SM Precision Measurements of Charm Decays at BESIII

Vietnam Flavour Physics Conference 2022

Christoph Herold (Suranaree University of Technology, Thailand), August 17, 2022

Beijing Electron-Positron Collider (BEPCII)

- 2020: Upgrade to 2.45 GeV
- 2004: Start of BEPCII upgrade, BESIII construction
- since 2009: BESIII physics run

➡1989 - 2004 (BEPC):

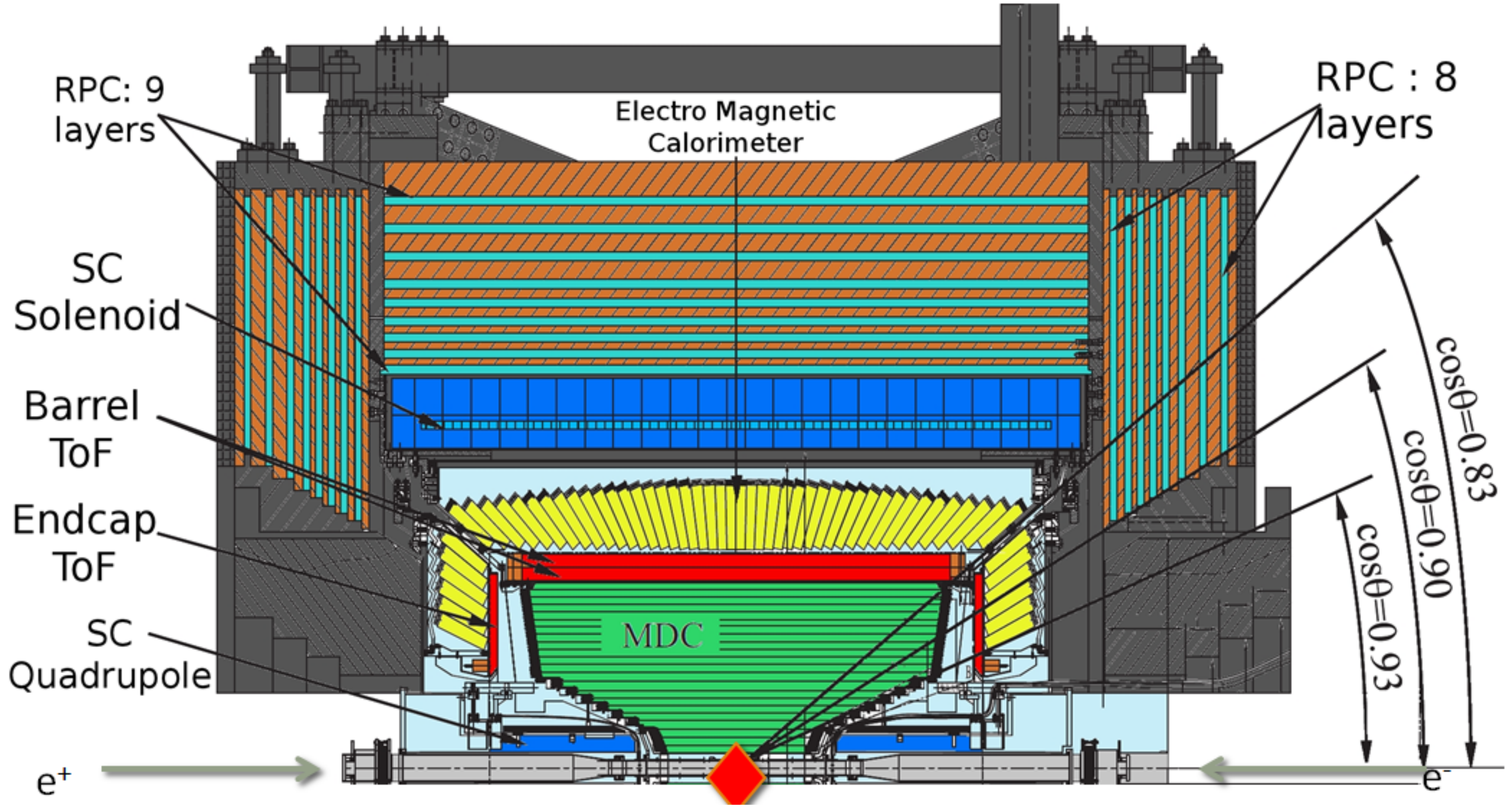
$L_{\mathrm{peak}} = 1.0 \times 10^{31}$/cm^{2}s

➡Since 2009 (BEPCII):

$L_{\mathrm{peak}} = 1.0 \times 10^{33}$/cm^{2}s

Beam energy: 1.0 - 2.3 (2.45) GeV

BESIII Detector



MDC:

- $\sigma_p/p = 0.5\,\%$ @ 1.0 GeV
- $\mathrm{d}E/\mathrm{d}x$ resolution 6%

TOF:

- $\sigma_T = 68$ ps (barrel)
- $\sigma_T = 60$ ps (end caps)

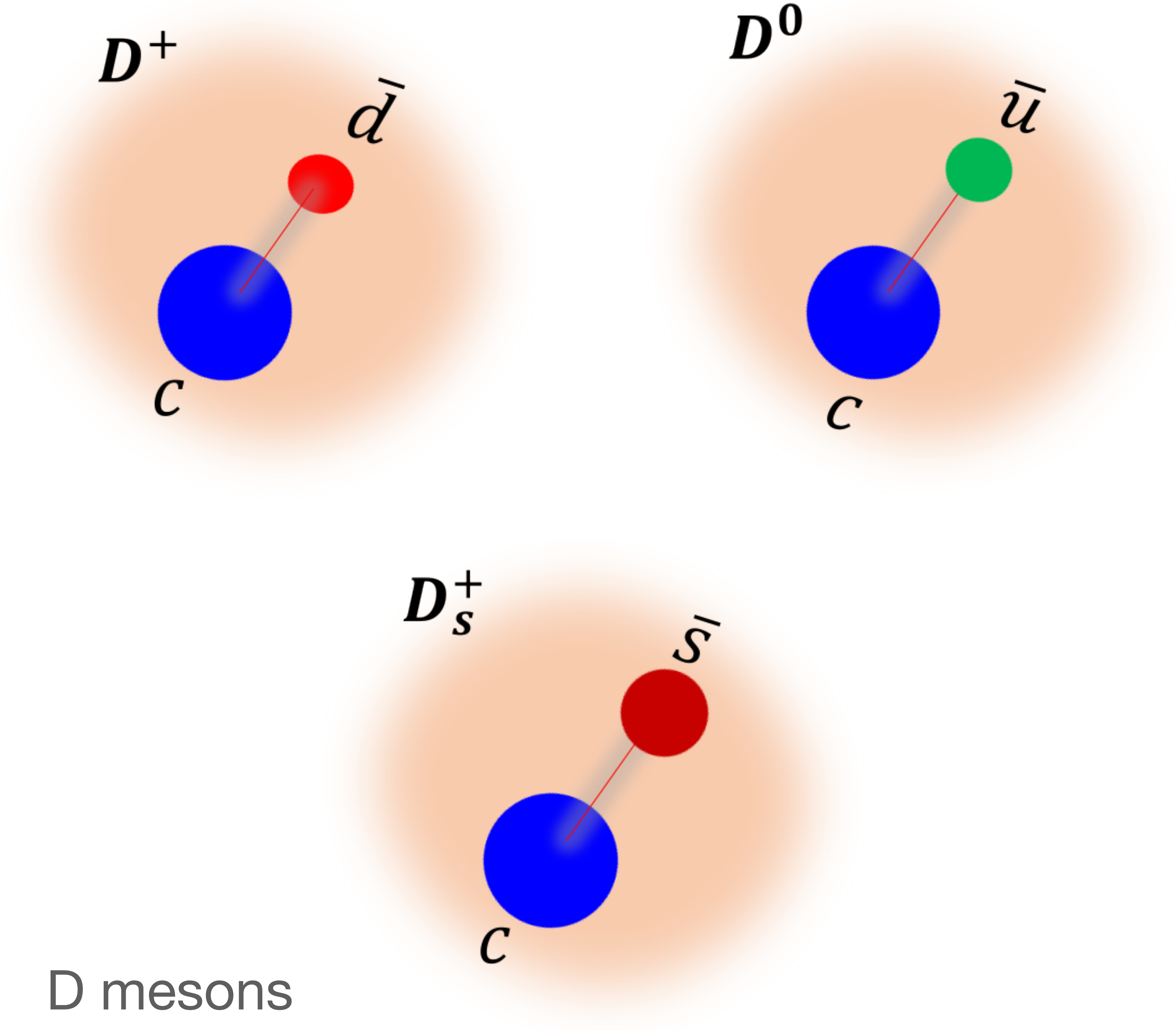
EMC:

- $\Delta E/E = 2.5\,\%$ @ 1.0 GeV (barrel)
- $\Delta E/E = 5.0\,\%$ @ 1.0 GeV (end caps)

