

Charm Physics at BESIII

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On behalf of the BESIII collaboration



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FAIRNESS2019

Arenzano, Genoa 20.-24. May 2019

Outline

- (Semi)-leptonic decay
- Hadronic decay
- Beyond SM

A double-ring collider with high luminosity

beam energy: 1.0 – 2.3 GeV

LINAC

South

BESIII
detector

2004: started BEPCII upgrade,
BESIII construction

2008: test run

2009 - now: BESIII physics run

- 1989-2004 (BEPC):

$$L_{\text{peak}} = 1.0 \times 10^{31} / \text{cm}^2 \text{s}$$

- 2009-now (BEPCII):

$$L_{\text{peak}} = 1.0 \times 10^{33} / \text{cm}^2 (4/5/2016)$$

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

➤ $D^{0(+)}$ data

■ @ $\sqrt{s} = 3.773$ GeV.

- Integrated luminosity = 2.93 fb^{-1} , the world's largest coherent $D\bar{D}$ sample
- 10M $D^0\bar{D}^0$ produced
- 8M D^+D^- produced

➤ D_s^+ data

■ @ $\sqrt{s} = 4.009$ GeV

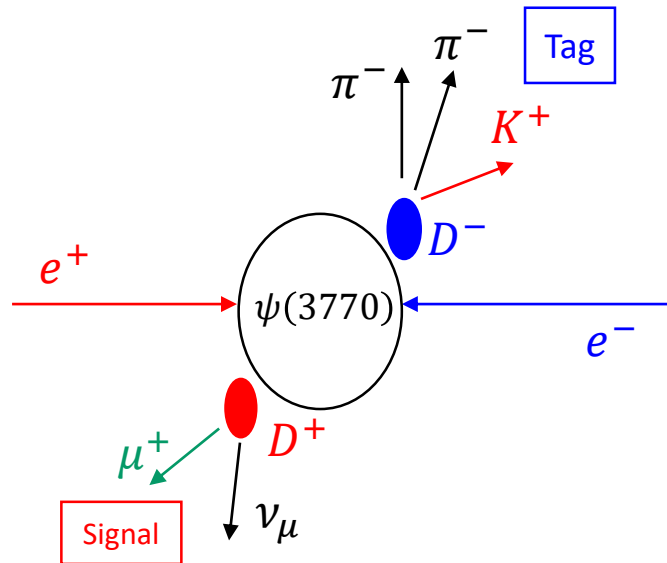
- Integrated luminosity = 0.482 fb^{-1}
- 0.15M $D_s^+D_s^-$ produced

■ @ $\sqrt{s} = 4.178$ GeV

- Integrated luminosity = 3.19 fb^{-1}
- 3M $D_s^+D_s^{*-}$ produced

Tagging method

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

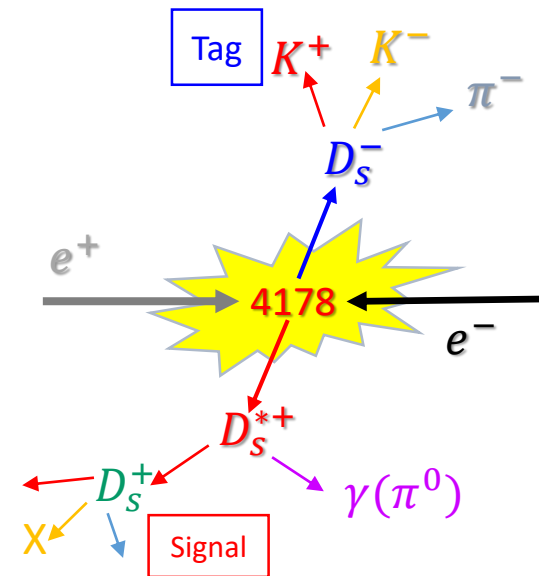


Charge conjugated processes are implied

The **signal** branching:

$$B_{sig} = \frac{N_{sig}}{N_{D(s)}^{tag} \times \epsilon}$$

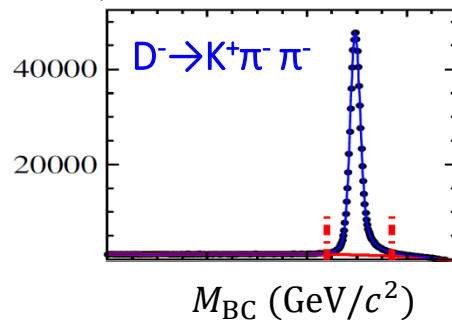
$e^+ e^- \rightarrow D_s^{*+} D_s^-$
 $3.19 \text{ fb}^{-1} @ 4.178 \text{ GeV}$



For Tag side(reconstructed from $K^+ \pi^- \pi^-$):

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

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



For Signal side(reconstruct μ^+):

$$E_{\text{miss}} = E_{\text{beam}} - E_{\mu^+}$$

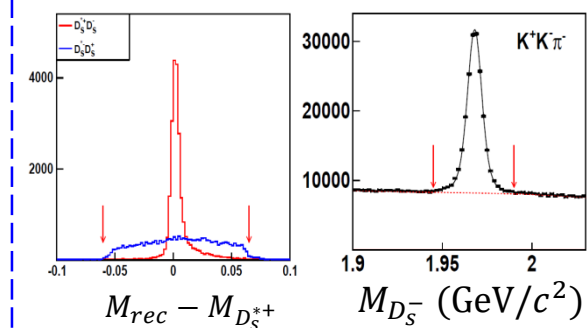
$$\vec{p}_{\text{miss}} = -\vec{p}_{D^-} - \vec{p}_{\mu^+}$$

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

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

For Tag side(reconstructed from $K^+ K^- \pi^-$):

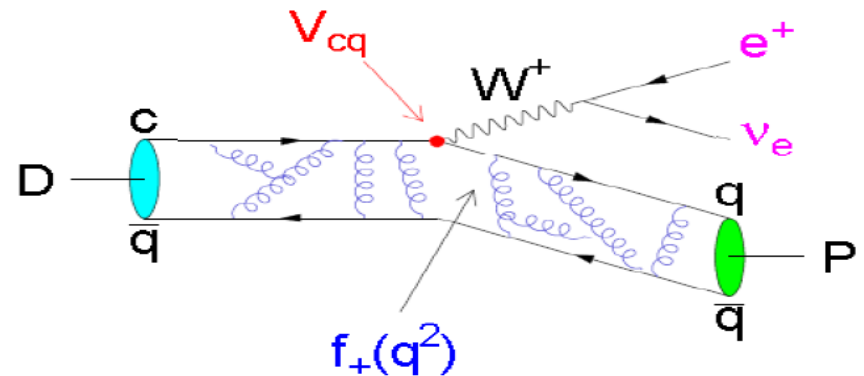
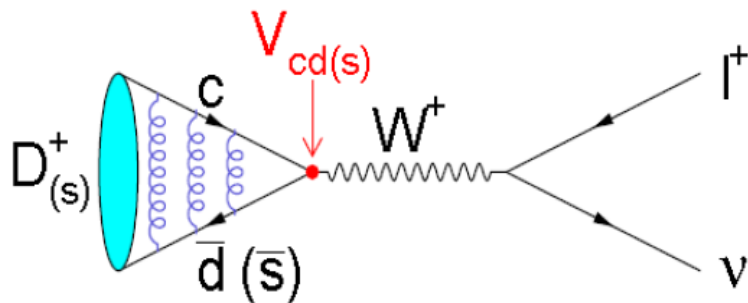
$$M_{\text{rec}} = \sqrt{\left(E_{\text{cm}} - \sqrt{|\vec{p}_{D_s^-}|^2 + m_{D_s^-}^2}\right)^2 - |\vec{p}_{D_s^-}|^2}$$



