Exploring Semileptonic $B_s \to D_s^* l \nu_l$ Decays

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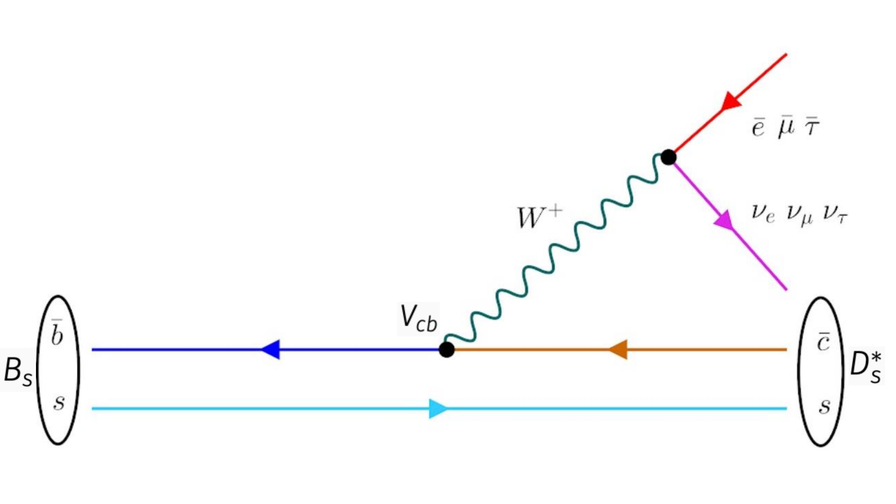
Semileptonic $B_s \to D_s^* l \nu_l$ Decays



- $B \to D^* l \nu_l$ similar, just different spectator

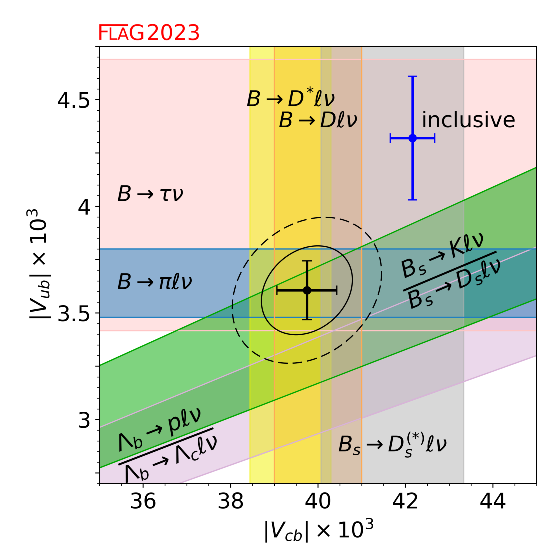
The CKM Matrix

- The Standard Model has six quark flavours
- Probability for transition of one flavour to another
- Parameters can be determined from a combination of experiment and theory
- Hierachical structure

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.97373 \pm 0.00031 & 0.2243 \pm 0.0008 & (3.82 \pm 0.20) \times 10^{-3} \\ 0.221 \pm 0.004 & 0.975 \pm 0.006 & (40.8 \pm 1.4) \times 10^{-3} \\ (8.6 \pm 0.2) \times 10^{-3} & (41.5 \pm 0.9) \times 10^{-3} & 1.014 \pm 0.029 \end{pmatrix}$$

[PDG, Workman et al. PTEP (2022) 083C01]

