Status and prospects of rare decays at BESIII

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on behalf of the BESIII collaboration

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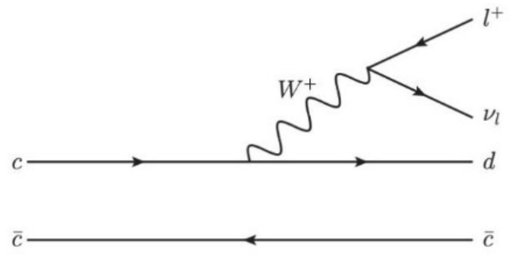
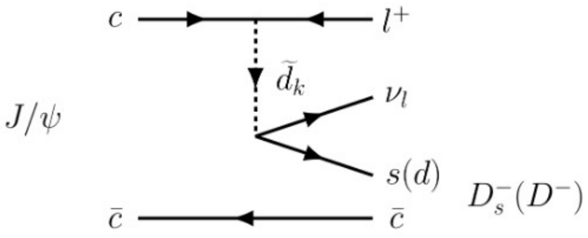
WIFAI 2025 – Bari - 13/11/2025

Why we do it?

- Rare decays are a portal towards:
  - Allowed SM processes



  - New phenomena beyond SM



  - A trip around October in Stockholm to test the recently bought tuxedo

What we do at BESIII?

Charmonium weak decays

SM Branching ratio magnitude

FCNC

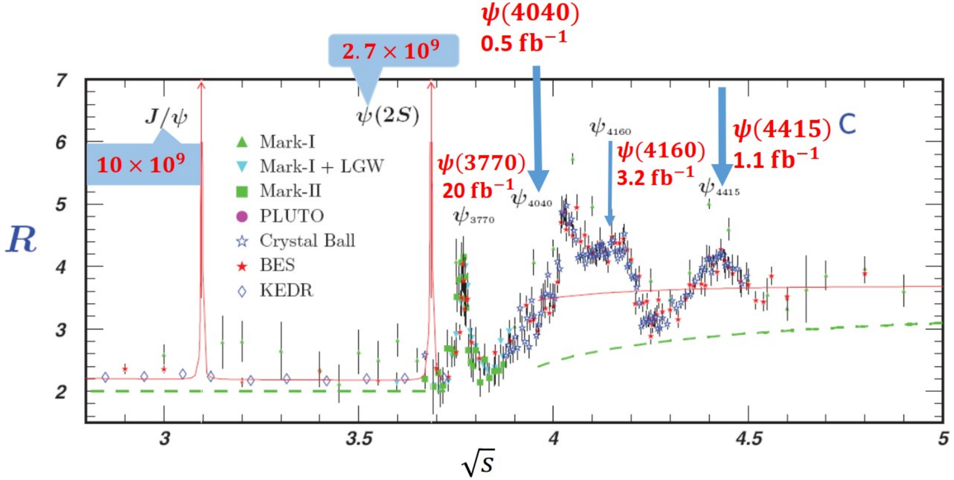
Standard Model violation

Charged Lepton Flavor violation

Lepton/Barion Number violation

How BESIII can be unique

Huge Datasets



Clean environment

Double-tag analysis:

"Tag" the missing mass

$\mathrm{D}, \mathrm{D_s}, \Lambda_c$

$\overline{\mathrm{D}}, \overline{\mathrm{D}}_s, \overline{\Lambda}_c$

Blind analysis

Recent results

Charmonium weak and FCNC:

2024: $J/\psi \to D^0\pi^0, D^0\eta, D^0\rho^0, D^-\rho^+, D^-\pi^+$ (PRD 110, 032 020)

2024: $J/\psi \to D^-\mu^+\nu_\mu$ (JHEP 01 126)

2024: $D_S^+ \to h(h') e^+e^-$ (PRL 133, 121 801)

2024: $J/\psi \to \gamma D^0$ (PRD 110, 112 012)

2025: $J/\psi \to D_S^-\rho^+, D_S^- \pi^+$ (arXiv:2506.09386v3, submitted to JHEP)

2025: $J/\psi, \psi(3686) \to K_SK_S$ (CPV, PRD 112, 052 010)

2025: $J/\psi \to D^0\mu^+\mu^-$ (JHEP04 061)

LNV/BNV/cLFV:

2025: $J/\psi \to \phi\eta, \phi \to \pi^+\pi^+e^-e^-$ (LNV, CPC 49, 043 001)

2025: $J/\psi \to K^+K^+e^-e^-$ (LNV, arXiv:2507.06872v1, accepted by CPC)

2025: $J/\psi \to \omega\eta, \omega \to \pi^+\pi^+e^-e^-$ (LNV, CPC 49, 103 002)

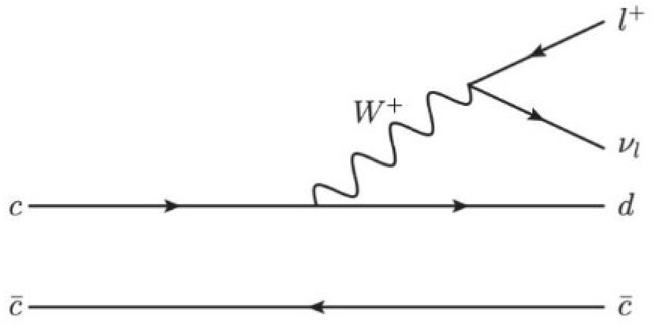
2025: $J/\psi \to \phi\eta, \eta \to \pi^+\pi^+e^-e^-$ (LNV, arXiv:2509.21921v3, submitted to PRD)

2025: $J/\psi \to D_S^+h^-h^0e^+e^+$ (LNV, JHEP 01 109)

2025: $\psi(3686) \to e^\pm\mu^\mp$ (LFV, arXiv:2507.10331v2, submitted to SCPMA)

2025: $J/\psi \to p^-e^-$ (BNV and LNV, PRD 111, 112 010)