(Semi)leptonic decay



(Semi)leptonic decay



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

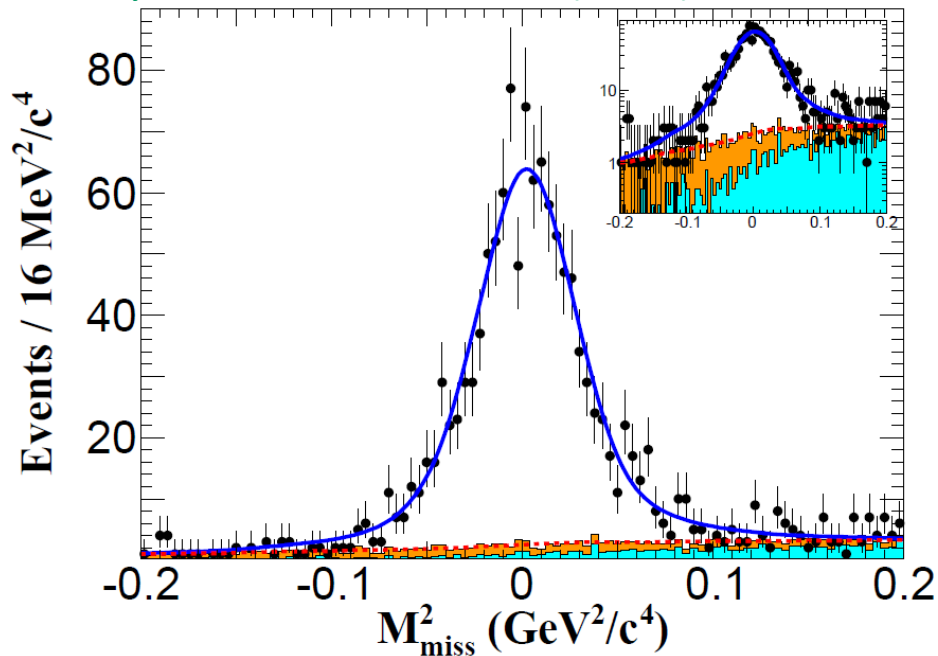
Neglect the mass of lepton

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

- ❖ Calibrate Lattice QCD
- ❖ Constrain on CKM matrix element $|V_{cs}|, |V_{cd}|$
- ❖ Test Lepton Flavor Universality (FLU)

Measure $|V_{cs}|$ via $D_s^+ \rightarrow \mu^+ \nu_\mu$

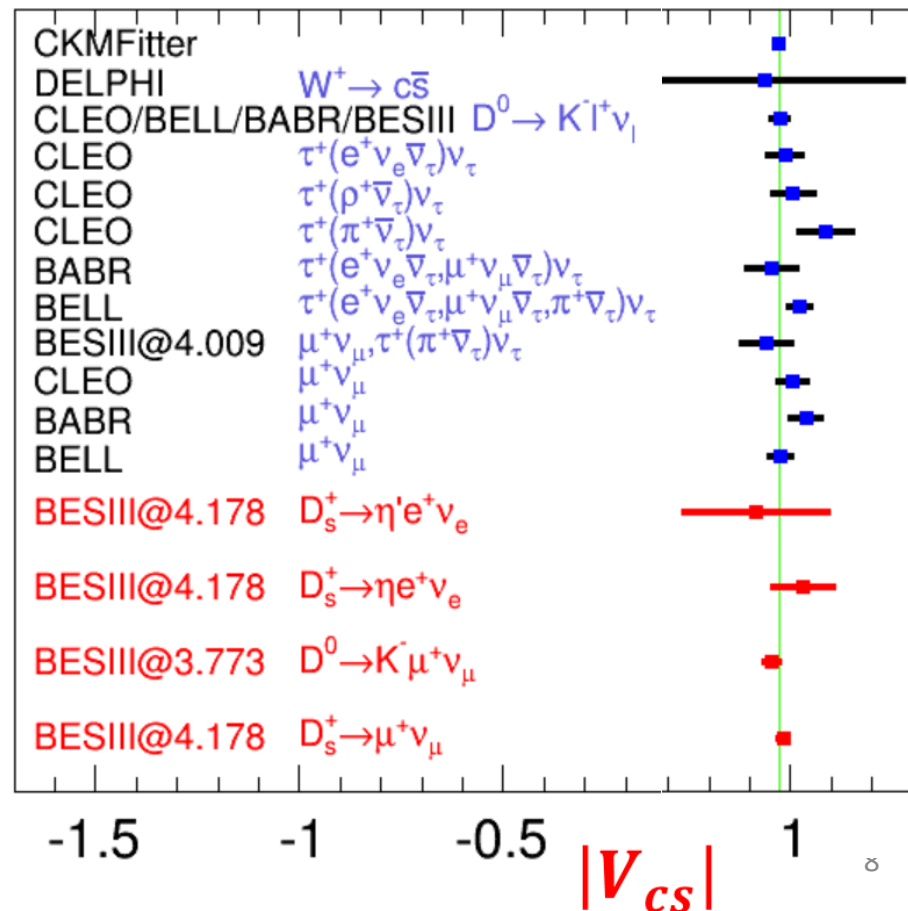
PhysRevLett.122.071802 (2019)



$$f_{D_s^+} |V_{cs}| = 246.2 \pm 3.6_{\text{stat.}} \pm 3.5_{\text{syst.}} \text{ MeV}$$

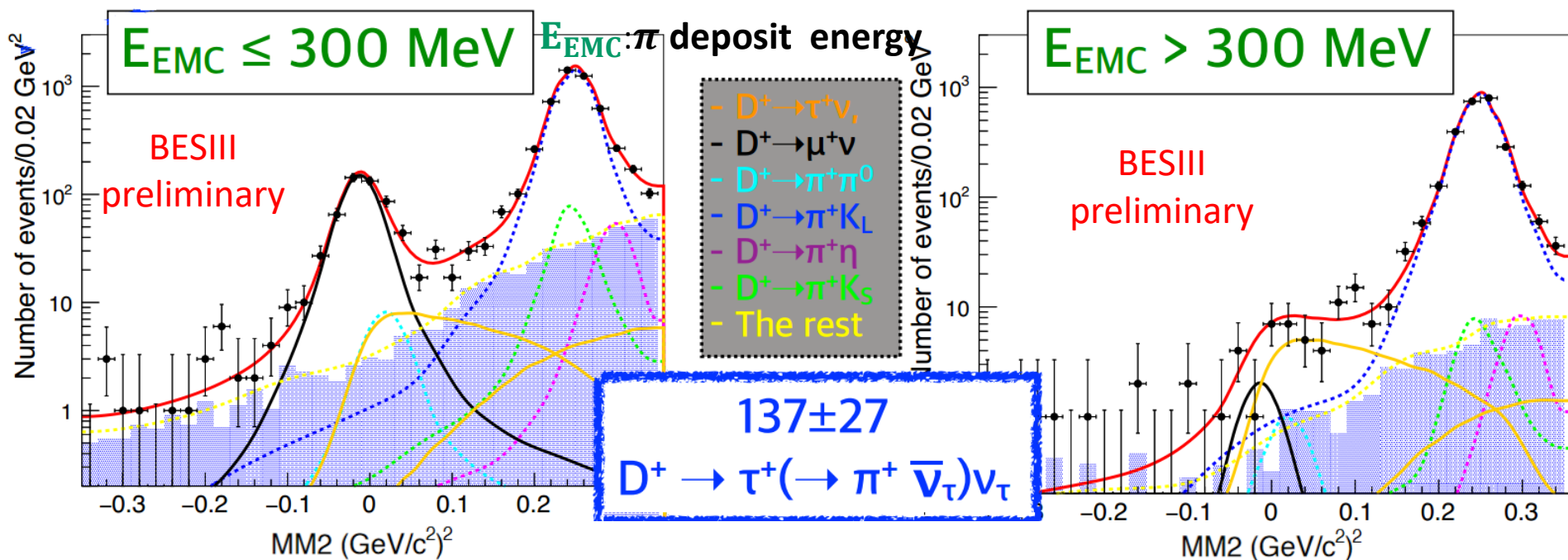
$$B(D_s^+ \rightarrow \mu^+ \nu) = (5.49 \pm 0.16 \pm 0.15) \times 10^{-3}$$

Contributes 28% to the measurement on $|V_{cs}|$



Observation and Test LFU

via $D^+ \rightarrow \tau^+ \nu_\tau$



➤ Test lepton flavor universality

$$\text{SM: } R = \frac{\Gamma(D^+ \rightarrow \tau^+ \nu)}{\Gamma(D^+ \rightarrow \mu^+ \nu)} = \frac{m_\tau^2 \left(1 - \frac{m_\tau^2}{m_D^2}\right)^2}{m_\mu^2 \left(1 - \frac{m_\mu^2}{m_D^2}\right)^2} = 2.67 \pm 0.01$$

BESIII preliminary: $B(D^+ \rightarrow \tau^+ \nu_\tau) = (1.20 \pm 0.24_{\text{stat}}) \times 10^{-3} \Rightarrow R^{\text{exp}} = 3.21 \pm 0.64$
 consistent with the LFU within 0.9σ

