(Semi-) leptonic decays of $D_{(s)}^{+}$ at BESIII

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(On behalf of BESIII Collaboration)

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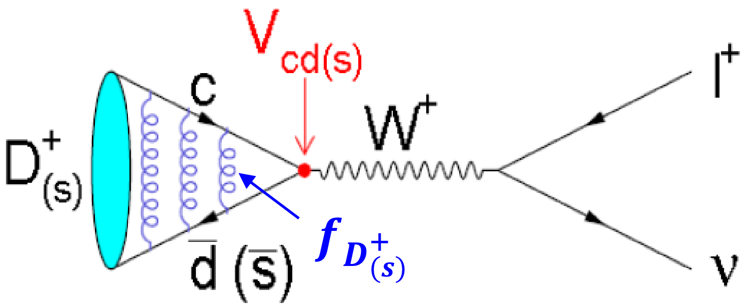
Outline

- Introduction
- Pure leptonic decay: $D_s^+ \to \mu^+ \nu_\mu$
- Semi-leptonic decay:
  - $D_s^+ \to \eta^{(\prime)} e^+ \nu_e$
  - $D_s^+ \to K^{(*)0} e^+ \nu_e$
  - $D^{0(+)} \to \pi^{-(0)} \mu^+ \nu_\mu$
  - $D^0 \to K^- \mu^+ \nu_\mu$
  - $D^{0/+} \to a_0(980)^{-/0} e^+ \nu_e$
  - $D^{+/0} \to \pi^- \pi^{+/0} e^+ \nu_e$
- Summary

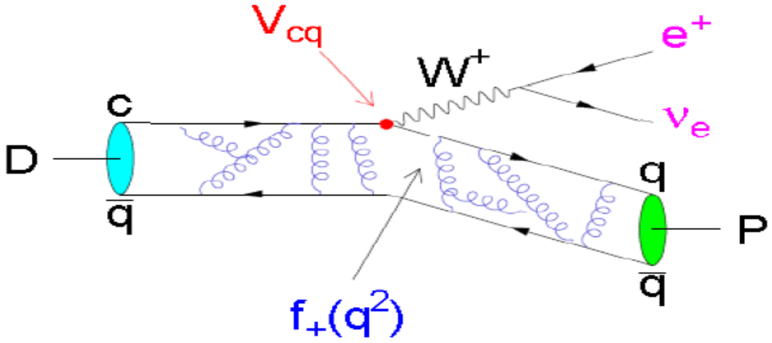
Main goals

$D_{(s)}$ pure leptonic decay



$$\Gamma(D^+_{(s)} \to l^+\nu_l) \propto \left|f_{D^+_{(s)}}\right|^2 \cdot \left|V_{cd(s)}\right|^2$$

$D_{(s)}$ semi-leptonic decay

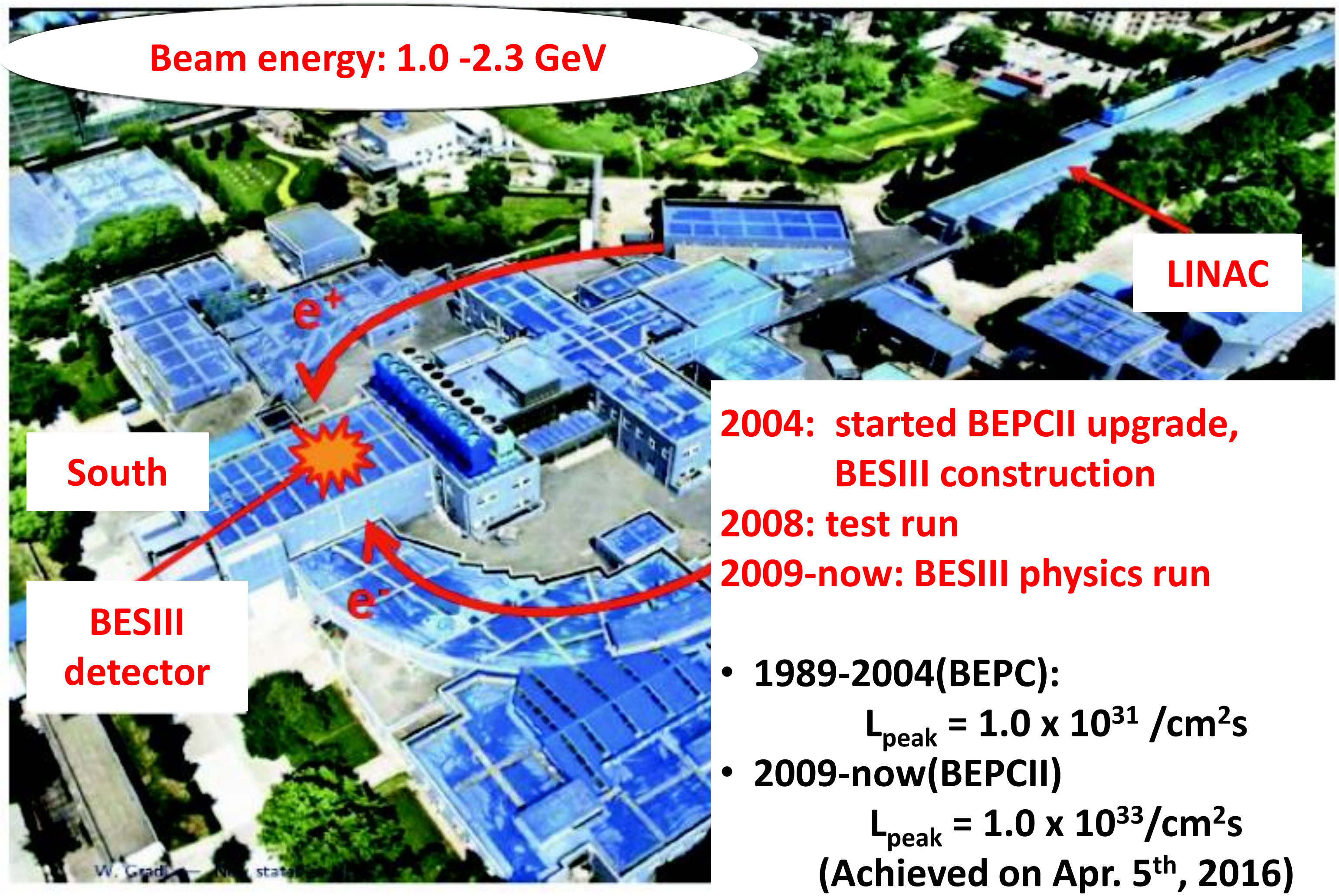


$$\Gamma\left(D_{(s)} \to P\, l^+\, \nu_l\right) \propto \left|f_+^{K(\pi)}(q^2)\right|^2 \cdot \left|V_{cd(s)}\right|^2$$

- **Decay constant $f_{D_s^+}$, form factor $f_+^K(0)$: better calibrate Lattice QCD;**
- **CKM matrix element $|V_{cs}|$: better test the unitarity of the CKM matrix;**
- **Lepton flavor universality test.**

Beijing Electron Positron Collider (BEPCII) in China

A double-ring collider with high luminosity



Beam energy: 1.0 -2.3 GeV

2004: started BEPCII upgrade,
BESIII construction
2008: test run
2009-now: BESIII physics run

- 1989-2004(BEPC):
  L_{peak} = 1.0 x 10^{31} /cm^{2}s
- 2009-now(BEPCII)
  L_{peak} = 1.0 x 10^{33}/cm^{2}s
  (Achieved on Apr. 5th, 2016)

BESIII detector

Nucl. Instr. Meth. A614, 345(2010)

From inner to outside:

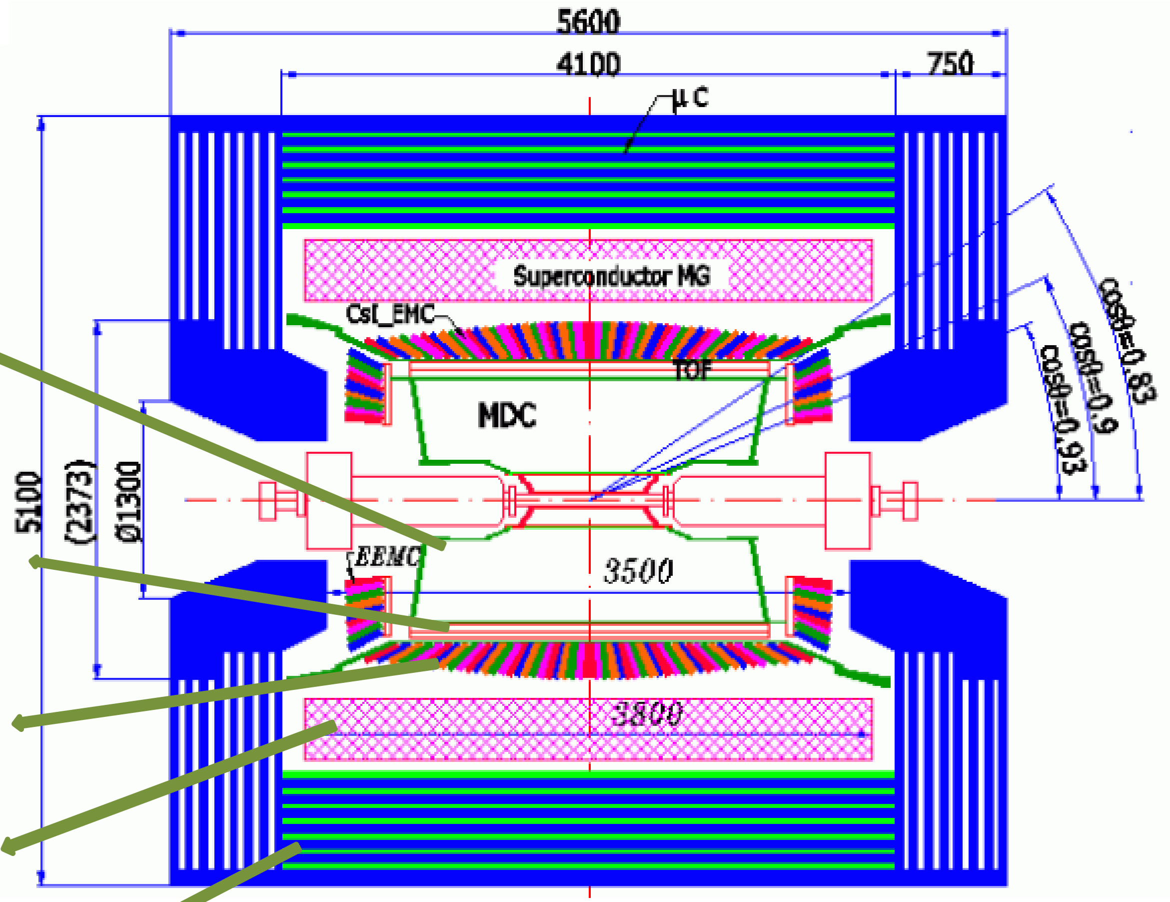
MDC: small cell & Gas:He/C_3H_8(60/40), 43 layers; σ_{xy} = 130 μm ; σ_p/p = 0.5% @1 GeV; dE/dx = 6%

TOF: σ_T = 100 ps Barrel, 110 ps Endcap

EMC: CsI crystal, 28 cm; $\Delta E/E$ = 2.5% @1 GeV ; σ_z = 0.6 cm/√E

Magnet: 1T Super conducting

MUC: 9 layers RPC, 8 layers for endcaps



Data Acquisition:
Event rate = 4k Hz
Total data volume ~ 50 MB/s

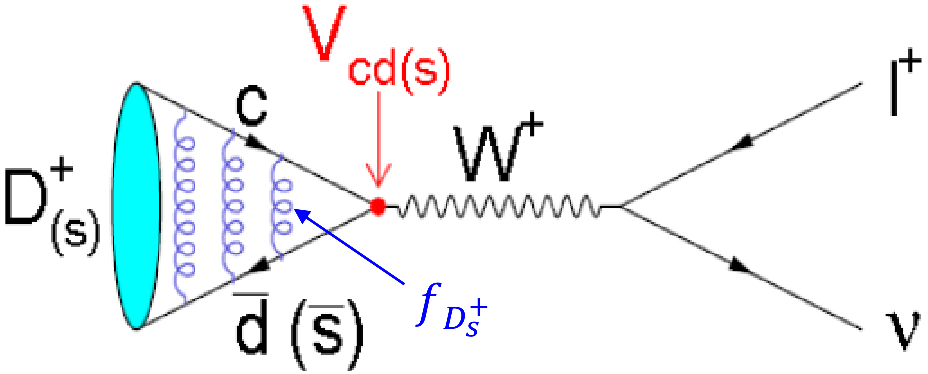
$D^{0(+)}$ and D_s^+ data set at BESIII

- $D^{0(+)}$ data:
  - Taken @ E_{cms} = 3.773 GeV
  - Integrated luminosity = 2.93 fb^{-1}

    (The world's largest e^+e^-annihilation sample taken at the mass-threshold)
  - cross section: $\sigma(e^+e^- \to D^0\bar{D}^0)$ ~ 3.6 nb ⇒ 21 M D^0 produced!
  - cross section: $\sigma(e^+e^- \to D^+D^-)$ ~ 2.9 nb ⇒ 16 M D^+ produced!

- D_s^+ data:
  - @ E_{cms} = 4.009 GeV
    - Integrated luminosity = 0.482 fb^{-1}
    - $\sigma(e^+e^- \to D_s^+D_s^-)$ ~ 0.3 nb ⇒ 0.3 M D_s produced
    - D_s is produced in pair with equal mass
  - @ E_{cms} = 4.178 GeV.
    - Based on the data accumulated in 2016!
    - Integrated luminosity = 3.19 fb^{-1}
    - $\sigma(e^+e^- \to D_s^*D_s)$ ~ 1 nb ⇒ ~ 6 M D_s produced!!

D_s^+ pure leptonic decay



In the SM: $$\Gamma(D_{(s)}^+ \to l^+\nu) = \frac{G_F^2 f_{D_{(s)}^+}^2}{8\pi} \left|V_{cd(s)}\right|^2 m_l^2 m_{D_{(s)}^+} \left(1 - \frac{m_l^2}{m_{D_{(s)}^+}^2}\right)^2$$

Measure the product of $f_{D_s^+}$ and $|V_{cs}|$ directly

Bridge to precisely measure

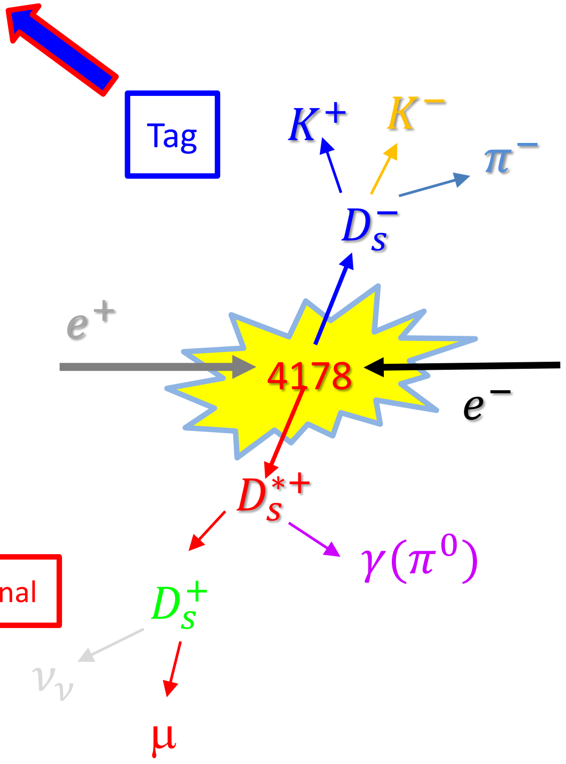
- Decay constant $f_{D_s^+}$ with input $|V_{cs}|^{\mathrm{CKMfitter}}$
- CKM matrix element $|V_{cs}|$ with input $f_{D_s^+}^{\mathrm{LQCD}}$

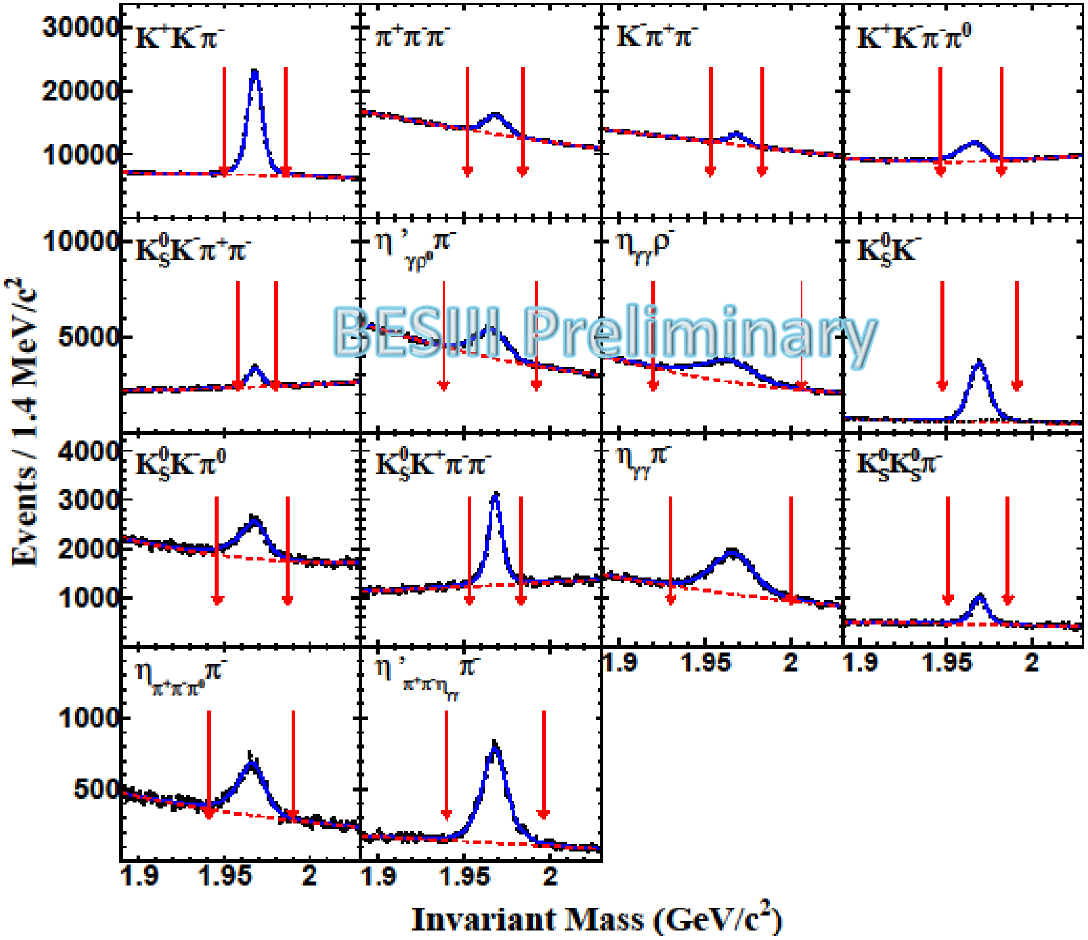
$D_s^+ \to \mu^+ \nu_\mu$

$e^+e^- \to D_s^{*+} D_s^-$ **3.19 fb^{-1} @4.178 GeV**

$$M_{rec} = \sqrt{\left(E_{cm} - \sqrt{|\vec{p}_{D_s^-}|^2 + m_{D_s^-}^2}\right)^2 - |-\vec{p}_{D_s^-}|^2}$$

