Rare charm/charmonium decays from BESIII

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(On behalf of the BESIII Collaboration)

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Outline

01 Motivation

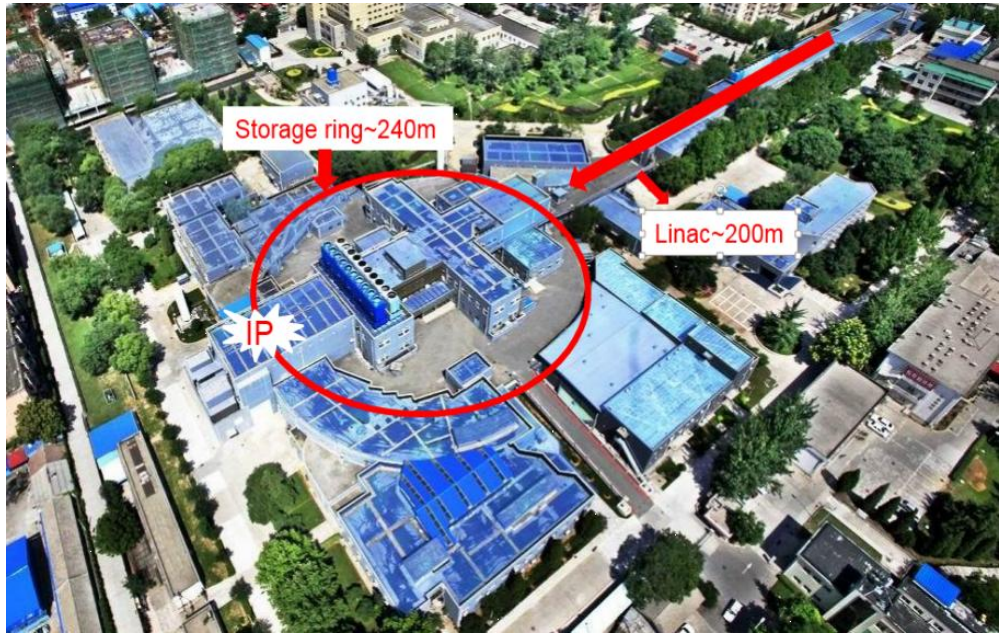
What we focus on?

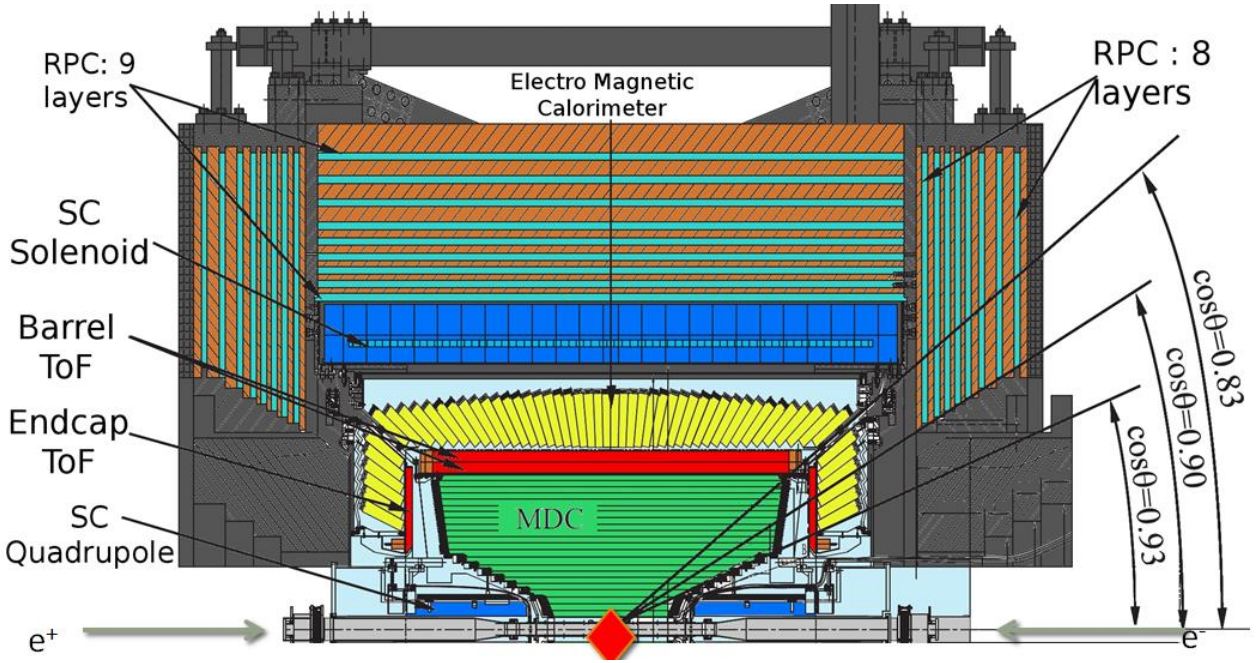
- Rare processes:
  - Flavor-changing neutral current (FCNC)
  - Lepton number violation(LNV)
  - J/ψ weak decays
  - Invisible decays

Why?

- These processes are forbidden at tree level and can only occur via loop diagrams.
- Strongly suppressed by the GIM mechanism, leading to extremely small branching fractions (10^{-9}~10^{-15})
- Provide insights into symmetry breaking (LNV, BNV, CP violation).
- Closely connected to fundamental questions in cosmology, such as the matter–antimatter asymmetry.

