Recent results of charm physics at BESIII

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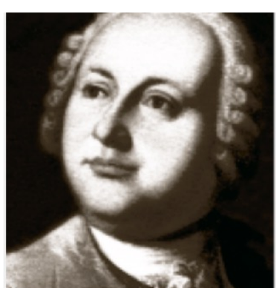
(On behalf of BESIII Collaboration)

Aug. 25 th, 2021



The 20 th Lomonosov Conference on Elementary Particle Physics

Moscow State University
Aug. 19-25 th, 2021

Outline

✍ **Introduction**

✍ **(Semi-) leptonic decays**

- ◻ $D_s^+ \to \tau^+ \nu_\tau$
  - $\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$ — arXiv: 2106.02218 [hep-ex]
  - $\tau^+ \to \pi^+ \pi^0 \bar{\nu}_\tau$ — arXiv: 2105.07178 [hep-ex], accepted by PRD
  - $\tau^+ \to \pi^+ \bar{\nu}_\tau$ } arXiv: 2102.11734 [hep-ex], accepted by PRD
- ◻ $D_s^+ \to \mu^+ \nu_\mu$ } arXiv: 2102.11734 [hep-ex], accepted by PRD
- ◻ $D_{(s)} \to P l^+ \nu_l \; (P = \eta, X, K_1(1270)^-)$ — PRL124(2020)231801; PRD104(2021)012003; arXiv: 2102.10850 [hep-ex]

✍ **Hadronic decays**

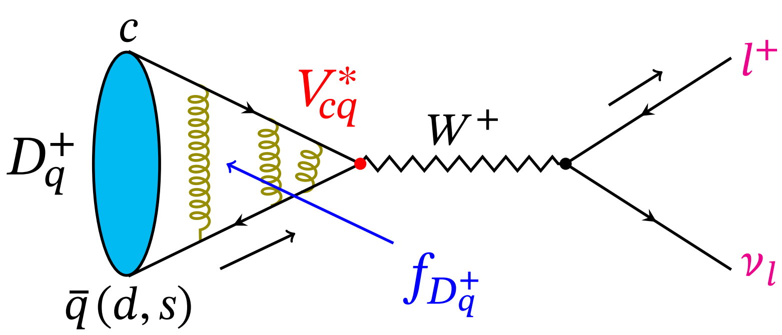
- ◻ $D \to K^0_{S,L} \pi^+ \pi^-$ — PRL124(2020)241802; PRD101(2020)112002
- ◻ $D \to K^0_{S,L} K^+ K^-$ — PRD102(2020)052008
- ◻ $D \to K^+ \pi^+ \pi^+ \pi^-$ and $D \to K^- \pi^+ \pi^0$ — JHEP05(2021)164
- ◻ $D^+ \to K^+ \pi^+ \pi^- \pi^0$ — PRL125(2020)141802

✍ **Summary**

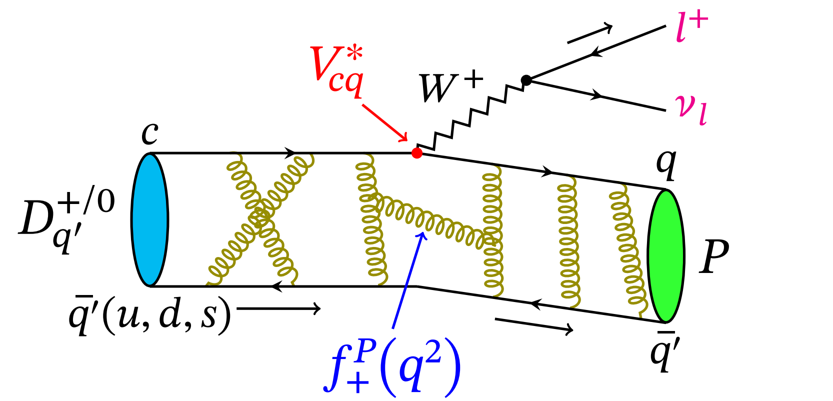
Main goals

In the SM:

$D_{(s)}$ pure leptonic decay



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



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

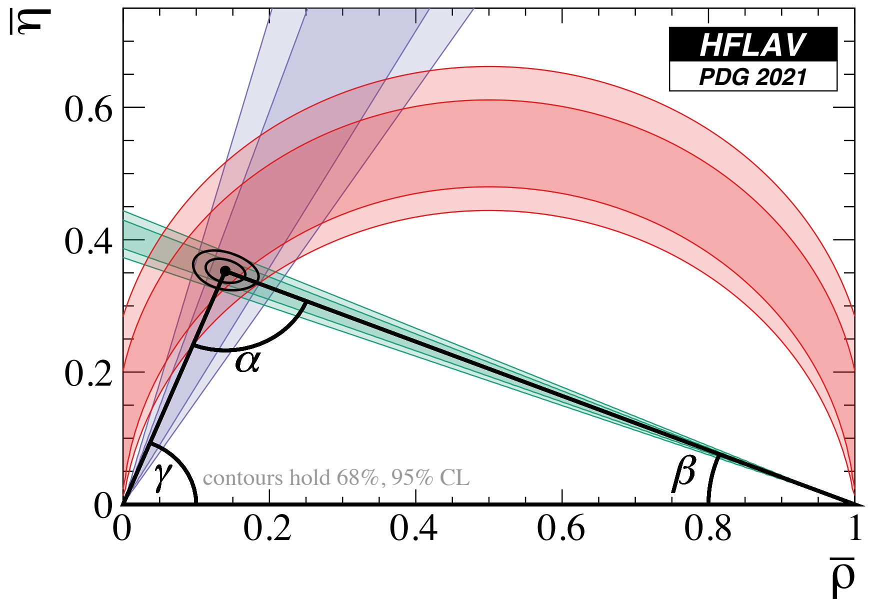
$$\Gamma\left(D_{(s)} \to P\, l^+\, \nu_l\right) \propto \left|f_+\left(q^2\right)\right|^2 \cdot \left|V_{cd(s)}\right|^2$$

- **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.**

Hadronic decays of charm mesons

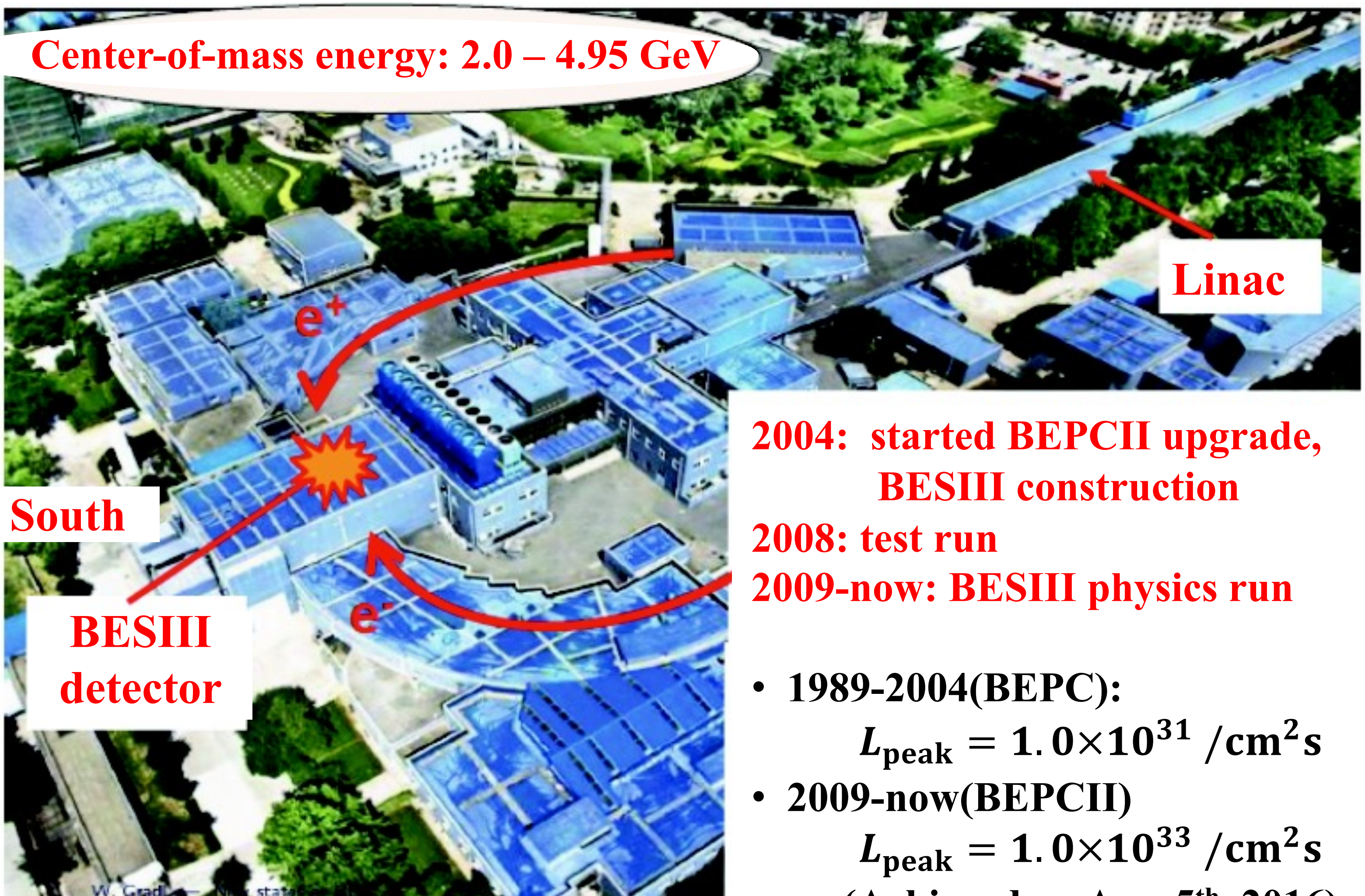
- **Strong phase measurement** with quantum correlated $\psi(3770) \to D^0\bar{D}^0$ is crucial in the model-independent determinations of γ/ϕ_3 and charm mixing/direct CPV.
  - In the SM, CP violation is studied by measuring CKM matrix, represented by unitarity triangle in complex plane. The angle is the only one that can be extracted from tree-level processes, for which the contribution of non-SM effect is small.

