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BESIII

(Semi-) leptonic charmed meson decays at BESIII

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(On behalf of BESIII Collaboration)

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Outline

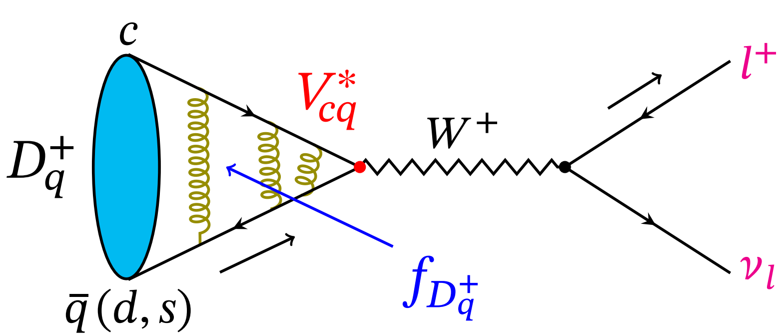
- **Introduction**
- **Pure leptonic decay**
  - $D_s^+ \to \tau^+\nu_\tau$
    - $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$ — BESIII Preliminary
    - $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$ — arXiv: 2105.07178 [hep-ex]
    - $\tau^+ \to \pi^+\bar{\nu}_\tau$ — arXiv: 2102.11734 [hep-ex]
  - $D_s^+ \to \mu^+\nu_\mu$ — arXiv: 2102.11734 [hep-ex]
- **Semi-leptonic decay**
  - $D^+ \to \eta\mu^+\nu_\mu$ — PRL124(2020)231801
  - $D^+ \to \bar{K}_1(1270)^0 e^+\nu_e$ — PRL123(2019)231801
  - $D^0 \to K_1(1270)^- e^+\nu_e$ — arXiv: 2102.10850 [hep-ex]
  - $D_s^+ \to X e^+\nu_e$ — arXiv: 2104.07311 [hep-ex]
- **Summary**

Main goals

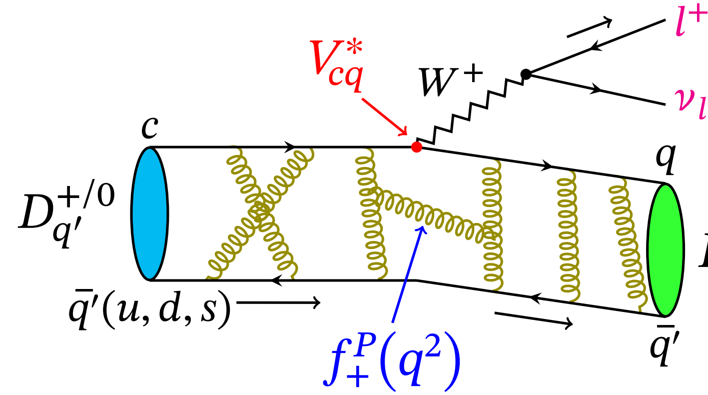
In the SM:

Please see Prof. Shen's talk

$D_{(s)}$ pure leptonic decay



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



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

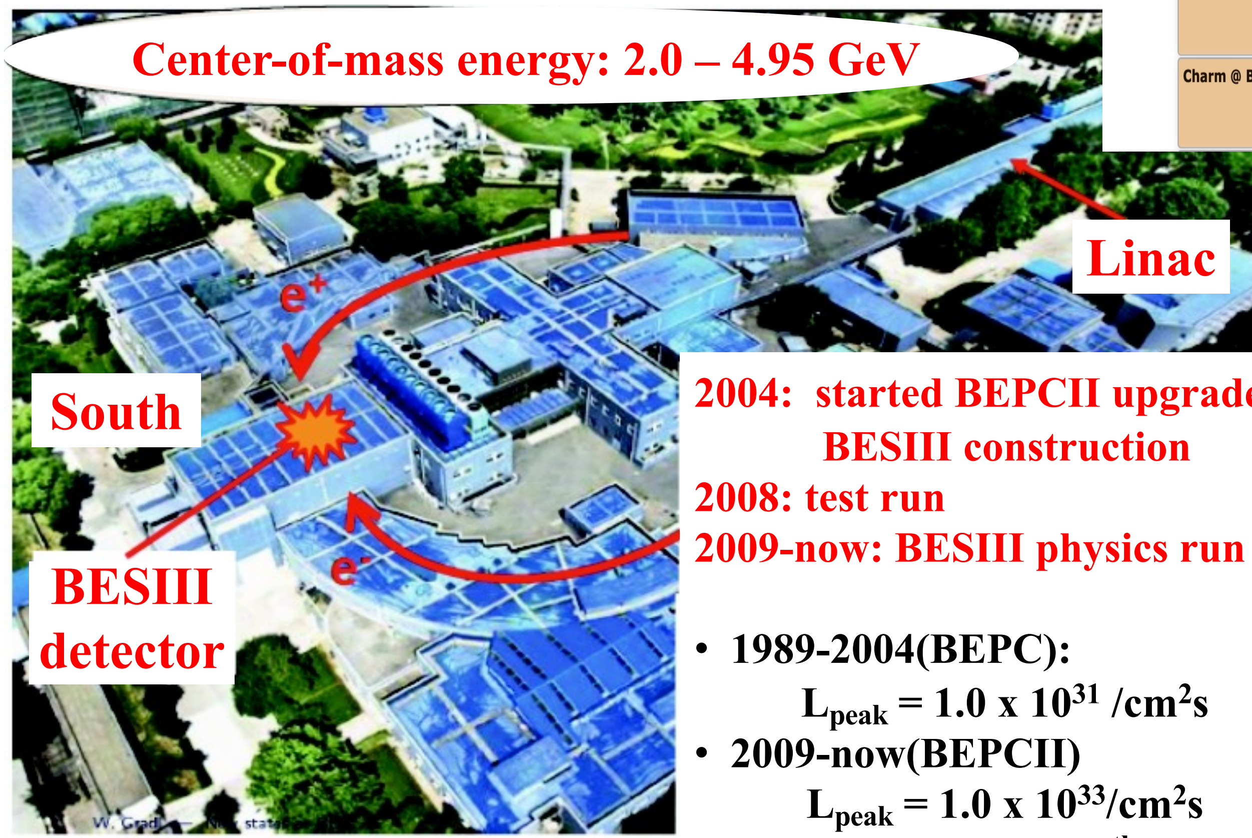
$$\Gamma\left(D_{(s)} \to P\, l^+\, \nu_l\right) \propto \left|f_+\left(q^2\right)\right|^2 \cdot \left|V_{cd(s)}\right|^2$$

- **Decay constant $f_{D_{(s)}^+}$, form factor $f_+(0)$: calibrate Lattice QCD**
- **CKM matrix element $|V_{cd(s)}|$: test the unitarity of the CKM matrix**
- **Lepton flavor universality (LFU) test.**

