Prospects for inclusive semileptonic charm decays

based on arXiv:2408.10063

Alex Gilman
in collaboration with Florian Bernlochner, Sneha Malde,
Markus Prim, Keri Vos, and Guy Wilikinson

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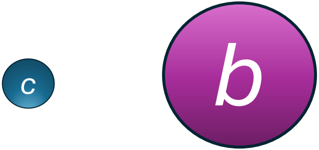
Challenges in Semileptonic B Decays
Vienna, Austria

UNIVERSITY OF OXFORD

The (not as) Heavy Quark Expansion

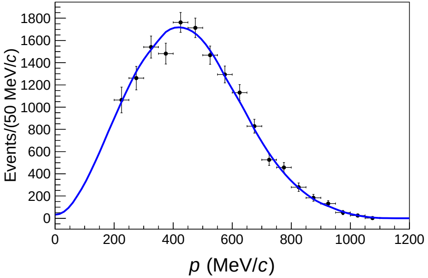


- Heavy-Quark Expansion (HQE) expands in $\frac{\Lambda_{QCD}}{m_q}$
- Since $m_c < m_b$. converges more slowly for charm than beauty, but more sensitive to hadronic matrix elements
- Inclusive semileptonic charm decays provide complementary analysis using the HQE and unique sensitivity to intrahadronic interactions in heavy quark systems

Inclusive SL Charm decays: Previous Experimental Work

- Previous studies of inclusive decays by CLEO-c and BESIII measured inclusive SL branching fractions and lab-frame momentum spectra for D^0, D^+, D_s^+ and Λ_c^+
- Used no information on hadronic system X in $D/\Lambda_c \to X\ell\nu$
- Measured decay widths indicate breakdown of factorisation

D_s^+ p_e spectrum



$$\frac{\Gamma_{SL}(D^+)}{\Gamma_{SL}(D^0)} = 0.985 \pm 0.028$$

$$\frac{\Gamma_{SL}(D_s^+)}{\Gamma_{SL}(D^0)} = 0.790 \pm 0.025$$

$$\frac{\Gamma_{SL}(\Lambda_c^+)}{\Gamma_{SL}(D^0)} = 1.28 \pm 0.05$$

PRD 81 (2010) 052007 PRD 104 (2021) 012003 PRD 107 (2023) 052005

Inclusive SL Charm decays: Previous Theoretical Work

- Measured D^0, D^+ and D_s^+ momentum spectra analysed to constrain effects of weak-annihilation in SL B decay rates
  - Estimated upper limits of 2% from Gambino & Kamenik[1] and 1% from Ligeti, Luke, & Manohar[2]
- Study of HQE in charm and it's potential application for determination of $|V_{cs}|$ and $|V_{cd}|$ from Fael, Mannel, Vos[3]
- Study of total & SL decay widths of charmed hadrons from King *et al.*[4]
- Recent analysis of measured momentum spectra to estimate α_s at the charm-mass from Wu *et al.*[5]
- Recent progress on inclusive charm decays on the lattice[6] (See R. Kellerman's talk)

[1] Nucl. Phys. B 840 (2010) 424

[2] PRD 82 (2010) 033003

[3] JHEP 12 (2019) 067

[4] King, Lenz, Piscopo, Rauh, Rusov, Vlahos, JHEP 08 (2022) 241

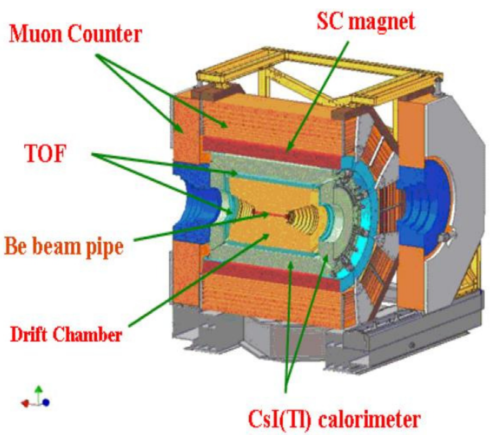
[5] Wu, Lou, Che, Li, Huang, Ye, arXiv 2406.16119

