

BESIII Status Quo & Prospects

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23/09/2025

More than a Lifetime

Siegen, Germany



Outline

Status Quo

Prospects

Outline

Status Quo

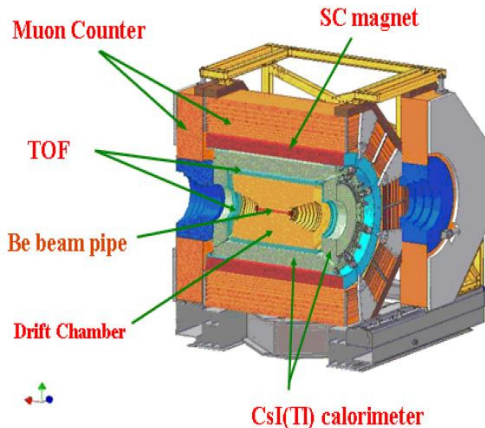
Prospects

Beijing Electron-Positron Collider Mk. II (BEPCII)

- ▶ Symmetric e^+e^- collider
- ▶ Diameter of storage rings: ~ 75 m
- ▶ E_{CM} : 2 – 5 GeV



Beijing Electron Spectrometer III (BESIII)



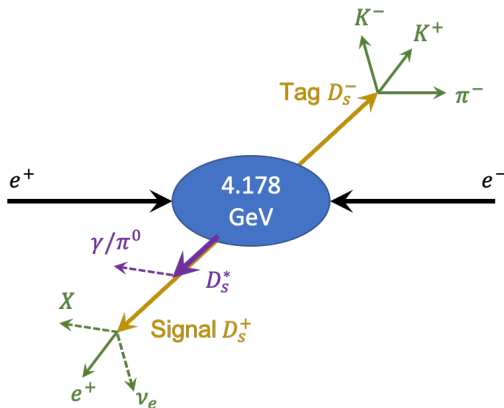
- ▶ Hermiticity: 93% of 4π
- ▶ Drift Chamber: $\sigma_p/p = 0.5\%$ at 1 GeV
- ▶ Time-of-Flight: $\sigma = 80$ ps
- ▶ EMC: $\sigma_E/E : 2.5\%$ at 1 GeV
- ▶ Superconducting Solenoid: 1T
- ▶ MUC: 9 layer RPC Muon System
- ▶ **N.B.:**
 - ▶ Momentum of final state particles in the lab frame: 50 – 1500 MeV/c
 - ▶ $\sim 100\%$ trigger efficiency
 - ▶ Excellent e^+ ID, muons more challenging!
 - ▶ Low boost $\Rightarrow$ (almost) no displaced vertices
[Exceptions: $K_S^0 \rightarrow \pi\pi$ and $\Lambda \rightarrow p\pi$]

What can BESIII say about lifetimes?

- ▶ Not much...

What can BESIII say about lifetimes?

- ▶ Not much... **directly**
- ▶ BESIII pair-produces open-charm hadrons
 - ▶ Unique opportunity to measure **inclusive charm branching fractions**

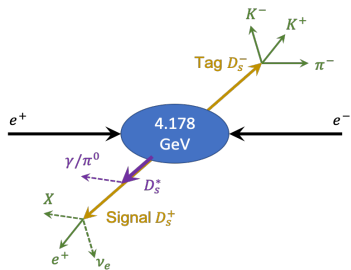


The (not as) Heavy Quark Expansion



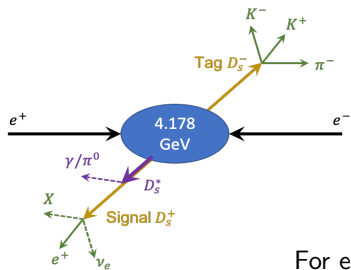
- ▶ Heavy-Quark Expansion (HQE) expands in $\frac{\Lambda_{QCD}}{m_q}$
- ▶ Since $m_c < m_b$, converges more slowly for charm than beauty, but more sensitive to hadronic matrix elements
- ▶ Inclusive semileptonic charm decays provide complementary analysis using the HQE and unique sensitivity to intrahadronic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