Measure $f_+^{D \rightarrow K}$ and Test LFU via $D^0 \rightarrow K^- l^+ \nu_l$

➤ SM predict

$$R = 0.975 \pm 0.001$$

Our result

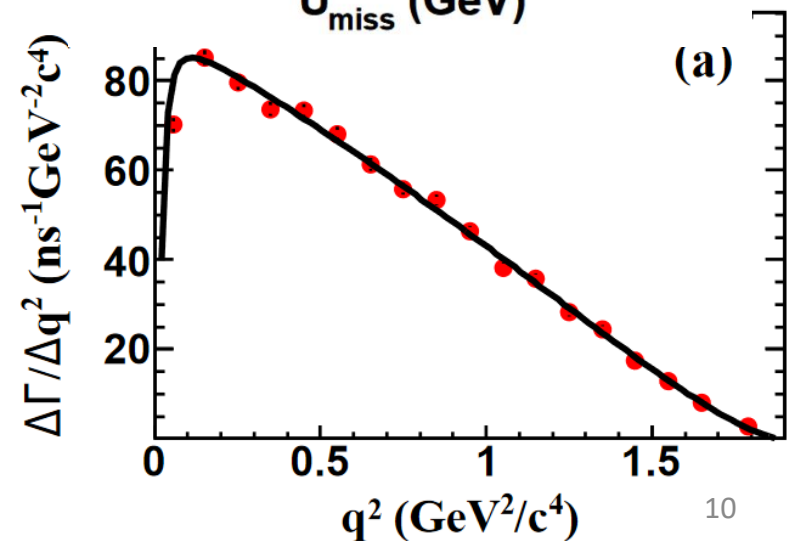
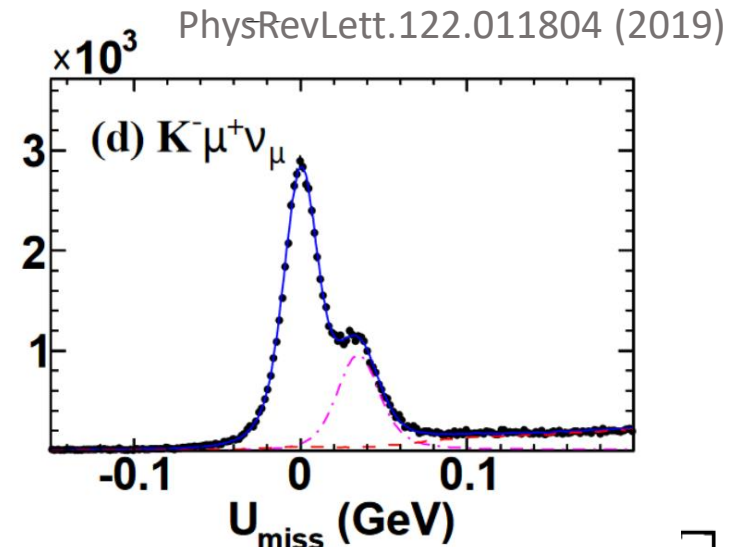
$$R = \frac{\Gamma(D^0 \rightarrow K^- \mu^+ \nu_\mu)}{\Gamma(D^0 \rightarrow K^- e^+ \nu_e)} = 0.974 \pm 0.007 \pm 0.012$$

Coincide with LFU within 1σ

➤ Constrain on $f_+^{D \rightarrow K}$ and V_{cs}

- 3 parameter SEP *Phys. Lett. B* 633, 61 (2006)

$$f_+^{D \rightarrow K}(0) |V_{cs}| = 0.7148 \pm 0.0038 \pm 0.0029$$



Firstly observe $D \rightarrow a_0 e^+ \nu_e$ decay

➤ Observe $D^0 \rightarrow a_0^- e^+ \nu_e$

$$B(D^0 \rightarrow a_0^- e^+ \nu_e) \times B(a_0^- \rightarrow \eta \pi^-)$$

$$= (1.33_{-0.29}^{+0.33} \pm 0.09) \times 10^{-4}$$

$$B(D^+ \rightarrow a_0^0 e^+ \nu_e) \times B(a_0^0 \rightarrow \eta \pi^0) < 3.0 \times 10^{-4} \text{ @ 90\% C.L.}$$

➤ Help to determine the structure of $a_0, f_0(500), f_0(980)$ (PRD, 82, 034016 (2016))

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

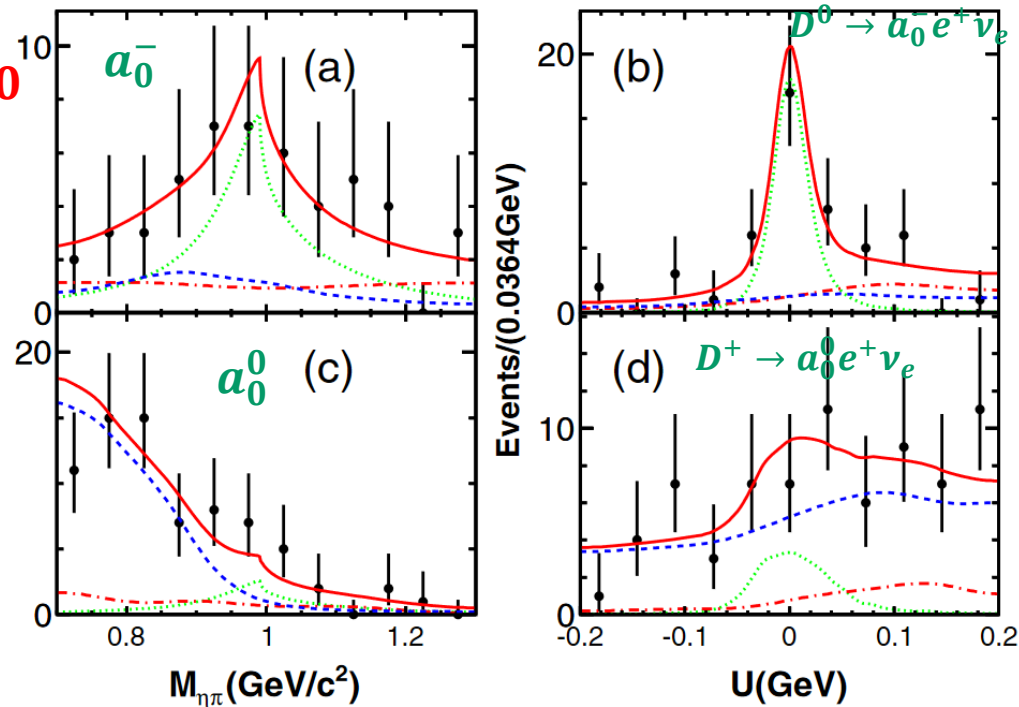
- $R = 1.0 \pm 0.3$

two-quark state

- $R = 3.0 \pm 0.9$

Tetraquark

PhysRevLett.121.081802 (2018) **6.4 σ**



Other results

- Measure Branching fraction and form factors of $D_s^+ \rightarrow K^{(*)0} e^+ \nu_e$
Phys.Rev.Lett. 122, 061801 (2019)
- Test Lepton Flavor Universality via $D^{0/+} \rightarrow \pi^{-/0} l^+ \nu_l$
PhysRevLett.121.171803 (2018)
- Measure form factor and $\eta - \eta'$ mixing angle via $D_s^+ \rightarrow \eta^{(\prime)} e^+ \nu_e$
Phys.Rev.Lett 122, 121801 (2019)
- Improve measurement on $D \rightarrow K/\pi e \nu$
PRD 96, 012002 (2017)
- Search for $D_s^+ \rightarrow \gamma e^+ \nu_e$
PRD 99.072002 (2019)
- Study of $D \rightarrow \pi \pi e^+ \nu_e$
Phys.Rev.Lett.122 , 062001 (2019)
- Study of $D^0 \rightarrow \bar{K} \pi e^+ \nu_e$
Phys.Rev.D.99, 011103 (2019)
- Measurements of the branching fractions of $D_s^+ \rightarrow \phi e^+ \nu_e, \phi/\eta^{(\prime)} \mu^+ \nu_\mu$
Phys. Rev. D 97, 012006 (2018)

An abstract painting featuring a dense, chaotic composition of black, swirling lines and numerous small, colorful splatters in shades of pink, yellow, green, and blue. The background is a light, off-white color. In the top right corner, there is a small, red, square seal or stamp. The overall style is reminiscent of mid-20th-century abstract art, possibly influenced by Jackson Pollock or similar expressionist painters.

