Search for rare charm decays at BESIII

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On behalf of BESIII Collaboration

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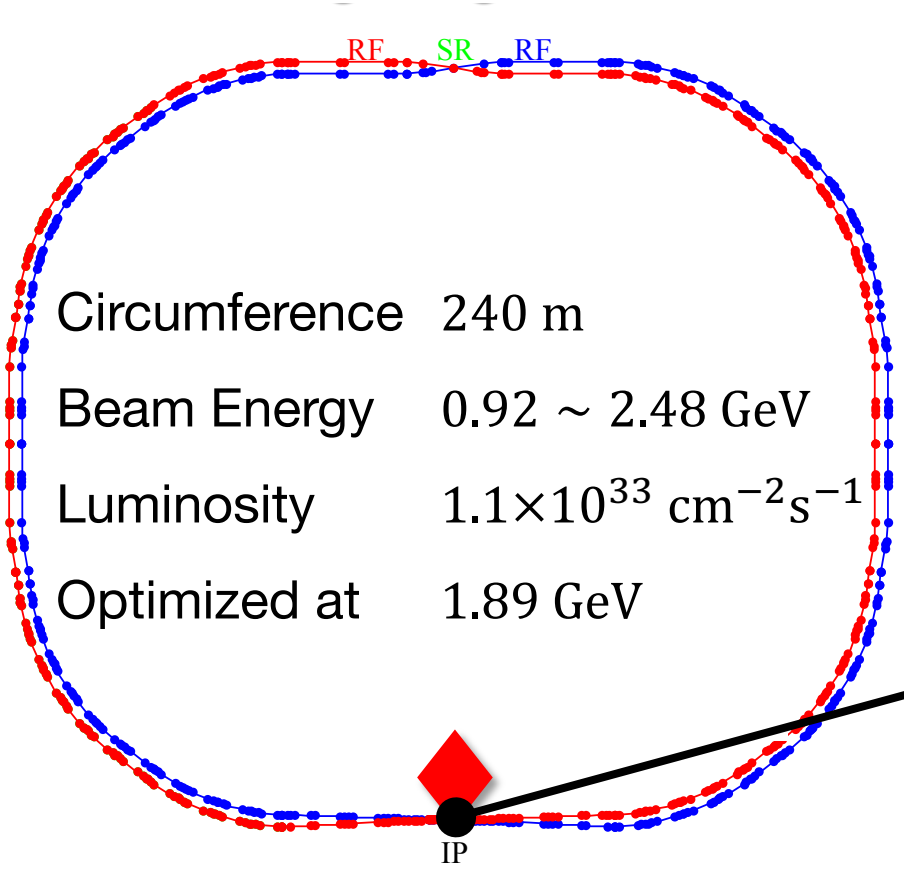
Contents

BEPCII & BESIII as Tau-Charm Factory

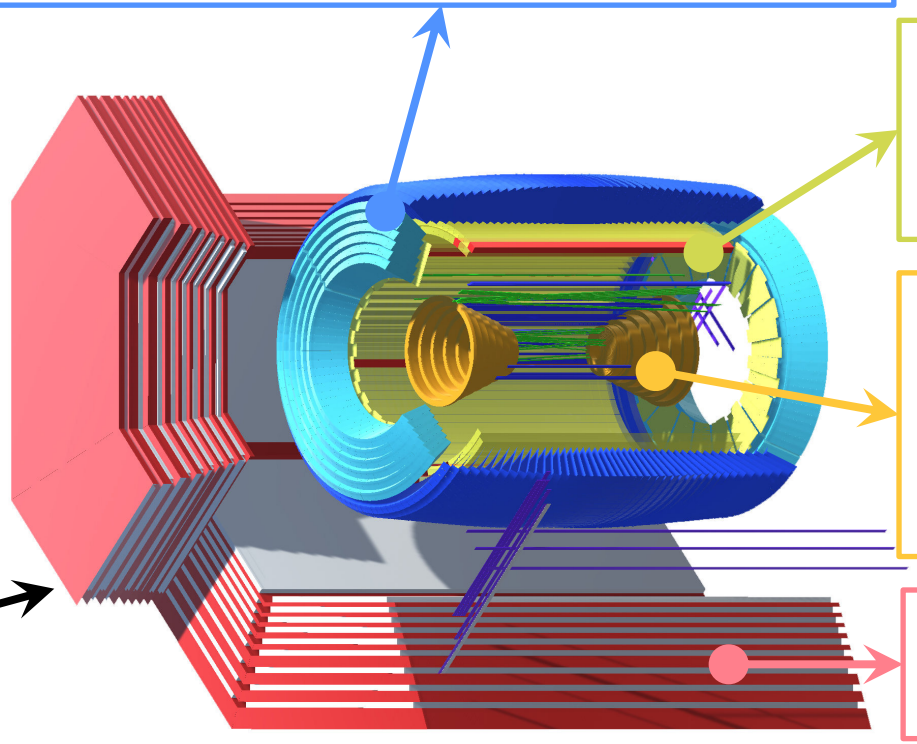
Beijing Electron Positron Collider II (BEPC II) Storage Rings



Circumference	$240\ \mathrm{m}$
Beam Energy	$0.92 \sim 2.48\ \mathrm{GeV}$
Luminosity	$1.1\times10^{33}\ \mathrm{cm^{-2}s^{-1}}$
Optimized at	$1.89\ \mathrm{GeV}$

Beijing Spectrometer III (BESIII) Detector Geometry

Electromagnetic Calorimeter (EMC)
- Barrel $\sigma_E/E = 2.5\%$ @ $1\ \mathrm{GeV}/c$
- Endcap $\sigma_E/E = 5.0\%$ @ $1\ \mathrm{GeV}/c$



Time-of-flight (TOF)
- Barrel $\sigma_T = 68\ \mathrm{ps}$
- Endcap $\sigma_T = 60\ \mathrm{ps}$

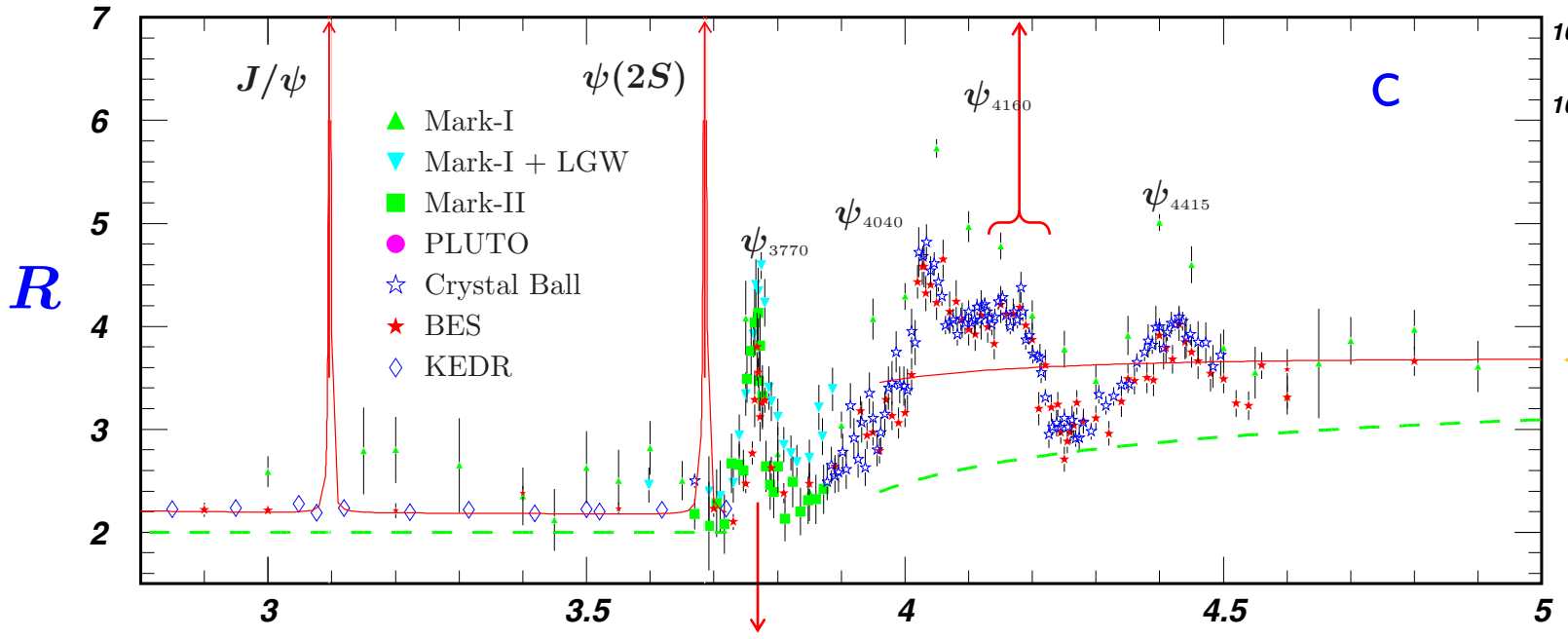
Main Drift Chamber (MDC)
- $\sigma_P/P = 0.5\%$ @ $1\ \mathrm{GeV}/c$
- $\sigma_{\mathrm{d}E/\mathrm{d}x} = 6\%$
- $\Delta\Omega/4\pi = 93\%$

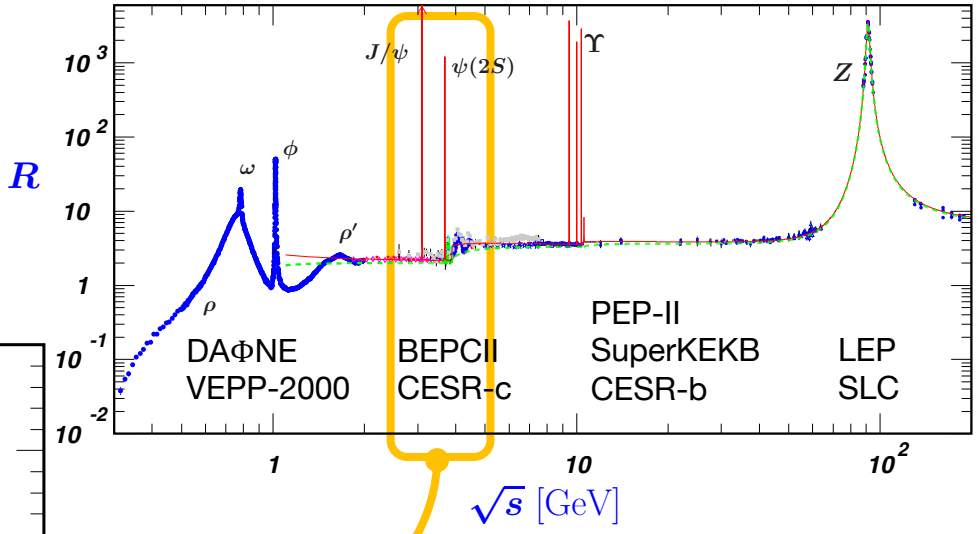
Muon Counter (MUC)
- $P_{\mathrm{cut-off}} = 0.4\ \mathrm{GeV}/c$

BESIII Data Sample

- The largest on-threshold charmonium data sets in the world!
- Pair-production charm mesons & Single/Double Tag

