$B \to D^{(*)} \ell \nu$ from lattice QCD with domain-wall quarks

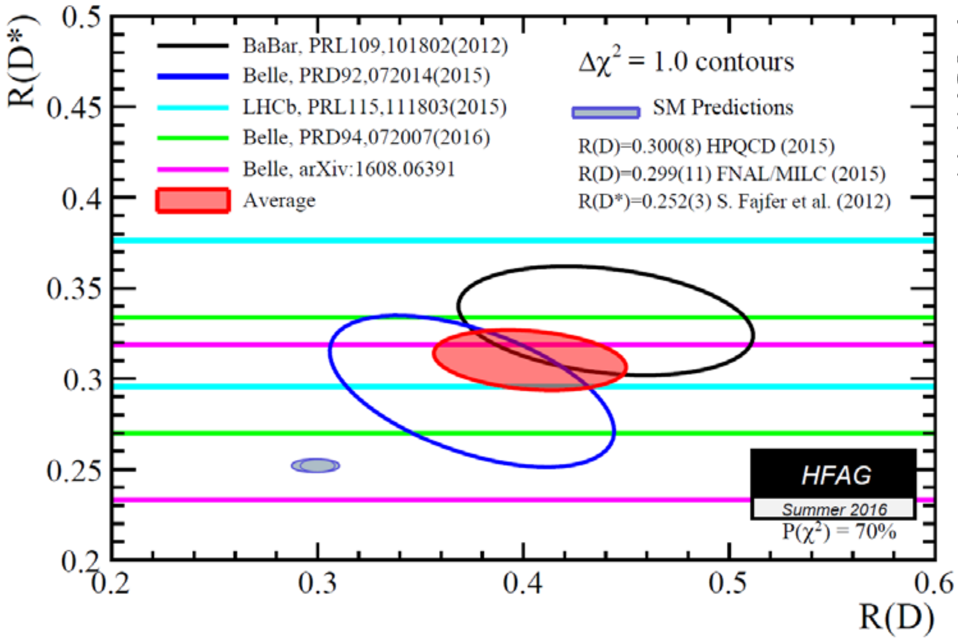
Takashi Kaneko (KEK, SOKENDAI)
for the JLQCD collaboration

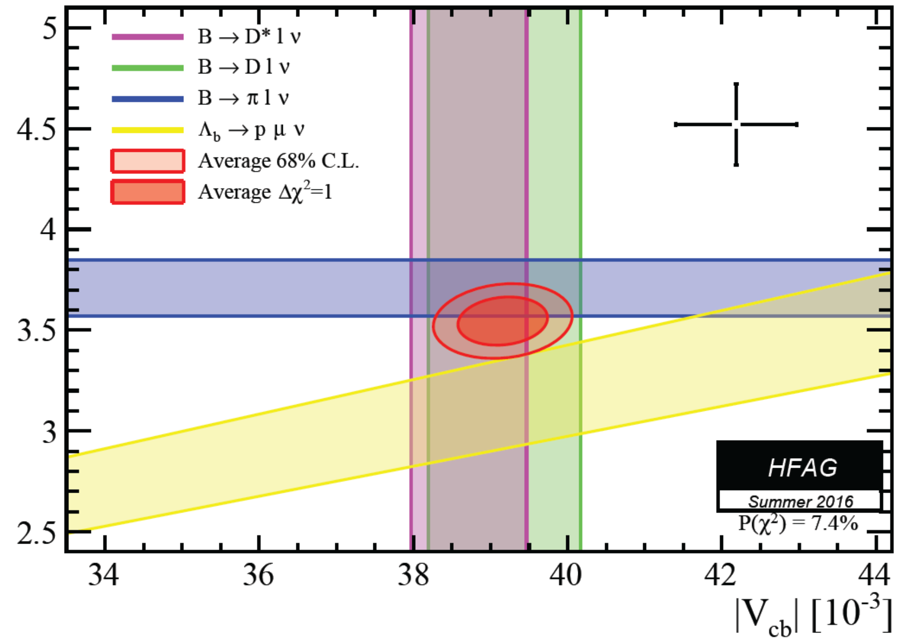
KEK-FF 2019, Feb 14-16, 2019

introduction

hint and puzzle

HFLAV'16





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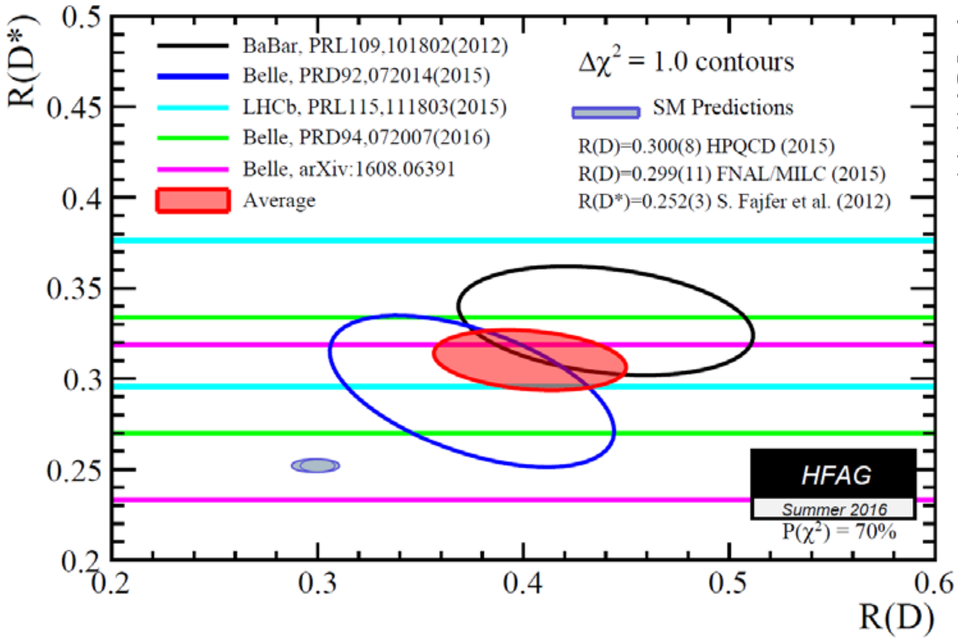

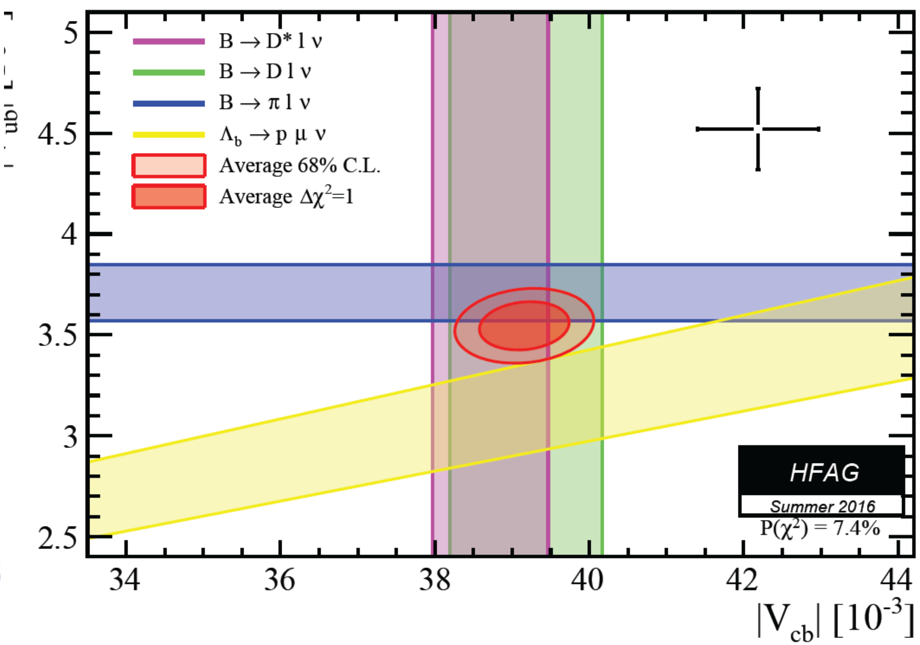

realistic lattice studies only with staggered-type light quarks

$B \to D\ell\nu$: Fermilab/MILC'15, HPQCD'15, HPQCD'17 (w ≥ 1)

$B \to D^*\ell\nu$: Fermilab/MILC'14, HPQCD'17 (w=1) … and previous talk!