Beijing Electron Positron Collider (BEPCII) in China

Please see Prof. Shen's talk

A double-ring collider with high luminosity

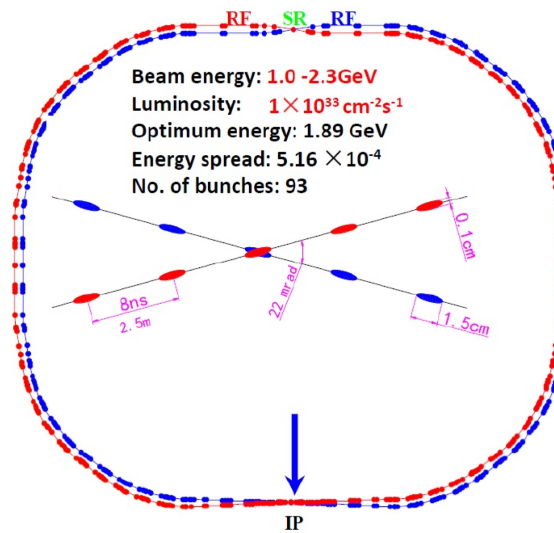


2004: started BEPCII upgrade, BESIII construction

2008: test run

2009-now: BESIII physics run

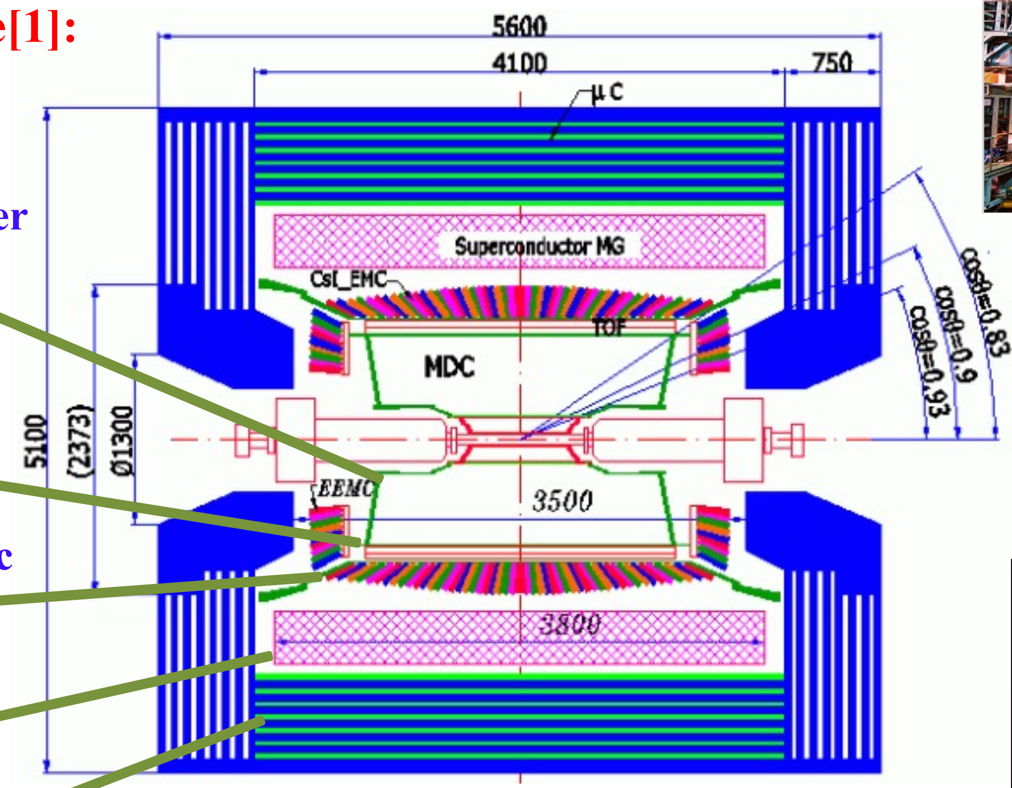
- 1989-2004(BEPC): $L_{peak} = 1.0 \times 10^{31}$ /cm^{2}s
- 2009-now(BEPCII) $L_{peak} = 1.0 \times 10^{33}$/cm^{2}s (Achieved on Apr. 5th, 2016)



BESIII Detector

Please see Prof. Shen's talk

From inner to outside[1]:



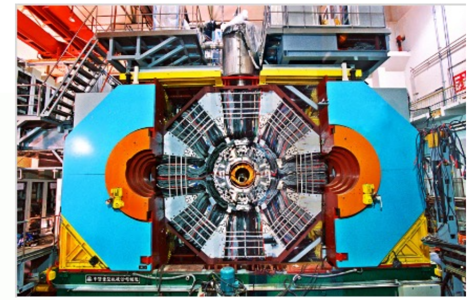
Helium-based multilayer drift chamber (MDC):

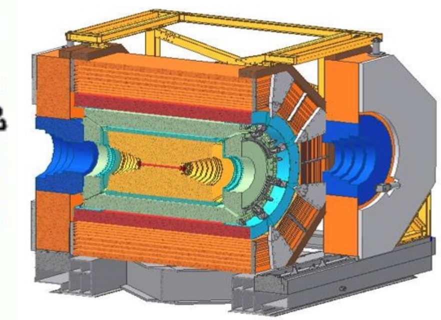
Plastic scintillator time-of-flight (TOF):

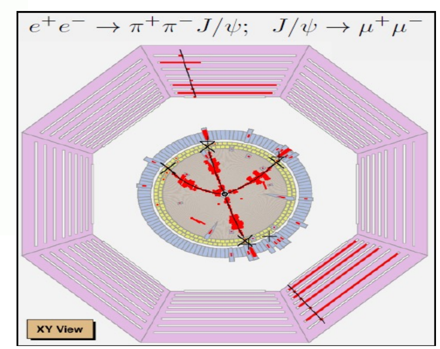
CsI (Tl) electromagnetic calorimeter (EMC):

Superconducting solenoidal magnet:

Muon Chamber (MUC):







[1] M. Ablikim *et al*. (BESIII Collaboration), Nucl. Instr. Meth. A**614**, 345 (2010).

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

Please see Prof. Shen's and Ms. Yulan Fan's talks

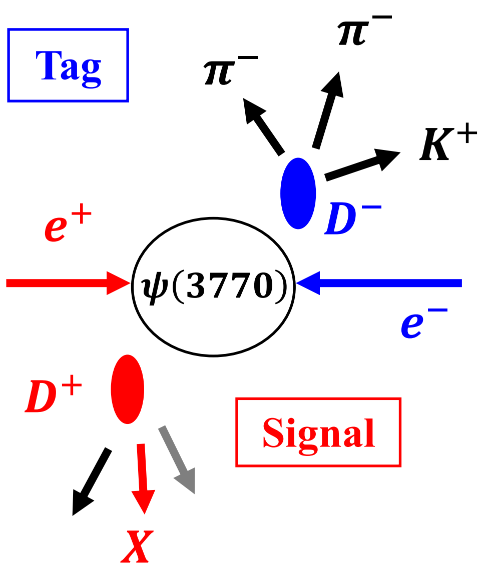
$\sqrt{s}$(GeV)	Integrated luminosity	Decay chain of interest
3.773	$2.93\ \mathrm{fb}^{-1}$	$e^+e^- \to \psi(3770) \to D^0\bar{D}^0$
		$e^+e^- \to \psi(3770) \to D^+D^-$