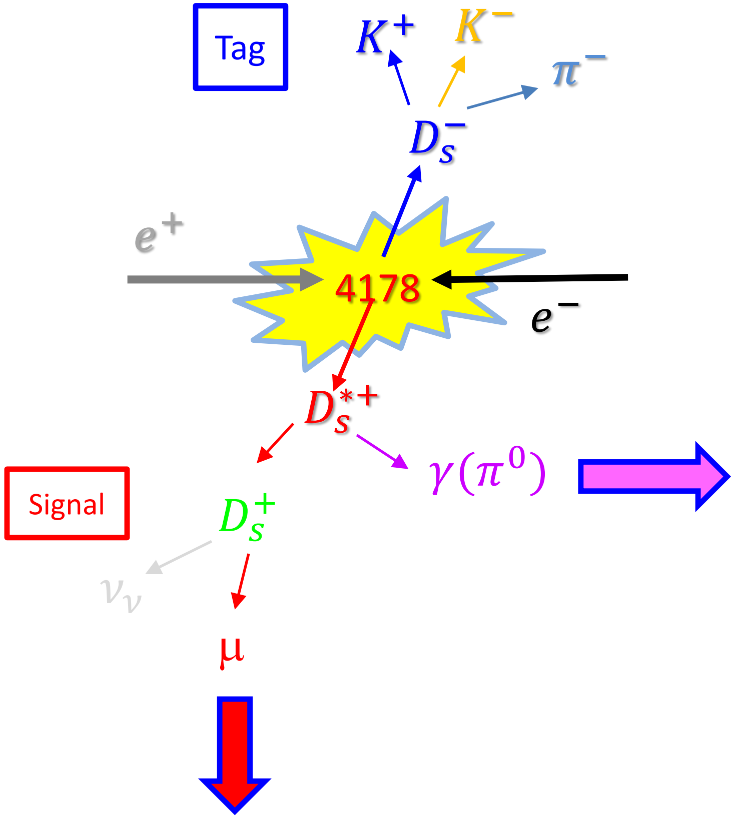
: closest to the D_s^* nominal mass





From 14 decays, we obtain about 0.389M ST D_s^- mesons

Charge conjugated processes are implied



Minimum $|\Delta E|$:

$$\Delta E \equiv E_{cm} - E_{tag} - E_{miss} - E_{\gamma(\pi^0)}$$

$$E_{\text{miss}} = \sqrt{|\vec{p}_{miss}|^2 + m_{D_s^+}^2}$$

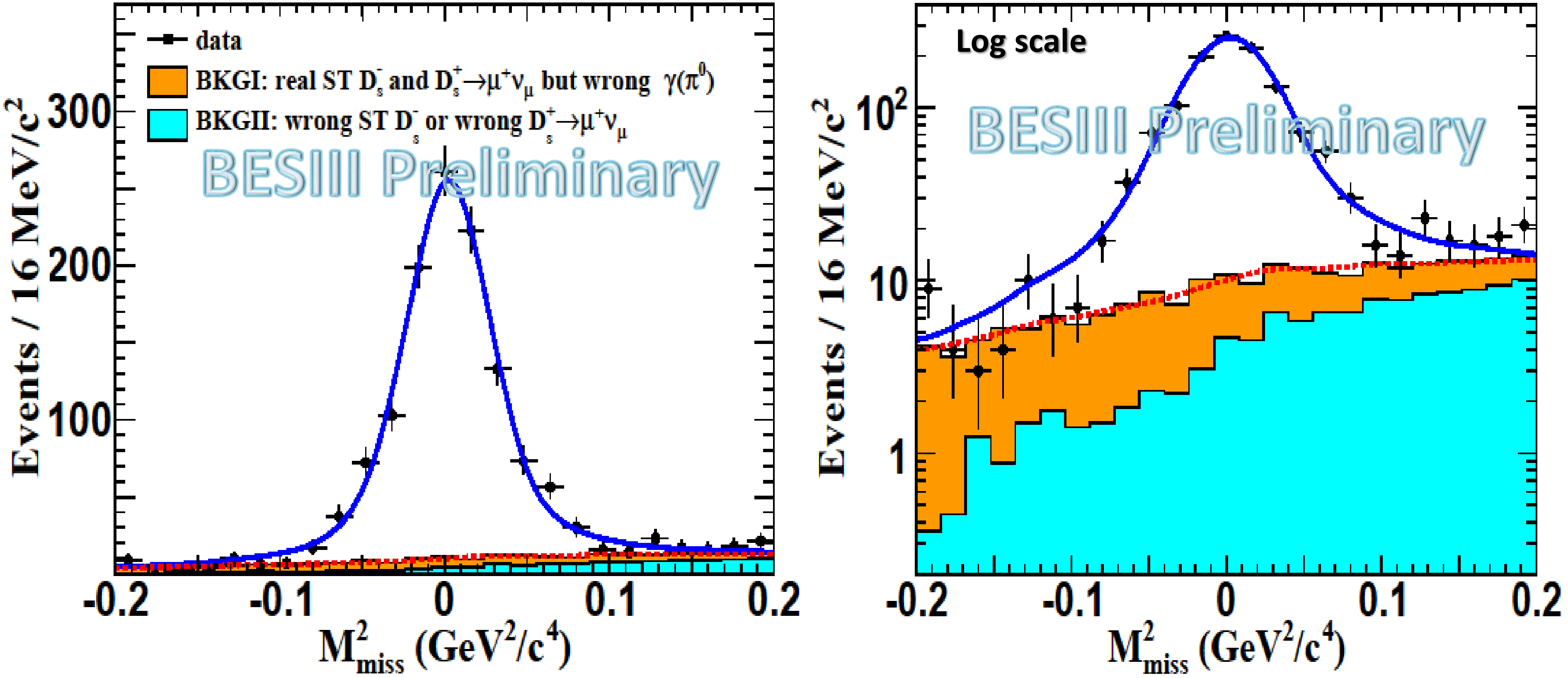
$$\vec{p}_{\text{miss}} = -\vec{p}_{tag} - \vec{p}_{\gamma(\pi^0)}$$

$$M_{miss}^2 = \left(E_{cm} - E_{tag} - E_{\gamma(\pi^0)} - E_\mu\right)^2 - \left|-\vec{p}_{tag} - \vec{p}_{\gamma(\pi^0)} - \vec{p}_\mu\right|^2$$

4C + D_s^+, D_s^-, D_s^* nominal mass constraint

Fitting result of M^2_{miss}

Unbinned fit



- M^2_{miss} **fit:**

1. Constraining signal/BKGI ratio via signal MC
2. Fixing BKGII via inclusive MC

$$N(D_s^+ \to \mu^+ \nu) = 1135.0 \pm 33.1$$

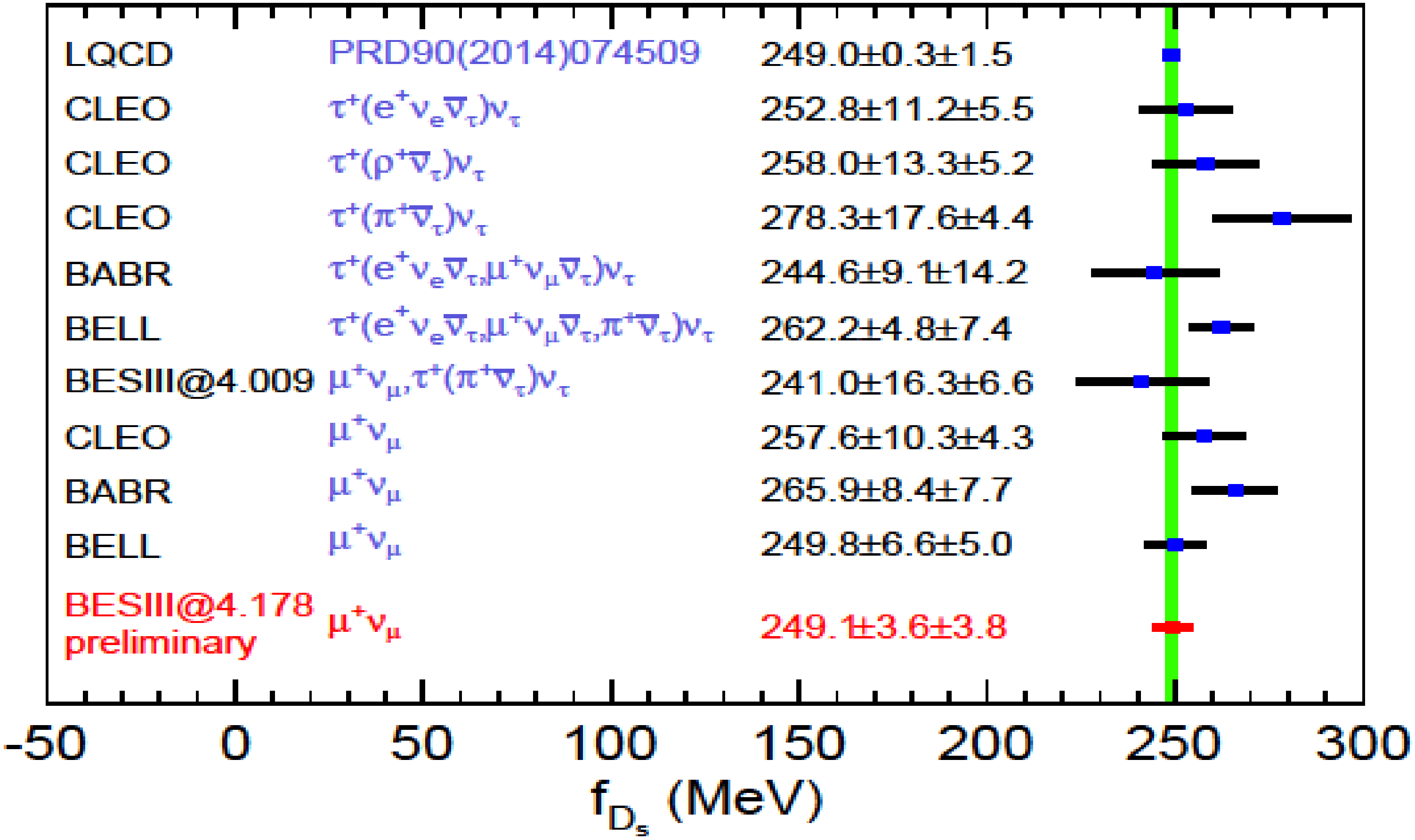
$$B(D_s^+ \to \mu^+ \nu) = (5.28 \pm 0.15 \pm 0.14) \times 10^{-3}$$

Comparisons of $f_{D_s^+}$

$$f_{D_s^+}|V_{cs}| = 242.5 \pm 3.5_{\text{stat.}} \pm 3.7_{\text{syst.}}\ \text{MeV}$$

- **Taking $|V_{cs}|^{\text{CKMfitter}}$ as input, we obtain**

$$f_{D_s^+} = 249.1 \pm 3.6_{\text{stat.}} \pm 3.8_{\text{syst.}}\ \text{MeV}$$



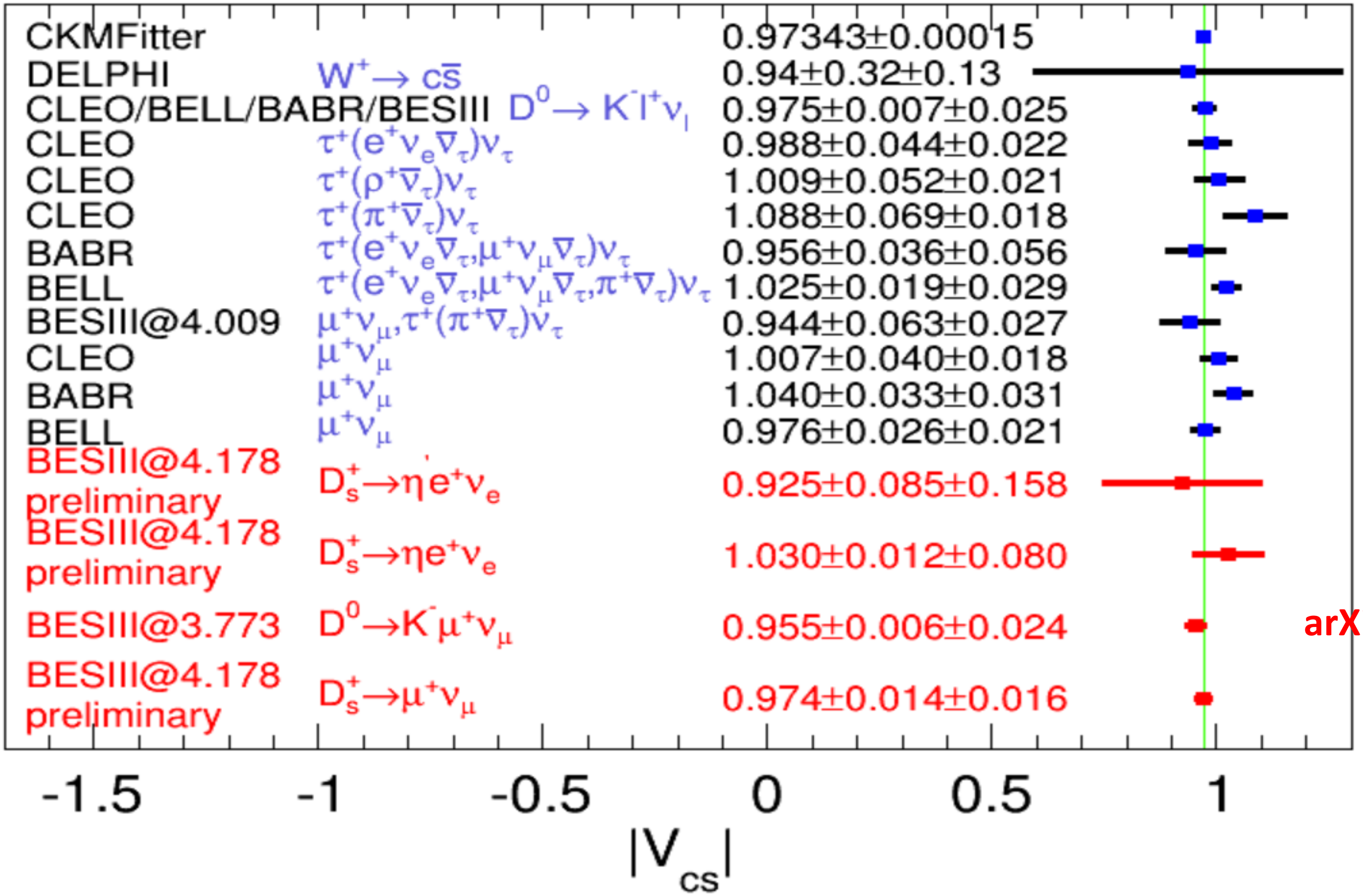
LQCD	PRD90(2014)074509	249.0±0.3±1.5
CLEO	$\tau^+(e^+\nu_e\bar{\nu}_\tau)\nu_\tau$	252.8±11.2±5.5
CLEO	$\tau^+(\rho^+\bar{\nu}_\tau)\nu_\tau$	258.0±13.3±5.2
CLEO	$\tau^+(\pi^+\bar{\nu}_\tau)\nu_\tau$	278.3±17.6±4.4
BABR	$\tau^+(e^+\nu_e\bar{\nu}_\tau,\mu^+\nu_\mu\bar{\nu}_\tau)\nu_\tau$	244.6±9.1±14.2
BELL	$\tau^+(e^+\nu_e\bar{\nu}_\tau,\mu^+\nu_\mu\bar{\nu}_\tau,\pi^+\bar{\nu}_\tau)\nu_\tau$	262.2±4.8±7.4
BESIII@4.009	$\mu^+\nu_\mu,\tau^+(\pi^+\bar{\nu}_\tau)\nu_\tau$	241.0±16.3±6.6
CLEO	$\mu^+\nu_\mu$	257.6±10.3±4.3
BABR	$\mu^+\nu_\mu$	265.9±8.4±7.7
BELL	$\mu^+\nu_\mu$	249.8±6.6±5.0
BESIII@4.178 preliminary	$\mu^+\nu_\mu$	249.1±3.6±3.8

Comparisons of $|V_{cs}|$

$$f_{D_s^+}|V_{cs}| = 242.5 \pm 3.5_{\text{stat.}} \pm 3.7_{\text{syst.}}\ \text{MeV}$$

