(Semi-) leptonic *D* decays at BESIII

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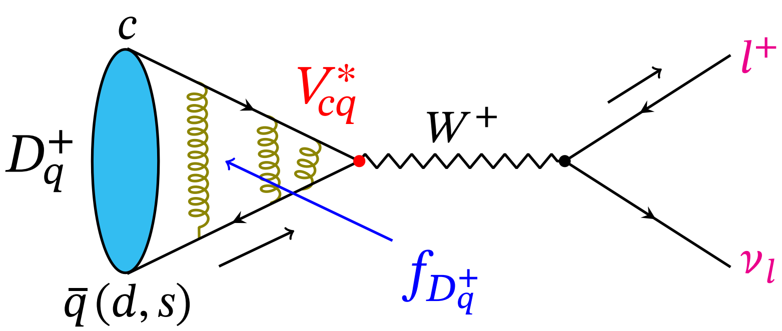
(On behalf of BESIII Collaboration)

Outline

- Introduction
- Pure leptonic D_s decays
- Semi-leptonic $D_{(s)}$ decays
- Summary

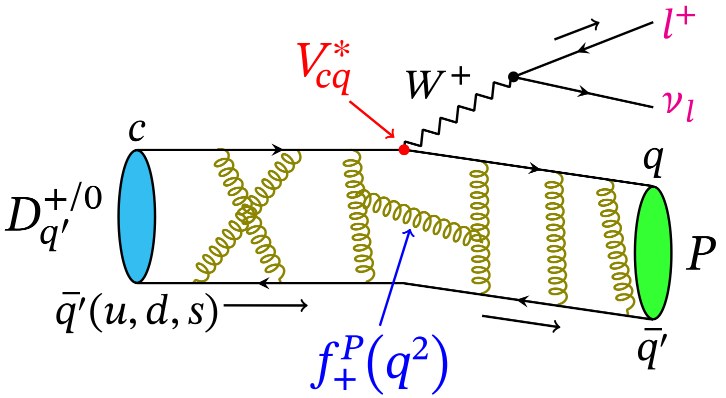
Introduction

$D_{(s)}$ 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



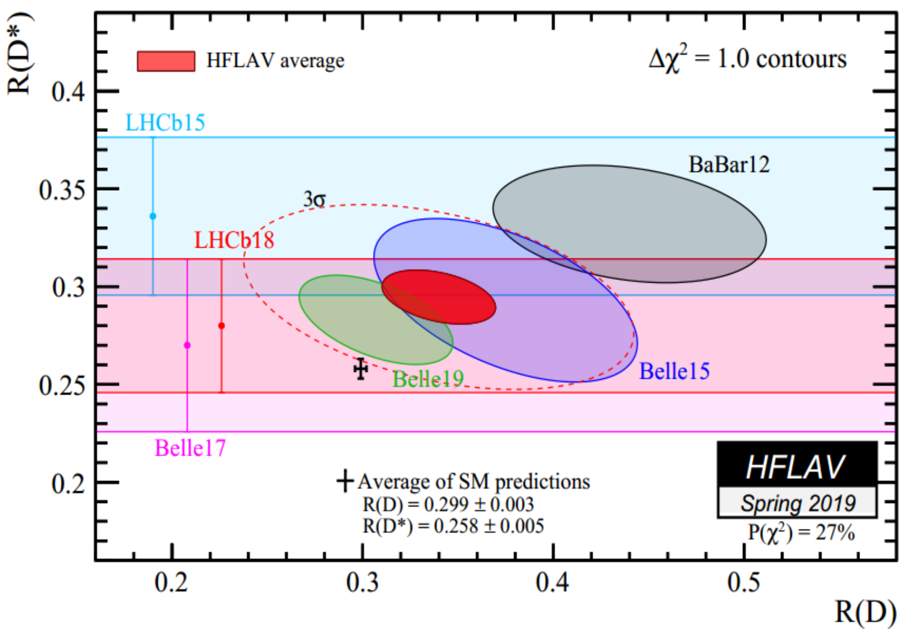
$$\Gamma\left(D_{(s)} \to P\, l^+\, \nu_l\right) \propto \left|f_+(q^2)\right|^2 \cdot \left|V_{cd(s)}\right|^2$$

- CKM matrix element $|V_{cd(s)}|$: Test the unitarity CKM matrix and search for NP beyond SM
- Decay constant $f_{D_{(s)}^+}$, form factor $f_+(q^2)$: Calibrate Lattice QCD
- To validate their application to the B-meson (f_{B^+})

Introduction

➢ Lepton flavor universality test in charm sector

$$R_{\tau/\mu} = \frac{\bar{\Gamma}(D_s^+ \to \tau^+\nu_\tau)}{\bar{\Gamma}(D_s^+ \to \mu^+\nu_\mu)} = \frac{m_{\tau^+}^2\left(1-\frac{m_{\tau^+}^2}{m_{D_s^+}^2}\right)^2}{m_{\mu^+}^2\left(1-\frac{m_{\mu^+}^2}{m_{D_s^+}^2}\right)^2}$$



Evidence of LFUV in semi-leptonic B decays :

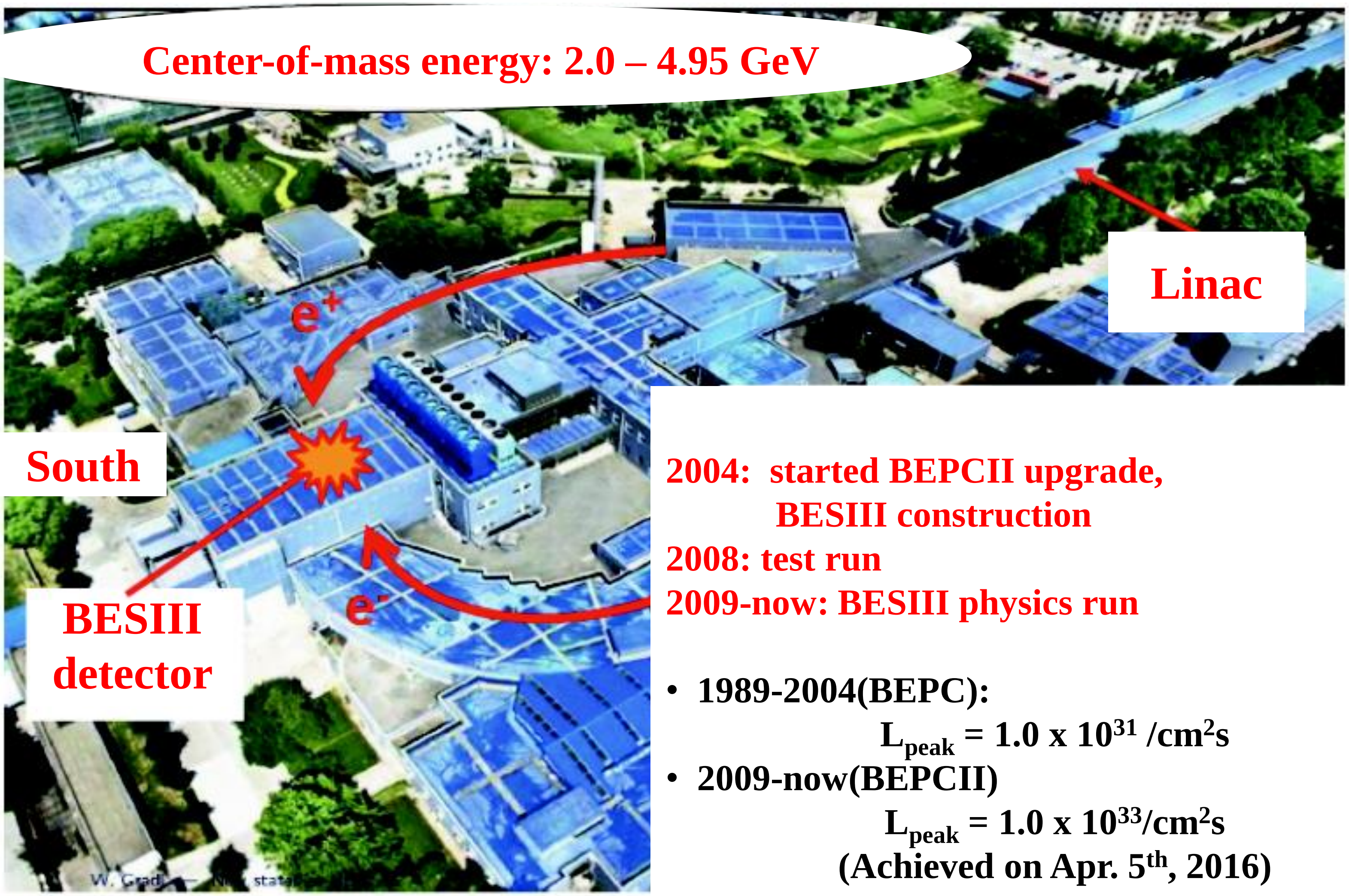
$$R_{D^{(*)}} = \frac{\Gamma(B \to D^{(*)}\tau^+\nu_\tau)}{\Gamma(B \to D^{(*)}\mu^+\nu_\mu)} \quad [1]$$

$$R_{K^{(*)}} = \frac{\Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^+ \to K^{(*)+}e^+e^-)} \quad [2]$$

[1]Phys. Rev. Lett. **109**, 101802 (2012) ; Phys. Rev. D **92**, 072014 (2015) ; Phys. Rev. Lett. **115**,111803 (2015) Phys. Rev. Lett. **118**, 211801 (2017) ; Phys. Rev. Lett. **120**, 171802 (2018); arXiv: 1904.08794 [hep-ex] .

[2]Phys. Rev. Lett. **113**, 151601 (2014) ; JHEP **1708**, 055 (2017).

