Search for new physics with charm rare decays at BESIII

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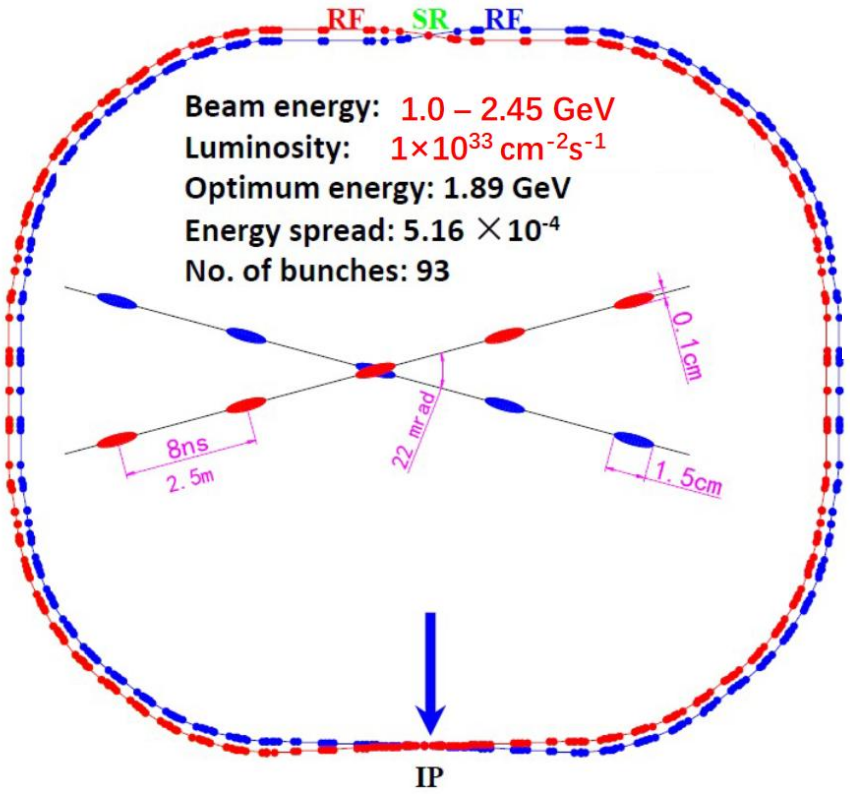
On behalf of BESIII Collaboration

