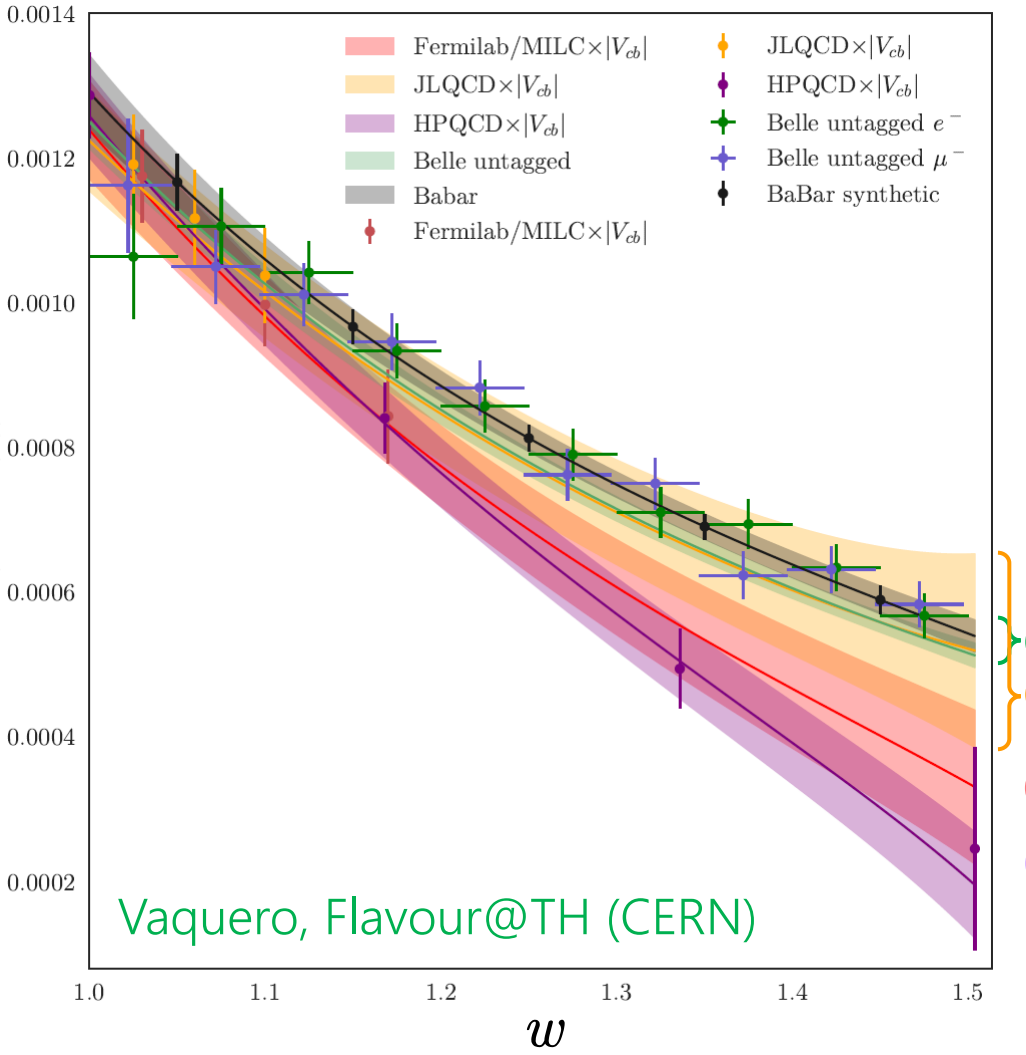

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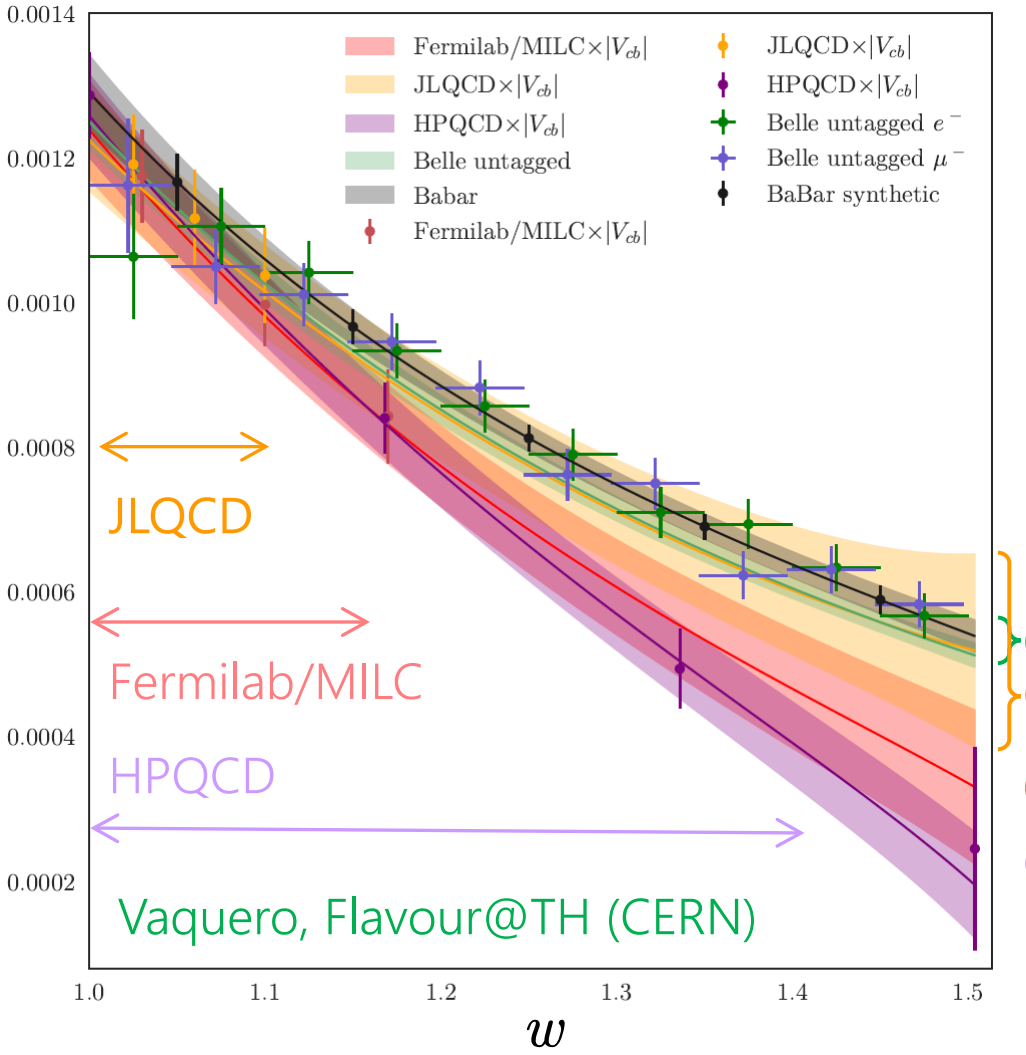

