Rare Charm decays at BESIII

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2024.10.28 衡阳

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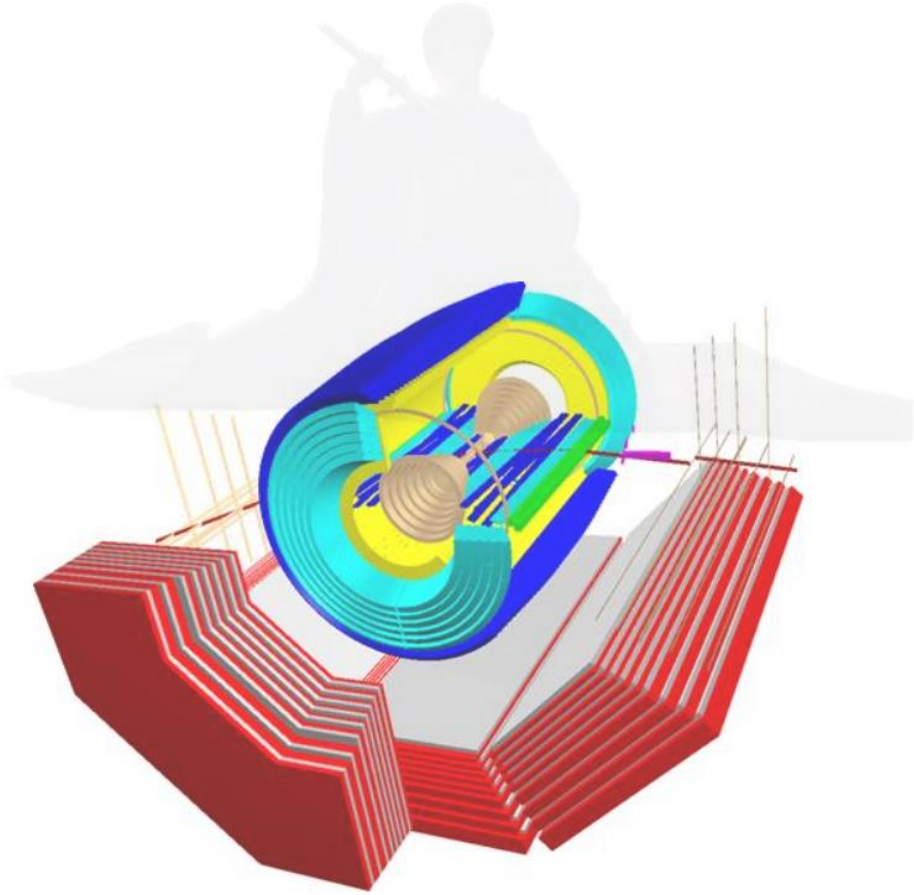
中山大學 SUN YAT-SEN UNIVERSITY

OUTLINE

- **Introduction**
- Rare decays of charm
- Exotic decays of charm
- Summary



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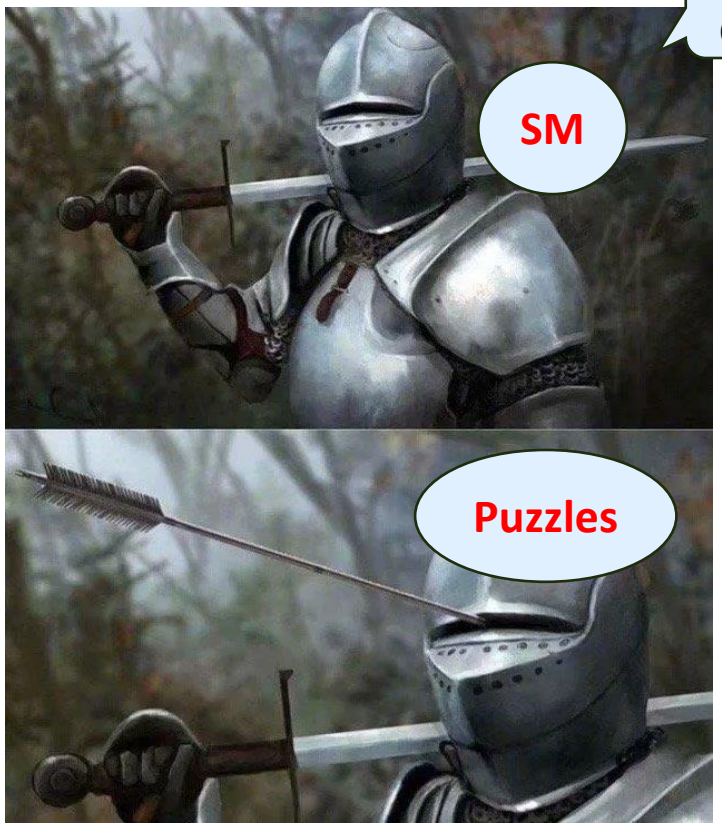
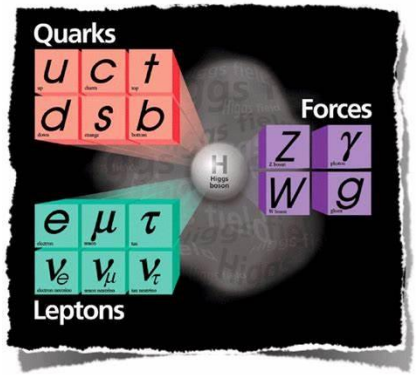
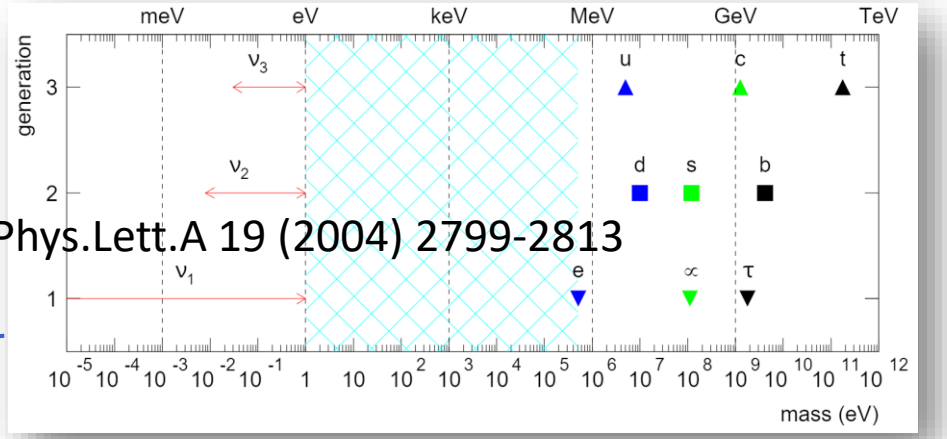
Beyond the SM (BSM)



There is nothing new to be discovered in physics now.

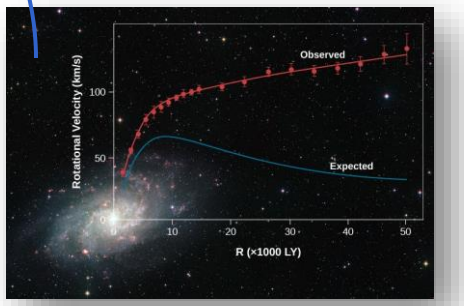


- Fermion mass hierarchy

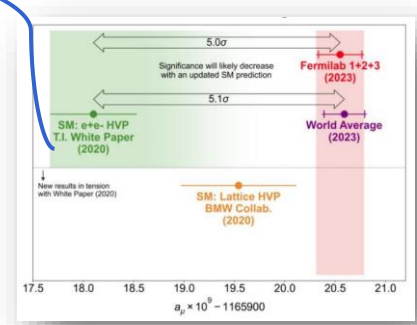


Mod.Phys.Lett.A 19 (2004) 2799-2813

- Dark matter

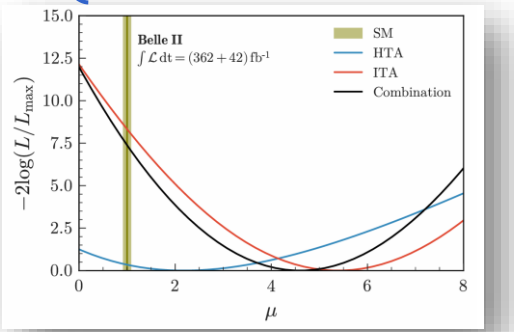


- $g_\mu - 2$ anomaly



PRL 131 (2023) 16, 161802

- $B^+ \to K^+ \nu\bar{\nu}$

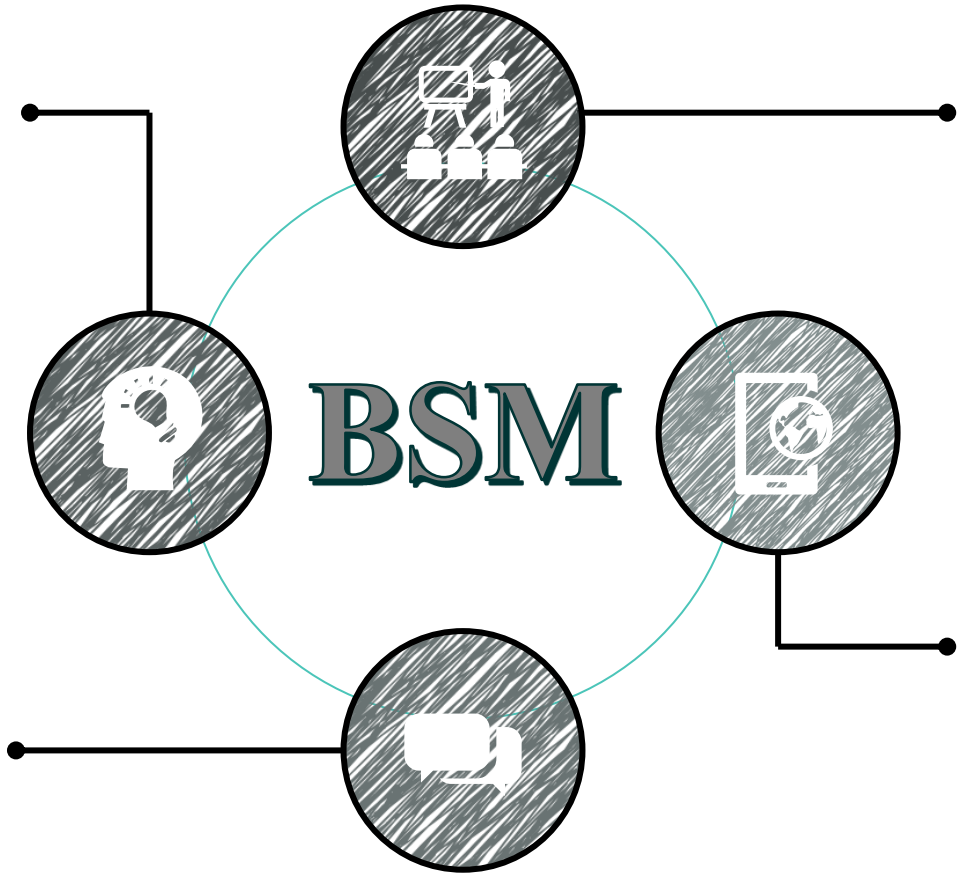


PRD109 (2024) 11, 112006

Physics BSM must exist!

BSM searches at BESIII

☐ Symmetry violation
- ✓ **C**harged **L**epton **F**lavor **V**iolation
- ✓ **L**epton **N**umber **V**iolation
- ✓ **B**aryon **N**umber **V**iolation
- ✓ CP violation
- ✓ C parity violation
- ✓ …



☐ Exotic particle
- ✓ Dark photon γ'
- ✓ Axion-like particle a
- ✓ Light Higgs Z^0
- ✓ SUSY particles
- ✓ …

☐ Vary rare decay
- ✓ Charmonium weak decay
- ✓ **F**lavor **C**hanging **N**eutral **C**urrent process
- ✓ …

☐ Other process
- ✓ Invisible decay
- ✓ Lepton universality test
- ✓ …

OUTLINE

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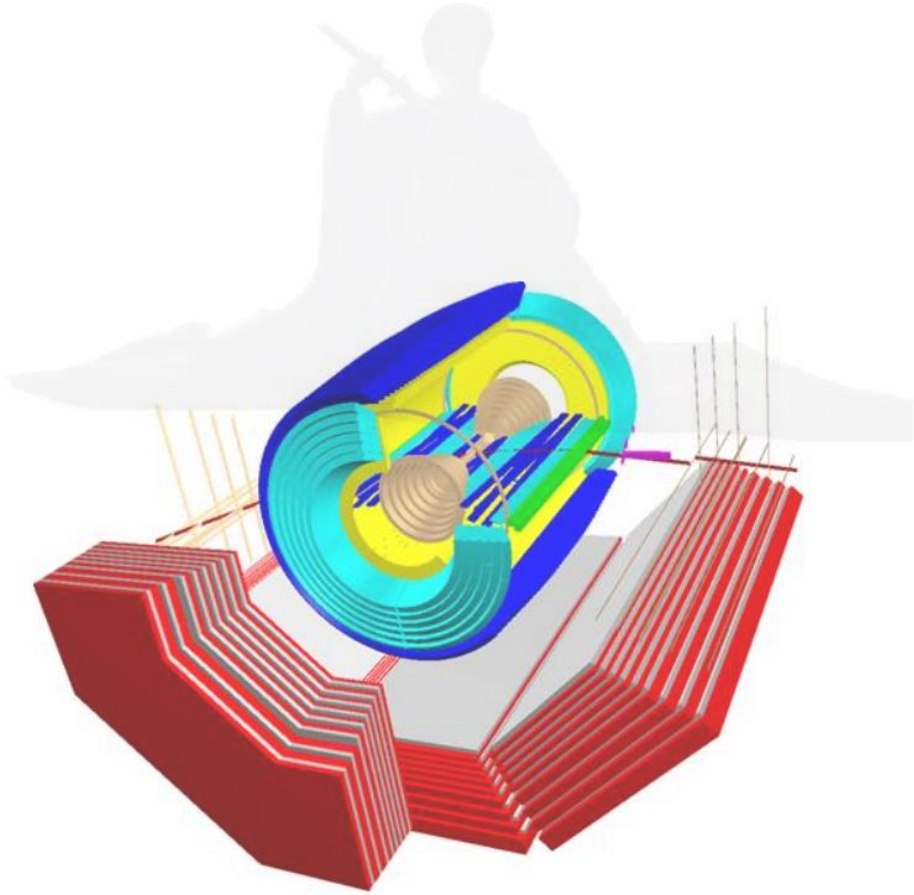
- **Rare decays of charm**
- Exotic decays of charm
- Summary