Charmonium weak decays

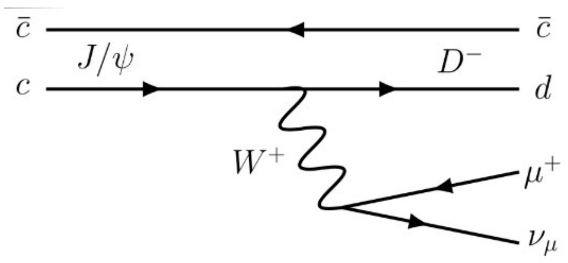


Everything is Standard Model, but small

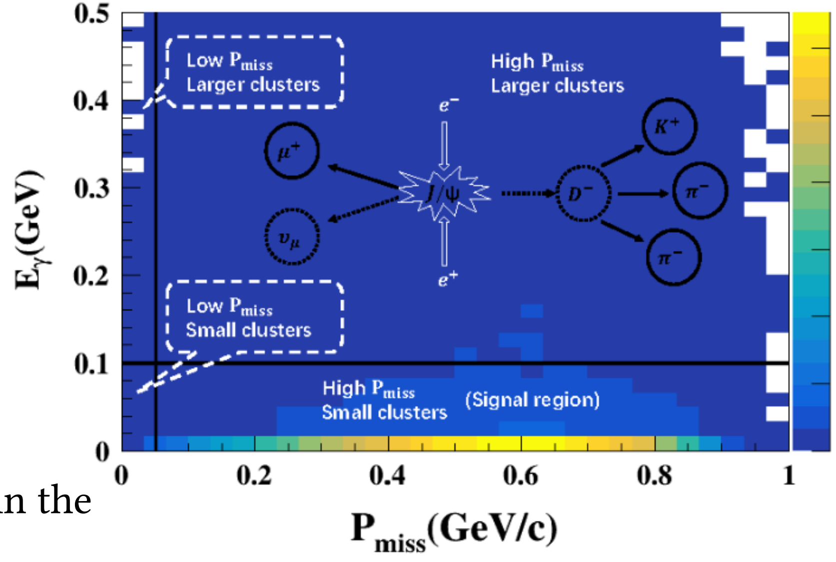
JHEP 01, 126(2024)

$J/\psi \rightarrow D^-\mu^+\nu_\mu$

BESIII MC



Fig(a) The Feynman diagram of $J/\psi \rightarrow D^-\mu^+\nu_\mu$



Use the full J/ψ dataset

Search for missing momentum (neutrino) and low energy deposit in the calorimeter (muon)

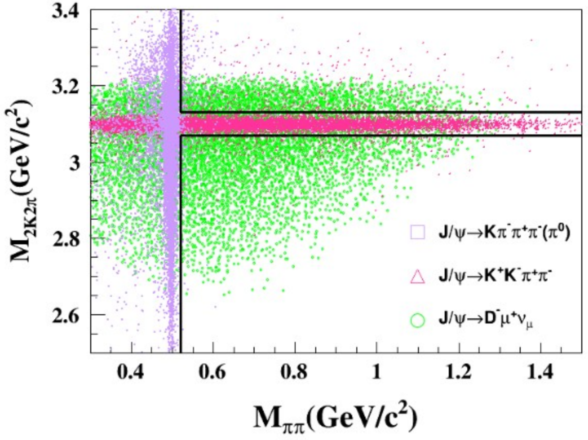
First search with the muons (electron UL 7.1×10^{-7} @90% C.L. JHEP 06,157(2021))

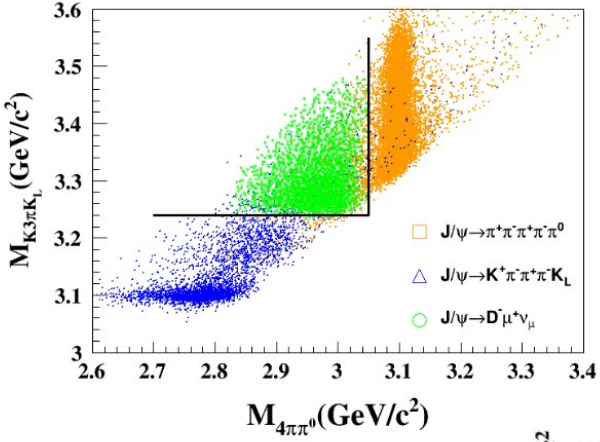
Model	BSW [1]	CCQM[2]	BSM[3]	CLFQM[4]	LQCD[5]
$\mathcal{B}(J/\psi \to D^- e^+ \nu_e)(\times 10^{-10})$	$6.0^{+0.8}_{-0.7}$	1.71	$2.03^{+0.29}_{-0.25}$	$6.10^{+0.11+0.10+0.14}_{-0.11-0.12-0.19}$	0.121
$\mathcal{B}(J/\psi \to D^- \mu^+ \nu_\mu)(\times 10^{-10})$	$5.8^{+0.8}_{-0.6}$	1.66	$1.98^{+0.28}_{-0.24}$	$5.78^{+0.11+0.11+0.16}_{-0.10-0.13-0.11}$	0.118

[1] Adv. High Energy Phys. 2013 (2013) 706543
[2] Phys. Rev. D 92 (2015) 074030
[3] J. Phys. G 44 (2017) 045004
[4] Eur. Phys. J. C 84, no.1, 65 (2024)
[5] arXiv:2407.13568

JHEP 01, 126(2024)

