Leptonic and Semileptonic Decays of Charmed Hadrons

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University of Warwick Particle Physics Seminar

Outline

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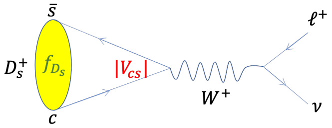
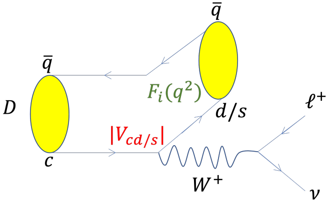
Heavy Quarks and Open-Flavour Hadrons

- Weak interactions of quarks are the only SM processes that allow for changes of flavour and generation
- Probability of an up-type quark transitioning to a down-type quark governed by elements of the 3×3 unitary Cabibbo-Kobayashi-Maskawa (CKM) Matrix
- Hadrons containing a heavy quark ($m_q \gg \Lambda_{\text{QCD}}$) and other-flavoured quarks have minimal strong interactions between constituents
- Open-flavoured mesons $Q\overline{q}$ provide (relatively) simple testing bed for strong and weak phsyics – light quarks q "spectate" decays of heavy quark Q

What can we learn from (semi)leptonic decays?





$\Gamma\left(D_s^+ \to \ell^+\nu\right) \propto f_{D_s}^2 |V_{cs}|^2$ $\frac{d\Gamma}{dq^2} \propto \sum_i F_i(q^2)|V_{cd/s}|^2$, $q^2 \equiv \ell^+\nu$ 4-mom.

- Charmed hadrons provide a rigorous testing ground for our understanding of heavy-quark physics and provide:
  - Test Electroweak theory: e.g. unitarity of CKM Matrix with $|V_{cd}|$ and $|V_{cs}|$
  - OR Test QCD predictions of f_{D_s} and $F_i(q^2)$

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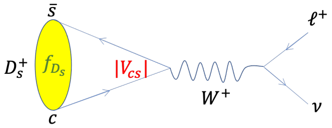

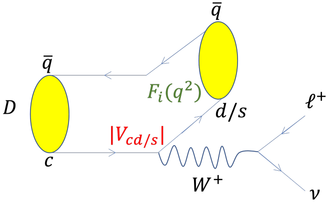

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  - Test lepton universality in the charm sector

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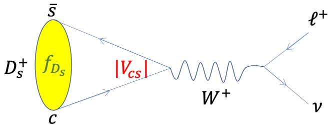

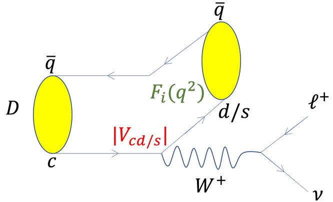

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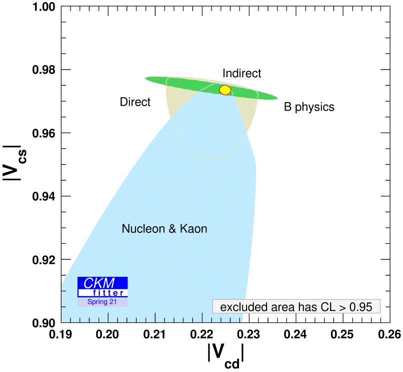
  - Test lepton universality in the charm sector
  - Semileptonic decays provide laboratory for light meson physics

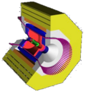
CKM Unitarity from Open Charm as of 2021

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97435(5) & 0.2250(2) & 3.67(9)\times 10^{-3} \\ 0.2249(2) & 0.97352(6) & 41.5(5)\times 10^{-3} \\ 8.52(7)\times 10^{-3} & 40.7(5)\times 10^{-3} & 0.99914(2) \end{bmatrix}$$



Experiments that contribute to SL Charm Measurements

CLEO-c



BABAR

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BESIII

Belle, Belle II

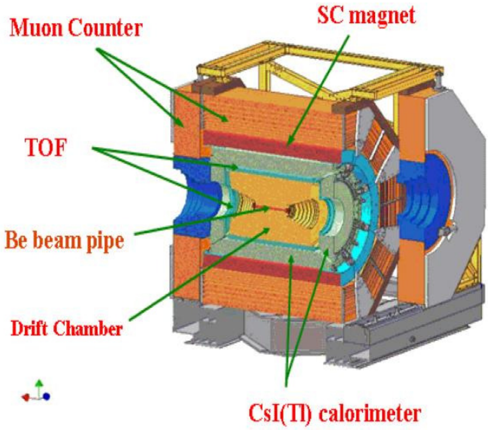
- Symmetric e^+e^-
- $\sqrt{s}$: $2.0 - 5.0$ GeV
- Charm collected through pair-production near threshold

- Asymmetric e^+e^-
- $\sqrt{s}$: 10.8 GeV
- Charm collected through $b\bar{b}$ decays and $c\bar{c}$

Beijing Electron-Positron Collider II (BEPCII)

- Diameter of storage rings: $\sim$ 75 m

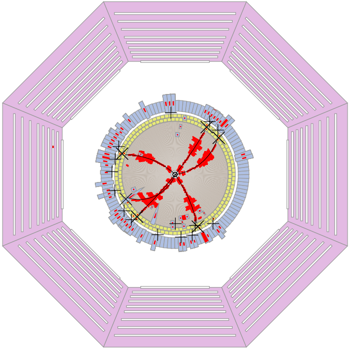
Beijing Electron Spectrometer III (BESIII)