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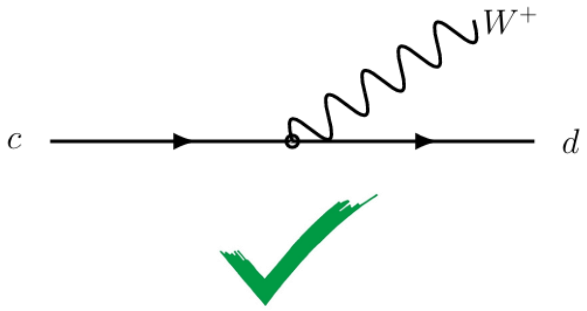
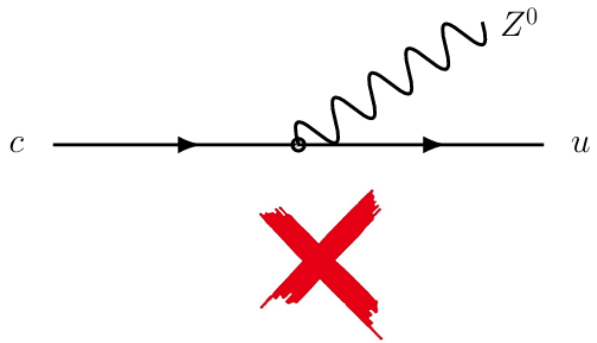
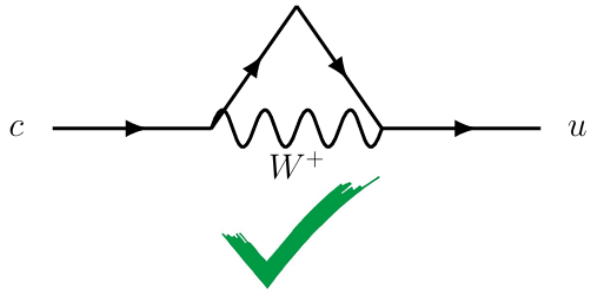
Flavor Changing Neutral Current process



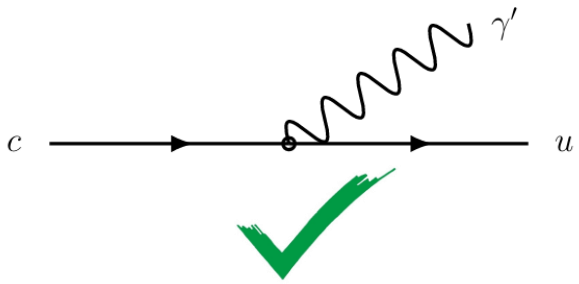
SM allowed



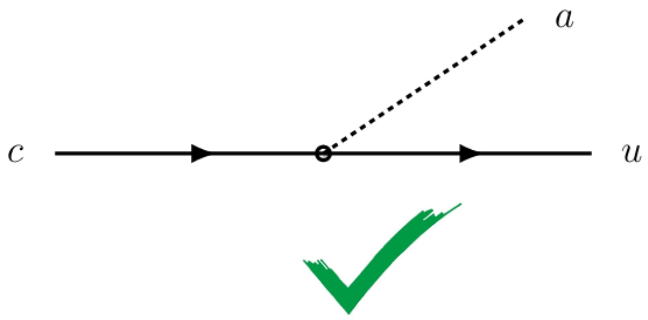
SM forbidden
(GIM mechanism)



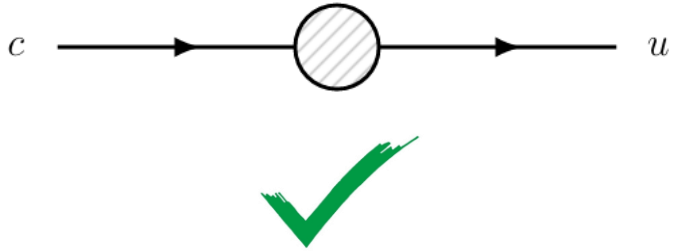
SM allowed
Loop diagram



Possible NP
Massless dark photon



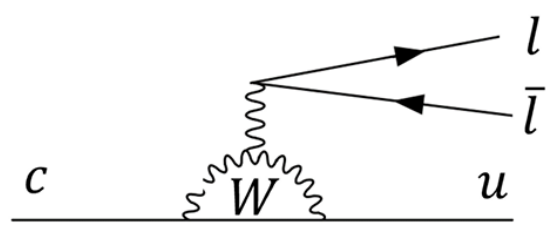
Possible NP
QCD axion



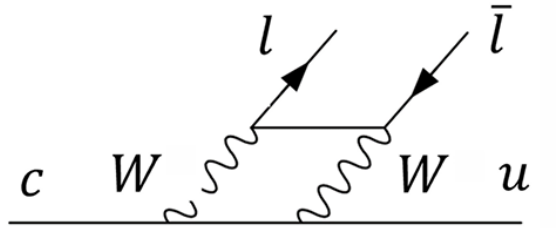
Possible NP
Loop diagram from dark sector

FCNC in charm decay

Usually using $D_{(s)} \to h(h')l\bar{l}$ decay to prob FCNC in charm

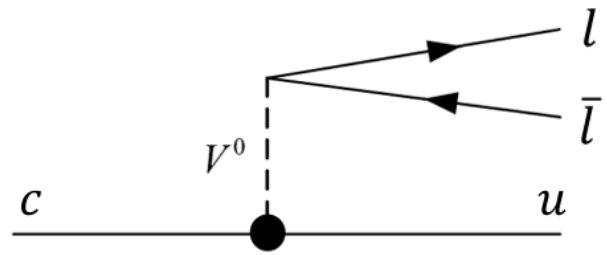


Penguin diagram

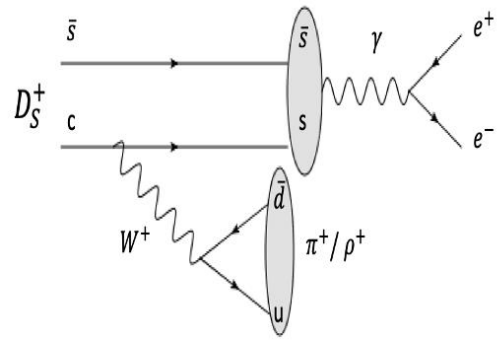


box diagram

- ✓ Short distance (**SD**) process: FCNC
- ✓ The suppression in charm decay is much stronger than B & K system
- ✓ **BF 10^{-9}~10^{-15} in SM for D meson**
- ✓ **NP contribution can enhance the BF of FCNC**



- ✓ Long distance (**LD**): Non-FCNC
- Through vector meson
- **Enhance the BF up to 10^{-5}**
- **eg.**



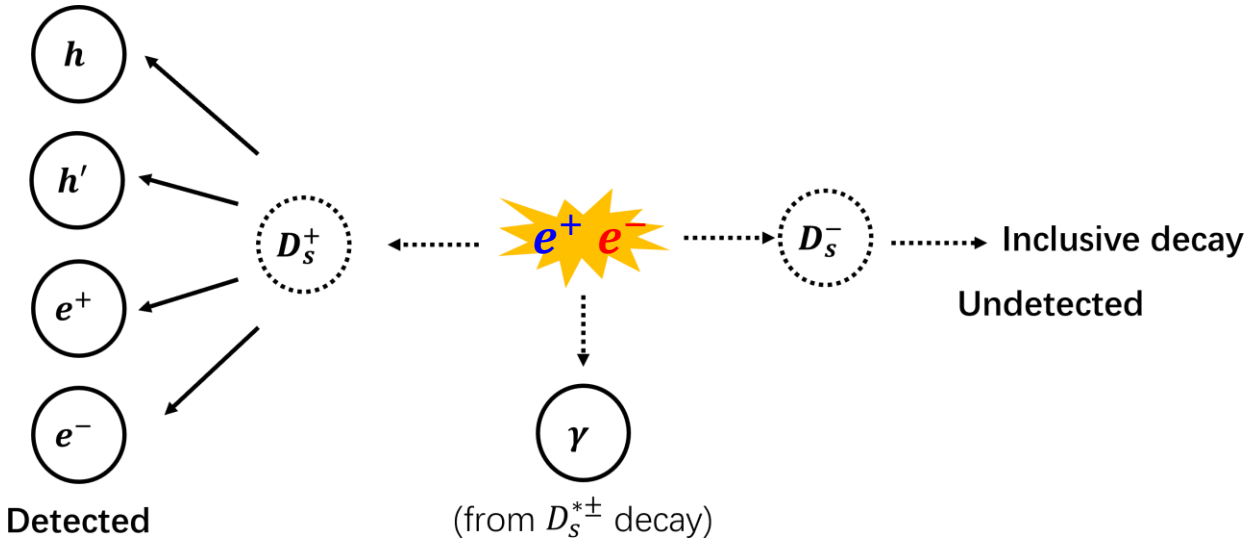
The FCNC processes are often overshadowed by the LD effects.

Search for $D_s^+ \to h(h')e^+e^-$ at BESIII

LD search	$D_s^+ \to \pi^+\phi(e^+e^-)$
	$D_s^+ \to \rho^+(\pi^+\pi^0)\phi(e^+e^-)$
SD (FCNC) search	$D_s^+ \to \pi^+\pi^0 e^+e^-$
	$D_s^+ \to K^+\pi^0 e^+e^-$
	$D_s^+ \to K_S^0\pi^+e^+e^-$

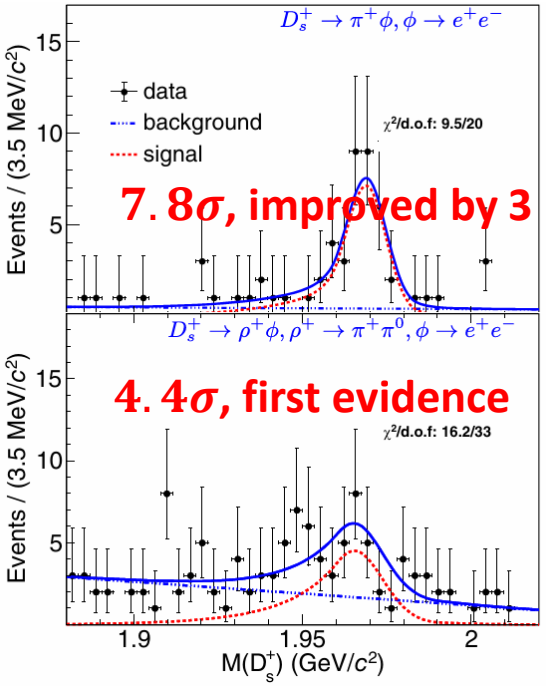
- **First search for four-body FCNC processed of D_s^+**
- Data set: 7.33 fb^{-1} data @ 4.128-4.226 GeV
- D_s^+ samples: mainly from $e^+e^- \to D_s^{*\pm}D_s^{\mp}$
  $N_{D_s^{*\pm}D_s^{\mp}} = (64.72 \pm 0.28) \times 10^5$