Motivation: Inclusive vs. Exclusive V_{cb}

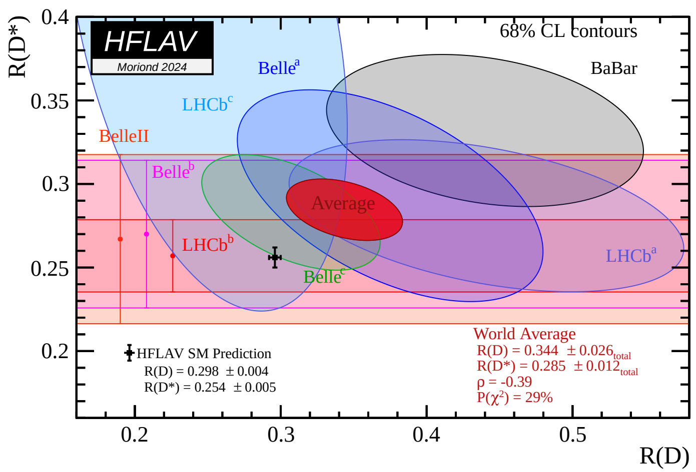


$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- 2 – 3σ tension between inclusive and exclusive
- $V_{cb}^{incl} = (42.2 \pm 0.8) \times 10^3$
- $V_{cb}^{excl} = (39.4 \pm 0.8) \times 10^3$

[PDG, Workman et al. PTEP (2022) 083C01]
FLAG 2023

Motivation: Test Lepton Flavour Universality



$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}l\nu_l)}$$

with $l = e, \mu$

HFLAV, Moriond 2024

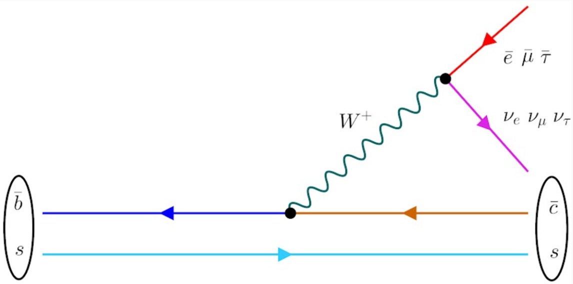
Determining V_{cb} from semileptonic Decays

$$\frac{d\Gamma(B_{(s)} \to D^*_{(s)} l \nu_l)}{dq^2} = \mathcal{K}_{D^*}(q^2, m_l) \cdot |\mathcal{F}(q^2)|^2 \cdot |V_{cb}|^2$$

From Experiment | Known Factors | Nonpert. Input | CKM

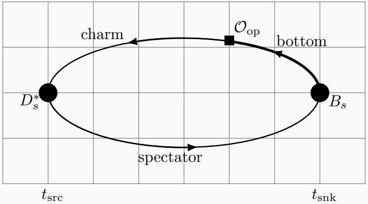
- Form factors from LQCD, LCSRs
- Experiments: BaBar, BELLE, BELLE 2, LHCb
- Vector final states are experimentally favoured

Exclusive $B_s \to D_s^*$ decay



- Use Narrow Width Approximation for $D^*_{(s)}$
  - Treated as stable particles
- Focus on B_s and D_s^*
  - LHCb data
  - Heavier spectator is easier to determine on lattice
  - In a later stage of this project: also $B \to D^*$

Relativistic Form Factors



$$\langle D^*_{(s)}(k,\lambda)|\bar{c}\gamma^\mu b|B_{(s)}(p)\rangle = V(q^2)\frac{2i\epsilon^{\mu\nu\rho\sigma}\varepsilon^*_\nu k_\rho p_\sigma}{M_{B_{(s)}}+M_{D^*_{(s)}}}$$

$$\begin{aligned}\langle D^*_{(s)}(k,\lambda)|\bar{c}\gamma^\mu\gamma_5 b|B_{(s)}(p)\rangle =& A_0(q^2)\frac{2M_{D^*_{(s)}}\varepsilon^*\cdot q}{q^2}q^\mu \\ &+ A_1(q^2)(M_{B_{(s)}}+M_{D^*_{(s)}})\left[\varepsilon^{*\mu}-\frac{\varepsilon^*\cdot q}{q^2}q^\mu\right] \\ &- A_2(q^2)\frac{\varepsilon^*\cdot q}{M_{B_{(s)}}+M_{D^*_{(s)}}}\left[k^\mu+p^\mu-\frac{M^2_{B_{(s)}}-M^2_{D^*_{(s)}}}{q^2}q^\mu\right]\end{aligned}$$

