$B_c \to J/\psi \ell^- \overline{\nu}$ Form Factors for the full q^2 range from Lattice QCD

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Background

- Experimental measurements of flavor-changing B decays are a source of tension with the standard model, e.g.[1].
- The $B_c \to J/\psi \ell^- \overline{\nu}$ decay has not yet been measured precisely. In future LHC runs we anticipate that the experimental precision of $R(J/\psi)$ (the ratio of $J/\psi \tau \overline{\nu}$ to $J/\psi \mu \overline{\nu}$ branching fraction) will be reduced significantly down to the 1% level.
- We calculate the form factors for B_c to J/ψ for the first time from lattice QCD and determine $R(J/\psi)$ in the Standard Model.

The differential decay rate with respect to $q^2 = (p_{B_c} - p_{J/\psi})^2$ is given by

$$\frac{d\Gamma}{dq^2} = \frac{G^2}{(2\pi)^3}|V_{cb}|^2 \frac{(q^2 - M_\ell^2)^2 p'}{12 M_{B_c}^2 q^2} \mathcal{B}(J/\psi \to \mu^+\mu^-) \times \Big[\left(H_-{}^2 + H_0{}^2 + H_+{}^2 \right) + \frac{M_\ell^2}{2q^2} \left(H_-{}^2 + H_0{}^2 + H_+{}^2 + 3H_t^2 \right) \Big]$$

where M_ℓ is the mass of the final state lepton, $\ell = e, \mu, \tau$, and the H_i are the helicity amplitudes defined in terms of form factors as

$$\begin{aligned} H_\pm(q^2) =& (M_{B_c} + M_{J/\psi}) A_1(q^2) \mp \frac{2 M_{B_c} p'}{M_{B_c} + M_{J/\psi}} V(q^2), \\ H_0(q^2) =& \frac{1}{2 M_{J/\psi}\sqrt{q^2}} \Big((M_{B_c}^2 - M_{J/\psi}^2 - q^2) A_1(q^2) - 4\frac{M_{B_c}^2 p'^2}{M_{B_c} + M_{J/\psi}} A_2(q^2) \Big), \\ H_t(q^2) =& \frac{2 M_{B_c} p'}{\sqrt{q^2}} A_0(q^2). \end{aligned}$$

And the form factors are in turn defined in terms of the QCD matrix elements [4]

$$\begin{aligned} \langle J/\psi(p',\epsilon)|\bar{c}\gamma^\mu b|B_c^-(p)\rangle =& \frac{2iV(q^2)}{M_{B_c} + M_{J/\psi}} \epsilon^{\mu\nu\rho\sigma} \epsilon^*_\nu p'_\rho p_\sigma \\ \langle J/\psi(p',\epsilon)|\bar{c}\gamma^\mu\gamma^5 b|B_c^-\rangle =& A_0(q^2) 2 M_{J/\psi} \frac{\epsilon^* \cdot q}{q^2} q^\mu \\ &+ A_1(q^2)(M_{B_c} + M_{J/\psi}) \Big[\epsilon^{*\mu} - \frac{\epsilon^* \cdot q}{q^2} q^\mu \Big] \\ &- A_2(q^2) \frac{\epsilon^* \cdot q}{M_{B_c} + M_{J/\psi}} \Big[p^\mu + p'^\mu - \frac{M_{B_c}^2 - M_{J/\psi}^2}{q^2} q^\mu \Big]. \end{aligned}$$

In this work we compute these form factors in lattice QCD across the full q^2 range and construct the differential decay rate and branching ratio $R(J/\psi)$.

Lattice QCD

Lattice QCD exploits the relation between the Euclidean path integral and operator formalisms in order to extract matrix elements and energies, eg.

$$\int \mathcal{D}[\psi,\overline{\psi},A] \mathcal{O}_1(t)\mathcal{O}_2(0) e^{-S^E[\psi,\overline{\psi},A]} = \sum_n \langle 0|\hat{\mathcal{O}}_1|n\rangle\langle n|\hat{\mathcal{O}}_2|0\rangle e^{-E_n t}.$$

For nonperturbative physics we must discretise space onto a finite volume lattice, evaluate path integral numerically, and then extract matrix elements and energies using statistical methods. Here we use HISQ quarks on the $2+1+1$ second generation MILC HISQ ensembles and Bayesian methods, implemented in the **corrfitter** python package [2], to extract matrix elements and energies.

Heavy-HISQ

To control discretisation errors we require that $am_q < 1$. Most lattices have $am_b > 1$. This leads us to use Heavy-HISQ, eg. [3]

- Use multiple unphysically light heavy quark masses with physical b masses on only the finest lattice.
- Fit the q^2 dependence using the z-expansion, including $\Lambda_{\rm QCD}/m_h$ and am_h terms in the coefficients.
- Extract the physical q^2 dependence by setting $m_h = m_b$ and $am_h = 0$.

