LQCD other modes: $B_c \to J/\psi$, $B_s \to D_s^{(*)}$,...

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Instant workshop on B-meson anomalies
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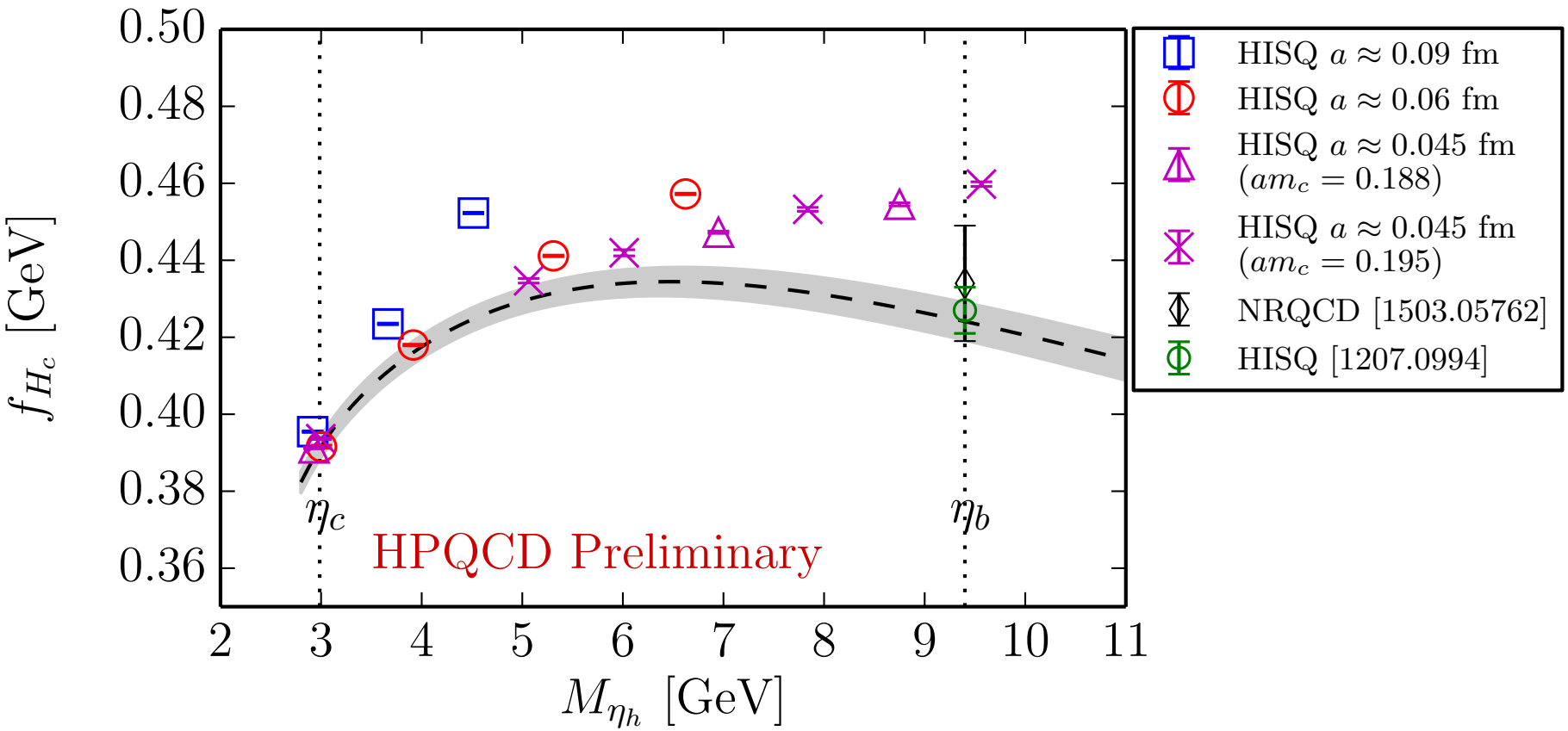
Intro & Motivation

- Compare observables testing LFU in as many channels as possible. Requires:
  - Expt'l measurements.
  - Reliable theory predictions.
- LQCD provides a from-first-principles approach to calculating hadronic matrix elements $\rightarrow$ form factors parameterising semileptonic decays.
- Will review status of the following semileptonic decay calculations:
  - $B_c \rightarrow J/\psi$ (and η_c)
  - $B_s \rightarrow D_s$
  - $B_s \rightarrow D_s^*$

Intro & Motivation

- Treatment of c and especially b quarks challenging in lattice simulations due to lattice artifacts which grow as $(am_q)^n$.
- HPQCD treats the charm quark relativistically using a highly improved staggered quark (HISQ) action.
- Generally one uses an effective theory framework to handle the b quark, here focus on NRQCD.
- HPQCD use two complementary approaches for b quarks:
  - Improved non-relativistic formalism (NRQCD) at m_b.
  - Highly improved relativistic action at small a, extrapolate $m_h \to m_b$.

Decay constant f_{H_c}



$B_c \to \eta_c$ and J/ψ

- All quarks are heavy (m_c or heavier) $\to$ good signal, can control calculation across full q^2 range, both in NRQCD and full relativistic calculation.

