



BESIII

# Experimental studies of charmonium weak decays at BESIII

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“对撞机上新物理寻找”研讨会, 2026.03.18, 南京大学

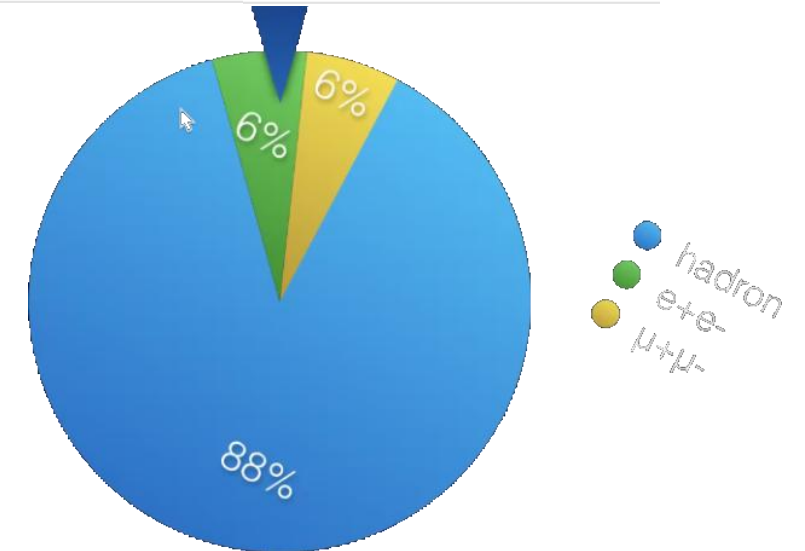
# Charmonium weak decays

- Charmonium decay is dominated by hadronic and electromagnetic decays
- The mass of  $J/\psi$  &  $\psi(3686)$  are below the  $D\bar{D}$  production threshold, making their lifetime longer than traditional hadrons (OZI suppression)
- The weak decay of charmonium is **allowed in SM**, but highly suppressed by strong and EM decays
- The rare charmonium weak decay processes makes it suitable to search for New Physics, if the branching fraction (BF) **deviates from the SM predictions**.
  - Semileptonic decays
  - Hadronic decays
  - Loop-level FCNC decays

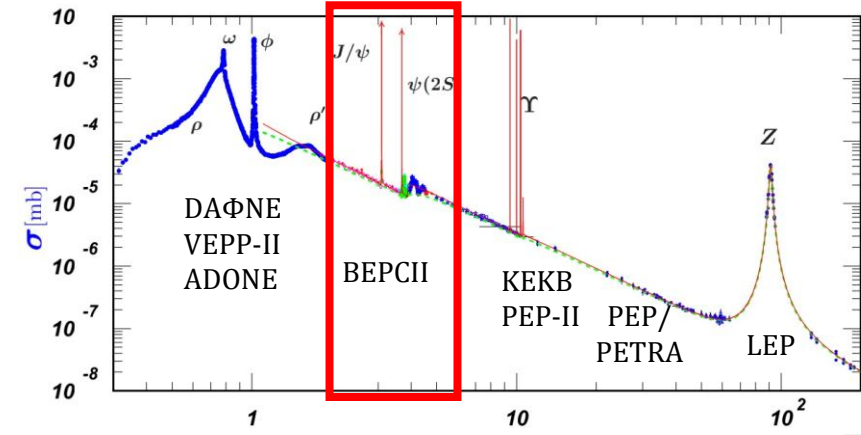
$c\bar{c}$  MESONS  
 $J/\psi(1S)$

|                    |                              |
|--------------------|------------------------------|
| $J/\psi(1S)$ MASS  | $3096.916 \pm 0.011$ MeV     |
| $J/\psi(1S)$ WIDTH | $92.9 \pm 2.8$ keV (S = 1.1) |

## Decay Modes

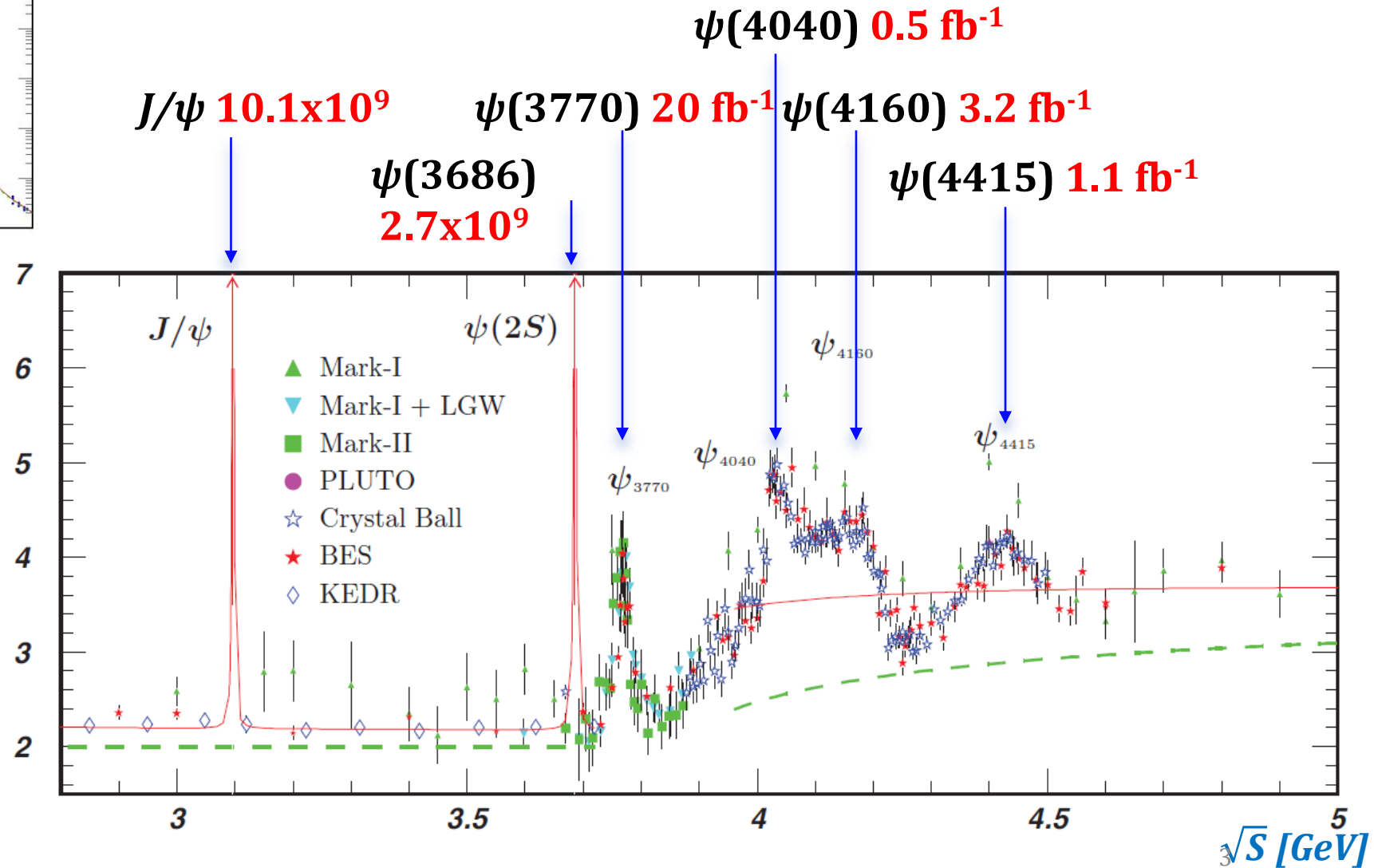


# Charmonium Data at BESIII



- BESIII has collected large data samples at  $J/\psi$ ,  $\psi(3686)$ ,  $D\bar{D}$  threshold
- More data at higher energy after upgrade