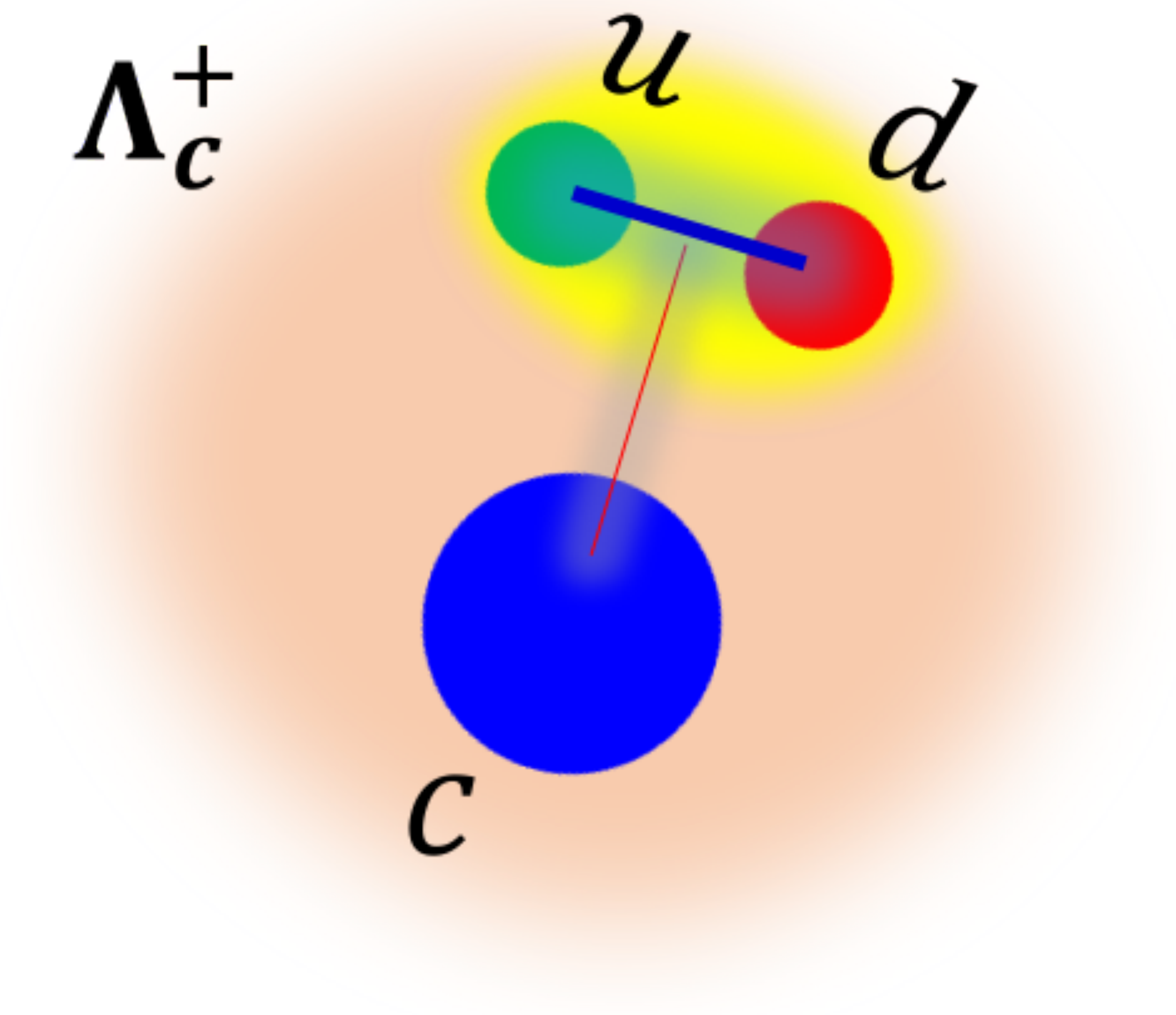
➡ 1.0 T magnetic field (superconducting solenoid)

➡ 93% geometrical acceptance of charged particles and photons

Charmed Hadrons



D mesons



Λ baryon

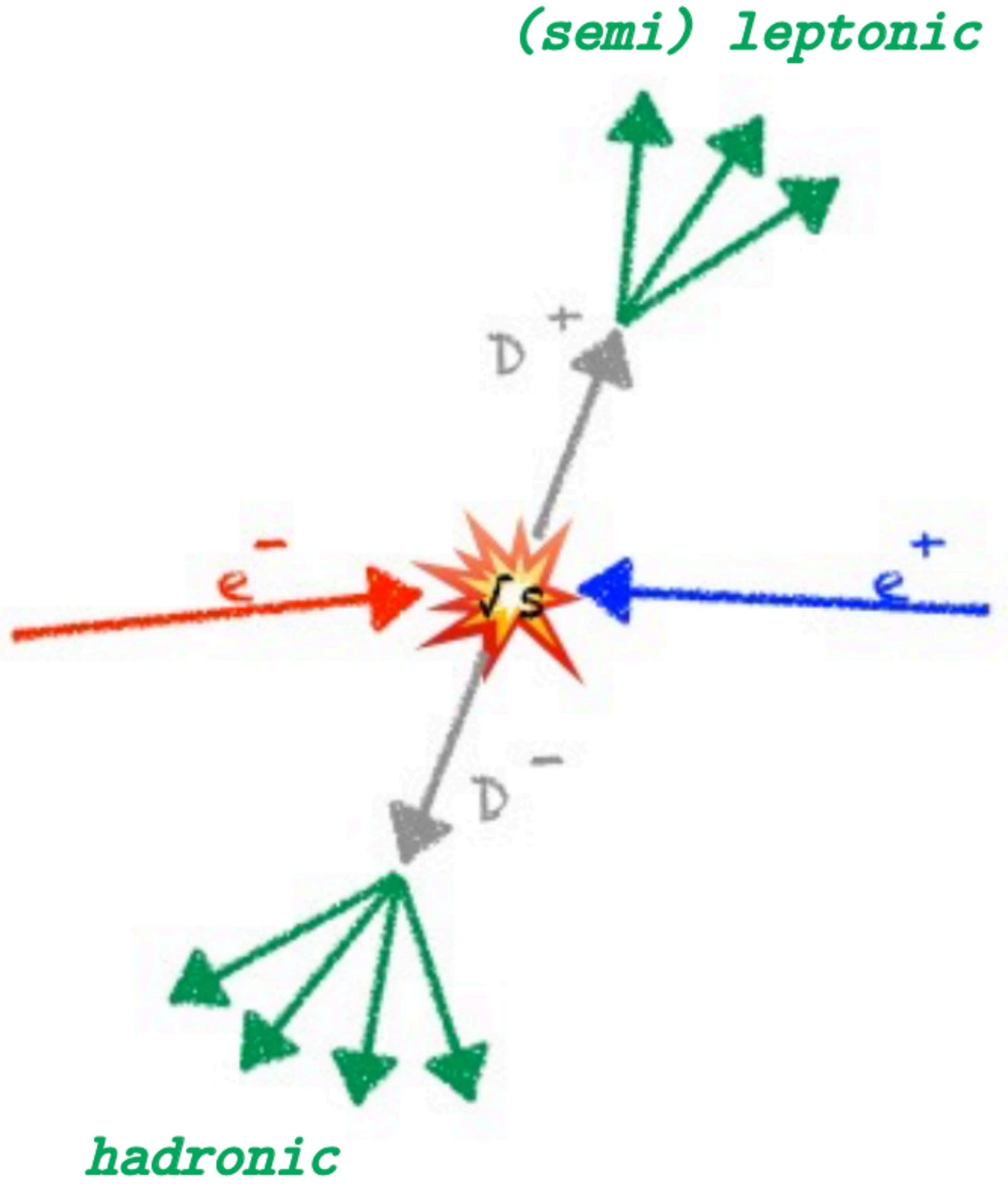
[Figures from Physics 2020; 49: 499–512]

Charmed Hadrons

Near threshold production at BESIII

Advantages of operating near $\psi(3770)$, $\psi(4140)$, $\Lambda_c\bar{\Lambda}_c$ threshold:

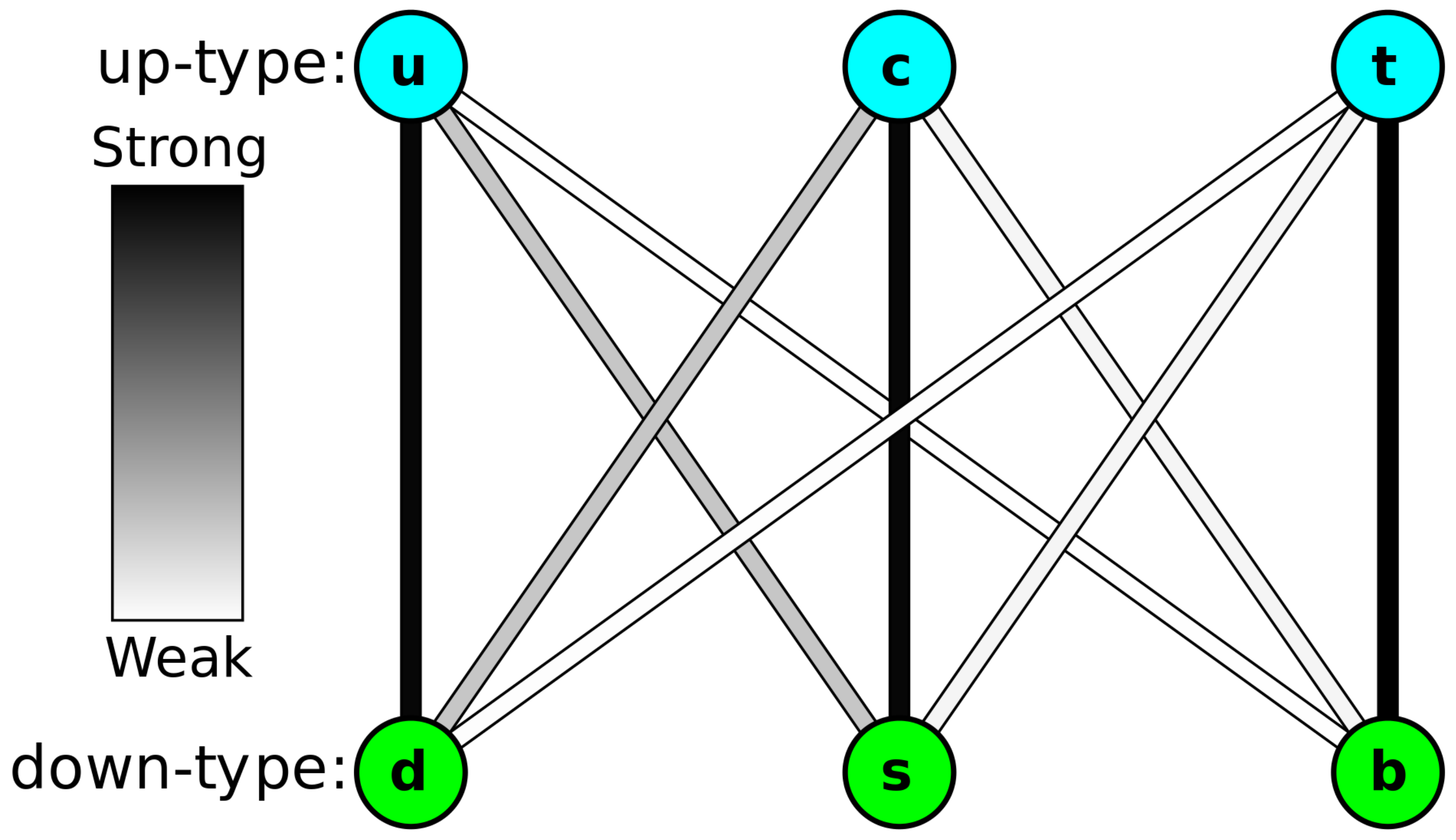
- Relatively high cross section for charm production
- $D\bar{D}$, $\Lambda_c\bar{\Lambda}_c$ produced in exclusive two-body channels
- Double-tag technique [Mark III, PRL 56 (1986)]
- $D\bar{D}$, $\Lambda_c\bar{\Lambda}_c$ in quantum-entangled state (S=1, C=-1)