➢ **Single-tag method**



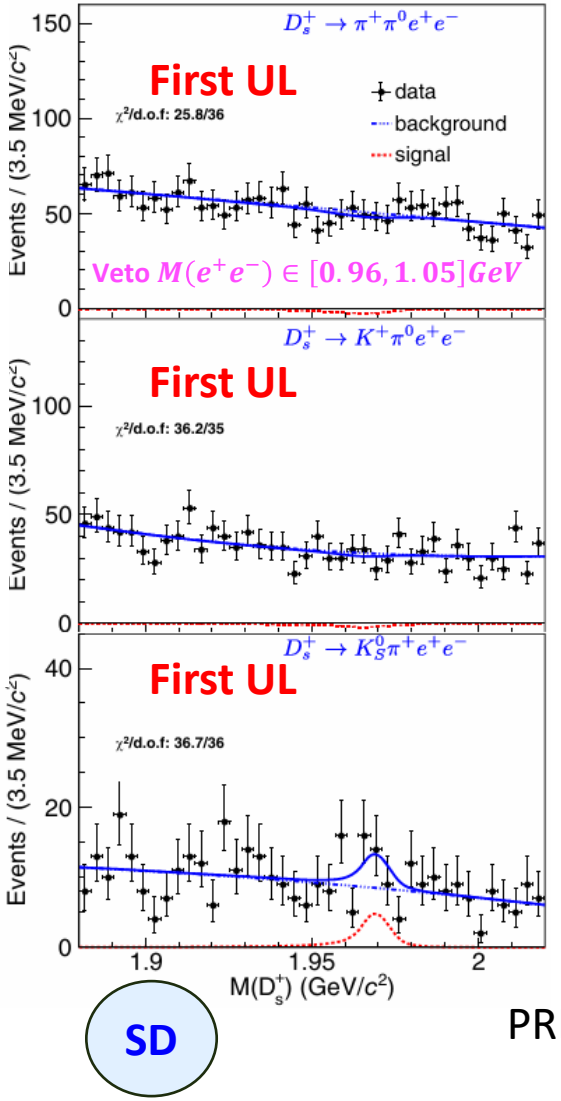
PRL 133, 121801 (2024)

Result on $D_s^+ \to h(h')e^+e^-$

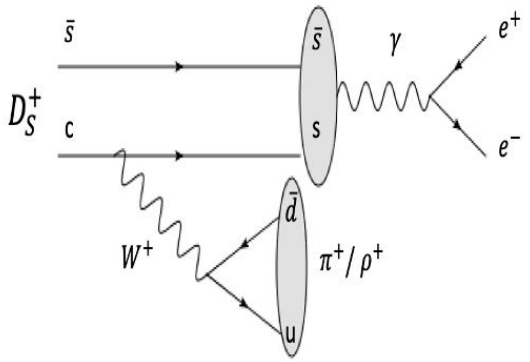


$M(e^+e^-) \in [0.98,1.04]$ GeV
$M(\pi^+\pi^0) \in [0.60,0.95]$GeV

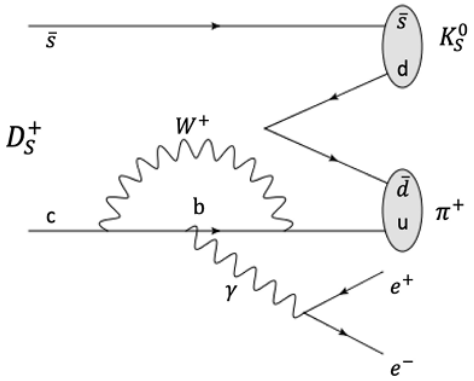
LD



SD



LD



SD

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	$2.44^{+0.67}_{-0.62} \pm 0.16$
$D_s^+ \to \pi^+\pi^0e^+e^-$	...	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

PRL 133, 121801 (2024)

Charmonium weak decay

- **In the 50 years since the discovery of the J/ψ particle, J/ψ weak decay has never been observed**

- The inclusive J/ψ weak decay branching fraction is predicted to be at the order of **10^{-8} or below in SM**

- Some **new physics models** can enhance the BF of J/ψ weak decay to 10^{-5}, e.g. Top-color model, two-Higgs doublet model PLB 345, 483 (1995) PLB 119, 136 (1982) PRD 15, 1958 (1977) PRD, 60, 014011 (1999)

- Semi-leptonic weak decay
  - $J/\psi \to D_{(s)}^{(*)-} l^+ \upsilon_l$
  - $l = e, \mu$

- Hadronic weak decay
  - $\psi(2S) \to \Lambda_c^+ \bar{\Sigma}^-$
  - $J/\psi \to D_{(s)}^{(*)-} \pi^+$

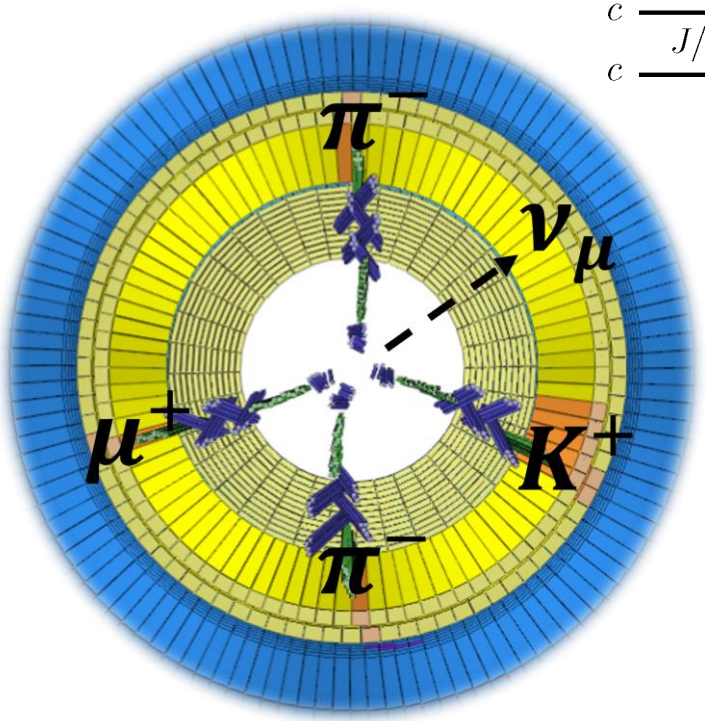
Theoretical model (SM)	QCDSR ($\times 10^{-11}$)	CLFQ ($\times 10^{-11}$)	BSW ($\times 10^{-11}$)	CCQW ($\times 10^{-11}$)	BSM ($\times 10^{-11}$)
$J/\psi \to D^- e^+ \upsilon_e$	$0.73^{+0.43}_{-0.22}$	$5.1 - 5.7$	$6.0^{+0.8}_{-0.7}$	1.71	$2.03^{+0.29}_{-0.25}$
$J/\psi \to D^- \mu^+ \upsilon_\mu$	$0.71^{+0.42}_{-0.22}$	$4.7 - 5.5$	$5.8^{+0.8}_{-0.6}$	1.66	$1.98^{+0.28}_{-0.24}$
$J/\psi \to D_s^- e^+ \upsilon_e$	18^{+7}_{-5}	$53 - 58$	$104.0^{+9.0}_{-7.5}$	33	$36.7^{+5.2}_{-4.4}$
$J/\psi \to D_s^- \mu^+ \upsilon_\mu$	17^{+7}_{-5}	$55 - 57$	$99.3^{+9.5}_{-6.5}$	32	$35.4^{+5.0}_{-4.3}$

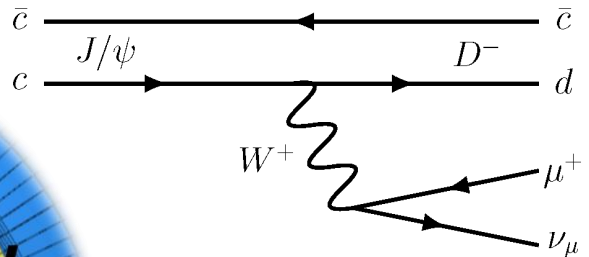
EPJC,54,107,2008
PRD,78:074012,2008
AHEP,2013:706543,2013
PRD,92:074030,2015
JPG:NPP,44:045004,2017

✓ **SM prediction for $J/\psi \to D_{(s)}^- l^+ \upsilon_l$: $\sim 10^{-10} - 10^{-11}$**

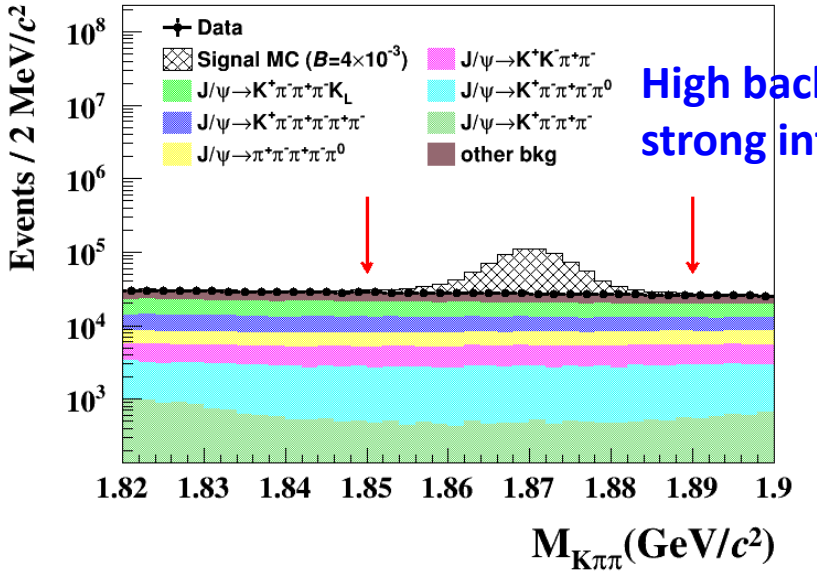
Search for $J/\psi \to D^- \mu^+ \nu_\mu + c.c.$

- Data set: $(10087 \pm 44) \times 10^6$ **J/ψ events** @ 3.097 GeV
- Using $D^- \to K^+\pi^-\pi^-$ to reconstruct D^-
- Extracting signals in $U_{miss}(= E_{miss} - c \cdot |P_{miss}|)$



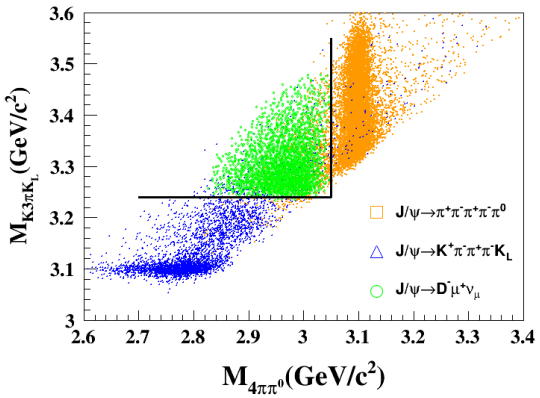


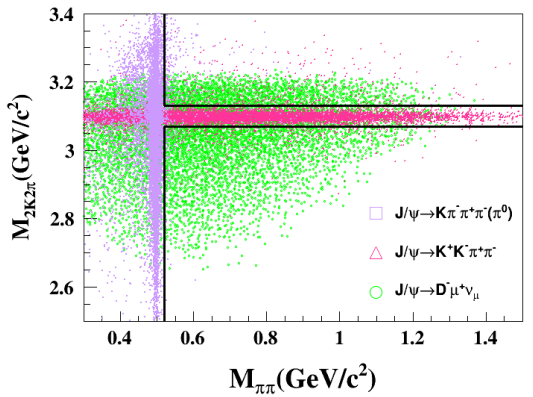
JHEP01(2024)126



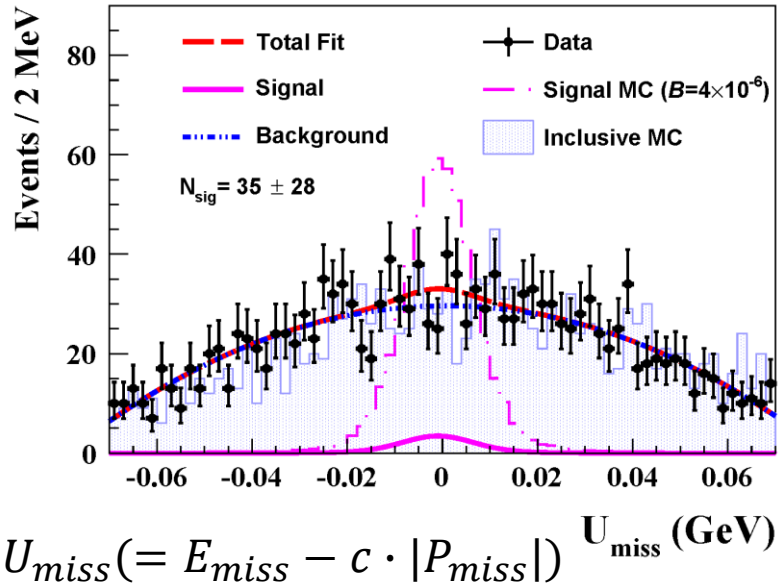
High background from J/ψ strong interaction decay