Inclusive SL Charm Decays: Status Quo



$$\mathcal{B}(D \rightarrow X e^+ \nu_e) = \frac{n_{\text{DT}}/\epsilon_{\text{DT}}}{n_{\text{ST}}/\epsilon_{\text{ST}}} = \frac{n_{\text{DT}}/\epsilon_{\text{Sig.}}}{n_{\text{ST}} \frac{\epsilon_{\text{ST}}^{\text{Sig.}}}{\epsilon_{\text{ST}}}}$$

Inclusive SL Charm Decays: Status Quo

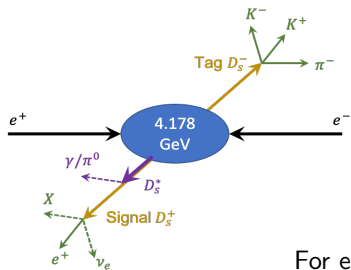


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For each momentum bin p_i ,

$$\begin{bmatrix} n_{\text{Obs.}}^e \\ n_{\text{Obs.}}^\pi \\ n_{\text{Obs.}}^K \end{bmatrix}$$

Inclusive SL Charm Decays: Status Quo

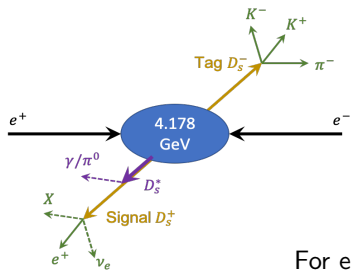


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For each momentum bin p_i ,

$$\begin{bmatrix} n_{\text{Trk.}}^e \\ n_{\text{Trk.}}^\pi \\ n_{\text{Trk.}}^K \end{bmatrix} = A_{\text{PID}}^{-1} \begin{bmatrix} n_{\text{Obs.}}^e \\ n_{\text{Obs.}}^\pi \\ n_{\text{Obs.}}^K \end{bmatrix} \quad A_{\text{PID}} = \begin{bmatrix} \epsilon_e & P_{\pi \rightarrow e} & P_{K \rightarrow e} \\ P_{e \rightarrow \pi} & \epsilon_\pi & P_{K \rightarrow \pi} \\ P_{e \rightarrow K} & P_{\pi \rightarrow K} & \epsilon_K \end{bmatrix}$$

Inclusive SL Charm Decays: Status Quo



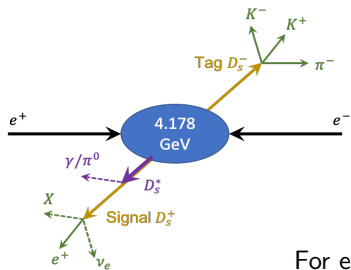
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$$\frac{n_{\text{DT}}}{\epsilon_{\text{Sig.}}}(p_j) = A_{\text{Trk.}}^{-1} n_{\text{Trk.}}^e(p_i)$$

Inclusive SL Charm Decays: Status Quo



$$\mathcal{B}(D \rightarrow X e^+ \nu_e) = \frac{n_{\text{DT}}/\epsilon_{\text{DT}}}{n_{\text{ST}}/\epsilon_{\text{ST}}} = \frac{n_{\text{DT}}/\epsilon_{\text{Sig.}}}{n_{\text{ST}} \frac{\epsilon_{\text{ST}}}{\epsilon_{\text{ST}}}}$$

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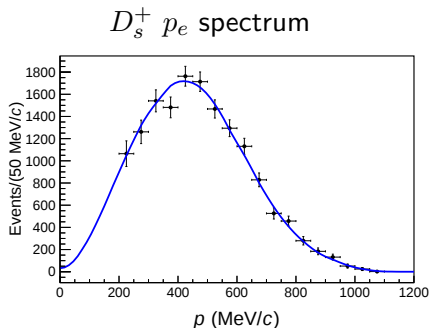
$$\frac{n_{\text{DT}}}{\epsilon_{\text{Sig.}}}(p_j) = A_{\text{Trk.}}^{-1} n_{\text{Trk.}}^e(p_i)$$

Note: Procedure also measures (not typically reported)

$$n(D \rightarrow K^- X), n(D \rightarrow K^+ X), n(D \rightarrow \pi^- X), n(D \rightarrow \pi^+ X)$$