- Hermiticity: 93% of 4π
- MDC: $\sigma_p/p = 0.5\%$ at 1 GeV
- ToF: $\sigma = 80$ ps
- EMC: $\sigma_E/E : 2.5\%$ at 1 GeV
- Superconducting Solenoid: 1T
- 9 layer RPC Muon System
- Some notable differences with a typical LHC experiment:
  - 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

Event Reconstruction

- Particles with long enough lifetimes for BESIII to directly detect:
  - Charged: $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p
  - Neutral: γ, n, K_L^0
  - Displaced: K_S^0, Λ



Simulated $D_s^{*+} D_s^-$ event

Datasets

- CLEO-c: Data collected until 2008
  - $D^{+(0)}$ 0.82 fb^{-1} @ $E_{cm} = 3.77$ GeV.
  - D_s^+ 0.57 fb^{-1} @ $E_{cm} = 4.170$ GeV.
- BESIII
  - $D^{+(0)}$ 2.93 fb^{-1} @ $E_{cm} = 3.773$ GeV. Collected in 2011
  - D_s^+ 6.32 fb^{-1} @ $E_{cm} = 4.178 - 4.230$ GeV. Collected in 2013-2017
  - D_s^+ collected through $D_s^{*+} D_s^-$, $D_s^{*+} \to \gamma/\pi^0 D_s^+$ due to higher $\sigma\left(e^+ e^- \to D_s^{*+} D_s^-\right)$
- BABAR: Data collected until 2008
  - ~ 0.5 ab^{-1} near $\Upsilon(4S)$
- Belle: Data collected until 2010
  - ~ 1 ab^{-1} near $\Upsilon(4S)$

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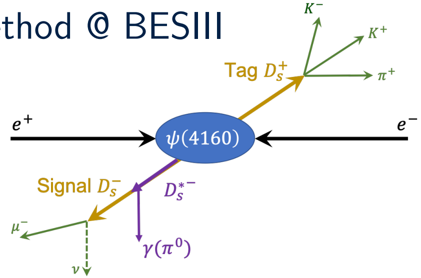
Tests of Lepton Universality

Insight into Light Hadrons

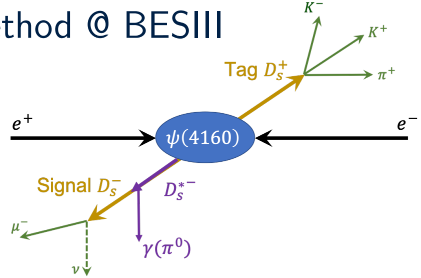
Outlook & Conclusions

Double Tag Method @ BESIII



- Reconstruct D_s^+ through clean decay mode (the tag)

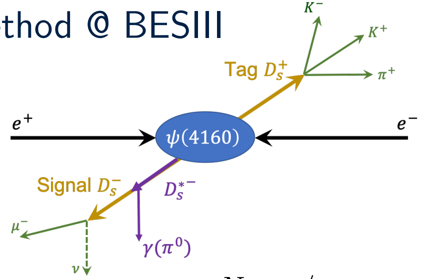
Double Tag Method @ BESIII



- Reconstruct D_s^+ through clean decay mode (the tag)
- Search for signal process of the D_s^- and determine N_{Signal} with

$$M^2_{\text{miss}} \text{ or } U_{\text{miss}} \equiv E_{\text{miss}} - p_{\text{miss}}$$

Double Tag Method @ BESIII



$$\mathcal{B}(D_s \to \text{signal}) = \frac{N_{\text{Signal}}/\epsilon_{\text{Tag \& Signal}}}{N_{\text{Tag}}/\epsilon_{\text{Tag}}}$$

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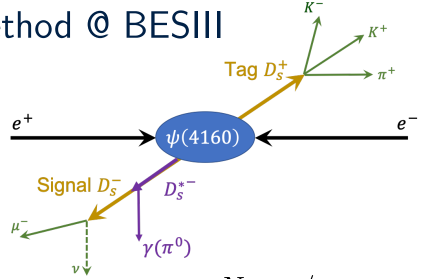
Double Tag Method @ BESIII



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- Search for signal process of the D_s^- and determine N_{Signal} with

$$M^2_{\text{miss}} \text{ or } U_{\text{miss}} \equiv E_{\text{miss}} - p_{\text{miss}}$$

- Advantages: Don't need to know $N_{D\overline{D}}$, removes large component of backgrounds, allows access to recoil variables

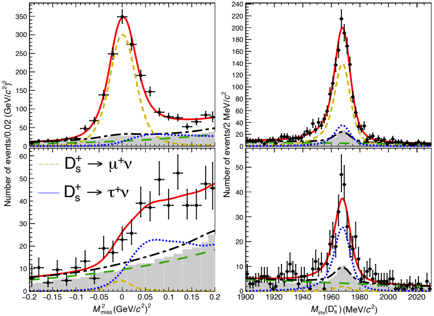
$D_s^+ \to \ell\nu_\tau$

- Using BESIII data @ $E_{CM} = 4.178 - 4.226$ GeV
- Double tag with 13 D_s^+ tag modes
- Allow 1 charged track in addition to tag
- Event is fully reconstructed including γ from D_s^*
- Separate π^+/μ^+ sample by energy deposit
- τ^+ identified through $\pi^+\nu$ decay

$$\mathcal{B}\left(D_s^+ \to \tau^+\nu\right) = (5.21 \pm 0.25 \pm 0.17)\,\%$$
$$\mathcal{B}\left(D_s^+ \to \mu^+\nu\right) = (5.21 \pm 0.13 \pm 0.16) \times 10^{-3}$$

