Charm leptonic and rare decays at BESIII

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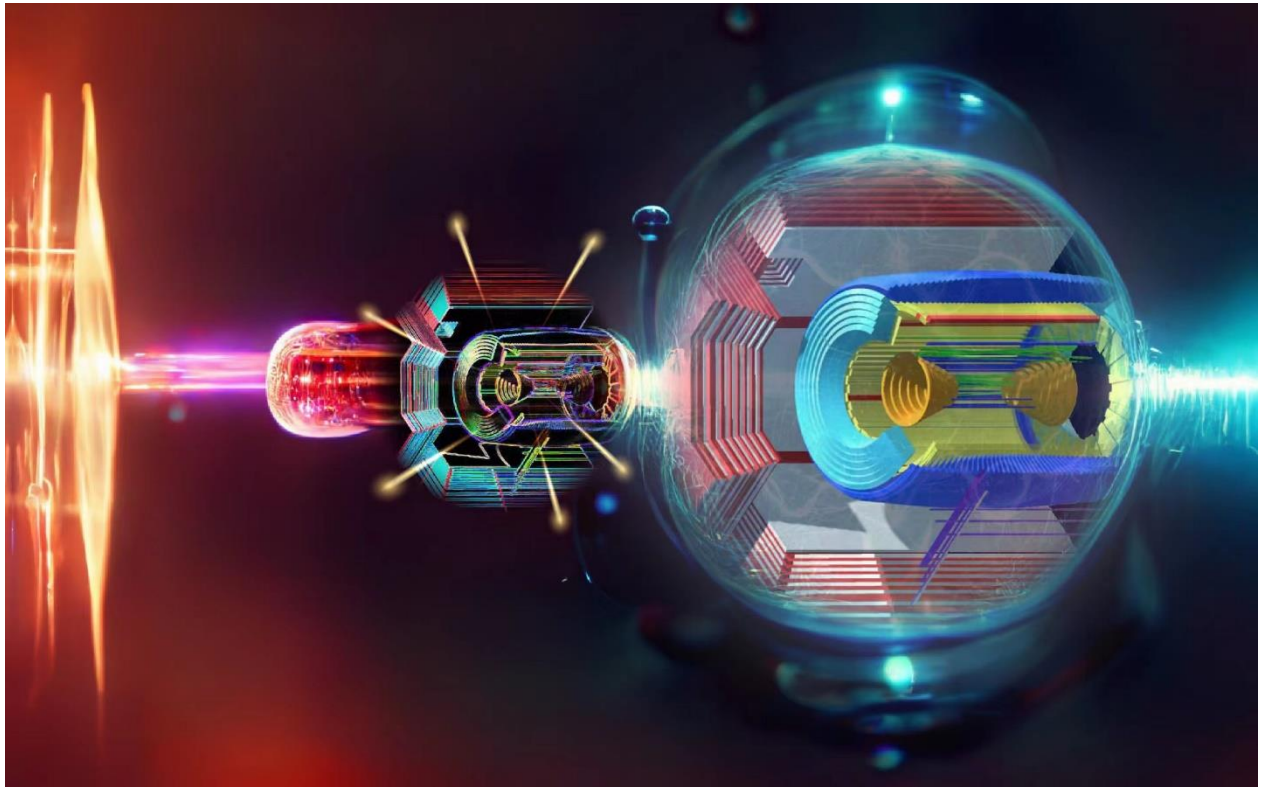
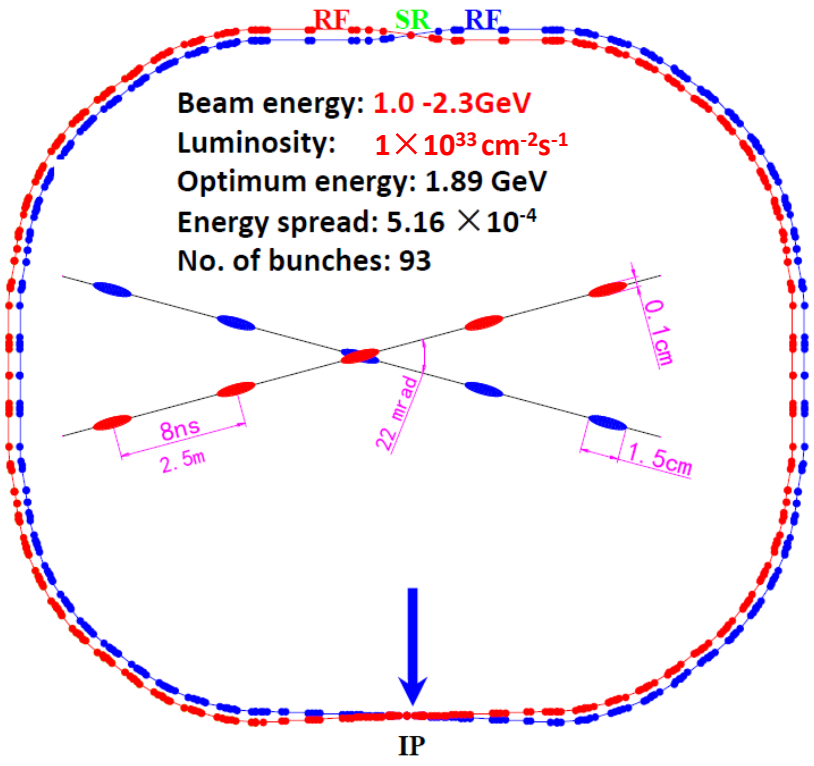
Outline

- BEPCII & BESIII
- Charm pure leptonic decays
- D semi-leptonic decays
- Ds semi-leptonic decays
- Charm meson rare decays
- Summary



BEPCII and BESIII

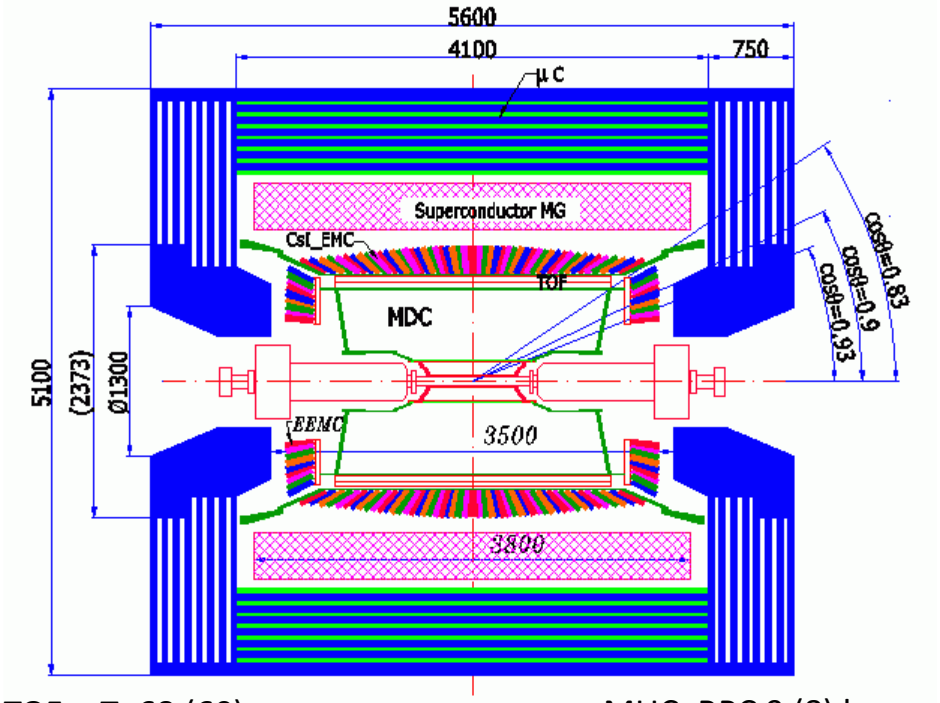
Beijing Electron Positron Collider II



BESIII Detector

MDC: Δp/p =0.5% @ 1GeV/c
dE/dx: ~ 6%

EMC: CsI (Tl) 2.5% (5.0%)
barrel (endcap) @ 1GeV



TOF: σT=68 (60) ps
barrel (endcap)

MUC: RPC 9 (8) layers
barrel (endcap)

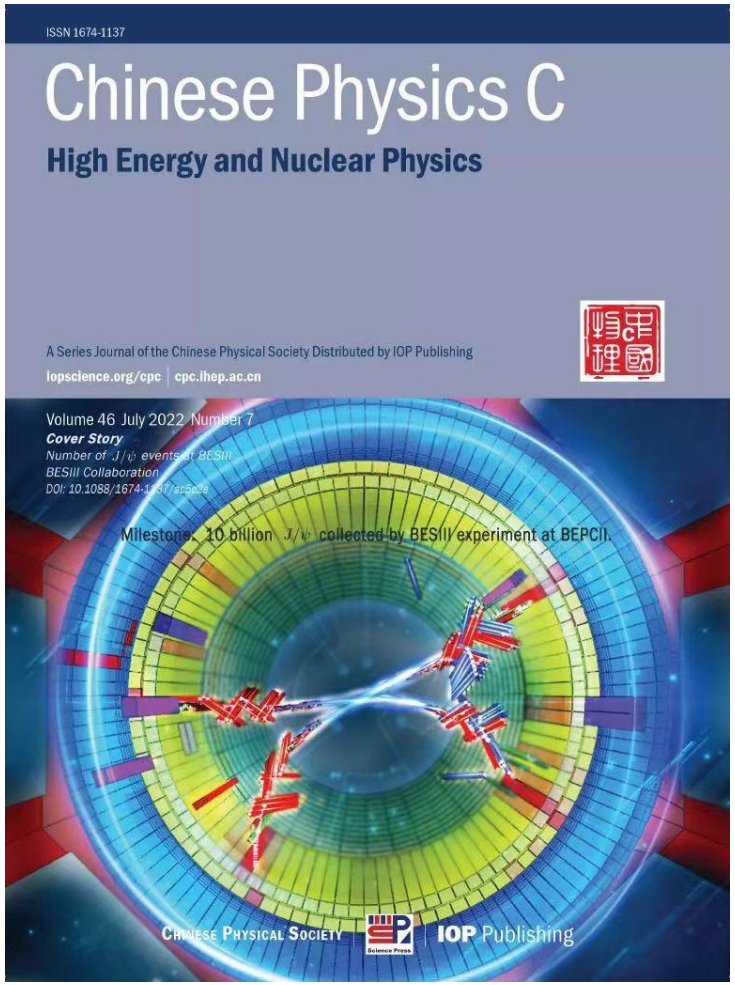
BESIII Physics Data

Physics of BESIII

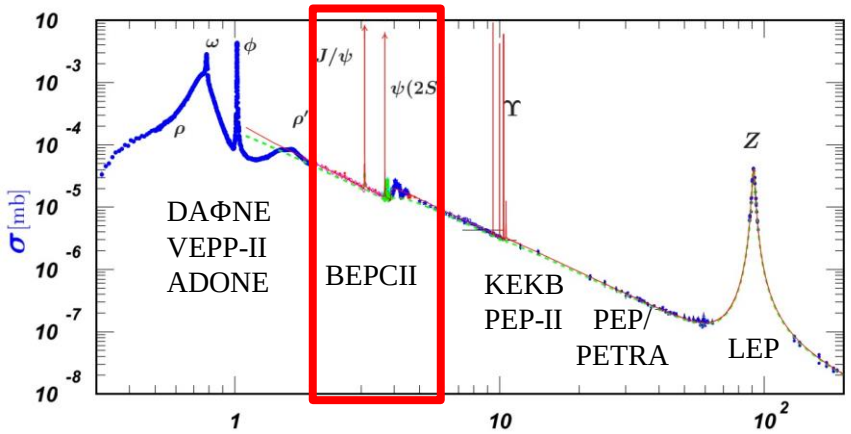
NSR 8 (11) 2021

10 Billion J/ψ collected by BESIII

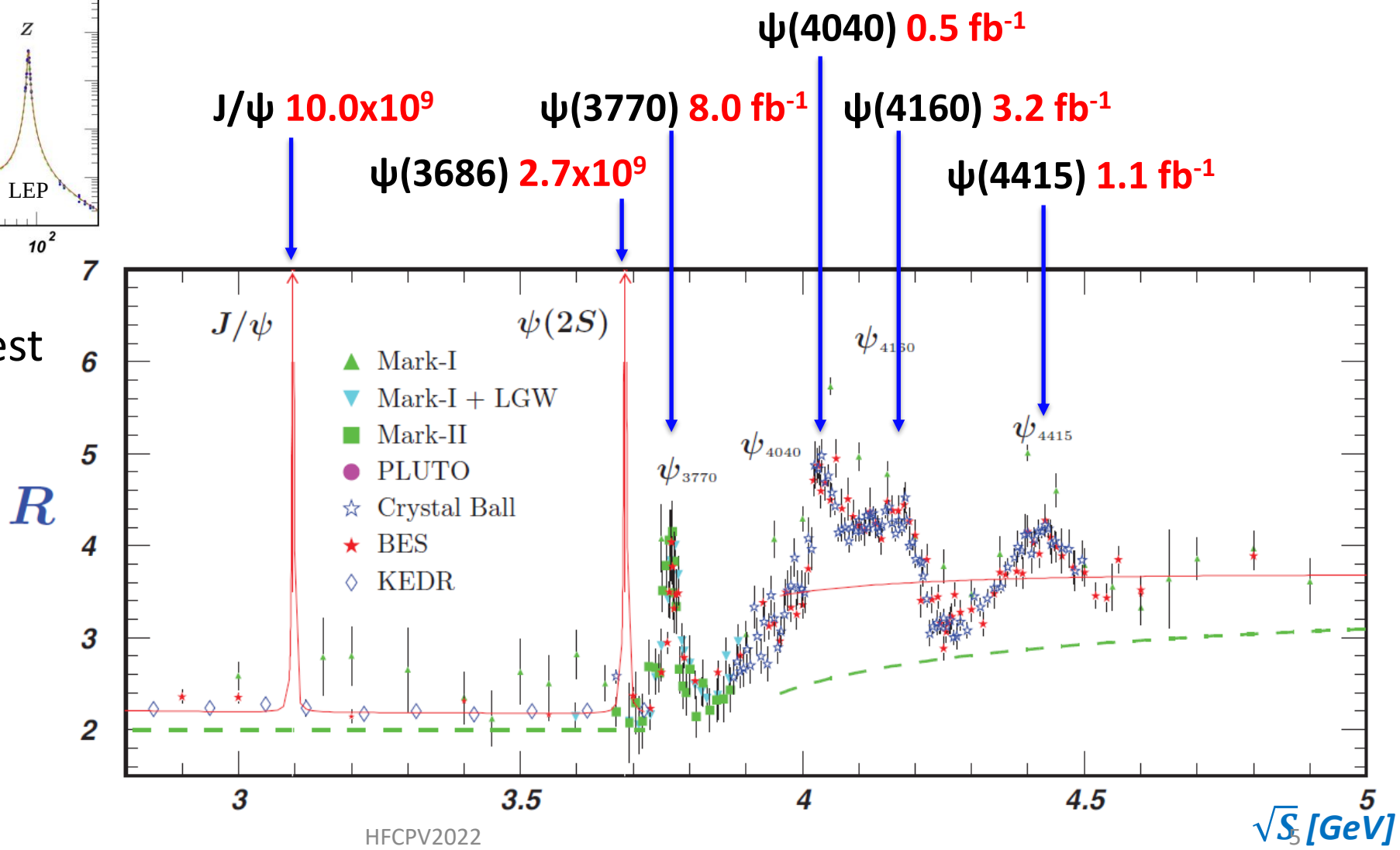
CPC 46 074001 (2022)