- **Taking $f_{D_s^+}^{\textbf{LQCD[PRD 90(2014)074509]}}$ as input, we obtain**

$$|V_{cs}| = 0.974 \pm 0.014_{\text{stat.}} \pm 0.016_{\text{syst.}}$$

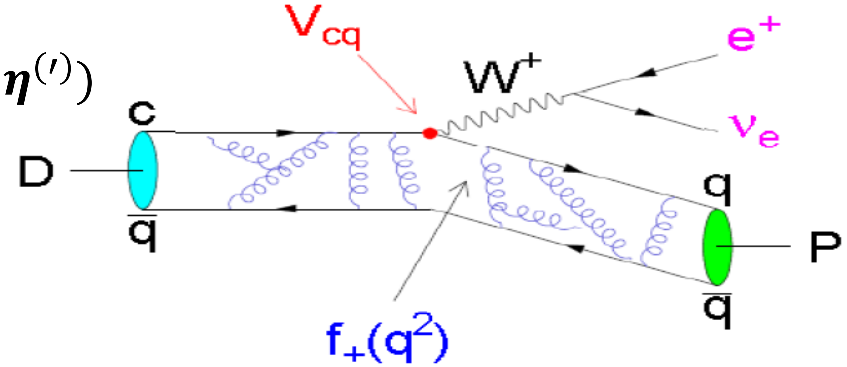


Thanks for Sifan's help!

arXiv:1810.03127

D_s semi-leptonic decay

$D \to P\, e^+ \nu\ (P = K, \pi, \eta^{(\prime)})$



Differential rates: $\frac{d\Gamma}{dq^2} = X \frac{G_F^2 p^3}{24\pi^3} |f_+(q^2)|^2 |V_{cd(s)}|^2\ (X = 1\ for\ K^-, \pi^-, \bar{K}^0, \eta^{(\prime)}; X = \frac{1}{2}\ for\ \pi^0)$

Bridge to precisely measure

- **Form factor $f_+(0)$, with input $|V_{cs}|^{\mathrm{CKMfitter}}$**

  -- **Single pole model**

$$f_+(q^2) = \frac{f_+(0)}{1 - q^2/M_{pole}^2}$$

  -- **Modified pole model**

$$f_+(q^2) = \frac{f_+(0)}{\left(1 - \frac{q^2}{M_{pole}^2}\right)\left(1 - \alpha \frac{q^2}{M_{pole}^2}\right)}$$

  -- **ISGW2 model**

$$f_+(q^2) = f_+(q_{max}^2)\left(1 + \frac{r^2}{12}(q_{max}^2 - q^2)\right)^{-2}$$

  -- **Series expansion**

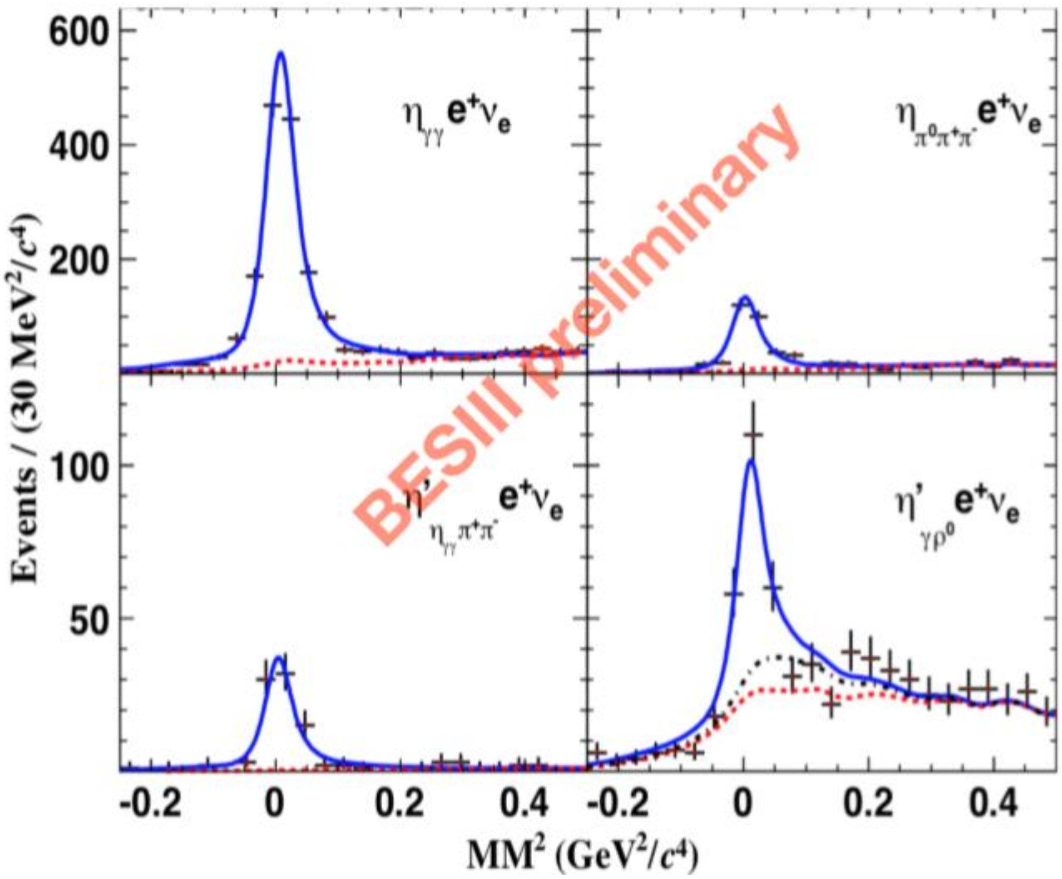
$$f_+(t) = \frac{1}{P(t)\Phi(t,t_0)} a_0(t_0)(1 + \sum_{k=1}^{\infty} r_k(t_0)[z(t,t_0)]^k)$$

- **CKM matrix element $|V_{cs}|$ with input $f_+^{\mathrm{LQCD}}(0)$**
- **Lepton flavor universality**

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

$e^+e^- \to D_s^{*+} D_s^-$ 3.19 fb^{-1} @4.178 GeV

Simultaneous unbinned fit



Non-peaking background

$D_s^+ \to \phi e^+ \nu_e$

$\mathbf{B(D_s^+ \to \eta e^+ \nu_e) = (2.32 \pm 0.06 \pm 0.06)\%}$

$\mathbf{B(D_s^+ \to \eta' e^+ \nu_e) = (0.82 \pm 0.07 \pm 0.03)\%}$

The measured branching fraction using two different mode are constrained to be same.

$\eta - \eta'$ mixing angle ϕ_P

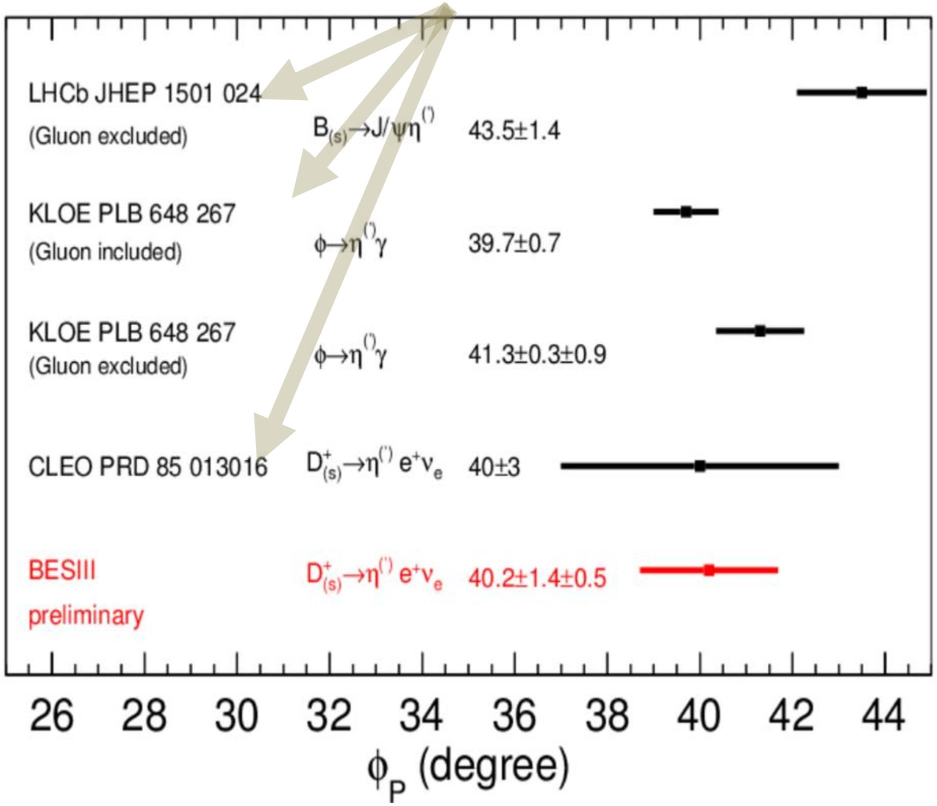
- **η-η′ mixing angle**

$$\begin{pmatrix} |\eta\rangle \\ |\eta'\rangle \end{pmatrix} = \begin{pmatrix} \cos\phi_P & -\sin\phi_P \\ \sin\phi_P & \cos\phi_P \end{pmatrix} \begin{pmatrix} |\eta_q\rangle \\ |\eta_s\rangle \end{pmatrix}$$

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

The contribution of the gluonic component is canceled;
provides a complementary constraint for the gluonium contribution to $\eta^{(\prime)}$, thus improving our understanding of nonpertubative QCD dynamics and allowing for more precise theoretical calculation of D and B decays involving $\eta^{(\prime)}$;

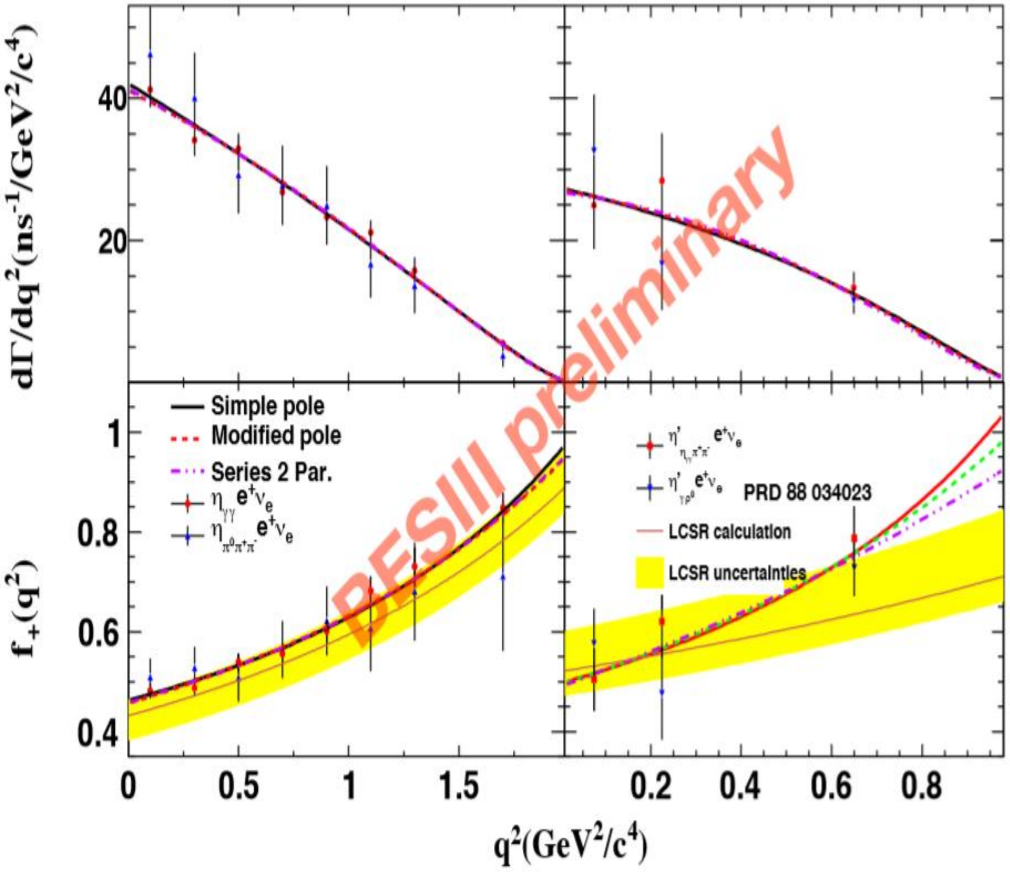
Paper only reported one uncertainty, but include both statistical and systematic

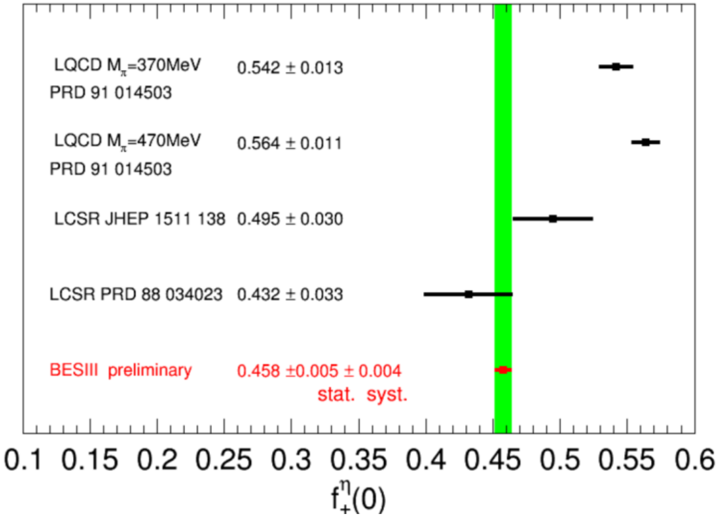


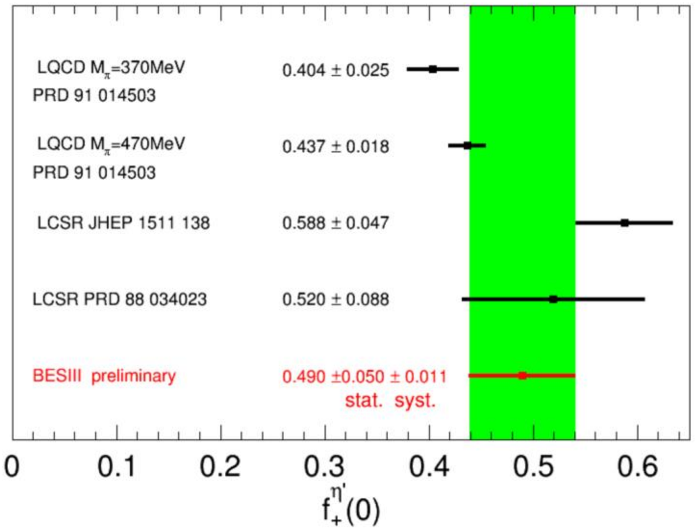
Form factor

First measurement on dynamics

Simultaneous fit







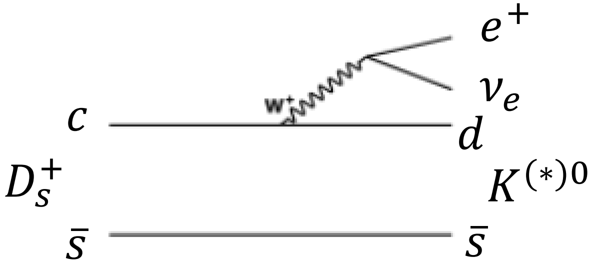
Case	Simple pole			Modified pole			Series 2 Par.		
	$f_+^{\eta^{(\prime)}}(0)\lvert V_{cs}\rvert$	$M_{\rm pole}$	χ^2/NDOF	$f_+^{\eta^{(\prime)}}(0)\lvert V_{cs}\rvert$	α	χ^2/NDOF	$f_+^{\eta^{(\prime)}}(0)\lvert V_{cs}\rvert$	r_1	χ^2/NDOF
$\eta e^+\nu_e$	0.450(5)(3)	3.77(8)(5)	12.2/14	0.445(5)(3)	0.30(4)(3)	11.4/14	0.446(5)(4)	−2.2(2)(1)	11.5/14
$\eta' e^+\nu_e$	0.494(45)(10)	1.88(54)(5)	1.8/4	0.481(44)(10)	1.62(91)(11)	1.8/4	0.477(49)(11)	−13.1(76)(11)	1.9/4

