Exploring Semileptonic $B_s \to D_s^* \ell \nu_\ell$ Decays

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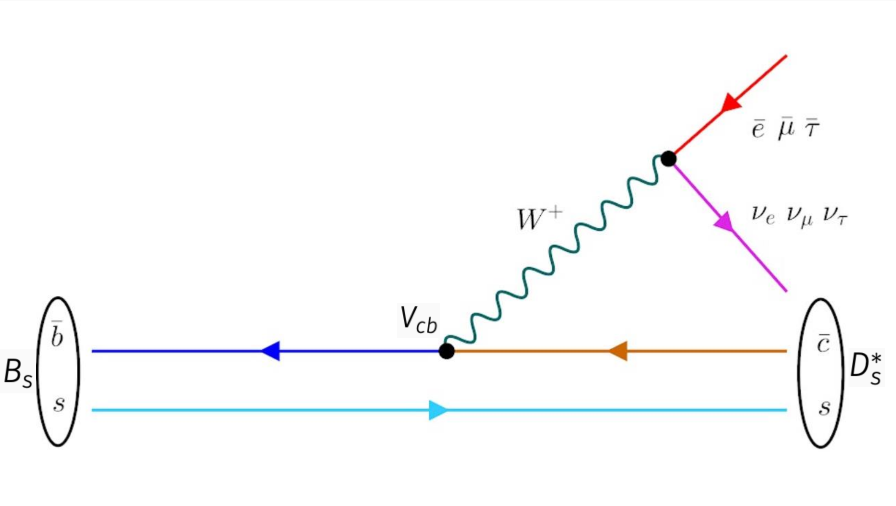
Semileptonic $B_s \to D_s^* \ell \nu_\ell$ Decays



- $B \to D^* \ell \nu_\ell$ similar, just different spectator

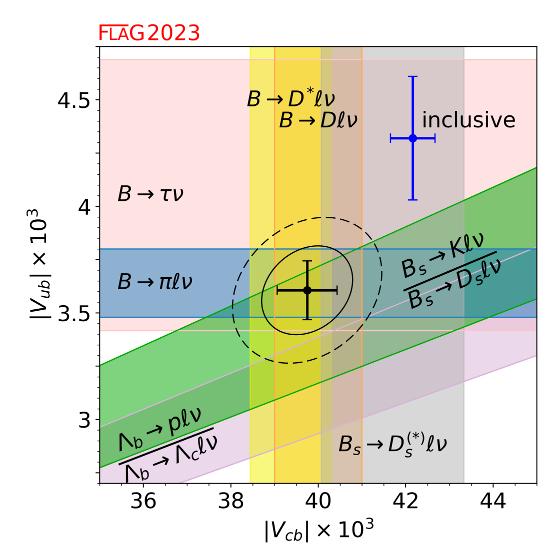
The CKM Matrix

- 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}

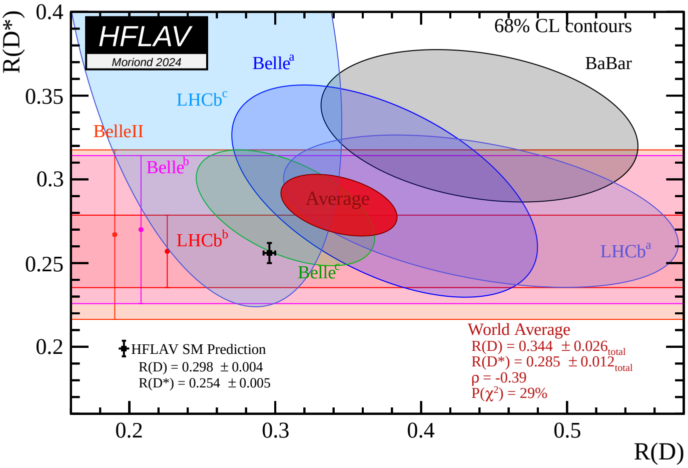


$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- $2 - 3\sigma$ tension between inclusive and exclusive
- $V_{cb}^{incl} = (42.16 \pm 0.51) \times 10^3$
- $V_{cb}^{excl} = (39.75 \pm 0.69) \times 10^3$

[FLAG, Aoki et al. EPJC (2022) 82.869]

Motivation: Test Lepton Flavour Universality



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

with $\ell = e, \mu$

[HFLAV, Moriond 2024]

