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University of Ljubljana
Faculty of Mathematics and Physics

Results about Charm Decays at BESIII

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On behalf of the BESIII Collaboration

October 3, 2019, Ljubljana, Slovenia

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Institute of High Energy Physics
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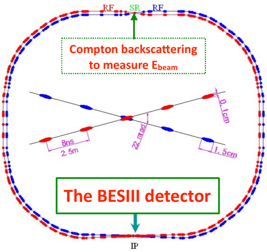
BESIII

Outline

BESIII Experiment

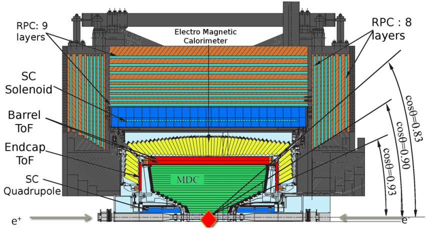
BESIII Experiment

Beijing Electron Positron Collider II(BEPCII)



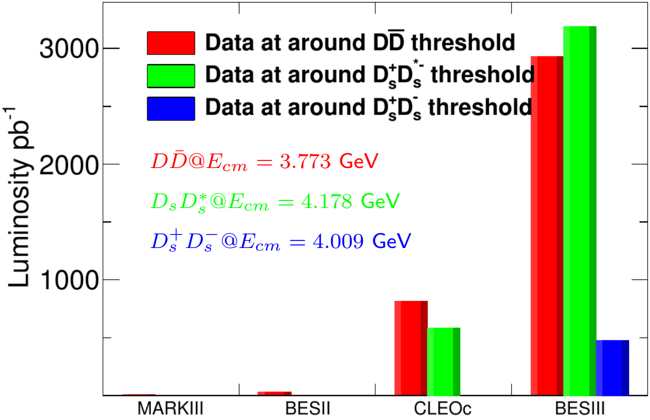
- Double ring e^+e^- collider
- E_{cm} : $2 \sim 4.6$ GeV, operated since 2008
- Designed Luminosity : $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ was achieved in April 2016!
- Beam crossing angle: 22 mrad

(Beijing Spectrometer III) BESIII



- Acceptance: 93% of 4π
- MDC: $\sigma_p/p = 0.5\%$ at 1 GeV
- EMC: $\sigma_E/E = 2.5\%$ at 1 GeV
- ToF: $\sigma = 80$ps (110 ps) in barrel (endcap)
- 9 layer RPC Muon System
- Superconducting Solenoid: 1 T

Data Sets for Charm Decays



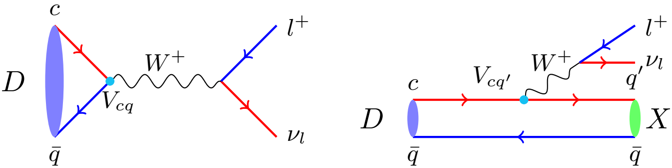
Introduction to BESIII

(Semi)-Leptonic Decay

Hadronic Decay

Summary

Motivation on $D_{(s)}$ (Semi)-Leptonic Decay



(a) Leptonic decay (b) Semileptonic decay

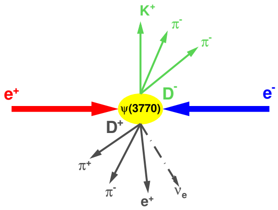
$\Gamma(D^+_{(s)} \to l^+\nu) \propto f^2_{D_{(s)}}|V_{cq}|^2$ X (pseudoscalar/scalar meson): $\frac{d\Gamma}{dq^2} \propto p^3_X f^2_+(q^2)|V_{cq'}|^2$

X (vector meson): $\frac{d\Gamma}{dq^2} \propto (V, A_{1,2})(q^2)|V_{cq'}|^2$

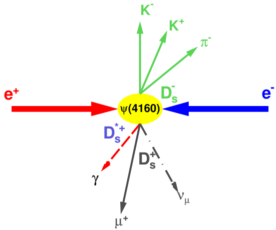
- Extract CKM matrix element and hadronic form facters (FFs) from measured branching fraction (BF):
  - Test unitarity of CKM matrix with $|V_{cd(cs)}|$ and search for new physics.
  - Test LQCD calculations of $f_{D_{(s)}}$ and FFs $f_+(q^2)/V(q^2)$, $A_{1,2}(q^2)$.
- Test the lepton flavour universality (LFU).
- Help to understand the internal structure of light scalar mesons.