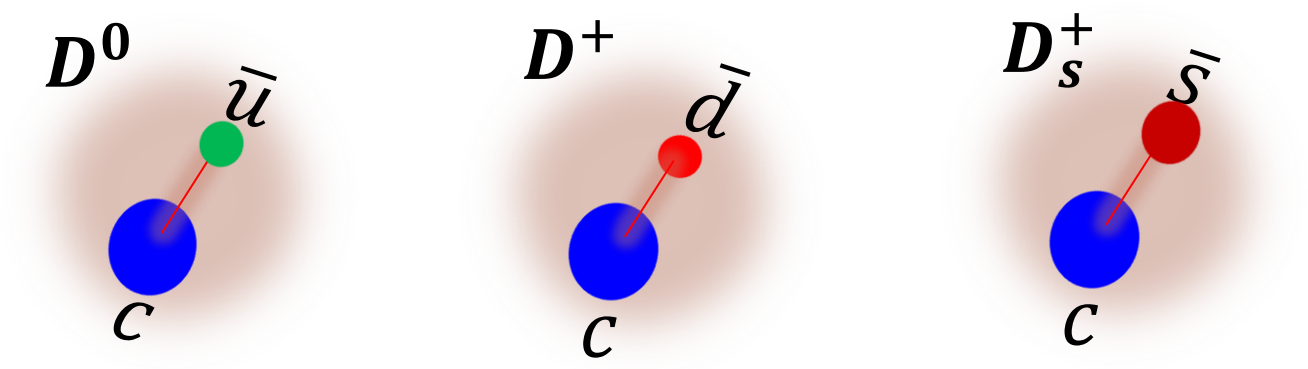
Charmonium Data at BESIII



- BESIII collected the largest J/ψ & $\psi(3686)$ data samples on threshold
- More then **37 fb^{-1}** data collected at 2~4.95 GeV
- **20 fb^{-1} $\psi(3770)$** data expected in the next 2 years

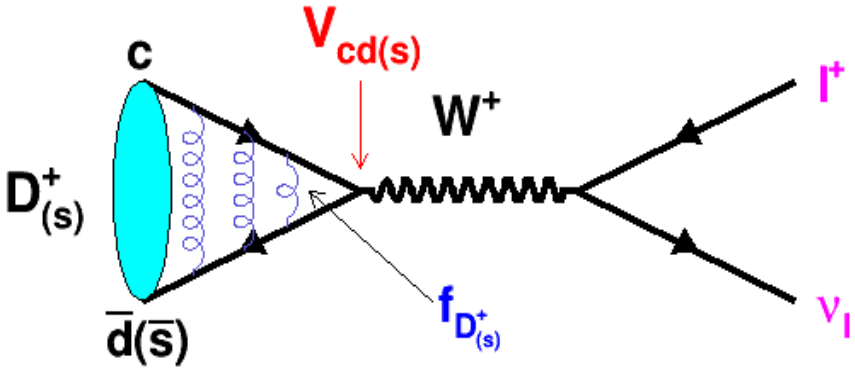


Charm leptonic decays



Charm leptonic decays

- Access the strong and weak effects between quarks
- CKM matrix elements
- $|V_{cs}|$, $|V_{cd}|$ → Test CKM matrix unitarity
- Decay constants and form factors
  → Calibrate LQCD calculations
- Branching fraction ratios
  → Test lepton flavor universality (LFU)
- Search for new physics beyond the SM



$$\Gamma(D^+_{(s)} \to \ell^+\nu_\ell) = \frac{G_F^2}{8\pi} f^2_{D^+_{(s)}} |V_{cd(s)}|^2 m_\ell^2 m_{D^+_{(s)}} \left(1 - \frac{m_\ell^2}{m^2_{D^+_{(s)}}}\right)^2$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} V_{us} V_{ub} \\ V_{cd} V_{cs} V_{cb} \\ V_{td} V_{ts} V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

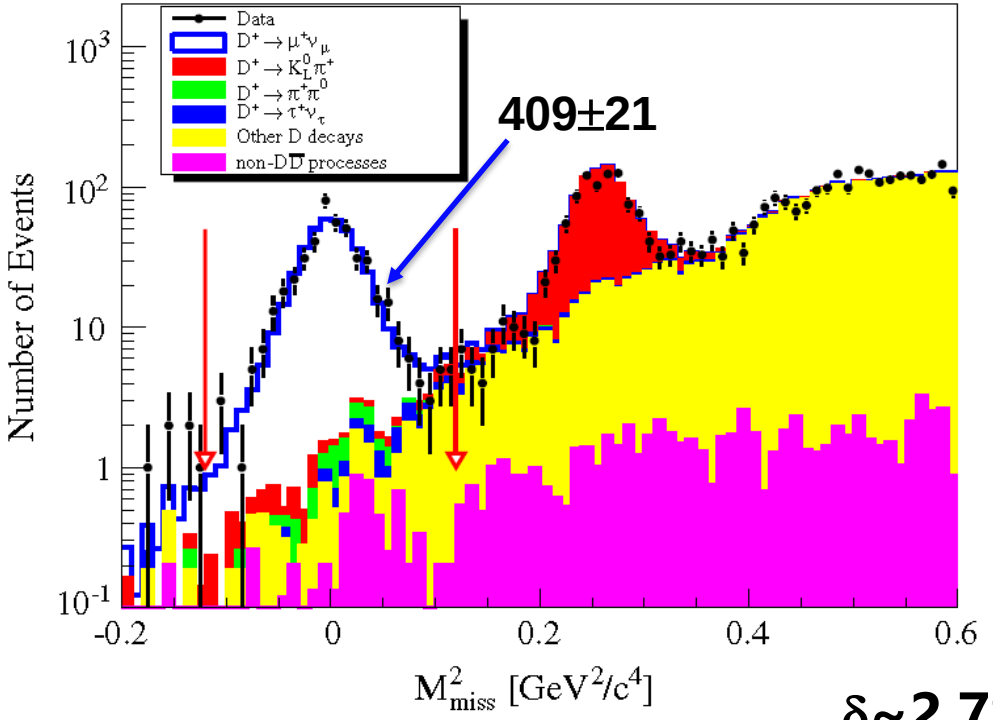
Pure leptonic decay $D^+ \to l^+ \nu_l$

- Measurement of $f_{D^+}|V_{cd}|$
- First observation of $D^+ \to \tau^+ \nu$

SM: $R_{\tau/\mu} = \frac{\Gamma(D^+ \to \tau^+ \nu_\tau)}{\Gamma(D^+ \to \mu^+ \nu_\mu)} = \frac{m_\tau^2 (M_{D^+}^2 - m_\tau^2)^2}{m_\mu^2 (M_{D^+}^2 - m_\mu^2)^2} = 2.66$

$$R_{\tau/\mu} \equiv \frac{\Gamma(D^+ \to \tau^+ \nu_\tau)}{\Gamma(D^+ \to \mu^+ \nu_\mu)} = 3.21 \pm 0.77$$

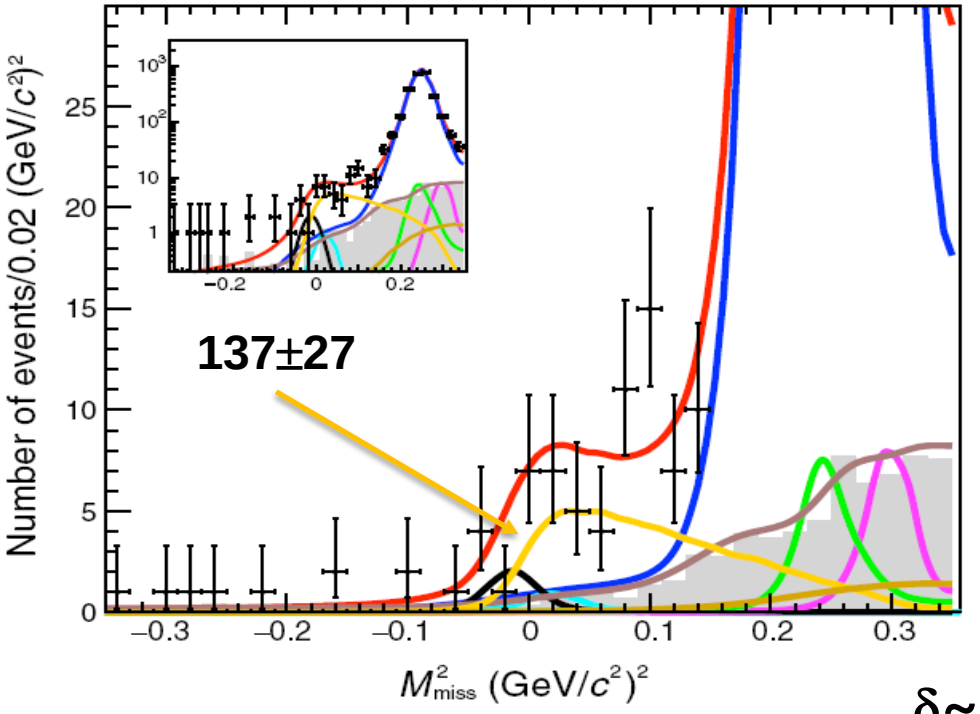
$D^+ \to \mu^+ \nu_\mu$ PRD 89 051104 (2014)



δ~2.7%

$f_{D^+}|V_{cd}| = 46.7 \pm 1.2 \pm 0.4$ MeV

$D^+ \to \tau^+ (\pi^+ \nu) \nu$ PRL 123 211802 (2019)



δ~11%

$f_{D^+}|V_{cd}| = 50.4 \pm 5.0 \pm 2.5$ MeV

Pure leptonic decay $D_s^+ \to l^+ \nu_l$

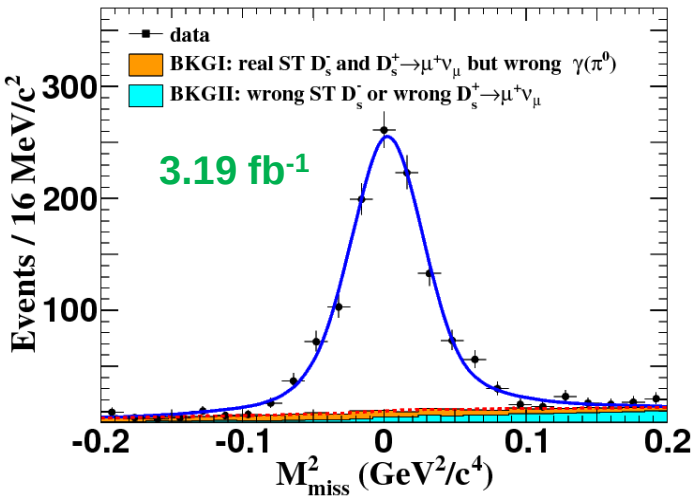
- Measurement of $f_{D_s^+}|V_{cs}|$
- Leptonic decays to μ and τ
- Different channels to tag τ

$D_s^+ \to \mu^+ \nu$

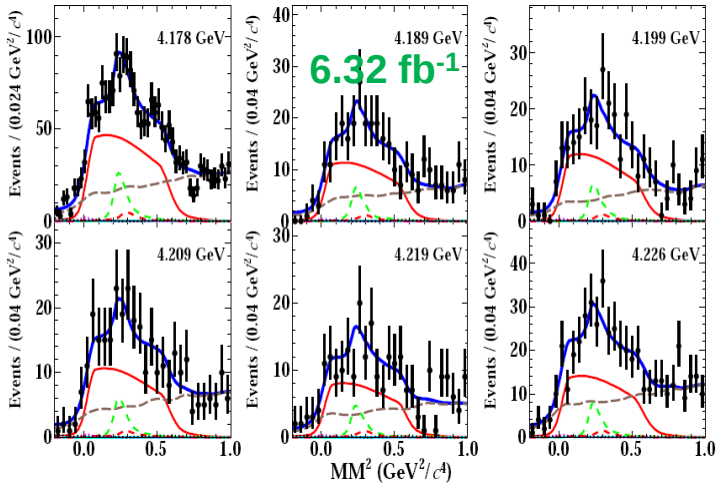
PRL 122 (2019) 071802

$f_{D_s^+}|V_{cs}| = 246.2 \pm 3.6 \pm 3.5\,\mathrm{MeV}$

$\delta \sim 2.1\%$



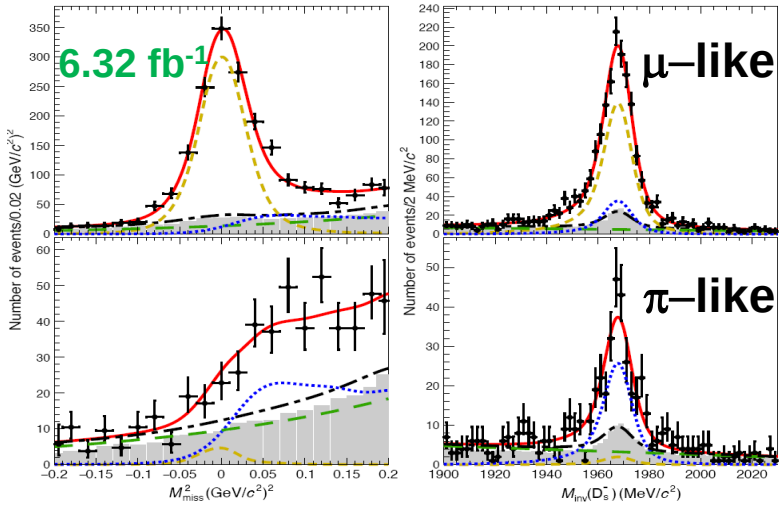
$D_s^+ \to \tau^+(\rho^+\nu)\nu$ PRD 104 032001 (2021)



$f_{D_s^+}|V_{cs}| = 244.8 \pm 5.8 \pm 4.8\,\mathrm{MeV}$

$\delta \sim 3.1\%$

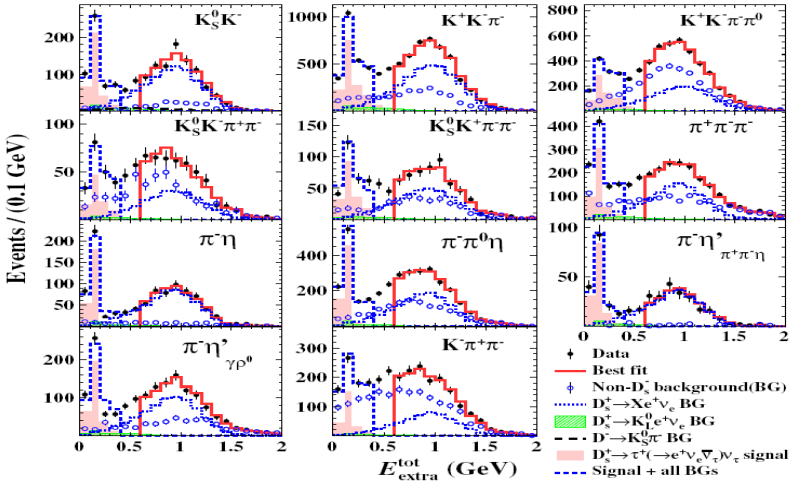
$D_s^+ \to \tau^+(\pi^+\nu)\nu$ PRD 104 052009 (2021)