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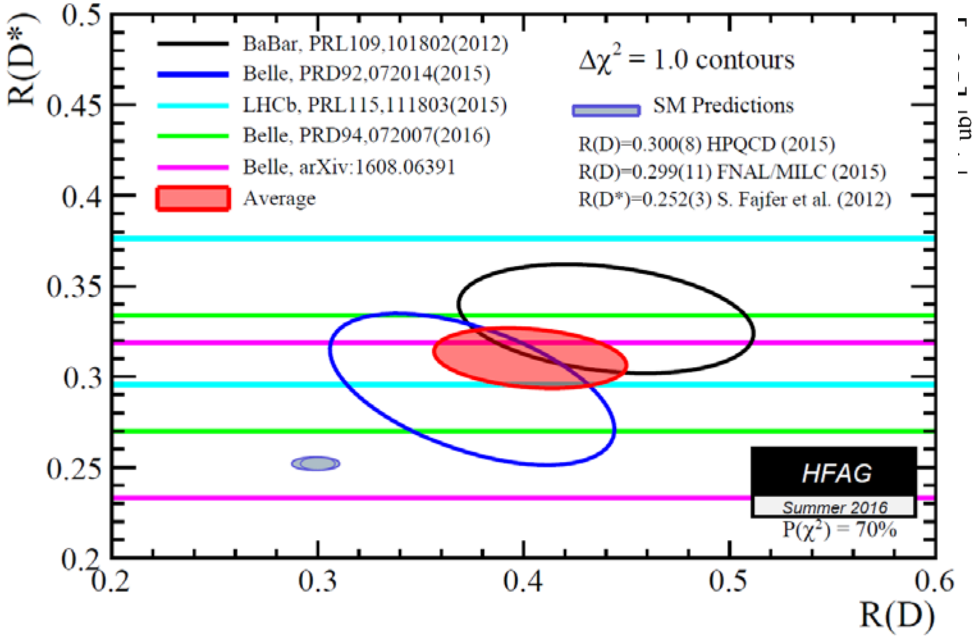

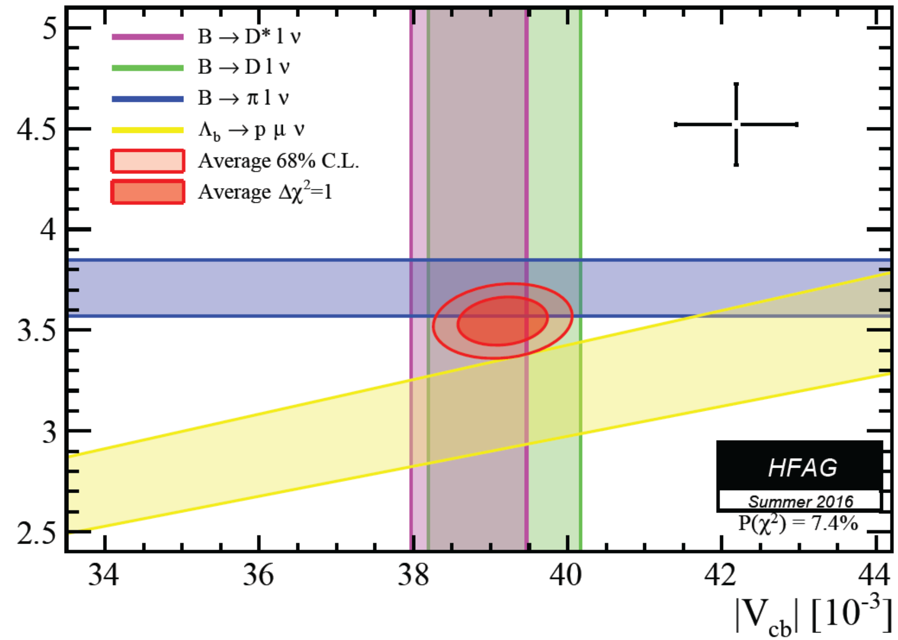

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independent calculations are welcome

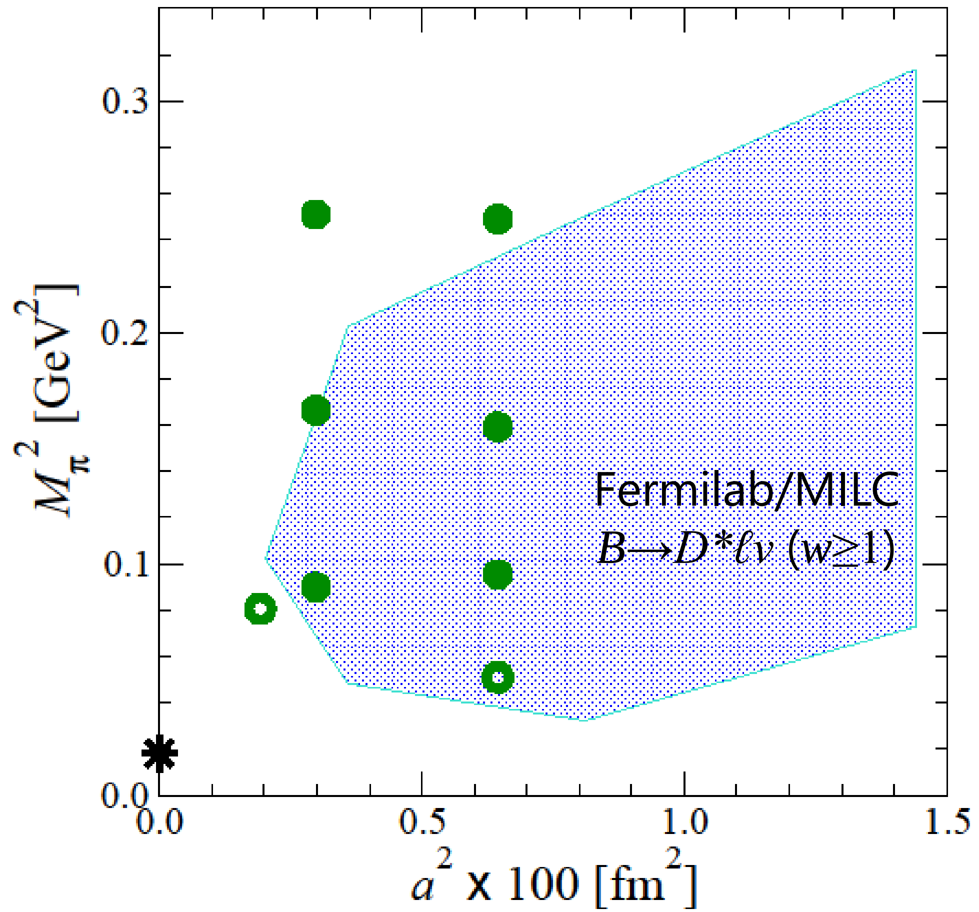
JLQCD's study

w/ good chiral symmetry

domain-wall quarks

good chiral symmetry

- simple renormalization
- no O(a) errors



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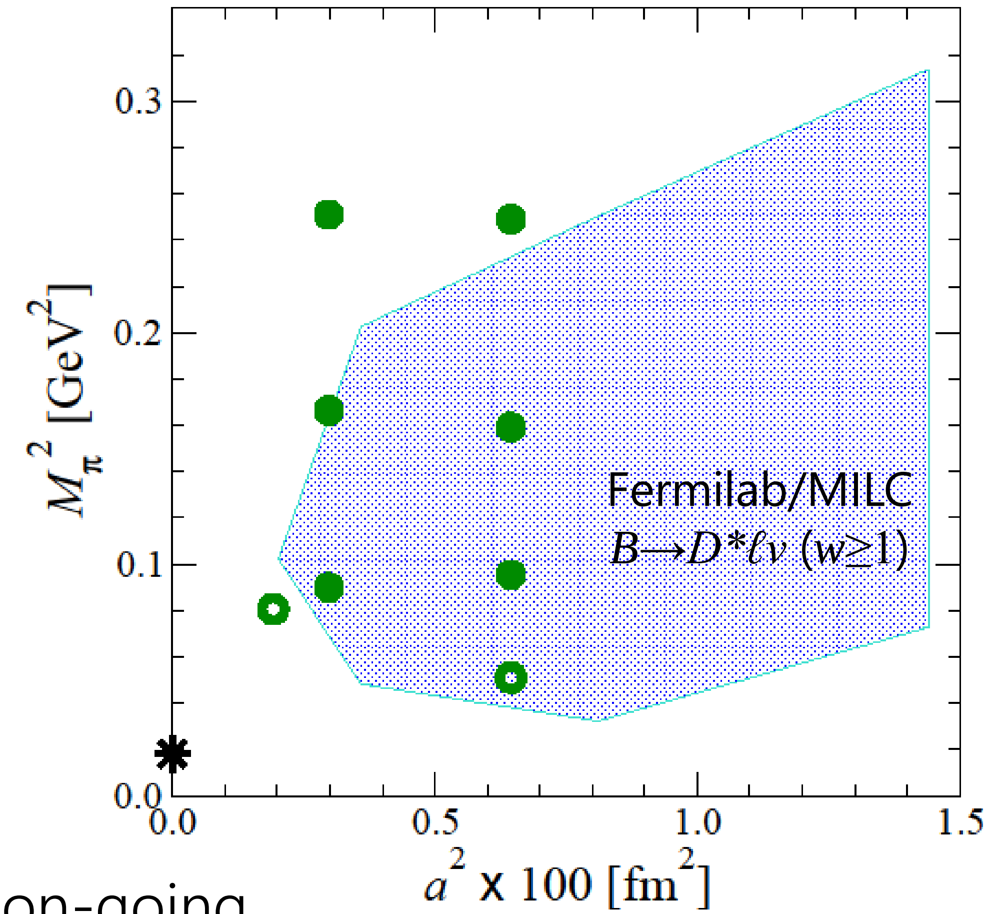
simulation parameters

- a^{-1} ~ 2.5, 3.6, 4.5 GeV
- M_π ~ 230, 300, 400, 500 MeV
- $M_\pi L \geq 4$
- a^{-1} ~ 4.5 GeV, M_π ~ 230 MeV: on-going