Double Tag Method

$e^+ e^- \to \psi(3770) \to D^- D^+$



$e^+ e^- \to \psi(4160) \to D_s^- D_s^{*+}$



$$@E_{cm} = 3.773\text{GeV} \Rightarrow \mathcal{B}_{sig} = \frac{N_{sig}}{\sum_\alpha N^\alpha_{tag} \epsilon^\alpha_{tag,sig} / \epsilon^\alpha_{tag}}$$

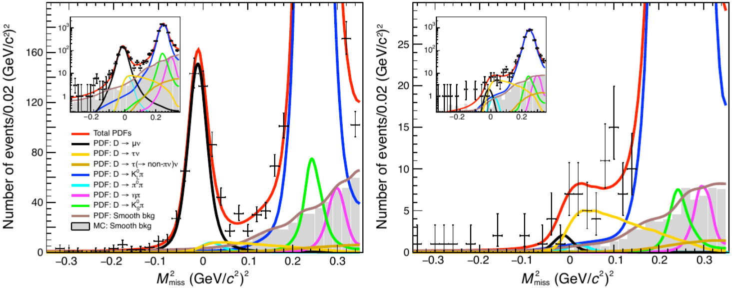
$$@E_{cm} = 4.178\text{GeV} \Rightarrow \mathcal{B}_{sig} = \frac{N_{sig}}{\mathcal{B}(D_s^* \to \gamma D_s) \sum_\alpha N^\alpha_{tag} \epsilon^\alpha_{tag,sig} / \epsilon^\alpha_{tag}}$$

- Charged conjugated processes are implied in this report

- Double tag (DT) method is used for most analyses
- Advantages: independent of $N_{D\bar{D}}$;identify ν through missing mass; low background; systematics associated with tag can be canceled in the ratio

$D^+ \to \tau^+\nu_\tau$ (2.93 fb^{-1} dataset @E_{cm}= 3.773 GeV with DT method)

Submitted to PRL(arXiv:1908.08877)

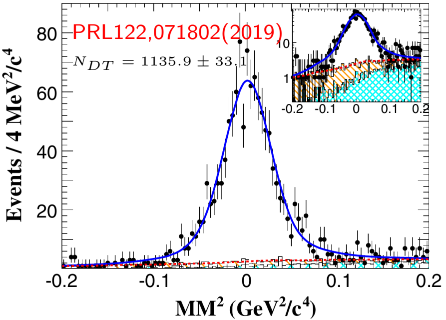


- **First observation** ($\sim 5\sigma$) of $D^+ \to \tau^+\nu_\tau,\ \tau \to \pi^+\bar{\nu}_\tau$

$$\mathcal{B}(D^+ \to \tau^+\nu_\tau) = (1.20 \pm 0.24 \pm 0.12) \times 10^{-3}$$
$$f_{D^+}|V_{cd}| = 50.4 \pm 5.1 \pm 2.5 \pm 0.2\ \mathrm{MeV}$$

$$\mathcal{R}_{\tau/\mu} = \frac{\mathcal{B}(D^+ \to \tau^+\nu_\tau)}{\mathcal{B}_{\mathrm{PDG2018}}(D^+ \to \mu^+\nu_\mu)} = 3.21 \pm 0.64 \pm 0.43$$
$$\mathcal{R}_{\tau/\mu}(\mathrm{SM}) = 2.67 \pm 0.1$$

$D_s^+ \to \mu^+\nu_\mu$ (3.19 fb^{-1} dataset @E_{cm}= 4.178 GeV with DT method)



$$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (5.49 \pm 0.16 \pm 0.15) \times 10^{-3}$$

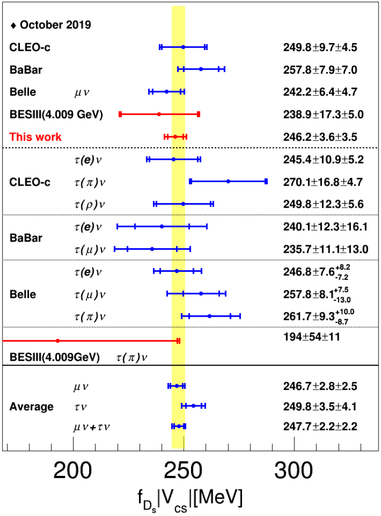
$$\mathcal{B}_{\rm CLEO}(D_s^+ \to \mu^+\nu_\mu) = (5.65 \pm 0.45 \pm 0.17) \times 10^{-3}$$

$$\mathcal{R}_{\tau/\mu} = \frac{\mathcal{B}_{\rm PDG2018}(D_s^+ \to \tau^+\nu_\tau)}{\mathcal{B}_{\rm combine}(D_s^+ \to \mu^+\nu_\mu)} = 9.98 \pm 0.52$$