01 Motivation: BEPCII/BESIII





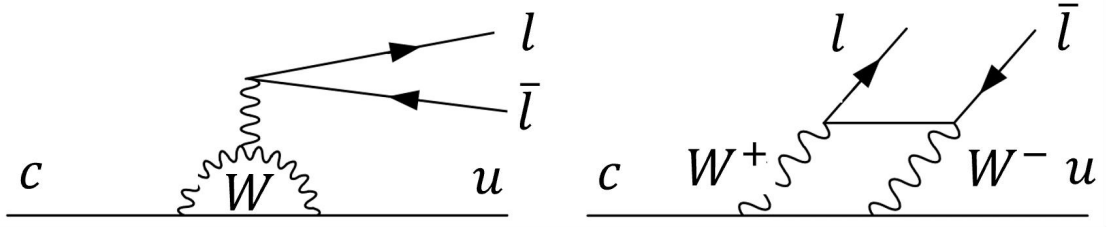
- $\sqrt{s} = (1.85 - 4.95)$ GeV
- Designed luminosity (L):
  1.00×10^{33} $\mathrm{cm^{-2}s^{-1}}$ @ 3.773 GeV
- In 2022, peak L reached 1.1 times of the designed L

- MDC: $\sigma_p/p = 0.5\%$@ 1 GeV, $\sigma_{dE/dx} = 6\%$
- TOF: $\sigma_T = 68(110)$ ps for barrel (edncap); end cap TOF was upgraded in 2015→ 60 ps
- EMC: $\sigma_E/E = 2.5\%(5\%)$ ps for barrel (edncap)

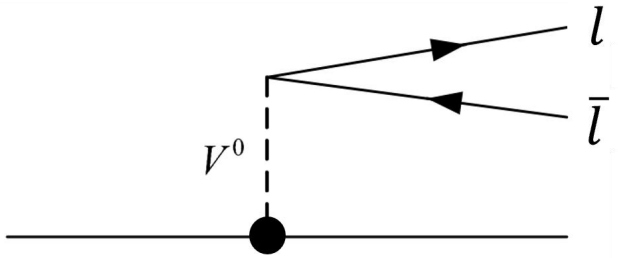
02 FCNC

- FCNC is strongly suppressed by GIM mechanism and can happen only through loop diagram
- BF $10^{-9}\sim10^{-15}$ in SM for D meson
- The suppression in charm decay is much stronger than B & K system, stronger diagram cancellation due to the down-type quarks involved

✓ **Short distance (SD): $c \to u l \bar{l},\ l = e, \mu, \nu$**



✓ **Long distance (LD) process, $V^0 = \eta, \rho, \omega, \phi$**



Strongly suppressed in SM → Sensitive probe for New Physics

02 FCNC: $D_s^+ \to h(h')e^+e^-$

Phys. Rev. Letter 133, 121801 (2024)

- Data: 7.33 fb^{-1} data taken @4.128-4.226 GeV
- The LD contributions dominate the decays of $D_s^+ \to h(h')e^+e^-$ **(10^{-6})**
- The SD effects can be accessed through measurements in the dilepton mass regions away from intermediate **(η, ρ, ω, ϕ)** mesons
- $D_s^+ \to Ve^+e^-$ (V is a light vector meson) receive considerable contributions from virtual photons: **10^{-5}**
- Distinguishes LD dominated modes from SD sensitive modes .

LD processes:

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

✓ $D_s^+ \to \rho^+\phi, \phi \to e^+e^-$

SD processes:

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

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

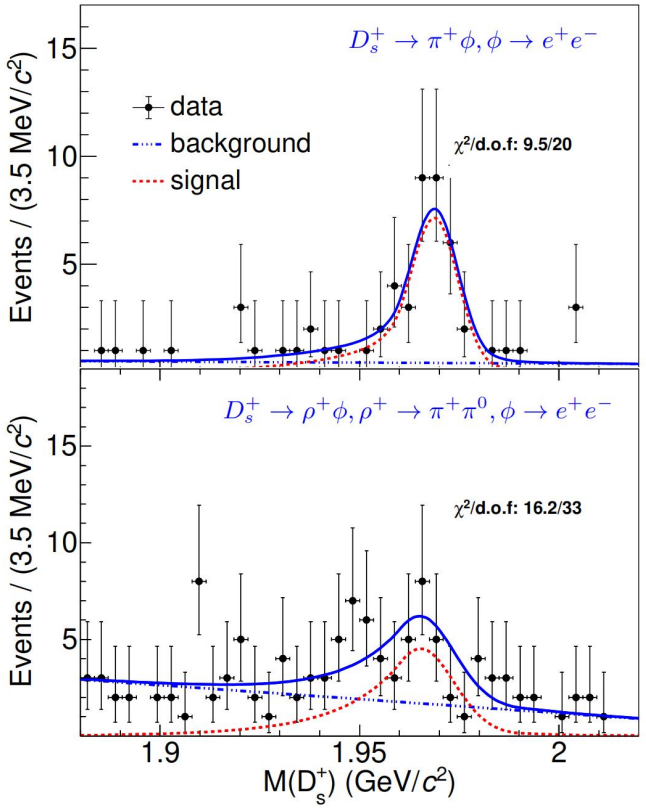
$D_s^+ \to K_s^0\pi^+e^+e^-$

First systematic search for $D_s^+ \to h(h')e^+e^-$ decays.