EPS-HEP 2025

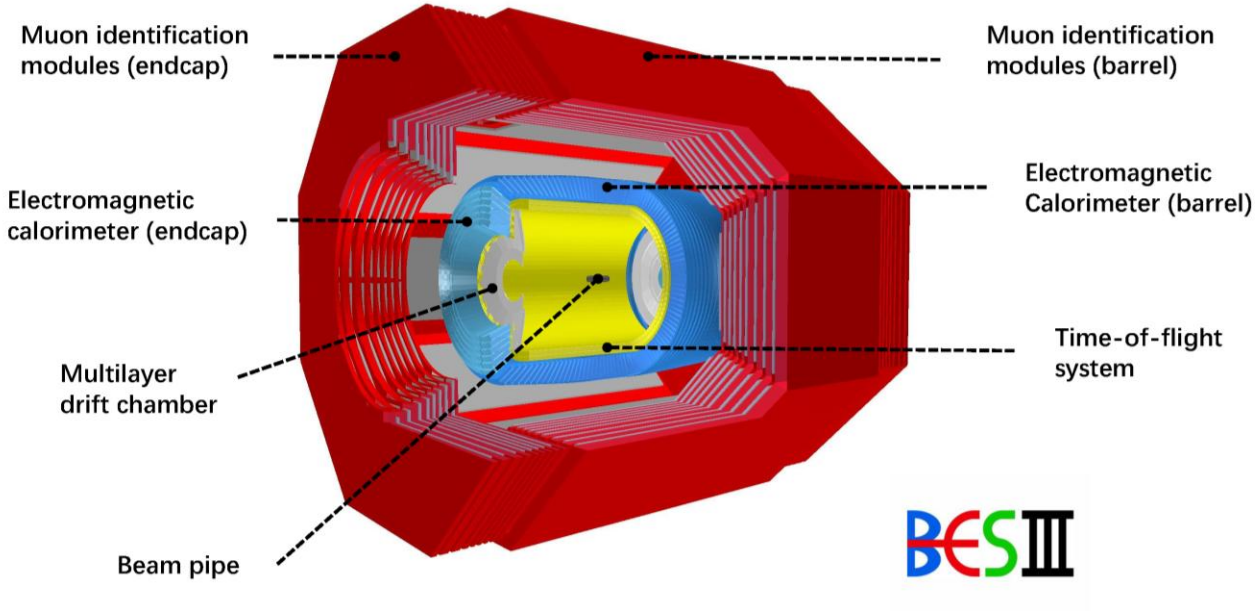
Outline

- BEPCII and BESIII
- FCNC decays with charm
- J/ψ weak decays
- Summary

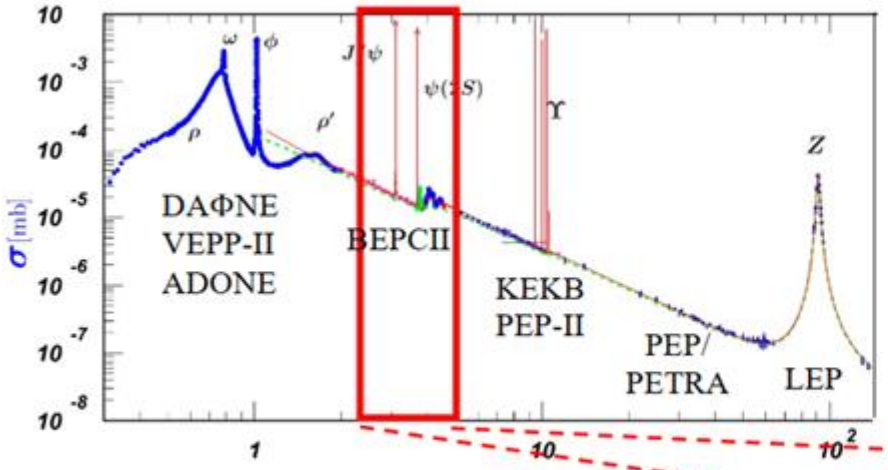
Beijing Electron Positron Collider II



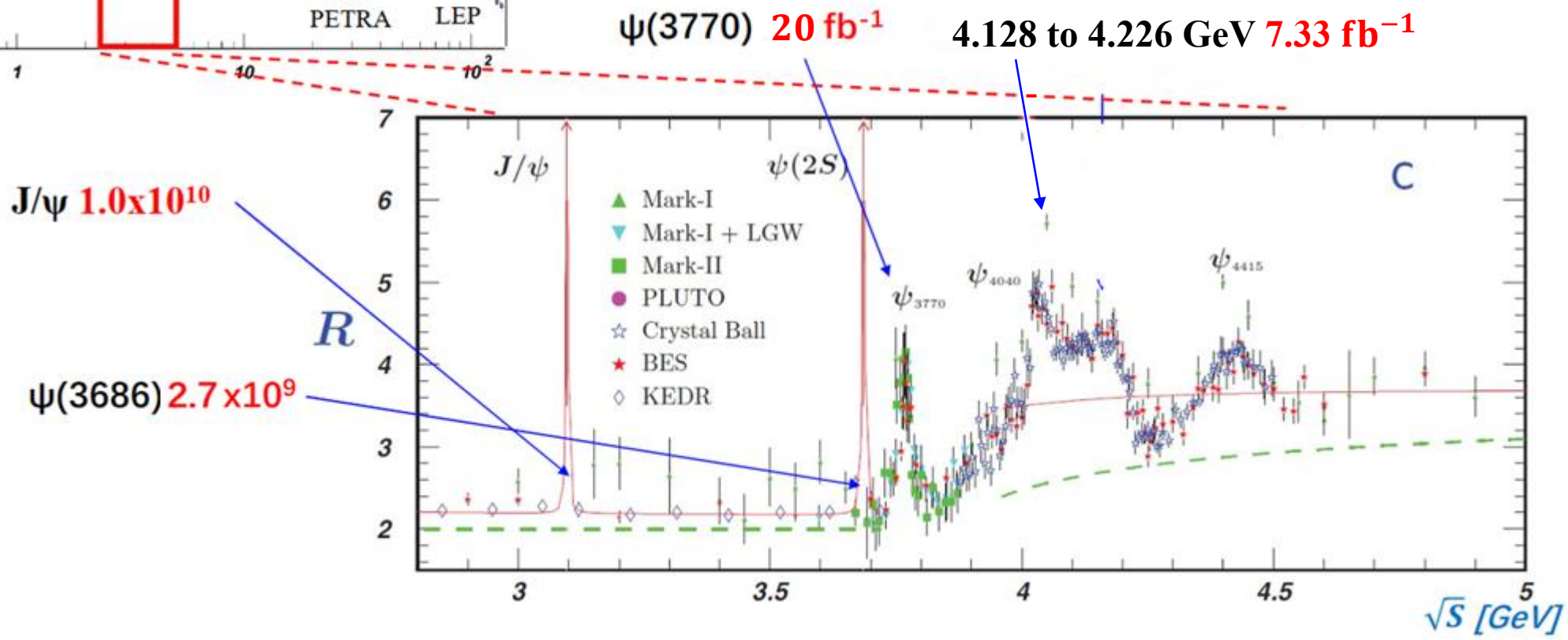
BESIII Detector



- Multilayer drift chamber (**MDC**)
  - The momentum resolution: 0.5% @ 1GeV/c
  - dE/dx resolution: 6%
- Time-of-flight (**TOF**) system
  - The time resolution: 68ps(barrel)/60ps(endcap)
- CsI(Tl) Electromagnetic calorimeter (**EMC**)
  - The energy resolution: 2.5%(barrel)/5.0%(endcap) @1GeV
- Supercon-ducting solenoidal magnet (1.0 T magnetic field)
- Muon chamber (**MUC**) system



- The BESIII experiment has collected 2.7 billion $\psi(3686)$ events, 10 billion J/ψ events, 20 fb^{-1} D meson pairs at 3.773 GeV, and 7.33 fb^{-1} $D_s D_s^*$ events from 4.128 to 4.226 GeV.



SM contribution is dominant

Good sensitivity to NP

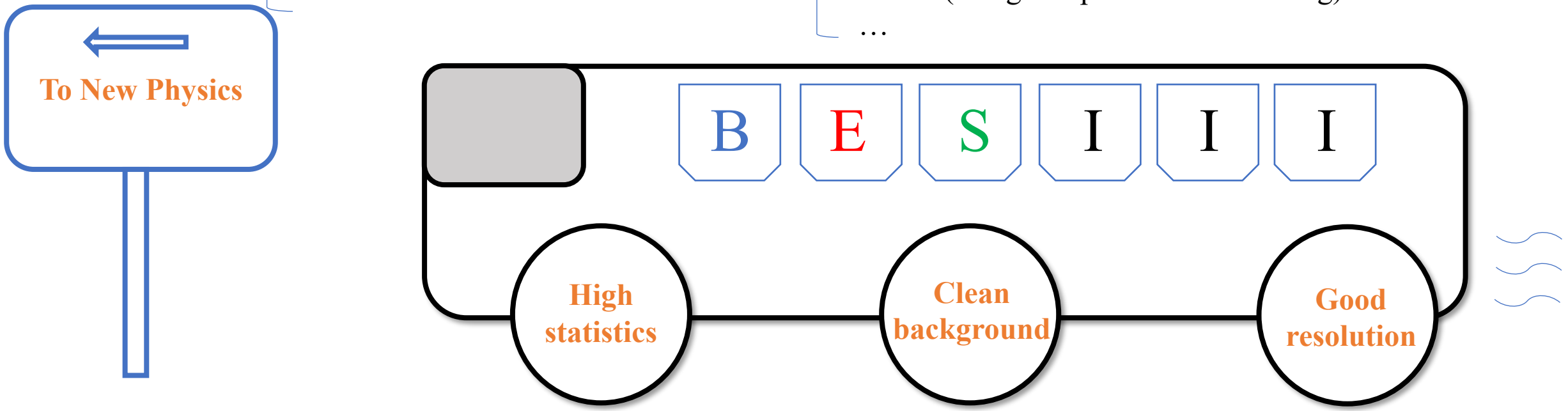
SM contribution is highly suppressed

- charmonium weak decays
- FCNC (flavor-changing neutral current)
- High order
- …

This work

SM contribution is forbidden

- BNV/LNV (baryon and lepton number violation)
- CLFV (charged lepton flavor violating)
- …



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FCNC decays with charm

- Flavor-changing neutral currents (FCNC) transitions such as $c \to u$ manifest solely through loop-level interactions, which result in low branching fractions (BFs) of the corresponding decays.
- Various new physics (NP) models beyond the SM suggest these BFs may be enhanced to exceed the SM prediction.
- Any enhancement of the BF with respect to the SM would be a strong indication of NP.