[6] Kellerman, Barone, Hashimoto, Jüttner, Kaneko PoS (Lattice2023) 272

Time to include more inclusive charm

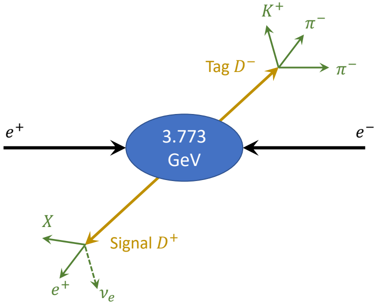
- Limitations of previous measurements:
  - No information on final-state hadronic system $X \Rightarrow$ No access q^2 or M_X
  - Due to lack of information on X, cannot separate $c \to s$ and $c \to d$ transitions and $\left(\frac{|V_{cd}|}{|V_{cs}|}\right)^2 \sim 5\%$ not small
  - Only measure lab-frame momentum spectra, and transformation to rest frame is non trivial in D_s^+ measurements due to production through $D_s^{*+}D_s^-$
- BESIII has robust datasets of D^0, D^+, D_s^+, and Λ_c^+ datasets that are ideal to deliver a new program of inclusive measurements in charmed hadrons

Beijing Electron Spectrometer III (BESIII)



- Housed in the Beijing Electron-Positron Collider Mk. II at the Institute of High Energy Physics
- Hermiticity: 93% of 4π
- Gaseous Drift Chamber for tracking
- Time-of-Flight system for PID
- Calorimeter for e^- identifcation and neutral particle reconstruction:
- Resistive Plate Chamber for identification of hard muons
- Things to keep in mind:
  - Low boost $\Rightarrow$ (almost) no displaced vertices
  - Momentum of final state particles in the lab frame: $50 - 1500$ MeV/c
  - e^+e^- leads to very clean environments
  - $\sim 100\%$ trigger efficiency

Overview of Proposed Measurement Technique



- Double-tag technique with golden D tag modes: $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to K^-K^+\pi^+(etc.)$, $\Lambda_c^+ \to pK^-\pi^+(etc.)$

- Identify charged lepton
- Reconstruct hadronic system X from additional
  - $K_S^0 \to \pi^+\pi^-$, $\Lambda \to p\pi^-$ with displaced vertices
  - Additional charged tracks with PID hypotheses ($K^\pm$, $\pi^\pm$, $p^\pm$)
  - Isolated calorimeter depositions
- Correct for detector resolution effects through linear calibration procedure similar to Belle, BelleII[1]

[1] PRD 104 (2021) 112011, PRD 107 (2023) 072002

BESIII datasets

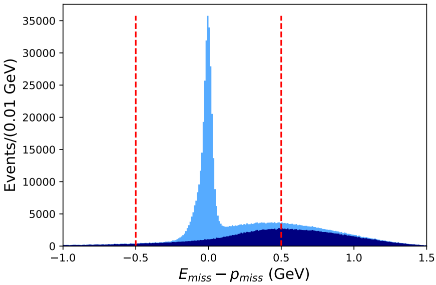
	D^0	D^+	D_s^+	Λ_c^+
E_{cm} GeV	3.773	3.773	4.130–4.230	4.600-4.699
Int. Lumi. $[\text{fb}^{-1}]$	21	21	7.1	4.5
Estimated DT Yields	200000	700000	30000	4300

- Large D^0, D^+ datasets recently collected, $\sim 7\times$ the previous BESIII dataset, $\sim 30\times$ the CLEO dataset
- D_s^+ data collected through $D_s^{*+}D_s^-$ due to higher constructions
  - $D_s^{*+} \to \gamma D_s^+$ decay must be reconstructed for full-event kinematic information, i.e. q^2

Measured D^+ distributions from Fast Simulation

- Verified on simulation samples based on EvtGen with estimates of BESIII resolution and detection efficiencies

Total Distribution $K_L^0, K_S^0 \to \pi^0\pi^0$

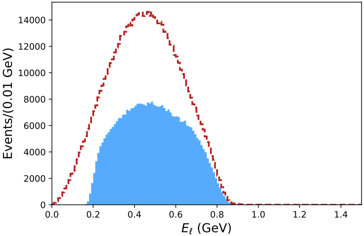


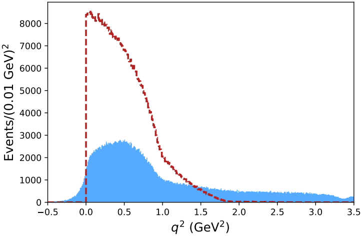
- Additionally require $|E_{\text{miss}} - p_{\text{miss}}| < 500$ MeV to remove poorly reconstructed events (primarily due to K_L^0 and $K_S^0 \to \pi^0\pi^0$)

