Experimental status of $|V_{cs}|$ and $|V_{cd}|$

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（On behalf of the BESIII Collaboration）

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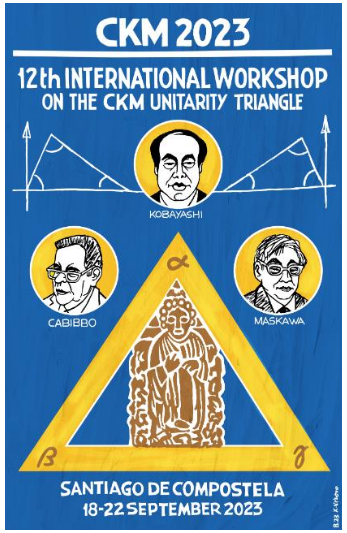


Nankai University

Outline

- Introduction
- Results from CLEO, BABAR and BELLE
- Recent results from BESIII
- Comparisons of $|V_{cd}|$
- Comparisons of $|V_{cs}|$
- Conclusions

Introduction

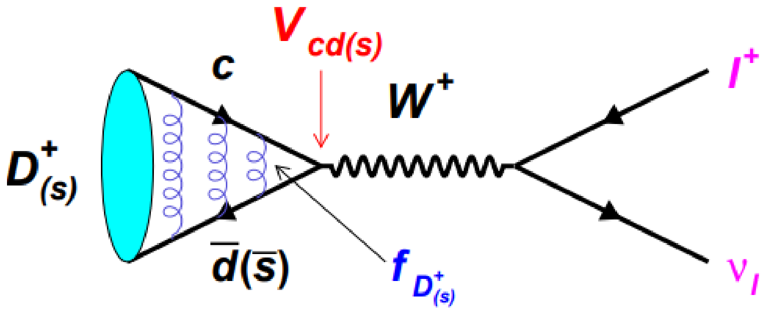
- Unitary matrix: $V^{+}V=1$

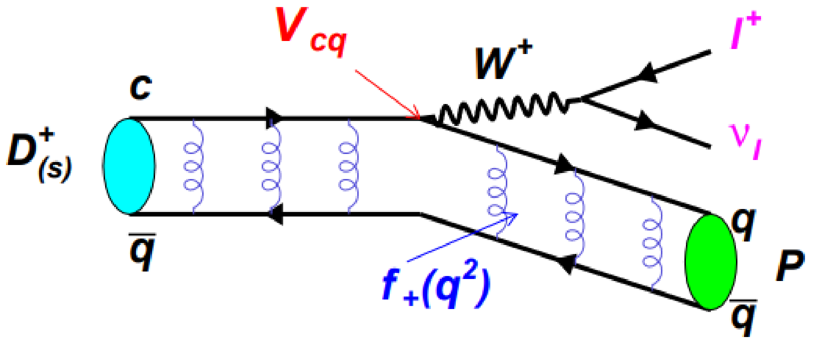
$$V_{CKM} = \begin{pmatrix} V_{ud} V_{us} V_{ub} \\ V_{cd}\, V_{cs}\, V_{cb} \\ V_{td}\, V_{ts}\, V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Only obtained at experimental

- Precise measurements of CKM matrix elements $|V_{cs}|$ and $|V_{cd}|$ can test unitarity of CKM matrix and search for NP beyond SM
- Calibrate LQCD calculations

Ideal bridge to access the strong and weak effects between quarks

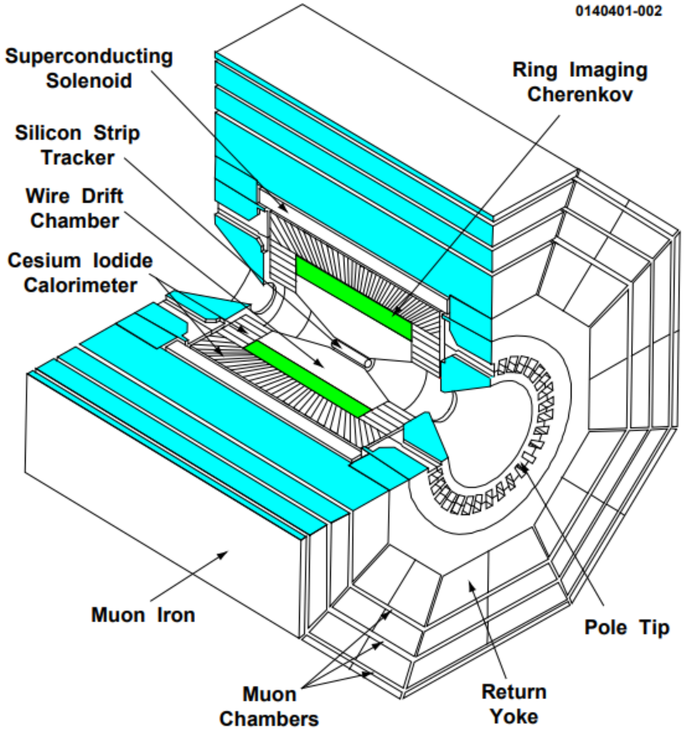




$$\Gamma(D^+_{(s)} \to l^+\nu_l) = \frac{G_F^2 f^2_{D^+_{(s)}}}{8\pi} |V_{cd(s)}|^2 m_l^2 m_{D^+_{(s)}} \left(1 - \frac{m_l^2}{m^2_{D^+_{(s)}}}\right)^2$$

$$\frac{d\Gamma(D^+_{(s)} \to P l \nu_l)}{dq} = \frac{G_F^2 p^3}{24\pi^3} |f_+(q^2)|^2 |V_{cq}|^2$$

Results from CLEO-c



Decay chain	Reference	N_{sig}	$\|V_{cd}\|$	Δ (%)
$D^+ \to \mu^+\nu_\mu$	PRD78(2008)052003	149.7	$0.219 \pm 0.009 \pm 0.003$	4.4
$D^{+(0)} \to \pi^{0(-)}e^+\nu_e$	PRD80(2009)032005	42(21)	$0.234 \pm 0.007 \pm 0.025$	11.1
Decay chain	**Reference**	N_{sig}	$\|V_{cs}\|$	Δ (%)
$D_s^+ \to \mu^+\nu_\mu$	PRD79(2009)052001	235.5	$1.000 \pm 0.040 \pm 0.016$	4.3
$D_s^+ \to \tau^+\nu_\tau{}^1$	PRD79(2009)052002	180.6	$0.981 \pm 0.044 \pm 0.021$	5.0
$D_s^+ \to \tau^+\nu_\tau{}^2$	PRD80(2008)112004	197.9	$1.001 \pm 0.052 \pm 0.019$	5.5
$D_s^+ \to \tau^+\nu_\tau{}^3$	PRD79(2009)052001	125.6	$1.079 \pm 0.068 \pm 0.016$	6.6
$D^{+(0)} \to K^-(\bar{K}^0)e^+\nu_e$	PRD80(2009)032005	27(54)	$0.985 \pm 0.009 \pm 0.103$	10.5

1 $\tau^+ \to e^+\nu_e\bar{\nu}$; **2** $\tau^+ \to \pi^+\pi^0\bar{\nu}$; **3** $\tau^+ \to \pi^+\bar{\nu}$

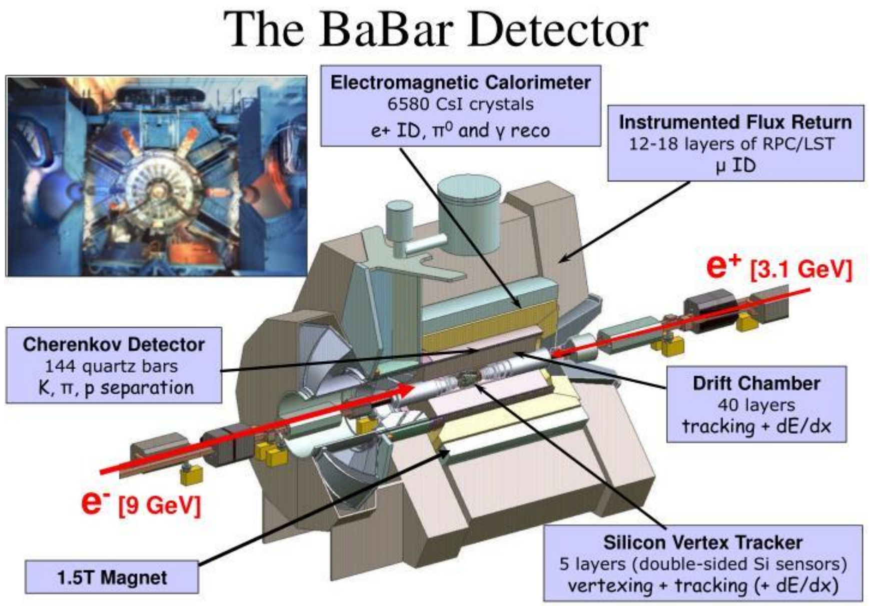
Data samples:

- ▶ 0.8 fb^{-1}@3.774 GeV
- ▶ 0.6 fb^{-1}@4.170 GeV

Precision of $|V_{cd(s)}|$:

- ▶ $|V_{cd}|$: $0.219 \pm 0.009 \pm 0.003$ 4.4%
- ▶ $|V_{cs}|$: $1.000 \pm 0.040 \pm 0.016$ 4.3%