Provides new experimental input for FCNC studies in the charm sector, LU tests, and $D_s^+ \to V\gamma$ research.

02 FCNC: $D_s^+ \to h(h')e^+e^-$

Phys. Rev. Letter 133, 121801 (2024)



Fit to $M_{D_S^+}$ distribution

The e^+e^- invariant mass to be consistent with a $\phi(1020)$, $\phi(1020) \in (0.98, 1.04)$ GeV/c^2

Decay	$N_{\rm sig}$	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	$2.44^{+0.67}_{-0.62} \pm 0.16$
$D_s^+ \to \pi^+\pi^0 e^+e^-$	...	7.4	< 7.0
$D_s^+ \to K^+\pi^0 e^+e^-$	...	5.3	< 7.1
$D_s^+ \to K_S^0\pi^+ e^+e^-$	...	6.7	< 8.1

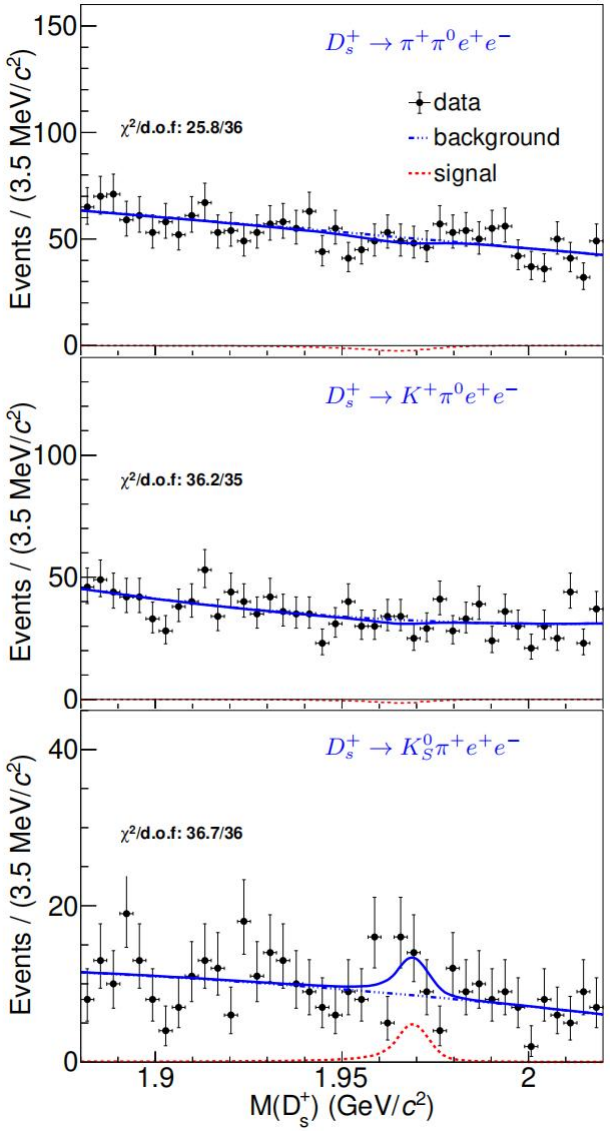
LD decays:

$D_s^+ \to \pi^+\phi, \phi \to e^+e^-$ is observed with a statistical significance of 7.8σ

$D_s^+ \to \rho^+\phi, \phi \to e^+e^-$ is found for the first time with a statistical significance of 4.4σ

Four body decays:

No obvious signal is observed and the ULs of BFs are about ~ 10^{-5} at 90% C.L.