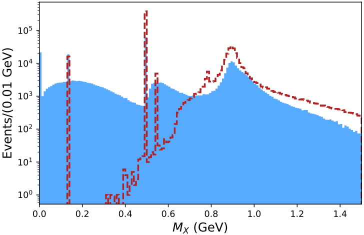
Measured D^+ distributions from Fast Simulation

Generated Distribution

Measured Distribution





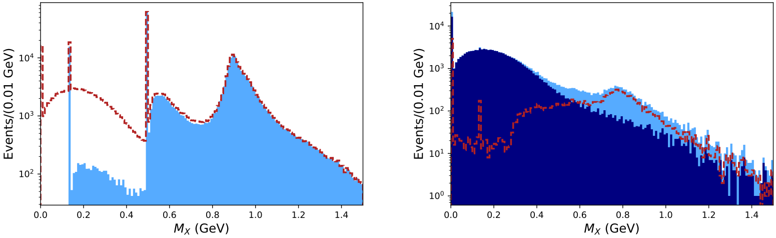


- BESIII $e^\pm$ ID imposes $E_\ell > 200$ MeV
- Discontinuous M_X distribution due to $D \to Ke\nu / D \to \pi e\nu$

Prospects for isolating $c \to s$ and $c \to d$ transitions

- $K^{\pm}$ identification and K^0_S/Λ reconstruction allows us to determine strangeness of hadronic system X
- Corrections required due to K^0_L, $K^0_S \to \pi^0\pi^0$.

D^+, $c \to s$ D^+, $c \to d$

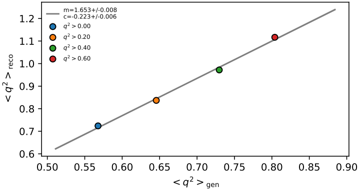


Truth Measured, correct Measured, incorrect

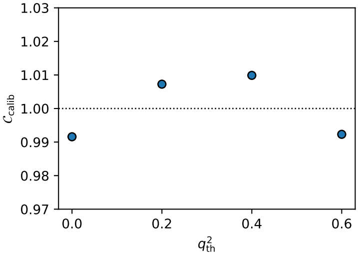
- $K^0_S \to \pi^+\pi^+$ identification could be used to control misidentified strangeness due to K^0_L

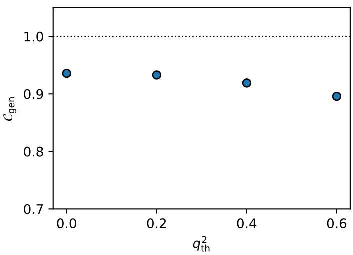
Corrections on measured moments

- Linear calibration for resolution :
  $q^{2n}_{\mathsf{cal}} = \left(q^{2n}_{\mathsf{reco}} - c_n\right)/m_n$
  (same for E^n_ℓ)



- Corrections for non-linearity (C_{calib}) and selection/acceptance (C_{gen})

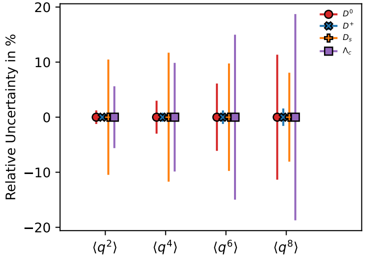


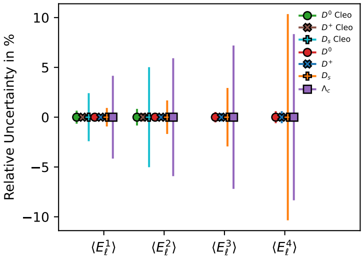


$$\langle q^{2n}\rangle = \sum_i q^{2n}_{i\,\mathsf{cal}} \times C_{\text{calib}} \times C_{\text{gen}}$$

Estimated sensitivity on spectral moments

- Based on fast simulation of currently available data, we estimate our sensitivity to spectral moments, including estimates of BESIII systematics
- Uncertainty budgets vary for different parameters (details in paper)
- We compare to Gambino & Kamenik[1] analysis of E_ℓ moments from CLEO-c measurements