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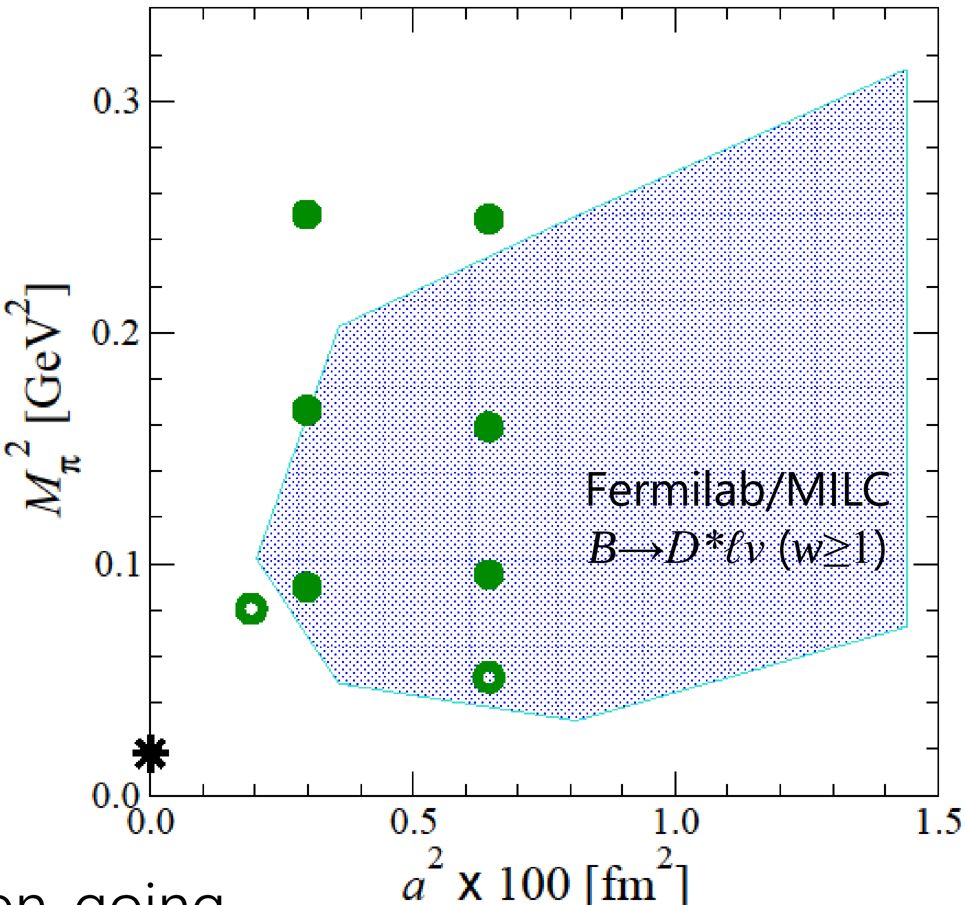

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⇒ preliminary results w/o extrapolations ...

JLQCD's simulation

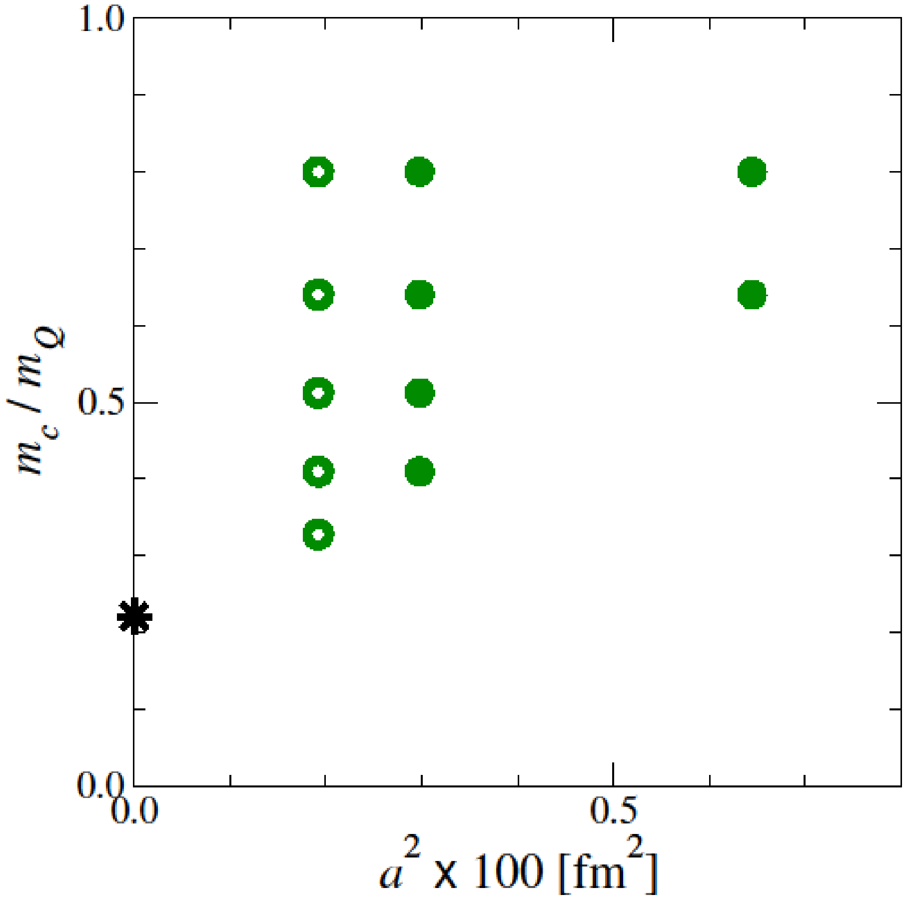
relativistic lattice QCD

w/ "relativistic" heavy quarks

- simple renormalization
- $m_Q < m_b$ ⇒ need extrapolation

  m_Q / m_c = 1.25, 1.25^2, ...

  and $m_Q < 0.8\ a^{-1}$



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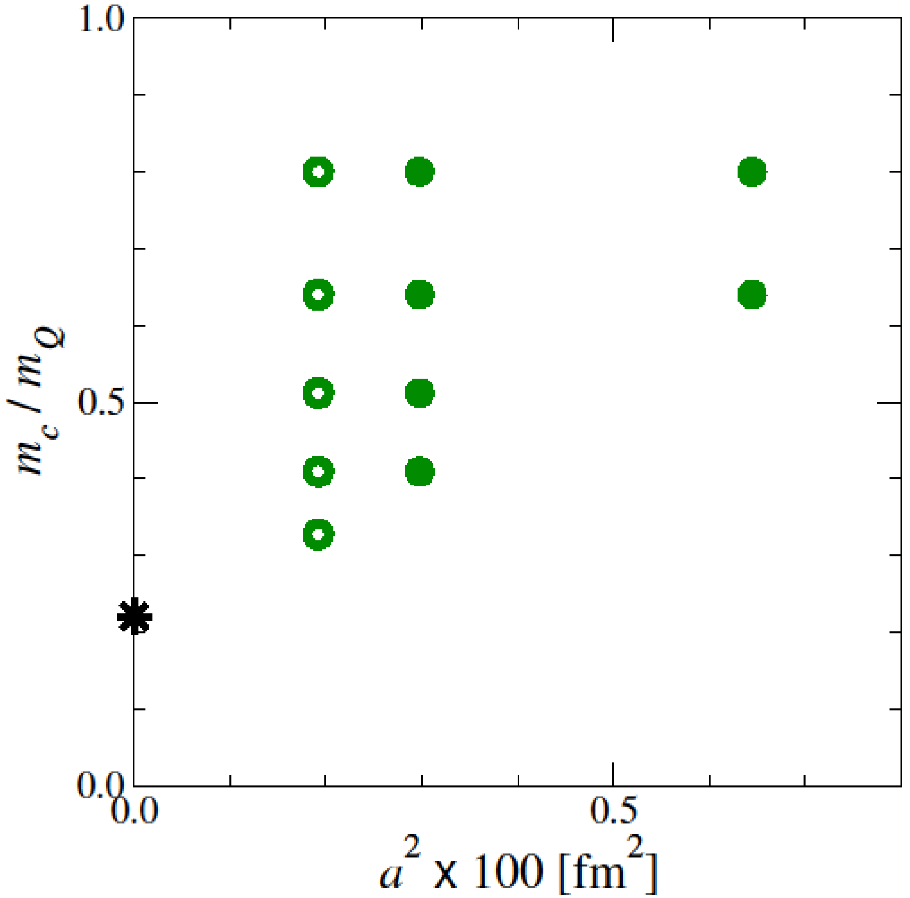
⇔ EFT-based heavy quarks

- NRQCD, Fermilab, RHQ, …
- need matching to QCD

  often perturbative …
- directly simulate m_b



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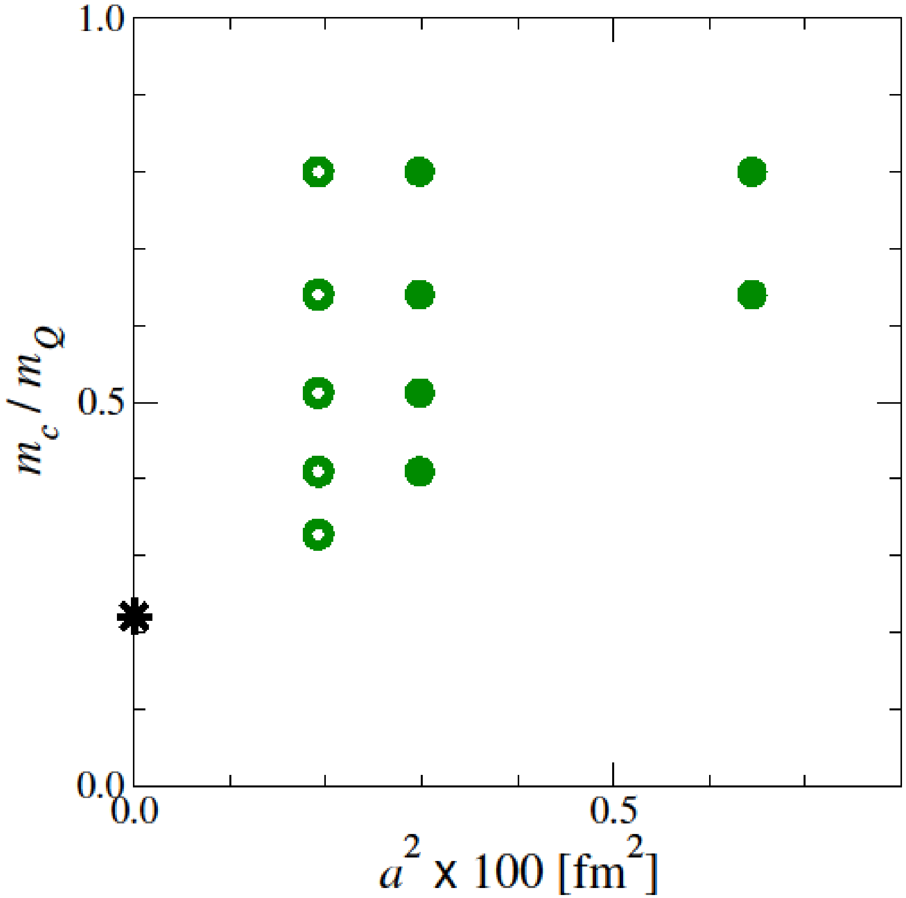


independent studies w/ (very) different systematics

B→D(*)ℓν form factors (FFs)