$J/\psi \rightarrow D^{-}\mu^{+}\nu_{\mu}$

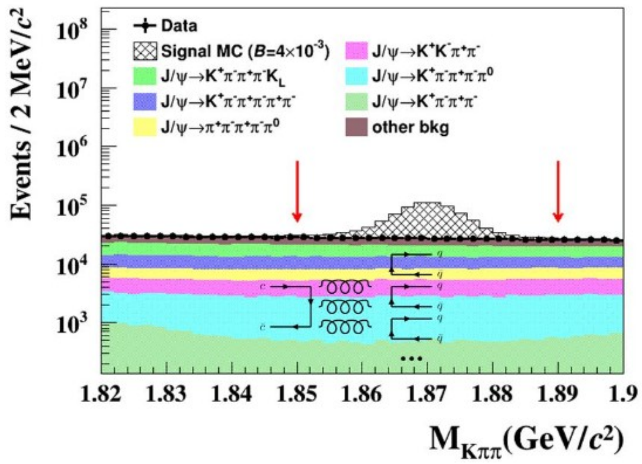




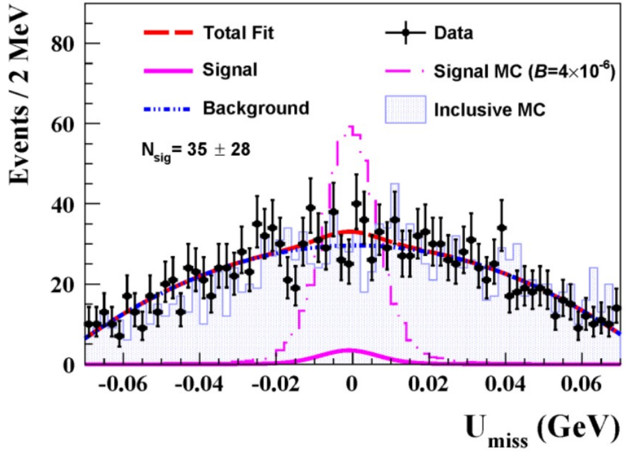
Main backgrounds comes J/ψ hadronic decay with many pions

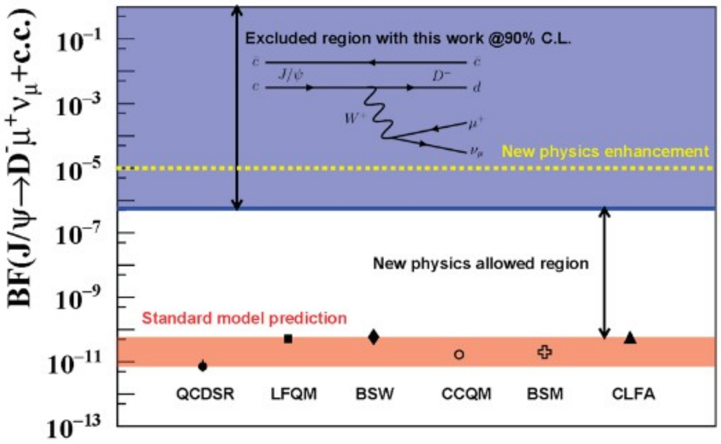
muon-pions misidentification since muon counter not efficient in the full range of signal muon momenta

Kinematic PID cut to suppress some of the backgrounds.



$J/\psi \to D^- \mu^+ \nu_\mu$





To extract the events, fit to the missing mass U_{miss}
Inclusive MC to fix the background shape

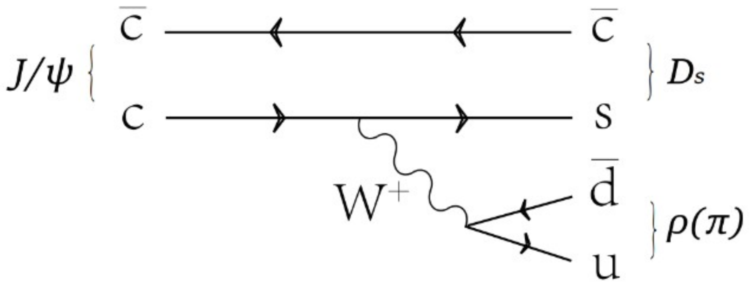
Extracted upper limits

$$\mathcal{B}(J/\psi \to D^-\mu^+\nu_\mu) < 5.6 \times 10^{-7} \text{ @90\% C.L.}$$

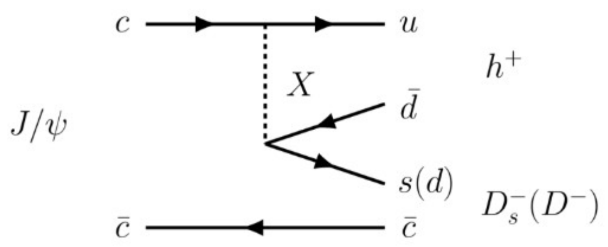
No NP now
Still large space to search for NP

More data not enough to get anywhere close to SM prediction: smarter techniques?

$J/\psi \to D_s\pi/D_s\rho$



Fig(a) The Feynman diagram of $J/\psi \to D_s^-\pi^+$ and $J/\psi \to D_s^-\rho^+$ in SM.



Fig(b) The Feynman diagram of $J/\psi \to D_s^-\pi^+$ and $J/\psi \to D_s^-\rho^+$ in NP Model.

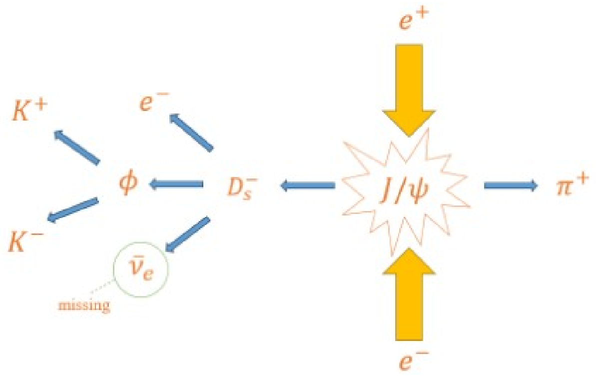
Similarly scheme as the previous analysis, but hadronic weak decay

