

Heavy flavour physics from lattice QCD

KEK, Sokensai, Nagoya Univ. KMI

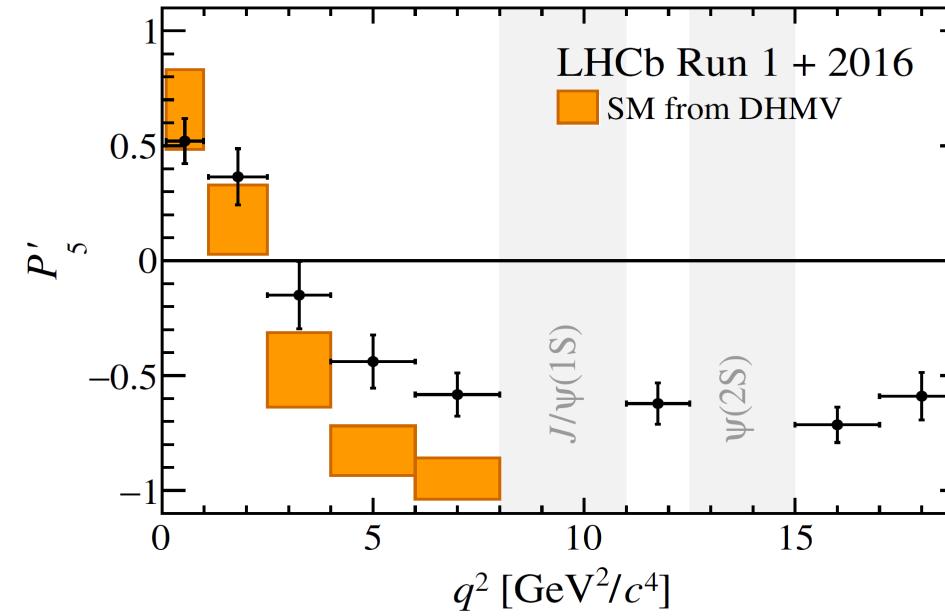
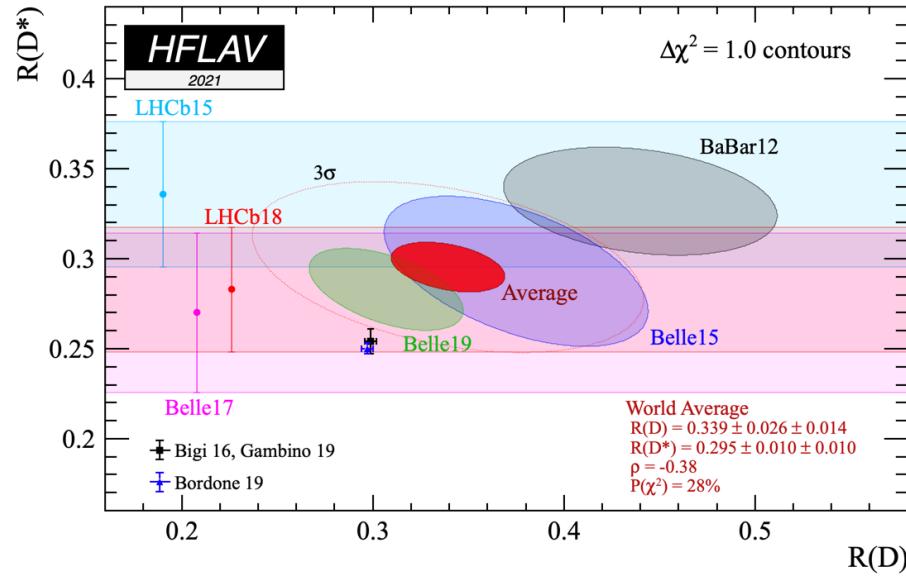
Takashi Kaneko



The 39th International Symposium on Lattice Field Theory,
Universität Bonn, Aug 8th, 2022

B anomalies

tantalizing 2-4 σ tensions b/w the SM and experiments



lepton flavor universality violation (LFUV)

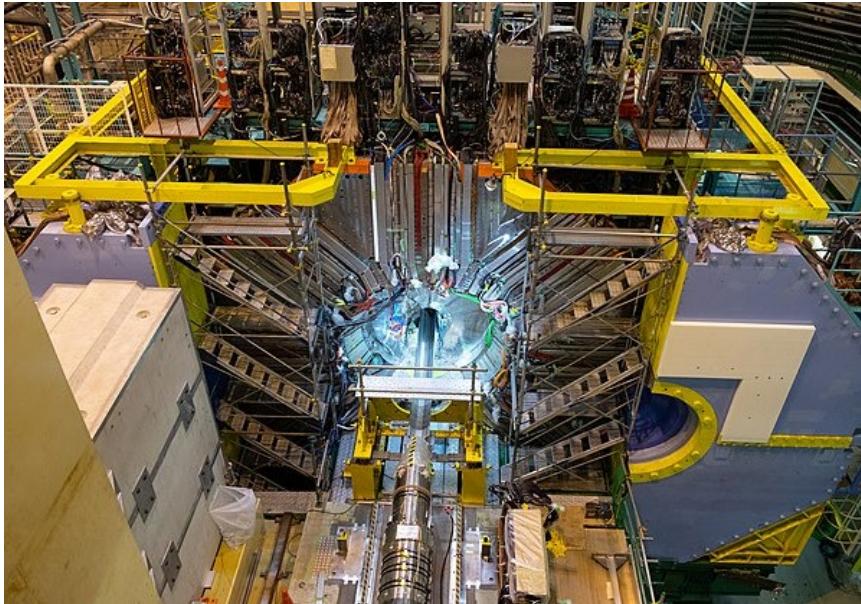
$$R(D^{(*)}) = \frac{\Gamma(B \rightarrow D^{(*)} \tau \nu)}{\Gamma(B \rightarrow D^{(*)} \{e, \mu\} \nu)}$$

flavor changing neutral current (FCNC), e.g. $b \rightarrow s \ell \ell$

$$B \rightarrow K^{(*)} \ell \ell, \quad B_s \rightarrow \mu \mu, \quad \dots$$

would be evidence of new physics, but we need much more to clarify it

in (tight) collaboration w/ experiments



SuperKEKB / Belle II @ KEK

- $e^+e^- \rightarrow BB$ pairs
- good at processes w/ ν
- Belle $\times 50$ data by 2031
- start to produce results competitive to Belle (Moriond'22, ICHEP'22,...)

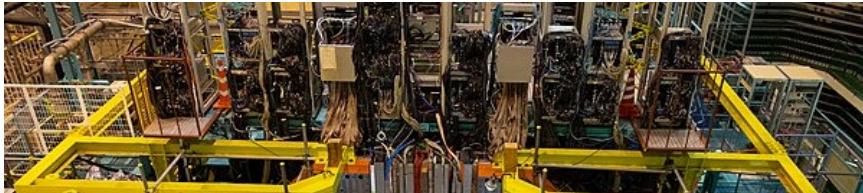


LHCb @ CERN

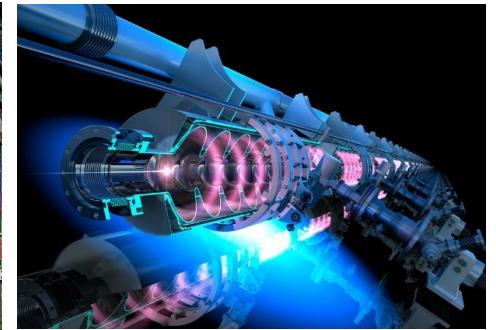
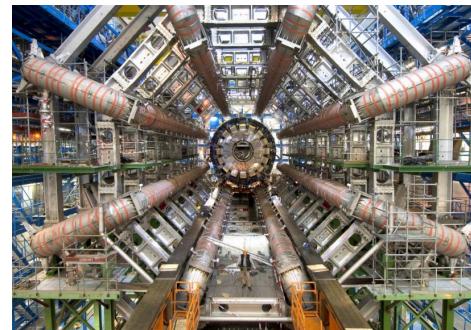
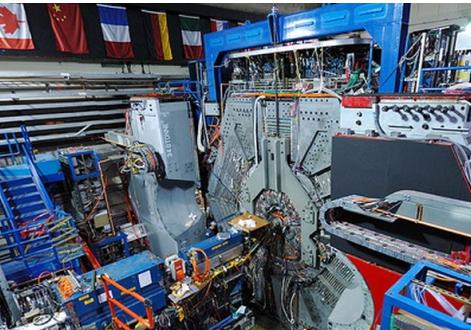
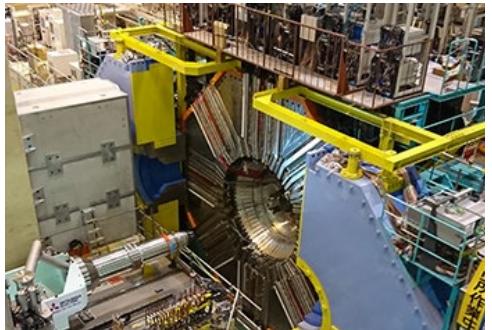
- $pp \rightarrow B, B_s, B_c, \Lambda_b, \dots$
- good at rare decays of various b hadrons
- Run 3, HL-LHC
- Run 3 started!

complementary, healthy competition to hunt new physics

in (tight) collaboration w/ experiments



of course



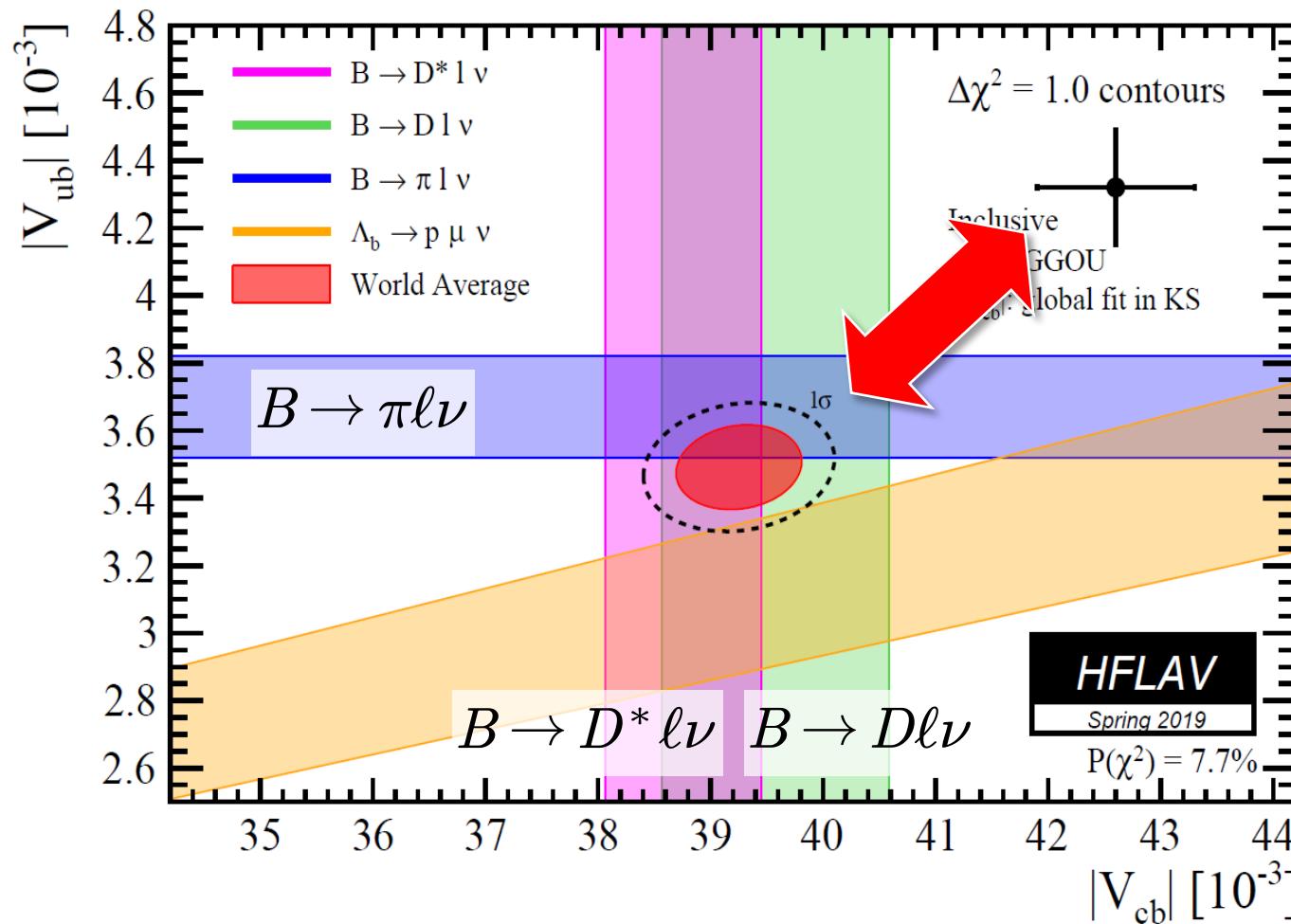
Belle, BaBar, ATLAS, CMS, ILC, ... are also important

- Belle \times 50 data by 2031
- start to produce results competitive to Belle (Moriond'22, ICHEP'22,...)
- Run 3, HL-LHC
- Run 3 started!

complementary, healthy competition to hunt new physics

long standing problem in CKM MEs...

exclusive vs inclusive



- exclusive : e.g. $B \rightarrow D\ell\nu, B \rightarrow D^*\ell\nu, \dots$
- inclusive: e.g. $B \rightarrow D\ell\nu + D^*\ell\nu + D^{**}\ell\nu + \dots$