In the SM

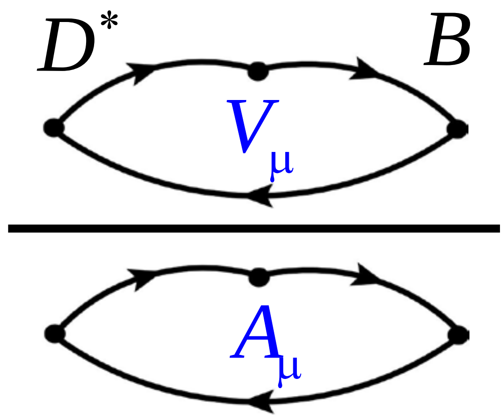
$$\left\langle D(p') \middle| V_\mu \middle| B(p) \right\rangle = (v + v')_\mu \, h_+(w) + (v - v')_\mu \, h_-(w)$$

$$\left\langle D^*(p', \varepsilon') \middle| V_\mu \middle| B(p) \right\rangle = i \varepsilon_{\mu\nu\rho\sigma} \varepsilon'^{*\mu} v'^{\rho} v^{\sigma} h_V(w)$$

$$\left\langle D^*(p', \varepsilon') \middle| A_\mu \middle| B(p) \right\rangle = \varepsilon'^{*}_{\mu} (1 + w) h_{A_1}(w) - \varepsilon'^{*} v \left\{ v_\mu h_{A_2}(w) + v_\mu h_{A_2}(w) \right\}$$

ratio method (Hashimoto et al. '99)

a standard way for precision calculation



$$= \frac{\langle D^* | V_\mu^{(\mathrm{lat})} | B \rangle}{\langle D^* | A_\mu^{(\mathrm{lat})} | B \rangle} \to \frac{h_V(w)}{h_{A_1}(w)}$$

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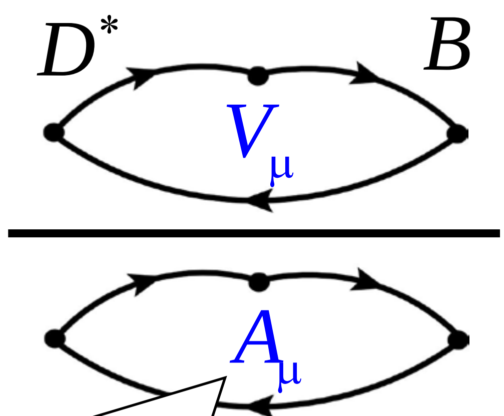

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$\langle B | O_B^\dagger \rangle$, $\exp[-M_B \Delta t]$, $\cdots$ cancel

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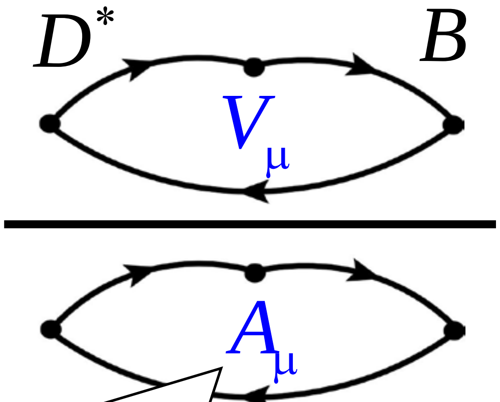

$$= \frac{\left\langle D^* \middle| V_\mu^{(\mathrm{lat})} \middle| B \right\rangle}{\left\langle D^* \middle| A_\mu^{(\mathrm{lat})} \middle| B \right\rangle} \rightarrow \frac{h_V(w)}{h_{A_1}(w)}$$

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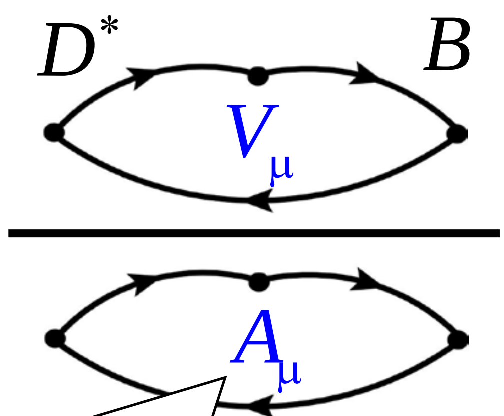

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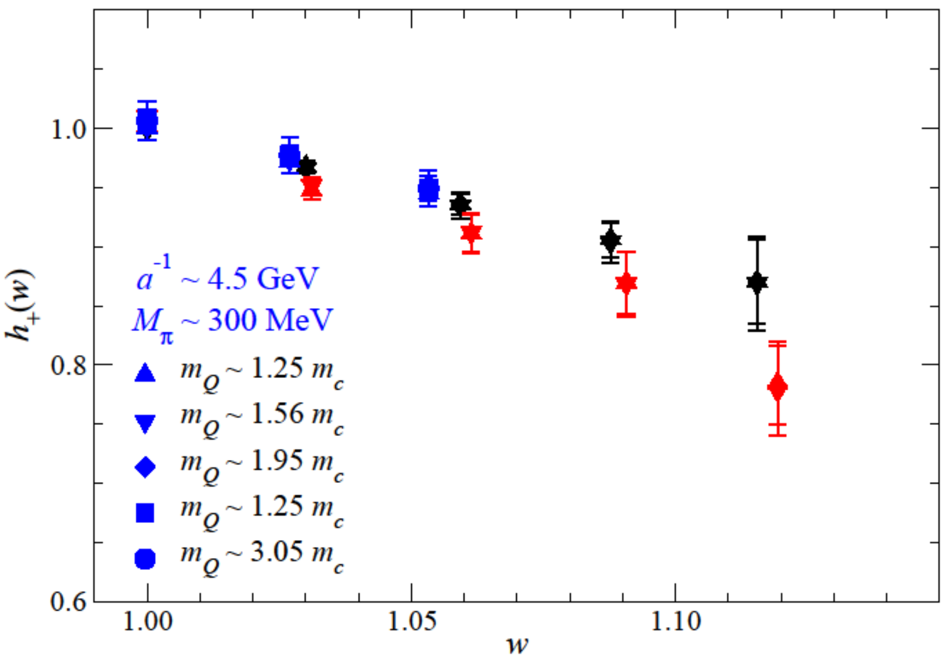
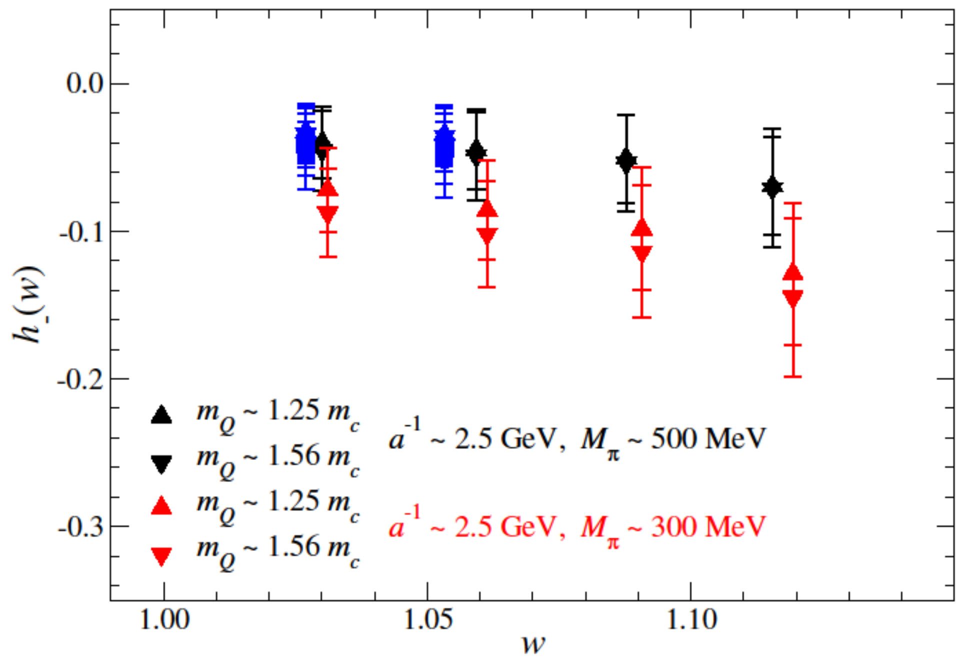
Z_A, Z_V cancel

- can calculate SM FFs w/o explicit renormalization
- $\mathbf{p}_B = \mathbf{0}$, $|\mathbf{p}_{D(*)}|^2$ = 0, 1, 2, 3, 4 in units of $(2\pi/L)^2$