Background Suppression

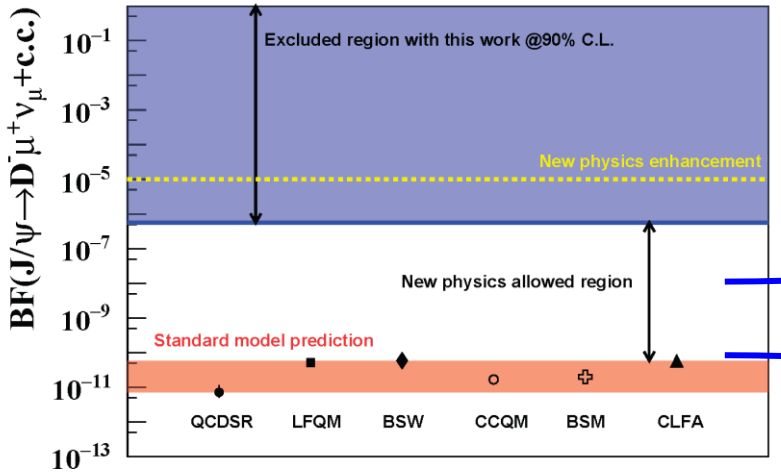


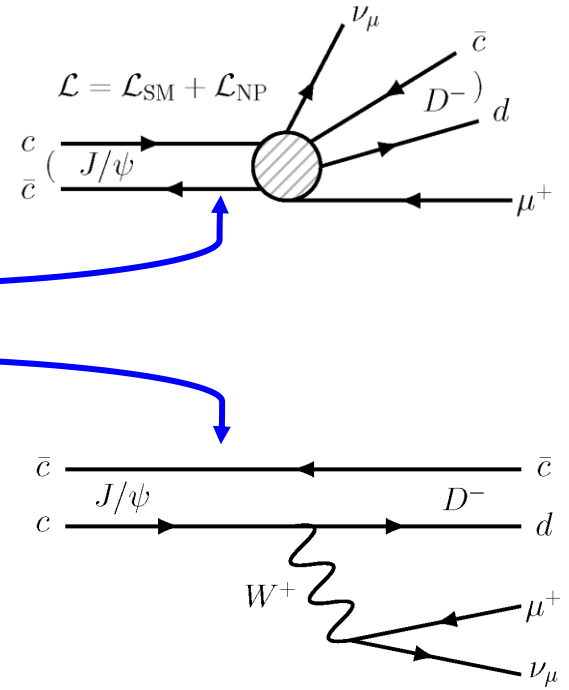


Result on $J/\psi \to D^- \mu^+ \nu_\mu + c.c.$



$U_{miss}(= E_{miss} - c \cdot |P_{miss}|)$



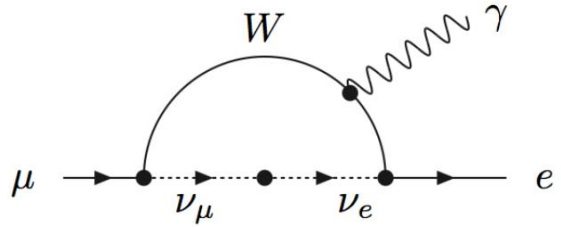


- $\mathcal{B}(J/\psi \to D^- \mu^+ \nu_\mu + c.c.) < 5.6 \times 10^{-7}$ @90% C. L.
- **The first search for the charmonium semi-muonic weak decay**
- SM prediction: $10^{-10} \sim 10^{-11}$

JHEP01(2024)126

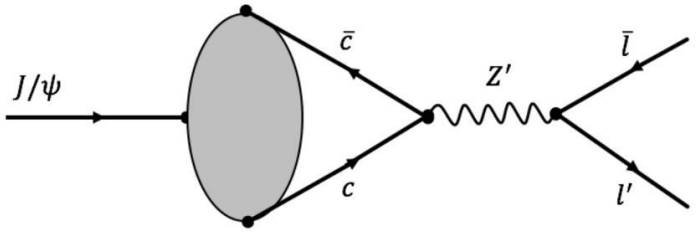
Charged Lepton Flavor Violation

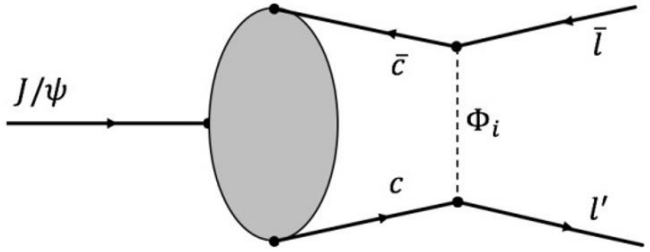
$$BR(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M_W^2}\right|^2 < 10^{-54}$$

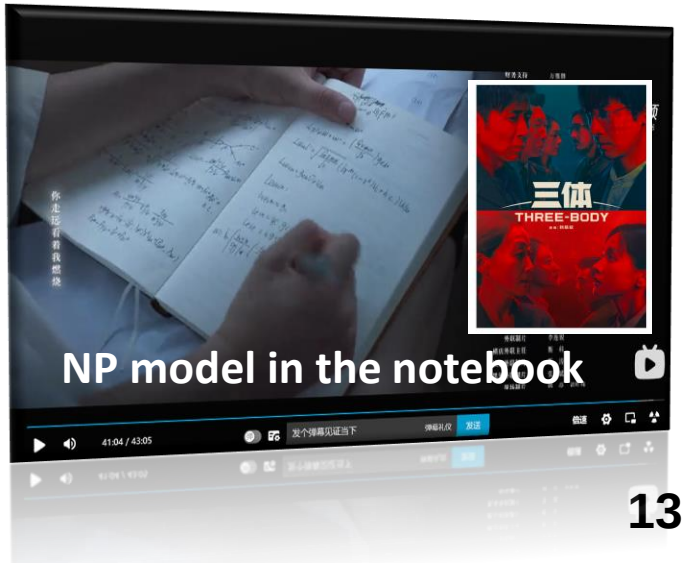


- ✓ Some new physics models can enhance the BF of CLFV to a detectable level:
  - $BF(J/\psi \to e\mu)$ @ 10^{-16}~10^{-9}
  - $BF(J/\psi \to e\tau)$ @ 10^{-10}~10^{-8}

Phys. Rev. D 63, 016003 (2000).
Rev. D 83, 115015 (2011).
Phys. Rev. D 63, 016006 (2000).
Phys. Lett. A 27, 1250172 (2012).
Phys. Rev. D 94, 074023 (2016).
Phys. Rev. D 97, 056027 (2018).

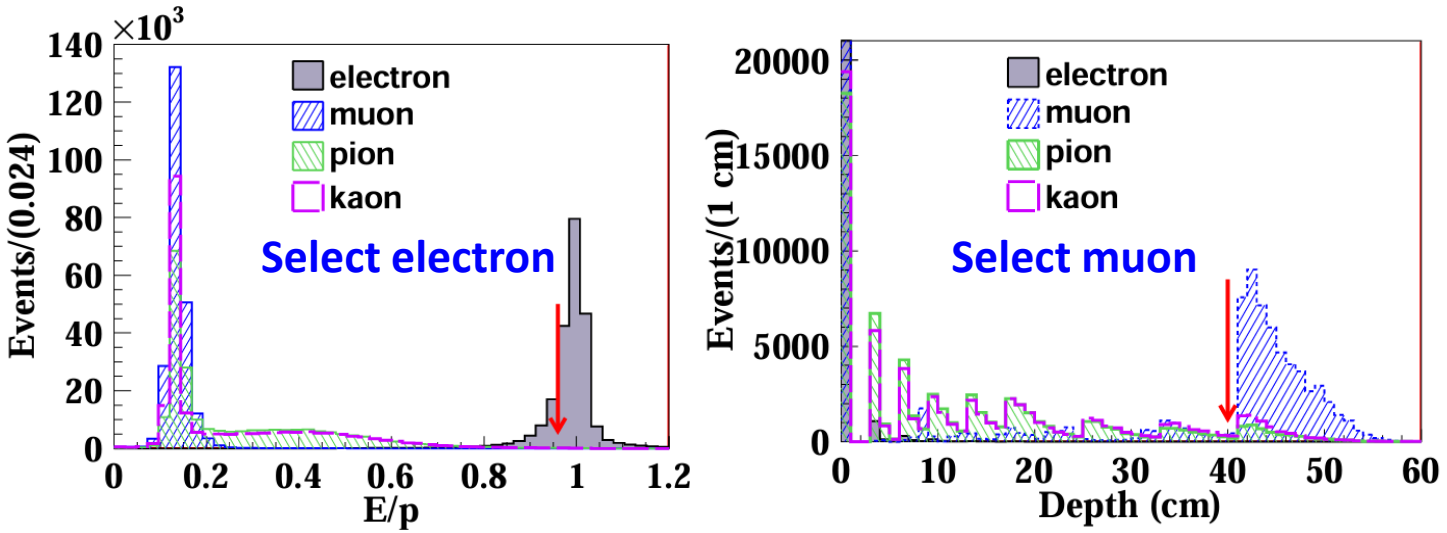


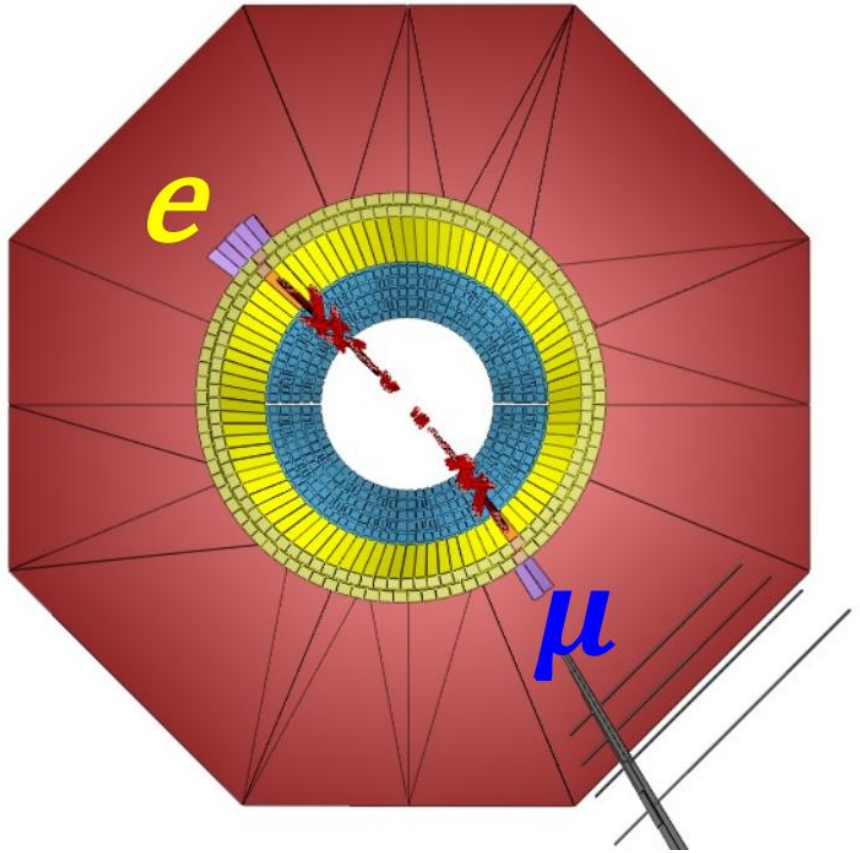




Search for $J/\psi \to e\mu$

- Data set: **8.998×10^9 J/ψ events** @ 3.097 GeV





- **Select an electron and a muon**
- **Clear background and high efficiency at BESIII**

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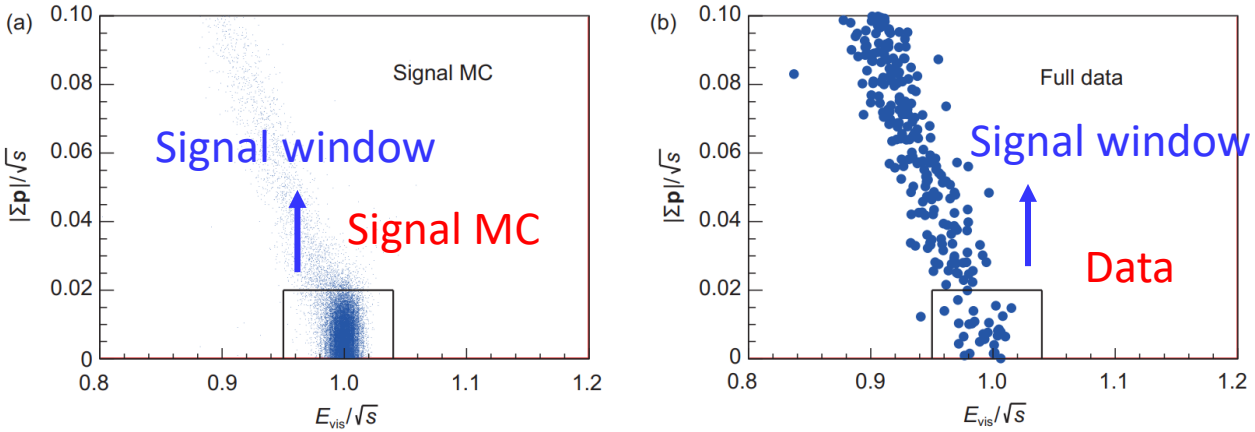
Result on $J/\psi \to e\mu$



- $\sum \vec{p}$: the magnitude of the vector sum of the momenta
- E_{vis}: the total reconstructed energy of e and μ

29 candidate events are observed
Estimated background: 36.8 ± 4.0

$$\mathcal{B}(J/\psi \to e\mu) < \mathbf{4.5 \times 10^{-9}} @ 90\%\ \text{C.L.}$$

$\mathcal{B}(\mu^+ \to e^+\gamma) < 3.1 \times 10^{-13} @ 90\%\ \text{CL}$	MEG II
$\mathcal{B}(\tau^+ \to e^+\gamma) < 3.3 \times 10^{-8} @ 90\%\ \text{CL}$	BABAR
$\mathcal{B}(\mu \to 3e) < 1.0 \times 10^{-12} @ 90\%\ \text{CL}$	SINDRUM
$\mathcal{B}(Z \to e^{\pm}\mu^{\mp}) < 2.62 \times 10^{-7} @ 95\%\ \text{CL}$	ATLAS
$\mathcal{B}(H^0 \to e^{\pm}\mu^{\mp}) < 4.7 \times 10^{-5} @ 95\%\ \text{CL}$	CMS
$\mathcal{B}(\phi \to e^{\pm}\mu^{\mp}) < 2 \times 10^{-6} @ 90\%\ \text{CL}$	SND
$\mathcal{B}(\Upsilon(1S) \to e^{\pm}\mu^{\mp}) < 3.6 \times 10^{-7} @ 90\%\ \text{CL}$	Belle
$\mathcal{B}(J/\psi \to e^{\pm}\tau^{\mp}) < 7.1 \times 10^{-8} @ 90\%\ \text{CL}$	BESIII
$\mathcal{B}(J/\psi \to e^{\pm}\mu^{\mp}) < 4.5 \times 10^{-9} @ 90\%\ \text{CL}$	BESIII
...	