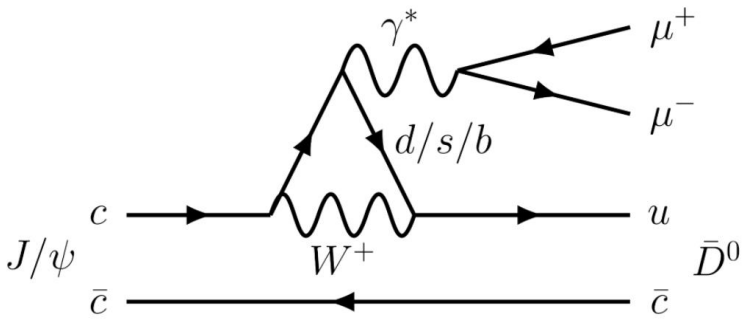


02 FCNC: $J/\psi \to D^0\mu^+\mu^-$

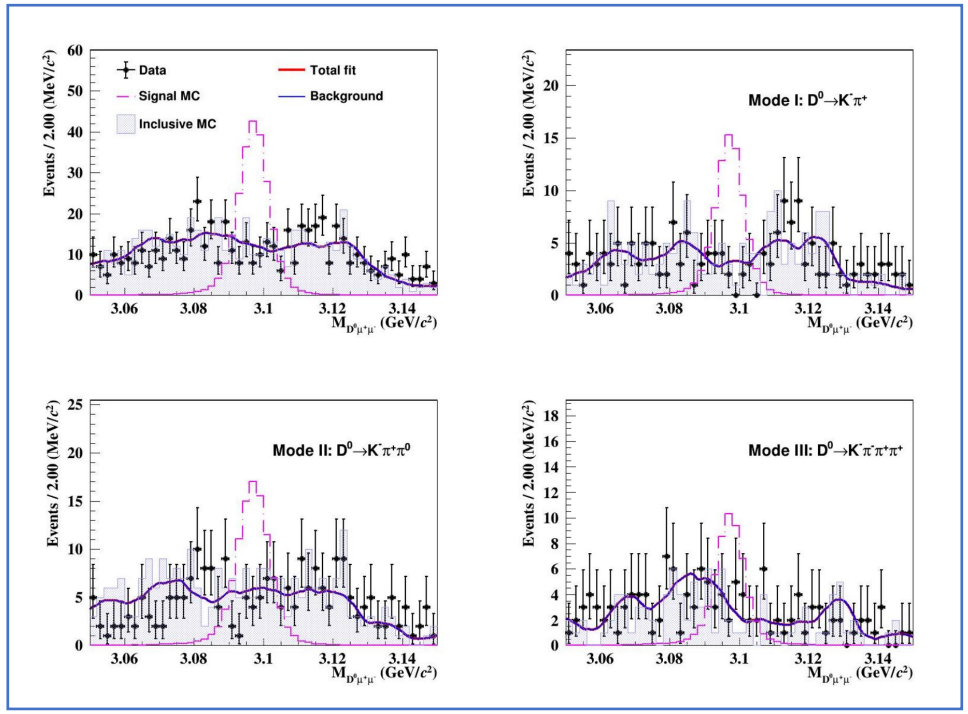
JHEP, 04, 061 (2025)

- Data: 10 billion J/ψ events taken @3.097 GeV
- The FCNC decay $J/\psi \to D^0\ell^+\ell^-$ to have a BFs on the order of $\sim 10^{-13}$ in the SM.
- FCNC processes have been probed in the charmonium:

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



Fit results for J/ψ mass with different decay mode.

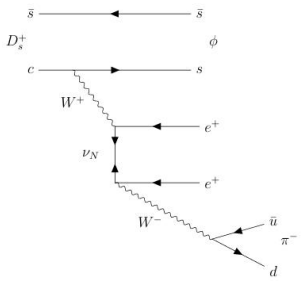


The first search for a charmonium FCNC process involving muons in the final state.
No signal events are found: 1.1×10^{-7} @90%C.L.

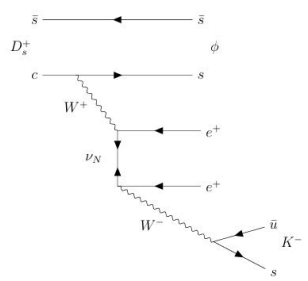
03 LNV: $D_s^+ \to h(h^0)e^+e^+$

JHEP 01, 109 (2024)

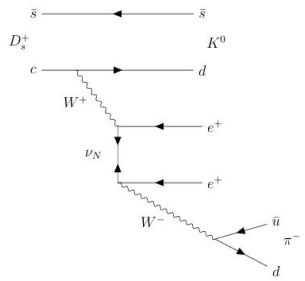
- Data: 7.33 fb^{-1} data taken @4.128-4.226 GeV
- Motivation 1:
  - Searched for LNV process



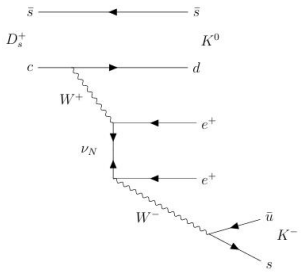
(a) $D_s^+ \to \phi\pi^-e^+e^+$ (CF).



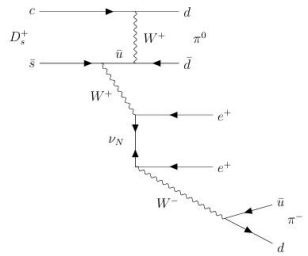
(b) $D_s^+ \to \phi K^-e^+e^+$ (SCS).



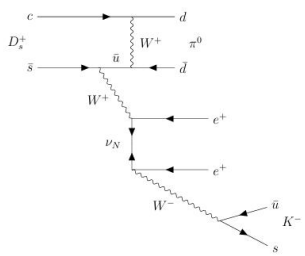
(c) $D_s^+ \to K_S^0\pi^-e^+e^+$ (SCS).



(d) $D_s^+ \to K_S^0K^-e^+e^+$ (DCS).