HFLAV '21

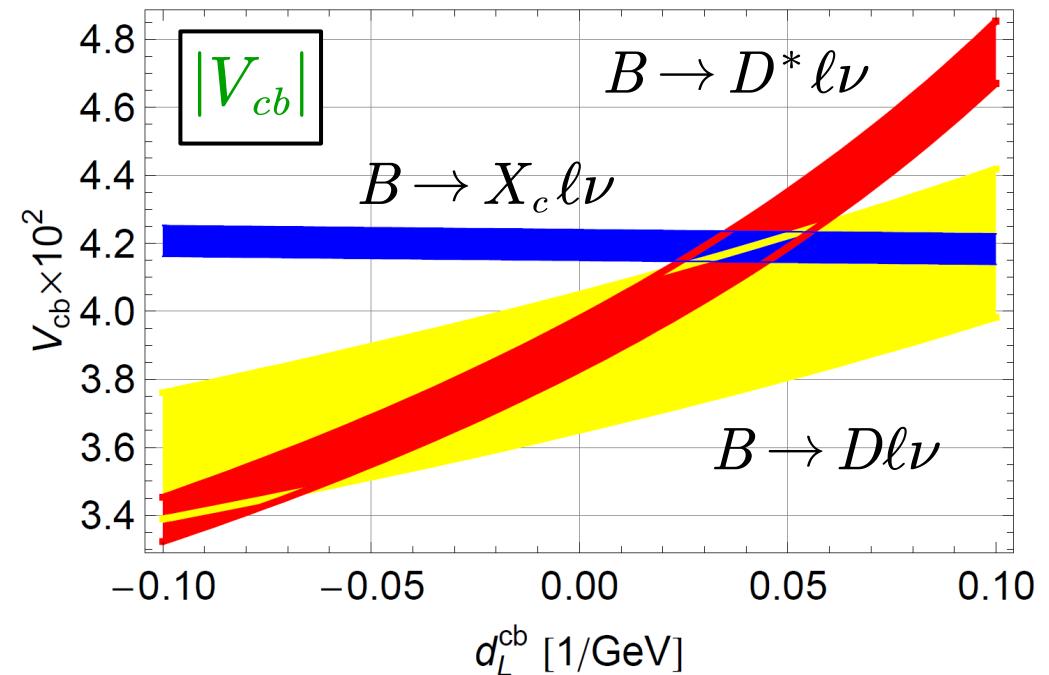
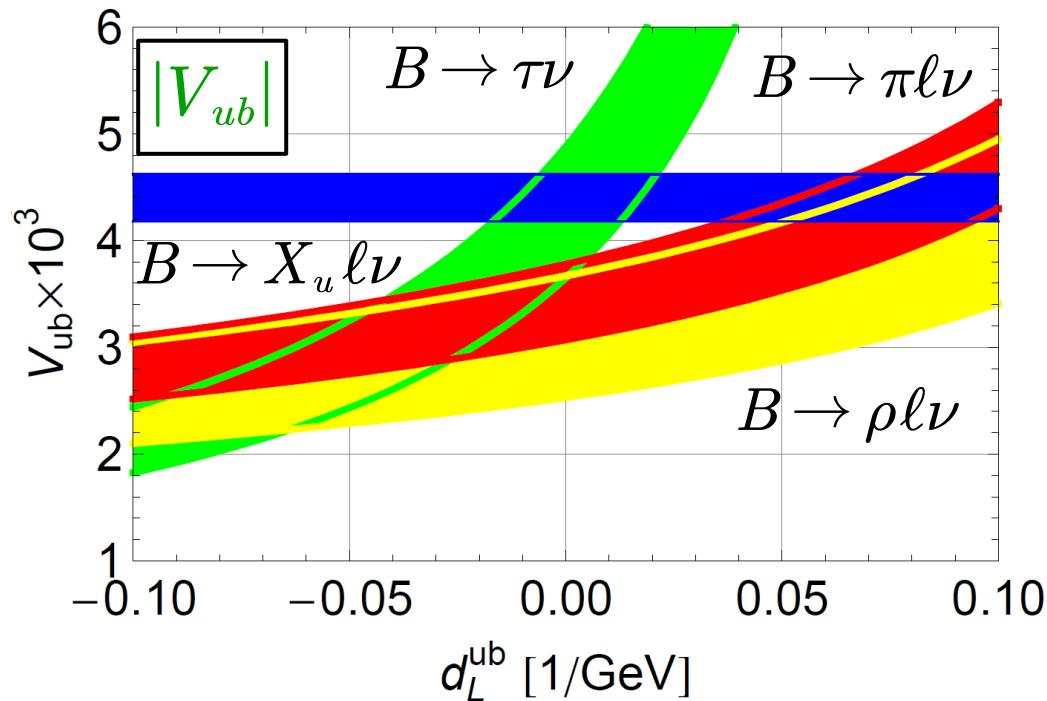
- $|V_{ub}| : 2.2\sigma (12\%)$
- $|V_{cb}| : 2.6 - 4.3\sigma (7-9\%)$

persist for 10 years ... due to new physics?

new physics ?

e.g. Crivellin-Pokorski '18

$$H_{eff} = \frac{4G_F V_{qb}}{\sqrt{2}} \bar{\ell} \gamma^\mu P_L \nu \left((1 + c_L^{qb}) \bar{q} \gamma_\mu P_L b + g_L^{qb} \bar{q} i \vec{D}_\mu P_L b + d_L^{qb} i \partial^\nu (\bar{q} i \sigma_{\mu\nu} P_L b) + L \rightarrow R \right)$$



dim=7, tensor can explain ... new tension w/ $B \rightarrow \tau \nu$ / too large $\Gamma(Z \rightarrow bb)$

th. and/or exp't uncertainties have not been fully understood – need deeper understanding

this talk

recent progress on heavy flavours from lattice QCD
focusing on determination of CKM & search for new physics

comprehensive review & world average ⇒ FLAG review 2111.09849 to be published in EPJC

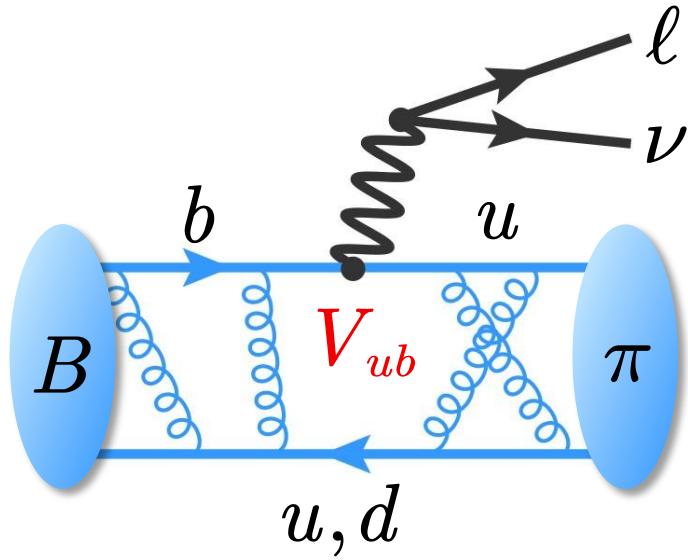
- exclusive semileptonic decays except $B \rightarrow D^{(*)} \ell \nu$ → plenary by Vaquero
- inclusive semileptonic decays
- leptonic decays
- FCNC processes
- D meson semileptonic decays

exclusive semileptonic decays

$B \rightarrow \pi \ell \nu$

- conventional determination of $|V_{ub}|$

$\Leftrightarrow 2.2\sigma$ (12%) tension w/ inclusive

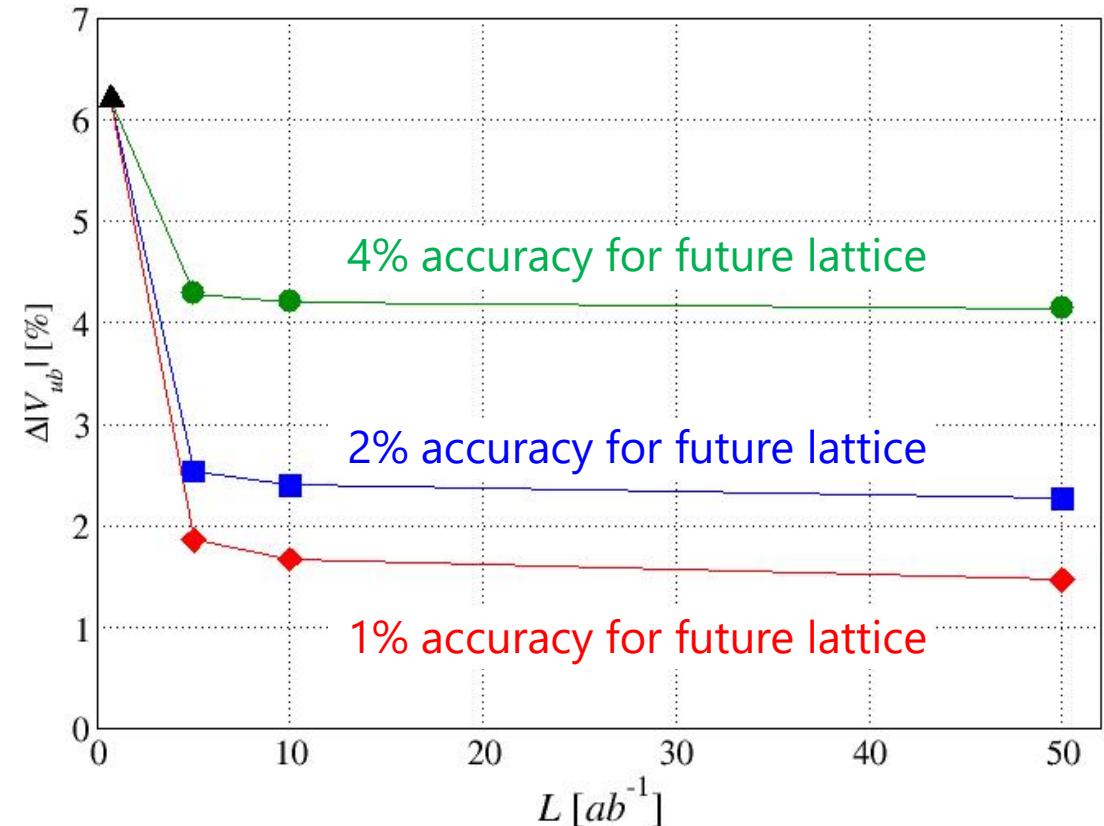


$$\langle \pi(p') | V_\mu | B(p) \rangle$$

$B \rightarrow \pi \ell \nu$

- conventional determination of $|V_{ub}|$
 - $\Leftrightarrow 2.2\sigma$ (12%) tension w/ inclusive
- to be improved by Belle II
 - + CKM suppressed: $\mathcal{B} \sim 1.5 \times 10^{-4} \%$ $\Leftrightarrow 2\text{-}5\% D^{(*)}\ell\nu$
 - + non-small statistical error reduced by $\times 50$ data
 - + $B \rightarrow \pi\{e,\mu\}\nu$: $\leq 2\%$ accuracy @ 10 ab^{-1} ($\sim 2025?$)
- $B \rightarrow \pi \tau \nu$: new physics in LFUV?
 - $\Leftrightarrow 3.4$ tension in $R(D^{(*)})$
 - + not yet measured : $\mathcal{B} < 2.5 \times 10^{-4} \%$
 - + 14% LFUV ratio by Belle II
$$R(\pi) \sim \Gamma(B \rightarrow \pi \tau \nu) / \Gamma(B \rightarrow \pi\{e,\mu\}\nu)$$

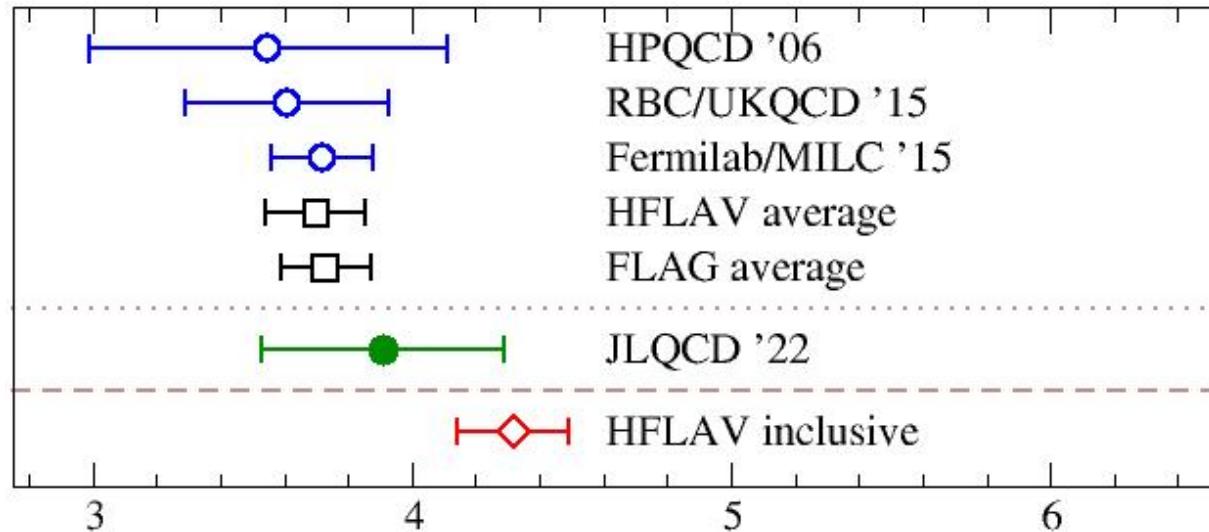
Belle II Theory Interface Platform (B2TIP) '19
 $|V_{ub}|$ expected accuracy (tagged)



a target : 1-2 % theory accuracy in 3-5 years

$B \rightarrow \pi \ell \nu$

$$\langle \pi(p') | V_\mu | B(p) \rangle = \left\{ P - \frac{\Delta M^2}{q^2} q \right\}_\mu f_+(q^2) + \frac{\Delta M^2}{q^2} q_\mu f_0(q^2) \quad (P = p + p', q = p - p', \Delta M^2 = M_B^2 - M_\pi^2)$$



JLQCD 2203.04938

- Möbius DWF $b, a^{-1} \leq 4.5$ GeV, $M_\pi \geq 230$ MeV
- statistics (7%) + chiral extrap (5%)

Fermilab/MILC '15 dominates WA

- Fermilab, $a^{-1} \leq 4.4$ GeV, $M_\pi \geq 165$ MeV
- statistics + $a \neq 0$ + chiral extrap

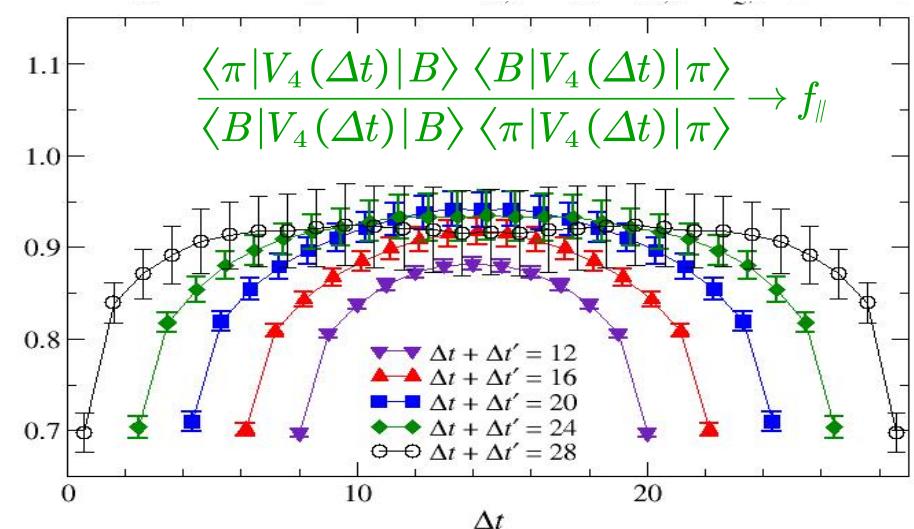
Lytle, Wed, 16:30- [Fermilab/MILC]