CKM Matrix

Testing Ground of the Standard Model

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

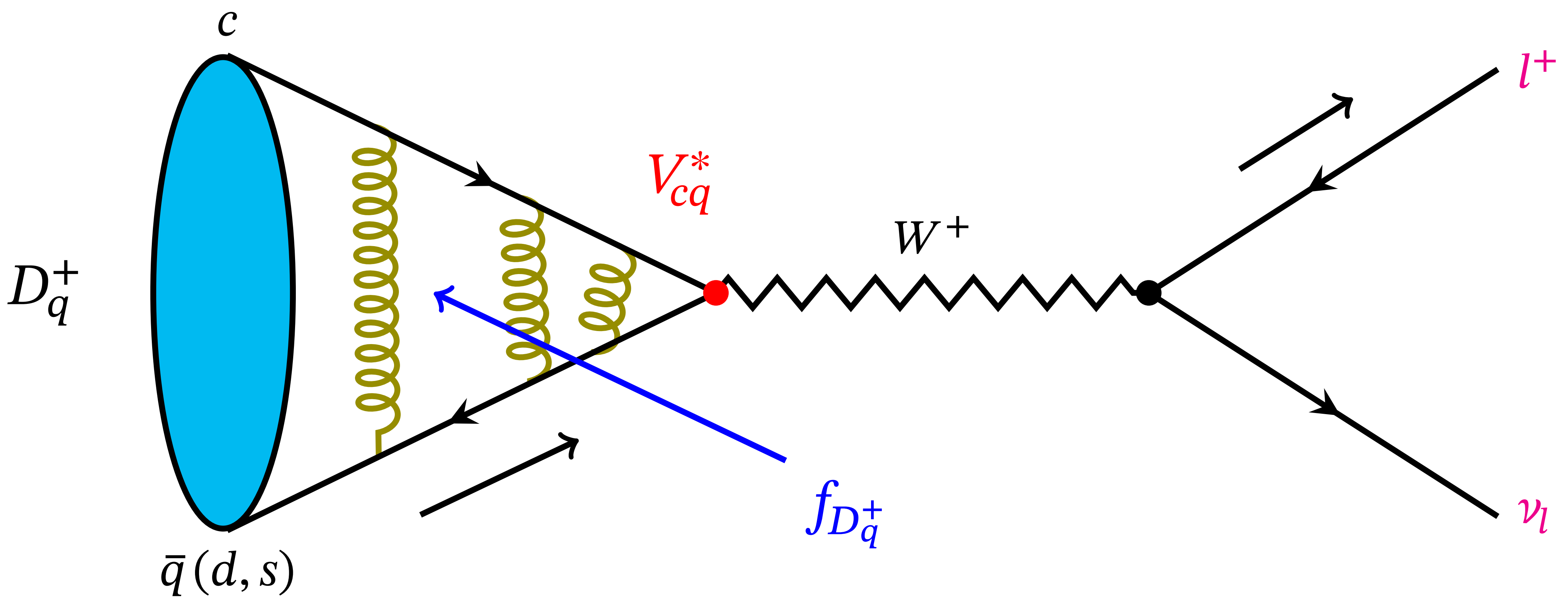


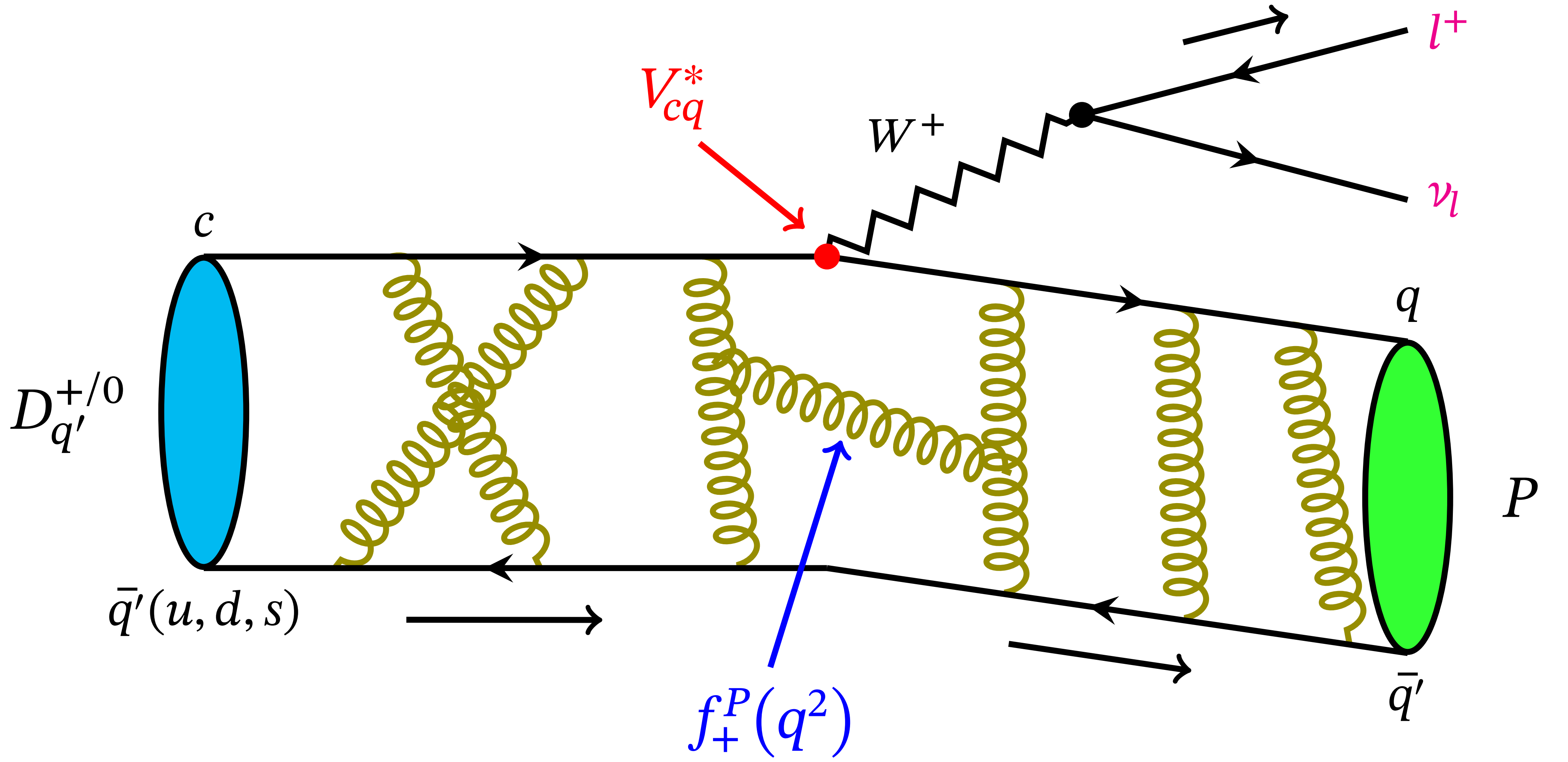
[Figure from wikipedia.org]

- CKM matrix elements are fundamental SM parameters
- Deviation from unitarity: New physics
- At BESIII:

  Precision measurement of $|V_{cd}|, |V_{cs}|$

D-meson decays





Purely leptonic decay

$$\Gamma(D_q^+ \to \ell^+\nu_\ell) = \frac{G_F^2 f_{D_q^+}^2}{8\pi} \mid V_{cq} \mid^2 m_\ell^2 m_{D_q^+} \left(1 - \frac{m_\ell^2}{m_{D_q^+}^2}\right)^2$$