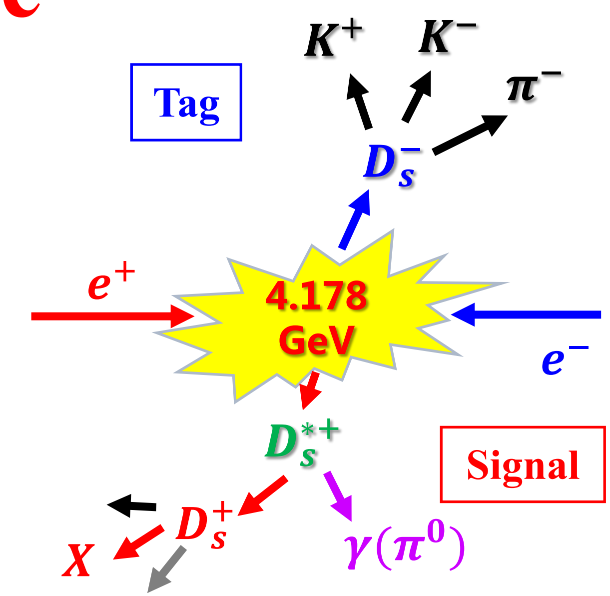
$\sqrt{s}$(GeV)	Integrated luminosity(pb^{-1})	
4.178	$3189.0 \pm 0.9 \pm 31.9$	$e^+e^- \to D_s^*D_s$ Total: $6.32\ \mathrm{fb}^{-1}$
4.189	$526.7 \pm 0.1 \pm 2.2$	
4.199	$526.0 \pm 0.1 \pm 2.1$	
4.209	$517.1 \pm 0.1 \pm 1.8$	
4.219	$514.6 \pm 0.1 \pm 1.8$	
4.226	$1047.3 \pm 0.1 \pm 10.2$	

Analysis technique

Please see Prof. Shen's and Ms. Yulan Fan's talks

Charge conjugated processes are implied





The signal branching fraction:

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

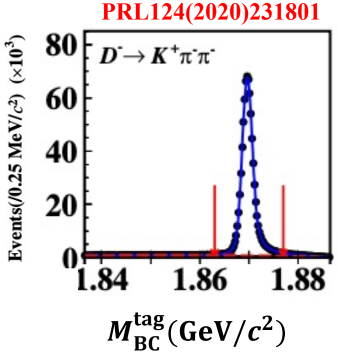
- **Single tag (ST):**

fully reconstruct one D^-

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

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

PRL124(2020)231801



- **Double tag (DT):**

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

analyze the signal $D_{(s)}^+$

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

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

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

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

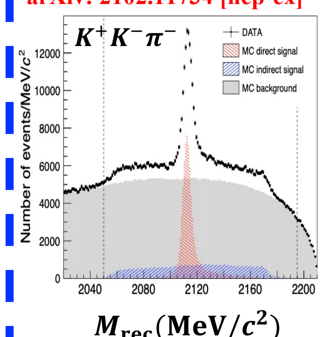
or other variables

- **Single tag (ST):**

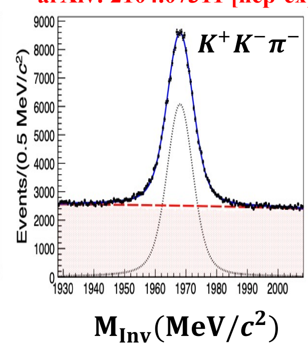
fully reconstruct one D_s^-

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

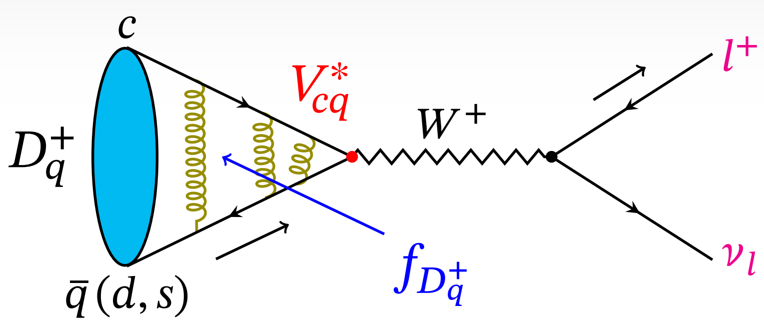
arXiv: 2102.11734 [hep-ex]



arXiv: 2104.07311 [hep-ex]



$D_{(s)}^{+}$ pure leptonic decay



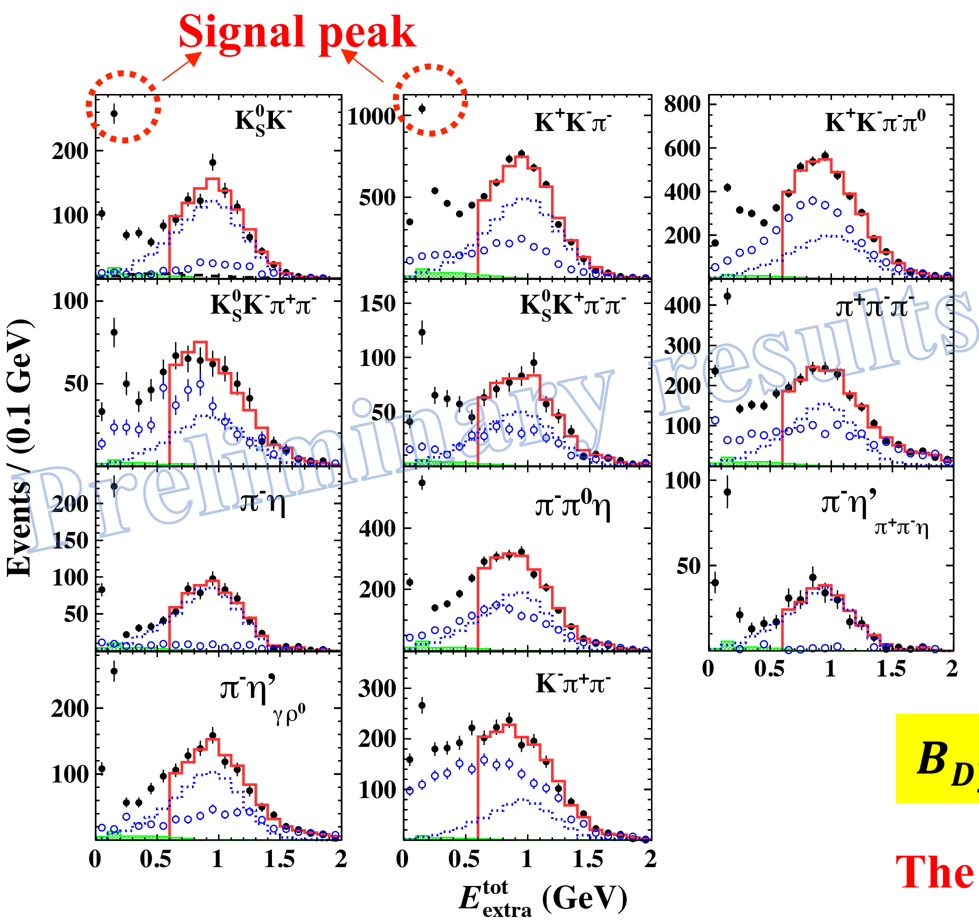
In the SM:

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

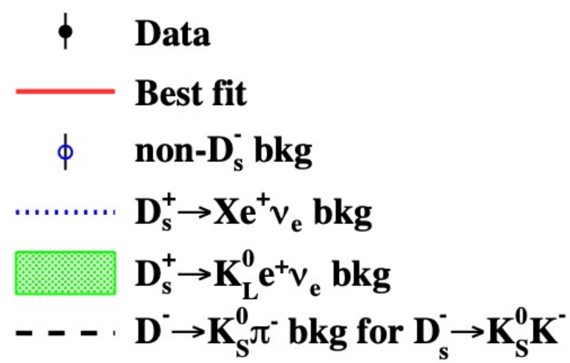
$D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$

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



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



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

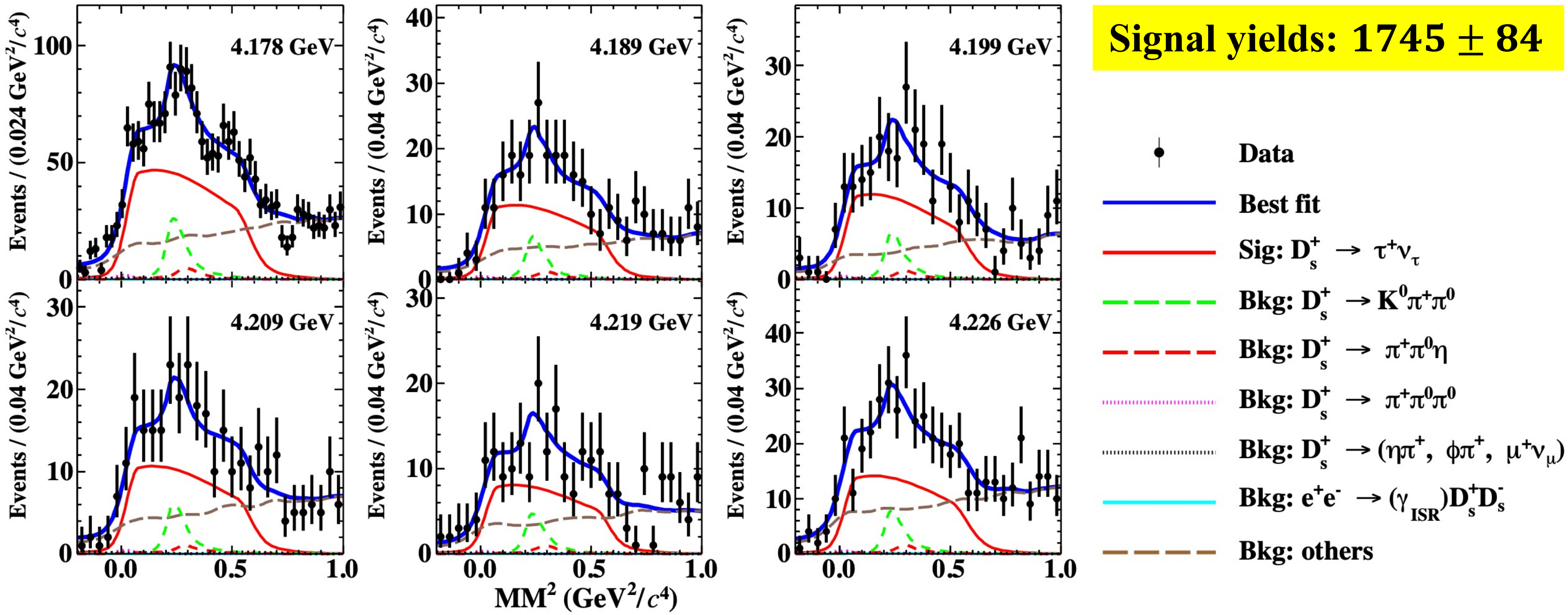
Preliminary results

The most precise result to date

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

arXiv: 2105.07178 [hep-ex]

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



Signal yields: 1745 ± 84

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

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

$$E_{\text{miss}} = E_{\text{cm}} - \sqrt{\left|\vec{p}_{D_s^-}\right|^2 + M_{D_s}^2} - E_\gamma - E_{\pi^+\pi^0}$$

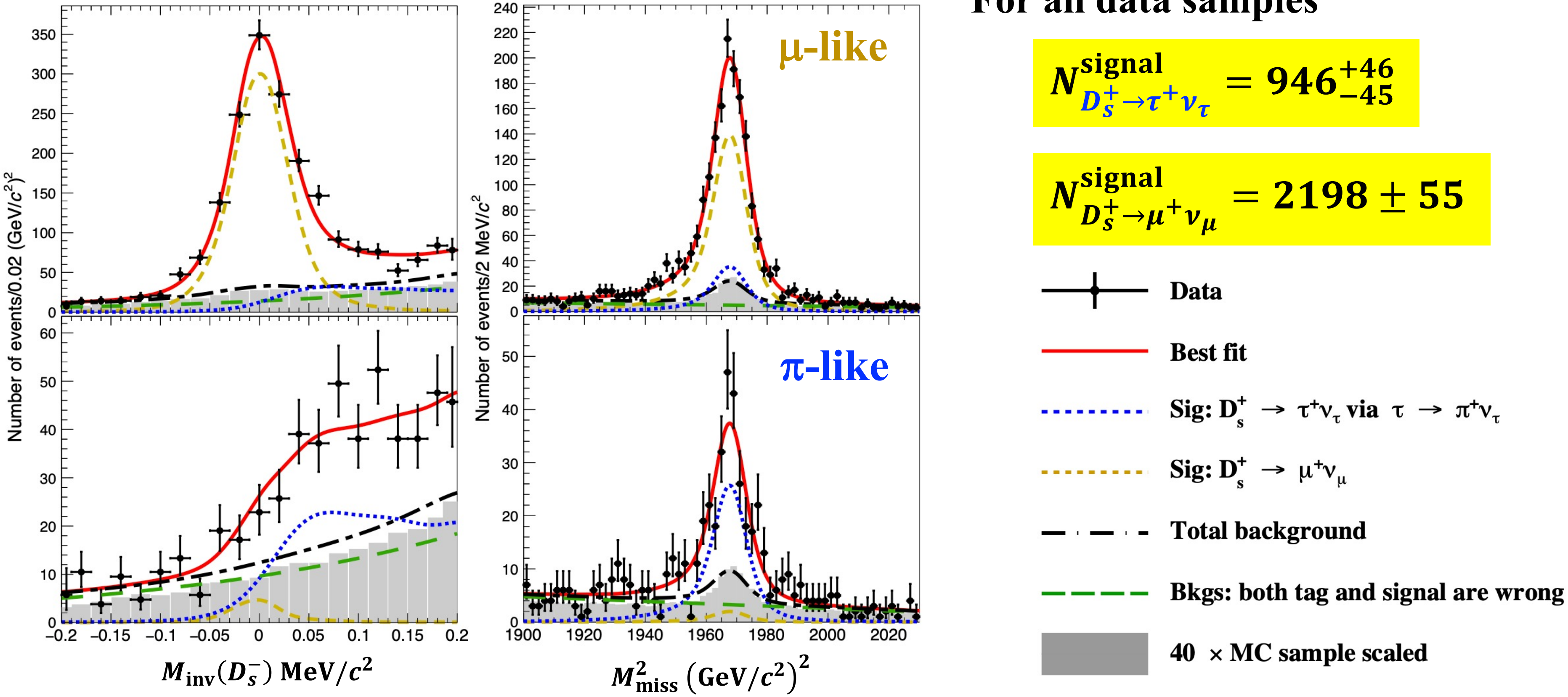
$$\vec{p}_{\text{miss}} = -\vec{p}_{D_s^-} - \vec{p}_\gamma - \vec{p}_{\pi^+\pi^0}$$