- HISQ $b, a^{-1} \leq 4.7$ (6.6?), $\leq m_{b,\text{phys}}, \geq M_{\pi,\text{phys}}$

on-going updates also by

RBC/UKQCD @ Lat'21, Quirks '22 : $M_\pi \geq 267$ MeV

JLQCD : $M_\pi \geq 230$ MeV, ground state saturation



$B^*\pi$ contamination

review by Hashimoto @ Lattice '18

- $H\pi$ state contamination towards $M_{\pi,\text{phys}}$

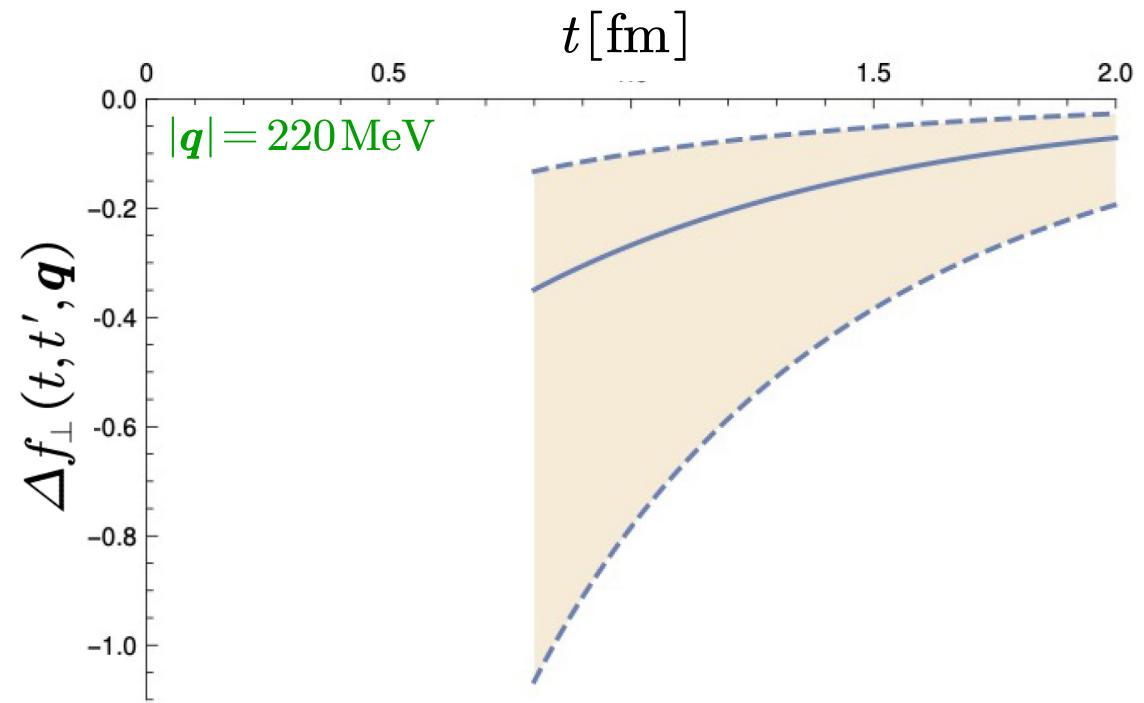
Bär, Mon, 15:00-, Broll, Mon, 15:20-

$B^*\pi$ state contamination within HMChPT

- LEC
 - + LO: $f = f_{\pi'}$ $g_{B^*B\pi} = 0.5$
 - + NLO: β, β' : unknown
 - $\Lambda_\chi^{-1} \leq \beta, \beta' \leq \Lambda_\chi^{-1}$
- source-sink separation $t = 1.3$ fm

$\Rightarrow B^*\pi$ contamination to $M_{B,\text{eff}}, f_B, B \rightarrow \pi$ FFs, ...

possibly large effects in f_\perp (!)



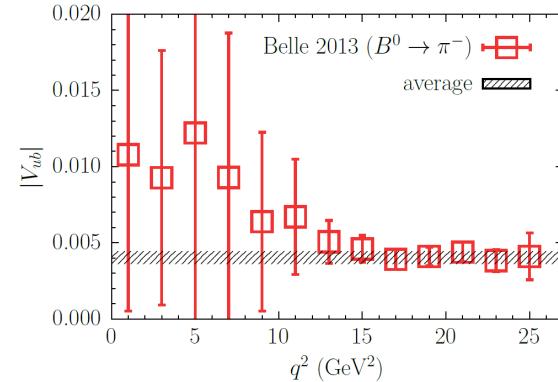
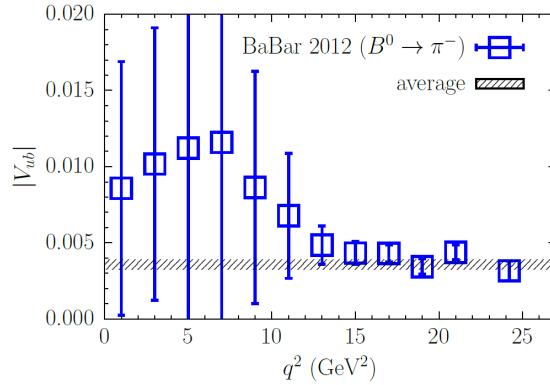
- depending on NLO LECs
- smearing may help ?
 \Rightarrow how to calculate NLO LECs from 3pt func

more on $|V_{ub}|$

Vittorio, Tue, poster

"dispersive matrix method"

- existing lattice data \Rightarrow bound on FF at any q^2
 - + positivity of $\langle 0 | J_{ub}^\dagger J_{ub} | 0 \rangle \rightarrow$ bound on FF
Bourrely+ '81, Lellouch '96
 - + VPF on the lattice: Martinelli+ '21

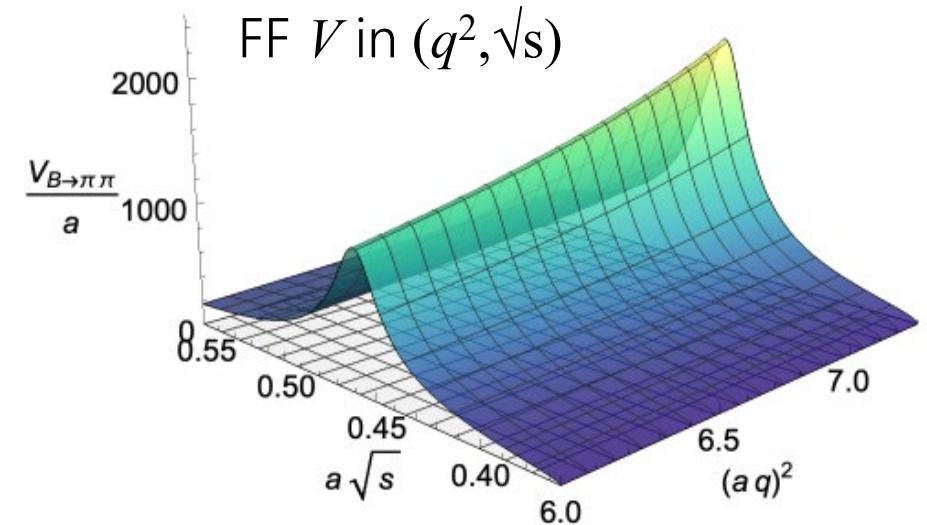


$$|V_{ub}| = 3.62(0.47) \times 10^{-3} \quad |V_{cb}| = 41.3(1.7) \times 10^{-3}$$

Leskovec, Mon, 14:40-

$B \rightarrow (\rho \rightarrow) \pi \pi \ell \nu$

- FV formalism for coupled channel analysis
Briceno+ '21
- clover ud + RHQ b , $M_\pi = 320$ MeV, $M_B = 5.3$ GeV



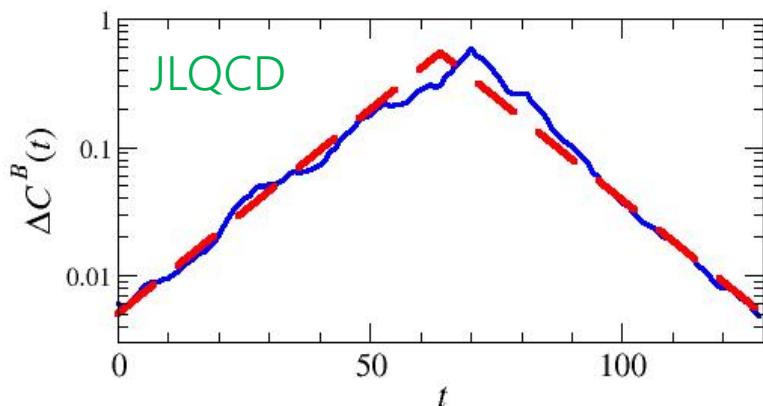
- can be extended to $B \rightarrow K^* \ell \nu$? $\Rightarrow R(K^*), P_5'$

alternatives : $B_s \rightarrow D_s \ell \nu$, $B_c \rightarrow J/\psi \ell \nu$

$B \rightarrow D^{(*)} \ell \nu$ w/ s or c spectator $\Rightarrow |V_{cb}|$

- better control of chiral extrap. $\Leftrightarrow M_{\pi, \text{phys}}$
- less statistical error: Parisi '83, Lepage '89

$$\Delta C^H(t) \sim \exp[(2M_H - M_{QQ} - M_{qq})t/2]$$

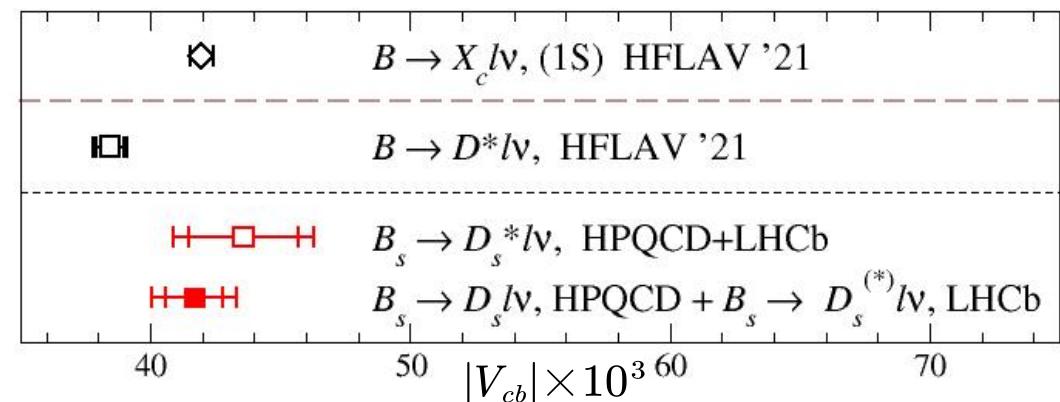


$$\begin{aligned} 2M_H - M_{QQ} - M_{qq} &= K \\ K &= 0.16 \\ D_{(s)} &= 0.60(0.24) \\ B_{(s)} &= 1.02(0.64) \end{aligned}$$

- e.g. "stable" D_s^* , J/ψ w/ tiny width

HPQCD '19, '20: $|V_{cb}|$ and $R(J/\psi)$

- w/ HISQ b, c w/ $m_b \leq 4m_c$, $a^{-1} \leq 4.5 \text{ GeV}$



- $R(J/\psi) \sim \Gamma(B \rightarrow J/\psi \tau \bar{\nu}) / \Gamma(B \rightarrow J/\psi \{e, \mu\} \bar{\nu})$
HPQCD $0.258(4) \Leftrightarrow 0.71(25)$ LHCb '18

largest errors: stat., $am_Q \rightarrow 0$, (short) $\eta_Q \rightarrow \eta_b$

Blossier+ '21, $N_f=2$; Lytle [Fermilab/MILC], Wed; Wingate [HPQCD], Poster; RBC/UKQCD@Quarks'22

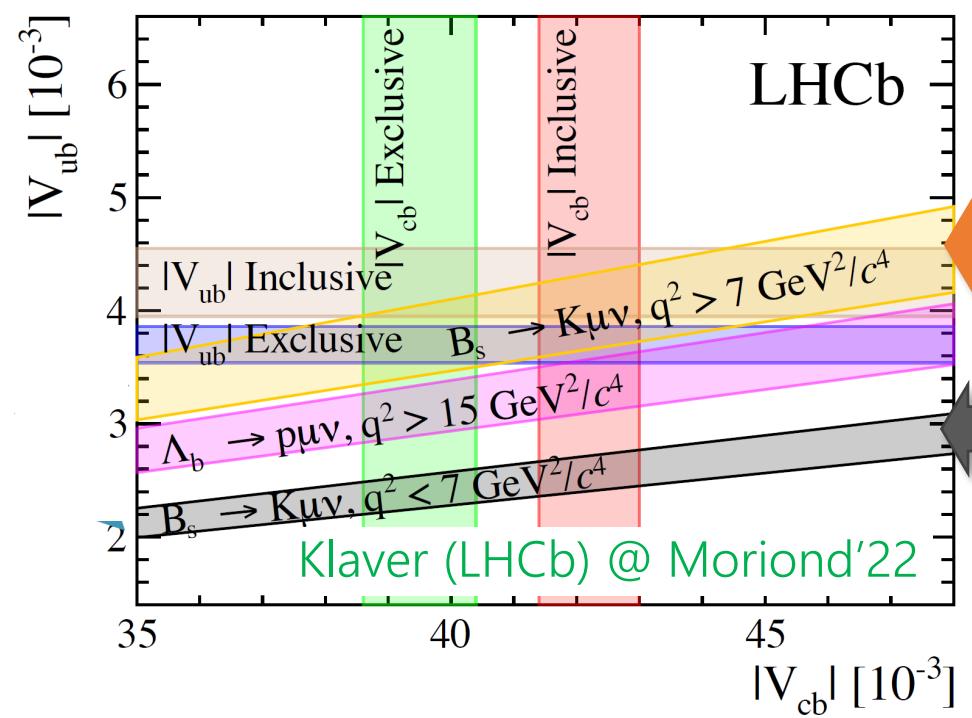
expecting th & exp improvement : realistic lattice & LHCb

e.g. LHCb 1808.08865 $\Delta R(J/\psi) = 0.07$ (Run-3, -2025), 0.02 (Upgrade II) \sim current $\Delta R(D^{(*)})$

$B_s \rightarrow K\ell\nu$

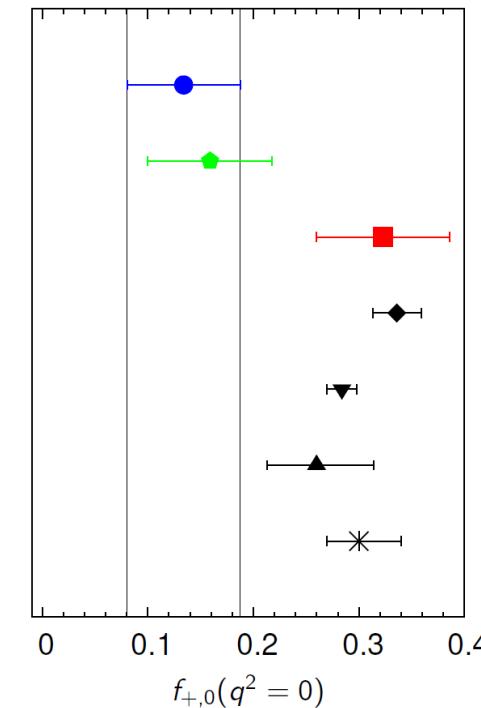
$B \rightarrow \pi\ell\nu$ w/ s spectator $\Rightarrow |V_{ub}|$

- FFs: HPQCD'14(NRQCD), RBC/UKQCD '15 (RHQ), Fermilab/MILC '19 (Fermilab), ALPHA '19 (HQET)
- CKM suppressed : 1st observation by LHCb '20



$\frac{B_s \rightarrow K\mu\nu}{B_s \rightarrow D_s\mu\nu} \Rightarrow \frac{|V_{ub}|}{|V_{cb}|}$
 $q^2 > 7 \text{ GeV}^2$
w/ lattice FFs
(Fermilab/MILC'19)
 $q^2 < 7 \text{ GeV}^2$
w/ LCSR FFs
(Khodjamirian+'17)