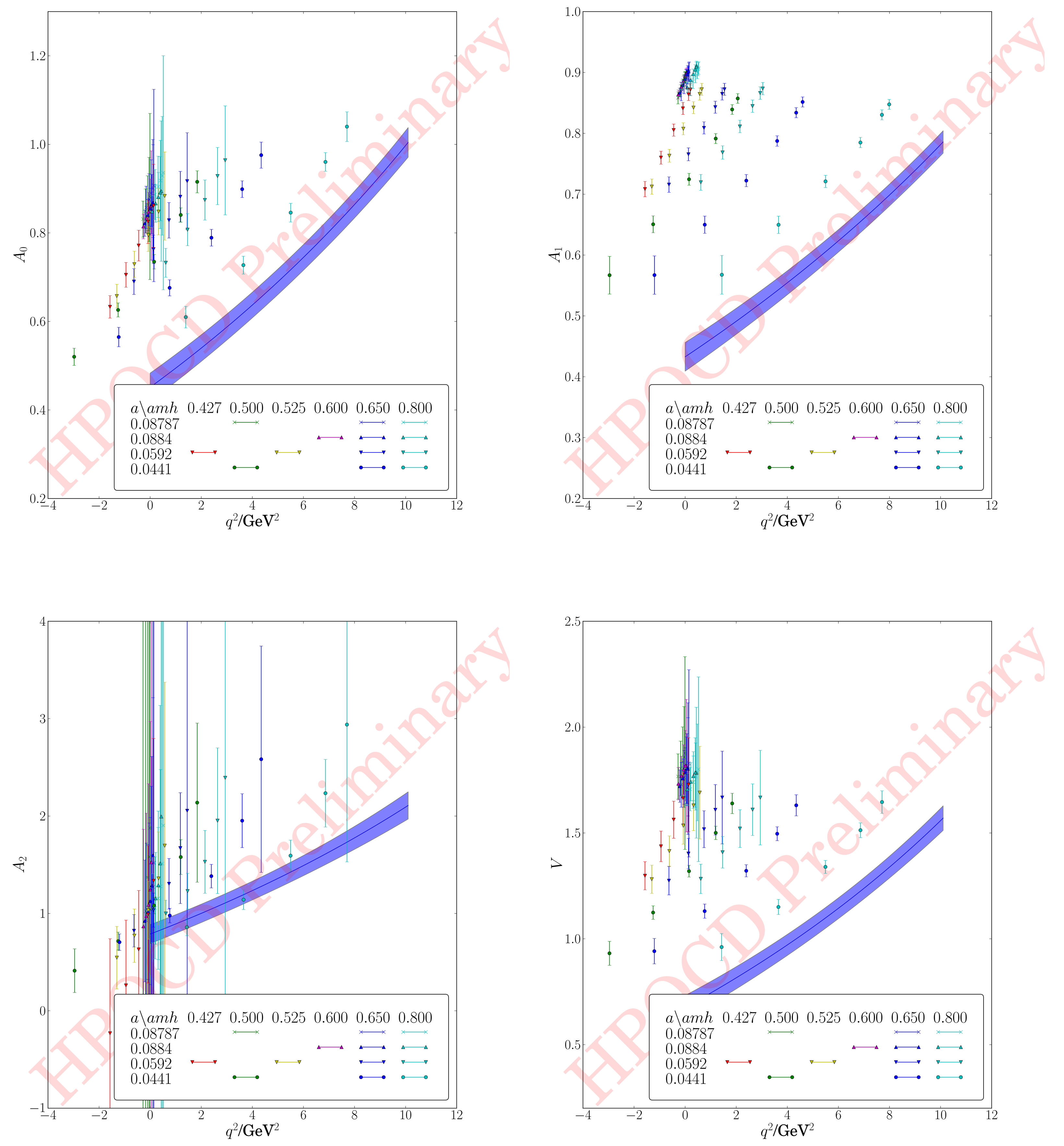
The use of HISQ quarks, which feature greatly suppressed am errors, minimises the am_h dependence of our lattice data, as well as allowing us to renormalise the lattice currents fully non-perturbatively. Our form factor fit function is then

$$\begin{aligned} F(q^2) =& P(q^2) \sum_{n=0}^{3} a_n z^n \mathcal{N}_n \\ a_n =& \sum_{j,k,l=0}^{3} b_n^{jkl} \left(\frac{2\Lambda}{M_{\eta_h}}\right)^j \left(\frac{am_c^{\rm val}}{\pi}\right)^{2k} \left(\frac{am_b^{\rm val}}{\pi}\right)^{2l} \end{aligned}$$