- **Probe non-perturbative QCD**
  - Help to understand hadron spectra
  - Study SU(3) flavor symmetry



Beijing Electron Positron Collider (BEPCII) in China

A double-ring collider with high luminosity



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

- **1989-2004(BEPC):**
  $L_{\text{peak}} = 1.0\times10^{31}\ /\text{cm}^2\text{s}$
- **2009-now(BEPCII)**
  $L_{\text{peak}} = 1.0\times10^{33}\ /\text{cm}^2\text{s}$
  (Achieved on Apr. 5th, 2016)

BESIII Detector

From inner to outside[1]:

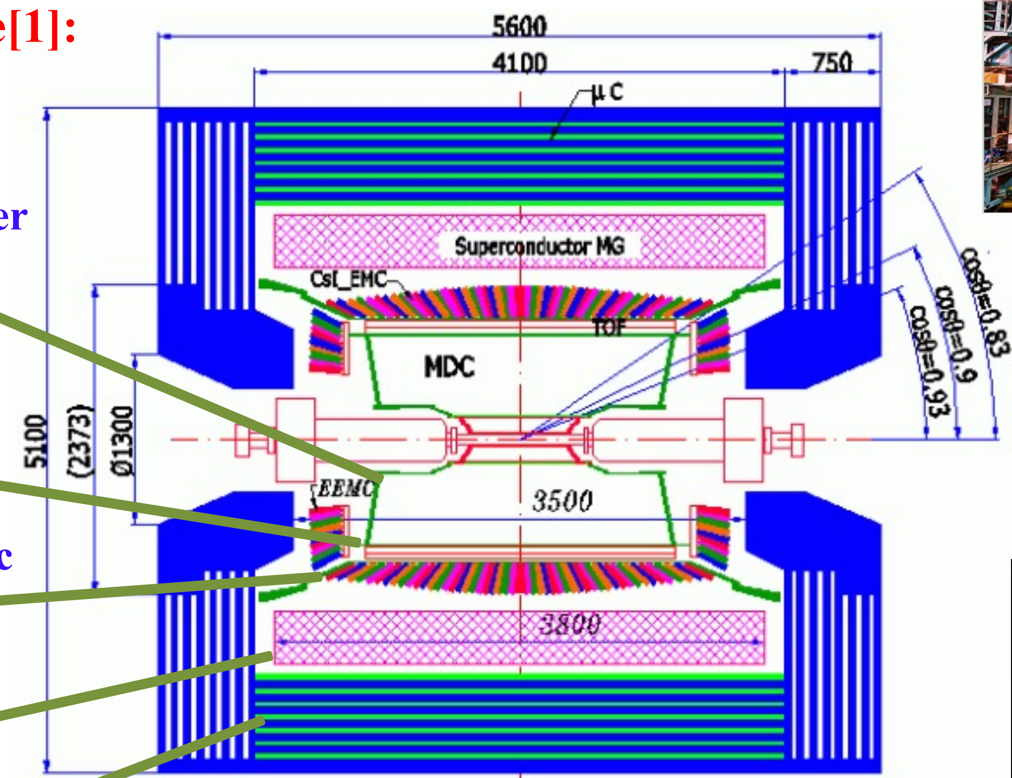
Helium-based multilayer drift chamber (MDC):

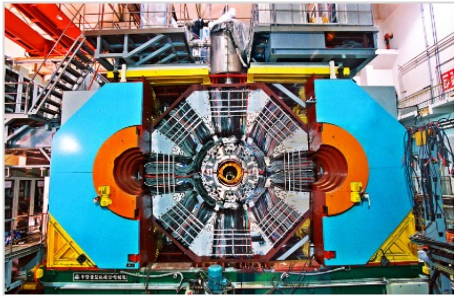
Plastic scintillator time-of-flight (TOF):

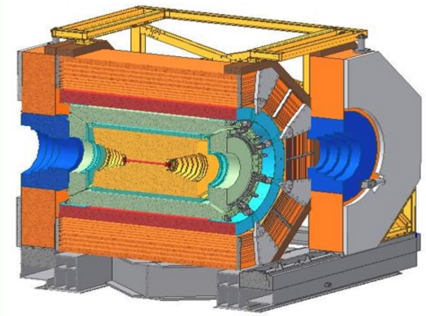
CsI (Tl) electromagnetic calorimeter (EMC):

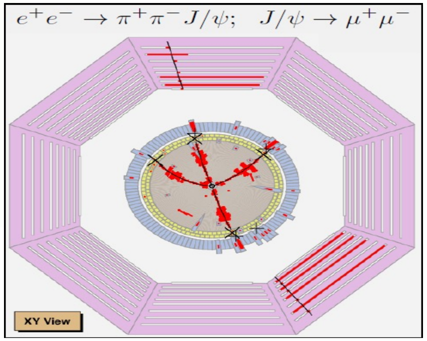
Superconducting solenoidal magnet:

Muon Chamber (MUC):









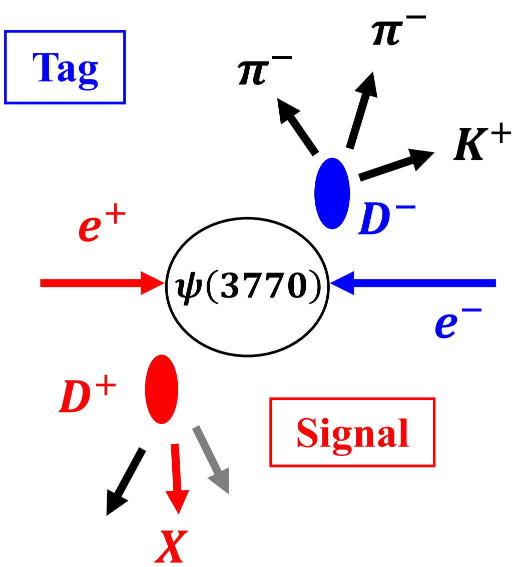
[1] M. Ablikim *et al*. (BESIII Collaboration), Nucl. Instr. Meth. A**614**, 345 (2010).

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

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

$\sqrt{s}$(GeV)	Integrated luminosity(pb^{-1})	
4.178	$3189.0 \pm 0.9 \pm 31.9$	$e^+e^- \to D_s^{*\pm}D_s^{\mp}$ Total: $6.32\ \text{fb}^{-1}$
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

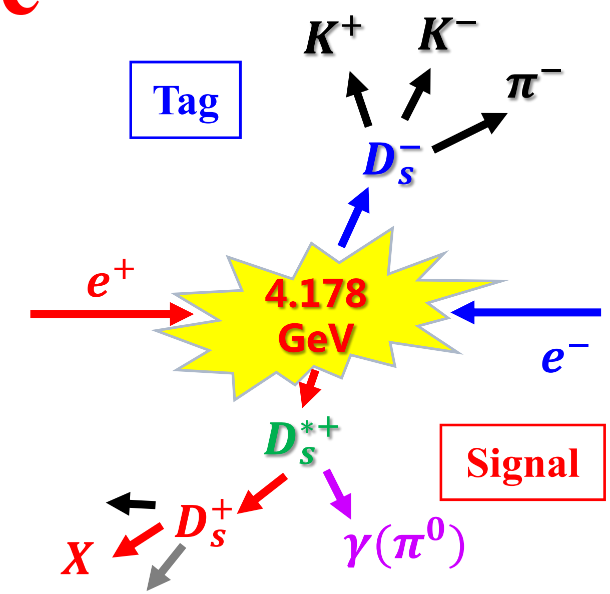


Similar for the hadronic decays

Charge conjugated processes are implied

The signal branching fraction:

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



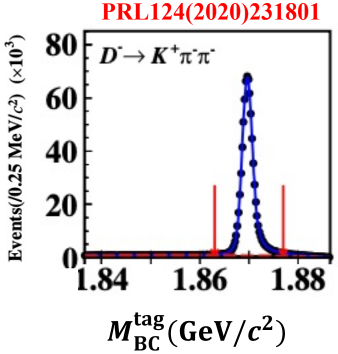
- **Single tag (ST):**

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 $D_{(s)}^+$

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

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

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

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

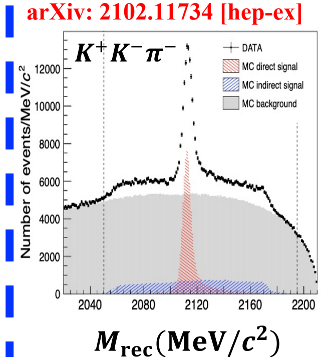
or other variables

- **Single tag (ST):**

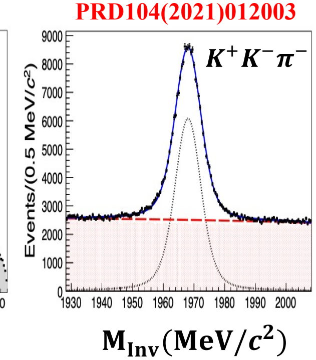
fully reconstruct one D_s^-

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

arXiv: 2102.11734 [hep-ex]