Results from BABAR @ PEP-II

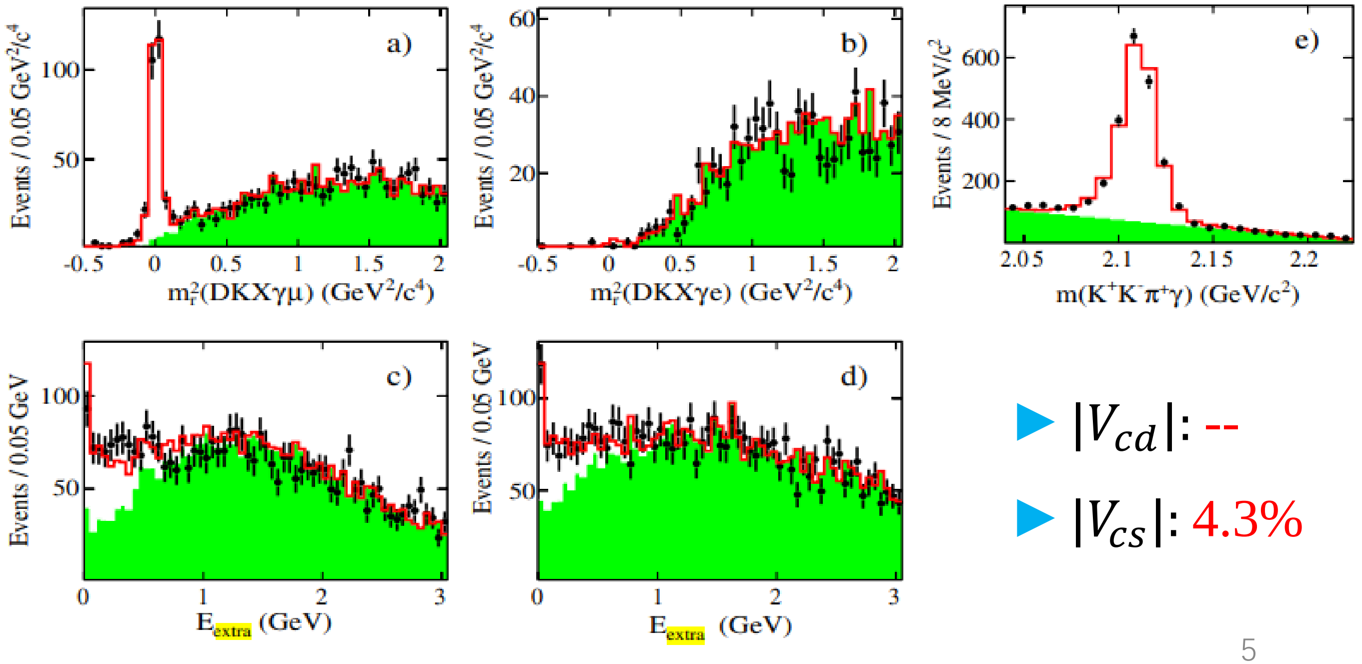


Decay chain	Reference	N_{sig}	$\lvert V_{cd}\rvert$	Δ (%)
–	-	-	-	-
Decay chain	Reference	N_{sig}	$\lvert V_{cs}\rvert$	Δ (%)
$D_s^+ \to \mu^+\nu_\mu$	PRD82(2010)091103	275	$1.032 \pm 0.033 \pm 0.029$	4.3
$D_s^+ \to \tau^+\nu_\tau$ [1]	PRD82(2010)091103	748	$0.953 \pm 0.033 \pm 0.047$	6.0

1 $\tau^+ \to e(\mu)^+\nu_{e(\mu)}\bar{\nu}$;

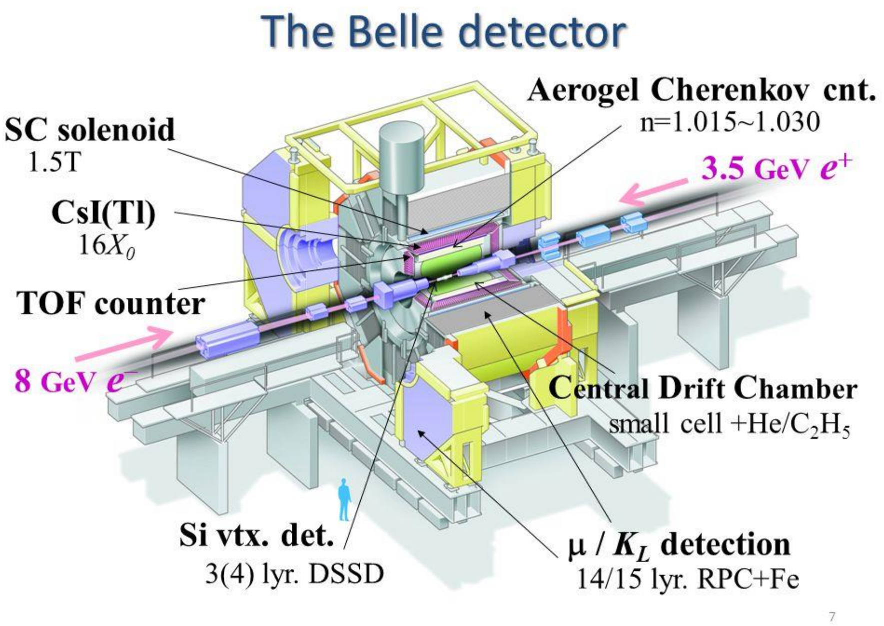
Data samples:

- 0.52 ab^{-1}@10.6 GeV (γ (4S))
- $\sigma(e^+e^- \to cc = 1.3)$ nb
- $L_{\text{peak}} = 1 \times 34\ \text{cm}^{-2}\text{s}^{-1}$



- $|V_{cd}|$: --
- $|V_{cs}|$: 4.3%

Results from BELLE @ KEKB

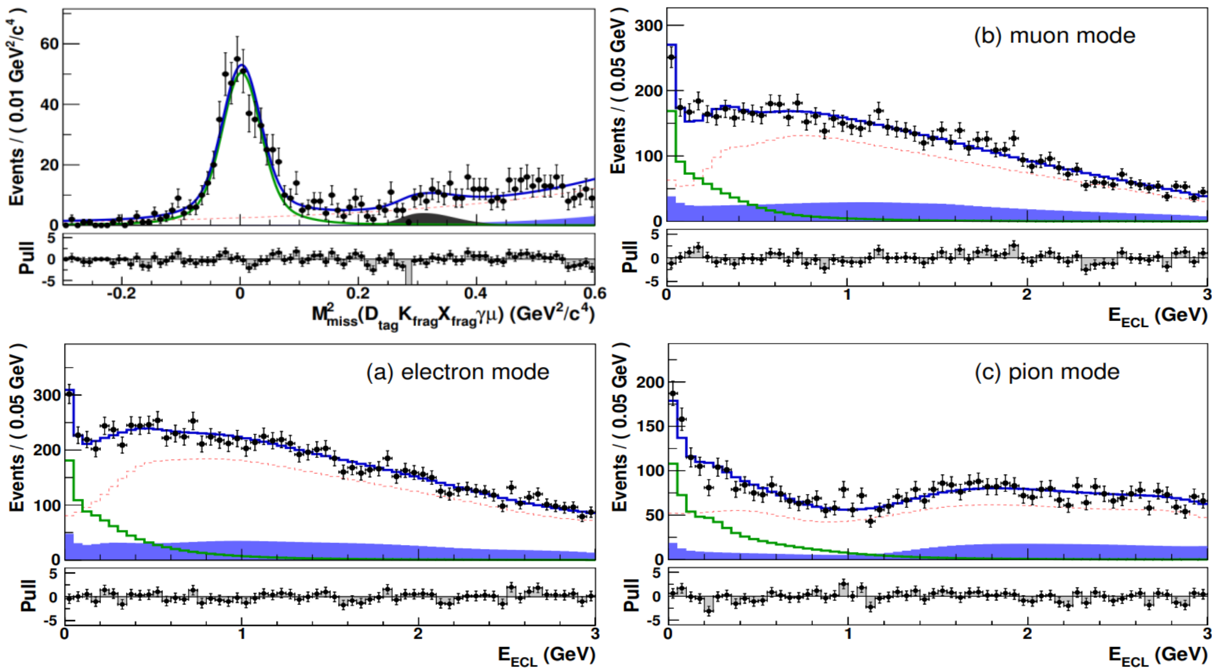


Decay chain	Reference	$N_{\rm sig}$	$\lvert V_{cd}\rvert$	Δ (%)
—	-	-		-
Decay chain	Reference	$N_{\rm sig}$	$\lvert V_{cs}\rvert$	Δ (%)
$D_s^+ \to \mu^+\nu_\mu$	JHEP1309(2013)139	492	$0.969 \pm 0.029 \pm 0.019$	3.6
$D_s^+ \to \tau^+\nu_\tau$ [1]	JHEP1309(2013)139	2206	$1.017 \pm 0.019 \pm 0.028$	3.3

1 $\tau^+ \to e^+\nu_e\bar{\nu}(\pi^+\bar{\nu}, \mu^+\nu_\mu\bar{\nu})$;

Data samples:

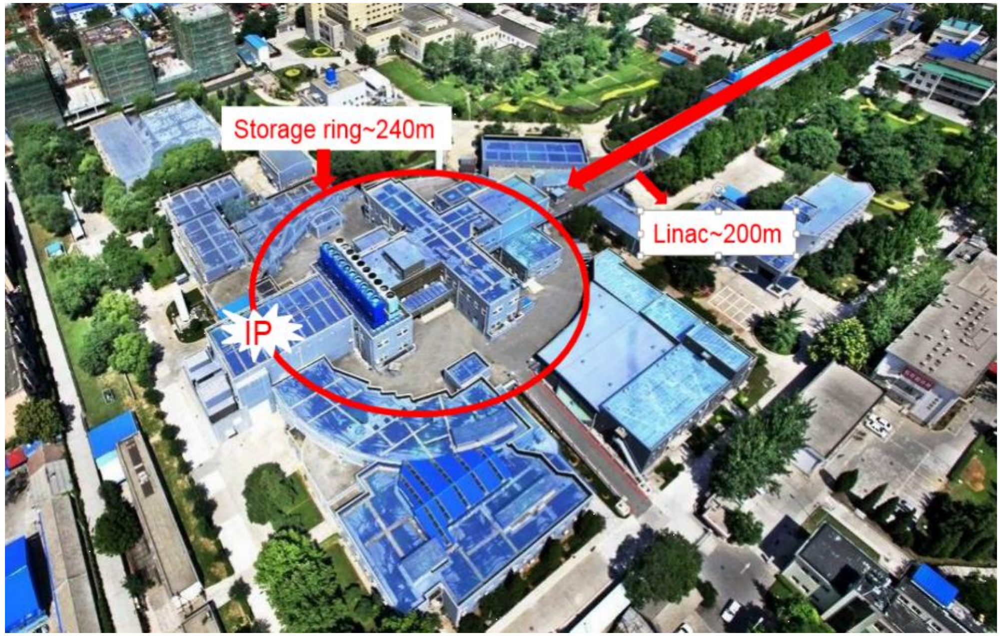
- 0.98 ab^{-1}@10.6 GeV (γ (4S))
- $\sigma(e^+e^- \to cc) = 1.3$ nb
- $L_{\rm peak} = 2 \times 34$ cm$^{-2}s^{-1}$