10.0 B J/ψ | 2.71 B $\psi(2S)$ | 7.33 fb^{-1} $D_s^* D_s$

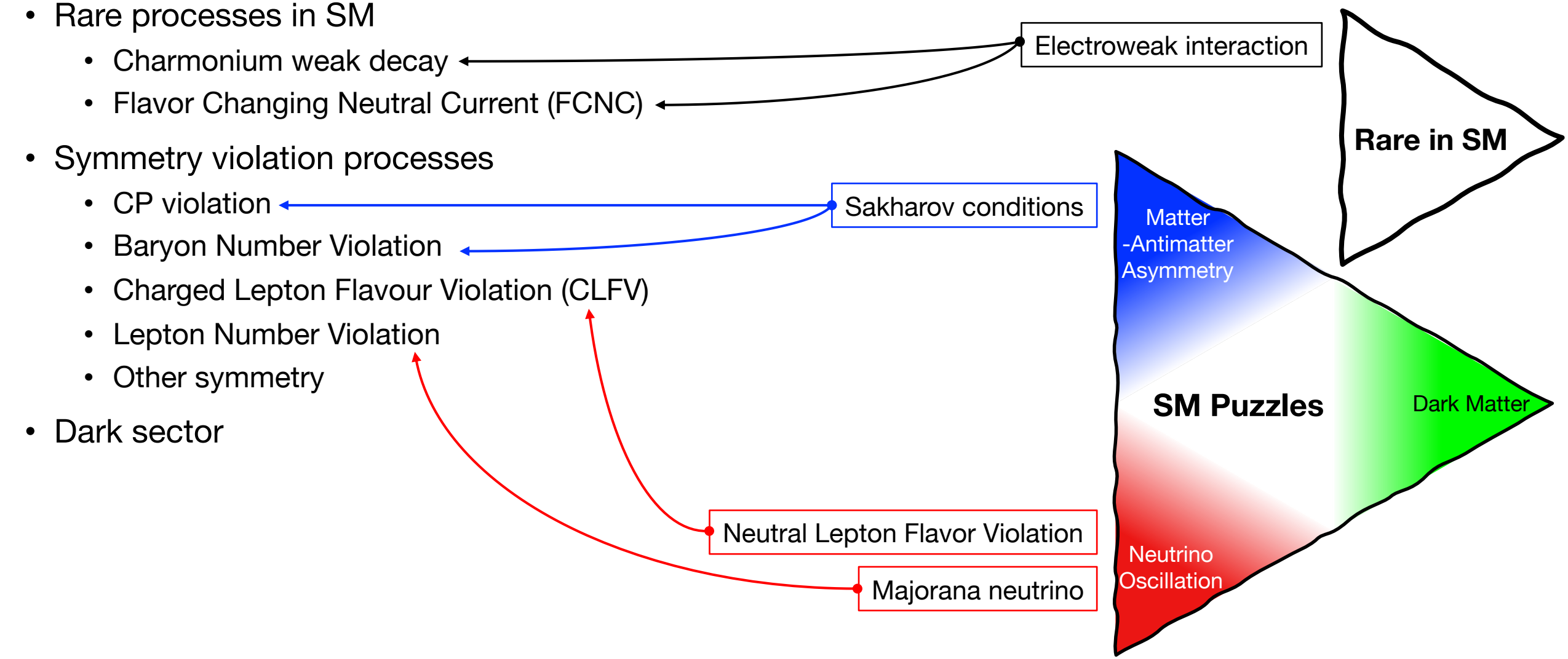




Chin. Phys. C 46, 074001 (2022)
Chin. Phys. C 48, 093001 (2024)
Chin. Phys. C 48, 123001 (2024)
Chin. Phys. C 45, 103001 (2021)
Chin. Phys. C 46, 113002 (2022)

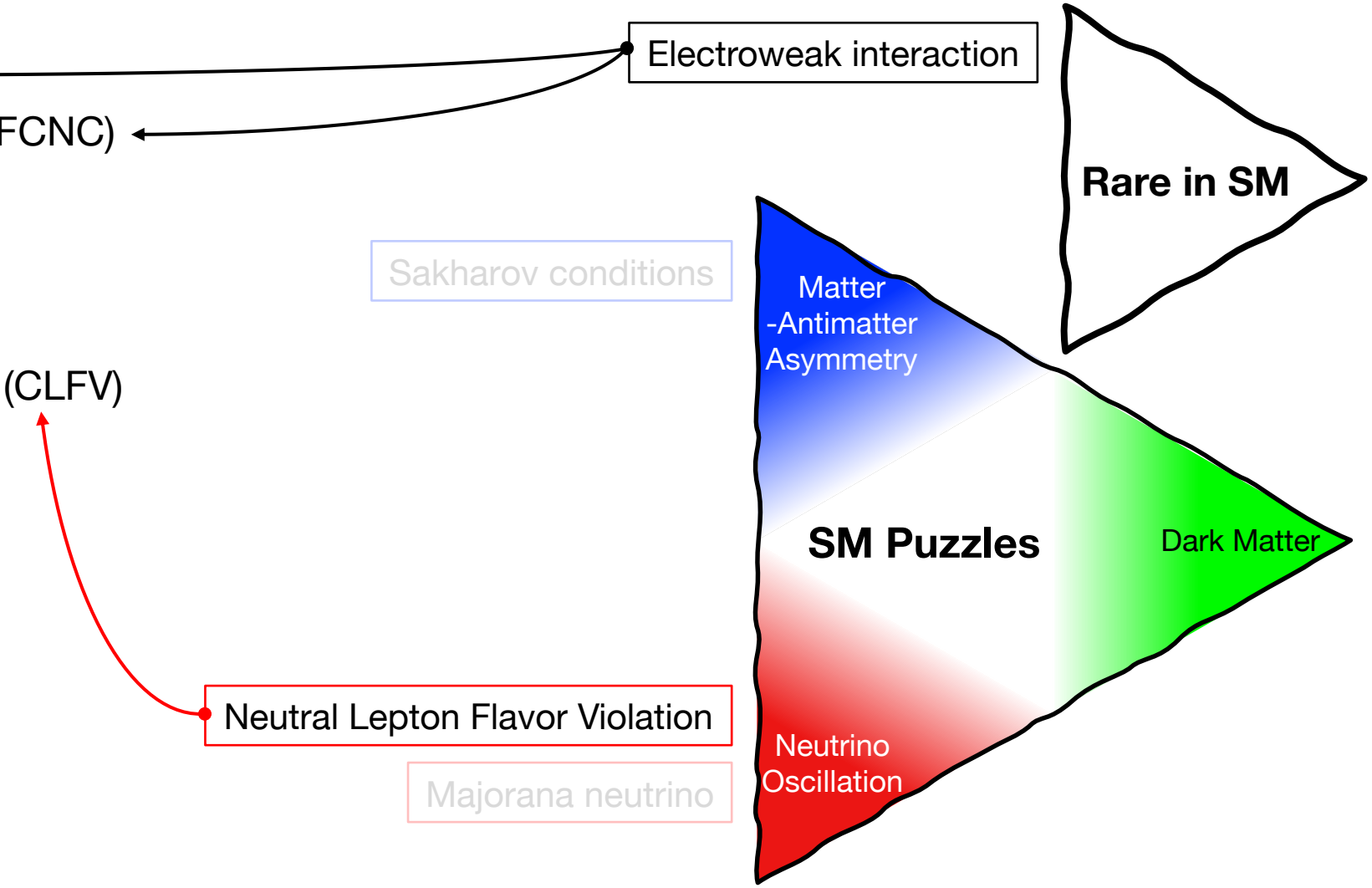
New Physics Searches at BESIII

- Rare processes in SM
  - Charmonium weak decay
  - Flavor Changing Neutral Current (FCNC)
- Symmetry violation processes
  - CP violation
  - Baryon Number Violation
  - Charged Lepton Flavour Violation (CLFV)
  - Lepton Number Violation
  - Other symmetry
- Dark sector



New Physics Searches at BESIII Selective update

- Rare processes in SM
  - Charmonium weak decay
  - Flavor Changing Neutral Current (FCNC)
- Symmetry violation processes
  - CP violation
  - Baryon Number Violation
  - Charged Lepton Flavour Violation (CLFV)
  - Lepton Number Violation
  - Other symmetry (Bose symmetry)
- Dark sector



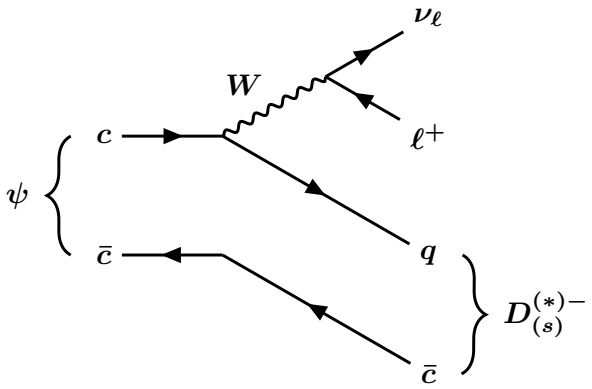
Contents

Charmonium weak decay Introduction

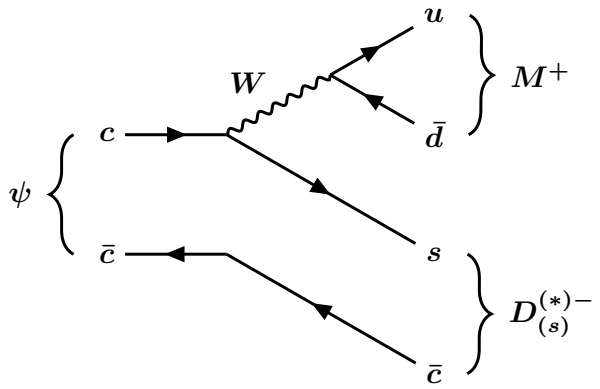
- Weak decays of $\psi \to D_{(s)}^{(*)} X$ are kinematically allowed, but rare in SM.
- Inclusive branching fraction (BF) is $\sim 10^{-8}$, exclusive BFs will be lower. [Z. Phys. C 62, 271 (1994)]
- New physics (NP) may enhance it to be observable. [Phys. Rev. D 60, 014011 (1999)]

- According to Feynman diagram topology
  - Semi-leptonic W-external
  - Hadronic W-external, W-internal

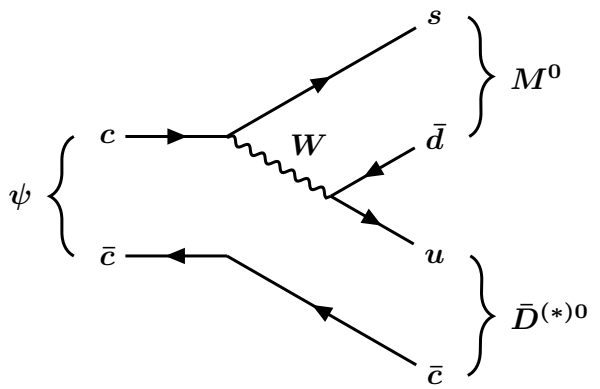
- According to CKM matrix element
  - Cabibbo favoured (CF) $c \to s$
  - Cabibbo suppressed (CS) $c \to d$



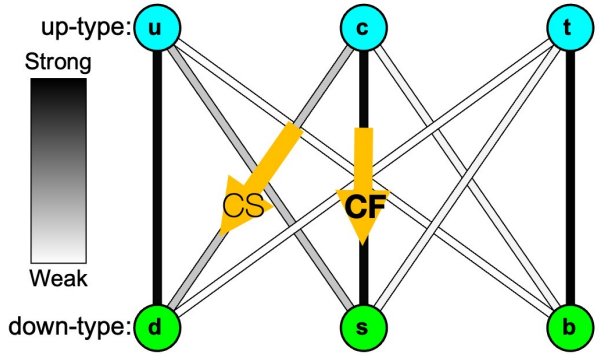
➢ Semi-leptonic decay



➢ Hadronic decay (W_{exter})



➢ Hadronic decay (W_{inter})

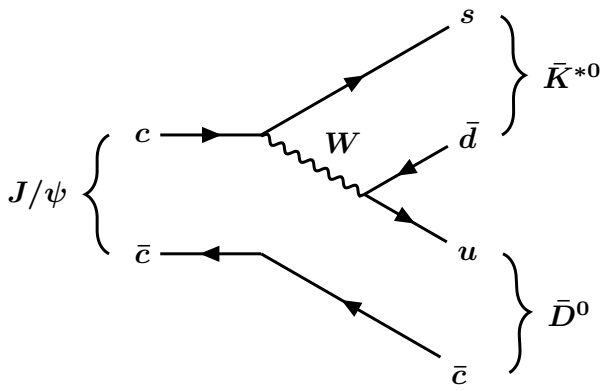


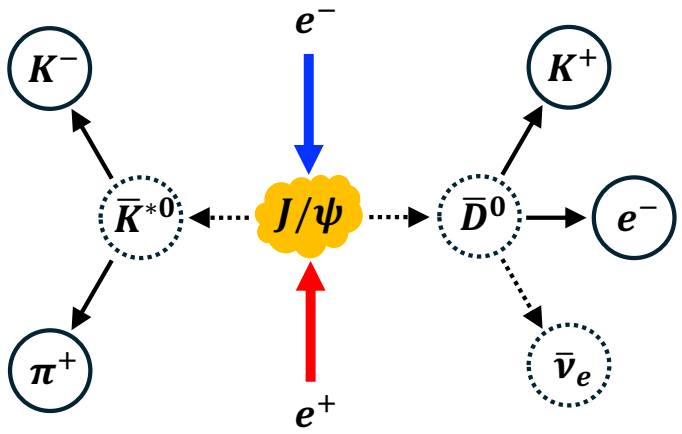
Charmonium weak decay $J/\psi \to \bar{D}^0 \bar{K}^{*0}$