Decay constant $f_{D_q^+}^2$

Semi-leptonic decay

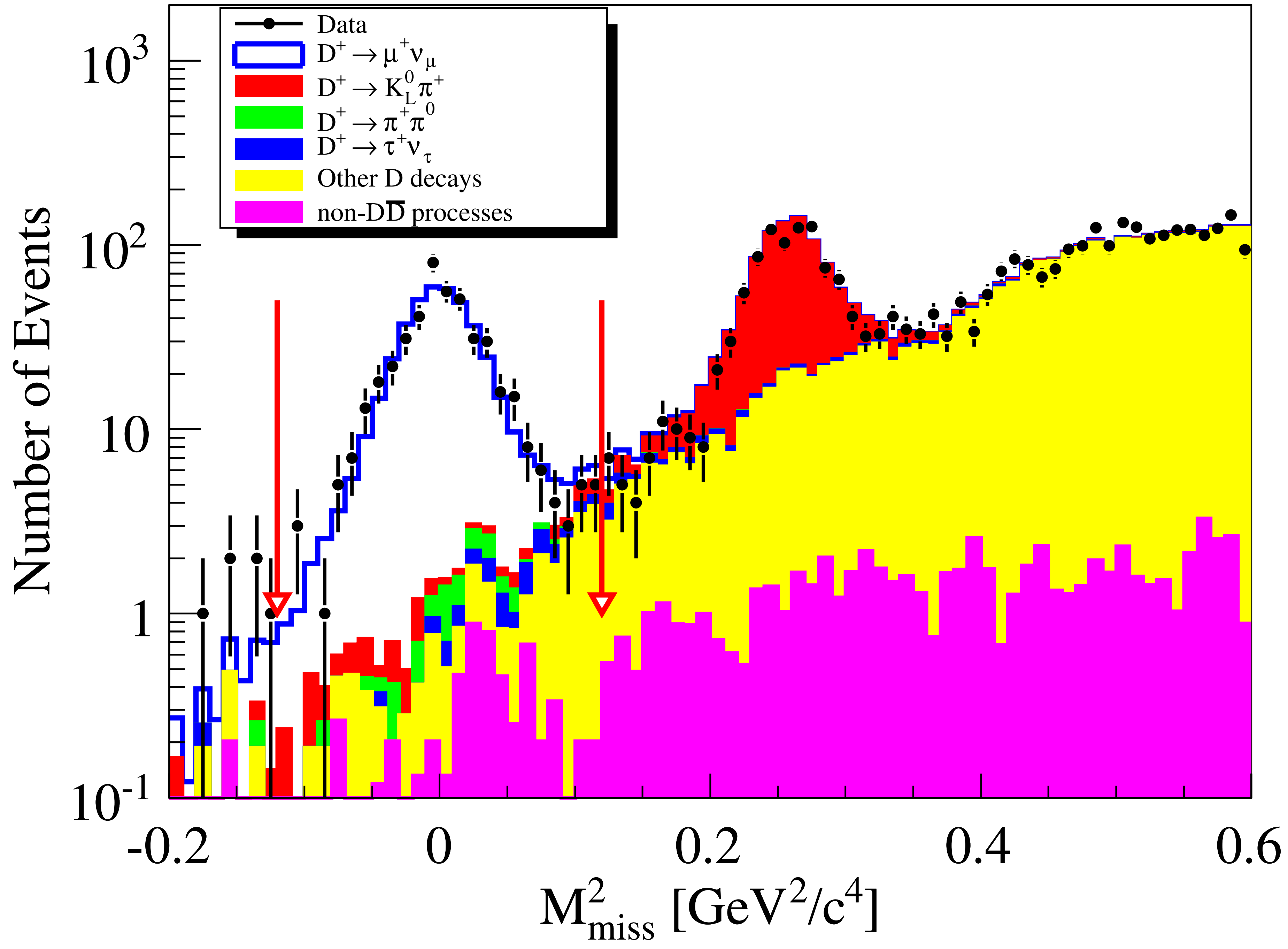
$$\frac{\mathrm{d}\Gamma(D^{0/+} \to P\ell^+\nu_\ell)}{\mathrm{d}q^2} = \frac{G_F^2 \mid V_{cq} \mid^2}{24\pi^3} p_P^3 \mid f_+^P(q^2) \mid^2$$

Form factor $f_+^P(0)$

Test for lepton flavor universality

[Figures by Hao-Kai Sun, Institute of High Energy Physics, Chinese Academy of Sciences]

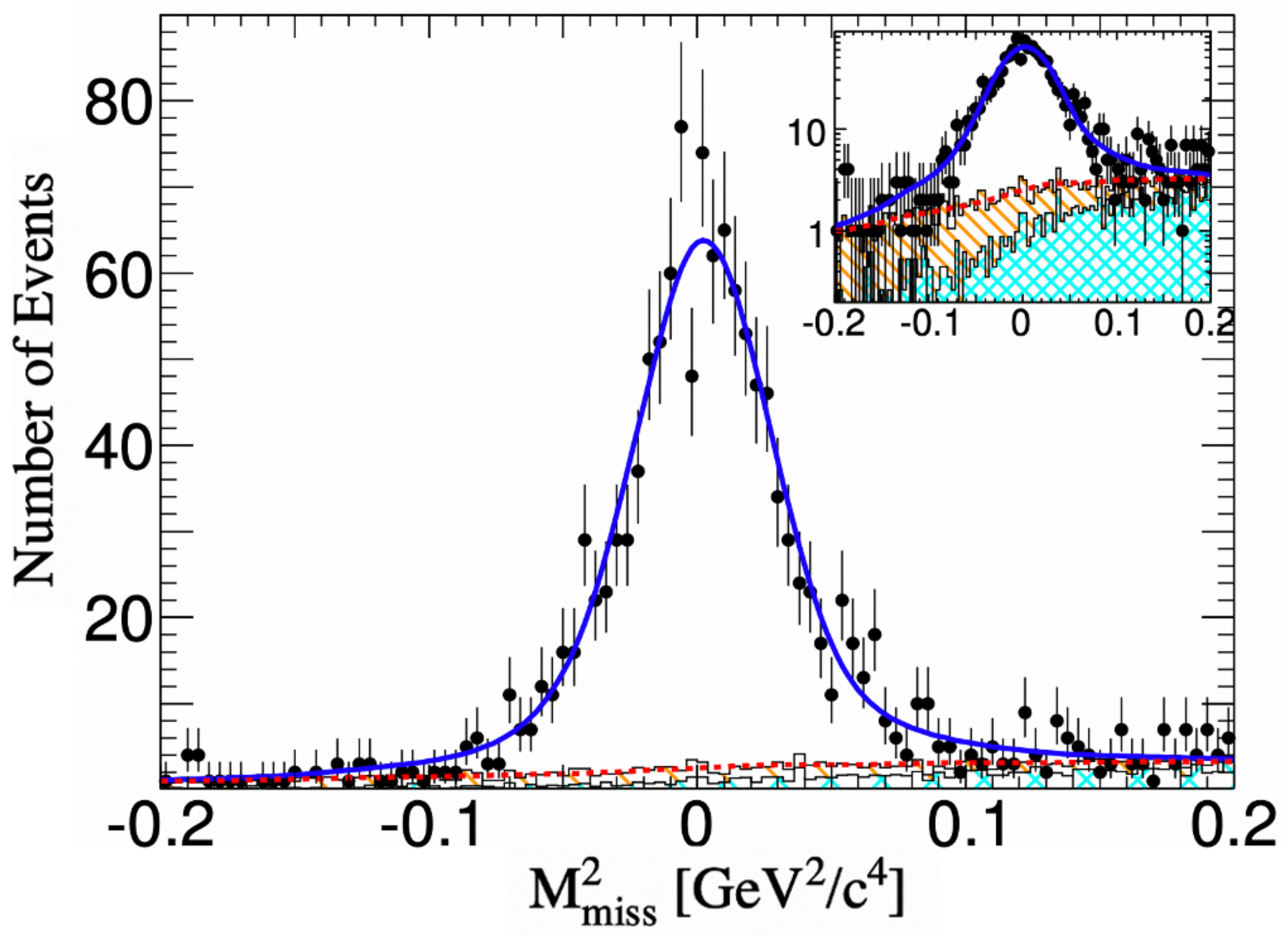
Decay channel $D_{(s)}^+ \to \mu^+ \nu_\mu$



$$\mathscr{B}(D^+ \to \mu^+ \nu_\mu) = (3.71 \pm 0.19_{\text{stat}} \pm 0.06_{\text{sys}}) \times 10^{-4}$$

$$f_{D^+} |V_{cd}| = (45.75 \pm 1.20_{\text{stat}} \pm 0.39_{\text{sys}}) \text{ MeV}$$

[Phys Rev D 89 (2014); 051104]

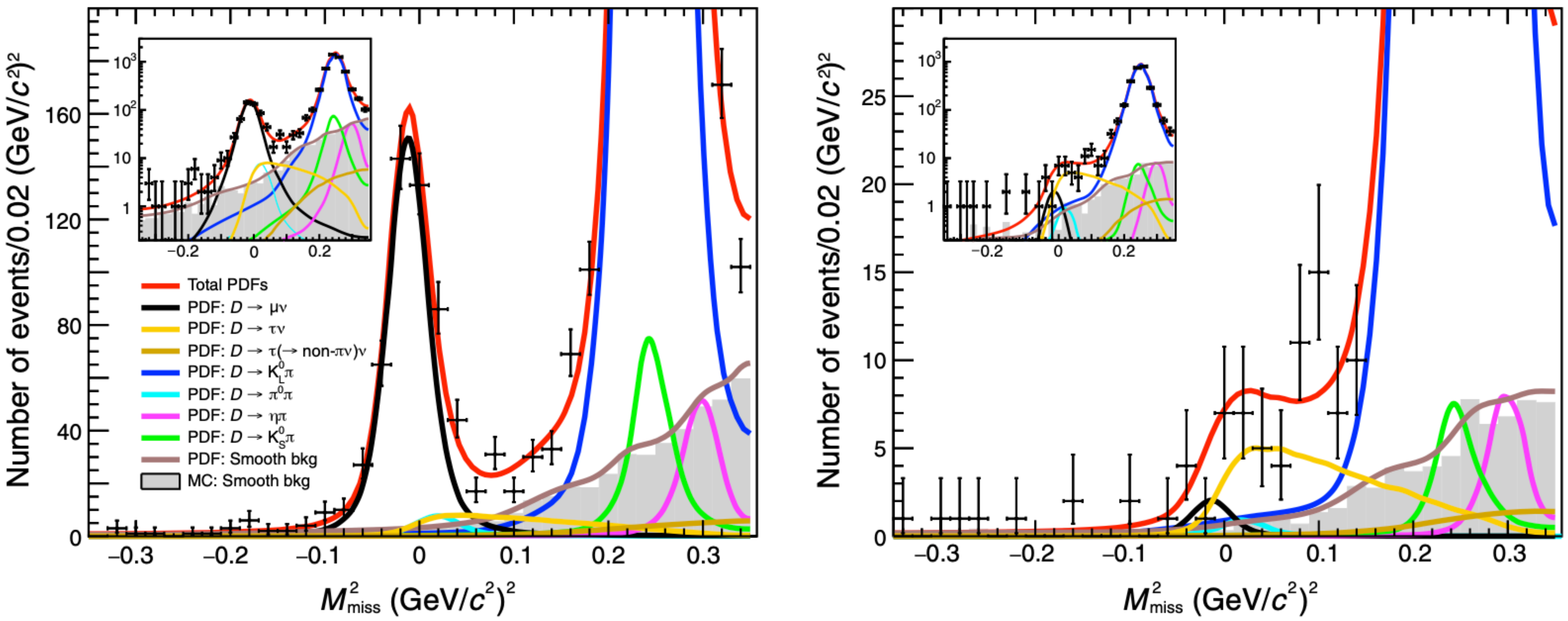


$$\mathscr{B}(D_s^+ \to \mu^+ \nu_\mu) = (5.49 \pm 0.16_{\text{stat}} \pm 0.15_{\text{sys}}) \times 10^{-3}$$