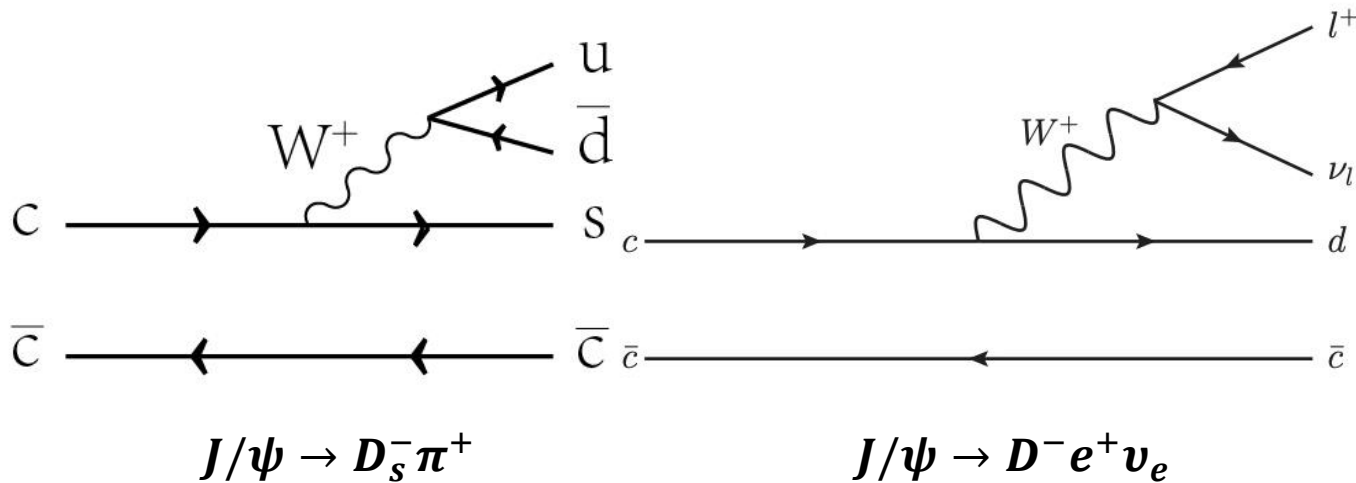
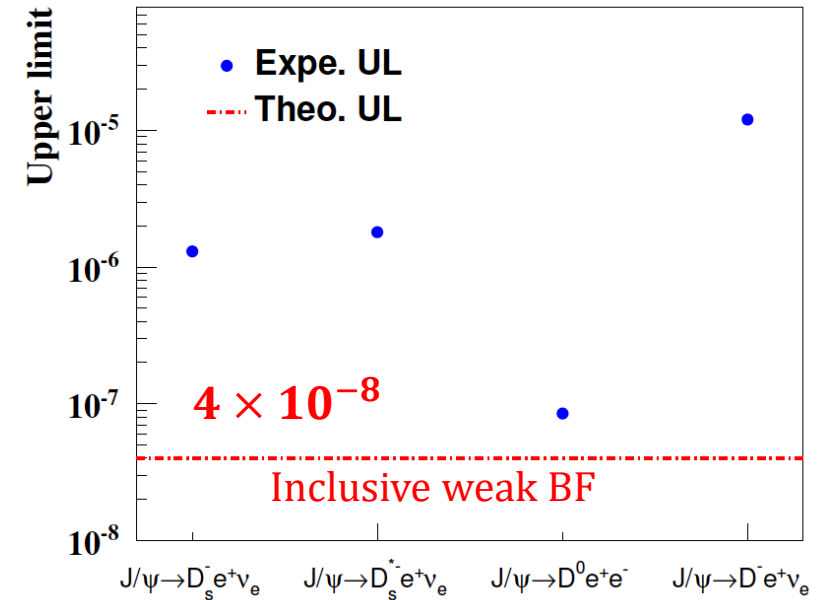
$R$



$\sqrt{s}$  [GeV]

# Charmonium weak decays

- The inclusive  $J/\psi$  weak decay BF is predicted to be at the order of  $10^{-8}$  or lower in SM
- Hadronic weak decays
  - $J/\psi \rightarrow D_s^{(*)-} \rho^+ / \pi^+, J/\psi \rightarrow D^- \rho^+, \psi(3686) \rightarrow \Lambda_c^+ \bar{\Sigma}^-$
- Semileptonic weak decays
  - $J/\psi \rightarrow D_s^{(*)-} e^+ \nu_e, J/\psi \rightarrow D^- e^+ \nu_e, J/\psi \rightarrow D^- \mu^+ \nu_\mu$

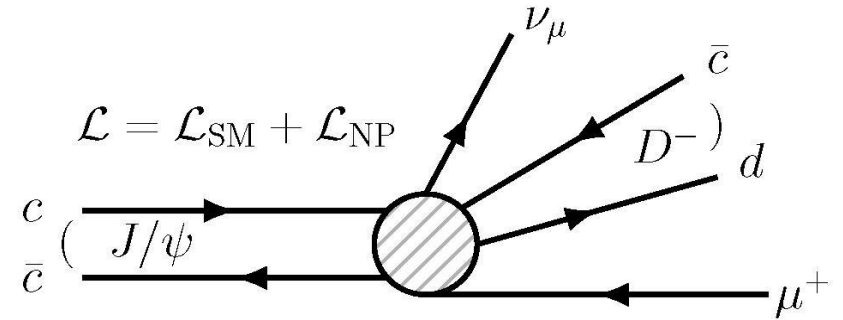


# Search for new physics in charmonium weak decays

- Some **new physics models** can enhance the BF of  $J/\psi$  weak decay to  $10^{-5}$

- Top-color model
- Two-Higgs doublet model

PLB 345, 483 (1995)  
 PLB 119, 136 (1982)  
 PRD 15, 1958 (1977)  
 PRD, 60, 014011 (1999)



- SM prediction of charmonium semi-leptonic decays

| Decay Channel                               | LQCD [10] | QCDSR [4] | CLFQM (2008) [5] (2024) [6] | CCQM [8] | BSW [7] | BS [9] | HQSS [3] |
|---|-----------|-----------|-----------------------------|----------|---------|--------|----------|
| $J/\psi \rightarrow D^- e^+ \nu_e$          | 0.121(11) | 0.073     | 0.51~0.57 0.610             | 0.171    | 0.60    | 0.203  | 1.4      |
| $J/\psi \rightarrow D^- \mu^+ \nu_\mu$      | 0.118(11) | 0.071     | 0.47~0.55 0.578             | 0.166    | 0.58    | 0.198  |          |
| $J/\psi \rightarrow D_s^- e^+ \nu_e$        | 1.90(8)   | 1.8       | 5.3~5.8 10.21               | 3.3      | 10.4    | 3.67   | 26.0     |
| $J/\psi \rightarrow D_s^- \mu^+ \nu_\mu$    | 1.84(8)   | 1.7       | 5.5~5.7 9.59                | 3.2      | 9.93    | 3.54   |          |
| $J/\psi \rightarrow D^{*-} e^+ \nu_e$       | -         | 0.37      | - -                         | 0.30     | -       | 0.440  | 2.3      |
| $J/\psi \rightarrow D^{*-} \mu^+ \nu_\mu$   | -         | 0.36      | - -                         | 0.29     | -       | 0.424  |          |
| $J/\psi \rightarrow D_s^{*-} e^+ \nu_e$     | -         | 5.6       | - -                         | 5.0      | -       | 7.08   | 42.0     |
| $J/\psi \rightarrow D_s^{*-} \mu^+ \nu_\mu$ | -         | 5.4       | - -                         | 4.8      | -       | 6.75   |          |
| $\psi(2S) \rightarrow D^- e^+ \nu_e$        | -         | -         | - 0.345                     | -        | -       | -      | -        |
| $\psi(2S) \rightarrow D^- \mu^+ \nu_\mu$    | -         | -         | - 0.339                     | -        | -       | -      | -        |
| $\psi(2S) \rightarrow D_s^- e^+ \nu_e$      | -         | -         | - 7.20                      | -        | -       | -      | -        |
| $\psi(2S) \rightarrow D_s^- \mu^+ \nu_\mu$  | -         | -         | - 7.02                      | -        | -       | -      | -        |