Fermilab/MILC '19

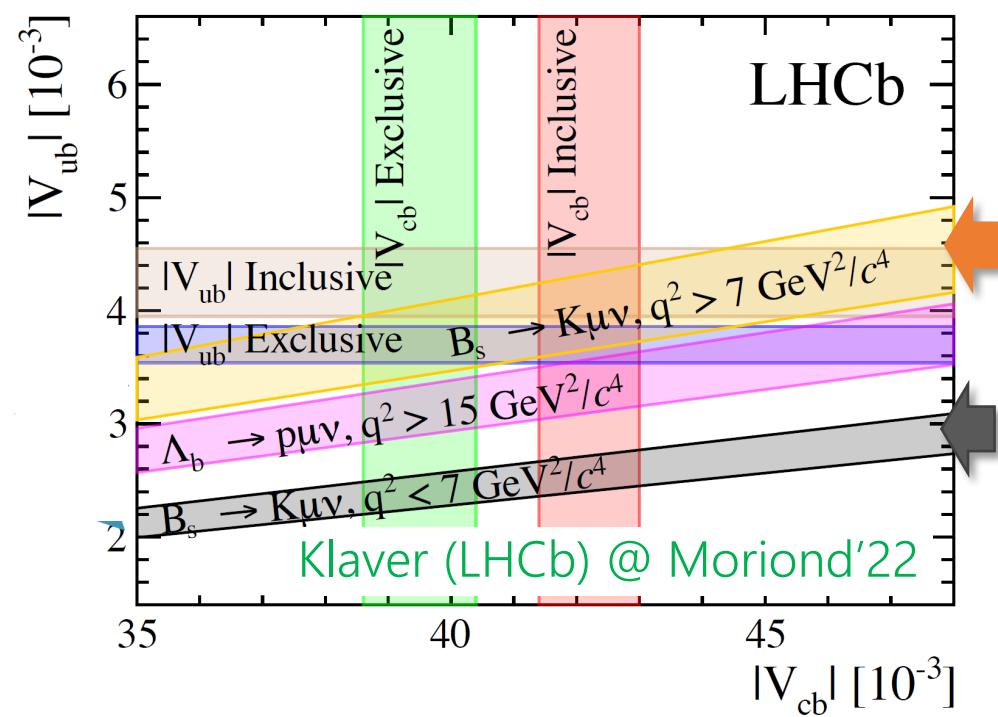


Fermilab/MILC 18
RBC/UKQCD 16
HPQCD 14
Khodjamirian 17 (LCSR)
Faustov 13 (RQM)
Wang 12 (pQCD)
Duplancic 08 (LCSR)

$B_s \rightarrow K \ell \nu$

$B \rightarrow \pi \ell \nu$ w/ s spectator $\Rightarrow |V_{ub}|$

- FFs: HPQCD'14(NRQCD), RBC/UKQCD '15 (RHQ), Fermilab/MILC '19 (Fermilab), ALPHA '19 (HQET)
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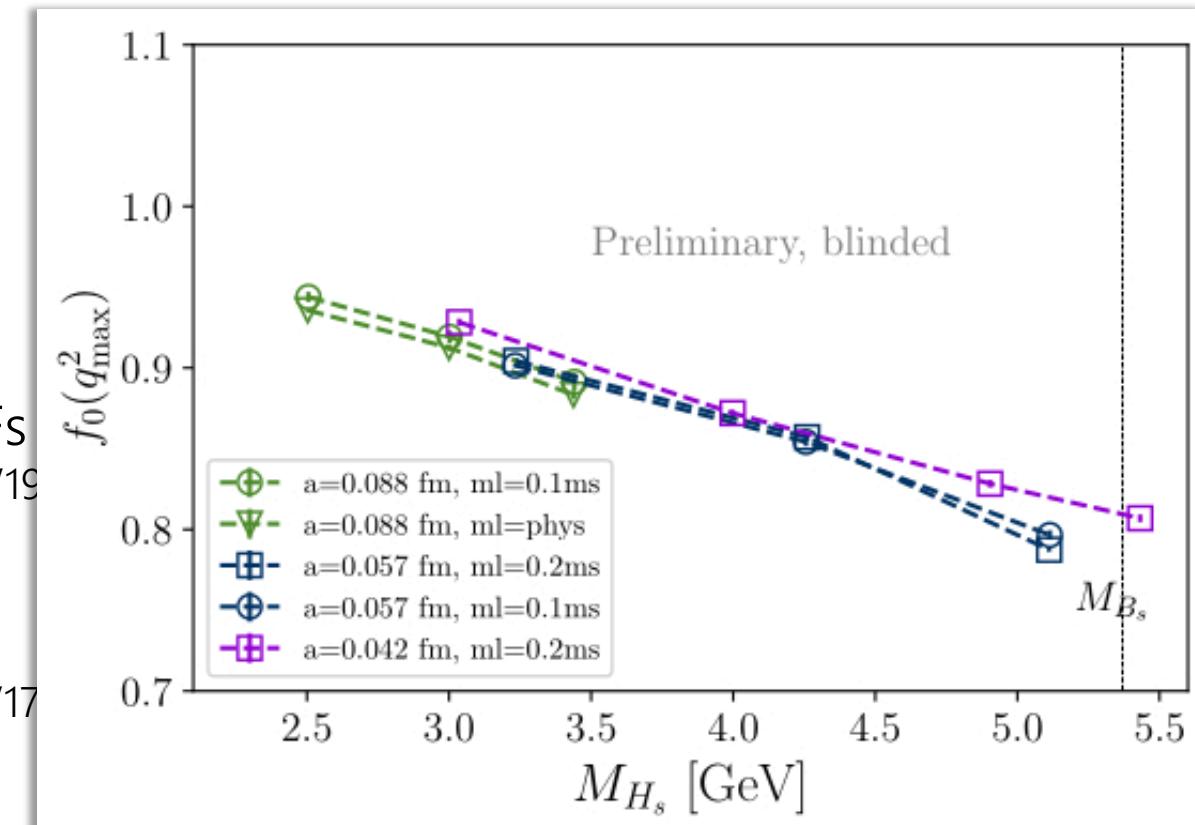


$q^2 > 7 \text{ GeV}^2$
w/ lattice FFs
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$q^2 < 7 \text{ GeV}^2$
w/ LCSR FFs
(Khodjamirian+ '17)

Lytle, Wed, 16:30- [Fermilab/MILC]

- HISQ b , $a^{-1} \leq 4.7$ (and 6.6(!)) GeV, $m_b \leq m_{b,\text{phys}}$
- blinded – tension persists ?



tension persists? / differential measurement by LHCb may help (Klaver@Moriond)

inclusive semileptonic decays

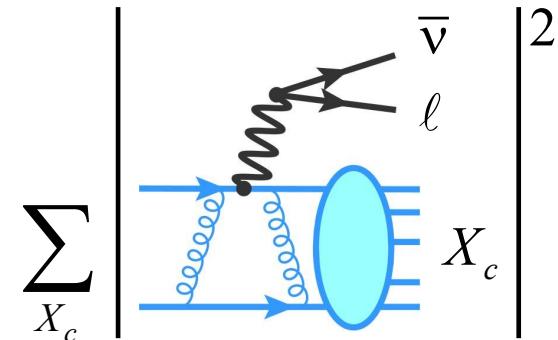
inclusive decays

= "summed over final state hadrons"

$$e.g. \ B \rightarrow X_c \ell \bar{\nu} = D \ell \bar{\nu} + D^* \ell \bar{\nu} + D\pi \ell \bar{\nu} + D\pi\pi \ell \bar{\nu} + \dots$$

exp : NOT observe final state hadron(s)
 th. : optical theorem + OPE

\neq simple sum of exclusive decays



$$\frac{d\Gamma}{dq^2 dq^0 dE_\ell} = \frac{G_F^2}{8\pi^3} |V_{cb}|^2 L^{\mu\nu} W_{\mu\nu}$$

optical theorem

OPE

$$\text{hadronic tensor } W_{\mu\nu} \sim \sum_{X_c} \langle B | J_\mu^\dagger | X_c \rangle \langle X_c | J_\nu | B \rangle = \text{im} \langle B | J_\mu^\dagger \otimes J_\nu | B \rangle = \sum_k \langle B | \mathcal{O}_k | B \rangle$$

- double expansions in $\alpha_s, 1/m_b$: convergence ?
- non-perturbative input : e.g. $\langle B | \bar{b}(iD)^2 b | B \rangle, \langle B | \bar{b}(g\sigma_{\mu\nu} F^{\mu\nu}) b | B \rangle, \dots$

HQET parameters: e.g. JLQCD '02, ETM '19, ...

$|V_{cb}|, |V_{ub}|$ tension \Leftrightarrow inclusive rate from lattice / vs exclusive on the same lattice

on the lattice

NOT straightforward : finite V MEs to multi-hadron final states + possibly many for "B" decays

Hansen-Meyer-Robaina '17, Gambino-Hashimoto '20

"spectral representation"

$$C_{\mu\nu}(t, \mathbf{q}) = \int_0^\infty d\omega W_{\mu\nu}(\omega, \mathbf{q}) e^{-\omega t}$$

lattice 4-pt function

$$C_{\mu\nu}(t, \mathbf{q}) = \langle B | J_\mu^\dagger(-\mathbf{q}) e^{-Ht} J_\nu(\mathbf{q}) | B \rangle$$

"spectral function"

$$W_{\mu\nu}(\omega, \mathbf{q}) = \langle B | J_\mu^\dagger(-\mathbf{q}) \delta(H - \omega) J_\nu(\mathbf{q}) | B \rangle$$

determine $W_{\mu\nu}$ from $C_{\mu\nu}$? - ill-posed inverse problem !!

- finite V spectral function \sim sum of δ function peaks
- finite / discrete data set w/ statistical uncertainty

see also RBC/UKQCD '18 (τ), Hashimoto '17 (B) : correlator @ unphysical pt. \Leftrightarrow dispersive integral
Liu-Dong '94 (DIS), Aglietti et al. '98 (B), DeGrand '22 (R) and plenary by Bulava

smeared / integrated spectral function

Hansen-Meyer-Robaina '17, Hansen-Lupo-Tantalo '19

$$W_{\mu\nu,L,\sigma}(\omega_*) = \int_0^\infty d\omega \Delta_\sigma(\omega_*, \omega) W_{\mu\nu,L}(\omega) \quad \Delta_\sigma(\omega_*, \omega) : \text{smooth approx. Dirac } \delta \text{ w/ width } \sigma$$

$$W_{\mu\nu}(\omega) = \lim_{\sigma \rightarrow 0} \lim_{L \rightarrow \infty} W_{\mu\nu,\sigma,L}(\omega) \quad \text{inverse problem for smooth function } W_{\mu\nu,L,\sigma} : \text{well-posed}$$

Gambino-Hashimoto '20

ω integral kernel for differential rate as smearing function $\propto \theta(\omega_{\max} - \omega)$

$$\Gamma \sim \int_0^{q^2_{\max}} d\mathbf{q}^2 \int_{\omega_{\min}}^{\omega_{\max}} d\omega K_{\mu\nu}(\omega, \mathbf{q}^2) W_{\mu\nu,L}(\omega, \mathbf{q}^2)$$

smooth approximation of $K_{\mu\nu,L,\sigma}$, and take the double limit

so, when $C_{\mu\nu}(t, \mathbf{q}) = \int_0^\infty d\omega W_{\mu\nu}(\omega, \mathbf{q}) e^{-\omega t}$ evaluate $I_{L,\sigma} = \int_0^\infty d\omega f_{L,\sigma}(\omega) W_{\mu\nu,L}(\omega, \mathbf{q}^2)$

implementations

Hansen-Lupo-Tantalo '19

by modified Backus-Gilbert method

$$\tilde{f}(\omega) = \sum_{t=0}^{t_{\max}} g_t e^{-\omega t}$$

- approximate "basis" functions
- g_t by minimizing

+ approx. error of f : $\int_0^\infty d\omega |f - \tilde{f}|^2$

+ stat. error of I : $\mathbf{g}_t^T \text{Cov}[C_{\mu\nu}] \mathbf{g}_t$

$$I_{L,\sigma} \cong \sum_{t=0}^{t_{\max}} g_t C_{\mu\nu,L}(t, \mathbf{q})$$

accuracy of $C_{\mu\nu,L}$ & approximation & take the double limit ($L \rightarrow \infty$, $\sigma \rightarrow 0$)

σ : smearing width of δ singularity / θ discontinuity

Gambino-Hashimoto '20

by Chebyshev approximation

$$\tilde{f}(\omega) = \frac{c_0^*}{2} + \sum_{k=1}^{k_{\max}} c_k^* T_k^*(e^{-a\omega})$$

$$c_k^* = \frac{2}{\pi} \int_0^\pi d\theta f(\theta') \cos[k\theta]$$

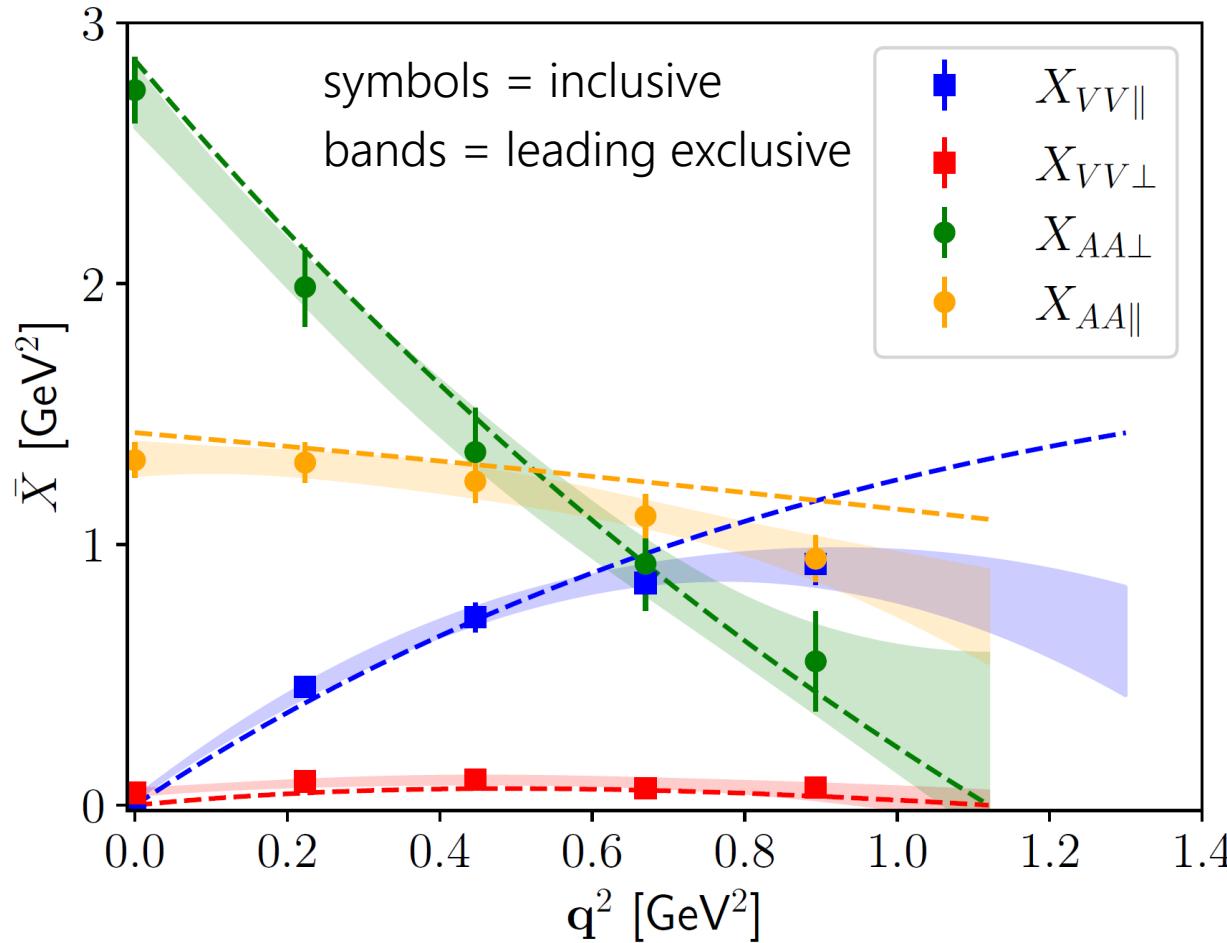
- minmax approximation
- possibly huge cancellation @ large k