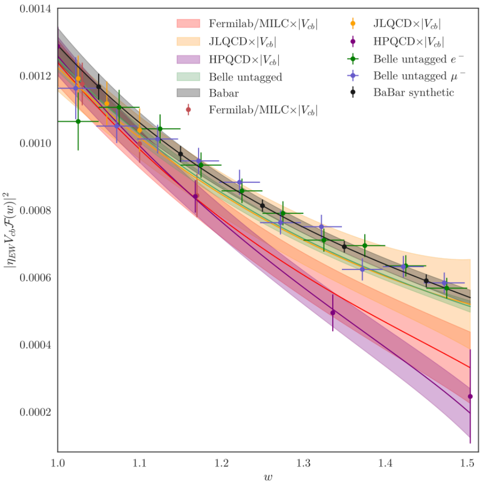
HQET Form Factors

$$\frac{\langle D^*_{(s)}(k,\varepsilon)|\,\mathcal{A}^\mu\,|B(p)\rangle}{\sqrt{M_{D^*}M_B}} = i\varepsilon^*_\nu\left[g^{\mu\nu}(w+1)h_{A_0}(w) - v^\nu_B(v^\mu_B h_{A_1}(w) + v^\mu_{D^*_{(s)}} h_{A_2}(w))\right]$$

$$\frac{\langle D^*_{(s)}(k,\varepsilon)|\,\mathcal{V}^\mu\,|B(p_B)\rangle}{\sqrt{M_{D^*}M_B}} = \epsilon^{\mu\nu}{}_{\rho\sigma}\varepsilon^*_\nu v^\rho_B v^\sigma_{D^*} h_V(w), \quad \text{with} \quad w = v_{B_s}\cdot v_{D^*_{(s)}}$$

- Heavy to heavy transitions $\rightarrow$ HQET form factors

Existing Results for Form Factors



- $V_{cb}^{\text{HPQCD}} = 39.31(74) \times 10^{-3}$
- $V_{cb}^{\text{JLQCD}} = 39.19(90) \times 10^{-3}$
- $V_{cb}^{\text{FNAL-MILC}} = 38.17(85) \times 10^{-3}$

[HPQCD, Harison et al. (2022), PRD 105.094506]
[JLQCD, Aoki et al. (2023), PRD 109.074503]
[FNAL-MILC, Bazavov et al. (2022), EPJC 81.1141]

[Plots/fits: A. Vaquero CKM 2023]

Our Work

Lattice Set Up

- RBC/UKQCD's 2+1 flavour gauge field ensembles
- Dynamical up/down and strange quarks in the sea and light sector using chiral domain-wall fermions
- Specifically optimized heavy domain-wall fermions for charm
- Relativistic heavy quark (RHQ) action for bottom
- Bottom, charm and strange close to physical

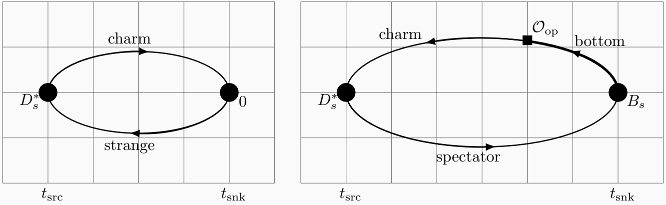
	L	T	a^{-1} GeV	am_l^{sea}	am_s^{sea}	M_π / MeV	srcs $\times$ N_{conf}
C1	24	64	1.7848	0.005	0.040	340	1 $\times$ 1636
C2	24	64	1.7848	0.010	0.040	433	1 $\times$ 1419
M1	32	64	2.3833	0.004	0.030	302	2 $\times$ 628
M2	32	64	2.3833	0.006	0.030	362	2 $\times$ 889
M3	32	64	2.3833	0.008	0.030	411	2 $\times$ 544
F1S	**48**	**96**	**2.785**	**0.002144**	**0.02144**	**268**	**24 $\times$ 98**