BEPCII: high luminosity double–ring collider



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

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

BESIII detector

From inner to outside[1]:

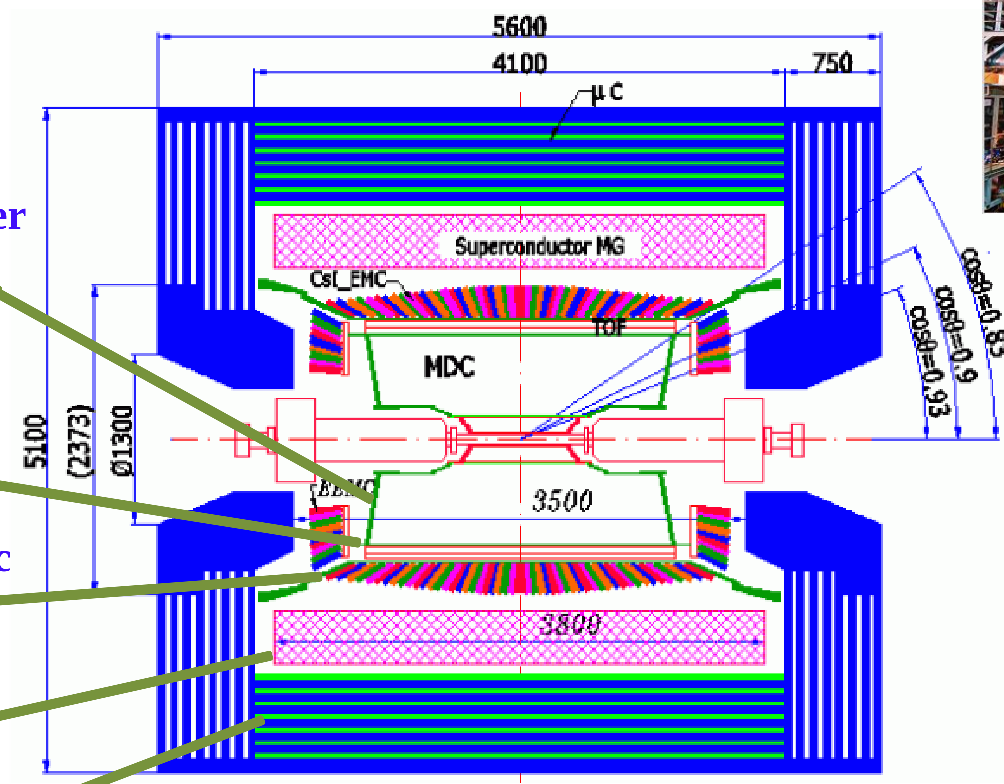
Helium-based multilayer drift chamber (MDC):

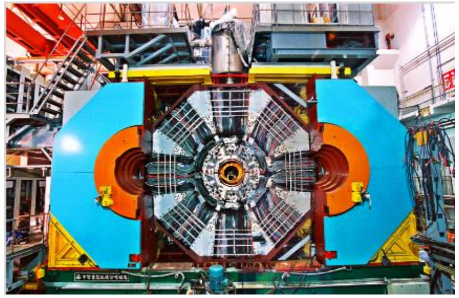
Plastic scintillator time-of-flight (TOF):

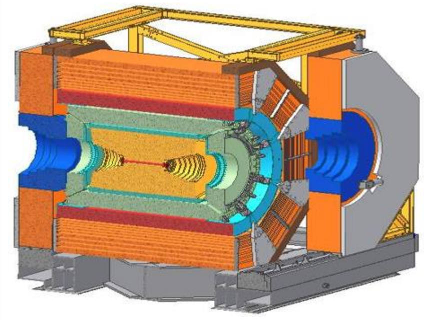
CsI (Tl) electromagnetic calorimeter (EMC):

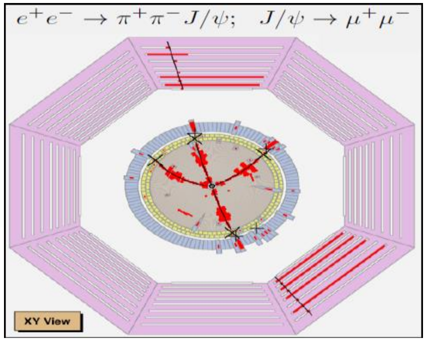
Superconducting solenoidal magnet:

Muon Chamber (MUC):







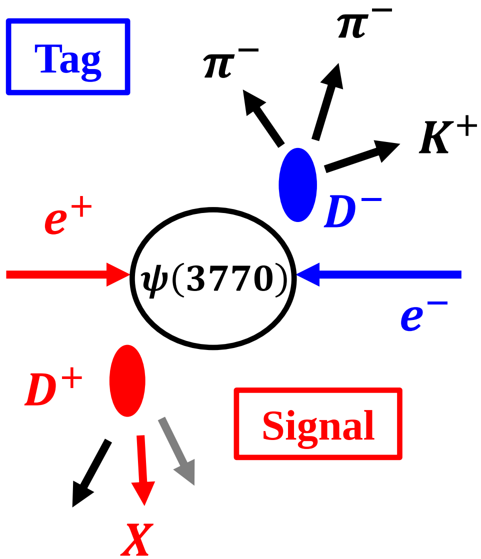


[3] M. Ablikim *et al*. (BESIII Collaboration), Nucl. Instr. Meth. A614, 345 (2010).

$D^{0(+)}$, D_s^+ samples at BESIII (in pb^{-1})

$\sqrt{s}$(GeV)	Integrated luminosity	Decay chain of interest
3.773	2930 pb^{-1}	$e^+e^- \to \psi(3770) \to D^0\bar{D}^0$
		$e^+e^- \to \psi(3770) \to D^+D^-$
$\sqrt{s}$(GeV)	Integrated luminosity(pb^{-1})	
4.178	$3189.0 \pm 0.9 \pm 31.9$	$e^+e^- \to D_s^*D_s$ Total: 6320 pb^{-1}
4.189	$526.7 \pm 0.1 \pm 2.2$	
4.199	$526.0 \pm 0.1 \pm 2.1$	
4.209	$517.1 \pm 0.1 \pm 1.8$	
4.219	$514.6 \pm 0.1 \pm 1.8$	
4.226	$1047.3 \pm 0.1 \pm 10.2$	

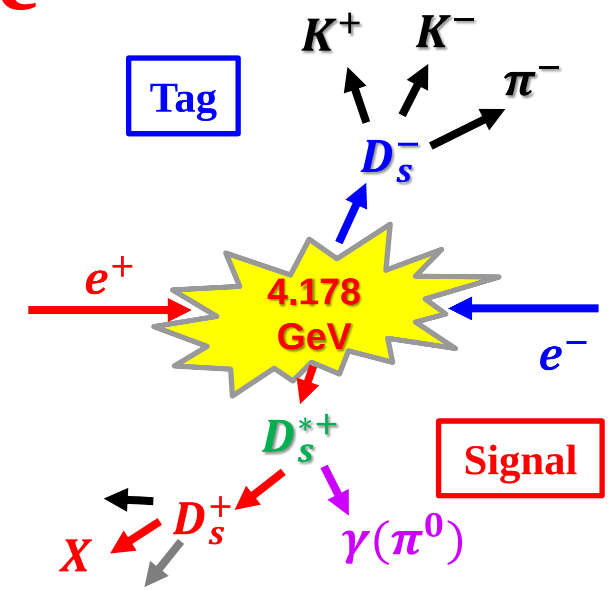
Analysis technique



Charge conjugated processes are implied

The signal branching fraction:

$$B_{\text{sig}} = \frac{N_{\text{DT}}^{\text{signal}}}{N_{D_{(s)}}^{\text{ST}} \times \epsilon}$$



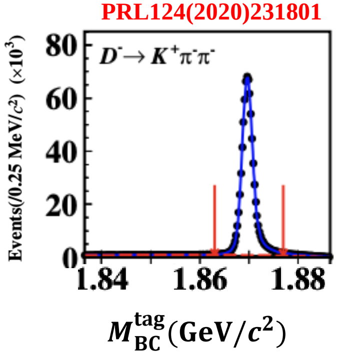
- **Single tag (ST):**

fully reconstruct one D^-

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

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

PRL124(2020)231801



□ **Double tag (DT):**

in the recoil ST $D_{(s)}^-$, analyze the signal $D_{(s)}^+$

$$\text{MM}^2 = E_{\text{miss}}^2 - |\vec{p}_{\text{miss}}|^2$$

$$E_{\text{miss}} = E_{\text{cm}} - \sqrt{\left|\vec{p}_{D_{(s)}^-}\right|^2 + M_{D_{(s)}}^2} - E_X$$

$$\vec{p}_{\text{miss}} = -\vec{p}_{D_{(s)}^-} - \vec{p}_X$$

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

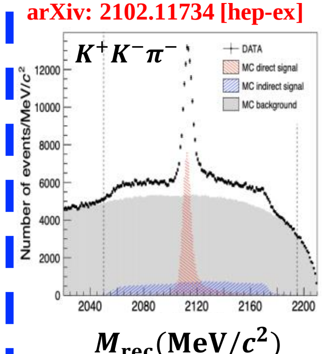
or other variables

- **Single tag (ST):**

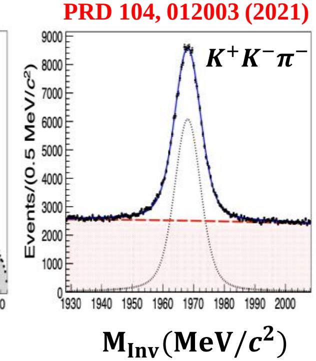
fully reconstruct one D_s^-

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

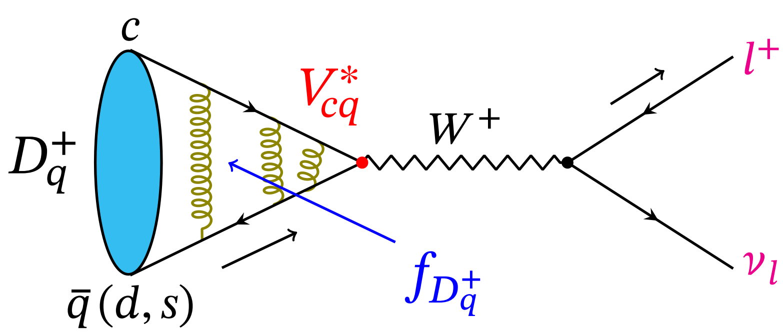
arXiv: 2102.11734 [hep-ex]