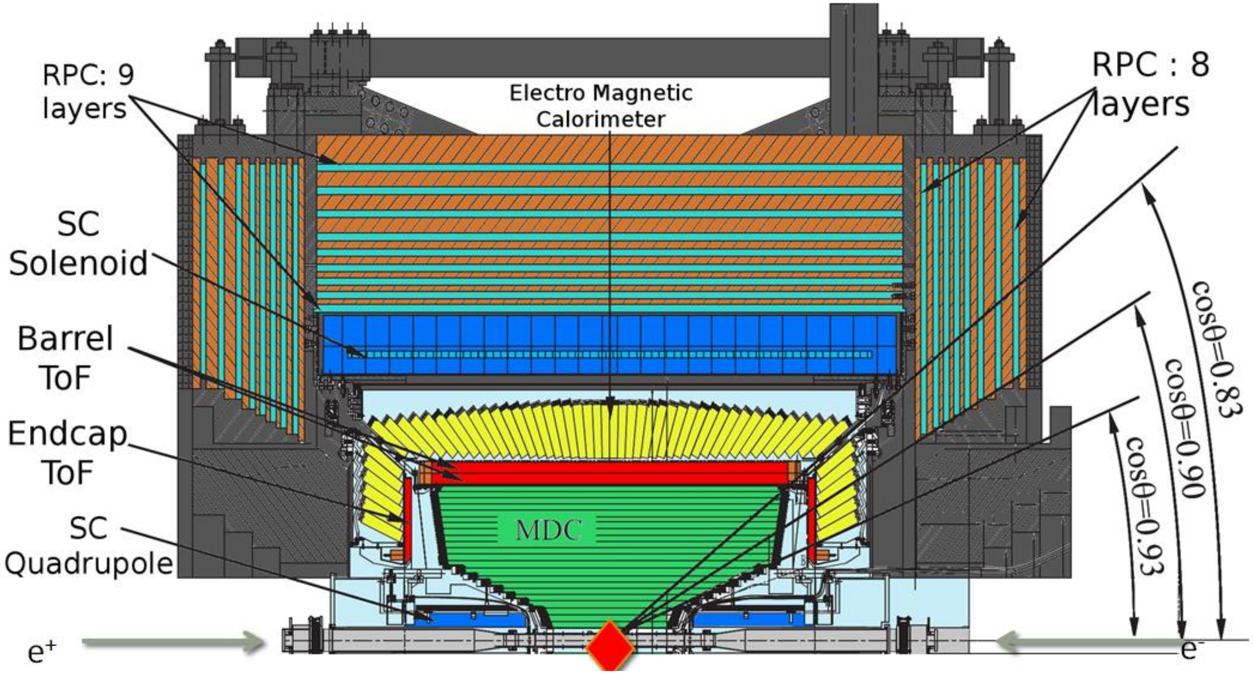


$\lvert V_{cd}\rvert$: --

$\lvert V_{cs}\rvert$: 3.3%

BESIII experiment



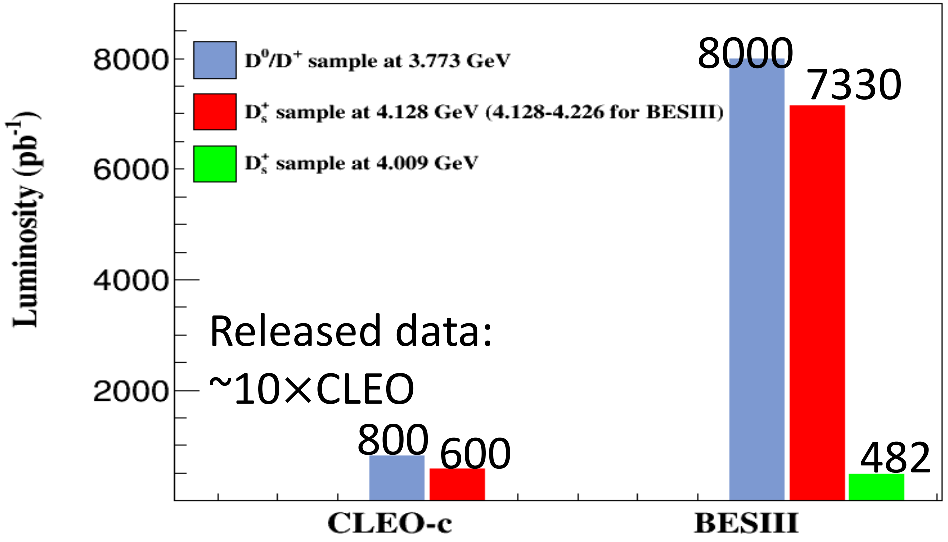


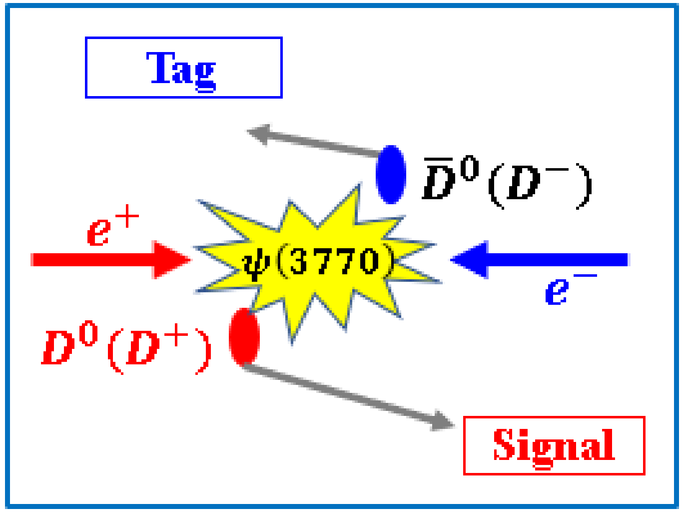
- E_{cm} : $\sqrt{s} = (2.0 - 4.95)$ GeV
- Designed luminosity (L):
  $1.00 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}}$ @ 3.89 GeV
- In 2022, L reach 1.1times of the designed L

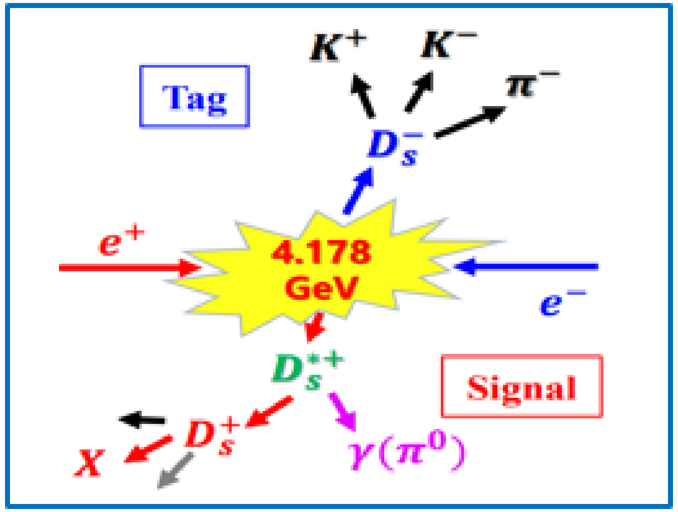
- MDC: $\sigma_p/p = 0.5\%$@ 1 GeV, $\sigma_{dE/dx} = 6\%$
- TOF: $\sigma_T = 68(110)$ ps for barrel (edncap); end cap TOF was upgraded in 2015→ 60 ps
- EMC: $\sigma_E/E = 2.5\%(5\%)$ ps for barrel (edncap)

In the future, E_{cm} will be updated to 4.95-5.6 GeV and the L will increase by 2-3 times

Data samples and double tag method







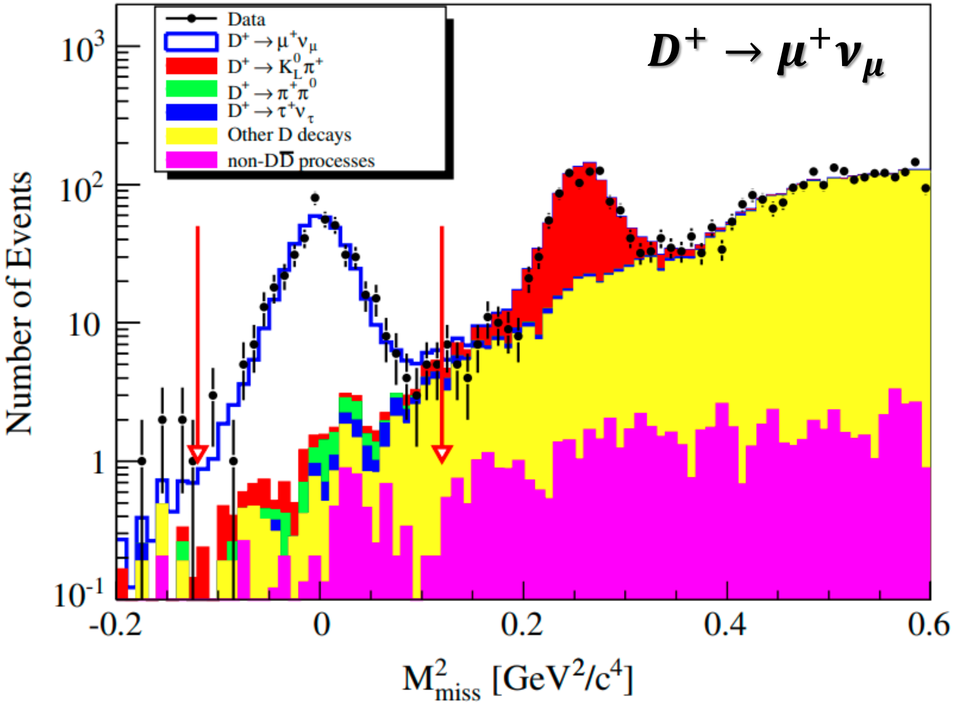
Candidates	E_{cm} (GeV)	Taking year	L (fb^{-1})	ST yield
$D^0\bar{D}^0$	3.773	2010-2011 (+2022)	2.93 (+4.98)	2.7 M×2.7
D^+D^-	3.773	2010-2011 (+2022)	2.93 (+4.98)	1.7 M×2.7
$D_s^+D_s^-$	4.009	2011	0.48	13K
$D_s^+D_s^{*-}$	4.13-4.23	2016,2017,2012,2019	7.33	8M
$\Lambda\bar{\Lambda}$	4.6-4.7	2014, 2020	4.5	0.12M

- Produced in pair → Double tag method
- Low background → low systematic uncertainties
- Quantum correlation for $\psi(3770) \to D^0\bar{D}^0$ pairs