Most precise determination to date

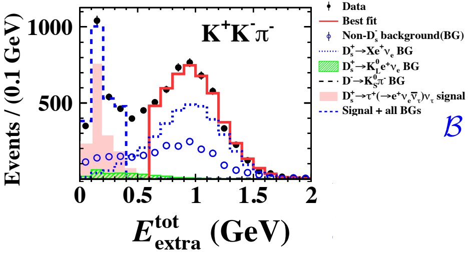
PRD 104(2021)052009



$D_s^+ \to \tau_{e\nu\nu}^+ \nu_\tau$

- Using data @ $E_{CM} = 4.178 - 4.226$ GeV
- Double tag with 11 D_s^+ tag modes
- Event is fully reconstructed EXCEPT γ/π^0 from D_s^* decay
- Yields determined from fits to sum of extra energy in the calorimeter

PRL127(2021)171801



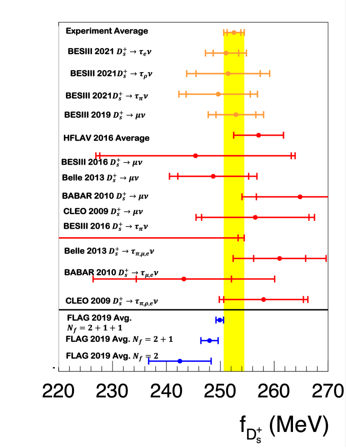
$\mathcal{B}\left(D_s^+ \to \tau^+\nu\right) = (5.21 \pm 0.10 \pm 0.12)\,\%$

Most precise determination of f_{D_s}

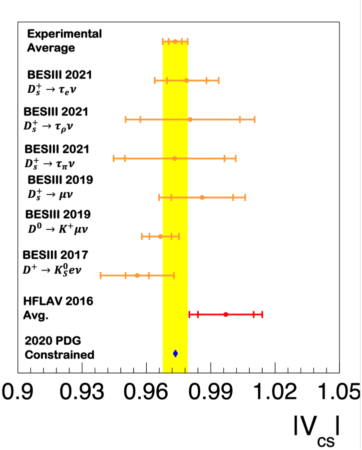
Close third for $|V_{cs}|$ after $D^0 \to K^- e^+/\mu^+\nu$

Status of f_{D_s} and $|V_{cs}|$

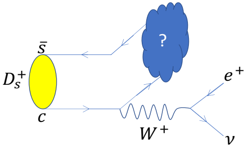
Inputs:
$|V_{cs}|$ from 2021 CKMFitter



Inputs:
f_{D_s} from 2019 FLAG $N_f = 2+1+1$
$f^{D\to K}$ from PRD104(2021)034505



Motivations for studying inclusive $D_s^+ \to X e^+ \nu_e$



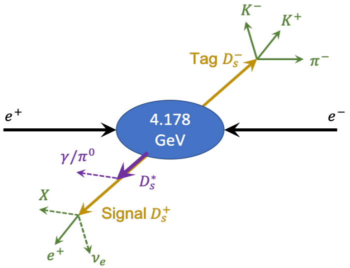
- Constrain branching fractions for unobserved decay modes
- $\frac{\Gamma(D_s)}{\Gamma(D^0)} = 0.813 \pm .007$ shows significant deviation from spectator model predictions[a], since $D^0 = c\overline{u}$ and $D_s^+ = c\overline{s}$
- Standard Model predictions[b] range from $\frac{\Gamma(D_s^+ \to X e^+ \nu_e)}{\Gamma(D^0 \to X e^+ \nu_e)} = 0.813 - 0.886$
- Positron momentum spectrum from $D_s^+ \to X e^+ \nu$ constrains effects of non-spectator effects[c] in determination of $|V_{c(u)b}|$ from $B \to X_{c(u)} e\nu$, which are in long-standing tension with exclusive determinations of $|V_{c(u)b}|$

[a] M.B. Voloshin, Phys. Lett B 515 (2001) 74-80

[b] M. Gronau and J. Rosner, Phys. Rev. D **83**, 034025 (2011) D. King, A. Lenz, M.L. Piscopo, T. Rauh, A.V. Rusov, C. Vlahos, arxiv:2109.13219 (2021)

[c] I.I. Bigi and N.G. Uraltsev, Z.Phys. C62 (1994) 623-632. Z. Ligeti, M. Luke, and A.V. Manohar, Phys. Rev. D 82, 033003 (2010).

Analysis of $D_s^+ \to X e^+ \nu_e$



$$\mathcal{B}\left(D_s^+ \to X e^+ \nu_e\right) = \frac{n_{\mathsf{DT}}/\epsilon_{\mathsf{DT}}}{n_{\mathsf{ST}}/\epsilon_{\mathsf{ST}}} = \frac{n_{\mathsf{DT}}/\epsilon_{\mathsf{Sig.}}}{n_{\mathsf{ST}}\frac{\epsilon_{\mathsf{ST}}^{\mathsf{Sig.}}}{\epsilon_{\mathsf{ST}}}}$$

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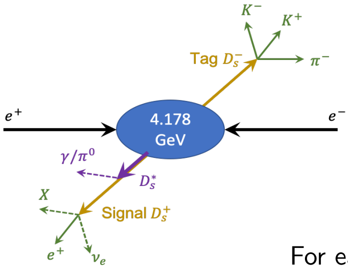

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For each momentum bin p_i,

$$\begin{bmatrix} n^e_{\mathsf{Obs.}} \\ n^\pi_{\mathsf{Obs.}} \\ n^K_{\mathsf{Obs.}} \end{bmatrix}$$