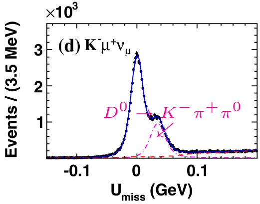
*BESIII, CLEO, BABAR, Belle

$$\mathcal{R}_{\tau/\mu}({\rm SM}) = 9.74$$

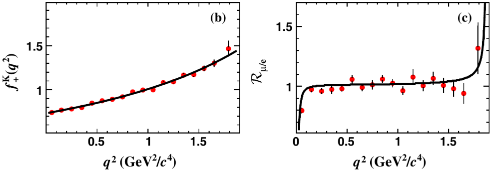
⇒ **Most precise measurement to date!**



$D^0 \to K^-\mu^+\nu_\mu$ (2.93 fb^{-1} dataset @E_{cm}= 3.773 GeV with DT method)



PRL122,011804(2019) $\mathcal{R}_{\mu/e} = (\Delta\Gamma_\mu/\Delta q^2)/(\Delta\Gamma_e/\Delta q^2)$



$$\mathcal{B}(D^0 \to K^-\mu^+\nu_\mu) = (3.413 \pm 0.019 \pm 0.035)\%$$

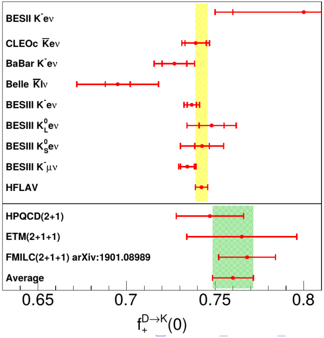
$$\mathcal{B}(\text{Belle})(D^0 \to K^-\mu^+\nu_\mu) = (3.45 \pm 0.10 \pm 0.21)\%$$

$$f_+^{D\to K}(0)|V_{cs}| = 0.7133 \pm 0.0038 \pm 0.0030$$

$$\mathcal{R}_{\mu/e} = \frac{\mathcal{B}(D^0 \to K^-\mu^+\nu_\mu)}{\mathcal{B}_{\text{BESIII}}(D^0 \to K^-e^+\nu_e)} = 0.974 \pm 0.007 \pm 0.012$$

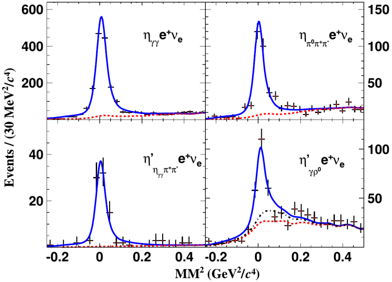
$$\mathcal{R}_{\mu/e}(\text{SM}) = 0.97$$

PDG2018 $|V_{cs}| = 0.97359^{+0.00010}_{-0.00011} \Rightarrow$

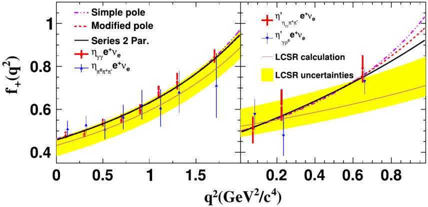


$D_s^+ \to \eta^{(\prime)} e^+ \nu_e$ (3.19 fb^{-1} dataset @E_{cm}= 4.178 GeV with DT method)

PRL122,121801(2019)



- First FFs Measurement



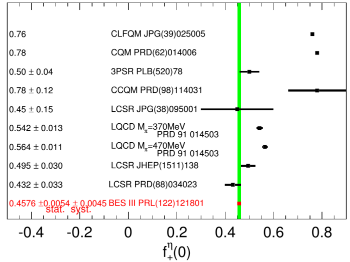
- Simultaneous fit ⇒ Combined results:

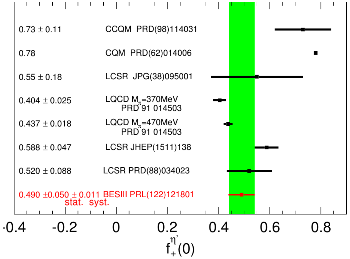
$$\mathcal{B}(D_s^+ \to \eta e^+ \nu_e) = (3.323 \pm 0.063 \pm 0.063)\%$$
$$\mathcal{B}(D_s^+ \to \eta' e^+ \nu_e) = (0.824 \pm 0.073 \pm 0.027)\%$$
$$\mathcal{B}_{\rm CLEO}(D_s^+ \to \eta e^+ \nu_e) = (2.28 \pm 0.14 \pm 0.19)\%$$
$$\mathcal{B}_{\rm CLEO}(D_s^+ \to \eta' e^+ \nu_e) = (0.68 \pm 0.15 \pm 0.06)\%$$

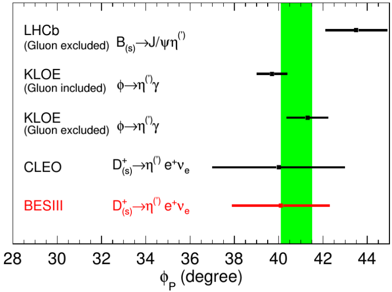
- LCSR line from PRD88,03402(2013)

$$f_+^{D_s^+ \to \eta}(0)|V_{cs}| = 0.4465 \pm 0.0051 \pm 0.0035$$
$$f_+^{D_s^+ \to \eta'}(0)|V_{cs}| = 0.477 \pm 0.049 \pm 0.011$$

$D_s^+ \to \eta^{(\prime)} e^+ \nu_e$ (3.19 fb^{-1} dataset @E_{cm}= 4.178 GeV with DT method)







- $\eta - \eta'$ mixing angle ϕ_P can be determined:

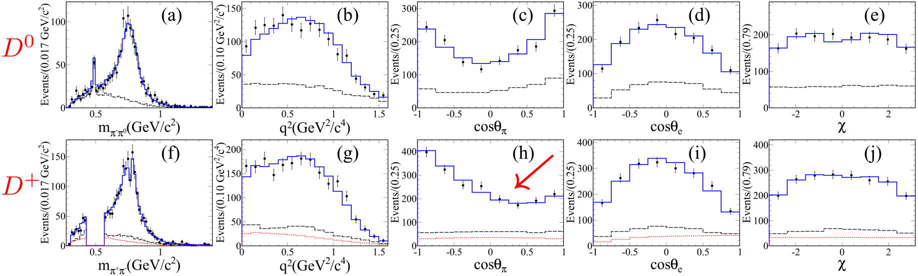
$$cot^4 \phi_P = \frac{\Gamma(D_s^+ \to \eta' e^+ \nu_e)/\Gamma(D_s^+ \to \eta e^+ \nu_e)}{\Gamma(D^+ \to \eta' e^+ \nu_e)/\Gamma(D^+ \to \eta e^+ \nu_e)}$$

D^+ BFs from BESIII PRD97, 092009(2018)

$$\Rightarrow \boldsymbol{\phi_P = (40.1 \pm 2.1 \pm 0.7)^\circ}$$

$D \to \pi\pi e\nu_e$ (2.93 fb^{-1} dataset @E_{cm}= 3.773 GeV with DT method)

PRL122,062001(2019)



- Simultaneous PWA fit to both channels
- **First observation of $D^+ \to f_0(500)e^+\nu_e(> 10\sigma)$**

$$f_{f_0(500)} = (25.7 \pm 1.6 \pm 1.1)\%$$

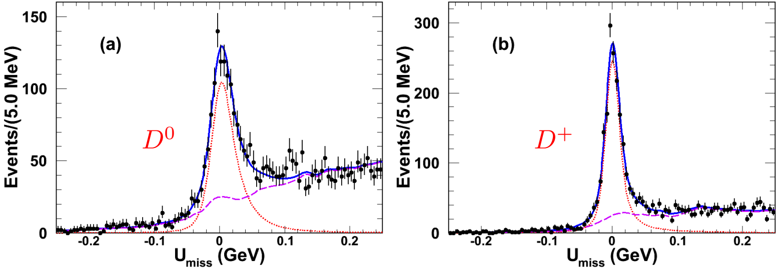
$$f_{\rho^0} = (76.0 \pm 1.7 \pm 1.11)\%$$

$$f_{\omega} = (1.28 \pm 0.41 \pm 0.15)\%$$

$$r_V = V(0)/A_1(0) = 1.695 \pm 0.083 \pm 0.051$$

$$r_2 = A_2(0)/A_1(0) = 0.845 \pm 0.056 \pm 0.039$$

$D \to \pi\pi e\nu_e$ (2.93 fb^{-1} dataset @E_{cm}= 3.773 GeV with DT method)