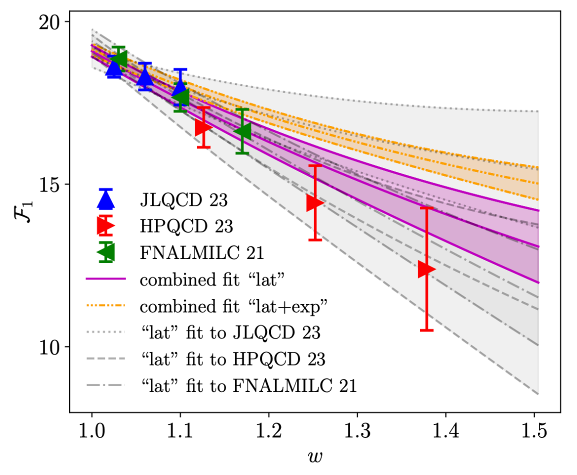
Determining V_{cb} from Exclusive Semileptonic Decays

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

From Experiment	Known Factors	Nonpert. Input	CKM

- Form factors from LQCD, LCSRs
- Experiments: BaBar, BELLE, BELLE 2, LHCb
- Vector final states are experimentally favoured
- Use narrow width approximation for $D^*_{(s)}$

Existing Results for $B \to D^* \ell \nu_\ell$ Form Factors



[M. Bordone, A. Jüttner arxiv:2406.10074 (2024)]

With $w = v_{B_s} \cdot v_{D_s^*}$

- $V_{cb}^{\text{excl}} = 39.03(87) \times 10^{-3}$
  [HPQCD, Harison et al. (2024), PRD 109.094515]
  For $B_s \to D_s^* \ell \nu_\ell$ see [HPQCD, Harison et al. (2022), PRD 105.094506]
- $V_{cb}^{\text{excl}} = 39.19(91) \times 10^{-3}$
  [JLQCD, Aoki et al. (2023), PRD 109.074503]
- $V_{cb}^{\text{excl}} = 38.40(78) \times 10^{-3}$
  [FNAL-MILC, Bazavov et al. (2022), EPJC 81.1141]
- $V_{cb}^{\text{excl}} = 40.25(71) \times 10^{-3}$
  [M. Bordone, A. Jüttner arxiv:2406.10074 (2024)]
- $V_{cb}^{\text{incl}} = 42.19(78) \times 10^{-3}$
  [HFLAV, Amhis et al. (2023), PRD 107.052008]

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**

Relativistic Form Factors

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

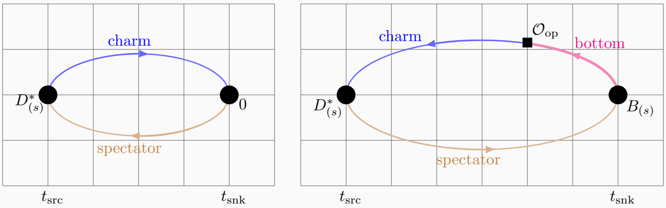
$$\begin{aligned}\langle D^*_{(s)}(k,\varepsilon)|\bar{c}\gamma^\mu\gamma_5 b|B_{(s)}(p)\rangle =& A_0(q^2)\frac{2M_{D^*_{(s)}}\varepsilon^*\cdot q}{q^2}q^\mu \\ &+ A_1(q^2)(M_{B_{(s)}}+M_{D^*_{(s)}})\left[\varepsilon^{*\mu}-\frac{\varepsilon^*\cdot q}{q^2}q^\mu\right] \\ &- A_2(q^2)\frac{\varepsilon^*\cdot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

Extract Form Factors

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

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

$$\xrightarrow[t_{sink}-t\to\infty]{t\to\infty} \varepsilon^\mu(k)\langle D^*_{(s)}(k,\varepsilon)|\bar{c}\Gamma b|B_{(s)}(p)\rangle$$



Extract Form Factors

- Next step: Relate matrix element to form factor

$$\widetilde{A}_0(q^2) = \frac{1}{2}\frac{M_{D^*_{(s)}}}{E_{D^*_{(s)}} M_{B_{(s)}}}\frac{1}{k^\nu} q_\mu \cdot \varepsilon^\nu(k)\langle D^*_{(s)}(k,\lambda)|\bar{c}\gamma^\mu\gamma_5 b|B_{(s)}(0)\rangle$$

- Calculate renormalisation factors using mostly NPR

  [Hashimoto et al. (1999), PRD 61.014502] , [El-Khadra et al. (2001), PRD D64.014502]

  - To be calculated independently and blinded

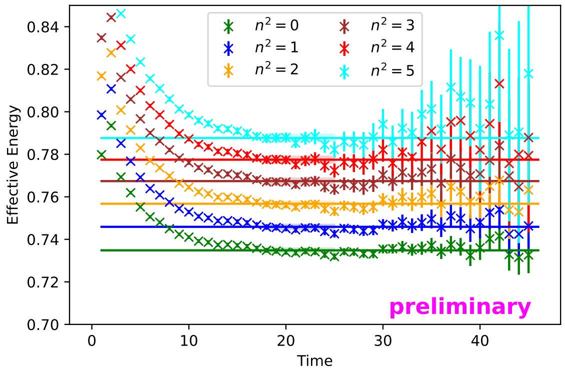
Exploratory Work

- Basic search for signal
- Simple ground state fits
- Taking advantage of existing data
- Get reference point for improvements
- Focus on $B_s \to D_s^* \ell \nu_\ell$