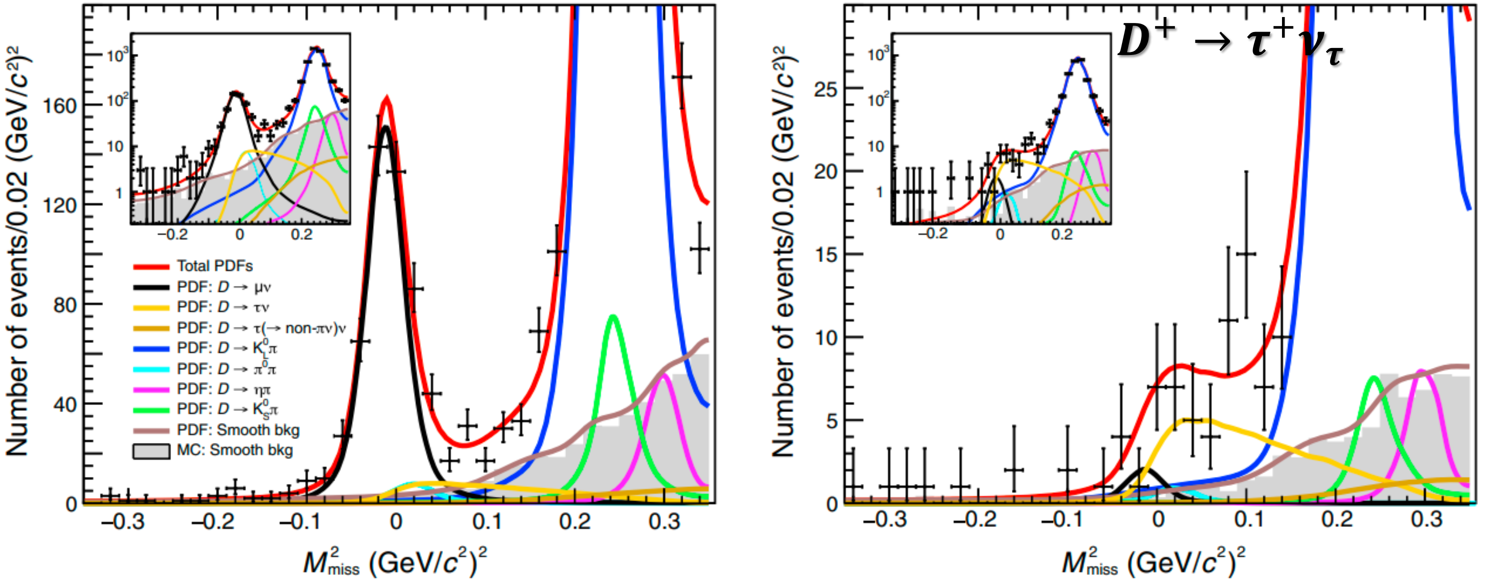
$|V_{cd}|$ from $D^+ \to \ell^+ \nu_\ell$

- Data Sample: 2.93 fb^{-1} @3.773 GeV (3.5× of CLEO-c) ; N_{ST}:~1.7 M

PRD89(2014)051104RC



PRL123(2019)211802



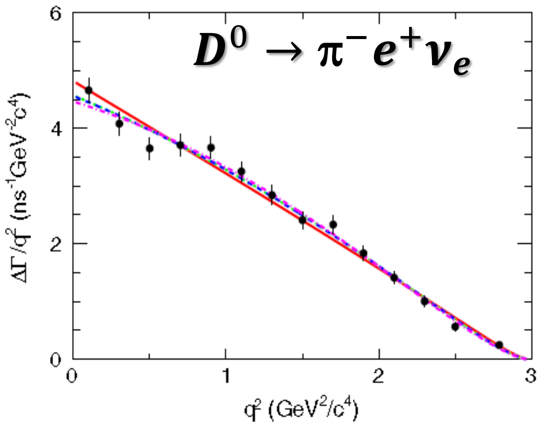
Simultaneous fit: μ^+-like (left) π^+-like (right)

- $N_{\text{sig}} = 409 \pm 21 \pm 2$
- $|V_{cd}| = (0.2210 \pm 0.0058_{\text{stat}} \pm 0.0047_{\text{syst}})$
- Precision of $|V_{cd}|$: 2.8%

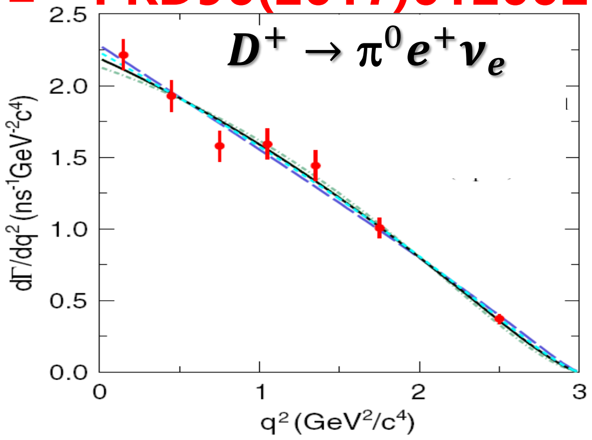
- $N_{\text{sig}} = 137 \pm 27$
- $|V_{cd}| = (0.237 \pm 0.024_{\text{stat}} \pm \pm 0.012_{\text{syst}} \pm 0.001_{\text{ex-syst}})$
- Precision of $|V_{cd}|$: 11.3%

$|V_{cd}|$ from $D^+ \to P\ell^+\nu_\ell$

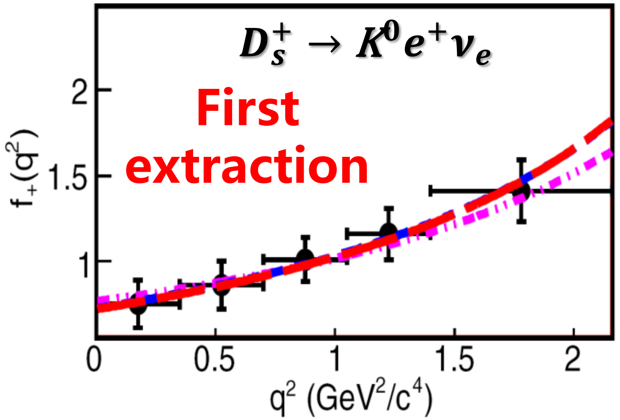
PRD92(2015)072012



PRD96(2017)012002

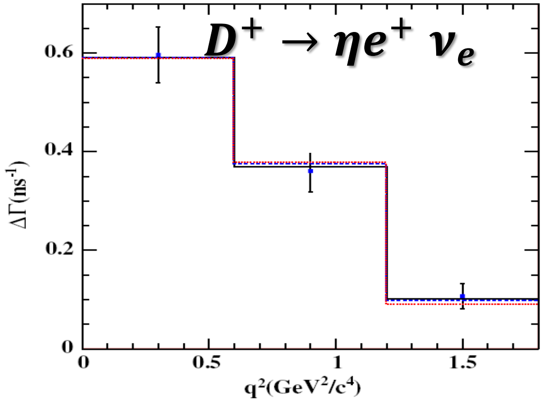


PRL122(2019)061801

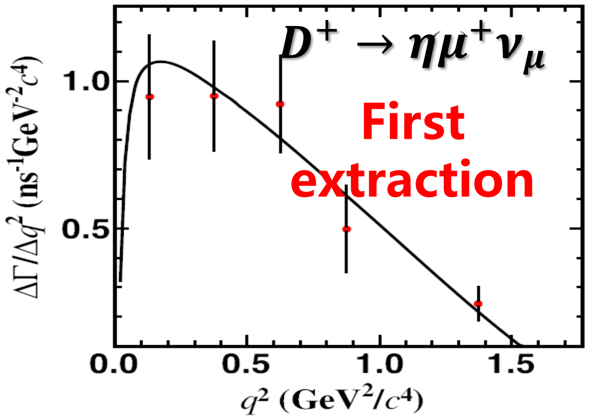


- 2.93 fb^{-1} @3.773 GeV; N_{ST}: ~1.7 M
- 3.19 fb^{-1} @4.178 GeV;

PRD97(2018)092009



PRL124(2020)231801



Reference	$f_+^\pi(0)\lvert V_{cd}\rvert$	$f_+^\pi(0)$	$\lvert V_{cd}\rvert$	Δ (%)
PRD92,072012	0.1435(18)(9)	0.6300(51)	0.2278(34)(23)	1.8
PRD96,012002	0.1413(35)(12)		0.2243(58)(26)	2.8
Reference	$f_+^K(0)\lvert V_{cd}\rvert$	$f_+^K(0)$	$\lvert V_{cd}\rvert$	Δ (%)
PRL122,061801	0.162(19)(3)	0.7452(31)	0.217(26)(4)	12.1
Reference	$f_+^\eta(0)\lvert V_{cd}\rvert$	$f_+^\eta(0)$	$\lvert V_{cd}\rvert$	Δ (%)
PRD97,092009	0.0815(45)(18)	0.36(5)	0.2264(338)(318)	20.5
PRL124,231801	0.087(8)(2)		0.242(41)(34)	21.8

(a) $f_+^\pi(0)$ and $f_+^K(0)$ are from PRD 107,094516 (2023).
(b) $f_+^\eta(0)$ is from Front. Phys. 14,64401 (2019).

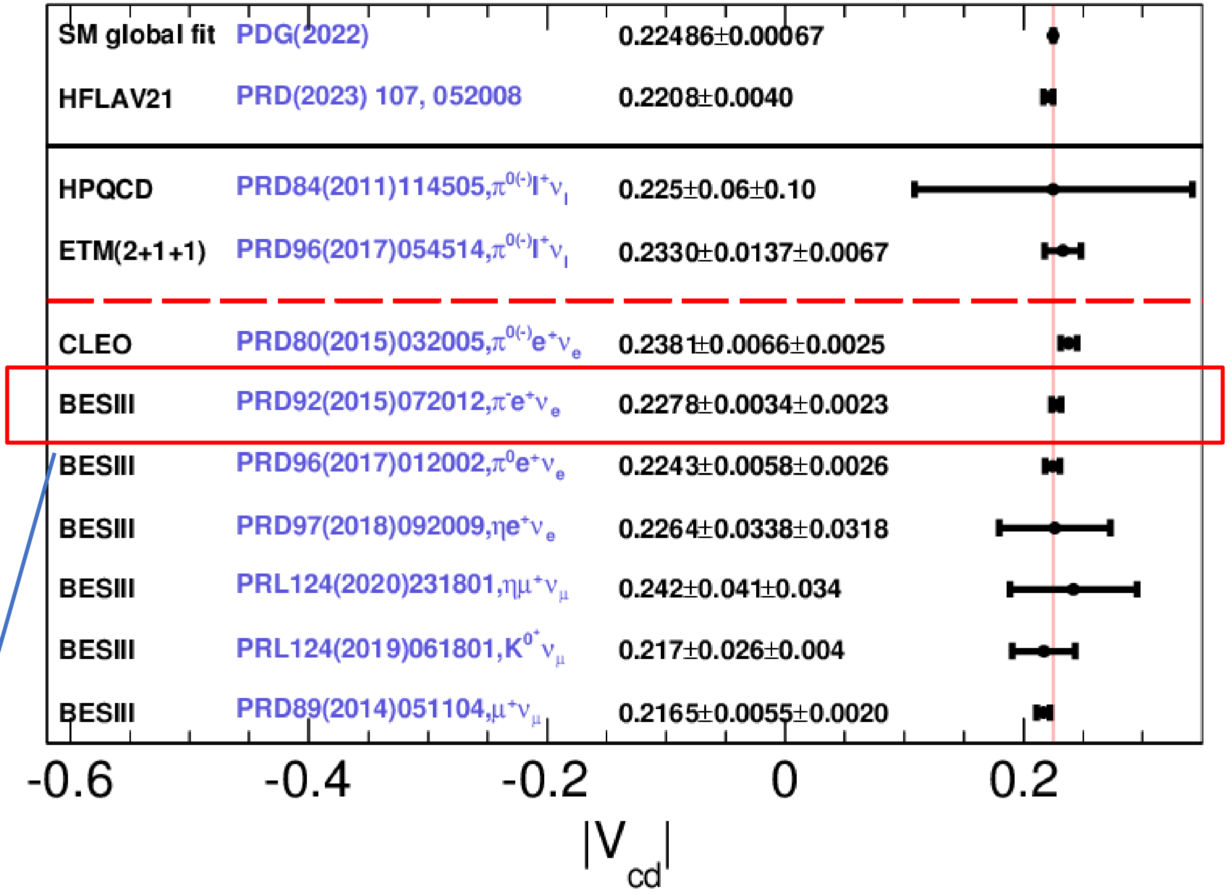
Comparison of $|V_{cd}|$

- With the values of $G_F, m_{D^+}, m_\tau, m_\mu$ [PDG2022]
- We use the following form factors as input to extra the CKM matrix elements