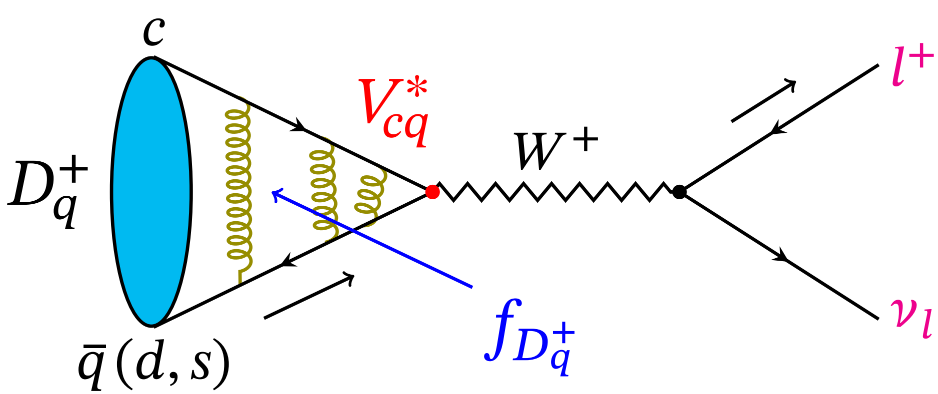


PRD104(2021)012003



Pure leptonic D_s^+ decays

In the SM



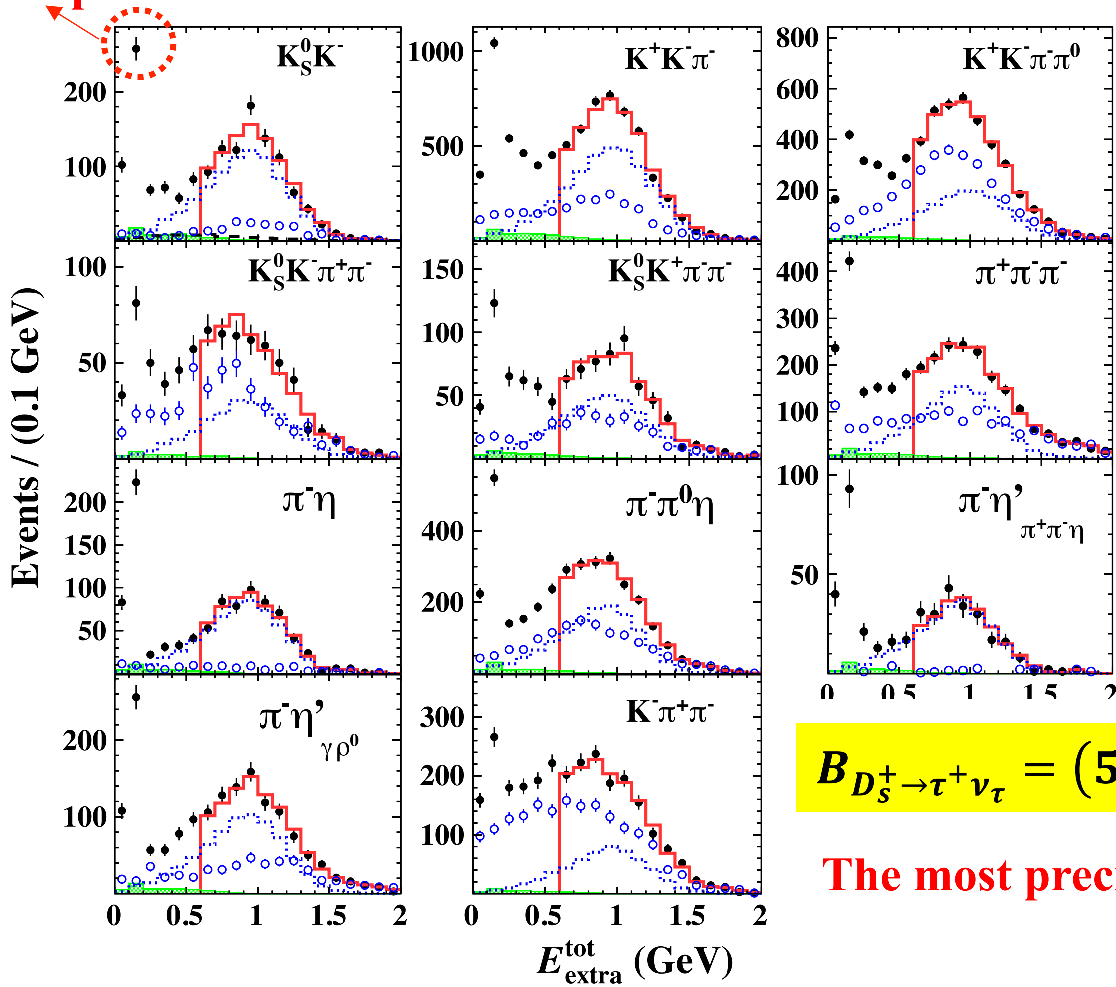
$$\Gamma(D_{(s)}^+ \to l^+\nu_l) = \frac{G_F^2\, f_{D_{(s)}^+}^2}{8\pi} \left|V_{cd(s)}\right|^2 m_l^2\, m_{D_{(s)}^+} \left(1 - \frac{m_l^2}{m_{D_{(s)}^+}^2}\right)^2$$

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

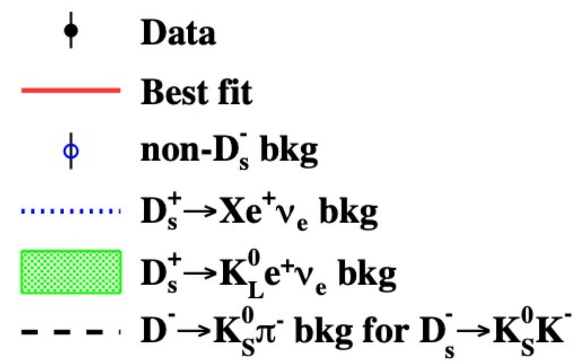
arXiv: 2106.02218 [hep-ex]