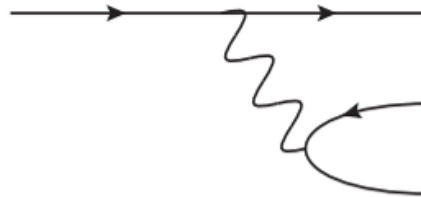
Hadronic decay

A theory model: Diagrammatic Approach

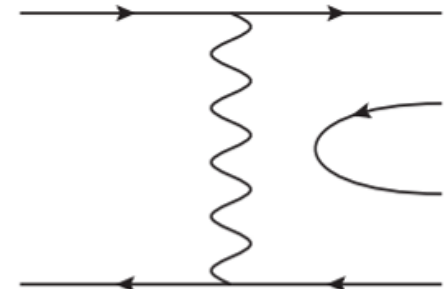
All decays can be described in terms of six different quark diagrams



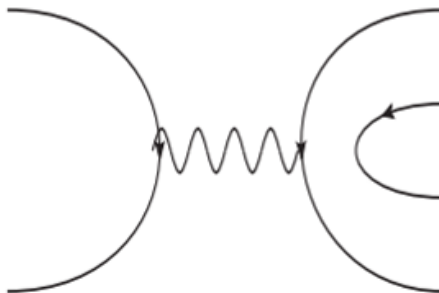
the external W emission



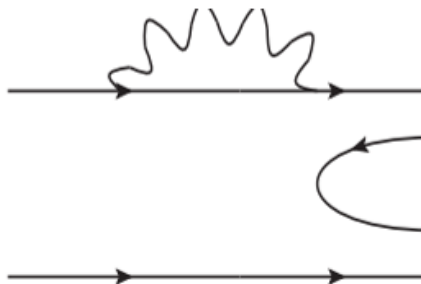
internal W emission



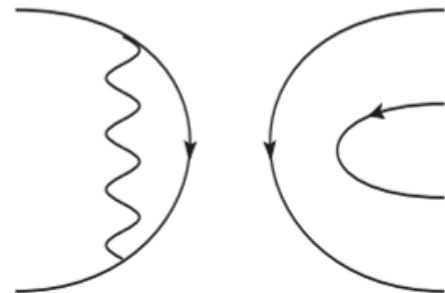
W exchange



W annihilation



horizontal W-loop diagram



vertical W-loop diagram

Each amplitude is determined by experiment!

$D_s^+ \rightarrow p \bar{n}$ decay

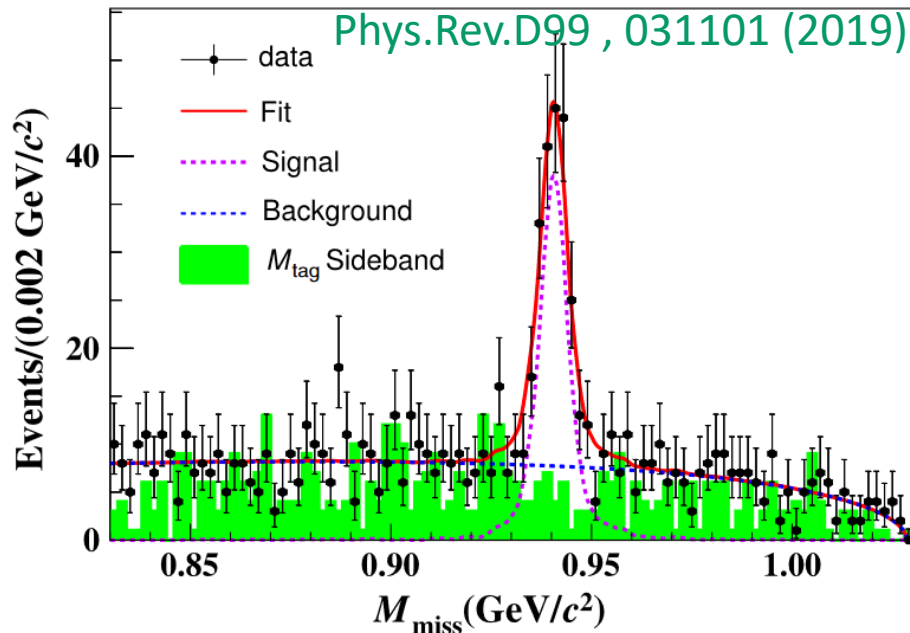
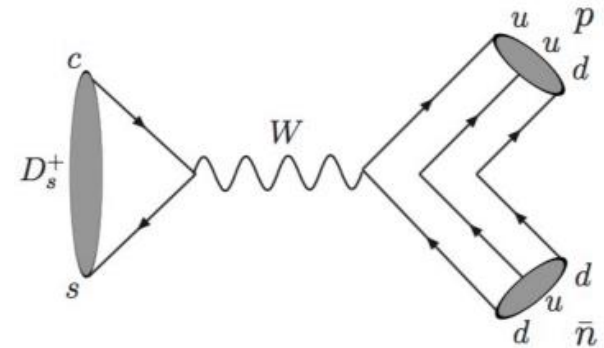
-as a “smoking gun” for W annihilation process

➤ If the annihilation mechanism dominate the D_s^+ decay

- $B(D_s^+ \rightarrow p \bar{n}) \sim 1\%$

➤ An open question to explain this BF
Phys. Rev. Lett.45, 1663 (1980)

Chiral suppression : 10^{-6}



● Our result

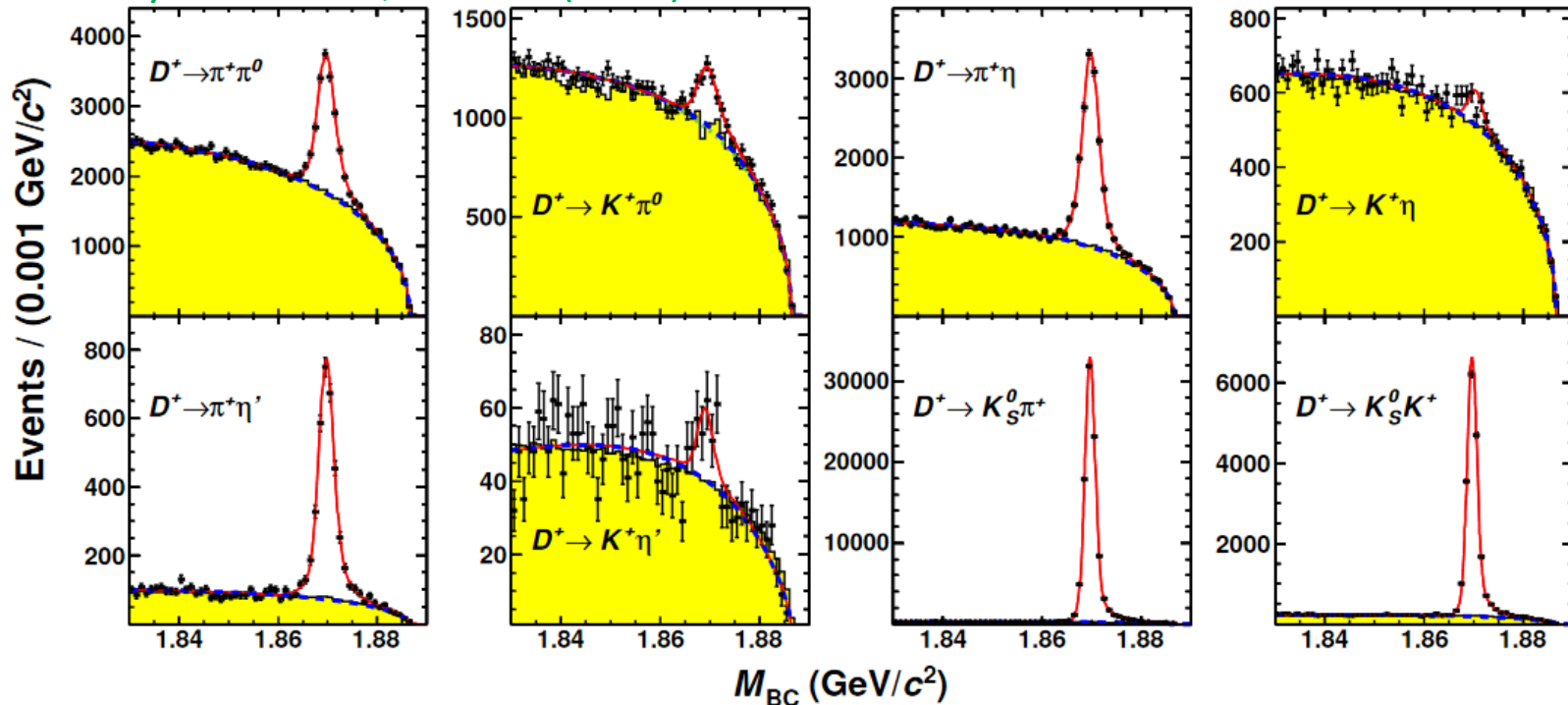
$$B(D_s^+ \rightarrow p \bar{n}) = (1.21 \pm 0.10 \pm 0.06) \times 10^{-3}$$