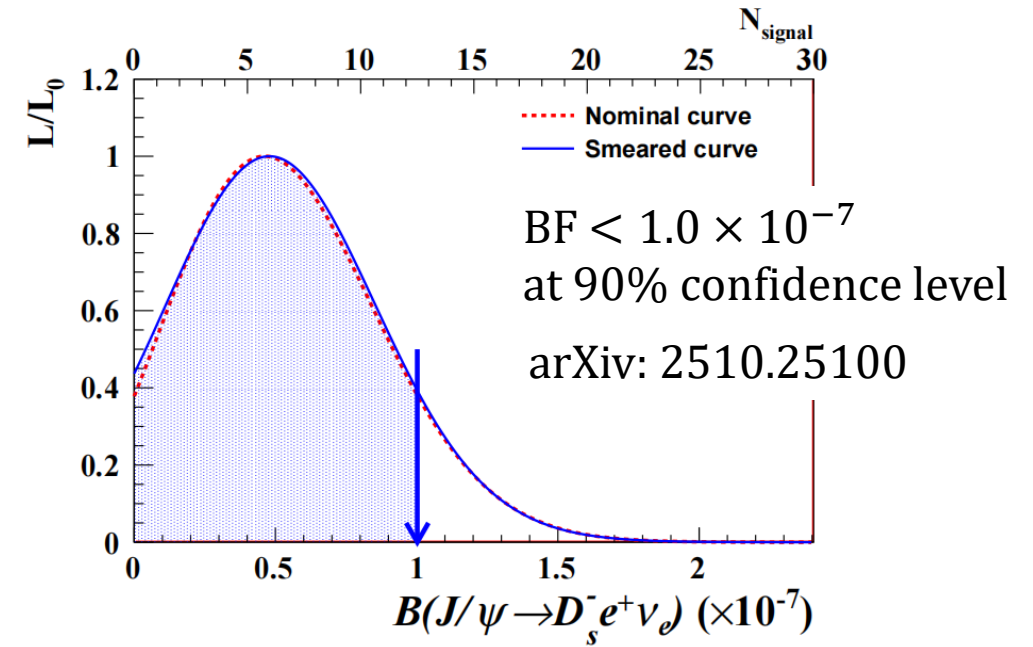
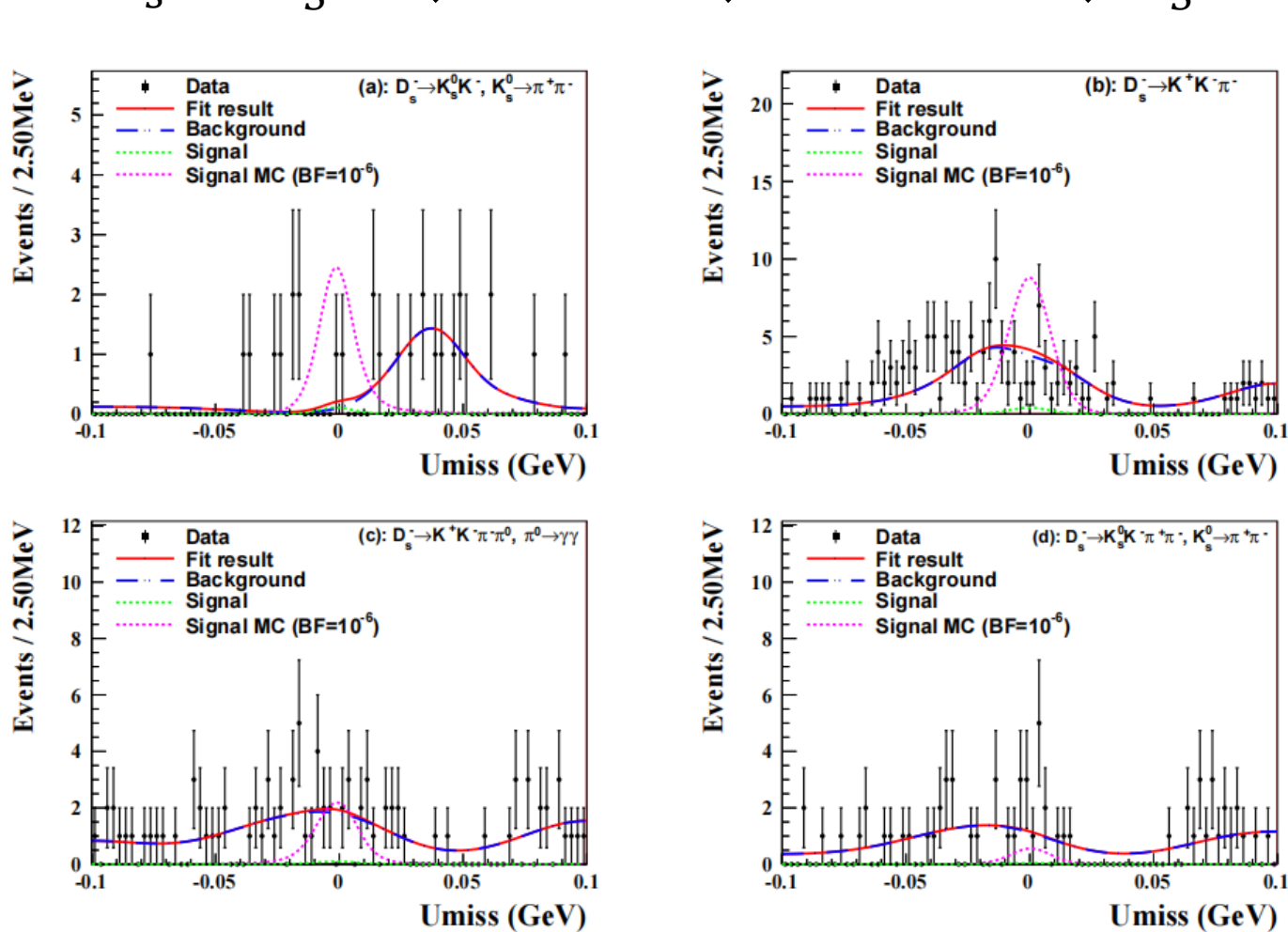
$\times 10^{-10}$

- [3] ZPC 62, 271 (1994)
- [4] EPJC 54,107 (2008)
- [5] PRD 78, 074012 (2008)
- [6] EPJC 84, 65 (2024)
- [7] AHEP 706543 (2013)
- [8] PRD 92, 074030 (2015)
- [9] JPG 44, 045004 (2017)
- [10] PRD 110, 074510 (2024)

# Search for the decays $J/\psi \rightarrow D_S^{(*)} l \nu$

Total dataset,  $J/\psi \rightarrow D_S e \nu$

$D_S^+ \rightarrow K_S^0 K^-, K^+ K^- \pi^-, K^+ K^- \pi^- \pi^0, K_S^0 K^- \pi^+ \pi^-$

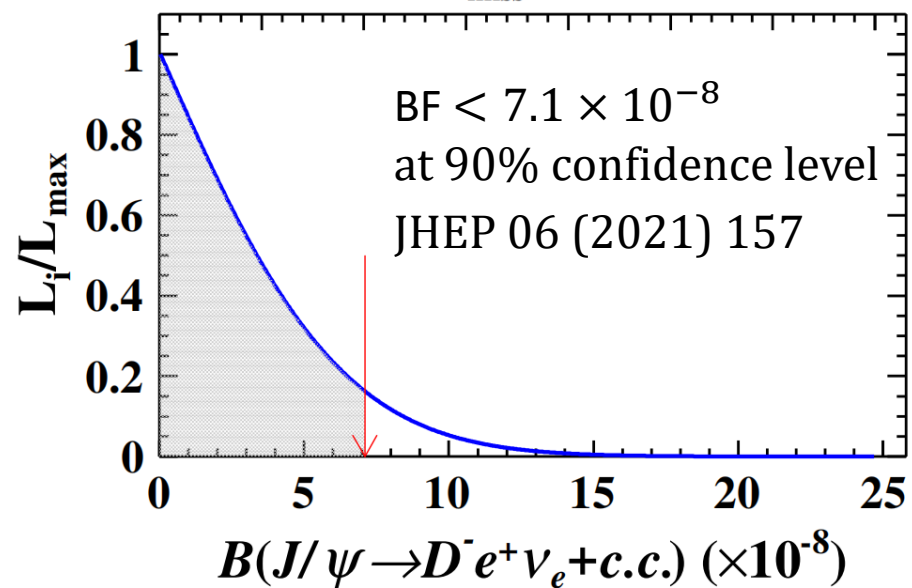
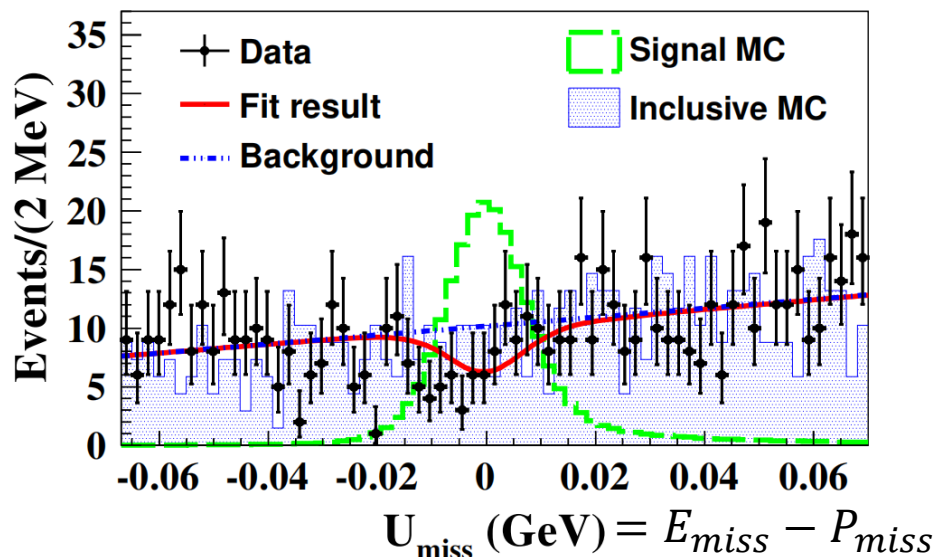


Improved upon the previous measurement by around 10 with  $2 \times 10^8 J/\psi$  events

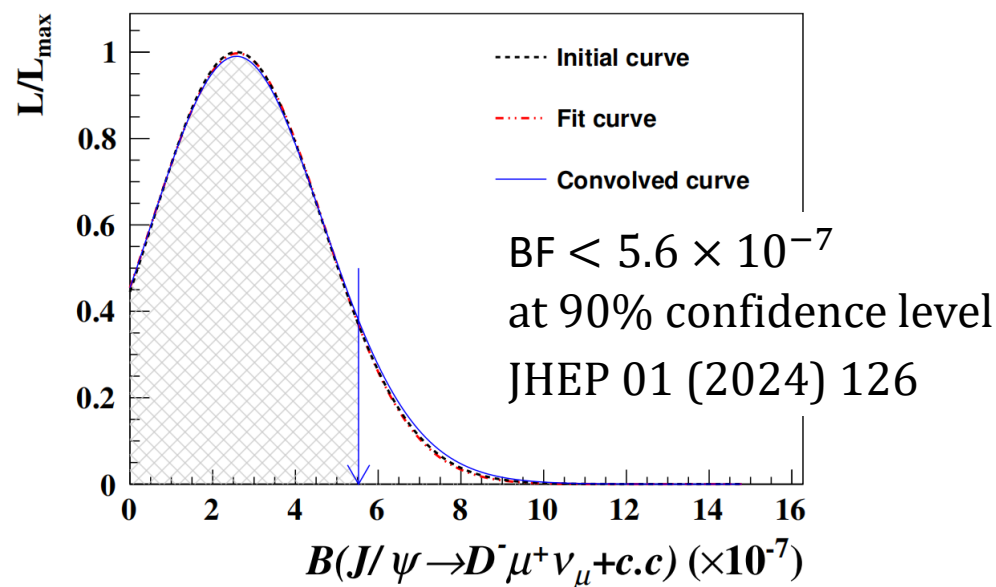
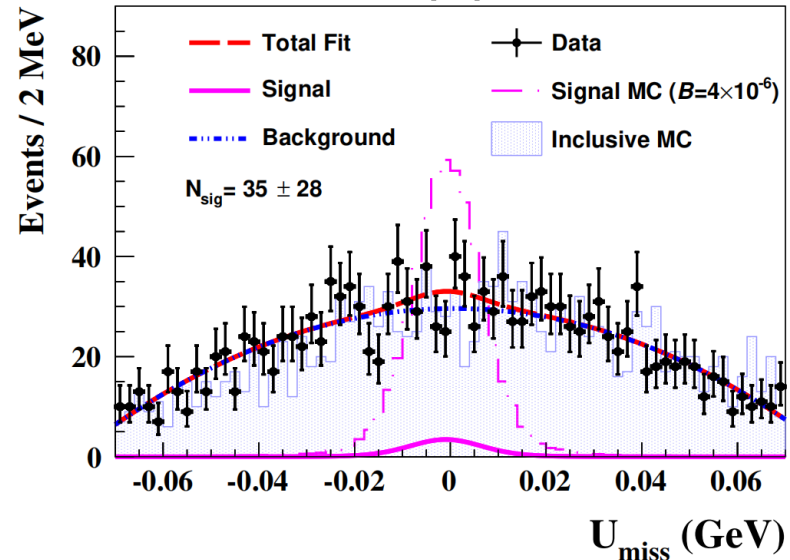
PRD 90 (2014) 112014