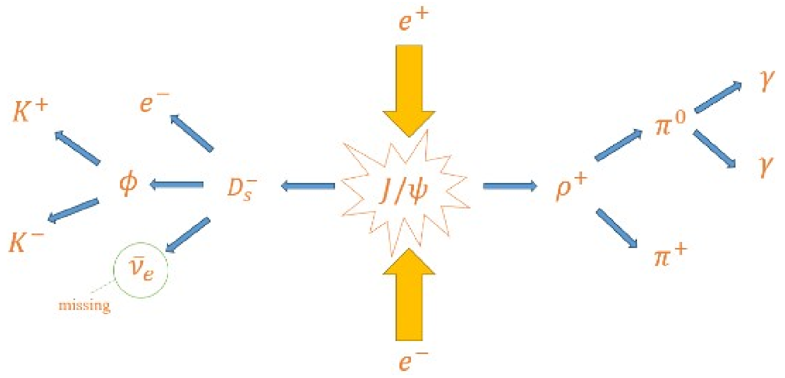
Model	QCDSR [2]	BSW [3]	CLFQM (2008) [4]	CLFQM (2024) [5]
$\mathcal{B}(J/\psi \to D_s^-\rho^+)(\times 10^{-10})$	$12.6^{+7.6}_{-6.0}$	$51.1^{+7.6}_{-6.0}$	28^{+0}_{-9}	$29.5^{+0.6+1.1+1.5}_{-0.5-1.4-1.9}$
$\mathcal{B}(J/\psi \to D_s^-\pi^+)(\times 10^{-10})$	$2.0^{+4.0}_{-0.2}$	$7.41^{+0.13}_{-0.23}$	$2.5^{+0.0}_{-0.1}$	$3.64^{+0.06+0.34+0.78}_{-0.06-0.38-0.96}$

[2] Eur. Phys. J.C 55, 607-613 (2008)
[3] High Energy Phys. 2013, 706543 (2013)
[4] Phys. Rev. D 78, 074012 (2008)
[5] Eur. Phys. J.C 84, no.1, 65 (2024)

ArXiv: 2506.09368

$J/\psi \rightarrow D_s\pi/D_s\rho$



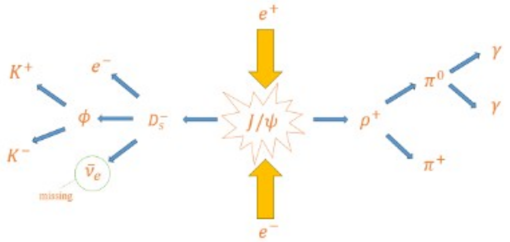


Ds hadronic decay has detection efficiency too low

Use the semileptonic $D_s \rightarrow \Phi e\nu$ and reconstruct the D_s through missing mass

Use of EMC energy, track momentum and PID to improve e/π identification

$J/\psi \to D_s\pi / D_s\rho$



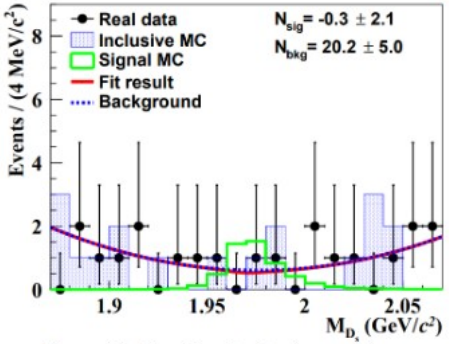


Figure (a): The M_{D_s} distributions of the $J/\psi \to D_s^-\rho^+$ Candidate events.

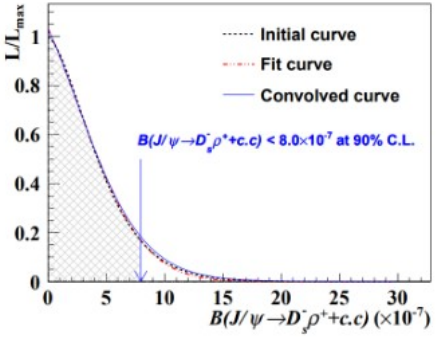
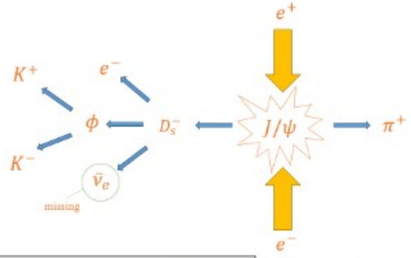


Figure (a): The distributions of the likelihood scan values for $J/\psi \to D_s^-\rho^+$.



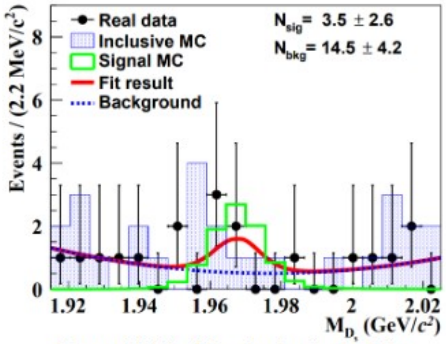


Figure (c): The M_{D_s} distributions of the $J/\psi \to D_s^-\pi^+$ Candidate events.

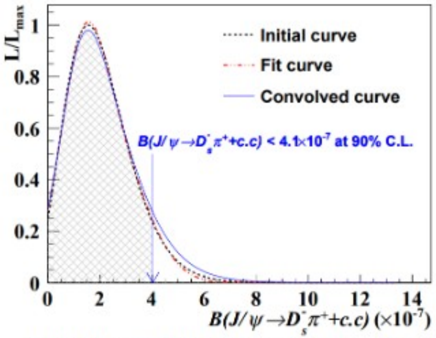


Figure (d): The distributions of the likelihood scan values for $J/\psi \to D_s^-\pi^+$.

$B(J/\psi \to D_s\rho) < 8.0 \times 10^{-7}$ @ 90% C.L.