Top-Color model[1]

Supersymmetric extensions of the SM with or without R-parity violation[2]

Two-Higgs doublet model[3]

Charmonium weak decay	Experimental upper limit (@90% C.L.)	data sample
$J/\psi \to D^0 e^+ e^-$	$< 8.5 \times 10^{-8}$ [4]	$13.11 \times 10^8\ J/\psi$
$\psi(3686) \to D^0 e^+ e^-$	$< 1.4 \times 10^{-7}$ [4]	$44.81 \times 10^7 \psi(3686)$
$J/\psi \to D^0 \mu^+ \mu^-$	$< 1.1 \times 10^{-7}$ [5]	$(1.01 \times 10^{10})\ J/\psi$
$J/\psi \to D^0 \gamma$	$< 9.1 \times 10^{-8}$ [6]	$(1.01 \times 10^{10})\ J/\psi$
$D_s^+ \to \pi^+ \pi^0 e^+ e^-$	$< 7.0 \times 10^{-5}$ [7]	$(7.33\ fb^{-1})\ \sqrt{s} = 4.128$–$4.226\ GeV$
$D_s^+ \to K^+ \pi^0 e^+ e^-$	$< 7.1 \times 10^{-5}$ [7]	
$D_s^+ \to K_S^0 \pi^+ e^+ e^-$	$< 8.1 \times 10^{-5}$ [7]	

[1] Phys. Lett. B 345, 483 (1995)
[2] Phys. Lett. B 119, 136 (1982)
[3] Phys. Rev. D15, 1958 (1977)
[4] Phys. Rev. D 96, 111101(R) (2017)
[5] JHEP 04,061 (2025)
[6] Phys.Rev.D 110, 112012 (2024)
[7] Phys.Rev.Lett. 133, 121801 (2024)

FCNC decays with charm

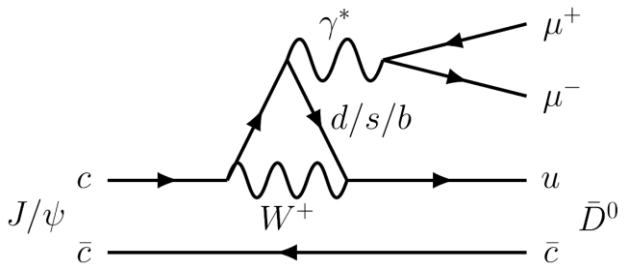


Figure (1): The Feynman diagram of $J/\psi \to D^0\mu^+\mu^-$

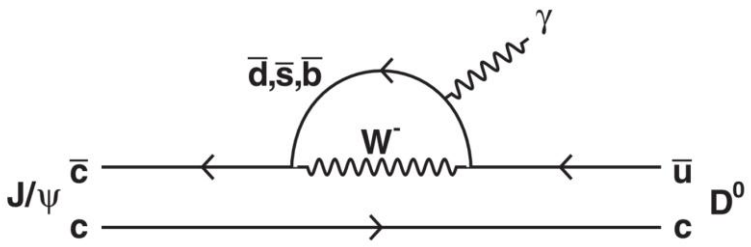


Figure (2): The Feynman diagram of $J/\psi \to D^0\gamma$

- Reconstruct D^0 meson:

$D^0 \to K^-\pi^+$(Mode I)

$D^0 \to K^-\pi^+\pi^0$ with $\pi^0 \to \gamma\gamma$ (Mode II)

$D^0 \to K^-\pi^-\pi^+\pi^+$ (Mode III)

$J/\psi \to D^0 l^+ l^-$ BFs ~ 10^{-13}

one fewer decay vertex

$J/\psi \to D^0\gamma$ BFs ~ $10^{-12} - 10^{-11}$

$J/\psi \to D^0\mu^+\mu^-$
JHEP 04,061 (2025)

$J/\psi \to D^0\gamma$
Phys.Rev.D 110, 112012 (2024)

- Using $(1.0087 \pm 0.0044) \times 10^{10} J/\psi$ events.
- To extract the BFs, an unbinned simultaneous maximum-likelihood fit is carried out to the selected samples of the three D^0 decay modes by sharing the same decay BF of $J/\psi \to D^0\gamma$ ($J/\psi \to D^0\mu^+\mu^-$).

$J/\psi \to D^0\mu^+\mu^-$
JHEP 04,061 (2025)

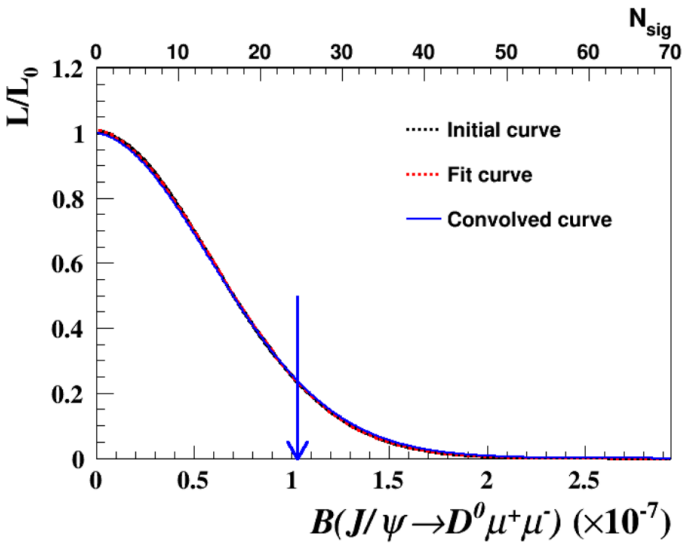


Figure (2): The distributions of normalized likelihoods versus signal yields N_{sig} or BF of $J/\psi \to D^0\mu^+\mu^-$.