# Search for the decays $J/\psi \rightarrow D l \nu$

Total dataset,  $J/\psi \rightarrow D[K\pi\pi]e\nu$



Total dataset,  $J/\psi \rightarrow D[K\pi\pi]\mu\nu$



# Search for new physics in charmonium weak decays

- SM prediction of BFs of hadronic charmonium decays at around  $10^{-12} - 10^{-9}$  level

| Transition Mode<br>$J/\psi \rightarrow PP$ | Decay Channel                            | QCDSR [13] | CLFQM (2024) [6] | BSW [7] | BS [9]  | HQSS [11] | Factorization [14] |
|--|--|------------|------------------|---------|---------|-----------|--------------------|
| $\Delta C = \Delta S = +1$                 | $J/\psi \rightarrow D_s^- \pi^+$         | 2.0        | 3.64             | 7.41    | 4.75    | 8.74      | 10.9               |
|  | $J/\psi \rightarrow \bar{D}^0 \bar{K}^0$ | 0.36       | -                | 1.39    | 0.803   | 2.80      | 1.44               |
| $\Delta C = +1, \Delta S = 0$              | $J/\psi \rightarrow D_s^- K^+$           | 0.16       | 0.202            | 0.53    | 0.312   | 0.55      | 0.618              |
|  | $J/\psi \rightarrow D^- \pi^+$           | 0.080      | 0.190            | 0.29    | 0.183   | 0.55      | 0.637              |
|  | $J/\psi \rightarrow \bar{D}^0 \pi^0$     | -          | -                | 0.024   | 0.0156  | 0.055     | 0.0350             |
|  | $J/\psi \rightarrow \bar{D}^0 \eta$      | -          | -                | 0.070   | 0.00263 | 0.016     | 0.0103             |
|  | $J/\psi \rightarrow \bar{D}^0 \eta'$     | -          | -                | 0.004   | 0.0371  | 0.003     | 0.00583            |
| $\Delta C = +1, \Delta S = -1$             | $J/\psi \rightarrow D^- K^+$             | -          | 0.0116           | 0.023   | 0.0131  | -         | 0.0379             |
|  | $J/\psi \rightarrow \bar{D}^0 K^0$       | -          | -                | 0.004   | 0.00224 | -         | 0.00416            |

## $J/\psi \rightarrow VV$

| Decay Channel                                  | QCDSR [13] | BS [9] |
|--|------------|--------|
| $J/\psi \rightarrow D_s^{*-} \rho^+$           | 52.6       | 58.6   |
| $J/\psi \rightarrow D_s^{*-} K^{*+}$           | 2.6        | 2.62   |
| $J/\psi \rightarrow D^{*-} \rho^+$             | 2.8        | 3.30   |
| $J/\psi \rightarrow \bar{D}^{*0} \bar{K}^{*0}$ | 9.6        | 11.1   |

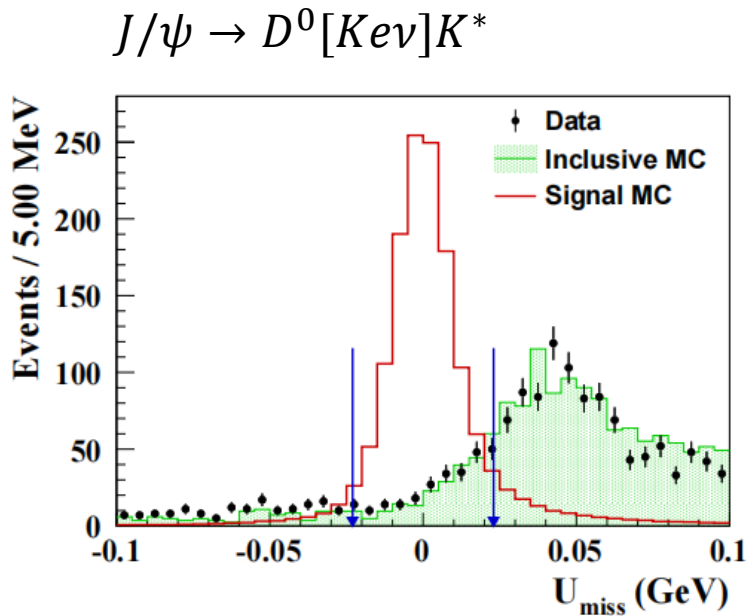
$\times 10^{-10}$

| Transition Mode<br>$J/\psi \rightarrow VP$ | Decay Channel                               | QCDSR [13] | CLFQM (2024) [6] | BSW [7] | BS [9] | HQSS [11] | Factorization [14] |
|--|---|------------|------------------|---------|--------|-----------|--------------------|
| $\Delta C = \Delta S = +1$                 | $J/\psi \rightarrow D_s^- \rho^+$           | 12.6       | 29.5             | 51.1    | 26.2   | 36.30     | 38.2               |
|  | $J/\psi \rightarrow \bar{D}^0 \bar{K}^{*0}$ | 1.54       | -                | 7.61    | 4.75   | 10.27     | 4.09               |
| $\Delta C = +1, \Delta S = 0$              | $J/\psi \rightarrow D_s^- K^{*+}$           | 0.82       | 1.42             | 2.82    | 1.67   | 2.12      | 2.00               |
|  | $J/\psi \rightarrow D^- \rho^+$             | 0.42       | 1.70             | 2.16    | 1.13   | 2.20      | 2.12               |
|  | $J/\psi \rightarrow \bar{D}^0 \rho^0$       | -          | -                | 0.18    | 0.0960 | 0.22      | 0.108              |
|  | $J/\psi \rightarrow \bar{D}^0 \omega$       | -          | -                | 0.16    | 0.0880 | 0.18      | 0.0810             |
|  | $J/\psi \rightarrow \bar{D}^0 \phi$         | -          | -                | 0.42    | 0.307  | 0.65      | 0.192              |
| $\Delta C = +1, \Delta S = -1$             | $J/\psi \rightarrow D^- K^{*+}$             | -          | 0.0859           | 0.13    | 0.0770 | -         | 0.114              |
|  | $J/\psi \rightarrow \bar{D}^0 K^{*0}$       | -          | -                | 0.021   | 0.0132 | -         | 0.0119             |