1 order of magnitude improvement

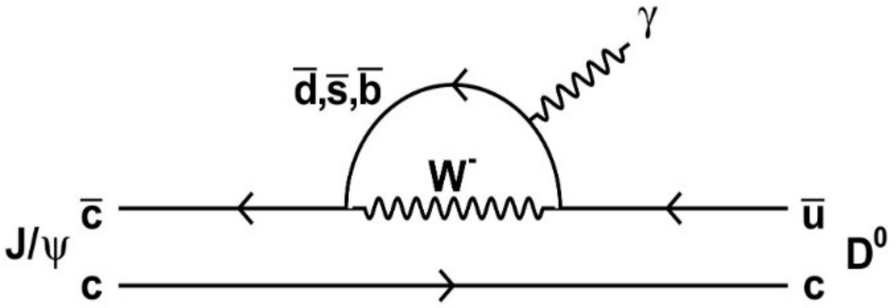
$B(J/\psi \to D_s\pi) < 4.1 \times 10^{-7}$ @ 90% C.L.

3 orders of magnitude improvement

Charmonium FCNC

Phys. Rev. D 110 (2024) 112 012

$J/\psi \longrightarrow D^0\gamma$



Three D decay mode:
- $D \longrightarrow K^-\pi^+$
- $D \longrightarrow K^-\pi^+\pi^0$
- $D \longrightarrow K^-\pi^+\pi^+\pi^-$

Decay less suppressed wrt ($J/\psi \longrightarrow Dl^+l^-$) since only one vertex

$$\mathrm{BR}(J/\psi \to \bar{D}^0 e^+e^-) = 1.14^{+0.71}_{-0.35} \times 10^{-13}, \quad \mathrm{BR}(J/\psi \to \bar{D}^0 \mu^+\mu^-) = 1.08^{+0.67}_{-0.33} \times 10^{-13},$$
$$\mathrm{BR}(J/\psi \to \bar{D}^{*0} e^+e^-) = 6.30^{+3.61}_{-2.30} \times 10^{-13}, \quad \mathrm{BR}(J/\psi \to \bar{D}^{*0} \mu^+\mu^-) = 5.94^{+3.36}_{-2.15} \times 10^{-13},$$

Theoretical prediction from J.Phys.G 36 (2009) 105 002 based on QCD sum rules

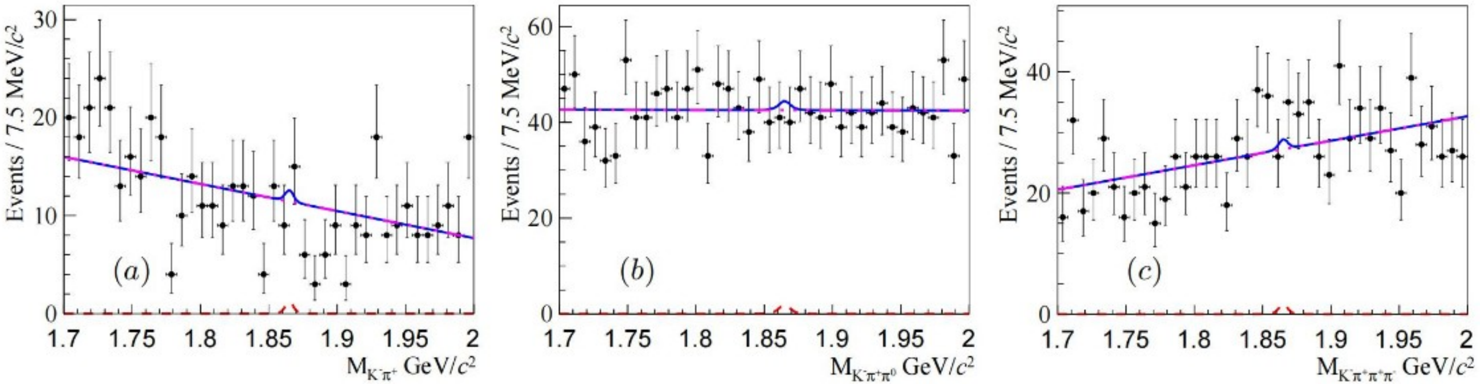
Phys. Rev. D 110 (2024) 112 012

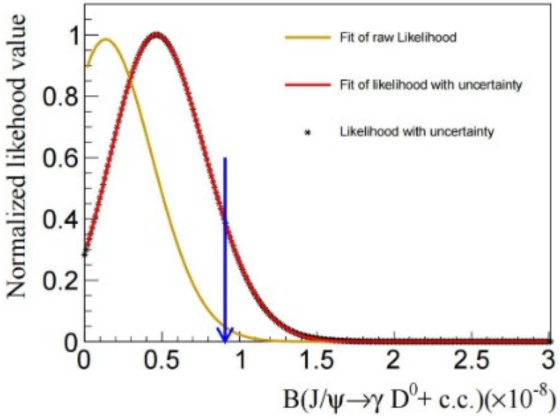
$J/\psi \rightarrow D^0\gamma$

D^0 invariant mass is used for signal extraction

First ever measurement of this final state. No signal observed

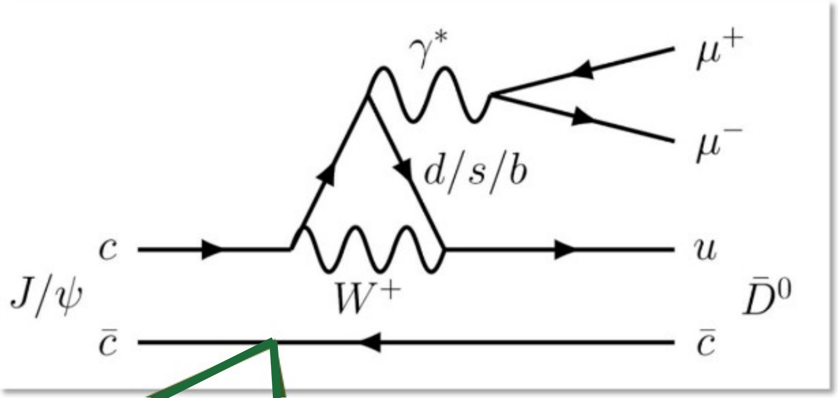
$B(J/\psi \rightarrow D^0\gamma)$ < 9.1 x 10-8 @ 90% C.L.