- NRQCD $b \to c$ transition currents of the form:
  $(1 + \alpha_s z + \cdots)(J_\mu^{(0)} + J_\mu^{(1)} + \cdots)$
  - Syst. error from the matching uncertainty appears in all $b \to c$ semileptonic transition calculations $B_{(s)} \to D_{(s)}^{(*)}$.
  - Can cross-check NRQCD systematics using the fully relativistic formulation.

- $B_c \to \eta_c$ (pseudoscalar): $f_0(q^2)$, $f_+(q^2)$
  $B_c \to J/\psi$ (vector): $A_{0,1,2,3}(q^2)$ (three independent), $V(q^2)$

$B_c \to \eta_c$ form factors

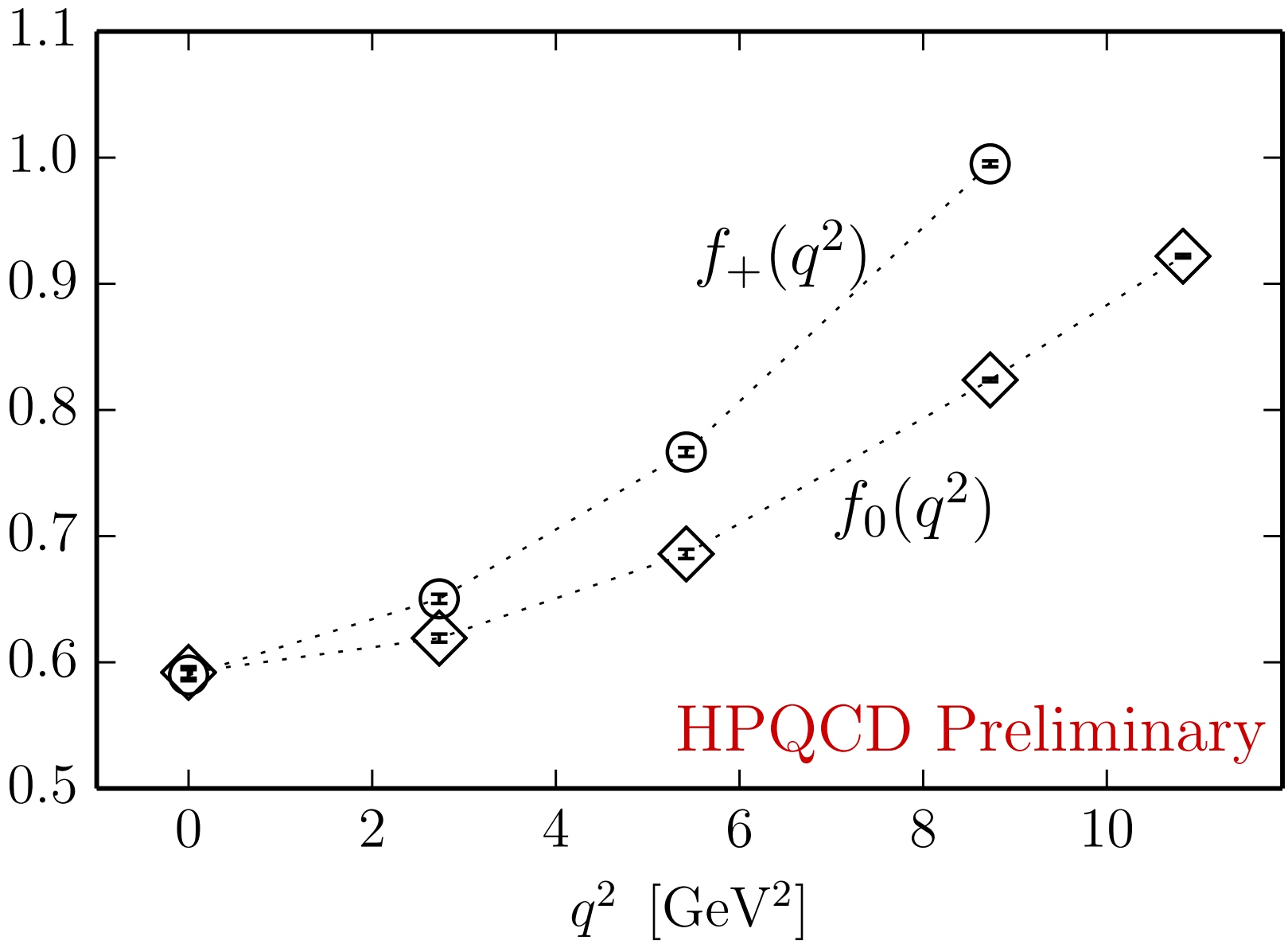
$$Z\langle \eta_c(p)|V^\mu|B_c(P)\rangle = f_+(q^2)\left[P^\mu + p^\mu - \frac{M^2-m^2}{q^2}q^\mu\right] + f_0(q^2)\,\frac{M^2-m^2}{q^2}\,q^\mu\,,$$