$D_s^+ \to K^{(*)0}\, e^+\, \nu_e$

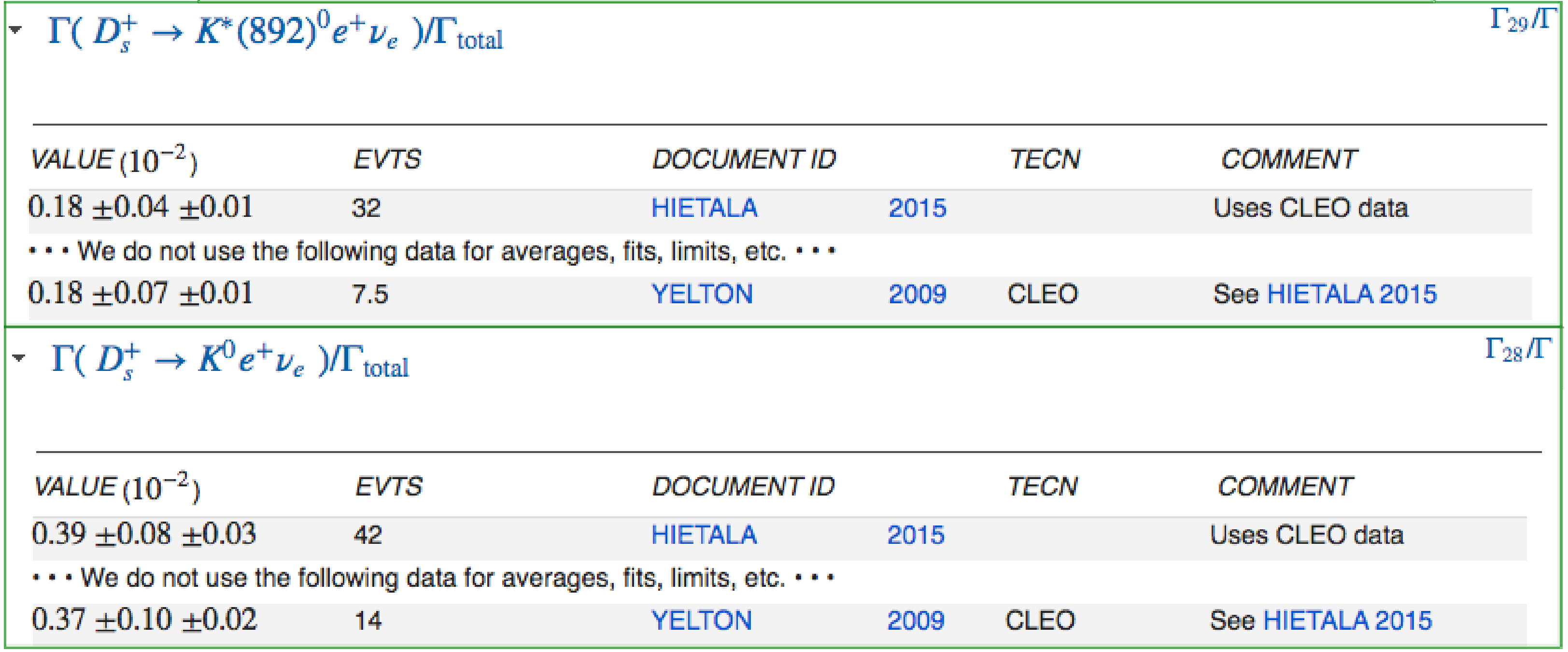
$e^+e^- \to D_s^{*+} D_s^-$ **3.19 fb^{-1} @4.178 GeV**

arXiv:1811.02911

Cabibbo-suppressed



Currently measurements are only from one single experiment



$\Gamma(D_s^+ \to K^*(892)^0 e^+ \nu_e)/\Gamma_{\text{total}}$ Γ_{29}/Γ

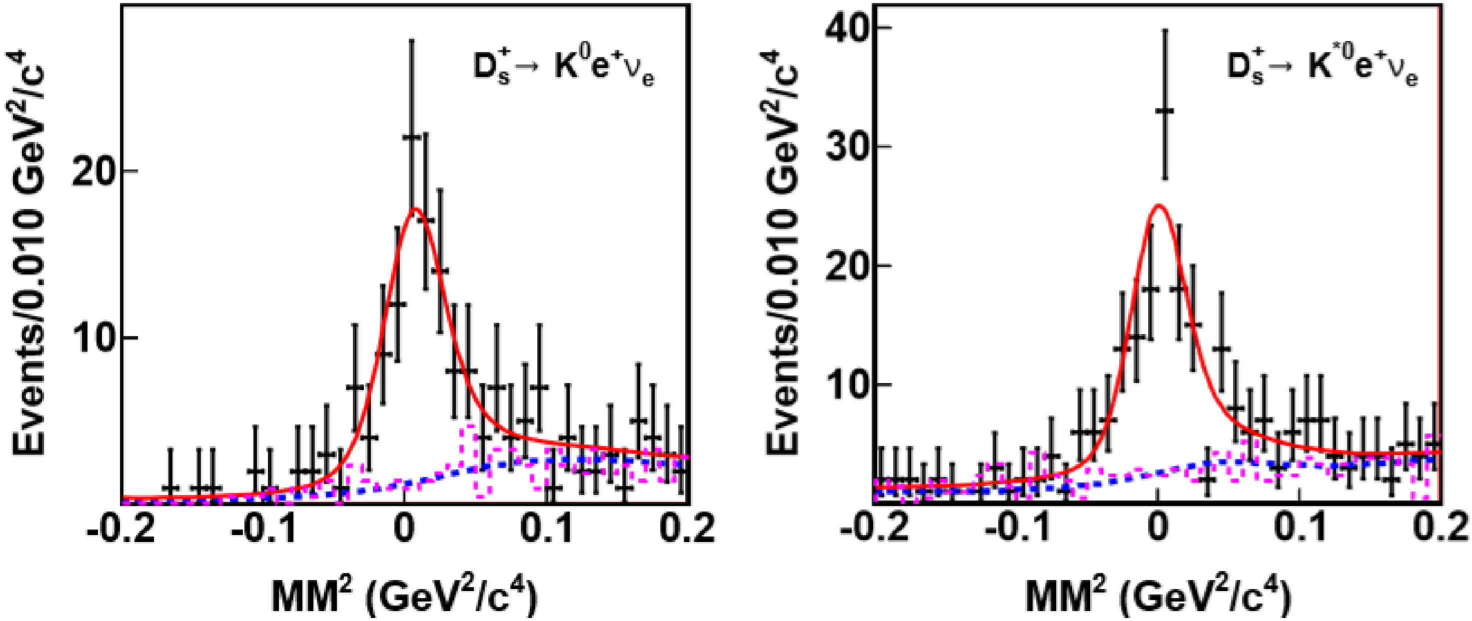
VALUE (10^{-2})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$0.18 \pm 0.04 \pm 0.01$	32	HIETALA	2015		Uses CLEO data
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.18 \pm 0.07 \pm 0.01$	7.5	YELTON	2009	CLEO	See HIETALA 2015

$\Gamma(D_s^+ \to K^0 e^+ \nu_e)/\Gamma_{\text{total}}$ Γ_{28}/Γ

VALUE (10^{-2})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$0.39 \pm 0.08 \pm 0.03$	42	HIETALA	2015		Uses CLEO data
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.37 \pm 0.10 \pm 0.02$	14	YELTON	2009	CLEO	See HIETALA 2015

Branching fraction of $D_s^+ \to K^{(*)0}\, e^+\, \nu_e$

arXiv:1811.02911



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

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

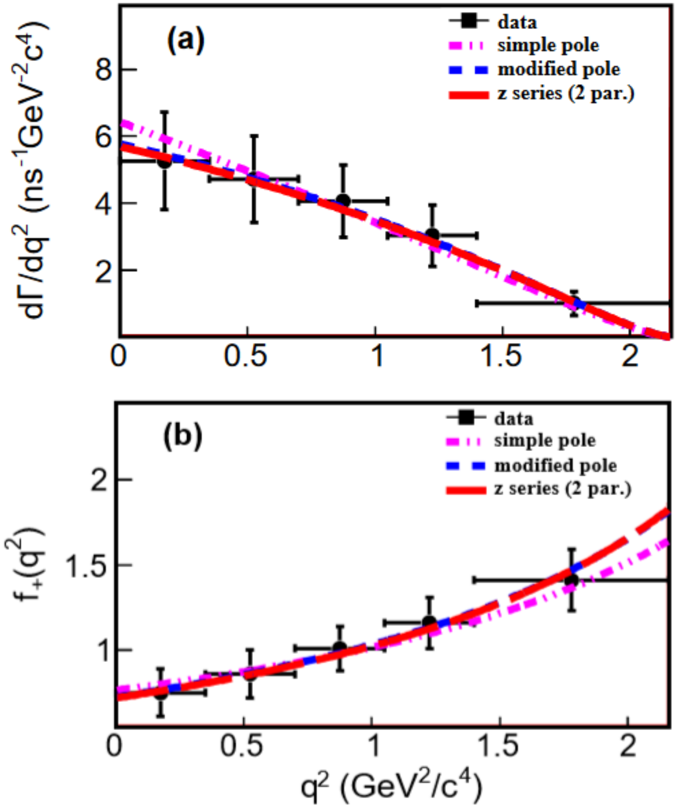
- **Consistent with the PDG.**
- **Still, statistically limited.**
- **Fitting error dominates systematics.**

First measurement

Form factor

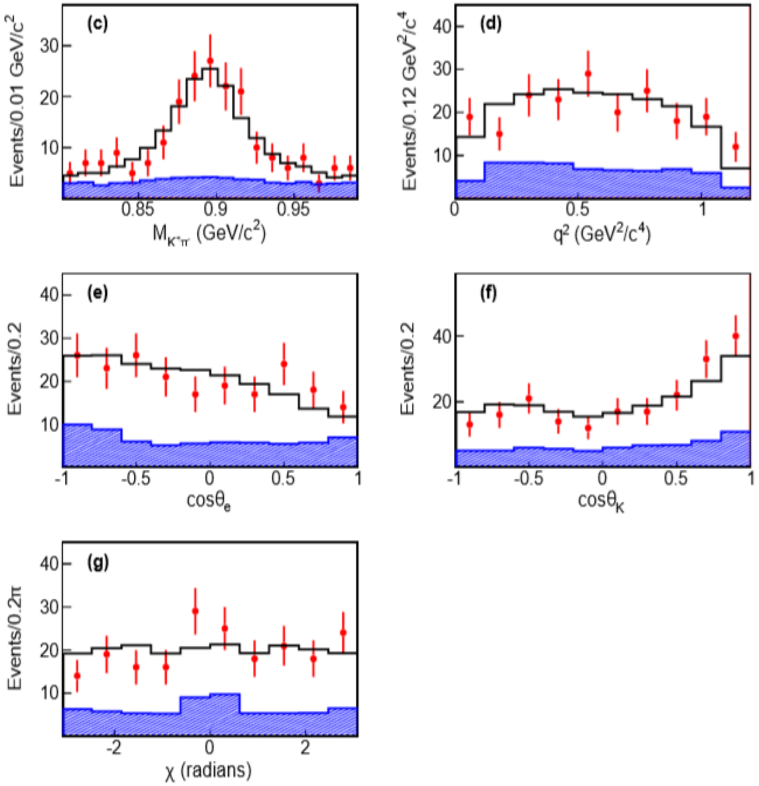
arXiv:1811.02911

$D_s^+ \to K^0 e^+ \nu_e$



Parameterizations	$f_+^K(0)\vert V_{cd}\vert$	$f_+^K(0)$
Simple pole [22]	$0.172 \pm 0.010 \pm 0.001$	$0.765 \pm 0.044 \pm 0.004$
Modified pole [22]	$0.163 \pm 0.017 \pm 0.003$	$0.725 \pm 0.076 \pm 0.013$
z series (2 par.) [23]	$0.162 \pm 0.019 \pm 0.003$	$0.720 \pm 0.084 \pm 0.013$

$D_s^+ \to K^{*0} e^+ \nu_e$



$$r_V = \frac{V(0)}{A_1(0)} = 1.67 \pm 0.34 \pm 0.16$$

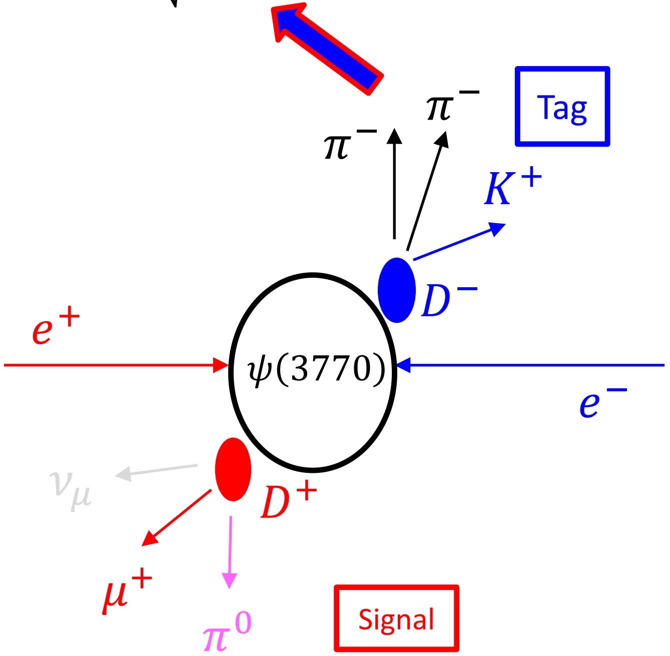
$$r_2 = \frac{A_2(0)}{A_1(0)} = 0.77 \pm 0.28 \pm 0.07$$

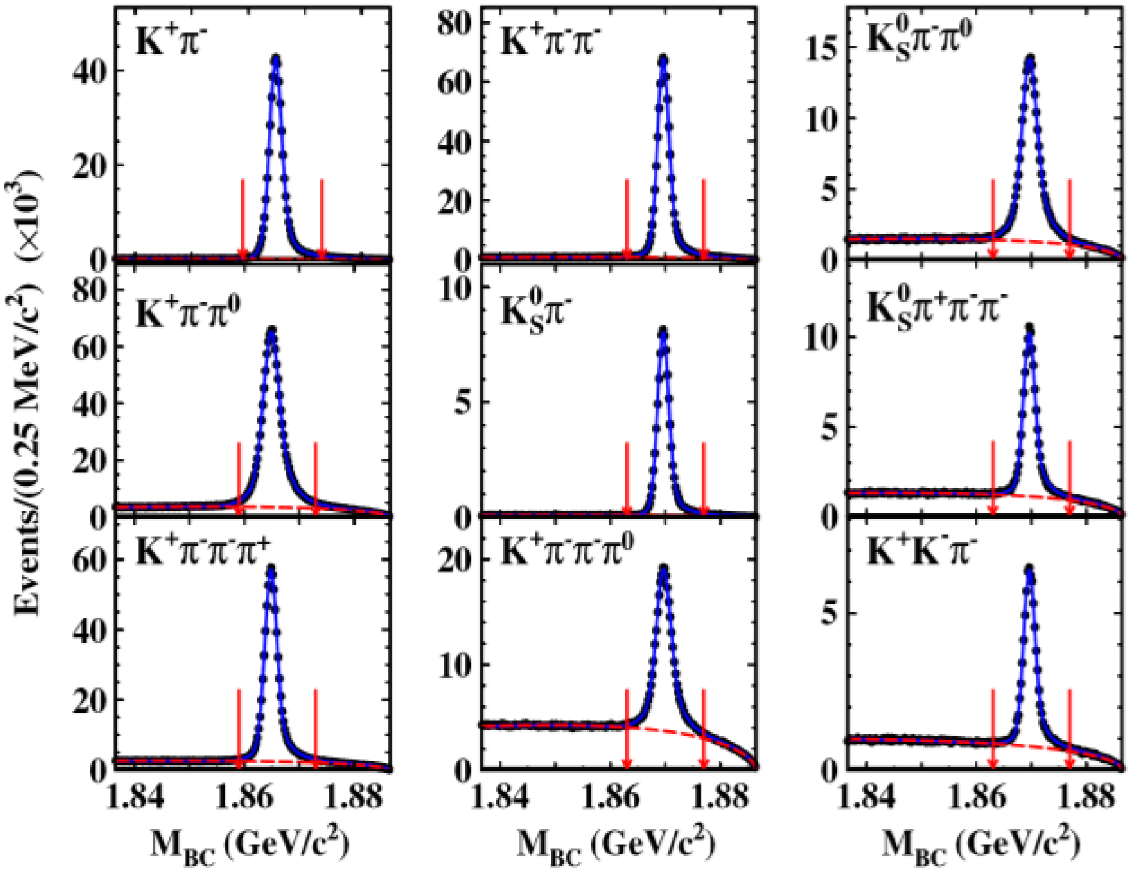
$D^{0(+)} \to \pi^{-(0)}\mu^+\nu_\mu$

$e^+e^- \to \psi(3770) \to D\bar{D}$ **2.93 fb^{-1} @3.773 GeV** **PRL 121 (2018) 171803**

$\Delta E = E_{D^-} - E_{\text{beam}}$： minimum $|\Delta E|$

$$M_{BC} = \sqrt{E_{\text{beam}}^2 - |\vec{p}_{D^-}|^2}$$

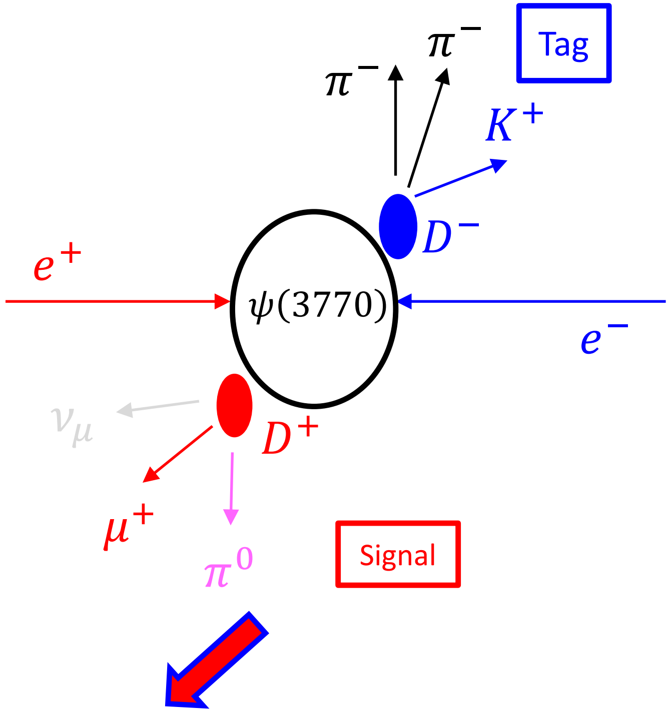


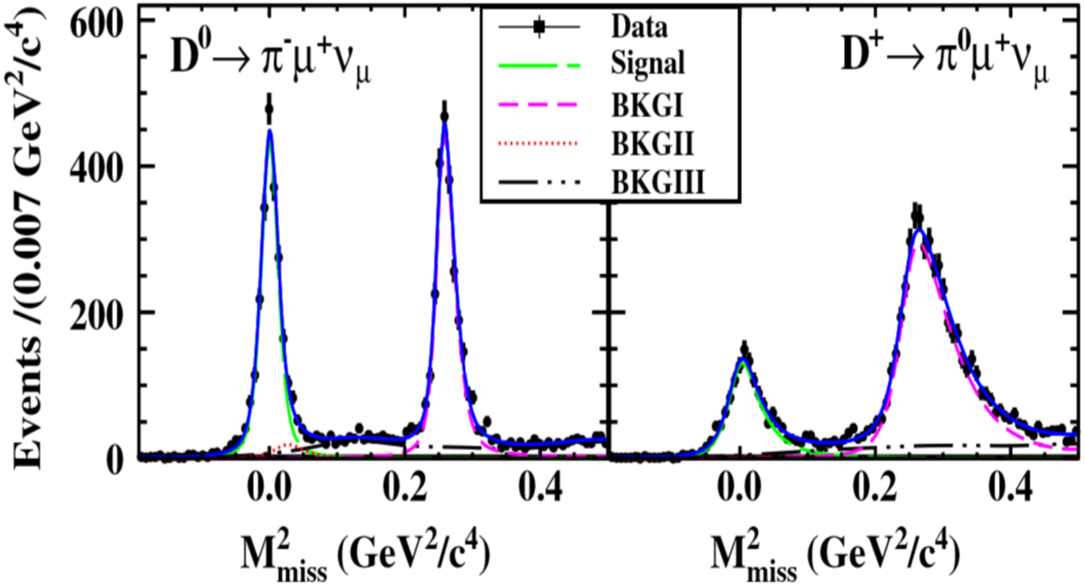


Mode	$N_{\rm ST}^{0(+)}$ $(\times 10^4)$
$\pi^-\mu^+\nu_\mu$	232.1(02)
$\pi^0\mu^+\nu_\mu$	152.2(02)