Reference	Form factor	Input value
EPJC82,869	f_{D^+}	212.7(0.7)
PRD107,094516	$f_+^\pi(0)$	0.6300(51)
PRD107,094516	$f_+^K(0)$	0.7452(31)
Front. Phys.14,64401	$f_+^\eta(0)$	0.36(5)

With the highest precision: 1.8%

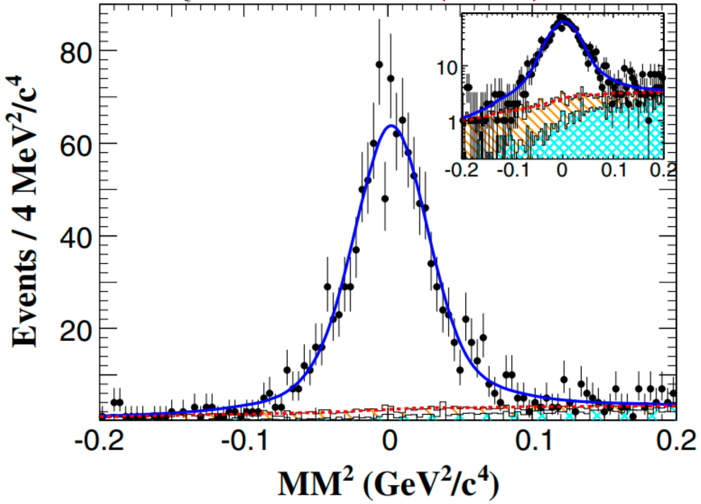
$f_+^{D\to\pi}(0)$@HPQCD[2021]
precision: 4.4%→0.8%



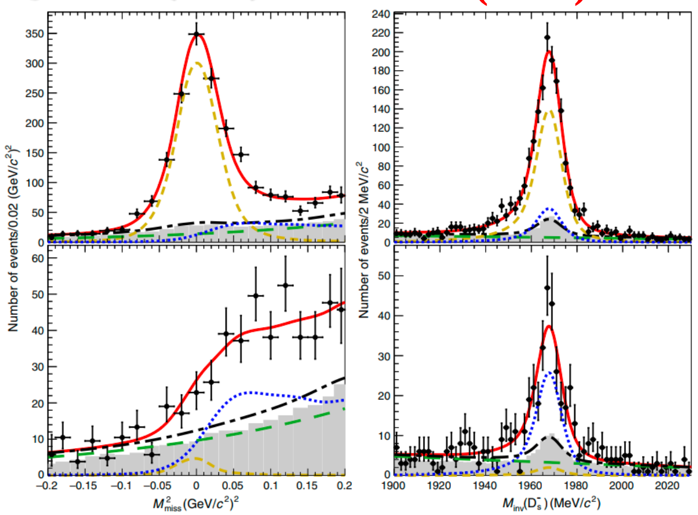
- The third uncertainty includes systematic uncertainty and uncertainty from LQCD
- Results from experimental consistent with the theoretical calculation.

$|V_{cs}|$ from $D_s^+ \to \ell^+ \nu_\ell$

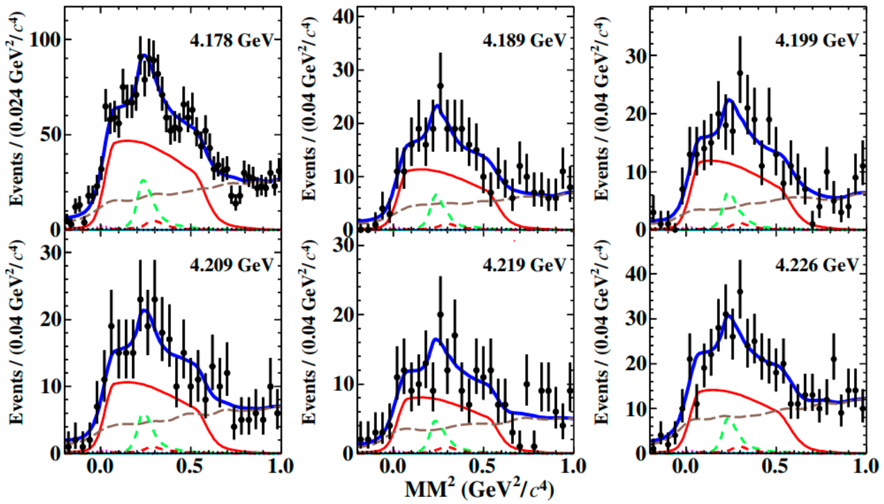
$D_s^+ \to \mu^+ v_\mu$ PRL122(2019) 071802



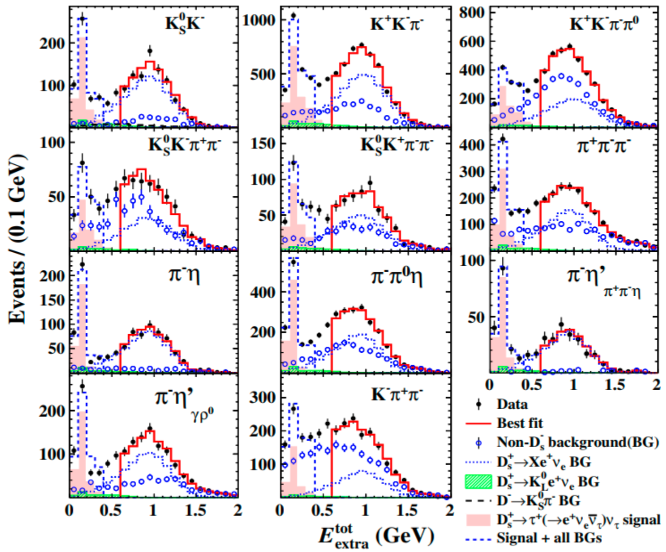
$D_s^+ \to \tau^+(\pi^+ v)v$ PRD104(2021)052009



$D_s^+ \to \tau^+(\rho^+ v)v$ PRD 104(2021)032001



$D_s^+ \to \tau^+(e^+ vv)v$ PRL127(2021) 0171801



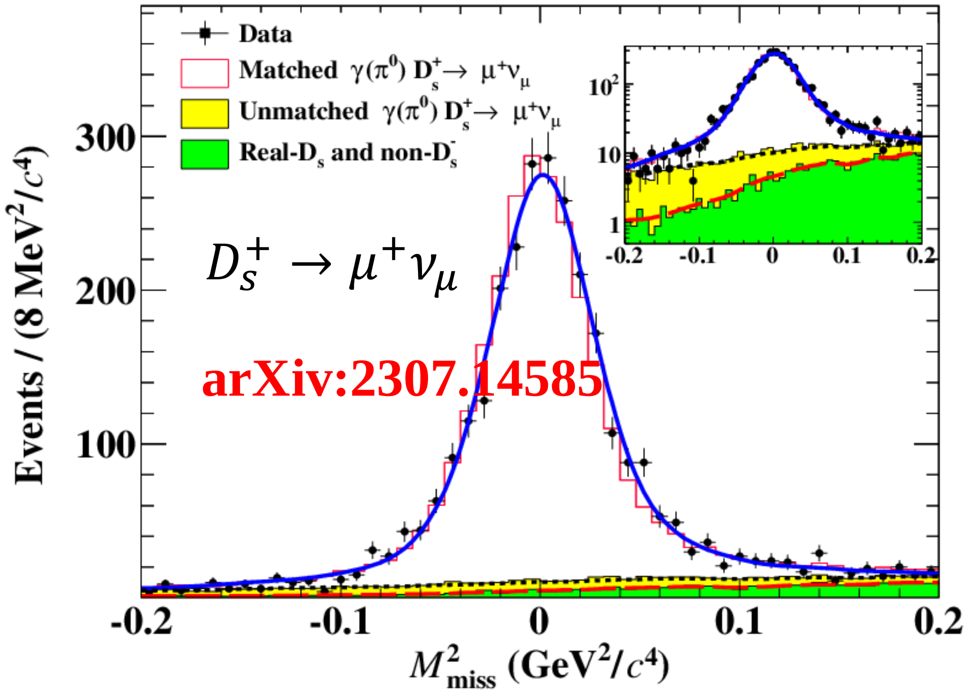
Reference	L/E_{cm} (fb^{-1}/GeV)	ℓ^+	N_{sig}	$\lvert V_{cs}\rvert$	Δ (%)
PRL122,071802	3.19/4.178	μ^+	1136 ± 33	0.985(14)(14)	2.0
PRD104,052009	6.32/4.178-4.226	μ^+	2198 ± 55	0.973(12)(15)(4)	2.0
PRD104,052009	6.32/4.178-4.226	$\tau^+{}_a$	956 ± 46	0.972(23)(16)(4)	2.9
PRD104,032001	6.32/4.178-4.226	$\tau^+{}_b$	1745 ± 84	0.981(44)(21)	3.1
PRL127,0171801	6.32/4.178-4.226	$\tau^+{}_c$	4940 ± 97	0.978(9)(12)	1.5

a $\tau^+ \to \pi^+\bar{\nu}$; **b** $\tau^+ \to \pi^+\pi^0\bar{\nu}$; **c** $\tau^+ \to e^+\nu_e\bar{\nu}$