$$I_{L,\sigma} \cong \frac{c_0^*}{2} + \sum_{k=1}^{k_{\max}} c_k^* \langle B | J_\mu^\dagger(-\mathbf{q}) T_k^*(e^{-aH}) J_\nu(\mathbf{q}) | B \rangle$$

$$C_{\mu\nu,L}(t, \mathbf{q}) = \langle B | J_\mu^\dagger(-\mathbf{q}) (e^{-aH})^t J_\nu(-\mathbf{q}) | B \rangle$$

vs exclusive

Smecca, Fri, 15:10- [Gambino+, JHEP07(2022)]



good consistency w/ exclusive $\Leftrightarrow |V_{cb}|$ tension

$B_s \rightarrow X_{sc} \ell \nu$

JLQCD ensemble + Chebyshev

- $48^3 \times 96$, $a = 0.11$ fm

- Möbius DWF b w/ $m_b = 2.44 m_c$

$$\Gamma = \frac{G_F^2}{24\pi^3} |V_{cb}|^2 \int_0^{q_{\max}^2} d\mathbf{q}^2 \sqrt{\mathbf{q}^2} \bar{X}(\mathbf{q}^2)$$

$$\bar{X}(\mathbf{q}^2) = \int_0^\infty d\omega K_{\mu\nu,\sigma}(\omega, \mathbf{q}^2) W_{\mu\nu,L}(\omega, \mathbf{q}^2)$$

$X_{VV,\parallel} : B_s \rightarrow D$ $X_{VV,\perp}$, $X_{AA,\parallel}$, $X_{AA,\perp} : B_s \rightarrow D_s^*$

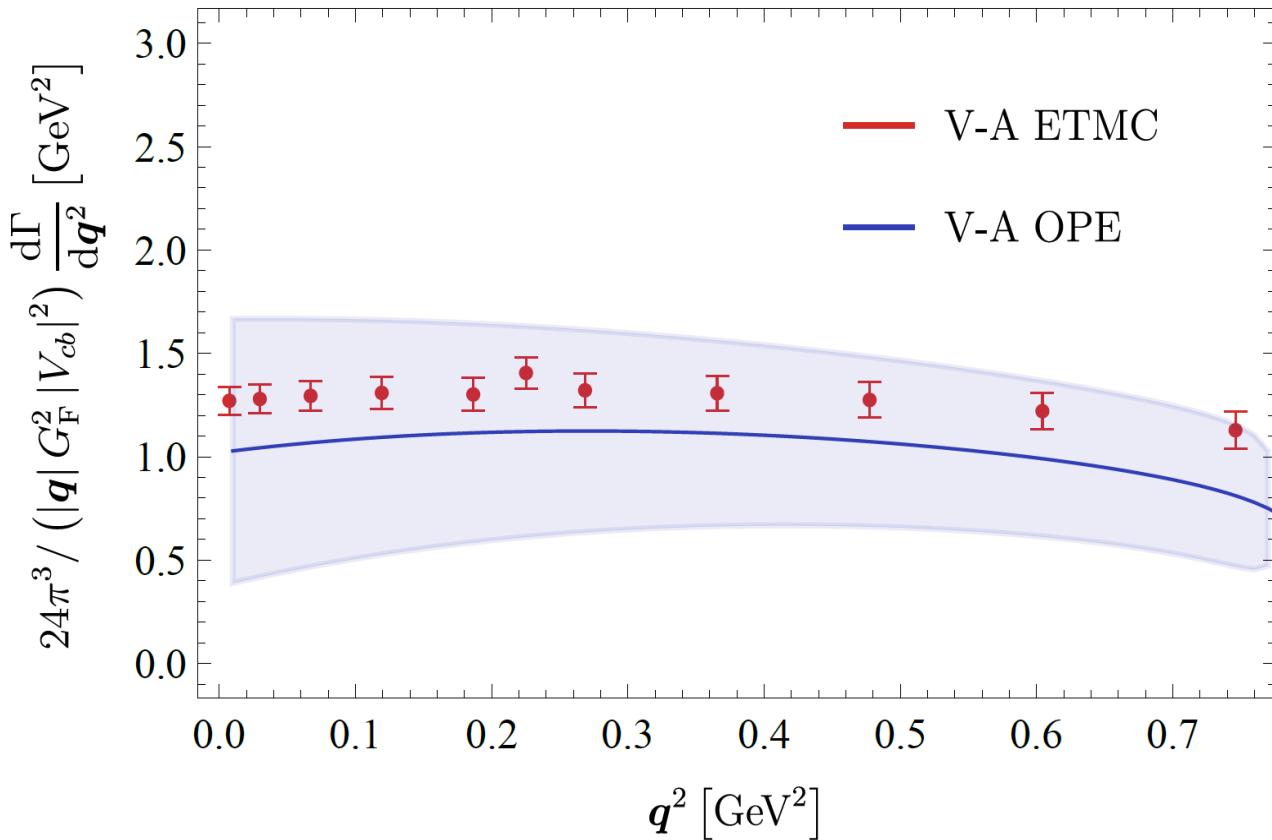
significant $B_s \rightarrow D_s^{**} \ell \nu$ in $C_{\mu\nu,L}$ (JLQCD @ Lat'19)

\Leftrightarrow rate nearly saturated by $B_s \rightarrow D_s^{(*)} \ell \nu$

/ larger $B \rightarrow D^{**} \ell \nu (+)$ towards $m_{b,\text{phys}}$ (?)

vs OPE

Smecca, Fri, 15:10- [Gambino+, JHEP07(2022)]



reasonable consistency in total contribution b/w lattice and OPE

contributions ($X_{VV,\parallel}$, ...) show poorer consistency \Leftrightarrow quark-hadron duality violation ?

$B_s \rightarrow X_{sc} \ell \nu$

ETM ensemble + Backus-Gilbert

- $N_f=2+1+1$, $32^3 \times 64$, $a = 0.08\text{fm}$, $M_\pi = 375\text{MeV}$
- twisted mass b w/ $m_b = 2 m_c$

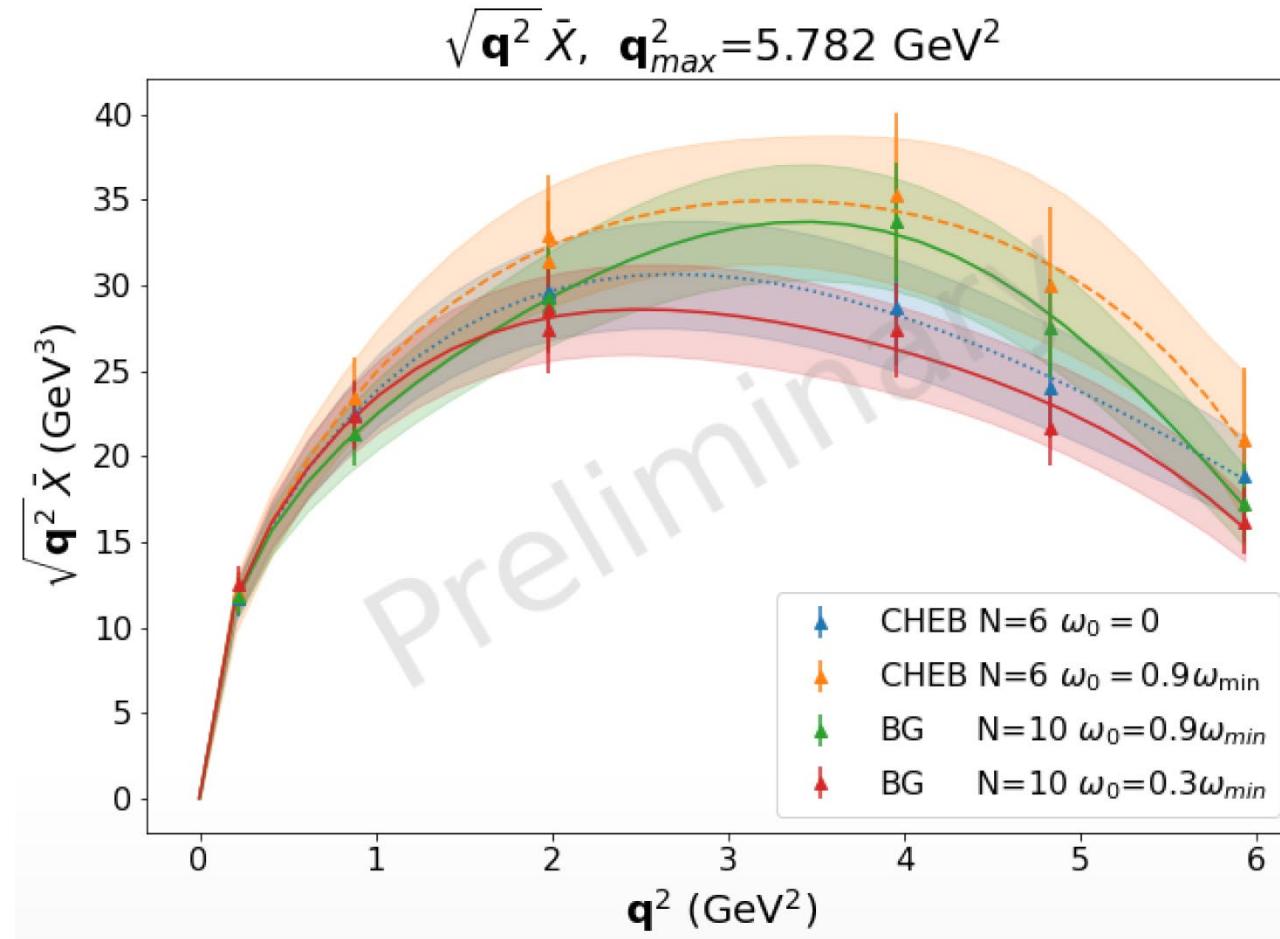
OPE

- $O(1/m_b^3)$ correction, NP MEs from fit to exp
- $O(\alpha_s)$ radiative correction

Gambino-Hashimoto '20 (JLQCD + Chebyshev)
better consistency w/ higher order corrections

Backus-Gilbert vs Chebyshev

Barone, Fri, 14:50-



$$B_s \rightarrow X_{sc} \ell \nu$$

RBC/UKQCD ensemble

- $24^3 \times 64, a = 0.11 \text{ fm}$, physical m_{ud}
- RHQ w/ physics m_b

$$\bar{X}(\mathbf{q}^2) = \int_{0 \rightarrow \omega_0}^{\infty} d\omega K_{\mu\nu,\sigma}(\omega, \mathbf{q}^2) W_{\mu\nu,L}(\omega, \mathbf{q}^2)$$

$$K_{\mu\nu,\sigma}(\omega, \mathbf{q}^2) = k_{\mu\nu}(\mathbf{q}^2) \theta_{\sigma}(\omega_{\max} - \omega)$$

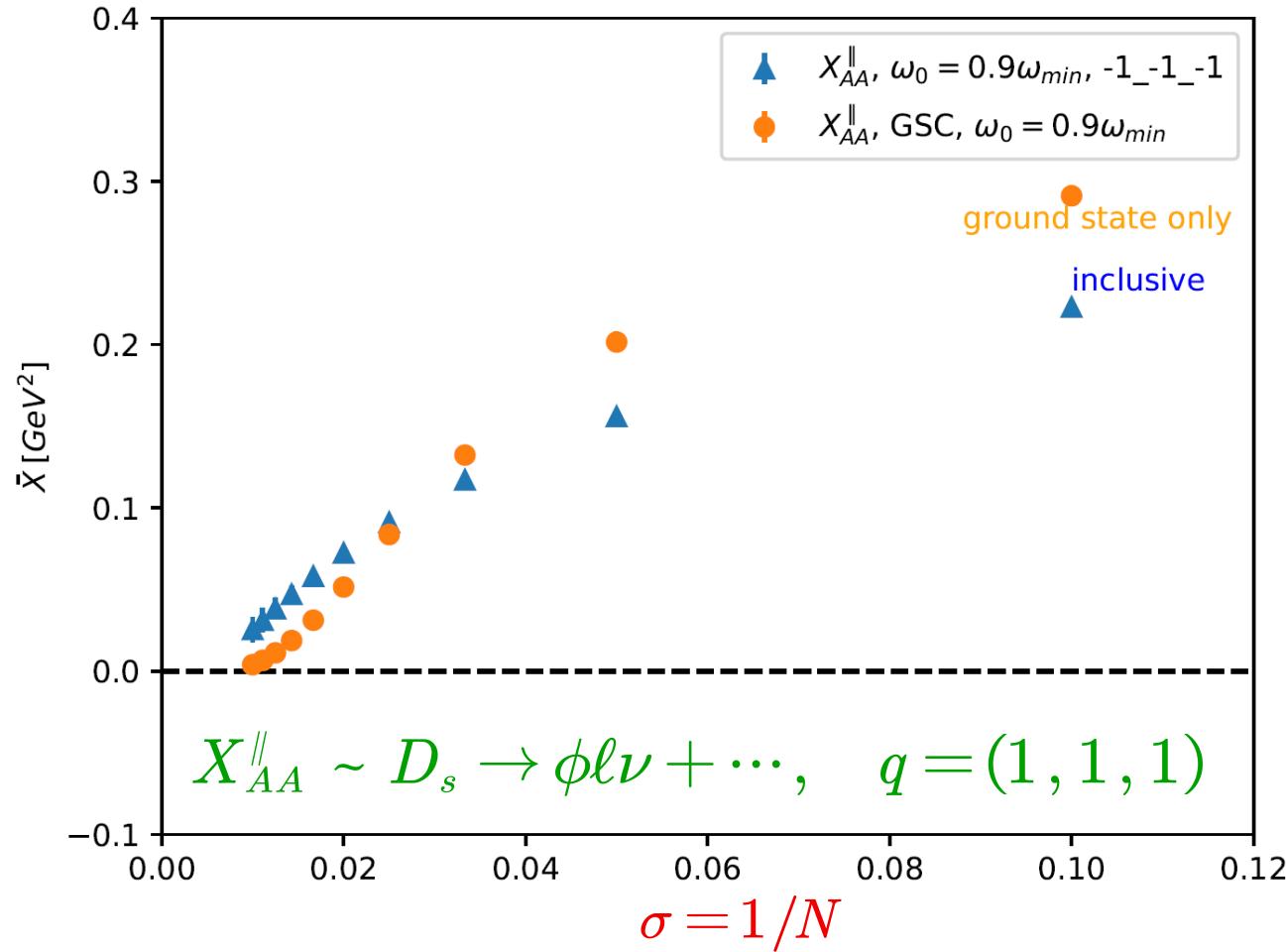
smooth approx. by BG or Chebyshev

$$0 \rightarrow \omega_0 \leq \omega_{\min} = \sqrt{M_D^2 + \mathbf{q}^2}$$

consistency b/w Backus-Gilbert and Chebyshev \Rightarrow ready for $B_{(s)}$ decays @ physical m_b