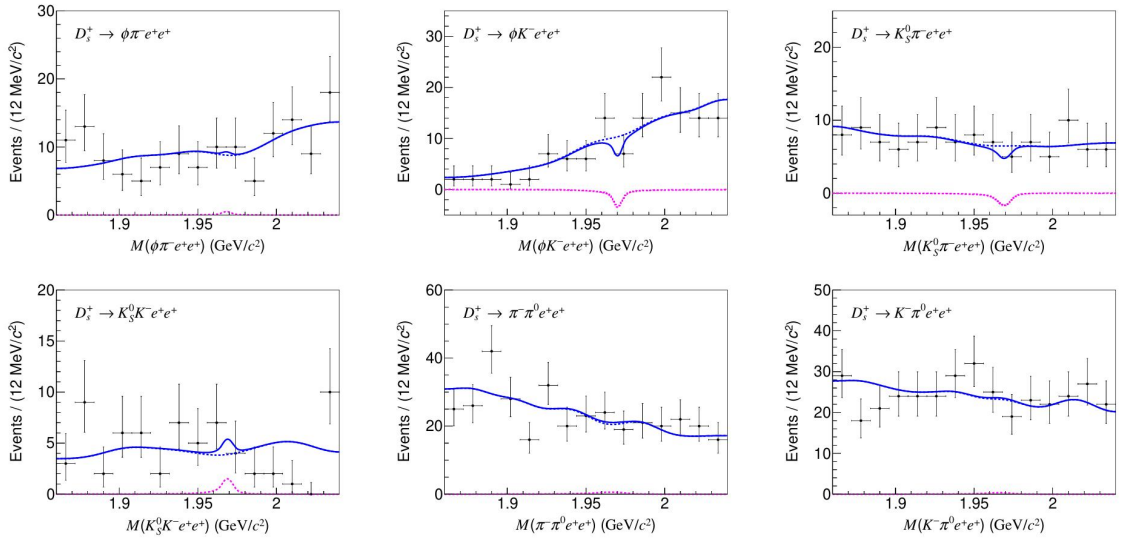


(e) $D_s^+ \to \pi^-\pi^0e^+e^+$ (W-exc.).



(f) $D_s^+ \to K^-\pi^0e^+e^+$ (W-exc.).

No signal events are found.

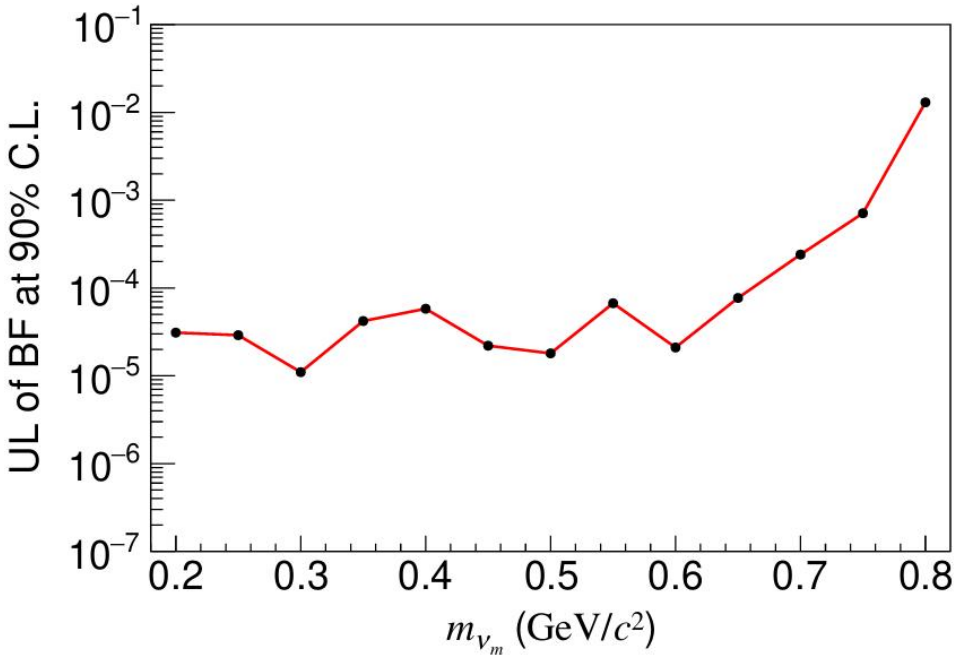


Decay channel	ϵ (%)	$\mathcal{B}_{\rm UL}$ ($\mathcal{B}_{\rm UL}^{\rm expected}$)
$D_s^+ \to \phi\pi^-e^+e^+$	3.0 ± 0.1	$6.9\ (3.5) \times 10^{-5}$
$D_s^+ \to \phi K^-e^+e^+$	1.8 ± 0.1	$9.9\ (10.8) \times 10^{-5}$
$D_s^+ \to K_S^0\pi^-e^+e^+$	6.4 ± 0.1	$1.3\ (2.4) \times 10^{-5}$
$D_s^+ \to K_S^0K^-e^+e^+$	4.0 ± 0.1	$2.9\ (2.3) \times 10^{-5}$
$D_s^+ \to \pi^-\pi^0e^+e^+$	6.4 ± 0.1	$2.9\ (2.7) \times 10^{-5}$
$D_s^+ \to K^-\pi^0e^+e^+$	5.1 ± 0.1	$3.4\ (3.9) \times 10^{-5}$

03 LNV: $D_s^+ \to h(h^0)e^+e^+$

- Motivation 2:
  - Searching for the Majorana (ν_m) in the decays of $D_s^+ \to \phi e^+ \nu_m$ with $\nu_m \to \pi^- e^+$

$0.2\text{GeV/c}^2 < \nu_m < 0.8\text{GeV/c}^2$



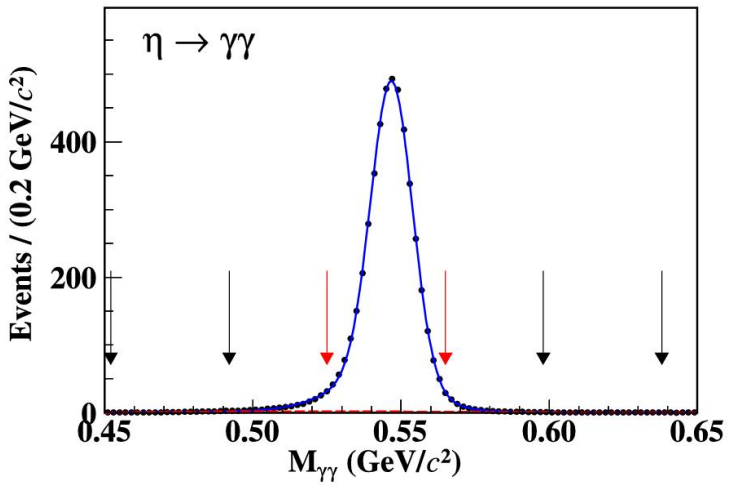
The ULs on the BFs at 90% CL: $10^{-5} \sim 10^{-2}$