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

Signal peak



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



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

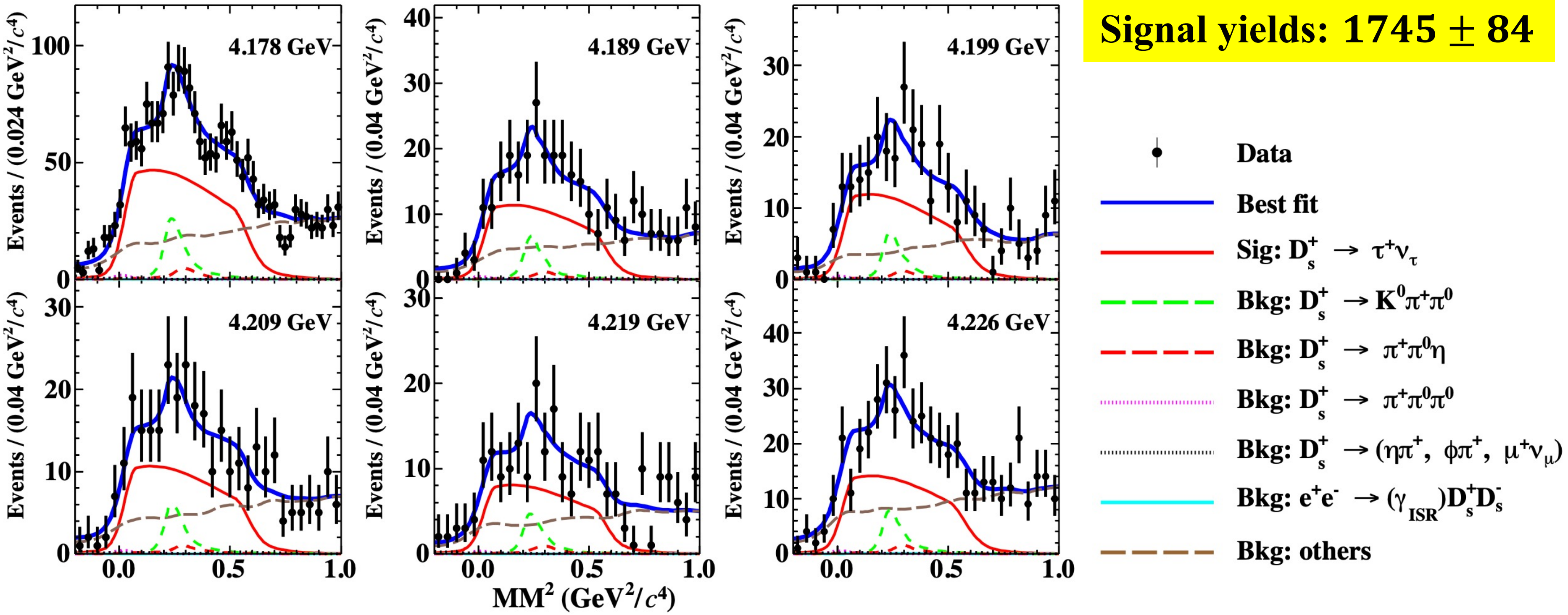
The most precise result to date

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

arXiv: 2105.07178 [hep-ex], accepted by PRD

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

Signal yields: 1745 ± 84



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

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

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

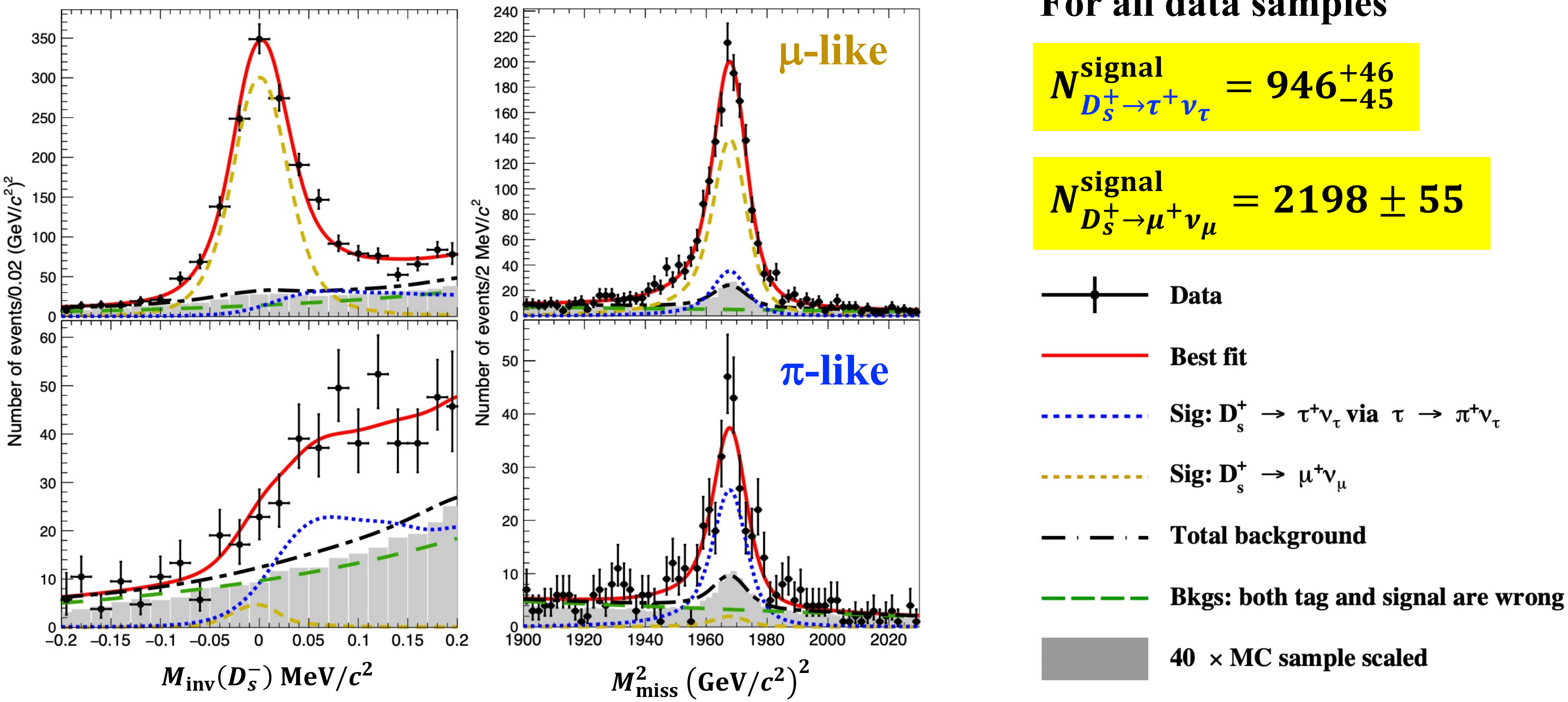
$$\vec{p}_{\mathrm{miss}} = -\vec{p}_{D_s^-} - \vec{p}_\gamma - \vec{p}_{\pi^+\pi^0}$$

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

arXiv: 2102.11734 [hep-ex], accepted by PRD

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

Only show @ 4.178 GeV



For all data samples

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

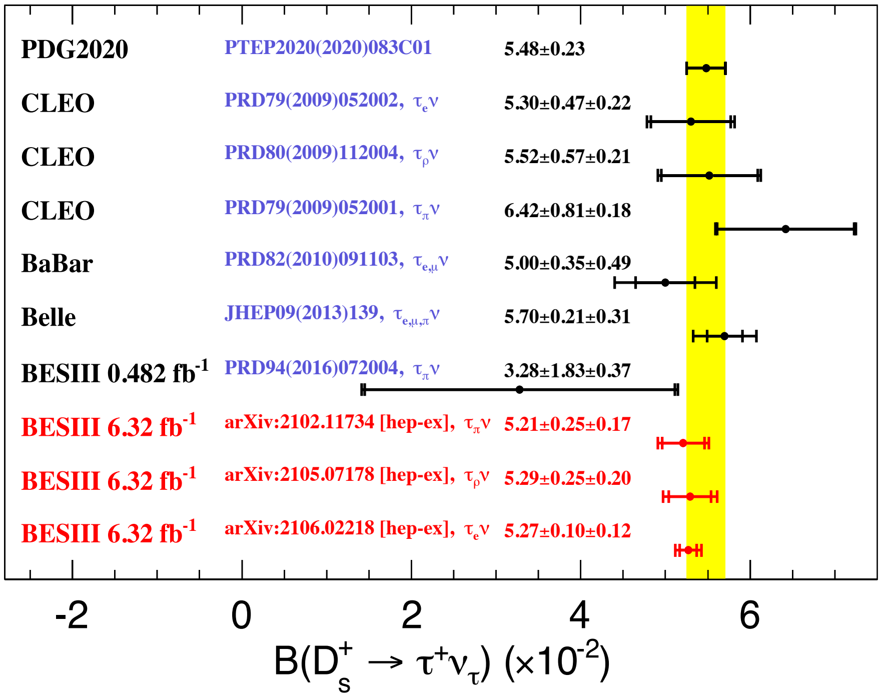
$N^{\rm signal}_{D_s^+\to\mu^+\nu_\mu} = 2198 \pm 55$

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

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

Lepton flavor universality

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



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

$= 9.67 \pm 0.34$

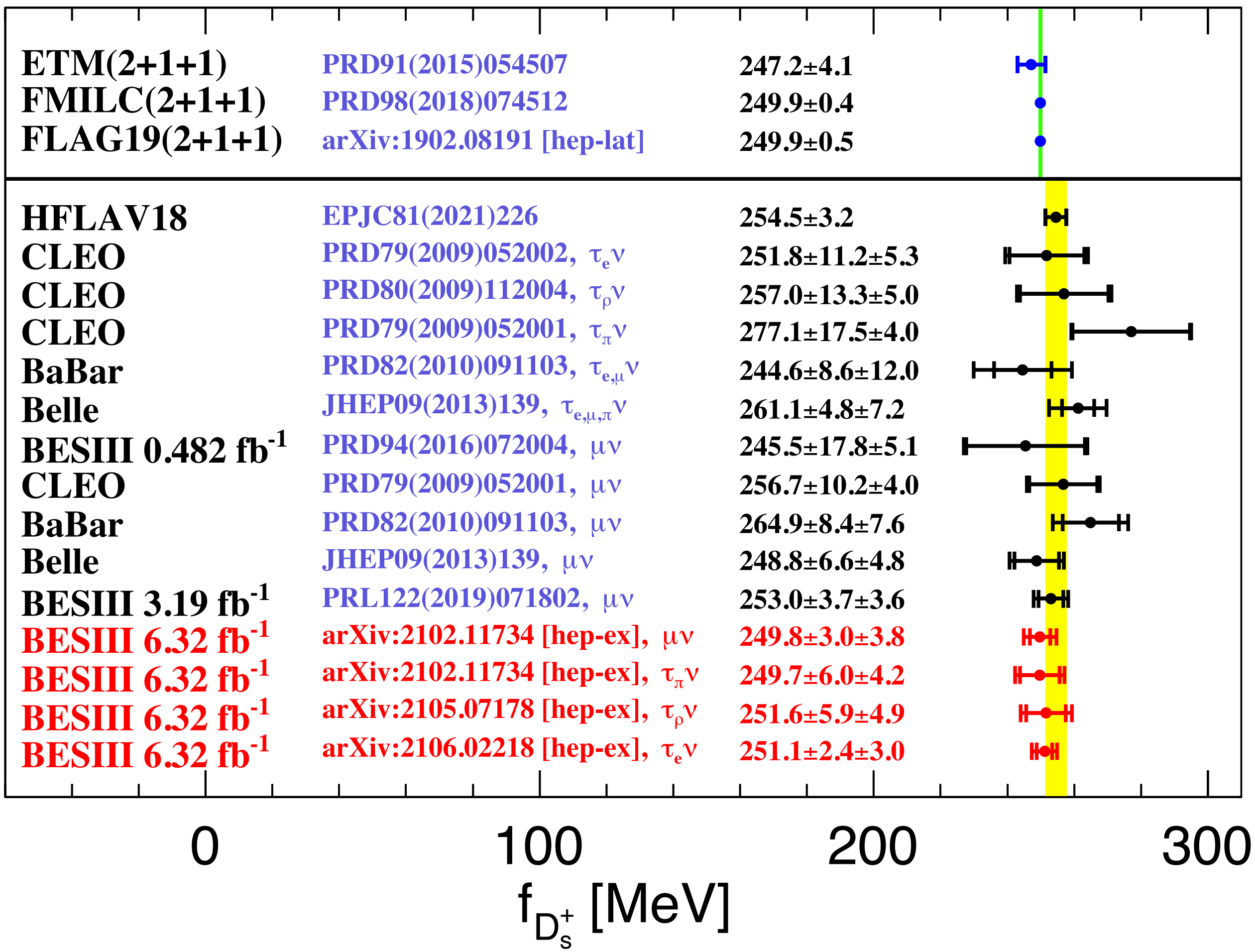
9.75 ± 0.01
(SM prediction)