From Wang and Lu PRD82, 034016(2010)

$$R = \frac{\mathcal{B}(D^+ \to f_0(500)e^+\nu_e) + \mathcal{B}(D^+ \to f_0(980)e^+\nu_e)}{D^+ \to a_0(980)^0 e^+\nu_e}$$

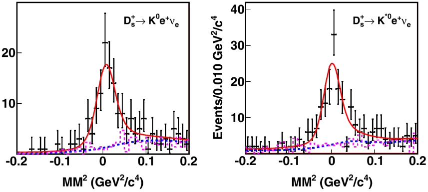
$$= \begin{cases} 1.0 \pm 0.3 & \text{two quark description} \\ 3.0 \pm 0.9 & \text{tetraquark description} \end{cases}$$

Use $\mathcal{B}(D^+ \to a_0(980)^0 e^+\nu_e) \times \mathcal{B}(a_0(980)^0 \to \eta\pi^0) < 3.0 \times 10^{-4}$ from BESIII PRL121,081802(2018) and other inputs from PDG.

$\Rightarrow R > 2.7$@90%CL $\Rightarrow$ Tetraquark favored for f_0 and a_0

$D_s^+ \to K^{(*)0} e^+ \nu_e$ (3.19 fb^{-1} dataset @E_{cm}= 4.178 GeV with DT method)

PRL122,061801(2019)



$$\mathcal{B}(D_s^+ \to K^0 e^+ \nu_e) = (3.25 \pm 0.38 \pm 0.16) \times 10^{-3}$$

$$\mathcal{B}(D_s^+ \to K^{*0} e^+ \nu_e) = (2.37 \pm 0.26 \pm 0.20) \times 10^{-3}$$

$$\mathcal{B}_{\rm CLEO}(D_s^+ \to K^0 e^+ \nu_e) = (3.9 \pm 0.8 \pm 0.3) \times 10^{-3}$$

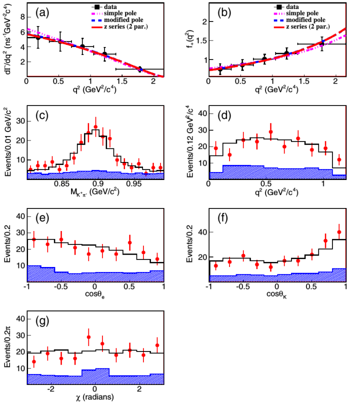
$$\mathcal{B}_{\rm CLEO}(D_s^+ \to K^{*0} e^+ \nu_e) = (1.8 \pm 0.4 \pm 0.1) \times 10^{-3}$$

Use BESIII and CLEO measurement

	Values
$f_+^{D_s^+\to K^0}(0)/f_+^{D^+\to\pi^0}(0)$	$1.16 \pm 0.14 \pm 0.02$
$r_V^{D_s^+\to K^{*0}}/r_V^{D^+\to\rho^0}$	$1.13 \pm 0.26 \pm 0.11$
$r_2^{D_s^+\to K^{*0}}/r_2^{D^+\to\rho^0}$	$0.93 \pm 0.36 \pm 0.10$