Confirm the measurement by CLEOc

Measurements of absolute BF of $D \rightarrow PP$

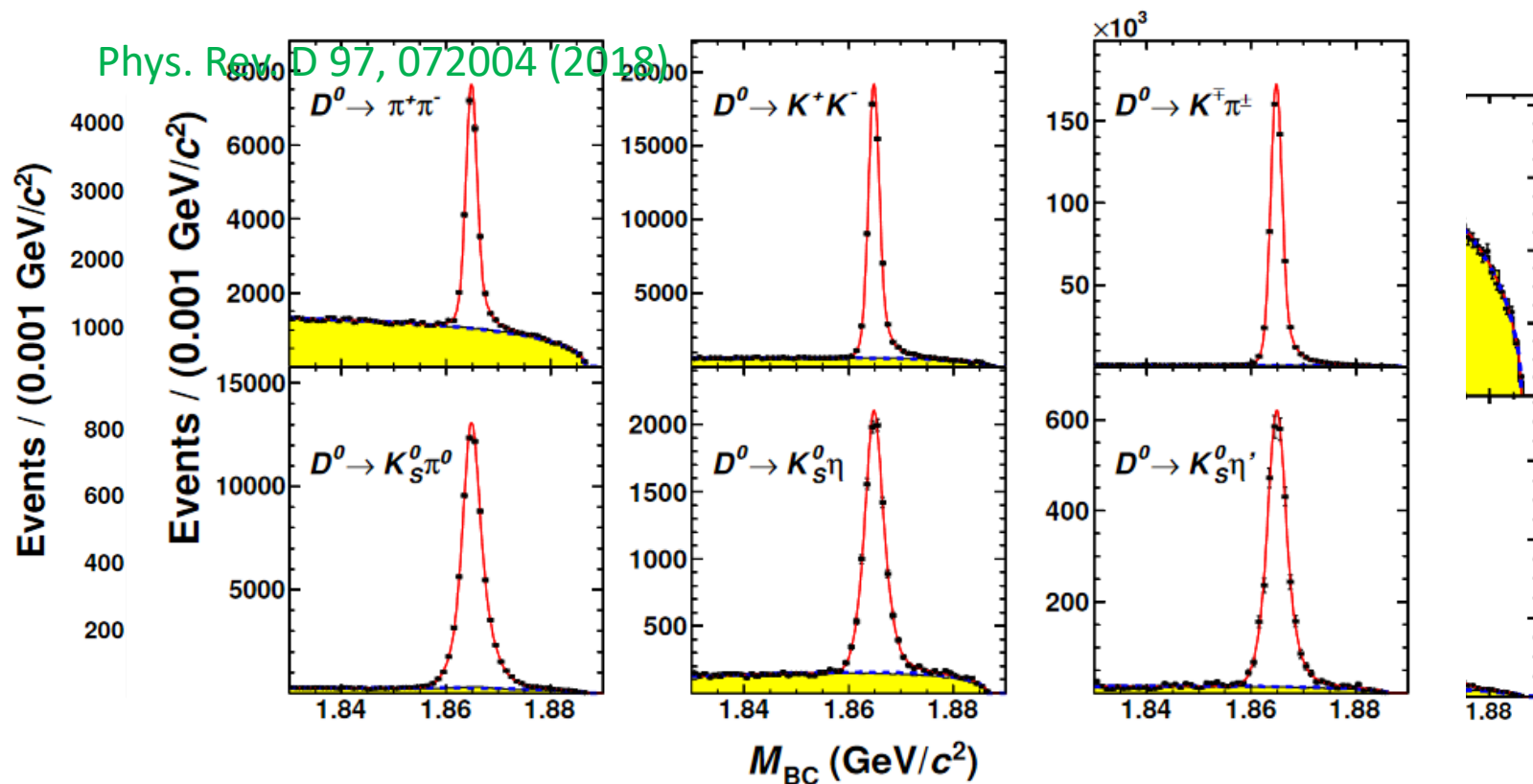
- Improved BF precision
- Important input for Diagrammatic Approach

Phys. Rev. D 97, 072004 (2018)



Measurements of absolute BF of $D \rightarrow PP$

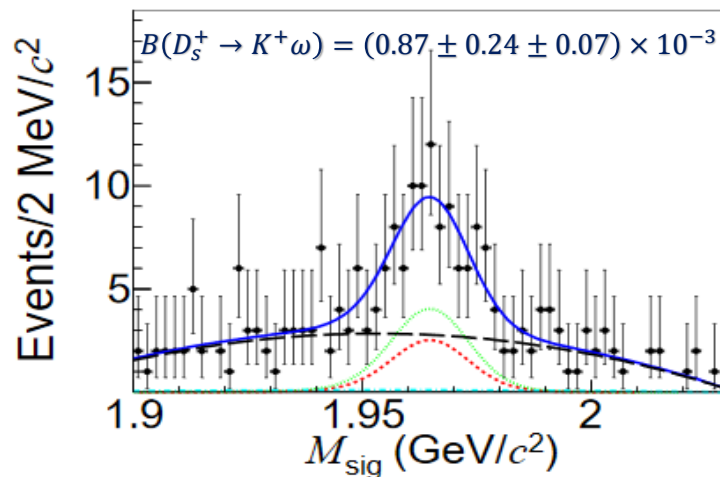
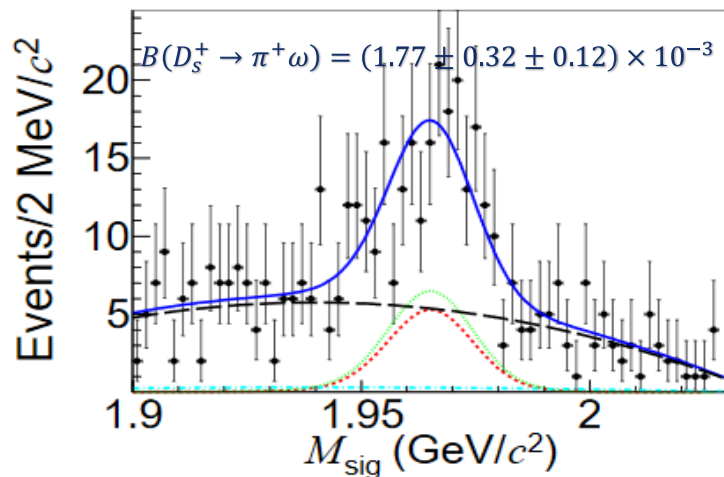
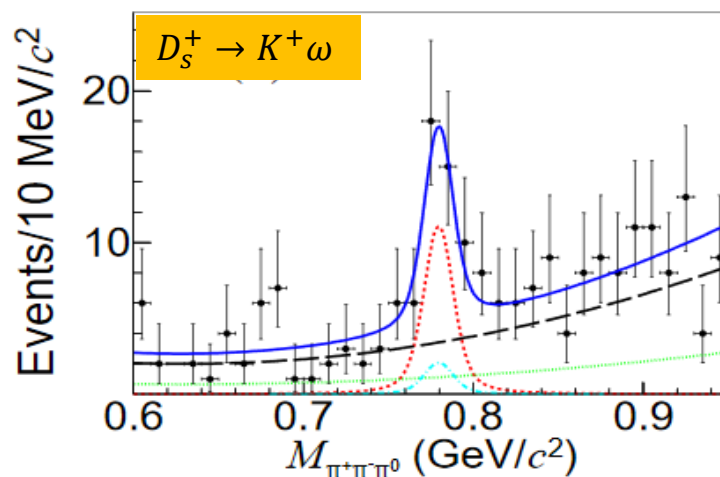
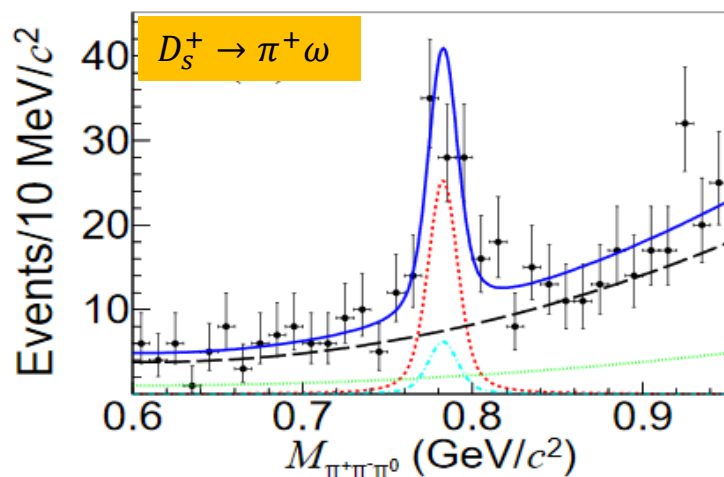
- Improved BF precision
- Important input for Diagrammatic Approach



$$D_s^+ \rightarrow K^+ \omega, \pi^+ \omega$$

◆ Firstly observe $D_s^+ \rightarrow K^+ \omega$

arXiv:1811.00392



$$\text{PWA of } D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-, \\ D^0 \rightarrow K^- \pi^+ \pi^0 \pi^0 \text{ and } D^+ \rightarrow K_S \pi^+ \pi^+ \pi^-$$