B→Dℓν form factors

h_+ vs w $\qquad$ h_- vs w



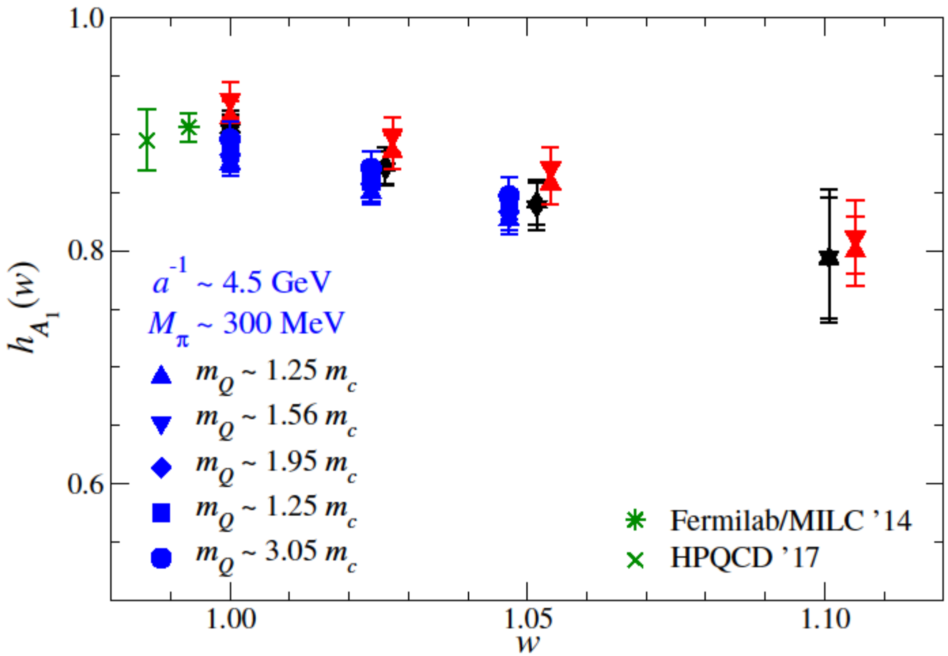


- mild dependence on a, M_π, m_Q $\Rightarrow$ reasonably close to physical pt.

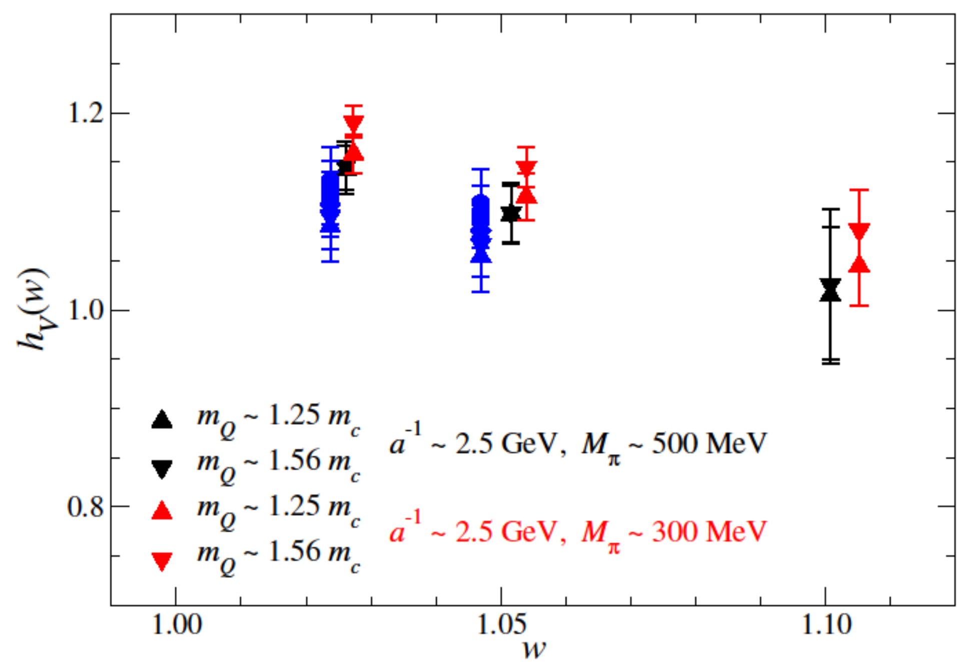
  larger m_Q $\Rightarrow$ larger h_+ [smaller h_-] $\Leftrightarrow$ $L_1/2m_Q$ [$-L_4/2m_Q$] $L_1, L_4 \geq 0$
- typical accuracy: $\Delta h_+ \leq 1$ - 3%, $\Delta h_- \sim 40 - 60$ %

B→D*ℓν form factors

h_{A1} vs w



h_V vs w

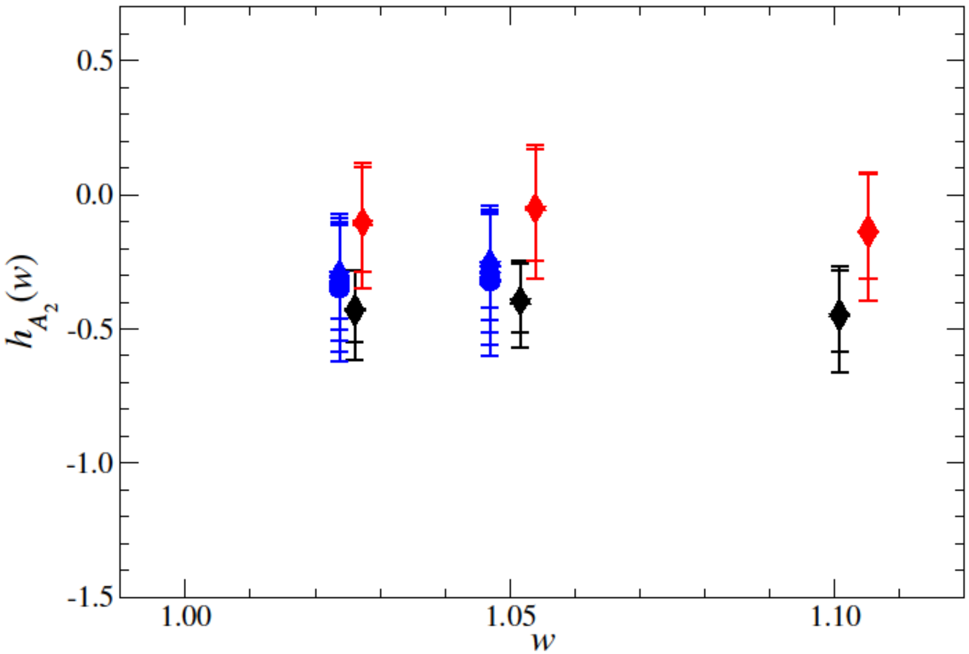


- mild a, m_Q, M_π dependences / consistent w/ previous studies
- typical accuracy: $\Delta h_{A1} \sim 1$ - 3%, $\Delta h_V \sim 3$ %

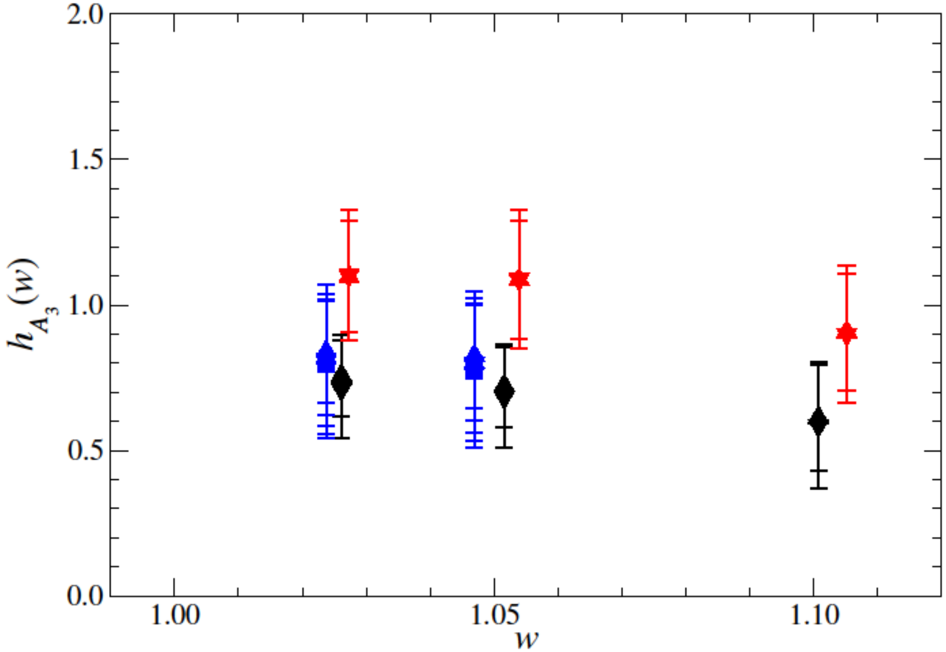
$$\left\langle D^*(p',\varepsilon')\middle|V_\mu\middle|B(p)\right\rangle \Rightarrow h_V(w) \quad \left\langle D^*(p',\varepsilon')\middle|A_\mu\middle|B(p)\right\rangle \Rightarrow h_{A_1}(w) \quad (\mathbf{p}' \perp \boldsymbol{\varepsilon}')$$

B→D*ℓν form factors

h_{A2} vs w



h_{A3} vs w



- h_+, h_{A1}, h_{A3}, h_V ($\rightarrow\xi$) ~ $O(1)$, h_-, h_{A2} ($\rightarrow 0$) ~ 0
- typical accuracy: $\Delta h_{A2} \geq 40$ %, Δh_{A3} ~ 20 - 30 %

$$\left\langle D^*(p',\varepsilon')\left|A_\mu\right|B(p)\right\rangle \Rightarrow \left\{h_{A_1}(w), h_{A_2}(w), h_{A_3}(w)\right\}$$