- ✓ Improves the previous published limits by a factor of more than 30
- ✓ The most precise CLFV search in heavy quarkonium

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OUTLINE

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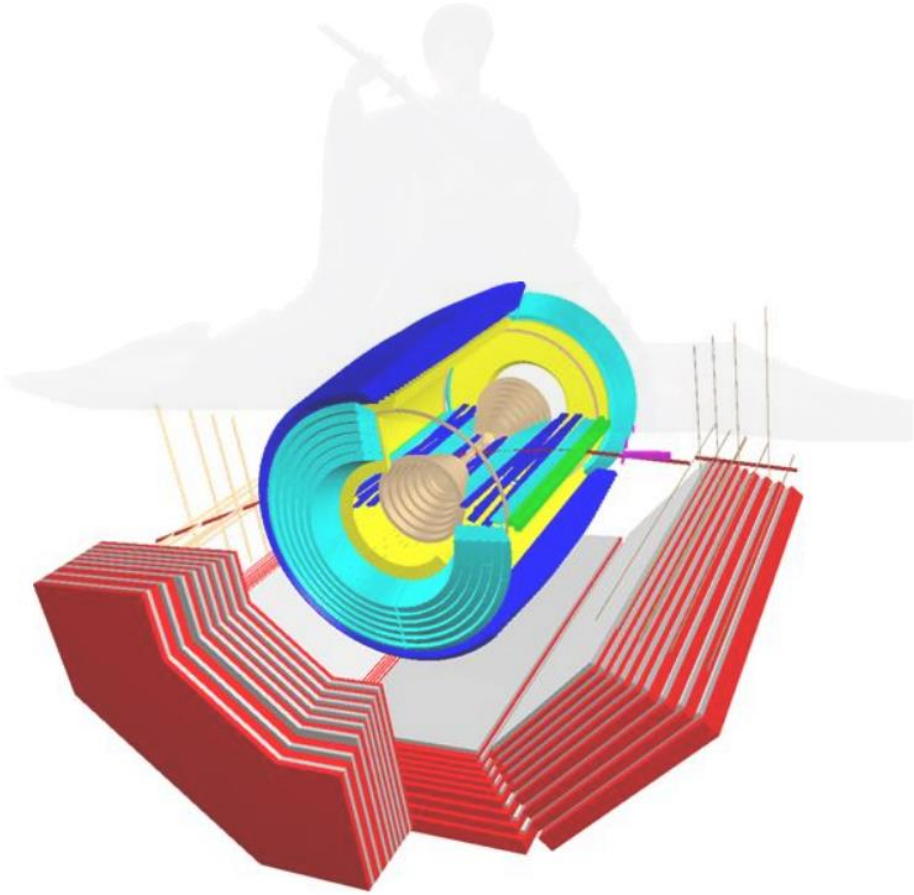
- **Exotic decays of charm**
- Summary



lizhj37@mail2.sysu.edu.cn

Massless dark photon

Massive dark photon

Symmetry broken spontaneously

Dark photon

Kinetic mixing: $\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$

ϵ: mixing strength

SM photon

Massless dark photon

Symmetry remains unbroken

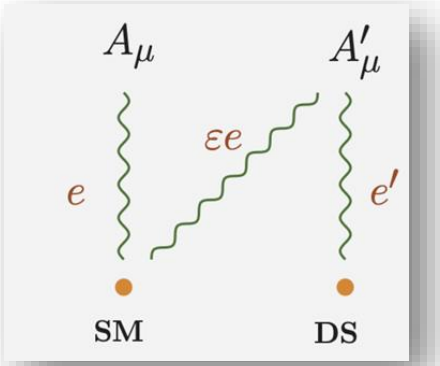
PRL 94, 151802 (2005)

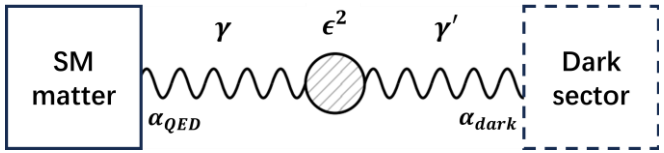
$$A^\mu \to A^\mu + \epsilon A'^\mu$$
$$\mathcal{L} = eJ_\mu A^\mu + e\epsilon J_\mu A'^\mu + e' J'_\mu A'^\mu$$

- **Dark photon couples to the SM matter**

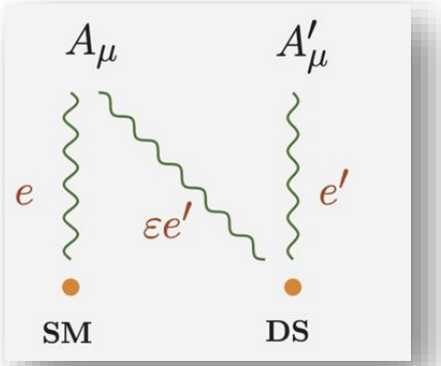
$$A'^\mu \to A'^\mu + \epsilon A^\mu$$
$$\mathcal{L} = eJ_\mu A^\mu + e'\epsilon J'_\mu A^\mu + e' J'_\mu A'^\mu$$

- **SM photon couples to the dark sector particles**





A portal to connect the SM matter and the dark sector

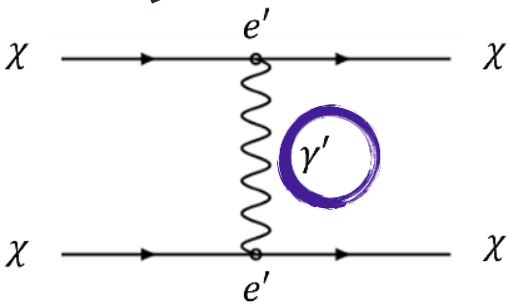


Massless dark photon has no interaction with the SM matter in the dimension-4 operator

arXiv:2005.01515

Why we need the massless dark photon

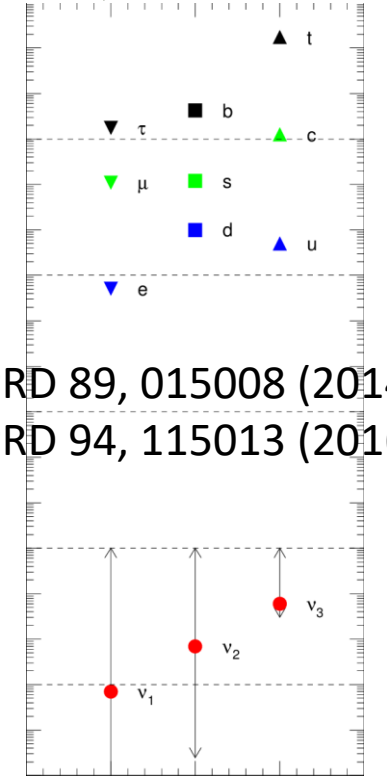
Provide a new long-range force of the DM



⟼ Explain the galaxy formation and dynamics

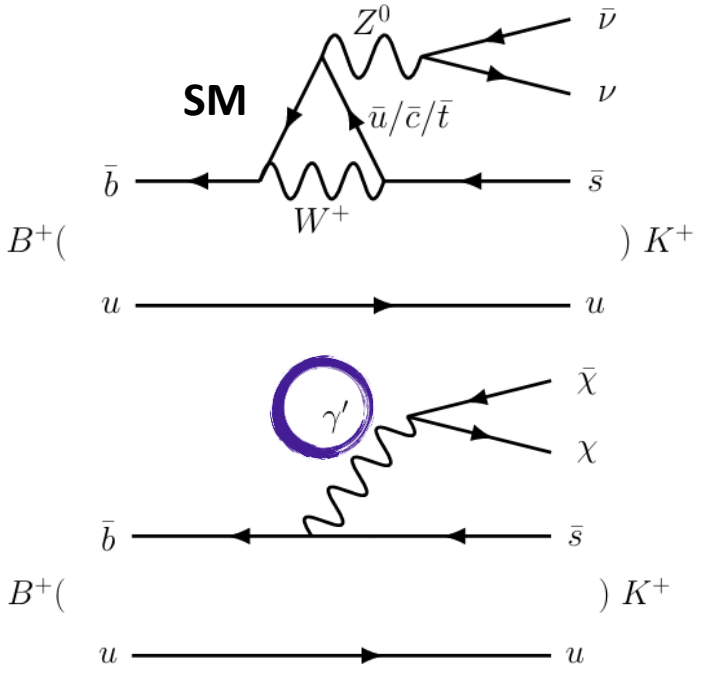
Phys.Rev.D 79 (2009) 023519
Phys.Rev.D 91 (2015) 023512
Phys.Lett.B 749 (2015) 236-241
JCAP 05, 022 (2017)
Phys.Rev.D 102 (2020) 8, 083009

Solution to the Fermion mass hierarchy



PRD 89, 015008 (2014)
PRD 94, 115013 (2016)

Explain exceeding of $B^+ \to K^+ \nu\bar{\nu}$ from Belle II



Phys.Rev.D 109 (2024) 11, 112006
Eur.Phys.J.C 84 (2024) 5, 460

More…

- **Solution to the origin of the CKM matrix structure**
- **Solution to the vacuum instability problem in SM Higgs Sector**
- **…**

PRD 101 (2020) 7, 075019
JHEP 01 (2022) 142

The interaction of the massless dark photon

$\mathcal{L} = eJ_\mu A^\mu + e'\epsilon J'_\mu A^\mu + e' J'_\mu A'^\mu$ (no interaction between γ' and SM matter)

PRL 94, 151802 (2005)

$$\mathcal{L}_{NP} = \frac{1}{\Lambda_{NP}^2}\left(C_{jk}^{U}\bar{q}_j\sigma^{\mu\nu}u_k\tilde{H} + C_{jk}^{D}\bar{q}_j\sigma^{\mu\nu}d_kH + C_{jk}^{L}\bar{l}_j\sigma^{\mu\nu}e_kH + h.c.\right)\bar{F}_{\mu\nu}$$

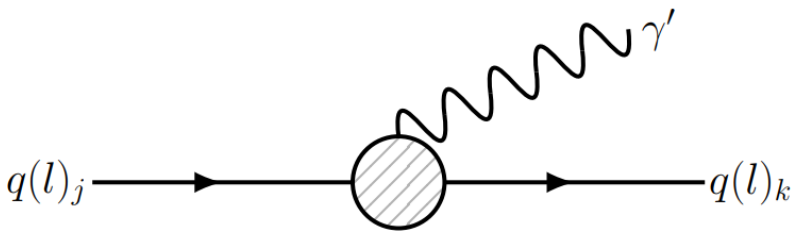
Dimension-six operator

Up type quarks coupling

Down type quarks coupling

Charged leptons coupling

Massless dark photon



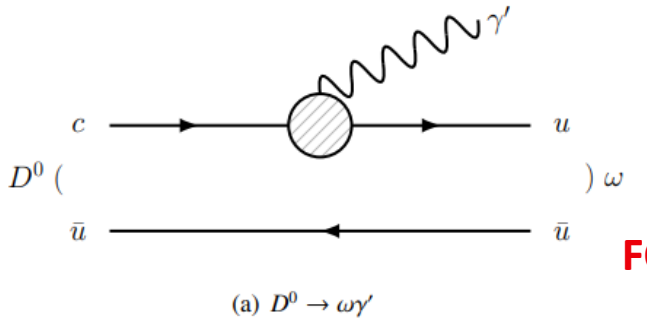
Experimental search:

- $H \to \gamma\gamma'$
- $\mu \to e\gamma'$
- $\Lambda_c^+ \to p\gamma'$

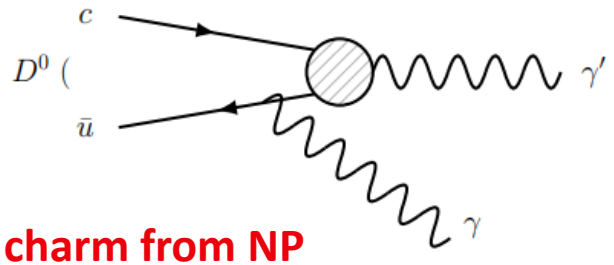
- **No signal observed**
- **The sensitivity still lie outside the theoretically predicted allowed region**

Search for $D^0 \to \omega\gamma'$ and $D^0 \to \gamma\gamma'$

- **Double tag method**: $\sim 6 \times 10^6$ $D^0(\bar{D}^0)$ are tagged with 7.9 fb^{-1} data @3.77 GeV
- **The massless dark photon is invisible**