From PCVC,

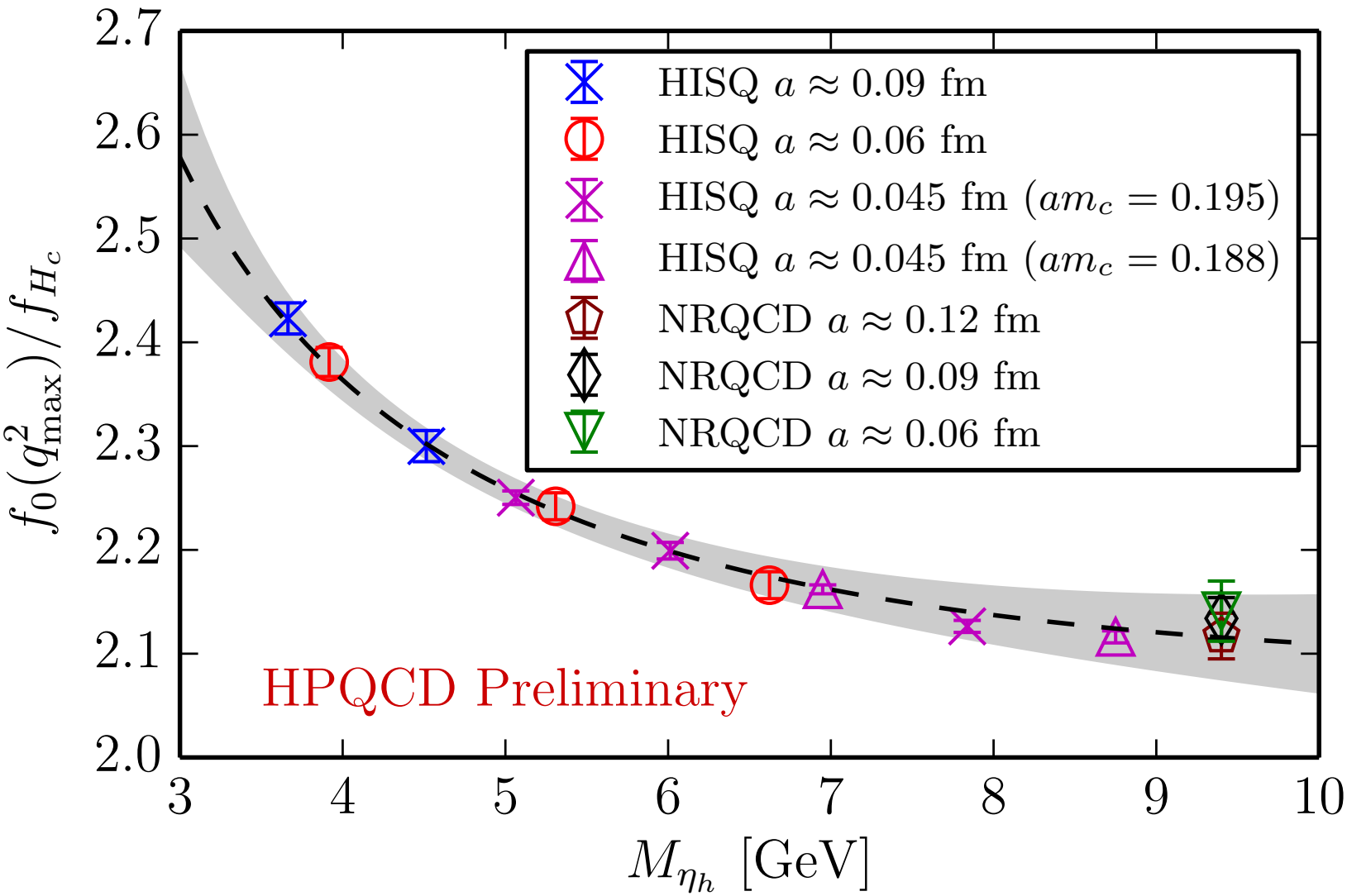
$$\langle \eta_c(p)|S|B_c(P)\rangle = \frac{M^2-m^2}{m_{b0}-m_{c0}} f_0(q^2)$$

Find Z by calculating both matrix elements at $q^2_{\max}$.