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

[PRL 122 (2019); 071802]

Decay channel $D^+ \to \tau^+\nu_\tau$



$$\mathscr{B}(D^+ \to \tau^+\nu_\tau) = (1.20 \pm 0.24_{\text{stat}} \pm 0.12_{\text{sys}}) \times 10^{-4}$$

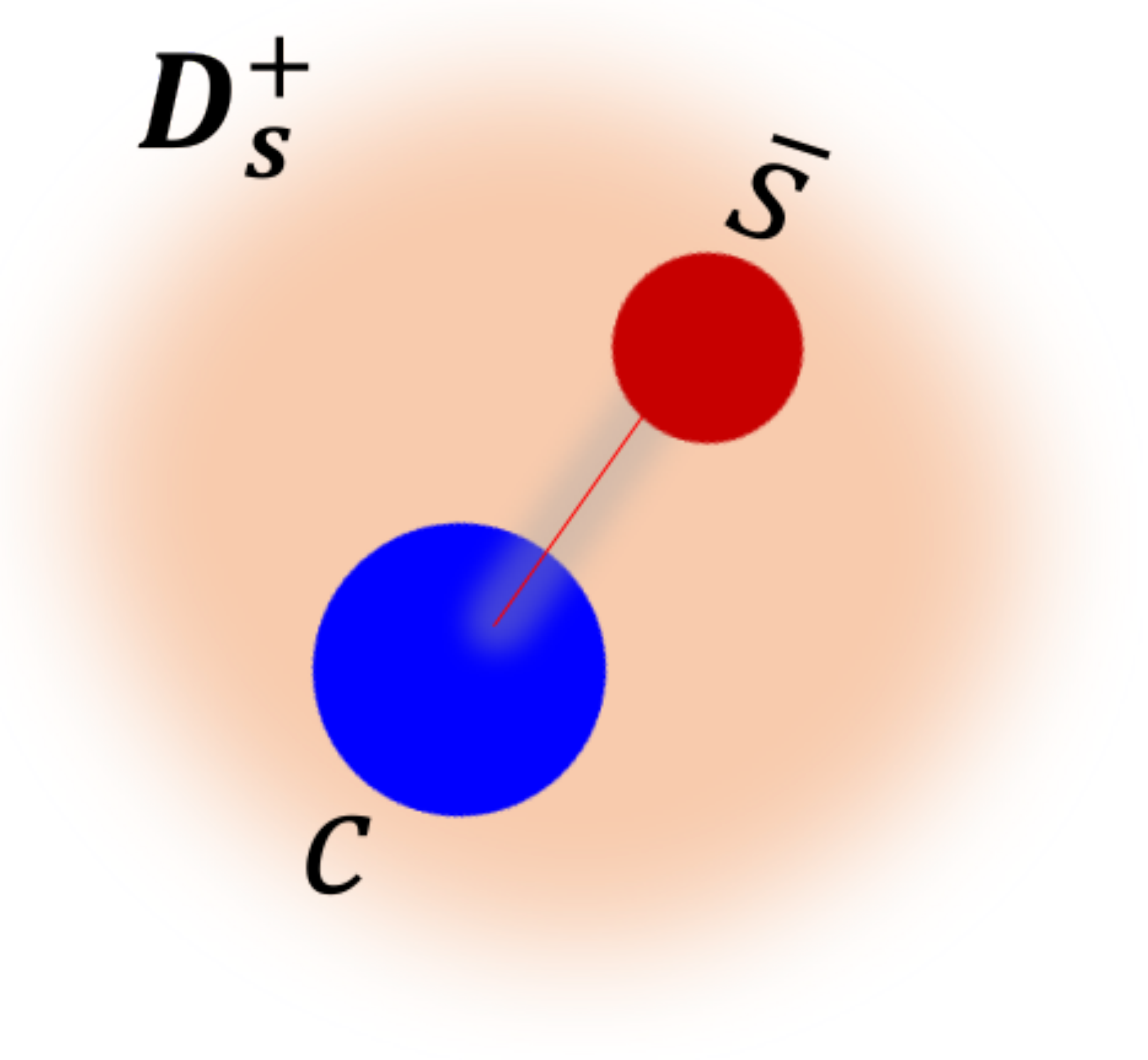
$$R^{D^+}_{\tau/\mu} = \frac{\Gamma(D^+ \to \tau\nu_\tau)}{\Gamma(D^+ \to \mu\nu_\mu)} = 3.21 \pm 0.64_{\text{stat}} \pm 0.43_{\text{sys}}$$

SM:

$$R^{D^+}_{\tau/\mu} = 2.67$$

[PRL 123 (2019); 211802]

Purely leptonic decays of D_s^+



PRD 104 (2021); 052009, $D_s^+ \to \tau\nu_\tau$, $\tau \to \pi\nu$

PRD 104 (2021); 032001, $D_s^+ \to \tau\nu_\tau$, $\tau \to \rho\nu$

PRL 127 (2021); 171801, $D_s^+ \to \tau\nu_\tau$, $\tau \to e\nu\nu$

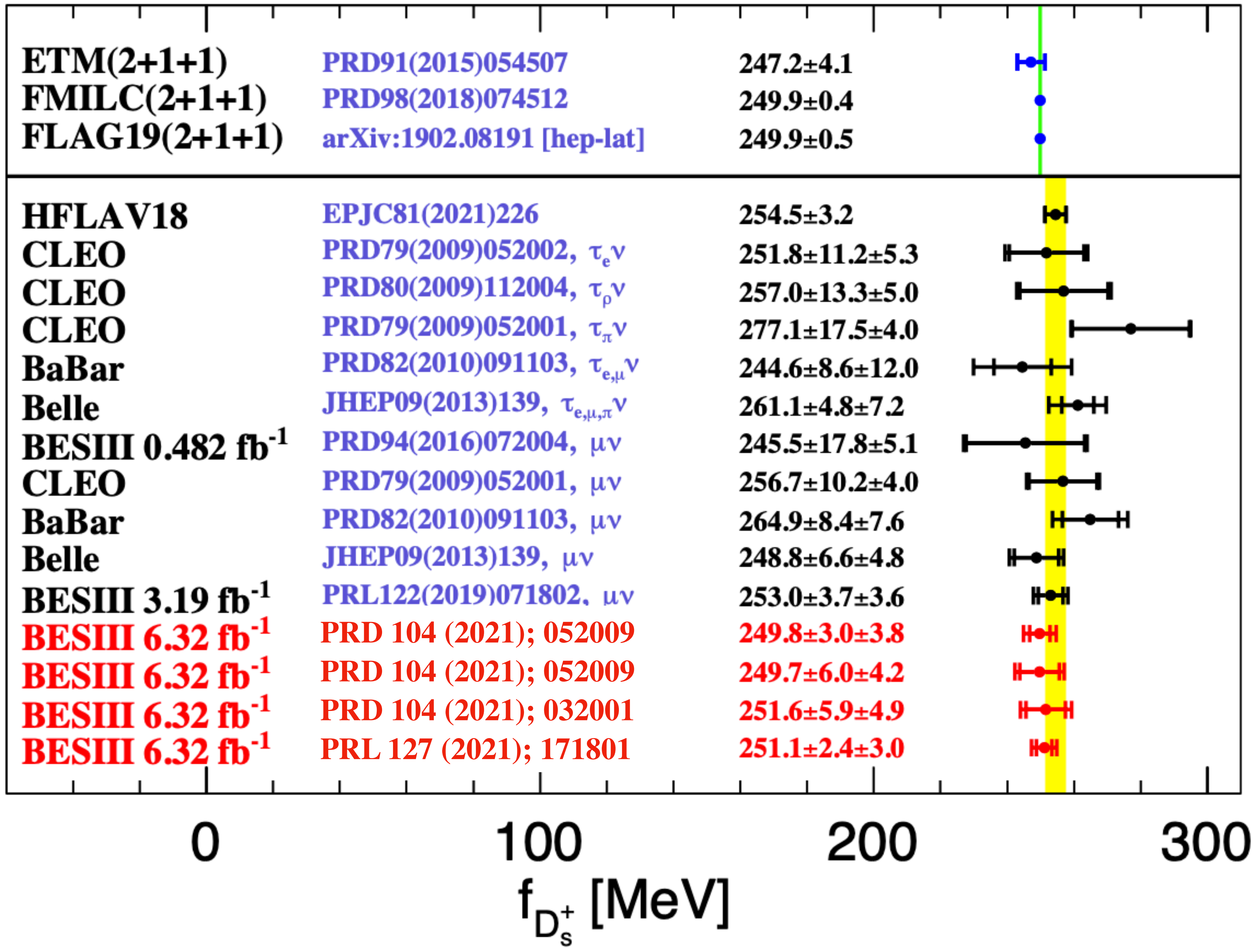
$$R_{\tau/\mu}^{D_s^+} = \frac{\Gamma(D_s^+ \to \tau\nu_\tau)}{\Gamma(D_s^+ \to \mu\nu_\mu)} = 9.67 \pm 0.34$$