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

arXiv: 2102.11734 [hep-ex]

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

Only show @ 4.178 GeV



For all data samples

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

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

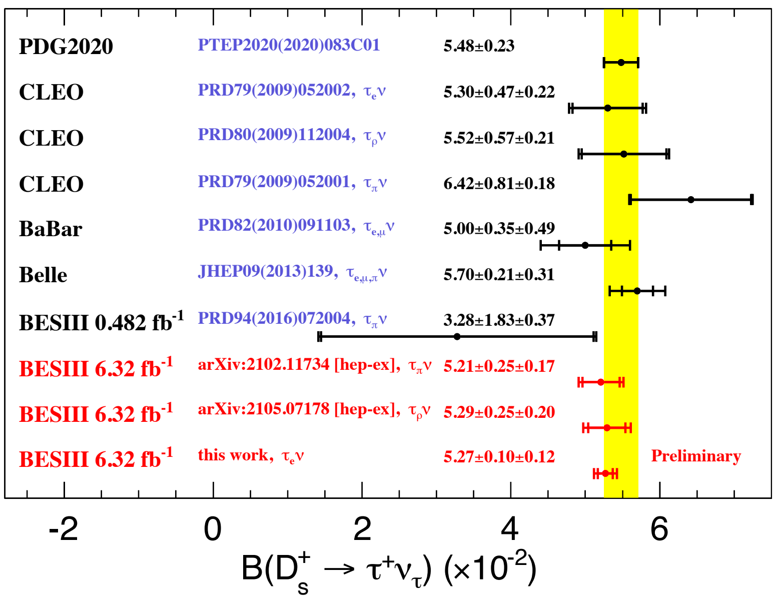
$$B(D_s^+ \to \tau^+\nu_\tau) = (5.21 \pm 0.25_{\rm stat.} \pm 0.17_{\rm syst.})\times 10^{-2}$$

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

The most precise to date.

Lepton flavor universality

- Combine results from **BESIII measurements** and PDG2020



In the SM:

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

$$= 9.67 \pm 0.34$$

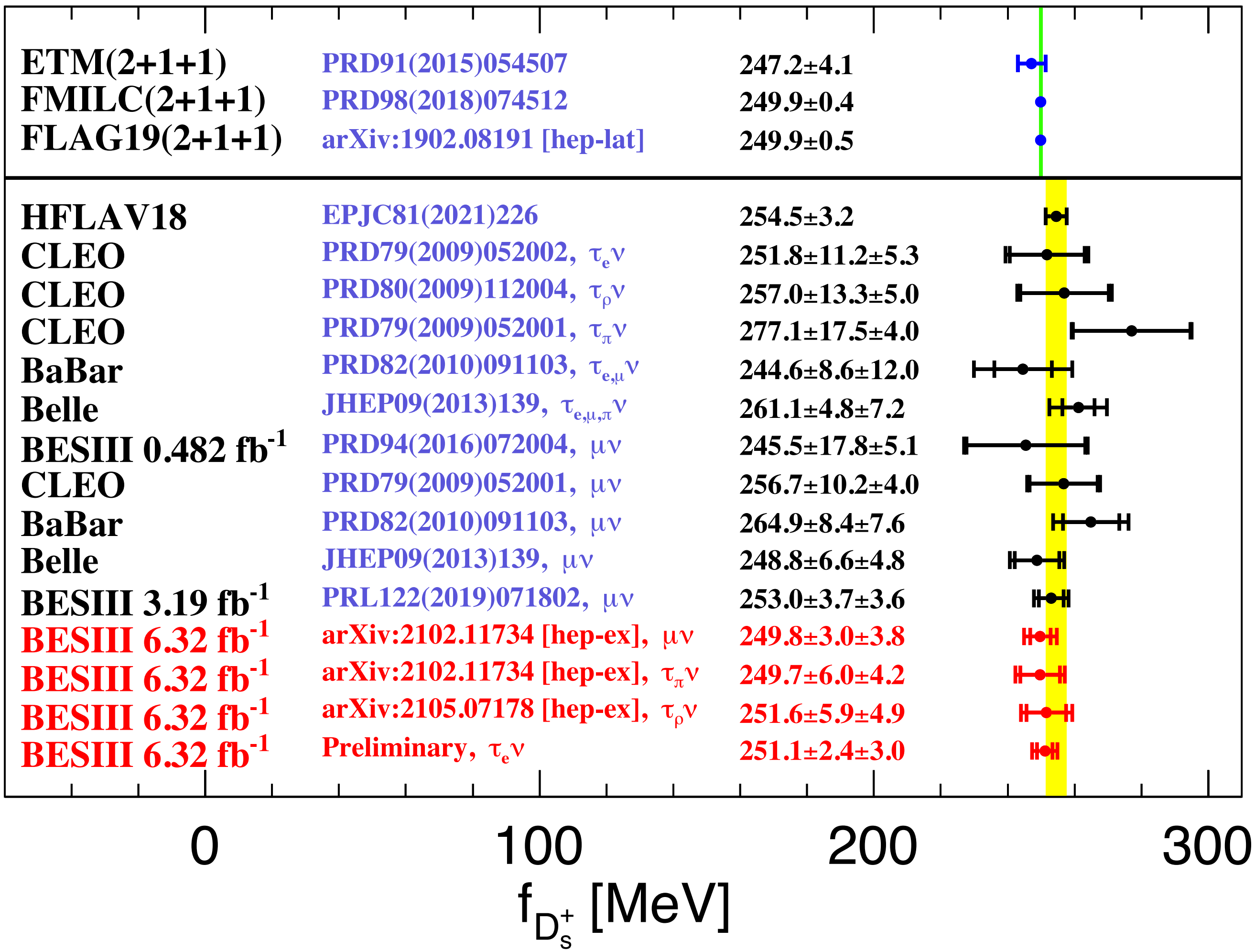
$$9.75 \pm 0.01$$

(SM prediction)

No LFU violation in $\tau - \mu$ flavors with the current precision.