$\sigma \rightarrow 0$ extrapolation

Kellermann, Fri, 14:30-



JLQCD ensemble + Chebyshev approx.

$$D_s \rightarrow X_{ss} \ell \nu$$

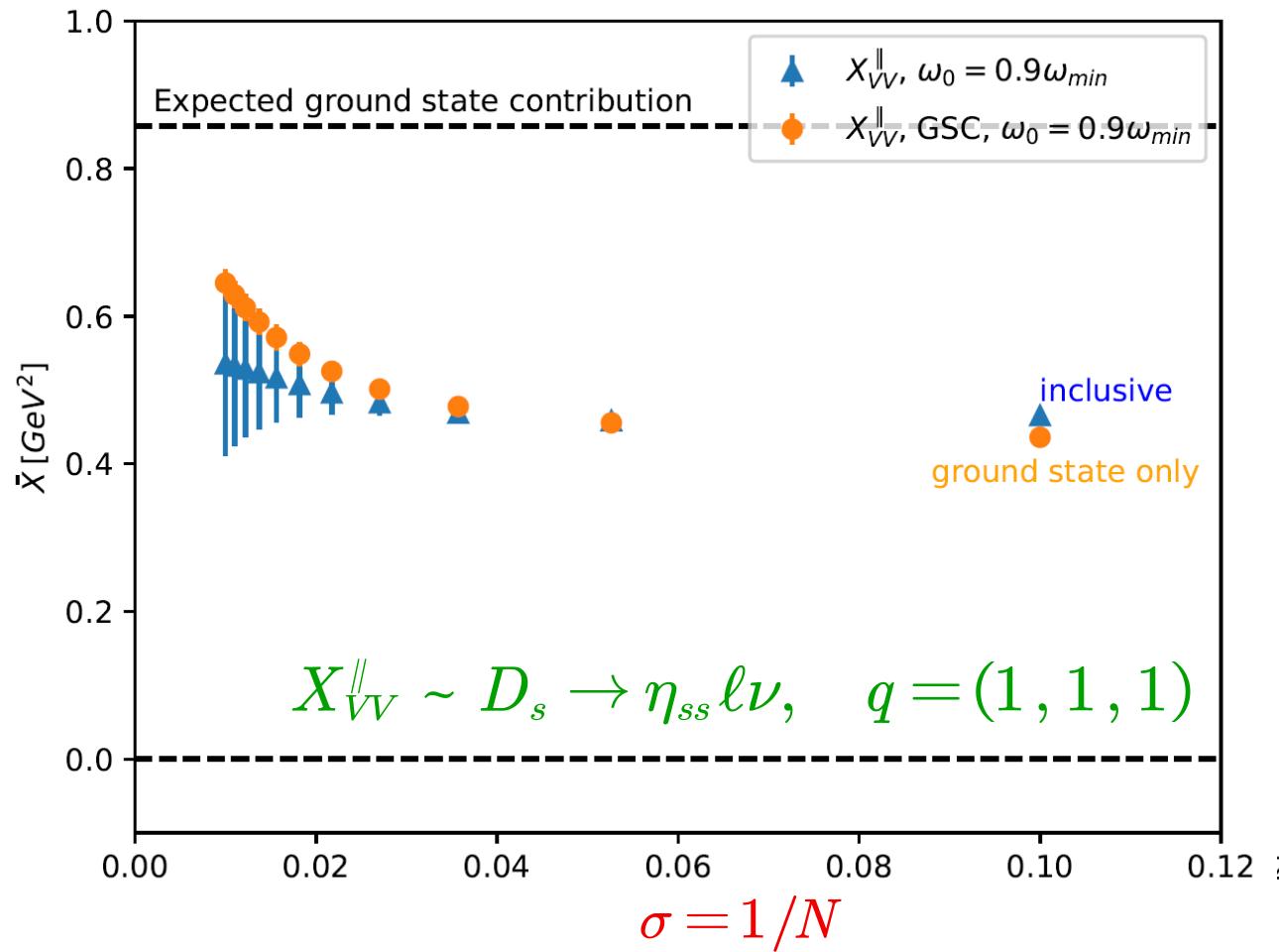
- good control of continuum+chiral extrap.
- careful study of non-trivial $\sigma \rightarrow 0$ extrap.

$$K_{\mu\nu,\sigma}(\omega, \mathbf{q}^2) = k_{\mu\nu}(\mathbf{q}^2) \theta_\sigma(\omega_{\max} - \omega)$$

- large $\mathbf{q} \Rightarrow$ too large $E_X = E_\Phi$
 $\Rightarrow X(q)$ vanishes after $\sigma \rightarrow 0$ extrapolation

$\sigma \rightarrow 0$ extrapolation

Kellermann, Fri, 14:30-



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 $\Rightarrow X(q)$ vanishes after $\sigma \rightarrow 0$ extrapolation
- a conservative error estimate
using maximum value of $|T_k^*| = 1$

ready for realistic study of $D_s \rightarrow X_{ss} \ell \nu$, comparison w/ exp't (CLEO '10, BESIII '22, ...)

lifetime

$$\Gamma = \frac{G_F^2}{192\pi^3} |V_{cb}|^2 m_b^5 \left\{ c_3 - c_3 \frac{\mu_\pi^2}{2m_b^2} - c_5 \frac{\mu_G^2}{2m_b^2} + \frac{c_6}{m_b^3} \frac{\langle B | (\bar{b}q)_\Gamma (\bar{q}b)_{\Gamma'} | B \rangle}{M_B} \right\}$$

OPE analysis of inclusive rate

- $1/m_b^n$ expansion
- w/ non-perturbative inputs

$$\mu_\pi^2 = \langle B | \bar{b}(iD)^2 b | B \rangle / 2M_B$$

$$\mu_G^2 = \langle B | \bar{b}(g\sigma_{\mu\nu}F^{\mu\nu})b | B \rangle / 2M_B$$

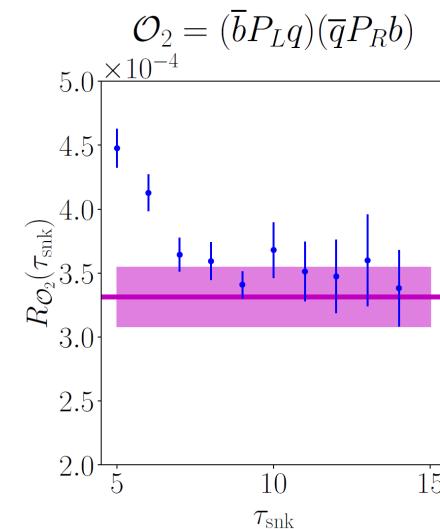
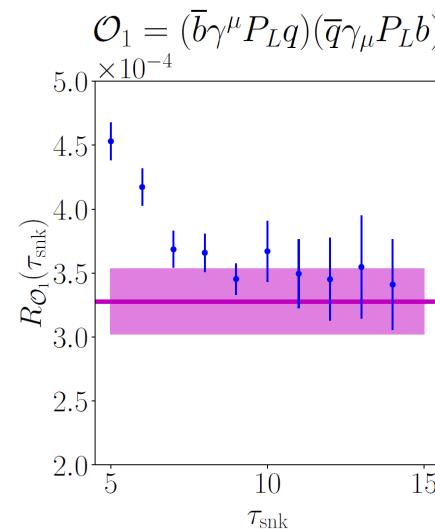
- $\Delta B = 0$ four-quark operator @ $1/m_b^3$

$$(\Gamma, \Gamma') = (\gamma_\mu P_L, \gamma_\mu P_L), (P_L, P_R), \\ (T^a \gamma_\mu P_L, T^a \gamma_\mu P_L), (T^a P_L, T^a P_R)$$

phase-space factor enhancement by $16\pi^2$

Lin, Fri, 15:30-

- lattice calculation of $\Delta B=0$ op.s for B and Λ_b
- RBC/UKQCD ensembles, DWF ud , static b



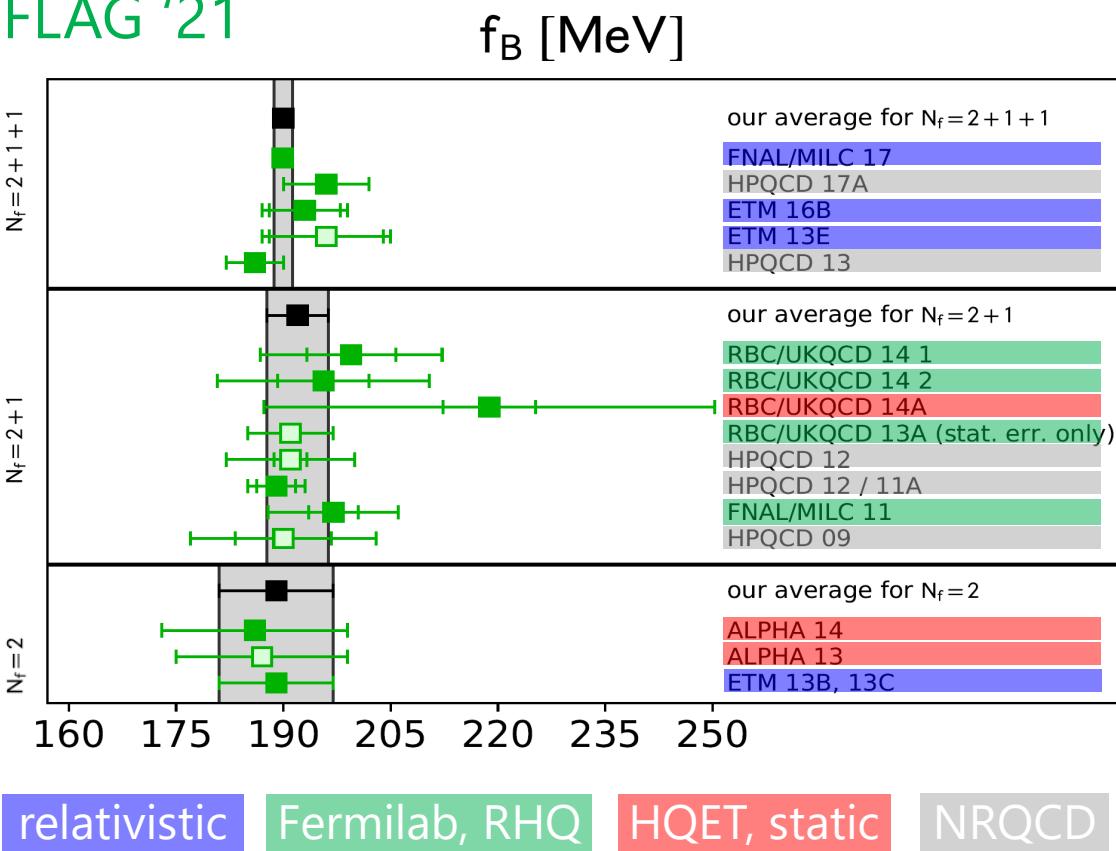
• • •

- renormalization is in progress

leptonic decays

decay constants

FLAG '21



- independent studies w/ different formulations

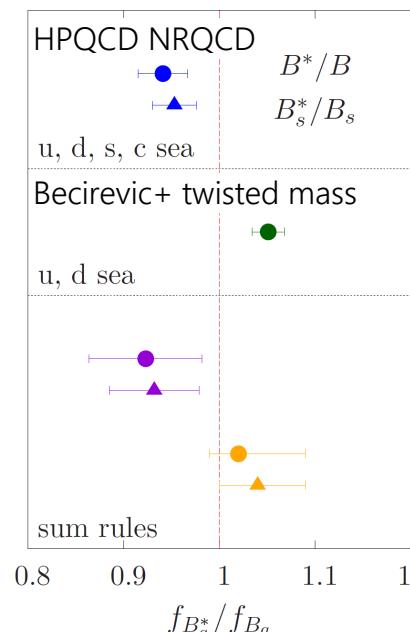
$$\Delta(f_{B_s}/f_B) \sim 0.4\%, \quad \Delta f_{B_{(s)}} \lesssim 0.7\%$$

- isospin correction? \Leftrightarrow EM correction of $\Gamma(K(\pi) \rightarrow \ell\nu)$: Rome-Southampton '17, '19

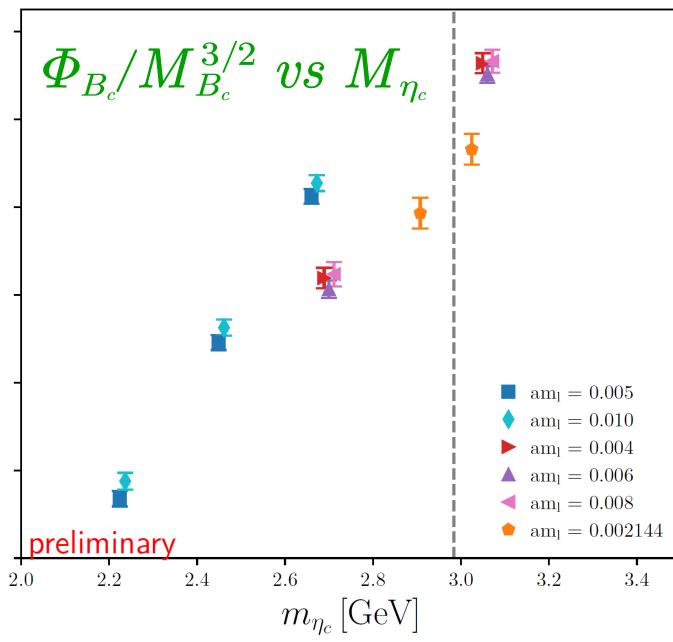
Black, Fri, 14:10- [RBC/UKQCD]

- DWF $ud, s, c, \text{RHQ } b$
- early analysis of $f_{B^*(s)\gamma}, f_{Bc}$
 \Leftrightarrow tension in $f_{B(s)^*}/f_{B(s)}$ b/w HPQCD vs Becirevic+