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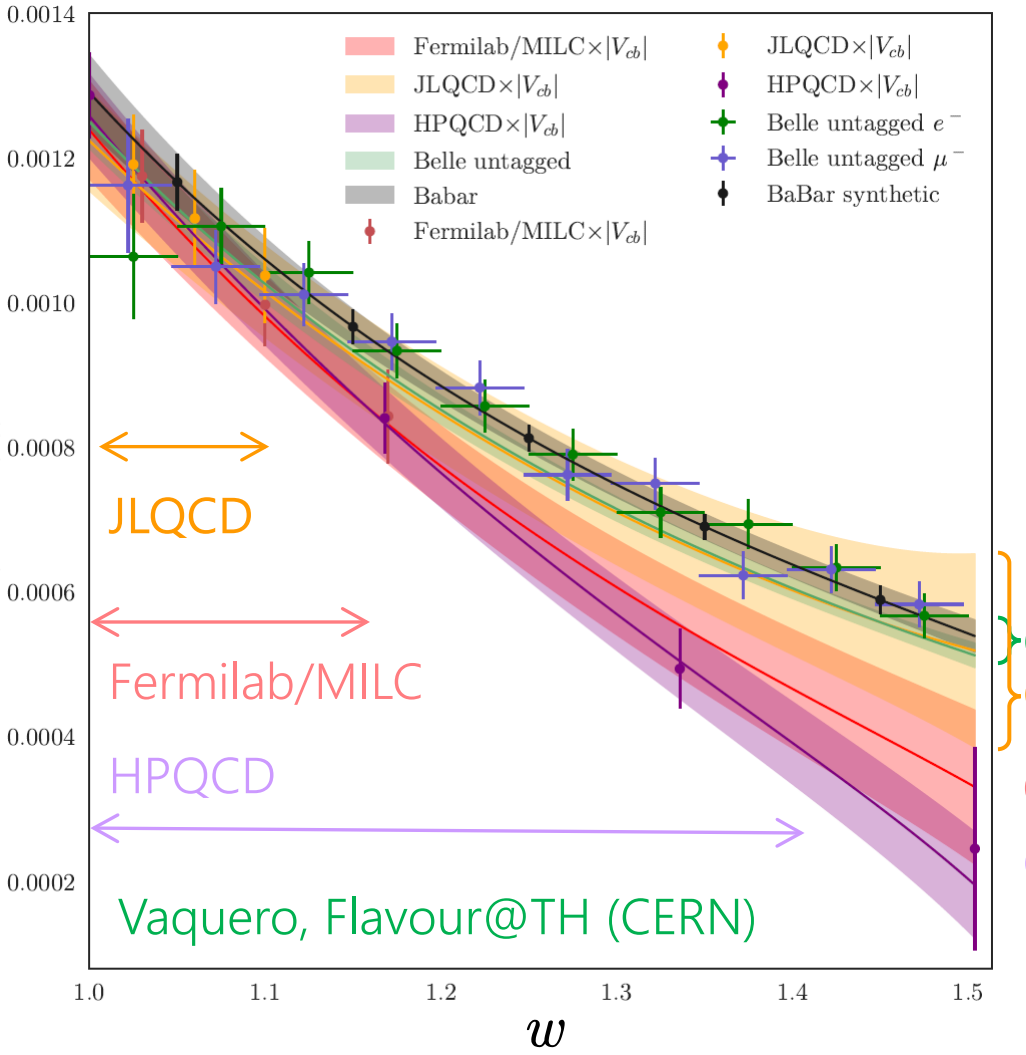

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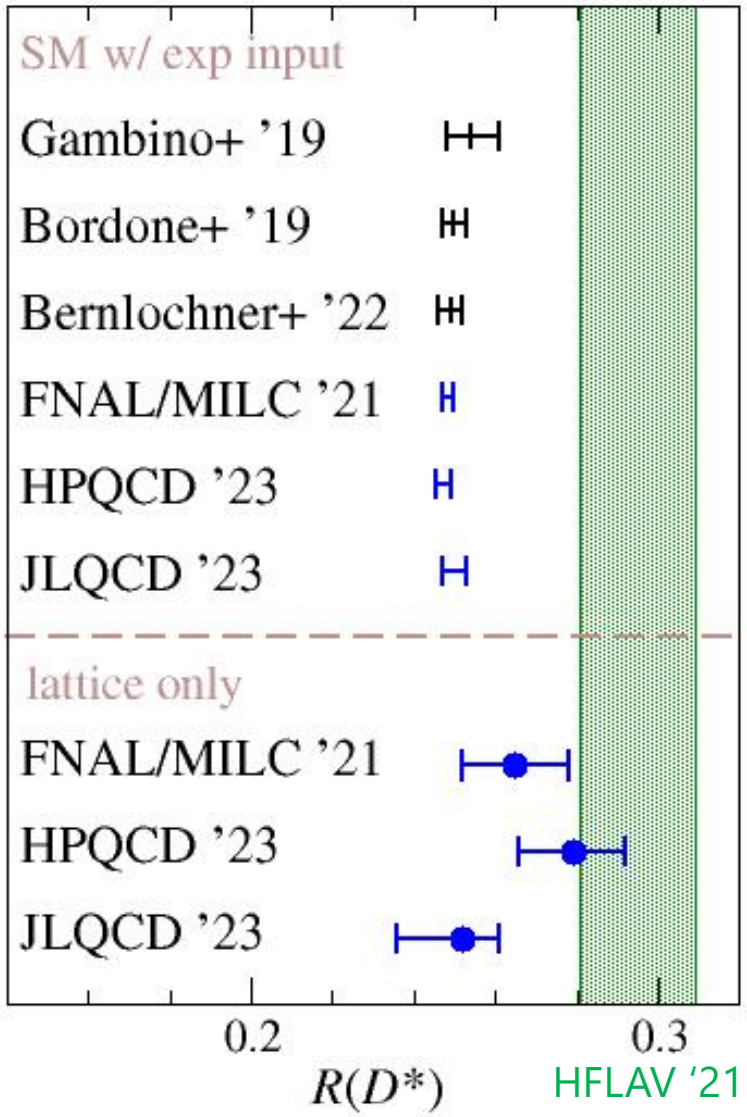
⇒ "safe" extension to large w: JLQCD; Fermilab/MILC a^{-1}~6.6GeV

$R(D^*)$

Vaquero [WG1+2] Tue 18:03

Colquhoun [WG2+3]: Thu 18:50

$$R(D^*) = \Gamma(B \to D^* \tau \nu)/\Gamma(B \to D^* \ell \nu) \quad (\ell = e, \mu)$$



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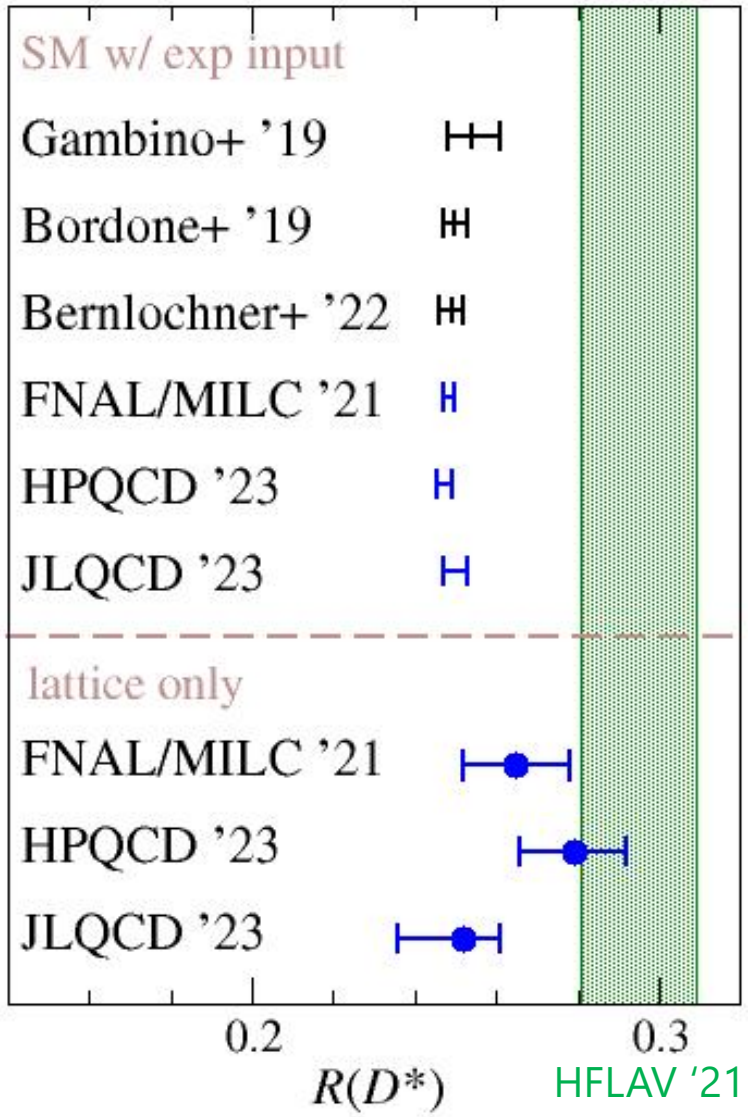