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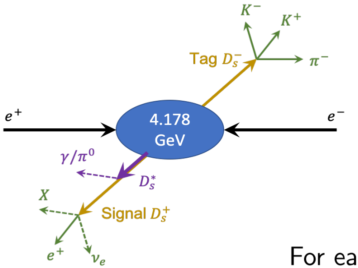

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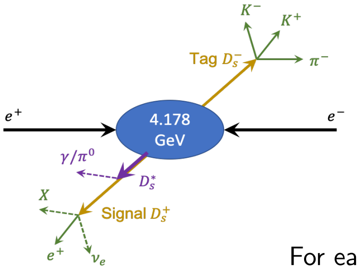
For each momentum bin p_i,

$$\begin{bmatrix} n^e_{\mathsf{Trk.}} \\ n^\pi_{\mathsf{Trk.}} \\ n^K_{\mathsf{Trk.}} \end{bmatrix} = A^{-1}_{\mathsf{PID}} \begin{bmatrix} n^e_{\mathsf{Obs.}} \\ n^\pi_{\mathsf{Obs.}} \\ n^K_{\mathsf{Obs.}} \end{bmatrix} \qquad A_{\mathsf{PID}} = \begin{bmatrix} \epsilon_e & \mathsf{P}_{\pi\to e} & \mathsf{P}_{K\to e} \\ \mathsf{P}_{e\to\pi} & \epsilon_\pi & \mathsf{P}_{K\to\pi} \\ \mathsf{P}_{e\to K} & \mathsf{P}_{\pi\to K} & \epsilon_K \end{bmatrix}$$

Analysis of $D_s^+ \to X e^+ \nu_e$



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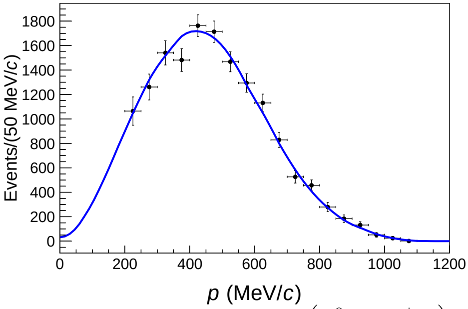
$$\frac{n_{\text{DT}}}{\epsilon_{\text{Sig.}}}(p_j) = A^{-1}_{\text{Trk.}} n^e_{\text{Trk.}}(p_i)$$

Analysis of $D_s^+ \to X e^+ \nu_e$

To account for electrons with $p < 200$ MeV$/c$, we produce a shape for the momentum spectrum $g(p)$ from the exclusive modes

$$g(p) = \sum_{X_i} w_i g_i(p) \quad X_i \in \{\phi, \eta, \eta', K^0, K^{*0}, f_0\}$$



With $\mathcal{B}\left(D^0 \to X e^+ \nu_e\right)$, τ_{D^0} and τ_{D^s}

$$\mathcal{B}\left(D_s^+ \to X e^+ \nu_e\right) = 6.30(13)(10)\%$$

$$\frac{\Gamma\left(D_s^+ \to X e^+ \nu_e\right)}{\Gamma\left(D^0 \to X e^+ \nu_e\right)} = 0.790(16)(11)(16)$$

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Lepton Flavour Universality

- Possible hints of LFU violation in the beauty sector:

$$\frac{\mathcal{B}_{B\to D^{(*)}\tau\nu}}{\mathcal{B}_{B\to D^{(*)}\ell\nu}}, \frac{\mathcal{B}_{B\to K^{(*)}\mu^+\mu^-}}{\mathcal{B}_{B\to K^{(*)}e^+e^-}} + \text{ angular observables...}$$

- If results persist, precision tests of LFU in charm decays will be essential in understanding the nature of these anomalies[a]
- SM Ratios of pure leptonic decays require no input from theory

$$R_L = m_\ell^2\left(1-\frac{m_\ell^2}{m_{D_{(s)}}^2}\right)^2 \Big/ m_{\ell'}^2\left(1-\frac{m_{\ell'}^2}{m_{D_{(s)}}^2}\right)^2$$

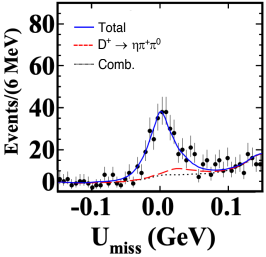
- SM Ratios of semileptonic decays are $\mathcal{O}(1)$, but require form factor-dependendent phase-space corrections

[a] Fafjer, Nišandžić, and Rojec PRD 91 (2015) 094009

▶ $D^+ \to \eta\mu^+\nu$

- Using BESIII data @ $E_{CM} = 3.773$ GeV
- Double tag with 6 D^+ tag modes
- Peaking Background: $D^0 \to \eta\pi^+\pi^0$

PRL124(2020)231801



$$\frac{\mathcal{B}\left(D^+ \to \eta\mu^+\nu\right)}{\mathcal{B}\left(D^+ \to \eta e^+\nu\right)} = 0.91 \pm 0.13$$

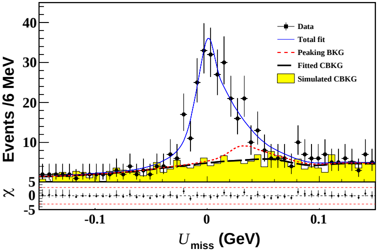
with PDG2020 Average of $\mathcal{B}(D^+ \to \eta e^+\nu)$