PRL 121 (2018) 171803

Unbinned maximum likelihood fit





$$M^2_{\rm miss} = E^2_{\rm miss} - |\vec{p}_{\rm miss}|^2$$

$$E_{\rm miss} = E_{\rm beam} - E_{\pi^{-(0)}} - E_{\mu^+}$$

$$\vec{p}_{\rm miss} = -\vec{p}_{D^-} - \vec{p}_{\pi^{-(0)}} - \vec{p}_{\mu^+}$$

BKGI: $D^{0(+)} \to \pi^{-(0)}\pi^+\overline{K}^0$
BKGII: $D^0 \to K^-\pi^+, D^{0(+)} \to \pi^{-(0)}\pi^+,$
$D^{0(+)} \to \pi^{-(0)}\pi^+\pi^0$
BKGIII: other non-peaking backgrounds

$\boldsymbol{B(D^0 \to \pi^- \mu^+ \nu)}$ = **(0.272±0.008±0.006)%**
$\boldsymbol{B(D^+ \to \pi^0 \mu^+ \nu)}$ = **(0.350±0.011±0.010)%**

PRL 121 (2018) 171803

Lepton flavor universality: [EPJC**78**(2018)501]

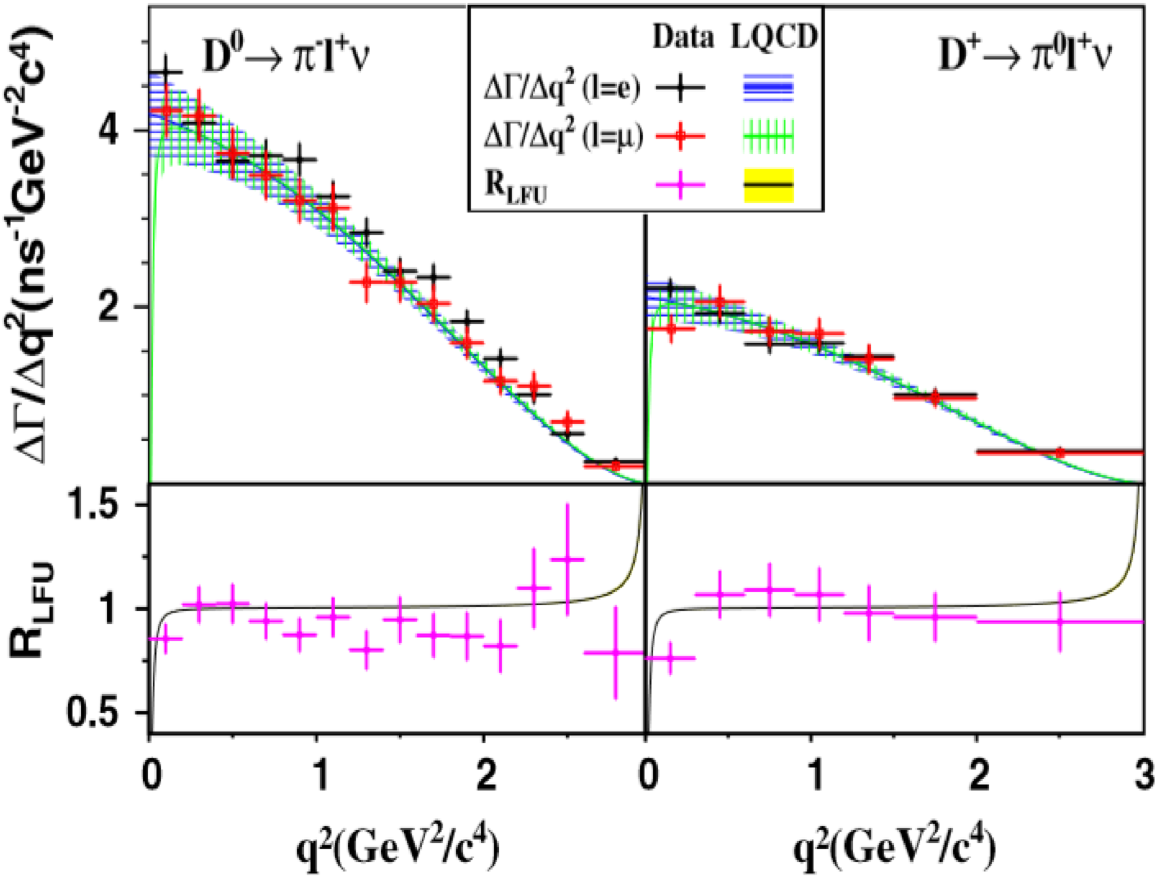
SM expectation: $\mathbf{0.985 \pm 0.002}$

$$R_{LFU}^{\pi^-} = \frac{\Gamma(D^0 \to \pi^- \mu^+ \nu_\mu)}{\Gamma(D^0 \to \pi^- e^+ \nu_e)} = 0.922 \pm 0.030 \pm 0.022$$

$\mathbf{1.7\sigma}$ **consistent**

$$R_{LFU}^{\pi^0} = \frac{\Gamma(D^+ \to \pi^0 \mu^+ \nu_\mu)}{\Gamma(D^+ \to \pi^0 e^+ \nu_e)} = 0.964 \pm 0.037 \pm 0.026$$

$\mathbf{0.5\sigma}$ **consistent**



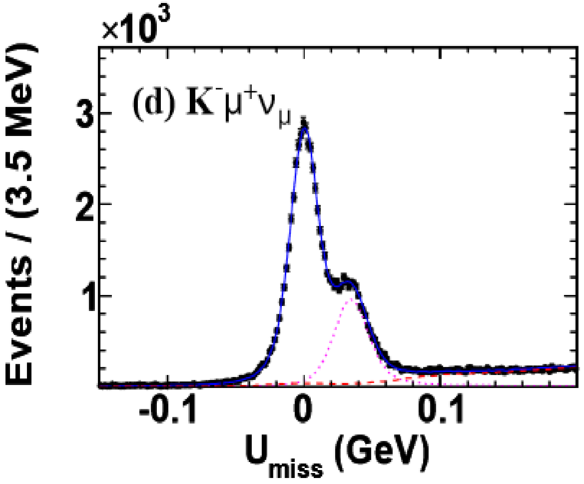
Consistent within 2σ

$D^0 \to K^-\mu^+\nu_\mu$

arXiv:1810.03127

$e^+e^- \to \psi(3770) \to D\bar{D}$ 2.93 fb^{-1} @3.773 GeV

$$U_{miss} = E_{miss} - |\vec{p}_{miss}|$$

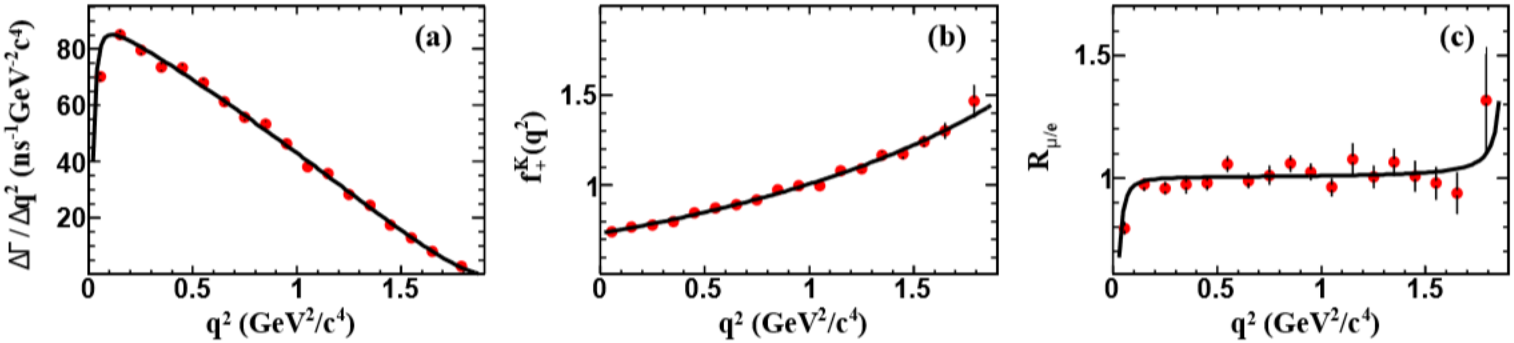


$$B\left(D^0 \to K^-\,\mu^+\,\nu_\mu\right) = (3.413 \pm 0.019 \pm 0.035)\%$$

Lepton flavor universality:

consistent

$$R_{\mu/e} = \frac{\Gamma\left(D^0 \to K^-\mu^+\nu_\mu\right)}{\Gamma\left(D^0 \to K^-\,e^+\nu_e\right)} = 0.974 \pm 0.007 \pm 0.012$$

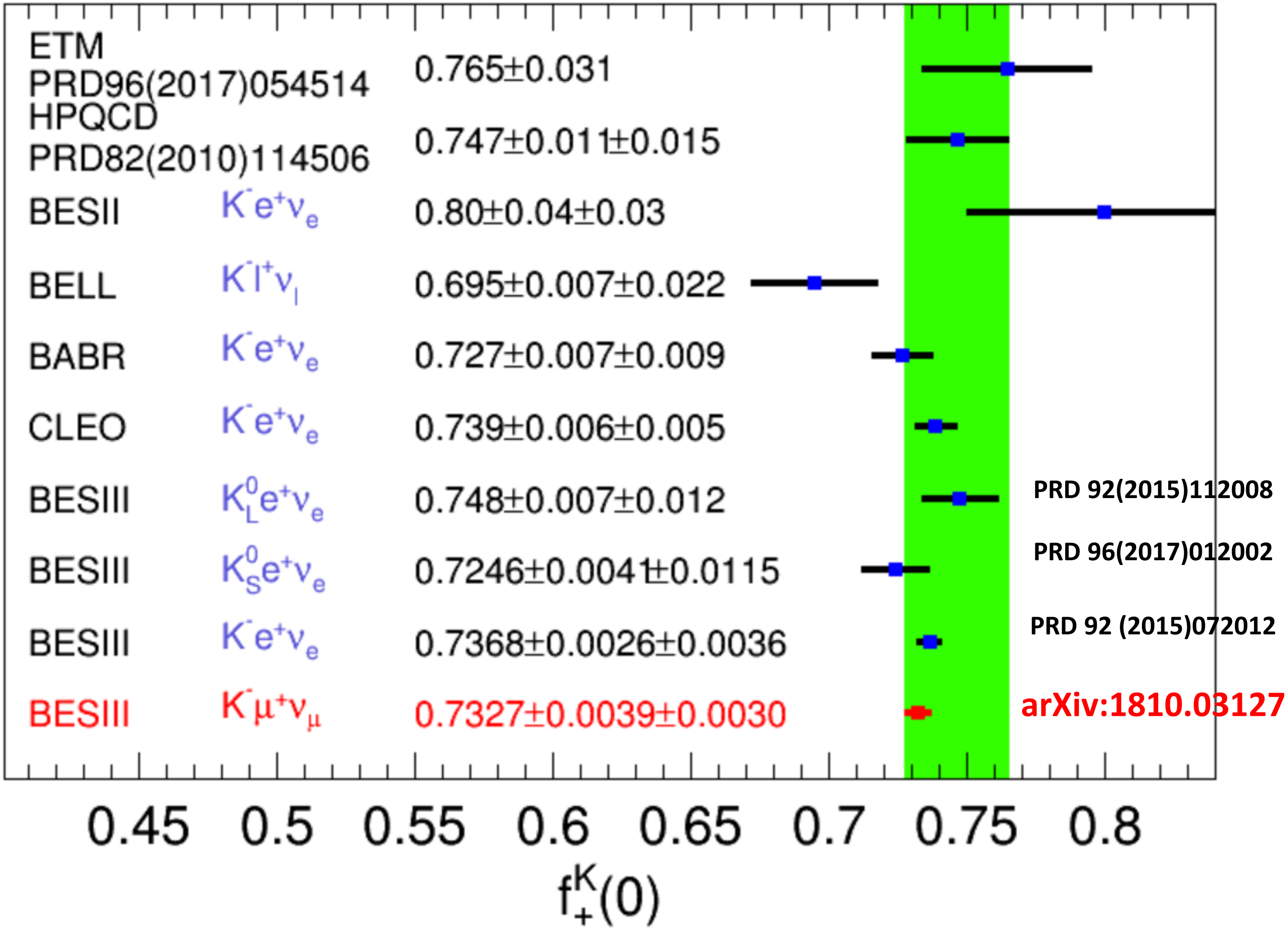


No evidence for LFU violation is found within current statistics.

Comparisons of $f_+^K(0)$

BESIII: higher precision; consistent with others.

arXiv:1810.03127



PRD 92(2015)112008

PRD 96(2017)012002

PRD 92 (2015)072012

arXiv:1810.03127

$D^{0/+} \to a_0(980)^{-/0} e^+ \nu_e$

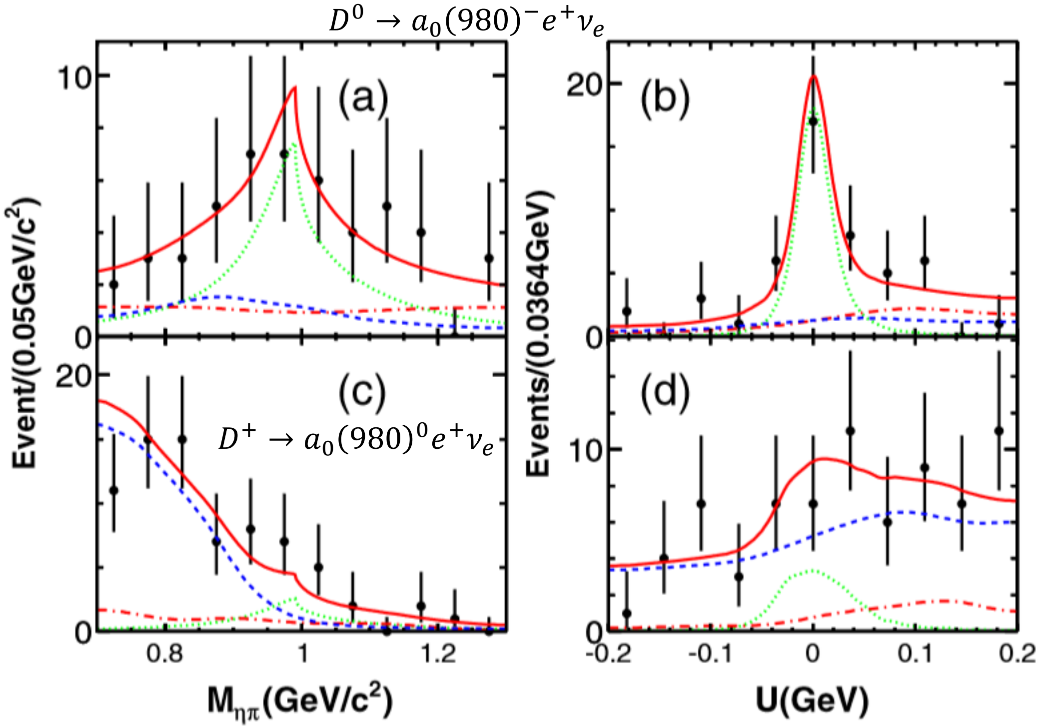
PRL 121 (2018) 081802

- **The first time the $a_0(980)$ meson measured in a D^0 semileptonic decay**
- **The nature of the puzzling $a_0(980)$ states: $q\bar{q}$ [1] or tetraquark [2]**

2-D unbinned maximum likelihood fit

$B(D^0 \to a_0(980)^- e^+ \nu_e) \times B(a_0(980)^- \to \eta\pi^-)$
$= (1.33^{+0.33}_{-0.29} \pm 0.09) \times 10^{-4}$ **$6.4\,\sigma$ sig.**

$B(D^+ \to a_0(980)^0 e^+ \nu_e) \times B(a_0(980)^0 \to \eta\pi^0)$
$= (1.66^{+0.81}_{-0.66} \pm 0.11) \times 10^{-4}$ **2.9σ sig.**
$< 3.0 \times 10^{-4}$ @ 90% C.L.