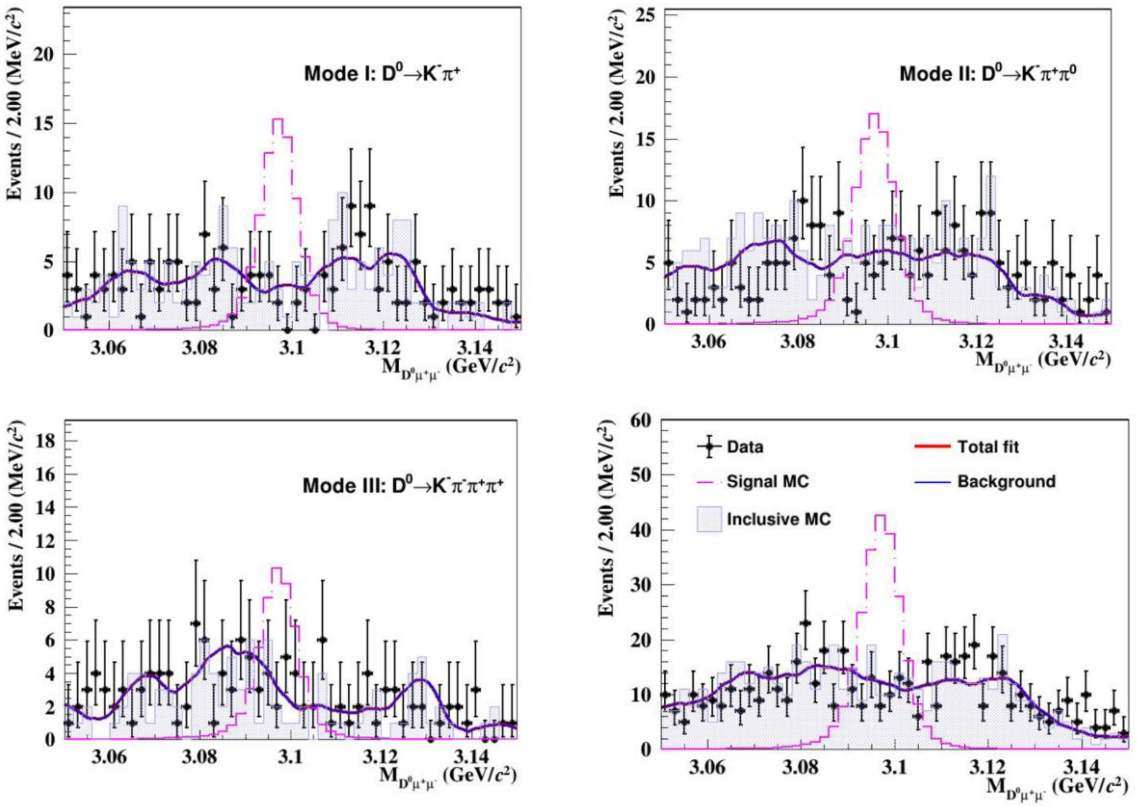


Figure (1): The distributions of $M_{D^0\mu^+\mu^-}$ for $J/\psi \to D^0\mu^+\mu^-$ of the selected candidates in data, signal MC sample, and inclusive MC sample.

- No significant signal is observed.
- $\mathcal{B}(J/\psi \to D^0\mu^+\mu^-) < 1.1 \times 10^{-7}$ @90% C.L.
- This is the first search for a charmonium FCNC process involving muons in the final state.

$J/\psi \to D^0\gamma$
Phys.Rev.D 110, 112012 (2024)

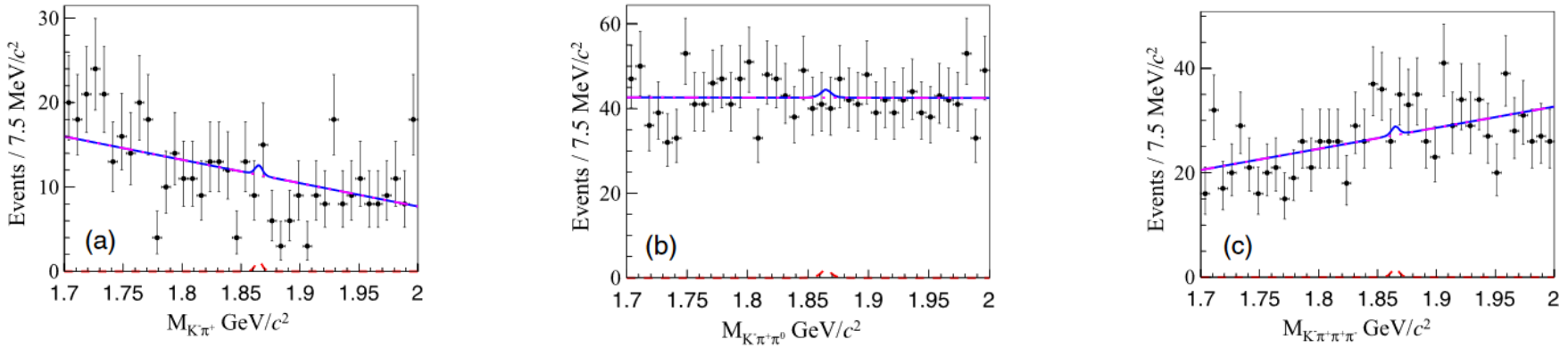


Figure (1): The unbinned simultaneous fit on the invariant mass distributions of modes (a) I, (b) II and (c) III, where the dots with error bar are data, the blue lines are the fit result, and the red dotted and purple curves are the fitted signal and background, respectively.

- The results are consistent with a background-only hypothesis.
- $\mathcal{B}(J/\psi \to D^0\gamma) < 9.1 \times 10^{-8}$ @90% C.L., representing the most stringent limit to date.
- It provides a valuable reference for studying different NP models and restrict the phase space of parameters.

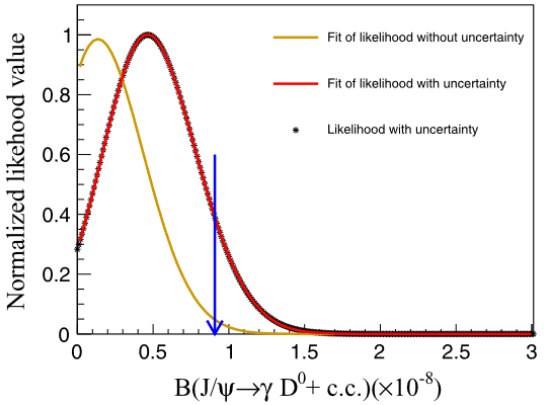


Figure (2): The likelihood profile for $J/\psi \to \gamma D^0$ combining the three decay modes to extract the upper limit on the BF.

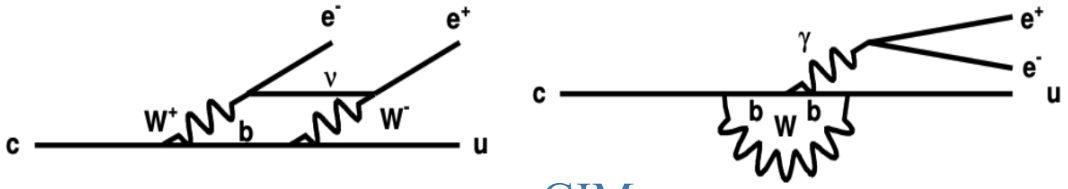
FCNC decays with charm

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

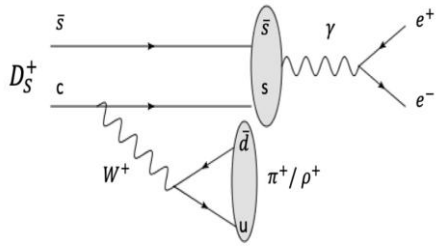
$D_s^+ \to \pi^+\phi$
$\phi \to e^+e^-$

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

- Short-distance (SD) and long-distance (LD) contributions.



SD-only BFs → GIM → 10^{-9}



LD BFs → 10^{-6}

- Use 7.33 fb^{-1} $D_sD_s^*$ events from 4.128 to 4.226 GeV.
- We apply a single tag (ST) method to search for D_s^+ candidates.