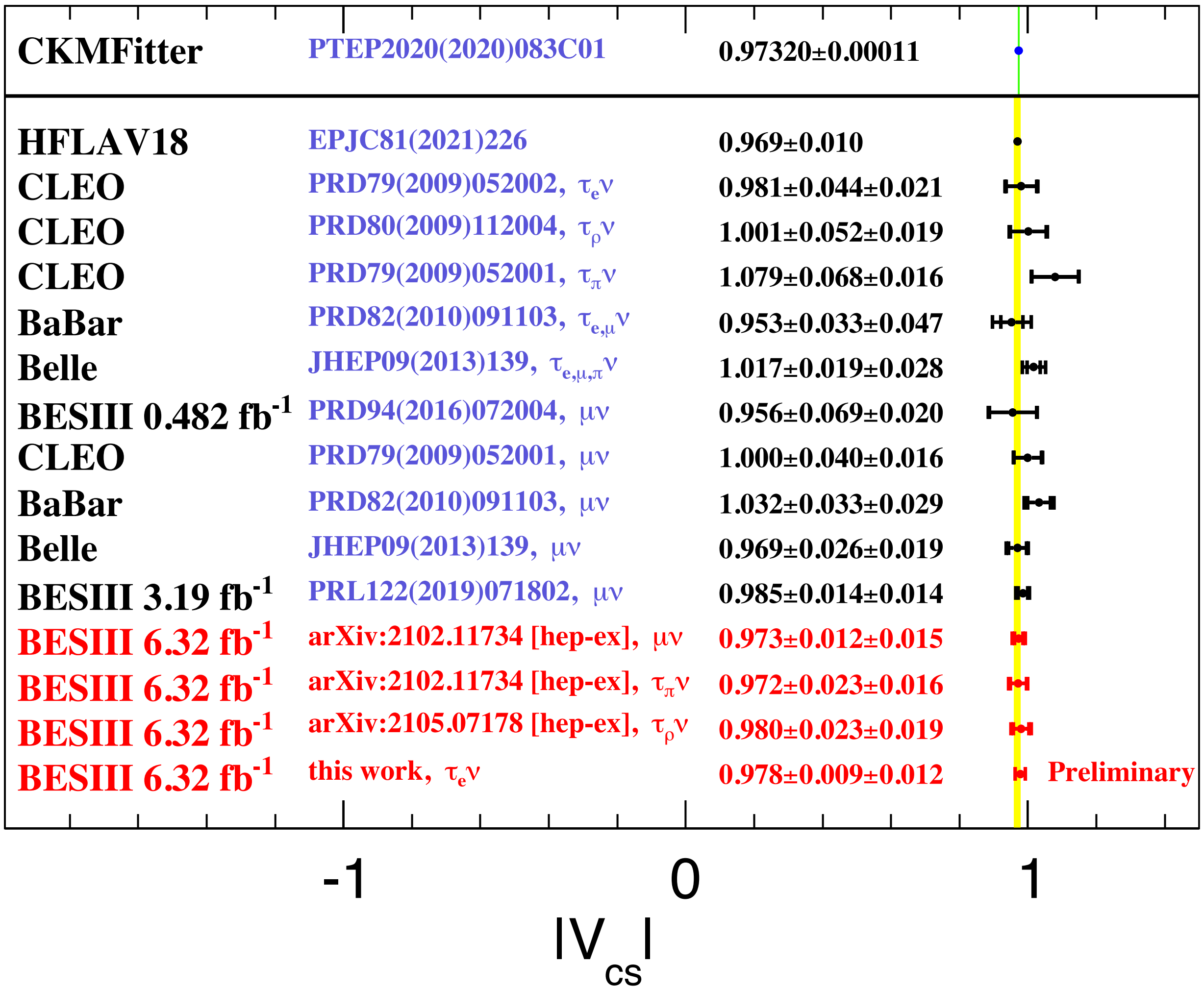
Comparison of decay constant $f_{D_s^+}$

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

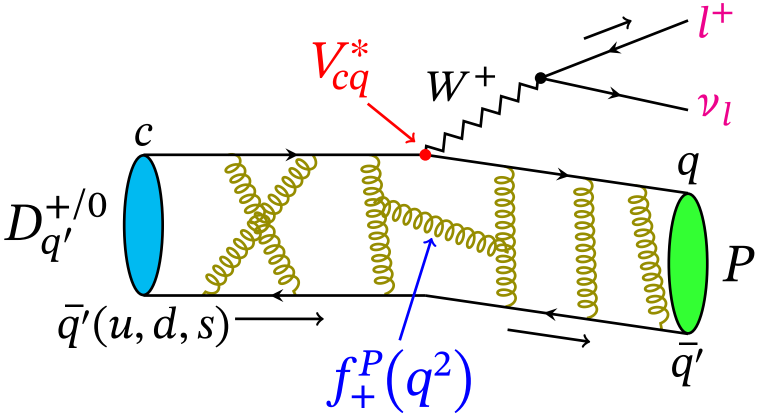


Comparison of $|V_{cs}|$

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



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



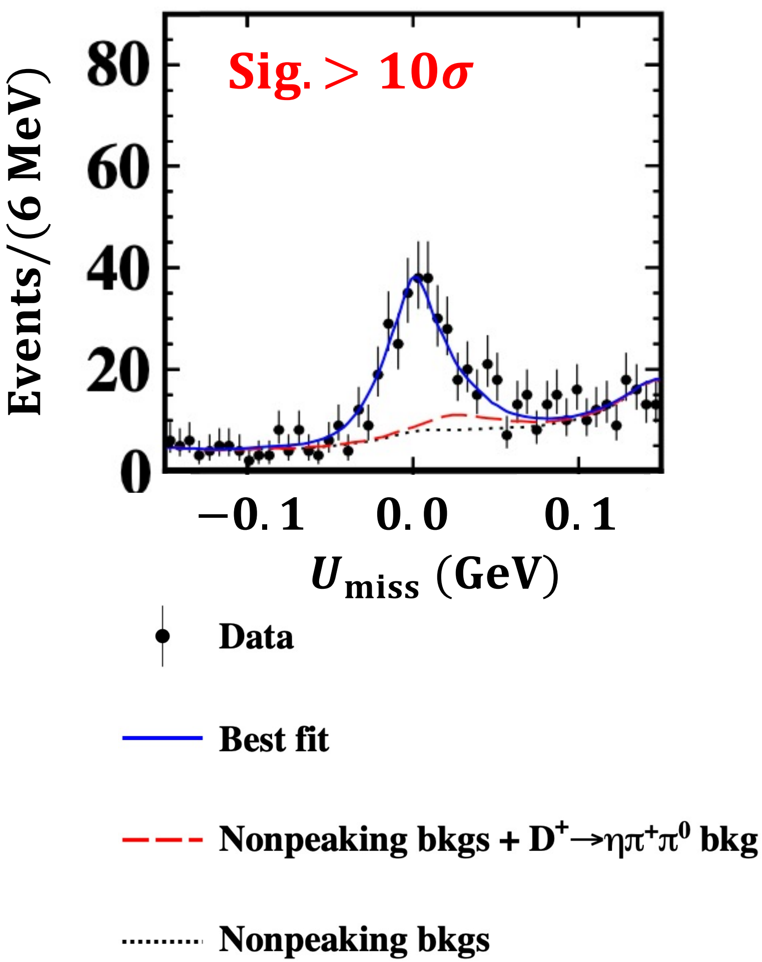
In the SM:

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

$D^+ \to \eta\mu^+\nu_\mu$

PRL124(2020)231801

- **Verification of LFU via $c \to d\, l^+\nu_l$**



✓ $\eta \to \gamma\gamma$

✓ Unbinned fit to $U_{\rm miss}$

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

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

$$R_{\mu/e} = \frac{B_{D^+\to\eta\mu^+\nu_\mu}}{B^{PDG}_{D^+\to\eta e^+\nu_e}} = 0.91 \pm 0.13$$

