$B_c \to J/\psi$ Form Factors and $R(J/\psi)$ using Lattice QCD

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$B_c \to J/\psi \ell \overline{\nu}_\ell$ Semileptonic decays

Semileptonic differential decay rate for $B_c \to J/\psi \ell \overline{\nu}_\ell$:

$$\frac{d\Gamma\left(B_c \to J/\psi \ell \overline{\nu}_\ell\right)}{dq^2} = \frac{G^2}{(2\pi)^3}|V_{cb}|^2 \frac{(q^2 - M_\ell^2)^2 p'}{12 M_{B_c}^2 q^2}\Big[$$

$$\left({H_-}^2 + {H_0}^2 + {H_+}^2\right)$$

$$+\frac{M_\ell^2}{2q^2}\left({H_-}^2 + {H_0}^2 + {H_+}^2 + 3{H_t}^2\right)\Big]$$

Easy part: Kinematics, Electroweak perturbation theory
Hard part: QCD matrix elements between B_c and J/ψ states

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

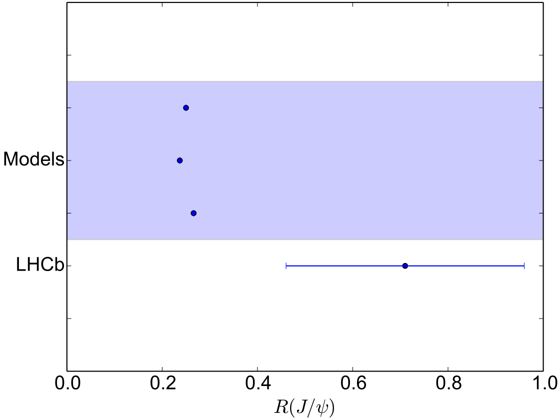
$$
\langle J/\psi(p', \epsilon) | \bar{c} \gamma^\mu b | B_c^-(p) \rangle = \frac{2iV(q^2)}{M_{B_c} + M_{J/\psi}} \, \epsilon^{\mu\nu\rho\sigma} \epsilon^*_\nu p'_\rho p_\sigma
$$

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

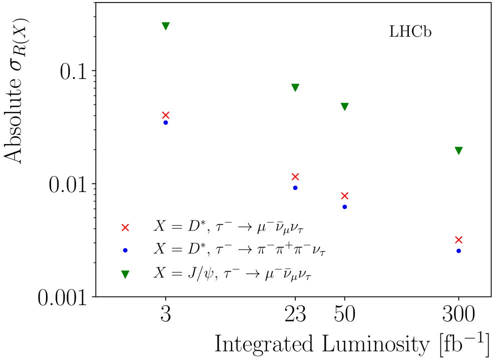
Experimental Status - $R(J/\psi)$

Useful to define dimensionless ratio of total decay rates to μ/e and τ final state.

$$R(J/\psi) = \frac{\Gamma(B_c \to J/\psi\tau^-\overline{\nu}_\tau)}{\Gamma(B_c \to J/\psi\mu^-\overline{\nu}_\mu)}$$



Experimental Status



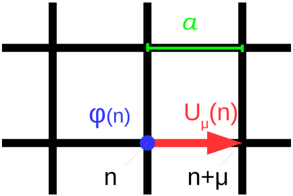
Projected uncertainties in $R(D^*)$ and $R(J/\psi)$ reproduced from arXiv:1808.08865v4

Lattice QCD

We want to extract matrix elements, amplitudes and energies from Euclidean correlation functions computed in the path integral formalism,

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

- discretise QCD onto a lattice
- Fermion integrals exact $\rightarrow$ need to invert dirac operator
- Monte-carlo integral over gauge fields U



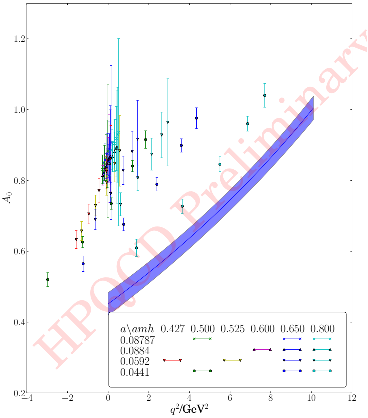
Heavy-HISQ

Discretisation effects enter as powers of am^n. Finest lattice has $am_b \approx 0.8 \to$ use unphysically light heavy quarks with $am_h < 1$ to constrain discretisation effects and heavy mass dependence in order to extract continuum physics.

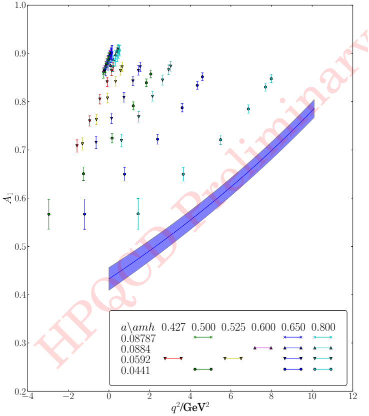
- use several am_h on each lattice.
- fit data to polynomial in $z(q^2)$ with coefficients dependent upon Λ_{QCD}/M_{η_h}, am_h and am_c.
- Set $M_{\eta_h} = M_{\eta_b}$, $am_h = am_c = 0$ in fit function to extract physical q^2 dependence.

We use Highly Improved Staggered Quarks (HISQ) $\to$ significantly reduced discretisation errors, crucial for calculations involving heavy quarks. Using all HISQ set up also allows for for non-perturbative renormalisation of lattice currents.