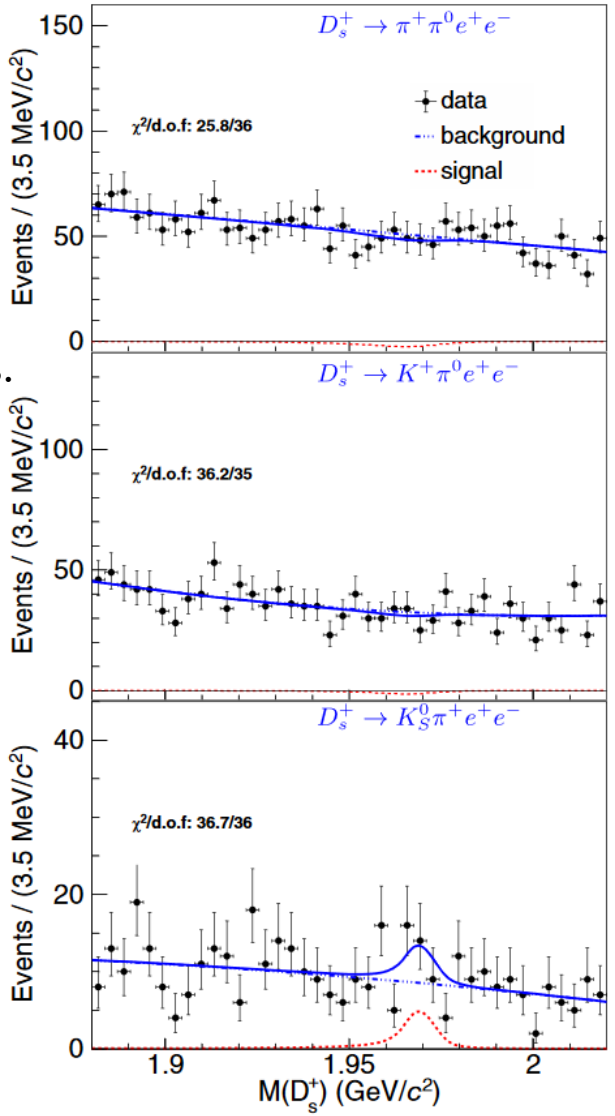


Figure (1): Fits to the M(D_s^+) distributions for $D_s^+ \to \pi^+\pi^0e^+e^-$, $D_s^+ \to K^+\pi^0e^+e^-$, and $D_s^+ \to K_S^0\pi^0e^+e^-$. For $D_s^+ \to \pi^+\pi^0e^+e^-$, the M($e^+e^-$) is required to be outside the ϕ mass window.

$D_s^+ \to h(h')e^+e^-$
Phys.Rev.Lett. 133, 121801 (2024)

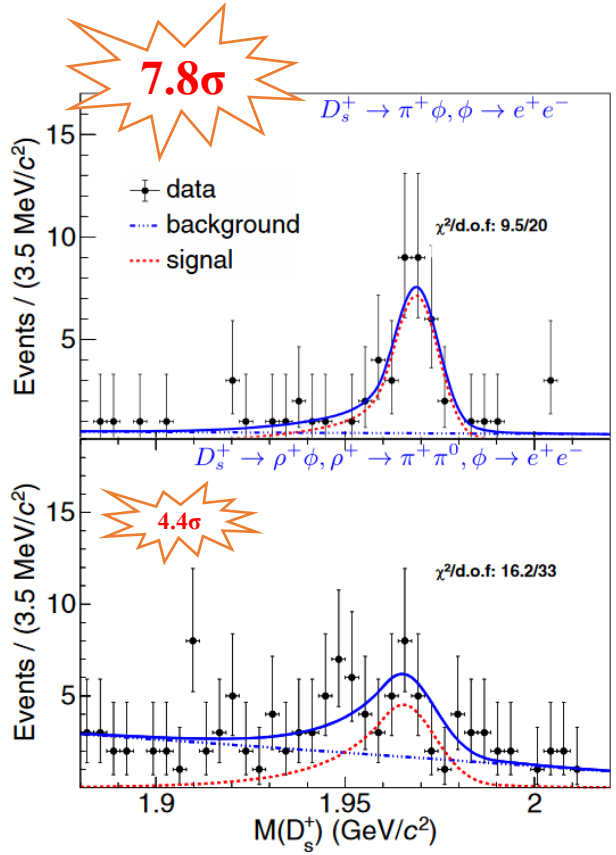


Figure (2): Fits to the M(D_s^+) distributions for $D_s^+ \to \pi^+\phi, \phi \to e^+e^-$ and $D_s^+ \to \rho^+\phi, \rho^+ \to \pi^+\pi^0, \phi \to e^+e^-$.

$D_s^+ \to h(h')e^+e^-$
Phys.Rev.Lett. 133, 121801 (2024)

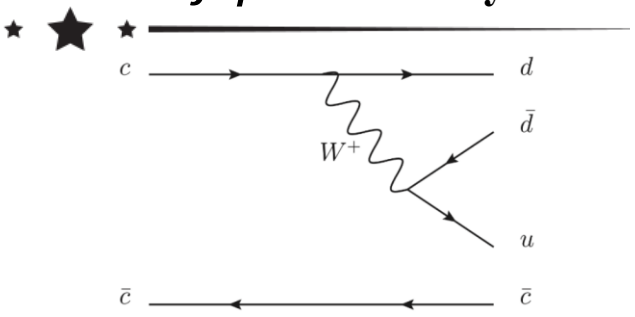
- These two values are consistent with the direct calculations of $\mathcal{B}(D_s^+ \to \pi^+\phi) \cdot \mathcal{B}(\phi \to e^+e^-) = (1.34 \pm 0.12) \times 10^{-5}$ and $\mathcal{B}(D_s^+ \to \rho^+\phi) \cdot \mathcal{B}(\phi \to e^+e^-) = (1.67 \pm 0.11) \times 10^{-5}$ from the PDG[1].
- For the three four-body decay modes, no significant signal is found. Therefore, we set upper limits on the BFs at the 90% confidence level.

Table 1: The signal yields (N_{sig}), signal efficiencies, the BFs, and the 90% confidence level upper limits, where the first uncertainty is statistical and the second systematic.