SM Pred[a]: 0.97-1.00

▶ $D^+ \to \omega\mu^+\nu$

- Using BESIII data @ $E_{CM} = 3.773$ GeV
- Double tag with 6 D^+tag modes
- Peaking Background: $D^0 \to \omega\pi^+\pi^0$

PRD101(2020)072005



$$\frac{\mathcal{B}\left(D^+ \to \omega\mu^+\nu\right)}{\mathcal{B}\left(D^+ \to \omega e^+\nu\right)} = 1.05 \pm 0.14$$

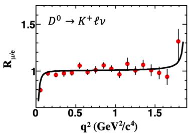
with PDG2020 Average of $\mathcal{B}(D^+ \to \omega e^+\nu)$

SM Pred[a]: 0.93-0.99

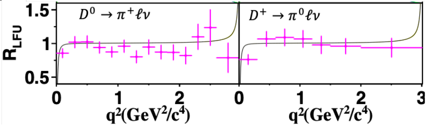
[a] See appendix for citations.

Charm LFU Overview

Mode	Measured $\mathcal{B}(\ell)/\mathcal{B}(\ell')$	SM Prediction
$D^+ \to \frac{\tau}{\mu}\nu$	3.21 ± 0.77	2.66
$D_s^+ \to \frac{\tau}{\mu}\nu$	9.72 ± 0.37	9.75
$D^0 \to \rho^- \frac{\mu}{e}\nu$	0.90 ± 0.11	$0.93 - 0.96$
$D^+ \to \eta \frac{\mu}{e}\nu$	0.91 ± 0.13	$0.97 - 1.00$
$D^+ \to \omega \frac{\mu}{e}\nu$	1.05 ± 0.14	$0.93 - 0.99$
$D^+ \to \pi^0 \frac{\mu}{e}\nu$	0.964 ± 0.045	~ 0.985
$D^0 \to \pi^+ \frac{\mu}{e}\nu$	0.922 ± 0.037	~ 0.985
$D^0 \to K^+ \frac{\mu}{e}\nu$	0.974 ± 0.014	~ 0.970
$\Lambda_c^+ \to \Lambda \frac{\mu}{e}\nu$	0.96 ± 0.16	~ 1
$\Xi_c^0 \to \Xi^- \frac{\mu}{e}\nu$ [a]	0.97 ± 0.08	~ 1
$\Omega_c^0 \to \Omega^- \frac{\mu}{e}\nu$ [a]	0.98 ± 0.10	~ 1



μ/e Ratios of $d\Gamma/dq^2$



[a] Results from Belle. See appendix for citations.

Outline

$\eta - \eta'$ Mixing

- η and η' are admixtures of flavour eigenstates:

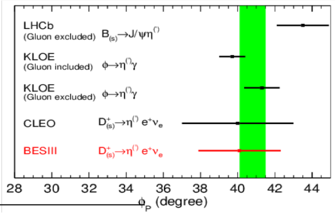
$$\begin{bmatrix} |\eta\rangle \\ |\eta'\rangle \end{bmatrix} = \begin{bmatrix} \cos\phi_P & -\sin\phi_P \\ \sin\phi_P & -\cos\phi_P \end{bmatrix} \begin{bmatrix} \frac{1}{2}\left|u\bar{u} + d\bar{d}\right\rangle \\ |s\bar{s}\rangle \end{bmatrix}$$

- $\eta - \eta'$ mixing angle ϕ_P can be determined[b] from

$$\cot^4\phi_P = \frac{\Gamma\left(D_s^+ \to \eta' e^+\nu\right)/\Gamma\left(D_s^+ \to \eta e^+\nu\right)}{\Gamma\left(D^+ \to \eta' e^+\nu\right)/\Gamma\left(D^+ \to \eta e^+\nu\right)}$$

with measured BESIII branching fractions & PDG lifetimes:

$$\phi_P = (40.1 \pm 2.1 \pm 0.7)^\circ$$



[b] From Donato, Ricciardi, and Bigi PRD85(2012)013016

Composition of Light Scalars $f_0(980), a_0(980), f_0(500)$

- Light scalars $f_0(980), a_0(980), f_0(500)$ are difficult to study in isolation due to wide decay widths
- Their structure is still an open question: Mesons? Tetraquarks? Hadronic Molecules?

From Wang and Lü PRD82(2010)034016

$D^+ \to Se^+\nu$ can provide insight on the nature of light scalars

$$R \equiv \frac{\mathcal{B}\left(D^+ \to f_0(500)e^+\nu\right) + \mathcal{B}\left(D^+ \to f_0(980)e^+\nu\right)}{\mathcal{B}\left(D^+ \to a_0^0(980)e^+\nu\right)}$$

Two quark description $\Rightarrow R = 1.0 \pm 0.3$

Tetraquark description $\Rightarrow R = 3.0 \pm 0.9$

Composition of Light Scalars $f_0(980), a_0(980), f_0(500)$

From Wang and Lü PRD82(2010)034016

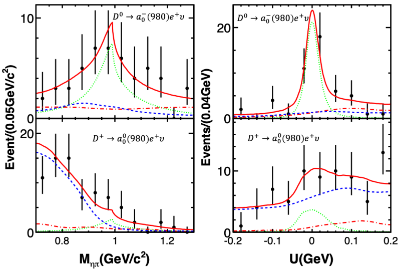
$D^+ \to S e^+ \nu$ can provide insight on the nature of light scalars

$$R \equiv \frac{\mathcal{B}\left(D^+ \to f_0(500) e^+ \nu\right) + \mathcal{B}\left(D^+ \to f_0(980) e^+ \nu\right)}{\mathcal{B}\left(D^+ \to a_0^0(980) e^+ \nu\right)}$$