➤ Golden reference channel

- Reduce systematic uncertainty of other BF measurement

➤ VV decay mode

- $K^* \rho$

➤ AP decay mode

- $K_1(1270)\pi, K_1(1400)\pi, K a_1(1260), K_S a_1(1260)$

➤ VP decay mode

- $K(1460)\pi$

Other results

➤ $D_s^+ \rightarrow a_0(980)^{0(+)}(\rightarrow \pi\eta)\pi^{+(0)}$

arXiv:1903.04118

➤ $D_s^+ \rightarrow K_L K^+, K_S K^+$

arXiv:1903.04164

➤ $D^0 \rightarrow \omega\eta, \eta\eta', \eta\eta', \eta\pi^0$ and $\eta'\pi^0$

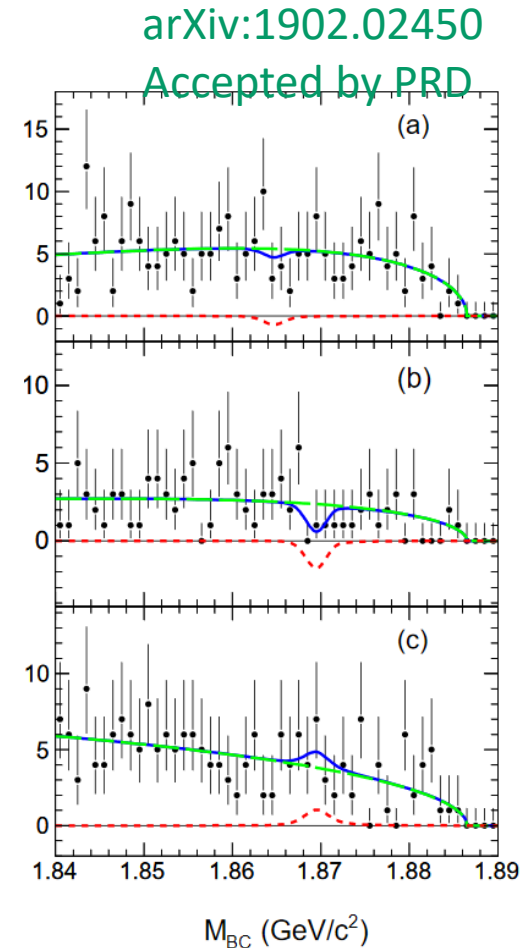
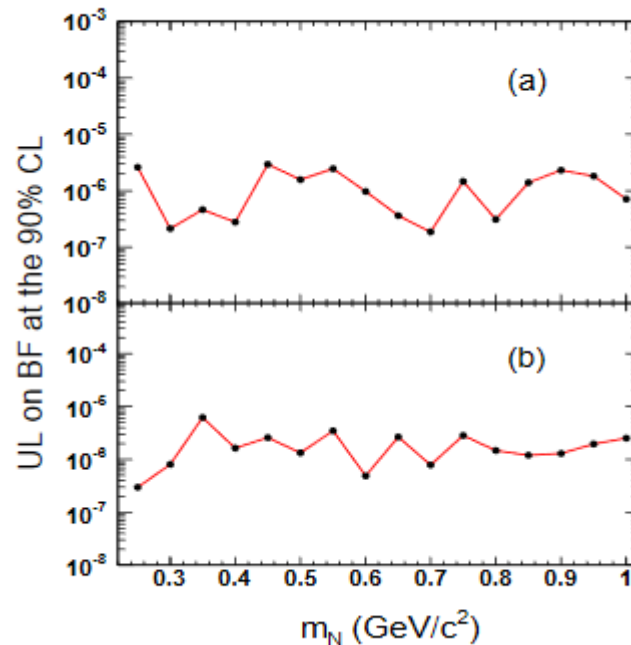
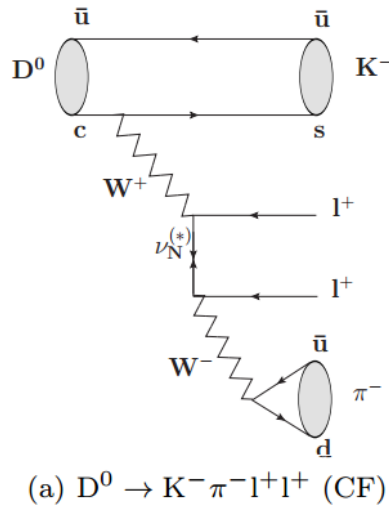
Phys. Rev. D 97, 052005(2018)



Beyond SM

Search for heavy Majorana neutrino in $D \rightarrow K\pi e^+ e^+$

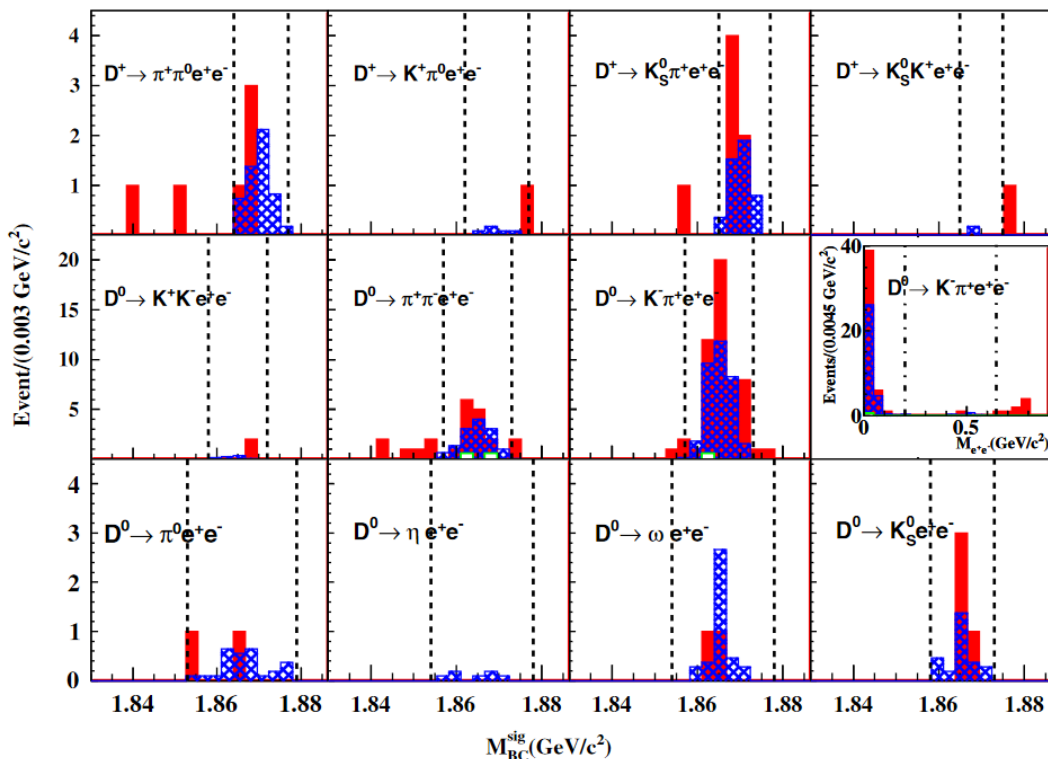
- LNV** process : exchange a single Majorana neutrino



Search for $D \rightarrow h(h')e^+e^-$ decays

- Clean FCNC process to search for NP
- Potential long distance (LD) effects

Phys. Rev. D 97, 072015 (2018)



Signal decays	$\mathcal{B} (\times 10^{-5})$
$D^+ \rightarrow \pi^+ \pi^0 e^+ e^-$	< 1.4
$D^+ \rightarrow K^+ \pi^0 e^+ e^-$	< 1.5
$D^+ \rightarrow K_S^0 \pi^+ e^+ e^-$	< 2.6
$D^+ \rightarrow K_S^0 K^+ e^+ e^-$	< 1.1
$D^0 \rightarrow K^- K^+ e^+ e^-$	< 1.1
$D^0 \rightarrow \pi^+ \pi^- e^+ e^-$	< 0.7
$D^0 \rightarrow K^- \pi^+ e^+ e^-^\dagger$	< 4.1
$D^0 \rightarrow \pi^0 e^+ e^-$	< 0.4
$D^0 \rightarrow \eta e^+ e^-$	< 0.3
$D^0 \rightarrow \omega e^+ e^-$	< 0.6
$D^0 \rightarrow K_S^0 e^+ e^-$	< 1.2
† in $M_{e^+e^-}$ regions:	
$[0.00, 0.20) \text{ GeV}/c^2$	$< 3.0 (1.5^{+1.0}_{-0.9})$
$[0.20, 0.65) \text{ GeV}/c^2$	< 0.7
$[0.65, 0.90) \text{ GeV}/c^2$	$< 1.9 (1.0^{+0.5}_{-0.4})$

Summary

✓ (Semi)-Leptonic decay

- Contribute 28% and 41% to the measurement of V_{cd} and V_{cs}
- Test the Lepton Flavor Universality widely
- Determine the form factor $f_+^{D \rightarrow X}$, ($X = K, \pi, K^* \dots$) precisely