NRQCD $B_c \to \eta_c$ form factors



$f_0(q^2_{\mathsf{max}})/f_{H_c}$



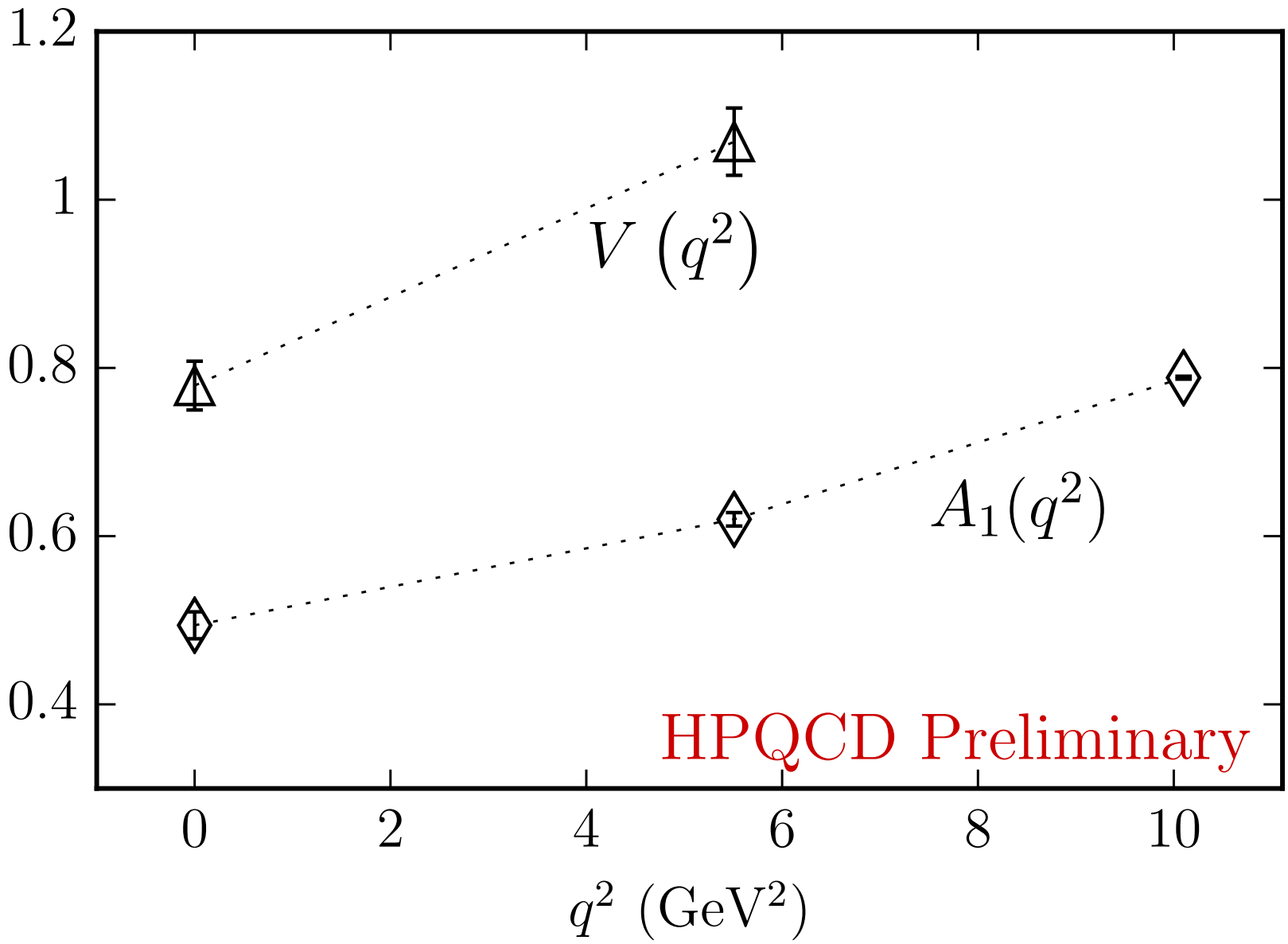
$B_c \to J/\psi$ form factors

$$\langle J/\psi(p,\varepsilon)|V^\mu - A^\mu|B_c(P)\rangle =$$

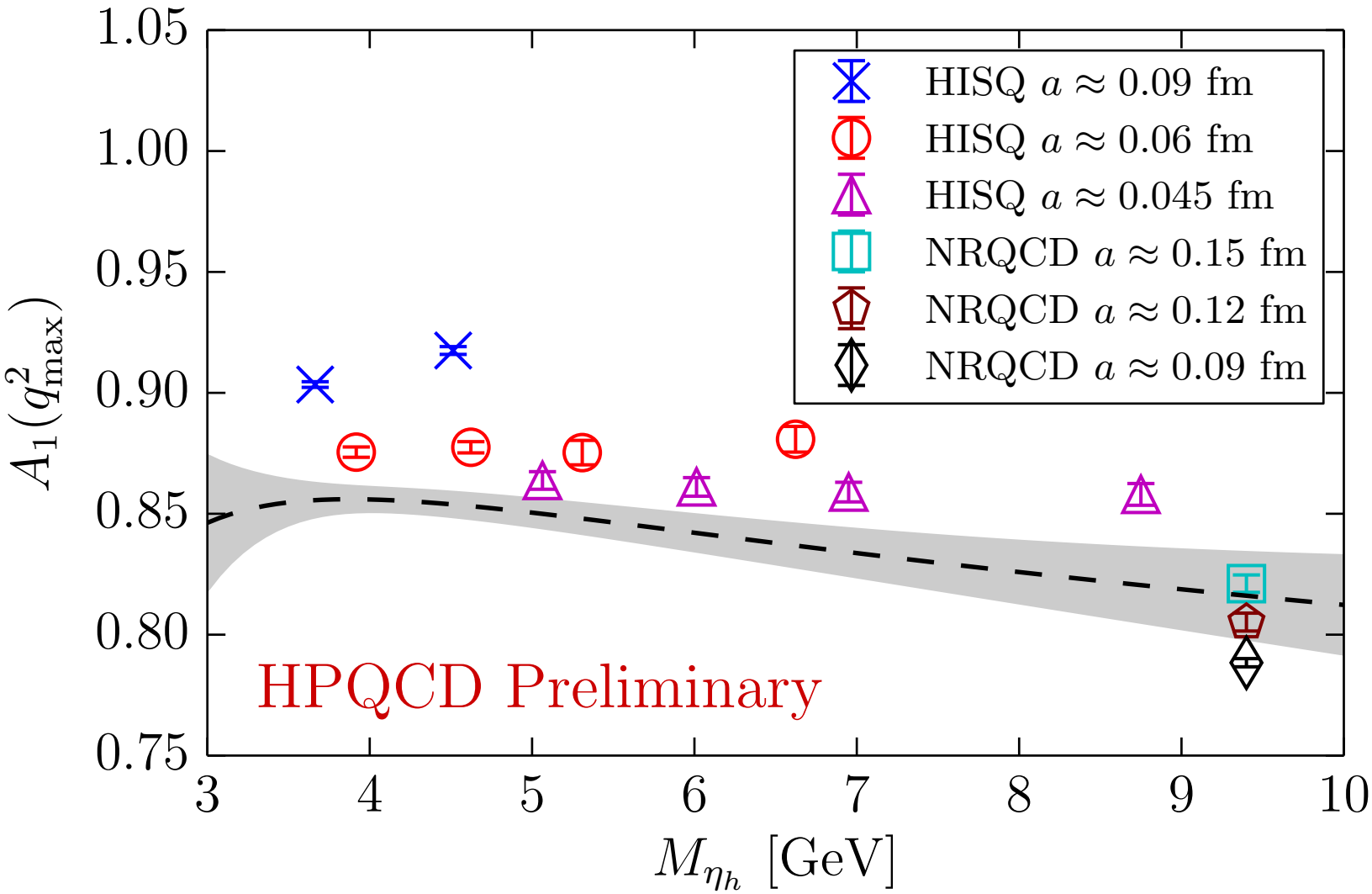
$$\frac{2i\epsilon^{\mu\nu\rho\sigma}}{M+m}\varepsilon^*_\nu p_\rho P_\sigma V(q^2) - (M+m)\varepsilon^{*\mu}A_1(q^2) +$$