SM:

$$R_{\tau/\mu}^{D_s^+} = 9.75 \pm 0.01$$

[PoS EPS-HEP2021 (2022) 543]

Purely leptonic decays of D_s^+



Decay constant $f_{D_s^+}$

From global SM fit:

$$|V_{cs}| = 0.97320 \pm 0.00011$$

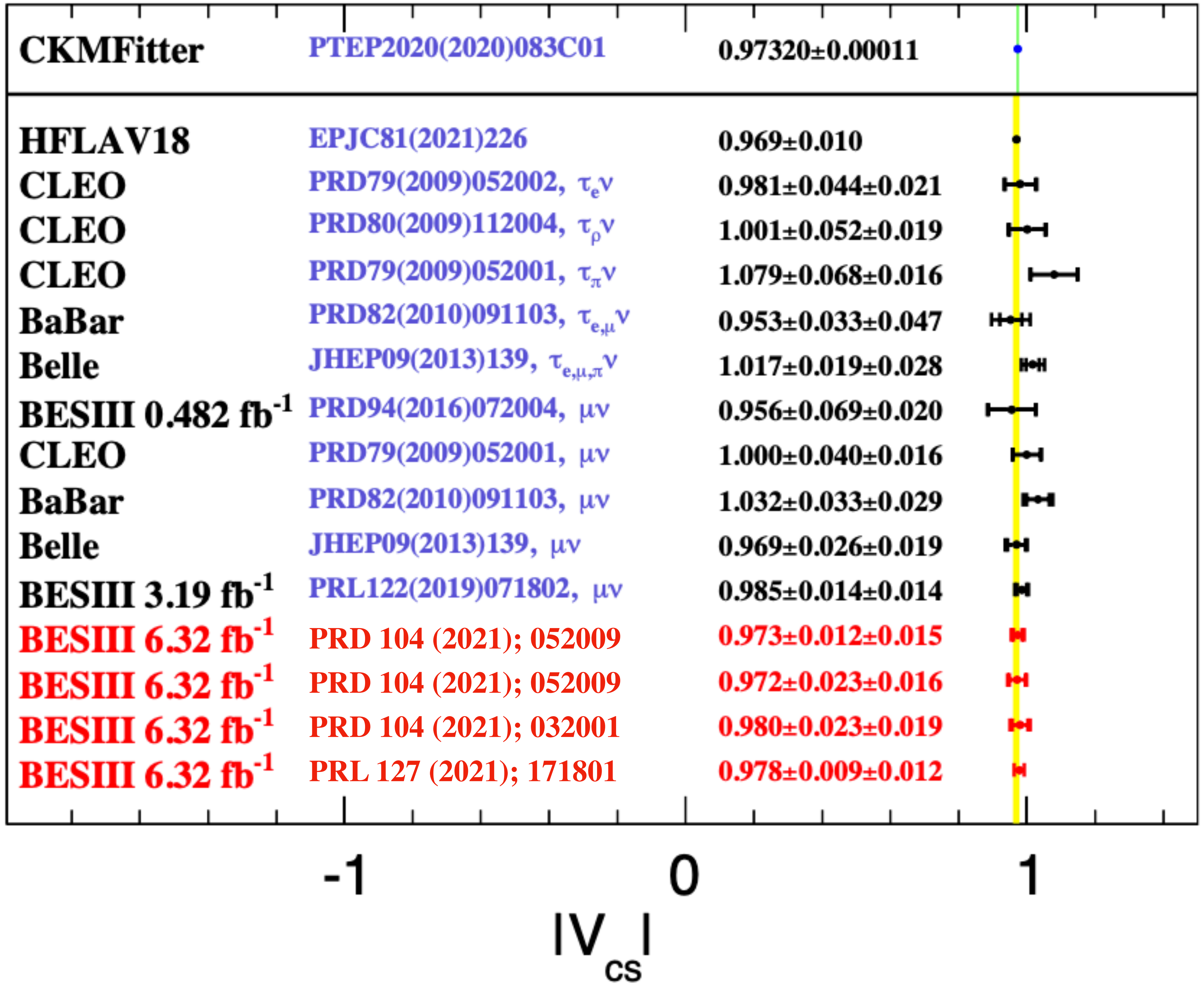
[Prog. Theor. Exp. Phys. 2020, 083C01 (2020)]

Our combined result:

$$f_{D_s^+} = (251.4 \pm 1.8_{\text{stat}} \pm 2.2_{\text{sys}})\ \text{MeV}$$

[PoS EPS-HEP2021 (2022) 543 Mar 4, 2022]

Purely leptonic decays of D_s^+



CKM matrix element $|V_{cs}|$

From LQCD:

$$f_{D_s^+} = 249.9 \pm 0.5 \text{ MeV}$$

[Eur. Phys. J. C 80, 113 (2020)]

Our combined result:

$$|V_{cs}| = 0.979 \pm 0.007_{\text{stat}} \pm 0.008_{\text{sys}}$$

[PoS EPS-HEP2021 (2022) 543]

Semi-leptonic decays

Recent highlights

- $D^0 \to \rho^- \mu^+ \nu_\mu$, first measurement [Phys. Rev. D 104 (2021), 091103]
- $\dfrac{\mathscr{B}(D^0 \to \rho^- \mu^+ \nu_\mu)}{\mathscr{B}(D^0 \to \rho^- e^+ \nu_e)} = 0.90 \pm 0.11$ [Phys.Rev.Lett. 122 (2019) 6, 062001]

SM:

$0.93 - 0.96$

- $\mathscr{B}(D_s^+ \to (f_0(980) \to \pi^0\pi^0)e^+\nu_e) = (7.9 \pm 1.4_{\mathrm{stat}} \pm 0.4_{\mathrm{sys}}) \times 10^{-4}$
- $\mathscr{B}(D_s^+ \to (\sigma \to \pi^0\pi^0)e^+\nu_e) < 7.3 \times 10^{-4}$ at 90% C.L.
- $\mathscr{B}(D_s^+ \to K_s K_s e^+\nu_e) < 7.3 \times 10^{-4}$ at 90% C.L.

[Phys. Rev. D 105 (2022), L03110]

Transition Form Factors

$D^0 \to K^- l^+ \nu_l, \pi^- l^+ \nu_l$
$D^+ \to K^0 l^+ \nu_l, \pi^0 l^+ \nu_l$

[Phys Rev D 2015; 92: 072012, Phys Rev D 2017; 96: 012002]

$\frac{f_0^\pi}{f_0^K} = 0.865 \pm 0.013$, compatible with LQCD

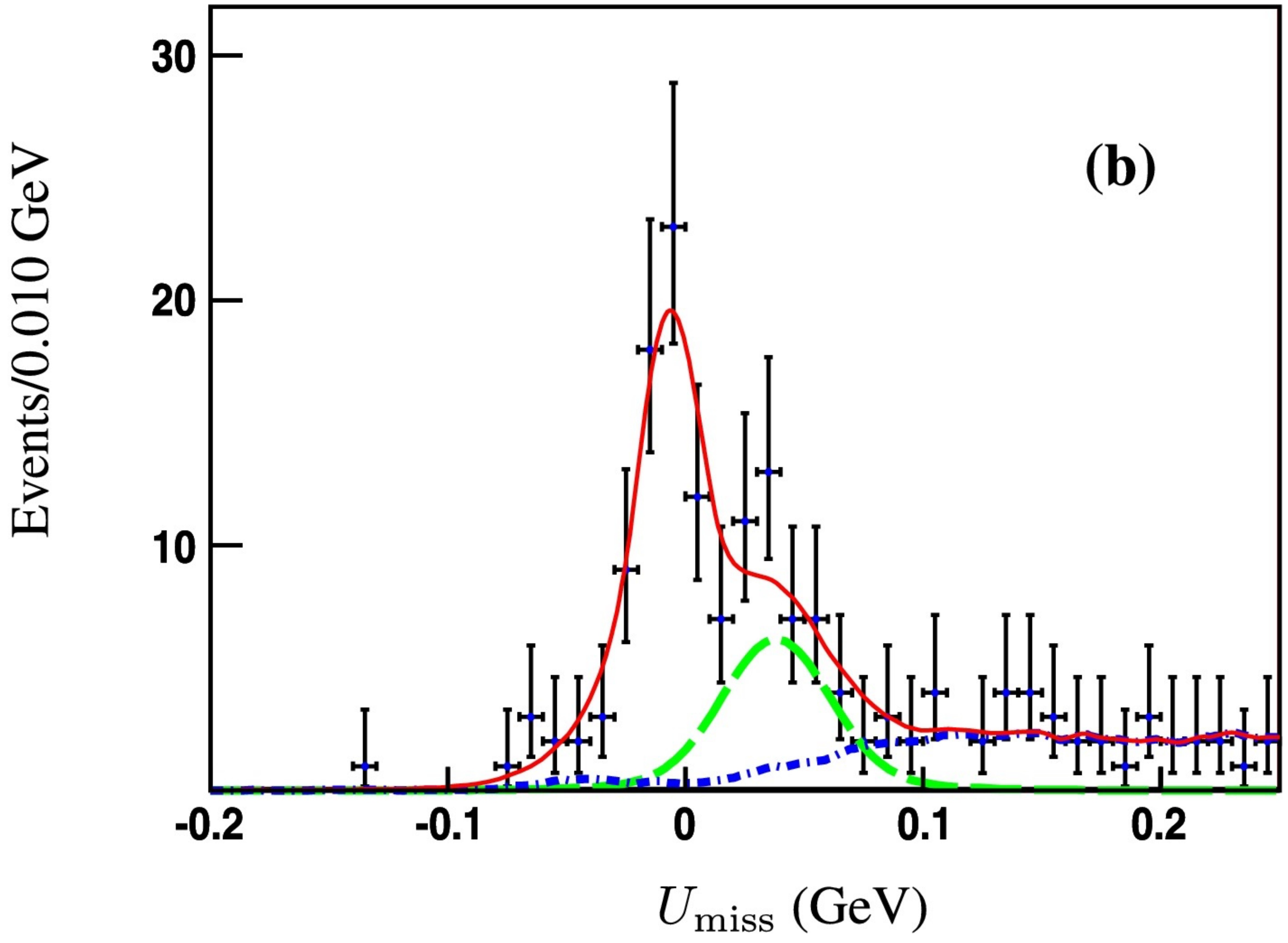
[Eur Phys J C 2020; 80: 113]