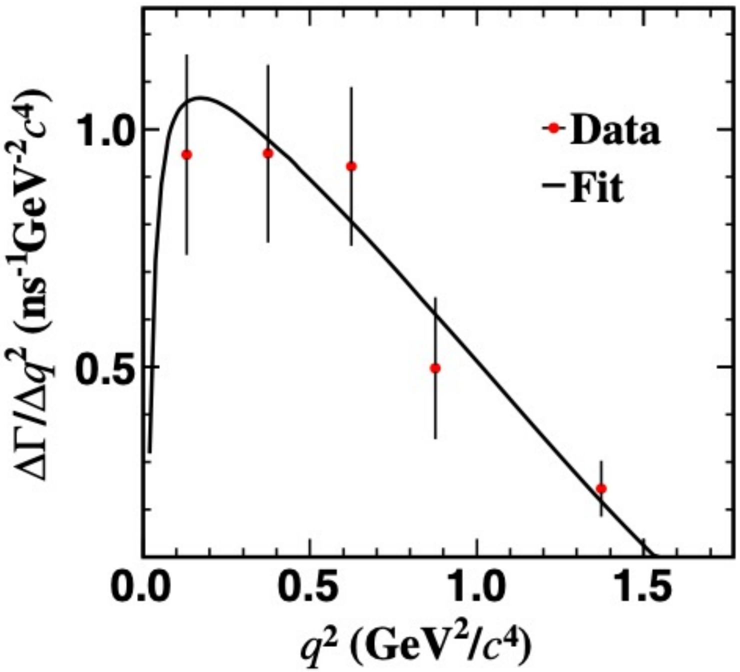
SM prediction: $(0.97 - 1.00)$

No LFU violation within current sensitivity.

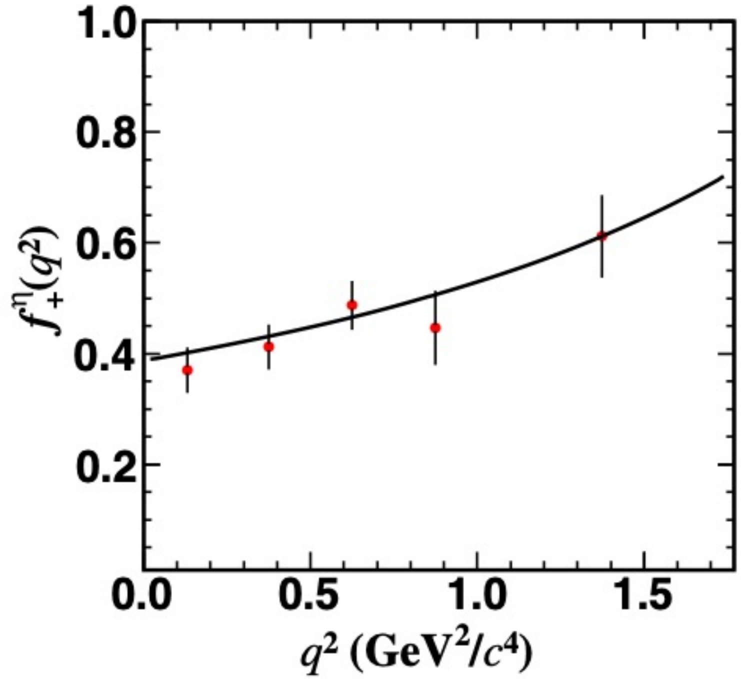
PRL124(2020)231801

- **First measurement on dynamics of $D^+ \to \eta\mu^+\nu_\mu$ decay**

Partial decay rates



Form factor $f_+^\eta(q^2)$



$$f_+^\eta(0)|V_{cd}| = 0.087 \pm 0.008_{\text{stat.}} \pm 0.002_{\text{syst.}}$$

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

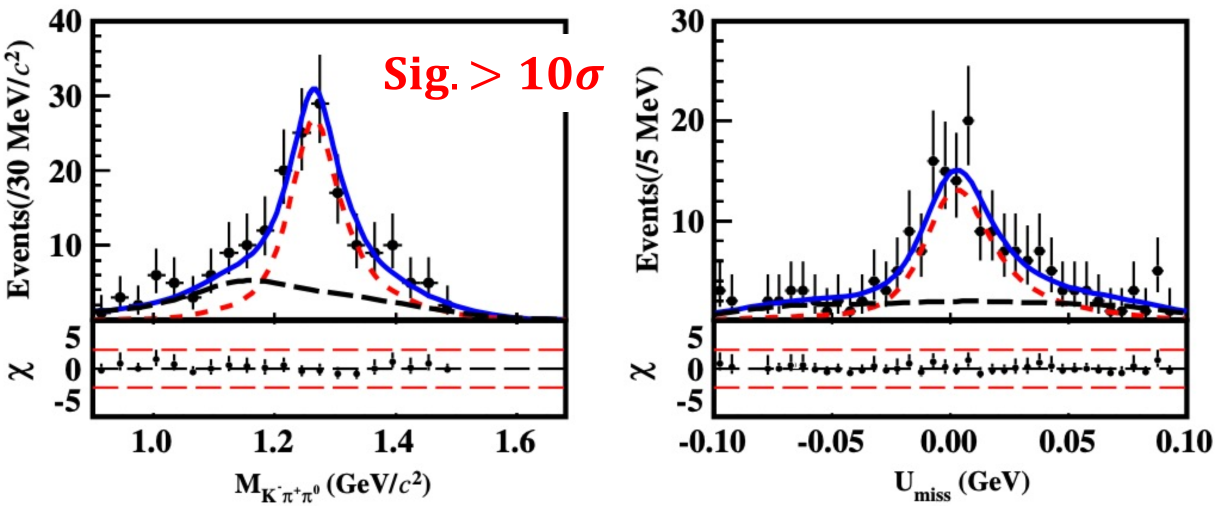
$$|V_{cd}| = 0.242 \pm 0.022_{\text{stat.}} \pm 0.006_{\text{syst.}} \pm 0.033_{\text{theory}}$$

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

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

PRL123(2019)231801

- The physical mass eigenstates of the strange axial-vector mesons $K_1(1270)$ and $K_1(1400)$ are the mixtures of the $^1P_1$ and $^3P_1$ with a mixing angle θ_{K_1}.



- Data
- Best fit
- Sig: $D^+ \to \bar{K}_1(1270)^0 e^+ \nu_e$
- MC-simulated bkgs