$$\frac{\varepsilon^*\cdot q}{M+m}(p+P)^\mu A_2(q^2) + 2m\frac{\varepsilon^*\cdot q}{q^2}q^\mu A_3(q^2) - 2m\frac{\varepsilon^*\cdot q}{q^2}q^\mu A_0(q^2)$$

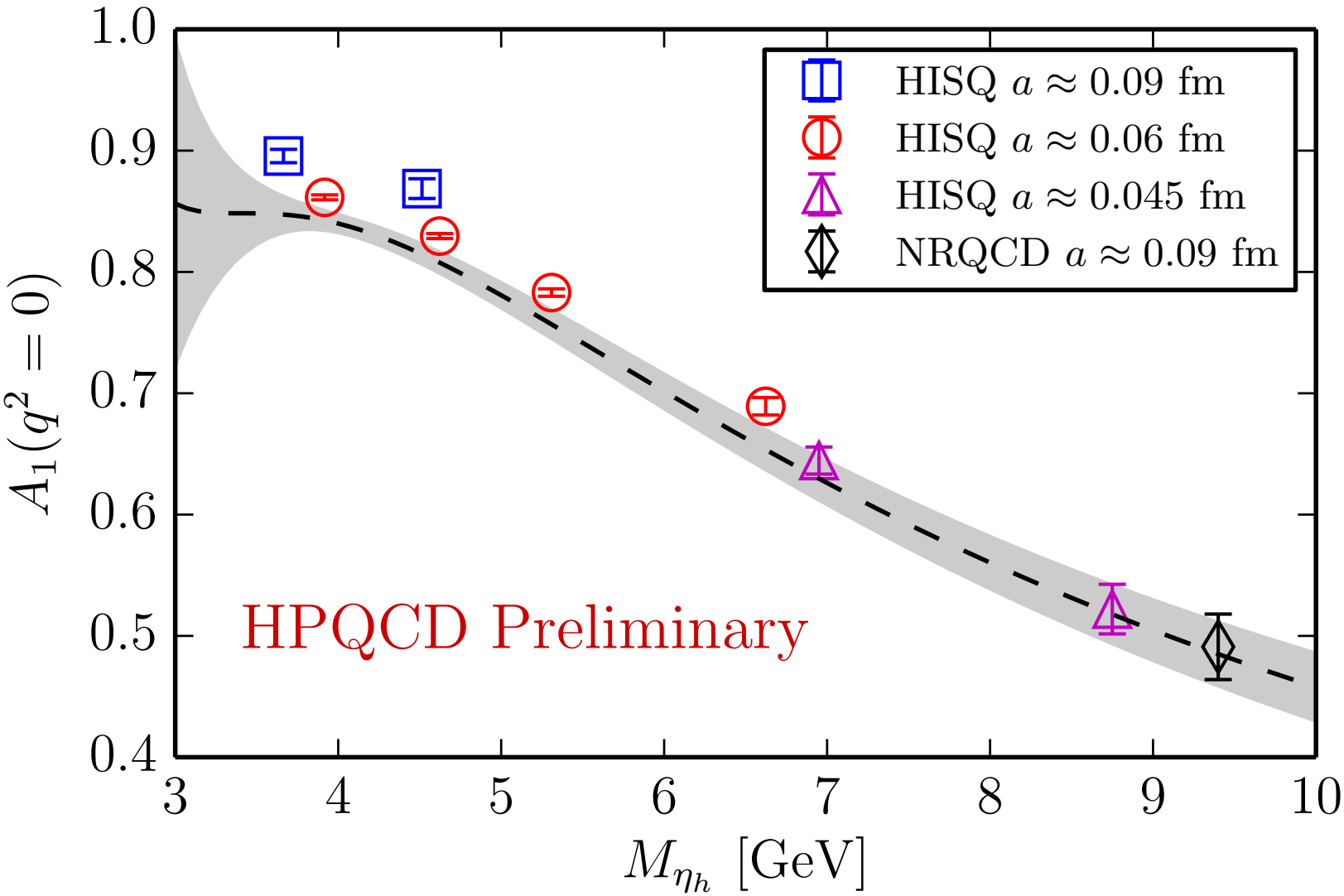
NRQCD $B_c \to J/\psi$ form factors