- CF Hadronic decay
- Reconstruction
  - $\bar{D}^0 \to K^+ e^- \bar{\nu}_e$(suppress hadronic backgrounds)
  - $\bar{K}^{*0} \to K^- \pi^+$
- Selection
  - Final states $K^+K^-\pi^+e^-$
  - Missing particle $\bar{\nu}_e$
  - Intermediate states $\bar{K}^{*0}, \bar{D}^0$

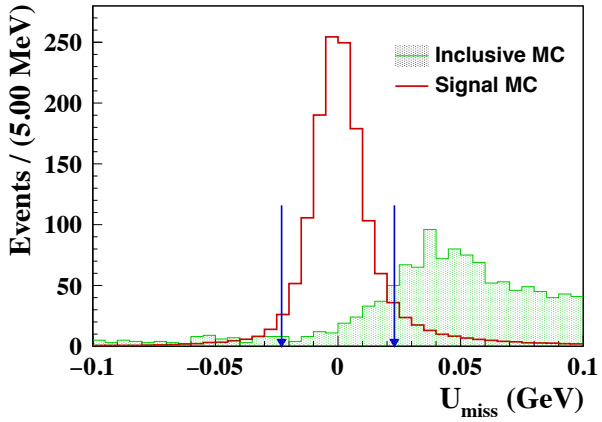
$$U_{\text{miss}} = E_{\text{miss}} - P_{\text{miss}} \to 0$$

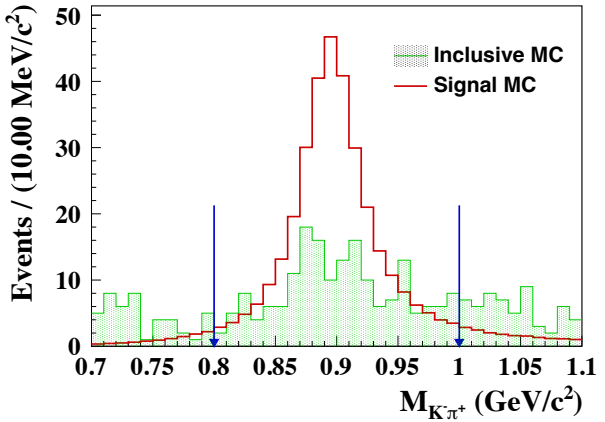
$$M_{K^-\pi^+} \to M_{K^{*0}}, \quad M^{\text{recoil}}_{K^-\pi^+} \to M_{D^0}$$

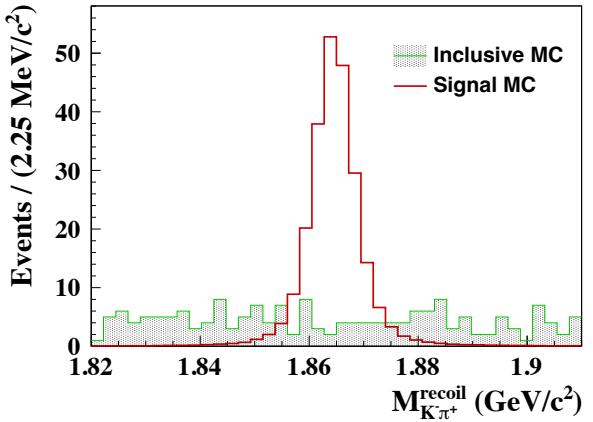




- Signal Window
  - $M^{\text{recoil}}_{K^-\pi^+}$



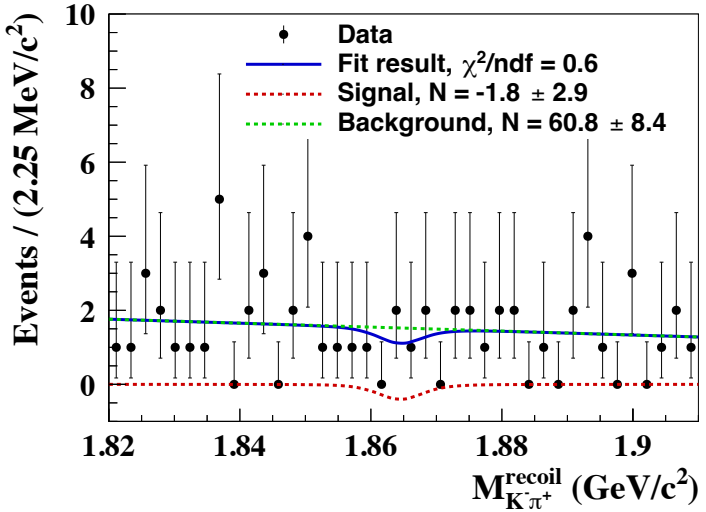


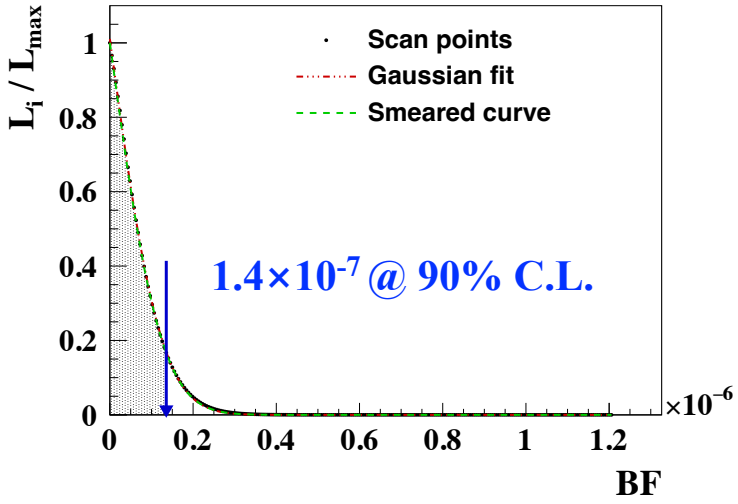


JHEP 05, 126 (2026)

Charmonium weak decay $J/\psi \to \bar{D}^0 \bar{K}^{*0}$

- Blind analysis
  - Selection criteria are determined by MC samples
  - Not unblind data sample until analysis procedure finalized
  - To avoid involuntary bias
- Signal extraction
  - $\mathcal{F}_{\rm fit} = f_{\rm sig}{\rm PDF}_{\rm sig} + f_{\rm bkg}{\rm Poly}_{\rm bkg}$
  - $\mathcal{B}(J/\psi \to \bar{D}^0 \bar{K}^{*0} + {\rm c.c.}) = \frac{N_{\rm sig}}{N_{J/\psi}\cdot\varepsilon\cdot\mathcal{B}(\bar{D}^0\to K^+e^-\bar{\nu}_e)\cdot\mathcal{B}(\bar{K}^{*0}\to K^-\pi^+)}$
- Result
  - $\mathcal{L} = {\rm Poisson}\cdot\prod_i \mathcal{F}_{\rm fit}$
  - $\mathcal{B}(J/\psi \to \bar{D}^0 \bar{K}^{*0} + {\rm c.c.}) < 1.4\times10^{-7}$ @ 90% CL





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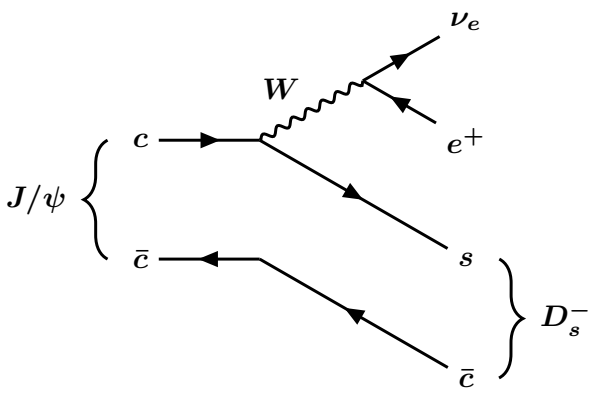
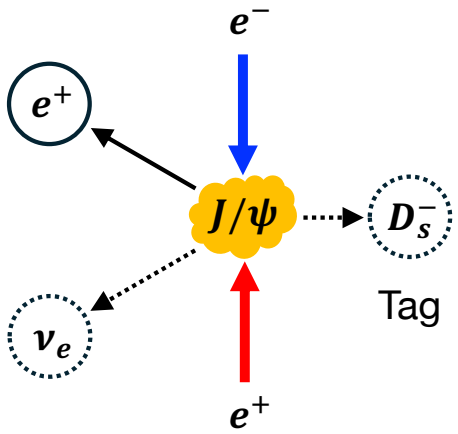
Charmonium weak decay

$J/\psi \to D_s^- e^+ \nu_e$

- CF Semi-leptonic decay
- Reconstruction of D_s
  - Mode I : $K_S^0 K^-$
  - Mode II : $K^+ K^- \pi^-$
  - Mode III: $K^+ K^- \pi^- \pi^0$
  - Mode IV: $K_S^0 K^- \pi^+ \pi^-$



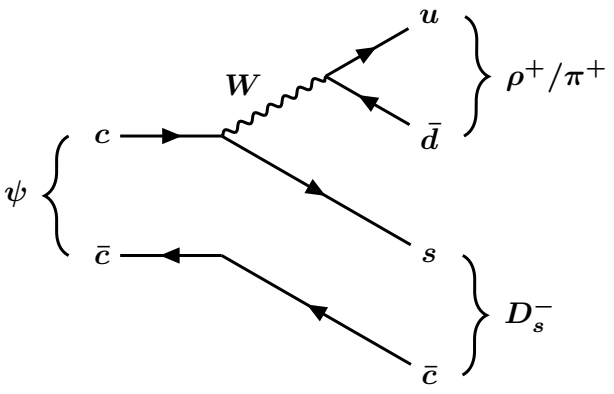


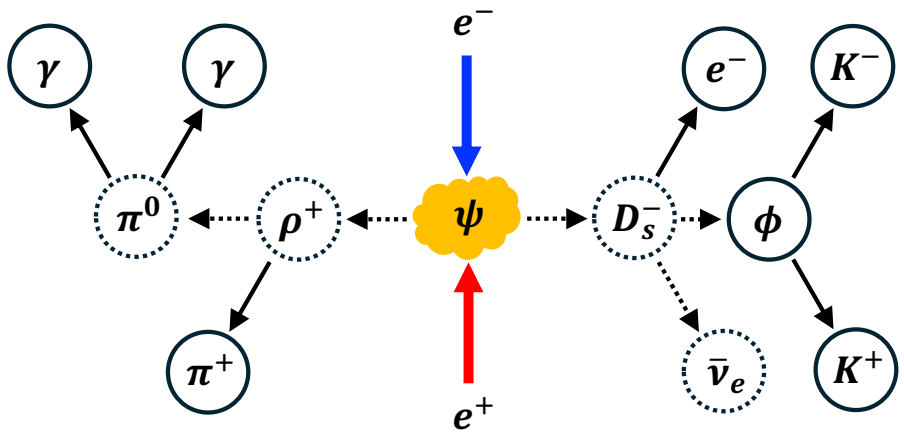
arXiv:2510.25100

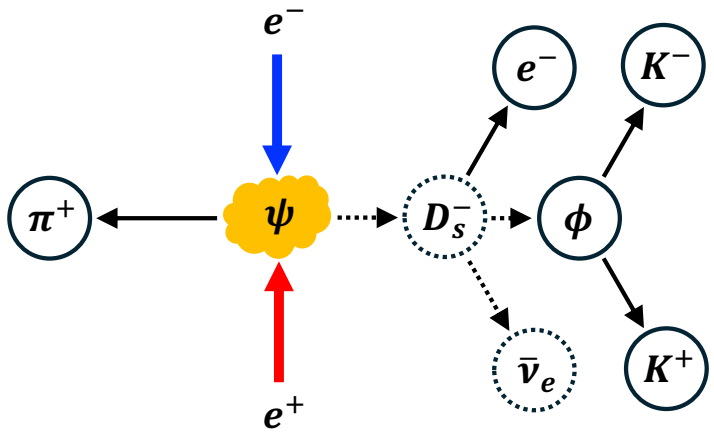
Others

$J/\psi, \psi(2S) \to D_s^- \rho^+, D_s^- \pi^+$

- CF Hadronic decay
- Reconstruction
  - $D_s^- \to \phi e^- \bar{\nu}_e$
  - $\phi \to K^+ K^-$
  - $\rho^+ \to \pi^+ \pi^0$