$f_{D_s^+}|V_{cs}| = 243.0 \pm 5.8 \pm 4.0\,\mathrm{MeV}$

$\delta \sim 2.9\%$

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

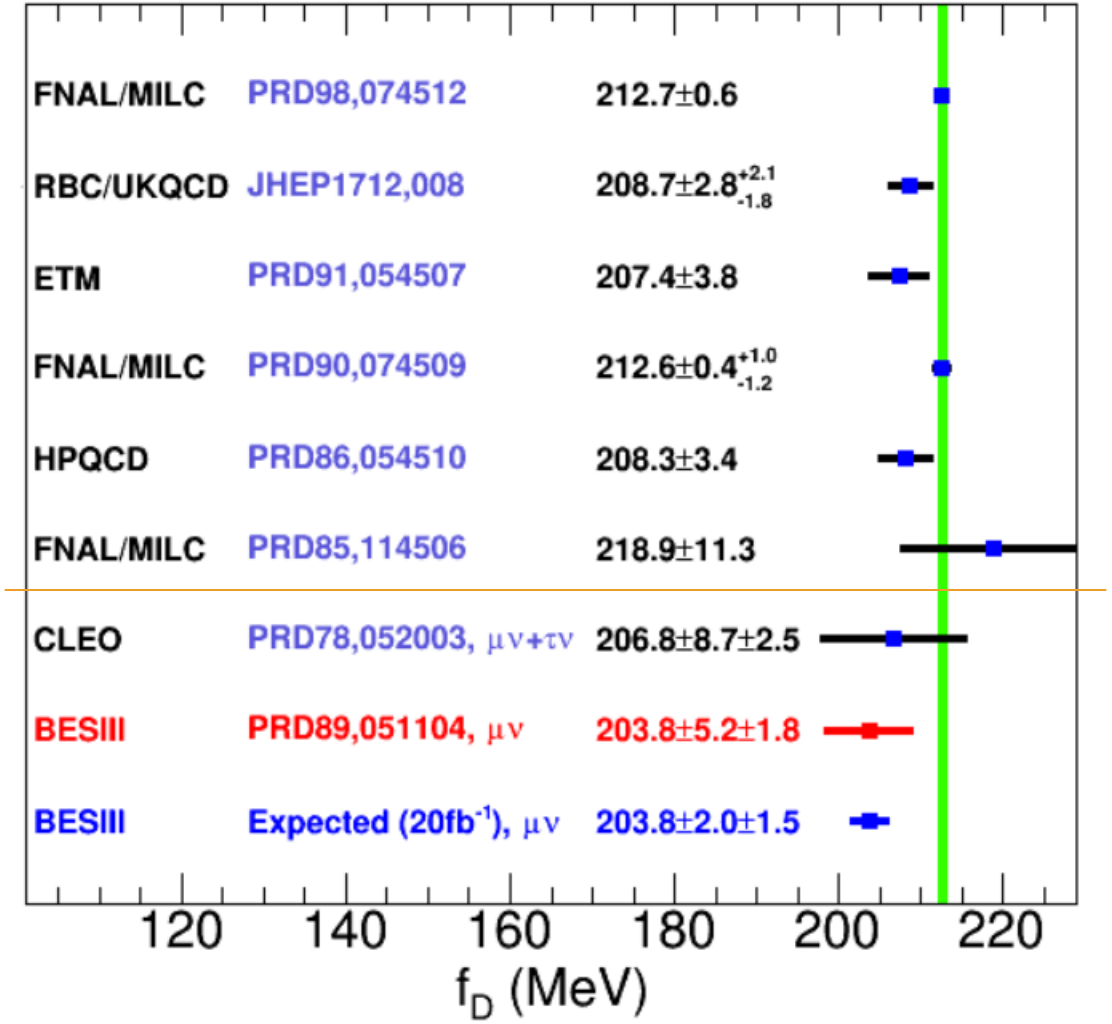


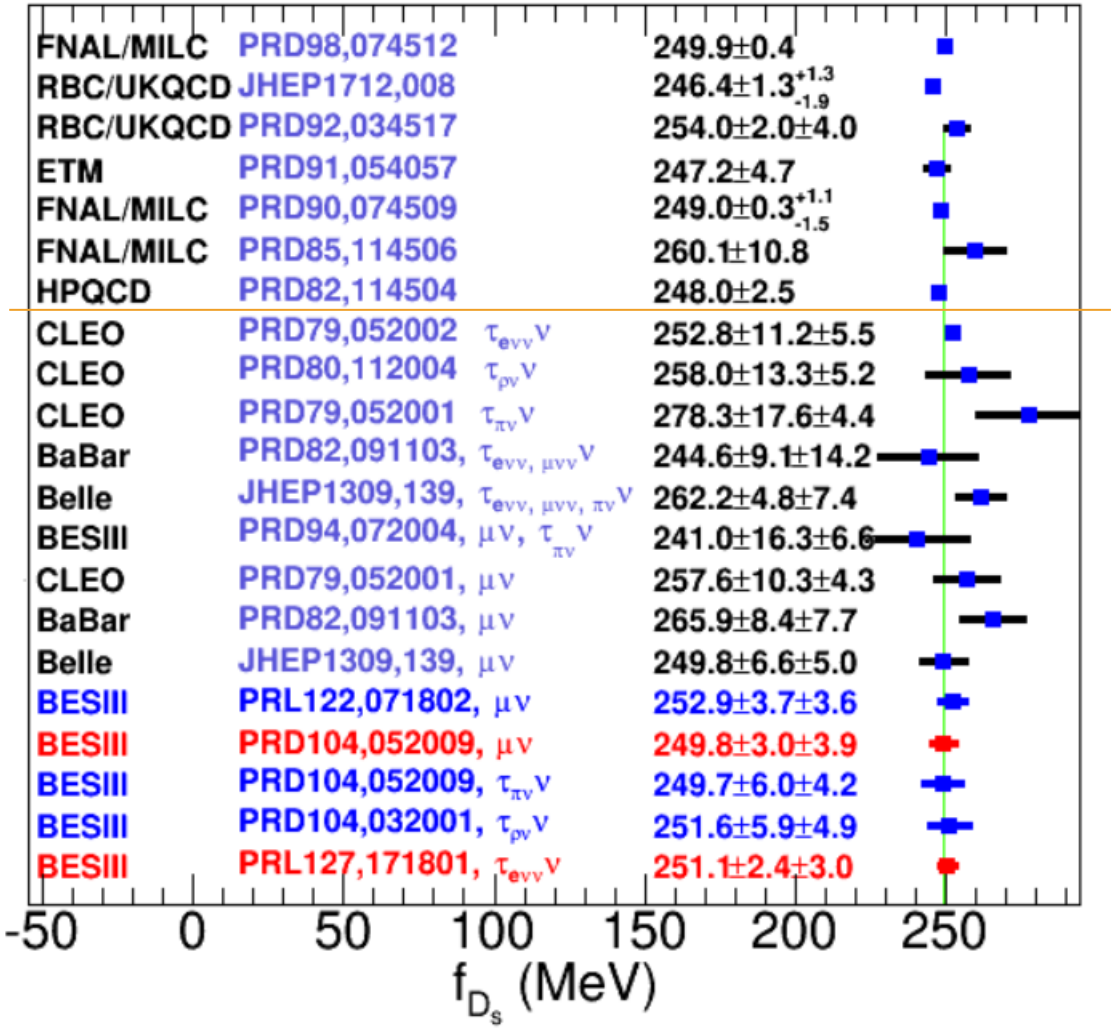
$f_{D_s^+}|V_{cs}| = 244.4 \pm 2.3 \pm 2.9\,\mathrm{MeV}$

$\delta \sim 1.5\%$

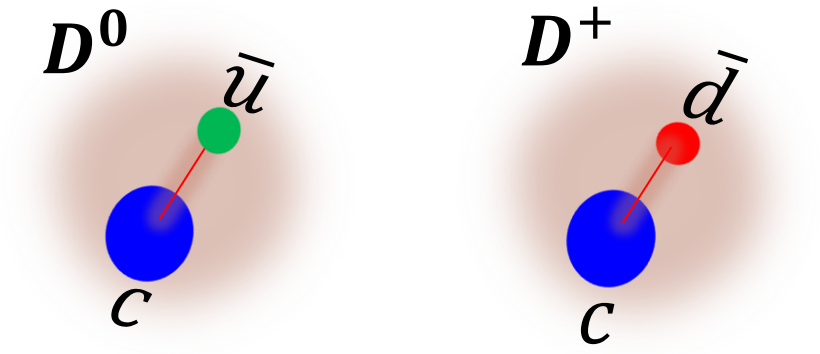
Comparisons of f_D and f_{D_s}

PDG $|V_{cd}|$, $|V_{cs}|$ as input



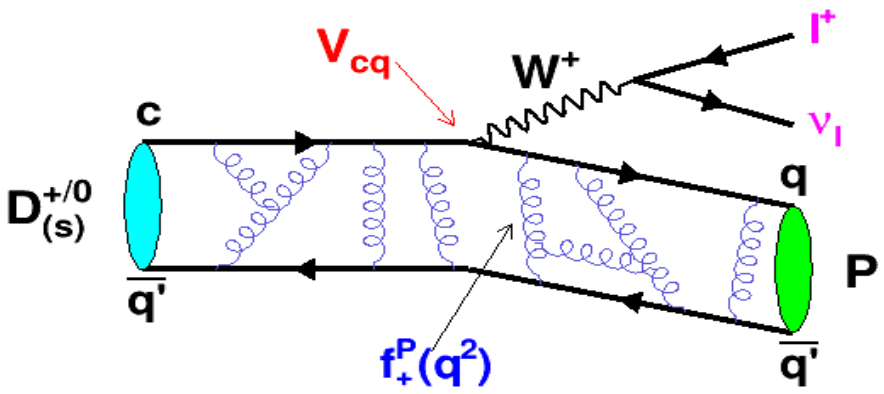


Charm semi-leptonic decays



Charm semi-leptonic decays

- $\boldsymbol{D}^+ \to Pl^+\boldsymbol{\nu}_l\ (P = K, \pi, \eta, \eta')$
- $|V_{cs}|$, $|V_{cd}|$ → Test CKM matrix unitarity
- Form factors → Calibrate LQCD calculations
- $\boldsymbol{R}_{\mu/e}$ → Test LFU



$$\frac{d\Gamma}{dq^2} = X\frac{G_F^2}{24\pi^3}|f_+^h(0)|^2|V_{cq}|^2|\vec{p}_h|^3$$

– **Single pole form**

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

– **Modified pole model**

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

– **ISGW2 model**

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

– **Series expansion model**

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

$D^{0(+)} \to \pi^{-(0)}\mu^+\nu_\mu$

- Test of LFU $R_{\mu/e}$
- Extraction of $f_+^{D\to\pi}(0)$

SM: $R_{\mu/e} = 0.985 \pm 0.002$

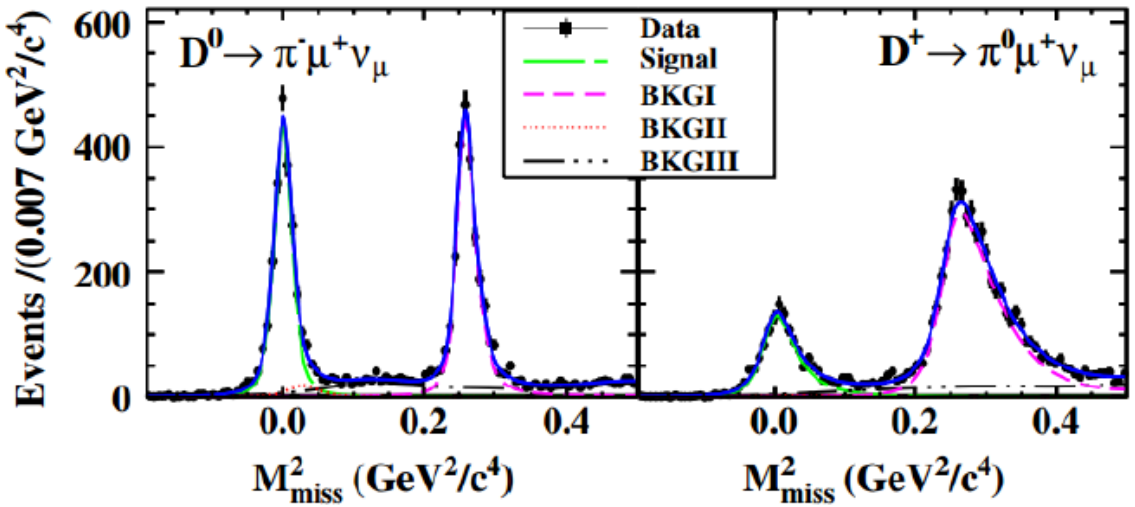
$$R_{\mu/e} \equiv \frac{\Gamma(D^0 \to \pi^-\mu^+\nu_\mu)}{\Gamma(D^0 \to \pi^-e^+\nu_e)} = 0.922 \pm 0.030 \pm 0.022$$

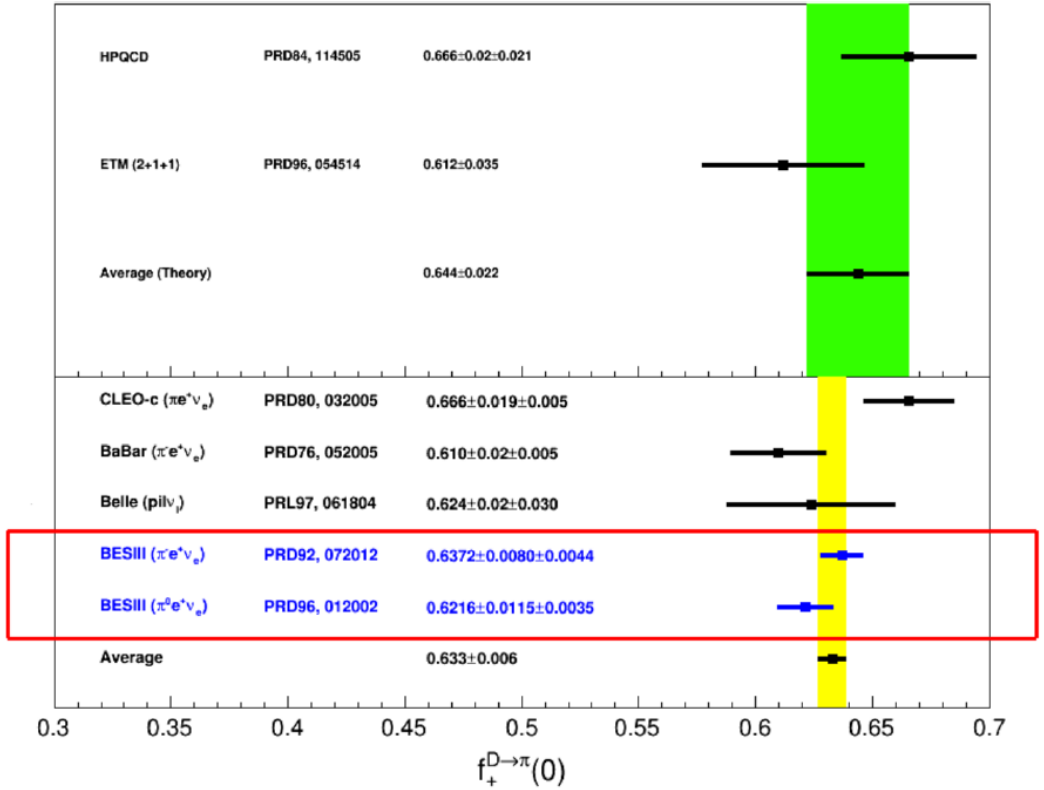
$$R_{\mu/e} \equiv \frac{\Gamma(D^+ \to \pi^0\mu^+\nu_\mu)}{\Gamma(D^+ \to \pi^0e^+\nu_e)} = 0.964 \pm 0.037 \pm 0.026$$

$$\mathcal{B}(D^0 \to \pi^-\mu^+\nu_\mu) = (0.272 \pm 0.008 \pm 0.006)\%$$

$$\mathcal{B}(D^+ \to \pi^0\mu^+\nu_\mu) = (0.350 \pm 0.011 \pm 0.010)\%$$

PRL 121 171803 (2018)