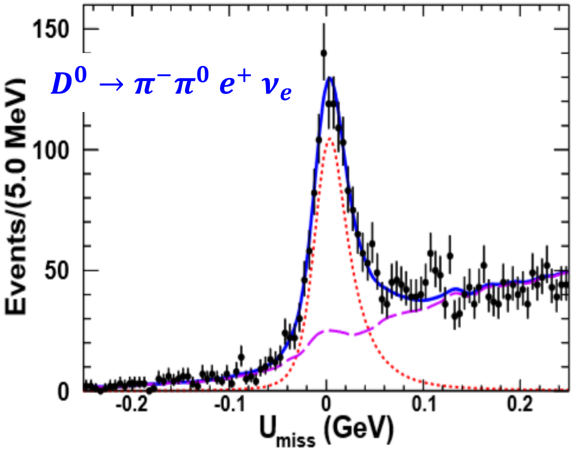


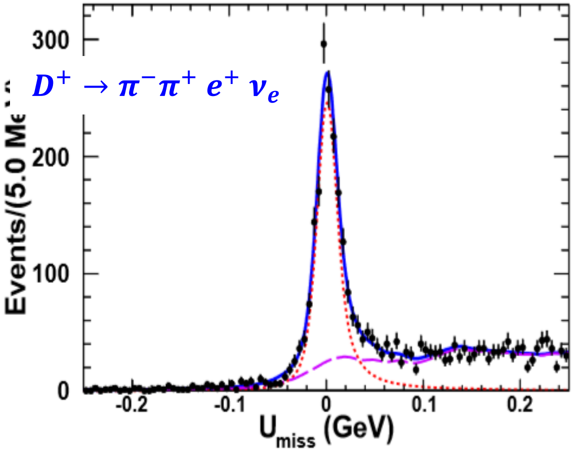
[1] PRD48(1993)1185
[2] PRD 81 (2010) 074031

$D^{+/0} \to \pi^-\pi^{+/0} e^+ \nu_e$

$e^+e^- \to \psi(3770) \to D\bar{D}$ 2.93 fb^{-1} @3.773 GeV

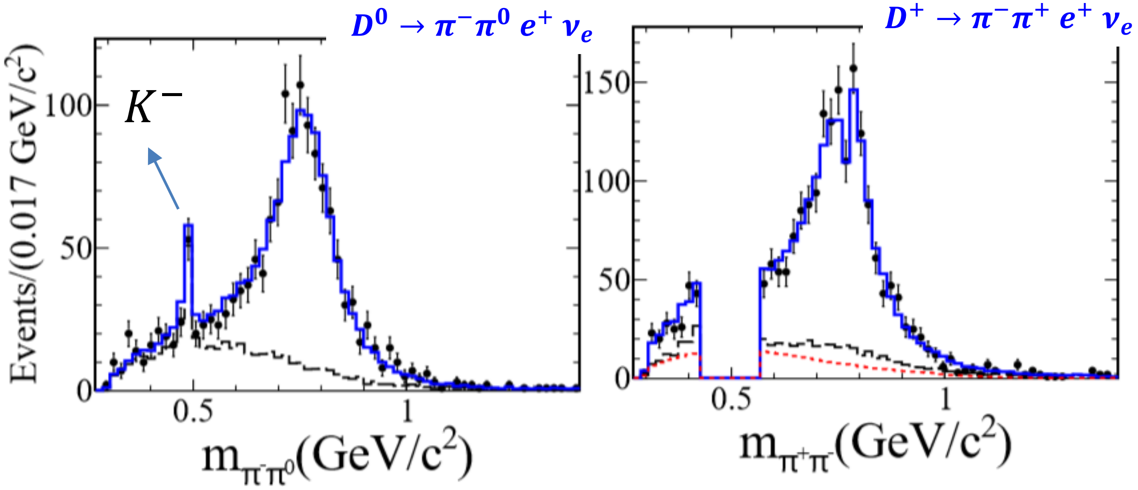
arXiv:1809.06496

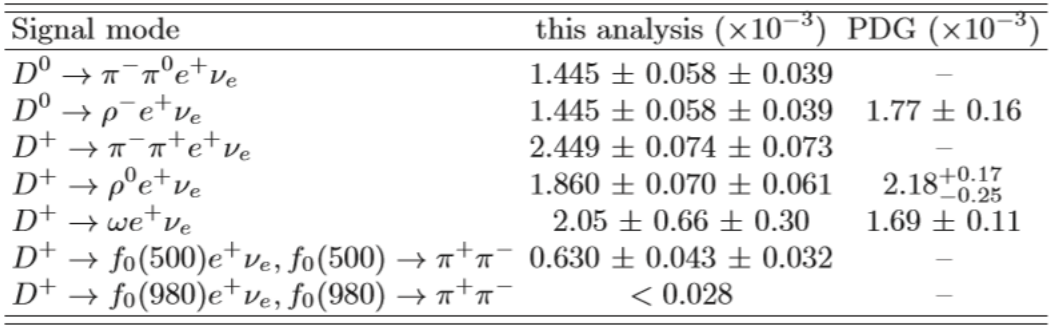




$|U_{miss}| < 0.06$ GeV

Simultaneous Partial wave analysis fit





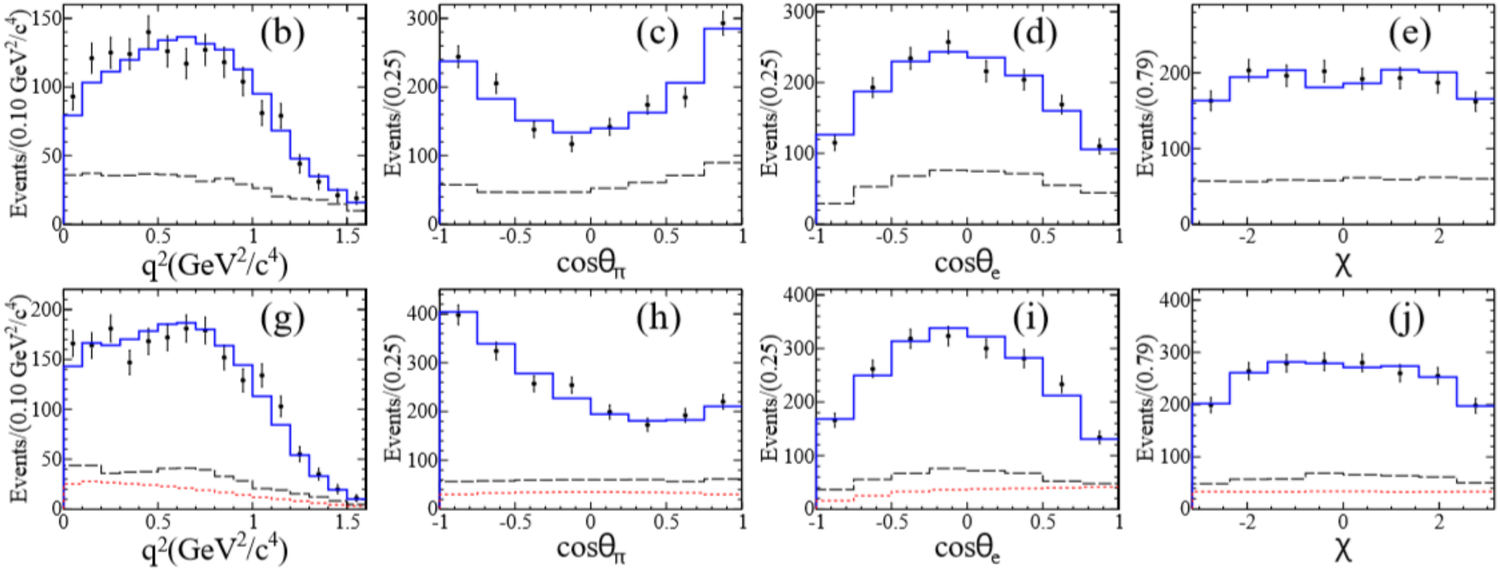
Signal mode	this analysis ($\times 10^{-3}$)	PDG ($\times 10^{-3}$)
$D^0 \to \pi^-\pi^0 e^+\nu_e$	$1.445 \pm 0.058 \pm 0.039$	–
$D^0 \to \rho^- e^+\nu_e$	$1.445 \pm 0.058 \pm 0.039$	1.77 ± 0.16
$D^+ \to \pi^-\pi^+ e^+\nu_e$	$2.449 \pm 0.074 \pm 0.073$	–
$D^+ \to \rho^0 e^+\nu_e$	$1.860 \pm 0.070 \pm 0.061$	$2.18^{+0.17}_{-0.25}$
$D^+ \to \omega e^+\nu_e$	$2.05 \pm 0.66 \pm 0.30$	1.69 ± 0.11
$D^+ \to f_0(500) e^+\nu_e, f_0(500) \to \pi^+\pi^-$	$0.630 \pm 0.043 \pm 0.032$	–
$D^+ \to f_0(980) e^+\nu_e, f_0(980) \to \pi^+\pi^-$	< 0.028	–

The $\pi^+\pi^-$ ***S*-wave** contribution is observed for the first time, with the significance greater than 10σ.

arXiv:1809.06496

$D^0 \to \pi^-\pi^0 e^+ \nu_e$

$D^+ \to \pi^-\pi^+ e^+ \nu_e$



Hadronic form factor ratios of $D \to \rho e^+ \nu_e$ at $q^2 = 0$:

$$r_2 = \frac{A_2(0)}{A_1(0)} = 0.845 \pm 0.056 \pm 0.039$$

$$r_V = \frac{V(0)}{A_1(0)} = 1.695 \pm 0.083 \pm 0.051$$

$$\rho_{r_V, r_2} = -0.206$$

arXiv:1809.06496

Proposed by [PRD82(2016)034016]: A model-independent way

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

$R = 1.0 \pm 0.3$ for two-quark description for $f_0(500)$ and $f_0(980)$;
$\mathrm{R} = 3.0 \pm 0.9$ for tetraquark description. Favor

$B(f_0(500) \to \pi^+\pi^-) = 67\%$ [PDG 2016]

$B(a_0(980) \to \pi^0\,\eta) = 85\%$ [PDG 2016]

Neglect the $f_0(980)$ component and assume that the dominant decays are $\pi\pi$ for $f_0(500)$ and $\pi\eta$ and $K\overline{K}$ for $a_0(980)^0$.

$R > 2.7$ @90% C. L.

Other analyses at BESIII

$D^+ \to \eta(\eta')e^+\nu_e$	PRD **97**(2018)092009
$D^+ \to \overline{K}^0\mu^+\nu_\mu$	EPJC **76** (2016) 369
$D^+ \to \overline{K}^0(\pi^0)e^+\nu_e$	PRD **96** (2017) 012002
$D^+ \to \gamma e^+\nu_e$	PRD **95** (2017)071102(R)
$D^+ \to D^0 e^+\nu_e$	PRD **96**(2017)092002
$D_s^+ \to \phi\, \mu/e^+\nu, \eta^{(\prime)}\mu^+\nu$	PRD **97**(2018)012006

…

Summary

- With 2.93 and 3.19 fb^{-1} data taken at 3.773 and 4.18 GeV, BESIII have studied the pure and semi-leptonic $D_{(s)}$ decay, and measure their branching fractions, decay constant $f_{D_s^+}$, form factor $f_+^K(0)$ and $f_+^{\eta^{(\prime)}}(0)$, and the CKM matrix element $|V_{cs}|$, the lepton universality test, as well as $\eta-\eta'$ mixing angle.

- Improved measurements of decay constant $f_{D_s^+}$ and form factor $f_+^K(0)$ and $f_+^{\eta^{(\prime)}}(0)$, which are important to test and calibrate LQCD calculations.

- Improved measurements of CKM matrix element $|V_{cs}|$, which are important to test the CKM matrix unitarity.

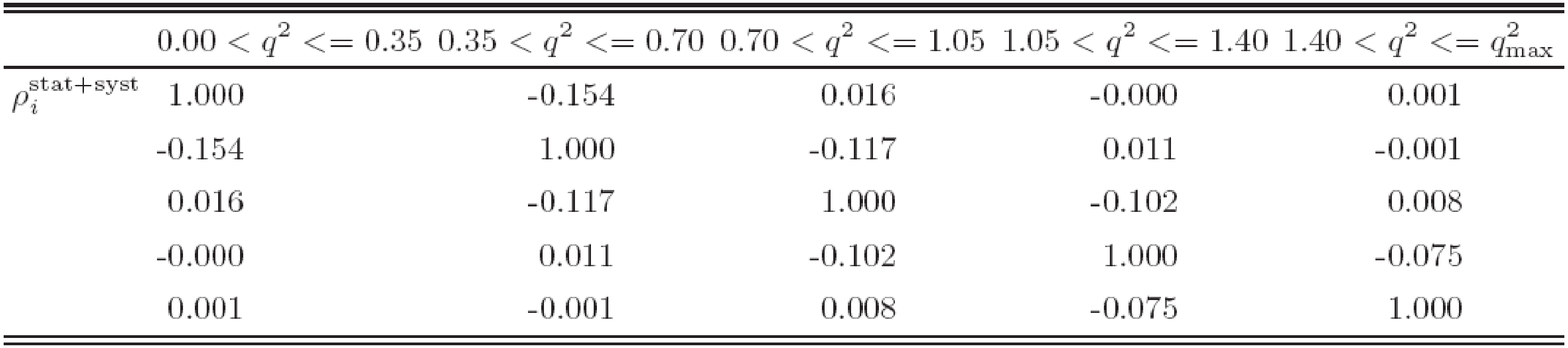
- Based on 3.19 fb^{-1} data at 4.178 GeV accumulated in 2016, the measurements of $f_{D_s^+}$ and $|V_{cs}|$ by other D_s^+ decays can be expected in the near future.

Thanks for your attention!

Back up

$D_s^+ \to K^0 e^+ \nu_e$

The correlation matrix including both statistical and systematic Uncertainties. [preliminary]



	$0.00 < q^2 <= 0.35$	$0.35 < q^2 <= 0.70$	$0.70 < q^2 <= 1.05$	$1.05 < q^2 <= 1.40$	$1.40 < q^2 <= q^2_{\rm max}$
$\rho_i^{\rm stat+syst}$	1.000	-0.154	0.016	-0.000	0.001
	-0.154	1.000	-0.117	0.011	-0.001
	0.016	-0.117	1.000	-0.102	0.008
	-0.000	0.011	-0.102	1.000	-0.075
	0.001	-0.001	0.008	-0.075	1.000

In the calculation of the systematic covariance matrix, we have considered the systematic uncertainties arising from the uncertainties in the number of D_s^- tags, D_s^+ lifetime, MC statistics, $E_{\gamma\rm max}$ cut, $M_{\rm Ks0e+}$ cut, fits to MM^2 distribution, tracking and PID efficiencies.

$D_s^+ \to K^{*0} e^+ \nu_e$

The differential decay rate for $D_s^+ \to K^{*0} e^+ \nu_e$ can be expressed in terms of three helicity amplitudes ($H_+(q^2)$, $H_-(q^2)$ and $H_0(q^2)$)

$$\begin{aligned}
\frac{d^5\Gamma}{dm_{K\pi}dq^2dcos\theta_K dcos\theta_e d\chi} &= \frac{3}{8(4\pi)^4}G_F^2|V_{cd}|^2\frac{p_{K\pi}q^2}{M_{D_s}^2}\mathcal{B}(K^{*0} \to K^+\pi^-)|\mathcal{BW}(m_{K\pi})|^2 \\
&\times \quad [(1 + cos\theta_e)^2 sin^2\theta_K |H_+(q^2, m_{K\pi})|^2 \\
&+ \quad (1 - cos\theta_e)^2 sin^2\theta_K |H_-(q^2, m_{K\pi})|^2 \\
&+ \quad 4sin^2\theta_e cos^2\theta_K |H_0(q^2, m_{K\pi})|^2 \\
&+ \quad 4sin\theta_e(1 + cos\theta_e)sin\theta_K cos\theta_K cos\chi H_+(q^2, m_{K\pi})H_0(q^2, m_{K\pi}) \\
&- \quad 4sin\theta_e(1 - cos\theta_e)sin\theta_K cos\theta_K cos\chi H_-(q^2, m_{K\pi})H_0(q^2, m_{K\pi}) \\
&- \quad 2sin^2\theta_e sin^2\theta_K cos2\chi H_+(q^2, m_{K\pi})H_-(q^2, m_{K\pi})].
\end{aligned}$$

The helicity amplitudes of $H_+(q^2)$, $H_-(q^2)$ and $H_0(q^2)$ take the form of
$H_\pm(q^2) = (M_{D_s} + m_{K\pi})A_1(q^2) \mp \frac{2M_{D_s}p_{K\pi}}{M_{D_s}+M_{K\pi}}V(q^2)$ and

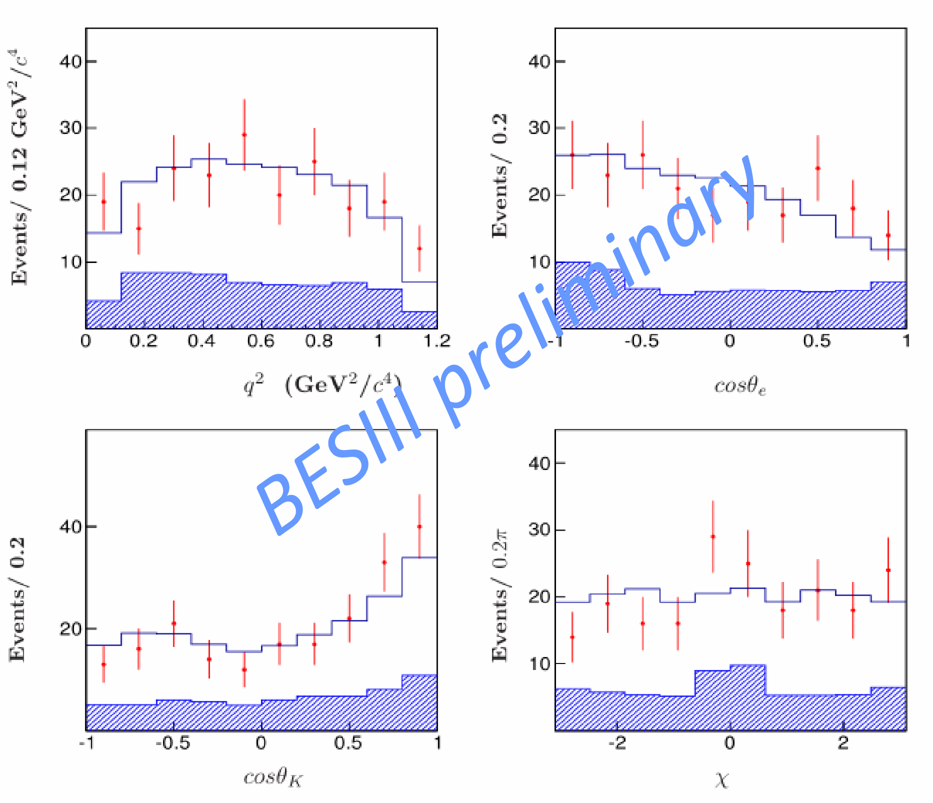
$H_0(q^2) = \frac{1}{2m_{K\pi}q}[(M_{D_s}^2 - m_{K\pi}^2 - q^2)(M_{D_s} + m_{K\pi})A_1(q^2) - \frac{4M_{D_s}^2 p_{K\pi}^2}{M_{D_s}+M_{K\pi}}A_2(q^2)]$,
$A_i(q^2) = \frac{A_i(0)}{1-q^2/M_A^2}$ and $V(q^2) = \frac{V(0)}{1-q^2/M_V^2}$, $r_V = \frac{V(0)}{A_1(0)}$ and $r_2 = \frac{A_2(0)}{A_1(0)}$.
The Breit-Wigner function of K^{*0} line shape takes the form as
$\mathcal{BW}(M_{K\pi}) = \frac{\sqrt{m_0\Gamma_0(p/p_0)}}{m_0^2 - m_{K\pi}^2 - im_0\Gamma(m_{K\pi})}\frac{B(p)}{B(p_0)}$
where $B(p) = \frac{1}{\sqrt{1+R^2p^2}}$ with $R = 3$ GeV^{-1} and $\Gamma(m_{K\pi}) = \Gamma_0(\frac{p}{p_0})^3\frac{m_0}{m_{K\pi}}(\frac{B(p)}{B(p_0)})^2$.