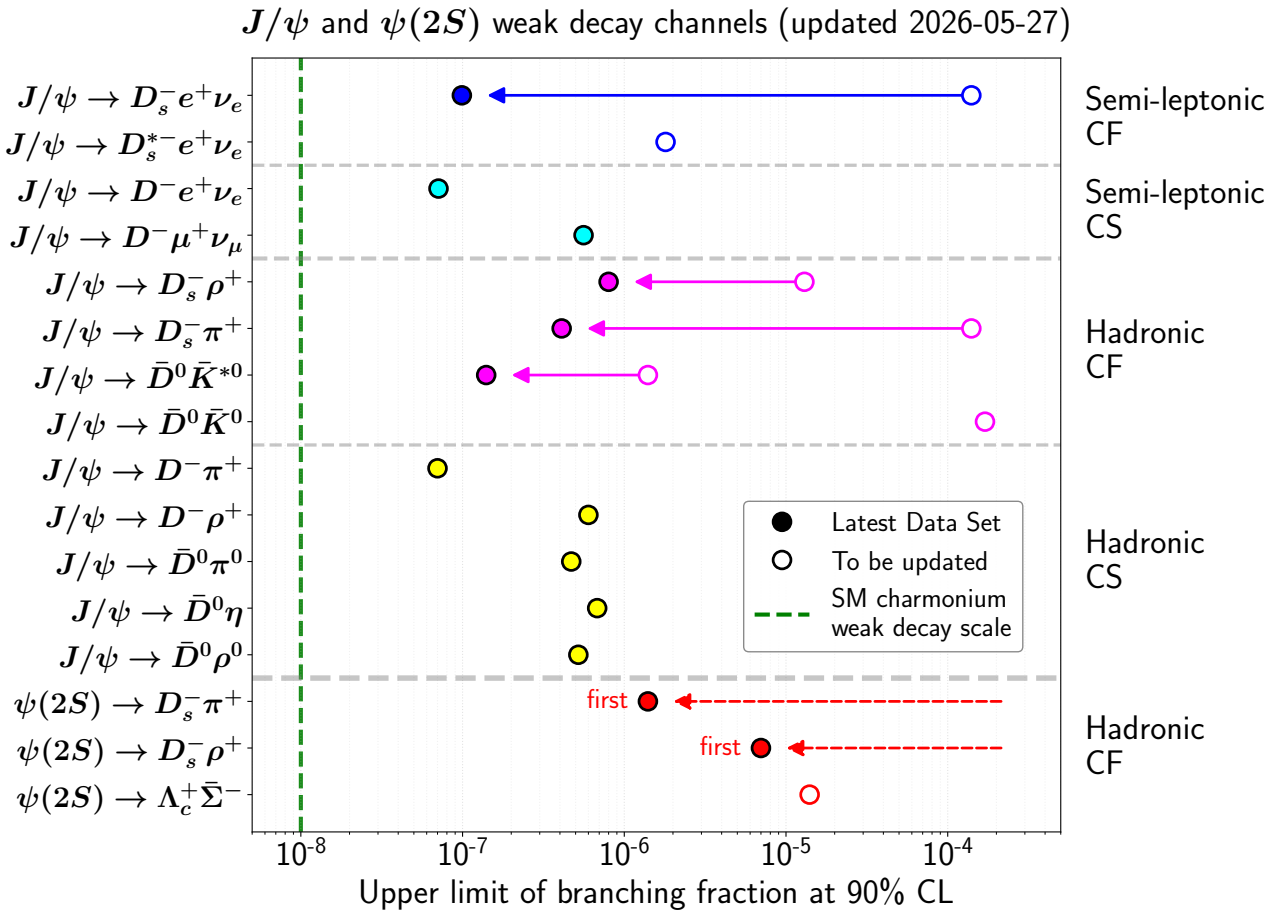


JHEP 12, 077 (2025); arXiv:2603.01777

Charmonium weak decay

- Update
  - 4 ULs improved 1~3 orders of magnitude.
  - 2 ULs are first measurements.
- Current status
  - No signal evidence
  - UL pushed to $10^{-7} \sim 10^{-6}$.
  - Few channels need to be updated.
- BESIII advantages
  - Largest on-threshold charmonium samples
  - Comprehensive research for J/ψ weak decays
  - The strictest UL of charmonium weak decays

BESIII brief summary



arXiv:2603.22082

Contents

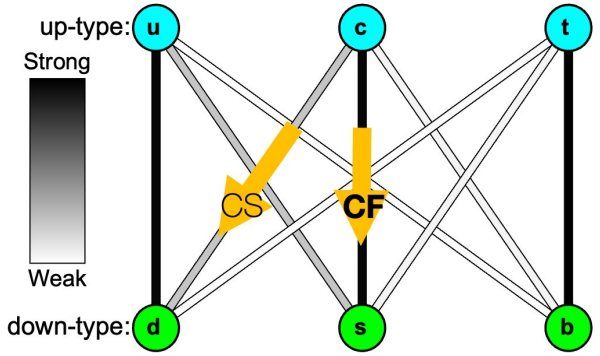
FCNC decay

- Flavor-changing charged current $c \to s(d)$
  - $c \to s(d)W^+,\ W^+ \to \ell^+\nu_\ell / u\bar{d}$
- Flavor-changing neutral current $c \to u$
  - $c \to u\gamma$
  - $c \to ug$
  - $c \to u\bar{q}q$
  - $c \to u\ell^+\ell^-$
  - $c \to u\bar{\nu}\nu$

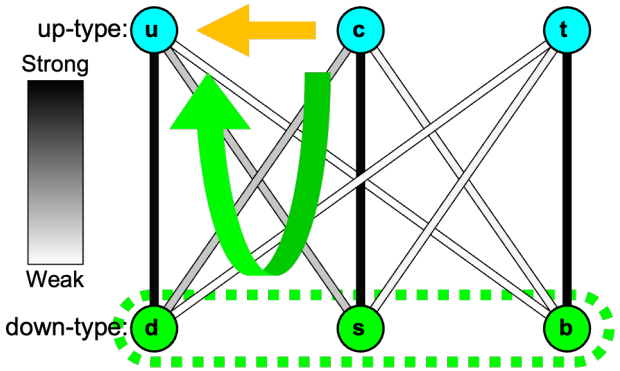
Suitable for BESIII

- $c \to u$ is the most strongly GIM-suppressed FCNC transition. [Phys. Rev. D 66, 014009 (2002)]
- Feynman diagram topology
  - Penguin
  - W box

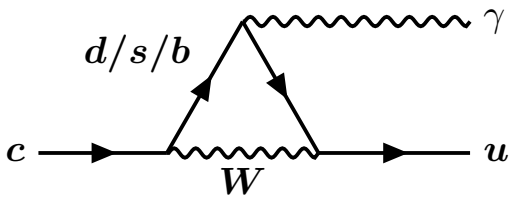
Introduction



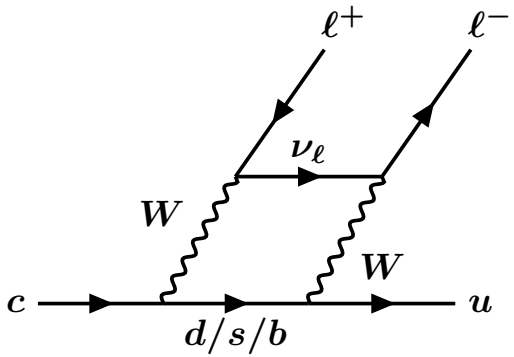
➢ FCCC $c \to s(d)$



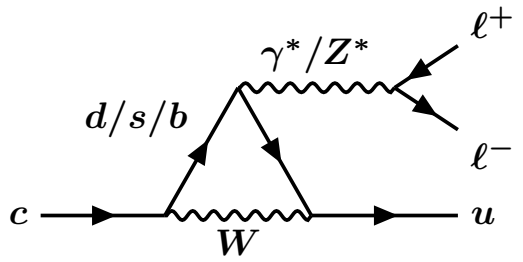
➢ FCNC $c \to u$



➢ $c \to u\gamma$ (Penguin)



➢ $c \to u\ell^+\ell^-$ (Box)



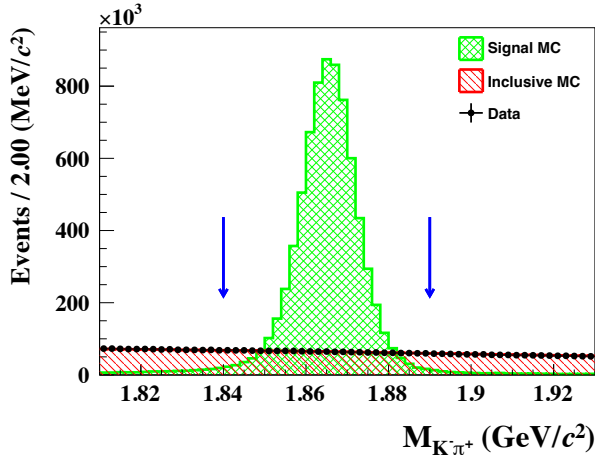
➢ $c \to u\ell^+\ell^-$ (Penguin)

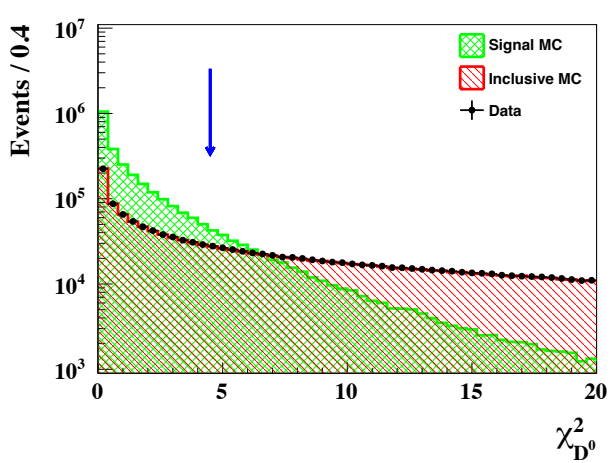
FCNC decay

$J/\psi \to \bar{D}^0 \mu^+ \mu^-$

- $c \to u\ell^+\ell^-$
- Reconstruction of D^0
  - Mode I : $K^-\pi^+$
  - Mode II : $K^-\pi^+\pi^0$
  - Mode III: $K^-\pi^-\pi^+\pi^+$
- Selection
  - J/ψ $M_{D^0\mu^+\mu^-} \to M_{J/\psi}$
  - K $M^{\text{Recoil}}_{K\ \text{other}} \to M_K$
  - D^0 tag M_{D^0}, $\chi^2_{D^0}$