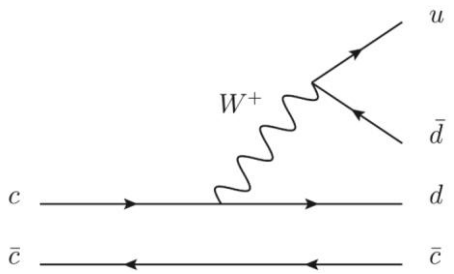
Decay	N_{sig}	ϵ(%)	$\mathcal{B}(\times 10^{-5})$
$D_s^+ \to \pi^+\phi, \phi \to e^+e^-$	$38.2^{+7.8}_{-6.8}$	25.1	$1.17^{+0.23}_{-0.21} \pm 0.03$
$D_s^+ \to \rho^+\phi, \phi \to e^+e^-$	$37.8^{+10.3}_{-9.6}$	12.1	$2.44^{+0.67}_{-0.62} \pm 0.16$
$D_s^+ \to \pi^+\pi^0e^+e^-$		7.4	< 7.0
$D_s^+ \to K^+\pi^0e^+e^-$		5.3	< 7.1
$D_s^+ \to K_S^0\pi^+e^+e^-$		6.7	< 8.1

[1] Phys. Rev. D 110,030001 (2024)

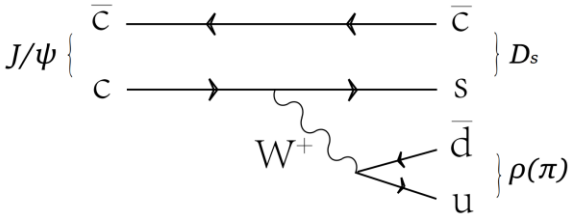
J/ψ weak decays



Fig(a) The leading-order Feynman diagram of $J/\psi \to \bar{D}^0\pi^0$, $J/\psi \to \bar{D}^0\eta$ and $J/\psi \to \bar{D}^0\rho^0$



Fig(b) The leading-order Feynman diagram of $J/\psi \to D^-\pi^+$ and $J/\psi \to D^-\rho^+$



Fig(c) The leading-order Feynman diagram of $J/\psi \to D_s^-\pi^+$ and $J/\psi \to D_s^-\rho^+$

- The inclusive branching fraction of the charmonium weak decays is predicted to be 10^{-8} in the standard model.
- If the BFs for weak decays of J/ψ are found to be within the range of 10^{-8} to 10^{-6}, it would suggest the presence of new physics beyond the Standard Model.
- Using $(1.0087 \pm 0.0044) \times 10^{10} J/\psi$ events.
- To avoid high background from conventional J/ψ hadronic decays, the $\bar{D}^0$, D^- and D_s^- mesons are tagged by the semi-leptonic decays.

Charmonium weak	Experimental upper limit (@90% C.L.)	Number of J/ψ data events
$J/\psi \to D_s^-\rho^+$	$< 8.0 \times 10^{-7}$ [1]	BESIII (1.01×10^{10})
$J/\psi \to D_s^-\pi^+$	$< 4.1 \times 10^{-7}$ [1]	BESIII (1.01×10^{10})
$J/\psi \to D^-\rho^+$	$< 6.0 \times 10^{-7}$ [2]	BESIII (1.01×10^{10})
$J/\psi \to D^-\pi^+$	$< 7.0 \times 10^{-8}$ [2]	
$J/\psi \to \bar{D}^0\rho^0$	$< 5.2 \times 10^{-7}$ [2]	
$J/\psi \to \bar{D}^0\eta$	$< 6.8 \times 10^{-7}$ [2]	
$J/\psi \to \bar{D}^0\pi^0$	$< 4.7 \times 10^{-7}$ [2]	
$J/\psi \to D^-\mu^+\nu_\mu$	$< 5.6 \times 10^{-7}$ [4]	BESIII (1.01×10^{10})
$J/\psi \to D^-e^+\nu_e$	$< 7.1 \times 10^{-8}$ [3]	BESIII (1.01×10^{10})
$J/\psi \to D_s^-e^+\nu_e$	$< 1.3 \times 10^{-6}$ [5]	BESIII (2.25×10^{8})
$J/\psi \to D_s^{*-}e^+\nu_e$	$< 1.8 \times 10^{-6}$ [5]	BESIII (2.25×10^{8})

[1] arXiv:2506.09386
[2] Phys. Rev. D 110, 032020 (2024)
[3] JHEP 01, 126 (2024)
[4] JHEP 06, 157 (2021)
[5] Phys. Rev. D 90, 112014 (2014)

- Select those events for which the recoiling mass against the $\pi^0, \eta, \rho^0, \pi^+$, and ρ^+ falls within the mass window $(1.80, 1.95)\ GeV/c^2$ for all decay modes.

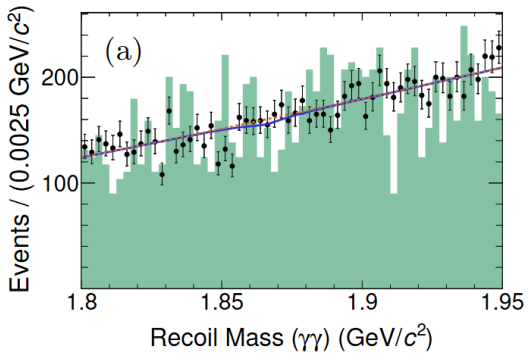
$J/\psi \to \bar{D}^0\pi^0$
$\bar{D}^0 \to K^+e^-\bar{\nu}_e$
$\pi^0 \to \gamma\gamma$

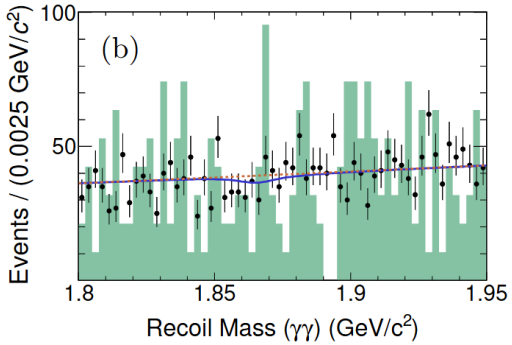
$J/\psi \to \bar{D}^0\eta$
$\bar{D}^0 \to K^+e^-\bar{\nu}_e$
$\eta \to \gamma\gamma$

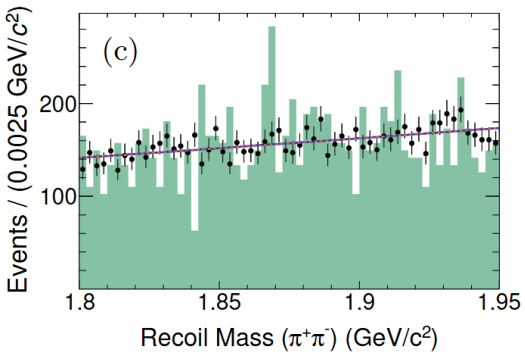
$J/\psi \to \bar{D}^0\rho^0$
$\bar{D}^0 \to K^+e^-\bar{\nu}_e$
$\rho^0 \to \pi^+\pi^-$