✓ Hadronic decay

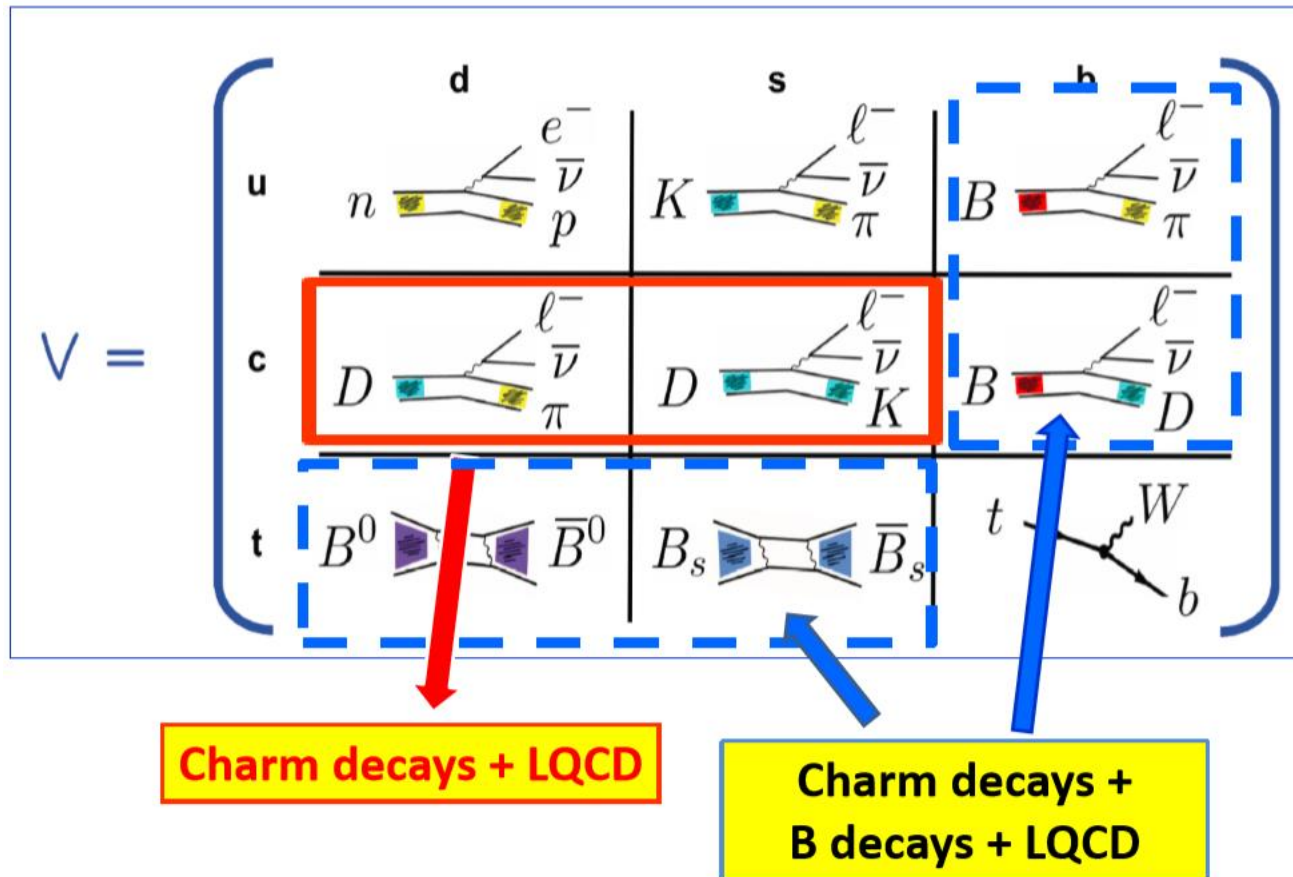
- Improve BF's of two body decay more and more
- Perform PWA for multiple body decay widely

✓ Rare decay

- Searching the FCNC process
- Searching for NP
- Found no NP clue

Thanks for your attention!

Back up



Test Lepton flavor universality via

$$D^{0/+} \rightarrow \pi^{-/0} l^+ \nu_l$$

PhysRevLett.121.171803 (2018)

- SM predict $R = 0.985 \pm 0.002$

$$R^0 = \frac{\Gamma(D^0 \rightarrow \pi \mu^+ \nu_\mu)}{\Gamma(D^0 \rightarrow \pi e^+ \nu_e)}$$

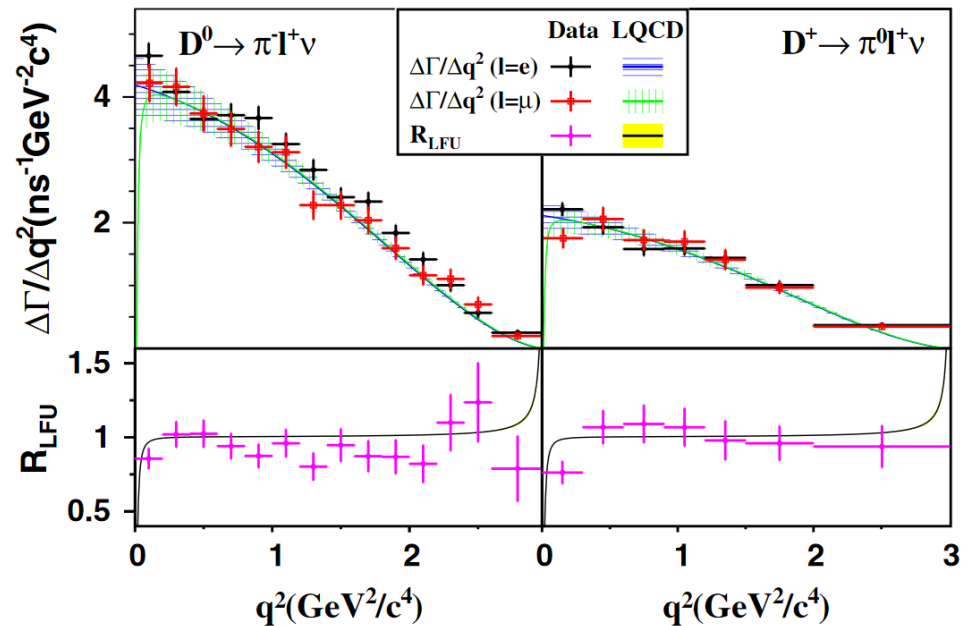
$$= 0.922 \pm 0.030 \pm 0.022$$

$$R^+ = \frac{\Gamma(D^+ \rightarrow \pi \mu^+ \nu_\mu)}{\Gamma(D^+ \rightarrow \pi e^+ \nu_e)}$$

$$= 0.964 \pm 0.037 \pm 0.02$$

Coincide with SM with 1.7σ and 0.5σ

- LQCD prediction is coincided with data very well.

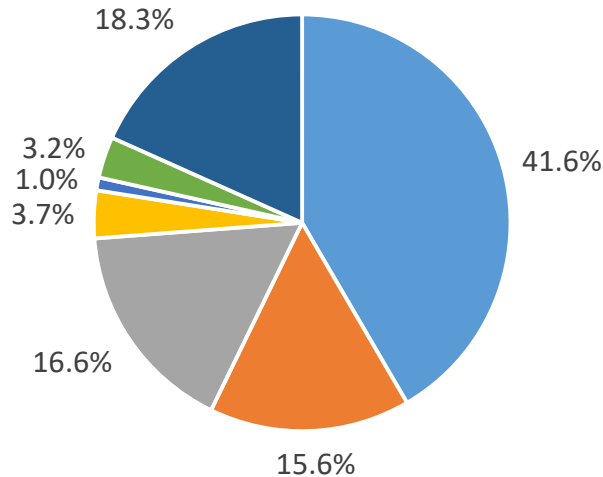


Weights of measurement on $|V_{cs(d)}|$

- BESIII : $D^+ \rightarrow \mu^+ \nu_\mu$
- BESIII : $D^0 \rightarrow \pi^- e^+ \nu_e$
- CLEO-c: $D^+ \rightarrow \mu^+ \nu_\mu$
- CLEO-c: $D^{0/+} \rightarrow \pi^- / 0 e^+ \nu_e$
- BELLE : $D_s^+ \rightarrow \mu^+ \nu_\mu$
- BELLE : $D^0 \rightarrow \pi^- e^+ \nu_e$
- Babbar: $D_s^+ \rightarrow \mu^+ \nu_\mu$
- BELLE: $D_s^+ \rightarrow \tau^+(e^+ \bar{\nu}_\tau, \pi^+ \bar{\nu}_\tau, \mu^+ \bar{\nu}_\tau) \nu_\tau$
- BaBar: $D_s^+ \rightarrow \tau^+(e^+ \bar{\nu}_\tau, \mu^+ \bar{\nu}_\tau) \nu_\tau$
- CLEO-c: $D_s^+ \rightarrow \tau^+(\pi^+ \bar{\nu}_\tau, \rho^+ \bar{\nu}_\tau, e^+ \bar{\nu}_\tau) \nu_\tau$
- CLEO-c/BaBar/BELLE/BESIII: $D^0 \rightarrow K^- \ell^+ \nu$
- BESIII: @4009 $D_s^+ \rightarrow \mu^+ \nu_\mu, D_s^+ \rightarrow \tau^+ \nu_\tau$
- DELPHI: $W^+ \rightarrow c \bar{s}$