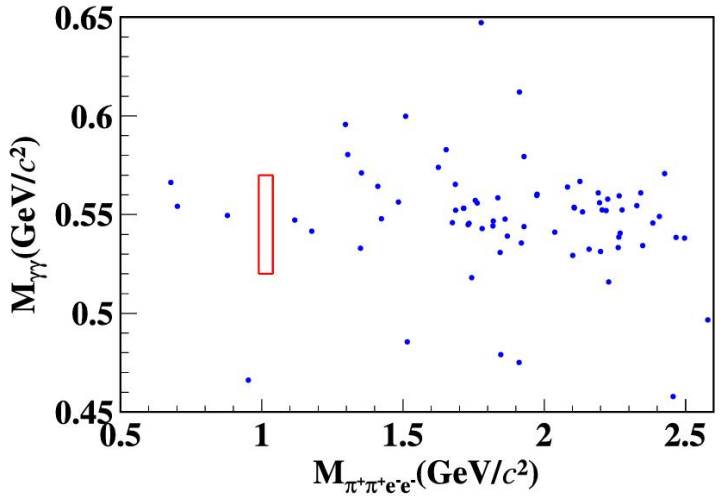
03 LNV: $\phi \to \pi^+\pi^+e^-e^-$ via $J/\psi \to \eta\phi$

CPC 49, 043001 (2025)

- Data: $(1.0087 \pm 0.0044) \times 10^{10}$ J/ψ events taken @3.097 GeV
- Reference channel: $\boldsymbol{\phi \to K^+K^-}$ via $\boldsymbol{J/\psi \to \eta\phi}$
- Method:

$$\mathcal{B}(\phi \to \pi^+\pi^+e^-e^-) < \mathcal{B}(\phi \to K^+K^-) \times \frac{N^{\rm up}_{\pi^+\pi^+e^-e^-}}{N^{\rm net}_{K^+K^-}/\varepsilon_{K^+K^-}}$$





No signal events are found: $\mathcal{B} < 1.3 \times 10^{-5}$ @90%C.L

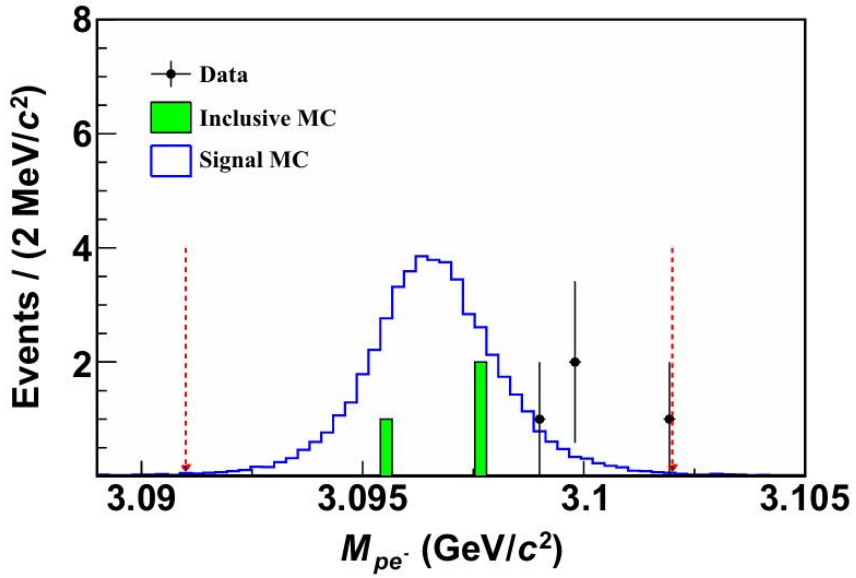
This study findings improve the experimental knowledge of LNV decay for hadrons composed of second generation quarks.

03 LNV: $J/\psi \to pe^- + c.c.$ via $\psi \to \pi^+\pi^- J/\psi$

Phys. Rev. D 111, 112010 (2025)

- Data: $(2712.4 \pm 14.3) \times 10^6$ ψ (3686) events taken @3.686 GeV
- Background mainly from particle misidentification, remaining events consist :
  - $J/\psi \to e^+e^-\gamma^f\gamma^f$ and $J/\psi \to e^+e^-\gamma^f$
- UL of BF obtained using a frequentist method, employing an unbounded profile likelihood approach to account for systematic uncertainties
- Results: No obvious signals have been observed.

$$\mathcal{B}(J/\psi \to pe^-) < \frac{N^{\rm up}}{\mathcal{B}_\psi N^{\rm tot}_{\psi(3686)}} = 3.1 \times 10^{-8}$$