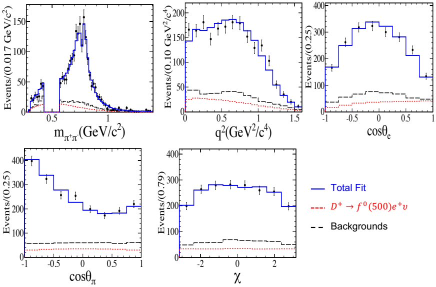
Two quark description $\Rightarrow R = 1.0 \pm 0.3$

Tetraquark description $\Rightarrow R = 3.0 \pm 0.9$

- $D \to a_0(980) e^+ \nu$ PRL121(2018)081802



- $D^+ \to f_0 e^+ \nu$ PRL122(2019)062001



Composition of Light Scalars $f_0(980), a_0(980), f_0(500)$

$$\mathcal{B}\left(D^0 \to a_0^-(980)e^+\nu\right) = \frac{\left(1.37^{+0.33}_{-0.29}\pm0.09\right)\times10^{-4}}{\mathcal{B}\left(a_0^-(980)\to\eta\pi^-\right)} \; (6.5\sigma)$$

$$\mathcal{B}\left(D^+ \to a_0^0(980)e^+\nu\right) = \frac{\left(1.66^{+0.81}_{-0.66}\pm0.11\right)\times10^{-4}}{\mathcal{B}\left(a_0^0(980)\to\eta\pi^0\right)} \; (3.0\sigma)$$

$$\mathcal{B}\left(D^+ \to f_0(500)e^+\nu\right) = \frac{(6.30\pm0.43\pm0.32)\times10^{-4}}{\mathcal{B}\left(f_0(500)\to\pi^+\pi^-\right)} \; (> 10\sigma)$$

$$\mathcal{B}\left(D^+ \to f_0(980)e^+\nu\right) < \frac{2.8\times10^{-5}}{\mathcal{B}\left(f_0(980)\to\pi^+\pi^-\right)} @ 90\% \text{ C.L.}$$

First Observations

Composition of Light Scalars $f_0(980), a_0(980), f_0(500)$

$$\mathcal{B}\left(D^0 \to a_0^-(980)e^+\nu\right) = \frac{\left(1.37^{+0.33}_{-0.29}\pm 0.09\right)\times 10^{-4}}{\mathcal{B}\left(a_0^-(980)\to\eta\pi^-\right)} \; (6.5\sigma)$$

$$\mathcal{B}\left(D^+ \to a_0^0(980)e^+\nu\right) = \frac{\left(1.66^{+0.81}_{-0.66}\pm 0.11\right)\times 10^{-4}}{\mathcal{B}\left(a_0^0(980)\to\eta\pi^0\right)} \; (3.0\sigma)$$

$$\mathcal{B}\left(D^+ \to f_0(500)e^+\nu\right) = \frac{(6.30\pm 0.43\pm 0.32)\times 10^{-4}}{\mathcal{B}\left(f_0(500)\to\pi^+\pi^-\right)} \; (> 10\sigma)$$

First Observations

$$\mathcal{B}\left(D^+ \to f_0(980)e^+\nu\right) < \frac{2.8\times 10^{-5}}{\mathcal{B}\left(f_0(980)\to\pi^+\pi^-\right)} \text{ @ 90\% C.L.}$$

Neglecting $f_0(980)$ contribution and assuming:

$$\mathcal{B}\left(f_0(500)\to\pi\pi\right) = 100\% \Rightarrow \mathcal{B}\left(f_0(500)\to\pi^+\pi^-\right) = 67\%$$

$$\Gamma\left(a_0(980)\right) = \Gamma\left(a_0(980)\to K\overline{K}\right) + \Gamma\left(a_0(980)\to\eta\pi^0\right)$$

$$\Rightarrow \mathcal{B}\left(a_0(980)\to\eta\pi^0\right) = (85\pm 11)\,\% \text{ with PDG avg. of } \frac{\Gamma\left(a_0(980)\to K\overline{K}\right)}{\Gamma\left(a_0(980)\to\eta\pi^0\right)}$$

$R > 2.7$ @ 90% C.L. $\Rightarrow$ Tetraquark favored

$D_s^+ \to f_0(980), f_0(500)e^+\nu$

- f_0's searched for through $\pi^0\pi^0$ and $K_S^0K_S^0$: no ρ/ϕ backgrounds

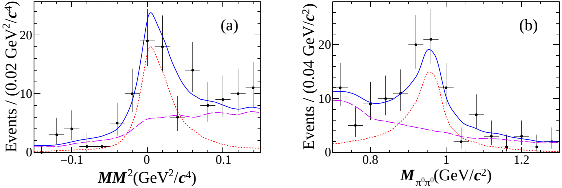
No evidence in $K_S^0K_S^0$ channel

$\mathcal{B}\left(D_s^+ \to K_S^0K_S^0e^+\nu_e\right) < 3.9\times10^{-4}$

No evidence in $f_0(500)\to\pi^0\pi^0$ channel

$\mathcal{B}\left(D_s^+ \to f_0(500)e^+\nu_e . f_0(500)\to\pi^0\pi^0\right) < 6.4\times10^{-4}$

arxiv:2110.13994
Submitted to PRL



$$\mathcal{B}\left(D_s^+ \to f_0(980)e^+\nu_e, f_0\to\pi^0\pi^0\right) = 7.9(1.4)(0.4)\times10^{-4}$$