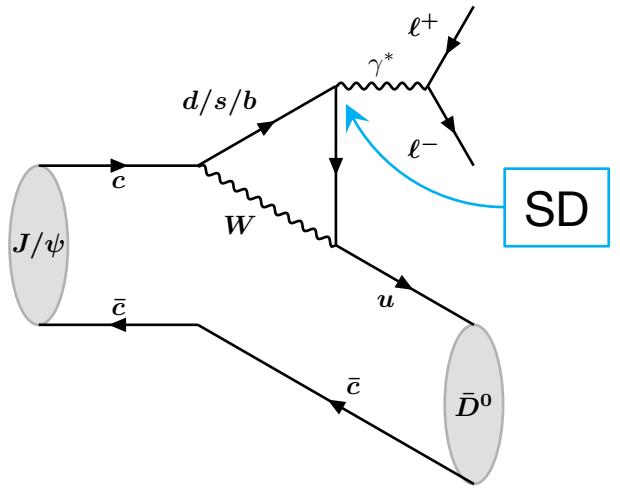
eg. Mode I



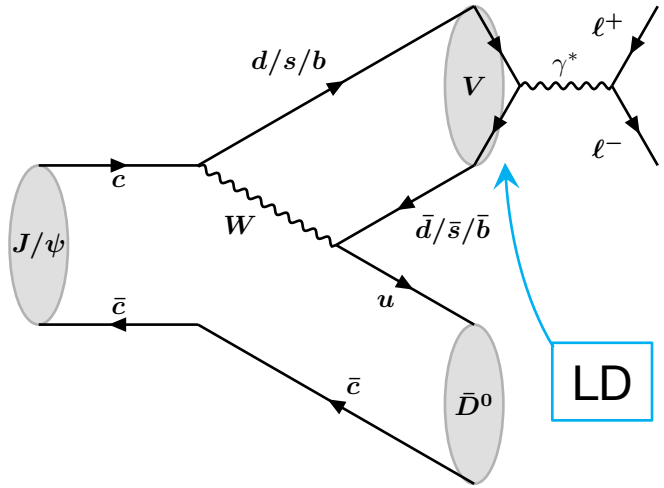


JHEP 04, 061 (2025)

- Short-distance (SD)
  - Suppressed by GIM mechanism
- Long-distance (LD)
  - Evades GIM suppression
  - ✓ Hadronization
  - ✓ Electromagnetic decay
  - ✗ Loop level diagram
- LD dominate



➢ One of SD contribution

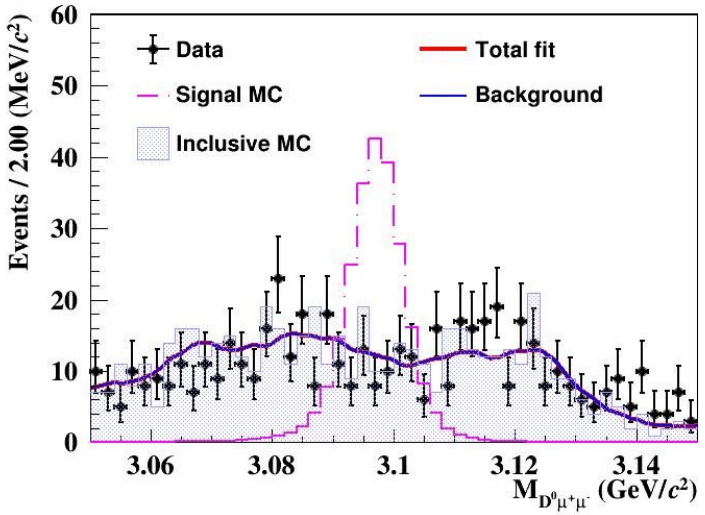


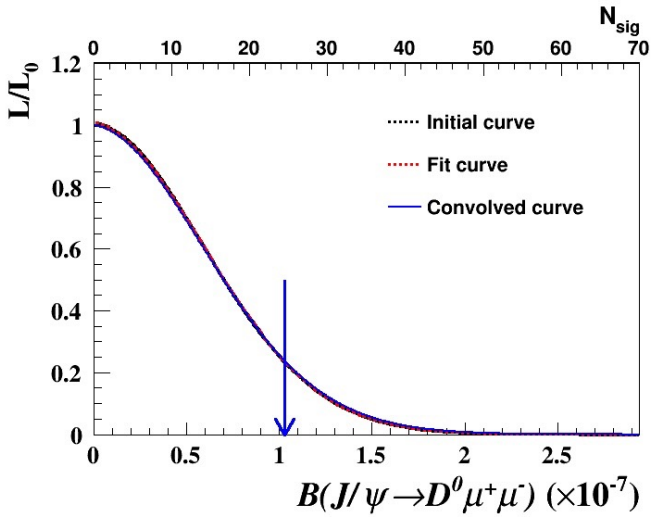
➢ One of LD contribution

FCNC decay

$J/\psi \to \bar{D}^0 \mu^+ \mu^-$

- Background Veto, eg.
  - Mode I: $J/\psi \to K_S^0 K^- \pi^+, J/\psi \to 4\pi$
  - $M_{\pi^+\pi^-} \notin M_{K_S^0}$
  - $M_{4\pi} \notin M_{J/\psi}$
- Blind analysis
- Signal Window $M_{D^0\mu^+\mu^-}$
- Simultaneous fitting with 3 tag modes
- Result
  - $\mathcal{B}(J/\psi \to \bar{D}^0\mu^+\mu^- + \text{c.c.}) < 1.1\times10^{-7}$ @ 90% CL



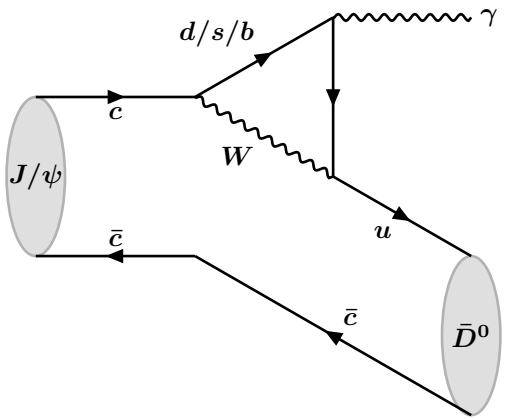


JHEP 04, 061 (2025)

FCNC decay

$J/\psi \to \bar{D}^0\gamma$

- $c \to u\gamma$
- Reconstruction of D^0
  - Mode I : $K^-\pi^+$
  - Mode II : $K^-\pi^+\pi^0$
  - Mode III: $K^-\pi^-\pi^+\pi^+$



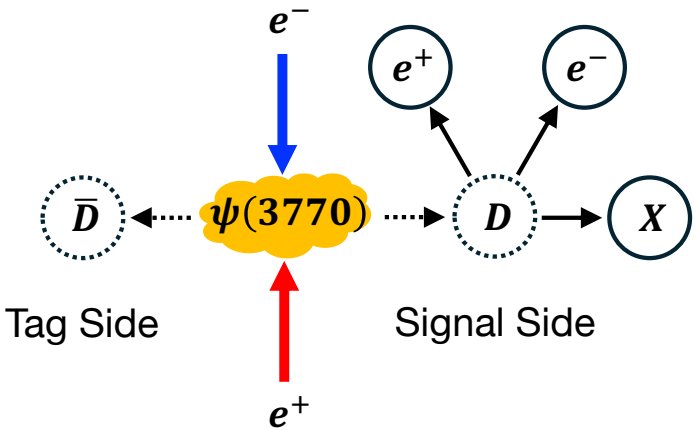
➢ $J/\psi \to \bar{D}^0\gamma$ (SD)

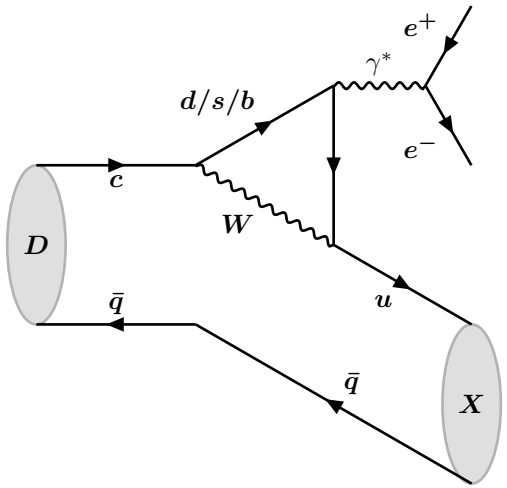
Phys. Rev. D 110, 112012 (2024)

Others

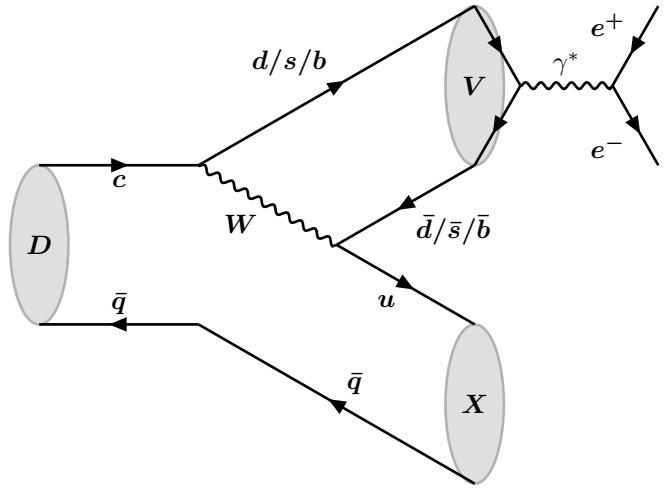
$D \to h(h')e^+e^-$

- $c \to u\ell^+\ell^-$
- Reconstruction of D
  - $\bar{D}^0$ - 3 tag modes
  - D^- - 6 tag modes





➢ $D \to Xe^+e^-$ (SD)

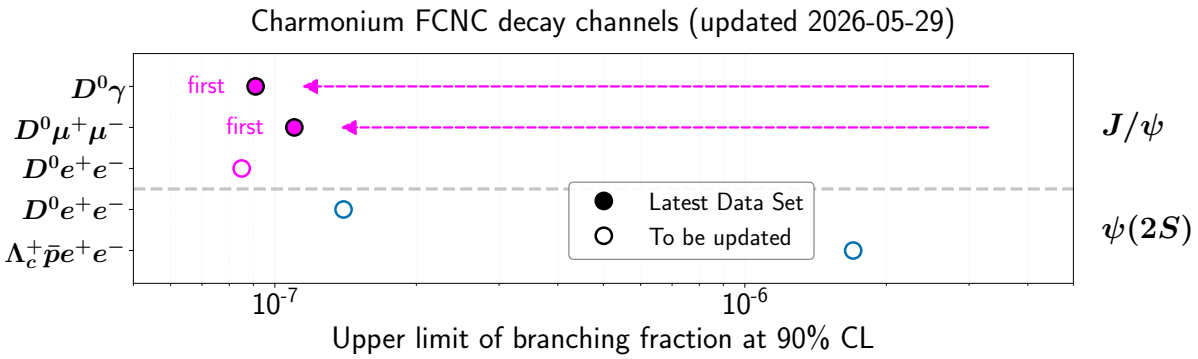


➢ $D \to Xe^+e^-$ (LD)