HPQCD '15



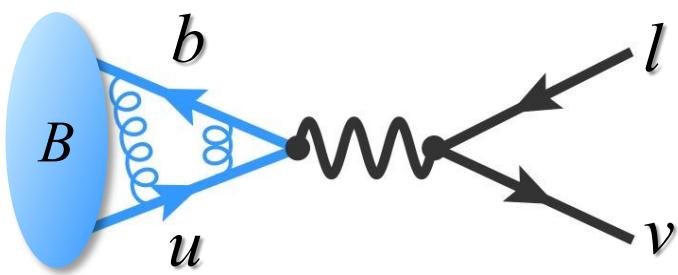
Black [RBC/UKQCD]



decay constants

charged B decay

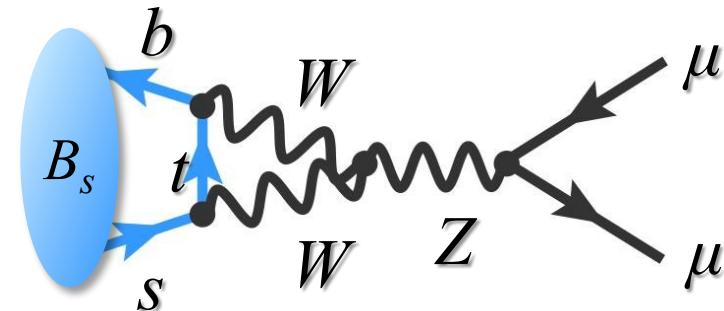
- determination of $|V_{ub}|$



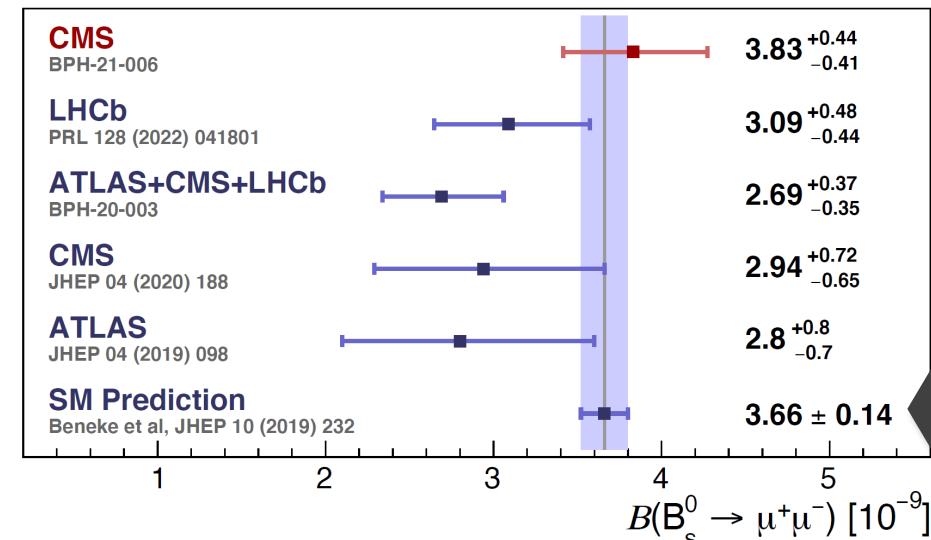
- tree-level, but helicity suppression !
FLAG, $N_f=4$: $|V_{ub}| = 4.05(3)_{\text{lat}}(64)_{\text{exp}} \times 10^{-3}$
- Belle II @ 50 ab⁻¹ (B2TIP '19)
 $\Delta|V_{ub}|_{\text{exp}} \sim 3\% \sim$ competitive to $B \rightarrow \pi \ell \nu, X_u \ell \nu$
 $\Rightarrow |V_{ub}|$ tension
- complementary probe of new physics (!)

neutral $B_{(s)}$ decay

- FCNC process suppressed in the SM



Kovalskyi (CMS) @ ICHEP '22 for $B_s \rightarrow \mu\mu$



theory (f_{B_s}) sufficiently accurate

HL-LHC \Rightarrow 4% (LHCb), 7% (CMS), 13% (ATLAS)

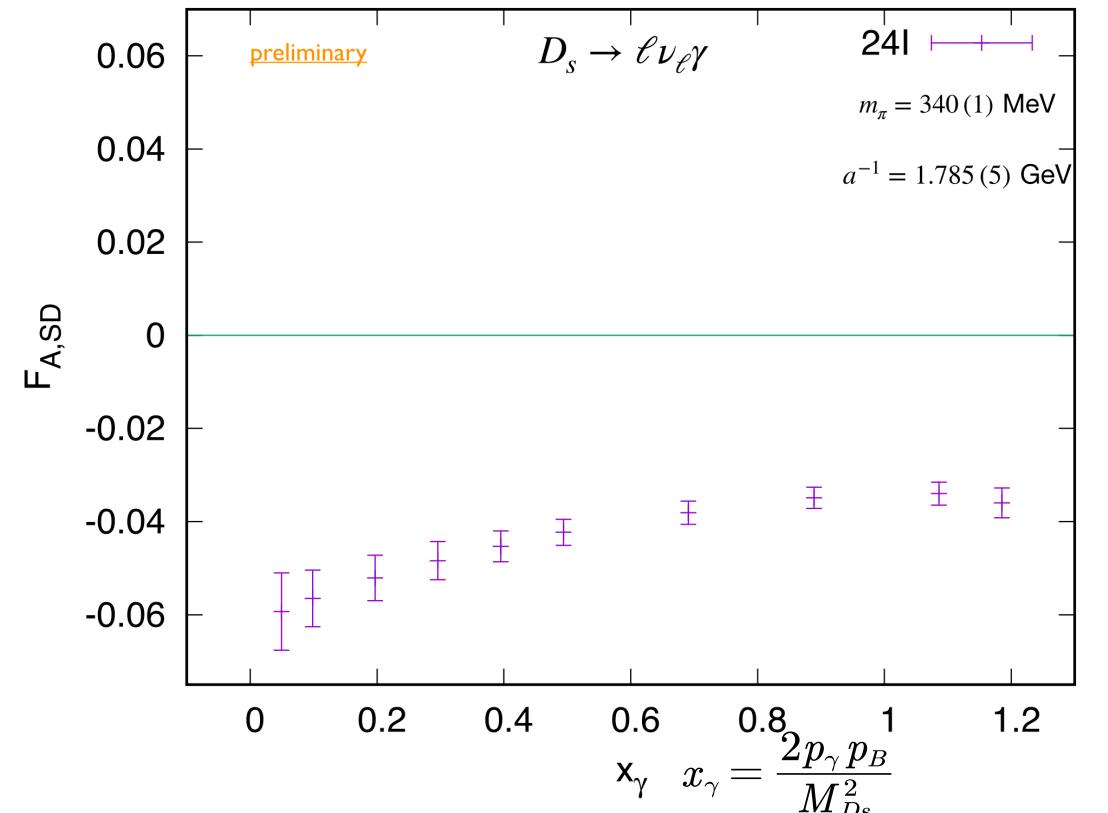
radiative leptonic decay $B \rightarrow \ell \nu \gamma$

$$T_{\mu\nu} = -i \int d^4x e^{ip_\gamma x} \langle 0 | T(J_\mu^{\text{EM}}(x) J_\nu^{\text{weak}}(0)) | B(p) \rangle = \varepsilon_{\mu\nu\rho\sigma} p_\gamma^\rho v_B^\sigma \mathbf{F}_V + i(-g_{\mu\nu} p_\gamma v_B + v_{B,\mu} p_{\gamma,\nu}) \mathbf{F}_A + \dots$$

- lift helicity suppression $\mathcal{B} < 3 \times 10^{-6} \Leftrightarrow \ell \nu < 10^{-[7-11]}$
- $|V_{ub}|?$ \Leftrightarrow Belle II (B2TIP '19) $(\Delta \mathcal{B})_{\text{stat}} \sim 4\%$ (!)
- hard $\gamma \Rightarrow$ **B meson structure** (LCDA, ...)
- only model-dep. prediction (factorization) for B
- Desiderio+ '20
1st lattice study of $\pi, K, D_{(s)}$ w/ limited E_γ range

Giusti, Mon, 17:30-

- K, D_s decays w/ full E_γ range targeting B
- DWF $ud, s, c, a^{-1} = 1.8 \text{ GeV}, M_\pi \sim 340 \text{ MeV}$
- various improvements over Lattice '19, '21
smearing, noise method, how to do
sequential source, mNPR, ...



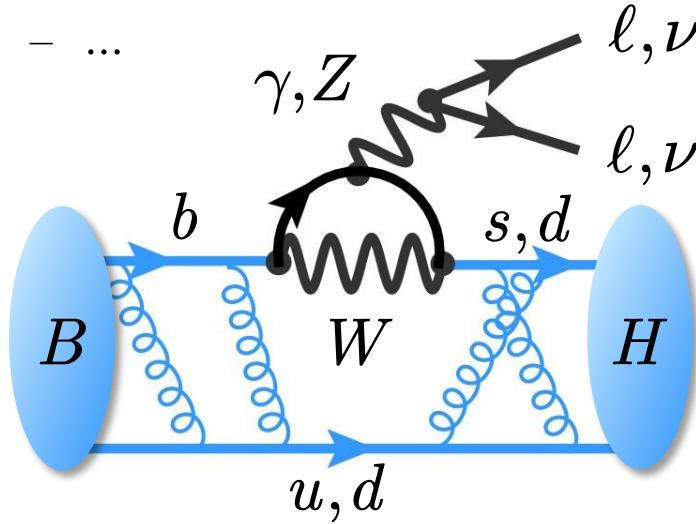
- to $a=0, M_{\pi,\text{phys}}$ \Rightarrow vs BESIII '19 $\mathcal{B}_e < 1.3 \times 10^{-3}$
- to B w/ much larger $E_{\gamma,\text{max}}$

FCNC processes

FCNC processes

$b \rightarrow s, d$ transitions

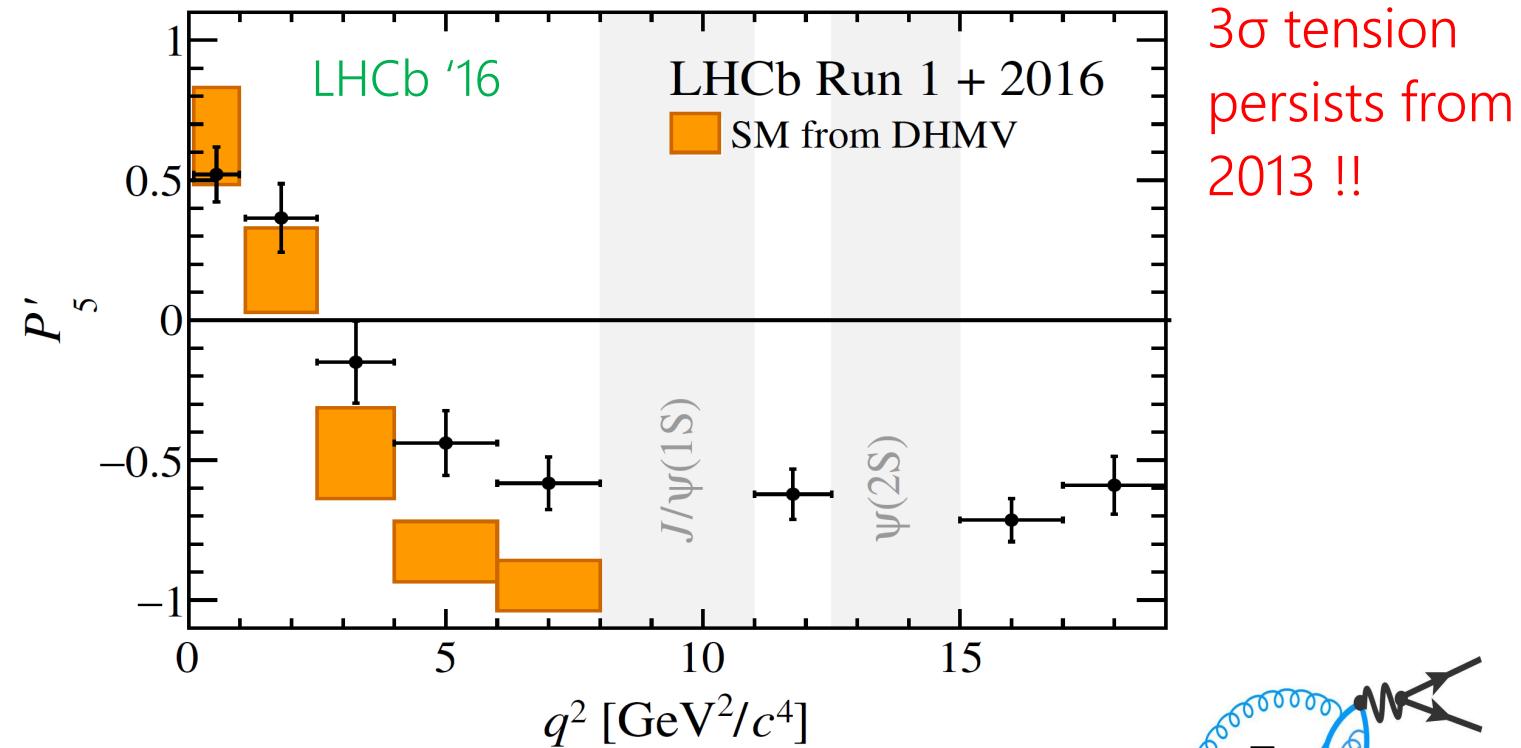
- $B_{(s)} \rightarrow \ell\ell$
- $B^0_{(s)} - \bar{B}^0_{(s)}$ mixings
- $B \rightarrow K^{(*)}\ell\ell, K^{(*)}vv$
- ...



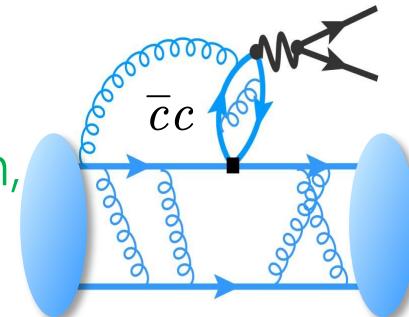
- occur only beyond tree-level of SM
 - GIM suppression
- $\Rightarrow B$ anomalies

e.g. $B \rightarrow K^*\ell\ell$

$$P'_5 = \left[- \int_{3\pi/2}^{2\pi} + \int_{\pi/2}^{3\pi/2} - \int_0^{\pi/2} \right] d\phi \left[\int_0^1 - \int_{-1}^0 \right] d\cos\theta_{K^*} \frac{d(\Gamma - \bar{\Gamma})}{dq^2 d\cos\theta_{K^*} d\phi}$$



- unstable $K^* \Leftrightarrow B \rightarrow \pi\pi\ell\nu$ Leskovec, Mon,
- long-distance $\bar{c}c \Rightarrow$ e.g. JLQCD @ Lat'19