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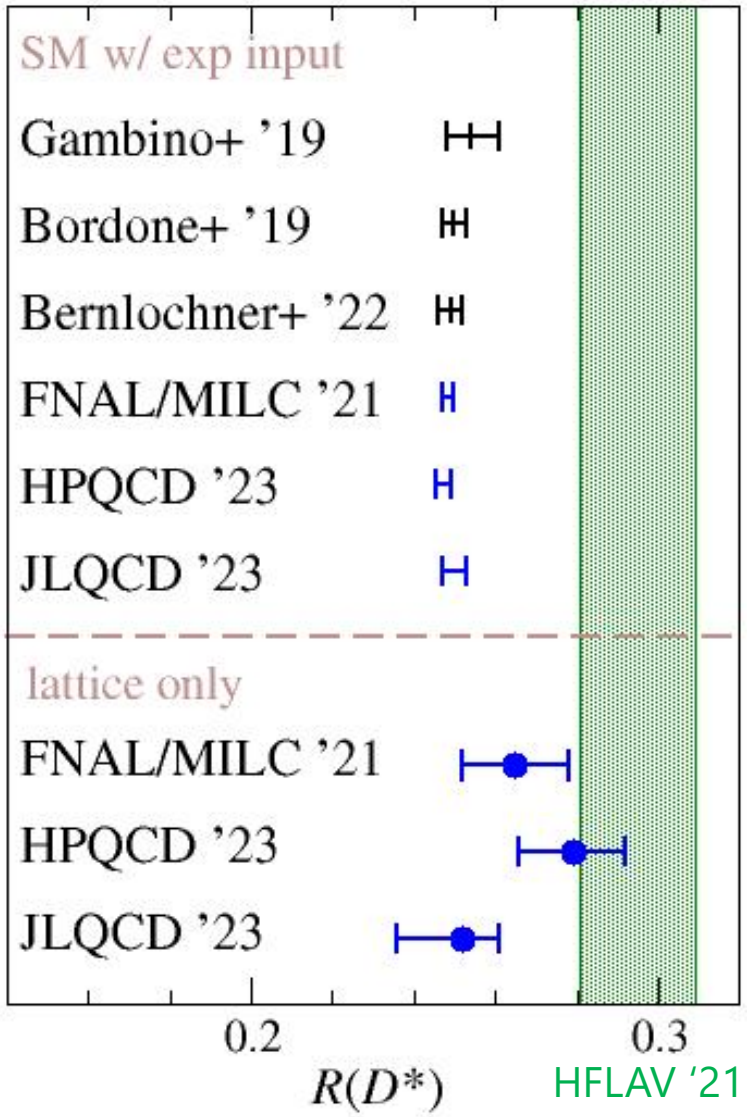

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  - HPQCD: fit $B \to D^*$ and $B_s \to D_s^*$ data $\Rightarrow$ χ^2/dof = 1.3, 1.5σ tension
- only from lattice data $\Rightarrow$ 5%
  - robust: reasonable ($\leq$ 1.7σ) consistency among 3 studies
  - phase factor $(w^2\text{-}1)^{1/2}$, $w_{\text{max},\tau} < w_{\text{max},\ell} \Leftrightarrow$ extension to large w

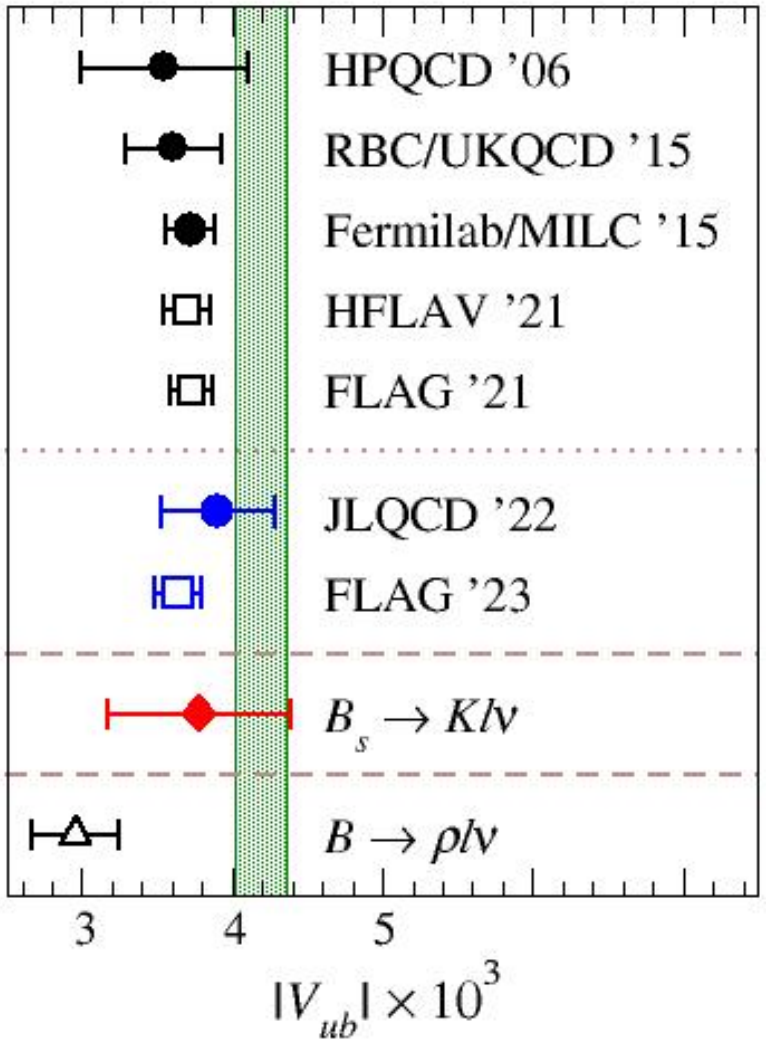
$|V_{ub}|$

Vittorio [WG2] Wed 9:00-

Leskovec [WG2+3] Thu 17:50

Colquhoun [WG2+3] Thu 18:50

$|V_{ub}|$ from $B_{(s)}$ decays



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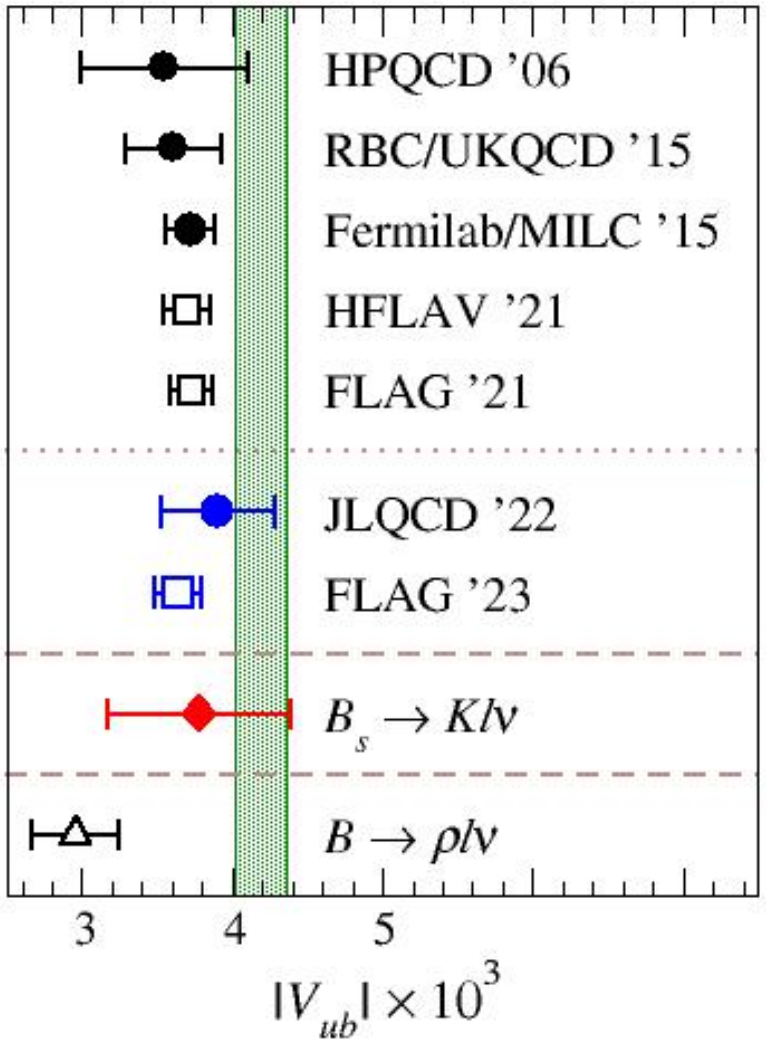