Inclusive SL Charm decays: Published 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^+
- ▶ Measured decay widths indicate breakdown of factorisation



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

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

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

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

Inclusive SL Charm decays: Previous Theoretical Work

- ▶ Measured D^0 , D^+ and D_s^+ momentum spectra from CLEO analysed to constrain effects of weak-annihilation in SL B decay rates
 - ▶ Estimated upper limits of 2% from Gambino & Kamenik¹ and 1% from Ligeti, Luke, & Manohar²
- ▶ Study of HQE in charm and it's potential application for determination of $|V_{cs}|$ and $|V_{cd}|$ from Fael, Mannel, Vos³
- ▶ Study of Γ & Γ_{SL} of charmed hadrons from King *et al.*⁴
- ▶ Analysis of p_e to estimate $\alpha_s(m_c)$ from Wu *et al.*⁵

¹ Nucl. Phys. B 840 (2010) 424

² PRD 82 (2010) 033003

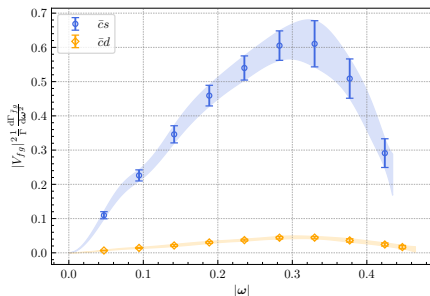
³ M. Fael, T. Mannel, K.K. Vos JHEP 12 (2019) 067

⁴ D. King, A. Lenz, M.L. Piscopo, T. Rauh, A.V. Rusov, C. Vlahos, JHEP 08 (2022) 241

⁵ J.F. Wu, X.C. Lou, Y.Z. Che, G. Li, Y.P. Huang, M.Q. Ruan, J.B. Ye, CPC 49 (2025) 023001

Inclusive SL Charm decays: Recent Theory Highlights

Inclusive D_s^+ on the Lattice



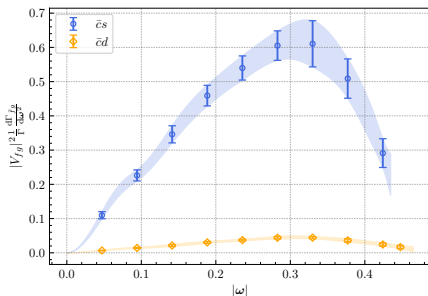
$$|V_{cs}| = 0.951(35)$$

A. De Santis et al., PRD 112 (2025), 054503

A. De Santis et al., PRL 135 (2025), 1219013

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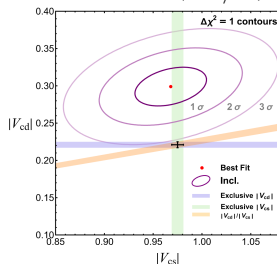
Charm HQET

Determination of Charm HQE

Parameters:

K. K. Shao et al., arXiv:2502.0591

Extraction of $|V_{cs}/cd|$



K. K. Shao et al., arXiv:2509.11404

Inclusive Hadronic Charm decays: Status Quo

- ▶ With a similar procedure can measure hadronic decays inclusively:
 - ▶ $D^{0/+} \rightarrow K_S^0 + X$: PRD 107 (2023) 112005
 - ▶ $\Lambda_c^+ \rightarrow K_S^0 + X$: arXiv:2502.20821
 - ▶ $\Lambda_c^+ \rightarrow \Lambda + X$: In Progress
 - ▶ $\Lambda_c^+ \rightarrow n + X$: PRD 108 (2023), L031101
 - ▶ $D^{0/+} \rightarrow \pi^+ \pi^+ \pi^- + X$: PRD 107 (2023) 032002
 - ▶ $D_s^+ \rightarrow \pi^+ \pi^+ \pi^- + X$: PRD 108 (2023) 032001
- ▶ With $D \rightarrow K^- + X$, could measure almost all of $D \rightarrow K + X$ transitions (not much hope for $D \rightarrow K_L^0 + X$)