[1] Nucl. Phys. B 840 (2010) 424

Setting up the HQE in Charm

- Following work of Fael, Mannel, & Vos[1], expand $c \to s$ transitions in $\frac{\Lambda_{QCD}}{m_c}$, $\alpha_s(m_c)$, and $\frac{m_s}{m_c}$ to order $\frac{1}{m_c^3}$.
- Similar to B HQE setup, with notable differences
  - HQE parameters $(\mu_\pi, \mu_G, \rho_D, \rho_{LS})$ vary for different hadrons
  - Introduce four-quark terms at weak-annihilation scale

$$2m_D T_1(\mu_{\rm WA}) \equiv \langle D|(\bar{c}_v \not{v} P_L s)\,(\bar{s}\not{v} P_L c_v)|D\rangle$$

$$2m_D T_2(\mu_{\rm WA}) \equiv \langle D|(\bar{c}_v \gamma^\mu P_L s)\,(\bar{s}\gamma_\mu P_L c_v)|D\rangle$$

can be absorbed in a single weak-annihilation parameter

$$\tau_0 = 128\pi^2\,(T_1 - T_2) + 8\log\left(\frac{\mu_{\rm WA}^2}{m_c^2}\right)\rho_D^3.$$

- ρ_D^3 & τ_0 important inputs to predictions[2] of charmed hadron lifetimes

[1] JHEP 12 (2019) 067

[2] King, Lenz, Piscopo, Rauh, Rusov, Vlahos, JHEP 08 (2022) 241

Extracting the HQE parameters

- Normalized spectral moments for q^2, E_ℓ defined through integrals of allowed phase space ($\sim E_\ell > 200$ MeV), considering $n = 4$

$$\langle M^n \rangle \equiv \frac{\int (M)^n \frac{\mathrm{d}\Gamma}{\mathrm{d}M}\,\mathrm{d}M}{\int \frac{\mathrm{d}\Gamma}{\mathrm{d}M}\,\mathrm{d}M}$$

- Λ_c setup similar to D decays, but no contributions from ρ_{LS} and μ_G
- Exploratory study to estimate experimental precision
- Fix quark masses to $\overline{\mathrm{MS}}$ definitions from 2020 2+1+1 FLAG avgs.[1]

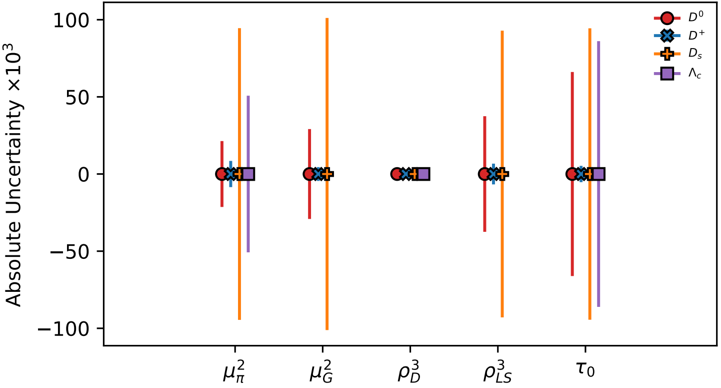
  $\overline{m}_s(2\ \mathrm{GeV}) = (93.44 \pm 0.68)\ \mathrm{MeV} \quad \overline{m}_c(\overline{m}_c) = (1.280 \pm 0.013)\ \mathrm{GeV}$

  and $\alpha_s(\overline{m}_c) = 0.386$ from RunDec[2] with $n_f = 3$
- Investigation of proper quark-mass definitions and other theory uncertainties for future work

[1] EPJC 80 (2020) 113

[2] Chetyrkin, Kuhn, Steinhauser, Comp. Phys. Comm. 133 (2000) 42

Expected experimental sensitivity to HQE Parameters



- Very strong prospects for first determinations of charm HQE parameters with current data and first HQE analysis of inclusive heavy baryon decays.
- Possibility for larger D_s^+ and Λ_c^+ datasets in near future

A new puzzle piece: Inclusive $|V_{cs}|$?