Assuming isotopic symmetry, agrees with CLEO-c measurement in $\pi^+\pi^-$ channel

$\mathcal{B}\left(D_s^+ \to f_0(980)e^+\nu\right) > \mathcal{B}\left(D_s^+ \to f_0(500)e^+\nu\right) \Rightarrow$ Favours tetraquark description

PRD86(2012)114010

Outline

Future Prospects

- $0 - 5$ years:
  - Collection of ~ 20 fb^{-1} @ $\psi(3770)$ has begun @ BESIII
  - Semimuonic D_s^+ decays currently being analyzed @ BESIII
  - Large BESIII data sets (~ 3.7 fb^{-1}) recently collected between $4.6 - 4.7$ GeV for Λ_c^+ physics
  - More detail on future prospects in BESIII white paper: Chin. Phys. C 44, 040001 (2020)
  - Belle II data will provide competitive measurements of charm SL decays, Belle II Physics Book: PTEP 12, 123C01 (2019)
  - Exciting prospects for semileptonic D decays at LHCb
- > 5 years:
  - Proposal for a Super Tau/Charm Factory (SCTF) to collect $\mathcal{O}(10$ ab$^{-1})$ of data at charm thresholds. (See recent sensitivity studies for $D_s^+ \to \mu\nu$ and $D_s^+ \to \tau_e\nu$)

Summary

- Several recent precision measurements of (semi)leptonic D decays and recent lattice improvements of f_{D_s} and $f_+^{D\to K}$ provide an experimental average from direct measurement with $\sim 1\%$ precision
- Lattice results are highly predictive in D^+, D_s^+ decay constants and in $D \to P$ form factors (under CKM unitarity assumptions)
- No evidence for LFUV in leptonic/semileptonic charm decays
- Studying light hadrons in the clean event environments provided by SL decays has allowed for
  - Competitive measurements of $\eta - \eta'$ mixing angle
  - Further evidence to support tetraquark content of light scalars $a_0(980), f_0(980), f_0(500)$
- Rich data sets to study charm to come in the near (and far) future

Thanks for your attention!

Appendix - Citations

Standard Model predictions for $\frac{\mathcal{B}(D^+\to\eta\mu^+\nu)}{\mathcal{B}(D^+\to\eta e^+\nu)}$:

- Y. L. Wu, M. Zhong, and Y. B. Zuo, Int. J. Mod. Phys. A21,6125 (2006)
- H. Y. Cheng and X. W. Kang, Eur. Phys. J. C77, 587(2017);77, 863(E) (2017)
- M. A. Ivanov, J. G. Körner, J. N. Pandya, P. Santorelli, N. R. Soni, and C. T. Tran, Front. Phys.14, 64401 (2019)

Standard Model predictions for $\frac{\mathcal{B}(D^+\to\omega\mu^+\nu)}{\mathcal{B}(D^+\to\omega e^+\nu)}$:

- H. Y. Cheng and X. W. Kang, Eur. Phys. J. C77, 587(2017);77, 863(E) (2017)
- T. Sekihara and E. Oset, Phys. Rev. D92, 054038 (2015)
- N. R. Soni, M. A. Ivanov, J. G. Körner, J. N. Pandya, P. Santorelli, and C. T. Tran, Phys. Rev. D98, 114031 (2018)
- M. A. Ivanov, J. G. Körner, J. N. Pandya, P. Santorelli, N. R. Soni, and C. T. Tran, Front. Phys.14, 64401 (2019)
- H.B. Fu, W. Cheng, L. Zheng, D.D. Hu, T. Zhong, Phys. Rev. Research 2, 043129 (2020)
- R. N. Faustov, V. O. Galkin, and X. W. Kang, Phys. Rev. D101, 013004 (2020)

Appendix - Citations

Standard Model predictions for $\frac{\mathcal{B}(D^0 \to \rho^- \mu^+ \nu)}{\mathcal{B}(D^0 \to \rho^- e^+ \nu)}$:

- Y. L. Wu, M. Zhong, and Y. B. Zuo, Int. J. Mod. Phys. A 21, 6125 (2006)
- T. Sekihara and E. Oset, Phys. Rev. D92, 054038 (2015)
- N. R. Soni, M. A. Ivanov, J. G. Körner, J. N. Pandya, P. Santorelli, and C. T. Tran, Phys. Rev. D98, 114031 (2018)
- M. A. Ivanov, J. G. Körner, J. N. Pandya, P. Santorelli, N. R. Soni, and C. T. Tran, Front. Phys.14, 64401 (2019)
- H. Y. Cheng and X. W. Kang, Eur. Phys. J. C77, 587(2017);77, 863(E) (2017)
- R. N. Faustov, V. O. Galkin, and X. W. Kang, Phys. Rev. D101, 013004 (2020)