PRD 104, 012003 (2021)



Pure leptonic decay



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

- $D_s^+ \to \tau^+\nu_\tau$
  - $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$ — arXiv: 2106.02218[hep−ex]
  - $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$ — Phys. Rev D 104, 032001 (2021)
  - $\tau^+ \to \pi^+\bar{\nu}_\tau$
- $D_s^+ \to \mu^+\nu_\mu$

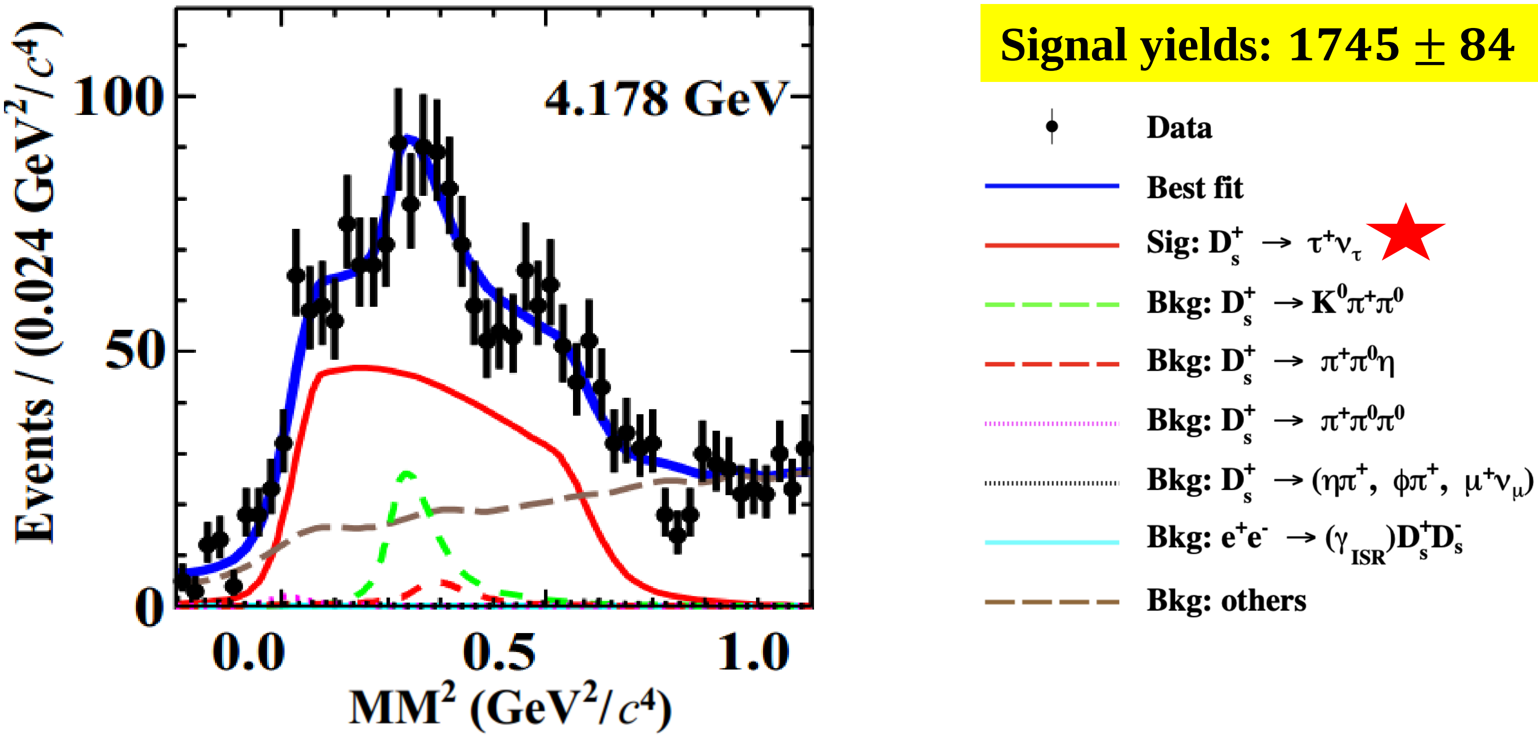
($\tau^+ \to \pi^+\bar{\nu}_\tau$ and $D_s^+ \to \mu^+\nu_\mu$): arXiv: 2102.11734 [hep-ex] Accepted by PRD

$D_s^+ \to \tau^+\nu_\tau \; via \; \tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$

Phys. Rev. D **104, 032001 (2021)**

- **Simultaneous** fit to the MM^2 for six energy points shared with **a common** leptonic branching fraction.

Only show @ 4.178 GeV



Signal yields: 1745 ± 84

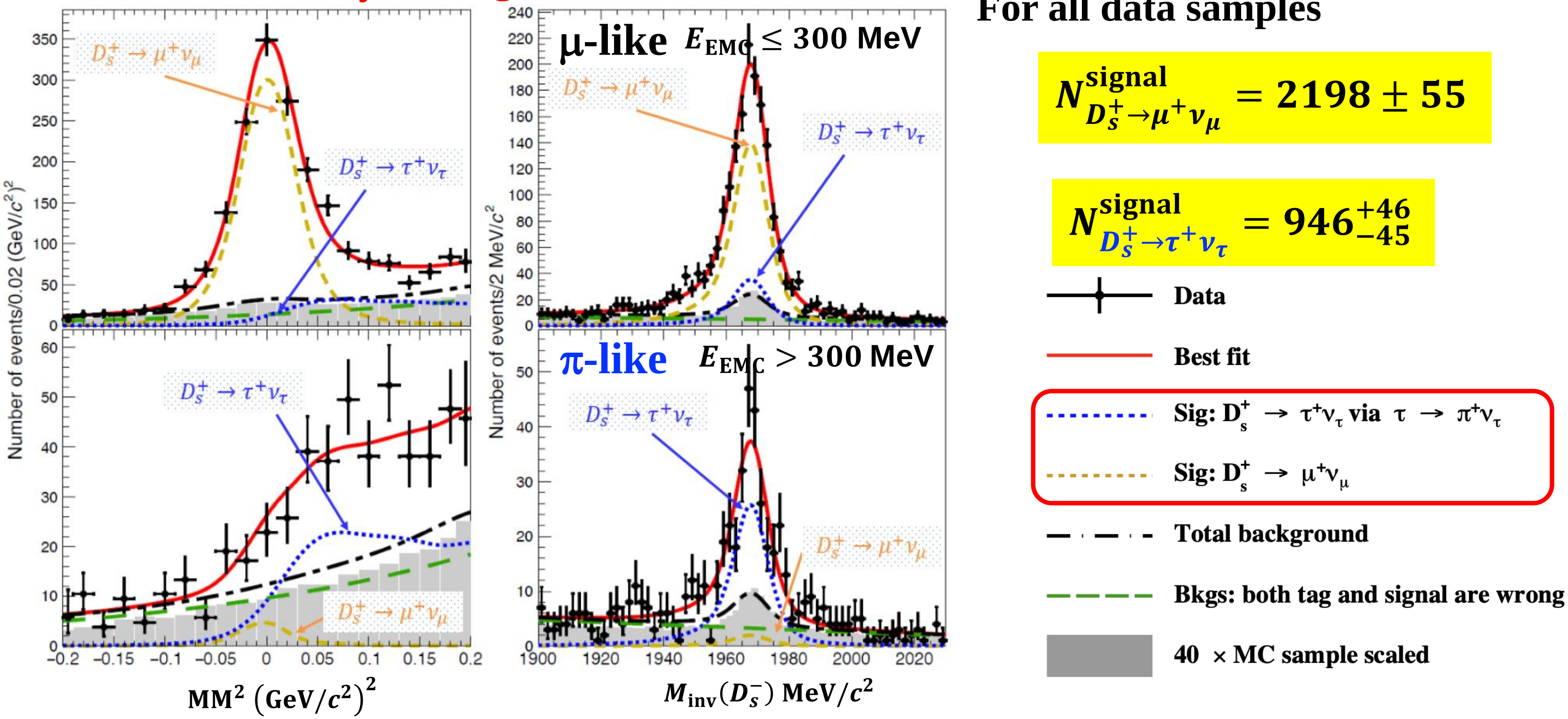
$$B_{D_s^+\to\tau^+\nu_\tau} = (5.29 \pm 0.25_{\text{stat.}} \pm 0.20_{\text{syst.}})\%$$

$D_s^+ \to \mu^+\nu_\mu$ and $D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\bar{\nu}_\tau$

arXiv:2102.11734[hep−ex] Accepted by PRD

- An unbinned **simultaneous** maximum likelihood fit to **two-dimensional** distributions

Only show @ 4.178 GeV



For all data samples

$$N^{\mathrm{signal}}_{D_s^+\to\mu^+\nu_\mu} = 2198 \pm 55$$

$$N^{\mathrm{signal}}_{D_s^+\to\tau^+\nu_\tau} = 946^{+46}_{-45}$$

$$B(D_s^+ \to \mu^+\nu_\mu) = (5.35 \pm 0.13_{\mathrm{stat.}} \pm 0.16_{\mathrm{syst.}}) \times 10^{-3}$$

The most precise to date.

$$B(D_s^+ \to \tau^+\nu_\tau) = (5.21 \pm 0.25_{\mathrm{stat.}} \pm 0.17_{\mathrm{syst.}}) \times 10^{-2}$$