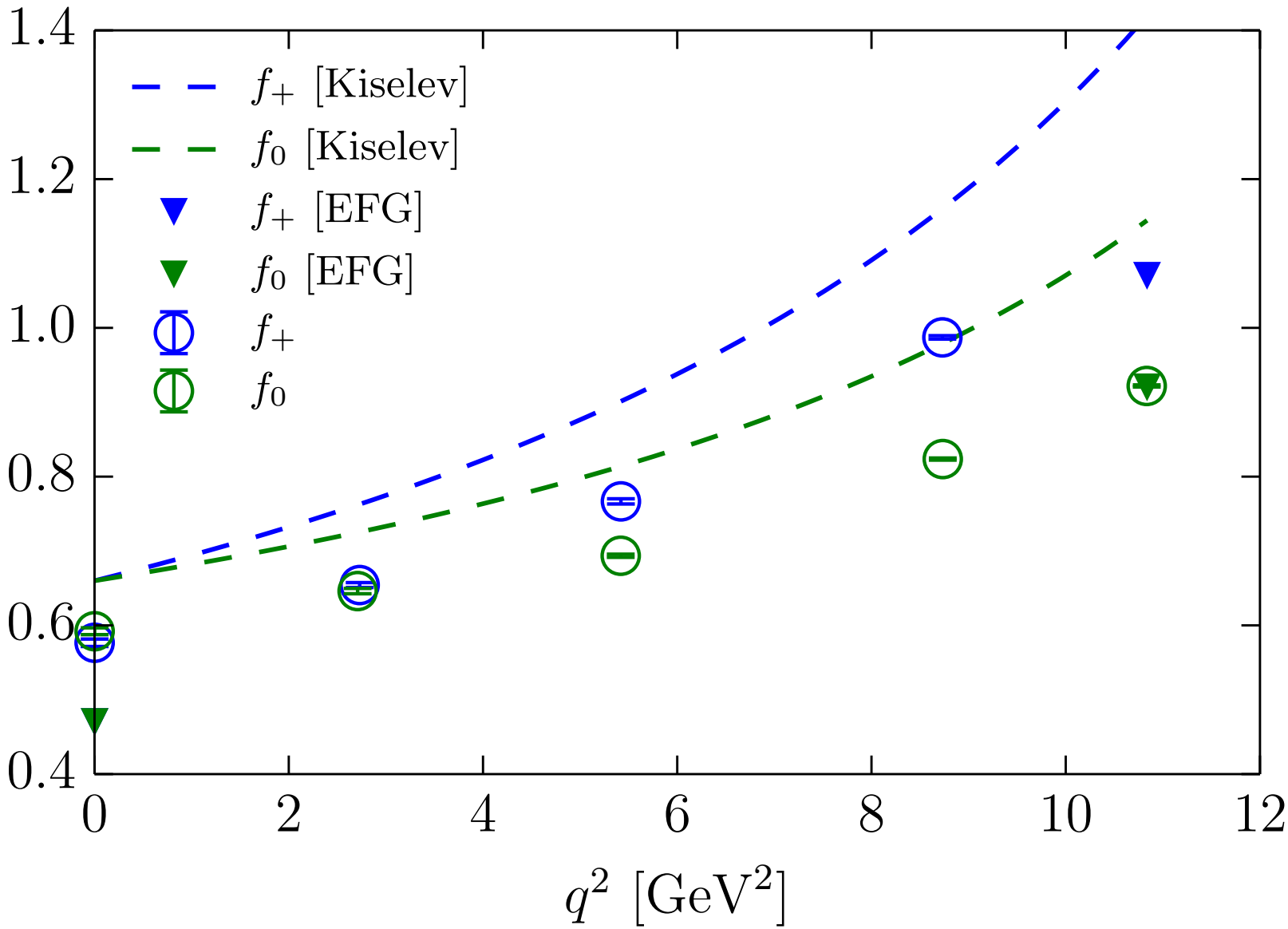
$A_1(q^2_{\mathsf{max}})$



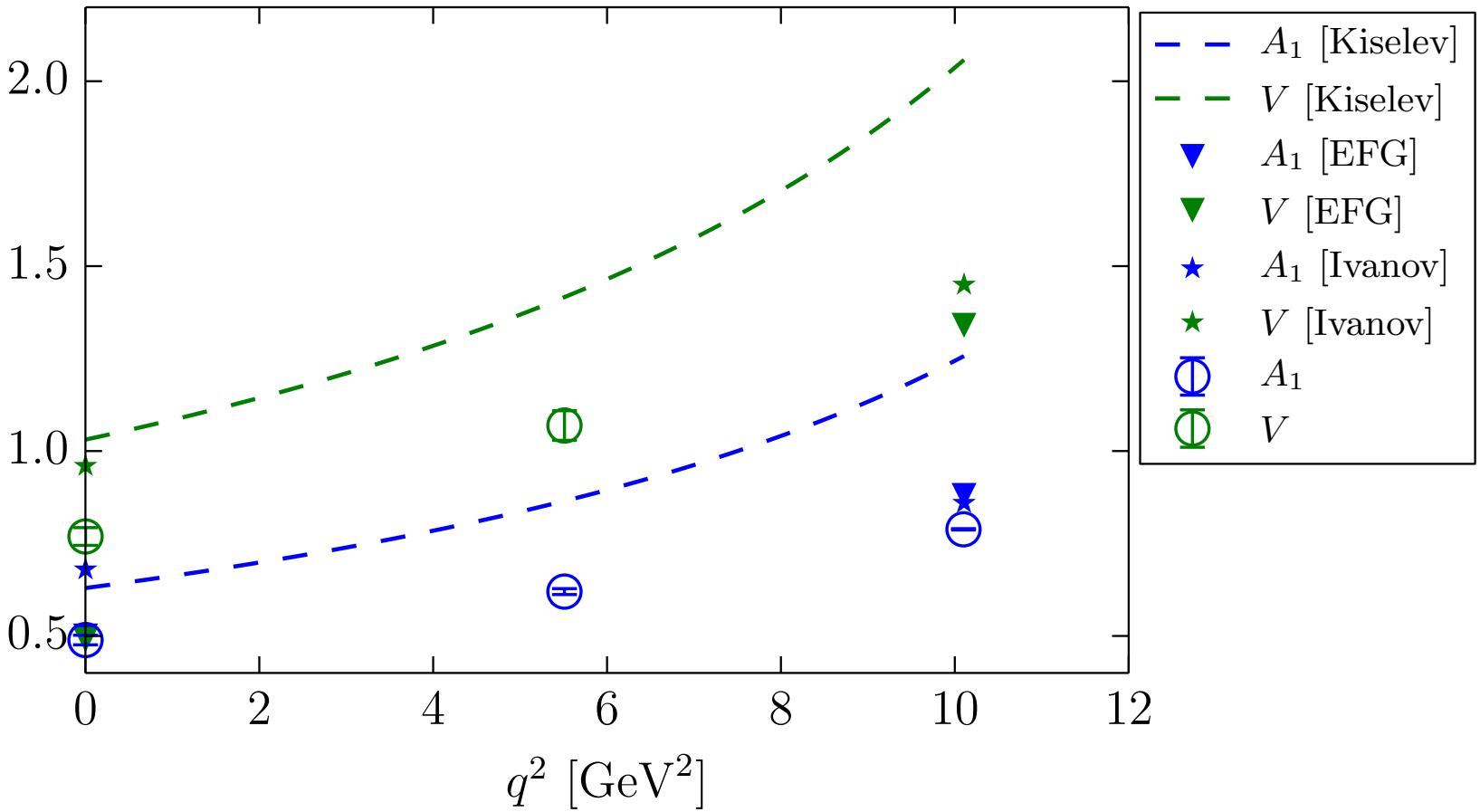
$A_1(q^2 = 0)$


HISQ $a \approx 0.09$ fm
HISQ $a \approx 0.06$ fm
HISQ $a \approx 0.045$ fm
NRQCD $a \approx 0.09$ fm
HPQCD Preliminary