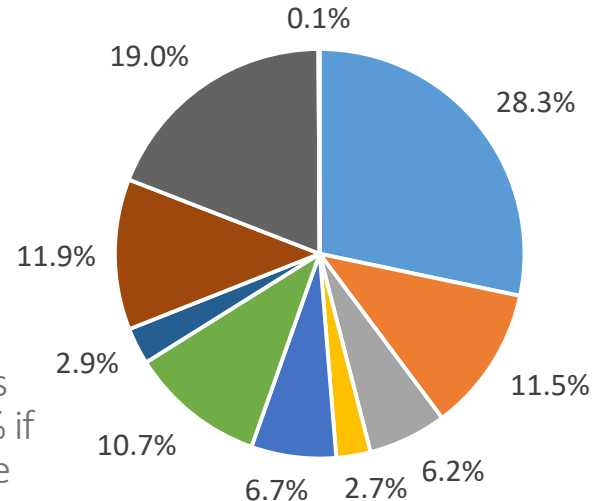
BESIII contributes more than 50%

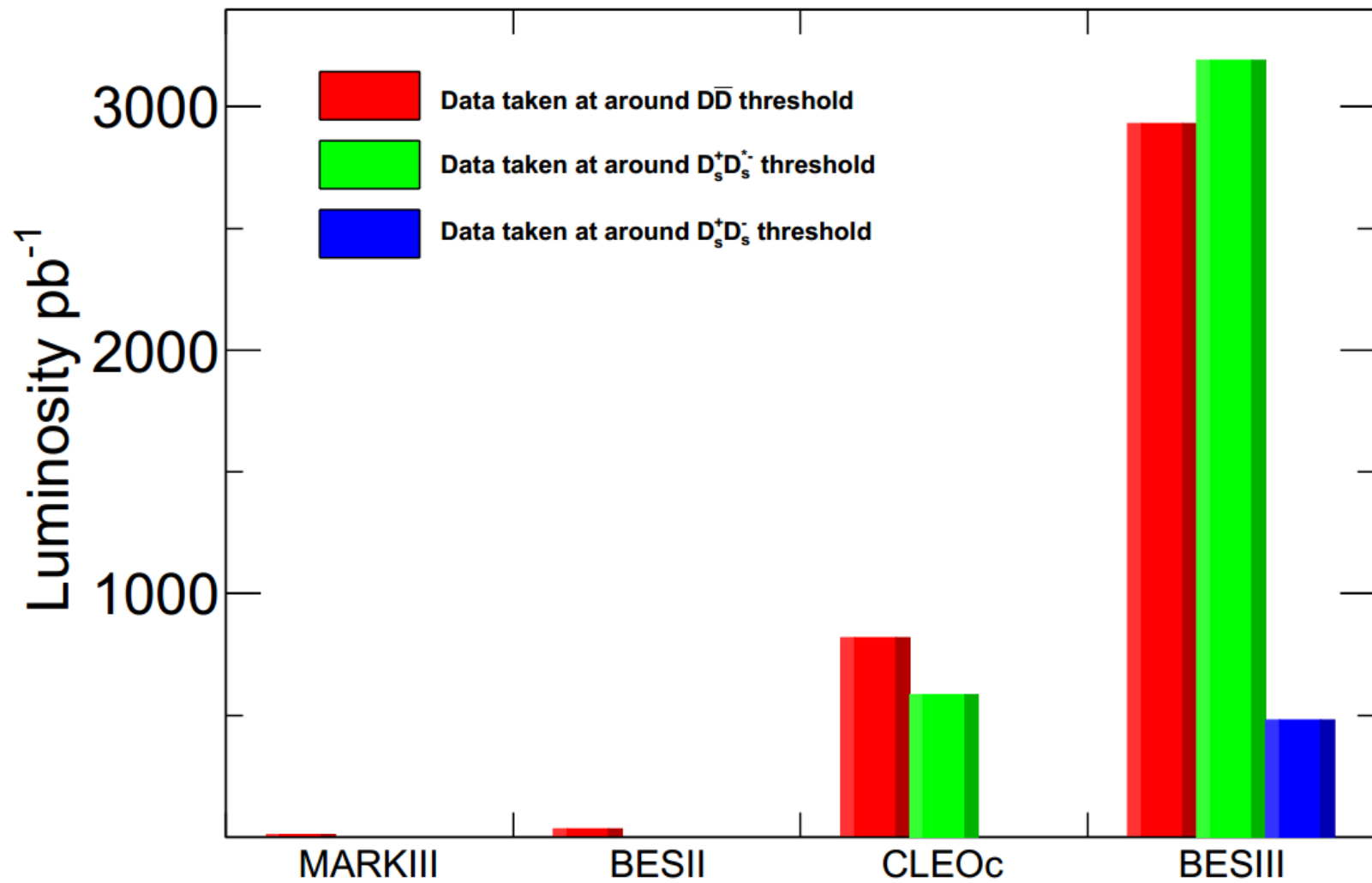
weight on $|V_{cd}|$



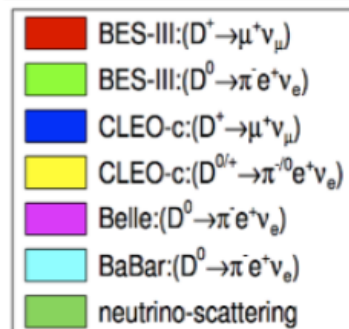
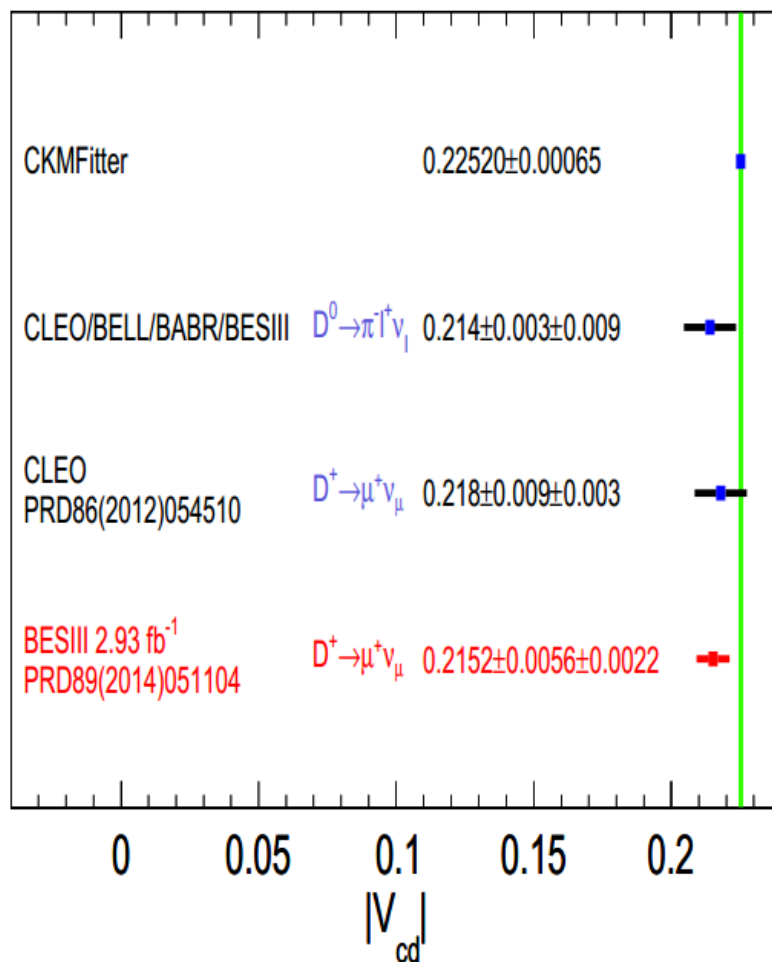
BESIII contributes 28%, reaching 50% if $D_s^+ \rightarrow \tau^+ \nu_\tau$ done

weight on $|V_{cs}|$





Comparison of $|V_{cd}|$



$D \rightarrow \pi e^+ \nu_e$: $|V_{cd}| = 0.214 \pm 0.003 \pm 0.009$ (PDG2016)

$D^+ \rightarrow \mu^+ \nu_\mu$: $|V_{cd}| = 0.219 \pm 0.005 \pm 0.003$ (PDG2016)

ν - $\bar{\nu}$: $|V_{cd}| = 0.230 \pm 0.011$ (PDG2016)

Weight Average: $|V_{cd}| = 0.220 \pm 0.005$ (PDG2016)