- Agree with LQCD predictions and U-spin ($d \leftrightarrow s$) symmetry

- First FFs Measurement



$$f_+^{D_s^+\to K^0}(0)|V_{cd}| = 0.162 \pm 0.019 \pm 0.003$$

$$r_V = 1.67 \pm 0.34 \pm 0.16$$

$$r_2 = 0.77 \pm 0.28 \pm 0.07$$

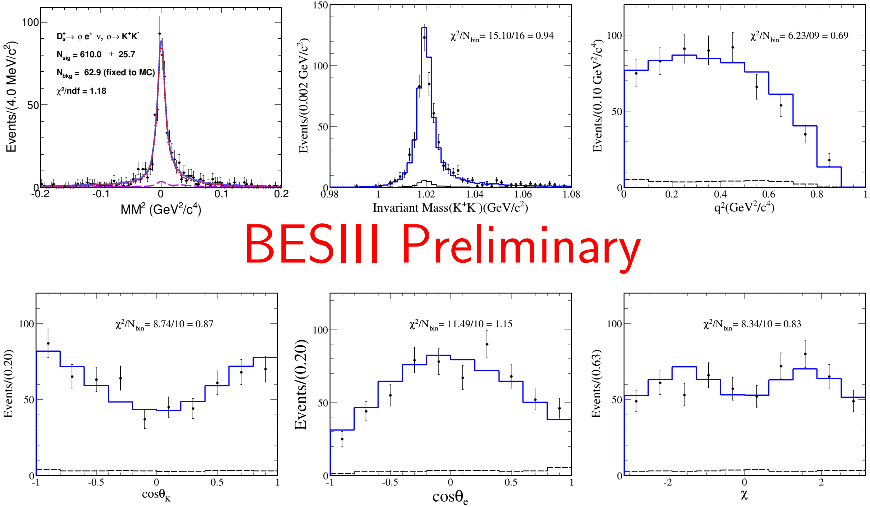
$D_s^+ \to \phi e^+ \nu_e$ (3.19 fb^{-1} dataset @E_{cm}= 4.178 GeV with DT method)

- PWA is performed to $D_s^+ \to K^+K^-e^+\nu_e$ with 604 events (~5% bkg).
- Data can be well described with $D_s^+ \to \phi e^+\nu_e$.
- No signal is observed ($< 3\sigma$) from $f_0(980)$ or non-resonant K^+K^- S-wave.

- Measured Lorentz invariant FFs ratio at $q^2 = 0$ and absolute BF, compared with theoretical predictions.

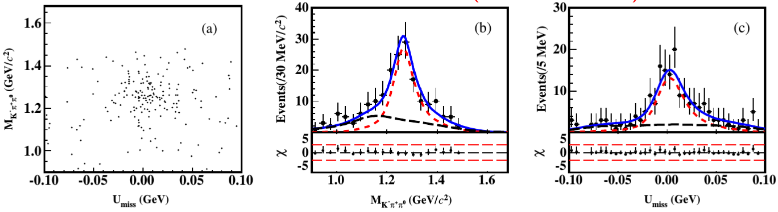
	$r_V = V(0)/A_1(0)$	$r_2 = A_2(0)/A_1(0)$	$\mathcal{B}(D_s^+ \to \phi e^+\nu_e)$(%)
PDG2018	1.80±0.08	0.84±0.11	2.39 ± 0.16
this work	1.79±0.19±0.06	0.77±0.15±0.07	$2.35 \pm 0.10 \pm 0.10$
BESIII(@4.009GeV)[PRD97,012006(2018)]	–	–	$2.26 \pm 0.45 \pm 0.09$
BABAR [PRD78,051101(R)(2008)]	1.807±0.046±0.065	0.816±0.036±0.030	$2.61 \pm 0.03 \pm 0.08 \pm 0.15$
CLEO [PRD80,052009(2009)]	–	–	$2.36 \pm 0.23 \pm 0.13$
CLEO [PRD92,012009(2015)]	–	–	$2.14 \pm 0.17 \pm 0.08$
LQCD [PRD90,074506(2014)]	1.72±0.21	0.74±0.12	–
CLFQM [EPJC77,587(2017)]	1.42	0.86	3.1 ± 0.3
CLFQM [PRD78,054002(2008)]	1.49	0.95	2.3
HQET [PRD72,034029(2005)]	1.80	0.52	2.4

$D_s^+ \to \phi e^+ \nu_e$ (3.19 fb^{-1} dataset @E_{cm}= 4.178 GeV with DT method)



$D^+ \to \bar{K}_1(1270)^0 e^+ \nu_e$ (2.93 fb^{-1} dataset @E_{cm}= 3.773 GeV with DT method)

Submitted to PRL(arXiv:1907.1137)



- $\bar{K}_1(1270)^0$ is reconstructed with $K^-\pi^+\pi^0$ final state
- **First observation** of semileptonic D decays into axial-vector meson ($> 10\sigma$)