Extract Form Factors

- Define 3pt - 2pt ratios
- Different combinations of polarizations, operators and momenta give access to formfactors

$$R^{\Gamma}_{B_s\to D_s^*}(t,t_{sink}) = \frac{C^{3pt,\Gamma,\mu}_{B_s\to D_s^*}(t,t_{sink},k)}{\frac{1}{3}\sqrt{\sum_i C^{2pt}_{D_s^*}(t,k)C^{2pt}_{B_s}(t_{sink}-t,p)}}\sqrt{\frac{4E_{D_s^*}M_{B_s}\sum_{\lambda,j}\varepsilon_j(k,\lambda)\varepsilon^{*j}(k,\lambda)}{e^{-E_{D_s^*}}e^{-M_{B_s}(t_{sink-t})}}}$$

$$\xrightarrow[t_{sink}-t\to\infty]{t\to\infty} \sum_\lambda \varepsilon^\mu(k,\lambda)\langle D_s^*(k,\lambda)|\bar{c}\Gamma b|B_s(p)\rangle$$

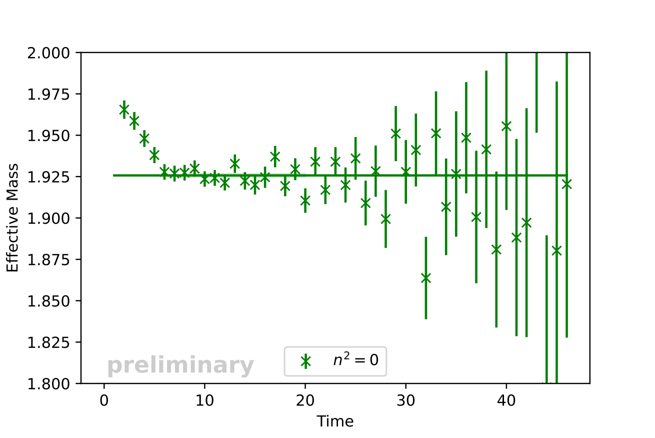


Extract Form Factors

- Define 3pt - 2pt ratios
- Different combinations of polarizations, operators and momenta give access to form factors
- Example for one **lattice** form factor

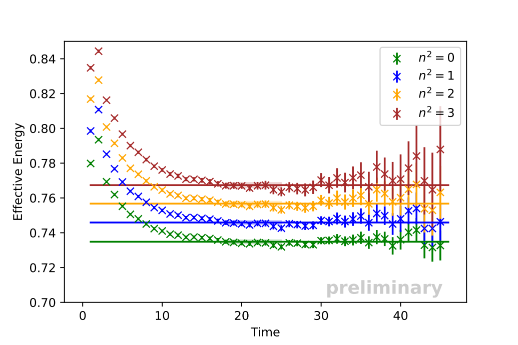
$$\widetilde{A_0}(q^2) = \frac{1}{2}\frac{M_{D_s^*}}{E_{D_s^*}M_{B_s}}\frac{1}{k^\nu}q_\mu \sum_\lambda \varepsilon^\nu(k,\lambda)\langle D_s^*(k,\lambda)|\bar{c}\gamma^\mu\gamma_5 b|B_s(0)\rangle$$

Effective Mass of B_s



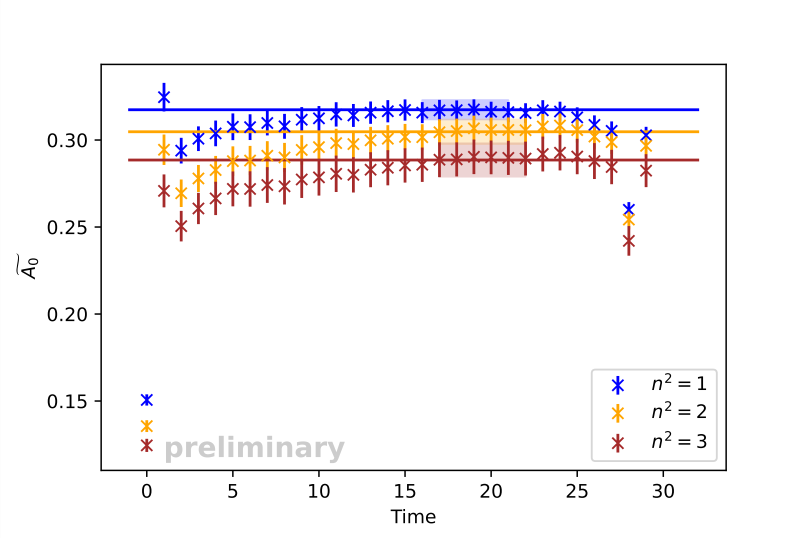
- Fit range: 8-20
- $M_{eff}^{B_s} = 1.92571(97)$
- In physical units: 5.3631(27) GeV (PDG: $M_{B_s} = 5.36696(10)$ GeV)