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

- Test of LFU $R_{\mu/e}$
- Extraction of $f_+^{D\to K}(0)$ and $|V_{cs}|$

SM: $R_{\mu/e} = 0.975$

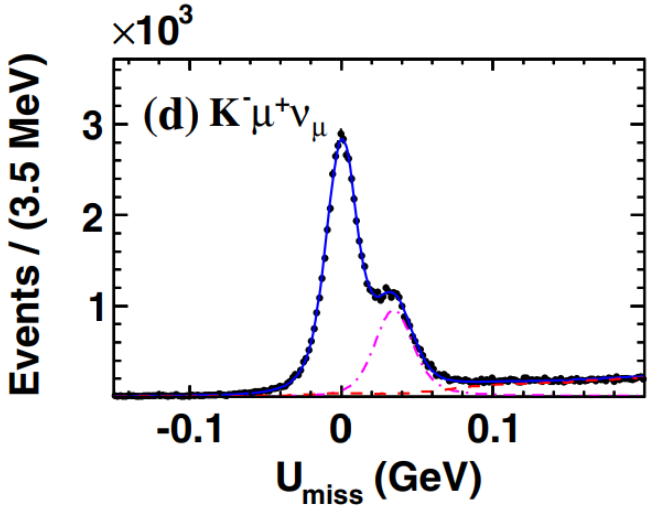
$$R_{\mu/e} \equiv \frac{\Gamma(D^0 \to K^- \mu^+ \nu_\mu)}{\Gamma(D^0 \to K^- e^+ \nu_e)} = 0.974 \pm 0.007 \pm 0.012$$

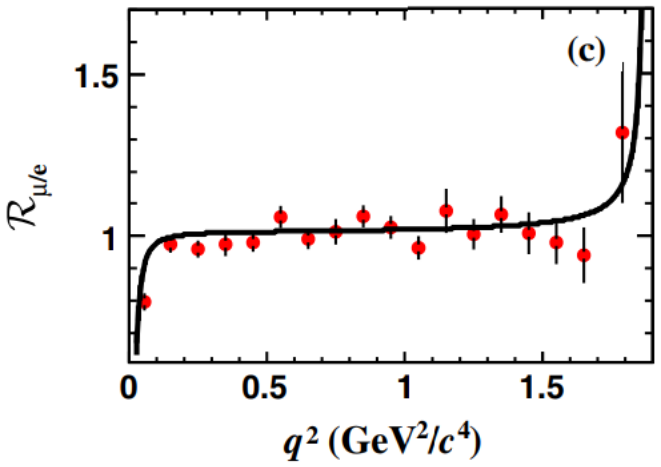
$$\mathcal{B}(D^0 \to K^- \mu^+ \nu_\mu) = (3.413 \pm 0.019 \pm 0.035)\%$$

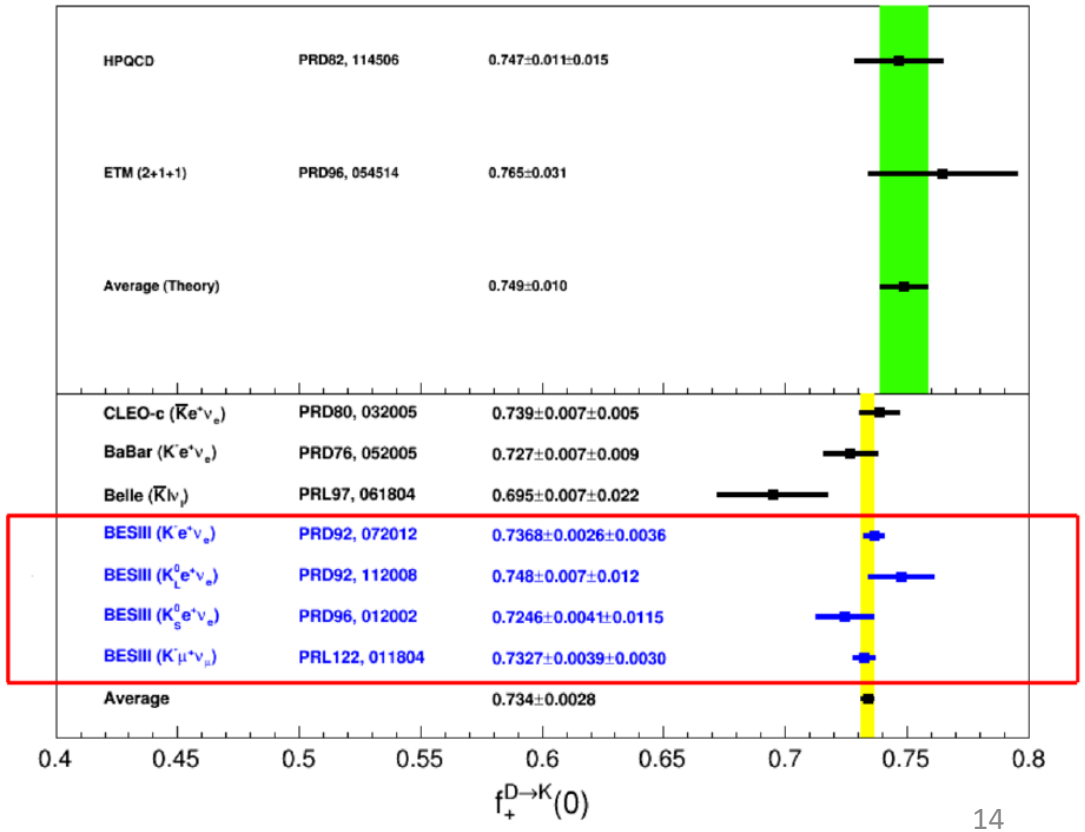
$$f_+^K(0) = 0.7327 \pm 0.0039 \pm 0.0030$$

$$|V_{cs}| = 0.955 \pm 0.005 \pm 0.004 \pm 0.024_{LQCD}$$

PRL 122 011804 (2019)







$D^{0(+)} \to K^{-(0)} e^+ \nu_e$ and $D^0 \to K_1(1270)^- e^+ \nu_e$

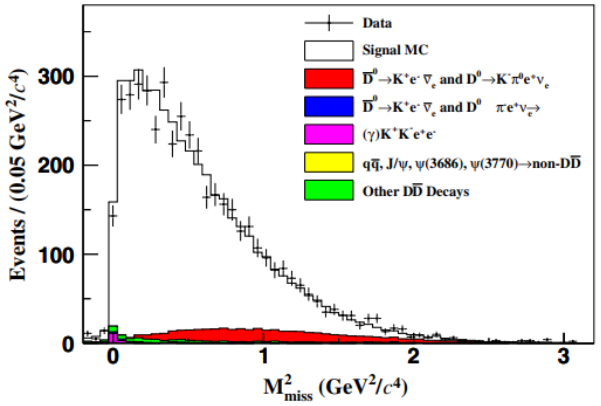
- Improved reconstruction and combined with previous BESIII results
- Supports isospin symmetry

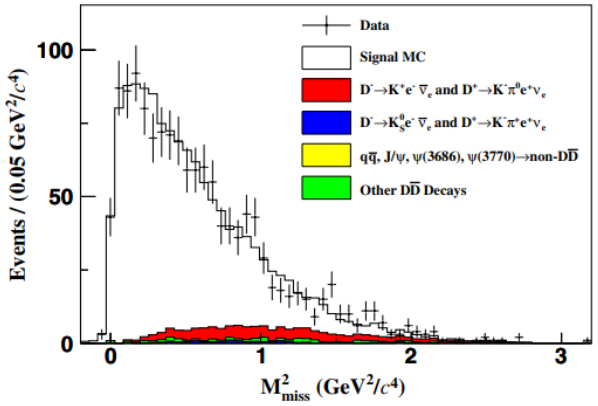
$\mathcal{B}(D^0 \to K^- e^+ \nu_e) = (3.531 \pm 0.024 \pm 0.017)\%$

$\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e) = (8.62 \pm 0.007 \pm 0.14)\%$

$$\frac{\Gamma(D^0 \to K^- e^+ \nu_e)}{\Gamma(D^+ \to \bar{K}^0 e^+ \nu_e)} = 1.039 \pm 0.021$$

PRD 104 052008 (2021)



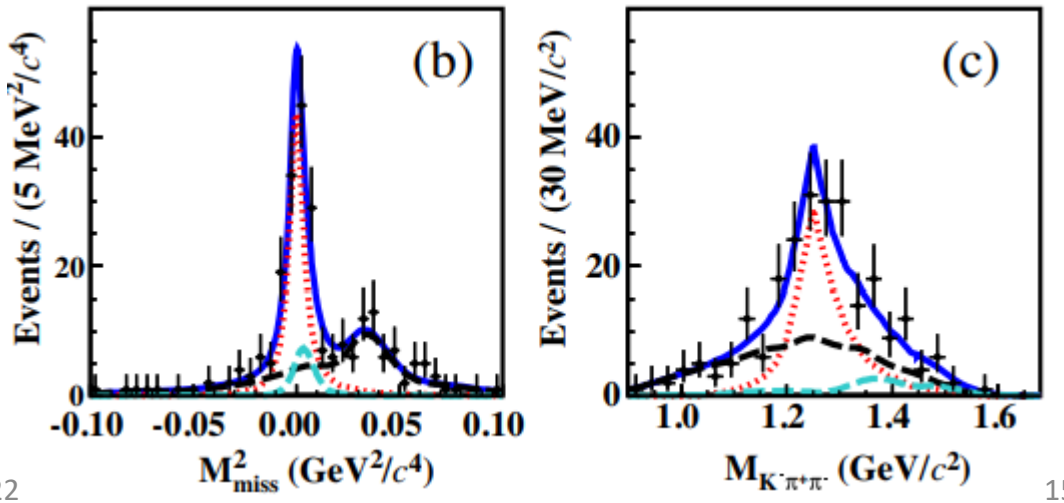


- First observation of D meson semi-leptonic decay into axial-vector meson
- Test of isospin conservation

$\mathcal{B}(D^0 \to K_1(1270)^- e^+ \nu_e) = (1.09 \pm 0.13^{+0.09}_{-0.13} \pm 0.12) \times 10^{-3}$

$$\frac{\Gamma(D^0 \to K_1(1270)^- e^+ \nu_e)}{\Gamma(D^+ \to \bar{K}_1(1270)^0 e^+ \nu_e)} = 1.20 \pm 0.20 \pm 0.14 \pm 0.04$$

PRL 127 131801 (2021)



$D^+ \to \eta/\omega\, \mu^+\nu_\mu$ and $D^0 \to \rho^-\mu^+\nu_\mu$

- Observation of $D^+ \to \eta\, \mu^+\nu_\mu$ and extraction of $|V_{cd}|$
- Observation of $D^+ \to \omega\, \mu^+\nu_\mu$, $D^0 \to \rho^-\mu^+\nu_\mu$ and probe LFU

$$f_+^\eta(0)|V_{cd}| = 0.087 \pm 0.008 \pm 0.002$$

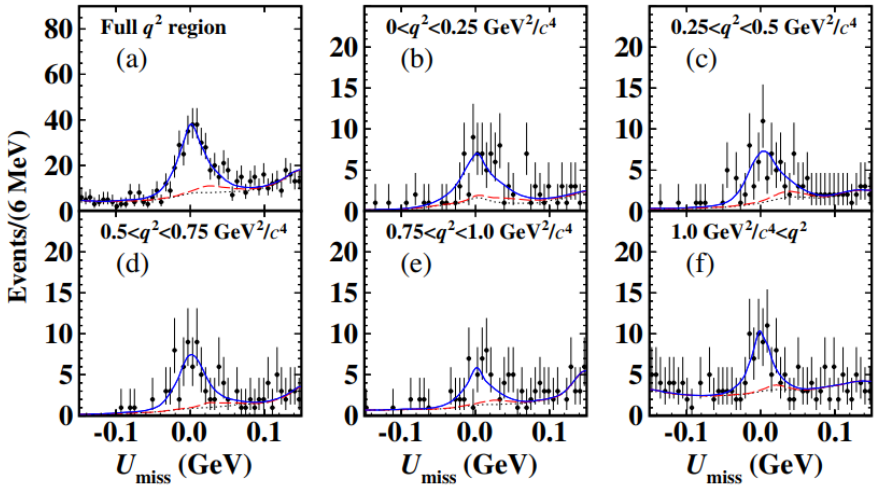
$$\frac{B_{D^+\to\omega\,\mu^+\nu_\mu}}{B^{PDG}_{D^+\to\omega\,e^+\nu_e}} = 1.05 \pm 0.14$$

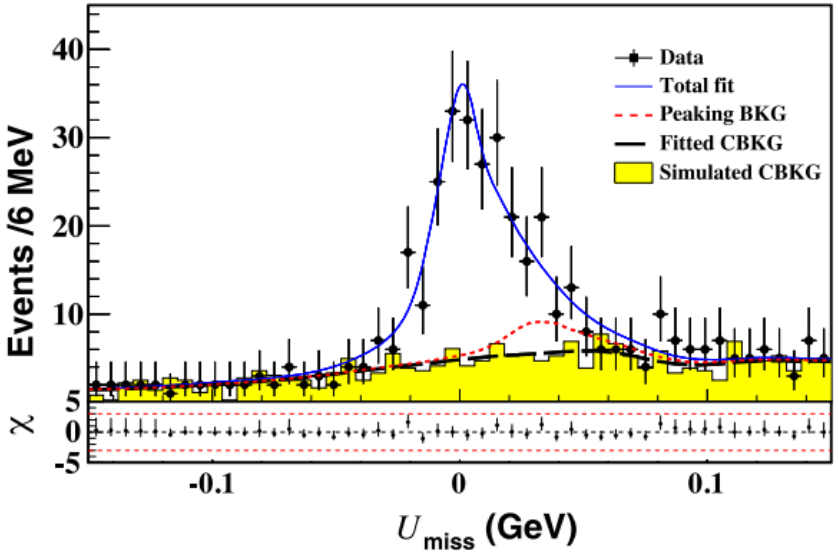
$$\frac{B_{D^0\to\rho^-\,\mu^+\nu_\mu}}{B_{D^0\to\rho^-\,e^+\nu_e}} = 0.90 \pm 0.11$$