PRL 127, 0171801 gives the $|V_{cs}|$ with the precision of 1.5%

New $|V_{cs}|$ from $D_s^+ \to \ell^+ \nu_\ell$

Three new works added more data sample taken at 4.128 GeV and 4.226 GeV

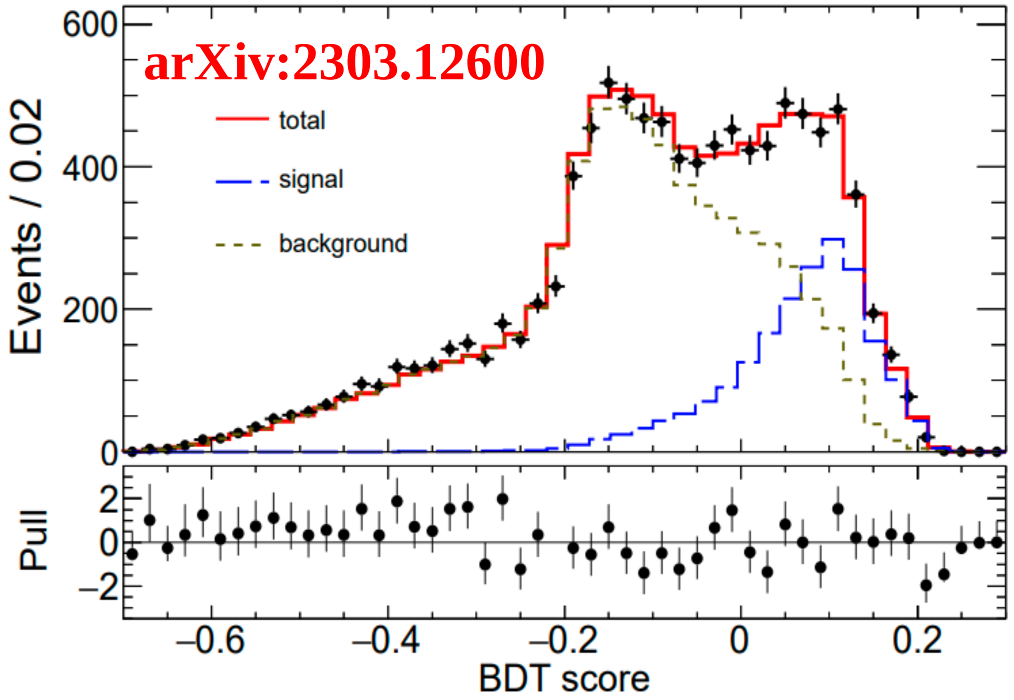


- Data sample: 7.33 fb^{-1} @ 4.128 – 4.226 GeV
- $N_{sig} = 2515 \pm 52$
- $f_{D_s^+}|V_{cs}| = (241.8 \pm 2.5_{stat} \pm 2.2_{syst})$ MeV
- $f_{D_s^+} = (248.4 \pm 2.5_{stat} \pm 2.2_{syst})$ MeV
- $|V_{cs}| = 0.968 \pm 0.010_{stat} \pm 0.009_{syst}$

Benefiting from a larger data sample, more tag modes, and measurement from MUC, $|V_{cs}|$ from this work with the highest Precision: 1.4%!

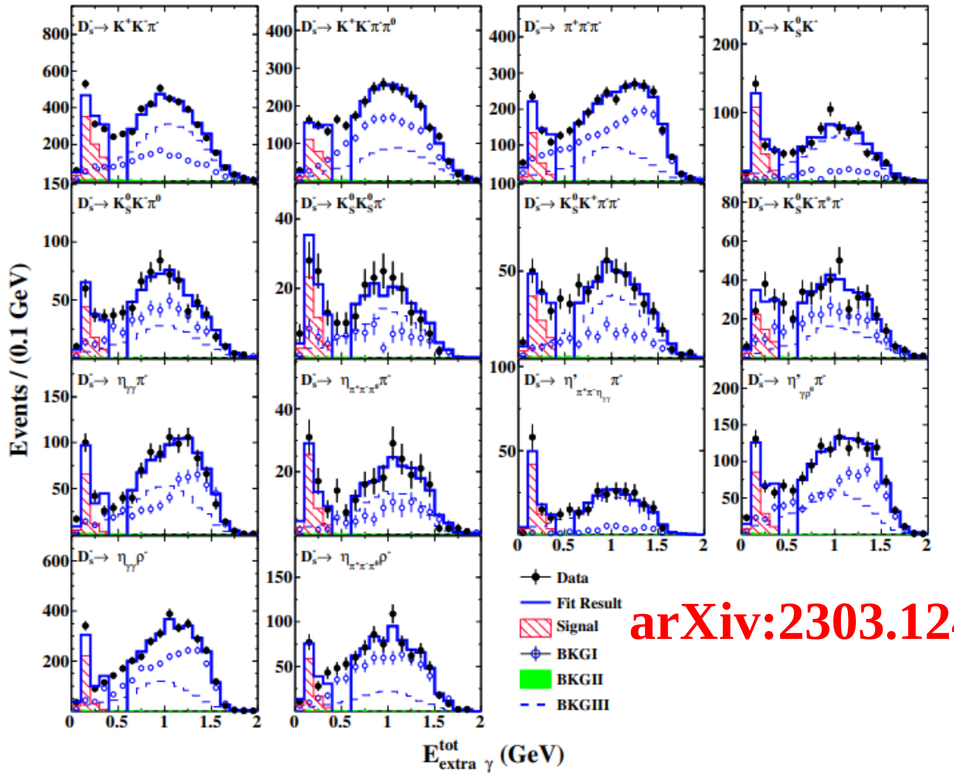
New $|V_{cs}|$ from $D_s^+ \to \ell^+\nu_\ell$

$D_s^+ \to \tau^+\nu_\tau, \tau^+ \to \pi^+\bar{\nu}$ with BDT method



$D_s^+ \to \tau^+\nu_\tau, \tau^+ \to \mu^+\nu_\mu\bar{\nu_\tau}$

Accepted by JHEP



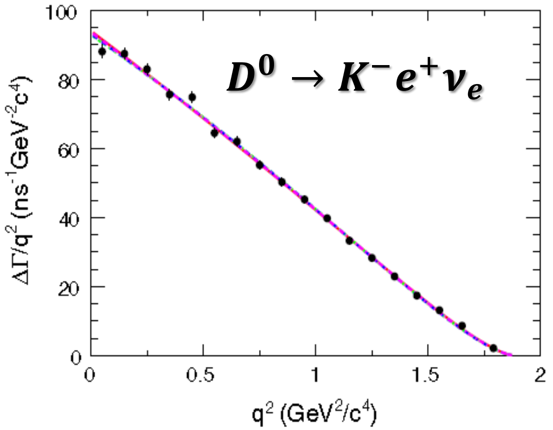
Benefiting from a larger data sample, more tag modes, and larger range of M^2_{miss}, the precision of $|V_{cs}|$ from arXiv:2303.12600 supersedes PRD 104, 052009(2021).

Reference	N_{sig}	$\lvert V_{cd}\rvert$	Δ (%)
arXiv:2303.12468	2285 ± 73	0.987(16)(14)	2.2
arXiv:2303.12600	2411 ± 75	0.993(15)(12)(4)	2.0

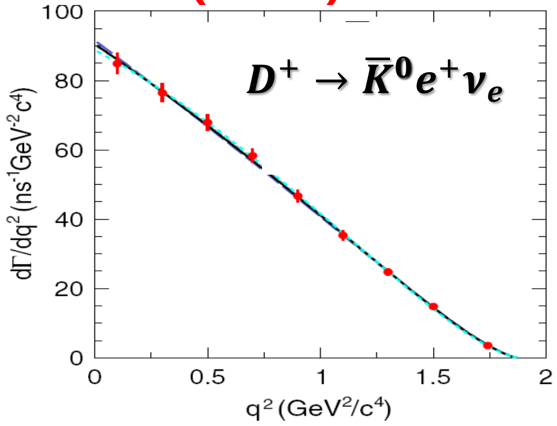
$|V_{cs}|$ from $D_s^+ \to P\ell^+\nu_\ell$

- 2.93 fb^{-1} @3.773 GeV; $N_{\rm ST}$: ~1.7 M

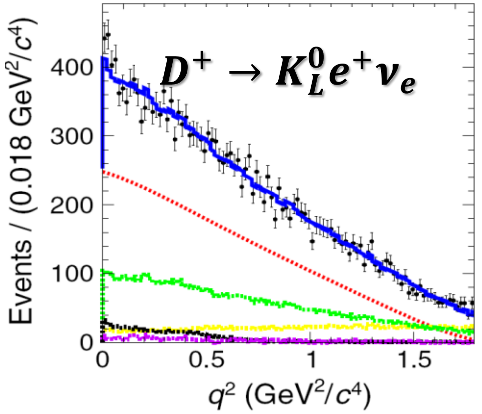
PRD92(2015)072012



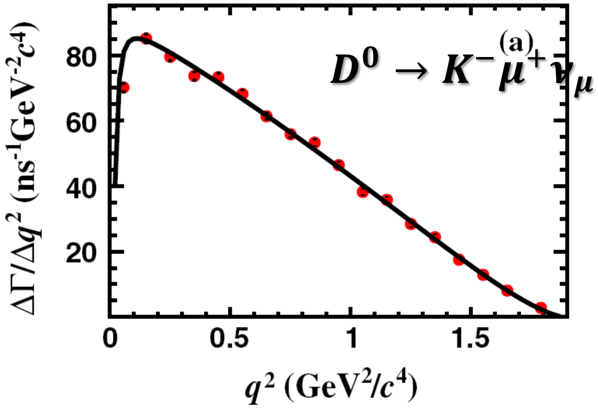
PRD96(2017)012002



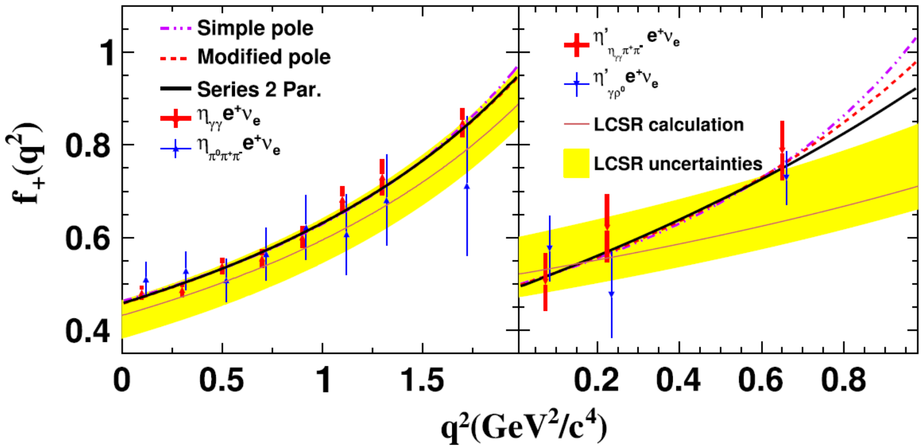
PRD92(2015)112008



PRL122(2019)011804



PRL123(2019)121801 $D_s^+ \to \eta^{(\prime)} e^+ \nu_e$



- 3.19 fb^{-1} @4.178 GeV;