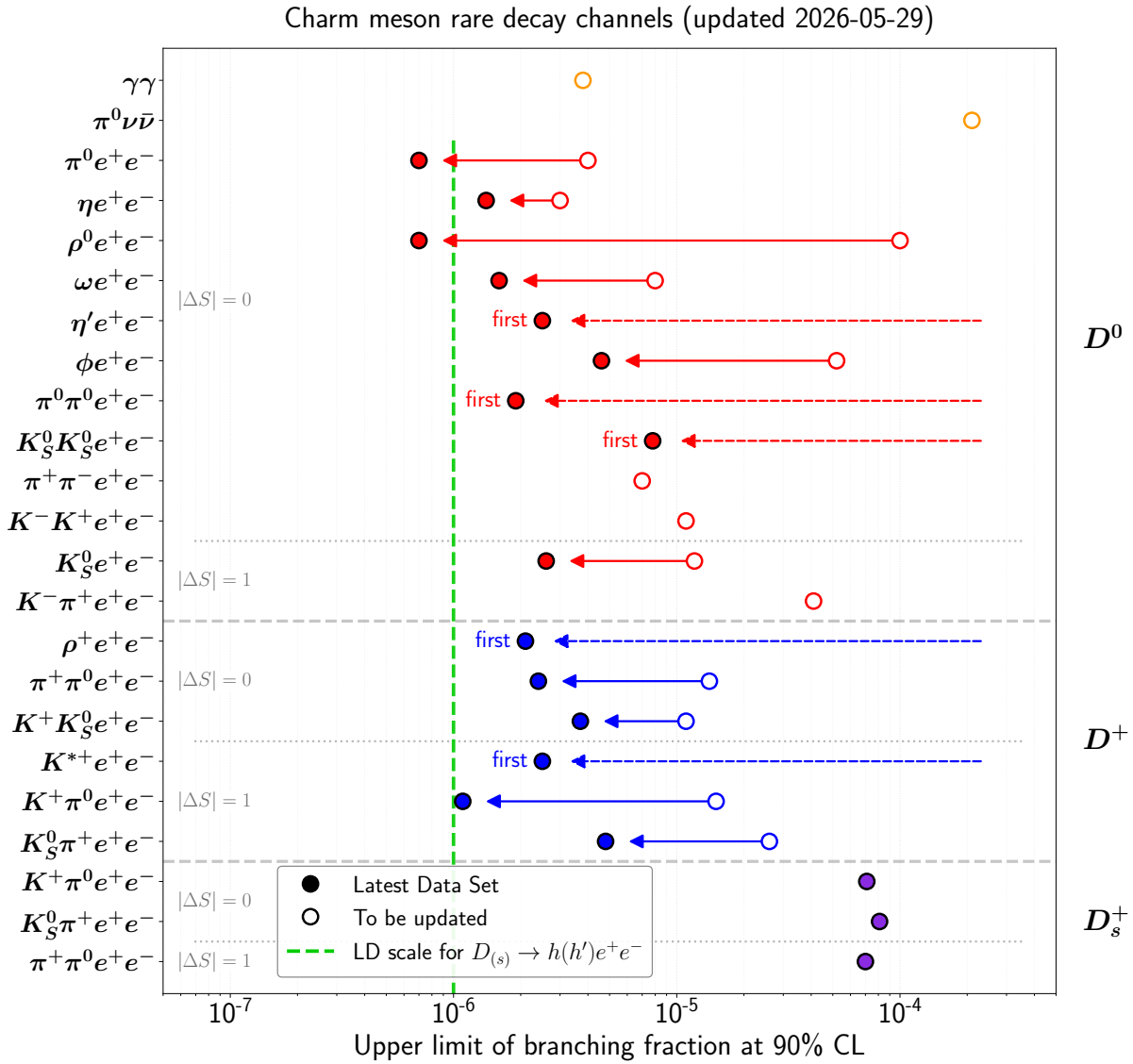
arXiv:2603.15575

FCNC decay

- Update
  - Wide coverage on charm mesons, charmonia are also included
- Current status
  - ULs reach LD scale
- BESIII advantages
  - Unique charmonium FCNC searches
  - Strong threshold constraints for invisible open-charm modes



BESIII brief summary

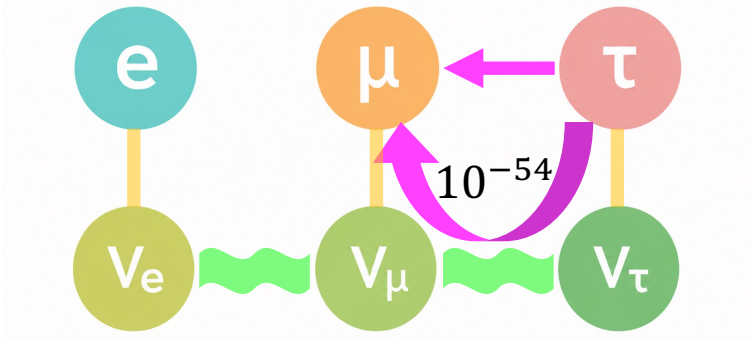


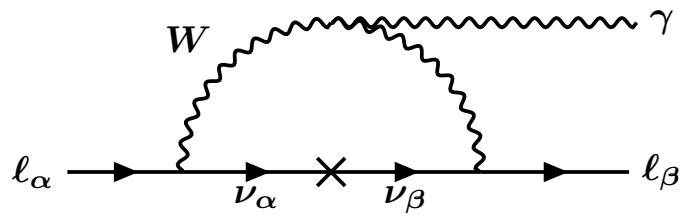
Contents

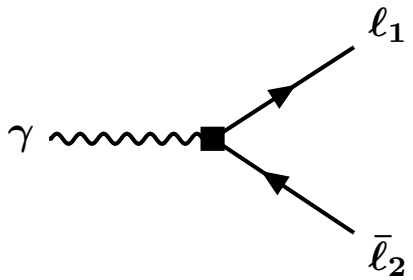
CLFV decay

Introduction

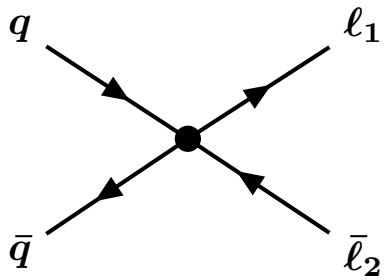
- Neutral lepton flavour violation $\nu_\alpha \to \nu_\beta$
- Charged lepton flavour violation $\ell_\alpha \to \ell_\beta$
  - Highly suppressed by tiny mass of neutrino $\left(\Delta m_{ij}^2 / M_W^2\right)^2$
  - Free from SM background
  - Any observation will be clear signal of NP
- Effective field theory (EFT)
  - $\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \Lambda^{-1} \sum_i C_i^{(5)} \mathcal{O}^{D=5} + \cdots$
  - Wilson coefficient C
- For quarkonium [Phys. Rev. D 94, 074023 (2016)]
  - $\mathcal{L}_{\text{EFT}} = \mathcal{L}_D + \mathcal{L}_{\ell q} + \mathcal{L}_G + \cdots$
  - $q\bar{q}(J^P) \to \ell_1 \bar{\ell}_2$ are sensitive to different C



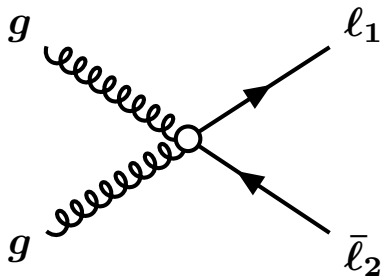




➢ Dipole $(\mathcal{L}_D, \mathcal{O}^{D=5})$



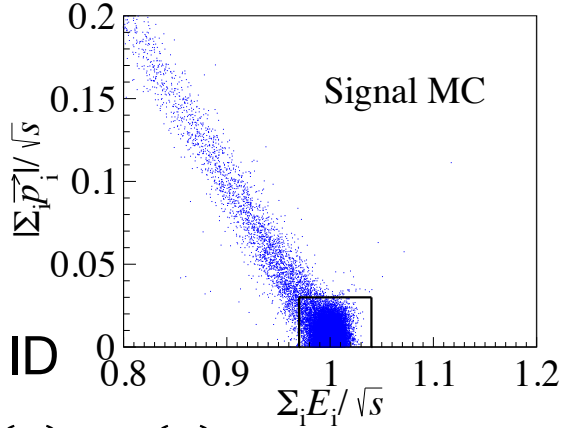
➢ Four-fermion $(\mathcal{L}_{\ell q}, \mathcal{O}^{D=6})$



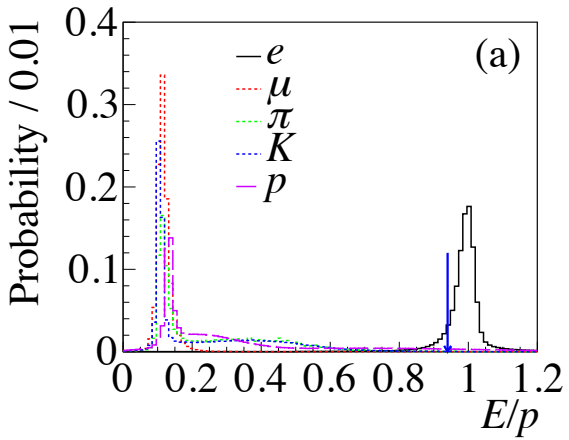
➢ Gluonic $(\mathcal{L}_G, \mathcal{O}^{D=7})$

CLFV decay

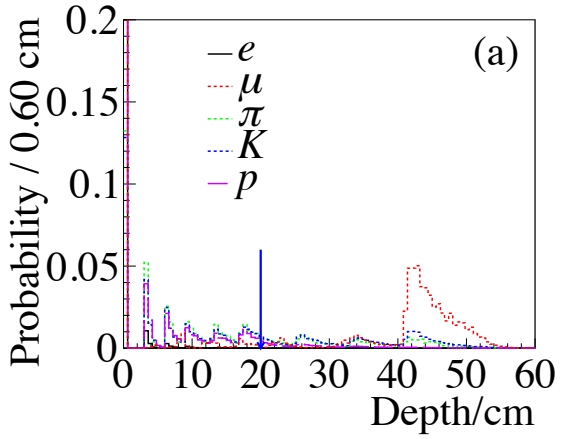
$\psi(2S) \to e\mu$



- Clear kinematics
- High requirement in particle ID
- Continuum backgrounds $ee(\gamma), \mu\mu(\gamma), \pi\pi$



➢ e ID (E_{EMC}/P)



➢ μ ID (penetration depth)

- Result
  - $\mathcal{B}(\psi(2S) \to e\mu) < 1.4\times10^{-8}$ @ 90% CL
- $V \to \ell_1\ell_2$ is sensitive to
  - Dipole one in $\mathcal{L}_D$ $C_{DL/DR}^{\ell_1\ell_2}$
  - Tensor, vector one in $\mathcal{L}_{\ell q}$ $C_{VL/VR}^{q\ell_1\ell_2}, C_{TL/TR}^{q\ell_1\ell_2}$
- Wilson coefficient
  - $|C/\Lambda^2| \propto \sqrt{\mathcal{B}(V \to \ell_1\ell_2)}$

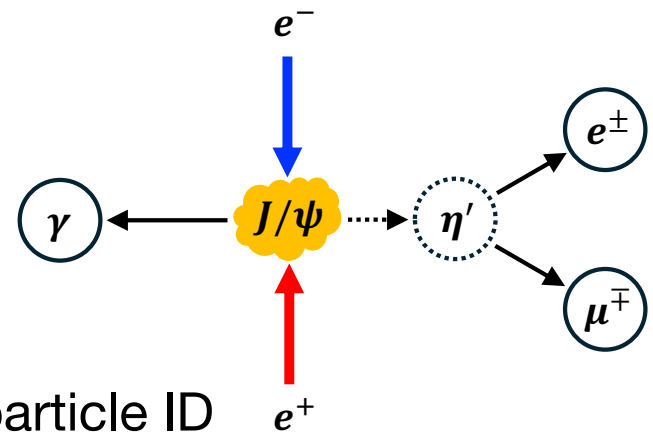
Wilson coef./GeV^{-2}	$\psi(2S)$
$\left\|C_{DL/DR}^{e\mu}/\Lambda^2\right\|$	7.3×10^{-4}
$\left\|C_{VL/VR}^{ce\mu}/\Lambda^2\right\|$	6.0×10^{-6}
$\left\|C_{TL/TR}^{ce\mu}/\Lambda^2\right\|$	2.7

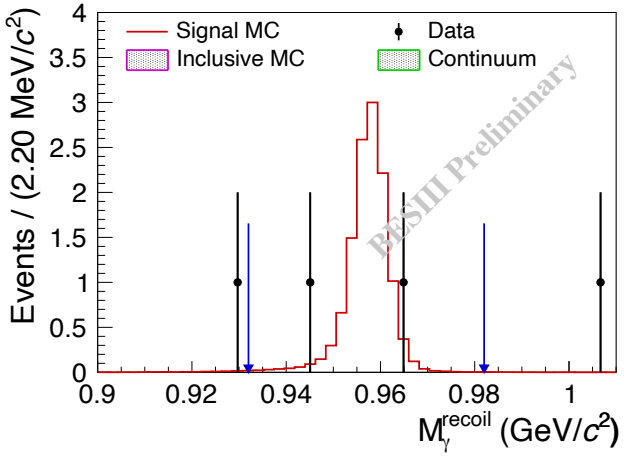
Sci. China Phys. Mech. Astron. 69, 251012 (2026)

CLFV decay

$\eta' \to e\mu$

- η' source: $J/\psi \to \gamma\eta'$
- Clear kinematics
- High requirement in particle ID
- Clean backgrounds around signal window