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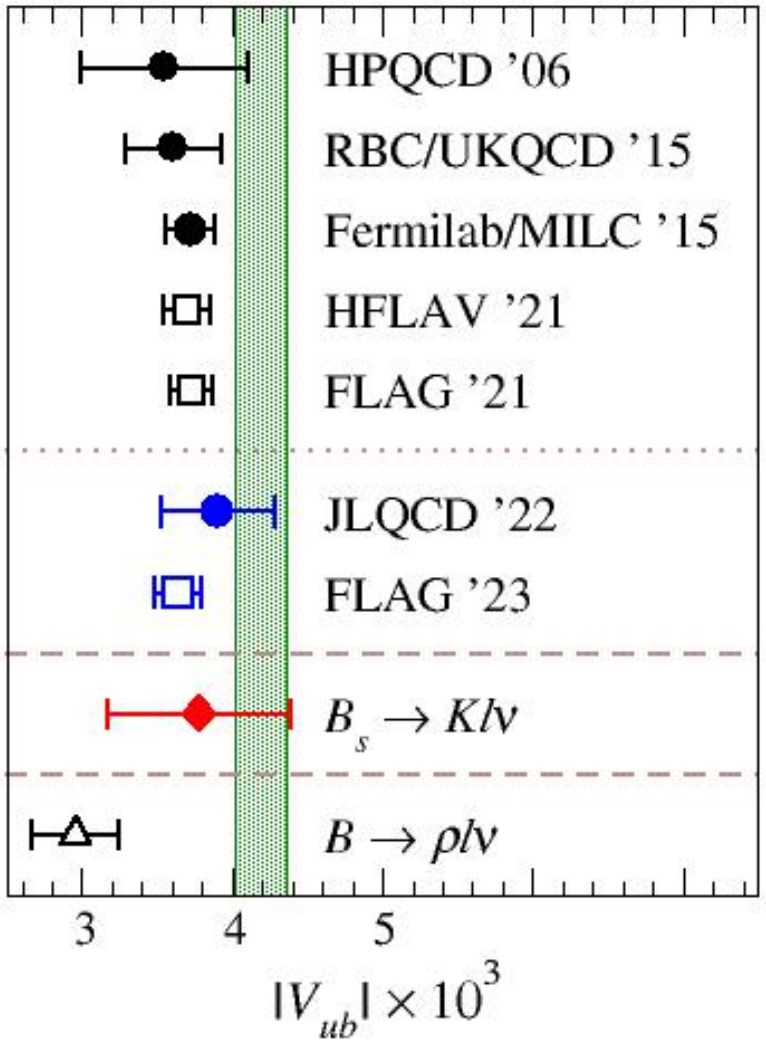

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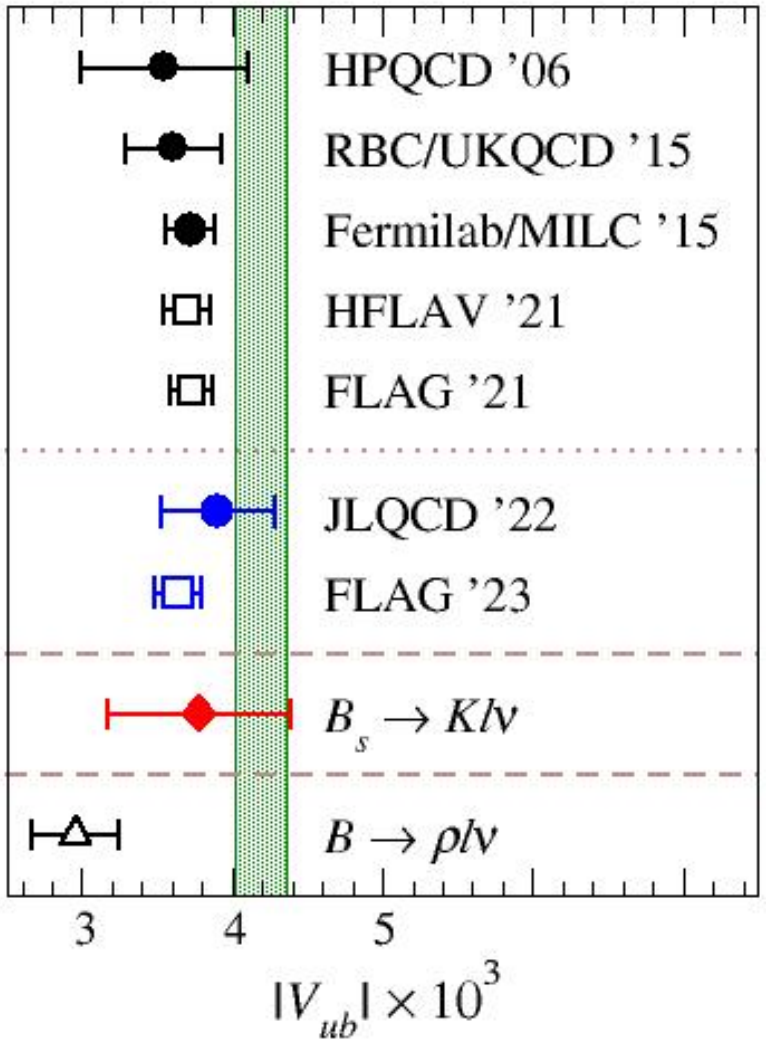

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  + w/ LHCb $R = \mathcal{B}(B_s \to K_s \mu\nu)/\mathcal{B}(B_s \to D_s \mu\nu)$, $\mathcal{B}(B_s \to D_s \mu\nu)$ ⇒ $|V_{ub}|$
  + w/ unitarity bound: Flynn+ 2303.11285 ⇔ dispersive matrix 2105.02497

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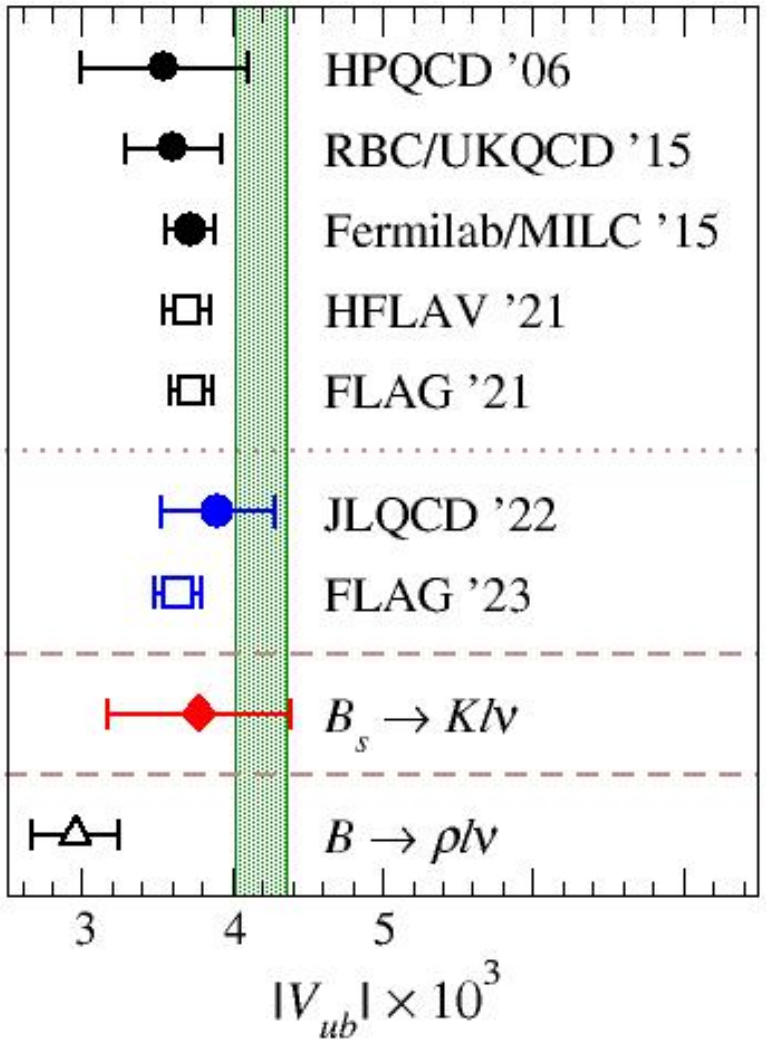

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$B \to \rho\ell\nu$: Bernlocknler+ 2104.05739 w/ LCSR for FFs

- lattice approach with a finite volume framework ⇒ Leskovec [WG2]

  ⇒ $B \to K^*\ell\ell$?