LQCD vs HQET+QCDSR

Caprini-Lellouch-Neubert (CLN) parametrization of FFs

- FFs w/ definite spin-parity quantum numbers

$$V_1^{(BD)} = h_+ - \frac{1-r}{1+r} h_- \qquad S_1^{(BD)} = h_+ - \frac{1+r}{1-r} \frac{w-1}{w+1} h_-$$

$$A_1^{(BD^*)} = h_{A_1} \qquad V_4^{(BD^*)} = h_V$$

$$A_5^{(BD^*)} = \frac{1}{1-r} \left[(w-r)\, h_{A_1} - (w-1)\left(r h_{A_2} + h_{A_3}\right) \right]$$

- use NLO HQET relations (QCDSR input) ~ small NNLO in ratios

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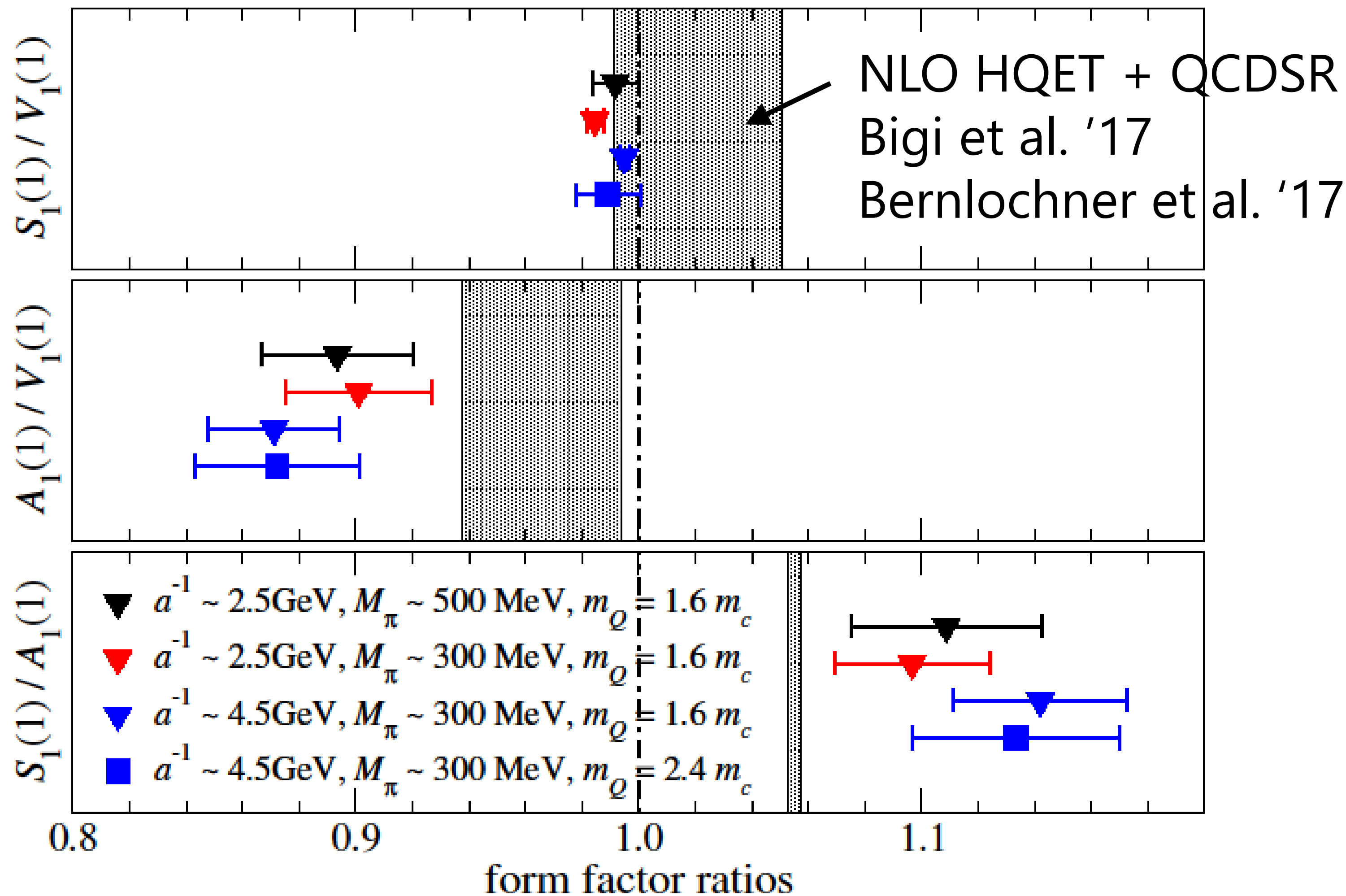
Bigi-Gambino-Schacht '17

- comparison b/w HQET+QCDSR and LQCD available at that time

LQCD vs HQET+QCDSR

at zero recoil



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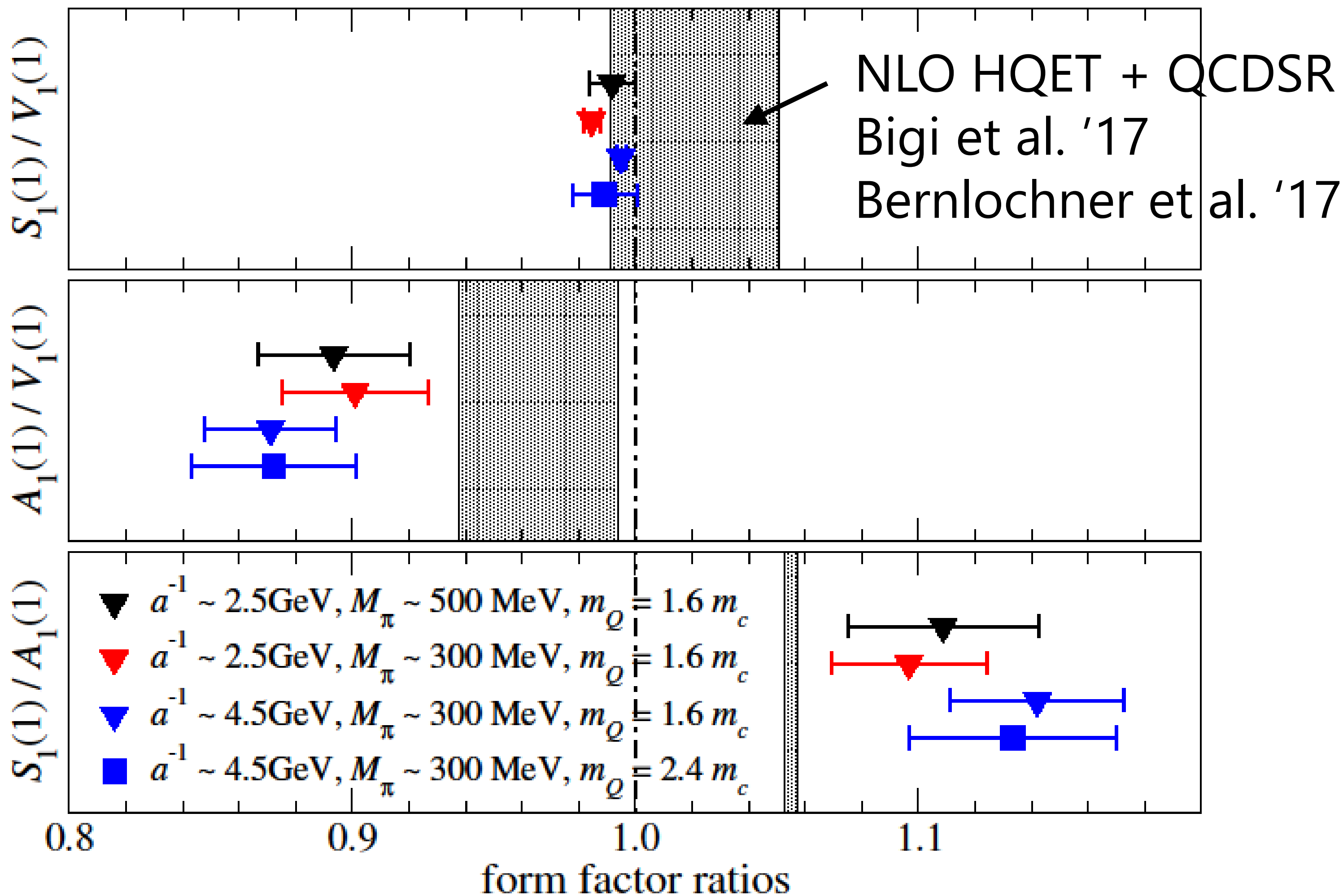
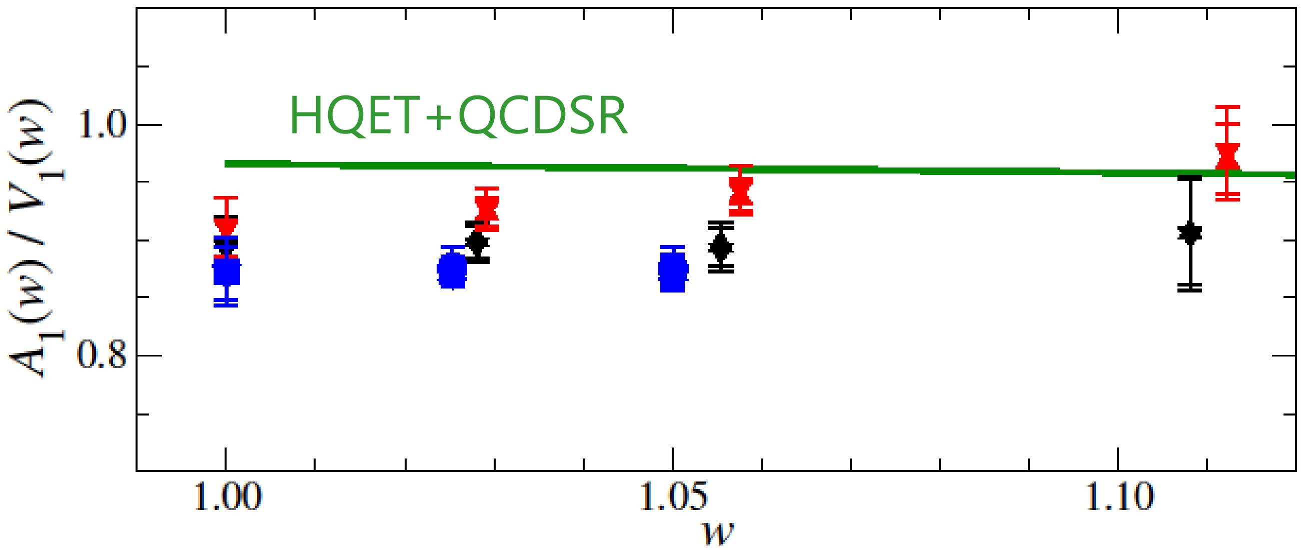


systematically lower / higher for A_1/V_1, S_1/A_1 ???