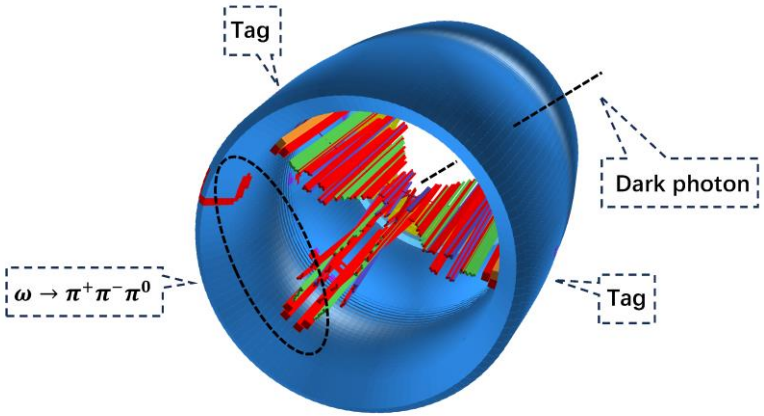


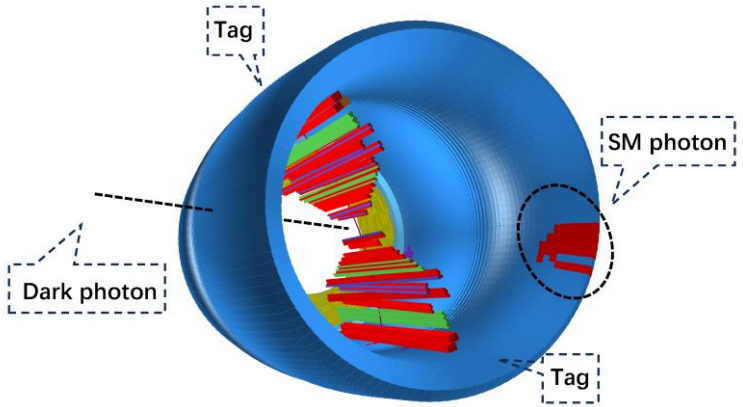
(a) $D^0 \to \omega\gamma'$



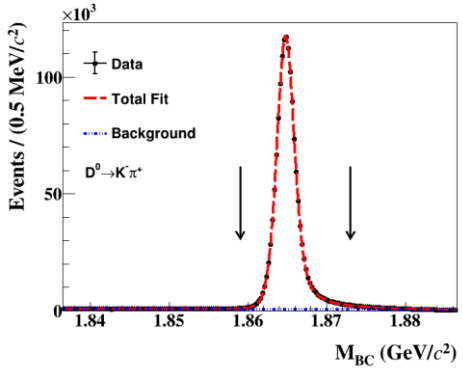
(b) $D^0 \to \gamma\gamma'$

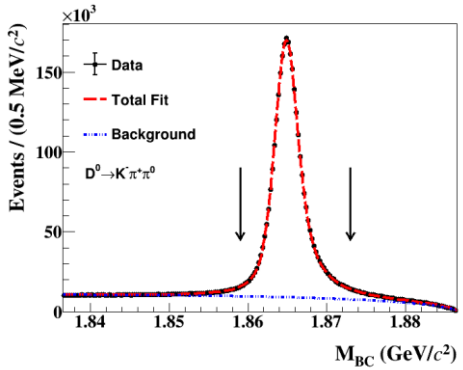
FCNC of charm from NP

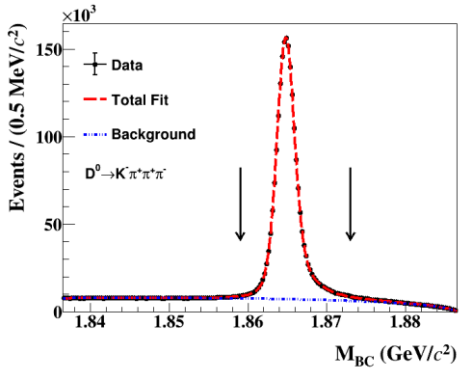




ST



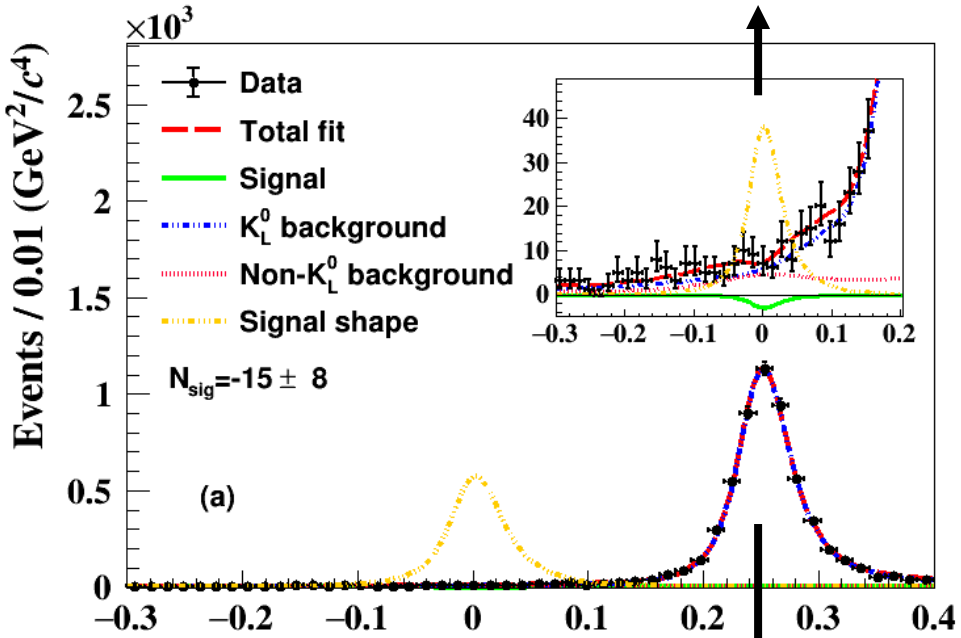




arXiv: 2409.02578

Signal extraction of the dark photon

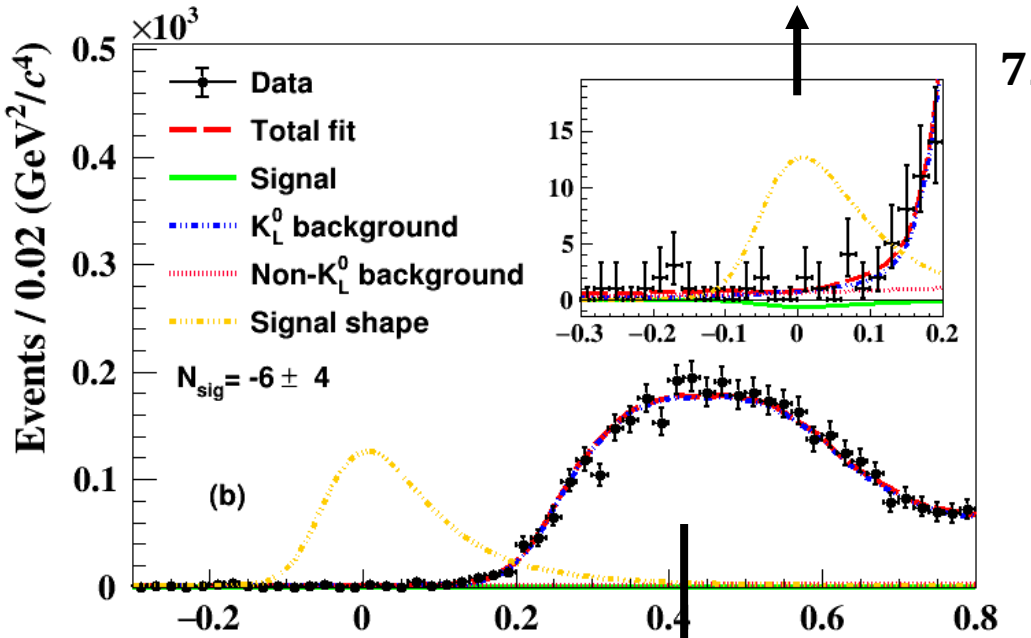
Signal should peak at zero



Signal extraction of $D^0 \to \omega\gamma'$

$D^0 \to \omega K_L$ background

Signal should peak at zero



Signal extraction of $D^0 \to \gamma\gamma'$

$D^0 \to \pi^0 K_L$ background

$7.9\ fb^{-1}$ data

arXiv: 2409.02578

Result on the massless dark photon

$$\mathcal{B}(D \to V\gamma') = \frac{\tau_D f_{DV}^2 (m_D^2 - m_V^2)^3}{2\pi m_D^3}(|\mathbb{C}|^2 + |\mathbb{C}_5|^2)$$

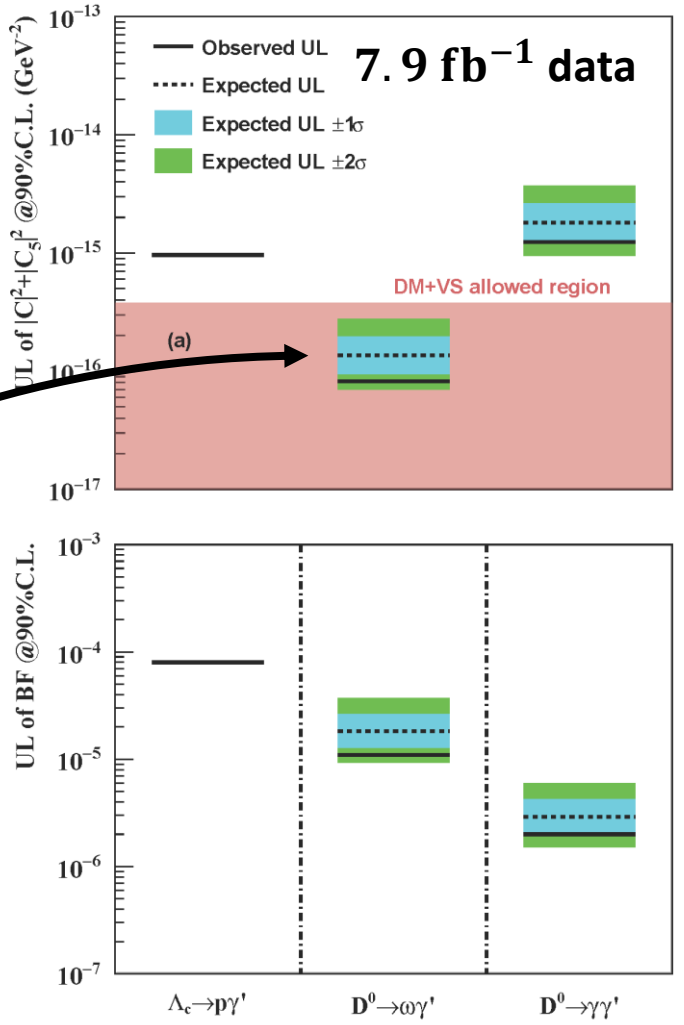
$$\mathcal{B}(D \to \gamma\gamma') = \frac{\alpha_e}{2}\tau_D f_{D\gamma}^2 m_D^3 (|\mathbb{C}|^2 + |\mathbb{C}_5|^2)$$

$$\mathcal{B}(\Lambda_c \to p\gamma') = \frac{\tau_{\Lambda_c} f_{\Lambda_c p}^2 (m_{\Lambda_c}^2 - m_p^2)^3}{2\pi m_{\Lambda_c}^3}(|\mathbb{C}|^2 + |\mathbb{C}_5|^2)$$

PRD 102, 115029 (2020)

- $\mathbb{C} = \Lambda_{NP}^{-2}(C_{12}^U + C_{21}^{U*})v/\sqrt{8}$
- $\mathbb{C}_5 = \Lambda_{NP}^{-2}(C_{12}^U - C_{21}^{U*})v/\sqrt{8}$

✓ $\mathcal{B}(D^0 \to \omega\gamma') < 1.1 \times 10^{-5}$
✓ $\mathcal{B}(D^0 \to \gamma\gamma') < 2.0 \times 10^{-6}$
✓ $|\mathbb{C}|^2 + |\mathbb{C}_5|^2 < 8.2 \times 10^{-17}\ GeV^{-2}$