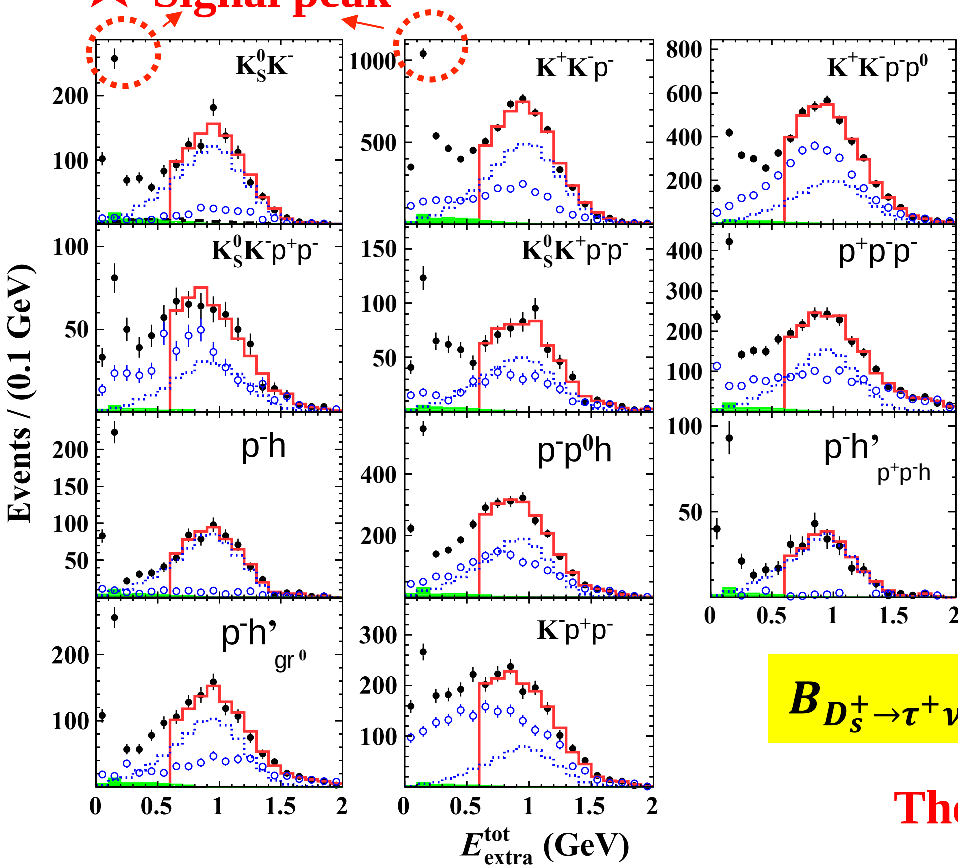
$D_s^+ \to \tau^+\nu_\tau \; via \; \tau^+ \to e^+\nu_e\bar{\nu}_\tau$

arXiv:2106.02218[hep−ex]

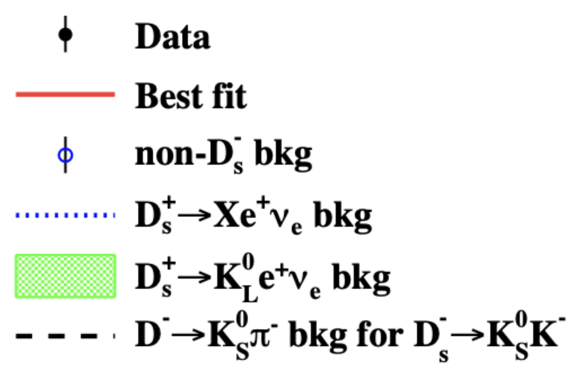
- ✓ $E_{\mathrm{extra}}^{\mathrm{tot}}$: the total energy of the good EMC showers, excluding those associated with the ST D_s^- candidates and those within 5° of the initial direction of the positron.

- ✓ **DT yield** $N_{\mathrm{DT}} = N_{\mathrm{DT}}^{\mathrm{tot}} - N_{\mathrm{DT}}^{\mathrm{non-}D_s^-} - N_{\mathrm{DT}}^{K_L^0 e^+\nu_e} - N_{\mathrm{DT}}^{Xe^+\nu_e}$ (in signal $E_{\mathrm{extra}}^{\mathrm{tot}} < 0.4$ GeV)

★ Signal peak



The background yields of $D_s^+ \to X\,e^+\nu_e$ extrapolated from the fits to $E_{\mathrm{extra}}^{\mathrm{tot}} > 0.6$ GeV.



$$B_{D_s^+\to\tau^+\nu_\tau} = (5.27 \pm 0.10_{\mathrm{stat.}} \pm 0.12_{\mathrm{syst.}})\%$$

The most precise result to date

Averaged result for $D_s^+ \to \tau^+ \nu_\tau$

BESIII results		
Mode	$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)$	$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)$
$\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$	$(5.29 \pm 0.25 \pm 0.20)\%$	-
$\tau^+ \to \pi^+\bar{\nu}_\tau$	$(5.21 \pm 0.25 \pm 0.17)\%$	$(0.535 \pm 0.013 \pm 0.016)\%$
$\tau^+ \to e^+\nu_e\bar{\nu}_\tau$	$(5.27 \pm 0.10 \pm 0.12)\%$	-
Average	$(5.26 \pm 0.09 \pm 0.09)\%$	$(0.535 \pm 0.013 \pm 0.016)\%$

(The correlated uncertainties of single-tag yields, tag bias, tracking/PID are considered)

$$R(\tau/\mu)_{\text{exp}} = \frac{B(D_s^+ \to \tau^+\nu_\tau)}{B(D_s^+ \to \mu^+\nu_\mu)} = 9.83 \pm 0.45$$

Consistent

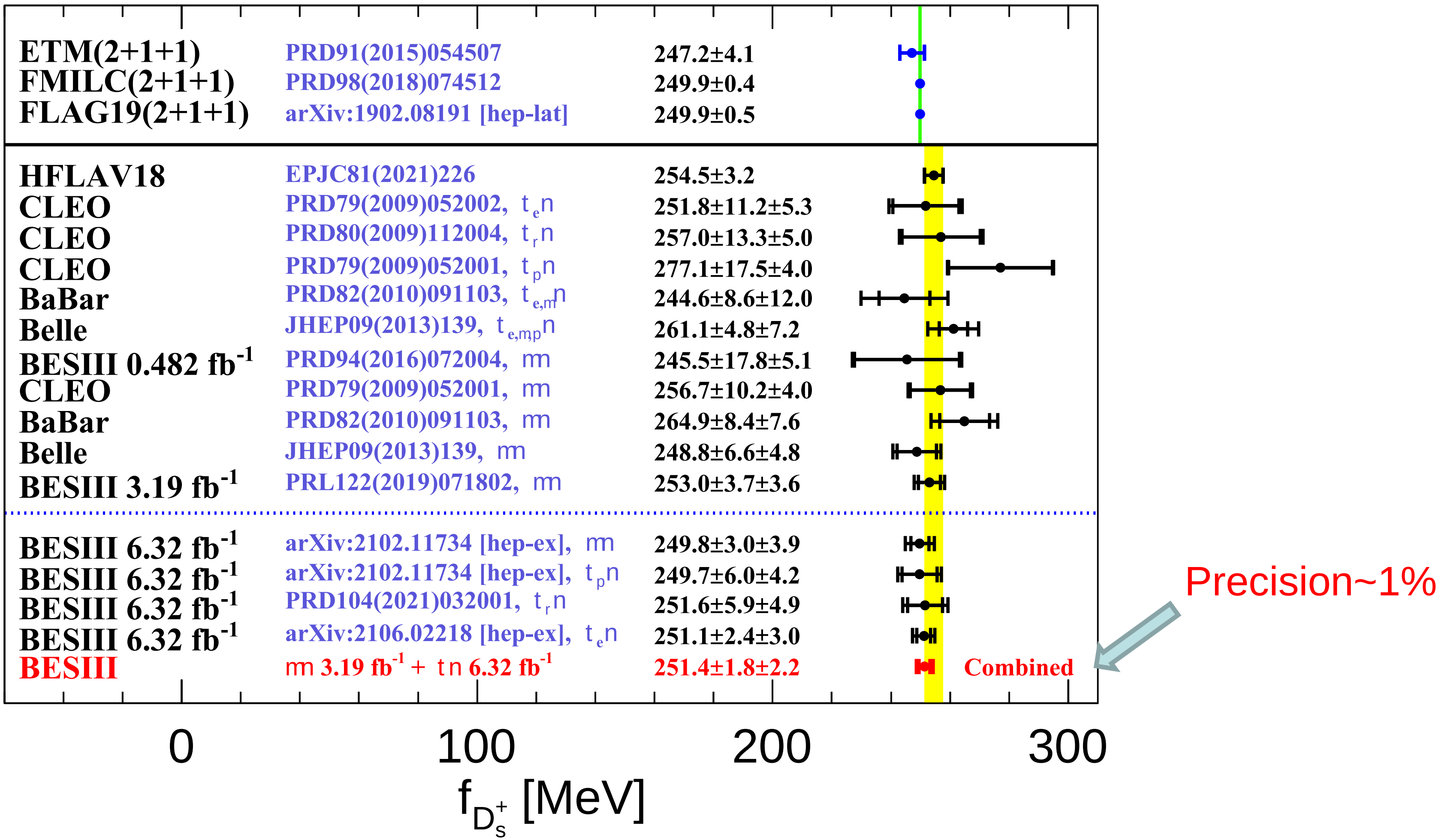
$$R(\tau/\mu)_{\text{SM}} = \frac{m_\tau^2\left(1 - \frac{m_\tau^2}{m_{D_s}^2}\right)^2}{m_\mu^2\left(1 - \frac{m_\mu^2}{m_{D_s}^2}\right)^2} = 9.75 \pm 0.01$$