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

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

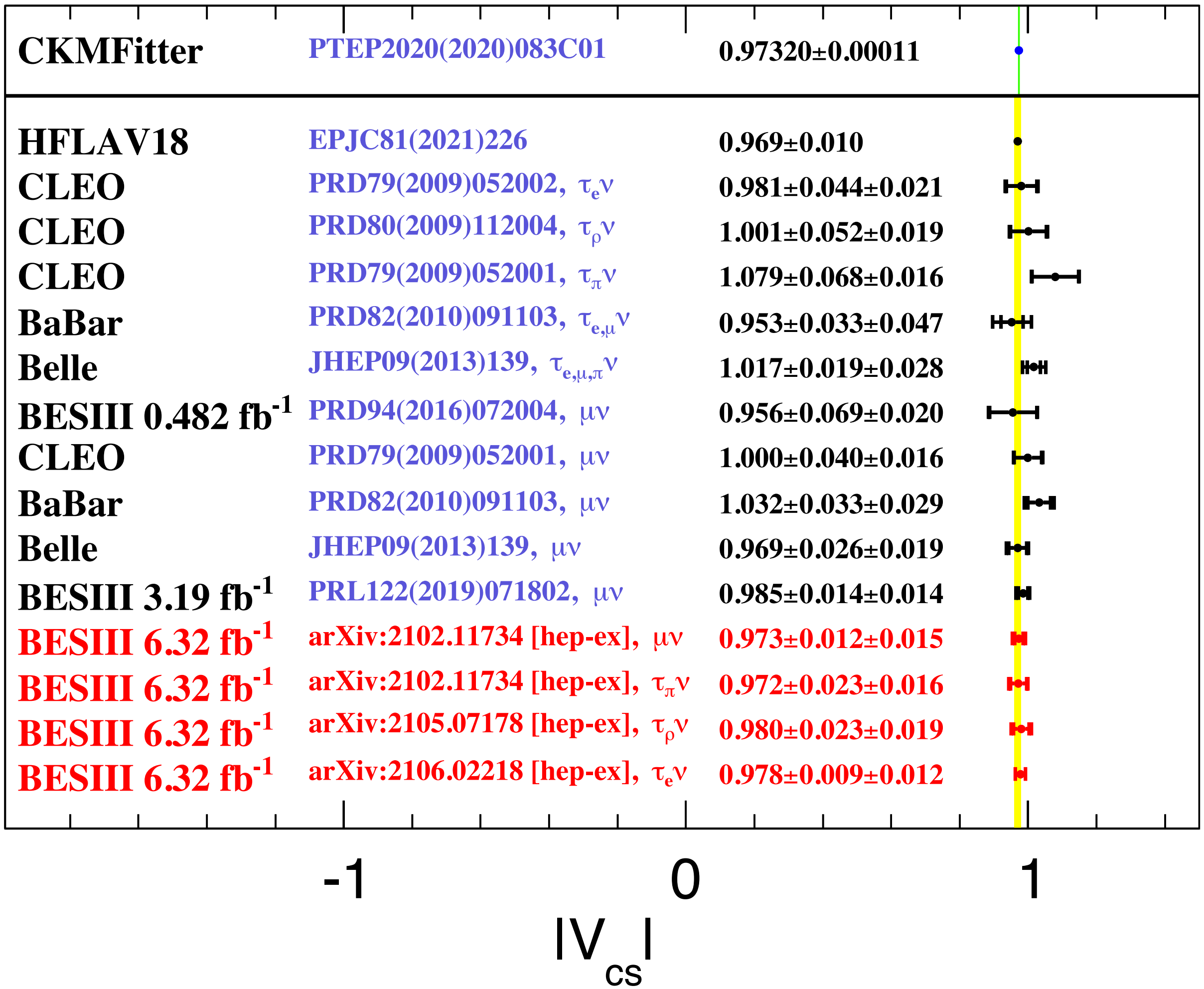
$$B(D_s^+ \to l^+ \nu_l) \propto \left[f_{D_s^+} |V_{cs}| \right]^2$$

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



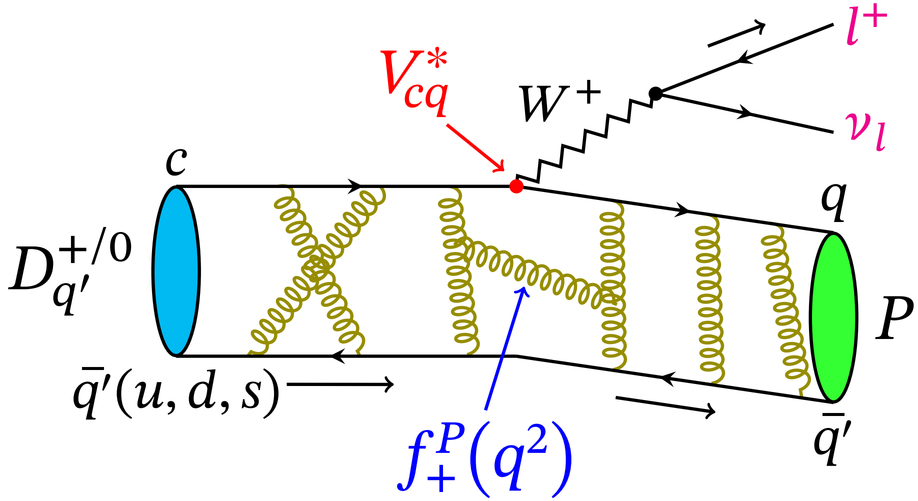
Comparison of $|V_{cs}|$

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



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

In the SM



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

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

PRL124(2020)231801

No. of single tags: $N_{\rm ST}^{\rm signal} = (1522.5 \pm 2.1)\times 10^3$

- ✓ $\eta \to \gamma\gamma$
- ✓ Unbinned fit to $U_{\rm miss}$

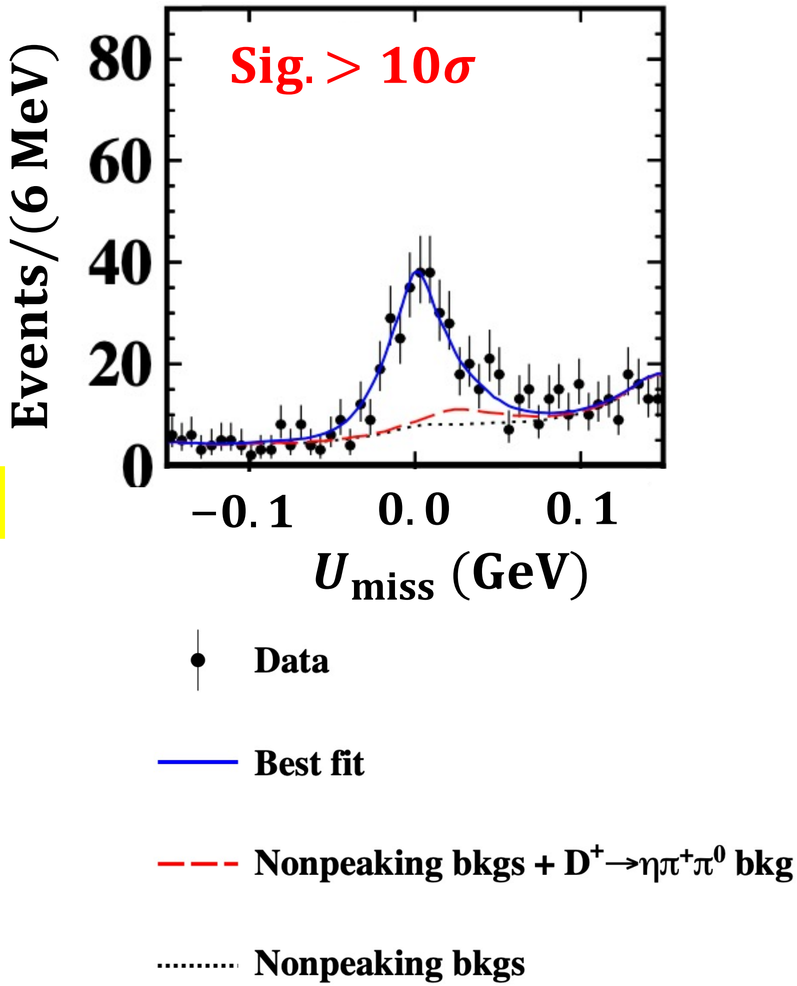
$N_{\rm DT}^{\rm signal} = 234 \pm 22$

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

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

SM prediction: $(0.97 - 1.00)$

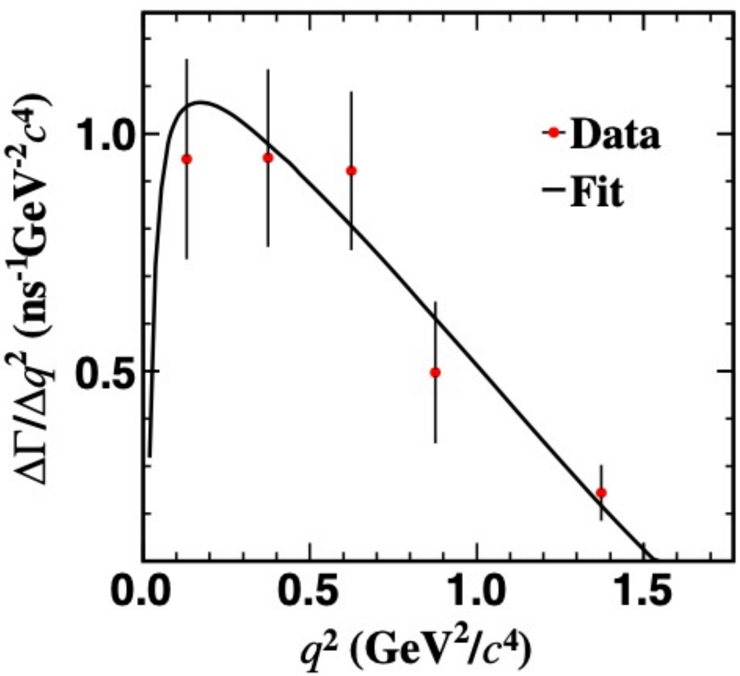
No LFU violation within current sensitivity.