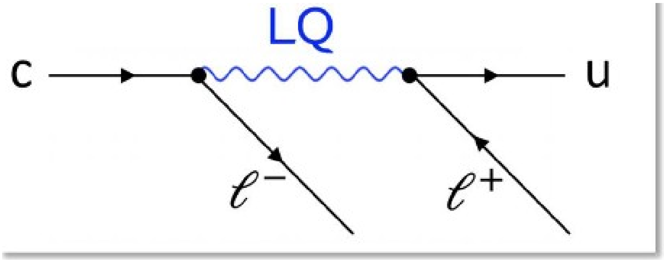


JHEP 04 (2025) 061

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



NP may enter to mediate the FCNC



Three D decay mode:

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

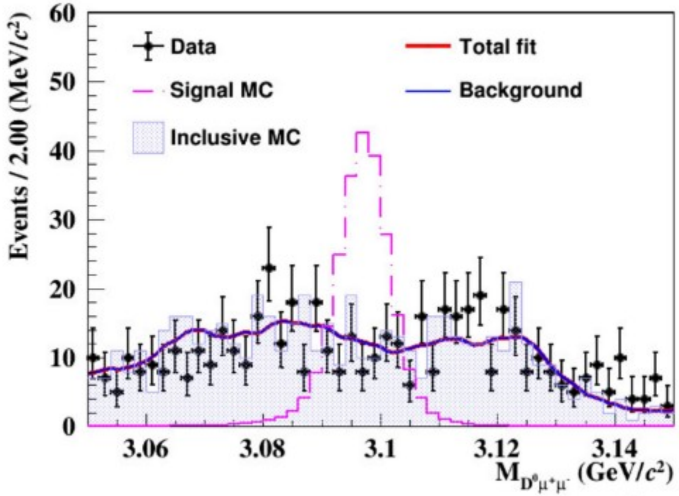
SM

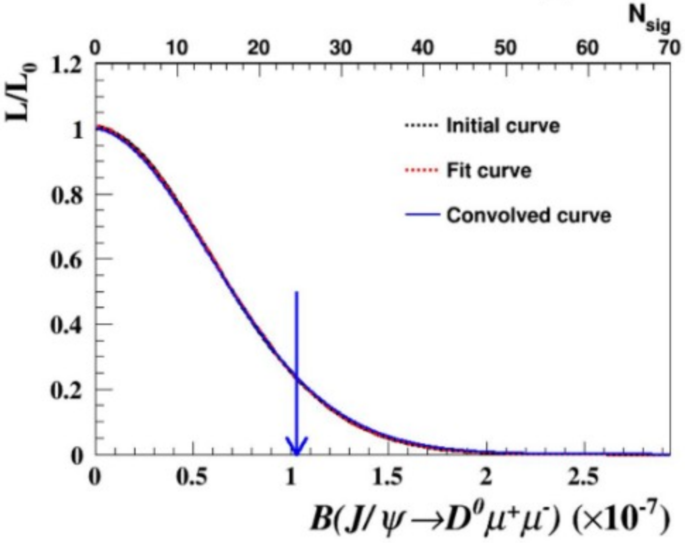
$$\mathrm{BR}(J/\psi \to \bar{D}^0\mu^+\mu^-) = 1.08^{+0.67}_{-0.33} \times 10^{-13},$$

$$\mathrm{BR}(J/\psi \to \bar{D}^{*0}\mu^+\mu^-) = 5.94^{+3.36}_{-2.15} \times 10^{-13},$$

JHEP 04 (2025) 061

$J/\psi \longrightarrow D^0\mu^+\mu^-$





Main backgrounds are due to π/μ and π/K misidentification (low momentum signal muon) (e.g. background $J/\psi \longrightarrow 5\pi$)

Use invariant mass combination to identify the signal region

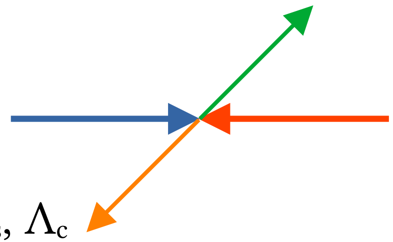
J/ψ invariant mass used for signal extraction

First ever measurement of this decay. No signal observed

$B(J/\psi \longrightarrow D^0\mu\mu)$ < 1.1 x 10-7 @ 90% C.L.

Phys.Rev.Lett. 133 (2024) 12, 121 801

$D_s \longrightarrow h(h') e^+e^-$



Using the D_s sample between 4.128-4.226 GeV (7.33 fb^{-1})

Single tag analysis (only one side of the decay is reconstructed)

Short distance contribution suppressed by GIM mechanism
Opportunity to observe long distance contribution that can be as large as 10^{-5}

At BESIII, yield of $D_s^*D_s$ ~ $6x10^6$

- $D_s^+ \to \pi^+\pi^0 e^+e^-$
- $D_s^+ \to K^+\pi^0 e^+e^-$
- $D_s^+ \to K_S\pi^+ e^+e^-$
- $D_s^+ \to \pi^+\phi, \phi \to e^+e^-$
- $D_s^+ \to \rho^+\phi, \phi \to e^+e^-$