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

$f_{D_s^+}|V_{cs}| = (243.8 \pm 1.7 \pm 2.1)$ MeV

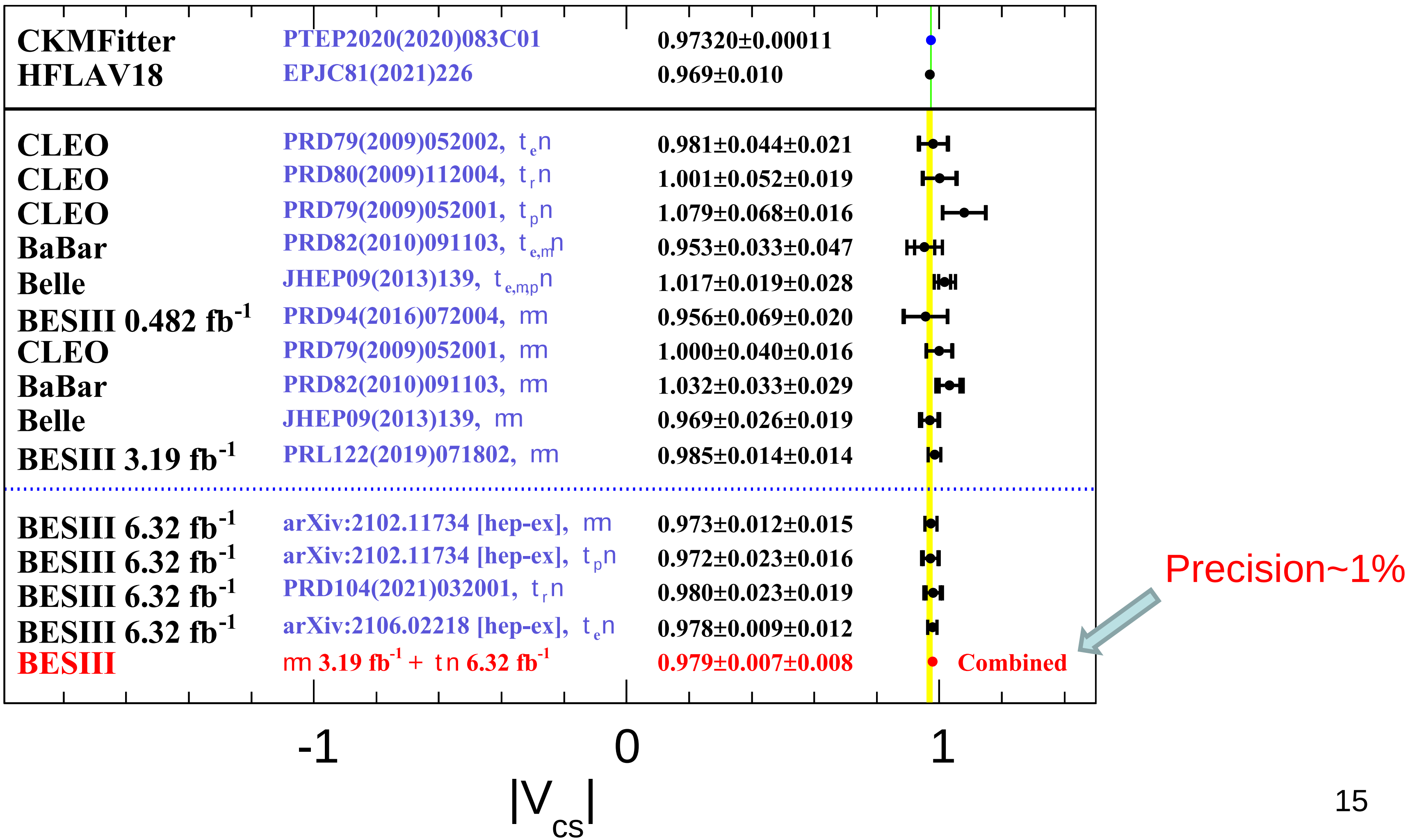
Comparison of decay constant $f_{D_s^+}$

- **Input $|V_{cs}| = 0.97320 \pm 0.00011$ from CKM global fit**

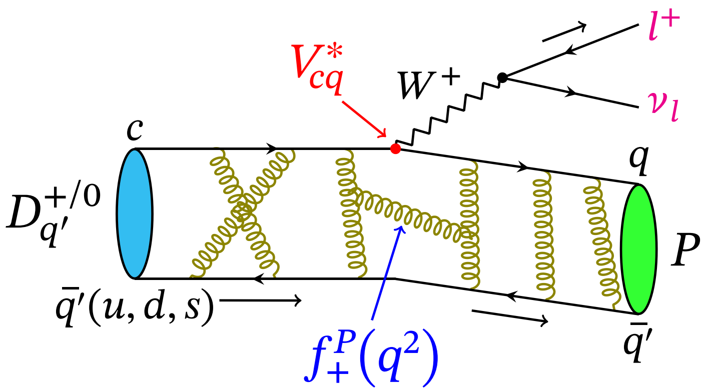


Comparison of $|V_{cs}|$

- **Input $f_{D_s^+} = 249.9 \pm 0.5$ from LQCD calculations (FLAVG19)**



Semi-leptonic decay



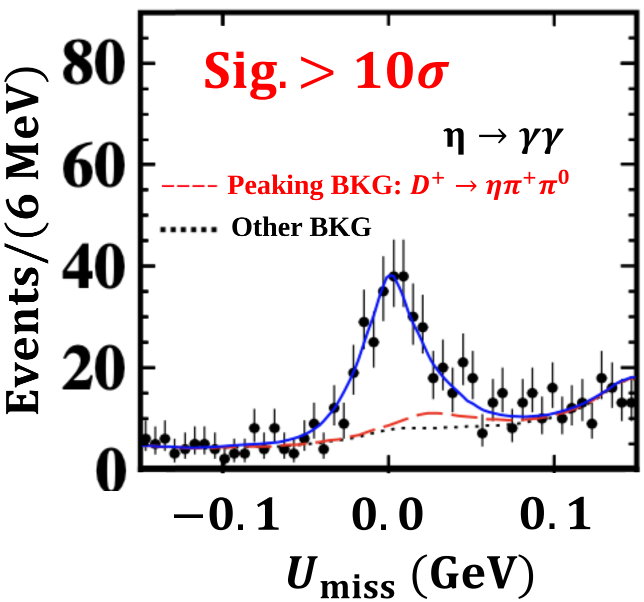
$$D \to P\, e^+ \nu\ (P = K, \pi, \eta^{(\prime)})$$

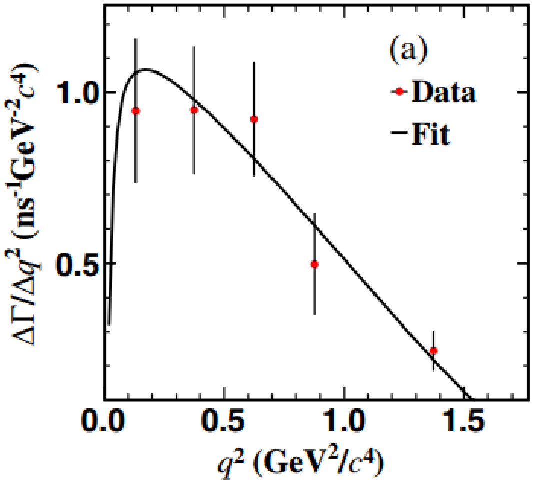
$$\frac{d\Gamma}{dq^2} = X \frac{G_F^2 p^3}{24\pi^3} |f_+(q^2)|^2 \left|V_{cd(s)}\right|^2\ (X = 1\ for\ K^-, \pi^-, \bar{K}^0, \eta^{(\prime)}; X = \frac{1}{2}\ for\ \pi^0)$$

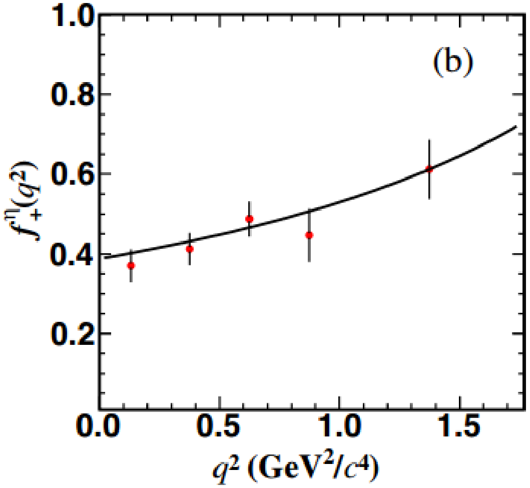
- $D^+ \to \eta \mu^+ \nu_\mu$ **PRL124(2020)231801**
- $D^0 \to K_1(1270)^- e^+ \nu_e$ **arXiv: 2102.10850 [hep-ex]**
- $D_s^+ \to X e^+ \nu_e$ **PRD104(2020)012003**
- $D^0 \to \rho^- \mu^+ \nu_\mu$ **arXiv: 2106.02292 [hep-ex]**

$D^+ \to \eta\, \mu^+ \nu_\mu$
Phys. Rev. Lett. 124, 231801(2020)

Unbinned fit to U_{miss}







$f_+^\eta(q^2)$ is parameterized by the two parameters series expansion.