LQCD vs HQET+QCDSR

at non-zero recoils



- HQET $A_1(w)/V_1(w)$ + $V(w)/V(1)$ dispersive bound $\Rightarrow$ CLN $A_1(w)$

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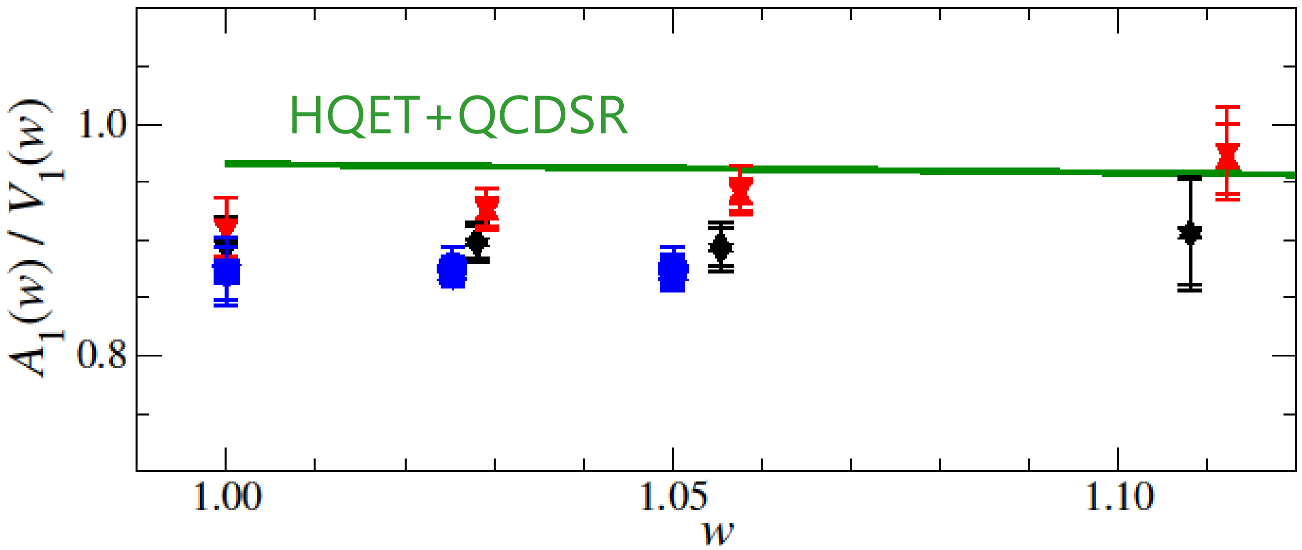


- HQET $A_1(w)/V_1(w)$ + $V(w)/V(1)$ dispersive bound $\Rightarrow$ CLN $A_1(w)$
- CLN $R_2 = (rh_{A2}+h_{A3}) / h_{A1}$: noisy at the moment
- CLN $R_1 = h_V / h_{A1}$

  $\Rightarrow$ Bernlochner et al. '17: analysis of Belle unfolded / tagged data

BGL vs CLN w/ Belle data

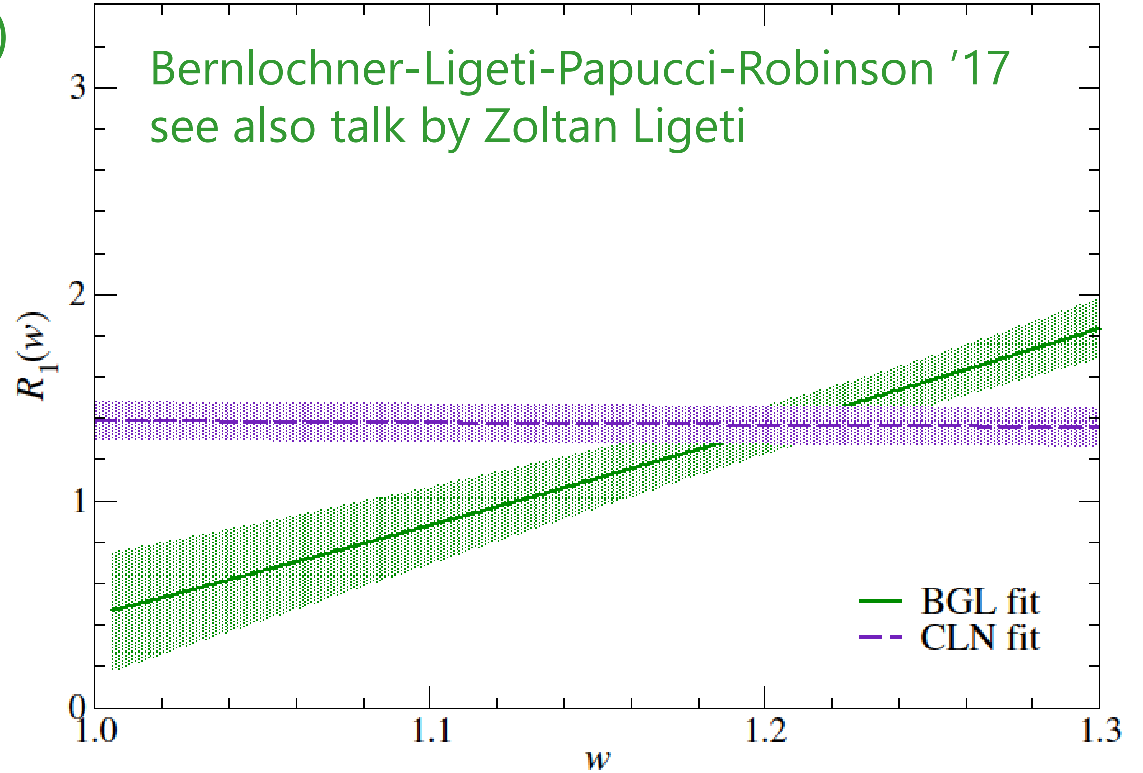
$$R_1 = h_V / h_{A1}$$

Boyd-Grinstein-Lebed (BGL)

$\Rightarrow |V_{cb}|$ close to inclusive

CLN $\Rightarrow$ lower than inclusive

Bigi-Gambino-Schacht '17
Grinstein-Kobach '17



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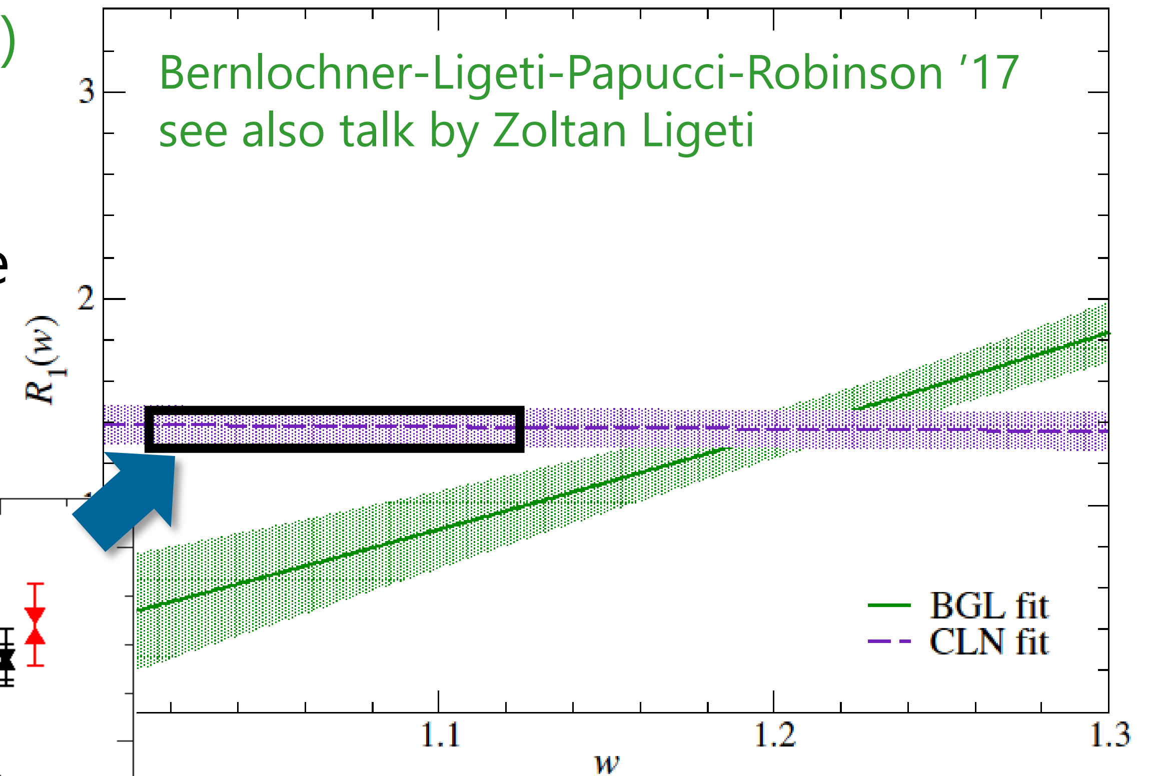