Outline

Status Quo

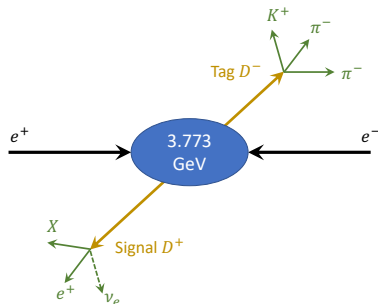
Prospects

Including more inclusive charm

- ▶ Limitations of previous $D \rightarrow X\ell\nu$ measurements:
 - ▶ No information on final-state hadronic system X
 $\Rightarrow$ No access to q^2 or M_X
 - ▶ Due to lack of information on X , cannot separate $c \rightarrow s$ and $c \rightarrow d$ transitions and $\left(\frac{|V_{cd}|}{|V_{cs}|}\right)^2 \sim 5\%$ not small
- ▶ 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
- ▶ I summarise a new technique¹ for studying inclusive charm decays and associated prospects with BESIII data

¹F. Bernlochner, AG, S. Malde, M. Prim, K. K. Vos, G. Wilkinson, JHEP05(2025)061

Overview of Proposed Measurement Technique



- Double-tag technique with golden D tag modes:

$$D^0 \rightarrow K^- \pi^+,$$

$$D^+ \rightarrow K^- \pi^+ \pi^+,$$

$$D_s^+ \rightarrow K^- K^+ \pi^+ (etc.),$$

$$\Lambda_c^+ \rightarrow p K^- \pi^+ (etc.)$$

- Identify charged lepton
- Reconstruct hadronic system X from additional
 - $K_S^0 \rightarrow \pi^+ \pi^-$, $\Lambda \rightarrow p \pi^-$ 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, BelleII¹

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

Assumed 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. [fb^{-1}]	21	21	7.1	4.5
Estimated DT Yields	200000	700000	30000	4300

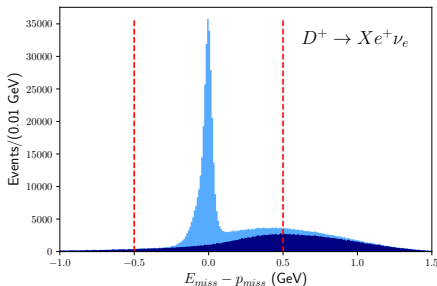
- ▶ Large D^0 , D^+ datasets recently collected, $\sim 7\times$ the previous BESIII dataset, $\sim 30\times$ the CLEO dataset
- ▶ D_s^+ data collected through $D_s^{*+} D_s^-$ due to higher constructions
 - ▶ $D_s^{*+} \rightarrow \gamma D_s^+$ decay must be reconstructed for full-event kinematic information, i.e. q^2
- ▶ Since our publication, BESIII has collected 20.3 fb^{-1} @ 3.773 GeV , and plans for a $\sim 15 \text{ fb}^{-1}$ Λ_c^+ sample

Measured D^+ distributions from Fast Simulation

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

Total Distribution

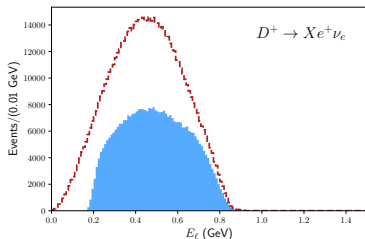
$K_L^0, K_S^0 \rightarrow \pi^0 \pi^0$



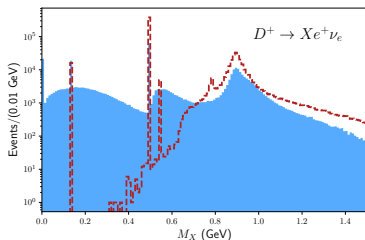
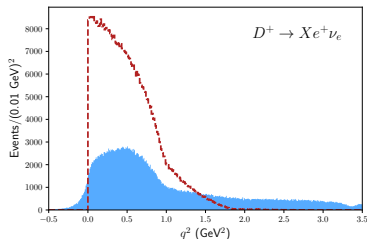
- Additionally require $|E_{\text{miss}} - p_{\text{miss}}| < 500$ MeV to remove poorly reconstructed events (primarily due to K_L^0 and $K_S^0 \rightarrow \pi^0 \pi^0$)