inclusive semileptonic decays

$$\frac{d\Gamma(B \to X_c \ell \nu)}{d\,\mathbf{q}^2\, dq^0\, dE_\ell} = \frac{G_F^2}{8\pi^3} |V_{cb}|^2 L^{\mu\nu} W_{\mu\nu} \qquad W_{\mu\nu} \sim \sum_{X_c} \langle B | J_\mu^\dagger | X_c \rangle \langle X_c | J_\nu | B \rangle = \mathrm{im} \langle B | J_\mu^\dagger \otimes J_\nu | B \rangle$$

hadronic tensor

optical theorem

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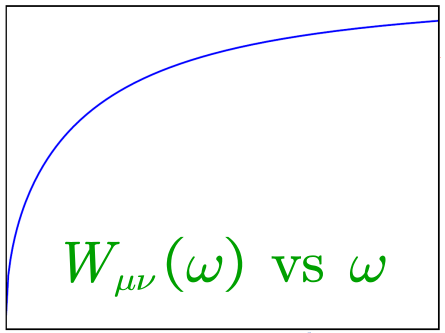
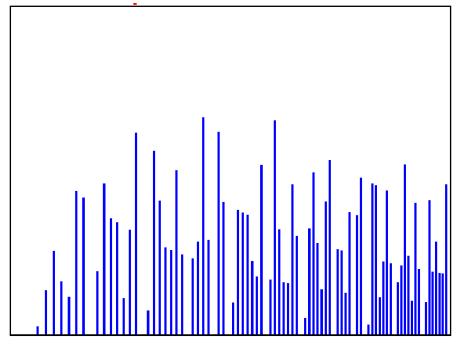
$C_{\mu\nu}(t) \Rightarrow W_{\mu\nu}(\omega)$ as a function of ω – ill-posed inverse problem

- deformed $W_{\mu\nu}(\omega)$
- limited input / non-exact $C_{\mu\nu}(t)$





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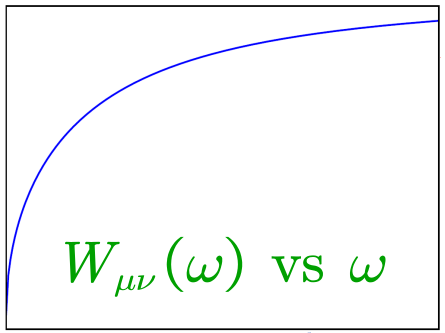
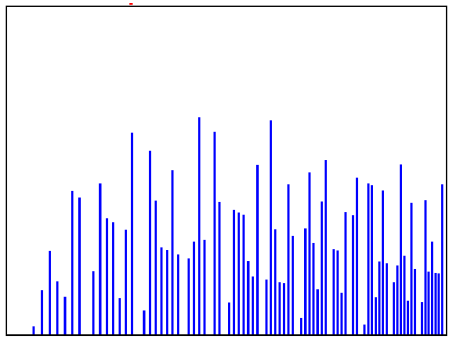
$C_{\mu\nu}(t)\Rightarrow W_{\mu\nu}(\omega)$ as a function of ω – ill-posed inverse problem

- deformed $W_{\mu\nu}(\omega)$
- limited input / non-exact $C_{\mu\nu}(t)$

$\Leftrightarrow$ smeared / integrated $W_{\mu\nu}(\omega)$ $\int d\omega K(\omega)$



$\overset{?}{\sim}$ $\int d\omega K_{L,\sigma}(\omega)$



Hanesen+ '17, Gambino-Hashitmoto '20

$$\frac{d\Gamma}{d\boldsymbol{q}^2}=\frac{G_F^2}{24\pi^3}|V_{cb}|^2\sqrt{\boldsymbol{q}^2}\,\bar{X}(\boldsymbol{q}^2) \qquad \bar{X}(\boldsymbol{q}^2)=\int_0^\infty d\omega K_{\mu\nu,\sigma}(\omega,\boldsymbol{q}^2)W_{\mu\nu,L}(\omega,\boldsymbol{q}^2)$$

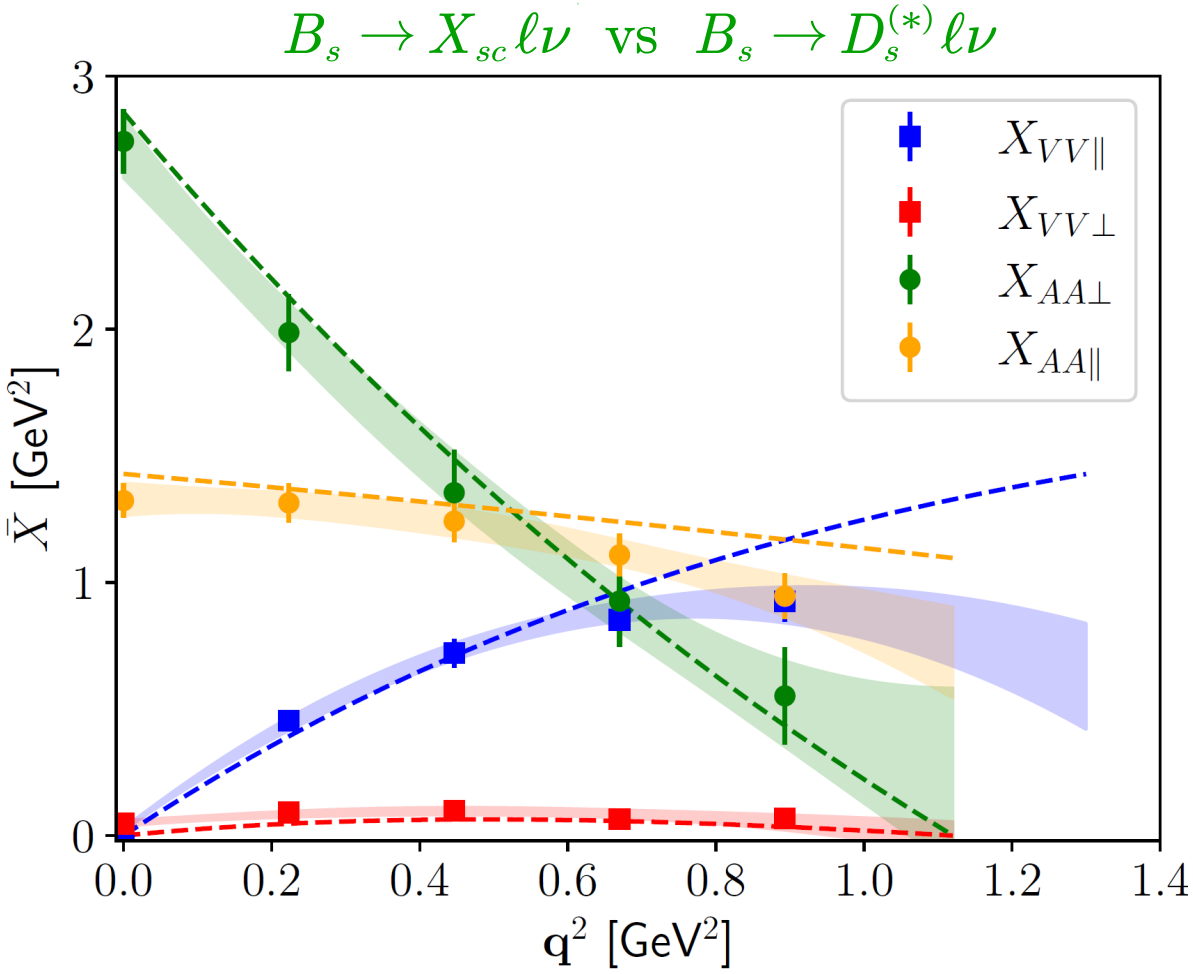
Kellermann [WG1+2] Tue 18:00

feasibility on the lattice

Gambino+ 2203.11762

$B_s \to X_{sc}\ell\nu$ on JLQCD conf (a = 0.1fm, $m_b = 2.4m_c$)