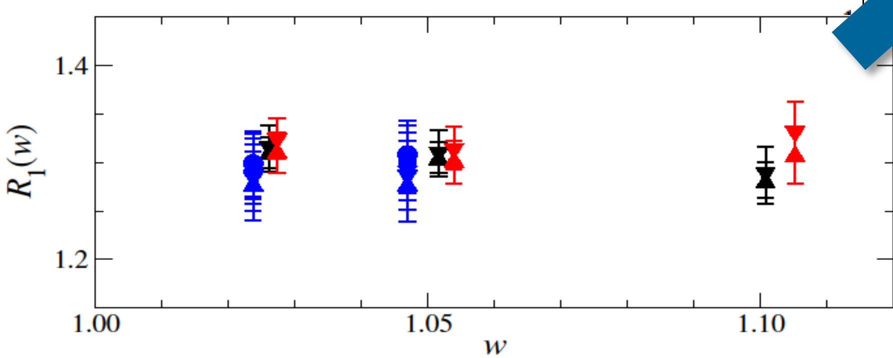

new data @ a^{-1}~4.5GeV w/ 5 m_Q's

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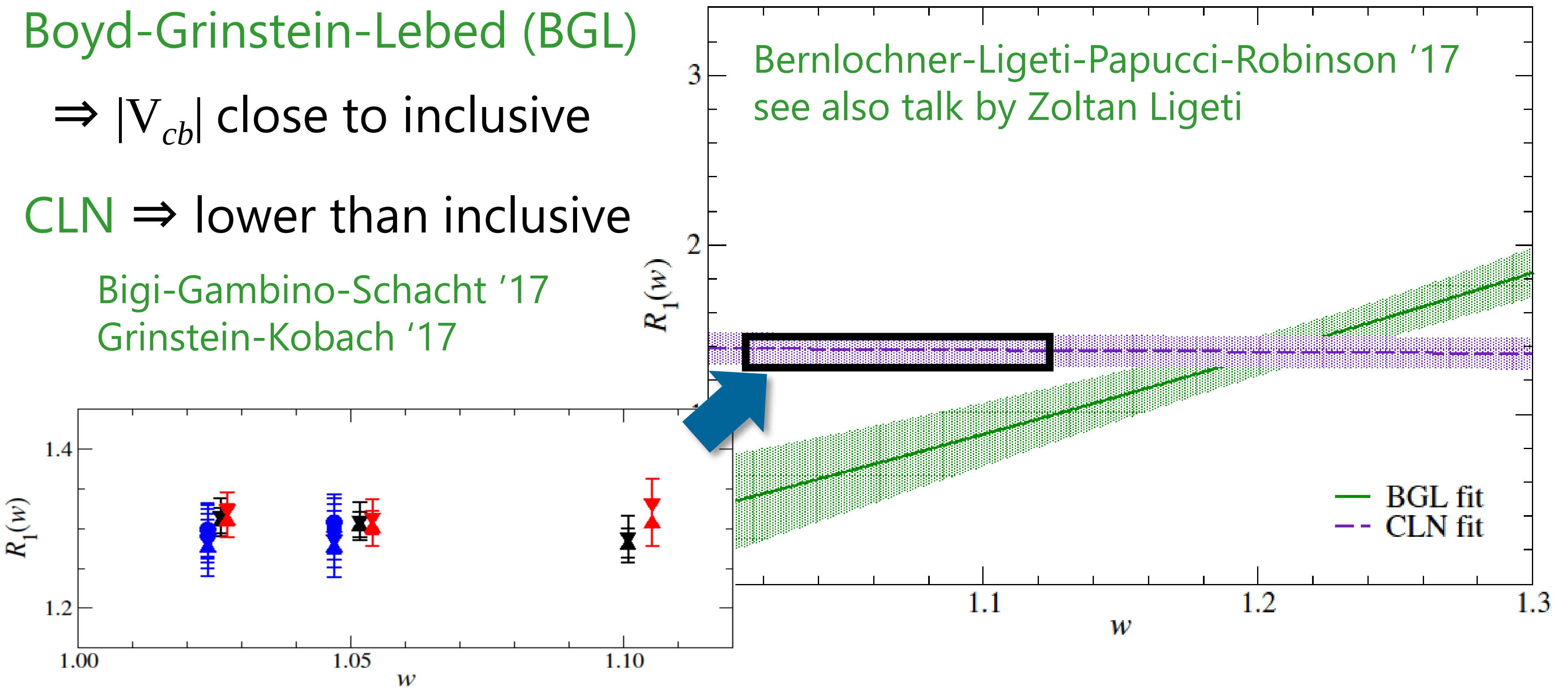

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- small a, m_Q, M_π dependence
- consistent w/ CLN and "BGL" fits
- Belle untagged ?

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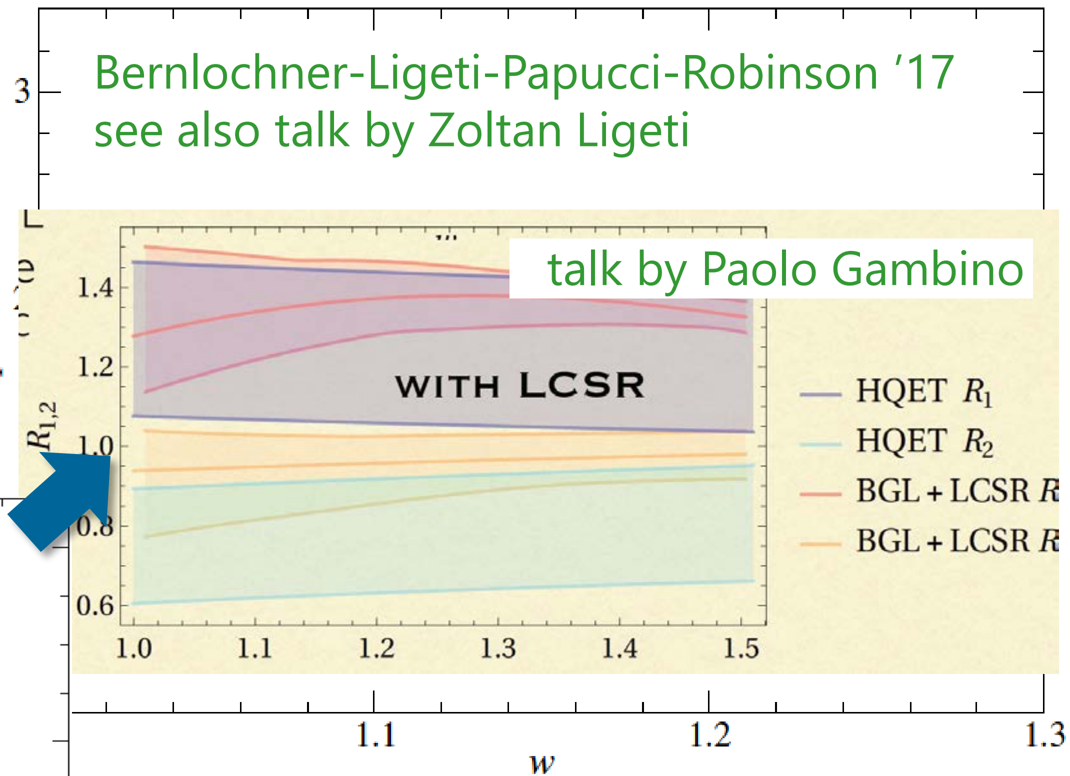

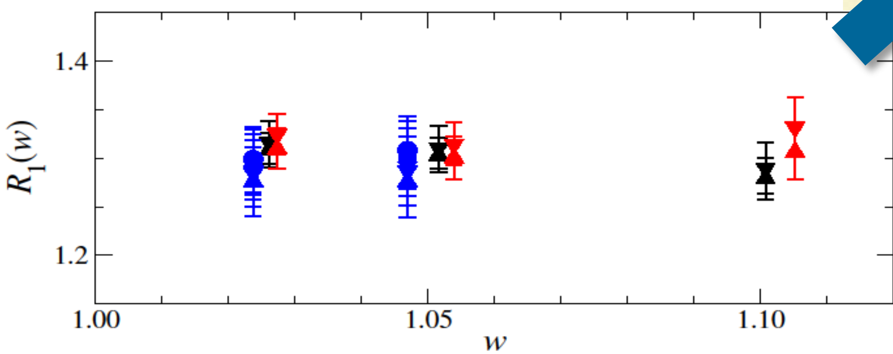

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Summary

JLQCD's calculation of $B \to D^{(*)} \ell \nu$ form factors

- relativistic approach w/ chiral symmetric formulation

  $\Leftrightarrow$ previous studies: very different systematics

  $\Rightarrow$ Hashimoto ($B \to X_c \ell \nu$, poster), Colquhoun ($B \to \pi \ell \nu$, Sat)

- extrapolation to the physical point: yet to be done

  mild a, M_π, m_Q dependences $\Leftrightarrow$ reasonably controllable

- interplay w/ phenomenology / experiment
  - LQCD prediction of FFs $\Rightarrow$ $|V_{cb}|$, $R(D^{(*)})$
  - heavy quark scaling $\Leftrightarrow$ data w/ different m_Q's
  - FFs beyond the SM $\Rightarrow$ NP search in the Belle II era