➢ Signal window $M_\gamma^{\text{recoil}} \to M_{\eta'}$

- Result
  - $\mathcal{B}(\eta' \to e\mu) < 6.3\times10^{-7}$ @ 90% CL
- $P \to \ell_1\ell_2$ is sensitive to
  - Pseudoscalar, axial one in $\mathcal{L}_{\ell q}$ $C_{PL/PR}^{q\ell_1\ell_2}, C_{AL/AR}^{q\ell_1\ell_2}$
  - Gluonic one in $\mathcal{L}_G$ $C_{\tilde{G}L/\tilde{G}R}^{\ell_1\ell_2}$
- Wilson coefficient
  - $|C/\Lambda^2| \propto \sqrt{\mathcal{B}(V \to \ell_1\ell_2)}$

Wilson coef./GeV^{-2}	η' $(q = u, d)$	η' $(q = s)$
$\left\|C_{AL/AR}^{qe\mu}/\Lambda^2\right\|$	7.4×10^{-3}	6.8×10^{-3}
$\left\|C_{PL/PR}^{qe\mu}/\Lambda^2\right\|$	1.4×10^{3}	1.3×10^{3}
$\left\|C_{\tilde{G}L/\tilde{G}R}^{e\mu}/\Lambda^2\right\|$	1.8×10^{2}	

CLFV decay

- Update
  - UL of $\eta' \to e\mu$ improved 3 orders of magnitude
  - $\psi(2S) \to e\mu$ is first measured
  - $\eta \to e\mu$ is also in plan
- Current status
  - No signal evidence
  - The strictest ULs of quarkonium CLFV decays
- BESIII advantages
  - The strictest limit on $\left|C^{e\ell}_{DL/DR}/\Lambda^2\right|$
  - Competitive limits on other Wilson coefficients

BESIII brief summary

➢ ULs on the Wilson coefficients from

$\lvert C/\Lambda^2\rvert/\mathrm{GeV}^{-2}$	$\eta'\ (q=u,d)$	$\eta'\ (q=s)$
$\left\lvert C^{qe\mu}_{AL/AR}/\Lambda^2\right\rvert$	7.4×10^{-3}	6.8×10^{-3}
$\left\lvert C^{qe\mu}_{PL/PR}/\Lambda^2\right\rvert$	1.4×10^{3}	1.3×10^{3}
$\left\lvert C^{e\mu}_{\tilde{G}L/\tilde{G}R}/\Lambda^2\right\rvert$	1.8×10^{2}	

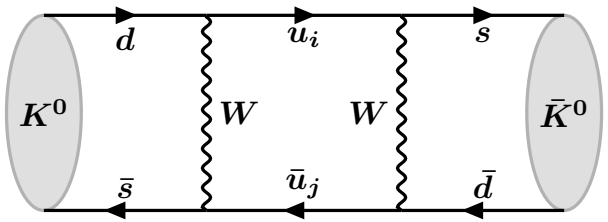
$\lvert C/\Lambda^2\rvert/\mathrm{GeV}^{-2}$	$\ell_1\ell_2$	J/ψ	$\psi(2S)$
$\left\lvert C^{\ell_1\ell_2}_{DL/DR}/\Lambda^2\right\rvert$	$e\mu$	1.8×10^{-4}	7.3×10^{-4}
	$e\tau$	5.0×10^{-5}	---
	$\mu\tau$	2.6×10^{-4}	---
$\left\lvert C^{q\ell_1\ell_2}_{VL/VR}/\Lambda^2\right\rvert$	$e\mu$	1.8×10^{-6}	6.0×10^{-6}
	$e\tau$	1.1×10^{-5}	---
	$\mu\tau$	5.5×10^{-5}	---
$\left\lvert C^{q\ell_1\ell_2}_{TL/TR}/\Lambda^2\right\rvert$	$e\mu$	0.80	2.7
	$e\tau$	0.23	---
	$\mu\tau$	1.2	---

Contents

Bose symmetry violation

$J/\psi, \psi(2S) \to K_S^0 K_S^0$

- Angular momentum conservation
  - $1^- \to PP$ requires PP in $L = 1$ state
- Bose symmetry
  - Bose-Einstein statistics requires identical spin-0 boson system in L-even state.
- Quantum entangled state
  - $\psi \to K^0\bar{K}^0, \quad \frac{1}{\sqrt{2}}(|K^0\bar{K}^0\rangle - |\bar{K}^0K^0\rangle)$
  - If ignore CPV, i.e. $\frac{1}{\sqrt{2}}(|K_SK_L\rangle - |K_LK_S\rangle)$



$i, j = u, c, t$

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- K^0-$\bar{K}^0$ oscillation contribution
  - $\mathcal{B}(J/\psi \to K_S^0 K_S^0) \sim 10^{-9}$
  - $\mathcal{B}(\psi(2S) \to K_S^0 K_S^0) \sim 10^{-10}$

[Phys. Rev. Lett. 96, 192001 (2006).]

- CPT violation
  - $|i\rangle \propto (|K^0\bar{K}^0\rangle - |\bar{K}^0K^0\rangle) + \omega(|K^0\bar{K}^0\rangle + |\bar{K}^0K^0\rangle)$
  - $|\omega|^2 \simeq \frac{\mathcal{B}(\psi \to K_SK_S)}{\mathcal{B}(\psi \to K_SK_L)}$
  - Some quantum gravity models imply $\omega \sim 10^{-3}$, i.e. $\mathcal{B}(\psi \to K_SK_S) \sim 10^{-10}$

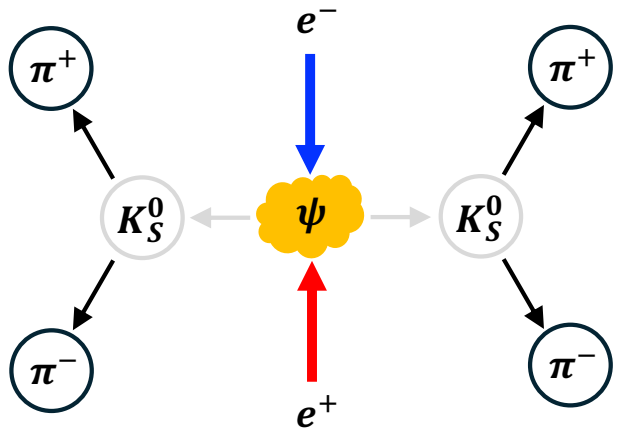
[Nucl. Phys. B 744, 180 (2006)]

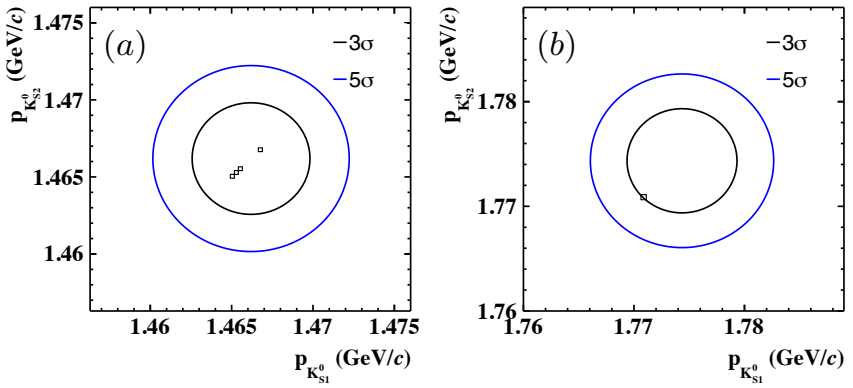
- EPR locality theory
  - $K^0, \bar{K}^0$ evolve separately
  - $\mathcal{B}(\psi \to K_SK_S) \sim 10^{-6}$

[Int. J. Mod. Phys. A 36, 2150178 (2021)]

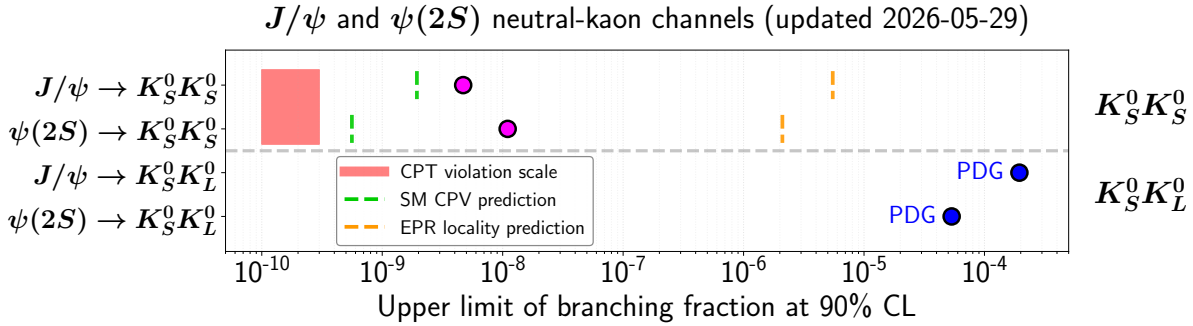
Bose symmetry violation $J/\psi, \psi(2S) \to K_S^0 K_S^0$

- Reconstruction
  - $K_S^0 \to \pi^+\pi^-$
  - Secondary vertex of K_S^0
- Selection
  - Pairing $\pi^+\pi^-$ by vertex
  - Decay length $L/\sigma_L > 2$
  - Four-momentum constraint χ^2_{4C}
- Signal Window
  - $p_{K_{S1}}$ vs $p_{K_{S2}}$





- Result (90% CL)
  - $\mathcal{B}(J/\psi \to K_S^0 K_S^0) < 4.7\times10^{-9}$
  - $\mathcal{B}(\psi(2S) \to K_S^0 K_S^0) < 1.1\times10^{-8}$
  - Exclude some EPR locality theories