- (too) good consistency w/ exclusive
- statistical error only



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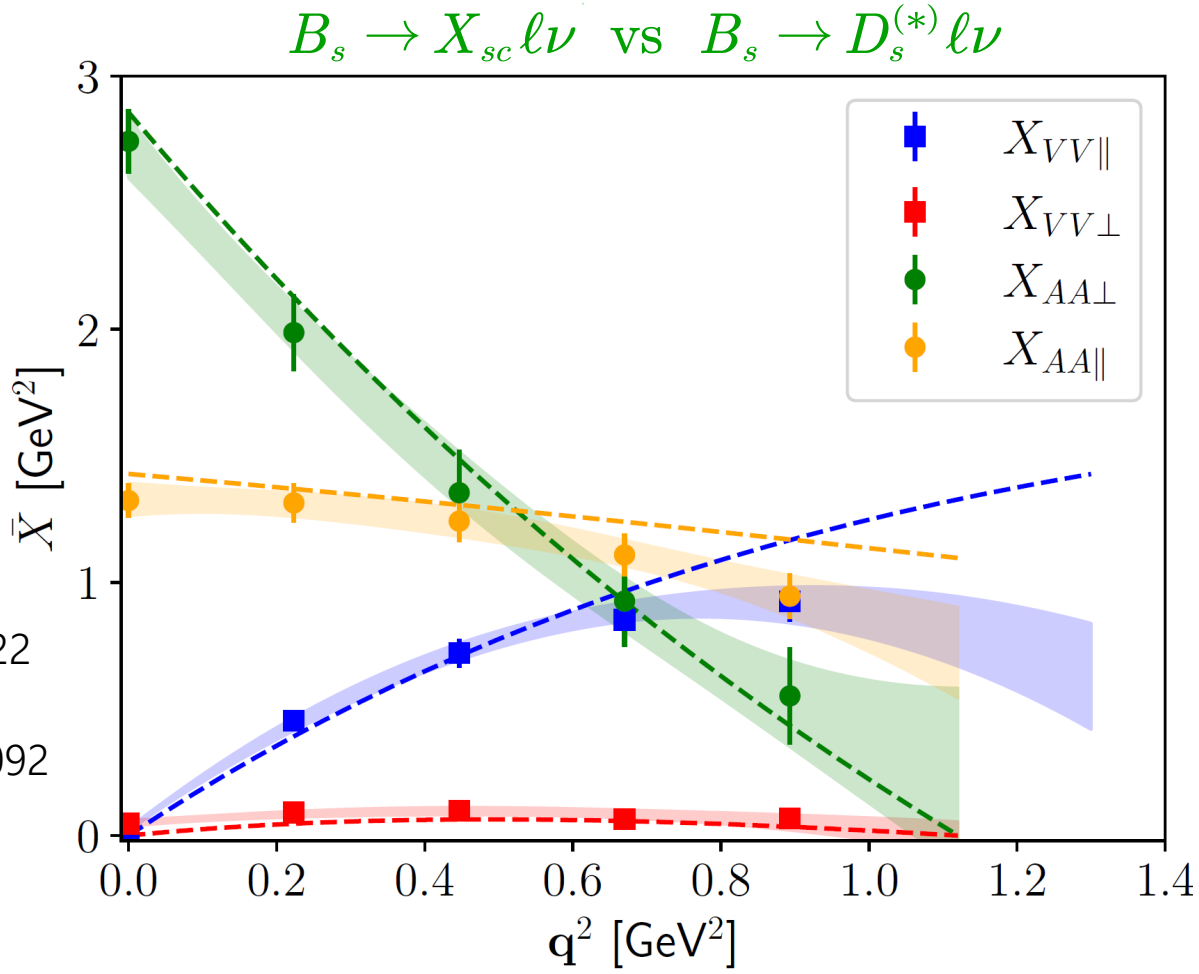
studies of systematics

Barone-Kellerman-Hashimoto-Jüttner-TK

- upper limit of $d\omega$ $K_{\mu\nu,\sigma}(\omega, \boldsymbol{q}^2) \propto \theta(\omega_{\max} - \omega)$ Baron+ Lat'22
- expression in $C_{\mu\nu}(t)$ $K_{\mu\nu,\sigma}(\omega, \boldsymbol{q}^2) = \sum_t k_{\mu\nu}(\mathbf{q}^2) e^{-\omega t}$ 2305.14092
- finite volume effects → Kellermann [WG1+2]
- …



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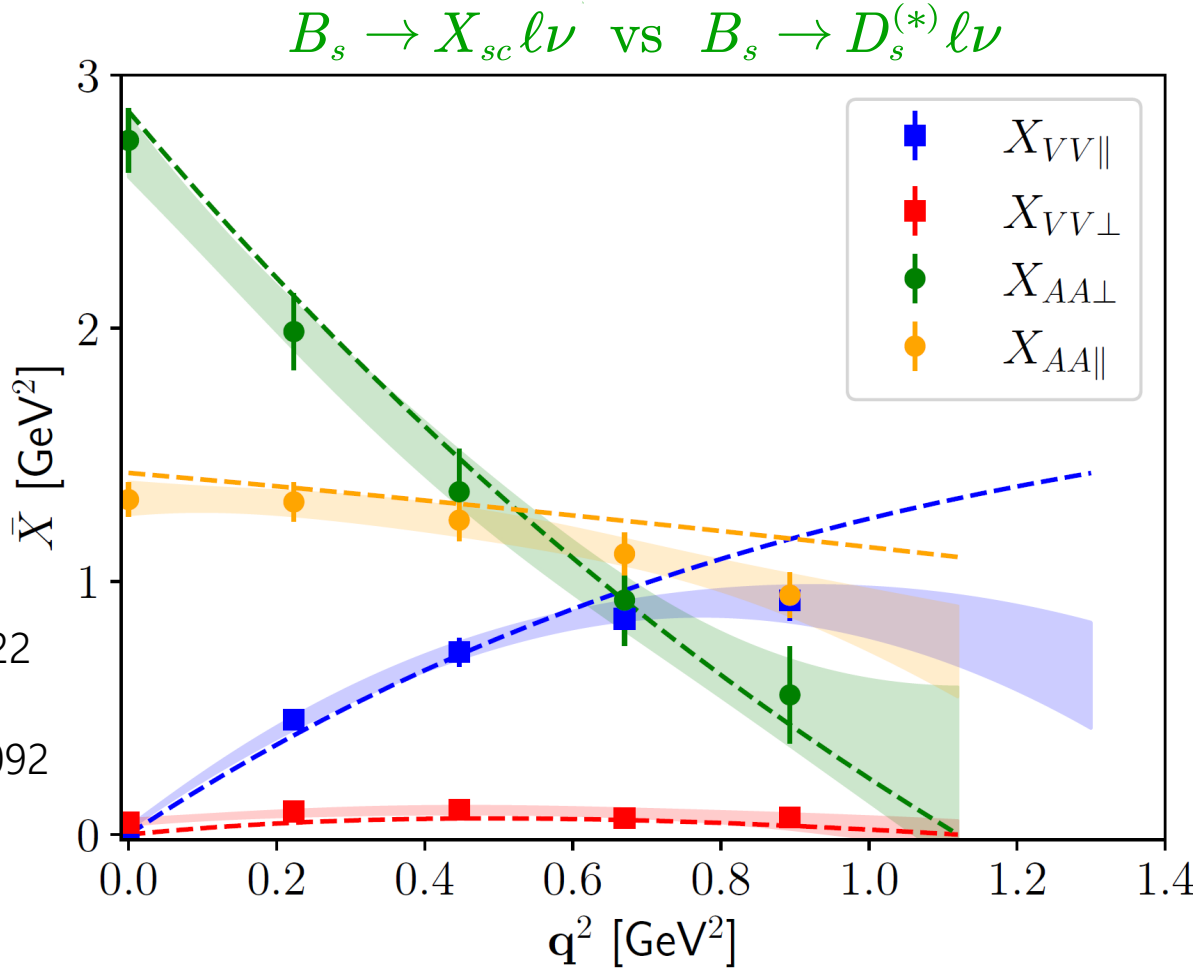

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⇒ inclusive vs exclusive analyses on the same lattice ⇒ tension in $|V_{cb}|$, $|V_{ub}|$

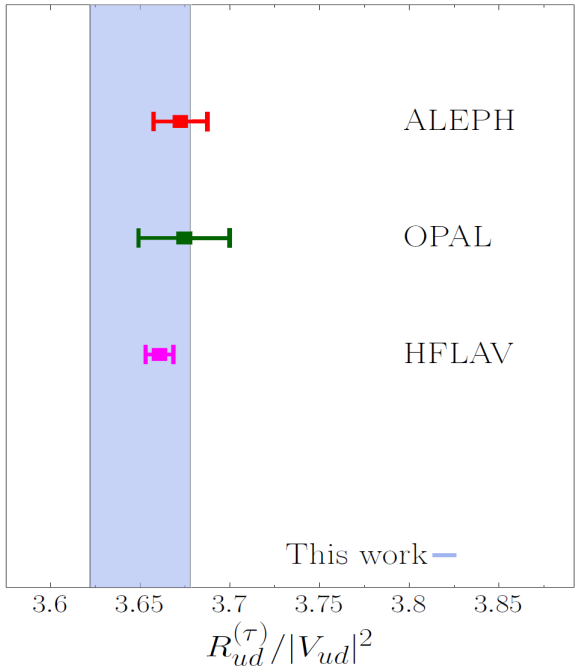
⇒ CCQE $N\nu \to X\ell$, γW box for $0^+ \to 0^+$ β decays, ... (Fukaya-Hashimoto-TK-Ohki 2010.01253)

inclusive τ decays

$$\Gamma(\tau \to X_D \nu_\tau) = \frac{G_F^2}{4m_\tau} |V_{uD}|^2 \int \frac{d^3q}{(2\pi)^3 2E_\nu} L_{\mu\nu}(p_\tau, p_\nu) W_D^{\mu\nu}(q) \quad (D = d, s) \qquad W_{\mu\nu}(q) \Leftrightarrow \langle 0 | J_\mu^\dagger(-\boldsymbol{q}) e^{-Ht} J_\mu^\dagger(\boldsymbol{q}) | 0 \rangle$$