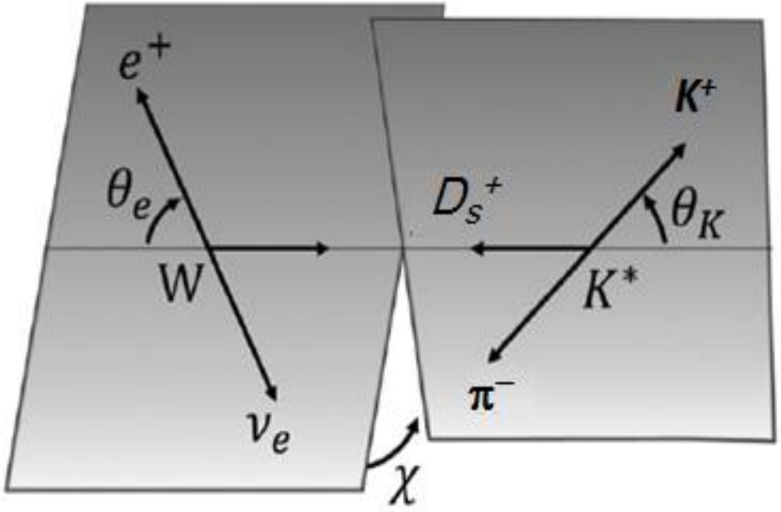
$D_s^+ \to K^{*0} e^+ \nu_e$

Following the same parametrization used in;

[1] BESIII Collaboration, M. Ablikim, *et al.*, Phys. Rev. D 94, 032001 (2016).

[1] CLEO Collaboration, S. Dobbs, *et al.*, Phys. Rev. Lett. 110, 131802 (2013).

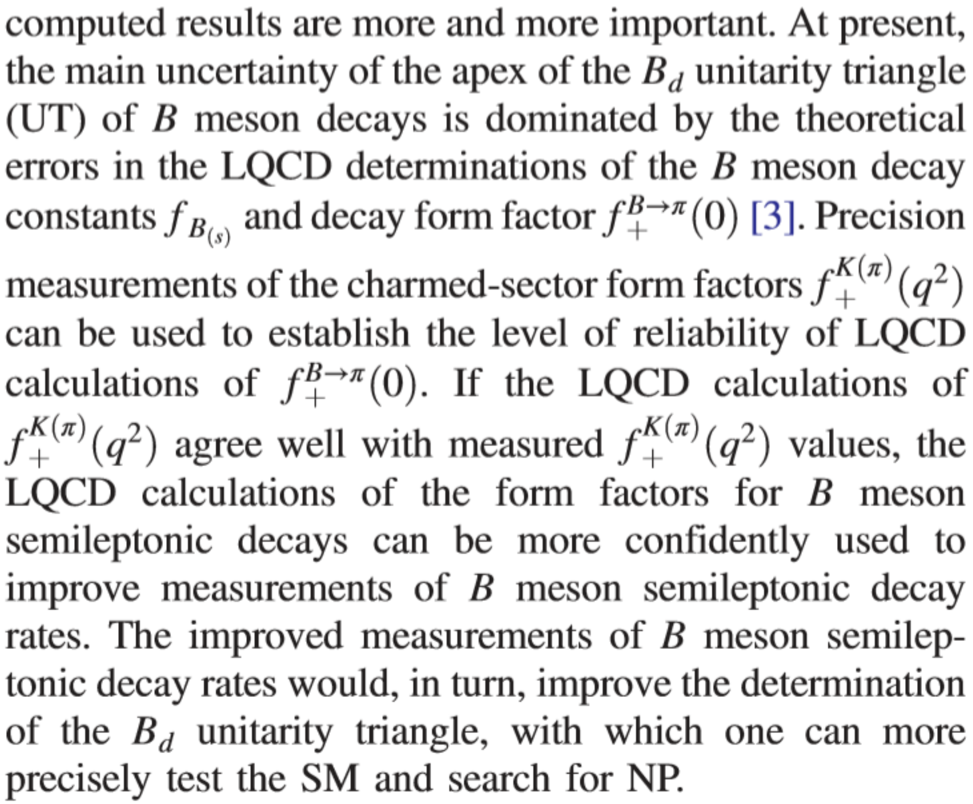




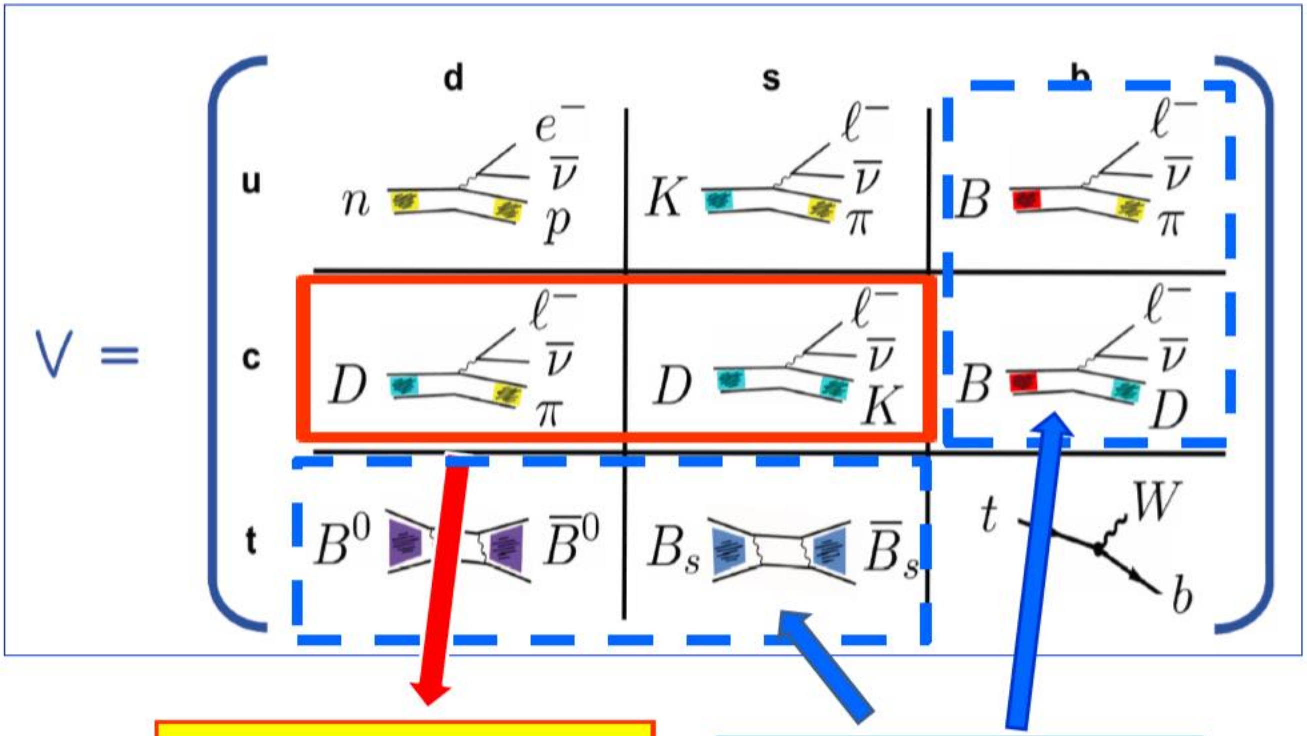
☐ The preliminary results for form factors:

r_V=1.67±0.34 ±0.16 and r_2=0.77 ± 0.28±0.07

The first errors are statistical and the second are systematic.



computed results are more and more important. At present, the main uncertainty of the apex of the B_d unitarity triangle (UT) of B meson decays is dominated by the theoretical errors in the LQCD determinations of the B meson decay constants $f_{B_{(s)}}$ and decay form factor $f_+^{B\to\pi}(0)$ [3]. Precision measurements of the charmed-sector form factors $f_+^{K(\pi)}(q^2)$ can be used to establish the level of reliability of LQCD calculations of $f_+^{B\to\pi}(0)$. If the LQCD calculations of $f_+^{K(\pi)}(q^2)$ agree well with measured $f_+^{K(\pi)}(q^2)$ values, the LQCD calculations of the form factors for B meson semileptonic decays can be more confidently used to improve measurements of B meson semileptonic decay rates. The improved measurements of B meson semileptonic decay rates would, in turn, improve the determination of the B_d unitarity triangle, with which one can more precisely test the SM and search for NP.



Charm decays + LQCD

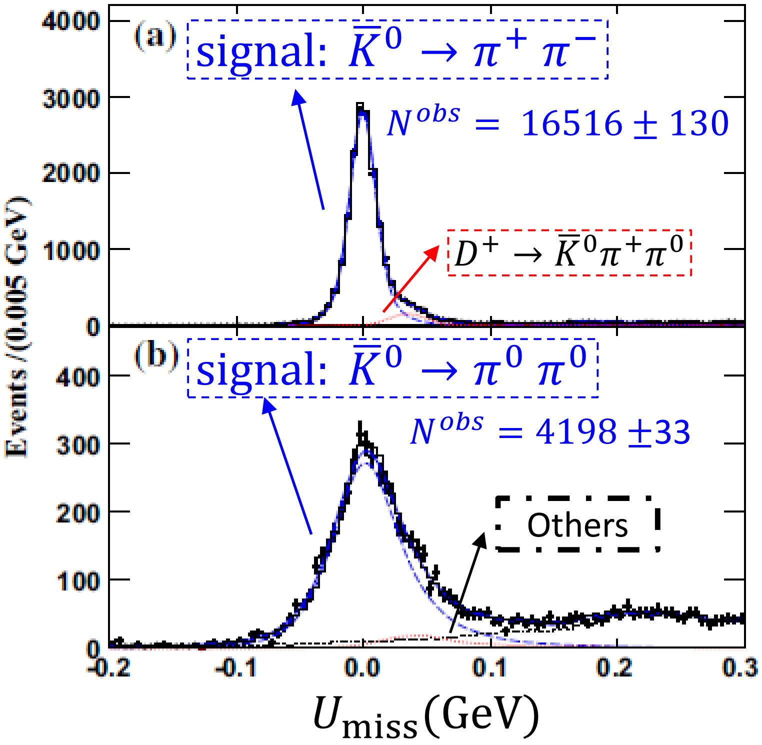
Charm decays +
B decays + LQCD

$D^+ \to \bar{K}^0 \mu^+ \nu_\mu$

EPJC 76, 369(2016)

$e^+e^- \to \psi(3770) \to D^+D^-$ **2.93 fb^{-1} @3.773 GeV**

Simultaneous fit: The double tag production yield has been constrained to be same for the two modes, which is corrected by the detector efficiency and daughter decay branching fractions: $N_{DT}^{\mathrm{prd}} = 132712 \pm 1041$



signal: $\bar{K}^0 \to \pi^+\pi^-$

$N^{obs} = 16516 \pm 130$

$D^+ \to \bar{K}^0\pi^+\pi^0$

signal: $\bar{K}^0 \to \pi^0\pi^0$

$N^{obs} = 4198 \pm 33$

Others

Lepton universality:

$$\frac{\Gamma(D^+ \to \bar{K}^0\mu^+\nu_\mu)}{\Gamma(D^+ \to \bar{K}^0 e^+\nu_e)} = 0.988 \pm 0.033$$ consistent

$B(D^+ \to \bar{K}^0 e^+ \nu_e)$ is from PDG

Isospin conversation:

$B(D^+ \to K^- \mu^+ \nu_\mu)$ is from PDG

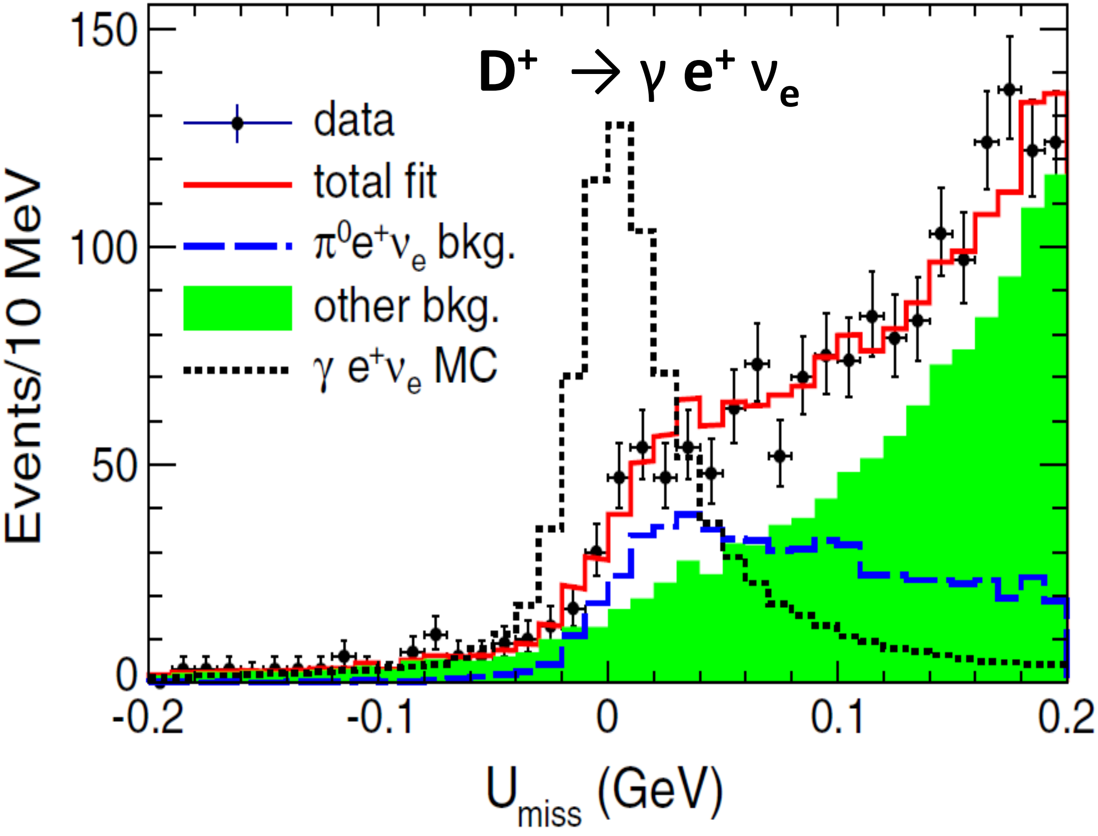
$$\frac{\Gamma(D^0 \to K^-\mu^+\nu_\mu)}{\Gamma(D^+ \to \bar{K}^0 \mu^+\nu_\mu)} = 0.963 \pm 0.044$$ consistent

$$\boldsymbol{B\left(D^+ \to \bar{K}^0 \mu^+ \nu_\mu\right) = (8.72 \pm 0.07 \pm 0.18)\%}$$

Search for the radiative leptonic decay $D^+ \to \gamma e^+ \nu_e$

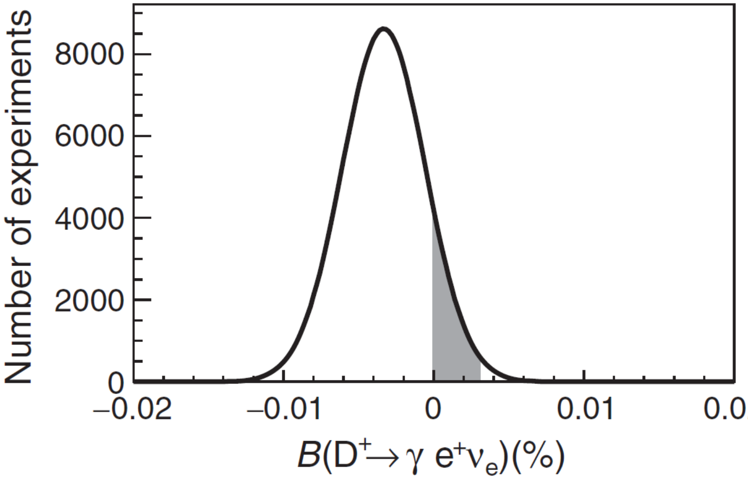
- **Not subject to the helicity suppression rule due to the presence of a radiative photon.**
- **Predicted rates are reachable range :**

  e.g., J.-C. Yang and M.-Z. Yang predict $B(D^+ \to \gamma e^+ \nu_e) \sim 2\times10^{-5}$ via Factorization.