	$\mathcal{B}(D^+ \to \bar{K}_1(1270)^0 e^+ \nu_e)$
This work	$(2.30 \pm 0.26 \pm 0.18 \pm 0.25) \times 10^{-3}$
CLFQM[EPJC77,863(2017)]($\theta_{K_1} = 33°$)	$(3.20 \pm 0.40) \times 10^{-3}$
LCSR[JPG46,105006(2019)]($\theta_{K_1} < 0$)	$(17 \sim 21) \times 10^{-3}$

- θ_{K_1} is the mixing angle of two states $K_{1A}(^1P_1)$ and $K_{1B}(^3P_1)$

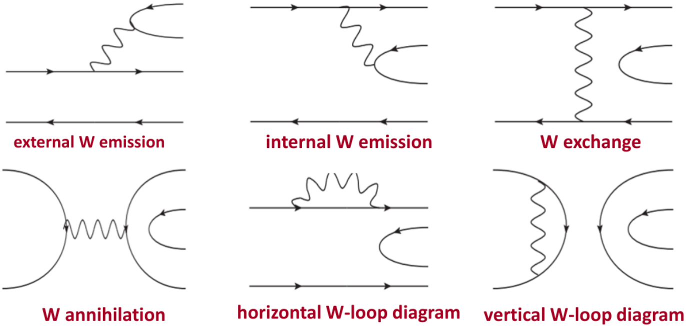
Introduction to BESIII

(Semi)-Leptonic Decay

Hadronic Decay

Summary

A theory model: Diagrammatic Approach



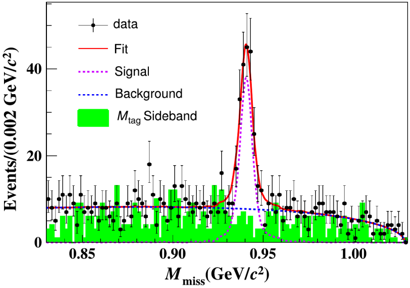
- Start from Chau and Cheng: PRL56,1655(1986),PRD36,137(1987)
- All decays can be described in terms of six different quark diagrams
- Each amplitude can be determined by experiment

$D_s^+ \to p\bar{n}$ (3.19 fb^{-1} dataset @E_{cm}= 4.178 GeV with DT method)

- W-annihilation featured as short-distance is expected to be small: $\mathcal{B} \sim 10^{-6}$
- Long-distance can enhance to $\mathcal{B} \sim 10^{-3}$ [PLB663,326(2008)]
- First evidence was reported by CLEO with 13.0 ± 3.6 signal events:

$\mathcal{B}(D_s^+ \to p\bar{n}) = (1.30 \pm 0.36^{+0.12}_{-0.16}) \times 10^{-3}$ [PRL100,181802(2008)]

PRD99,031101(R)(2019)



- **First observation** with 193 ± 17 signal events ($> 10\sigma$)

  $\boldsymbol{\mathcal{B}(D_s^+ \to p\bar{n}) = (1.21 \pm 0.10 \pm 0.05) \times 10^{-3}}$
- Short distance dynamics is not the driven mechanism
- Hadronization process driven by nonperturbative dynamics determines the underlying physics

$D_s^+ \to \omega\pi^+(K^+)$ (3.19 fb^{-1} dataset @E_{cm}= 4.178 GeV with DT method)

- Q.Qin et al.[PRD89,054006(2014)] predicts:

  $\mathcal{B}(D_s^+ \to \omega K^+) \sim 0.6 \times 10^{-3}(\mathcal{A}_{cp} \sim -0.6 \times 10^{-3})$ (ρ-ω mixing is neglected)

  $\mathcal{B}(D_s^+ \to \omega K^+) \sim 0.07 \times 10^{-3}(\mathcal{A}_{cp} \sim -2.3 \times 10^{-3})$ (ρ-ω mixing is considered)

- First result from CLEO [PRD80,051102(R)(2009)]:

  $\mathcal{B}(D_s^+ \to \omega\pi^+) = (2.1 \pm 0.9 \pm 0.1) \times 10^{-3}$
  $\mathcal{B}(D_s^+ \to \omega K^+) < 2.4 \times 10^{-3}$@90%CL

- **First observation** (6.7σ):
  $\boldsymbol{\mathcal{B}(D_s^+ \to \omega\pi^+) = (1.77 \pm 0.32 \pm 0.13) \times 10^{-3}}$