$|V_{ud}|$ from $\tau \to X_d \nu_\tau$ ETM 2308.03125

$$R_d = \Gamma(\tau \to X_d \nu_\tau) / \Gamma(\tau \to e \bar{\nu}_e \nu_\tau)$$



L = 5.1, 7.6fm
$\Rightarrow$ FVEs

a^{-1}
= 2.5- 3.5GeV
$\Rightarrow$ $a = 0$

$\Rightarrow |V_{ud}| = 0.9752(39)$ (0.4%)

$\Leftrightarrow$ 0.97373(31) ($0^+ \to 0^+$ β decays)

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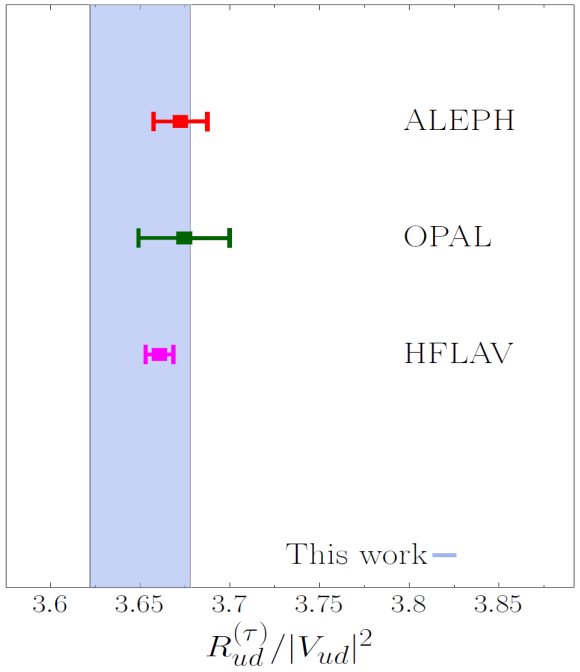

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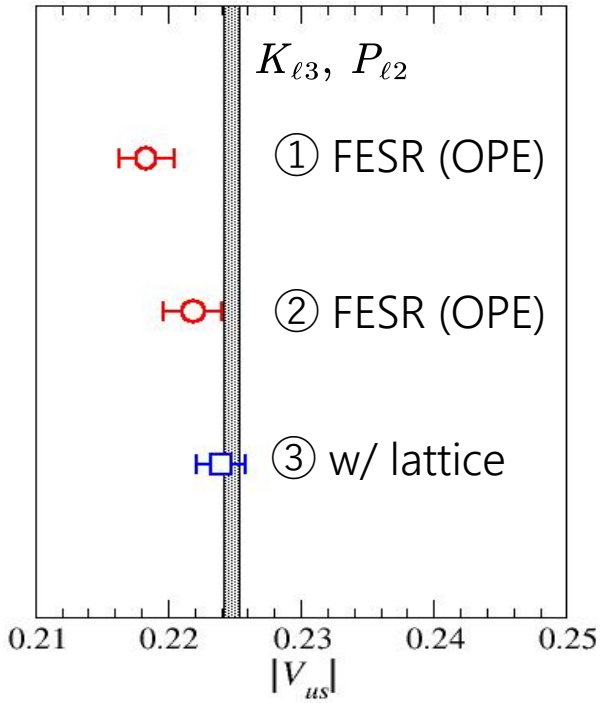
$|V_{us}|$ from $\tau \to X_s \nu_\tau$

R_s w/ generic weight for decay channels



① Gamiz+ hep-ph/0612154

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- new treatment HO in OPE
- partly different exp. input

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- large weights for $K\nu$, $K\pi\nu$

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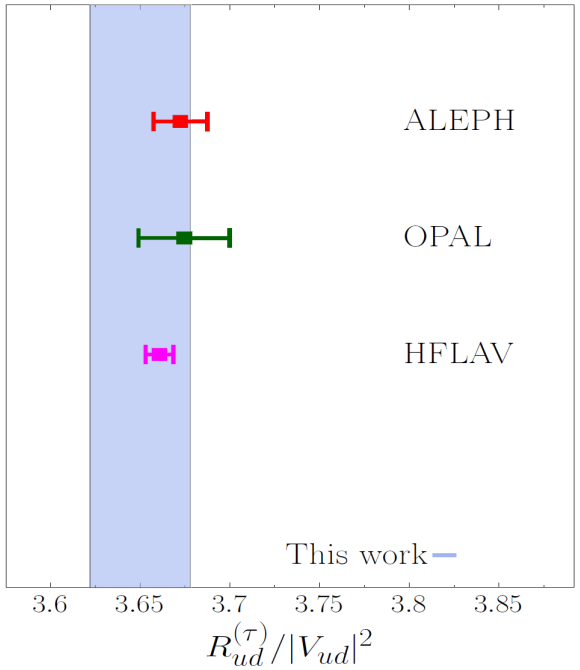

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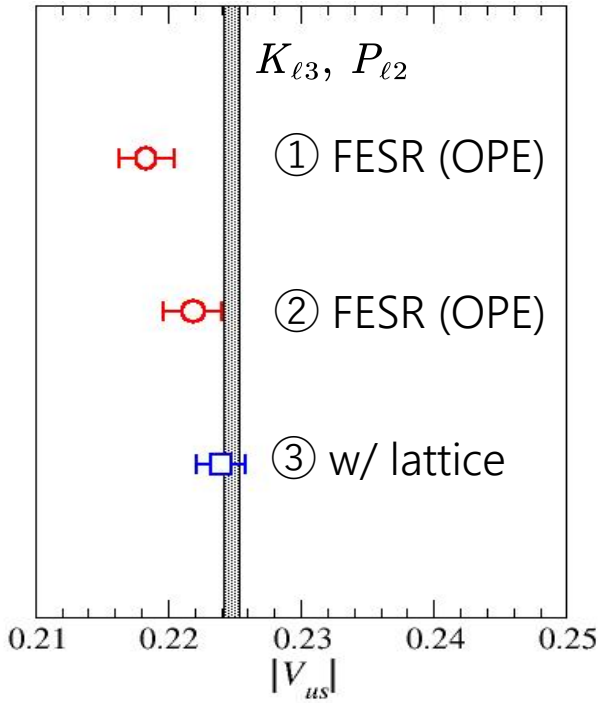