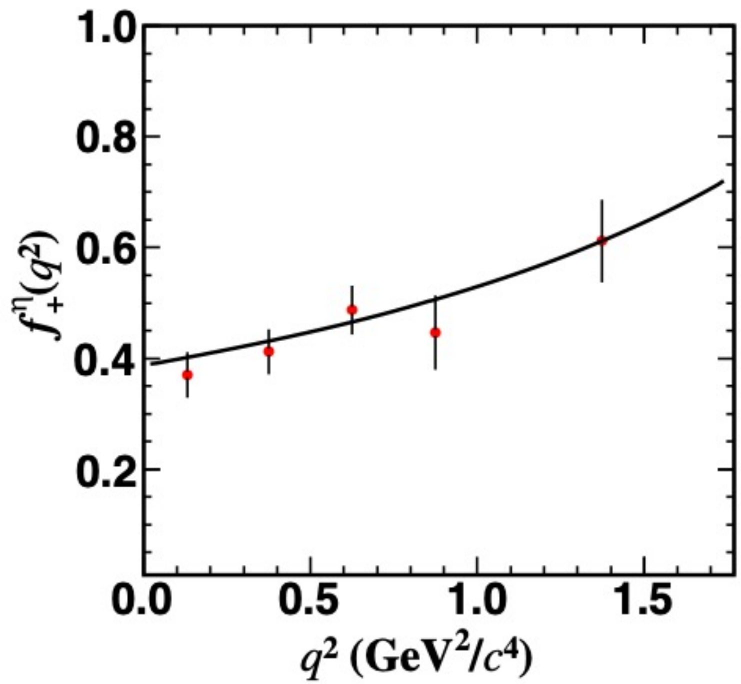
PRL124(2020)231801

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

Partial decay rates



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



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

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

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

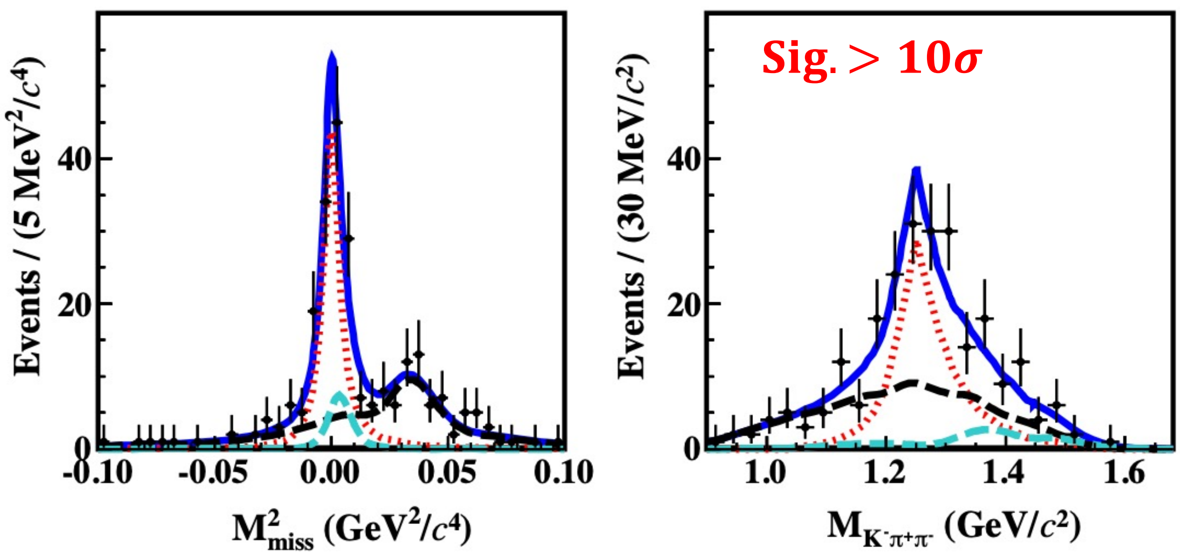
$|V_{cd}| = 0.242 \pm 0.022_{\text{stat.}} \pm 0.006_{\text{syst.}} \pm 0.033_{\text{theory}}$

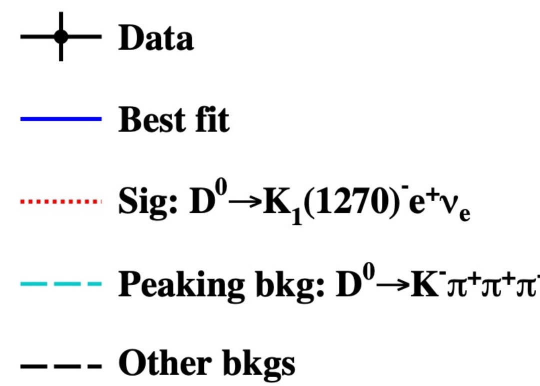
$D^0 \to K_1(1270)^- e^+\nu_e$

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.

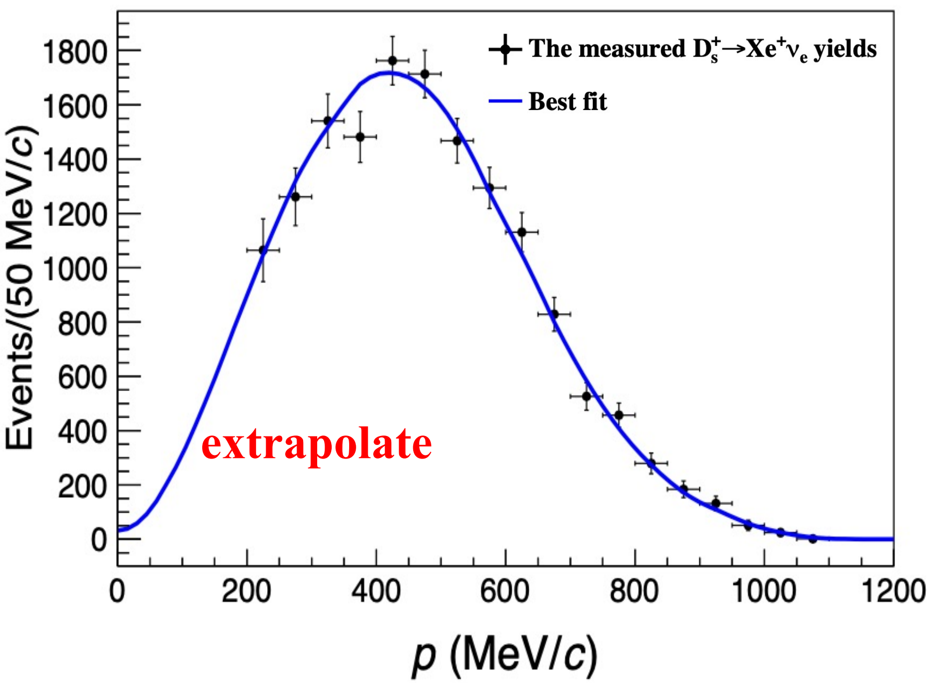
$D_s^+ \to Xe^+\nu_e$

PRD104(2021)012003

- ✓ 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)

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

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



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

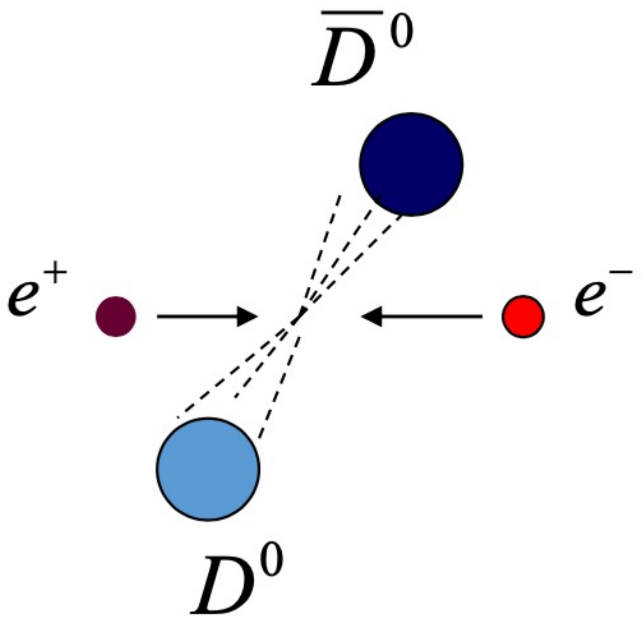
- Consistent with the prediction of 0.813
- Supports the conclusion that the difference in the semileptonic decay widths of D_s^+ ($c\bar{s}$) and D^0($c\bar{u}$) mesons can be accounted for within the Standard model by non-spectator interactions.

Hadronic decays

The $\psi(3770)$ has a $C = -1$ quantum number and this is conserved in the strong decay in which two neutral D mesons are produced. Hence, the two neutral mesons have an antisymmetric wave function. This also means that the two D mesons do not decay independently of one another.