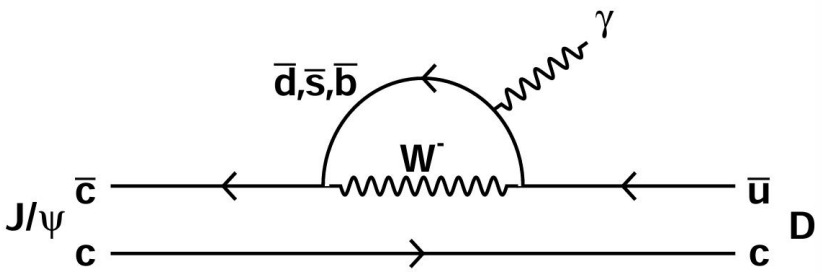


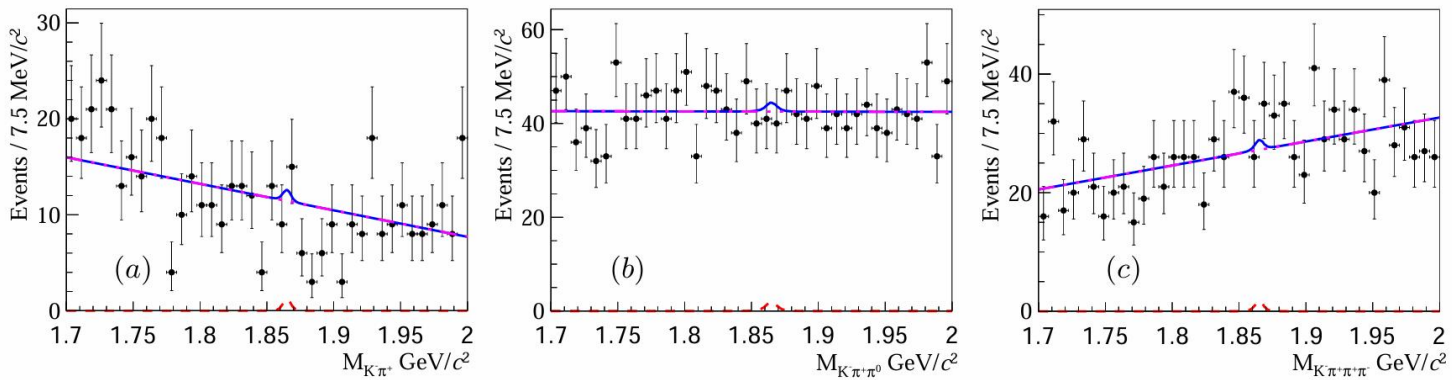
Stimulates new BNV models involving second-generation quarks.
Future sensitivity: up to 10^3 improvement at next-generation super τ-charm factory.

04 J/ψ weak decay process: $J/\psi \to \gamma D^0 + c.c.$

PRD 110, 112012 (2024)

- Data: 10 billion J/ψ events taken @3.097 GeV
- D0 is reconstructed through its three prominent exclusive hadronic decay modes:
  - $D^0 \to K^+\pi^-$ (Mode I)
  - $D^0 \to K^-\pi^+\pi^0$ (Mode II)
  - $D^0 \to K^-\pi^+\pi^+\pi^-$ (ModeIII)
- As the data are consistent with the background-only hypothesis, a Bayesian approach is employed to set the 90% C.L. upper limit on the branching fraction of $J/\psi \to \gamma D^0$.



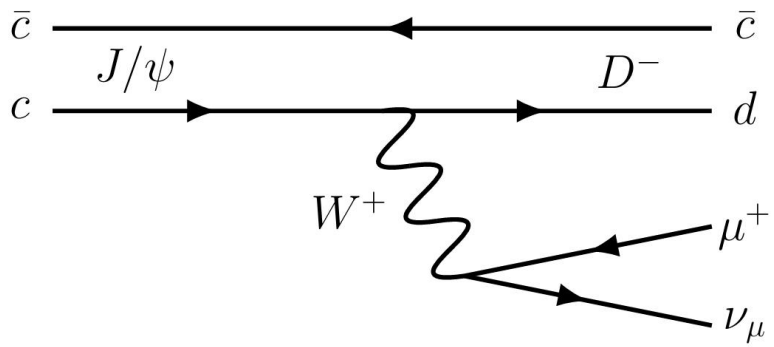


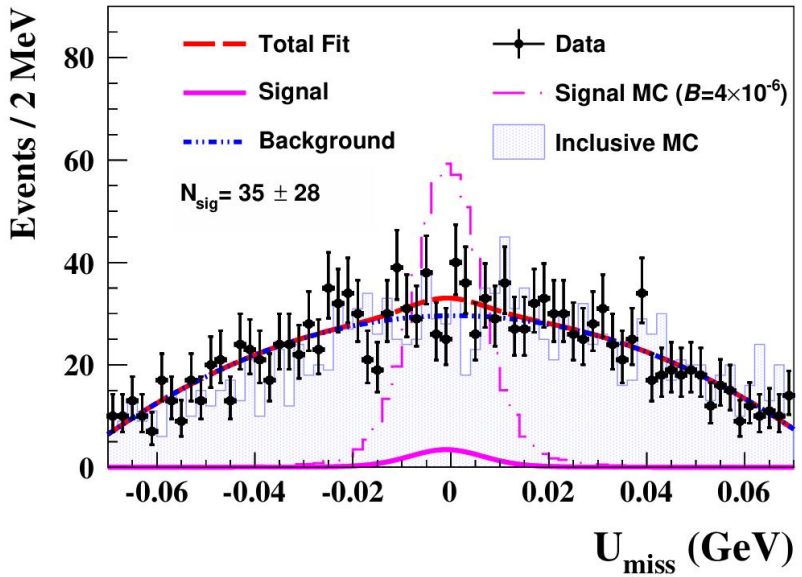
No signal events are found: 9.1×10^{-8} @90%C.L. with the systematic uncertainties

04 J/ψ weak decay process: $J/\psi \to D^- \mu^+ \nu_u$

JHEP 01, 126 (2024)

- Data: 10 billion J/ψ events taken @3.097 GeV
- This is the first search for the weak decay of charmonium with a muon in the final state.
- For the semi-muonic decay $J/\psi \to D^- \mu^+ \nu_u$, the theoretical predictions within the SM are at the order of 10^{-11}





No signal events are found: 5.6×10^{-7} @90%C.L.