Measured D^+ distributions from Fast Simulation

Generated Distribution



Measured Distribution

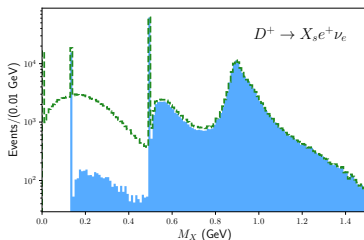


- ▶ BESIII $e^\pm$ ID imposes $E_\ell > 200$ MeV
- ▶ Discontinuous M_X distribution due to $D \rightarrow K e \nu / D \rightarrow \pi e \nu$

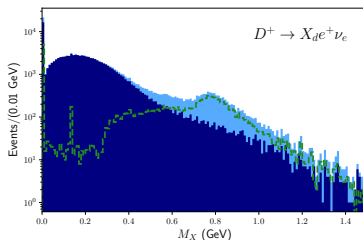
Prospects for isolating $c \rightarrow s$ and $c \rightarrow d$ transitions

- ▶ $K^\pm$ identification and K_S^0/Λ reconstruction allows us to determine strangeness of hadronic system X
- ▶ Corrections required due to K_L^0 , $K_S^0 \rightarrow \pi^0\pi^0$.

$D^+, c \rightarrow s$



$D^+, c \rightarrow d$



Truth

Measured, correct

Measured, incorrect

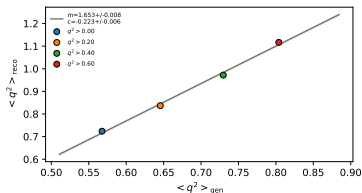
- ▶ $K_S^0 \rightarrow \pi^+\pi^+$ identification could be used to control misidentified strangeness due to K_L^0

Corrections on measured moments

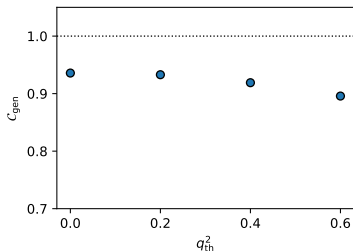
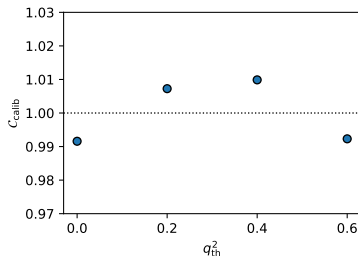
- Linear calibration for resolution :

$$q_{\text{cal}}^{2n} = (q_{\text{reco}}^{2n} - c_n) / m_n$$

(same for E_{ℓ}^n)



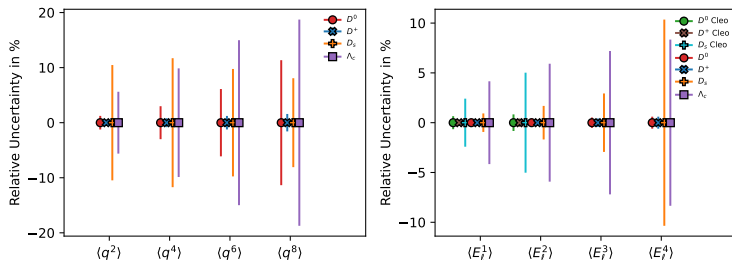
- Corrections for non-linearity (C_{calib}) and selection/acceptance (C_{gen})



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

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 & Kamenik¹ analysis of E_ℓ moments from CLEO-c measurements



¹Nucl. Phys. B 840 (2010) 424

Setting up the HQE in Charm

- ▶ Following work of Fael, Mannel, & Vos¹, expand $c \rightarrow s$ 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

$$2m_D T_1(\mu_{WA}) \equiv \langle D | (\bar{c}_v \not{P}_L s) (\bar{s} \not{P}_L c_v) | D \rangle$$

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

can be absorbed in a single weak-annihilation parameter

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

- ▶ ρ_D^3 & τ_0 important inputs to predictions² 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 $n = 4$

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

- ▶ 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 $\overline{MS}$ definitions from 2020 2+1+1 FLAG avgs.¹