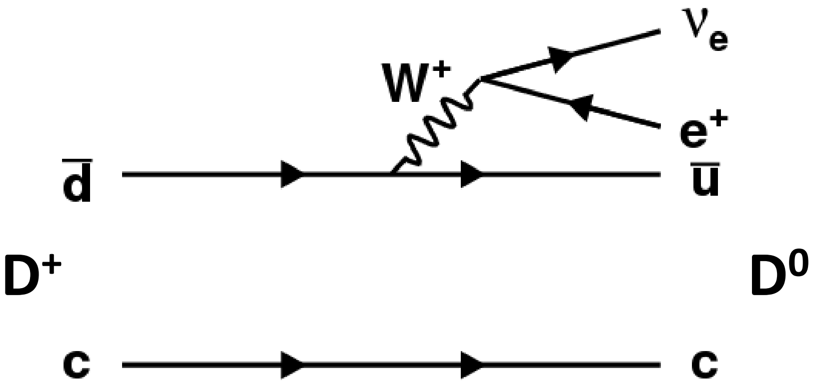
PRD 95, 071102(R) (2017)

- **Only $E_\gamma > 10$ MeV considered.**
- **(-21 ± 23) signal events.**

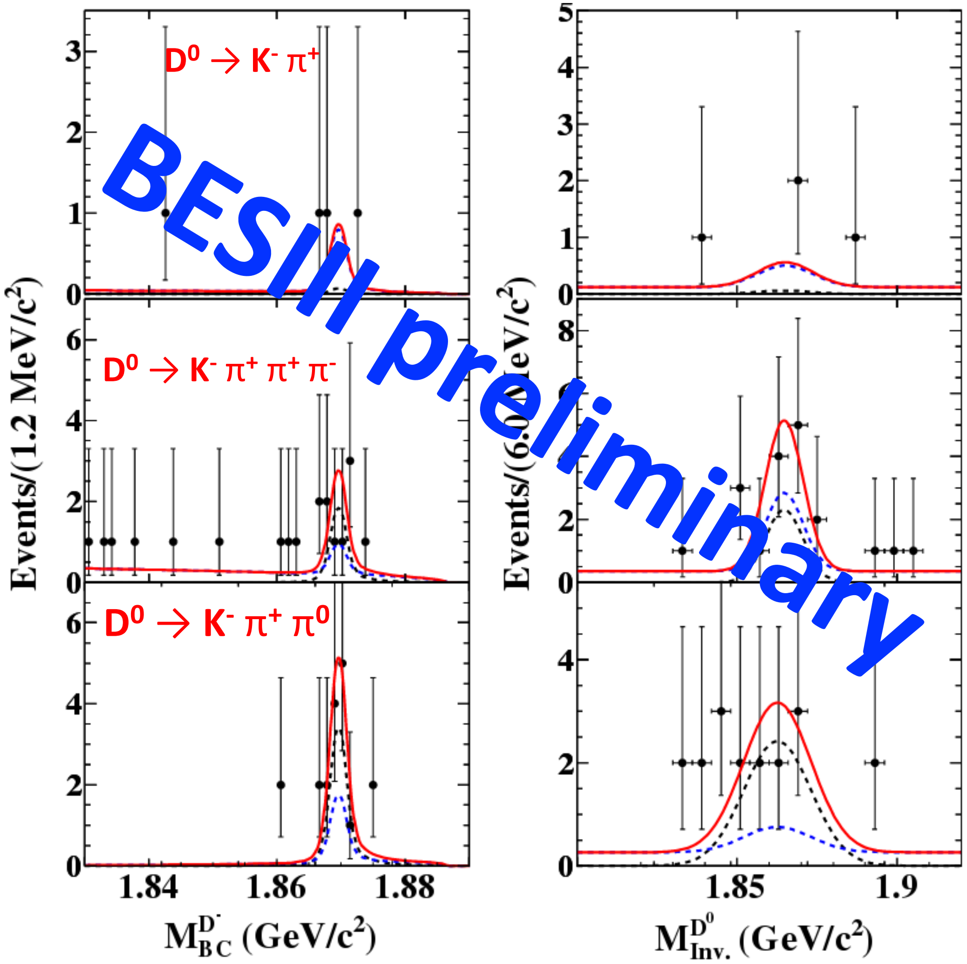


$B(D^+ \to \gamma e^+ \nu_e) < 3.0 \times 10^{-5}$ at 90% C.L.

Search for the rare decay $D^+ \rightarrow D^0 e^+ \nu_e$



Applying the SU(3) symmetry for the light quarks, this rare decay branching fraction can be predicted by theoretical calculation, and its theoretical value is 2.78 x 10^{-13} [EPJC 59, 841 (2009)]



$B(D^+ \rightarrow D^0 e^+ \nu_e) < 8.7 \times 10^{-5}$ at 90% C.L..

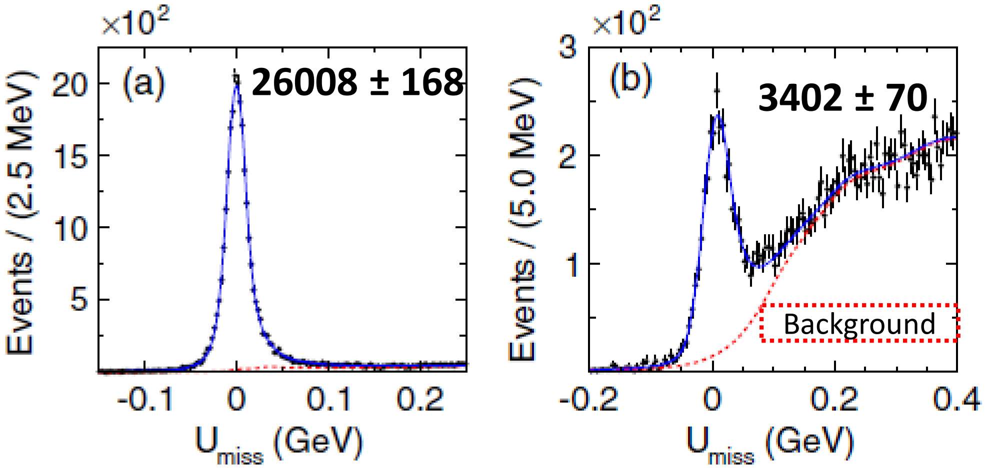
$D^+ \to \bar{K}^0(\pi^0)e^+\nu_e$

PRD 96 (2017) 012002

$e^+e^- \to \psi(3770) \to D^+D^-$ **2.93 fb^{-1} @3.773 GeV**

A binned extended maximum likelihood fit

$D^+ \to \bar{K}^0 e^+\nu_e$ $D^+ \to \pi^0 e^+\nu_e$



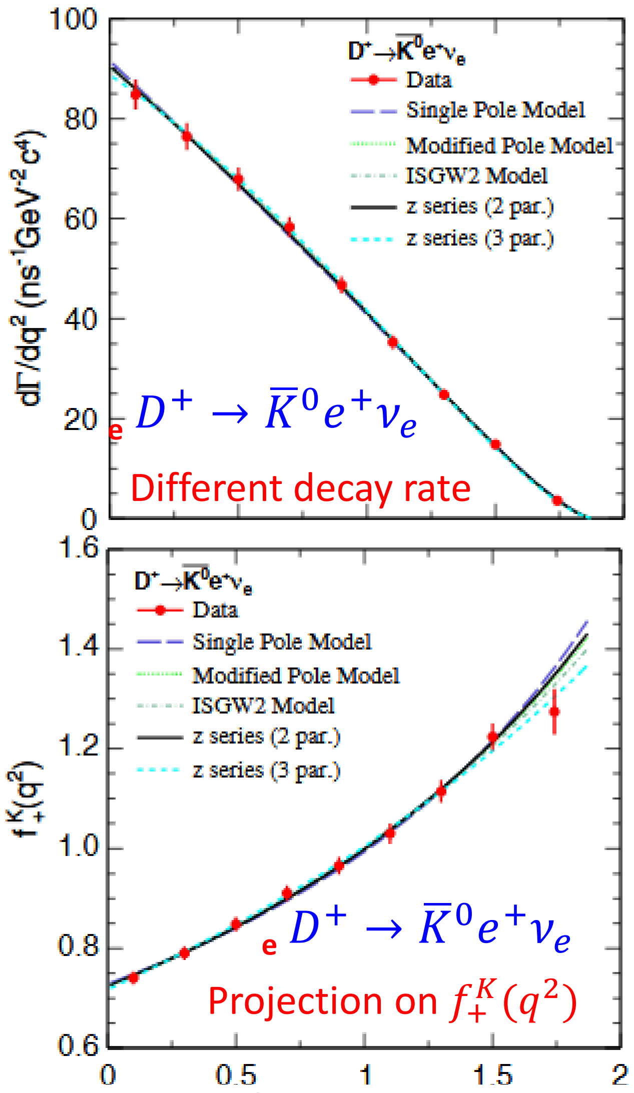
26008 ± 168

3402 ± 70

Background

$$\boldsymbol{B}\left(\boldsymbol{D}^+ \to \bar{\boldsymbol{K}}^0\, \boldsymbol{e}^+\, \boldsymbol{\nu}_e\right) = (\mathbf{8.60 \pm 0.06 \pm 0.15})\%$$

$$\boldsymbol{B}\left(\boldsymbol{D}^+ \to \boldsymbol{\pi}^0\, \boldsymbol{e}^+\, \boldsymbol{\nu}_e\right) = (\mathbf{0.363 \pm 0.008 \pm 0.005})\%$$



$D^+ \to \bar{K}^0 e^+\nu_e$

Different decay rate

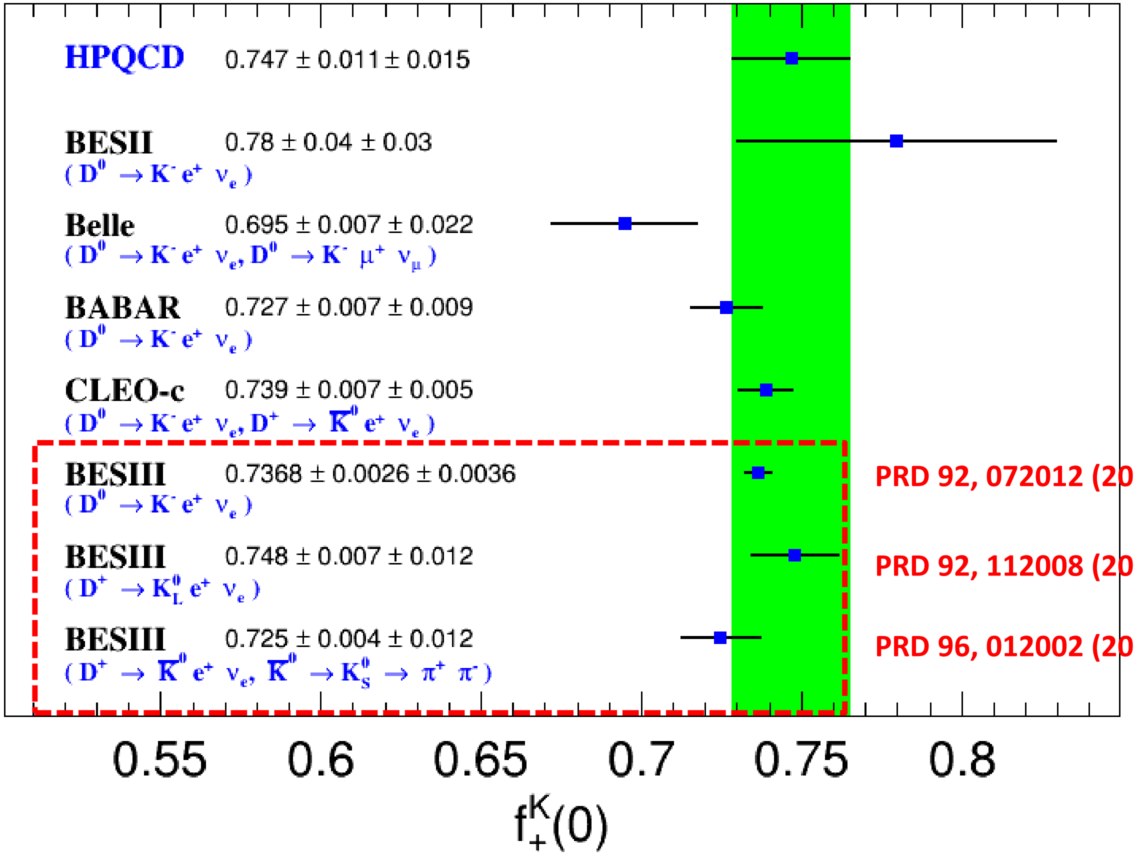
$D^+ \to \bar{K}^0 e^+\nu_e$

Projection on $f_+^K(q^2)$

$$q^2 = \left(E_{e^+} + E_{\nu_e}\right)^2/\mathrm{c}^4 - \left(\vec{p}_{e^+} + \vec{p}_{\nu_e}\right)^2/\mathrm{c}^2$$

Comparisons of $f_+^K(0)$ for $D \to K e^+ \nu_e$

BESIII: higher precision; consistent with others.

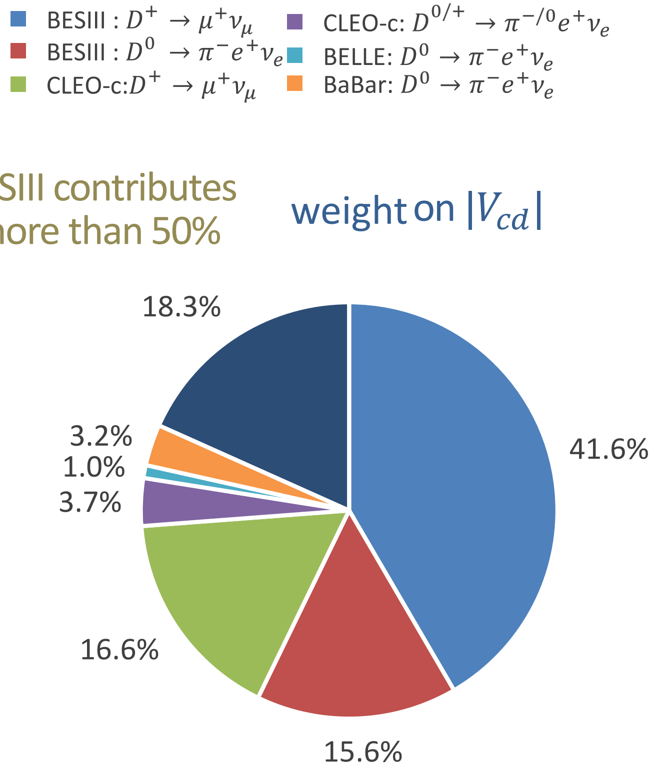


PRD 92, 072012 (2015)

PRD 92, 112008 (2015)

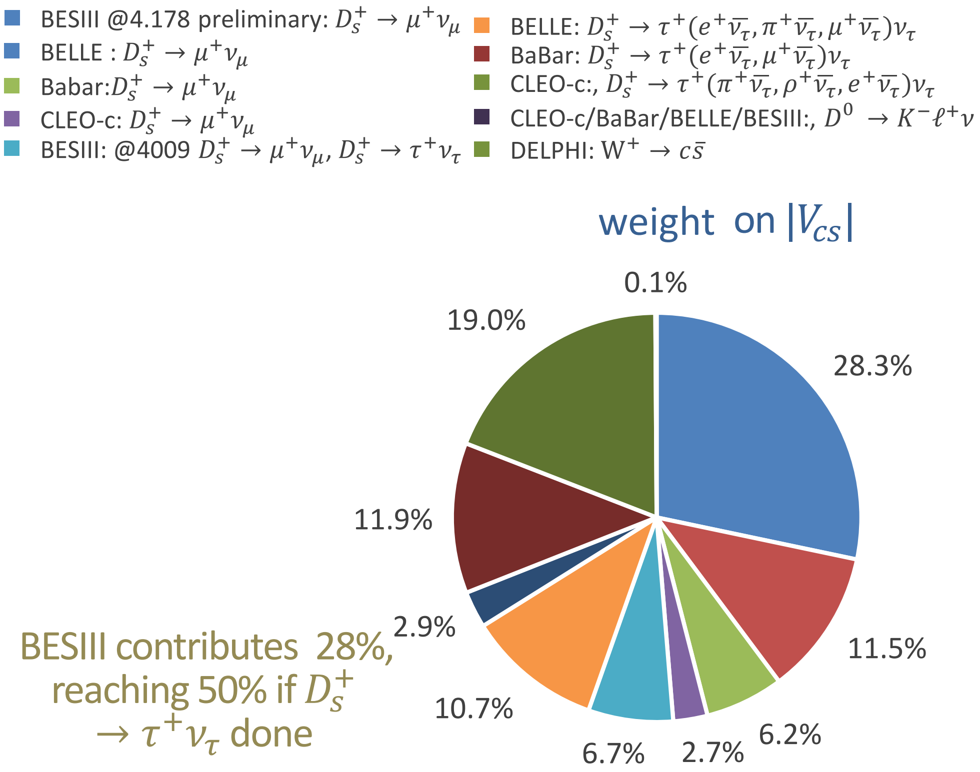
PRD 96, 012002 (2017)

Weights of measurement on $|V_{cs(d)}|$



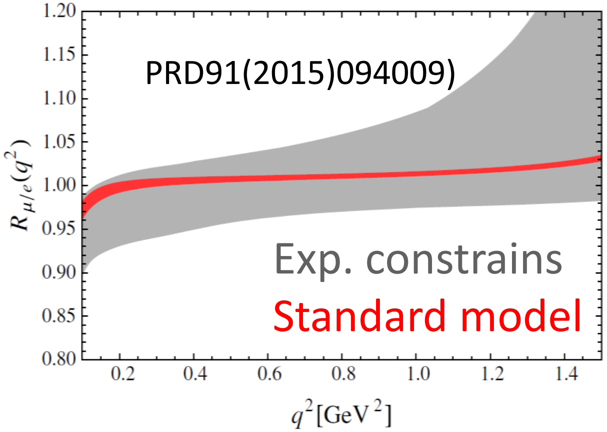
weight on $|V_{cd}|$

BESIII contributes more than 50%



weight on $|V_{cs}|$

BESIII contributes 28%, reaching 50% if $D_s^+ \to \tau^+\nu_\tau$ done



PRD91(2015)094009)

Exp. constrains

Standard model