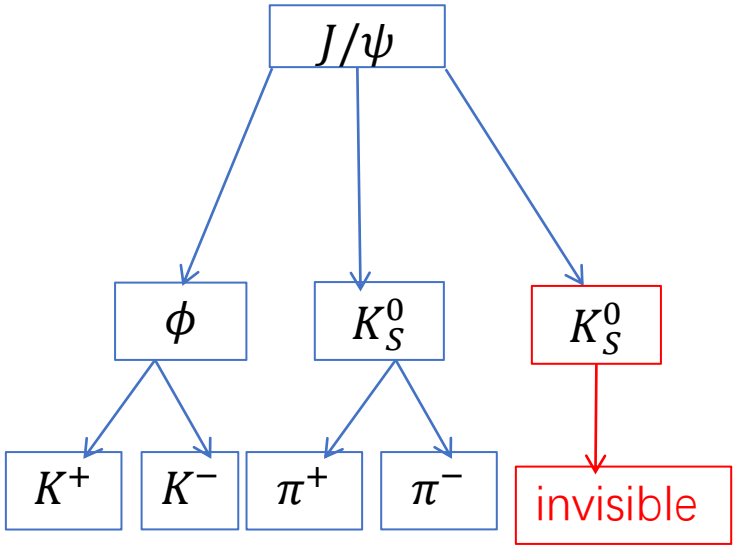
05 Invisible decays: $K_S^0 \to invisible\ decay$

JHEP 05, 092 (2025)

- Data: 10 billion J/ψ events taken @3.097 GeV
- Study process: K_S^0 →invisible , via $J/\psi \to \phi K_S^0 K_S^0$
- Motivation & Advantages
  - $J/\psi \to \phi K_S^0 K_S^0$: unique channel to probe K_S^0 invisible decays, most $J/\psi \to K_S^0 X$: contaminated by K_L^0 background, in this channel: $J/\psi \to \phi K_S^0 K_L^0$ forbidden by C-parity

⇒ Provides a clean K_S^0 sample for invisible decay search

- Tag one K_S^0 (control side), search invisible on the other (signal side)
- By summing all the known K_S^0 decay modes, an indirect estimation of the BF allowing K_S^0 to decay invisibly is established at the order of 10^{-4}



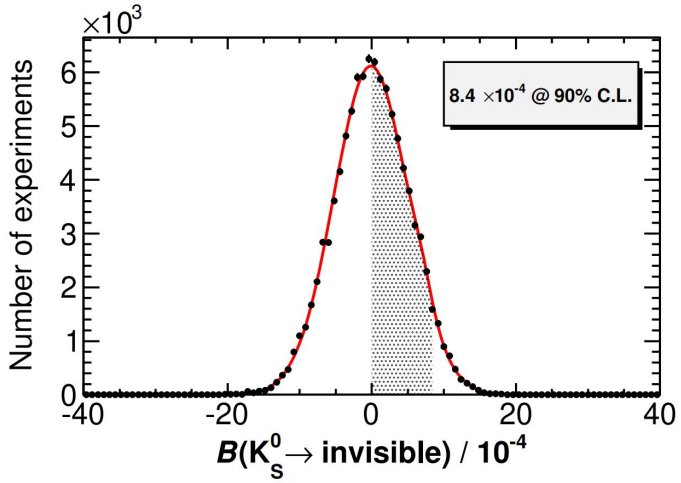
05 Invisible decays: $K_s^0 \to invisible\ decay$

JHEP 05, 092 (2025)

- Analysis method:

$$N_{\text{non}-\pi^+\pi^-} = 2 \times N_{J/\psi\to\phi K_S^0 K_S^0} \times \mathcal{B}(\phi \to K^+K^-) \times \mathcal{B}(K_S^0 \to \pi^+\pi^-) \times (1 - \mathcal{B}(K_S^0 \to \pi^+\pi^-)) \times \varepsilon_{\text{non}-\pi^+\pi^-},$$

$$N_{\text{signal}} = 2 \times N_{J/\psi\to\phi K_S^0 K_S^0} \times \mathcal{B}(\phi \to K^+K^-) \times \mathcal{B}(K_S^0 \to \pi^+\pi^-) \times \mathcal{B}(K_S^0 \to \text{invisible}) \times \varepsilon_{\text{signal}},$$



No signal events are found: 8.4×10^{-4} @90%C.L.

This is the first experimental search for K_s^0 invisible decays.

Summary

- No clear evidence of New Physics (NP) has been observed so far.
- Rare and symmetry-violating decays (LNV, BNV, FCNC) provide essential probes for physics beyond the Standard Model.
- BESIII plays a key role in NP searches, benefiting from unique datasets and advanced analysis techniques.
- Recently, BESIII collected 20 fb^{-1} at 3.773 GeV ($D\overline{D}$ threshold) — more precise and exciting results are expected soon!

Thanks!