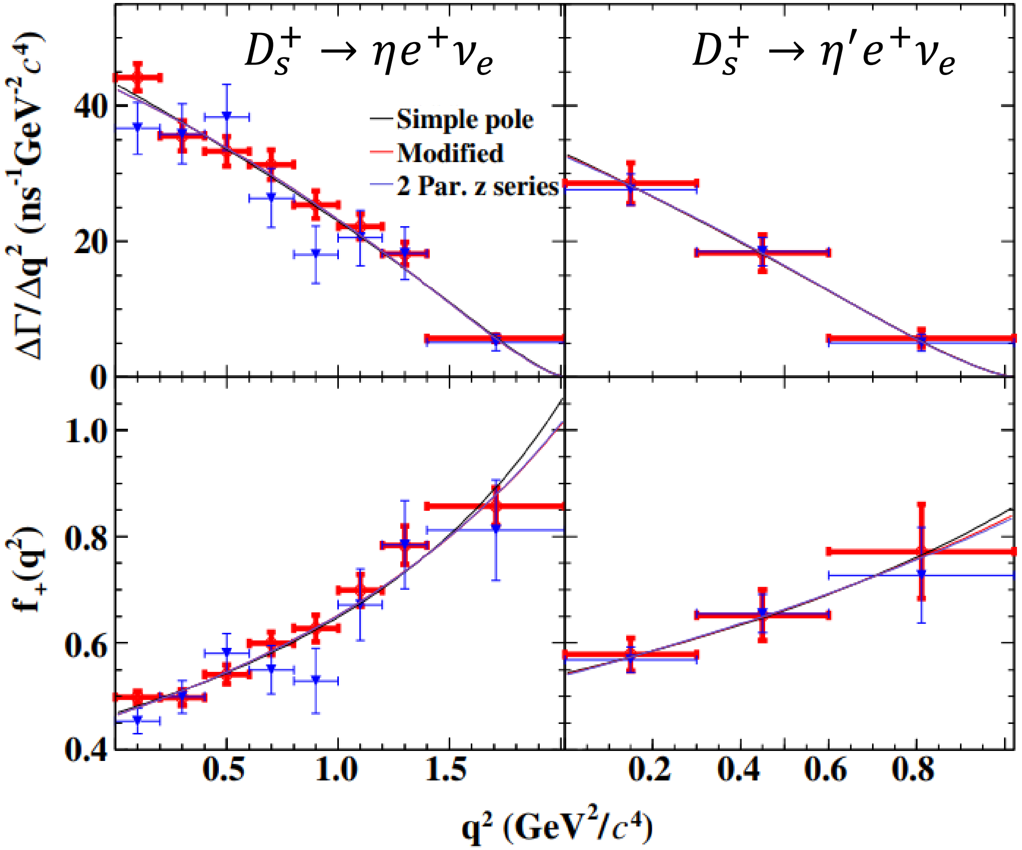
Reference	$f_+^K(0)\lvert V_{cs}\rvert$	$f_+^K(0)$	$\lvert V_{cs}\rvert$	Δ (%)
PRD92,072012	0.717(03)(04)	0.7452(31)	0.9622(57)(67)	0.9
PRD96,012002	0.705(04)(11)		0.9461(67)(153)	1.8
PRD92,112008	0.728(06)(11)		0.9769(90)(153)	1.8
PRL122,011804	0.7148(38)(29)		0.9592(65)(56)	0.9
Reference	$f_+^\eta(0)\lvert V_{cs}\rvert$	$f_+^\eta(0)$	$\lvert V_{cs}\rvert$	Δ (%)
PRL123,121801	0.446(10)(8)	0.495(5)	0.9010(582)(569)	9.0
Reference	$f_+^{\eta'}(0)\lvert V_{cs}\rvert$	$f_+^{\eta'}(0)$	$\lvert V_{cs}\rvert$	Δ (%)
PRL123,121801	0.477(100)(22)	0.558^{+47}_{-45}	$0.8548(1920)^{+821}_{-794}$	24.4

(a) $f_+^K(0)$ is from PRD 107,094516 (2023).
(b) $f_+^\eta(0)$ is from JHEP 11,138 (2015).
(c) $f_+^{\eta'}(0)$ is from JHEP 11,138 (2015).

New $|V_{cs}|$ from $D_s^+ \to P\ell^+\nu_\ell$

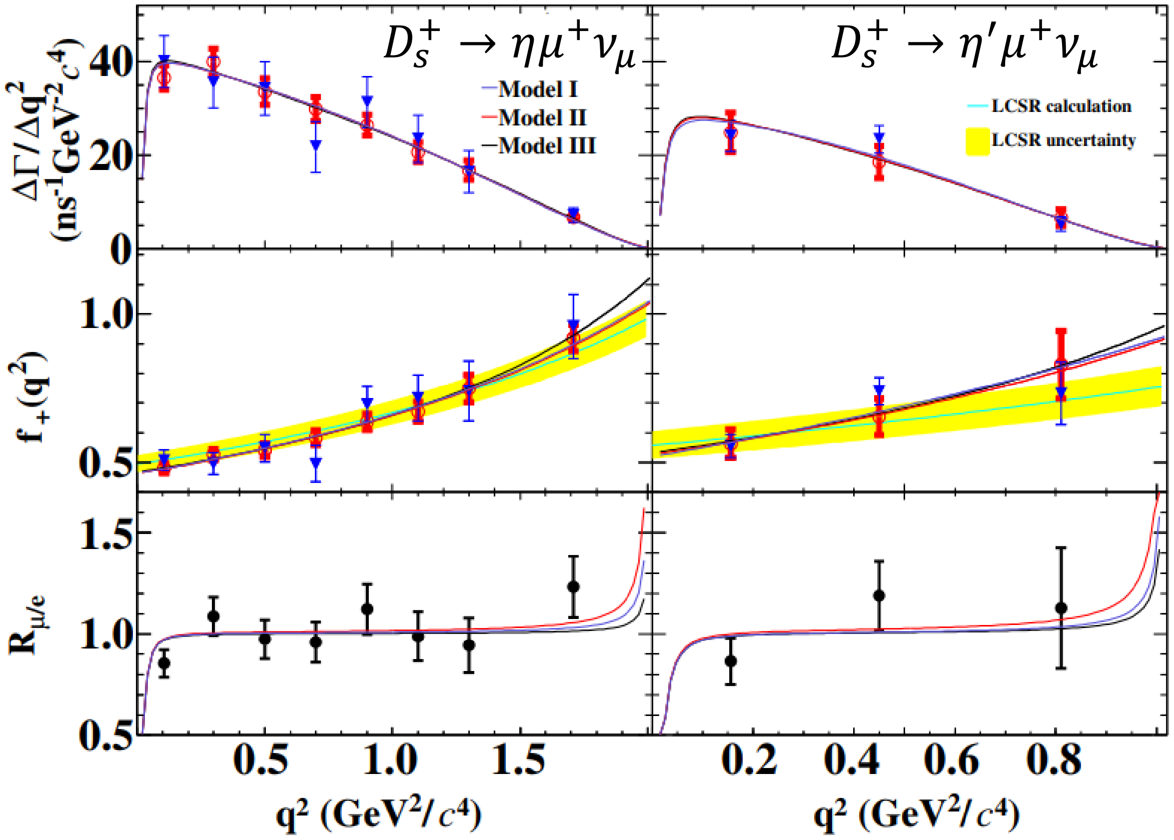
7.33 fb^{-1} @ 4.128 – 4.226 GeV

arXiv:2306.05194



- $|V_{cs}|_\eta = 0.913(14)(13)\,^{+55_{theo}}_{-53_{theo}}$ Δ: ~6.4%
- $|V_{cs}|_{\eta'} = 0.941(44)(16)\,^{+79_{theo}}_{-76_{theo}}$ Δ: ~9.6%

arXiv:2307.12852



- $|V_{cs}|_\eta = 0.911(20)(16)\,^{+55_{theo}}_{-53_{theo}}$ Δ: ~6.7%
- $|V_{cs}|_{\eta'} = 0.907(67)(19)\,^{+76_{theo}}_{-73_{theo}}$ Δ: ~11.2%

New $|V_{cs}|$ from $\Lambda_c^+ \to \Lambda \ell^+ \nu_\ell$

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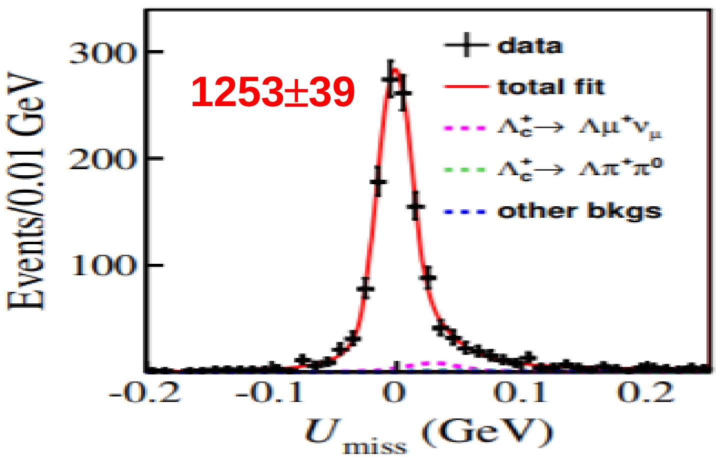
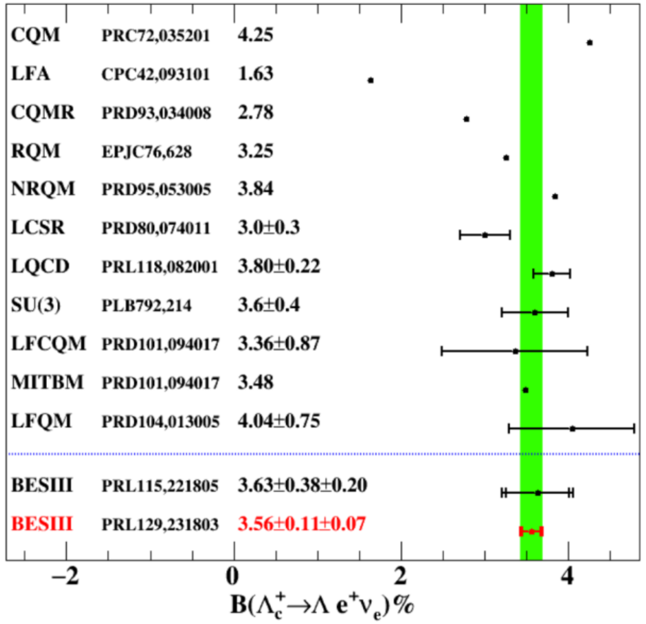
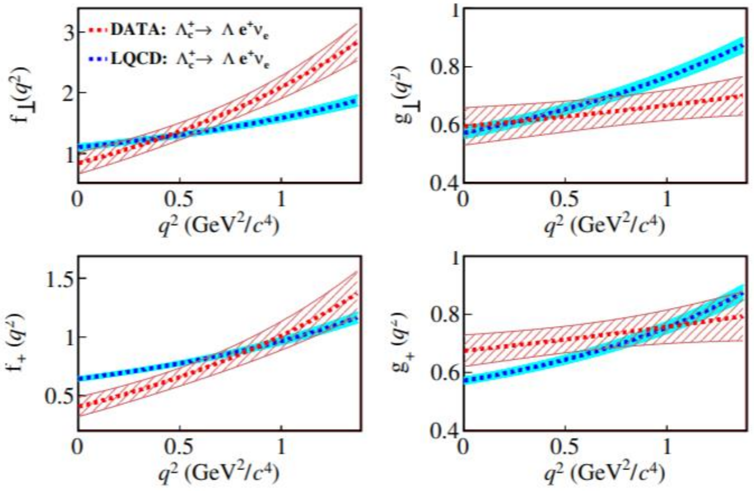
- 4.5 fb^{-1} @4.600 – 4.900 GeV