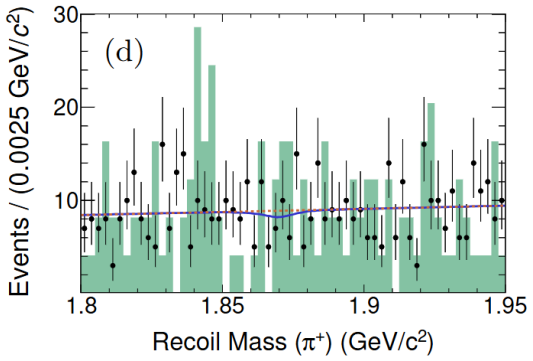
$J/\psi \to D^-\pi^+$
$D^- \to K_S^0e^-\bar{\nu}_e$
$K_S^0 \to \pi^+\pi^-$

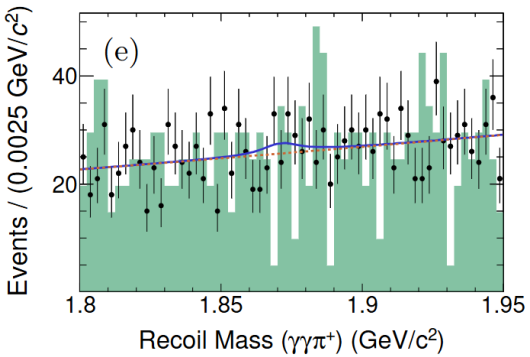
$J/\psi \to D^-\rho^+$
$D^- \to K_S^0e^-\bar{\nu}_e$
$K_S^0 \to \pi^+\pi^-$
$\rho^+ \to \pi^+\pi^0$
$\pi^0 \to \gamma\gamma$











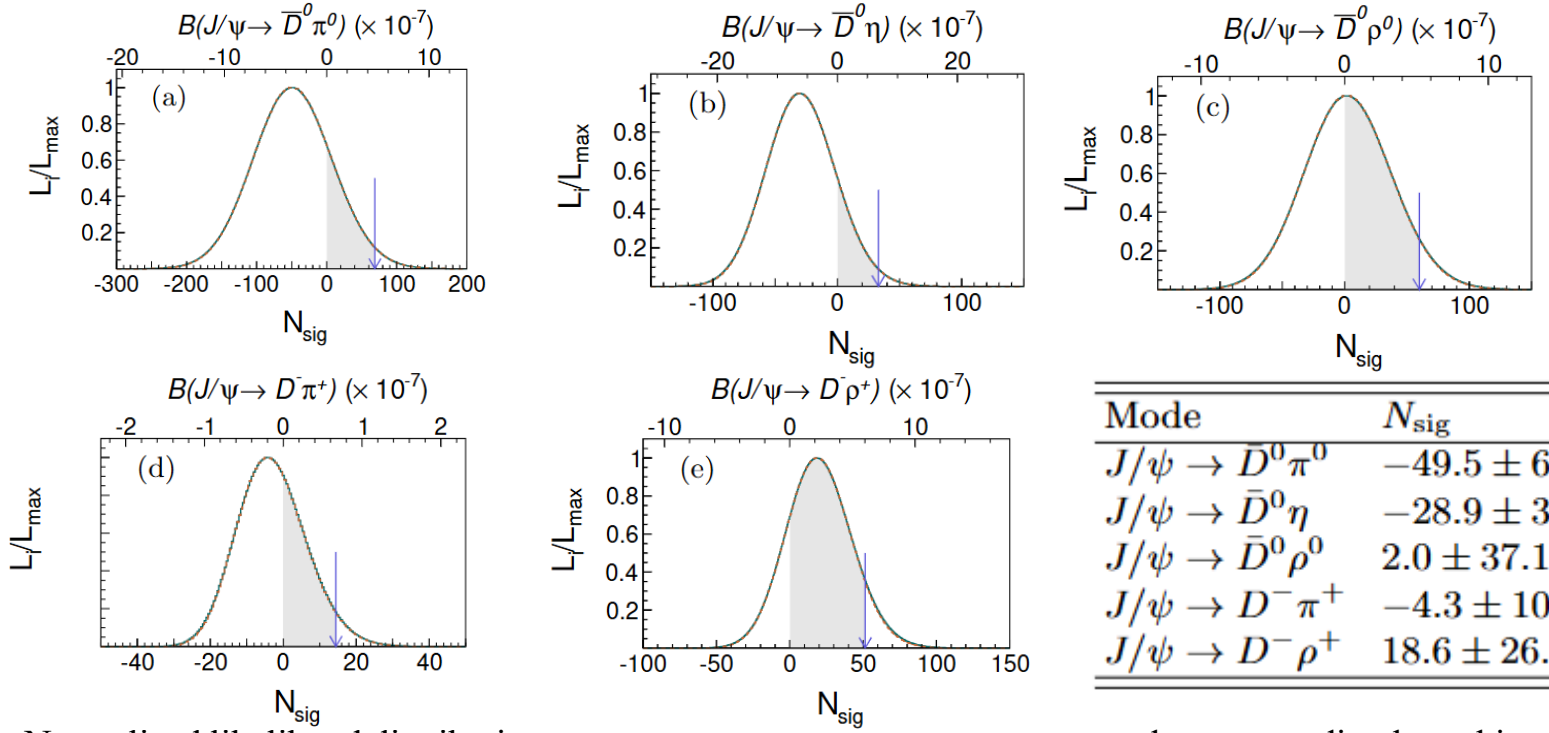
J/ψ weak decays containing a D meson
Phys. Rev. D 110, 032020(2024)

Figure: Fits of the accepted candidates to the recoiling mass spectra for $(a)\ J/\psi \to \bar{D}^0\pi^0, (b)\ J/\psi \to \bar{D}^0\eta, (c)\ J/\psi \to \bar{D}^0\rho^0, (d)\ J/\psi \to D^-\pi^+ and\ (e)\ J/\psi \to D^-\rho^+$.

- No significant signal is observed in any of the decay modes. The branching fraction of signal decay is calculated as

$$\mathcal{B}(J/\psi \to DM(N)) = \frac{N_{\rm sig}}{N_{J/\psi} \times \epsilon \times \mathcal{B}_{\rm sub}}$$

where N_{sig} is the number of signal events, $N_{J/\psi}$ is the total number of J/ψ events, ε is the signal detection efficiency, and B_{sub} is the product of the branching fractions of all possible intermediate decays.