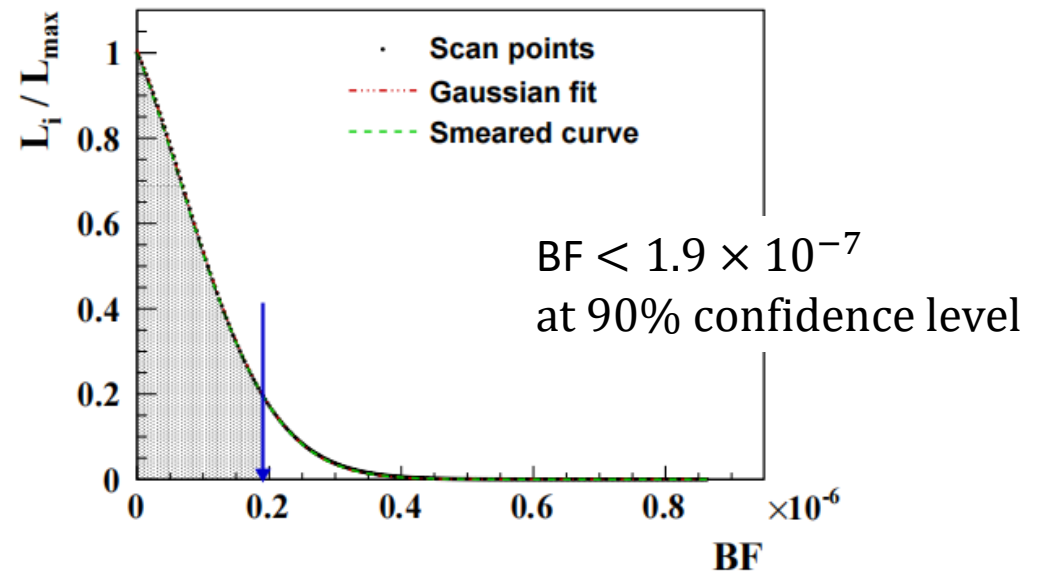
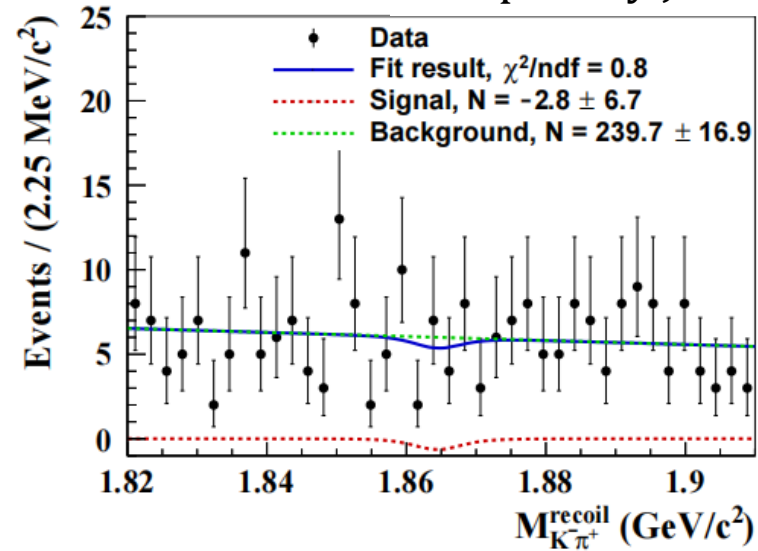
- [6] EPJC 82,65 (2024)
- [7] AHEP 706543 (2013)
- [9] JPG 44, 045004 (2017)
- [11] IJMPA 14, 937 (1999)
- [13] EPJC 55, 607 (2008)
- [14] AHEP 5071671 (2016)

# Search for the decay $J/\psi \rightarrow D^0 K^*$

arXiv: 2511.16083,  
accepted by JHEP



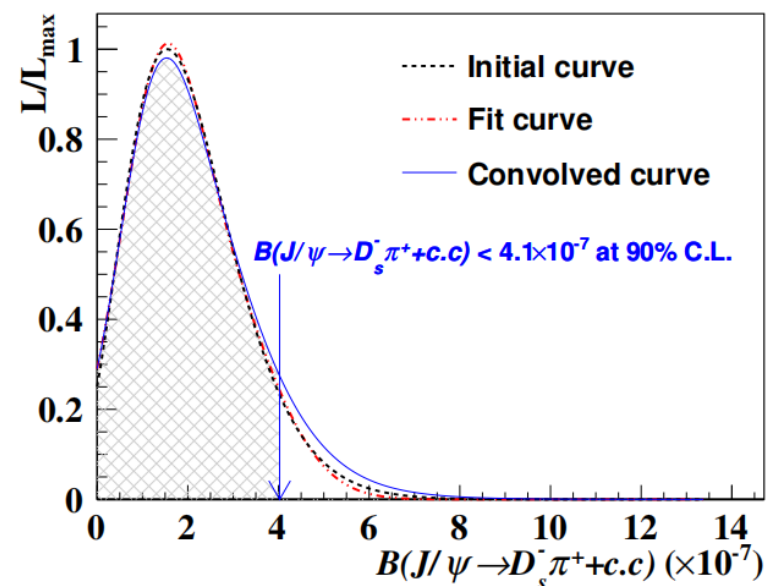
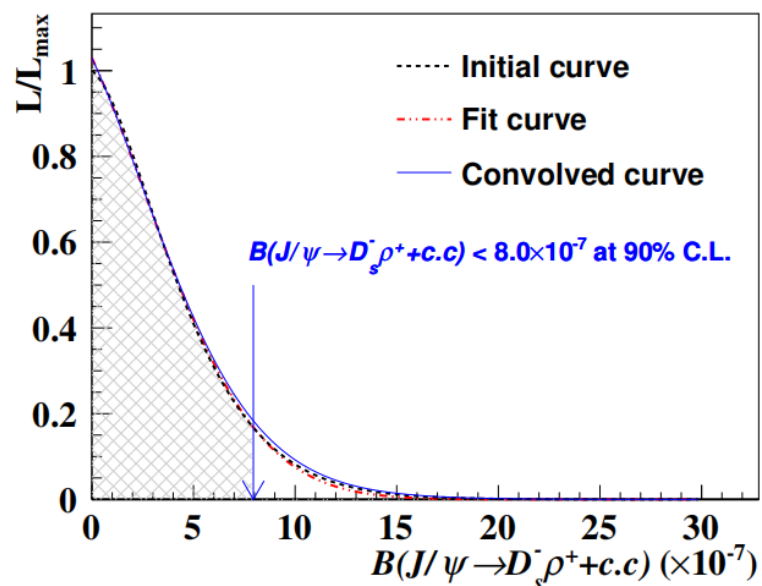
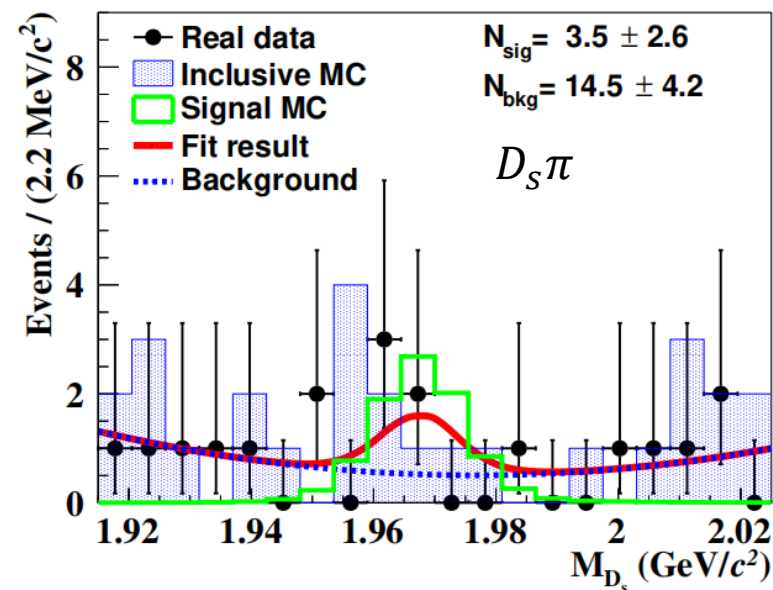
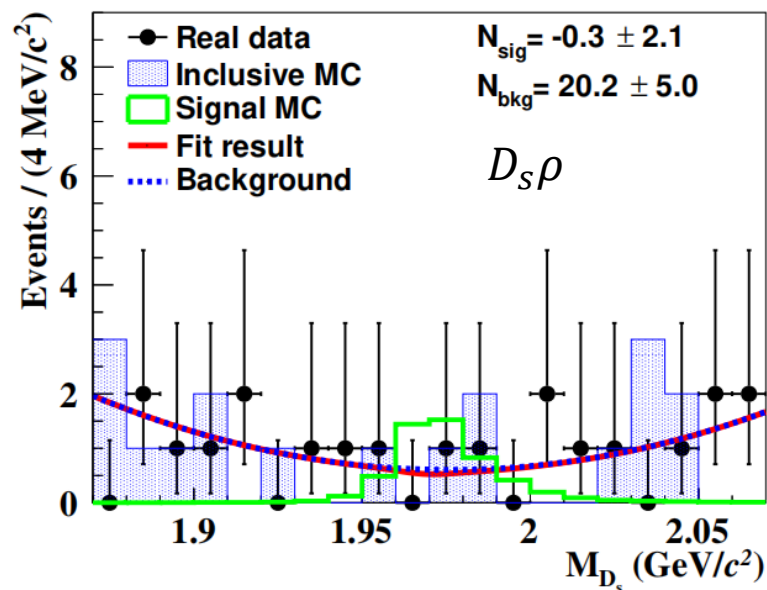
Avoid huge background contribution from  $J/\psi$  decays to multiple hadrons