Observable	Measurement	Prediction/fit
$\mathcal{B}(D^0 \to K^- e^+ \nu_e)$	$(3.505 \pm 0.014_{stat} \pm 0.033_{syst})\%$ [30]	–
$\|V_{cs}\| f_+^K(0)$	$0.7172 \pm 0.0025_{stat} \pm 0.0035_{syst}$ [30]	–
$f_+^K(0)$	$0.7368 \pm 0.0026_{stat} \pm 0.0036_{syst}$ [30]	$0.747 \pm 0.011 \pm 0.015$ [28]
$\mathcal{B}(D^0 \to \pi^- e^+ \nu_e)$	$(0.295 \pm 0.004_{stat} \pm 0.003_{syst})\%$ [30]	–
$\|V_{cd}\| f_+^\pi(0)$	$0.1435 \pm 0.0018_{stat} \pm 0.0009_{syst}$ [30]	–
$f_+^\pi(0)$	$0.6372 \pm 0.0080_{stat} \pm 0.0044_{syst}$ [30]	$0.66 \pm 0.02 \pm 0.02$ [28]
$\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e)$	$(8.60 \pm 0.06_{stat} \pm 0.15_{syst})\%$ [31]	–
$f_+^K(0)$	$0.725 \pm 0.004_{stat} \pm 0.012_{syst}$ [31]	$0.747 \pm 0.011 \pm 0.015$ [28]
$\mathcal{B}(D^+ \to \pi^0 e^+ \nu_e)$	$(0.363 \pm 0.008_{stat} \pm 0.005_{syst})\%$ [31]	–
$f_+^\pi(0)$	$0.622 \pm 0.012_{stat} \pm 0.003_{syst}$ [31]	$0.66 \pm 0.02 \pm 0.02$ [28]
$f_+^\pi(0)/f_+^K(0)$	0.865 ± 0.013 [31]	0.84 ± 0.04 [32]
$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$	$(3.63 \pm 0.38_{stat} \pm 0.20_{syst})\%$ [33]	–
$\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu)$	$(3.49 \pm 0.46_{stat} \pm 0.27_{syst})\%$ [34]	–
$\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu)/\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$	$0.96 \pm 0.16_{stat} \pm 0.04_{syst}$ [34]	≈ 1.0

[28] Eur Phys J C 2020; 80: 113
[30] Phys Rev D 2015; 92: 072012
[31] Phys Rev D 2017; 96: 012002
[32] Phys Lett B 2006; 641: 50–6
[33] Phys Rev Lett 2015; 115: 221805
[34] Phys Lett B 2017; 767: 42–7

Λ_c^+ decay

First direct measurement of muonic decay



Decay $\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$

$$\mathscr{B}(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu) = (3.49 \pm 0.46_{\text{stat}} \pm 0.27_{\text{sys}}) \times 10^{-2}$$

$$\frac{\mathscr{B}(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu)}{\mathscr{B}(\Lambda_c^+ \to \Lambda e^+\nu_e)} = 0.96 \pm 0.16_{\text{stat}} \pm 0.04_{\text{syst}}$$

Consistent with lepton flavor universality

[Physics Letters B 767 (2017); 42-47]

Λ_c^+ hadronic decays

Decay channel	BESIII (%)	Previous world averages (%) [78]
Two-body CF		
pK_S^0	$1.52 \pm 0.08 \pm 0.03$ [76]	1.15 ± 0.30
$\Lambda\pi^+$	$1.24 \pm 0.07 \pm 0.03$ [76]	1.07 ± 0.28
$\Sigma^0\pi^+$	$1.27 \pm 0.08 \pm 0.03$ [76]	1.05 ± 0.28
$\Sigma^+\pi^0$	$1.18 \pm 0.10 \pm 0.03$ [76]	1.00 ± 0.34
$\Sigma^+\omega$	$1.56 \pm 0.20 \pm 0.07$ [76]	2.7 ± 1.0
Ξ^0K^+	$0.590 \pm 0.086 \pm 0.039$ [81]	0.50 ± 0.12
$\Xi(1530)^0K^+$	$0.502 \pm 0.099 \pm 0.031$ [81]	0.4 ± 0.1
$\Sigma^+\eta$	$0.41 \pm 0.19 \pm 0.05$ [82]	0.70 ± 0.23
$\Sigma^+\eta'$	$1.34 \pm 0.53 \pm 0.19$ [82]	First evidence
$\Sigma(1385)^+\eta$	$0.91 \pm 0.18 \pm 0.09$ [83]	1.22 ± 0.37
Neutron-involved		
$nK_S^0\pi^+$	$1.82 \pm 0.23 \pm 0.11$ [84]	First observation
$\Sigma^-\pi^+\pi^+$	$1.81 \pm 0.17 \pm 0.09$ [85]	2.1 ± 0.4
$\Sigma^-\pi^+\pi^+\pi^0$	$2.11 \pm 0.33 \pm 0.14$ [85]	First observation
SCS		
$p\phi$	$0.106 \pm 0.019 \pm 0.014$ [86]	0.082 ± 0.027
$p\eta$	$0.124 \pm 0.028 \pm 0.010$ [87]	First evidence
$p\pi^0$	< 0.027at90%˜C.L. [87]	First measurement
$p\pi^+\pi^-$	$0.391 \pm 0.028 \pm 0.039$ [86]	0.35 ± 0.2
pK^+K^- (non-ϕ)	$0.0547 \pm 0.0130 \pm 0.0074$ [86]	0.035 ± 0.017

[76] Phys Rev Lett 2016; 116: 052001

[81] Phys Lett B 2018; 783: 200–6

[82] Chin Phys C 2019; 43: 083002

[83] Phys Rev D 2019; 99: 032010

[84] Phys Rev Lett 2017; 118: 112001

[85] Phys Lett B 2017; 772: 388–93

[86] Phys Rev Lett 2016; 117: 232002

[87] Phys Rev D 2017; 95: 111102

Λ_c^+ decay

Singly Cabibbo Suppressed Decay to $n\pi^+$

Decay $\Lambda_c^+ \to n\pi^+$

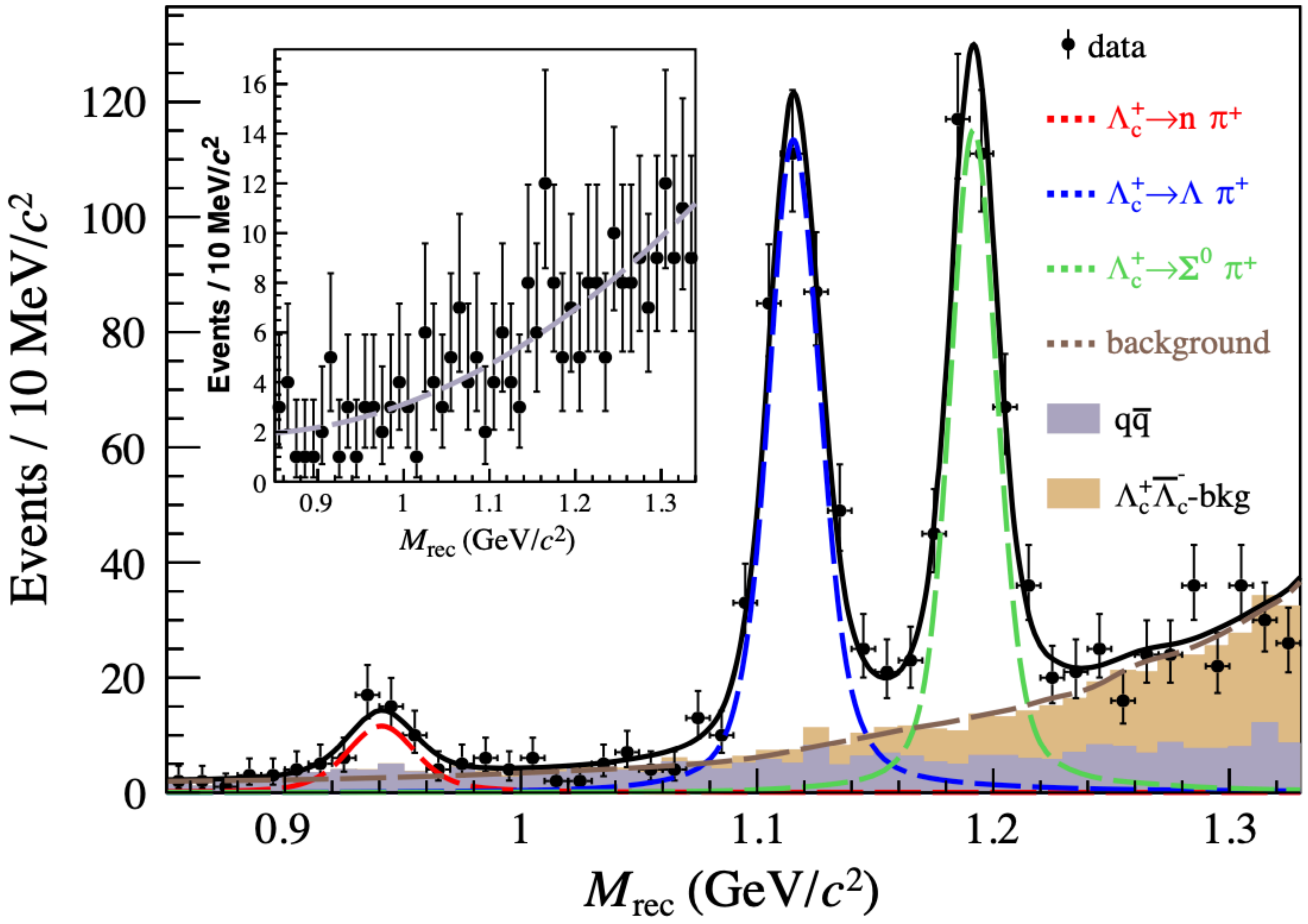
$$\mathscr{B}(\Lambda_c^+ \to n\pi^+) = (6.6 \pm 1.2_{\text{stat}} \pm 0.4_{\text{sys}}) \times 10^{-4}$$

$$\frac{\mathscr{B}(\Lambda_c^+ \to n\pi^+)}{\mathscr{B}(\Lambda_c^+ \to p\pi^0)} > 7.2 \text{ at 90\% C.L.}$$