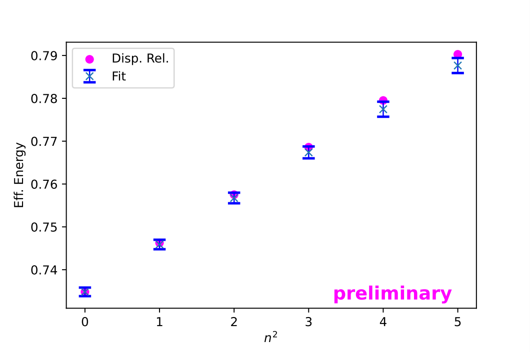
Effective Energy of D_s^*

- $E_{eff}^{D_s^*}(n^2 = 0) = 0.7348(10)$
- $E_{eff}^{D_s^*}(n^2 = 1) = 0.7458(11)$
- $E_{eff}^{D_s^*}(n^2 = 2) = 0.7567(12)$
- $E_{eff}^{D_s^*}(n^2 = 3) = 0.7673(14)$
- $E_{eff}^{D_s^*}(n^2 = 4) = 0.7775(16)$
- $E_{eff}^{D_s^*}(n^2 = 5) = 0.7877(18)$

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



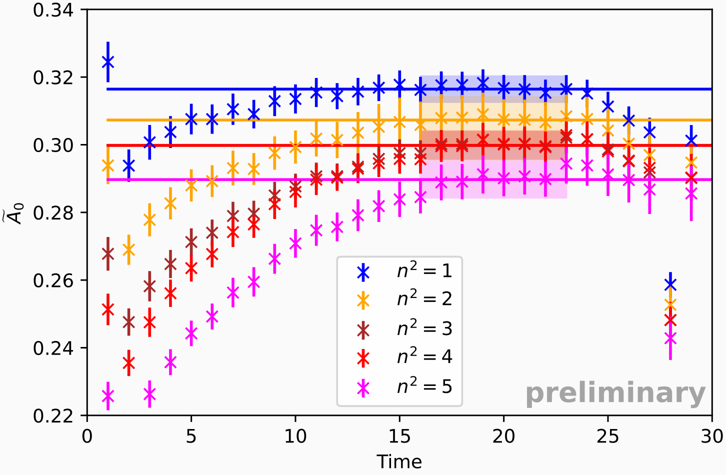
Effective Energy of D_s^*: Dispersion Relation



$$E = 2a^{-1}\sinh^{-1}\sqrt{\sinh^2\left(\frac{am}{2}\right) + \sum_{i=1}^{3}\sin^2\left(\frac{ap_i}{2}\right)}$$

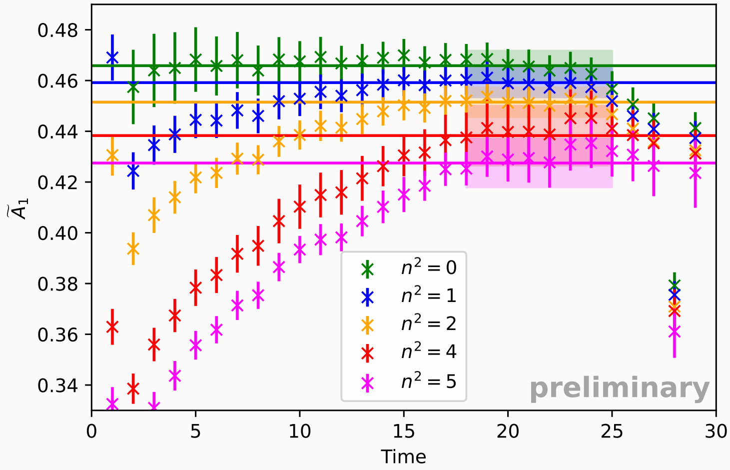
Excellent agreement between measured values and lattice dispersion relation