$N_{\text{DT}}^{\text{signal}} = 234 \pm 22$

$B_{D^+\to\eta\mu^+\nu_\mu} = (10.4 \pm 1.0_{\text{stat.}} \pm 0.5_{\text{syst.}}) \times 10^{-4}$

$f_+^\eta(0) = 0.39 \pm 0.04_{\text{stat.}} \pm 0.01_{\text{syst.}}$

$|V_{cd}| = 0.242 \pm 0.022_{\text{stat.}} \pm 0.006_{\text{syst.}} \pm 0.033_{\text{theory}}$

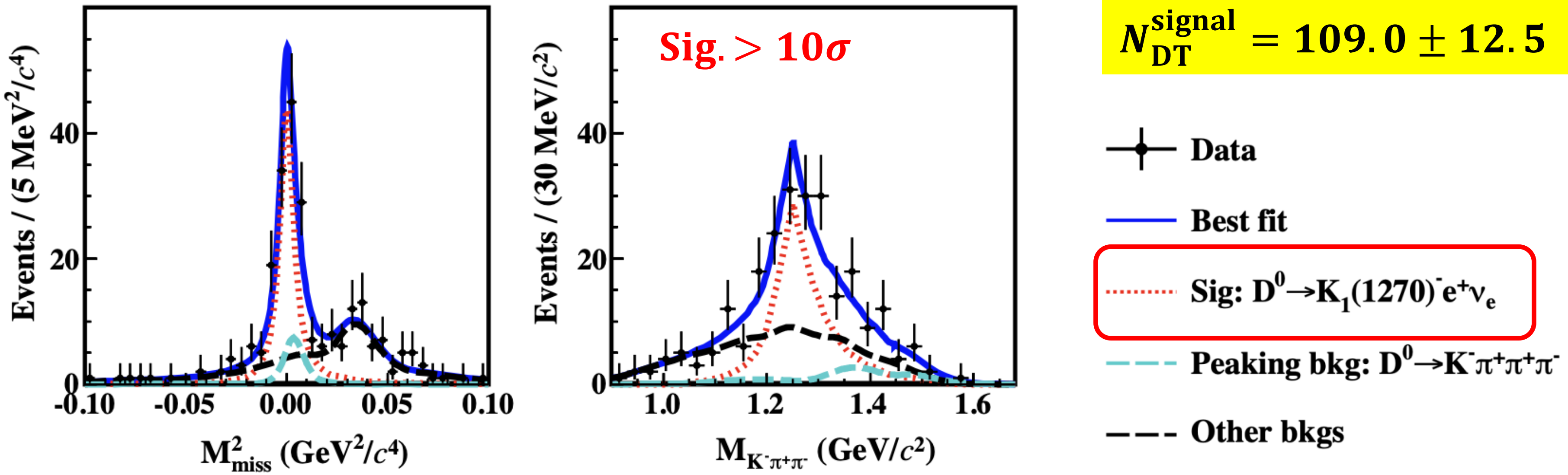
Experimental confirmation for the first time since it was predicted 30 years ago.
Phys. Rev. D 39, 799 (1989).

$R_{\mu/e} = \frac{B_{D^+\to\eta\mu^+\nu_\mu}}{B^{PDG}_{D^+\to\eta e^+\nu_e}} = 0.91 \pm 0.13$ consistent ⟺ SM prediction: $(0.97 - 1.00)$

$D^0 \to K_1(1270)^- e^+\nu_e$

arXiv: 2102.10850 [hep−ex] Accepted by PRL

- ✓ $K_1(1270)^- \to K^-\pi^+\pi^-$
- ✓ **Two-dimensional** unbinned extended maximum-likelihood **simultaneous** fits shared with the **same value of** $[B_{D^0\to K_1(1270)^- e^+\nu_e} \cdot B_{K_1(1270)^-\to K^-\pi^+\pi^-}]$.



$N_{\mathrm{DT}}^{\mathrm{signal}} = 109.0 \pm 12.5$

$$B_{D^0\to K_1(1270)^- e^+\nu_e} = \left(1.09 \pm 0.13^{+0.09}_{-0.16} \pm 0.12_{\mathrm{ex.}}\right) \times 10^{-3}$$

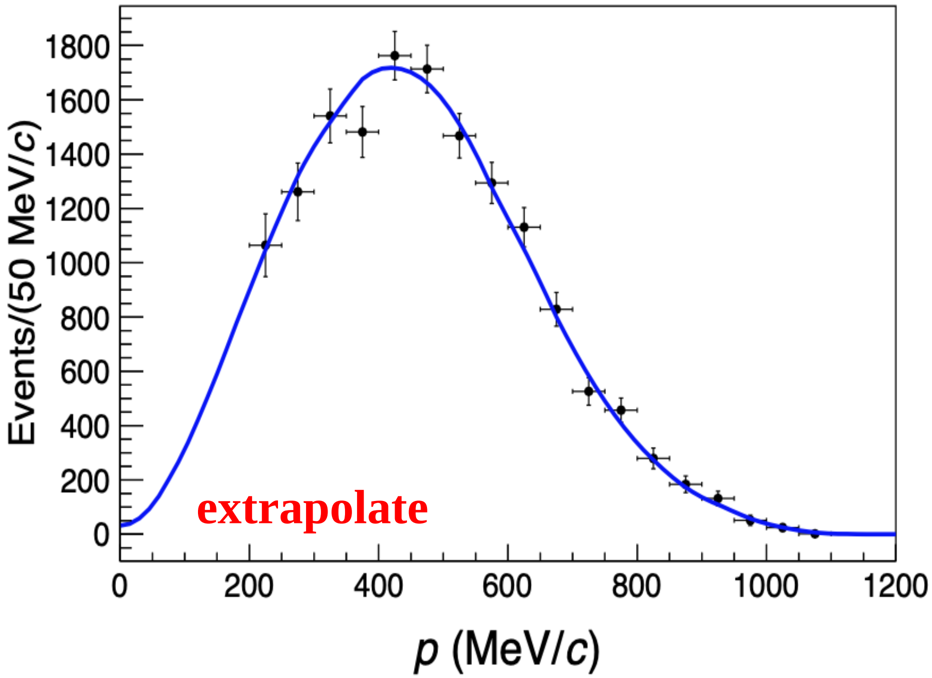
$$\frac{\Gamma_{D^0\to K_1(1270)^- e^+\nu_e}}{\Gamma_{D^+\to \bar{K}_1(1270)^0 e^+\nu_e}} = 1.20 \pm 0.02_{\mathrm{stat.}} \pm 0.14_{\mathrm{syst.}} \pm 0.04_{\mathrm{ex.}}$$

Agrees with unity as predicted by isospin symmetry.

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

Phys. Rev. D **104, 012003 (2021)**

✓ X means inclusive decays



$$N^{\text{signal}}_{D_s^+ \to X e^+ \nu_e} = 16648 \pm 326$$

The measured $D_s^+ \to X e^+ \nu_e$ yields

Best fit

$$B(D_s^+ \to X e^+ \nu_e) = (6.30 \pm 0.13_{\text{stat.}} \pm 0.10_{\text{syst.}}) \times 10^{-2}$$

Consistent, improved by a factor of 2.5 compared to that from CLEO

$$B(D_s^+ \to X e^+ \nu_e) - \sum_i B(D_s^+ \to X_i e^+ \nu_e)_{\text{known}} = (-0.04 \pm 0.13_{\text{stat.}} \pm 0.20_{\text{syst.}}) \times 10^{-2}$$

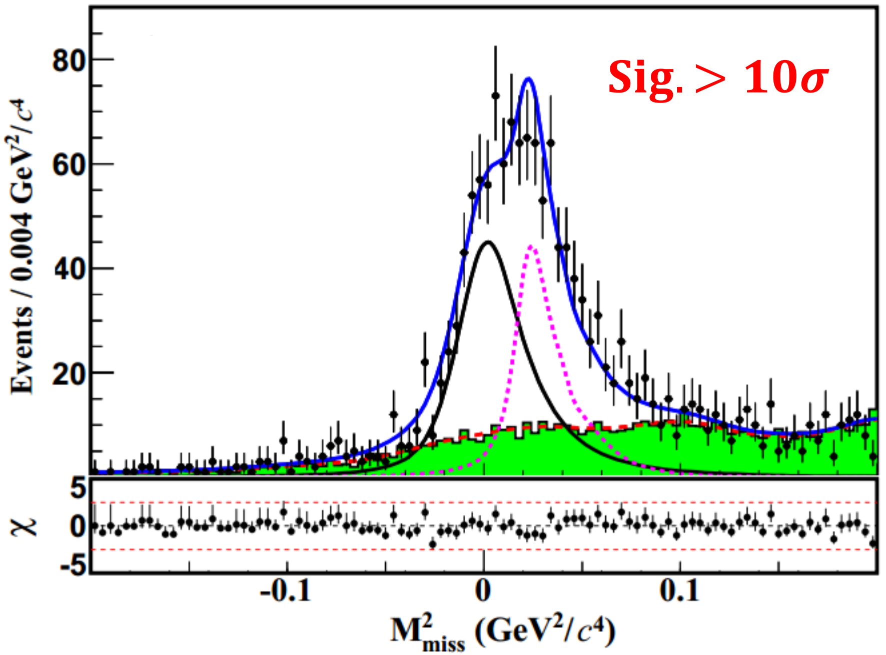
No evidence for the existence of unobserved D_s^+ semileptonic decay modes

$$\frac{\Gamma_{D_s^+ \to X e^+ \nu_e}}{\Gamma_{D^0 \to X e^+ \nu_e}} = 0.790 \pm 0.016_{\text{stat.}} \pm 0.020_{\text{syst.}}$$

consistent ⟺ 0.813 (prediction)

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

arXiv:2106.02292[hep−ex]



$N_{\mathrm{DT}}^{\mathrm{signal}} = 570 \pm 40$

The semileptonic decay $D^0 \to \rho^- \mu^+ \nu_\mu$ has been observed for the first time.

$$B_{D^0 \to \rho^- \mu^+ \nu_\mu} = (1.35 \pm 0.09 \pm 0.09) \times 10^{-3}$$

$$\frac{B_{D^0 \to \rho^- \mu^+ \nu_\mu}}{B_{D^0 \to \rho^- e^+ \nu_e}} = 0.90 \pm 0.11$$ **SM prediction: (0.93-0.96)**

No LFU violation within current sensitivity

Other analyses

- $D^+ \to \omega\mu^+\nu_\mu$ **Phys. Rev. D 101, 072005(2020)**

- **We report the first observation of the semimuonic decay $D^+ \to \omega\mu^+\nu_\mu$, The absolute BF is measured to be $(17.7 \pm 1.8_{stat.} \pm 1.1_{syst.}) \times 10^{-4}$**