Appendix - Citations

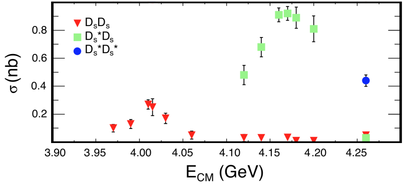
- $D^+ \to \tau^+\nu_\tau$: M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 123, 211802 (2019)
- $D_s^+ \to \tau^+\nu_\tau$: M. Ablikim et al. (BESIII Collaboration), arXiv:2106.02218
- $D^0 \to \rho^-\mu^+\nu_\mu$: M. Ablikim et al. (BESIII Collaboration), arXiv:2106.022924
- $D^+ \to \eta^-\mu^+\nu_\mu$: M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 124, 231801 (2020)
- $D^+ \to \omega^-\mu^+\nu_\mu$: M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D101, 072005 (2020)
- $D \to \pi\mu^+\nu_\mu$: M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 121, 171803 (2018)
- $D^0 \to K^-\mu^+\nu_\mu$: M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 122, 011804 (2019)
- $\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$: M. Ablikim et al. (BESIII Collaboration), Phys. Lett. B, 767 (2017), p. 42
- $\Xi_c^0 \to \Xi^-\ell^+\nu_\mu$: Y. B. Li et al. (Belle Collaboration), arXiv:2103.06496

$D_s^* D_s$ Samples

$$\frac{dN_{D_s^* D_s}}{dt} = \mathcal{L} \times \sigma\left(e^+e^- \to D_s^* D_s\right)$$

E_{CM} (MeV)	$\int \mathcal{L}\, dt$ (pb^{-1})	N_{D_s}
~ 4178 on avg.	$3189.0 \pm 0.9 \pm 31.9$	$\sim 6.4 \times 10^6$
$4188.99 \pm 0.06 \pm 0.41$	$526.7 \pm 0.1 \pm 2.2$	$\sim 1.0 \times 10^6$
$4199.03 \pm 0.05 \pm 0.41$	$526.0 \pm 0.1 \pm 2.1$	$\sim 1.0 \times 10^6$
$4209.25 \pm 0.06 \pm 0.42$	$517.1 \pm 0.1 \pm 1.8$	$\sim 0.9 \times 10^6$
$4218.84 \pm 0.05 \pm 0.40$	$514.6 \pm 0.1 \pm 1.8$	$\sim 0.8 \times 10^6$
$4225 - 4230$	$1047.34 \pm 0.14 \pm 10.16$	$\sim 1.3 \times 10^6$

CLEO Phys. Rev. D 80, 072001 (2009)



$\Xi_c^0 \to \Xi^- \ell^+ \nu$

- Using Belle data @ $E_{CM} = 10.52, 10.58$ GeV
- Ξ^- reconstructed through $\Lambda\pi^-, \Lambda \to p\pi^-$
- BF measured in reference to $\Xi_c^0 \to \Xi^-\pi^+$
- After selections, signal yields determined with fits to $M_{\Xi^- X^+}$ in bins of $p^*_{\Xi^- X}/p^*_{\text{max}}$

$$\mathcal{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right) = 1.31(04)(07)(38)\%$$

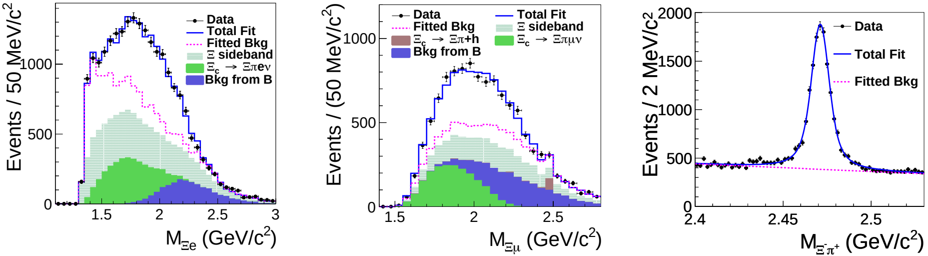
$$\mathcal{B}\left(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu\right) = 1.27(06)(10)(37)\%$$

$$\frac{\mathcal{B}\left(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu\right)}{\mathcal{B}\left(\Xi_c^0 \to \Xi^- e^+ \nu_e\right)} = 0.97(05)(07)$$

PRL127(2021)121803

$p^*_{\Xi^- X}/p^*_{\text{max}} \in (0.55, 0.65)$

Ξe $\Xi\mu$ $\Xi\pi$



$\Omega_c^0 \to \Omega^- \ell^+ \nu$

- Using Belle data @ $E_{CM} = 10.52, 10.58, 10.86$ GeV
- Ω^- reconstructed through $\Lambda\pi^-, \Lambda \to p\pi^-$
- BF measured in reference to $\Omega_c^0 \to \Omega^-\pi^+$
- After selections, signal yields determined with fits to $M_{\Omega^- X^+}$

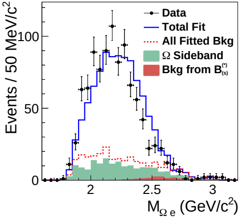
$$\frac{\mathcal{B}\left(\Omega_c^0 \to \Omega^- e^+ \nu_e\right)}{\mathcal{B}\left(\Omega_c^0 \to \Omega^- \pi^+\right)} = 1.98(13)(08)\%$$

$$\frac{\mathcal{B}\left(\Omega_c^0 \to \Omega^- \mu^+ \nu_\mu\right)}{\mathcal{B}\left(\Omega_c^0 \to \Omega^- \pi^+\right)} = 1.94(18)(10)\%$$

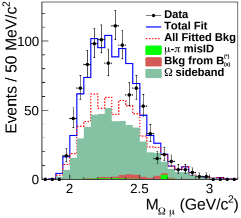
$$\frac{\mathcal{B}\left(\Omega_c^0 \to \Omega^- \mu^+ \nu_\mu\right)}{\mathcal{B}\left(\Omega_c^0 \to \Omega^- e^+ \nu_e\right)} = 0.98(10)(02)$$

arXiv:2112.10367
Submitted to PRL

Ωe



$\Omega\mu$



$\Omega\pi$