Form Factor $\widetilde{A}_0$



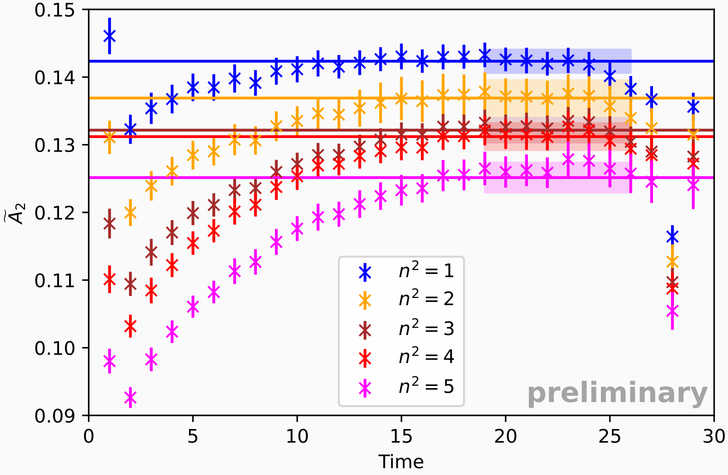
$\widetilde{A}_0(n^2 = 1) = 0.3164(38)$
$\widetilde{A}_0(n^2 = 2) = 0.3073(68)$
$\widetilde{A}_0(n^2 = 3) = 0.2998(40)$
$\widetilde{A}_0(n^2 = 4) = 0.2998(42)$
$\widetilde{A}_0(n^2 = 5) = 0.2897(53)$

Form Factor $\widetilde{A}_1$



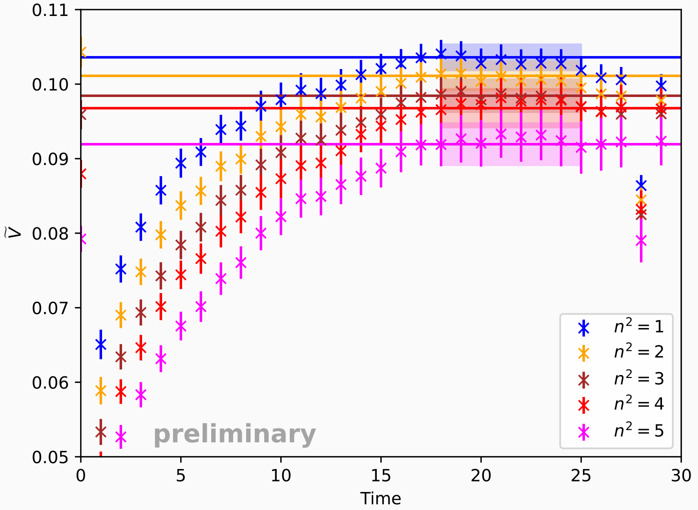
$$\widetilde{A}_1(n^2 = 0) = 0.4658(59)$$
$$\widetilde{A}_1(n^2 = 1) = 0.4592(58)$$
$$\widetilde{A}_1(n^2 = 2) = 0.4514(58)$$
$$\widetilde{A}_1(n^2 = 4) = 0.438(12)$$
$$\widetilde{A}_1(n^2 = 5) = 0.427(10)$$

Form Factor $\widetilde{A}_2$



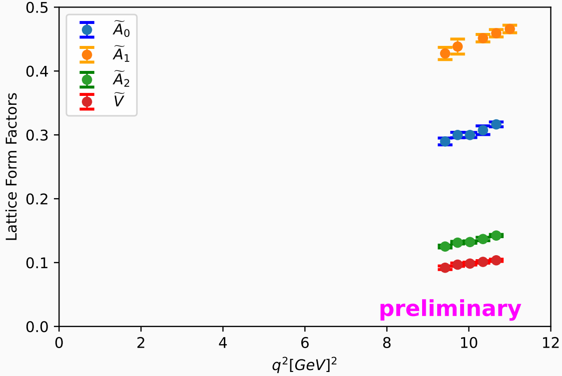
$\widetilde{A}_2(n^2 = 1) = 0.1423(17)$
$\widetilde{A}_2(n^2 = 2) = 0.1368(26)$
$\widetilde{A}_2(n^2 = 3) = 0.1322(18)$
$\widetilde{A}_2(n^2 = 4) = 0.1311(20)$
$\widetilde{A}_2(n^2 = 5) = 0.1251(22)$

Form Factor $\widetilde{V}$



$$\widetilde{V}(n^2 = 1) = 0.1036(18)$$
$$\widetilde{V}(n^2 = 2) = 0.1011(11)$$
$$\widetilde{V}(n^2 = 3) = 0.0984(22)$$
$$\widetilde{V}(n^2 = 4) = 0.0967(26)$$
$$\widetilde{V}(n^2 = 5) = 0.0919(28)$$

All Form Factors vs. q^2



- Only small range at high q^2 resolved
- Simulating D_s^* with larger momenta desired

Next Steps

Improve fits

- Account for correlations
- Include excited states
- Variation of fit ranges

Exploit full data set

- Analyse other ensembles
- Include 1-loop $O(a)$ improvement
- Study other charm and strange quark masses
- Extend analysis to $B \to D^* \ell \nu$

Study improvements

- Z2 wall sources w and w/o smearing vs. large number of random point sources
- Several source-sink separations
- D_s^* with higher momenta

Perturbative calculation

- Mostly NP renormalisation factors (blinded)
- Coefficients for 1-loop O(a) improvement