✓ $\bar{K}_1(1270)^0 \to K^- \pi^+ \pi^0$

✓ A two-dimensional unbinned extended maximum-likelihood fit

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

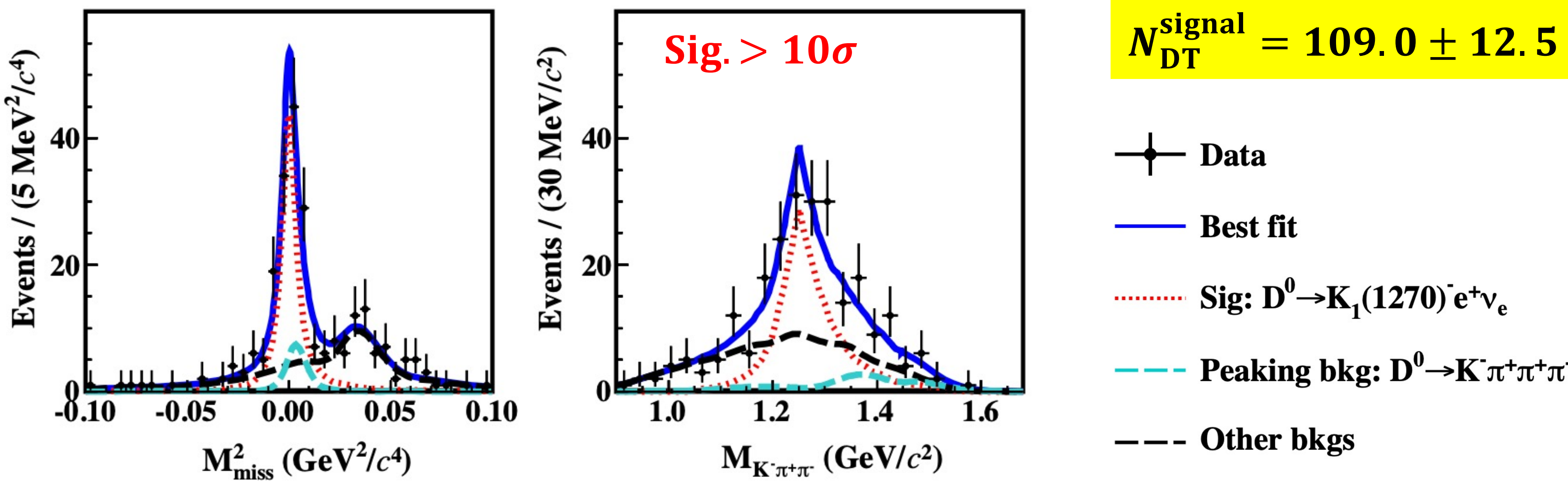
$B_{D^+ \to \bar{K}_1(1270)^0 e^+ \nu_e} = (2.30 \pm 0.26^{+0.18}_{-0.21} \pm 0.25_{ex.}) \times 10^{-3}$

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

arXiv: 2102.10850 [hep-ex]

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

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



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

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

Agrees with unity as predicted by isospin symmetry.

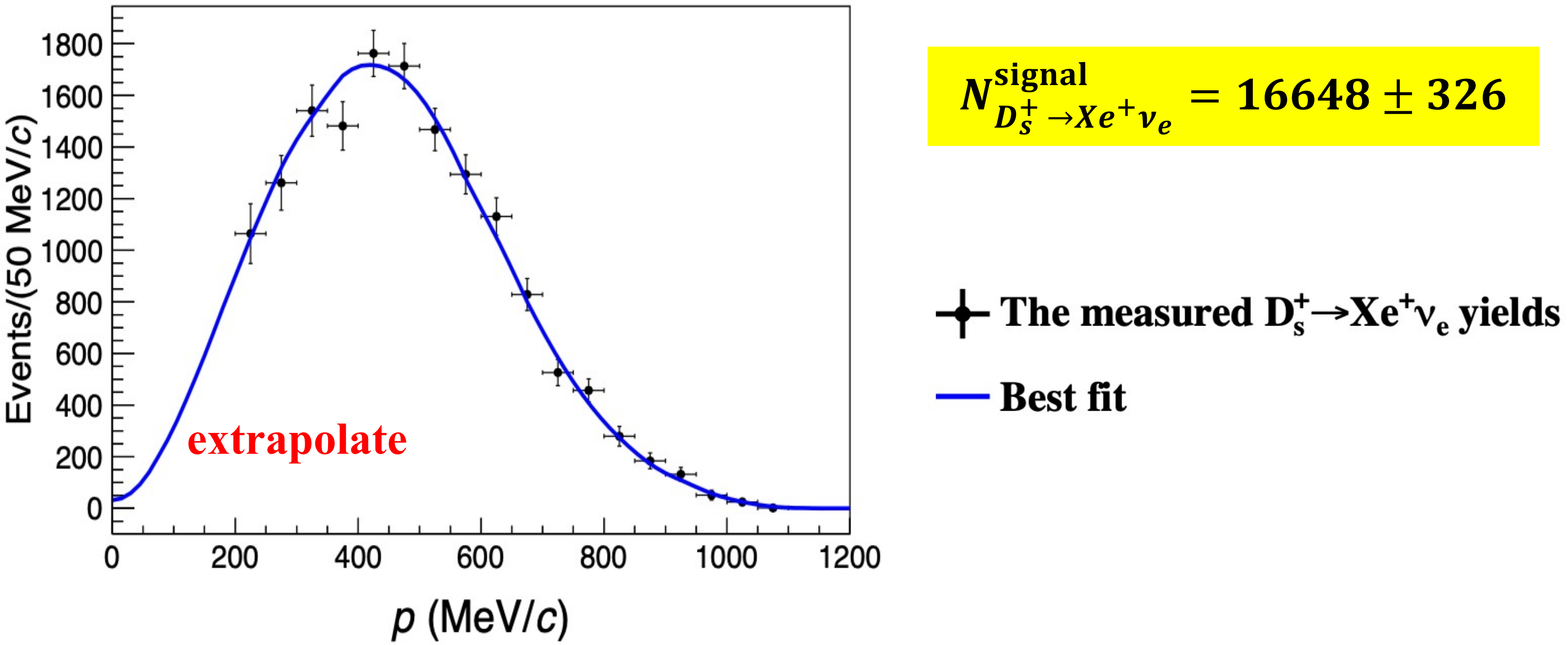
$D_s^+ \to Xe^+ \nu_e$

arXiv: 2104.07311 [hep-ex]

✓ X means inclusive decays

✓ Sort recoil-side selected tracks into eighteen momentum (p_e) bins for $p_e > 200$ MeV/c

✓ The signal yield $N^{\text{signal}}_{D_s^+ \to Xe^+\nu_e} = N_{p_e > 200\ \text{MeV}/c} + N_{p_e \leq 200\ \text{MeV}/c}$ (extrapolate)



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

- The measured spectrum can be used to further constrain the decay rates of modes with characteristic momentum spectra.

arXiv: 2104.07311 [hep-ex]

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

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)**

Supports the conclusion that the difference in the semileptonic decay widths of D_s^+ $(c\bar{s})$ and $D^0(c\bar{u})$ mesons can be accounted for within the Standard model by non-spectator interactions.

Other analyses

- $D^+ \to \omega\mu^+\nu_\mu$ PRD101(2020)072005
- $D^0 \to K^-e^+\nu_e$ and $D^+ \to \bar{K}^0 e^+\nu_e$ arXiv: 2104.08081 [hep-ex]
- $D_s^+ \to a_0(980)^0 e^+\nu_e$ arXiv: 2103.11855 [hep-ex], accepted by PRD
- $D^{0(+)} \to b_1(1235)^{-(0)} e^+\nu_e$ PRD102(2020)112005
- …

Summary

- With 2.93 fb^{-1} @ 3.773 GeV and 6.32 fb^{-1} from 4.178-4.226 GeV data samples, BESIII have studied the pure and semi-leptonic $D_{(s)}$ decay,

➢ Results with a higher 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 measurement on dynamics of
- ✓ $D^+ \to \eta \mu^+ \nu_\mu$

➢ First observations for
- ✓ $D^+ \to \eta \mu^+ \nu_\mu (> 10\sigma)$
- ✓ $D^- \to \bar{K}_1(1270)^0 e^+ \nu_e (> 10\sigma)$
- ✓ $D^0 \to K_1(1270)^- e^+ \nu_e (> 10\sigma)$

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

Backup

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

■ **Single pole model**

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

■ **ISGW2 model**

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

■ **Modified pole model**

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

■ **Series expansion**

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