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

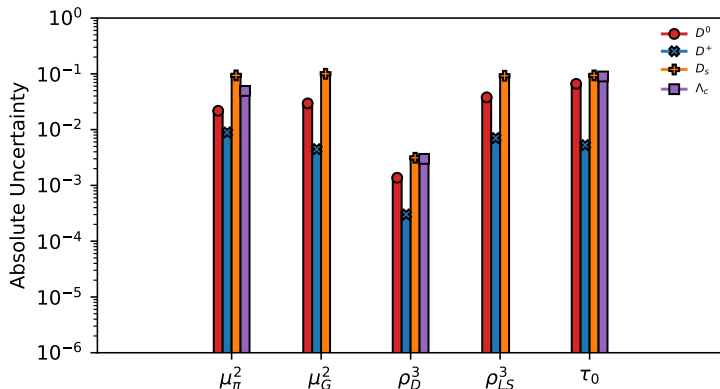
and $\alpha_s(\overline{m}_c) = 0.386$ from RunDec² with $n_f = 3$

- ▶ Investigation of proper quark-mass definitions and other theory uncertainties for future work

¹EPJC 80 (2020) 113

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

Expected experimental sensitivity to HQE Parameters



- ▶ Very strong prospects for charm HQE parameters and first HQE analysis of inclusive heavy baryon decays.
- ▶ Plan for larger Λ_c^+ datasets in near future and possibility for larger D_s^+ datasets

A possible timeline

► 1-2 years:

- Updated measurements of $\mathcal{B}(D^0 \rightarrow Xe^+\nu)$ and $\mathcal{B}(D^+ \rightarrow Xe^+\nu)$ and p_e spectra using previously established technique
- New measurements of $\mathcal{B}(D^{0/+} \rightarrow X\mu^+\nu)$, $\mathcal{B}(D_s^+ \rightarrow X\mu^+\nu)$, $\mathcal{B}(\Lambda_c^+ \rightarrow X\mu^+\nu)$ and p_μ spectra using previously established technique

► 3-5 years:

- New measurements of $D^{0/+} q^2$ moments and $\mathcal{B}(D^{0/+} \rightarrow X_s e^+\nu)$, with other channels to follow

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 precision measurements of HQE parameters in charm hadrons and first measurements of HQE parameters in heavy baryons
- ▶ 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
$\epsilon_{\text{track.}}$	2.28	2.91	0.20	3.56	1.07
$\sigma_{\text{track.}}$	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
$\mathcal{B}(D^+ \rightarrow \eta' \ell \nu_\ell)$	0.40	0.07	0.02	0.52	1.05
$\mathcal{B}(D^+ \rightarrow \eta \ell \nu_\ell)$	1.40	0.32	0.05	1.39	2.17
$\mathcal{B}(D^+ \rightarrow K^{*-} \ell \nu_\ell)$	2.63	0.61	0.04	1.68	0.49
$\mathcal{B}(D^+ \rightarrow K^- \ell \nu_\ell)$	2.18	0.86	0.06	2.24	0.47
$\mathcal{B}(D^+ \rightarrow \omega \ell \nu_\ell)$	0.60	0.89	0.08	0.16	0.93
$\mathcal{B}(D^+ \rightarrow \pi^- \ell \nu_\ell)$	1.60	1.28	0.04	0.52	2.34
$\mathcal{B}(D^+ \rightarrow \rho^- \ell \nu_\ell)$	0.95	1.05	0.06	1.33	0.65
$\mathcal{B}(D^+ \rightarrow (K\pi)_{S\text{-wave}} \ell \nu_\ell)$	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
$\mathcal{B}(D_s \rightarrow \eta' \ell \nu_\ell)$	54.18	9.78	0.21	27.81	10.61
$\mathcal{B}(D_s \rightarrow \eta \ell \nu_\ell)$	33.33	90.26	2.34	60.96	86.46
$\mathcal{B}(D_s \rightarrow f_0 \ell \nu_\ell)$	14.43	3.31	0.16	8.57	3.12
$\mathcal{B}(D_s \rightarrow K^{*-} \ell \nu_\ell)$	30.21	21.02	0.96	30.77	5.91
$\mathcal{B}(D_s \rightarrow K^- \ell \nu_\ell)$	34.83	12.75	0.21	26.67	15.53
$\mathcal{B}(D_s \rightarrow \phi \ell \nu_\ell)$	33.44	19.63	0.22	36.21	23.75