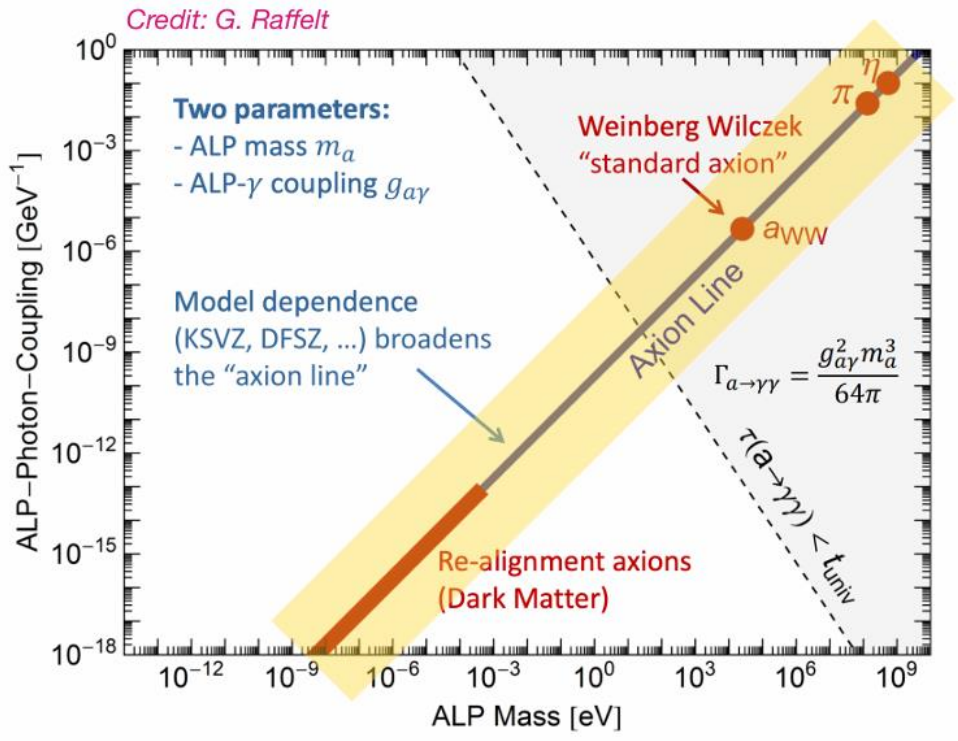


20 fb^{-1} prepared now

The constraint from $D^0 \to \omega\gamma'$ goes into the dark matter (DM) and vacuum stability (VS) allowed region for the first time, the most stringent constraint

arXiv: 2409.02578

Axion-like particle (ALP)



✓ **QCD axion**

- Predicted by the Peccei-Quinn (PQ) solution to the strong CP problem — PRL 40, 223 (1978) PRL 40, 279 (1978)
- Two parameter: mass m_a, coupling g

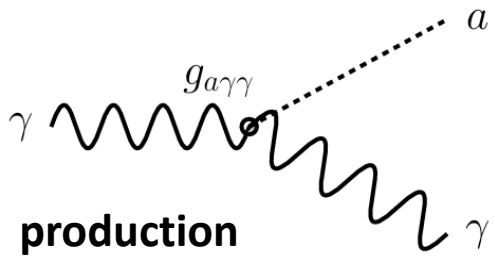
$$m_a = 5.691(51)\mu eV\left(\frac{10^{12}\ GeV}{f_a}\right),\ g \sim \frac{c}{f_a}$$

- An excellent cold dark matter candidate

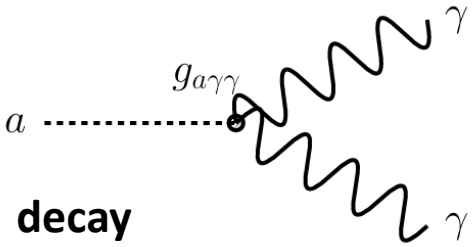
✓ **Axion-like particle (ALP)**

- Similar to QCD axion
- **But arbitrary masses and couplings**

➢ **ALPs can have interaction with photons**: $\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu}\tilde{F}_{\mu\nu}$ JHEP 06 (2019) 091



production

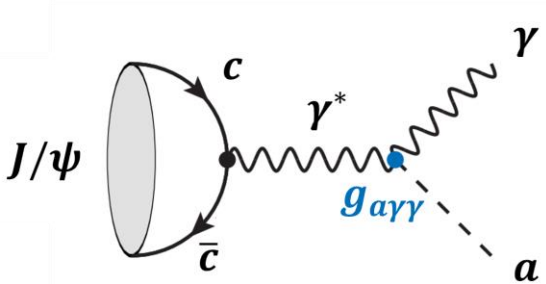


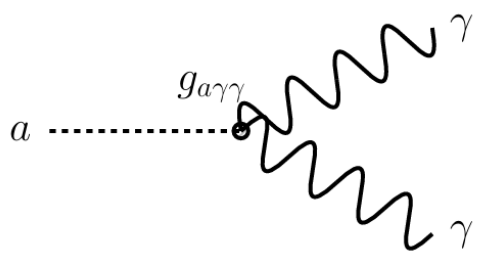
decay

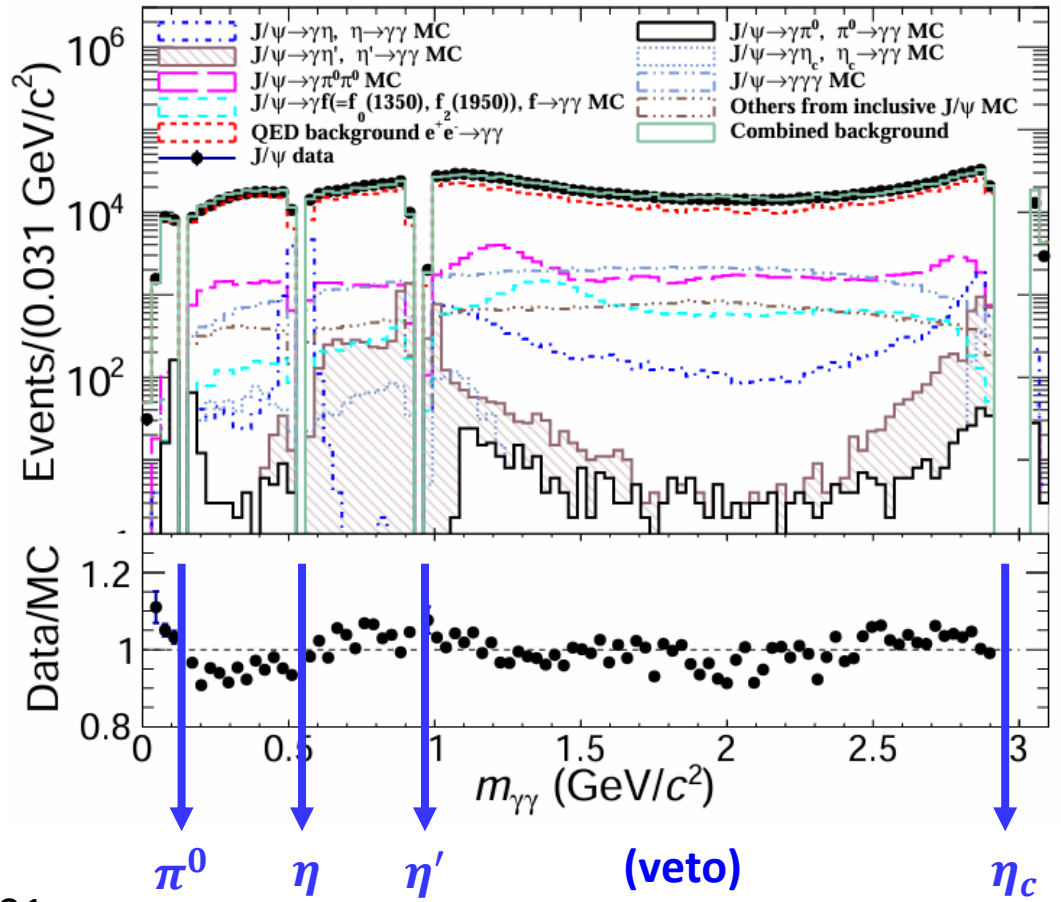
$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

Search for $J/\psi \to \gamma a \to \gamma\gamma\gamma$ at BESIII

- Data set: $(10087 \pm 44) \times 10^6$ **J/ψ events** @ 3.097 GeV
- The decay width of $a \to \gamma\gamma$: $\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$
- Taking $g_{a\gamma\gamma}\sim 10^{-4}$ GeV^{-1}, $m_a\sim$GeV, the lifetime of ALP is short in the detector
  short-lived, visible via $a \to \gamma\gamma$
- Three $\gamma\gamma$ combinations per event, perform unbinned maximum-likelihood fit on $M_{\gamma\gamma}$



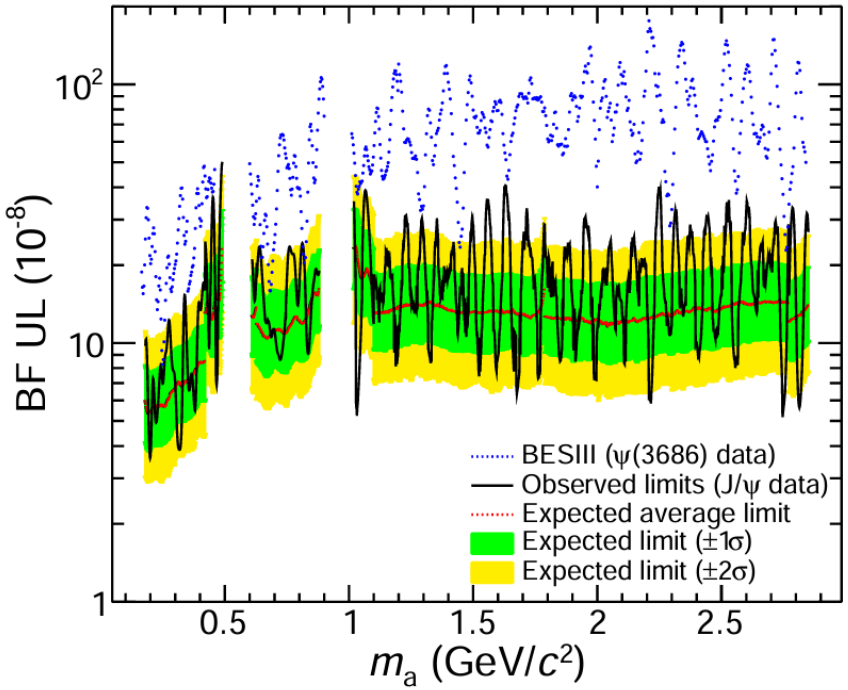


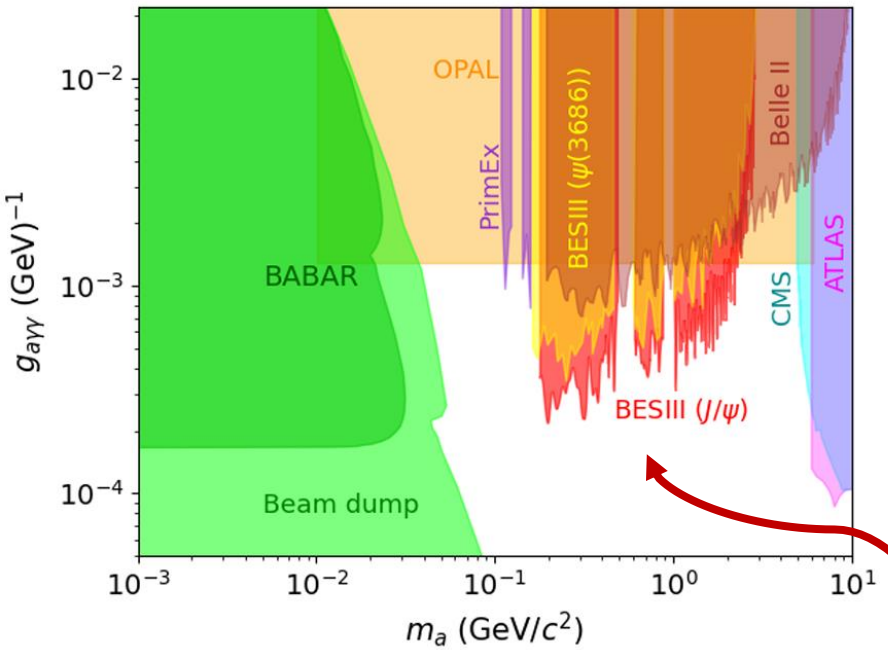


Phys.Rev.D 110 (2024) 3, L031101

Maximum signal significance: $< 3\sigma$

Results on the ALP





- UL of $\mathcal{B}(J/\psi \to \gamma a) \times \mathcal{B}(a \to \gamma\gamma)$ @ 90% C.L.:
  $(3.6 \sim 53.1) \times 10^{-8}$
- $\frac{\mathcal{B}(J/\psi \to \gamma a)}{\mathcal{B}(J/\psi \to e^+e^-)} = \frac{m_{J/\psi}^2}{32\pi\alpha} g_{a\gamma\gamma}^2 (1 - \frac{m_a^2}{m_{J/\psi}^2})^3$

- Assuming that $\mathcal{B}(a \to \gamma\gamma) \sim 100\%$
- **UL of $g_{a\gamma\gamma}$: $(2.2 \sim 97.5) \times 10^{-4}\ GeV^{-1}$**