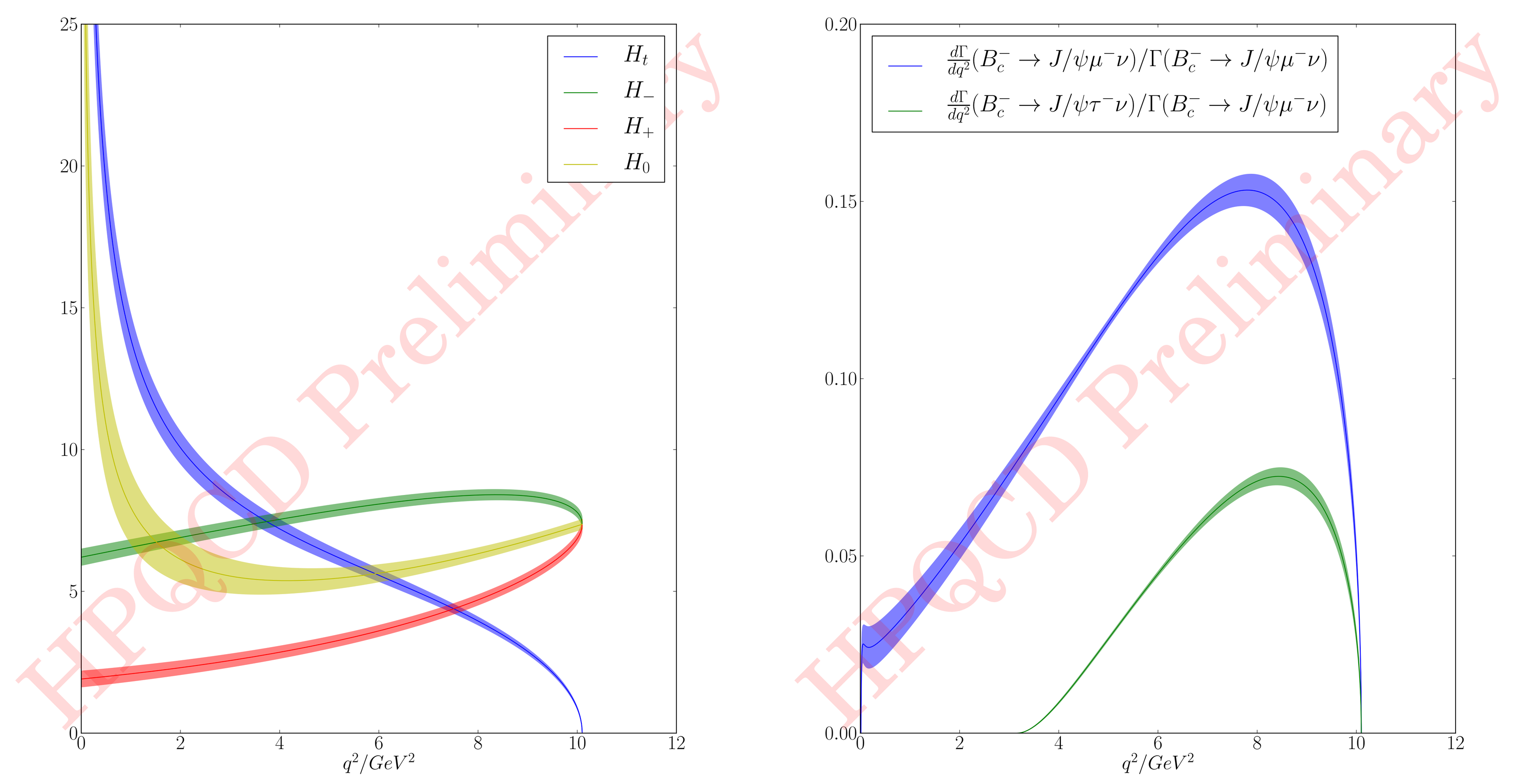
$P(q^2)$ incorporates poles arising from $b\bar{c}$ (axial-)vector states coupling to the current and $\mathcal{N}$ includes quark mass mistuning effects.

Results

Form factor data, together with the extrapolated physical point curves:



We then assemble the computed form factors into helicity amplitudes, from which we may construct the differential decay rates.



We find

$$\Gamma(B_c^- \to J/\psi \mu^- \overline{\nu}_\mu) = 2.14(14) \times 10^{10} s^{-1} \text{(preliminary)},$$

$$\Gamma(B_c^- \to J/\psi \tau^- \overline{\nu}_\tau) = 6.53(34) \times 10^{9} s^{-1} \text{(preliminary)},$$

and the ratio

$$R(J/\psi) = 0.3050(74) \text{(preliminary)}.$$

References

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