$A_1(q^2 = 0)$
M_{η_h} [GeV]
1.0
0.9
0.8
0.7
0.6
0.5
0.4
3
4
5
6
7
8
9
10

Comparisons $B_c \to \eta_c$ [hep-ph/0211021,0306306]

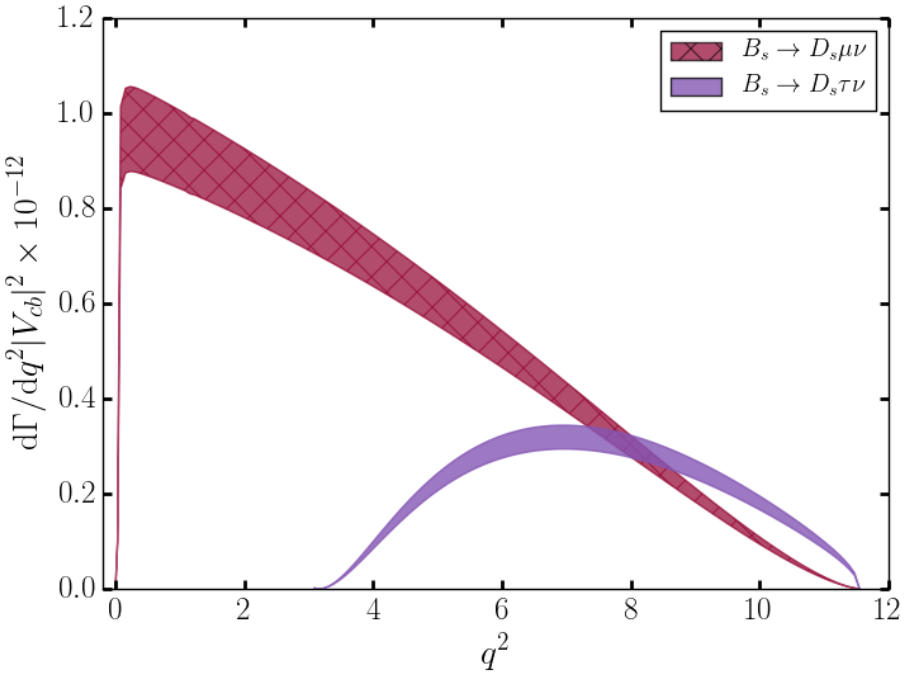


Comparisons $B_c \to J/\psi$ [hep-ph/0007169,0211021,0306306]