The $D^0\overline{D}^0$ pair will be a quantum-correlated state

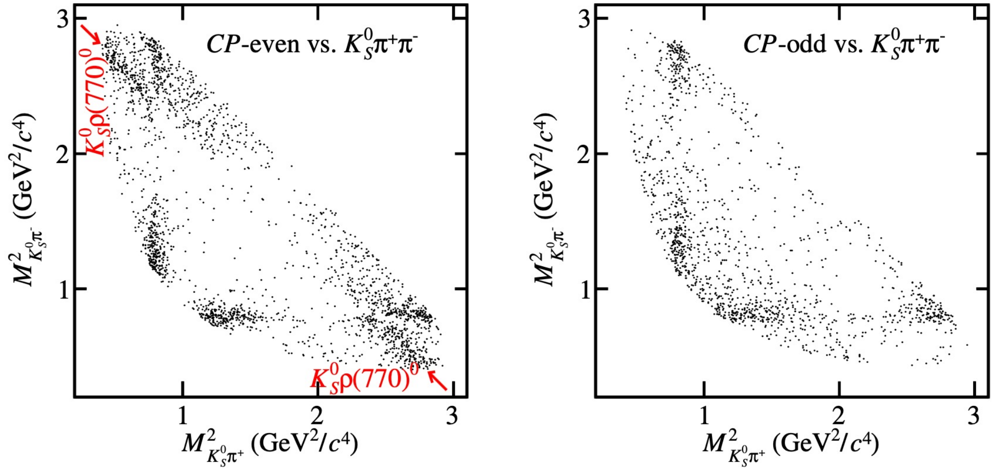
$$e^+e^- \rightarrow \psi(3770) \rightarrow D^0\overline{D}^0$$

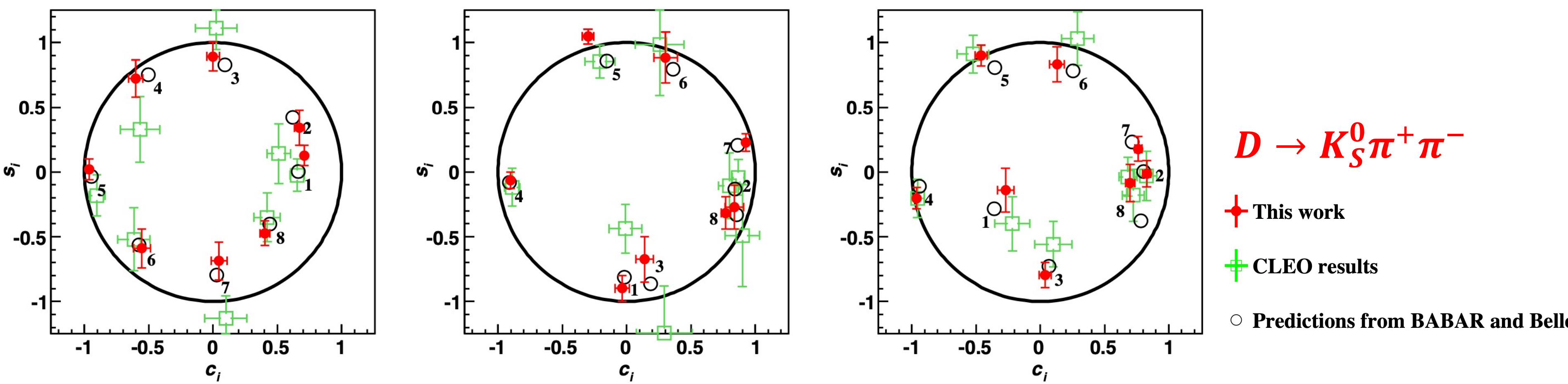


$D \to K^0_{S,L}\pi^+\pi^-$

PRL124(2020)241802; PRD101(2020)112002

- $\psi(3770) \to D^0\bar{D}^0$ quantum correlation → Directly measure the strong-phase difference $\Delta\delta_D$ between D^0 and $\bar{D}^0$ decays → The key inputs for a binned model-independent determination of the CKM angle γ/ϕ_3 with B decays.
- c_i and s_i are the amplitude-weighted averages of $\cos\Delta\delta_D$ and $\sin\Delta\delta_D$ over each Dalitz plot bin.
- **The estimated uncertainties on γ/ϕ_3: between 0.7° and 1.2°.**





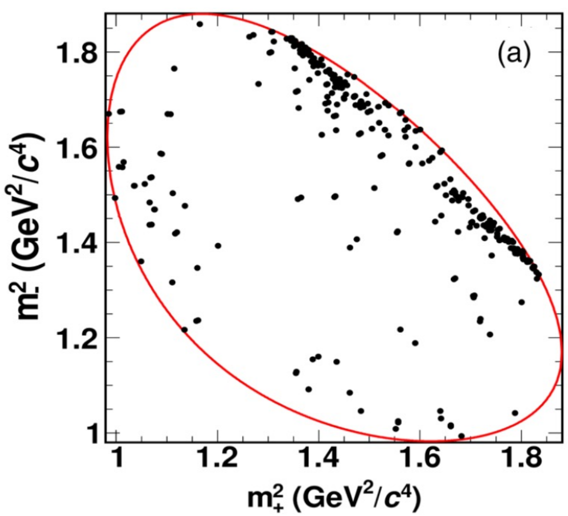
Equal $\Delta\delta_D$ binnings　　Optimal $\Delta\delta_D$ binnings　　Modified optimal $\Delta\delta_D$ binnings

$D \to K^0_{S,L} K^+ K^-$

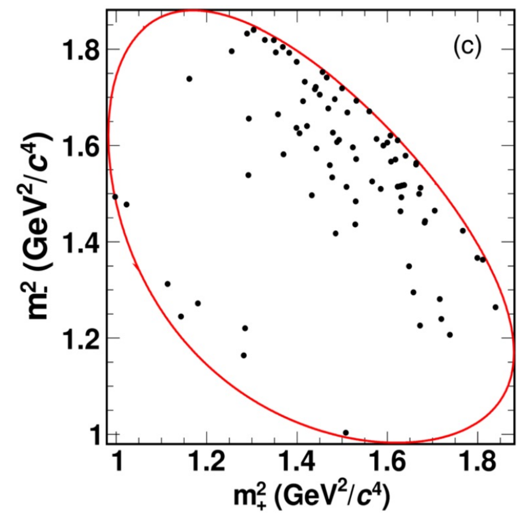
PRD102(2020)052008

- **Equal $\Delta\delta_D$ binnings scheme: with 2/3/4 pairs of bins.**
- $m_\pm$: $m(K^0_S K^\pm)$.
- **The estimated uncertainties on γ/ϕ_3: 2.3°, 1.3°, and 1.3°** **for 2, 3, 4 pairs of bins schemes.**

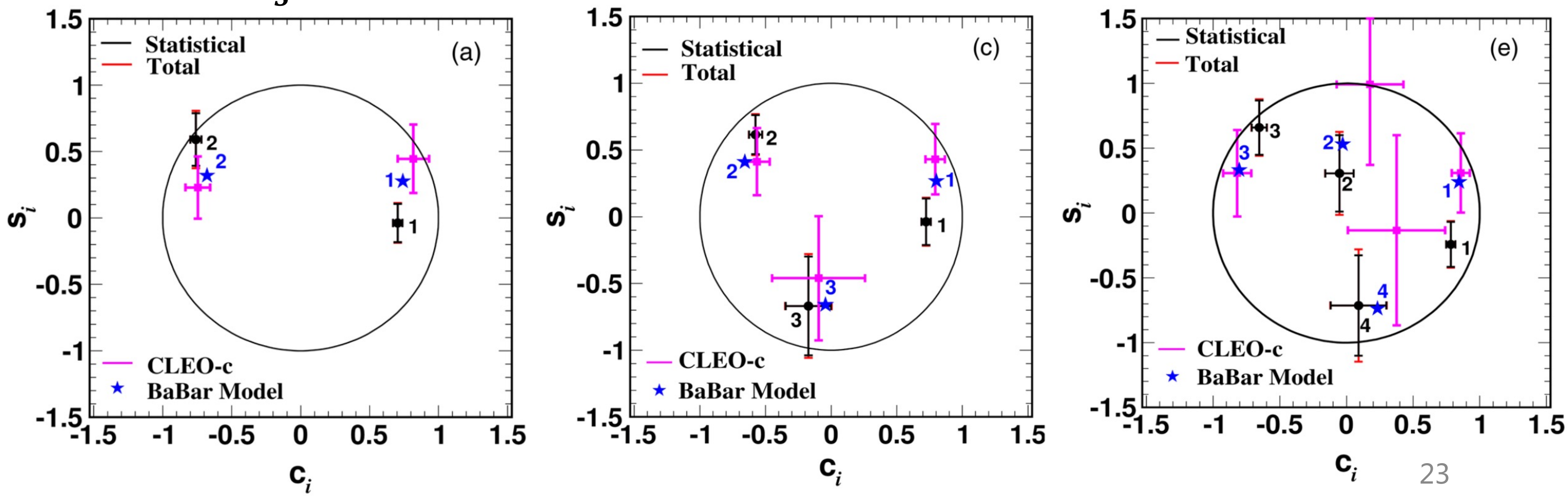
CP − even vs. $K^0_S K^+ K^-$



CP − old vs. $K^0_S K^+ K^-$



$D \to K^0_S K^+ K^-$



$D \to K^+\pi^+\pi^+\pi^-$ and $D \to K^-\pi^+\pi^0$

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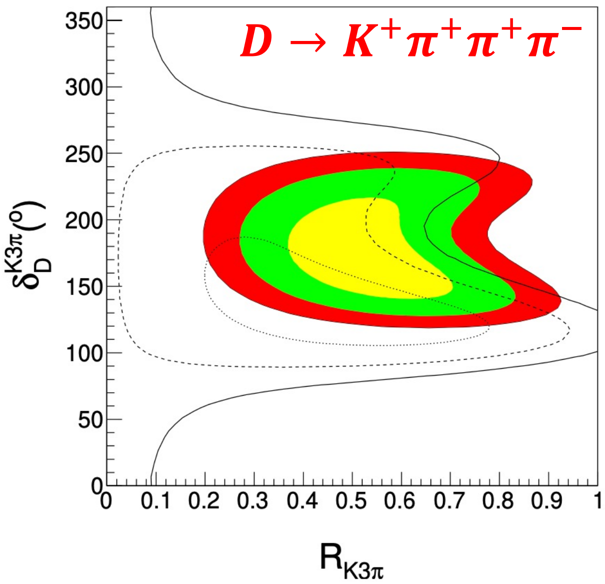
- A χ^2 fit : obtain the coherence factors (R) and the average strong-phase differences (δ_D)