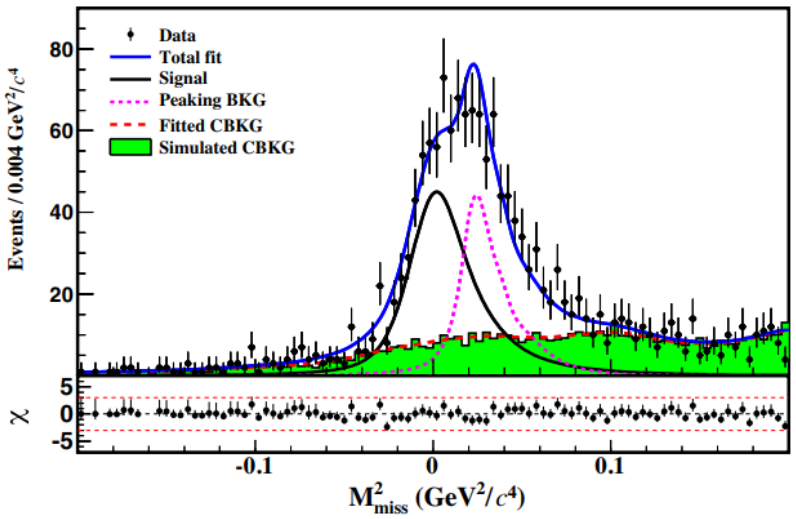
$D^+ \to \eta\, \mu^+\nu_\mu$ PRL 124 231801 (2020)

$D^+ \to \omega\, \mu^+\nu_\mu$ PRD 101 072005 (2020)

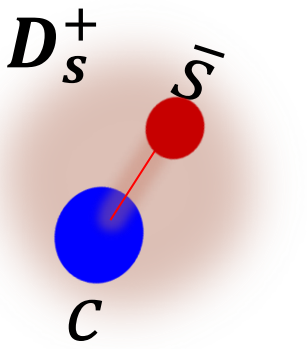
$D^0 \to \rho^-\mu^+\nu_\mu$ PRD 104 L091103 (2021)







Ds semi-leptonic decays

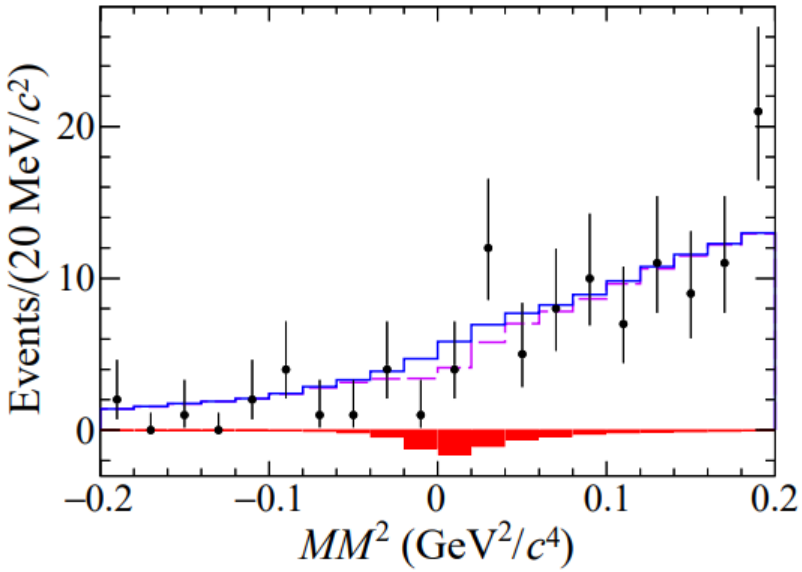


Search for $D_s^+ \to \pi^0 e^+ \nu_e$ and $D_s^+ \to a_0(980)^0 e^+ \nu_e$

- Sensitive to $\pi^0 - \eta$ mixing
- Setting the upper limit

$\mathcal{B}(D_s^+ \to \pi^0 e^+ \nu_e) < 6.4 \times 10^{-3}$ @ 90% C. L.

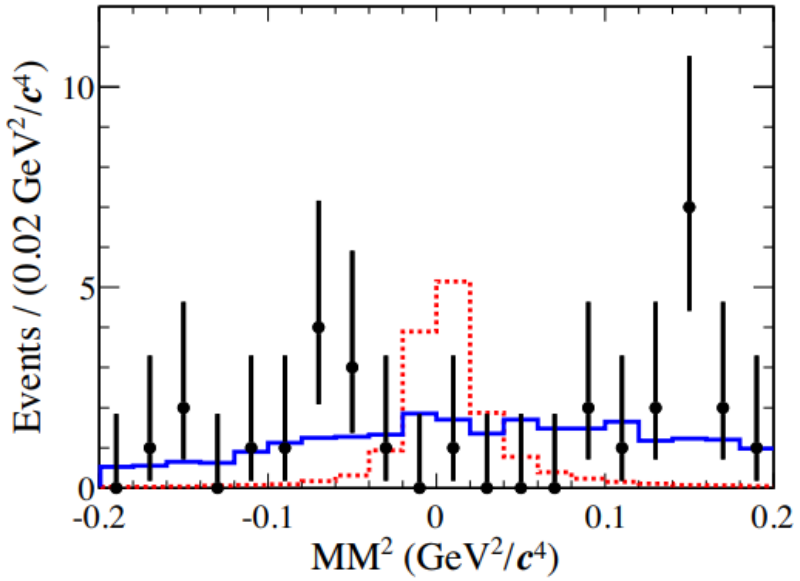
arXiv: 2206.13870



- Probe $a_0(980) - f_0(980)$ mixing
- Setting the upper limit

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

PRD 103 092004 (2021)

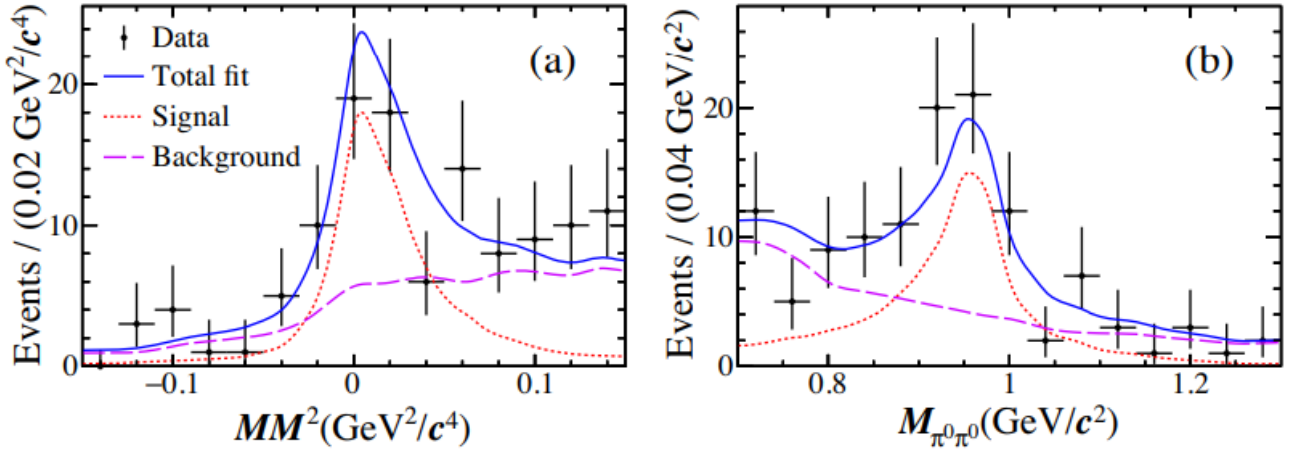


$D_s^+ \to f_0(980)\, e^+\nu_e$ and $D_s^+ \to K_S^0 K_S^0 e^+\nu_e$

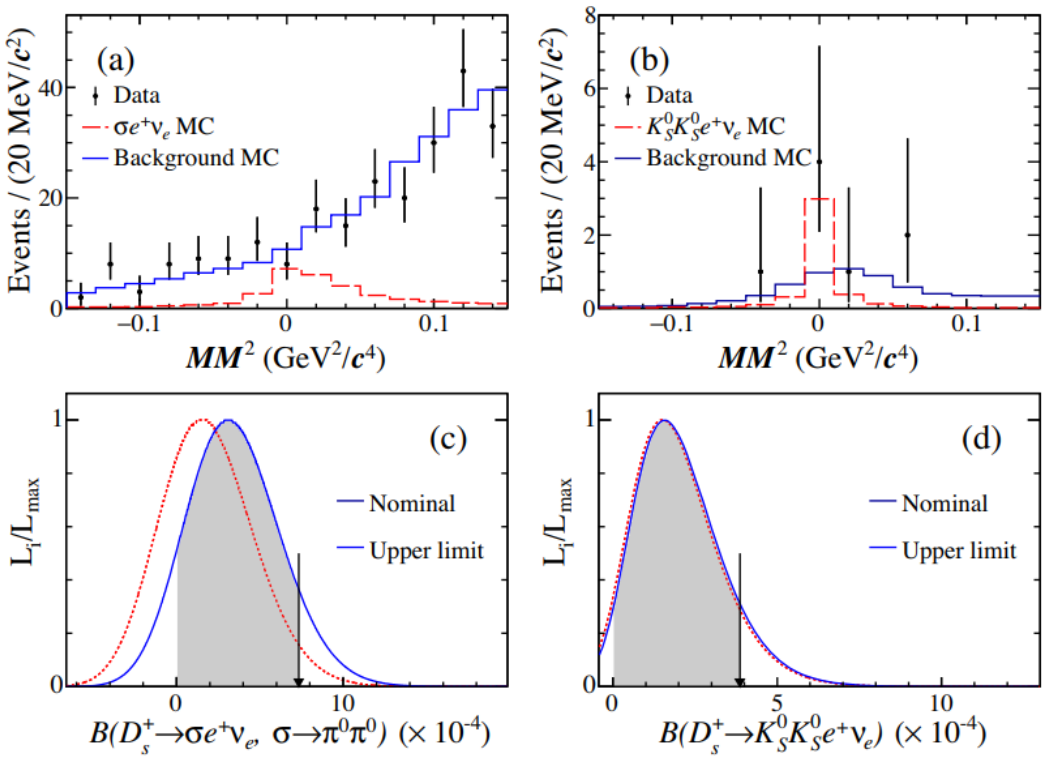
- First measurement
- Help to understand the structures of light scalar mesons

$\mathcal{B}(D_s^+ \to f_0(980)^0 e^+\nu_e) \times \mathcal{B}(f_0(980)^0 \to \pi^0\pi^0)$
$= (7.9 \pm 1.4 \pm 0.4) \times 10^{-4}$

PRD 105 L031101 (2022)



$\mathcal{B}(D_s^+ \to K_S^0 K_S^0 e^+\nu_e) < 3.8 \times 10^{-4}$ @ 90% C. L.



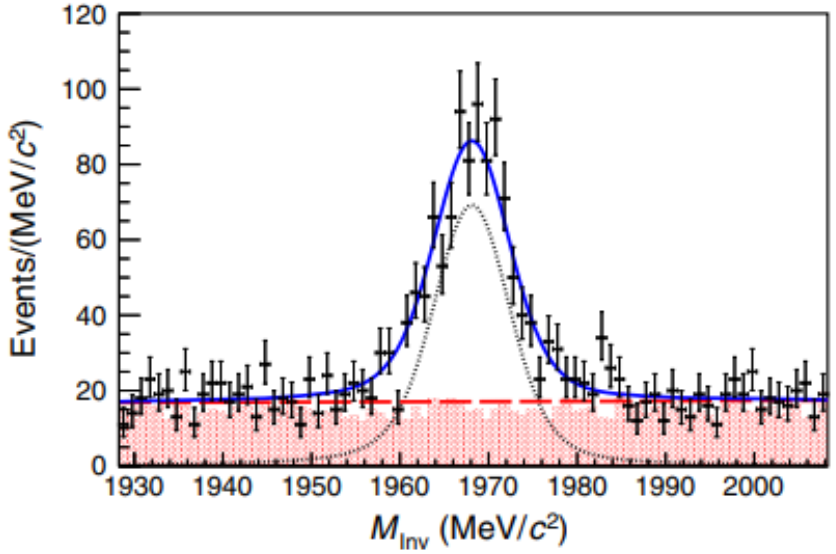
$D_s^+ \to X\, e^+ \nu_e$

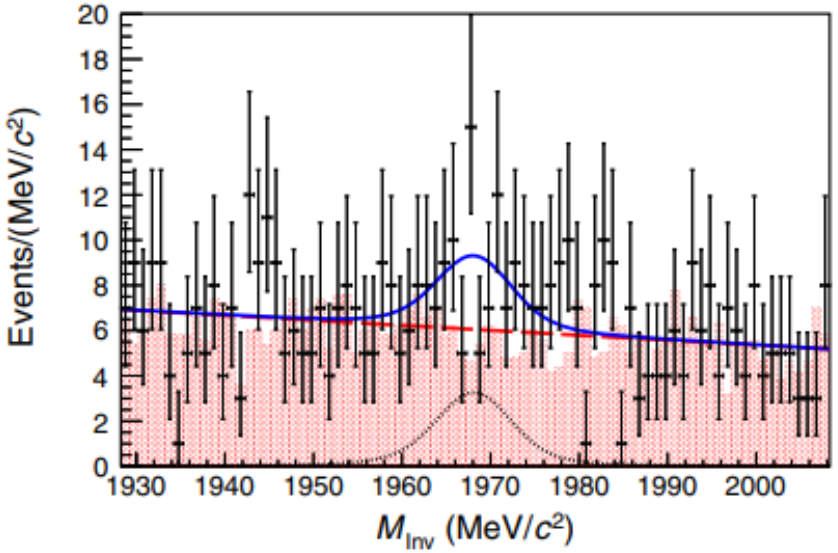
PRD 104 012003 (2021)

- Double tag analysis
- No evidence for unobserved exclusive semi-leptonic modes
- Determine the ratio of D_s^+ and D^+ semi-leptonic width