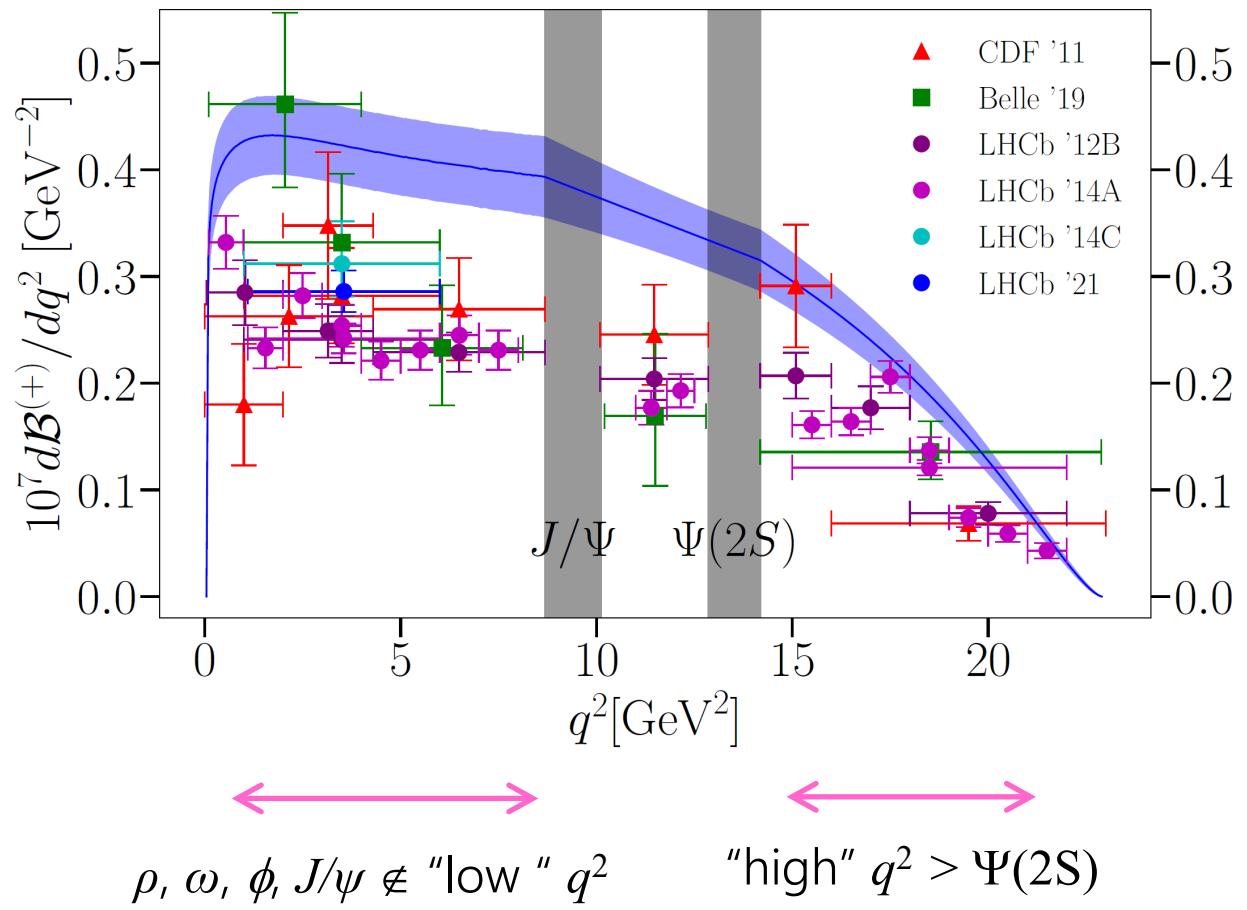
$B \rightarrow K\ell\ell$

$$\langle K(p') | V_\mu | B(p) \rangle = \left\{ P - \frac{\Delta M^2}{q^2} q \right\}_\mu f_+(q^2) + \frac{\Delta M^2}{q^2} q_\mu f_0(q^2) \quad \langle K(p') | T_{k0} | B(p) \rangle = \frac{2i M_B p_{K,k}}{M_B + M_K} f_T(q^2)$$

Parrott, Mon, 16:50-

[HPQCD:2207.12468, 2207.13371]

- HISQ ud, s, b w/ $m_b/m_{b,\text{phys}} = 0.85$
 \Leftrightarrow HPQCD '13, Fermilab/MILC '15
- full q^2 region
- 4-7% uncertainty, dominated by stat.error
- Fermilab/MILC '15 $\approx 2\sigma$ tension
 $\Rightarrow 4.7\sigma$ (vs LHCb '14 @ low q^2)
- significant shift in tensor couplings from SM
 $C_9(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma_\mu \ell), \quad C_{10}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma_\mu \gamma_5 \ell),$



dark sector search

$B \rightarrow Kvv$

- share missing energy signature w/ $B \rightarrow KX_{\text{dark}}$
 \Rightarrow light dark scalar's mass, ... Filimonova+ '20

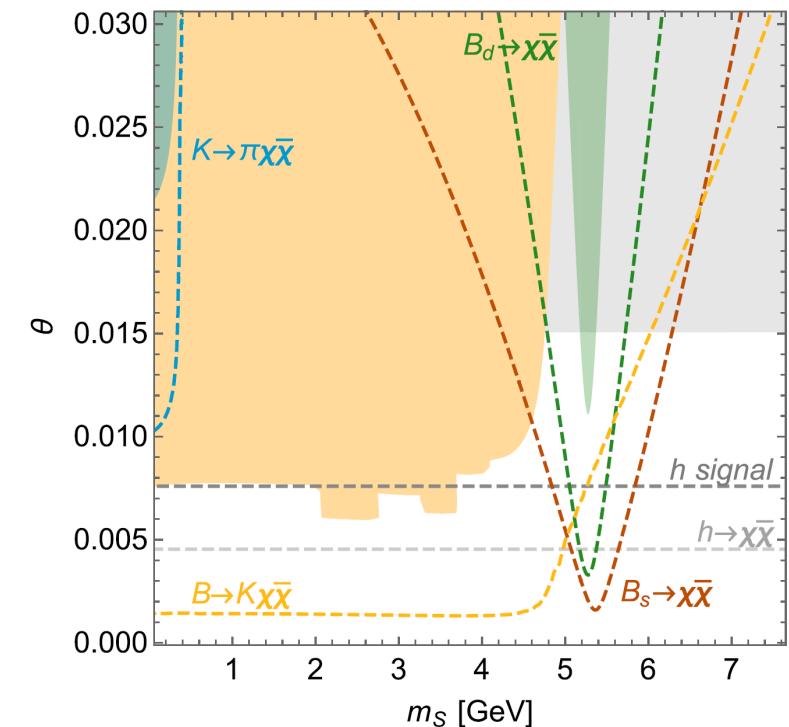
Belle II $50\text{ab}^{-1} \Rightarrow \Delta\mathcal{B} \sim 10\% \Rightarrow m_{\text{dark}} \leq 5\text{GeV}$

$$\frac{d\Gamma}{dq^2} \Big|_{\text{SD}} = \frac{(G_F \eta_{\text{EW}} \alpha_{\text{EW}} X_t)^2}{32\pi^5 \sin^4 \theta_W} |V_{tb} V_{ts}^*|^2 |\mathbf{p}_K|^3 f_+^2(q^2)$$

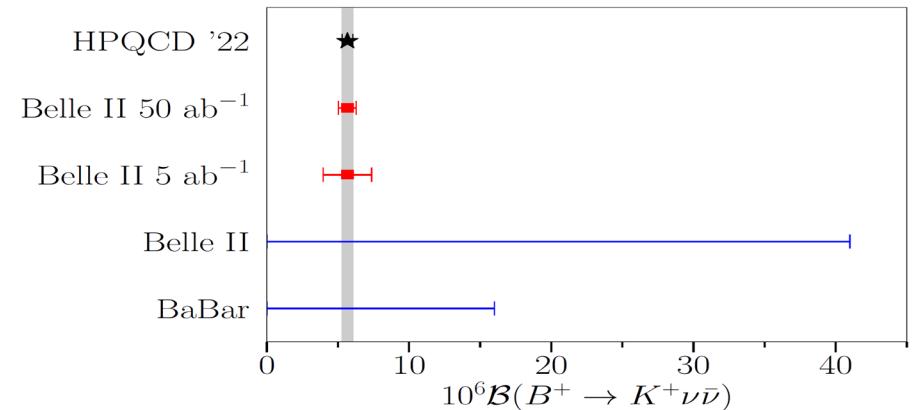
$\mathcal{B}(B^+ \rightarrow K^+ vv) \times 10^5$

- Belle II '21: $1.9(+1.6/-1.5)$
- Fermilab/MILC '15: $0.43(5)$
- Parrot [HPQCD], Mon, 14:40: $0.57(4)$
- \approx Belle II target accuracy (!)

Filimonova et al. '20



HPQD '22

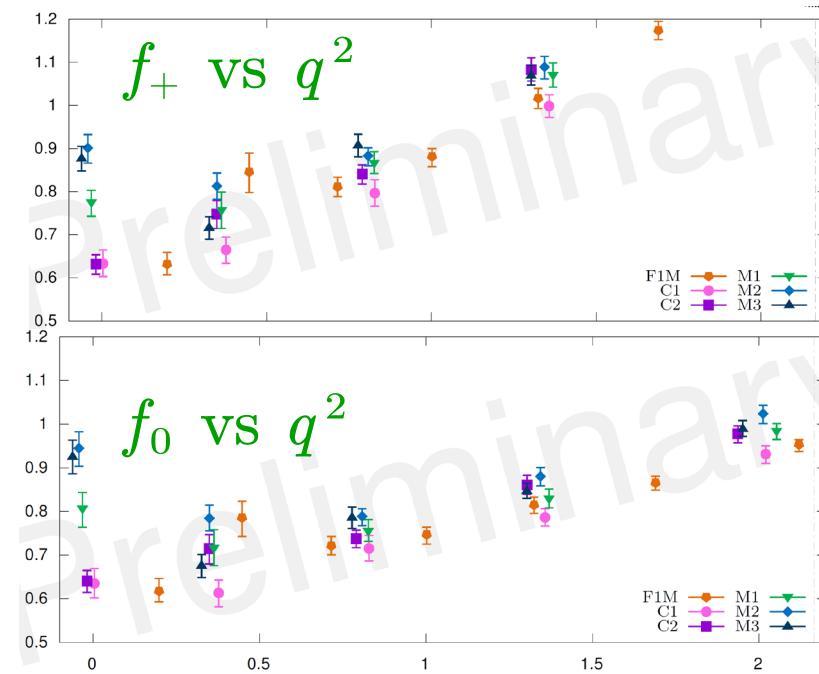


***D* meson semileptonic decays**

$|V_{cd}|$

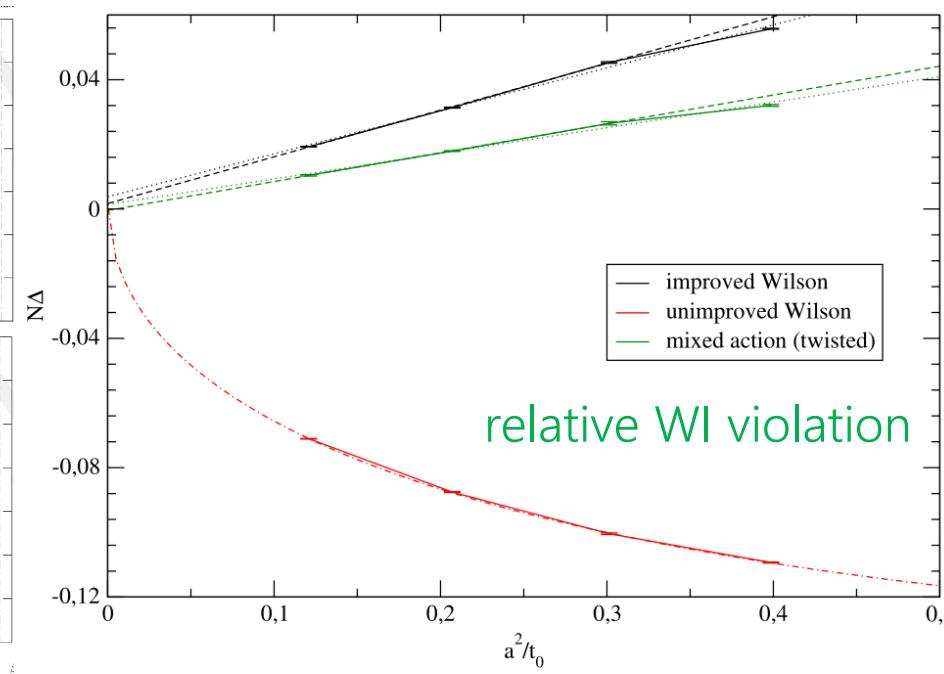
Marshall, Mon, 16:30-
[RBC/UKQCD]

- DWF
- $D \rightarrow K\ell\nu, D \rightarrow \pi\ell\nu, D_s \rightarrow K\ell\nu$



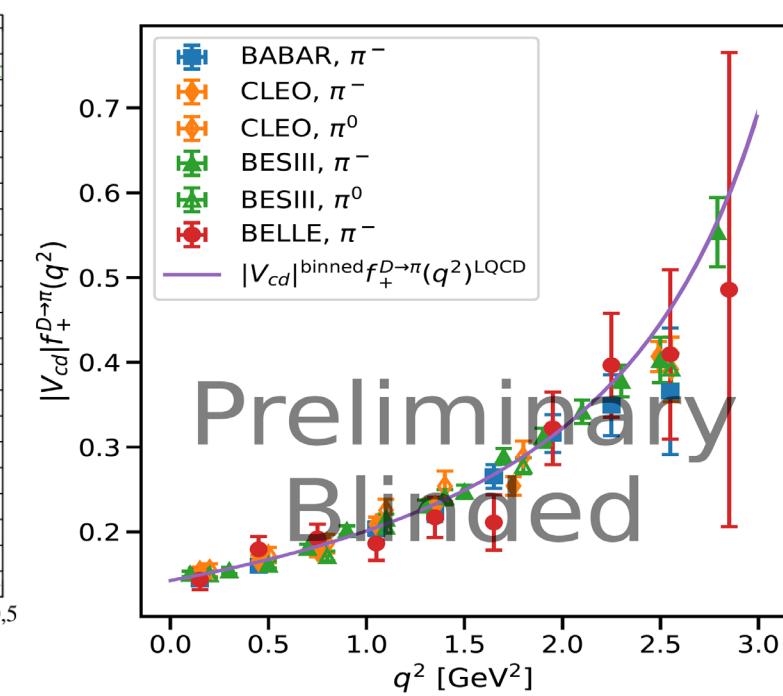
Frison, Wed, 15:00-
[ALPHA / CLS]

- Wilson, twisted mass
- $D \rightarrow \pi\ell\nu$



Jay, Wed, 16:50-
[Fermilab/MILC]

- HISQ
- $D \rightarrow K\ell\nu, D \rightarrow \pi\ell\nu, D_s \rightarrow K\ell\nu$



and Conigli, Wed, 15:40- for leptonic decays

blinded and/or preliminary..., but expect improvement in $|V_{cd}|$ and crosscheck of $D \rightarrow K\ell\nu$

summary

recent progress on heavy flavour physics from lattice QCD

"gold-plated"

- good accuracy \Rightarrow Belle II, LHCb accuracy
- tensions to be understood: $f_{B(s)*}/f_{B(s)}$, f_+^{BsK} (low q^2), $f_{+,T}^{DK}(q^2_{\max})$, $B_{B(s)}^{(5)}$
- B semileptonic @ full q^2 , EM correction to semileptonic, ...

new applications involving unstable / multi-particle states

- $B \rightarrow \ell \nu \gamma$, $B \rightarrow \rho(\rightarrow \pi\pi) \ell \nu$, life time, ...
- inclusive decays: study of systematics (approx., $\sigma \rightarrow 0$, $L \rightarrow \infty$?) \Rightarrow realistic studies
wide applications: e.g. ℓN scattering – Yoo @Lat'21; τ decays - Evangelista, Tue, poster, ...
- long distance contributions to $B \rightarrow K^* \ell \ell$, D mixing; QCD factorization [$B \rightarrow DH$], ...

acknowledgements

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A. Lytle, M. Marshall, S. Mishima, W. Parrott, A. Smecca, R. Sommer, A. Soni,
A. Vaquero, L. Vittorio, ...