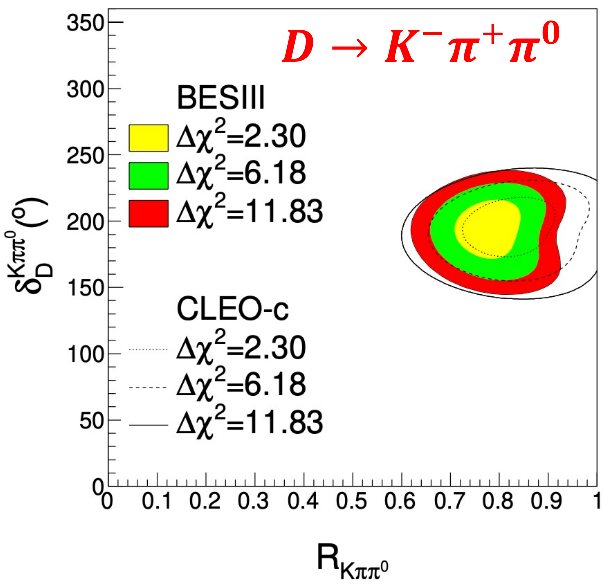
$$R_{K3\pi} = 0.52^{+0.12}_{-0.10}$$

$$R_{K\pi\pi^0} = 0.78 \pm 0.04$$

$$\delta_D^{K3\pi} = (167^{+31}_{-19})^\circ$$

$$\delta_D^{K\pi\pi^0} = (196^{+14}_{-15})^\circ$$





- $\Delta\chi^2$ scans: $\Delta\chi^2 = 2.30, 6.18, 11.83$ intervals correspond to 68.3%, 95.4%, and 99.7% confidence levels in the 2D parameter space:

- Besides, the phase space of $D \to K^+\pi^+\pi^+\pi^-$ is divided into four bins. Based on this results, the estimated uncertainty on γ/ϕ_3 is around 6°.

$D^+ \to K^+\pi^+\pi^-\pi^0$

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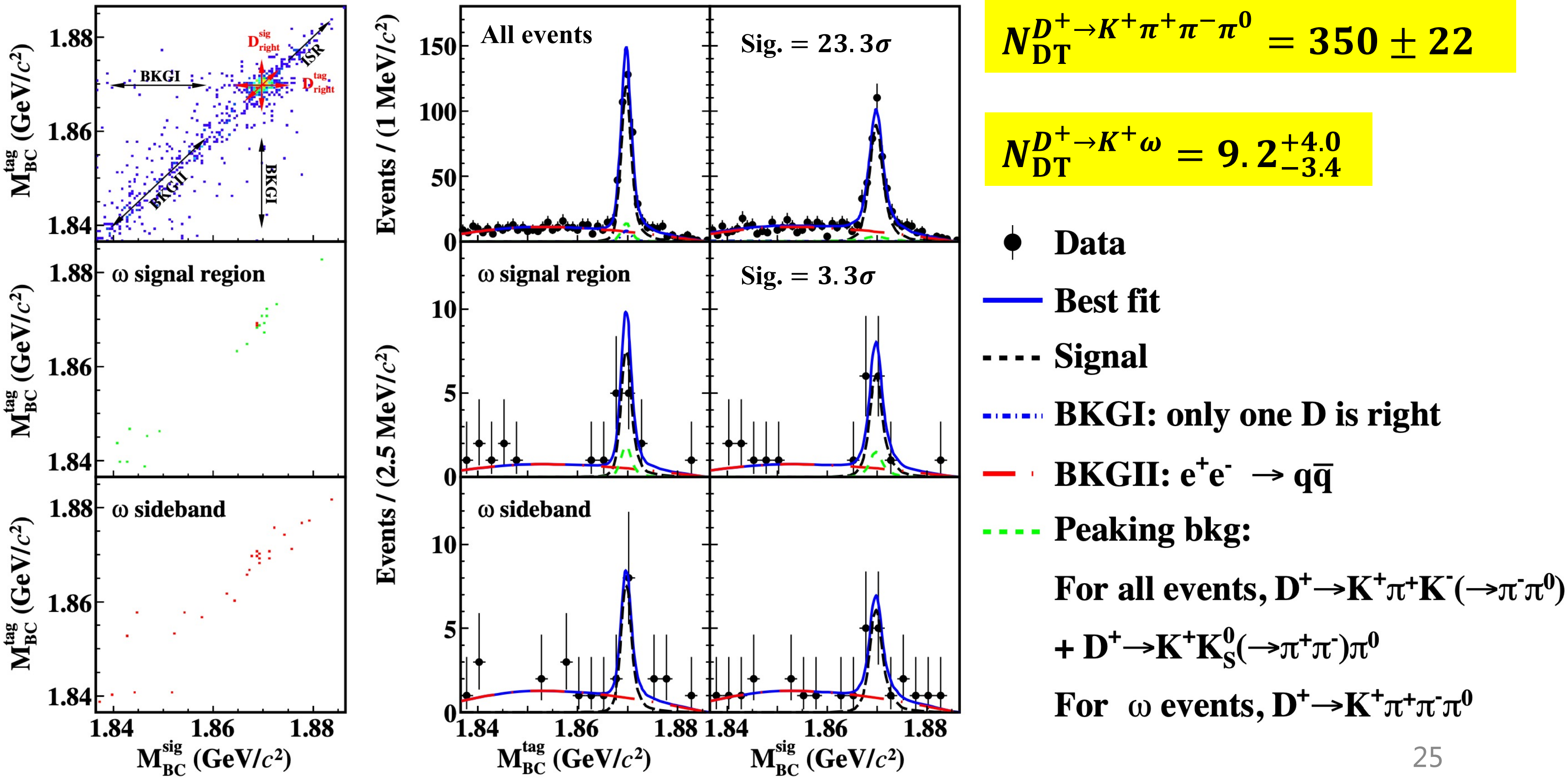
- The naive expectation for the doubly Cabibbo-suppressed (DCS) decay rate relative to its Cabibbo-favored (CF) counterpart $R = \mathcal{B}(\text{DCS})/\mathcal{B}(\text{CF})$ is of the order $\tan^4\theta_C(\sim 0.29\%)$ level, where θ_C is the Cabibbo mixing angle.

- 2D fits for all events; simultaneous 2D fits for ω events



$N_{\rm DT}^{D^+\to K^+\pi^+\pi^-\pi^0} = 350 \pm 22$

$N_{\rm DT}^{D^+\to K^+\omega} = 9.2^{+4.0}_{-3.4}$

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$$\boldsymbol{B_{D^+\to K^+\omega} = \left(5.7^{+2.5}_{-2.1}{}_{\text{stat.}} \pm 0.2_{\text{syst.}}\right)\times 10^{-5}}$$

$$\boldsymbol{B^*_{D^+\to K^+\pi^+\pi^-\pi^0} = \left(1.13 \pm 0.08_{\text{stat.}} \pm 0.03_{\text{syst.}}\right)\times 10^{-3}}$$

***Remove contributions from $\boldsymbol{\eta/\omega/\phi \to \pi^+\pi^-\pi^0}$**

- **The ratio $\boldsymbol{B(\text{DCS})/B(\text{CF})}$:**

$$\boldsymbol{\frac{B^*_{D^+\to K^+\pi^+\pi^-\pi^0}}{\overline{B}^{\text{PDG}}_{D^+\to K^-\pi^+\pi^+\pi^0}} = (1.81 \pm 0.15)\% = (6.28 \pm 0.52\,)\tan^4\theta_C}$$

This ratio is significantly larger than the values $\boldsymbol{(0.21\sim 0.58)\%}$ from other DCS decays, which implies that there is a massive isospin symmetry violation

- **The asymmetry:**

$$\boldsymbol{A_{CP}^{D^\pm\to K^\pm\pi^\pm\pi^\mp\pi^0} = \frac{B_{D^+\to K^+\pi^+\pi^-\pi^0} - B_{D^-\to K^-\pi^-\pi^+\pi^0}}{B_{D^+\to K^+\pi^+\pi^-\pi^0} + B_{D^-\to K^-\pi^-\pi^+\pi^0}} = (-0.04 \pm 0.06_{\text{stat.}} \pm 0.01_{\text{syst.}})}$$

No evidence for CP violation is found.

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

- pure and semi-leptonic $D_{(s)}$ decays, which provide precision calibration of LQCD and precision measurements of CKM matrix elements.
- charm hadronic decays, which are key labs to understand non-perturbative QCD, and provide important inputs to model-independent determination of CKM angle γ/ϕ_3 and charm mixing/CPV.

✍ In the near future, BESIII will collect 20 fb^{-1} @ 3.773 GeV data sample, and another 3 fb^{-1} @ 4.178 GeV[1], the single precisions will be further improved→ a new era of precision charm physics.

[1] M. Ablikim *et al.*, Chin. Phys. C 44, 040001 (2020).

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**

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