J/ψ weak decays containing a D meson
Phys. Rev. D 110, 032020(2024)

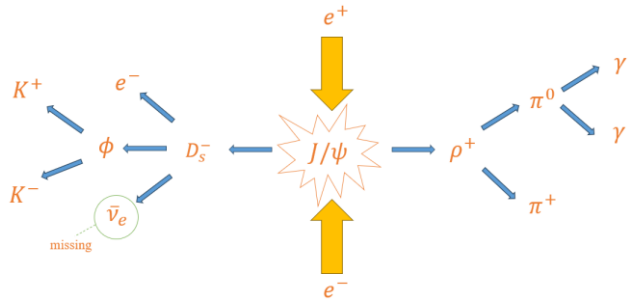
Mode	$N_{\rm sig}$	$N_{\rm sig}^{\rm UL}$	$\mathcal{B}$ (90% C.L.)	$\mathcal{B}$ (90% C.L.)
$J/\psi \to \bar{D}^0\pi^0$	-49.5 ± 69.3	< 68.8	$< 4.7 \times 10^{-7}$	···
$J/\psi \to \bar{D}^0\eta$	-28.9 ± 34.5	< 32.9	$< 6.8 \times 10^{-7}$	···
$J/\psi \to \bar{D}^0\rho^0$	2.0 ± 37.1	< 59.9	$< 5.2 \times 10^{-7}$	···
$J/\psi \to D^-\pi^+$	-4.3 ± 10.3	< 14.4	$< 7.0 \times 10^{-8}$	$< 7.5 \times 10^{-5}$ [3]
$J/\psi \to D^-\rho^+$	18.6 ± 26.2	< 51.4	$< 6.0 \times 10^{-7}$	···

Figure: Normalized likelihood distributions for the fitted yields of signal events and corresponding branching fractions of $(a)\ J/\psi \to \bar{D}^0\pi^0$, $(b)\ J/\psi \to \bar{D}^0\eta$, $(c)\ J/\psi \to \bar{D}^0\rho^0$, $(d)\ J/\psi \to D^-\pi^+ and\ (e)\ J/\psi \to D^-\rho^+$, with (green solid curves) and without (orange dashed lines) smearing the systematic uncertainties. The blue arrows mark the upper limits at the 90% C.L..

J/ψ weak decays

- Decay： $J/\psi \to D_s^- \rho^+$ and $J/\psi \to D_s^- \pi^+$
- Predicted relative ratio[1]: $\frac{\mathcal{B}(J/\psi \to D_s^- \rho^+)}{\mathcal{B}(J/\psi \to D_s^- \pi^+)} = 4.2$

$J/\psi \to D_s^- \rho^+$ and $J/\psi \to D_s^- \pi^+$
arXiv:2506.09386



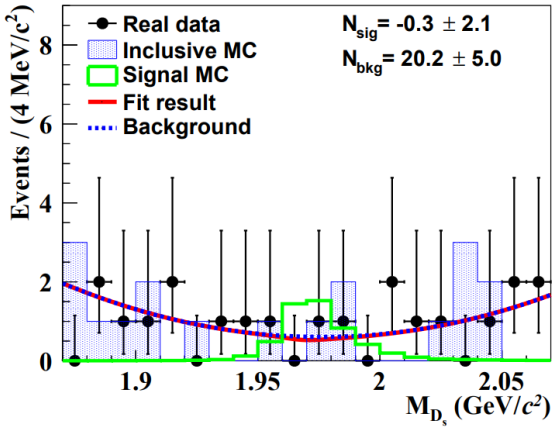


Figure (1): The M_{D_s} distributions of the $J/\psi \to D_s^- \rho^+$ Candidate events.

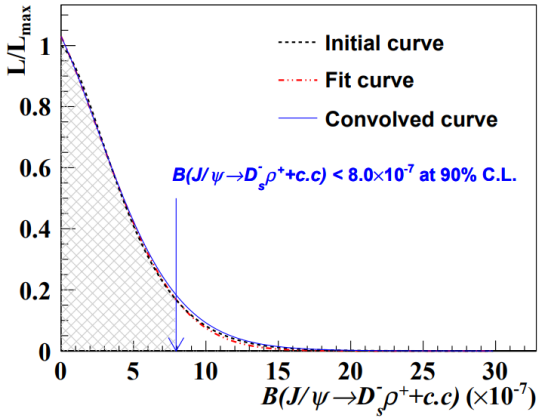
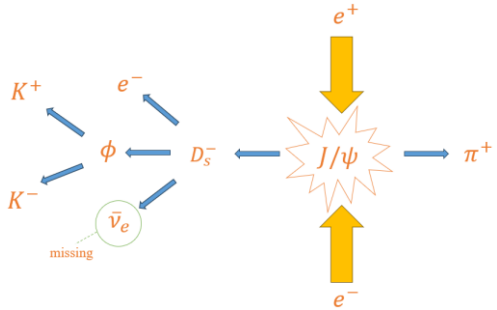


Figure (2): The distributions of the likelihood scan values for $J/\psi \to D_s^- \rho^+$.

- $\mathcal{B}(J/\psi \to D_s^- \rho^+) < 8.0 \times 10^{-7}$ @90% C.L.
- The UL for $J/\psi \to D_s^- \rho^+$ has been improved by about an order of magnitude.



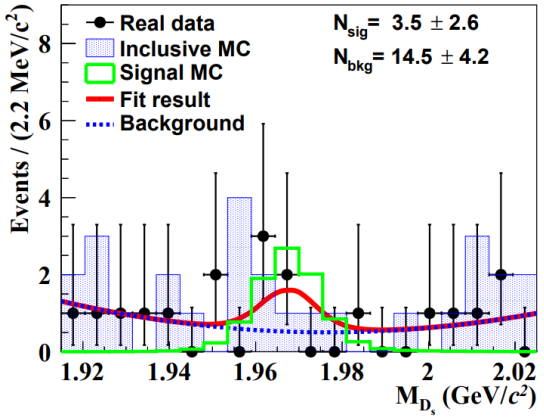


Figure (3): The M_{D_s} distributions of the $J/\psi \to D_s^- \pi^+$ Candidate events.

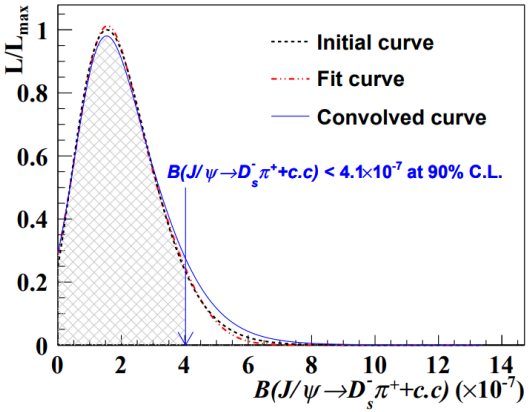


Figure (4): The distributions of the likelihood scan values for $J/\psi \to D_s^- \pi^+$.

- $\mathcal{B}(J/\psi \to D_s^- \pi^+) < 4.1 \times 10^{-7}$ @90% C.L.
- The UL for $J/\psi \to D_s^- \pi^+$ has been improved by about three orders of magnitude.

[1] Int. J. Mod. Phys. A 14, 937-946 (1999)

- BESIII performed a wide range study of new physics, with many first searches or best limits.
- The latest search results for rare decays with charm in BESIII are reported.
- BESIII has great potential with unique (and increasing) datasets and analysis techniques.

Thanks