# Search for the decays $J/\psi \rightarrow D_s \rho / \pi$

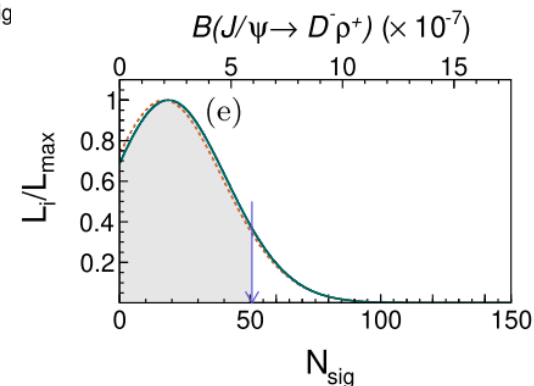
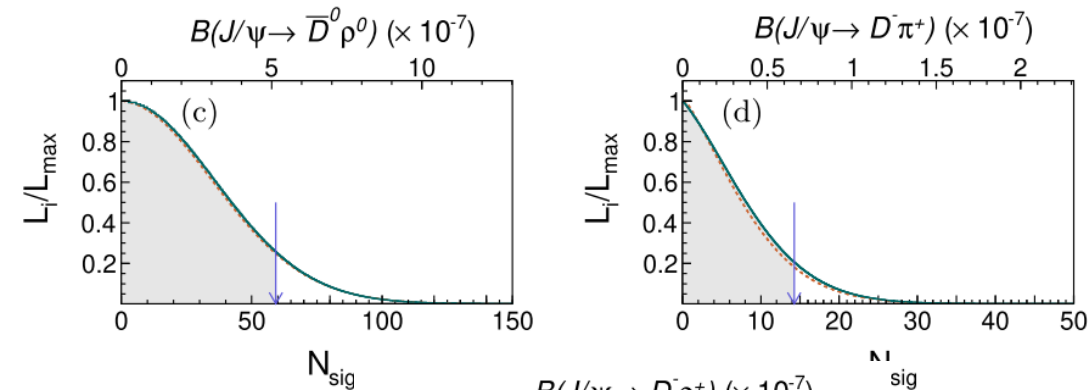
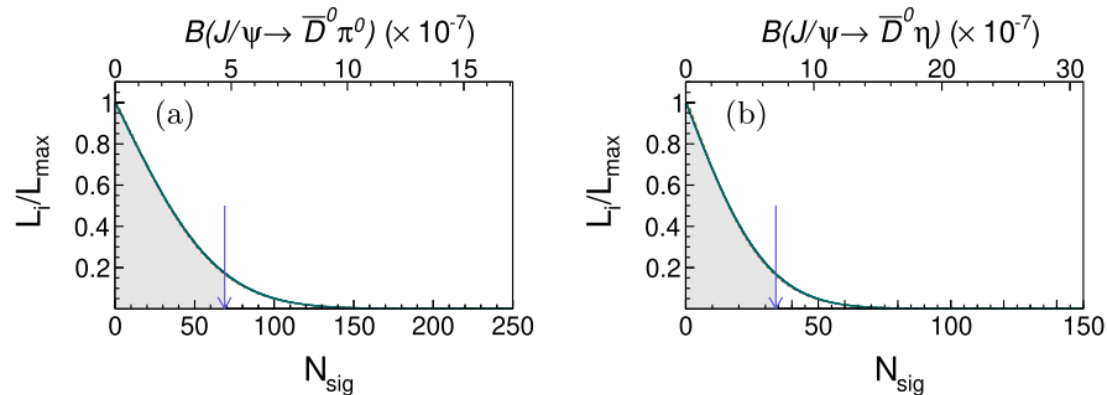
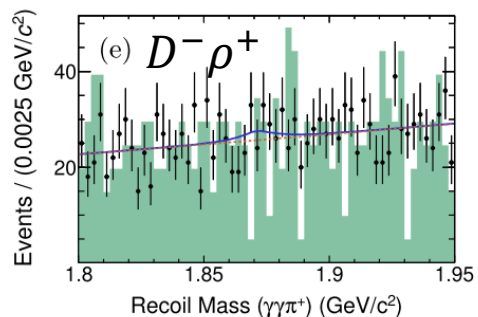
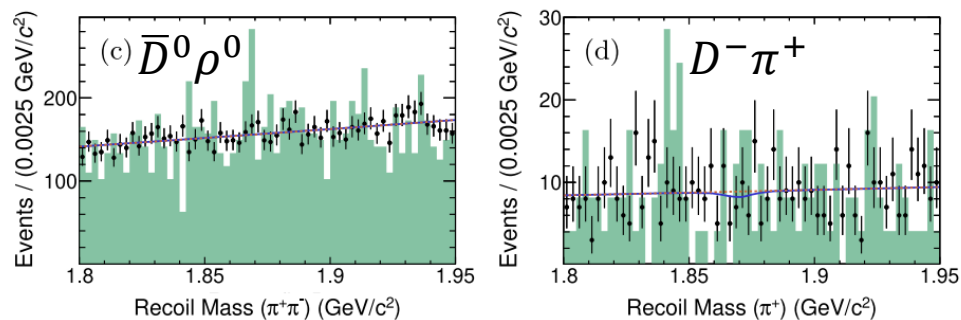
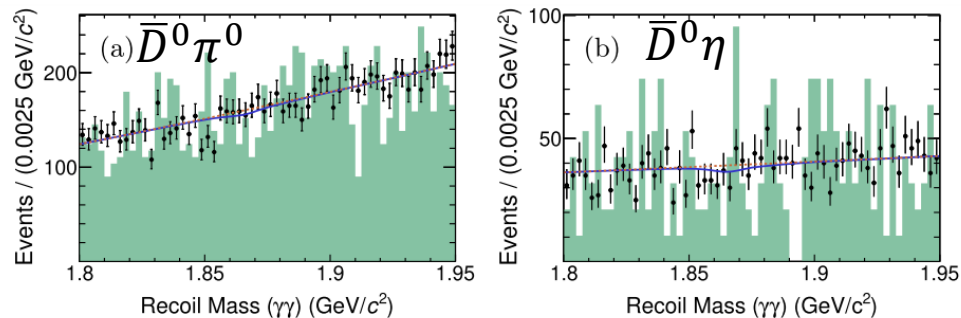
Total dataset  
 $J/\psi \rightarrow D_s[\phi e \nu] \rho / \pi$

JHEP 12 (2025) 077

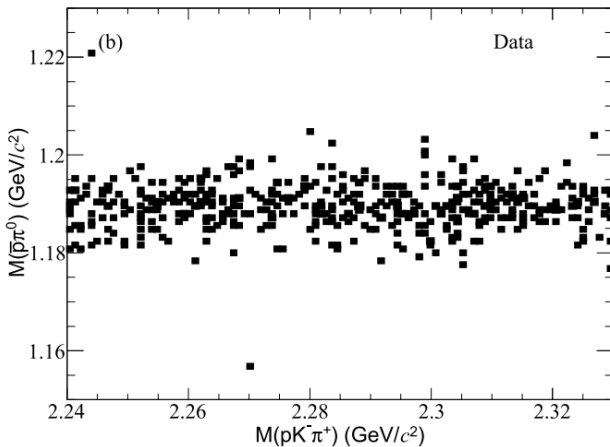
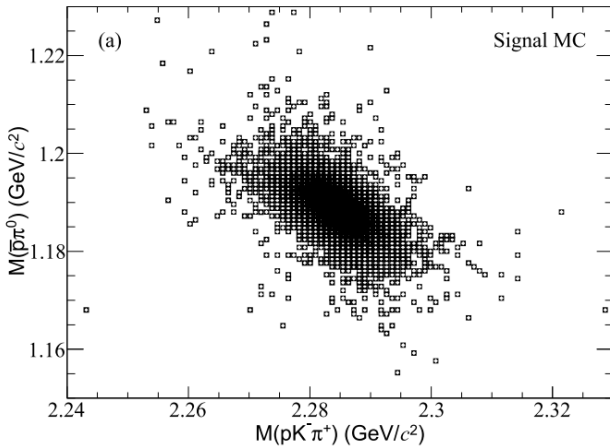
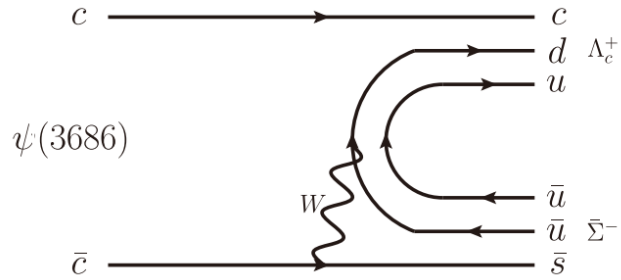


# Search for the decays $J/\psi \rightarrow D\pi/\eta/\rho$

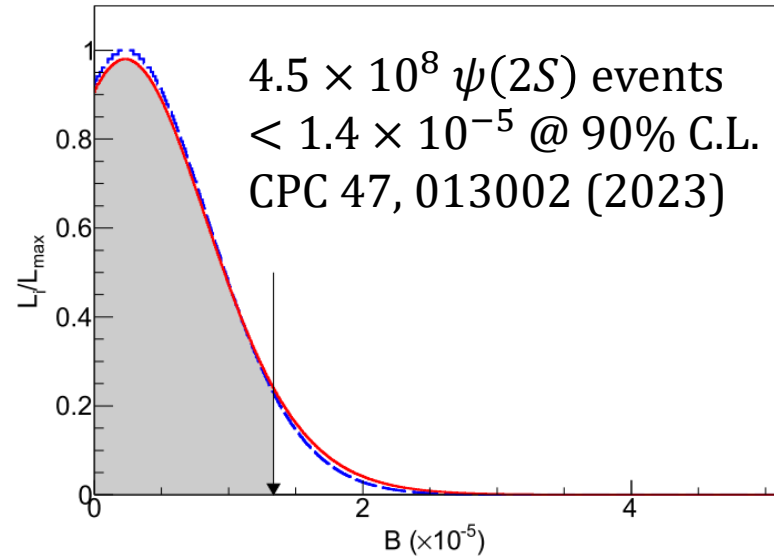
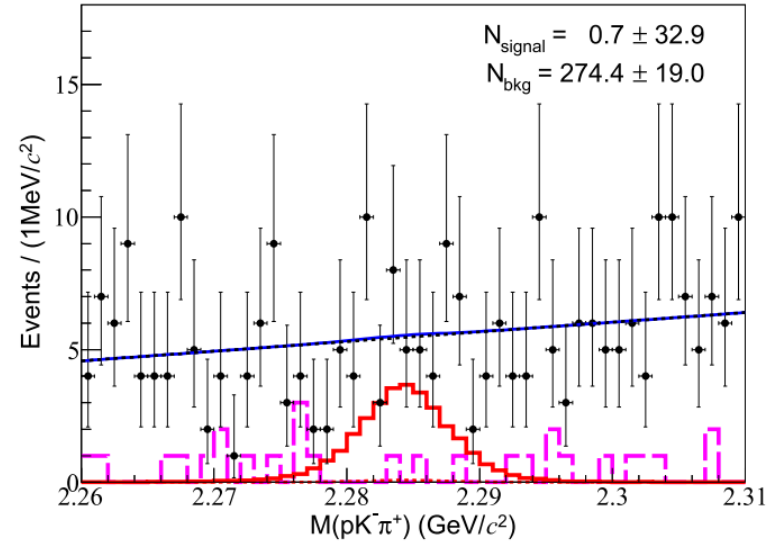
Total dataset,  $J/\psi \rightarrow D[K/K_S^0 e\nu]M$   
PRD 110, 032020 (2024)