- As in the B system, we can use HQE parameters and measurements of inclusive branching fractions to determine $|V_{cs}|$
- With currently available data/inputs we estimate experimental precision of 3.3% from D^0/D^+ and 3.8% from D_s^+ on $|V_{cs}|$
  - In combination, $\sim 2\%$ experimental precision
  - Expected to improve with better measurements of D^0/D^+ exclusive branching fractions and more D_s^+ data
- Compare to $< \mathcal{O}(1\%)$ total precision from both $D \to K\ell\nu$ and $D_s^+ \to \ell\nu$,
  - Meaningful comparisons of $|V_{cs}|$ from inclusive SL, exclusive SL, and pure leptonic determinations
- Similar possibilities for comparisons on $|V_{cd}|$, subject to isolating $c \to d$ at BESIII

Summary

- Inclusive charm decays provide excellent opportunities for better-understanding the HQE and weak-annihilation effects in heavy hadrons
- Currently available BESIII data can be utilised to provide first measurements of HQE parameters in charm hadrons and first measurements of HQE parameters in heavy baryons
- Strong prospects for competitive inclusive determinations of $|V_{cs}|$, maybe also for $|V_{cd}|$
- Achieving the above requires further work and collaboration from both experiment and theory

BACKUPS

D^+ Systematics

	μ_π^2	μ_G^2	ρ_D^3	ρ_{LS}^3	τ_0
Full	8.49	4.47	0.30	6.72	5.28
Stat.	4.99	0.85	0.06	3.34	1.59
MC Stat.	3.14	1.42	0.07	2.00	2.71
$\epsilon_{\mathrm{track.}}$	2.28	2.91	0.20	3.56	1.07
$\sigma_{\mathrm{track.}}$	0.17	0.03	0.00	0.12	0.06
$\epsilon_{K_S^0}$	3.24	1.66	0.15	2.08	1.92
$\sigma_{K_S^0}$	0.07	0.06	0.00	0.05	0.04
ϵ_γ	1.53	0.93	0.04	0.95	0.94
σ_γ	0.51	0.25	0.04	0.28	1.10
PID	0.03	0.03	0.00	0.04	0.02
$\mathcal{B}(D^+ \to \eta' \ell \nu_\ell)$	0.40	0.07	0.02	0.52	1.05
$\mathcal{B}(D^+ \to \eta \ell \nu_\ell)$	1.40	0.32	0.05	1.39	2.17
$\mathcal{B}(D^+ \to K^{*-} \ell \nu_\ell)$	2.63	0.61	0.04	1.68	0.49
$\mathcal{B}(D^+ \to K^- \ell \nu_\ell)$	2.18	0.86	0.06	2.24	0.47
$\mathcal{B}(D^+ \to \omega \ell \nu_\ell)$	0.60	0.89	0.08	0.16	0.93
$\mathcal{B}(D^+ \to \pi^- \ell \nu_\ell)$	1.60	1.28	0.04	0.52	2.34
$\mathcal{B}(D^+ \to \rho^- \ell \nu_\ell)$	0.95	1.05	0.06	1.33	0.65
$\mathcal{B}(D^+ \to (K\pi)_{S-\mathrm{wave}} \ell \nu_\ell)$	4.11	1.75	0.04	1.47	1.32

D_s^+ Systematics

	μ_π^2	μ_G^2	ρ_D^3	ρ_{LS}^3	τ_0
Full	94.54	101.15	3.05	92.91	94.44
Stat.	34.58	9.63	0.64	28.61	18.03
MC Stat.	25.55	25.78	1.06	21.32	15.39
$\epsilon_{\text{track.}}$	22.50	28.12	0.96	27.57	21.09
$\sigma_{\text{track.}}$	8.43	10.08	0.53	5.64	4.20
$\epsilon_{K_S^0}$	7.98	6.90	0.22	6.68	12.05
$\sigma_{K_S^0}$	8.56	10.05	0.52	5.69	4.22
ϵ_γ	7.90	4.28	0.24	11.25	2.37
σ_γ	10.19	7.87	0.56	8.82	7.07
PID	8.56	10.03	0.52	5.68	4.21
$\mathcal{B}(D_s \to \eta' \ell \nu_\ell)$	54.18	9.78	0.21	27.81	10.61
$\mathcal{B}(D_s \to \eta \ell \nu_\ell)$	33.33	90.26	2.34	60.96	86.46
$\mathcal{B}(D_s \to f_0 \ell \nu_\ell)$	14.43	3.31	0.16	8.57	3.12
$\mathcal{B}(D_s \to K^{*-} \ell \nu_\ell)$	30.21	21.02	0.96	30.77	5.91
$\mathcal{B}(D_s \to K^- \ell \nu_\ell)$	34.83	12.75	0.21	26.67	15.53
$\mathcal{B}(D_s \to \phi \ell \nu_\ell)$	33.44	19.63	0.22	36.21	23.75