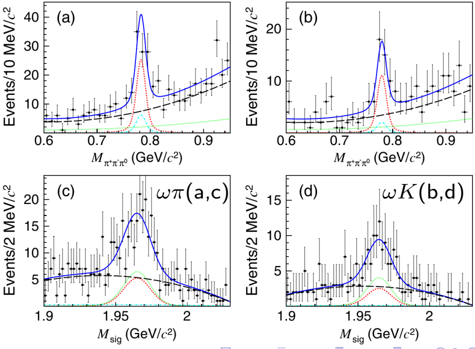
  First evidence (4.4σ):
  $\boldsymbol{\mathcal{B}(D_s^+ \to \omega K^+) = (0.87 \pm 0.24 \pm 0.08) \times 10^{-3}}$

- According to Qin et al, implies:

  $\mathcal{A}_{cp} \sim -0.6 \times 10^{-3}$

- $D_s^+ \to \omega K^+$: a good decay to search for **CPV**

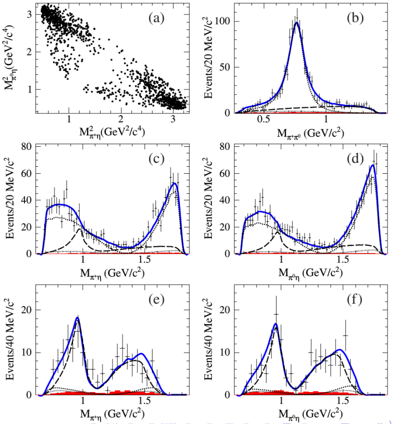
PRD99,091101(R)(2019)



$D_s^+ \to \pi^+\pi^0\eta$ (3.19 fb^{-1} dataset @E_{cm}= 4.178 GeV with DT method)

PRL123,112001(2019)

Amplitude	ϕ_n (rad)	FF$_n$
$D_s^+ \to \rho^+\eta$	0.0 (fixed)	0.783±0.050±0.021
$D_s^+ \to (\pi^+\pi^0)_V\eta$	0.612±0.172±0.342	0.054±0.021±0.025
$D_s^+ \to a_0(980)\pi$	2.794±0.087±0.044	0.232±0.023±0.033



- $D_s^+ \to \rho^+\eta$ (External W emission) is dominant
- PWA with 1239 DT events (purity 97.7%) and BF:

  $\boldsymbol{\mathcal{B}(D_s^+ \to \pi^+\pi^0\eta) = (9.50 \pm 0.28 \pm 0.41)\%}$

  $\mathcal{B}_{\mathrm{CLEO}}(D_s^+ \to \pi^+\pi^0\eta) = (9.2 \pm 0.4 \pm 1.1)\%$
- **First observation** of $D_s^+ \to a_0(980)\pi$:

  $\boldsymbol{\mathcal{B}(D_s^+ \to a_0(980)\pi, a_0(980) \to \pi\eta)}$

  $\boldsymbol{= (1.46 \pm 0.15 \pm 0.23)\%}$

  Why is it so large(W-annihilation decays?)?
- Attract attention from theorists quickly:

  Y.K. Hsiao et al [arXiv:1909.07327]: $a_0(980)$ as **tetraquark**

  Raquel Molina et al [arXiv:1908.11557]: $a_0(980)$ as **molecular state**

Introduction to BESIII

(Semi)-Leptonic Decay

Hadronic Decay

Summary

Summary and Outlook

- In this report, some recent results about $D_{(s)}$ decays are discussed. Thanks to the largest data samples produced at threshold, in a very clean environment, BESIII has a leading role as follow:
  - Precise measurement of decay constants, FFs and CKM elements $\Rightarrow$ precision improved much, up to less than 1% ($f_+^{D\to K}(0)|V_{cs}|$)
  - LFU test $\Rightarrow$ No evidence of violation found in charm sector at 1.5% precision level
  - PWA with high purity $\Rightarrow$ provide necessary information for dynamic study
  - Study the nature of light scalar mesons in semileptonic decay $\Rightarrow$ tetraquark description favored for f_0 and a_0, the mixing angle information for η-η' and $K_1(1270)$
- Many analyses about $D_{(s)}$ decays are in process.
- BESIII will take more data at threshold in the future, more results are expected!

Thank you!