# Search for the decay $\psi(3686) \rightarrow \Lambda_c^+ \bar{\Sigma}^-$

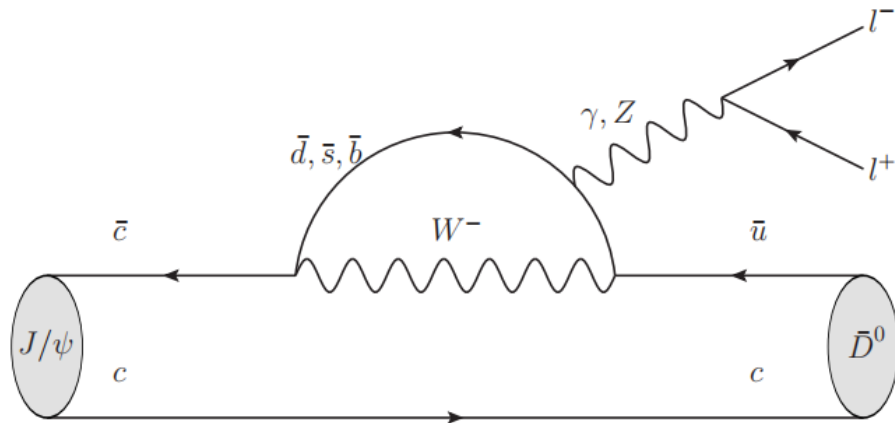


Fit to the events in the  $\Sigma$  signal region



# FCNC processes

- In SM, Flavor Changing Neutral Current (FCNC) is highly suppressed by GIM mechanism, can happen only through loop diagram, a very small BF  $10^{-9} \sim 10^{-15}$
- The suppression in charm decay is much stronger than B & K system, **stronger diagram cancellation** due to the d quarks involved



| Decay Channel                                 | QCDSR [15] |
|---|------------|
| $J/\psi \rightarrow \bar{D}^0 e^+ e^-$        | 1.14       |
| $J/\psi \rightarrow \bar{D}^{*0} e^+ e^-$     | 6.30       |
| $J/\psi \rightarrow \bar{D}^0 \mu^+ \mu^-$    | 1.08       |
| $J/\psi \rightarrow \bar{D}^{*0} \mu^+ \mu^-$ | 5.94       |

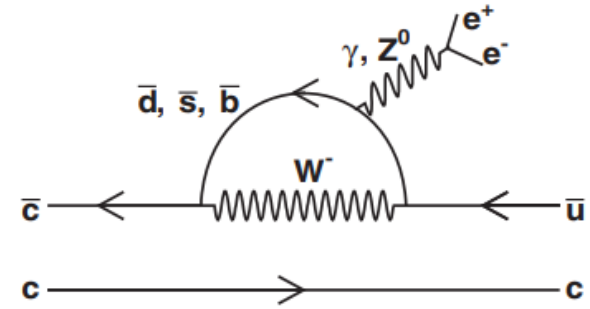
$\times 10^{-13}$

[15] JPG 36, (2009) 105002

# FCNC searches at BESIII

- Charmonium FCNC decays

- $J/\psi \rightarrow D^0 e^+ e^-$ ,  $\psi(3686) \rightarrow D^0 e^+ e^-$ ,  $J/\psi \rightarrow \gamma D^0$
- $J/\psi \rightarrow D^0 \mu^+ \mu^-$
- UL measured at the order of  $10^{-8} \sim 10^{-7}$

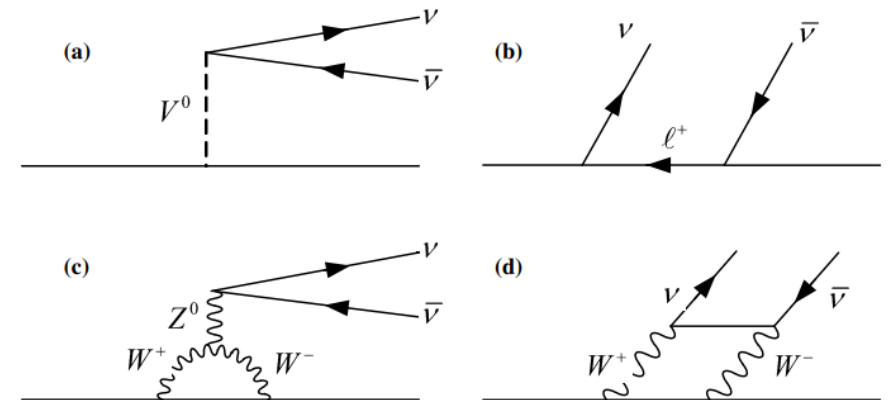


| Experiment | Decay mode                           | $N_{J/\psi}$ or $N_{\psi(3686)}$ | UL                   | Year      |
|------------|--------------------------------------|----------------------------------|----------------------|-----------|
| BESIII     | $J/\psi \rightarrow D^0 e^+ e^-$     | $1310.6 \times 10^6$             | $8.5 \times 10^{-8}$ | 2017 [28] |
| BESIII     | $\psi(3686) \rightarrow D^0 e^+ e^-$ | $447.9 \times 10^6$              | $1.4 \times 10^{-7}$ | 2017 [28] |
| BESIII     | $J/\psi \rightarrow \gamma D^0$      | $10087 \times 10^6$              | $9.1 \times 10^{-8}$ | 2024 [29] |

PRD 96, 111101 (2017)  
 PRD 97, 072015 (2018)  
 PRD 97, 091102 (2018)  
 PRD 105, L071102 (2022)  
 PRD 110, 112012 (2024)  
 PRL 133, 121801 (2024)  
 JHEP 04 (2025) 061

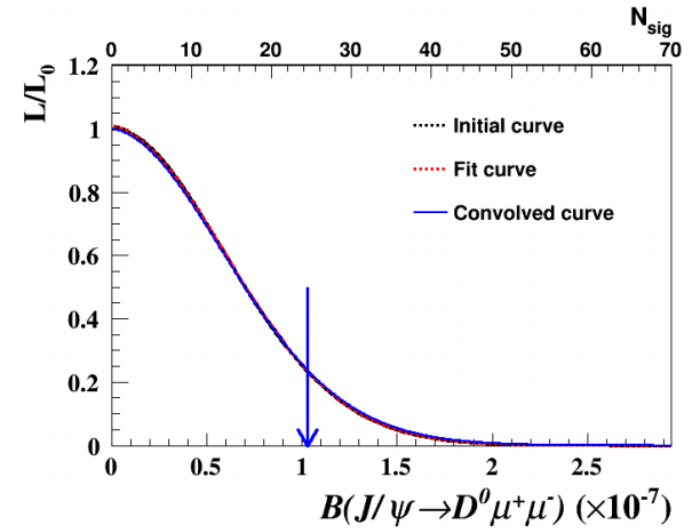
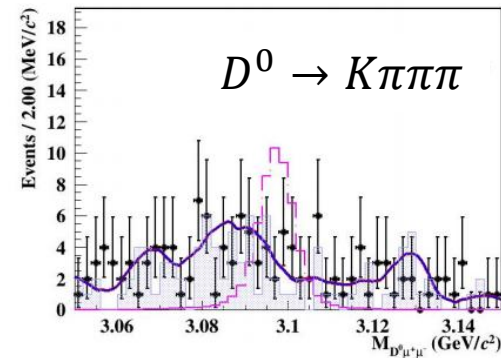
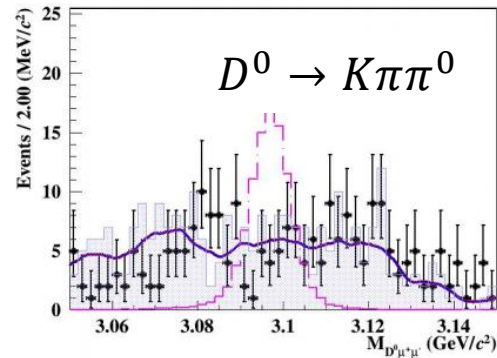
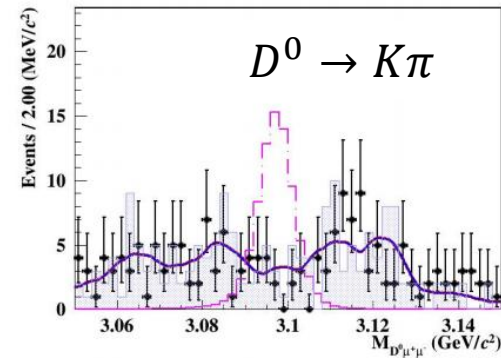
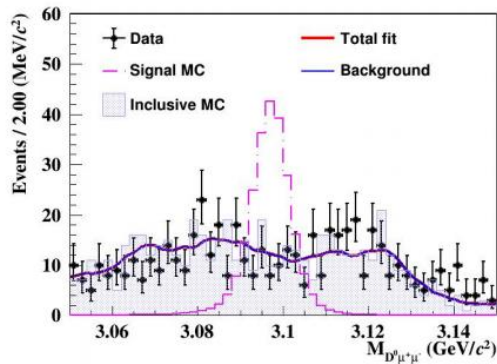
- $D/D_{(s)}$  meson FCNC decays