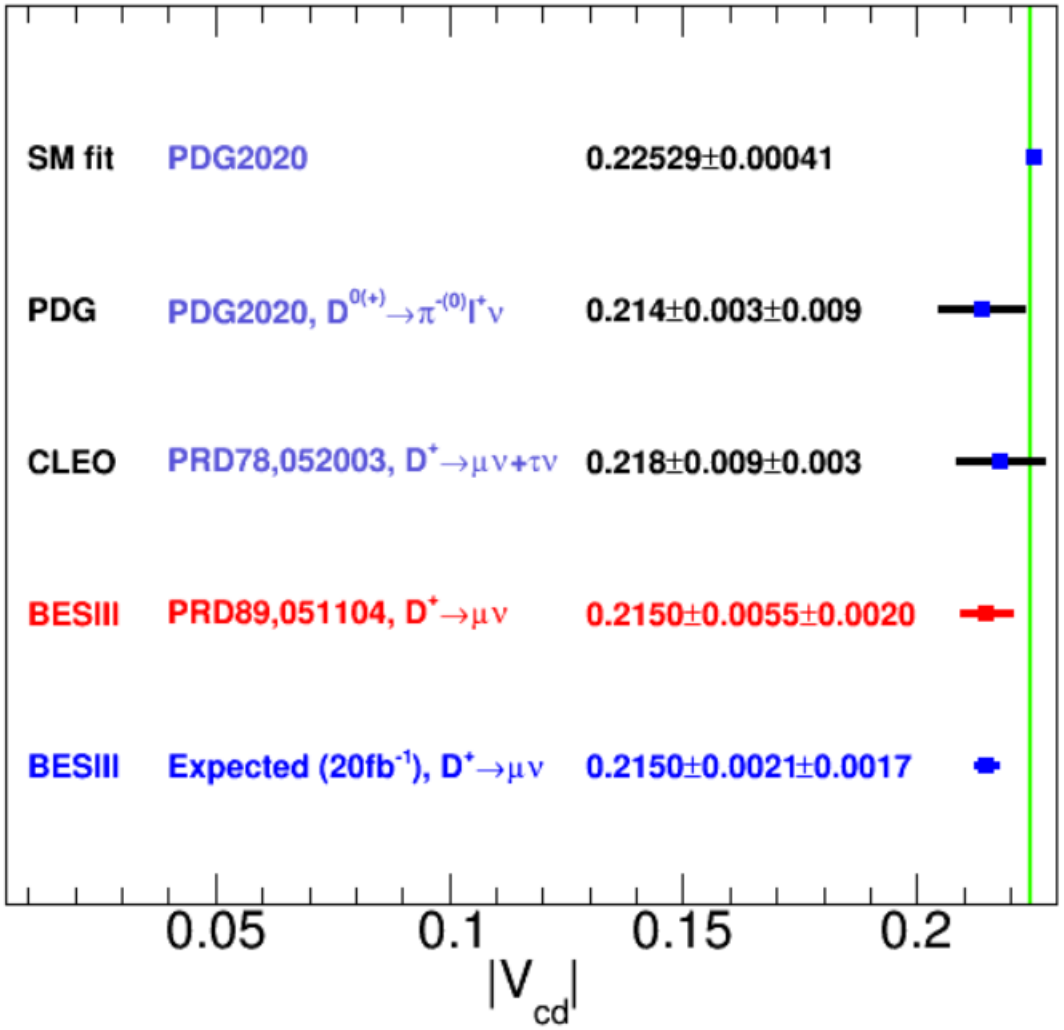
$$\mathcal{B}(D_s^+ \to X e^+ \nu_e) = (6.30 \pm 0.13 \pm 0.09 \pm 0.04)\%$$

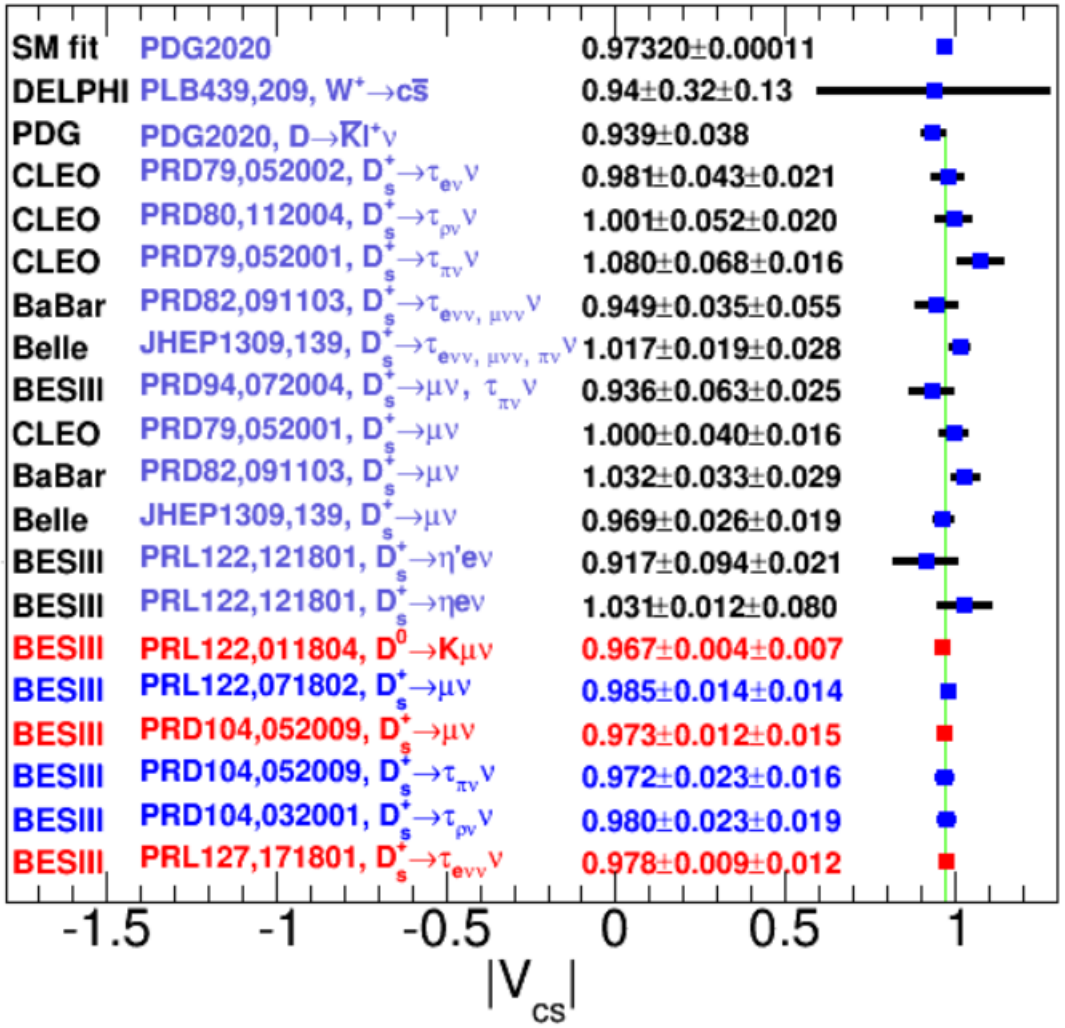
$$\frac{\Gamma(D_s^+ \to X e^+ \nu_e)}{\Gamma(D_0^+ \to X e^+ \nu_e)} = 0.790 \pm 0.016 \pm 0.011 \pm 0.016$$





Comparisons of $|V_{cd}|$ and $|V_{cs}|$





Charm meson rare decays

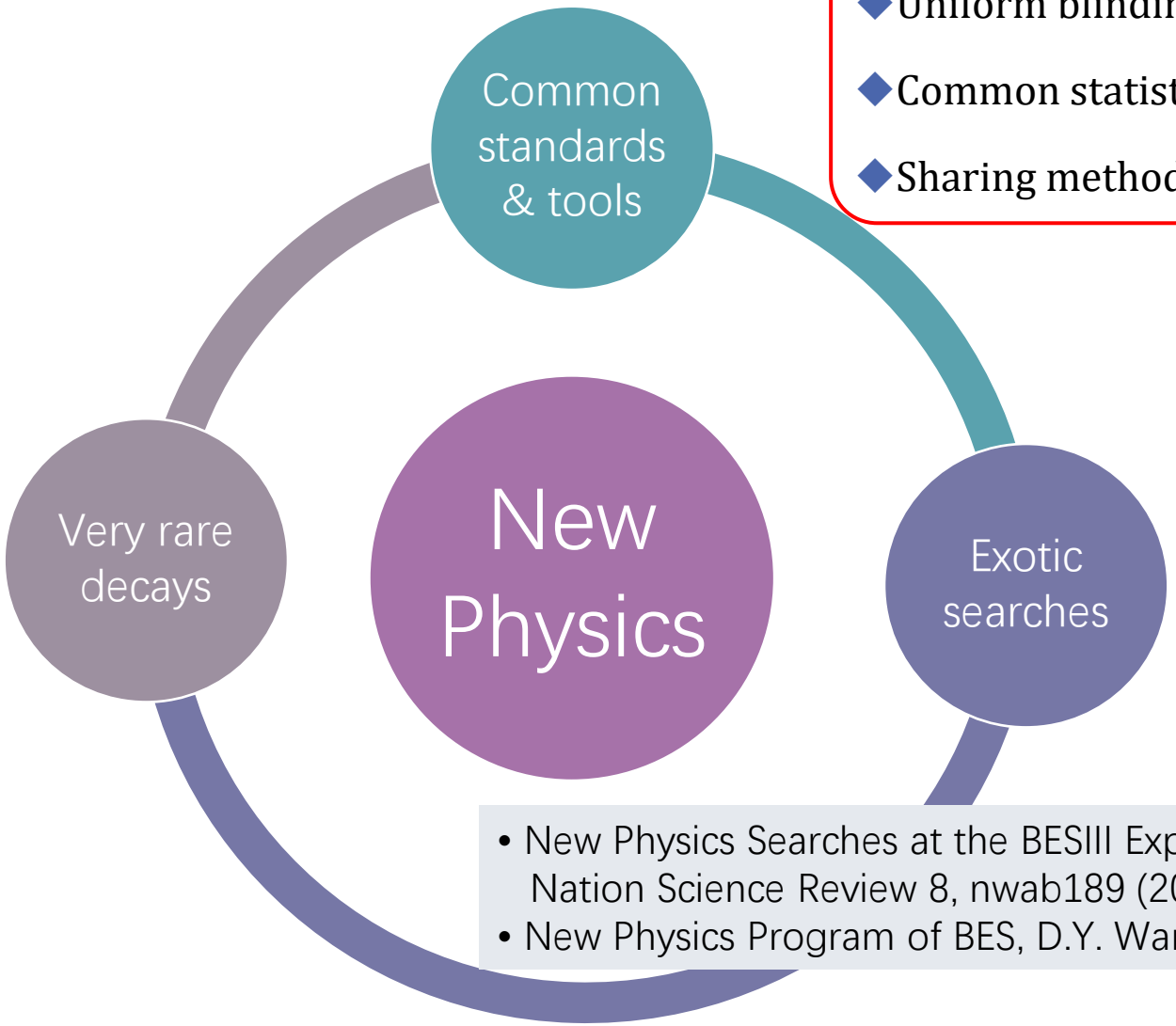
New Physics Searches at BESIII

Symmetry

- BNV & LNV processes
- LFV processes
- Other symmetry violation

- FCNC processes
- Charmonium weak decays
- Other rare decays

Very rare



- Uniform blinding strategy and datasets
- Common statistic and standards
- Sharing methods, tools and codes

Exotic

- Dark photon
- Invisible signatures
- Light Higgs, Z'
- Exotic resonances

- New Physics Searches at the BESIII Experiment, S.J. Chen and S. Olsen, Nation Science Review 8, nwab189 (2021), arXiv: 2102.13290
- New Physics Program of BES, D.Y. Wang, in "30 Years of BES Physics"

EM Dalitz decay $D^{*0} \to D^0 e^+ e^-$

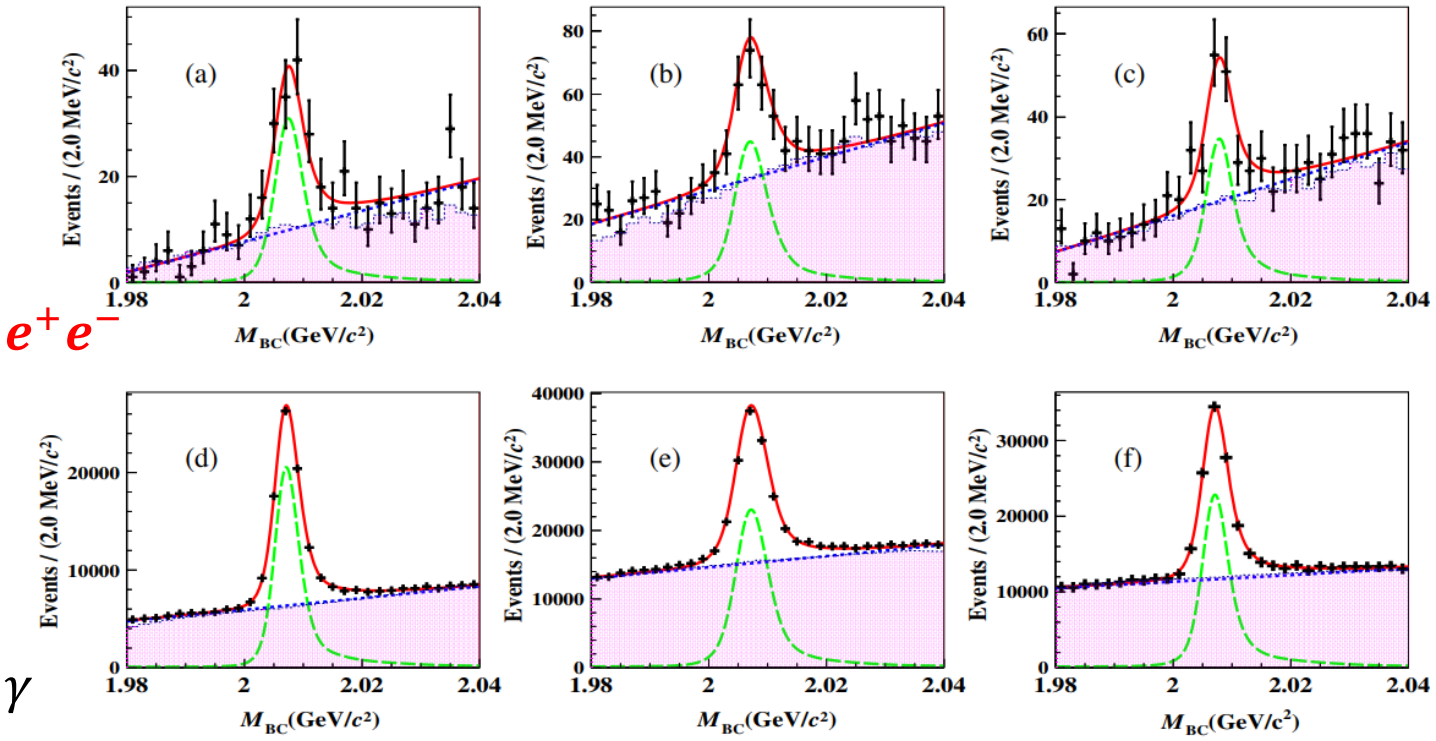
- EM Dalitz decay $D^{*0} \to D^0 e^+ e^-$ observed for the first time with 13.2σ
- Determine the branching fraction ratio relative to $D^{*0} \to D^0 \gamma$