$B_s \to D_s$ [1703.09728]

HPQCD used NRQCD + improved staggered (asqtad) quarks to obtain $\frac{d\Gamma}{dq^2}$ over full q^2 range.



- $R(D_s) = 0.314(6)$
- Rel. q model result $R(D_s) = 0.274(20)$ [A. Bhol (2014)]

See also ETMC [1310.5238], FNAL/MILC [1202.6346], and HPQCD (HISQ) in progress [E. McLean]

$B_s \to D_s^*$

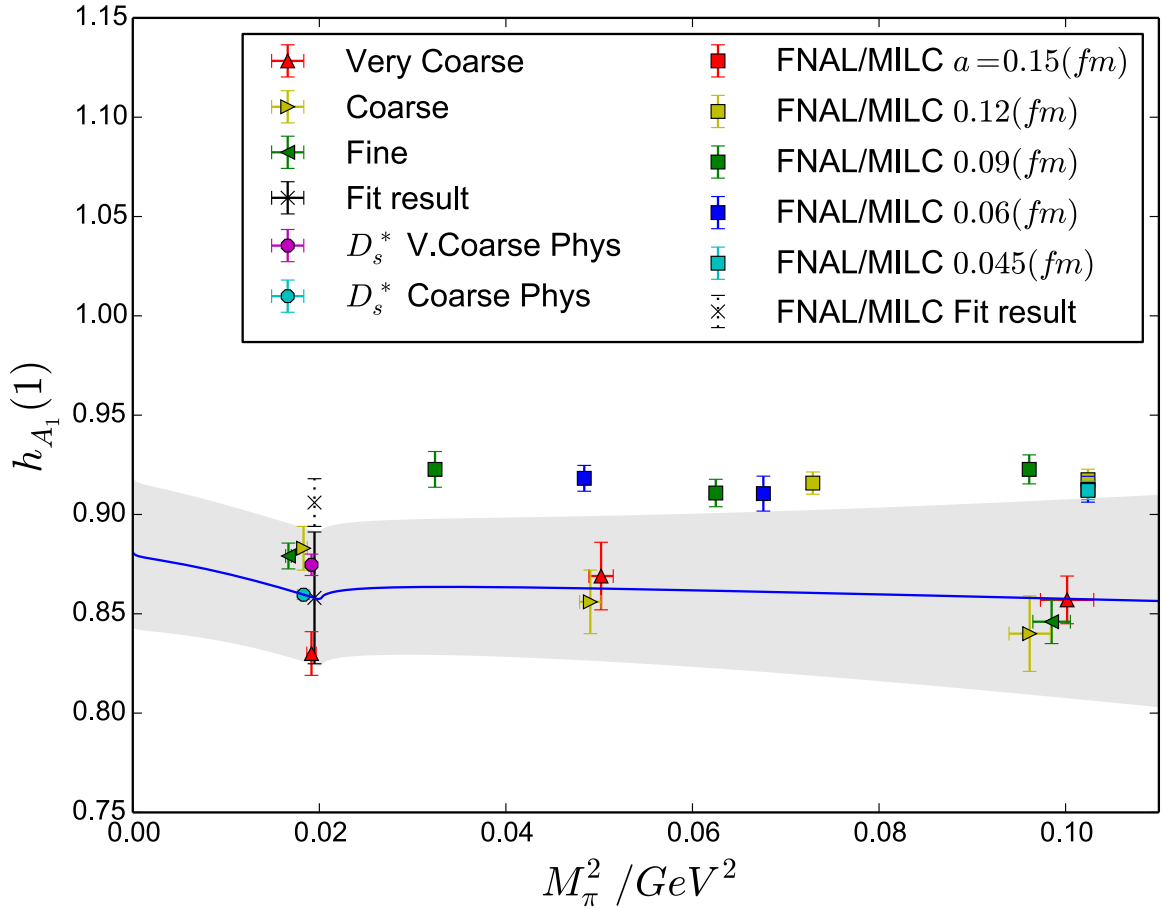


Figure courtesy Judd Harrison
[1612.06716]

Summary

- Extremely important to have reliable Standard Model determinations of observables testing LFU.
- HPQCD working hard to compute $B_c \to J/\psi$ form factors across the full q^2 range.
  - $\to$ SM prediction for $R(B_c \to J/\psi)$.
  - Test systematics in NRQCD shared by all $b \to c$ decays.
- HPQCD is also working on range of B decays using NRQCD formalism, in particular $B_{(s)} \to D_{(s)}^{(*)}$. Stay tuned..

Thank you!