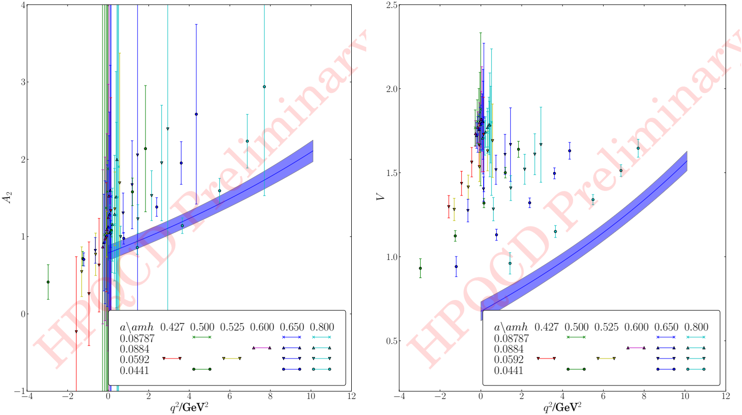
Results



A_0
q^2/GeV^2
$a \backslash amh$ 0.427 0.500 0.525 0.600 0.650 0.800
0.08787
0.0884
0.0592
0.0441
HPQCD Preliminary



A_1
q^2/GeV^2
$a \backslash amh$ 0.427 0.500 0.525 0.600 0.650 0.800
0.08787
0.0884
0.0592
0.0441
HPQCD Preliminary


A_2
q^2/GeV^2
V
q^2/GeV^2
HPQCD Preliminary
HPQCD Preliminary
$a \backslash amh$ 0.427 0.500 0.525 0.600 0.650 0.800
0.08787
0.0884
0.0592
0.0441
$a \backslash amh$ 0.427 0.500 0.525 0.600 0.650 0.800
0.08787
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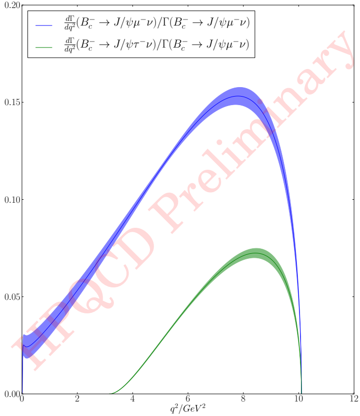
0.0592
0.0441

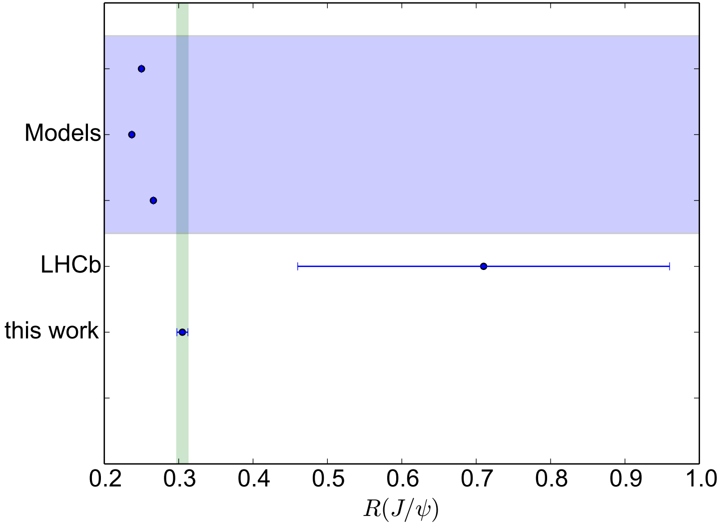


We find

$$\Gamma(B_c^- \to J/\psi\mu^-\overline{\nu}_\mu) = 2.14(14) \times 10^{10} s^{-1}(\text{Preliminary}),$$
$$\Gamma(B_c^- \to J/\psi\tau^-\overline{\nu}_\tau) = 6.53(34) \times 10^{9} s^{-1}(\text{Preliminary}),$$

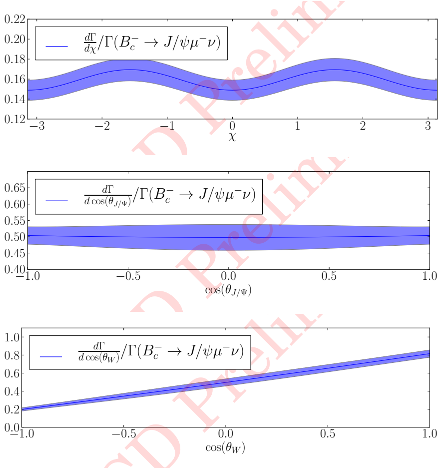
and the ratio

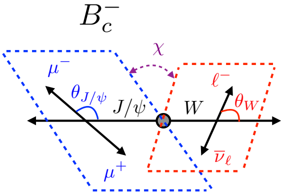
$$R(J/\psi) = 0.3050(74)(\text{Preliminary}).$$



Models
LHCb
this work
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
$R(J/\psi)$

Can also construct angular differential rates, with $J/\psi \to \mu^+\mu^-$





Outlook

- We have computed $R(J/\psi)$ in the full SM for the first time.
- The precision of our result is expected to remain competitive with experiment for the foreseeable future.
- The similar calculation for $B_s \to D_s^*$ is underway, as is $B \to D^*$
  $\to$ Calculation of $R(D^*)$
  $\to$ Model independent determination of V_{cb}

Thanks