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⇒ mostly rely on these ch.s

⇒ independent lattice study to clarify the situation

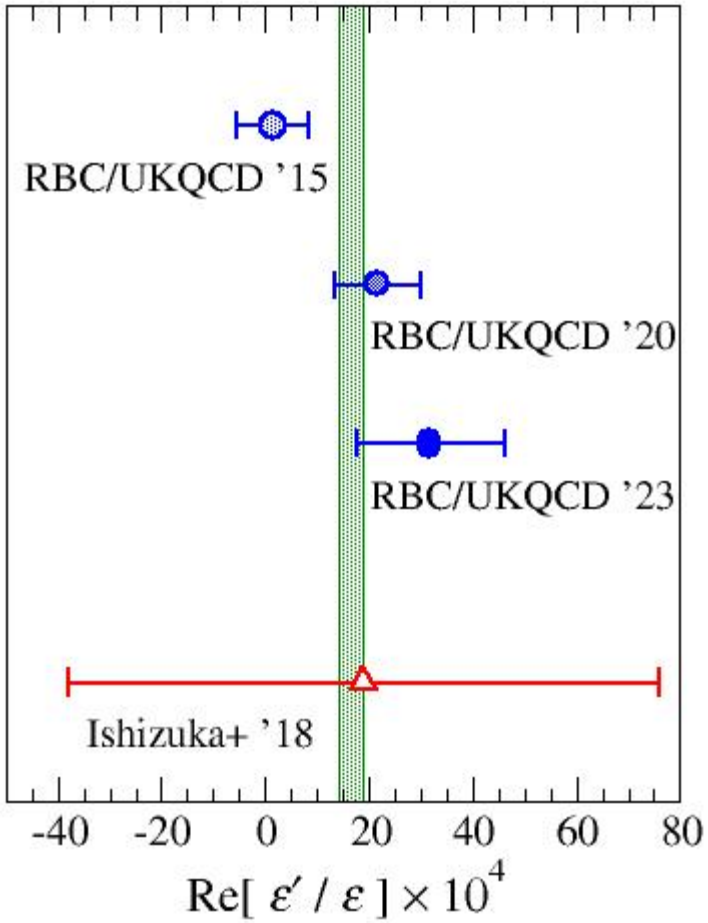
at this workshop

- Elvira Gamiz, "Overview of D form factors and decay constants (lattice)", WG1 Tue 10:00-
- Felix Erben, "Input to V_{us} from lattice QCD including the progress on hyperon decays", WG1 Wed 10:00-
- Mikhail Gorchtein, "Improved radiative corrections for $K_{\ell 3}$ decays and superallowed β decays", WG1 Thu 11:30-
- Ryan Kellermann, "Updates on inclusive charmed and bottomed meson decays from lattice", WG1&2 Tue 12:00-
- Alejandro Vaquero, "$B_{(s)} \to D^{(*)}_{(s)}$ from FNAL/MILC", WG2 Tue 18:03-
- Ludovico Vittorio, "Unitarity constraints and the dispersive matrix", WG2 Wed 9:00-
- Carolina Bolognani, "Combining lattice and sum rules to determine $|V_{ub}|/|V_{cb}|$", WG2 Wed 9:24-
- Luka Leskovec, "Lattice outlook on B->rho and B->K*", WG2&3 Thu 17:50-
- Chris Bouchard, "Rare $B \to \pi$ and $B \to K$ decays on the lattice", WG2&3 Thu 18:20-
- Brian Colquhoun, "$B \to \pi$, $B \to D^{(*)}$ from JLQCD", WG2&3 Thu 18:50-
- En-Hung Chao, "$K \to \mu\mu$ on the lattice", WG3 Mon 14:45-
- Ryan Hill, "Rare kaons on the lattice", WG3 Tue 14:45-
- Felix Erben, "Update on SU(3)-breaking ratios and bag parameters for $B_{(s)}$ mesons", WG4

$K \to \pi\pi$

sensitive to NP

challenging on the lattice : ππ state, disconnected digrams



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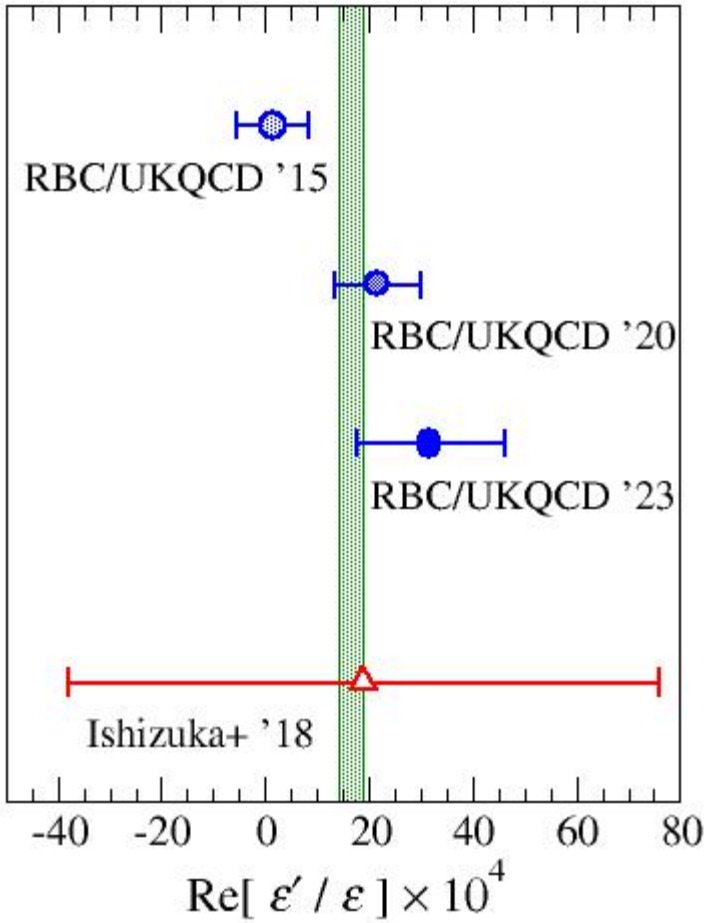

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RBC/UKQCD w/ "G parity boundary condition"

- G parity BC : flavor rotation
  - + avoid exponentially large off-shell contributions
  - + need dedicated gauge ensembles
- $\mathrm{Re}[\varepsilon'/\varepsilon] \times 10^4 = 21.7(2.6)_{\mathrm{stat}}\ (5.0)_{\mathrm{EM+iso}}\ (6.2)_{\mathrm{sys\text{-}else}}$
- continued efforts to control $a \neq 0$ error [Kelly @ Lattice 2023]
- independent calculations are welcome!! [cf. Ishizuka+ '18 w/ Wilson quarks]

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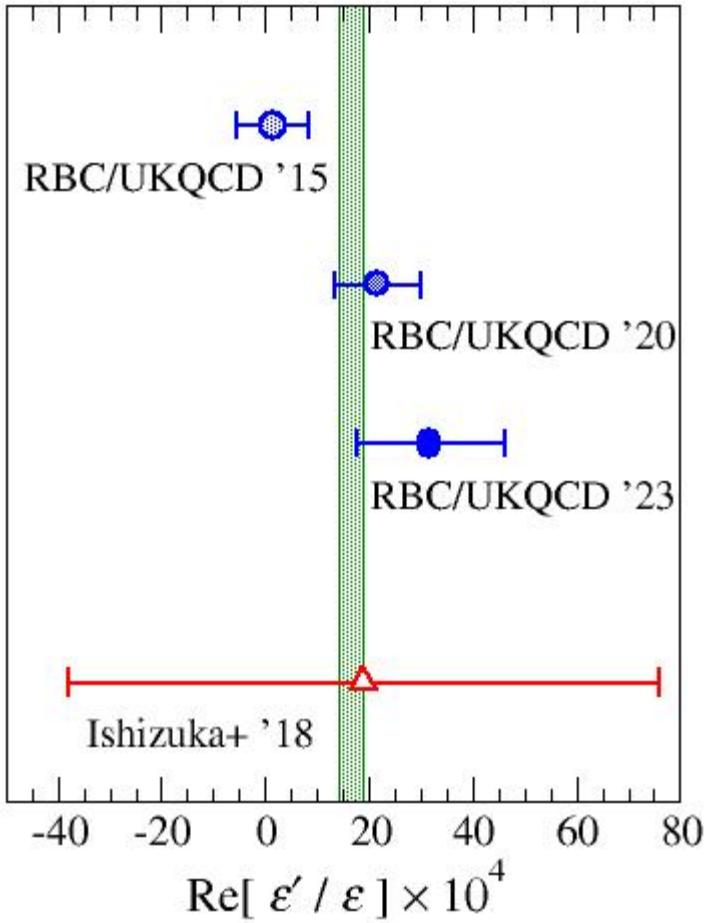

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RBC/UKQCD w/ periodic boundary condition

- + Generalized Eigen Value Prob. to extract "excited state contributions"
- + configurations shared w/ other subjects
- + straightforward for future control of the largest isospin corrections
- $\mathrm{Re}[\varepsilon'/\varepsilon] \times 10^4 = 31.8(6.3)_{\mathrm{stat}}(5.0)_{\mathrm{EM+iso}}(11.8)_{\mathrm{sys\text{-}else}}$
- largest errors from $a \neq 0$, EM+isospin, Wilson coefficients to be controlled

summary

good progress from lattice QCD

for leptonic / semileptonic decays & mixing

- independent calculations with different setups by different group also for B physics
- tensions among precision lattice studies $\Rightarrow$ more realistic simulations
- tension in $|V_{cb}|$, $|V_{ub}|$ $\Rightarrow$ interplay w/ experiments & phenomenology

for processes involving unstable / multi-particle states

- new applications w/ newly-developed methods: inclusive, $B \to \rho \ell \nu$, ...
- studies of systematics towards precise calculation
- future subjects: resonance contribution to $B \to K^{(*)} \ell\ell$, D mixing, ...