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Contents

Summary

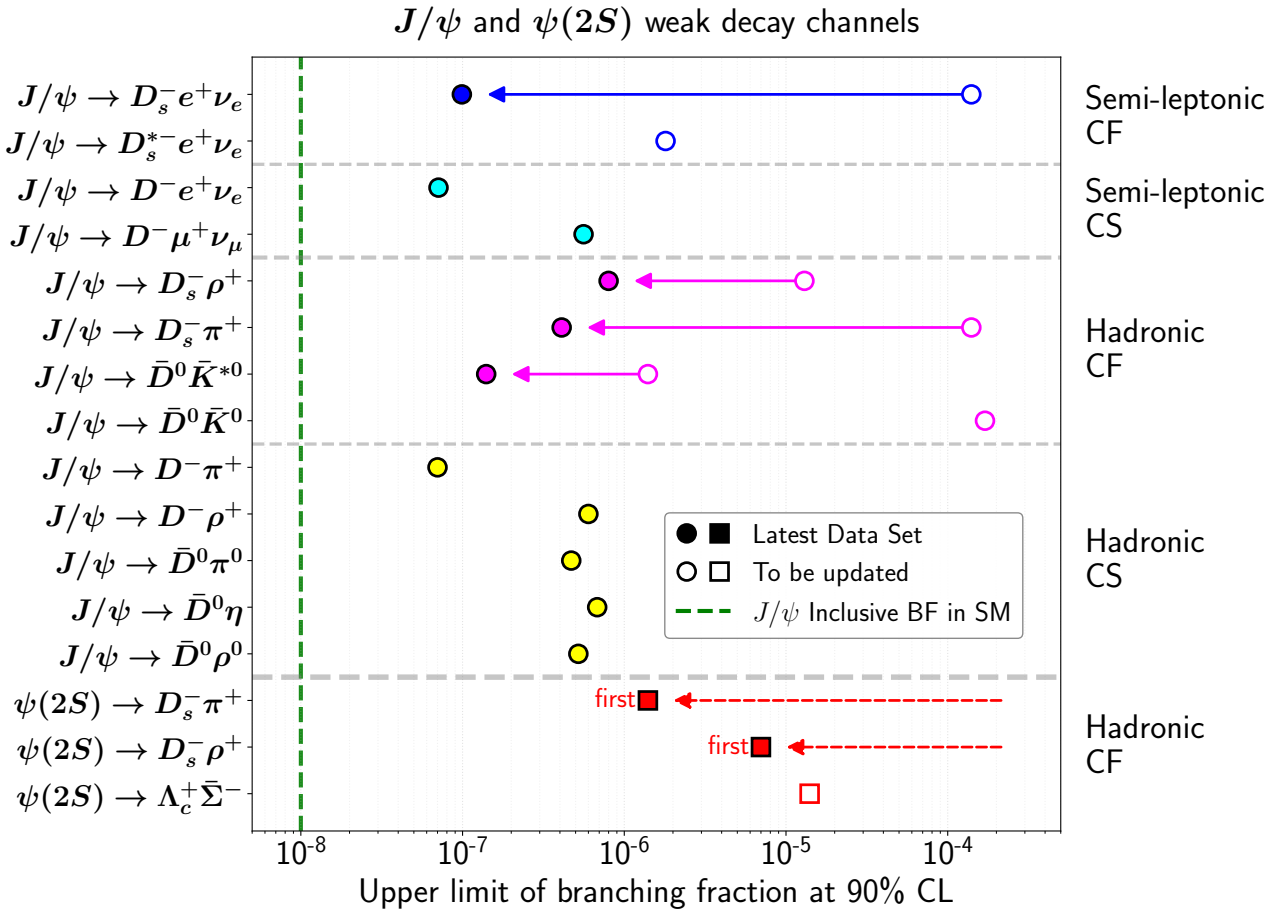
- BESIII Data Sets
  - Most on-threshold charmonium - 10.0 B J/ψ 2.71 B $\psi(2S)$
  - Pair-production charm mesons - 20.3 fb^{-1} $D^0\overline{D}^0$ 7.33 fb^{-1} $D_s^* D_s$
- New Physics searches overview
  - $\psi \to D_{(s)}^{(*)} X$ Exclusive ULs still 2~3 orders above SM, exclude aggressive NP enhancements.
  - $c \to u$ ULs touch the LD scale; charmonium FCNC is accessible nowhere else.
  - $\psi \to \ell_1 \ell_2$ The strictest BF ULs and the best bound on the $e\ell$ dipole coefficient.
  - $J/\psi, \psi(2S) \to K_S^0 K_S^0$ Unique probe to multiple symmetries.
- Upgrade
  - BEPC II ➡ BEPCII-U: $\sim$ 3x luminosity @ $E_{\rm beam} = 2.35$ GeV, enable larger charm-threshold samples.
  - BESIII: inner MDC ➡ CGEM-IT, improve rate capability and secondary-vertex reconstruction.

Thanks for your listening !

JINST 21, P01026 (2026)
Nucl. Instrum. Meth. A 1069, 169821 (2024)

Reference

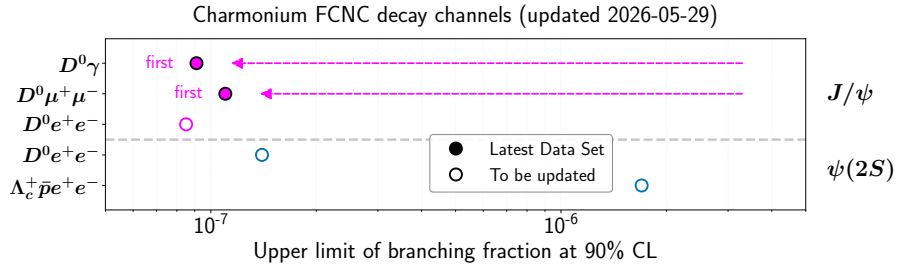
Channel	Latest	Previous
$J/\psi \to D_s^- e^+ \nu_e$	arXiv:2510.25100	arXiv:hep-ex/0604005
$J/\psi \to D_s^{*-} e^+ \nu_e$	arXiv:1410.8426	–
$J/\psi \to D^- e^+ \nu_e$	arXiv:2104.06628	arXiv:hep-ex/0604005
$J/\psi \to D^- \mu^+ \nu_\mu$	arXiv:2307.02165	–
$J/\psi \to D_s^- \rho^+$	arXiv:2506.09386	arXiv:1402.4025
$J/\psi \to D_s^- \pi^+$	arXiv:2506.09386	arXiv:0707.3005
$J/\psi \to \bar{D}^0 \bar{K}^{*0}$	arXiv:2511.16083	arXiv:1402.4025
$J/\psi \to \bar{D}^0 \bar{K}^0$	arXiv:0707.3005	–
$J/\psi \to D^- \pi^+$	arXiv:2310.07277	arXiv:0707.3005
$J/\psi \to D^- \rho^+$	arXiv:2310.07277	–
$J/\psi \to \bar{D}^0 \pi^0$	arXiv:2310.07277	–
$J/\psi \to \bar{D}^0 \eta$	arXiv:2310.07277	–
$J/\psi \to \bar{D}^0 \rho^0$	arXiv:2310.07277	–
$\psi(2S) \to D_s^- \pi^+$	arXiv:2603.01777	–
$\psi(2S) \to D_s^- \rho^+$	arXiv:2603.01777	–
$\psi(2S) \to \Lambda_c^+ \bar{\Sigma}^-$	arXiv:2207.10877	–

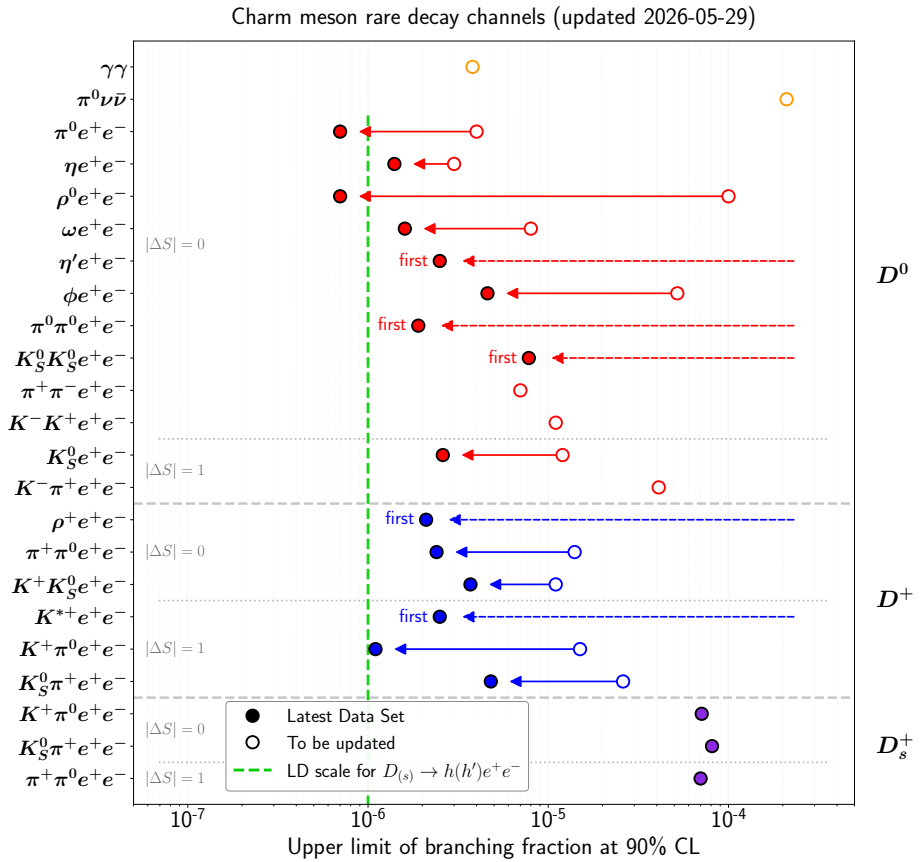


Reference

Channel	Latest	Previous
$J/\psi \to D^0\gamma + \text{c.c.}$	arXiv:2408.08826	–
$J/\psi \to D^0\mu^+\mu^- + \text{c.c.}$	arXiv:2501.08080	–
$J/\psi \to D^0e^+e^- + \text{c.c.}$	arXiv:1710.02278	arXiv:hep-ex/0604005
$\psi(2S) \to D^0e^+e^- + \text{c.c.}$	arXiv:1710.02278	–
$\psi(2S) \to \Lambda_c^+\bar{p}e^+e^- + \text{c.c.}$	arXiv:1802.04057	–

Channel	Latest	Previous
$D^0 \to \gamma\gamma$	arXiv:1505.03087	–
$D^0 \to \pi^0\nu\bar{\nu}$	arXiv:2112.14236	–
$D^0 \to \pi^0e^+e^-$	arXiv:2603.15575	arXiv:1802.09752
$D^0 \to \eta e^+e^-$	arXiv:2603.15575	arXiv:1802.09752
$D^0 \to \rho^0e^+e^-$	arXiv:2603.15575	arXiv:1802.09752
$D^0 \to \omega e^+e^-$	arXiv:2603.15575	arXiv:1802.09752
$D^0 \to \eta' e^+e^-$	arXiv:2603.15575	–
$D^0 \to \phi e^+e^-$	arXiv:2603.15575	arXiv:1802.09752
$D^0 \to \pi^0\pi^0e^+e^-$	arXiv:2603.15575	–
$D^0 \to K_S^0K_S^0e^+e^-$	arXiv:2603.15575	–
$D^0 \to \pi^+\pi^-e^+e^-$	arXiv:1802.09752	–
$D^0 \to K^-K^+e^+e^-$	arXiv:1802.09752	–
$D^0 \to K_S^0e^+e^-$	arXiv:2603.15575	arXiv:1802.09752
$D^0 \to K^-\pi^+e^+e^-$	arXiv:1802.09752	–
$D^+ \to \rho^+e^+e^-$	arXiv:2603.15575	–
$D^+ \to \pi^+\pi^0e^+e^-$	arXiv:2603.15575	arXiv:1802.09752
$D^+ \to K^+K_S^0e^+e^-$	arXiv:2603.15575	arXiv:1802.09752
$D^+ \to K^{*+}e^+e^-$	arXiv:2603.15575	–
$D^+ \to K^+\pi^0e^+e^-$	arXiv:2603.15575	arXiv:1802.09752
$D^+ \to K_S^0\pi^+e^+e^-$	arXiv:2603.15575	arXiv:1802.09752
$D_s^+ \to K^+\pi^0e^+e^-$	arXiv:2404.05973	–
$D_s^+ \to K_S^0\pi^+e^+e^-$	arXiv:2404.05973	–
$D_s^+ \to \pi^+\pi^0e^+e^-$	arXiv:2404.05973	–





Reference

Channel	Reference
$\phi \to e^{\pm}\mu^{\mp}$	arXiv:0911.1232
$J/\psi \to e^{\pm}\mu^{\mp}$	arXiv:2206.13956
$J/\psi \to e^{\pm}\tau^{\mp}$	arXiv:2103.11540
$J/\psi \to \mu^{\pm}\tau^{\mp}$	arXiv:hep-ex/0406018
$\psi(3686) \to e^{\pm}\mu^{\mp}$	arXiv:2507.10331
$\Upsilon(1S) \to e^{\pm}\mu^{\mp}$	arXiv:2201.09620
$\Upsilon(1S) \to e^{\pm}\tau^{\mp}$	arXiv:2201.09620
$\Upsilon(1S) \to \mu^{\pm}\tau^{\mp}$	arXiv:2201.09620
$\Upsilon(2S) \to e^{\pm}\tau^{\mp}$	arXiv:1001.1883
$\Upsilon(2S) \to \mu^{\pm}\tau^{\mp}$	arXiv:1001.1883
$\Upsilon(3S) \to e^{\pm}\tau^{\mp}$	arXiv:1001.1883
$\Upsilon(3S) \to \mu^{\pm}\tau^{\mp}$	arXiv:1001.1883
$\Upsilon(3S) \to e^{\pm}\mu^{\mp}$	arXiv:2109.03364

Quarkonium	$e\mu$	$e\tau$	$\mu\tau$
ϕ	2×10^{-6}	$\times$	$\times$
J/ψ	4.5×10^{-9}	7.5×10^{-8}	2.0×10^{-6}
$\psi(2S)$	1.4×10^{-8}	---	---
$\Upsilon(nS)$	$\mathcal{O}(10^{-6}) \sim \mathcal{O}(10^{-7})$		