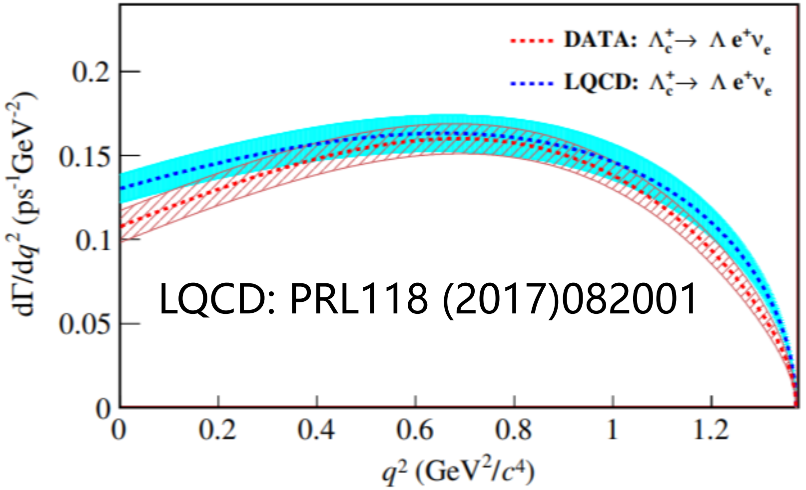




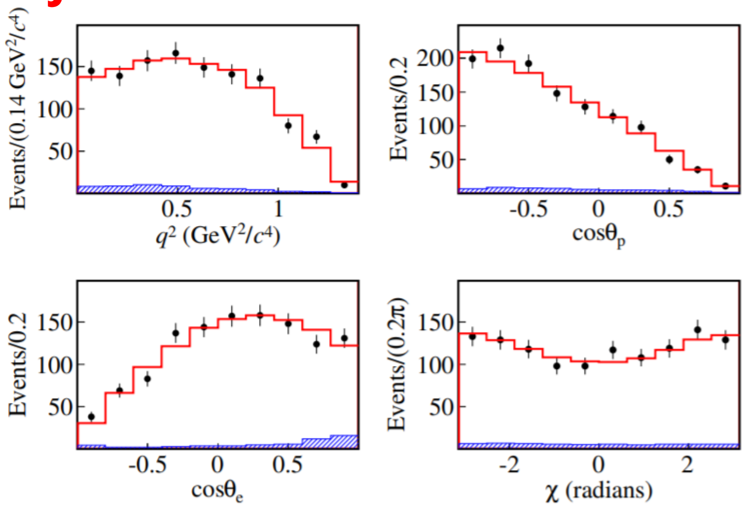
Projections on form factors



Compared to LQCD decay rates



Projections on kinematic variables



- $|V_{cs}| = 0.936(17)(24)(7)$

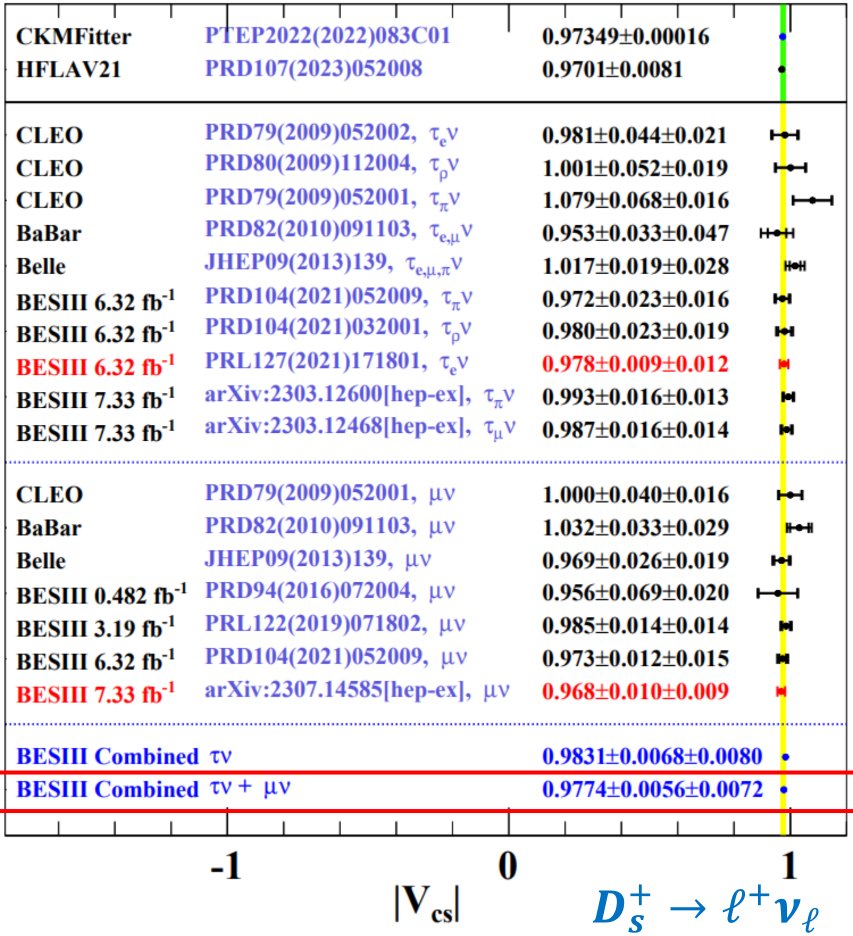
  Δ: ~3.2%

Provide the first direct comparisons of the differential decay rate and form factors with those predicted from LQCD

Comparison of $|V_{cs}|$

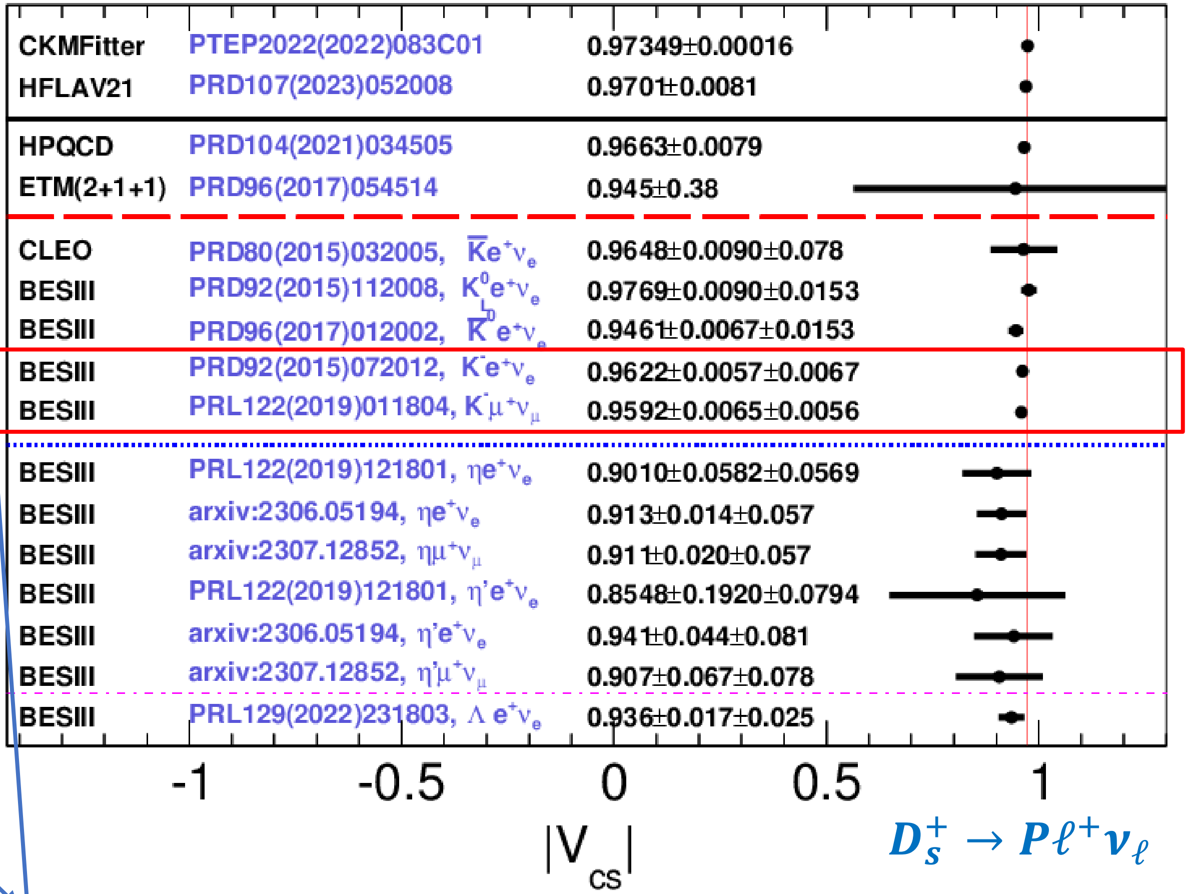
- With the values of $G_F, m_{D_s^+}, m_\tau, m_\mu$[PDG2022]
- Input $f_{D_s^+} = 249.9(0.5)$, $f_+^K(0) = 745.2(3.1)$, $f_+^\eta(0) = 0.495(5)$ and $f_+^{\eta'}(0) = 0.558(^{+47}_{45})$

$f_+^{D\to K}(0)$@HPQCD[2021]
precision: 2.4%→0.6%



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

With the highest precision: 0.9%



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

The third uncertainty includes systematic uncertainty and uncertainty from LQCD

Conclusions

- In recent two years, with 2.93 fb^{-1} @3.773 GeV and 7.33 fb^{-1} @4.128-4.226 GeV data samples, BESIII have systematically studied leptonic and semi-leptonic decays.
- The precision of $|V_{cd}|$ and $|V_{cs}|$ are improved to 1.8% and 0.9% at experiment, respectively.
- Data coming：
  - 5 fb^{-1} @3.773 GeV data taken in 2022 (ready)
  - 8 fb^{-1} @3.773 GeV data taken in 2023 (undergoing)
  - 4 fb^{-1} @3.773 GeV data taken in 2024 (to be ready)
- Precision of $|V_{cs}|$ and $|V_{cd}|$ will be further improved with the total 20 fb^{-1} @3.773 GeV data sample.

Thanks for your listening
and thanks for the local committee!