- $D^0 \to K^- e^+\nu_e$ **and** $D^+ \to \bar{K}^0 e^+\nu_e$ **arXiv: 2104.08081 [hep-ex] Accepted by PRD**

- **We measure the absolute branching fractions of the decays with a new method, This ratio of the two decay partial widths supports isospin symmetry in the decay**

- $D_s^+ \to a_0(980)^0 e^+\nu_e$ **Phys. Rev. D 103, 092004 (2021)**

- **We present the first search for the decay, an upper limit of 1.2$\times 10^{-4}$ at the 90% confidence level is set**

- $D^{0(+)} \to b_1(1235)^{-(0)} e^+\nu_e$ **Phys. Rev. D 102, 112005(2020)**

- **We search for the semileptonic $D^{0(+)}$ decays into a $b_1(1235)^{-(0)}$ axial-vector meson for the first time. The upper limits are set**

Summary

- With 2.93 fb^{-1} @ 3.773 GeV and 6.32 fb^{-1} from 4.178-4.226 GeV data samples

Results with improved precision for:

- ✓ $D_s^+ \to \tau^+ \nu_\tau$
  - $\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$
  - $\tau^+ \to \pi^+ \pi^0 \bar{\nu}_\tau$
  - $\tau^+ \to \pi^+ \bar{\nu}_\tau$
- ✓ $D_s^+ \to \mu^+ \nu_\mu$
- ✓ $D_s^+ \to X e^+ \nu_e$

First observations for:

$D^+ \to \eta \mu^+ \upsilon_\mu$ ($> 10\sigma$)
$D^0 \to K_1(1270)^- e^+ \nu_e$ ($> 10\sigma$)
$D^0 \to \rho^- \mu^+ \nu_\mu$ ($> 10\sigma$)

First measurement on the dynamics of:
$D^+ \to \eta \mu^+ \upsilon_\mu$

- **In the near future, BESIII will collect 20 fb^{-1} @ 3.773 GeV data sample, and another 3 fb^{-1} @ 4.178 GeV, the precisions will be further improved.**

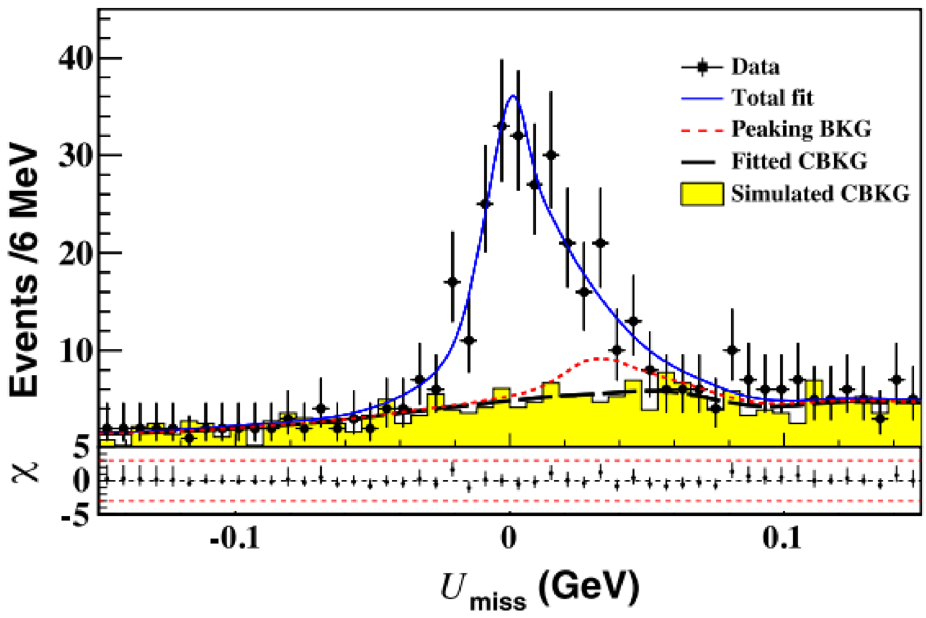
Chinese Physics C 44, 040001 (2020)

Thanks!

Back up

$D^+ \to \omega\, \mu^+ \nu_\mu$

Phys. Rev. D **101, 072005(2020)**



$$\mathcal{B}(D^+ \to \omega\mu^+\nu_{\mu^+}) = (17.7 \pm 1.8 \pm 1.1) \times 10^{-4}$$

This BF is consistent with theretical calculation (LFQM, CCQM, and LCSR methods).

$$R = \frac{\mathcal{B}(D^+ \to \omega\mu^+\nu_\mu)}{\mathcal{B}(D^+ \to \omega e^+\nu_e)_{\mathrm{PDG}}} = 1.05 \pm 0.14$$

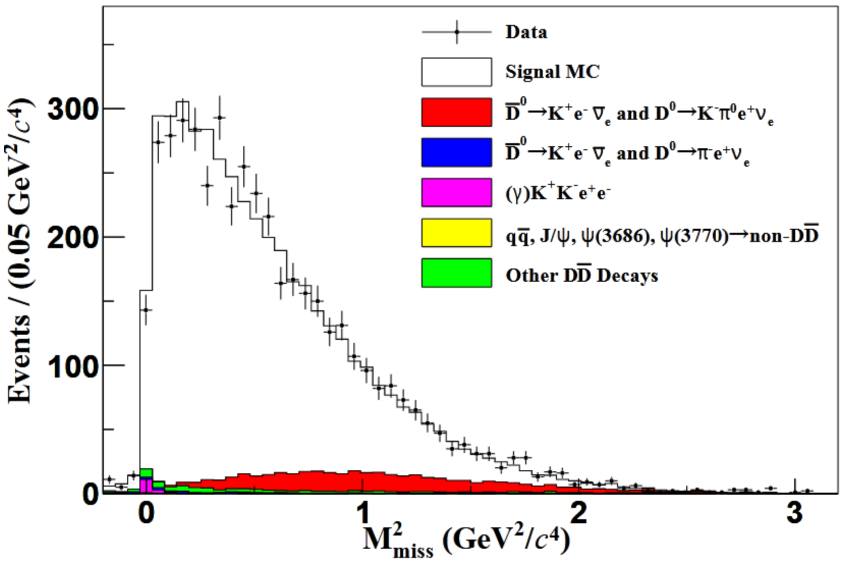
SM prediction: (0.93-0.99)

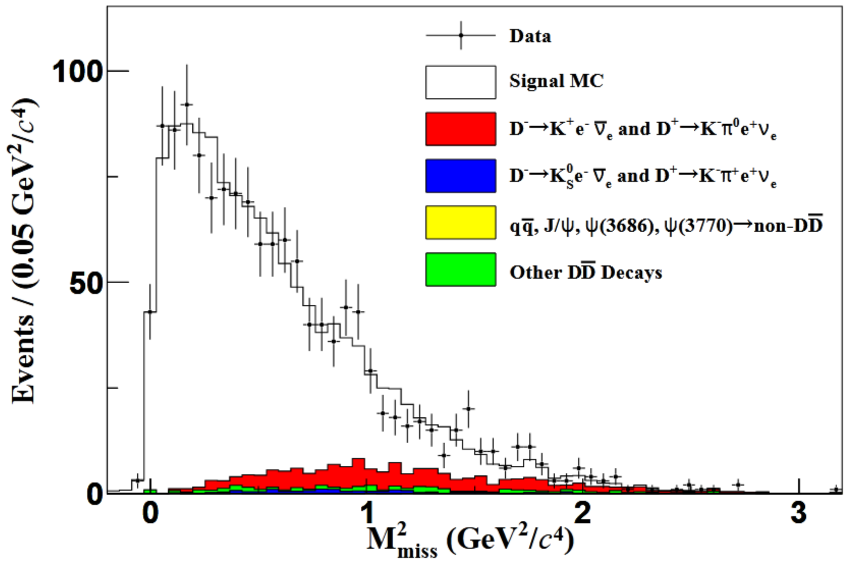
no LFU violation within current statistics

Experimental confirmation for the first time since it was predicted in 30 years ago. Phys. Rev. D 39, 799 (1989).

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

arXiv: 2104.08081 [hep−ex] accpected by PRD





$$B_{SL} = \sqrt{N_{DT}/N_{D\bar{D}} \cdot \epsilon_{DT}}$$

$$\frac{\bar{\Gamma}_{D^0\to K^- e^+ \nu_e}}{\bar{\Gamma}_{D^+\to \bar{K}^0 e^+ \nu_e}} = 1.040 \pm 0.021$$

$$B(D^0 \to K^- e^+ \nu_e) = (3.574 \pm 0.031 \pm 0.025)\%$$

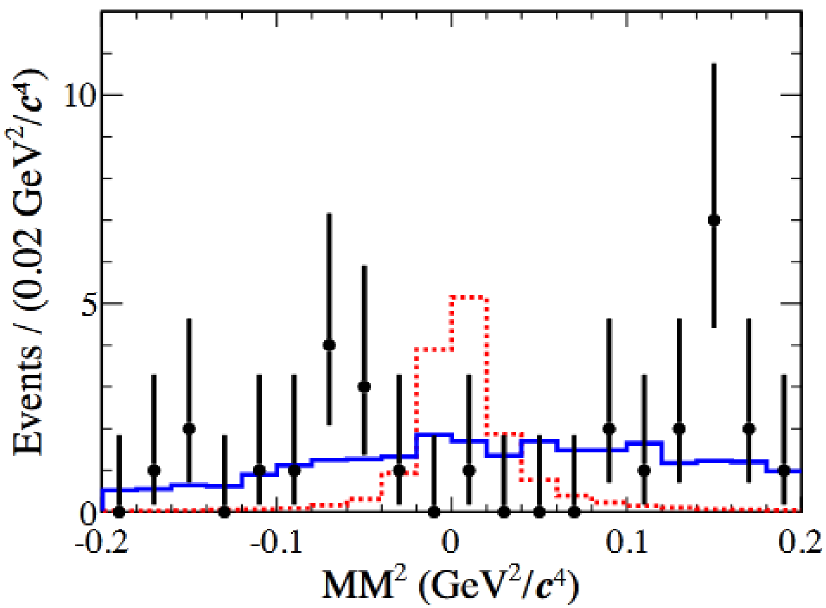
$$B(D^+ \to \bar{K}^0 e^+ \nu_e) = (8.70 \pm 0.14 \pm 0.16)\%$$