Effective Energy of D_s^*



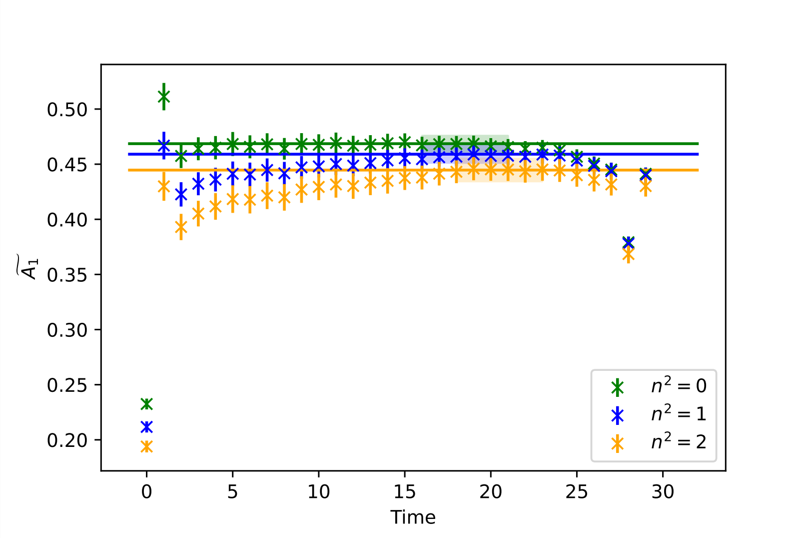
- $E_{eff}^{D_s^*}(n^2 = 0) = 0.7348(10)$
- $E_{eff}^{D_s^*}(n^2 = 1) = 0.7458(11)$
- $E_{eff}^{D_s^*}(n^2 = 2) = 0.7567(12)$
- $E_{eff}^{D_s^*}(n^2 = 3) = 0.7673(14)$

- In physical units: 2.0464(28) GeV
- PDG: $M_{D_s^*} = 2.12212(4)$ GeV
- Fit ranges: 18-25

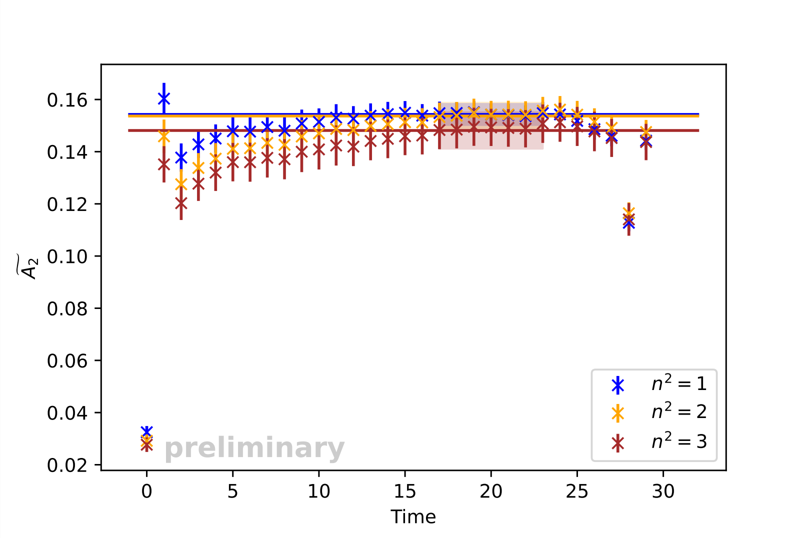


$$\widetilde{A}_0(n^2 = 1) = 0.3174(55)$$
$$\widetilde{A}_0(n^2 = 2) = 0.3047(70)$$
$$\widetilde{A}_0(n^2 = 3) = 0.2885(95)$$