- $D^0 \rightarrow \pi^0 \nu \bar{\nu}$ ,  $D/D_{(s)} \rightarrow h(h') e^+ e^-$
- Upper limit measured at the order of  $10^{-6} \sim 10^{-5}$
- Expect at the order of  $10^{-7} \sim 10^{-6}$  with the updates from  $20 \text{ fb}^{-1} D\bar{D}$  data



# Search for the decay $J/\psi \rightarrow D^0 \mu^+ \mu^-$

Total dataset, JHEP 04 (2025) 061

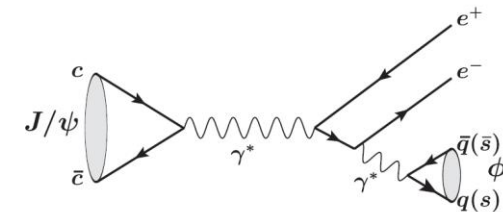
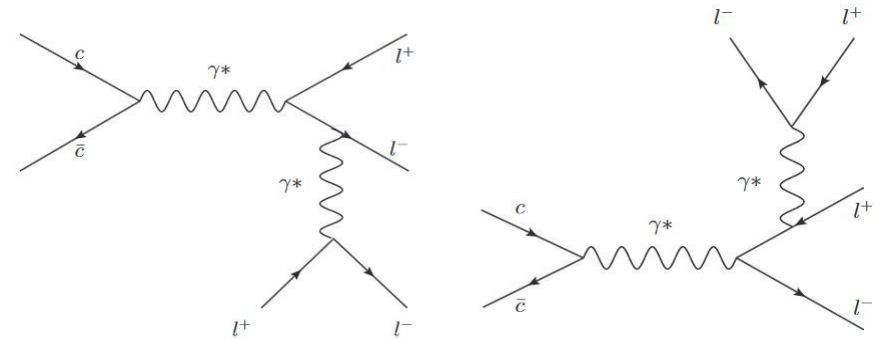
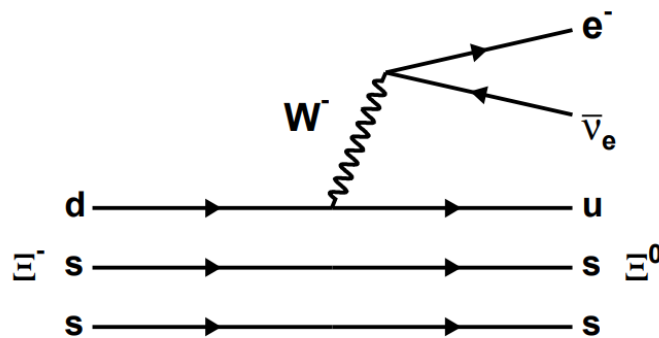


$< 1.1 \times 10^{-7}$  @ 90% C.L.

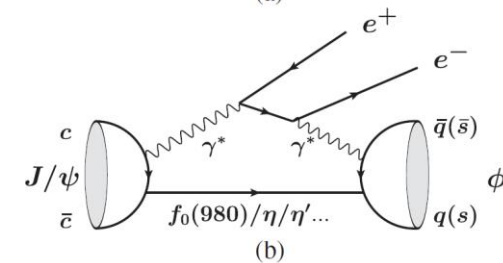
# Other rare decays

- $J/\psi$  leptonic decays at the order of  $10^{-7} \sim 10^{-5}$
- In SM,  $J/\psi \rightarrow \phi e^+ e^-$  is predicted to be at the order of  $10^{-8} \sim 10^{-11}$ 
  - New particles (dark  $\gamma$  / glueball) could enhance the contribution to an observable level
- Measurement of EM Dalitz decay
  - $\psi(3686) \rightarrow \eta_c e^+ e^-$
- Hyperon semi-leptonic decay
  - $\Xi^- \rightarrow \Xi^0 e^- \bar{\nu}_e$

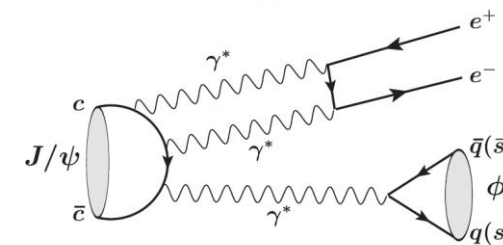
PRD 106, 112002 (2022)  
 CPC 47, 013002 (2023)  
 PRD 107, 012002 (2023)  
 JHEP 05, 141 (2024)



(a) the leading-order EM process



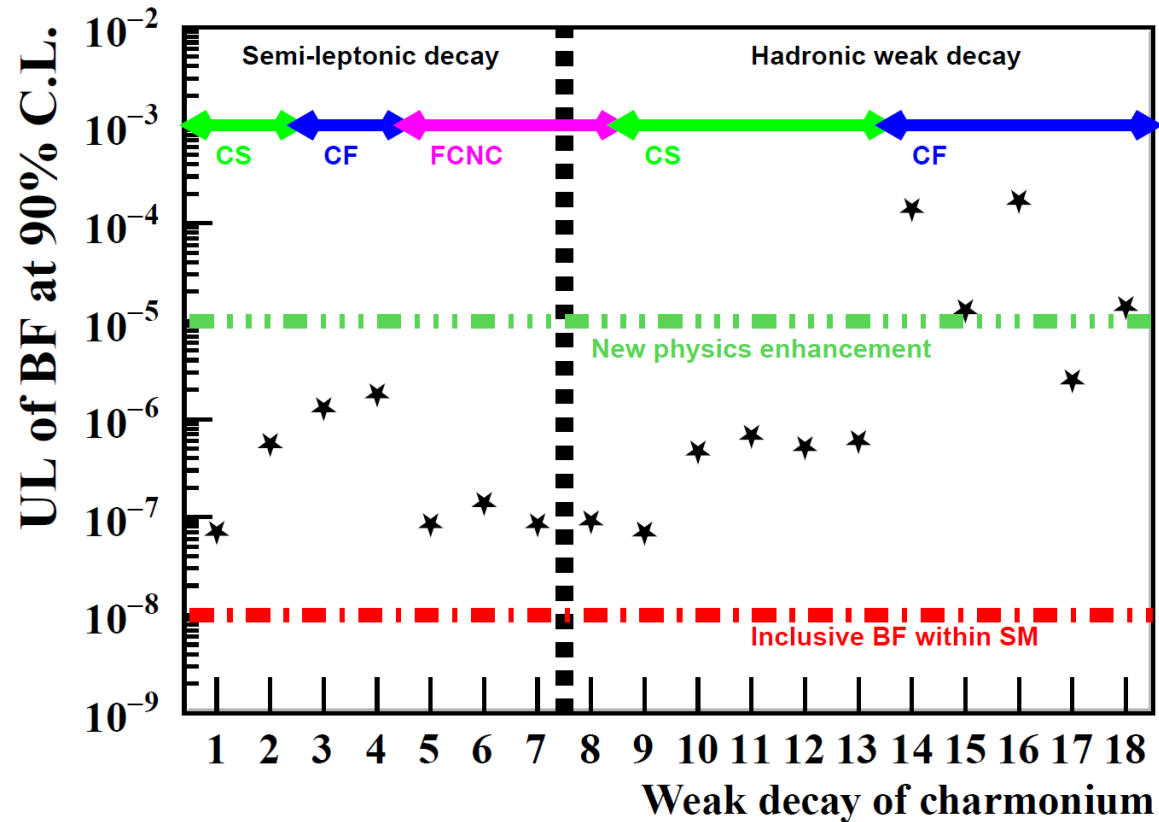
(b) the EM and strong mixed loop process



(c) the EM process proceeding through three virtual photons

# Summary

- With 10 billion  $J/\psi$  and 2.7 billion  $\psi(3686)$ , the search for charmonium weak decay BF has reached the order of  $10^{-8} \sim 10^{-7}$
- **Mini-review of charmonium weak decays at BESIII, arXiv: 2603.22082 by Xu-Ze Li, Kai-Xin Fan, Zheng-Yun You et al.**



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

PRD 89, 071101 (2014) PRD 90, 112014 (2014)  
 JHEP 06, 157 (2021) CPC 47, 013002 (2023)  
 JHEP 01, 126 (2024) PRD 110, 032020 (2024)