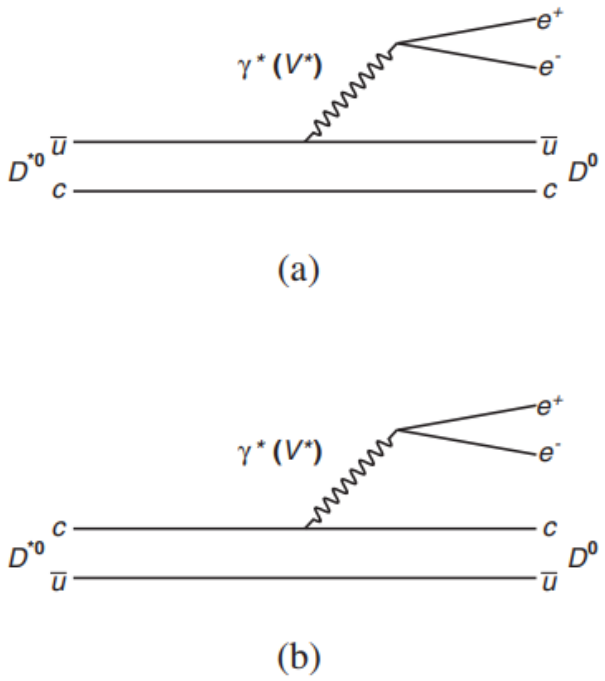
$$\mathcal{B}\left(D^{*0} \to D^0 e^+ e^-\right) = (3.91 \pm 0.27 \pm 0.17 \pm 0.10) \times 10^{-3}$$

PRD 104 112012 (2021)

$D^{*0} \to D^0 e^+ e^-$

$D^{*0} \to D^0 \gamma$

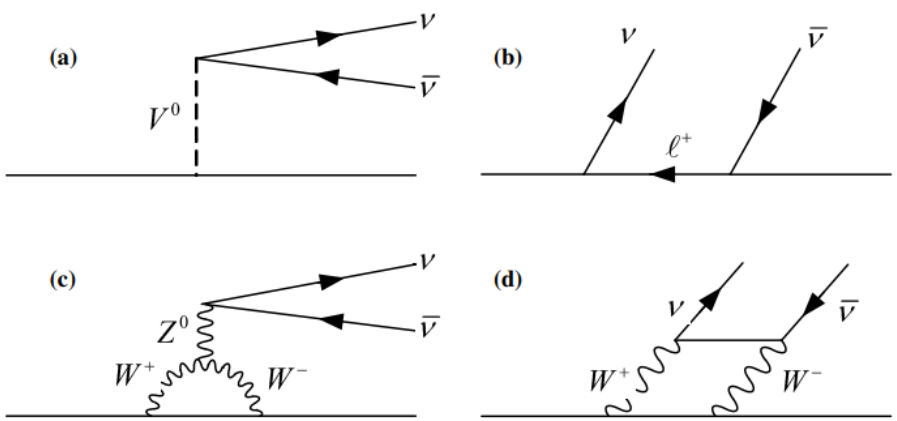


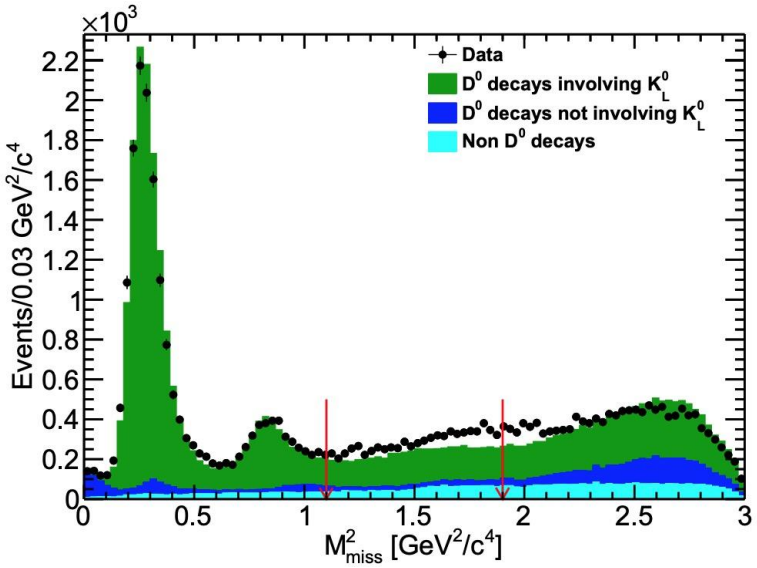


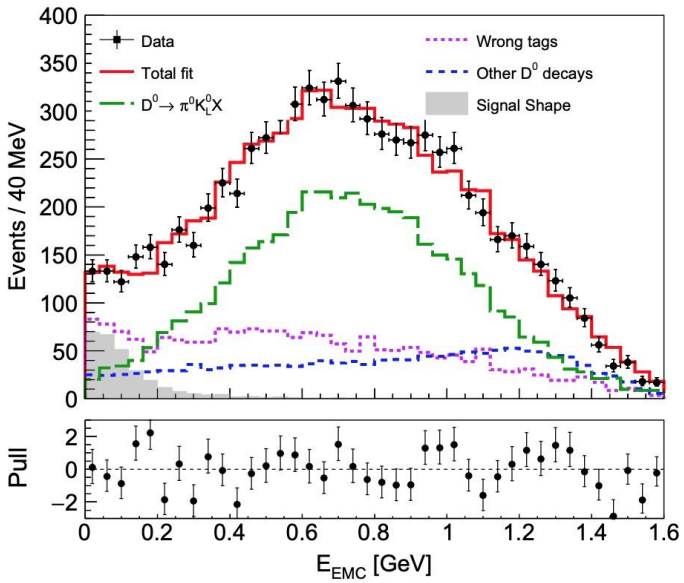
Search for FCNC process $D^0 \to \pi^0 \nu\bar{\nu}$

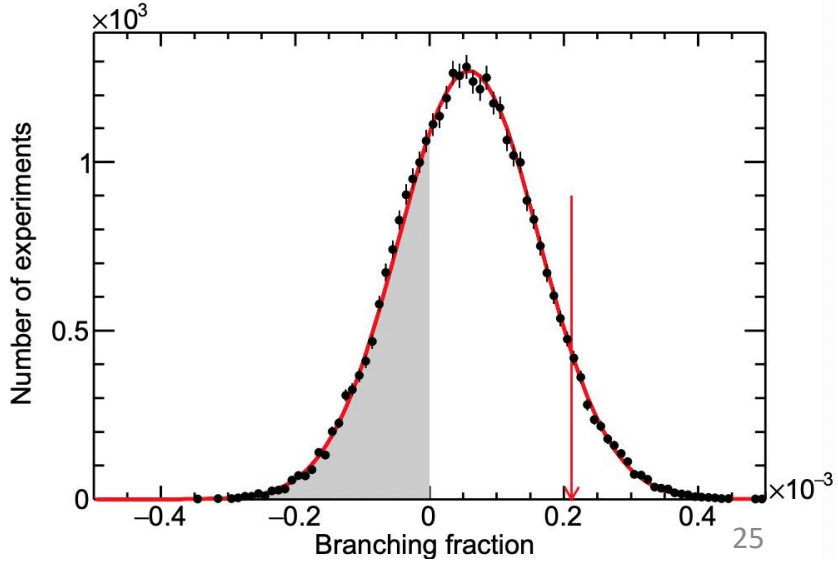
PRD 105 L071102 (2022)

- In SM, FCNC is highly suppressed by GIM mechanism, only through loop diagram, a very small BF **10^{-9} ~10^{-15}**
- The suppression in charm decay is much stronger than B & K system, stronger diagram cancellation
- Analyzing **10.6×10^6** $D^0\bar{D}^0$ pairs
- $\mathcal{B}(D^0 \to \pi^0 \nu\bar{\nu}) < 2.1 \times 10^{-4}$ @ 90%C.L.
- The first constraint on charmed hadron to di-neutrino





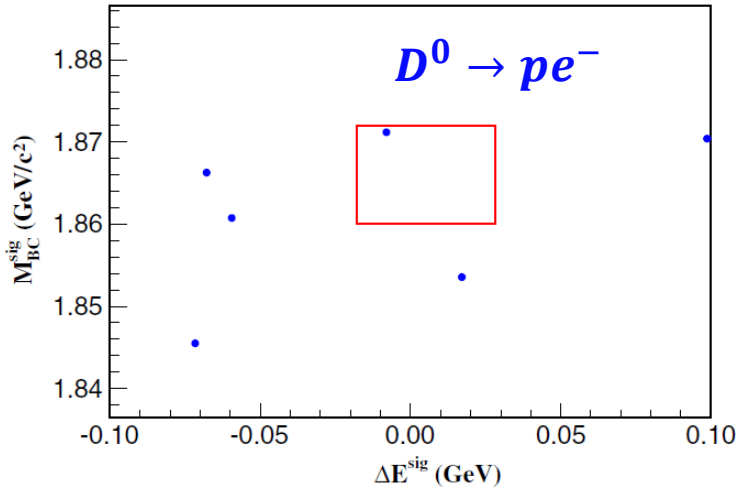




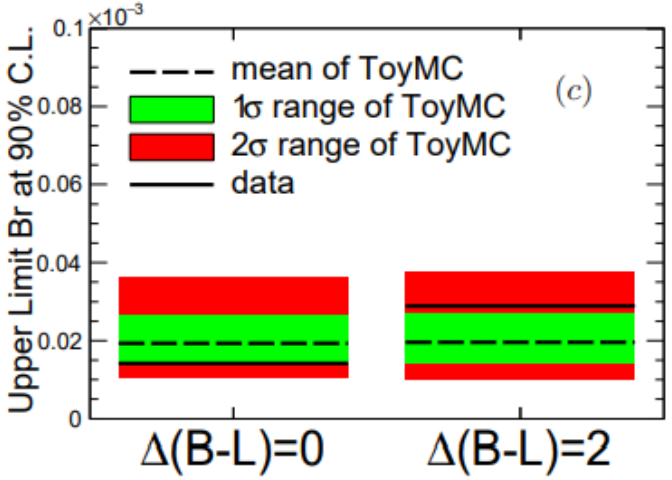
Search for LNV & BNV decay $D^0 \to pe^-, D^\pm \to n(\bar{n})e^\pm$

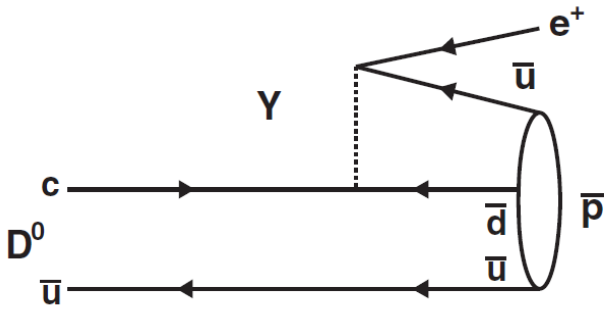
PRD 105 032006 (2022)

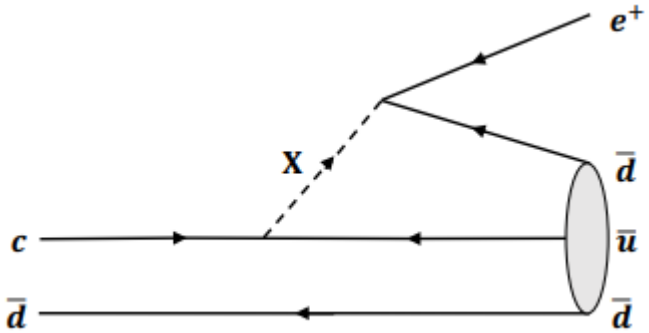
- BNV can happen with $\Delta(B-L)=0$ at dimension-six operators
- While $\Delta(B-L)=2$ allowed at dimension-seven operators
- $\mathcal{B}(D^0 \to \bar{p}e^+) < 1.2 \times 10^{-6}$ @ 90%C. L.
- $\mathcal{B}(D^0 \to pe^-) < 2.2 \times 10^{-6}$ @ 90%C. L.
- $\mathcal{B}(D^{+(-)} \to \bar{n}(n)e^{+(-)}) < 1.43 \times 10^{-5}$ @ 90%C. L. $\Delta|B-L|=0$
- $\mathcal{B}(D^{+(-)} \to n(\bar{n})e^{+(-)}) < 2.91 \times 10^{-5}$ @ 90%C. L. $\Delta|B-L|=2$
- The most stringent ones to date for these processes
- Still far above higher generation model prediction



arXiv: 2209.05787



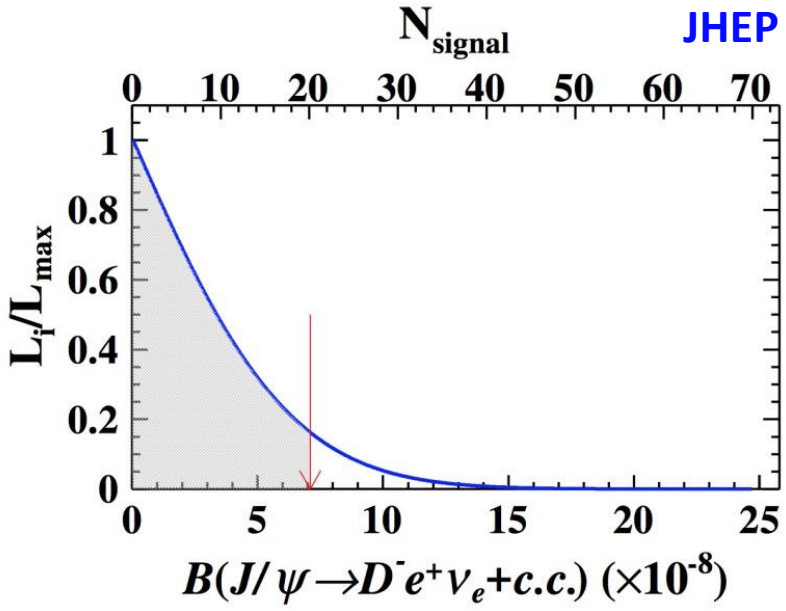


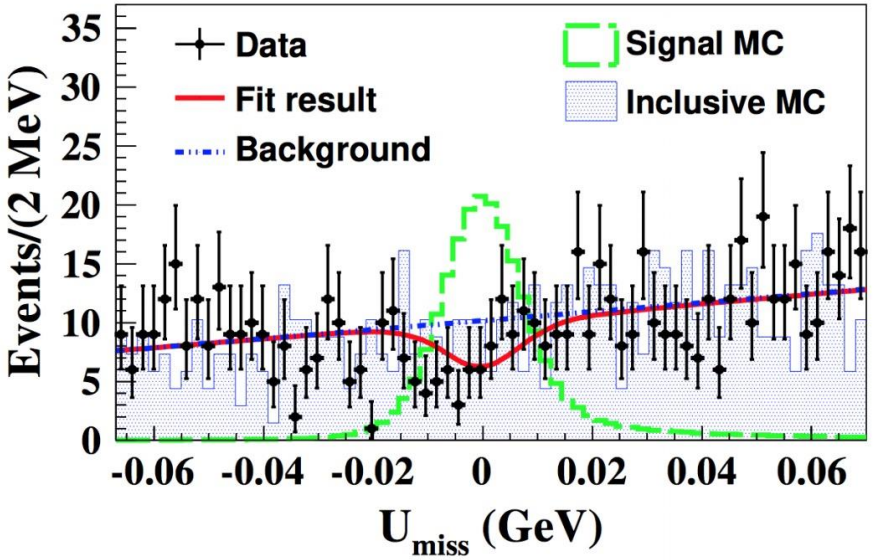


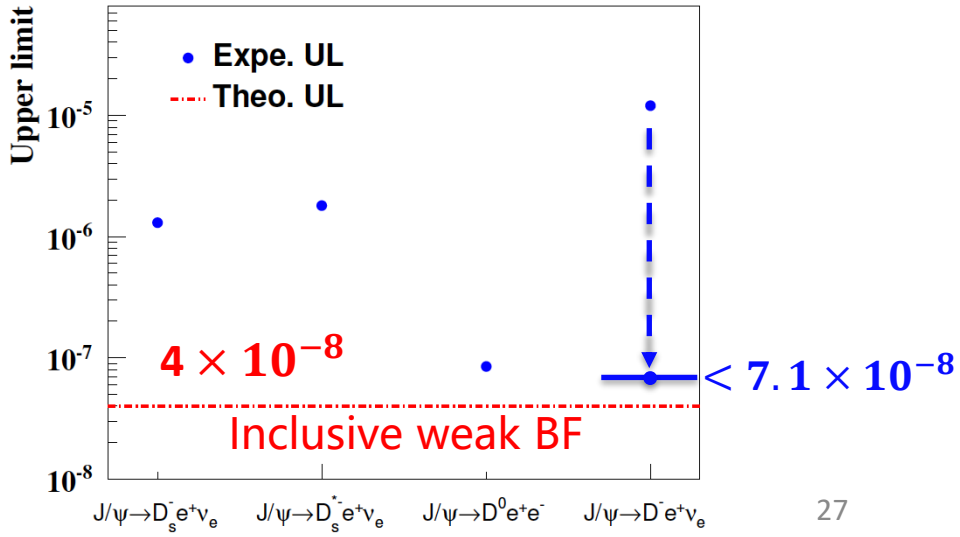
Search for charmonium weak decay $J/\Psi \to D^- e^+ \upsilon_e$