Phys.Rev.Lett. 133 (2024) 12, 121 801

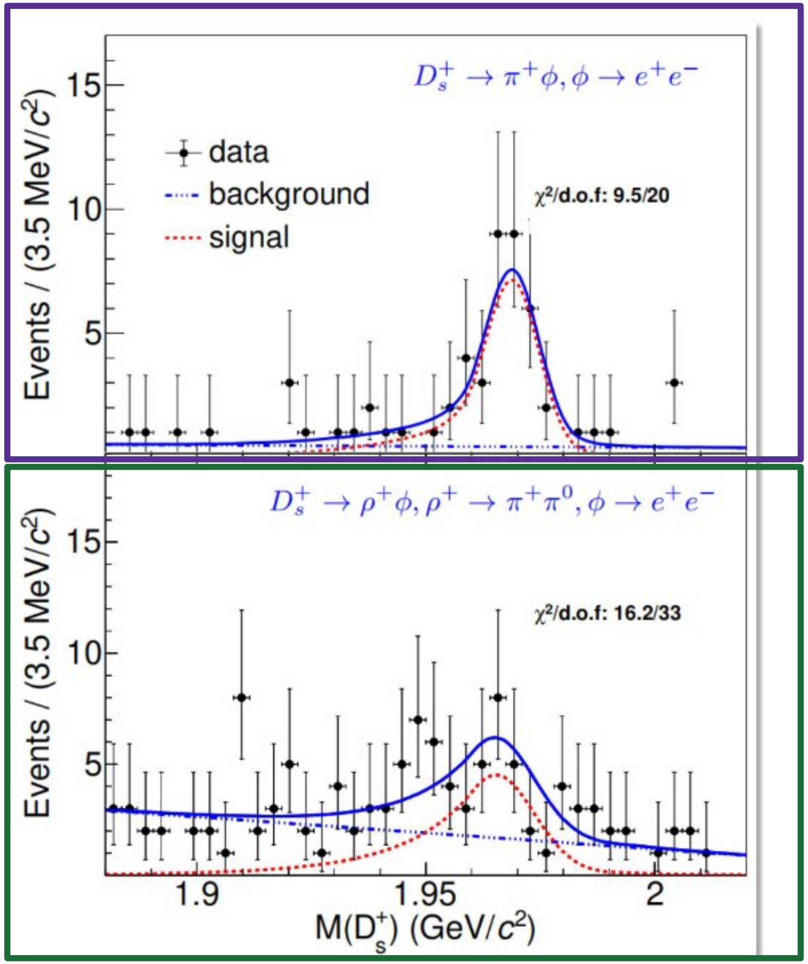
$D_s \longrightarrow h(h') e^+e^-$

Branching fraction is calculated as:

$$B(D_s^+ \to h(h')e^+e^-) = \frac{N_{sig,\,fit}}{2 \times N_{D_s^{*\pm} D_s^{\mp}} \times \epsilon \times B_{inter}}$$

First evidence of $D_s \longrightarrow \Phi\rho$, $\Phi \longrightarrow e^+e^-$
$B(D_s \longrightarrow \Phi\rho) \times B(\Phi \longrightarrow e^+e) = (2.44^{+0.62}_{-0.67} \pm 0.16) \times 10^{-5}$,
4.4σ significance

Observation of $D_s \longrightarrow \Phi\pi$, $\Phi \longrightarrow e^+e^-$
$B(D_s \longrightarrow \Phi\pi) \times B(\Phi \longrightarrow e^+e) = (1.17^{+0.23}_{-0.21} \pm 0.3) \times 10^{-5}$,
8.7σ significance in accordance with CLEO



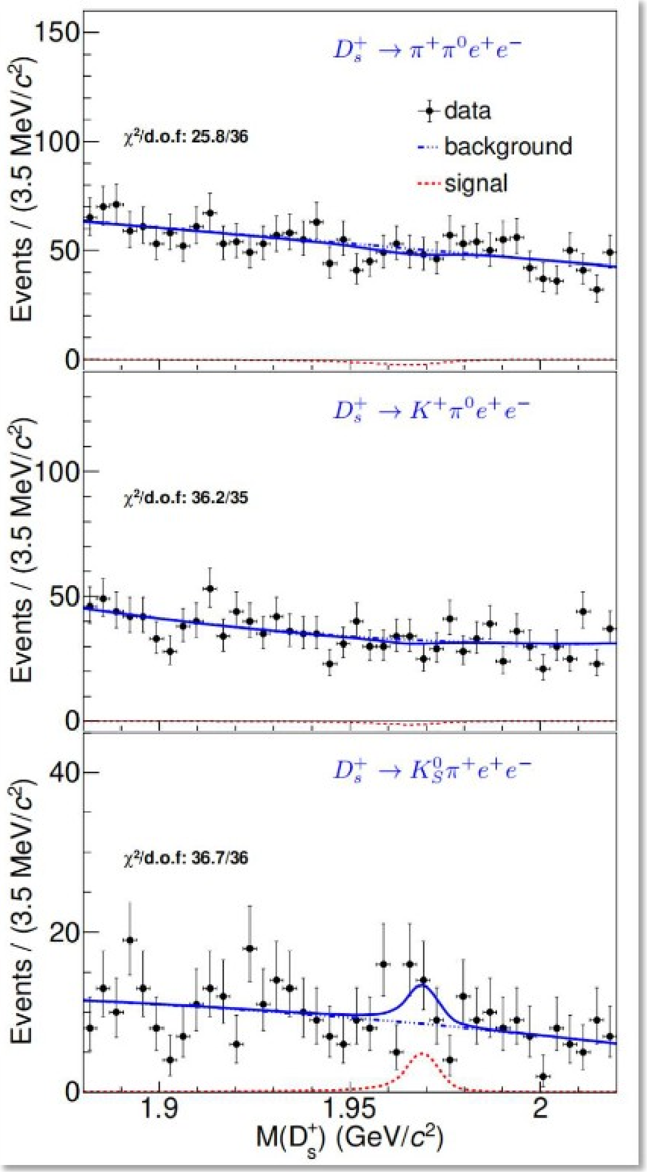
Phys.Rev.Lett. 133 (2024) 12, 121 801

$D_s \longrightarrow h(h') e^+e^-$

The $D_s \longrightarrow \pi^+\pi^0e^+e^-$ includes the LD contribution $D_s \longrightarrow \Phi\rho$. By excluding it, extracted the upper limit for the pure SD process for the first time
$B(D_s \longrightarrow \pi^+\pi^0e^+e^-) < 7.0 \times 10^{-5}$ @ 90% C.L.