Form Factor $\widetilde{A}_1$

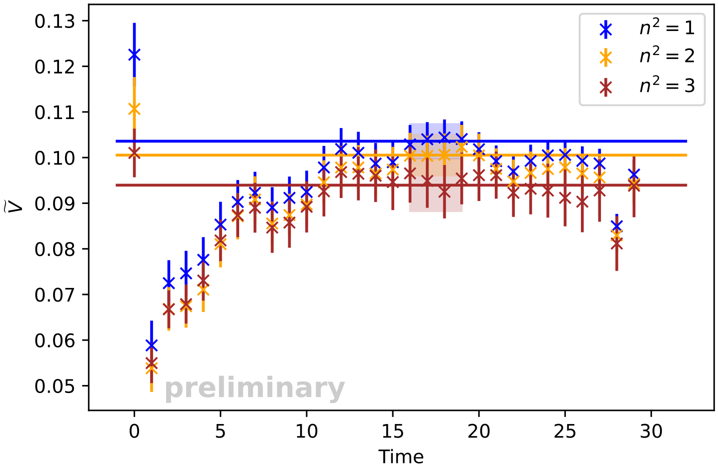


$$\widetilde{A}_1(n^2 = 0) = 0.4686(72)$$
$$\widetilde{A}_1(n^2 = 1) = 0.4591(78)$$
$$\widetilde{A}_1(n^2 = 2) = 0.445(10)$$



$$\widetilde{A}_2(n^2 = 1) = 0.1542(40)$$
$$\widetilde{A}_2(n^2 = 2) = 0.1537(51)$$
$$\widetilde{A}_2(n^2 = 3) = 0.1481(70)$$

Form Factor $\widetilde{V}$



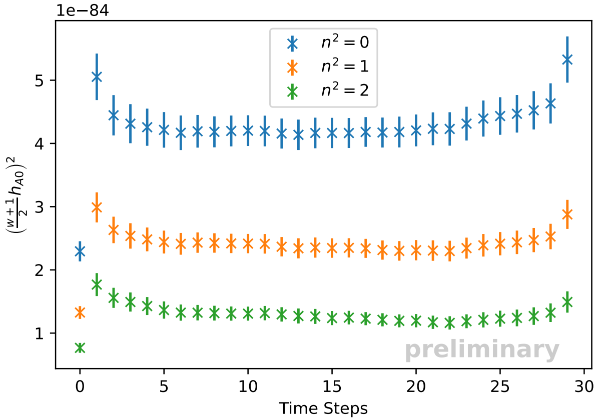
$$\widetilde{V}(n^2 = 1) = 0.1036(37)$$
$$\widetilde{V}(n^2 = 2) = 0.1005(45)$$
$$\widetilde{V}(n^2 = 3) = 0.0940(57)$$

Extract HQET Form Factors

- Different approach than relativistic form factors: Double ratios of 3pt functions
- So far: Denominator set to 1 as blinding factor

$$\frac{\langle D^*(p_\perp)| A_j |B(0)\rangle \langle B(0)| A_j |D^*(p_\perp)\rangle}{\langle D^*(0)| V^4 |D^*(0)\rangle \langle B(0)| V^4 |B(0)\rangle} \sim \left[\frac{w+1}{2} h_{A_0}(w)\right]^2$$

First Results for HQET Form Factors



Next Steps

Short term:

- Analyse other ensembles
- Include other charm masses
- Include order a improvement terms
- Perform excited state fits
- Determine renormalization factors
- Explore improved set-up

Long term:

- Combine into global fit: remove dicretization artifacts
- Extra- / interpolate to physical quark mass
- Take continuum limit
- Kinematical extrapolation
- Estimate systematic effects
- Analyse $B \to D^*$