- **Allowed in SM**, but highly suppressed
- J/ψ inclusive weak decays predicted at **10^{-8}**
- $\mathcal{B}(J/\Psi \to D^- e^+ \overline{\nu}_e) < 7.1 \times 10^{-8}$ @ 90%C.L.
- The upper Limit (UL) is improved by more than two orders of magnitude
- The result is compatible with theory prediction and approaching the inclusive BF limit.

JHEP 157 (2021)





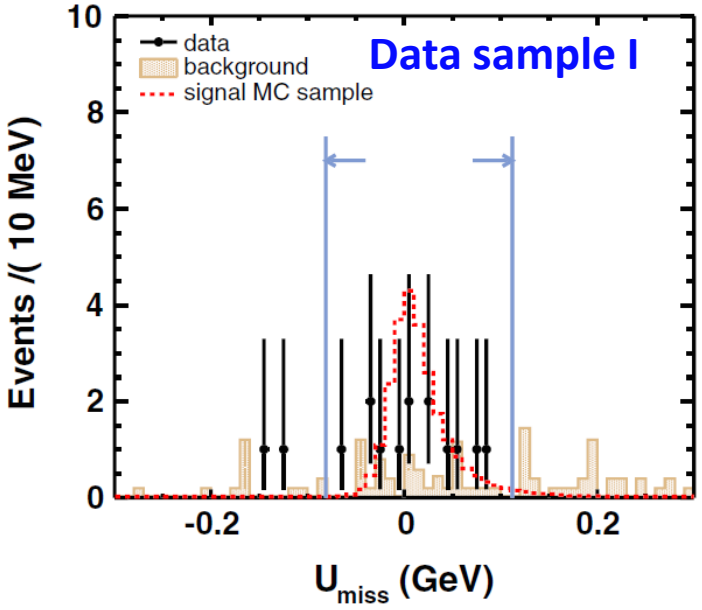


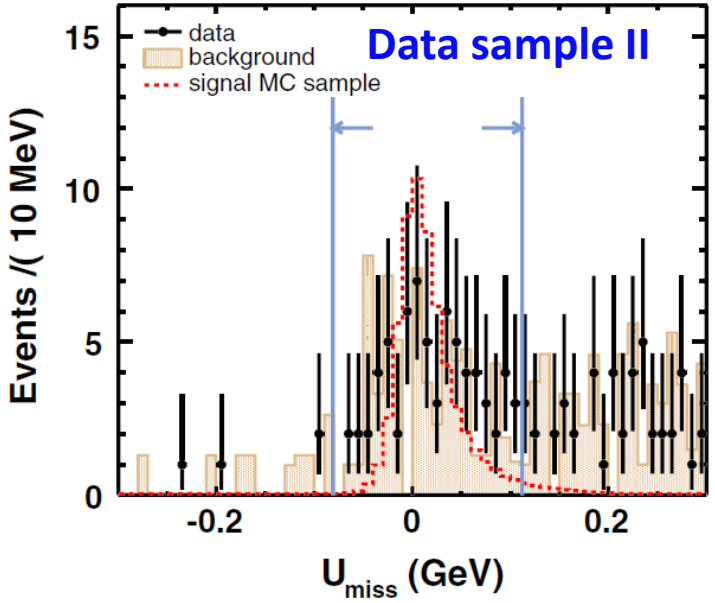
Search for LFV decay $J/\psi \to e^{\pm}\tau^{\mp}$

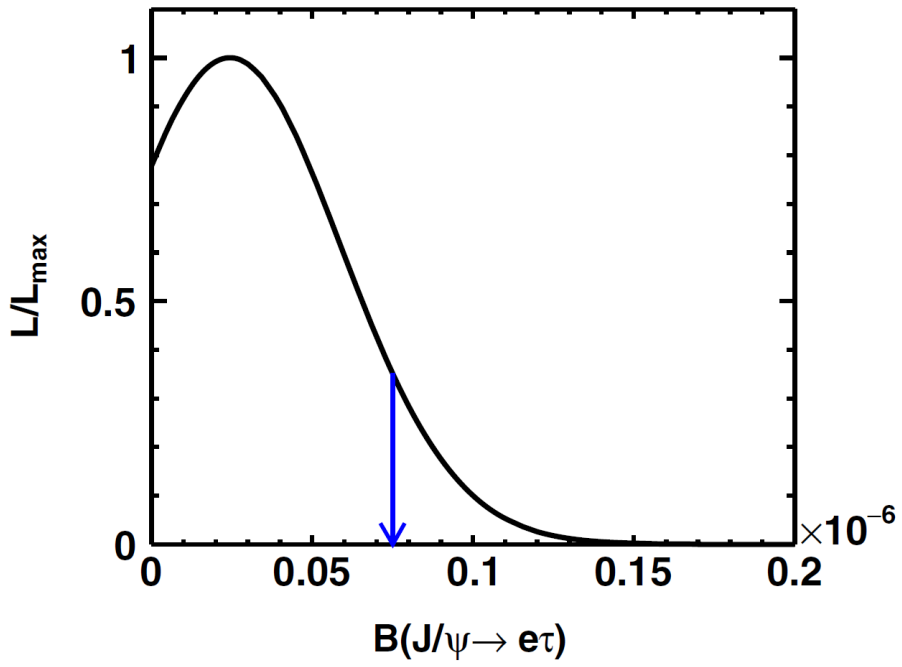
PRD 103 112007 (2021)

- Analyzing **10.087×10⁹ J/ψ** events
- Two data samples: 2009+2012 (I), 2017-2019 (II)
- Searching process $J/\psi \to e\tau, \tau \to \pi\pi^0\nu$
- $\mathcal{B}(J/\psi \to e\tau) < 7.5 \times 10^{-8}$ @ 90%C. L.
- Improve the previous best limits by two orders of magnitude, comparable with theoretical predictions

The 1st submitted paper based on full 10 billion J/ψ data of BESIII



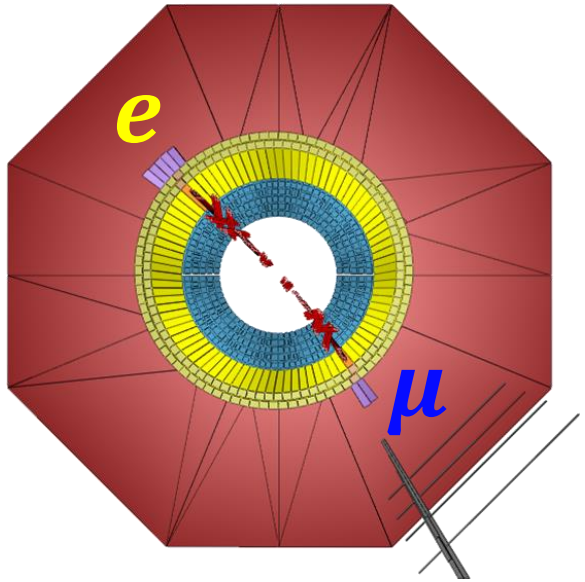


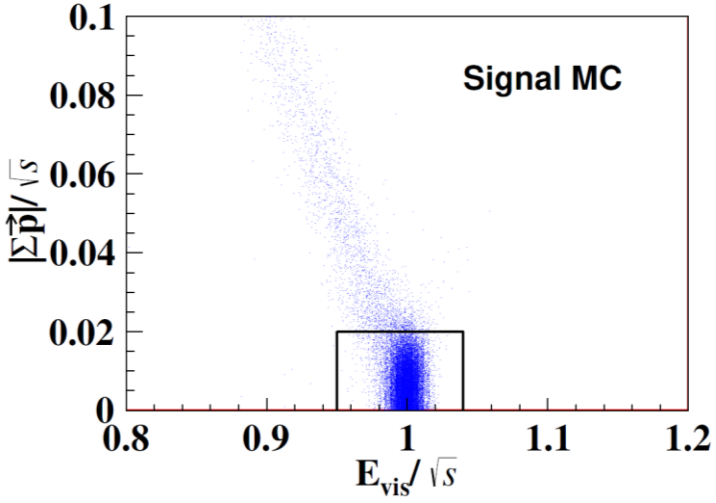


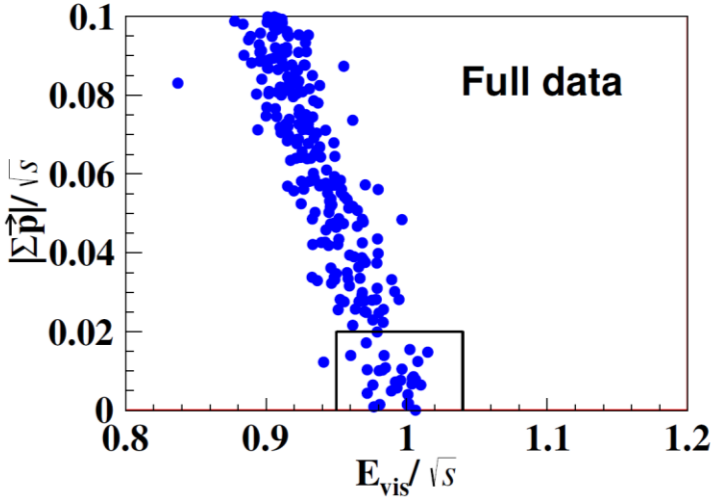
Search for LFV decay $J/\psi \to e^{\pm}\mu^{\mp}$

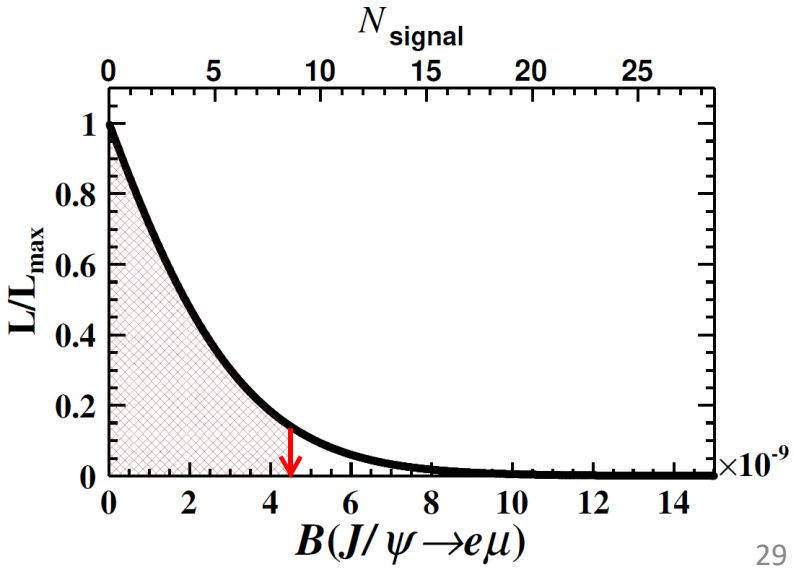
- Analyzing **8.998×10⁹ J/ψ** events
- Searching for two back-to-back $e\ \mu$
- $\mathcal{B}(J/\psi \to e\mu) < 4.5 \times 10^{-9}$ @ 90%C. L.
- Improve the previous best limit by a factor of > 30
- The most stringent BESIII upper limit measurement
- The most precise CLFV search in heavy quarkonium
- Excluding the parameter space of some models

SCIENCE CHINA: Physic, Mechanics & Astronomy 66, 221011 (2023)



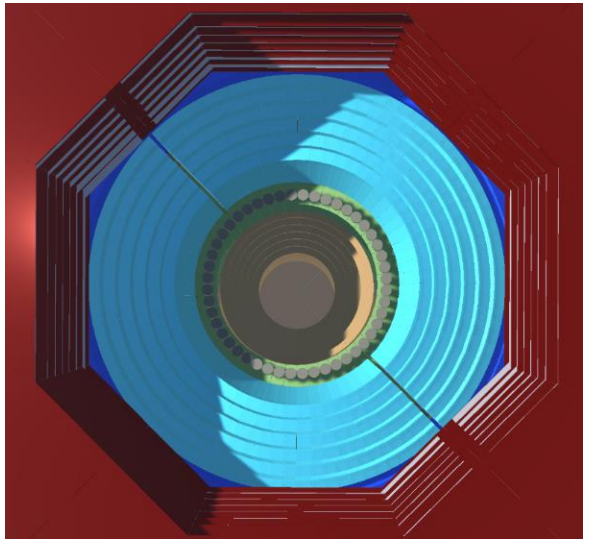






Summary

- Improve CKM matrix $|V_{cs}|, |V_{cd}|$ & form factors $\mathbf{f}_{\mathbf{D}_s^+}, \mathbf{f}_{\mathbf{D}^+}$ with charm leptonic decays
- Rare decays and violating decays (LNV, BNV, LFV) to probe New Physics beyond SM
- BESIII has great potential with unique datasets and advanced analysis techniques
- BESIII has collected $\mathbf{10^{10}}$ J/ψ and $\mathbf{2.7 \times 10^9}$ ψ' events
- BESIII will collect 20 $\mathbf{fb^{-1}}$ @ 3.773 GeV $D\bar{D}$
- More & better results are coming soon!



Thank you!