Most stringent constraints to date for $0.18 \leq m_a \leq 2.85\ GeV$

Phys.Rev.D 110 (2024) 3, L031101

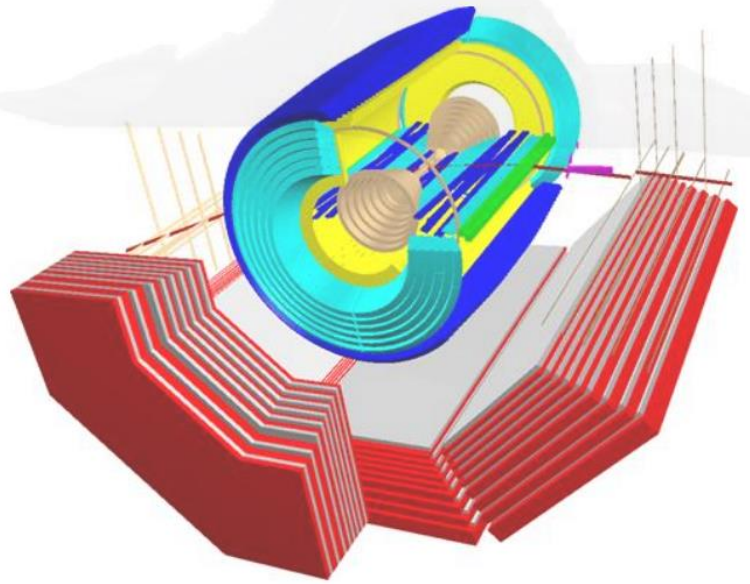
Summary

- New results of FCNC, J/ψ weak decay, CLFV, dark photon, ALP at BESIII

- Unfortunately, No evidence is found
- Stringent constraints are set

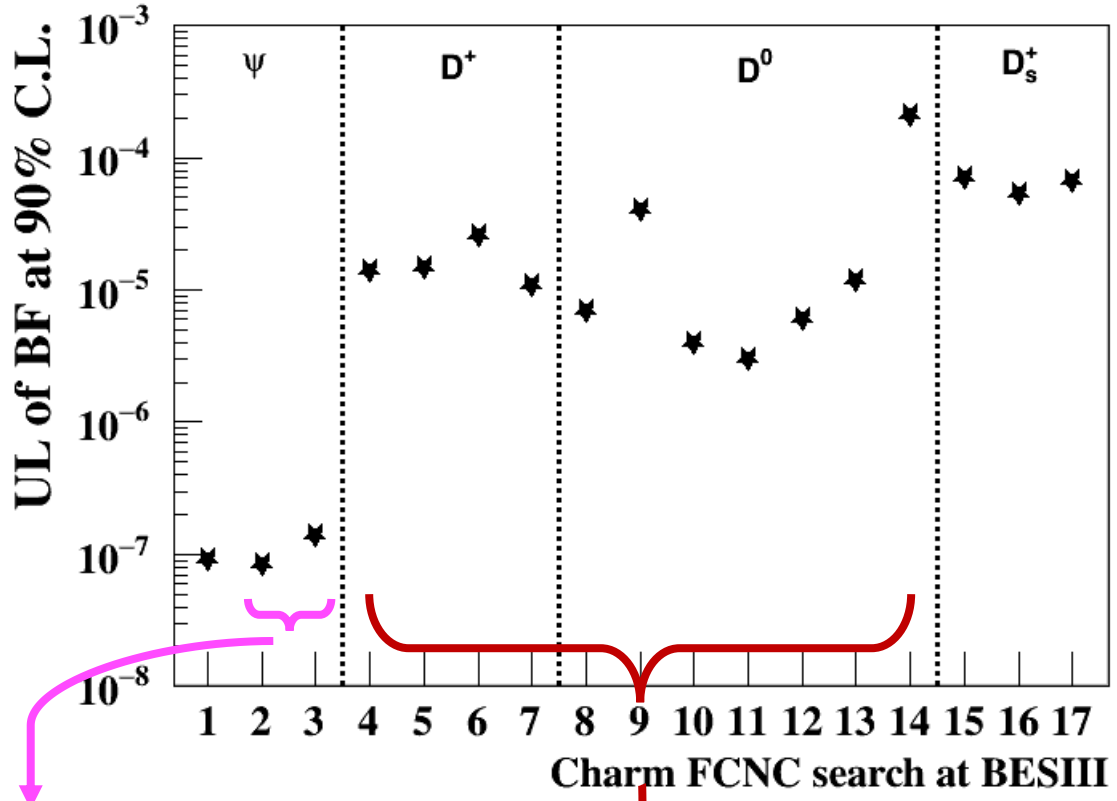
- BESIII has collected 10^{10} J/ψ , 2.7×10^{9} ψ', 20 fb^{-1} @ 3.77 GeV data ($D\bar{D}$) and more…
- More & better results are coming soon

The future of Dark Sector is Bright !



thank you

FCNC at BESIII



1: $J/\psi \to \gamma D^0$

2: $J/\psi \to D^0 e^+ e^-$

3: $\psi(2S) \to D^0 e^+ e^-$

4: $D^+ \to \pi^+ \pi^0 e^+ e^-$

5: $D^+ \to K^+ \pi^0 e^+ e^-$

6: $D^+ \to K^0_S \pi^+ e^+ e^-$

7: $D^+ \to K^0_S K^+ e^+ e^-$

8: $D^0 \to \pi^+ \pi^- e^+ e^-$

9: $D^0 \to K^- \pi^+ e^+ e^-$

10: $D^0 \to \pi^0 e^+ e^-$

11: $D^0 \to \eta e^+ e^-$

12: $D^0 \to \omega e^+ e^-$

13: $D^0 \to K^0_S e^+ e^-$

14: $D^0 \to \pi^0 \nu \bar{\nu}$

15: $D^+_s \to \pi^+ \pi^0 e^+ e^-$

16: $D^+_s \to K^+ \pi^0 e^+ e^-$

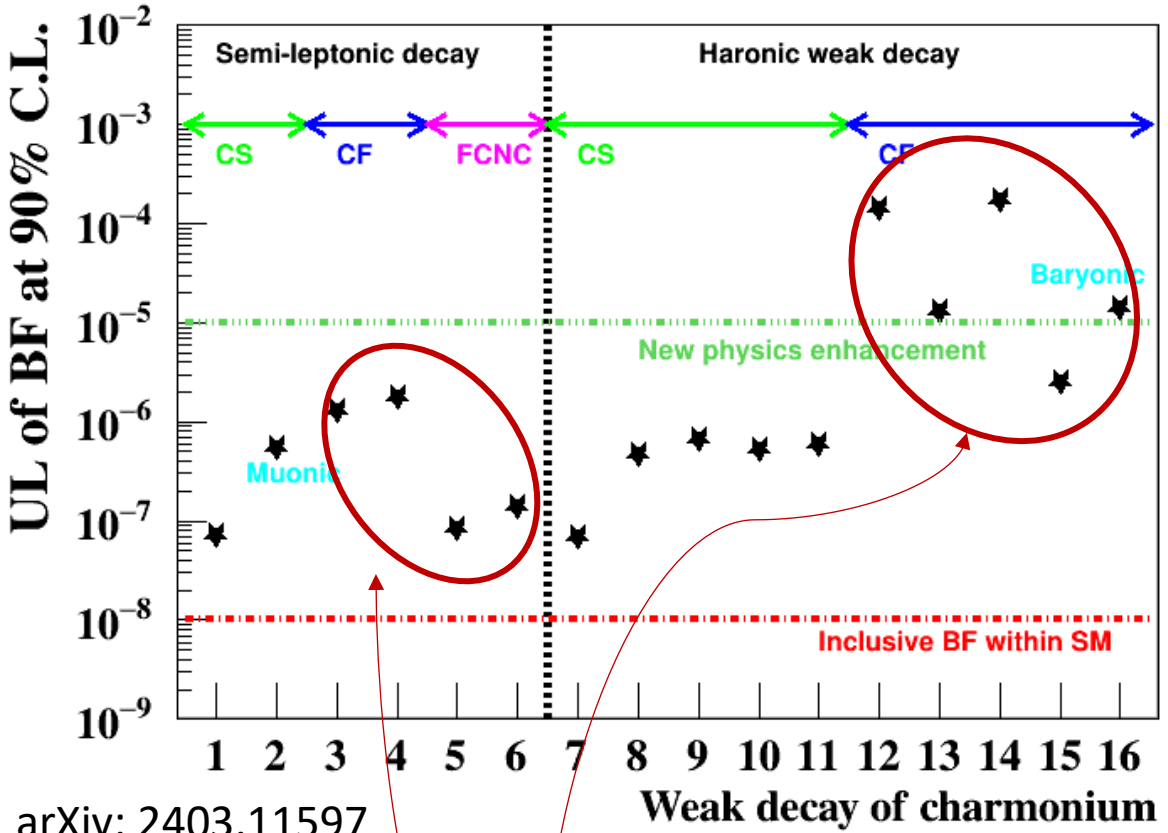
17: $D^+_s \to K^0_S \pi^+ e^+ e^-$

$\sim 10 \times$ data set prepared now

$2.9\ \mathrm{fb}^{-1}$ data set before
$20.3\ \mathrm{fb}^{-1}$ data set prepared now

Updating Ongoing

Charmonium weak decay at BESIII



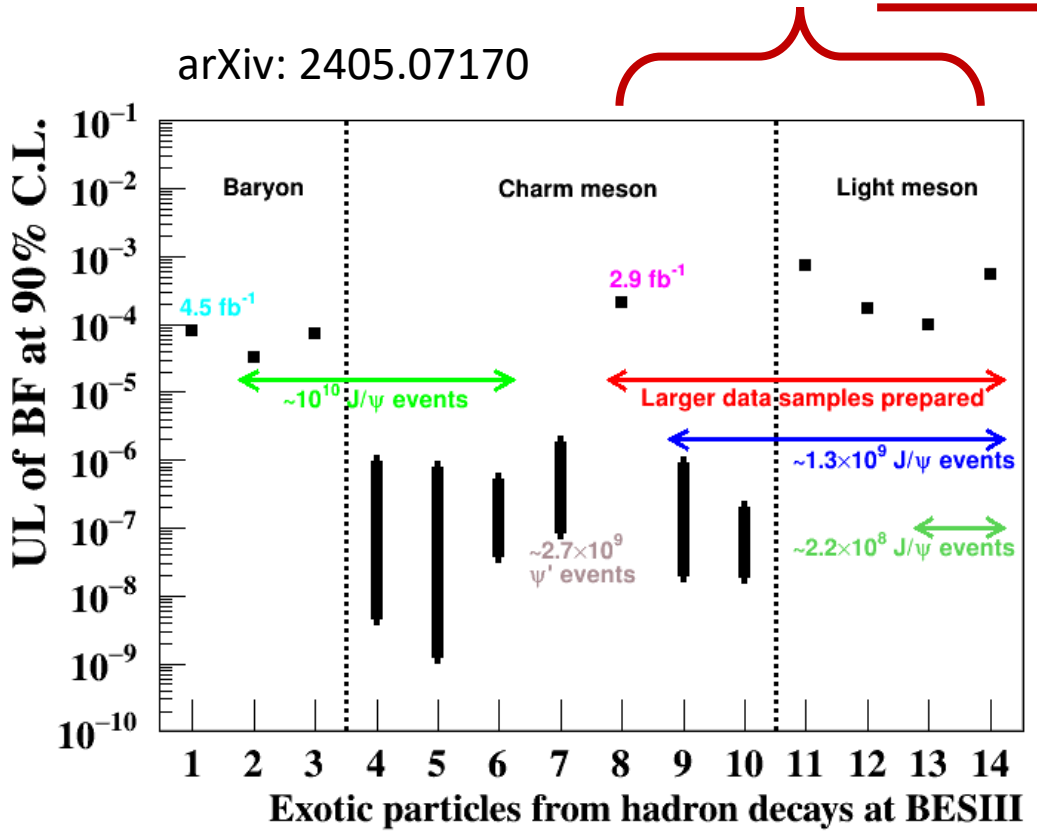
arXiv: 2403.11597

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: $J/\psi \to D^- \pi^+$+c.c.
8: $J/\psi \to D^0 \pi^0$+c.c.
9: $J/\psi \to D^0 \eta$+c.c.
10: $J/\psi \to D^0 \rho^0$+c.c.
11: $J/\psi \to D^- \rho^+$+c.c.
12: $J/\psi \to D_s^- \pi^+$+c.c.
13: $J/\psi \to D_s^- \rho^+$+c.c.
14: $J/\psi \to D^0 K^0$+c.c.
15: $J/\psi \to D^0 K^{*0}$+c.c.
16: $\psi(2S) \to \Lambda_c^+ \bar{\Sigma}^-$+c.c.

- BESIII exclusive sensitivity: $10^{-7} \sim 10^{-8}$
- SM inclusive BF: 10^{-8} or below
- More results are updating with 10^{10} J/ψ and 2.7×10^9 $\psi(2S)$ events

Exotic particles search at BESIII

arXiv: 2405.07170



More data samples prepared now
Updating ongoing

1. Massless dark photon: $\Lambda_c \to p\gamma'$
2. QCD axion: $\Sigma \to pa$
3. Invisible dark matter: $\Lambda \to \chi\chi$
4. Muon-philic particle: $J/\psi \to \mu^+\mu^- X$
5. Light Higgs: $J/\psi \to \gamma A^0$, $A^0 \to \mu^+\mu^-$
6. ALPs: $J/\psi \to \gamma a$, $a \to \gamma\gamma$
7. ALPs (ψ' data): $J/\psi \to \gamma a$, $a \to \gamma\gamma$
8. Invisible dark matter: $D^0 \to \pi^0\chi\chi$
9. Dark photon: $J/\psi \to \eta\gamma'$, $\gamma' \to e^+e^-$
10. Dark photon: $J/\psi \to \eta'\gamma'$, $\gamma' \to e^+e^-$
11. Invisible dark matter: $\omega \to \chi\chi$
12. Invisible dark matter: $\phi \to \chi\chi$
13. Invisible dark matter: $\eta \to \chi\chi$
14. Invisible dark matter: $\eta' \to \chi\chi$

QCD axion , massive dark photon, light Higgs, muon-philic particle, pure invisible decay….