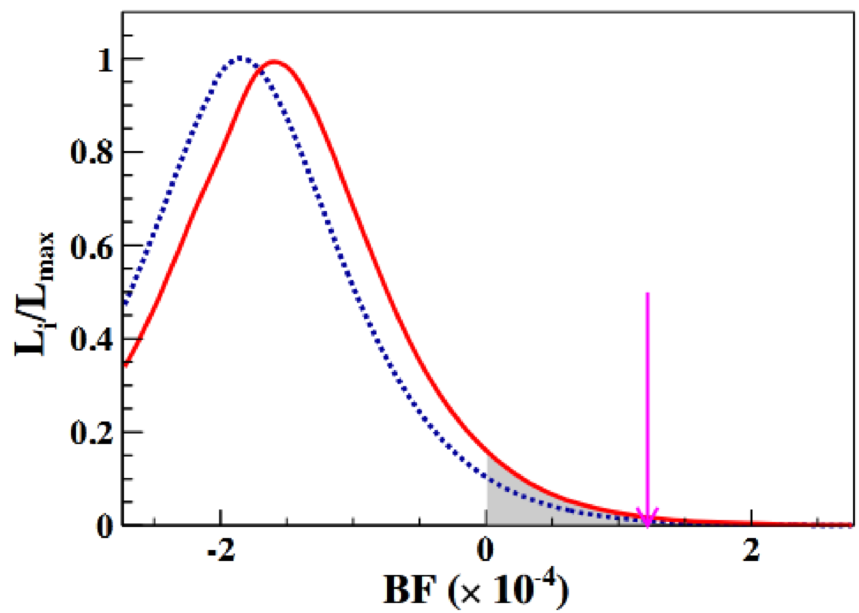
Consistent with isospin symmetry within 1.9σ

This BF is consistent with the previous BESIII measurements

$D_s^+ \to a_0(980)^0 e^+ \nu_e$

***Phys. Rev. D* 103. 092004(2021)**



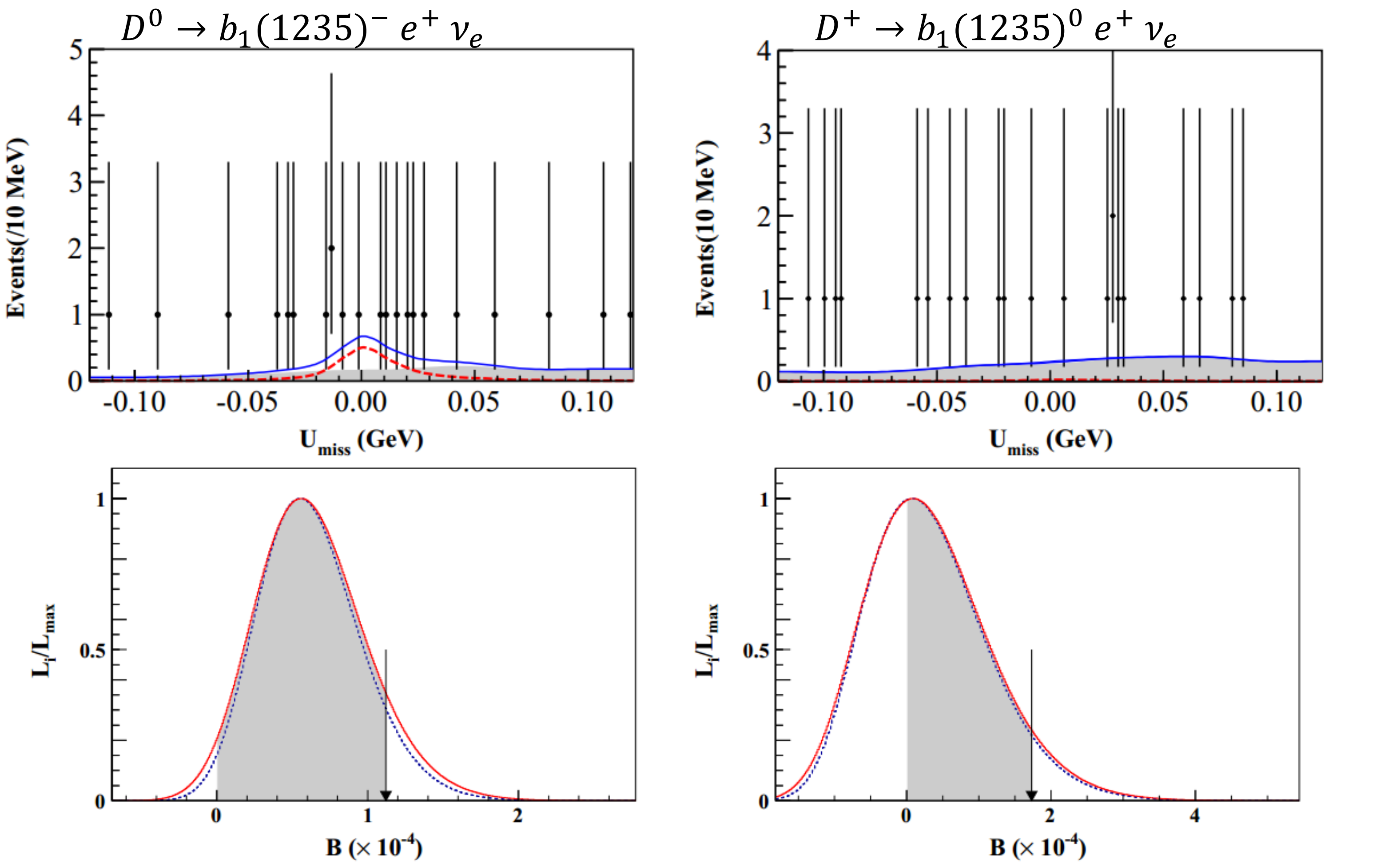


$$B(a_0(980)^0 e^+ \nu_e) \times B(a_0(980)^0 \to \pi^0 \eta) < 1.2 \times 10^{-4} \text{ @90\% } C.L.$$

No significant signal is observed!

$D^{0(+)} \to b_1(1235)^{-(0)}\, e^+\, \nu_e$

Phys. Rev. D **102. 112005(2020)**



$$\mathcal{B}_{D^0\to b_1(1235)^- e^+\nu_e} \cdot \mathcal{B}_{b_1(1235)^-\to\omega\pi^-} < 1.12 \times 10^{-4}$$

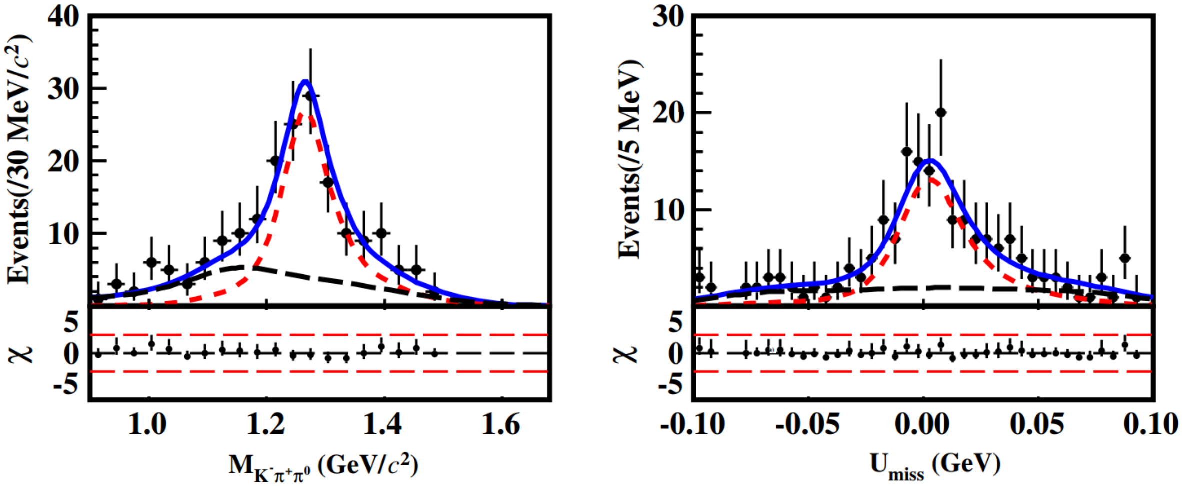
$$\mathcal{B}_{D^+\to b_1(1235)^0 e^+\nu_e} \cdot \mathcal{B}_{b_1(1235)^0\to\omega\pi^0} < 1.75 \times 10^{-4}$$

No significant signal is observed!

$D^+ \to \overline{K}_1(1270)^0\, e^+\, \nu_e$

Phys. Rev. Lett. **122, 062001(2019)**

First observation of D meson semi-leptonic decay into axial-vector mesons.



A two-dimensional unbinned fit

Sig. $> 10\sigma$

$N_{DT}^{signal} = 119.7 \pm 13.3$

$$B_{D^+\to\overline{K}_1(1270)^0\, e^+\nu_e} = \left(2.30 \pm 0.26^{+0.18}_{-0.21} \pm 0.25_{ex.}\right)$$

Test the various theoretical calculations(agree with the CLFQM and LCSR prediction when θ_K~33° or 55° .)

Provide important input to study the photon polarization in $B \to K_1\gamma$ by measuring the ration of up-down asymmetries. (enough statistics)

$\frac{\Gamma(D^+\to\overline{K}_1(1270)^0\, e^+\, \nu_e)}{\Gamma(D^0\to K_1(1270)^-\, e^+\, \nu_e)} = 1.2^{+0.7}_{-0.5}$ （Isospin conservation test）