For the $D_s \longrightarrow K_s\pi^+e^+e^-$ and $D_s \longrightarrow K^+\pi^0e^+e^-$ processes, the LD $\Phi \longrightarrow e^+e^-$ process is insignificant, only SD with BF of the 10^{-8} order

Extracted first limits
$B(D_s \longrightarrow K^+\pi^0e^+e^-) < 7.1 \times 10^{-5}$ @ 90% C.L.
$B(D_s \longrightarrow K_s\pi^+e^+e^-) < 8.1 \times 10^{-5}$ @ 90% C.L.



Bonus Track:
cLFV @ BESIII

arXiv:2507.10331

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

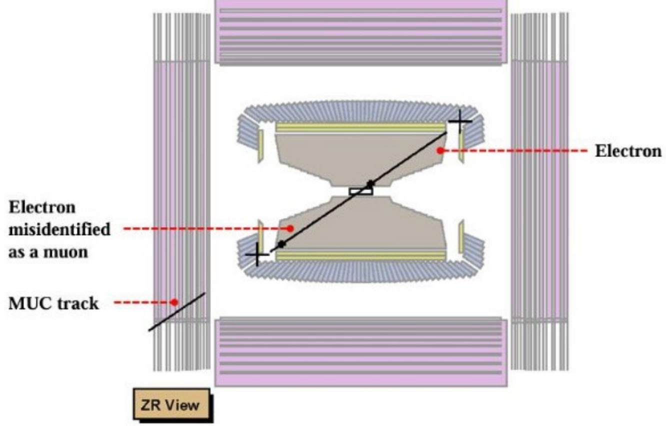
Search for cLFV in ψ(2S) decays usign the full 2.7B dataset

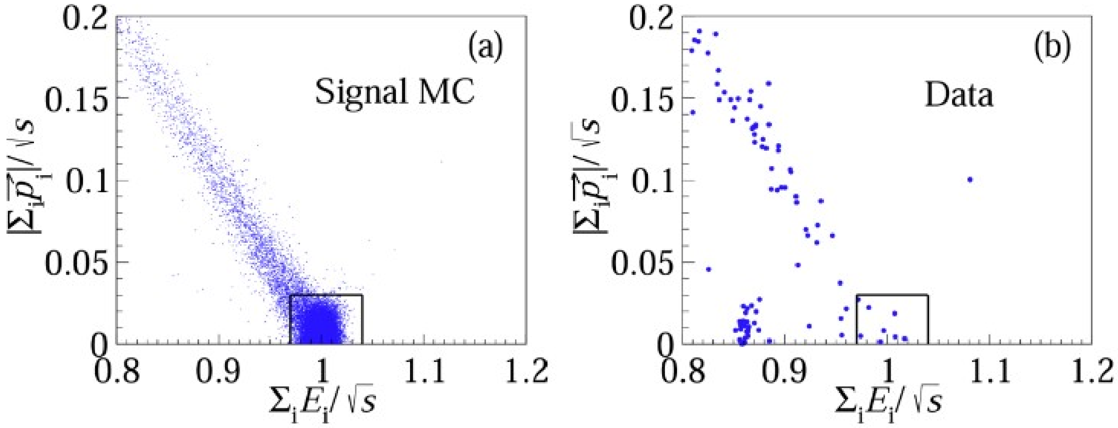
Signal box:

- $|\sum\vec{p}|/\sqrt{s} \leq 0.03$
- $0.97 \leq E_{vis}/\sqrt{s} \leq 1.04$

No missing
momentum or energy

Front. Phys. 19, 64201 (2024)



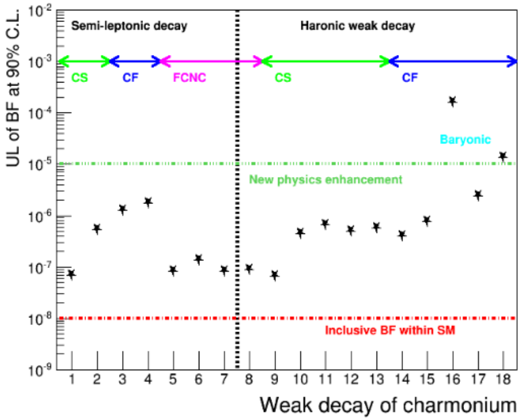


Maximum likelihood estimator for the BR extraction

B(psi(2S) ⟶ eu) < 1.4 x 10-8 @ 90% C.L.
First measurement

Summary and prospect

- BESIII has unique datasets to search for rare decays of charmed particles
- Using the 10B J/ψ, stringent constraints on charmonium weak decay and search for new physics
- Unique place to search for J/ψ FCNC
- Clean environment can help in studying Ds mesons LD contribution (since SD too small)



1: $J/\psi \to D^- e^+ \nu_e$+c.c.
2: $J/\psi \to D^- \mu^+ \nu_\mu$+c.c.
3: $J/\psi \to D_s^- e^+ \nu_e$+c.c.
4: $J/\psi \to D_s^{*-} e^+ \nu_e$+c.c.
5: $J/\psi \to D^0 e^+ e^-$+c.c.
6: $\psi(2S) \to D^0 e^+ e^-$+c.c.
7: $J/\psi \to D^0 \mu^+ \mu^-$+c.c.
8: $J/\psi \to \gamma D^0$+c.c.
9: $J/\psi \to D^- \pi^+$+c.c.
10: $J/\psi \to D^0 \pi^0$+c.c.
11: $J/\psi \to D^0 \eta$+c.c.
12: $J/\psi \to D^0 \rho^0$+c.c.
13: $J/\psi \to D^- \rho^+$+c.c.
14: $J/\psi \to D_s^- \pi^+$+c.c.
15: $J/\psi \to D_s^- \rho^+$+c.c.
16: $J/\psi \to D^0 K^0$+c.c.
17: $J/\psi \to D^0 K^{*0}$+c.c.
18: $\psi(2S) \to \Lambda_c^+ \bar{\Sigma}^-$+c.c.

Figure: The summary of charmonium weak decay