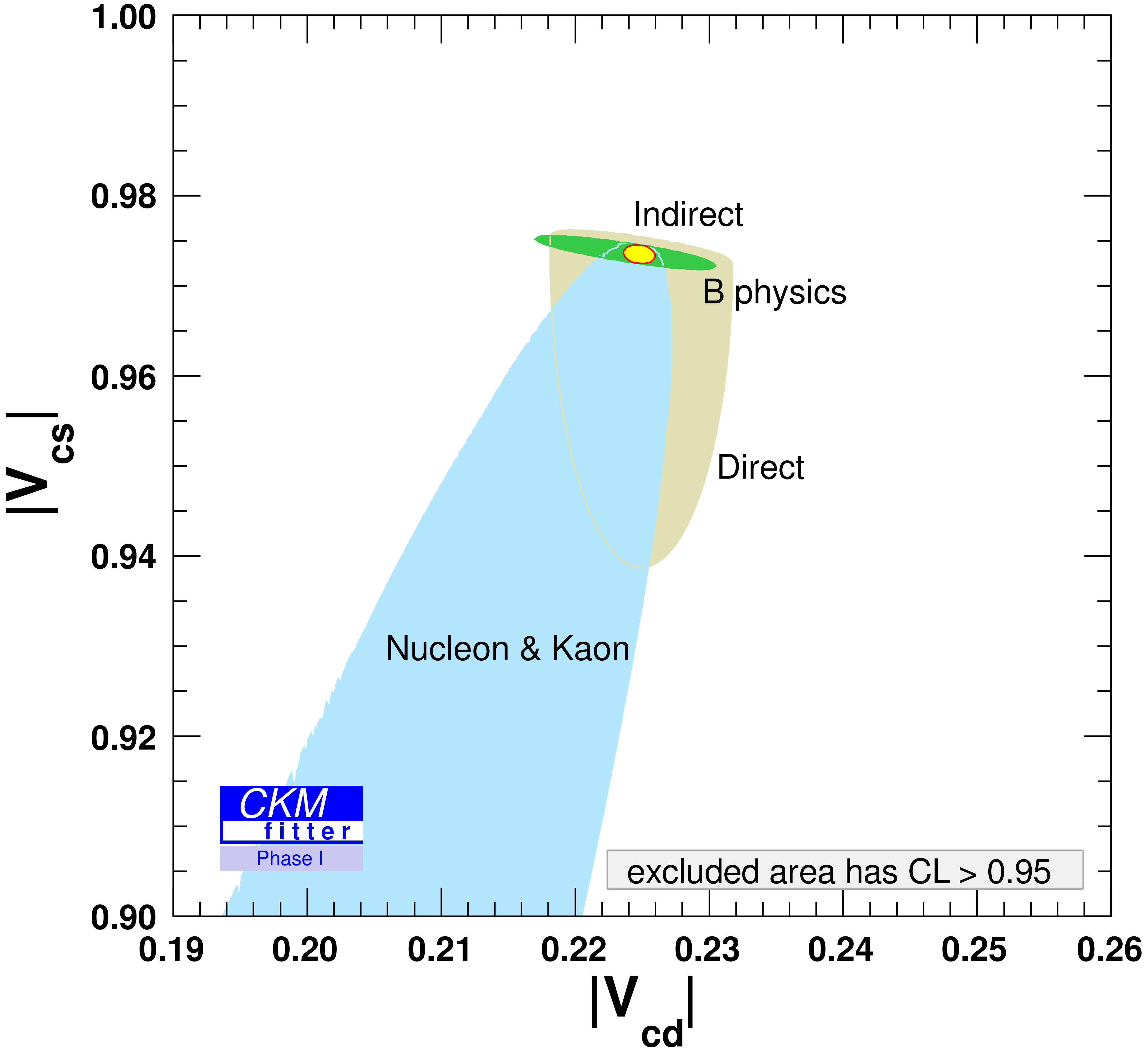
$p\pi^0$ from Belle [PRD 103, 072004 (2021)]

Inconsistent with phenomenological models

[Phys Rev Lett 128 (2022); 142001]

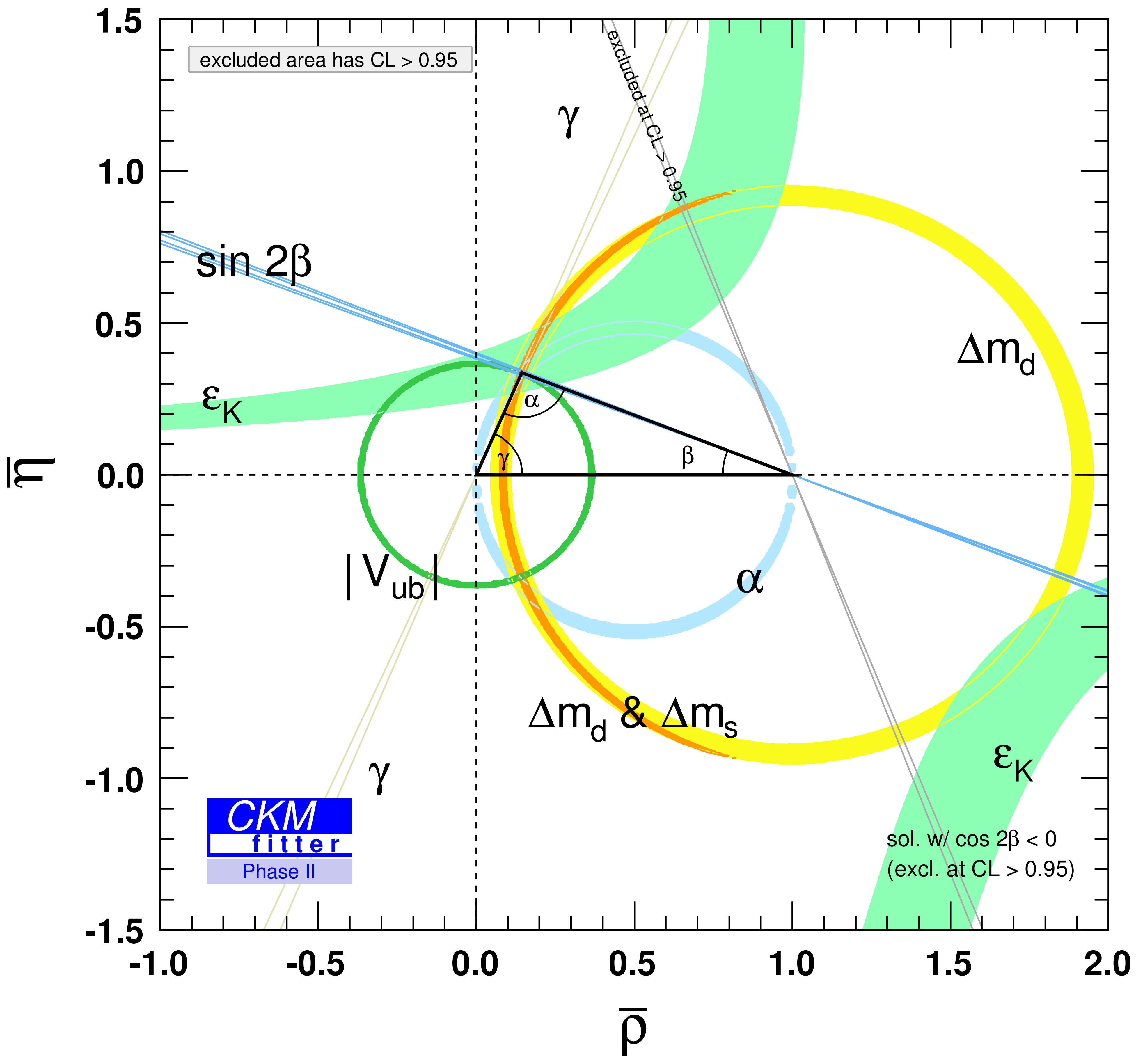


CKM Matrix Elements



- Constraints expected from future data taking plan [Chin Phys C 2020; 44: 040001]
- Indirect constraints (from B decays) related to $|V_{cd}|$, $|V_{cs}|$ by unitarity
- Direct constraints combine purely leptonic and semi-leptonic $D_{(s)}$ decays from BESIII experiment
- Circled region of the global combination corresponds to 68% confidence level

Strong Phase Difference between D_0, $\bar{D}_0$



[Chin Phys C 2020; 44: 040001]

- Strong phase differences between CF and DCS
- Input for CP violation phase angle (phase of V_{ub})
- Test physics beyond SM

$$\bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

Recent results:

- PHYS. REV. D 101, 112002 (2020): $\bar{D}_0 \to K^0_{S,L}\pi^+\pi^-$
- PHYS. REV. D 102, 052008 (2020): $\bar{D}_0 \to K^0_{S,L}K^+K^-$
- JHEP 2021, Article number: 164 (2021): $D \to K^-\pi^+\pi^0, D \to K^-\pi^+\pi^+\pi^-,$

THANK YOU!